Decoding the Cosmos

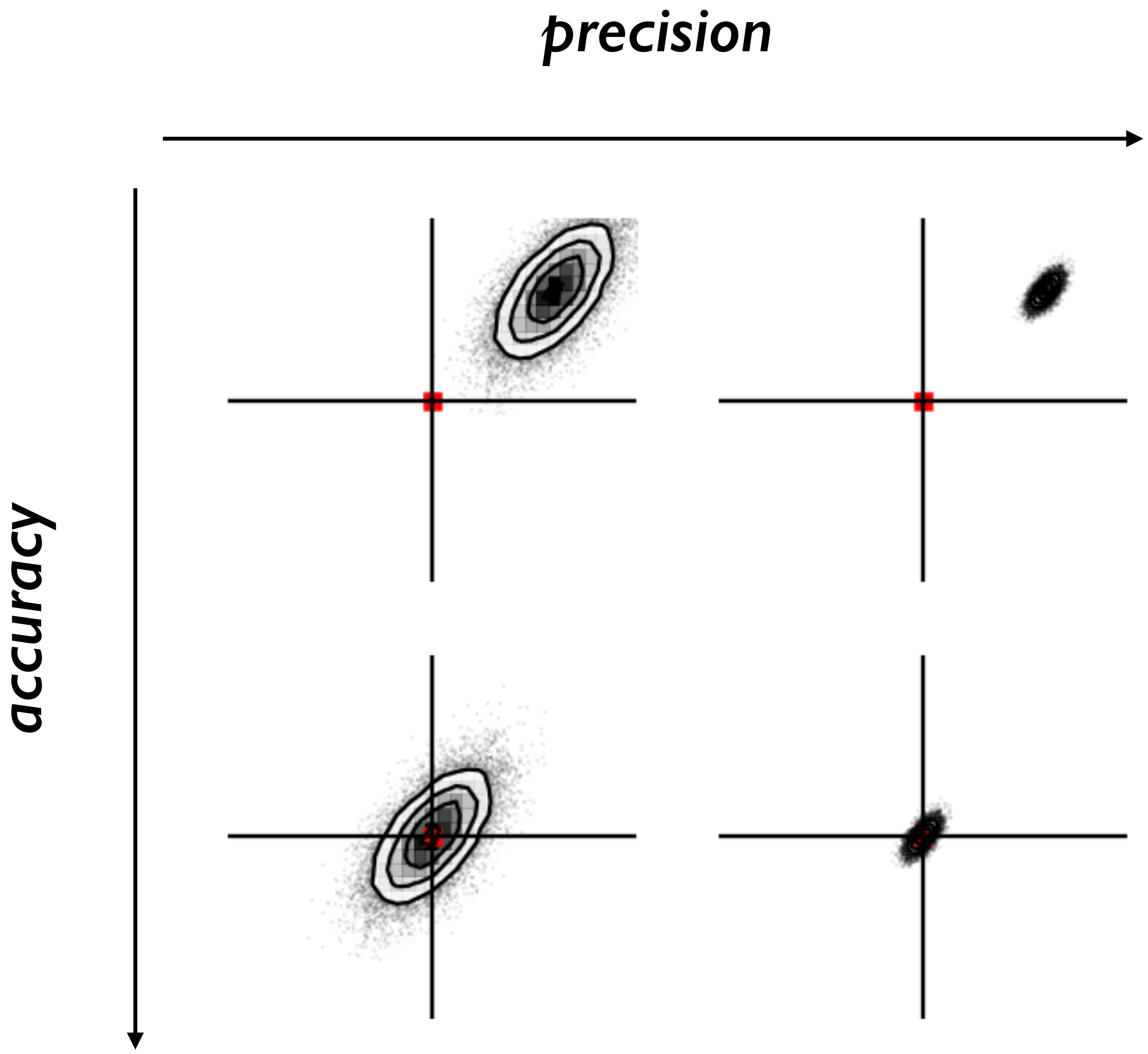
Hiranya V. Peiris

Former Hubble/Fermi/KICP Fellow
2004-2007

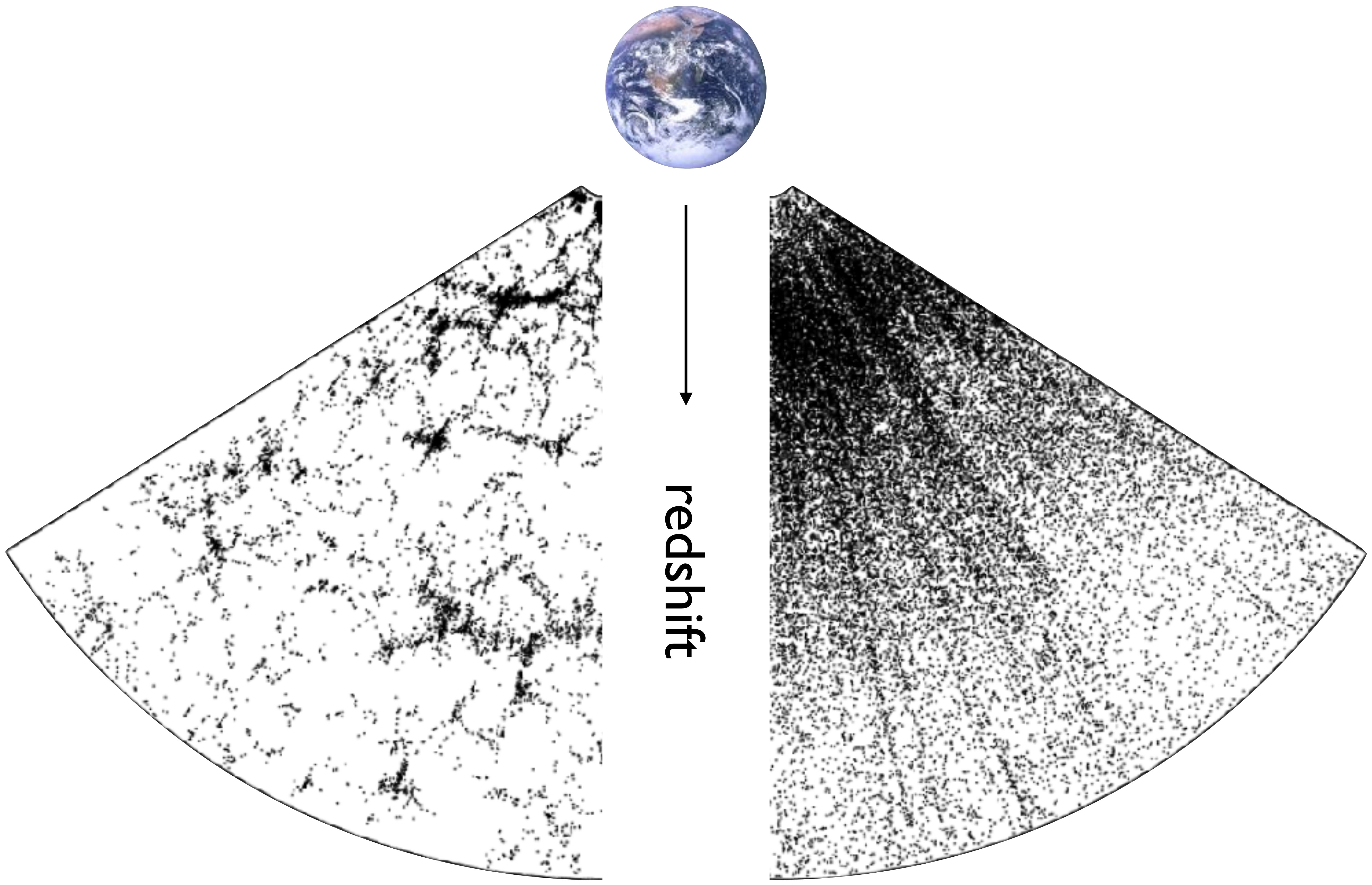
European Research Council
Established by the European Commission

UNIVERSITY OF CAMBRIDGE

UK Research and Innovation


precision
accuracy

Observational frontier with galaxy surveys



<u>Spectroscopic</u>
DESI (ground)

<u>Photometric</u>
LSST (ground), Euclid (space), Roman (space)

VERA C. RUBIN OBSERVATORY

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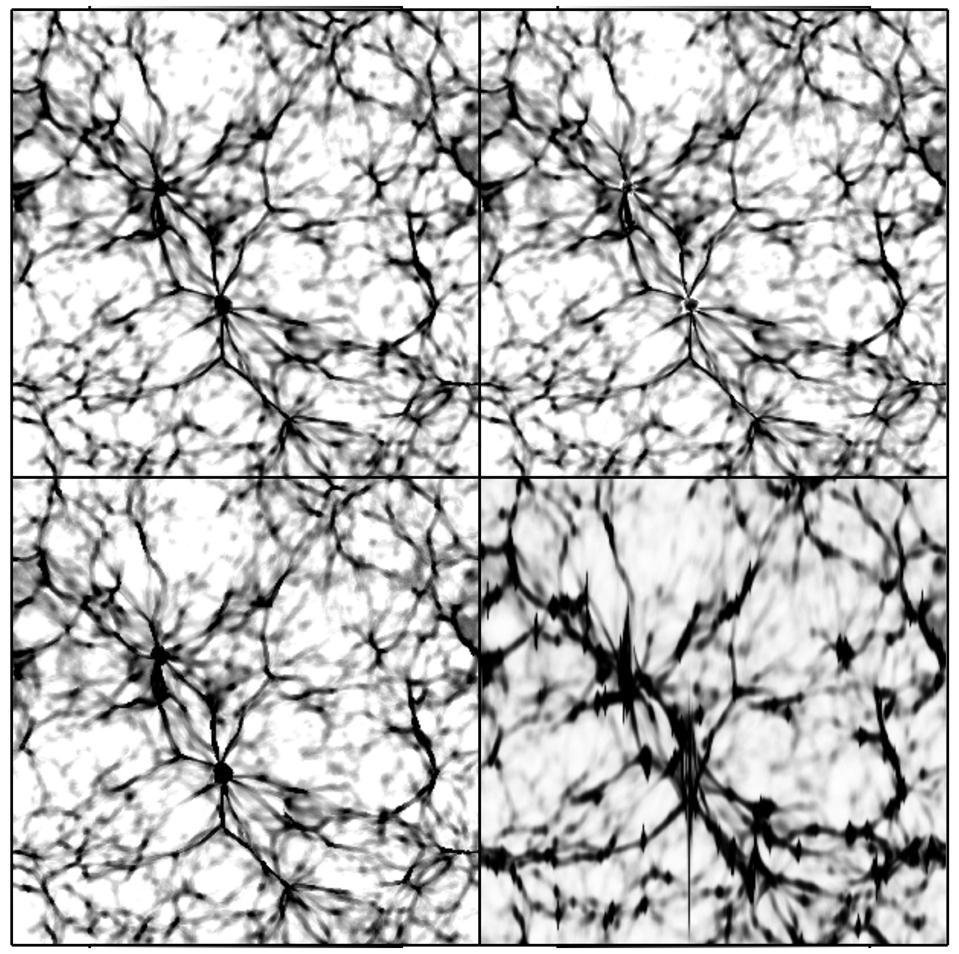
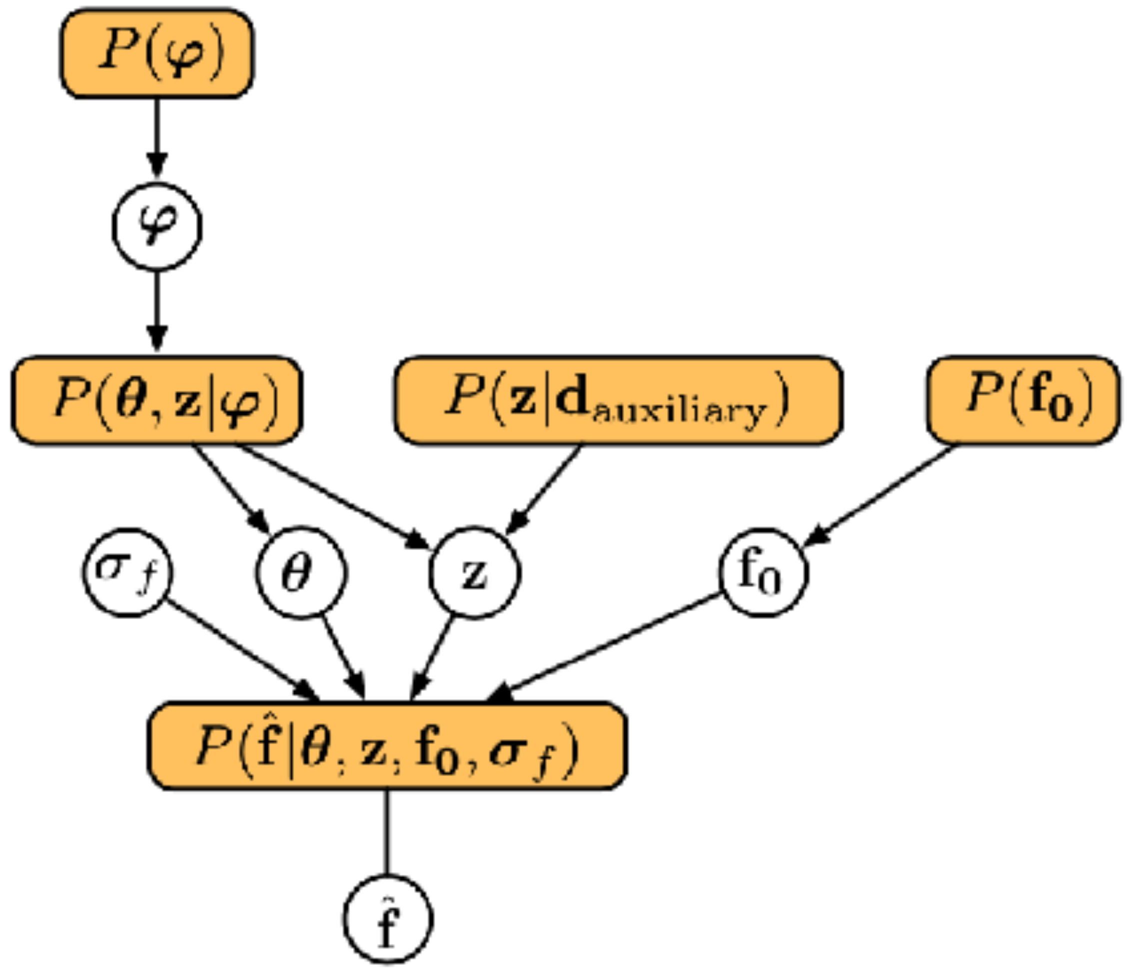
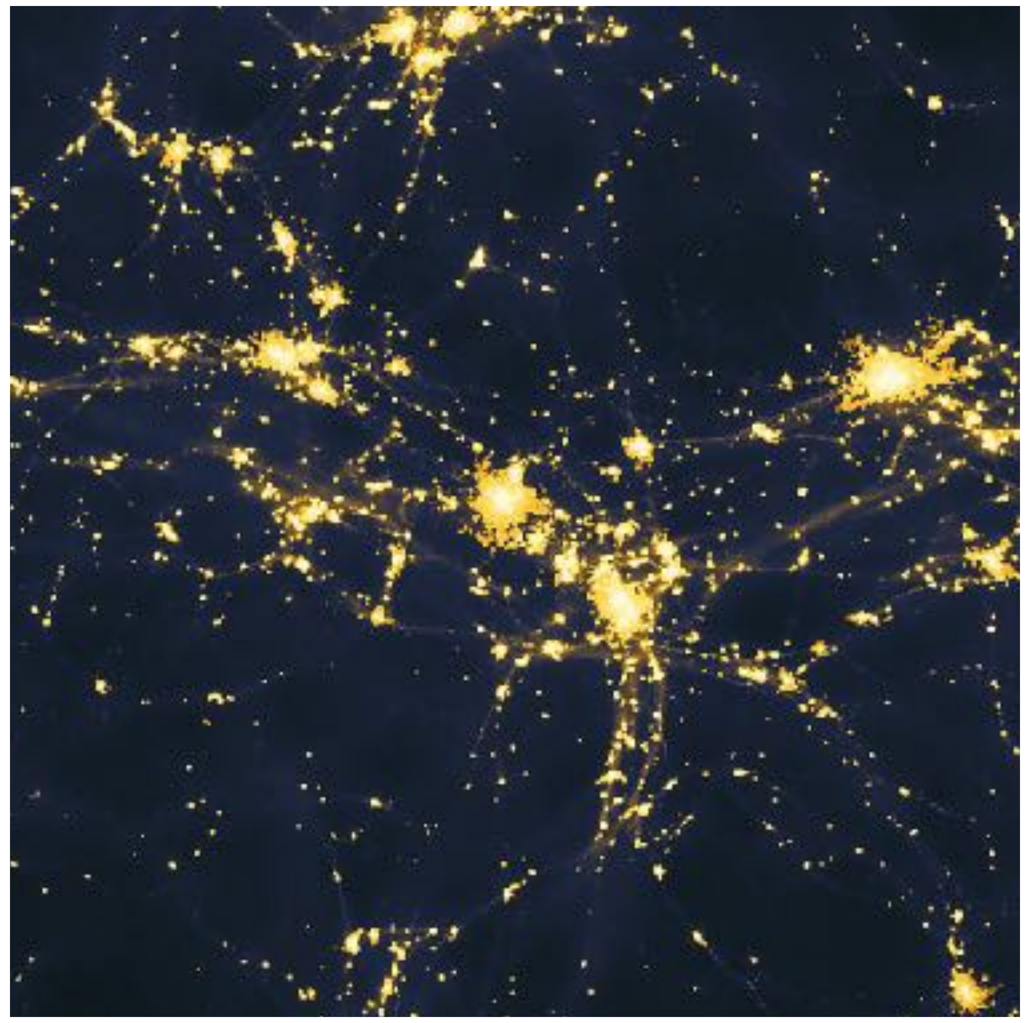
OBSERVATORY

Dec 2023

Solving cosmological modelling challenges with machine learning



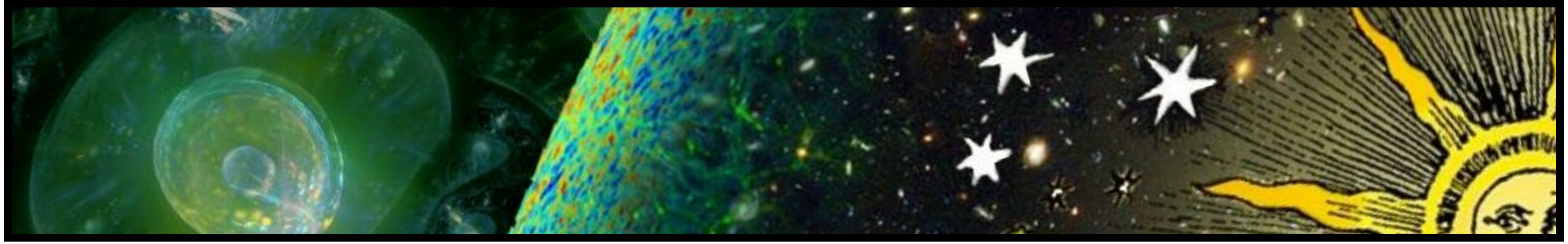




Emulation:
ML-accelerated forward-modelling of observations

Simulation-based inference:
high dimensional cosmological inference with ML-accelerated parts

Explainable AI:
machine-assisted knowledge extraction



Simulation-based inference with ML-accelerated components

Justin Alsing
(OKC/Stockholm)

Stephen Thorp
(OKC/Stockholm)

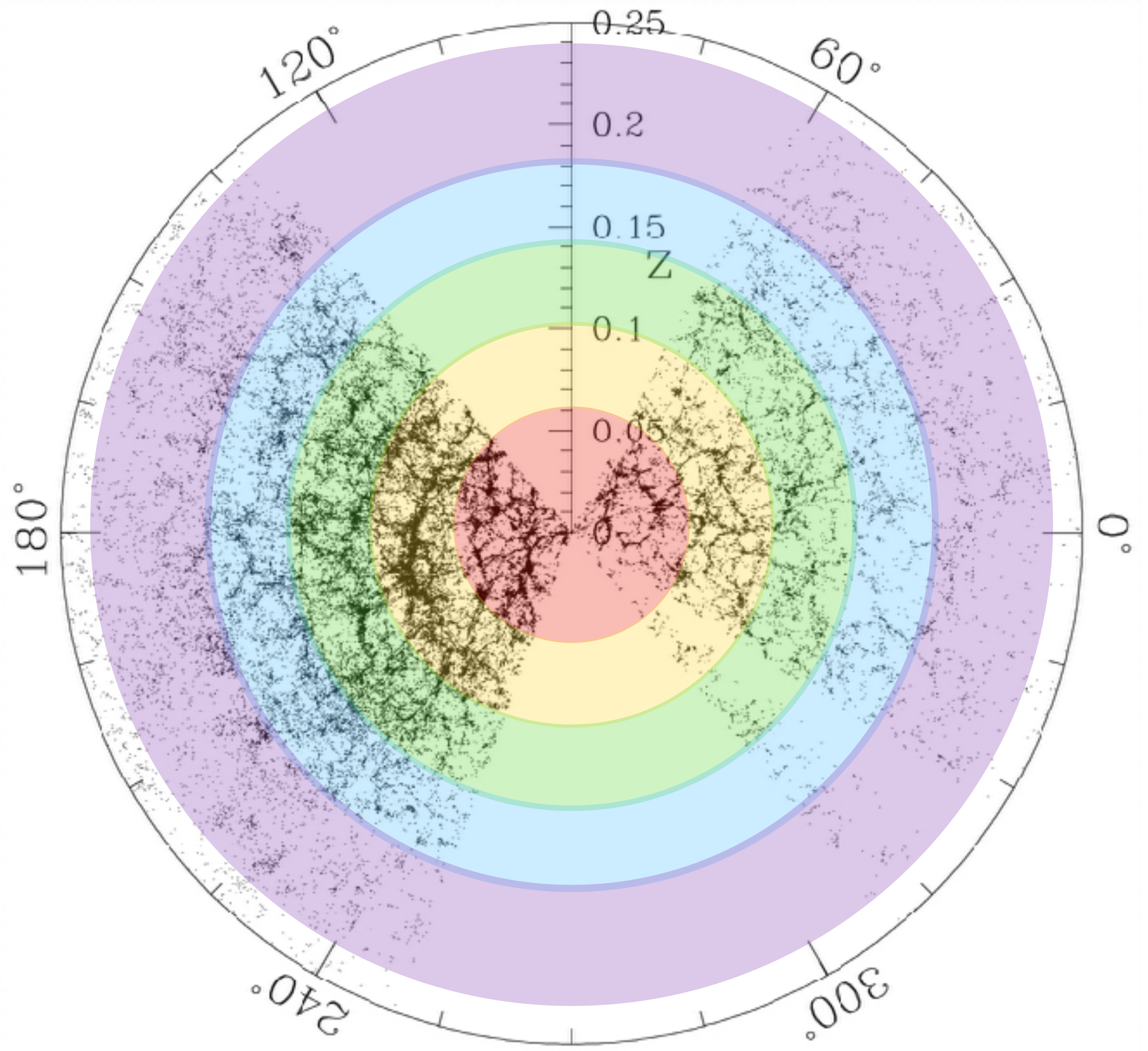
Sinan Deger
(IoA/KICC/Cambridge)

Boris Leistedt
(Imperial College London)

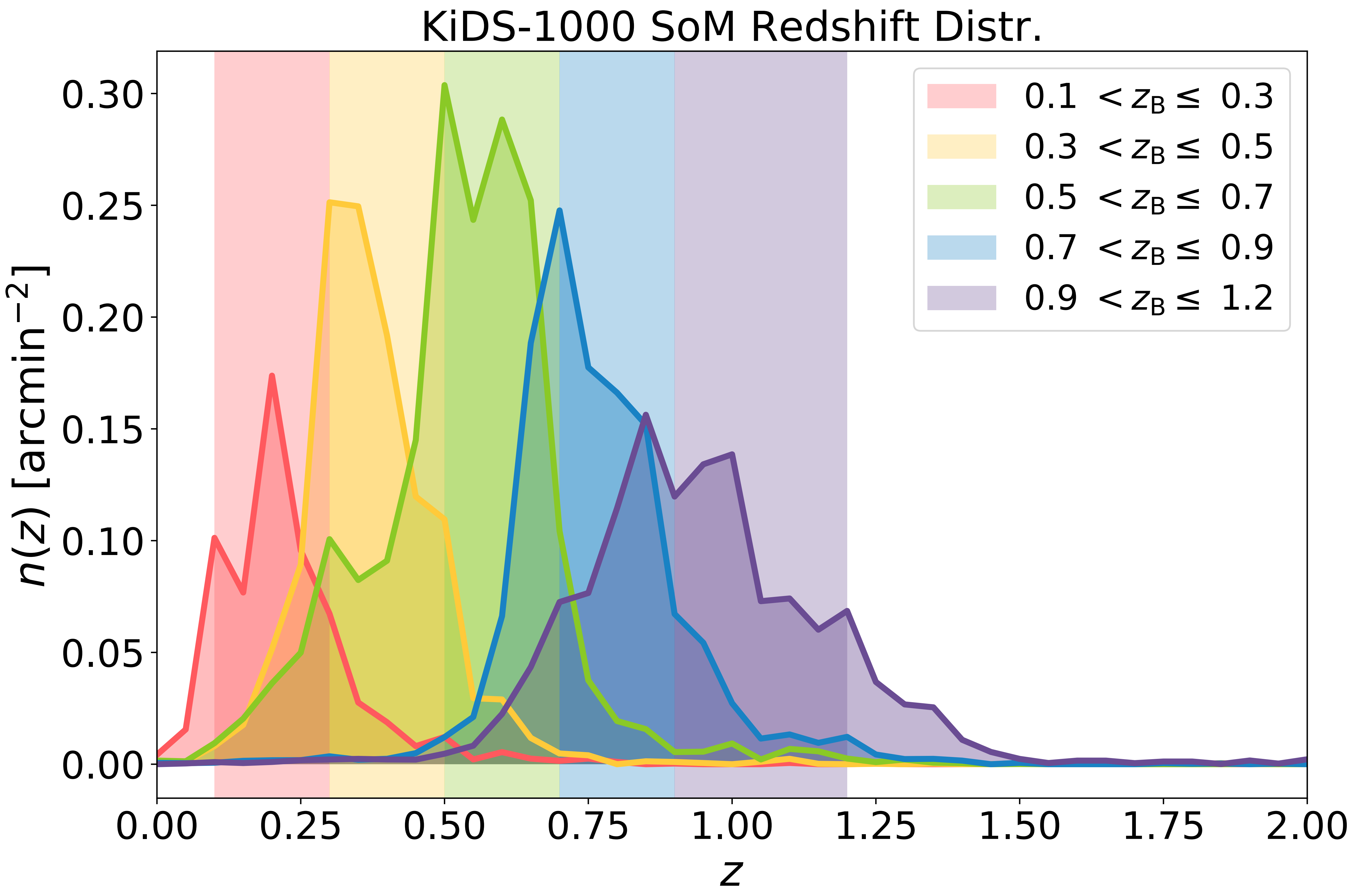
Arthur Loureiro
(OKC/Stockholm)

With: Joel Leja, Daniel Mortlock

Photometric catalogues require redshift estimation



Blanton et al. (2003)



Loureiro et al. (2023)

Adapted from Justin Alsing

Key idea: learn joint distribution of galaxy properties over cosmic history

Machine learning models can accurately describe this complicated web of interdependencies

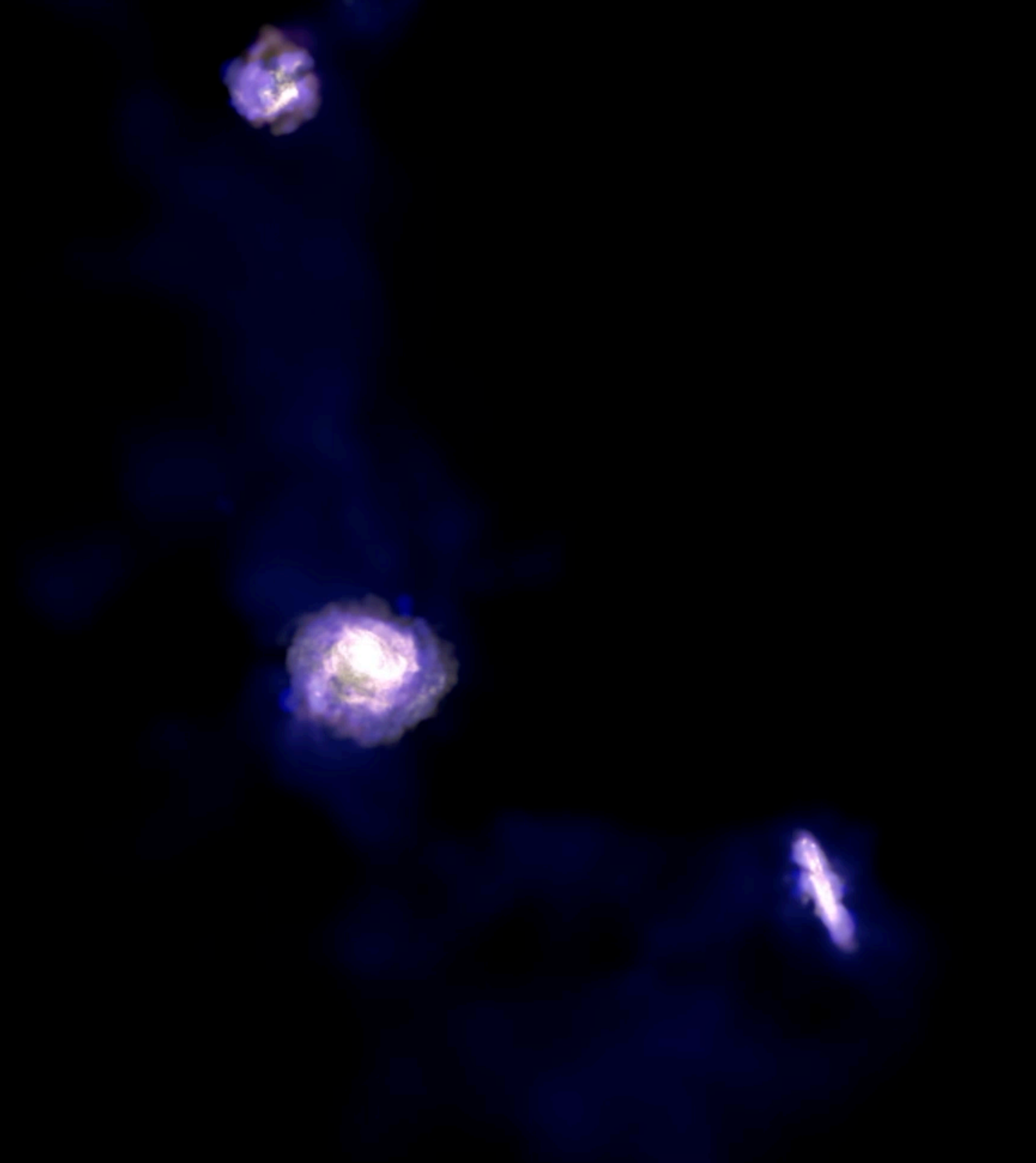
Figure: Hubble Ultra Deep Field

To decode the cosmos,
we need to understand galaxies

Recipe for making galaxy spectra and colours

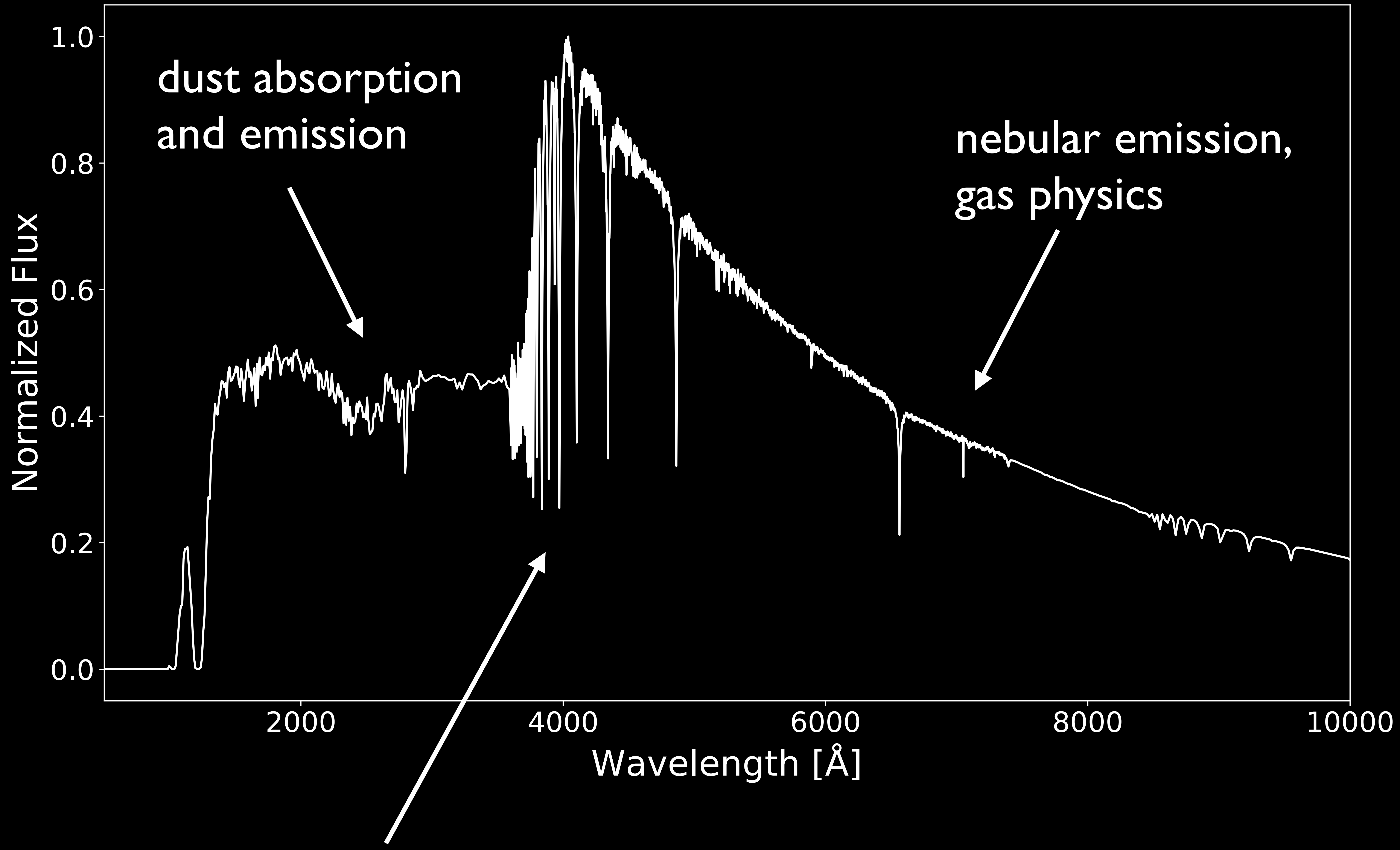
- mass
- star formation history
- dust
- gas
- metallicity
- active galactic nuclei
- redshift

  …



Andrew Pontzen

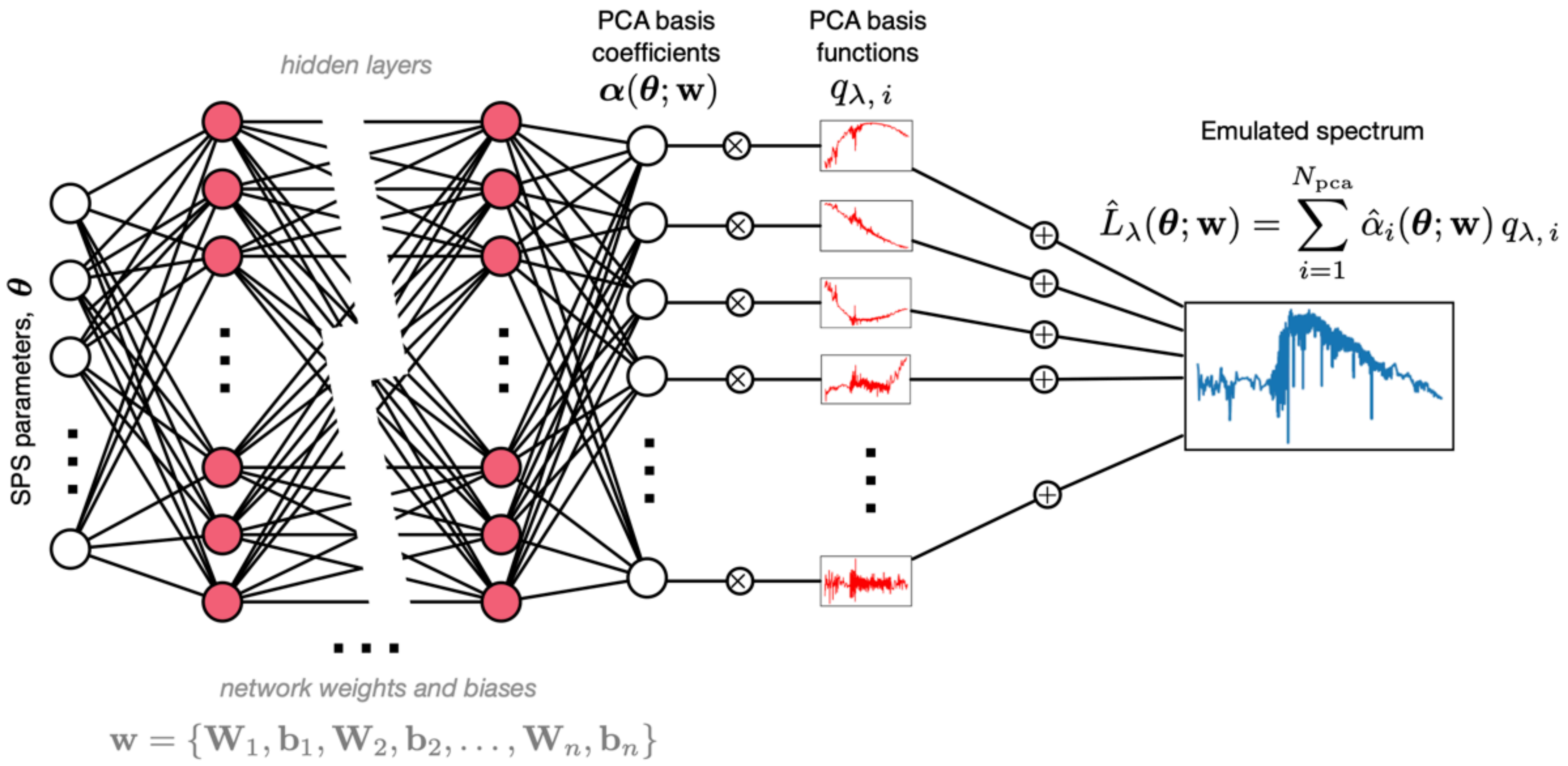
Model galaxy spectra using stellar population synthesis



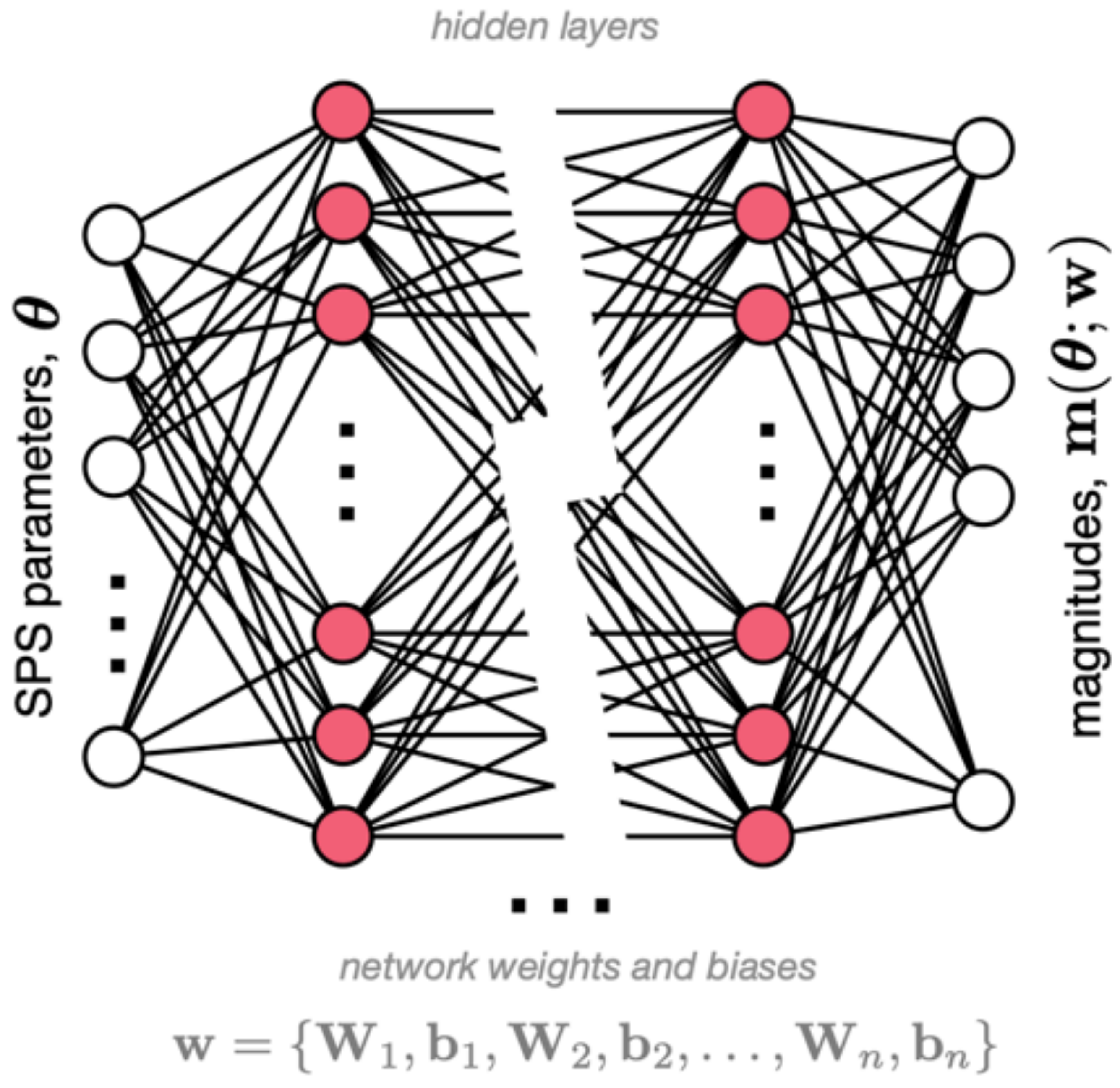
add up light from all the stars (at their ages and metallicities)

CONROY, GUNN AND WHITE (2009), CONROY AND GUNN (2010)

Speeding things up with neural emulators



Emulating spectra



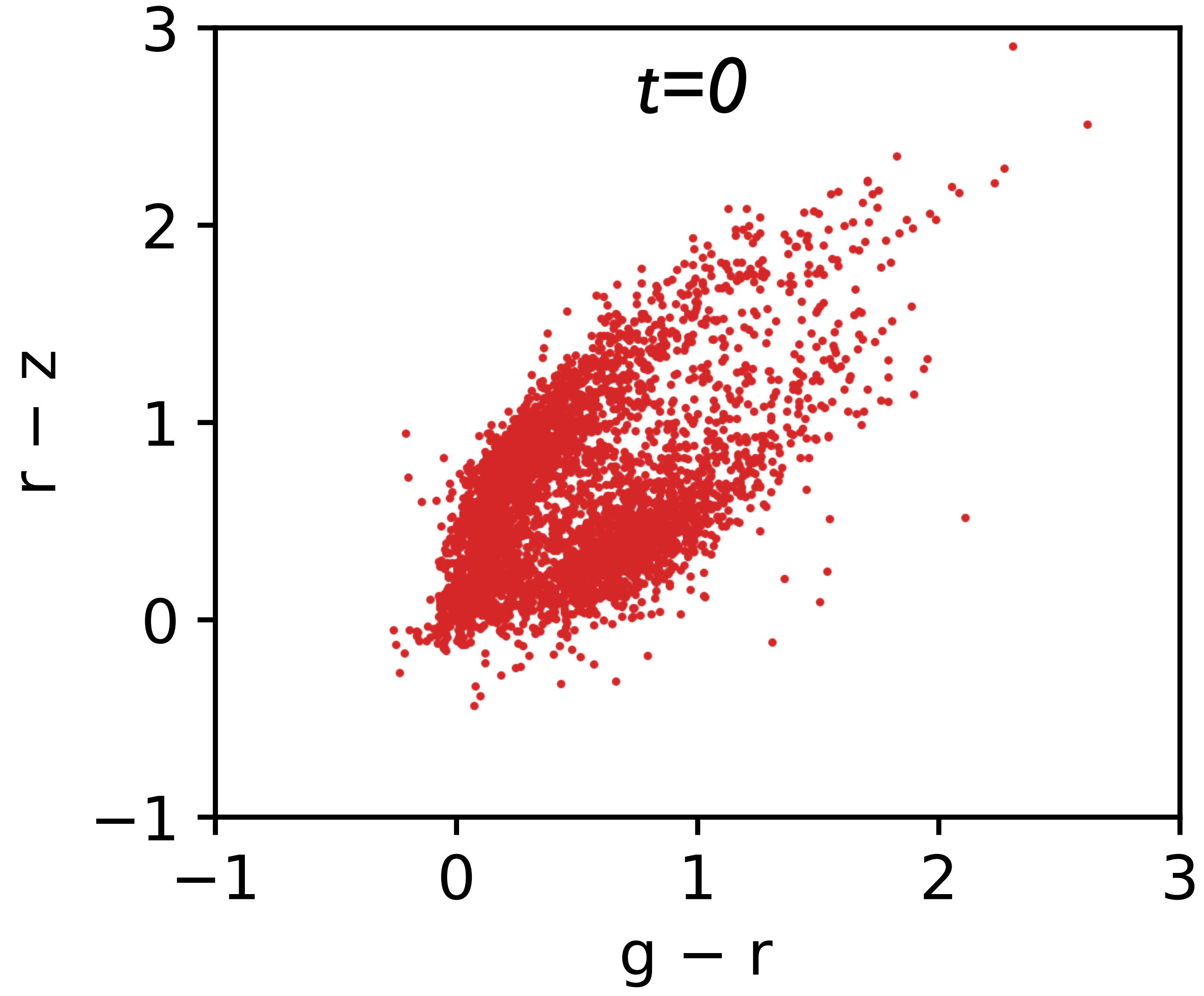
Emulating photometry

16-parameter SPS model | sub-percent accuracy | factors x 10^4 speed-up | differentiable

Alsing, Peiris, Leja, Hahn, Tojeiro, Mortlock, Leistedt, Johnson, Conroy (ApJS, 2020)

Flexible neural models for distribution of galaxy properties

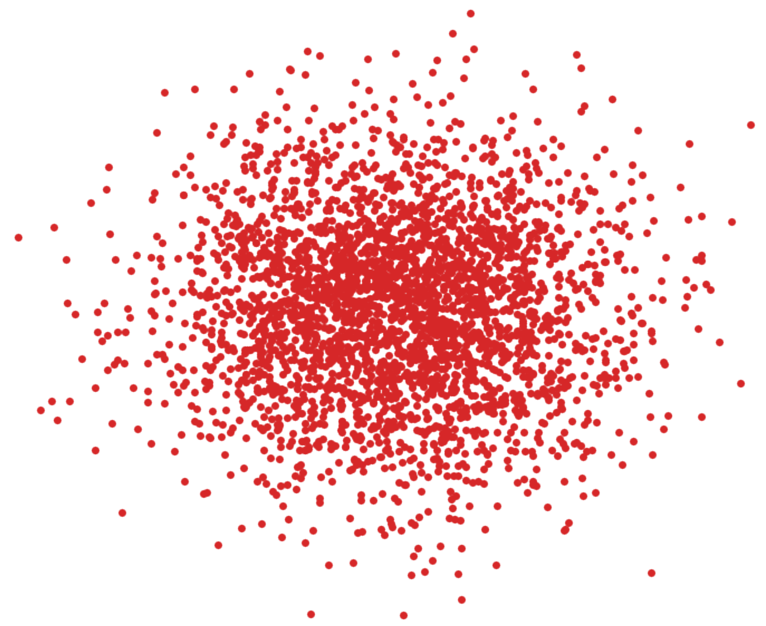
learn transformation that degrades
target distribution to Gaussian noise



~Brownian motion

~reverse Brownian motion

t=T



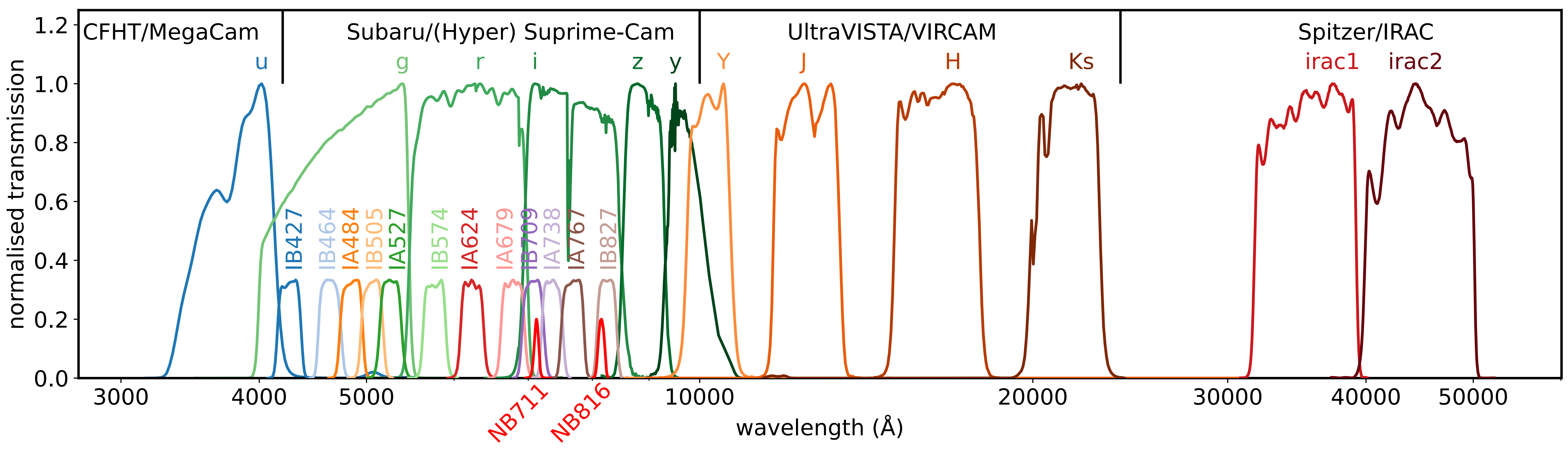
Gaussian distribution

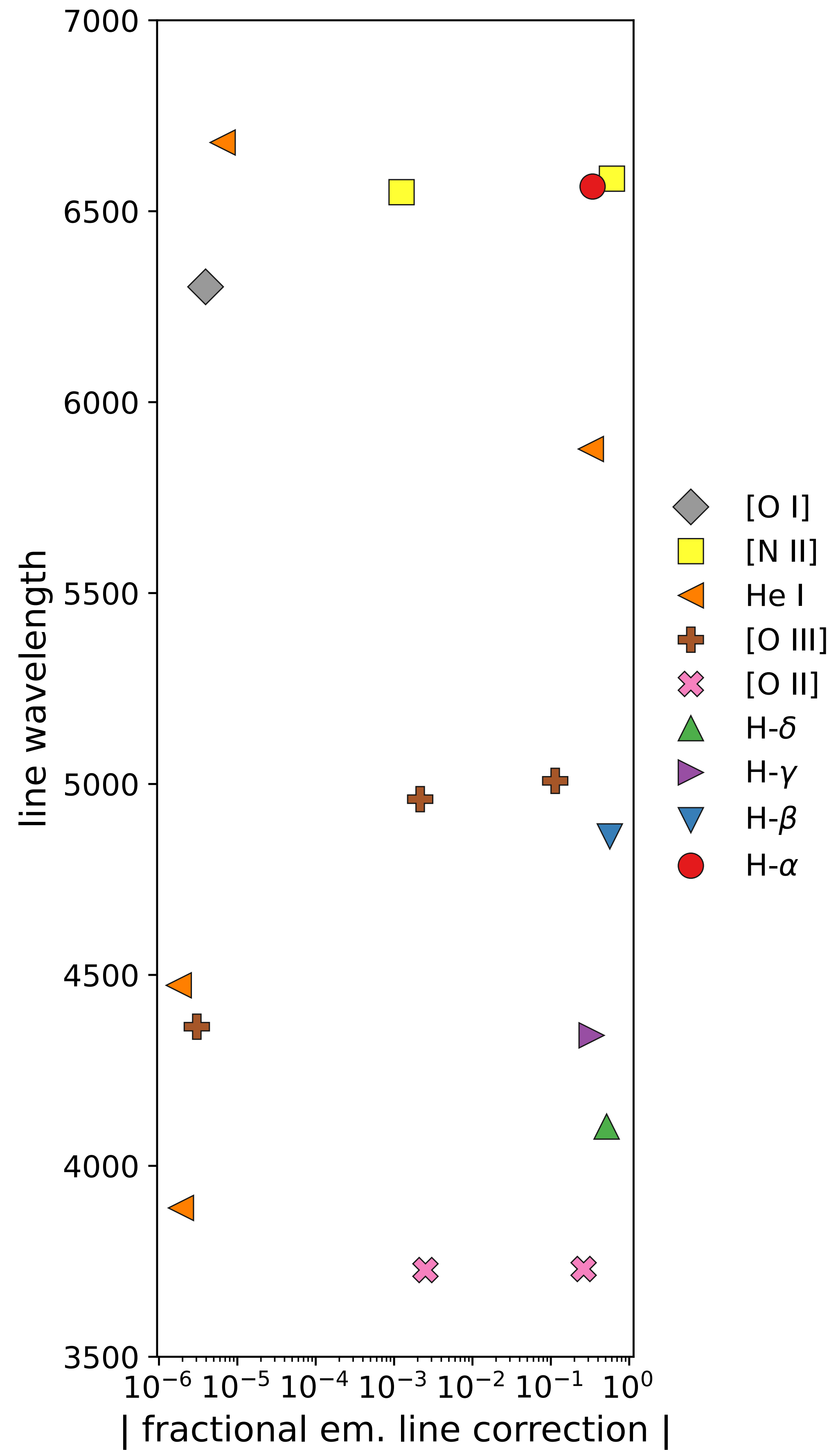
draw from random distribution:
invert learned transformation to
sample from target distribution

score-based diffusion model

Song and Ermon (2019), Song+ (2020a,b)

Pop-Cosmos: galaxy population model calibrated with COSMOS2020



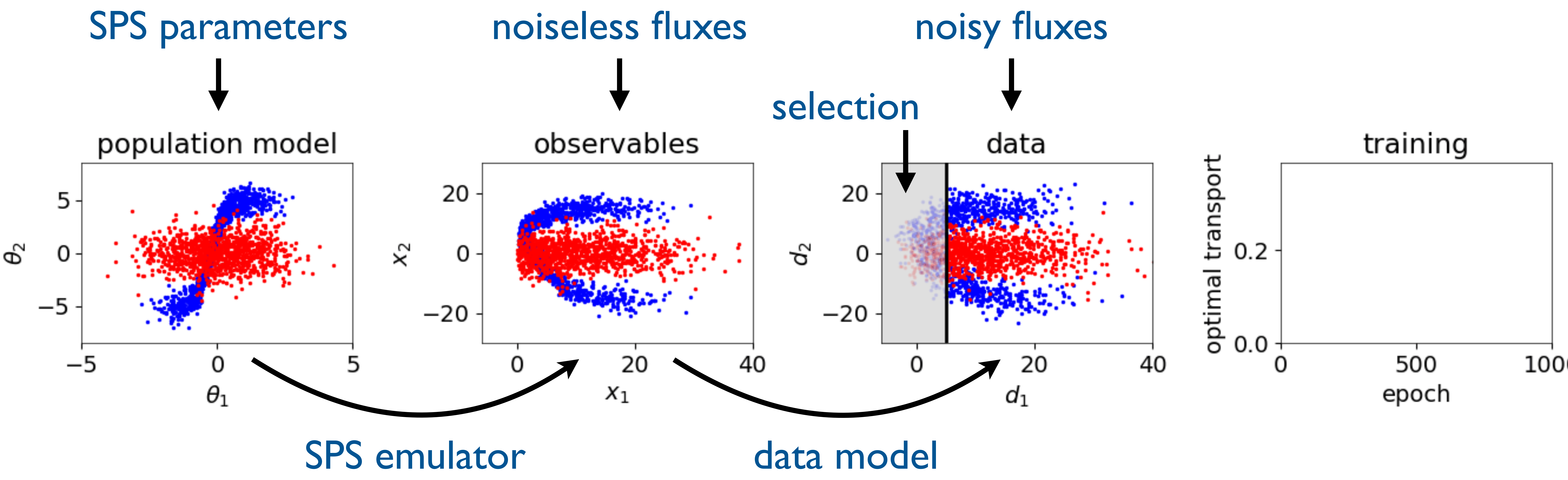


~140,000 galaxies | 26 bands near-UV to mid-IR | deep z < 4 | simple selection r<25

Zero-point calibration | emission line corrections | Student-t uncertainty model

Weaver et al (2021), Alsing et al (2022, ApJS), Leistedt et al. (2022, ApJS), Alsing et al (arXiv:2402.00935)

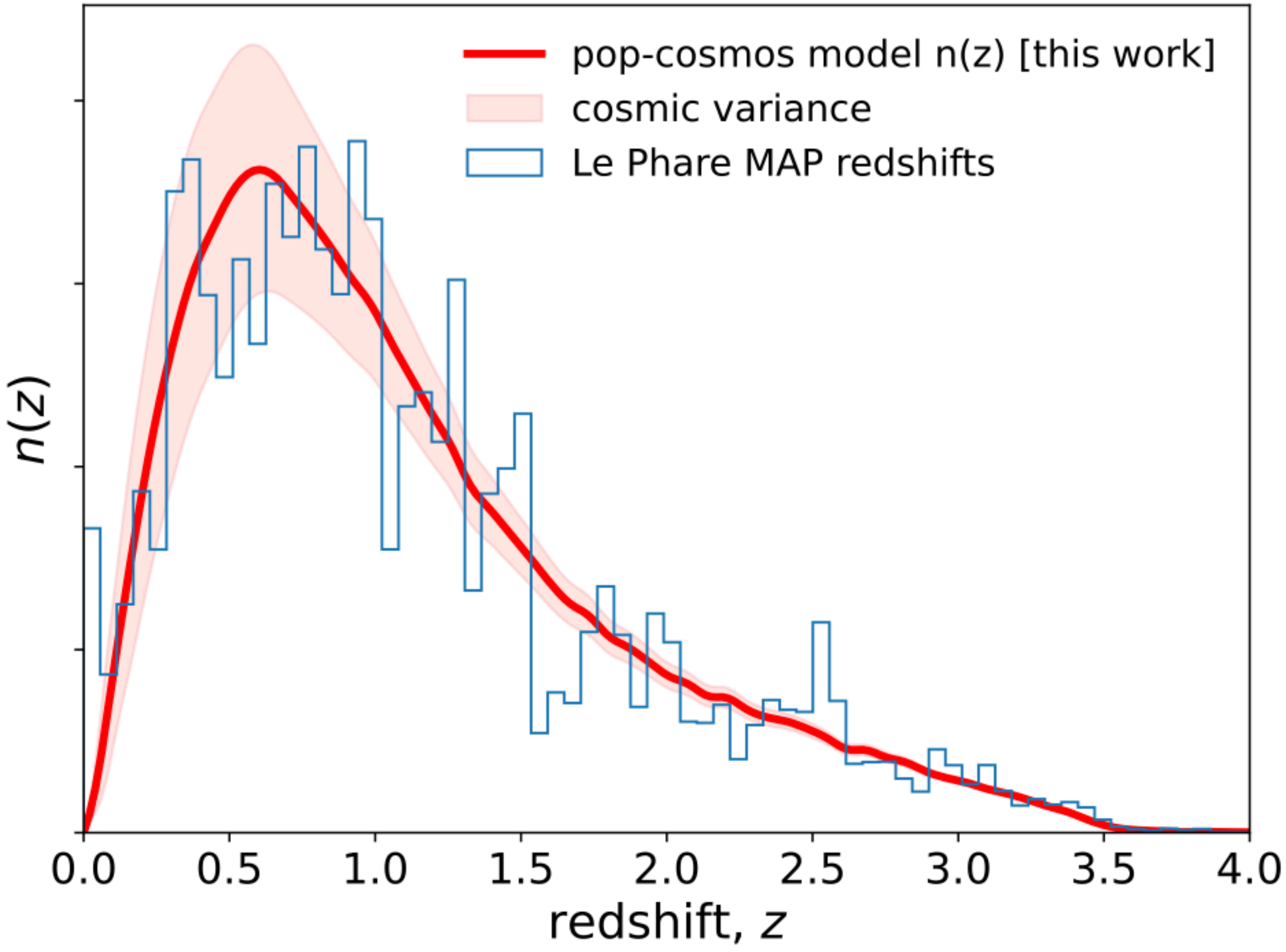
Learning the galaxy population model



TOY MODEL SIMULATION BY JUSTIN ALSING

Pop-Cosmos: a generative model for galaxy surveys

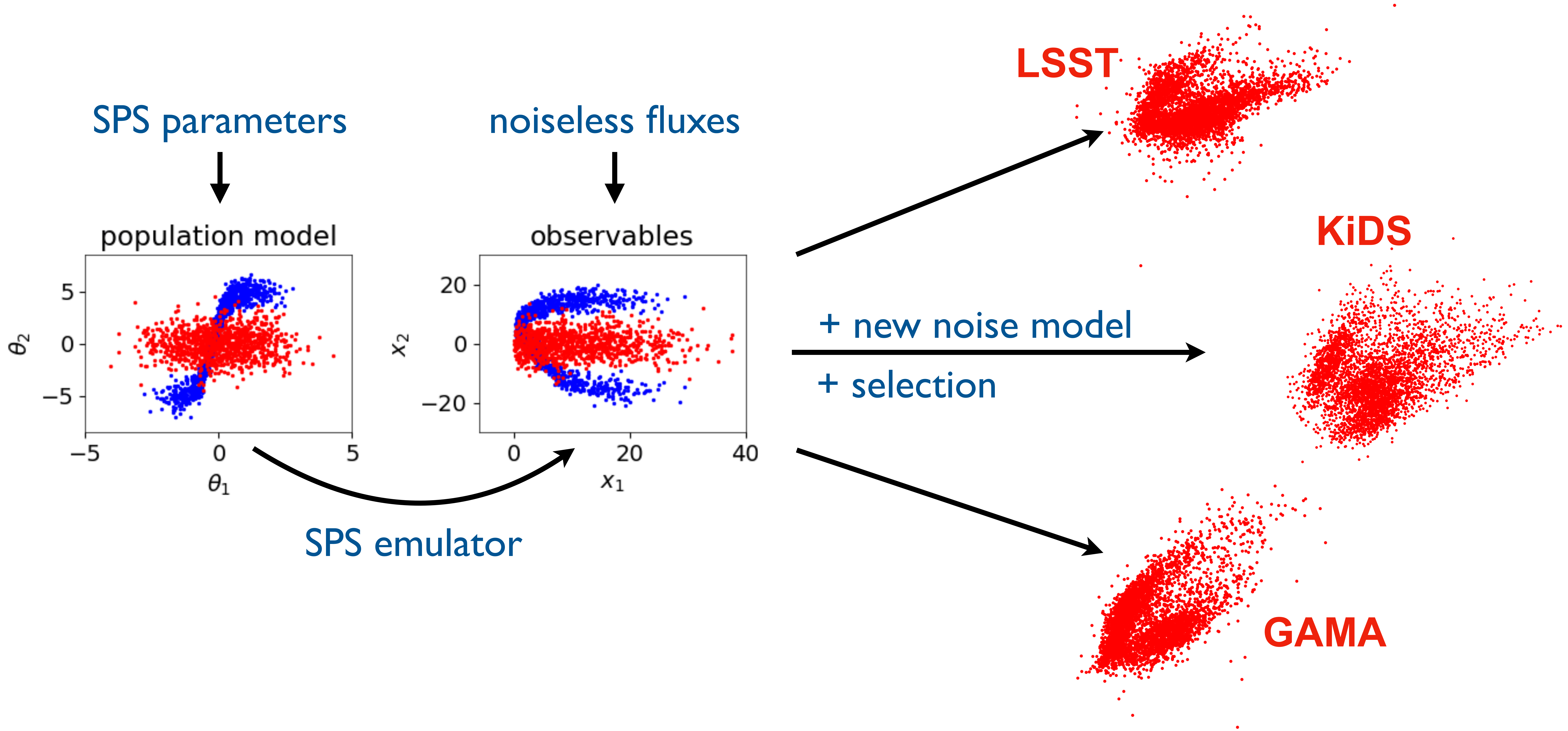
Pop-Cosmos prediction for COSMOS2020 redshift distribution



- *First time full joint density of galaxy properties has been estimated from large galaxy catalogue*
- *Can predict properties (incl. redshift distribution) of any catalogue of comparable / shallower depth*
- *Bonus: information on full galaxy population over cosmic time*

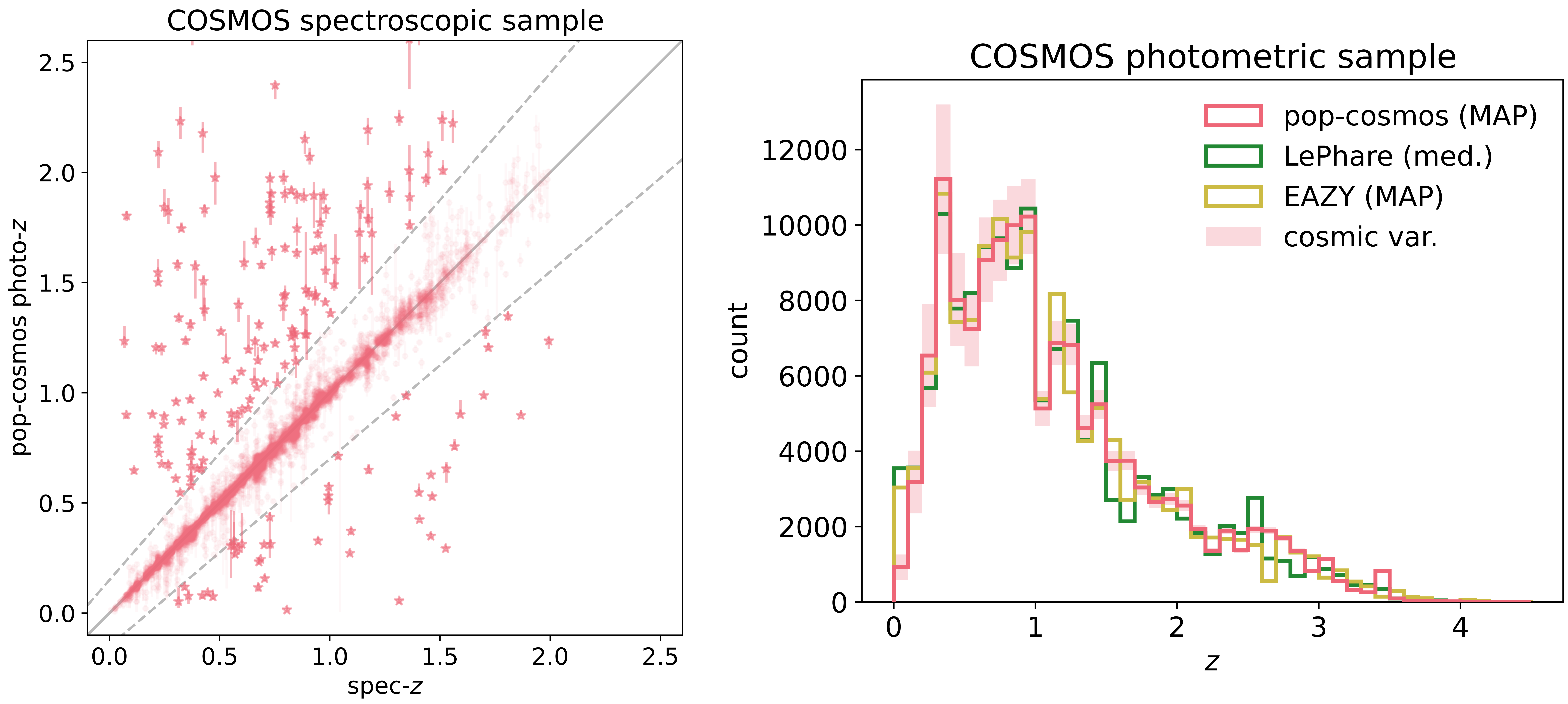
ALSING ET AL (2022, APJS), LEISTEDT ET AL. (2022, APJS), ALSING ET AL (2024, SUBMITTED), THORP ET AL (2024, SUBMITTED)

Forward-modelling other catalogues



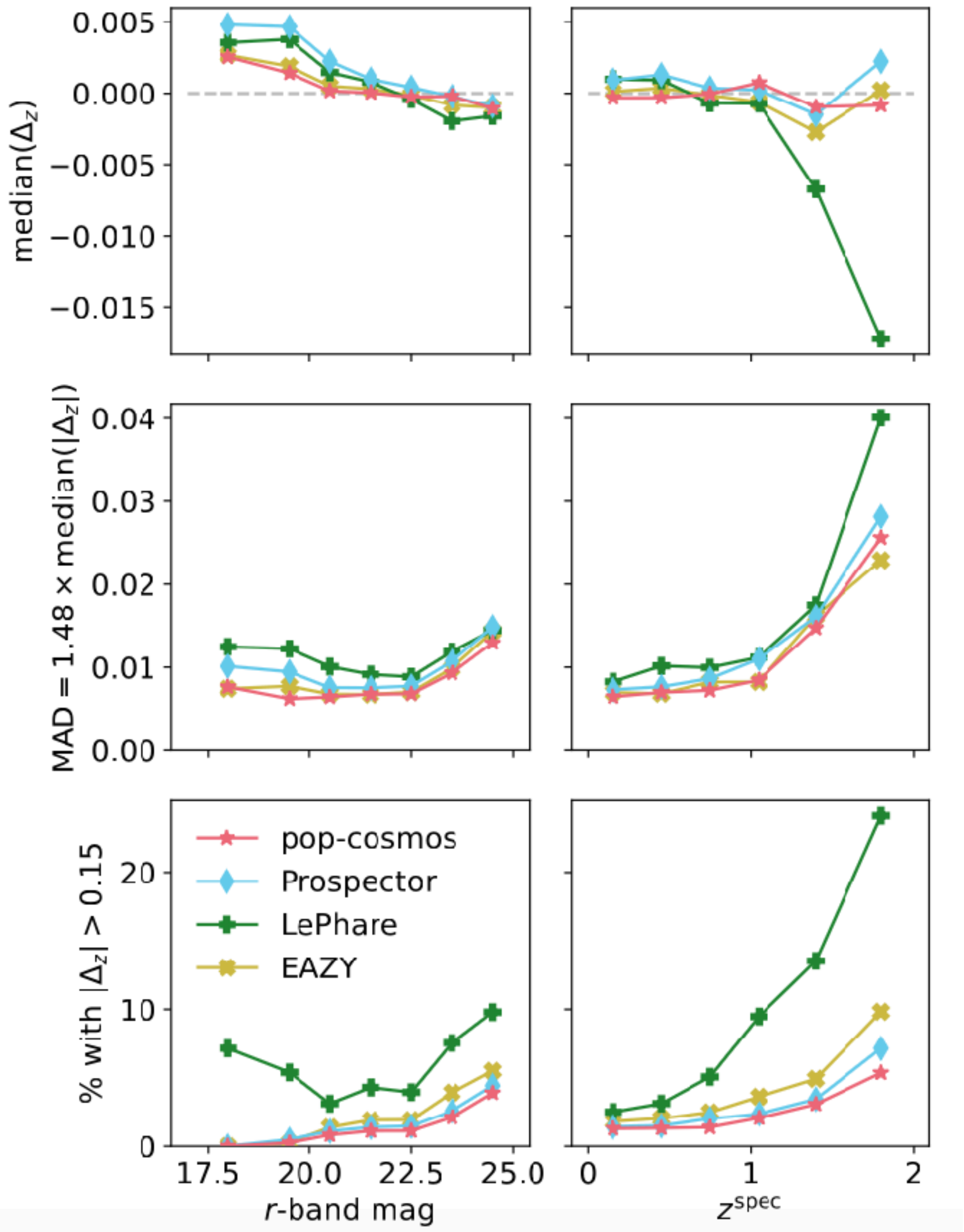
ADAPTED FROM STEPHEN THORP

Pop-Cosmos as a prior for galaxy photo-z inference



THORP ET AL (2024, IN PREP)

Quality of individual redshifts



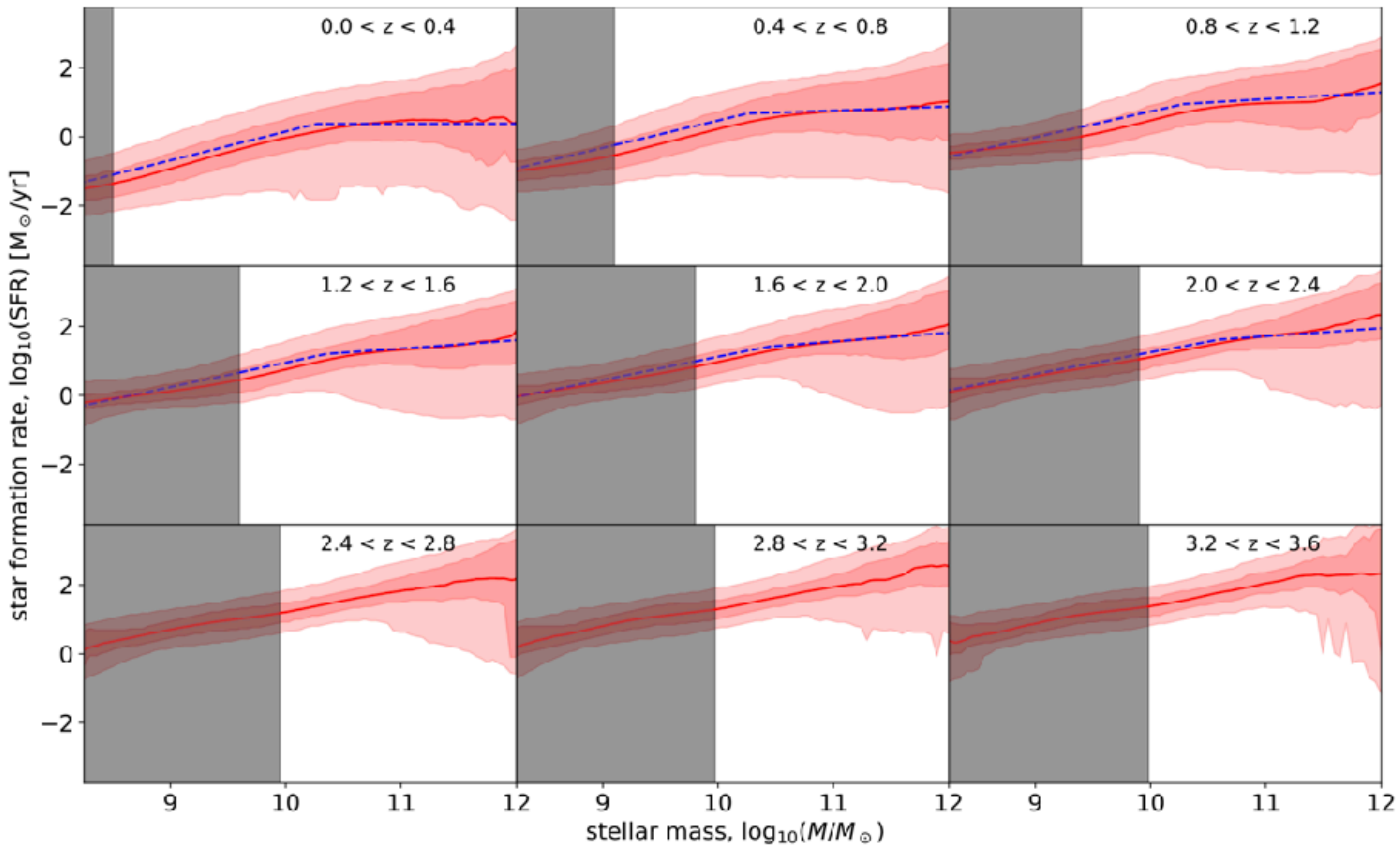
less biased

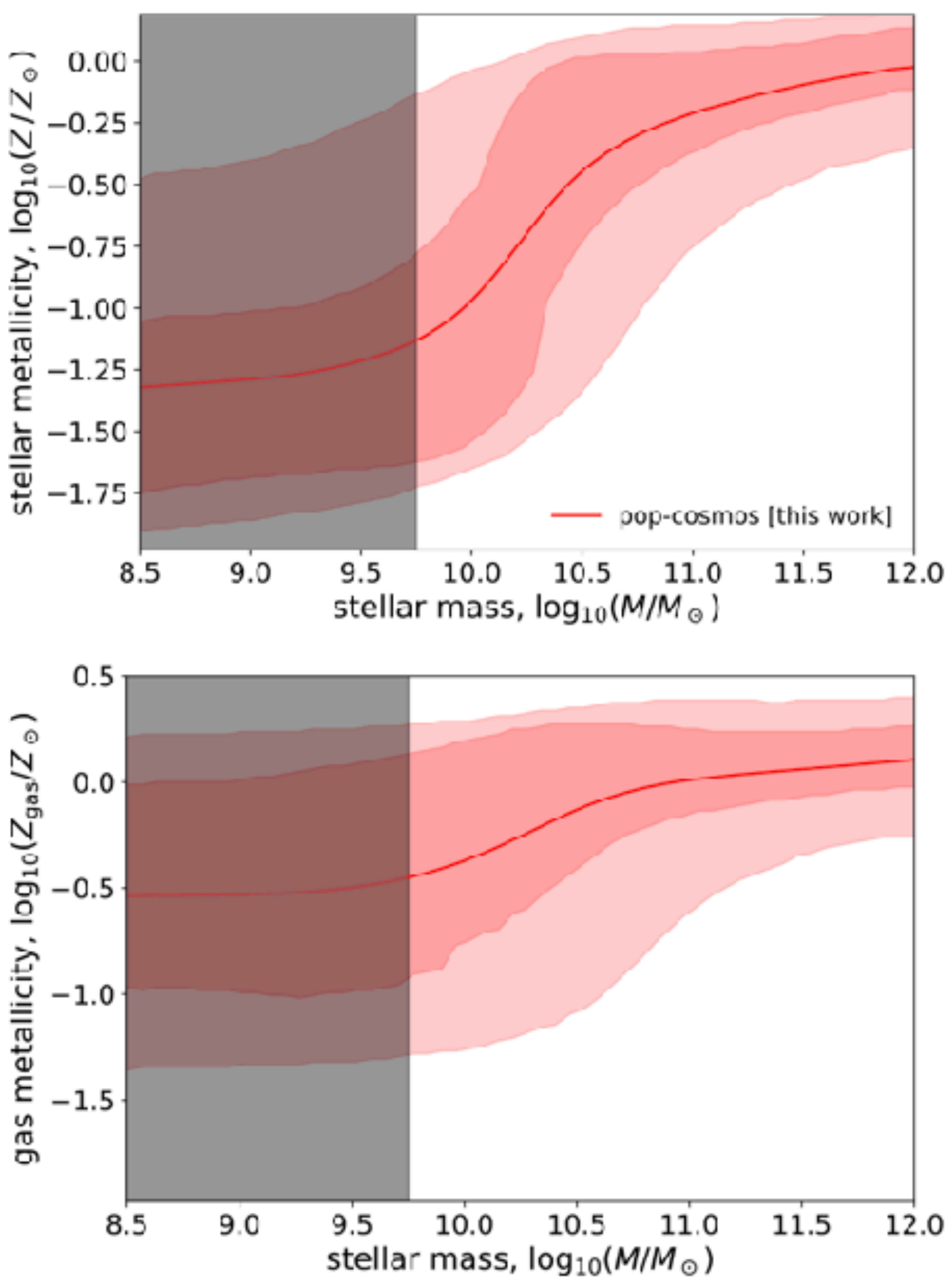
smaller errors

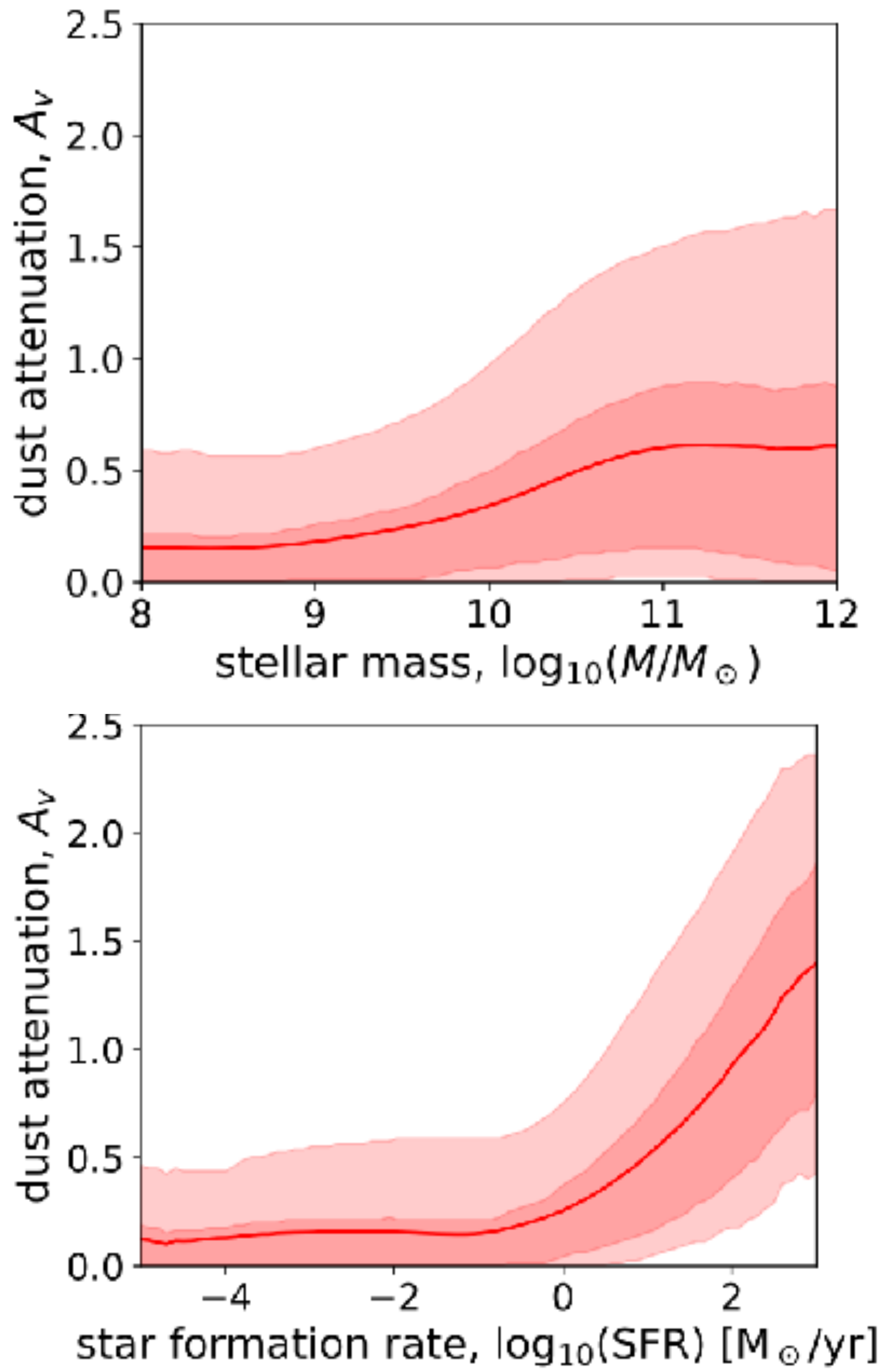
fewer outliers

THORP ET AL (2024, IN PREP)

Bonus: information on full galaxy population over cosmic time

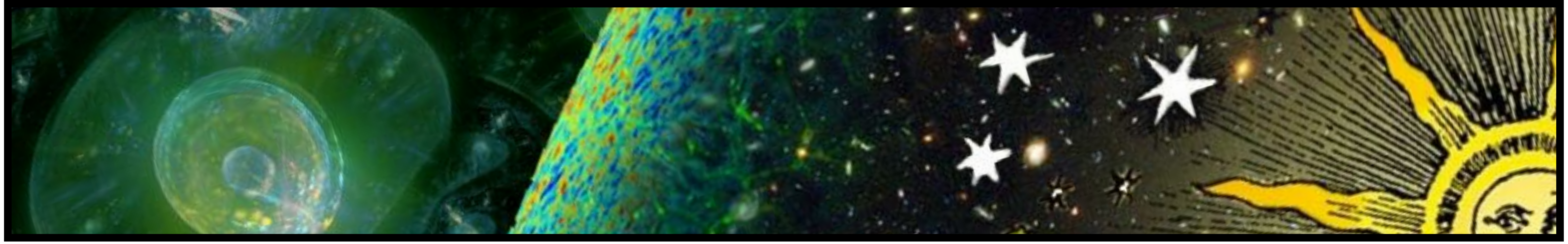






star forming sequence *metallicity* *dust*

ALSING, THORP, DEGER, PEIRIS ET AL (SUBMITTED, ARXIV:2402.00935), THORP, PEIRIS, ALSING ET AL (SUBMITTED, ARXIV:2402.00930)



Knowledge extraction using deep learning

Luisa Lucie-Smith
(MPA/Garching)

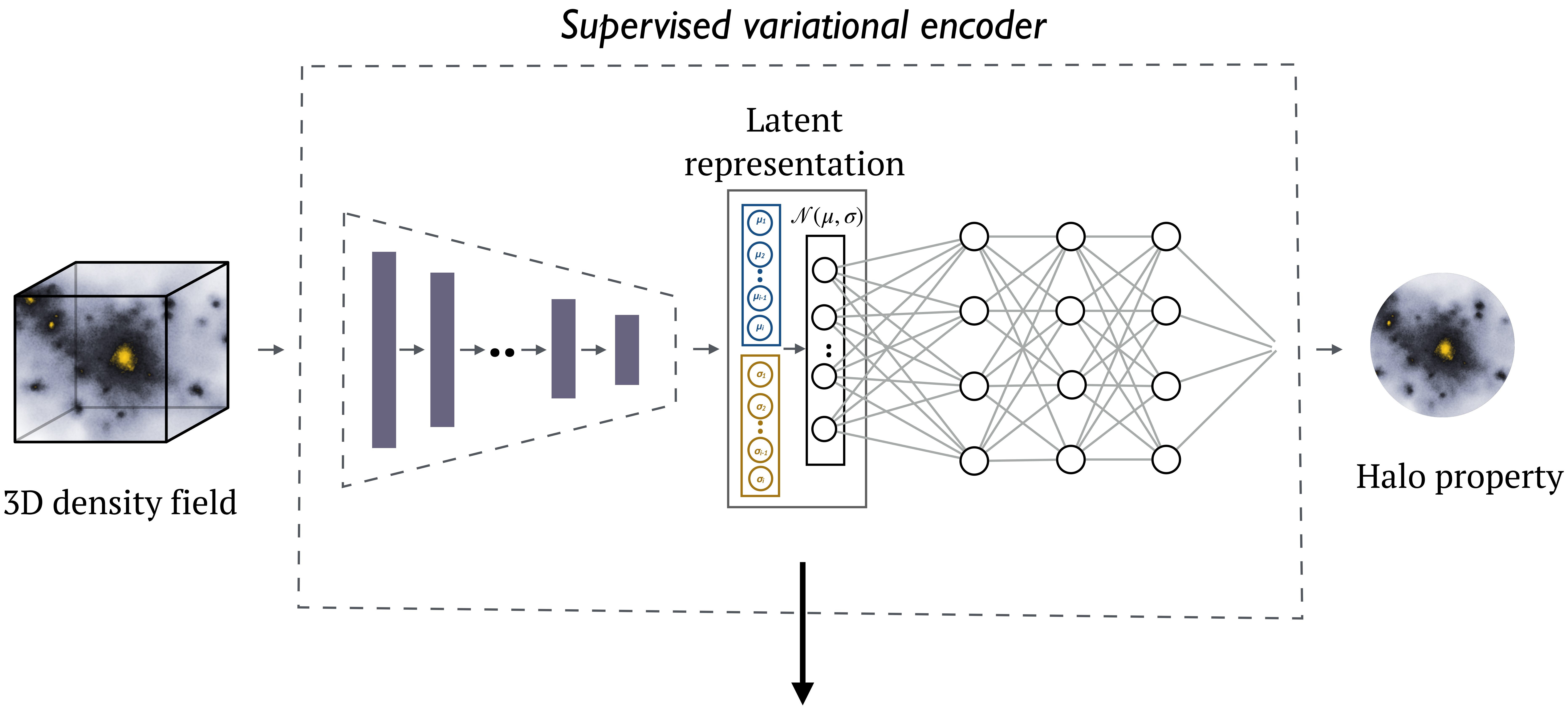
Andrew Pontzen
(UCL)

Lillian Guo
(UCL)

Davide Piras
(Geneva)

With: Brian Nord, Jeyan Thiyagalingam

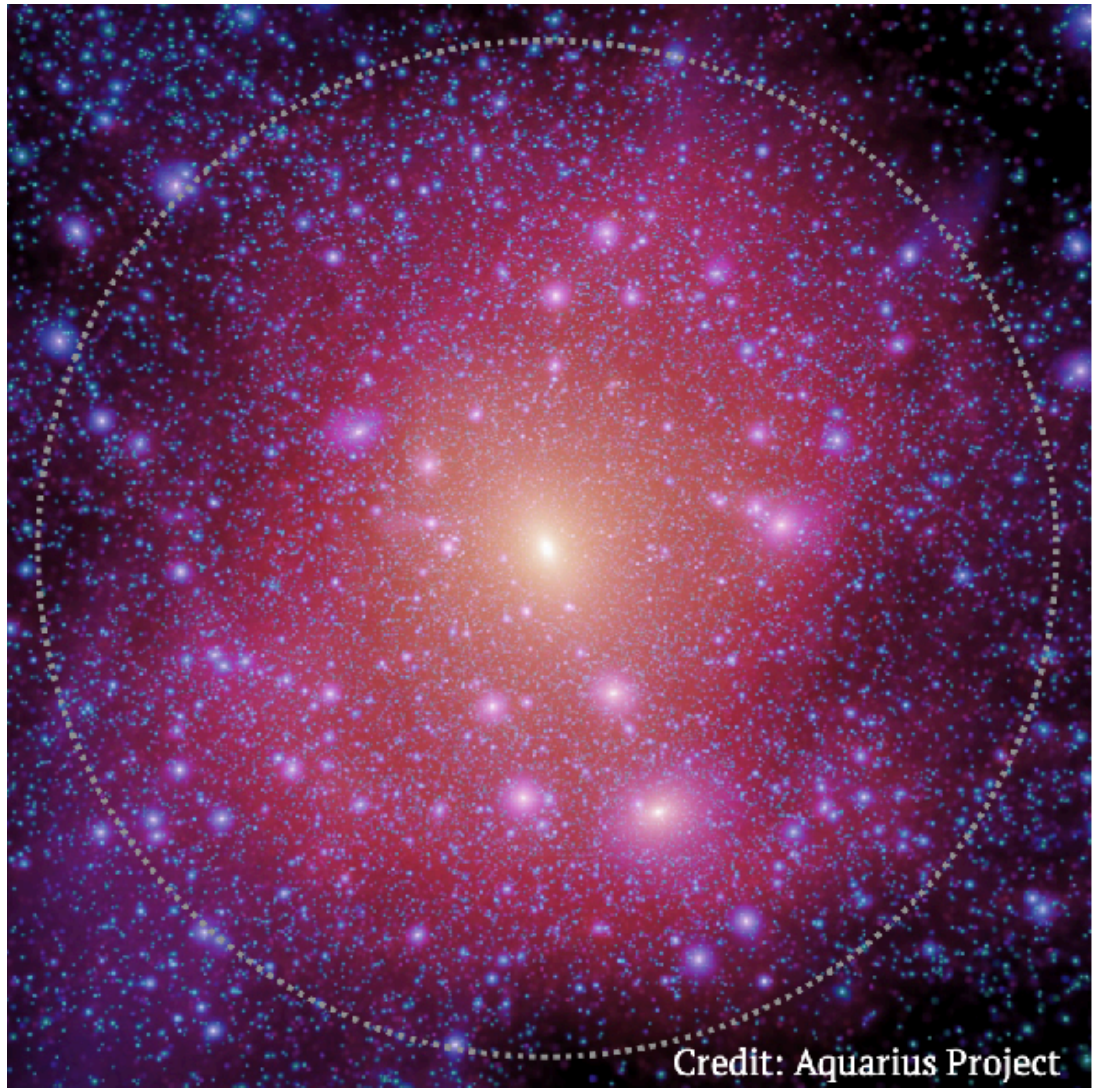
Frameworks for knowledge extraction using AI

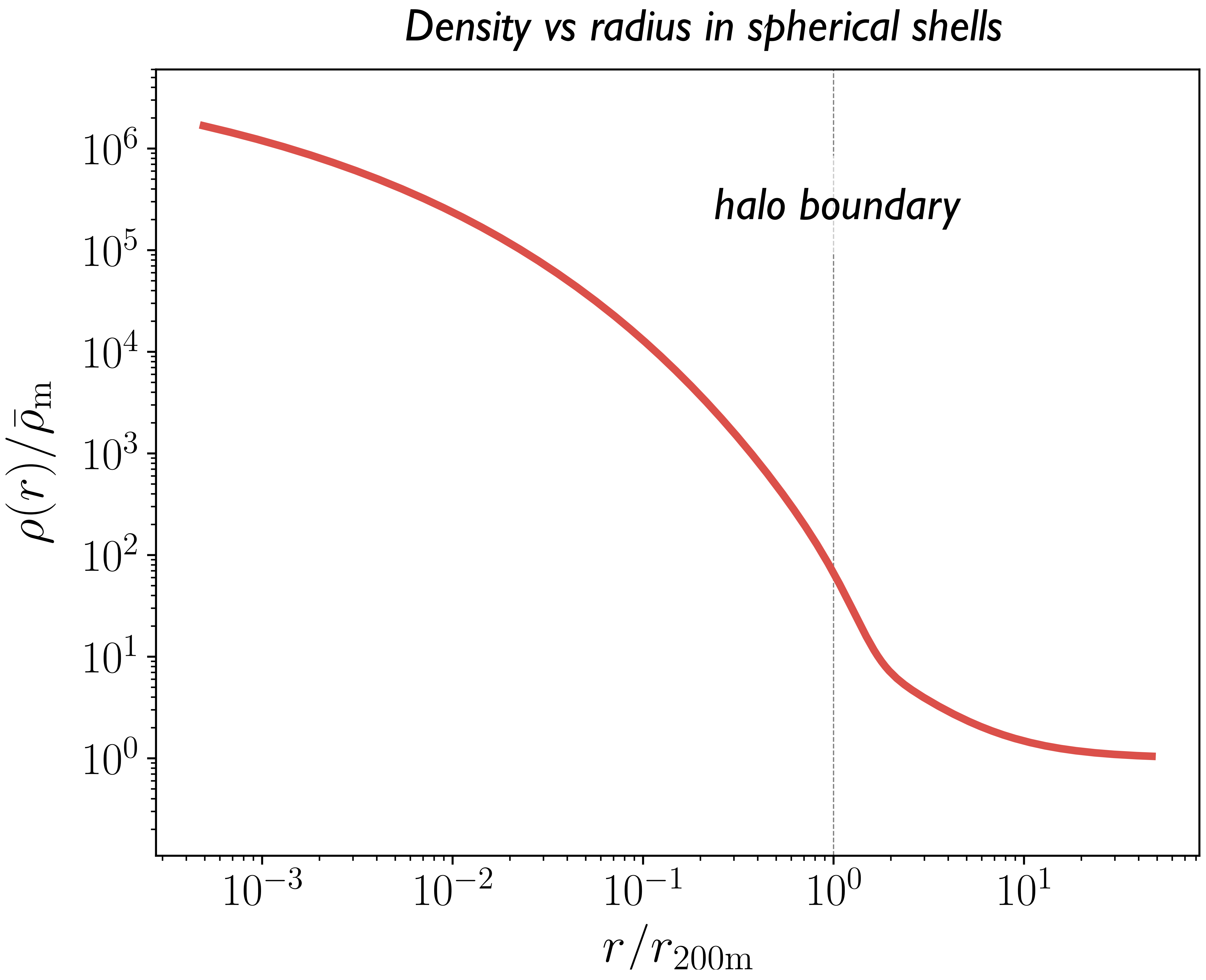


Model compression to enable "explainable" AI

LUCIE-SMITH, PEIRIS, PONTZEN, NORD + (PRD, 2022), LUCIE-SMITH, PEIRIS, PONTZEN, (PRL, 2024)

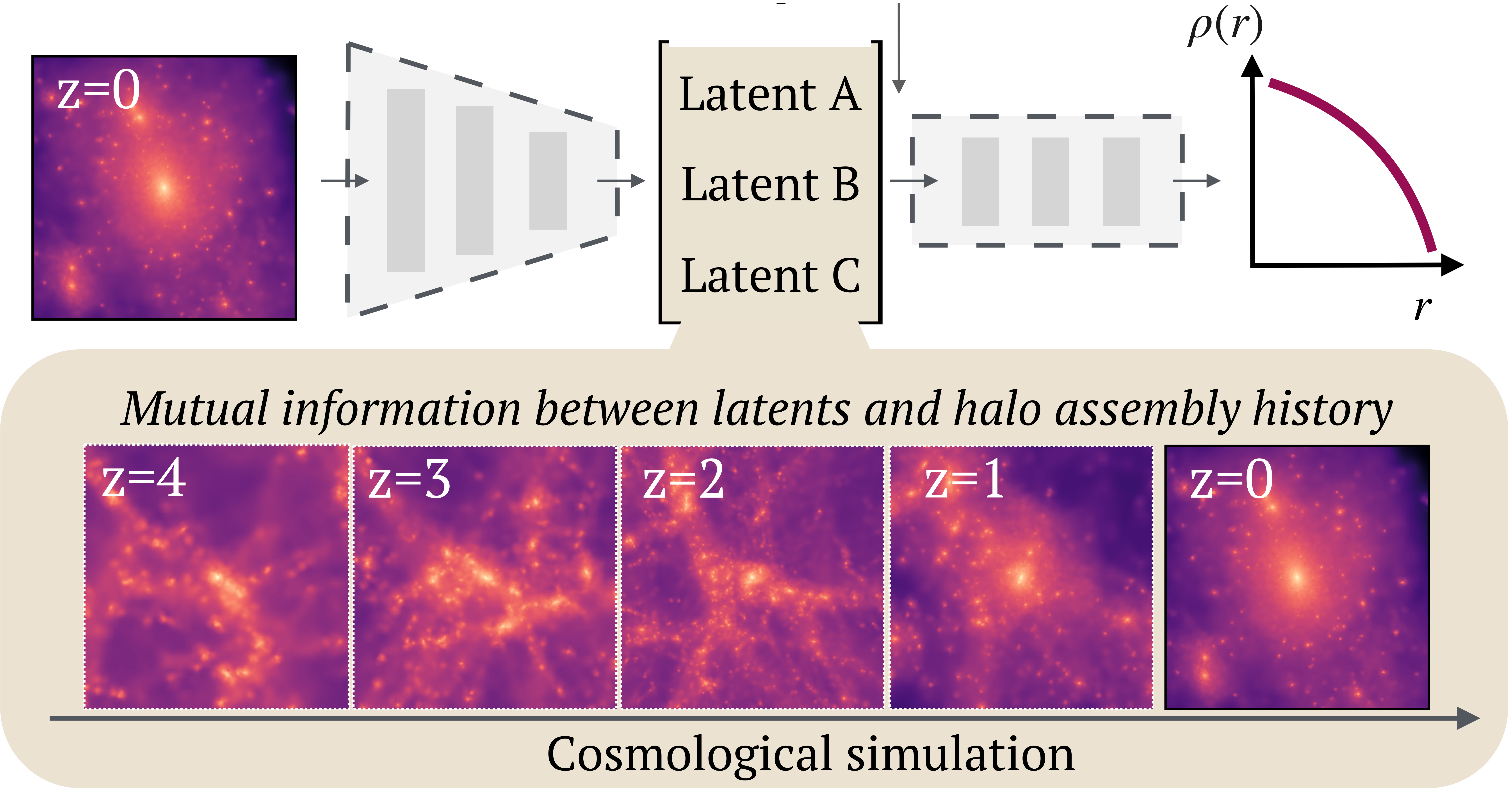
Dark matter halo density profiles





Key ingredient in cosmological analyses and beyond
(e.g. dark matter detection)

What physics is encoded in the dark matter halo profile?



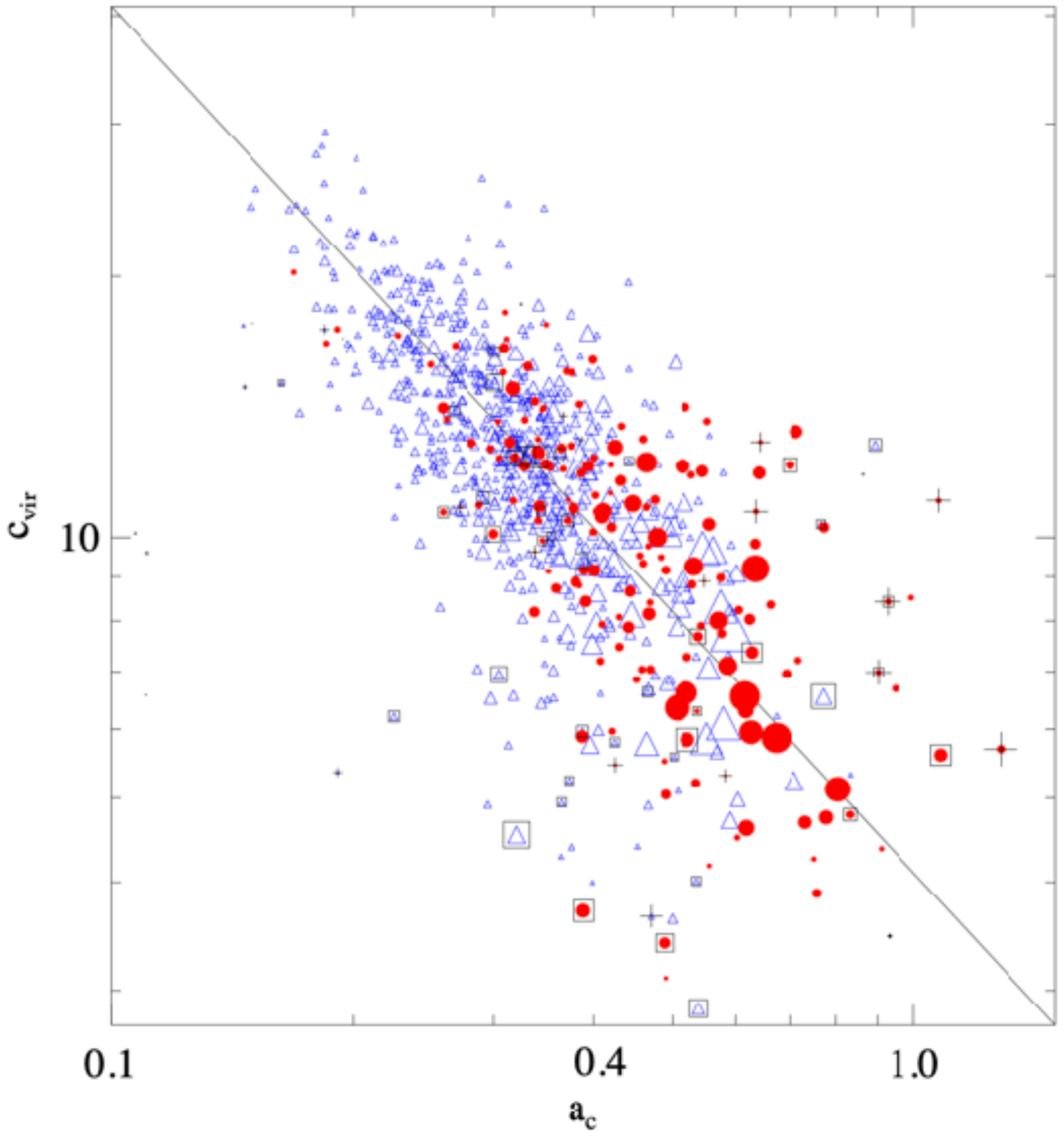
Network ***not given assembly history of halos during training****.*

The learnt degrees of freedom nevertheless ***relate to halos' mass accretion history in specific, interpretable ways.***

Lucie-Smith, Peiris, Pontzen, Nord + (PRD, 2022), Lucie-Smith, Peiris, Pontzen, (PRL, 2024)

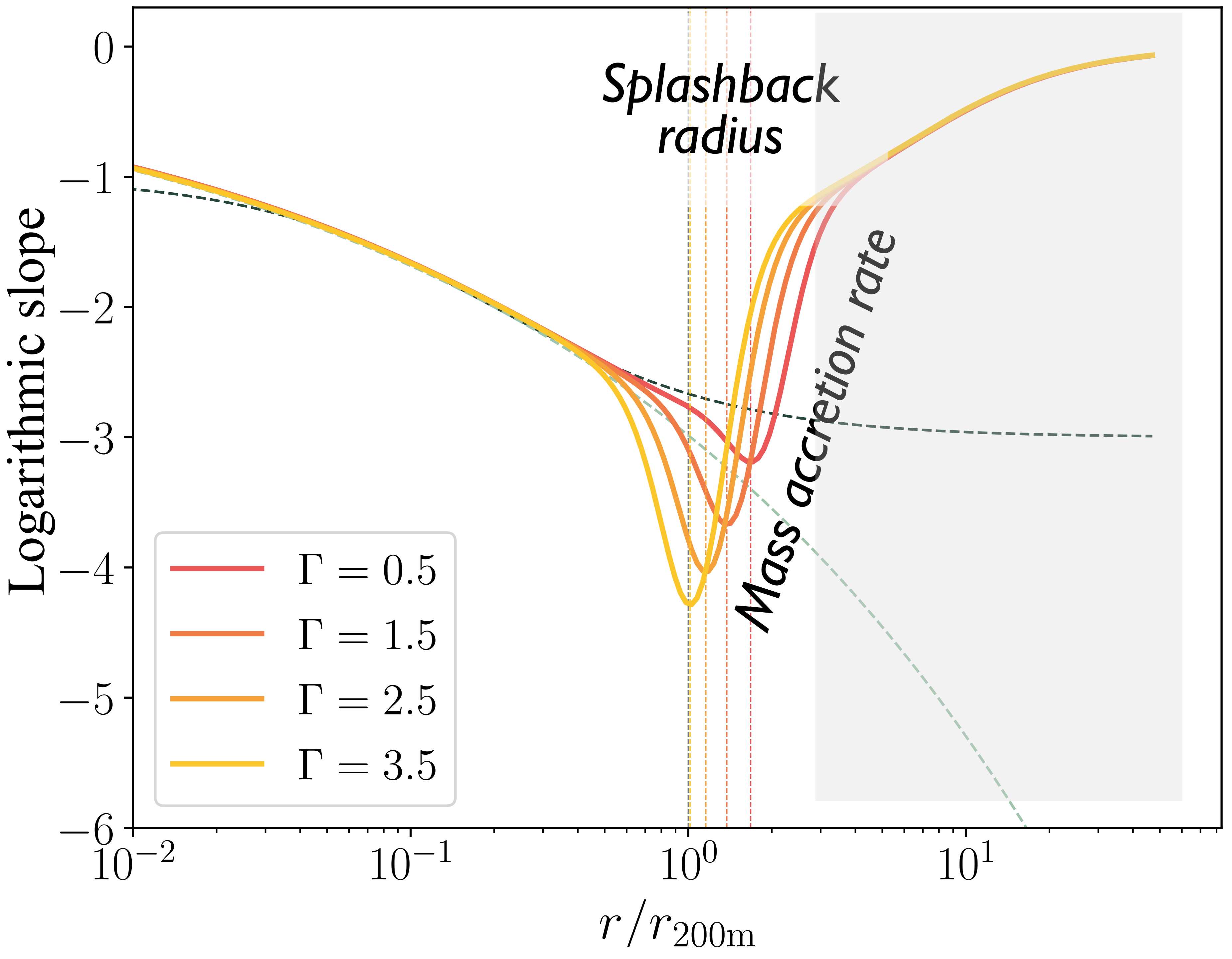
Seeing halo properties in terms of their full evolution histories

IVE recovers known relation between
inner profile and ***early assembly history***



Halo concentration versus formation epoch
(e.g. Wechsler et al 2002)

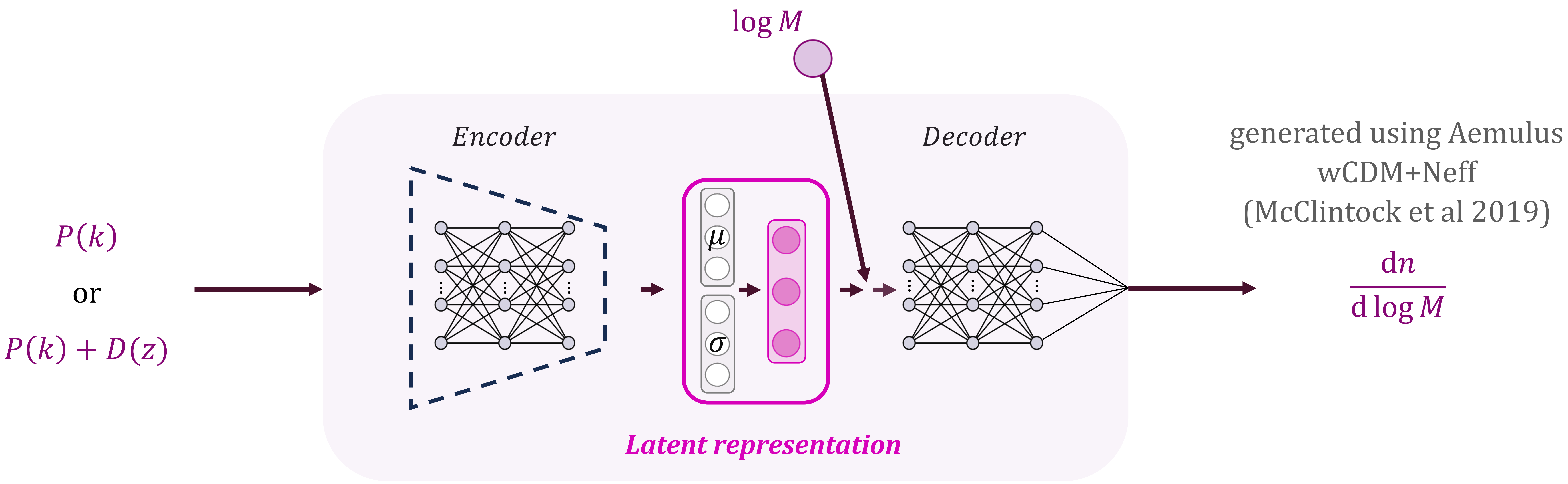
IVE discovers that ***outer profile*** depends on
single dof related to ***most recent accretion rate***



Relation to splashback radius
(e.g. Diemer 2020)

LUCIE-SMITH, PEIRIS, PONTZEN (PHYS. REV. LETT, 2024)

Understanding non-universality in halo mass function



- *How many independent degrees of freedom are needed to describe the HMF to percent-accuracy?*
- *Can we isolate and quantify universal and non-universal information in the HMF?*

  Previous work suggests linear growth related to non-universality
  (Ondaro-Mallea et al 2021; Euclid collaboration et al. 2023)

GUO, LUCIE-SMITH, PEIRIS, PONTZEN, PIRAS (ARXIV:2405.15850)

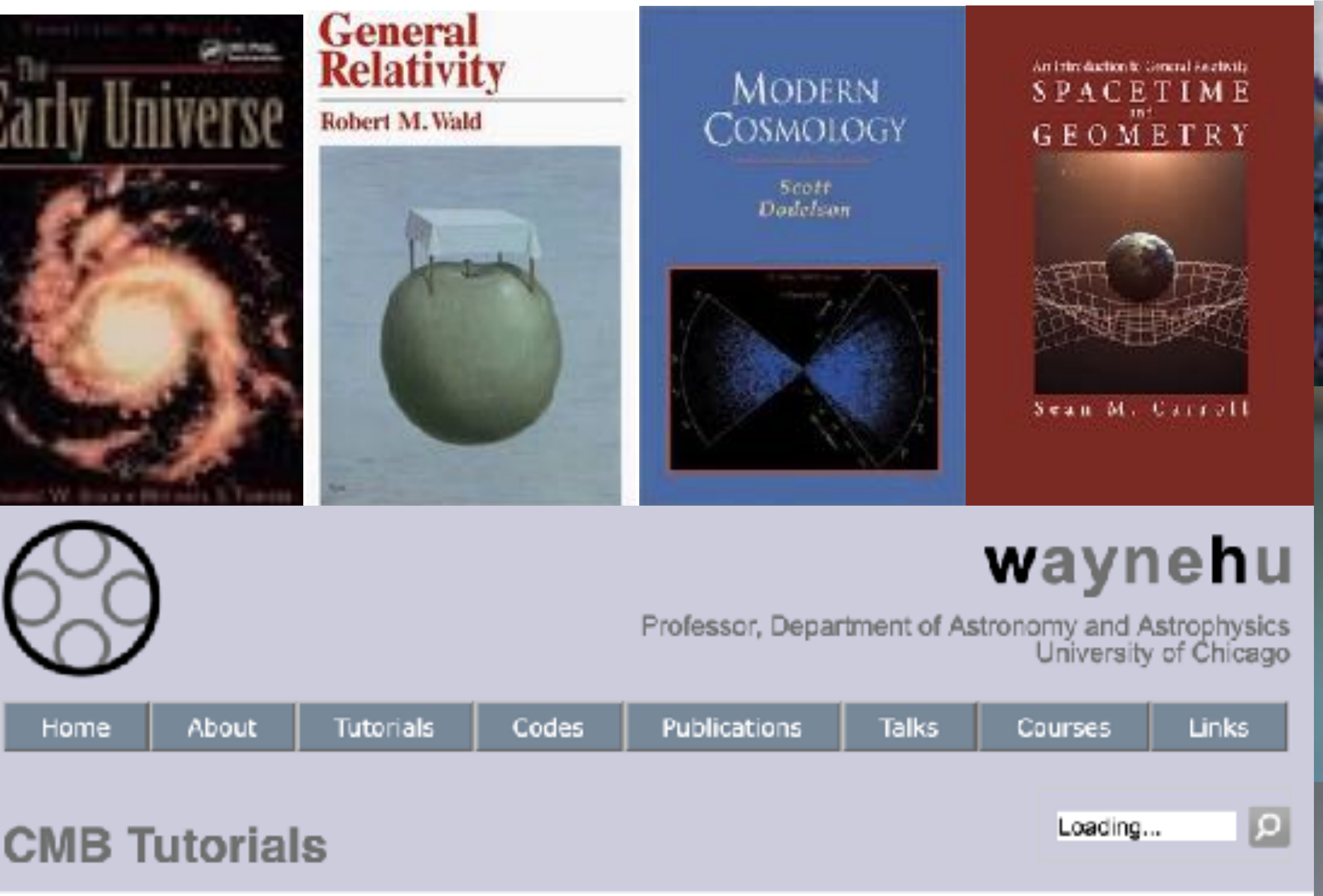
"More is different": emergent phenomena in cosmology

- Modern machine learning methods can help us **embrace the complexity** and assist us in **gaining new insight.**

CREDIT: UCL / PONTZEN

What I found at KICP 2004—2007

It's all about the people



Inspiring faculty

Inspiring students

Inspiring peers

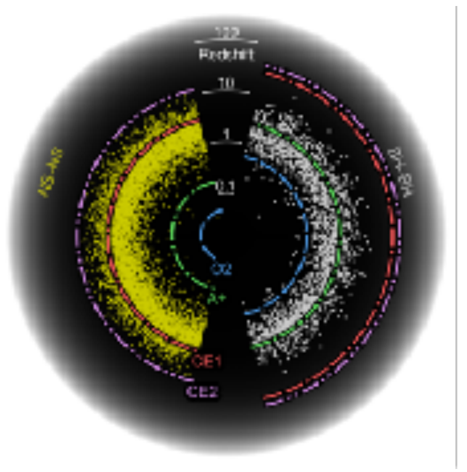
Successful environment for enabling interdisciplinary research

Laying down the tracks as the train of data-driven cosmology got going.

My current research snapshot

CosmicExplorer: Exploring the Cosmos with the Vera Rubin Observatory

ERC Advanced Grant project focusing on Data-intensive (static and transient) cosmology with Rubin data (with a strong focus on explainable AI methods)



Fundamental physics from populations of compact object mergers

Leveraging ML methods and simulation-based inference to accelerate and enable population studies with next generation gravitational wave facilities.

Detecting Axion Dark Matter in the Sky and in the Lab

Exploring axion dark matter hypothesis through its cosmological signatures + searching for QCD axion in the lab via tunable plasmon haloscopes (founding member of ALPHA Collaboration)

Cosmology x Quantum

Emulating early universe physics within an analogue quantum simulator in the laboratory (collaboration with Cambridge Physics / Hazibabic BEC Lab)

Happy 20th birthday and congratulations KICP!

From your friends at KICC.

COSMOPARTICLE, WWW.PENELOPEROSECOWLEY.COM