

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our [Editorial Policies](#) and the [Editorial Policy Checklist](#).

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

- | | |
|-------------------------------------|--|
| n/a | Confirmed |
| ☐ | ☒ The exact sample size (<i>n</i>) for each experimental group/condition, given as a discrete number and unit of measurement |
| ☐ | ☒ A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly |
| ☐ | ☒ The statistical test(s) used AND whether they are one- or two-sided
<i>Only common tests should be described solely by name; describe more complex techniques in the Methods section.</i> |
| ☒ | ☐ A description of all covariates tested |
| ☒ | ☐ A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons |
| ☐ | ☒ A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals) |
| ☐ | ☒ For null hypothesis testing, the test statistic (e.g. <i>F</i> , <i>t</i> , <i>r</i>) with confidence intervals, effect sizes, degrees of freedom and <i>P</i> value noted
<i>Give P values as exact values whenever suitable.</i> |
| ☒ | ☐ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings |
| ☒ | ☐ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes |
| ☐ | ☒ Estimates of effect sizes (e.g. Cohen's <i>d</i> , Pearson's <i>r</i>), indicating how they were calculated |

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection	No software was used for data collection.
Data analysis	Data preprocessing: Scanpy (v1.9.3), pySCENIC (0.12.1) RNA-seq analysis: GSVA (1.46.0) scRNA-seq analysis: ikarus (0.0.3), PreCanCell (1.1.0), Cancer-Finder, infercnvpy (0.4.2), CopyKAT (1.1.0). ST analysis: Squidpy (1.3.1), Cancer-Finder, Cottrazm (0.1.1) The analysis performed in this study primarily utilized publicly available software, as described in the Methods section. The custom code for the main analysis can be accessed at https://doi.org/10.5281/zenodo.12194623 .

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

All the bulk RNA-seq, single-cell RNA-seq (scRNA-seq), and spatial transcriptomics (ST) datasets used in this study are publicly available (Supplementary Data 1). The TCGA bulk RNA-seq datasets, covering sixteen cancer types, were collected from UCSC Xena Browser [https://xenabrowser.net/datapages/?dataset=tcga_RSEM_Hugo_norm_count&host=https%3A%2F%2Ftoil.xenahubs.net&removeHub=https%3A%2F%2Fxena.treehouse.gi.ucsc.edu%3A443]. The scRNA-seq datasets retrieved from the NCBI Gene Expression Omnibus (https://www.ncbi.nlm.nih.gov/geo/) can be downloaded using the following accession numbers: GSE13246517, GSE14473517, GSE15153018, GSE15722024, GSE13452032. Additionally, scRNA-seq datasets covering six cancer types (pancreas, kidney, prostate, breast, ovarian, and head and neck cancer)²³ were collected from the website https://www.weizmann.ac.il/sites/3CA/. The remaining scRNA-seq datasets were obtained through the links provided in CZ CELLxGENE Data Explorer⁵⁵: Salcher et al.¹⁴ [https://cellxgene.cziscience.com/collections/edb893ee-4066-4128-9a6c-5eb2b03f8287], Nowicki-Osuch et al.¹⁵ [https://cellxgene.cziscience.com/collections/a18474f4-ff1e-4864-af69-270b956cee5b], Chen et al.¹⁶ [https://cellxgene.cziscience.com/collections/a48f5033-3438-4550-8574-cdff3263fdff], Tabula Sapiens²⁵ [https://cellxgene.cziscience.com/collections/e5f58829-1a66-40b5-a624-9046778e74f5], Sikkema et al.²⁶ [https://cellxgene.cziscience.com/collections/6f6d381a-7701-4781-935c-db10d30de293], Chan et al.²⁷ [https://cellxgene.cziscience.com/collections/62e8f058-9c37-48bc-9200-e767f318a8ec]. The ST data were acquired from the following hyperlinks or accession numbers: Prostate cancer [https://www.10xgenomics.com/datasets/human-prostate-cancer-adenocarcinoma-with-invasive-carcinoma-ffpe-1-standard-1-3-0], Breast Cancer [https://www.10xgenomics.com/datasets/human-breast-cancer-block-a-section-1-1-standard-1-1-0] and [https://www.10xgenomics.com/datasets/human-breast-cancer-ductal-carcinoma-in-situ-invasive-carcinoma-ffpe-1-standard-1-3-0], Renal cell carcinoma (GSE17554040 and https://data.mendeley.com/datasets/g67bkbhnhg/139), Squamous cell carcinoma (GSE14424038), Oral squamous cell carcinoma (GSE20825341). The cancer gene signatures used in this study were obtained from the following hyperlinks: 14 cancer functional states from CancerSEA²⁰ [http://biocc.hrbmu.edu.cn/CancerSEA/goDownload], 10 cancer hallmarks²² [https://static-content.springer.com/esm/art%3A10.1038%2Fs41598-018-25076-6/MediaObjects/41598_2018_25076_MOESM10_ESM.xlsx], 5 epithelial cell states from EcoTyper²¹ [https://ars.els-cdn.com/content/image/1-s2.0-S0092867421010618-mmc4.xlsx]. List of known targets with approved drugs was obtained from PHAROS database³⁴ [https://pharos.nih.gov/].

Research involving human participants, their data, or biological material

Policy information about studies with [human participants or human data](#). See also policy information about [sex, gender \(identity/presentation\), and sexual orientation](#) and [race, ethnicity and racism](#).

Reporting on sex and gender

Reporting on race, ethnicity, or other socially relevant groupings

Population characteristics

Recruitment

Ethics oversight

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☒ Life sciences ☐ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

Sample size

Data exclusions

Replication

Randomization

Blinding

Not applicable.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks	Not applicable.
Novel plant genotypes	Not applicable.
Authentication	Not applicable.