pop-cosmos

investigating the explainability of a high-dimensional, data-driven generative model in cosmology

Hiranya V. Peiris

European Research Council
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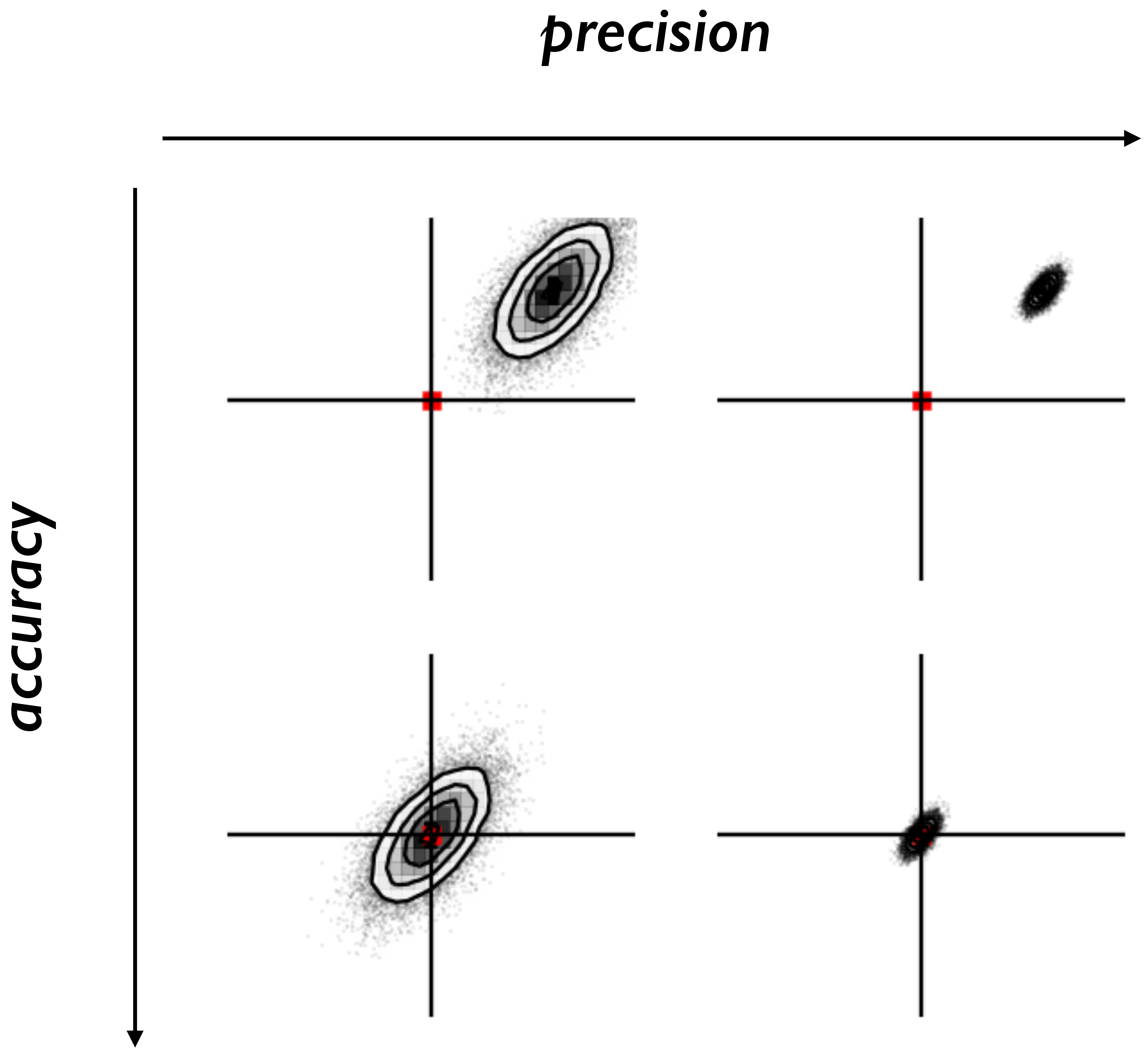

precision
accuracy

Characteristics of (good) physical models

- *Follow from explicitly enumerable set of assumptions and physical principles*
- *Leads to mathematical models that can be solved (analytically/numerically) to yield useful* ***predictions*** *(deterministically/probabilistically).*
- ***Explainable*** *(rooted in cause-effect relationships grounded in domain knowledge.)*
- ***Generalises*** *beyond initial domain to explain wider range of phenomena.*
- ***Compresses*** *information: explains wide range of phenomena from minimal set of ingredients (~Occam's razor.)*
- ***Domain of validity*** *can be quantified explicitly.*

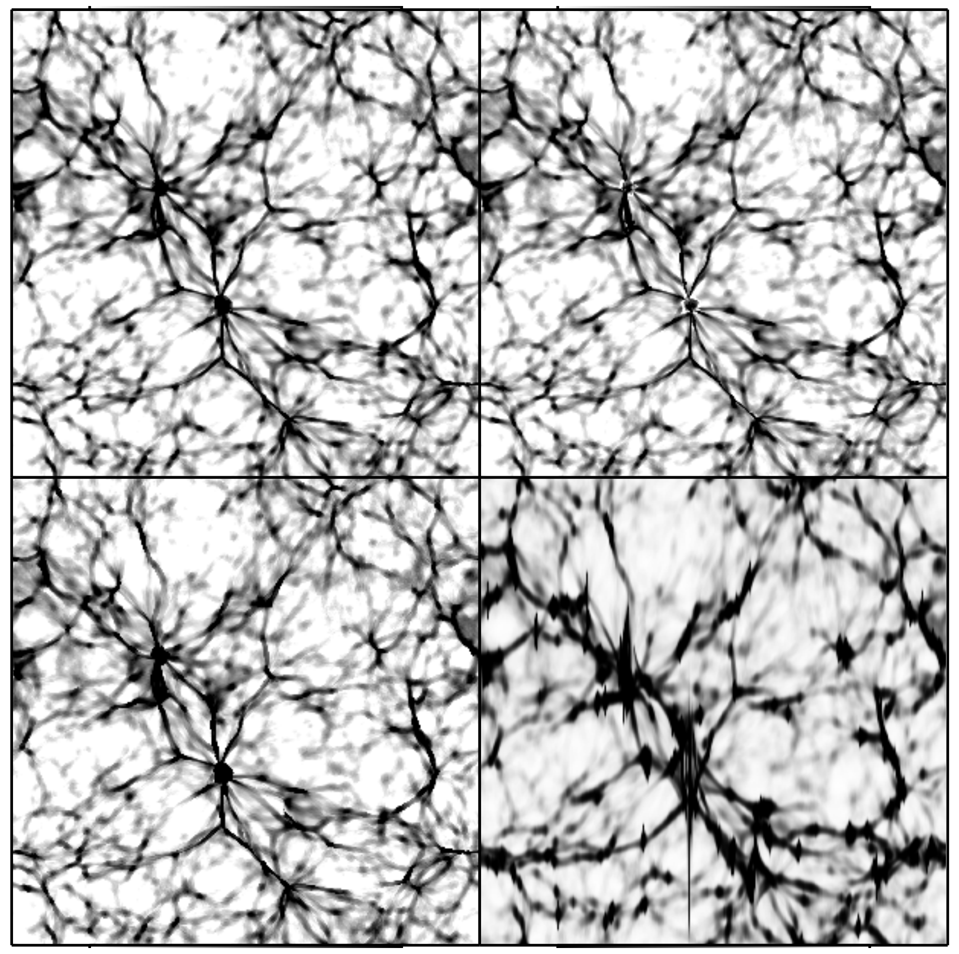
My definitions

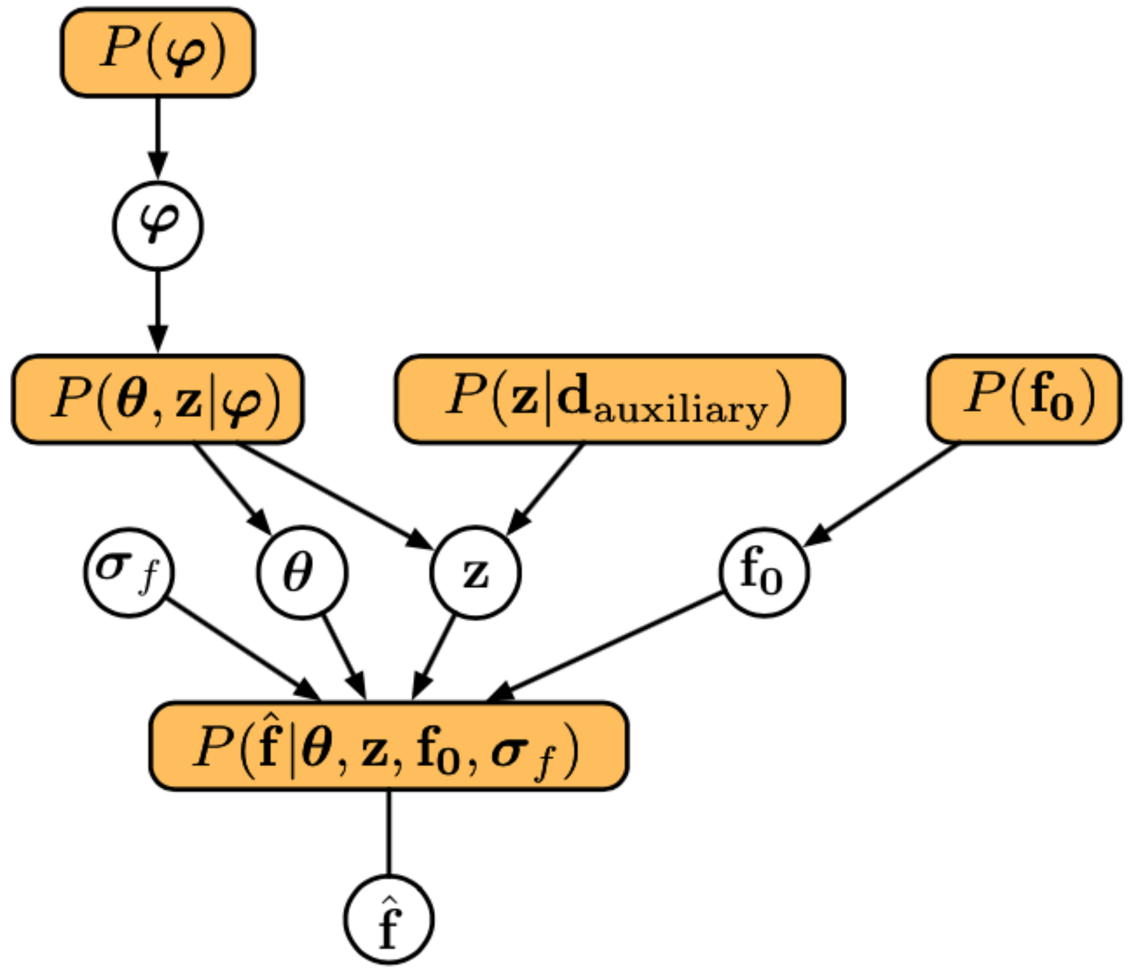
(i) ***interpretability****: account for why ML system reaches particular decision or prediction;*

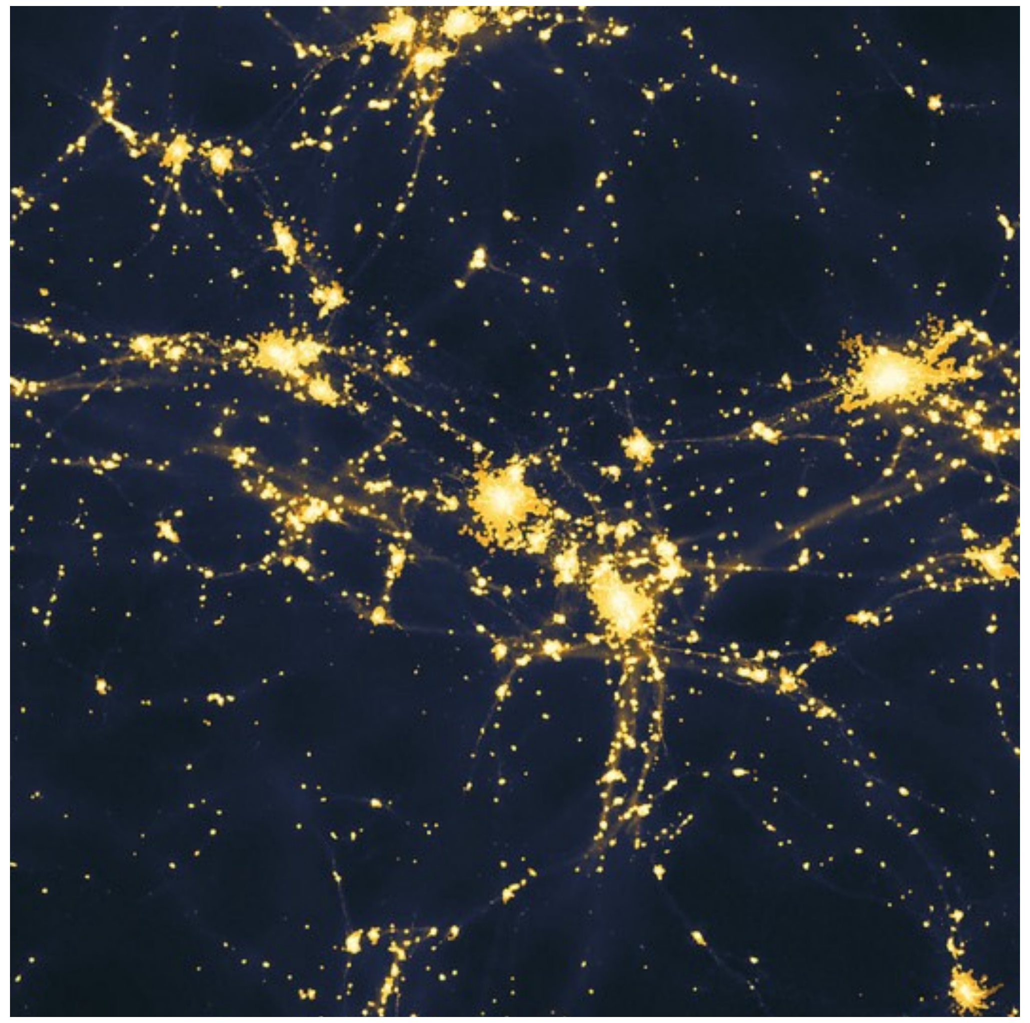
(ii) ***explainability:*** *map this account onto existing knowledge in relevant science domain.*

- *Currently challenging because of "black box" nature of ML architectures.*
- *Many physical models satisfy my list of characteristics only partially, e.g. systems exhibiting emergent phenomena, chaotic systems.*

Solving cosmological modelling challenges with machine learning





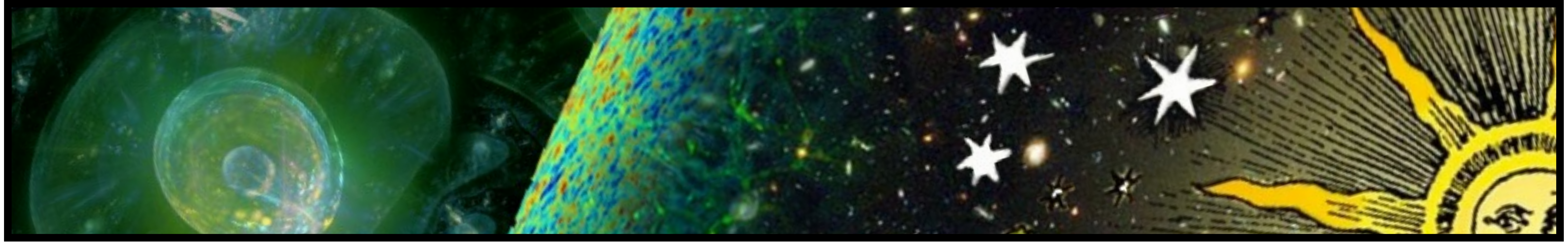


Emulation:
ML-accelerated forward-modelling of observables

Simulation-based optimisation:
data-driven calibration of high-dimensional generative models

Explainable AI:
machine-assisted knowledge extraction

See Luisa Lucie-Smith talk



pop-cosmos team

Justin Alsing

Stephen Thorp

Sinan Deger

Boris Leistedt

Arthur Loureiro

Daniel Mortlock

Joel Leja

Hiranya Peiris

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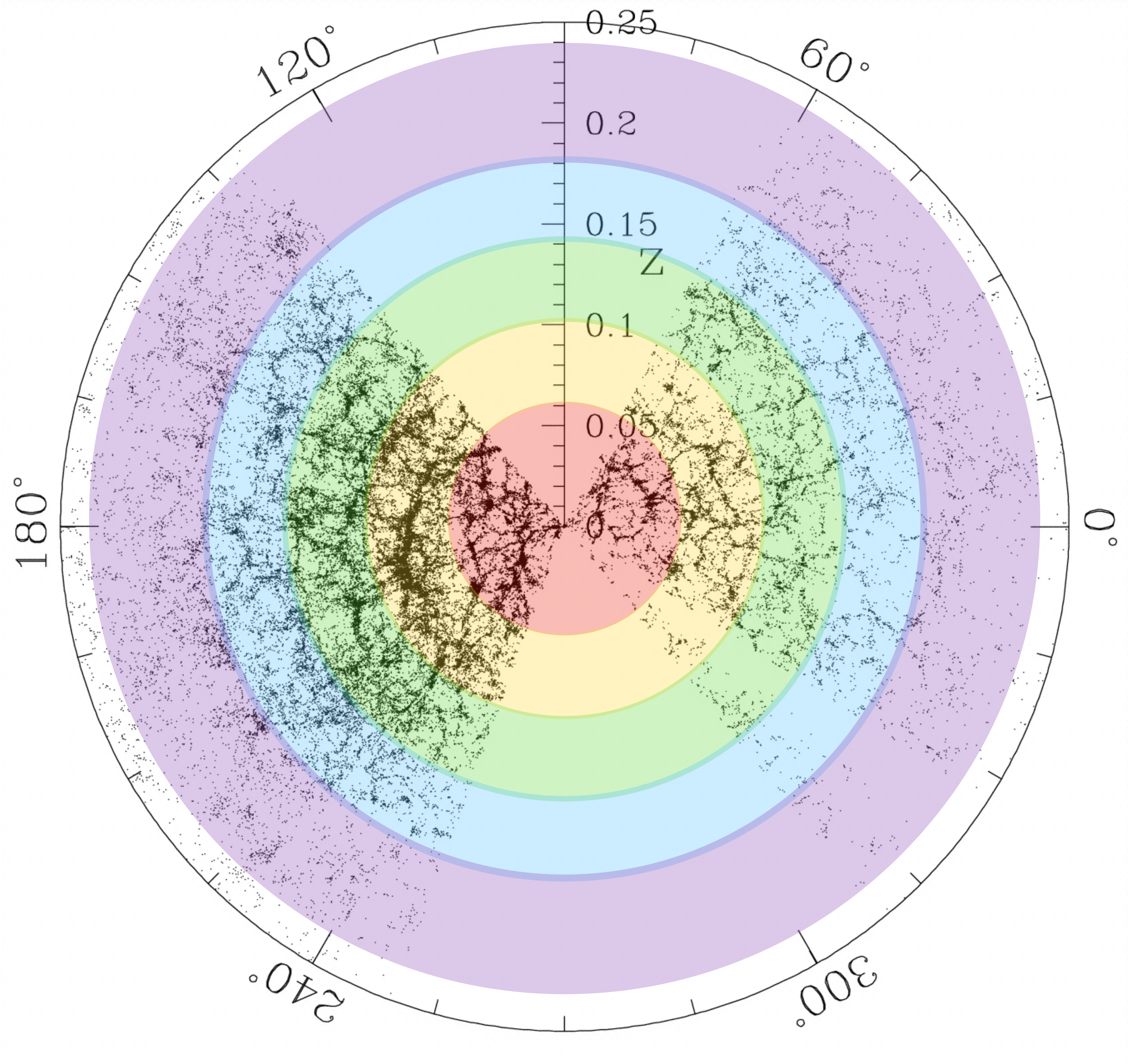
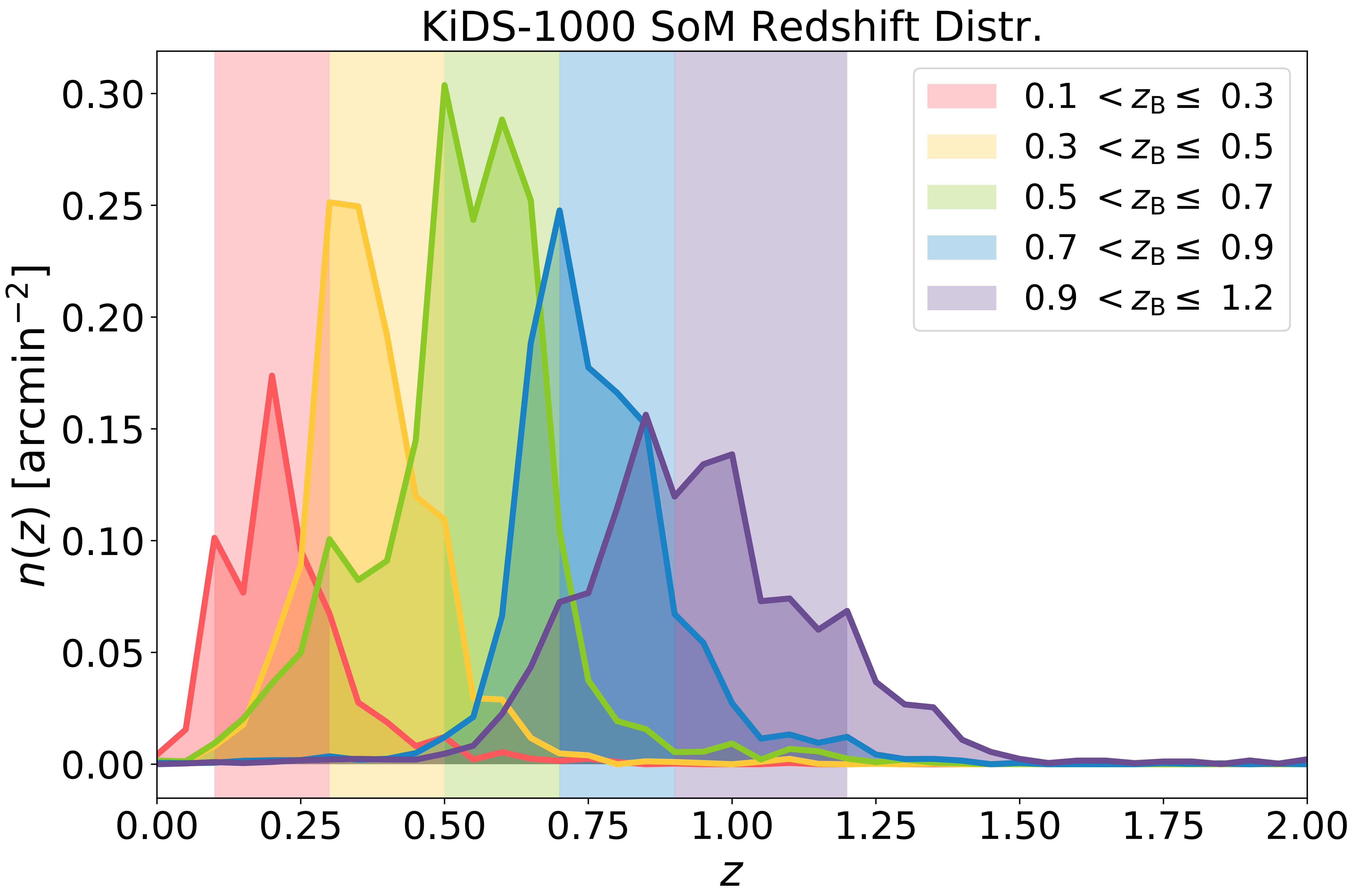
Photometric catalogues require redshift estimation



Blanton et al. (2003)



Loureiro et al. (2023)

Adapted from Justin Alsing

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

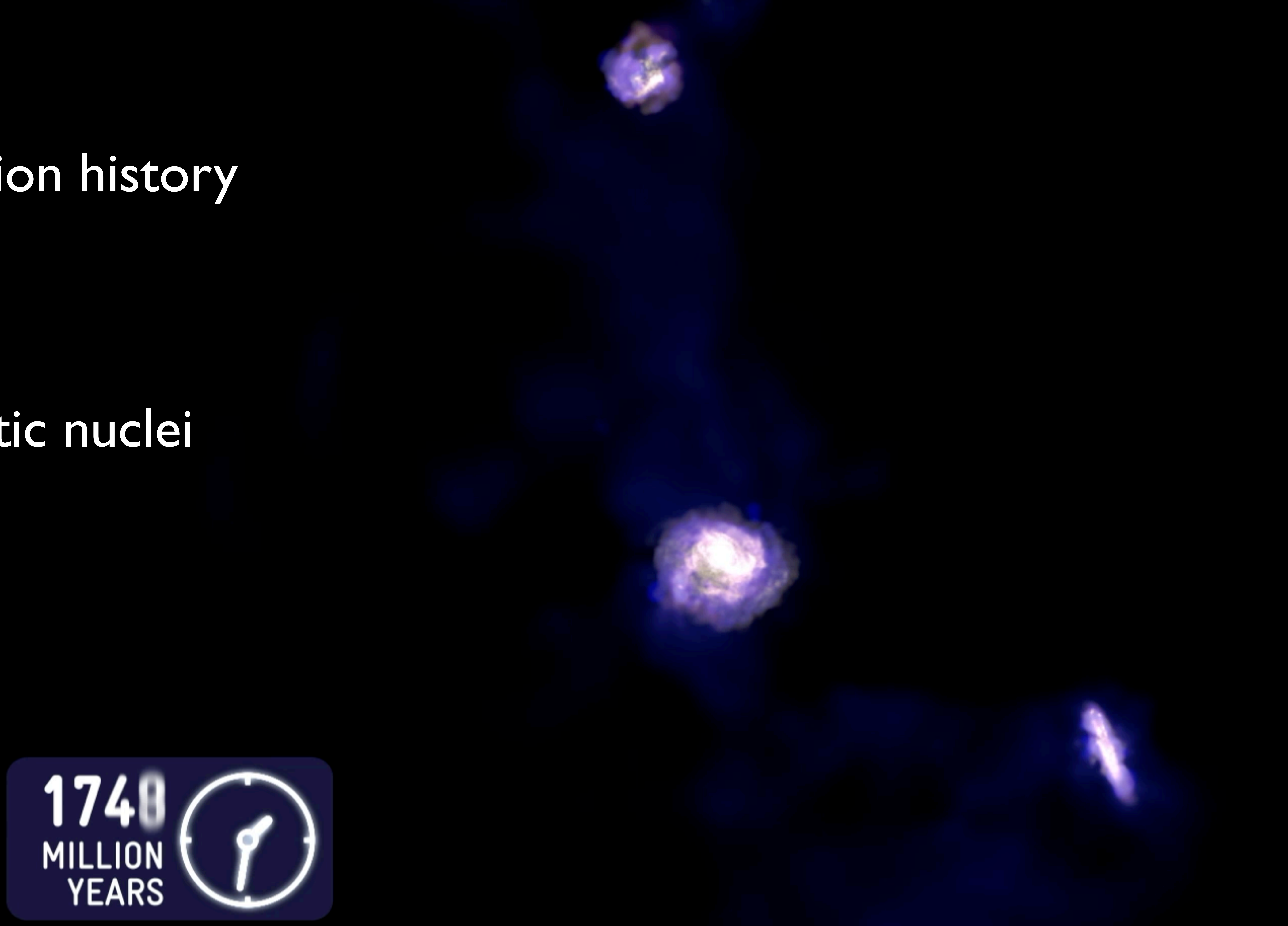
Machine learning models can accurately describe this complicated web of interdependencies

Figure: Hubble Ultra Deep Field

Recipe for making galaxy spectra and colours

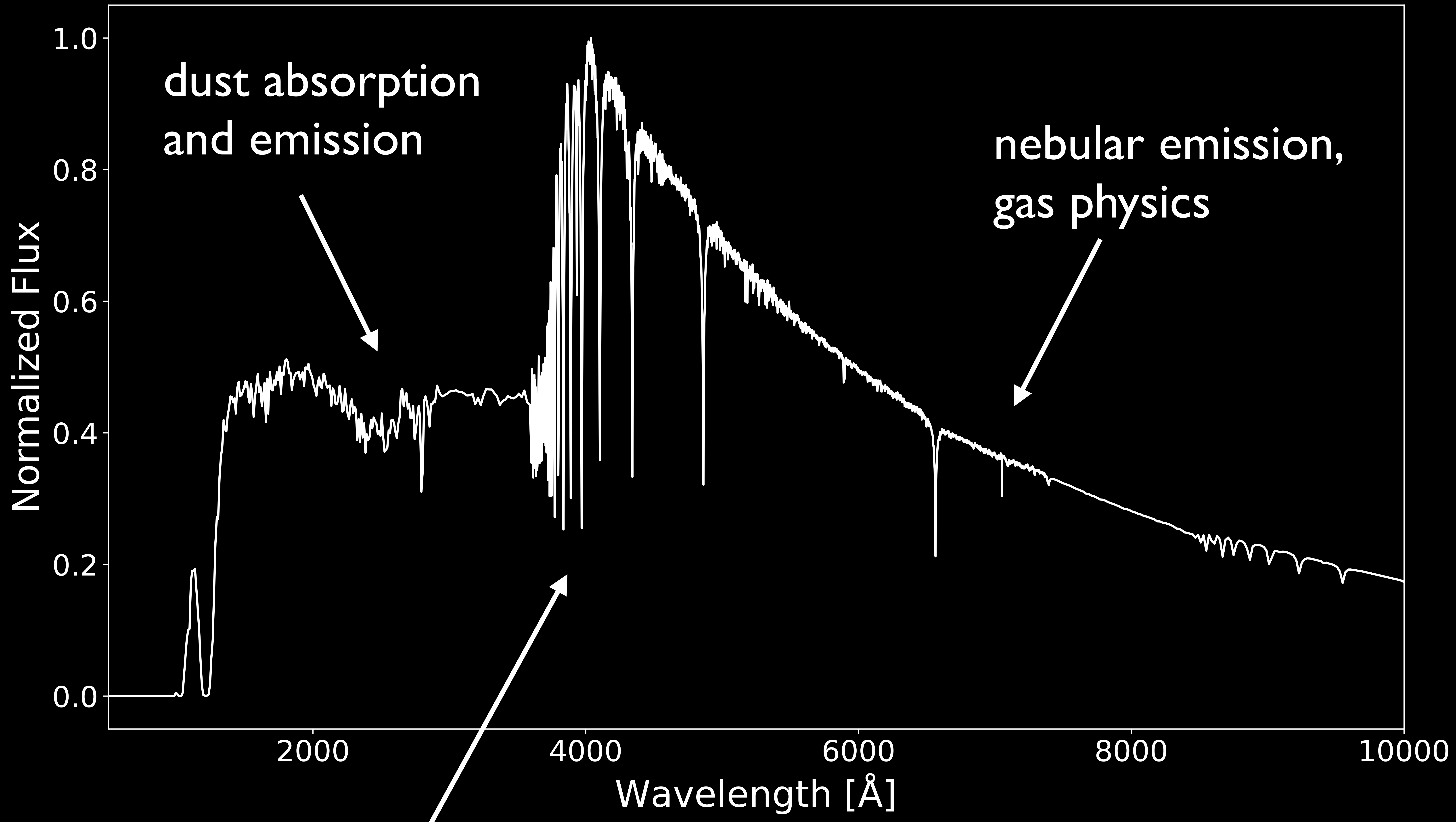
- mass
- star formation history
- dust
- gas
- metallicity
- active galactic nuclei
- redshift

…



Andrew Pontzen

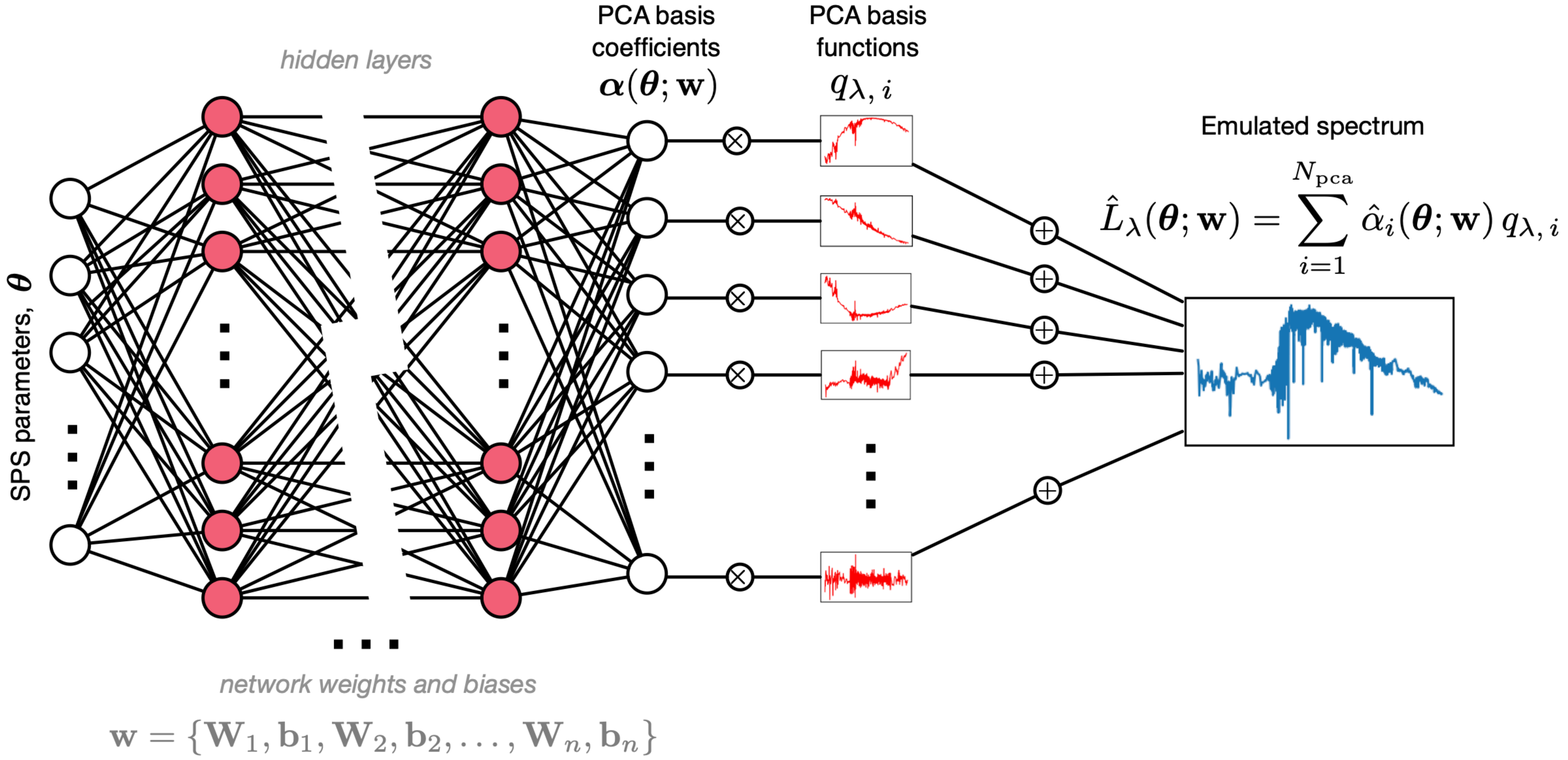
Model galaxy spectra using stellar population synthesis



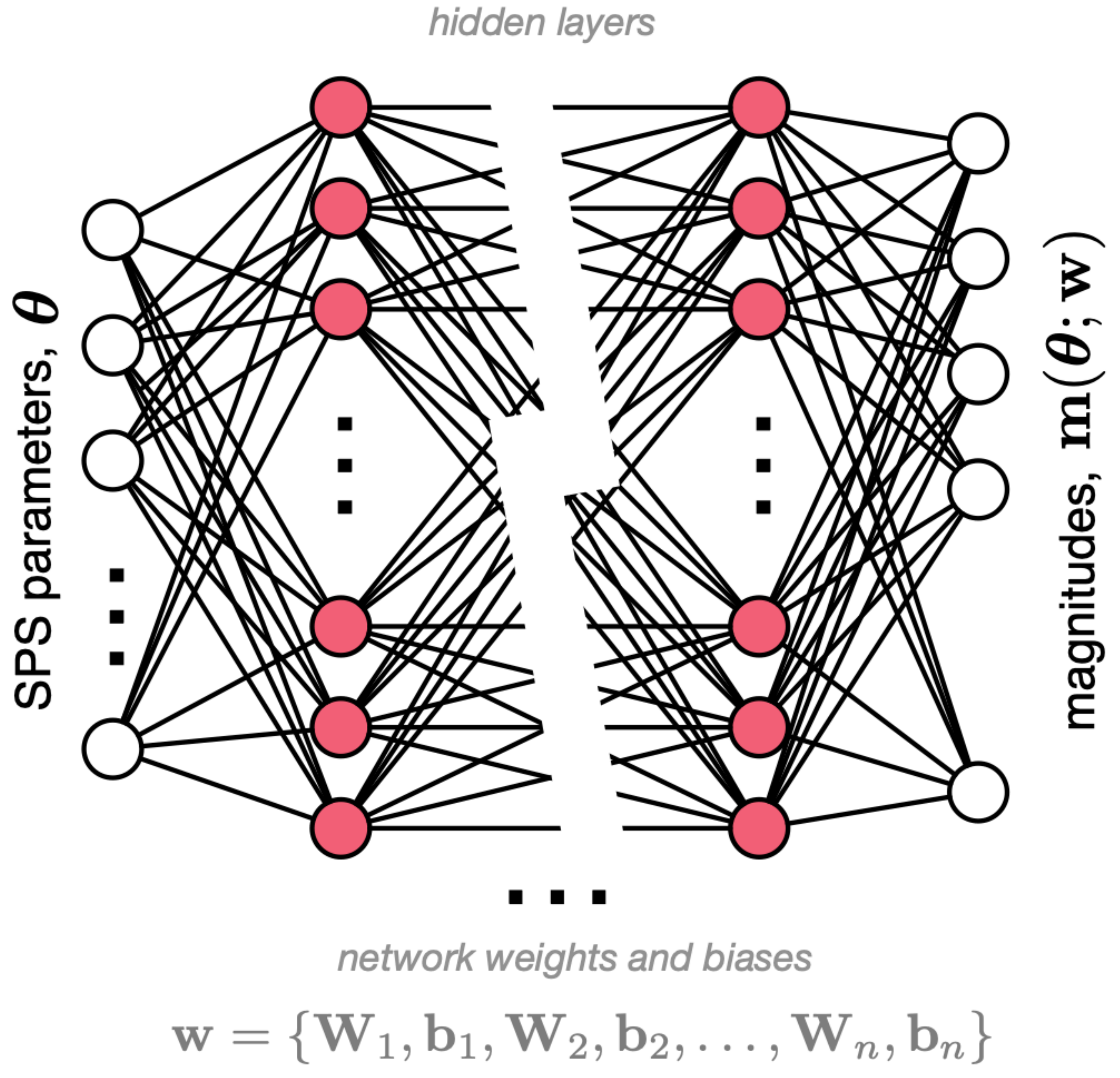
add up light from all the stars (at their ages and metallicities)

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

Speeding things up with neural emulators



Emulating spectra



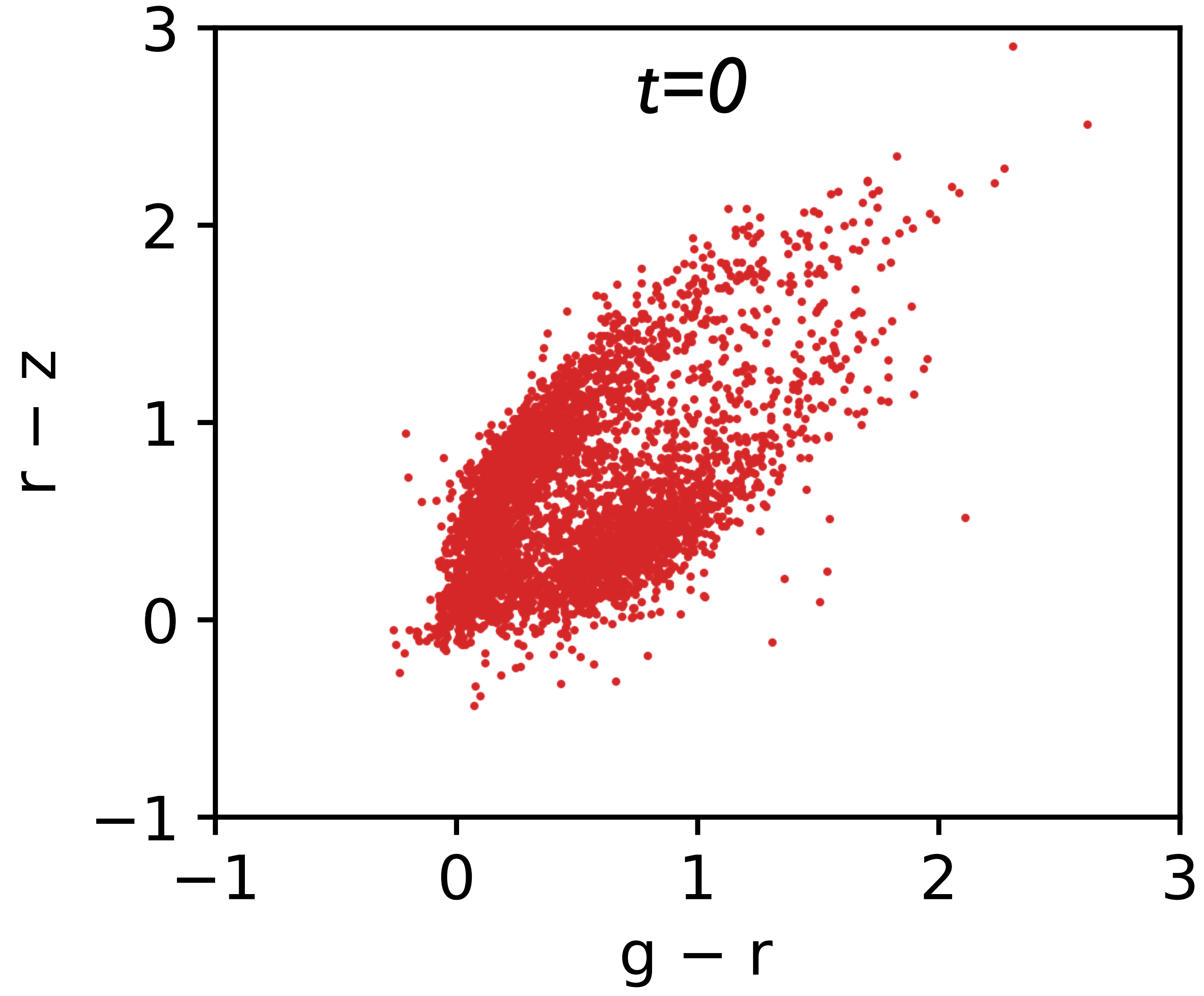
Emulating photometry

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)

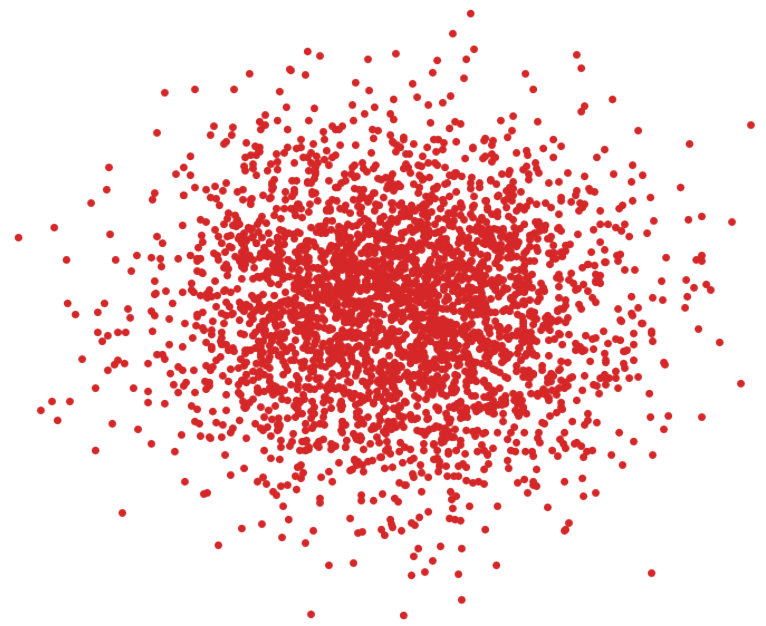
Flexible neural models for distribution of galaxy properties

learn transformation that degrades
target distribution to Gaussian noise



~Brownian motion

t=T



~reverse Brownian motion

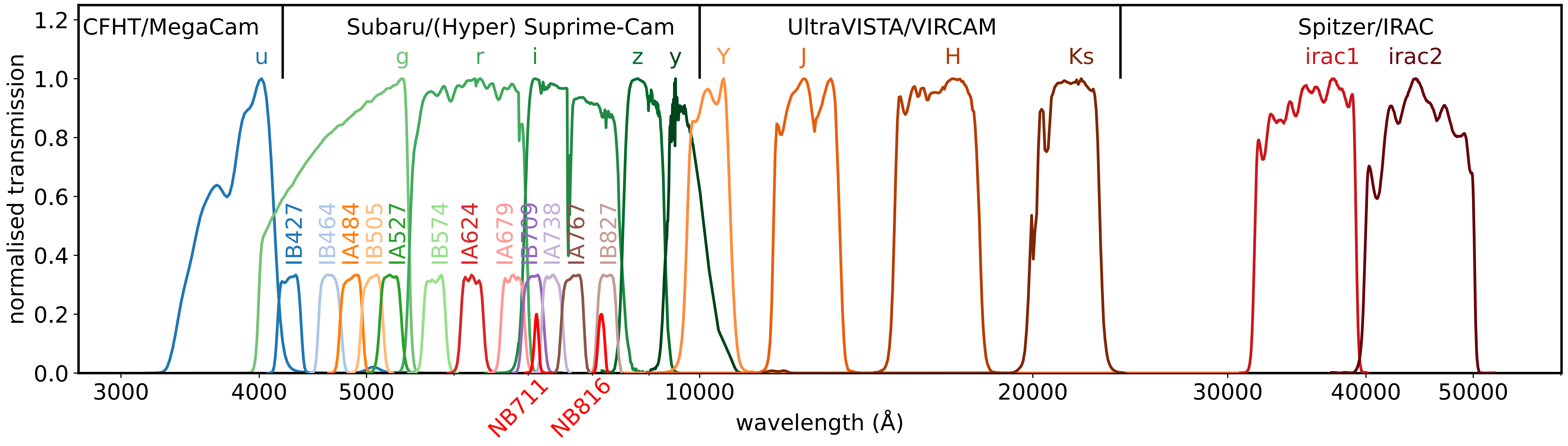
Gaussian distribution

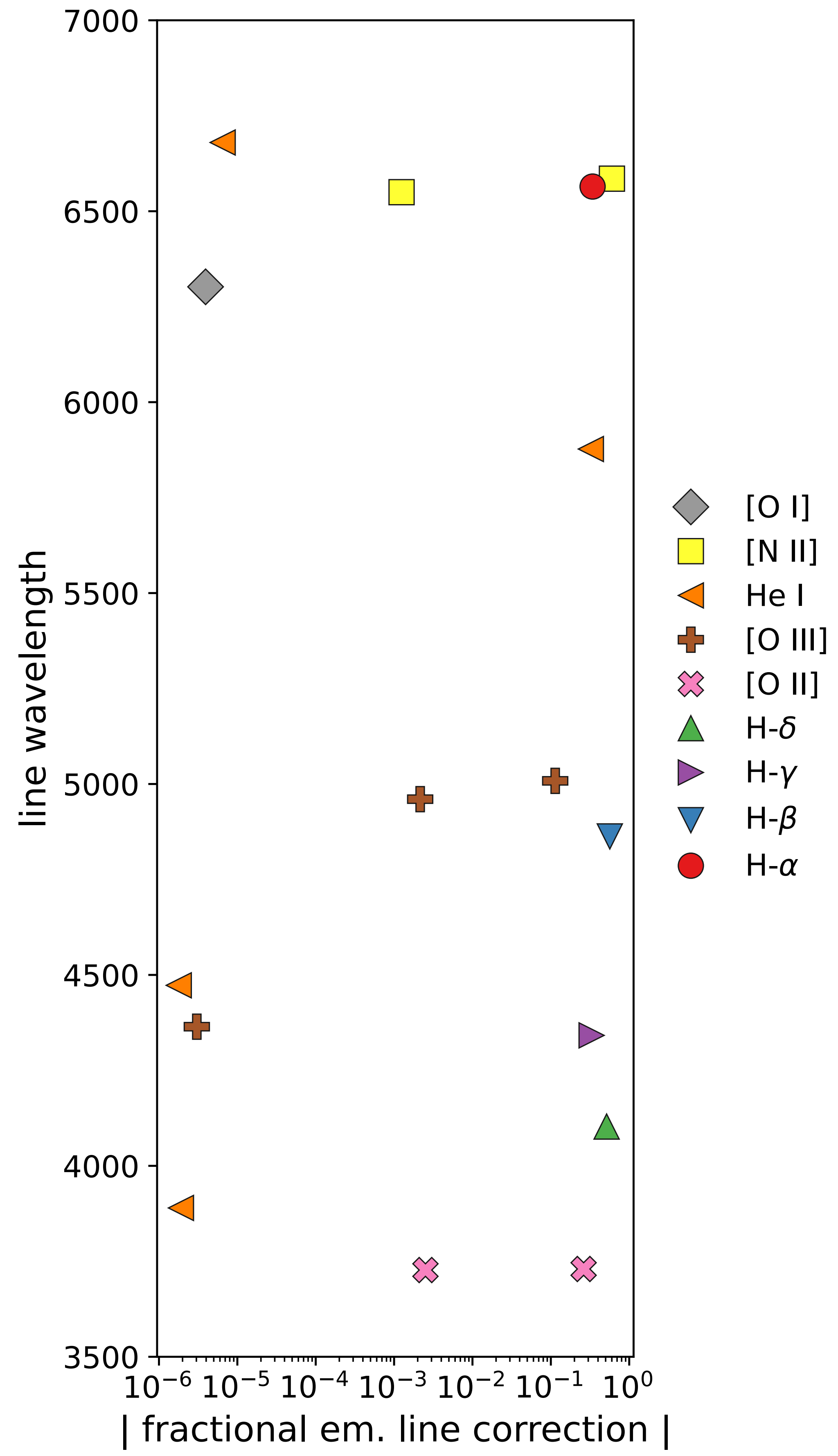
draw from random distribution:
invert learned transformation to
sample from target distribution

score-based diffusion model

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

Pop-Cosmos: galaxy population model calibrated with COSMOS2020



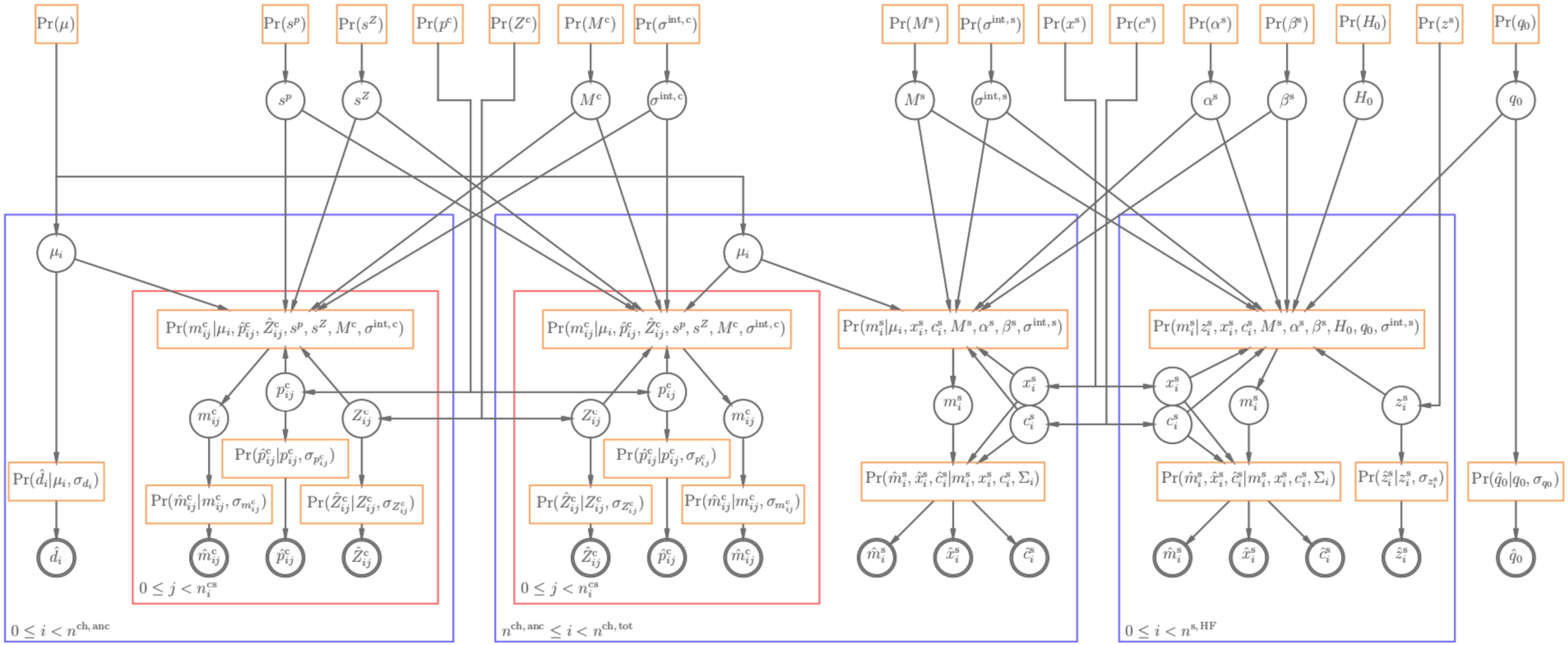


~140,000 galaxies | 26 bands near-UV to mid-IR | deep z < 4 | simple selection r<25

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 (2024, ApJS)

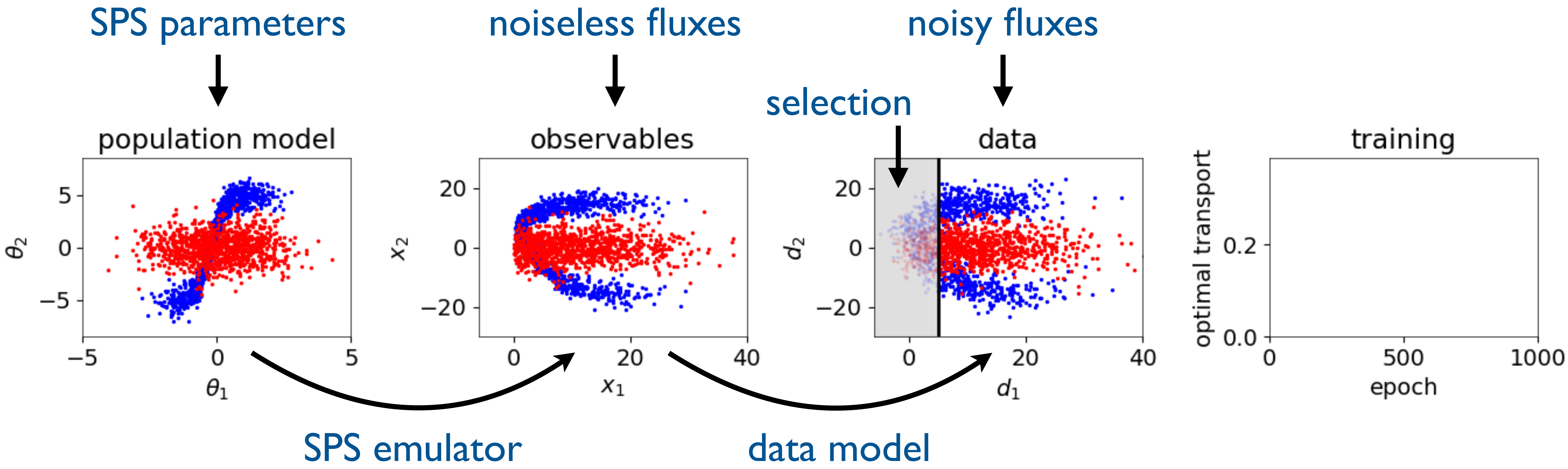
Solving explicit parametric BHM intractable even in principle



forward model of dataset = selection x data model x population model

intractable *no good parametric model*

Learning the galaxy population model

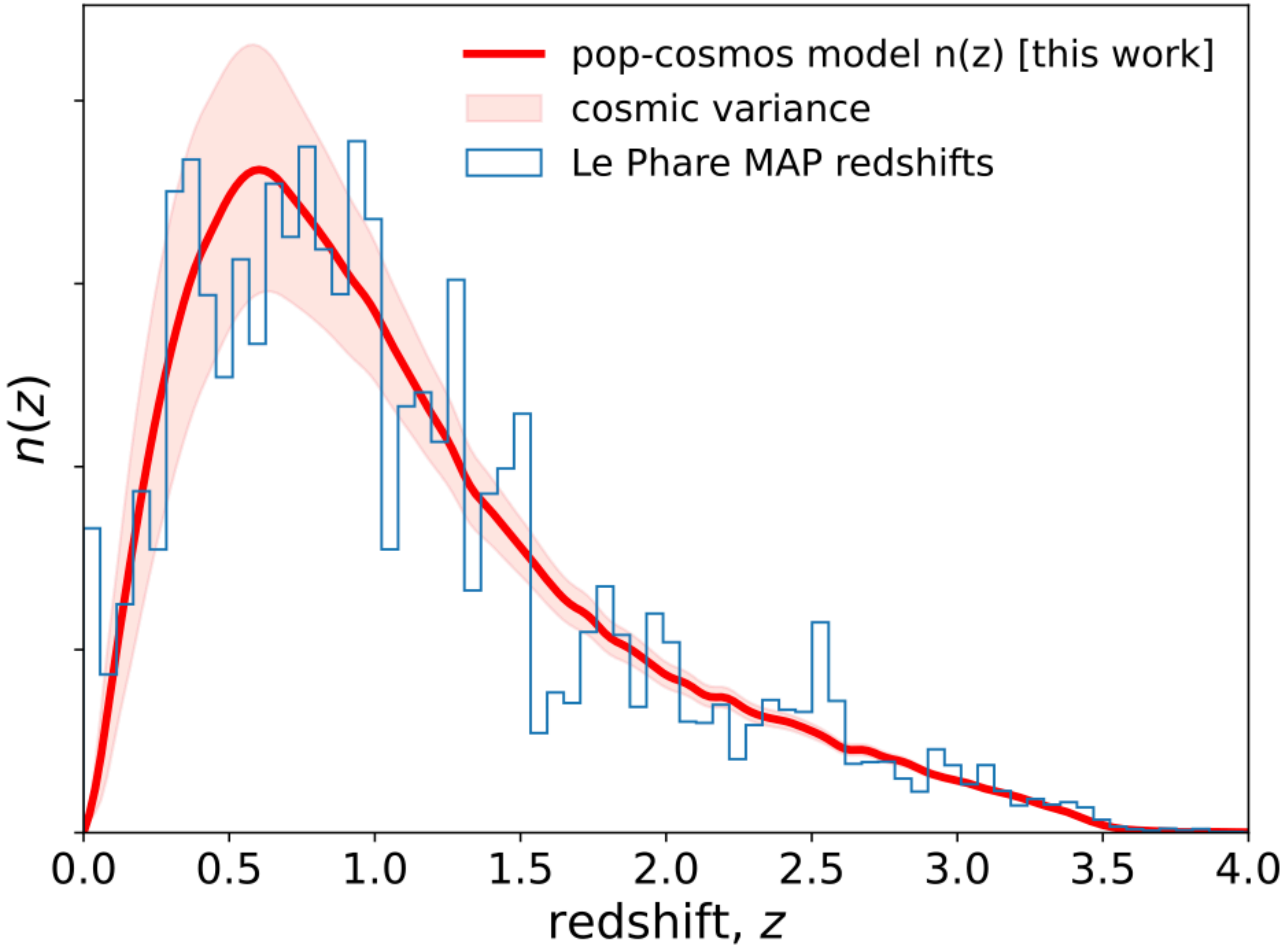


Equivalent to data-driven calibration of population prior in hierarchical Bayes

Toy model simulation by Justin Alsing

Pop-Cosmos: a generative model for galaxy surveys

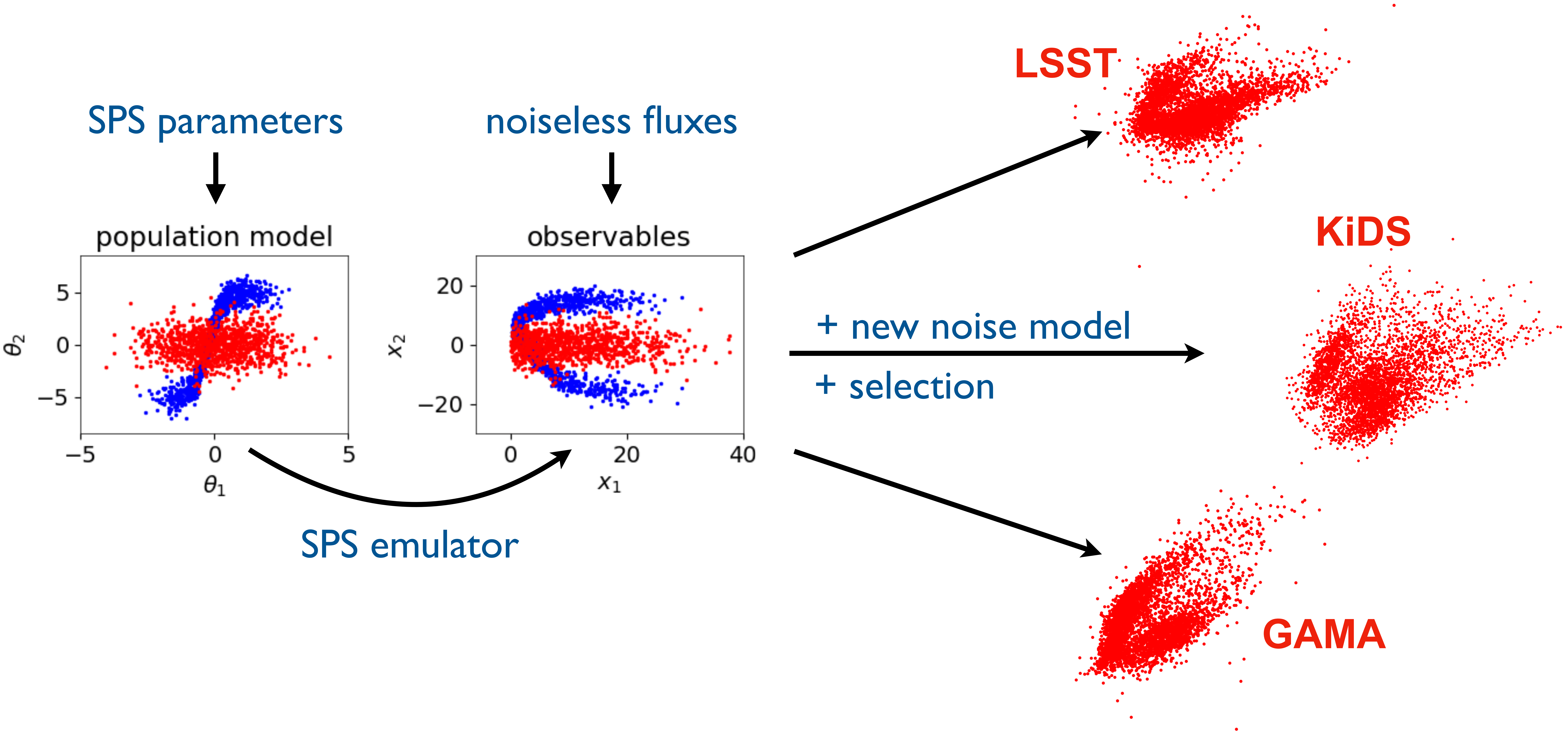
Pop-Cosmos prediction for COSMOS2020 redshift distribution



- *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*

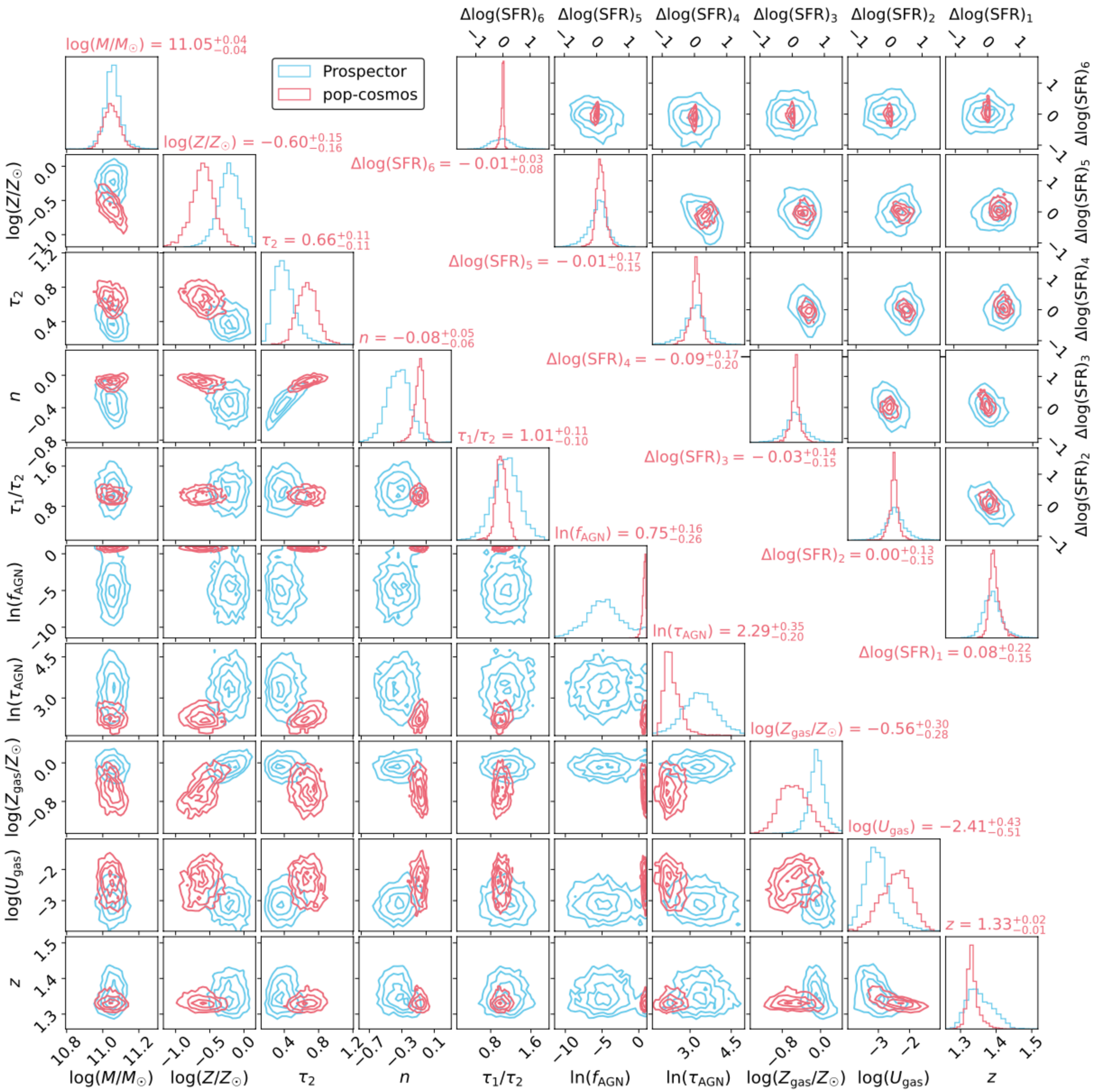
ALSING ET AL (2022, APJS), LEISTEDT ET AL. (2022, APJS), ALSING ET AL (2024, APJS), THORP ET AL (2024, APJ)

Forward-modelling other catalogues



ADAPTED FROM STEPHEN THORP

Full Bayesian SED fitting of large photometric catalogues



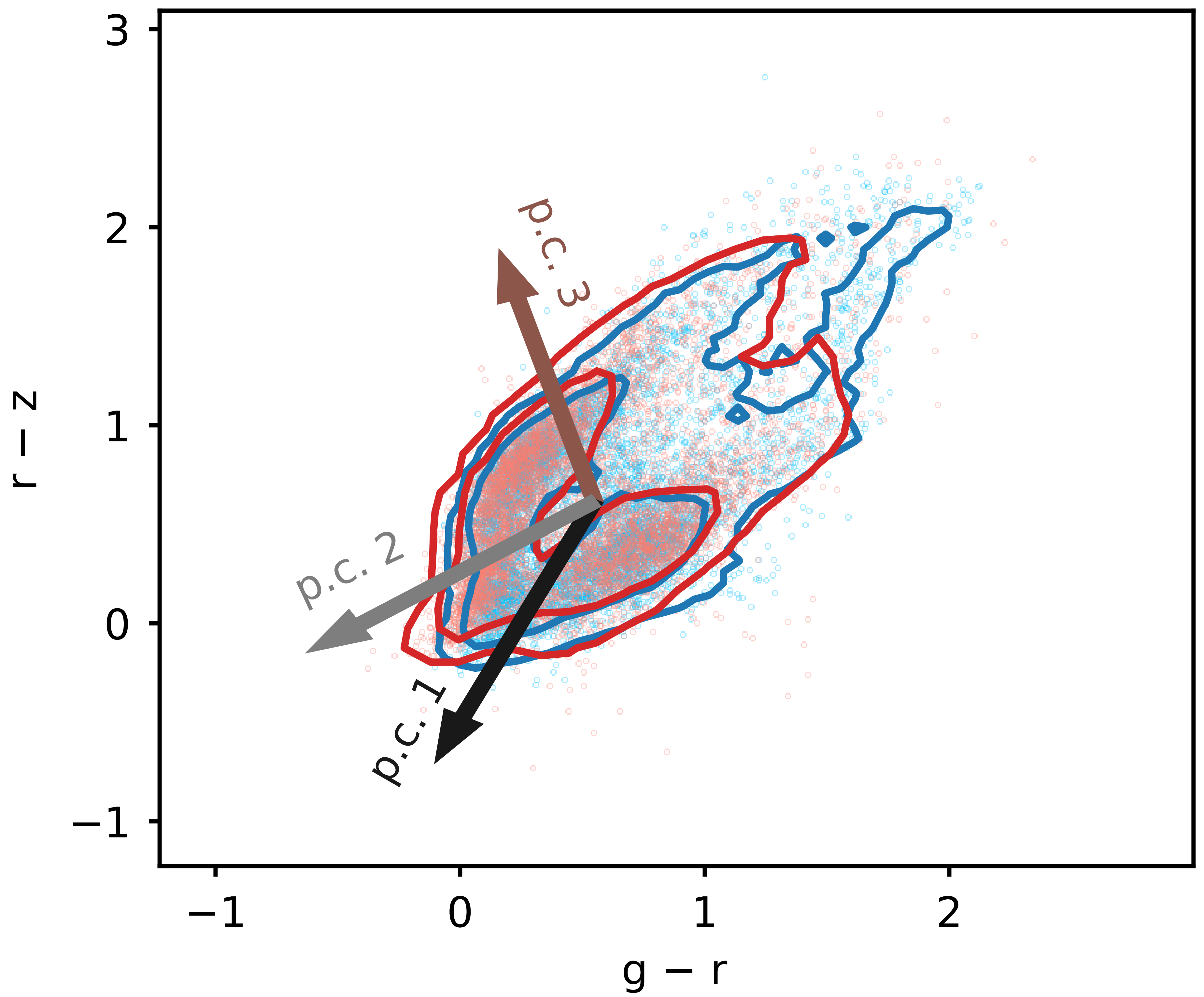
15 GPU-sec / galaxy under pop-cosmos prior | 0.6 GPU-sec / galaxy under Prospector prior.

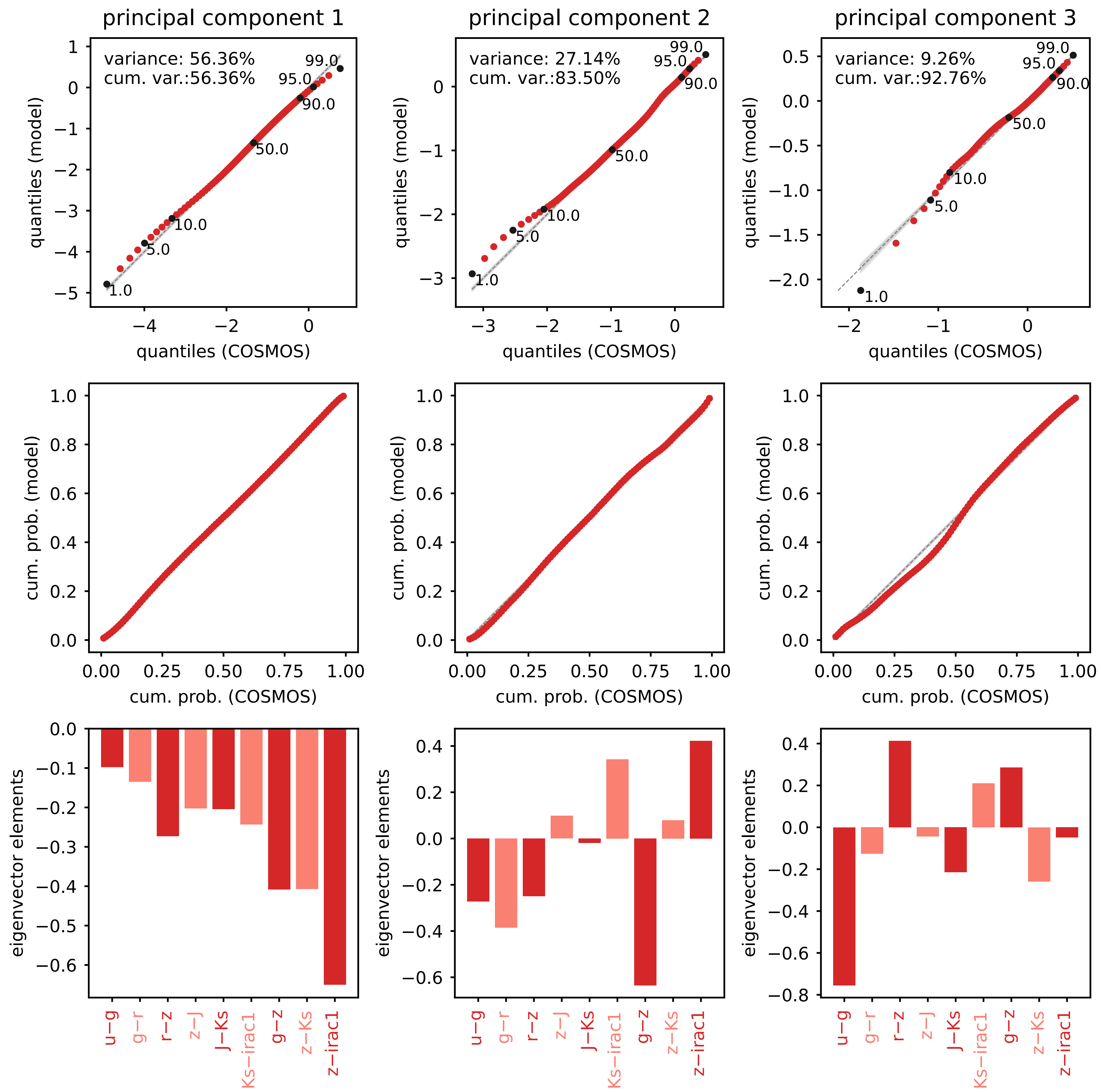
https://zenodo.org/records/13627489

- *Demonstration analysis of ~300,000 COSMOS2020 galaxies — 3 x larger than previously possible under full SPS prior, with modest GPU requirements.*
- *Comparison: FSPS under Prospector 25 CPU-hrs / galaxy*

THORP ET AL (2024, ApJ)

Data-space validation of high-dimensional generative model

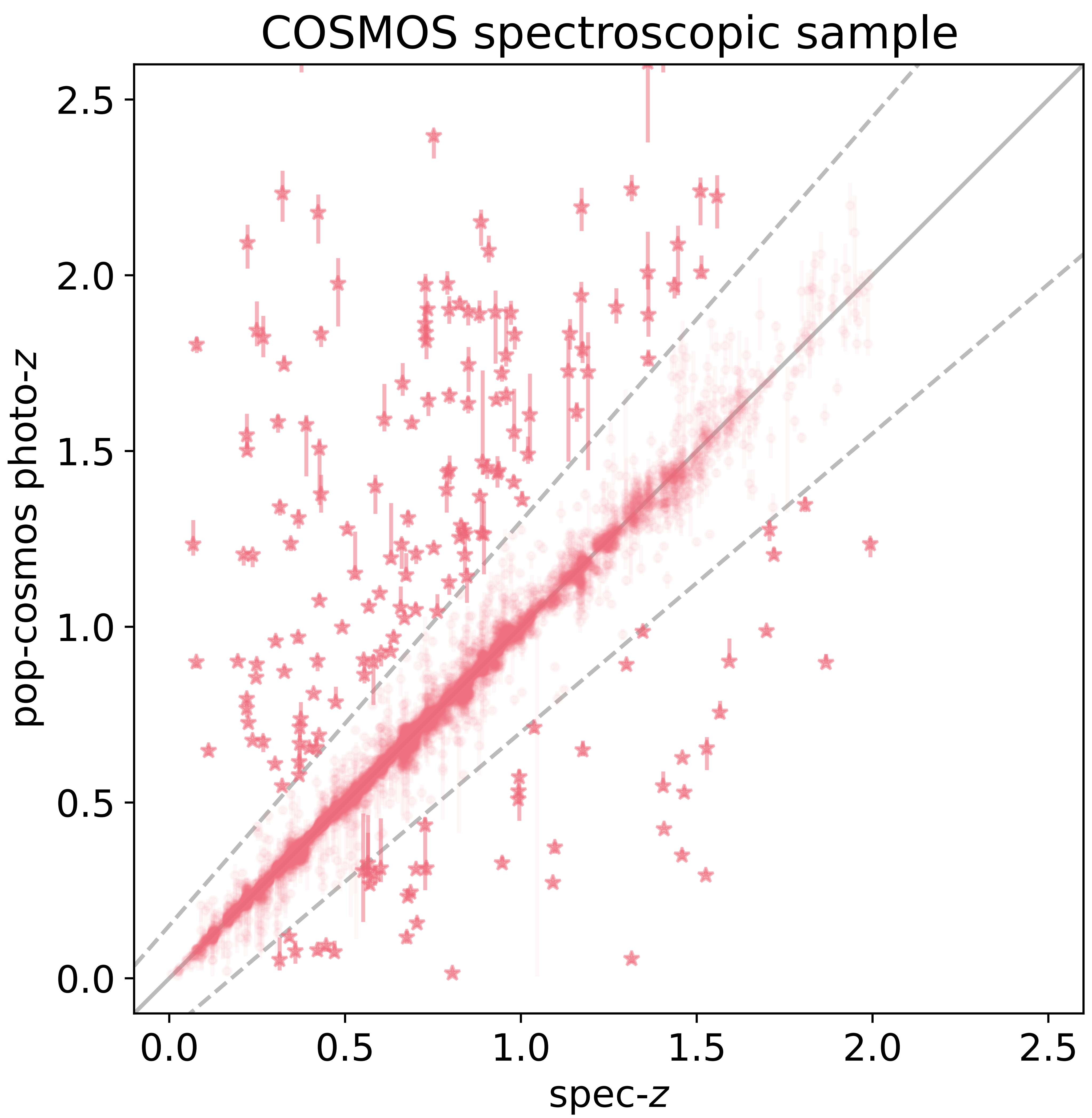




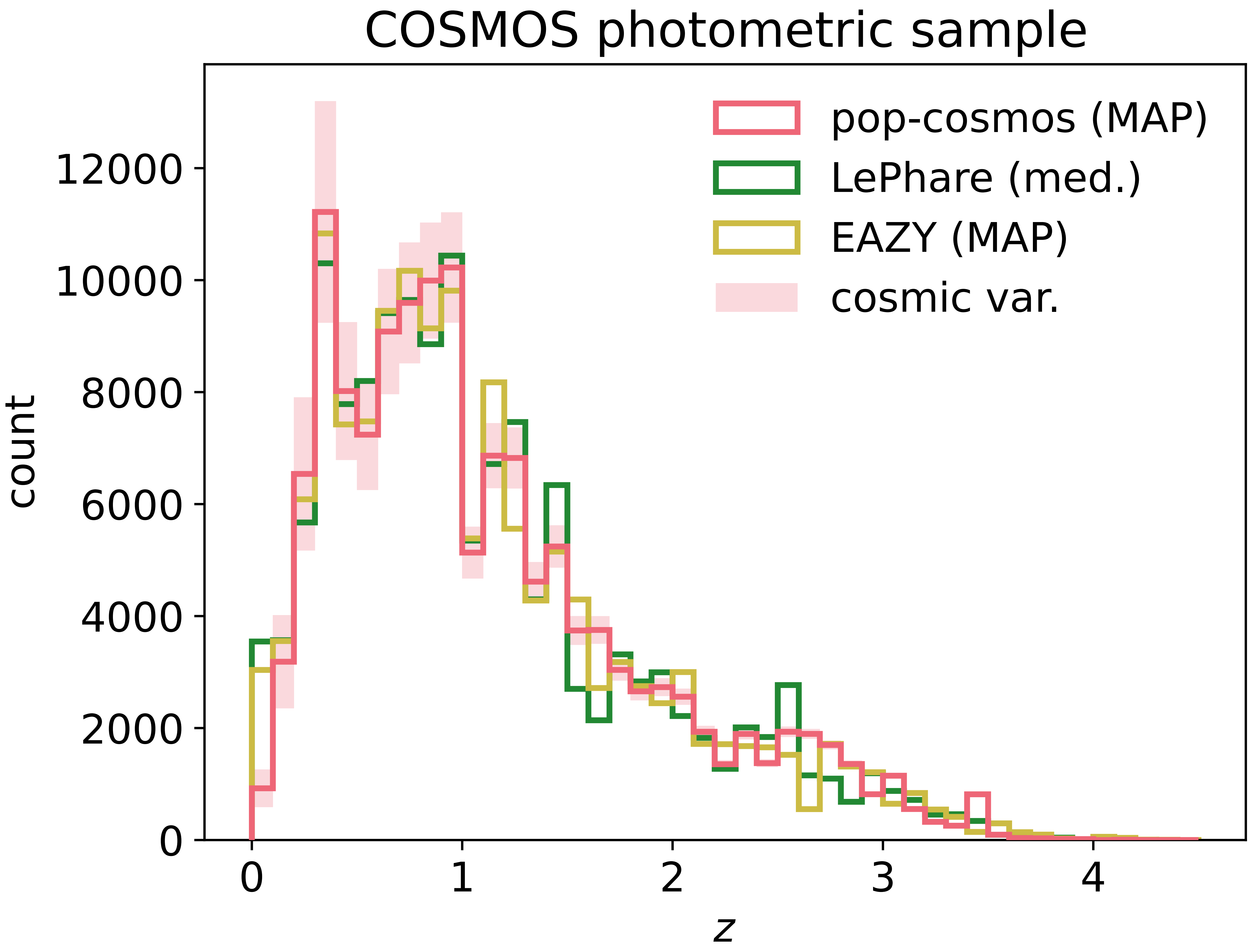
Validated using magnitude marginals, densities in colour pairs, and PP and QQ plots in PCA projections

THORP ET AL (2024, ApJS SUBMITTED)

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



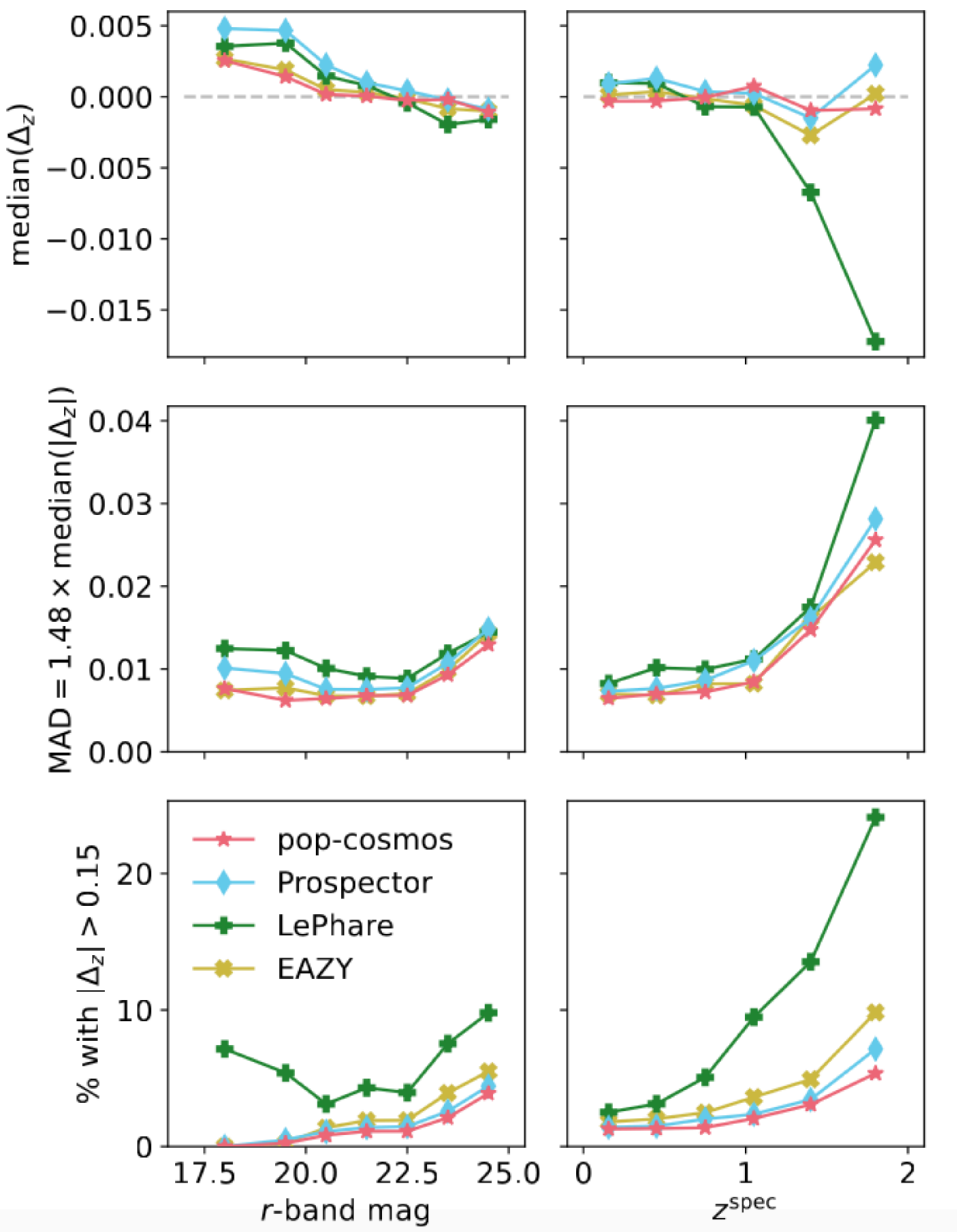
Validate where "ground truth" known



Validate against state-of-the-art

THORP ET AL (2024, APJ)

Quality of individual redshifts



less biased

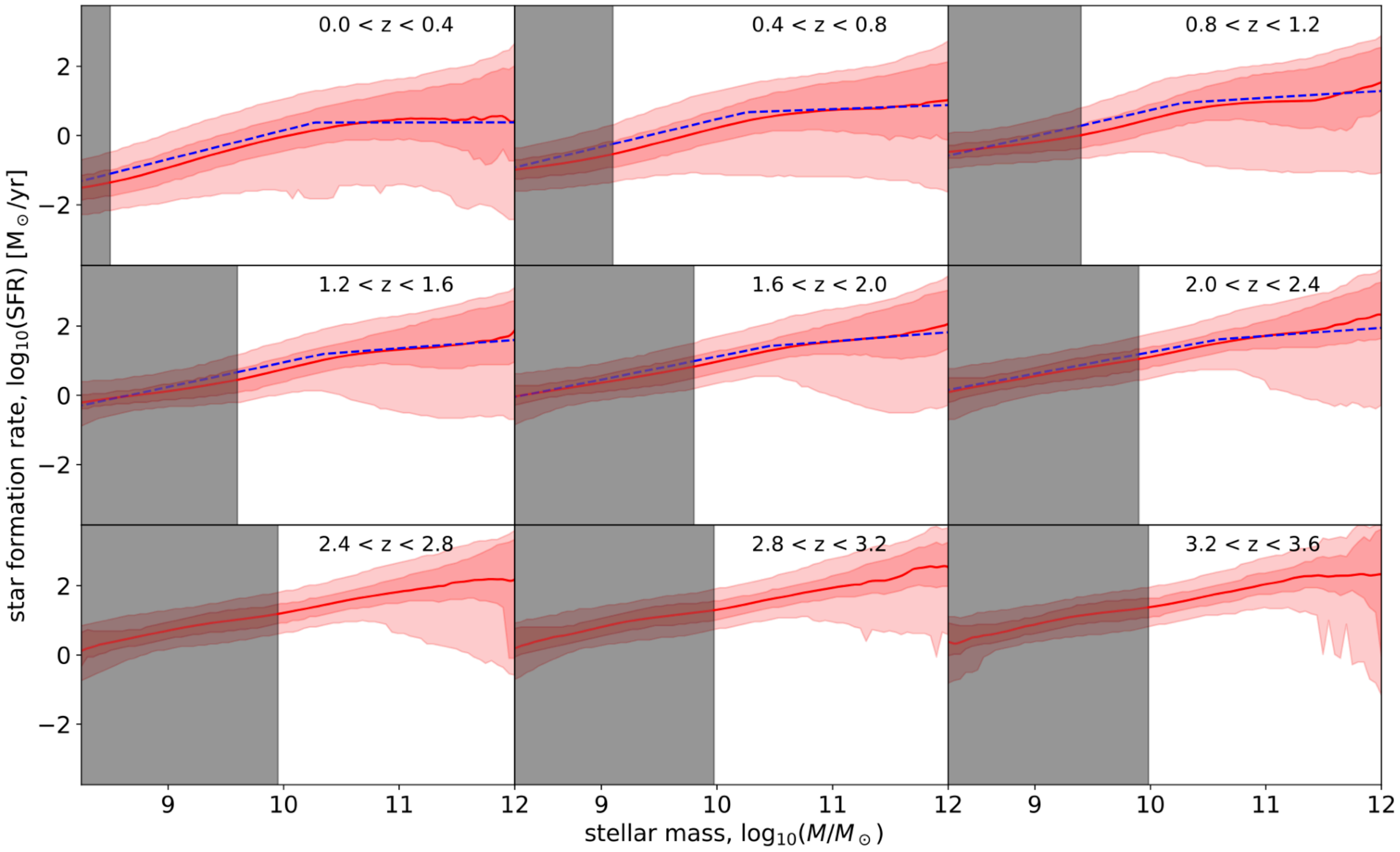
smaller errors

fewer outliers

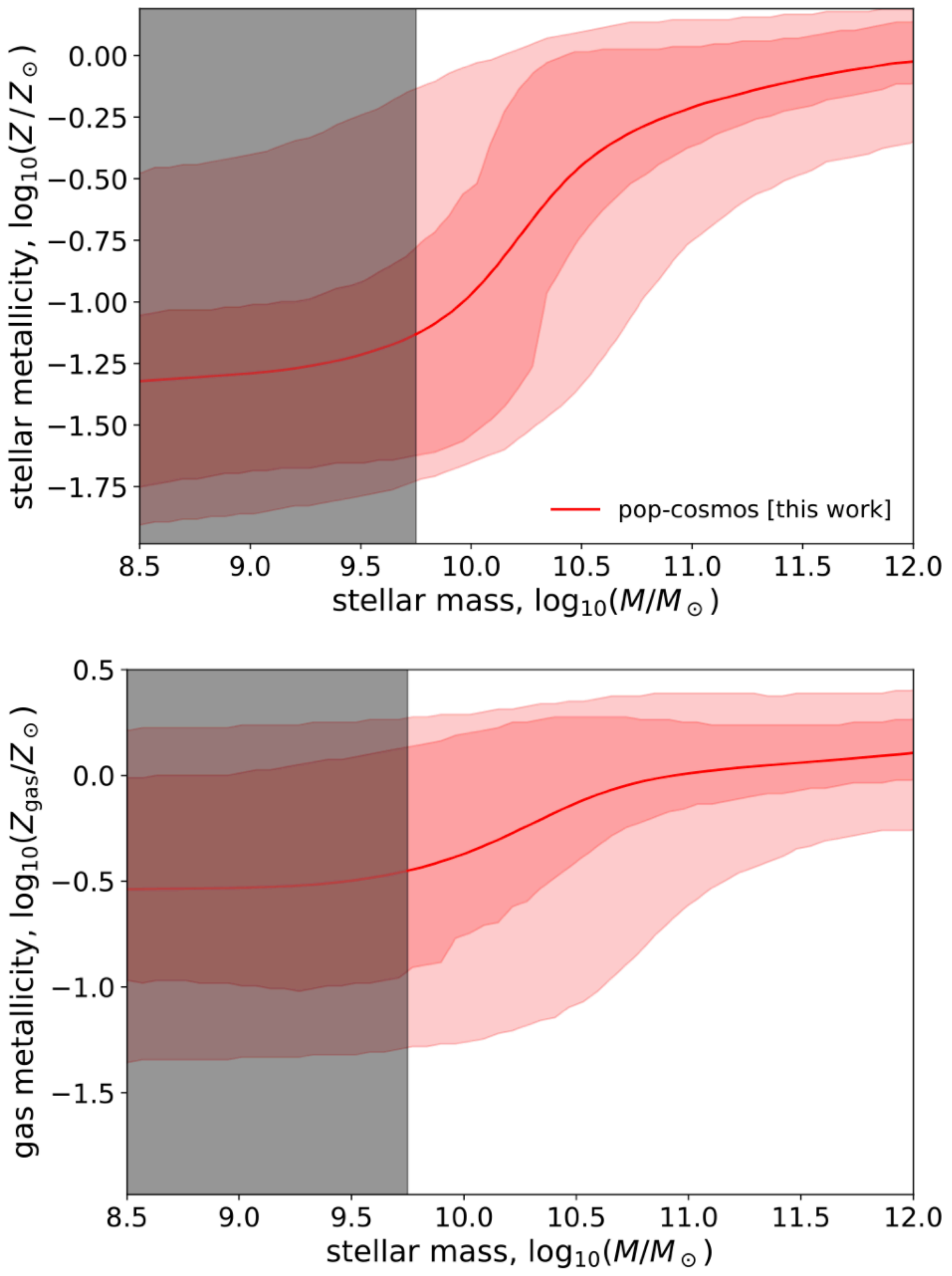
Validate with standard domain-specific metrics

THORP ET AL (2024, APJ)

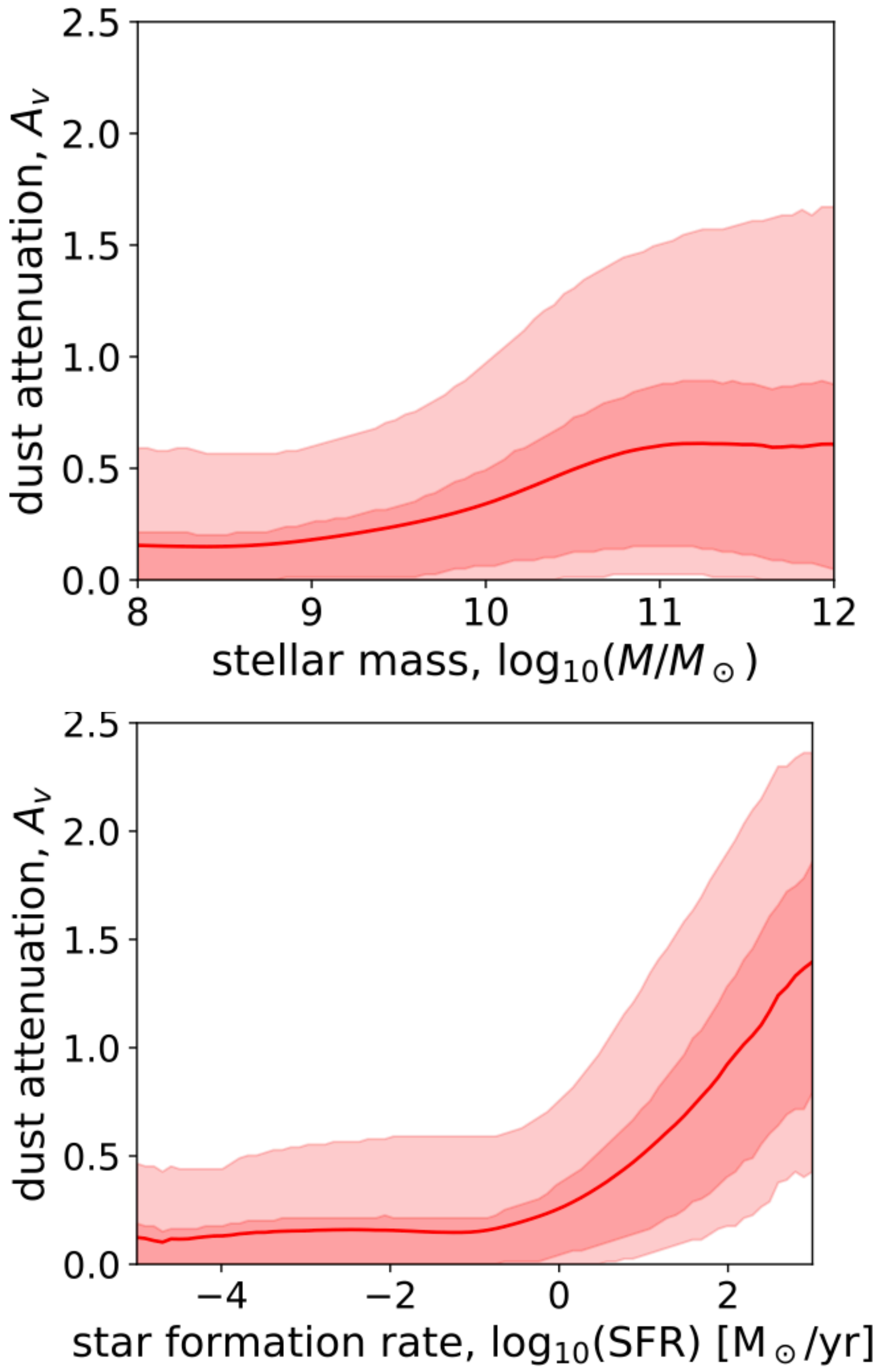
Bonus: information on full galaxy population over cosmic time



star forming sequence



metallicity

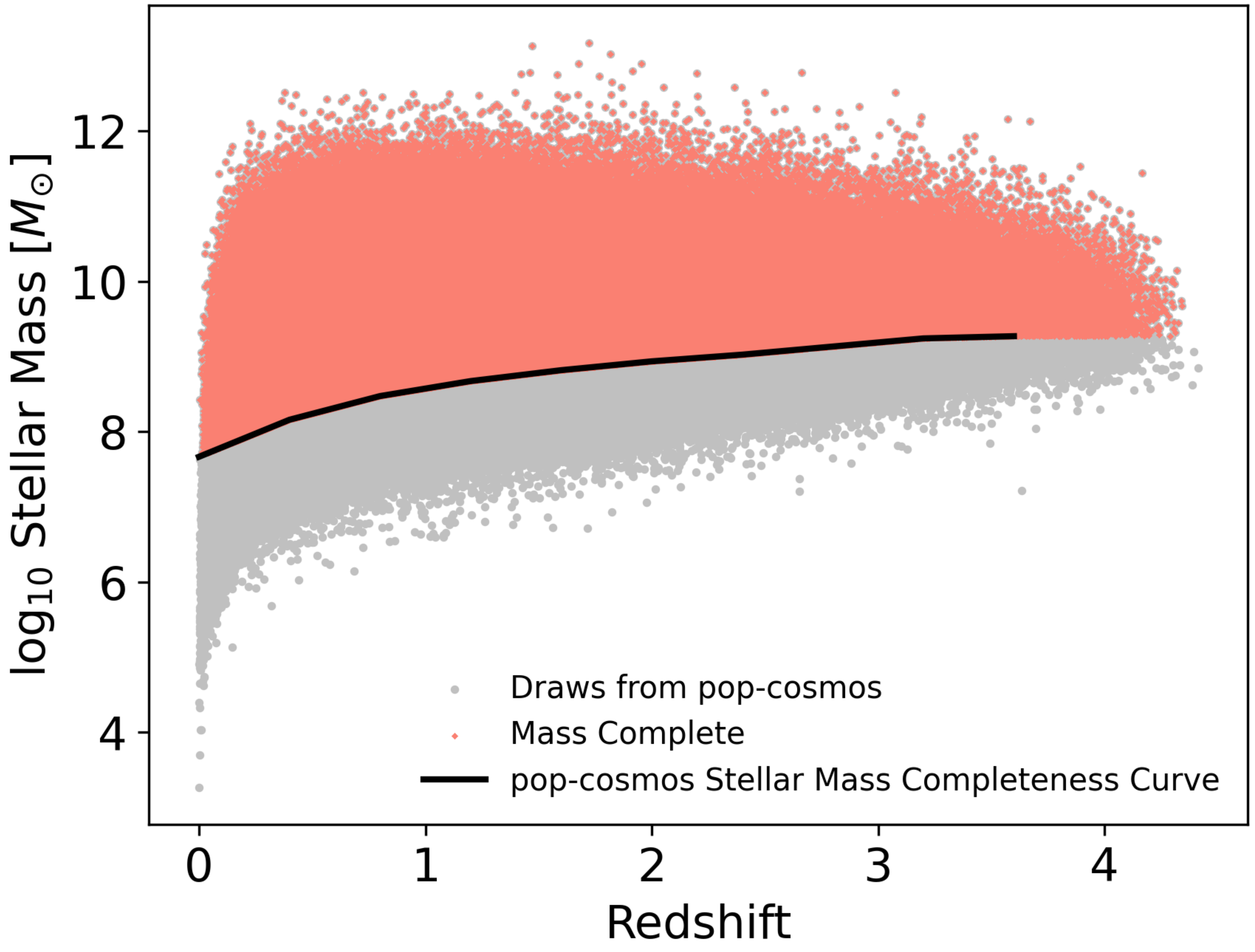


dust

Validate against domain knowledge for key population properties in lower-dimensional projections

ALSING ET AL (APJS, 2024)

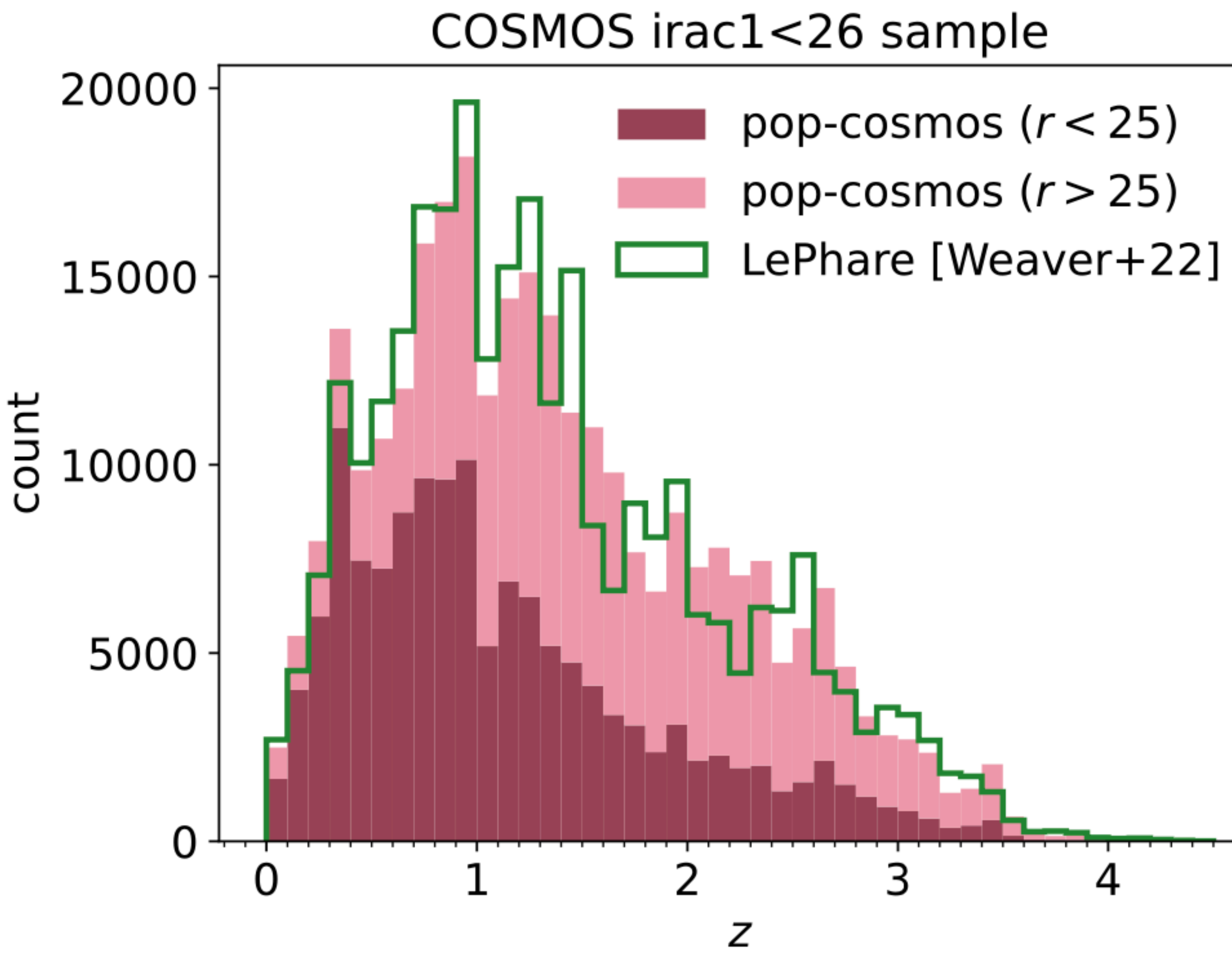
Mass-completeness of pop-cosmos



Establish explicit domain of validity for pop-cosmos so we know when we are extrapolating

DEGER ET AL (IN PREP)

Extrapolation to redshifts of IRAC1<26 galaxies



Test generalisation of model to deeper selection of COSMOS2020 galaxies

THORP ET AL (APJ, 2024)

Characteristics of pop-cosmos generative model

✓ *Follow from explicitly enumerable set of assumptions and physical principles*

✓ *Leads to mathematical models that can be solved (analytically/numerically) to yield useful* ***predictions*** *(deterministically/probabilistically).*

✓ ***Explainable*** *(rooted in cause-effect relationships grounded in domain knowledge.)*

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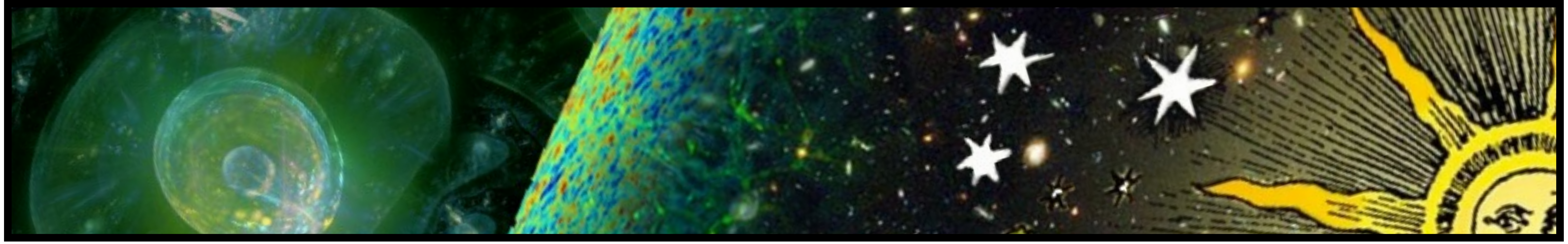

For more details

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