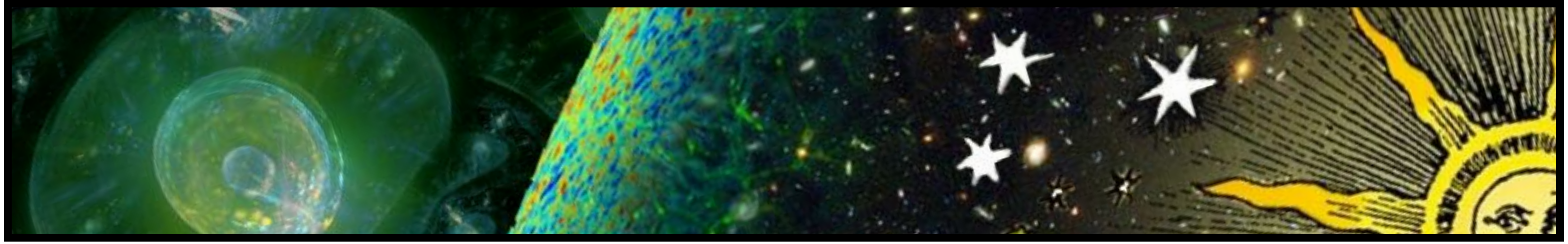
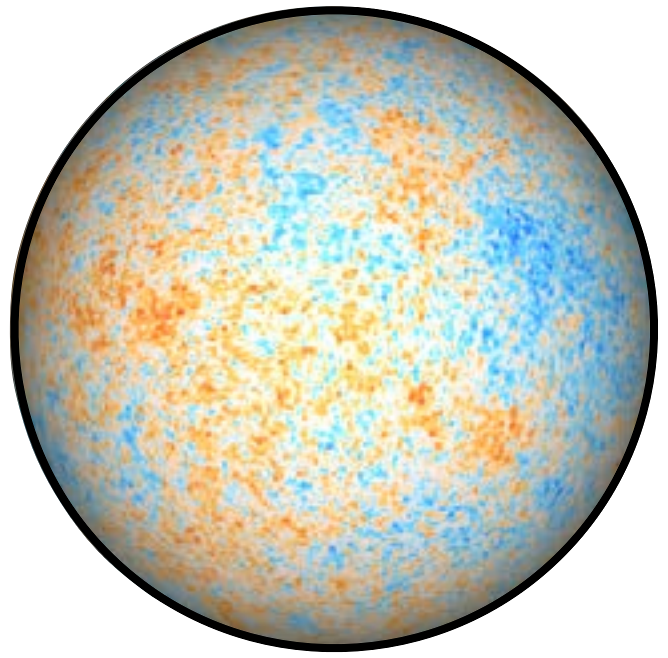


Survey Cosmology in the Rubin Era

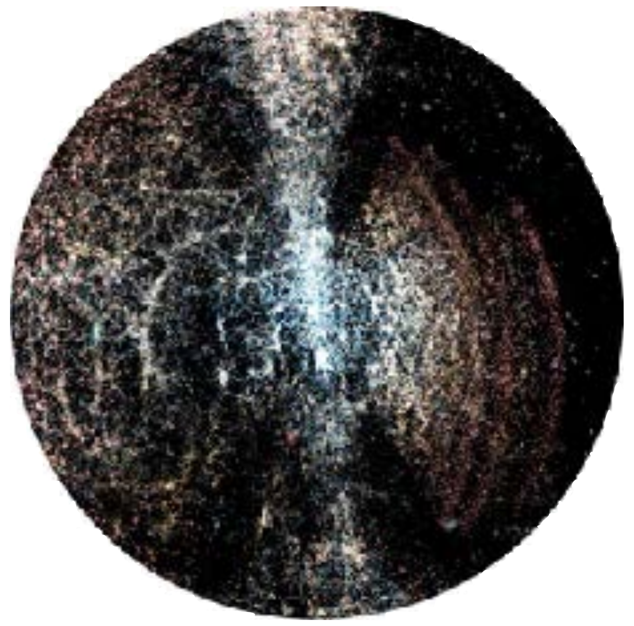
Hiranya V. Peiris

UCL and Oskar Klein Centre Stockholm

Electromagnetic cosmological probes in the next decade



Cosmic Microwave Background



Large Scale Structure

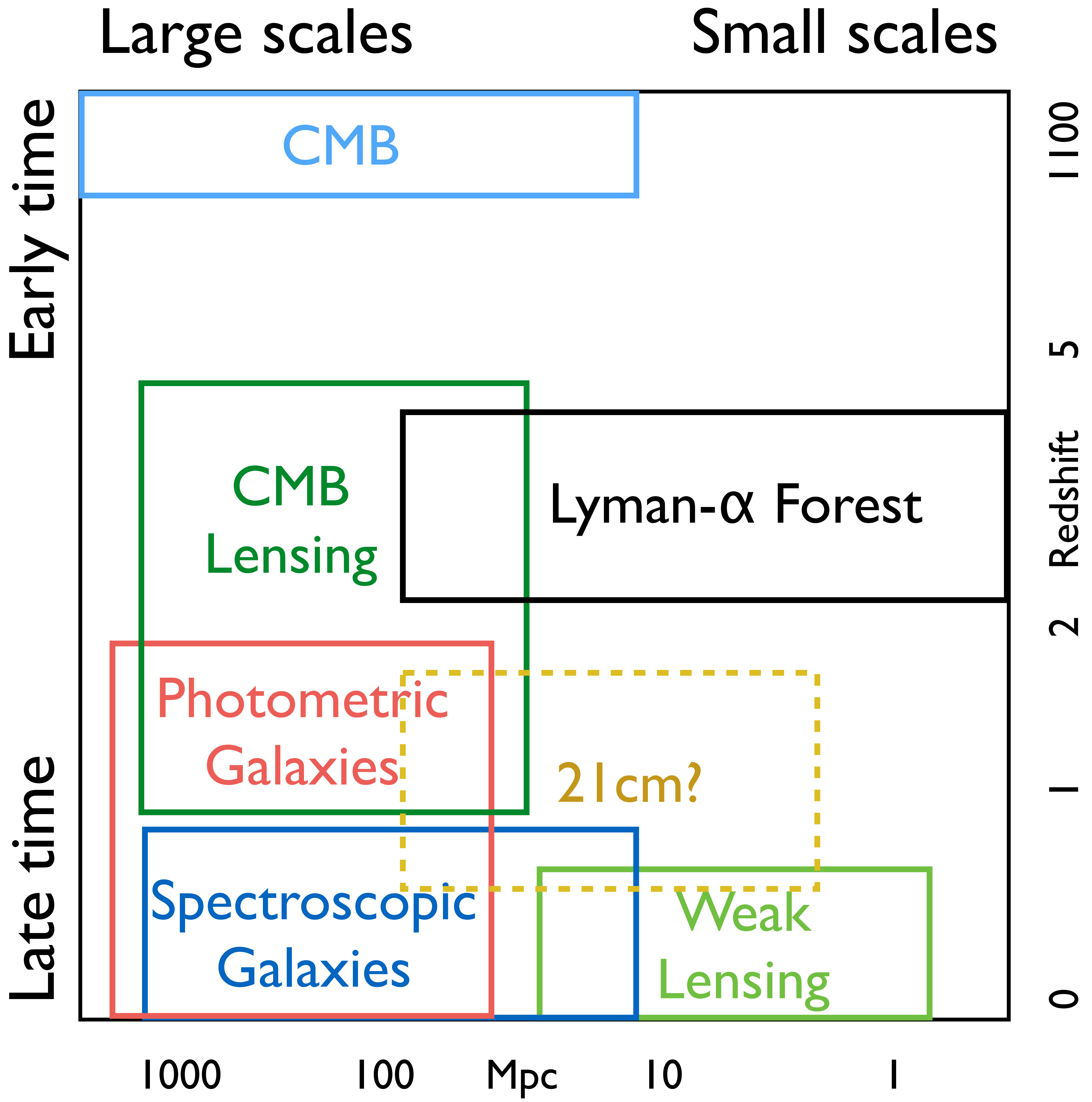
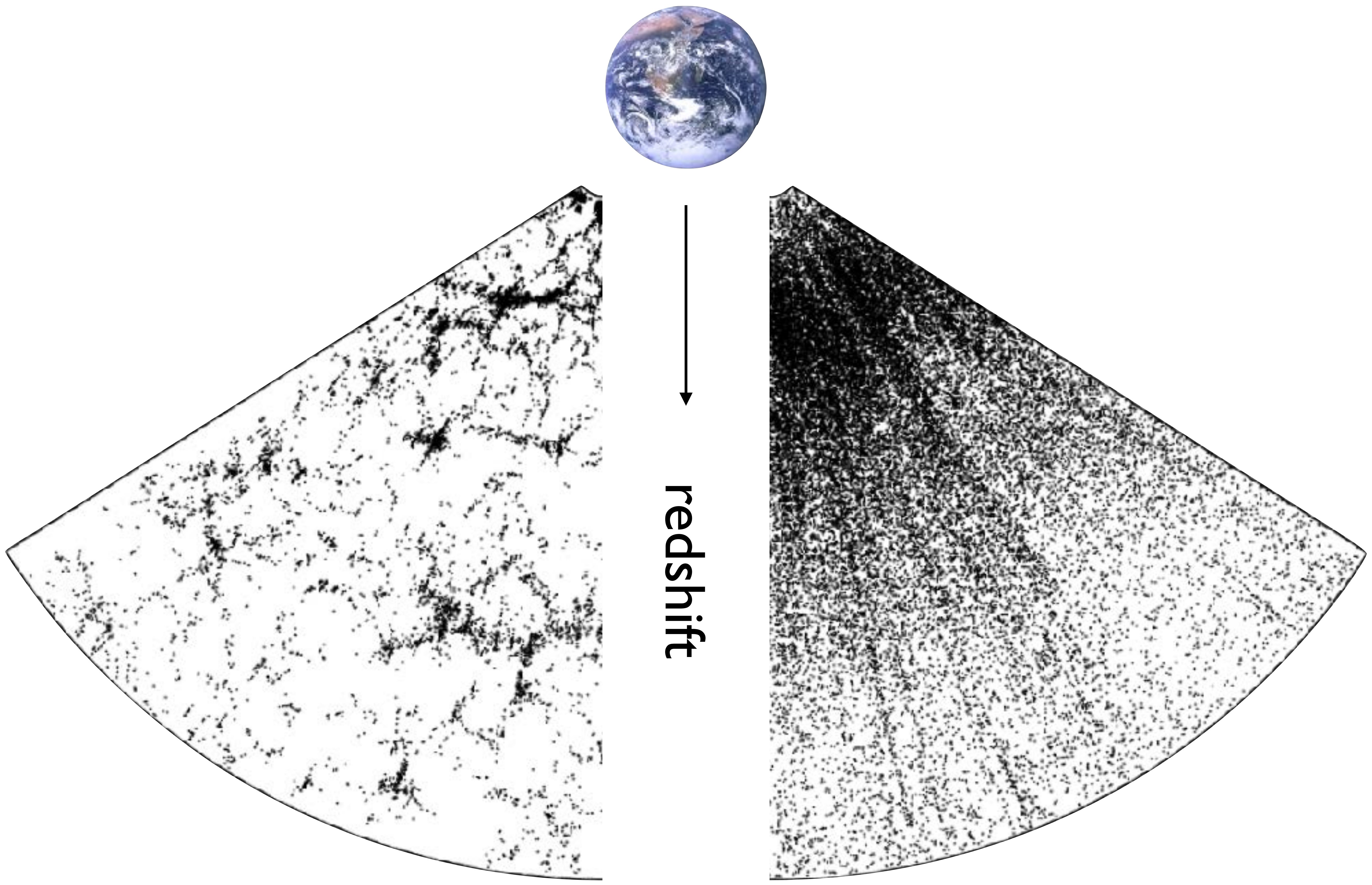


Figure: Andreu Font-Ribera

Observational frontier with galaxy surveys



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

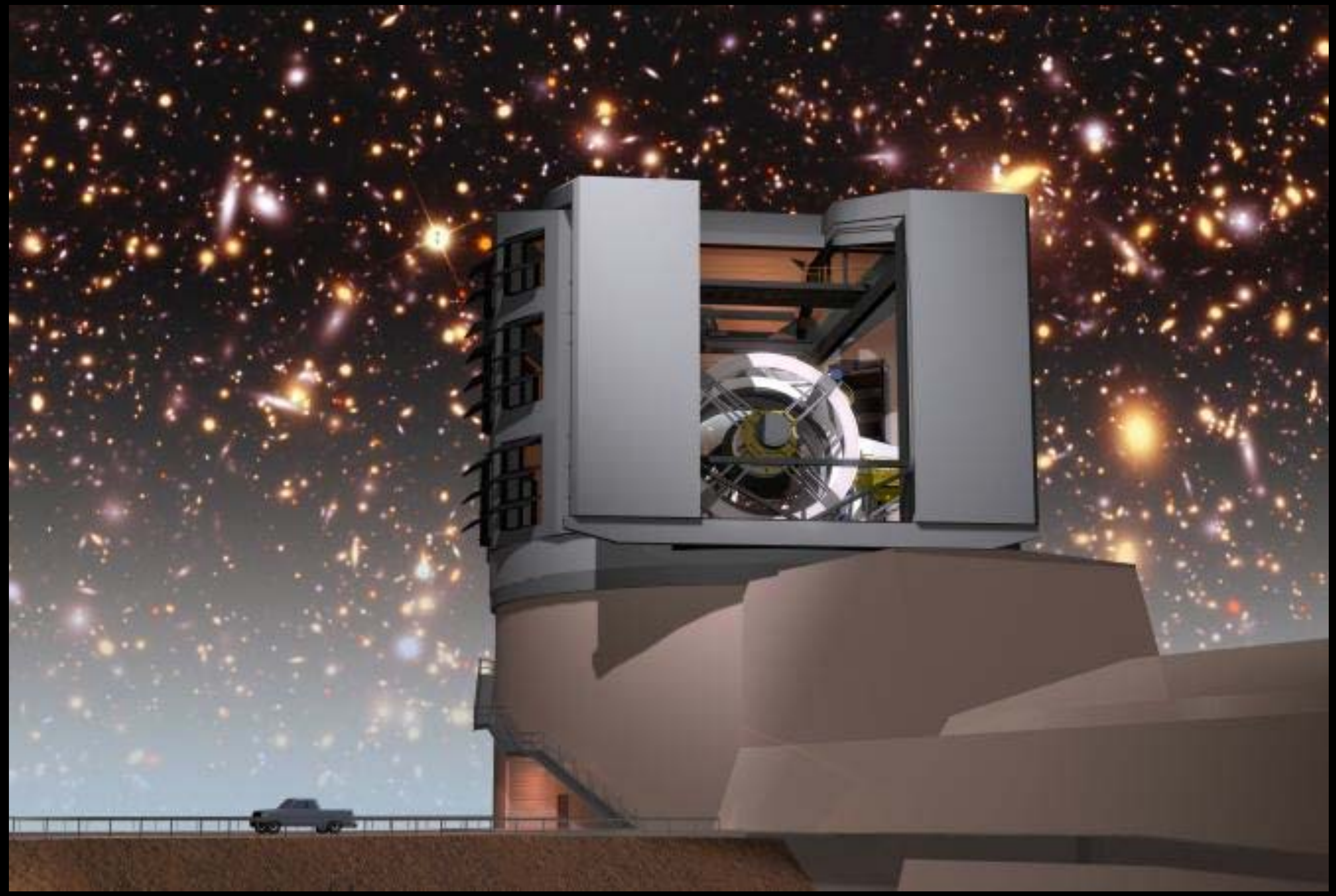
<u>Photometric</u>
LSST (ground), Euclid (space), Roman (space)

VERA C. RUBIN OBSERVATORY

LSST Legacy Survey of Space and Time

LSST: survey of 18,000 sq deg

(half the sky)



37 billion objects in space and time

30 trillion measurements

60 PB raw data (20 TB/night)

Dark matter-Dark energy

Solar system inventory

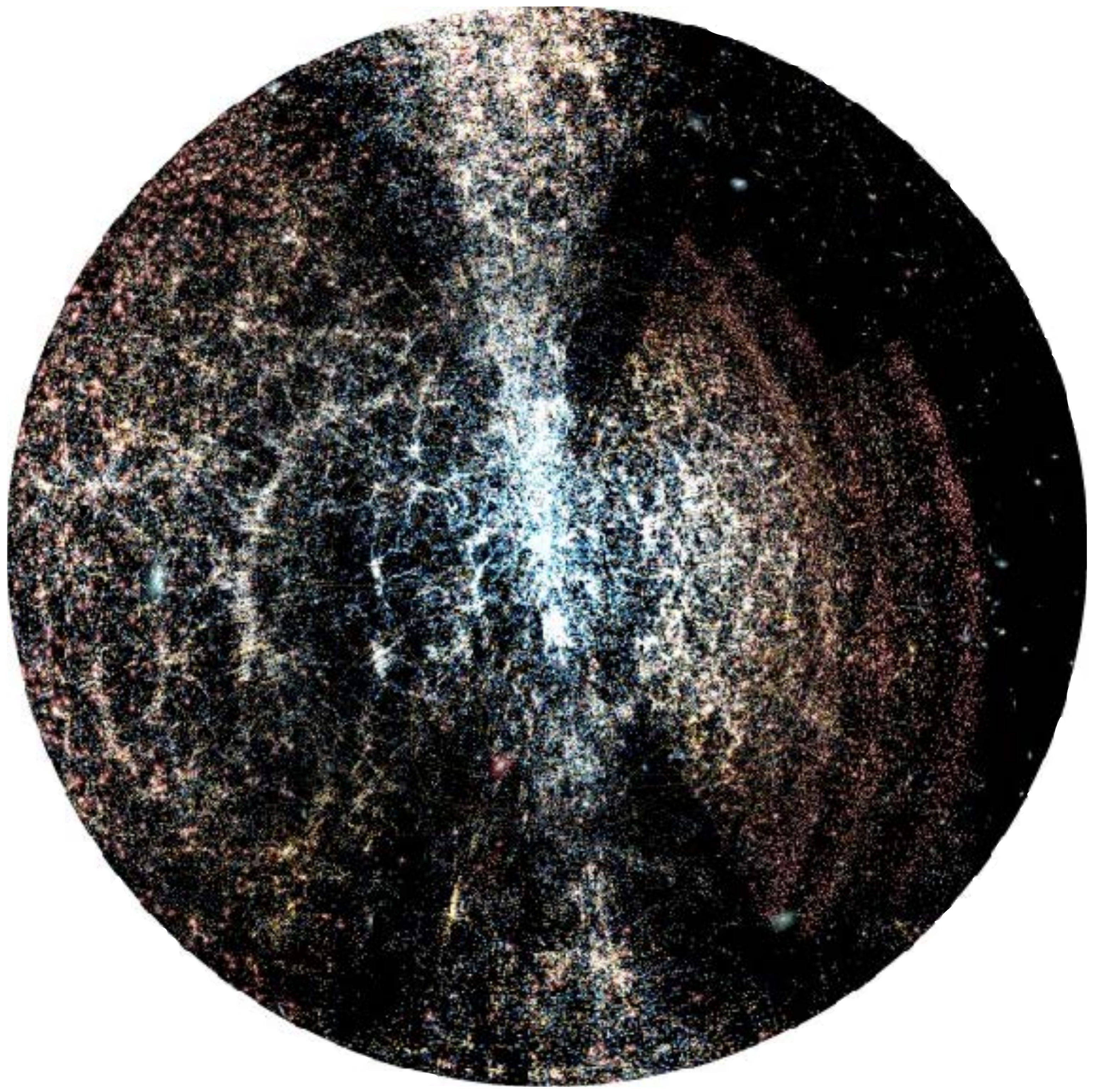
“Movie of the Universe”

Mapping the Milky Way

Slide adapted from Ian Shipsey

How should we compare

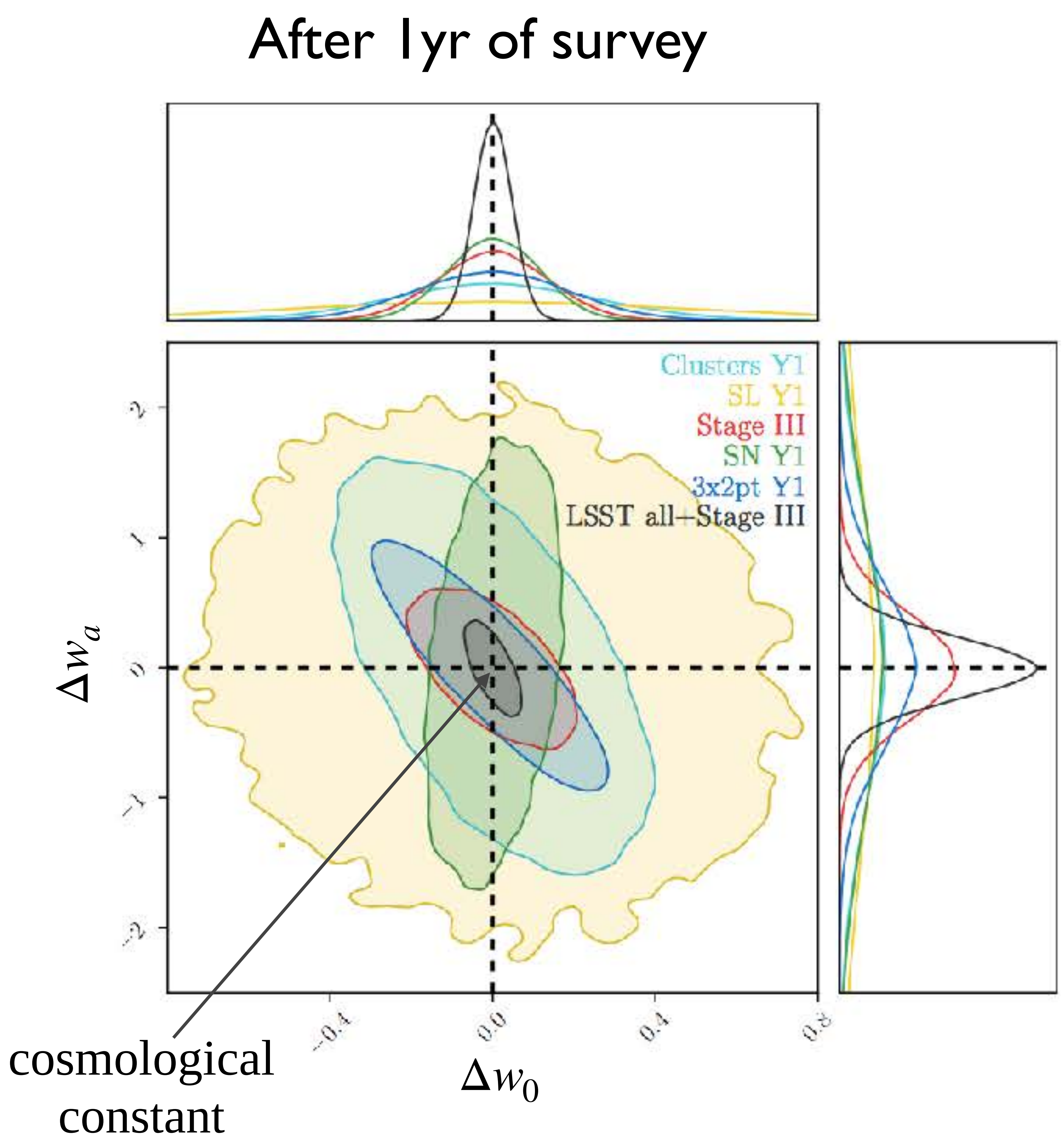
vs

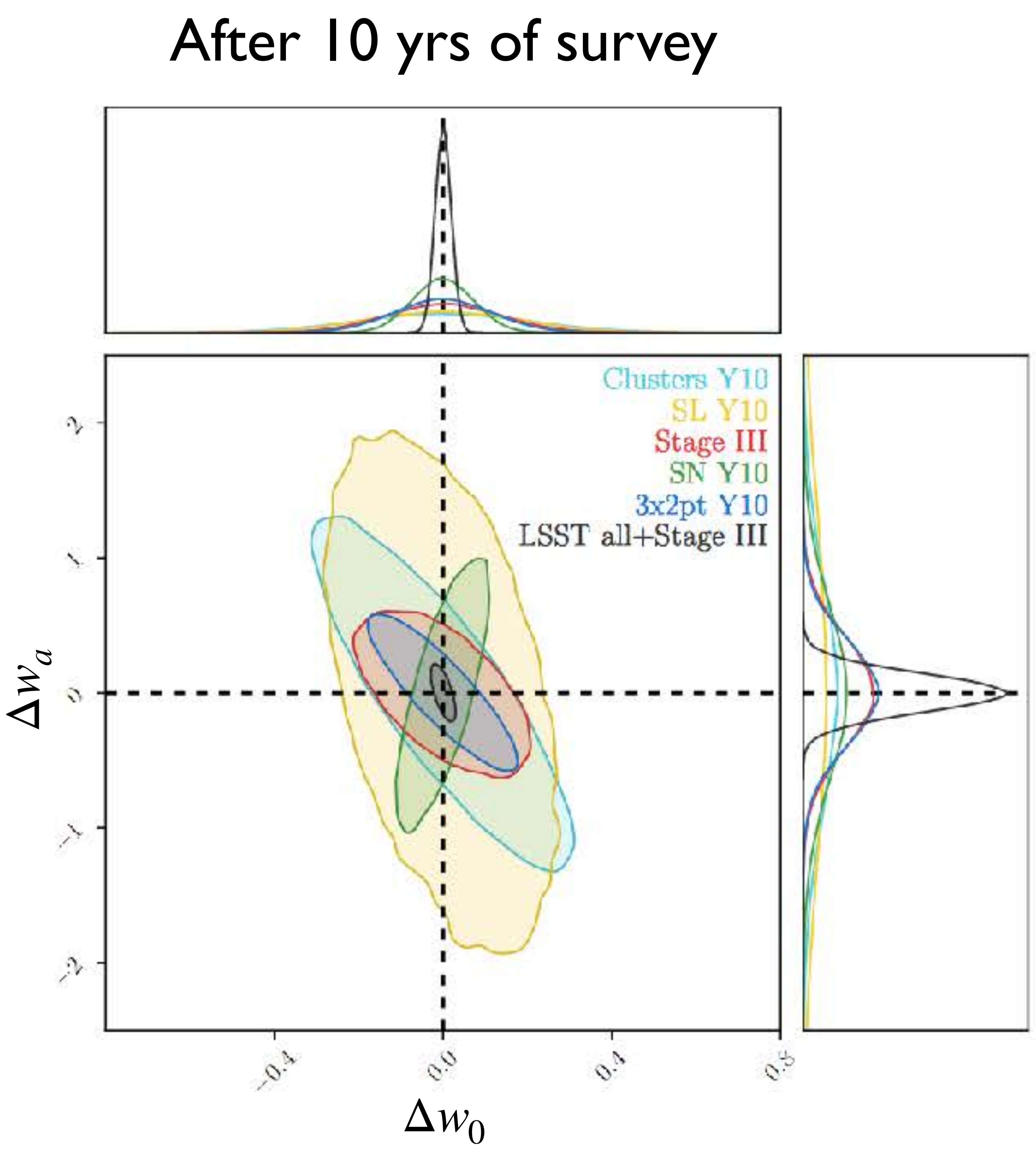


Theory

Data?

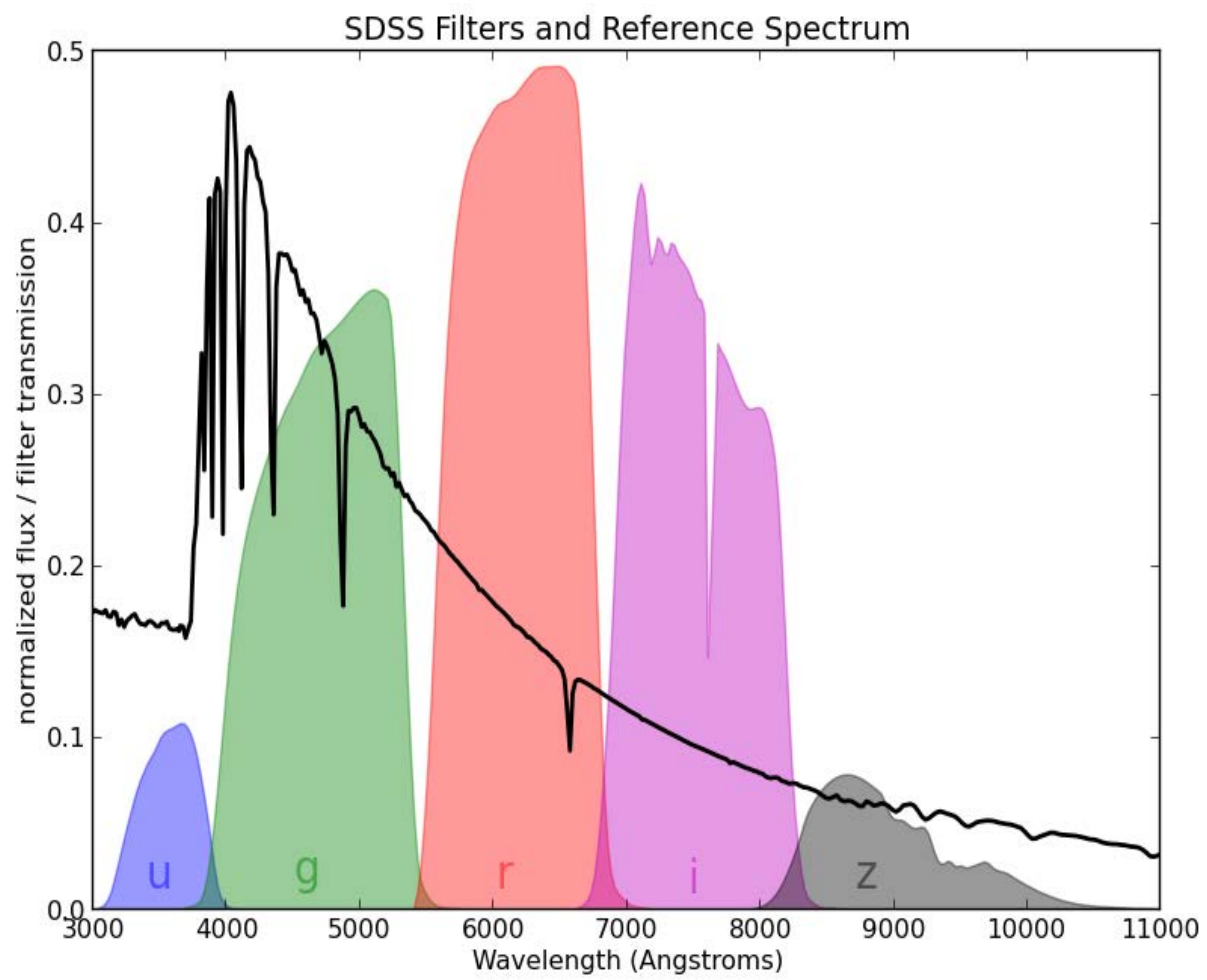
LSST and Dark Energy Science



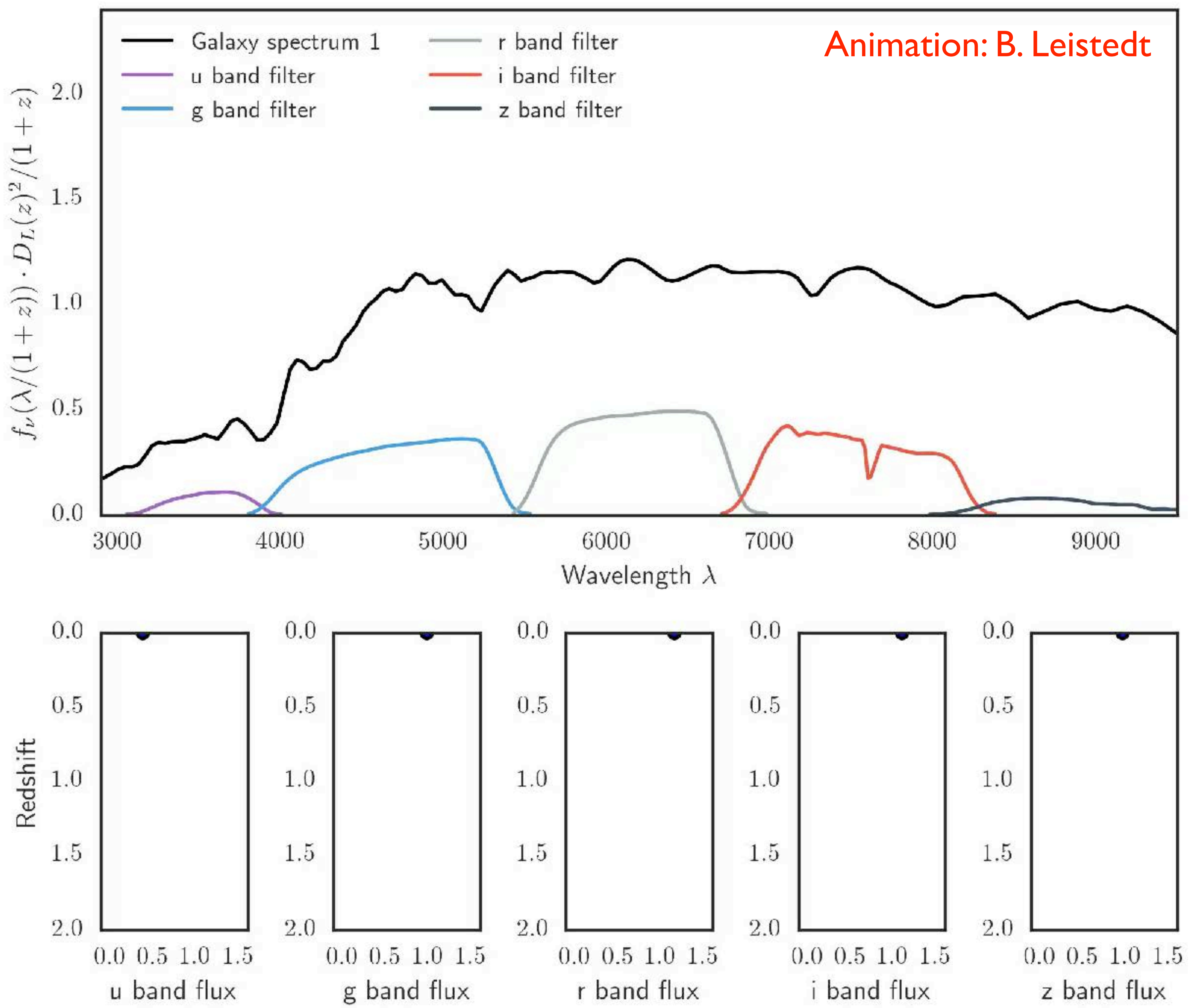


Measuring if / how dark energy evolves with time

Spectroscopic vs photometric samples

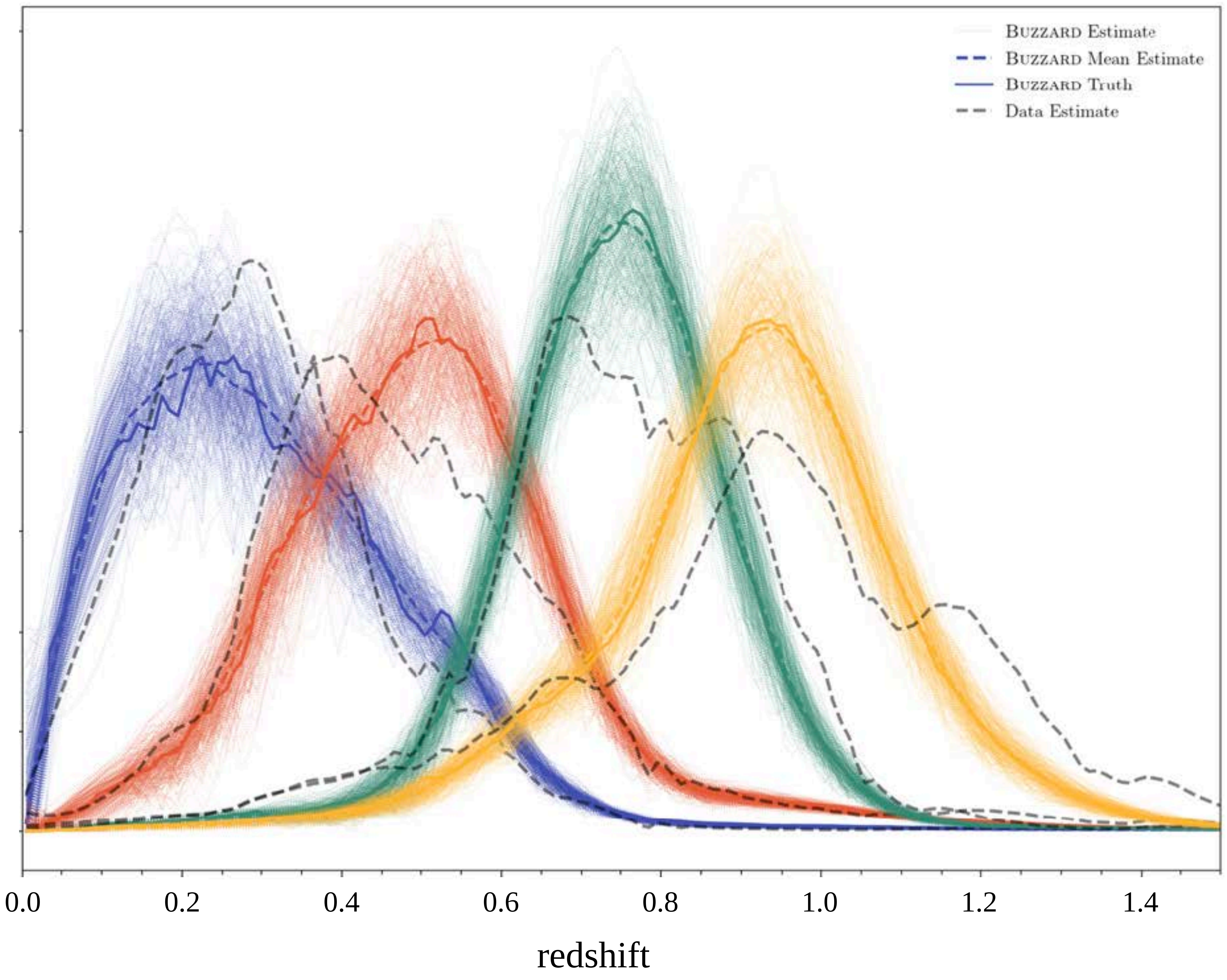


Photometric catalogues require ***redshift estimation***



Animation: B. Leistedt
Galaxy spectrum 1
u band filter
g band filter
r band filter
i band filter
z band filter
$f_\nu(\lambda/(1+z)) \cdot D_L(z)^2/(1+z)$
Wavelength λ
Redshift
u band flux
g band flux
r band flux
i band flux
z band flux

N(z): redshift distribution inference is challenging



- *Spectroscopic training / calibration samples are:*
    - *not representative of photometric catalogues (due to brighter flux limits and population evolution)*
    - *heterogeneous and contain difficult-to-model selection effects*
- *Introduces biases which are difficult to mitigate at required precision*

Figure: Myles et al (DES Collaboration 2021)

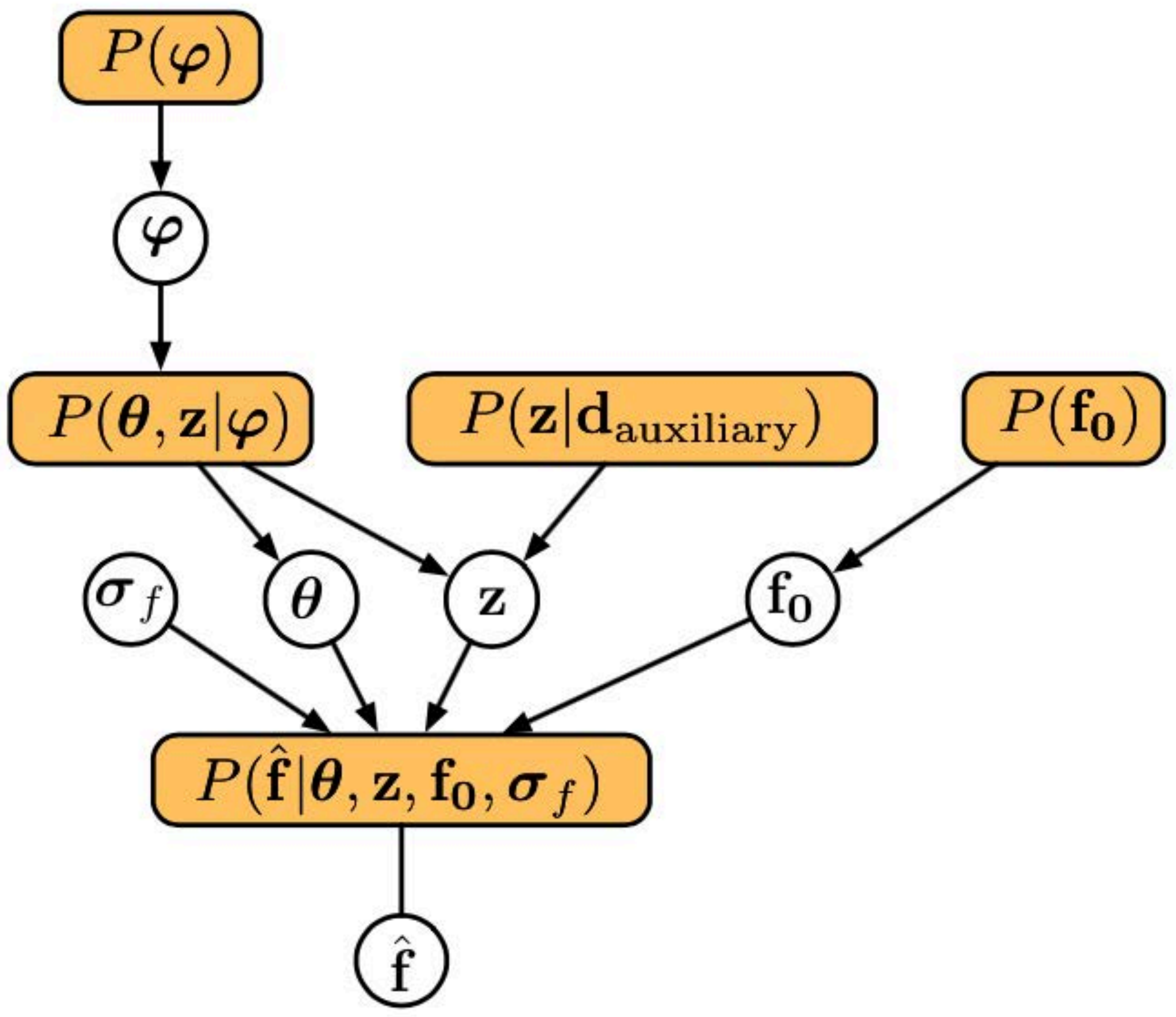
Forward modelling for n(z)

n(z): integral over **selection** **x** **data model** **x** **population model**

$$
\begin{aligned}
n(z) &\equiv P(z|S) \\
&= \frac{1}{P(S)} \int \left[\iint P(S|\hat{\mathbf{f}}, \theta, z) P(\hat{\mathbf{f}}|\theta, z, \sigma) P(\sigma) d\hat{\mathbf{f}} d\sigma \right] P(\theta, z) d\theta
\end{aligned}
$$

Redshift distribution inference for static cosmology

- **Key idea:** *high-dimensional Bayesian hierarchical model with machine-learned parts.*



- *Neural network emulation of FSPS population synthesis model, describing realistic galaxy populations (replace templates).*

- *Flexible NN-parameterised probability density models (e.g. normalising flows) to describe population prior and selection effects.*

ALSING, PEIRIS, LEJA, HAHN, TOJEIRO, MORTLOCK, LEISTEDT, JOHNSON, CONROY (APJS, 2020);
LEISTEDT, MORTLOCK AND PEIRIS (MNRAS, 2016)

Forward modelling for n(z)

n(z): integral over **selection** **x** **data model** **x** **population model**

$$n(z) \equiv P(z|S)$$
$$= \frac{1}{P(S)} \int \left[\iint P(S|\hat{\mathbf{f}}, \theta, z) P(\hat{\mathbf{f}}|\theta, z, \sigma) P(\sigma) d\hat{\mathbf{f}} d\sigma \right] P(\theta, z) d\theta$$

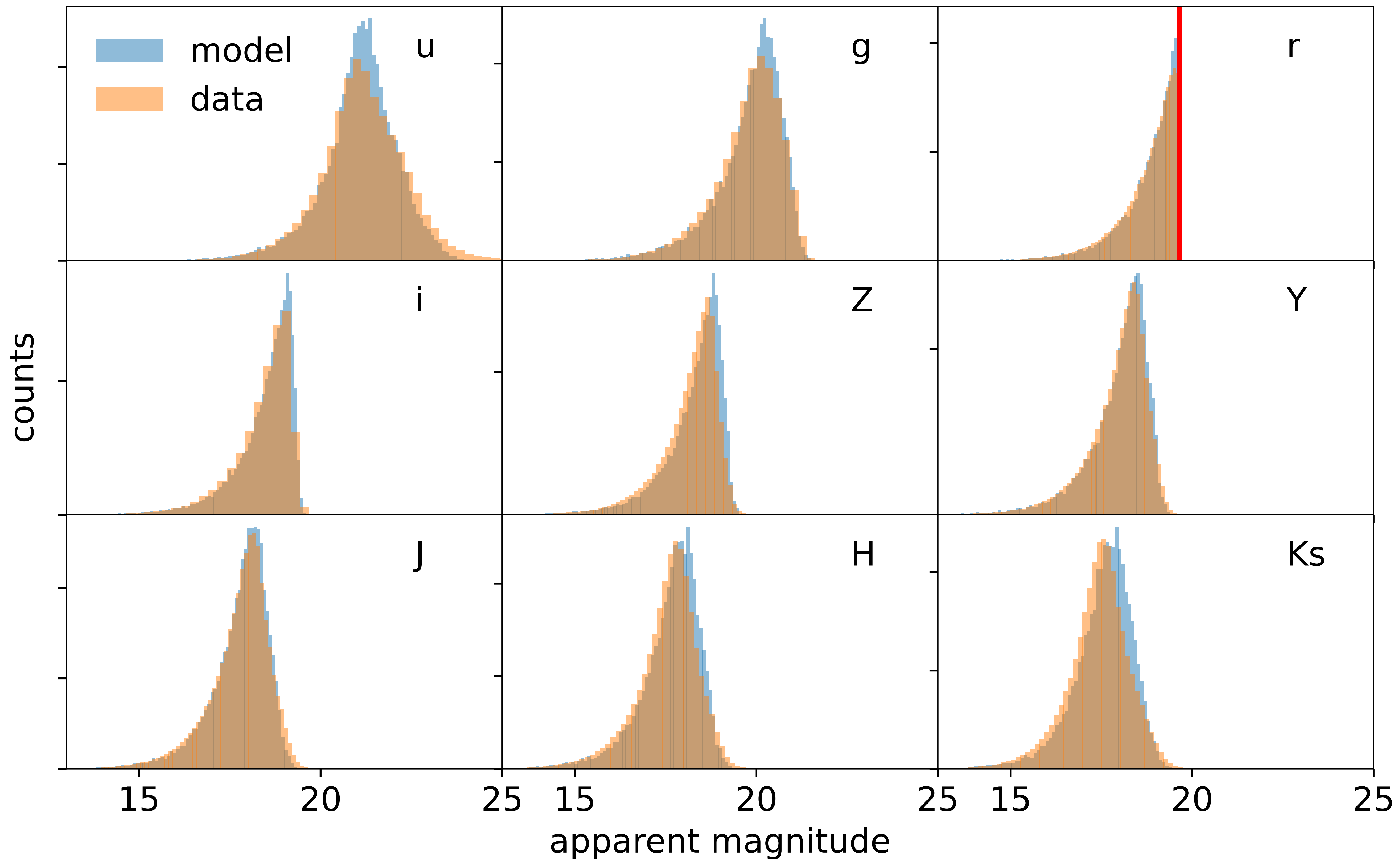
Advantages:

- *Does not rely on spectroscopic redshift calibration — spec-z catalogues not representative of photometric catalogues (due to brighter flux limits and population evolution)*
- *Auxiliary data (spec-z, extra surveys) can be included seamlessly (extended data vector or extra priors for objects with extra information)*
- *Connects cosmology with galaxy evolution*

"Turns photo-z back into an astrophysics problem" — Justin Alsing

Broadband data: does it work?

Simulated galaxy population (encoding galaxy evolution calibrated to observations), combined with data model and selection cuts, should be able to predict redshift distribution.



Selection for GAMA survey

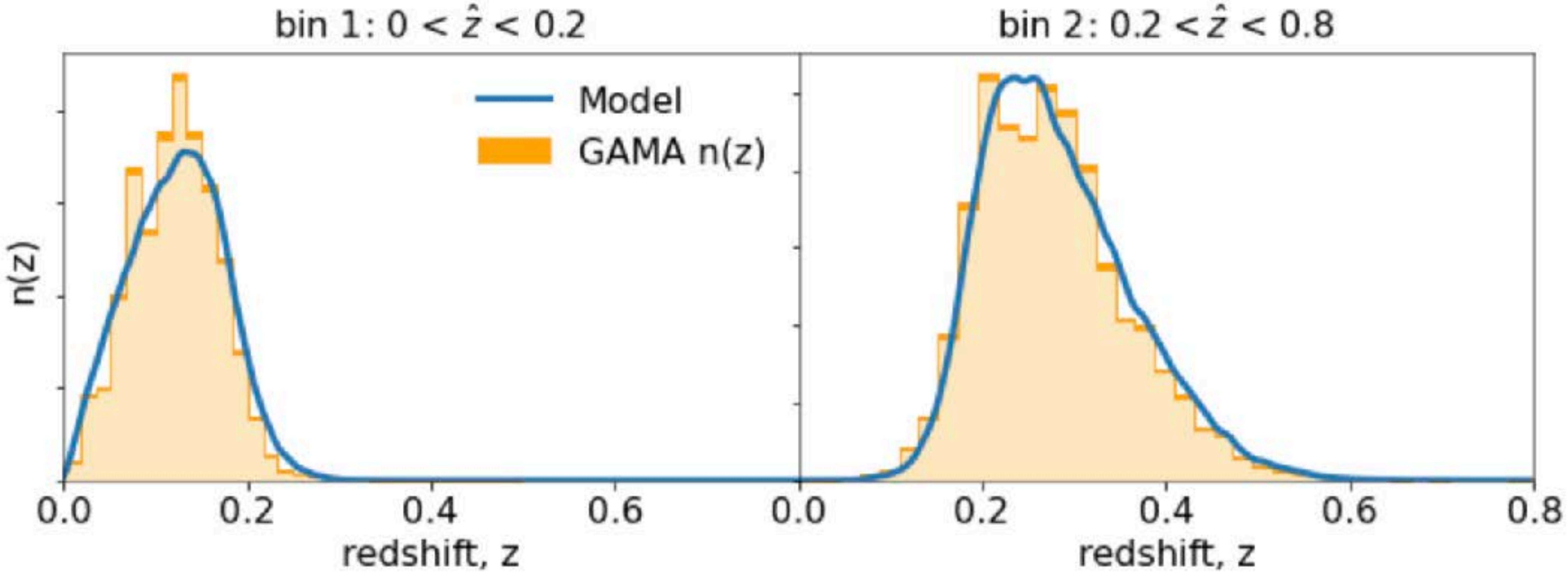
Validation: *two spectroscopic surveys with straightforward selection cuts*

1. GAMA (ugriZYJHKs): *r < 19.65, (J-Ks) > 0.01*
2. VVDS (UBVRI): *I < 22.5, star-galaxy separation done at level of spectra*

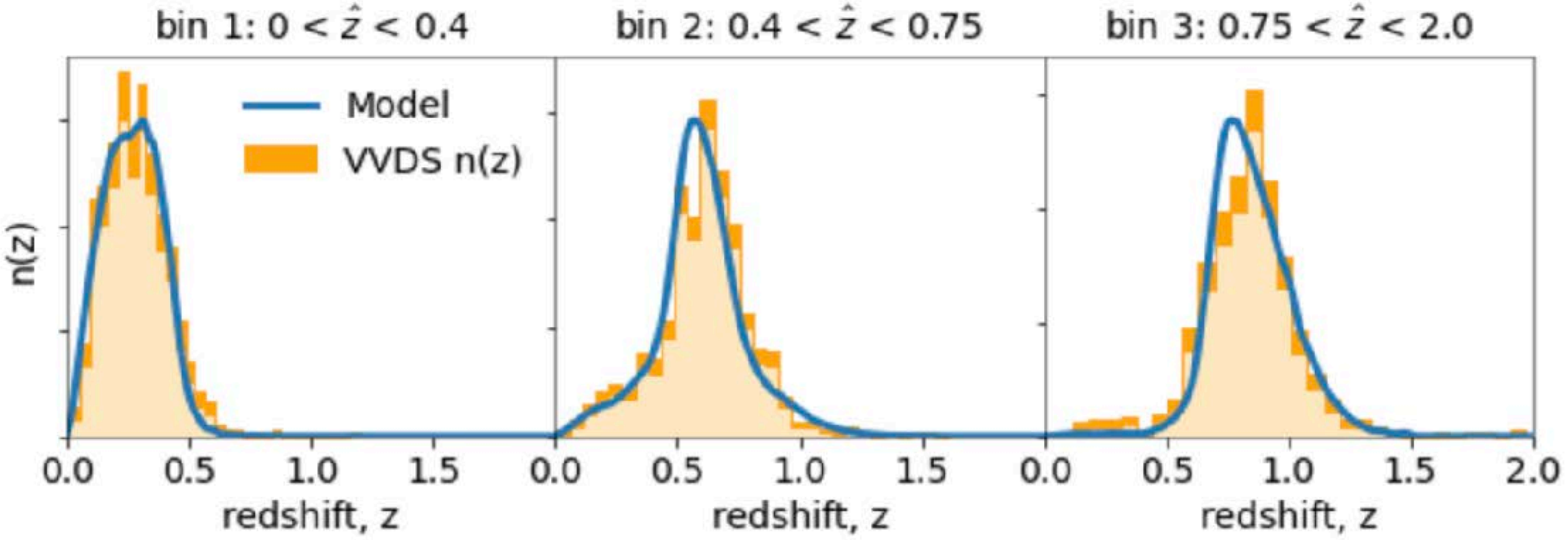
ALSING ET AL. (2022 APJS)

Validation with broadband data

GAMA n(z) tomography
population model X data model X selection



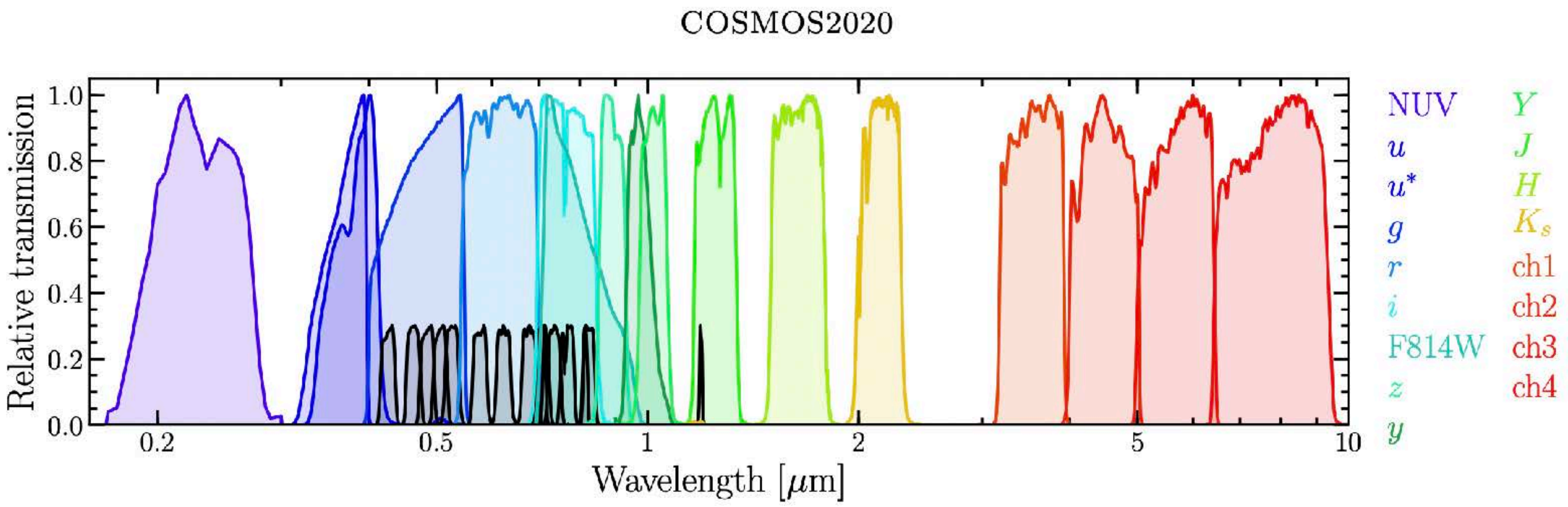
VVDS n(z) tomography
population model X data model X selection



Baseline model n(z) bias < 0.01 *before parameter inference* *(no data!)*

ALSING ET AL. (2022, ApJS)

Narrow-band data: validation with COSMOS2020



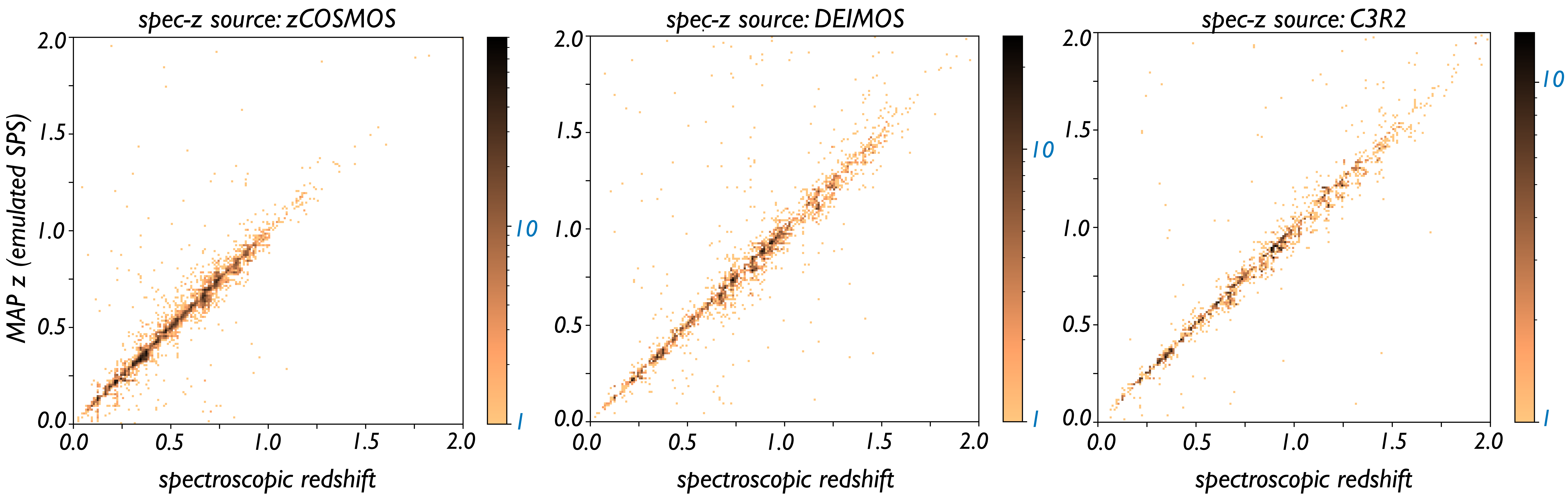
Photometric data: COSMOS2020 multiwavelength Farmer catalogue

Population model: Prospector-alpha emulators of both fluxes and emission lines

Data model: Optimization of zero-points per band and (broadband and emission line) hyperparameters

Weaver et al (2021), Leistedt et al. (2022, ApJS)

Validation with narrow-band data



Representative of bright sources

Representative of colours

"Spec-z quality"

Photometric data: COSMOS2020 multiwavelength Farmer catalogue

Population model: Prospector-alpha emulators of both fluxes and emission lines

Data model: Optimization of zero-points per band and (broadband and emission line) hyperparameters

Leistedt et al. (2022, ApJS)

Next steps!

- ***Hierarchical inference not scalable?***

  Already made progress on simulation-based inference approach — advantage of not needing to explicitly model selection effects parametrically, only to forward model them in a simulation.

- ***Is the SPS population prior good enough for deeper data?***

  Improvements to population prior (star formation history and dust modelling). Population prior being calibrated on COSMOS2020 catalogue.

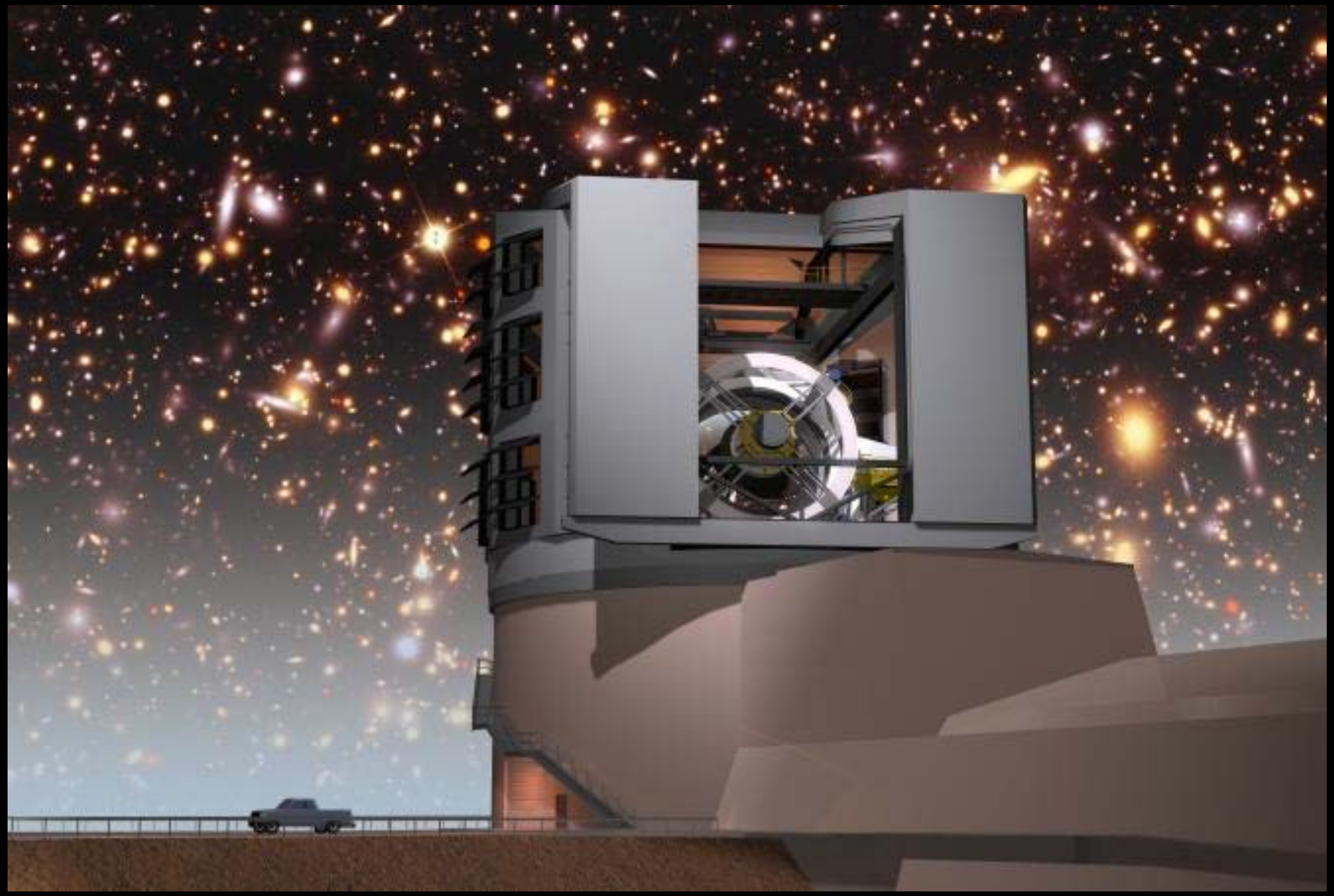
- ***How do we validate analyses of deeper data when little spectroscopy available?***

  Developing posterior predictive checks in colour/flux space (Bayesian "cross-validation")

Sinan Deger, Stephen Thorp, work in progress

LSST: survey of 18,000 sq deg

(half the sky)



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"Movie of the Universe"

Mapping the Milky Way

37 billion objects in space and time

30 trillion measurements

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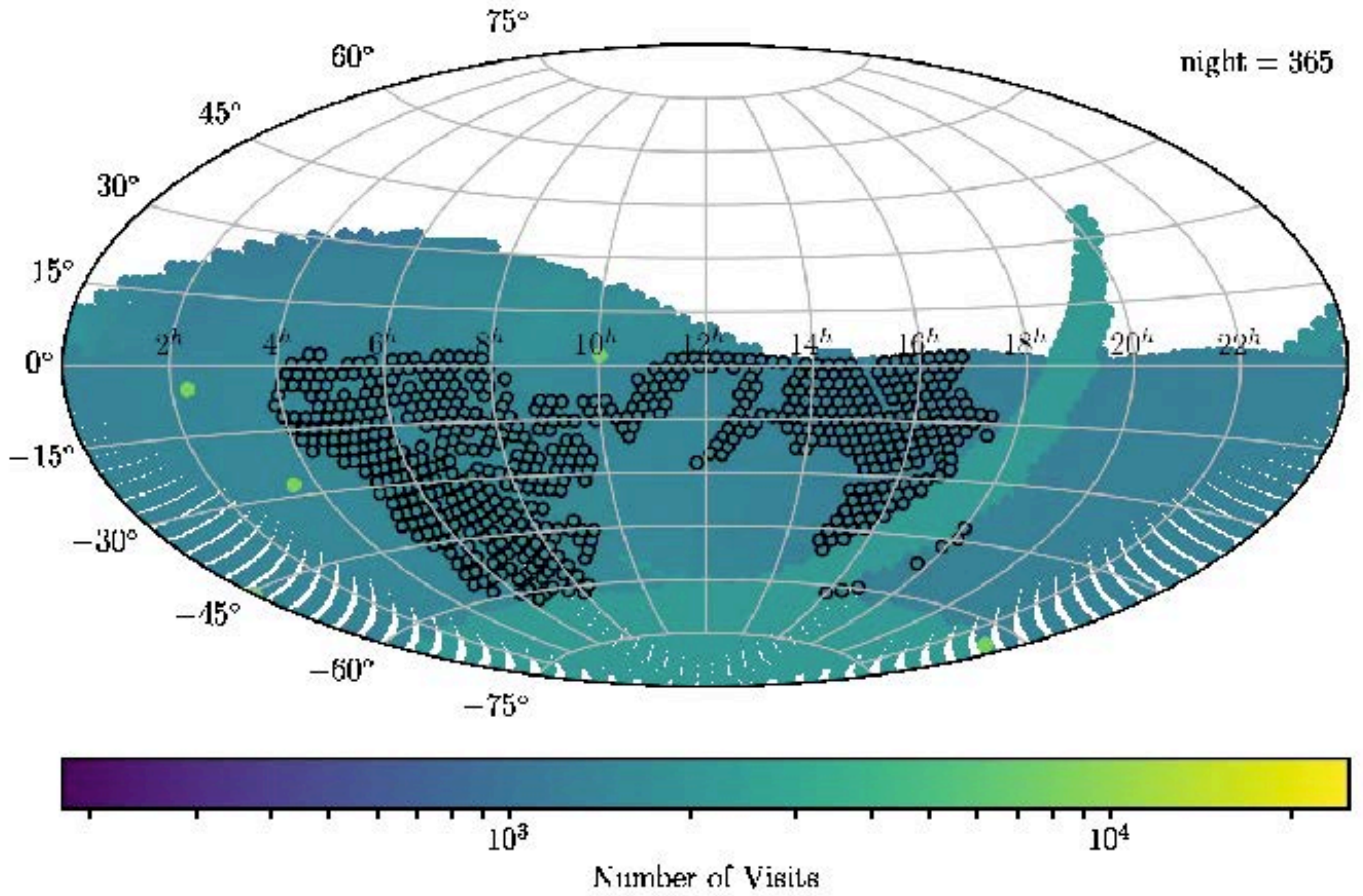
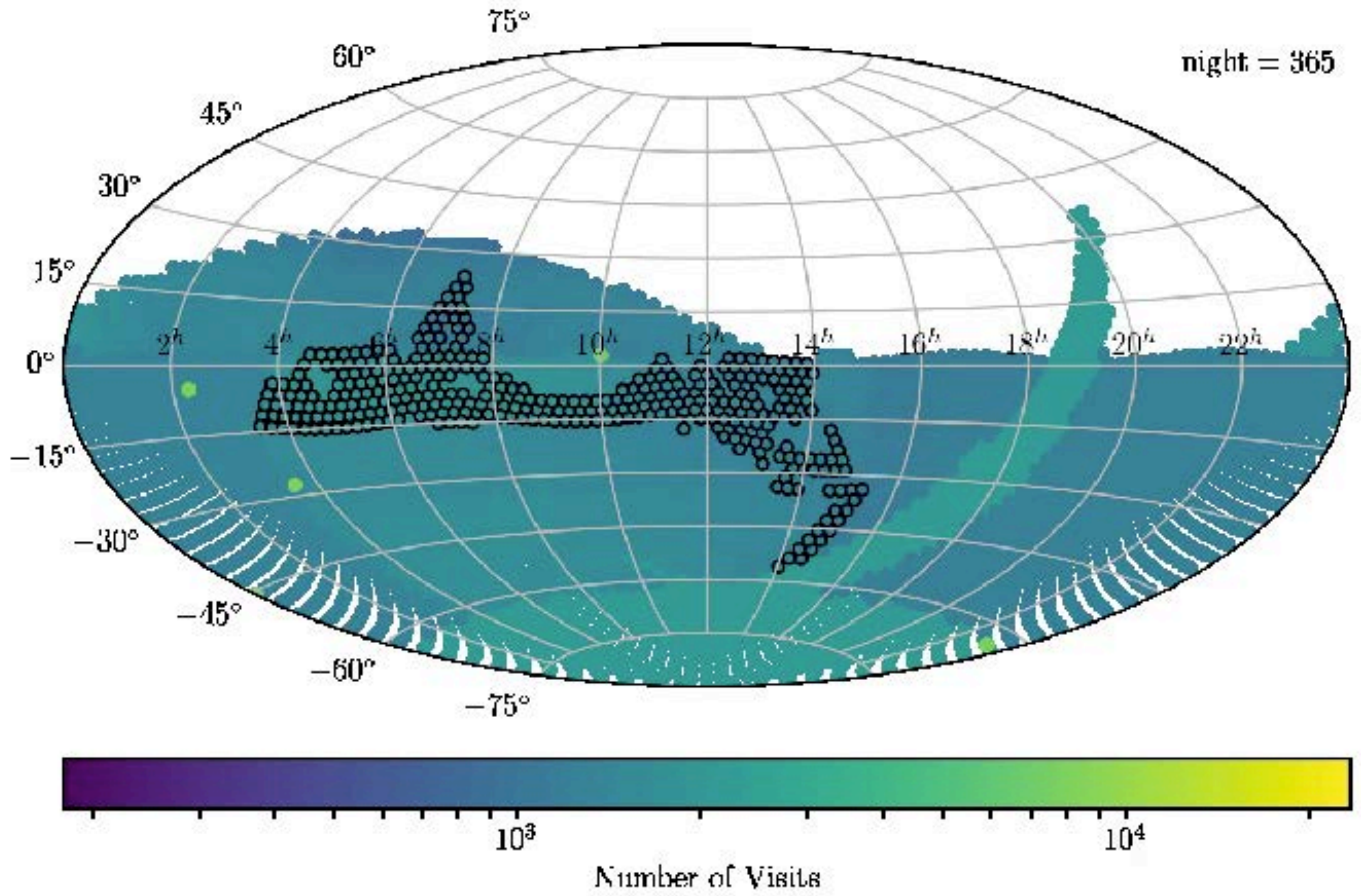
Slide adapted from Ian Shipsey

LSST observing strategy



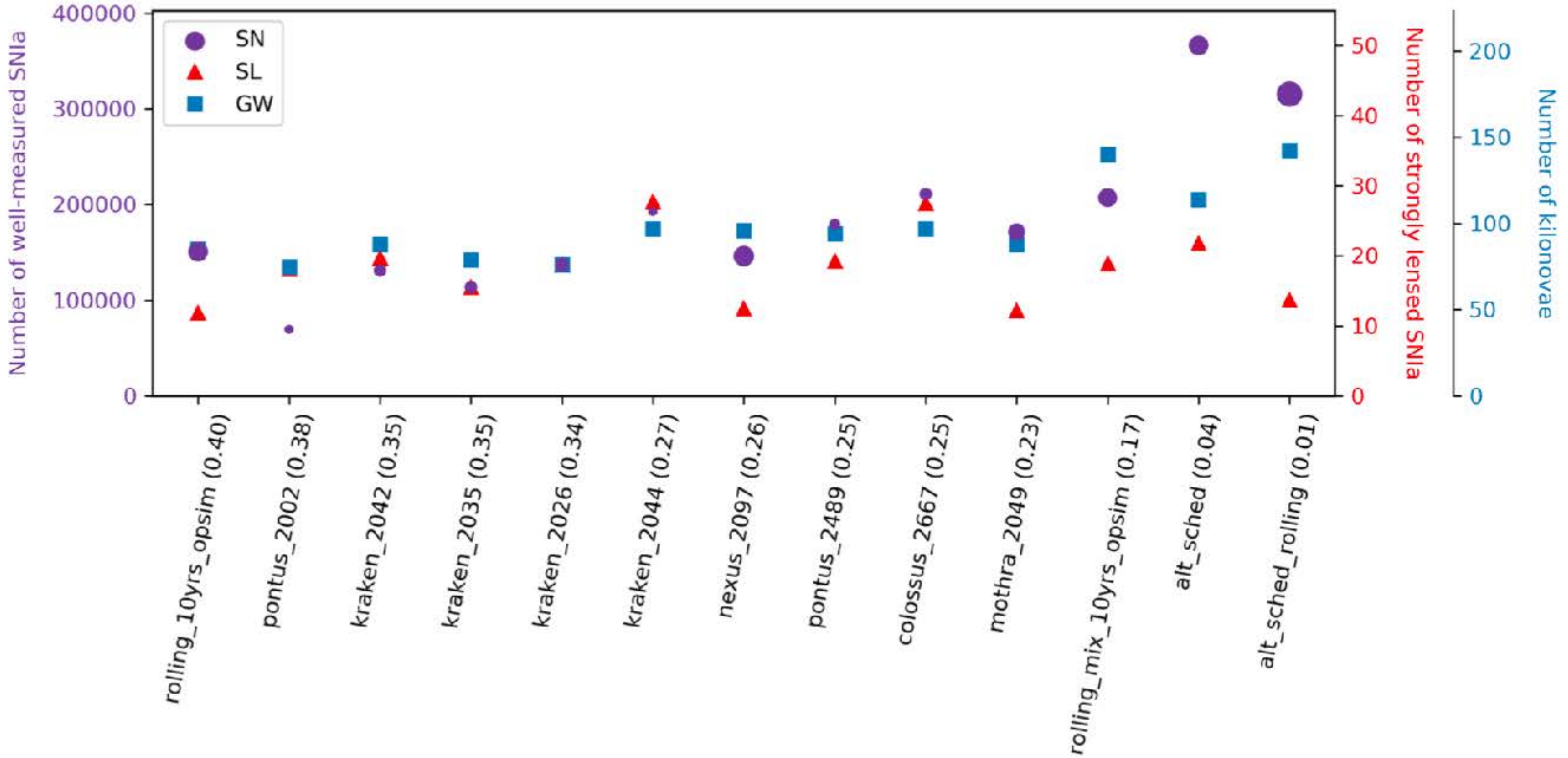


WFD baseline strategy

A rolling WFD proposal

MOVIES: ROB FIRTH

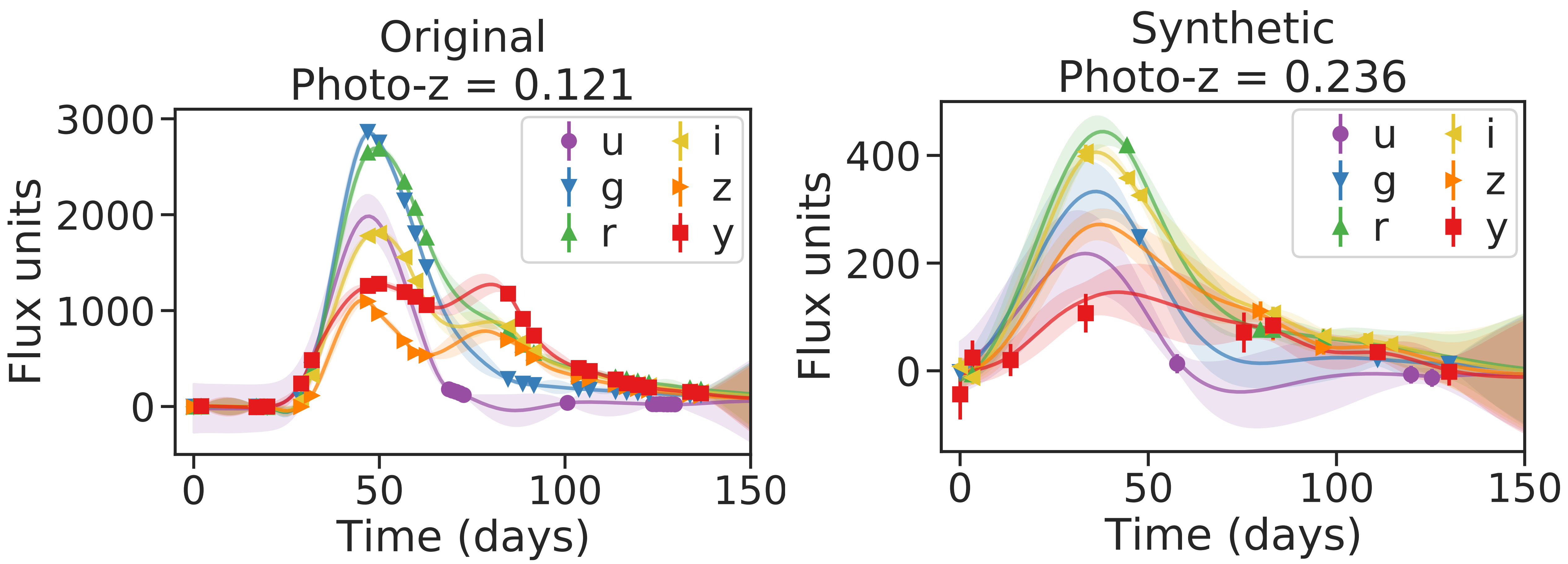
LSST and the transient universe



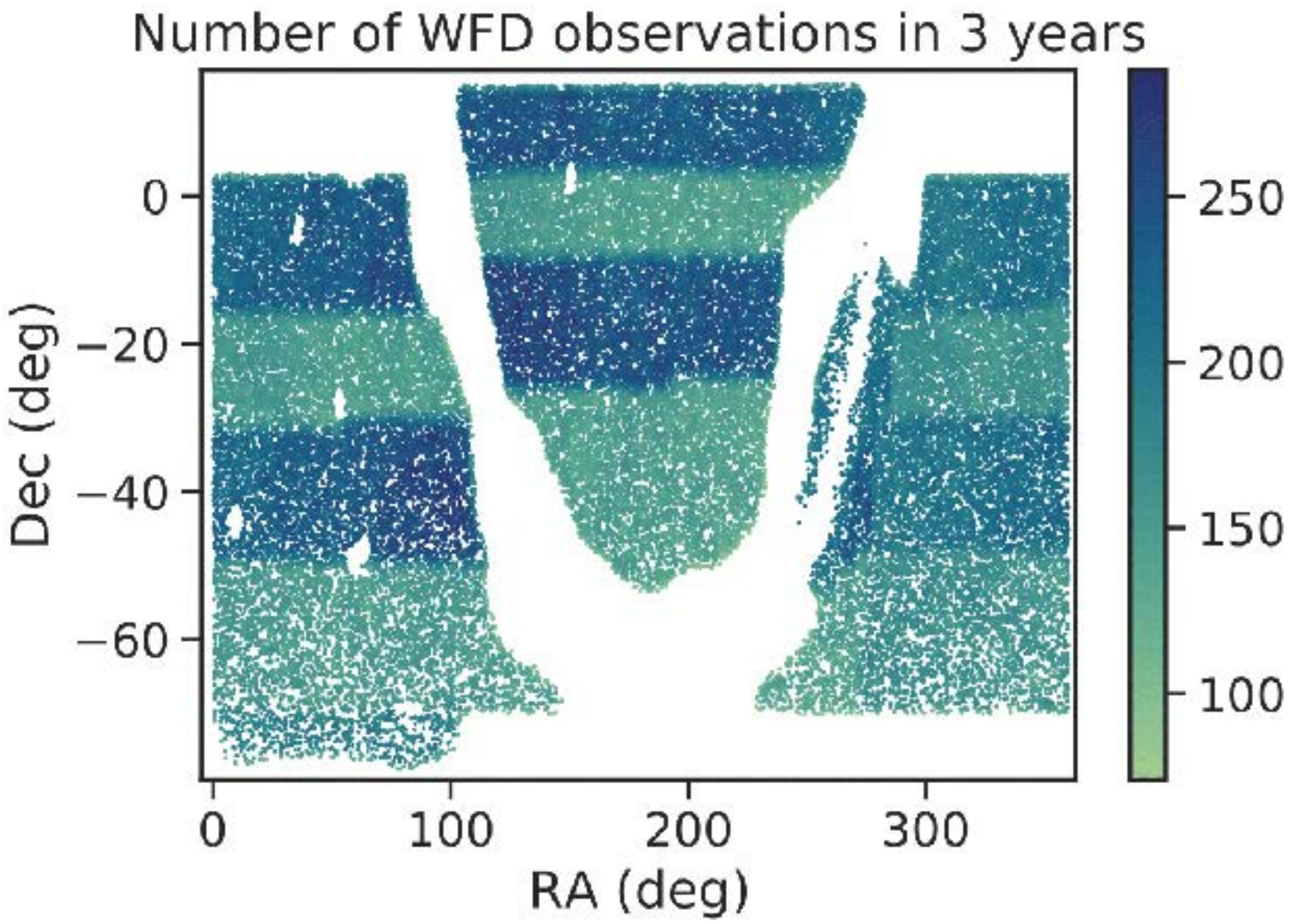
Number of kilonovae, strongly lensed type Ia supernovae with well-measured time delays (both assuming follow-up with other telescopes) and well-measured type Ia supernovae for Y10 as a function of observing strategy, ordered by percentage of visits in r-band separated by more than 15 days (in brackets).

LSST DESC WFD (ArXiv:1812.00515) and DDF (ArXiv:1812.00516) white papers

Observing strategy and photometric supernovae classification



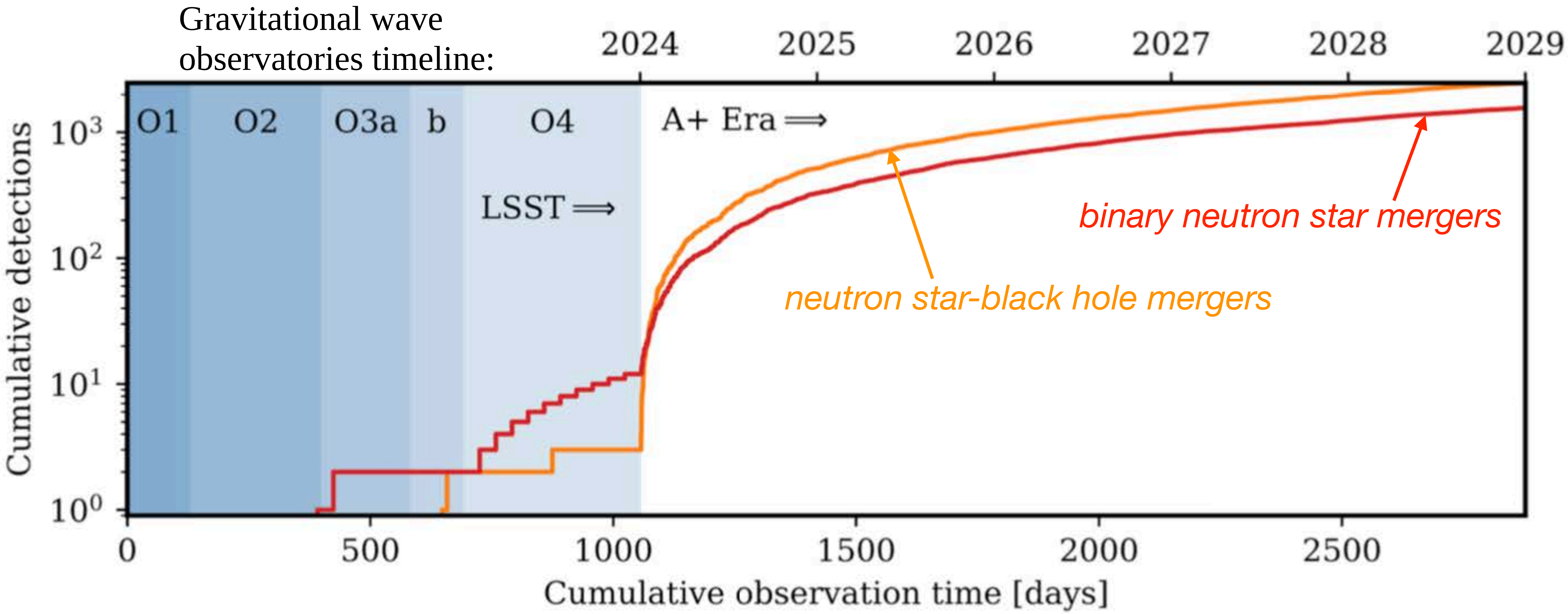
- Data augmentation of spectroscopic training samples essential for classification
- Median inter-night gap should be <3.5-5 days

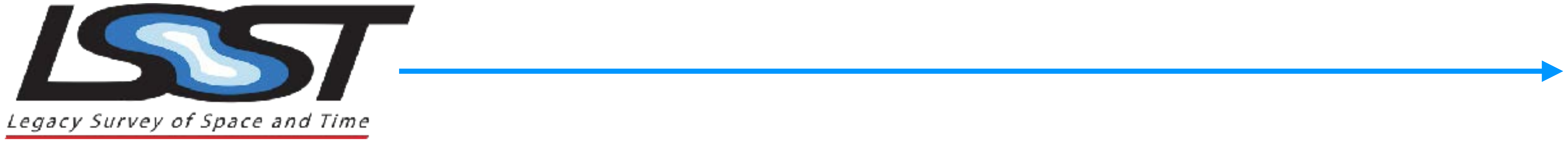


- Actively-rolling region yields ~3x cosmologically useful SNe than background region.
- Strongly advocates ***rolling cadence***

ALVES, PEIRIS, LOCHNER, MCEWEN ET AL (2022, APJS), ALVES, PEIRIS, LOCHNER, MCEWEN ET AL (2023, APJS)

Multimessenger observational frontier

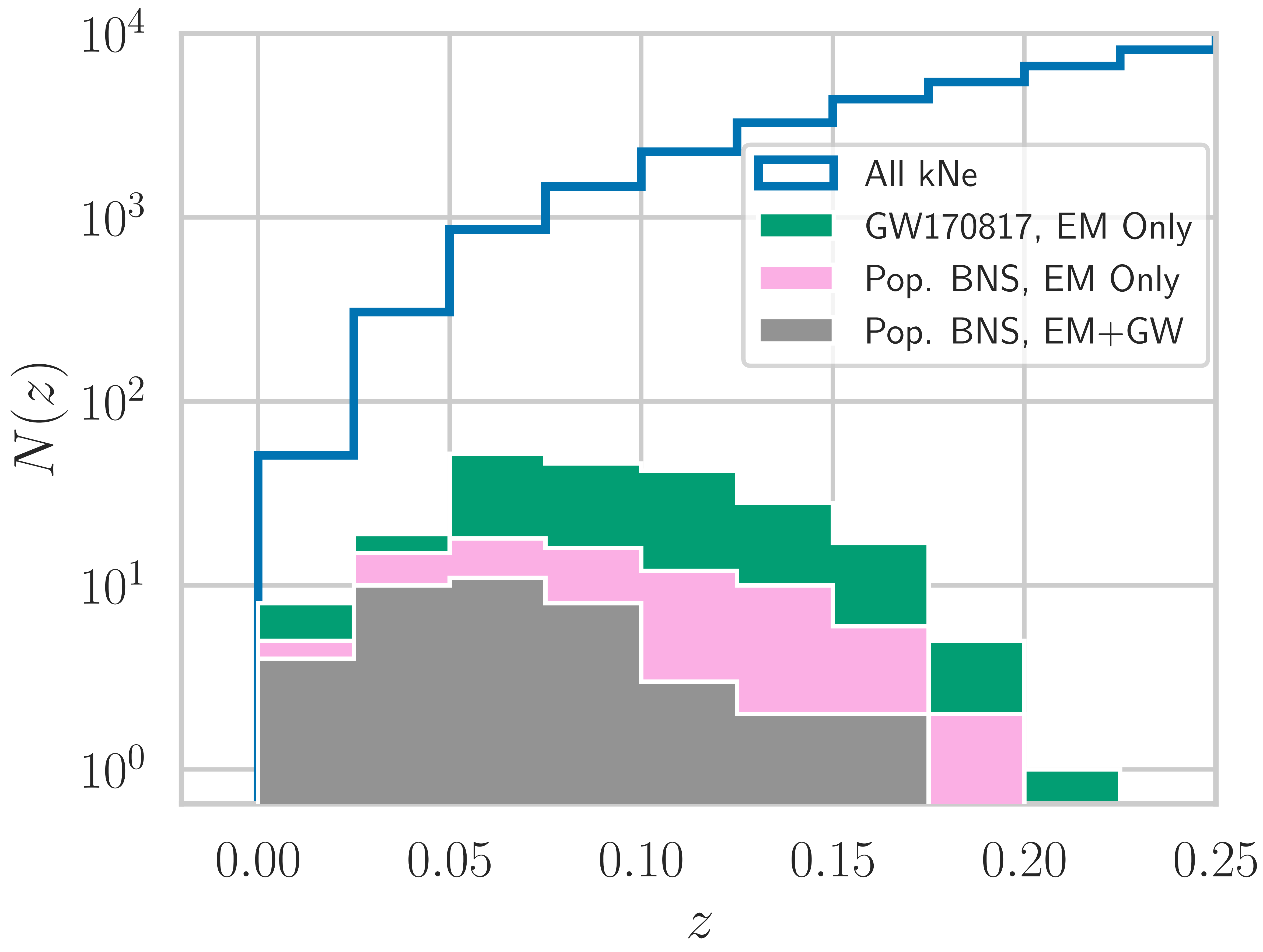




Expected yield of gravitational wave events with potential electromagnetic counterparts

Figure: S. Feeney

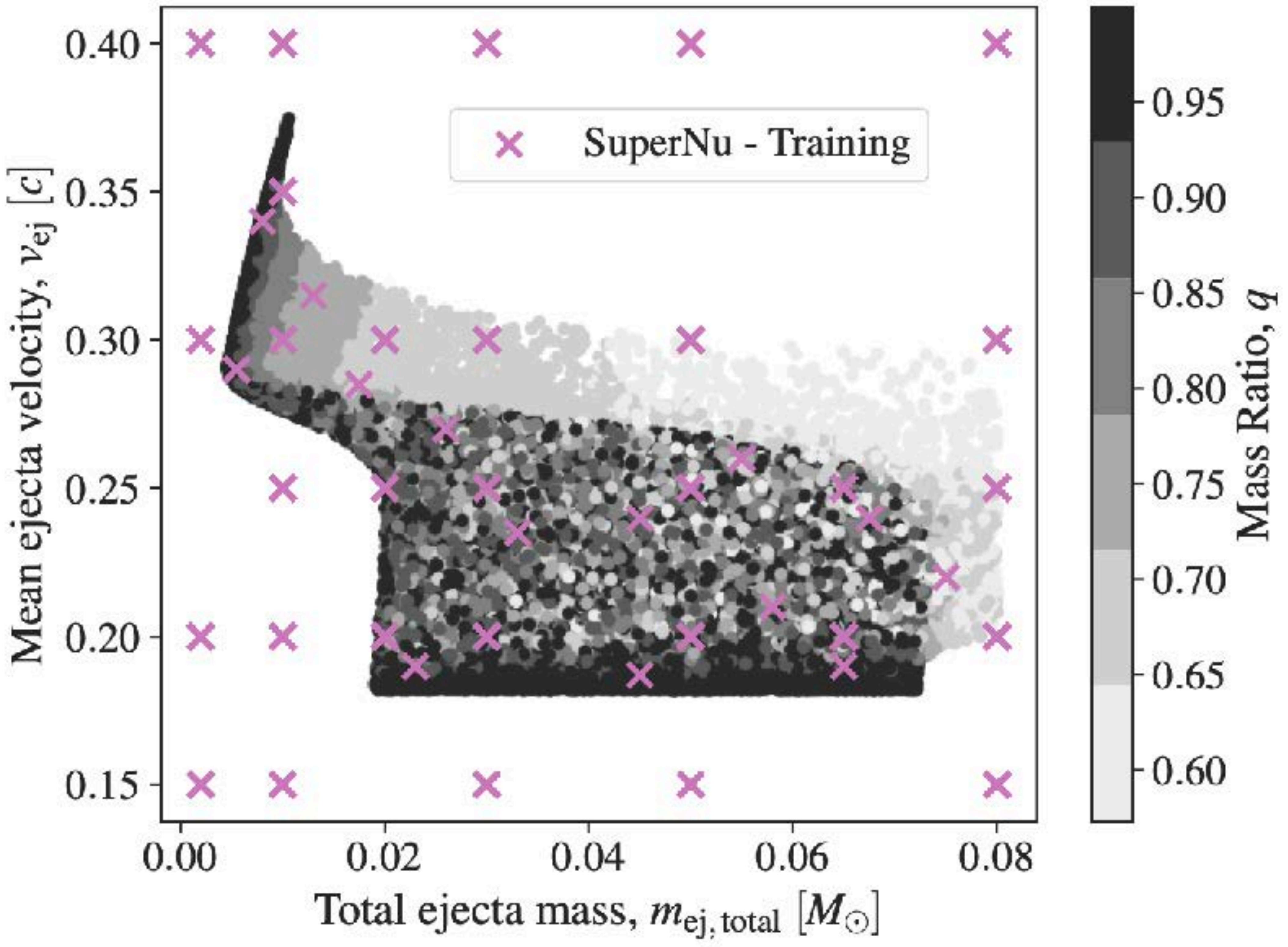
Serendipitous detections of kilonovae in LSST

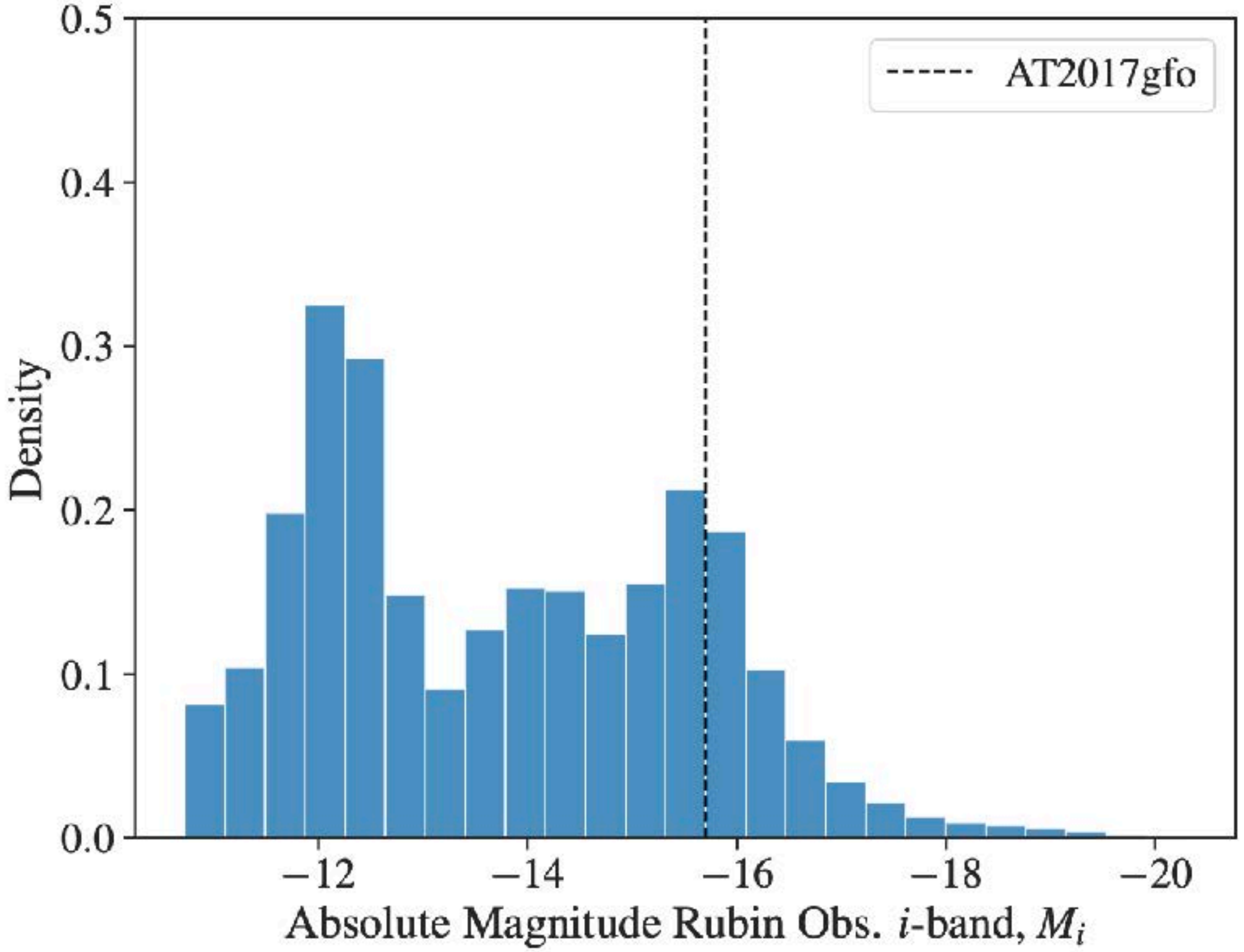


Can optical kilonovae detections be used to "reverse-trigger" searches for sub-threshold GW events in archival data?

SETZER ET AL (LSST DESC, MNRAS 2019)

Serendipitous detections of kilonovae in LSST





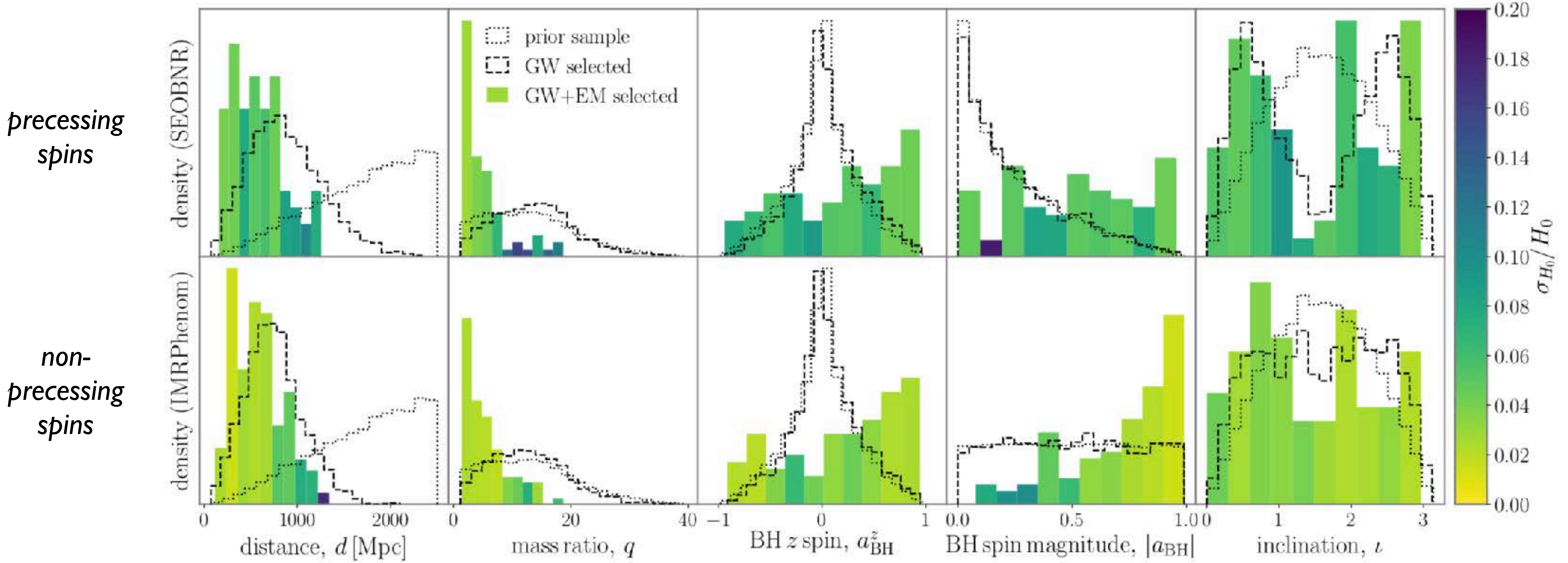
- Gaussian process Grey Opacity emulator calibrated to SuperNu radiative transfer simulations
- Self-consistent EM-GW kilonova population model designed for optical surveys

HTTPS://GITHUB.COM/CNSETZER/KILOPOP

SETZER ET AL (2023 MNRAS)

Planning for A+ era science with GW-EM populations

NS-BH population study



- Hierarchical Bayesian pipeline for population studies at A+ scale.
- Customised bilby wrapper + lalsimulation library + tuned polychord sampler.
- Accounting for selection effects crucial; understanding EM selection likely to be challenging.

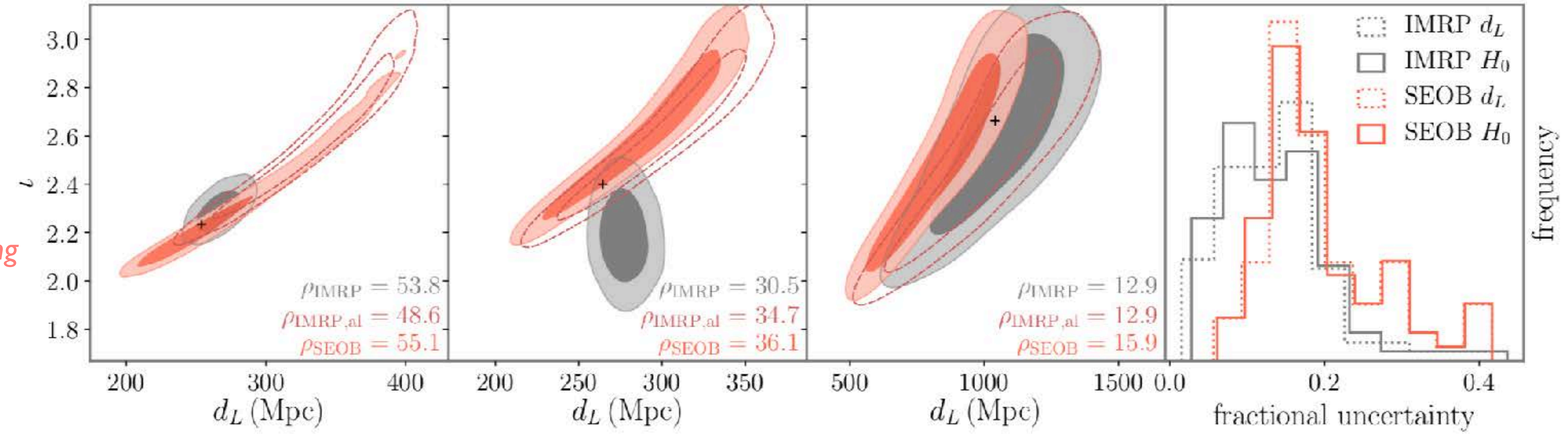
FEENEY, PEIRIS, MORTLOCK, NISSANKE (2021, PHYS. REV. LETT.)

Planning for A+ era science with GW-EM populations

NS-BH population study

precessing spins

non-precessing spins



signal-to-noise (decreasing) →

precessing spins important: equivalent to doubling sample size.

FEENEY, PEIRIS, MORTLOCK, NISSANKE (2021, PHYS. REV. LETT.)

European Research Council
Established by the European Commission

CosmicExplorer: Exploring the Cosmos with the Vera Rubin Observatory

Aims: (i) AI-boosted modelling for cosmological analysis (ii) new cross-validation methods for diagnosis of systematics (iii) explainable AI to develop cosmic web as robust cosmological probe.

COSMOPARTICLE, WWW.PENELOPEROSECOWLEY.COM