PRIYA: A Cosmological Emulator with Black Holes

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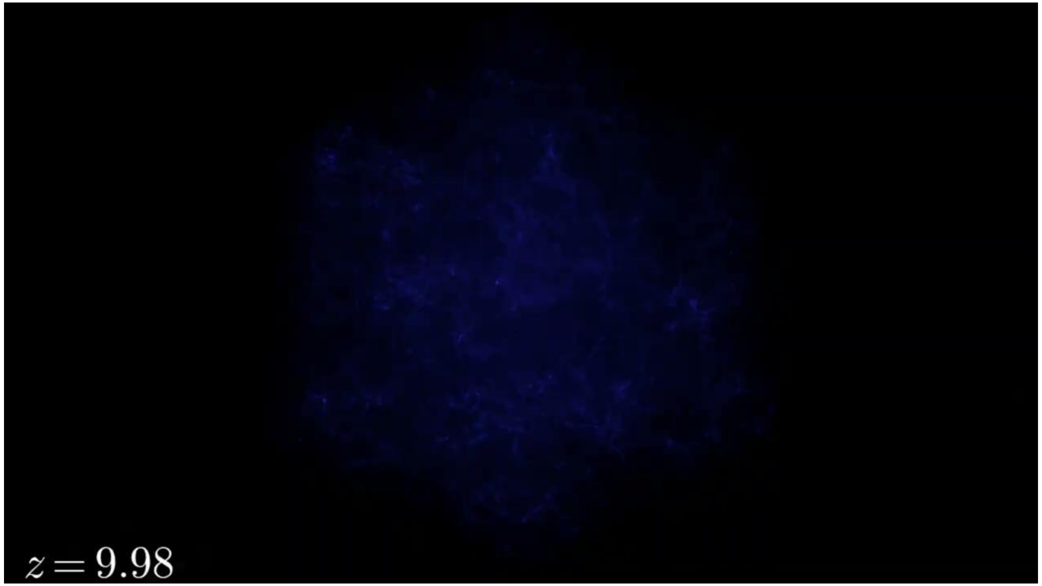
What are cosmological simulations?

The evolution of a statistically representative region of an artificial Universe from the first galaxies to today.

Initially uniform 20-1000 Mpc periodic box.

Forms structure, galaxies



Thanks to the ASTRID-CAMELS team

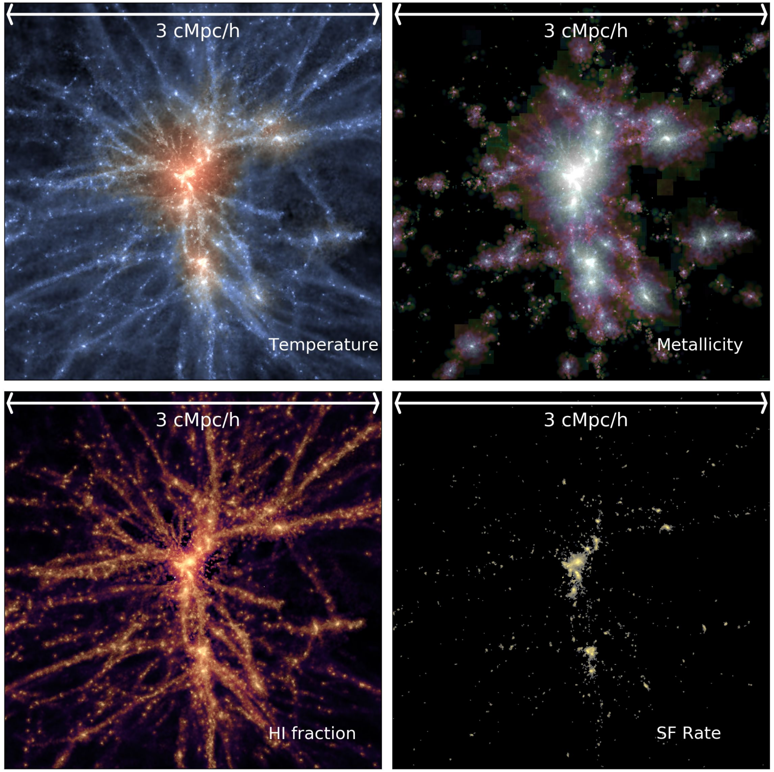
Cosmological Simulations: Why?

ASTRID: Single big model for galaxies

PRIYA: Cosmology

Multiple models
with different parameters

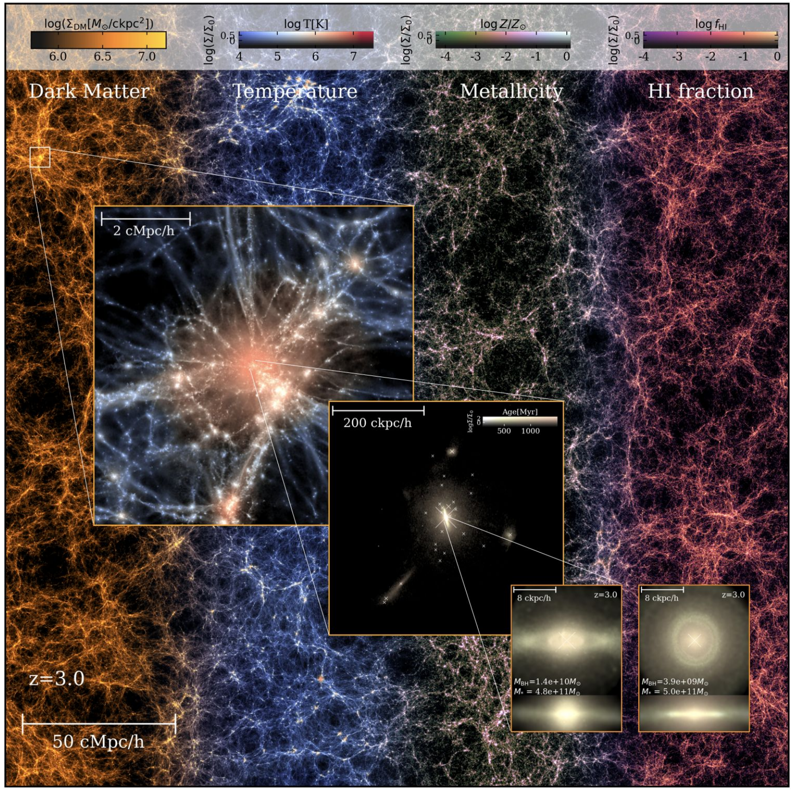
Interpolate and compare
to observations



Self-Gravity Dominated Dynamics

Dominated by self-gravity:

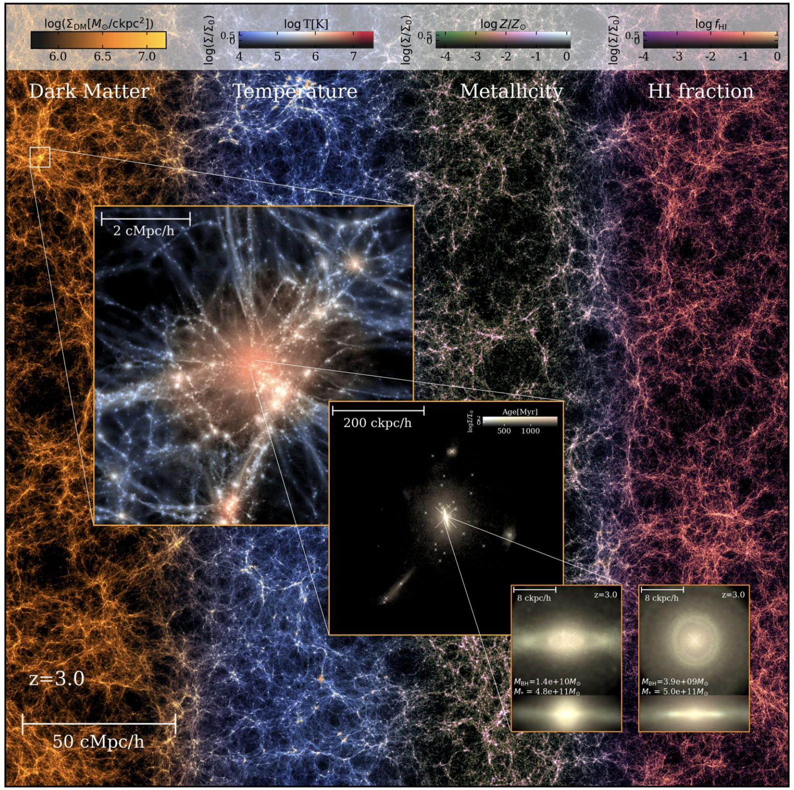
- Treat as many collisionless ‘particles’ (fluid elements).
- 10^6 density contrast
- Hydro collisional particles
- Stars/black hole particles



Cosmological Parameter Suite

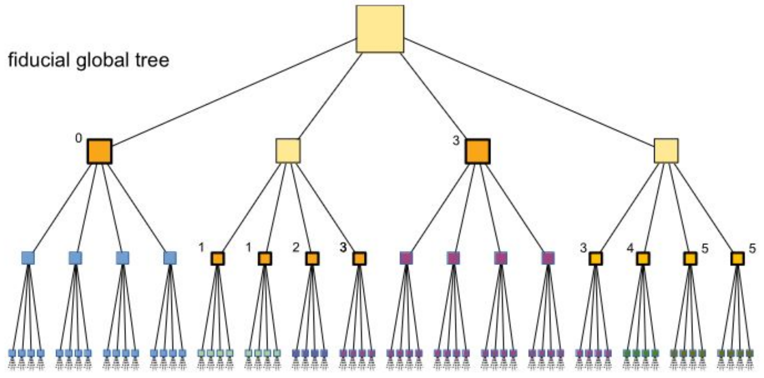
– We have: 3072^3 and 1536^3
- Illustris-TNG: 2500^3
- ASTRID: 5500^3

Frontera is very fast!
~10,000 SUs for 1536^3
~100,000 SUs for 3072^3
(Our Gadget is also fast)



Self-Gravity Dominated Dynamics

Adaptive timesteps so most particles are not active



(Gadget-4: Springel+ 2020)

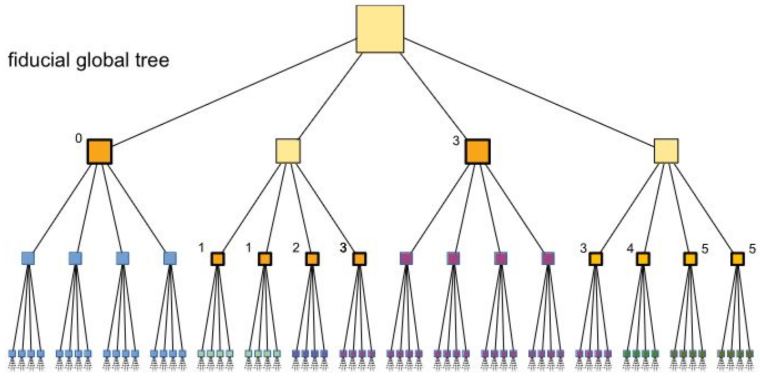
Gravity is an FFT/tree method

Gravity tree only has active particles

Uses mass moments to avoid walking whole tree

Gas/Galaxy is Neighbour Tree

- Contains all particles
- Variable length branches
- Hard to predict



(Gadget-4: Springel+ 2020)

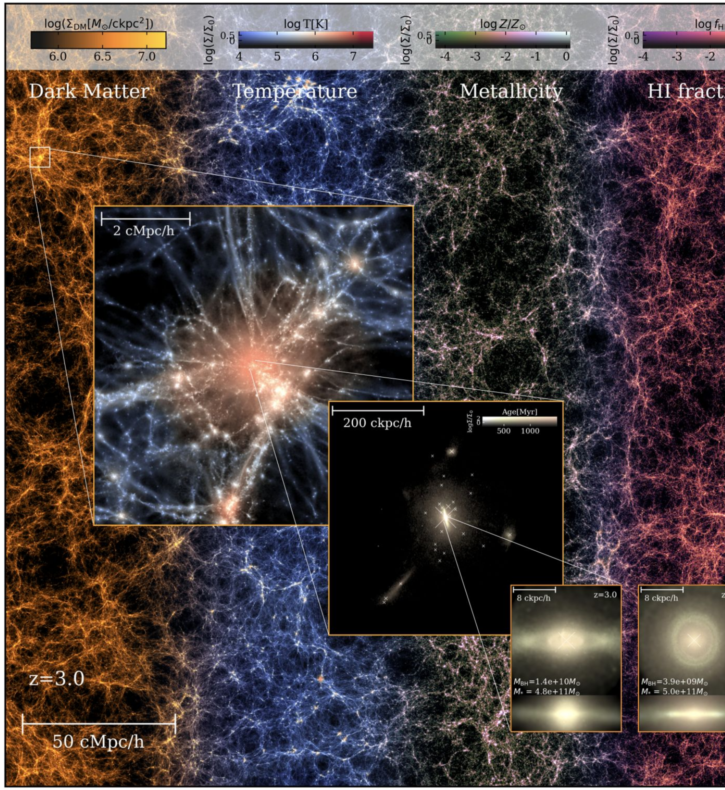
Dominates time, no-one has done it fast on GPUs

MPI/OpenMP

Shared memory
(reduces communication)

Use dynamic OpenMP scheduling

Memory bandwidth limited, try to avoid loops over all particles

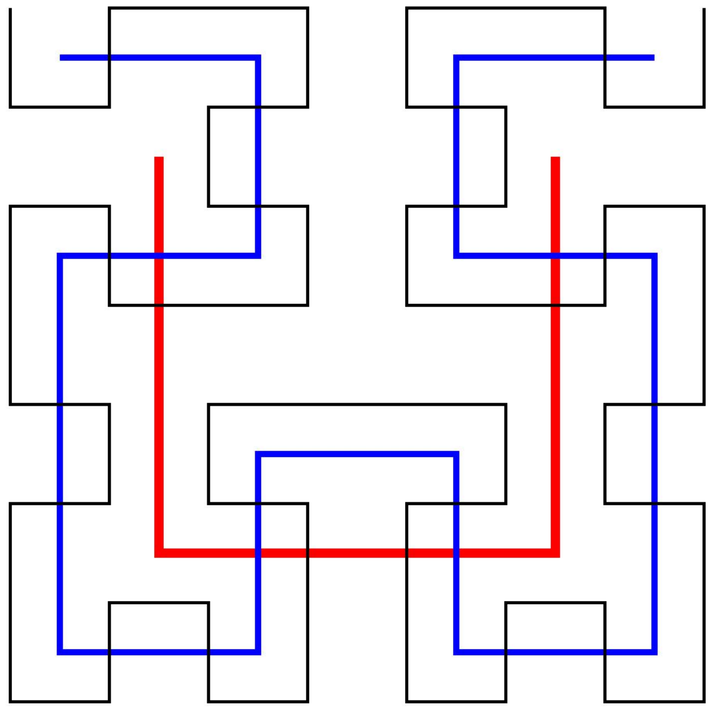


Node Load Balancing

Equal length Hilbert curve chunks
Equal particle loads per node

Work balance was more equal
but **slower**.

Shared memory means large
amount per node

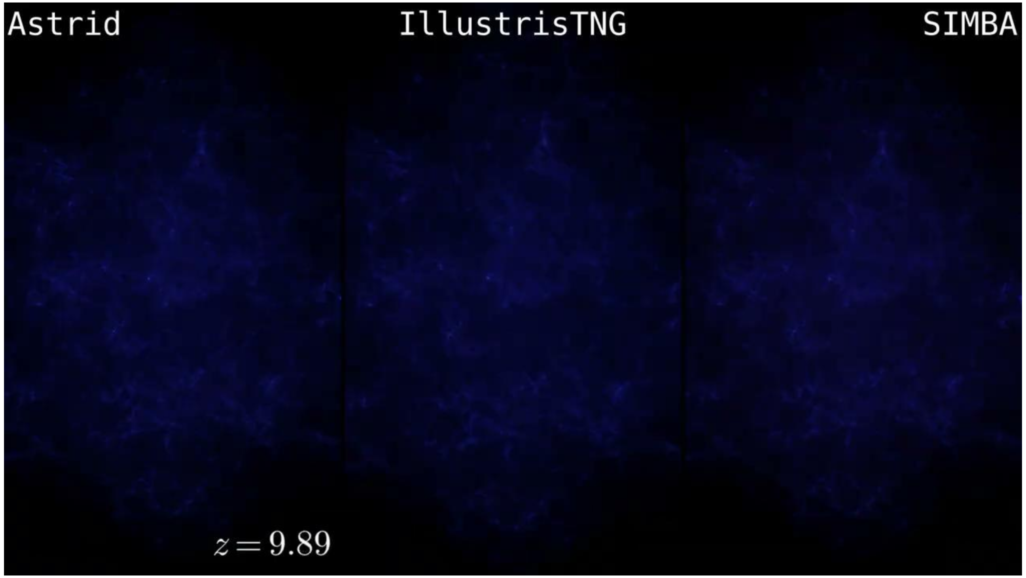


PRIYA Cosmology Suite

First big cosmology suite with galaxy formation!
First cosmology suite with reionization!

Includes black hole mechanics

ASTRID galaxy model.

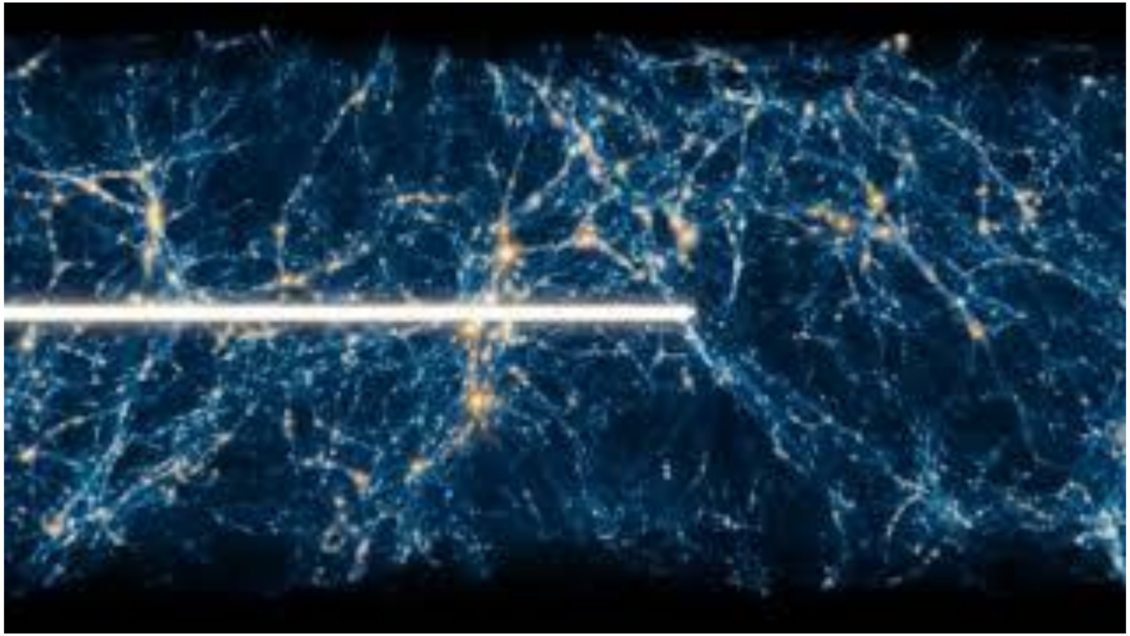


PRIYA Cosmology Suite

Simulations to model growth of gas structure

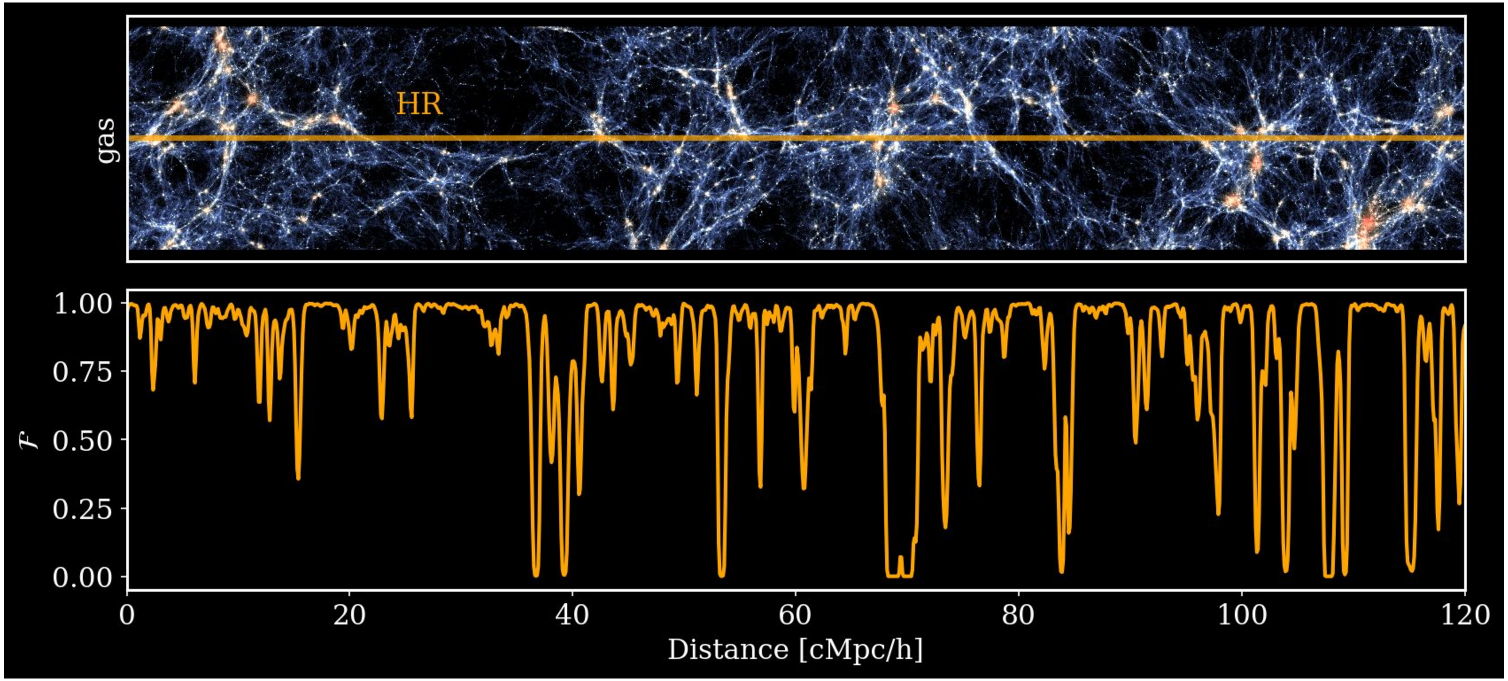
3 High fidelity: 3072^3
48 Low fidelity: 1536^3
120 Mpc/h box

9 emulated parameters



PRIYA for Lyman-α forest Inference

Absorption from neutral hydrogen in quasar
Clustering tells you about cosmology



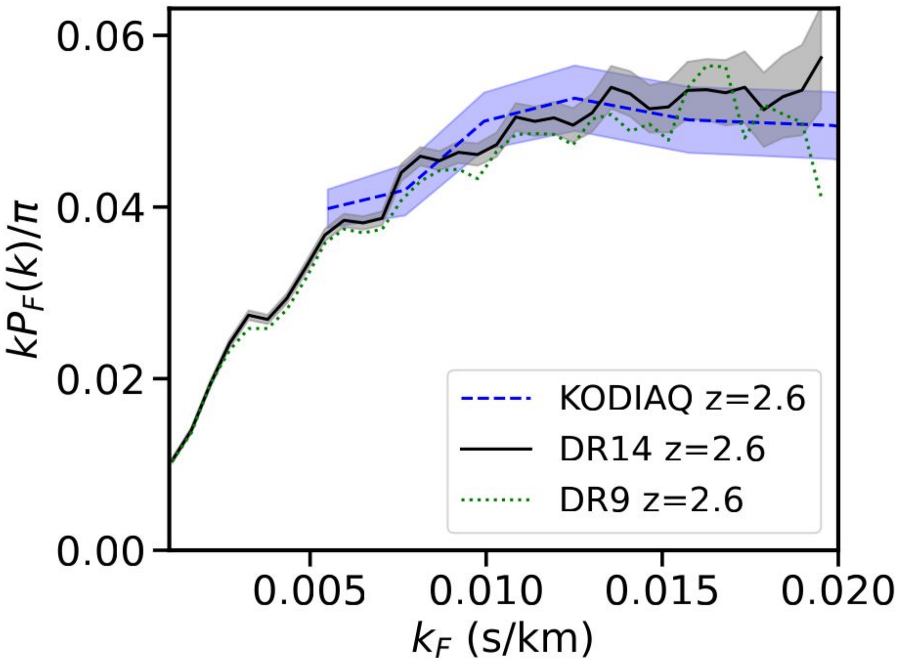
Emulate a Summary Statistic

Power spectrum of absorption along line of sight to averaged quasar

v = H(z) (a r)

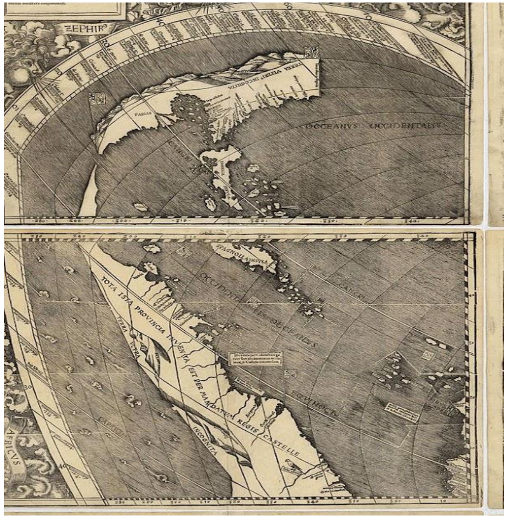
k = 0.001 s/km ~ 0.1 h/Mpc

k = 0.02 s/km ~ 2 h/Mpc



Simulation Interpolation

- For inference need simulation output for all cosmologies
- Gaussian Process interpolation using ~50 simulations
- Interpolation needs 50 large simulations



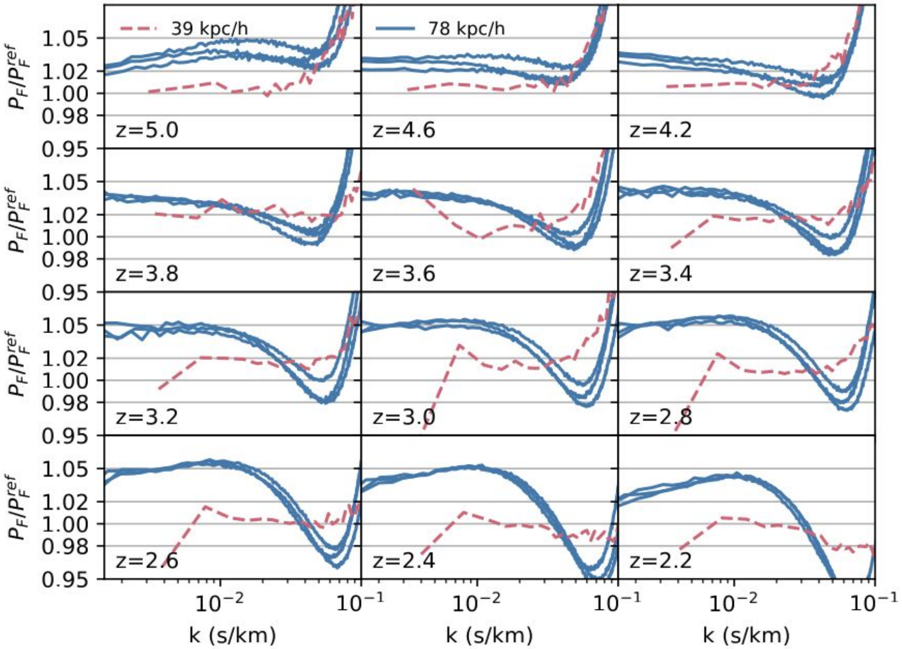
Multi-Fidelity Emulation

Combine simulations at **different resolutions**.

- Low resolution for parameter space exploration

- Correct with high resolution.

- **Parameter-dependent** correction function.



Multi-Fidelity Emulation

Correction function:

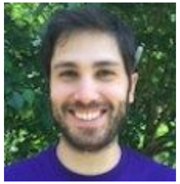
f is the GP at fidelity t

$$f_t(k, x) = \rho_{t,j}\, f_{t-1}(x, k) + \delta_t(x, k),$$

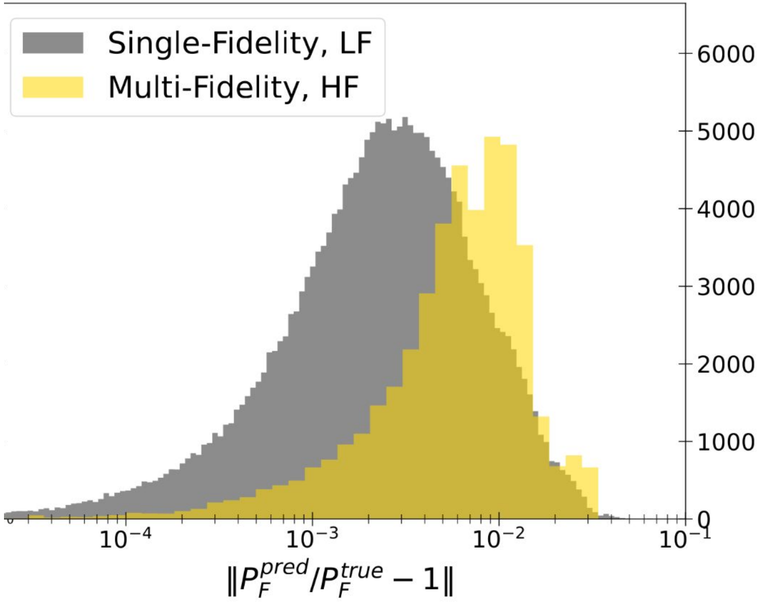
Optimize for rho and delta

1 HR GP, 1 LR GP, correction

Leave-one-out Validation



Emulation is 1% accurate! Multi-fidelity leave-one-out is missing ⅓ simulations



3 High fidelity: 3072^3

48 Low fidelity: 1536^3

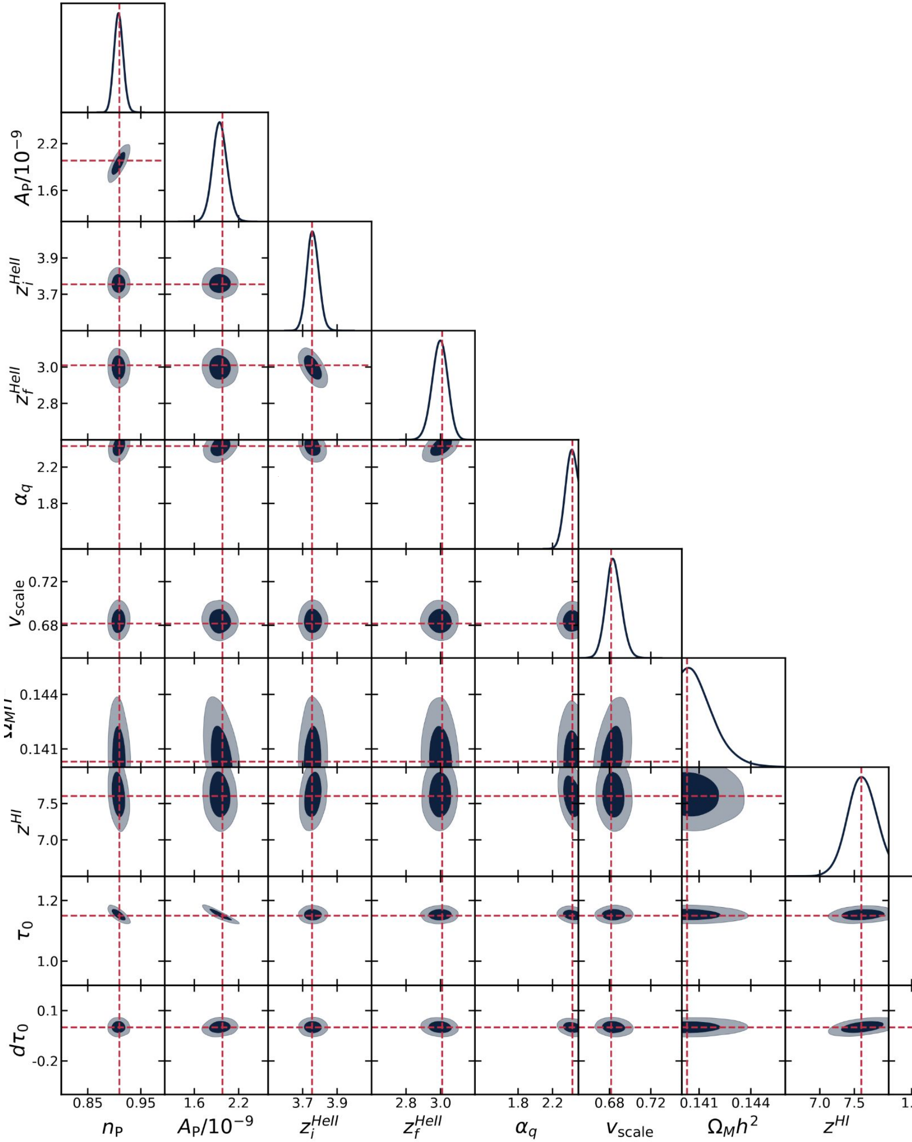
120 Mpc/h box

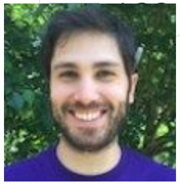
Likelihood function

Posterior constraints
simulated data

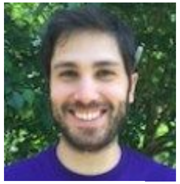
Included:
- Metals
- DLAs
- Temperature data

We ran chains!



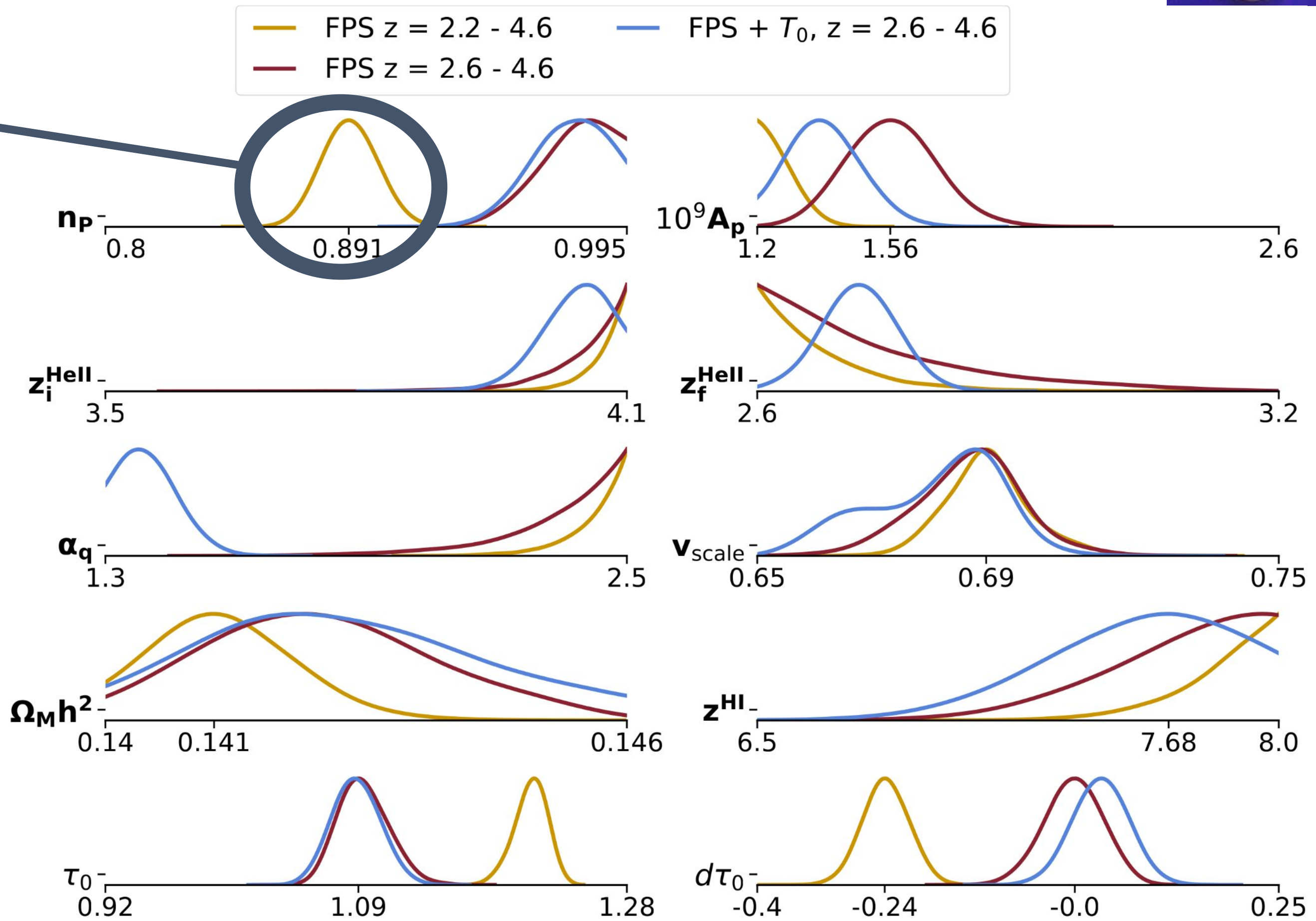


Preliminary Results



Probable data Systematic at z = 2.2,2.4

Inconsistent with CMB measurements



Implications: Neutrino Mass

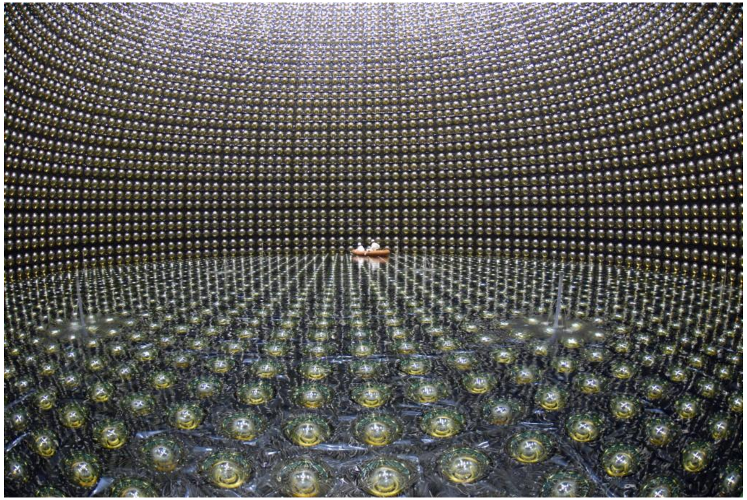
Neutrinos: Neutral massive but light particles

Last unknown standard model parameter

Connected to matter / antimatter asymmetry

Kamiokande says:

$\Sigma\ m_\nu > 0.06$ eV



Relic Neutrino Background

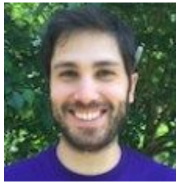
Neutrinos are non-clustering dark matter

Total clustering sets upper limit on non-clustering fraction.

Previously from this data ‘tightest constraints’:
$\Sigma\, m_\nu < 0.11$ eV

Hard to measure this on earth

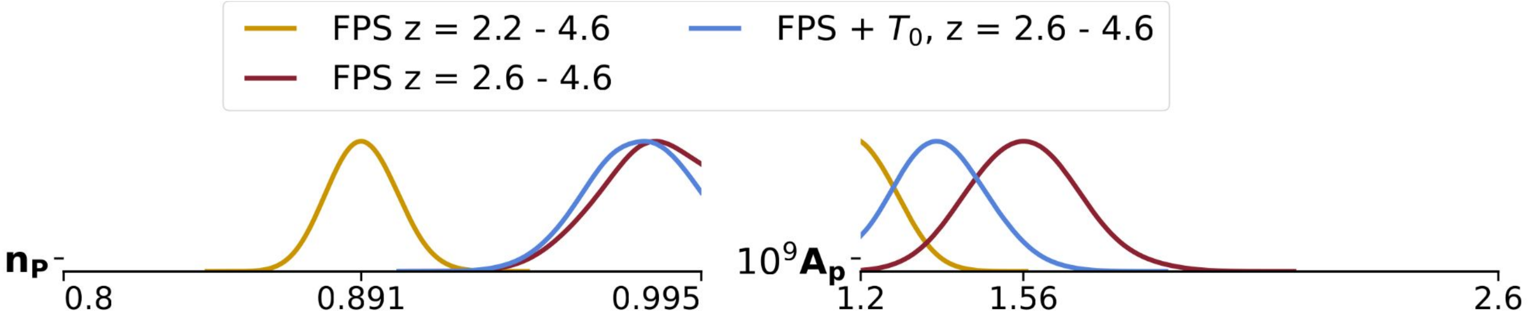
Cosmology Implications



Amplitude and slope of the power spectrum
of matter structures

Slope now in agreement with other measurements

Total neutrino mass scale: now prefers non-zero mass



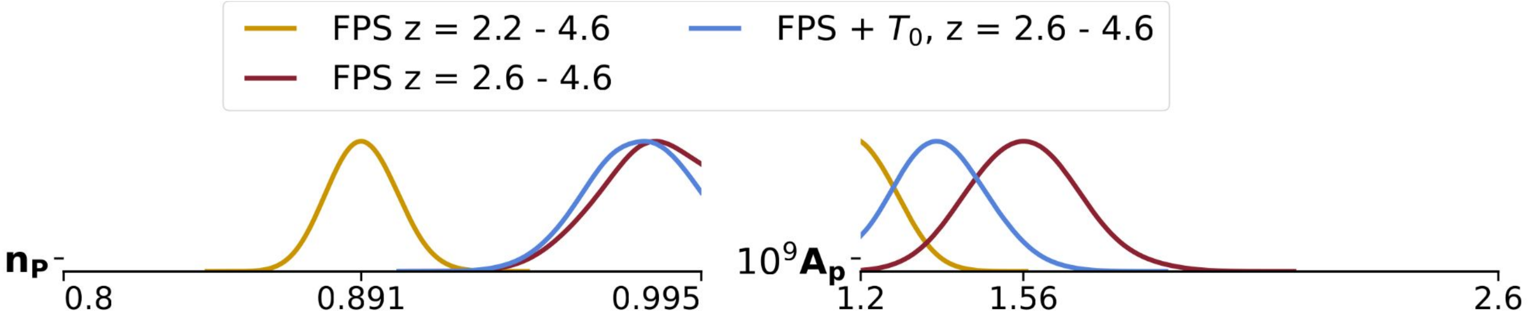
Conclusions 2306.05471 & soon

PRIYA suite and multi-fidelity emulation

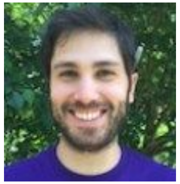
First hydro-based cosmology suite with big boxes

Reanalysis of eBOSS Lyman alpha data

Maybe a neutrino mass?



Latin Hypercube Selection



Circle: HF. Cross: LF.

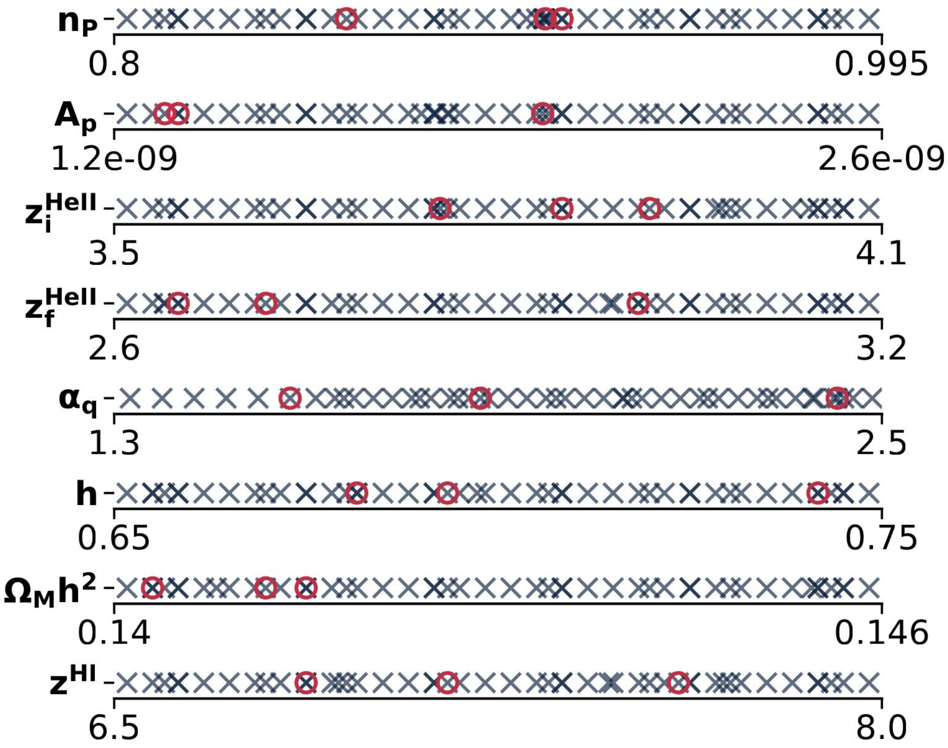
Parameters:

A_p n_p - cosmology

z_i z_f α_q - helium reionization

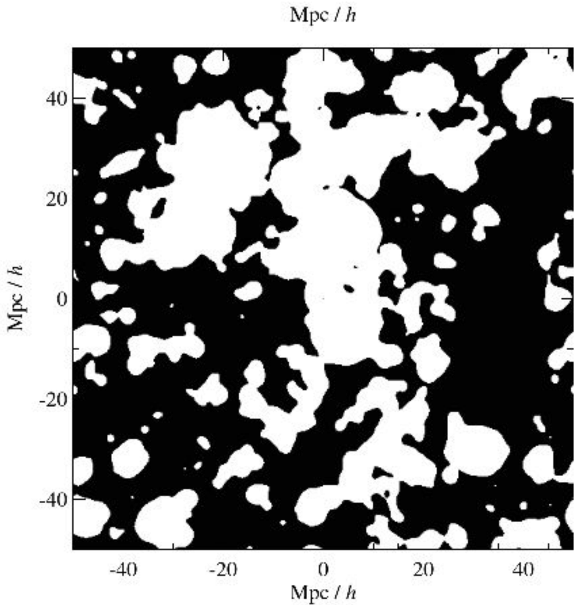
z_{HI} - hydrogen reionization

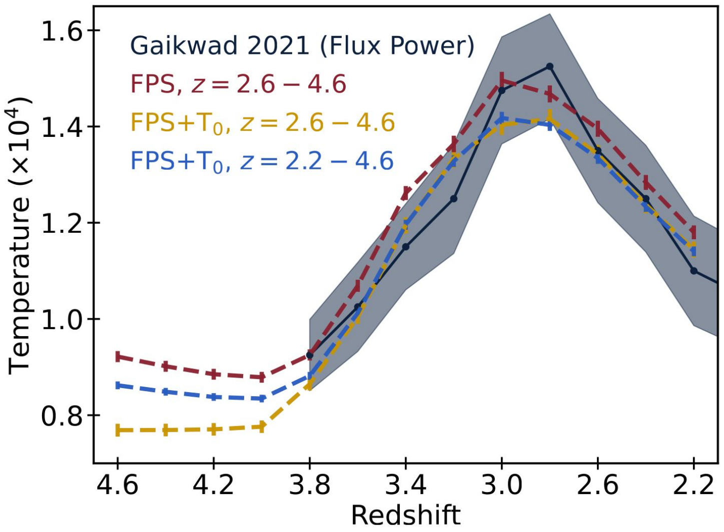
$\Omega_M h^2$ - Growth rate



First with Reionization Models

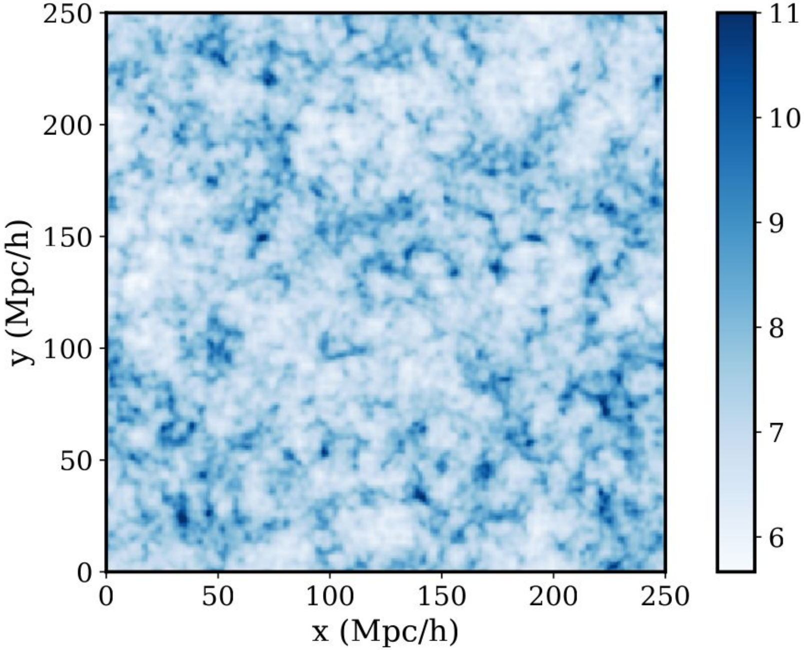
- Patchy hydrogen reionization model
- Patchy helium ~30 Mpc bubbles z ~ 3.8 - 2.8
- Match gas temperature history





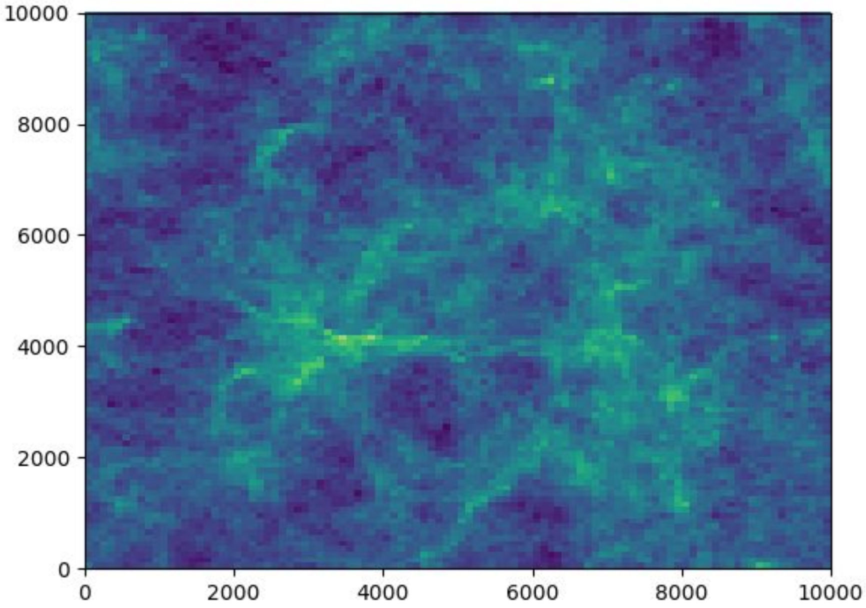
Reionization Model

- Each point in space has **reionization redshift.**
- 1 Mpc/h cubes correlated with over-density from FastPM
- High density early low density late



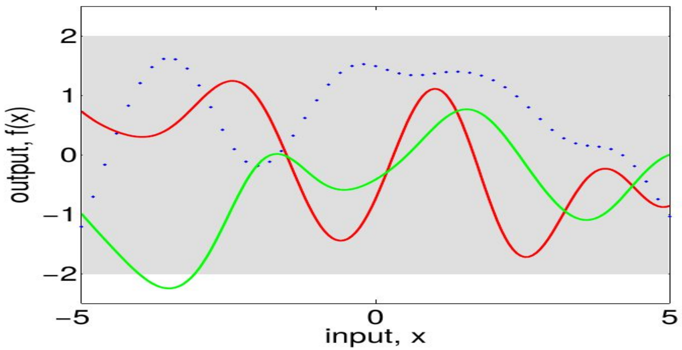
Helium Reionization

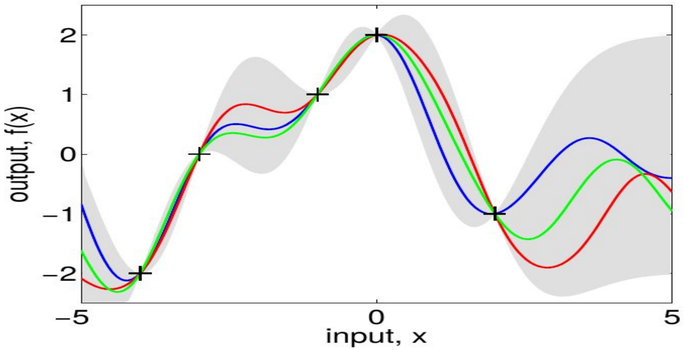
- Each blue star is a quasar, randomly placed in a halo
- Each red bubble is a 30 Mpc ionized region
- Placed to match an ionization history



Gaussian Process on Simulations

- Bayesian function interpolation, which computes probability distribution of f(x) conditional on input set.
- Magic in **kernel function:** how correlation between function depends on parameter distance.
- Left: Prior on function Right: Posterior





Rasmussen & Williams (GPML)

Gaussian Processes

- Magic in: **Kernel function**
- Describes how correlation between function values depends on parameter distance.
- Kernel is squared exponential:

$$k(x_i, x_j) = \exp\left(-\frac{1}{2}||x_i - x_j||^2/l^2\right)$$

- L is estimated from the samples, for every parameter

Rasmussen & Williams (GPML)

Like Richardson Extrapolation

To correct low resolution: power spectra corrected at a single cosmology to higher resolution

$R_{Corr}(k) = P_{high}(k, \cos = C) / P_{low}(k, \cos{=}C)$

$P(k, \cos) = P_{low}(k, \cos)\, R_{Corr}(k)$

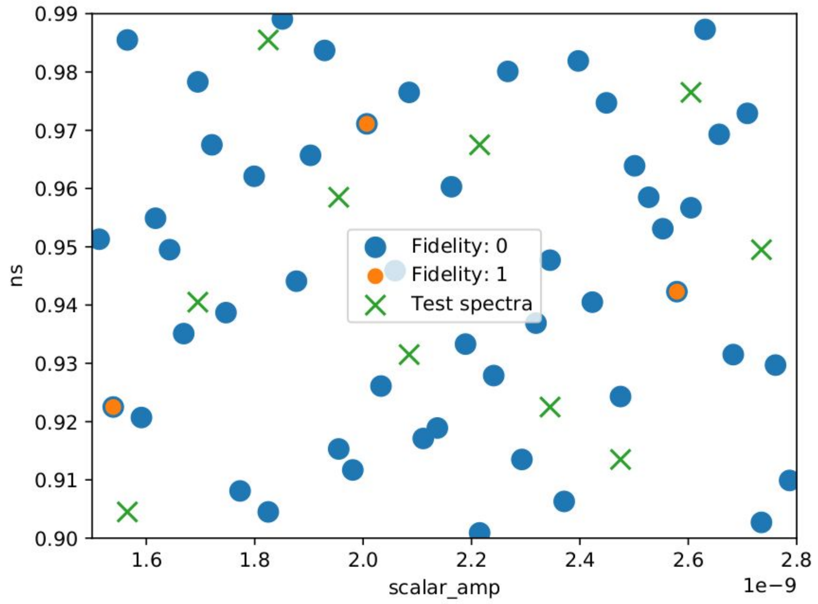
Multi-fidelity is a generalisation: R_{Corr} is a GP.

Multi-Fidelity Emulation

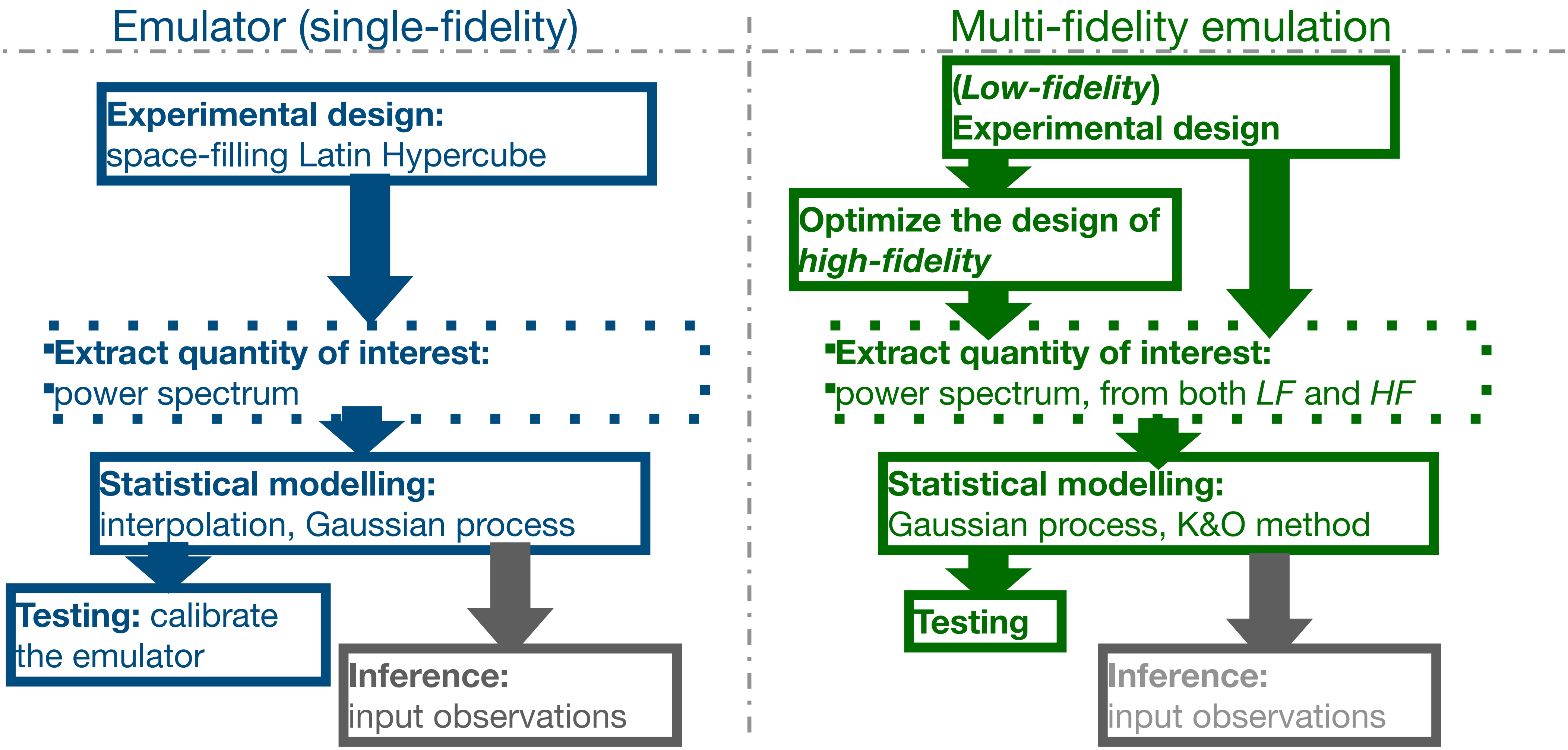
Fidelities 0 (low resolution)
1 (high resolution)

f_t=P(k) is the GP at fidelity t

$$f_t(k, x) = \rho_{t,j}\, f_{t-1}(x, k) + \delta_t(x, k),$$



Train rho and delta



Emulator (single-fidelity)
Multi-fidelity emulation
Experimental design:
space-filling Latin Hypercube
Extract quantity of interest:
power spectrum
Statistical modelling:
interpolation, Gaussian process
Testing: calibrate the emulator
Inference:
input observations
(Low-fidelity)
Experimental design
Optimize the design of
high-fidelity
Extract quantity of interest:
power spectrum, from both LF and HF
Statistical modelling:
Gaussian process, K&O method
Testing
Inference:
input observations

Multi-Fidelity Emulation

Works because of **halo model**

2-halo term learned by low fidelity simulations.

Resolution correction is 1 halo term: not much cosmology dependence.