The Landscape of Prostate Tumour Methylation

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Abstract

Prostate cancer is characterized by profound clinical and molecular heterogeneity. While its genomic heterogeneity is well-characterized, its epigenomic heterogeneity remains less understood. We therefore created a compendium of 3,001 multi-ancestry prostate methylomes spanning normal tissue through localized disease of all grades to poly-metastatic disease. A subset of 884 samples had multi-omic DNA and/or RNA characterization. We identify four epigenomic subtypes that risk-stratify patients and reflect distinct evolutionary trajectories. We demonstrate extensive regulatory interplay between DNA ploidy and DNA methylation, with transcriptional consequences that vary across genes and disease stages. We define the epigenetic dysregulation signatures of the 15 most important clinico-molecular features, creating predictive models for each. For example, we identify specific epigenetic features that predict patient outcome and that are synergistic with clinico-genomic prognostic features. These results define a complex interplay between tumour genetics and epigenetics that converges to modify gene-expression programs and clinical presentation.

Introduction

Over 280,000 men were diagnosed with prostate cancer in the United States in 2023; it was the second leading cause of cancer mortality amongst men (1). Prostate cancer is highly heritable, with ~60% of variability in incidence being explained by rare and common germline genetics (2). While the majority of new diagnoses occur when the disease is localized and thus potentially curable, treatment outcomes vary widely (3). Current clinical prognostic factors only partially explain the heterogeneity in clinical outcomes to first-line local and systemic therapies (4). Once prostate cancer has metastasized, it is currently incurable with a five-year survival rate of 37% (5).

While most localised prostate cancers follow a relatively indolent clinical course, a significant number will progress to early metastasis and death. This clinical heterogeneity is matched by extensive genomic heterogeneity. Localized disease in particular exhibits extensive intra- and inter-tumoural variability, which is associated with differences in clinical outcomes (6-10). Somatic genetic heterogeneity is observed alongside extensive epigenomic and gene-expression variability (7,11-16). Aberrant methylation of CpG Islands (CGI) in gene promoter regions is associated with transcriptional inactivation of tumour suppressor genes, oncogene activation and genome instability (17-20). A hypermethylated subtype has been identified in numerous cancers including prostate cancer (21,22). The methylation states of hundreds of individual loci are associated with adverse clinical outcomes (8,23-26) and are additive or synergistic with clinically used biomarkers (27). RNA methylation drives aberrant gene-expression and prostate cancer progression (28). While informative, these studies have been limited in sample size and clinical data, and do not cover the full natural history of the disease. As a result, we have little understanding of how DNA methylation interacts with tumor genetics to shape clinico-molecular phenotypes across disease stages.

To fill this gap, we created a compendium of DNA methylation from 3,001 prostates: 2,355 prostate cancers and 646 non-cancerous prostate tissue. The tumours represent the full range of risk groups within both localized and metastatic disease, and arise in individuals with a range of ancestries. We identify distinct DNA methylation subtypes associated with disease stage and evolution. This allows us to quantify how DNA methylation and copy number jointly regulate gene-expression, and how this regulation evolves throughout the course of the disease. We comprehensively define the epigenomic and transcriptomic consequences of somatic driver mutations in prostate cancer, and demonstrate that these accurately predict clinical outcomes.

These data significantly extend our understanding of the interplay between genetic and epigenetic variability, and how these jointly rationalize the clinical heterogeneity that characterizes prostate cancer.

Results

Methylation subtypes of prostate cancer

We created a cohort of 3,001 prostate tissue methylomes from 14 published and one unpublished cohorts (7,8,13,15,24,29-37). This compendium represents the full spectrum from normal tissue (22%; n = 646) to localized cancer (70%; n = 2,102) to castrate-resistant metastatic cancer (8%; n = 253). The localized tumours represent all five ISUP grade groups (117 to 403 patients in each group; **Supplementary Figure 1a-e**; **Supplementary Table 1**).

We first derived comprehensive methylation subtypes in the largest single cohort (498 tumours and 50 normal prostates), then verified them in the remaining 14 cohorts. Expanding on previous smaller subtyping studies (7,31,38,39), we define four methylation subtypes, termed MS-1 through MS-4 (**Figure 1a**; **Supplementary Figure 1f**). To allow these subtypes to be readily applied to new samples, we identified 5,486 subtype-defining CpGs and created a classifier for single-sample subtype-assignment (**Figure 1b-e**, **Supplementary Figure 1g**; **Supplementary Figure 2**). We implemented this in a new open-source R package called *PrCaMethy* to facilitate application and extension of all methods and signatures reported here.

The four methylation subtypes are tightly associated with clinical features of the disease. For example, subtype MS-2 overwhelmingly occurs in non-malignant prostatic tissue (95%; **Figure 1d-e**, **Supplementary Table 2**) and is the least common subtype in metastatic (1%) disease. In localized disease, it preferentially occurred in low-grade tumours (64% ISUP grades 1 or 2). By contrast, metastatic prostate tumours were enriched for subtype MS-4 (80% of metastatic *vs.* 34% of localized and 1% of normal prostate) (**Figure 1e**). Subtypes were not driven by tumour purity (**Supplementary Figure 3a**). Subtype distributions varied between normal prostate and localized disease ($p = 3.6 \times 10^{-285}$) and between localized and metastatic disease ($p = 2.0 \times 10^{-46}$; **Supplementary Figure 3b**), suggestive of subtype evolution during disease progression and response to treatment.

For patients with localized disease, subtypes MS-1 and MS-2 had the lowest risk of biochemical recurrence (BCR), while MS-4 had the highest risk (HR = 2.4; $p = 3.9 \times 10^{-5}$; **Figure 1f**). MS-4 remained independently prognostic after adjusting for cohort, age, pathologic T-category, ISUP

grade group, pre-treatment serum PSA and total copy number aberration (CNA) burden (adjusted HR = 2.01, p = 0.0078). These associations held for all cohorts of localized disease except ICGC PRAD-FR, and for a composite outcome of metastasis or death (**Supplementary Figure 3c-j**). Meta-analysis of seven cohorts with BCR-related outcomes (n = 1,534) showed MS-4 had 2.7 times greater risk than MS-1 (95% CI 1.9-3.9, $p = 1.1 \times 10^{-7}$) (**Figure 1f** inset; **Methods**) with no evidence of heterogeneity in effect sizes between cohorts (p = 0.52). Methylation subtypes were also significantly associated with pre-treatment prognostic features including tumor size and extent (T-category), ISUP grade group and serum PSA abundance, with consistent effect-sizes across cohorts and in the full compendium (q-values < 0.05, **Figure 1g**; **Supplementary Figure 3k-n**).

The vast majority of subtype-defining CpGs (5,407/5,486; 98.6%) showed significant tumour-normal differences (U-test q-value < 0.05; **Supplementary Figure 4a**). Subtype-defining CpGs were modestly more likely to differ between tumour and normal samples than non-subtype-defining CpGs (relative risk = 1.16; $p = 7.2 \times 10^{-259}$). Similarly, 96.3% of subtype-defining CpGs showed significant differences between localized and metastatic samples, compared to 80.8% of non-subtype-defining CpGs (relative risk = 1.19; $p = 9.0 \times 10^{-257}$; **Supplementary Figure 4b**). Subtype-defining CpGs were significantly enriched on five chromosomes and depleted on seven (**Figure 1h**), and preferentially occurred in open sea rather than islands or shores (**Figure 1i**) and in intergenic regions rather than promoters or gene bodies (**Figure 1j**).

Tumour ploidy drives regional methylation & gene-expression

These positional biases in the genomic locations of subtype-defining CpGs suggested an association between copy number state and methylation status (8,40-42). We therefore considered the 870 tumours in our compendium with matched CNA profiling. Methylation was predominantly inversely correlated with ploidy, with 86% of genes showing negative correlations (**Figures 2a-b**). Given the inability of array-based technologies to quantify allele-specific methylation status, it remains unclear if the average methylation per allele differs as a function of the number of copies. Methylation of promoter CpG islands was strongly associated with decreased transcript abundance, with negative correlations for 92% of genes (**Figure 2c**).

Given that CNAs are common and early driver events in prostate cancer, we hypothesized DNA ploidy changes may interact with methylation to jointly regulate RNA abundance. We first verified that CNA status was positively associated with mRNA abundance in most genes (86%;

Figure 2d). Next, we asked if the effects of CNAs on mRNA were modulated by the methylation status of the locus. We quantified these CNA-methylation effects on mRNA as the interaction term in linear regressions, focusing on the 725 tumours with all three data-types available. Almost half of all genes exhibited significant CNA-methylation interactions (4,950 of 10,919 = 45.3%; $q < 0.05$; **Figure 2e**). Thus for about half the genome, fully understanding the gene-expression consequences of tumour ploidy changes requires quantifying the methylation status of that genomic region. These CNA-methylation interactions were an even mix of synergy and antagonism, so in some cases methylation changes countered the effects of the CNA and in other cases they enhanced it. Six examples of notable interactions are given in **Figure 2f**, including the driver gene *PTEN*. In each case, the difference in RNA abundance between hyper- and hypo-methylated groups is much greater in patients with CNA gain or loss compared to patients with neutral copy number. The *PTEN* interaction was independent of both T-category and ISUP grade-group (**Supplementary Figure 4c-d**).

To determine if these CNA-methylation changes preferentially influence cancer driver genes, we considered 91 established prostate cancer driver genes (8,43-45) to the rest of the genome. We stratified our analyses by CNA status and disease stage (localized *vs.* metastatic). In localized disease methylation changes in driver and passenger genes were indistinguishable on average: driver genes showed similar amounts of differential methylation as non-driver genes: this was true for both losses and gains (**Figure 2g**). By contrast, in metastatic disease CNA changes were associated with much larger methylation changes overall, and these were significantly enhanced in driver genes (**Figure 2g**). This reflected a general pattern: increased ploidy was strongly associated with reduced methylation in localized, but not metastatic disease (**Figure 2h, Supplementary Figure 5a**). Similarly, increased mRNA was strongly associated with reduced methylation in localized, but not metastatic disease (**Figure 2i, Supplementary Figure 5b**). By contrast, the association of copy-number and mRNA abundance was largely indistinguishable between localized and metastatic disease (**Figure 2j**; **Supplementary Figure 5c**). These data suggest methylation is more central to gene regulation in localized than in metastatic prostate cancer (**Supplementary Figure 5d**). To confirm this result, we assessed the mutual information between pairs of data types, which can capture nonlinear relationships. Consistent with our simple correlation analyses, mutual information showed substantial differences between localized and metastatic prostate cancer, particularly in methylation-RNA

and methylation-CNA associations. By contrast, the influence of CNAs on RNA abundance was relatively consistent across both localized and metastatic disease (**Supplementary Figure 6**).

Given the inter-patient and stage-dependent heterogeneity in CNA-methylation interactions, we hypothesized that genes with highly variable methylation status may tend to be driver genes. Of the top 500 genes with highest variation in methylation ("HVM genes"), 30 were significantly associated with BCR ($q < 0.05$; **Supplementary Figure 7a**). The HVM genes showed greater variation in size and direction of their correlation with PGA compared to non-HVM genes, with 30% of HVM genes being positively correlated with PGA, compared to only 9% of non-HVM genes (**Supplementary Figure 7b**). The HVM genes were not more likely to have copy number alterations compared to non-HVM genes (**Supplementary Figure 7c**) and did not show enrichment based on chromosomal location (**Supplementary Figure 7d**). Rather, the 30 HVM genes that were significantly associated with BCR showed strong CNA-methylation correlations indicating that they reflect individual outlier events (**Supplementary Figure 7e-f**).

Overall, these data reveal a complex interplay between DNA ploidy changes, methylation and downstream gene-expression in prostate cancer. Copy number changes have stage-specific influences on methylation, allowing a single somatic mutation to influence gene-expression in different ways as the disease evolves. Further, they reveal an unexpected inter-tumoural heterogeneity in the epigenomic consequences of DNA ploidy changes, affecting driver genes.

Methylation subtypes reflect tumour genetics and microenvironments

The complex association between DNA ploidy, methylation and mRNA abundance led us to explore the genomic hallmarks of the methylation subtypes. We compared the CNA frequency for each CpG using ordinal logistic regression, adjusting for total copy number burden and cohort. A fifth of genes containing subtype defining CpGs showed significant copy number alteration differences between the four subtypes (**Figure 3a**). Methylation subtypes MS-3 and MS-4 had noticeably higher percent of patients with copy number gains across the genome, while MS-4 had a higher percent of patients with copy number loss in chromosomes 2, 5, 6 and 13 (**Figure 3b**; **Supplementary Figure 8**). The subtypes differed significantly in their overall CNA burden (Kruskal-Wallis $p = 2.02 \times 10^{-55}$; **Figure 3c**). Tumours in MS-2 had the fewest CNAs, consistent with the observation that most normal samples (95%) had this subtype. Taken together, these data show that subtype-defining CpGs discriminate between tumour *vs.* normal tissue, localized *vs.* metastatic tissue, and have copy number alteration profiles that differ

across subtypes. Subtypes MS-3 and MS-4 had significantly larger percentages of the genome with a CNA (PGA), consistent with their higher risk of biochemical recurrence (BCR). Similarly the methylation subtype most similar to normal prostate tissue (MS-2) had the fewest CNAs.

To determine if the genome-epigenome interactions were associated with downstream gene-expression, we next considered 738 prostate tumours with matched methylation and RNA profiling. When assessing subtype differences, 40,496 of 53,078 (76%) mRNA transcripts significantly differed between subtypes ($q < 0.05$; adjusting for PGA and cohort differences). We chose to focus on a subset of 3,516 significant transcripts with large effect sizes. These transcripts showed unique expression profiles between the methylation subtypes (**Supplementary Figure 9a**) with subtypes MS-1 and MS-2 tending to have higher levels of expression (**Figure 3d**). These differences reflected a broad range of cancer hallmark pathways (**Figure 3e**), with MYC targets showing the largest differences between subtypes (46,47).

Hypoxia, or low oxygen levels in the tumor microenvironment, is a strong predictor of disease recurrence and metastasis in prostate cancer (42,48-50). We compared a validated hypoxia RNA signature (51) between the four methylation subtypes. MS-2 (the normal-like subtype) was significantly less hypoxic than the other subtypes (**Supplementary Figure 9b**). Subtype-defining CpGs had 1.6 times greater odds of being correlated with hypoxia compared to non-subtype-defining CpGs (95% CI 1.4-1.8, $p = 1.48 \times 10^{-15}$; **Supplementary Figure 9c**). CpGs throughout the genome were correlated with hypoxia, mostly inversely (69%; $q < 0.05$; **Supplementary Figure 9d**). Methylation of CpG islands in gene promoters was significantly correlated with hypoxia score in 32 genes (**Supplementary Figure 9e**).

Somatic driver mutations shape the prostate cancer epigenome

Prostate cancer is a C-class tumour (8,52), with few recurrent driver SNVs, but many driver CNAs and genomic rearrangements (GRs). We evaluated the association of global methylation with 28 recurrent driver aberrations (8), as well as the mutation burden of SNVs, CNAs and GRs in 870 prostate tumours (**Figure 4a**). Consistent with our gene-expression analyses, ploidy (PGA) had the largest effect on methylation levels (87.5% significant CpGs, $q < 0.05$), followed by global SNV burden, *MYC* copy number gain and GR burden (**Figure 4b**). These CpG changes were distributed across the genome and affected both CpG Island and non-CpG Island sites (**Supplementary Figures 10a-b**), and influenced down-stream mRNA abundance (**Supplementary Figure 10c**).

To determine if different somatic mutations on a single gene induce similar methylation effects, we focused on the tumour suppressor *TP53*. We compared *TP53* inactivation by point mutations only (6% of patients), copy number loss only (24%) or both (8%). Point mutation of *TP53* was associated with a much larger methylome change than loss of *TP53* (56% of CpGs *vs.* 20%; **Figure 4c**). The specific CpGs affected only partially overlapped (**Supplementary Figure 10d**), indicating that different mutation types induce different methylation changes.

Consistent with these results, the methylation subtypes were significantly associated with 12 of 28 driver mutations ($q<0.05$, logistic regression adjusting for cohort and PGA), with MS-3 and MS-4 having greater odds of each mutation relative to the normal subtype MS-2 (**Figure 4d**; **Supplementary Figure 10e-f**). Similarly, MS-4 had more total driver events and MS-2 fewer (**Figure 4e**; **Supplementary Figure 10g**), even after controlling for the large differences in mutation burden and driver mutation frequency between localized and metastatic cancers (**Supplementary Figure 11**).

It is relatively uncommon to have sufficient resources and tissue to simultaneously profile tumour DNA and methylation. Given the strong associations between methylation and the mutational composition of a cancer, we attempted to create prediction models that infer features of a cancer's somatic genome from it's epigenome. We randomly split 1,436 patients into 70% for training (n=1,005) and 30% for testing (n=431). We focused on 15 important clinico-molecular features with sufficient data for model training: patient age and serum PSA (both continuous and discretized), tumour grade and T-category, mutation burden (SNVs and CNAs), seven tumour suppressors and one oncogene. We fit random forest and glmnet models in the training dataset, with standard feature selection, hyper-parameter optimization and assessment of over-fitting (**Methods**; **Supplementary Figures 12-13**).

The final models performed well on the final held-out test dataset, with all except age achieving performances >0.60 (**Figure 4f**; **Supplementary Figure 14**). For example, tumour SNV mutational burden was very well-predicted by our methylation model, with a Pearson's correlation of 0.72 between our predictions and actual DNA sequencing (**Figure 4g**). Similarly our MYC gain prediction model accurately predicted 83% of MYC neutral cases and 76% of MYC wildtype cases despite only 34% of cancers having a MYC gain (**Figure 4h**). Only one model showed cohort-specific bias: PSA, reflecting the strong clinical bias between localized and metastatic disease (**Supplementary Figure 15**). All prediction models are available in the

PrCaMethy R package (**Supplementary Figure 16a**) and we define a subset of ~7000 CpGs that overlap across prediction models for targeted assays (**Supplementary Figure 16b**).

A multi-omic signature predicts disease recurrence

To extend these clinico-molecular methylation signatures to patient risk-stratification, we focused on 774 localized prostate cancer patients with time to BCR and multi-omic data available. We again split these randomly into 70% for training and 30% for testing, and employed standard model- and feature-selection (**Methods**; **Supplementary Figure 17**). The optimal model in the training dataset was carried forward to the validation dataset, and included 2 clinical features (PSA, ISUP grade group), methylation subtype, 10 promoter-methylation events and RNA abundance of 7 genes. Risk scores from this model predicted outcome in the test dataset with a C-index of 0.86 (95% CI 0.77-0.91), compared with 0.81 for a clinical-only model (95% CI for the difference: 0.0011 to 0.11). Median-dichotomized risk-scores identified a group of patients with 8.2-fold greater risk of BCR in the held-out test dataset (95% CI 1.9-36.1; p = 0.0055; **Figure 4k**). Model risk scores differed significantly between non-malignant, localized and metastatic prostate samples (**Figure 4l**), and remained prognostic even within the subset of held-out testing patients classified as intermediate risk (HR = 16.23, p = 0.013; **Supplementary Figure 17e**). Overall, these results suggest the prostate cancer epigenome and its interactions with the transcriptome may serve as very accurate predictors of clinical outcomes.

Inverse associations between DNA methylation age and driver mutations

The single clinico-molecular feature we were unable to accurately model from tumour methylation was patient age (**Figure 4f**). This suggested to us that prostate tumour epigenetic age might differ significantly from patient chronological age. We estimated the DNA methylation (DNAm) age of 102 normal samples using ten widely available methylation clocks (53). The Horvath clock achieved the highest correlation (Pearson's r = 0.48, 95% CI 0.31 – 0.61, q-value = 5.18×10^{-6}; **Figure 5a-b**), consistent with the original study of that clock (54). We then analyzed paired normal and tumour samples using the Horvath clock. Tumour samples exhibited decelerated DNAm ages compared to their normal counterparts, suggesting that the aging pathways in tumours differ from those in adjacent normal tissues (**Figure 5c**).

Next, we investigated the associations between clinico-molecular features and epigenetic age acceleration, adjusting for chronological age (**Methods**). Both the methylation subtypes (p =

1.32×10^{-6}) and ISUP grade ($p = 8.43 \times 10^{-3}$) demonstrated significant associations with relative age acceleration (**Figure 5d-e**). Global mutation burden showed an inverse correlation with relative DNAm acceleration (SNVs/Mbp: Spearman's $\rho = -0.30$, $p = 2.82 \times 10^{-16}$; PGA: Spearman's $\rho = -0.26$, $p = 2.53 \times 10^{-13}$), mirroring the previously observed association between SNV burden and DNAm age in other cancers (55). Two specific drivers were associated with significant DNAm age deceleration: *MYC* copy number gain ($p = 2.47 \times 10^{-5}$) and *NKX3-1* loss ($p = 8.00 \times 10^{-4}$; **Figure 5f-h**). Taken together, these data show that prostate tumours exhibit the hallmarks of reduced age, and this is associated with clinical phenotypes, global mutation burden and with specific somatic driver mutations.

Discussion

Cancer is a disease of continual genomic evolution. The epigenome serves as the critical mediator between somatic mutations and their gene-expression consequences, which ultimately drive clinical phenotypes like diagnosis, prognosis and response to therapy. A range of evidence has shown that various forms of epigenomic (dys)regulation, such as chromatin modifications, can drive prostate cancer phenotypes (56-58). Here we focus on DNA methylation to maximize sample-size and infer general principles of how it changes and influences phenotypes across the course of disease evolution.

We show that prostate cancers fit into four general methylation subtypes. Unexpectedly, each subtype can be identified at all stages from normal prostate through to metastatic disease, although at different frequencies. This suggests that methylation subtypes tend to evolve over time, but at least in part reflect the initial tumour initiation. Consistent with that, the subtypes are associated with specific somatic mutational, gene expression and clinical profiles. Understanding the single-cell heterogeneity of the prostate cancer methylome (and of its subtypes) is a major opportunity to better understand how methylation shapes cancer evolution.

The best known driver of prostate tumour evolution is changes in DNA ploidy, which are well-known to lead to methylation changes. We demonstrate that these changes vary significantly across individuals and across disease stages. The PTEN tumour suppressor serves as an excellent example of this, where both hypermethylation and hemizygous deletion can (but do not always) result in decreased gene expression, with characteristic DNA methylation profiles (59) that may lead to functional changes from *PTEN* haploinsufficiency (60-62). We extend previous correlative studies (63) to define precise epigenomic signatures of key prostate cancer

driver events, and demonstrate that these are highly predictable. As methylation profiling of circulating tumour DNA grows in popularity, these provide an avenue to develop techniques to estimate both individual driver events and global mutational features longitudinally.

Collectively, our data elucidates central roles for DNA methylation in regulating prostate cancer throughout its lifespan, from early aging deceleration through to extensive gene-regulatory effects in localized disease and strong biomarkers of clinically important events like relapse and metastasis. Despite the size of our compendium, it lacks coverage of untreated and lymph node metastases, and these may help fill a key missing piece in our understanding of the mechanisms of prostate cancer evolution from localized lesions into lethal metastatic ones.

Materials and Methods

Patient cohorts

The TCGA cohort (n = 498 tumour samples) (7) was used to derive the methylation subtypes which were validated in 14 external prostate cancer cohorts (13 published and one unpublished - Melbourne) (7,8,13,15,24,29-37) (**Figure 1b-e**, **Supplementary Figure 2**, **Supplementary Tables 1-2**). TCGA, ICGC PRAD-CA and Zhao *et al.* 2020 prostate cancer cohorts were included in the methylation, mRNA, CNA, and somatic driver mutation analyses. See **Supplementary Figure 1a** for sample sizes per cohort and data type used in each analysis.

All International Cancer Genome Consortium (ICGC) samples were processed from prostate cancer tissue taken from patients with localized disease, following ethics approval from the University Health Network Research Ethics Board (REB)–approved study protocols (UHN 06-0822-CE, UHN 11-0024-CE, CHUQ 2012-913:H12-03-192) as previously described (8).

Pathology and Tissue Processing

ICGC PRAD-CA fresh-frozen tissue specimens were audited for tumour content, Gleason/International Society of Urological Pathologists (ISUP) grade, and tumour cellularity by two independent genitourinary pathologists, as previously reported (8). Specimens of at least 70% tumour cellularity were manually macro-dissected and digested for nucleic acid extraction, as previously reported (8,9).

Microarray data generation

ICGC PRAD-CA methylation, SNP and mRNA microarray data were generated as previously described (8). Briefly, Illumina Infinium HumanMethylation450 BeadChip kits were used to

assess global methylation levels with 500 ng of input genomic DNA at the McGill University and Genome Quebec Innovation Centre (Montreal, QC). SNP microarrays were performed with 200 ng of DNA on Affymetrix OncoScan FFPE Express 2.0 and 3.0 arrays. Where DNA quantities were limiting (17 samples), we used whole-genome amplification (WGA; WGA2, Sigma-Aldrich, St. Louis, MO), and validated that WGA of genomic DNA does not significantly alter CNA profiles (9). Total RNA was extracted from alternating adjacent sections (to reduce potential heterogeneity relative to the DNA specimen), using the mirVana miRNA Isolation Kit (Life Technologies). Extracted total RNA (100-150 ng) was assayed on Affymetrix Human Gene 2.0 ST (HuGene 2.0 ST) array and Human Transcriptome Array 2.0 (HTA 2.0) platforms at The Centre for Applied Genomics (The Hospital for Sick Children, Ontario, Canada) and the London Regional Genomics Centre (Robarts Research Institute, London, Ontario, Canada).

Methylation

Methylation processing was performed in R statistical environment (v3.4.0). Methylation data for the ICGC PRAD-CA cohort is in the Gene Expression Omnibus (GEO): GSE107298, and was processed using the Dasen method (64,65) as previously described (8). Probes that have detectability below background noise, non-CpG methylation, SNPs with an annotated minor allele frequency of greater than 5% with a maximum distance of two nucleotides to the nearest CpG site, and those known to cross-hybridize to multiple genomic locations were excluded. Probe average intensity levels were calculated across technical replicates. Probes were annotated to gene symbols *via* the IlluminaHumanMethylation450kanno.ilmn12.hg19 annotation package (v0.6.0). Unless stated otherwise, all methylation analyses were performed using the β-value, which represents the ratio of methylated intensity over combined methylated and unmethylated intensity and reflects the methylation level of a specific CpG loci. Tumour purities were estimated using LUMP as previously described (66).

Illumina Infinium Human Methylation 450K or 850K BeadChip CpG processed beta-values were obtained for the following cohorts: Kirby *et al*. 2017 (30), Zhao *et al.* 2017 (24), TCGA (7,67), ICGC PRAD-FR (31), Ramakrishnan *et al.* 2024 (33), Ylitalo *et al.* 2021 (35) and Mundbjerg *et al.* 2017 (37). Additional details about data processing can be found in the corresponding citations. In all analyses, only CpGs from the Illumina 450K array were used.

For Melbourne methylation data, Illumina's Infinium Human Methylation 450K array was used to profile the methylation status of all Australian prostate cancer samples. Raw signal data were

processed and normalised for both within-array and between-array variations using the minfi package (68). Minfi's implementation of the Illumina's reference-based normalisation and the SWAN method within the minfi package were used for between-array and within-array (correcting for the probe-type bias) normalisations, respectively. Any methylation measurement with detection p-value greater than 0.01 were omitted from further analysis.

For cohorts Brocks *et al.* 2014 (13), Toth *et al.* 2019 (36) and Dairo *et al.* 2024 (34), raw Illumina methylation .idat files were processed using the minfi R package (v1.52.1) (68). Methylation values with detection p-values greater than 0.05 were excluded. Probes with detection failure rates exceeding 10% across samples were also removed. Additionally, any sample in which more than 10% of probes failed detection was excluded from further analysis. Normalization was done using the dasen method in the wateRmelon R package (v2.12) (64,65).

Whole genome bisulfite sequencing methylation data was used in Li *et al.* 2020 and Zhao *et al.* 2020 as detailed in (15,29). The "illumina450k_hg38" dataset from the Rockermeth R package (v.0.1.1) (69) was used to identify locations of the CpGs corresponding to the HumanMethylation450 BeadChip, thus allowing us to obtain the same CpGs used in the other cohorts. In Zhao *et al.* 2020, CpGs with a median number of reads < 10 and patient-level CpG calls with < 10 reads were omitted from analyses; while a cutoff of 5 was used in Li *et al.* 2020 due to lower coverage. For each CpG, the β-value was calculated as the proportion of methylated reads at that CpG site: # methylated reads / (# methylated reads + # unmethylated reads).

Copy number aberrations (CNAs)

ICGC PRAD-CA copy number alteration data was obtained as previously described (8). The output from the Affymetrix OncoScan FFPE Express 3.0 SNP probe assay was aligned to a custom reference (8) using the OncoScan Console v1.1. Copy number segments were subsequently called using the BioDiscovery's Nexus Express for OncoScan software using the SNP-FASST2 algorithm. Parameters were identical to the default one except for the minimum number of probes per segment which was set to 20. Diploid re-centering was performed when needed using the Nexus Express software. Using BEDTools the gene level copy number alterations were identified with the RefGene annotation (2014-07-15). Percent genome alteration was defined as PGA = (base-pair length of all genome regions with gain or loss) / 3.2 billion bases * 100. Zhao *et al.* 2020 CNA data was obtained from (70) and TCGA CNA data

was downloaded from the TCGAbiolinks R package v2.25.3 (7,67) with copy number calls of 2 treated as “neutral”, less than 2 as “loss” and greater than 2 as “gain”.

mRNA

ICGC PRAD-CA pre-processed mRNA data was downloaded from GSE107299 and processed in R (v3.4.3). Briefly, the RMA algorithm implemented in the affy (v1.48.0) package (71) was used with modified Entrez Gene CDFs to pre-process the raw intensity data. Probes were mapped to Entrez gene ID using custom CDF files (v18) for HTA 2.0 and HuGene 2.0 ST array (72). The sva package (v3.24.4) was used to correct for batch effects between different arrays. mRNA abundance levels from HuGene 2.0 ST and HTA 2.0 were combined based on Entrez Gene IDs. The mRNA abundance levels were averaged amongst duplicated Entrez Gene IDs. Entrez gene IDs were then converted into gene symbols and chromosome locations based on the human reference genome GRCh37 from UCSC table browser (download date: 2018/01/30). TCGA processed mRNA abundance levels were downloaded from the TCGAbiolinks R package v2.25.3 (7,67). Zhao *et al.* 2020 FASTQ files were aligned to GRCh38 with GENCODE v36 using STAR (v2.7.6a) and mRNA abundance was calculated using RSEM (v1.3.3). All mRNA abundance levels were analyzed as $\log_2$ transcripts per million ($\log_2$ TPM), unless specified otherwise.

Whole-genome sequencing

Data processing and variant calling for the ICGC PRAD-CA cohort is described in (16). Chromothripsis scores were generated using ShatterProof (v0.14, default settings) (73). Kataegis was quantified using a fixed-width sliding window to test deviation of observed SNV trinucleotide content and inter-mutational distance from expected using an exact binomial test (74).

Corresponding whole-genome sequencing data for the Zhao *et al.* 2020 cohort (15,70) was downloaded as BAM files (See Data Availability Section). The BAM files were converted to FASTQs and realigned with variants called using Metapipeline-DNA (v5.0.0-rc.4 - 5.3.1) (75). A consensus SNV call set was created by retaining SNVs that were present in two or more callers using BCFtools (v1.17) (76). Consensus SNVs were then filtered using allow- and deny-lists. Deny-lists that were used included AccuSNP, Complete Genomics, dbSNP (v156) (77), duplicate gene (v68) (78), Encode DAC and Duke (79), gnomAD (v3.1.2, variants with ‘PASS’ flag) (80) and 1000 Genome project (81,82). Allow-lists involved Catalogue of Somatic

Mutations in Cancer (COSMIC) (v92) (83) coding and non-coding variants. Somatic structural variants were called using Manta (v1.6.0) (84) and annotated using the StructuralVariantAnnotation R package (v1.18.0) (85).

General statistical considerations

The Benjamini-Hochberg method was used to calculate multiple testing adjusted p-values to control the false discovery rate (FDR) at level 0.05 (referred to as 'q' or 'q-value' throughout) (86). When using Fisher's Exact Test on larger than 2x2 contingency tables, the stats R package fisher.test function was used with 100,000 simulation replicates.

Methylation subtypes

Methylation subtypes were identified in the TCGA cohort (n = 498) using Interpretable MiniPatch Adaptive Consensus Clustering (IMPACC v0.1.0) (87) with default settings, 10,000 clustering partitions and CpG beta-values. CpGs were filtered to keep the top 50,000 highest variance CpGs for clustering. The silhouette method (88) was used to choose the number of subtypes that maximized the median silhouette score, resulting in 4 subtypes. Specifically, the total number of subtypes was varied from 2 to 6, and each time the median silhouette score was calculated for each cluster, with the median of the cluster-wise scores used as an overall measure of clustering accuracy. A nearest shrunken centroid classifier (89) was trained on the TCGA subtypes to classify samples from seven cohorts, with missing values imputed by k-nearest neighbors imputation (impute R package v1.74.1, default settings) (90). As additional cohorts were incorporated into the project, several were profiled using the Illumina 850K methylation array, which lacks approximately 9% of the CpG sites present on the Illumina 450K array used to derive the subtypes. To address the resulting missing data, a random forest classifer (randomForestSRC R package v3.3.3) was trained on the TCGA subtypes. This method was chosen for its built-in imputation capabilities, enabling robust classification of samples from the remaining seven cohorts despite incomplete CpG coverage (91).

Subtypes *vs.* clinical features

Categorical pre-treatment clinical features were summarized in **Supplementary Table 1** using counts and percentages. Race was self-reported, except for Chinese patients from Li *et al.* 2020 (29), whom we classified as Asian. The subtypes were tested for association with pre-treatment clinical features of age, tumour category, ISUP grade group and PSA. Each of the clinical variables was categorized as in **Supplementary Table 1** and tested for an association

with the methylation subtypes using Fisher's Exact Test and the bias-corrected Cramer's V effect size (92). The subtypes were then tested for associations with the following outcomes: time until biochemical recurrence (logrank test; TCGA, ICGC PRAD-CA, Kirby *et al*. 2017, ICGC PRAD-FR), time until death (logrank test; Zhao *et al*. 2020) and binary outcomes of metastasize or death during follow-up (Zhao *et al.* 2017), BCR within 5 years (Dairo *et al.* 2024) and BCR within 3 years (Toth *et al.* 2019). Fisher's exact test was used for binary outcomes. A permutation logrank test was used in cohorts Kirby *et al*. 2017 and Zhao *et al*. 2020, due to small and uneven group sample sizes (10,000 permutations) (93). Furthermore, the association between subtypes and BCR was assessed when pooling all patients with available BCR data (n = 882) where hazard ratios with 95% confidence intervals and Wald-test p-values were estimated using a Cox proportional hazard model treating MS-1 as the reference group, and adjusting for cohort differences. BCR was defined as two consecutive post radical prostatectomy (RP) PSA measurements of > 0.2 ng/mL, within 6 months. Patients who underwent successful salvage radiotherapy following RP (*i.e.* post-RP PSA below 0.2 ng/mL) were classified as non-failures; those that underwent unsuccessful salvage radiotherapy (*i.e.* two post-RP PSA readings above 0.2 ng/mL) were classified as failures, backdated to the original date of post-RP PSA rise. Patients who underwent other salvage treatments (*e.g.* hormones, chemotherapy) to control rising PSA were considered as having BCR.

Lastly, meta-analysis was performed for seven cohorts of localized disease with BCR-related outcomes. Four cohorts had right-censored time until BCR (TCGA, ICGC PRAD-CA, Kirby *et al.* 2017, ICGC PRAD-FR) and three cohorts had binary BCR-related outcomes: BCR within 5 years (Dairo *et al.* 2024), BCR within 3 years (Toth *et al.* 2019) and metastasize or death during follow-up (Zhao *et al.* 2017). A Cox proportional hazards model was used to estimate hazard ratios for time until BCR comparing subtype MS-4 to MS-1. For binary outcomes, the relative risk of MS-4 versus MS-1 was converted to a log hazard ratio and standard error using the approach of Watkins and Bennett (94). All log hazard ratios and standard errors were input to a random effects meta analysis using the metagen() function from the meta R package v8.0.2 with the DerSimonian-Laird estimator of between-study variance (95,96). The heterogeneity Q-test was used to assess heterogeneity in effect sizes between cohorts.

Subtype-defining CpGs

IMPACC intrinsically performs variable selection and identified 5,486 CpGs that were important for deriving the subtypes (referred to as 'subtype-defining CpGs' throughout). The subtype-

defining CpGs were compared between subtypes using Kruskal-Wallis rank sum test and the epsilon-squared effect size (97), while further compared between tumour and normal samples, and localized *vs.* metastatic tumour samples using the Mann-Whitney U-test. Chromosome position, CpG type (island, open sea, shelf, shore: https://www.illumina.com/content/dam/illumina-marketing/documents/products/other/field_guide_methylation.pdf), and gene region (gene body, intergenic, or gene promoter) were compared between the subtype-defining CpGs and non-subtype-defining CpGs using Fisher's Exact Test and odds ratio. The gene regions were defined as follows: CpGs were annotated using the IlluminaHumanMethylation450kanno.ilmn12.hg19 bioconductor R package (v0.6.0) where CpGs in gene promoter regions were defined as within 200 or 1500 base pairs from a transcription start site (TSS). CpGs that were not mapped to any gene symbol were defined as "intergenic regions", and remaining CpGs were defined as occurring within the gene body.

Methylation interaction with mRNA and CNAs

Adjusted mRNA abundance was calculated by fitting a linear regression model to each mRNA transcript ($\log_2$ TPM) with cohort (TCGA, ICGC PRAD-CA, Zhao *et al.* 2020) and PGA as predictors, and using the standardized residuals (z-scores) in subsequent analyses. The adjusted mRNA abundance was compared between methylation subtypes using Kruskal-Wallis rank-sum test. Pathway analysis was performed using 50 hallmark pathways (47) by first calculating patient-specific pathway scores using adjusted mRNA abundance with the GSVA R package (v.1.50.0, default settings) (98) and comparing the pathway scores between methylation subtypes using Kruskal-Wallis rank-sum test.

An mRNA signature of hypoxia was calculated separately for the TCGA and ICGC PRAD-CA cohorts using the a panel of 51 genes (51). The hypoxia score was calculated by median-dichotomizing each feature, then a patient's score would receive +1 for each feature above the median, otherwise -1 if less than or equal to the median. The hypoxia score was then z-score transformed (separately by cohort), and compared between methylation subtypes using Kruskal Wallis rank sum test and pairwise Mann-Whitney U-tests. Spearman's correlation was used to assess the association between each CpG and hypoxia score, with Fisher's exact test and odds ratio to assess whether subtype-defining CpGs were more likely to be correlated with hypoxia compared to non-subtype-defining CpGs. Lastly, Spearman's correlation was used to assess

the association of hypoxia score with gene-level methylation, where the latter was calculated for each patient as the median beta-value of CpG islands in the gene promoter region.

To test the association of prostate tumour methylation levels with CNAs and mRNA abundance level, we first examined copy number effect on CpG methylation β-values. For each patient, we generated segmented CNA profiles and called each segment as: homozygous deletion, hemizygous deletion, neutral, gain or high gain. The β-values for each CpG from all patients within any given segmented CNA state were then used to examine CNA effect on methylation levels.

Spearman's correlation was used to test the within-gene associations of CNA and methylation of CpG island in gene promoters (CGIp) and CGIp methylation with mRNA abundance levels, when pooling TCGA, ICGC PRAD-CA and Zhao *et al.* 2020 cohorts. Furthermore, linear regression of z-score transformed $\log_2$ TPM was used to test the interaction between CNA and methylation. This model considered binary methylation (hyper *vs.* hypomethylation; median dichotomized), binary CNA status (loss *vs.* neutral if loss was the more common mutation, otherwise gain *vs.* neutral), adjusted for cohort (TCGA, ICGC PRAD-CA, Zhao *et al.* 2020) as a covariate, and removed genes with < 5 CNA events in either methylation group.

The copy number alteration status of genes containing the subtype-defining CpGs were compared between the four methylation subtypes using ordinal logistic regression from the polr function in the MASS R Package (99). A given gene's copy number status (loss, neutral, gain) was used as the dependent variable, with subtype, PGA and cohort as the independent variables, and a likelihood ratio test was calculated for subtype. Percent genome alteration was defined as PGA = (length of all genome regions with gain or loss) / 3.2 billion bases * 100 and was compared between the four subtypes using Kruskal-Wallis rank sum test and pairwise Mann-Whitney U-tests.

The top 500 genes with highest variation in methylation ("HVM genes") were tested for associations with time-until-BCR using a Cox proportional hazards model Wald test. Spearman's correlation was used to test the association between each HVM gene with PGA and compared with the distribution of PGA correlations for non-HVM genes. The percent of patients with CNA loss or gain was calculated separately for HVM and non-HVM genes and compared using Mann-Whitney U-test.

Lastly, we investigated whether the associations between methylation, CNA and RNA within each gene differed between localized and metastatic prostate cancers. Two approaches were taken: 1) visually comparing the distribution of Spearman's correlations for each pair of data types, and 2) comparing the distribution of mutual information for each pair of data types. Unlike Spearman or Pearson's correlation, mutual information can capture arbitrary linear or nonlinear relationships. The mutual information was calculated as follows: for each pairwise data type comparison, data from each gene were discretized into $N^{1/3}$ bins, where N is the intersection of the samples with data available for each pair of datatypes (100). Mutual information (MI) between two data types was defined as:

$$MI_{xy} = H_x + H_y - H_{xy}$$

where H_x and H_y are the marginal entropies of data types x and y and H_{xy} is the joint entropy, calculated using the R package Entropy (v1.2.1) (101). To reduce bias in MI estimates, the James-Stein shrinkage estimator (102) was applied, as implemented via the entropy.shrinkage function of the entropy R package (101). MI was normalized over the mean entropy of the two input vectors. To assess statistical significance of normalized MI values, permutation testing was performed. Gene-level data were permuted 1000 times to generate a null MI distribution, and p-values were calculated as the proportion of null MI values greater than or equal to the true observed MI. Multiple testing adjusted $q < 0.05$ was regarded as statistically significant.

Driver mutations

Within the TCGA, ICGC PRAD-CA and Zhao *et al.* 2020 cohorts, CpG methylation levels were compared with each of 28 previously established somatic events (8). Spearman's correlation test was used for continuous events and Kruskal-Wallis rank-sum test for discrete events. Somatic features were divided into six categories: mutational burden (chromothripsis, kataegis, number of GRs, number of SNVs and PGA). SNVs, CNAs (losses of *CDH1*, *CDKN1B*, *CHD1*, *NKX3-1*, *PTEN*, *RB1, TP53* and gain of *MYC)*, *ETS* fusion, CTXs (translocations with break-ends within chr4:148, chr6:97, chr7:61, chr17:25 and chr21:42 Mbp blocks) and INVs (inversions with break-ends within chr3:125, chr3:129, chr10:89 and chr21:42 Mbp blocks). CpG β-values were tested for an association with the 28 somatic events and clinical features, using Spearman's ρ and Kruskal-Wallis tests for continuous and discrete features, respectively. Driver events that were significantly associated with at least one CpG ($q < 0.05$), were summed

to calculate the total number of significant driver events per patient, and then compared between subtypes using the Kruskal-Wallis test and pairwise Mann-Whitney U-tests.

Lastly, the distribution of each driver mutation was compared between localized and metastatic prostate cancers. Mann-Whitney U-test p-value was calculated for continuous drivers. Fisher's exact test q-value and odds ratio were calculated for categorical drivers, as well as logistic regression odds ratio adjusting for total mutation burden (CNA drivers adjusted for PGA, SNVs adjusted for $\log_2$ SNVs/Mbp, and genomic rearrangements adjusted for $\log_2$ GR count).

Epigenetic predictors of clinical features and driver mutations

A sample of 1,436 patients were randomly split into a 70% train (n=1,005) and 30% test (n=431) dataset. Two machine learning models were compared for predicting time-until-BCR: random forest and a regularized general linear model (glmnet) (103,104). These two models were considered because both random forests and regularized linear models have been shown to perform well across a wide variety of applications (105,106). Random forest can automatically capture potential interactions or non-linear effects (107), but is harder to interpret compared to glmnet. In contrast, glmnet assumes linear and additive effects (no interactions) by default, and has a similar interpretation as traditional logistic or multinomial classification models (estimates log odds ratios for each predictor) but performs automatic feature selection by shrinking coefficients towards zero, attempting to remove unimportant features. Random forest was fit using the randomForest R package (v4.7.1.1) with the mtry parameter tuned by the caret R package (v6.0.94) (108) with 5-fold cross-validation to select the best value. Glmnet was fit with the glmnet R package (v4.1.8) (103) setting the alpha parameter to 0.5 (*i.e.* "elastic net" penalty that is half way between ridge and LASSO (109,110)) with the main penalty parameter lambda chosen by 5-fold cross validation. Missing values were imputed by k-nearest neighbors imputation (impute R package v1.74.1, default settings) (90).

Prediction accuracy was assessed by Pearson's correlation for continuous features and balanced accuracy (BA = (sensitivity + specificity) / 2) for categorical features. For categorical features with three or more categories, BA was calculated separately for each category using a "one-versus-all" approach (*i.e.* a given category compared to all other categories combined) and then averaged. The predictors consisted of prostate cancer gene-level methylation for 13,603 genes, defined as the median beta-value among CpG islands in the gene promoter region. Feature selection methods were performed in the training dataset in attempt to improve

performance and identify a smaller subset of important predictors. Specifically, the univariate association of each gene methylation predictor with each clinical feature and driver mutation was assessed using Kruskal-Wallis rank-sum test for categorical features and Spearman's correlation for continuous features. To account for cohort differences, linear regression was used to regress each gene against cohort, and the residuals were used in the aforementioned univariate test. Then models were fit using only the top 10, 50, 100, 1000 or 5000 most significant genes, as well as a model that considered all 13,603 genes. To encourage a more parsimonious model, the final model for predicting a given feature was chosen as the model with the smallest number of predictors that was within 0.02 of the best Pearson's correlation or balanced accuracy for numeric and categorical features, respectively. Lastly, using the test-dataset, patients were resampled with replacement and 95% bootstrap BCa confidence intervals were calculated for performance metrics using the boot R package (v1.3.28.1) (111).

Predicting time-until-BCR using multi-omic data

A total of 774 localized prostate cancer patients with time-until biochemical recurrence (BCR) and multiomic data (methylation, RNA, CNA) were randomly split into a 70% train and 30% test dataset. Two machine learning models were compared for predicting time-until-BCR: random survival forest (112) and a regularized Cox proportional hazards model (113), with prediction accuracy assessed using the C-index (114). The random forest was fit using the randomForestSRC R package (v3.2.30) (112) with 1000 trees and default settings, while the regularized Cox model was fit with the glmnet R package (v4.1.8) (113) setting the alpha parameter to 0.5 (*i.e.* "elastic net" penalty that is half way between ridge and LASSO (109,110)) with the main penalty parameter lambda chosen by using 10-fold cross validation to maximize the C-index in the training data. Missing values were imputed by k-nearest neighbors imputation (impute R package v1.74.1, default settings) (90).

Several combinations of data types were considered for model training (**Supplementary Figure 17a**). Given the large number of potential features, feature selection was performed in the training dataset to identify a smaller subset of potential predictors. To perform feature selection, a separate Cox model was fit to each feature treating it as a predictor of time-until-BCR, while adjusting for the pre-treatment clinical features. Then only features with Wald-test p-value < α were retained. Several values for α were considered (0.001, 0.005, 0.01, 0.05, and 1) with the final value of α=0.005 chosen that maximized the random forest C-index in the training and test datasets (**Supplementary Figure 17d**).

The best machine learning model (highest C-index on test-dataset) was compared to the test C-index from a model that only considered pre-treatment clinical features. Using the test-dataset, patients were resampled with replacement and a 95% bootstrap BCa confidence interval was calculated for the difference in C-indices between the two models, using 50,000 bootstrap replications with the boot R package (v1.3.28.1) (111). Similarly, a 95% bootstrap BCa CI was calculated for the test C-index of the best performing model. Lastly, the predicted BCR risk score from the best model was compared between 52 non-malignant TCGA samples, 161 localized prostate cancer samples from the test dataset, and 99 metastatic samples. Given that the best model included PSA and ISUP grade as predictors, and these were not measured for the non-malignant samples (ISUP grade was not measured for metastatic samples), their values were imputed using the randomForestSRC impute.rfsrc R function (default settings) (91).

DNA Methylation Age Correlations with Clinical and Genomic Features

DNA methylation (DNAm) age was computed using the methylclock R package (v1.4.0) (53) for cohorts with available continuous chronological age data (TCGA, ICGC PRAD-CA, Kirby *et al*. 2017). Whole-genome bisulfite sequencing datasets were excluded, as methylation clocks were trained on microarray data. Relative DNAm age acceleration was defined to capture proportional age-related changes under the assumption of linear aging in senior adult cancer patients:

$$\textbf{Relative DNAm Age Acceleration} = \frac{\textbf{DNAm Age} - \textbf{Chronological Age}}{\textbf{Chronologial Age}}$$

Relative DNAm age acceleration was compared across age categories, methylation subtypes, and ISUP grades using the Kruskal-Wallis rank sum test with epsilon-squared effect size. Driver mutations present in ≥20% of tumor samples were analyzed in relation to relative DNAm age acceleration using the Mann-Whitney U test. False discovery rate (FDR)-adjusted q-values were computed. To account for chronological age, linear regression was applied to regress relative DNAm age acceleration against chronological age, and residuals were used in the aforementioned univariate tests.

Data Availability

The data download sources for each cohort are given in **Supplementary Table 3**.

Software Availability

The PrCaMethy R package offers tools for predicting methylation subtype, clinical features and somatic driver mutations using prostate cancer DNA methylation data generated from Illumina 450K and 850K arrays. The R package is publicly available on GitHub at: https://uclahs-cds.github.io/package-PrCaMethy/.

Data Visualization

Data visualization was performed in the R statistical environment (v4.4.2) using the BPG package (v7.1.2)(115). Venn Diagrams were made using the VennDiagram package (v1.7.3) (116).

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Author's Contributions

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Statistical and machine-learning analyses: JA, AW, YJS, TNY, RMAD, KEH, FY

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Competing Interests

MLKC declared the following potential conflict of interest unrelated to the submitted work: personal fees from Astellas, Axiom, Bicara Therapeutics, IQVIA, Janssen, MSD, Seagen, Varian; non-financial support from Veracyte Inc; personal fees and grants from Bayer; personal fees and grants from BeiGene; consults for Bicara Therapeutics; consults for ImmunoScape; consults for PVMed; consults for Varian Thought Leadership Council; and is a co-inventor of the patent of a High Sensitivity Lateral Flow Immunoassay For Detection of Analyte in Sample (10202107837T), Singapore, and serves on the Board of Directors of Digital Life Line Pte Ltd that owns the licensing agreement of the patent. PCB sits on the Scientific Advisory Board of Intersect Diagnostics Inc., and formerly sat on those of Sage Bionetworks and of BioSymetrics Inc.

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Figure Legends

Figure 1: The epigenomic landscape of prostate cancer

a. Subtype methylation profiles of 2,355 prostate tumours and 646 normal samples from 15 cohorts, including clinical pre-treatment variables. The heatmap includes 5,486 CpGs which were selected by IMPACC as important for deriving the subtypes. CpGs were sorted using hierarchical clustering with complete linkage and Euclidean distance, then split into five equally sized groups for visualization. Missing values are colored in white and clinical variables are not shown for normal samples (other than age).

b-e. For each cohort (vertical bar), the percentage of samples across subtypes is shown stratified by localized prostate tumor samples (**b**), metastatic samples (**c**), normal samples (**d**), and when pooling all cohorts together (**e**). The total sample size within each cohort is given above the bars. L: localized, M: metastatic, N: normal sample.

f. Kaplan–Meier curves were used to estimate BCR-free probabilities separately in each subtype, pooling all patients with available BCR data (n = 882). The p-value in the top-right corner is from a log-rank test. In the upper-left plot, hazard ratios with 95% confidence intervals and Wald-test p-values were estimated using a Cox proportional hazard model treating MS-1 as the reference group and adjusting for cohort. The table below the plot gives the number of patients at risk from 0-5 years. The bottom-right forest plot is a meta-analysis of 7 cohorts with BCR-related outcomes (see **Methods** for details). The "Overall" row contains the overall meta-analysis hazard ratio for comparing MS-4 to MS-1. Dots represent the estimated hazard ratio with 95% CI given by the adjacent lines.

g. The dot-map summarizes the overall association of subtypes with four clinical features: age, tumour category (T), ISUP grade group and PSA when pooling all patients together (Overall) and separately by cohort. Each of the clinical variables was categorized as in **Supplementary Table 1** and tested for an association with the four methylation subtypes using Fisher's Exact Test. The size of the dots reflects the bias-corrected Cramer's V effect size and the background color represents the q-value, which adjusts for multiple testing separately for each clinical variable. An x within a cell means that feature was unavailable for that cohort.

h-j. Fisher's exact test and odds ratio were used to compare the rates of subtype-defining and non-subtype-defining "background" CpGs within each chromosome (**h**), within different types of CpGs (island, open sea, shelf, and shore) (**i**) and within gene body, intergenic and gene promoter regions (as defined in Methods) (**j**).

Figure 2: The regulatory landscape of prostate cancer

a. The y-axis indicates the percent of patients with copy number gain (red bar) or loss (blue bar) within a gene at that location of the genome (x-axis). The vertical magenta bars indicate genes later shown in (**f**).

b-d. Spearman's correlation of methylation and CNA (**b**), methylation and mRNA (**c**), and CNA and mRNA (**d**) within each gene. Positive correlations are shown in blue and

negative correlations in orange. Gene-level methylation was measured for each patient by the median beta-value among CpG islands in the gene promoter region.

e. Linear regression interaction coefficient of binary methylation (hyper *vs.* hypomethylation; median dichotomized) and binary CNA status (loss *vs.* neutral if loss was the more common mutation, otherwise gain *vs.* neutral). The dependent variable is RNA abundance (z-score transformed $\log_2$ TPM). Genes with significant interaction effects ($q < 0.05$) are shown as well as gene BCL2L10 ($q = 0.055$).

f. Examples of methylation-CNA interactions on mRNA abundance for six genes. The q-value for testing the interaction effect is indicated by q_{int}.

g. For each gene, the more common "major" mutation was identified (CNA loss or gain). Then the median methylation in the gene promoter region was compared between the major mutation and neutral copy number ($\log_2$ fold change; y-axis). Results were compared by tumour type and for known cancer driver genes *vs.* other genes (x-axis).

h-j. The distributions of Spearman's correlation for within-gene methylation, CNA and RNA in localized and metastatic samples.

Figure 3: Methylation subtypes have different CNA and RNA profiles

a. Copy number alteration of 1653 genes containing the subtype-defining CpGs. Each gene (row of heatmap) was summarized by the percent of patients with copy number gain and loss within each subtype (columns), which was discretized to >30% for visualization. Rows were sorted by hierarchical clustering with Euclidean distance and complete linkage. Ordinal logistic regression was used to model a gene's copy number status (loss, neutral, gain) as the dependent variable, with subtype, PGA and cohort as the independent variables. A likelihood ratio test p-value was calculated for subtype, and multiple testing-adjusted q-values are displayed in the right barplot.

b. The y-axis indicates the percent of patients with copy number gain (red bar) or loss (blue bar) at that location of the genome (x-axis). Results are stratified by methylation subtype (row).

c. Percent genome alteration (PGA) was compared between the methylation subtypes with Kruskal-Wallis rank sum test p-value. Groups sharing the same letter do not significantly differ (Mann-Whitney U-test $q > 0.05$), while groups with different letters have $q < 0.05$.

d. For 3,516 mRNA transcripts (adjusted for PGA and cohort, see **Methods**) that significantly differed between subtypes (Kruskal Wallis rank-sum test $q<0.05$ and standard deviation (SD) of subtype-medians >0.4), the subtype medians were ranked from 1-4 (smallest to largest). Column-wise percentages show the percent of time a given subtype had each rank.

e. Patient-specific pathway scores were calculated for 50 hallmark pathways using GSVA (47,98) adjusted for PGA and cohort (Methods). For each pathway, the subtype median adjusted mRNA abundance z-score is displayed in the heatmap. Kruskal Wallis test q-values are shown in the right barplot, and pathways were sorted in descending

order by the standard deviation of the subtype medians. The top 20 most significant pathways are shown.

Figure 4: Somatic driver mutations impact the prostate cancer epigenome; and epigenetic signatures of clinico-molecular features

a. CpG β-values were tested for an association with 28 somatic events and clinical features. Somatic features were divided into five categories: mutational burden (mutation density), CNAs, INVs, SNVs, and CTXs including ETS fusions. Barplot on the left shows different q-value category percentages, resulting from Spearman's ρ and Kruskal-Wallis tests for continuous and discrete features, respectively. Barplot on the right shows the number of significantly differentially methylated CpGs associated with each feature ($q < 0.05$), with methylated *vs.* unmethylated status (median β-value threshold = 0.61).

b. Methylation profiles of the top 4 driver events with the most number of significant CpG associations. For each driver event, rows were sorted using hierarchical clustering with the top 100 significant CpGs ($q < 0.05$), complete linkage and Euclidean distance. PGA, SNV count and number of genomic rearrangements were median-dichotomized into high *vs.* low groups.

c. Heatmap of CpG methylation (columns) of patients (rows) stratified by *TP53* CNA loss and SNV mutation status (left covariate bars). The top 1000 CpGs that were significantly positively associated with *TP53* CNA loss ($q<0.05$) and top 1000 inversely associated were combined with the top 1000 positively associated with *TP53* SNV, and top 1000 inversely associated. Columns and rows were sorted using hierarchical clustering with complete linkage and Euclidean distance.

d. Logistic regression was used to test the association between driver events and subtypes while adjusting for cohort and PGA. The odds of having a given mutation (row) are shown for each subtype (column) when treating MS-2 as the reference group. PGA and SNVs/Mbp were median-dichotomized; 12 drivers with $q<0.05$ are shown.

e. Boxplots of the total number of driver events by methylation subtype, with Kruskal-Wallis p-value. Pairwise comparisons between groups were conducted using the Mann-Whitney U-test, such that groups with different letters significantly differ ($q < 0.05$).

f. Performance of the final selected models for predicting features (y-axis labels). Dots indicate the estimated performance on the test dataset with adjacent lines giving 95% bootstrap confidence intervals. Pearson's correlation (r) and balanced accuracy (BA) were used for numeric and categorical features, respectively.

g. Test dataset performance for predicting $\log_2$ SNVs/Mbp. Pearson's r is reported with 95% bootstrap confidence interval in parentheses.

h. Test dataset confusion matrix for predicting *MYC* copy number gain. Balanced accuracy (BA) is reported with 95% bootstrap confidence interval in parentheses. Each cell is shaded by the percentage of the row total.

i. A random forest (RF, blue) and regularized Cox proportional hazards model (rCoxPH, red) were trained for predicting time-until-BCR using different combinations of data as predictors (x-axis labels; see (**j**) for definitions). The height of the bars indicates the estimated C-index in the training and test datasets. Higher C-index indicates better performance.

j. The combinations of predictors used in figure (**i**). For a given row, the y-axis label names the data combination and the boxes indicate which data types are included.

k. The best model from (**i**) was used to predict BCR risk score in the test dataset of 161 patients and median-dichotomized into High *vs.* Low risk. The Kaplan-Meir plot shows the BCR-free probabilities for the High and Low risk groups, with hazard ratio, 95% confidence interval, and Wald-test p-value estimated from a Cox proportional hazards model. The table below the plot gives the number of patients at risk from 0-5 years.

k. The best model from (**i**) was used to predict the BCR risk score for 52 normal samples, 161 localized prostate cancer samples from the test dataset, and 99 metastatic samples. The risk score was compared between the three tissue groups using Kruskal-Wallis rank sum test p-value. Groups with different letters have significantly different risk score profiles (pairwise Wilcoxon test $q < 0.05$).

Figure 5: Somatic driver mutations influence prostate cancer aging

a. Performance of the ten DNA methylation clocks. Pearson's correlation coefficient (r) is reported with a 95% confidence interval. False discovery rate (FDR)-adjusted q-values are shown in the right bar plot.

b. Pairwise correlations (Pearson's r) among the ten DNAm clocks.

c. Pairwise comparison of DNAm age between normal and tumour samples. The dotted line represents the fitted linear model (slope = 0.53, intercept = 23.1)

d, e. Relative age acceleration was compared among methylation subtypes (**d**) and ISUP groups (**e**) using the Kruskal-Wallis rank sum test on residuals adjusted for chronological age.

f, g. Relative age acceleration was compared based on *MYC* CNA gain (**f**) and *NKX3-1* CNA loss (**g**) using the Mann-Whitney U test on residuals adjusted for chronological age.

h. Summary of associations between CNA drivers and relative age acceleration (adjusting for chronological age) in ICGC PRAD-CA, TCGA, and the combined cohorts. Dots represent effect sizes, with background colour indicating q-values.

Figure 1

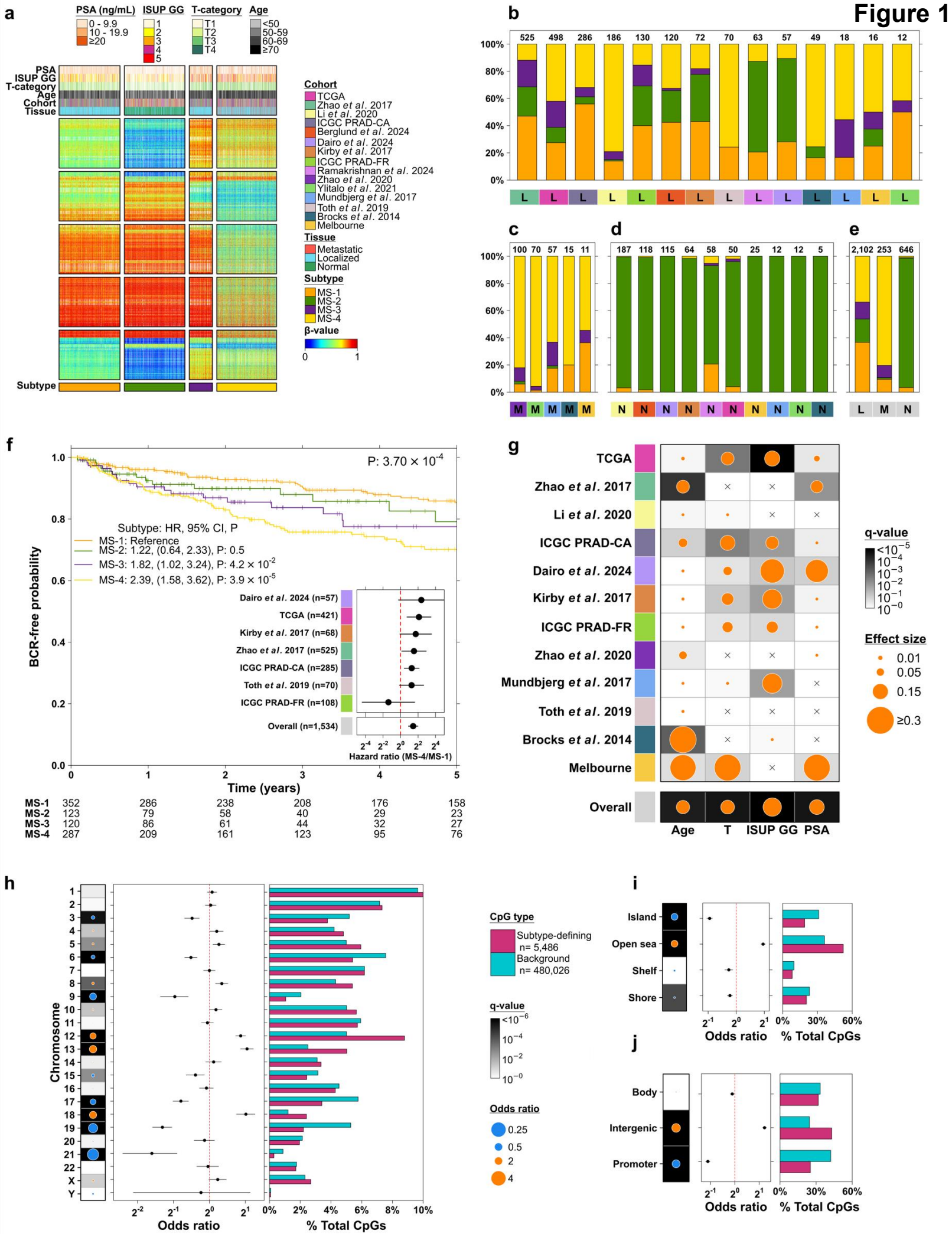

a
PSA (ng/mL)
0 - 9.9
10 - 19.9
≥20
ISUP GG
1
2
3
4
5
T-category
T1
T2
T3
T4
Age
<50
50-59
60-69
≥70
PSA
ISUP GG
T-category
Age
Cohort
Tissue
Subtype
Cohort
TCGA
Zhao et al. 2017
Li et al. 2020
ICGC PRAD-CA
Berglund et al. 2024
Dairo et al. 2024
Kirby et al. 2017
ICGC PRAD-FR
Ramakrishnan et al. 2024
Zhao et al. 2020
Ylitalo et al. 2021
Mundbjerg et al. 2017
Toth et al. 2019
Brocks et al. 2014
Melbourne
Tissue
Metastatic
Localized
Normal
Subtype
MS-1
MS-2
MS-3
MS-4
β-value
0
1
b
525 498 286 186 130 120 72 70 63 57 49 18 16 12
100%
80%
60%
40%
20%
0%
L L L L L L L L L L L L L L
c
100 70 57 15 11
M M M M M
d
187 118 115 64 58 50 25 12 12 5
N N N N N N N N N N
e
2,102 253 646
L M N
f
P: 3.70 × 10^-4
BCR-free probability
Time (years)
Subtype: HR, 95% CI, P
MS-1: Reference
MS-2: 1.22, (0.64, 2.33), P: 0.5
MS-3: 1.82, (1.02, 3.24), P: 4.2 × 10^-2
MS-4: 2.39, (1.58, 3.62), P: 3.9 × 10^-5
Dairo et al. 2024 (n=57)
TCGA (n=421)
Kirby et al. 2017 (n=68)
Zhao et al. 2017 (n=525)
ICGC PRAD-CA (n=285)
Toth et al. 2019 (n=70)
ICGC PRAD-FR (n=108)
Overall (n=1,534)
Hazard ratio (MS-4/MS-1)
MS-1 352 286 238 208 176 158
MS-2 123 79 58 40 29 23
MS-3 120 86 61 44 32 27
MS-4 287 209 161 123 95 76
g
TCGA
Zhao et al. 2017
Li et al. 2020
ICGC PRAD-CA
Dairo et al. 2024
Kirby et al. 2017
ICGC PRAD-FR
Zhao et al. 2020
Mundbjerg et al. 2017
Toth et al. 2019
Brocks et al. 2014
Melbourne
Overall
Age
T
ISUP GG
PSA
q-value
<10^-5
10^-4
10^-3
10^-2
10^-1
10^-0
Effect size
0.01
0.05
0.15
≥0.3
h
Chromosome
Odds ratio
% Total CpGs
CpG type
Subtype-defining
n= 5,486
Background
n= 480,026
q-value
<10^-6
10^-4
10^-2
10^-0
Odds ratio
0.25
0.5
2
4
i
Island
Open sea
Shelf
Shore
Odds ratio
% Total CpGs
j
Body
Intergenic
Promoter
Odds ratio
% Total CpGs

Figure 2

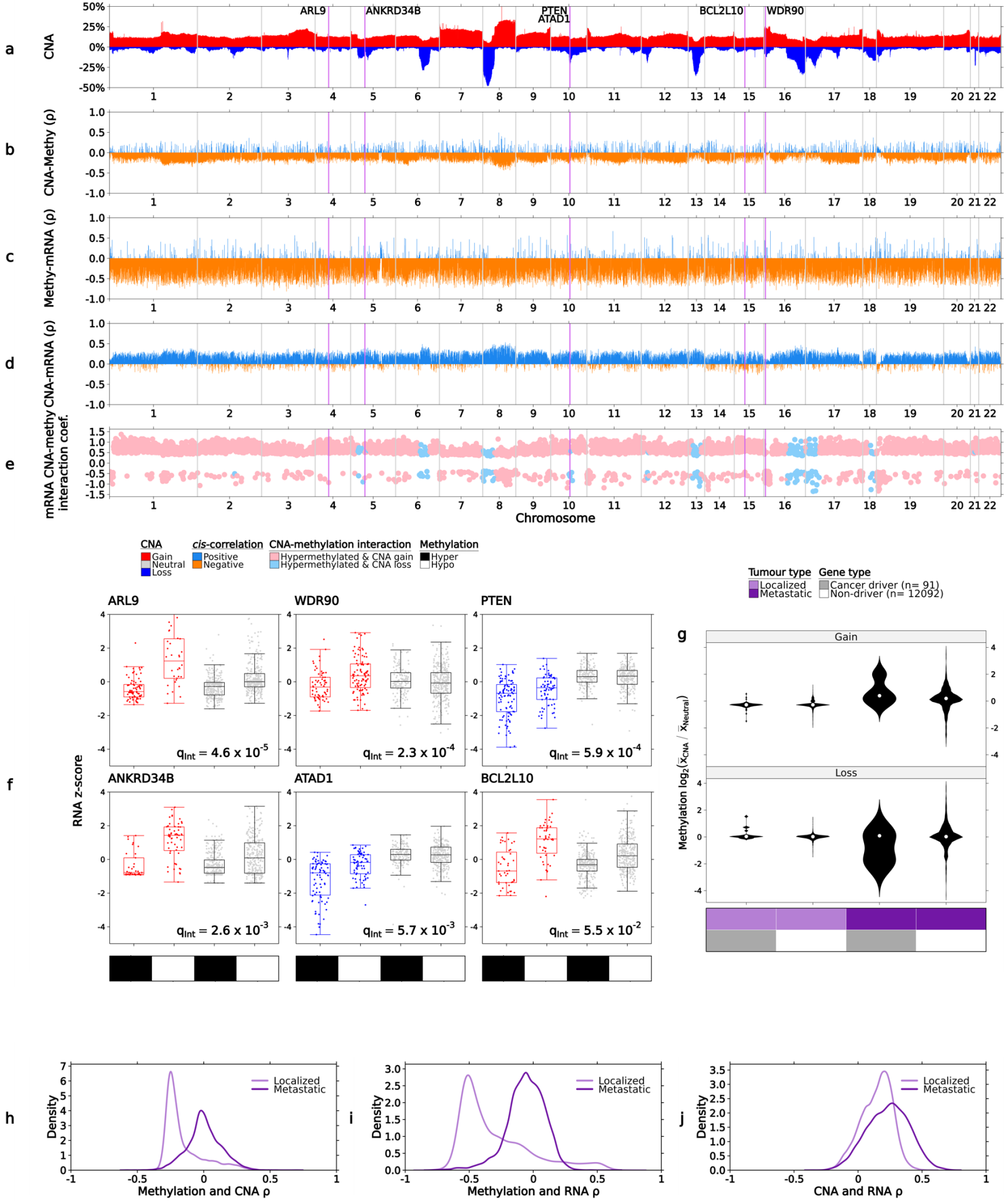

a
CNA
ARL9
ANKRD34B
PTEN
ATAD1
BCL2L10
WDR90
b
CNA-Methy (ρ)
c
Methy-mRNA (ρ)
d
CNA-mRNA (ρ)
e
mRNA CNA-methy interaction coef.
Chromosome
CNA
Gain
Neutral
Loss
cis-correlation
Positive
Negative
CNA-methylation interaction
Hypermethylated & CNA gain
Hypermethylated & CNA loss
Methylation
Hyper
Hypo
Tumour type
Localized
Metastatic
Gene type
Cancer driver (n= 91)
Non-driver (n= 12092)
f
RNA z-score
ARL9
WDR90
PTEN
ANKRD34B
ATAD1
BCL2L10
$q_{Int} = 4.6 \times 10^{-5}$
$q_{Int} = 2.3 \times 10^{-4}$
$q_{Int} = 5.9 \times 10^{-4}$
$q_{Int} = 2.6 \times 10^{-3}$
$q_{Int} = 5.7 \times 10^{-3}$
$q_{Int} = 5.5 \times 10^{-2}$
g
Gain
Loss
Methylation $\log_2(\bar{x}_{CNA} / \bar{x}_{Neutral})$
h
Density
Localized
Metastatic
Methylation and CNA ρ
i
Methylation and RNA ρ
j
CNA and RNA ρ

Figure 3

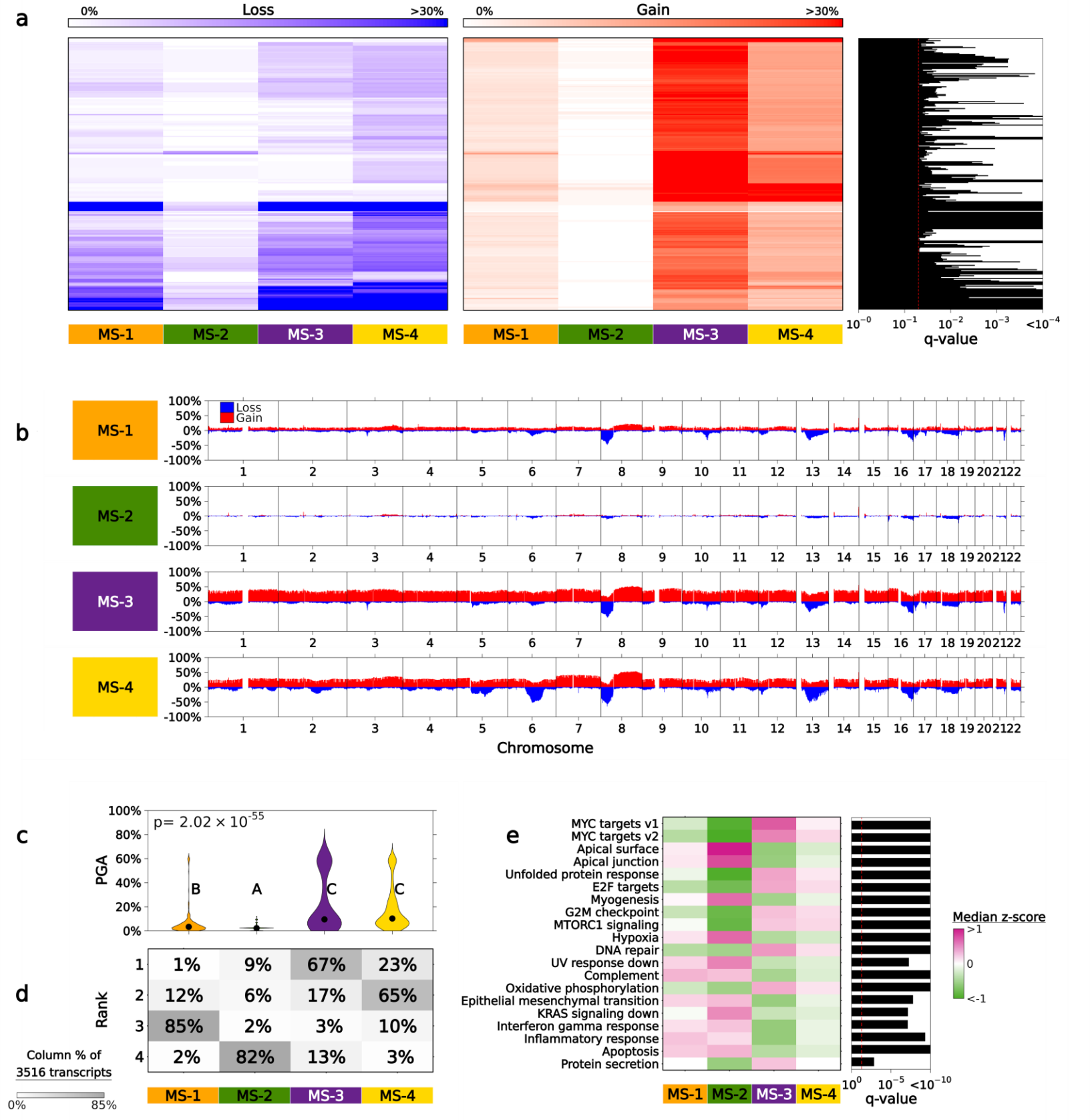

a
0%
Loss
>30%
0%
Gain
>30%
MS-1
MS-2
MS-3
MS-4
MS-1
MS-2
MS-3
MS-4
10^{-0}
10^{-1}
10^{-2}
10^{-3}
$<10^{-4}$
q-value
b
Loss
Gain
MS-1
MS-2
MS-3
MS-4
100%
50%
0%
-50%
-100%
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
Chromosome
c
$p= 2.02 \times 10^{-55}$
PGA
100%
80%
60%
40%
20%
0%
B
A
C
C
d
Rank
1 1% 9% 67% 23%
2 12% 6% 17% 65%
3 85% 2% 3% 10%
4 2% 82% 13% 3%
MS-1
MS-2
MS-3
MS-4
Column % of
3516 transcripts
0%
85%
e
MYC targets v1
MYC targets v2
Apical surface
Apical junction
Unfolded protein response
E2F targets
Myogenesis
G2M checkpoint
MTORC1 signaling
Hypoxia
DNA repair
UV response down
Complement
Oxidative phosphorylation
Epithelial mesenchymal transition
KRAS signaling down
Interferon gamma response
Inflammatory response
Apoptosis
Protein secretion
MS-1
MS-2
MS-3
MS-4
10^{0}
10^{-5}
$<10^{-10}$
q-value
Median z-score
>1
0
<-1

Figure 4

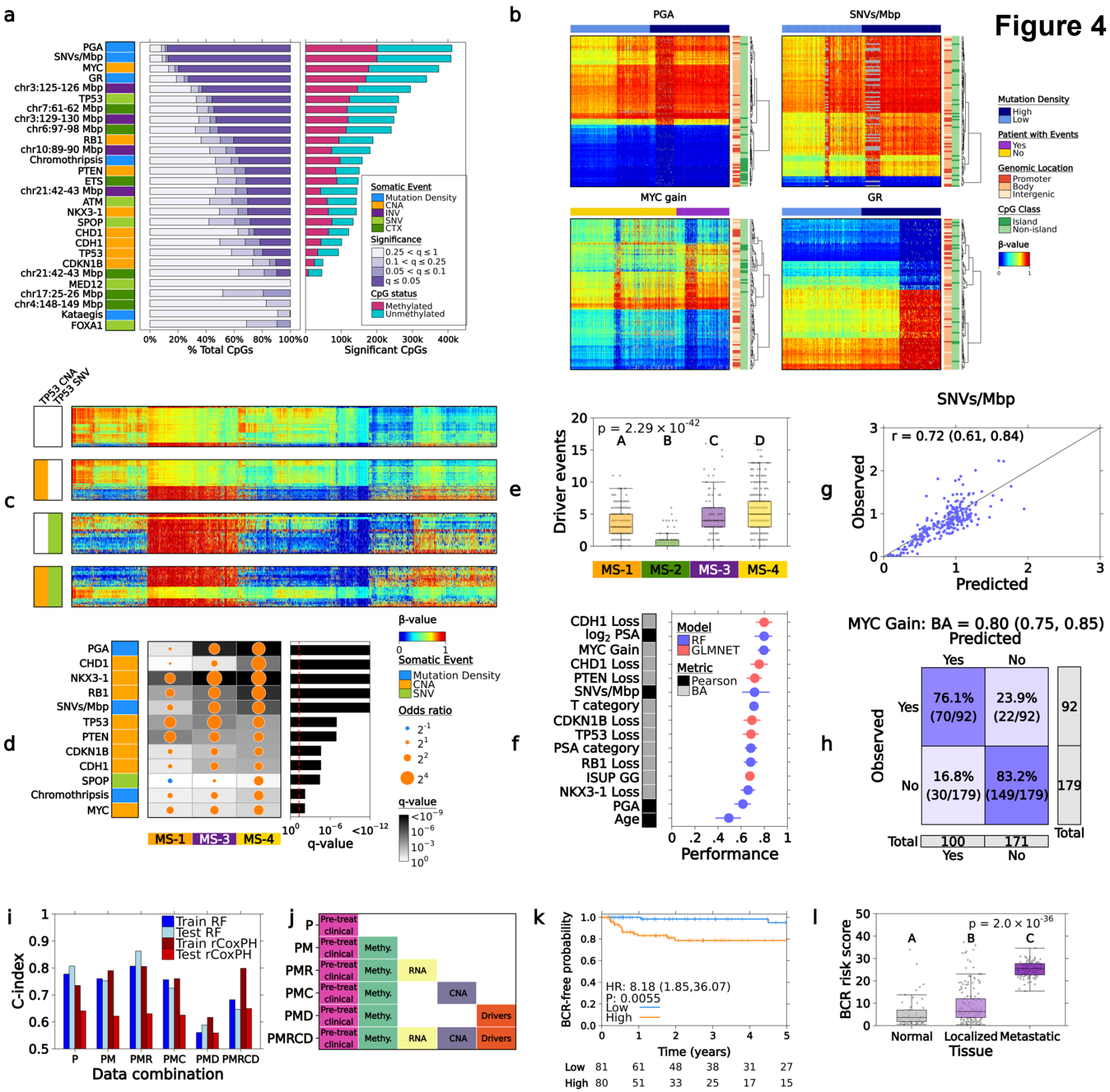
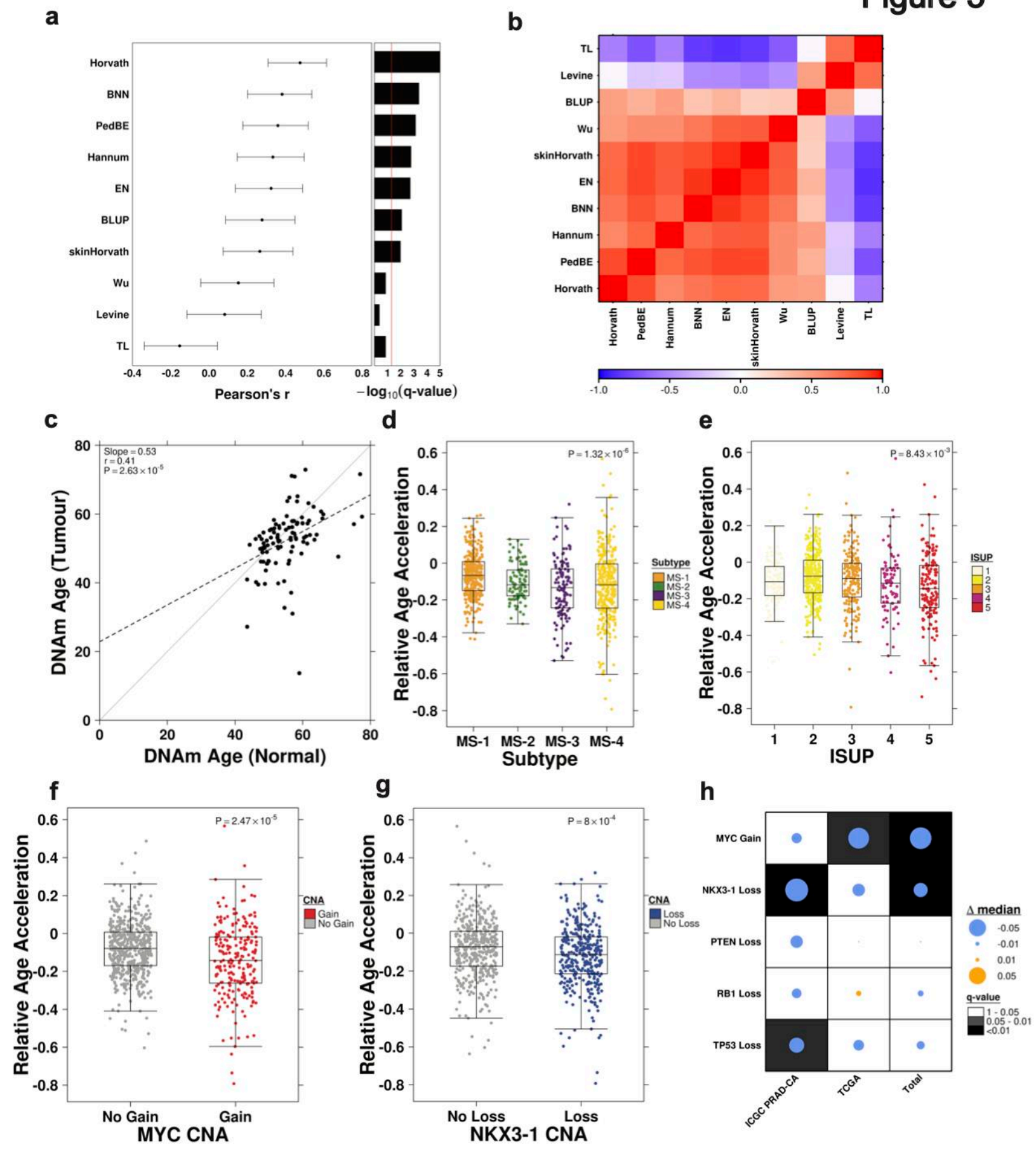
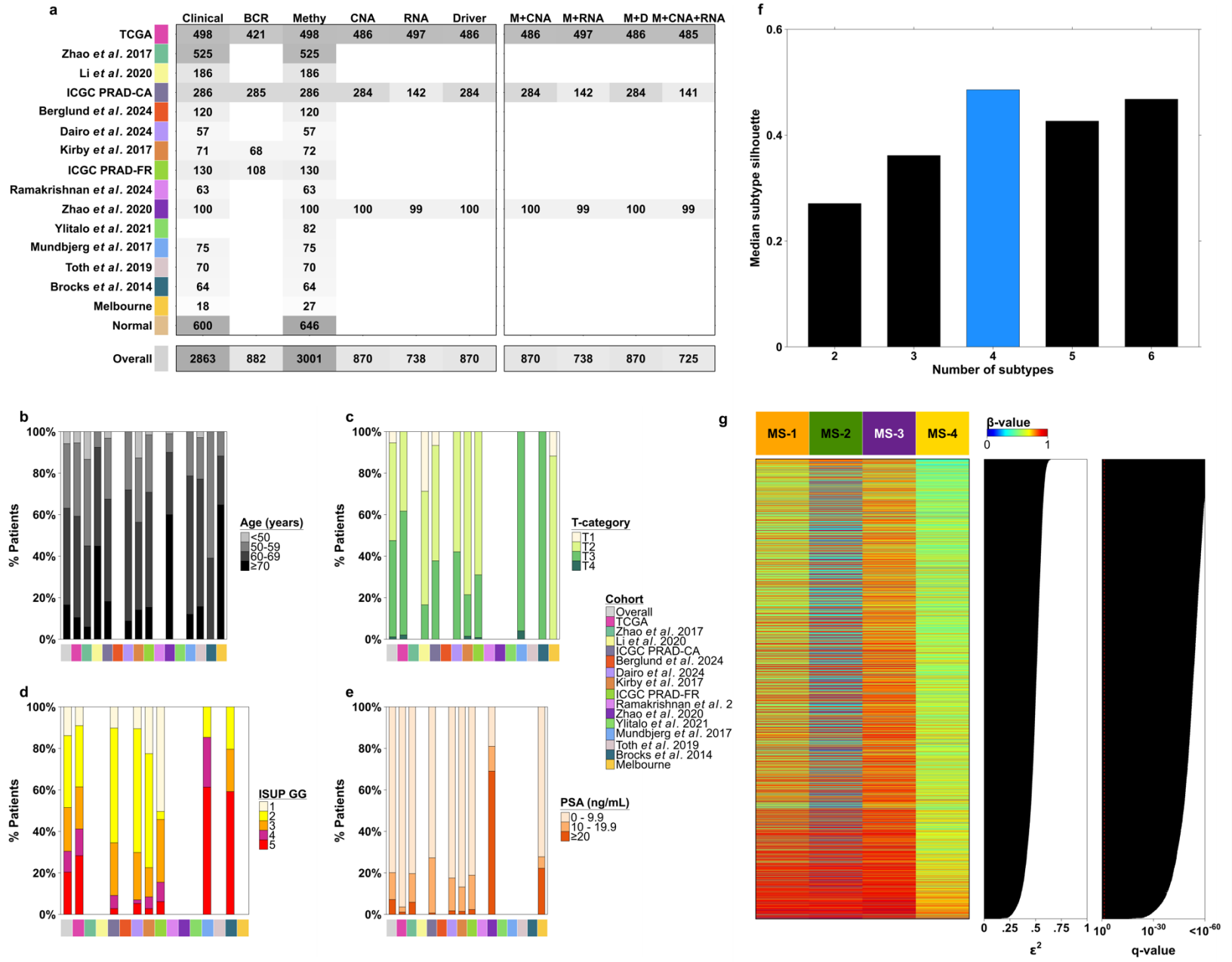

a
PGA
SNVs/Mbp
MYC
GR
chr3:125-126 Mbp
TP53
chr7:61-62 Mbp
chr3:129-130 Mbp
chr6:97-98 Mbp
RB1
chr10:89-90 Mbp
Chromothripsis
PTEN
ETS
chr21:42-43 Mbp
ATM
NKX3-1
SPOP
CHD1
CDH1
TP53
CDKN1B
chr21:42-43 Mbp
MED12
chr17:25-26 Mbp
chr4:148-149 Mbp
Kataegis
FOXA1
% Total CpGs
Significant CpGs
Somatic Event
Mutation Density
CNA
INV
SNV
CTX
Significance
0.25 < q ≤ 1
0.1 < q ≤ 0.25
0.05 < q ≤ 0.1
q ≤ 0.05
CpG status
Methylated
Unmethylated
b
PGA
SNVs/Mbp
MYC gain
GR
Mutation Density
High
Low
Patient with Events
Yes
No
Genomic Location
Promoter
Body
Intergenic
CpG Class
Island
Non-island
β-value
c
TP53 CNA
TP53 SNV
d
PGA
CHD1
NKX3-1
RB1
SNVs/Mbp
TP53
PTEN
CDKN1B
CDH1
SPOP
Chromothripsis
MYC
MS-1
MS-3
MS-4
q-value
β-value
Somatic Event
Mutation Density
CNA
SNV
Odds ratio
q-value
e
Driver events
p = 2.29 × 10^-42
A
B
C
D
MS-1
MS-2
MS-3
MS-4
f
CDH1 Loss
log2 PSA
MYC Gain
CHD1 Loss
PTEN Loss
SNVs/Mbp
T category
CDKN1B Loss
TP53 Loss
PSA category
RB1 Loss
ISUP GG
NKX3-1 Loss
PGA
Age
Model
RF
GLMNET
Metric
Pearson
BA
Performance
g
SNVs/Mbp
r = 0.72 (0.61, 0.84)
Observed
Predicted
h
MYC Gain: BA = 0.80 (0.75, 0.85)
Predicted
Yes
No
Observed
Yes
No
76.1% (70/92)
23.9% (22/92)
16.8% (30/179)
83.2% (149/179)
92
179
Total
100
171
Total
Yes
No
i
Train RF
Test RF
Train rCoxPH
Test rCoxPH
C-index
P
PM
PMR
PMC
PMD
PMRCD
Data combination
j
P
PM
PMR
PMC
PMD
PMRCD
Pre-treat clinical
Methy.
RNA
CNA
Drivers
k
BCR-free probability
HR: 8.18 (1.85,36.07)
P: 0.0055
Low
High
Time (years)
Low 81 61 48 38 31 27
High 80 51 33 25 17 15
l
BCR risk score
p = 2.0 × 10^-36
A
B
C
Normal
Localized
Metastatic
Tissue

Figure 5


a
Horvath
BNN
PedBE
Hannum
EN
BLUP
skinHorvath
Wu
Levine
TL
Pearson's r
−log10(q-value)
b
TL
Levine
BLUP
Wu
skinHorvath
EN
BNN
Hannum
PedBE
Horvath
c
Slope = 0.53
r = 0.41
P = 2.63 × 10-5
DNAm Age (Tumour)
DNAm Age (Normal)
d
P = 1.32 × 10-6
Relative Age Acceleration
Subtype
MS-1
MS-2
MS-3
MS-4
e
P = 8.43 × 10-3
Relative Age Acceleration
ISUP
f
P = 2.47 × 10-5
Relative Age Acceleration
CNA
Gain
No Gain
MYC CNA
g
P = 8 × 10-4
Relative Age Acceleration
CNA
Loss
No Loss
NKX3-1 CNA
h
MYC Gain
NKX3-1 Loss
PTEN Loss
RB1 Loss
TP53 Loss
ICGC PRAD-CA
TCGA
Total
Δ median
-0.05
-0.01
0.01
0.05
q-value
1 - 0.05
0.05 - 0.01
<0.01



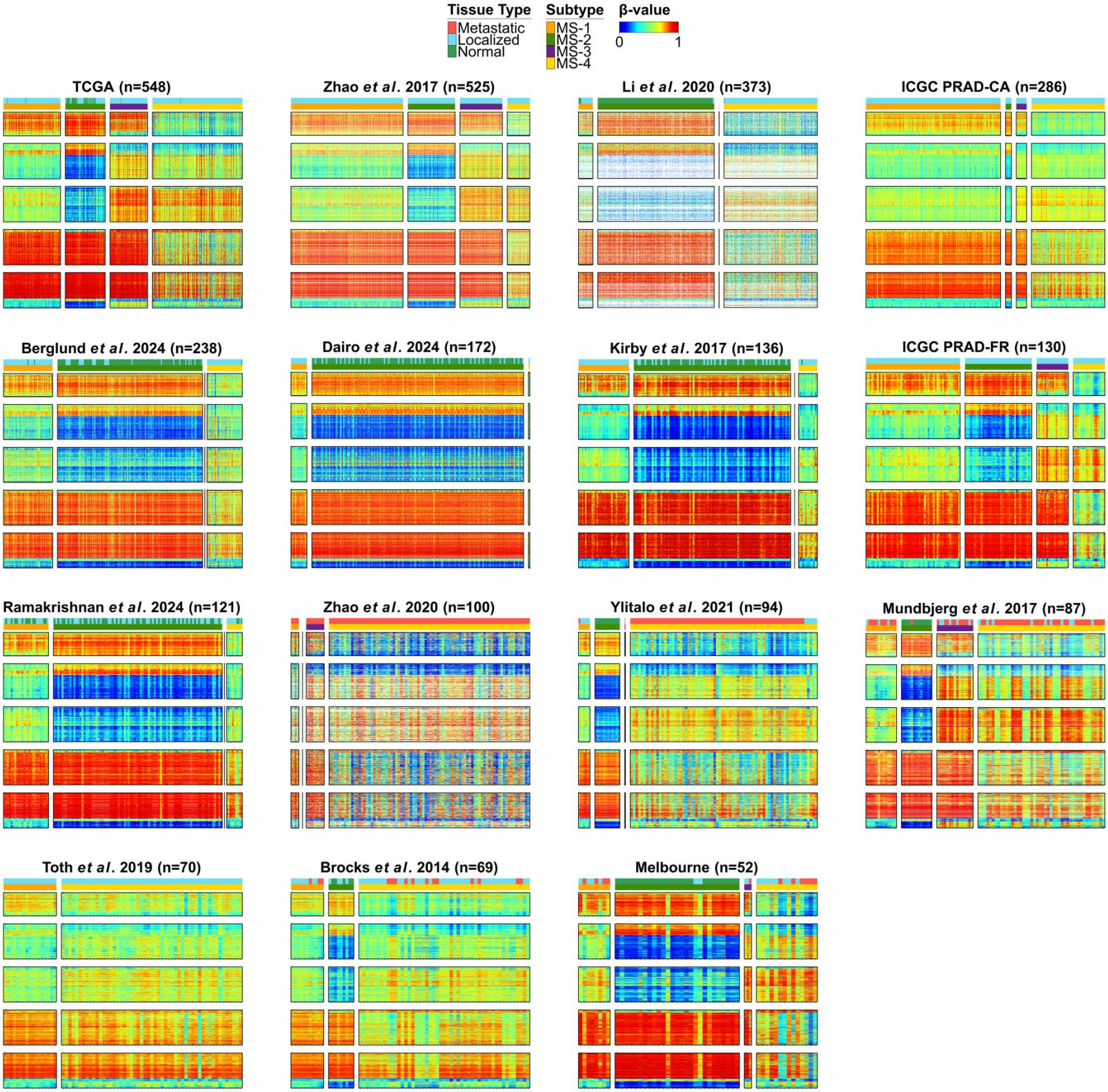
Supplementary Figure 1: Sample size, pre-treatment clinical features and subtype-defining CpGs

a. Sample size by cohort (row) and data type (column). Normal samples from all cohorts are pooled into the "Normal" row. Columns: Clinical stands for pre-treatment clinical features; BCR is time-until biochemical reoccurrence; Driver is the panel of 28 driver mutations; M = methylation, D = driver.

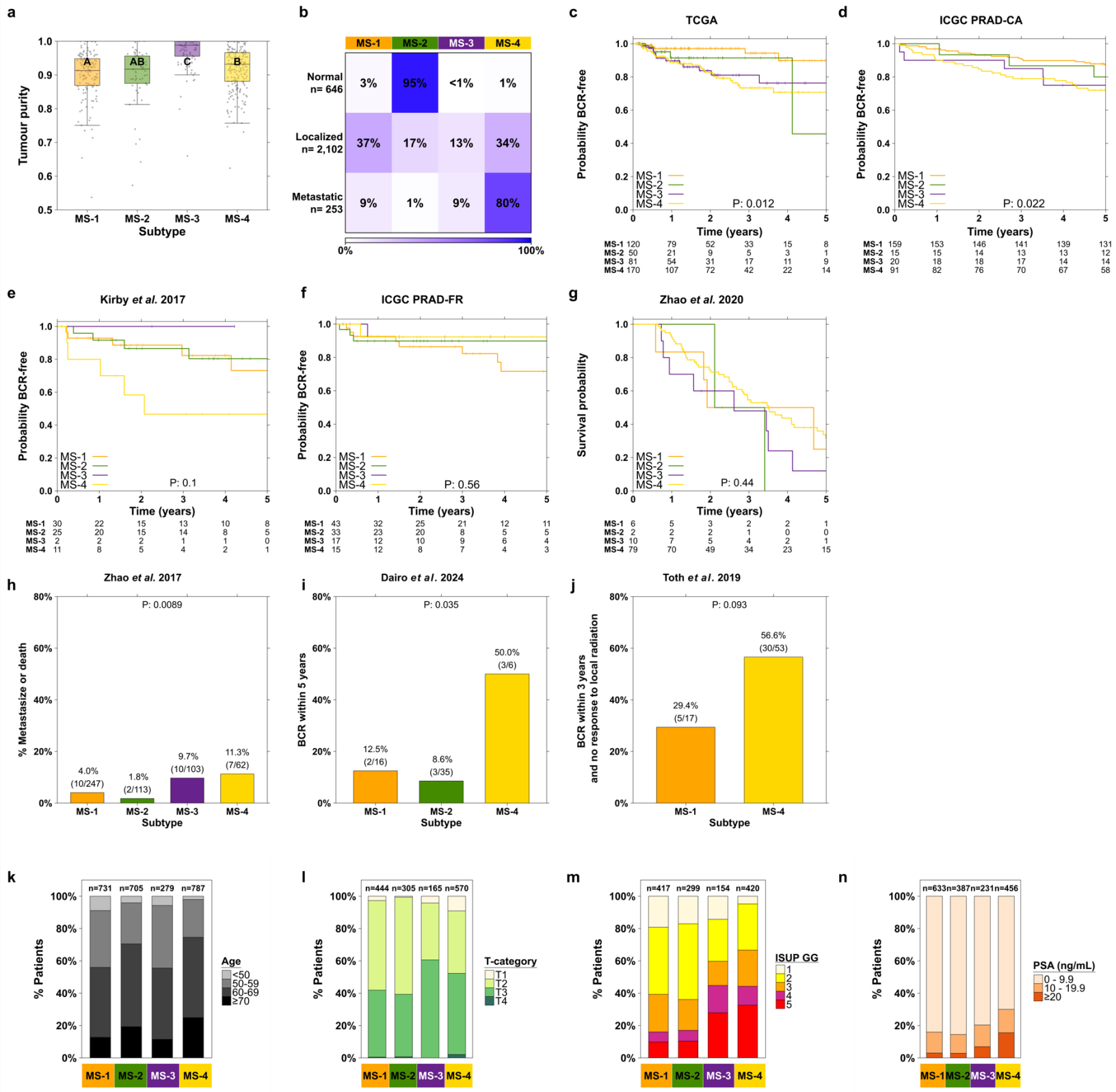
b-e. Stacked barplots showing the percent of patients in each category (y-axis) stratified by cohort (x-axis). T-category: tumour category; ISUP GG: International Society of Urologic Pathologists grade group; PSA: prostate-specific antigen.

f. The silhouette method was used to choose the number of subtypes that maximized the median silhouette score, resulting in 4 subtypes (blue).

g. Each of 5,486 subtype-defining CpGs (rows) is summarized by the median methylation β-value within each subtype (column). Kruskal-Wallis test was used to compare each CpG between the subtypes, with q-values displayed in the right barplot and epsilon-squared ε^2 effect size in the middle barplot.



Supplementary Figure 2: Subtype methylation profiles by cohort, tissue type
Methylation profiles stratified by cohort, subtype and tissue type (covariate bars beneath each cohort's title). Patient-wise consensus clustering was performed using IMPACC to derive four subtypes within the TCGA cohort. The heatmaps include 5,486 CpGs which were selected by IMPACC as important for deriving the subtypes. A classifier was trained to classify all remaining samples to their respective subtypes identified in the TCGA cohort. CpGs were sorted using hierarchical clustering with complete linkage and Euclidean distance in the TCGA cohort, then split into five equally sized groups for easier visualization. Missing values are colored in white.



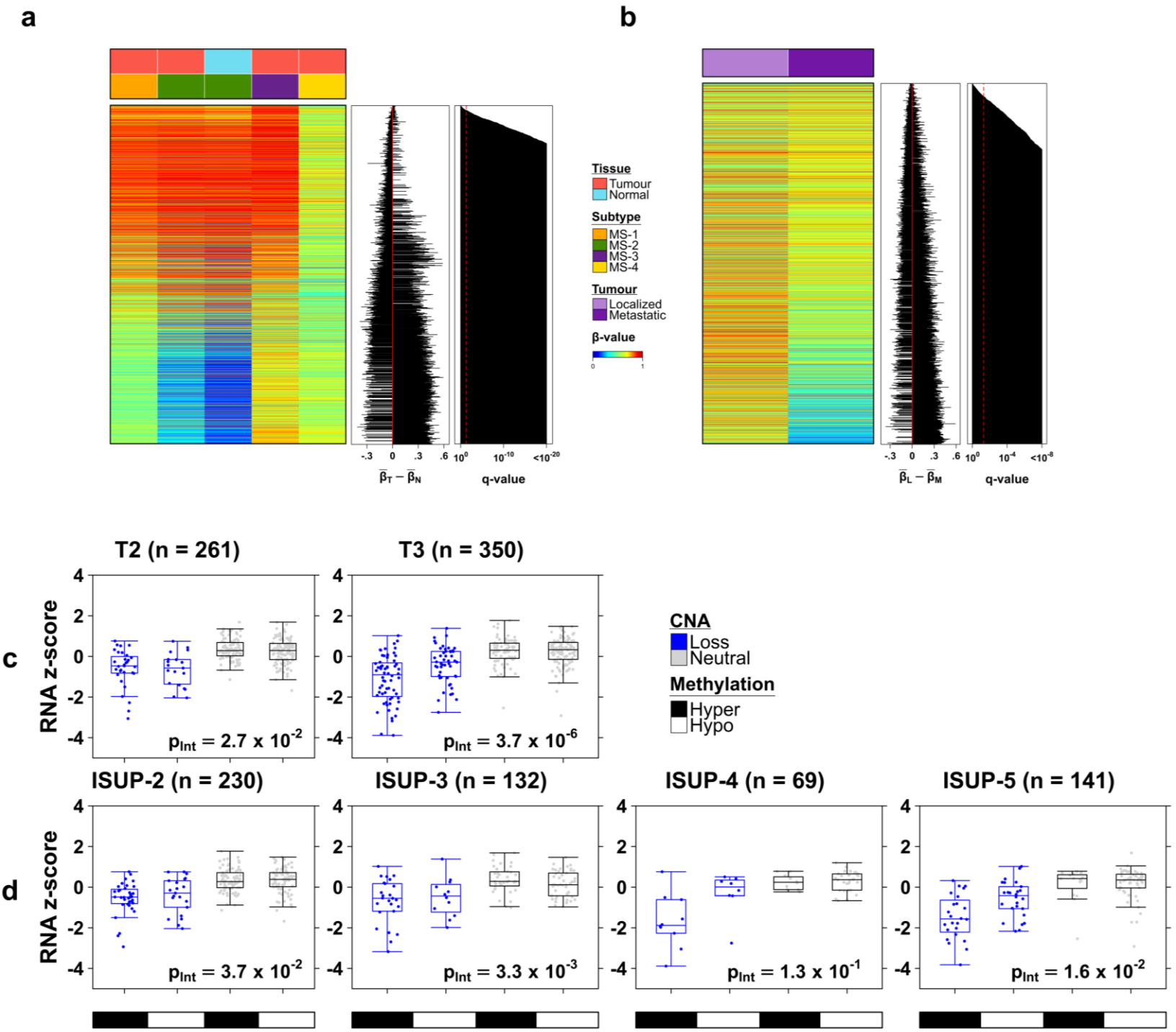
Supplementary Figure 3: Methylation subtypes *vs.* tumour purity and clinical features

a. Tumour purity was compared between subtypes within the TCGA derivation cohort. Groups sharing the same letter do not significantly differ, U-test q > 0.05.

b. Within each tissue type (row), the percent of samples assigned to each subtype (column) is shown.

c-j. The subtypes were tested for association with time until biochemical recurrence (BCR) using a logrank test in cohorts (**c,d,f**) and a permutation logrank test in Kirby *et al.* 2017 (**e**), due to small/uneven group sample sizes (10,000 permutations). The permutation logrank test was used for time until death in Zhao *et al.* 2020 (**g**), while Fisher's Exact Test was used for the binary outcomes of (**h-j**).

k-n. Stacked barplots showing % of patients in each category (y-axis) stratified by methylation subtype (x-axis). T-category: tumour category; ISUP GG: International Society of Urologic Pathologists grade group; PSA: prostate-specific antigen.

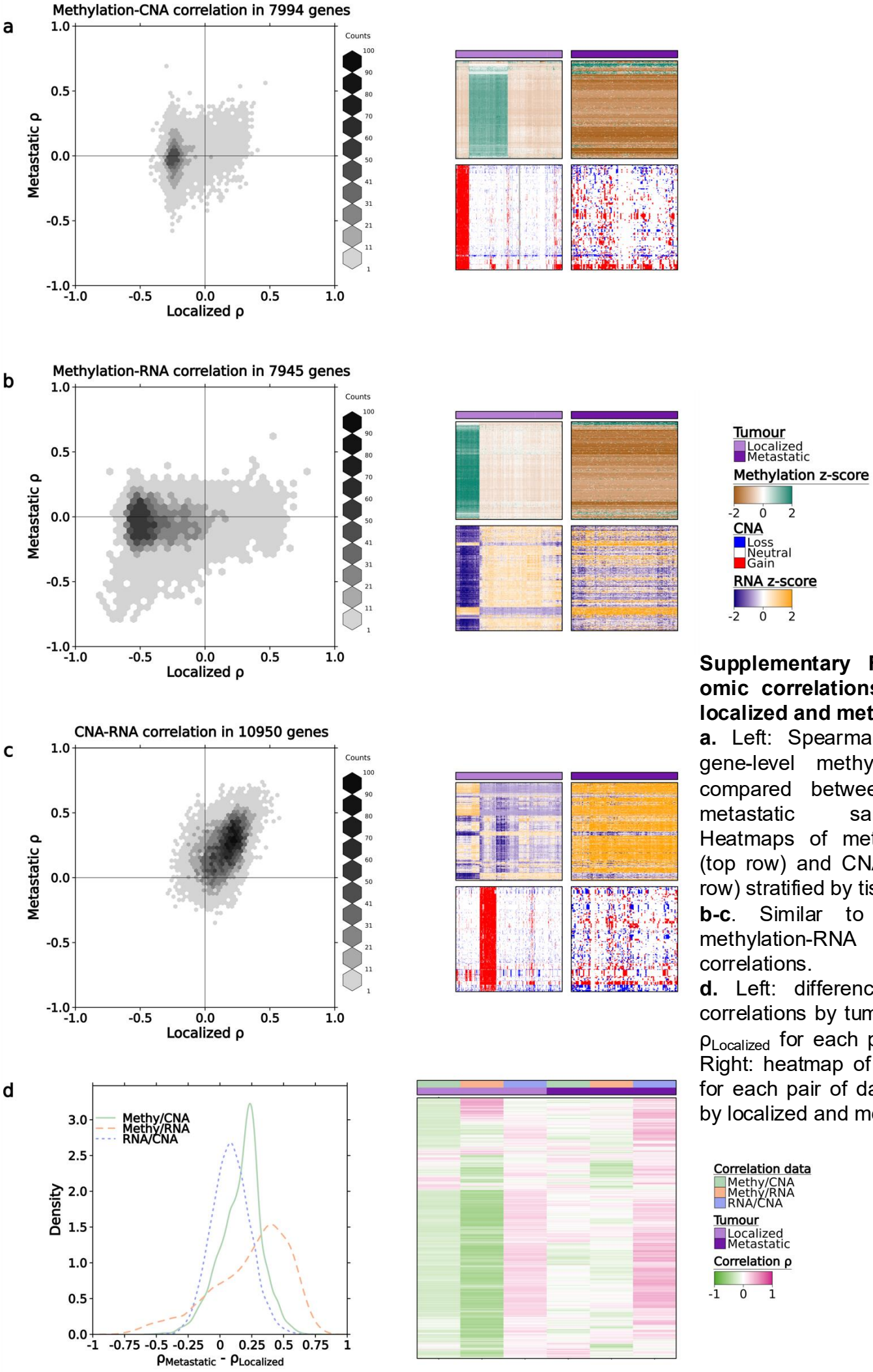


Supplementary Figure 4: Subtype defining CpGs *vs.* tissue type; PTEN interaction sensitivity analysis

a. Tumour *vs.* normal samples: Heatmap of 5,486 subtype-defining CpGs, sorted by $|\bar{\beta}_T - \bar{\beta}_N|$, where $\bar{\beta}_T$ is the median methylation beta-value in tumour samples, and $\bar{\beta}_N$ is the median beta-value in normal samples. The Mann–Whitney U test was used to test for differences between the tumour and normal distributions of each CpG, with q-values displayed in the right barplot.

b. Localized *vs.* metastatic samples: Similar to **a.**, except CpGs sorted by $|\bar{\beta}_L - \bar{\beta}_M|$, where $\bar{\beta}_L$ is the median methylation beta-value in localized prostate cancers, and $\bar{\beta}_M$ is the median beta-value in metastatic prostate cancers.

c,d. A sensitivity analysis was performed for the PTEN methylation-CNA interaction on mRNA abundance (from Figure 2e,f) to determine whether the same association held across tumour categories (**c**) and ISUP grade groups (**d**). Linear regression was used to test the interaction between binary methylation (hyper vs. hypomethylation; median dichotomized) and binary CNA status (loss vs. neutral), with the interaction p-value given by p_{Int}. The dependent variable is RNA abundance (z-score transformed $\log_2$ TPM). Boxplots are only shown for tumour categories and ISUP grades where each of the four groups had sample size greater than five.

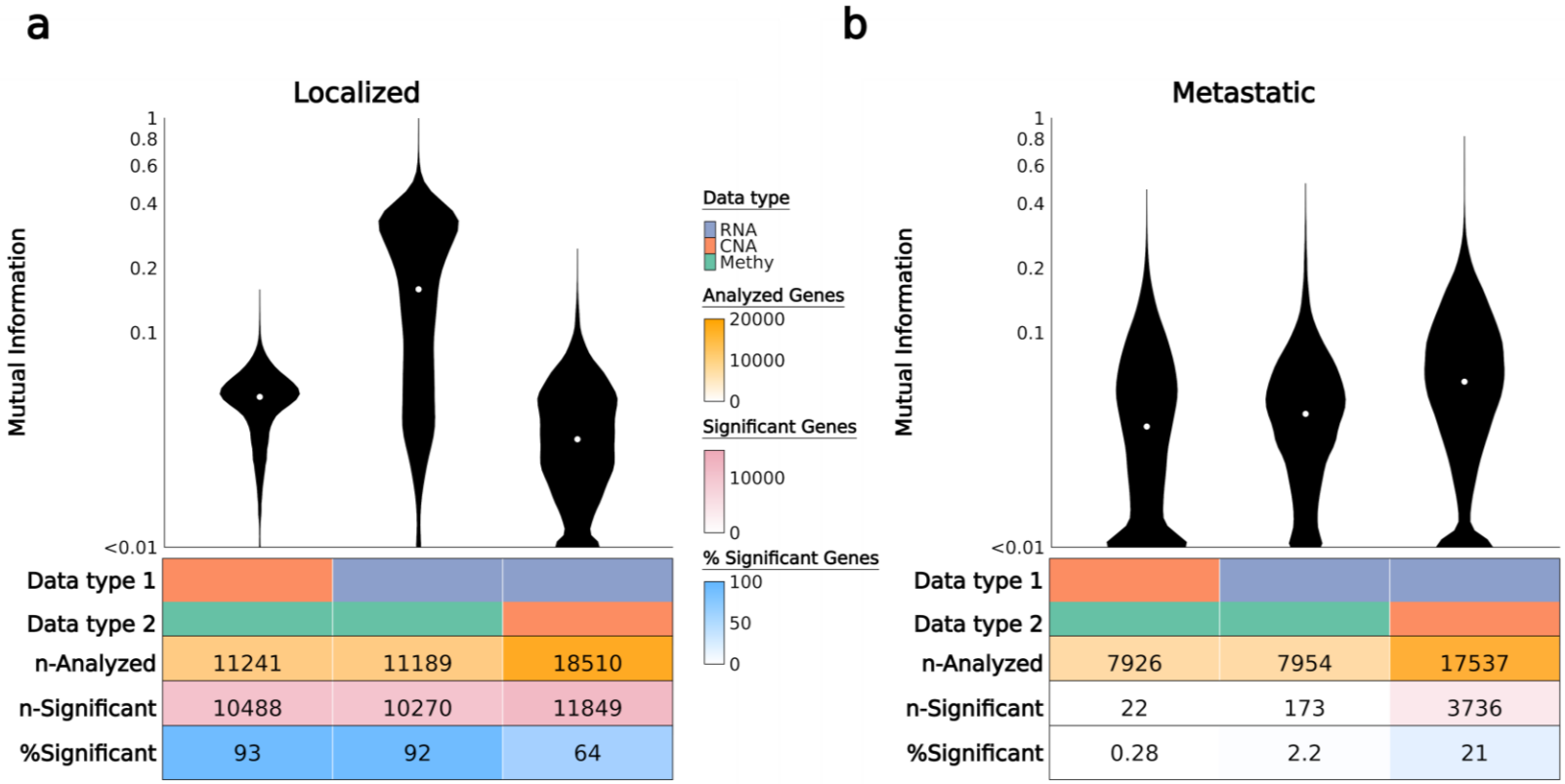


Supplementary Figure 5: Multi-omic correlations differ between localized and metastatic samples

a. Left: Spearman's correlation of gene-level methylation and CNA compared between localized and metastatic samples. Right: Heatmaps of methylation z-scores (top row) and CNA profiles (bottom row) stratified by tissue type.

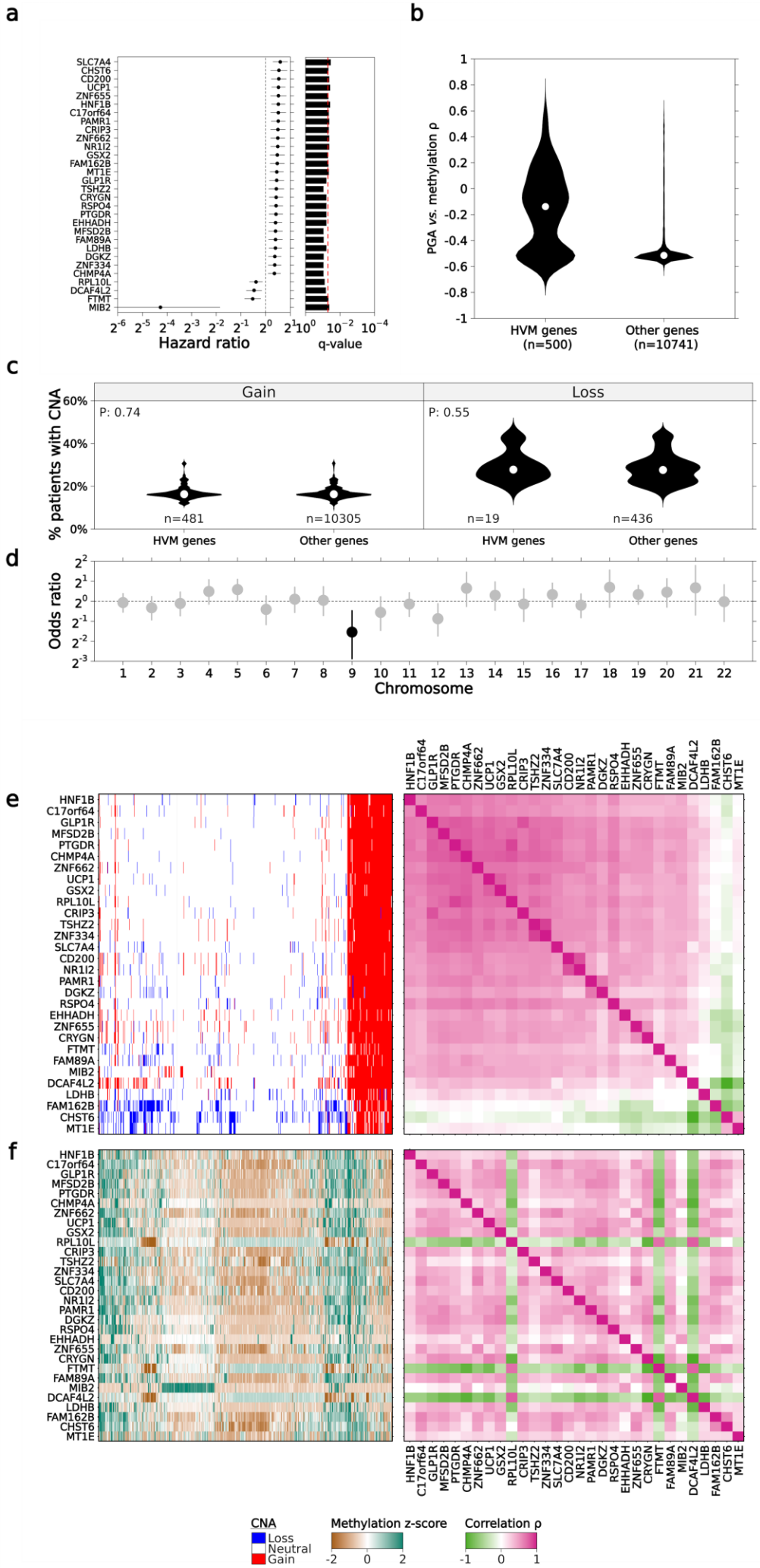
b-c. Similar to (a) except for methylation-RNA and CNA-RNA correlations.

d. Left: differences in gene-level correlations by tumor type $\rho_{Metastatic}$ - $\rho_{Localized}$ for each pair of data types. Right: heatmap of gene correlations for each pair of data types stratified by localized and metastatic samples.



Supplementary Figure 6: Mutual information of multi-omic data differs in localized and metastatic samples

a-b. Mutual information was calculated for all features within each pair of data types (RNA, CNA, methylation) and displayed in a violin plot. A permutation test with 1000 permutations was used to calculate p-values and results with multiple-testing adjusted q<0.05 were regarded as statistically significant. Results were stratified by localized (**a**) and metastatic (**b**) prostate cancers.



Supplementary Figure 7: Genes with high variation in methylation (HVM) *vs.* BCR and CNA

a. 30/500 HVM genes significantly associated with time-until-BCR (Cox proportional hazard Wald test q < 0.05). Gene methylation measured by median beta-value of CpG islands in the gene promoter region.

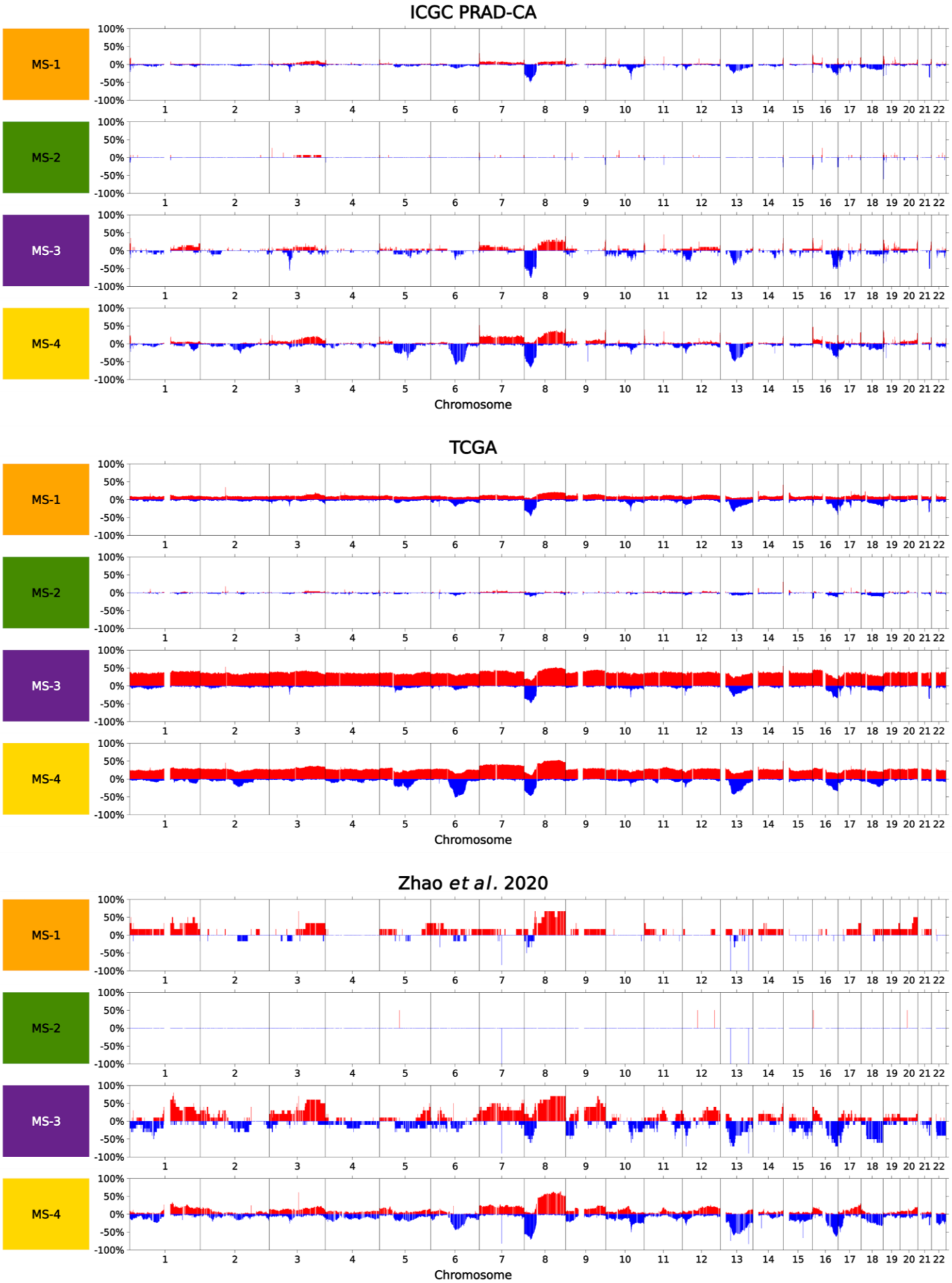
b. Spearman correlation of HVM and non-HVM gene methylation vs. PGA.

c. Percent of patients with CNA loss or gain was calculated separately for HVM and non-HVM genes and compared using Mann-Whitney U-test.

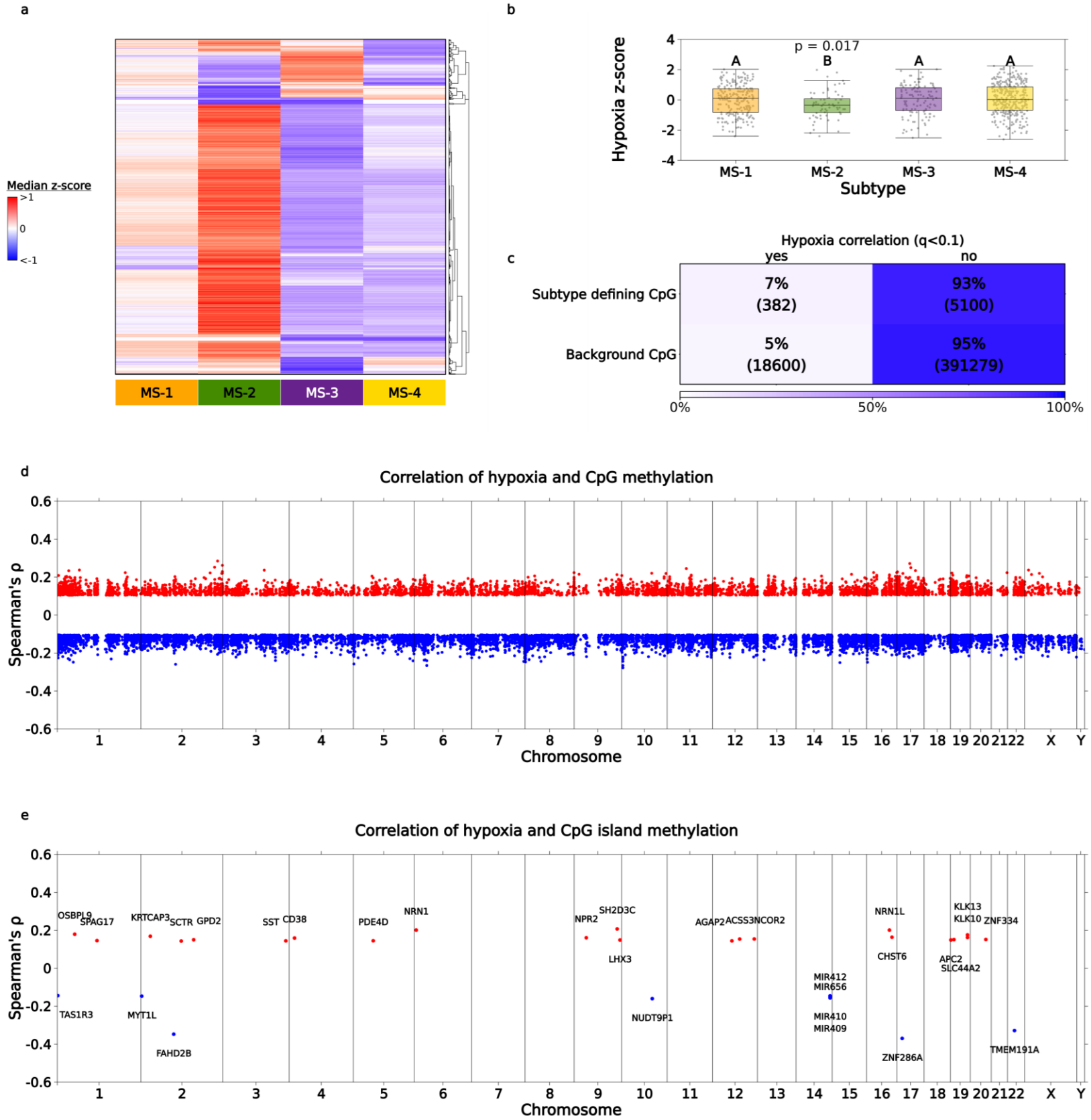
d. The number of HVM and non-HVM genes was compared within each chromosome using Fisher's exact test and odds ratio. Significant results shown in black, q < 0.05.

e. Left: CNA profiles for the 30 HVM genes in (a). Both rows and columns were sorted using hierarchical clustering with Euclidean distance and complete linkage. Right: Spearman's correlation heatmap of the CNA profiles.

f. Left: Methylation profiles for the 30 HVM genes in (a). Rows/columns were sorted to match (e). Right: Spearman's correlation heatmap of the methylation profiles.



Supplementary Figure 8: Genome-wide CNA profiles by subtype and cohort
The genome-wide copy number alteration (CNA) profile is shown for each subtype (row), stratified by the ICGC PRAD-CA, TCGA and Zhao *et al.* 2020 cohorts. Bars indicate the percent of patients with copy number gain or loss (y-axis) at each location of the genome (x-axis).



Supplementary Figure 9: RNA *vs.* subtypes and hypoxia *vs.* methylation

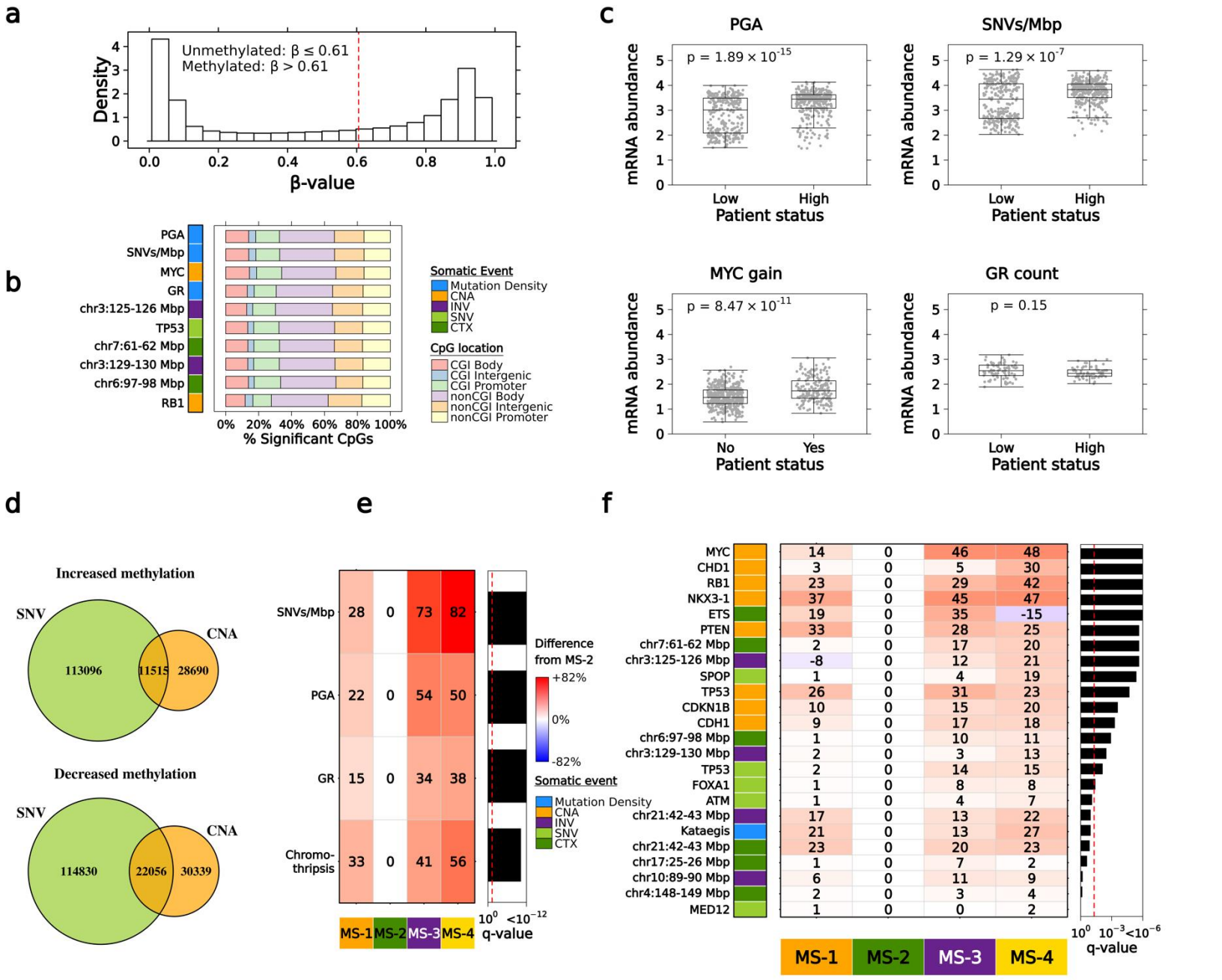
a. Heatmap of median adjusted RNA abundance z-score (adjusted for cohort and PGA) by subtype for 3,516 significant transcripts (Kruskal Wallis q < 0.05, standard deviation (SD) of subtype median z-scores > 0.4).

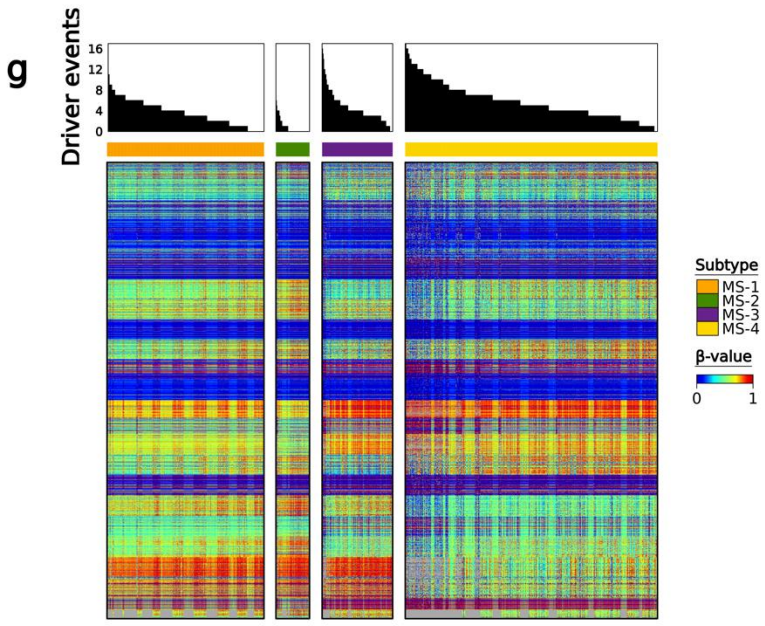
b. Hypoxia z-score was compared between subtypes using Kruskal-Wallis rank sum test. Pairwise comparisons between groups were conducted using the Mann-Whitney U-test, such that groups with different letters significantly differ (q < 0.05).

c. Spearman's correlation was calculated for each CpG with hypoxia score. The table compares the rate of significant CpG-hypoxia correlation (q < 0.05) between subtype-defining and non-subtype-defining background CpGs. Subtype defining CpGs have greater odds of hypoxia correlation: OR = 1.6 (95% CI: 1.4, 1.8).

d. Spearman's correlation between each CpG with hypoxia score. 18,982 significant CpGs shown (q<0.1) out of 415,361 tested; 69% negative correlations.

e. Spearman's corr. of hypoxia and methylation of CpG islands in gene promoters. 32 significant genes shown (q<0.1) out of 13,816 tested.





Supplementary Figure 10: Driver events *vs.* methylation

a. The median methylation β-value was calculated for each CpG and displayed as a histogram (498 TCGA patients; 418,822 CpGs). The red dotted line represents a median β-value = 0.61.

b. Top 10 driver events with the most number of significant CpG associations (q < 0.05). CpG locations were categorized into six groups with a combination of CpG island/non-CpG island and different genomic regions (gene promoter, body and intergenic). Percentages were calculated based on how many significant differentially methylated CpGs in each group.

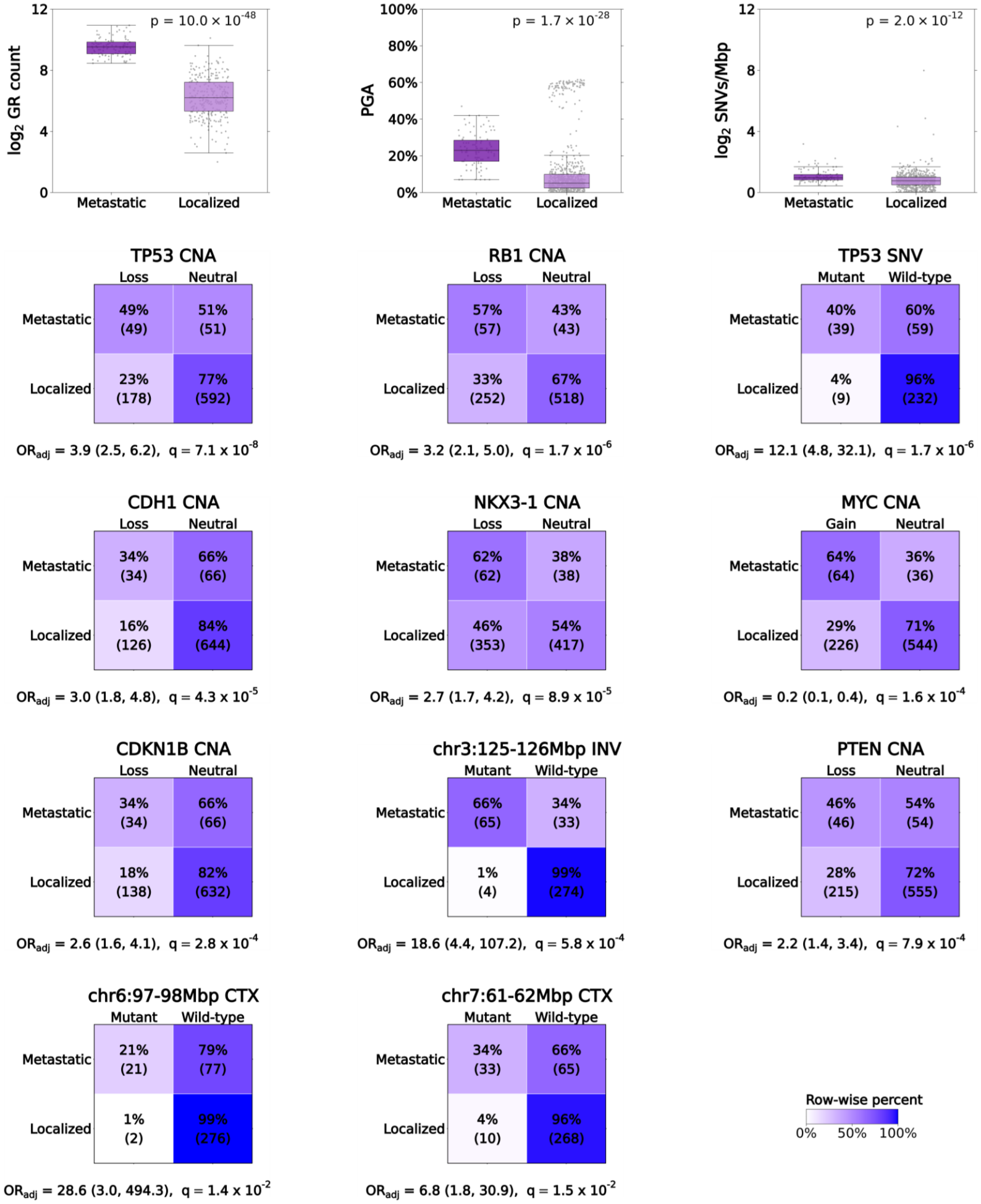
c. mRNA abundance levels of the top four driver events with the most number of significant CpG associations. For a given driver event, patient-level mRNA abundance was calculated as the median abundance among all genes that map to the top 100 most significant CpG associations. SNV count and PGA were median-dichotomized into high *vs.* low groups. P-value was generated from the Mann-Whitney U-test.

d. Compares the overlap of CpGs significantly associated (q < 0.05) with *TP53* SNV (green) and *TP53* CNA loss (orange). Positive and inverse associations are shown in the top and bottom Venn Diagrams, respectively.

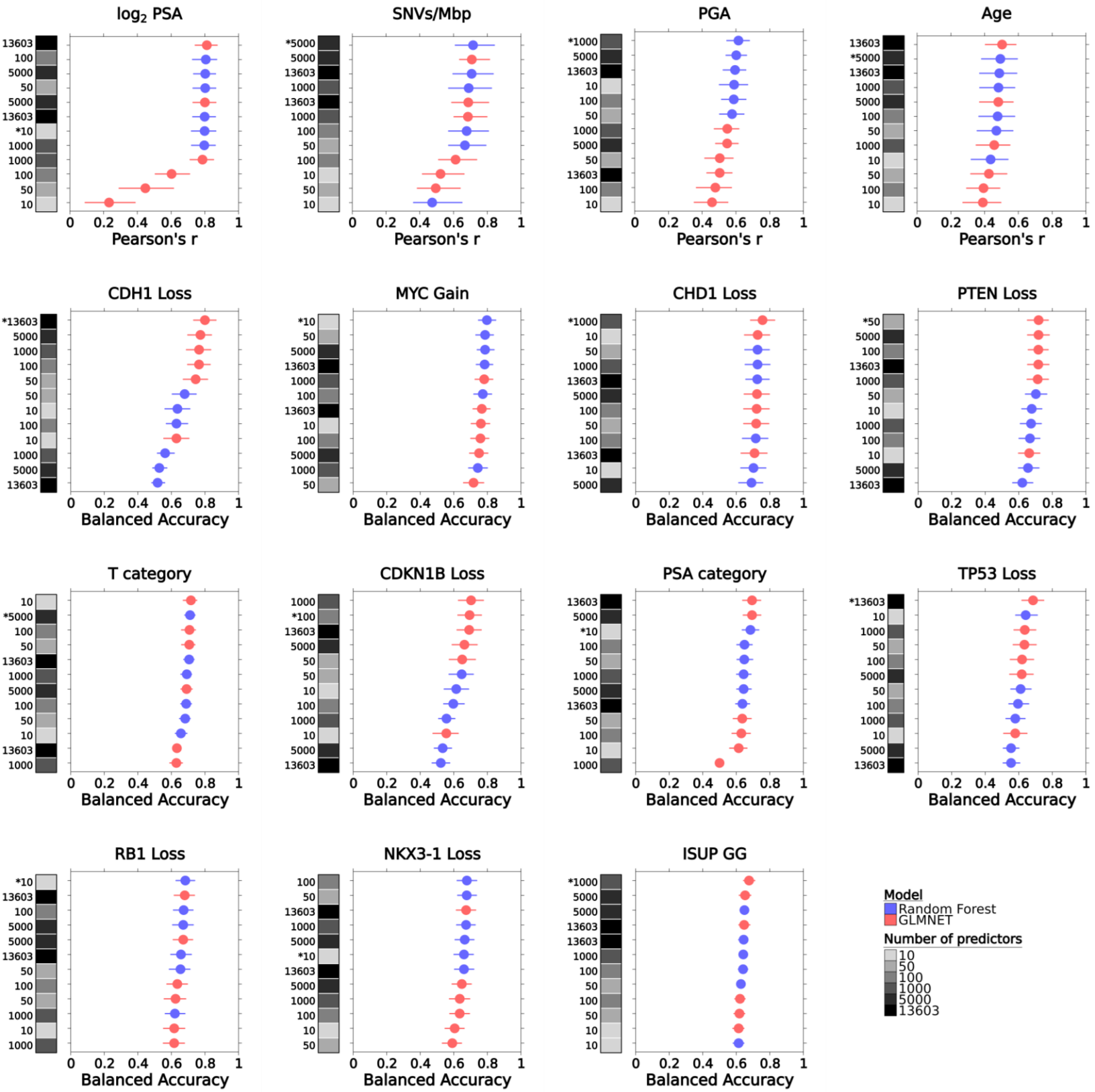
e. Numeric drivers *vs.* subtypes: the median percentile was calculated for each subtype then subtracted from MS-2; Kruskal-Wallis test q-value.

f. Binary drivers *vs.* subtypes: the percent of patients with the driver event was calculated for each subtype then subtracted from MS-2; chi-square test q-value (or Fisher's exact test if 2x2 table or cell with <5 expected counts).

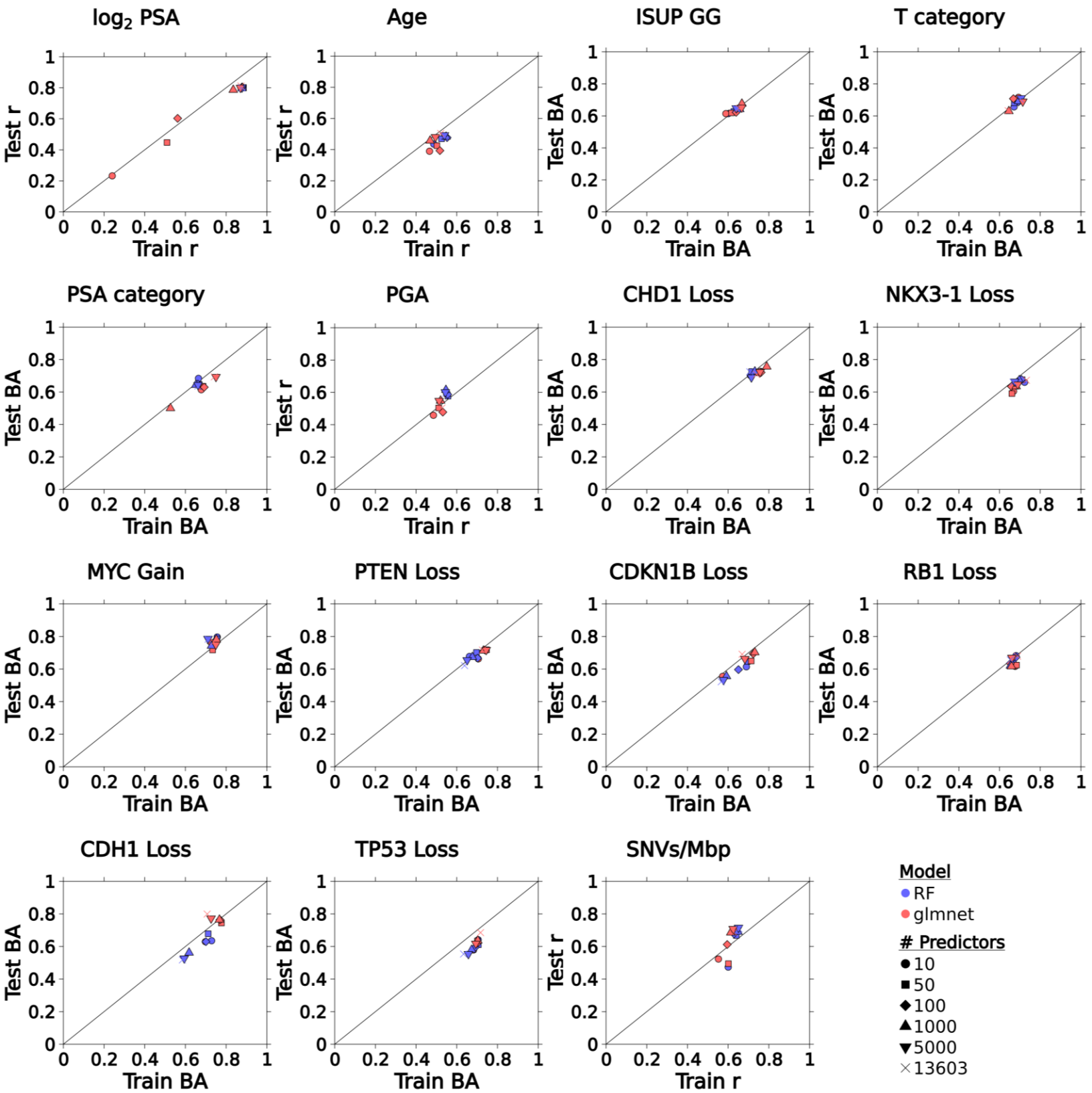
g. Heatmap of union of top 100 significant CpGs from each driver event (2,196 total CpGs). For each patient, the total number of driver events was calculated by summing binary indicator variables. Continuous drivers were median dichotomized into high *vs.* low, with high adding to the total score.



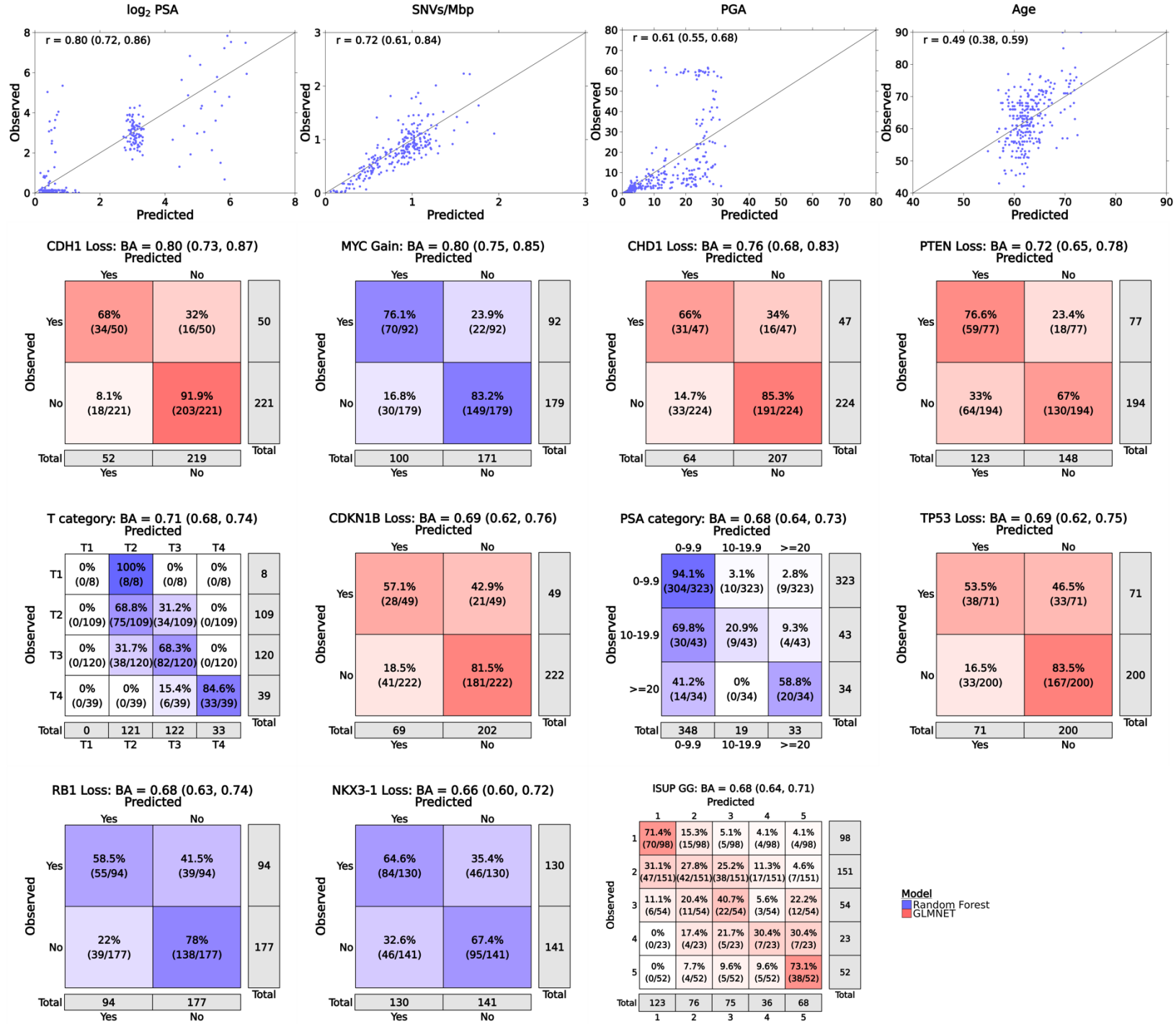
Supplementary Figure 11: Driver mutations in localized *vs.* metastatic prostate cancers
Mann-Whitney U-test p-value shown for continuous drivers (top row). For categorical drivers, logistic regression odds ratio (OR_{adj} with 95% confidence interval) adjusting for total mutation burden (CNA drivers adjusted for PGA, SNVs adjusted for log_2 SNVs/Mbp, and genomic rearrangements adjusted for log_2 GR count). INV = inversion, CTX = translocation.



Supplementary Figure 12: Performance on the test dataset after feature selection
For a given plot, the left black-grey covariate bar indicates how many features were kept after feature selection (see Methods). Pearson's correlation and balanced accuracy were used for numeric and categorical features, respectively. An asterisk in the black-grey covariate bar indicates the final selected model, which was the smallest model within 0.02 of the best model. Results for random forest are shown in blue and glmnet in red. 95% bootstrap confidence intervals are indicated by the lines besides each point.

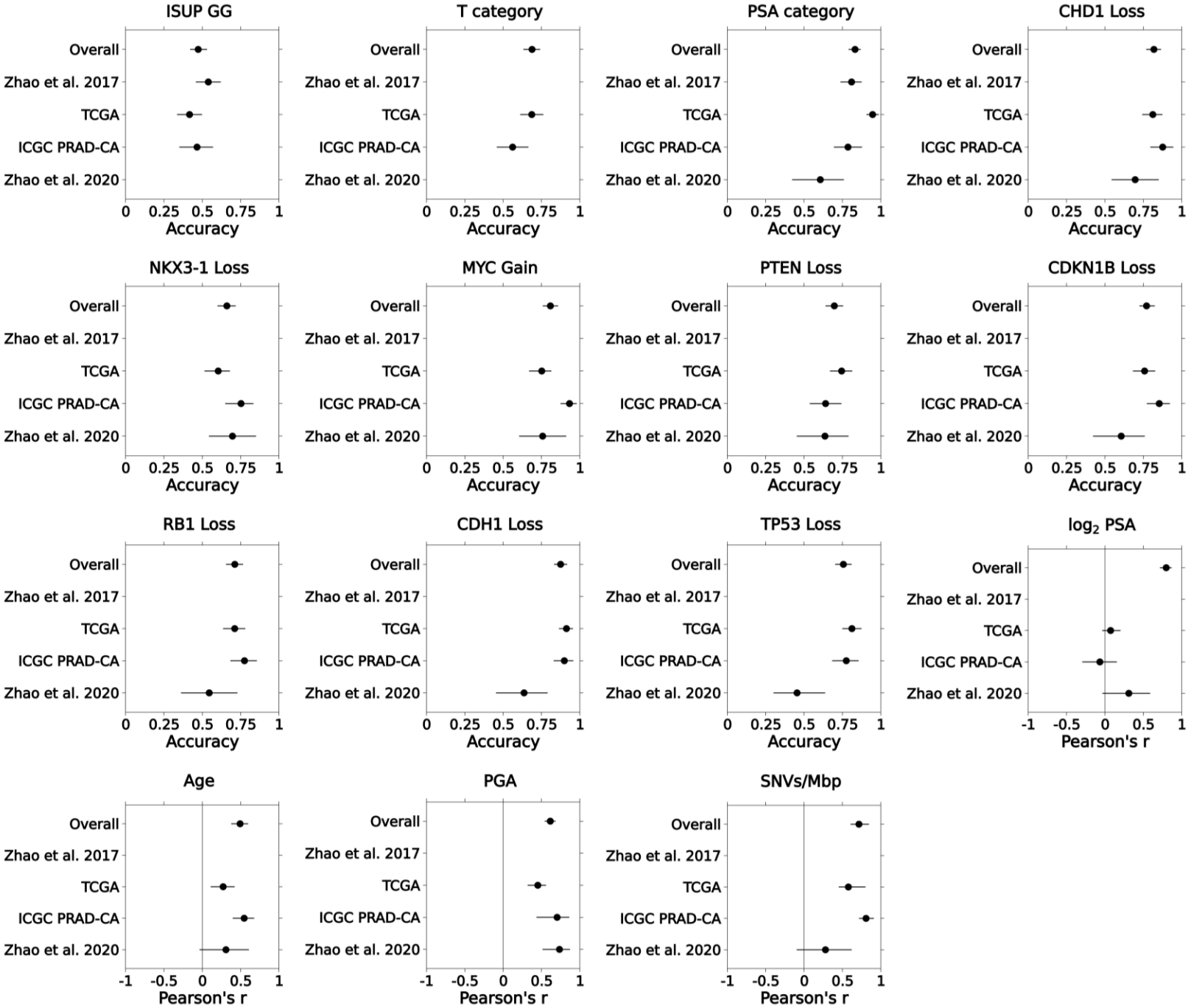


Supplementary Figure 13: Performance on the training and test datasets for all models
For a given scatterplot, the model performance is shown for the training dataset (x-axis) and test dataset (y-axis) for random forest (RF; blue) and glmnet (red), and different combinations of number of predictors used after feature selection (see legend for shapes of points). Pearson's correlation (r) and balanced accuracy (BA) were used for numeric and categorical features, respectively.

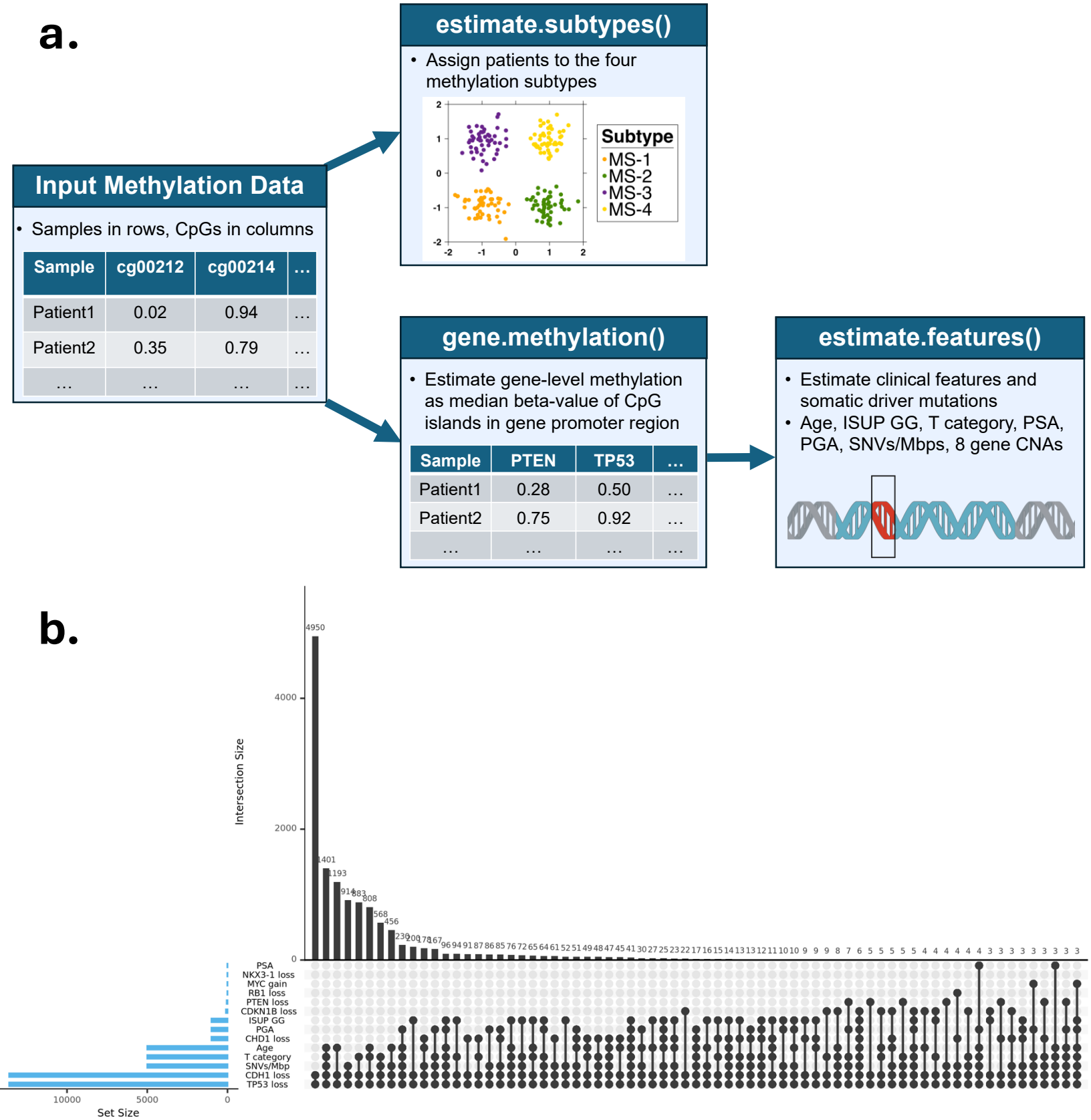


Supplementary Figure 14: Performance of the final models on the test dataset

Results are shown for the final selected models (see Methods for model section details), using scatterplots for numeric outcomes and confusion matrices for categorical. Results for random forest are shown in blue and glmnet in red. The shading of the confusion matrices is determined by the row-wise percentages, with higher percentages given darker color. Pearson's correlation is in the upper left corner of scatterplots and balanced accuracy (BA) in the title of the confusion matrix; 95% bootstrap confidence intervals are shown in parentheses.



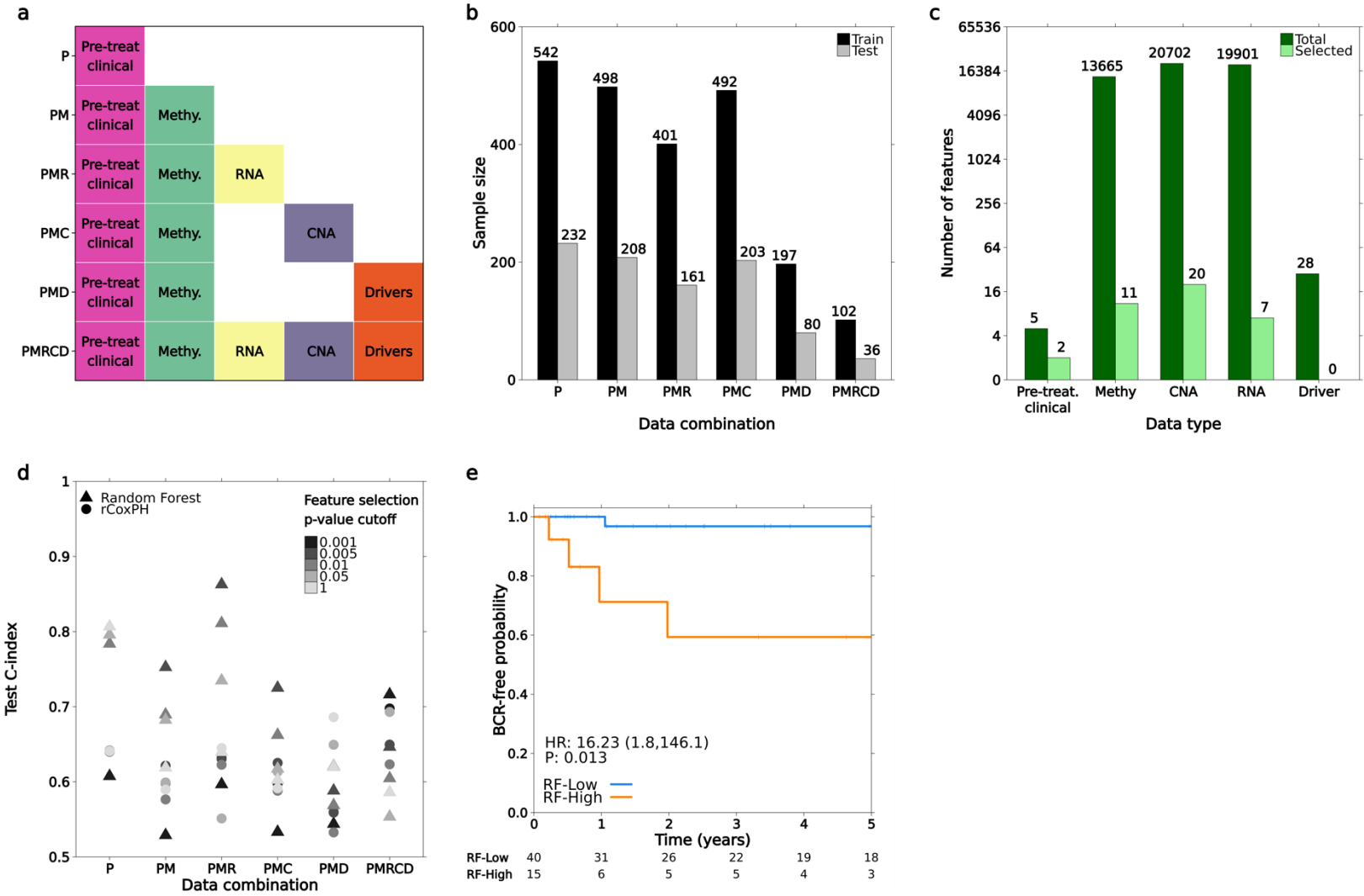
Supplementary Figure 15: Model performance on the test dataset stratified by cohort
For a given plot, results are shown for the final model when pooling all cohorts together ("Overall") or when fit separately by cohort as indicated in the y-axis labels. Pearson's r is used for numeric outcomes and accuracy for categorical outcomes (% of observations correctly classified). Although balanced accuracy (BA) was used to tune and select the final models for categorical outcomes, accuracy is shown here since we were unable to calculate BA for some of the cohorts due to small cell counts resulting in the BA being undefined. 95% bootstrap confidence intervals are indicated by the lines besides each point.



Supplementary Figure 16: PrCaMethy R package

a. User's input a data.frame of methylation CpGs from the Illumina 450K or 850K arrays. Samples are in rows and CpGs in columns. The matrix contains beta-values (continuous proportions ranging from 0 to 1). Using this input dataset, the flowchart demonstrates the workflow of the 3 main R functions.

b. Overlap of predictors used between the 14 models. Left barplot shows total genes per model. Top barplot shows overlap of genes for various combinations of models. For a given column of the barplot, the black dots with lines indicate which models are represented by that bar. The number above the bar indicates the number of genes shared in common between those models. Combinations that share at least 3 genes are shown.



Supplementary Figure 17: Multi-omic data for predicting time-until-BCR

a. Models for predicting time-until-BCR were built using different combinations of data types (Pre-treatment clinical, methylation, RNA, CNA and somatic driver mutations). The acronyms on the yaxis-labels indicate the combinations of data types and correspond to the xaxis-labels in parts (b) and (d).

b. A total of 774 localized prostate cancer patients with available time-until-BCR data were were randomly split into 70% Train (black) and 30% Test datasets (grey). The height of bars indicates the train and test set sample sizes for the different combinations of data types in (a).

c. The height of bars indicates the total number of features (dark green) and the number of features after performing feature selection (light green) with p-value cutoff 0.005. To perform feature selection, a separate Cox model was fit to each feature treating it as a predictor of time-until-BCR, while adjusting for the pre-treatment clinical features. Then only features with Wald-test p-value < 0.005 were retained.

d. The following p-value cutoffs were considered for the feature selection in part b: 0.001, 0.005, 0.01, 0.05 and 1 (1 meaning no feature selection, *i.e.* all features were considered in the model). Notice a random forest model with p-value cutoff 0.005 resulted in the highest C-index in the test dataset.

e. The best random forest model from Figure 4i. was used to predict BCR risk score in the test dataset and median-dichotomized into RF-High vs. RF-Low risk. The Kaplan-Meir plot shows the BCR-free probabilities for a subset of 55 patients classified as intermediate risk according to the National Comprehensive Cancer Network (NCCN) risk categories. The hazard ratio (HR), 95% confidence interval, and Wald-test p-value were estimated from a Cox proportional hazards model. The table below the plot gives the number of patients at risk from 0-5 years. Results for all 161 test patients are shown in Figure 4k.

Supplementary Table 1: Clinical characteristics of prostate cancer samples

Characteristic	Methylation Subtype				
	Overall (N = 2,355)	**MS-1** (N = 795)	**MS-2** (N = 363)	**MS-3** (N = 286)	**MS-4** (N = 911)
Cohort					
Zhao *et al.* 2017	525 (22%)	247 (31%)	113 (31%)	103 (36%)	62 (6.8%)
TCGA	498 (21%)	137 (17%)	56 (15%)	96 (34%)	209 (23%)
ICGC PRAD-CA	286 (12%)	160 (20%)	15 (4.1%)	20 (7.0%)	91 (10.0%)
Li *et al.* 2020	186 (7.9%)	26 (3.3%)	2 (0.6%)	11 (3.8%)	147 (16%)
ICGC PRAD-FR	130 (5.5%)	52 (6.5%)	38 (10%)	20 (7.0%)	20 (2.2%)
Berglund *et al.* 2024	120 (5.1%)	51 (6.4%)	28 (7.7%)	2 (0.7%)	39 (4.3%)
Zhao *et al.* 2020	100 (4.2%)	6 (0.8%)	2 (0.6%)	10 (3.5%)	82 (9.0%)
Ylitalo *et al.* 2021	82 (3.5%)	7 (0.9%)	0 (0%)	3 (1.0%)	72 (7.9%)
Mundbjerg *et al.* 2017	75 (3.2%)	13 (1.6%)	1 (0.3%)	15 (5.2%)	46 (5.0%)
Kirby *et al.* 2017	72 (3.1%)	31 (3.9%)	25 (6.9%)	3 (1.0%)	13 (1.4%)
Toth *et al.* 2019	70 (3.0%)	17 (2.1%)	0 (0%)	0 (0%)	53 (5.8%)
Brocks *et al.* 2014	64 (2.7%)	11 (1.4%)	4 (1.1%)	0 (0%)	49 (5.4%)
Ramakrishnan *et al.* 2024	63 (2.7%)	13 (1.6%)	42 (12%)	0 (0%)	8 (0.9%)
Dairo *et al.* 2024	57 (2.4%)	16 (2.0%)	35 (9.6%)	0 (0%)	6 (0.7%)
Melbourne	27 (1.1%)	8 (1.0%)	2 (0.6%)	3 (1.0%)	14 (1.5%)
Age (years)					
<50	120 (5.8%)	64 (8.9%)	24 (8.2%)	16 (5.8%)	16 (2.0%)
50-59	647 (31%)	256 (35%)	100 (34%)	107 (38%)	184 (23%)
60-69	967 (47%)	313 (43%)	141 (48%)	123 (44%)	390 (50%)
≥70	344 (17%)	90 (12%)	27 (9.2%)	32 (12%)	195 (25%)
Missing	277	72	71	8	126
Self-reported Race					
Black	269 (17%)	81 (16%)	79 (27%)	18 (8.1%)	91 (16%)
White	1,112 (70%)	404 (78%)	213 (72%)	190 (86%)	305 (55%)
Asian	203 (13%)	30 (5.8%)	3 (1.0%)	12 (5.4%)	158 (29%)
American Indian or Alaska Native	1 (<0.1%)	0 (0%)	0 (0%)	1 (0.5%)	0 (0%)
Missing	770	280	68	65	357
PSA (ng/mL)					
0 - 9.9	1,270 (80%)	532 (84%)	235 (87%)	184 (80%)	319 (70%)
10 - 19.9	206 (13%)	82 (13%)	27 (10%)	31 (13%)	66 (14%)
≥20	114 (7.2%)	19 (3.0%)	8 (3.0%)	16 (6.9%)	71 (16%)
Missing	765	162	93	55	455
ISUP Grade Group					
1	161 (14%)	80 (19%)	39 (23%)	22 (14%)	20 (4.8%)
2	403 (35%)	173 (41%)	70 (41%)	40 (26%)	120 (29%)
3	245 (21%)	97 (23%)	31 (18%)	23 (15%)	94 (22%)
4	117 (10%)	26 (6.2%)	16 (9.3%)	26 (17%)	49 (12%)
5	237 (20%)	41 (9.8%)	16 (9.3%)	43 (28%)	137 (33%)
Missing	1,192	378	191	132	491
T-category					
T1	73 (5.4%)	12 (2.7%)	2 (1.1%)	7 (4.2%)	52 (9.1%)
T2	638 (47%)	246 (55%)	114 (65%)	58 (35%)	220 (39%)
T3	629 (46%)	184 (41%)	59 (34%)	100 (61%)	286 (50%)
T4	15 (1.1%)	2 (0.5%)	1 (0.6%)	0 (0%)	12 (2.1%)
Missing	1,000	351	187	121	341

Supplementary Table 2: Clinical characteristics of non-cancerous prostate samples

Characteristic	Methylation Subtype				
	Overall (N = 646)	**MS-1** (N = 22)	**MS-2** (N = 615)	**MS-3** (N = 2)	**MS-4** (N = 7)
Cohort					
Li *et al.* 2020	187 (29%)	6 (27%)	180 (29%)	0 (0%)	1 (14%)
Berglund *et al.* 2024	118 (18%)	2 (9.1%)	115 (19%)	0 (0%)	1 (14%)
Dairo *et al.* 2024	115 (18%)	0 (0%)	115 (19%)	0 (0%)	0 (0%)
Kirby *et al.* 2017	64 (9.9%)	0 (0%)	63 (10%)	0 (0%)	1 (14%)
Ramakrishnan *et al.* 2024	58 (9.0%)	12 (55%)	42 (6.8%)	1 (50%)	3 (43%)
TCGA	50 (7.7%)	2 (9.1%)	46 (7.5%)	1 (50%)	1 (14%)
Melbourne	25 (3.9%)	0 (0%)	25 (4.1%)	0 (0%)	0 (0%)
Ylitalo *et al.* 2021	12 (1.9%)	0 (0%)	12 (2.0%)	0 (0%)	0 (0%)
Mundbjerg *et al.* 2017	12 (1.9%)	0 (0%)	12 (2.0%)	0 (0%)	0 (0%)
Brocks *et al.* 2014	5 (0.8%)	0 (0%)	5 (0.8%)	0 (0%)	0 (0%)
Age (years)					
<50	6 (1.4%)	1 (13%)	5 (1.2%)	0 (0%)	0 (0%)
50-59	81 (19%)	1 (13%)	79 (19%)	1 (100%)	0 (0%)
60-69	224 (53%)	3 (38%)	220 (53%)	0 (0%)	1 (50%)
≥70	113 (27%)	3 (38%)	109 (26%)	0 (0%)	1 (50%)
Missing	222	14	202	1	5
Self-reported Race					
Black	165 (29%)	6 (27%)	155 (29%)	1 (50%)	3 (50%)
White	203 (36%)	10 (45%)	190 (35%)	1 (50%)	2 (33%)
Asian	198 (35%)	6 (27%)	191 (36%)	0 (0%)	1 (17%)
Missing	80	0	79	0	1

Supplementary Table 3: Data availability by cohort

Cohort	PMID	Data types	Source
TCGA	26544944	clinical, methylation, CNA, RNA	TCGAbiolinks R package (v2.25.3)
Zhao *et al.* 2017	27358489	clinical, methylation	dbGaP study accession phs001921.v1.p1
Li *et al.* 2020	32238934	clinical, methylation	NGDC MethBank Project HRA000099
ICGC PRAD-CA	28068672	clinical, methylation, CNA, RNA	NCBI GEO (GSE84043) and the European Genome-Phenome Archive (EGAS00001000900)
Berglund *et al.* 2024	39162297	methylation	NCBI GEO (GSE269244)
Kirby *et al.* 2017	28412973	clinical, methylation	Methylation from NCBI GEO (GSE76938) and clinical data through correspondence with the authors
ICGC PRAD-FR	29945238	clinical, methylation	ArrayExpress Accession E-MTAB-6131
Ramakrishnan *et al.* 2024	38566104	methylation	NCBI GEO (GSE262522)
Dairo *et al.* 2024	38112617	clinical, methylation	NCBI GEO (GSE183040)
Zhao *et al.* 2020	32661416	clinical, methylation, CNA, RNA	Clinical data was obtained from https://github.com/DavidQuigley/WCDT/blob/master/clinical_metadata/2021_05_13_european_urology_2019.txt Methylation data was obtained through correspondence with the authors. CNA data from https://quigleylab.ucsf.edu/data, BAM files for whole-genome sequencing and RNA data from https://portal.gdc.cancer.gov/projects/WCDT-MCRPC
Ylitalo *et al.* 2021	34193246	methylation	NCBI GEO (GSE174613)
Mundbjerg *et al.* 2017	28081708	clinical, methylation	NCBI GEO (GSE73549)
Toth *et al.* 2019	31640781	clinical, methylation	NCBI GEO (GSE127985)
Brocks *et al.* 2014	25066126	clinical, methylation	European Genome-Phenome Archive (EGAD00010000600)
Melbourne		clinical, methylation	Correspondence with co-authors Drs. Hovens and Jung

RNA: Ribonucleic Acid
CNA: Copy Number Alteration
PMID: PubMed Unique Identifier
dbGaP: Database of Genotypes and Phenotypes
NGDC: National Genomics Data Center
NCBI GEO: National Center for Biotechnology Information Gene Expression Omnibus