



Autophagosome formation is initiated at phosphatidylinositol synthase-enriched ER subdomains

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Abstract

The autophagosome, a double-membrane structure mediating degradation of cytoplasmic materials by macroautophagy, is formed in close proximity to the endoplasmic reticulum (ER). However, how the ER membrane is involved in autophagy initiation and to which membrane structures the autophagy-initiation complex is localized have not been fully characterized. Here, we were able to biochemically analyze autophagic intermediate membranes and show that the autophagy-initiation complex containing ULK and FIP200 first associates with the ER membrane. To further characterize the ER subdomain, we screened phospholipid biosynthetic enzymes and found that the autophagy-initiation complex localizes to phosphatidylinositol synthase (PIS)-enriched ER subdomains. Then, the initiation complex translocates to the ATG9A-positive autophagosome precursors in a PI3P-dependent manner. Depletion of phosphatidylinositol (PI) by targeting bacterial PI-specific phospholipase C to the PIS domain impairs recruitment of downstream autophagy factors and autophagosome formation. These findings suggest that the autophagy-initiation complex, the PIS-enriched ER subdomain, and ATG9A vesicles together initiate autophagosome formation.

Keywords ATG9A; autophagy; FIP200; phosphatidylinositol synthase; the ULK complex

Subject Categories Autophagy & Cell Death; Membrane & Intracellular Transport

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Introduction

Macroautophagy (hereafter referred to as autophagy) is a catabolic process that is highly conserved among eukaryotes. When autophagy is induced, a part of the cytoplasm is surrounded by a membrane sac, termed the isolation membrane (also known as the phagophore). The isolation membrane expands to form a double-membrane autophagosome, which subsequently fuses with lysosomes for degradation of engulfed materials. Autophagosome formation involves a number of autophagy-related (ATG) proteins (Xie & Klionsky, 2007; Mizushima *et al*, 2011). Systematic hierarchical analysis revealed that the serine/threonine kinase Atg1 (UNC-51-like kinases (ULKs) in mammals) complex is the most upstream unit among the ATG proteins (Suzuki *et al*, 2007; Itakura & Mizushima, 2010). This complex is composed of Atg1, Atg13, Atg17, Atg29, and Atg31 in yeast and ULK1 (or ULK2), ATG13, FIP200 (also known as RB1CC1 and partially homologous to yeast Atg11 and Atg17), and ATG101 in mammals (Mizushima *et al*, 2011). Atg17 and FIP200 are proposed to act as a scaffold for recruitment of downstream Atg proteins (Ragusa *et al*, 2012; Suzuki *et al*, 2013). Upon nutrient deprivation, Atg1/ULK is activated and phosphorylates downstream effectors, such as BECLIN1 (Russell *et al*, 2013), ATG14 (Park *et al*, 2016), and Atg9/ATG9A (Papinski *et al*, 2014; Zhou *et al*, 2017), to induce autophagosome formation. Thus, it is critical to understand the membrane structures/domains on which the activated Atg1/ULK complex acts. It is well known that early autophagic structures are formed in close apposition to the endoplasmic reticulum (ER)-related subdomains such as the omega-some (Axe *et al*, 2008), ER-mitochondrial contact site (Hamasaki *et al*, 2013), ER exit site (Graef *et al*, 2013; Suzuki *et al*, 2013), ER-Golgi intermediate compartment (ERGIC; Ge *et al*, 2013), and isolation membrane-associated tubular/vesicular structures (Uemura *et al*, 2014). In mammalian cells, the ULK complex is translocated to punctate structures in tight association with the ER by both phosphatidylinositol (PI)3P-dependent and -independent mechanisms

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(Itakura & Mizushima, 2010; Karanasios *et al*, 2013). It was also reported that the ULK complex localizes to transferrin receptor-positive recycling endosomes (Longatti *et al*, 2012). However, the precise target membrane of the Atg1/ULK complex remains unknown.

Here, we performed systematic biochemical analysis using various ATG knockout cells and found that the ULK complex first localizes to PI synthase (PIS)-enriched ER subdomains and then translocates to the ATG9A-positive autophagosome precursors in a PI3P-dependent manner. PI in the PIS-enriched membrane is required for autophagosome formation.

Results

The autophagy-initiation complex associates with two distinct membrane structures

To analyze the autophagic membranes, cell homogenates of mouse embryonic fibroblasts (MEFs) were subjected to flotation analysis. As for wild-type (WT) MEF homogenates, ATG proteins, except for the membrane protein ATG9A and membrane-bound microtubule-associated protein light chain 3 (LC3)-II, mostly remained in the bottom cytosolic fractions (Fig 1A). Consistent with a previous report (Chan *et al*, 2009), small proportions of the ULK complex components were found in floated membrane fractions under growing conditions. Flotation of FIP200, ATG13, ATG101, and WIPI2 into lighter density fractions became clearer under starvation condition (Fig EV1A), indicating that autophagic membranes were floated. In order to enrich these autophagic membranes, we used several ATG-deficient cell lines, in which autophagosome formation is blocked at various steps leading to accumulation of autophagic intermediate structures at specific stages under growing conditions (Fig EV1B; Itakura & Mizushima, 2010; Kageyama *et al*, 2011; Kishi-Itakura *et al*, 2014).

We first analyzed homogenates obtained from ATG14 knockout (KO) and ATG3 KO MEFs. ATG14, a component of the PI 3-kinase complex, and ATG3 are required for the nucleation step and the elongation or closure step during autophagosome formation, respectively (Fig 1B; Mizushima *et al*, 2011; Kishi-Itakura *et al*, 2014). Thus, early autophagosome precursors and elongating isolation membranes accumulate in ATG14 KO and ATG3 KO cells, respectively. As for the ATG14 KO homogenate, in addition to ATG9A and LC3-II, the ULK complex components (FIP200, ATG13, ATG101, and ULK1) were floated into middle-density fractions (fractions 5–7) even under growing conditions (Fig 1C, *). On the other hand, the isolation membrane-resident proteins WIPI2 and ATG5 were not clearly floated. These results suggest that these middle-density fractions contain autophagic precursor membranes, to which the ULK complex is recruited in a PI 3-kinase-independent manner. Similarly, when ATG3 KO homogenates were used, the ULK complex components and autophagy-specific PI 3-kinase complex components (ATG14, VPS34, and BECLIN1) were floated into the middle-density fractions (fractions 4–7; Fig 1D, **). In contrast to ATG14 KO homogenates, the ULK complex components, WIPI2, and ATG5 were also enriched in the top (lightest) fraction (fraction 1) in ATG3 KO homogenates (Fig 1D, ***), suggesting that the top fraction contains elongating isolation membranes. To confirm whether the

flotation of these ATG proteins was dependent on formation of the isolation membrane, the effect of acute inhibition of the PI 3-kinase, which is required for isolation membrane elongation (Kishi-Itakura *et al*, 2014), was examined using wortmannin. The amounts of the ULK complex components, WIPI2, and ATG5 in the top fraction were markedly reduced in ATG3 KO cells after wortmannin treatment (Fig 1E and F), suggesting that isolation membranes are indeed enriched in the top fraction. On the other hand, the flotation of the ULK complex components into the middle-density fractions was unaffected by wortmannin treatment (Fig 1F), which is consistent with the results in ATG14 KO cells (Fig 1C). While the puncta of WIPI2, a PI3P-binding protein, were sensitive to wortmannin, a significant proportion of the FIP200 puncta was not (Fig EV1H). These results suggest that the ULK complex is sequentially recruited to the two distinct membrane structures with middle and light densities in PI3P-independent and -dependent manners, respectively. These structures can be separated using ATG14 KO and ATG3 KO cells.

FIP200 tethers the ULK complex subunits to membranes

Next, we examined which component of the ULK complex determines its membrane targeting. In FIP200 KO cells, ATG13, ATG101, and ULK1 were not clearly floated into the middle-density fractions (Fig EV1C). By contrast, FIP200 was floated in all of the ULK1/2 double KO (DKO), ATG13 KO, and ATG101 KO cells (Fig EV1D–F). ATG101 and ULK1 were not clearly floated in ATG13 KO cells (Fig EV1E). Consistently, FIP200 localized to punctate structures in ATG13 KO, ATG101 KO, and ULK1/2 DKO MEFs (Fig EV1G). These results suggest that FIP200 has the ability to target membranes independently of the other components of the ULK complex.

FIP200 is co-purified with the ER-related membranes and ATG9A-positive isolation membranes

Our flotation analysis demonstrated that a significant population of the ATG9A-positive membranes was also collected in the middle- and light-density fractions, in which the ULK complex components accumulated when autophagosome formation was blocked (Fig 1C and D, asterisks). In mammals, it has been reported that ATG9A dynamically associates with the isolation membrane, but is not contained in the isolation membrane or autophagosomal membranes (Orsi *et al*, 2012; Lamb *et al*, 2016). On the other hand, in yeast, Atg9-containing vesicles are thought to be a seed membrane for autophagosome biogenesis and Atg9 is indeed incorporated into autophagic membranes (Yamamoto *et al*, 2012). These findings prompted us to investigate the relationship between the ULK complex and ATG9A vesicles in these fractions. When ATG9A vesicles were purified from the middle-density fractions derived from non-starved WT (Fig EV2A) and ATG14 KO MEF homogenates (Fig EV2B), RAB1A (a mammalian Ypt1 homolog) was co-precipitated (Fig 2A–C). This is consistent with previous reports that Ypt1 is recruited to Atg9 vesicles in yeast (Kakuta *et al*, 2012). However, FIP200 was not detected in these FLAG-ATG9A immunoprecipitates from the middle-density fractions of WT or ATG14 KO MEFs (Fig 2B and C), although both ATG9A and FIP200 were present in these fractions in ATG14 KO MEFs (Fig EV2B). These data suggest that FIP200 is mainly recruited to membrane structures other than

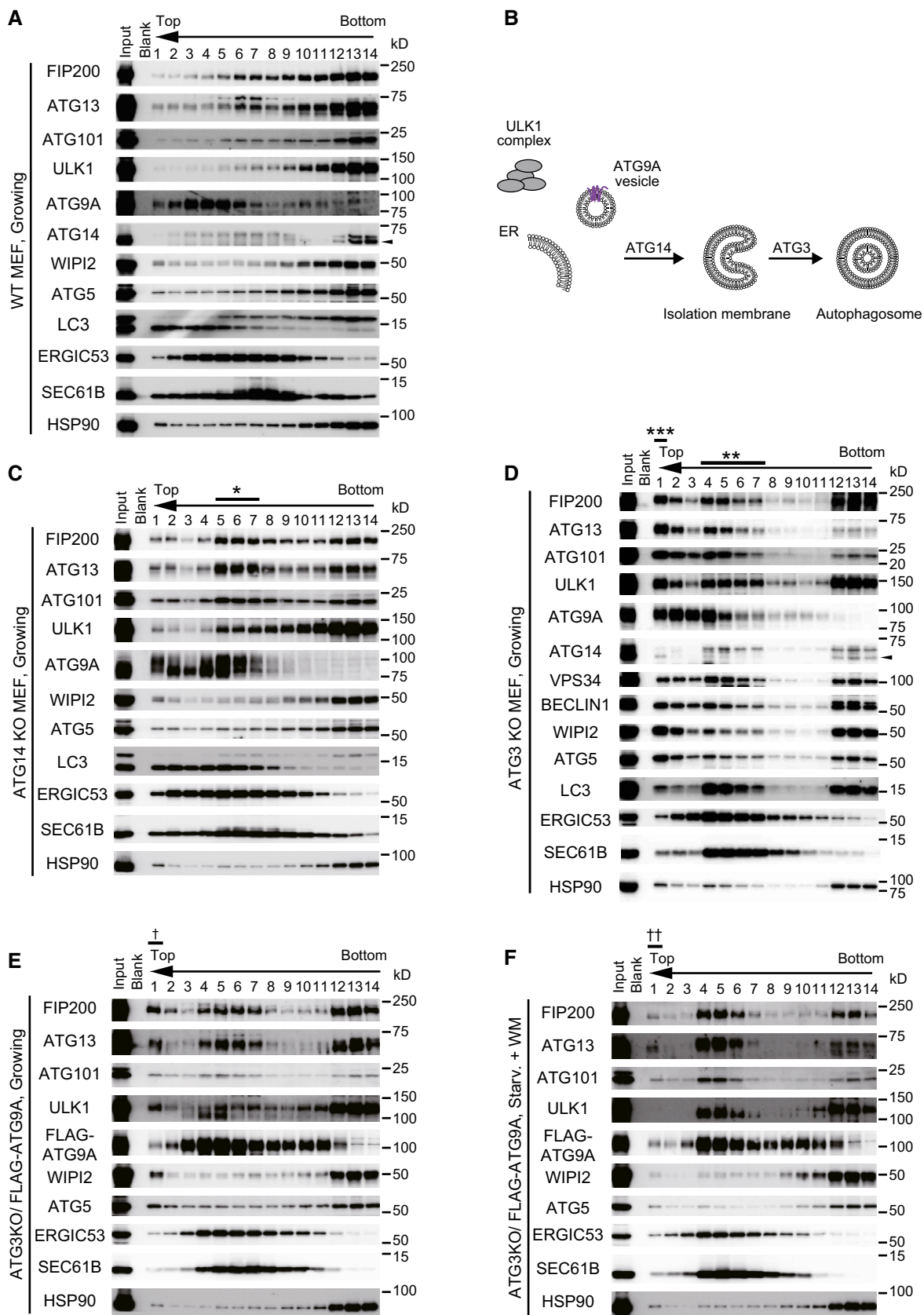


Figure 1.

Figure 1. Flotation of ATG proteins derived from ATG14 KO and ATG3 KO cell homogenates.

- A OptiPrep membrane flotation analysis of WT MEFs cultured in regular DMEM (Growing). After fractionation, each fraction was centrifuged at $100,000 \times g$ for 40 min to enrich the membranes. Arrow indicates the position of ATG14.
- B Autophagosome formation. ATG14 and ATG3 are required for the nucleation and elongation or closure steps during autophagosome formation, respectively.
- C, D ATG14 KO (C) and ATG3 KO MEFs (D) were cultured in regular DMEM and subjected to OptiPrep flotation analysis as described above. Asterisks indicate the flotation of ATG proteins from ATG14 KO and ATG3 KO homogenates. Arrow in (D) indicates the position of ATG14.
- E, F ATG3 KO MEFs stably expressing FLAG-ATG9A were cultured in regular DMEM (E) or starvation medium in the presence of 200 nM wortmannin (Starv. + WM) (F) for 2 h. Note that wortmannin treatment significantly reduced the amounts of the ULK complex components, WIPI2, and ATG5 in the top fraction (compare † in E with †† in F).

ATG9A vesicles in ATG14 KO MEFs. In line with this, FIP200 was clearly floated to the middle-density fractions in the absence of ATG9A (Fig EV2C). Furthermore, FIP200 formed punctate structures in ATG9A KO MEFs (Fig EV1G), as did ULK1 (Itakura *et al*, 2012; Orsi *et al*, 2012). These results suggest that the ULK complex can target some membrane structures other than ATG9A vesicles at an early step during autophagosome formation. We further found that the middle-density fractions contained the ER membranes, and in these fractions of ATG14 KO homogenates, FIP200 was co-precipitated with ER membranes purified with FLAG-tagged SEC61B (Fig 2D). These results suggest that the ULK complex localizes to the ER-related membrane in the absence of autophagy-specific PI 3-kinase.

Although FIP200 and ATG9A were not co-purified in the middle-density fractions of ATG14 KO homogenate, FIP200 and WIPI2, another isolation membrane protein, were co-purified with FLAG-ATG9A from the top fraction of ATG3 KO homogenates (Fig 3A). These results suggest that FIP200 resides on isolation membranes together with ATG9A in ATG3 KO MEFs. In contrast to ATG14 KO homogenates (Fig 2C), small amounts of FIP200 and WIPI2 were co-precipitated with FLAG-ATG9A from the middle-density fractions of ATG3 KO homogenates (Fig 3B). Similarly, SEC61B and GFP-ATG14 were co-precipitated with FLAG-ATG9A in these middle fractions (Fig 3B and C). SEC61B was co-precipitated with FLAG-ATG9A from the middle-density fractions of ATG3 KO homogenates more efficiently than from those of WT or ATG14 KO homogenates (Fig 2B and C). These data suggest that ATG9A-containing autophagosome precursor membranes are associated with the ER in ATG3 KO cells. Overall, we conclude that FIP200 can be recruited to two different membranes: the ER-related membrane (ATG14 KO, fractions 4–7) and the isolation membrane (ATG3 KO, fraction 1; Fig 3D). The co-purification of ATG9A, FIP200, WIPI2, ATG14 and SEC61B from the middle-density fractions of ATG3 KO homogenates would reflect the ER-isolation membrane contact (ATG3 KO, fractions 4–7; Fig 3D).

FIP200 is recruited to the PIS-enriched ER subdomain at the initiation stage

In spite of the fact that FIP200 associates with the ER membrane at an early stage of autophagy, it does not show an ER-like reticular pattern but a punctate distribution. This led us to hypothesize that FIP200 might be recruited to an ER subdomain. The ER is known to be the major site of cellular phospholipid synthesis, which would be required for autophagosome biogenesis. Recent studies have demonstrated that several phospholipid-metabolizing enzymes are segregated on the ER membrane (English & Voeltz, 2013; Pol *et al*, 2014). To characterize the ER subdomain that associates with

FIP200, we screened phospholipid biosynthetic enzymes involved in the *de novo* synthesis and remodeling pathways that colocalized with FIP200 (Fig 4A; Shindou & Shimizu, 2009; Pol *et al*, 2014). To facilitate the accumulation of FIP200 at the ER subdomain, cells were treated with wortmannin. We found that phosphatidylinositol synthase (PIS), cholinephosphotransferase 1 (CPT1), choline/ethanolaminephosphotransferase 1 (CEPT1), phosphatidylserine synthase 1 (PSS1), and phospholipase D1A (PLD1A) were colocalized with FIP200 in these wortmannin-treated cells under starvation conditions (Fig 4B). Among these enzymes identified, we focused on PIS because this enzyme catalyzes the formation of PI, which is a precursor of PI3P required for autophagosome formation (Kihara *et al*, 2001). It was reported that PIS localizes to unique compartments: PIS is located in a highly dynamic ER-related compartment (Kim *et al*, 2011) and leading edges of ER tubules (English & Voeltz, 2013). When autophagosome formation was blocked at an early stage by wortmannin treatment, more than 70% of the FIP200 puncta were colocalized with PIS-GFP (Fig 5A and B), suggesting that FIP200 is recruited to PIS puncta at an early stage. PIS-GFP was not degraded in response to starvation unlike p62, a typical autophagy substrate (Fig EV3), ruling out the possibility that PIS accumulates as an autophagic substrate. In these wortmannin-treated starved cells, PIS and FIP200 double-positive puncta did not colocalize with the ER exit site marker SEC31A or mitochondria (Fig 5C and D). Furthermore, clearly separated PIS structures did not colocalize with ERGIC53 under wortmannin-treated conditions (Fig EV4). These results suggest that the PIS puncta are distinct from the ERGIC, ER exit site, and ER-mitochondrial contact site. The colocalization of PIS and FIP200 was also observed in ATG14 KO MEFs, in which early autophagic structures accumulated (Fig 5A). Also, we observed biochemically that FIP200 associated with PIS-enriched membranes purified from ATG14 KO MEFs (Fig 5E). This association disappeared in the presence of detergent, suggesting that the FIP200 co-precipitation was not simply caused by non-physiological aggregation but in a membrane-dependent manner. Moreover, in line with our model (Fig 3D; ATG14 KO, fractions 4–7), co-precipitation of ATG9A with PIS-enriched membranes was not observed (Fig 5E). Overall, we conclude that FIP200 is recruited to the PIS-enriched ER subdomain at an early stage of autophagy, upstream of the action of PI 3-kinase.

The ULK complex forms a punctate structure on PIS-positive membranes

To further characterize the localization of FIP200, we used a super-resolution structured illumination microscope (SR-SIM), which has ~120-nm lateral resolution. In starved cells, approximately 20% of FIP200 puncta colocalized with PIS-GFP almost completely (Fig 6A

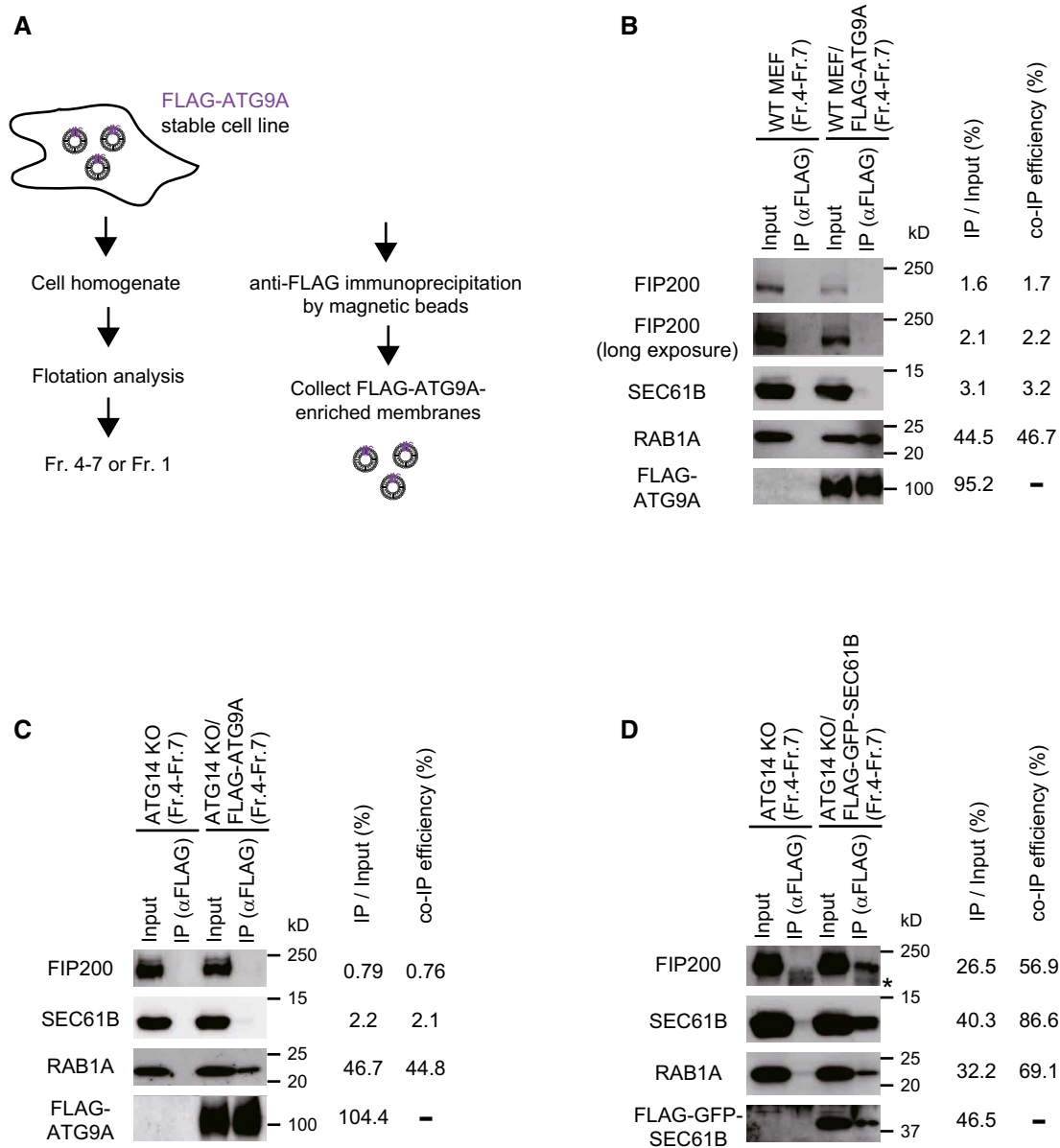


Figure 2. FIP200 is co-purified with the ER membranes from ATG14 KO MEF homogenates.

- A** Experimental scheme of autophagic membrane purification. Cells stably expressing FLAG-ATG9A were cultured in regular DMEM and subjected to OptiPrep flotation analysis. FLAG-ATG9A-enriched membranes were precipitated from the middle-density fractions (fractions 4–7 mixture) or the top fraction (fraction 1) under detergent-free conditions using anti-FLAG antibody-coated magnetic beads.
- B, C** Purification of ATG9A-positive membranes. WT (**B**) and ATG14 KO MEFs (**C**) expressing FLAG-ATG9A were cultured in regular DMEM and subjected to OptiPrep flotation analysis as described in the legend to Fig. 1. FLAG-ATG9A-enriched membranes were purified from middle-density fractions derived from WT (**B**) (Fig EV2A) and ATG14 KO MEF homogenates (**C**) (Fig EV2B). The resulting precipitates were examined by immunoblot analysis with the indicated antibodies.
- D** The ER membranes were purified from middle-density fractions derived from ATG14 KO MEF homogenates by immunoprecipitation with FLAG-GFP-SEC61B. An asterisk indicates non-specific signals. The intensities of the bands in the input and IP fractions were measured using ImageJ software. The ratio of IP to input was calculated. Each value was normalized to the ratio of IP to input of FLAG-tagged protein (co-IP efficiency).

right top panels, and C), whereas more than 50% of FIP200 puncta only partially associated with PIS-GFP-positive structures (Fig 6A right bottom panels, and C). These results indicate that FIP200 at least partially colocalizes with PIS-GFP even under wortmannin-untreated condition. By contrast, most FIP200 puncta colocalized with PIS-GFP puncta in wortmannin-treated starved cells (Fig 6B

and C), which is consistent with that observed by conventional confocal microscopy (Fig 5A and B).

Next, we investigated puncta formation of the ULK complex in live cells. Live imaging analysis of super enhanced cyan fluorescent protein (SECFP)-PIS showed that Venus-ULK1 puncta were formed on SECFP-PIS puncta (Fig 7A and B, and Movies EV1 and EV2).

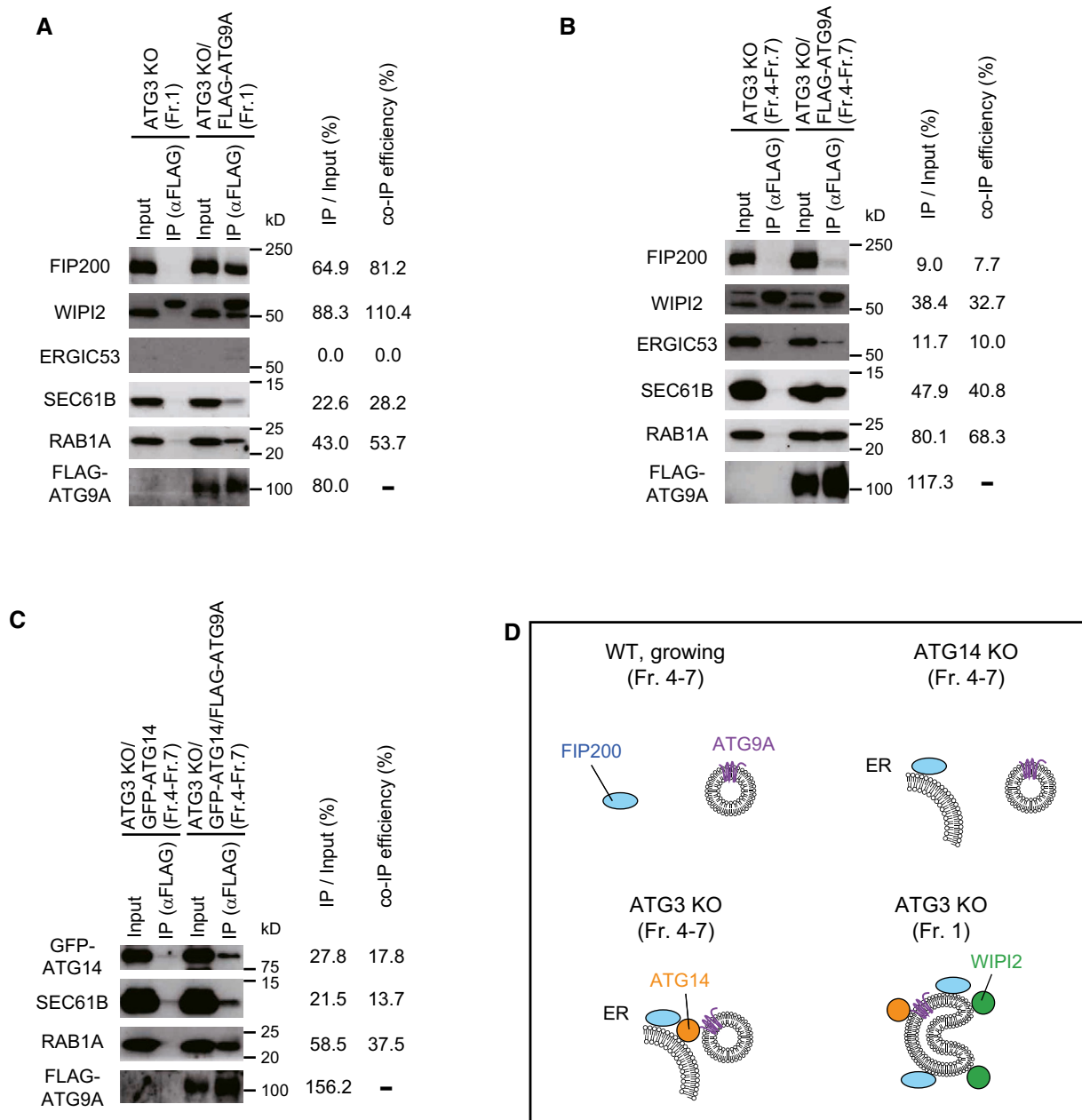


Figure 3. FIP200 and the ER membrane are co-purified with ATG9A-positive membranes from ATG3 KO MEF homogenates.

A–C Purification of ATG9A-positive membranes. ATG3 KO MEFs expressing indicated constructs were cultured in regular DMEM and subjected to OptiPrep flotation analysis as shown in Fig 1E. FLAG-ATG9A-enriched membranes were purified from the top fraction (fraction 1) (A) and middle-density fractions (fractions 4–7) (B, C). The immunoprecipitation efficiency was calculated as in Fig 2.

D Summary of autophagic membrane purification. FIP200 was co-precipitated with the ER membranes purified from middle-density fractions of ATG14 KO homogenates (ATG14 KO, fractions 4–7; Fig 2D). The FLAG-ATG9A immunoprecipitates from the middle-density fractions of ATG3 KO homogenates contained the ER marker SEC61B and GFP-ATG14 as well as small amounts of FIP200 and WIPI2, which might reflect the ER-isolation membrane contact (ATG3 KO, fractions 4–7; Fig 3B and C). FIP200 and the isolation membrane protein WIPI2 were co-precipitated with ATG9A-enriched membrane from the top fraction of ATG3 KO homogenates (ATG3 KO, fraction 1; Fig 3A).

Before disappearance of the ULK1 signal, a part of the ULK1 structures seemed to dissociate from the PIS puncta (yellow arrows in Fig 7A and B), which suggests a translocation of the ULK complex to distinct autophagosome precursors. Quantitative analysis revealed that more than 50% of Venus-ULK1 puncta emerged on the PIS

puncta (Fig 7C). The remaining ULK1 puncta were formed on PIS-positive reticular structures, which may represent similar ER subdomains, but the amount of PIS was not large enough to be detected as puncta (Fig 7C and Movie EV3). Considering that the colocalization ratio between the ULK complex components and PIS puncta was

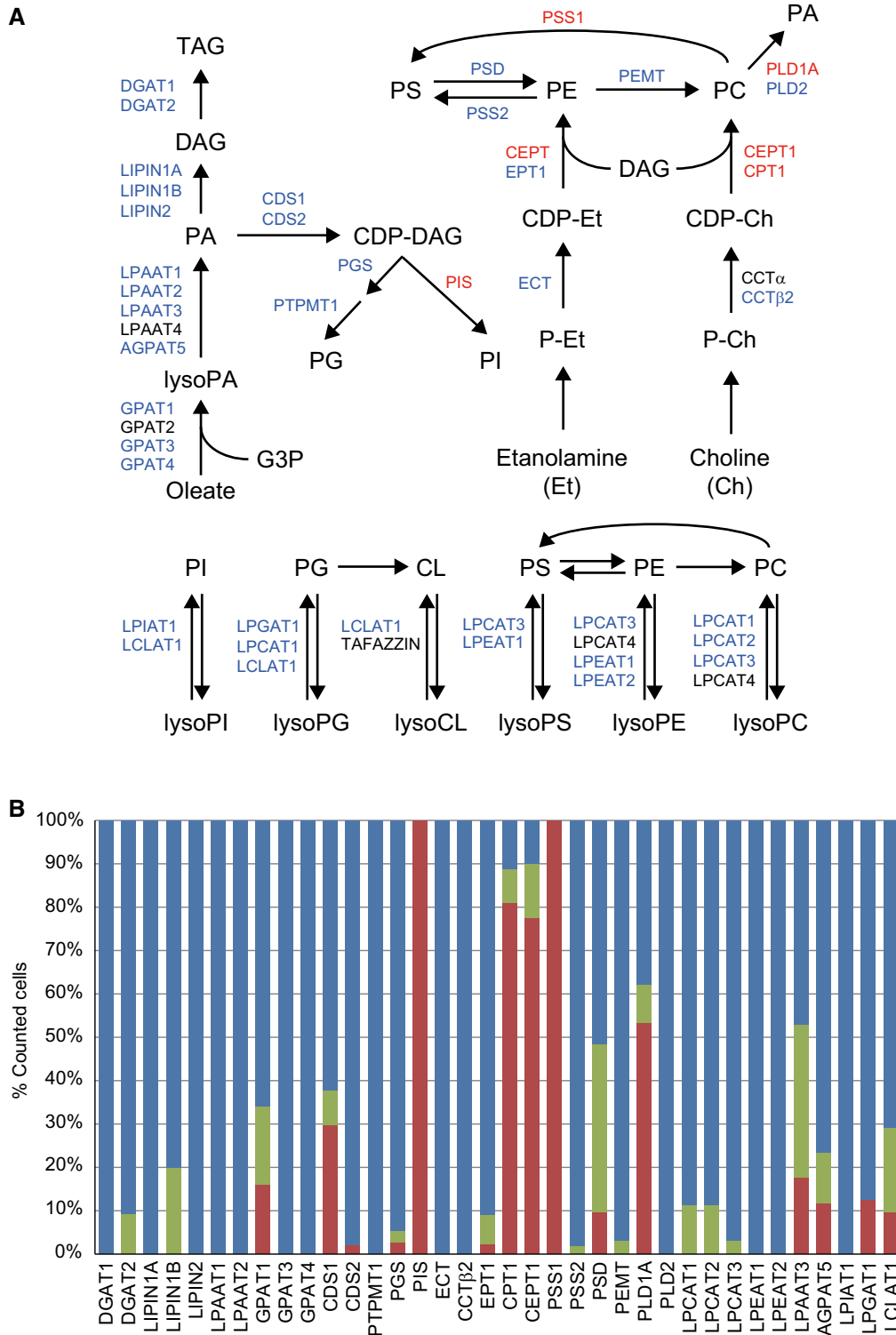


Figure 4. Several phospholipid biosynthetic enzymes colocalize with FIP200 in wortmannin-treated cells under starvation conditions.

A The phospholipid synthesis pathways in mammalian cells. *De novo* synthesis (top) and remodeling (bottom) pathways are shown. Enzymes that colocalize with endogenous FIP200 in WT MEFs cultures in starvation medium in the presence of 200 nM wortmannin for 1 h are shown in red, and those that do not colocalize are shown in blue.

B WT MEFs stably expressing the indicated GFP- or FLAG-tagged enzymes were cultured in starvation medium in the presence or absence of 200 nM wortmannin for 1 h. The cells were fixed and stained with anti-FIP200 antibody. Subcellular distributions of the indicated enzymes and FIP200 were examined by immunofluorescence microscopy. The cells were classified into three categories based on the colocalization of the indicated enzyme and FIP200: clear colocalization (red), partial colocalization (green), and no colocalization (blue). More than 30 cells were analyzed for each protein.

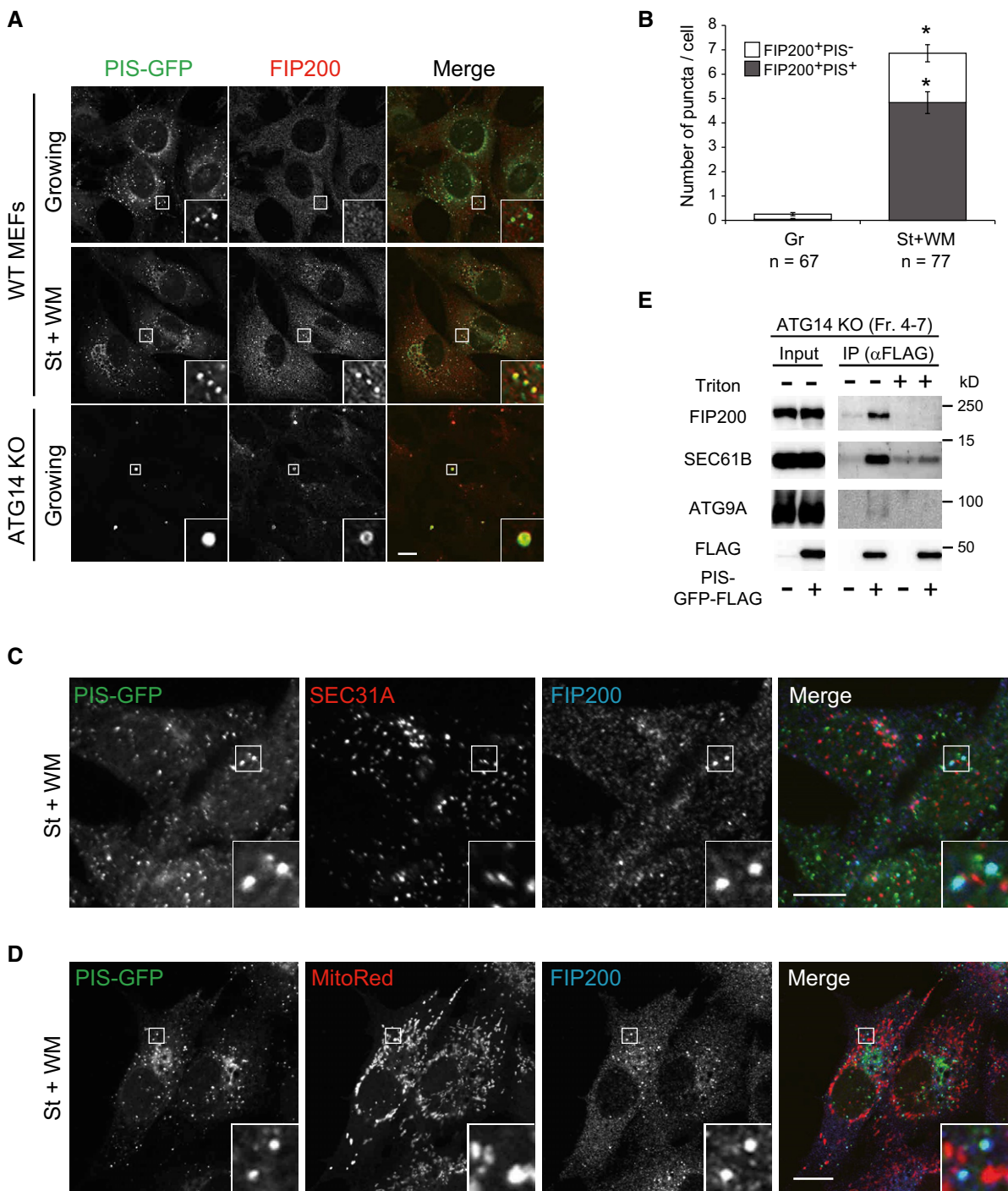


Figure 5. FIP200 is recruited to PIS-enriched ER subdomains at the initiation stage of autophagy.

A WT or ATG14 KO MEFs stably expressing PIS-GFP were cultured in regular DMEM or starvation medium in the presence of wortmannin (WM) for 1 h. Scale bar, 10 μm.
 B Quantification of the number of FIP200⁺PIS⁻ and FIP200⁺PIS⁺ puncta in growing cells and wortmannin-treated starved cells. The number of puncta was quantified from more than 60 randomly selected cells from three independent samples as described in the Materials and Methods. Data represent mean ± SEM. *P < 0.0001 vs. growing condition. Differences were statistically analyzed by two-tailed Mann-Whitney U-test.
 C HeLa cells stably expressing PIS-GFP were cultured in starvation medium in the presence of wortmannin for 1 h. Cells were analyzed by immunofluorescence microscopy using anti-FIP200 and anti-SEC31A antibodies. Scale bar, 10 μm.
 D WT MEFs stably expressing PIS-GFP were cultured in starvation medium in the presence of wortmannin for 1 h. For mitochondrial staining, cells were treated with 50 nM Mitotracker Red CMXRos for 15 min before fixation. Scale bar, 10 μm.
 E PIS-GFP-FLAG was precipitated from the middle-density fractions of ATG14 KO MEF homogenates in the absence or presence of 1% Triton X-100. The resulting precipitates were examined by immunoblot analysis with the indicated antibodies.

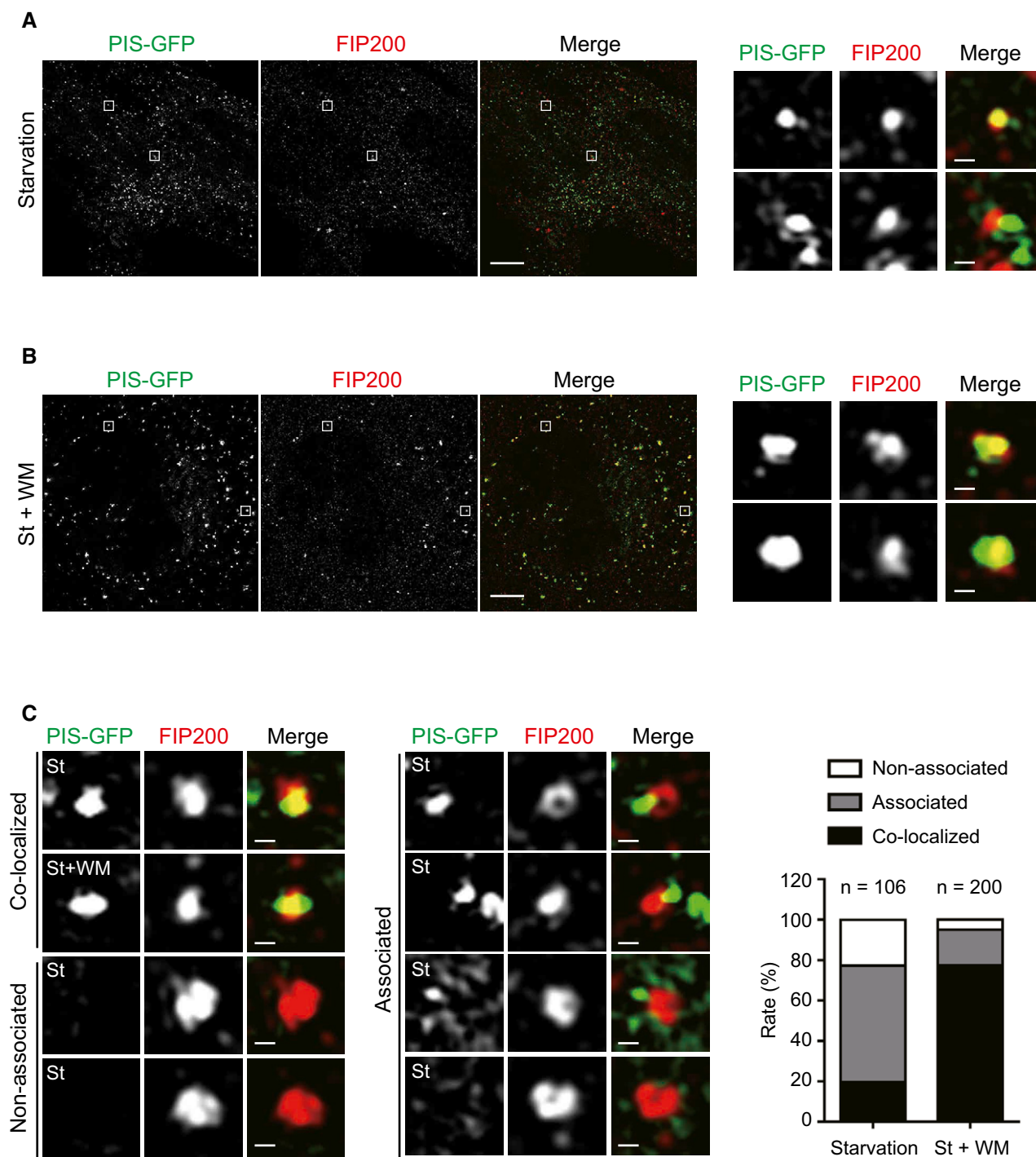


Figure 6. Super-resolution structured illumination microscopy of association of FIP200 with the PIS-enriched ER subdomains.

A, B WT MEFs stably expressing PIS-GFP were cultured in starvation medium in the absence (A) or presence (B) of wortmannin (WM) for 1 h. The cells were fixed and stained with anti-FIP200 antibody.

C Quantification of experiments in (A and B). FIP200 puncta were classified into three categories: “colocalized” with PIS-GFP, “associated” with (next to) PIS-GFP, and “non-associated” with (away from) PIS-GFP.

Data information: Experimental conditions are indicated in panels: starvation (St) (A) or starvation with wortmannin (St + WM) (B). More than 100 puncta were analyzed. Scale bars, 5 μ m (A, B), 0.2 μ m (insets, C).

relatively higher in wortmannin-treated cells (Figs 5A and B, and 6) and in ATG14 KO cells (Fig 5A), autophagy inhibition at early stages likely causes accumulation of PIS (and other enzymes such as CPT1

and CEPT1) at the autophagosome formation site. Collectively, these results suggest that the ULK complex forms a punctate structure on PIS-enriched ER subdomain at an early stage of autophagy.

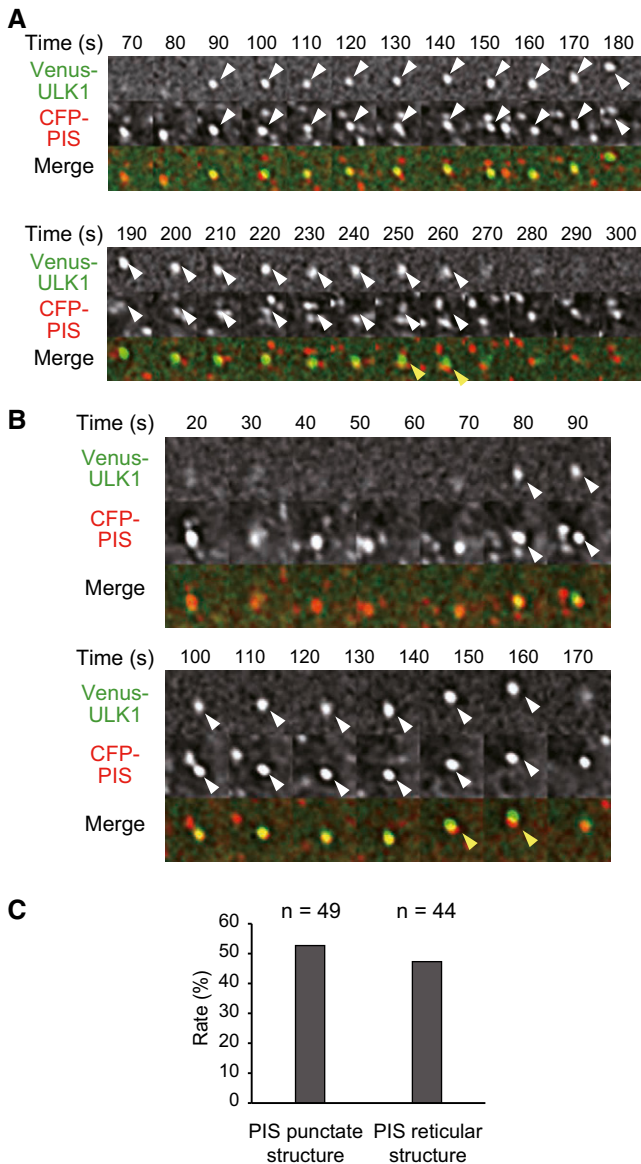


Figure 7. Puncta formation of the ULK complex on PIS-positive structures in live cells.

A, B Two representative live-cell time-lapse images of WT MEFs stably expressing Venus-ULK1 and SECFP-PIS. Cells were cultured in starvation medium and observed using a DeltaVision microscopy system. Frames were captured every 10 s. White arrowheads indicate colocalization of Venus-ULK1 with SECFP-PIS. Some Venus-ULK1 puncta were detached from SECFP-PIS puncta at last 2–3 frames before disappearance (indicated by yellow arrowheads; see Movies EV1 and EV2).

C Quantification of colocalization of newly formed Venus-ULK1 puncta and PIS-positive punctate or reticular structures. To identify newly formed ULK1 puncta, sequential images were subjected to single-particle tracking analysis. More than 90 areas were analyzed.

PI is required for isolation membrane formation

We finally sought to examine whether PI in the PIS-enriched membrane is required for autophagy. Since RNAi-mediated knock-down of PIS did not induce significant reduction in the cellular PI

level (unpublished observations), *Listeria monocytogenes* PI-specific phospholipase C (PIPLC), which degrades unphosphorylated PI, was used to deplete PI (Kim *et al*, 2011). To validate the effect of PIPLC, cell homogenates were incubated with recombinant PIPLC and subjected to lipid analysis. The level of PI was significantly reduced in the presence of recombinant PIPLC, whereas the levels of other phospholipids were not affected (Fig EV5A), indicating that PIPLC can specifically degrade PI *in vitro*. To target PIPLC to the PIS-enriched membrane *in vivo*, we engineered cells that express PIPLC fused to a catalytic inactive mutant of PIS H105Q (PISHQ) under the control of doxycycline (PISHQ-GFP-PIPLC MEFs). Forced expression of PISHQ-GFP-PIPLC was effective and reduced the level of PI (Fig 8A). In contrast, the levels of other phospholipids were relatively maintained or increased as a compensatory reaction (Fig EV5B). In these cells expressing PISHQ-GFP-PIPLC, although the cellular PI level was reduced to only ~50% of that in DOX-untreated cells, autophagic activity was profoundly suppressed; starvation-induced LC3 turnover and p62 degradation were inhibited (Fig 8B). Furthermore, FIP200-positive but PI3P-binding WIPI2-negative abnormal autophagic structures accumulated (Fig 8C and D). By contrast, the number of WIPI2-positive puncta was significantly reduced by the expression of PISHQ-GFP-PIPLC (Fig 8D–F), suggesting that PI production at the PIS domain is important for autophagosome formation. In these cells, punctate structures labeled with RFP-2xFYVE, a PI3P probe that primarily labels endosomes were also abolished, suggesting a reduction in not only autophagosomal but also the total cellular PI3P level (Fig 8F). On the other hand, cytosolic PIPLC did not affect the formation of WIPI2 puncta (Fig 8G). These data suggest that PI produced at the PIS-enriched subdomain actively contributes to autophagy initiation through a direct effect on autophagic structures and/or indirect effects on other membrane compartments.

Discussion

In this study, we biochemically analyze the membranes carrying upstream ATG proteins and found that FIP200 can be recruited to two different membranes: the ER-related membrane and the isolation membrane carrying ATG9A. We also identified the PIS-enriched ER subdomain as a site for the initiation of autophagosome formation. Furthermore, we showed that PI reduction in the PIS-enriched membrane significantly inhibited autophagosome formation. Based on these results, we hypothesize that the autophagy-initiating ULK complex first translocates to the PIS-enriched ER subdomain in an ATG9A- and PI 3-kinase-independent manner (Fig 8H). Next, ATG9A-containing vesicles, which could be a seed for autophagosome biogenesis, associate with this domain, and the ULK complex translocates to ATG9A vesicles to elongate the membrane.

The ULK complex targets to two distinct membranes: the ER-related membrane and ATG9A-enriched membrane

We have shown that ATG proteins are floated into membrane fractions derived from ATG KO cells (Fig 1). To our knowledge, this is the first systematic biochemical analysis of membrane

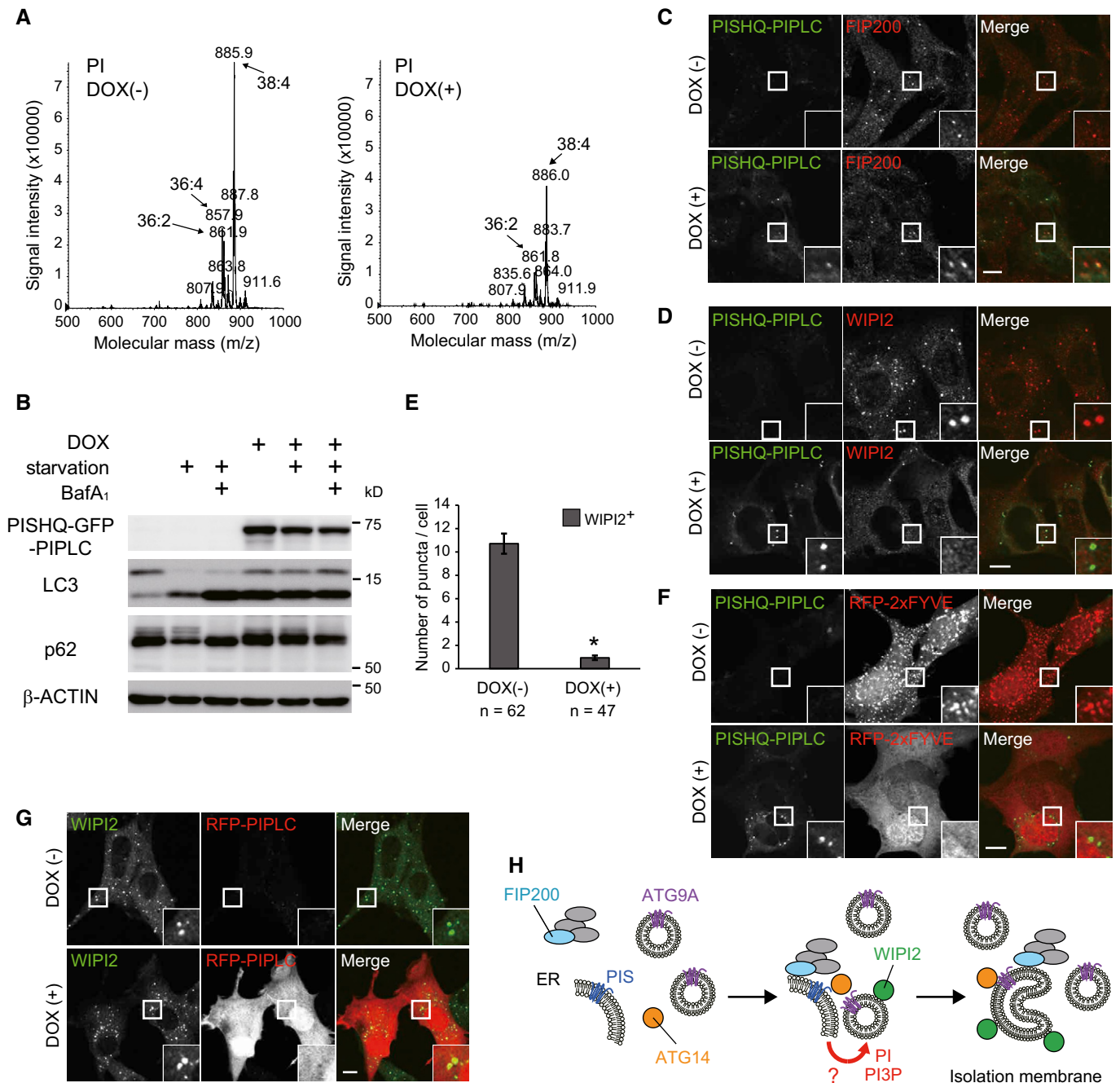


Figure 8. PI in the PIS-enriched membranes is required for isolation membrane formation.

- A** PISHQ-GFP-PIPLC MEFs were pre-cultured in the absence or presence of 2 μg/ml doxycycline (DOX) for 4 h to induce PISHQ-GFP-PIPLC expression. The level of PI was measured by liquid chromatography–electrospray ionization–tandem mass spectrometry. Values indicate individual molecular species of PI.
- B** Autophagic flux assay. PISHQ-GFP-PIPLC MEFs were pre-treated with DOX for 8 h and then cultured in regular DMEM or starvation medium in the presence or absence of 100 nM bafilomycin A₁ (BafA₁) for 2 h.
- C, D** PISHQ-GFP-PIPLC MEFs were pre-cultured in the absence or presence of DOX for 4 h and then cultured in starvation medium for 1 h. Scale bars, 10 μm.
- E** Quantification of the number of WIPI2 puncta. In DOX-treated condition, the number of WIPI2 puncta was quantified from the cells expressing PISHQ-GFP-PIPLC. Data present mean ± SEM. **P* < 0.0001 vs. DOX-untreated cells. Differences were statistically analyzed by two-tailed Mann-Whitney *U*-test.
- F** PISHQ-GFP-PIPLC MEFs stably expressing mRFP-2xFYVE were pre-treated with DOX for 3 h and then cultured in starvation medium with DOX for 1 h. Scale bar, 10 μm.
- G** RFP-PIPLC MEFs were pre-cultured in the absence or presence of DOX for 24 h. Scale bar, 10 μm.
- H** Model of the initial stages of autophagosome formation. The ULK complex translocates to the PIS-enriched ER subdomains and induces recruitment of downstream factors such as ATG14. At least a part of ATG9A is incorporated into the isolation membrane. The PIS-enriched ER membrane supplies PI (and/or PI3P) to ATG9A vesicles or isolation membrane precursors, leading to isolation membrane formation.

association status of endogenous ATG proteins. We have also demonstrated the physical interaction of ULK complex component with the ER membrane and ATG9A-positive isolation membrane (Figs 2 and 3). As well as in yeast (Yamamoto *et al*, 2012), our results suggest that the ATG9A vesicle can be a seed membrane of the autophagosome in mammals. However, our results do not necessarily rule out the possibility that mammalian ATG9A fulfills other functions by its transient interaction with autophagic membranes (Orsi *et al*, 2012; Lamb *et al*, 2016), rather than acting only as a seed membrane of the autophagosome. Currently, it is not clear why the ULK complex needs to be recruited to the ER membrane in addition to ATG9A-positive membranes. One possibility is that the ULK complex might induce reorganization of the ER membrane and stimulate the formation of membrane contacts between the ER and ATG9A vesicles. In line with this model, it was recently reported that Atg1 kinase complex can tether Atg9-vesicles *in vitro* experiments (Rao *et al*, 2016). A similar mechanism might mediate tethering between the ER and ATG9A vesicles.

The recruitment mechanism of the ULK complex seems to be complicated. Consistent with a previous report that Atg17, a yeast counterpart of FIP200, can be recruited to pre-autophagosomal structure in *atg1Δ* and *atg13Δ* cells (Suzuki *et al*, 2007), FIP200 has an ability to associate with membranes independently of the other ULK complex components (Fig EV1). It is also possible that FIP200 is recruited to the membrane via its interaction with the ATG12—ATG5—ATG16L1 complex (Fujita *et al*, 2013; Gammoh *et al*, 2013; Nishimura *et al*, 2013), which further interacts with WIPI2 (Dooley *et al*, 2014). A part of WIPI2 can associate with membranes even in the presence of wortmannin (Polson *et al*, 2010). By contrast, previous studies showed that other Atg1/ULK complex components have lipid-binding domains. For example, the N-terminus of ATG13 interacts with acidic phospholipids (Karanasios *et al*, 2013). The EAT domain of yeast Atg1 can be co-precipitated with small unilamellar vesicles (Ragusa *et al*, 2012) and Atg1 also shows high affinity with PI-containing liposomes *in vitro* (Rao *et al*, 2016). During autophagosome formation, the ULK complex seems to translocate from the ER to ATG9A vesicles, potential autophagosome precursors (Fig 7A and B), although we do not rule out a possibility that additional cytosolic ULK complexes are also directly recruited. This change may be caused by production of PI3P because PI 3-kinase activity is known to stabilize the ULK1 complex on the autophagic membranes (Karanasios *et al*, 2013). Furthermore, the ULK complex components interact with ATG8 family proteins and are recruited to autophagic membranes dependently on their LC3-interacting region motifs (Alemu *et al*, 2012). All these factors could determine the unique behavior of the Atg1/ULK complex.

We previously reported that ULK1, ATG13, FIP200, and ATG101 form a stable complex in the cytosol (Hosokawa *et al*, 2009a,b). By contrast, in the present study, behaviors of ATG13 and FIP200 are somewhat different from that of ULK1. One possibility is that FIP200 and ATG13 could associate with the membrane more tightly than ULK1, and therefore, ULK1 is released from the membranes during sample preparation and flotation experiments. Another possibility is that the stoichiometry of the complex subunits is different between the cytosolic and membrane complexes.

Contribution of PIS-enriched ER subdomains in the initiation stage of autophagy

We have uncovered that early autophagic structures are formed in close apposition to the PIS-enriched ER subdomains. In wortmannin-treated condition (Fig 4) and ATG14KO cells (unpublished observations), other phospholipid biosynthetic enzymes, such as PSS1, CPT1, CEPT1, and PLD1A, were also co-localized with the ULK complex. Inhibition of autophagosome formation at an early stage might affect local phospholipid metabolism and induce recruitment of phospholipid biosynthetic enzymes to the autophagosome formation site via an unknown feedback loop. While only PIS clearly shows punctate structures that co-localize with the ULK complex in wortmannin-untreated cells, we speculate that other enzymes are also present at the same membrane at undetectable levels to facilitate autophagosome formation. The involvement of other phospholipid biosynthetic enzymes in autophagy has been investigated. CPT1 positively regulates autophagosome formation under oleic acid-treated conditions (Dupont *et al*, 2014). The role for PLD1 is rather controversial; it could regulate autophagy either positively or negatively (Dall'Armi *et al*, 2010; Bae *et al*, 2014; Jang *et al*, 2014; Holland *et al*, 2016). How these enzymes contribute to autophagy initiation, autophagosome formation or autophagosome maturation remains to be determined in more detail.

The presence of phospholipid biosynthetic enzymes at the site of autophagosome formation suggests that newly synthesized PI and other phospholipids are directly used for autophagosome formation. Consistent with this idea, we showed that PI in the PIS-enriched membrane is required for autophagosome formation (Fig 8B–E). However, as the total cellular PI3P level was also reduced by expression of PISHQ-GFP-PIPLC (Fig 8F), we cannot rule out a possibility that PI depletion affects autophagosome formation through an indirect effect on other membranes. Membrane contacts between the ER membrane and the isolation membrane have been observed by EM analysis in several previous studies (Kovacs *et al*, 2007; Hayashi-Nishino *et al*, 2009; Yla-Anttila *et al*, 2009; Uemura *et al*, 2014). There is accumulating evidence that phospholipids are synthesized and transported at membrane contact sites between ER and other organelles (Drin, 2014; Prinz, 2014; Raiborg *et al*, 2015; Levine & Patel, 2016; Phillips & Voeltz, 2016). Therefore, contact sites between the ER and ATG9A-enriched membranes might facilitate transport of newly synthesized PI and other phospholipids between these two compartments. However, factors involved in non-vesicular lipid transport between the ER and ATG9A-enriched membranes remain unidentified. Future studies are needed to elucidate whether lipid transfer proteins contribute to autophagosome formation.

Materials and Methods

Plasmids, antibodies, and reagents

cDNAs encoding the full length of PIS (NP_080914, Open biosystems, Huntsville, AL, USA), CPT1 (NP_064629, Open biosystems), EPT1 (NP_277040, Kazusa DNA Research Institute, Chiba, Japan), CEPT1 (NP_001007795, Open biosystems), ECT (NP_001171846), CCTβ2 (NP_004836), PSS1 (NP_055569), PSS2 (NP_110410), PSD

(NP_055153), PEMT (NP_680477), CDS1 (NP_001254), CDS2 (NP_003809), PLD1A (NP_002653, Kazusa DNA Research Institute), PLD2 (NP_002654, Kazusa DNA Research Institute), DGAT1 (NP_036211), DGAT2 (NP_115953), LIPIN1A (NP_663731), LIPIN1B (NP_056578, Open biosystems), LIPIN2 (NP_055461), LPAAT1/AGPAT1 (NP_116130), LPAAT2/AGPAT2 (NP_006403), LPAAT3/AGPAT3 (NP_064517), AGPAT5 (NP_060831), GPAT1 (NP_065969), GPAT3 (NP_116106), GPAT4 (NP_848934), LPCAT1 (NP_079106), LPCAT2 (NP_060309), LPCAT3/MBOAT5 (NP_005759), LPEAT1/MBOAT1 (NP_001073949), LPEAT2/LPCAT4 (NP_705841), PGS (NP_077733), LPIAT1/MBOAT7 (NP_077274), LCLAT1/LYCAT (NP_872357), LPGAT1 (NP_055688), PTPMT1 (NP_783859, Kazusa DNA Research Institute), SEC61B (NP_006799), and ATG14 (NP_055739) were amplified by PCR and subcloned into pMRX-IP backbone vectors together with the EGFP or FLAG tag. PIS cDNA was cloned into pMRX-IP with SECFP (provided by Atsushi Miyawaki, Riken) to generate pMRX-IP-SECFP-PIS. mRFP-2xFYVE was subcloned into pMRX-IP vector. ATG9A (NP_076990) was subcloned into N-TAP-MXs-puro vector (Yamaguchi *et al*, 2013). *Listeria monocytogenes* PIPLC cDNA (Kim *et al*, 2011) was subcloned into pGEX-6P-3 vector (GE Healthcare, Piscataway, NJ, USA). pMRX-IP-PIS (H105Q)-GFP was generated by inverse PCR. For generation of pCW57.1-PISHQ-GFP-PIPLC and pCW57.1-RFP-PIPLC plasmid, PIS (H105Q)-GFP, PIPLC, and RFP-PIPLC were subcloned into pCW57.1 backbone vector. pMRX-IP-Venus-ULK1 plasmid has been previously described (Koyama-Honda *et al*, 2013). Antibodies used for immunoblotting were as follows: rabbit polyclonal anti-FIP200 (17250-1-AP, Protein Tech, Chicago, IL, USA), anti-ATG13 (SAB4200100, Sigma-Aldrich, St. Louis, MO, USA), anti-ATG101 (Hosokawa *et al*, 2009b), anti-ULK1 (A7481, Sigma-Aldrich), anti-ATG9A (Itakura *et al*, 2012), anti-ATG14 (Itakura *et al*, 2008), anti-WIPI2 (SAB4200400, Sigma-Aldrich), anti-ATG5 (A0731, Sigma-Aldrich), anti-LC3 (#1; Hosokawa *et al*, 2006), anti-ERGIC53 (E1031, Sigma-Aldrich), anti-SEC61B (07-205, Millipore, Billerica, MA, USA), anti-FLAG (F7425, Sigma-Aldrich), anti-RAB1A (C-19, Santa Cruz, Dallas, TX, USA), anti-GFP (A6455, Invitrogen, Carlsbad, CA, USA), anti-ATG3 (A3231, Sigma-Aldrich), anti-p62 (PM045, MBL, Nagoya, Japan), anti-VPS34 (#3811, Cell Signaling, Beverly, USA), and anti-BECLIN1 (#3738, Cell Signaling) antibodies, mouse monoclonal anti-HSP90 (clone 68, BD Biosciences, San Jose, CA, USA), anti- β ACTIN (clone AC74, Sigma-Aldrich), anti-LC3 (clone 1703, Cosmo bio, Tokyo, Japan), anti-FLAG (clone M2, Sigma-Aldrich), and anti-DYKDDDDK (clone 1E6, Wako, Osaka, Japan). Antibodies used for immunostaining were as follows: rabbit polyclonal anti-FIP200 (see above) and anti-ERGIC53 (see above) antibodies, mouse monoclonal anti-SEC31A (clone 32, BD Biosciences) and anti-WIPI2 (clone 2A2, Millipore) antibodies, AlexaFluor 488-conjugated anti-rabbit IgG, AlexaFluor 568-conjugated anti-mouse IgG and anti-rabbit IgG, and AlexaFluor 660-conjugated anti-mouse IgG and anti-rabbit IgG secondary antibodies (Molecular Probes, Eugene, OR, USA). Doxycycline hydrochloride (Dox) and wortmannin were purchased from Sigma-Aldrich. Bafilomycin A₁ was purchased from Wako.

Cell culture and transfection

ATG14 KO (Nishimura *et al*, 2013), ATG3 KO (Sou *et al*, 2008), FIP200 KO (Gan *et al*, 2006), ATG13 KO (Kaizuka & Mizushima, 2015), ATG101 KO (Suzuki *et al*, 2015), ULK1/2 DKO (Cheong *et al*,

2011), and ATG9A KO MEFs (Saitoh *et al*, 2009) were generated previously. Stable cell lines were generated as follows: HEK293T cells were transiently transfected using Lipofectamine 2000 (Invitrogen) reagent with the indicated retrovirus vector (pCG-VSV-G and pCG-gag-pol for retrovirus infection) or lentivirus vector (pCW57-PISHQ-GFP-PIPLC, pCMV-VSVG, and psPAX2 for lentivirus infection). WT and ATG3 KO MEFs were also transfected using the indicated retrovirus or lentivirus. Cells were cultured in DMEM supplemented with 10% fetal bovine serum (FBS) in a 5% CO₂ incubator. For starvation treatment, cells were washed twice with phosphate-buffered saline (PBS) and incubated in amino acid-free DMEM without FBS (starvation medium).

OptiPrep flotation analysis

Cells from four to eight 10-cm dishes were harvested and washed twice with ice-cold PBS. The cell pellets were collected after centrifugation at 600 × *g* for 5 min and resuspended in 2 ml ice-cold homogenization buffer (250 mM sucrose, 20 mM HEPES-KOH (pH 7.4), 1 mM EDTA, 1 mM phenylmethanesulfonyl fluoride, complete EDTA-free protease inhibitor (Roche, Indianapolis, IN, USA)). Cells were then disrupted by N₂ cavitation (Parr Instrument, Moline, IL, USA; 800 psi, 10 min, 4°C). The homogenized cells were centrifuged twice at 3,000 × *g* for 10 min to remove cell debris and undisrupted cells. The supernatant was diluted with an equal volume of OptiPrep (Sigma, St. Louis, MO, USA). Discontinuous OptiPrep gradients were generated in SW41 tubes (Beckman Instruments, Berkeley, CA, USA) by overlaying the following OptiPrep solutions all in homogenization buffer: 2.4 ml of the diluted supernatant in 30% OptiPrep, 2.4 ml in 25%, 2.4 ml in 20%, 2 ml in 15%, 2 ml in 10%, 0.5 ml in 5%, and 0.5 ml in 0%. The gradients were centrifuged at 150,200 × *g* in SW41Ti rotors (Beckman Instruments) for 3 h, and subsequently, 14 fractions (0.85 ml each) were collected from the top. Fractions were diluted with an equal volume of homogenization buffer, and membranes were enriched by centrifugation at 100,000 × *g* for 40 min. The pellets were solubilized with SDS-PAGE sample buffer and heated at 55°C for 10 min.

Immunoisolation of membrane fractions

Anti-FLAG magnetic beads were prepared according to the manufacturer's instructions. In brief, 1 mg NHS-FG magnetic beads (TAS8848N1141, Tamagawa Seiki, Nagano, Japan) was pre-treated with methanol and incubated with 100 μ l anti-FLAG M2 or anti-DYKDDDDK antibodies (0.25 μ g/ μ l, dissolved in 25 mM MES-NaOH, pH 6.0) at 4°C for 30 min. The magnetic beads were treated with 1 M ethanolamine to block unreacted NHS-ester groups at 4°C for 16 h, washed three times in washing buffer (10 mM HEPES-KOH (pH 7.9), 50 mM KCl, 1 mM EDTA, 10% glycerol), and stored in 200 μ l washing buffer at 4°C until use. Anti-FLAG magnetic beads and 1.5-ml tubes (MS-4215M, Sumitomo Bakelite, Akita, Japan) were blocked with homogenization buffer containing 250 mM NaCl and 1% BSA for 1 h at 4°C. MEFs stably expressing the indicated FLAG-tagged protein were subjected to OptiPrep flotation analysis as described above. 400 μ l of the indicated fractions was mixed with 20 μ l 5 M NaCl and 20 μ l anti-FLAG magnetic beads (50% slurry) and rotated for 2 h at 4°C. The magnetic beads were washed four

times with homogenization buffer containing 250 mM NaCl and 1% BSA. The magnetic beads were transferred to a new 1.5-ml tube and washed with homogenization buffer containing 250 mM NaCl. The immunoprecipitated membranes were solubilized with 60 μ l of 1 \times SDS-PAGE sample buffer and heated at 55°C for 10 min.

Immunoblotting

Cells were collected in ice-cold PBS by scraping and precipitated by centrifugation at 1,000 \times *g* for 3 min. Precipitated cells were suspended in 0.1 ml homogenization buffer and homogenized by sonication (3 \times 5 s; Astrason, XL2020 (Misonix, Inc., Farmingdale, NY, USA)). After centrifugation at 1,000 \times *g* for 20 min, the protein concentration of the supernatant was determined using the BCA method (Pierce Chemical Co., Rockford, IL, USA), mixed with SDS-PAGE sample buffer, and heated at 55°C for 10 min. Samples were subsequently separated by SDS-PAGE and transferred to Immobilon-P polyvinylidene difluoride membranes (Millipore). Immunoblot analysis was performed with the indicated antibodies and visualized with Super-Signal West Pico Chemiluminescent substrate (Pierce Chemical Co.) or Immobilon Western Chemiluminescent HRP substrate (Millipore). Signal intensities were analyzed using the LAS-4000mini image analyzer (GE Healthcare).

Lipid analysis

Recombinant PIPLC was prepared as follows. pGEX6P-3-PIPLC were transformed into *Escherichia coli* strain BL21. GST-PIPLC expression was induced with 0.5 mM IPTG at 18°C. GST-PIPLC recombinant protein was purified with glutathione-Sepharose (GE Healthcare) and cleaved from GST using PreScission protease (50 mM Tris-HCl (pH 7.4), 400 mM NaCl, 1 mM EDTA, 1 mM dithiothreitol, and 0.1 U/ μ l PreScission protease). Untagged PIPLC protein was dialyzed with PBS for 3 days and stored at -80°C. Phospholipids were extracted using the methanol method (Zhao & Xu, 2010). In brief, methanol was added into cell pellets, sonicated in a bath sonicator for 2 min, and centrifuged at 15,000 \times *g* for 10 min. The supernatant was applied to Cosmospin Filter G (Nacalai Tesque, Kyoto, Japan) and centrifuged at 5,000 \times *g* for 5 min. 10 μ l of sample was injected into the LC-ESI-MS/MS system. LC-ESI-MS/MS analysis was performed using a Shimadzu Nexera ultra high-performance liquid chromatography system (Shimadzu, Kyoto, Japan) coupled with a QTRAP 4500 hybrid triple quadrupole linear ion trap mass spectrometer (AB SCIEX, Toronto, Canada). Chromatographic separation was performed on an Acquity UPLC HSS T3 column (100 \times 2.1 mm, 1.8 μ m; Waters) maintained at 40°C using mobile phase A (water/methanol (50/50, v/v) containing 10 mM ammonium acetate and 0.2% acetic acid) and mobile phase B (isopropanol/acetone (50/50, v/v)) in a gradient program (0–3 min: 30% B \rightarrow 50% B; 3–24 min: 50% B \rightarrow 90% B; 24–28 min: 30% B) with a flow rate of 0.3 ml/min. Neutral loss scans of 74 and 87 Da in the negative ion mode were used to detect phosphatidylcholine and phosphatidylserine, respectively. Precursor ion scan of *m/z* 196, 241, 153, and 384 in the negative ion mode was used to detect phosphatidylethanolamine, phosphatidylinositol, phosphatidic acid, and cytidine diphosphate-diacylglycerol, respectively. The total cycle time was 1.7 s, which allowed the collection of sufficient data points over the chromatographic peak. The instrument parameters

were as follows: curtain gas, 10 psi; collision gas, 7 arb. unit; ionspray voltage, -4,500 V; temperature, 700°C; ion source gas 1, 30 psi; ion source gas 2, 70 psi; declustering potential, -96 V; entrance potential, -10 V; collision energy, -36 V; collision cell exit potential, -15.4 V.

Fluorescence microscopy

Cells grown on coverslips were fixed with 4% paraformaldehyde, permeabilized using 50 μ g/ml digitonin, and then stained with specific antibodies. For mitochondrial staining, cells were pre-treated with 50 nM Mitotracker Red CMXRos (Molecular Probes) for 15 min before fixation. For ERGIC53 staining, cells were fixed with methanol. These cells were observed using a confocal laser microscope FV1000D IX81 (Olympus, Tokyo, Japan) with FV12-HSD system using a 60 \times PlanApoN oil-immersion lens (1.42 NA; Olympus). Images were acquired at room temperature using FV10-ASW software (Olympus). For the final output, images were processed using Adobe Photoshop 7.0.1 software. The number of dots was determined using MetaMorph software (Molecular Devices, Sunnyvale, CA, USA) as follows: Dots were extracted using the top hat operation, and a binary image was created. Small dots were removed using an open operation. The number of dots was counted using the integrated morphometry analysis program. False dots were removed by comparison with the original image.

Super-resolution structured illumination microscopy (SR-SIM)

Super-resolution imaging was performed on a Zeiss Elyra PS.1 microscope equipped with a Plan-Apochromat 63 \times /1.4 oil DIC M27 objective and a sCMOS camera (1,280 \times 1,280 pixels of 6.5 \times 6.5 μ m). Fifteen images per plane (five phases and three angles) were acquired with the 561 nm (34 μ m grating period) and the 488 nm (28 μ m grating period) lasers. For channel alignment, 0.2- μ m multicolored beads immobilized on a sample coverslip were imaged using the same image acquisition settings and used to correct for chromatic shifts between different color channels. Raw data were processed using Zeiss Zen software.

Live-cell imaging

For autophagy induction, cells were washed twice with PBS and incubated in starvation medium. Images were acquired with a 60 \times PlanAPO oil-immersion objective lens (1.42 NA; Olympus), using a Deltavision microscope system (GE Healthcare) coupled with an Olympus IX81-ZDC and a cooled CCD camera CoolSNAP HQ2 (Photometrics, Tucson, AZ, USA). WT MEFs stably expressing SECFP-PIS and Venus-ULK1 were grown on a glass bottom dish (11-004-006; IWAKI, Tokyo, Japan). During live-cell imaging, the culture dish was mounted in a chamber INUB-ONI-F2 (TOKAI HIT, Shizuoka, Japan) to maintain the culture conditions (37°C and 5% CO₂). SECFP-PIS and Venus-ULK1 were illuminated with a mercury arc lamp attenuated to 5 and 50% by neutral density filters, respectively. Exposure times were 0.2 s for SECFP-PIS and 0.5 s for Venus-ULK1. Time-lapse images were acquired at 10-s intervals. Deconvoluted images were obtained using softWoRx software. To find newly formed ULK1, sequential images were subjected to single-particle tracking analysis using MetaMorph software. For the

final output, images were processed using ImageJ and Adobe Photoshop 7.0.1 software.

Data analysis

Differences were statistically analyzed by two-tailed Mann–Whitney *U*-test. Statistical analysis was carried out using GraphPad Prism 6 (GraphPad Software, La Jolla, CA, USA). All data are presented as the mean \pm SEM. Reproducibility of all results reported here was confirmed.

Expanded View for this article is available online.

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Author contributions

TN and NM designed the experiments; TN, NT, and HY performed the experiments; NK, YS, and HA contributed to lipid analysis; TN, NT, NK, HY, and NM analyzed the data; and TN and NM wrote the manuscript. All authors discussed the results and commented on the manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

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