Fundamental physics from the Lyman-alpha forest

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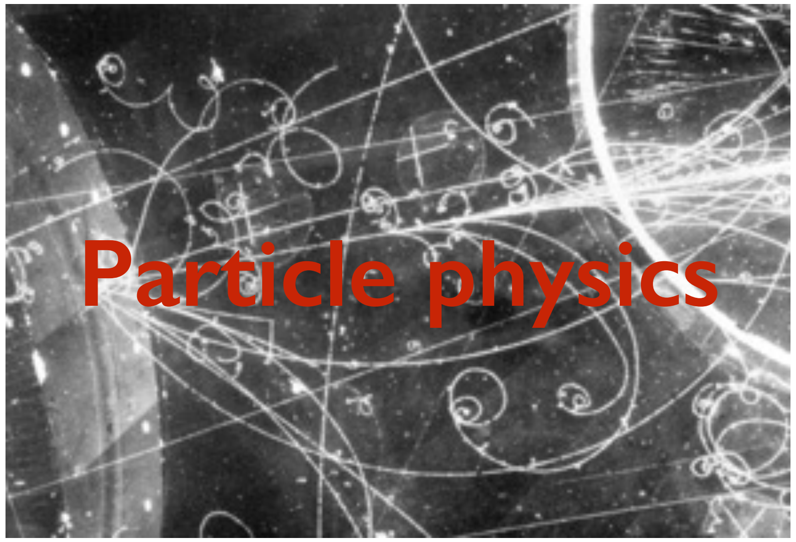
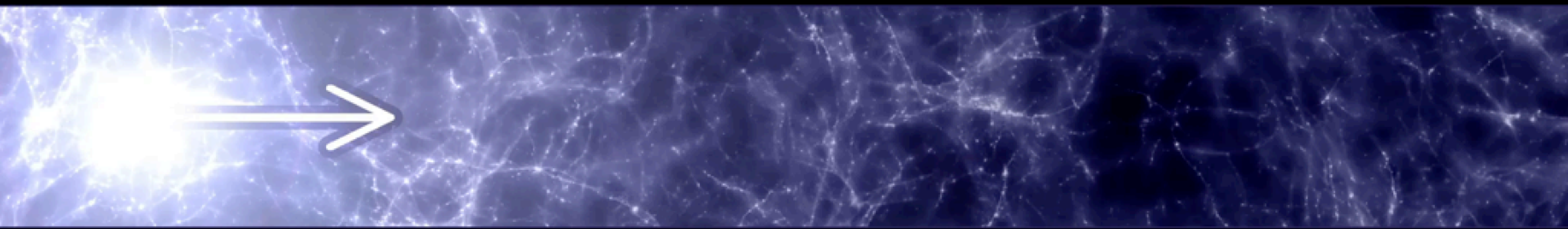
Stockholm University

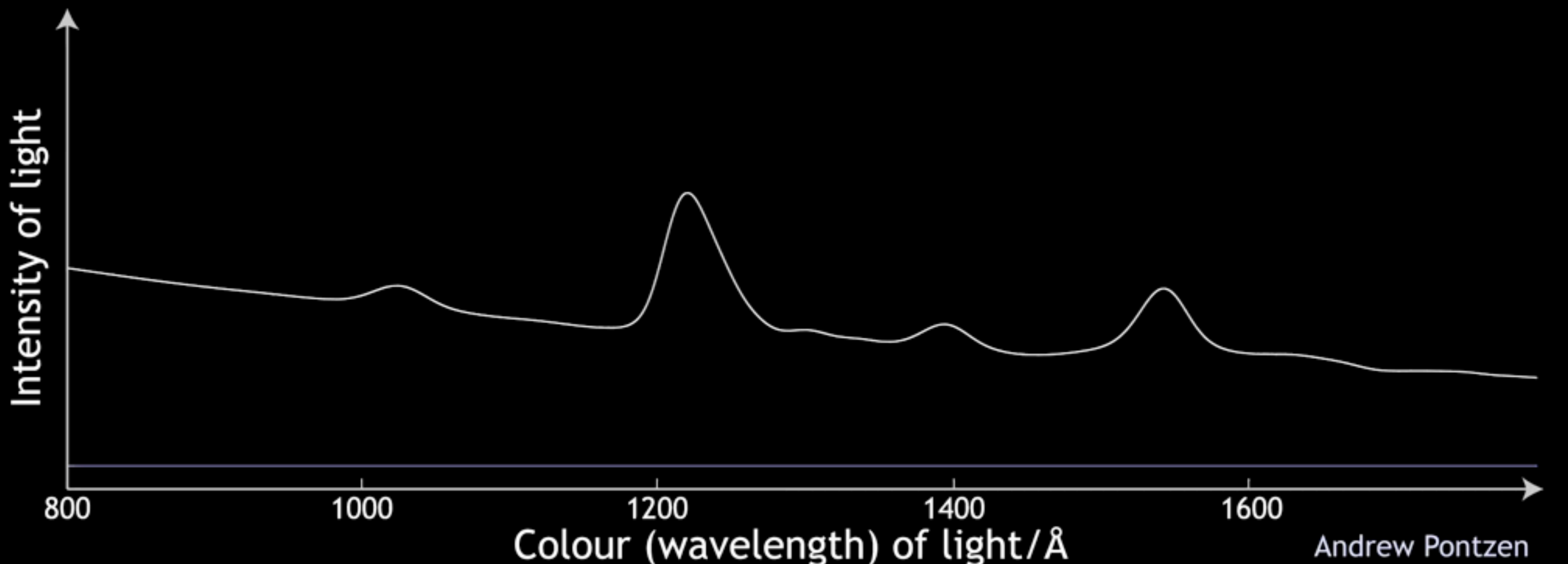
Beyond the Standard Models of…



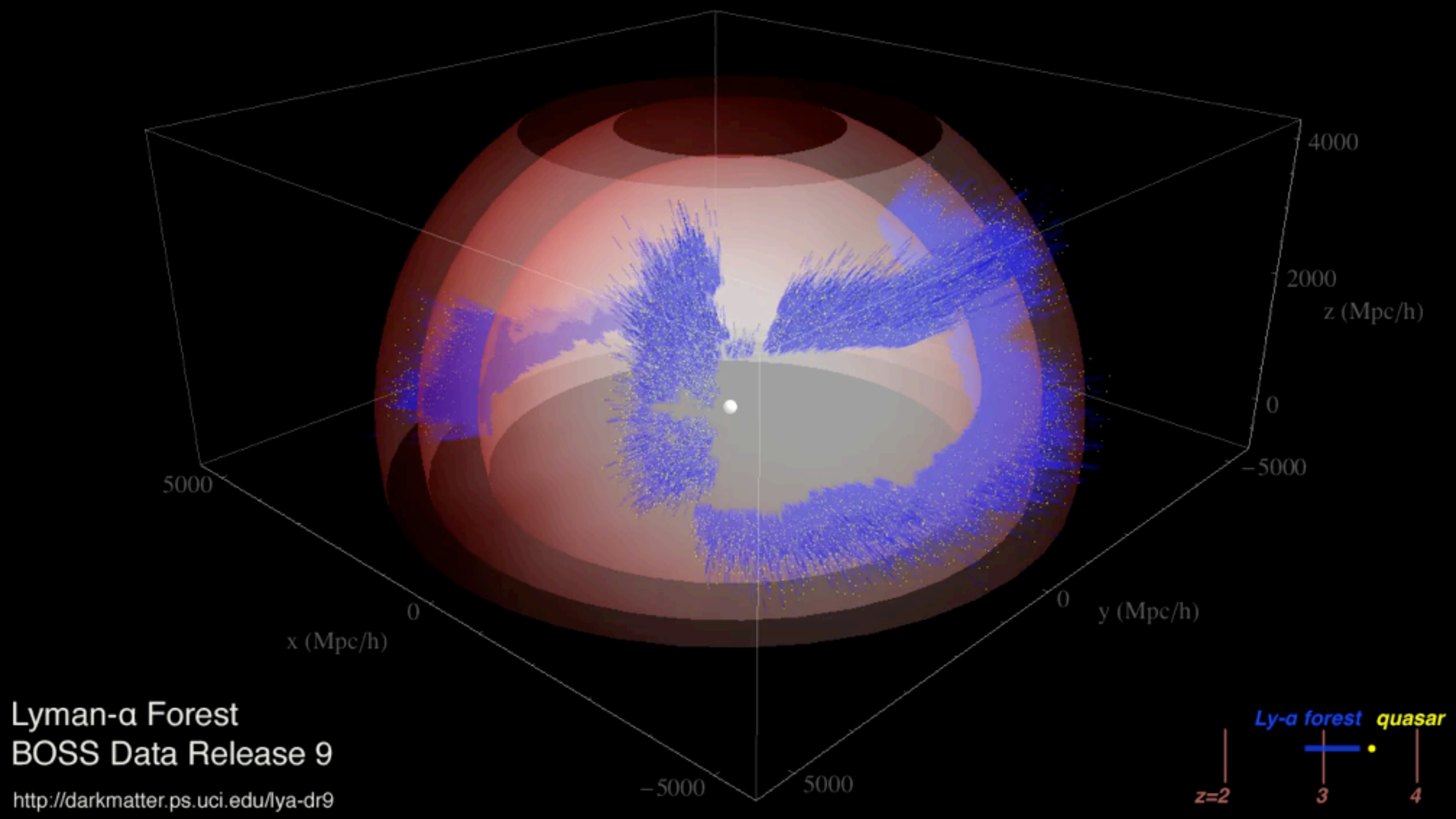
- Lyman-alpha forest probes **early Universe from small to large scales**
- Need to **disentangle cosmology and astrophysics** of intergalactic medium
- **High-density hydrogen absorbers** & **patchy reionisation**
- Need "emulator" for **statistical inference with cosmological simulations**

The Lyman-alpha forest

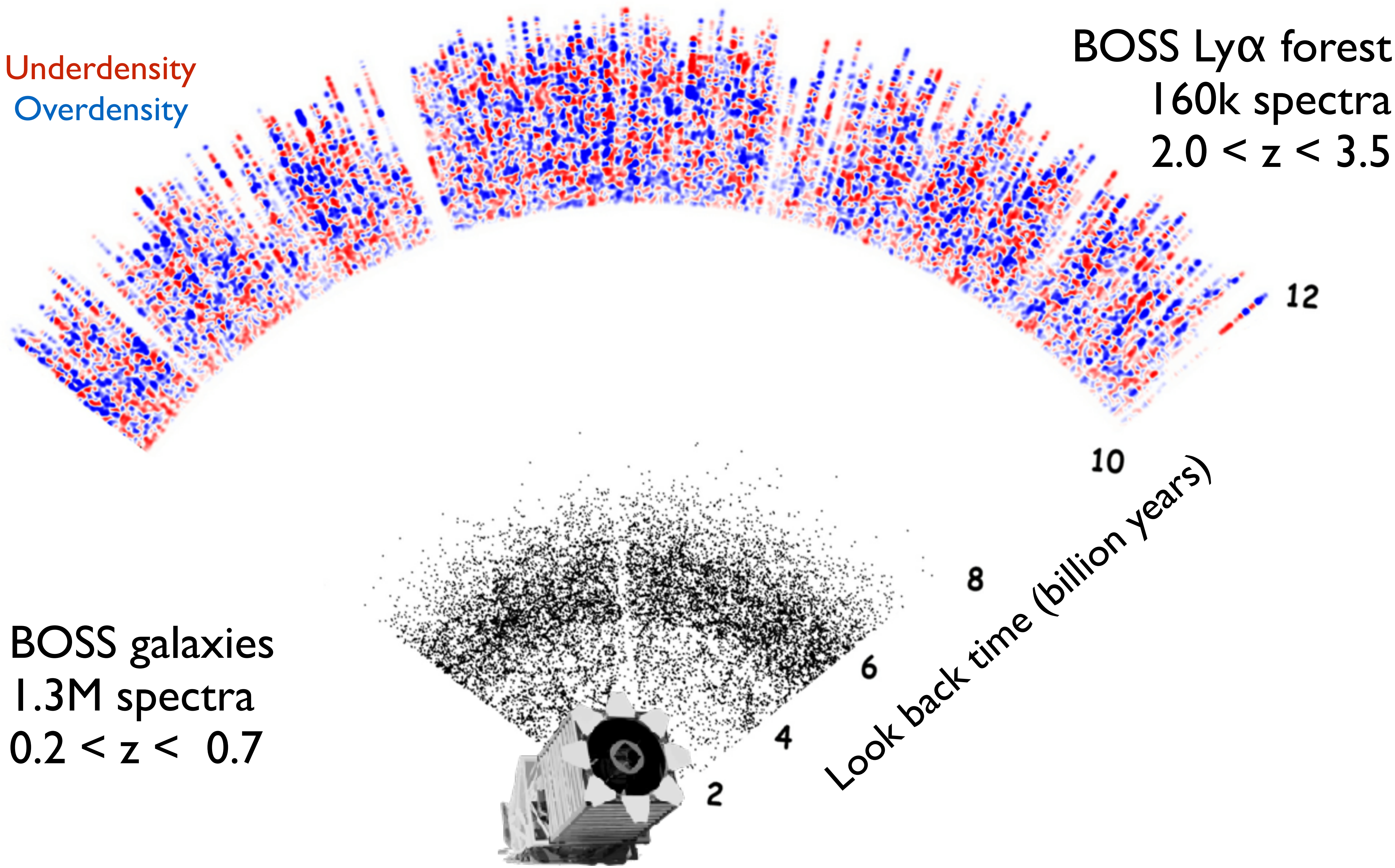




Lyman-alpha forest surveys

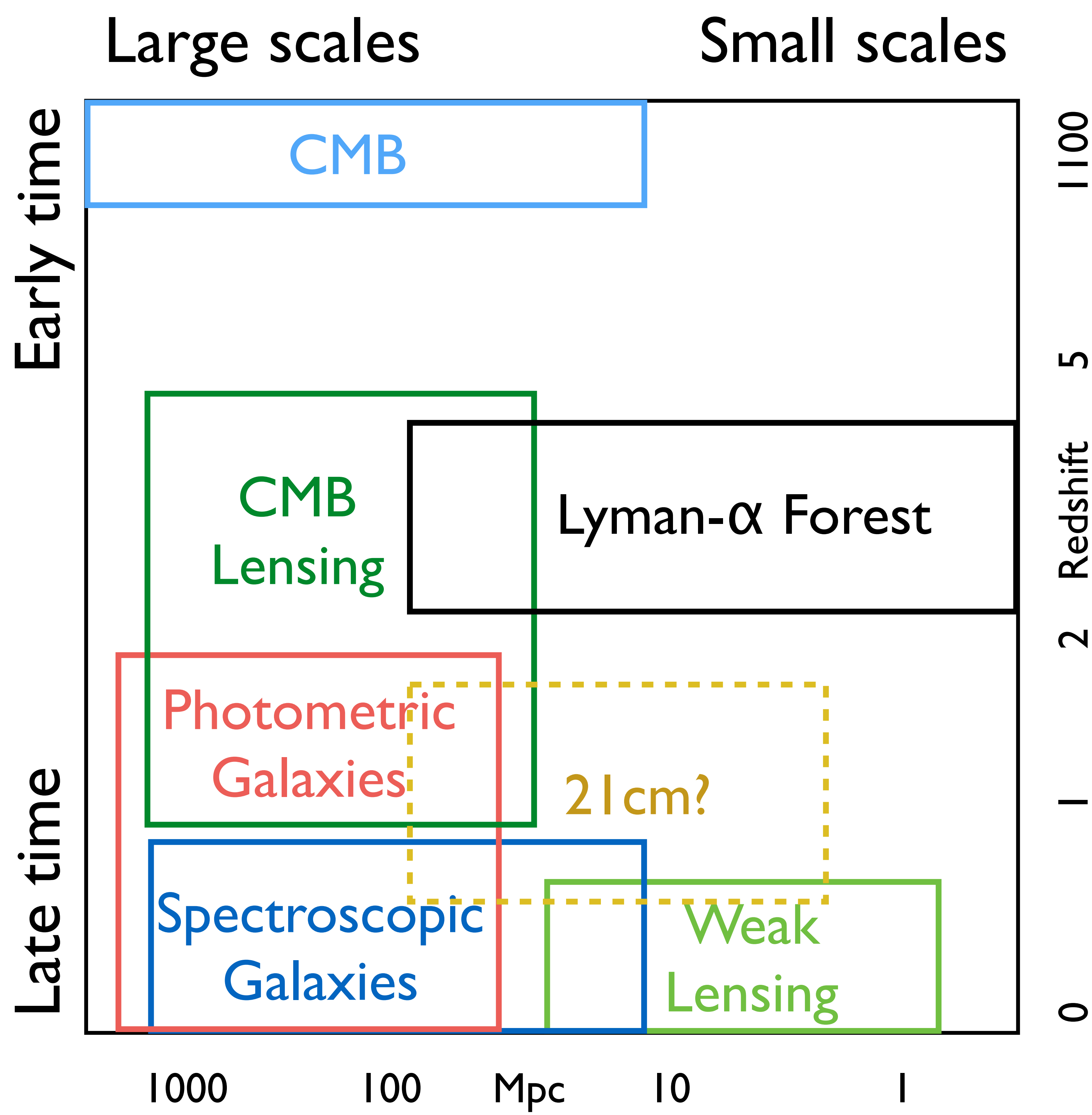


The Lyman-alpha forest traces matter at high redshift

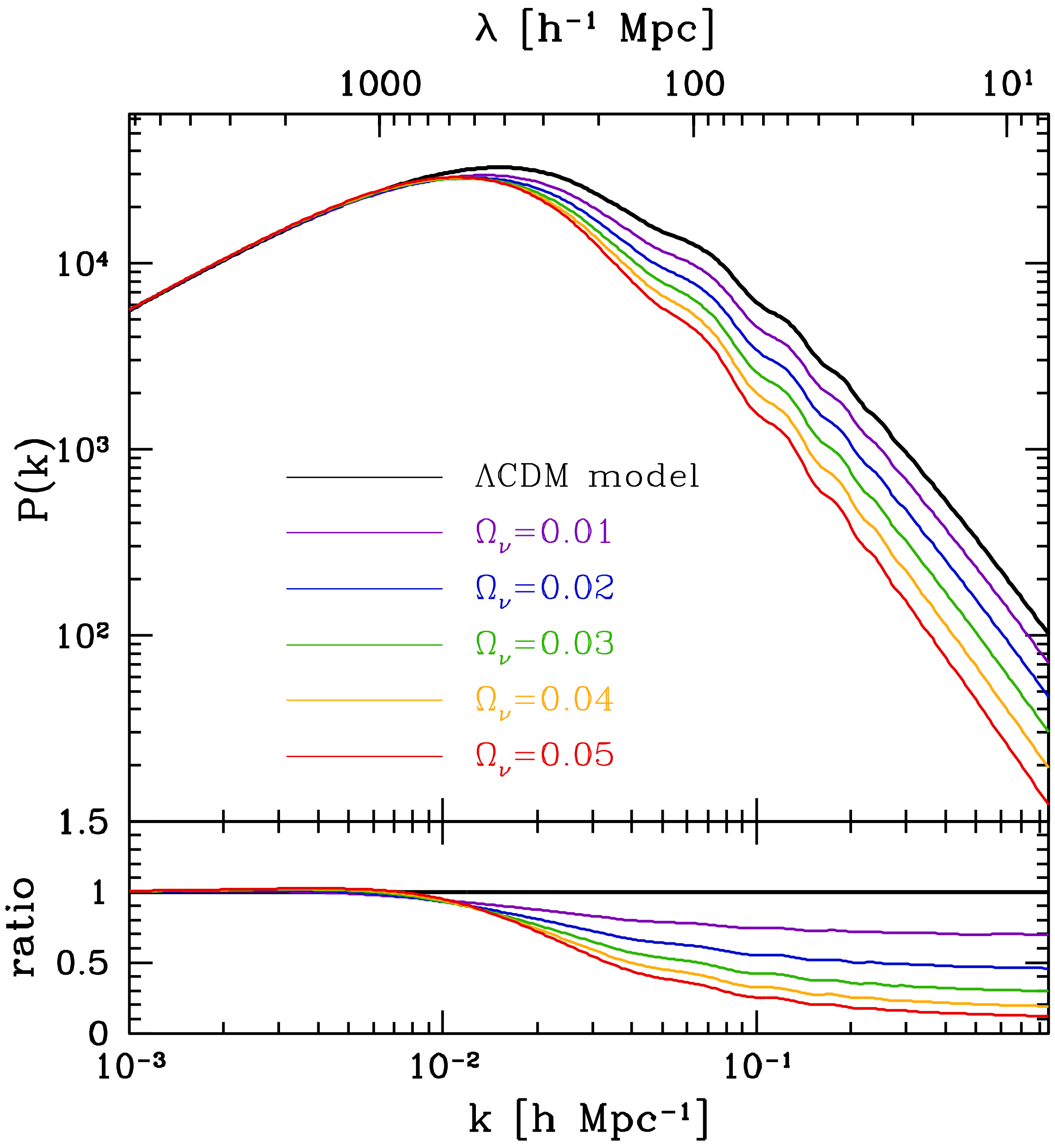


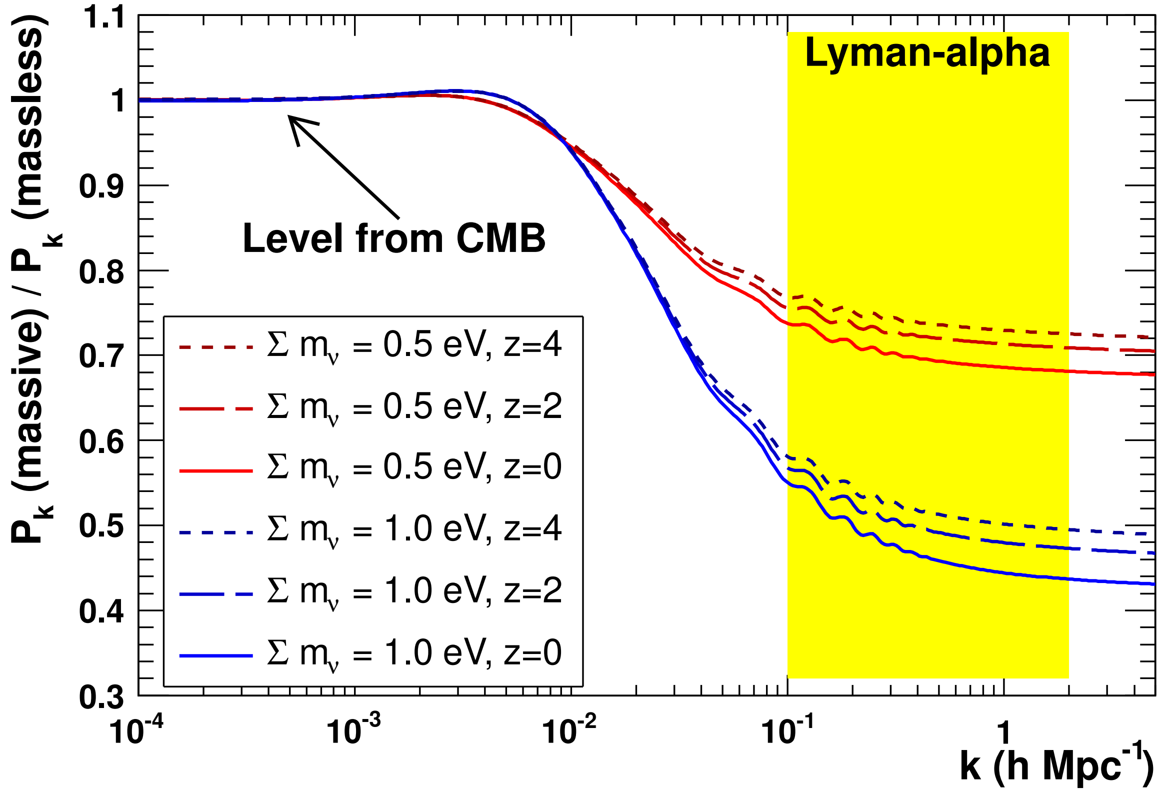
Andreu Font-Ribera

The Lyman-alpha forest traces linear-order matter fluctuations at high redshift from large to small scales



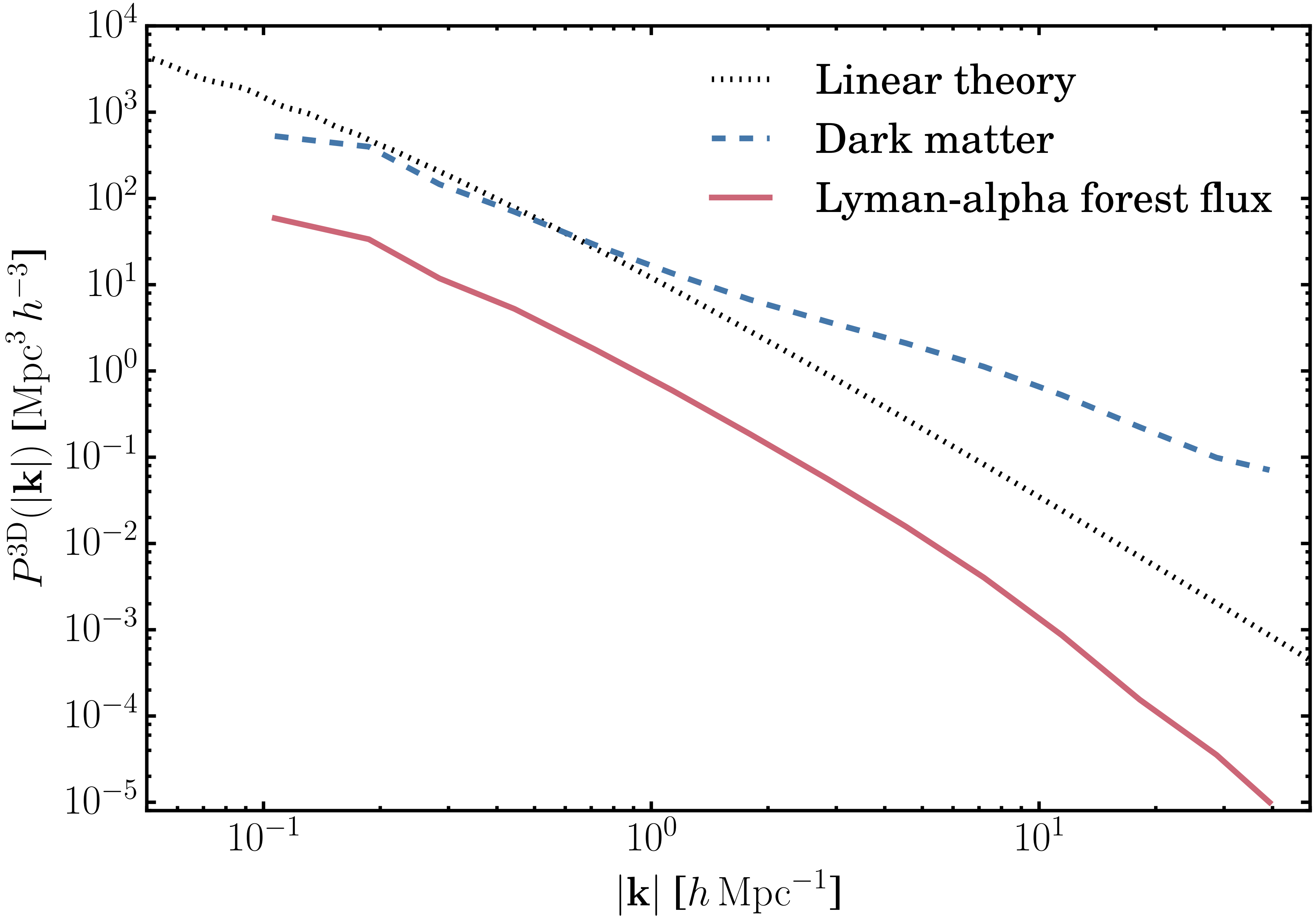
Massive neutrinos





Park et al. (2012); Palanque-Delabrouille et al. (2015)

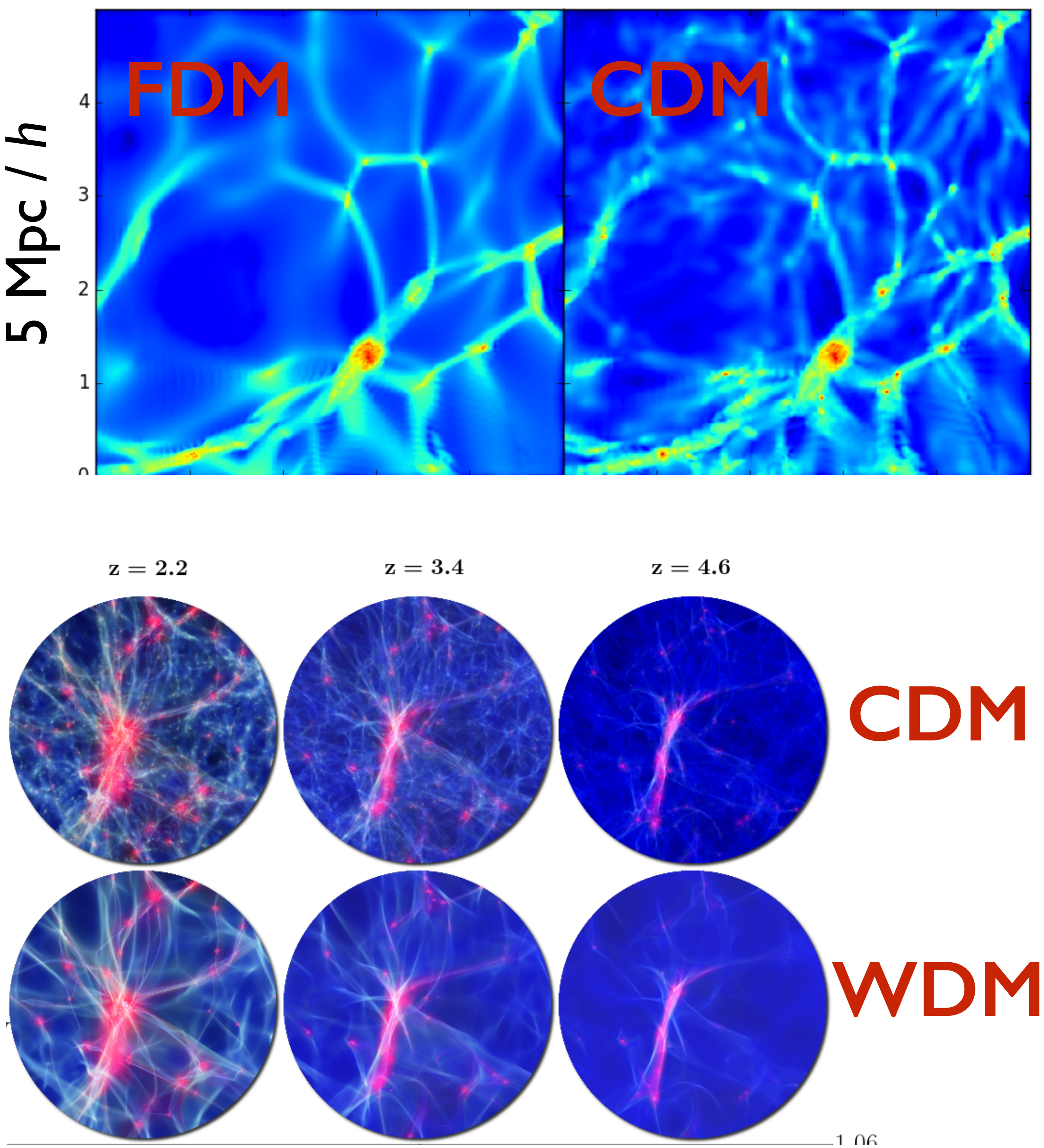
Primordial power spectrum from the Lyman-alpha forest

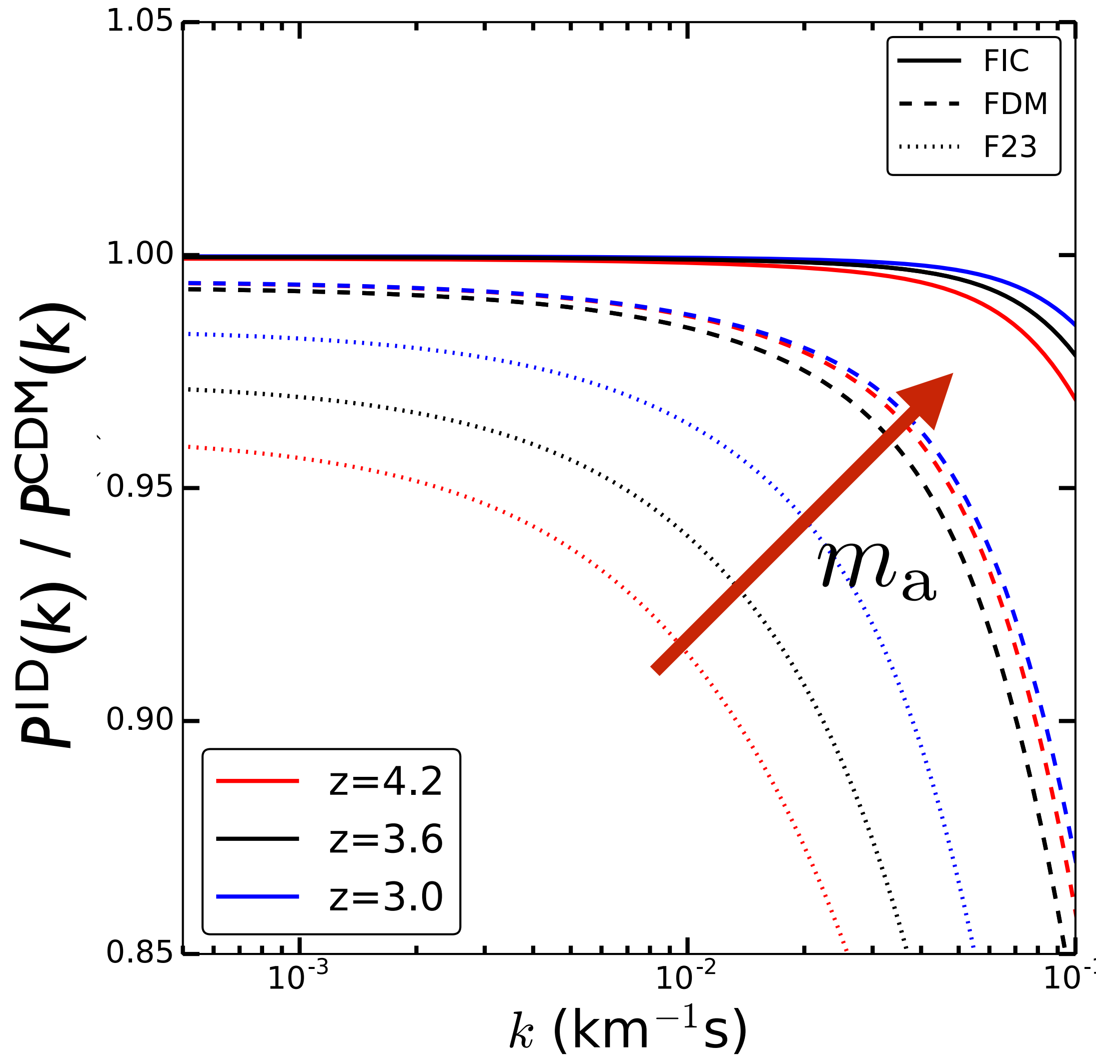


Rogers et al. (2018)

Ultra-light axion (fuzzy) dark matter [FDM]

+ warm dark matter [WDM] / interacting dark matter



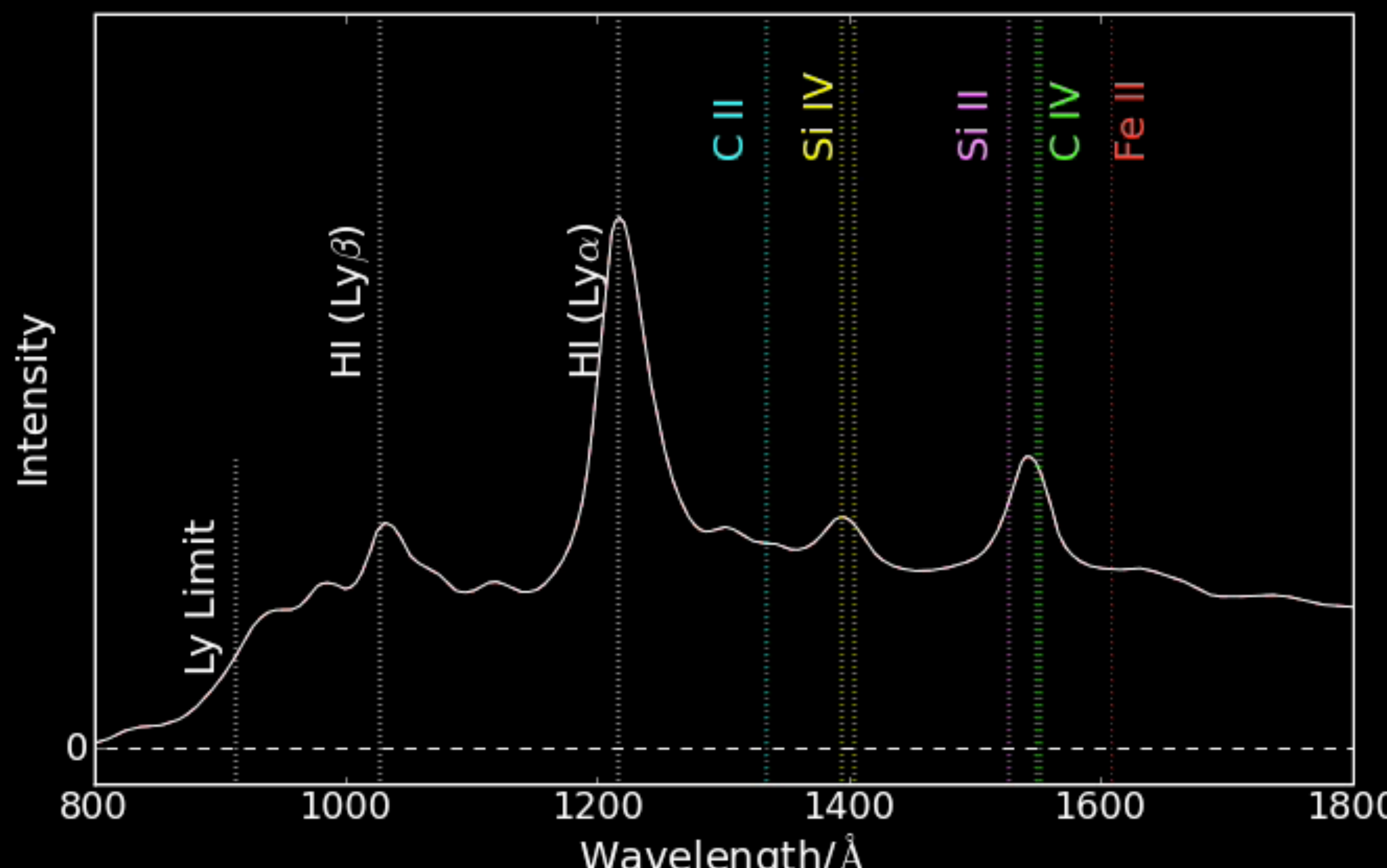


Armengaud et al. (2017); Zhang et al. (2017); Baur et al. (2016); Rogers et al. (in prep.)

Dense hydrogen absorbers

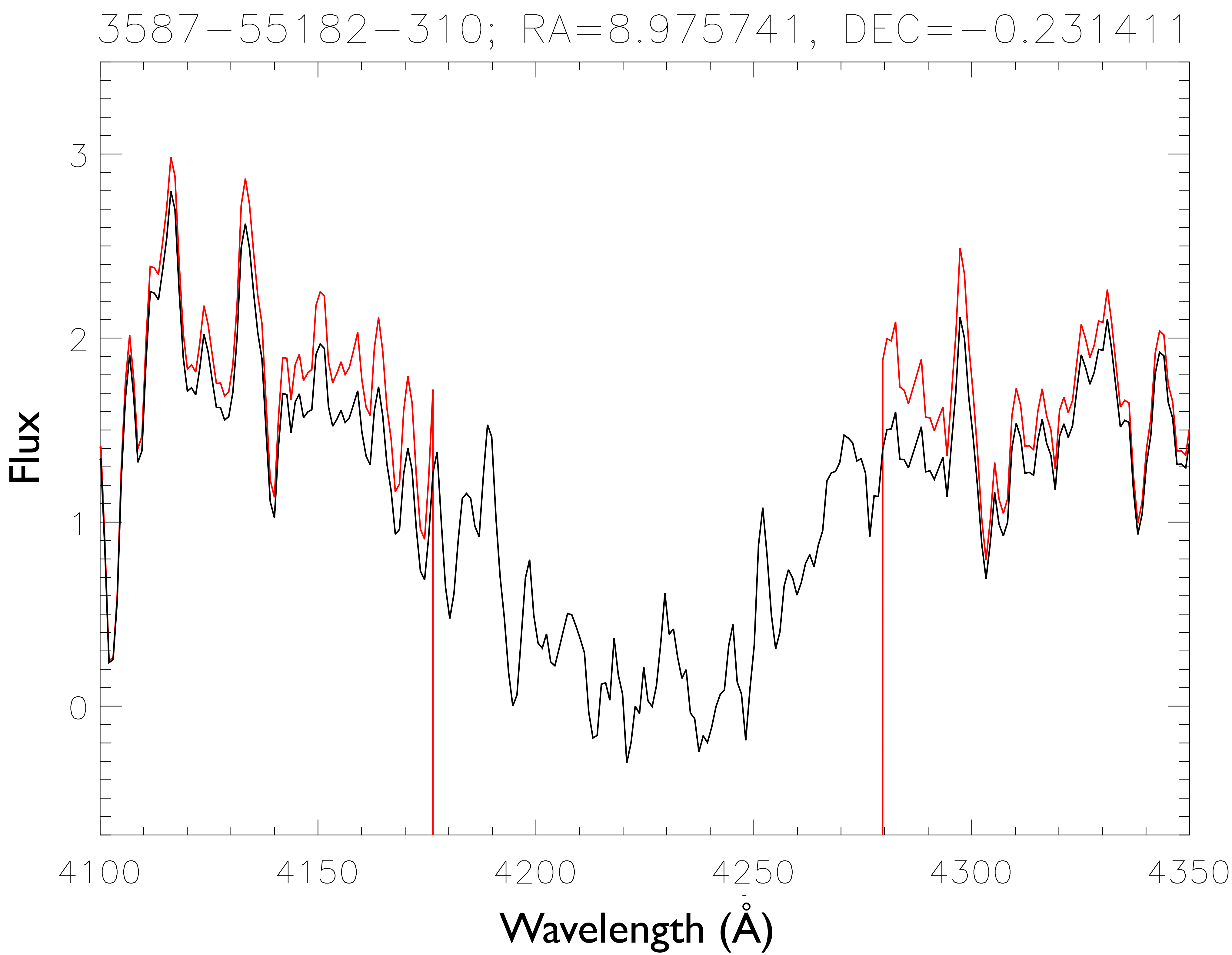
K. Rogers *et al.*, 2018, MNRAS, 474, 3032
K. Rogers *et al.*, 2018, MNRAS, 476, 3716

High column density hydrogen absorbers are leading "foreground" to the Lyman-alpha forest

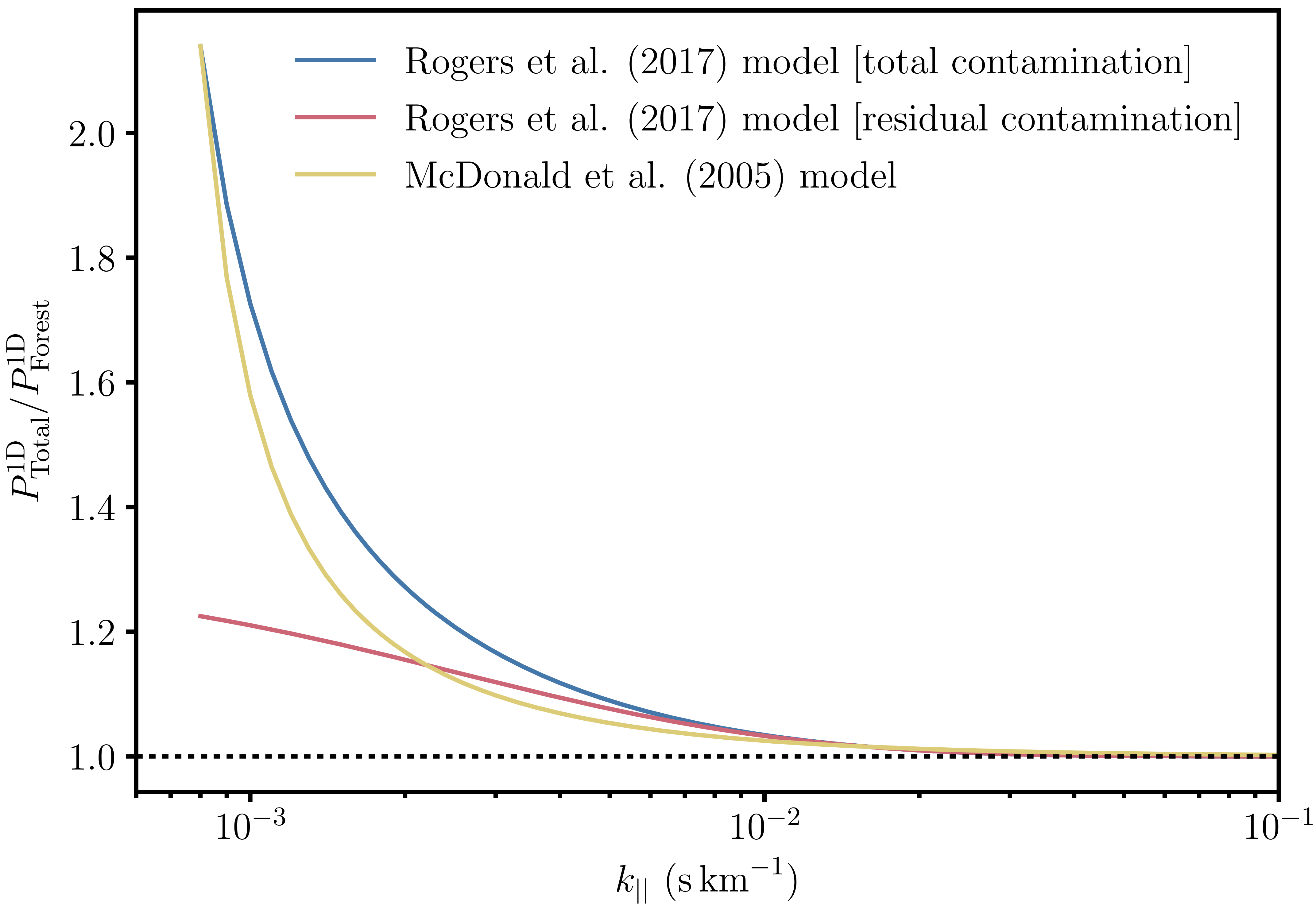


Illustris cosmological hydrodynamical simulations

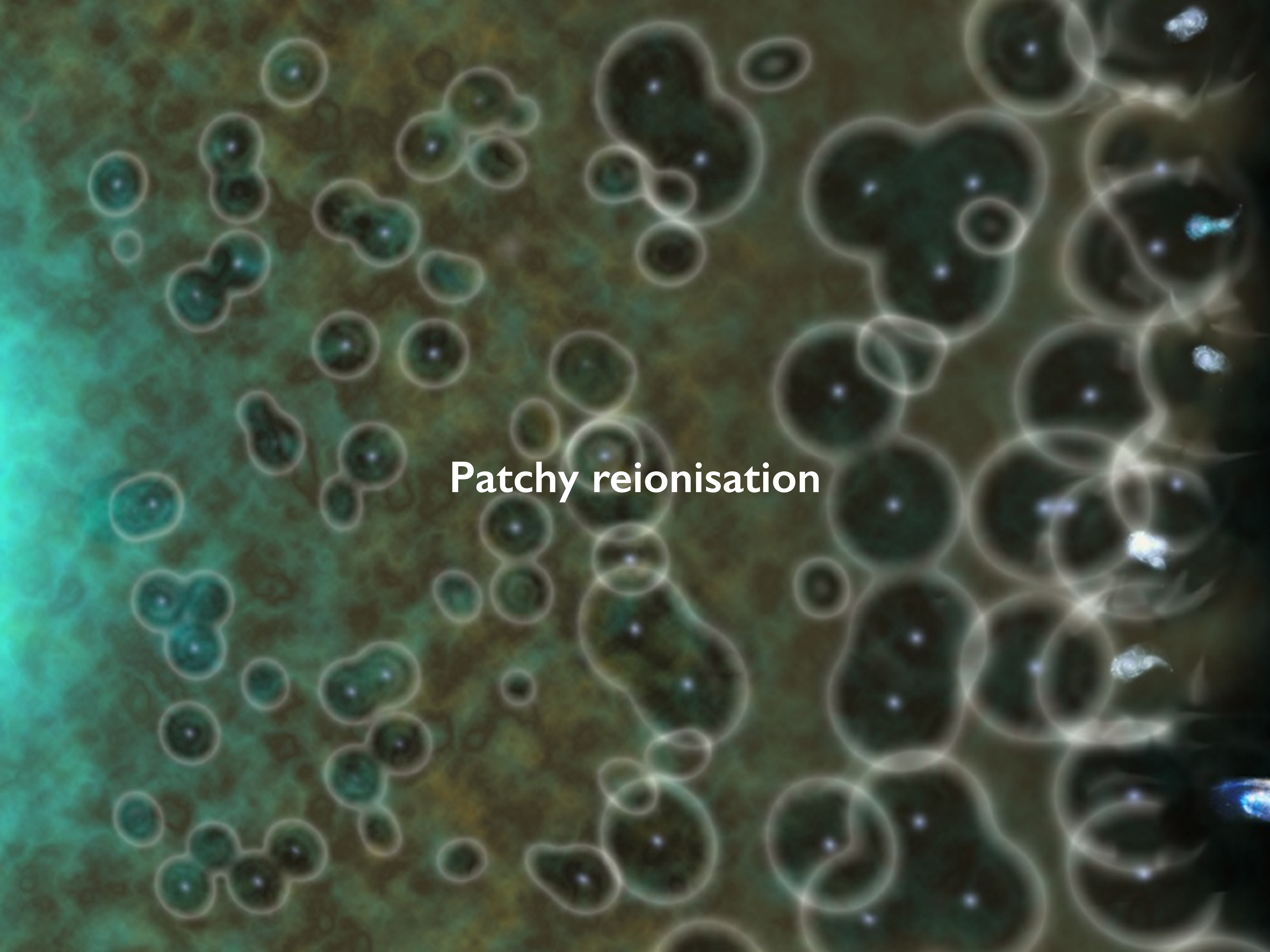
Densest systems are identified and masked but there always remains a residual contamination



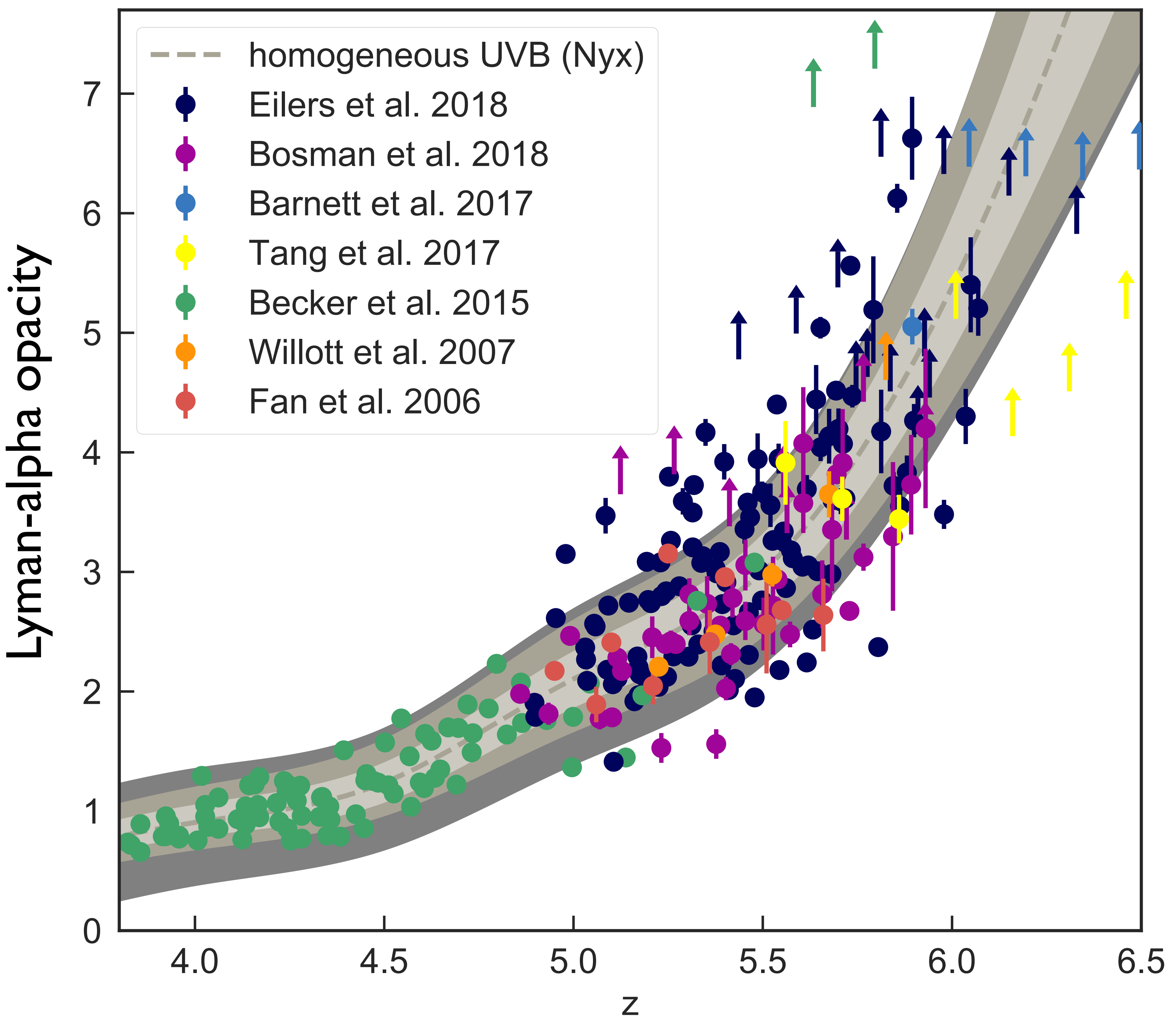
Scale-dependent bias of residual contamination is very different to previous models of total contamination



Patchy reionisation

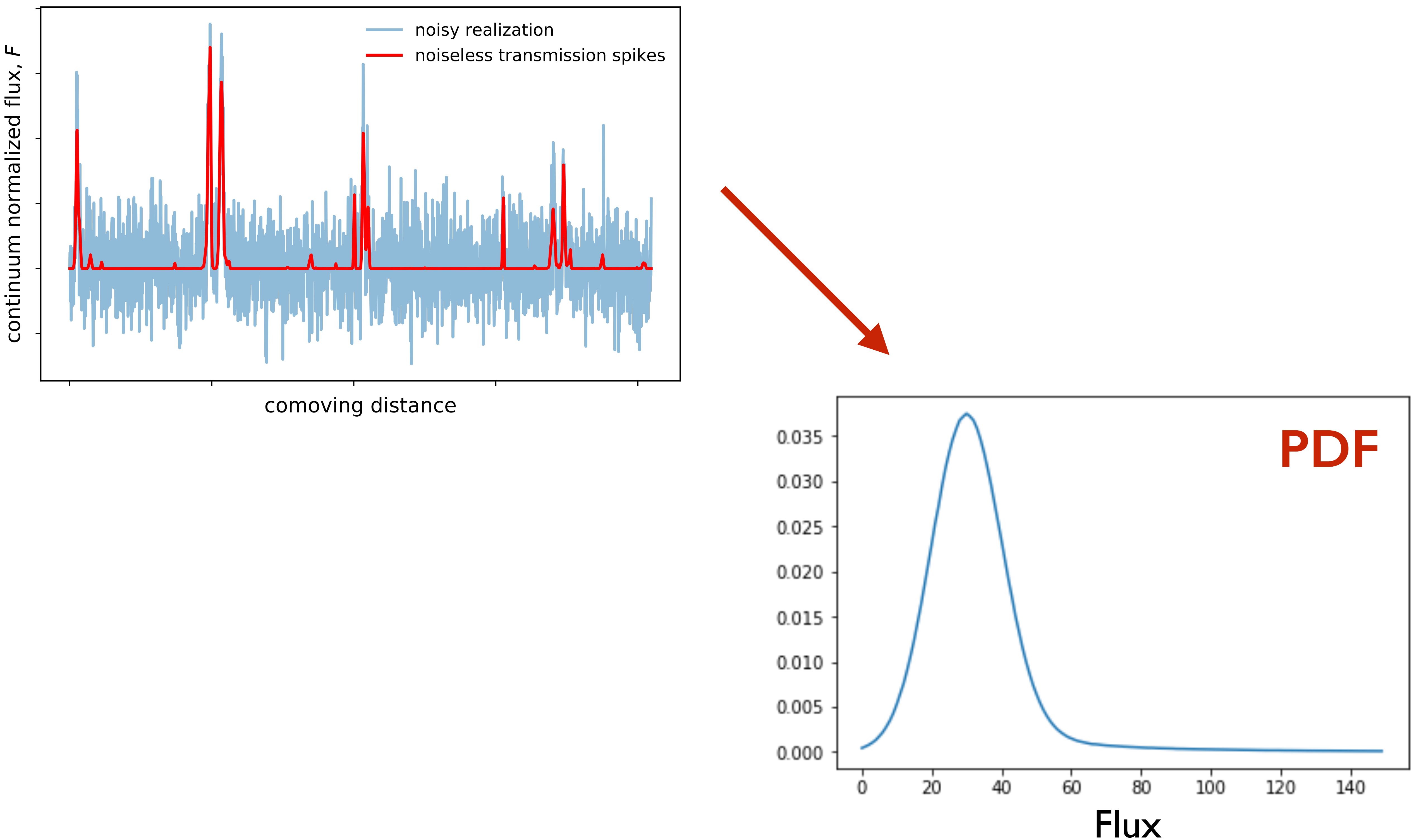


The observed scatter in Lyman-alpha opacities at z > 5 cannot be explained by density fluctuations alone



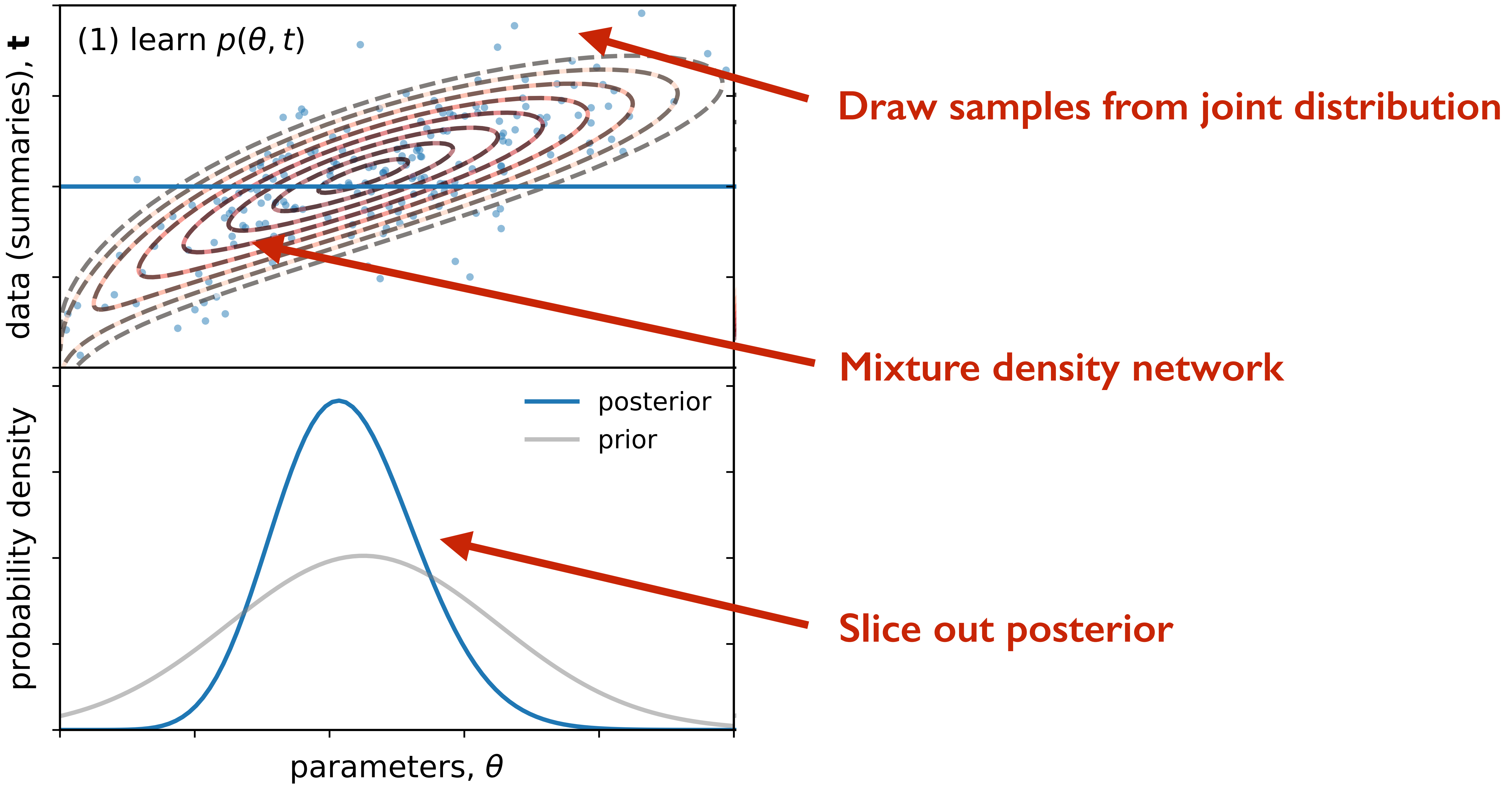
Eilers et al. (2018)

There is un-extracted information in the full distribution of transmission spikes



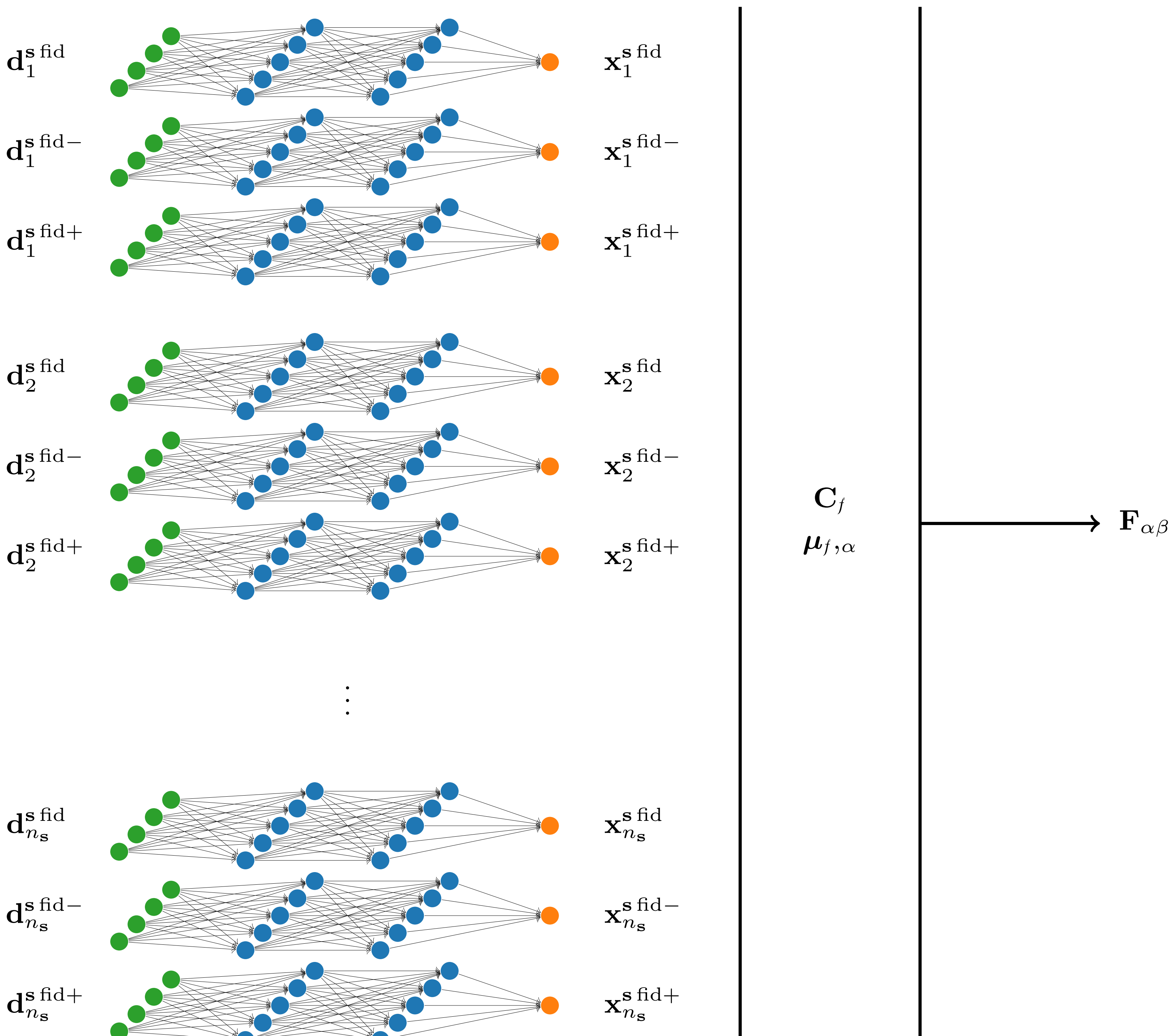
Rogers & Alsing (in prep.)

Density-estimation likelihood-free inference

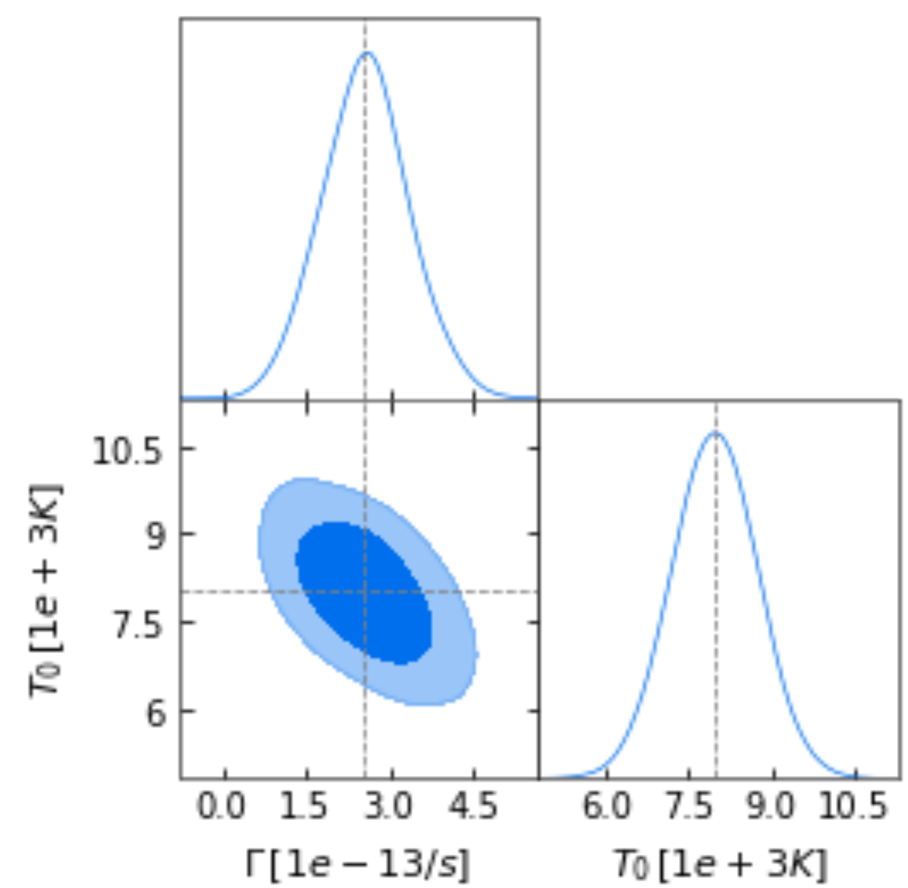


Alsing et al. (2019); Rogers & Alsing (in prep.)

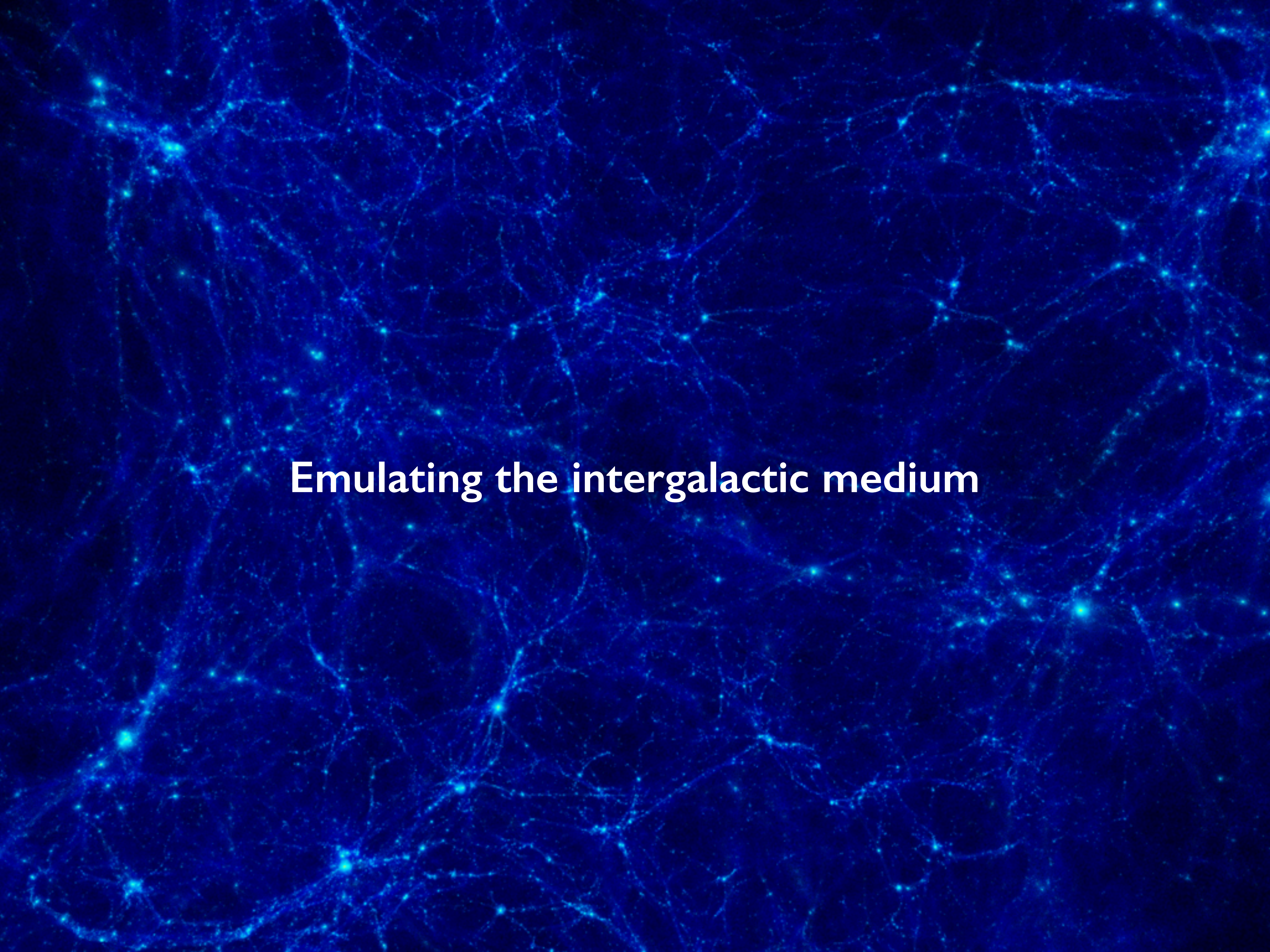
Information-maximising neural networks



IMNN + DELFI



Charnock et al. (2018); Rogers & Alsing (in prep.)



Emulating the intergalactic medium

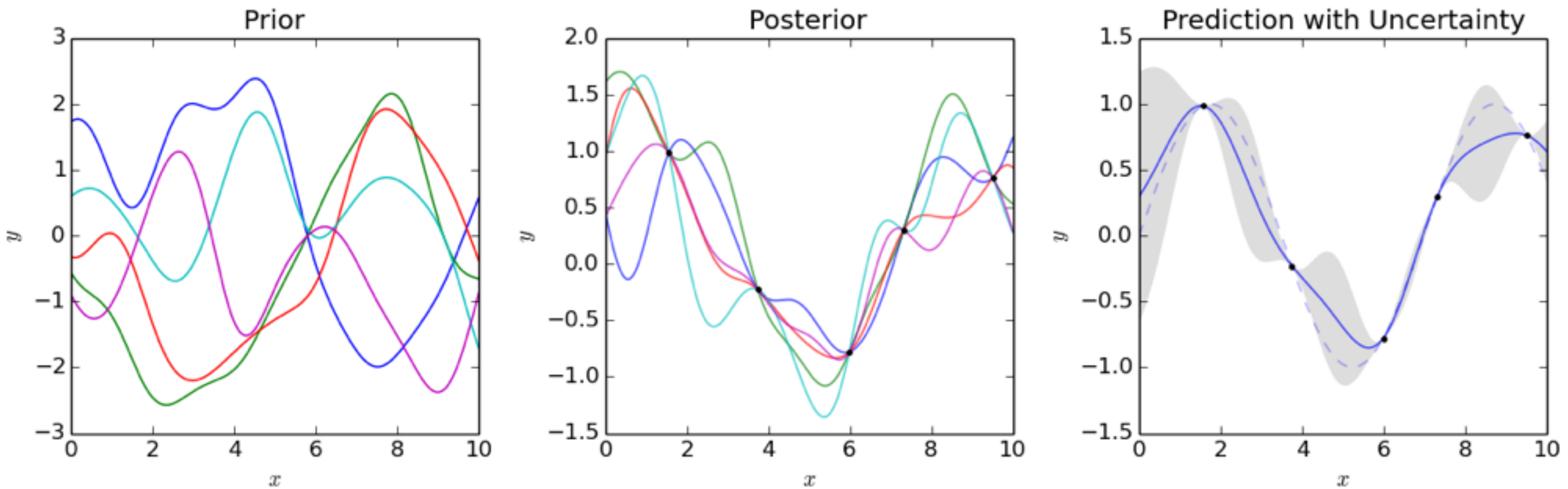
Stockholm University

Oskar Klein centre

arxiv: 1812.04631, 1812.04654

K. Rogers, H. Peiris, *et al.*, 2019, JCAP, 02, 031
S. Bird, K. Rogers, *et al.*, 2019, JCAP, 02, 050

Gaussian process model allows probabilistic interpolation of cosmological simulations



$$f(\mathbf{x}) \sim \mathcal{N}(0, K(\mathbf{x}, \mathbf{x}'; \theta))$$

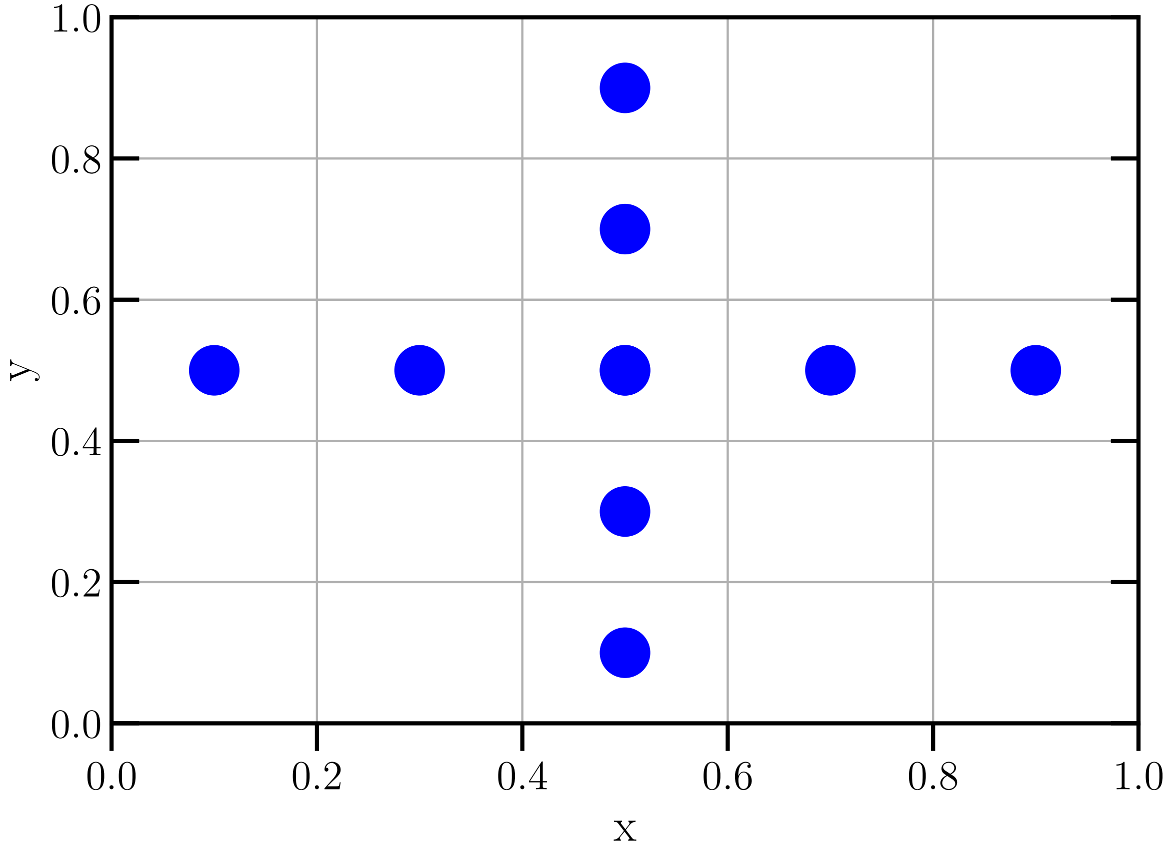
Simulation output

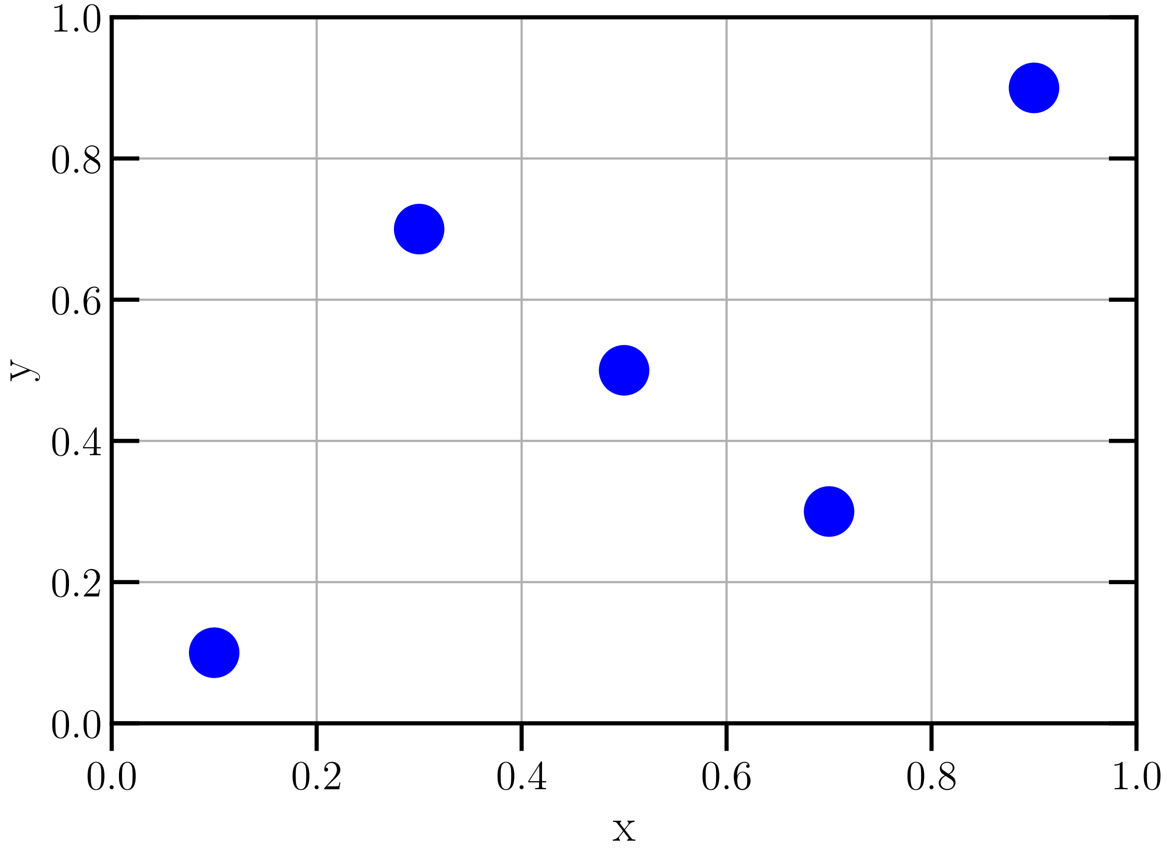
Simulation parameters

Kernel hyperparameters

PPD: $p(f(\mathbf{x}^*)|f(\mathbf{x}), \mathbf{x}, \mathbf{x}^*) \sim \mathcal{N}(K_* K^{-1} f(\mathbf{x}), K_{**} - K_* K^{-1} K_*^{\mathrm{T}})$

We need an emulator



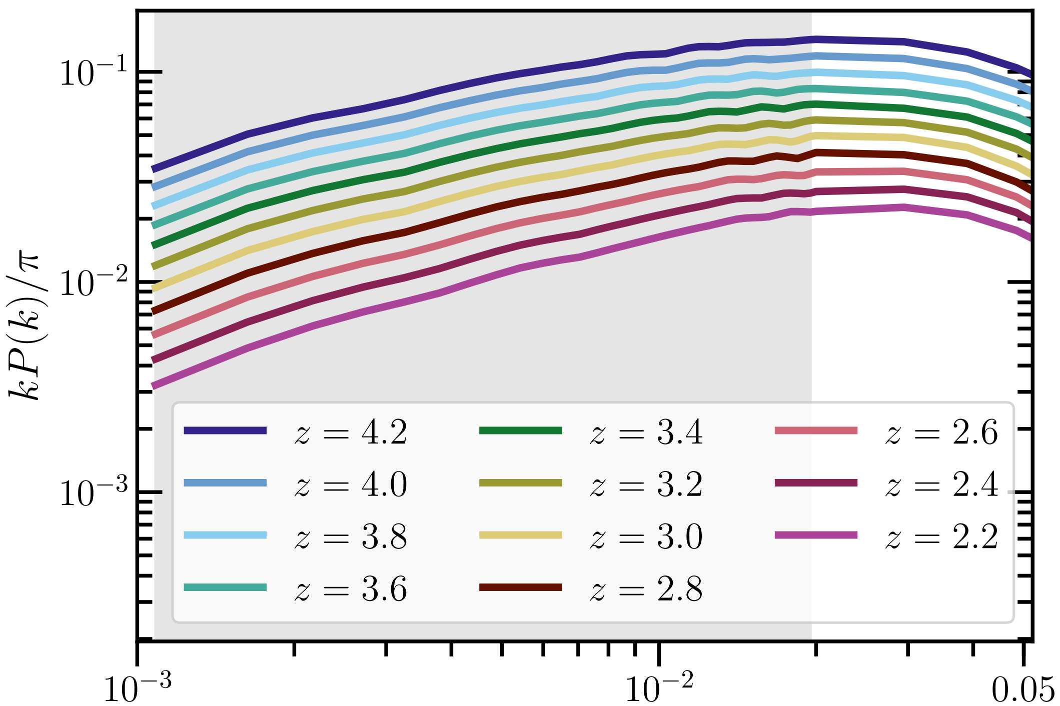


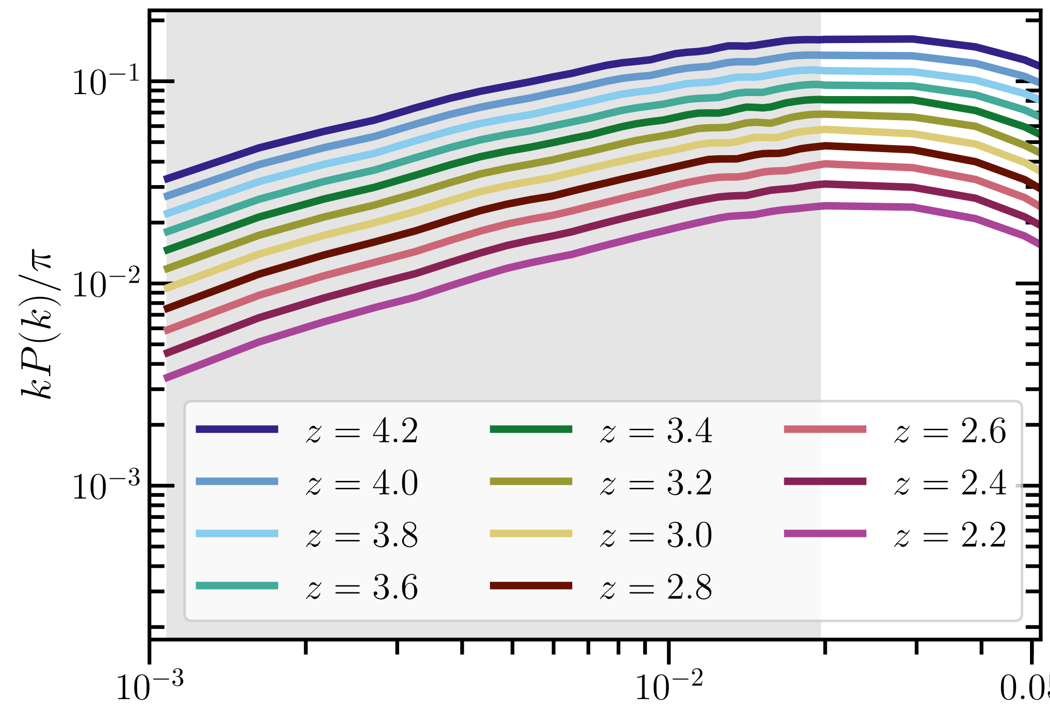
Quadratic polynomial interpolation

Latin hypercube
Gaussian process emulator

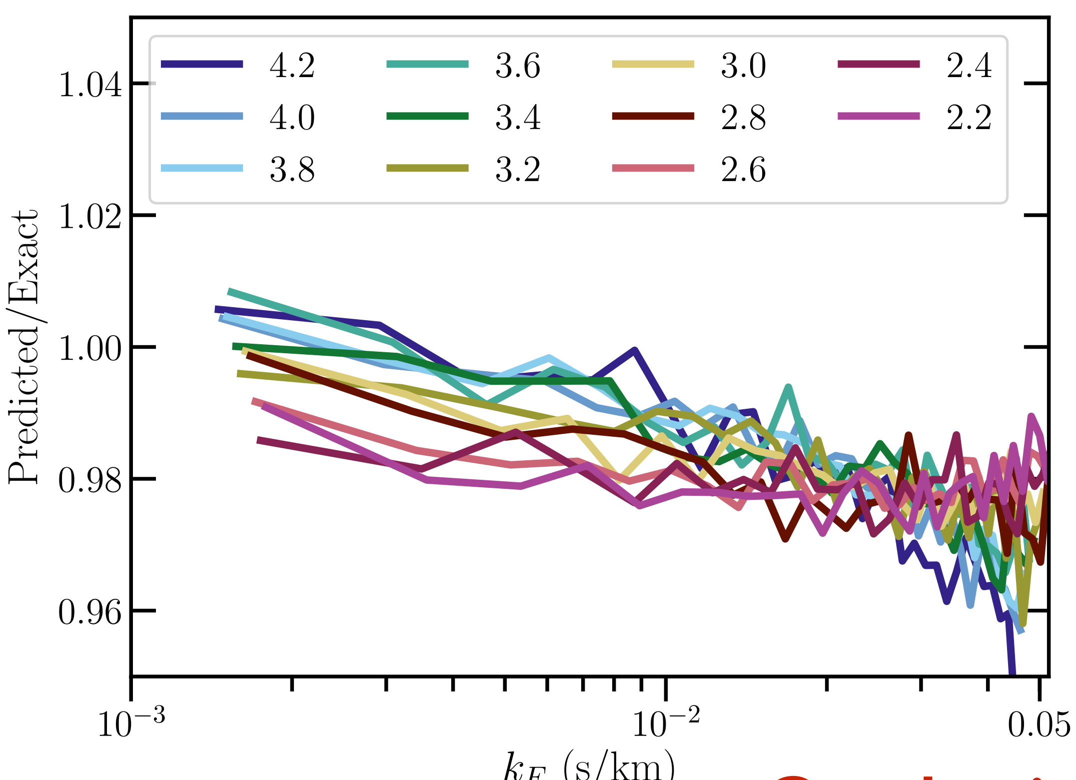
Test simulation *A*

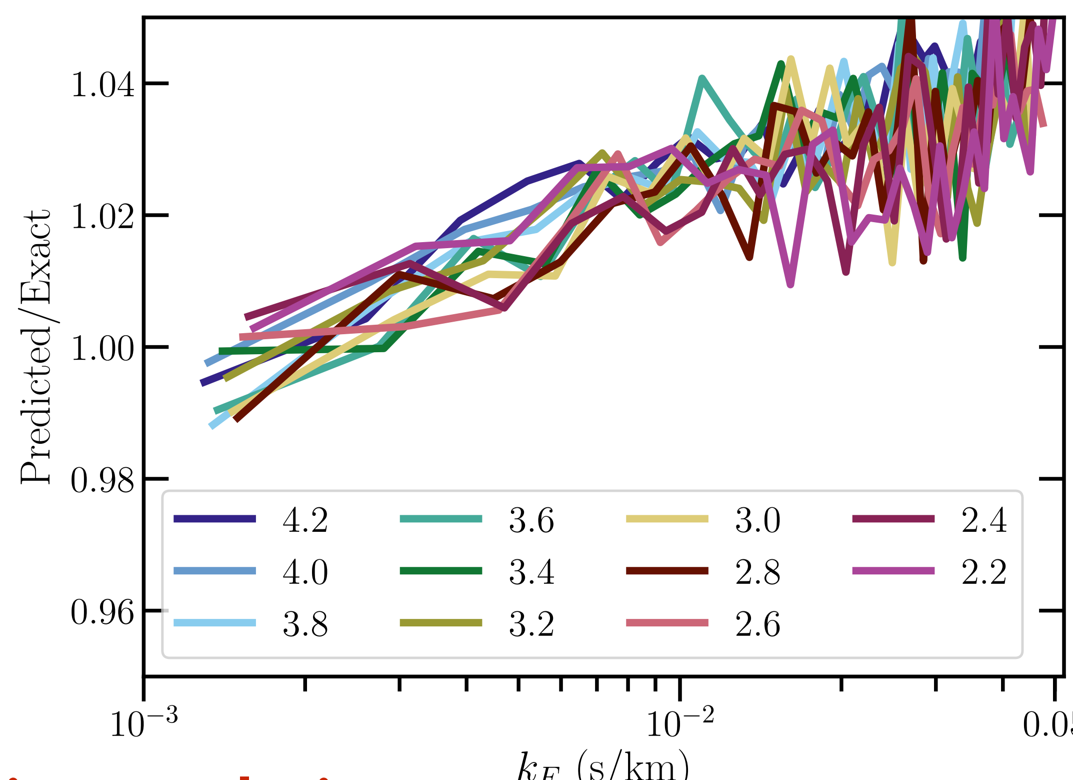
Test simulation *B*





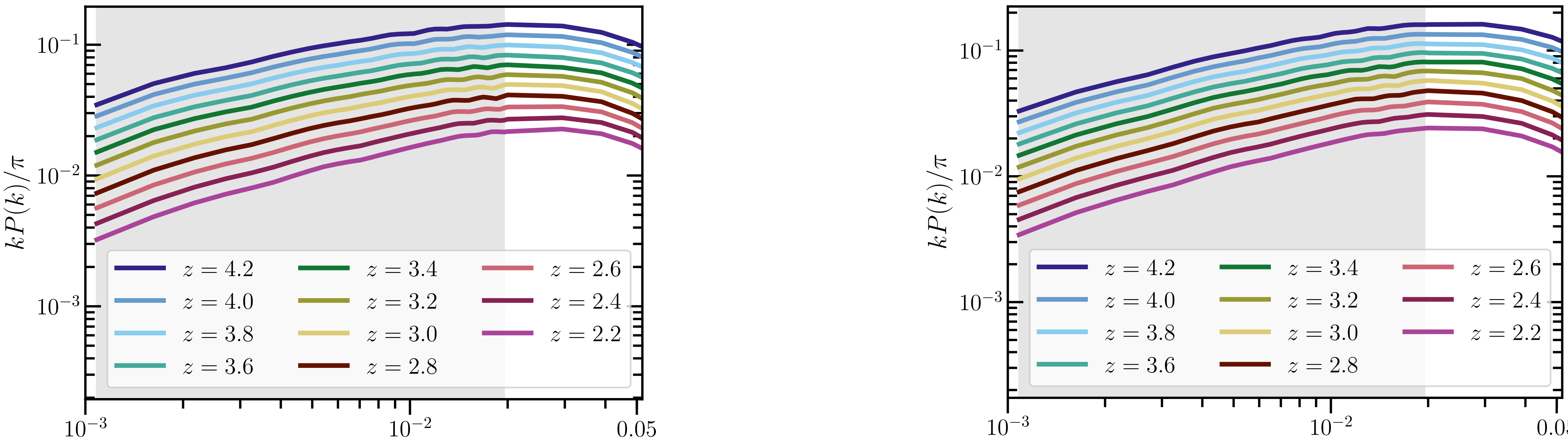
Lyman-alpha forest flux power spectrum



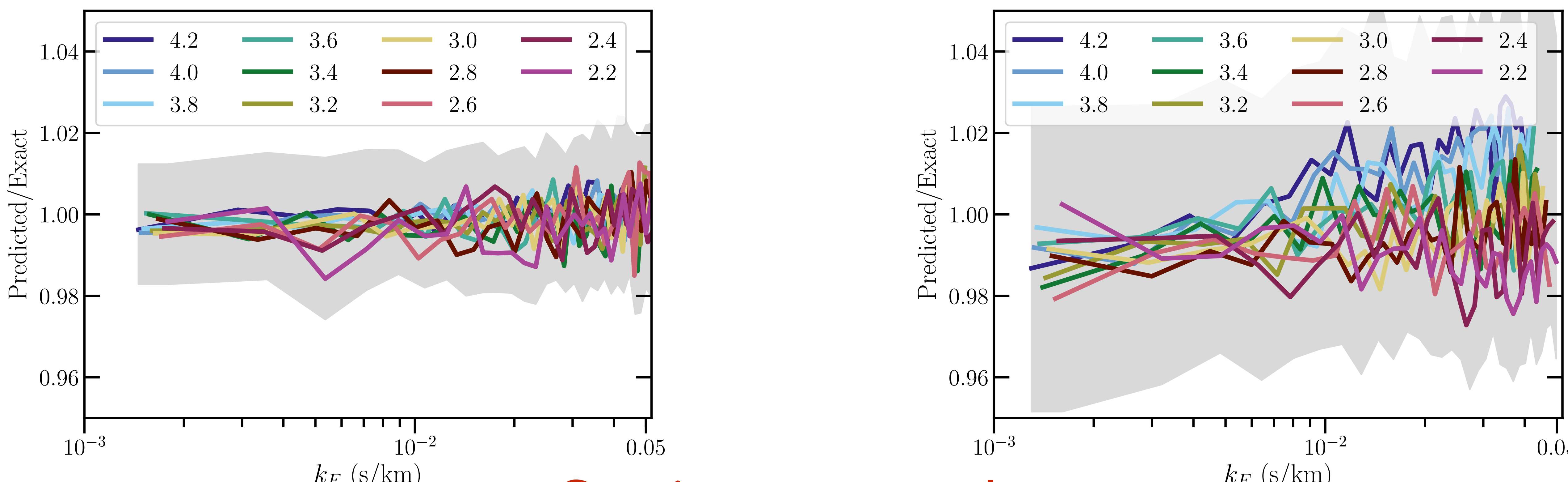


Quadratic polynomial interpolation

Test simulation *A* **Test simulation *B***

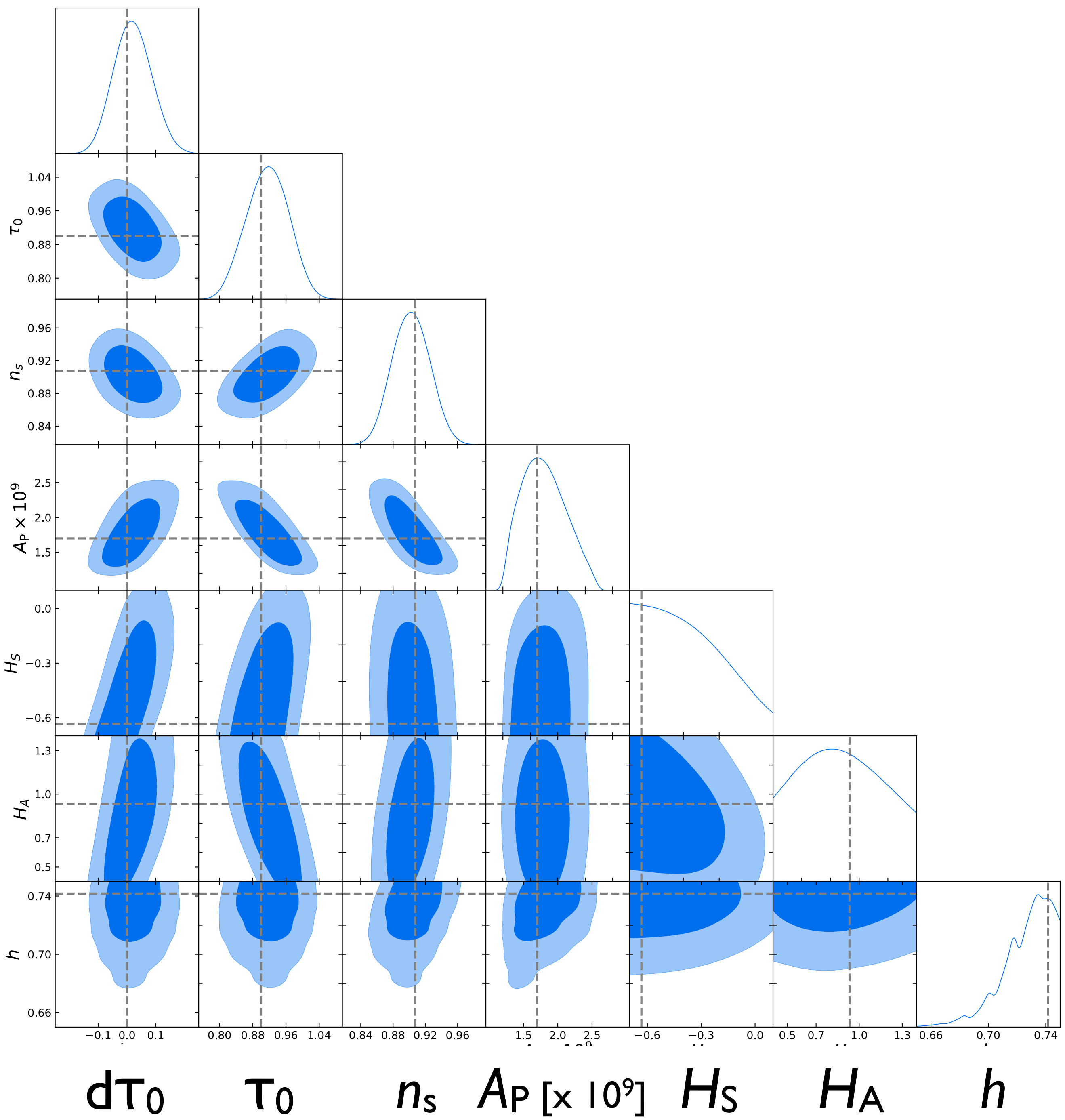


Lyman-alpha forest flux power spectrum

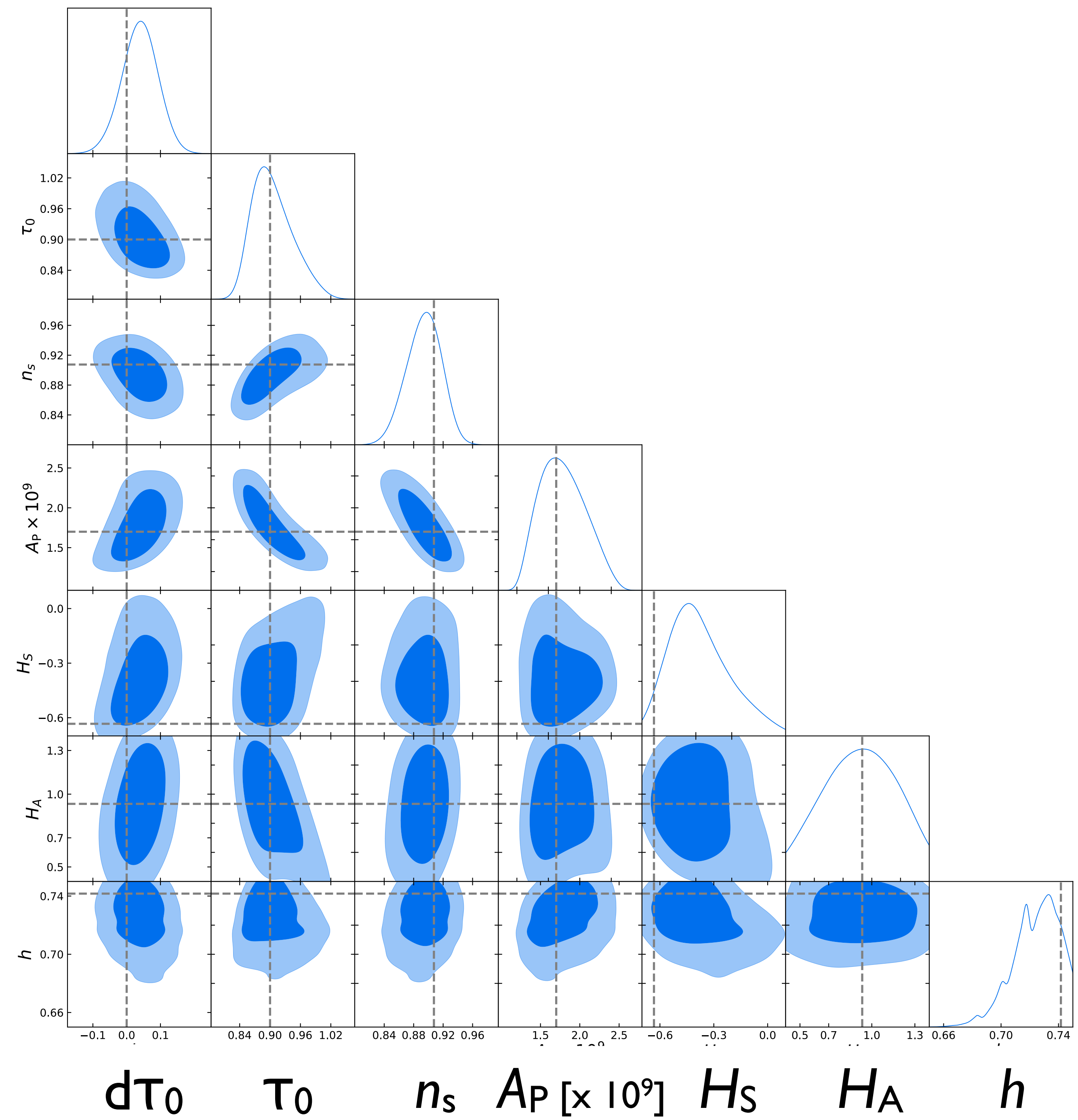


Gaussian process emulator

Smaller emulator error propagates to better parameter constraints

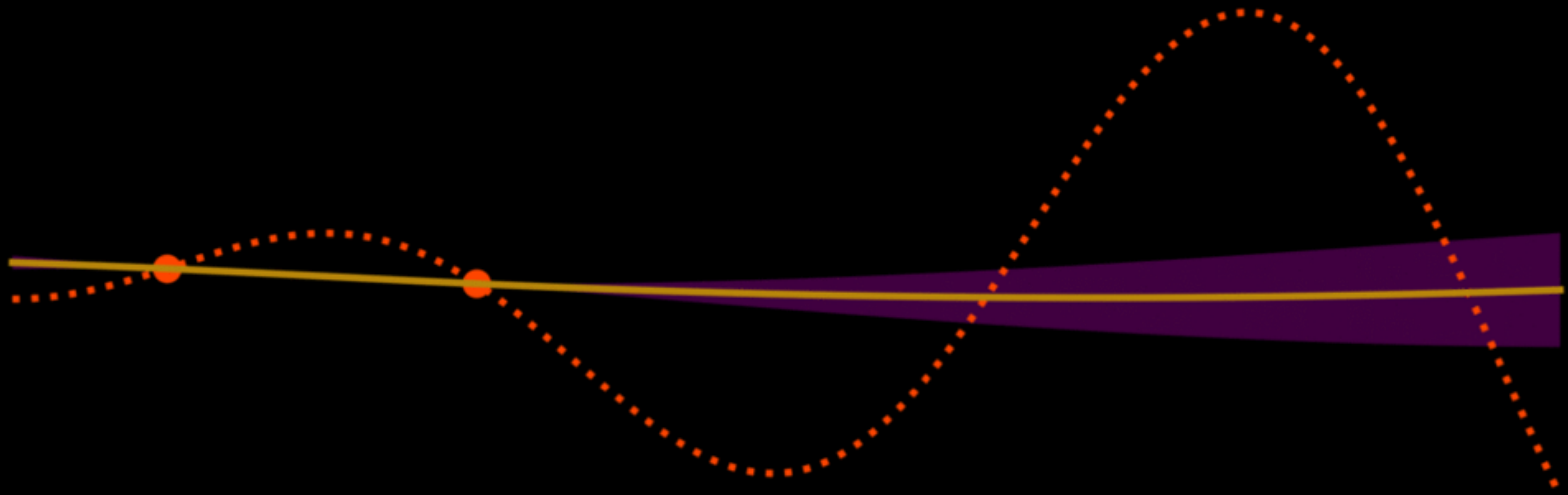


Quadratic polynomial interpolation



Latin hypercube
Gaussian process emulator

Can we actively construct the training set?



Bayesian optimisation

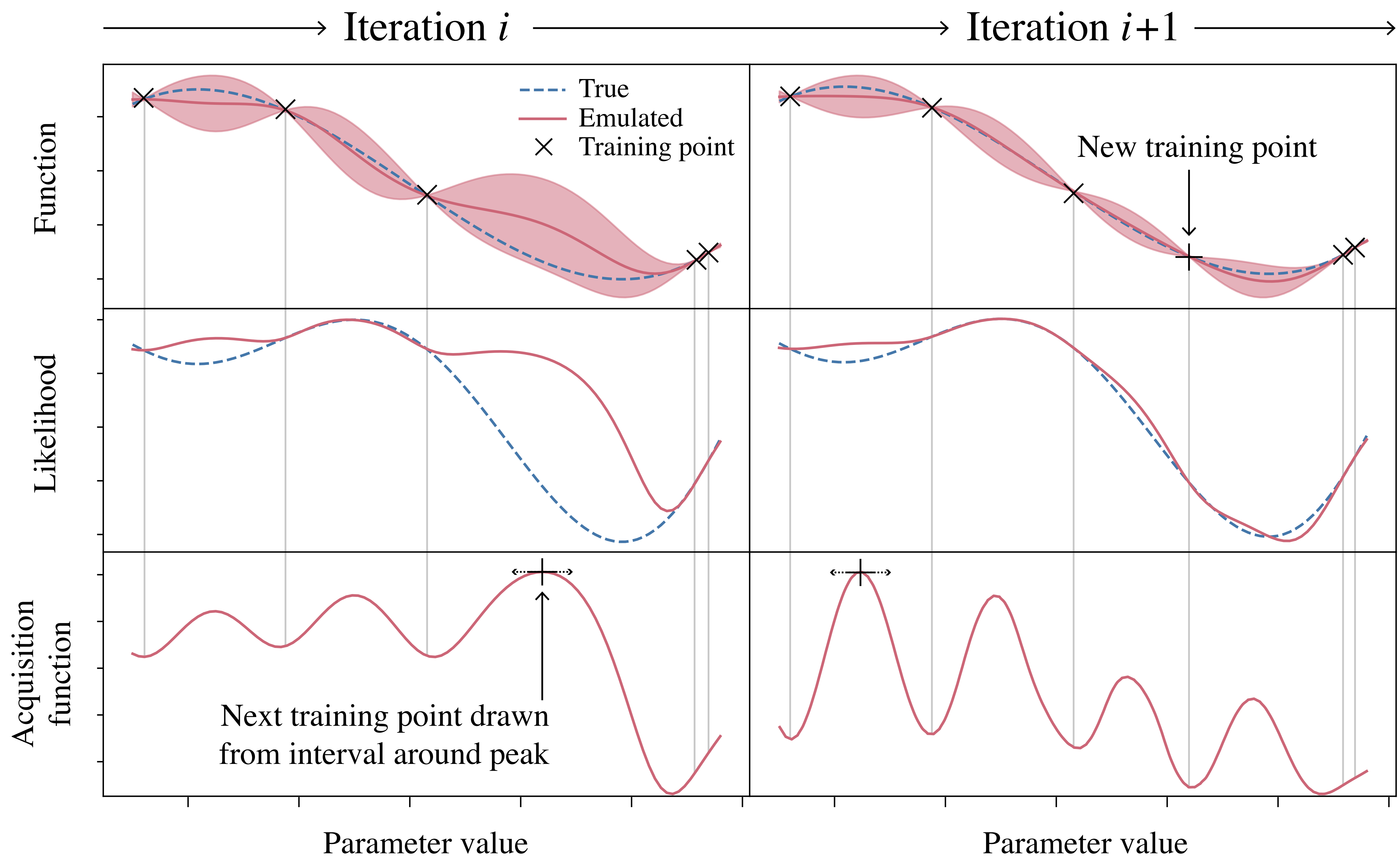
We need a balance between

vs

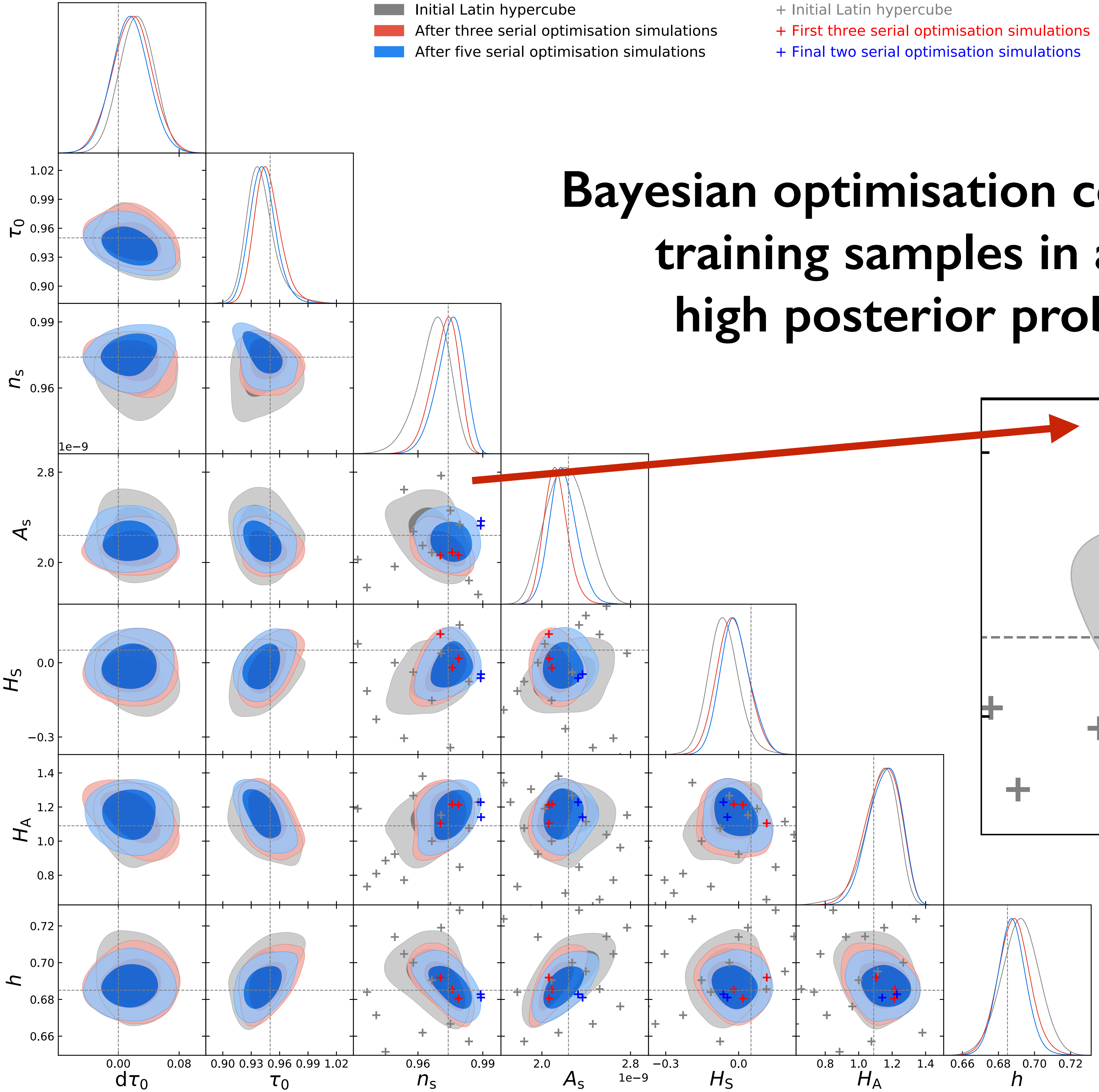
Exploitation

where interpolation error
is large

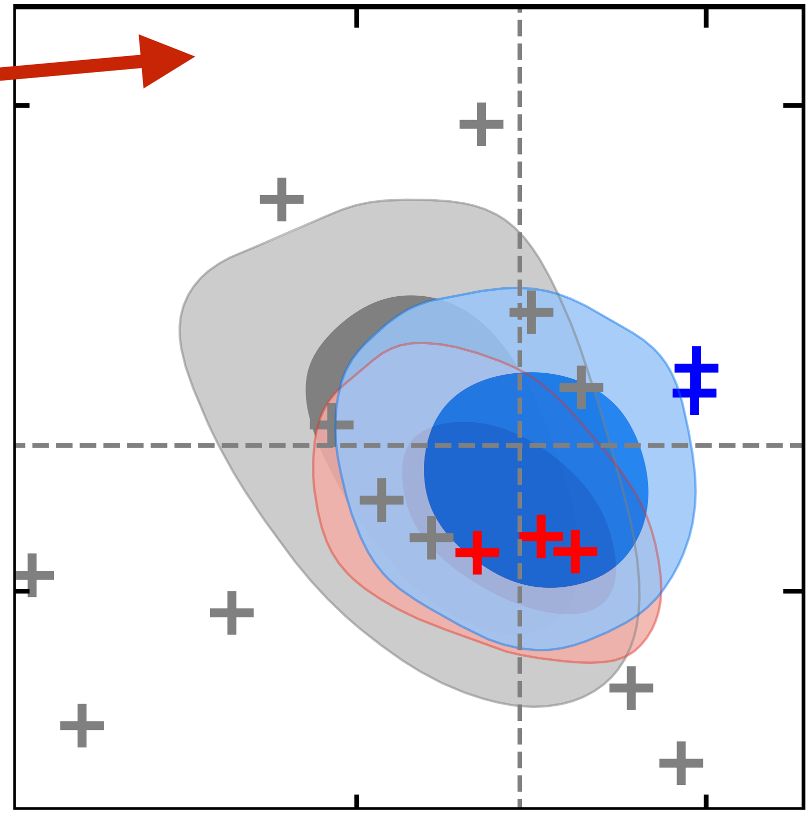
where posterior probability
is large



Can also optimise emulator in "batches"

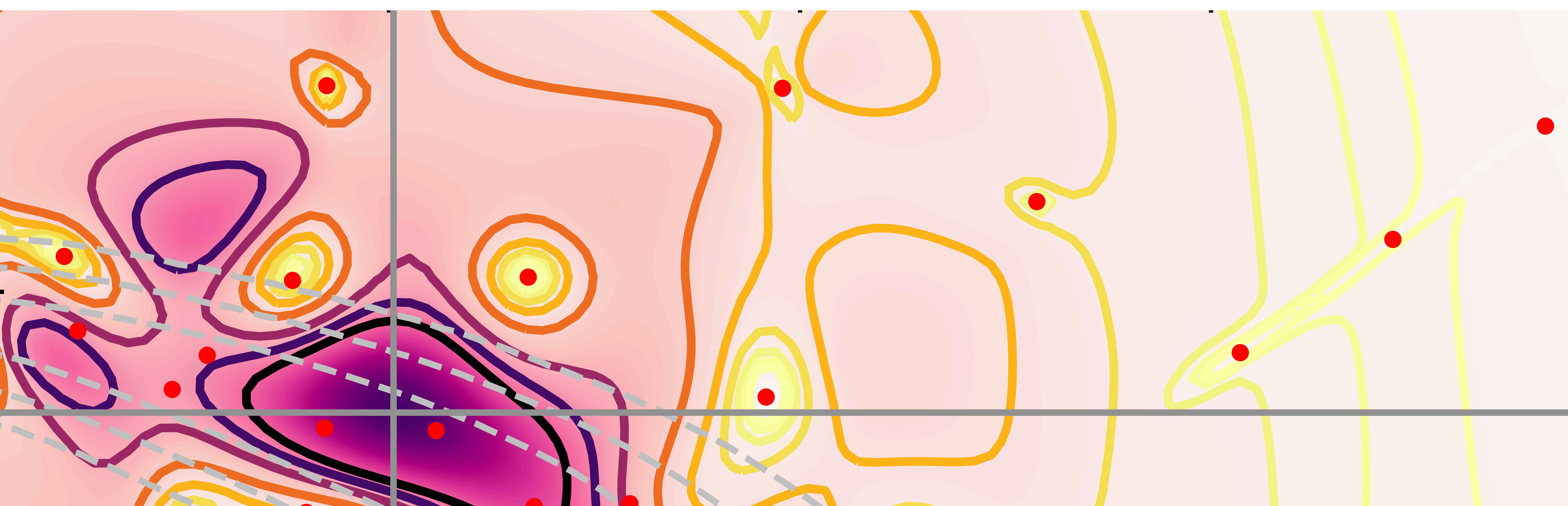


Bayesian optimisation concentrates training samples in areas of high posterior probability

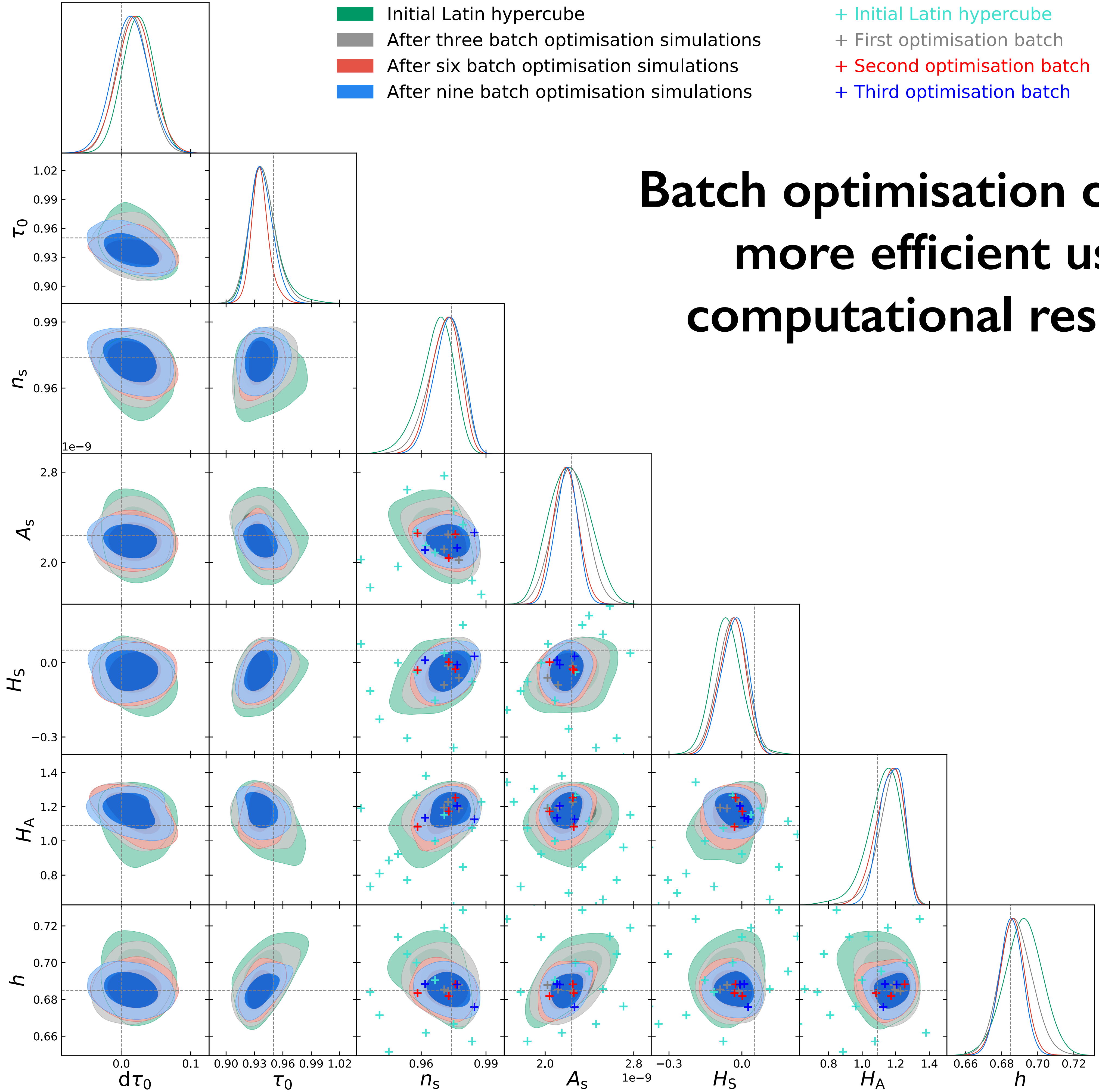


Batch Bayesian optimisation

- Many simulations **too costly to run in serial**
- Must choose **batch of simulations simultaneously** from acquisition function
- **Can update uncertainty** as Gaussian process variance independent of output

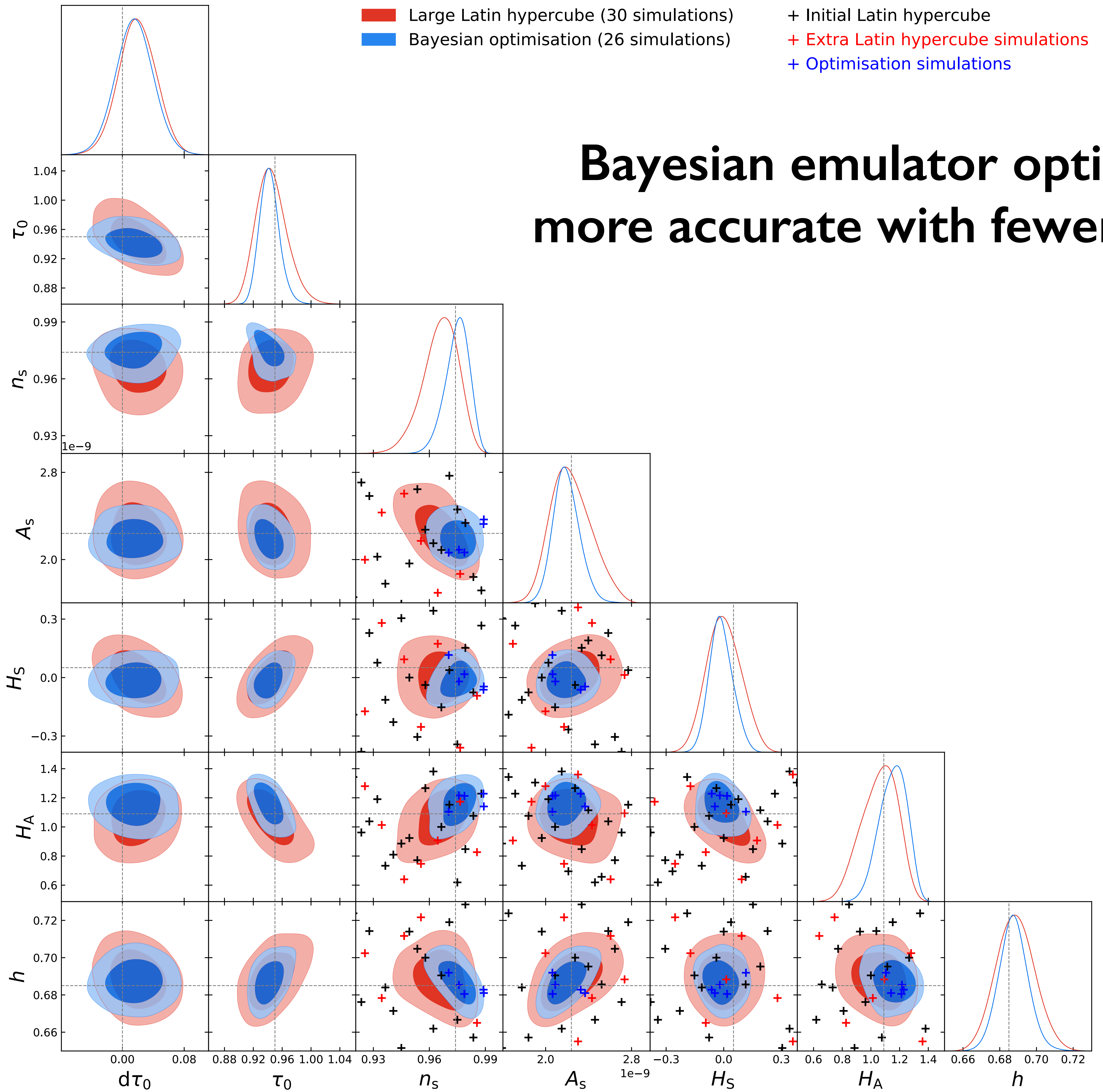


Batch optimisation can make more efficient use of computational resources



But is Bayesian optimisation more efficient than the "brute force" approach?

Bayesian emulator optimisation is more accurate with fewer simulations



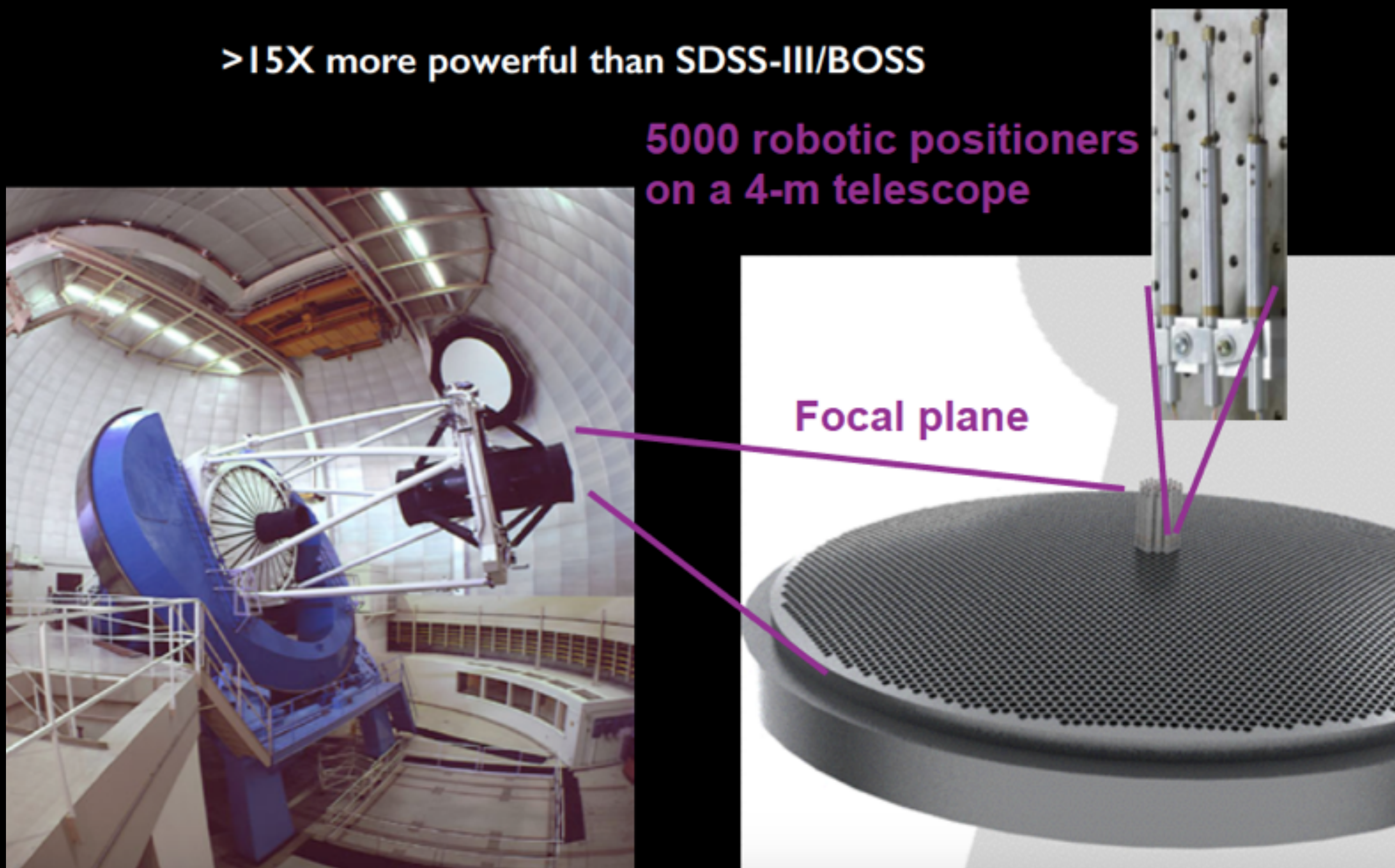
Other emulators of the cosmic large-scale structure

- **Dark matter & halo statistics** — small-scale non-linear matter power spectrum (*Heitmann et al. 2009*); halo mass function (*McClintock et al. 2018*)
- **Galaxy clustering** — galaxy power spectrum (*Kwan et al. 2015*; *Zhai et al. 2018*); higher-order statistics
- **Galaxy weak lensing** — weak lensing peak counts (*Liu et al. 2015*); power spectrum (*Petri et al. 2015*); covariance matrices
- **21 cm** — 21 cm power spectrum (*Jennings et al. 2018*)

Dark Energy Spectroscopic Instrument

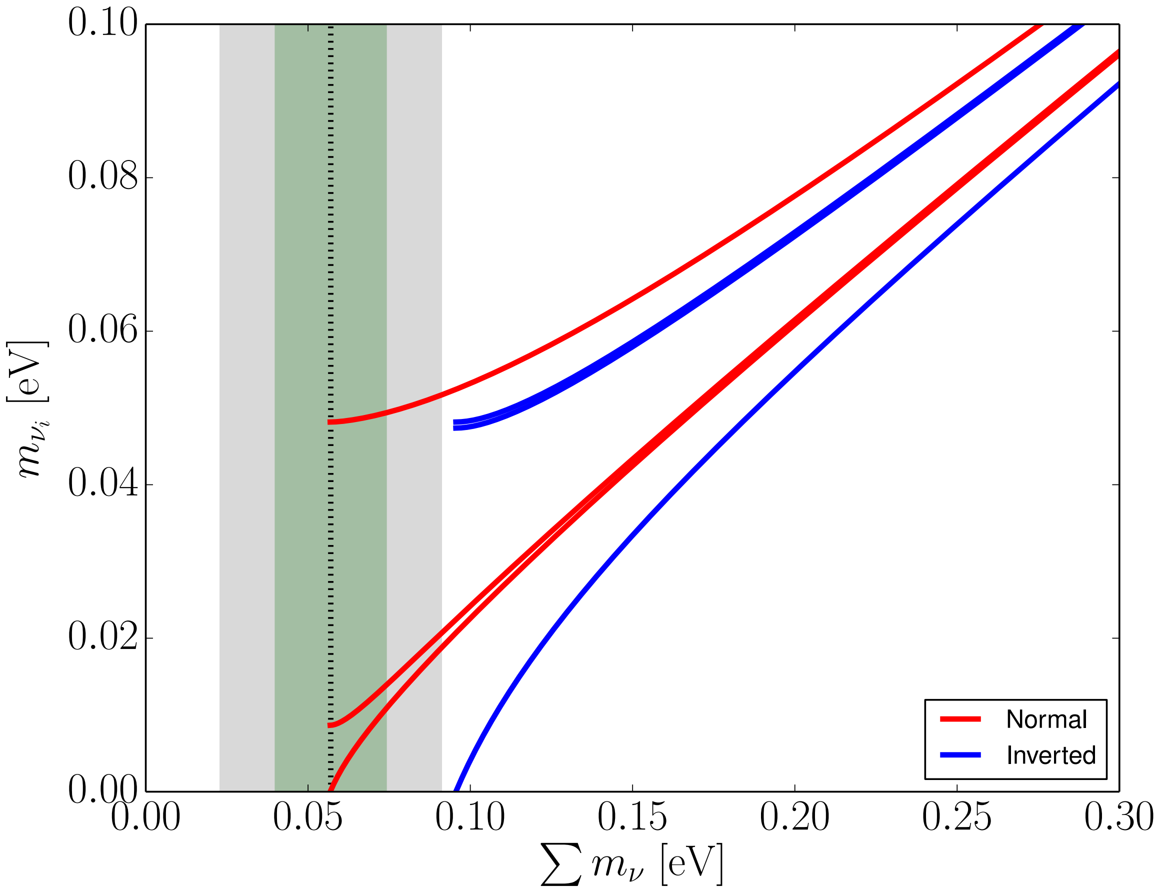
DESI is the next big step in mapping the Universe

>15X more powerful than SDSS-III/BOSS



Beyond the Standard Model(s) with DESI

Font-Ribera et al. (2014)



$$P_{\rm primordial}(k) \propto (k/k_0)^{n_s+\frac{1}{2}\alpha_s \ln(k/k_0)}$$

Data	σ_{n_s}	σ_{α_s}
Gal ($k_{\rm max} = 0.1$ h^{-1}Mpc)	0.0024 (1.6)	0.0051 (1.1)
Gal ($k_{\rm max} = 0.2$ h^{-1}Mpc)	0.0022 (1.7)	0.0040 (1.3)
Ly-α forest	0.0029 (1.3)	0.0027 (2.0)
Ly-α forest + Gal ($k_{\rm max} = 0.2$)	0.0019 (2.0)	0.0020 (2.7)

PI: Font-Ribera

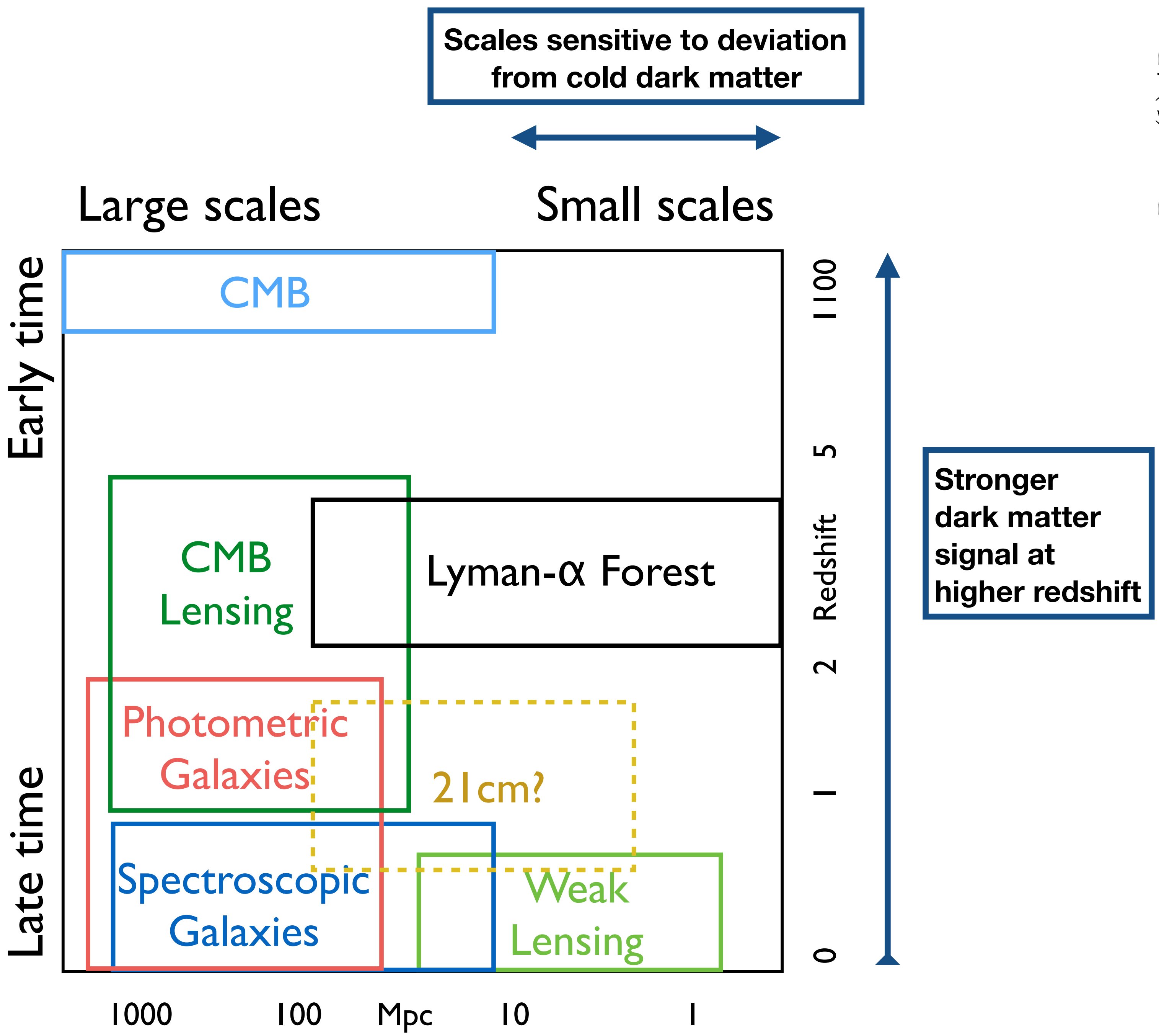
Co-I: Rogers, Kitching, McDonald, Pedersen, Peiris, Pontzen, Slosar

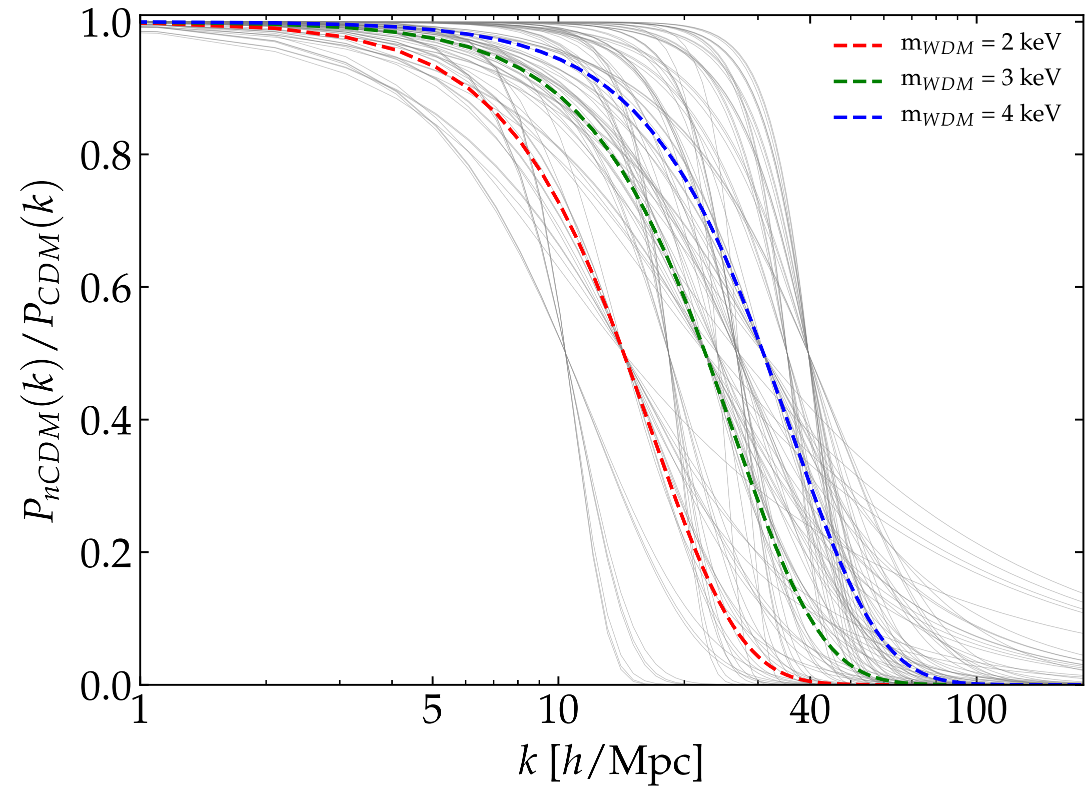
Science & Technology Facilities Council

DiRAC Distributed Research utilizing Advanced Computing

Testing the paradigm of cold dark matter

Testing the paradigm of cold dark matter



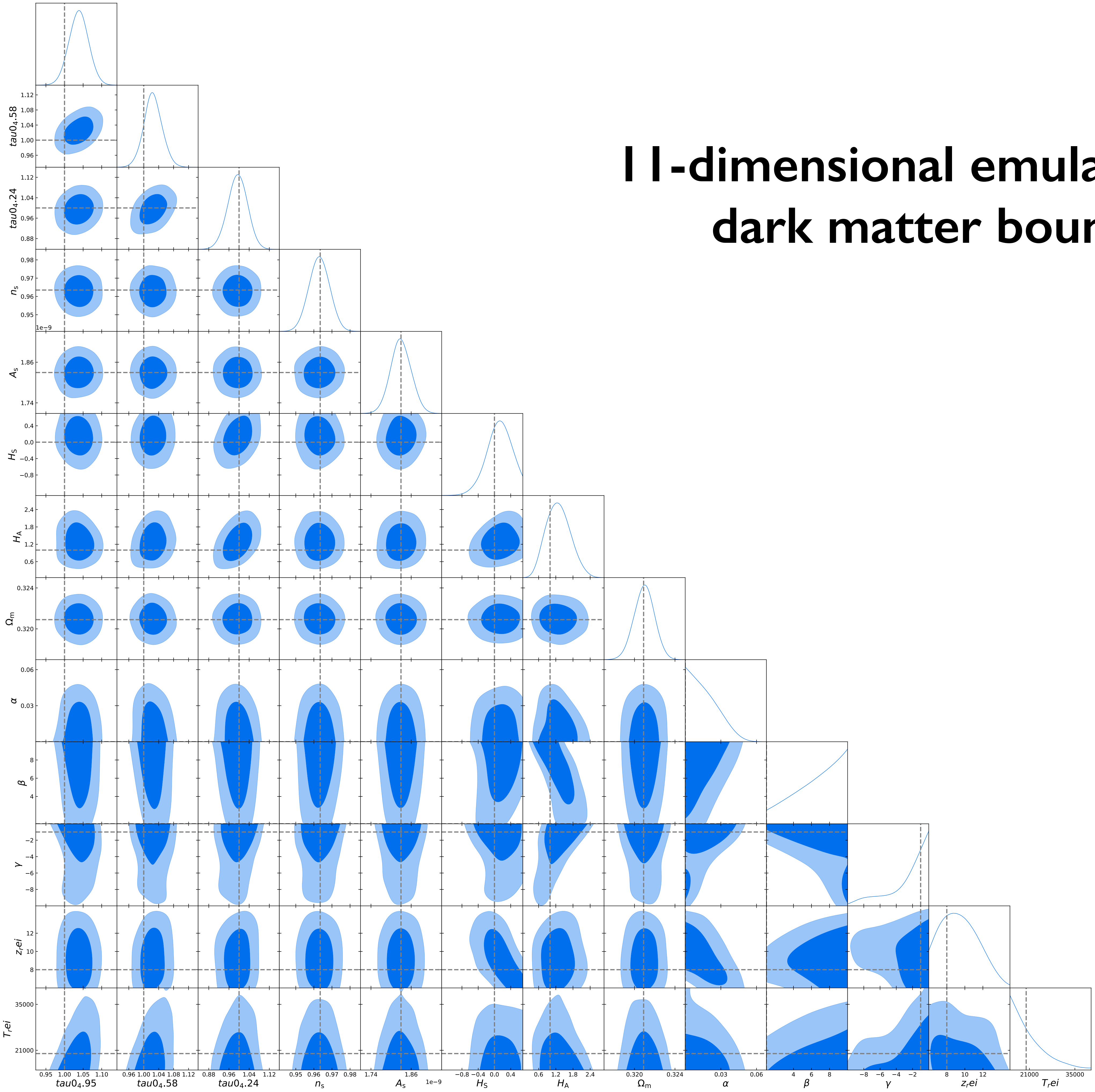


$$T^2(k) = \frac{P_{\mathrm{nCDM}}(k)}{P_{\mathrm{CDM}}(k)}$$

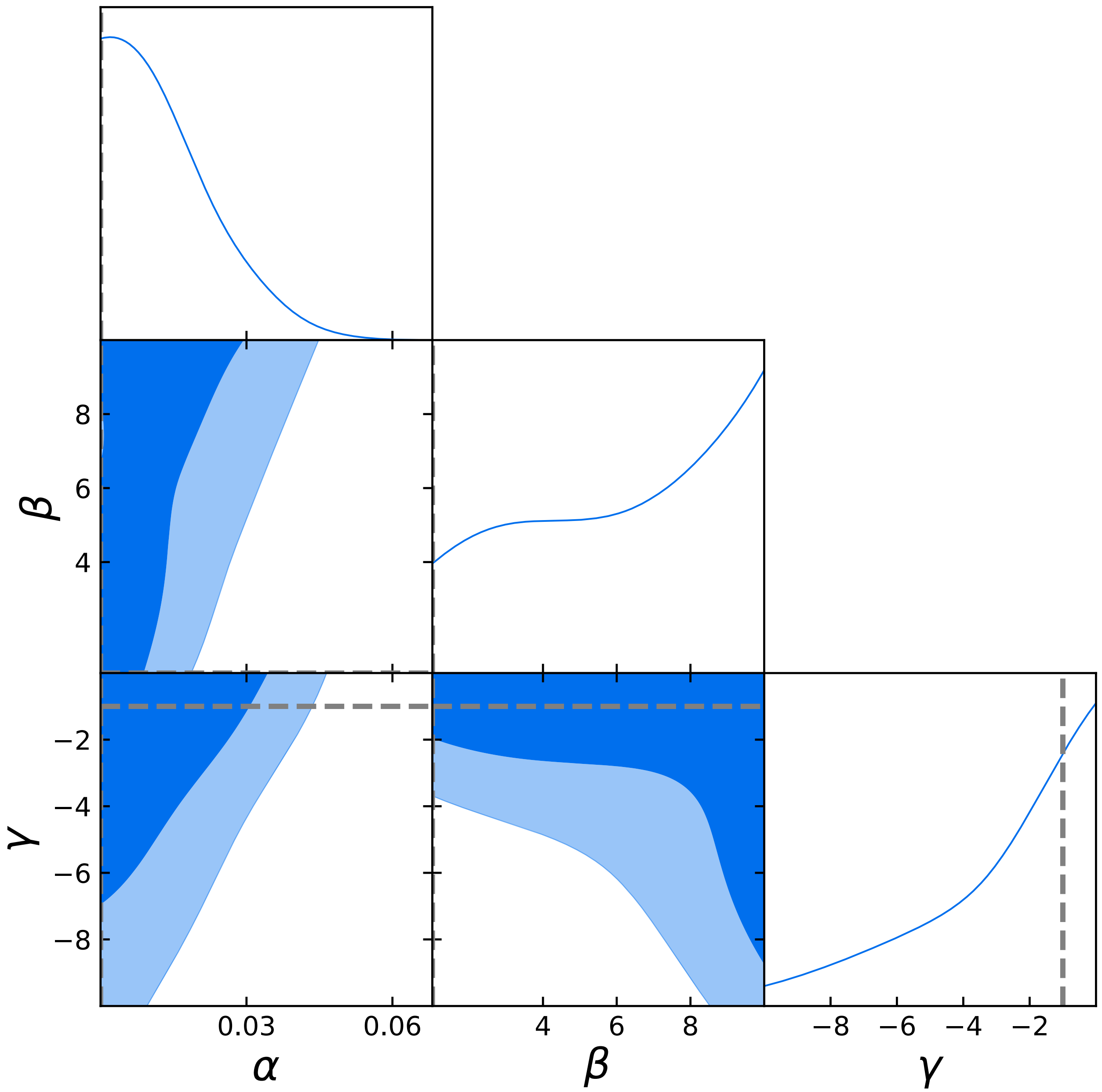
$$T(k) = [1 + (\alpha k)^{\beta}]^{\gamma}$$

Murgia et al. (2018)

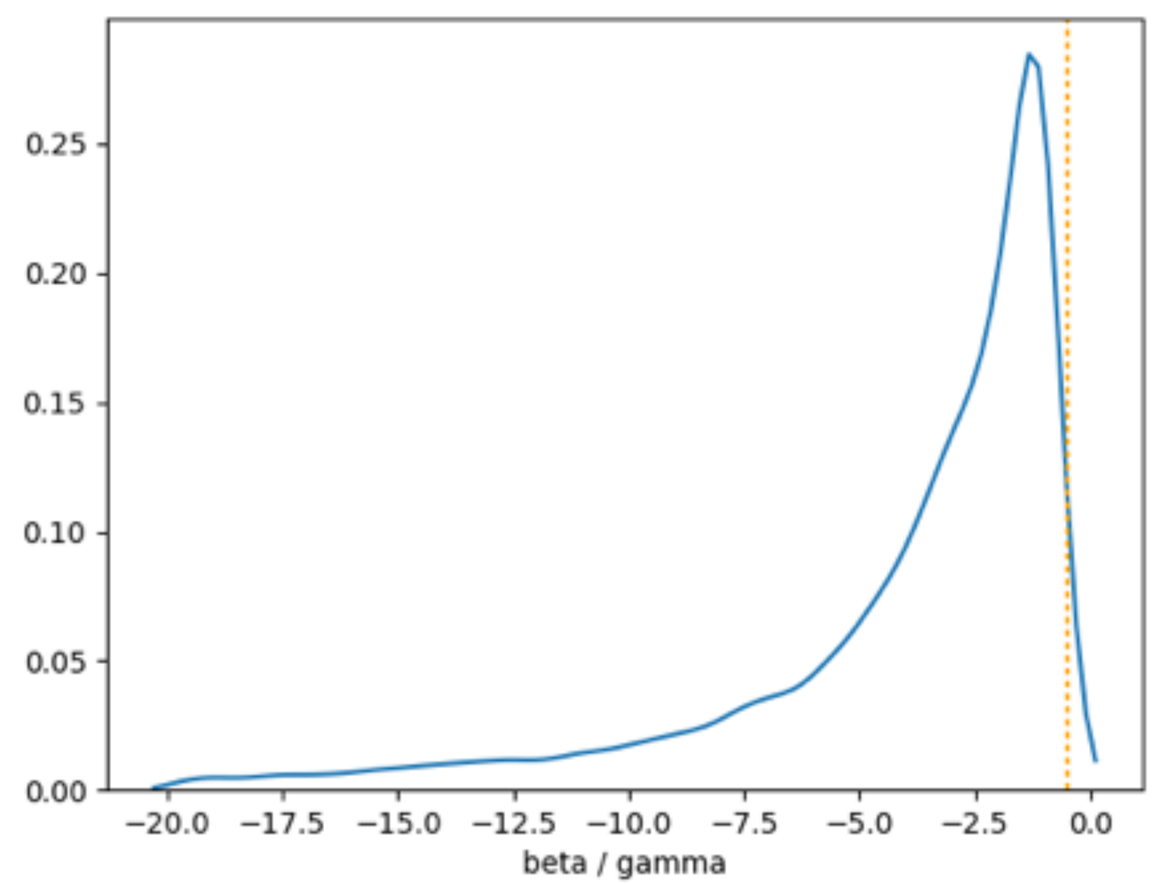
11-dimensional emulator for dark matter bounds



The Lyman-alpha forest constrains dark matter model space by scale and shape of power spectrum suppression

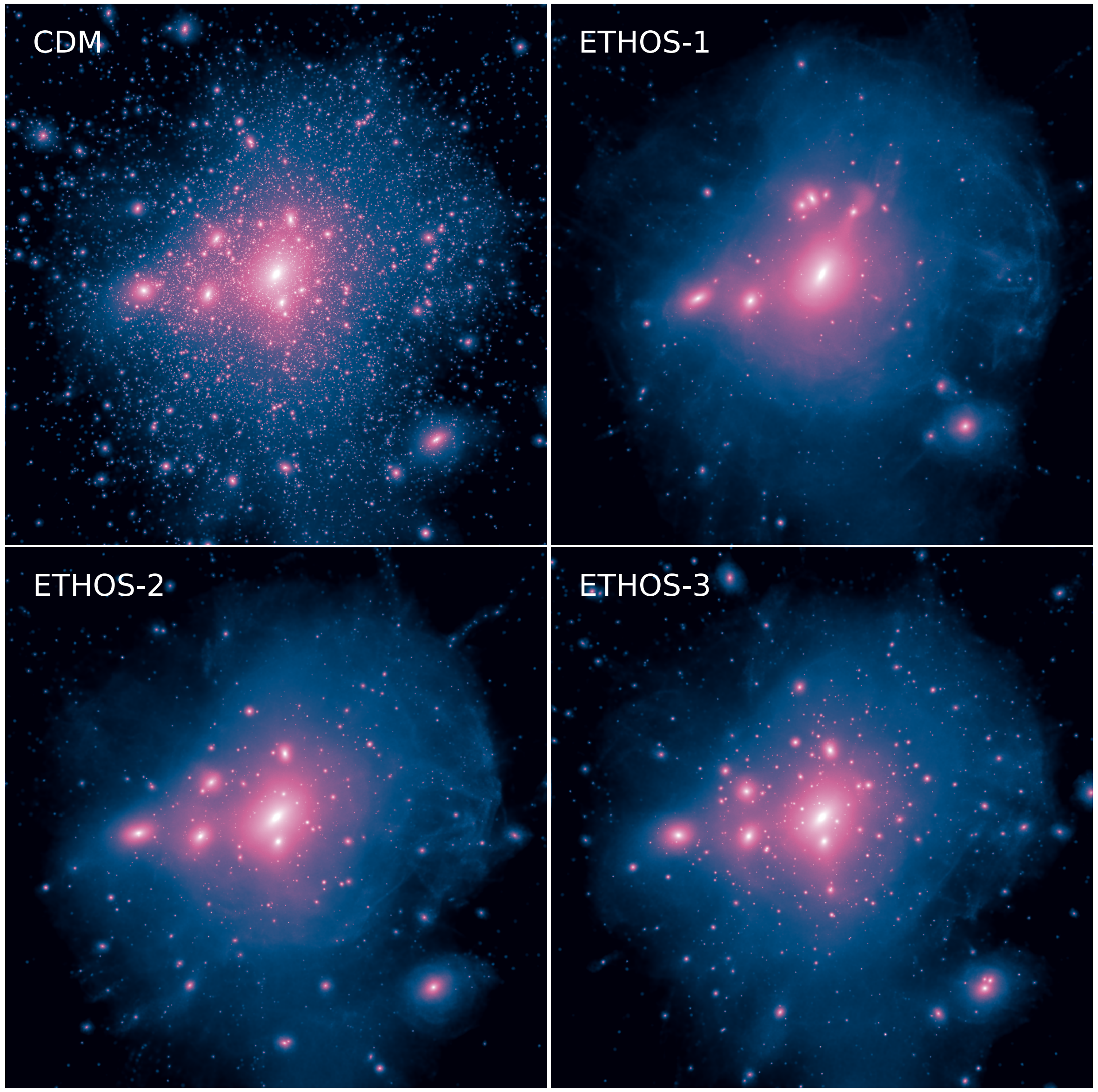


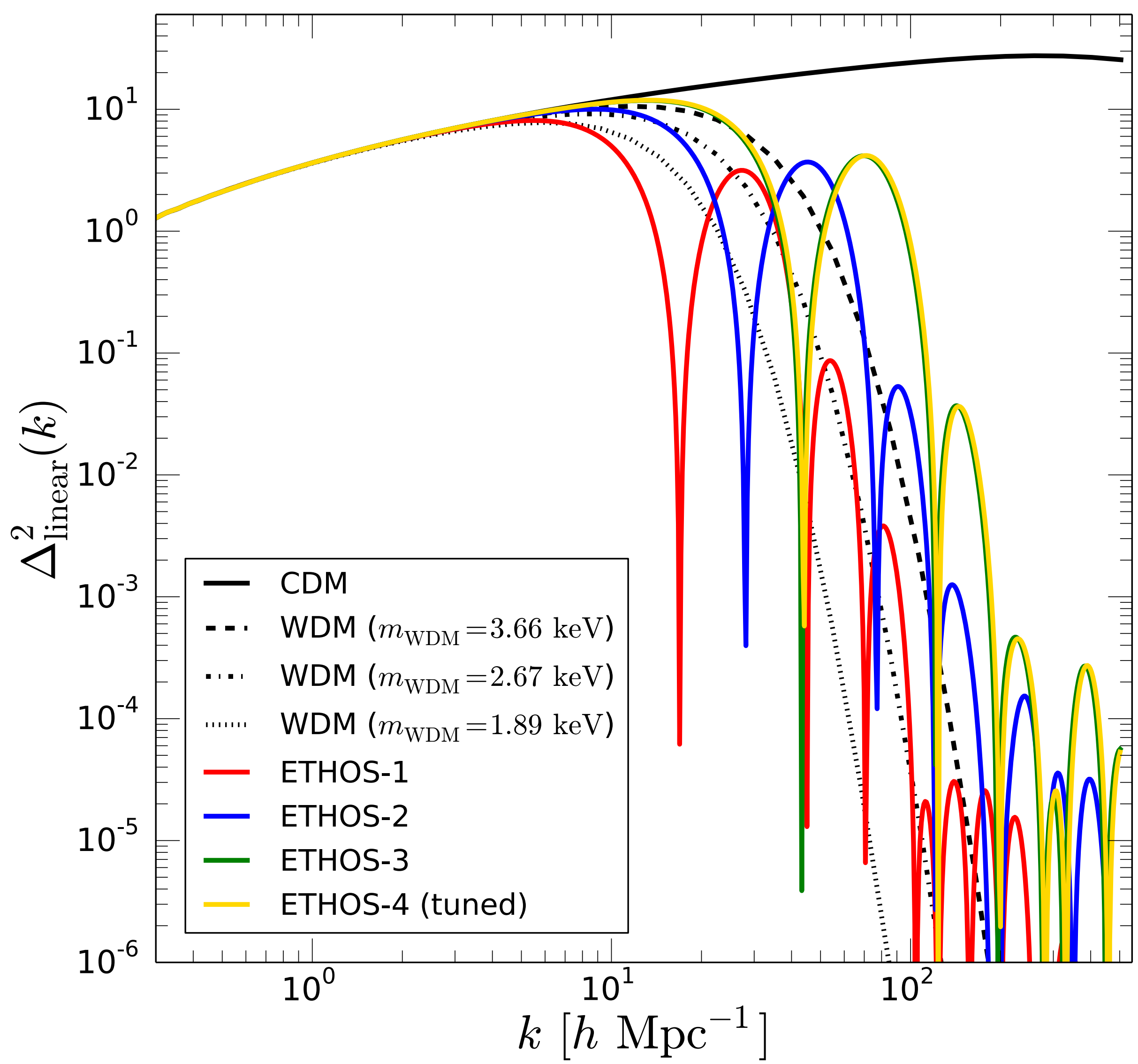
$$m_{\rm ULA} \geq 10^{-21}\,{\rm eV}$$



Dark acoustic oscillations

500 kpc





Vogelsberger et al. (2016)

Summary

- Lyman-alpha forest constrains extensions to cosmology and particle physics

- Need to robustly marginalise over uncertainty in astrophysics of hydrogen gas

- Search for deviation from CDM using full shape of power spectrum