

# Passenger mutations in 2500 cancer genomes: Overall molecular functional impact and consequences

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## Abstract

The Pan-cancer Analysis of Whole Genomes (PCAWG) project provides an unprecedented opportunity to comprehensively characterize a vast set of uniformly annotated coding and non-coding mutations present in thousands of cancer genomes. Classical models of cancer progression posit that only a small number of these mutations strongly drive tumor progression and that the remaining ones (termed “nominal passengers”) are considered inconsequential for tumorigenesis. In this study, we leverage the comprehensive variant data from PCAWG to ascertain the molecular functional impact of each variant, including nominal passengers. This allows us to decipher their overall impact uniformly over different genomic elements, both coding and non-coding. The molecular impact distribution of PCAWG mutations shows that, in addition to high-impact drivers and low-impact passengers, there is a group of medium-impact passenger variants predicted to influence gene expression or activity. Furthermore, we find that functional impact relates to the underlying mutational signature: different signatures confer contrasting molecular impact, differentially affecting distinct regulatory subsystems and different categories of genes. Also, we find that molecular functional impact varies based on subclonal architecture (i.e. early vs. late mutations) and can be related to patient survival. Furthermore, we adapt an additive effects model from complex trait studies to show that low & medium impact variants in combination are highly predictive of observed cancer genotypes against a neutral (null) model. We further use the additive effects model to provide a conservative estimate of the number of weak drivers and deleterious passengers in different cancer cohorts. Finally, we delineate multiple suggestive lines of evidence that correlate the overall burdening of cancer mutations with the existence of both weak positive and negative selection during tumor evolution.

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## Introduction

Previous studies have focused on characterizing variants occupying coding regions of cancer genomes [\cite{24071849}](#). However, the extensive Pan-cancer Analysis of Whole Genomes (PCAWG) dataset, which includes variant calls from ~2500 uniformly processed whole cancer genomes, offers an unparalleled opportunity to investigate the overall molecular functional impact of variants influencing [coding and](#) different non-coding genomic elements. Given that the majority of cancer variants lie in non-coding regions [\cite{26781813}](#), this variant dataset serves as a substantially more informative resource than the many existing datasets focused on exomes. Moreover, it also contains a full spectrum of variants, including copy number variants (CNVs) and large structural variants (SVs), in addition to single-nucleotide variants (SNVs) and small insertion & deletions (INDELS).

Of the 30 million SNVs in the PCAWG [variant](#) data set, a few thousand ( $< 5/\text{tumor}^1$ ) [\cite{26559569}](#) can be identified as driver variants, [i.e.](#) positively selected variants that favor tumor growth, [by recurrence based driver detection methods](#). The remaining ~99% of SNVs are termed passenger variants, with poorly understood molecular consequences and fitness effects. Recent studies have proposed that, among variants that have not been found to be driver variants (i.e. nominal passenger variants), some may weakly affect tumor cell fitness by promoting or inhibiting tumor growth. In prior studies, these variants have been described as “mini-drivers” [\cite{26456849}](#) and “deleterious passengers” [\cite{2338863}](#), respectively. [Presence of mini-drivers and deleterious passengers in a cancer genome is difficult to detect but conceivable. For example, due to the interconnectedness of cellular pathways, it is plausible that mutations in many pathways could impact cellular growth and survival. However, it is computationally challenging to detect mini-drivers and deleterious passengers because power analyses indicate that variants under weak selection cannot be reliably identified by recurrence analysis \cite{24390350}.](#)

[Presence of few drivers \(with high positive fitness effects\) and large numbers of nominal passengers \(with weak fitness effects\) is analogous to prior observations in genome-wide association studies \(GWAS\) that implicate a handful of moderate-effect variants that influence complex traits. Moreover, these modest number of variants explain only a small proportion of the predicted genetic variance, thus contributing to the “missing heritability” problem, in GWAS \cite{20562875,19571811}.](#) However, aggregating [remaining variants with weak-effect can explain a significant part of “missing heritability” and is predictive of disease risk. A recently proposed “omnigenic model” takes this logic a step further, arguing that the majority of complex traits are influenced by thousands of variants with individually small effects \cite{28622516}](#). Although these models for complex disease are intriguing, [they are also controversial, and further studies are required to test them. Nonetheless, such models](#)

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highlight the importance of investigating the cumulative effect of nominal passenger mutations in cancer to understand their potential roles in cancer progression.

Thus, we leverage the comprehensive PCAWG variant dataset to address this key question. We built on existing tools [\cite{25273974}](#) to annotate and score the predicted molecular impact of each variant, including SNVs, INDELS and SVs in the pan-cancer dataset. We observed that disruption of genetic regulatory elements in the noncoding genome correlates with altered gene expression. Moreover, various [\cite{25273974}](#) processes have different impacts on the regulatory elements as elucidated by our signature analysis. We also found that overall functional impact correlates with patient survival, subclonal architecture, and tumor heterogeneity. Finally, we observed suggestive evidences consistent with the notion that aggregated subsets of functionally impactful passenger variants may confer weak selection avenues to tumor cells.

### Aggregated nominal passengers and additive variance

We first adapted an additive effects model, originally used in complex trait analysis, to quantify aggregated effects of nominal passengers on tumorigenesis, and the relative size of these aggregated effects in relation to known drivers [\cite{20562875,21167468}](#). We created a balanced sample of observed tumor and matched neutral (null) model samples, where the latter preserve the mutational signatures and local mutation rates of the observed samples. We tested the ability of this model to predict cancerous from null samples using the additive model. Briefly, we apply different thresholds on predicted molecular functional impact levels (using Funseq impact scores [\cite{24092746}](#); See Supplemental Note) to identify set of variants. The additive effects model associates a positive or negative effect (coefficient) to each SNV in a linear model, and considers them to be sampled from a normal distribution. The variance of the distribution controlling the effect/coefficient sizes is optimized as a hyper-parameter along with the variance of residuals using restricted maximum-likelihood (REML) [\cite{21167468}](#). Consequently, predictive power of the model can be measured by quantifying the additive variance, which is equivalent to  $\sigma_A^2$ .

We applied this model in 8 cancer cohorts (where sample size > 100) and observed significant predictive power in 5 cohorts while considering only non-coding nominal passenger SNVs, at FDR<0.1 (Supp Fig. X). In contrast, including nominal passengers from both coding and non-coding regions provided significant predictive power in seven cohorts at an FDR<0.001. Furthermore, we observed that across tumor types, the predictive power of nominal passengers is optimized at a higher impact threshold in coding regions than in non-coding regions, suggesting an enrichment of medium impact SNVs with non-neutral effects in coding regions. Additionally, we compared a variation of the additive effects model in which variants are pooled at the gene level, which demonstrated increased predictive power, and

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showed that, as a whole, the nominal passengers increase the predictive power by ~X% relative to known drivers.

### **Predicted functional impact**

If these nominal passenger variants do indeed exert a combined effect on tumor cell fitness, one would expect that this effect is mediated through their molecular functional impact. Therefore, we surveyed the putative molecular functional impact distribution of somatic variants in different cancer genomes. The predicted molecular functional impact distribution varies among different cancer types and for different genomic elements. A closer inspection of the pan-cancer impact score distributions for non-coding variants demonstrated three distinct peaks. The upper and the lower extremes of this distribution correspond to traditional definitions of high-impact putative driver variants and low impact neutral passengers respectively. In contrast, the middle peak in the intermediate molecular functional impact regime corresponds to what we term *impactful nominal passengers*. This intermediate functional impact category potentially includes undiscovered drivers (strong & weak) as well as potentially deleterious passengers (Fig 1a).

Subsequently, we investigated whether frequency of these *impactful nominal passengers* in a cancer cohort is proportionate to its total mutational burden. For a uniform mutation distribution, we would expect that the fraction of *impactful nominal passengers* will remain constant as one accumulates large number of mutations in a given cancer sample. In contrast, we observed that as we acquire more SNVs in cancer, the fraction of impactful passengers decreases. This trend is particularly strong in CNS medulloblastoma ( $p < 4e-8$ , Bonferroni's correction), lung adenocarcinoma ( $p < 3e-4$ , Bonferroni's correction), and a few other cancers (Fig 1b).

In addition to SNVs, large structural variations (SVs) also play important role in cancer progression. Thus, we quantified the putative molecular functional impact of SVs (deletions and duplications). A close inspection of both SV and SNV impact scores suggest that certain cancer subtypes tend to harbor large number of high impact SVs, while others were more burdened with high impact SNVs. Many of these correlations have previously been observed <sup>24071851</sup>. For example, it is known that large deletions play role of drivers in ovarian cancer, whereas clear cell kidney cancer is often driven by SNVs. However, we also find new associations, such as the predominance of high impact large deletions compared to impactful SNVs in the bone leiomyoma cohort.

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### Burdening of different genomic elements

Simplistically, one might assume that the overall burden of nominal passengers in a cancer genome will be uniformly distributed across different functional elements and among different gene categories. In contrast, we observe that the predicted molecular impact burden in certain cancers is concentrated in particular regulatory regions and gene categories. This is easiest to understand in terms of coding loss-of-function (LoF) variants, where the putative molecular impact is most intuitive. Consequently, we examined the fraction of deleterious LoFs affecting genes across four categories of cancer-related functional annotation (Fig 2a). As expected, driver LoF variants showed significant enrichment in each category of cancer-related genes compared to a random (shuffled-variant) control ( $p < 0.001$ ). Conversely, non-driver LoF SNVs displayed depletion in each of these categories ( $p < 0.001$ ). As expected, driver, non-driver, and random loss of function mutations were all enriched in comparison to germline LoF mutations ( $p < 0.001$ ).

Similar to LoF variants, we can also quantify the overall burden of the noncoding SNVs in a cancer genome. However, for majority of noncoding variant, predicted molecular functional impact is less easy to gauge. For instance, coding and noncoding variants occupying the terminal region of the gene or intronic regions, will most likely have little functional consequence. In contrast, transcription factor binding site (TFBS) variants are among the noncoding variants, where molecular impact is clearly manifested through the creation or destruction of transcription factor (TF) binding motifs (gain or loss of motif). In both cases (gain or loss), we observed significant differential burdening of TFBS among different cancer cohorts. For instance, we detect significant enrichment of high impact variants creating new motifs in various TFs including GATA, PRRX2 and SOX10 (Fig 2b) across major cancer types, compared with uniform expectation. Similarly, high impact variants breaking motifs, were highly enriched in TFs such as IRF, POU2F2, NR3C1 and STAT (Fig 2b) in the majority of cohorts. This selective enrichment or depletion suggests distinct alteration profiles associated with different components of regulatory networks in various cancers.

Furthermore, for a particular TF family, one can identify their target genes affected due to bias towards creation or disruption of specific motifs in their regulatory elements (promoters and enhancers). For instance, TERT shows the largest alteration bias for ETS motif creation across a variety of cancer types (Fig 3d), with other genes (such as BCL6) showing a similar bias, albeit in fewer cancers. Furthermore, enrichment of SNVs in selective TF motifs leads to gain and break events in promoter that significantly perturb the overall downstream gene expression (Fig 2c). For example, ETS family transcription factor at the regulatory region of TERT and PIM1 gene displayed a strong motif creation bias and a significant change in gene expression (with p-value TERT=0.001 and p-value PIM1=0.019) (supplement X).

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Finally, we also analyzed the overall burden of structural variants (SVs) in various genomic elements and compared the pattern of somatic SV enrichment in cancer genomes with those from germline. First, we observed that as expected, somatic SVs were more enriched among functional regions compared to germline SVs, because the latter ones will be under negative selection for disrupting functional regions. Furthermore, we observed a distinct pattern of enrichment for SVs that split a functional element versus those that engulf it. As has been previously noted, there is greater enrichment of germline SVs that engulf an entire functional element rather than for those break a functional element partially. Moreover, we observed the same pattern for somatic SVs, which is contrary to what one would expect from a purely random expectation.

### Signature Analysis

The differential burdening of various genomic elements can be further explained by closely inspecting the underlying mutational processes generating SNVs. These mutational processes are considered to play an important role during tumor growth through their frequent occurrence among specific tri-nucleotides, genes and regulatory elements. For instance, it is expected that mutational processes targeting stop codons will be highly correlated with the number of nonsense mutations observed in a cancer sample. Indeed, we found a high correlation between the mutation pattern and the number of expected nonsense mutations within cancer types. However, these correlations are highly heterogeneous among different cancer cohorts. For instance, we observed a high degree of correlation between mutation spectrum profile and the number of nonsense mutations within melanoma and colorectal adenocarcinoma cohorts. However, these correlations are relatively lower among samples in melanoma compared to colorectal cancer cohort.

Similarly, the disproportionate functional load on certain TFs in cancers can be related to an underlying mutational spectrum (signature) influencing their binding sites. For instance, the mutational spectrum of motif breaking events observed in SP1 TFBS, suggests major contribution from C>T and C>A mutations (Fig 4b). In contrast, motif-breaking events at TFBS of HDAC2 and EWSR1 have relatively uniform mutational profiles. In addition, comparing the signature composition of low and high impact SNVs in certain cancer-cohorts can help us to distinguish between mutational processes that generate distinct variant impact classes. We observed distinct signature distributions for the low and high impact non-coding passengers for multiple cancer cohorts including Liver-HCC, Prost-AdenoCA and Kidney-RCC. For instance, in the Kidney-RCC cohort, although the majority of passenger variants can be explained by signature 5, high impact passengers have a higher fraction of SNVs explained by signature 4 (Fig4c). Finally, we also observed that cancers showing microsatellite instability (MSI), due to failure of DNA mismatch repair, have a higher percentage of high impact non-coding passengers (Fig4d) compared

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to microsatellite stable (MSS) cancer samples. Collectively, these findings suggest that various mutational processes shape and disproportionately burden cancer genomes.

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### Subclonal architecture and cancer progression

Furthermore, we also explored the role of impactful passenger variants in cancer evolution by analyzing variants in the context of their associated tumor sub-clone. One might hypothesize that high impact mutations achieve greater prevalence in tumor cells if they are advantageous to the tumor, and a lower prevalence if deleterious. Interestingly, there is evidence to corroborate this hypothesis. We observed that high impact passenger variants in coding regions have greater prevalence among parental subclones (Fig 5a) – an effect driven by high impact nominal passenger SNVs in tumor suppressor and apoptotic genes (Fig 5a). In contrast, high impact passenger SNVs in oncogenes appear slightly depleted. Similarly, impactful SNVs in DNA repair genes and cell cycle genes are depleted in early subclones (Fig 5a).

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Furthermore, we also measured divergence in variant allele frequency (VAF) to indirectly quantify tumor prevalence heterogeneity in the pan-cancer data. As expected, we observe lower heterogeneity among high impact nominal passenger SNVs. This observation is consistent for both coding and non-coding nominal passenger variants (Fig 5b).

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Similarly, we closely analyzed VAF of cancer variants to explore whether nominal passengers with high functional impact correlates with their underlying conservation score. Highly conserved positions (i.e. those with high GERP) are expected to be important as polymorphisms at those positions could potentially hurt cellular function and in other cases it could potentially promote undue cellular fitness (i.e. cancer). As expected, we observe that in PCAWG driver genes, VAF and GERP have a small but statistically significant positive correlation (with coefficient 0.0040 and p-value 0.0046). Interestingly, among nominal passengers, we observed that increasing impact scores correlated with decreasing VAF.

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Additionally, we also sought to examine whether the observed cumulative molecular impact of variants can be associated with tumor initiation and progression. Therefore, we performed survival analysis to see if somatic molecular impact burden – the mean GERP of somatic passenger variants per patient – predicted patient survival within individual cancer subtypes. Furthermore, patient age at diagnosis and total number of mutations were used as covariates in the survival analysis. We obtained significant correlation between overall molecular impact burden and survivability in two cancer subtypes after multiple test correction. For instance, we observed that somatic mutation burden predicted substantially better patient survival in lymphocytic leukemia (Lymph-CLL, p-value 0.00023) and ovary adenocarcinoma (Ovary-AdenoCA, p-value 0.0020) (Fig2b). The prolonged survival of high mean GERP patients in these subtypes is consistent with the possibility that an important subset of mutations at conserved positions are deleterious to tumor cells and benefit the patient.

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### **Categorizing nominal passenger variants**

Through our analysis of the molecular functional impact of nominal passenger variants, we observed multiple manifestations that are suggestive of nominal passenger's impact on tumor cell fitness.

Conceptually, variants can be classified into three categories based on their impact on tumor cell fitness:

drivers with positive selective effects, passengers with neutral selective effects, and deleterious passengers with negative selective effects. This broad classification can be further refined by considering ascertainment-bias and the putative molecular impact of different variants (Fig 6). Previous power analyses [24390350] suggest that existing cohort sizes support the identification of strong positively-selected driver variants, but that many weaker drivers, and even some moderately strong driver variants would be missed. However, these moderately strong and weak driver variants can also provide potential fitness advantage to tumor cells. As for the functional-impact-based-classification: any positively or negatively selected variants will have some functional impact (i.e. effect on gene expression or activity). The relevance of molecular functional impact is firmly established for driver mutations - positively-selected variants promoting tumor growth. However, rapid accumulation of weak and strong deleterious passengers, which undergo negative selection, could adversely affect the fitness of tumor cell [23388632]. Moreover, a majority of low impact and some high functional impact variants may alter tumor gene expression or activity in ways that are not ultimately relevant for tumor fitness; hence, these variants will undergo neutral evolution.

### **Estimating number of weak drivers and deleterious passenger variants**

In the context of this conceptual categorization of variants in cancer, we used the additive effects model to estimate the frequency of weak drivers and deleterious passengers in various cancer cohorts through their combined ability to predict cancerous from matched neutral samples. As observed, these variants tend to have small effect sizes and current datasets are underpowered to detect them individually. However, we can estimate a lower bound on the number of the nominal passengers with non-neutral effects. This can be estimated to be the size of the smallest subset of SNVs needed to reach the same predictive accuracy (measured using  $\sigma_A^2$ ) as when using all nominal passengers collectively (See Supplemental Note). Further, having estimated  $\sigma_A^2$ , we find the maximum a-posteriori predictor for the effect of each individual SNV, and use the predicted effect signs to estimate the number of weak drivers and deleterious passengers per tumor across the smallest subset. A conservative estimate of the number of deleterious passengers removed can be made by comparing the mean estimate in the neutral samples with that in the observed tumors. In general, we observe that the number of deleterious passengers removed is predicted to exceed the number of weak drivers across most tumors, with a pan-cancer average of ~18 weak drivers per tumor, and ~60 deleterious passengers removed (Fig. 6B). We also observe differential proportions of

Moved up [2]: variants in cancer evolution by analyzing variants in the context of their associated tumor sub-clone. One might hypothesize that high impact mutations achieve greater prevalence in tumor cells if they are advantageous to the tumor, and a lower prevalence if deleterious. Interestingly, there is evidence to corroborate this hypothesis. We observed that high impact passenger variants in coding regions have greater prevalence among parental subclones (Fig 5a) – an effect driven by high impact nominal passenger SNVs in tumor suppressor and apoptotic genes (Fig 5a). In contrast, high impact passenger SNVs in oncogenes appear slightly depleted. Similarly, impactf [... [7]

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weak drivers and deleterious passengers across different cancer cohorts. For instance, melanoma samples are highly mutated as well as predicted to have a large proportion of removed deleterious passengers. We further analyze the enrichment of functional gene categories within the smallest subset of weak drivers and deleterious passengers, and show it to be enriched in essential genes, and specific gene categories for particular tumors (Supp. Fig. X).

Similarly, we also employed a VAF-based alternative approach to estimate the number of deleterious passenger mutations, which are removed and retained during tumor progression. To estimate the number of removed noncoding deleterious passengers per tumor, we compared the observed number of high-impact noncoding mutations with the number expected under a neutral model. We observed a slight (2%) depletion in high-impact mutations in the observed mutation set versus the null, corresponding to a median of 48 high-impact noncoding mutations removed per tumor. This depletion was most pronounced at the promoters of essential genes in genomic regions impacted by loss-of-heterozygosity (32%). This depletion was most pronounced at the promoters of essential genes in genomic regions. Similar calculations applied to VAF differences among impact levels of variants outside driver gene sets suggests that there are on average 8.6 retained deleterious passenger variants per tumor. These are again conservative estimates, as we naively assume that latent drivers and deleterious passengers exert a VAF effect equal in magnitude to discovered drivers, when in fact, their true effect is likely smaller.

### Discussion

Previous studies [cite{20562875}](#) related to the missing heritability problem in GWAS, indicate that cumulative effect of SNVs can explain the majority of missing associations. Similarly, here we investigate whether the cumulative molecular impact of many weak somatic SNVs can have a meaningful role in cancer progression. Intuitively, tumor cells must maintain function of some minimal set of essential genes in order to achieve homeostasis. It is plausible that the aggregate effect of functionally impactful passenger variants on these essential genes would be deleterious to tumor cells, [cite{23388632}](#). For instance, radiation therapy and some chemotherapies are believed to kill tumor cells by causing DNA damage, [cite{PARP inhibitor}](#). Similarly, increased mutation counts in coding genes or regions relevant for splicing increase the antigenic cross-section of tumor cells, potentially making them vulnerable to immune surveillance, [cite{}](#). Conversely, any variant that optimizes cell-division at the expense of organism-supporting functions is expected to have a small positive effect on tumor fitness that may be challenging to detect. Moreover, certain variants through their complex genetic regulatory interactions may moderately increase the expression levels of canonical oncogenes. It has been proposed

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that these weak undiscovered driver variants benefit tumor growth and have a small associated positive selection.

In this work, several observations support the notion that some nominal passenger variants undergo weak selection. First, we observed overall enrichment and depletion of nominal passenger variants among TSGs and oncogenes, respectively. An interpretation of this finding is that passenger variants in tumor suppressor genes have weak driver activity, while passenger variants in oncogenes impair oncogenic activity to the detriment to tumor fitness. Similarly, our finding of depletion of nominal passenger variants among DNA repair and cell cycle genes may indicate that high impact variants affecting these genes decrease tumor cell survival in relation to greater mutational burden. Consistent with a possible deleterious effect of passenger variants on tumor growth, in some cancer subtypes, the most mutated tumors have a lower fraction of impactful variants. This may relate to the aggregate impact of passenger variants becoming more deleterious at higher mutation loads. Alternatively, a fixed number of undiscovered drivers may become diluted by neutral passengers at higher mutation counts. Our LoF mutation analysis indicates that driver LoF mutations exert a positive selective effect, whereas non-driver LoF mutations apparently exert a net negative selective pressure. This observation is consistent with prior evidence of net negative selective effect among nominal passenger missense mutations [\cite{}](#). The aggregate fitness impact of nominal passenger variants may help explain why patient survival times are correlated with functional impact load in select cancer subtypes. Finally, using the additive variance model, we provide a conservative [estimate](#) of the number of weak drivers and deleterious passengers in various cancer cohorts.

[Despite these evidences, current background models have limitations as our understanding of different mutational processes in cancer is incomplete. Nonetheless, these observations are intriguing and motivate follow up experiments and further genomic analyses to further explore the role of weak drivers and deleterious passengers in cancer.](#) In conclusion, our work highlights that an important subset of somatic variants originally identified as passengers nonetheless show biologically and clinically relevant functional roles across a range of cancers.

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In the context of germline variants, significant variants found in current GWAS studies only explain a small proportion of total heritability of quantitative traits, the combined analysis of all common variants can account for most of the missing heritability through additive effects. Thus, here we investigate the combined effect of somatic nominal passengers by estimating their additive variance explained as a proportion of the total variance observed in a cancer cohort and the corresponding null model which preserves mutational signatures. Here, we treat the observed (cancerous) versus null model (non-cancerous) labels as a discrete phenotypic trait, and use a liability scale to estimate the additive variance as in genetic disease models. The additive variance is expected to form a component of the heritability of a subclone's fitness, although non-additive effects are expected to play a significant role also in the context of asexual heritability in cancer evolution (supplemental note). We use a linear model with random effects, in which the effect of each SNV is sampled independently from a normal distribution with a common variance parameter,  $\sigma_A^2$ , which estimates the additive variance. Furthermore, we constrain the SNVs in each gene to have a common effect size (creating a 'pooled' model), and estimate  $\sigma_A^2$  from the variance of the random gene-level effects. Using this approach, we identify low & medium impact somatic nominal passengers in non-coding regions to account for significant proportions of the total variance observed in Liver Carcinoma (24.2%) and Skin Melanoma (42.9%).

### **Impactful passengers and their prevalence**

One would expect that if nominal passenger variants does indeed impact tumor cell fitness, its effect should be mediated through its

### **TF binding landscape**

### **Mutational**

### **Overall variant impact**

For a uniform mutation distribution, we would expect that the fraction of *impactful variants* will remain constant as one accumulates large number of mutations in a given cancer sample. In contrast, we observed that as we acquire more SNVs in cancer, the fraction of impactful mutations decreases. This suggests that earlier variants tend to be impactful, and drive the cancer progression. Conversely, later variants are more likely to be random, i.e. collateral damage. This trend is particularly strong in CNS medulloblastoma ( $p < 4e-8$ , Bonferroni's correction), lung adenocarcinoma ( $p < 3e-4$ , Bonferroni's correction), and a few other cancers (**Fig 2c**).

In addition to SNVs, we also analyzed the annotation and overall impact of structural variants (SVs) in the PCAWG dataset. We compared the pattern of somatic SV enrichment in cancer genomes with those from germline.

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### Subclonal architecture and impact score

Furthermore, we also explored the role of impactful

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variants in cancer evolution by analyzing variants in the context of their associated tumor sub-clone. One might hypothesize that high impact mutations achieve greater prevalence in tumor cells if they are advantageous to the tumor, and a lower prevalence if deleterious. Interestingly, there is evidence to corroborate this hypothesis. We observed that high impact passenger variants in coding regions have greater prevalence among parental subclones (**Fig 5a**) – an effect driven by high impact nominal passenger SNVs in tumor suppressor and apoptotic genes (**Fig 5a**). In contrast, high impact passenger SNVs in oncogenes appear slightly depleted. Similarly, impactful SNVs in DNA repair genes and cell cycle genes are depleted in early subclones (**Fig 5a**).

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Furthermore, we also observe low heterogeneity in prevalence among higher impact variants compared to lower impact variants. This observation is consistent for both coding and non-coding variants (**Fig 5c**).

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positively-selected driver variants, neutrally-selected passenger variants, and negatively-selected deleterious passenger variants.

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the philosophy of molecular reductionism holds that

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In addition to increasing the sample size, power to detect these variants can be increased by testing for their combined effect. We

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contributing causally to the cancer phenotype, by determining

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account for an equivalent proportion of the total variance

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they are incrementally added to the model according to their

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sizes. This approach leads to estimates of at least 225 and 140

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