PLA2G15 is a Lysosomal BMP Hydrolase with Ester Position Specificity and its Targeting Ameliorates Lysosomal Disease

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Abstract

Lysosomes catabolize lipids and other biological molecules, a function essential for cellular and organismal homeostasis. Key to lipid catabolism in the lysosome is bis(monoacylglycero)phosphate (BMP), a major lipid constituent of intralysosomal vesicles (ILVs) and a stimulator of lipid-degrading enzymes. BMP levels are altered in a broad spectrum of human conditions, including neurodegenerative diseases. Although BMP synthase was recently discovered, it has long been thought that BMP's unique stereochemistry confers resistance to acid phospholipases, a requirement for its role in the lysosome. Here, we demonstrate that PLA2G15, a major lysosomal phospholipase, efficiently hydrolyzes BMP with primary esters regardless of stereochemistry. Interestingly, we discover that BMP's unique esterification position is what confers resistance to hydrolysis. Purified PLA2G15 catabolizes most BMP species derived from cell and tissue lysosomes under acidic conditions. Furthermore, PLA2G15 catalytic activity against synthesized BMP stereoisomers with primary esters was comparable to its canonical substrates. Conversely, BMP with secondary esters is intrinsically stable in vitro and requires acyl migration for hydrolysis in lysosomes. Consistent with our biochemical data, PLA2G15-deficient tissues and cells accumulate multiple BMP species, a phenotype reversible by supplementing wildtype PLA2G15 but not its catalytically dead mutant. Increasing BMP levels by targeting PLA2G15 reverses the cholesterol accumulation phenotype in Niemann Pick Disease Type C (NPC1) patient fibroblasts and significantly ameliorate disease pathologies in NPC1-deficient mice leading to extended lifespan. Our findings establish the rules that govern the stability of BMP in the lysosome and identify PLA2G15 as a lysosomal BMP hydrolase and as a potential target for modulating BMP levels for therapeutic intervention.

Keywords

Lysosome; bis(monoacylglycero)phosphate (BMP) catabolism; PLA2G15; phospholipase; neurodegeneration; lysophosphatidylglycerol (LPG); glycerophosphoglycerol (GPG)

Introduction

Lysosomes are vital for cellular waste removal, nutrient recycling, and maintaining homeostasis, particularly through breaking down complex lipids using hydrolytic enzymes. Lipid degradation within lysosomes is facilitated by intralysosomal vesicles (ILVs) rich in a unique lipid called bis(monoacylglycero)phosphate (BMP) [1]. BMP significantly enhances lysosomal lipid metabolism, and its imbalance is a hallmark of various lysosome-associated diseases, including age-related neurodegeneration, viral infection, cancer, and atherosclerotic cardiovascular disease [1-4].

While a BMP synthase has recently been identified, many questions remain on the degradation of BMPs. BMP is a structural isomer of phosphatidylglycerol (PG) with symmetrical acyl chain positions on the two glycerol moieties and a unique *S,S* stereoconfiguration (Figure 1A) [4,5]. Partial deacylation of these phospholipids generates one fatty acid and lysophosphatidylglycerol (LPG) (Figure 1B), while its complete deacylation releases two fatty acids and glycerophosphorylglycerol (GPG) (Figure 1C) [6-9]. BMP is stable in the lysosomal environment, however, the rules that govern BMP catabolism remain unclear. Some reports speculate its unique stereochemistry may confer resistance to its degradation by lysosomal hydrolases, a necessity for its proposed function in stimulating lipid degradation in the lysosome [10,11], while others suggest BMP is susceptible to enzyme-mediated hydrolysis [6,8,12-15]. Because of its therapeutic potential, understanding BMP turnover and identifying its hydrolases, if it exists, in the lysosome is of great interest. Here, we show that contrary to the dogma, BMP with *S,S* stereoconfiguration is susceptible to lysosomal hydrolysis and it is the unique *sn2, sn2'* position of acyl chains that protects BMPs from lysosomal hydrolysis by the abundant lysosomal phospholipase PLA2G15, which we establish as a BMP hydrolase in addition to its role as a general acid phospholipase. We then leverage this knowledge to show that modulating BMP levels by genetic inactivation of PLA2G15 in the NPC mouse increases lifespan and reduces expression of key disease biomarkers while knockdown of PLA2G15 induces cholesterol clearance in NPC patient fibroblasts. Thus, targeting PLA2G15 holds therapeutic potential in Niemann Pick Disease Type C and possibly other lysosomal storage diseases.

RESULTS

Lysosomes hydrolyze BMP lipids

To test if BMP lipids are susceptible to phospholipase A (PLA)-mediated hydrolysis, we first used brain and liver lysates and commercially available BMP with the physiologically relevant stereoconfiguration (*S,S* BMP) and monitored the release of the LPG intermediate (Figure 1D). Consistent with a previous report [8], we observed a BMP hydrolase activity under both acidic and alkaline conditions, with relatively higher activity at neutral and mildly alkaline pH (Figure 1D), probably due to the abundance of extralysosomal PLAs in the lysate with minimal lysosomal protein contribution [16-18]. While these results indicate that BMP is not inherently resistant to PLAs, BMP could be protected by residing in the lysosome[19,20]. To test if lysosomal PLAs can degrade BMP lipids under acidic pH, we purified lysosomes from both tissues [9,21]. Indeed, lysosomal lysates efficiently hydrolyzed BMP with a pH optimum of 4-5, reminiscent of that of the acid PLA (Figure 1E) [9,17,22]. Of importance, this activity was diminished by amiodarone, a well-established inhibitor of lysosomal PLAs [23,24] (Figure 1F). These data support the notion that BMP lipids are susceptible to lysosomal phospholipases [6,12-14], challenging the role of their unique stereoconfiguration in their stability inside the lysosomal lumen.

PLA2G15 hydrolyzes BMP lipids derived from lysosomes

PLA2G15 is the major lysosomal phospholipase [25-27], and we recently established its function as a phospholipase B capable of catalyzing the complete hydrolysis of phospholipids with high efficiency [9]. Given our results, we asked if PLA2G15 can degrade BMP lipids. To this end, we incubated lysosomal lipid extracts isolated from LysoTag mouse tissues [9,21] with purified PLA2G15 (Figures S1A-C) and monitored the abundance of glycerophospholipids with a focus on PG, the structural isomer of BMP (Figure 2A). Consistent with its function, the abundance of most measured glycerophospholipids was significantly decreased (Figure 2B), with a concomitant increase in lysophospholipid intermediates (Figure 2C). Interestingly, most BMP lipid species were also significantly hydrolyzed independent of their acyl chain length and saturation (Figure 2D). Of importance, no change was observed in the levels of

sphingomyelin and triglycerides [26,27] (Figure 2E), suggesting a specific phospholipase activity towards BMP rather than an overall reduction in lipid abundance during the reaction. Similar results were obtained when using lysosomal lipids derived from HEK293T cells as substrates incubated with PLA2G15 (Figures S2A-D). Finally, using synthesized *S,S* BMP, the physiological stereoisomer, we validated the activity of PLA2G15 towards BMP using thin layer chromatography (Figures 1A and 2F) [28]. Importantly, BMP hydrolysis was abolished by purified PLA2G15 S198A catalytic mutant (Figures S3A-C) [9,29] as well as in the presence of amiodarone or fosinopril, known inhibitors of PLA2G15 [23], thus confirming BMP hydrolase activity (Figures 2G and 2H). Altogether, our data indicate that BMP lipids are susceptible to PLA2G15 activity.

Esterification position and not stereoconfiguration of BMP confers resistance to PLA2G15 in vitro

While BMP levels significantly decreased after incubating lysosomal lipid extracts with recombinant PLA2G15, a resistant fraction remained (Figures 2 and S2). BMPs can be defined by acyl chain composition, position, and stereochemistry of chiral carbons (Figure 3A). To gain mechanistic insight into their hydrolysis, we first performed kinetic studies of PLA2G15 activity towards BMPs with different acyl chain lengths under optimum conditions (Figures S4A-C) [9,25]. Consistent with its role as a very efficient phospholipase B [9], kinetic analyses of PLA2G15 monitoring the LPG intermediate and GPG product from the first and second steps, respectively, demonstrated high catalytic efficiencies (k_{cat}/K_m = ~10^5 – 10^7 M^{-1} s^{-1}) against two commercially available BMP lipids, which were comparable to those against PG counterparts (Figures S5A-H) [9]. As expected, the first step (Figures S5A-D) is faster than the overall reaction (Figures S5E-H), indicating that the second step controls the rate of the overall reaction [9]. These results establish PLA2G15 as a potent degrader of BMP. While BMP usually displays *S,S* stereoconfiguration, other forms have been isolated including the *S,R* stereoisomer (Figure 3A) [4,30-33]. Therefore, we tested PLA2G15 activity against all three potential BMP stereoisomers with acyl chains at the primary glycerol carbon positions (*R,R*, *S,R,* and *S,S*). To our surprise, all stereoisomers were equally hydrolyzed in short time

experiments (30 seconds) monitoring LPG release and long time ones (12 hours) monitoring remaining BMP levels (Figures 3A, 3B and S6A). Endogenous BMP can be monoacylated either on the secondary carbons *sn2, sn2'* (2,2' BMP) or primary carbons *sn3, sn3'* (3,3' BMP) of the glycerol (Figure 3A) [33,34]. Though the 3,3' BMP is considered thermodynamically stable and readily synthesized, the 2,2' BMP is thought to be a more abundant and physiologically active isoform [33-37]. To examine BMP hydrolase activity against positional isomers, we obtained synthesized 2,2' BMP and 3,3' BMP standards, both of which contain a small amount of 2,3' positional isomer that can be separated using our mass spectrometry methods and thus leveraged to monitor the stability of all positional isomers (Figures 3A and S6C, and see below). We found a striking reduction in BMP hydrolysis from 2,2' BMP monitoring total BMP levels after prolonged incubation (12 hour), compared to 3,3' BMP (Figure 3B), despite only milder difference observed when monitoring LPG release following short time (30 sec) incubation (Figure S6B). Intriguingly, a similar observation regarding the resistance of 2,2' BMP is made when using lysosomal lysates (Figure 3C). Of importance, these lysates are derived from CLN5-deficient cells, and thus have very low levels of endogenous BMP [2]. To further understand the hydrolysis of BMP isomers, we monitored time-dependent total BMP depletion for all isoforms incubated with PLA2G15 (Figures 3D and 3E). Consistent with our earlier observation (Figures 3B and S6A), all three stereoisomers were depleted at the same rate (Figure 3D). However, 2,2' BMP has a much slower rate of depletion compared to 3,3' BMP (Figure 3E), suggesting that esterification at the secondary carbon confers resistance to hydrolysis. Consistent with this, we found the minimal reduction observed in the total BMP in the reaction containing 2,2' BMP is mainly attributed to the hydrolysis of the 2,3' positional isomer (Figure 3F). Interestingly, we found that LPG released from 2,2' BMP is stable and not degraded to GPG during time course experiments (Figure S6D and S6E), thus explaining why LPG monitoring gives a different result (Figure S6B) and establishing that monitoring LPG release could be misleading in studying BMP hydrolysis and stability. Additionally, when an equimolar mixture of both synthesized 2,2' and 3,3' BMPs is monitored for total BMP depletion, or LPG and GPG release, the results resemble the average of each positional isoform, supporting the notion that 3,3' BMP is easily degraded compared to 2,2' BMP (Figures

3E, S6D and S6E). Indeed, careful analysis of all positional BMP peaks confirms that 3,3' isoform is quickly degraded followed by 2,3' isoform while the 2,2' isoform is resistant (Figures 3G and 3H).

Substrates bind to enzyme active site for effective catalysis and BMP is thought to activate lysosomal hydrolases including PLA2G15 [3,38]. Interestingly, in silico docking experiments identified a plausible binding pocket that positioned the carbonyl carbon of BMP near the active site of PLA2G15 [29] (Figure S6F). Indeed, BMP binds inactive PLA2G15 (Figures S6G) indicating a similar phospholipase mechanism for BMP by PLA2G15 that involves the serine, aspartate, and histidine catalytic triad [29]. Finally, rigorous kinetic analyses monitoring individual peaks indicated PLA2G15 has high catalytic efficiency against 3,3' BMP peak ($k_{cat}/K_m = 10^7\ M^{-1}\ s^{-1}$) while there is no concentration dependent enzyme activity for 2,2' BMP peak (Figures 3I and 3J). Altogether, these results elucidate PLA2G15 as a major BMP hydrolase independent of stereoconfiguration while 2,2' esterification position protects BMP from hydrolysis.

PLA2G15-deficient cells and tissues accumulate BMP

Several enzymes were reported to have catabolic activity against BMP in vitro, yet neither was validated as BMP hydrolase in cells or tissues [6,8,12-15]. Targeted lipidomics revealed a significant increase in almost all BMPs in PLA2G15-deficient HEK293T [9] lysosomes and cells compared to their wildtype (WT) counterparts (Figure S7A, S7B and Table S1). To confirm these results, we generated additional HEK293T cells depleted for PLA2G15 using a multiple guide CRISPR technology (Figure S7C). Indeed, all three PLA2G15-deficient clones significantly accumulate most if not all BMPs compared to WT parental cells (Figure 4A, 4B and Table S2). Using our established lysosomal enzyme supplementation protocol [2], we delivered WT or catalytically dead PLA2G15 proteins (Figures S7D-F) to PLA2G15-deficient lysosomes and confirmed that these increases are dependent on the loss of its catalytic activity (Figure 4C). Interestingly, one fifth of BMP levels were not rescued by PLA2G15, hinting that longer treatment is required or that there may be other enzymes contributing to BMP degradation (Figure 4D) [6,8,12-15]. Of note, the majority of non-degraded BMPs have at least one 22:6 acyl chain, which showed a mixed phenotype in the *PLA2G15* knockout

clones (Figure 4A and Table S2), indicating an interesting biology that is yet to be discovered [10,30,33,35]. Consistent with our cellular data (Figures 4A and 4B), there is a significant increase in most BMPs isolated from brain, kidney, and liver tissues from PLA2G15-deficient mice compared to their wildtype counterparts (Figures 4E, 4F, 4G and Table S3). Importantly, sphingomyelin, a non-phospholipid species, remains unchanged (Figures 4H and S7G) as previously reported [26,27]. Altogether, PLA2G15 loss of function increases BMP levels indicating its vital role in BMP hydrolysis and homeostasis.

PLA2G15 controls lysosomal lipid metabolism through BMP regulation

To further validate the role of PLA2G15 activity in regulating BMP homeostasis in the lysosome and the impact of this role on lysosomal function, we first determined that lysosomal lysates from PLA2G15-deficient HEK293T indeed have lower activity against BMP (Figure 5A). Next, we traced the fate of BMP lipids in the presence and absence of PLA2G15 in cells by delivering BMP lipids to lysosomes using established protocols (Figure 5B) [2,9,39]. Of importance, we depleted PLA2G15 (Figure S8A) in *CLN5* knockout cells, whose endogenous BMP levels are minimal thus allowing tracing of unlabeled exogenously-delivered BMP (Figure S8B) [2]. Of note, retention time analysis after delivery of either 2,2' BMP or 3,3' BMP to HEK293T cells indicated 2,2' BMP as the major isoform in cells (Figure S8C), as previously reported [33-37]. Using a pulse-chase approach to track BMP hydrolysis with or without PLA2G15 proteins (Figures S8D and S8E) following exogenous 2,2' BMP delivery to *CLN5 PLA2G15* double knockout cells (Figures 5B and S8F), we found that BMP is hydrolyzed faster in lysosomes with catalytically active PLA2G15 (Figures 5C and S8G). To determine the effect of the esterification position, we delivered either 2,2' BMP or 3,3' BMP and monitored their hydrolysis over time (Figures 5B, 5D, S8H and S8I). Careful peak analysis for 4-hour chase following 2,2' BMP delivery showed a moderate 2,2' peak decrease with a concomitant time-dependent increase in both 2,3' and 3,3' peaks (Figures 5D and S8H), suggesting the need for a conversion of 2,2' BMP to 3,3' BMP for effective degradation in cells. Consistent with this notion and our in vitro data (Figures 3 and S3), 3,3' and 2,3' peaks from 3,3' BMP rapidly decreased especially in the presence of PLA2G15 while

conversion of 3,3' BMP to 2,2' BMP is minimal if any (Figures 5D and S8H). To confirm this observation and minimize positional isomer conversion, we delivered an equimolar mixture of 2,2' BMP and 3,3' BMP (Figures 5B, 5E and S8J). Consistently, we observed rapid degradation of 3,3' and 2,3' BMP compared to 2,2' BMP, confirming 2,2' BMP as a more resistant BMP isomer (Figures 5E and 5F). Notably, 2,2' BMP peak is not affected by active PLA2G15 (Figure 5E), suggesting that acyl migration is required for degradation by PLA2G15 (Figures 5E and 5F). Importantly, *S,S* stereoconfiguration does not protect BMP from hydrolysis in cells (Figure S8K).

BMP is crucial for lysosomal lipid metabolism, in particular glucocerebrosidase (GCase) activity and cholesterol efflux [2,40]. Consistent with PLA2G15 function as BMP hydrolase, we found that supplementation of the active enzyme decreases GCase activity in bone marrow-derived macrophages (BMDMs) (Figures S9A and S9B). As previous reports showed that BMP supplementation can rescue cholesterol accumulation through an NPC2-dependent, NPC1-independent mechanism [41-43], we asked whether PLA2G15 inhibition might ameliorate cholesterol accumulation in NPC disease. Consistent with this hypothesis, PLA2G15 was identified as a genetic modifier using a genome-wide haploid genetic screen for cholesterol accumulation in NPC1-deficient cells (Figures S10A-C and Table S4). Furthermore, RNAi-mediated knock down of PLA2G15 reduced cholesterol accumulation in two independent NPC1 patient fibroblast lines (Figures 5G, 5H). Finally, to test if PLA2G15 depletion is of therapeutic value to NPC1 disease, we generated PLA2G15-deficient mice and crossed these to the *Npc1*^{m1N}/J mouse model. First, we measured well-established disease biomarkers including neurofilament light chain (Nfl) in CSF and plasma for neurodegeneration and aspartate aminotransferase (AST) and alanine aminotransferase (AST) for liver damage [44-46]. Depletion of PLA2G15 in NPC1-deficient mice significantly reversed these disease biomarkers (Figures 5I and 5J). Consistently, genetically targeting PLA2G15 strongly improved neurological composite score and ataxia symptoms in NPC1-deficient mice, leading to a significantly extended lifespan of disease mice (Figures 5K-M) [47]. Overall, these results, in conjunction with our in vitro and in vivo data, indicate that PLA2G15 possesses a BMP hydrolase activity that is required for BMP homeostasis in the lysosome, and its

targeting can boost BMP-mediated functions and lysosomal activity in diseases with lysosomal dysfunction.

DISCUSSION

BMP is a unique lipid known to potently stimulate lysosome-mediated lipid turnover, a crucial cellular process, that when defective leads to a plethora of human diseases including neurodegeneration [1,4]. Despite the therapeutic potential in targeting the BMP pathway and its significant functions in the lysosome little is known about BMP synthesis and degradation [1,4]. We have recently discovered CLN5 as a BMP synthase in the lysosome, however, the rules that govern BMP stability and the enzymes that mediate its hydrolysis, if any, are yet to be discovered. For over fifty years, the belief has been that lysosomes do not have BMP hydrolase or that the unique stereochemistry of BMP (*S,S*) is protective from such hydrolase if exists [10,11]. Here, we identify the lysosomal phospholipase PLA2G15 as an efficient BMP hydrolase regardless of BMP stereoconfiguration, challenging both assumptions and leading us to ask what protects BMP from hydrolysis within the lysosomal environment. Interestingly, we found that the *sn2, sn2'* (2,2' BMP) esterification position, another unique feature of BMP, to be what shields BMP from lysosomal degradation, facilitated in part by PLA2G15. Consistent with these biochemical findings, loss of PLA2G15 leads to accumulation of BMP lipids in cells and tissues. These results indicate that acyl migration within the BMP molecule is an active process that allows regulated turnover of BMP in the lysosome. Indeed, we observed that 2,2' BMP is converted to 2,3' BMP and 3,3' BMP, both of which are susceptible to PLA2G15 activity. While this conversion is favored thermodynamically, we still found 2,2' BMP to be more abundant than 3,3' BMP in the lysosome, consistent with the notion of it being the biologically active form [33-37]. We speculate that BMP stability is maintained by an unidentified biological machinery that protects its 2,2' BMP isoform from acyl migration [1]. Future studies should investigate the preferential synthesis or preservation of 2,2' BMP, as well as the enzymes or processes required for its conversion to the 3,3' isoform during its catabolism. Furthermore, it would be important to determine the functions of the *S,S* configuration and whether it is a prerequisite for the formation of the stable 2,2' BMP in the lysosome or has other biologically unexplored functions.

Consistent with BMP's role in promoting lysosomal functions such as lipid degradation and cholesterol trafficking [1-4,42,48], we showed that supplementing PLA2G15 to BMDMs reduces GCase activity, while depleting PLA2G15 can reduce cholesterol accumulation in patient derived NPC1-deficient fibroblasts. Importantly, we found that genetic depletion of PLA2G15 strongly ameliorates neurodegeneration and liver damage leading to increased survival of NPC1-deficient mouse model [44-47]. These data suggest that inhibiting PLA2G15 represents a potential therapeutic strategy to boost BMP levels and treat multiple lysosome-related diseases, an observation consistent with the BMP therapeutic hypothesis [1].

In summary, our work identifies PLA2G15 as a key hydrolase actively degrading BMP in the lysosome and establishes the rules that protect BMP from lysosomal hydrolysis, thus resolving the longstanding mystery of how BMP's unique characteristics mediate its functions. These insights pave the way for new therapeutic strategies targeting the BMP pathway in diseases where it is disrupted.

Figure legends

Figure 1: BMP lipids are susceptible to lysosomal hydrolases

(A-C) Bis(monoacylglycero)phosphate (BMP) is a structural isomer of phosphatidylglycerol (PG) with similar catabolic products. Chemical structures of BMP (top) and PG (bottom) in (A) and their degradation intermediates lysophosphatidylglycerol (LPG, all possible structures) in (B) and glycerophosphorylglycerol (GPG) in (C). Red represents two glycerol groups while blue represents the acyl chains. **(D)** BMP hydrolase activity in brain (left) and liver (right) lysates shows BMP is degraded across a broad pH spectrum including acidic environment. Hydrolysis of 3,3' 18:1-*S,S* BMP (1 µM) in buffers with pH rage between 3.0 and 9.0 (see methods). Controls had similar reaction buffers except with no lysate or BMP. Data are mean ± SD. *n* = 3 biological replicates. **(E)** Lysosomal lysates hydrolyze BMP with an acidic optimum. The same experiment as in (D) using brain lysosomal lysate (left) and liver lysosomal lysate (right). **(F)** Amiodarone inhibits BMP lysosomal hydrolase activity in a concentration dependent manner. Activity assays were performed using 3,3' 18:1-*S,S* BMP (1 µM) under acidic conditions (pH=5.0). Data are mean ± SD. *n* = 3 biological replicates.

Figure 2: PLA2G15 catabolizes lysosomal phospholipids including BMP

(A-D) PLA2G15 hydrolyzes BMP and other phospholipid substrates isolated from mouse liver lysosomes. **(A)** Depiction of experimental design showing LysoIP to collect lysosomal lipids and incubation with PLA2G15 to monitor phospholipid abundances for 30 min or 120 min reactions. **(B-D)** Fold changes in the abundance of known PLA2G15 substrates (PC, PE, PG, PI and PS) in (B), lysophospholipid intermediates (LPC, LPE, LPG, LPI, LPS) in (C) and BMPs in (D). **(E)** Non-phospholipids are unchanged in PLA2G15 reaction. Fold changes in sphingomyelin (SM) and triacylglycerol (TG). Each incubation time was compared to control (no enzyme) samples from the same mouse incubated for the same time. Data are mean ± SD of *n* = 5 biological replicates. Statistical analysis was performed using two-tailed unpaired *t*-tests. *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$ and ****$p \leq 0.0001$. **(F)** PLA2G15 degrades synthesized BMP in vitro. Thin Layer Chromatography (see methods) was used to measure the presence of LPG

intermediate after incubating wildtype recombinant PLA2G15 with 3,3' 18:1-*S,S* BMP under acidic conditions (pH=5.0). Controls had similar reaction buffers except with no enzyme. FA: fatty acid. **(G)** PLA2G15 S198A mutation completely abolishes BMP hydrolase activity. Hydrolysis of 1 µM of 3,3' 18:1-*S,S* BMP by 100 nM recombinant PLA2G15 wildtype and S198A mutant under acidic conditions for 30 sec reaction time. BMP hydrolase activity was determined using LC-MS by calculating the abundance of LPG intermediate. Data are mean ± SD of *n* = 3 independent replicates from each protein. ****p $\leq$ 0.0001. **(H)** PLA2G15 inhibitors attenuate BMP hydrolase activity. The same experiment as in (G) using wildtype PLA2G15 in the presence of 20 µM amiodarone and fosinopril compared to no inhibitor control. Data are mean ± SD of *n* = 3 independent replicates. ****p $\leq$ 0.0001. See also Figures S1, S2 and S3.

Figure 3: Esterification position and not stereoconfiguration of BMP confers resistance to PLA2G15

(A) Chemical structures of BMP lipids used in this study. **(B)** PLA2G15 degrades BMP independent of stereoconfiguration while positional isomers are differentially hydrolyzed. Hydrolysis of 1 µM of indicated BMPs with different stereo and positional isomers by 100 nM recombinant PLA2G15 for 12 hours under acidic conditions (pH=5.0). Control has similar reaction components without the enzyme. BMP hydrolase activity was determined using LC-MS by calculating the abundance of total BMP remaining. Data are mean ± SD of *n* = 3 independent replicates. ****p $\leq$ 0.0001. **(C)** Lysosomal lysates derived from *CLN5* KO HEK293T cells exhibit differential phospholipase activity towards positional isomers but not stereoisomers. Assay as in (B) for 2 hours using 10 µg of lysosomal lysate. *n* = 3 individual replicates for each BMP isomer or PG substrate. **p $\leq$ 0.01 and ****p $\leq$ 0.0001. **(D)** Time dependent hydrolysis of BMP stereoisomers by PLA2G15 confirms BMP degradation is independent of stereoconfiguration. Hydrolysis of 20 µM 3,3' *S,S* BMP, 3,1' *S,R* BMP or 1,1' *R,R* BMP stereoisomers by 100 nM recombinant PLA2G15 over 10 hours under acidic conditions (pH=5.0). Controls had similar reaction buffers except with no enzyme. BMP hydrolase activity was determined using LC-MS by calculating the abundance of total BMP remaining at the indicated time points. Data are mean ± SD of *n* = 3 independent replicates. **(E-H)** Time dependent

BMP hydrolysis shows 2,2' BMP positional isomer to be resistant to PLA2G15-mediated hydrolysis in vitro. **(E)** Same as in (D) using 20 µM BMP with either 2,2' *S,S* BMP or 3,3' *S,S* BMP positional isomer as well as a mixture of equimolar amounts. Data are mean ± SD of *n* = 3 independent replicates. **(F)** A representative image of the extracted ion chromatograms from (E) showing BMP peaks for each isomer at indicated time points in overlaid mode. **(G and H)** Time course analysis from the reaction with equimolar mixture of 2,2' BMP and 3,3' BMP in (E) shows 3,3' peak is preferentially decreased followed by 2,3' peak while 2,2' peak is unchanged. Intensity of each BMP peak was carefully integrated at each time point in (G) and a representative image of the extracted ion chromatograms at indicated time points in (H) showing peaks representing the three positional isomers of BMP both in list and overlaid modes. **(I and J)** PLA2G15 protein deacylates 3,3' BMP with faster kinetics than 2,2' BMP. PLA2G15 was incubated with 3,3' 18:1-*S,S* BMP in (I) and 2,2' 18:1-*S,S* BMP in (J) under acidic conditions (pH= 5.0) for 10 min and reactions were stopped by heating before quantifying 2,2' BMP or 3,3' BMP peaks. Each experiment was repeated at least three times, and a representative graph is shown using 3,3' and 2,2' BMP peaks for analysis. K_{cat}/K_m is a measure of kinetic efficiency. The phospholipids in these experiments were incorporated in liposomes with non-cleavable 18:1 Diether PC. See also Figures S1, S3, S4, S5 and S6.

Figure 4: PLA2G15-deficient cells and tissues accumulate BMP

(A and B) Targeted analyses of BMP lipids reveal that a deficiency in PLA2G15 increases BMP levels. (A) Heatmap representation of log2-transformed changes in BMP abundances in PLA2G15-deficient HEK293T cells compared to wildtype control (*n* = 3 WT and *n* = 3 *PLA2G15* KO)**.** Data are the ratio of the mean of each BMP. Significant changes from the graph are represented by *$p \leq 0.05$. P values were calculated using two-tailed unpaired tests and are presented in Table S2. (B) Fold changes in total BMP abundances. The sum of all abundances of measured BMPs was used to generate these values. Data are mean ± SD. Statistical analysis was performed using two-tailed unpaired *t*-tests. ****$p \leq 0.0001$. **(C and D)** Recombinant PLA2G15 rescues elevated levels of most BMPs resulting from PLA2G15 loss. Fold changes in the levels of BMPs

in *PLA2G15* KO HEK293T cells after supplementation with wildtype or mutant PLA2G15 in (C, rescued) and (D, was not rescued) (n = 3 WT, n = 3 *PLA2G15* KO, n = 3 *PLA2G15* KO +PLA2G15 and n = 3 *PLA2G15* KO +PLA2G15 S198A)**.** Data are mean ± SD. Statistical analysis was performed using two-tailed unpaired *t*-tests. *p $\leq$ 0.05, **p $\leq$ 0.01, ***p $\leq$ 0.001 and ****p $\leq$ 0.0001. **(E-H)** Targeted analyses reveal the accumulation of BMP lipids in mouse tissues with PLA2G15 deficiency. **(E)** Heatmap representation of log2-transformed changes in BMP abundances in PLA2G15-deficient mouse tissues (mouse brain, kidney and liver) compared to their control counterparts (n = 6 *Pla2g15*$^{+/+}$ and n = 6 *Pla2g15*$^{-/-}$)**.** Data are the ratio of the mean of each BMP. Significant changes from the graph are represented by *p < 0.05. P values were calculated using two-tailed unpaired tests and are presented in Table S3. **(F)** Normalized abundances of BMP 20:4/20:4 in the same samples. This lipid was undetected in some samples; thus, it is reported separately. Data are mean ± SD. Statistical analysis was performed using two-tailed unpaired *t*-tests. *p < 0.05. **(G)** Fold changes in total BMP abundances. The sum of all abundances of measured BMPs was used to generate these values. Data are mean ± SD. Statistical analysis was performed using two-tailed unpaired *t*-tests. ****p $\leq$ 0.0001. **(H)** Non PLA2G15 substrates are unchanged in PLA2G15-deficient mouse tissues. Fold changes in sphingomyelin (SM 34:3) in the same samples. Data are mean ± SD. See also Figure S7.

Figure 5: PLA2G15 controls lysosomal lipid metabolism through BMP regulation **(A)** Lysosomes derived from *PLA2G15* KO cells exhibit reduced BMP hydrolase activity. Hydrolysis of 1 µM 3,3' *S,S* BMP by 5 µg WT or *PLA2G15* KO lysosomal lysates for 10 min under acidic conditions (pH=5.0). BMP hydrolase activity was determined using LC-MS by calculating the abundance of LPG intermediate and GPG product. Data are mean ± SD. n = 3 individual replicates for each genotype. P values were calculated between *PLA2G15* KO versus WT. ****, p < 0.0001. **(B)** Depiction of experimental design for pulse-chase experiments. **(C)** PLA2G15 enzyme degrades BMP in cells, while inactive PLA2G15 S198A disrupts cells' ability to degrade BMP. 10 µM 2,2' BMP was added for two hours on cells and then washed, and 100 nM protein was supplemented to cells. Measurements were done by LCMS after 2-day chase. PBS was

used as vehicle. Data are mean ± SD. *n* = 3 individual replicates for each condition. Statistical analysis was performed using two-tailed unpaired *t*-tests. ****p ≤ 0.0001. **(D)** PLA2G15 degrades 3,3' and 2,3' BMP from 3,3 BMP while 2,2' BMP is converted to 2,3' and 3,3' BMP. Representative images of the extracted ion chromatograms showing all three positional BMP isomers peaks during a 4-hour PLA2G15 WT chase after delivering 2,2' BMP (left) and 3,3' BMP (right). **(E-F)** PLA2G15 preferentially degrades 3,3' BMP while 2,2' BMP turnover is slower. **(E)** 2,2' BMP peak (first), 2,3' BMP peak (second) and 3,3' BMP peak (third) was measured following a 2-hour chase with PLA2G15 proteins after addition of equimolar mixture of 2,2' BMP and 3,3' BMP. P values were calculated by one-way ANOVA. *p ≤ 0.05, **p ≤ 0.01. **(F)** Esterification position determines the rate of BMP hydrolysis. Quantitation of BMP peaks from (E) during the chase time with PLA2G15 WT confirms 3,3' and 2,3' BMP isomers are readily hydrolyzed while 2,2' BMP may require conversion for efficient degradation. **(G and H)** PLA2G15 knockdown reduces intracellular cholesterol in NPC1 patient-derived fibroblasts. **(G)** Representative microscopy images of Filipin staining of two independent NPC1 patient fibroblast cell lines (Coriell GM03123 and GM18453) after two-day treatment with 10 nM control siRNA or two different siRNA that target PLA2G15. **(K)** Quantification of signal intensity of Filipin. Signals are normalized to the vehicle-treated patient fibroblast. ****, p<0.0001, by one-way ANOVA. **(I-M)** Genetic depletion of PLA2G15 ameliorates neurodegenerative symptoms and extend lifespan in NPC1-deficient mouse. **(I and J)** PLA2G15 depletion rescues elevated levels of neurodegenerative and liver damage biomarkers in NPC1-deficient mice. Neurofilament light chain concentrations in CSF (left) and plasma (right) were measured in (I), while plasma levels of liver transaminases ALT (left) and AST (right) were measured in (J) at day 56. Data are mean ± SD (*n* = 6, 3 males and 3 females per genotype)**.** *, p<0.05, **, p<0.01, ***, p<0.001, ****, p<0.0001, by one-way ANOVA. **(K-M)** Genetic depletion of PLA2G15 improves neurological composite score (K), motor defect (L) and increases survival rate (M) in NPC1-deficient mice. Note: Higher neurological composite score means worse neurological performance and was calculated using hindlimb clasping, grooming, tremor, gait, kyphosis, and ledge test. Data are mean ± SEM (*n* = 12, 6 males and 6 females per genotype). In (L) ataxia symptoms were measured using rotarod.

Data are mean ± SEM (*n* = 12, 6 males and 6 females per genotype)**.** ****, p<0.0001, by two-way ANOVA comparing *Npc1*$^{-/-}$ to either *Npc1*$^{-/-}$ *Pla2g15*$^{-/-}$ or *Npc1*$^{+/+}$ *Pla2g15*$^{+/+}$ **(M)** Kaplan-Meier graph for animal survival. Data from *n* = 12, 6 males and 6 females per genotype. The curves for *Npc1*$^{+/+}$ *Pla2g15*$^{+/+}$ and *Pla2g15*$^{-/-}$ completely overlap. ****, p<0.0001, by Log-rank (Mantel-Cox) test. See also Figure S8 and S9.

MATERIALS and METHODS

Chemicals and Antibodies

Antibodies and chemicals used in this study are listed with their details in tables below.

Antibodies

Antibody	**Company**	**Catalogue number or Research Resource Identifiers**	**Dilution factor**
His	Cell Signaling Technology	2365/ RRID:AB_2115720	1:1000
Mouse HRP	Cell Signaling Technology	7076/ RRID:AB_330924	1:3000
Rabbit HRP	Cell Signaling Technology	7074/ RRID:AB_2099233	1:3000

Chemicals and reagents

Chemical name	**Company**	**Catalogue number**
LysoTracker Red DND-99	Thermo Fisher Scientific	L7528
Applied Biosystems PowerUp SYBR Green Master Mix	Thermo Scientific	A25742

Cambridge Isotope Laboratories Metabolomics Amino Acid Mix Standard	Cambridge Isotope Laboratories	MSK-A2-1.2
SPLASH™ Lipidomix® Mass Spectrometry Standard	Avanti	330707
L-α-Glycerophosphorylcholine (GPC)	Sigma	G5291
18:1 (Δ9-Cis) PG	Avanti	840475
18:1 (Δ9-Cis) PC	Avanti	850375
18:1 Diether PC	Avanti	999989
18:1 Lyso PG	Avanti	858125
14:0 Lyso PG	Avanti	858120
18:1 Diether PC	Avanti	999989
18:1 BMP (S,S)	Avanti	857135
18:1 BMP (R,R)	Avanti	857136
18:1 BMP (S,R)	Avanti	857133
14:0 PG	Avanti	840445
14:0 BMP (S,R)	Avanti	857131
2,2’ BMP (S,S)	Echelon	L-B181
Amiodarone hydrochloride	Sigma-Aldrich	A8423
Fosinopril	Sigma-Aldrich	F1308
Amino acid standards, physiological, analytical standard, acidics and neutrals	Sigma-Aldrich	A6407
Pierce™ HisPur™ Ni-NTA Agarose resin	Thermo Scientific	88221
Valproic acid sodium salt	Sigma	P4543
Inactivated fetal calf serum	Thermo Fisher Scientific	10438026

Anti-HA magnetic beads	Thermo Fisher Scientific	88837
DMEM high glucose	Thermo Fisher Scientific	11965118
ECL2 western blotting substrate	Thermo Fisher Scientific	PI80196X3
Complete Protease Inhibitor Cocktail	Sigma-Aldrich	05056489001
XtremeGene9 DNA Transfection Reagent	Sigma-Aldrich	06365787001
PhosSTOP phosphatase inhibitor	Sigma-Aldrich	04906837001
QuickExtract DNA Extraction Solution	Lucigen	76081766
Silica plates	EMD Millipore	1057210001
Iodine crystals	Sigma Aldrich	207772
Silica gel	Sigma Aldrich	60737
Freestyle 293 expression media	Thermo Fisher Scientific	12338026
Expi293 expression media	Thermo Fisher Scientific	A1435102
HisPur Ni-NTA resin	Thermo Fisher Scientific	88221
Protein label Kit RED-NHS	Nanotemper Technologies	MOL011
Alexa Fluor 488 NHS Ester	Thermo Fisher Scientific	A20000
Hoechst 33342	Thermo Fischer Scientific	H3570
Tycho NT.6 capillaries	Nanotemper Technologies	NC1619020

Monolith NT.115 premium capillaries	Nanotemper Technologies	MOK025
FectoPRO Transfection Kit	Genesee Scientific	55331

Experimental models

Model name	**Source**	**Identifier**
HEK293T cells	ATCC	CRL-3216; RRID: AB_2140114
Mice	Jackson Laboratory	Laqtom et al. [21] and Hiraoka et al. [27]

Software

Software name	**Source**	**Identifier**
Agilent LC/MS Data Acquisition software	Agilent	https://www.agilent.com
Agilent Qualitative Analysis software	Agilent	https://www.agilent.com
Agilent Qualitative Analysis software	Agilent	https://www.agilent.com

Plasmid	**Addgene ID**	**Reference**
PLA2G15-6xHis WT	213603	Nyame et al. [9]
PLA2G15-6xHis S198A	213605	Nyame et al. [9]

Plasmids

The Plasmids used in this study are in the plasmid table, and their references are included.

Animal Studies

The mice were acquired and maintained as described before [21]. The mice were housed in a controlled environment with regulated temperature and humidity, 12 hour light/dark cycles, and with access to food and water. Supplies were checked daily, and the cages were cleaned every 4-5 days. All mice procedures were conducted in adherence to the approved guidelines at Stanford University. PLA2G15-deficient mice were obtained, housed, and used in accordance with approved IACUC protocols at the University of Wisconsin-Madison [27,49]. Before euthanasia and necropsy PLA2G15-deficient mice were fasted 6 hours prior.

Mouse genotypes were confirmed by PCR using DirectPCR (Thermo Fisher #AA4647500) according to manufacturer guidelines. Briefly, tail clippings were incubated in DirectPCR overnight at 60°C for 16 hours, proteinase K was added an incubated for 1 hour. PCR was performed with PLA2G14 primers (Pla2g15_1: 5'-GAATTCCTAGACCCCAGCAAGAGGAATGTG -3'; Pla2g15_2:5'-ACTGCTCCCCCTCCCCAGAGATGGATATTT-3') using a program of 4 minutes at 95°C, followed by thirty-five cycles of 1 minute 95°C, 1 minute 55°C, 1 minute 72°C, and ended with an 8 minute incubation at 72°C. Results of genotyping were validated using RT-PCR and western blots of excised tissue. These mice were used in figure 4.

Generation of *Pla2g15*$^{-/-}$ mice:

Constitutive *Pla2g15*$^{-/-(TAC)}$ mice were obtained via CRISPR/Cas9-mediated gene editing at Taconic Biosciences in Denmark in accordance with national and international regulations. Animal procedures were evaluated by veterinarians and Taconic's IACUC or equivalent oversight body to ensure elimination or minimization of the potential for pain or distress. The gene targeting strategy was based on NCBI transcript NM_133792.3 (*Pla2g15*) and was designed to delete exon3 from the transcript (proximal sgRNA: 5'-TCGATGCCATTCATGGACTT-3' and distal sgRNA: 5'-GGCCTACTACGTTGCTTTGA-3'), resulting in loss of function of PLA2G15 by generating a frameshift from exon 2 to all downstream exons and creating a premature stop codon in exon 4.

Pla2g15 exon 3 flanking primers (forward: 5'-ACTCACTTTATAGACCAGGTTGGC-3' and reverse: 5'- CAGAGACAGTGAACCTAAGGGC-3') were designed to amplify and confirm both the wild-type and edited *Pla2g15* allele.
Briefly, Cas9 protein and sgRNAs were injected into BALB/c zygotes and G0 animals were genotyped by PCR analysis as described above. Founders were identified and used for further breeding activities to create heterozygous *Pla2g15*$^{-/-(TAC)}$ mice. These mice were subsequently used for generation of homozygous *Pla2g15*$^{-/-(TAC)}$ mice. These mice were used in therapeutic experiments in figure 5.

Life span analysis and neurological phenotyping

Pla2g15$^{-/-(TAC)}$ Balb/C animals were crossed with *Npc1*$^{m1N/J}$ heterozygous (HET) animals, and from the resulting offspring, double heterozygous mice were used to obtain the following genotypes (gene order: *Npc1*$^{m1N/J}$*/Pla2g15*): WT/WT, HOM/WT, HOM/HET, HOM/KO and WT/KO. WT represents *Npc1*$^{+/+}$ or *Pla2g15*$^{+/+}$, KO represents *Pla2g15*$^{-/-}$, HOM represents *Npc1*$^{-/-}$, and HET represents *Pla2g15*$^{+/-}$. In total 60 animals were enclosed for the phenotypic analysis, 12 animals of each of the different genotypes (6 male and 6 female). Bodyweight of all animals was assessed every other day starting at three weeks of age after the pups are weaned. Motor coordination was assessed weekly in the rotarod test from 6 to 9 weeks of age. Neurological composite phenotype score consisting of ledge test, hindlimb clasping, gait, kyphosis, tremor, and grooming scores was performed on a weekly basis starting at 6 weeks of age. These tests were performed following established protocol [50]. Higher composite score means worse neurological performance. Daily monitoring of clinical signs or termination criteria scoring and special care (e.g. wet food) exceeding standard health checks and animal care was assessed daily in all animals carrying the *Npc1*$^{m1N/J}$ HOM genotype starting at an age of 8 weeks). Experiments were performed at QPS Austria in compliance with the Animal Care and Welfare committee, as well as animal welfare regulations from local authorities.

Cerebrospinal fluid and plasma analysis

At 8 weeks of age (P56 ± 2 days) animals were terminally anesthetized by intraperitoneal injection of Pentobarbital (600 mg/kg) and CSF and blood plasma was obtained. Neurofilament light chain (NfL) levels were assessed using ELISA 10-7001 CE from Uman Diagnostics in plasma and CSF. Plasma samples were diluted 1:3 and CSF 1:30 (wherever possible) in assay buffer and analyzed according to the manufacturers protocol.

AST and ALT levels were determined with a Kit (AST: Cat# 04467493190, Roche; ALT: Cat No 04467388190, Roche) according to International Federation of Clinical Chemistry and Laboratory Medicine (IFCC) with pyridoxal phosphate activation (Roche). Therefore, a kinetic measurement of the enzyme activity with a redox reaction of NADH was performed, using L-Aspartate and 2-Oxoglutarat as substrate for the AST measurement and L-Alanine and 2-Oxoglutarat as substrate for the ALT determination. The two enzyme levels were measured on a Roche Cobas 6000/c501 analyzer.

Cell culture

HEK293T cells and their derivatives were cultured in Dulbecco's modified Eagle's medium (DMEM; Gibco) base medium supplemented with 10% inactivated fetal bovine serum (FBS) (Thermo Fisher Scientific) with 2 mM glutamine, penicillin, and streptomycin (Thermo Fisher Scientific). Cell cultures were maintained at 37 °C in an incubator with 5% CO_2. PLA2G15-deficient clone1 cells with LysoTag were obtained from the previous study [9]. For protein expression, Expi293F cells were maintained in a shaking incubator at 37 °C with 8% CO_2.

Generation of knock-out (KO) cell lines using CRISPR-Cas9 technology

PLA2G15 KO clone1 cells were described before [9]. *PLA2G15* KO HEK293T clone 2 and 3 cells were generated following the Synthego Gene Knockout Kit v2 protocol and using the following mixed guide sgRNAs sequences:

GGGGCGGAGGUGGAGGCCCA

UUAGCAGCAGCAAGAGGAAC

CCUCACCCAGCACCACUGGG

In short, a combined 180 pmol sgRNA and 20 pmol Cas9 (IDT) were incubated at room temperature for 10 minutes. Concurrently, HEK293Ts were washed with PBS, detached using enzyme-free dissociation buffer (ThermoFisher), and counted to determine their density. A suspension of 150,000 cells was added to the newly formed RNP complexes, transferred to a Lonza Nucleocuvtte™, and electroporated using the CM-130 program code. Following electroporation, cells were placed in growth medium and transferred to a 24-well plate. Single cell populations were obtained using limited dilution and the sgRNA target sites were sequenced following PCR-amplification. Finally, genetic knockouts were confirmed by Synthego ICE CRISPR analysis, an indel deconvolution web-based tool (https://synthego.com).

Cell volume measurement

The Beckman Z2 particle counter and size analyzer was used to determine cell count and volume. The filtering criteria were configured to select cells that were between 10 and 30 µm in size.

Lysosomal Immunopurification (LysoIP) from mouse tissues and HEK293Ts

Lysosomes were purified from mouse brain and liver as well as HEK293T cells, following established protocols [16,21]. Mouse brains were obtained post-euthanasia. Small uniform liver samples were collected using a 4 mm diameter biopsy punch to minimize variability between samples. Both the brain and liver tissues were utilized immediately without freezing, employing the steps described in the LysoIP protocols [16,21]. During the lysosomal lysate enzyme assays, whole brain or liver tissue was sectioned into three pieces and dounced 30X with 3 ml Phosphate Buffer Saline supplemented with protease inhibitor (PBSI). The resulting lysates were centrifuged at 1000*xg* at 4 ºC for 10 min. The supernatant was then transferred to a 15 ml falcon tube containing 0.5 ml anti-HA beads and incubated at 4 ºC for 1 hour with a rotational mixing. Subsequently, the mixture underwent thorough washing steps and isolation processes to obtain protein fractions suitable for lysosomal lysate experiments as previously described [9]. Before enzymatic assays were performed, protein concentrations in the lysates were quantified using Pierce BCA Protein Assay kit

(Thermo Fisher Scientific). For cell-based assay, an equal number of cells were cultured and allowed to reach at least 80% confluence before each lysoIP. The homogenization and LysoIP from HEK293Ts were adapted from [16] and (dx.doi.org/10.17504/protocols.io.bybjpskn).

Expression and purification of proteins

Expi293F cells were cultured using a combination of 2/3 Freestyle293 and 1/3 Expi293 media and transfected with the PLA2G15 plasmids at a density of 3E6 cells/mL. Using FectoPRO transfection reagent (Polyplus), transfection was performed at a ratio of 1.3 µL FectoPRO to 0.5 µg plasmid DNA per mL of cells. Following transfection, glucose and valproic acid were added right away to reach final concentrations of 0.4% glucose (w/v) and 0.05% valproic acid (w/v). An equivalent amount of valproic acid and glucose were added 1-day post-transfection and cells were harvested 3 days post-transfection. The culture media was harvested and combined with PBS in a 1:1 ratio. HisPur Ni-NTA resin was added to the mixture and incubated at 4 °C for 16 hours. The resin was washed 4 times consecutively using different wash compositions and packed onto a column. The first wash included 50 mM HEPES pH 7.25, 500 mM NaCl, 0.1 mM EDTA, 5 mM beta-mercaptoethanol, 1 mM DTT, 1 mM PMSF, 20 mM imidazole at pH 7.25, cOmplete EDTA-free protease inhibitor cocktail (Roche), 5% glycerol [v/v], and 1% Triton X-100 [v/v]. The second wash was identical to the first wash except for the addition of 10 mM imidazole pH 7.25 and absence of Triton X-100 and protease inhibitor. Imidazole was absent from the third wash, which was identical to the second wash, except that it contained 250 mM NaCl. Except for the addition of 125 mM NaCl, the fourth wash was identical to the third wash. A buffer containing 300 mM imidazole pH 7.25, 50 mM HEPES pH 7.25, 125 mM NaCl, 5% glycerol [v/v], 5 mM BME, 1 mM DTT, 0.1 mM EDTA, 1 mM PMSF and protease inhibitors was used to elute the protein. Using an Amicon 10-kDa MWCO concentrator, the eluted protein was concentrated and further purified by size-exclusion chromatography (SEC) on a Superdex 200 10/300 column. After that, fractions were combined, concentrated using an Amicon 10-kDa MWCO concentrator to achieve a final protein concentration of 1 mg/mL, and swiftly frozen in liquid nitrogen.

Preparation of liposomes

Unless otherwise specified, 18:1 diether PC (Avanti) was used to make lipid liposomes. The lipids were dried and then combined in a tube with 2 mL water and 3 mL diisopropyl ether to create liposomes that did contain just glycerophospholipids. The resultant mixture was sonicated for 10 min in a water bath to create tiny unilamellar vesicles, which were subsequently dried. Dried liposomes were resuspended in water and Stewart assay was used to determine their concentration.

Enzyme assays

Recombinant PLA2G15-6xHis at 100 nM concentration was mixed with phospholipid substrates (BMP or PG isomers) of varying concentrations in 50 mM Sodium Acetate:Acetic Acid at pH 5 and 150 mM NaCl. The liposomes containing phospholipids had an 18:1 diether PC that was non-cleavable. The mixture was incubated for 30 seconds when monitoring products and 10 min when monitoring substrates at 37 °C and then heat-inactivated at 95 °C for 5 min. To adjust for background in each experiment, controls including all components, but the enzyme were also made for each substrate. A time course at various substrate concentrations was carried out to guarantee the linearity of the velocity. The reaction mixture was transferred to plastic autosampler vials to monitor GPG release. In the case of BMP or LPG monitoring, lipids were extracted as described below and transferred to glass autosampler vials. For kinetic studies, corresponding standard GPG LPG or BMP was measured in increasing concentration to extrapolate the concentrations of the products. For time dependent BMP isomer comparison, 100 nM recombinant WT PLA2G15-6xHis was mixed with 20 µM BMP substrates in 50 mM Sodium Acetate:Acetic Acid at pH 4.5 and 150 mM NaCl. The pH optimum was determined by using buffers containing Sodium Acetate:Acetic Acid, HEPES, and Boric acid at their respective pH ranges.

Enzyme activity assays in lysosomal protein extract

Lysosomes obtained from mouse tissues or HEK293T cells were lysed using hypotonic water for a duration of 1 hour to release soluble lysosomal proteins. Lysosomal protein

extract was then combined with 1 µM 3,3' *S,S* BMP and incubated at 37 °C in 50 mM Sodium Acetate:Acetic Acid pH 5 and 150 mM NaCl for indicated time points. The reaction was then stopped using chloroform:methanol solution in a ratio of 2:1 (v/v) for lipids or 80% methanol for polar metabolite measurements.

Inhibition assays

For inhibition assays, each inhibitor was preincubated with the substrates before either purified PLA2G15-6xHis or lysosomal lysate was added. The reaction buffer has (50 mM Sodium Acetate:Acetic Acid at pH 5 and 150 mM NaCl) and we followed the enzyme assays described earlier.

Pulse chase experiments

A 10X concentration of BMP isomers at a concentration of 100 µM in ethanol, along with fatty acid-free BSA at the same concentration in PBS, was initially prepared. This concentrated solution was then diluted to a final concentration of 1X in DMEM (ThermoFisher). *CLN5 PLA2G15* double knockout cells were seeded on each well of a poly-l-lysine coated 6-well plate. Next day, medium was gently aspirated and replaced with serum-free DMEM containing 1X solution of BSA-conjugated BMP and incubated for 2 hours. After incubation, cells were washed once with serum free medium and replaced with complete DMEM containing vehicle solution (1XPBS), 150 nM WT PLA2G15-6XHis or 150 nM PLA2G15(S198A) mutant to chase BMP degradation at varying times. Subsequently, both treated and untreated cells were collected in 200 µL 80% methanol and lipids were extracted using a two-phase extraction method involving a 2:1 chloroform:methanol (v/v) mixture as described below. Finally, lipids were analyzed with LC-MS.

Enzyme supplementation

To validate the lysosomal localization of recombinant enzymes, PLA2G15-6xHis and mutant were labeled with NHS-Alexa488 dye (Thermo Fisher Scientific) according to the manufacturer's protocol. Afterwards, 50,000 of *PLA2G15* knockout or *CLN5 PLA2G15* double knockout cells were seeded with 700 µl DMEM medium on each division of a 4-

chamber 35 mm glass bottom dish (Cellvis). Then, cells were treated with 50 nM fluorescently labeled protein in complete media for 2 days. After 2-day incubation, medium was replaced with 700 µl of DMEM medium containing 1 µM LysoTracker Red DND-99 (ThermoFisher) and 1 µg/ml Hoechst 33342 and incubated for 30 min. Medium were then replaced again with fresh medium and immediately imaged with Leica LSM980 confocal microscope and images were analyzed using ImageJ.
For enzyme supplementation experiments, 600,000 cells were seeded on a 6-well plate. After 24 hours, cells were treated with 50 nM PLA2G15 wildtype and mutant proteins in complete media. After 48 hours, lipids were extracted as described above and analyzed by lipidomics.

Lipid and polar metabolite extraction

Samples were processed for lipid or polar metabolite extraction following previous protocol [21]. For lipid extraction, 950 µL of 2:1 (v/v) chloroform:methanol containing SPLASH LipidoMIX internal standard mix at a concentration of 750 ng/ml was added to all samples. The mixture was vortexed for 1 hour at 4 °C. Subsequently, 200 µL of 0.9% (w/v) NaCl was added and vortexed for 10 min at 4 °C. Then, the mixture was spun at 3,000*xg* for 15 min at 4 °C. The lower chloroform phase, which contained the lipids, was collected and dried using a SpeedVac. Next, the dried lipid extracts were reconstituted in 50 µL of 13:6:1 (v/v/v) acetonitrile(ACN):isopropyl alcohol:water and vortexed for 10 min at 4 °C in a cold room. Then, the samples were centrifuged at max speed for 10 min at 4 °C and 45 µL transferred into glass vials with insert for LC-MS analysis. For GPG analysis, samples were extracted using 80% methanol in LC-MS grade water containing 500 nM isotope-labeled amino acids as internal standards (Cambridge Isotope Laboratories). Samples were then vortexed for 10 min at 4 °C, centrifuged at 20,627*xg* and transferred into polar vials for LC-MS.

Targeted lipidomics and polar metabolomics

Targeted analyses were adapted and performed as previously described [2,9,39]. Lipids were separated on an Agilent RRHD Eclipse Plus C18,2.1x100mm,1.8u-BC column with an Agilent guard holder (UHPLC Grd, Ecl. Plus C18,2.1mm,1.8µm) while polar

metabolites were separated using hydrophilic interaction chromatography (HILIC) using a SeQuant® ZIC®-pHILIC 50 x 2.1 mm column (Millipore Sigma 1504590001) with a 20 x 2.1 mm (Millipore Sigma 1504380001) guard. Before mass spectrometry, the columns were connected to a 1290 LC system for lipid and metabolite separation. The LC system was linked to an Ultivo triple quadrupole (QQQ) mass spectrometer with an LC-ESI (electrospray ionization) probe. External mass calibration was done weekly using a QQQ standard tuning mix. The column compressor and autosampler were held at 45 °C and 4 °C, respectively. For lipidomics, the mass spectrometer parameters included a capillary voltage of 4.4 kV in positive mode and 5.5 kV in negative mode, and gas temperature and sheath gas flow were held at 200 °C and 275 °C, respectively. Both gas flow and sheath gas flow were 10 L/min and 11 L/min, respectively, while the nebulizer was maintained at 45 psi. The nozzle voltages were maintained at 500 in positive mode and 1000 in negative mode. These conditions were held constant for both ionization modes acquisition. For metabolomics, similar conditions were used except gas temperature and sheath gas flow were held at 250 °C and 300 °C, respectively. Additionally, gas flow and nebulizer were 13 L/min and 30 psi.

For lipid measurements, 2-4 µL injection volumes were used for each sample for polarity switching. A mobile phase with two distinct components, A and B, was employed for the chromatographic process. Mobile phase A was a mixture of acetonitrile: water (2:3 [v/v]), while mobile phase B was composed of isopropanol: acetonitrile (9:1 [v/v]), both also containing 0.1% formic acid and 10 mM ammonium formate. The elution gradient was carried out over a total of 16 min, with an isocratic elution of 15% B for the first min, followed by a gradual increase to 70% of B over 3 min, and then to 100% of B from 3 to 14 min. Subsequently, this was maintained from 14 to 15 min, after which solvent B was decreased to 15% and maintained for 1 min plus 2 min to allow for column re-equilibration. The flow rate was set at 0.400 mL/min.

For polar metabolite measurements, each sample was injected with a volume of 1-2.5 µl. Mobile phase A is made of 20 mM ammonium carbonate and 0.1% ammonium hydroxide dissolved in LC/MS grade water, while B is composed of 100% LC/MS grade acetonitrile. Elution was performed over a 10-min gradient; the B component was linearly decreased from 80% to 20% between 0-7 min, rapidly increased from 20-80%

between 7-7.5 min, and was held at 80% B from 7.5-10 min. The flow rate was set to 0.15 mL/min.

The QQQ was set to operate in multiple reaction monitoring (MRM) to analyze compounds of interest. Standard lipids, glycerophosphodiesters (GPDs) and amino acids were optimized using MassHunter Optimizer MRM, a software used for automated method development. For most species, the two most abundant transitions were selected to detect it. The precursor-product ion pairs (m/z) of the compounds used for MRM are listed in the MRM table.

Multiple reaction monitoring (MRM) table

Compound	Precursor Ion	Neutral Product Ion	Fragmentor Voltage	Collision energy
BMP (14:0/18:1)	738.6	285.3	150	27
BMP (14:0/18:1)	738.6	339.3	150	27
BMP (16:0/16:0)	740.5	313.5	150	27
BMP (16:0/16:1)	738.5	311.5	150	27
BMP (16:0/16:1)	738.5	313.5	150	27
BMP (16:0/18:0)	768.5	313.5	150	27
BMP (16:0/18:0)	768.5	341.3	150	27
BMP (16:0/18:1)	766.6	313.5	150	27
BMP (16:0/18:1)	766.6	339.3	150	27
BMP (16:0/22:6)	812.5	313.5	150	27
BMP (16:0/22:6)	812.5	385.3	150	27
BMP (16:1/18:1)	764.5	339.3	150	27
BMP (16:1/18:1)	764.5	311.5	150	27
BMP (16:1/20:3)	788.6	311.3	150	27
BMP (16:1/20:3)	788.6	363.0	150	27
BMP (16:1/22:6)	810.5	311.3	150	27
BMP (16:1/22:6)	810.5	385.3	150	27
BMP (18:0/18:0)	796.6	341.3	150	27

BMP (18:0/18:1)	794.6	339.3	150	27
BMP (18:0/18:1)	794.6	341.3	150	27
BMP (18:1/18:1)	792.6	339.3	150	27
BMP (18:1/18:2)	790.6	337.3	150	27
BMP (18:1/18:2)	790.6	339.3	150	27
BMP (18:1/20:0)	822.6	339.3	150	27
BMP (18:1/20:1)	820.6	339.3	150	27
BMP (18:1/20:1)	820.6	367.3	150	27
BMP (18:1/20:2)	818.6	339.3	150	27
BMP (18:1/20:3)	816.6	363.3	150	27
BMP (18:1/20:3)	816.6	339.3	150	27
BMP (18:1/20:4)	814.6	361.3	150	27
BMP (18:1/20:4)	814.6	339.3	150	27
BMP (18:1/22:1)	848.6	339.3	150	27
BMP (18:1/22:2)	846.6	339.3	150	27
BMP (18:1/22:3)	844.6	339.3	150	27
BMP (18:1/22:4)	842.6	339.3	150	27
BMP (18:1/22:5)	840.6	339.3	150	27
BMP (18:1/22:6)	838.6	339.3	150	27
BMP (18:1/22:6)	838.6	385.3	150	27
BMP (18:2/18:2)	788.5	337.3	150	27
BMP (18:2/20:3)	814.6	363.3	150	27
BMP (18:2/20:3)	814.56	336.9	150	27
BMP (18:2/22:6)	836.5	385.3	150	27
BMP (18:2/22:6)	836.5	336.9	70	20
BMP (18:4/22:6)	832.5	385.6	150	27
BMP (20:4/20:4)	836.5	357.3	150	27
BMP (20:4/22:6)	860.5	385.3	150	27
BMP (20:4/22:6)	860.5	361.3	150	27
BMP (20:5/22:6)	858.5	385.3	150	27

BMP (22:5/22:5)	888.6	387.3	150	27
BMP (22:5/22:6)	886. 6	385.3	150	27
BMP (22:5/22:6)	886.6	387.3	150	27
BMP (22:6/22:6)	884.5	385.3	150	27
BMP (14:0/14:0)	684.4	285.63	70	24
BMP (16:1/16:1)	736.5	309.27	150	27
BMP (16:1/18:2)	762.5	337.3	150	27
BMP (16:1/18:2)	762.5	311.3	150	27
BMP (18:2/20:4)	812.5	361.3	70	24
BMP (18:2/20:4)	812.5	336.9	70	24
DG (16:0/18.1)	612.6	313.3	166	25
DG (16:0/22:6)	658.5	313.2	166	21
LPC (15:0)	482.3	184.1	166	21
LPC (16:0)	496.3	184.1	166	21
LPC (16:0)	496.3	104.1	166	21
LPC (18:1)	522.4	184.1	166	21
LPC (18:1)	522.4	104.1	180	24
LPC (18:1D7)	529.4	104.1	180	24
LPE (16:0)	454.3	313.3	166	17
LPE (18:0)	482.3	341.3	166	17
LPE (18:1)	480.3	339.3	166	17
LPE (18:0)	480.3	283.1	180	24
LPE (18:1)	478.3	281.1	180	24
LPE (18:1D7)	487.3	346.3	166	17
LPG (16:0)	483.27	255.23	163	32
LPG (18:0)	511.29	283.25	163	32
LPG (18:1)	509.29	281.25	163	32
LPG (18:2)	507.3	279.23	163	32
LPG (20:4)	531.27	303.23	163	32
LPG (20:5)	529.26	301.27	163	32

LPG (22:4)	559.3	331.26	163	32
LPG (22:5)	557.29	329.25	163	32
LPG (22:6)	555.27	327.23	163	32
LPI (18:0)	618.3	341.3	166	17
LPI (18:1)	616.3	339.3	166	17
LPI (18:2)	614.3	337.3	166	17
LPI (20:3)	640.3	363.1	166	17
PC (16:0/18:1)	760.6	86.1	215	50
PC (16:0/18:1)	760.6	124.9	215	50
PC (16:0/22:6)	806.6	184.1	166	21
PC (18:1/18:1)	786.6	184.1	166	21
PC (18:1/18:1)	786.6	104.1	180	24
PE (18:1/18:1)	744.6	603.5	166	17
PE (16:0/18:1)	718.5	577.5	166	17
PG (18:2/20:4)	812.54	623.5	85	36
PG (20:4/20:4)	836.54	647.5	85	32
PG (20:4/22:4)	864.6	675.5	85	20
PG (16:0/16:0)	740.5	551.5	110	9
PG (16:0/18:0)	768.5	579.5	110	9
PG (16:0/18:1)	766.6	577.5	110	9
PG (16:0/20:4)	788.6	599.5	110	9
PG (16:0/22:6)	812.5	623.5	110	9
PG (16:1/18:1)	764.5	575.5	110	9
PG (16:1/22:6)	810.5	621.5	110	9
PG (18:0/18:1)	794.6	605.5	110	9
PG (18:1/18:1)	792.6	603.5	110	9
PG (18:1/18:2)	790.6	601.5	110	9
PG (18:1/20:1)	820.6	631.5	110	9
PG (18:1/20:4)	814.6	625.5	110	9
PG (18:1/22:6)	838.6	649.5	110	9

PG (18:2/22:6)	836.5	647.5	110	9
PG (20:4/22:6)	860.5	671.5	110	9
PG (20:5/22:6)	858.5	669.5	110	9
PG (22:4/22:6)	888.6	699.5	110	9
PG (22:5/22:6)	886.6	697.5	110	9
PG (22:6/22:6)	884.5	695.5	110	9
PI (16:0/18.1)	854.6	577.5	166	17
PI (18:0/18:1)	882.6	605.6	166	17
PI (18:1/18:1)	880.6	603.3	166	17
PS (16:0/18:1)	760.5	575.5	166	25
PS (18:0/18:1)	790.6	605.6	166	25
PS (18:1/18:1)	788.5	603.5	166	25
SM (34:3)	699.5	184	166	25
SM (38:3)	755.6	184	166	25
SM (40:3)	783.6	184.1	166	25
TG (52:1)	878.8	577.5	166	21
TG (52:2)	876.8	603.6	166	21
GPG	247.1	99	95	16
GPG	247.1	172.9	95	8
GPC	258.1	86.1	97	32
GPC	258.1	104.1	97	15
Methionine	150.1	56.1	80	16
Isolabeled Tyrosine	192.1	174.0	70	8
Serine	106.1	88.1	75	8
Valine	118.1	72.2	75	8

Polar metabolites and lipids were annotated, and their abundances were measured using the Qualitative MassHunter acquisition software and QQQ quantitative analysis software (Quant-My-Way), respectively. The peak areas of all metabolites were integrated using the retention time and MRM method, and the resulting raw abundances

were exported to Microsoft Excel for further analysis. The raw abundances of the internal controls, endogenous amino acids and highly abundant lipids were examined to ensure accuracy of the analysis. Quality control samples were consistently measured to ensure optimal instrument performance and linearity. The average of the blank samples was subtracted from all raw abundances. For fold change calculations, each sample was divided by the average of the wildtype or control samples.

Immunoblotting

Purified proteins were run on SDS-PAGE (Thermo Fisher Scientific) at 120V and transferred to PVDF membranes at 40V for 2 hours. The membranes were then blocked with 5% non-fat dry milk in Tris-buffered saline with Tween 20 (TBST) for 30 min and incubated overnight with primary antibodies in 5% BSA in TBST at 4 °C using dilutions listed in the antibody table. After incubation, membranes were washed 3X with TBST for 5 min per wash and then incubated with appropriate secondary antibodies diluted 1:3,000 in 5% BSA for 1 hour at room temperature. Membranes were then washed 3X with TBST followed by ECL2 western blotting substrate (Thermo Fisher Scientific) prior to visualization.

Thermal Stability Assay

A Tycho NT.6 instrument (Nanotemper Technologies) was used to determine the melting stability of human PLA2G15-6xHis wildtype and S198A. A concentration of 5 µM purified proteins in 50 mM Sodium Acetate-Acetic Acid (pH=5.0) and 150 mM NaCl were loaded into Tycho NT.6 capillaries. The melting temperature (Tm) was obtained by plotting the absorbance ratio of solvent-exposed tryptophan vs buried tryptophan (350 nm/330 nm) throughout a temperature gradient and determining the inflection temperature from the first derivative.

Microscale Thermophoresis (MST)

Recombinant human PLA2G15-6xHis S198A were labeled using RED-NHS Protein Label Kit following the manufacturer's protocol. Monolith NT.115 instrument was used for binding experiments. A 100 nM labeled protein was incubated with serial dilutions of

substrates in 50 mM Sodium Acetate-Acetic Acid (pH=5.0), 150 mM NaCl, and 5 µM BSA for 30 min at room temperature. Using premium capillaries, binding measurements were conducted at 20%, 40%, or 60% MST power for 30 s with 5 s of cooling. The dissociation constant Kd was derived by plotting the fraction bound against logarithmic substrate concentrations according to the law of mass action.

Synthesis of GPG

Standard GPG was prepared for the kinetic assays. Phosphatidylglycerol (18:1/18:1 PG) (Avanti) was saponified to produce GPG according to the following protocol:
100 mg of PG was dissolved in a 20 ml scintillation vial that contained a 12 ml solution of 2:1 chloroform:methanol with a magnetic stirring bar. NaOH (4 ml of 2 M) was added to the mixture and the reaction was stirred for 2 hours at room temperature. To neutralize the reaction, HCl (4 ml of 2 M) was used, and GPG was extracted with 8 ml water into separate vessels twice. After mixing the aqueous phases, they were frozen in liquid nitrogen, lyophilized, and cleaned with 8 mL of chloroform. To separate the crude product from inorganic salts, lyophilates were dissolved in a minimal amount of methanol. The desired products were then extracted from the precipitate using paper filtering.

Thin Layer Chromatography (TLC)

100 nM of PLA2G15-6xHis WT was mixed with 20 µM BMP and incubated at 37 °C for 1 hour as described for the enzyme assay. Two microliters of reaction were spotted on silica and optimized to observe product release. The silica was placed in a thin layer chromatography (TLC) solvent ($CHCl_3$/CH_3OH/conc ammonia/water (90:54:5.5:2 [v/v]) and dipped into an iodine stain (Iodine crystals and silica gel mixture) after the solvent run prior to visualization.

Diffdock Docking

Structure of *H. Sapiens* PLA2G15 was obtained from the AlphaFold entry of Q8NCC3 (UniProt). The predicted protein structure was prepared for docking using ChimeraX to add hydrogens according to the expected protonation state at pH 5. The substrates

were drawn in ChemDraw to extract the SMILES string. The structure of the protein (pdb format) and the SMILES string were used as input for DiffDock. We ran DiffDock in a web server using the following parameters: twenty inference steps, eighteen actual inference steps, and forty samples. The docking results with the best confidence score were used for the analysis using ChimeraX.

LysoFQ-GCase activity assay

About 50,000 of bone marrow derived macrophages were seeded with 700 µL macrophage medium on each division of a 4-chamber 35 mm glass bottom dish (Cellvis). Then, 300 nM recombinant PLA2G15 wildtype or mutant or vehicle solution (1X PBS) was added during cell seeding. After overnight incubation, 10 µM of LysoFQ-GBA probe [51] was added to the medium and incubated for 30 min. After incubation, medium was washed once with macrophage medium and then replaced with fresh medium containing 100 nM AT3375 (GCase inhibitor) to stop the reaction. Cells were then imaged with Leica LSM confocal microscope and images were analyzed using image J.

Haploid genetic screens

To identify regulators of intracellular cholesterol levels we prepared libraries of mutagenized Hap1 wild-type and NPC1-deficient cells using a gene-trap retrovirus expressing blue fluorescent protein (BFP), as described previously [52]. For each genotype, mutagenized cells were cultured and expanded for one week after mutagenesis. Subsequently, cells were washed with PBS, dissociated, pelleted, and fixed with BD Fix buffer I (BD Biosciences) for 10 min at 37 °C. After washing once with FACS buffer (PBS containing 1% BSA) and once with PBS, the cells were pelleted and resuspended in permeabilization buffer (PBS containing 0.1% saponin). Cells were incubated for 5 min at room temperature while rotating. Cells were pelleted, washed twice with FACS buffer, and incubated with FACS buffer containing 3 µg/ml AlexaFluor647-labeled Perfringolysin O (PFO) [53] and 1 µg/ml 4′,6-diamidino-2-phenylindole (DAPI) for 45 min at room temperature while rotating. Cells were subsequently pelleted, washed twice with FACS buffer before sorting two populations of

cells (i.e. PFO-LOW and PFO-HIGH) that represent ~5% of the lowest and highest cholesterol containing cells from the total cell population, respectively. In addition, cells were sorted in parallel for haploid DNA content (G1 phase) using the DAPI signal. Cell sorting was carried out on a FACS Aria III cell sorter (BD Biosciences) until ~10 million cells of each population were collected. Sorted cells were pelleted and genomic DNA was isolated. Gene-trap insertion sites of each sorted cell population were amplified and mapped by deep sequencing. For each gene in a single screen, a mutation index (MI) was calculated corresponding to the ratio of the number of disruptive integrations per gene in both populations normalized by the number of total integrations in each channel (i.e. PFO-LOW and PFO-HIGH) as previously described [52]. Genes significantly enriched for disruptive gene-trap integrations in either the PFO-HIGH or PFO-LOW query populations were identified using a two-sided Fisher's exact test. Resulting P values were adjusted for multiple testing using the Benjamini–Hochberg false discovery rate correction.

siRNA knockdown in NPC1 patient fibroblast

Two NPC1 patient fibroblast cells (GM03123 and GM18453) were acquired from Coriell with agreement. 30,000 cells of two NPC1 patient fibroblasts were seeded on each well of an 8-chamber cell culture slide (Celltreat, Pepperell, MA) that contains 500 µL complete DMEM. Next day, cells were transfected with scrambled siRNA (ThermoFisher 4390844) or two siRNAs targeting human PLA2G15 (ThermoFisher s24296, s24297) using RNAiMax (ThermoFisher) according to the manufacturer's instruction. 2 days post transfection, medium was gently aspirated, and cells were washed once with 800 µL PBS, followed by immediate 15 min fixation with 200 µL of 4% PFA in PBS. Then, cells were washed once with 800 µL PBS and stained with 200 µl of 1 mg/ml Filipin (Cayman). Slides were sealed with glass coverslip and mounting solution (Thermo Scientific) and imaged with Leica LSM980 confocal microscope.

Data preparation and statistics

For quantitative data presentation, GraphPad Prism v.10.2 was used and figures were assembled in Adobe Illustrator 2023. All statistical analyses were performed in Prism. Unless otherwise stated in the legends, all measurements presented were derived from independent samples or biological replicates. Western blot data displayed were representative experiments. BioRender was used with permission to illustrate the figure schematics for Figures 2A, 5B and S7D. ChemDraw 22.2.0 was used in chemical structures depicted in Figures 1A, 1B, 1C, and 3A.

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Data and materials availability: All data needed to evaluate the conclusions stated in the paper are present in the paper and/or the Supplementary Materials. This paper does not report original code. Plasmids can be acquired from addgene, and cell lines can be requested, and requests will be fulfilled by, the lead author, Monther Abu-Remaileh (monther@stanford.edu).

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Supplementary Information

Supplementary Figures

Figure S1: Purification of recombinant PLA2G15

(A) Purification of wildtype recombinant His-tagged lysosomal phospholipase PLA2G15. Representative image of 47.5 kDa PLA2G15-6xHis protein purified to homogeneity and stained with Coomassie Blue. **(B)** Immunoblot analysis of purified PLA2G15 using anti-His antibody. **(C)** Purified PLA2G15 is active protein. Phospholipase activity determined using 100 nM PLA2G15 against phosphatidylcholine (PC) or phosphatidylglycerol (PG) under acidic conditions. Glycerophosphodiester products (GPD) detected using LC-MS. n = 3 independent replicates for each protein. Statistical analysis was performed using two-tailed unpaired *t*-tests. ***$p \leq 0.001$ and ****$p \leq 0.0001$. Control has all reaction component with no enzyme.

Figure S2: PLA2G15 catabolizes lysosomal phospholipids including BMP derived from cells

(A-C) PLA2G15 hydrolyzes BMP and other phospholipid substrates extracted from HEK293T lysosomes. Lysosomal lipids were isolated from HEK293T lysosomes and incubated with recombinant PLA2G15 for 30 min or 120 min. **(A-C)** Fold changes in phospholipid substrates (PC, PE, PG, PI and PS) in (B), lysophospholipid intermediates (LPC, LPE, LPG, LPI, LPS) in (C) and BMPs in (D). **(D)** Non PLA2G15 substrates remained unchanged. Fold changes in diacylglycerol (DG) and sphingomyelin (SM). Each incubation time was compared to control samples from each biological replicate incubated at the same time. Data are mean ± SD of n = 4 biological replicates. Statistical analysis was performed using two-tailed unpaired *t*-tests. *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$ and ****$p \leq 0.0001$.

Figure S3: Purification and characterization of mutant recombinant PLA2G15

(A) Purification of recombinant His-tagged PLA2G15 S198A. Representative image of 47.5 kDa PLA2G15 S198A-6xHis protein purified to homogeneity and stained with Coomassie Blue. **(B)** Immunoblot analysis of PLA2G15 S198A using anti-His antibody. **(C)** Melting temperature (Tm) curves indicate that wildtype and S198A mutant maintain thermal stability. Tm is indicated on the graph.

Figure S4: Optimization of enzyme reaction conditions

(A) BMP hydrolase activity of PLA2G15 has an acidic pH optimum. PLA2G15-6xHis was incubated with 3,3' 18:1-*S,S* BMP under the indicated pH conditions. A representative graph is shown for an experiment repeated at least 3 times. **(B)** PLA2G15-6xHis was incubated with 1 µM of 3,3' 18:1-*S,S* BMP and at different time points and enzyme concentrations. A representative graph indicates linearity in increments across multiple enzyme concentrations at a 30 second time point. **(C)** Standard curves generated from measuring the indicated LPG intermediates and GPG product. **(D)** Standard curves generated from measuring the indicated BMP standards.

Figure S5: PLA2G15 has high activity towards BMP

(A-D) PLA2G15 deacylates BMP to LPG with high catalytic efficiency that is comparable to that against PG phospholipid and this activity correlates with acyl chain length. Recombinant PLA2G15 was incubated with the indicated phospholipids under acidic conditions (pH= 5.0) for 30 seconds and reactions were stopped by heating. Phospholipids were incorporated in liposomes with non-cleavable 18:1 diether PC and indicated LPG intermediates were measured. Each experiment was repeated at least three times, and a representative graph is shown. K_{cat}/K_m is a measure of kinetic efficiency. **(E-H)** PLA2G15 deacylates BMP to GPG with high efficiency. Recombinant PLA2G15 was incubated with the indicated phospholipids under acidic conditions (pH= 5.0) for 30 seconds and reactions were stopped by heating. Phospholipids were incorporated in liposomes with non-cleavable 18:1 diether PC and GPG product was measured. Each experiment was repeated at least three times, and a representative graph is shown.

Figure S6: Esterification position in BMP confers resistance to PLA2G15-mediated hydrolysis in vitro

(A) PLA2G15 efficiently deacylates BMP independent of stereoconfiguration. Hydrolysis of 1 µM BMP stereoisomers by 100 nM recombinant PLA2G15 for 30 seconds under acidic conditions (pH=5.0). LPG intermediate was measured with LC-MS. Data are mean ± SD of n = 3 independent replicates. **(B)** LPG monitoring shows

minimal difference in the activity of PLA2G15 against positional BMP isomers. Same experiment as in (A) using 1 μM of either 3,3' *S,S* BMP or 2,2' *S,S* BMP as substrate incubated for 30 secs. Data are mean ± SD of *n* = 3 independent replicates. **(C)** A representative image of the extracted ion chromatogram of 2,2; and 3,3' positional BMP isomers used in this paper. Each compound has a minor amount of 2,3' isomer. **(D and E)** Time course of BMP hydrolysis shows 2,2' BMP positional isomer confers resistance to PLA2G15 degradation. Hydrolysis of 20 μM 2,2' *S,S* BMP or 3,3' *S,S* BMP positional isomers as well as equimolar amount of both by 100 nM recombinant PLA2G15 over 10 hours under acidic conditions (pH=5.0). Controls had similar reaction buffers except with no enzyme. BMP hydrolase activity was determined using LC-MS by calculating the abundance of LPG intermediate in (D) and GPG product in (E). Data are mean ± SD of *n* = 3 independent replicates. **(F)** DiffDock of 3,3' *S,S* BMP onto AlphaFold human PLA2G15 structure. Catalytic triad residues Ser198, Asp360 and His392 of the active site of PLA2G15 are annotated. **(G)** BMP binds to PLA2G15 S198A at low micromolar concentration. Binding affinity was determined using microscale thermophoresis for 3,3' *S,S* BMP. Data presented as mean ± SEM from three measurements and the experiments were repeated at least three times.

Figure S7: PLA2G15-deficient cells and lysosomes accumulate BMP

(A and B) Targeted analyses of BMP lipids in PLA2G15-deficient cells reveal their accumulation in lysosomes and whole cells. (A) Heatmap representation of log2-transformed changes in BMP abundances in lysosomes (IP) and whole cells (WC) of PLA2G15-deficient HEK293T clone1 compared to wildtype control (*n* = 3 WT and *n* = 3 *PLA2G15* KO)**.** Data are the ratio of the mean of each BMP. Significant changes from the graph are represented by *p $\leq$ 0.05. P values were calculated using two-tailed unpaired tests and are presented in Table S1. (B) Fold changes in total BMP abundance. The sum of all abundances of measured BMPs was used to generate these values. Data are mean ± SD. Statistical analysis was performed using two-tailed unpaired *t*-tests. ****p $\leq$ 0.0001. **(C)** Generation of PLA2G15-deficient clones 2 and 3. **(D)** Schematic for fluorescently labeled PLA2G15 uptake experiments. Labeled recombinant PLA2G15 protein was supplemented to *PLA2G15* KO or *CLN5 PLA2G15*

double knockout HEK293T cells for 48 hours and imaged. **(E)** Representative images of labeled PLA2G15 wildtype and mutant proteins (Alexa488) and lysosomes (Lysotracker) show successful uptake and trafficking in *PLA2G15* KO HEK293T cells. Scale bar = 5µm. Experiment was repeated at least three times. **(F)** Curve represents overlap correlation showing that labeled proteins colocalizes with lysotracker. **(G)** Non PLA2G15 substrates remain unchanged in PLA2G15-deficient mouse tissues. Fold changes in sphingomyelin (SM 38:3) in PLA2G15-deficient tissues (mouse brain, kidney and liver) compared to control counterparts. n = 6 *Pla2g15*$^{+/+}$ and n = 6 *Pla2g15*$^{-/-}$. Data are mean ± SD.

Figure S8: Esterification position in BMP confers resistance to hydrolysis in cells **(A)** Generation and validation of *PLA2G15* KO on a background of *CLN5* KO HEK293T cells. **(B)** BMP signal is diminished in *CLN5 PLA2G15* double KO HEK293T cells compared to wildtype. Fold changes of normalized BMP 18:1/18:1 abundance. Data are mean ± SD. Statistical analysis was performed using two-tailed unpaired *t*-tests. ****, $p < 0.0001$. **(C)** Supplementation of synthesized positional isomers to HEK293T cells demonstrate 2,2' BMP as the major BMP form in cells. Representative smoothened graphs of the extracted ion chromatograms following addition of 2,2' and 3,3' BMP standards to *CLN5 PLA2G15* double KO HEK293T cells. The retention times are shown in the list mode (left) while the alignment of standards in overlaid mode (right) indicate 2,2' BMP as the predominant endogenous form. **(D)** Representative images of labeled PLA2G15 wildtype and mutant proteins (Alexa488) and lysosomes (Lysotracker) show successful uptake and trafficking in *CLN5 PLA2G15* KO HEK293T cells. Scale bar = 5µm. Experiment repeated at least three times. **(E)** Curve represents overlap correlation showing that labeled proteins colocalizes with lysotracker. **(F)** Exogenous BMP feeding to cells was optimized for pulse-chase experiments. Normalized BMP abundance was measured following addition of 2,2' BMP at indicated time points. **(G)** PLA2G15 WT hydrolyze BMP in cells while cells supplemented with inactive PLA2G15 S198A exhibit reduced BMP hydrolysis capacity. 100 nM PLA2G15 proteins were supplemented in the chase period after delivery of 10 µM 2,2' BMP for two hours. **(H-J)** Turnover of 3,3' BMP is rapid while 2,2' BMP may require positional isomerization for efficient degradation in

cells. **(H)** The intensity of each BMP peak (2,2' BMP peak; left, 2,3' BMP peak; middle, 3,3' BMP peak; right) was quantified following a 4-hour chase by PLA2G15 proteins or no enzyme control following addition of either 10 μM of 2,2' BMP (top) or 3,3' BMP (bottom) standards. PLA2G15 quickly degrades 3,3' and 2,3' BMP after 3,3 BMP supplementation while 2,2' BMP is converted to 2,3' and 3,3' BMP. **(I)** Quantitation of endogenous BMP peaks during pulse-chase experiment in (H). These levels are minimal compared to cells supplemented with the lipids. **(J)** Quantitation of endogenous BMP peaks during pulse-chase experiment using equimolar mixture of 2,2' BMP and 3,3' BMP. **(K)** BMP stereoisomers are degraded similarly in cells. Same experiment in (H) using *S,S* BMP (left) and *S,R* BMP (right) to measure total BMP levels during chase.

Figure S9: PLA2G15 role in lysosomal lipid metabolism

(A and B) PLA2G15 reduces GCase activity in bone marrow derived macrophages (BMDMs). **(A)** Representative fluorescence microscopy images of BMDMs treated with 300 nM recombinant PLA2G15 WT, inactive PLA2G15 S198A or vehicle buffer (PBS) overnight followed by a 30-minute incubation of 10 μM LysoFQ-GBA. **(B)** Quantification of signal intensity of LysoFQ-BSA. Signals are normalized to the vehicle treated BMDMs. *, $p < 0.05$, by one way ANOVA. **(C)** PLA2G15 knockdown in two independent NPC1 patient fibroblast cell lines (Coriell GM03123 and GM18453) after two-day treatment with 10 nM control siRNA or two different siRNA that target PLA2G15. qPCR quantification of PLA2G15 mRNA abundance normalized to GAPDH. ****, $p<0.0001$, by one-way ANOVA.

Figure S10: Haploid genetic screens for intracellular cholesterol accumulation

(A and B) Mutagenized libraries of cells were stained for intracellular cholesterol levels using fluorescently labeled PFO. Subsequently, cells are sorted by flow cytometry to obtain cell populations with high and low levels of PFO signal (i.e. PFO-HIGH versus PFO-LOW, respectively). Insertion sites were mapped in each population of cells and the log mutational index (MI; see Methods) was plotted against the number of trapped alleles per gene. Statistically significant hits ($p < 0.05$) in the isolated PFO-HIGH and PFO-LOW cell populations are indicated in dark grey. **(A)** The screen in wild-type Hap1

cells identified NPC1 as a strong negative regulator of cholesterol accumulation as expected (in red). **(B)** The screen in NPC1-deficient Hap1 cells identified PLA2G15 as a genetic modifier of cholesterol staining (in blue). Note that PLA2G15 was not identified to affect staining in wild-type Hap1 cells. **(C)** Lysosomal hydrolases significantly enriched for PFO high (red) or PFO low (blue) staining in NPC1-deficient versus wild-type Hap1 cells. PLA2G15 was identified as the strongest regulator of low PFO signal in NPC1 deficient cells. LIPA (Lipase A, lysosomal acid type), TTP1 (Palmitoyl-protein thioesterase 1), NAGLU (N-acetyl-alpha-glucosaminidase), HSNGAT (Heparan-alpha-glucosaminide N-acetyltransferase).

Supplementary Tables

Table S1: Targeted BMP analyses of lysosomes and whole cells from PLA2G15-deficient and wildtype HEK293T cells.

Table S2: Targeted BMP analyses from wildtype and PLA2G15-deficient HEK293T cells.

Table S3: Targeted BMP analyses from PLA2G15-deficient mouse tissues and their control counterparts.

Table S4: Haploid genetic screening data for PFO staining in WT and NPC1-deficient cells.

Figure 1: BMP lipids are susceptible to lysosomal hydrolases

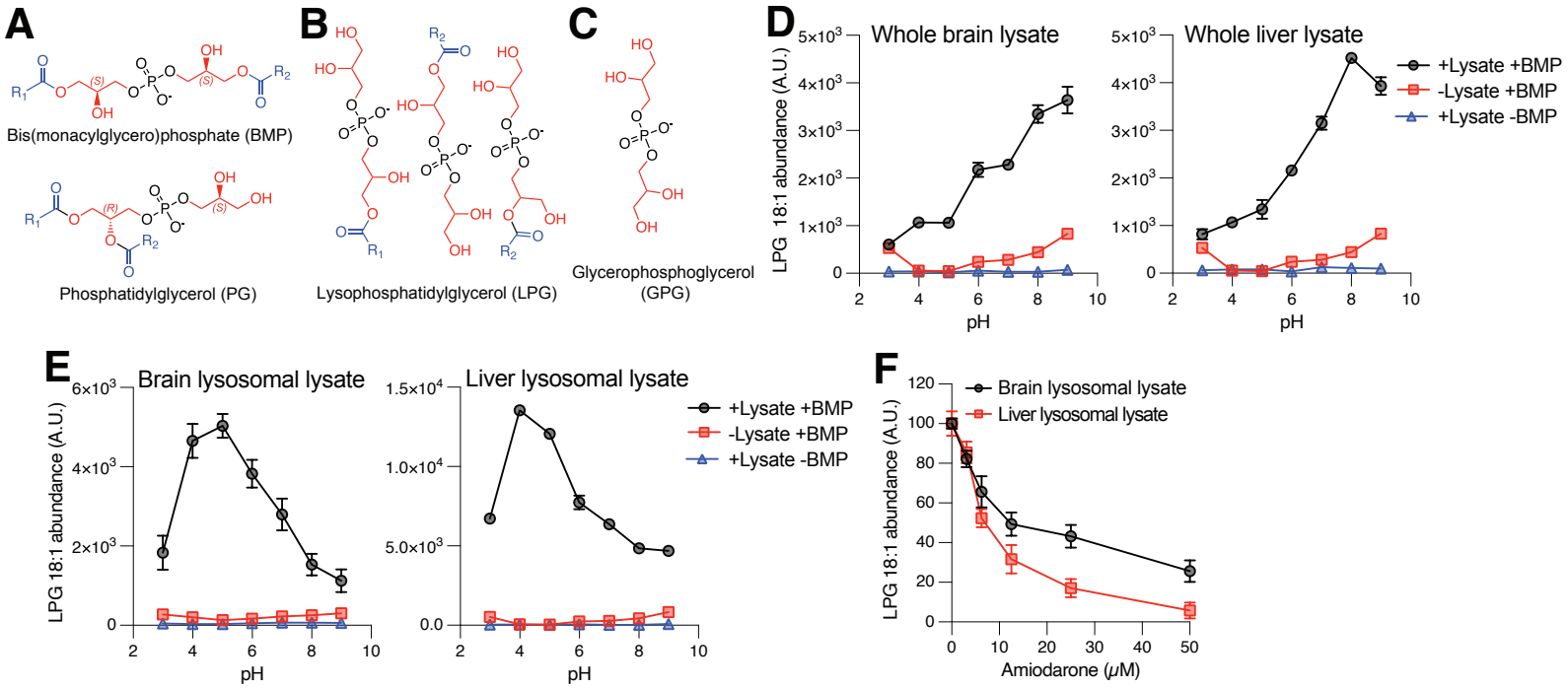


Figure 2: PLA2G15 catabolizes lysosomal phospholipids including BMP

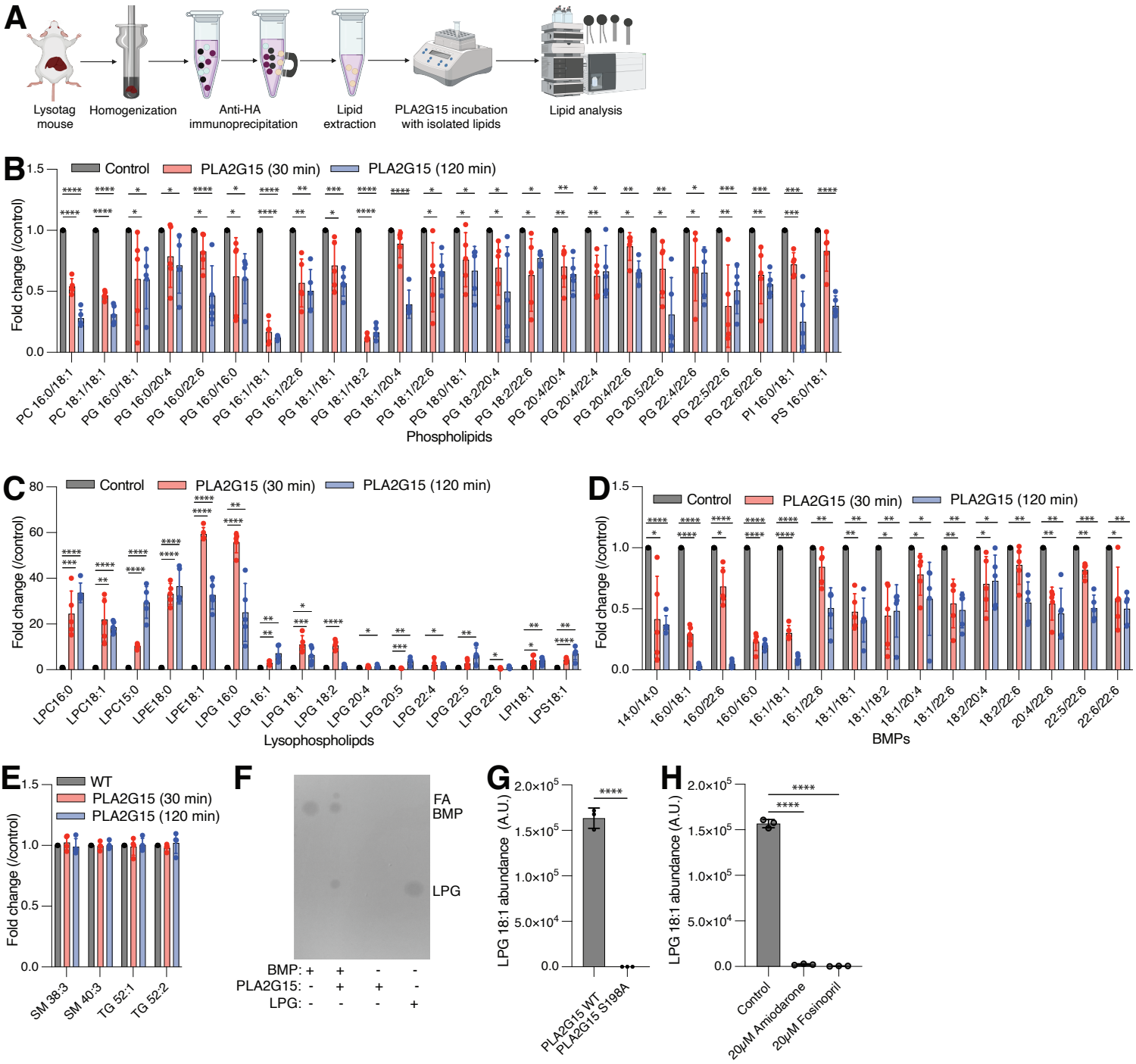


Figure 3: Esterification position and not stereoconfiguration of BMP confers resistance to PLA2G15

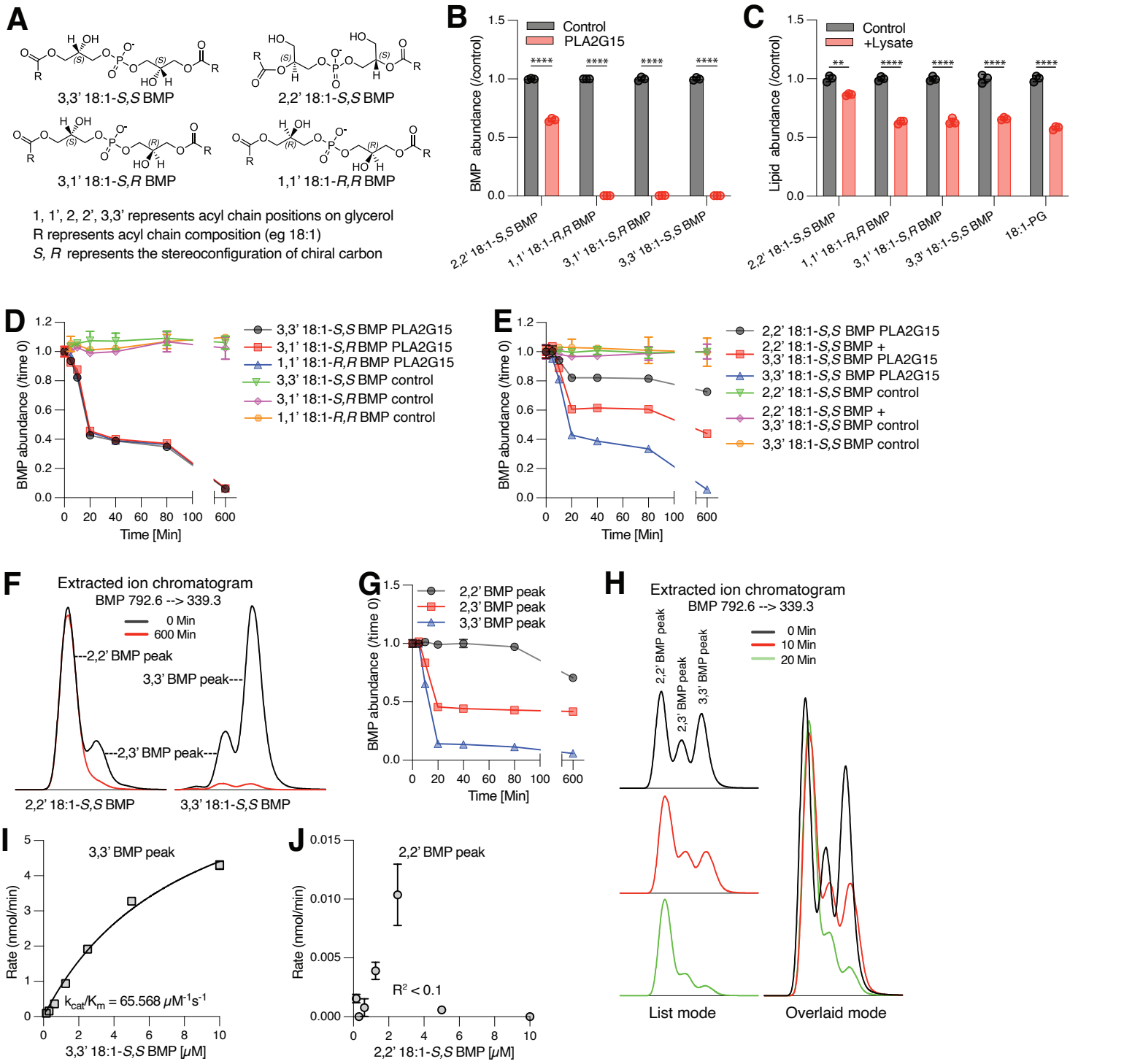


Figure 4: PLA2G15-deficient cells and tissues accumulate BMP

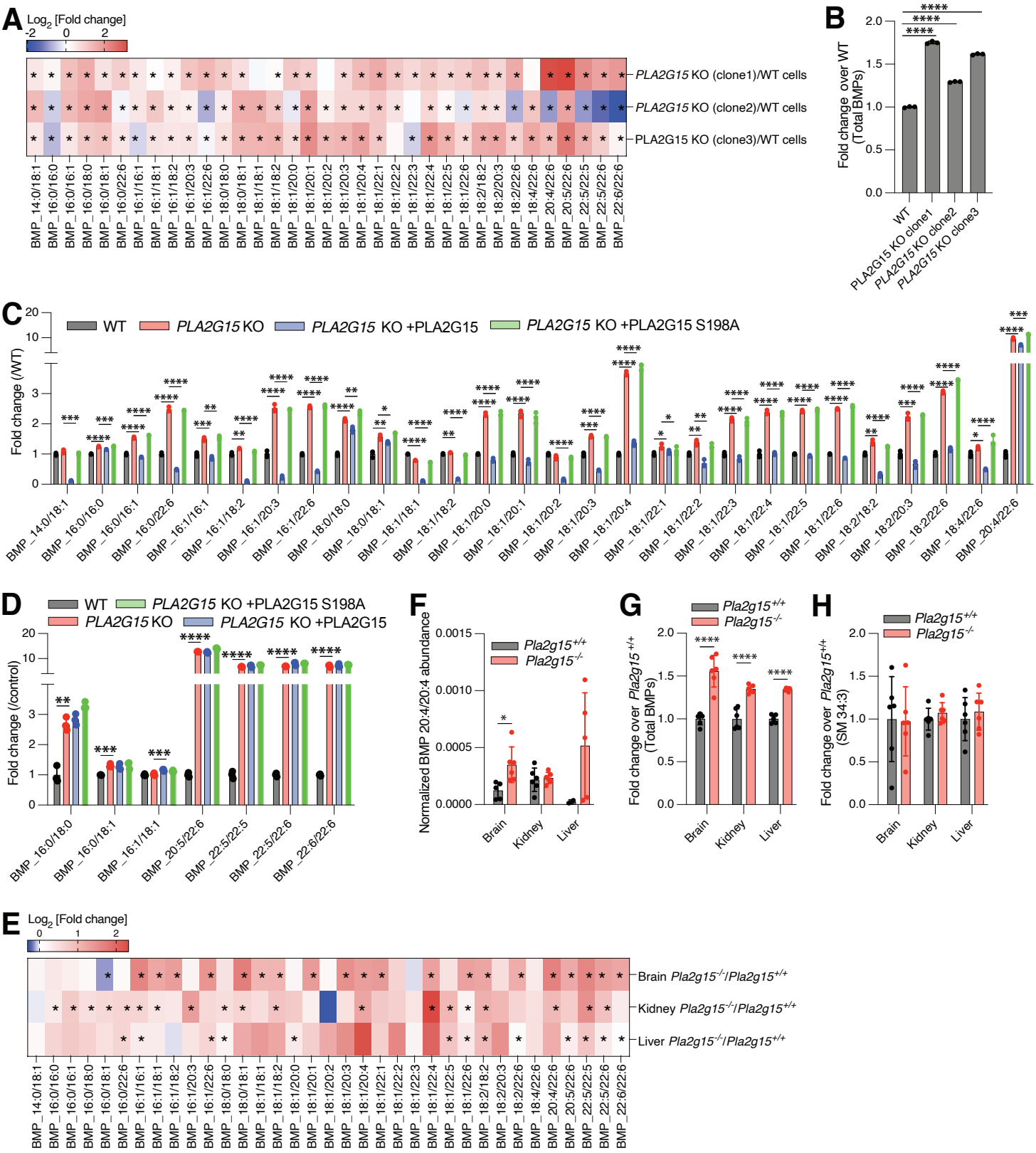


Figure 5: PLA2G15 controls lysosomal lipid metabolism through BMP regulation

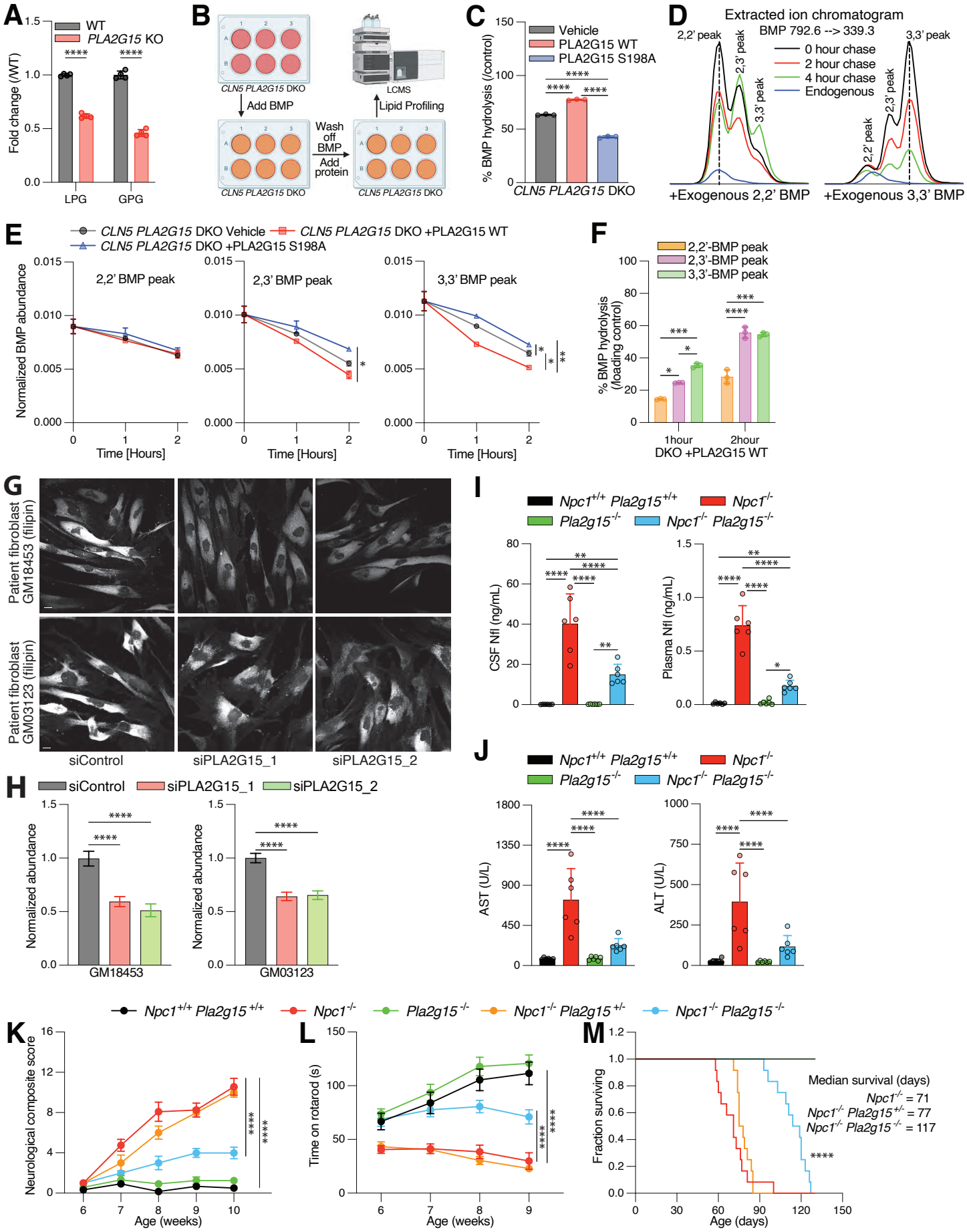


Figure S1: Purification of recombinant PLA2G15

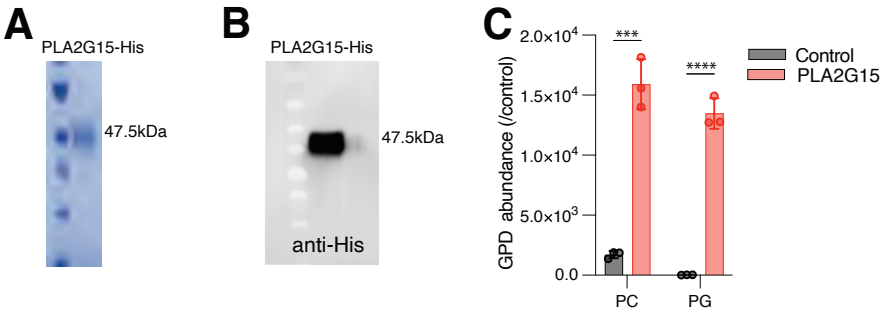


Figure S2: PLA2G15 catabolizes lysosomal phospholipids including BMP derived from cells

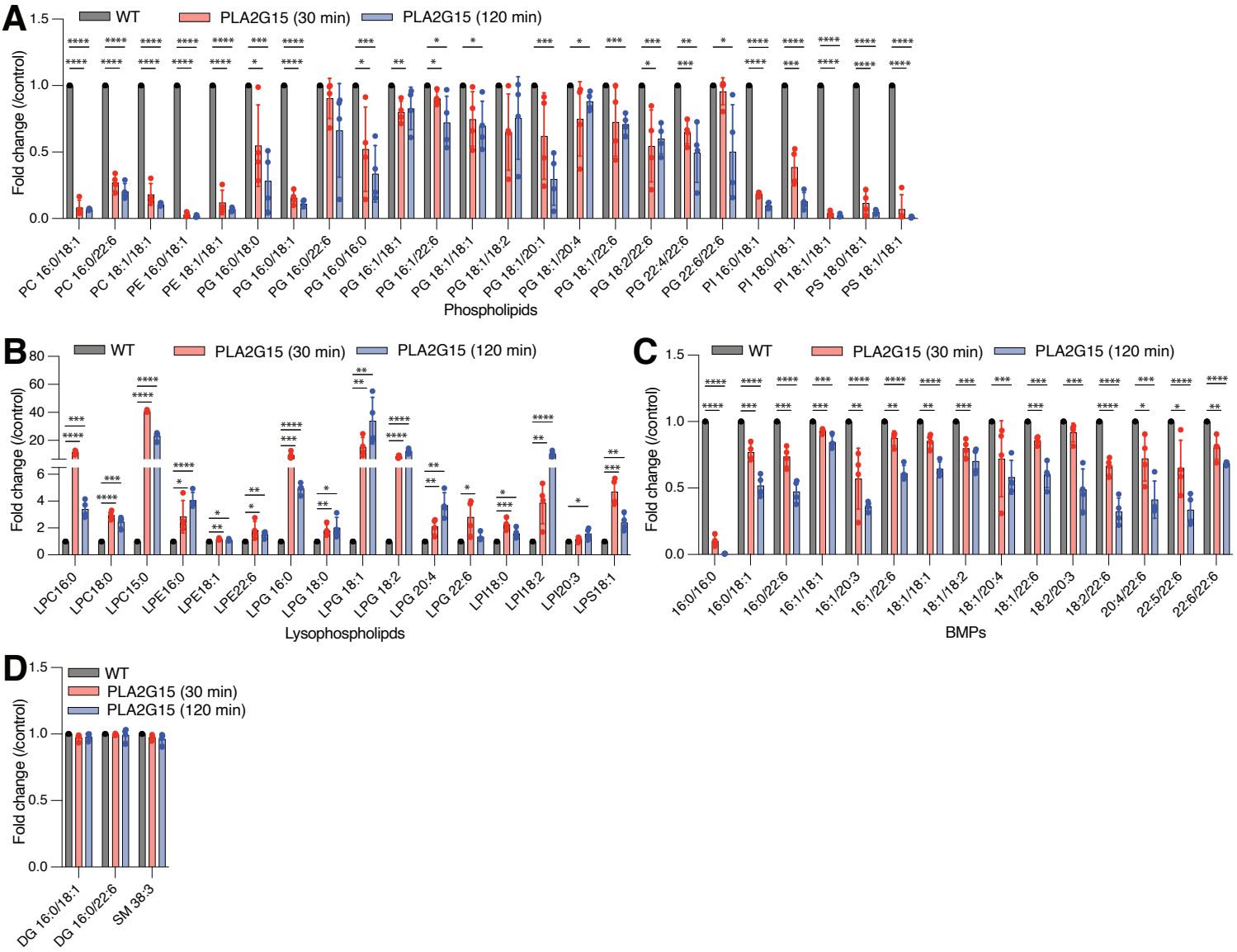


Figure S3: Purification and characterization of mutant recombinant PLA2G15

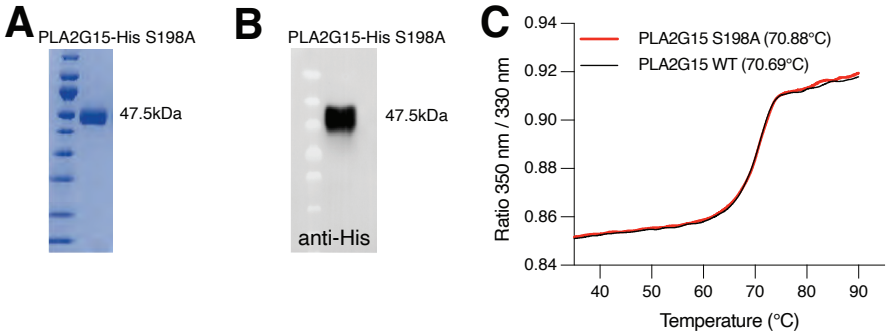


Figure S4: Optimization of enzyme reaction conditions

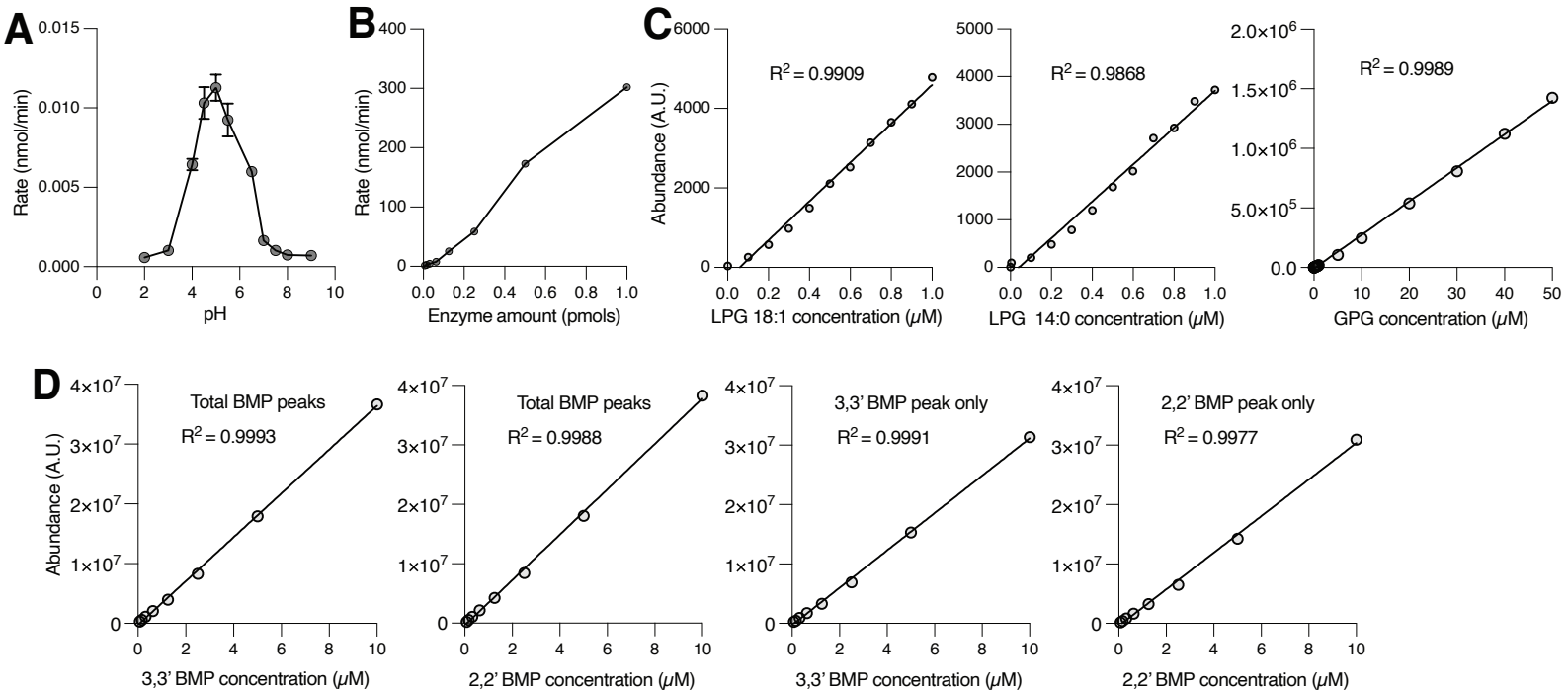


Figure S5: PLA2G15 has high activity towards BMP

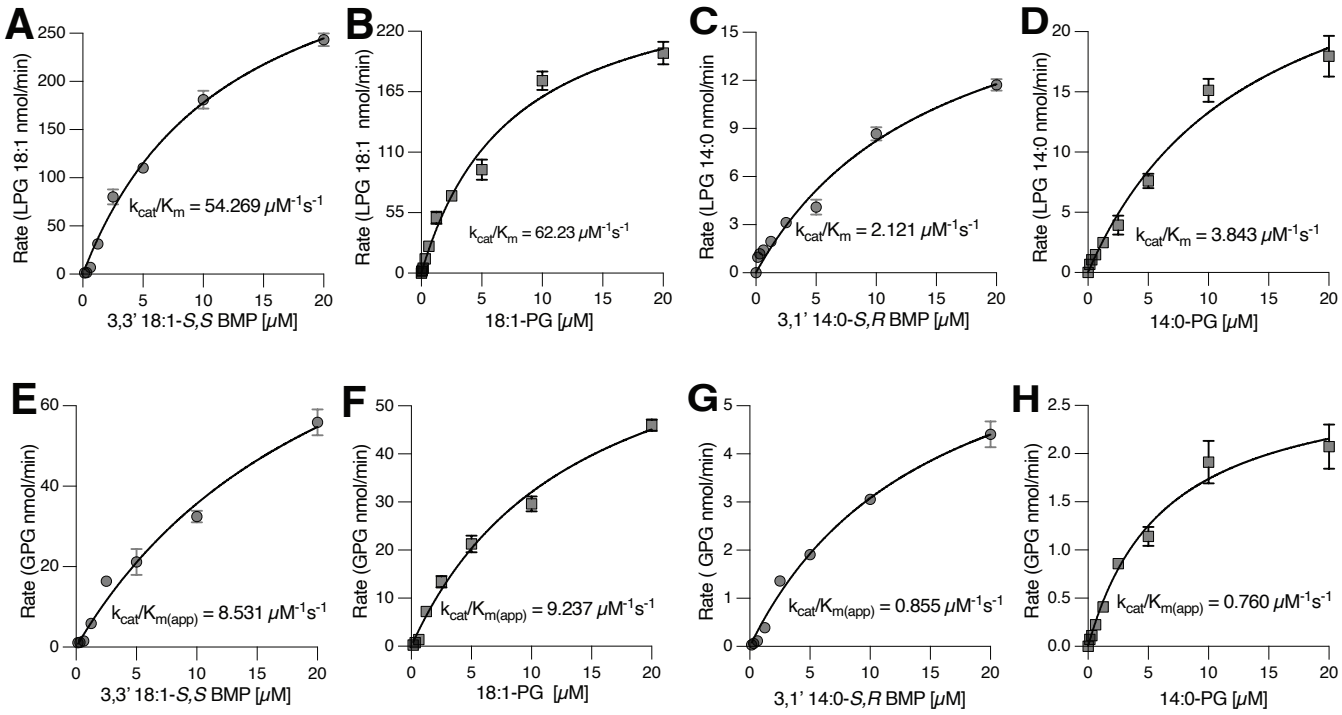


Figure S6: Esterification position in BMP confers resistance to PLA2G15-mediated hydrolysis in vitro

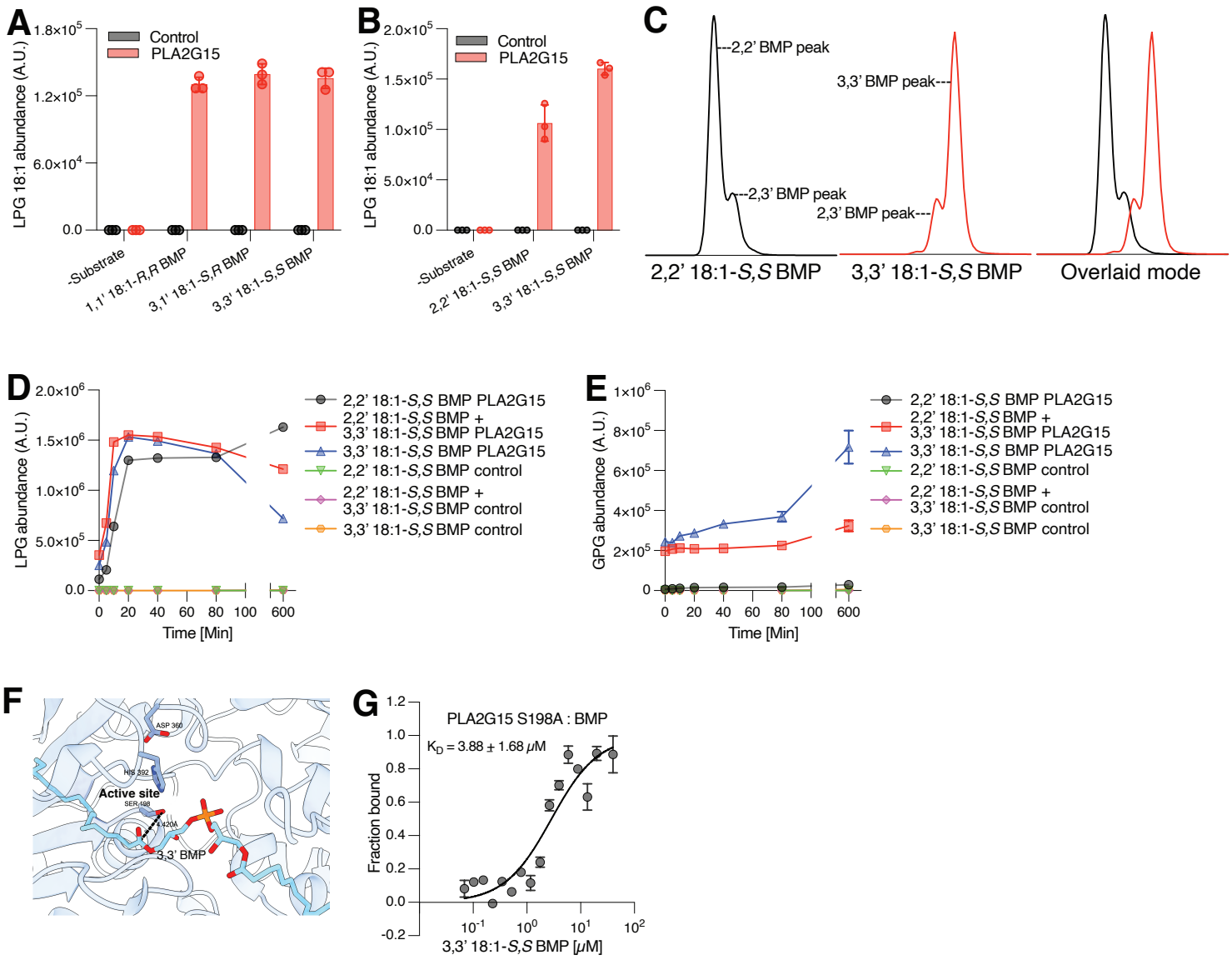
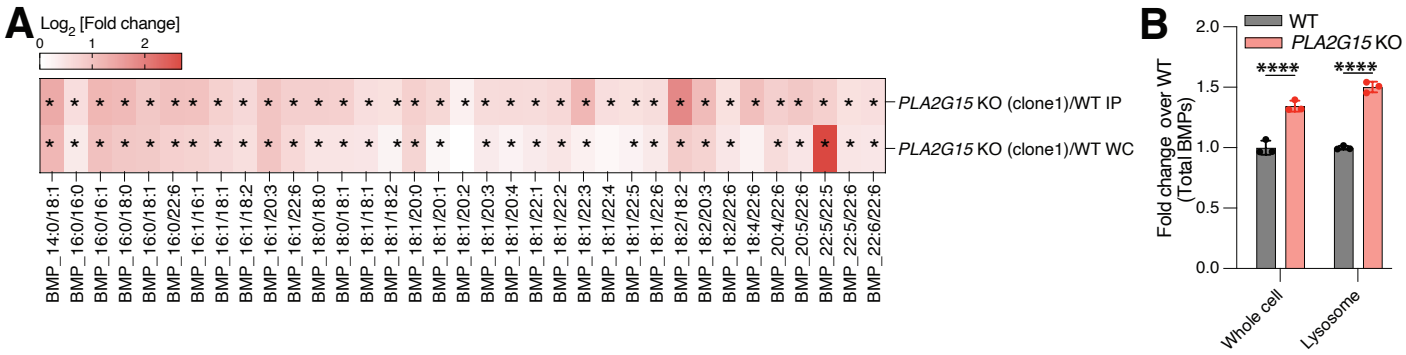
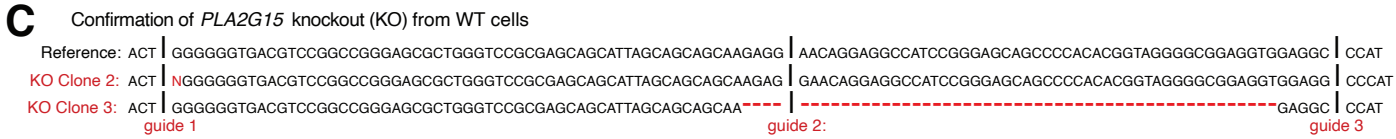
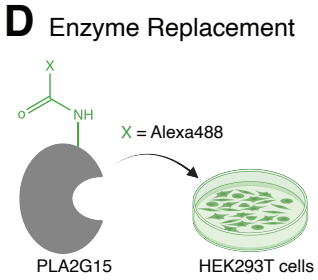
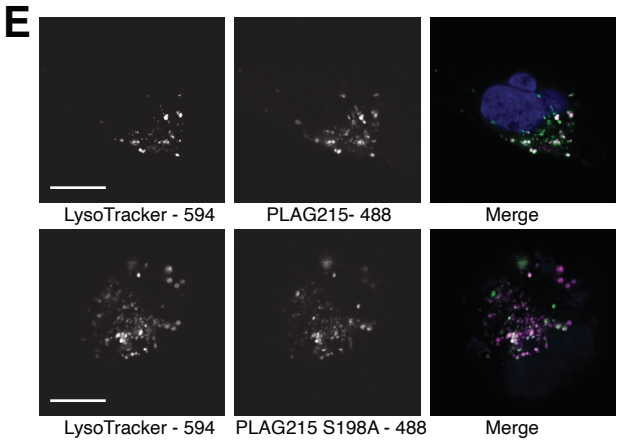


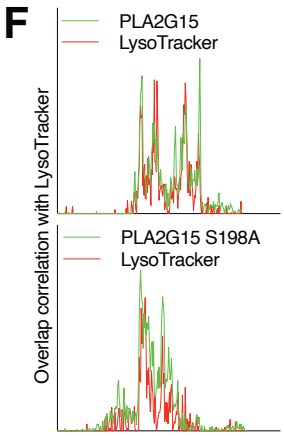
Figure S7: PLA2G15-deficient cells and lysosomes accumulate BMP











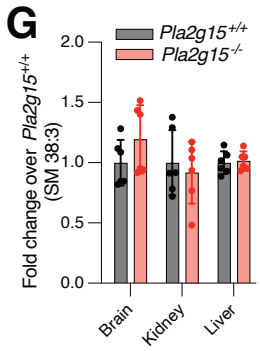


Figure S8: Esterification position in BMP confers resistance to hydrolysis in cells

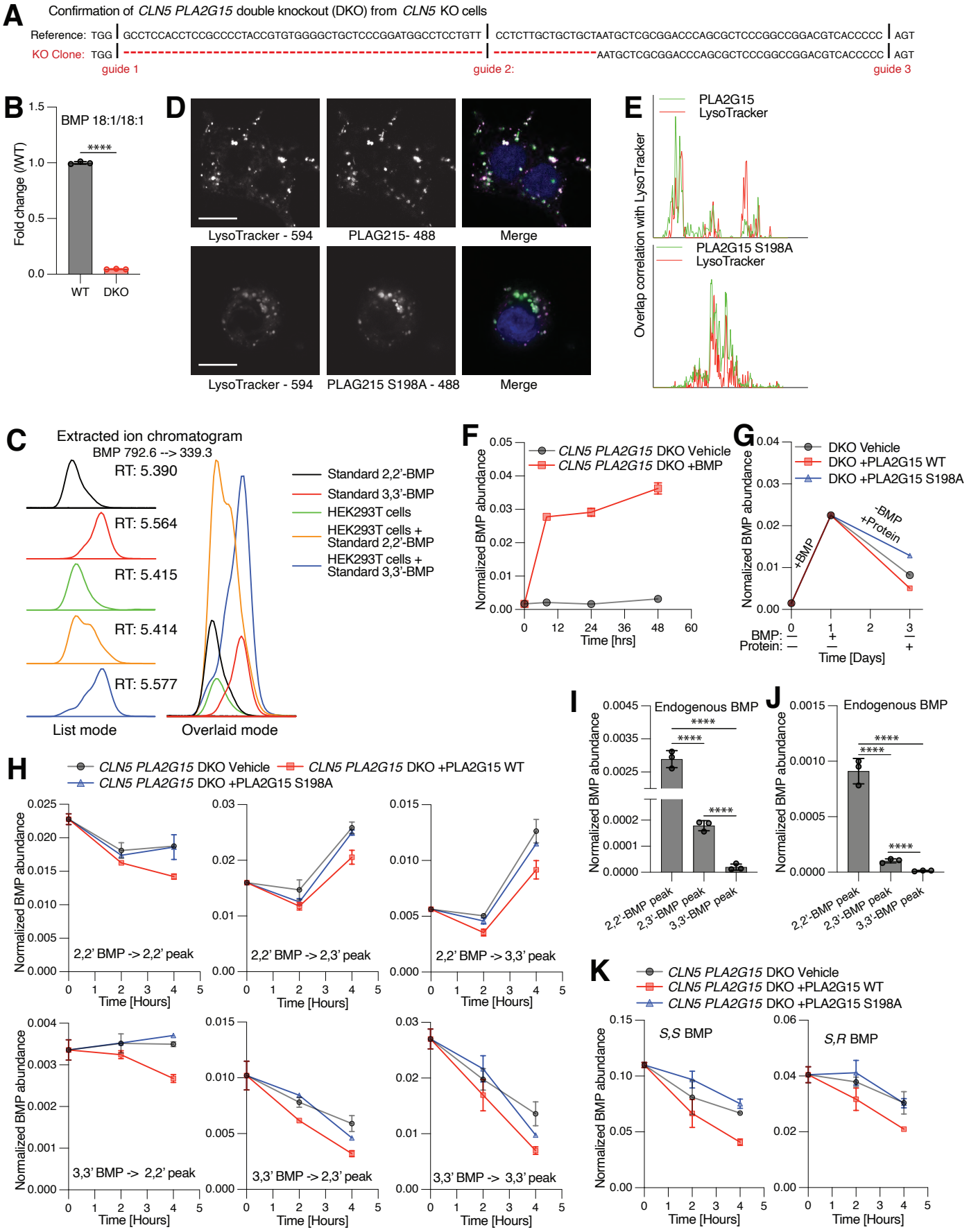


Figure S9: PLA2G15 role in lysosomal lipid metabolism

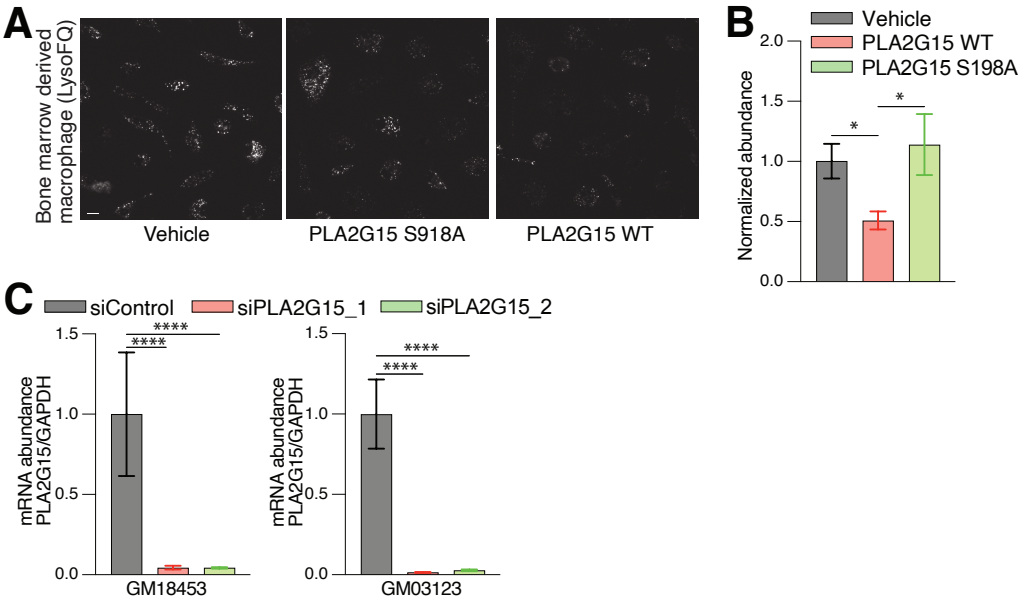
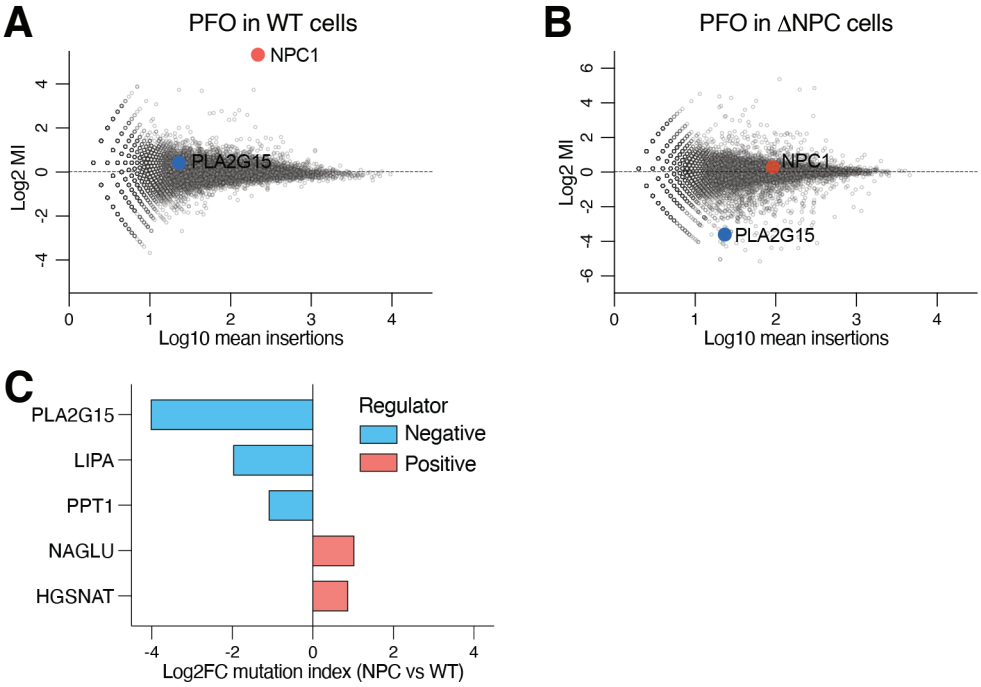



Figure 10: Haploid genetic screens for intracellular cholesterol accumulation