# SEARCHING FOR AXION DARK MATTER IN THE LYMAN-ALPHA FOREST

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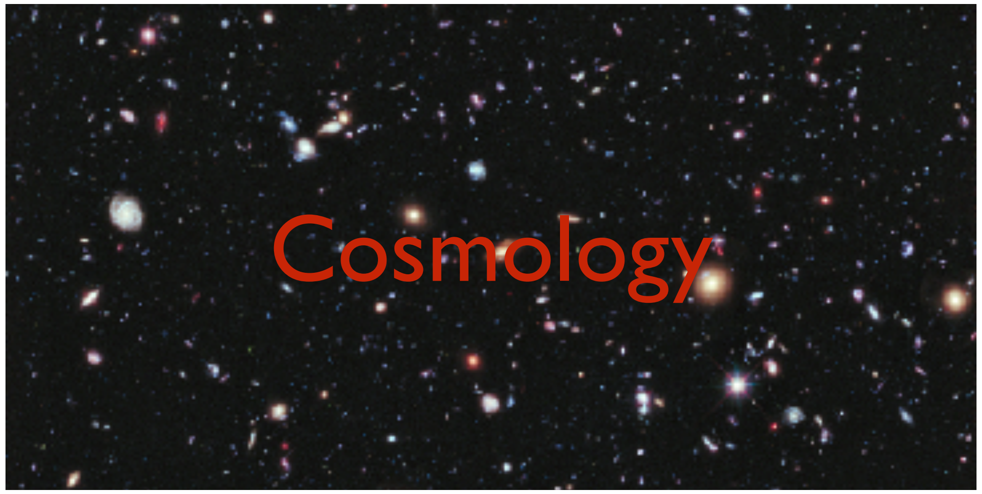
# Connecting models of

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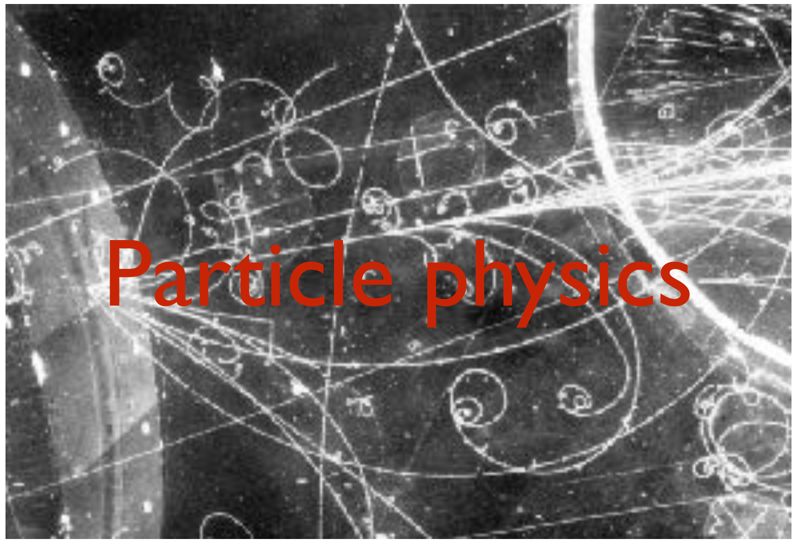


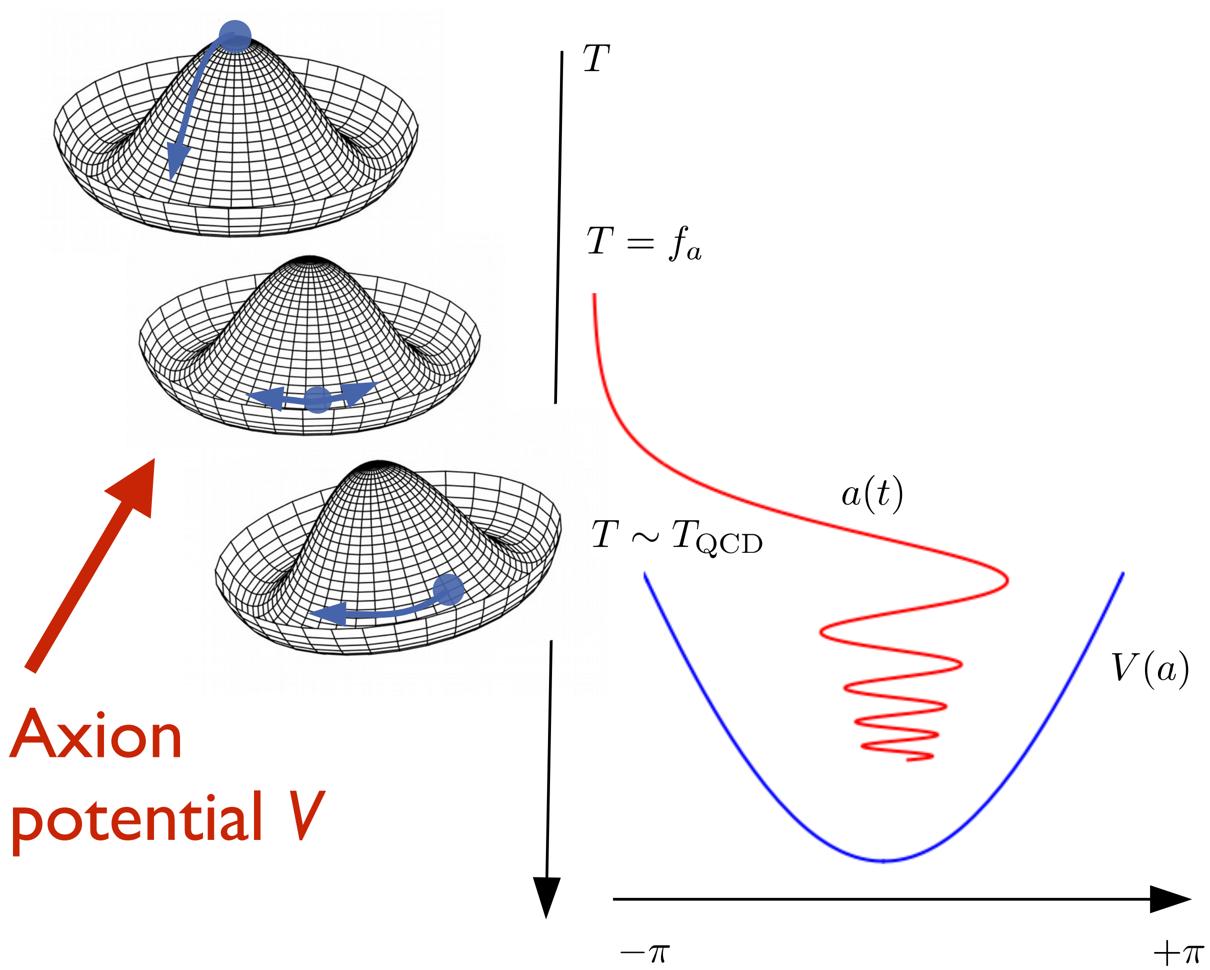

- Axion-like particle well-motivated dark matter yet largely unexplored

- Lyman-alpha forest very sensitive to ultra-light axion phenomenology (cut-off)

- Robust analysis needs Bayesian-optimised emulator to test convergence

- New stronger bounds significantly disfavour canonical mass scale $m_a \sim 10^{-22}$ eV

# Ultra-light axions are a compelling dark matter candidate




- **Axion-like particles** generalisation of axion
- Generically produced in BSM theories, inc. **string "axiverse"**
- ~ **$10^{-22}$ - $10^{-21}$ eV** (ultra-light axions) may be preferred mass scale in axiverse

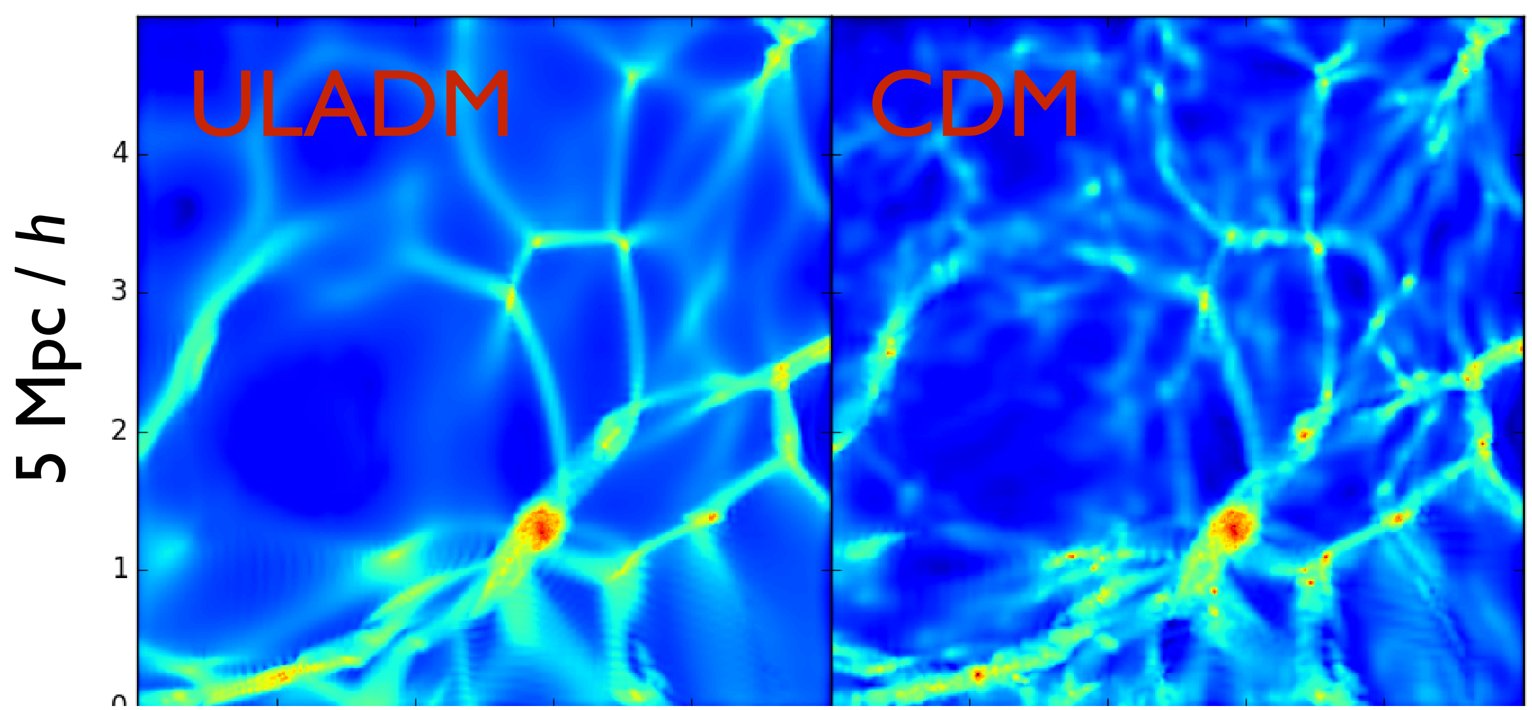
Peccei & Quinn (1977); Weinberg (1978); Wilczek (1978); Pargner (2019); Visinelli & Vagnozzi (2019); Hui et al. (2017)

# Ultra-light axions are invoked to resolve so-called cold dark matter "small-scale crisis"


$$\lambda_{\mathrm{dB}} \sim \mathrm{kpc}$$

$$\lambda_{\mathrm{QP}} \sim 100\,\mathrm{kpc}$$

CDM "small-scale crisis" prefers DM **mass scale ~ $10^{-22}$ - $10^{-21}$ eV**

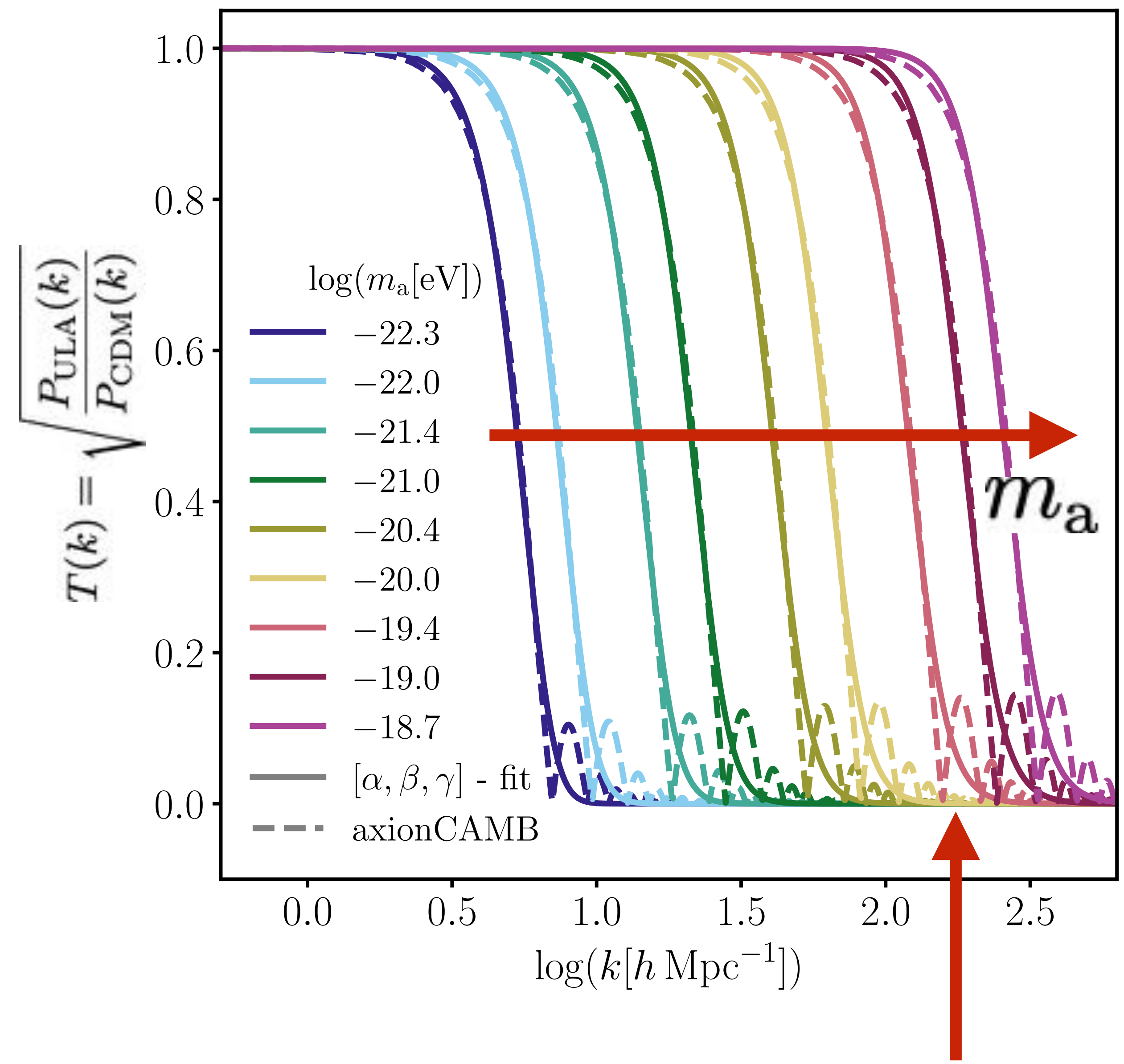



Hu et al. (2000); Armengaud et al. (2017)

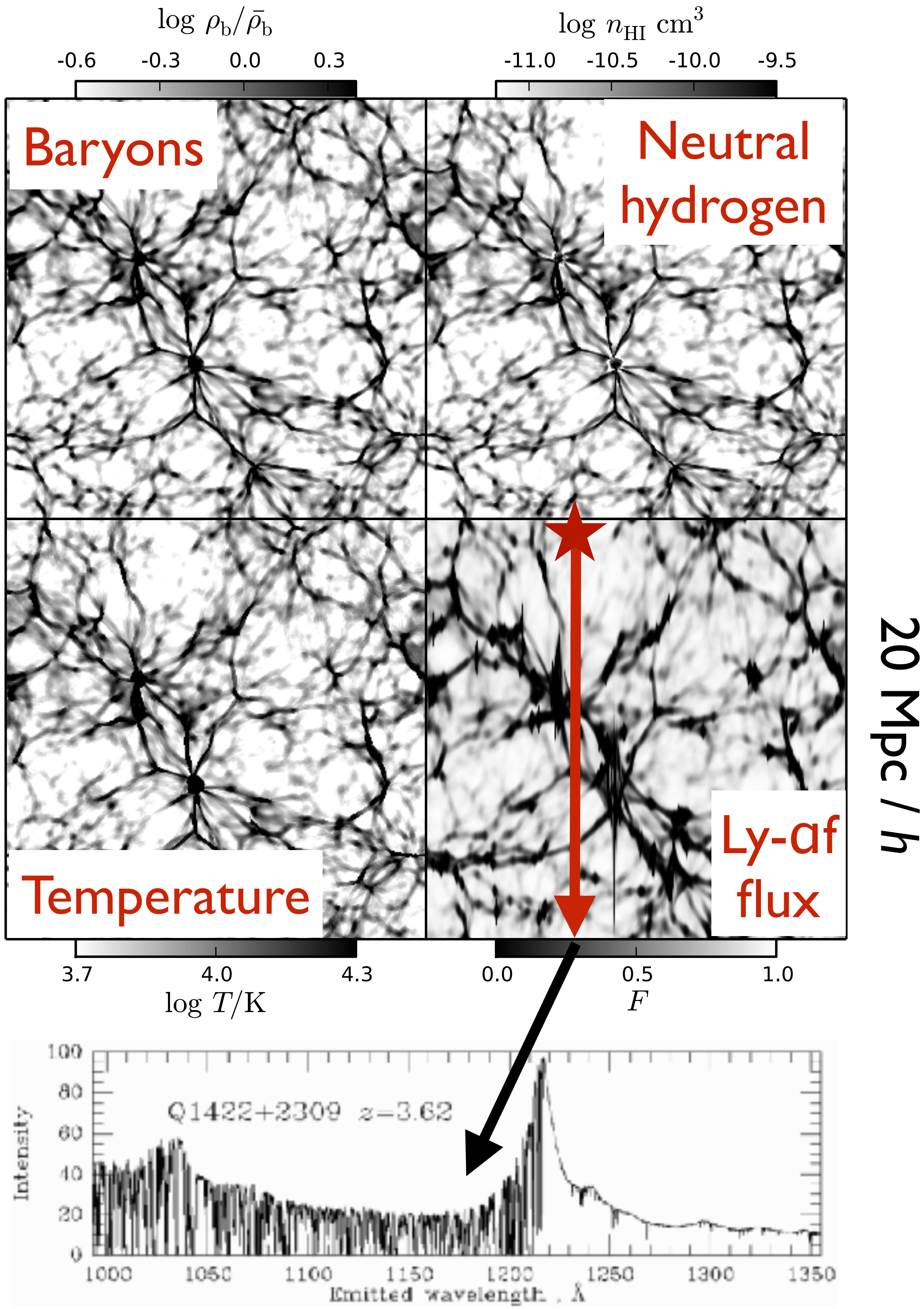
# Ultra-light axion dark matter cut-off scale is traced by the Lyman-alpha forest

$$k_{\frac{1}{2}} \propto m_{\mathrm{a}}^{\frac{4}{9}}$$

Hu et al. (2000)




Ly-alpha forest traces **linear**, **high-redshift** (z ~ 5), **small-scale** density perturbations



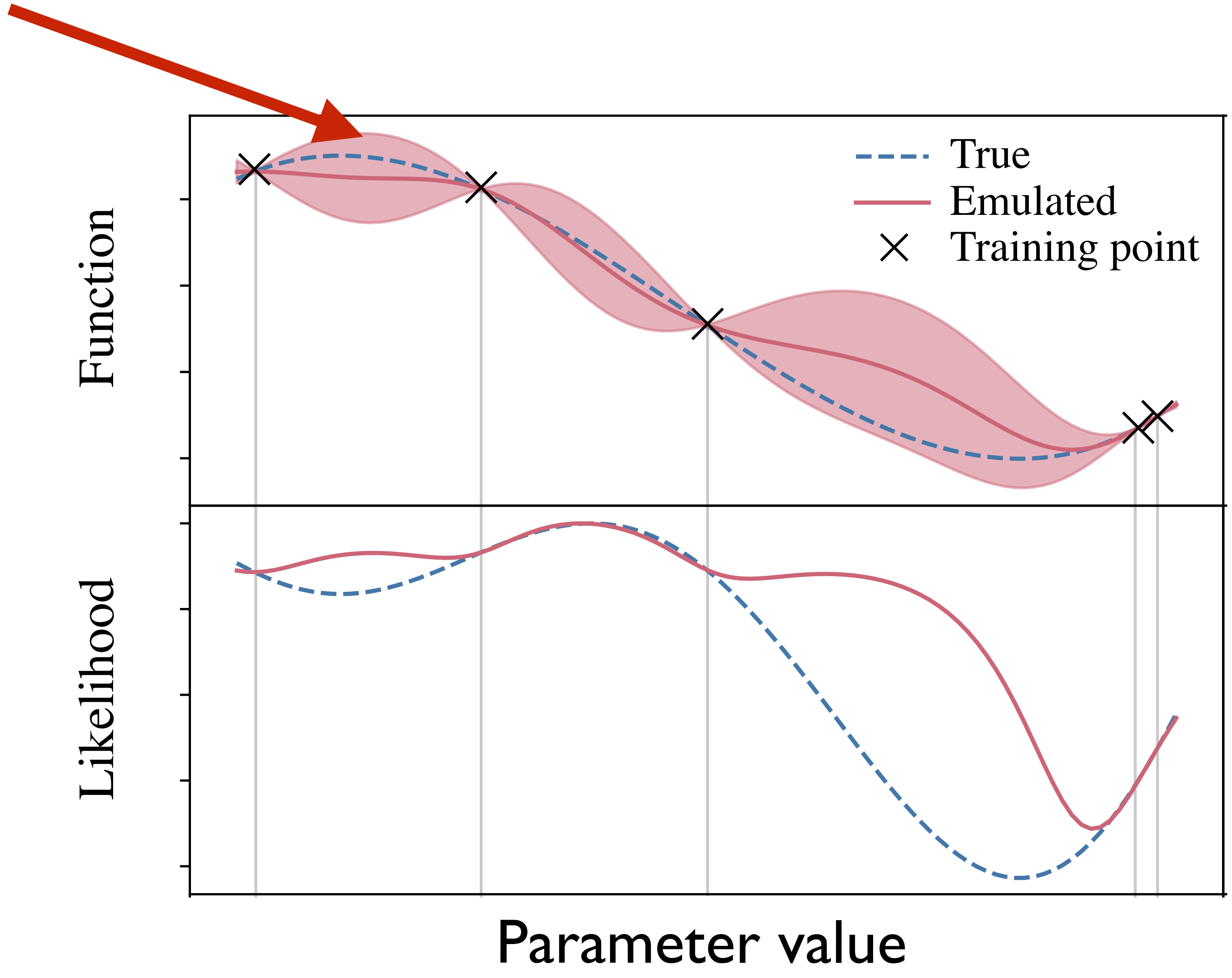

- Ly-alpha forest **traces cosmic density field**
- Model with **hydrodynamical simulations**
- ~ **3000 CPU-hours per simulation** in 12-D parameter space

Lukić et al. (2015)

# Bayesian emulator optimisation

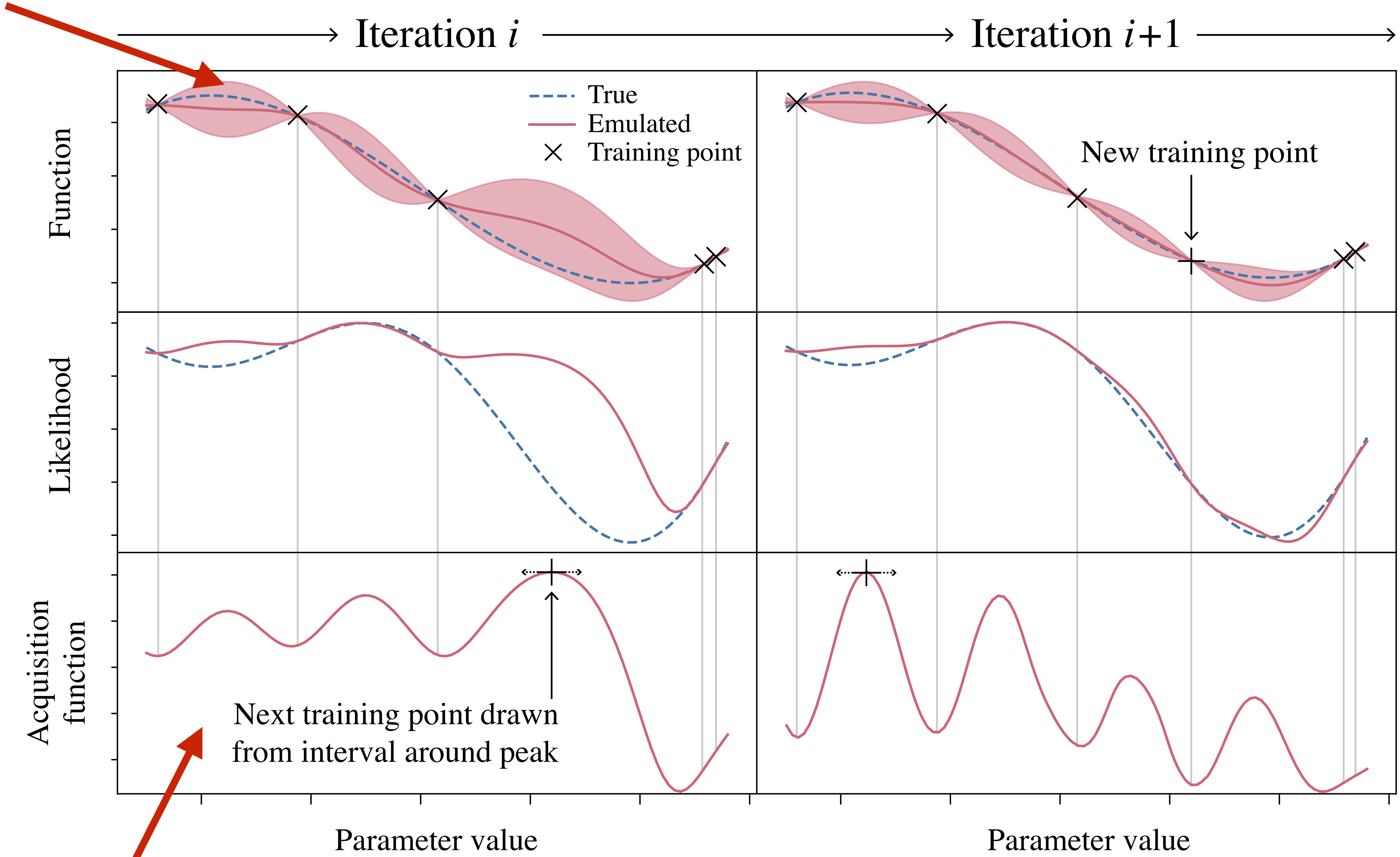
JCAP, 02, 031, 2019
JCAP, 02, 050, 2019
*with Peiris, Bird, Pontzen, Verde, Font-Ribera*

Gaussian process smoothly & probabilistically interpolates between training sims




Rogers et al. (2019, JCAP)

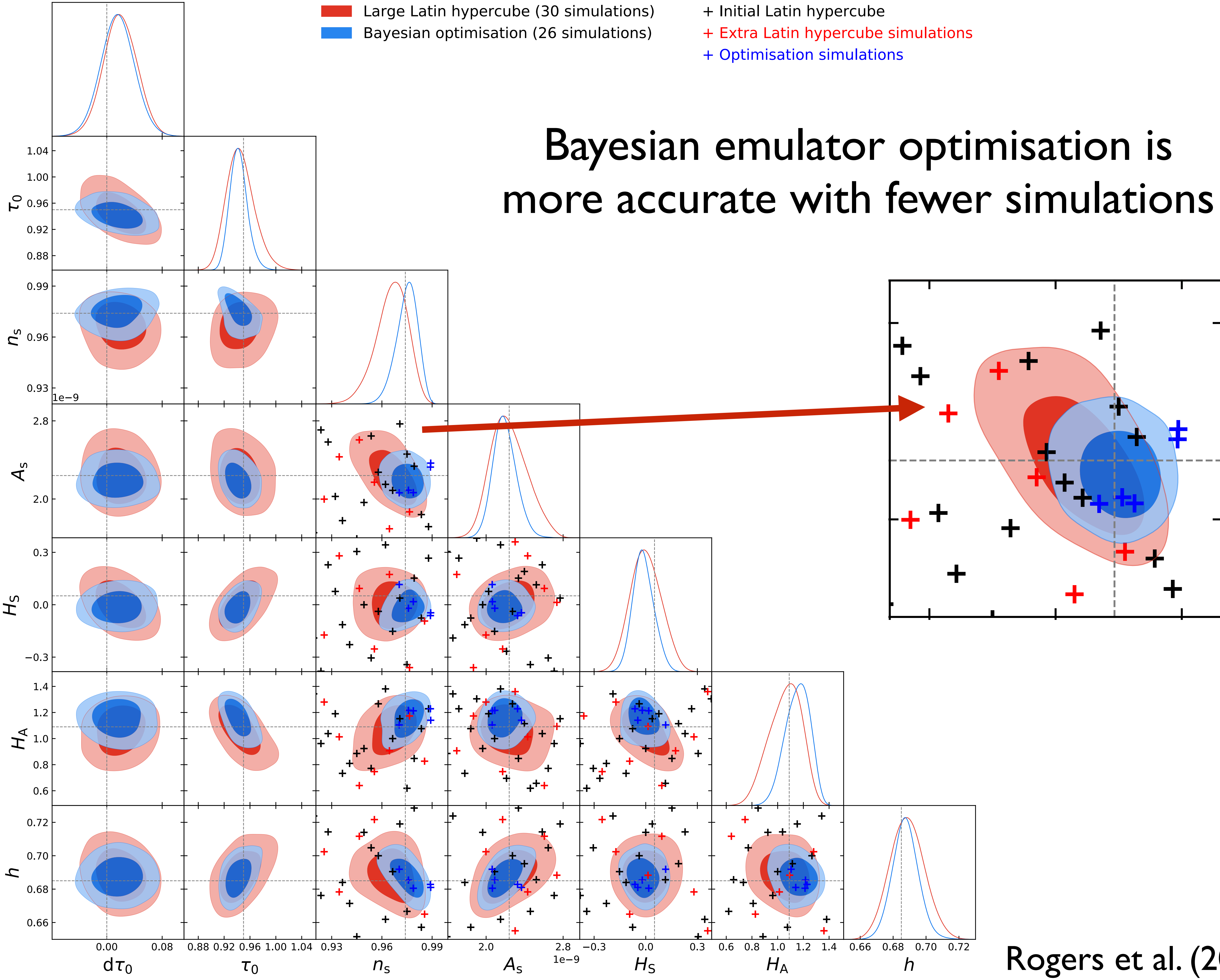
Gaussian process smoothly & probabilistically interpolates between training sims




Bayesian optimisation actively learns training set & tests for convergence

Rogers et al. (2019, JCAP)

# Bayesian emulator optimisation is more accurate with fewer simulations




Rogers et al. (2019)

# Other emulators of the cosmic large-scale structure

- Dark matter & halo statistics — small-scale non-linear matter power spectrum (*Heitmann et al. 2009*; *Giblin et al. 2019; Ho et al. 2021; Mootoovaloo et al. 2021*); halo mass function (*McClintock et al. 2018*; *Bocquet et al. 2020*)

- Galaxy clustering — galaxy power spectrum (*Kwan et al. 2015*; *Zhai et al. 2018*); higher-order statistics

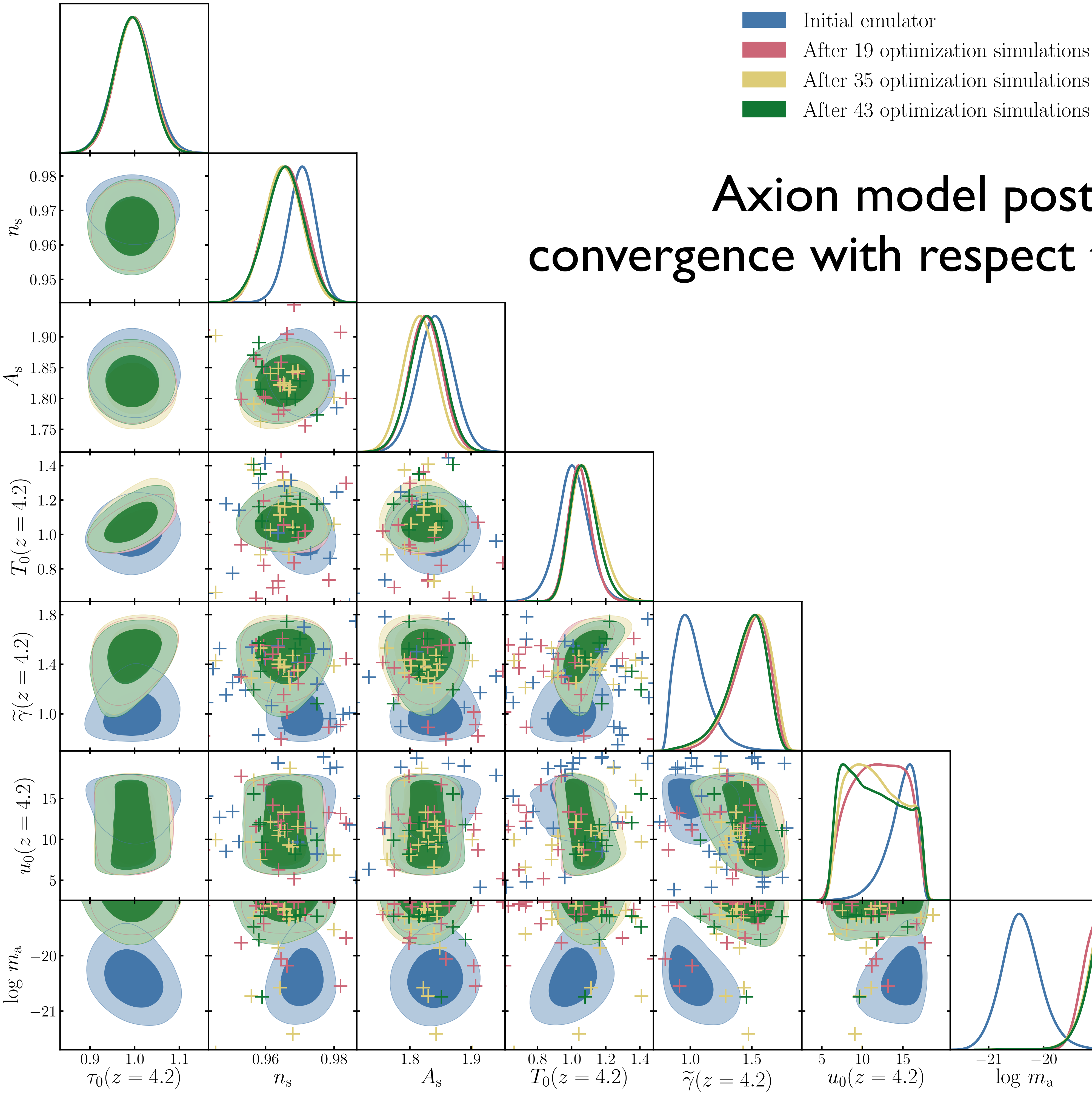
- Galaxy weak lensing — weak lensing peak counts (*Liu et al. 2015*); power spectrum (*Petri et al. 2015*); covariance matrices

- 21 cm — global signal (*Bevins et al. 2021*); 21 cm power spectrum (*Jennings et al. 2018*)

# STRONG BOUND ON ULTRA-LIGHT AXION DARK MATTER

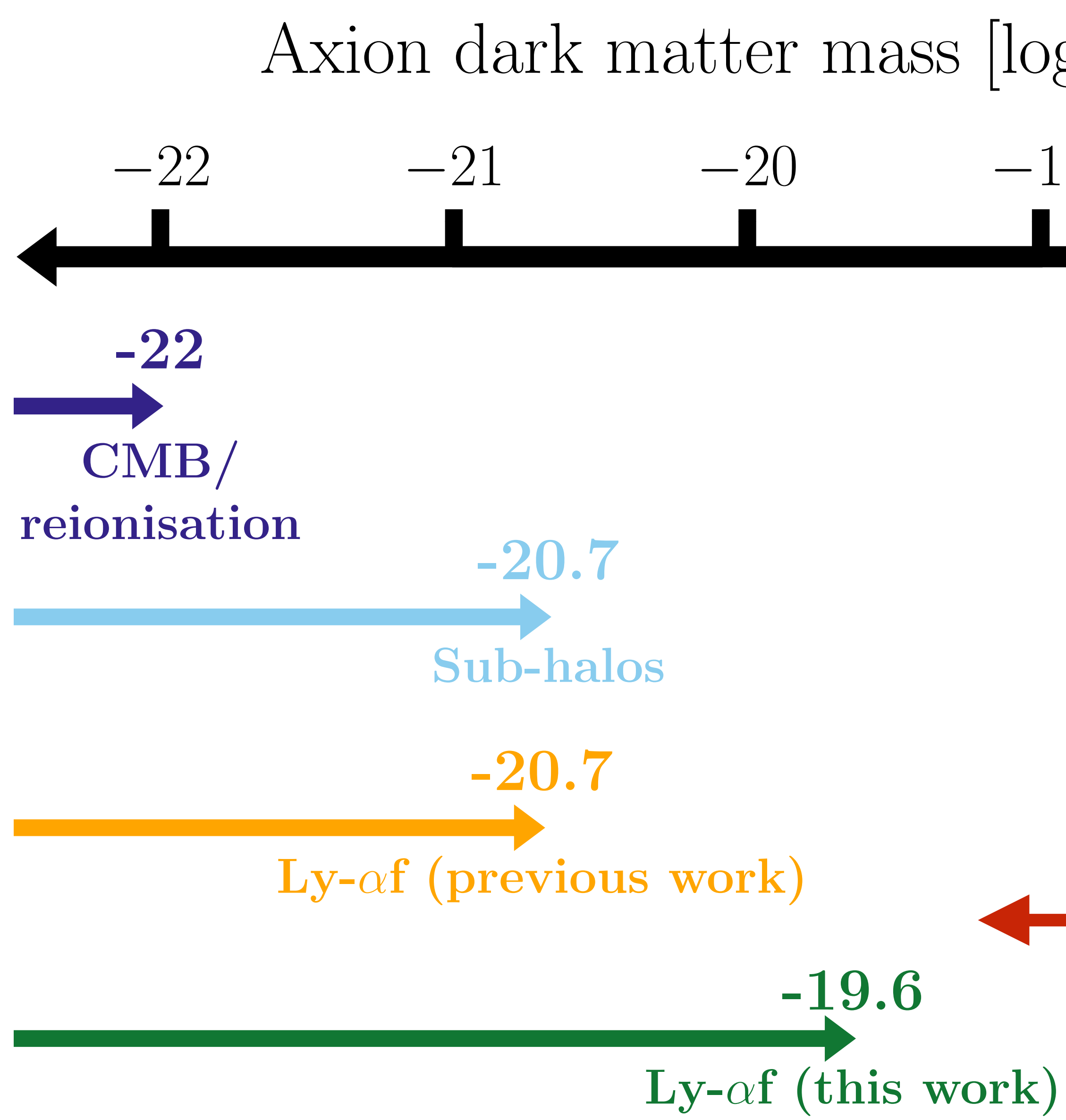
Phys. Rev. Lett., 126, 071302, 2021
Phys. Rev. D, 103, 043526, 2021
*with Peiris*

# Axion model posterior convergence with respect to training set




Rogers & Peiris (2021)

# “Canonical” $10^{-22}$ - $10^{-21}$ eV ULA DM is strongly disfavoured by new bound

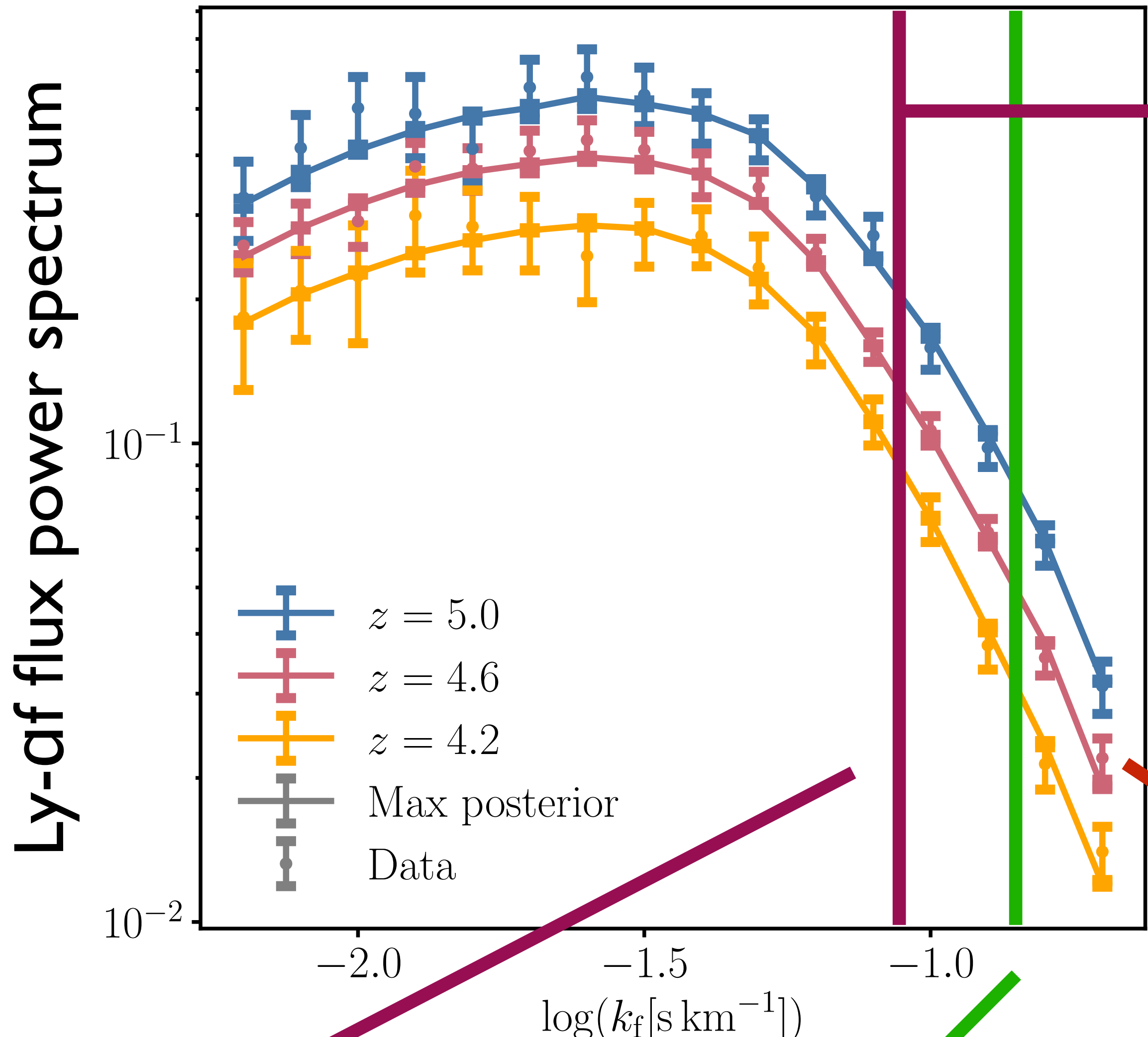



**Improve bound by ~ order of magnitude**

$$m_{\rm a} > 2 \times 10^{-20}\,{\rm eV}$$

# Removing small-scale data weakens axion mass bound

Data: Boera et al. (2019)




Smallest scale previously accessed

$$m_{\mathrm{a}} > 2.3 \times 10^{-21}\,\mathrm{eV}$$

$$m_{\mathrm{a}} > 5.8 \times 10^{-21}\,\mathrm{eV}$$

$$m_{\mathrm{a}} > 2 \times 10^{-20}\,\mathrm{eV}$$

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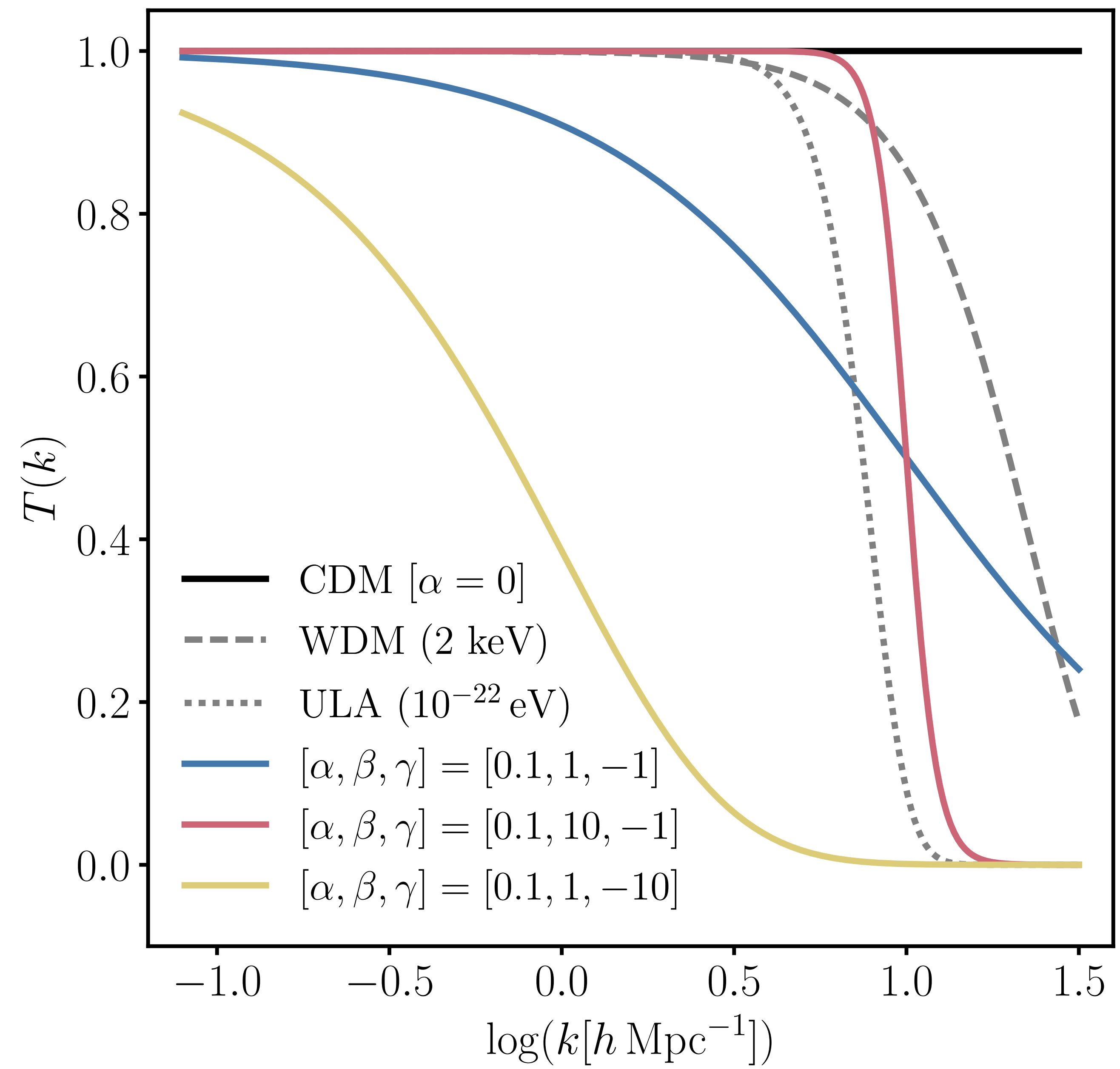
Stockholm University

Rogers & Peiris (2021ab, Phys. Rev. Lett., Phys. Rev. D)

# Emulator-inference framework can test other dark matter models

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

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




Murgia et al. (2018)

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Rogers & Peiris (2021ab, Phys. Rev. Lett., Phys. Rev. D)

# Summary

- **Canonical ULA DM strongly disfavoured**: $m_a > 2 \times 10^{-20}$ eV (95% c.l.)
- **Emulator/active learning** to marginalise robustly astrophysical uncertainty
- Framework **tests other DM models**