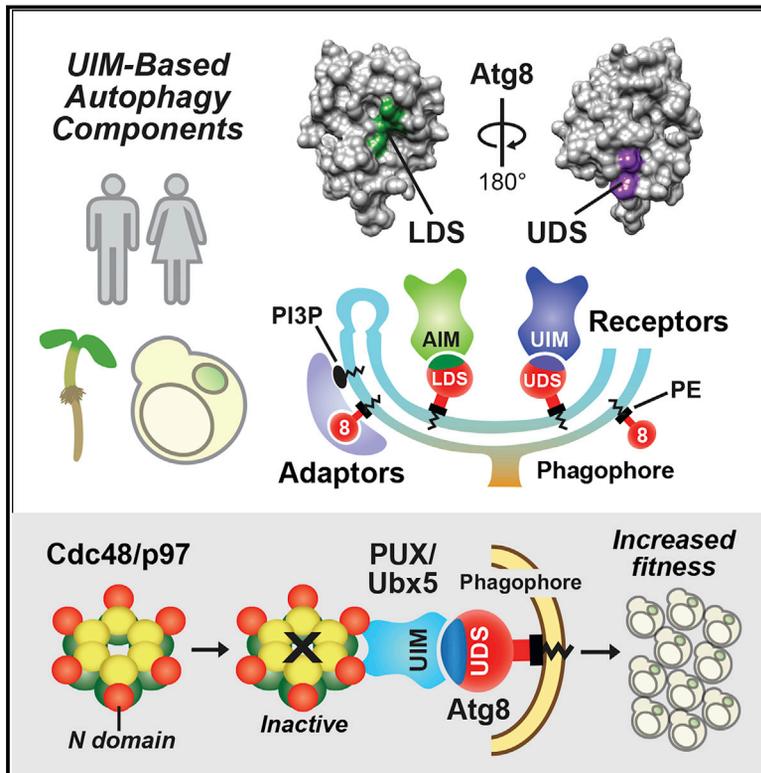


# ATG8-Binding UIM Proteins Define a New Class of Autophagy Adaptors and Receptors

## Graphical Abstract



## Authors

Richard S. Marshall, Zihua Hua, Sujina Mali, Fionn McLoughlin, Richard D. Vierstra

## Correspondence

rdvierstra@wustl.edu

## In Brief

Across organisms, the key autophagy protein ATG8/LC3 binds a group of proteins on a site distinct from its classical interacting region, raising the possibility of dual binding interactions and identifying an array of previously unknown selective autophagic adaptors and receptors, including some involved in human disease.

## Highlights

- A new binding site for autophagy adaptors and receptors was discovered on ATG8
- This site engages UIM-like sequences rather than the canonical ATG8-interacting motif
- UIM-type autophagy adaptors and receptors can be found in plants, yeast, and humans
- UIM-containing UBX domain proteins mediate autophagic clearance of CDC48/p97

# ATG8-Binding UIM Proteins Define a New Class of Autophagy Adaptors and Receptors

Richard S. Marshall,<sup>1</sup> Zhihua Hua,<sup>2</sup> Sujina Mali,<sup>1</sup> Fionn McLoughlin,<sup>1</sup> and Richard D. Vierstra<sup>1,3,\*</sup>

<sup>1</sup>Department of Biology, Washington University in St. Louis, St. Louis, MO 63130, USA

<sup>2</sup>Department of Environmental and Plant Biology, Ohio University, Athens, OH 45701, USA

<sup>3</sup>Lead Contact

\*Correspondence: [rdvierstra@wustl.edu](mailto:rdvierstra@wustl.edu)

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## SUMMARY

During autophagy, vesicle dynamics and cargo recruitment are driven by numerous adaptors and receptors that become tethered to the phagophore through interactions with lipidated ATG8/LC3 decorating the expanding membrane. Most currently described ATG8-binding proteins exploit a well-defined ATG8-interacting motif (AIM, or LC3-interacting region [LIR]) that contacts a hydrophobic patch on ATG8 known as the LIR/AIM docking site (LDS). Here we describe a new class of ATG8 interactors that exploit ubiquitin-interacting motif (UIM)-like sequences for high-affinity binding to an alternative ATG8 interaction site. Assays with candidate UIM-containing proteins together with unbiased screens identified a large collection of UIM-based ATG8 interactors in plants, yeast, and humans. Analysis of a subset also harboring ubiquitin regulatory X (UBX) domains revealed a role for UIM-directed autophagy in clearing non-functional CDC48/p97 complexes, including some impaired in human disease. With this new class of adaptors and receptors, we greatly extend the reach of selective autophagy and identify new factors regulating autophagic vesicle dynamics.

## INTRODUCTION

All cellular organisms maintain internal homeostasis and avoid proteotoxic stress by engaging sophisticated catabolic pathways that identify and recycle unwanted or dysfunctional components. One dominant pathway in eukaryotes is macroautophagy (henceforth referred to as autophagy), which sequesters cytoplasmic material into vesicles for delivery to vacuoles (in plants and yeast) or lysosomes (in animals; [Marshall and Vierstra, 2018](#); [Levine and Kroemer, 2019](#)). These vesicles emerge from the endoplasmic reticulum (ER) as a cup-shaped phagophore that eventually seals to generate a double membrane-bound autophagosome encapsulating substrates. Autophagosomes then fuse with the limiting membrane of the vacuole or lysosome to release the internal vesicle, called an autophagic body, into the lumen for degradation by resident hydrolases.

Because autophagy is essential for protection against nutrient deprivation and often becomes misregulated in a variety of human diseases, its modulation has considerable therapeutic potential ([Levine and Kroemer, 2019](#)).

Central to autophagy is the ubiquitin-fold protein ATG8, which decorates the emerging phagophore and autophagosome following its modification with the lipid phosphatidylethanolamine (PE). Using an ATP-dependent conjugation cascade mechanistically analogous to ubiquitylation, mature ATG8 is activated by the E1 enzyme ATG7, transferred to the E2 enzyme ATG3, and finally conjugated to PE using a ligase complex containing an ATG12-ATG5 conjugate and ATG16 ([Ohsumi, 2001](#); [Marshall and Vierstra, 2018](#)). When inserted into autophagic membranes, lipidated ATG8 provides a docking platform for numerous autophagy adaptors and receptors that drive autophagic vesicle dynamics and cargo selection, respectively ([Khaminets et al., 2016](#); [Gatica et al., 2018](#); [Marshall and Vierstra, 2018](#)).

In the last few years, the list of known ATG8-binding proteins has grown substantially, including receptors for unwanted or dysfunctional mitochondria, peroxisomes, ER, lipid droplets, ribosomes, proteasomes, and pathogens ([Gatica et al., 2018](#)). These interactors typically contain an ATG8-interacting motif (AIM, also known as LC3-interacting region [LIR]) with the consensus sequence W/F/Y-X-X-L/I/V that tightly fits into two conserved hydrophobic pockets on ATG8 collectively termed the LIR/AIM docking site (LDS; [Noda et al., 2008](#); [2010](#); [Behrends et al., 2010](#)). Although most studies have focused on the AIM-LDS interface, possibilities for alternative ATG8 binding mechanisms have recently emerged, with several ATG8-interacting proteins now known to bind ATG8 in an AIM-independent manner ([Behrends et al., 2010](#); [Lin et al., 2013](#); [Marshall et al., 2015](#)). One example is *Arabidopsis* RPN10, which serves as the receptor for recruiting inactive 26S proteasomes. Instead of using the canonical AIM sequence, RPN10 exploits an unrelated ubiquitin-interacting motif (UIM) for high-affinity binding to ATG8 ([Marshall et al., 2015](#)).

Under the premise that the UIM of RPN10 interacts with ATG8 through a novel contact that provides an alternative mechanism for tethering adaptors and receptors to autophagic membranes, we examined its interaction with ATG8 in detail. Remarkably, these studies led to the discovery of a previously unknown adaptor and receptor binding patch on ATG8, which we termed the UIM-docking site (UDS). By combining unbiased screens and candidate-based approaches to search for additional

UIM-containing ATG8 interactors, we identified numerous *Arabidopsis*, yeast, and human proteins that use this UIM-UDS interface. Detailed studies on a family of ATG8-interacting UIM and ubiquitin regulatory X (UBX) domain-containing proteins from *Arabidopsis* and yeast revealed that UIM-UDS binding facilitates the autophagic degradation of non-functional CDC48/p97 complexes, including mutant forms connected to several human pathologies (Tang and Xia, 2016). Through our discovery of the UIM-UDS interface and a large collection of adaptors and receptors that exploit this interaction, we greatly expand the reach of selective autophagy and identify new factors that might regulate autophagosome dynamics.

## RESULTS

### RPN10 Binds ATG8 at a Site Distinct from the LDS

Our discovery that the *Arabidopsis* proteaphagy receptor RPN10 uses its UIM2 sequence to bind ATG8 instead of the commonly employed AIM (Marshall et al., 2015) raised the possibility that a distinct surface on ATG8 other than the canonical LDS participates in this interaction. To test this possibility, we analyzed, by yeast two-hybrid (Y2H) assay, pairwise interactions between RPN10 and representatives of the four *Arabidopsis* ATG8 subclades harboring alanine substitutions within the LDS (Y50A L51A in ATG8a [ $\Delta$ LDS]; Table S1). In all cases, the  $\Delta$ LDS variants successfully bound to RPN10 but failed to interact with ATG1a, which is known to bind ATG8 via an AIM-LDS interface (Figures 1A and S1A; Suttangkakul et al., 2011). Because this interaction could be specific for proteaphagy receptors, we similarly tested binding of the yeast receptor Cue5 to Atg8 (Marshall et al., 2016) and found that the typical AIM-LDS interface is involved (Figures 1B and S1B). We thus speculated that UIM2 of *Arabidopsis* RPN10 connects with ATG8 via a novel interaction.

Given that RPN10-ATG8 binding appears to be universal among plants (Marshall et al., 2015), we reasoned that a conserved surface outside of the LDS is involved. An alignment of 332 plant ATG8 sequences (Table S2; Kellner et al., 2017) revealed conserved clusters of amino acids (Figure 1C) that, when mapped onto the 3-dimensional structure of yeast Atg8, identified 8 additional surface patches besides the LDS as candidate UIM-binding sites (Figure 1D). When alanine substitutions of these sites were systematically tested, only one mutation cluster, centered on I77, F78, and V79, specifically blocked binding of ATG8 to RPN10 by Y2H assay (Figures 1E and S1C).

The importance of this patch (designated the UIM docking site [UDS]) for binding RPN10 was confirmed using  $\Delta$ UDS and  $\Delta$ UIM mutants in *in vitro* pull-down, isothermal titration calorimetry (ITC), and *in planta* bimolecular fluorescence complementation (BiFC) assays. Although hexahistidine (His<sub>6</sub>)-ATG8 beads readily pulled down glutathione S-transferase (GST)-tagged RPN10, they did not pull down RPN10 bearing a  $\Delta$ UIM2 mutant substituting the core Leu-Leu-Asp-Gln-Ala UIM2 sequence (Marshall et al., 2015), nor could the  $\Delta$ UDS form of ATG8 pull down wild-type (WT) RPN10, showing that both UIM2 and the UDS were essential (Figure 1F). Similarly, although binding of RPN10 to ATG8 was clearly detected by ITC, this binding was absent when the UDS mutant of ATG8 was used (Figure S2G). By BiFC, we found that ATG8 and RPN10 bearing the N- and C-ter-

minal halves of yellow fluorescent protein (YFP) in either orientation easily reconstituted fluorescence in *Nicotiana benthamiana* (Figure 1G; Marshall et al., 2015). Although cytoplasmic fluorescence was retained with the  $\Delta$ LDS mutant form of ATG8, it was absent with the  $\Delta$ UDS version (Figures 1G and S1D). Given the possibility that UDS mutations compromised binding of proteins to the LDS, we compared binding of the  $\Delta$ LDS and  $\Delta$ UDS mutants with RPN10 and DSK2, the latter of which uses an AIM for ATG8 binding (Nolan et al., 2017). Pull-down assays showed that neither the  $\Delta$ LDS or  $\Delta$ UDS variants affected interaction of these ATG8-binding proteins with their corresponding non-mutated patch (Figure S1E).

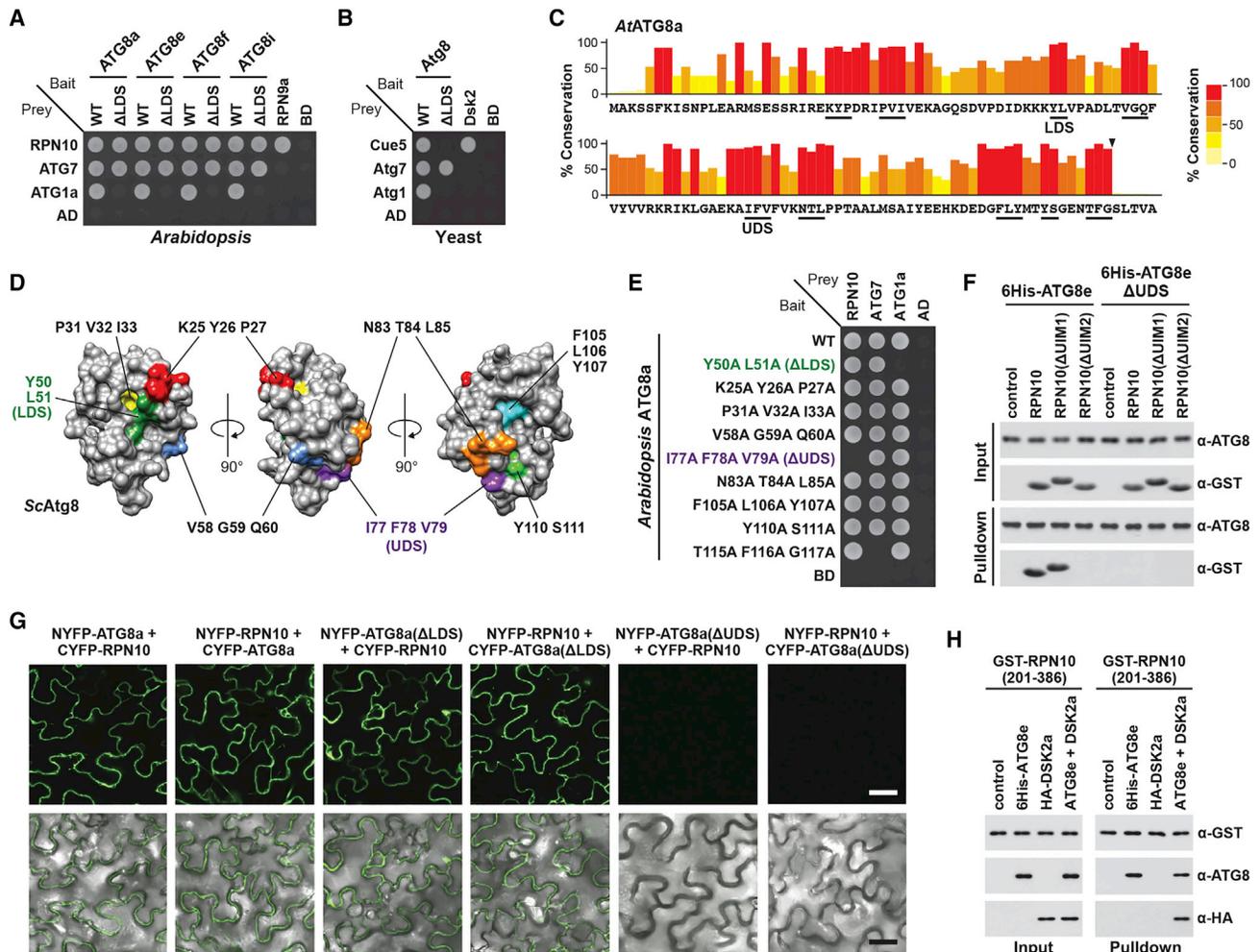
The presence of separate binding sites on ATG8 suggested that a single ATG8 could dock UIM- and AIM-containing proteins simultaneously. Using a tripartite binding assay in which beads coated with GST-tagged RPN10 were used to pull down HA-tagged DSK2, we found that RPN10 could only pull down DSK2 when ATG8 was present (Figure 1H). Such dual binding raised the possibility that ATG8 can tether two adaptors and/or receptors simultaneously.

### The UIM-UDS Interface Is Widely Used by ATG8-Interacting Proteins in *Arabidopsis*

To examine whether UIMs are employed by other autophagy adaptors and receptors, we tested, by Y2H assay, 13 *Arabidopsis* proteins predicted to contain one or more UIMs for binding to ATG8. Strikingly, three PLANT UBIQUITIN REGULATORY X DOMAIN (PUX) proteins were identified that displayed robust interactions (Figures 2A and S1G). All three (PUX7, PUX8 and PUX9) showed little preference for an ATG8 sub-clade and equally bound ATG8a, ATG8e, ATG8f, and ATG8i (Figures 2G and S1F). These PUX proteins are part of a 16-member family in *Arabidopsis* defined by a ubiquitin-like UBX domain, with some members also harboring ubiquitin-binding ubiquitin-associated (UBA) domains and one or more UIMs (Figures S2A and S2B). Like relatives from yeast and animals, *Arabidopsis* PUX proteins bind CDC48 (p97 in humans) and play important roles in regulating the assembly and activity of this ATPase associated with diverse cellular activities (AAA-ATPase; Rancour et al., 2004; Gallois et al., 2013).

Asking whether other *Arabidopsis* PUX proteins not annotated to have UIMs might also bind ATG8, we tested the entire family by Y2H assay. Besides PUX7, PUX8, and PUX9, PUX13 also bound ATG8, thus identifying four isoforms with this activity (Figure S2C). Notably, when we re-analyzed the PUX13 sequence, a UIM-related sequence (residues 180–198) was discovered that might provide the ATG8-binding interface (Figure S2J).

To confirm that the UIMs in PUX7, PUX8, PUX9, and PUX13 were solely responsible for their binding to ATG8, we examined by Y2H assay deletion mutants individually missing the UBA or UBX domains, along with a set of substitutions affecting the UIMs (designated  $\Delta$ UIM; Table S1), for binding to WT,  $\Delta$ LDS, or  $\Delta$ UDS versions of ATG8. Collectively, we found that the PUX UIMs (and not the UBA or UBX domains) were essential for ATG8 binding, with the sole UIM in PUX7 and PUX13 and the N-terminal UIM (designated UIM1) in PUX8 and PUX9 providing the interfaces (Figures 2B and S1I). These binding activities were further supported by *in vitro* pull-down, ITC, and BiFC assays

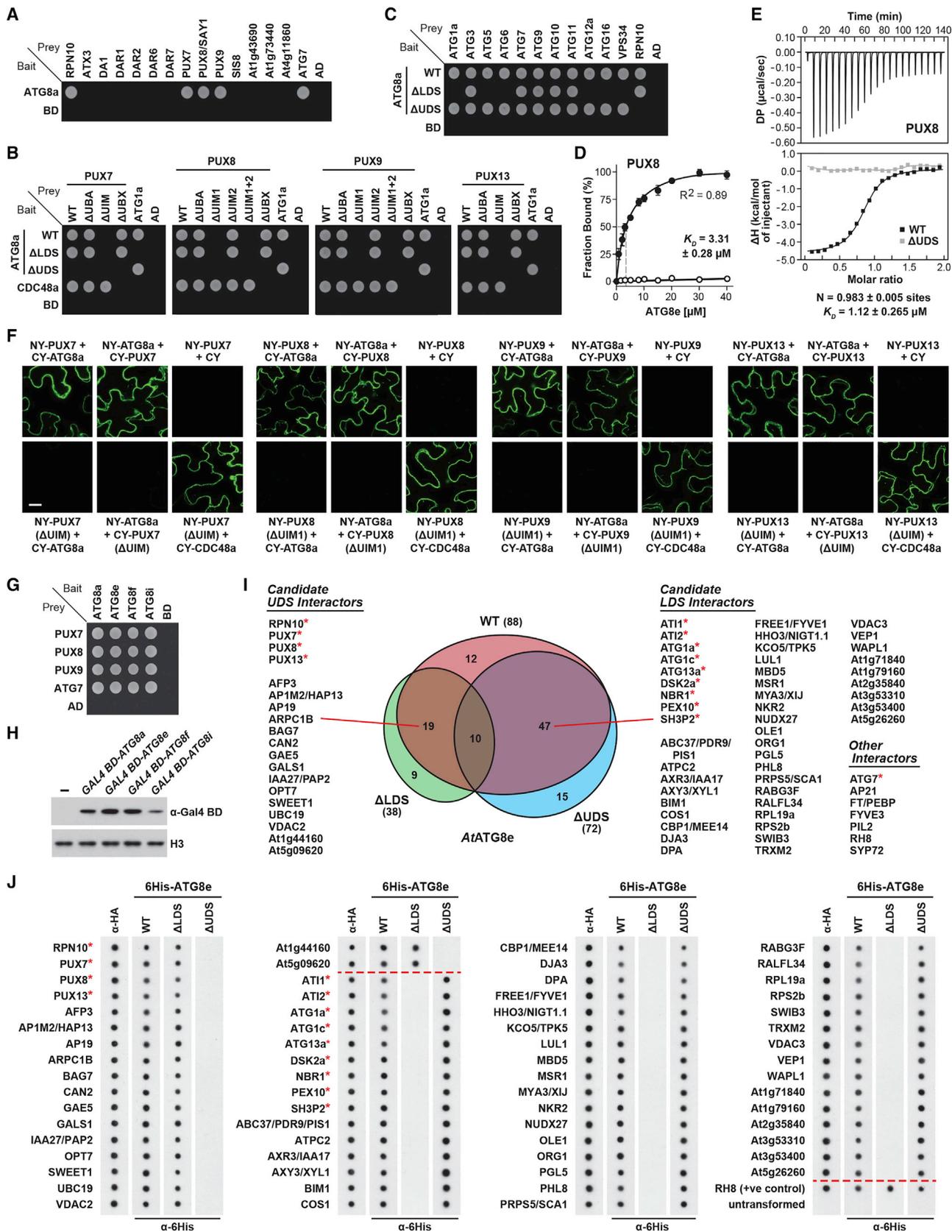


**Figure 1. Arabidopsis RPN10 Interacts with ATG8 via a Novel Binding Site**

(A) Y2H assays reveal that RPN10 binds ATG8a in an LDS-independent manner. Interactions of RPN10 with RPN9a and ATG8 with ATG7 and ATG1a were used as controls. Growth of cells on medium lacking leucine and tryptophan is shown in Figure S1 (also for B and E). (B) Y2H assays reveal that the yeast proteophagy receptor Cue5 binds Atg8 via the LDS. Interactions of Cue5 with Dsk2 and Atg8 with Atg7 were used as controls. (C) Identification of potential RPN10 binding sites in Arabidopsis ATG8a. Plant ATG8 sequences were aligned, and the percent identity at each position was calculated. Conserved, surfaced-exposed positions are underlined; the arrowhead indicates the ATG4 cleavage site that releases mature ATG8. (D) The 3-dimensional structure of yeast Atg8 (PDB: 3VXW), highlighted to locate the conserved surface patches identified in (C). (E) Y2H assays identify a surface patch on Arabidopsis ATG8a that binds RPN10. Interactions of ATG8a with ATG7 and ATG1a were used as controls. (F) *In vitro* binding assays confirm the UIM-UDS interface between RPN10 and ATG8e. Purified proteins were mixed and pulled down with nickel-nitrilotriacetic acid (Ni-NTA) agarose beads. Input and bound proteins were visualized by immunoblotting with anti-ATG8 and anti-GST antibodies. (G) BiFC assays show that RPN10 interacts with ATG8a at the UDS *in planta*. Fluorescence signals in *N. benthamiana* leaf cells were detected by confocal fluorescence microscopy 36 h after infiltration. Scale bar, 10  $\mu$ m. (H) ATG8e can simultaneously interact with LDS and UDS binding partners. Purified proteins were mixed, pulled down with GST-Bind resin, and visualized as in (F).

(Figures 2D–2F and S2D–S2G). By adjusting the pull-down conditions to provide quantitative equilibrium binding measurements, we determined a  $K_D$  of between 3.3 and 7.4  $\mu$ M for binding of the PUX proteins to ATG8e, which is comparable with the known affinity of Arabidopsis RPN10 and AIM-containing proteins for ATG8 (Marshall et al., 2015). This was further supported by ITC measurements, which detected a single binding site and confirmed the  $K_D$  values to be in the low micromolar range (Figures 2E, S2F, and S2G).

A number of proteins within the ATG system interact with ATG8, several of which use the AIM-LDS interface (Suttangkakul et al., 2011; Marshall and Vierstra, 2018). To test whether the others might alternatively engage the UDS, we examined their binding to WT,  $\Delta$ LDS, or  $\Delta$ UDS versions of ATG8 by Y2H assay (Figures 2C and S1H). Although some indeed required the LDS for ATG8 binding (ATG1a, ATG5, ATG6, ATG12a, ATG16, and VPS34), none required the UDS. Interestingly, although binding of ATG3, ATG7, and ATG10 to ATG8 was expected to be



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independent of both the LDS and UDS, given that they thioester-link to the C-terminus of ATG8, the independence of ATG9 and ATG11 implied that additional binding surfaces exist.

Assuming that other *Arabidopsis* proteins besides PUX13 might bind ATG8 at the UDS but were not yet annotated to have a UIM, we performed non-biased screens of an *Arabidopsis* cDNA library using either WT,  $\Delta$ LDS, or  $\Delta$ UDS variants of ATG8e as bait (Figure 2H). Overall, 112 ATG8e interactors were identified across the three Y2H screens (Table S3). These included 47 proteins that interacted with both WT and  $\Delta$ UDS versions of ATG8e but not with the  $\Delta$ LDS version, which we considered to be candidate LDS interactors, and 19 proteins that interacted with WT and  $\Delta$ LDS versions of ATG8e but not with the  $\Delta$ UDS version, which we considered to be candidate UDS interactors (Figure 2I). Importantly, the screen identified numerous ATG8-interacting proteins shown here and elsewhere to bind at the LDS or UDS. For the UDS, these included RPN10 (Marshall et al., 2015) and three of the four PUX proteins identified here by the candidate-based approach, whereas for the LDS, these included two isoforms of ATG1, the adaptor protein SH3P2, and the cargo receptors ATI1/2, DSK2a, and NBR1 (Suttangkakul et al., 2011; Nolan et al., 2017; Marshall and Vierstra, 2018).

To verify that these candidates indeed bound ATG8, we developed a dot blot assay to demonstrate binding *in vitro* (Figure 2J). Here, the prey cDNAs were excised from the Y2H vector and inserted into an isopropyl- $\beta$ -D-thiogalactopyranoside (IPTG)-inducible vector in-frame with an N-terminal hemagglutinin (HA) tag for expression in *E. coli*. Following induction, the bacterial cells were lysed, spotted onto a nitrocellulose membrane, and probed with purified His<sub>6</sub>-ATG8e, either WT or harboring the  $\Delta$ LDS or  $\Delta$ UDS mutations, followed by immunoblot analysis with anti-His<sub>6</sub> antibodies to locate bound ATG8e. Probing the membranes with anti-HA antibodies confirmed adequate expression of each prey. All 66 of the candidate interactors (47 for the LDS and 19 for the UDS) bound WT His<sub>6</sub>-ATG8e, and this binding was absent with either the  $\Delta$ LDS or  $\Delta$ UDS variants, confirming the specificity of the associations (Figure 2J). Both the LDS- and UDS-specific lists contained numerous

proteins not previously known to be associated with ATG8 and/or autophagy that could function as specific cargo receptors, adaptors important for autophagic vesicle dynamics, or even cargo bearing their own ATG8-binding sites for self-recruitment. These included the clathrin adaptors AP19 and AP1M2/HAP13, the ATP synthase subunit ATPC2, the SWI/SNF complex subunit SWIB3, the ER-localized co-chaperone BAG7, the lipid body protein OLE1, plus a number of ion channels (KCO5/TPK5, VDAC2, and VDAC3) and transporter proteins (OPT7 and SWEET1; Figure 2I).

### A Hydrophobic Patch Defines the UIM-Binding UDS

Beyond I77, F78, and V79, the region surrounding the UDS in ATG8 includes a number of other conserved residues that could promote UIM binding. To better define the UDS and identify permissible residues, we analyzed the region in *Arabidopsis* ATG8a by saturating mutagenesis, followed by Y2H and dot blot binding assays with both RPN10 and PUX7. None of the mutations appeared to substantially affect ATG8 folding, because they all retained their ability to bind both ATG7 and DSK2 (Figure S3A). The results in Figures 3A and 3B showed remarkable consistency among binding partners and methods, with over 97% of the assays in agreement. They defined the UDS as a 4-residue region encompassing amino acids 77–80 that is enriched in hydrophobic residues and intolerant of charged amino acids. At its center is a phenylalanine that could not be fully replaced by any other amino acid and is thus considered essential (Figures 3A and 3B). Quantification of the interaction data and comparison with evolutionary mutation frequencies revealed a consensus motif for permitted residues of  $\Psi$ -F- $\Psi$ - $\Omega$ /T, where  $\Psi$  and  $\Omega$  represent small hydrophobic and aromatic residues, respectively (Figure 3C).

When the UDS sequence was placed on an alignment of ATG8 proteins from a spectrum of eukaryotes, conservation of this hydrophobic patch was apparent (Figure 3D). Mapping this core region onto the 3-dimensional structure of yeast Atg8 showed that the UDS is located near the C-terminal glycine on the surface opposite the LDS used by AIM-containing interactors (Figure 3E), explaining how AIM and UIM proteins could bind simultaneously.

### Figure 2. Multiple *Arabidopsis* UIM Proteins Bind ATG8 through the UDS

(A) A subset of *Arabidopsis* UIM proteins interacts with ATG8a by Y2H assay. The interaction of ATG8a and ATG7 was used as a control. Growth of cells on medium lacking leucine and tryptophan is shown in Figure S1 (also for B, C, and G).

(B) Y2H assays reveal that the UIMs in *Arabidopsis* PUX7, PUX8, PUX9, and PUX13 are required for binding ATG8a at the UDS. Interactions of the PUX proteins with CDC48a and ATG8a with ATG1a were used as controls.

(C) Y2H assays reveal that components of the core autophagy pathway do not use the UDS interface to bind ATG8a.

(D) Quantification of the PUX8-ATG8e binding affinity. Various concentrations of His<sub>6</sub>-ATG8e were incubated with 1  $\mu$ M GST-PUX8 and pulled down with Ni-NTA agarose beads. PUX8 remaining in the supernatant was quantified and expressed as a percentage of the input. Values represent the mean ( $\pm$ SD) from three independent biological replicates. Similar experiments for PUX7, PUX9, and PUX13 are shown in Figures S2D and S2E.

(E) ITC assays confirm the PUX8-ATG8e binding affinity. Shown are heats of injection (top and bottom, squares) and the best fit to a single-site binding model (solid lines) for interaction with WT (black) or  $\Delta$ UDS (gray) forms of His<sub>6</sub>-ATG8e. N and K<sub>D</sub> values represent the mean ( $\pm$ SD) from three independent biological replicates. Similar experiments for RPN10, PUX7, PUX9, and PUX13 are shown in Figure S2G.

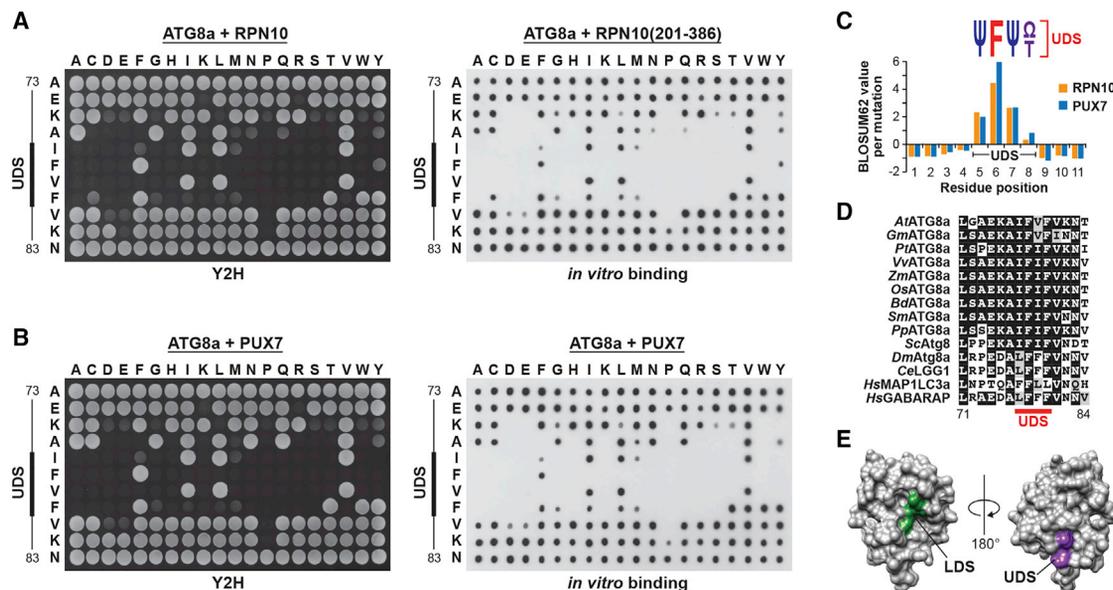
(F) BiFC assays in *N. benthamiana* leaf cells show that PUX proteins interact with ATG8a via their UIM sequences *in planta*. Scale bar, 10  $\mu$ m.

(G) PUX7, PUX8, and PUX9 interact by Y2H assay with members of each *Arabidopsis* ATG8 sub-clade.

(H) Comparison of ATG8 isoform levels when expressed as Gal4 DNA-binding domain fusions in yeast.

(I) Screening of an *Arabidopsis* cDNA library by Y2H assay using WT,  $\Delta$ LDS, or  $\Delta$ UDS forms of ATG8e identified multiple LDS- and UDS-binding proteins. A Venn diagram of the interaction categories is included; asterisks indicate proteins identified previously as ATG8 interactors.

(J) Dot blot binding assays confirm the candidate interactors identified in (I). Lysed *E. coli* cells expressing HA-tagged interactors were spotted onto a nitrocellulose membrane and probed with WT,  $\Delta$ LDS, or  $\Delta$ UDS forms of His<sub>6</sub>-ATG8e. Binding of ATG8 variants and expression of the interactors were detected with anti-His<sub>6</sub> and anti-HA antibodies, respectively.



**Figure 3. The UDS Contains a Conserved Phenylalanine Surrounded by Hydrophobic Residues**

(A and B) Amino acid sequence specificity of the ATG8 UDS for binding to UIMs. A panel of ATG8a mutants generated by saturating mutagenesis was tested for binding to *Arabidopsis* RPN10 (A) or PUX7 (B) by Y2H assay (left) or dot blot binding assays (right). Control interactions and expressions are shown in Figure S3. (C) Quantification of the binding assays in (A) and (B), and comparison with expected substitution rates, identify a core UDS sequence containing an invariant phenylalanine bracketed by hydrophobic amino acids.  $\Psi$ , small hydrophobic residues;  $\Omega$ , aromatic residues. (D) Sequence alignment of the UDS region from plant, fungal, and animal ATG8 proteins. The core UDS is indicated by the solid red line. Identical and similar amino acids are shown with black and grey backgrounds, respectively. Numbers correspond to the *Arabidopsis* ATG8a sequence. (E) The 3-dimensional structure of yeast Atg8 (PDB: 3VXW), highlighting the opposed positions of the LDS (green) and UDS (purple).

### UIM-UDS Interactions Are Conserved in Yeast

Both the conservation of the UDS and the widespread distribution of UIM-containing proteins outside of plants raised the possibility that the UIM-UDS interface is universally exploited. As a first test of this hypothesis, we examined, by Y2H assay, the seven yeast proteins annotated to contain a UIM for binding to Atg8 (Figures 4A and S4A). Positive interactions were seen for three proteins: Ent1 and Ent2, which are yeast Epsins that help generate membrane curvature during endocytosis (Wendland et al., 1999), and Ufo1, which is an F-box ubiquitin ligase component (Kaplun et al., 2003). Focused Y2H assays of Ent1 and Ent2 harboring Epsin N-terminal homology (ENTH) domain deletions or  $\Delta$ UIM mutations revealed that the N-terminal UIM (designated UIM1) is critical for binding the UDS of Atg8 (Figures 4B and S4B). Similar assays surprisingly failed to connect any of the three predicted UIMs in Ufo1 to Atg8 binding, thus leaving this interface unresolved (Figure S4C).

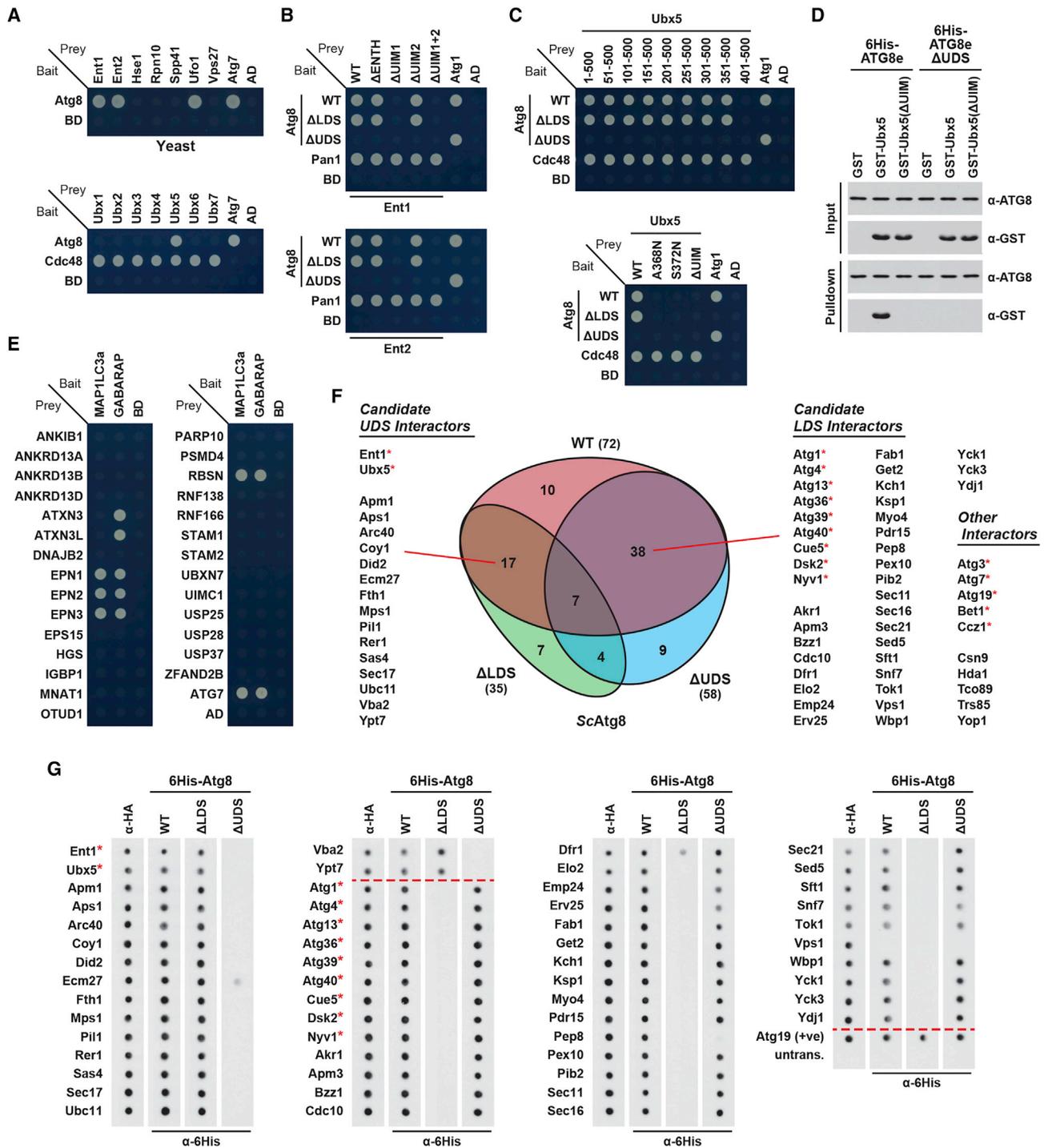
Based on the confirmed interactions of *Arabidopsis* PUX proteins with ATG8, we considered it likely that one or more of the orthologous yeast Ubx proteins also bind Atg8 via the UIM-UDS interface. Testing all seven Ubx family members by Y2H assay revealed that only Ubx5 has affinity for Atg8 (Figures 4A and S4D) and that this binding requires the UDS (Figures 4C, 4D, S4E, and S4F). Mapping of the UDS-binding site in Ubx5 localized the interacting region to residues 351–400 (Figures 4C and S4E), which we then found to contain a cryptic UIM at residues 360–379 (den Besten et al., 2012). Y2H and *in vitro* pull-down assays with substitution mutants confirmed that this patch is required (Figures 4C, 4D, and S4F).

To expand the list of UDS-interacting proteins in yeast, we next screened a cDNA library prepared from exponential phase cells, using WT,  $\Delta$ LDS, or  $\Delta$ UDS versions of Atg8 as bait. From this screen, 92 interactors were identified (Table S3), including 38 candidate LDS interactors and 17 candidate UDS interactors (Figure 4F). The strength of the screen was again supported by the identification of numerous proteins shown previously to bind Atg8 (Figure 4F). Importantly, when assayed by *in vitro* dot blot binding, 51 of the 55 LDS or UDS interactors were confirmed (Figure 4G).

### The UIM-UDS Interface Functions in Humans

Because humans also express UIM proteins, we tested by Y2H assay whether they too might bind ATG8 via a UIM-UDS interface. Here, the MAP1LC3a and GABARAP isoforms, which represent the two main ATG8 sub-clades, were tested against 28 UIM candidates. Robust interactions were seen for six proteins (Figures 4E and S4G); of these, four (Epsin [EPN]-1, EPN2, EPN3, and Rabenosyn [RBSN]) interacted with both ATG8 isoforms, whereas two (Ataxin [ATXN]-3 and ATXN3L) interacted only with GABARAP (Figures 4E and S4G).

EPN1–EPN3 are the human orthologs of yeast Ent1/2 (Ford et al., 2002) and are thus consistent with our prior identification of Ent1/2 as UDS interactors (Figures 4A, 4B, 4F, and 4G). Like Ent1/2, they possess multiple UIMs; of the three predicted UIMs in EPN1, both UIM1 and UIM3 docked to MAP1LC3a and GABARAP, requiring mutation of each to prevent a Y2H interaction (Figure S4H). Similarly, elimination of both UIMs in EPN2 and EPN3 was needed to block MAP1LC3a and



**Figure 4. The UIM-UDS Interface Mediates ATG8 Binding in Yeast and Humans**

(A) A collection of yeast UIM proteins binds Atg8 by Y2H assay. Shown are interactions with 7 UIM proteins (top) and 7 UBX domain-containing proteins (bottom). Interactions of Atg8 with Atg7 and the Ubx proteins with Cdc48 were used as controls. Growth of cells on medium lacking leucine and tryptophan is shown in Figure S4 (also for B, C, and E).

(B) Y2H assays reveal that UIM regions in yeast Ent1 and Ent2 bind Atg8 at the UDS. Interactions of Ent1 and Ent 2 with Pan1, and Atg8 with Atg1, were used as controls.

(C) Ubx5 interacts with the UDS of Atg8 via a UIM, from Y2H analysis of Ubx5 truncations (top) or mutations (bottom) paired with WT, ΔLDS, or ΔUDS forms of Atg8. Interactions Ubx5 with Cdc48 and Atg8 with Atg1 were used as controls.

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GABARAP binding (Figure S4H). ATXN3 and ATXN3L also contain at least two predicted UIMs; in both proteins, only the N-terminal UIM (UIM1) was needed for GABARAP binding (Figure S4I). RBSN contains a single predicted UIM, and its substitution blocked binding to both MAP1LC3a and GABARAP (Figure S4J). Together with our results from *Arabidopsis* and yeast, we propose that the UIM-UDS interface is a widely employed mechanism to dock autophagy adaptors and receptors to ATG8.

### ATG8-Interacting UIM Sequences Have Diverse Amino Acid Properties

UIMs in general are a 20-amino acid stretch of considerable sequence diversity predicted to fold into an  $\alpha$  helix preceded by a short hairpin loop (Hofmann and Falquet, 2001). Using the same saturating mutagenesis approach as above for the UDS, we examined the UIM regions in *Arabidopsis* RPN10 (residues 282–301) and PUX7 (residues 328–347) for interaction with ATG8 by Y2H and dot blot binding assays (Figures 5A and 5B). The introduced mutations did not affect overall protein structure, because the mutant forms of RPN10 and PUX7 retained their ability to bind RPN9 and CDC48, respectively (Figures S3B and S3C), although local destabilization of the UIM  $\alpha$  helix could not be ruled out. As with the UDS, UIM mapping revealed remarkable consistency when comparing both binding partners and methods. Collectively, the assays defined a broad consensus sequence for ATG8 binding ( $\Psi$ - $\zeta$ -X-A- $\Psi$ -X-X-S) that contains invariant alanine and serine residues, with  $\Psi$ ,  $\zeta$  and X representing small hydrophobic residues, hydrophilic residues, and any amino acid, respectively (Figures 5A–5C). Alignment of the UIM regions demonstrated here to bind the UDS of ATG8 (17 UIMs from 14 proteins) confirmed this consensus sequence (Figure 5D), and visualization on a helical wheel indicated that the required residues cluster on one side of the predicted helix (Figure 5E).

### The ATG8-Interacting PUX Proteins Are Selective Autophagy Receptors for CDC48

To demonstrate the significance of UIM-type autophagy adaptors and receptors, we focused on the *Arabidopsis* PUX proteins, given their potential to commit CDC48 to autophagy upon docking to ATG8 (Figures 2B and 2F). CDC48 assembles into a homohexameric ring that plays essential roles in protein quality control by using ATP hydrolysis to extract polypeptides from protein complexes or membranes for eventual turnover (Stach and Freymont, 2017), with its best-understood function being retrograde transport of proteins from the ER lumen during ER-associated protein degradation (ERAD; Ye et al., 2001; Marshall et al., 2008).

As a first step in connecting the ATG8-interacting PUX proteins and CDC48 to autophagy, we exploited an *Arabidopsis* line expressing a GFP-PUX7 fusion (Gallois et al., 2013) for interaction studies. Co-immunoprecipitation of GFP-PUX7

from seedling extracts with anti-GFP antibody beads detected four species (120, 95, 55, and 15 kDa) not found in extracts containing GFP alone (Figure S2H). Immunoblot analyses identified CDC48 and ATG8 in addition to GFP-PUX7, confirming that PUX7 can bind both *in planta* (Figure S2I). Mass spectrometry analysis confirmed CDC48 isoforms as the most abundant PUX7 interactors (Data S1).

To test whether both PUX7 and CDC48 are targets of autophagy, we subjected the GFP-PUX7 line and a second line that expresses YFP-CDC48a (Park et al., 2008) to nitrogen starvation and assayed each by autophagy-specific GFP release assay. As is widely exploited (Lu et al., 2014; Marshall and Vierstra, 2018), autophagic degradation of proteins tagged with GFP (or relatives such as YFP) invariably results in loss of the tagged protein concomitant with the appearance of free GFP, because of its relative stability in vacuoles. This assay confirmed that both PUX7 and CDC48 are autophagy substrates, with accelerated release of free GFP/YFP from the GFP-PUX7 and YFP-CDC48a reporters being seen after starving WT seedlings for nitrogen, but not with similarly starved *atg7-2*, *atg10-1*, and *atg13a-2 atg13b-2* seedlings missing key autophagy components (Figures 6A and 6B). Released GFP from GFP-PUX7 was seen even in well-fed WT seedlings, implying that PUX7 is continually turned over by autophagy (Figure 6A).

Beside nutritional stress, inhibitors often trigger autophagic turnover of proteins and their complexes, presumably as part of a quality control mechanism to purge non-functional species (Marshall et al., 2015; 2016). To test if inactivated CDC48 complexes become autophagy substrates, we examined whether a suite of CDC48 inhibitors designed to block the mammalian complex (CB-5083, DBEQ, ML240, and NMS-873), but not yet confirmed as effective in plants, could be exploited. Because direct assays for CDC48 activity are not yet available in *Arabidopsis*, we indirectly monitored inhibitor efficacy by assessing the expression of the ER stress-responsive genes *BIP1* and *CRT1*, which should be up-regulated upon inhibitor treatment when CDC48 activity and subsequent ERAD are compromised. Only CB-5083 robustly up-regulated these transcripts at micromolar concentrations (Figure S5A), whereas the other inhibitors were ineffective, possibly because of their insolubility in the *Arabidopsis* growth medium. A strong influence of CB-5083 on plant growth was also seen, with seedlings germinated on 10  $\mu$ M CB-5083 barely emerging from the seed coat (Figure S5B).

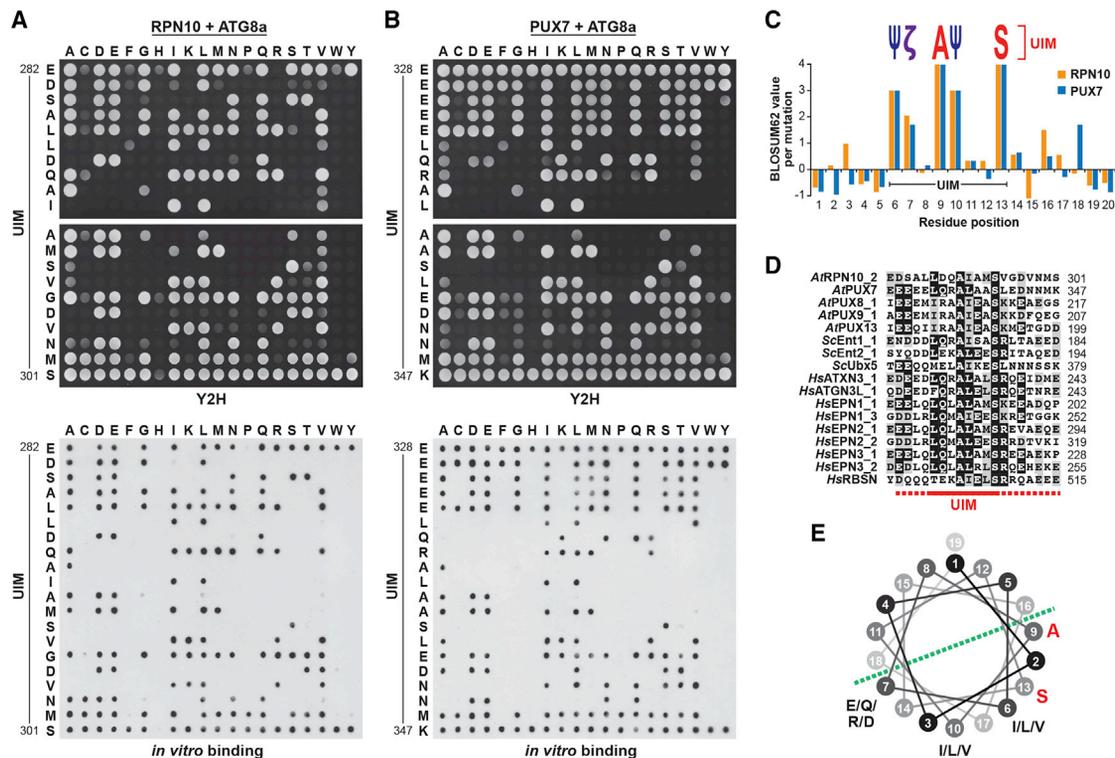
Given the potency of CB-5083, we assayed whether it could stimulate autophagy of YFP-CDC48a *in planta* by GFP release assay. As shown in Figures 6C, 6D, S5C, and S5D, CB-5083 treatment strongly induced the liberation of both free YFP from YFP-CDC48a and free GFP from GFP-PUX7 by a process requiring ATG7 and ATG10. CB-5083 also partially suppressed overall autophagic flux, as shown by the dampened release of free GFP from the GFP-ATG8a reporter upon nitrogen starvation

(D) *In vitro* binding assays confirm the UIM-UDS interaction interface between Ubx5 and Atg8. Purified proteins were mixed and pulled down with Ni-NTA agarose beads. Input and bound proteins were visualized as in Figure 1F.

(E) Several human UIM-containing proteins interact with the ATG8 homologs MAP1LC3a and GABARAP by Y2H. Interactions with ATG7 were used as controls.

(F) Screening of a yeast cDNA library by Y2H using WT,  $\Delta$ LDS, or  $\Delta$ UDS forms of yeast Atg8 identified multiple LDS- and UDS-binding proteins. A Venn diagram of the interaction categories is included; asterisks indicate proteins identified previously as Atg8 interactors.

(G) Dot blot binding assays confirm the candidate interactors identified in (F). The assay was performed as in Figure 2J.



**Figure 5. Identification of a UIM Consensus Sequence that Binds the UDS**

(A and B) Amino acid sequence specificity of UIM-like sequences for binding the UDS. A panel of mutants generated by saturating mutagenesis of the *Arabidopsis* RPN10 (A) or PUX7 (B) UIMs was tested for binding to ATG8a by Y2H (top) or dot blot binding assays (bottom). Control interactions and expressions are shown in Figure S3.

(C) Quantification of the assays in (A) and (B), and comparison with expected substitution rates, identify residues within the UIM important for ATG8a binding. Ψ, small hydrophobic residues; ζ, hydrophilic residues.

(D) Sequence alignment of ATG8-binding UIM sequences from *Arabidopsis*, yeast, and humans. The core UIM is indicated by the solid red line; flanking residues are indicated by the dashed red line. Identical and similar amino acids are shown with black and grey backgrounds, respectively. Numbers correspond to the C-terminal amino acids of the regions shown.

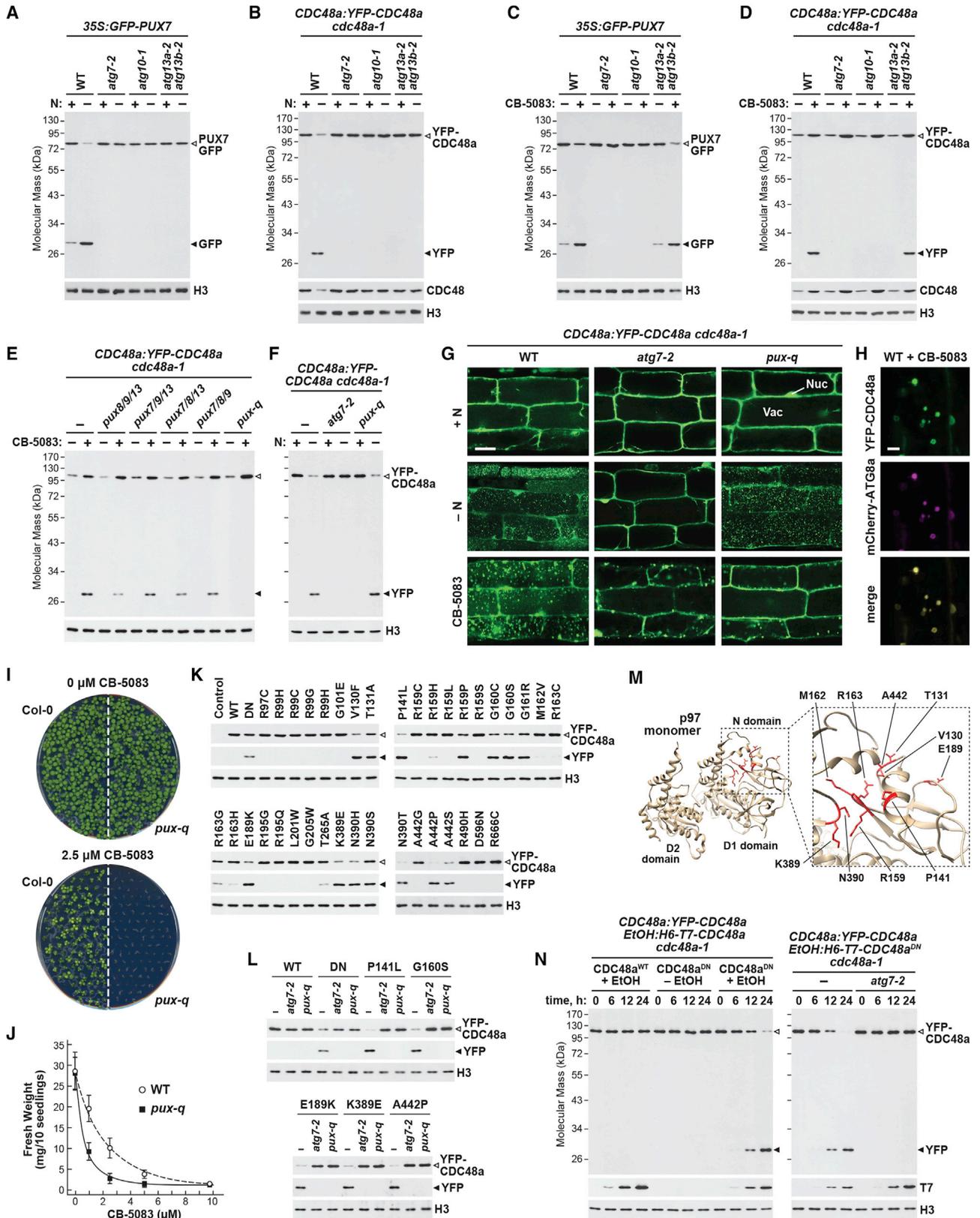
(E) Helical wheel representation of the core *Arabidopsis* ATG8-binding UIM, showing the positions of conserved residues in the predicted helical structure.

following inhibitor treatment (Figures S5E and S5F). This effect was consistent with prior data from yeast and mammals showing that CDC48/p97 promotes autophagosome assembly (Krick et al., 2010).

Assuming that PUX7, PUX8, PUX9, and/or PUX13 are receptors for the autophagic clearance of inactive CDC48, we tested this genetically using a mutant missing all four isoforms. Likely null alleles for each locus that prevented accumulation of the full-length transcripts were identified in the transfer DNA (T-DNA) insertion collections (Figures S5G and S5H). Single homozygous *pux7-2*, *pux8-4*, *pux9-4*, and *pux13-3* mutants, along with higher-order combinations, were fertile and phenotypically indistinguishable from their WT parents under well-fed conditions (Figure S5I). The effects of the mutants on turnover of inactive CDC48 were then tested by GFP release assay using the assembled quadruple mutant line lacking all four ATG8-interacting PUX proteins (designated *pux-q*) also expressing the YFP-CDC48a reporter. Although the *pux-q* background had no effect on autophagic turnover of YFP-CDC48a upon nitrogen starvation, it effectively blocked this turnover when CDC48 was inhibited by CB-5083 (Figures 6E and 6F). None of the *pux* triple

mutant combinations were as effective as *pux-q* in blocking YFP-CDC48a degradation, implying that all four isoforms work redundantly in clearing inactive CDC48 (Figure 6E). As one might predict, this failure to remove CDC48 made *Arabidopsis* hypersensitive to CB-5083, with *pux-q* seedling growth substantially repressed by increasing concentrations of the inhibitor compared with the WT (Figures 6I and 6J).

Confirmation that YFP-CDC48a was targeted to autophagy was provided by confocal fluorescence microscopy of root cells treated with CB-5083. Strong accumulation of YFP-labeled puncta in vacuoles was evident upon CB-5083 treatment of WT cells, but not in the *pux-q* mutant or the *atg7-2* control, with cytoplasmic foci possibly representing aggregated YFP-CDC48a instead becoming visible (Figure 6G). By contrast, vacuolar YFP-CDC48a puncta accumulated in nitrogen-starved root cells either WT or harboring the *pux-q* combination, consistent with the PUX proteins recruiting only inactive CDC48 (Figure 6G). Co-localization of YFP-CDC48a with the autophagic reporter mCherry-ATG8a upon CB-5083 treatment demonstrated that these vacuolar puncta were indeed autophagic bodies (Figure 6H).



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In addition to exploiting inhibitors to block CDC48, we tested a suite of compromising amino acid substitutions that have been implicated in human disease (Figure S6; Tang and Xia, 2016). In total, 37 mutations, along with a dominant-negative (DN) variant impaired in ATP hydrolysis (E308Q E581Q; Marshall et al., 2008; Park et al., 2008), were introduced into *Arabidopsis* CDC48a, and these variants were transiently expressed as YFP fusions in leaf mesophyll protoplasts. Autophagic degradation of the mutant proteins was then monitored by YFP release assay. WT YFP-CDC48a and several mutant forms accumulated to high levels in the protoplasts and did not display released free YFP (Figure 6K). By contrast, versions of YFP-CDC48a containing either the DN mutations or numerous other point mutations, including P141L, G160S, E189K, K389E, and A442P, poorly accumulated, with free YFP instead being strongly detected (Figure 6K), indicating that these variants had become autophagy substrates. This scenario was confirmed by analyzing the fate of the YFP-CDC48a mutants in protoplasts generated from WT, *atg7-2*, and *pux-q* leaves. In each case, the release of free YFP was robust in the WT but not evident in the *atg7-2* and *pux-q* backgrounds (Figure 6L).

Mapping the effective mutations onto the 3-dimensional structure of human CDC48 (p97) revealed that they cluster within the N-terminal domain, which is responsible for co-factor binding and structural integrity of the complex (Stach and Freymont, 2017). Consequently, these mutations likely trigger autophagy by compromising the structure of the CDC48 hexamer (Figure 6M). To test this hypothesis, we generated *Arabidopsis* lines that accumulate YFP-CDC48a together with either WT or DN versions of His<sub>6</sub>-T7-CDC48a, whose expression was inducible by ethanol (Park et al., 2008), allowing us to test whether integration of impaired CDC48 into the hexamer would induce autophagy of a functional subunit. As shown by YFP release assays, only upon expression of the DN form did WT YFP-CDC48a become an autophagy substrate (Figure 6N). Taken together, our *Arabidopsis* data identified an autophagic route of potential

medical relevance that removes dysfunctional CDC48 complexes through dedicated PUX receptors and the UIM-UDS interface.

### Ubx5 Is a UIM-Type Autophagy Receptor for Cdc48 in Yeast

Given that Ubx5 is the likely yeast ortholog of the ATG8-interacting PUX proteins, we examined whether it could target dysfunctional yeast Cdc48 for autophagy. We first assessed whether yeast Cdc48 is an autophagy substrate, using the YFP release assay with cells expressing YFP-Cdc48 and starved for nitrogen. As shown in Figure 7A, yeast degrades Cdc48 upon nitrogen stress via an autophagic route analogous to that in *Arabidopsis*, requiring Atg7 and Atg13 but not Ubx5 or the alternative autophagy receptor Cue5. Confocal fluorescence microscopy then demonstrated autophagic deposition of YFP-Cdc48 into vacuoles. Although cells grown in nitrogen-rich medium localized the YFP signal to the cytoplasm and nucleus, it moved to the vacuole upon nitrogen starvation via a process dependent on Atg7 but not Ubx5 (Figure 7B).

To examine whether non-functional Cdc48 is similarly degraded by autophagy, we attempted to find conditions that would inactivate this ATPase. None of the CDC48/p97 inhibitors tested above (CB-5083, DBE9, ML240, and NMS-873) appeared to be effective in yeast, based on their failure to activate ER stress-responsive genes (*DER1* and *ERO1*), inhibit cell growth, or even affect autophagic flux, as assayed with the engineered Pho8Δ60 reporter assay, which quantifies autophagic transport (Noda et al., 1995), even when applied to the *Δerg6* or *Δpdr5* backgrounds, which might facilitate drug uptake (Figures S7A–S7D).

As an alternative, we tested mutations that might trigger autophagic turnover of Cdc48 like that seen in *Arabidopsis*. Because Cdc48 is necessary for autophagosome assembly in yeast (Krick et al., 2010), the mutations were introduced into a YFP-CDC48 reporter under the control of the galactose-inducible *GAL1*

### Figure 6. The *Arabidopsis* ATG8-Interacting PUX Proteins Are Autophagy Receptors for Dysfunctional CDC48 Complexes

(A and B) PUX7 and CDC48a are degraded via autophagy upon nitrogen starvation. WT or autophagy-defective *atg7-2*, *atg10-1*, or *atg13a-2 atg13b-2* seedlings were starved for nitrogen for 16 h, and release of free GFP or YFP from the GFP-PUX7 (A) or YFP-CDC48a (B) reporters was monitored by immunoblot analysis of total protein extracts with anti-GFP antibodies. Open and closed arrowheads indicate fused and free GFP/YFP, respectively. Immunodetection of histone H3 was used to confirm near-equal protein loading.

(C and D) PUX7 (C) and CDC48a (D) are degraded via autophagy upon treatment with CB-5083. Seedlings treated with or without 20 μM CB-5083 for 16 h were monitored for GFP or YFP release as in (A) and (B).

(E and F) Inhibitor-induced autophagy of CDC48 requires PUX7, PUX8, PUX9, or PUX13. WT, *atg7-2*, or various combinations of *pux* mutant seedlings were subjected to CB-5083 treatment (E) or N starvation (F) as in (B) or (D), and YFP release was monitored as in (B).

(G) Inhibited YFP-CDC48a accumulates in the vacuole in an autophagy- and PUX-dependent manner. Seedlings were treated as in (B) and (D) and imaged by confocal fluorescence microscopy. Scale bar, 10 μm. Nuc, nucleus; Vac, vacuole.

(H) CB-5083-induced vacuolar puncta containing YFP-CDC48a co-localize with the autophagic body marker mCherry-ATG8a. Seedlings were grown and analyzed as in (G).

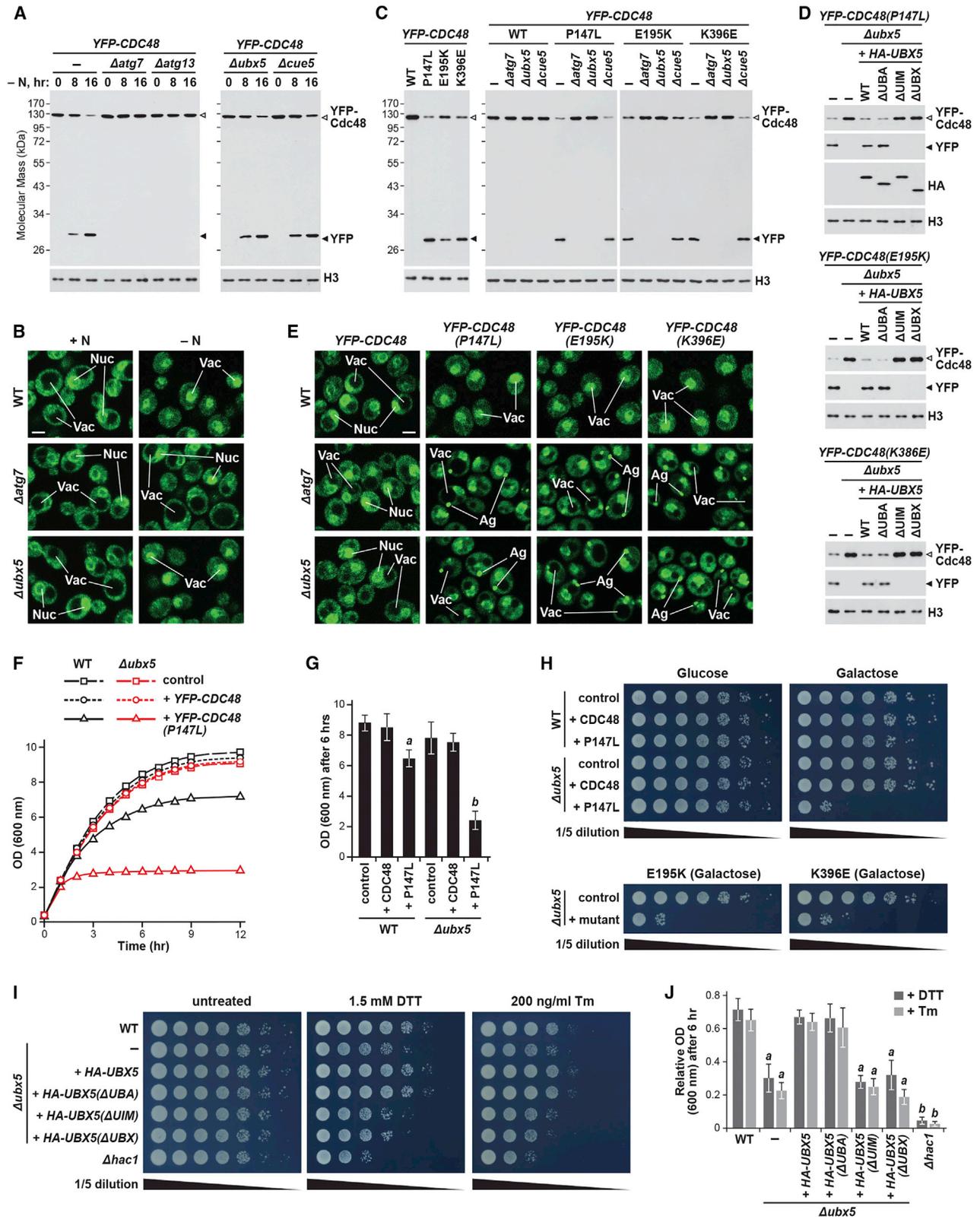
(I) Homozygous *pux-q* plants are hypersensitive to CB-5083. WT or *pux-q* seedlings were grown for 10 days on GM medium containing either DMSO (control) or 2.5 μM CB-5083.

(J) Quantification of WT and *pux-q* seedling sensitivity to CB-5083; values represent the mean fresh weight (±SD) from three independent biological replicates.

(K and L) Mutations connected to human disease trigger PUX-dependent autophagy of *Arabidopsis* CDC48a. YFP-CDC48a variants were transiently expressed in protoplasts derived from WT (K), *atg7-2*, or *pux-q* (L) plants, and YFP release was monitored as in (A).

(M) Mutations that trigger CDC48a degradation cluster within the N domain. The 3-dimensional structure of human CDC48 (p97; PDB: 5FTK) is shown, with residues identified in (K) highlighted in red.

(N) WT CDC48 is degraded by autophagy when associated with a mutant version. Seedlings expressing YFP-CDC48a were induced to express 6His-T7-CDC48a (either WT or DN mutant) with ethanol in the WT or *atg7-2* backgrounds and harvested at the indicated times. YFP release was assayed as in (A), whereas immunodetection of the T7 tag confirmed transgene induction.



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promoter in cells retaining their functional copy of *CDC48*. In this way, expression of the mutant YFP-Cdc48 variants would only mildly impair bulk autophagic flux, in contrast to the dramatic reduction seen when the mutants replaced the genomic locus (Figures S7E and S7F). We first tested YFP-Cdc48 harboring the temperature-sensitive *cdc48-3* and *cdc48-6* alleles, which contain P257L R387K and P257L A540T mutations, respectively (Ruggiano et al., 2016). However, even prolonged incubation of YFP-*cdc48-3* and YFP-*cdc48-6* cells for 48 h at 37°C did not yield high levels of free YFP, indicating that these thermosensitive variants were only weakly targeted to autophagy (Figure S7G).

Finally, we tested three mutations shown to trigger robust autophagic turnover of *Arabidopsis* CDC48a (Figure 6K; P147L, E195K and K396E in yeast). Although their expression only minimally affected autophagic flux (Figure S7H), each strongly induced autophagic breakdown of YFP-Cdc48, based on the YFP release assay, via a process requiring Ubx5 and the core autophagy components Atg7 and Atg8, but not Cue5 (Figures 7C and S7I). To confirm that Ubx5 was required and acted through its UIM, we introduced HA-tagged WT Ubx5 or mutants eliminating the UBA, UIM, or UBX domains into *Δubx5* cells expressing the YFP-Cdc48 mutants. Although free YFP was released in WT cells and in *Δubx5* mutants complemented with full-length Ubx5, it was absent when Ubx5 variants lacking the UIM or UBX domain were used instead (Figure 7D).

The UIM of Ubx5 was expected to bind Atg8 at the UDS and, as confirmation, we found that free YFP was released from the YFP-Cdc48 mutants in *Δatg8* cells complemented with HA-tagged WT Atg8 but not when the  $\Delta$ UDS variant was expressed instead (Figure S7I). Given the remote possibility that the  $\Delta$ UDS mutant slowed YFP-Cdc48 turnover by discouraging Atg8 lipidation, we assayed for this adduct by subjecting total protein extracts from nitrogen-starved cells to SDS-PAGE in the presence of 6 M urea, which permits separation of the free and lipidated forms of Atg8 (Krick et al., 2010), with the identity of Atg8-PE then confirmed by its loss upon treatment of the extracts with phospholipase D (Figure S7J). However, as shown in Figures S7J and S7K, lipidated Atg8 accumulated to nearly normal levels in cells expressing the  $\Delta$ UDS mutant.

Autophagic transport of the P147L, E195K, and K396E variants of YFP-Cdc48 was additionally confirmed by confocal fluo-

rescence microscopy; non-mutated YFP-Cdc48 remained in the cytoplasm and nucleus, whereas the YFP-Cdc48 mutants mainly localized to the vacuole in WT cells (Figure 7E). As expected for an autophagy target requiring Ubx5, this vacuolar movement was blocked in *Δatg7* and *Δubx5* cells, with these cells instead accumulating the YFP-Cdc48 signal in cytoplasmic puncta (Figure 7E). These puncta resembled the foci seen for YFP-CDC48a in *Arabidopsis* and with other autophagic targets (Figure 6G; Marshall et al., 2016; Gatica et al., 2018), suggesting that they represent mis-folded Cdc48 aggregates awaiting autophagy, although their degradation was independent of the autophagy receptor Cue5 (Figure 7C; Lu et al., 2014).

We predicted that this failure to degrade inactive Cdc48 would have physiological consequences in yeast as it does in *Arabidopsis*. To test this notion, we compared the growth rates of WT and *Δubx5* strains expressing either unaltered YFP-Cdc48 or the three mutant forms prone to autophagy. Although the *Δubx5* mutation did not compromise growth of cells expressing WT YFP-Cdc48, growth was substantially slowed when the mutant variants were expressed (Figures 7F, 7G, and 7H). Each mutant was modestly toxic to WT cells, which could reflect their ability to interfere with the Cdc48 hexamer, but became strongly toxic when the non-functional complexes could no longer be cleared by Ubx5-mediated autophagy.

Reasoning that the stabilization of non-functional Cdc48 in *Δubx5* cells should compromise ERAD and protein homeostasis, we examined the sensitivity of these cells to the ER stress agents DTT and tunicamycin. Although growth of WT cells was modestly impaired by both treatments, the *Δubx5* cells were more sensitive (Figures 7I and 7J). This growth suppression was alleviated by complementation with HA-tagged Ubx5, but was not alleviated with the  $\Delta$ UIM or  $\Delta$ UBX versions (Figures 7I and 7J). These results are consistent with Ubx5 helping direct autophagic degradation of Cdc48 complexes that become non-functional during ER stress, using its UBX domain to bind Cdc48 and its UIM to bind the UDS of Atg8.

## DISCUSSION

As our understanding of autophagy has progressed, one focus has been to define the array of ATG8-binding proteins that

### Figure 7. Ubx5 Is an Autophagy Receptor for Dysfunctional Cdc48 Complexes in Yeast

(A) Yeast Cdc48 is degraded via autophagy upon nitrogen starvation. WT, *Δatg7*, *Δatg13*, *Δcue5*, and *Δubx5* cells expressing YFP-CDC48 were starved for nitrogen for the indicated periods of time, and release of free YFP was monitored as in Figure 6A.

(B) Cdc48 accumulates in yeast vacuoles in an autophagy-dependent manner upon nitrogen starvation. Cells were treated as in (A) for 24 h and imaged by confocal fluorescence microscopy. Scale bar, 2  $\mu$ m. Nuc, nucleus; Vac, vacuole.

(C) Mutant forms of Cdc48 are degraded in an autophagy- and Ubx5-dependent manner. WT, *Δatg7*, *Δcue5*, and *Δubx5* cells expressing YFP-CDC48 variants under control of the *GAL1* promoter were grown in medium containing galactose for 16 h, and YFP release was monitored as in (A).

(D) Autophagic degradation of Cdc48 mutants requires the UIM and UBX domains of Ubx5. WT or *Δubx5* cells expressing YFP-CDC48 variants, with or without rescue with HA-tagged WT Ubx5 or the  $\Delta$ UBA,  $\Delta$ UIM or  $\Delta$ UBX mutants, were grown as in (C), and YFP release was monitored as in (A).

(E) Mutant Cdc48 accumulates in yeast vacuoles in an autophagy- and Ubx5-dependent manner. Cells were grown as in (C) and imaged as in (B). Ag, aggregate.

(F–H) Yeast cell growth is hypersensitive to expression of Cdc48 mutants in the absence of Ubx5. Cells as in (C) were switched to medium containing galactose, and growth was monitored by measuring culture density at OD<sub>600</sub> (F and G) or by spotting 5-fold serial dilutions onto synthetic dropout medium and incubating at 30°C for 36 h (H).

(I and J) Yeast cells unable to degrade Cdc48 are hypersensitive to ER stress. Cells as in (D) were grown as in (F) in the presence or absence of 1.5 mM DTT or 200 ng/mL tunicamycin (Tm), and growth was monitored by spotting 5-fold serial dilutions onto synthetic dropout medium (I), or by measuring culture density at OD<sub>600</sub> (J) with values in the presence of each chemical normalized to the value in its absence.

In (G) and (J), values represent the mean ( $\pm$ SD) from three independent biological replicates, while letters indicate values that are significantly different from one another and the control ( $p < 0.05$ ).

help generate and transport autophagic vesicles and recruit appropriate substrates. Although these adaptors and receptors were thought to be limited to the collection of AIM (LIR)-containing proteins that bind the LDS on ATG8 (Noda et al., 2008; 2010), we discovered that a second, conserved ATG8-binding mechanism exists that uses a UIM-UDS interface, thus greatly expanding the number of components involved in autophagy. As an example, our studies of the *Arabidopsis* and yeast PUX/Ubx5 family showed that the UIM-UDS contact is critical for clearing non-functional CDC48 complexes. Because CDC48/p97 is essential for ERAD and other protein quality control pathways relevant to several human pathologies, this turnover has strong medical implications (Ye et al., 2001; Tang and Xia, 2016).

The UIM-binding UDS sequence within ATG8 is highly conserved, with only a few differences among species. Although our saturating mutagenesis approach identified a clear  $\Psi$ -F- $\Psi$ - $\Omega$ /T consensus motif for residues permitted within the UDS, it should be noted that, like the LDS, adjacent residues within the tertiary structure of ATG8 also likely contribute. By contrast, a clear description of the UIM subtypes that bind ATG8 as opposed to other ubiquitin-fold proteins remains elusive. In fact, we emphasize that many currently annotated UIM-containing proteins do not bind ATG8, at least by Y2H assay (10 of 14, 4 of 8, and 22 of 28 tested from *Arabidopsis*, yeast, and humans, respectively), whereas some without a predicted UIM did, demonstrating that the presence of a UIM does not *a priori* confer ATG8 binding and should be confirmed empirically. Although our ATG8 binding assays generated a list of permissible residues within the UIM, the limited number of known ATG8-binding UIMs across species (17 to date) prevented us from developing a robust consensus sequence beyond the internal  $\Psi$ - $\zeta$ -X-A- $\Psi$ -X-X-S motif. Clearly, 3-dimensional structures of one or more UIM-UDS interfaces are now needed to fully resolve this interaction.

Our combined ATG8 interactomes identified 204 ATG8-binding proteins in plants and yeast, including over 40 proteins that utilize the UDS. Although some were described previously, a majority had no prior connections to autophagy and likely represent new autophagy adaptors, receptors, or even cargo that bind ATG8 directly. Our identification of the four *Arabidopsis* PUX proteins and yeast Ubx5 as *bona fide* autophagy receptors expands the reach of selective autophagy in these organisms. The PUX proteins join ATI1/2, DSK2, NBR1/Joka2, ORM1/2, RPN10, and TSPO as the only autophagic cargo receptors so far described in plants (Nolan et al., 2017; Marshall and Vierstra, 2018; Yang et al., 2019).

Many proteins regulating vesicle dynamics were also found to bind ATG8, particularly in yeast; these likely modulate autophagosome expansion, closure, and trafficking to the vacuole. Examples include eight SNAREs, three Rab GTPases, three p24 complex components, four clathrin adaptors, and the UDS-binding Epsins Ent1 and Ent2 (plus their human counterparts EPN1-EPN3), suggesting an intimate cross-talk between the autophagic and vesicular trafficking machineries mediated directly by Atg8. Surprisingly, several ATG8 interactors also influence ubiquitylation, including the human ATXN3 and ATXN3L deubiquitylases, the Ufo1 F box component of a yeast SKP1-Cullin-F-box (SCF) ubiquitin ligase, and two potentially or-

thologous ubiquitin-conjugating enzymes, *Arabidopsis* UBC19 and yeast Ubc1, further connecting ubiquitin to autophagy (Khaminets et al., 2016). It should also be noted that several ATG8-interacting proteins required neither the LDS or UDS for binding, implying that additional interactions interfaces exist between ATG8 and its partners.

CDC48/p97 is an essential, highly abundant segregase that uses the energy from ATP hydrolysis to mechanically extract proteins from membranes or multi-subunit complexes (Stach and Freemont, 2017). As such, it plays crucial roles in, among others, ERAD, ribosome-mediated quality control, chromatin re-modeling, extraction of membrane-bound transcription factors, capping of 20S proteasomes, and autophagic clearance of stress granules and ruptured lysosomes (Ye et al., 2001; Marshall et al., 2008; Park et al., 2008; Krick et al., 2010; den Besten et al., 2012; Stach and Freemont, 2017). Regulating the activity and abundance of CDC48/p97 is therefore likely critical for maintaining proteostasis. Although little is currently known about post-transcriptional mechanisms that might control CDC48/p97, our results with the PUX proteins in *Arabidopsis* and Ubx5 in yeast place autophagy as a crucial regulator. In fact, *Arabidopsis pux-q* seedlings unable to degrade CDC48 are hypersensitive to the CB-5083 inhibitor, whereas yeast cells missing Ubx5 or expressing only the  $\Delta$ UDS variant of Atg8 have strongly impaired growth and are hypersensitive to ER stress.

Two autophagic routes were identified for CDC48 turnover, promoted by either nitrogen starvation or inactivation. The former requires signaling from the ATG1 kinase complex and is independent of the PUX/Ubx proteins, whereas the latter is independent of ATG1 but dependent on these receptors. Thus, as with proteaphagy (Marshall et al., 2015; 2016), cells have the capacity to separately adjust CDC48 degradation in response to nutritional cues or upon recognition of non-functional complexes. Whether there is a selective receptor for the former route, or whether ubiquitylation acts a signal for the latter, remains unknown.

Importantly, mutations in CDC48/p97 have been implicated in several human diseases, including inclusion body myopathy with early-onset Paget's disease of bone and frontotemporal dementia (IBMPFD), familial amyotrophic lateral sclerosis (FALS), and Charcot-Marie-Tooth disease (Tang and Xia, 2016). We found here that numerous mutations associated with these pathologies trigger autophagic clearance of CDC48 in both *Arabidopsis* and yeast (e.g., P141L, G160S, E189K, K389E, and A442P), implying that this recycling influences disease onset and/or severity. Here, two scenarios are possible: either accelerated degradation of functional CDC48/p97 in complex with mutant forms triggers disease symptoms because of CDC48 insufficiency, or the known age-associated decline in autophagic capacity allows cytotoxic accumulation of impaired complexes (Levine and Kroemer, 2019). Our observation that a DN mutant of CDC48 stimulates the degradation of presumably functional subunits implies that hexameric complexes are degraded *in toto*, even though some subunits might retain normal activity. Given that the PUX proteins and Ubx5 bind functional CDC48 (Rancour et al., 2004; Gallois et al., 2013), a plausible model is that inhibition or mutation of CDC48 causes a conformational change that increases the accessibility and/or affinity of bound PUX/Ubx5

for ATG8. Taken together, novel curative strategies for CDC48/p97-associated disorders might be possible by manipulating its autophagic clearance, possibly involving the human orthologs of PUX/Ubx5.

In conclusion, we discovered a novel UIM-UDS interface within the autophagy system that is exploited by a large, heretofore unknown collection of adaptors and receptors to bind ATG8. This discovery should greatly expand the complexity of the autophagy system and the pathways involved in selective cargo recruitment beyond the well-described AIM-LDS interface (Noda et al., 2008; 2010). Additionally, the discovery that CDC48/p97 is targeted to autophagy by a collection of UIM- and UBX domain-containing proteins that recruit non-functional complexes to ATG8-decorated autophagic vesicles demonstrates the importance of the UIM-UDS interface for multiple facets of eukaryotic proteostasis and human health.

## STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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## SUPPLEMENTAL INFORMATION

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## AUTHOR CONTRIBUTIONS

R.S.M. performed most experimental work. Z.H. performed cDNA library screens and computational analyses. S.M. assisted with PCR genotyping, protein purification, and analysis of cDNA library screens. F.M. performed mass spectrometry analyses. R.S.M., Z.H., and R.D.V. designed the research and analyzed the data. R.S.M. and R.D.V. wrote the paper with input from all authors.

## DECLARATION OF INTERESTS

The authors declare no competing interests.

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## STAR★METHODS

### KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
<b>Antibodies</b>		
Chicken polyclonal anti-CDC48a	<a href="#">Rancour et al., 2004</a>	N/A
Mouse monoclonal anti-GFP	Sigma-Aldrich	Cat# 11814460001; RRID: AB_390913
Mouse monoclonal anti-GST	Santa Cruz Biotechnology	Cat# SC138; RRID: AB_627677
Mouse monoclonal anti-HA	Covance	Cat# MMS-101R; RRID: AB_2314672
Mouse monoclonal anti-6His	Covance	Cat# MMS-156P; RRID: AB_2565061
Rabbit polyclonal anti-ATG8a	<a href="#">Thompson et al., 2005</a>	N/A
Rabbit polyclonal anti-Gal4 BD	Sigma-Aldrich	Cat# G3042; RRID: 439688
Rabbit polyclonal anti-H3	Abcam	Cat# AB1791; RRID: AB_302613
Goat anti-mouse HRP conjugate	Seracare	Cat# 074-1806; RRID: AB_2307348
Goat anti-rabbit HRP conjugate	Seracare	Cat# 074-1506; RRID: AB_2721169
Rabbit anti-chicken IgY HRP conjugate	<a href="#">Rancour et al., 2004</a>	N/A
<b>Bacterial and Virus Strains</b>		
<i>Agrobacterium tumefaciens</i> strain GV3101	Lab stock	N/A
<i>Escherichia coli</i> strain BL21(DE3) pLysS	Promega	Cat# L1195
<i>Escherichia coli</i> strain BNN132	<a href="#">Elledge et al., 1991</a>	N/A
<i>Escherichia coli</i> strain DH5 $\alpha$	Lab stock	N/A
<b>Biological Samples</b>		
Human HeLa cell total RNA	Clontech	Cat# 636543
<i>Arabidopsis thaliana</i> universal normalized cDNA library	Clontech	Cat# 630487
<i>Saccharomyces cerevisiae</i> cDNA library	<a href="#">Elledge et al., 1991</a>	N/A
<b>Chemicals, Peptides, and Recombinant Proteins</b>		
Acetosyringone	Sigma-Aldrich	Cat# D134406
3-amino-1,2,4-triazole	Sigma-Aldrich	Cat# A8056
Bovine serum albumin	Affymetrix	Cat# AAJ10857
CB-5083	Selleckchem	Cat# S8101
Cellulase “Onozuka” R-10	Yakult Pharmaceutical Industries	N/A
2-chloroacetamide	Sigma-Aldrich	Cat# C0267
Concanavalin A	Sigma-Aldrich	Cat# C2010
DBeQ	Selleckchem	Cat# S7199
Dithiothreitol	Sigma-Aldrich	Cat# D9779
DNase I, RNase-free	Thermo Fisher Scientific	Cat# EN0521
FastDigest restriction enzymes ( <i>Bam</i> HI; <i>Bgl</i> II; <i>Eco</i> RV; <i>Nco</i> I; <i>Sal</i> I; <i>Sfi</i> I; <i>Xba</i> I; <i>Xho</i> I)	Thermo Fisher Scientific	Cat# FD0054; FD0084; FD0304; FD0574; FD0644; FD1824; FD0684; FD0694
<i>Influenza</i> haemagglutinin (HA) peptide	Sigma-Aldrich	Cat# I2149
Isopropyl- $\beta$ -D-thiogalactopyranoside	Research Products International	Cat# I56000
Klenow fragment	Thermo Fisher Scientific	Cat# EP0051
Lyticase from <i>Arthrobacter luteus</i>	Sigma-Aldrich	Cat# L4025
Macerozyme R-10	Yakult Pharmaceutical Industries	N/A
MG132	Selleckchem	Cat# S2619
ML240	Sigma-Aldrich	Cat# SML1071
NMS-873	Selleckchem	Cat# S7285
Phenylmethylsulphonyl fluoride	Sigma-Aldrich	Cat# P7626
Phospholipase D from <i>Streptomyces chromofuscus</i>	Enzo Life Sciences	Cat# BML-SE301-0025

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**Continued**

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Polyethylene glycol 4000	Sigma-Aldrich	Cat# 81240
p-nitrophenol	Sigma-Aldrich	Cat# 1048
p-nitrophenyl phosphate disodium salt hexahydrate	Sigma-Aldrich	Cat# N4645
Sequencing grade modified porcine trypsin	Promega	Cat# V5111
Silver nitrate	Sigma-Aldrich	Cat# S8157
Sodium thiosulphate pentahydrate	Sigma-Aldrich	Cat# 217247
Trifluoroacetic acid	Sigma-Aldrich	Cat# 302031
Tunicamycin	Sigma-Aldrich	Cat# T7765
Urea	Thermo Fisher Scientific	Cat# BP169-212
<b>Critical Commercial Assays</b>		
LightCycler 480 SYBR Green I master mix	Roche Diagnostics	Cat# 04707516001
Pierce BCA protein assay kit	Thermo Fisher Scientific	Cat# 23225
ProQuest two-hybrid system	Thermo Fisher Scientific	Cat# PQ1000101
QIAprep spin miniprep kit	QIAGEN	Cat# 27106
QuikChange II site-directed mutagenesis kit	Agilent Technologies	Cat# 200524
RNeasy mini kit	QIAGEN	Cat# 74106
RNeasy plant mini kit	QIAGEN	Cat# 74904
SuperScript III first strand synthesis system	Thermo Fisher Scientific	Cat# 18080051
SuperSignal West Femto maximum sensitivity substrate	Thermo Fisher Scientific	Cat# 34096
SuperSignal West Pico Plus chemiluminescent substrate	Thermo Fisher Scientific	Cat# 34578
Zymoprep-96 yeast plasmid miniprep kit	Zymo Research	Cat# D2006
<b>Deposited Data</b>		
Mass spectrometric analysis of GFP-PUX7 immunoprecipitations	ProteomeXchange consortium	PXD011397
<b>Experimental Models: Organisms/Strains</b>		
<i>Arabidopsis thaliana</i> wild type ecotypes (Col-0; Col-3; Ws)	<i>Arabidopsis</i> Biological Resource Center	Cat# CS60000; CS908; CS1602
<i>Arabidopsis thaliana</i> transgenic plant lines	<a href="#">Thompson et al., 2005</a> ; <a href="#">Park et al., 2008</a> ; <a href="#">Suttangkakul et al., 2011</a> ; <a href="#">Gallois et al., 2013</a>	See <a href="#">Table S4</a> for details
<i>Arabidopsis thaliana</i> T-DNA insertion mutants	<i>Arabidopsis</i> Biological Resource Center; Versailles <i>Arabidopsis</i> Stock Center; GABI-Kat collection	See <a href="#">Table S4</a> for details
<i>Nicotiana benthamiana</i> plants	Michael Dyer (Washington University in St. Louis)	N/A
<i>Saccharomyces cerevisiae</i> wild type strains (BY4741; BY4742; DF5; SEY6210; W303-1B)	Daniel Finley (Harvard Medical School); Audrey P. Gasch (University of Wisconsin); Mark Hochstrasser (Yale University)	See <a href="#">Table S5</a> for details
<i>Saccharomyces cerevisiae</i> gene knockout collection strains (multiple)	Dharmacon	See <a href="#">Table S5</a> for details
<i>Saccharomyces cerevisiae</i> strains <i>cdc48-3</i> ; <i>cdc48-6</i>	Pedro Carvalho (Centre de Regulació Genòmica)	See <a href="#">Table S5</a> for details
<i>Saccharomyces cerevisiae</i> strain PHO8 $\Delta$ 60	<a href="#">Noda et al., 1995</a>	See <a href="#">Table S5</a> for details
<i>Saccharomyces cerevisiae</i> strain YFP-CDC48	This study	See <a href="#">Table S5</a> for details
<b>Oligonucleotides</b>		
Oligonucleotide primers	Integrated DNA Technologies	See <a href="#">Table S6</a> for details
<b>Recombinant DNA</b>		
pBlueScript II SK(+)	Agilent Technologies	Cat# 212205
pDHA	<a href="#">Marshall et al., 2008</a>	N/A

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REAGENT or RESOURCE	SOURCE	IDENTIFIER
pDONR221	Thermo Fisher Scientific	Cat# 12536017
pET17-b	EMD Millipore	Cat# 69663
pGEX-4T-1	GE Healthcare	Cat# 28-9545-49
pGBK-T7	Clontech	Cat# 630443
pSITE-N-EYFP-C1; pSITE-C-EYFP-C1	<i>Arabidopsis</i> Biological Resource Center	Cat# CD3-1648; CD3-1649
<i>Escherichia coli</i> Gateway destination vectors (pDEST14; pDEST15; pDEST17)	Thermo Fisher Scientific	Cat# 11801016; 11802014; 11803012;
<i>Saccharomyces cerevisiae</i> Gateway destination vectors (pAG423-GAL-EYFP-ccdB; pAG424-GAL-EYFP-ccdB; pAG425-GPD-ccdB)	Addgene	Cat# 14341; 14343; 14154
<b>Software and Algorithms</b>		
Adobe Illustrator CC; Adobe Photoshop CC	Adobe Systems	N/A
BoxShade version 3.21	ExPASy Bioinformatics Resource Portal	<a href="https://embnet.vital-it.ch/software/BOX_form.html">https://embnet.vital-it.ch/software/BOX_form.html</a>
Clustal Omega	European Bioinformatics Institute	<a href="http://www.clustal.org/omega">http://www.clustal.org/omega</a>
eulerAPE version 3	University of Kent	<a href="http://www.eulerdiagrams.org/eulerAPE">http://www.eulerdiagrams.org/eulerAPE</a>
FigTree version 1.4.2	University of Edinburgh	<a href="http://tree.bio.ed.ac.uk/software/figtree">http://tree.bio.ed.ac.uk/software/figtree</a>
ImageQuant version 5.2	GE Healthcare	N/A
Jalview version 2	University of Dundee	<a href="http://www.jalview.org">http://www.jalview.org</a>
MrBayes version 3.2.2	Ronquist and Huelsenbeck, 2003	<a href="http://www.mrbayes.sourceforge.net/">http://www.mrbayes.sourceforge.net/</a>
Nikon Elements Viewer	Nikon Imaging Software	<a href="https://www.microscope.healthcare.nikon.com/products/software">https://www.microscope.healthcare.nikon.com/products/software</a>
Origin version 7.0	MicroCal	N/A
Proteome Discoverer version 2.0.0.802	Thermo Fisher Scientific	N/A
ProtParam	ExPASy Bioinformatics Resource Portal	<a href="https://web.expasy.org/protparam">https://web.expasy.org/protparam</a>
T-DNA Express	Salk Institute Genomic Analysis Laboratory	<a href="http://signal.salk.edu/cgi-bin/tdnaexpress">http://signal.salk.edu/cgi-bin/tdnaexpress</a>
TotalLab Quant	Non-linear Dynamics	<a href="http://www.totallab.com/home/cliqs">http://www.totallab.com/home/cliqs</a>
UCSF Chimera	University of California, San Francisco	<a href="http://www.cgl.ucsf.edu/chimera">http://www.cgl.ucsf.edu/chimera</a>
<b>Other</b>		
Amicon Ultra-15 centrifugal filter units	EMD Millipore	Cat# UFC901024
Bond Elut OMIX C18 pipette tips	Agilent Technologies	Cat# A57003100
BugBuster master mix	EMD Millipore	Cat# 71456
EZview red anti-HA affinity gel	Sigma-Aldrich	Cat# E6779
Gamborg's B5 basal medium with minimal organics	Sigma-Aldrich	Cat# G5893
Gateway BP clonase II/LR clonase II enzyme mix	Thermo Fisher Scientific	Cat# 11789; 11791
GFP-Trap_A beads	ChromoTek	Cat# GTA-20
GST-Bind resin	EMD Millipore	Cat# 70541
Hybond-C Extra nitrocellulose membrane	GE Healthcare	Cat# RPN303E
Immobilon-P PVDF transfer membrane	EMD Millipore	Cat# IPVH00010
Murashige and Skoog basal salts with macronutrients and micronutrients	Caisson Labs	Cat# MSP01
Murashige and Skoog basal salt micronutrient solution	Sigma-Aldrich	Cat# M0529
Nickel-nitrilotriacetic acid agarose beads	QIAGEN	Cat# 30230
Plant protease inhibitor cocktail	Sigma-Aldrich	Cat# P9599
Yeast complete supplement mixture lacking histidine, leucine and tryptophan	MP Biomedicals	Cat# 114530522

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REAGENT or RESOURCE	SOURCE	IDENTIFIER
Yeast complete supplement mixture lacking adenine, histidine, leucine and tryptophan	MP Biomedicals	Cat# 114540422
Yeast nitrogen base without amino acids and ammonium sulfate	Sigma-Aldrich	Cat# Y1251

### CONTACT FOR REAGENT AND RESOURCE SHARING

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Richard D. Vierstra ([rdvierstra@wustl.edu](mailto:rdvierstra@wustl.edu)).

### EXPERIMENTAL MODEL AND SUBJECT DETAILS

#### Plant Materials and Growth Conditions

All *Arabidopsis thaliana* plants were the Columbia-0 (Col-0) ecotype, except for the SAIL T-DNA insertion lines, which were the Columbia-3 (Col-3) ecotype, and the FLAG T-DNA insertion lines and the 35S::GFP and 35S::GFP-PUX7 lines, which were the Wassilewskija (Ws) ecotype. Details of all T-DNA insertion mutants and stable transgenic lines are provided in Table S4. Sterilized seeds (obtained via vapor-phase or liquid-phase sterilization) were vernalized at 4°C for 3 to 4 days and germinated on solid GM medium (3.2 g/L Gamborg's B5 basal medium with minimal organics, 1% (w/v) sucrose, 0.05% (w/v) 2-(N-morpholino)ethanesulfonic acid (MES; pH 5.7), 0.7% (w/v) agar) at 21 to 23°C under a long-day photoperiod (16 h light/8 h darkness) with a light intensity of 75 to 100  $\mu\text{mol}/\text{m}^2/\text{sec}$  and a relative humidity of 40 to 50%.

For selection and maintenance of transgenic plants, agar plates were supplemented with appropriate combinations of antibiotics or herbicide (50  $\mu\text{g}/\text{mL}$  kanamycin, 25  $\mu\text{g}/\text{mL}$  hygromycin B, 7.5  $\mu\text{g}/\text{mL}$  sulphadiazine or 10  $\mu\text{g}/\text{mL}$  BASTA). For growth assays, plates were supplemented with the indicated concentrations of CB-5083 (1-(4-(benzylamino)-7,8-dihydro-5H-pyrano-(4,3-d)-pyrimidin-2-yl)-2-methyl-1H-indole-4-carboxamide), DBEQ (N<sup>2</sup>,N<sup>4</sup>-dibenzylquinazoline-2,4-diamine), ML240 ((2-(2-aminobenzimidazol-1-yl)-N-benzyl-8-methoxyquinazolin-4-amine) or NMS-873 (3-(3-(cyclopentylsulphanyl)-5-((3-methyl-4-(4-methylsulfonylphenyl)-phenoxy)-methyl)-1,2,4-triazol-4-yl)-pyridine) and grown horizontally or vertically for 10 or 7 days, respectively. When required, seedlings were transferred to soil (mixed in a 1:1 ratio with organic Coco Coir planting mixture, supplemented before use with 2 g/L Peters 20-20-20 fertilizer, 80 mg/L Ca(NO<sub>3</sub>)<sub>2</sub> and 80 mg/L MgSO<sub>4</sub>) after 2 to 3 weeks, and again grown at 21 to 23°C under a long-day photoperiod. Plants for protoplast preparation were grown as above, except under a short-day photoperiod (8 h light/16 h darkness).

For chemical treatments, seedlings were grown in either 2 mL or 50 mL cultures of liquid GM medium (as above, but without agar) at 21 to 23°C under continuous light with gentle shaking (90 rpm). On the sixth day, fresh medium was supplemented with the indicated concentrations of CB-5083, DBEQ, ML240, NMS-873 and/or MG132 ((N-benzyloxycarbonyl)-leucinyll-leucinyll-leucinal) for the indicated times, with equivalent volumes of DMSO added to the controls. For nitrogen starvation, seedlings were grown in liquid MS medium (4.4 g/L Murashige and Skoog basal medium, 1% (w/v) sucrose, 0.05% (w/v) MES (pH 5.7)) before transfer to fresh MS medium or MS medium lacking nitrogen (Murashige and Skoog basal salt micronutrient solution supplemented with 3 mM CaCl<sub>2</sub>, 1.5 mM MgSO<sub>4</sub>, 1.25 mM KH<sub>2</sub>PO<sub>4</sub>, 5 mM KCl, 1% (w/v) sucrose, 0.05% (w/v) MES (pH 5.7)) for the indicated times. Both control and treated seedlings were washed three times in fresh medium prior to treatment. For induction of 6His-T7-CDC48a variants (Park et al., 2008), fresh medium was supplemented with 2% ethanol, again for the indicated times. Following all treatments, tissue was harvested, immediately frozen in liquid nitrogen, and stored at -80°C before analysis.

Tobacco (*Nicotiana benthamiana*) plants for *Agrobacterium tumefaciens*-mediated leaf infiltration were sown directly onto soil (pre-treated as described above), vernalized at 4°C for 4 to 5 days, and grown at 21 to 23°C under a 12 h light/12 h darkness photoperiod, with a light intensity of 75 to 100  $\mu\text{mol}/\text{m}^2/\text{sec}$  and relative humidity of 60 to 75%. Plants were re-fertilized once a week.

#### Yeast Strains and Manipulations

Unless otherwise stated, all yeast (*Saccharomyces cerevisiae*) manipulations were performed according to standard protocols (as described in Marshall et al., 2016). Details of all strains used in this study are given in Table S5. Strains BY4741 and BY4742 were used as WT controls. Deletion strains ( $\Delta\text{atg7}$ ,  $\Delta\text{atg13}$ ,  $\Delta\text{cue5}$ ,  $\Delta\text{hac1}$ ,  $\Delta\text{pr5}$  and  $\Delta\text{ubx5}$ ) were obtained from the yeast knockout collection (Dharmacon) and cultured on YPDA medium containing 200  $\mu\text{g}/\text{mL}$  Geneticin, except for the  $\Delta\text{erg6}$  deletion, which was grown on YPDA medium containing 200  $\mu\text{g}/\text{mL}$  hygromycin B (Marshall et al., 2016). All genomic deletions were confirmed by PCR genotyping (using primer pairs A + B, A + KanB, C + D, KanC + D, and A + D for each deletion collection strain; details of all oligonucleotide primers are provided in Table S6).

Yeast strains expressing YFP-CDC48 from the genomic CDC48 locus in WT or deletion backgrounds were generated by standard PCR-based homologous recombination, with the coding sequence for EYFP (amplified from pAG424-GAL-EYFP-ccdB (Addgene, product number 14343)) integrated following the initiator methionine. Strains in which the endogenous ATG8 locus was replaced

by *ATG8 $\Delta$ LDS* or *ATG8 $\Delta$ UDS* variants were generated in the same way. Correct integration was confirmed by sequencing of the genomic region and, where appropriate, confocal fluorescence microscopy (see below). Plasmid-based expression of *YFP-CDC48*, *HA-ATG8* or *HA-UBX5* variants was driven from the pAG423-GAL-EYFP-ccdB or pAG425-GPD-ccdB vectors (Addgene, product numbers 14341 and 14154, respectively; see below for cloning details). The sequence for the HA-tag on the N terminus of *ATG8* or *UBX5* was incorporated into the appropriate PCR amplification primer. Transformation with the indicated plasmids was performed using the standard lithium acetate procedure, and transformed cells were cultured on synthetic dropout medium lacking leucine or histidine as required.

For time course experiments, 15 mL liquid cultures in YPDA medium were grown overnight at 30°C with vigorous shaking, diluted to an OD<sub>600</sub> of 0.1 in 15 mL, then grown for an additional 2 to 3 h until an OD<sub>600</sub> of approximately 0.5 was reached. To initiate nitrogen starvation, cells were harvested by centrifugation at 1,000 x g for 2 min, washed twice in sterile distilled H<sub>2</sub>O, and re-suspended in synthetic dropout medium lacking nitrogen (0.17% yeast nitrogen base without amino acids and ammonium sulfate, 2% glucose), followed by continued incubation at 30°C. For expression of *YFP-CDC48* variants from the *GAL1* promoter, cells were harvested and washed as above then re-suspended in YPDA medium containing 2% galactose instead of 2% glucose, followed by continued incubation at 30°C. Cell aliquots corresponding to 1.5 OD units were collected at the indicated times, pelleted by centrifugation at 5,000 x g for 1 min, washed once in sterile distilled H<sub>2</sub>O, pelleted again, and immediately frozen in liquid nitrogen. For treatment with CB-5083, DBE-Q, ML240 or NMS-873, cultures were grown and diluted as above before the inhibitor was added to the indicated concentration (with equivalent volumes of DMSO for the controls).

## METHOD DETAILS

### Gene Cloning and Site-directed Mutagenesis

To clone required coding sequences, total RNA was first extracted from *Arabidopsis* seedlings or yeast cells and then converted into cDNA. *Arabidopsis* RNA was extracted from 50 to 100 mg of 7-day-old liquid grown seedlings using the RNeasy plant mini kit (QIAGEN). To obtain total yeast RNA, the cell walls of  $2 \times 10^7$  freshly harvested BY4741 cells (taken from a 15 mL culture grown in YPDA) were digested with 100 U of lyticase (from *Arthrobacter luteus*) in 100  $\mu$ L buffer Y1 (1 M sorbitol, 100 mM EDTA, 0.1% (v/v)  $\beta$ -mercaptoethanol (pH 7.4)) for 1 h at 30°C, and RNA was then extracted using the RNeasy mini kit (QIAGEN). For human RNA, a commercially available batch of total HeLa cell RNA (Clontech, product number 636543) was used. In all cases, the RNA concentration was determined using a NanoDrop 1000 spectrophotometer (Thermo Fisher Scientific), 1  $\mu$ g of total RNA was treated with DNase I (Thermo Fisher Scientific), and RNA integrity was assessed via a combination of OD<sub>260</sub>/OD<sub>280</sub> and OD<sub>260</sub>/OD<sub>230</sub> measurements, and by analyzing selected samples on a denaturing formaldehyde agarose gel. RNA was converted into cDNA using the SuperScript III first-strand synthesis system (Thermo Fisher Scientific) and oligo(dT)<sub>20</sub> primers.

For yeast two-hybrid, bimolecular fluorescence complementation, and recombinant protein expression in *E. coli* or yeast, coding sequences amplified from cDNA by PCR were first recombined into pDONR221 via the Gateway BP clonase II reaction (Thermo Fisher Scientific). When required, site-directed mutagenesis was performed at this step using the QuikChange II site-directed mutagenesis kit (Agilent Technologies). Mutation of individual or small groups of adjacent residues was performed using single primer pairs, while mutations of larger groups of residues were introduced in two stages. For large-scale saturating mutagenesis, degenerate primers were used in which the three bases of the relevant codon were permitted to be any of A, C, G or T. Details of all  $\Delta$ LDS,  $\Delta$ UDS and  $\Delta$ UIM mutations are given in Table S1. Sequence-confirmed genes were recombined in-frame with appropriate Gateway-compatible destination vectors via the Gateway LR clonase II reaction (Thermo Fisher Scientific; see relevant sections above and below). To prepare plasmids for cDNA library screening or transient expression in *Arabidopsis* mesophyll protoplasts, standard restriction enzyme-based cloning was used (see relevant sections below).

### Immunological Techniques

Frozen *Arabidopsis* tissue samples were homogenized in 3 volumes of protein extraction buffer (50 mM Tris-HCl (pH 7.5), 150 mM NaCl, 2 mM dithiothreitol (DTT), 1 mM phenylmethylsulfonyl fluoride (PMSF), 50  $\mu$ M MG132, 1X plant protease inhibitor cocktail) and clarified by centrifugation at 16,000 x g for 5 min at 4°C. The supernatant was then mixed with 0.25 volumes of 5X SDS-PAGE sample buffer (200 mM Tris-HCl (pH 6.8), 25% (v/v) glycerol, 2% (w/v) SDS, 5% (v/v)  $\beta$ -mercaptoethanol, 0.1% (w/v) bromophenol blue). Total protein extracts from yeast were usually obtained by re-suspending harvested cells in 500  $\mu$ L of lysis buffer (0.2 N NaOH, 1%  $\beta$ -mercaptoethanol), followed by precipitation of proteins with 50  $\mu$ L of 50% trichloroacetic acid. Proteins were collected by centrifugation at 16,000 x g for 5 min at 4°C, washed once with 1 mL of ice-cold acetone, and re-suspended in 150  $\mu$ L 2X SDS-PAGE sample buffer (80 mM Tris-HCl (pH 6.8), 10% (v/v) glycerol, 0.8% (w/v) SDS, 2% (v/v)  $\beta$ -mercaptoethanol, 0.04% (w/v) bromophenol blue).

For analysis of Atg8 lipidation, yeast cell walls were first digested with 200 U of lyticase in 100  $\mu$ L 1X PBS (137 mM NaCl, 2.7 mM KCl, 10 mM Na<sub>2</sub>HPO<sub>4</sub>, 1.8 mM KH<sub>2</sub>PO<sub>4</sub>). Resulting spheroplasts were harvested by centrifugation at 100 x g for 5 min at 4°C, then lysed by re-suspension in yeast homogenization buffer (50 mM Tris-HCl (pH 8.0), 150 mM NaCl, 1 mM PMSF, 10 mM iodoacetamide, 1% (v/v) Triton X-100) followed by vigorous mixing with a vortex. Extracts were clarified by centrifugation at 16,000 x g for 5 min at 4°C, and the supernatant was incubated for 1 h at 37°C in the presence or absence of 250 U phospholipase D (from *Streptomyces chromofuscus*; Enzo Life Sciences), then mixed with 0.25 volumes of 5X SDS-PAGE sample buffer. All protein samples were heated at 95°C for 5 min and then subjected to SDS-PAGE analysis, with 10 to 20  $\mu$ L of each sample being run on linear gels containing

between 10 and 14% acrylamide, as appropriate. To enable separation of Atg8 and Atg8-PE, gels were supplemented with 6 M urea.

For direct protein visualization, gels were subjected to staining with Coomassie Brilliant Blue R-250 or silver nitrate, exactly as previously described (Marshall et al., 2015; 2016). For immunoblot analyses, proteins separated by SDS-PAGE were electrophoretically transferred onto Immobilon-P polyvinylidene difluoride (PVDF) membrane (Millipore) for 16 h at 80 mA, and the membrane was blocked for at least 60 min with a 10% (w/v) non-fat dry milk solution in 1X PBS, which was first filtered through two layers of Miracloth. All incubations were performed at room temperature. The membrane was incubated with primary antibody solution (in 1% (w/v) non-fat dry milk solution in PBS) for 60 min, before being washed once with PBS, once with PBST (PBS containing 0.1% (v/v) Triton X-100), and once with PBS for 10 min each. The membrane was re-blocked with 10% (w/v) non-fat dry milk solution in PBS for 30 min, incubated for 60 min with secondary antibody solution (in 1% (w/v) non-fat dry milk solution in PBS), then washed again as above. Details of all primary and secondary antibodies are given in the Key Resources Table. Blots were developed using the SuperSignal West Pico Plus Chemiluminescent Substrate or the SuperSignal West Femto Maximum Sensitivity Substrate (both from Thermo Fisher Scientific). Densitometric quantifications were performed using TotalLab software (Non-linear Dynamics), with at least three different exposures of the same blot being quantified to ensure that the exposure level was within the linear range of the film.

To assay 6His-ATG8e/Atg8 binding via dot blots, 1 mL cultures of *E. coli* strain BL21(DE3) pLysS (Promega) expressing the indicated genes from either pDEST15 (Thermo Fisher Scientific) or pET17-b (Novagen; see below for growth and induction conditions) were harvested by centrifugation at 5,000 x g for 5 min at 4°C, frozen in liquid nitrogen, and lysed in 100  $\mu$ L BugBuster Master Mix (EMD4 Biosciences). An appropriate volume of cell lysate (normalized for expression of the GST- or HA-tagged protein; typically between 1 and 10  $\mu$ L) was then spotted onto Hybond-C Extra nitrocellulose membrane (GE Healthcare). The membrane was blocked with 3% (w/v) bovine serum albumin (BSA) in 1X TBS (10 mM Tris-HCl (pH 7.3), 125 mM NaCl), then incubated with 500 nM purified 6His-ATG8e or 6His-Atg8 variants (see below for purification details) in 10 mL of binding buffer (150 mM Tris-HCl (pH 7.4), 50 mM NaCl, 5 mM MgCl<sub>2</sub>, 1 mM DTT, 5% (v/v) glycerol, 1% (w/v) BSA, 0.01% (v/v) Triton X-100) for 60 min with gentle rotation. All incubations were performed at 4°C. The membranes were then washed once with TBST (TBS plus 0.1% (w/v) BSA, 0.1% (w/v) SDS, 0.1% (v/v) Triton X-100) and twice with TBS for 10 min each, incubated with primary anti-6His antibody (in 1% (w/v) BSA in TBS) for 60 min, washed as above, re-blocked with 3% (w/v) BSA in TBS for 30 min, incubated for 60 min with secondary goat anti-rabbit antibody conjugated to horseradish peroxidase (in 1% (w/v) BSA in TBS), then washed again and developed as above.

### Yeast Two-Hybrid Assays

Assays for direct protein-protein interaction by Y2H were performed using the ProQuest two-hybrid system (Thermo Fisher Scientific). Sequence-confirmed coding sequences cloned into pDONR221 as above were recombined in-frame with either the GAL4 activation domain or GAL4 DNA-binding domain in the pDEST22 or pDEST32 vectors (Thermo Fisher Scientific), respectively, via the Gateway LR clonase II reaction. Pairwise combinations of coding sequences in pDEST22 and pDEST32 (or the empty vectors as controls) were then co-transformed into yeast strain MaV203. Cells transformed with both plasmids were selected for by growth for 2 days at 30°C on synthetic dropout medium lacking leucine and tryptophan. Protein-protein interactions were then identified by growing for 2 days at 30°C on synthetic dropout medium lacking leucine, tryptophan and histidine, and containing 25 mM 3-amino-1,2,4-triazole (3-AT), with at least four individual colonies tested for each interaction pair. To confirm interactions, single colonies were diluted in sterile H<sub>2</sub>O to an OD<sub>600</sub> of 0.1, and 5  $\mu$ L was spotted onto both types of selective medium and again grown for 2 days at 30°C.

The following interaction pairs were included as positive controls in the Y2H assays: *Arabidopsis* ATG1a/ATG8, ATG7/ATG8, CDC48a/PUX1-16 and RPN9a/RPN10; yeast Atg1/Atg8, Atg7/Atg8, Cdc48/Ubx1-7, Dsk2/Cue5, Pan1/Ent1-2 and Skp1/Ufo1; and human ATG7/GABARAP, ATG7/MAP1LC3a, EPS15/EPN1-3, KLF5/ATXN3-3L and VPS45/RBSN.

### Bimolecular Fluorescence Complementation

*In planta* protein-protein interactions were assayed using bimolecular fluorescence complementation in *N. benthamiana* leaves. Sequence-confirmed coding sequences cloned into pDONR221 as above were recombined in-frame with the N- or C-terminal halves of EYFP in the pSITE-N-EYFP-C1 or pSITE-C-EYFP-C1 vectors (ABRC stock numbers CD3-1648 and CD3-1649, respectively) via the Gateway LR clonase II reaction, with expression driven by the cauliflower mosaic virus (CaMV) 35S promoter. The resulting plasmids were introduced into *A. tumefaciens* strain GV3101, overnight cultures of which were re-suspended in 5 mL infiltration buffer (10 mM MgCl<sub>2</sub>, 10 mM MES (pH 5.7), 100  $\mu$ M 3',5'-dimethoxy-4'-hydroxyacetophenone (acetosyringone)), incubated at room temperature for 8 to 12 h, and then used for direct infiltration of 4 to 6-week-old *N. benthamiana* leaves. Leaf sections of approximately 2 mm x 2 mm were excised 36 to 48 h after infiltration and visualized by confocal fluorescence microscopy as described below.

### Confocal Laser Scanning Microscopy

*Arabidopsis* seedlings expressing GFP, YFP or mCherry reporters were grown in 2 mL liquid GM medium at 21 to 23°C under continuous light for 4 days with gentle shaking (90 rpm), then transferred to fresh medium either containing or lacking nitrogen and/or supplemented with 20  $\mu$ M CB-5083, with an equivalent volume of DMSO added to the controls. Following incubation for 16 h, root cells within the lower elongation zone were visualized with a Nikon A1<sup>+</sup> confocal laser scanning microscope, using 20X or 40X oil objectives (numerical apertures 0.75 and 1.30, respectively). Excitation was performed at 488 nm and 543 nm, and emission was collected

between 500 and 530 nm or 565 and 615 nm, for GFP/YFP and mCherry signals, respectively. Identical settings were used for imaging of *N. benthamiana* leaf sections subjected to *A. tumefaciens*-mediated infiltration as described above.

For imaging of yeast, cells expressing YFP reporters grown in YPDA medium (containing 2% glucose or 2% galactose as required), or subjected to nitrogen starvation as described above, were visualized using a 100X oil objective (numerical aperture 1.46) with the same settings as above. To prevent cell movement, all coverslips were washed in 1 N NaOH, rinsed with sterile distilled H<sub>2</sub>O, and coated with a 2 mg/mL solution of concanavalin A for 10 min. The slips were then air-dried, rinsed with sterile distilled H<sub>2</sub>O, left to dry again, and stored for up to 2 months before use. To avoid auto-fluorescence from the YPDA medium, cells were first pelleted by centrifugation at 1,000 x g for 1 min, and then re-suspended in synthetic dropout medium lacking appropriate amino acids prior to imaging.

All confocal images were scanned in single-track mode, except for co-localization studies, where the GFP and mCherry signals were detected simultaneously in multi-track mode. Images were processed using Elements Viewer (Nikon Imaging Software) and/or Adobe Photoshop CC, before conversion to TIFF files for use in the figures. Within each figure, all images (including negative controls) were captured using identical microscope settings, with the exception of bright field images, where channel gain was adjusted to provide uniform exposure between images.

### Recombinant Protein Expression and Purification

Sequence-confirmed coding sequences cloned into pDONR221 as above were recombined in-frame with either no tag, a glutathione S-transferase (GST) tag, or a 6His tag in the pDEST14, pDEST15 or pDEST17 vectors (Thermo Fisher Scientific), respectively, via the Gateway LR clonase II reaction. The sequence for the HA-tag at the N terminus of *DSK2a* was incorporated into the appropriate PCR amplification primer. The GST protein alone, encoded in the unmodified pGEX-4T-1 plasmid (GE Healthcare), was used as a control for the GST fusions. All proteins were expressed in *E. coli* strain BL21(DE3) pLysS (Promega). The cells were cultured at 37°C in 800 mL LB medium to an OD<sub>600</sub> of between 0.6 and 0.8, followed by a 4 h induction with 1 mM isopropyl-β-D-thiogalactopyranoside at either 30 or 37°C. Cells were harvested by centrifugation at 5,000 x g for 20 min at 4°C, frozen in liquid nitrogen, and lysed in two rounds of 10 mL BugBuster Master Mix (EMD4 Biosciences).

GST or GST fusion proteins were affinity purified using GST-Bind Resin (EMD4 Biosciences). Bacterial cell lysates were incubated with 1 mL PBS-washed GST-Bind Resin for 1 h at 4°C with continual rotation, and then applied to a 30 mL EconoPac chromatography column (Bio-Rad). After 5 min, the flow-through was allowed to run out, and the beads were washed twice with PBS containing 1 M NaCl, and once with PBS containing 2 M NaCl. Bound proteins were eluted by incubating the beads with 10 mL of 25 mM 3-(*N*-morpholino)propanesulphonic acid (MOPS)-KOH (pH 7.5) containing 10 mM reduced glutathione (GSH), and the eluants were dialyzed overnight at 4°C against 25 mM MOPS-KOH (pH 7.5), before being concentrated 10-fold using an Amicon Ultra-15 centrifugal filter unit with a 10 kDa cut-off limit (Millipore).

Proteins tagged with 6His were affinity purified using nickel-nitrilotriacetic acid (Ni-NTA) agarose beads (QIAGEN). Bacterial cell lysates in BugBuster Master Mix containing 10 mM imidazole were applied three times to either 1 or 3 mL of PBS-washed Ni-NTA beads in a 30 mL EconoPac chromatography column at 4°C. For *in vitro* binding assays, the beads were washed once with NaH<sub>2</sub>PO<sub>4</sub> wash buffer (50 mM NaH<sub>2</sub>PO<sub>4</sub> (pH 7.8), 300 mM NaCl, 20 mM imidazole), once with Tris-40 buffer (50 mM Tris-HCl (pH 7.8), 300 mM NaCl, 40 mM imidazole), and once with Tris-60 buffer (50 mM Tris-HCl (pH 7.8), 300 mM NaCl, 60 mM imidazole). Bound proteins were then eluted with 2 or 6 mL of Tris elution buffer (50 mM Tris-HCl (pH 7.8), 100 mM NaCl, 300 mM imidazole). For isothermal titration calorimetry (ITC) experiments, the beads were washed once with NaP-20 buffer (20 mM Na<sub>2</sub>HPO<sub>4</sub>, 5 mM NaH<sub>2</sub>PO<sub>4</sub>, 300 mM NaCl, 20 mM imidazole, 500 mM urea, 2% glycerol), once with NaP-40 buffer (20 mM Na<sub>2</sub>HPO<sub>4</sub>, 5 mM NaH<sub>2</sub>PO<sub>4</sub>, 300 mM NaCl, 40 mM imidazole, 500 mM urea, 2% glycerol), and once with NaP-60 buffer (20 mM Na<sub>2</sub>HPO<sub>4</sub>, 5 mM NaH<sub>2</sub>PO<sub>4</sub>, 300 mM NaCl, 60 mM imidazole, 500 mM urea, 2% glycerol). Bound proteins were then eluted with 5 mL of NaP elution buffer (20 mM Na<sub>2</sub>HPO<sub>4</sub>, 5 mM NaH<sub>2</sub>PO<sub>4</sub>, 150 mM NaCl, 300 mM imidazole, 500 mM urea, 2% glycerol). All eluants were dialyzed overnight at 4°C to remove the imidazole.

The HA-DSK2a protein was purified using EZview red anti-HA affinity gel (Sigma-Aldrich). The bacterial cell lysate was incubated with 100 μL PBS-washed anti-HA antibody beads for 1 h at 4°C with continual rotation, then applied to a 12 mL PolyPrep chromatography column (Bio-Rad). After 5 min the flow-through was allowed to run out, and the beads were washed three times with PBS containing 1 M NaCl. Bound protein was eluted by incubating the beads for 30 min at 4°C with 300 μL of PBS containing 500 ng/μL of the HA peptide (YPYDVPDYA; Sigma-Aldrich), and the eluant was dialyzed overnight at 4°C against PBS. In all cases, protein concentration was determined using the Pierce BCA protein assay kit (Thermo Fisher Scientific). For ITC experiments, protein concentrations were additionally confirmed using OD<sub>280</sub> measurements on a DU 800 spectrophotometer (Beckman Coulter), using extinction co-efficients calculated in ProtParam (<https://web.expasy.org/protparam>).

### Quantitative *in vitro* Binding Assays

For testing of protein-protein interactions *in vitro*, full-length proteins were used, except for *Arabidopsis* ATG8e and yeast Atg8, where the processed forms (i.e., amino acids 1 to 118 and 1 to 116, respectively) were used, and RPN10, where only the C-terminal portion (i.e., amino acids 201 to 386) was used, due to the insolubility of recombinant full-length GST-RPN10. To assay direct binding between 6His-ATG8e/Atg8 and their potential interactors, equal amounts (5 μg) of both proteins were combined in 500 μL of binding buffer (150 mM Tris-HCl (pH 7.4), 300 mM NaCl, 5 mM MgCl<sub>2</sub>, 1 mM DTT, 5% (v/v) glycerol, 0.01% (v/v) Triton X-100). Binding was allowed to proceed for 2 h at 4°C, before the addition of 100 μL Ni-NTA agarose beads pre-equilibrated with binding

buffer. Samples were incubated for a further 2 h at 4°C with continual rotation, and the beads were then pelleted by centrifugation at 3,000 × *g* for 1 min at 4°C. The beads were washed 5 times with binding buffer, and bound proteins were eluted into 100 μL of 2X SDS-PAGE sample buffer by heating at 95°C for 5 min. Samples were analyzed by SDS-PAGE followed by immunoblotting with appropriate antibodies as described above. Three-way binding assays to confirm the simultaneous interaction of *Arabidopsis* ATG8e with DSK2a and RPN10 were performed as above with equal amounts (2 μg) of the three interactors, except that the binding buffer contained 150 mM NaCl, and GST-Bind Resin was used to perform the pull-downs.

To determine the affinity of the interactions between *Arabidopsis* ATG8e and the four PUX proteins, quantitative equilibrium binding assays were performed as previously described (Marshall et al., 2015), with minor modifications. Varying concentrations of purified 6His-ATG8e (from 0 to 40 μM) were incubated with 1 μM purified GST-PUX7, GST-PUX8, GST-PUX9 or GST-PUX13 in 100 μL of binding buffer. Binding was allowed to proceed as above and, after pelleting of the Ni-NTA agarose beads, 10 μL of supernatant was analyzed by SDS-PAGE followed by immunoblotting with anti-ATG8 or anti-GST antibodies. Densitometric quantification of the PUX protein bands was performed as above, and the amount remaining in the supernatant when 6His-ATG8e was absent was set at 100% (i.e., 0% bound). The percentage of PUX protein bound was then plotted against the concentration of 6His-ATG8e, with the  $K_D$  being the concentration of 6His-ATG8e at which 50% of the GST-PUX protein was bound.

ITC experiments were conducted using a MicroCal VP-ITC instrument (Malvern Panalytical) at 15°C, with a syringe protein concentration of 100 μM, a cell protein concentration of 10 μM, and a stirring speed of 300 rpm. Thermodynamic analyses were performed by titrations of RPN10, PUX7, PUX8, PUX9 or PUX13 (syringe proteins) into ATG8e (cell protein), with an initial injection of 2 μL followed by 21 consecutive injections of 12 μL, each separated by a time interval of 360 s. The syringe samples were also titrated to a cell filled only with buffer, and the obtained reference data were used for subtracting the heat of dilution. The raw titration data (excluding the initial 2 μL injection) were integrated and fitted to a single-site binding model using MicroCal Origin software version 7.0, and the resulting curve was used to determine the stoichiometry of binding (*N*), the dissociation constant ( $K_D$ ), and the change in enthalpy ( $\Delta H$ ).

### Arabidopsis and Yeast cDNA Library Screens

Coding sequences of the processed forms of *Arabidopsis* ATG8e and yeast ATG8 were PCR-amplified from cDNA using primers encoding *Xho*I and *Nco*I restriction enzyme sites at the 5' end and a *Bam*HI restriction enzyme site at the 3' end. Amplified PCR products were digested with FastDigest *Xho*I and *Bam*HI (Thermo Fisher Scientific) and ligated into pBlueScript II (Agilent Technologies) cut with the same enzymes. Site-directed mutagenesis to obtain the  $\Delta LDS$  and  $\Delta UDS$  mutations was then performed using the QuikChange II site-directed mutagenesis kit. Sequence-confirmed genes were excised by digestion with FastDigest *Nco*I and *Bam*HI (Thermo Fisher Scientific) and ligated into pGBK-T7 (Clontech) cut with the same enzymes. Resulting clones were then transformed into yeast strain AH109 (Clontech).

Strains expressing the above bait plasmids were either mated to strain Y187 that had been transformed with an *Arabidopsis* cDNA library, or subsequently transformed with 500 μg of a yeast cDNA library. The commercially available *Arabidopsis* cDNA library in pGADT7-RecAB was constructed from a mixture of poly(A)-containing mRNAs isolated from 11 tissues chosen to represent a broad range of expressed genes, and was normalized to reduce the copy number of abundant cDNA derived from highly represented mRNAs (Clontech, product number 630487). A yeast cDNA library in the pACT2 vector, derived via automatic sub-cloning from bacteriophage  $\lambda$ -YES in *E. coli* strain BNN132 (Elledge et al., 1991), was generously provided by Stephen J. Elledge (Harvard Medical School).

Positive yeast clones expressing putative interacting partners were identified by growth at 30°C for up to 12 days on synthetic dropout medium lacking adenine, histidine, leucine and tryptophan. Prey plasmids were then extracted from the resulting colonies using the Zymoprep-96 yeast plasmid miniprep kit (Zymo Research), transformed into *E. coli* strain DH5 $\alpha$ , and extracted again using the QIAprep spin miniprep kit (QIAGEN). The prey cDNAs were then identified by DNA sequencing. To confirm the interacting pairs, bait and prey plasmids were individually transformed into strain MaV203, and interactions re-tested by standard Y2H as described above. Proportional Venn diagrams displaying the interactors were produced using eulerAPE (<http://www.eulerdiagrams.org/eulerAPE>), and homology identification was performed by reciprocal BLASTn searches (<https://www.ncbi.nlm.nih.gov/blast>).

To confirm the positive Y2H interactions via dot blot assays, cDNA inserts were excised from the prey plasmids and ligated into an *E. coli* expression vector. *Arabidopsis* inserts were excised by digestion with FastDigest *Sfi*I (Thermo Fisher Scientific), while yeast inserts were excised by digestion with appropriate restriction enzymes that cut either side of the insert within the multiple-cloning site (FastDigest *Bgl*II (Thermo Fisher Scientific) was the preferred option, followed by FastDigest *Xho*I). In all cases, the resulting sticky ends were converted to blunt ends using Klenow fragment (Thermo Fisher Scientific), and the product was ligated into pET17-b (Novagen) digested with FastDigest *Eco*RV (Thermo Fisher Scientific). With the exception of yeast cDNAs excised with *Bgl*II, ligation occurred into a version of pET17-b pre-engineered to encode an N-terminal HA tag between the *Nhe*I and *Eco*RI restriction sites. Sequence-confirmed clones were transformed into *E. coli* strain BL21(DE3) pLysS, and proteins were expressed in 1 mL cultures. Cell growth, induction, lysis, and subsequent dot blot binding assays were performed as described above.

### Immunoprecipitation of GFP-PUX7

*Arabidopsis* seedlings of the indicated genotype (WT (Ws), 35S::GFP or 35S::GFP-PUX7) were grown in 50 mL liquid GM medium as above, with ~100 mg of dry seeds used per culture, resulting in ~5 g of fresh weight tissue. Frozen tissue was ground to a fine powder at liquid N<sub>2</sub> temperatures, and proteins were extracted on ice for 20 min with 1.5 volumes of extraction buffer (50 mM HEPES (pH 7.5),

150 mM NaCl, 10 mM MgCl<sub>2</sub>, 10% (v/v) glycerol, 2% (w/v) polyvinylpyrrolidone, 5 mM DTT, 2 mM PMSF, 0.1% (v/v) Triton X-100, 1X plant protease inhibitor cocktail). Extracts were filtered through two layers of Miracloth, clarified at 30,000 × g for 20 min at 4°C, and the resulting supernatants were immediately applied three times at 4°C over a 12 mL PolyPrep chromatography column containing 100 μL (equal to a 50 μL bead volume) of GFP-Trap\_A beads (ChromoTek) pre-equilibrated in extraction buffer. The column was washed five times with wash buffer (50 mM HEPES (pH 7.5), 150 mM NaCl, 10 mM MgCl<sub>2</sub>, 10% (v/v) glycerol, 2 mM DTT), and remaining bound proteins were eluted with 100 μL of 200 mM glycine-HCl (pH 2.5) and immediately neutralized with 20 μL of 1 M Tris-HCl (pH 8.0). Samples of the crude extract, flow through (both diluted 1/10), third wash step and elution were analyzed by SDS-PAGE followed by silver staining or immunoblotting with appropriate antibodies (as above). Alternatively, elution fractions were subjected to tandem mass spectrometry (see below).

### Tandem Mass Spectrometry

Protein samples from the GFP immunoprecipitation experiments (80 μL of the 120 μL elution volume, from three independent biological replicates) were vacuum dried in a SpeedVac centrifugal evaporator (Savant Instruments, model number SUC100H) to a final volume of approximately 20 μL and denatured in 8 M urea, 25 mM (NH<sub>4</sub>)HCO<sub>3</sub> in a total volume of 300 μL. Proteins were then reduced with 10 mM DTT at room temperature for 1 h, and alkylated in the dark in the presence of 50 mM 2-chloroacetamide at room temperature for a further 1 h. Excess alkylating agent was quenched with 50 mM DTT for 5 min at room temperature, and the samples were diluted with 1.2 mL of 25 mM (NH<sub>4</sub>)HCO<sub>3</sub> to reduce the urea concentration to below 1.5 M. Proteolytic digestion was then initiated by adding 1 μg of sequencing grade modified porcine trypsin (Promega), and the samples were incubated overnight at 37°C. Peptides were vacuum dried as above to a final volume of approximately 300 μL, acidified with 10% trifluoroacetic acid (TFA) until the pH was less than 3.0, and desalted and concentrated on a 100 μL Bond Elut OMIX C18 pipette tip (Agilent Technologies). The peptides were eluted in 50 μL of 75% acetonitrile, 0.1% acetic acid, then lyophilized and re-suspended in 17 μL 5% acetonitrile, 0.1% formic acid.

Nano-scale liquid chromatography (LC) separation of tryptic peptides was performed on a Dionex Ultimate 3000 Rapid Separation LC system (Thermo Fisher Scientific). 6.8 μL of each protein digest was loaded onto a 20 μL nanoViper sample loop (Thermo Fisher Scientific) and separated on a C18 analytical column (Acclaim PepMap RSLC C18 column, 2 μm particle size, 100 Å pore size, 75 μm × 25 cm (Thermo Fisher Scientific)) by the application of a linear 2 h gradient from 4.0% to 36.0% acetonitrile in 0.1% formic acid, with a column flow rate set to 250 nL/min. Analysis of the eluted tryptic peptides was performed online using a Q Exactive Plus mass spectrometer (Thermo Fisher Scientific) possessing a Nanospray Flex ion source (Thermo Fisher Scientific) fitted with a stainless steel nano-bore emitter operated in positive electro-spray ionization (ESI) mode at a capillary voltage of 1.9 kV. Data-dependent acquisition of full MS scans within a mass range of 380–1500 m/z was performed at a resolution of 70,000, with the automatic gain control (AGC) target set to 3.0 × 10<sup>6</sup>, and the maximum fill time set to 200 msec. High energy collision-induced dissociation (HCD) fragmentation of the top 8 most intense peaks was performed with a normalized collision energy of 28, an intensity threshold of 1.3 × 10<sup>4</sup> counts, and an isolation window of 3.0 m/z, excluding precursors that had an unassigned, +1, +7 or +8 charge state. MS/MS scans were conducted at a resolution of 17,500, with an AGC target of 2.0 × 10<sup>5</sup> and a maximum fill time of 300 msec. Dynamic exclusion was performed with a repeat count of 2 and an exclusion duration of 30 s, while the minimum MS ion count for triggering MS/MS was set to 4.0 × 10<sup>3</sup> counts.

The resulting MS/MS spectra were analyzed using Proteome Discoverer (version 2.0.0.802; Thermo Fisher Scientific), which was set up to search the *Arabidopsis* Col-0 proteome database, as downloaded from the *Arabidopsis* Information Resource (<https://www.arabidopsis.org/>; ID number TAIR10\_pep\_20101214). Peptides were assigned using SEQUEST HT, with search parameters set to assume the digestion enzyme trypsin with a maximum of 1 missed cleavage, a minimum peptide length of 6, precursor mass tolerances of 10 ppm, and fragment mass tolerances of 0.02 Da. Carbamidomethylation of cysteine was specified as a static modification, while oxidation of methionine and N-terminal acetylation were specified as dynamic modifications. The target false discovery rate (FDR) of 0.01 (strict) was used as validation for peptide-spectral matches (PSMs) and peptides. Proteins that contained similar peptides, and which could not be differentiated based on the MS/MS analysis alone, were grouped to satisfy the principles of parsimony. All samples were injected in duplicate, with the resulting values combined for the final analysis.

### Quantitative Real-Time PCR Analysis

Total RNA extraction from *Arabidopsis* seedlings or yeast cells treated with or without the indicated concentrations of CDC48/p97 inhibitors, and its subsequent conversion into cDNA, were performed as described above. Quantitative real-time PCR of ER stress-responsive transcripts (*BIP1* and *CRT1* for *Arabidopsis*, and *DER1* and *ERO1* for yeast) was then performed on three independent biological replicates using a LightCycler 480 machine (Roche Diagnostics) and LightCycler 480 SYBR Green I master mix (Roche Diagnostics), with three technical replicates for each reaction. In all cases, the amplification factor of the primer pair was experimentally determined to be between 1.90 and 2.10, with the gradient of the standard curve being between −3.59 and −3.10, and the R<sup>2</sup> value being greater than 0.975.

For each PCR reaction, 5 μL of cDNA (diluted 1/30 following first-strand synthesis) was amplified in a 20 μL reaction volume also containing 10 μL SYBR Green I master mix, 3 μL sterile H<sub>2</sub>O, and 1 μL each of 10 μM forward and reverse primers. Reaction parameters were 95°C for 5 min, 45 cycles of 95°C for 10 s, 55°C for 10 s and 72°C for 30 s, followed by a melting curve program and cooling at 40°C for 2 min. Fluorescence data were collected at the end of each 72°C extension step, and continuously during the melting

curve program. Relative transcript abundance of target genes was determined using the comparative threshold cycle method, using as internal controls the reference genes *ACT2* and *PP2A* for *Arabidopsis*, and *ALG9* and *TFC1* for yeast. All data were normalized to untreated Col-0 seedlings or BY4741 cells for *Arabidopsis* and yeast, respectively.

### Identification of *Arabidopsis* T-DNA Insertion Mutants

T-DNA insertion mutants were identified in the SALK T-DNA Express database (<http://signal.salk.edu/cgi-bin/tdnaexpress>) and obtained from the *Arabidopsis* Biological Resource Center (Ohio State University, USA), the Versailles *Arabidopsis* Stock Center (Institut Jean-Pierre Bourgin, France) or the GABI-Kat collection (Universität Bielefeld, Germany). All insertions were confirmed by genomic PCR using 5' and 3' gene-specific primers (LP and RP, respectively) in conjunction with an appropriate T-DNA left border-specific primer (BP). Details of all oligonucleotide primers are provided in Table S6. Before analysis, each mutant was backcrossed at least twice to its WT ecotype and then selfed to obtain homozygous progeny. Higher order mutants were generated by multiple rounds of standard introgression and selfing.

### Transient Expression in *Arabidopsis* Protoplasts

The coding sequence of *Arabidopsis CDC48a* was PCR-amplified from Col-0 cDNA using primers encoding *Sall* and *XbaI* restriction enzyme sites at the 5' end and a *Sall* restriction enzyme site at the 3' end. The amplified PCR product was digested with FastDigest *Sall* (Thermo Fisher Scientific) and ligated into pBlueScript II cut with the same enzyme. An internal *XbaI* site within *CDC48a* was then mutated synonymously using the QuikChange II site-directed mutagenesis kit, and the sequence-confirmed gene was excised by digestion with FastDigest *XbaI* and *Sall* and ligated into pDHA (Marshall et al., 2008) cut with the same enzymes, for transient expression driven by the CaMV 35S promoter. Further site-directed mutagenesis to insert coding substitutions associated with various human diseases (Tang and Xia, 2016) was then performed.

*Arabidopsis* mesophyll protoplasts from Col-0, *atg7-2* or *pux-q* leaves were prepared and transfected as previously described (Yoo et al., 2007), with minor modifications. Leaves from 4 to 5-week-old soil-grown plants were scarified on their underside using a sterilized scalpel blade and incubated in 1X enzyme solution (1.5% (w/v) cellulase "Onozuka" R-10, 0.4% (w/v) macerozyme R-10 (both from Yakult Pharmaceutical Industries), 400 mM mannitol, 20 mM KCl, 20 mM MES (pH 5.7)) for 6 h in the dark. Protoplasts were released by gentle swirling, and the protoplast/enzyme mixture was diluted with 1 volume of W5 buffer (150 mM NaCl, 125 mM CaCl<sub>2</sub>, 5 mM KCl, 4 mM MES (pH 5.7)) and filtered through a 75 μm nylon mesh to remove remaining leaf debris. Protoplasts were collected by centrifugation at 100 x g for 5 min, washed once in 20 mL W5 buffer, incubated on ice for 30 min, re-suspended in MMG buffer (400 mM mannitol, 15 mM MgCl<sub>2</sub>, 4 mM MES (pH 5.7)) at a concentration of 10<sup>7</sup> cells/mL, and then incubated in the dark for 30 min.

Protoplasts were transfected by mixing 500 μL of cells with 20 μg plasmid DNA, followed by drop-wise addition of 500 μL PEG buffer (40% polyethylene glycol 4000, 400 mM mannitol, 100 mM CaCl<sub>2</sub>) with gentle mixing. Protoplasts were then incubated for a further 30 min at room temperature, 1 mL of W5 solution was added drop-wise and gently mixed, and the cells were collected by centrifugation at 100 x g for 5 min, followed by re-suspension in 1 mL WI buffer (400 mM mannitol, 20 mM KCl, 4 mM MES (pH 5.7)). The cells were then incubated in the dark for 16 h to permit gene expression, collected by centrifugation at 100 x g for 5 min, and the cell pellets were frozen on dry ice. Cells were homogenized by addition of 300 μL homogenization buffer (150 mM Tris-HCl (pH 7.5), 150 mM NaCl, 1.5% (v/v) Triton X-100, 1X plant protease inhibitor cocktail) followed by vigorous mixing with a vortex, clarified twice by centrifugation at 16,000 x g for 5 min at 4°C, and the supernatant was made 1X with 5X SDS-PAGE sample buffer. Samples were then heated at 95°C for 5 min before analysis by SDS-PAGE and immunoblot as above.

### Yeast Growth and Viability Assays

Cells of the indicated genotypes were grown in 15 mL synthetic dropout medium lacking appropriate amino acids and containing 2% glucose as the carbon source. Following 12 h overnight growth, cultures were diluted to an OD<sub>600</sub> of 0.2 in 50 mL synthetic dropout medium lacking appropriate amino acids and containing either 2% glucose or 2% galactose as the carbon source. Growth was then monitored by measurement of OD<sub>600</sub> values in the presence or absence of 1.5 mM DTT or 200 ng/mL tunicamycin (both from Sigma-Aldrich) using a Smartspec 3000 UV/Vis spectrophotometer (Bio-Rad), or by growth of cells on solid synthetic dropout medium lacking appropriate amino acids and containing glucose or galactose as indicated. Susceptibility to DTT or tunicamycin was determined by normalizing the OD<sub>600</sub> value of each strain in the presence of the chemical to growth in their absence. For growth on solid medium, cells were re-suspended in liquid synthetic dropout medium lacking appropriate amino acids, and containing glucose or galactose as the carbon source, to an OD<sub>600</sub> of 1.0, then subjected to a series of 5-fold dilutions, before 5 μL of each dilution was spotted onto the same medium containing or lacking 1.5 mM DTT or 200 ng/mL tunicamycin. Cells were then grown for 48 h at 30°C prior to imaging.

### Pho8Δ60 Enzyme Assays

The Pho8Δ60 assay for quantitative measurement of yeast autophagic flux was performed essentially as described (Noda et al., 1995), using the spectrophotometric assay with minor modifications. Strains TN124 or RSM294-302 were grown in 250 mL cultures with an appropriate carbon source, subjected to nitrogen starvation, and aliquots corresponding to 5.0 OD units were collected at the indicated time points, all as described above. Cell pellets were re-suspended in 500 μL lysis buffer (20 mM piperazine-N,N'-bis-2-ethanesulfonic acid (PIPES)-KOH (pH 8.5), 50 mM KCl, 100 mM KCH<sub>3</sub>COO, 10 mM MgSO<sub>4</sub>, 10 μM ZnSO<sub>4</sub>,

0.5% (v/v) Triton X-100, 1 mM PMSF) and lysed by the addition of acid-washed glass beads to a volume of approximately 200  $\mu$ L, followed by vigorous mixing with a vortex for a total of 5 min at 4°C (10 rounds of mixing for 30 s, then resting on ice for 30 s). Non-lysed cells and insoluble debris were pelleted by centrifugation at 16,000  $\times$  g for 5 min at 4°C, and the supernatant was collected for subsequent analysis.

The total protein concentration of each sample was determined by Pierce BCA protein assay kit, and equal amounts of protein (20  $\mu$ g) were assayed for alkaline phosphatase activity. Protein samples in a volume of 100  $\mu$ L were mixed with 400  $\mu$ L pre-warmed assay buffer (250 mM Tris-HCl (pH 8.5), 10 mM MgSO<sub>4</sub>, 10  $\mu$ M ZnSO<sub>4</sub>, 1.5 mM *p*-nitrophenyl phosphate, 1% (v/v) Triton X-100) and incubated for 10 min at 37°C. Reactions were quenched by addition of 500  $\mu$ L 1 M glycine-KOH (pH 11.0), and the absorbance of *p*-nitrophenol at 400 nm was measured spectrophotometrically, as above. Following subtraction of the appropriate enzyme and substrate only controls, specific alkaline phosphatase activity was calculated from a *p*-nitrophenol standard curve. Three technical replicates were performed for each sample, and the data from three independent biological replicates was averaged and normalized to the activity observed at the 0 h time point.

### Sequence Alignments and Phylogenetic Analysis

Predicted full-length nucleotide and protein sequences were obtained from appropriate databases (for full details see [Tables S1 and S2](#)), while domain positions were predicted by the SMART (<http://smart.embl-heidelberg.de>) and PFAM (<http://pfam.xfam.org>) databases. Progressive alignments of predicted full-length amino acid sequences were performed using Clustal Omega ([www.clustal.org/omega](http://www.clustal.org/omega)) with the default settings and, following minor manual editing, final alignments were displayed with BoxShade version 3.2.3 ([https://embnet.vital-it.ch/software/BOX\\_form.html](https://embnet.vital-it.ch/software/BOX_form.html)). Species abbreviations used are: *At*, *Arabidopsis thaliana*; *Bd*, *Brachypodium distachyon*; *Ce*, *Caenorhabditis elegans*; *Dm*, *Drosophila melanogaster*; *Gm*, *Glycine max*; *Hs*, *Homo sapiens*; *Os*, *Oryza sativa*; *Pp*, *Physcomitrella patens*; *Pt*, *Populus trichocarpa*; *Sc*, *Saccharomyces cerevisiae*; *Sm*, *Selaginella moellendorffii*; *Vv*, *Vitis vinifera*; *Zm*, *Zea mays*. Sequence conservation of the plant ATG8 isoforms was calculated and displayed using JalView version 2 (<http://www.jalview.org>).

To determine UDS and UIM consensus sequences, the interaction strength of each point mutation variant of the ATG8a UDS and RPN10 and PUX7 UIMs was determined based on its mean interaction signal, as quantified using ImageQuant version 5.2 (GE Healthcare); the variant was considered a true interactor when both Y2H and dot blot binding signals were above the background level. The mean BLOSUM62 value for each site within the UDS or UIMs was then calculated to give the complete set of mutations that yielded true interaction variants (<ftp://ftp.ncbi.nlm.nih.gov/blast/matrices>). Since a higher BLOSUM62 value implies stronger conservation of the mutation, mean BLOSUM62 values were applied to quantify the evolutionary relevance of the complete set of mutations for each site within or surrounding the UDS and UIMs. The stretch of amino acids with high positive mean BLOSUM62 values were defined as the consensus region for each domain.

Bayesian phylogenetic analyses of the full-length *Arabidopsis* PUX proteins was performed with MrBayes version 3.2.2 ([Ronquist and Huelsenbeck, 2003](#)), using the General Time Reversible evolutionary model with the mixed amino acid model and  $\gamma$ -distributed rate variation with a proportion of invariable sites. The software was run for 1,000,000 generations, with a sampling frequency of every 1,000 generations. The first 250,000 generations (25%) were discarded as “burn-in” after checking that the log likelihood values had plateaued and that the potential scale reduction factor was close to 1.000. The resulting consensus tree was displayed using FigTree version 1.4.2 (<http://tree.bio.ed.ac.uk/software/figtree>).

### Protein Structure Modeling

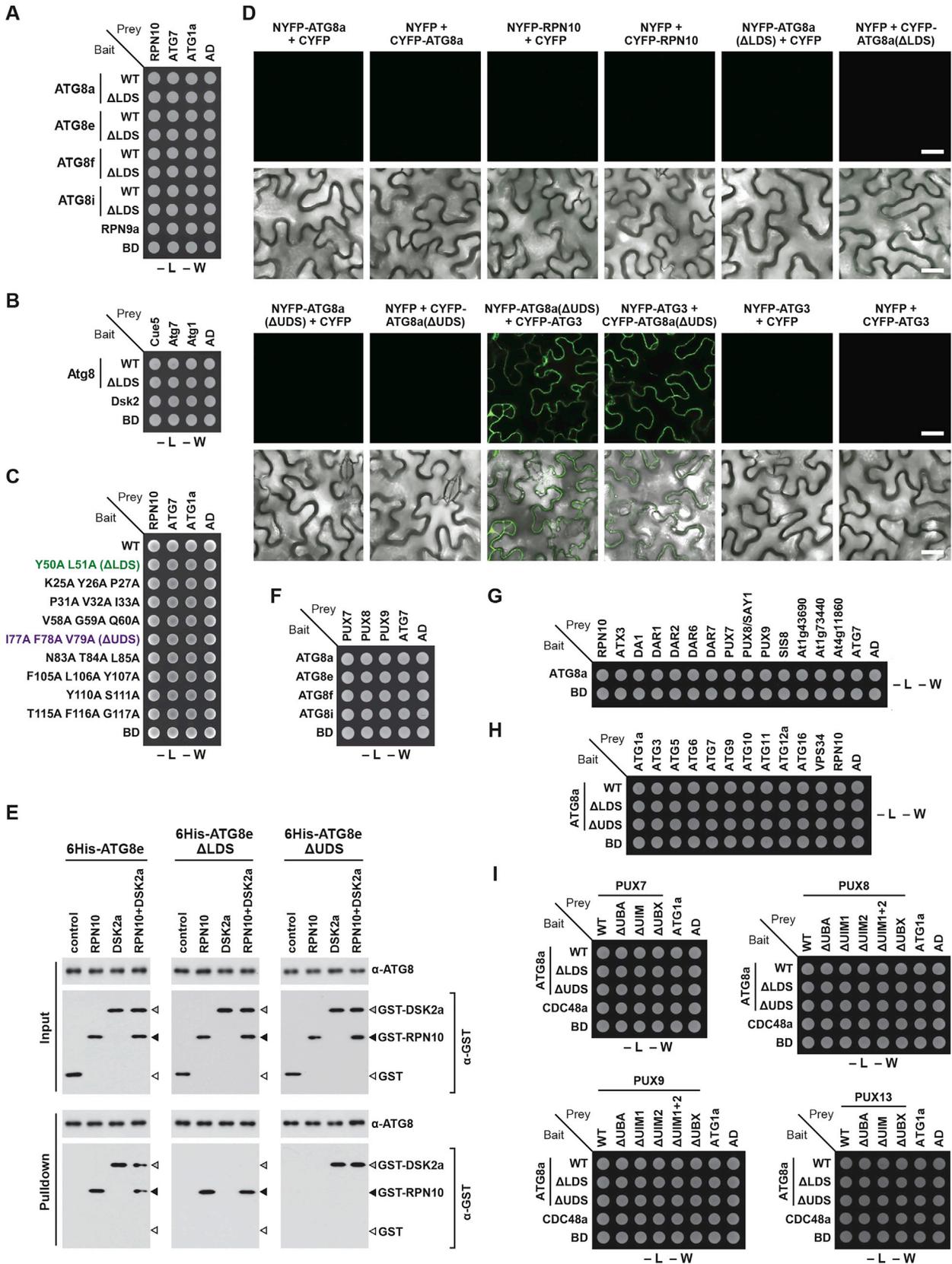
The 3-dimensional positions of potential UIM-binding sites in *Arabidopsis* ATG8, and of mutated residues within CDC48/p97 that trigger its autophagic degradation, were mapped with UCSF Chimera (<https://www.cgl.ucsf.edu/chimera/>), using as templates the structures 3VXW and 5FTK, respectively, from the Protein Data Bank (<https://www.rcsb.org/pdb>).

## QUANTIFICATION AND STATISTICAL ANALYSIS

All datasets were statistically analyzed using one-way analysis of variance (ANOVA), followed by Tukey’s post hoc tests to identify significantly different data points. Significance was defined as  $p \leq 0.05$  or  $p \leq 0.01$ . Statistical details for each experiment can be found in the Figure Legends. At least three biological replicates were performed in all cases, unless otherwise noted. Due to the nature of the experiments, no methods were employed to determine strategies for sample randomization, stratification, and/or size estimation.

## DATA AND SOFTWARE AVAILABILITY

Datasets generated from cDNA library screens are provided in [Table S3](#). The mass spectrometry-based proteomics data have been deposited to the ProteomeXchange Consortium (<http://www.proteomexchange.org>) via the PRIDE partner repository with the dataset identifier PXD011397. All accession numbers for genes and proteins used in this study are provided in [Table S1](#).



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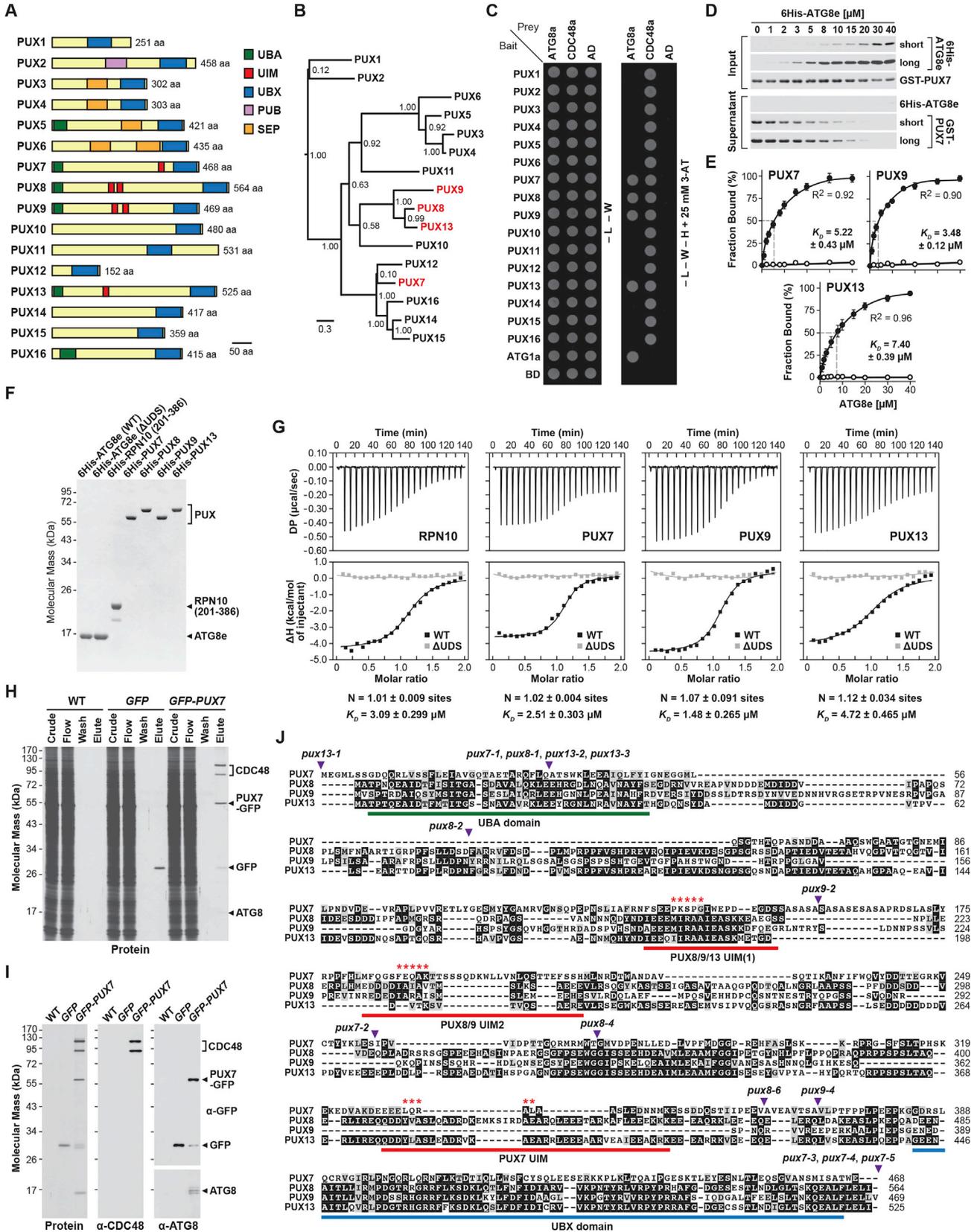
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**Figure S1. Control Y2H, BiFC, and *In Vitro* Binding Assays Used to Map the RPN10 Binding Site on ATG8, Related to Figures 1 and 2**

(A, B and C) Growth of transformed yeast cells on synthetic dropout medium lacking leucine and tryptophan from the Y2H assays in Figures 1A, 1B, and 1E, confirming that all plasmid combinations are able to support growth on non-selective medium.

(D) BiFC assays showing that the NYFP- or CYFP-tagged RPN10 and ATG8a constructs do not produce a fluorescence signal due to auto-activation. *N. benthamiana* leaf epidermal cells were co-infiltrated with the indicated plasmid combinations, and fluorescence signals were detected by confocal fluorescence microscopy 36 h following infiltration. Merged bright field (BF) and fluorescence images are shown. Scale bar, 10  $\mu$ m.

(E) Mutation of the ATG8e LDS or UDS does not impair binding of RPN10 or DSK2a to the alternate site. Equal amounts (2  $\mu$ g) of purified protein were incubated together and pulled down with Ni-NTA agarose beads. Input and bound proteins were then visualized by immunoblotting with anti-ATG8 and anti-GST antibodies. (F, G, H and I) Growth of transformed yeast cells on synthetic dropout medium lacking leucine and tryptophan from the experiments in Figures 2A–2C and 2G, confirming that all plasmid combinations are able to support growth on non-selective medium.



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**Figure S2. Four *Arabidopsis* PUX Proteins Interact with Both ATG8 and CDC48, Related to Figures 2 and 6**

(A) Box diagrams of the 16-member *Arabidopsis* UBX domain-containing family. Positions of the UBA, PUB, SEP and UBX domains are indicated by the green, purple, orange and blue boxes, respectively, while the UIMs are highlighted in red. The amino acid length of each polypeptide is shown on the right. Accession numbers for the given proteins are listed in [Table S1](#).

(B) Phylogenetic analysis of the *Arabidopsis* PUX protein family. The full-length predicted amino acid sequences of the 16 *Arabidopsis* PUX proteins were aligned in Clustal Omega, subjected to Bayesian phylogenetic analysis with MrBayes version 3.2, and the resulting consensus tree displayed using FigTree. ATG8-interacting PUX proteins are highlighted in red; the scale bar represents substitutions per site.

(C) Y2H assays testing interactions between ATG8a and the 16 *Arabidopsis* PUX proteins. Full-length proteins fused with either the GAL4 activating (AD) or DNA-binding (BD) domains at their N-termini were co-expressed in the indicated pairwise orientations. Shown are cells grown on medium lacking leucine and tryptophan (left panel), or leucine, tryptophan and histidine and containing 25 mM 3-amino-1,2,4-triazole (3-AT; right panel).

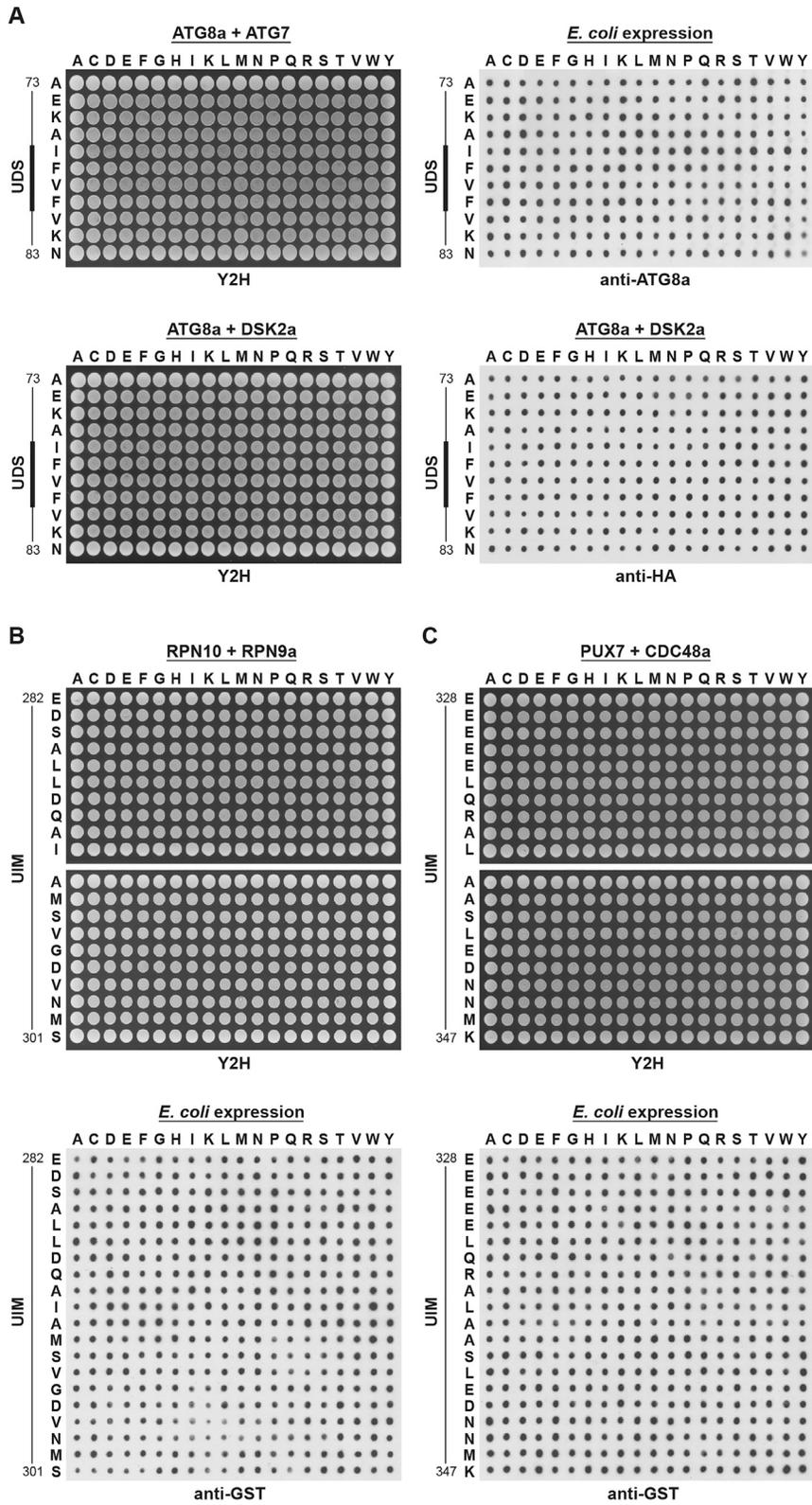
(D and E) Quantification of the binding affinity between PUX7, PUX9 or PUX13 and ATG8e. Various concentrations of 6His-ATG8e were incubated with 1  $\mu$ M GST-tagged PUX protein and pulled down with Ni-NTA beads. PUX protein remaining in the supernatant was then quantified by immunoblotting with anti-GST antibodies and expressed as a percentage of the input. Values represent the mean ( $\pm$ SD) from three independent biological replicates.

(F) Purity of the proteins used for isothermal titration calorimetry (ITC) analysis. The indicated proteins were expressed and purified from *E. coli* by Ni-NTA affinity chromatography, and equal amounts of protein (2  $\mu$ g) were subjected to SDS-PAGE and stained for protein with Coomassie Brilliant Blue.

(G) Quantification of the binding affinity between RPN10, PUX7, PUX9 or PUX13 and ATG8e, as determined by ITC. Top panels show heat differences upon successive injections of 6His-tagged RPN10 or PUX protein into WT 6His-ATG8e, while lower panels show integrated heats of injection (squares) and the best fit to a single site binding model (solid lines) for interaction with WT (black) or  $\Delta$ UDS (gray) forms of ATG8e. The N and  $K_D$  values represent the mean ( $\pm$ SD) from three independent biological replicates.

(H and I) CDC48 and ATG8 co-immunoprecipitate together with GFP-PUX7 from *Arabidopsis* seedlings. Total protein extracts from 7-day-old WT, GFP or GFP-PUX7 seedlings were incubated with GFP-Trap\_A beads, washed, and eluted at low pH. Fractions were subjected to SDS-PAGE and either stained for protein with silver, or immunoblotted with anti-CDC48, anti-GFP or anti-ATG8 antibodies.

(J) Sequence alignment of all ATG8-interacting PUX proteins from *Arabidopsis*. Identical amino acids (50% threshold value) are shown with a black background; similar amino acids are shown with a gray background. Positions of the UBA and UBX domains and the UIMs are indicated by green, blue and red lines, respectively. The amino acids mutated to abolish UIM binding activity are indicated by red asterisks; the positions of T-DNA insertions analyzed in [Figures S5G](#) and [S5H](#) are shown by purple arrowheads. Amino acid numbers are indicated on the right.



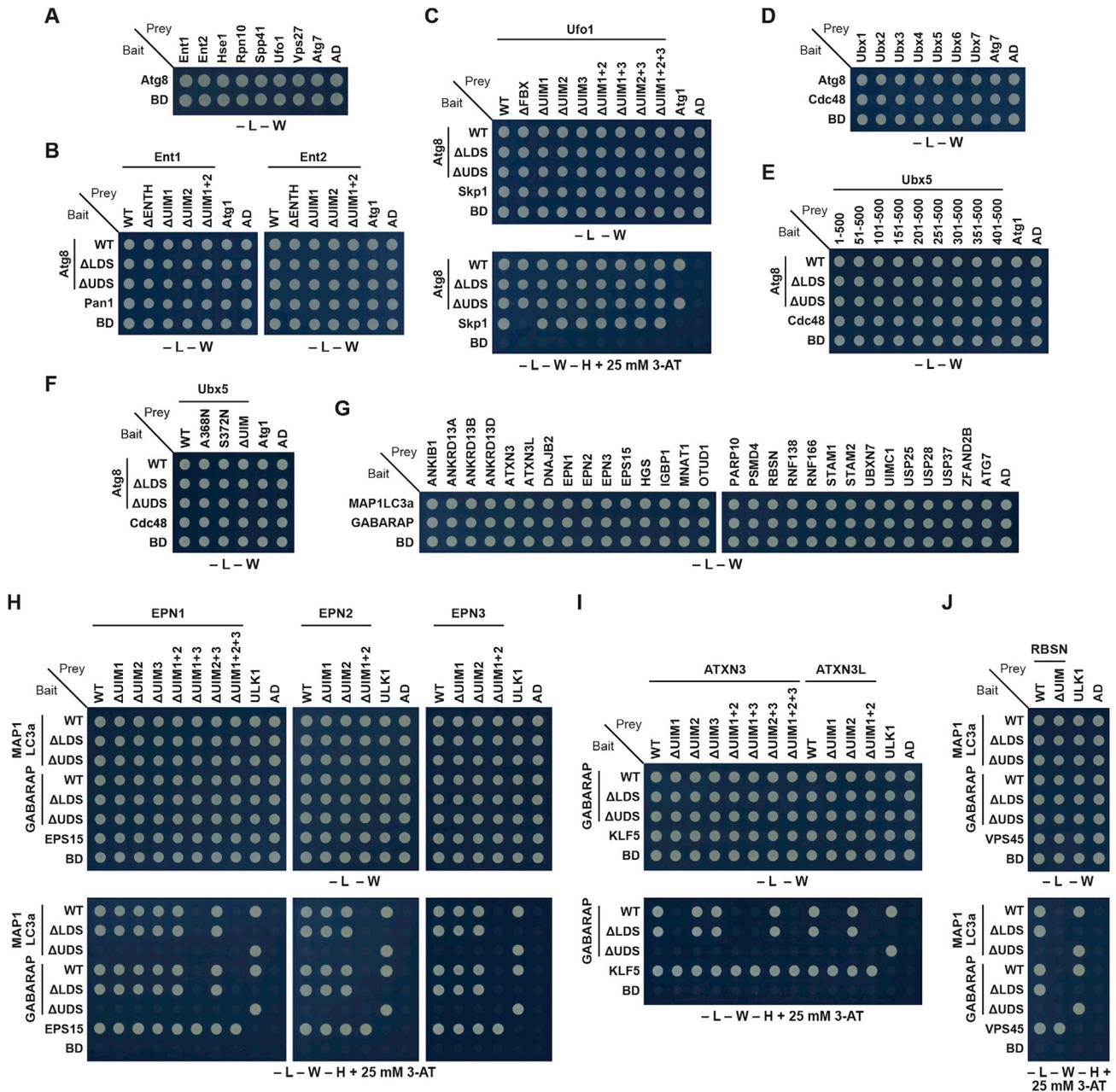
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**Figure S3. Control Y2H and Dot Blot Binding Assays Used to Determine the Requirements for UIM-UDS Interaction, Related to Figures 3 and 5**

(A) Saturating mutagenesis of the *Arabidopsis* ATG8a UDS does not impact its interaction with ATG7 or DSK2a, or its expression in *E. coli*. The panel of mutants employed in Figures 3A and 3B were tested for their ability to interact with ATG7 by Y2H (upper left panel), with DSK2a by Y2H and *in vitro* dot blot binding assay (lower panels), or to accumulate in *E. coli*, as detected by immunoblot of lysed cell extracts with anti-ATG8a antibodies (upper right panel).

(B and C) Saturating mutagenesis of the *Arabidopsis* RPN10 and PUX7 UIMs does not impact their interaction with RPN9a and CDC48a, respectively, or their expression in *E. coli*. The panel of mutants employed in Figures 5A and 5B were tested for their ability to interact with RPN9a or CDC48a by Y2H (upper panel), or to accumulate in *E. coli*, as detected by immunoblot of lysed cell extracts with anti-GST antibodies (lower panel).

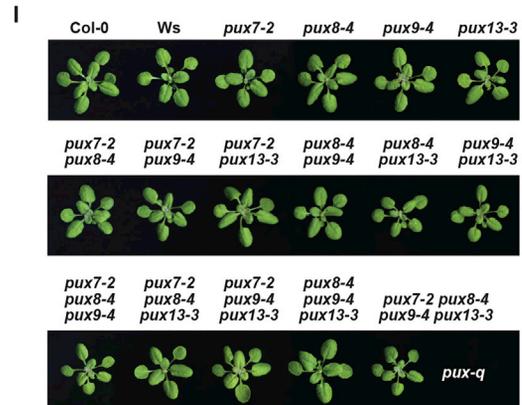
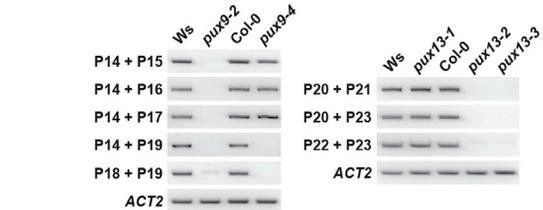
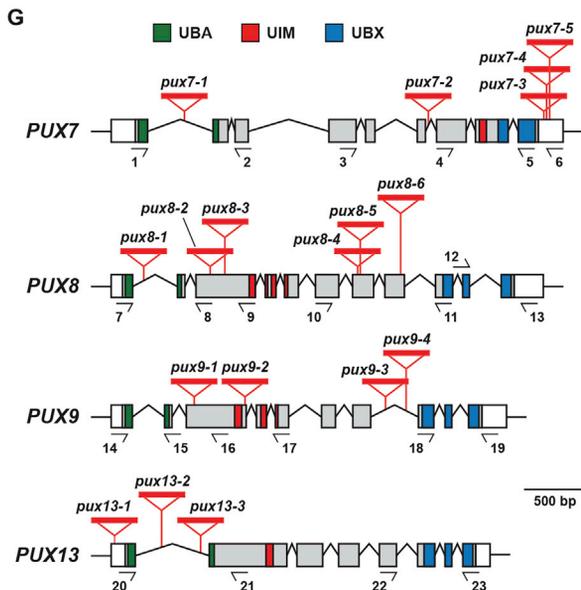
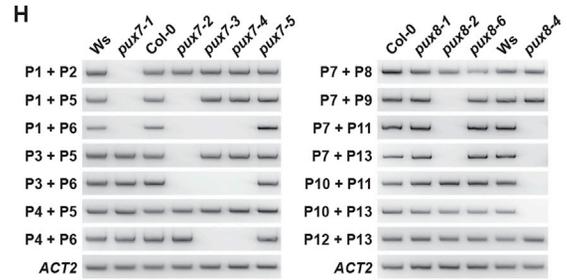
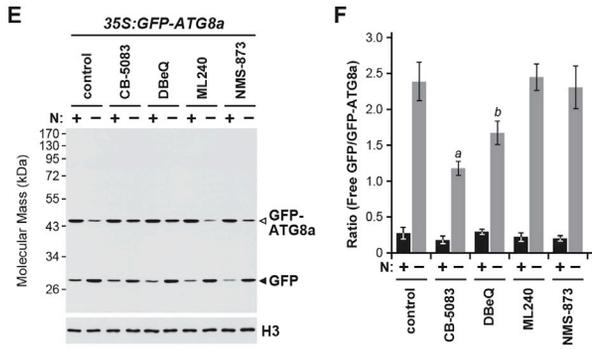
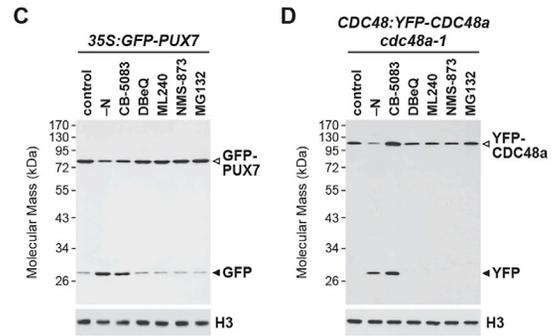
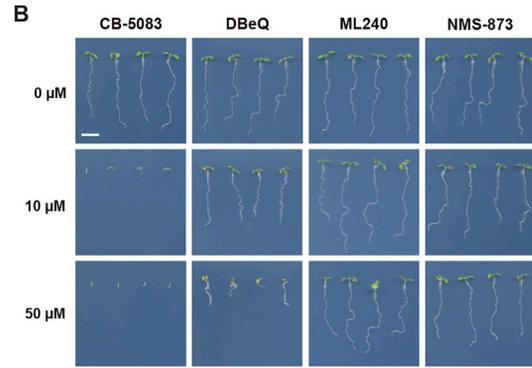
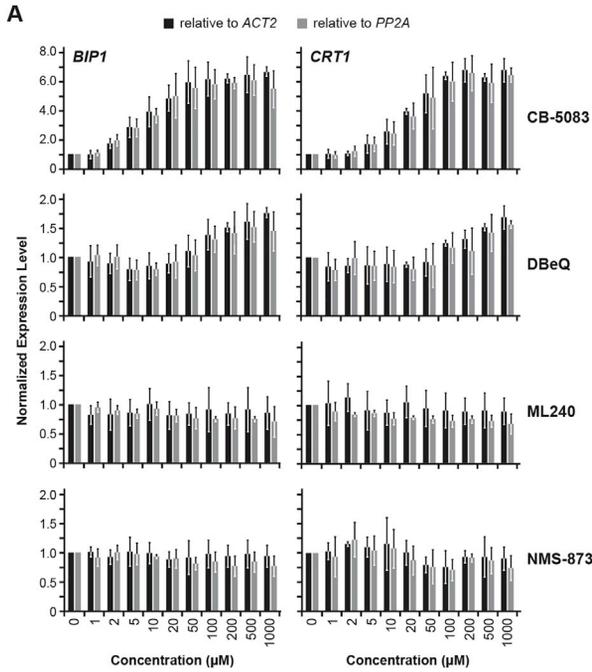


**Figure S4. Control Y2H Assays Used to Identify and Map UIM-Containing ATG8-Interacting Proteins from Yeast and Humans, Related to Figure 4**

(A, B, D, E, F and G) Growth of transformed yeast cells on synthetic dropout medium lacking leucine and tryptophan from the experiments in Figures 4A–4C and 4E, confirming that all plasmid combinations are able to support growth on non-selective medium. Interactions of Atg8 with Atg7 and Atg1, Ent1 and Ent2 with Pan1, Ubx proteins with Cdc48, and MAP1LC3a and GABARAP with ATG7 were used as controls.

(C) Yeast Ufo1 does not use a UIM to interact with Atg8. Various Ufo1 combinations, either full length, missing the FBX domain, or with mutations in one or more UIM sequences, were tested for interaction with WT, ΔLDS or ΔUDS forms of Atg8. Details of all mutations are given in Table S1. Shown are cells grown on selective and non-selective medium, as in Figure S2C. The interaction of Ufo1 with Skp1 was used as a control.

(H, I and J) The UIM regions in human ATXN3, ATXN3L, EPN1, EPN2, EPN3 and RBSN are required for binding to MAP1LC3a and/or GABARAP at the UDS. Various combinations of the above proteins, either WT or with mutations in one or more of their UIM sequences, were tested for interaction with WT, ΔLDS or ΔUDS forms of MAP1LC3a or GABARAP. Shown are cells grown on both selective and non-selective medium, as in panel (C). Interactions of MAP1LC3a and GABARAP with ULK1, EPN1–EPN3 with EPS15, ATXN3 and ATXN3L with KLF5, and RBSN with VPS45 were used as controls.



**Figure S5. Identification of p97 Inhibitors Effective in Plants and Assembly of a Quadruple Mutant Eliminating the Four *Arabidopsis* ATG8-Interacting PUX Proteins, Related to Figure 6**

(A) The human CDC48/p97 inhibitor CB-5083 induces ER stress in *Arabidopsis*. Total RNA was extracted from 7-day-old WT seedlings treated with the given concentrations of CB-5083, DBeQ, ML240 or NMS-873 for 16 h, and converted to first-strand cDNA. Relative transcript abundance of the ER stress-responsive genes *BIP1* and *CRT1* was determined by quantitative real-time PCR, using the *ACT2* and *PP2A* genes as internal reference standards. All data points were normalized to untreated seedlings; the bars represent mean ( $\pm$ SD) from three independent biological replicates, each with three technical replicates.

(B) CB-5083 treatment impairs *Arabidopsis* seedling growth. WT seedlings were grown for 7 days on solid GM medium containing the indicated concentrations of CB-5083, DBeQ, ML240 or NMS-873.

(C and D) CB-5083 stimulates the autophagic turnover of both GFP-PUX7 (panel (C)) and YFP-CDC48a (panel (D)), as determined by the GFP/YFP-release assay. Seedlings were grown for 6 days and then switched from nutrient-rich medium to either medium lacking nitrogen or medium containing 20  $\mu$ M of CB-5083, DBeQ, ML240 or NMS-873 for 16 h. Total protein extracts were assayed for GFP or YFP release as in Figure 6A.

(E) CB-5083 treatment reduces bulk autophagic flux in *Arabidopsis*. Seedlings expressing *GFP-ATG8a* were grown for 6 days, treated with 20  $\mu$ M CB-5083, DBeQ, ML240 or NMS-873 for 16 h, then switched from nutrient-rich medium to medium lacking nitrogen for an additional 16 h. Total protein extracts were assayed for GFP release as in panel (C).

(F) Quantification of the ratio of free GFP to GFP-ATG8a from the experiment shown in panel (E) and two additional independent biological replicates. Bars represent the mean ( $\pm$ SD) from three independent biological replicates; letters indicate values statistically significantly different from one another and the control ( $p < 0.05$ ).

(G) Diagram of the *PUX7*, *PUX8*, *PUX9* and *PUX13* genes. The boxes represent coding regions (colored) or predicted untranslated regions (white), while lines represent introns. The green, red and blue boxes identify UBA domains, UIMs and UBX domains, respectively. Positions of the T-DNA insertions are indicated by the red triangles; sites of amino acid sequence disruption are shown in Figure S2D. Positions of oligonucleotide primers used for reverse transcription (RT)-PCR in panel (H) are indicated by the half arrowheads.

(H) RT-PCR analysis of the *PUX7*, *PUX8*, *PUX9* and *PUX13* transcripts in the indicated T-DNA insertions. Total RNA was extracted from 7-day-old WT or homozygous mutant seedlings, converted to first-strand cDNA, and subjected to RT-PCR using the primer pairs shown in panel (G). Amplification of *ACT2* was included to confirm analysis of equal amounts of cDNA.

(I) Phenotypes of individual and higher order *pux* mutant plants. Plants with the indicated *pux* genotypes were grown on soil for 3 weeks under a long-day photoperiod.

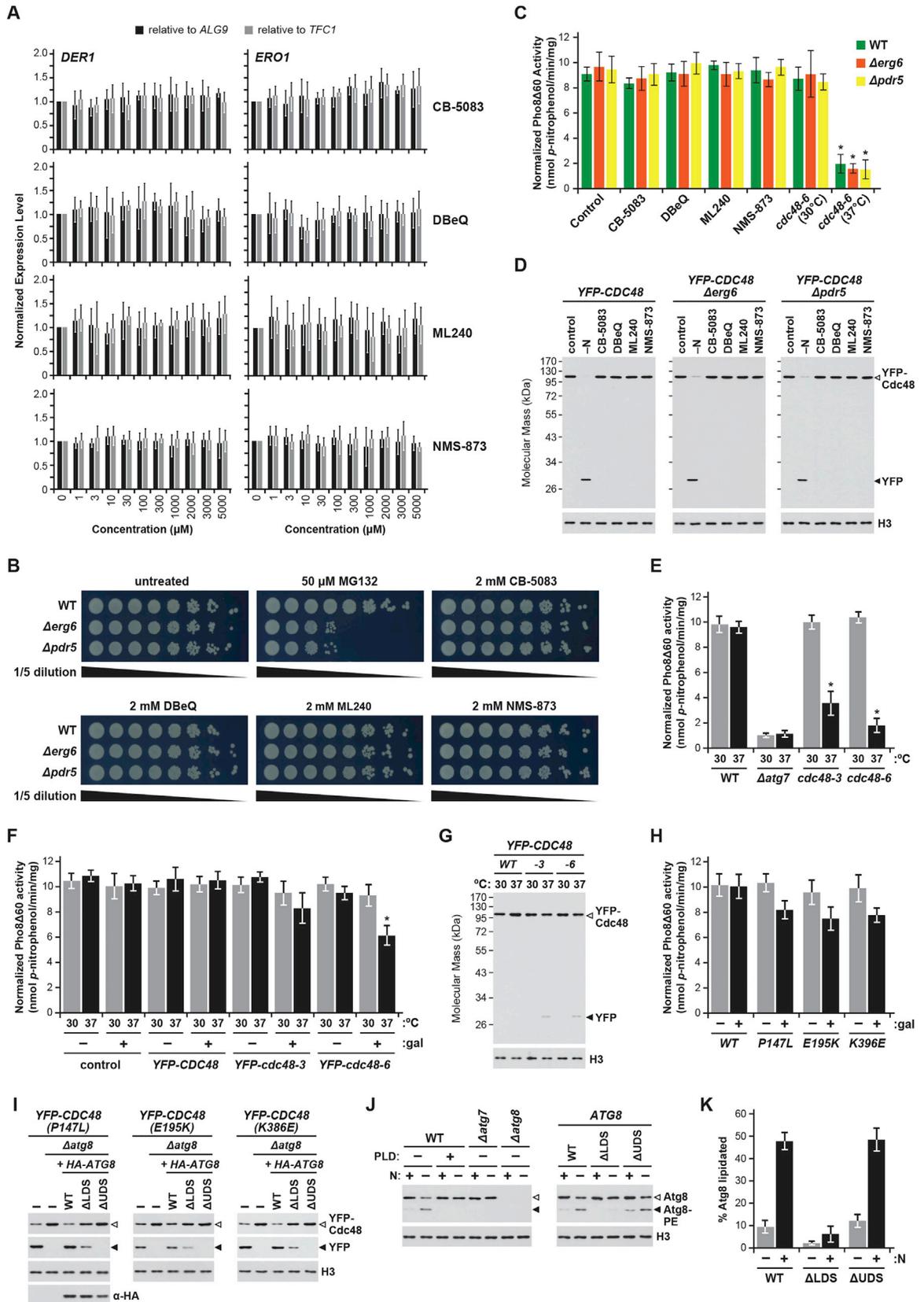
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Ai CDC48b	MA-----NQAESD-S-KSGTKKDFSTAI--L-----EKKK-----AANRLVVDVAINDDNSVSVLHPPTMEKQLQFRGDT	61
Ai CDC48c	MS-----NEPESD-S-KTKKDFSTAI--L-----FRKK-----SPNRLVVDVAINDDNSVSVLHPPTMEKQLQFRGDT	60
Ai CDC48d	MGRRGGGGGGGGGGINRRY-LGQVMDTCCKDLSTAEIDVDDLRSRYGNFARLTRQVLLNVRQVLLNVRNKRKVKDEDEDDNIGDEEGSA	89
Sc Cdc48	MGE-----EHKPLLDASGVDPREEDKDTAT--L-----RRKK-----KDNMLVVDVAINDDNSVIAINSNMDKIELFRGDT	66
Hs p97	-----MAGS-ADSKGDDLSTAI--L-----KQKN-----RPNRLVVDVAINDDNSVSVLSQPKMDELQQLFRGDT	56
Ai CDC48a	ILIKGKKRKDVTCTALADETCDEPKIRMNKVVRSNLRVRL-----GDVISVHQCPDVKYGRVHHLFVDDTVEGVVGNLF	135
Ai CDC48b	ILIKGKKRKDVTCTALADETCDEPKIRMNKVVRSNLRVRL-----GDVISVHQCPDVKYGRVHHLFVDDTVEGVVGNLF	136
Ai CDC48c	ILIKGKKRKDVTCTALADETCDEPKIRMNKVVRSNLRVRL-----GDVISVHQCPDVKYGRVHHLFVDDTVEGVVGNLF	135
Ai CDC48d	SQRKQR-----VDKEEKLRARQESHLRKRNMERSVSSSPSSSSSEDSGDVSTSEDAVYGEKLSPPRFDLI-----NDSLR	163
Ai CDC48e	VLVKGKKRKDVTCTALADETCDEPKIRMNKVVRSNLRVRL-----GDLVTIHPCPDKYATRISVLPFADTTECTVGNLF	141
Sc Cdc48	VLLKGGKRRREAVCVLSDDTCSDEKIRMNKVVRSNLRVRL-----GDVISIQPCPDVYKGRVHHLFVDDTVEGVVGNLF	131
Ai CDC48a	DAYLKPYFLEAYRPVRKGDIFLVRGGMRSVEFKVIETD-PAEYCVV---APDTEFFCEGEPVKREDE-ERLDDVGYDDVGGVRKQMAQI	219
Ai CDC48b	DAYLKPYFLEAYRPVRKGDIFLVRGGMRSVEFKVIETD-PAEYCVV---APDTEFFCEGEPVKREDE-ERLDEVGYDDVGGVRKQMAQI	220
Ai CDC48c	DAYLKPYFLEAYRPVRKGDIFLVRGGMRSVEFKVIETD-PAEYCVV---APDTEFFCEGEPVKREDE-ERLDEVGYDDVGGVRKQMAQI	219
Ai CDC48d	-----MLETSSVCDNIA-----GNEKWRAEAEVGGNERALQAL	34
Ai CDC48e	DNVAKLN-SSSKKPIGSP-----AEKNVEVETVSNKGRSKLATMGARKEAKVLSLSGATGNGDLEVGTGKPTFDGFGIKRLDEL	245
Sc Cdc48	DVELKPYFLEAYRPVRKGDIFLVRGGMRSVEFKVIETD-PAEYCVV---AQDTIHHWEGEPNREDEENNMNEVGYDDIGCCRKQMAQI	226
Hs p97	EVLKPYFLEAYRPVRKGDIFLVRGGMRAVEFKVIETD-PSYCVI---APDTEVHCEGEPVKREDEESLNEVGYDDIGCCRKQMAQI	216
Ai CDC48a	RELVELPLRHPOLFKSIGVKPKGILLYGPPGSGKTLIARAVANETGAFFFCINGPEIMSKLAGESESNLRKAFEEA-----KNAPSIF	305
Ai CDC48b	RELVELPLRHPOLFKSIGVKPKGILLYGPPGSGKTLIARAVANETGAFFFCINGPEIMSKLAGESESNLRKAFEEA-----KNAPSIF	306
Ai CDC48c	RELVELPLRHPOLFKSIGVKPKGILLYGPPGSGKTLIARAVANETGAFFFCINGPEIMSKLAGESESNLRKAFEEA-----KNAPSIF	305
Ai CDC48d	RELIFFRVYLEARTLGLKWRGILLYGPPGSGKTLVRAVVECDALHILVLSPHSVHRAHAGESEKVLREAEASHAVSDKPSVIF	124
Ai CDC48e	EMNVLFPILNPEPFKIKVKKPKGILFHGPPGSGKTKLANATANRACVFFYKISATEVHSGVSGASENTRLEFSKAY-----RTAPSIF	331
Sc Cdc48	RELVELPLRHPOLFKAIGVKPKGILLYGPPGSGKTLIARAVANETGAFFFCINGPEIMSKLAGESESNLRKAFEEA-----KNAPSIF	312
Hs p97	KEMVELPLRHPALFKAIGVKPKGILLYGPPGSGKTLIARAVANETGAFFFCINGPEIMSKLAGESESNLRKAFEEA-----KNAPSIF	302
Ai CDC48a	IDEIDSAPKREKTHGEVERRIVSOLLTMDGLKSR-----AHVIVMGATNRPNSIDPALRRFRGFRDREIDICVDEIGRLEVL	385
Ai CDC48b	IDEIDSAPKREKTHGEVERRIVSOLLTMDGLKSR-----AHVIVMGATNRPNSIDPALRRFRGFRDREIDICVDEIGRLEVL	386
Ai CDC48c	IDEIDSAPKREKTHGEVERRIVSOLLTMDGLKSR-----AHVIVMGATNRPNSIDPALRRFRGFRDREIDICVDEIGRLEVL	385
Ai CDC48d	IDEIDVLCFRDA-RREQDVRIASOLFTLMDSNK-----PSSAPRVVASTNRVDAIDPALRRAGRDALVEVETPNEDRKLQ	206
Ai CDC48e	IDEIDAHSKRENOQREMEKRIVTQLLTCMDGPGNKGDKNAPDSSAGFVLVHGATNRPDIDPALRRSGRFETETALTPDARAEI	421
Sc Cdc48	IDEIDSAPKREKTHGEVERRIVSOLLTMDGLKSR-----SNVVVAAATNRPNSIDPALRRFRGFRDREIDICVDEIGRLEVL	392
Hs p97	IDEIDAAPKREKTHGEVERRIVSOLLTMDGLKSR-----AHVIVMAATNRPNSIDPALRRFRGFRDREIDICVDEIGRLEVL	382
Ai CDC48a	IHTKMKMLADVDLERISKDTHGYVGADLAALCEAALQCREKMDVIDLE-----DSIDAEILNSMAVNEHHTALGNSN	463
Ai CDC48b	IHTKMKMLADVDLERISKDTHGYVGADLAALCEAALQCREKMDVIDLE-----EEDAEILNSMAVNDHHTALGNSN	464
Ai CDC48c	IHTKMKMLADVDLERISKDTHGYVGADLAALCEAALQCREKMDVIDLE-----DSIDAEILNSMAVNEHHTALGNSN	463
Ai CDC48d	LYTKKVNIDPVDVQAIATSCNGYVADLALCREATISAKRSSD-----STLISQDKIKAKSVVG	269
Ai CDC48e	VVAQKRLRLEGFVKRIARLTPCFVGDTEKVAFLGRKAKRIILSRKESGSDGEDDKSWLRMPWPEEETKIFVKMSDEEAVNLVQ	511
Sc Cdc48	IHTKMKMLADVDLEALAAETHGYVGADLALCEAALQCREKMDVIDLE-----DEIDAEVLDISGVMDNDRFALGNSN	470
Hs p97	IHTKMKMLADVDLEQVANEETHGYVGADLAALCEAALQARKKMDVIDLE-----ETIDAEVMNSLAVTMDDRWALSQSN	460
Ai CDC48a	PSALRETVVEVPNVSWNDIGGLENVKRELOETVQYVPEHFKFKFGMSPSKGVLYFGPPGCGKTLAKAIANECOANFISVKGPELLTM	553
Ai CDC48b	PSALRETVVEVPNVSWNDIGGLENVKRELOETVQYVPEHFKFKFGMSPSKGVLYFGPPGCGKTLAKAIANECOANFISVKGPELLTM	554
Ai CDC48c	PSALRETVVEVPNVSWNDIGGLENVKRELOETVQYVPEHFKFKFGMSPSKGVLYFGPPGCGKTLAKAIANECOANFISVKGPELLTM	553
Ai CDC48d	PSNRGTTFVPEKVVWDDVGGGKDLKDKLQAVVPEPKHSAAFVKMGSPMRRGILHGGPPGCKTLLAKAANAQAQSFISLSCALFISM	359
Ai CDC48e	ASLTRGFSVTPDKVWDDVGGGDLHLRLOFNRYVVRKPKPDVYKAFVGDLELGFLLYGGPPGCGKTLAKAANAAGANFMHFKGALLNK	601
Sc Cdc48	PSALRETVVEVPNVWDDVGGGDEIKRELVETVYVHPDQVYKFGMSPSKGVLYFGPPGCGKTLAKAIANECOANFISVKGPELLTM	560
Hs p97	PSALRETVVEVPNVWDDVGGGDLVKKRELOELVQYVPEHFKFKFGMSPSKGVLYFGPPGCGKTLAKAIANECOANFISVKGPELLTM	550
Ai CDC48a	WFGSEANVREIFDKARQSAFCVLFDFELDSIATQRCGSGGDEGGAADRVLNOLLTMDGMNAKTVFIIGATNRPDIDIPALLRPGRL	643
Ai CDC48b	WFGSEANVREIFDKARQSAFCVLFDFELDSIATQRCNS-VGDAGGAADRVLNOLLTMDGMNAKTVFIIGATNRPDIDIPALLRPGRL	643
Ai CDC48c	WFGSEANVREIFDKARQSAFCVLFDFELDSIATQRCNS-AGDAGGAADRVLNOLLTMDGMNAKTVFIIGATNRPDIDIPALLRPGRL	643
Ai CDC48d	YVSGEALNRTFORARLASPSIFDFEAVVAKCRKDESSNSSTVGERLSTLLTMDGLEFAKGLVLAATNRPDIDIPALLRPGRF	449
Ai CDC48e	YVSGEALNRTFORARLARTCAPVIFDFEVALTMSRKE-----GANVVERLNLQVLEDDGG-ERRNVVIGATNRPDIDIPALLRPGRF	686
Sc Cdc48	WFGSEANVREIFDKARQSAFCVLFDFELDSIATQRCNS-LGDAGGASDRVNLNOLLTMDGMNAKTVFIIGATNRPDIDIPALLRPGRL	649
Hs p97	WFGSEANVREIFDKARQSAFCVLFDFELDSIATQRCGN-IGDGGGAADRVLNOLLTMDGMNAKTVFIIGATNRPDIDIPALLRPGRL	639
Ai CDC48a	DQLIYIPLPDESRNLNFKAALRKSPVAKDVDLALAKY-TQGFSGADITEICORACKYAIRENIEKDIKERRKNSNPE	722
Ai CDC48b	DQLIYIPLPDESRNLIKFKSCLRKSPVAKDVDLALAKY-TQGFSGADITEICORACKYAIRENIEKDIKERRKNSNPE	722
Ai CDC48c	DQLIYIPLPDESRNLNFKAALRKSPVAKDVDLALAKY-TQGFSGADITEICORACKYAIRENIEKDIKERRKNSNPE	721
Ai CDC48d	DLVLVYVFPDLLEARFEILQVHTRNMTLGDVDRKKAIEE-TDLFGALELEGCRESGTSLRENIAATAVFN-----	520
Ai CDC48e	GNLVYVPLPNADERASILKAIARKKIDPVDLDTGAIKNNCEGFSGADLHLVQKATFOVEMIGSSSE	758
Sc Cdc48	DQLIYIPLPDESRNLNFKAALRKSPVAKDVDLALAKY-TQGFSGADLTVVORAAKAIKDSIEAHRQEAKEVKVVEGEDVEMTDEG	738
Hs p97	DQLIYIPLPDEKSRVAILKANLRKSPVAKDVDLEFLAKM-TNGFSGADLITEICORACKLAIRESEIERREREQOTNS-----	718
Ai CDC48a	-AMEEDGVD-EVSEIKAAHFESMKVARRSVSDADIRKYQAFQTLQOSRGGSEFRFENSAG-----SATTGVA--D--PFA TSA-A	799
Ai CDC48b	-AMEEDE--EETAEIKAHFESMKVARRSVSDADIRKYQAFQTLQOSRGGSEFRFPDAPTGTGAFPCAATVGVAD--PFA TSA-G	806
Ai CDC48c	-AMEEDMVDVEVSEIRAAHFESMKVARRSVSDADIRKYQAFQTLQOSRGGSEFRFDSTAG-----VCRTTGVAAD--PFA TSA-A	801
Ai CDC48d	-----RHFORAKSKLKPALTIIEVETVYSPRKAARSDSKPIPIKPKATSTVF-----GFSWQLGVLSSLLLATGNYY	549
Ai CDC48e	-----DDVTITICTKTRHFQALSLSVSNKQQRHYVLSLTKQASVGRNTEQVTT-GPSFTLE-----	820
Sc Cdc48	AKAQQEPEVDPVYHTKBFHAEAMNNAKRSVSDAELRYEYLSQOMKASRGFSNINFNDAPLGTATDANSNNSAPSG--AGAFG-S	825
Hs p97	-AMEVEG-DDVWPEIRRRHFEAMRARRSVSDADIRKYQAFQTLQOSRGGFS-RRFSGNGGGAGPSQSGGTTGGSV--Y	796
Ai CDC48a	AAAGDDDDLYN-----809	
Ai CDC48b	AA-DDDDLYS-----815	
Ai CDC48c	AA-DDDDLYS-----811	
Ai CDC48d	FNHTKHEILVASAT 603	
Ai CDC48e	-----820	
Sc Cdc48	NAEEDDDLYS-----835	
Hs p97	TEDNDDLYG-----806	

\* Residues critical for ATP binding  
 \* Residues critical for ATP hydrolysis  
 ▼ Conserved residues implicated in human disease  
 — CDC48 N-terminal domain  
 — AAA-ATPase D1 domain  
 — AAA-ATPase D2 domain  
 — HbYX motif

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**Figure S6. CDC48 (p97) Amino Acids Associated with Human Disease Are Conserved in *Arabidopsis* CDC48, Related to Figure 6**

Sequence alignment of CDC48 proteins from *Arabidopsis thaliana*, *Saccharomyces cerevisiae* and humans. Identical amino acids (55% threshold value) are shown with a black background; similar amino acids are shown with a gray background. Positions of the N-terminal domain and the D1 and D2 ATPase domains are indicated by green, red and blue lines, respectively, while the C-terminal HbYX motif that docks onto the 20S proteasome is indicated with a yellow line. Conserved residues implicated in human disease are indicated by purple arrowheads; residues critical for ATP binding or hydrolysis are indicated by the red and brown asterisks, respectively. Amino acid numbers are indicated on the right; accession numbers for these proteins are listed in [Table S1](#).



**Figure S7. Human p97 Inhibitors Do Not Affect Yeast Cdc48, but Genetic Cdc48 Mutants Can Affect Autophagic Flux, Related to Figure 7**

(A) Human p97 inhibitors do not induce ER stress in yeast. Total RNA was extracted from WT cells following 16 h incubation with the given concentrations of CB-5083, DBE-Q, ML240 or NMS-873, and converted to first-strand cDNA. The relative transcript abundance of the ER stress-responsive genes *DER1* and *ERO1* was determined by quantitative real-time PCR, using the *ALG9* and *TFC1* genes as internal reference standards. All data points were normalized to untreated cells. Similar results were obtained with  $\Delta erg6$  and  $\Delta pdr5$  cells.

(B) Yeast growth is not impacted by p97 inhibitors. Cells of the indicated genotype were treated for 16 h with or without 50  $\mu$ M MG132 or 2 mM CB-5083, DBE-Q, ML240 or NMS-873, and equal numbers of cells were subjected to 5-fold serial dilutions, spotted onto synthetic dropout medium also containing the inhibitors, and incubated at 30°C for 36 h. The treatment with MG132 was included as a positive control for the  $\Delta erg6$  and  $\Delta pdr5$  deletions.

(C) Bulk autophagic flux in yeast is not impacted by p97 inhibitors, as measured by assay of the Pho8 $\Delta$ 60 reporter. Cells of the indicated genotypes expressing *PHO8 $\Delta$ 60* were treated with or without 2 mM CB-5083, DBE-Q, ML240 or NMS-873, or switched to growth at 37°C (for *cdc48-6* cells only) for 16 h, then subjected to nitrogen starvation for 0 or 8 h. All data points were normalized to those obtained after 0 h nitrogen starvation.

(D) Yeast Cdc48 is not subject to autophagy following treatment with human p97 inhibitors, as determined by the YFP release assay. Release of free YFP from the YFP-Cdc48 reporter upon nitrogen starvation or treatment with 2 mM CB-5083, DBE-Q, ML240 or NMS-873 for 16 h was monitored in WT,  $\Delta erg6$  or  $\Delta pdr5$  cells by immunoblot analysis of total protein extracts with anti-GFP antibodies, as in Figure 7A.

(E) Mutations in genomic *CDC48* impact bulk autophagic flux as induced by nitrogen starvation. Cells of the indicated genotypes expressing *PHO8 $\Delta$ 60* were grown at 30 or 37°C for 8 h, then subjected to nitrogen starvation for 0 or 8 h, as in panel (C).

(F) Mutant versions of Cdc48 ectopically expressed from a galactose-inducible promoter in WT cells have less impact on autophagic flux than when they replace the genomic locus. Cells expressing *PHO8 $\Delta$ 60* were transformed with plasmids encoding *YFP-CDC48*, *YFP-cdc48-3* or *YFP-cdc48-6* under control of the *GAL1* promoter. Cells were then grown at either 30 or 37°C in medium containing glucose (–) or galactose (+) for 8 h, and subjected to nitrogen starvation for 0 or 8 h, as in panel (C).

(G) The *cdc48-3* and *cdc48-6* proteins are poor autophagy substrates, as determined by the YFP release assay. WT cells were transformed with the same plasmids as in panel (F), grown at 30°C, then switched to growth at 30 or 37°C in medium containing galactose for 48 h. Total protein extracts were assayed for YFP release by immunoblot analysis as in panel (D).

(H) Ectopic expression of Cdc48 variants containing mutations in conserved disease-associated amino acids only mildly impacts bulk autophagic flux. WT cells expressing *PHO8 $\Delta$ 60* were transformed with plasmids encoding *YFP-CDC48* or the P147L, E195K or K396E variants under control of the *GAL1* promoter. Cells were grown in medium containing glucose (–) or galactose (+) for 8 h, and then subjected to nitrogen starvation for 0 or 8 h, as in panel (C).

(I) Autophagic degradation of Cdc48 mutants requires the UDS of Atg8. WT or  $\Delta atg8$  cells expressing *YFP-CDC48* mutants, with or without rescue with HA-tagged WT Atg8 or the  $\Delta$ LDS or  $\Delta$ UDS variants, were grown in medium containing galactose for 16 h, and YFP release was monitored as in panel (D).

(J) The UDS is not required for Atg8 lipidation. Cells expressing WT Atg8 or the  $\Delta$ LDS or  $\Delta$ UDS variants were grown in nutrient-rich medium then subjected to nitrogen starvation for 2 h. Total cell extracts were treated for 1 h with or without phospholipase D, separated by SDS-PAGE in the presence of 6 M urea, and subjected to immunoblot analysis with anti-ATG8a antibodies.

(K) Quantification of the ratio of Atg8 to Atg8-PE from the experiment shown in panel (J) and two additional independent biological replicates.

In each of panels (A), (C), (E), (F), (H) and (K), bars represent the mean ( $\pm$ SD) from three independent biological replicates, each comprised of three technical replicates (except panel (K)). Asterisks indicate data points that are statistically significantly different to the control ( $p < 0.05$ ).