Learning Gravity from Cosmological Data

Marco Raveri

The universe as a physics laboratory

The Planck scale 10^{28} eV

Energy

The Horizon 10^{-33} eV

$\sim 10^{-32}$ seconds	1 second	380 000 years	400 million years	13.8 billion years

Inflation	Hydrogen Recombination	Dark Matter	Dark Energy

(Based on ESA cosmic history)

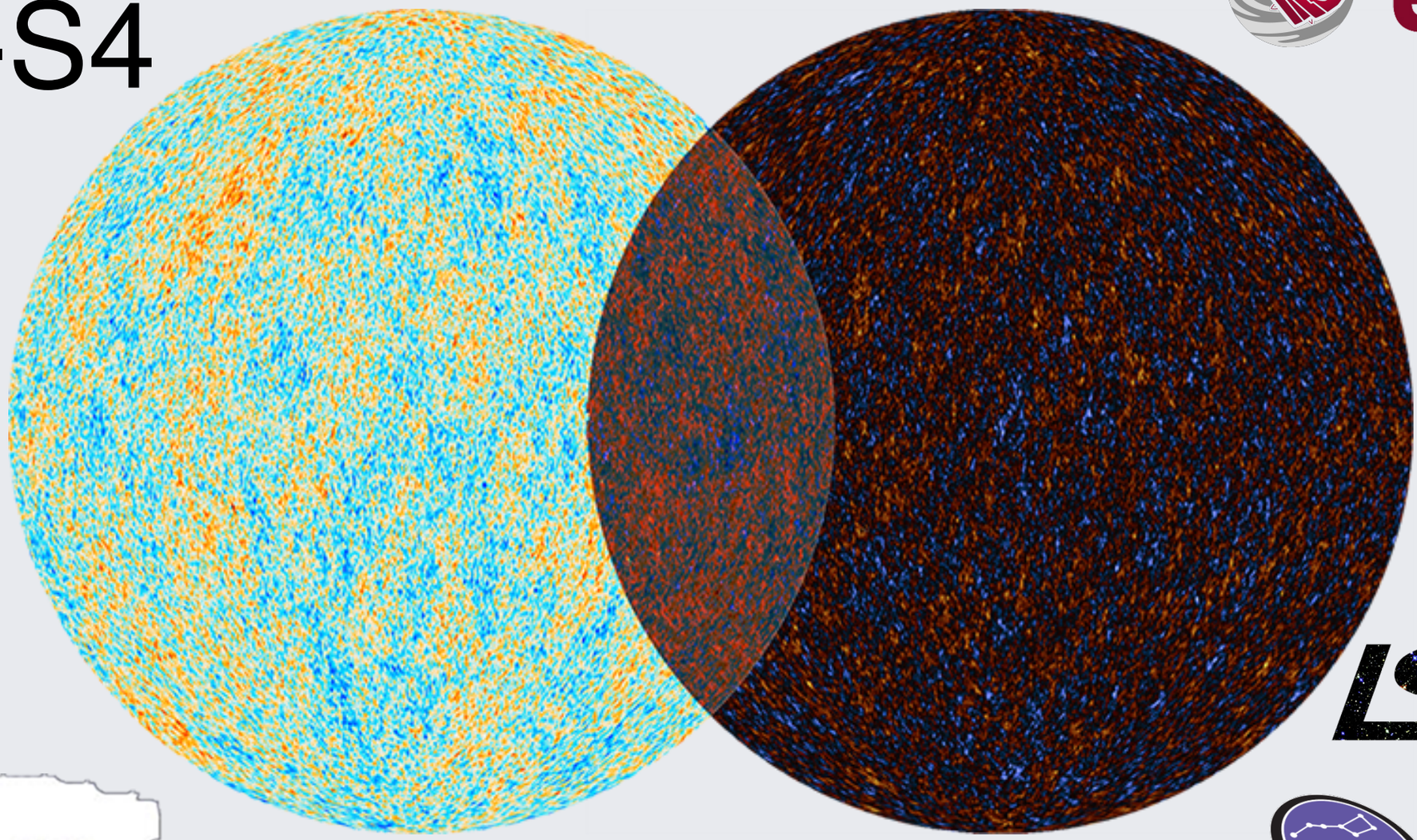
The modern picture of our Universe

planck

DES

euclid

CMB-S4



ACT

SPT

KiDS

LSST

SDSS

(and many more…)

In search of Dark Energy

How did we do so far?

O(100) models have been tested

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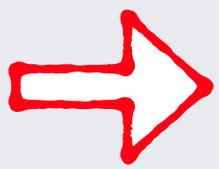
Random uncorrelated trials



five models detected at 2 sigma

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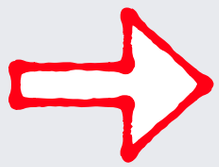

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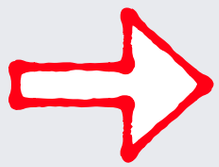

one model detected at 3 sigma

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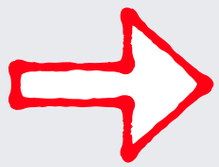

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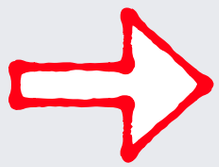

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Not even one

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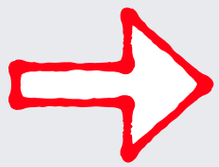

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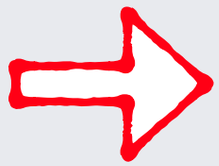

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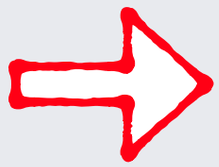

correlated trials

In search of Dark Energy

How did we do so far?

O(100) models have been tested

Random uncorrelated trials → five models detected at 2 sigma

→ one model detected at 3 sigma

Not even one → correlated trials

→ in the wrong direction

EFT approach to Dark Energy

When it comes to DE and MG we have poor theoretical guidance

… but we have plenty data power …

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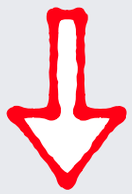
Bottom-up approach



“Blind” Effective Field Theory techniques

(arXiv:1210.0201, arXiv:1211.7054 and the EFT of inflation literature, arXiv:1907.03150 for a review)

EFT approach to Dark Energy

symmetries of FRW

linear cosmological scales

Most general description of Gravity and DE models compatible with FRW symmetries

(arXiv:1210.0201, arXiv:1211.7054 and the EFT of inflation literature, arXiv:1907.03150 for a review)

EFT approach to Dark Energy

Gravity and DE models at linear scales:
one extra scalar
at most two derivatives
universal and minimal coupling to matter (WEP)

$$\{\Lambda(t), M_P^2(t), \alpha_K(t), \alpha_B(t), \alpha_T(t)\}$$

(Gubitosi et al arXiv:1210.0201, Bloomfield et al arXiv:1211.7054, Bellini and Sawicki arXiv:1404.3713)

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Derivative couplings

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Derivative couplings

Speed of GWs

(Gubitosi et al arXiv:1210.0201, Bloomfield et al arXiv:1211.7054, Bellini and Sawicki arXiv:1404.3713)

Measuring functions of time from the data

Measuring functions of time from the data?

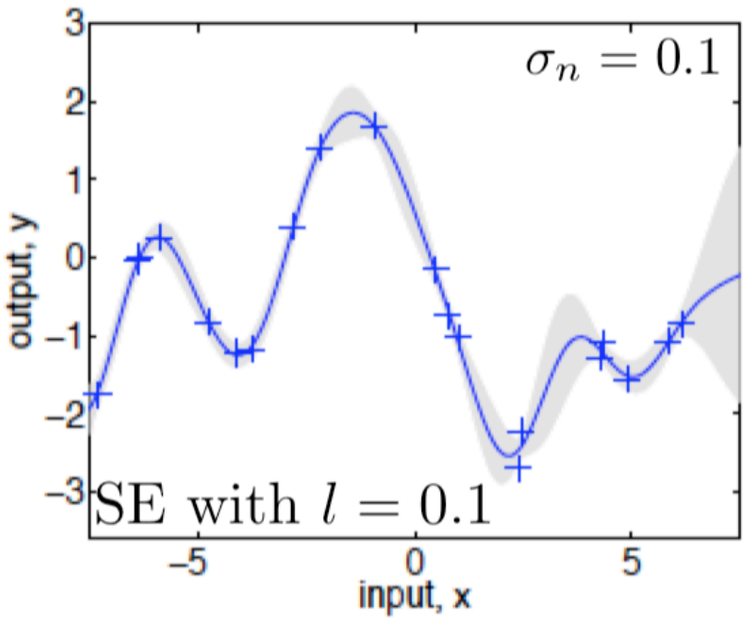
Space of 1d functions is infinite dimensional
Our data is (inconveniently) finite

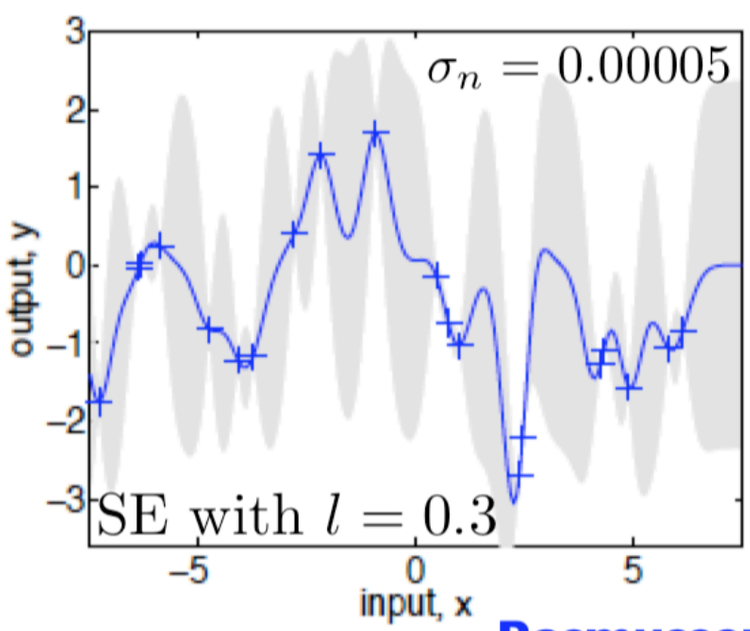
Descope: reconstruct over band-limited functions

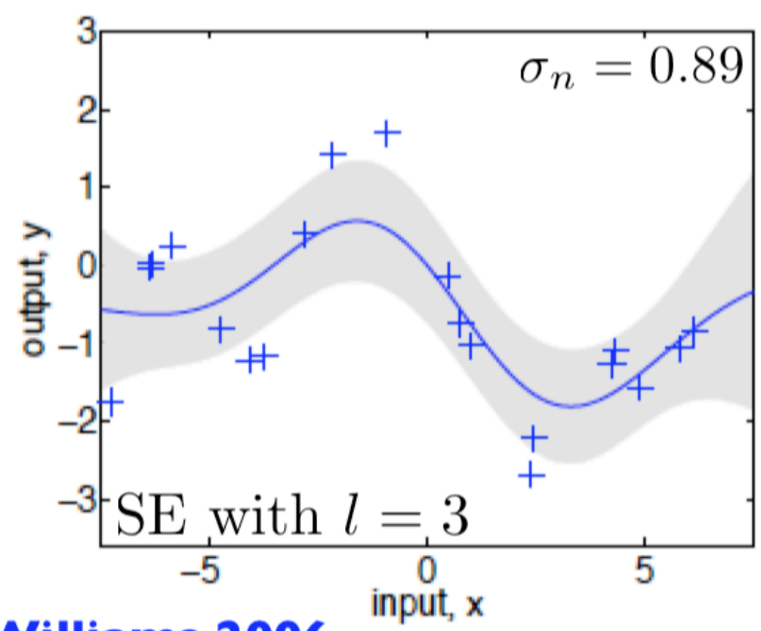
Measuring functions of time from the data

Descope: reconstruct over band-limited functions

Gaussian processes and machine learning



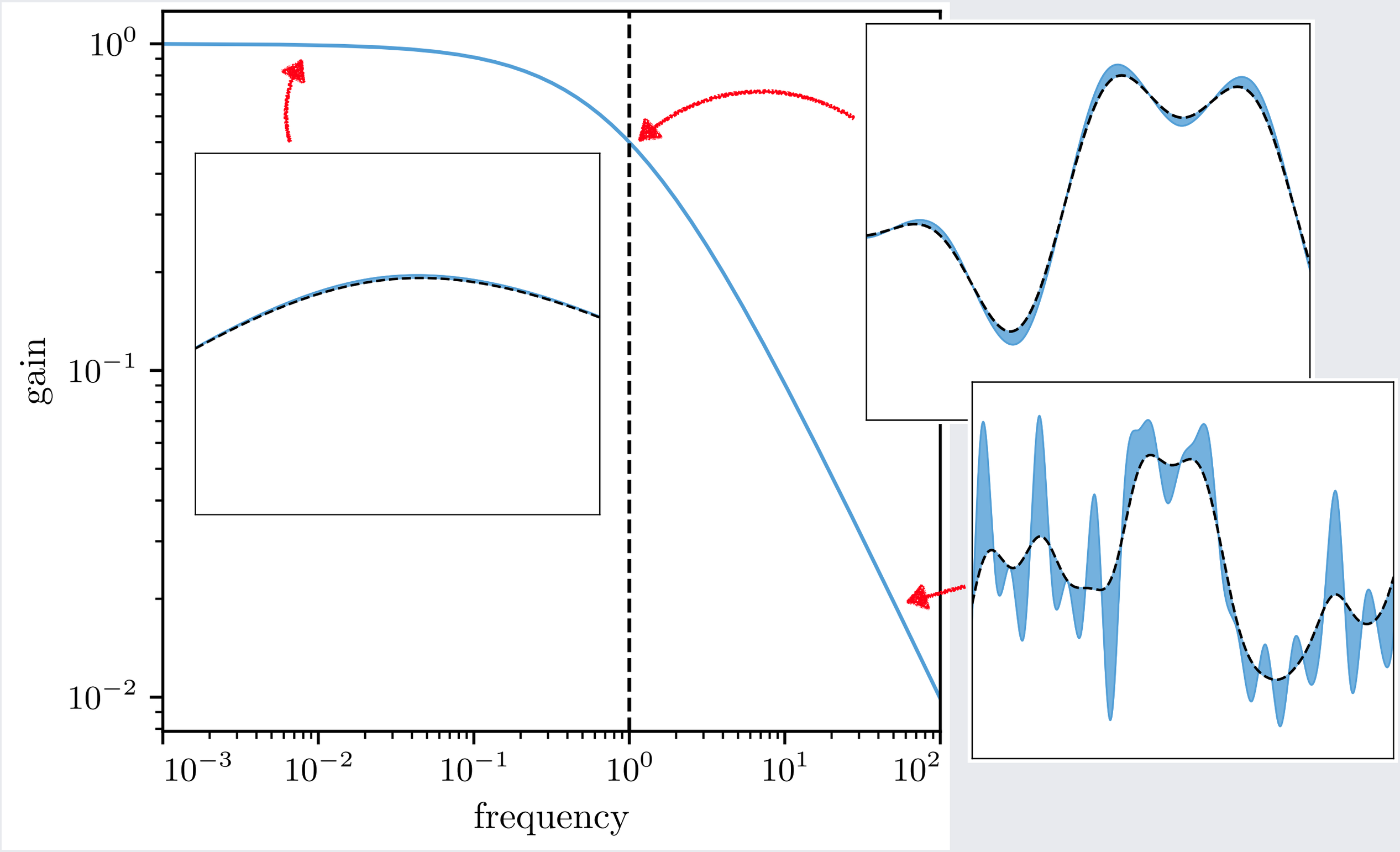




Rasmussen & Williams 2006

(with some differences: non-Gaussian posterior, not working directly in data space)

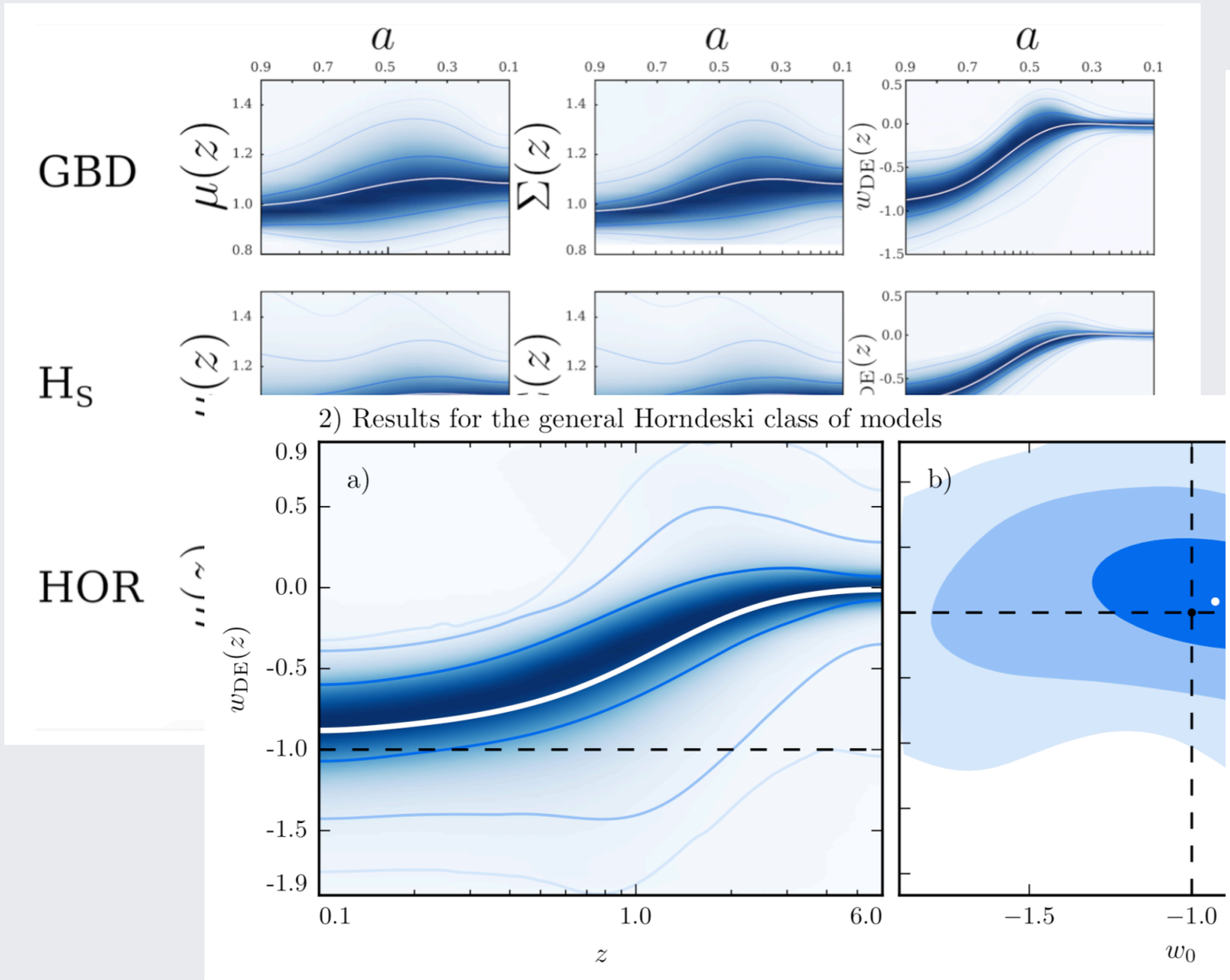
Smoothness priors as a low pass filter

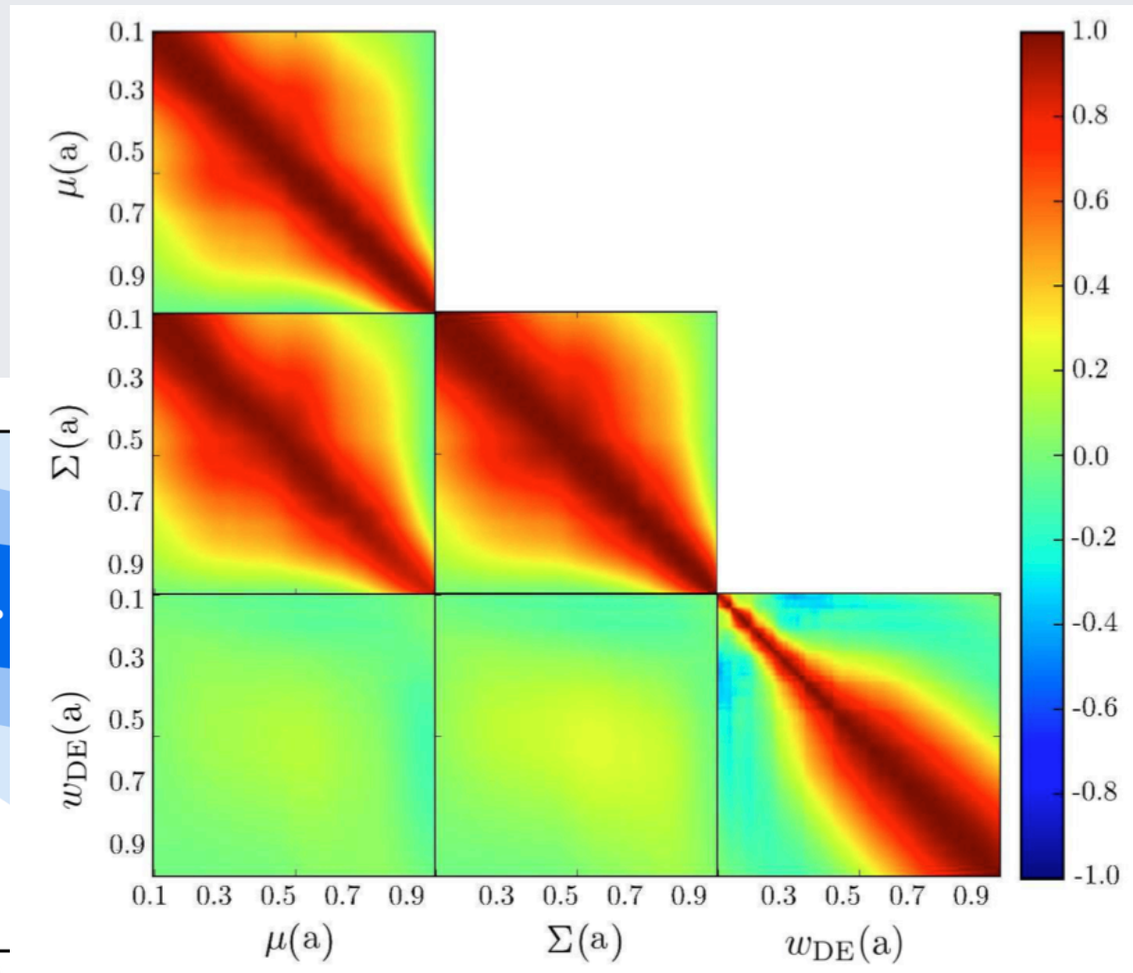


(R.Crittenden, GB.Zhao, L.Pogosian et al., arXiv:1112.1693 and some Gaussian process literature)

Model training

Training on (some billions of) existing models:
1/3 of an e-fold is a good time-scale





(MR, P.Bull, A.Silvestri, L.Pogosian, arXiv:1703.05297, J.Espejo, S.Peirone, MR, K.Koyama, L.Pogosian, A.Silvestri, arXiv:1809.01121)

Gearing up for the task

Noemi Frusciante

Bin Hu

Simone Peirone

Giampaolo Benevento

Alessandra Silvestri

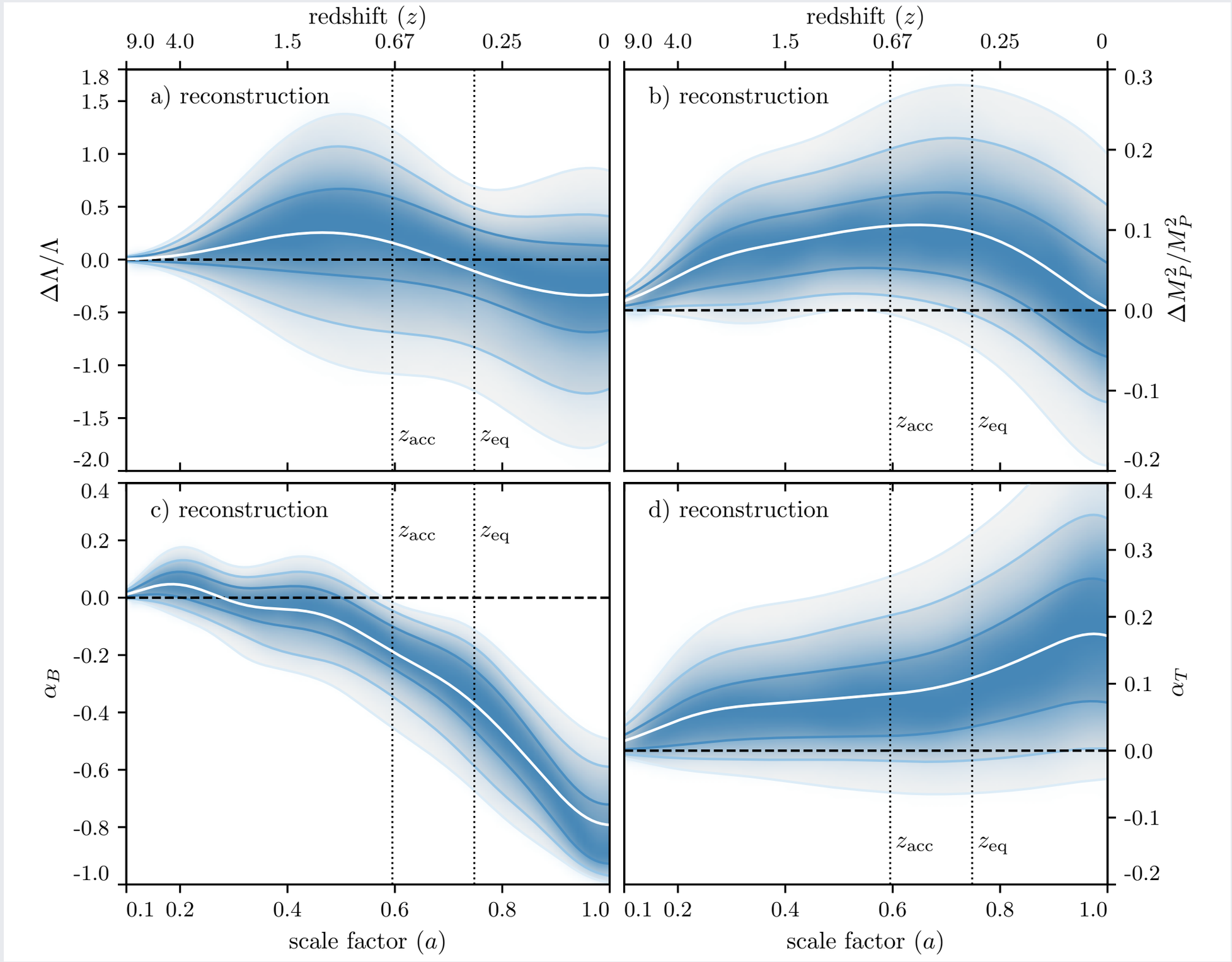
(a lot of hard work with G. Benevento, N.Frusciante, B.Hu, S.Peirone, A.Silvestri)

Gearing up for the task

Stack all available data power

- Planck CMB temperature, polarization and lensing
- Supernovae (Pantheon)
- BAO measurements (BOSS)
- Local Hubble constant measurements
- (linear) CFHTLenS shear measurements

Complete gravity reconstruction



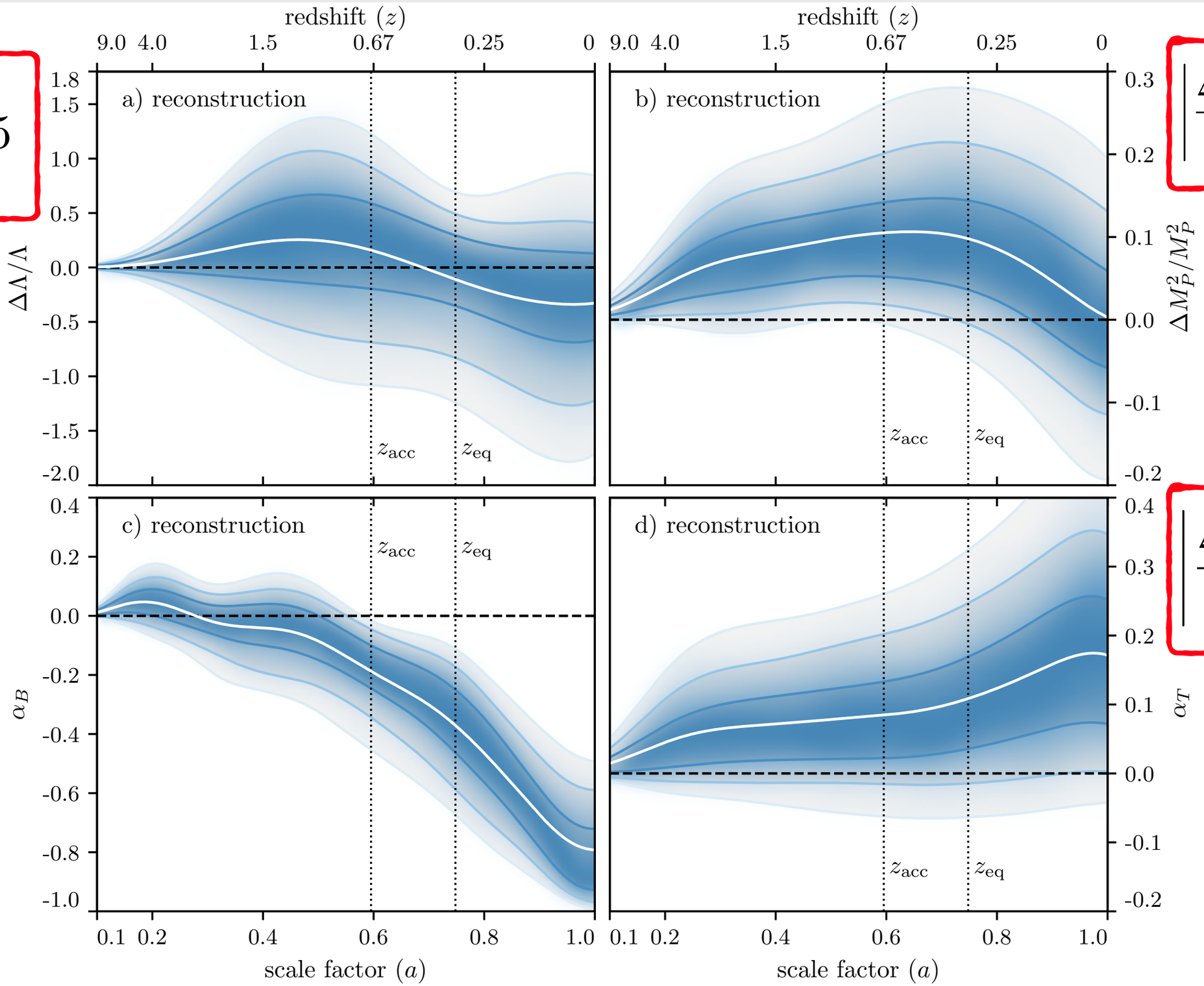
(MR, arXiv:1902.01366)

Complete gravity reconstruction

$$\left|\frac{\Delta\Lambda}{\Lambda}\right| \lesssim 1.5$$

$$\left|\frac{\Delta M_P}{M_P}\right| \lesssim 0.3$$

$$\left|\frac{\Delta c_T}{c_T}\right| \lesssim 0.4$$



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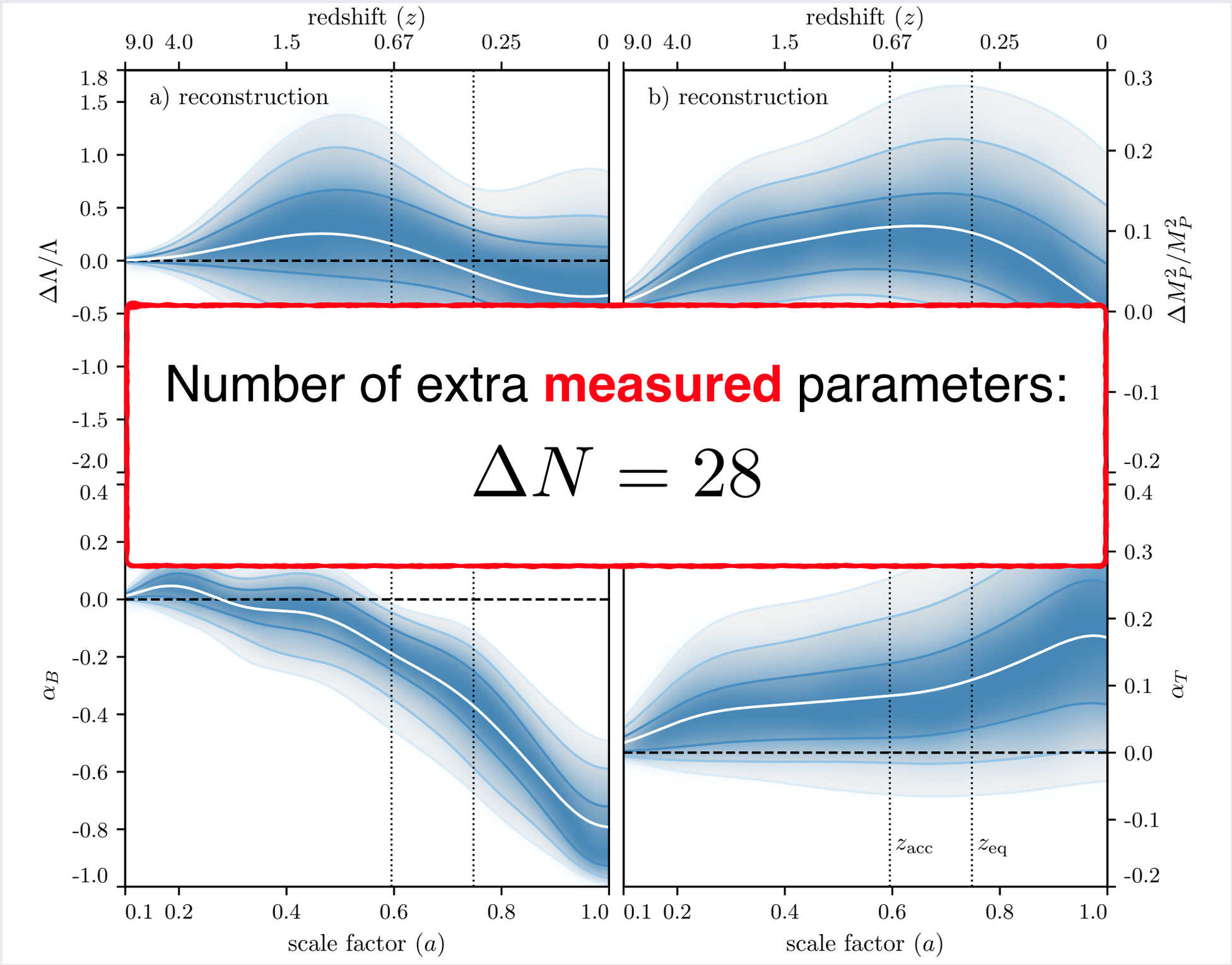

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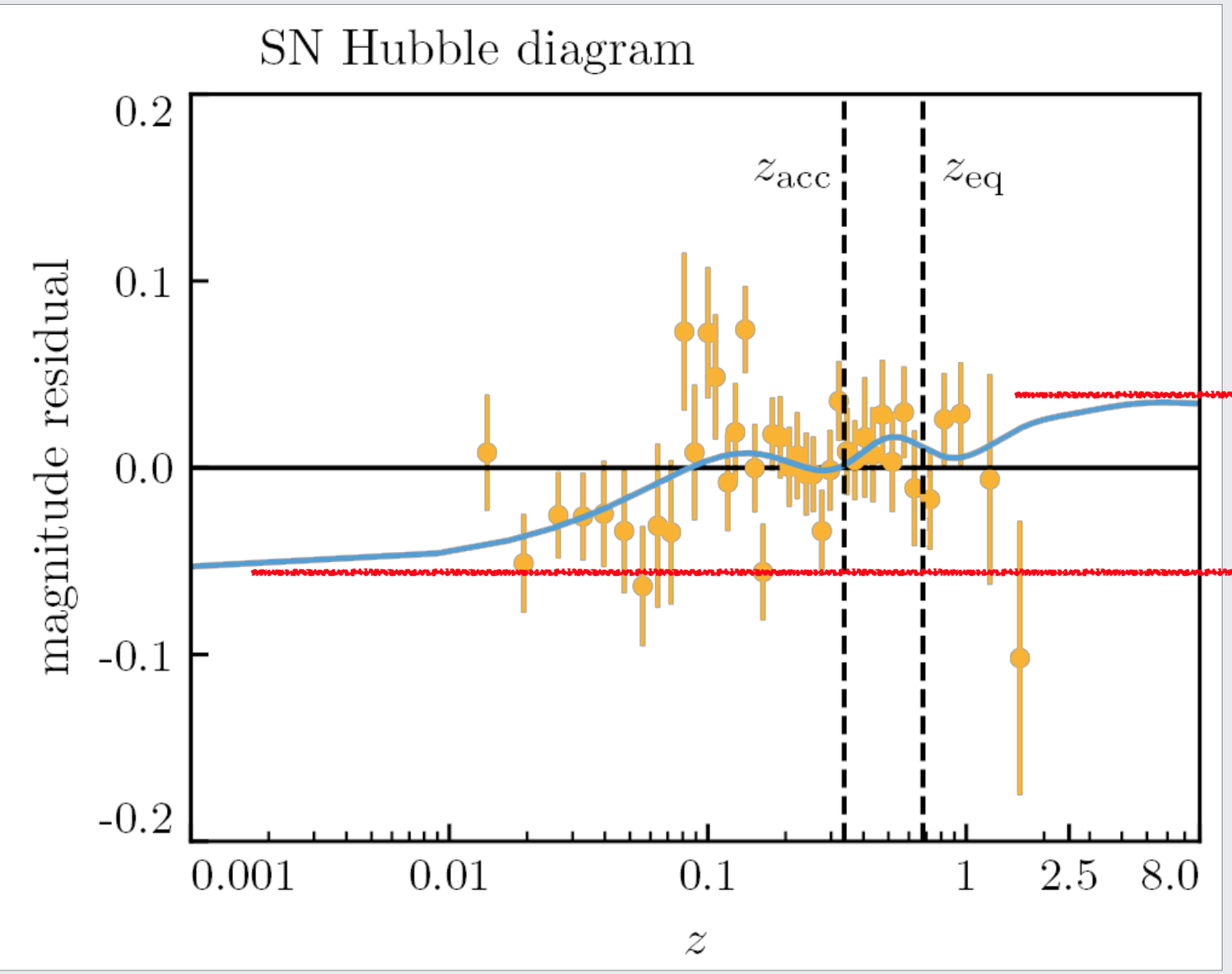
Role of the Hubble constant tension

best fit reconstruction



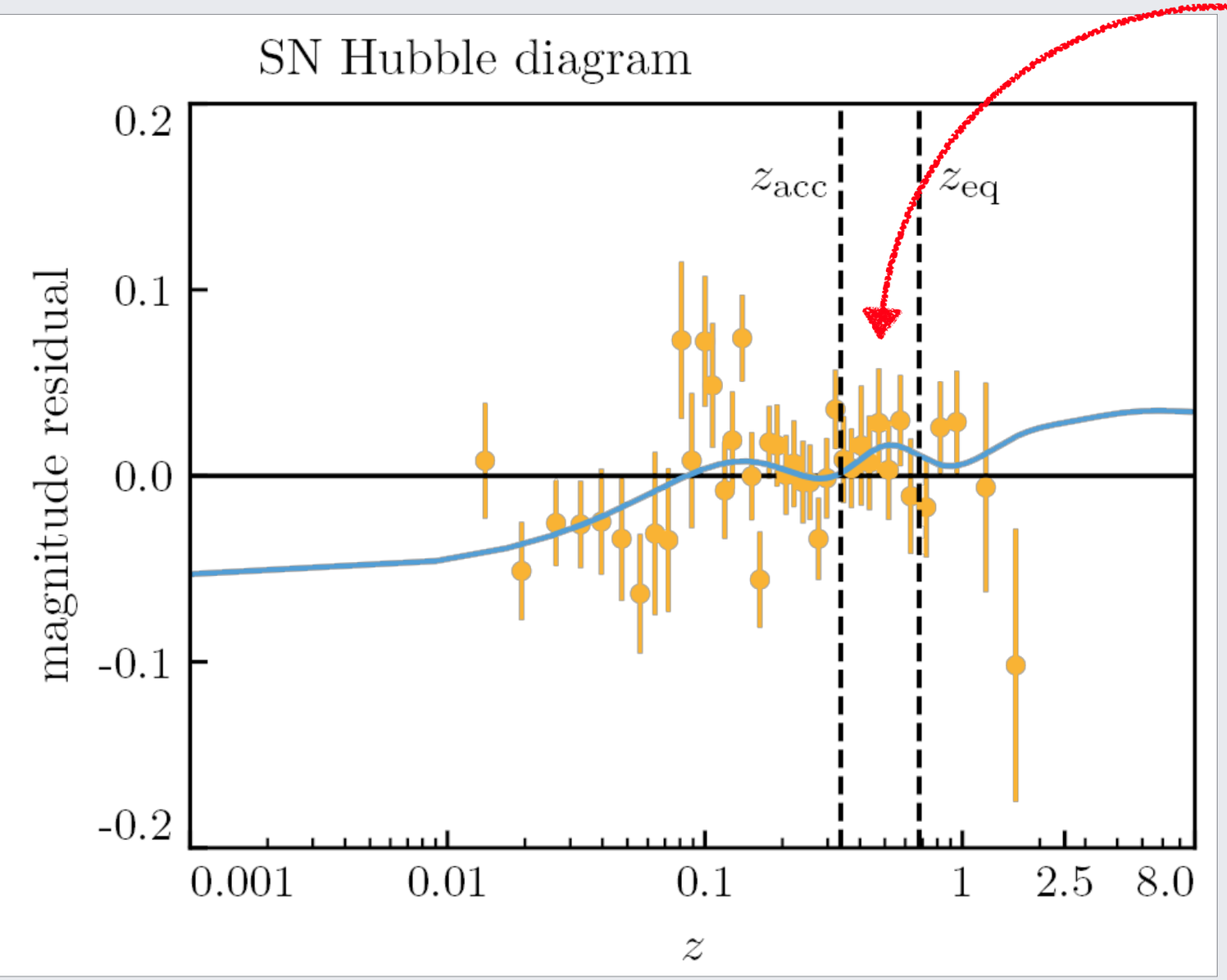
H0=71 vs H0=73.5

This is doing part of the H0 tension

Observational no-go

(MR, arXiv:1902.01366)

Role of the Hubble constant tension

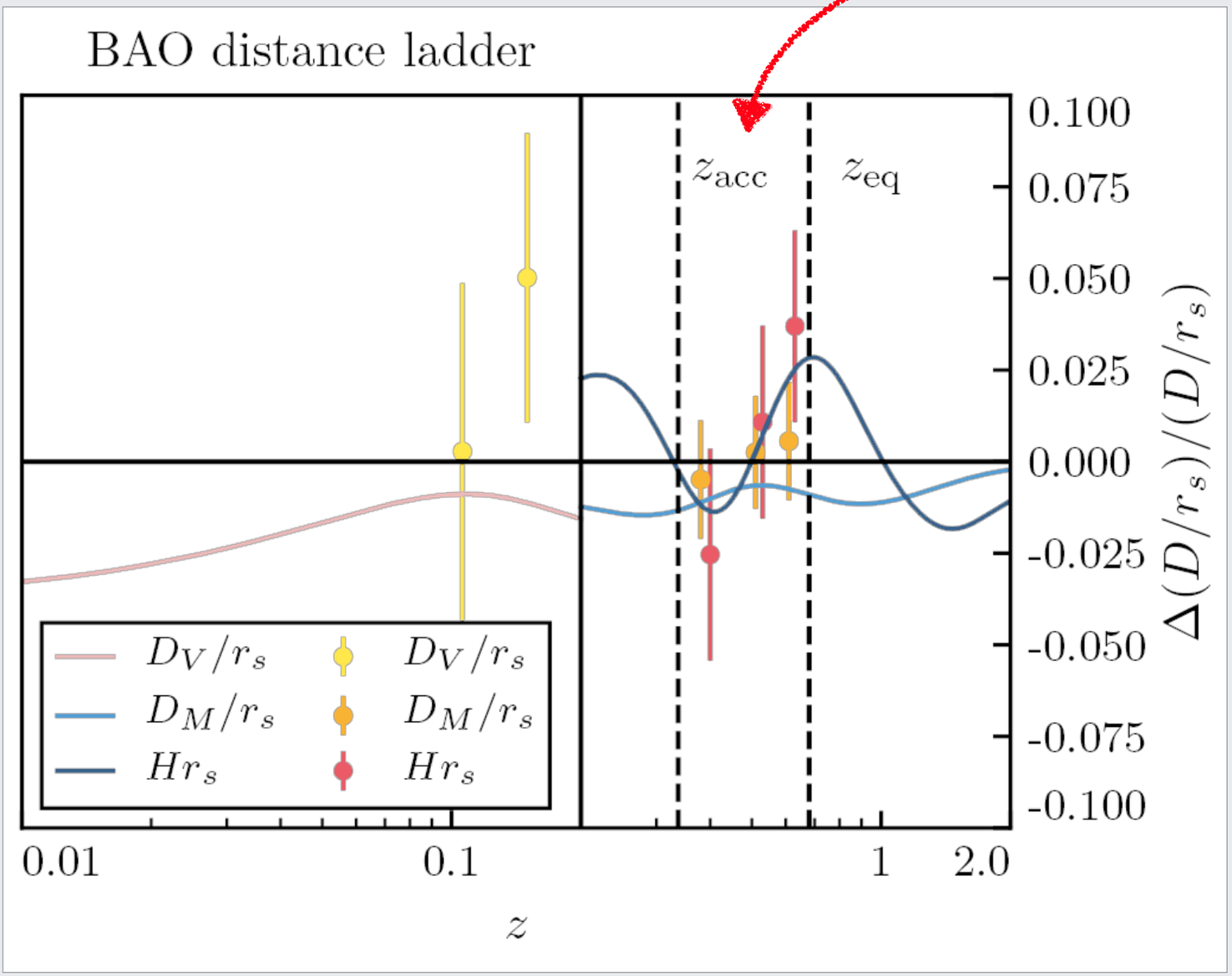


relies on this small feature

In model space this is achieved by changing both $\Lambda(z)$ and $M_P(z)$, and stabilizing the model with $\alpha_B(z)$.

(MR, arXiv:1902.01366)

The role of BAO



this is the
small feature

improved fit
to SN and BAO

Feature to look at as
data improves

(MR, arXiv:1902.01366)

Summary and outlook

- There is enough data power to constrain DE and Gravity on cosmological scales, as a function of time. **What did we learn for specific models?**

- Current constraints are still O(10%). **Future constraints?**

- Guaranteed to find features in the data (if there). **Will they remain there?**

- At present observational no-go for late time solutions of the Hubble constant tension

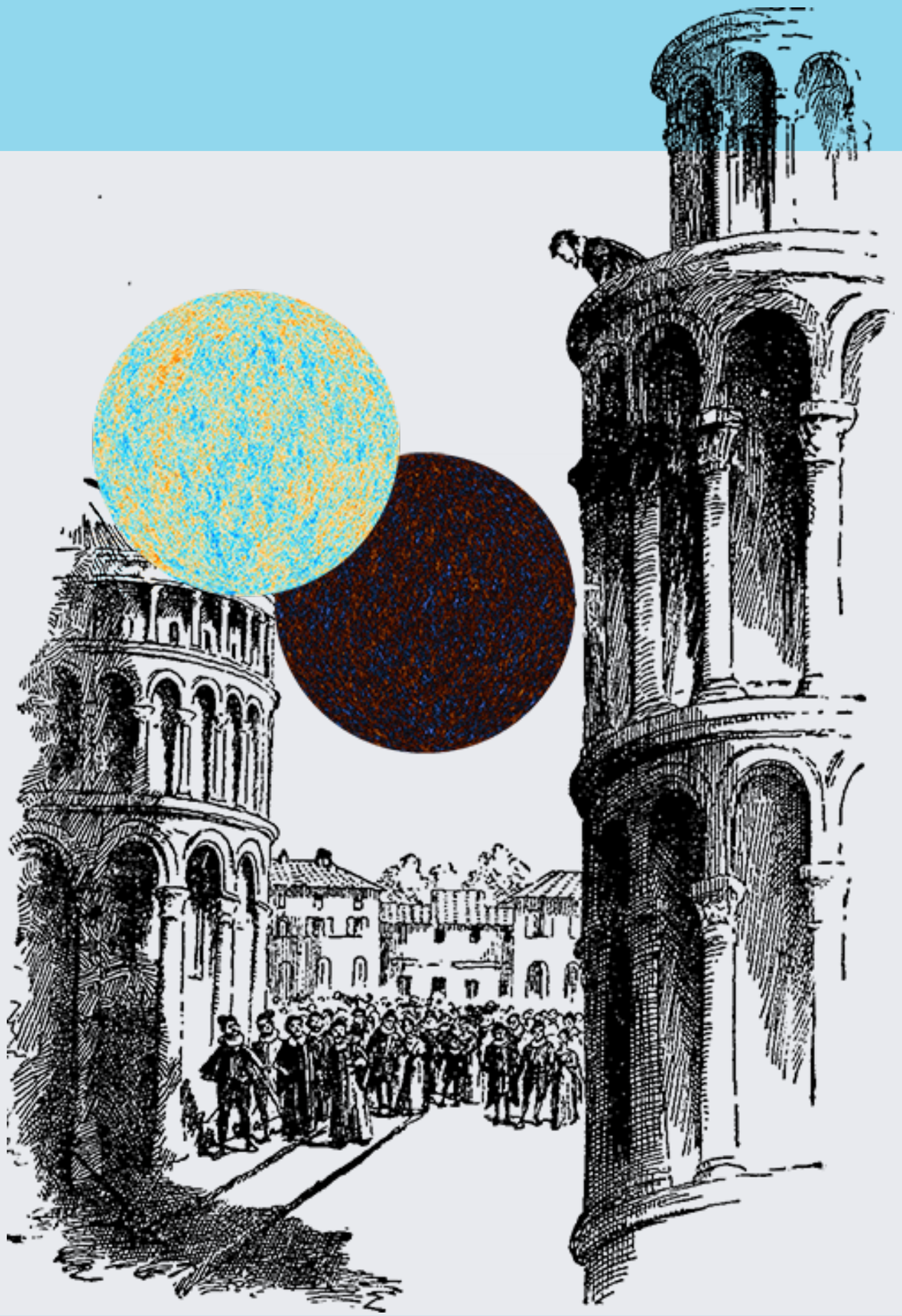
Summary and outlook

Practical feasibility scales logarithmically

Testing gravity

↓

Learning gravity



(Reinterpretation of Galileo's leaning tower of Pisa experiment)