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

Gravity is an FFT/tree method

Gravity tree only has active particles

Uses mass moments to avoid walking whole tree

(Gadget-4: Springel+ 2020)
Gas/Galaxy is Neighbour Tree

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

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

\( v = H(z) (a \ r) \)

\( k = 0.001 \text{ s/km} \sim 0.1 \text{ h/Mpc} \)

\( k = 0.02 \text{ s/km} \sim 2 \text{ h/Mpc} \)
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:

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

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 $\frac{1}{3}$ 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!
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:

\[ \sum m_\nu > 0.06 \text{ eV} \]
Neutrinos are non-clustering dark matter

Total clustering sets upper limit on non-clustering fraction.

Previously from this data ‘tightest constraints’:
\[ \Sigma m_\nu < 0.11 \text{ eV} \]

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:

- $A_p$ - cosmology
- $n_p$ - cosmology
- $z_i$, $z_f$ - helium reionization
- $\alpha_q$ - helium reionization
- $z_{HI}$ - hydrogen reionization
- $\Omega_M h^2$ - Growth rate
First with Reionization Models

- Patchy hydrogen reionization model
- Patchy helium \( \sim 30 \) Mpc bubbles \( z \sim 3.8 - 2.8 \)
- 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

\[ R_{\text{Corr}}(k) = \frac{P_{\text{high}}(k, \cos = C)}{P_{\text{low}}(k, \cos=C)} \]

\[ P(k, \cos) = P_{\text{low}}(k, \cos) \cdot R_{\text{Corr}}(k) \]

Multi-fidelity is a generalisation: \( R_{\text{Corr}} \) 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
Experimental design: space-filling Latin Hypercube

Extract quantity of interest: power spectrum

Statistical modelling: interpolation, Gaussian process

Testing: calibrate the emulator

Inference: input observations

Multi-fidelity emulation

(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.