Control of endoplasmic reticulum membrane biogenesis by regulators of lipid metabolism

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ABSTRACT

Cells dynamically adapt organelle size to current physiological demand. Organelle growth and proliferation require membrane biogenesis and need to be coordinated with lipid metabolism. The endoplasmic reticulum (ER) can undergo massive expansion but the mechanisms that govern ER membrane biogenesis are unclear. Here, we genetically screen for factors mediating ER expansion in budding yeast and identify lipid synthesis enzymes and the ER transmembrane protein Ice2 as strong hits. Ice2 inhibits the conserved phosphatidic acid phosphatase Pah1 by opposing the activity of the Nem1-Spo7 complex. This regulation counteracts the production of storage lipids and directs lipid metabolism towards membrane biogenesis. Furthermore, Ice2 acts in concert with the transcriptional control of lipid synthesis enzymes and cooperates with the unfolded protein response to maintain ER homeostasis. These findings establish the regulation of the lipin ortholog Pah1 as a key determinant of ER membrane biogenesis.

INTRODUCTION

Cells reshape and resize their organelles when they undergo differentiation or adapt to changing conditions. An increase in organelle size or number typically involves enhanced membrane biogenesis, which in turn requires an adequate supply of membrane lipids. As a result, organelle biogenesis depends on whether cells employ available lipids as building blocks for new membranes, consume them for energy production or store them for future use. Accordingly, the mechanisms that control lipid synthesis and utilization are fundamental for organelle biogenesis and, consequently, for cell differentiation and adaptation.

The ER is a morphologically complex organelle with essential functions in protein folding and lipid synthesis (Westrate et al., 2015). It forms the nuclear envelope and extends into the cytoplasm as an interconnected network called the peripheral ER. The principal structural elements of the ER are tubules and sheets (Shibata et al., 2010). In addition, intermediate structures exist, such as tubular matrices and sheets with fenestrations or nanoholes (Puhka et al., 2012; Nixon-Abell et al., 2016; Schroeder et al., 2019). A variety of organelle morphologies can arise according to physiological demand, ranging from mainly tubular ER in lipid hormone-producing cells of the testis to mainly cisternal ER in secretory cells of the pancreas (Fawcett, 1981). ER size is also tuned to cellular need. The ER expands several-fold when B lymphocytes differentiate into antibody-secreting plasma cells or when cells face protein folding stress in the ER (Wiest et al., 1990; Bernales et al., 2006). Stress-induced ER expansion is mediated by signaling through the unfolded protein response (UPR), which induces genes encoding ER-resident protein folding enzymes to restore homeostasis (Walter and Ron, 2011). Besides determining the abundance of protein folding enzymes, the UPR also regulates the biogenesis of the ER membrane. It does so, at least in part, through the induction of genes that encode lipid synthesis enzymes (Sriburi et al., 2007; Bommiasamy et al., 2009; Schuck et al., 2009).

47 Yeast synthesize membrane phospholipids primarily from phosphatidic acid (PA)
48 through the CDP-DAG pathway (Henry et al., 2012). Many enzymes of this pathway
49 are controlled transcriptionally by the activators Ino2/4 and the repressor Opi1. Ino2
50 and Ino4 form a heterodimer that binds to promoter elements of lipid synthesis
51 genes. Opi1 inhibits Ino2/4 by binding to Ino2 (Heyken et al., 2005). Repression of
52 Ino2/4 by Opi1 is relieved when accumulating PA tethers Opi1 to the ER membrane
53 and sequesters it away from the nucleoplasm (Loewen et al., 2004). The PA-Opi1-
54 Ino2/4 system thus forms a feedback loop and matches PA availability to the cellular
55 capacity for converting PA into other phospholipids. Removal of Opi1 results in
56 activation of lipid synthesis and ER membrane expansion, even in cells lacking the
57 UPR (Schuck et al., 2009). This membrane expansion without a corresponding
58 upregulation of the protein folding machinery increases resistance to ER stress,
59 highlighting the physiological importance of ER membrane biogenesis. However, it is
60 unknown whether activation of Ino2/4 is the only mechanism relevant for ER
61 membrane biogenesis. Furthermore, Ino2/4 and Opi1 are not conserved in
62 metazoans. Lipid metabolism could therefore be regulated in unique ways in yeast.
63 Alternatively, conserved lipid metabolism regulators unrelated to Ino2/4 and Opi1
64 could determine ER size in both yeast and higher eukaryotes.
65
66 Here, we systematically search for genes involved in ER membrane expansion in
67 budding yeast, *Saccharomyces cerevisiae*, to better define the regulatory circuitry
68 that connects lipid metabolism and organelle biogenesis.

RESULTS

An inducible system for ER membrane biogenesis

Removal of Opi1 induces Ino2/4-driven lipid synthesis genes and thereby leads to expansion of the ER (Schuck et al., 2009). To improve experimental control over ER membrane biogenesis, we developed an inducible system using ino2(L119A), which is an Ino2 variant that cannot be inhibited by Opi1 (Heyken et al., 2005). We placed ino2(L119A), here termed ino2*, under the control of the *GAL1* promoter and employed an expression system that activates this promoter upon addition of the metabolically inert sterol ß-estradiol (Pincus et al., 2014). High-level expression of ino2* is expected to displace endogenous Ino2 from the promoters of its target genes, stimulate lipid synthesis and drive ER membrane biogenesis (Figure 1A; Schuck et al., 2009). Fluorescence microscopy confirmed that expression of ino2* triggered pronounced ER expansion (Figure 1B). In untreated cells, the peripheral ER mostly consisted of tubules, which appeared as short membrane profiles along the cell cortex in optical mid sections and as a network in cortical sections. In contrast, estradiol-treated cells had a peripheral ER that predominantly consisted of ER sheets, as evident from long membrane profiles in mid sections and solid membrane areas in cortical sections.

To test whether ino2*-induced ER expansion causes ER stress, we measured UPR activity by means of a transcriptional reporter. This reporter is based on the UPR response element controlling expression of GFP (Jonikas et al., 2009). Treatment with the ER stressor DTT activated the UPR reporter, as expected, whereas expression of ino2* from the *GAL1* promoter did not (Figure 1C). Furthermore, expression of ino2* or removal of Opi1 did not alter the abundance of the chromosomally tagged ER proteins Sec63-mNeon or Rtn1-mCherry, even though Sec63 is encoded by a UPR-regulated gene (Figure 1D; Pincus et al., 2014). These observations indicate that ino2*-induced ER expansion is not an indirect consequence of ER stress but directly arises from enhanced lipid synthesis.

101 To assess ER membrane biogenesis quantitatively, we developed three metrics for
102 the size of the peripheral ER at the cell cortex, as visualized in mid sections. These
103 metrics are: (1) total area of the peripheral ER relative to cell periphery length, (2)
104 mean length of individual ER profiles relative to cell periphery length and (3) number
105 of gaps between ER profiles per micrometer cell periphery (Figure 1E). These new
106 metrics are less sensitive to variation in image quality than the index of expansion
107 we used previously (Schuck et al., 2009). Measurements of ER size upon induction
108 of ino2* expression with different concentrations of estradiol showed a dose-
109 dependent increase in total area and mean profile length, and a decrease in the
110 number of gaps. At 800 nM estradiol, ER size was indistinguishable from that in
111 *Δopi1* cells and we used this concentration in subsequent experiments. These
112 results show that this inducible system allows titratable control of ER membrane
113 biogenesis without causing ER stress.
114
115 *A genetic screen for regulators of ER membrane biogenesis*
116
117 To identify genes involved in ER expansion, we introduced the inducible ER
118 biogenesis system and the ER markers Sec63-mNeon and Rtn1-mCherry into the
119 knockout strain collection. This collection contains single deletion mutants for most of
120 the approximately 4800 non-essential genes in yeast (Giaever et al., 2002). We
121 induced ER expansion by ino2* expression and acquired images by high-throughput
122 microscopy. Based on inspection of Sec63-mNeon images of optical mid sections,
123 we defined six phenotypic classes. Mutants were grouped according to whether their
124 ER was (1) underexpanded, (2) properly expanded and hence morphologically
125 normal, (3) overexpanded, (4) overexpanded with extended cytosolic sheets, (5)
126 overexpanded with disorganized cytosolic structures, or (6) clustered. Figure 2A
127 shows two examples of each class. To refine the search for mutants with an
128 underexpanded ER, we applied the three ER size metrics described above (Figure
129 2B and Table S1A). This computational analysis confirmed the underexpansion
130 mutants identified visually and retrieved a number of additional, weaker hits. In total,
131 we found 141 mutants that fell into at least one phenotypic class other than
132 morphologically normal (Table S1B).

133

134 Hits included mutants lacking the ER-shaping gene *LNP1*, which had an
135 overexpanded cortical ER with large gaps, and mutants lacking the *SEY1* gene
136 important for homotypic ER fusion, which displayed ER clusters (Figure 2C; Hu et
137 al., 2009; Chen et al., 2012). The re-identification of these known ER morphogenesis
138 genes validated our screening approach. About two thirds of the identified mutants
139 had an overexpanded ER, one third had an underexpanded ER and some showed
140 ER clusters together with an otherwise underexpanded, normal or overexpanded ER
141 (Figure 2D). Overexpansion mutants were significantly enriched in gene deletions
142 that cause UPR activation (Table S1C; Jonikas et al., 2009). This enrichment
143 suggested that ER expansion in these mutants results from ER stress and not
144 enforced lipid synthesis. Indeed, re-imaging of the overexpansion mutants revealed
145 that their ER was expanded also in the absence of ino2* (data not shown).
146 Underexpansion mutants included those lacking *INO4*, as expected, or the known
147 lipid synthesis genes *OPI3*, *CHO2* and *DGK1*. In addition, mutants lacking *ICE2*
148 showed a particularly strong underexpansion phenotype (Figure 2B).
149

150 Overall, our screen showed that a large number of genes impinge on ER membrane
151 biogenesis, as might be expected for a complex biological process. The functions of
152 many of these genes in ER biogenesis remain to be uncovered. We here follow up
153 on *ICE2* because of its apparent key role in building an expanded ER. In addition,
154 Ice2 is a polytopic ER membrane protein and has previously been implicated in the
155 formation or maintenance of the peripheral ER network (Estrada de Martin et al.,
156 2005). Ice2 may thus have an immediate role in ER membrane biogenesis.
157

158 *Ice2 promotes ER membrane biogenesis*
159

160 To more precisely define the contribution of *ICE2* to ER membrane biogenesis, we
161 analyzed optical sections of the cell cortex. Well-focused cortical sections are more
162 difficult to acquire than mid sections but provide more morphological information.
163 Qualitatively, deletion of *ICE2* had little effect on ER structure at steady state but
164 severely impaired ER expansion upon ino2* expression (Figure 3A).

165

166 To describe ER morphology quantitatively, we developed a semi-automated
167 algorithm that classifies ER structures as tubules or sheets based on images of
168 Sec63-mNeon and Rtn1-mCherry in cortical sections (Figure 3B). First, the image of
169 the general ER marker Sec63-mNeon is used to segment the total ER. Second,
170 morphological opening, that is the operation of erosion followed by dilation, is applied
171 to the segmented image to remove narrow structures. The structures removed by
172 this step are defined as tubules and the remaining structures are provisionally
173 classified as sheets. Third, the same procedure is applied to the image of Rtn1-
174 mCherry, which marks high-curvature ER (Westrate et al., 2015). Rtn1 structures
175 that remain after morphological opening and overlap with persistent Sec63 structures
176 are termed tubular clusters. These structures appear as sheets in the Sec63 image
177 but the overlap with Rtn1 identifies them as tubules. Tubular clusters made up only a
178 minor fraction of the total ER and may correspond to so-called tubular matrices
179 observed in mammalian cells (Nixon-Abell et al., 2016). Last, for a simple two-way
180 classification, tubular clusters are added to the tubules and any remaining Sec63
181 structures are defined as sheets. This analysis using a general and a high-curvature
182 ER marker allows densely packed tubules to be distinguished from sheets.
183

184 Application of this algorithm showed that the ER covered approximately 50% of the
185 cell cortex in untreated wild-type cells and consisted mostly of tubules, in agreement
186 with previous studies (Figure 3C; Schuck et al., 2009; West et al., 2011). Expression
187 of ino2* triggered ER expansion by inducing the formation of sheets. *Δice2* cells had
188 a defect in sheet formation already at steady state and membrane expansion upon
189 ino2* expression failed almost completely. Importantly, activation of the prototypic
190 Ino2/4 target gene *INO1* upon ino2* expression was intact in *Δice2* cells, ruling out
191 that *ICE2* deletion disrupts the inducible ER biogenesis system (Figure 3D). In
192 addition, *ICE2* deletion also abrogated the constitutive ER expansion in *Δopi1* cells,
193 excluding that the expansion defect in *Δice2* cells merely reflects a delay (Figure 3E).
194

195 Next, we tested whether Ice2 is also required for ER expansion induced by ER
196 stress. DTT treatment of wild-type cells triggered rapid ER expansion, which was

197 again driven by ER sheet formation (Figures 4A). Expansion appeared to be
198 retarded in *Δice2* cells. Furthermore, induction of the UPR reporter by ER stress was
199 reduced in *Δice2* cells, showing slowed UPR activation (Figure 4B). However,
200 images of DTT-treated wild-type and *Δice2* cells revealed that ER expansion in *ice2*
201 mutants was aberrant rather than delayed. Specifically, DTT induced the appearance
202 of striking puncta positive for Rtn1-mCherry but not Sec63-mNeon, and these puncta
203 were much more abundant in *Δice2* than in wild-type cells (Figure 4C-E). Hence,
204 removal of Ice2 also impairs ER expansion during ER stress.
205
206 Finally, we asked whether raising Ice2 levels is sufficient to expand the ER. Indeed,
207 *ICE2* overexpression caused ER expansion, and this still occurred in UPR-deficient
208 *Δhac1* cells (Figure 4F; Emmerstorfer et al., 2015). In addition, *ICE2* overexpression
209 did not activate the UPR (Figure 4G). These data show that Ice2 can drive ER
210 membrane biogenesis independently of the UPR. However, the UPR could still
211 function upstream of Ice2 and induce ER expansion by activating it.
212
213 Collectively, these data show that Ice2 is required for and promotes ER membrane
214 biogenesis. These effects do not result from disrupted Ino2/4 target gene induction in
215 the absence of Ice2 or from activation of the UPR upon *ICE2* overexpression.
216
217 *Ice2 acts in the same pathway as Nem1, Spo7 and Pah1*
218
219 Ice2 has been implicated in ER morphogenesis and lipid metabolism (Estrada de
220 Martin et al., 2005; Tavassoli et al., 2013; Markgraf et al., 2014). In particular, Ice2
221 has been suggested to channel diacylglycerol (DAG) from lipid droplets (LDs) to the
222 ER for membrane lipid synthesis (Markgraf et al., 2014). We therefore tested
223 whether defective ER membrane biogenesis in *Δice2* cells could result from an
224 insufficient supply of lipids from LDs. Deletion of *ICE2* causes a growth defect
225 (Markgraf et al., 2014). Abolishing LD formation by combined deletion of *ARE1*,
226 *ARE2*, *LRO1* and *DGA1* (Sandager et al., 2002) did not affect growth under our
227 assay conditions, and deletion of *ICE2* still impaired growth in the absence of LDs
228 (Figure S1A). Therefore, Ice2 must have functions that are independent of LDs.

229 Furthermore, lack of LDs had no effect on ER expansion after ino2* expression or
230 DTT treatment, and deletion of *ICE2* still impaired ER expansion in the absence of
231 LDs (Figure 5A, B). Hence, the role of Ice2 in ER membrane biogenesis cannot be
232 explained by LD-related functions. These experiments additionally show that ER
233 expansion can occur without lipid mobilization from LDs.
234
235 To define the functional context of Ice2, we carried out protein proximity screens
236 using split-DHFR (Tarassov et al., 2008). An amino- or carboxy-terminal fragment of
237 a methotrexate-resistant dihydrofolate reductase (DHFR*) was fused to the carboxy-
238 terminus of Ice2. These Ice2 fusion proteins were functional as judged by growth
239 assays (Figure S1B). The two Ice2-DHFR* variants were introduced into genome-
240 wide strain collections in which the respective other DHFR* fragment was fused to
241 every open reading frame. The resulting strains were grown in the presence of
242 methotrexate, which blocks endogenous DHFR and prevents cell proliferation.
243 Proximity of Ice2 and a protein fused to the other DHFR* fragment reconstitutes
244 dihydrofolate reductase activity and restores growth (Figure 5C). To remove spurious
245 hits, we performed identical screens with Hmg2, a polytopic ER membrane protein
246 with similar abundance and distribution as Ice2 (Tkach et al., 2012). Proximity hits
247 specific for Ice2 predominantly localized to the ER and included many proteins
248 involved in lipid metabolism, including Cho1, Pis1, Spo7 and Ice2 itself (Figure 5C).
249
250 High-throughput studies have identified numerous genetic interactions between *ICE2*
251 and lipid synthesis genes (Schuldiner et al., 2005; Costanzo et al., 2010; Surma et
252 al., 2013). An interesting pattern emerged from mapping these genetic data onto the
253 biochemical pathways for membrane biogenesis and lipid storage (Figure 5D and
254 Table S2). *ICE2* displays negative interactions with genes for membrane lipid
255 synthesis but positive interactions with *NEM1*, *SPO7* and *PAH1*, which together
256 control the conversion of PA into DAG for lipid storage. Negative genetic interactions
257 typically indicate involvement in parallel pathways relevant for the same biological
258 process, whereas positive genetic interactions often reflect involvement in the same
259 pathway (Costanzo et al., 2019).
260

261 In light of these data, we focused on *NEM1*, *SPO7* and *PAH1*. To validate the
262 positive genetic interactions between these three genes and *ICE2*, we performed
263 growth assays. Remarkably, the growth defect caused by *ICE2* deletion was
264 completely suppressed by deletion of *NEM1*, *SPO7* or *PAH1*, confirming strong
265 positive genetic interactions (Figures 5E and S2A, C). Next, we analyzed ER
266 morphology. Deletion of *NEM1*, *SPO7* or *PAH1* drastically expands the ER and
267 causes nuclear morphology defects (Siniossoglou et al., 1998; Santos-Rosa et al.,
268 2005; Campbell et al., 2006). Additional deletion of *ICE2* in *Δnem1*, *Δspo7* or *Δpah1*
269 cells had no effect on ER morphology, consistent with *ICE2* acting in the same
270 pathway as the other three genes (Figures 5F and S2B, D). In contrast, deletion of
271 *DGK1* rescued the aberrant ER morphology of *Δnem1*, *Δspo7* and *Δpah1* cells
272 (Figure S2E). This was expected because Dgk1 opposes Nem1, Spo7 and Pah1
273 through a distinct pathway, namely the conversion of DAG into PA (Figure 5D; Han
274 et al., 2008). In conclusion, *ICE2*, *NEM1*, *SPO7* and *PAH1* likely control ER
275 membrane biogenesis as part of the same pathway.
276
277 *Ice2 promotes ER membrane biogenesis by inhibiting Pah1*
278
279 Pah1 is a phosphatidic acid phosphatase that converts PA into DAG (Figure 5D; Han
280 et al. 2006). In yeast, PA is a precursor of all phospholipids, whereas DAG is the
281 precursor of the storage lipid triacylglycerol (Henry et al., 2012). Pah1 thus promotes
282 LD biogenesis (Figure 5D; Adeyo et al., 2011). Pah1 activity is regulated by
283 reversible membrane association, which in turn depends on the phosphorylation
284 status of Pah1 (Figure 6A). Phosphorylated Pah1 is cytosolic and inactive. Activation
285 of Pah1 requires its dephosphorylation by the ER-localized phosphatase Nem1 in
286 complex with Spo7. Pah1 can then associate with the ER membrane and gain
287 access to its substrate, PA (O'Hara et al., 2006; Karanasios et al., 2010).
288
289 Even though Ice2 and Pah1 appear to act in the same pathway, deletion of *ICE2*
290 impairs ER biogenesis whereas deletion of *PAH1* promotes it. These contrasting
291 phenotypes raised the possibility that Ice2 inhibits Pah1. To test this idea, we
292 separated different phospho-forms of Pah1 on Phos-tag gels and used the

293 phosphorylation status of Pah1 as a readout for its activity (Dubots et al., 2014).
294 Removal of Ice2 strongly stimulated dephosphorylation of Pah1, and this effect was
295 dependent on Nem1 (Figure 6B). These result suggests that Ice2 opposes the
296 activity of the Nem1-Spo7 complex to restrain Pah1 activity.
297
298 We challenged this model in two ways. First, we compared the lipidome of wild-type,
299 *Δice2*, *Δnem1* and *Δspo7* cells to determine whether they showed the expected shifts
300 in the relative abundance of storage and membrane lipids. Compared with wild-type
301 cells, *ice2* mutants had increased levels of ergosterol esters and triacylglycerol, the
302 two lipid classes that make up LDs (Figure 6C, D). In contrast, the levels of the major
303 phospholipids phosphatidylethanolamine and phosphatidylcholine were decreased.
304 These changes agree with earlier data (Markgraf et al., 2014) and indicate that
305 deletion of *ICE2*, and hence activation of Pah1, shifts lipid metabolism towards lipid
306 storage. In contrast, *Δnem1* and *Δspo7* cells showed shifts in the opposite direction.
307 These data confirm that removal of Nem1 or Spo7, and hence inactivation of Pah1,
308 shifts lipid metabolism towards membrane biogenesis. The lipidomes of *Δnem1*
309 *Δice2* and *Δspo7 Δice2* double mutants were indistinguishable from those of *Δnem1*
310 and *Δspo7* single mutants. These observations are consistent with the prediction that
311 removal of Nem1 or Spo7 should abrogate the effects of their inhibitor Ice2.
312
313 As a second test of the above model, we asked whether the impact of Ice2 on ER
314 biogenesis depends on inactivation of Pah1. We employed pah1(7A), which carries
315 mutations in seven of the residues that are phosphorylated by various kinases and
316 dephosphorylated by Nem1-Spo7 (O'Hara et al., 2006; Carman and Han, 2019). As
317 a result, pah1(7A) displays constitutive activity, although some phospho-regulation
318 by Nem1-Spo7 remains (Su et al., 2012). We quantified ER expansion upon *ICE2*
319 overexpression in wild-type and pah1(7A)-expressing cells. Overexpression of *ICE2*
320 in wild-type cells expanded the ER, as before (Figure 6E, also see Figure 4F).
321 Replacement of Pah1 with pah1(7A) caused a slight shrinkage of the ER at steady
322 state, consistent with reduced membrane biogenesis. Moreover, pah1(7A) almost
323 completely blocked ER expansion upon *ICE2* overexpression. Similarly, pah1(7A)
324 impaired ER expansion upon DTT treatment, almost completely phenocopying the

325 effects of *ICE2* deletion (Figures 6F, G and 4A, E). These data further support the
326 idea that Ice2 contributes to ER membrane biogenesis by restricting Pah1 activity.
327
328 In summary, Ice2 inhibits Pah1 dephosphorylation by the Nem1-Spo7 complex,
329 thereby promoting ER membrane biogenesis and opposing Pah1-mediated
330 channeling of lipids towards LDs.
331
332 *Ice2 cooperates with the PA-Opi1-Ino2/4 system and the UPR*
333
334 Deletion of *OPI1* and overexpression of *ICE2* both cause ER expansion. These
335 effects could be independent of each other or they could be linked. For instance,
336 *ICE2* overexpression could inactivate Opi1 by causing an accumulation of PA
337 (Loewen et al., 2004). However, combined deletion of *OPI1* and overexpression of
338 *ICE2* produced an extreme ER expansion, which exceeded that in *Δopi1* mutants or
339 *ICE2*-overexpressing cells (Figures 7A, B). This hyperexpanded ER covered most of
340 the cell cortex and contained an even greater proportion of sheets than the ER in
341 DTT-treated wild-type cells (Figures 7B and 4A). Therefore, the PA-Opi1-Ino2/4
342 system and Ice2 make independent contributions to ER membrane biogenesis.
343
344 Last, to gain insight into the physiological significance of Ice2, we analyzed the
345 possible interplay between Ice2 and the UPR. UPR-deficient *Δhac1* mutants
346 behaved like wild-type cells under standard growth conditions (Sidrauski et al., 1996)
347 and *Δice2* cells showed a modest growth defect. However, *Δhac1 Δice2* cells grew
348 worse than *Δice2* cells (Figure 7C). This synthetic phenotype indicates that Ice2 and
349 the UPR cooperate to maintain ER homeostasis.

350 **DISCUSSION**

351

352 In this study, we identify factors involved in ER membrane expansion upon enforced
353 lipid synthesis in yeast. Among these are the DAG kinase Dgk1, which generates PA
354 for membrane biogenesis. Furthermore, we find that Ice2 is essential for proper ER
355 expansion, both upon enforced lipid synthesis and during ER stress. We show that
356 Ice2 inhibits the phosphatidic acid phosphatase Pah1 by opposing the activity of the
357 Nem1-Spo7 phosphatase complex, thereby promoting membrane lipid synthesis.
358 Finally, we provide evidence that Ice2 cooperates with the PA-Opi1-Ino2/4 system
359 and the UPR to regulate ER membrane biogenesis and maintain ER homeostasis.

360

361 Together with earlier findings, our results help delineate a regulatory network
362 controlling ER membrane biogenesis (Figure 7D). At the core of this network is the
363 interconversion of DAG and PA by Dgk1 and Pah1. The activity of Pah1 depends on
364 its dephosphorylation by the Nem1-Spo7 complex, which is opposed by Ice2. The
365 Pah1-regulated production of the critical metabolic precursor PA is coordinated with
366 the production of lipid synthesis enzymes that convert PA into other phospholipids.
367 Active Pah1 directly represses Ino2/4-controlled lipid synthesis genes (Santos-Rosa
368 et al., 2005). In addition, PA sequesters Opi1 and thereby derepresses Ino2/4 target
369 genes (Loewen et al., 2004). Hence, Pah1 inactivation favors net PA production and
370 both directly and indirectly induces lipid synthesis genes. Figuratively speaking,
371 Pah1 is a shunt that diverts lipids to LDs, and Ice2 restricts the flow through this
372 shunt to direct lipids towards ER membrane biogenesis.

373

374 The above model readily accounts for the available data on Ice2. The fact that *ICE2*
375 deletion disrupts ino2*-driven ER expansion may be explained by the need to
376 coordinate the production of lipid metabolic precursors with the expression of lipid
377 synthesis genes. As we show, ino2* still induces genes encoding lipid synthesis
378 enzymes in *ice2* mutants. Nevertheless, ER expansion fails, likely because the
379 supply of substrates for these enzymes is insufficient. The same reasoning can
380 explain the additive effects of *OPI1* deletion and *ICE2* overexpression on ER
381 membrane biogenesis. *ICE2* overexpression favors PA production and presumably

382 releases some repression of Ino2/4 target genes. However, *OPI1* deletion likely
383 further boosts the abundance of lipid synthesis enzymes. Conversely, constitutive
384 Pah1 activation upon *ICE2* deletion can explain the increase in LD abundance in
385 *ice2* mutants (Markgraf et al., 2014), although our data do not exclude additional
386 roles of Ice2 in lipid mobilization from LDs. It now needs to be determined exactly
387 how Ice2 inhibits Pah1. A possibility consistent with our protein proximity data is that
388 Ice2 inhibits Spo7. However, we currently cannot exclude more indirect explanations,
389 for example that Ice2 activates a Pah1 kinase.
390
391 Changing physiological conditions impose an additional layer of control onto the
392 regulatory network outlined above. For instance, entry into stationary phase, when
393 cell division ceases, promotes LD formation at the expense of ER proliferation. In
394 contrast, growth resumption upon stationary phase exit is accompanied by LD
395 consumption and the biogenesis of new ER. These changes are brought about, at
396 least in part, through the phosphorylation of Pah1, Nem1 and possibly Dgk1 by
397 nutrient-responsive kinases (Kwiatek et al., 2020). Whether Ice2 activity is regulated
398 under these conditions needs to be explored. Another relevant setting is ER
399 membrane expansion during ER stress. Since ER expansion is unaffected in LD
400 mutants, it does not require lipid mobilization from LDs and can be fueled exclusively
401 by *de novo* lipid synthesis. This notion is supported by the upregulation of Ino2/4
402 target genes by ER stress (Schuck et al., 2009). In addition, *DGK1* is a UPR target
403 gene (Pincus et al., 2014) and the resulting increase in Dgk1 protein abundance
404 during ER stress presumably contributes to ER expansion. In contrast, the UPR
405 does not control the *ICE2* gene and it is a question for future investigation whether
406 and how ER stress regulates Ice2 and Pah1 activity. Interestingly, ER stress upon
407 inhibition of protein N-glycosylation can stimulate not only ER expansion but also LD
408 formation (Schuck et al., 2009; Fei et al., 2009; James et al., 2019). This may,
409 however, depend on exactly how N-glycosylation is perturbed (James et al., 2016).
410 The effects of ER stress on lipid droplet biogenesis clearly warrant further study.
411
412 Bioinformatic analysis using HHpred suggests mammalian SERINC proteins as
413 distant Ice2 orthologs (unpublished results). SERINC1 was initially proposed to be at

414 the ER, but later work detected SERINC proteins only at endosomes and the plasma
415 membrane (Inuzuka et al., 2005; Rosa et al., 2015; Davies et al., 2018). Whether
416 SERINC proteins have similar roles as Ice2 remains to be tested. In contrast, Nem1,
417 Spo7 and Pah1 are known to be conserved (Han et al., 2012). The Pah1 orthologs
418 lipin-1/2/3 are phospho-regulated in a similar manner as Pah1 and function in lipid
419 storage in mice and humans (Harris and Fink, 2011; Zhang and Reue, 2017). Like in
420 yeast, removal of lipins causes ER expansion in protozoa, plants, worms and flies
421 (Golden et al., 2009; Eastmond et al., 2010; Bahmanyar et al., 2014; Grillet et al.,
422 2016; Pillai et al., 2017). However, an important difference is that metazoans
423 synthesize phospholipids mainly through the Kennedy pathway, which uses DAG
424 and not PA as a precursor (McMaster, 2018). Therefore, DAG is a precursor for both
425 LD and membrane biogenesis, seemingly ruling out the possibility that the balance
426 between DAG and PA could determine whether LD or ER biogenesis is favored. This
427 incongruence may be resolved by the finding from *A. thaliana* that CCT, the rate-
428 limiting enzyme for phosphatidylcholine synthesis by the Kennedy pathway, is
429 allosterically activated by PA (Craddock et al., 2015). Activation of CCT by PA may
430 also exist in mice (Zhang et al., 2019). Thus, accumulation of PA may increase flux
431 through the Kennedy pathway and channel DAG towards phospholipid synthesis
432 (Jacquemyn et al., 2017). This model raises the unifying possibility that lipins
433 inversely govern LD and ER biogenesis in all eukaryotes.
434
435 The regulation of lipid metabolism determines whether lipids are consumed, stored
436 or used to build membranes. Elucidating how this decision is made will yield a
437 deeper understanding of differentiation processes, for example the massive
438 expansion of the ER during plasma cell development or the huge increase in LD
439 abundance during adipogenesis. Moreover, it may enable therapeutic intervention in
440 diseases associated with ER overload and aberrant lipid metabolism, such as
441 diabetes and obesity. Besides organelle biogenesis, lipin activity has an impact on
442 autophagy, axon regeneration, myopathy, dystonia and neurodegeneration (Zhang
443 et al., 2014; Grillet et al., 2016; Zhang and Reue, 2017; Fanning et al., 2019; Yang et
444 al., 2019; Schäfer et al., 2020). Unraveling the regulation of lipin will therefore have
445 implications for a wide variety of cellular processes and associated diseases.

446 # MATERIALS AND METHODS

447

448 **Plasmids**

449 Plasmids used in this study are listed in Table S3. To generate pNH605-P_{ADH1}-GEM-
450 P_{GAL1}-ino2(L119A), the *ino2(L119A)* coding sequence was first subcloned from
451 pRS415$_{MET25}$-ino2(L119A) into pRS416-P_{GAL1}. The P_{GAL1}-ino2(L119A)-T_{CYC1} cassette
452 was then transferred into pNH605-P_{ADH1}-GEM. Similarly, pRS306-P_{ADH1}-GEM-P_{GAL1}-
453 ino2(L119A) was generated by transferring the P_{GAL1}-ino2(L119A) cassette from
454 pRS416-P_{GAL1}-ino2(L119A) into pRS306-P_{ADH1}-GEM. To generate pFA6a-mNeon-
455 kanMX6 and pFA6a-mNeon-HIS3MX6, mNeonGreen (Shaner et al., 2013) was
456 amplified from pFA6a-mNeon-kanMX4 and inserted into pFA6a-GFP(S65T)-kanMX6
457 and pFA6a-GFP(S65T)-HISMX6, replacing GFP(S65T). To generate pRS415-P_{ADH1}-
458 Ice2, the *ICE2* coding sequence was amplified from yeast W303 genomic DNA and
459 inserted into pRS415-P_{ADH1}. To generate expression plasmids for HA-tagged Pah1,
460 YCplac111-Pah1-PrtA was linearized by inverse PCR and religated using the
461 NEBuilder HiFi DNA assembly mix (New England Biolabs, Ipswitch, Massachusetts)
462 such that the sequence encoding Protein A was replaced with a triple HA tag. A
463 segment of the *pah1(7A)* coding sequence containing the seven alanine
464 substitutions was amplified from YCPlac111-pah1(7A)-PrtA and inserted into
465 YCPlac111-Pah1-3HA to yield YCplac111-pah1(7A)-3HA.

466

467 **Yeast strain generation and growth**

468 Strains used in this study are listed in Table S4. Strains generated for screening
469 procedures were in the S288C background. All other strains were in the W303
470 background. Chromosomal modifications were introduced using PCR products or
471 linearized plasmids (Longtine et al., 1998; Janke et al., 2004). The marker-free
472 strains SSY2836 and SSY2837 were derived from SSY2809 by transformation with
473 the *pah1(7A)-3HA* sequence amplified from plasmid pSS1047, followed by
474 counterselection on 5-fluoroorotic acid.
475 Strains were grown at 30°C on YPD, SCD-MSG or SCD medium as indicated. YPD
476 medium consisted of 1% yeast extract (Becton Dickinson, Heidelberg, Germany), 2%
477 peptone (Becton Dickinson) and 2% glucose (Merck, Darmstadt, Germany). SCD-

478 MSG medium consisted of 0.17% yeast nitrogen base without amino acids and
479 ammonium sulfate (Formedium, Norfolk, UK), 0.1% monosodium glutamate, amino
480 acids and 2% glucose. SCD medium consisted of 0.7% yeast nitrogen base without
481 amino acids (Sigma, Taufkirchen, Germany), amino acids and 2% glucose. Media
482 contained antibiotics or lacked certain amino acids as appropriate for selection.
483
484 **Light microscopy**
485 Precultures were grown in liquid SCD medium during the day, diluted into fresh
486 medium and grown overnight for 16 h so that they reached mid log phase (OD_{600} =
487 0.5 - 1). For induction of the GEM-GAL system, overnight cultures were diluted to
488 OD_{600} = 0.05 in fresh medium and treated with the indicated concentrations of ß-
489 estradiol (Sigma) for up to 6 h. For DTT treatment, overnight cultures were diluted to
490 OD_{600} = 0.1 and treated with 8 mM DTT (Roche, Mannheim, Germany) for up to 2 h.
491 Immediately before imaging, cells were harvested by centrifugation, mounted on
492 coverslips and covered with a 1% (w/v) agarose pad. Images were acquired with a
493 DMi8 inverted microscope (Leica, Wetzlar, Germany) equipped with a CSU-X1
494 spinning-disk confocal scanning unit (Yokogawa, Musashino, Japan) and an ORCA-
495 Flash 4.0 LT camera (Hamamatsu, Hamamatsu, Japan). A HC PL APO 63x/1.40-
496 0.60 or a HC PL APO 100x/1.4 CS2 oil objective lens (Leica) was used.
497
498 **UPR assays**
499 UPR activity was measured by flow cytometry as described in Schmidt et al., 2019.
500 Cells expressing cytosolic BFP and the 4xUPRE-GFP transcriptional reporter for
501 UPR activity (Jonikas et al., 2009) were grown to mid log phase. Where indicated,
502 cells were treated with estradiol or DTT as above. Fluorescence was measured with
503 a FACS Canto flow cytometer (BD Biosciences, Franklin Lakes, New Jersey)
504 equipped with a high-throughput sampler. Background autofluorescence was
505 determined with identically grown isogenic control strains not harboring the UPR
506 reporter. Background-subtracted GFP fluorescence was divided by BFP
507 fluorescence to account for differences in protein translation capacity. GFP/BFP
508 ratios were normalized to untreated wild-type cells.
509

510 **Cell lysis and western blotting**

511 For standard western blotting, cells were harvested by centrifugation, washed once
512 with water, resuspended in 50 mM HEPES pH 7.5 containing 0.5 mM EDTA, 1 mM
513 PMSF and complete protease inhibitors (Roche), and disrupted with glass beads
514 using a FastPrep 24 (MP Biomedicals). SDS was added to 1.5% (w/v) and proteins
515 were solubilized by incubation at 65ºC for 5 min. Equal protein amounts, as
516 determined with the BCA assay kit (Thermo Fisher Scientific Pierce, Waltham,
517 Massachusetts), were resolved by SDS-PAGE and transferred onto nitrocellulose
518 membranes. Membranes were probed with primary and HRP-coupled secondary
519 antibodies and developed with homemade ECL. Chemiluminescence was detected
520 with an ImageQuant LAS 4000 imaging system (GE Healthcare, Chalfont St Giles,
521 UK). Primary antibodies were rabbit anti-Sec63 (Feldheim et al., 1992), mouse anti-
522 mCherry 1C51 (Abcam, Cambridge, UK), mouse anti-Pgk1 22C5 (Abcam) and rat
523 anti-HA 3F10 (Roche). To assess the phosphorylation status of Pah1, cells were
524 lysed by alkaline extraction and incubation in a modified SDS-PAGE sample buffer at
525 65ºC for 3 min (Kushnirov, 2000). Proteins were resolved on Zn^{2+}-containing Phos-
526 tag gels according to Nagy et al., 2018 with minor modifications. Gels contained 8%
527 acrlylamide/bisacrylamide (29:1), 25 μM Phos-tag acrylamide (Fujifilm Wako
528 Chemicals, Neuss, Germany) and 50 μM $ZnCl_2$ in 350 mM Bis-Tris-HCl pH 6.8. Gels
529 were run at 200 V at room temperature, washed 3 x 10 min in transfer buffer (25 mM
530 Tris-HCl, 192 mM glycine, 20% methanol) containing 1 mM EDTA and 2 x 20 min in
531 transfer buffer. Blotting was done at 100 V at 4ºC for 3 h.

532

533 **Construction of diploid ER marker knockout library**

534 Using strains SSY2589 and SSY2590, the ER marker proteins Sec63-mNeon and
535 Rtn1-mCherry along with the GEM-P_{GAL1}-ino2* cassette were integrated into the
536 yeast knockout collection through modified SGA methodology (Giaever et al., 2002;
537 Tong and Boone 2007). SSY2589 and SSY2590 were independently mated to the
538 knockout collection on YPD medium using a Singer RoToR robot. For each library,
539 diploids were selected on SCD-MSG lacking uracil and containing G418. Cells were
540 pinned onto enriched sporulation medium (1% potassium actetate, 0.1% yeast
541 extract, 0.05% glucose, 0.01% amino acid supplement consisting of only histidine,

542 leucine, lysine and uracil) and kept at 23°C for 5 days. Haploids were selected by
543 two rounds of pinning onto SCD-MSG lacking histidine/arginine/lysine with
544 canavanine and thialysine or SCD-MSG lacking leucine/arginine/lysine with
545 canavanine and thialysine to select for MATa (Sec63-mNeon library) and MATα
546 (Rtn1-mCherry library) cells, respectively. Haploid cells harboring the required
547 markers were selected by sequential pinning onto appropriate media. The two
548 libraries were then mated together and diploids were selected on YPD containing
549 nourseothricin and hygromycin to generate the final library with the genotype:
550 *xxxΔ::kan/xxxΔ::kan SEC63-mNeon::HIS3/SEC63 RTN1-mCherry::nat/RTN1*
551 *can1Δ::GEM-*P_{GAL1}*-ino2*-URA3/can1Δ::*P_{STE2}*-HIS3 lyp1Δ::GEM-*P_{GAL1}*-ino2*-*
552 *URA3/lyp1Δ::*P_{STE3}*-LEU2 his3Δ::*P_{GPD}*-TagBFP-hph/his3Δ0.* This diploid library
553 afforded two benefits compared with a haploid library. The larger size of diploid cells
554 facilitated acquisition of informative images and the fact that cells were heterozygous
555 for the fluorescently tagged ER marker proteins reduced the risk that specious
556 morphological phenotypes arose from impaired functionality of Sec63 or Rtn1.
557
558 **High-throughput microscopy**
559 Cells were grown to saturation overnight in 100 μl cultures in SCD medium in regular
560 96 well microtiter plates. Prior to imaging, 7 μl of culture was transferred into 1 ml
561 fresh SCD medium containing 800 nM estradiol and grown for 5 h in 96 deep-well
562 microtiter plates to reach logarithmic growth phase. One-hundred μl of each sample
563 was transferred into 96 well glass bottomed microtiter plates (Brooks Life Sciences,
564 Chelmsford, Massachusetts) coated with concanavalin A and allowed to attach.
565 Medium was refreshed after 1 h to remove non-attached cells. Samples were
566 imaged with a Nikon Ti-E wide-field microscope equipped with a motorized stage, a
567 Nikon perfect focus system, a Flash4 Hamamatsu sCMOS camera and a 60x/1.49
568 oil immersion lens. For each sample, two fields of view were acquired consisting of
569 five optical slices spaced 1 μm apart. Untreated wild-type control strains were
570 included in duplicate on each plate as a reference for unexpanded ER.
571
572 **Automated cell segmentation and peripheral ER size measurement**
573 Image analysis was conducted in MATLAB using custom scripts. Initial cell objects

574 were identified based on the cytoplasmic BFP. The best overall mid-section image
575 was selected by assessing the standard deviation in the BFP image, which is highest
576 when the image is in focus. Next, a fast Fourier transformation and bandpass filter
577 were used to enhance contrast at the cell border. A Frangi filter (based on the
578 implementation by D.J. Kroon, “Hessian based Frangi Vesselness filter”, MATLAB
579 Central File Exchange. Retrieved May 2017) followed by Otsu thresholding was then
580 used to generate a mask of apparent cell borders. Morphological opening followed
581 by a minimum size filter was used to remove false labeling created by yeast
582 vacuoles. The resulting image highlighted the cell borders. Because the borders of
583 many cells touched each other, the internal space was used to identify and separate
584 the individual cell objects. The intensity of these initial cell objects was measured
585 and only objects brighter than two median absolute deviations below the median
586 were kept. Finally, any remaining touching cells, including connected mother cells
587 and buds, were separated by watershedding. The segmentation of individual cell
588 objects obtained through this procedure was then optimized to generate more
589 accurate cell boundaries and peripheral ER segmentation. For this, cells were
590 cropped and the best mid-section was reassessed on a per cell basis using the
591 standard deviation of the Rtn1-mCherry image. The BFP images were re-segmented
592 using the above procedure based on the new mid-section. To accurately define the
593 cell periphery for image quantification, object borders were expanded but contained
594 within watershed boundaries. The ER was segmented in both the Sec63-mNeon and
595 Rtn1-mCherry images using a Frangi tubeness filter. A more accurate cell border
596 was defined by fitting a minimum volume ellipse (based on the implementation by N.
597 Moshtagh, “Minimum Volume Enclosing Ellipsoid”, MATLAB Central File Exchange.
598 Retrieved July 2017) to the combined masks of the segmented ER. Based on this
599 segmentation, cell area, mean Sec63-mNeon and Rtn1-mCherry fluorescence, and
600 cell roundness were calculated. An area five pixels from the border was used to
601 define the peripheral ER. From this, total ER area (peripheral ER area divided by cell
602 periphery length), ER profile length (mean length of ER profiles divided by cell
603 periphery length) and ER gaps (number of gaps in the peripheral ER mask per
604 micrometer) were calculated. Finally, to remove false cell objects, poorly segmented
605 cells and dead cells, all of these measurements were used to limit the cell population

606 to values within 2.5 standard deviations of the population mean. On average, 248
607 cells were analyzed per mutant, with the minimum being 25.
608
609 **Visual ER morphology analysis**
610 To identify mutants with aberrant ER morphology, images were assessed visually
611 using a custom image viewer application made in MATLAB. Segmented cells were
612 arrayed in a montage displaying 7 x 15 cells at a time. Any strains with abnormal ER
613 morphology were re-imaged as described above to ensure that the phenotype was
614 robust. ER morphologies were independently annotated by two individuals with one
615 or more of the following features: underexpanded, overexpanded, extended sheets,
616 disorganized and clustered.
617
618 **Computational ER expansion analysis**
619 Since most gene deletions did not affect ER expansion, mutants from the same
620 imaging plate can serve as a plate-specific background population for comparison to
621 individual deletion strains. Sec63-mNeon intensity was used to define this
622 background population and exclude the influence of extreme outliers. First, to
623 remove plate effects, mNeon intensities were normalized by subtracting the plate
624 means. Next, values were corrected for cell size (bigger cells being brighter) and cell
625 count (densely crowded areas having an overall higher fluorescence) by local
626 regression. Finally, the background population (BP) was defined for each plate as
627 mutants that were within 1.5 standard deviations of the mean. To normalize the ER
628 expansion measurements, a Z score was calculated as (sample - BP mean)/BP
629 standard deviation, thereby removing plate effects. The time spent imaging each
630 plate (approximately 50 minutes) was accounted for by correcting for well order by
631 local regression. Similarly, cell density effects were corrected for by local regression
632 against cell count. Scores were calculated separately for each field of view and the
633 maximum value was taken for each sample. False positives were removed by visual
634 inspection, which were often caused by an out of focus field of view. Strains passing
635 arbitrary thresholds of significance (Z score less than -2 for total ER area and ER
636 profile length, and greater than 2 for ER gaps) in at least two of the measurements
637 and no overall morphology defects as defined above were re-imaged in triplicate

638 along with wild-type control strains under both untreated and estradiol-treated
639 conditions. Images were inspected visually as a last filter to define the final list of
640 strains with ER expansion defects.
641
642 **Semi-automated cortical ER morphology quantification**
643 For cell segmentation, bright field images were processed in Fiji to enhance the
644 contrast of the cell periphery. For this, a Gaussian blur (sigma = 2) was applied to
645 reduce image noise, followed by a scaling down of the image (x = y = 0.5) to reduce
646 the effect of small details on cell segmentation. A tubeness filter (sigma = 1) was
647 used to highlight cell borders and the images were scaled back up to the original
648 resolution. Cells were segmented using CellX (Dimopoulos et al., 2014) and out of
649 focus cells were removed manually. A user interface in MATLAB was then used to
650 assist ER segmentation. Users input images of Sec63-mNeon and Rtn1-mCherry
651 from cortical sections (background subtracted in Fiji using the rolling ball method with
652 a radius of 50 pixels) and the cell segmentation file generated in CellX. Adjustable
653 parameters controlled the segmentation of ER tubules and sheets for each image.
654 These parameters were tubule radius, tubule strength and sheet background.
655 Manual fine-tuning of these parameters was important to ensure consistent ER
656 segmentation across images with different signal intensities. These parameters were
657 set independently for Sec63-mNeon and Rtn1-mCherry images together with one
658 additional parameter called 'trimming factor', which controls the detection of ER
659 sheets. ER masks were calculated across entire images and were assigned to
660 individual cells based on the CellX segmentation. For each channel, the background
661 (BG) levels were automatically calculated using Otsu thresholding and fine tuned by
662 multiplying the threshold value by the 'tubule BG' (Rtn1 channel) or 'sheet BG'
663 (Sec63 channel) adjustment parameters. A 3x3 median filter was applied to
664 smoothen the images and reduce noise that is problematic for segmentation. Two
665 rounds of segmentation were passed for each image channel (Sec63 or Rtn1) with
666 one optimised for finding smaller features (i.e. ER tubules) and the other for larger
667 features (i.e. ER sheets). Firstly, convolution kernels were calculated for small and
668 large features, respectively, defined as a ring of radius +1, where the radius is given
669 in the 'tubule radius' (small feature) or 'sheet radius' (large feature) parameters.

670 These convolution kernels were applied pixel-wise to determine if a pixel is brighter
671 than the mean intensity of the surrounding ring of pixels. The strength of this filter
672 was fine-tuned by adjusting the 'tubule strength' or 'sheet strength' parameters.
673 Additionally, segmented pixels had to be brighter than the background levels defined
674 above. This procedure generated two segmented images per channel, which were
675 then combined to generate the 'total ER' mask for that channel. To define which
676 regions in each channel represented sheets or tubules a morphological opening was
677 applied, the degree of which was controlled by the parameter 'trimming factor'.
678 Features that remained in the Sec63 segmentation mask after morpholical opening
679 were provisionally designated as sheets, whereas the remainder of the ER mask
680 was designated tubules. Finally, areas that were sheet-like in the Rtn1 segmentation
681 mask and overlapped with the Sec63 mask were designated tubular clusters.
682 Tubular clusters were subtracted from provisonal sheets to obtain the final
683 designation of sheets. The median size measurements of each class were taken
684 from the whole cell population for further analyses.
685
686 **Quantitative real-time PCR**
687 Quantitative real-time PCR was done exactly as described (Schmidt et al., 2019).
688
689 **Ice2 protein proximity screen**
690 Ice2 proximity was screened by split DHFR protein complementation assay
691 (Tarassov et al., 2008). Hmg2 served as a control for non-specific hits. *MATa ICE2-*
692 *DHFR[1,2]* and *MATα ICE2-DHFR[3]* strains as well as the control strains *MATa*
693 *HMG2-DHFR[1,2]* and *MATα HMG2-DHFR[3]* were mated to the library of the
694 opposite mating type in 1536 colony format. Diploid cells were pinned onto SCD
695 medium containing 200 μg/ml methotrexate (Merck). Colonies were grown for 4 days
696 at 30°C before imaging using a Singer PhenoBooth with bottom illumination. Since
697 methotrexate is light sensitive, plate preparation and cell growth were carried out in
698 the dark. Data analysis was conducted in R. Colony size was measured using the
699 Gitter package (Wagih and Parts, 2014). Raw colony size measurements were
700 median polished to remove row and column effects. Z scores were calculated to
701 remove plate effects. Scores were converted into p-values and subjected to

702 Benjamini Hochberg multiple testing correction with corrected p-values below 0.05
703 being considered significant. The Ice2 screen was conducted twice and the Hmg2
704 screen once. Proteins were considered hits if they were significant in three out of
705 four possible outcomes (MATa and MATα libraries in duplicate). Proteins that were
706 only present in one of the MAT type libraries were also considered hits if they were
707 significant in both repeats. Finally, any proteins that were also hits in either of the
708 Hmg2 libraries (MATa or MATα) were excluded.
709
710 **Growth assays**
711 For growth assays in liquid culture, cells were grown to saturation and diluted to
712 OD_{600} = 0.05. For each strain, 500 *µ*l culture was transferred into 48-well plates in
713 triplicate and absorbance at 600 nm was measured at room temperature in 5 minute
714 intervals for 24 hours using a Tecan Infinite M1000 Pro plate reader. The area under
715 the curve was calculated with the R package Growthcurver (Sprouffske and Wagner,
716 2016) and used as a measure for cell growth. For the growth assays shown in Figure
717 7C, cells were grown to mid log phase, diluted as above and absorbance was
718 measured at 30°C using a Tecan Spark Cyto plate reader. This experimental regime
719 ensured that *Δhac1* mutants grew as well as wild-type cells.
720
721 **Lipidomics**
722 For each sample, approximately 2 x 10^8 cells (10 ODs) were harvested from cultures
723 grown to mid log phase and snap frozen in liquid nitrogen. Cells were disrupted with
724 glass beads as above in 50 mM HEPES pH 7.5 containing 0.5 mM EDTA. Aliquots
725 were subjected to acidic Bligh and Dyer lipid extractions in the presence of internal
726 lipid standards added from a master mix containing 40 pmol d7-PC mix (15:0/18:1-
727 d7, Avanti Polar Lipids), 25 pmol PI (17:0/20:4, Avanti Polar Lipids), 25 pmol PE and
728 15 pmol PS (14:1/14:1, 20:1/20:1, 22:1/22:1, semi-synthesized as described in
729 Özbalci et al., 2013), 20 pmol DAG (17:0/17:0, Larodan), 20 pmol TAG (D5-TAG-
730 Mix, LM-6000 / D5-TAG 17:0,17:1,17:1, Avanti Polar Lipids), 20 pmol PA (PA
731 17:0/20:4, Avanti Polar Lipids), 5 pmol PG (14:1/14:1, 20:1/20:1, 22:1/22:1, semi-
732 synthesized as described in Özbalci et al., 2013), 40 pmol ergosteryl ester (15:0 and
733 19:0, semi-synthesized as described in Gruber et al., 2018) and 20 pmol t-Cer (18:0,

734 Avanti Polar Lipids). Lipids recovered in the organic extraction phase were
735 evaporated by a gentle stream of nitrogen. Prior to measurements, lipid extracts
736 were dissolved in 10 mM ammonium acetate in methanol and transferred into
737 Eppendorf twin.tec 96-well plates. Mass spectrometric measurements were
738 performed in positive ion mode on an AB SCIEX QTRAP 6500+ mass spectrometer
739 equipped with chip-based (HD-D ESI Chip, Advion Biosciences) nano-
740 electrospray infusion and ionization (Triversa Nanomate, Advion Biosciences) as
741 described (Özbalci et al., 2013). The following precursor ion scanning (PREC) and
742 neutral loss scanning (NL) modes were used for the measurement of the various
743 lipid classes: +PREC 184 (PC), +PREC282 (t-Cer), +NL141 (PE), +NL185 (PS),
744 +NL277 (PI), + NL189 (PG), +NL115 (PA), +PREC 77 (ergosterol), +PREC379
745 (ergosteryl ester). Ergosterol was quantified following derivatization to ergosterol
746 acetate in the presence of 200 pmol of the internal standard (22E)-Stigmasta-5,7,22-
747 trien-3-beta-ol (Aldrich, R202967) using 100 μl acetic anhydride/chloroform (1:12 v/v)
748 overnight under argon atmosphere (Ejsing et al., 2009). Mass spectrometry settings:
749 Resolution: unit, low mass configuration; data accumulation: 400 MCA; curtain gas:
750 20; Interface heater temperature: 60; CAD: medium; DR: open; separation voltage:
751 3800; DMO: -3; compensation voltage: 10; DMS temperature: 60°C. Data evaluation
752 was done using LipidView (Sciex) and a software developed in house, ShinyLipids.

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AUTHOR CONTRIBUTIONS

Conceptualization: Peter Bircham, Dimitrios Papagiannidis, Sebastian Schuck; Formal analysis: Peter Bircham; Investigation: Peter Bircham, Dimitrios Papagiannidis, Christian Lüchtenborg, Giulia Ruffini; Software: Peter Bircham; Supervision: Britta Brügger, Sebastian Schuck; Writing - original draft: Dimitrios Papagiannidis, Sebastian Schuck; Writing - review and editing: all authors.

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1048 **FIGURE LEGENDS**

1049

1050 **Figure 1.** An inducible system for ER membrane biogenesis. **(A)** Schematic of the
1051 control of lipid synthesis by estradiol-inducible expression of ino2*. **(B)** Sec63-
1052 mNeon images of mid and cortical sections of cells harboring the estradiol-inducible
1053 system (SSY1405). Cells were untreated or treated with 800 nM estradiol for 6 h.
1054 Estradiol induces expansion of the peripheral ER. **(C)** Flow cytometric measurement
1055 of GFP levels in cells containing the UPR reporter. WT cells containing the UPR
1056 reporter (SSY2306), cells additionally harboring an estradiol-inducible *GAL* promoter
1057 (SSY2307) and cells additionally harboring the system for estradiol-inducible
1058 expression of ino2* under the *GAL* promoter (SSY2308) were untreated, treated with
1059 800 nM estradiol for 6 h or treated with 8 mM DTT for 1 h, as indicated. Data are
1060 normalized to untreated wild-type cells. Mean ± SEM, n = 3. WT, wild-type. **(D)**
1061 Western blot of Sec63, mCherry and Pgk1 from WT cells (SSY1404), cells harboring
1062 the estradiol-inducible system (SSY1405) or *Δopi1* cells (SSY1607), all of which
1063 expressed Sec63-mNeon and Rtn1-mCherry. Cells were untreated or treated with
1064 800 nM estradiol for 6 h. Pgk1 served as a loading control. **(E)** Quantification of ER
1065 size in estradiol-treated cells harboring the inducible system (SSY1405), untreated
1066 *Δopi1* cells (SSY1607) and WT cells (SSY1404) treated with 8 mM DTT for 1 h. The
1067 three metrics for the size of the peripheral ER at the cell cortex show dose-
1068 dependent ER expansion upon estradiol treatment, reaching the constitutive
1069 expansion in *Δopi1* cells. Mean ± SEM, n = 3.

1070

1071 **Figure 2.** A genetic screen for factors involved in ER membrane biogenesis. **(A)**
1072 Sec63-mNeon images of cells of the indicated genotypes harboring the inducible
1073 system. Cells were treated with 800 nM estradiol for 6 h. Two examples of each
1074 phenotypic class are shown. WT, wild-type. **(B)** Violin plots of Z scores from the
1075 three metrics for ER size determined for each of the 4800 mutants strains in the
1076 yeast knockout collection. The untreated WT is shown for reference. **(C)** Sec63-
1077 mNeon and Rtn1-mCherry images of *Δlnp1* and *Δsey1* cells harboring the inducible
1078 system and treated with 800 nM estradiol for 6 h. **(D)** Classification of hits. Numbers

1079 in brackets indicate the number of mutants in each class. Striped areas indicate
1080 mutants falling into two classes.
1081
1082 **Figure 3.** Ice2 is required for ER membrane biogenesis upon activation of Ino2/4.
1083 **(A)** Sec63-mNeon images of the cortical ER of WT and *Δice2* cells harboring the
1084 inducible system (SSY1405 and 1603). Cells were untreated or treated with 800 nM
1085 estradiol for 6 h. WT, wild-type. **(B)** Classification of peripheral ER structures from
1086 cortical sections of cells expressing Sec63-mNeon and Rtn1-mCherry as tubules
1087 (purple), sheets (green) or tubular clusters (yellow). Tubular clusters are added to
1088 the tubules in the final classification, as illustrated by the overlay. **(C)** Quantification
1089 of peripheral ER structures in WT and *Δice2* cells harboring the inducible system
1090 (SSY1405 and 1603) and treated with 800 nM estradiol for the times indicated.
1091 Plotted is the percentage of cell cortex covered by tubules (purple) or sheets (green).
1092 Error bars show the SEM for tubules and sheets, respectively. n = 3. ER expansion
1093 is driven by sheet formation, which fails in *Δice2* cells. **(D)** Activity of the Ino2/4 target
1094 gene *INO1* before and after ino2* expression in WT and *Δice2* cells harboring the
1095 inducible system (SSY1405 and 1603) as judged by mRNA levels measured by
1096 quantitative real-time PCR. Data are normalized to untreated WT cells. Mean ± SEM.
1097 n = 3. **(E)** Quantification of peripheral ER structures in untreated WT, *Δice2*, *Δopi1*
1098 and *Δice2 Δopi1* cells (SSY1404, 2356, 2595 and 2811). Deletion of *ICE2* impaires
1099 ER expansion caused by deletion of *OPI1*.
1100
1101 **Figure 4.** Ice2 is required for ER membrane biogenesis upon ER stress and *ICE2*
1102 overexpression is sufficient to induce ER expansion. **(A)** Quantification of peripheral
1103 ER structures in WT and *Δice2* cells (SSY1405 and 1603) treated with 8 mM DTT for
1104 the times indicated. Plotted is the percentage of cell cortex covered by tubules
1105 (purple) or sheets (green). Error bars show the SEM for tubules and sheets,
1106 respectively. n = 3. WT, wild-type. **(B)** Flow cytometric measurement of GFP levels
1107 of WT and *Δice2* cells containing the UPR reporter (SSY2306 and 2312). Cells were
1108 treated with 8 mM DTT for the times indicated. Data are normalized to untreated WT
1109 cells. Mean ± SEM, n = 3. **(C)** Fluorescence images of cortical sections of untreated
1110 WT and *Δice2* cells expressing Sec63-mNeon and Rtn1-mCherry (SSY1405 and

1111 1603). **(D)** As in panel C, but after treatment with 8 mM DTT for 1 h. **(E)**
1112 Quantification of WT and *Δice2* cells with Rtn1-mCherry puncta after treatment with 8
1113 mM DTT for the times indicated. Mean ± SEM. n = 3. **(F)** Quantification of peripheral
1114 ER structures in untreated WT and UPR-deficient *Δhac1* cells (SSY2228 and 2331),
1115 overexpressing *ICE2* from a centromeric plasmid where indicated. **(G)** Flow
1116 cytometric measurement of GFP levels of WT and *Δhac1* cells containing the UPR
1117 reporter (SSY2306 and 2314) and overexpressing *ICE2* from a centromeric plasmid
1118 where indicated. Data are normalized to untreated WT cells. Mean ± SEM, n = 3.
1119
1120 **Figure 5.** Ice2 cooperates with Nem1, Spo7 and Pah1. **(A)** Quantification of
1121 peripheral ER structures in WT, *Δice2*, *ΔLD* and *ΔLD Δice2* cells harboring the
1122 inducible system (SSY2598, 599, 2600 and 2601), which were untreated or treated
1123 with 800 nM estradiol for 6 h. Plotted is the percentage of cell cortex covered by
1124 tubules (purple) or sheets (green). Error bars show the SEM for tubules and sheets,
1125 respectively. n = 3. WT, wild-type; *ΔLD*, *Δlipid droplet*. The absence of lipid droplets
1126 has no effect on ER expansion or the expansion defect caused by deletion of *ICE2*.
1127 **(B)** As in panel A but after treatment with 8 mM DTT for 1 h. **(C)** Principle of the Ice2
1128 protein proximity screen (left) and table of the hits obtained (right). DHFR*$_N$ and
1129 DHFR*$_C$ are the amino-terminal and carboxy-terminal fragments of methotrexate-
1130 resistant dihydrofolate reductase. **(D)** Genetic interactions between *ICE2* and
1131 selected lipid synthesis genes. CDP, cytidine diphosphate; DAG, diacylglycerol; PA,
1132 phosphatidic acid; PI/PS/PE/PC, phosphatidyl-inositol/serine/ethanolamine/choline.
1133 **(E)** Growth assays of untreated WT, *Δice2*, *Δpah1* and *Δpah1Δice2* cells (SSY1404,
1134 2356, 2807 and 2808). Numbers represent the areas under the curves and serve as
1135 growth indices. Mean ± SEM. n = 3. Deletion of *PAH1* suppresses the growth
1136 phenotype caused by deletion of *ICE2*. **(F)** Fluorescence images of WT, *Δpah1* and
1137 *Δpah1Δice2* cells expressing Sec63-mNeon (SSY1404, 2807 and 2808). *ICE2*
1138 deletion has no effect on nuclear or peripheral ER morphology in *Δpah1* cells.
1139
1140 **Figure 6.** Ice2 promotes ER membrane biogenesis by opposing Pah1 activity. **(A)**
1141 Schematic of Pah1 phospho-regulation. Phosphorylated Pah1 is cytosolic and
1142 inactive. Interaction between Pah1 and the ER-localized Nem1-Spo7 complex

1143 results in Pah1 dephosphorylation and activation, leading to conversion of PA into
1144 DAG. **(B)** Western blot of HA from WT, *Δice2*, *Δnem1* and *Δnem1 Δice2* cells
1145 expressing endogenously tagged Pah1-3HA (SSY2592, 2593, 2595 and 2718).
1146 SDS-PAGE (top) and Phos-tag PAGE (bottom) gels are shown. WT, wild-type. Loss
1147 of Ice2 results in dephosphorylation and hence activation of Pah1 by Nem1,
1148 indicating that Ice2 opposes Pah1 activity. **(C)** Lipidomic analysis of WT, *Δice2*,
1149 *Δnem1* and *Δice2 Δnem1* cells (SSY1404, 2356, 2482 and 2484). Mean ± SEM. n =
1150 4. TAG, triacylglycerol; DAG, diacylglycerol; PA, phosphatidic acid; PI/PS/PE/PC,
1151 phosphatidyl-inositol/serine/ethanolamine/choline. **(D)** As in panel C, but of WT,
1152 *Δice2*, *Δspo7* and *Δice2 Δspo7* cells (SSY1404, 2356, 2481 and 2483). Data for WT
1153 and *Δice2* cells are the same as in panel C. **(E)** Quantification of peripheral ER
1154 structures in WT cells and cells in which *PAH1* was replaced by *pah1(7A)*, without
1155 and with overexpression of *ICE2* (SSY2841, 2842, 2843 and 2844). Plotted is the
1156 percentage of cell cortex covered by tubules (purple) or sheets (green). Error bars
1157 show the SEM for tubules and sheets, respectively. n = 3. The constitutively active
1158 *pah1(7A)* prevents ER membrane expansion upon *ICE2* overexpression. **(F)**
1159 Quantification of peripheral ER structures in WT cells and cells in which *PAH1* was
1160 replaced by *pah1(7A)* (SSY2841 and 2842), treated with 8 mM DTT for 1 h. **(G)**
1161 Quantification of WT and *Δice2* cells with Rtn1-mCherry puncta after treatment with 8
1162 mM DTT for the times indicated. Mean ± SEM. n = 3.
1163
1164 **Figure 7.** Ice2 cooperates with the PA-Opi1-Ino2/4 system and the UPR. **(A)** Sec63-
1165 mNeon images of mid and cortical sections of untreated WT and *Δopi1* cells,
1166 overexpressing *ICE2* where indicated (SSY1404, 2595, 2588 and 2596). WT, wild-
1167 type. **(B)** Quantification of peripheral ER structures in the strains shown in panel A.
1168 Plotted is the percentage of cell cortex covered by tubules (purple) or sheets (green).
1169 Error bars show the SEM for tubules and sheets, respectively. n = 3. **(C)** Growth
1170 assays of untreated WT, *Δhac1*, *Δice2*, and *Δhac1Δice2* cells (SSY1404, 2356,
1171 2805 and 2806). Numbers represent the areas under the curves and serve as growth
1172 indices. Mean ± SEM. n = 3. **(D)** Model for the regulation of ER membrane
1173 biogenesis. High Pah1 activity promotes conversion of phosphatidic acid (PA) into
1174 diacylglycerol (DAG) for lipid droplet biogenesis. Low Pah1 activity allows net DAG-

1175 to-PA conversion by Dgk1 and derepression of Ino2/4-driven lipid synthesis genes,
1176 resulting in phospholipid production and ER membrane biogenesis. These
1177 mechanisms coordinate the production of lipid metabolic precursors and lipid
1178 synthesis enzymes.
1179
1180 **Figure S1. (A)** Growth assays of untreated WT, *Δice2*, *ΔLD* and *ΔLD Δice2* cells
1181 (SSY2228, 2229, 2230 and 2256). Numbers represent the areas under the curves
1182 and serve as growth indices. WT, wild-type. Mean ± SEM. n = 3. *ΔLD*, *Δlipid droplet*.
1183 The absence of lipid droplets has no effect on ER expansion or the expansion defect
1184 caused by deletion of *ICE2*. **(B)** Growth assay of untreated S288C WT cells mating
1185 type a or alpha, the corresponding cells harboring Ice2 fused to either fragment of
1186 DHFR*, and *Δice2* cells. Numbers represent the areas under the curves and serve
1187 as growth indices. n = 1. Ice2-DHFR fusion proteins support normal growth,
1188 indicating that they are functional.
1189
1190 **Figure S2.** Ice2 but not Dgk1 acts in the same pathway as Nem1, Spo7 and Pah1.
1191 **(A)** Growth assays of untreated WT, *Δice2*, *Δnem1* and *Δnem1Δice2* cells
1192 (SSY1404, 2356, 2482 and 2484). Numbers represent the areas under the curves
1193 and serve as growth indices. Mean ± SEM. n = 3. WT, wild-type. Deletion of *NEM1*
1194 suppresses the growth phenotype caused by deletion of *ICE2*. **(B)** Sec63-mNeon
1195 images of untreated WT, *Δice2*, *Δnem1* and *Δnem1Δice2* cells (SSY1404, 2356,
1196 2482 and 2484). *ICE2* deletion has no effect on nuclear or peripheral ER morphology
1197 in *Δnem1* cells. **(C)** As in panel A but for WT, *Δice2*, *Δspo7* and *Δspo7Δice2* cells
1198 (SSY1404, 2356, 2481 and 2483). Data for WT and *Δice2* cells are the same as in
1199 panel A. **(D)** As in panel B but for WT, *Δice2*, *Δspo7* and *Δspo7Δice2* cells
1200 (SSY1404, 2356, 2481 and 2483). **(E)** Sec63-mNeon images of untreated cells of
1201 the indicated genotypes (SSY1404, 2482, 2481, 2807, 2480, 2485, 2486 and 2822).
1202 *DGK1* deletion rescues the nuclear envelope defects and constitutive ER expansion
1203 in *Δnem1*, *Δspo7* and *Δpah1* cells.

Table S3. Plasmids used in this study. GEM = GAL4DBD-EstR-Msn2TAD.

Plasmid	Alias	Source
pRS415-P_{MET25}-ino2(L119A)	pSS108	Heyken et al., 2005
pRS416-P_{GAL1}	pSS031	Mumberg et al., 1994
pRS415-P_{GAL1}-ino2(L119A)	pSS448	this study
pNH605-P_{ADH1}-GEM	pDEP151	David Pincus
pNH605-P_{ADH1}-GEM-P_{GAL1}	pSS474	Schmidt et al., 2019
pNH605-P_{ADH1}-GEM-P_{GAL1}-ino2(L119A)	pSS475	this study
pRS306-P_{ADH1}-GEM	pDEP001	Pincus et al., 2014
pRS306-P_{ADH1}-GEM-P_{GAL1}	pSS476	Schmidt et al., 2019
pRS306-P_{ADH1}-GEM-P_{GAL1}-ino2(L119A)	pSS477	this study
pRS303H-P_{GPD}-TagBFP	pMaM245	Szoradi et al., 2018
pFA6a-mNeon-kanMX4	pMaM375	Michael Knop
pFA6a-GFP(S65T)-kanMX6	pSS037	Longtine et al., 1998
pFA6a-GFP(S65T)-HISMX6	pSS039	Longtine et al., 1998
pFA6a-mNeon-kanMX6	pSS445	Schäfer et al., 2020
pFA6a-mNeon-HIS3MX6	pSS447	this study
pRS415-P_{ADH1}	pSS022	Mumberg et al., 1995
pRS415-P_{ADH1}-Ice2	pSS761	this study
pRS304-4xUPRE-GFP	pDEP017	Pincus et al., 2010
YCplac111-Pah1-PrtA	pSS1005	O'Hara et al., 2006
YCplac111-pah1(7A)-PrtA	pSS1006	O'Hara et al., 2006
YCplac111-Pah1-3HA	pSS1045	this study
YCplac111-pah1(7A)-3HA	pSS1047	this study

Table S4. Yeast strains used in this study. mNeon = mNeonGreen. GEM = P_{ADH1}-GAL4DBD-EstR-Msn2TAD.

Strain	Relevant genotype	Source
SSY122	*ADE2 leu2-3,112 trp1-1 ura3-1 his3-11,15 MATa*	Szoradi, 2018
SSY1404	*Sec63-mNeon::kan Rtn1-mCherry::HIS3*	this study
SSY2328	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 leu2::GEM-LEU2*	this study
SSY1405	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 leu2::GEM-P_{GAL1}-ino2(L119A)-LEU2*	this study
SSY2306	*his3::P_{GPD}-TagBFP-hph trp1::4xUPRE-GFP-TRP1*	this study
SSY2307	*his3::P_{GPD}-TagBFP-hph trp1::4xUPRE-GFP-TRP1 ura3::GEM-P_{GAL1}-URA3*	this study
SSY2308	*his3::P_{GPD}-TagBFP-hph trp1::4xUPRE-GFP-TRP1 ura3::GEM-P_{GAL1}-ino2(L119A)-URA3*	this study
SSY1607	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 leu2::GEM-P_{GAL1}-ino2(L119A)-LEU2 opi1Δ::hph*	this study
Y8205	*can1Δ::P_{STE2}-Sp_his5 lyp1Δ::P_{STE3}-LEU2 his3Δ1 leu2Δ0 ura3Δ0 MATα*	Tong, 2007
SSY2589	*Y8205 Sec63-mNeon::HIS3 his3::P_{GPD}-TagBFP-hph can1::GEM-P_{GAL1}-ino2(L119A)-URA3*	this study
SSY2590	*Y8205 Rtn1-mCherry::nat lyp1::GEM-P_{GAL1}-ino2(L119A)-URA3*	this study
SSY1603	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 leu2::GEM-P_{GAL1}-ino2(L119A)-LEU2 ice2Δ::hph*	this study
SSY2356	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 ice2Δ::nat*	this study
SSY2595	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 opi1Δ::hph*	this study
SSY2811	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 opi1Δ::hph ice2Δ::nat*	this study
SSY2312	*his3::P_{GPD}-TagBFP-hph trp1::4xUPRE-GFP-TRP1 ice2Δ::nat*	this study
YMG1	*ade2-1 leu2-3,112 trp1-1 ura3-1 his3-11,15 can1-100 MATa*	Velazquez, 2016
SSY2228	*YMG1 Sec63-mNeon::URA3 Rtn1-mCherry::kan*	this study
SSY2331	*YMG1 Sec63-mNeon::URA3 Rtn1-mCherry::kan hac1Δ::nat*	this study
SSY2314	*his3::P_{GPD}-TagBFP-hph trp1::4xUPRE-GFP-TRP1 hac1Δ::nat*	this study
YMG5	*YMG1 dga1Δ::TRP1 lro1Δ::HIS3 are1Δ::TRP1 are2Δ::HIS3*	Velazquez, 2016
SSY2598	*YMG1 ADE2 Sec63-mNeon::URA3 Rtn1-mCherry::kan leu2::GEM-P_{GAL1}-ino2(L119A)-LEU2*	this study
SSY2599	*SSY2598 ice2Δ::nat*	this study
SSY2600	*YMG5 ADE2 Sec63-mNeon::URA3 Rtn1-mCherry::kan leu2::GEM-P_{GAL1}-ino2(L119A)-LEU2*	this study
SSY2601	*SSY2600 ice2Δ::nat*	this study
BY4741	*his3Δ1 leu2Δ0 met15Δ0 ura3Δ0 MATa*	Michael Knop
BY4742	*his3Δ1 leu2Δ0 leu2Δ0 ura3Δ0 MATα*	Michael Knop
	BY4741 Ice2-DHFR$_{1,2}$ (from DHFR fusion collection)*	Tarassov, 2008
	BY4742 Ice2-DHFR$_{3}$ (from DHFR fusion collection)*	Tarassov, 2008
	BY4741 Hmg2-DHFR$_{1,2}$ (from DHFR fusion collection)*	Tarassov, 2008
	BY4742 Hmg2-DHFR$_{3}$ (from DHFR fusion collection)*	Tarassov, 2008
	BY4741 ice2Δ::kan (from knockout strain collection)	Giaever, 2002
SSY2807	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 pah1Δ::hph*	this study
SSY2808	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 ice2Δ::nat pah1Δ::hph*	this study
SSY2229	*YMG1 Sec63-mNeon::URA3 Rtn1-mCherry::kan ice2Δ::nat*	this study
SSY2230	*YMG5 Sec63-mNeon::URA3 Rtn1-mCherry::kan ice2Δ::nat*	this study
SSY2256	*YMG5 Sec63-mNeon::URA3 Rtn1-mCherry::kan*	this study
SSY2482	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 nem1Δ::hph*	this study
SSY2484	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 ice2Δ::nat nem1Δ::hph*	this study
SSY2481	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 spo7Δ::hph*	this study
SSY2483	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 ice2Δ::nat spo7Δ::hph*	this study
SSY2480	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 dgk1Δ::nat*	this study
SSY2485	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 spo7Δ::hph Δdgk1::nat*	this study
SSY2486	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 nem1Δ::hph Δdgk1::nat*	this study
SSY2822	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 dgk1Δ::nat Δpah1::hph*	this study
SSY2592	*Pah1-3HA::HIS3*	this study
SSY2593	*Pah1-3HA::HIS3 ice2Δ::nat*	this study
SSY2594	*Pah1-3HA::HIS3 nem1Δ::nat*	this study
SSY2718	*Pah1-3HA::HIS3 ice2Δ::nat nem1Δ::hph*	this study
SSY2809	*pah1Δ::URA3*	this study
SSY2836	*Pah1-3HA*	this study
SSY2837	*pah1(7A)-3HA*	this study
SSY2841	*Pah1-3HA Sec63-mNeon::kan Rtn1-mCherry::HIS3*	this study
SSY2842	*pah1(7A)-3HA Sec63-mNeon::kan Rtn1-mCherry::HIS3*	this study
SSY2843	*Pah1-3HA Sec63-mNeon::kan Rtn1-mCherry::HIS3 ura3::P_{ADH1}-Ice2-LEU2*	this study
SSY2844	*pah1(7A)-3HA Sec63-mNeon::kan Rtn1-mCherry::HIS3 ura3::P_{ADH1}-Ice2-LEU2*	this study
SSY2588	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 ura3::Padh-Ice2-LEU2*	this study

SSY2596	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 ura3::Padh-Ice2-LEU2 opi1Δ::hph*	this study
SSY2805	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 hac1Δ::hph*	this study
SSY2806	*Sec63-mNeon::kan Rtn1-mCherry::HIS3 ice2Δ::nat hac1Δ::hph*	this study

Figure 1

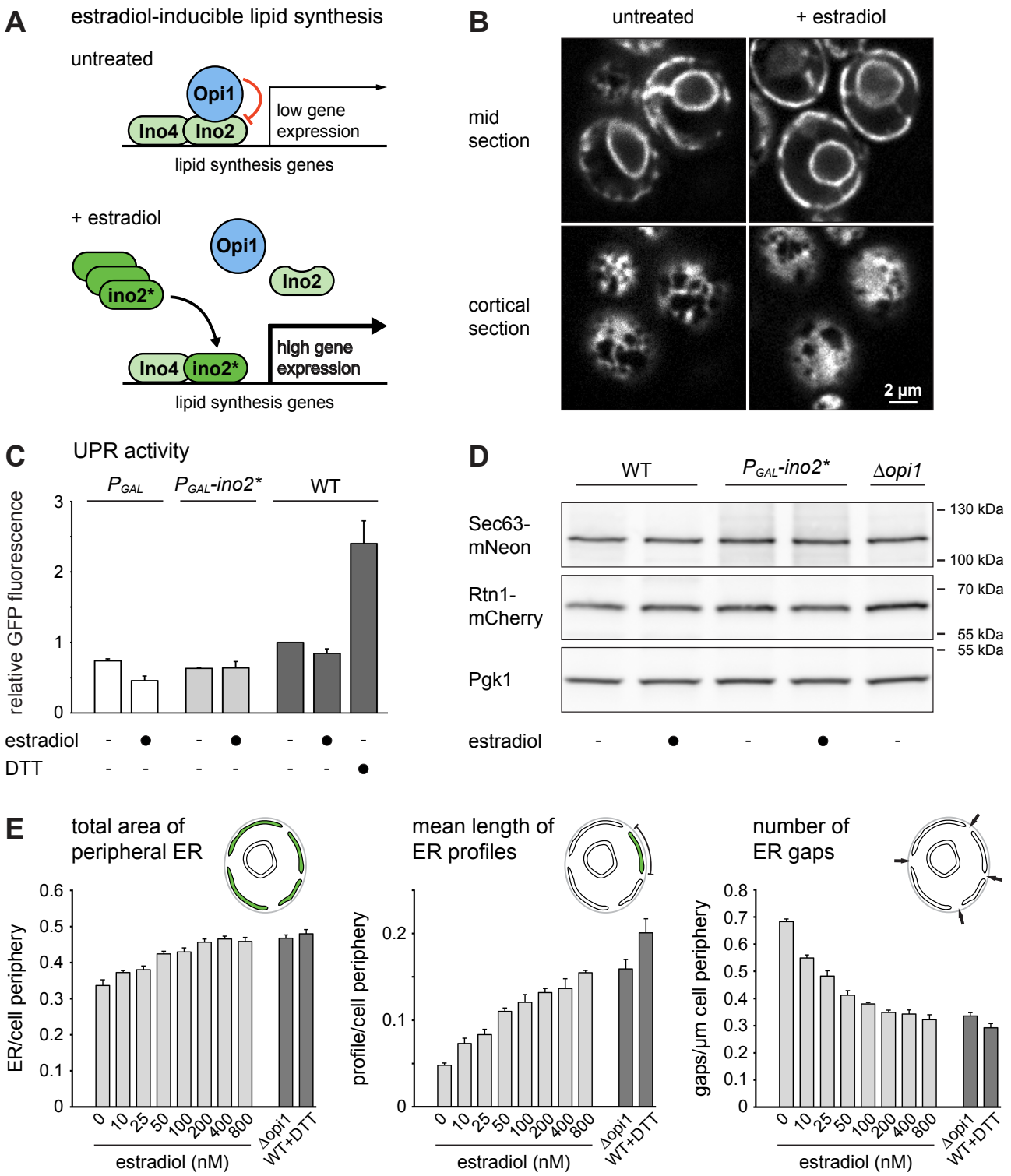

A
estradiol-inducible lipid synthesis
untreated
Opi1
Ino4
Ino2
low gene expression
lipid synthesis genes
+ estradiol
Opi1
ino2*
Ino2
Ino4
ino2*
high gene expression
lipid synthesis genes
B
untreated
+ estradiol
mid section
cortical section
2 µm
C
UPR activity
P_{GAL}
P_{GAL}-ino2*
WT
relative GFP fluorescence
estradiol
DTT
D
WT
P_{GAL}-ino2*
Δopi1
Sec63-mNeon
Rtn1-mCherry
Pgk1
130 kDa
100 kDa
70 kDa
55 kDa
55 kDa
estradiol
E
total area of peripheral ER
ER/cell periphery
estradiol (nM)
Δopi1
WT+DTT
mean length of ER profiles
profile/cell periphery
estradiol (nM)
Δopi1
WT+DTT
number of ER gaps
gaps/µm cell periphery
estradiol (nM)
Δopi1
WT+DTT

Figure 2

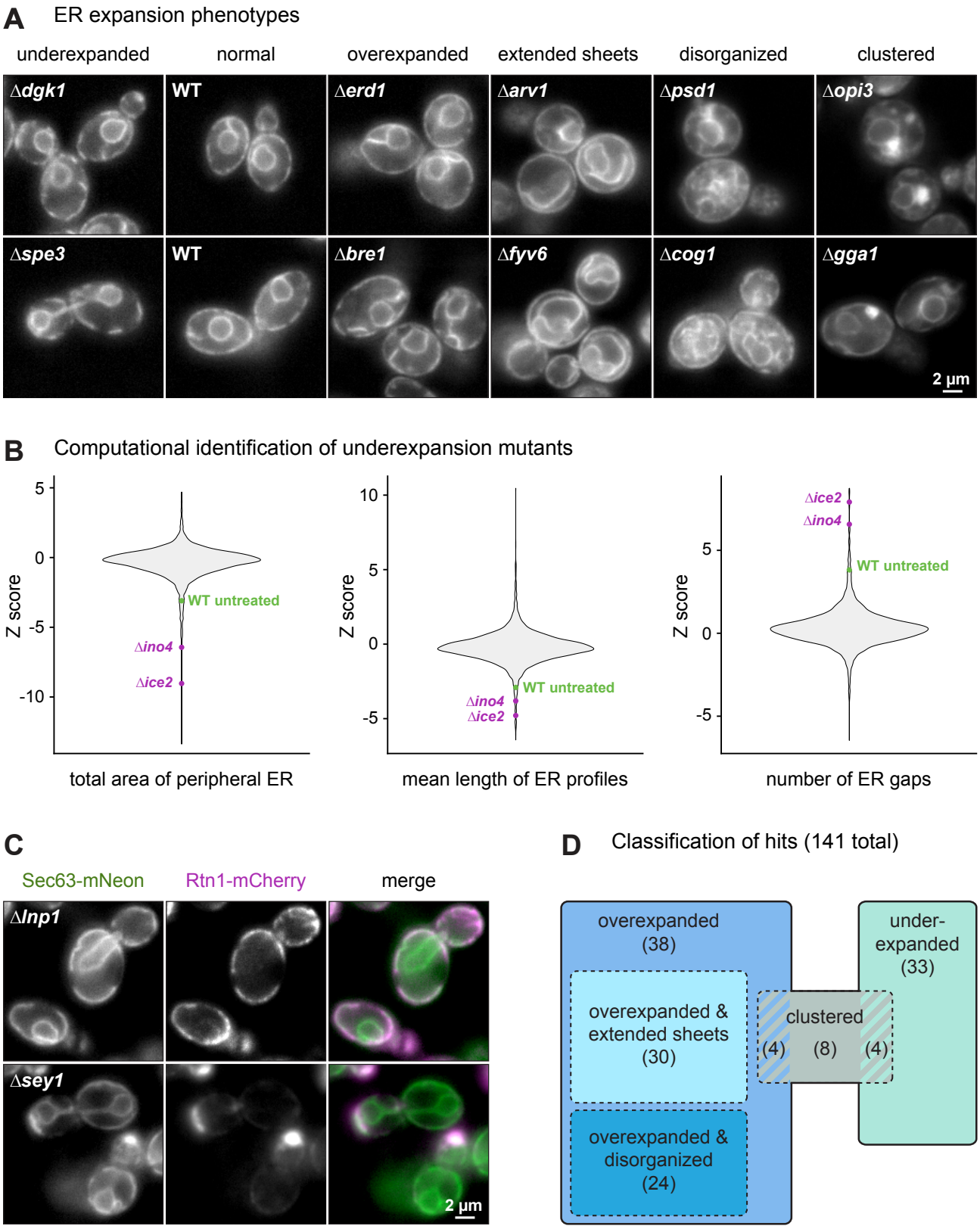

A
ER expansion phenotypes
underexpanded
normal
overexpanded
extended sheets
disorganized
clustered
Δdgk1
WT
Δerd1
Δarv1
Δpsd1
Δopi3
Δspe3
WT
Δbre1
Δfyv6
Δcog1
Δgga1
2 µm
B
Computational identification of underexpansion mutants
Z score
WT untreated
Δino4
Δice2
total area of peripheral ER
mean length of ER profiles
number of ER gaps
C
Sec63-mNeon
Rtn1-mCherry
merge
Δlnp1
Δsey1
2 µm
D
Classification of hits (141 total)
overexpanded (38)
under-expanded (33)
overexpanded & extended sheets (30)
clustered
(4)
(8)
(4)
overexpanded & disorganized (24)

Figure 3

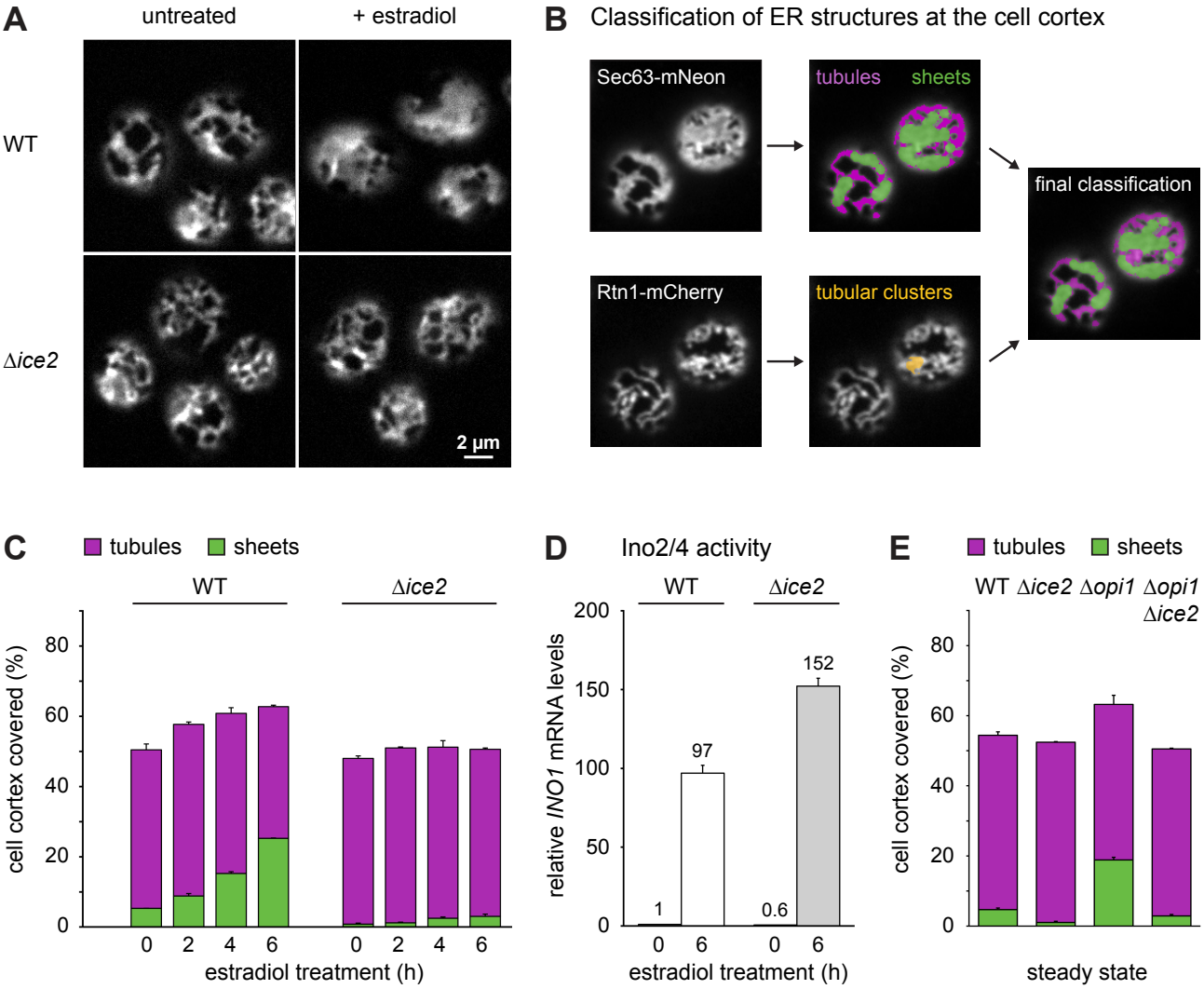

A
untreated
+ estradiol
WT
Δice2
2 µm
B
Classification of ER structures at the cell cortex
Sec63-mNeon
tubules
sheets
final classification
Rtn1-mCherry
tubular clusters
C
tubules
sheets
WT
Δice2
cell cortex covered (%)
0
20
40
60
80
0 2 4 6
0 2 4 6
estradiol treatment (h)
D
Ino2/4 activity
WT
Δice2
relative INO1 mRNA levels
0
50
100
150
200
1
97
0.6
152
0 6
0 6
estradiol treatment (h)
E
tubules
sheets
WT Δice2 Δopi1 Δopi1 Δice2
cell cortex covered (%)
0
20
40
60
80
steady state

Figure 4

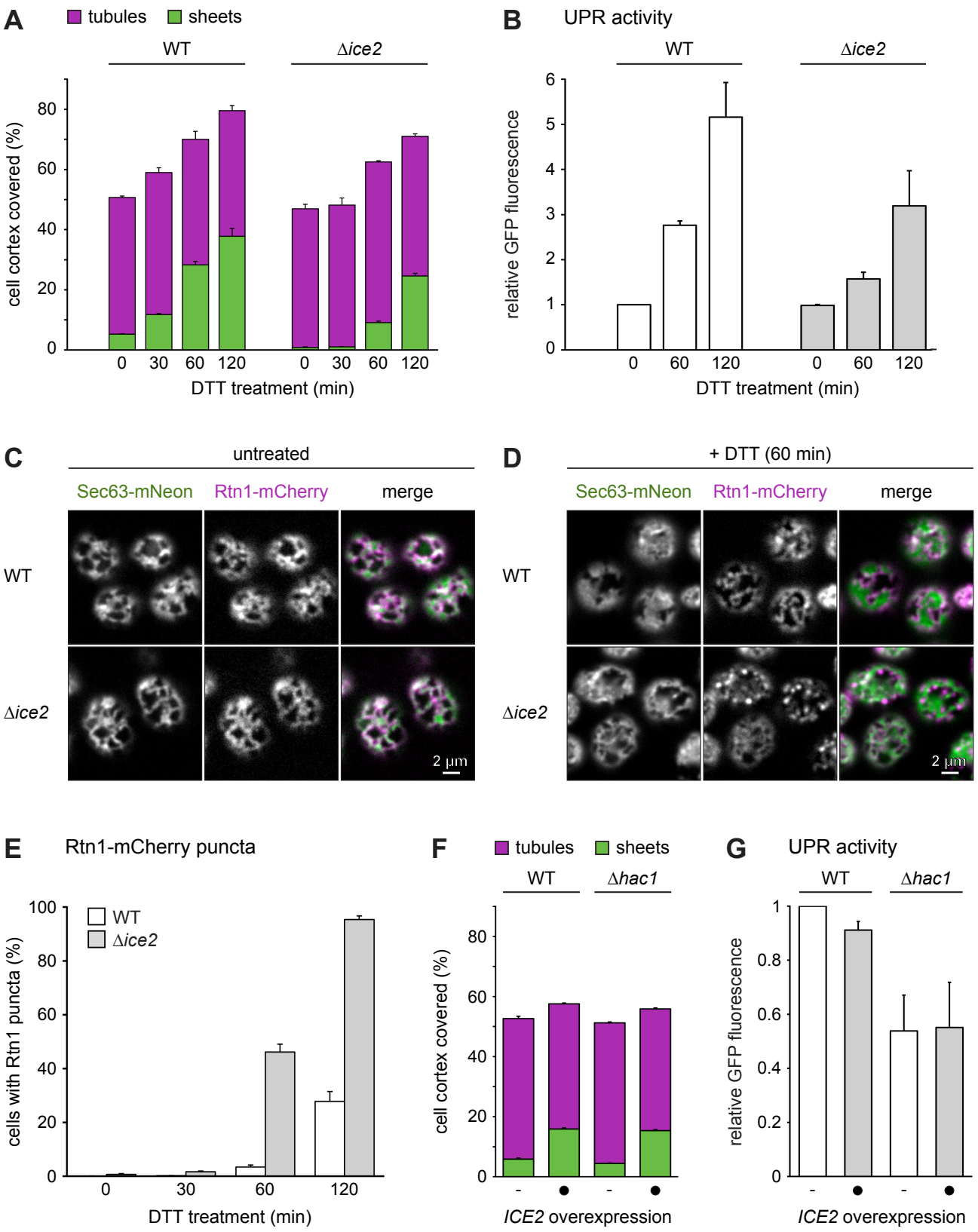
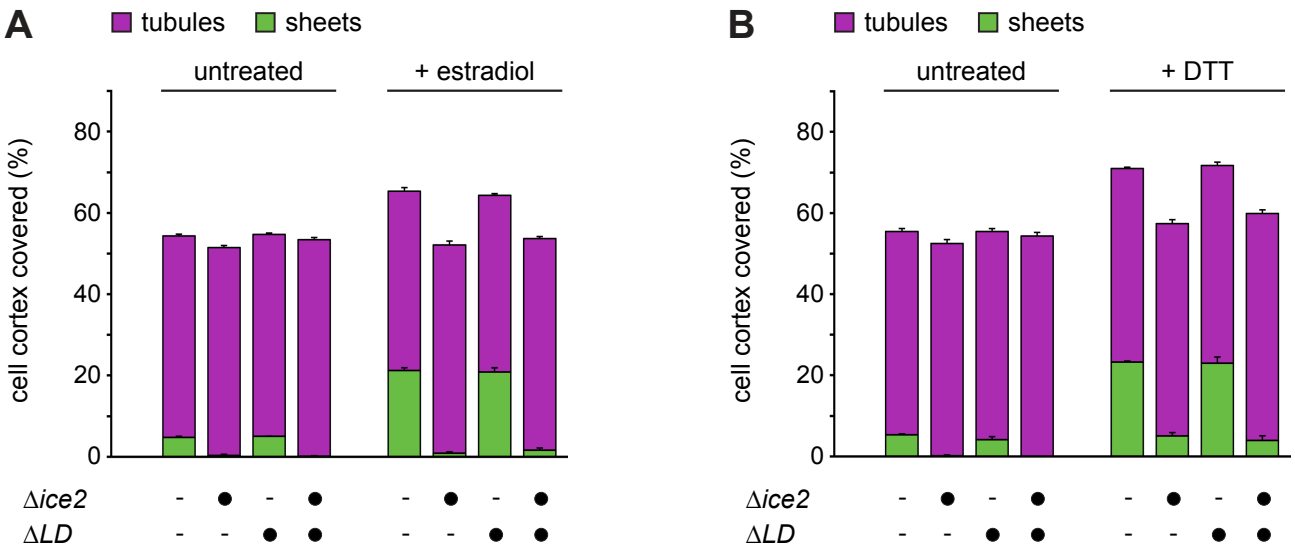
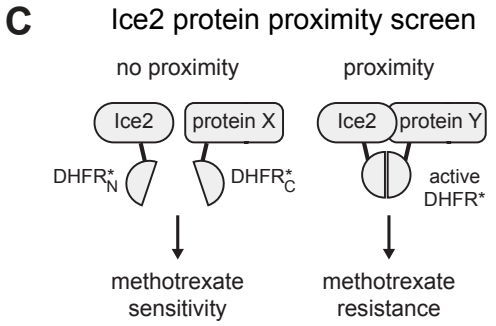
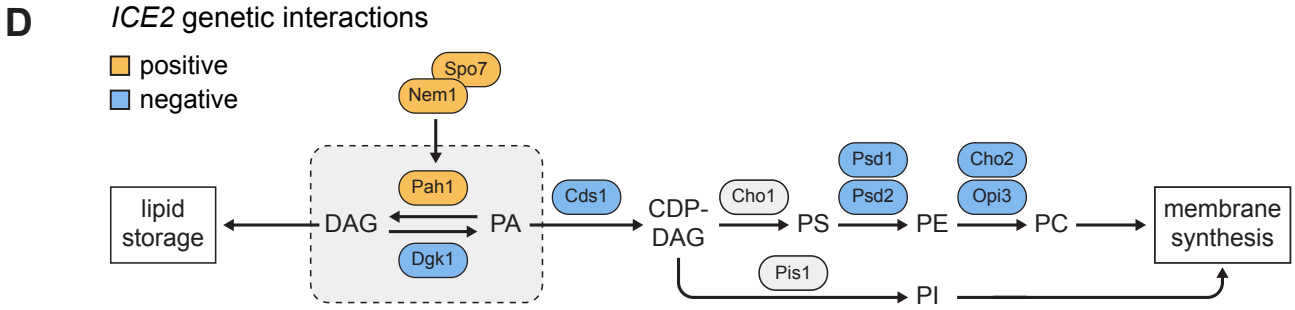

A
tubules
sheets
WT
Δice2
cell cortex covered (%)
0
20
40
60
80
0 30 60 120 0 30 60 120
DTT treatment (min)
B
UPR activity
WT
Δice2
relative GFP fluorescence
0
1
2
3
4
5
6
0 60 120 0 60 120
DTT treatment (min)
C
untreated
Sec63-mNeon
Rtn1-mCherry
merge
WT
Δice2
2 µm
D
+ DTT (60 min)
Sec63-mNeon
Rtn1-mCherry
merge
WT
Δice2
2 µm
E
Rtn1-mCherry puncta
WT
Δice2
cells with Rtn1 puncta (%)
0
20
40
60
80
100
0 30 60 120
DTT treatment (min)
F
tubules
sheets
WT
Δhac1
cell cortex covered (%)
0
20
40
60
80
- ● - ●
ICE2 overexpression
G
UPR activity
WT
Δhac1
relative GFP fluorescence
0
0.2
0.4
0.6
0.8
1
- ● - ●
ICE2 overexpression

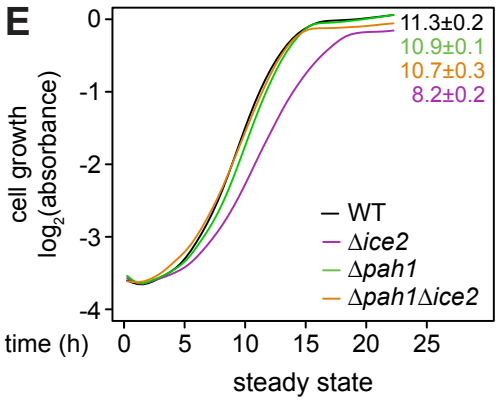
Figure 5





category	proteins
lipid metabolism	Cho1, Csg2, Elo1, Erg25, Ice2, Orm1, Phs1, Pis1, Sac1, Scs7, Spo7, Tsc13
protein targeting	Emc1, Emc3, Erp1, Got1, Shr3, Srp102, Yip3
protein glycosylation	Alg5, Ost1, Ost4, Wbp1
ER morphogenesis	Rtn1, Yop1
other/unknown function	Irc22, Ist2, Per33, Pmr1, Ubp1, Ypr114w
not an ER protein	Ccw12, Dfg5, Rpl22A, Rpl38, Zeo1, Ynl190w





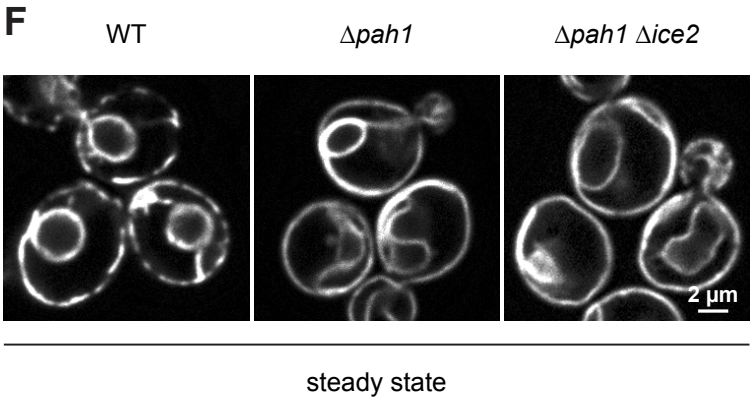


Figure 6

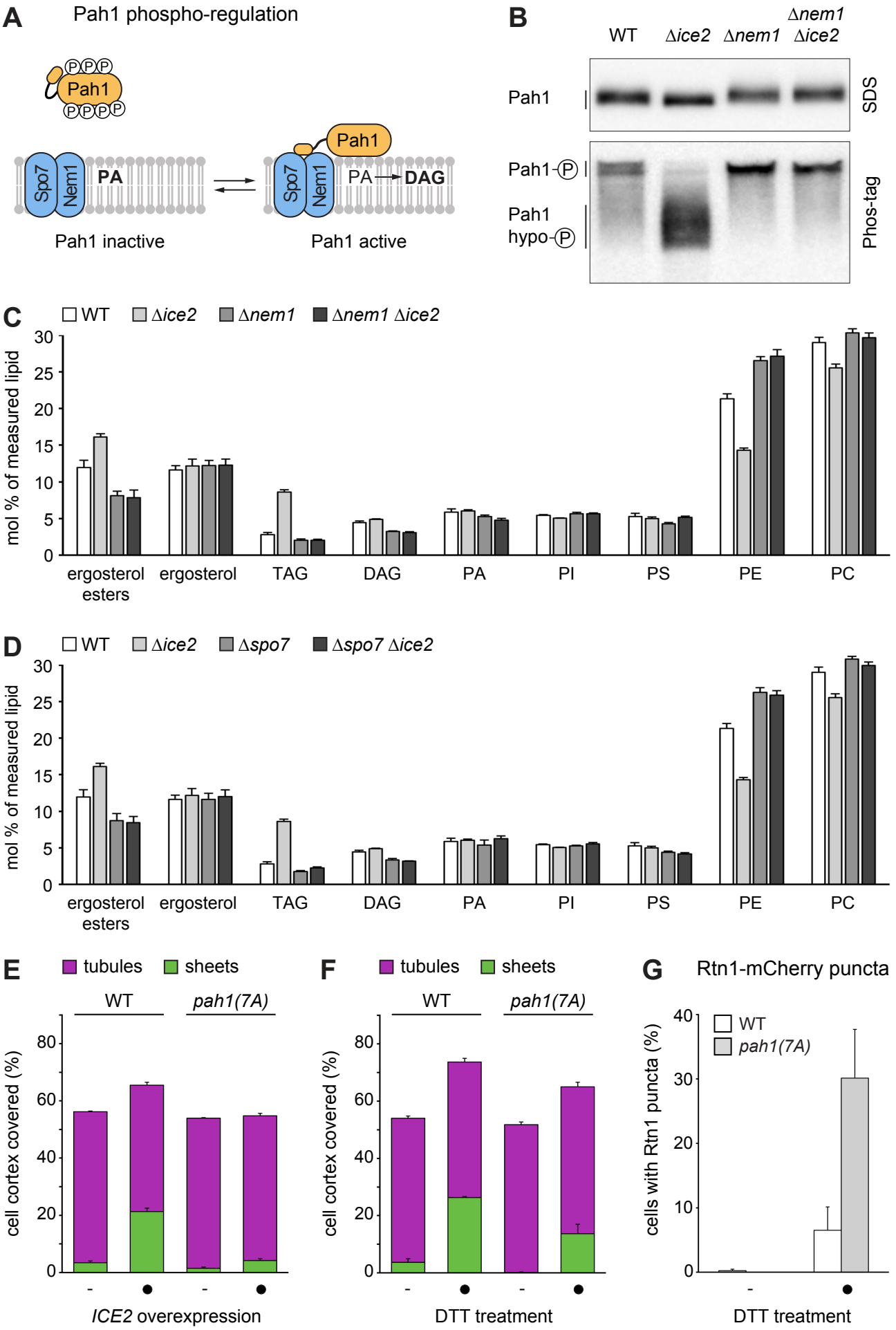

A
Pah1 phospho-regulation
Pah1
Spo7
Nem1
PA
PA → DAG
Pah1 inactive
Pah1 active
B
WT
Δice2
Δnem1
Δnem1 Δice2
Pah1
Pah1-P
Pah1 hypo-P
SDS
Phos-tag
C
WT
Δice2
Δnem1
Δnem1 Δice2
mol % of measured lipid
ergosterol esters
ergosterol
TAG
DAG
PA
PI
PS
PE
PC
D
WT
Δice2
Δspo7
Δspo7 Δice2
mol % of measured lipid
ergosterol esters
ergosterol
TAG
DAG
PA
PI
PS
PE
PC
E
tubules
sheets
WT
pah1(7A)
cell cortex covered (%)
ICE2 overexpression
F
tubules
sheets
WT
pah1(7A)
cell cortex covered (%)
DTT treatment
G
Rtn1-mCherry puncta
WT
pah1(7A)
cells with Rtn1 puncta (%)
DTT treatment

Figure 7

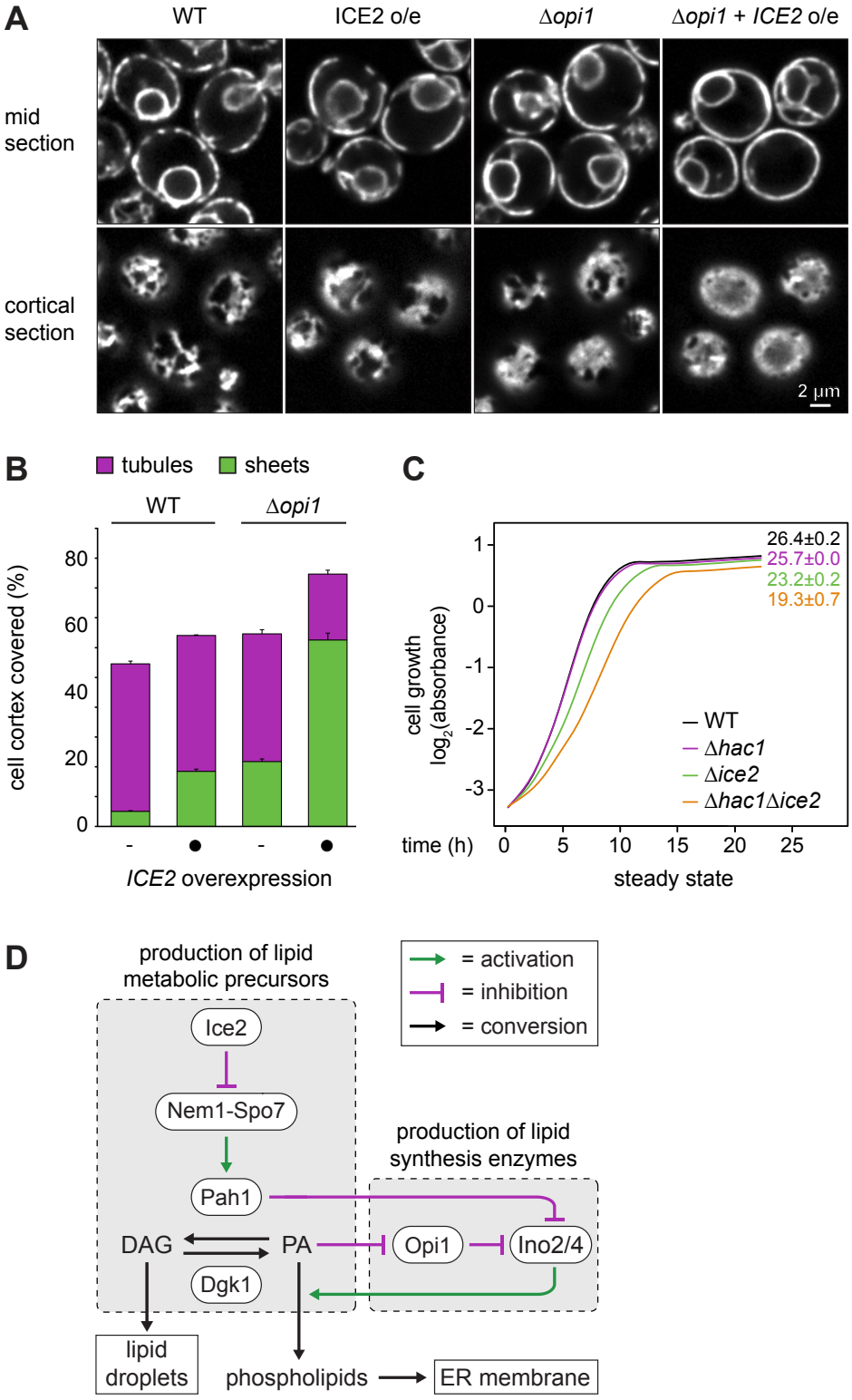

A
WT
ICE2 o/e
Δopi1
Δopi1 + ICE2 o/e
mid section
cortical section
2 µm
B
tubules
sheets
WT
Δopi1
cell cortex covered (%)
80
60
40
20
0
-
●
-
●
ICE2 overexpression
C
26.4±0.2
25.7±0.0
23.2±0.2
19.3±0.7
cell growth
log2(absorbance)
1
0
-1
-2
-3
WT
Δhac1
Δice2
Δhac1Δice2
time (h)
0
5
10
15
20
25
steady state
D
production of lipid metabolic precursors
= activation
= inhibition
= conversion
Ice2
Nem1-Spo7
Pah1
DAG
PA
Dgk1
production of lipid synthesis enzymes
Opi1
Ino2/4
lipid droplets
phospholipids
ER membrane

Figure S1

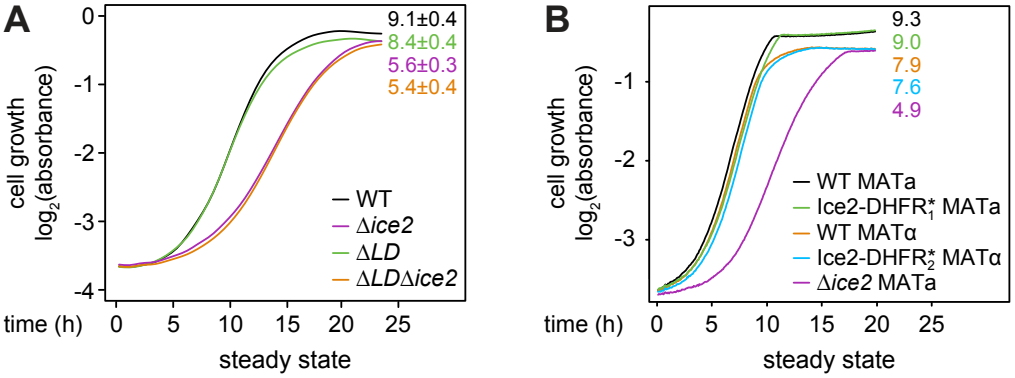
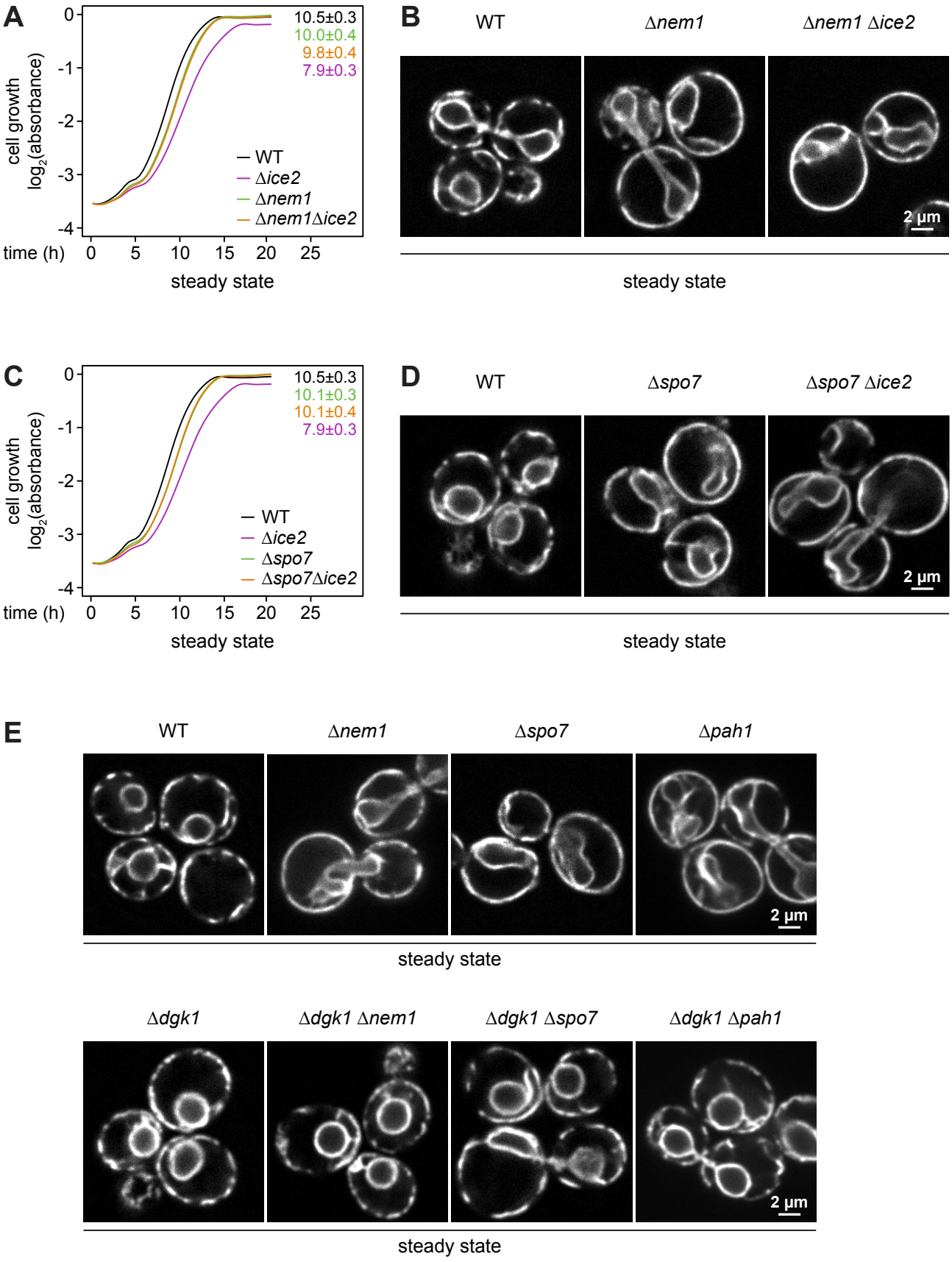

A
cell growth
log2(absorbance)
0
-1
-2
-3
-4
9.1±0.4
8.4±0.4
5.6±0.3
5.4±0.4
WT
Δice2
ΔLD
ΔLDΔice2
time (h)
0
5
10
15
20
25
steady state
B
cell growth
log2(absorbance)
-1
-2
-3
9.3
9.0
7.9
7.6
4.9
WT MATa
Ice2-DHFR*1 MATa
WT MATα
Ice2-DHFR*2 MATα
Δice2 MATa
time (h)
0
5
10
15
20
25
steady state

Figure S2


A
cell growth
log2(absorbance)
0
-1
-2
-3
-4
time (h)
0
5
10
15
20
25
steady state
10.5±0.3
10.0±0.4
9.8±0.4
7.9±0.3
WT
Δice2
Δnem1
Δnem1Δice2
B
WT
Δnem1
Δnem1 Δice2
2 µm
steady state
C
cell growth
log2(absorbance)
0
-1
-2
-3
-4
time (h)
0
5
10
15
20
25
steady state
10.5±0.3
10.1±0.3
10.1±0.4
7.9±0.3
WT
Δice2
Δspo7
Δspo7Δice2
D
WT
Δspo7
Δspo7 Δice2
2 µm
steady state
E
WT
Δnem1
Δspo7
Δpah1
2 µm
steady state
Δdgk1
Δdgk1 Δnem1
Δdgk1 Δspo7
Δdgk1 Δpah1
2 µm
steady state