 0 - 0 

Cosmology from the Lyman-α Forest with the PRIYA Simulations

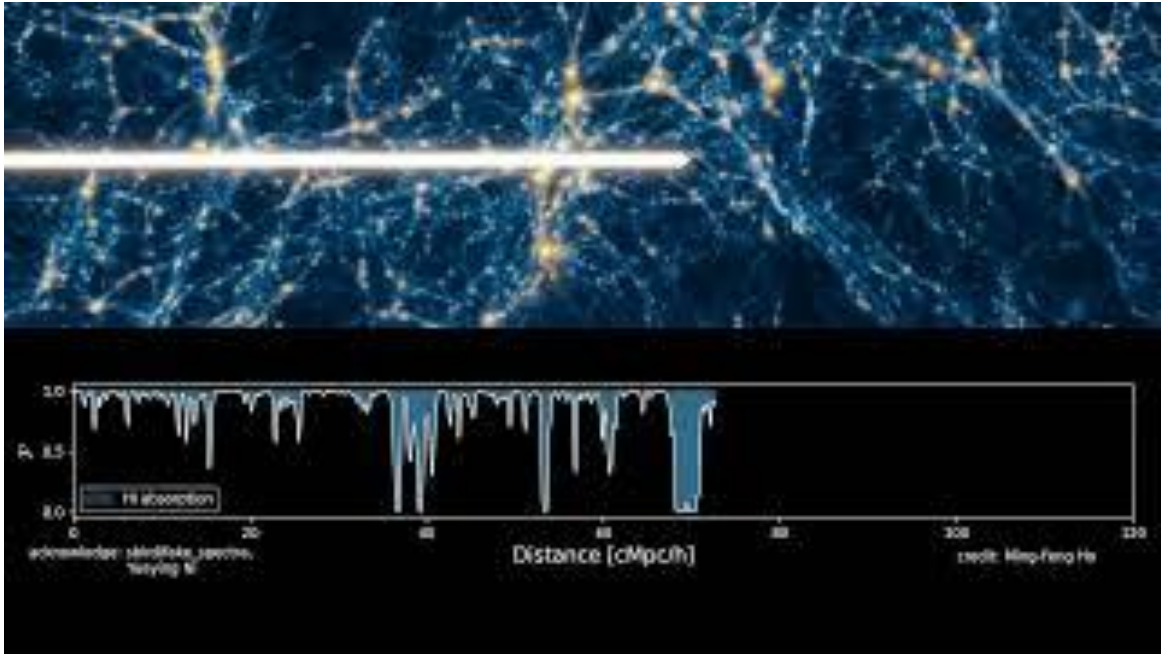
Papers: 2306.05471, 2309.03943, 2503.15592, 2509.18271
Likelihood: https://github.com/sbird/lya_emulator
Chains: https://github.com/mafern/InferenceLyaData

Video: Ming-Feng Ho & Yueying Ni

Cosmology from Hydrogen Gas

Lyman alpha forest: Neutral hydrogen illuminated by a background quasar.

Gas follows dark matter gravitational potentials, so the forest traces dark matter.



PRIYA simulations: cosmology variations to z=2

60 different cosmology simulations at low resolution: 120 Mpc/h, 2×1536^3 particles, 40 kpc/h mean spacing, 2.6 kpc/h softening.

6 different cosmology simulations at high resolution: 120 Mpc/h, **2×3072^3** particles, 20 kpc/h mean spacing, 1.3 kpc/h softening.

Full hydro with galaxies/stars/black holes

Why? Measure Matter Clustering on Small Scales

Small scales: 0.001 s/km ~ 0.1 h/Mpc

to: 0.02 s/km ~ 4 h/Mpc (DESI)

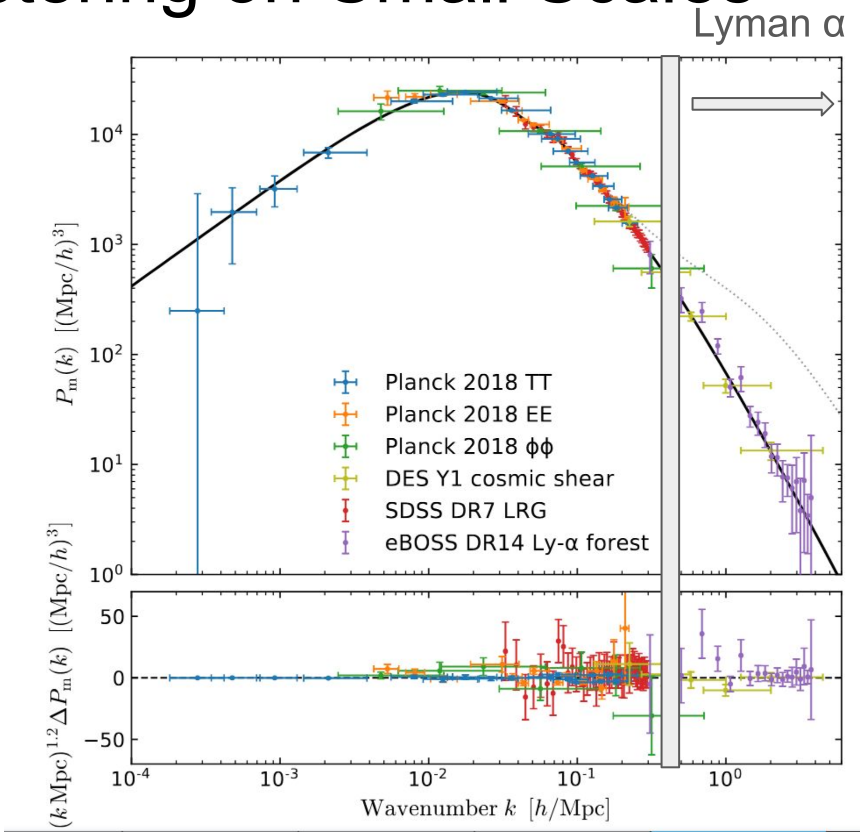
or: 0.1 s/km ~ 30 h/Mpc (HIRES)

High redshift: z=2.6 - 5.2

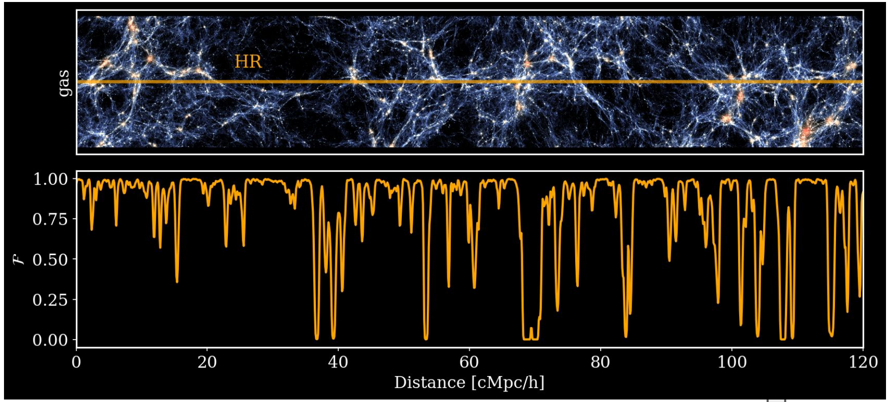
Units:

H(z) ~ (km/s)/Mpc

1 s/km = (1/H(z)) Mpc^{-1}



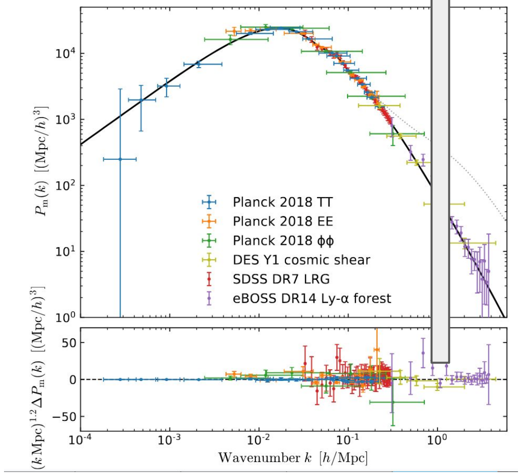
Measure **Filtered** Matter Clustering



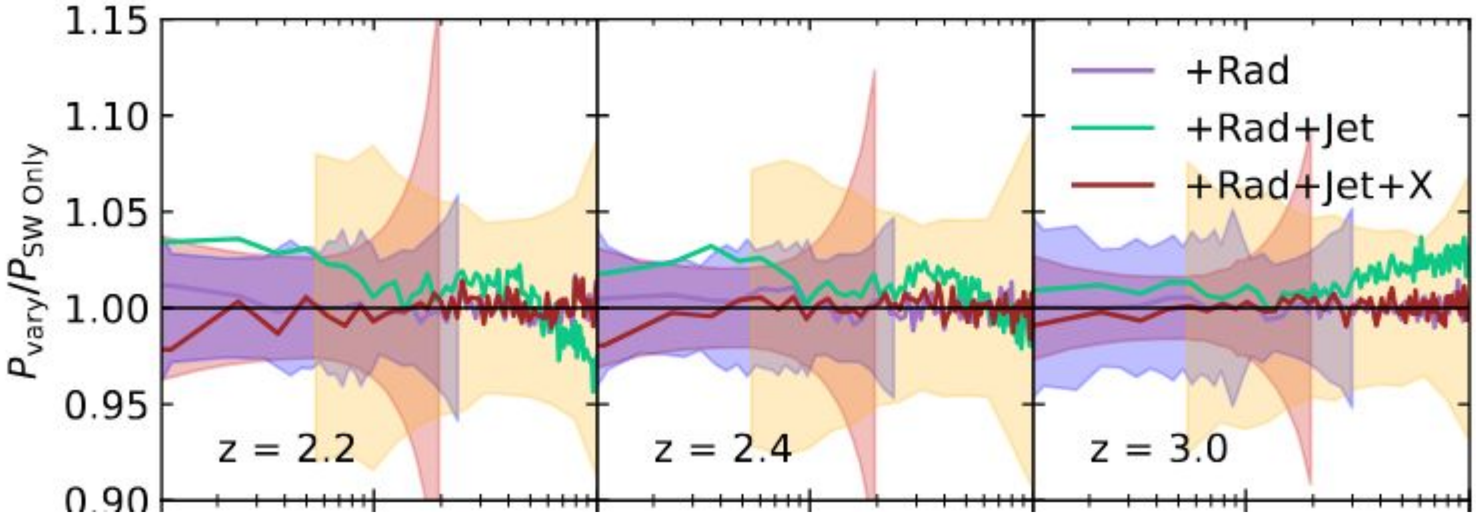
Absorption from galaxies **saturates:** forest is most sensitive to gas where there are no galaxies.

Forest probes over-densities **before virialisation**

NOT sensitive to supernova feedback!



Lyman Alpha is Relatively Insensitive to AGN



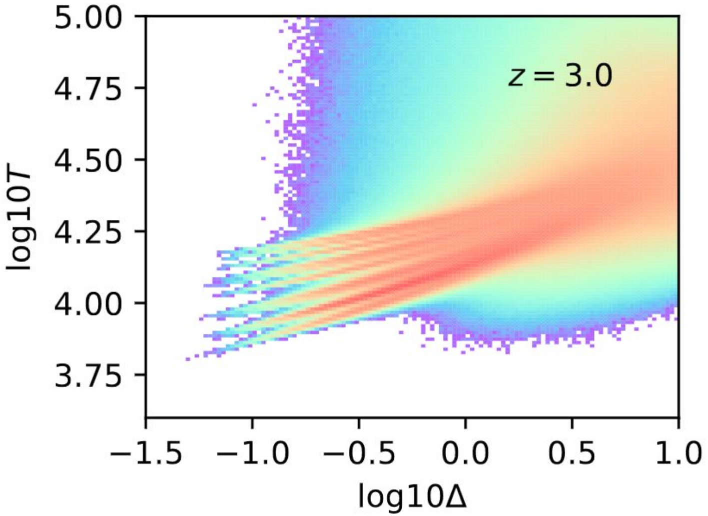
Insensitive to AGN feedback that **matches stellar mass function**:

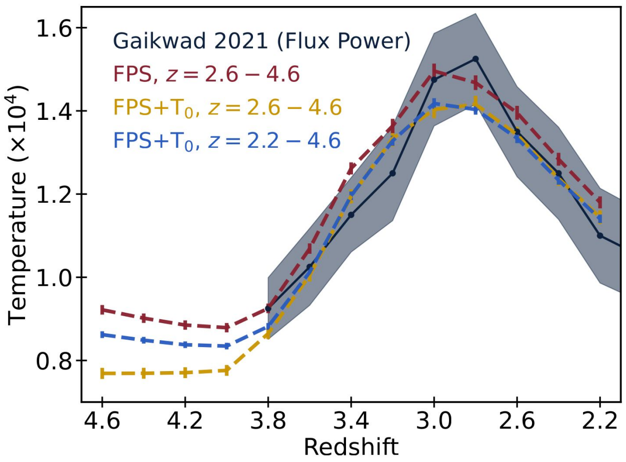
At z=2 there are not enough jet-mode BHs: (see SIMBA).

Tillman+
2410.05383

Gas Heating

Gas pressure over time smoothes gas relative to dark matter. Heating comes from photons, especially **Helium Reionization**





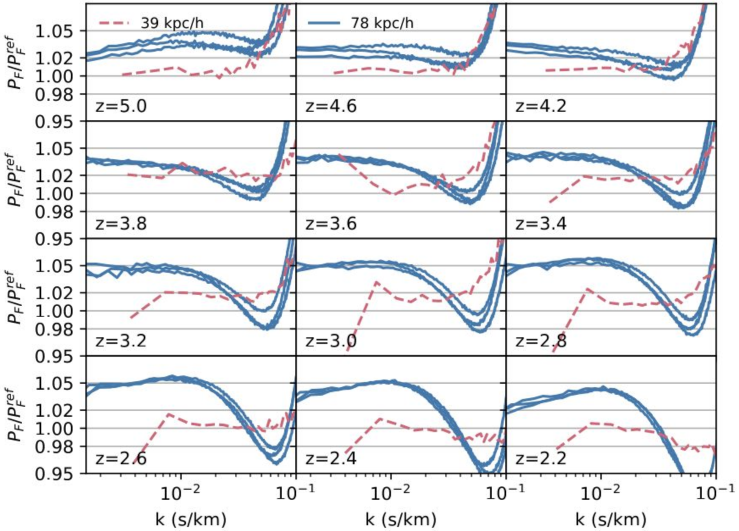
Multi-Fidelity Emulation

Combine simulations at **different resolutions**.

- Cheap low resolution to explore cosmology

- Correct with high resolution.

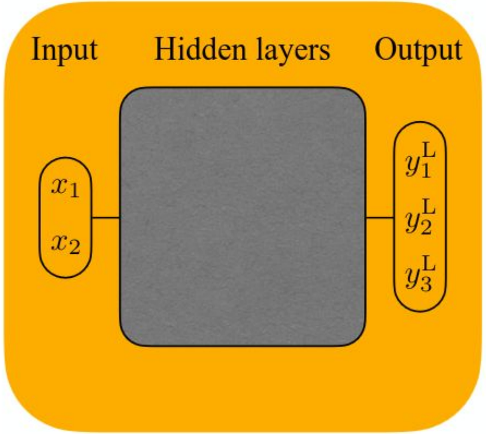
Like a university:
Many grad students (LR) to do the work
One professor (HR) to correct their calculations



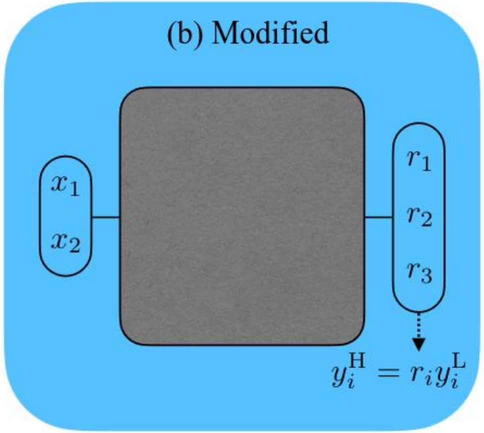
Cheaper than having many professors!

2-step Neural Network Architecture

Step 1: NN_{L}



Step 2: NN_{LH}



Train NN on low fidelity model and a separate NN on high / low ratio

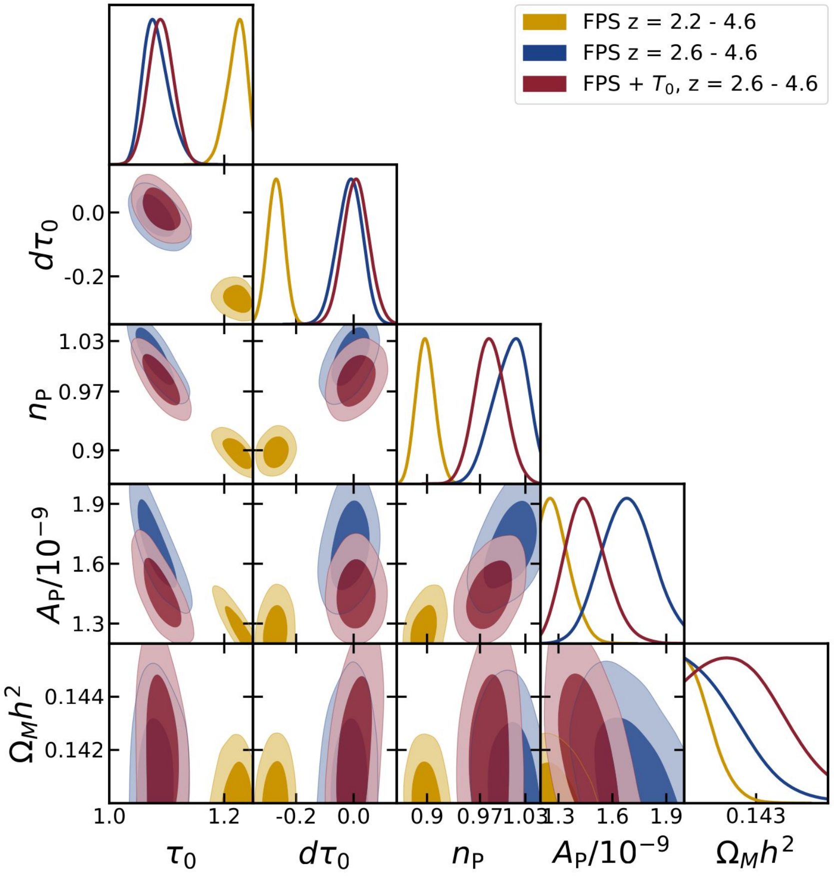
Yang+2026

After running eBOSS DR14 Likelihood

n_P = 0.983 ± 0.02 (1 sigma)
[Planck n_s = 0.965 ± 0.004 :)]

σ_8 = 0.703 + 0.023 - 0.027
[Planck σ_8 = 0.811 ± 0.006 :( ]

τ_0: 1.098 ± 0.02
Consistent:
Becker 2013 (1.1 ± 0.01),
Kim 2008 (1.0 ±0.3)



Clustering Amplitude: S8 tension at z=2.8!

eBOSS Lya:

$\boldsymbol{\sigma}_8 = 0.703 + 0.023 - 0.027$

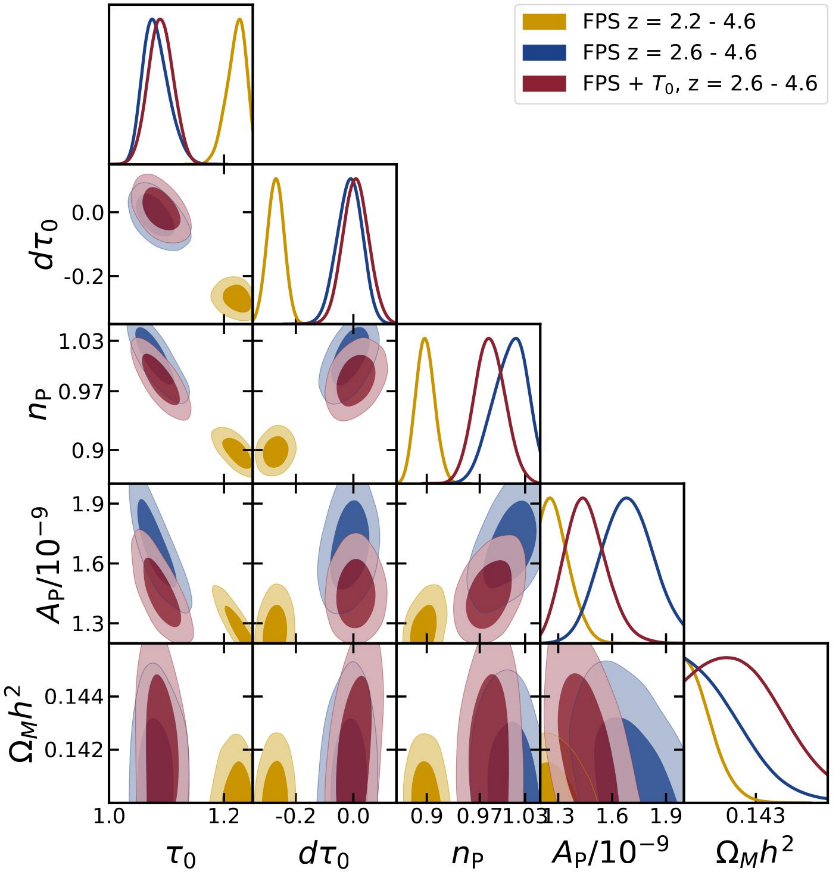
Planck:

$\boldsymbol{\sigma}_8 = 0.811 \pm 0.006$

~ 4 sigma lower

DES WL (2105.13549, Table II):

$\boldsymbol{\sigma}_8 = 0.733 + 0.039 - 0.049$



Small scales agree

eBOSS Lya:

$\sigma_8 = 0.703 + 0.023 - 0.027$

Planck:

$\sigma_8 = 0.811 \pm 0.006$

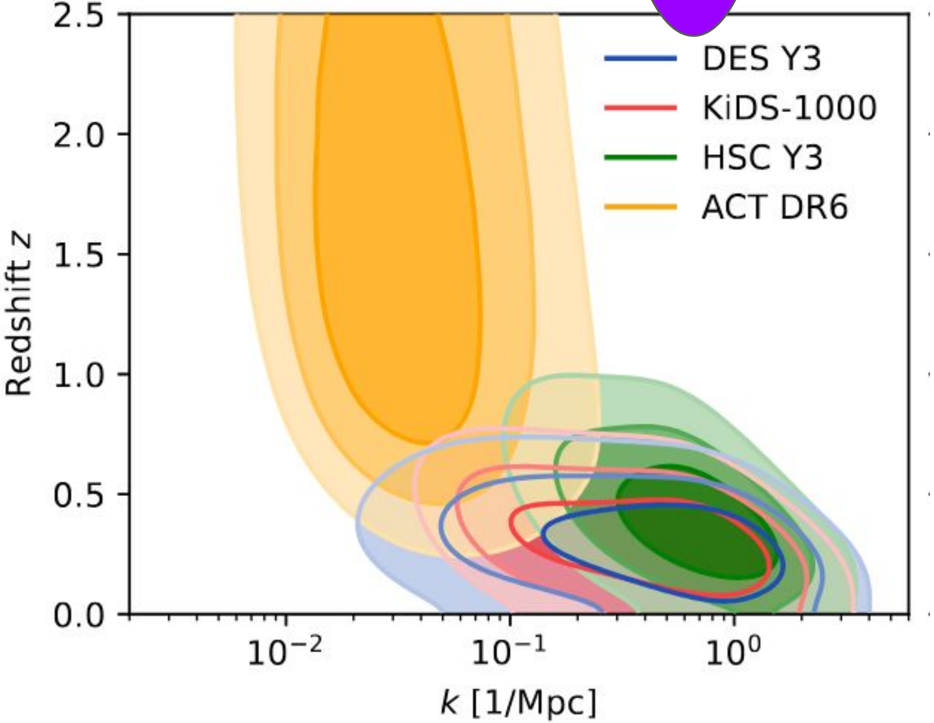
~ 4 sigma lower

DES WL (2105.13549, Table II):

$\sigma_8 = 0.733 + 0.039 - 0.049$

Galaxy x CMB lensing (larger scales: 2407.04607):

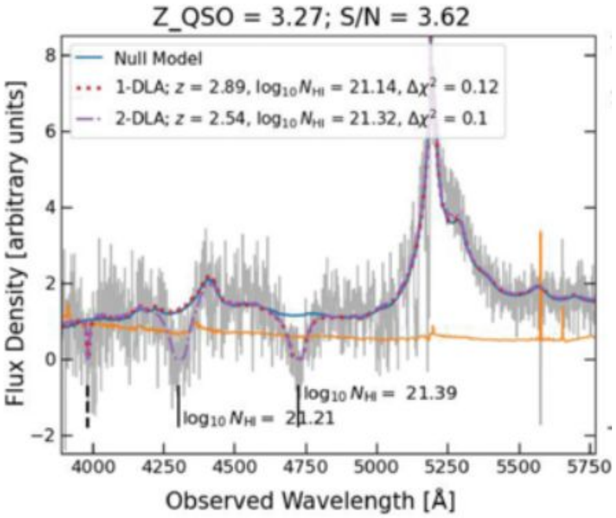
$\sigma_8 = 0.772{+}0.020{-}0.023$



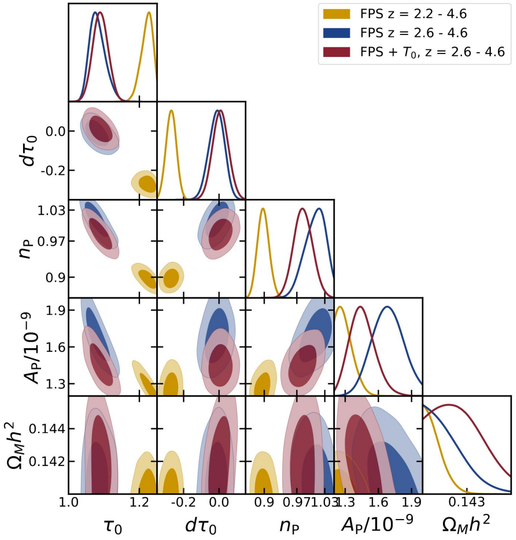
Karwal+ 2506.16434

What is it?

- Neutrino mass around 0.2-0.4 eV fits
- But exceeds DESI limits: < 0.163 eV
- Could be an eBOSS systematic: stay tuned for DESI.



Conclusions: PRIYA



- Consistent improved Lyman alpha analysis
- Suggests S8 tension not AGN feedback

DESI analysis forthcoming.

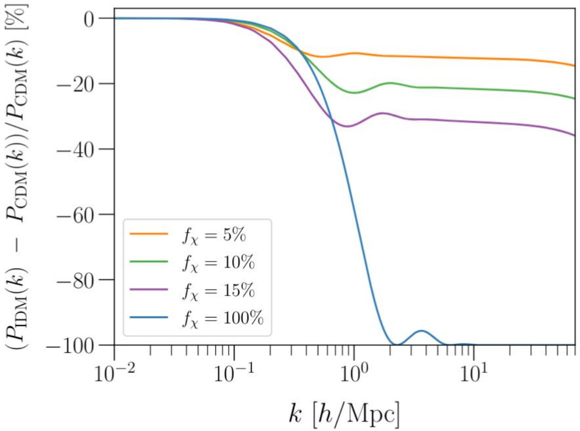
Papers: 2306.05471, 2309.03943, 2503.15592

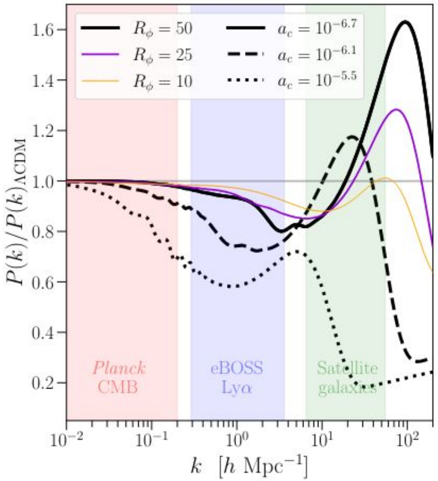
Likelihood: https://github.com/sbird/lya_emulator

Chains: https://github.com/mafern/InferenceLyaData

What is it?

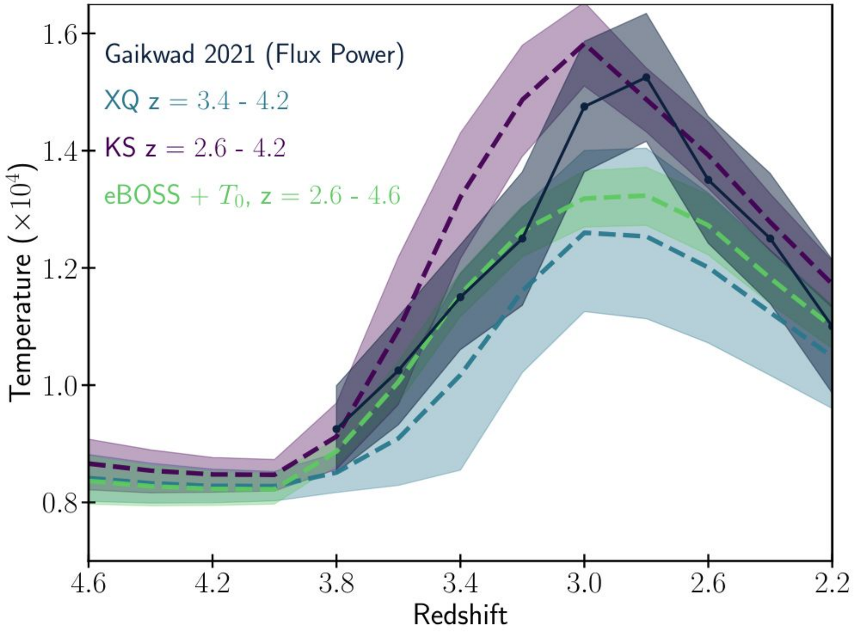
- Neutrino mass around 0.2-0.4 eV fits
- But exceeds DESI limits: < 0.163 eV
- eBOSS has a foreground: galaxies saturate and cleaning process is not completely effective.
- DESI does cleaning better: stay tuned





Temperature priors

eBOSS+T0 chain includes priors on the thermal history from external data (Gaikwad 2021):
XQ100 dataset using PRIYA prefers the same thermal history as the prior.



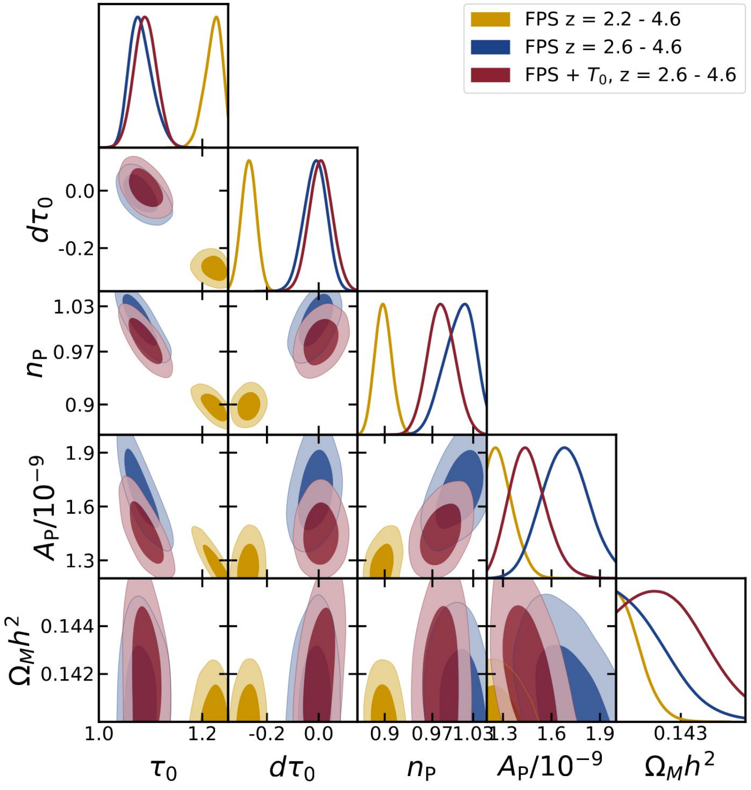
2509.18271

eBOSS DR14

All redshifts: z = 2.2 - 4.6

$n_P \sim 0.9$ and $A_P < 1.4$

Low n_p driven by tension between
z < 2.6 and z > 2.6



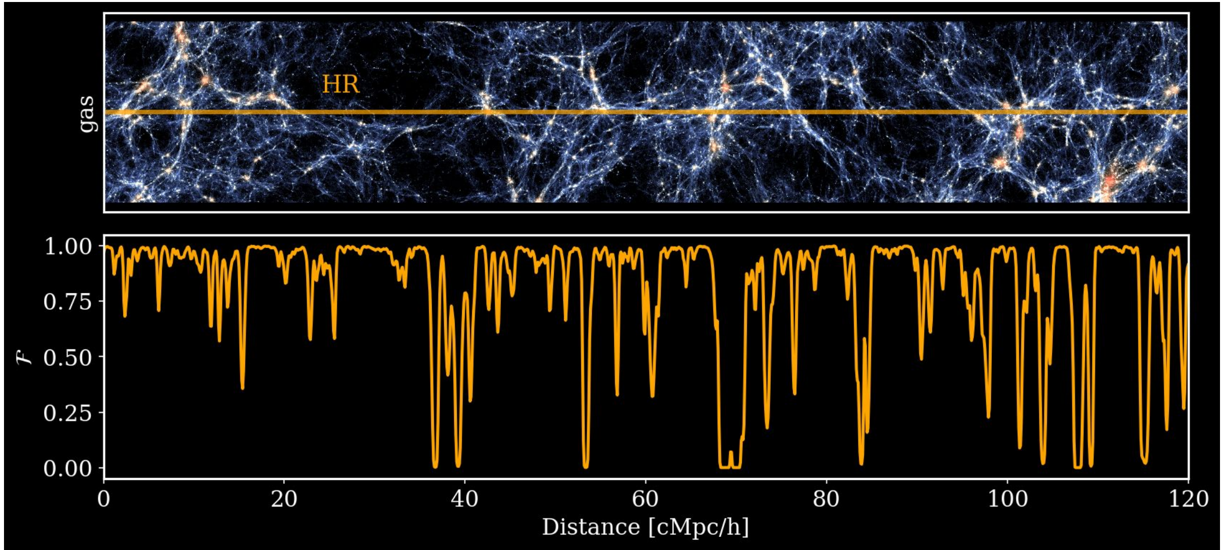
Images: Ming-Feng Ho & Yueying Ni

Cosmology from Hydrogen Gas

Gas is everywhere: 75% hydrogen, 25 % helium.

Lyman alpha forest: Hydrogen illuminated by a bright background source (usually a quasar)

Gas follows dark matter gravitational potentials, so the forest traces dark matter.

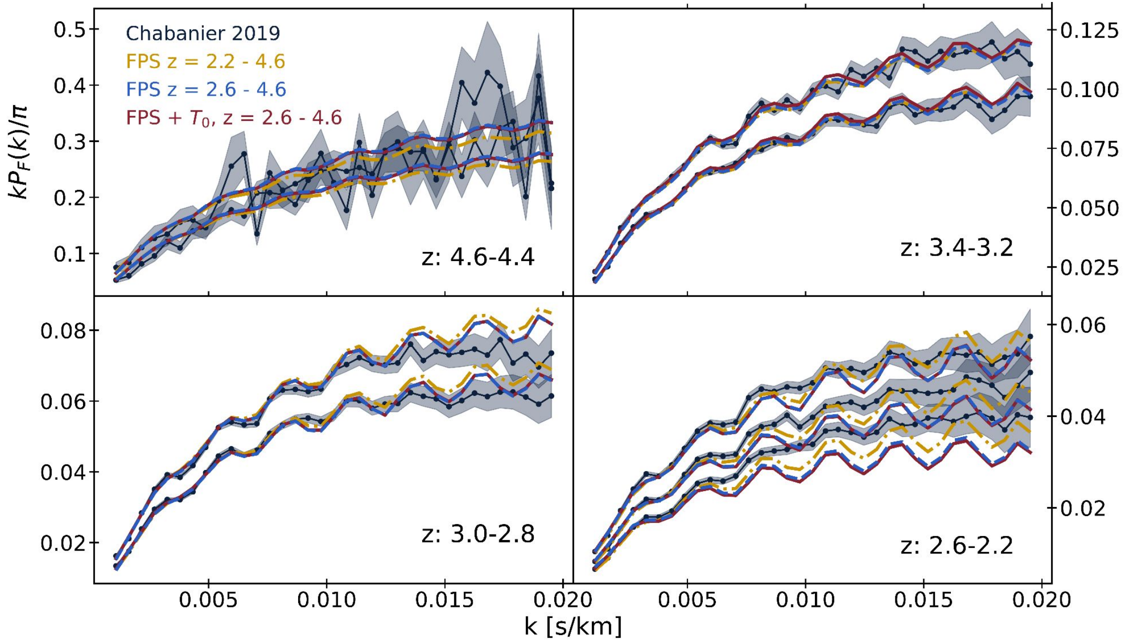


eBOSS DR14

Best-fit power:

z= 2.2 & 2.4 are discrepant with model:

Metal line modelling?
Data Systematic?

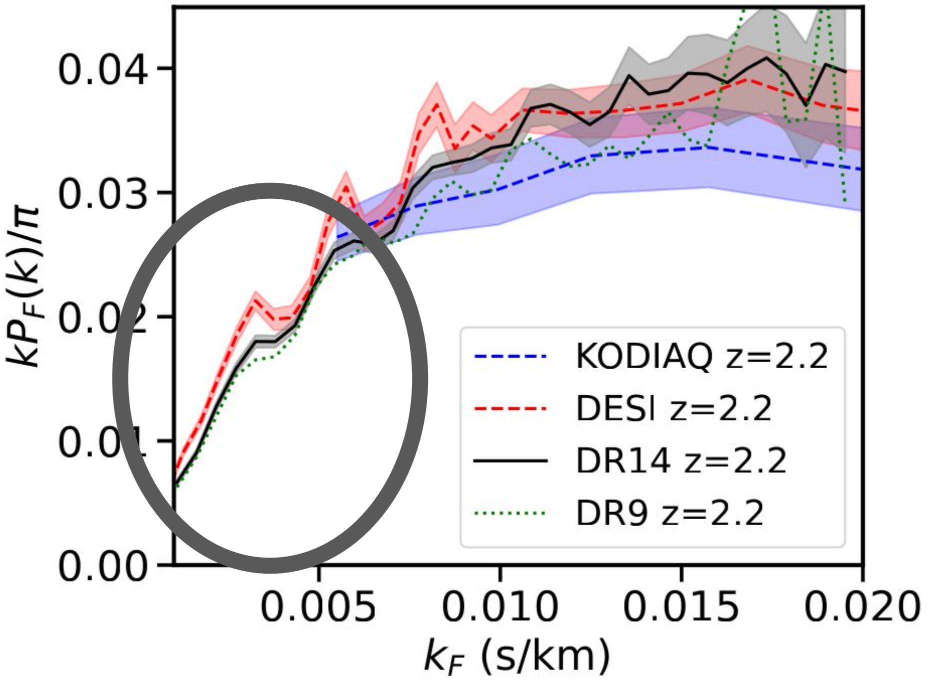


eBOSS DR14

DESI data does not agree at z < 2.6, suggests systematic

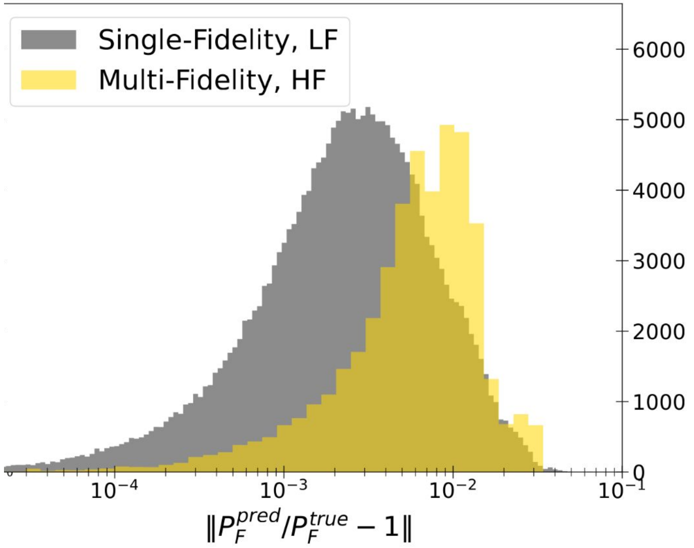
Agreement is much better at z > 2.6

Low redshift spectra are blue end of the spectrograph: DLAs are harder to find as the spectrum is shorter and noisier



Multi-Fidelity Emulation Validation

Build an emulator to predict flux power spectrum for arbitrary cosmologies.



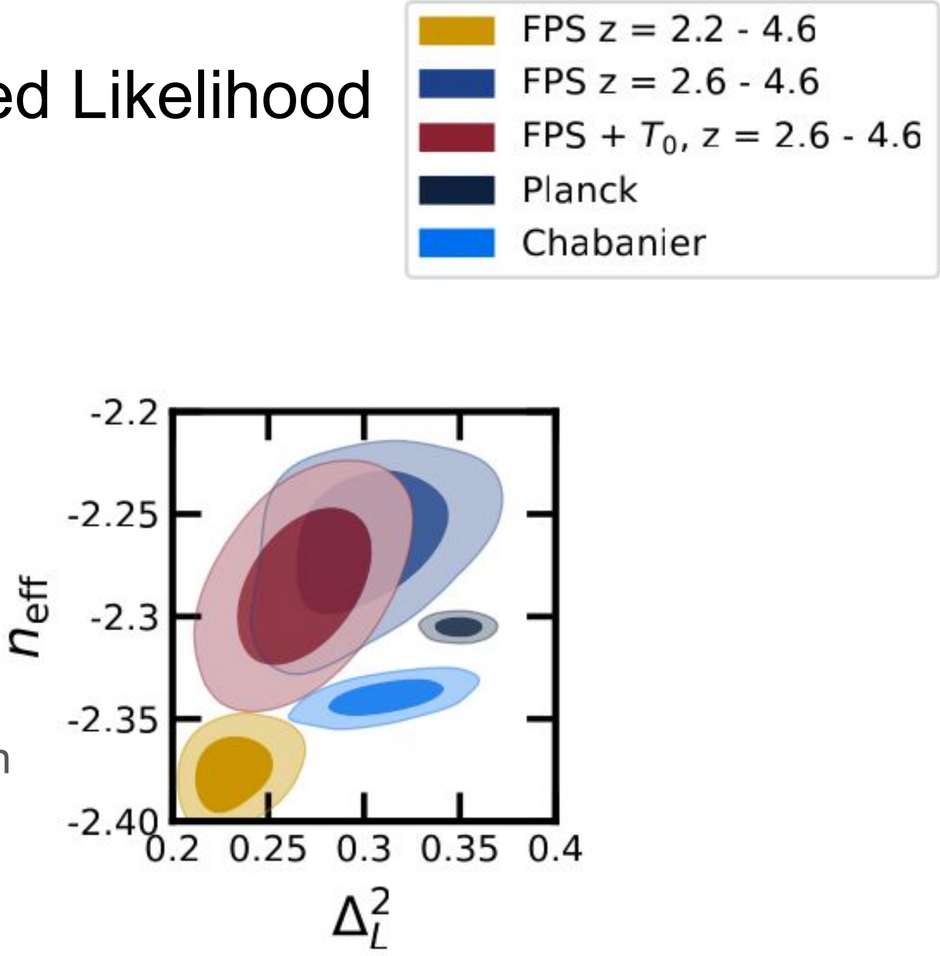
Emulation is 1% accurate! Multi-fidelity leave-one-out is missing ⅓ simulations

Previous Analysis: Reduced Likelihood

Constraints on amplitude and slope
At $k_* = 1/\text{Mpc}$, $z_* = 3$:

$$\Delta_L^2(k_*, z_*) = k_*^3 P_L(k_*, z_*)/(2\pi^2)$$
$$n_{\text{eff}}(k_*, z_*) = \frac{d \ln P_L}{d \ln k}(k_*, z_*) \, .$$

Larger error on neff: helium reionization opens a degeneracy



Why? Interpolation and Simulations

Big full hydro simulations: 60 x 120 Mpc/h, 2×3072^3 particles

Gaussian process interpolation

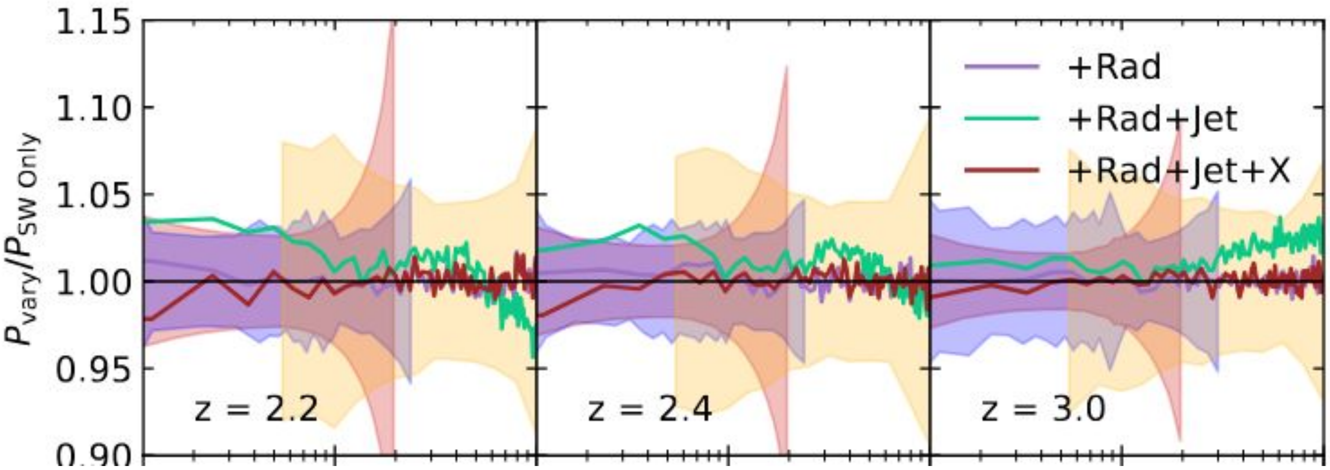
Confirmed by eBOSS group: 2412.05372

What is it? Probably Not AGN

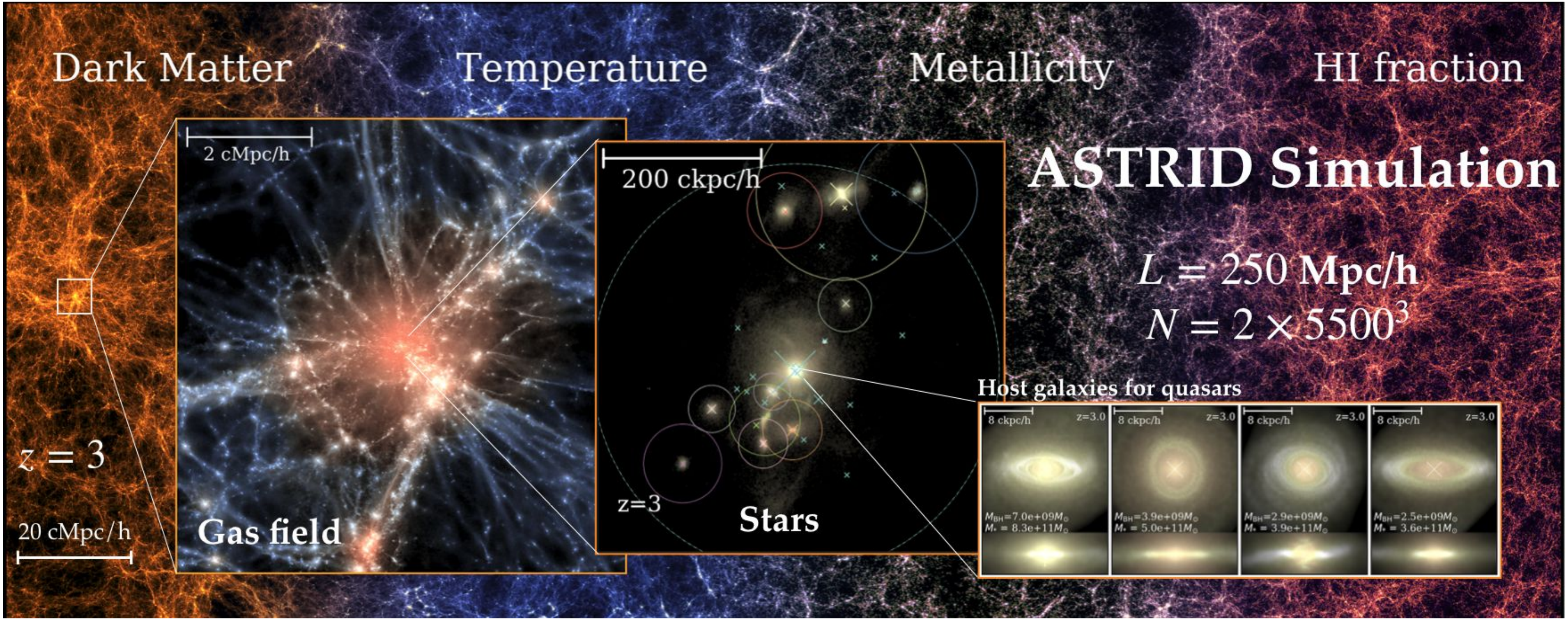
- Unlikely AGN feedback at z > 2 as number density of big SMBHs is << than at z ~ 0
- Enough AGN at z > 2 means no stars at z = 0

Strongest current AGN model (SIMBA):

Tillman+2410.05383

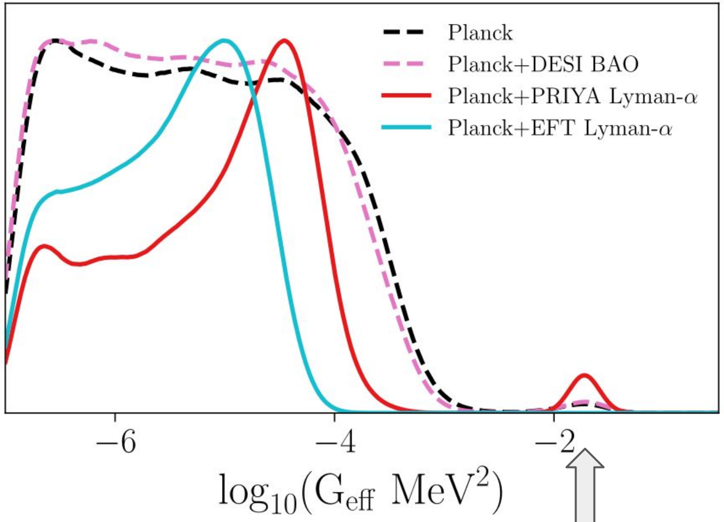


ASTRID Stars/Black holes Galaxy Models



Neutrino Self-Interactions

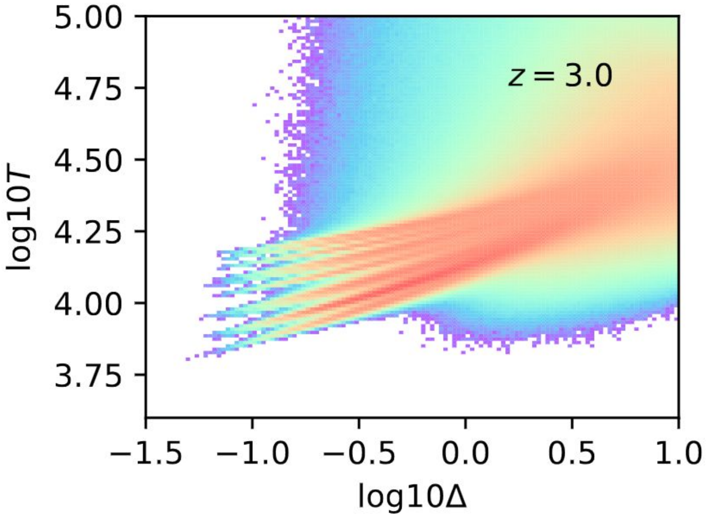
New likelihood does not like
Neutrino self-interactions

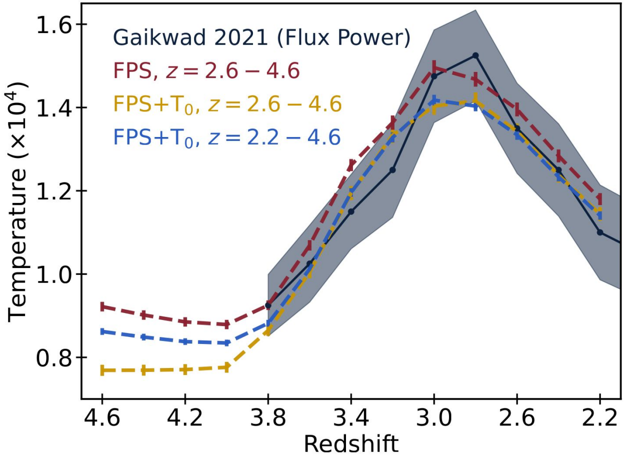


Preferred by old likelihood

Thermal History: Patchy Helium

- Physics model is the **input**
- T0 is output with an emulator





Like Richardson Extrapolation

To correct low resolution: run a higher resolution simulation and build a correction function

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

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

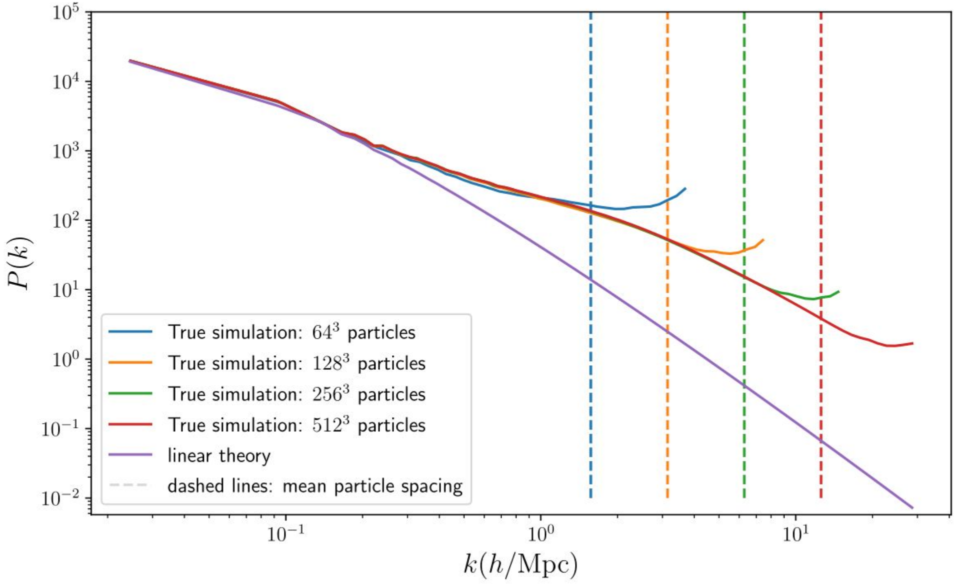
Multi-fidelity is a generalisation: R_{Corr} is a GP and depends on cosmology

Multi-Fidelity Emulation

Works because of **halo model**

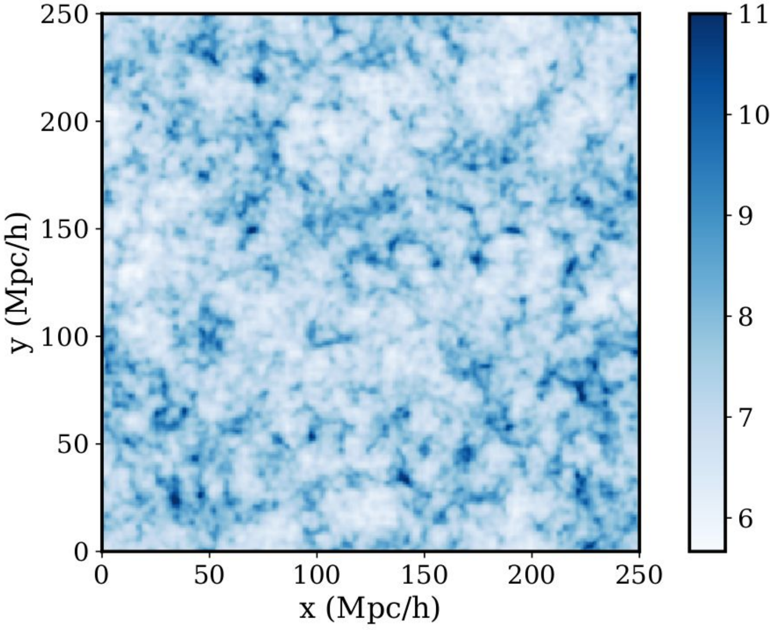
2-halo term learned by low fidelity simulations.

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



New PRIYA Models

- H+He patchy reionization
- High redshift cosmology/ galaxy formation effects
- Black hole dynamics close to merger



Reionization redshift

Neutrino Mass

The effect of neutrino mass on the matter clustering

Grey is Lyman alpha
Dashed purple line is CMB

Neutrinos behave like
non-clustering dark matter