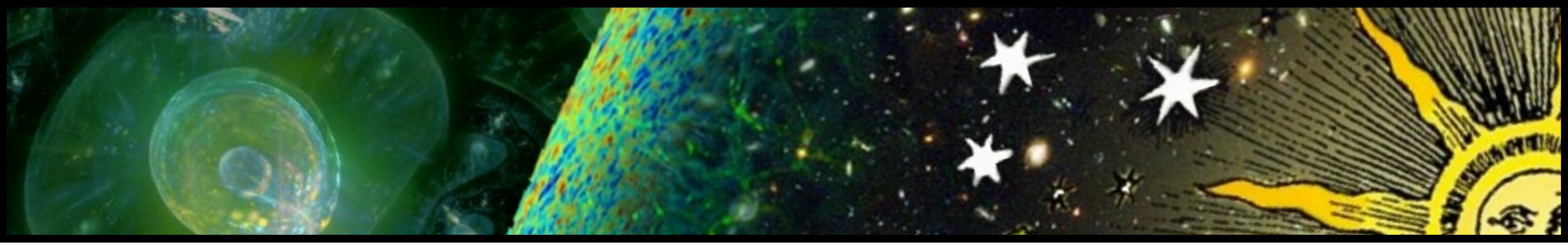


Emulating the Universe

Hiranya V. Peiris

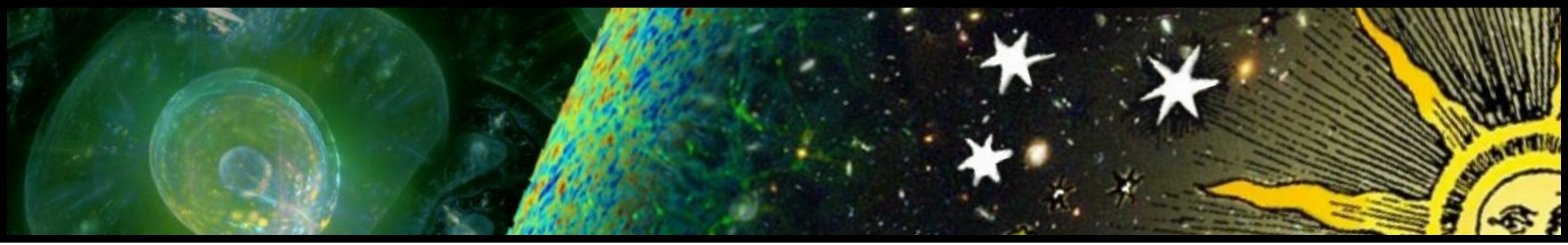
UCL and Oskar Klein Centre Stockholm

How should we compare

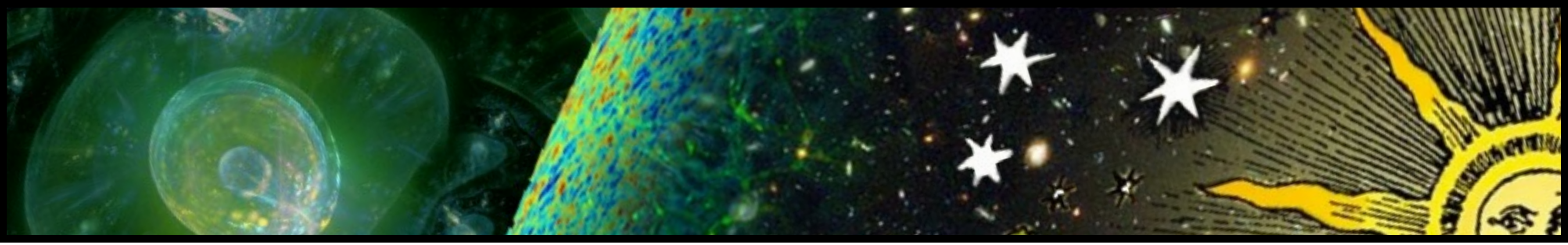
vs

Theory

Data?



Cosmological interpretation increasingly reliant on evaluating computationally-costly, non-linear models with many parameters

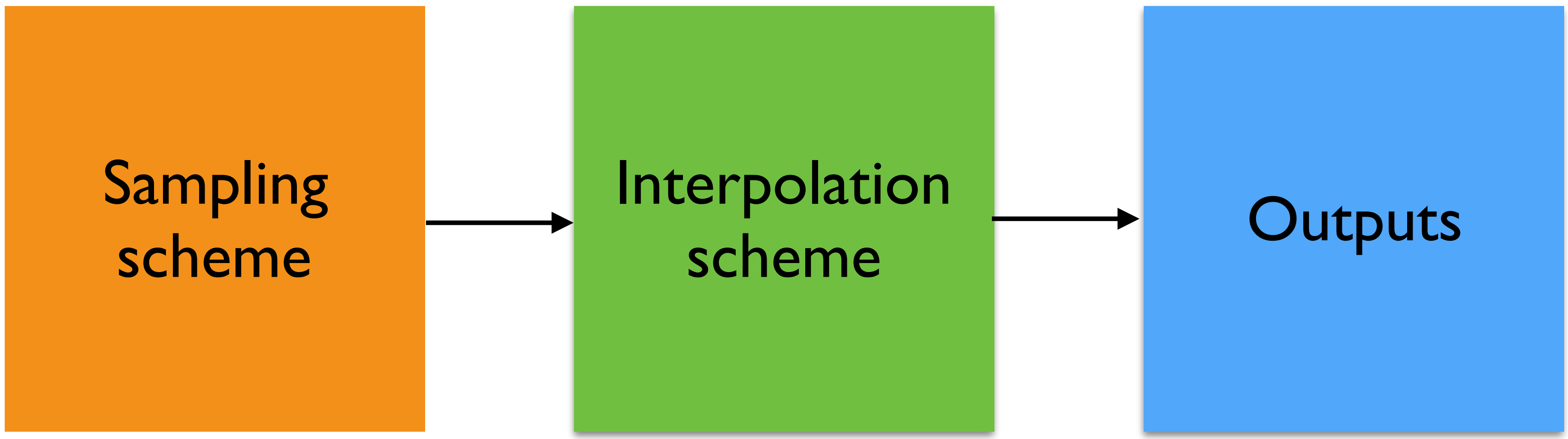


Solutions

- *reduce number of model evaluations required for robust/accurate inference*
- *speed up individual model evaluations*

Emulators for small training sets — very costly simulations (hours-days-weeks each)

Basic emulator setup



Typical implementation

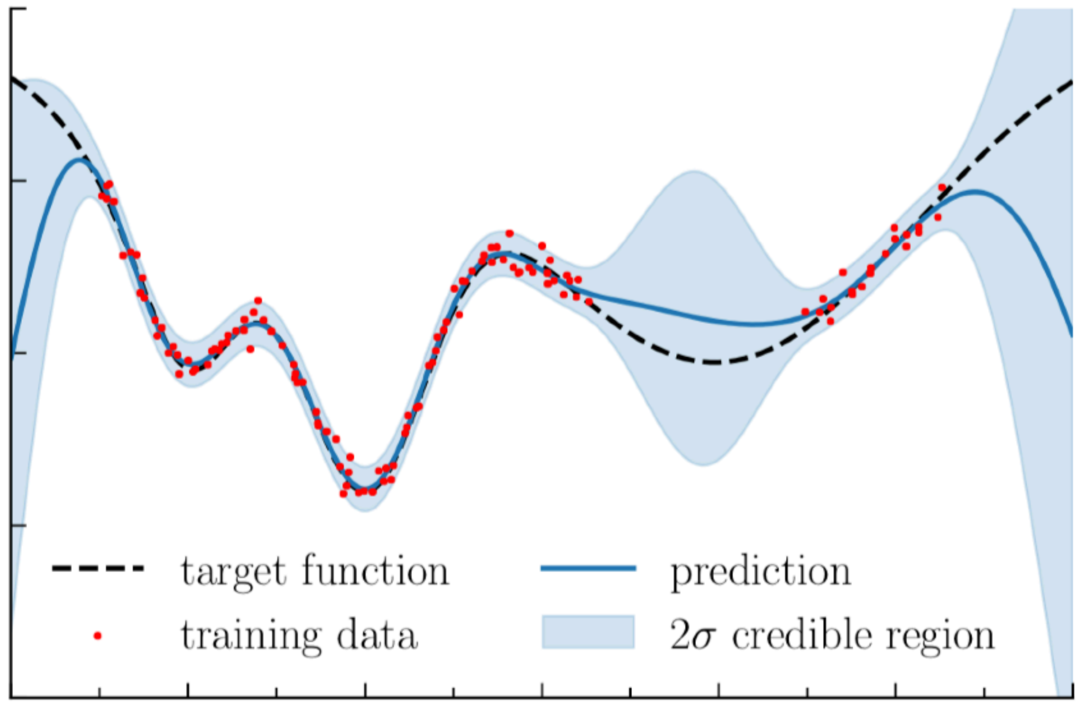
Latin Hypercube sampling → Gaussian Process interpolation → Typical use cases:

- non-linear matter power spectrum
- galaxy survey observables

- ***Pioneering work:*** *Coyote Universe simulations (2008—) (Katrin Heitmann and collaborators)*
- ***State of the art examples:*** *AEMULUS, EuclidEmulator…*

Gaussian process

- *Smooth interpolation scheme* *that gives tight constraints where there are training points and broad constraints where there are none*



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

Simulation output

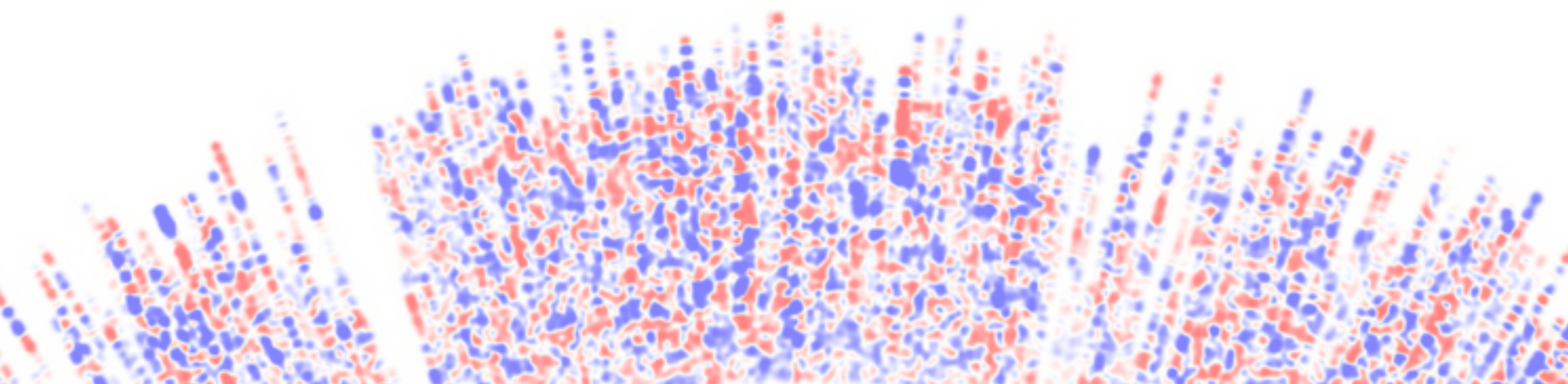
Simulation parameters

Kernel hyperparameters (covariance model)

Figure: Leclercq (2018)

Active acquisition of training set

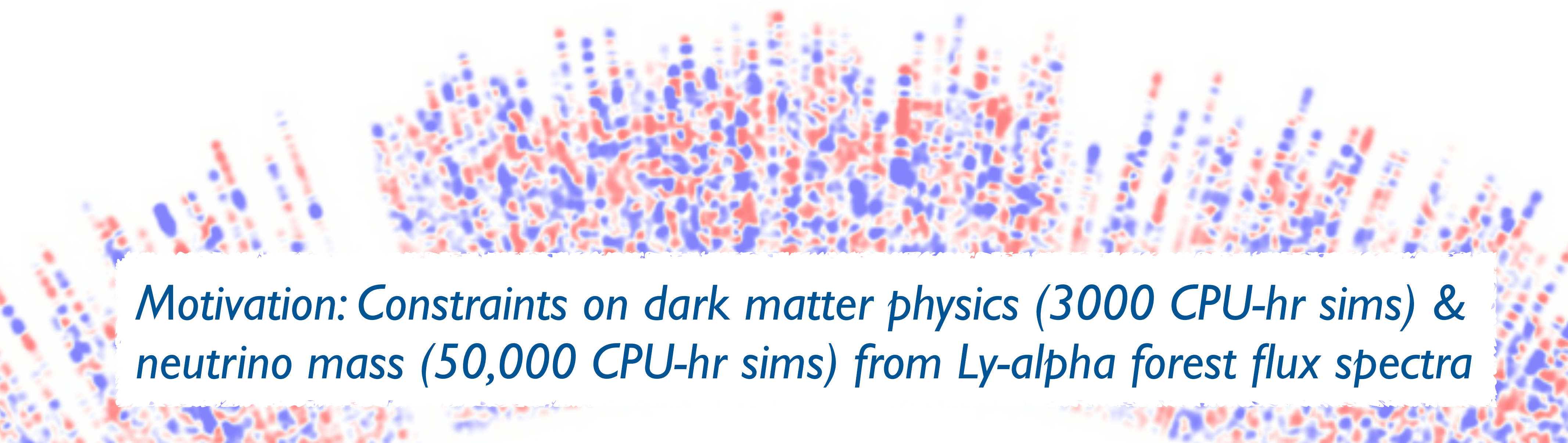
- **Bayesian optimisation** *(see e.g. Gutman and Corander 2016 / Leclercq 2018) can be used to actively construct emulator GP training set.*
- *Balance* ***exploration*** *(where interpolation error is large) against* ***exploitation*** *(where posterior probability is large)*
- *Reach target accuracy with fewer simulations!*



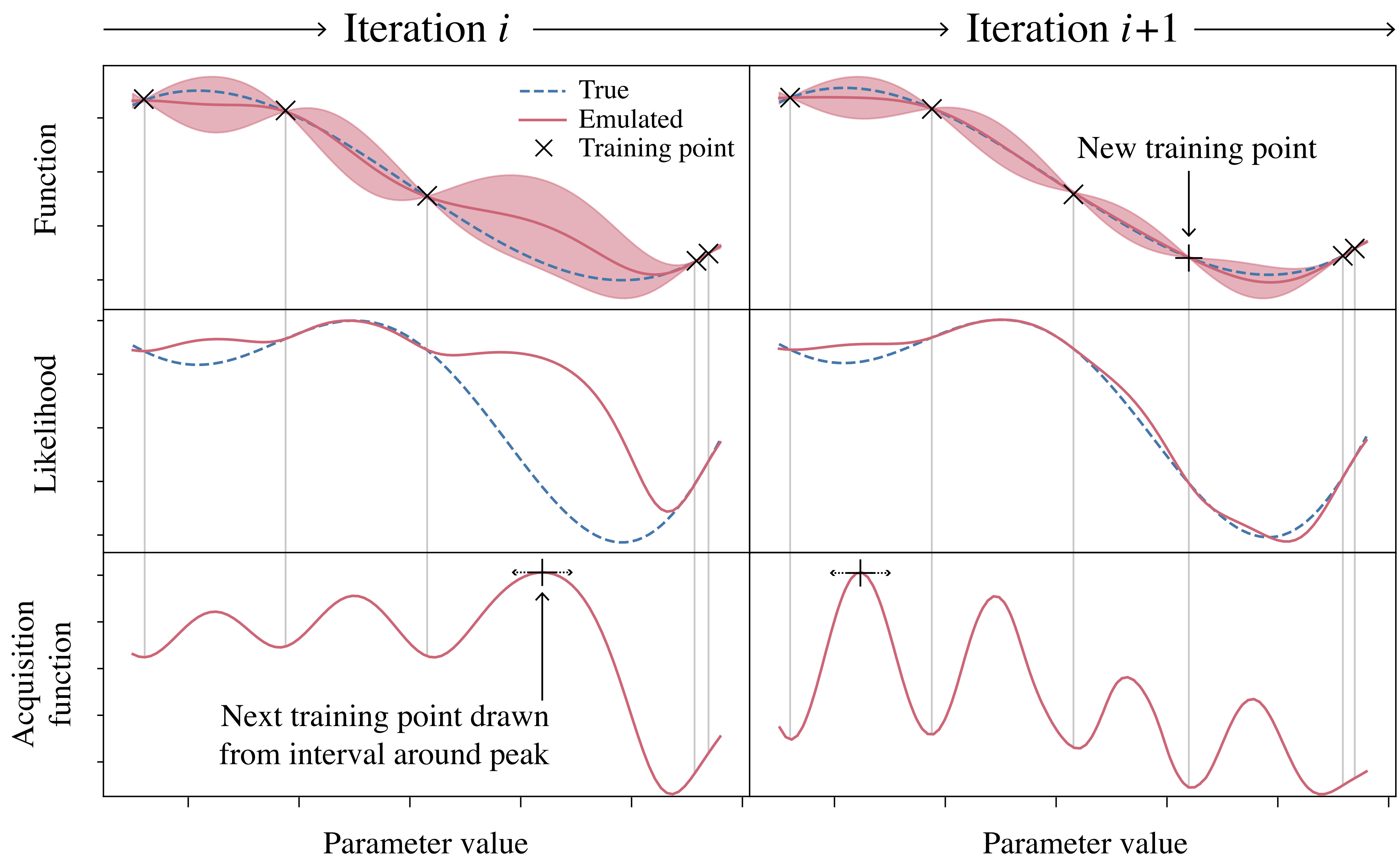
arxiv: 1812.04631, 1812.04654 (JCAP, 2019)

with

Keir Rogers (Stockholm)
Simeon Bird (UC Riverside)
Andrew Pontzen (UCL)
Andreu Font-Ribera (UCL)
Licia Verde (Barcelona)

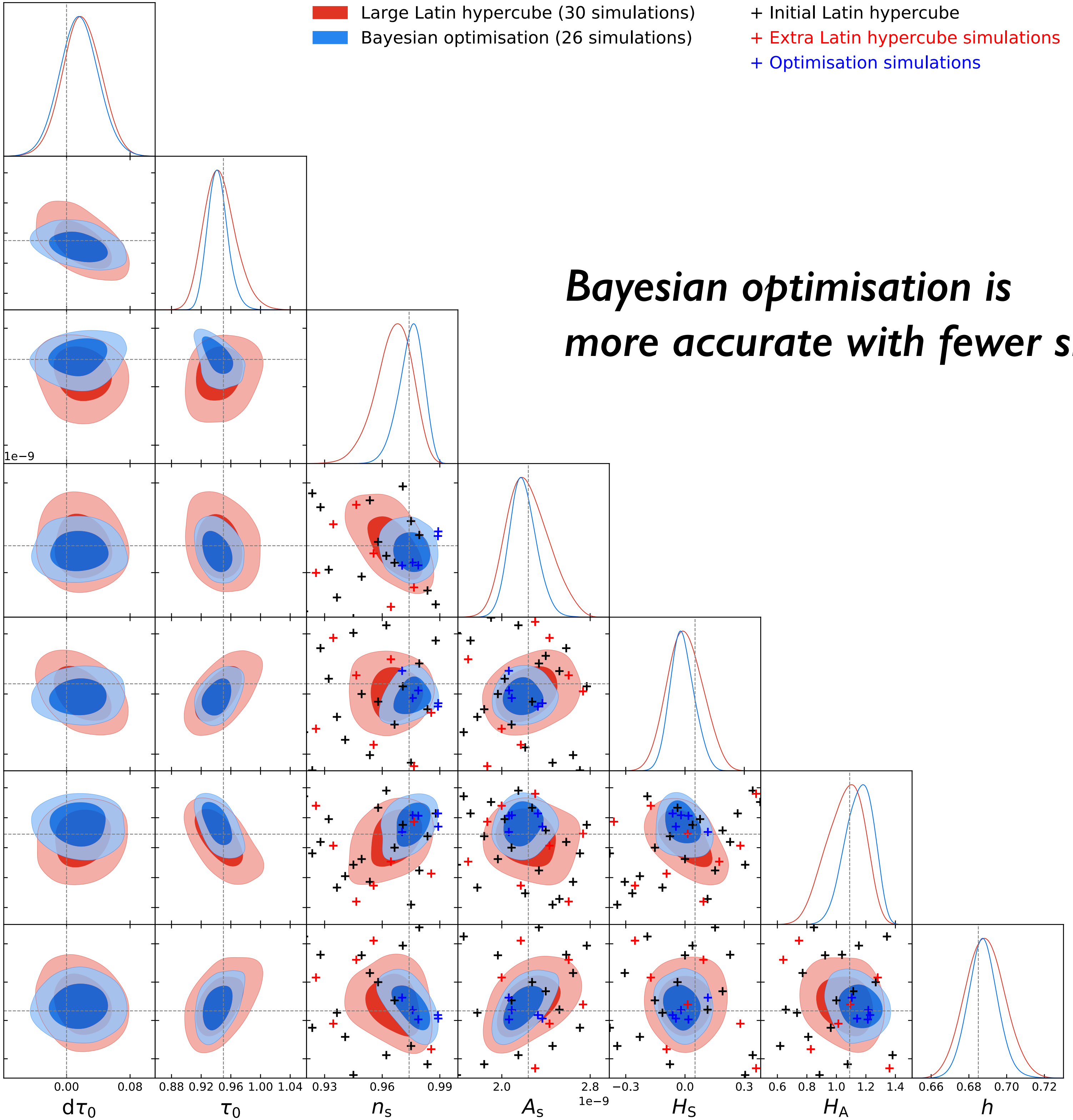


Motivation: Constraints on dark matter physics (3000 CPU-hr sims) & neutrino mass (50,000 CPU-hr sims) from Ly-alpha forest flux spectra



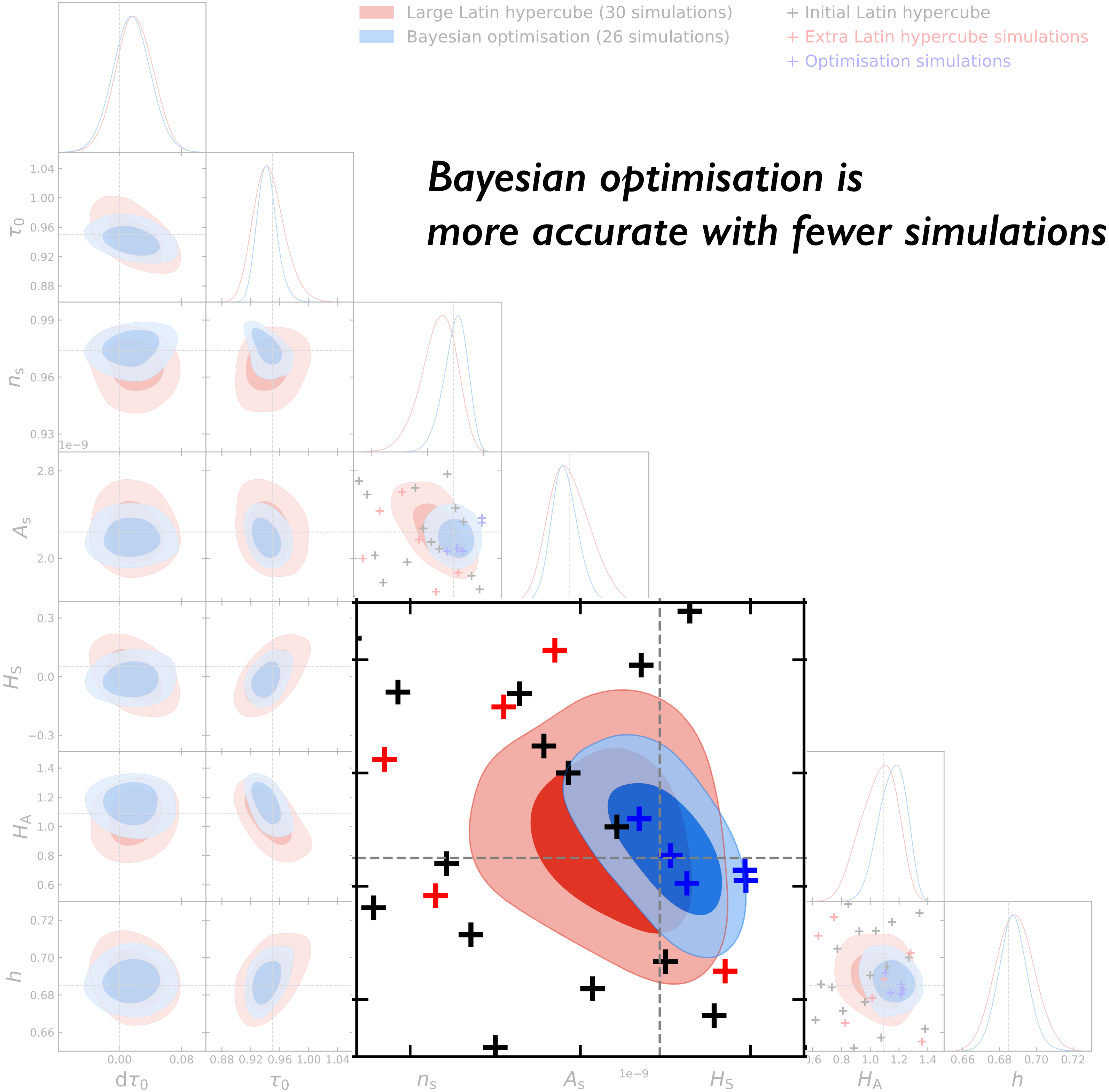
Rogers et al (2019)

Bayesian optimisation is more accurate with fewer simulations

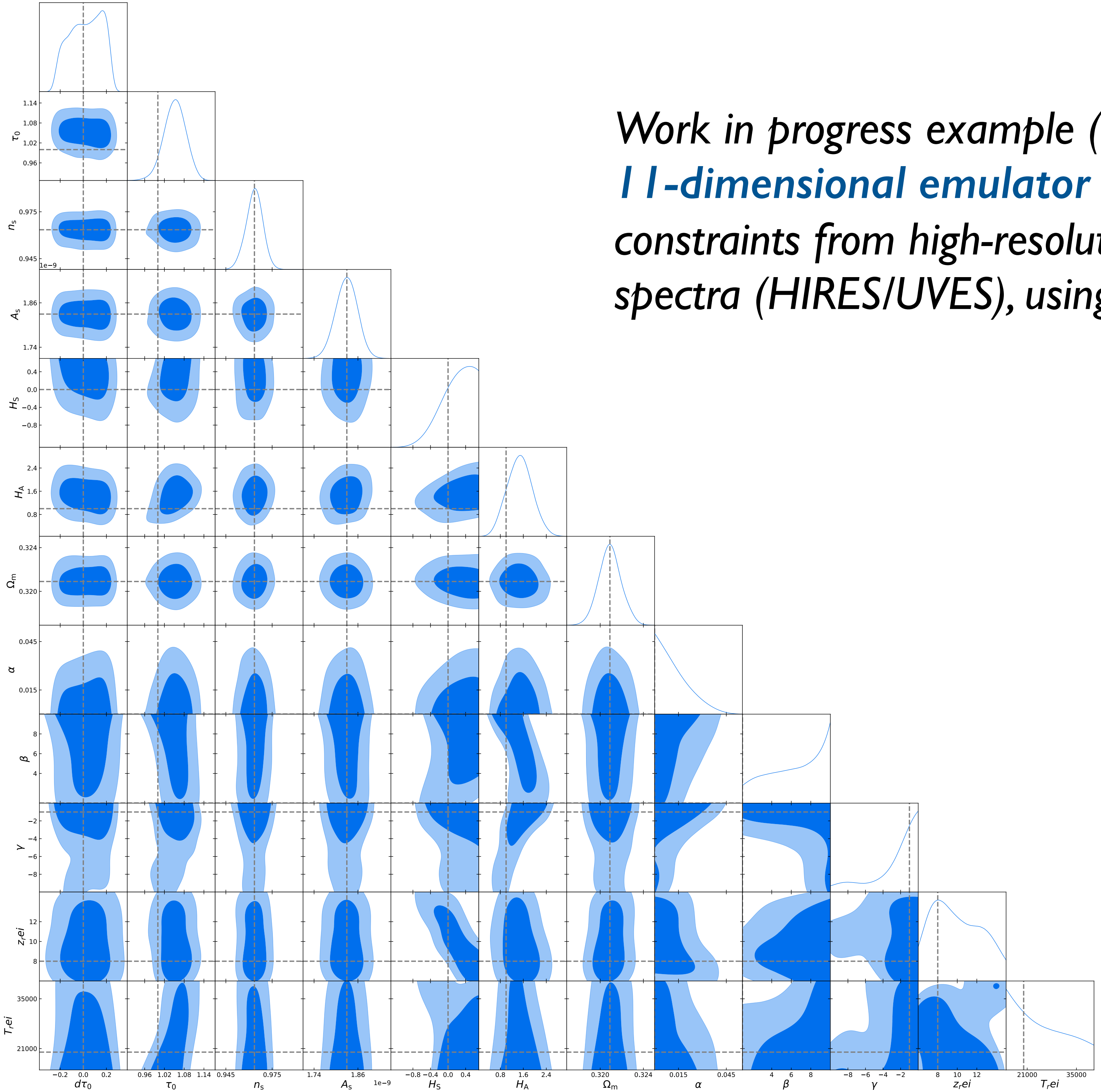


Rogers et al (2019)

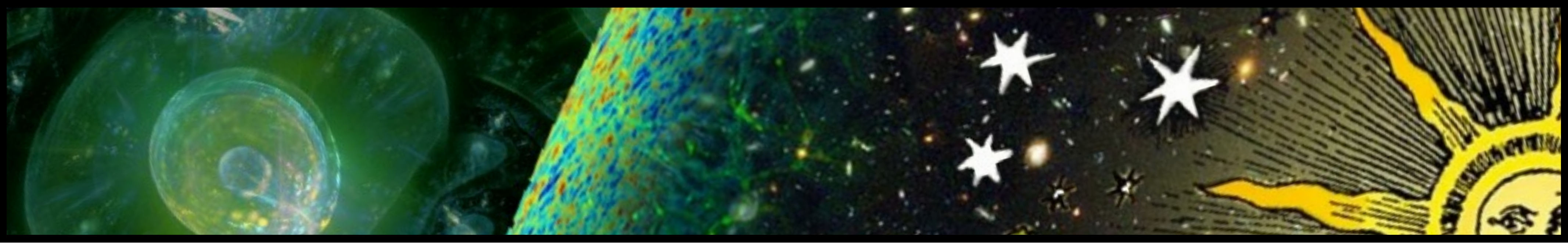
Bayesian optimisation is more accurate with fewer simulations



Rogers et al (2019)



*Work in progress example (Keir Rogers): **11-dimensional emulator** for dark matter constraints from high-resolution high-z Lya spectra (HIRES/UVES), using **~50 sims**.*



Emulators for medium training sets — faster simulations (seconds each)

Case study: emulating population synthesis

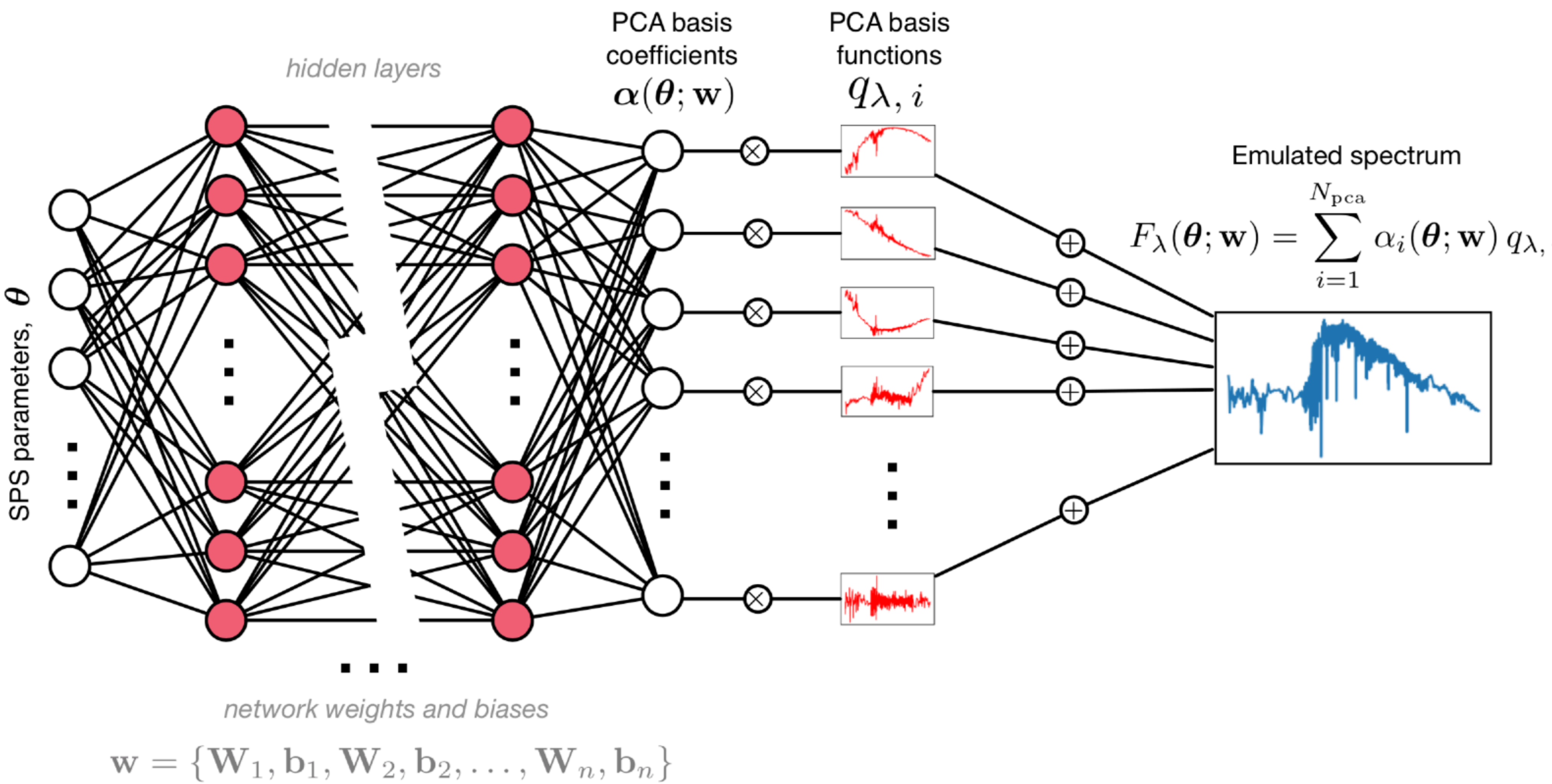
- *SPS models (e.g. FSPS, Charlie Conroy and collaborators) are fast (<1 sec) but use cases require **large numbers of model evaluations**.*

- *Stage IV galaxy survey catalog sim ~ 10^{10} SPS evaluations*

- *Leja et al (2019) analysis of 60,000 galaxies under 14-parameter SPS model cost1.5 million CPU-hrs.*

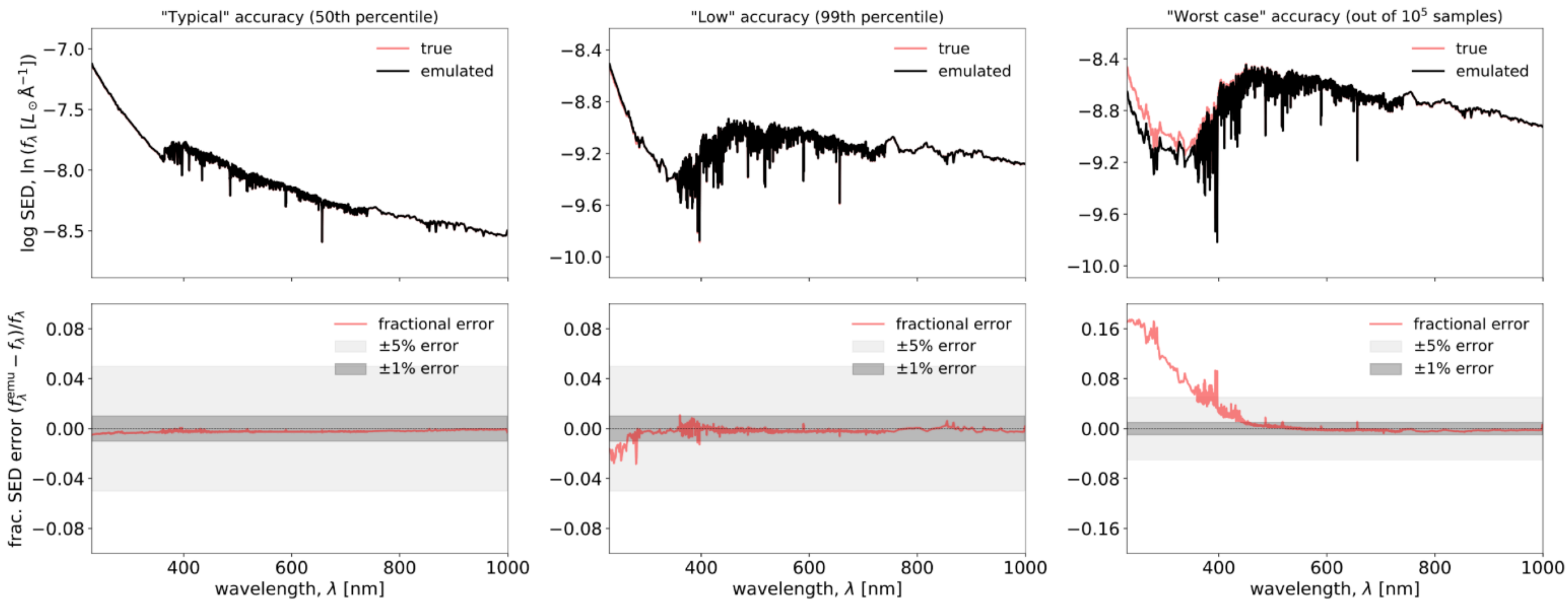
- *Can generate training sets of ~10^5 **enabling neural network emulators.***

SPECULATOR architecture



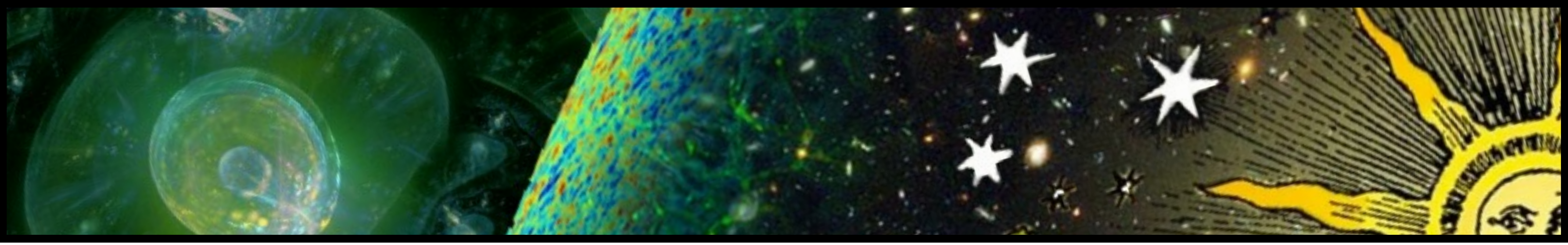
Alsing, Peiris, Leja, Hahn, Tojeiro, Mortlock, Leistedt, Johnson, Conroy (in prep)

Example: DESI Bright Galaxy Survey SEDs



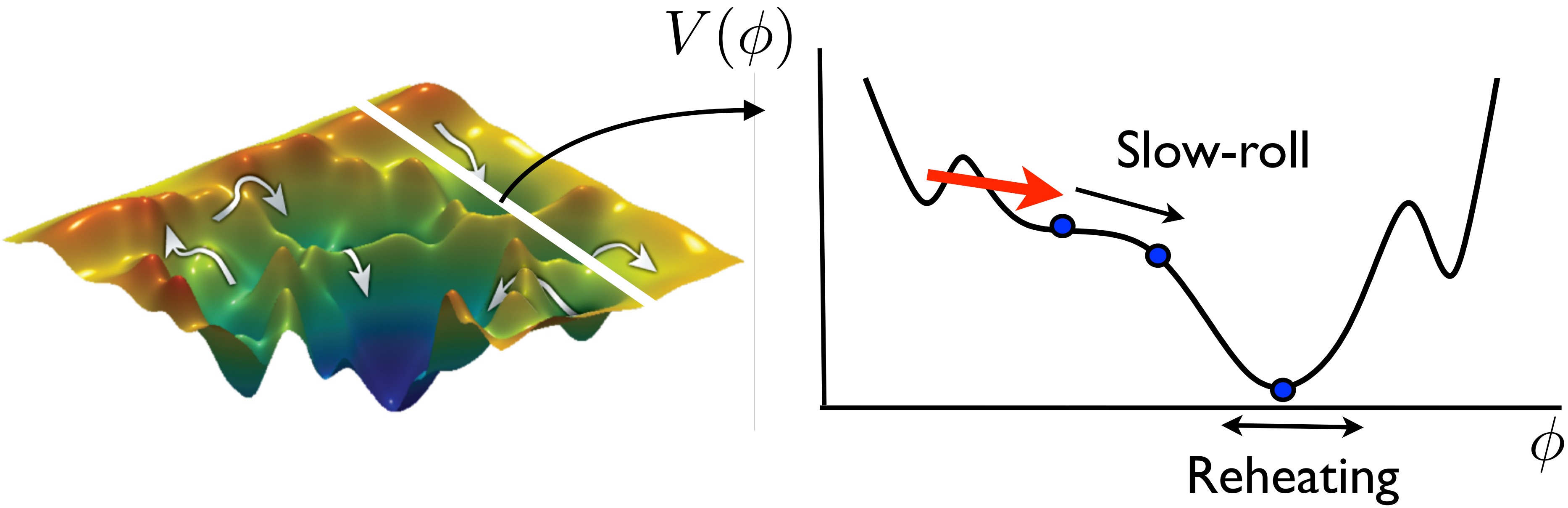
- *Accuracy <1% over the 8-parameter FSPS model for >99% of SEDs*
- *Generating 10^6 SEDs takes 2s on Tesla K80 GPU (Speedup 10^5 over FSPS on CPU); inference under SPS models can make use of gradients*

Alsing et al in prep (2019)



Emulating cosmological processes in the lab

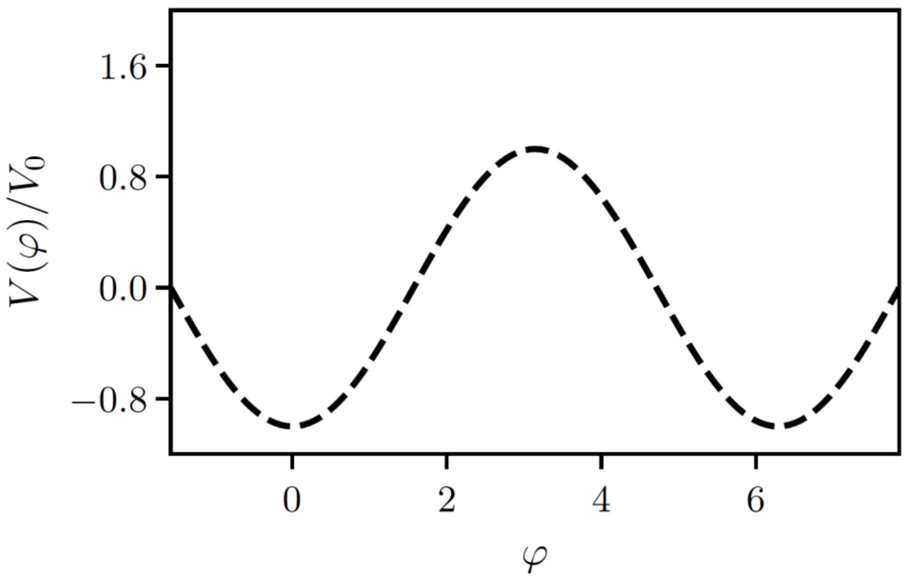
Origin of Universe through vacuum decay?



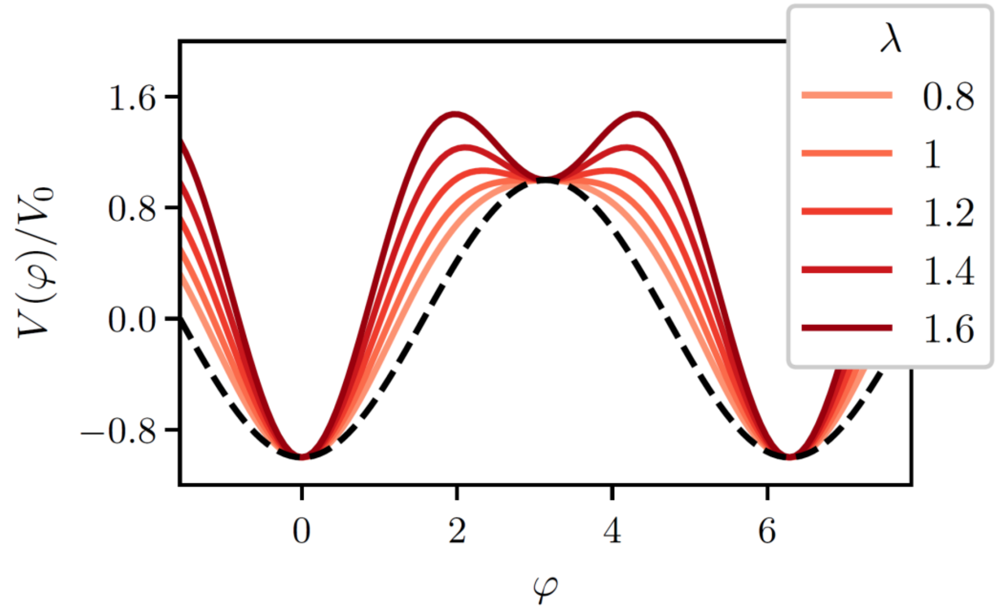
- *Particle physics-inspired cosmological theories exhibit **false vacuum decay** via **bubble nucleation***
- *Relativistic first-order phase transition: non-perturbative, non-linear, non-equilibrium process*
- *Understanding dynamics could shed light on origin of Universe.*

Universe on a table-top

- *Fialko proposal: "emulate" full dynamics in condensed-matter system!*
- *They propose 2-component coupled Bose-Einstein Condensate (BEC) system (ultra-cold dilute boson gas, in two single-particle states)*



Dynamics of relative phase exhibits Sine-Gordon Lagrangian

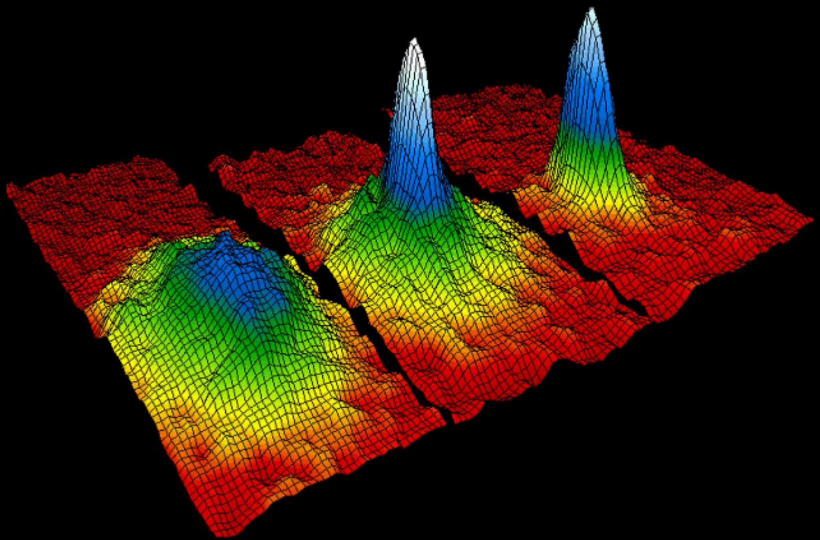


Engineer metastable vacuum by adding high-frequency modulation in transition coupling

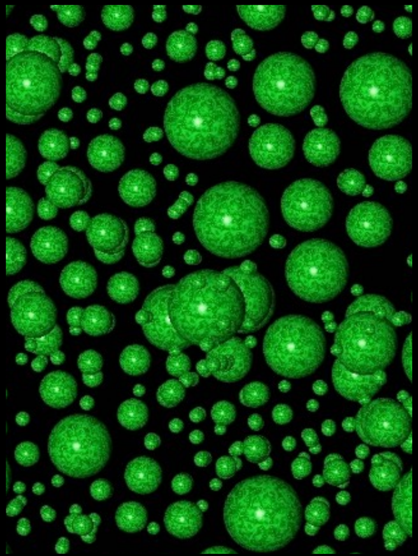
Fialko, Sidorov, Drummond, Brand, J.Phys.B50 (2017), 024003 [1607.01460]

Experiment

Early Universe



$=$



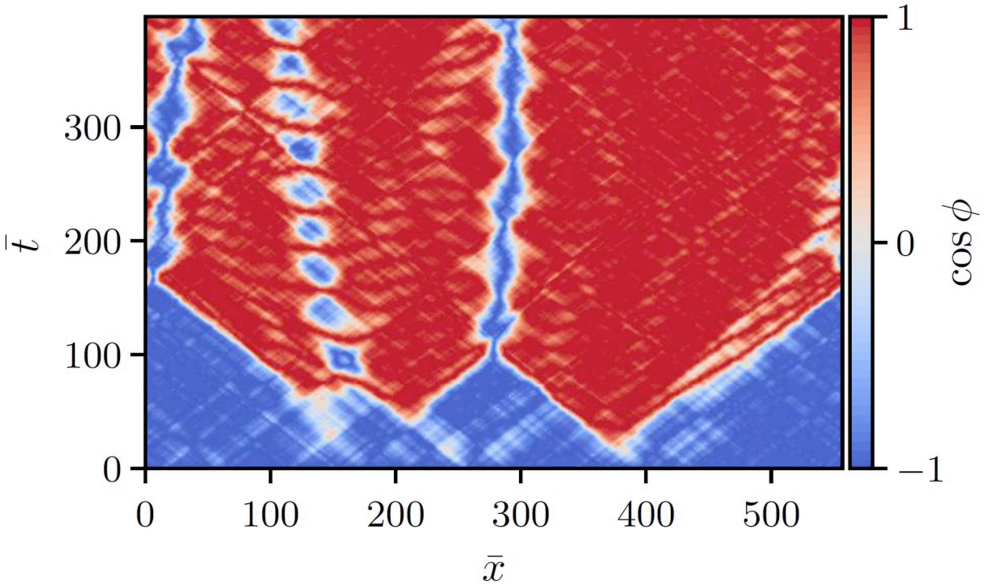
?

$\mathscr{L}_{\mathrm{CM}}$

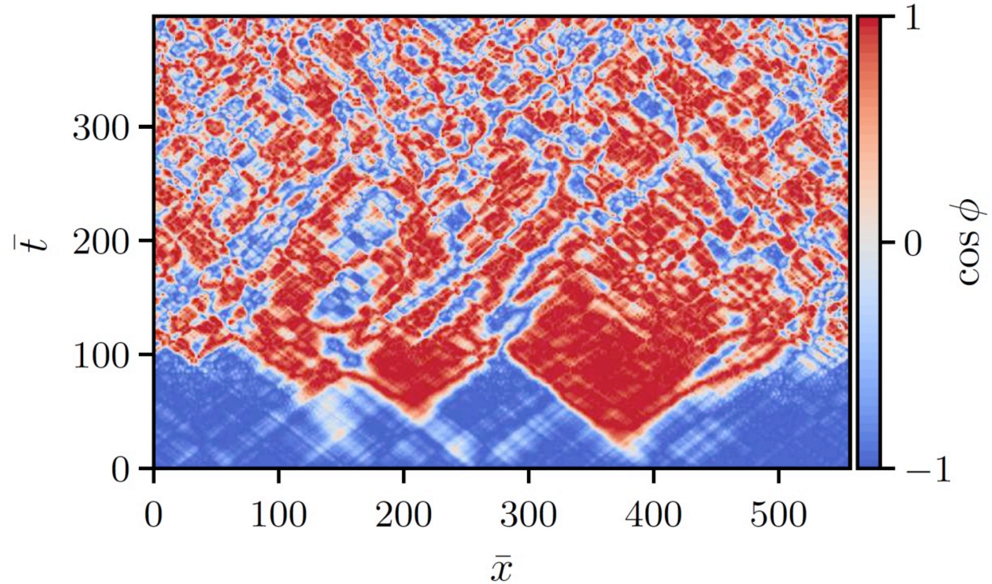
$\mathscr{L}_{\mathrm{eff}}$

How good is this mapping when experimental systematics are taken into account?

Investigating experimental feasibility



false vacuum decay



Floquet instability

- *Investigated effects that impact validity of analogue if not controlled, feeding back into experimental design.*
- *Linear stability analysis, confirmed by stochastic lattice simulations.*
- *Further experimental effects need to be quantified and mitigated.*

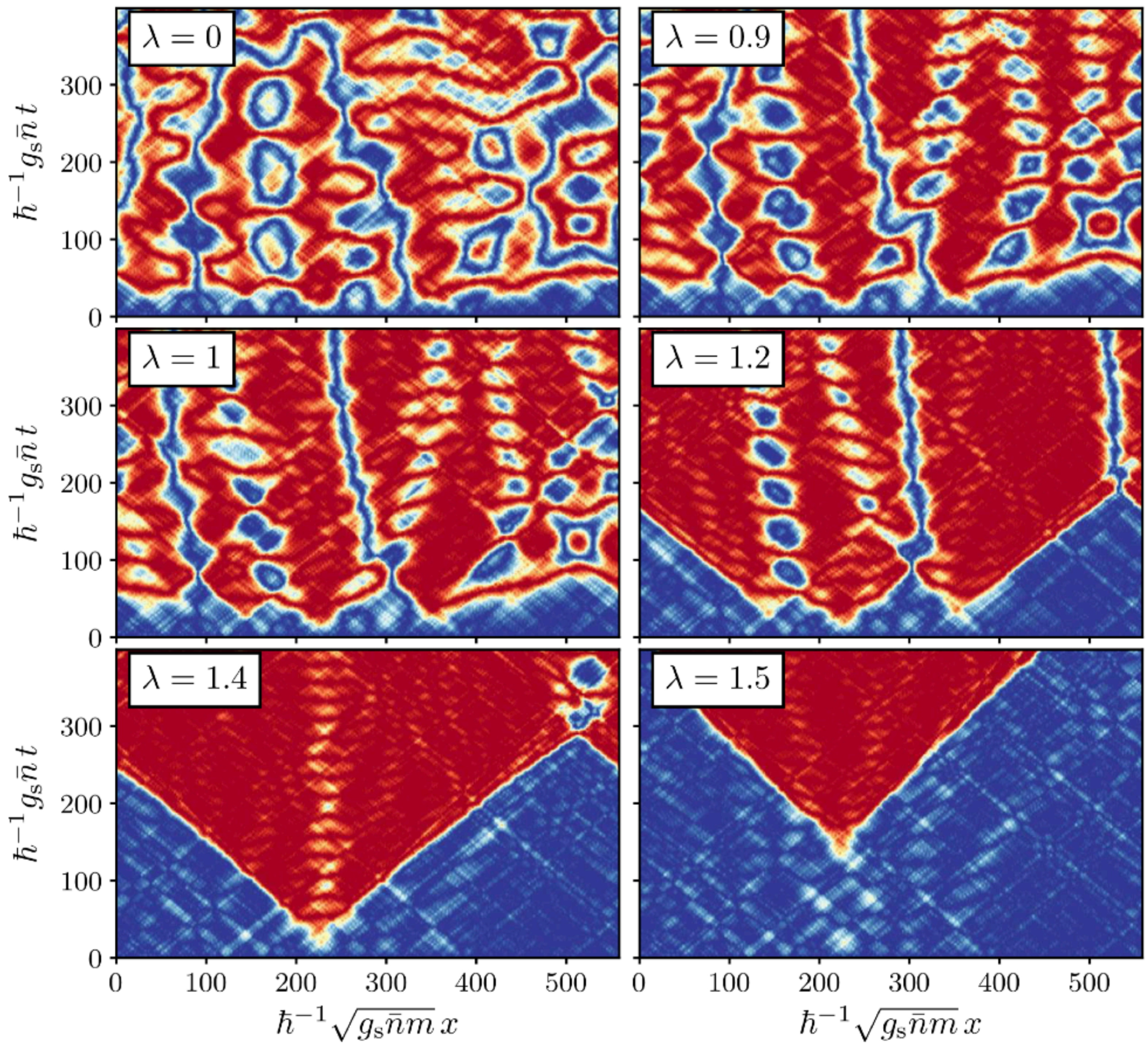
Braden, Johnson, Peiris, Pontzen, Weinfurtner, JHEP (2018), JHEP in review (2019)

Experiments are tunable

second-order phase transition

rapid nucleation

slower nucleation

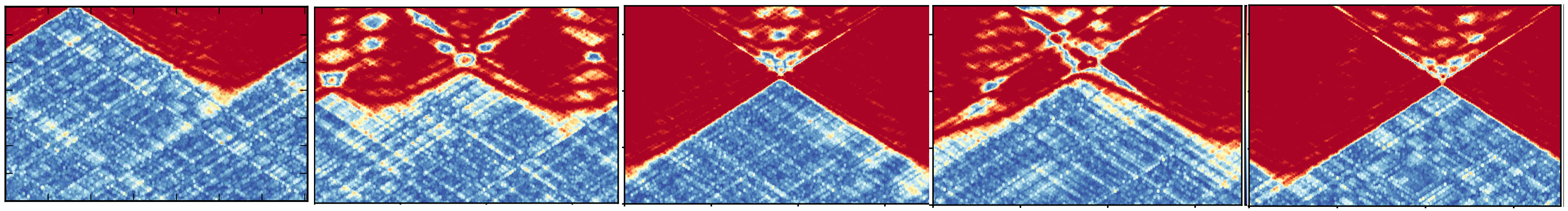


experimentally tunable parameter λ

Braden, Johnson, Peiris, Pontzen, Weinfurtner, JHEP in review, 1904.07873

A new description of vacuum decay?

- *Can compute decay rates to high precision by stacking many simulations*



- *Compare with "quantum tunnelling" instanton predictions*

- *Surprise! Rates are very similar (given semiclassical stochastic lattice sims only capture classical decay paths)*

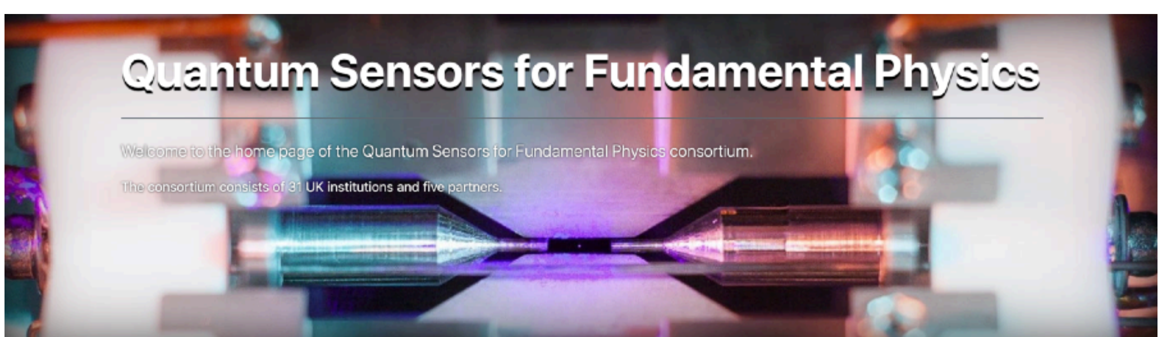
- *New "real time" semiclassical interpretation of false vacuum decay? Technique enables computation of observables inaccessible to instanton formalism*

Braden, Johnson, Peiris, Pontzen, Weinfurtner, Phys. Rev. Lett. (2019),
Hertzberg and Yamada (2019), Blanco-Pillado, Deng, Vilenkin (2019)
See also early work on stochastic approach to tunnelling e.g. Linde (1991)

Pathway to experiment

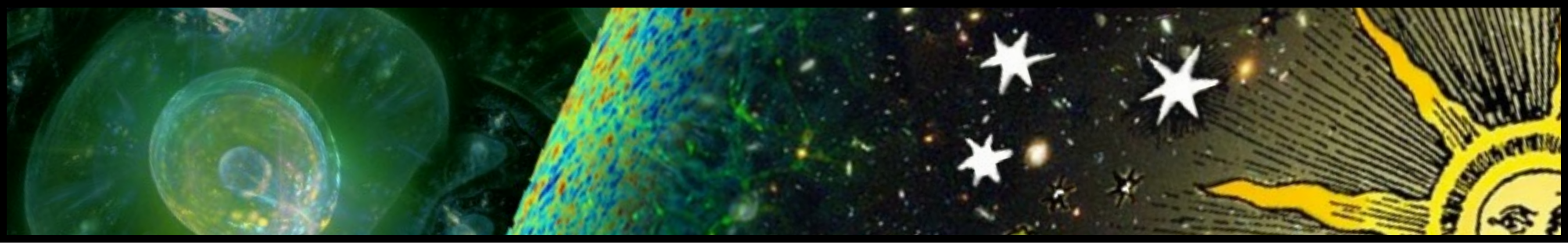
- *Working with Zoran Hadzibabic (Cambridge Quantum Gases) towards experimental implementation! Several other experimental efforts internationally.*

- *Part of "Quantum Simulators for Fundamental Physics" (QSimFP) workpackage of QSFP Consortium.*



QSimFP

http://qsfp.physics.ox.ac.uk



Powerful methods available now to enable cosmology with complex, costly models.

Allows machines to take on the drudgery, leaving humans to focus on the physics.