Acquired resistance to sotorasib in *KRAS*^{G12C} mutant NSCLC is vulnerable to PI3K-mTOR pathway inhibition mediated by 4E-BP1 regulator of cap-dependent translation

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Overcoming sotorasib-acquired resistance by targeting PI3K/AKT/mTOR pathway in patient-derived xenograft model

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Abstract

Sotorasib (AMG510) and adagrasib (MRTX849) have shown significant efficacy in *KRAS*^{G12C} mutant NSCLC, but acquired resistance occurs within 6–12 months. While some resistance arises from new mutations, over half of the resistant cases lack identifiable genomic alterations. We hypothesize that resistance is driven by signaling network rewiring, creating new therapeutic vulnerabilities. To investigate acquired resistance (AR) mechanisms, multiple AR models, including cell lines (H23AR & H358AR), PDXs (TC303AR & TC314AR), CDXs (H358AR CDX), and PDXOs (PDXO303AR & PDXO314AR) were developed. H23AR and H358AR cells displayed >600-fold and 200-fold and PDXO303AR and PDXO314AR, exhibited >300-fold and >100-fold resistance to sotorasib, respectively compared to their parental counterparts, however, no additional mutations in KRAS or other potential genetic alterations were identified. The AR cells and PDXOs also showed comparable resistance to adagrasib. Proteomic and phosphoproteomic analyses in TC303AR & TC314AR PDXs identified distinct protein signatures associated with KRAS reactivation, mTORC1 signaling upregulation, and PI3K/AKT/mTOR pathway activation. PI3K protein levels were significantly elevated in AR PDXs, H23AR, and H358AR cells. Pharmacological inhibition of PI3K with copanlisib or genetic knockout via CRISPR-Cas9 restored sotorasib sensitivity, suppressed colony formation, and inhibited downstream effectors, including p-AKT, p-mTOR, p-S6, p70S6K, p-GSK3β, and p-PRAS40 in AR cells. copanlisib also sensitized both acquired and primary resistant PDXOs and synergized with sotorasib in restoring drug sensitivity. We found that p4E-BP1 was significantly upregulated in H23AR and H358AR cells, and copanlisib suppressed its expression. The level of p4E-BP1 expression was correlated with Sotorasib sensitivity in PI3K knockout clones, where the most sensitive clone displayed reduced or no p4E-BP1 expression.

CRISPR-Cas9-mediated knockout of 4E-BP1, either alone or in combination with PI3K knockout, dramatically restored sotorasib sensitivity to levels comparable to parental cells. Suppression of 4E-BP1 hyperphosphorylation required dual inhibition of mTORC1 and mTORC2, and treatment with AZD8055 or sapanisertib (mTORC1/2 dual inhibitors) significantly dephosphorylated 4E-BP1 and restored sotorasib sensitivity in resistant cells and PDXOs. In contrast, everolimus (a mTORC1-selective inhibitor) did not restore sotorasib sensitivity. In PDX, CDX, and xenograft models in vivo, the combination of sotorasib with either copanlisib or sapanisertib resulted in robust, synergistic, and durable tumor regression at well-tolerated doses. These findings showed the critical role of PI3K/mTOR signaling as a bypass mechanism of resistance to $KRAS^{G12C}$ inhibitors. We conclude that mTORC1/2 mediated inhibition of p4E-BP1 and combination strategies targeting this pathway effectively overcomes acquired resistance to $KRAS^{G12C}$ inhibitors in NSCLC.

Introduction

KRAS mutations represent the most common gain-of-function alterations in cancer, accounting for approximately 30% of lung adenocarcinomas— a significantly higher prevalence than other oncogenic drivers, such as *EGFR* (15%), *ALK* rearrangements (5%), and *MET* alterations (3%), for which targeted therapies are available (1-3). Among *KRAS* mutations, the $KRAS^{G12C}$ variant is one of the most frequent activating alterations, occurring in approximately 14% of lung adenocarcinomas and 0.5% to 4% of squamous cell carcinomas (4). This mutation is also found in 3% to 4% of colorectal cancers (CRC) and 1% to 2% of biliary and pancreatic cancers (5). Unlike protein kinases that utilize ATP as substrate, the KRAS protein is a GTPase that hydrolyzes guanosine triphosphate (GTP) to guanosine diphosphate (GDP) and normally functions as a molecular switch that cycles between an active, GTP–bound state and an inactive, GDP–bound form. Oncogenic *KRAS* mutations impair GTP hydrolysis, resulting in an accumulation of the active GTP-bound form, which drives pro-tumorigenic signaling predominantly through the mitogen-activated protein kinase (MAPK) and phosphatidylinositol 3-kinase (PI3K) pathways, promoting tumor growth and proliferation. Although inhibitors targeting several components of the MAPK and PI3K signaling pathways have been clinically approved, no direct *KRAS* inhibitors were available until recently. The attempts to use these drugs targeting downstream effectors in *KRAS* mutant cancers have largely been unsuccessful in the clinic (6). The recent discovery and development of new targeted therapeutic agents against $KRAS^{G12C}$ renewed the clinical interest in *KRAS* biology, which was long considered undruggable for decades because of its high affinity for nucleotide and the lack of tractable binding pockets for small-molecule inhibitors (7,8).

Two FDA-approved small-molecule *KRAS*^{G12C} inhibitors, adagrasib (MRTX849) and sotorasib (AMG510), have showed potent, selective, and irreversible inhibition of *KRAS*^{G12C} activity, showing promising efficacy in non–small-cell lung cancer (NSCLC) and more modest activity in colorectal cancer in early-phase clinical trials (9-11). In advanced NSCLC patients harboring *KRAS*^{G12C} mutations, both agents exhibited encouraging clinical outcomes, with objective response rates ranging between 37% and 45% and disease control rates of 81% to 96%, respectively (12). These inhibitors covalently bind to the switch II pocket of KRAS, which becomes accessible in the GDP-bound inactive state, irreversibly locking the protein in its inactive conformation (13). This mechanism inhibits downstream MAPK signaling, as evidenced by reduced ERK phosphorylation (p-ERK), and suppresses the viability of *KRAS*^{G12C}-mutant cancer cell lines (9,10). Despite these promising results, approximately half of the patients treated with sotorasib or adagrasib in clinical trials did not achieve significant tumor shrinkage, highlighting the limited overall therapeutic benefit (14). Moreover, like other targeted therapies, virtually all patients who initially experience objective responses or stable disease eventually develop disease progression within 6–12 months of therapy initiation due to the emergence of resistance mechanisms. Therefore, the identification of these acquired resistance mechanisms, along with the development of alternative therapeutic strategies, including combination therapies with *KRAS* inhibitors, represents an urgent unmet clinical need.

Various possible mechanisms of acquired resistance to *KRAS*^{G12C} inhibitors have been identified in recent studies and can be broadly categorized into the following events: genetic alterations, reactivation of KRAS signaling, and non-genetic alternative bypass pathways (15). Genetic alterations, particularly the emergence of secondary *KRAS* mutations or new mutations in other oncogenic drivers, have been

frequently observed as a primary cause of acquired resistance. However, these genetic events alone cannot fully explain treatment failure, as no identifiable mutations were detected in nearly half of patients treated with sotorasib or adagrasib (16,17). In addition, the new secondary mutations developed in KRAS inhibitors treated patients usually appeared with low allelic frequency, raising the possibility that they may not be solely responsible for the observed tumor resistance (16-18). Reactivation of KRAS signaling has emerged as a predominant mechanism of acquired resistance, predominantly through the reactivation of two major canonical downstream pathways: the BRAF-MEK-ERK (MAPK) and PI3K-AKT-mTOR cascades. Beyond these canonical pathways, several alternative bypass mechanisms have also been identified, which either converge on RAS pathway reactivation or activate parallel signaling pathways, such as the PI3K/mTOR axis, to sustain tumor growth and survival (16-20). Notably, inhibition of both MAPK and PI3K/mTOR pathways is often required to achieve significant antitumor effects, underscoring the necessity of combination therapies to overcome resistance. Combination therapy represents a crucial approach to prevent or delay the onset of resistance, as well as to enhance the efficacy of $KRAS^{G12C}$ inhibitors. Rational combination strategies that either overcome resistance mechanisms or synergize with $KRAS^{G12C}$ inhibitors to suppress tumor growth and promote cancer cell death are urgently needed in clinical practice. A recent preclinical study showed that the combination of a $KRAS^{G12C}$ inhibitor with a selective mTORC1 kinase inhibitor causes synergistic antitumor effect through the inhibition of cap-dependent translation, a critical process in cancer cell survival and proliferation (21). Consistent with this, our recent study identified a non-genetic bypass resistance mechanism to osimertinib in *EGFR*-mutant NSCLC, in which PDK1 (3-phosphoinositide-dependent kinase 1) amplification drives resistance through upregulation of the AKT-mTOR signaling pathway (19).

Here we take advantage of a series of paired sotorasib-resistant patient-derived xenografts (PDX), cell-derived xenografts (CDX), acquired resistant PDX-derived organoids (PDXO) and sotorasib-resistant isogeneic cell lines to identify acquired resistance mechanisms and explore potential therapeutic approaches. Reactivation of KRAS signaling was identified in acquired resistant tumors, which was evidenced by the impaired inhibition of ERK1/2 signaling. The upregulation of PI3K signaling in resistant cells was found as a major bypass mechanism for the acquired resistance. Genetic ablation of PI3K through CRISPR-mediated knockout or pharmacological inhibition with copanlisib restored sensitivity to both sotorasib and adagrasib in vitro and in vivo. The combination of PI3K inhibition with *KRAS*^{G12C} inhibitors exerted a synergistic antitumor effect by suppressing 4E-BP1 phosphorylation, thereby limiting cap-dependent protein translation, which was dependent on the simultaneous inhibition of both mTORC1 and mTORC2.

Results

Development and Characterization of Acquired Sotorasib-Resistant NSCLC PDX Models Harboring *KRAS*^{G12C} Mutations

Among more than 200 NSCLC PDXs in our UT MD Anderson lung cancer PDX core, eleven well-characterized models harboring the *KRAS*^{G12C} mutation were identified. Whole-exome sequencing (WES) confirmed their co-mutation profiles in Table in **Figure 1A**. Four PDX models—TC247 (*KRAS*^{mt}*/STK11*^{mt}*/KEAP1*^{mt}), TC303 (*KRAS*^{mt}*/TP53*^{mt}*/KEAP1*^{mt}), TC314 (*KRAS*^{mt}*/TP53*^{mt}), and TC453 (*KRAS*^{mt}*/STK11*^{mt})—were selected for evaluating sotorasib sensitivity based on their distinct co-mutation patterns.

To investigate the sotorasib sensitivity in vivo, these PDXs were engrafted in NSG mice and treated with sotorasib when tumors reached ~200 mm^3. Despite co-mutations in *STK11, TP53, or KEAP1*, all four models exhibited high sensitivity to sotorasib, leading to significant tumor growth suppression (**Figure 1B**). Notably, TC247, TC303, and TC314 showed substantial tumor regression, whereas TC453 displayed only moderate sensitivity without significant regression.

To generate sotorasib-resistant models, the two most sensitive PDXs (TC303 and TC314) underwent prolonged in vivo treatment. Third generation (G3) resistant PDXs—TC303AR and TC314AR—were established by re-passaging the PDXs into new mice followed by sotorasib treatment for at least 3 cycles. These resistant models no longer responded to sotorasib (**Figure 1C**).

WES of TC303AR and TC314AR confirmed that both retained the $KRAS^{G12C}$ mutation, with no additional mutations detected in *KRAS*.

Development and Characterization of Acquired Resistance to Sotorasib in NSCLC PDX-Derived Organoids

Ten PDX-derived organoids (PDXOs) listed in the table in **Figure 1E** were established and characterized from their corresponding PDX models. All organoids were characterized by sequencing and flow cytometry. WES confirmed that all established organoids retained the $KRAS^{G12C}$ mutation, while flow cytometry analysis detected no mouse cell contamination, as indicated by the absence of H2kb staining (mouse MHC class I) and the presence of human EpCAM, an epithelial marker.

Sotorasib sensitivity was assessed for all PDXOs, with IC50 values (μM) listed in the table shown in **Figure 1E**. The sensitivity testing revealed that PDXO303 and PDXO314 were the most responsive, with

IC50 values of 0.03 μM and 0.11 μM**,** respectively. These two organoids were also challenged for Adagrasib sensitivity. Both models also exhibited high sensitivity to adagrasib, the second FDA-approved *KRAS*^{G12C} inhibitor.

Of the remaining PDXOs, six out of seven displayed primary resistance to sotorasib (IC50 ≥10 μM), with only one of the seven showing sensitivity to adagrasib. Specifically, PDXO303, PDXO314, and PDXO723 were highly sensitive to adagrasib (IC50 0.03 μM, 0.09 μM, and 0.1 μM, respectively, **Figure 1E & F**).

PDXO303 and PDXO314, the two most sensitive PDXOs to both sotorasib and adagrasib, underwent prolonged exposure to increasing doses of sotorasib in culture. This resulted in the development of sotorasib-resistant PDXO303AR and PDXO314AR, exhibiting >300-fold and >100-fold resistance, respectively. Their IC50 values increased from 0.03 μM to >10 μM (PDXO303AR) and 0.11 μM to >10 μM (PDXO314AR) (**Figure 1G**). Both resistant models also displayed significant resistance to adagrasib.

To verify the KRAS mutation status, WES was performed for the resistant PDXOs. Both PDXO303AR and PDXO314AR retained the *KRAS*^{G12C} mutation, and no additional mutations were detected in *KRAS*.

Development of Acquired Sotorasib-Resistant NSCLC Isogenic Cell Lines and Their Sensitivity to *KRAS*^{G12C} Inhibitors

Two NSCLC cell lines (H23 and H358) harboring the *KRAS*^{G12C} mutation were selected to develop acquired resistance. Cells were continuously exposed to increasing doses of sotorasib until they showed sustained growth in the presence of 2.5 μM (H23) and 1 μM (H358). The resulting resistant cell lines, H23AR and H358AR, exhibited over 600-fold and 200-fold resistance, respectively (**Figure 2A**).

Both resistant lines were also tested for sensitivity to adagrasib and opnurasib, two additional *KRAS*^{G12C} inhibitors. Like sotorasib, H23AR, and H358AR displayed high resistance to both inhibitors, with no significant cell death observed (**Figure 2B**).

Whole-exome sequencing (WES) confirmed the retention of the *KRAS*^{G12C} mutation in both resistant cell lines, with no additional mutations detected in *KRAS*. However, H23AR acquired 23 SNPs and 3 indels, while H358AR acquired 82 SNPs and 7 indels compared to their sotorasib-sensitive counterparts (**Figure 2-figure supplement 1**).

In Vivo Evaluation of Sotorasib Resistance in NSCLC Xenograft Models Derived from Acquired-Resistant H23AR Cells

To evaluate the in vivo sensitivity of sotorasib in acquired resistant cells, H23AR cells, which exhibited over 600-fold resistance in vitro, were implanted into mice to generate xenograft tumors. Before implantation, H23AR cells were expanded in culture under sotorasib pressure to maintain resistance.

Both H23 (parental) and H23AR xenografts were established, and sotorasib treatment was initiated when tumors reached approximately 200 mm^3 (treatment strategy shown in **Figure 2C**). Although there were significant differences in tumor growth between H23 and H23AR tumors, however, as expected, sotorasib exerted a significant antitumor effect on H23 parental tumors, leading to tumor growth suppression. In contrast, tumors derived from H23AR cells showed no tumor growth inhibition, confirming that H23AR cells retained their resistance in vivo (**Figure 2D**).

Development of Sotorasib Acquired-Resistant H358 Cell Line-Derived Xenograft Model

The H358 cell line, which harbors the *KRAS*^{G12C} mutation, is among the most sotorasib-sensitive NSCLC cell lines, with an IC50 of 27 nM. To develop a sotorasib-acquired resistant cell line-derived xenograft (CDX) model, xenograft tumors were established using parental H358 cells and treated daily with sotorasib for two months. Tumors in the sotorasib-treated group exhibited a significant reduction in growth compared to the vehicle-treated controls (**Figure 2E**).

Following two months of treatment, residual tumor tissues were re-implanted into new mice and subjected to another two-month sotorasib treatment cycle. This process was repeated for three cycles, ultimately generating a third generation (G3) sotorasib-resistant H358AR CDX (**Figure 2F**). By the third generation, H358AR CDX tumors no longer exhibited significant antitumor responses to sotorasib (**Figure G**).

To confirm the extent of sotorasib resistance, parental H358 xenografts and H358AR CDX (G3) tumors were implanted and subsequently treated with sotorasib. After 21 days of treatment, parental H358 tumors remained highly sensitive, whereas H358AR CDX tumors displayed minimal to no response (**Figure H**).

Whole-exome sequencing (WES) confirmed that H358AR CDX tumors retained the *KRAS*^{G12C} mutation, with no additional KRAS mutations detected.

Reactivation of KRAS and upregulation of PI3K signaling in acquired sotorasib-resistant PDX models

To investigate the mechanisms underlying sotorasib-acquired resistance, an unbiased mass spectrometry (MS)--based proteomics approach was utilized to profile the global and

phosphoproteome of sotorasib-resistant TC303AR and TC314AR isogenic PDXs. The global and phosphoproteomic analyses identified over 8,000 and 4,000 gene protein products (GPPs), respectively. Samples were analyzed using label-free nanoscale liquid chromatography coupled with tandem mass spectrometry (nanoLC-MS/MS) on a Thermo Fusion Mass Spectrometer. The resulting data were processed and quantified using the Proteome Discoverer 2.5 interface with the Mascot search engine, referencing the NCBI RefSeq protein database (Saltzman, Ruprecht).

Dendrogram clustering showed that TC303 and TC314 PDX samples formed distinct clusters, highlighting their biological differences. Within each model, parental and resistant PDXs clustered separately, confirming proteomic alterations associated with sotorasib resistance (**Figure 3A**). A two-component analysis further distinguished sensitive from resistant PDXs, while also differentiating TC303 from TC314 PDX models (**Figure 3B**).

Global proteomic heatmap analysis revealed unique protein expression profiles in TC303AR and TC314AR PDXs compared to their sensitive counterparts (**Figure 3C**). A distinct set of proteins was upregulated, and another set of proteins was downregulated in TC303AR PDX which were completely different than their sensitive counterpart (**Figure 3C; left**). Similarly, a distinct set of global proteins was significantly altered in TC314AR PDX as compared with sensitive TC314 PDX (**Figure 3C; right**) (Heatmap cutoff p-value <0.01). A total of 293 proteins in TC303AR and 535 proteins in TC314AR were significantly altered as compared with their respective sensitive counterpart. A Venn diagram showed that only 32 proteins (~4%) were commonly dysregulated in both resistant models. Notably, 65% of altered proteins were unique to TC314AR, whereas 33% were distinct to TC303AR (**Figure 3-figure supplement 1**).

Pathway enrichment analysis of TC314AR global proteomics identified 26 upregulated gene sets, of which 15 were significant at FDR <25%, 10 at nominal p <5%, and 5 at nominal p <1%. MTORC1 signaling emerged as one of the most upregulated pathways in TC314AR PDXs (FDR q <0.001), along with *KRAS* signaling (nominal p <0.08) (**Figure 3D**). When enrichment analysis was performed across both resistant PDX models (TC303AR and TC314AR), MTORC1 signaling remained one of the most upregulated pathways (FDR q <0.003) (**Figure 3E**).

Further phosphoproteomic analysis in TC314AR PDXs revealed significant activation of the MTORC1 and PI3K-AKT-mTOR pathways, suggesting a potential adaptive resistance mechanism (**Figure 3F**). Upregulation of mTORC1 and PI3K/AKT/mTOR signaling was found in the phosphoproteomic analysis in TC303AR data as well as in TC314AR+TC303AR combined data (**Figure 3-figure supplement 2**).

Upregulation of PI3K-AKT-mTOR Signaling in Sotorasib-Resistant PDX Models

Reverse Phase Protein Array (RPPA) analysis in sotorasib-resistant TC314AR and TC303AR PDX models showed a significant upregulation of proteins associated with the PI3K-AKT-mTOR signaling pathway compared to their sensitive counterparts. Specifically, the expression levels of MEK1, p-MEK1, p-MAPK, PDK1, p-PRAS40, p-GSK-3β, p-4E-BP1, p-PI3K, p-Akt, p-PRAS40, p-p38-MAPK, p-AMPK, and p-MAPK were markedly increased in resistant TC303AR and TC314AR PDXs (**Figure 3G**).

To further investigate the role of PI3K signaling in sotorasib response, RPPA analysis was performed on residual tumors from sotorasib-responding and non-responding PDX models. KRASG12C-mutant PDXs (TC247, TC314, TC453) were implanted into mice to generate PDX tumors and treated with sotorasib for three weeks. Heatmap analysis revealed that PI3K expression was significantly elevated in non-

responding PDX tumors, whereas it was downregulated in sotorasib-responsive tumors (**Figure 3H, lower panel**).

Furthermore, PI3K expression was found to be upregulated in sotorasib-treated vs. control tumors among non-responding PDXs, suggesting that PI3K signaling activation is associated with resistance to sotorasib treatment (**Figure 3H, upper panel**). These findings indicate that PI3K-AKT-mTOR pathway activation may play a critical role in mediating sotorasib resistance in KRASG12C-mutant NSCLC and could represent a potential therapeutic target for overcoming resistance.

KRAS Reactivation in Sotorasib-Resistant Cells via ERK Phosphorylation

KRAS inhibition is commonly assessed by evaluating the inhibition of ERK phosphorylation (p-ERK) (9). To confirm KRAS reactivation in acquired resistance, p-ERK levels were analyzed following sotorasib treatment. In parental H23 and H358 cells, which are highly sensitive to sotorasib, treatment resulted in significant inhibition of p-ERK, indicating effective KRAS suppression (**Figure 3-figure supplement 3**). However, in acquired resistant H23AR and H358AR cells, p-ERK levels remained unaffected by sotorasib treatment, suggesting KRAS reactivation and continued downstream signaling despite drug exposure (**Figure 3-figure supplement 3**).

Pharmacological inhibition of PI3K signaling by copanlisib sensitizes sotorasib-resistant cells and PDXOs

To assess the role of PI3K in acquired resistance, copanlisib, a pan-PI3K inhibitor, was tested on resistant cells and PDX-derived organoids (PDXOs). Treatment with copanlisib showed that both H23 and H23AR cells were highly sensitive, with IC50 values of 0.256 ± 0.038 μM and 0.394 ± 0.029 μM, respectively

(**Figure 4A**). Similarly, H358 and H358AR cells showed high sensitivity to copanlisib, with IC50 values of 0.083 ± 0.011 μM and 0.063 ± 0.009 μM, respectively (**Figure 4A**).

Upregulation of PI3K signaling was observed in sotorasib-resistant PDXs, with a significant increase in PI3K (p85) expression in H23AR and H358AR cells compared to their respective parental counterparts (**Figure 4B**).

Copanlisib efficacy was also tested in sotorasib-resistant organoids, PDXO303AR and PDXO314AR, where copanlisib was effective in sotorasib-resistant organoids (**Figure 4C**). Notably, both parental and resistant PDXO303 and PDXO314 organoids exhibited comparable sensitivity to copanlisib, indicating its strong therapeutic potential.

Further, copanlisib sensitivity was evaluated in additional KRASG12C-mutant PDXOs that were intrinsically resistant to sotorasib. PDXO780 and PDXO864 organoids were highly sensitive to copanlisib, with IC50 values of 0.059 μM and 0.145 μM, respectively (**Figure 4C**). Moreover, PDXO481, PDXO551, and PDXO723 organoids, which did not respond to sotorasib treatment, exhibited remarkable sensitivity to copanlisib (**Figure 4C**).

Expression of PI3K was upregulated in both H23AR and H358AR cells compared to their sensitive counterparts. Treatment with copanlisib effectively inhibited PI3K signaling, as evidenced by a significant reduction in AKT phosphorylation at S473 (p-AKT S473) and T308 (p-AKT T308) in both H23AR and H358AR cells (**Figure 4B**). Similarly, copanlisib treatment led to a marked decrease in AKT phosphorylation in parental H23 and H358 cells.

To evaluate the functional impact of PI3K inhibition, a colony formation assay was performed. H23 and H358 isogenic cells were treated with increasing concentrations of copanlisib (25 nM, 50 nM, 100 nM, 250 nM, and 500 nM). Even at 50 nM, copanlisib reduced colony formation in both resistant cell lines, with a significant inhibitory effect observed at 100 nM (**Figure 4D**).

To further investigate the role of AKT signaling, resistant cells were treated with MK2206, an AKT inhibitor, alone and in combination with copanlisib. MK2206 alone (0.5 μM) moderately reduced colony formation and its combination with copanlisib (250 nM) resulted in a significantly enhanced inhibitory effect, indicating a strong combinatorial effect on sensitizing sotorasib-resistant cells (**Figure 4E**).

Previous analyses showed significant enrichment of mTORC1 signaling in sotorasib-resistant PDXs (**Figure 3**). To investigate the role of mTORC1 inhibition in resistant cells, H23, H23AR, H358, and H358AR cells were treated with everolimus, an mTORC1 inhibitor. Everolimus significantly inhibited colony formation in both resistant cell lines at a concentration of 50 nM. Notably, the combination of everolimus with a low dose of copanlisib (50 nM) resulted in a profound reduction in colony formation (**Figure 4F**). These findings suggest that PI3K inhibition with copanlisib effectively sensitizes sotorasib-resistant cells and highlight the critical role of PI3K signaling in acquired resistance.

copanlisib modulates PI3K-AKT-mTOR signaling in sotorasib resistant cells by regulating downstream molecules

PI3K-AKT-mTOR signaling was found to be a major signaling pathway upregulated in resistant cells. Inhibition of PI3K by copanlisib sensitizes the resistant cells. Here, we investigated the effect of copanlisib on various upstream and downstream molecules in the PI3K-AKT-mTOR pathway associated with copanlisib sensitivity. H23 & H23AR and H358 & H358AR cells were treated with multiple doses of

copanlisib, and western blots evaluated the expression of upstream and downstream molecules associated with PI3K signaling.

Phosphorylation of mTOR at serine 2448 (s2448) was significantly inhibited by copanlisib treatment in both resistant H23AR and H358AR cells as compared to their respective sensitive parental cells, although the total level of mTOR remained unchanged (**Figure 4G**). The level of total PDK and phospho-PDK (s241) were upregulated in H23AR cells vs H23 and were not inhibited by the copanlisib treatment in both resistant cells (**Figure 4G**). The basal level of pPTEN was found to be decreased in both resistant cells (H23AR vs H23 and H358AR vs H358), and the level was not altered by the copanlisib treatment (**Figure 4G**).

The expression and alterations by copanlisib treatment on various downstream molecules in the PI3K-AKT-mTOR pathway were also assessed in both resistant cell lines. The level of inhibition of phospho-p70S6 (T389), S6 (S235/236), GSK3B (S9), and PRAS40 (T246) was significant with copanlisib treatment in both H23AR and H358AR, similar to what was found in copanlisib-treated parental cells (H23 and H358) (**Figure 4H**). The expression of p4E-BP1 was found to be upregulated in both H23AR and H358AR as compared with their sensitive counterparts (**Figure 4H** & **Figure 5E-F**), and the degree of inhibition by copanlisib was more limited in H358AR vs H358 and H23AR vs H23 cells.

Taken together, copanlisib sensitivity in acquired resistant cells is associated with the downregulation of various downstream molecules.

PI3K knockout via CRISPR-Cas9 restores sotorasib sensitivity in acquired resistant cells by dephosphorylating 4E-BP1

PI3K expression is upregulated in resistant cells, and its inhibition by copanlisib sensitizes these cells to treatment. To further validate the role of PI3K in resistance, we generated PI3K alpha-subunit knockout clones in both H23AR and H358AR cells using CRISPR-Cas9 technology and evaluated their sensitivity to sotorasib.

In H23AR cells, four PI3K-knockout clones (H23AR$^{PI3K\text{-}KO\text{-}2\text{-}15}$, H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$, H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$, and H23AR$^{PI3K\text{-}KO\text{-}3\text{-}12}$) were verified via PI3K sequencing and western blot analysis, confirming the complete loss of PI3K/p110α expression (**Figure 5A**). Cell viability assays showed that all PI3K-knockout clones exhibited significantly increased sensitivity to sotorasib compared to the parental H23AR cells (p=0.035, p=0.0002, p=0.09, & p= 0.012 respectively), although the degree of sensitivity varied among clones (**Figure 5B**). Similarly, in H358AR cells, three PI3K-knockout clones (H358AR$^{PI3K\text{-}KO\text{-}1\text{-}4}$, H358AR$^{PI3K\text{-}KO\text{-}2\text{-}4}$, and H358AR$^{PI3K\text{-}KO\text{-}2\text{-}7}$) were generated and confirmed by western blot analysis, showing no detectable PI3K/p110α expression (**Figure 5C**). These PI3K-knockout clones also exhibited significantly increased sensitivity to sotorasib compared to the resistant H358AR cells (**Figure 5D**), indicating that PI3K inhibition plays a direct role in restoring sotorasib sensitivity in resistant cells.

Among the H23AR knockout clones, H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$ showed the highest sensitivity to sotorasib, with a response comparable to the original resistant H23AR cells (p=0.0002). In contrast, H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$ exhibited the lowest sensitivity to sotorasib, though still significantly more sensitive than the original H23AR-resistant cells (**Figure 5B**). To further investigate the molecular basis of this differential sensitivity, we analyzed downstream signaling pathways in the most and least sensitive clones.

Like the effects of copanlisib on molecular signaling in H23AR cells (Figures 4B & H), robust downregulation of p-AKT (S473 & T308), pS6 (S235/236), pPRAS40 (T246), and p4E-BP1 (S65) was

observed in the highly sensitive H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$ clone. Notably, copanlisib treatment did not further reduce the levels of these signaling molecules in this clone (**Figure 5E**). In contrast, in the least sensitive PI3K-knockout clone (H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$), similar levels of p-AKT (S473 & T308), pS6 (S235/236), and pPRAS40 (T246) downregulation were observed; however, p4E-BP1 (S65) remained elevated, resembling the levels found in H23AR cells suggesting a critical role of 4E-BP1 in sotorasib sensitivity (**Figure 5F**).

The expression of p4E-BP1 (S65) was significantly upregulated in H23AR compared to H23, the expression was completely depleted in the highly sensitive PI3K-knockout clone (H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$). Conversely, in the least sensitive PI3K-knockout clone (H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$), p4E-BP1 (S65) levels remained high, maintaining partial resistance. However, treatment of this least sensitive clone with copanlisib effectively reduced p4E-BP1 (S65) levels, along with significant inhibition of p-AKT (S473 & T308), pS6 (S235/236), and pPRAS40 (T246) (**Figure 5F**). Importantly, copanlisib treatment completely abolished p4E-BP1 (S65) expression in H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$, reducing it to levels comparable to those in the highly sensitive clone H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$. Taken together, these findings suggest that *PI3K* knockout or inhibition by copanlisib restores sotorasib sensitivity in resistant cells, primarily through the suppression of p4E-BP1.

Phosphorylation of 4E-BP1, which is dependent of both mTOCC1 and mTORC2 kinases, is associated with acquired resistance and 4E-BP1 knockout via CRISPR-Cas9 restores sotorasib sensitivity.

4E-BP1 is a negative regulator of protein translation that, in its non-phosphorylated state, binds to the translation initiation factor eIF4E, thereby inhibiting 5'-cap-dependent translation (22). We have shown

that in sotorasib-resistant H23AR and H358AR cells, the 4E-BP1 and phosphorylated 4E-BP1 (p4E-BP1 at S65) were significantly upregulated compared to their parental counterparts. Treatment with copanlisib or PI3K knockout effectively suppressed p4E-BP1 in resistant cells **(Figure 5E & F**). Here, we compared the level of activated p4E-BP1 among PI3K-knockout clones and its correlation with sotorasib sensitivity.

Among four PI3K-knockout clones in H23AR cells clones (H23AR$^{PI3K\text{-}KO\text{-}2\text{-}15}$, H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$, H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$, and H23AR$^{PI3K\text{-}KO\text{-}3\text{-}12}$), sotorasib sensitivity was inversely correlated with their respective p4E-BP1 (S65) expression (**Figure 6A**). The most sensitive clone, H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$, exhibited almost the lowest level of p4E-BP1 expression, whereas the least sensitive clone, H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$, retained relatively higher levels of p4E-BP1. Notably, p-S6 was downregulated in all PI3K-knockout clones, but its inhibition did not correlate with sotorasib sensitivity (**Figure 6A**).

To further examine the role of 4E-BP1 in resistance, we generated 4E-BP1-knockout clones using CRISPR-Cas9 in both H23AR cells and the least responsive PI3K-knockout clone (H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$). Western blot analysis confirmed the absence of 4E-BP1 expression in all selected clones, including one knockout clone in H23AR cells (H23AR$^{4E\text{-}BP1\text{-}KO\text{-}1\text{-}1}$) and five clones in H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$ cells (H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3/4E\text{-}BP1\text{-}KO\text{-}1\text{-}2}$; H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3/4E\text{-}BP1\text{-}KO\text{-}1\text{-}4}$; H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3/4E\text{-}BP1\text{-}KO\text{-}2\text{-}1}$; H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3/4E\text{-}BP1\text{-}KO\text{-}3\text{-}2}$; H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3/4E\text{-}BP1\text{-}KO\text{-}3\text{-}4}$) (**Figure 6B & C**).

Cell viability assays showed that 4E-BP1 knockout significantly restored sotorasib sensitivity. The H23AR$^{4E\text{-}BP1\text{-}KO\text{-}1\text{-}1}$ clone exhibited sensitivity comparable to parental H23 cells (p=0.00001 vs. H23AR; p=0.49 vs. H23) (**Figure 6D**).

All three 4E-BP1-knockout clones in the PI3K-KO cells (H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3/4E\text{-}BP1\text{-}KO\text{-}1\text{-}2}$; H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3/4E\text{-}BP1\text{-}KO\text{-}1\text{-}4}$; H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3/4E\text{-}BP1\text{-}KO\text{-}3\text{-}2}$) displayed significantly enhanced sotorasib sensitivity compared to their parental PI3K-knockout counterparts (p=0.00002, p=0.005, p=0.0001) (**Figure 6E**).

mTORC1 and mTORC2 Mediate 4E-BP1 Hyperphosphorylation in Resistant Cells

Since p4E-BP1 (S65) was associated with sotorasib resistance and knocking down PI3K or 4E-BP1, or copanlisib treatment restores sotorasib sensitivity in acquired resistant cells, we further investigated the role of mTORC1 and mTORC2 in 4E-BP1 phosphorylation in resistant cells. Everolimus, a mTORC1 inhibitor, and AZD8055, a dual mTORC1/2 inhibitor, were used to treat H23 parental, H23AR, H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$ (most sensitive clone), and H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$ (least sensitive clone) cells.

Everolimus treatment significantly downregulated pS6 (S235/236) in H23AR and H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$, but did not reduce p4E-BP1 (S65) levels (**Figure 6F**). Everolimus induced only moderate cytotoxicity in resistant cells and organoids, as observed in cell viability assays (**Figure 4I and 6I**). These findings suggest that while mTORC1 inhibition suppresses pS6 phosphorylation, it does not directly regulate p4E-BP1 in resistant cells, implicating a mTORC1-independent kinase in 4E-BP1 phosphorylation.

In contrast, treatment with AZD8055, a dual mTORC1/2 inhibitor, completely abolished p4E-BP1 (S65) expression in both parental H23 and resistant H23AR cells, as well as in both the least and most sensitive PI3K-knockout clones (H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$ and H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$, respectively) (**Figure 6G**). pS6 downregulation was observed in all cells, irrespective of their sotorasib sensitivity.

mTORC1/2 Dual Inhibition Restores Sotorasib Sensitivity in Resistant Cells

Dual inhibitor AZD8055 treatment significantly reduced cell viability in sotorasib-resistant H23AR, H358AR, and the least sensitive PI3K-knockout clone (H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$) (**Figure 6H**). When comparing AZD8055 with everolimus in resistant H23AR and H358AR cells, the dual inhibitor induced significantly greater cytotoxicity than the mTORC1-specific inhibitor (**Figure 6I**).

Further analysis of the combination index (CI) between sotorasib and AZD8055 revealed strong synergy in resistant cells. In H23AR cells, sotorasib (0.031 μM) combined with AZD8055 (0.03 μM) yielded a CI of 0.283, indicating strong synergism. In H358AR cells, sotorasib (0.031 μM) combined with AZD8055 (0.01 μM) exhibited an even stronger synergy, with a CI of 0.053 (**Figure 6H**).

This data suggests that dephosphorylation of 4E-BP1 through PI3K knockout, 4E-BP1 knockout, or copanlisib treatment restores sotorasib sensitivity. Notably, mTORC1 inhibition alone is insufficient to suppress p4E-BP1, while dual inhibition of mTORC1 and mTORC2 effectively abolishes p4E-BP1 expression, leading to robust cytotoxicity and enhanced sotorasib sensitivity indicating the suppression of p4E-BP1 is dependent on both mTORC1 and mTORC2 complexes.

Overcoming Resistance by Targeting PI3K-AKT-mTOR Signaling with copanlisib or sapanisertib in acquired resistant NSCLC PDX, CDX, and Xenograft Tumors

Our findings thus far indicate that PI3K inhibition, either through copanlisib treatment or genetic knockout, restores sotorasib sensitivity in resistant cells by suppressing p4E-BP1, a process mediated by both mTORC1 and mTORC2 kinases. We previously showed that the dual mTORC1/2 inhibitor, AZD8055, enhances sotorasib sensitivity and synergistically inhibits cell proliferation in resistant models. To further evaluate the therapeutic potential of these inhibitors, we examined their efficacy in vivo in

sotorasib-resistant patient-derived xenografts (PDX), cell-derived xenografts (CDX), and other xenograft models.

Cell viability assays confirmed that copanlisib was cytotoxic for sotorasib-acquired resistant H23AR and H358AR cells, as well as primary and acquired sotorasib-resistant organoids (PDXOs) (**Figure 4A & C**). Furthermore, copanlisib not only restored sotorasib sensitivity in H23AR and H358AR cells but also exhibited strong synergy when combined with sotorasib (**Figure 7A**).

Combination index (CI) analysis revealed a strong to very strong synergism when sotorasib (0.031–0.31 μM) was combined with copanlisib (0.05 μM) in both H23AR and H358AR cells (**Figure 7A**). Notably, the least responsive PI3K-knockout clone (H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$) also exhibited significant sensitivity to the combination treatment, with a CI of 0.093 at sotorasib (0.031 μM) + copanlisib (0.05 μM) (**Figure 7A**).

To evaluate the in vivo efficacy of this combination, we established sotorasib-resistant H358AR-CDX tumors in NSG mice. Once tumor volumes reached approximately 200 mm^3, mice were treated with copanlisib, sotorasib, or their combination, following the strategy outlined in **Figure 7B**.

Copanlisib monotherapy showed significant antitumor activity compared to the control group. However, the combination of sotorasib and copanlisib exhibited a synergistic antitumor effect, with statistically significant tumor suppression observed at D40, D44, and D47 (**Figure 7D**). The combination treatment was superior to either monotherapy in controlling tumor growth.

Individual tumor growth curves (**Figure 7C**) revealed that in the combination group, tumor volumes remained stable, with no significant growth observed between pre-treatment (D26) and post-treatment (D44) measurements. In contrast, tumors in the sotorasib monotherapy group continued to grow

significantly between D26 and D44, further highlighting the superior efficacy of the combination strategy.

To investigate the underlying mechanism, tumors were harvested after three weeks of treatment and analyzed using RPPA. The expression levels of total 4E-BP1, phosphorylated 4E-BP1 at T37/46 and S65 were significantly suppressed by both copanlisib monotherapy and the combination treatment (**Figure 7E**). Additionally, other key downstream effectors of the PI3K-AKT-mTOR pathway, including phosphorylated S6 (S235/236), phosphorylated mTOR (S2448), GSK-3β, phosphorylated Src (Y527), and p70-S6K1, were also downregulated (**Figure 7E**). In contrast, sotorasib monotherapy failed to reduce the phosphorylation of key signaling proteins such as p-mTOR (S2448), p-S6 (S235/236), p4E-BP1 (S65), and p-Src (Y527). This indicates that the PI3K-AKT-mTOR signaling pathway remained functionally active in resistant tumors, thereby sustaining resistance to sotorasib treatment.

The combination of sotorasib and copanlisib was evaluated to determine its in vivo efficacy in overcoming sotorasib-acquired resistance in H23AR xenograft tumors. H23AR cells were continuously cultured under sotorasib pressure during cell expansion to develop resistance, and these resistant cells were subsequently implanted into NSG mice. Treatment was initiated once the tumor volumes reached approximately 200 mm^3, following the experimental strategy illustrated in **Figure 7F**. When administered as a monotherapy, sotorasib did not demonstrate a statistically significant antitumor effect against H23AR xenografts compared to the control group ($p = 0.40$). However, treatment with copanlisib alone resulted in a strong antitumor response, which was statistically significant when compared to both sotorasib monotherapy and the control group ($p < 0.001$) (**Figure 7G**). Although the combination of copanlisib and sotorasib did not exhibit a synergistic effect due to the strong copanlisib

single agent effect ($p = 0.82$; comb vs copanlisib), the combination therapy successfully overcame sotorasib resistance by significantly inhibiting tumor growth compared to both sotorasib monotherapy ($p = 0.001$) and the control group ($p < 0.001$) (**Figure 7G**). Individual mouse responses showed that tumor growth was inhibited in every mouse treated with the combination treatment (**Figure 7H**).

Like the H23AR xenograft model, the therapeutic efficacy of sotorasib in combination with copanlisib was also investigated in the TC314AR patient-derived xenograft (PDX) model, which has acquired resistance to sotorasib. TC314AR-resistant PDXs were implanted into NSG mice, and the experimental design followed an individualized PDX trial approach. In this strategy, each mouse was blindly assigned to one of the four treatment groups—control, sotorasib, copanlisib, or combination once the PDX tumor volume reached approximately 200 mm^3. The treatment regimen was continued for three weeks to assess the antitumor effects of each therapy. As anticipated, sotorasib monotherapy failed to exert a significant inhibitory effect on tumor growth when compared to the control/vehicle-treated group (p = ns vs control). In contrast, copanlisib monotherapy showed a potent antitumor response, which was statistically significant when compared to both the control and sotorasib monotherapy groups ($p < 0.005$). The combination of sotorasib and copanlisib produced an even stronger tumor-suppressive effect than either monotherapy (**Figure 7I)**. Individual mouse responses are shown in **Figure 7J**. The efficacy of this combination was analyzed using the CombPDX tool, a unified statistical platform designed to evaluate drug synergy in PDX models (23). The treatment effect shown in **Figure 7-figure Supplement 1A** was measured based on tumor growth inhibition (TGI) with a 95% confidence interval in comparison with the control group, and the combination treatment showed superior efficacy. The Combination Index (CI), calculated based on the Highest Single Agent (HSA) method, yielded a positive

value, indicating a synergistic interaction between sotorasib and copanlisib **(Figure 7-figure supplement 1B)**.

We showed above that the dual mTORC1/mTORC2 inhibitor AZD8055 was synergistic in vitro against sotorasib-resistant cells and PDX organoids **(Figure 6H**). We therefore investigated the antitumor efficacy of combining sotorasib with sapanisertib, another dual mTORC1/mTORC2 inhibitor, in the TC314AR PDX model. In vitro cell viability assays showed that sapanisertib exhibited a significant cytotoxic effect, significantly inhibiting the proliferation of acquired-resistant cell lines, including H23AR, H358AR, and PDXO models (**Figure 7-figure Supplement 2A-B**). TC314AR PDX tumors were established in NSG mice, and once tumor volumes reached approximately 200 mm^3, treatment with either sotorasib monotherapy, sapanisertib monotherapy, or the combination of both agents was administered for three weeks. As observed in prior resistance models, sotorasib alone did not elicit a significant antitumor response, with no notable tumor growth inhibition observed. In contrast, the combination of sotorasib with sapanisertib led to a dramatic and highly significant antitumor effect (**Figure 7K**). This combination therapy was further evaluated using the CombPDX analysis tool (23), a comprehensive statistical tool to analyze the drug synergy on PDXs, which confirmed that the antitumor response observed with the combination was markedly superior to that of either monotherapy. Tumor growth inhibition (TGI) was assessed with a 95% confidence interval, revealing that the combination treatment resulted in a TGI value exceeding 0.75 (on a scale of 0 to 1.0), whereas sotorasib and sapanisertib monotherapies showed TGI values of less than 0.2 (**Figure 7L**). The Combination Index (CI) was calculated as previously reported and indicated synergy for the combination (23). (**Figure 7L**).

These findings underscore the critical role of PI3K-AKT-mTOR signaling in sotorasib resistance and show that targeting this pathway with copanlisib or dual mTORC1/2 inhibition can effectively restore sensitivity to sotorasib. The combination of sotorasib with copanlisib exhibited robust synergy both in vitro and in vivo, providing a promising therapeutic strategy to overcome acquired resistance in PDX and CDX tumor models.

Discussion

Due to the intrinsic characteristics of KRAS proteins, KRAS has been considered an undruggable target. The recent advent of compounds allowing direct inhibition of the *KRAS*^{G12C} oncogene such as adagrasib and sotorasib has initiated a new era in the clinical management of *KRAS*^{G12C} mutant NSCLC. Both AMG510 (Sotorasib) and MRTX849 (Adagrasib), bind covalently to the GDP-bound form of the KRAS^{G12C} protein (KRAS OFF), preventing oncogenic signaling and cause tumor regression in preclinical models (9,24,25). Current *KRAS*^{G12C} (OFF) inhibitors cause responses in less than half of patients and these responses are not durable. Other than sotorasib and adagrasib, other new inhibitors are developing, targeting either the KRAS active state (KRAS ON) where RAS coupled with GTP, or inactive state (KRAS OFF) where RAS binds with GDP, and evaluating the clinical efficacy (26). In early-phase clinical trials, adagrasib and sotorasib have shown promising results against non–small cell lung cancer and more modest efficacy against colorectal cancer (9,11). Despite high initial efficacy, there is a relatively short progression-free survival due to resistance that develops in virtually all patients to single-agent therapy. Moreover, the responsiveness of NSCLC to *KRAS*^{G12C} inhibitors is not sufficient compared with that of TKIs such as EGFR-TKI and ALK-TKI, which show response rates of 70% and 80%, respectively (27,28).

An improved understanding of the biological basis of acquired resistance is necessary, which will provide more opportunities to optimize *KRAS*^{G12C} inhibitor regimens and new combinations. Multiple mechanisms of resistance have been described in the clinic upon treatment with direct *KRAS* inhibitors (15,29). Acquired resistance to KRAS^{G12C} inhibitors is mainly driven by genomic mutations and monogenetic alteration events (30). Development of secondary mutations in *KRAS*^{G12C} oncoprotein that interfere with the binding of covalent inhibitors to cysteine 12 residues, or mutations in the normal *KRAS* alleles that could not be targeted by the KRAS inhibitors or other mutations in BRAF, MAP2K1, RTKs that are related to the reactivation of the RAS-RAF-MEK-ERK signaling pathway are the major genetic events associated with sotorasib resistance (16,18). Other tumors displayed mutations in *PI3K*, *PTEN, SMAARCA4, KEAP1,* and *PTCH1* effectors in additional oncogenic pathways (16,17,31,32). In this study, sotorasib acquired resistant isogenic patient-derived xenografts (PDXs: TC314AR and TC303AR), CDX, PDX-derived organoids (PDXOs: (PDXO314AR & PDXO303AR), and H23AR and H358AR cell lines were developed and investigated to explore the underlying mechanism of resistance. Whole exome sequence was performed in all acquired resistant models, no additional mutations were found in *KRAS,* and no new mutations were found in major proteins associated with bypass pathways. Although each resistant model has its distinct molecular profiling pattern, all resistant models retained *KRAS*^{G12C} mutation regardless.

Yet about half of the resistant tumors examined did not display additional mutations, thus indicating the existence of additional mechanisms that might cause resistance to KRAS inhibition (29,33). Identification of these resistance mechanisms is an urgent prerequisite to developing improved therapeutic strategies. Reactivation of KRAS and/or upregulation of additional bypass signaling

pathways are found to be one of the potential central mechanisms of KRASi-related acquired resistance. Reactivation of the MAPK pathway without developing new mutations in *KRAS* or its downstream mediators has been reported in *KRAS*^{G12C} lung adenocarcinomas resistant to the KRAS^{G12C} inhibitor AMG 510 and adagrasib (18,34). Consistent with that, we also found upregulation of ERK signaling determined by the level of phosphorylation of ERK1/2 in sotorasib-resistant H23AR and H358AR cells which was inhibited by the treatment of KRASi. On the other hand, the complete inhibition of ERK1/2 phosphorylation by sotorasib treatment was noticed in parental H23 and H358 cells. This hyper-phosphorylation of EKR1/2 in acquired resistant cells could be explained by the hyper-formation of new KRAS^{G12C} proteins and reactivating downstream signaling in resistant cells (35). High throughput Mass-Spectrometry (MS) was performed in acquired resistant TC314AR and TC303AR PDXs to understand the bypass resistance mechanisms. Enrichment analysis showed that PI3K-AKT-mTOR signaling was significantly upregulated in resistant PDXs as compared with their parental counterpart. Over-expression of PI3K was also found in acquired resistant cell lines that was found in consistent with other studies where activation of PI3K-AKT-mTOR canonical pathway was found as an additional bypass mechanism in acquired resistance (15,29). Other alternative pathways such as epidermal growth factor receptor or Aurora kinase A (AURKA) signaling, FAK, and Hippo pathways are also reported to be associated with resistance to KRAS inhibitors (29,36). These alternative pathways were not found significantly upregulated in our study indicating heterogeneous mechanisms involved in KRASG12C inhibitor resistance notably being tissue specific.

The PI3K–AKT–mTOR signaling pathway is frequently activated in cancer, deregulates control of metabolism, cell proliferation, and apoptosis (37). Pharmaceutical inhibition of PI3K by copanlisib or

genetic knock-out of PI3K by CRISPR-Cas9 restores the sensitivity of sotorasib in sotorasib-resistant cells or organoids. Copanlisib is a potent pan-PI3K inhibitor, an FDA-approved compound that has been shown to inhibit cellular proliferation of relapsed or refractory, indolent, or aggressive lymphoma (38). However, there are no studies investigating the use of copanlisib in NSCLC preclinical models. PI3K expression was upregulated in sotorasib-resistant H23AR and H358AR cells and inhibition of PI3K by copanlisib induced cytotoxicity in the cells. Similarly, sotorasib-acquired resistant PDXOs such as PDXO314AR and PDXO303AR were also found to be very sensitive to copanlisib.

We have developed around PDXOs from their respective PDXs. Over 50% of those PDXOs were primarily resistant to sotorasib or adagrasib. No additional KRAS mutation was found in any of those PDXs, and no significant correlation was found with any co-mutation with either PI3K, STK11, KEAP1, SMARCA4 etc. However, no co-mutation was associated with sotorasib resistance. As a majority of PDXOs showed primary resistance to sotorasib this suggests that other bypass signaling mechanisms are involved in sotorasib resistance. Primarily resistant PDXOs were found to be very sensitive to copanlisib in the PDXO viability assay suggesting the role of PI3K-AKT-mTOR signaling in the inactivation of sotorasib sensitivity. Copanlisib overcame sotorasib resistance in the sotorasib-resistant H23AR and H358AR cells and PDXOs (PDXO303AR and PDXO314AR) and worked synergistically with sotorasib in-vitro and in-vivo. The drug combination index (CI) analysis showed that a very low dose of copanlisib (50nM) worked synergistically in sensitizing resistant cells to sotorasib which could mitigate copanlisib-associated drug toxicity.

To understand the underlying resistance mechanism of the PI3K-AKT-mTOR pathway, blocking the upstream PI3K by pan-PI3K inhibitor copanlisib which inhibits the catalytic activity of the class I PI3Kα,

β, γ, and δ isoforms, inhibited AKT phosphorylation at both T308 and S347 and its direct substrates PRAS40 (T246) and GSK3β (S9) which was consistent with breast tumor models (37,39). Inhibition of AKT by MK2206, an AKT inhibitor, moderately inhibited the colony formation and worked significantly better when combined with copanlisib suggesting overcoming resistance by copanlisib is not solely dependent on AKT inhibition. The moderate activity in resistant cells by AKT inhibitor, MK2206 can be explained by its moderate inhibition of downstream mTORC1 targets. Will et al reported that targets of mTOR such as pS6 and p4EBP1 were also inhibited by both MK2206 and copanlisib, although PI3K inhibition blocked 4E-BP1 phosphorylation more potently and longer than AKT inhibition (37). In our study, copanlisib was found to be very effective in downregulating the mTORC1 signaling through inhibiting the phosphorylation of the target molecules such as S6 and 4E-BP1.

Like AKT inhibition by MK2206, inhibition of mTORC1 by everolimus which targets S6 and inhibited the phosphorylation of S6, inhibited colony formation moderately in sotorasib resistant H23AR and H358AR cells but the inhibition of colony formation increased significantly when combined with copanlisib. In cell viability assays in acquired resistant isogeneic cells or PDXOs, copanlisib was found to be very effective and the effect was much stronger for copanlisib compared to everolimus. This data suggested that the downstream mechanism of PI3K inhibition by copanlisib involves more than S6 mediated mTORC1 activity. To verify the precise involvement of mTORC1, we investigated two downstream effector molecules S6 and 4E-BP1 which are involved in protein translation. Both S6 and 4E-BP1 phosphorylation was significantly inhibited by copanlisib treatment in resistant cells, although basal expression of 4E-BP1 was significantly higher only in resistant cells. Everolimus, an mTORC1 inhibitor,

downregulated S6 phosphorylation in resistant cells where 4E-BP1 expression remained unaffected indicating dephosphorylation of 4E-BP1 is essential for overcoming sotorasib resistance.

4E-BP1 is a member of the 4E-BP family that represses translation by competing with eIF4G for binding to eIF4E, thereby preventing the formation of the eIF4F complex. In cancer cells, however, 4E-BP1 is frequently phosphorylated by its upstream oncogenic signals such as PI3K/AKT and RAS/RAF/MEK/ERK pathways, which causes 4E-BP1 disassociation from eIF4E and increases cap-dependent protein translation. The mTOR kinase complex 1 (mTORC1) is the master regulator of eIF4E-initiated cap-dependent translation by phosphorylating 4E-BP1 on Thr37 and Thr46 that act as priming sites for its subsequent phosphorylation on Ser65 (40). Hyperphosphorylation of 4E-BP1 was found in sotorasib-resistant cells as compared with sensitive cells which was consistent with other studies that found an association with malignant progression and poor prognosis with 4E-BP1 hyperphosphorylation (41,42). PI3K inhibition by copanlisib sensitizes the cells by downregulating 4E-BP1 which emphasizes the role of 4E-BP1 in overcoming sotorasib resistance. We also found a clear inverse association between the level of sotorasib cytotoxicity and phosphorylation of 4E-BP1 among PI3K-knockout clones. The clone H23AR-PI3K-KO-2-17, the most sensitive clone, showed complete inhibition of phosphorylation of 4E-BP1 (S65) which resembles the status found in the parental H23 cells. On the other hand, the clone H23AR-PI3K-KO-3-3, the least sensitive clone, showed partial dephosphorylation of 4E-BP1 and correlated with the expression found in sotorasib-resistant H23AR cells. To verify the precise role of 4E-BP1, CRISPR-Cas9 knock-out of 4E-BP1 clones was created in resistant cells. After knocking out 4E-BP1, both resistant cells H23AR and H358AR became sensitive to sotorasib. When 4E-BP1 was knocked out from sotorasib's least sensitive PI3K knock-clone (H23AR-PI3K-KO-3-3), the double knock-out clone

(PI3K and 4E-BP1) restored sotorasib sensitivity to the level of sensitive cells suggesting the pivotal role of 4E-BP1 in overcoming sotorasib resistance.

4E-BP1 is the downstream target of mTORC1. To verify the dependency on mTORC1 kinase on 4E-BP1 phosphorylation and subsequent protein translation, everolimus (mTORC1 specific inhibitor) and AZD8055, a dual inhibitor that inhibits both mTORC1 and mTORC2, were used to treat the resistant cells. Everolimus can stop S6 phosphorylation without having any effect on 4E-BP1 in resistant cells whereas AZD8055 reduced p4E-BP1 and pS6 in resistant cells suggesting the hyperphosphorylation of 4E-BP1 in resistant cells was independent of mTORC1. ADZ8055 dual mTOR inhibitor also synergized with sotorasib in restoring the sensitivity in sotorasib-resistant cells and PDXOs. In our study, mTORC1 inhibition by everolimus did not restore sotorasib (KRAS OFF inhibitor) sensitivity, but a recent study found a synergistic effect of KRASi (KRAS ON inhibitor) with mTORC1 kinase inhibition (21). Another recent study showed that RAS-ON inhibition can overcome resistance developed from RAS-OFF blockade which is sotorasib or adagrasib (43). In conclusion, our study found a strong synergistic antitumor effect of sotorasib with upstream PI3K inhibitor or downstream mTORC1 and mTORC2 dual inhibitor in sotorasib-acquired resistant PDXs, CDX, and xenograft tumors suggesting a possible combination to overcome the acquired resistance that merits translation into clinical trials.

Materials and Methods

Sotorasib-acquired resistant cell lines, cell culture, and maintenance.

The human parental NCI-H23 and NCI-H358 NSCLC cell lines, which carry *KRAS*^{G12C} mutations, were obtained from ATCC and their sotorasib-resistant isogenic clones, H23AR and H358AR, were obtained from Dr. Srikumar P Chellappan's laboratory (Moffitt Cancer Center, Tampa, FL). H23 and H358 cells

were cultured and maintained in RPMI-1640 complete media supplemented with 10% heat-inactivated fetal bovine serum (GE Healthcare Life Sciences, HyClone Laboratories) and 1% penicillin-streptomycin (Thermo Fisher Scientific). The H23AR and H358AR resistant clones were cultured in RPMI-1640 complete medium with 2.5 μM and 1 μM AMG510 (Sotorasib) (Medchemexpress (MCE), NJ, USA) respectfully, which was dissolved in DMSO, stored at -70°C, and diluted in culture medium for in-vitro experiments. *KRAS*^{G12G} inhibitors including sotorasib, adagrasib, and opnurasib were purchased from MedChemExpress (MCE), NJ, USA. Other targeted molecules used in this study such as copanlisib (PI3K inhibitor), AZD8055 (mTORC1/2 inhibitor), Everolimus (mTORC1 inhibitor), MK2206 (AKT inhibitor), and Sapanisertib (mTORC1/2 inhibitor) were purchased from Selleckchem (Houston, TX, USA). All cell lines tested negative for mycoplasma before use in experiments. The cell lines were tested for mycoplasma routinely by ELISA in a core lab at MD Anderson Cancer Center. The cell lines were also authenticated before the experiment by the core lab at The University of Texas MD Anderson Cancer Center.

In-vivo animal studies

NOD. Cg-*Prkdc*^{scid} *Il2rg*^{tm1Wjl}/SzJ (NSG) mice were obtained from The Jackson Laboratory, which was used for subcutaneous patient-derived xenograft (PDX), Cell line-derived xenograft (CDX) and xenograft tumors development for sotorasib acquired resistant studies. Female 6-to-8-week-old mice were used in these studies. Mice were housed in micro isolator cages under specific pathogen-free conditions in a dedicated mice room in the animal facility at The University of Texas MD Anderson Cancer Center. Mice were given autoclaved acidified water and fed a special diet (Uniprim diet). All animal experiments were carried out under approved IACUC (Institutional Animal Care and Use Committee (IACUC)

protocols following approval by the MDACC institutional review board and were performed by the Guidelines for the Care and Use of Laboratory Animals published by the National Institutes of Health.

H23 and H23AR xenograft tumors were generated by subcutaneously injecting 5–8 million cells per mouse into NSG mice. To ensure the maintenance of acquired resistance, H23AR cells were expanded in cell culture with sotorasib (2.5 μM) prior to implantation. Tumors were allowed to develop over a period of 4–6 weeks, after which all tumor-bearing mice were randomized blindly into different treatment groups, as specified in each in vivo experiment.

Once tumor volumes reached approximately 200 mm^3, treatment was initiated and continued for at least three weeks. In studies evaluating the combination of sotorasib and copanlisib, single-agent treatment groups were included, with each group consisting of at least 5–7 mice. Control group mice received vehicle treatment, while the experimental groups were treated with sotorasib (50 mg/kg) and copanlisib (6 mg/kg) administered once daily (QD) for five days per week over a three-week period.

Mice were monitored daily for potential side effects, and tumor growth was assessed by measuring two perpendicular tumor diameters two to three times per week. Tumor surface area was calculated using the formula: $1/2 \times (\text{Length} \times \text{Width}^2)$.

Development of sotorasib-acquired resistant cell line-derived xenograft (CDX) model

The *KRAS*^{G12C}-mutant H358 cell line, recognized as one of the most sensitive models to sotorasib treatment, was implanted into NSG mice via subcutaneous injection, with each mouse receiving approximately 5–8 million cells. Once the tumors reached a volume of 200 mm^3, the mice were

administered sotorasib (AMG510) at a dosage of 100 mg/kg once daily (QD) for five days per week over a period of two months.

Tumors that grew beyond 500 mm^3 were harvested, reimplanted into new NSG mice, and allowed to establish at 200 mm^3 before initiating a second round of sotorasib treatment for an additional two months. Following this treatment period, the first-generation (G1) resistant tumors were collected and reimplanted into a new cohort of mice, where they were subjected to another four months of sotorasib treatment to generate the second-generation resistant CDX (G2). These G2-resistant CDXs were subsequently reimplanted into new mice and underwent another two-month cycle of sotorasib treatment to develop the third generation (G3) H358AR CDX model.

To evaluate the resistance potential of the G3 CDX model, G3 H358AR CDXs were implanted into a fresh batch of NSG mice, while a separate group of NSG mice received subcutaneous injections of parental H358 cells. Once tumors from both the G3 H358AR CDX and H358 xenografts reached 200 mm^3, sotorasib treatment was initiated and maintained for three weeks. Tumor growth inhibition was assessed at Day 21 of treatment, revealing that the G3 H358AR CDX exhibited no detectable antitumor response. Whole-exome sequencing (WES) was performed on these CDXs to confirm the presence of the $KRAS^{G12C}$ mutation.

Development and therapeutic studies on NSCLC PDX models

12 $KRAS^{G12C}$ mutant PDXs were selected from our core with over 200 NSCLC PDXs in UT MD Anderson Cancer Center (Dr. Jack Roth, PI) developed under the NCI–funded PDX Development and Trial Centers Research Network (PDXNet) program. All the PDXs were well characterized and well annotated based on RNASeq, whole exome sequencing (WES) (44). PDXs were established from frozen stocks through

implantation into NSG mice according to the protocol published previously (45,46). The PDX studies were conducted according to the approved institutional animal care and use committee protocol in accordance with the procedures outlined in the Guide for Care and Use of Laboratory Animals.

For the sotorasib sensitive study, PDXs TC247, TC314, TC303, and TC453 were established in NSG mice simultaneously or 1-2 models at a time. Tumor-bearing mice were randomized to treatment and control groups (n=5-7 mice/group) when tumor volume reached approximately 200 mm^3. Treatments were started simultaneously for the models within an acceptable size window (such as 200 mm^3) or independently for each mouse when a certain tumor size was reached (e.g., at a predetermined size such as 200 mm^3) if mice were enrolled in all groups in a parallel fashion. PDX-bearing mice treated with sotorasib at the dose of 100 mg/kg or 50 mg/kg unless otherwise mentioned. The treatment was continued for 5 days/week for 3 weeks.

For the sotorasib combination studies with either copanlisib (6 mg/kg) or sapanisertib (1mg/kg) in the TC314AR PDX model, treatment arms included single-agent administration of each agent to assess the contributions of each agent. Control mice were treated with solvent. Sotorasib, copanlisib or sapanisertib or solvent were administered orally QD for 21 days. Tumor growth was monitored 2-3 times/week.

The following formula approximates the volume of the ellipsoid corresponding to the tumor: tumor volume (mm^3) = [tumor length X (tumor width)^2]/2. Tumor growth curves show median or average tumor volumes, and the standard error (SE) or standard deviation was added to demonstrate variability. Changes in tumor volume were assessed by comparing the volume at a defined time point with the baseline volume, thus adjusting for baseline tumor volume. For an individual mouse, the tumor

response according to the percent change in tumor volume was calculated from baseline to the time of assessment as follows: % tumor volume change $\Delta Vt = (Vt - V0/ V0) \times 100$, where Vt is the tumor volume at time t and $V0$ is the tumor volume at baseline. We used the following criteria to determine treatment responses: 1) Tumor Regression (or partial response): tumor regression ≥ -30% based on tumor volume changes calculated by $AUC_{0\text{-}21day}$ or at day 21 after treatment start when compared with baseline (beginning of treatment at day 0); 2) Tumor Growth Inhibition (or stable disease): Tumor growth was significantly suppressed when compared with control ($p < 0.05$), but no tumor regression was observed, or tumor regression was less than -30% based on tumor volume changes calculated by $AUC_{0\text{-}21day}$ or at day 21 after treatment start when compared with baseline; 3) Resistance: Tumor volume changes calculated by $AUC_{0\text{-}21day}$ was not significantly different from control group ($p>0.05$).

Development of sotorasib-acquired resistant PDX models

To develop NSCLC PDXs with acquired resistance to sotorasib (AMG510), $KRAS^{G12C}$ mutation harboring TC303 and TC314 PDXs, the two most sotorasib sensitive PDXs, were implanted into NSG mice. when the tumor volume of these PDXs reached approximately 200 mm3, mice were treated with AMG510 (100mg/Kg) daily for at least 3 weeks, paused if tumor size shrank below 200 mm^3. We monitored mice with regressed tumors for tumor re-growth. When those tumors regrew to 200 mm^3 in size, we retreated again, until mice were euthanized at tumor size at around 500-100 mm3. The tumors were passaged to new NSG mice for another round of AMG510 treatment. Third generation (G3) PDXs TC303AR and TC314AR were generated in which each generation was treated with three or more cycles. Susceptibility to AMG510 (sotorasib) was reduced in each passage. We performed whole exome sequencing for at least 2-3 tumors from each PDX obtained in passage 3 (G3) that were under constant AMG510

treatment and did not regress during treatment. All resistant tumors from third generations from both PDXs had the same *KRAS*^{G12C} mutation as the parental PDXs (TC303 and TC314), with no other *KRAS* mutations.

PDX-derived organoid (PDXO) culture, maintenance, and development of sotorasib-acquired resistant PDXO models:

PDX tissues were harvested and processed into 2-3-mm-diameter pieces and washed with ice-cold PBS. Tumor pieces were dissociated into single cells in Advanced DMEMF12 (GIBCO) with Liberase TM (Sigma) for 1 hour followed by 10-minute incubation with TrypLE Express (Invitrogen) in 37^{0}C with gentle shaking. The establishment of organoids in culture was done according to the protocol described in Shi R et al (47) with little modification. Briefly, single cells from freshly harvested PDX tissues were counted and resuspended in 100% growth factor–reduced Matrigel (VWR), plated in 24-well tissue culture plates as Matrigel domes, and maintained in 37^{0}C 5% CO2 with media overlaying the Matrigel dome. Growth factors and supplements used in the media for the organoid culture are followed according to the reference article. Organoid growth was monitored weekly for the detection of initiated organoids, and organoids were kept in the same passage for no longer than four weeks. To make the sotorasib resistant PDXOs, PDX TC303 and PDX TC314 tissues were harvested, and single-cell suspension and establishment of organoids (PDXO303 & PDXO314) were prepared according to the protocol mentioned above. These organoids were cultured in a complete medium with all supplements and growth factors and incremental doses of sotorasib for 1-4 weeks before passaging. Repeated these passaging steps with sotorasib for several cycles until the organoids grew smoothly without cell death with 1 μM sotorasib containing medium and developed the sotorasib resistant PDXO303AR and

PDXO314AR isogeneic organoids. The resistant organoids were then subjected to whole exome sequencing to verify *KRAS*^{G12C} mutation status.

To check the purity of organoids, we prepared the single cells from fresh organoids and stained them with mouse cells detecting antibody (H-2Kb/H-2Db; BioLegend, CA, USA) and human epithelial marker (EpCAM; BioLegend, CA, USA) and ran flow cytometry using Attune NxT cytometer (Invitrogen, CA, USA). Data were analyzed by Flow Jo software. Organoid cultures were tested routinely for Mycoplasma. The established organoid samples were subjected to whole exome sequence (method mentioned above) for detecting *KRAS*^{G12C} mutation.

Generation of 4E-BP1 and PI3K/p110a knockout clones by CRISPR-Cas9 technology

CRISPR-Cas9 technology was used to knock out PI3K and 4E-BP1 genes so that the corresponding functional proteins are no longer produced. These experiments involved transfecting H23AR and H358AR cells with a target-specific guide RNA (gRNA) and a Cas9 nuclease. All the reagents which included Gene Knockout Kit v2, sgRNA, and SpCas9 Nuclease were purchased from Synthego (Synthego, CA, USA). The experiment was performed according to the manufacturer's protocol. Briefly, for one knockout test, 3 ul sgRNA (30 uM), 0.5 ul Cas9 (20 uM), and 3.5 ul Buffer R were mixed and kept at Room Temperature for 10 min, and then added 1 x 10^5 cells in 3 ul Buffer R to the above mixture, followed by electroporation (Invitrogen Neon electroporation system: 10-ul tip type) (Pulse voltage, 1100 v; Pulse width, 30 ms; Pulse number, 1). After electroporation, the knockout cells were cultured in a 24-well plate at 37 ^{0}C for 3 days. Total genomic DNA was extracted, PCR for specific genes was conducted, a certain DNA fragment was sequenced with the Sanger technique, and sequencing results were analyzed using Inference of CRISPR Edits (ICE) (a free online tool on Synthego website) that

provides an easy quantitative assessment of indels generated by CRISPR in pools and clones. The ICE report outputs both the total indel percentage and the Knockout Score (the percentage of outcomes that lead to a putative knockout). Finally, the knockout efficiency was carried out using western blot for the specific knockout gene protein products.

Cell viability assay in organoids (PDXOs)

Organoids were dissociated into single cells, counted, and prepared cell suspension with media containing Matrigel and plated cells in 96 well u-shaped plates (5000-10000 cells per well) in triplicate for 24-72 hours before drug treatment. Organoids were treated with a range of drug concentrations (0.01– 10 mmol/L) for 7 days and cell viability was determined by Cell Titer Glo 3D viability assay according to the manufacturer protocol (Promega, WI, USA). Drug–response curves were graphed and IC50 values were calculated using GraphPad Prism 10.0. CompuSyn software (47) was used to calculate the combination indices for combination drug studies.

Drug sensitivity assay

Sotorasib-resistant isogenic cells were seeded at a density of $3X10^3$ cells/well in a 96-well microplate and treated with sotorasib or adagrasib at concentrations ranging from 0.001 to 10 μM in DMSO. Cells were incubated in 37°C incubators, 5% CO_2, for three days. Cytotoxicity assays were performed using colorimetric XTT (Sigma-Aldrich, USA) and SRB (Sulforhodamine B) Assay Kit (Abcam, USA) reagents according to manufactured protocol. Optical density (OD) was measured using a microplate reader (FLUOstar Omega, BMG Labtech USA) at 570 nm. Cell viability (%) = [OD (Drug) - OD (Blank)] / [OD (Control) - OD (Blank)] × 100.

Colony formation assay

NCI-H23, NCI-HH23AR, NCI-H358, and NCI-H358AR cells were seeded into 6-well plates at a density of 300 cells per well, and treated with copanlisib alone, MK2206 alone, copanlisib + MK2206 combination, everolimus alone and copanlisib + everolimus combination at the concentrations listed in the experiment for 72 h. The media was replaced every 2-3 days with drugs containing medium. After twelve days, colonies were fixed with 4% PFA, stained with crystal violet solution, and photographed.

Western blot analysis

Cells were seeded at a density of 3X 10^6 in 90 mm Prime Surface plates (Corning), incubated overnight in RPMI1640 complete medium, treated with appropriate inhibitors, and harvested. Western blotting was performed according to the manufacturer's protocol. Total protein was harvested using Ripa lysis buffer (Merck, Burlington, MA), and their concentrations were evaluated with BCA™ protein assay kit (Pierce, Rockford, IL, USA). Equal amounts of proteins were separated by 8-15% SDS-PAGE gel, electro-transferred onto a Hybond ECL transfer membrane (Amersham Pharmacia, Piscataway, NJ), and blocked with 2-5% non-fat skim milk. Then, membranes were probed with specific primary antibodies at 1:1000 dilution overnight at 4 °C, washed with PBS, and incubated with corresponding secondary antibodies at 1:2000 dilution at room temperature for 1 h. The specific protein bands were visualized with an ECL advanced western blot analysis detection kit (GE Health Care Biosciences, NJ, USA). Antibodies used in this study were purchased from Cell Signaling (Beverly, MA): Anti- PI3K(p110a) (#4249S), PI3K (p85), AKT (CS#4691), p-AKT (Ser473) (CS#9271), p-AKT (Thr308) (CS #4056), mTOR, p-mTOR (Ser2448) (CS#2971), PDK1 (CS#13037), p-PDK1(Tyr373/376) (bs-3017R), p-PDK1(Ser241) (CS#3061), MAPK (CS#4695), p-MAPK (Thr202/Tyr204) (CS#4370), PTEN (CS#9559), p-PTEN (CS#9549), p-S6 (Ser240), p-

S6 (Ser235), 4E-BP1 (#9644S), p4E-BP1 (Ser65) (#9456S), p4E-BP1 (T37/46), p-PRAS40 (Thr246), p-GSK-3b (Ser9), p70S6 (T389). Monoclonal anti-β-actin (Sigma#A5449) was purchased from Sigma Aldrich (St Louis, MO). GAPDH mouse monoclonal antibody (sc-365062) was from Santa Cruz Biotechnology (CA, USA).

Whole Exome Sequence

H23 & H23AR and H358 & H358AR isogeneic cells were seeded in triplicates at a cell density of 2 X 10^6/plate. DNA was isolated and purified using a Qiagen kit (Germantown, MD). DNA was also isolated from acquired resistant PDXO303AR, PDXO314AR organoids, as well as TC303AR & TC314AR PDXs with their sensitive counterparts for whole exome sequencing. The quality of DNA was evaluated and the whole exome was sequenced at the sequencing core lab (MDACC, Houston, TX) using a next-generation sequencer (NextSeq500, Illumina, USA). Sequencing data were analyzed by the Department of Bioinformatics and Computational Biology, MDACC.

Reverse Phase Protein Array (RPPA)

NSCLC PDXs treated with sotorasib and the residual PDX samples were harvested and snap-frozen for RPPA analysis. Similarly, H358AR CDX tumors were treated with sotorasib, copanlisib, and their combination. After the experiments, the residual tumor tissues were harvested, snap-frozen, and stored at -80^{0}C. RPPA analysis was performed using 400 antibodies at the RPPA core lab at UT MD Anderson Cancer Center. Bioinformatics analysis was performed by the Department of Bioinformatics and Computational Biology at MD Anderson Cancer Center.

Mass Spectrometry.

Sotorasib-acquired resistant PDXs (TC303AR and TC314AR) and their parental counterpart PDXs (TC303 and TC314) were submitted to the core lab in Baylor College of Medicine (BCM) (Houston, TX) for mass spec analysis. Three biological replicates were used in each PDX. The samples were denatured and lysed by three cycles of LN2 snap freeze and thaw at 95°C. For global profiling, 10 mg of lysate was trypsinized to obtain 10 mg of digested peptides. After fractionation using a small-scale basic pH reverse phase (sBPRP) step elution protocol with increasing acetonitrile concentrations, fractions were combined into 5 pools that were resolved and sequenced online with Fusion Lumos and timsTOF fleX mass spectrometer. For phospho-proteome profiling, a 100 µg protein lysate was digested with trypsin and dried under vacuum. Global and phospho-proteomic analyses covered over 8000 gene protein products (GPS), and over 4000 GPS, respectively, which included the kinome profile. After label-free nanoscale liquid chromatography coupled to tandem mass spectrometry (nanoLC-MS/MS) analysis using a Thermo Fusion Mass spectrometer, the data was processed and quantified against NCBI RefSeq protein databases in Proteome Discover 2.5 interface with a Mascot search engine (Saltzman, Ruprecht). The Skyline program was used to obtain precise quantification. To decipher phospho-proteome signal pathway analysis we utilized protein external data contributions for phosphorylation-related data mining sets, including PhosphoSitePlus (http://www.phosphosite.org/), Phospho.ELM, PhosphoPep, and the Phosphorylation Site Database (PHOSIDA).

Statistics and Reproducibility

In-vivo xenograft, CDX, and PDX data analysis

All in-vivo experiments were designed and planned with biostatistician Dr. Jing Wang (Co-author) from the bioinformatics department at MD Anderson Cancer Center. For therapeutic studies in subcutaneous

xenografts, CDX or PDX tumors were developed in immune-deficient NSG mice, and generalized linear regression models were used to study the tumor growth over time. Statistical analyses were performed with GraphPad Prism 7 software. Tumor volume change per time point was calculated as a relative level of tumor volume change from baseline. Two-way ANOVA with the interaction of treatment group and time point was performed to compare the difference of tumor volume changes from baseline between each pair of the treatment groups at each time point. Means ± standard errors of the mean are shown in all graphs. The nonparametric Mann-Whitney U test was applied to compare cell numbers in different treatment groups. Differences of $P < 0.05$, $P < 0.01$, and $P < 0.001$ were considered statistically significant. All in-vivo tumor growth and treatment experiments were repeated N =3 times with N = 5-7 mice/group each time.

Combination Index analysis to determine treatment synergy

We evaluated the potential synergistic effect of the drug combinations sotorasib + copanlisib or sotorasib + sapanisertib under the Highest Single-agent (HSA) framework (48), where the synergistic effect of a drug combination is declared if the combination effect is greater than that of the more effective individual component. The combination index (CI) under the HSA and the corresponding standard error were approximated by the Delta method (49). We considered the three most well-established reference models: Highest Single Agent (HAS), response additivity (RA), and Bliss Independent (BI) in a unified statistical quantification method (49). The in-vivo experiment was repeated N =3 times with at least N = 5 mice/group at each time.

Reverse Phase Protein Array (RPPA) data analysis: Slides were scanned using a CanoScan 9000F and spot intensities were quantified using ArrayPro Analyzer 6.3 (Media Cybernetics Washington DC).

SuperCurve, a software developed in-house, was used to estimate relative protein levels (50). After SuperCurve fitting, protein measurements were normalized for loading using median centering across antibodies. One-way analysis of variance (ANOVA) was used to assess the differences in protein expressions between control and treatment groups on a protein-by-protein basis. First, for one feature(protein) at a time, we carried out an over-all F test to detect any significant difference among the means of all the groups. Next, for the featured (proteins) identified in this process, we then compared between desired groups to identify the sources of difference. The R library "multcomp" was used for this purpose. Note that the FC (fold change) values were calculated as the estimated ratio between the 2 groups in comparison, with the following conventional modification: For the rations > 1 (up-regulation), FCs were noted as the same as the ratio. For the rations ≤ 1 (down-regulation), FC were noted as the negative inverse of the ratio. Furthermore, to account for multiple testing, we estimated the false discovery rates (FDR) of the overall test of the model using the Benjamini-Hochberg method. An FDR adjusted p-value less than 0.05 was considered as statistically significant unless otherwise mentioned. The criteria of significant protein selection were: 1. Significant in overall F-test (FDR-adjusted p-value<0.05); 2. Significant in pairwise comparison (FDR-adjusted p-value<0.05). N=3-5 tumor samples per group were used for RPPA analysis.

Mass Spectrometry data analysis: Statistical analysis was performed using R software (R version 4.0.1). The log2 transformation was applied to the iFOT Half Min proteomic data. The student's t-test was used to compare expression values between the groups. P values obtained from multiple tests were adjusted using FDR. Statistical significance was defined as FDR < 0.05. The enriched pathways and hallmarks were identified by pre-ranked GSEA using the gene list ranked by log-transformed P values with signs set to

positive/negative for a fold change of >1 or <1, respectively. N=3 samples/group were analyzed for Mass spectrometry.

Whole Exome Sequence data analysis

The quality of raw FASTQ reads was assessed using FastQC and then mapped to human reference genome GRCh38, using BWA (51,52). The reference genome refers to the b38 version with decoy sequences for human GRCh38 provided in the genome analysis toolkit (GATK) resource bundle (53). The mutations were called following GATK best practice pipeline. The candidate mutations were be filtered for high confident somatic mutations and annotated for functional changes using ANNOVAR (54). At least N=3 samples/group were analyzed for WES.

Cell Survival Assay data analysis

The percentage of viable cells was determined by the ratio of absorbance of treatment and control groups: ODT/ODC x 100%. Univariate analysis was performed to evaluate the distribution of data for each treatment group. To determine whether SRB % was different between treatment groups, two methods were used: 1) ANOVA was performed to compare the variance between treatment groups for all samples within each cell line, and 2) Tukey's multiple comparisons test was performed for pairwise differences between treatment groups. $P<0.05$ was considered statistically significant; all tests were two-sided. Analyses were performed using SAS 9.3 (SAS Institute Inc., Cary, NC). Values represent the mean of three independent experiments. Each assay was performed $N \geq 3$ times with at least 3 replicates each time.

Data Availability Statement

All data generated or analyzed during this study are included in this published article. The source data underlying most graphs and charts used in this manuscript will be provided as Excel files in source Data 1. All uncropped and unedited western blot images used in this manuscript will be provided as supplementary information in Supplementary Figures. Request for any source data or materials that are not provided should be made to the corresponding author.

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Competing Interest

Jack A. Roth reports receiving a commercial research grant from The University of Texas MD Anderson Cancer Center, a sponsored research agreement from Genprex, Inc., has ownership interest (including stock, patents, etc.) in Genprex, Inc., and is a consultant/advisory board member for Genprex, Inc.

The other authors disclosed no potential conflicts of interest or competing interests.

Figure legends:

Figure 1: Development and characterization of sotorasib-acquired resistant patient-derived xenografts (PDXs) and PDX-derived organoids (PDXOs). A) A list of *KRAS*^{G12C} mutant-bearing NSCLC PDXs was developed in our PDX core. All the PDXs underwent whole-exome sequencing to identify their co-mutation status. **B)** Sotorasib treatment responses in four *KRAS*^{G12C} mutant NSCLC PDXs (TC247, TC303, TC314 and TC453). Tumors were treated with sotorasib (100 mg/kg) when tumor volume reached around 200 mm^3. Control mice were treated with solvent. Sotorasib or solvent was administered orally QD for 21 days. Tumor volume changes in individual mice were calculated for treatment starting day 0. **C)** Third-generation sotorasib-acquired resistant TC303AR and TC314AR PDXs were shown and compared with their parental TC303 and TC314 PDXs. **D)** PDXOs were developed and characterized. Whole exome sequence (WES) in PDXOs showed the KRASG12C mutation status (right panel) and PDXOs purity was determined by flow cytometry for detecting any mouse cells contamination by staining with mouse MHC Class I antibody (H2kb) and human epithelial marker (EpCAM) (left panel). **E)** The list of PDXOs developed from their respective PDXs and their sensitivity to sotorasib and adagrasib were determined based on IC50 (μM). **F)** Cell viability assay was performed on PDXOs for sotorasib (Left panel) and adagrasib (Right panel) sensitivity. Bold black lines indicate the PDXOs that were sensitive and ash color lines indicate the PDXOs that were resistant to KRAS inhibitors. **G)** Sotorasib-acquired

resistant PDXO303AR and PDXO314AR were developed and these acquired resistant PDXOs were treated with sotorasib (top panel) and adagrasib (bottom panel) and compared with their parental counterparts (PDXO303 & PDXO314). Data shown represent the mean ± SE of three independent experiments.

Figure 2: in-vitro & in-vivo characterization of sotorasib-acquired resistant isogeneic cell lines and acquired-resistant cell line-derived xenograft (CDX) development. A) SRB (Sulforhodamine B) assay was performed to compare the sotorasib sensitivity between H23 (parental) vs H23AR (resistant) cells and H358 (parental) vs H358AR (resistant) cells. The fold of resistance is listed in the table (bottom panel). **B)** Cell viability assay showed the sensitivity of H23 & H23AR and H358 & H358AR isogeneic cells to adagrasib (top panel) and Opnurasib (bottom panel). **C)** The strategy for in-vivo resistance to sotorasib for H23AR xenograft tumors is shown. **D)** Evaluation of in-vivo resistance to sotorasib. H23 and H23AR cells were implanted into mice and treated with sotorasib for at least 3 weeks when tumor sizes reached approximately 200 mm3. H23AR cells were expanded in culture under sotorasib pressure before implantation. The antitumor effect of sotorasib was evaluated in both H23 xenograft (control tumor vs treated tumors) and H23AR xenograft tumor models (control vs sotorasib). Statistical significance was calculated. **E)** The antitumor effect of sotorasib on H358 parental tumors was evaluated and their statistical significance was calculated. **F)** The strategy shown here for the development of sotorasib-acquired resistant H358AR CDX. **G)** Third-generation sotorasib-resistant H358AR CDX showed no significant effect with sotorasib treatment whereas H358 parental xenograft tumors showed significant sensitivity to sotorasib. **H)** Sotorasib antitumor effect was calculated based on tumor volume shrinkage after 21 days of treatment where H358AR CDX showed no significant effect of sotorasib

treatment. Each experiment was repeated three times. Statistics are shown at a significance level of $p<0.05$ unless otherwise noted. Data is shown as mean percentage ±SD, n>5 mice/group was used in each experiment. *, $P < 0.05$; **, $P < 0.005$; *** $P < 0.0005$.

Figure 2-figure supplement 1: Whole exome sequencing (WES) on acquired resistant cells. Two sotorasib-resistant isogeneic cell lines were subjected to WES to identify additional mutations in *KRAS*. Three biological replicates for each sample were used. Top left; number of SNPs and Indels found in H358AR as compared with the parental H358 cells. Top right; SNPs and Indels found in H23AR cells as compared with H23 cells. Bottom; $KRAS^{G12C}$ mutation is shown present in both H358 and H358AR cells.

Figure 3: Reactivation of KRAS and Upregulation of PI3K/AKT/mTOR Signaling in Acquired Sotorasib-Resistant PDX Models. Acquired resistant TC303AR and TC314AR PDXs and their isogeneic TC303 and TC314 PDXs snap frozen samples underwent global and phospho-proteomics by mass spectrometry. The data were analyzed in the Biostatistics Department in the MD Anderson Cancer Center. **A-B)** Dendrogram plot and two-component analysis curve showed the clustering of the samples indicating the similarities and distances among samples. **C)** Heat-map was generated among the proteins that were statistically significantly upregulated or downregulated between parental TC314 and resistant TC314AR PDX samples (right panel) and parental TC303 vs resistant TC303AR PDX samples (left panel). **D)** Pathway Enrichment analysis was performed among significantly altered global proteins in TC314AR samples. A list of gene-sets enriched was shown in the top panel with their FDR values, and the enrichment of gene-sets associated with mTORC1 and KRAS signaling are shown in the bottom panel with their significant p-value and FDR. **E)** Enrichment analysis was performed for global proteomics for combined TC303AR and TC314AR data. A list of enriched gene-sets was listed in the

right panel and the mTORC1 signaling enrichment graph was shown in the left panel. **F)** Pathway Enrichment analysis in phosphoproteomics in TC314AR PDX was performed. The enriched mTORC1 signaling is shown in the left panel, and the PI3K/AKT/mTOR pathway enrichment is shown in the right panel. FDR and p-values are displayed in the graphs. **G)** RPPA data derived from TC303AR and TC314AR isogenic PDX samples and the significantly altered proteins associated with MAPK and PI3K/AKT/mTOR pathways were analyzed and compared. The increased expression by fold-change of these proteins between TC303 parental vs TC303AR resistant samples (top) and TC314 parental vs TC314AR resistant samples (bottom) were shown. **H)** PDXs TC247, TC314, & TC453 were implanted into mice and when PDX tumor volume reached 200 mm^3, tumors were treated with sotorasib (100 mg/kg) for 3 weeks. After 21 days of treatment, the treatment efficacy was determined based on percentage of tumor growth inhibition (details in method section) and categorized between responders and non-responders. PDX samples underwent RPPA analysis. Heat-maps (bottom panel) were generated based on the significantly altered proteins and compared between responder vs non-responder groups. Non-responder PDXs were grown again and treated with sotorasib for 21 days. After treatment, tumors were harvested and RPPA was performed. The RPPA data derived from sotorasib treated non-responders and control non-responders were compared and a heat-map was generated among significantly altered proteins between control vs treated among non-responder PDXs (top panel). N≥3 biological replicates were used for each PDX for Mass Spectrometry, and RPPA, N=5 PDX-tumors/treatment group and N ≥ 3 PDX samples from each treatment group used for RPPA analysis. The criteria of protein selection for significantly up- down-regulation were: 1. Significant in overall F-test (FDR-adjusted p-value<0.05); 2. Significant in pairwise comparison. (FDR-adjusted p-value<0.05).

Figure 3-figure supplement 1: Venn Diagram. Mass spectrometry was performed for two sotorasib resistant isogenic PDXs (TC303AR and TC314AR) samples. Altered proteins from each pair of isogenic PDXs were used for the Venn Diagram. The percentage of commonly altered proteins is shown in the middle (white area).

Figure 3-figure supplement 2: Mass spectrometry analysis for phosphoproteomics in resistant PDXs. Mass spectrometry was performed for two sotorasib resistant isogenic PDXs (TC303AR and TC314AR) samples. Phosphoproteomics data was analyzed for enrichment pathway analysis. Enrichment graph for PI3K/AKT/mTOR signaling in TC303AR PDX (Left) and Enrichment graphs for mTORC1 and PI3K/AKT/mTOR signaling in TC314AR+TC303AR PDXs combined data analysis (middle and right).

Figure 3-figure supplement 3: KRAS Reactivation in Sotorasib-Resistant Cells via ERK Phosphorylation. H23, H23AR and H358 & H358AR cells were compared for their p-ERK1/2 expression. Both H23AR and H358AR resistant cells were cultured and maintained under sotorasib pressure. Western blots for total ERK and p-ERK in these cells are shown.

Figure 4: Pharmacological inhibition of PI3K signaling by copanlisib inhibits colony formation and downregulates PI3K/AKT/mTOR signaling molecules in acquired resistant cells and PDXOs. Both acquired resistant H23AR and H358AR were cultured and maintained under sotorasib pressure. **A)** SRB (Sulforhodamine B) assay was performed to compare the copanlisib sensitivity between H23 (parental) vs H23AR (resistant) cells and H358 (parental) vs H358AR (resistant) cells. IC50 values of copanlisib for each cell line were shown at the bottom of each respective graph. **B)** H23AR and H358AR cells were cultured in sotorasib containing media and plated for copanlisib treatment in different doses for 24h. For no treatment control samples, H23AR and H358AR were omitted from sotorasib for the last

24h, otherwise acquired cells were always maintained under sotorasib pressure. Western blot was performed for PI3K (p85), AKT and phospho-AKT (S473 & T308). **C)** Cell viability assay for copanlisib sensitivity on acquired resistant PDXO303AR and PDXO314AR isogeneic organoids and primary resistant organoids (PDXO780 & PDXO664). Cell viability of copanlisib was also compared with sotorasib on the sotorasib primary resistant organoids PDXO481, PDXO551, PDXO723. **D)** Inhibition of colony proliferation by copanlisib treatment at different doses on H23AR and H358AR isogeneic cells was shown in colony formation assay. **E)** Effect of copanlisib and MK2206, and **F)** copanlisib and everolimus combination on the inhibition of cell proliferation on both resistant H23AR and H358AR cells shown in colony formation assays. **G-H)** H23AR and H358AR cells cultured, maintained, and seeded in media containing sotorasib and cells were treated with copanlisib doses mentioned in the figure for 24h. For no treatment control samples, H23AR and H358AR were omitted from sotorasib for the last 24h, otherwise acquired cells were always maintained under sotorasib pressure. Western blot was performed for upstream **(G)** mTOR, p-mTOR, PDK, p-PDK and p-PTEN and downstream **(H)** p70S6, p-S6, p-GSK-3b, p-PRAS40, p-4E-BP1 molecules. **I)** Cell viability assay on PDXO780 & PDXO481 organoids to compare the sensitivity between copanlisib and everolimus. Each experiment was repeated three times. Data is shown as mean percentage ±SD, n=3.

Figure 5: PI3K knockout via CRISPR-Cas9 restores sotorasib sensitivity in acquired resistant cells by dephosphorylating 4E-BP1. A) PI3K/p110α subunit was knocked out using CRISPR-Cas9 technology on H23AR. Five clones H23AR$^{PI3K\text{-}KO\text{-}2\text{-}15}$, H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$, H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$, H23AR$^{PI3K\text{-}KO\text{-}3\text{-}12}$ & H23AR$^{PI3K\text{-}KO\text{-}2\text{-}1}$ from H23AR cells were selected and verified the PI3K expression on these clones by western blots. **B)** Cell viability assay was performed on these PI3K knockout clones generated from

H23AR cells to compare the sotorasib sensitivity to determine the most sensitive and least sensitive clone. The sotorasib sensitivity on PI3K clones was also compared with the parental H23 and resistant H23AR cells. The statistical significance was compared among the clones and H23AR isogeneic cells shown in the table below the graph. **C)** PI3K/p110α subunit was knocked out by CRISPR-Cas9 technology on H358AR. Three clones H358AR$^{PI3K\text{-}KO\text{-}1\text{-}4}$, H358AR$^{PI3K\text{-}KO\text{-}2\text{-}4}$, H358AR$^{PI3K\text{-}KO\text{-}2\text{-}7}$ from H358AR cells were selected and the knockout status of PI3K expression on these clones was verified by western blots. **D)** Cell viability assay was performed on these PI3K knockout clones generated from H358AR cells to compare the sotorasib sensitivity to H358AR resistant and H358 parental cells. **E)** H23, H23AR and the most sensitive PI3K knockout clone H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$ were seeded and treated with copanlisib for 24h and the downstream PI3K, AKT, p-AKT, p-S6 and p-4E-BP1 status was determined by the western blot. Effect of copanlisib treatment on downstream molecules and the level of expression was also compared among PI3K knockout and H23AR isogeneic cells. **F)** H23, H23AR and the least sensitive PI3K knockout clone H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$ were seeded and treated with copanlisib for 24h and the downstream PI3K, AKT, p-AKT, p-S6 and p-4E-BP1 status was determined by the western blot. The effect of copanlisib treatment on downstream molecules and the level of expression was also compared among PI3K knockout and H23AR isogeneic cells is shown. Each experiment was repeated three times. Data is shown as mean percentage ±SD, n ≥ 3.

Figure 6: mTORC1/2 mediated phosphorylation of 4E-BP1 is associated with acquired resistance and 4E-BP1 knockout via CRISPR-Cas9 restores sotorasib sensitivity. A) The level of expression of p-GSK-3B, p-S6, p-4E-BP1 and 4E-BP1 in H23 parental, H23AR resistant, and a series of PI3K knockout clones H23AR$^{PI3K\text{-}KO\text{-}2\text{-}15}$, H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$, H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$, H23AR$^{PI3K\text{-}KO\text{-}3\text{-}12}$ was compared (left panel).

The sotorasib sensitivity was compared among the most sensitive H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$, the least sensitive H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$ clones and H23AR isogeneic cells (right panel). The association between 4E-BP1 expression and sotorasib sensitivity among sensitive and resistant clones was determined. **B)** 4E-BP1 knockout clones were generated by the CRISPR-Cas9 technology on H23AR cells. The clones were confirmed based on the complete absence of 4E-BP1 expression in western blots. H23AR$^{4E\text{-}BP1\text{-}KO\text{-}1\text{-}1}$ clone was selected after screening several clones. **C)** Similarly, 4E-BP1 knockout clones were generated by CRISPR-Cas9 technology on sotorasib least sensitive H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$ cells to make the double PI3K and 4E-BP1 knockout clones. Several clones were screened for their 4E-BP1 expression and H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3/4E\text{-}BP1\text{-}KO\text{-}1\text{-}2}$, H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3/4E\text{-}BP1\text{-}KO\text{-}1\text{-}4}$, H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3/4E\text{-}BP1\text{-}KO\text{-}3\text{-}4}$ clones were selected based on no expression of 4E-BP1. **D)** Cell viability assay was performed for sotorasib sensitivity on 4E-BP1 knockout clone H23AR$^{4E\text{-}BP1\text{-}KO\text{-}1\text{-}1}$ that was compared with parental H23 and H23AR cells. Statistical significance was determined based on p-value calculation, which is shown in the table below the graph. **E)** Cell viability assays were performed for sotorasib sensitivity on 4E-BP1 knockout clones H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3/4E\text{-}BP1\text{-}KO\text{-}1\text{-}2}$, H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3/4E\text{-}BP1\text{-}KO\text{-}1\text{-}4}$, H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3/4E\text{-}BP1\text{-}KO\text{-}3\text{-}4}$ and their sensitivity was compared with that of resistant H23AR cells. Statistical significance was determined based on p-value calculation, which is shown in the table below the graph. **F)** The effect of everolimus, an mTORC1 inhibitor on expression of p-S6 and p-4E-BP1 (S65) in resistant H23AR and sensitive PI3K knockout clone H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$ treated with everolimus for 24h. **G)** The effect of AZD8055, an mTORC1/2 dual inhibitor, on the expression of p-S6, p-4E-BP1 (S65) and p-4E-BP1 (T37/46) on parental H23, resistant H23AR, sotorasib most sensitive PI3K knockout clone H23AR$^{PI3K\text{-}KO\text{-}2\text{-}17}$ and the least sensitive PI3K knockout clone H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$ after AZD8055 treatment for 24h. **H)** A cell viability assay was performed for AZD8055, mTORC1/2 dual inhibitor, and its combination with sotorasib on H23, H23AR,

H358AR and H23ARPI3K-KO-3-3 clone. Drug synergy was calculated based on their combination index (CI) on both H23AR and H358AR cells. Combination Index (CI) is synergistic if the CI value is <0.7 (synergism if CI = 0.3-0.7, strong synergism if CI = 0.1-0.3, very strong synergism if CI <0.1). **I)** Cell viability assay on H23AR and H358AR cells to compare the cytotoxicity effect among Everolimus, AZD8055, and sotorasib. Each experiment was repeated three times. Data is shown as mean percentage ±SD, n ≥ 3.

Figure 7: Overcoming resistance by targeting PI3K-AKT-mTOR signaling with copanlisib or sapanisertib in acquired resistant NSCLC PDX, CDX, and xenograft Tumors. A) In vitro cell viability assay was performed to evaluate the synergistic effect of sotorasib + copanlisib on H23AR, H358AR and H23AR$^{PI3K\text{-}KO\text{-}3\text{-}3}$ cells. Cells were treated with sotorasib, copanlisib, and their combination. In combination, very low fixed copanlisib dose (either 0.05μM or 0.03μM) was combined with variable doses of sotorasib and cell viability assays were performed after 72h of treatment. The combination index (CI) was calculated and presented in the table listed under the graph. Combination Index (CI) is synergistic if CI value is <0.7 (synergism if CI = 0.3-0.7, strong synergism if CI = 0.1-0.3, very strong synergism if CI <0.1). **B-D)** In vivo antitumor efficacy of copanlisib and sotorasib combination on acquired resistant H358AR CDX tumors. Mice were engrafted with freshly harvested 3rd-generation acquired resistant H358AR CDX tumor tissues into experimental mice. When the tumor volumes reached approximately 200 mm^3, mice were randomized into four treatment groups (control, sotorasib (100 mg/kg), copanlisib (6 mg/kg) and sotorasib + copanlisib combination) and treated for at least 3 weeks. **B)** Treatment strategy is shown, **C)** Individual mouse response for each group. **D)** Antitumor effect of copanlisib and sotorasib combination on H358AR CDX tumors. **E)** The residual tumor tissues from

H358AR CDX tumors were harvested and subjected to RPPA analysis. The level of p-Src, p-mTOR, p70.S6, GSK-3b, p-S6, 4E-BP1, p-4E-BP1 (T37/46) and p-4E-BP1 (S65) expression in residual tissues was determined and compared among the treatment groups. **F-H)** Antitumor effect of sotorasib + copanlisib combination on acquired resistant H23AR xenograft tumors. **F)** The treatment strategy is shown where 5-8 million cells/mouse were subcutaneously injected. When tumor sizes reached 200 mm^3, tumors were treated for 3 weeks with sotorasib (50 mg/kg), copanlisib (6 mg/kg), and the combination. **G)** Antitumor effect is shown. **H)** Individual mouse responses were compared with mice from every treatment group. **I)** Antitumor effect of sotorasib + copanlisib combination on acquired resistant TC314AR PDX tumors. Mice were engrafted with freshly harvested 3rd-generation acquired resistant TC314AR PDX tumor tissues into experimental mice. When the tumor volumes reached approximately 200 mm^3, mice were randomized into four treatment groups (control, sotorasib (50 mg/kg), copanlisib (6 mg/kg) and sotorasib+copanlisib combination) and treated for 3 weeks. Tumor growth curves were generated for each treatment group from the beginning to the end of the treatment. **J)** Individual mouse responses were compared with mice from every treatment group. **K)** Antitumor effect of sotorasib + sapanisertib combination on acquired resistant TC314AR PDX tumors. Mice were engrafted with freshly harvested 3rd-generation acquired resistant TC314AR PDX tumor tissues into experimental mice. When the tumor volumes reached approximately 200 mm^3, mice were randomized into four treatment groups (control, sotorasib (50 mg/kg), sapanisertib (1 mg/kg) and sotorasib + sapanisertib combination) and treated for 3 weeks. Tumor growth curves were generated for each treatment group from the beginning to the end of the treatment. **L)** The antitumor data were analyzed by a statistical program, CombPDX, to evaluate the synergistic antitumor effect between sotorasib and sapanisertib on this TC314AR PDX model. Top left) shows the individual mouse response.

Top right) Treatment effect for combination, sotorasib alone, and sapanisertib alone treatment. The treatment effect was calculated based on percentage of tumor growth inhibition with 95% confidence interval. Bottom panels) The combination index (CI) was calculated by using two different methods, including Highest Single Agent analysis (HAS) and Bliss Independent (BI) analysis with 95% confidence interval. In-vivo experiments were repeated three times with 5-7 mice/group used in each experiment. Statistics are shown at a significance level of $p<0.05$ unless otherwise noted. Data is shown as mean percentage ±SD, n=5. *, $P < 0.05$; **, $P < 0.005$; *** $P < 0.0005$.

Figure 7-figure Supplement 1A. Treatment effect on TC314AR PDX by sotorasib + Copanlisib combination treatment. The resistant TC314AR PDX tumors were treated with the combination and single agents. The antitumor effect data were analyzed by CombPDX analysis software to determine treatment effect. The treatment effect is measured as the percentage of tumor growth inhibition with 95% confidence interval.

Figure 7-figure Supplement 1B. The analysis of the synergistic effect of sotorasib + copanlisib combination treatment on TC314AR PDX tumors. The resistant TC314AR PDX tumors were treated with the combination and single agents. The synergistic antitumor effect was calculated by analyzing the combination index (CI) analyzed by CombPDX analysis software to determine the synergy between these two drugs. Highest single agent method with 95% confidence interval was used to determine the combination index (CI). CI values <1 are synergistic.

Figure 7-figure Supplement 2A. Cell viability assay for sotorasib + sapanisertib combination on H23AR and H358AR cells. The experiment was done three times. Data is shown as mean percentage ±SD, n=3

Figure 7-figure Supplement 2B. Cell viability assay for sotorasib + sapanisertib combination on PDXO303AR and PDXO314AR organoids. The organoids were treated with sotorasib in combination with sapanisertib. Combination index (CI) for cell viability was calculated using the CalcuSyn software using Chou-Talalay method. If the CI value is <0.7, the combination is synergistic, if the CI value is between 0.3-0.1, the combination is strongly synergistic, and if CI value is <0.1, the combination is very strongly synergistic. The experiment was done three times. Data is shown as mean percentage ±SD, n=3

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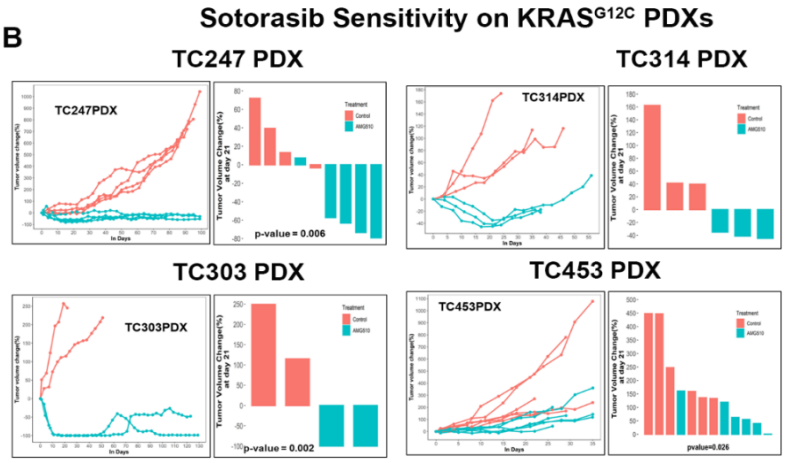
Figure 1

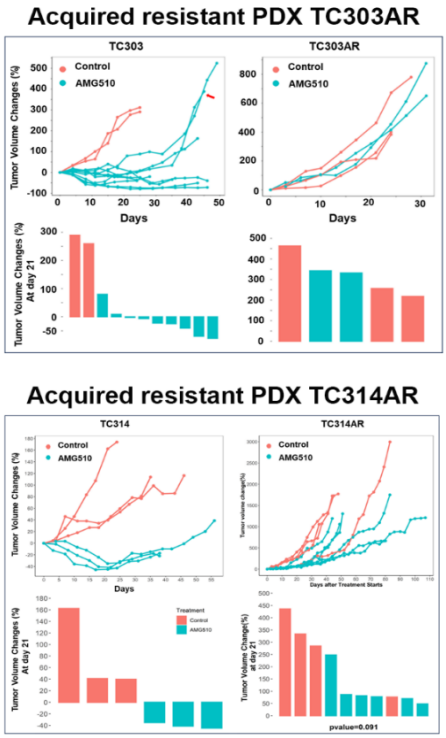
A

No.	PDX-ID	*KRAS*	*TP53*	*STK11*	*PIK3CA*	*KEAP1*
1	TC247	*G12C*		*Splicing*		*A522P*
2	TC303	*G12C*	*R175H*			*Q292**
3	TC314	*G12C*	*R248L*			
4	TC453	*G12C*		*Splicing*		
5	TC481	*G12C*		*Y36sf*		*Y525C*
6	TC527	*G12C*	*M160N*			
7	TC539	*G12C*				
8	TC551	*G12C*				
9	TC569	*G12C*				
10	TC723	*G12C*				
11	TC807	*G12C*		*Splicing*	*G122D*	

B



C



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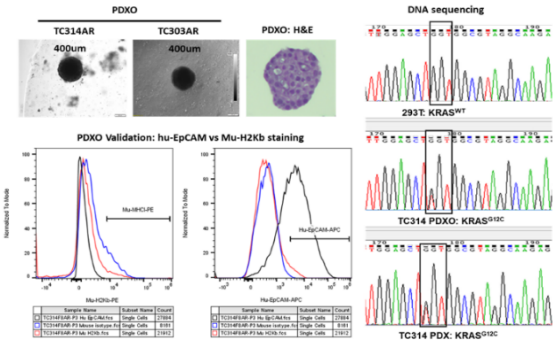
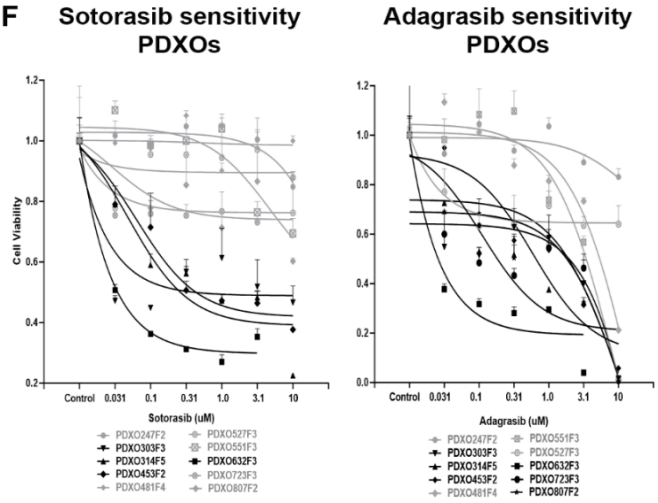


E

PDXOs & KRASi sensitivity on PDXOs

		PDX derived organoid		*IC50 (uM)*	
No.	PDX-ID	PDXO ID	*KRAS*	*Sotorasib*	*Adagrasib*
1	TC247	PDXO247	*G12C*	*>10*	*>10*
2	TC303	PDXO303	*G12C*	*0.03*	*0.03*
3	TC314	PDXO314	*G12C*	*0.11*	*0.09*
4	TC453	PDXO453	*G12C*	*1*	*1*
5	TC481	PDXO481	*G12C*	*>10*	*4*
6	TC527	PDXO527	*G12C*	*10*	*10*
7	TC551	PDXO551	*G12C*	*10*	*4*
8	TC632	PDXO632	*G12C*		
9	TC723	PDXO723	*G12C*	*10*	*0.1*
10	TC807	PDXO807	*G12C*	*10*	*1.26*

F



G

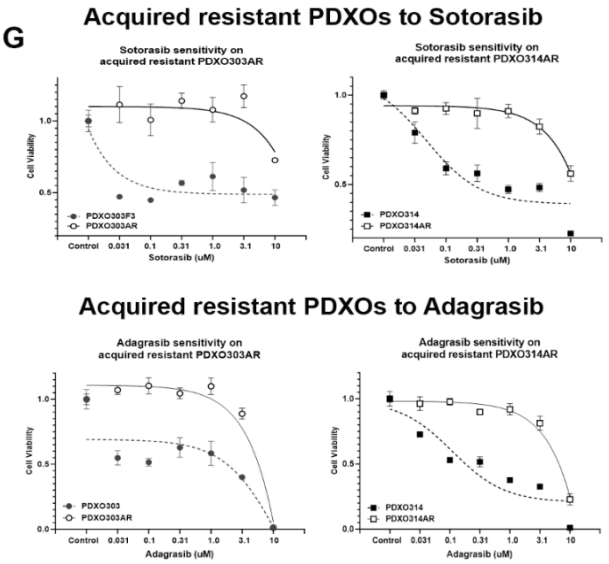
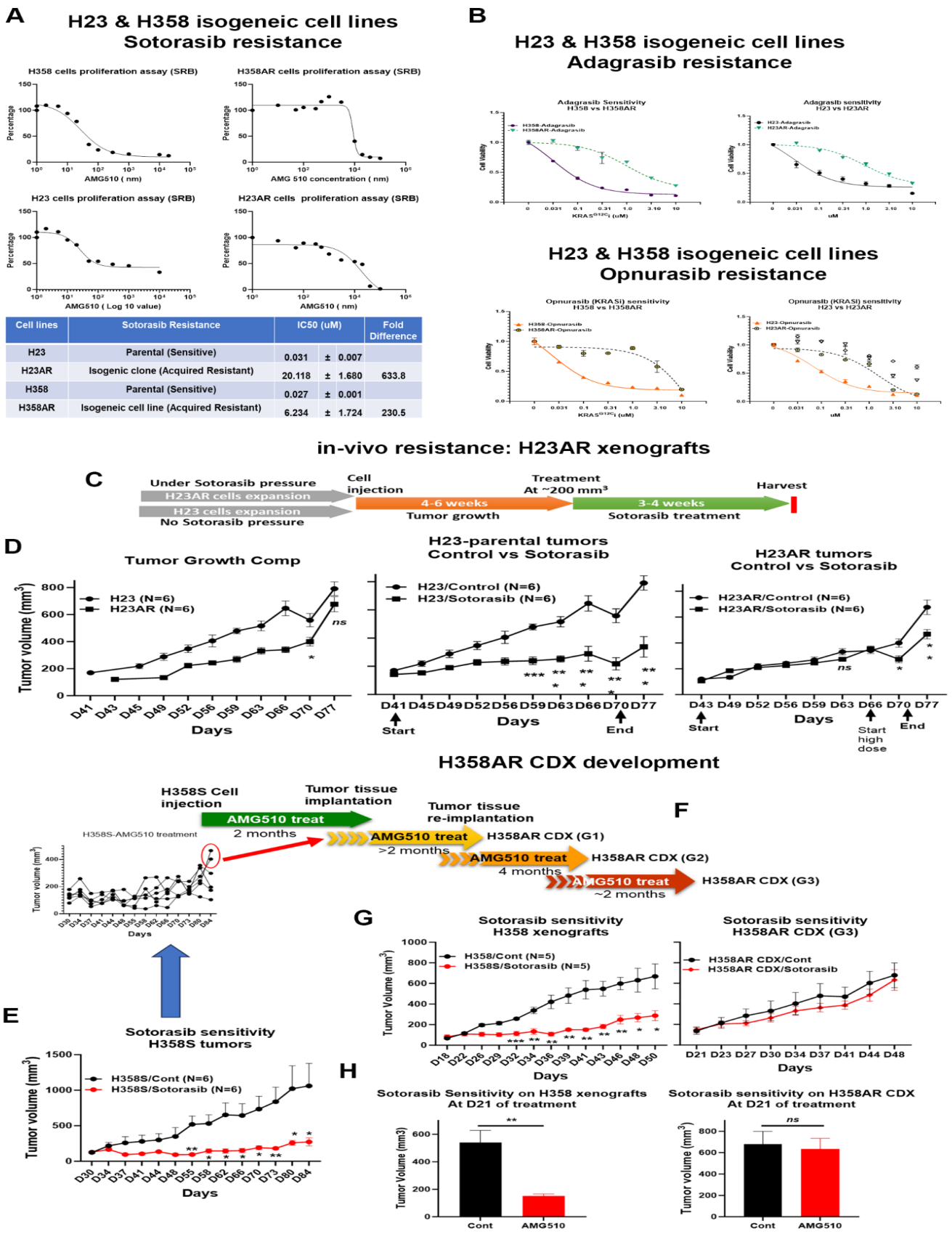
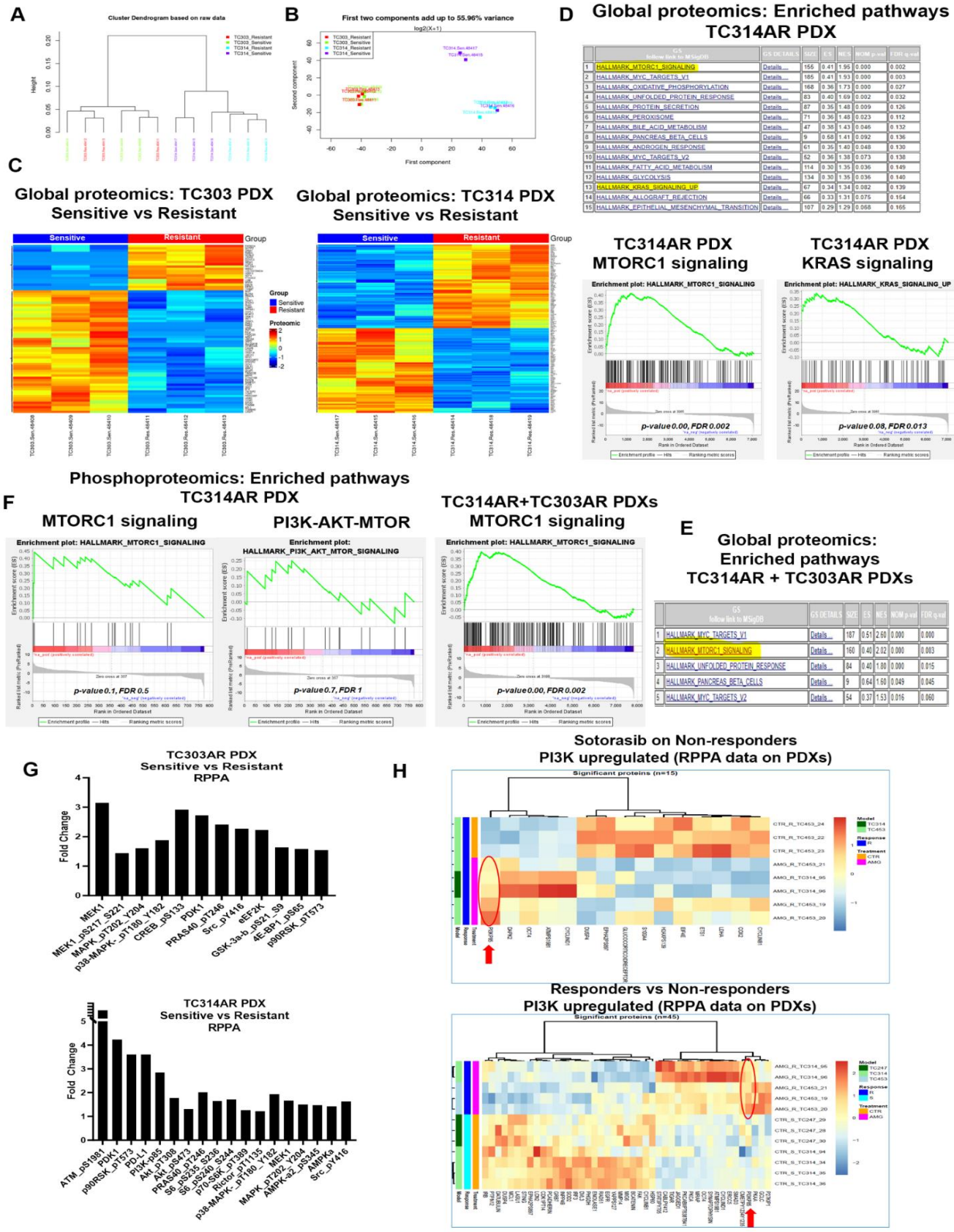


Figure 2



Cell lines	Sotorasib Resistance	IC50 (uM)	Fold Difference
H23	Parental (Sensitive)	0.031 ± 0.007	
H23AR	Isogenic clone (Acquired Resistant)	20.118 ± 1.680	633.8
H358	Parental (Sensitive)	0.027 ± 0.001	
H358AR	Isogeneic cell line (Acquired Resistant)	6.234 ± 1.724	230.5

Figure 3



	GS follow link to MSigDB	GS DETAILS	SIZE	ES	NES	NOM p-val	FDR q-val
1	HALLMARK_MTORC1_SIGNALING	Details....	155	0.41	1.95	0.000	0.002
2	HALLMARK_MYC_TARGETS_V1	Details....	185	0.41	1.93	0.000	0.003
3	HALLMARK_OXIDATIVE_PHOSPHORYLATION	Details....	168	0.36	1.73	0.000	0.027
4	HALLMARK_UNFOLDED_PROTEIN_RESPONSE	Details....	83	0.40	1.69	0.002	0.032
5	HALLMARK_PROTEIN_SECRETION	Details....	87	0.35	1.48	0.009	0.126
6	HALLMARK_PEROXISOME	Details....	71	0.36	1.48	0.023	0.112
7	HALLMARK_BILE_ACID_METABOLISM	Details....	47	0.38	1.43	0.046	0.132
8	HALLMARK_PANCREAS_BETA_CELLS	Details....	9	0.58	1.41	0.092	0.136
9	HALLMARK_ANDROGEN_RESPONSE	Details....	61	0.35	1.40	0.048	0.130
10	HALLMARK_MYC_TARGETS_V2	Details....	52	0.36	1.38	0.073	0.138
11	HALLMARK_FATTY_ACID_METABOLISM	Details....	114	0.30	1.35	0.036	0.149
12	HALLMARK_GLYCOLYSIS	Details....	134	0.30	1.35	0.036	0.149
13	HALLMARK_KRAS_SIGNALING_UP	Details....	67	0.34	1.34	0.082	0.139
14	HALLMARK_ALLOGRAFT_REJECTION	Details....	66	0.33	1.31	0.075	0.154
15	HALLMARK_EPITHELIAL_MESENCHYMAL_TRANSITION	Details....	107	0.29	1.29	0.068	0.165

	GS follow link to MSigDB	GS DETAILS	SIZE	ES	NES	NOM p-val	FDR q-val
1	HALLMARK_MYC_TARGETS_V1	Details....	187	0.51	2.60	0.000	0.000
2	HALLMARK_MTORC1_SIGNALING	Details....	160	0.40	2.02	0.000	0.003
3	HALLMARK_UNFOLDED_PROTEIN_RESPONSE	Details....	84	0.40	1.80	0.000	0.015
4	HALLMARK_PANCREAS_BETA_CELLS	Details....	9	0.64	1.60	0.049	0.045
5	HALLMARK_MYC_TARGETS_V2	Details....	54	0.37	1.53	0.016	0.060

Figure 4

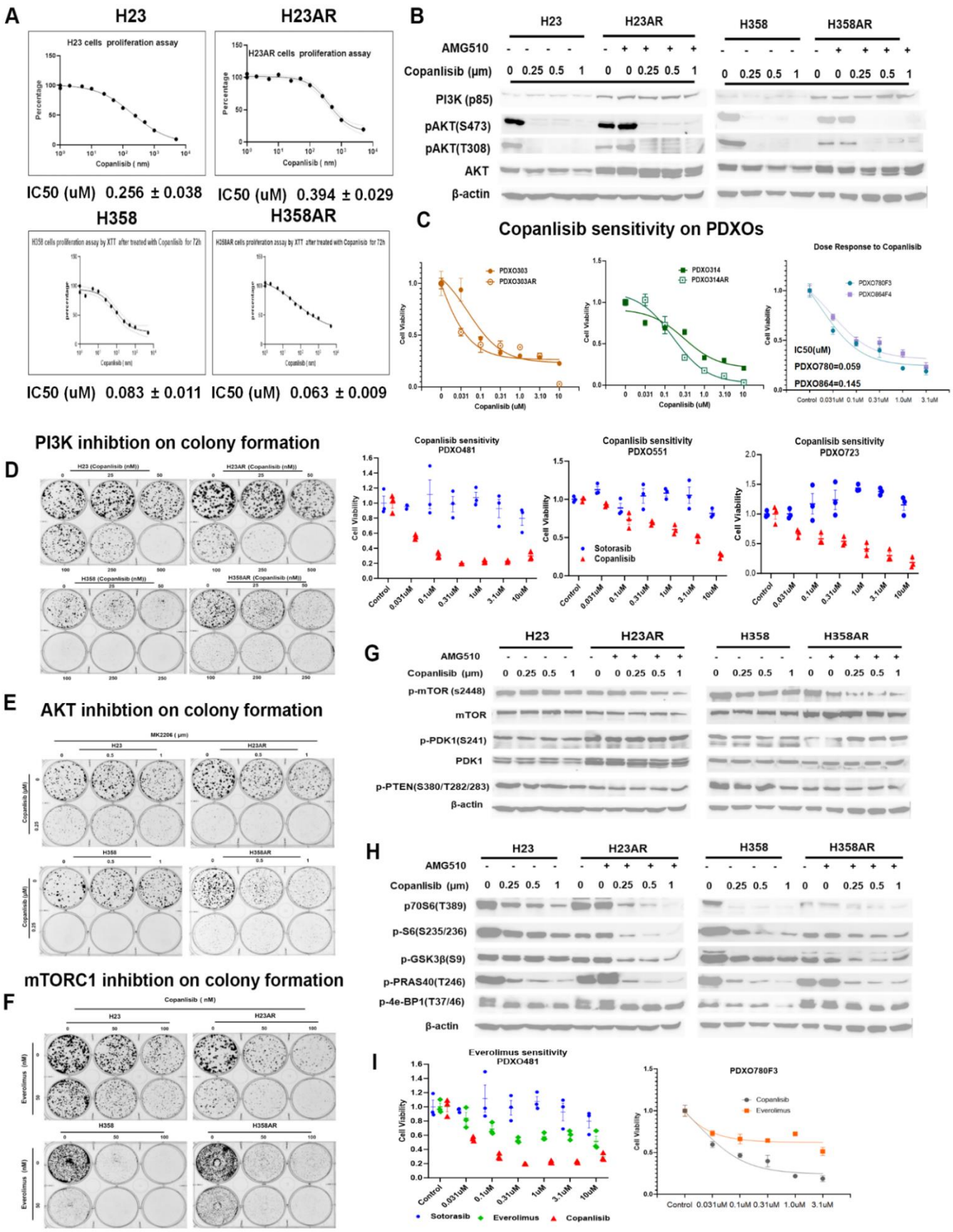
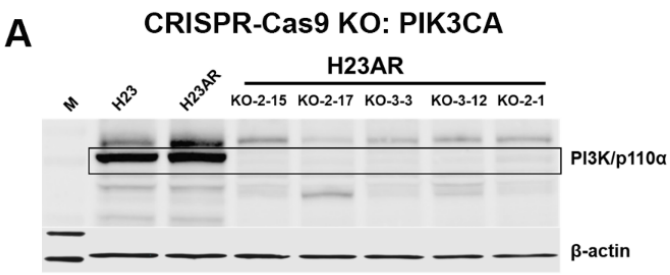
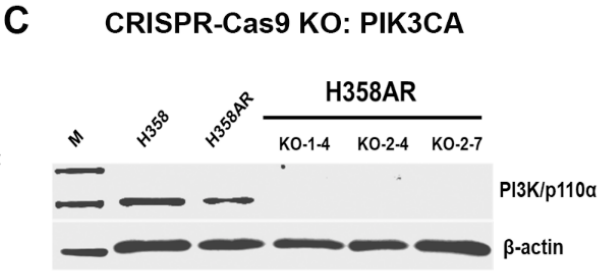
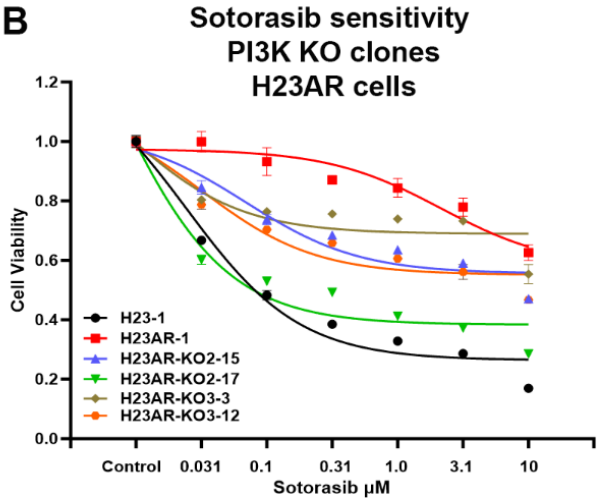
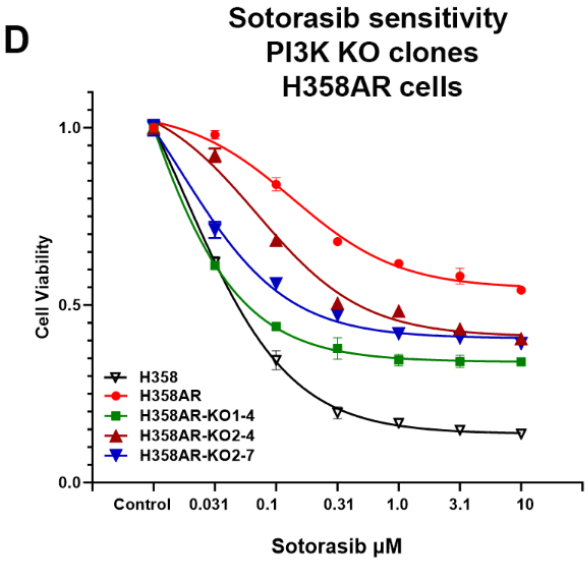

A
H23
H23AR
H23 cells proliferation assay
H23AR cells proliferation assay
Percentage
Copanlisib (nm)
IC50 (uM) 0.256 ± 0.038
IC50 (uM) 0.394 ± 0.029
H358
H358AR
IC50 (uM) 0.083 ± 0.011
IC50 (uM) 0.063 ± 0.009
B
H23
H23AR
H358
H358AR
AMG510
Copanlisib (μm)
PI3K (p85)
pAKT(S473)
pAKT(T308)
AKT
β-actin
C
Copanlisib sensitivity on PDXOs
PDXO303
PDXO303AR
PDXO314
PDXO314AR
Dose Response to Copanlisib
PDXO780F3
PDXO864F4
IC50(uM)
PDXO780=0.059
PDXO864=0.145
Cell Viability
Copanlisib (uM)
PI3K inhibtion on colony formation
D
H23 (Copanlisib (nM))
H23AR (Copanlisib (nM))
H358 (Copanlisib (nM))
H358AR (Copanlisib (nM))
Copanlisib sensitivity PDXO481
Copanlisib sensitivity PDXO551
Copanlisib sensitivity PDXO723
Sotorasib
Copanlisib
E
AKT inhibtion on colony formation
MK2206 (μm)
mTORC1 inhibtion on colony formation
F
Everolimus (nM)
G
p-mTOR (s2448)
mTOR
p-PDK1(S241)
PDK1
p-PTEN(S380/T282/283)
H
p70S6(T389)
p-S6(S235/236)
p-GSK3β(S9)
p-PRAS40(T246)
p-4e-BP1(T37/46)
I
Everolimus sensitivity PDXO481
PDXO780F3
Everolimus

Figure 5

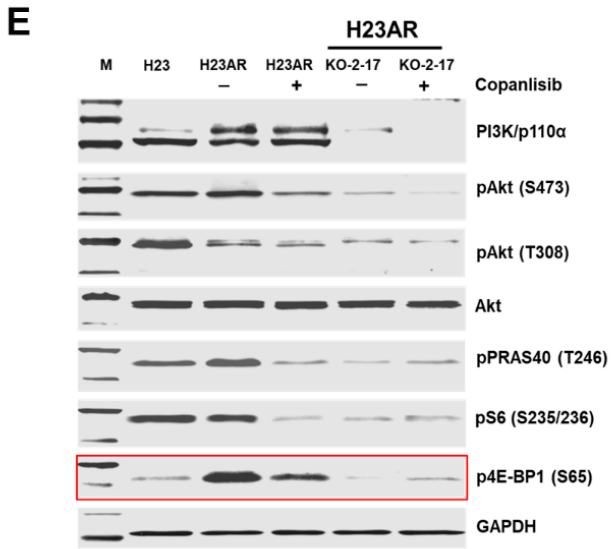








Cells/p-value	H23	H23AR	H23AR-KO-2-15	H23AR-KO-2-17	H23AR-KO-3-3	H23AR-KO-3-12
H23		0.000425				
H23AR	0.000425					
H23AR-KO-2-15	0.010842	0.035376				
H23AR-KO-2-17	0.477957	0.000245	0.013082			
H23AR-KO-3-3	0.001602	0.097578	0.333670	0.000863		
H23AR-KO-3-12	0.01566	0.013135	0.677878	0.019629	0.136164	



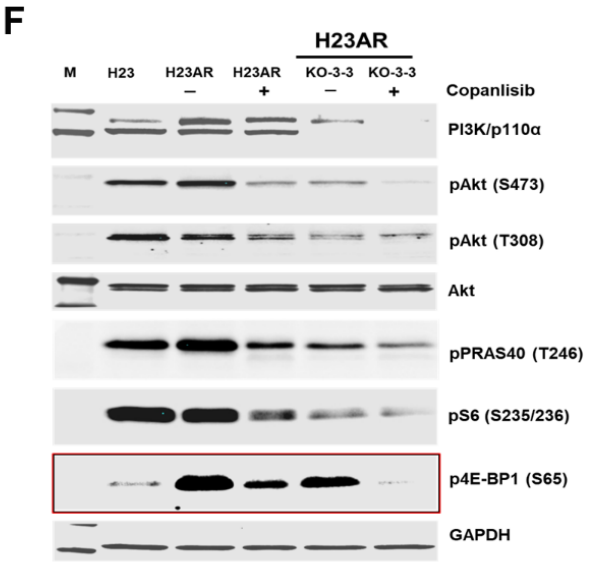
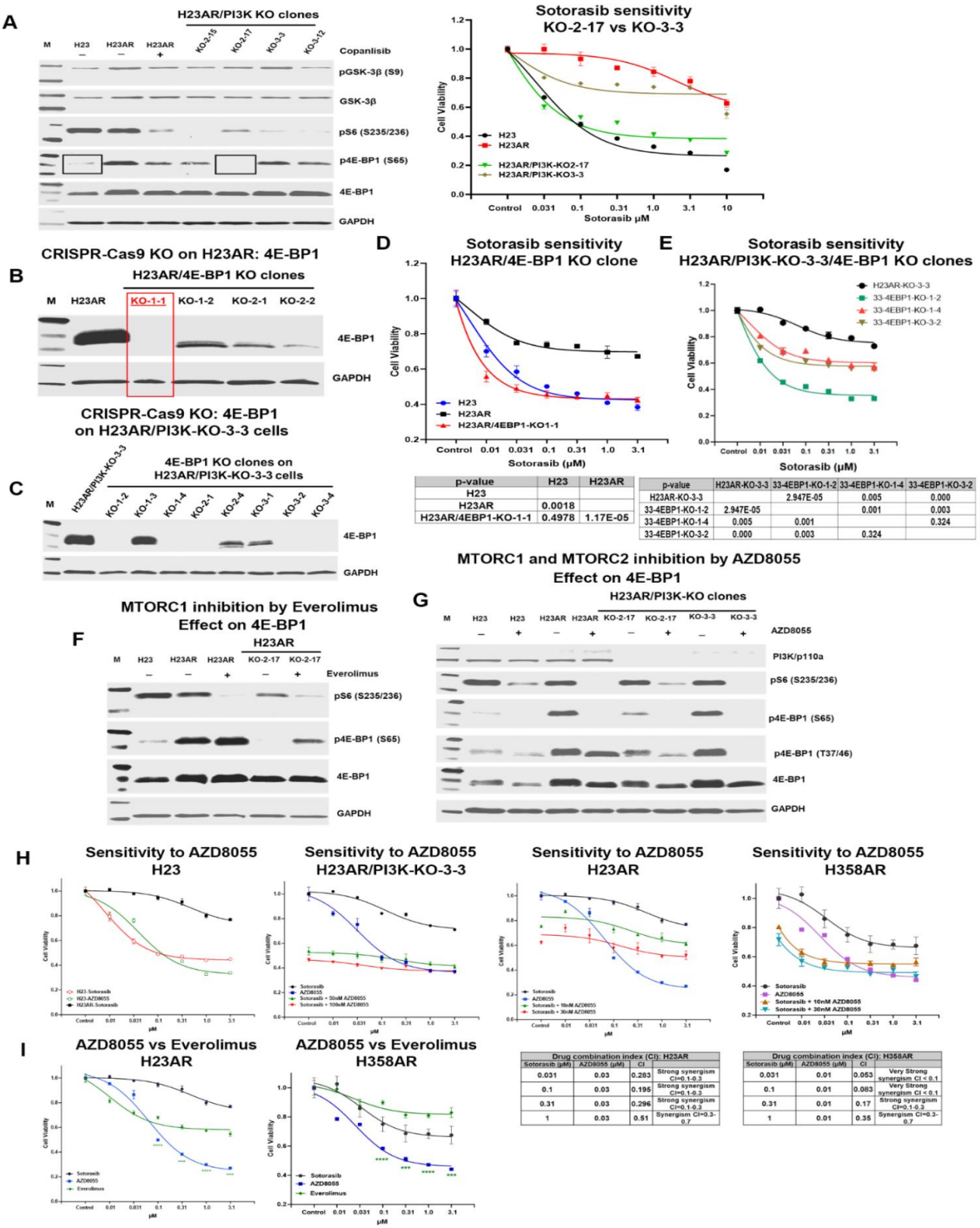


Figure 6



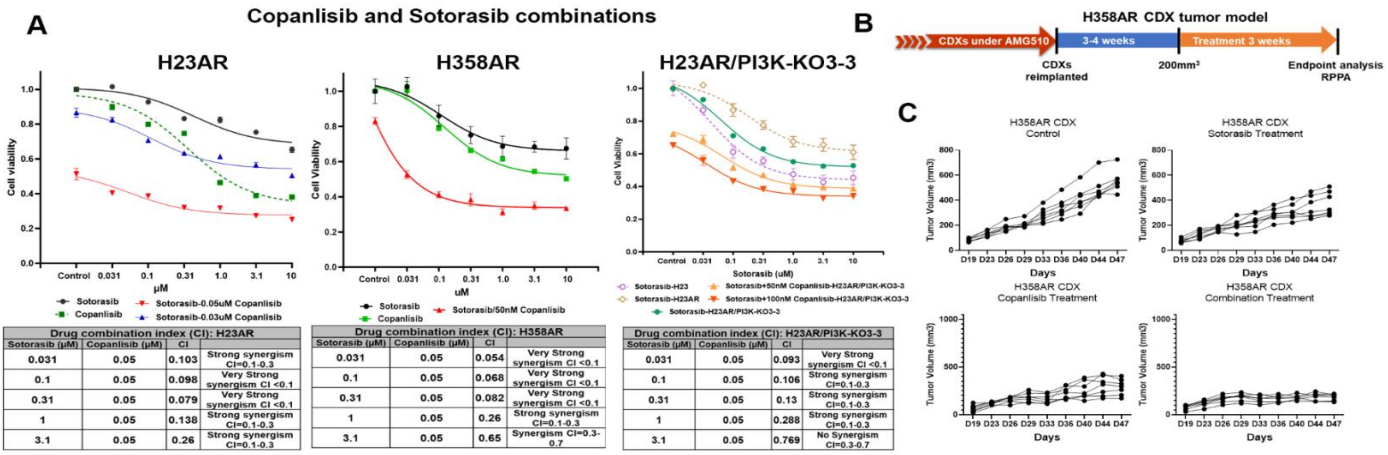
p-value	H23	H23AR
H23		
H23AR	0.0018	
H23AR/4EBP1-KO-1-1	0.4978	1.17E-05

p-value	H23AR-KO-3-3	33-4EBP1-KO-1-2	33-4EBP1-KO-1-4	33-4EBP1-KO-3-2
H23AR-KO-3-3		2.947E-05	0.005	0.000
33-4EBP1-KO-1-2	2.947E-05		0.001	0.003
33-4EBP1-KO-1-4	0.005	0.001		0.324
33-4EBP1-KO-3-2	0.000	0.003	0.324	

Drug combination index (CI): H23AR			
Sotorasib (μM)	AZD8055 (μM)	CI	
0.031	0.03	0.283	Strong synergism CI=0.1-0.3
0.1	0.03	0.195	Strong synergism CI=0.1-0.3
0.31	0.03	0.296	Strong synergism CI=0.1-0.3
1	0.03	0.51	Synergism CI=0.3-0.7

Drug combination index (CI): H358AR			
Sotorasib (μM)	AZD8055 (μM)	CI	
0.031	0.01	0.053	Very Strong synergism CI < 0.1
0.1	0.01	0.083	Very Strong synergism CI < 0.1
0.31	0.01	0.17	Strong synergism CI=0.1-0.3
1	0.01	0.35	Synergism CI=0.3-0.7

Figure 7



Drug combination index (CI): H23AR

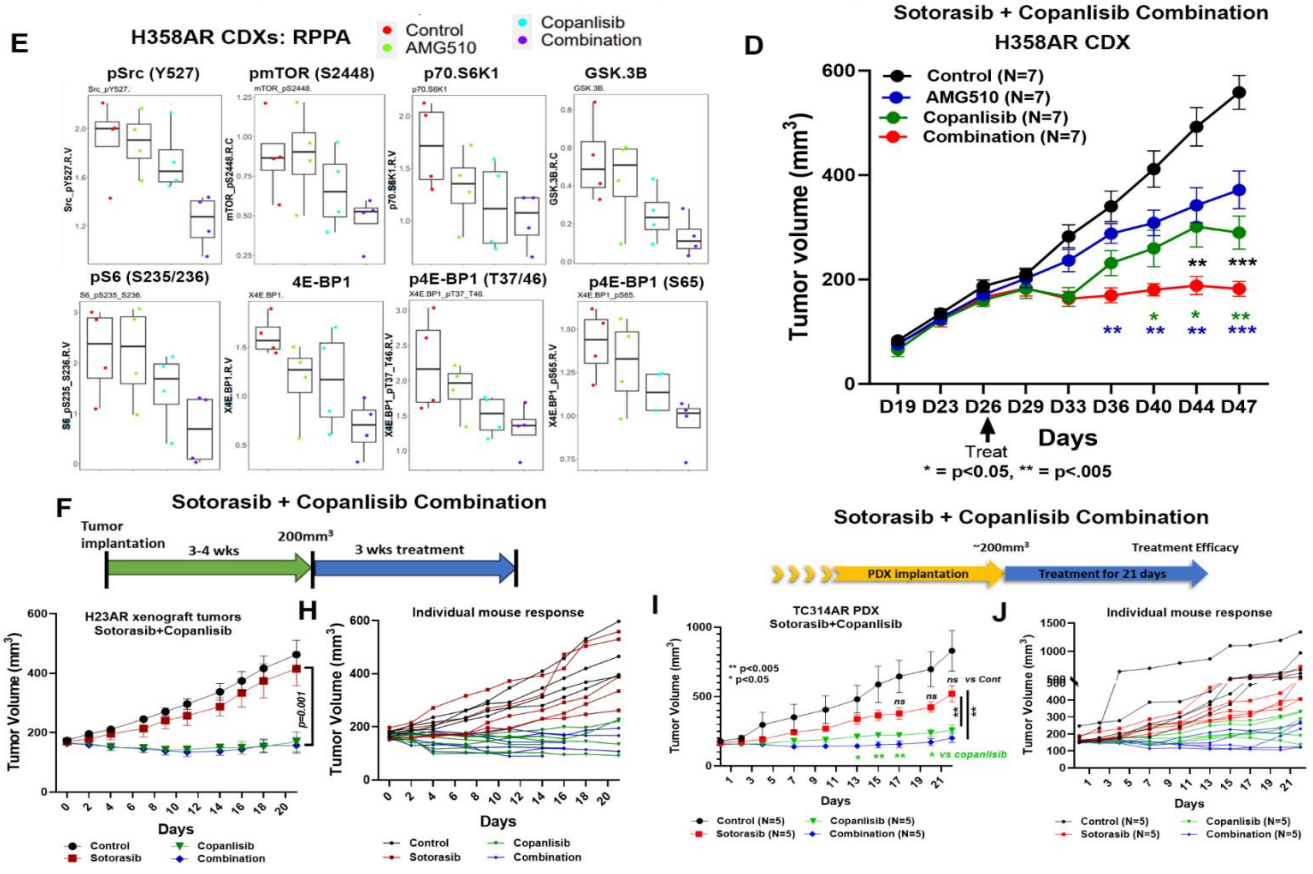
Sotorasib (μM)	Copanlisib (μM)	CI	
0.031	0.05	0.103	Strong synergism CI=0.1-0.3
0.1	0.05	0.098	Very Strong synergism CI <0.1
0.31	0.05	0.079	Very Strong synergism CI <0.1
1	0.05	0.138	Strong synergism CI=0.1-0.3
3.1	0.05	0.26	Strong synergism CI=0.1-0.3

Drug combination index (CI): H358AR

Sotorasib (μM)	Copanlisib (μM)	CI	
0.031	0.05	0.054	Very Strong synergism CI <0.1
0.1	0.05	0.068	Very Strong synergism CI <0.1
0.31	0.05	0.082	Very Strong synergism CI <0.1
1	0.05	0.26	Strong synergism CI=0.1-0.3
3.1	0.05	0.65	Synergism CI=0.3-0.7

Drug combination index (CI): H23AR/PI3K-KO3-3

Sotorasib (μM)	Copanlisib (μM)	CI	
0.031	0.05	0.093	Very Strong synergism CI <0.1
0.1	0.05	0.106	Strong synergism CI=0.1-0.3
0.31	0.05	0.13	Strong synergism CI=0.1-0.3
1	0.05	0.288	Strong synergism CI=0.1-0.3
3.1	0.05	0.769	No Synergism CI=0.3-0.7



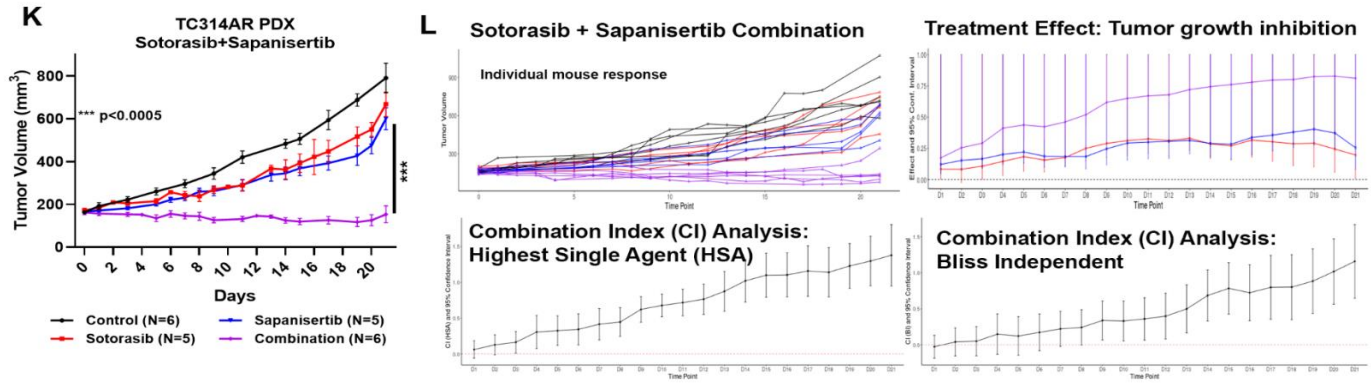


Figure 2-figure supplement 1

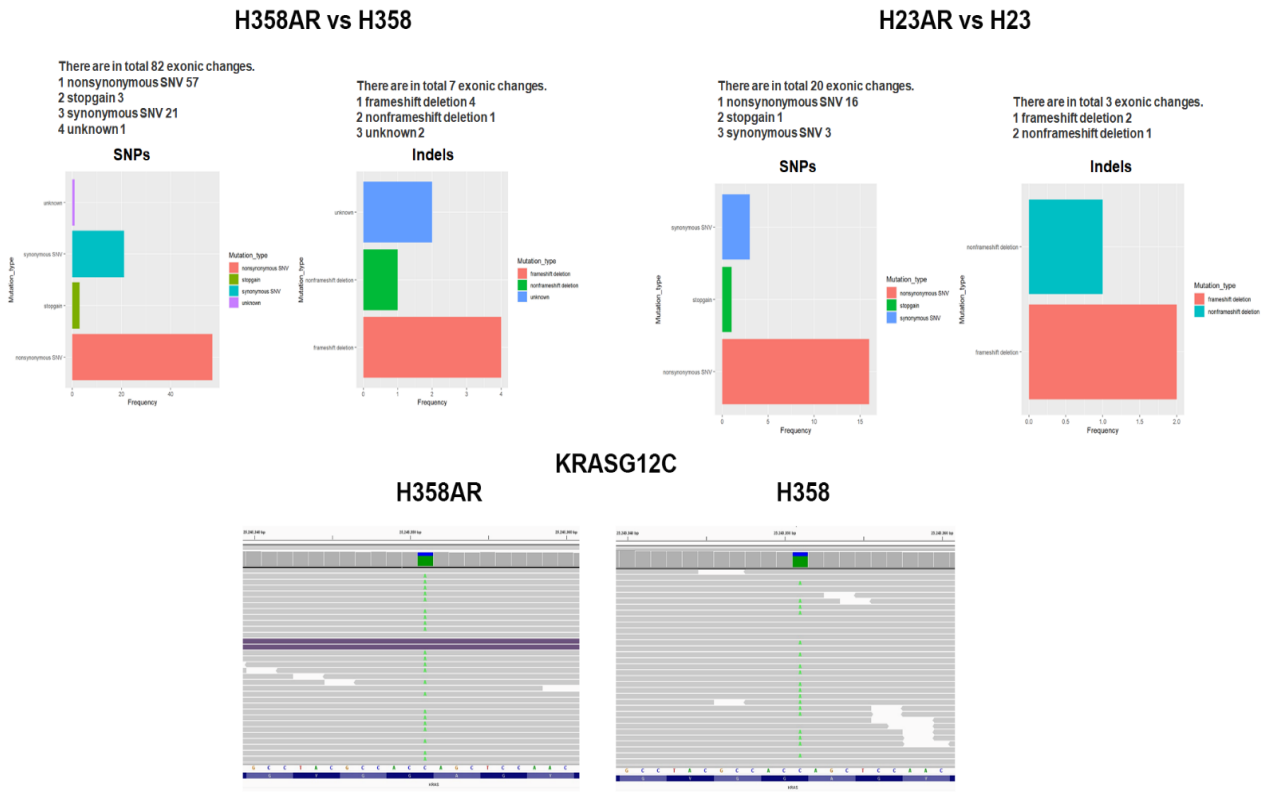


Figure 3-figure supplement 1

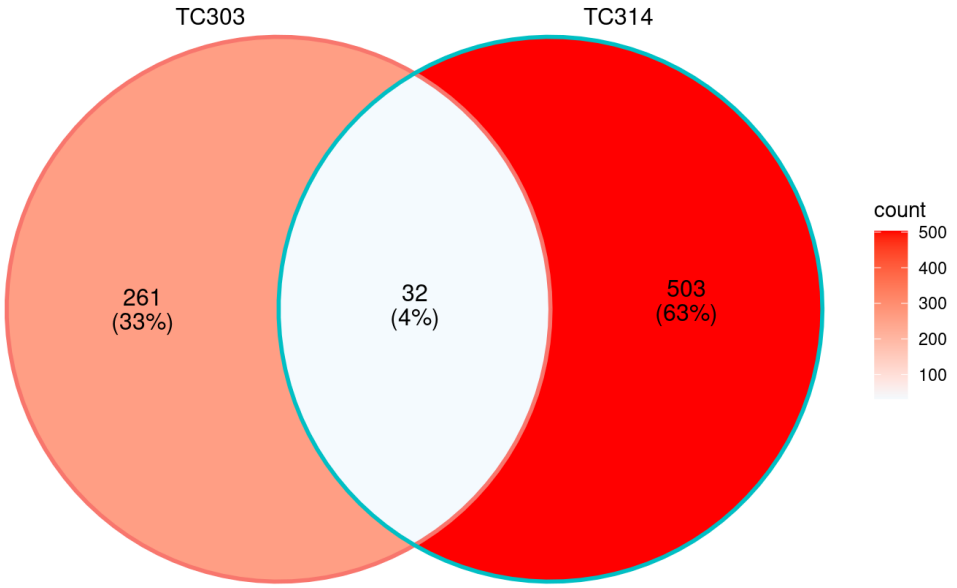
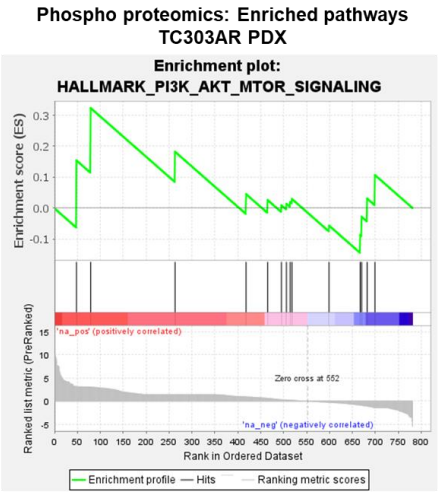
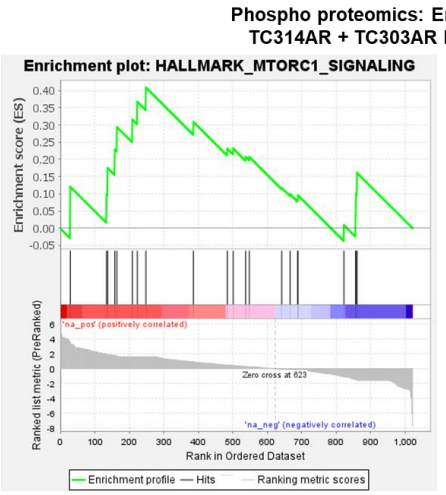


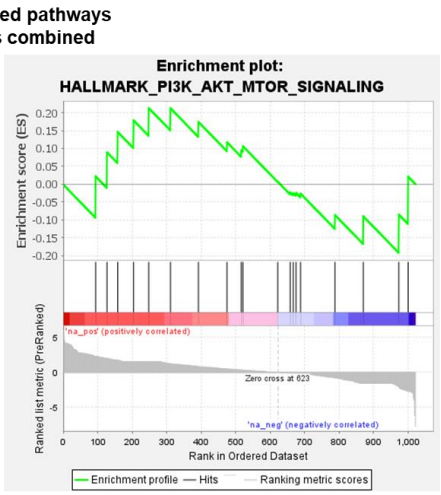
Figure 3-figure supplement 2



GeneSet	HALLMARK_PI3K_AKT_MTOR_SIGNAL
Enrichment Score (ES)	0.3233773
Normalized Enrichment Score (NES)	0.8251487
Nominal p-value	0.7
FDR q-value	1.0
FWER p-Value	1.0

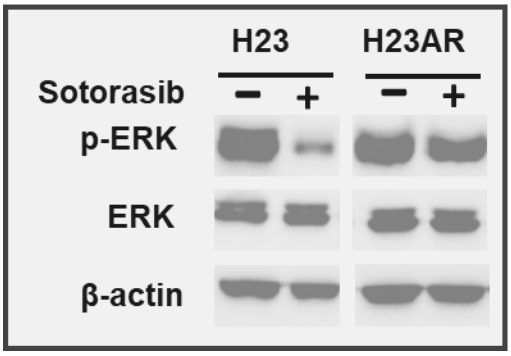


GeneSet	HALLMARK_MTORC1_SIGNALING
Enrichment Score (ES)	0.4084348
Normalized Enrichment Score (NES)	1.1978571
Nominal p-value	0.23219374
FDR q-value	0.8130257
FWER p-Value	0.998



GeneSet	HALLMARK_PI3K_AKT_MTOR_SIGNAL
Enrichment Score (ES)	0.21299917
Normalized Enrichment Score (NES)	0.611151
Nominal p-value	0.94524497
FDR q-value	0.989439
FWER p-Value	1.0

Figure 3-figure supplement 3



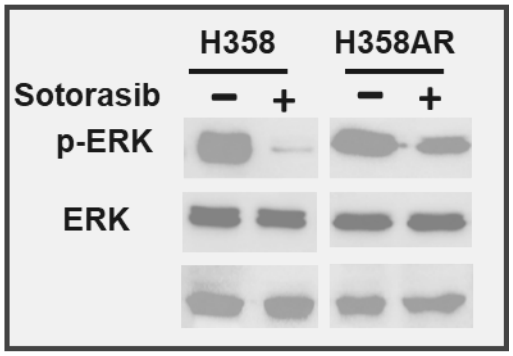


Figure 7-figure supplement 1A

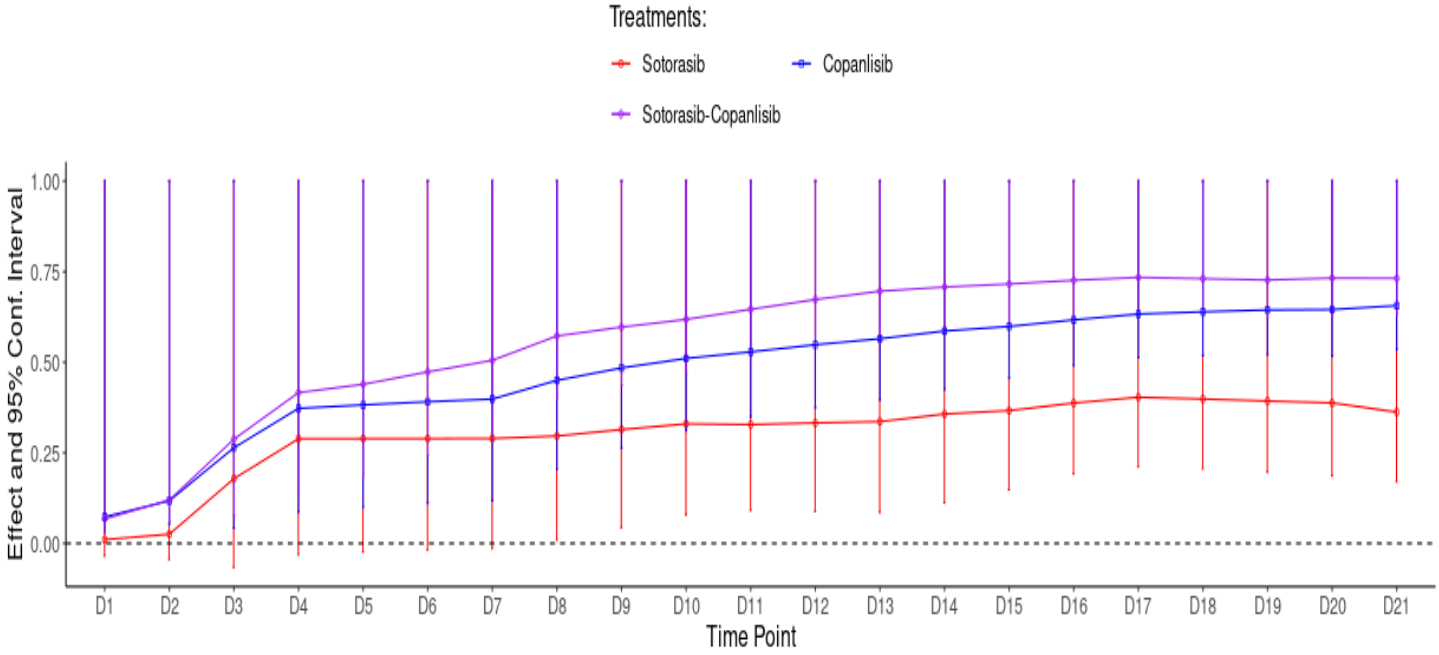
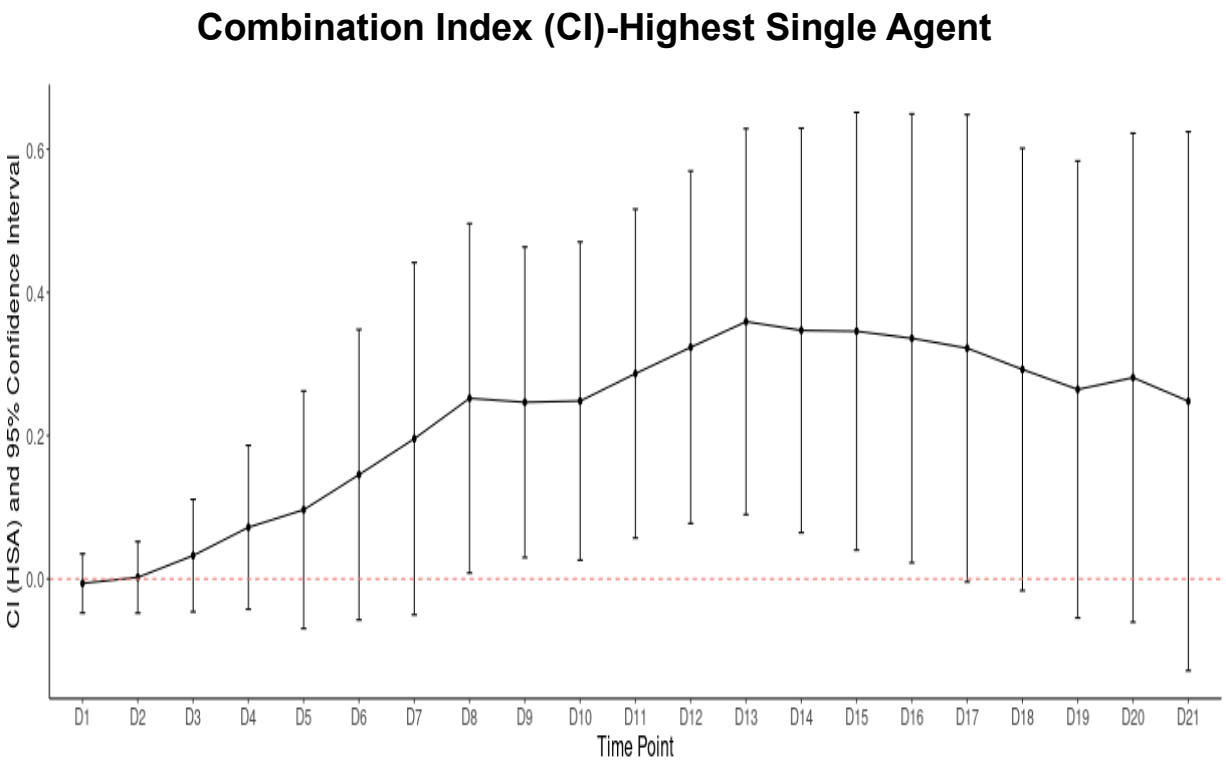


Figure 7-figure supplement 1B



Highest Single Agent analysis Results

Time Point	CI	se	L95	U95	p.value	n.C	n.A	n.B	n.AB
D1	-0.006	0.021	-0.047	0.035	0.771	5	5	5	5
D2	0.002	0.025	-0.048	0.052	0.929	5	5	5	5
D3	0.033	0.040	-0.046	0.111	0.414	5	5	5	5
D4	0.072	0.058	-0.042	0.187	0.217	5	5	5	5
D5	0.097	0.085	-0.069	0.262	0.253	5	5	5	5
D6	0.146	0.103	-0.057	0.348	0.159	5	5	5	5
D7	0.196	0.125	-0.050	0.442	0.119	5	5	5	5
D8	0.252	0.124	0.008	0.496	0.043	5	5	5	5
D9	0.247	0.111	0.030	0.463	0.026	5	5	5	5
D10	0.248	0.113	0.026	0.471	0.028	5	5	5	5
D11	0.287	0.117	0.057	0.516	0.014	5	5	5	5
D12	0.323	0.125	0.078	0.569	0.010	5	5	5	5
D13	0.359	0.137	0.090	0.629	0.009	5	5	5	5
D14	0.347	0.144	0.065	0.629	0.016	5	5	5	5
D15	0.346	0.156	0.040	0.651	0.027	5	5	5	5
D16	0.336	0.160	0.023	0.649	0.036	5	5	5	5
D17	0.322	0.166	-0.004	0.648	0.053	5	5	5	5
D18	0.292	0.158	-0.016	0.601	0.063	5	5	5	5
D19	0.265	0.163	-0.054	0.584	0.104	5	5	5	5
D20	0.281	0.174	-0.060	0.622	0.107	5	5	5	5
D21	0.248	0.192	-0.128	0.624	0.196	5	5	5	5
Global	0.223	NA	NA	NA	NA	5	5	5	5

Figure 7-figure supplement 2A

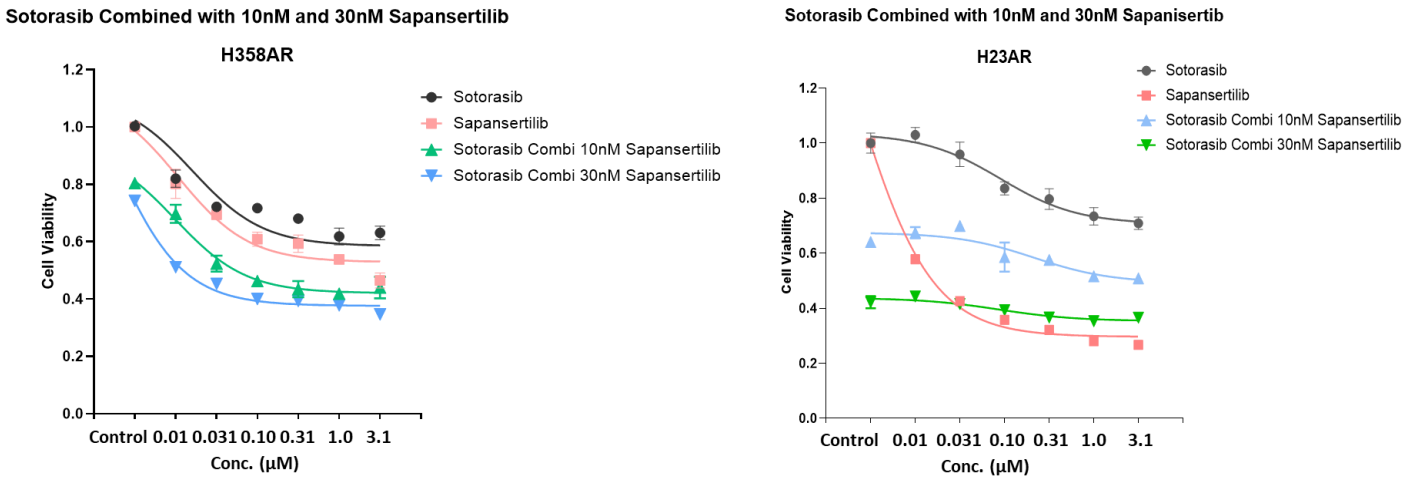
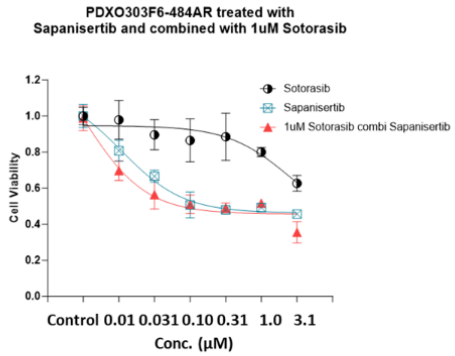
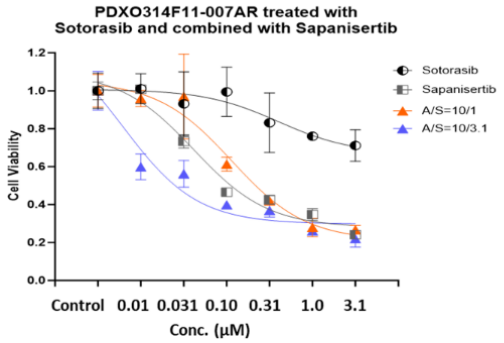


Figure 7-figure supplement 2B





CI For experimental values			
Sapanisertib	AMG510	Fa	CI
(μM)	(μM)		
0.01	1	0.31287	0.365
0.031	**1**	**0.44405**	**0.126**
0.1	**1**	**0.49668**	**0.178**
0.31	**1**	**0.51673**	**0.404**
1	1	0.49091	1.948
3.1	1	0.65036	0.464

A(Sotorasib)/S(Sapanisertib)=10/1

CI For experimental values			
AMG510	Sapanisertib	Fa	CI
(μM)	(μM)		
0.01	0.001	0.0001	6.64E+05
0.031	0.0031	0.029643	17.423
0.1	**0.01**	**0.38657**	**0.165**
0.31	**0.031**	**0.580157**	**0.154**
1	**0.1**	**0.720508**	**0.224**
3.1	0.31	0.732607	0.648

A(Sotorasib)/S(Sapanisertib)=10/3.1

CI For experimental values			
AMG510	Sapanisertib	Fa	CI
(μM)	(μM)		
0.01	**0.0031**	**0.401311**	**0.036**
0.031	**0.00961**	**0.437728**	**0.085**
0.1	**0.031**	**0.600874**	**0.085**
0.31	**0.0961**	**0.631464**	**0.212**
1	**0.31**	**0.739257**	**0.313**
3.1	0.961	0.780044	0.705