Probing Atomic Dark Matter with the Lyman-alpha Forest

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PART III

Outline:

1. Atomic dark matter (aDM) and its motivations
2. Cosmology of atomic dark matter
3. The Lyman-α forest
4. Can atomic dark matter hide in the forest?

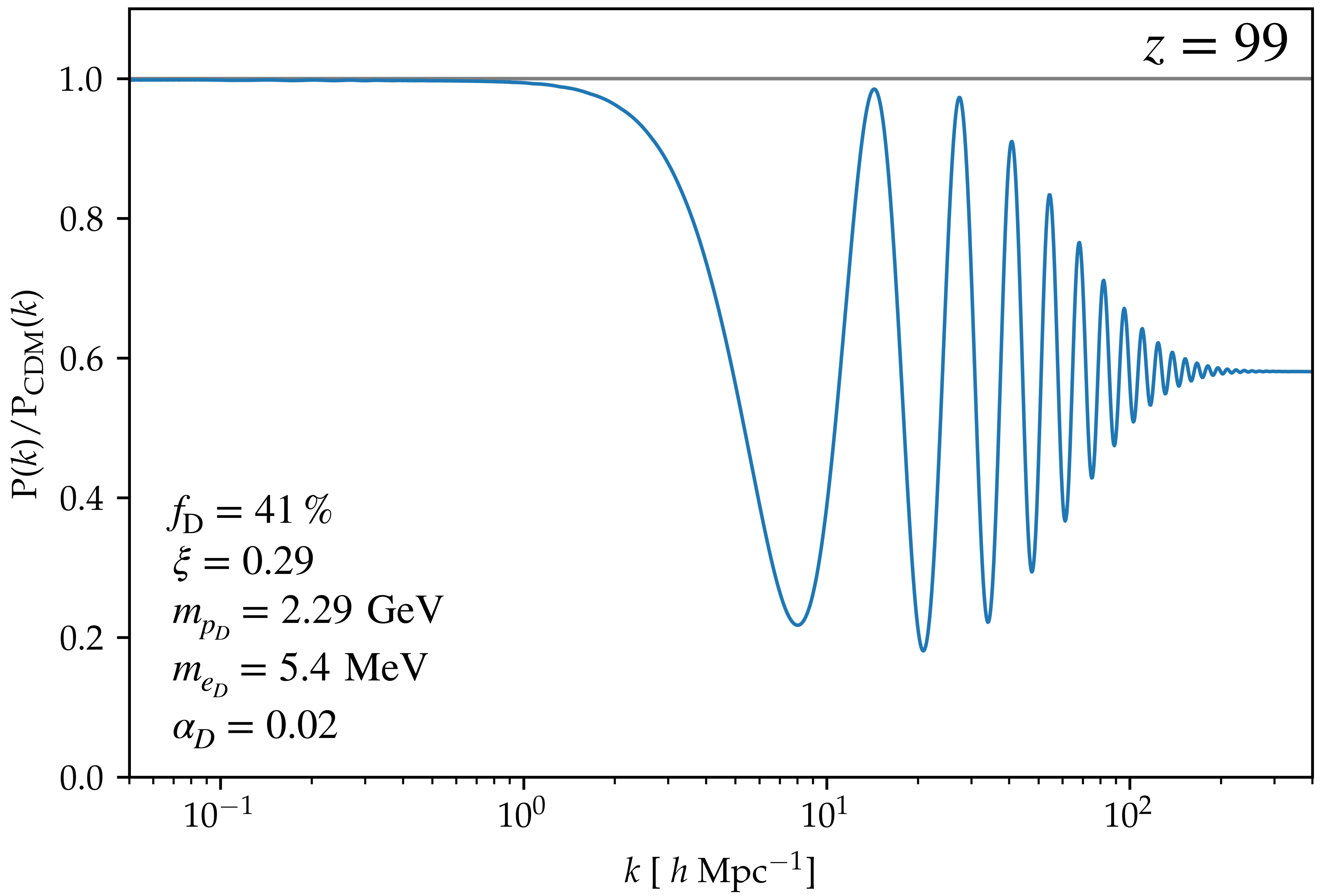
Quickly Recap Motivation:

- ΛCDM does a good job at matching data on large astrophysical scales
  - Variety of structure problems still exist on small, sub galactic scales
  - Cosmological tensions (H_0 , S_8)
- Additionally, ADM as an implementation of a complex dark sector / hidden valley model, dark U(1)
  - Can address naturalness issues, e.g. Little Hierarchy Problem
  - Inspired by the complexity of the SM, Twin Higgs models
- What region of aDM parameter space is even allowed ???

Cosmology of Atomic Dark Matter

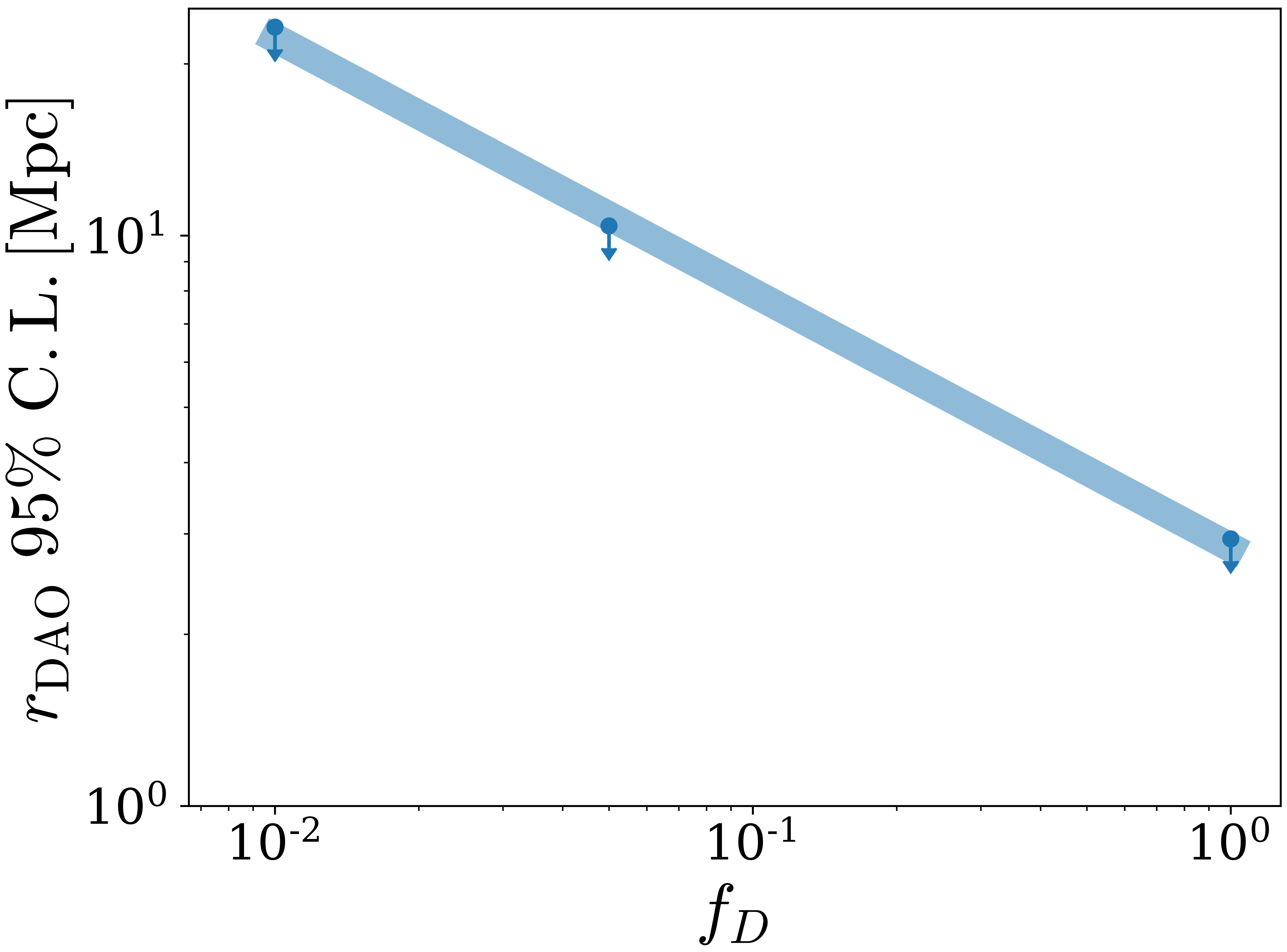
Dark Acoustic Oscillations (DAOs)

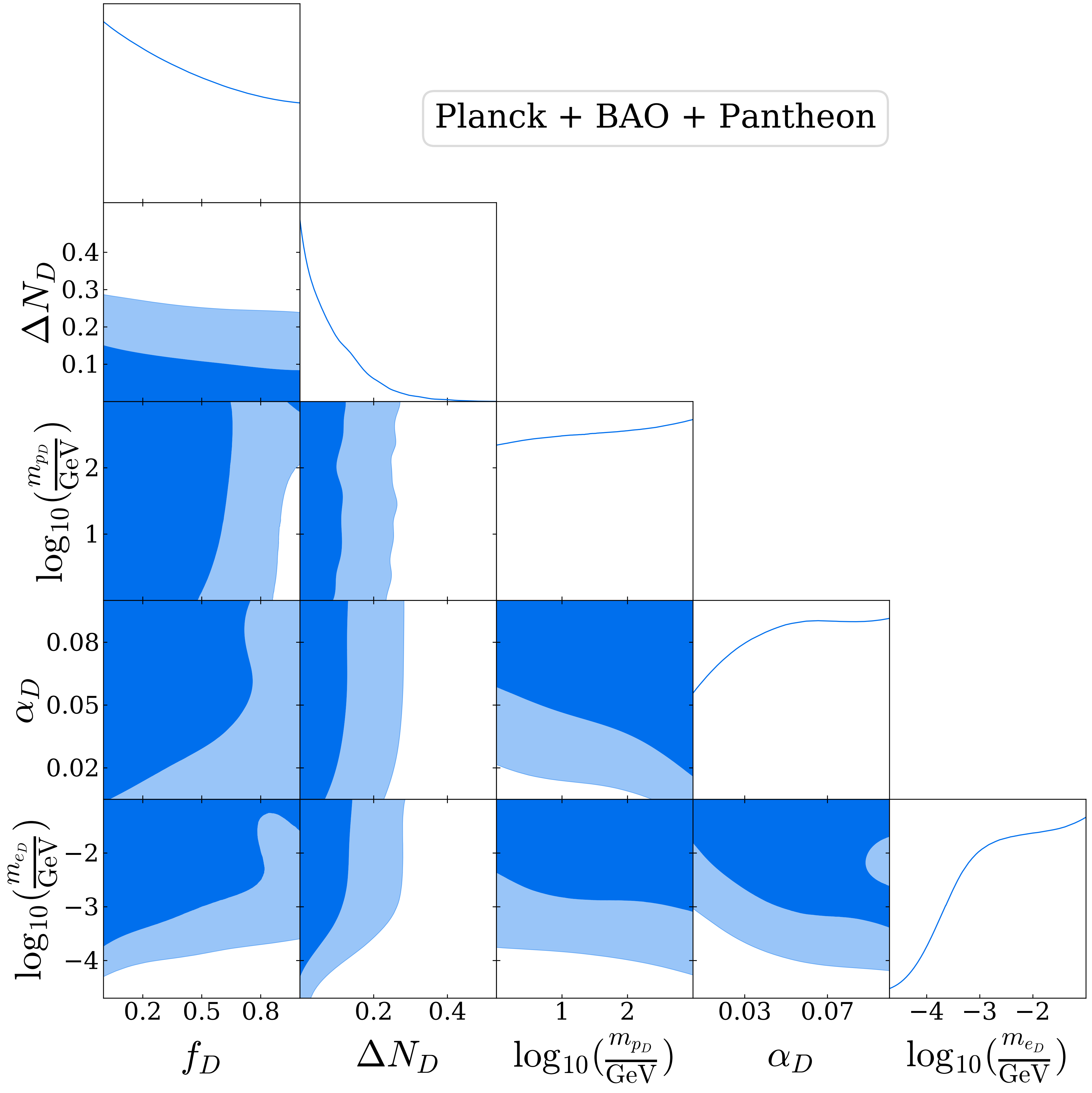
- **Dark photon pressure opposes gravitational collapse**
  - **Analogous to SM baryons**
- **Causes oscillations and suppression in the aDM matter power spectrum, compared to CDM**
- **Matter Power spectrum ~ scales at which DM is clumping at**



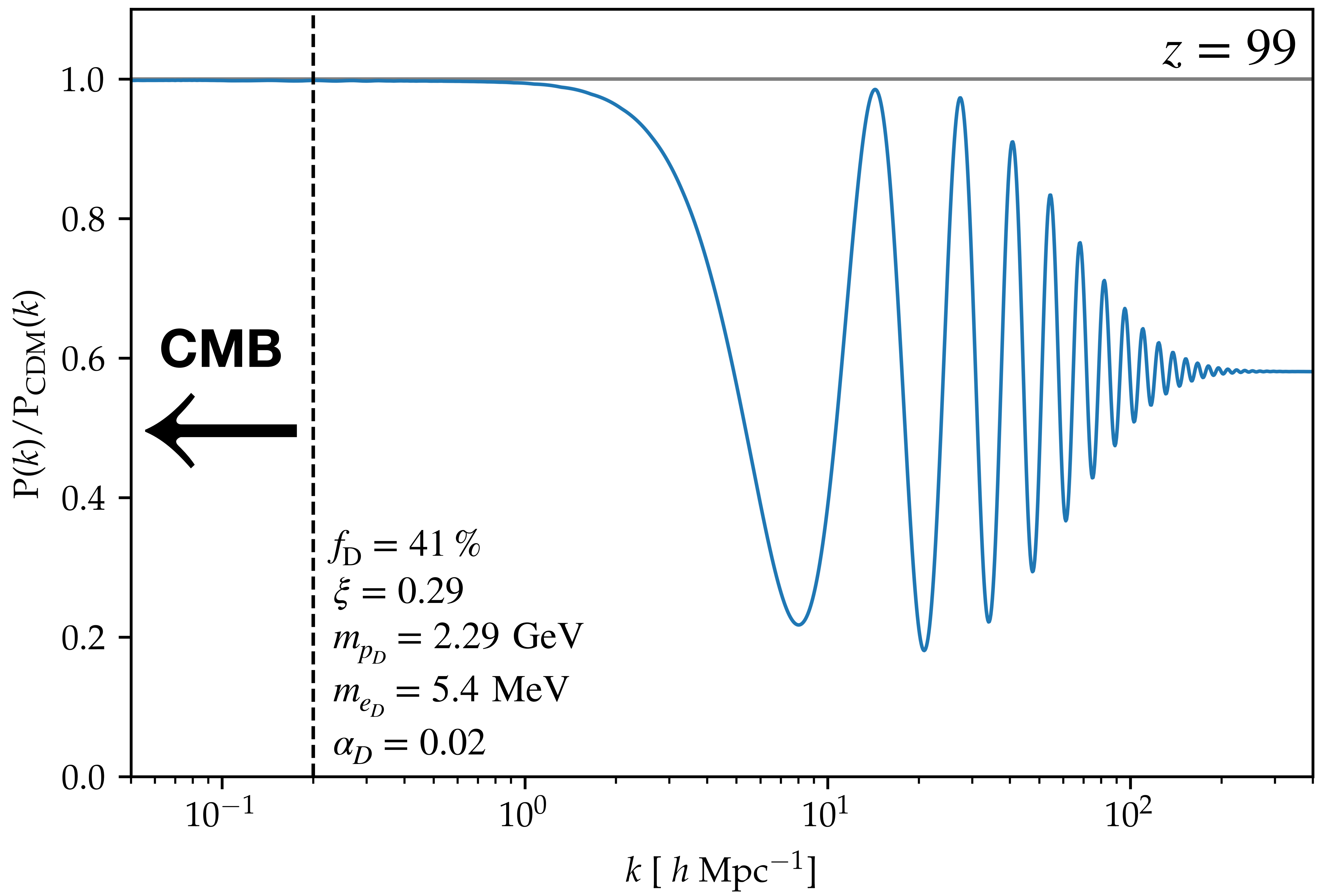
Constraints from Cosmology

Bansal, Barron, Curtin, Tsai, arXiv: 2212.02487





But cosmology can only get us so far...



The Lyman-α Forest

Redshift and Scale Landscape

- **Existing studies have looked at CMB bounds and galactic observables at late times**

  Cyr-Racine, Sigurdson, arXiv: 1209.5752
  Bansal, Barron, Curtin, Tsai, arXiv: 2212.02487

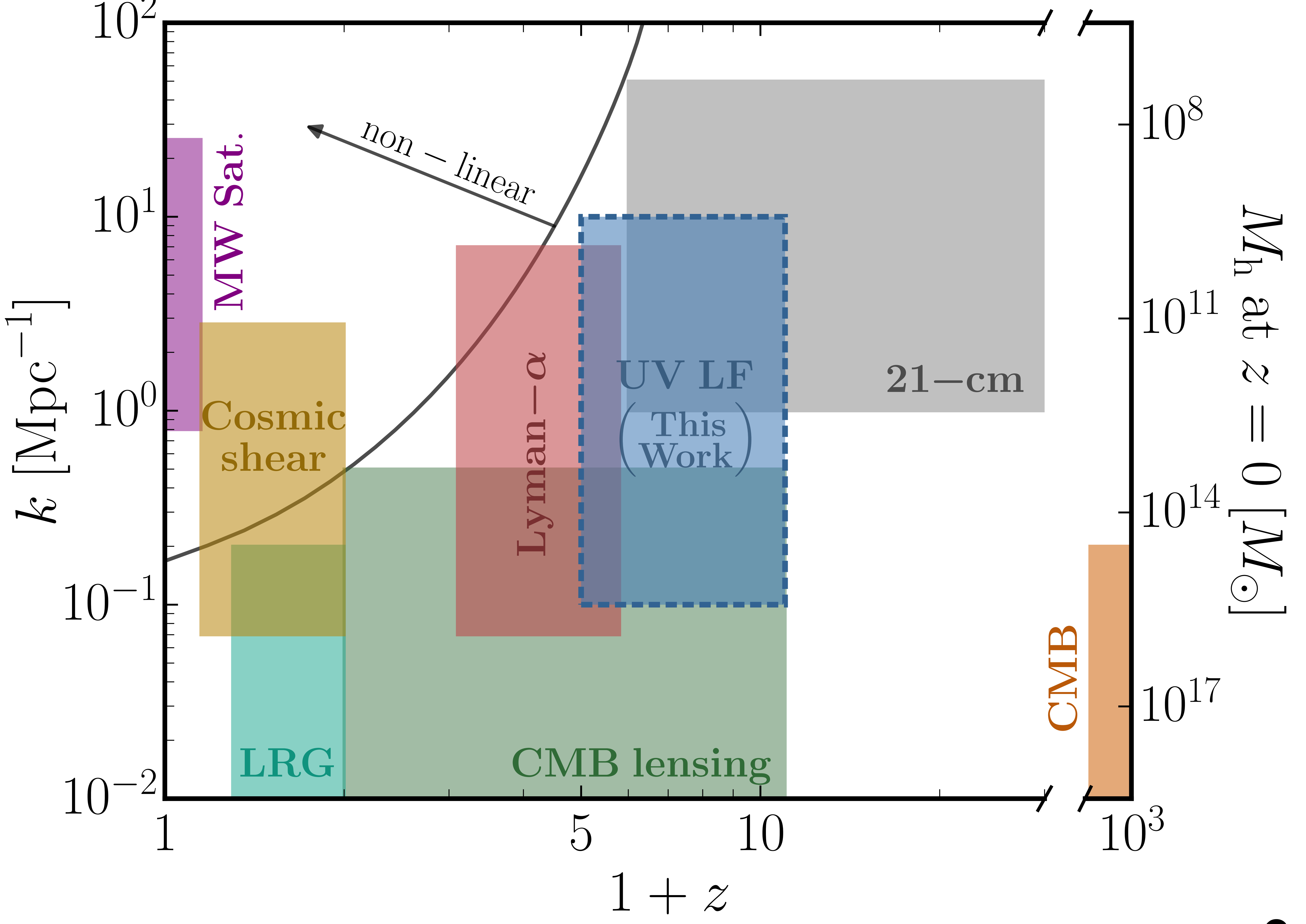
  Roy et al., arXiv: 2304.09878
  Gemmell et al., arXiv: 2311.02148

- **Lyman-α measurements are able to probe intermediate physical scales and redshifts,** $z = 4.2 - 5$

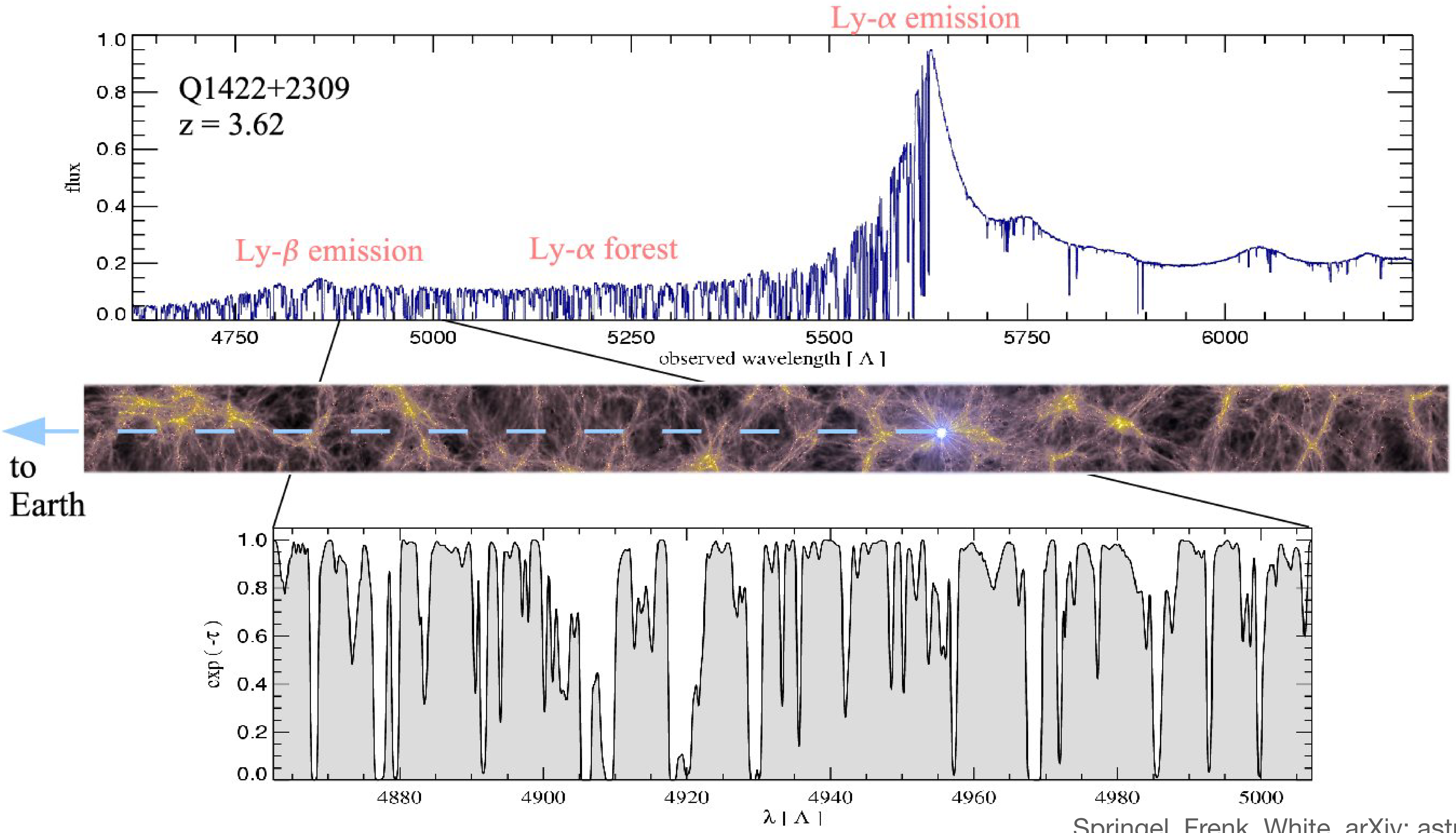
- **Entering the non-linear regime, N-body simulations are required to compute the power spectrum**

Bose et al., arXiv: 1811.10630

Sabti, Muñoz, Blas, arXiv: 2110.13161



The Lyman-α Signal

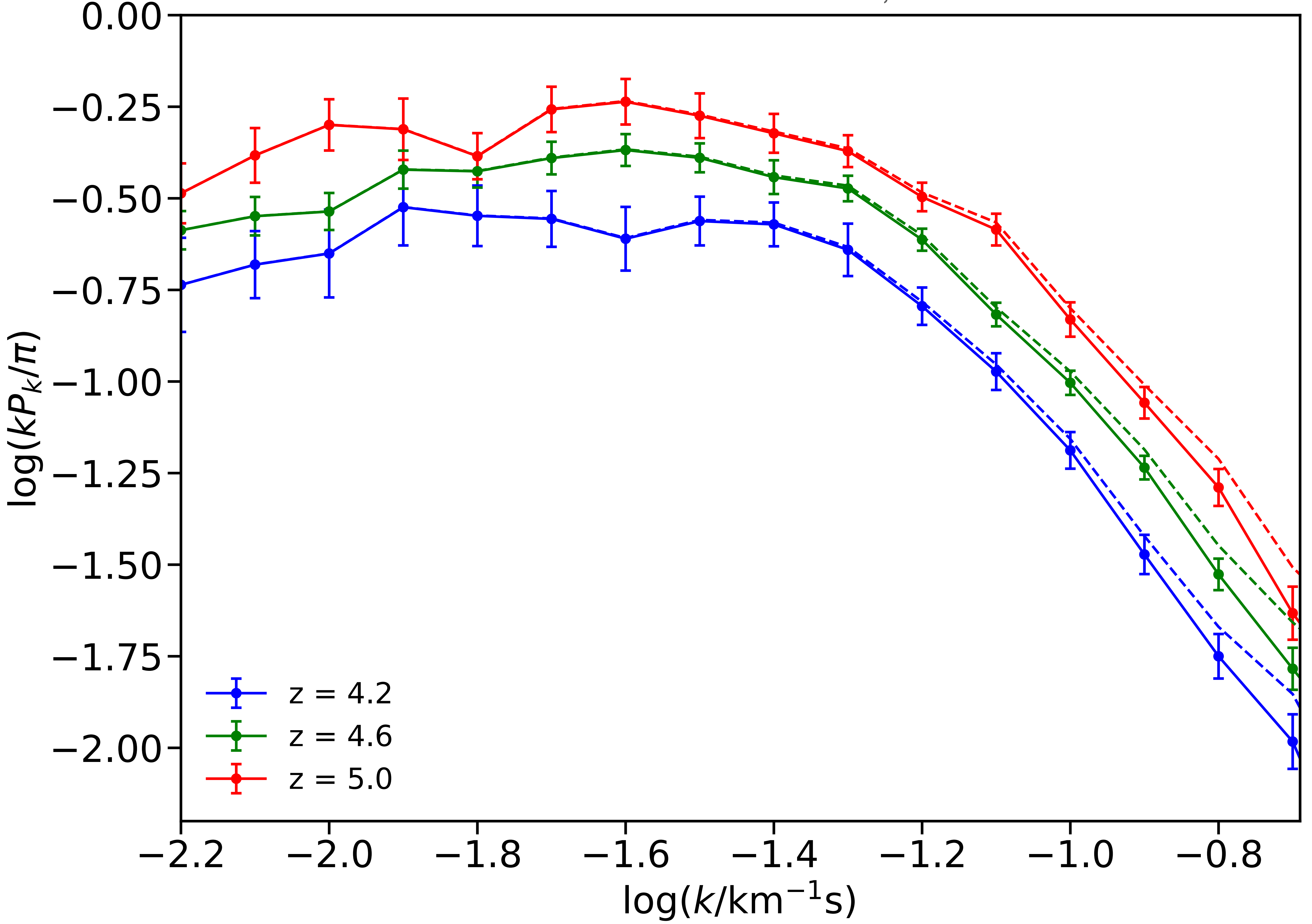


Springel, Frenk, White, arXiv: astro-ph/0604561

The Lyman-α Signal

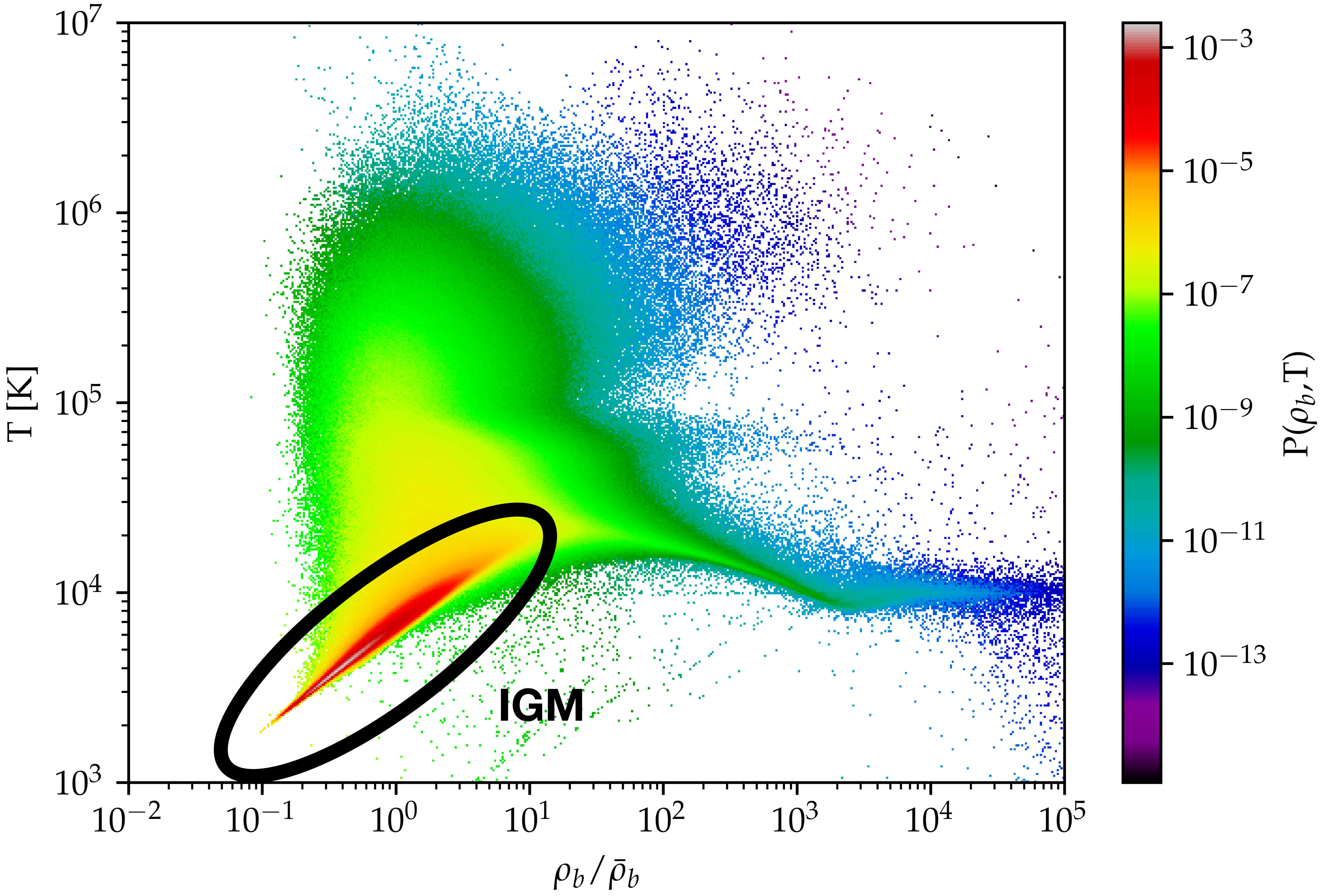
The 1D flux power spectrum is a TRACER of the underlying scales dark matter is clumping at

Boera et al., arXiv: 1809.06980

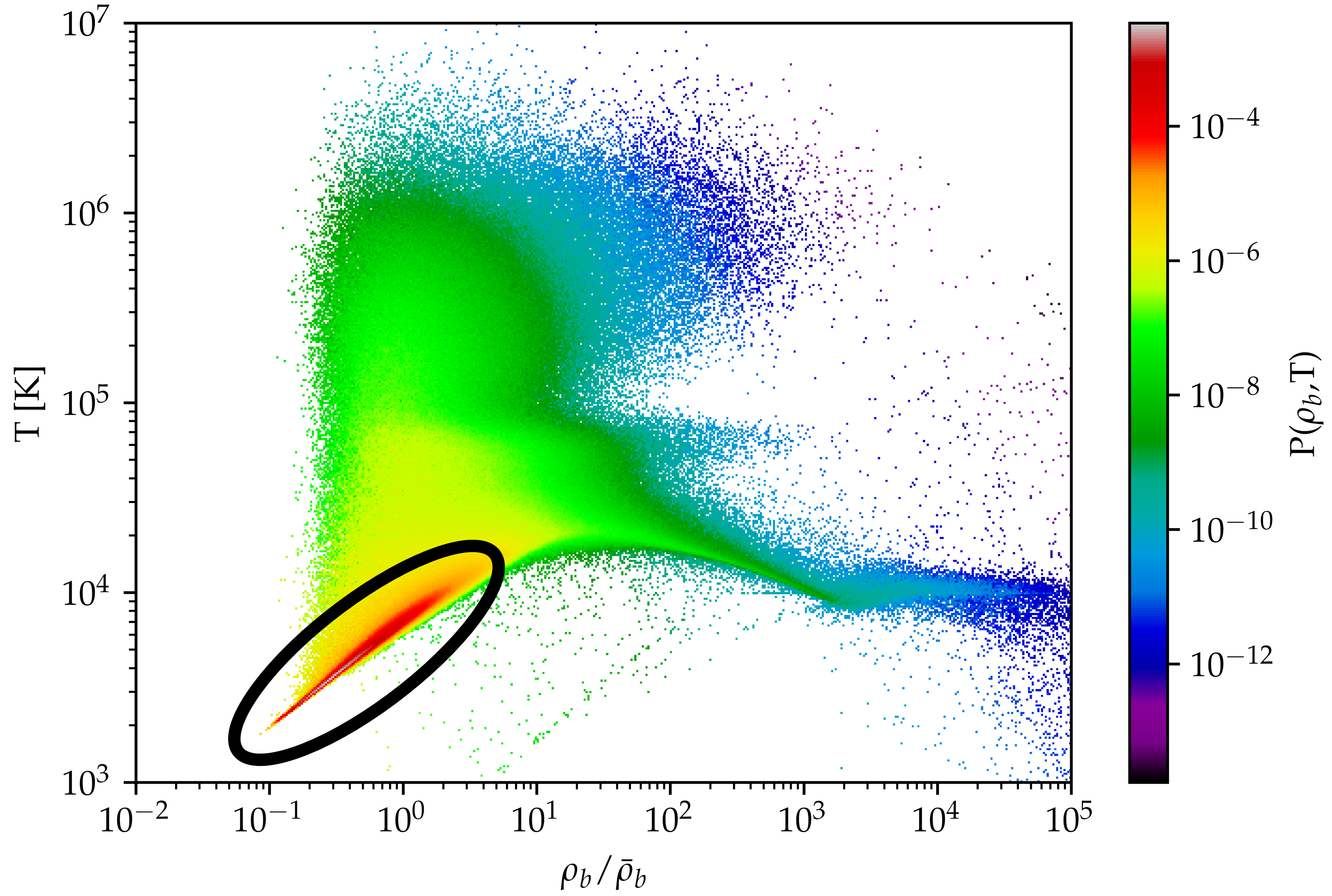


Flux Power Spectra Uncertainties

- **The 1D flux power spectrum is NOT equivalent to the 3D matter power spectrum**
  - **Transverse directions integrated line-of-sight**
- **Sensitive to the properties of the intergalactic medium (IGM), determined by the UVB photon heating rates, ϵ_0**



Flux Power Spectra Uncertainties



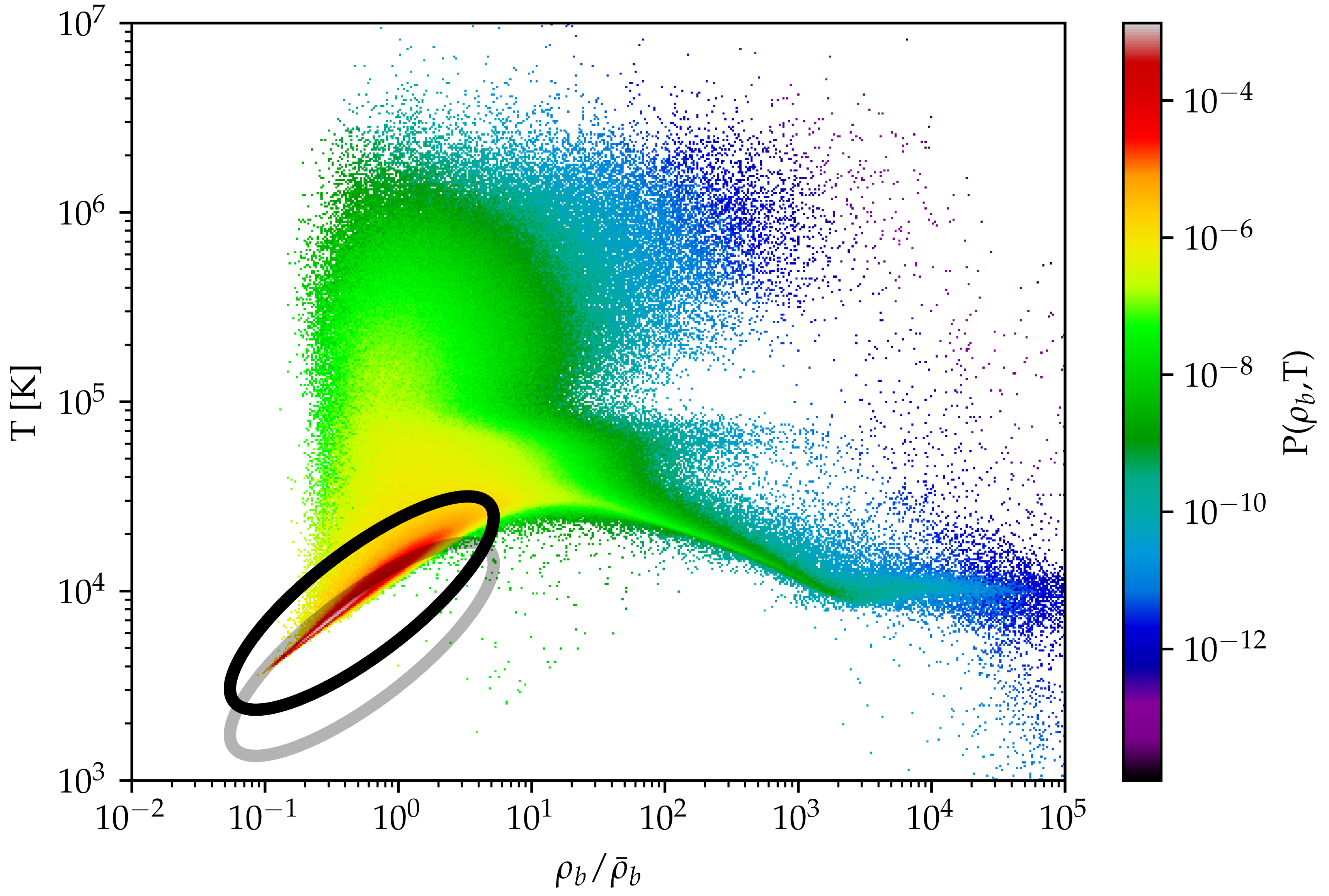
$$\epsilon = H_A * \epsilon_0 * \left(\frac{\rho_b}{\overline{\rho_b}}\right)^{H_S}$$

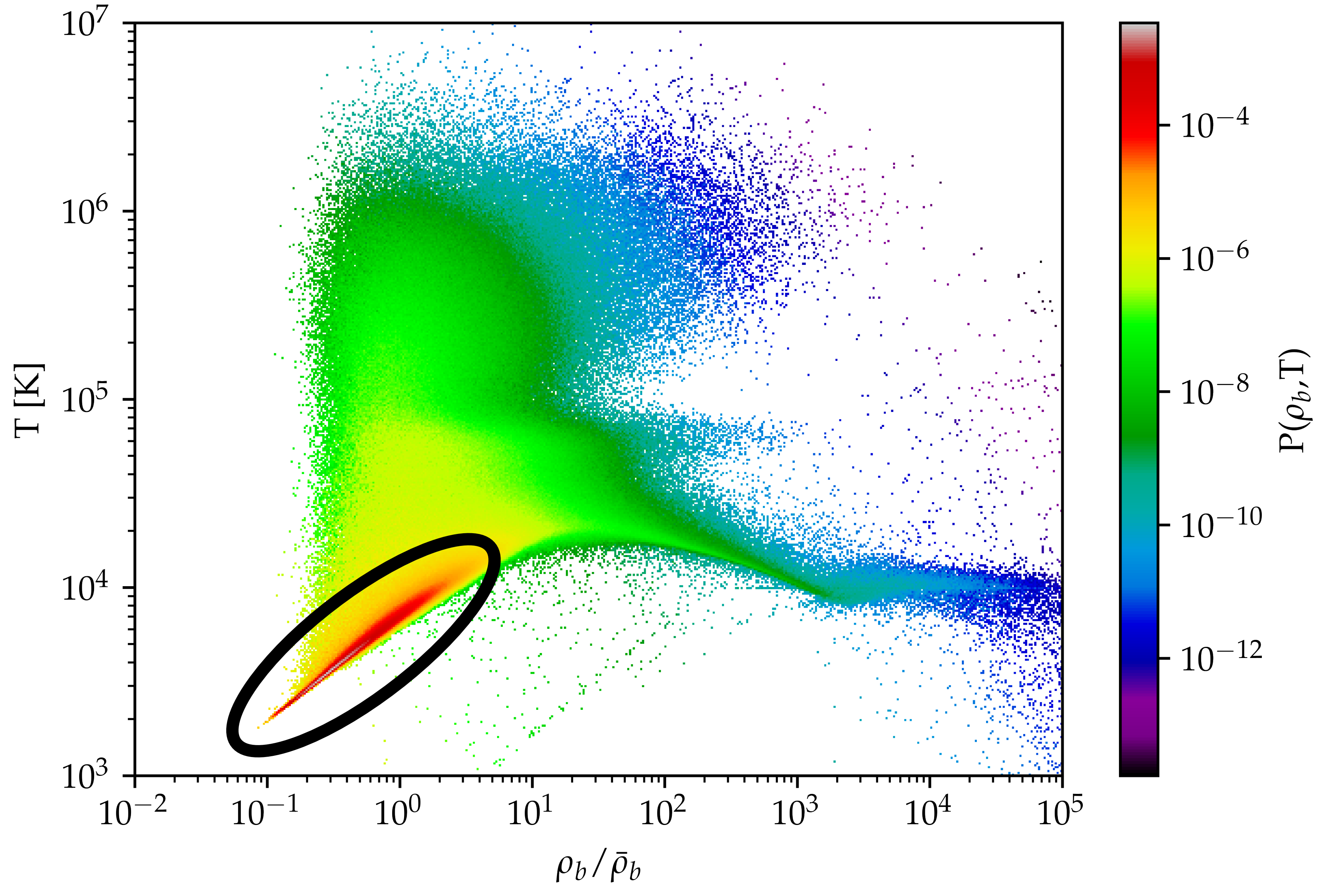
Default heating rate

Nuisance parameters

Flux Power Spectra Uncertainties

$H_A \uparrow\uparrow$





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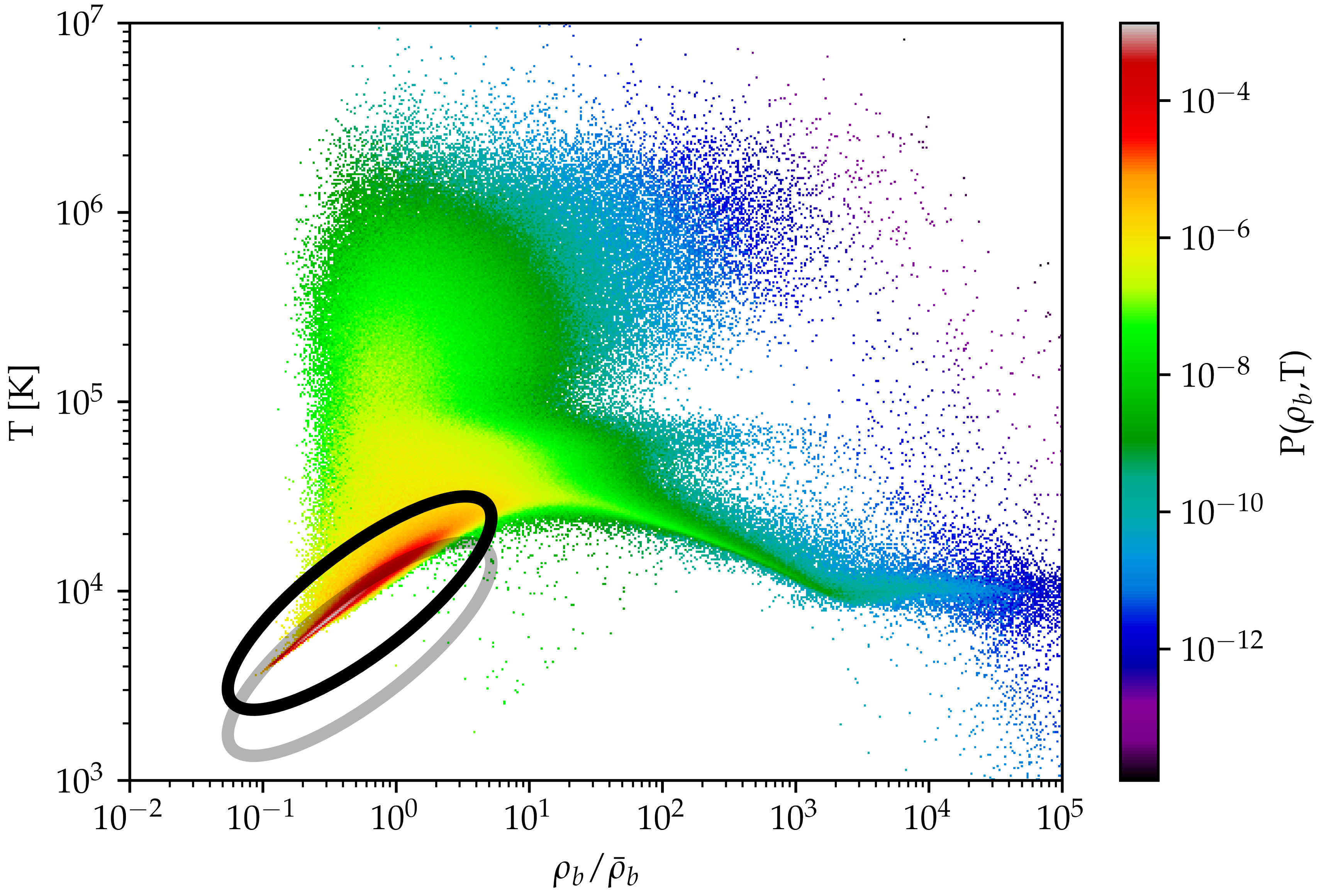

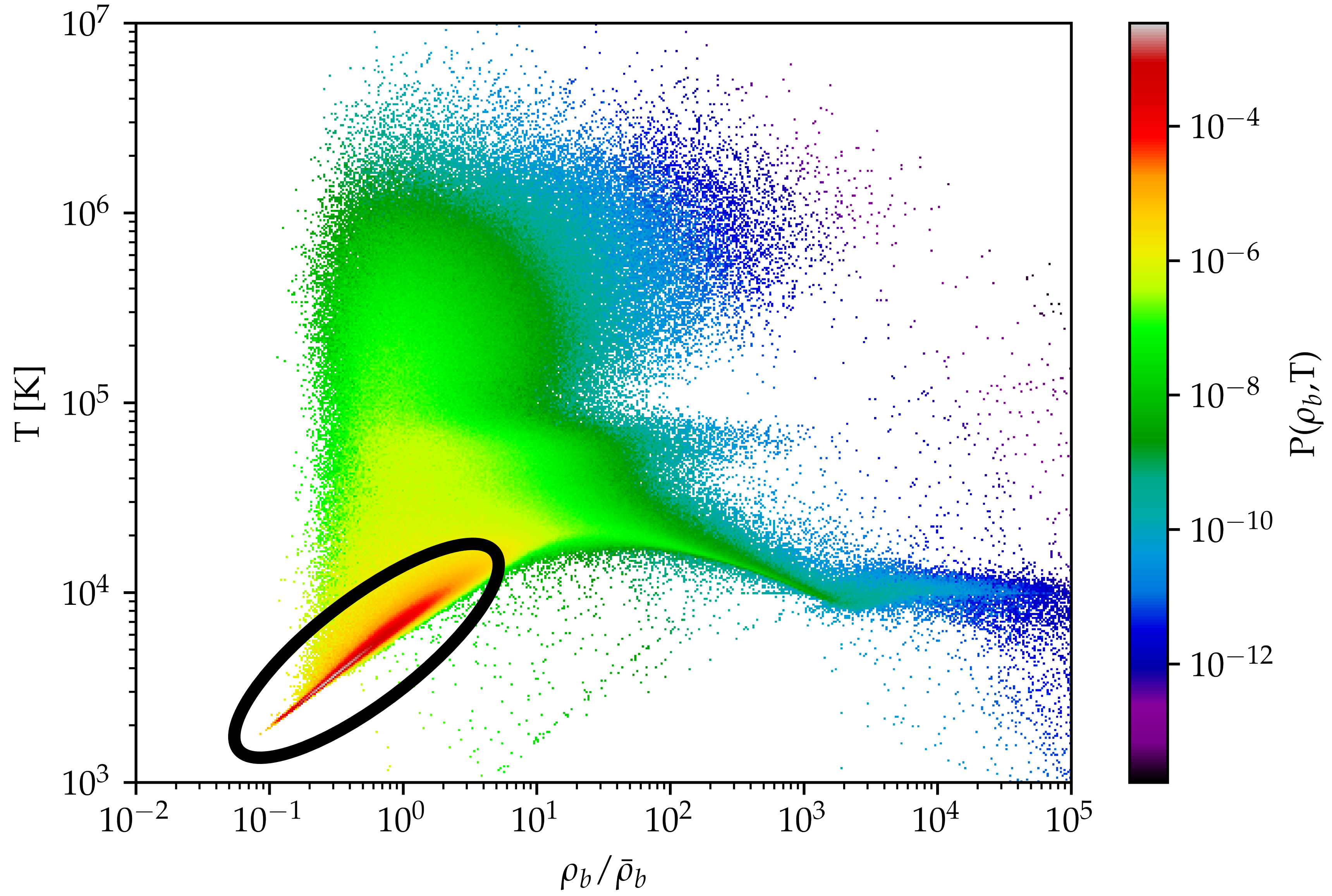

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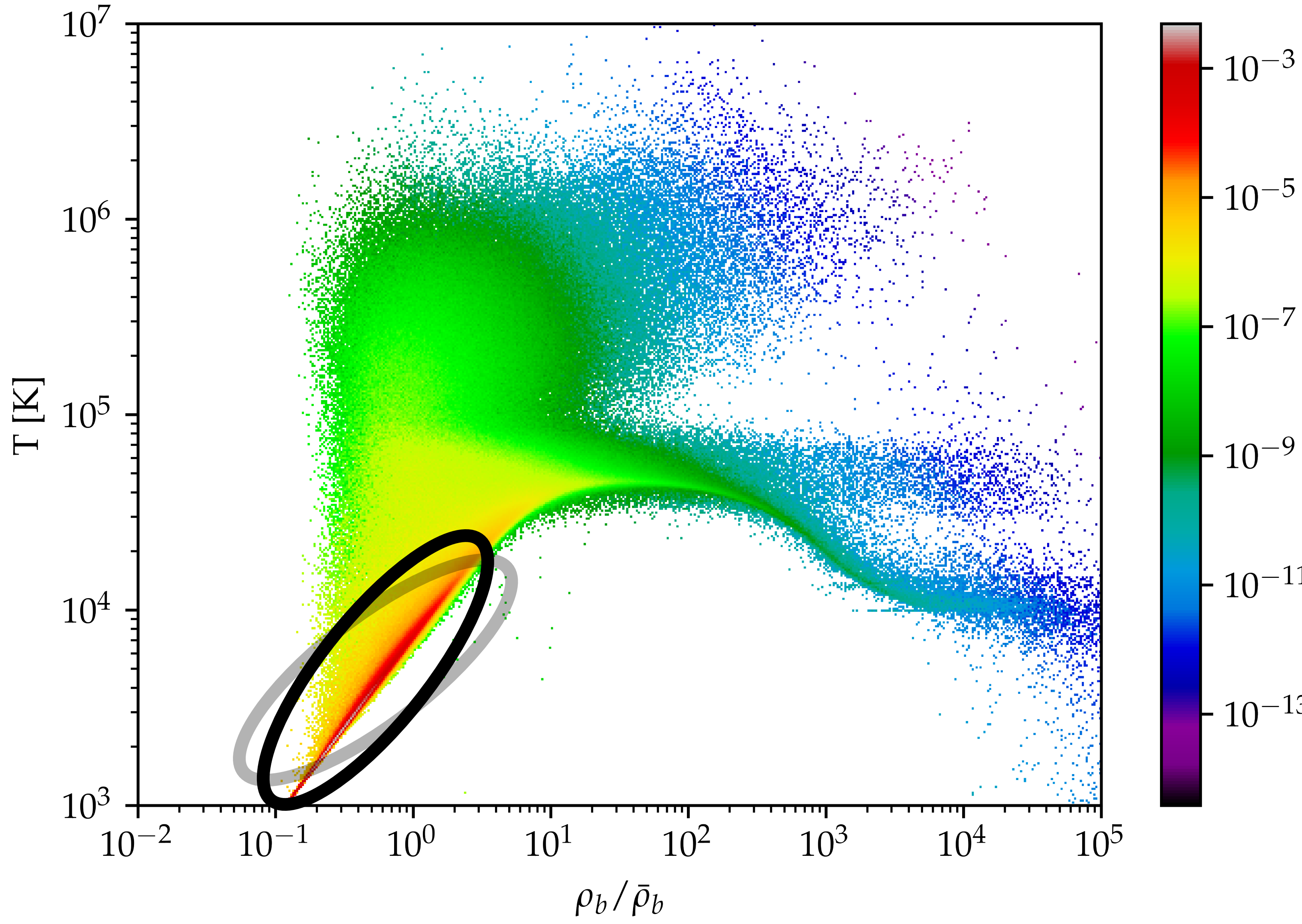
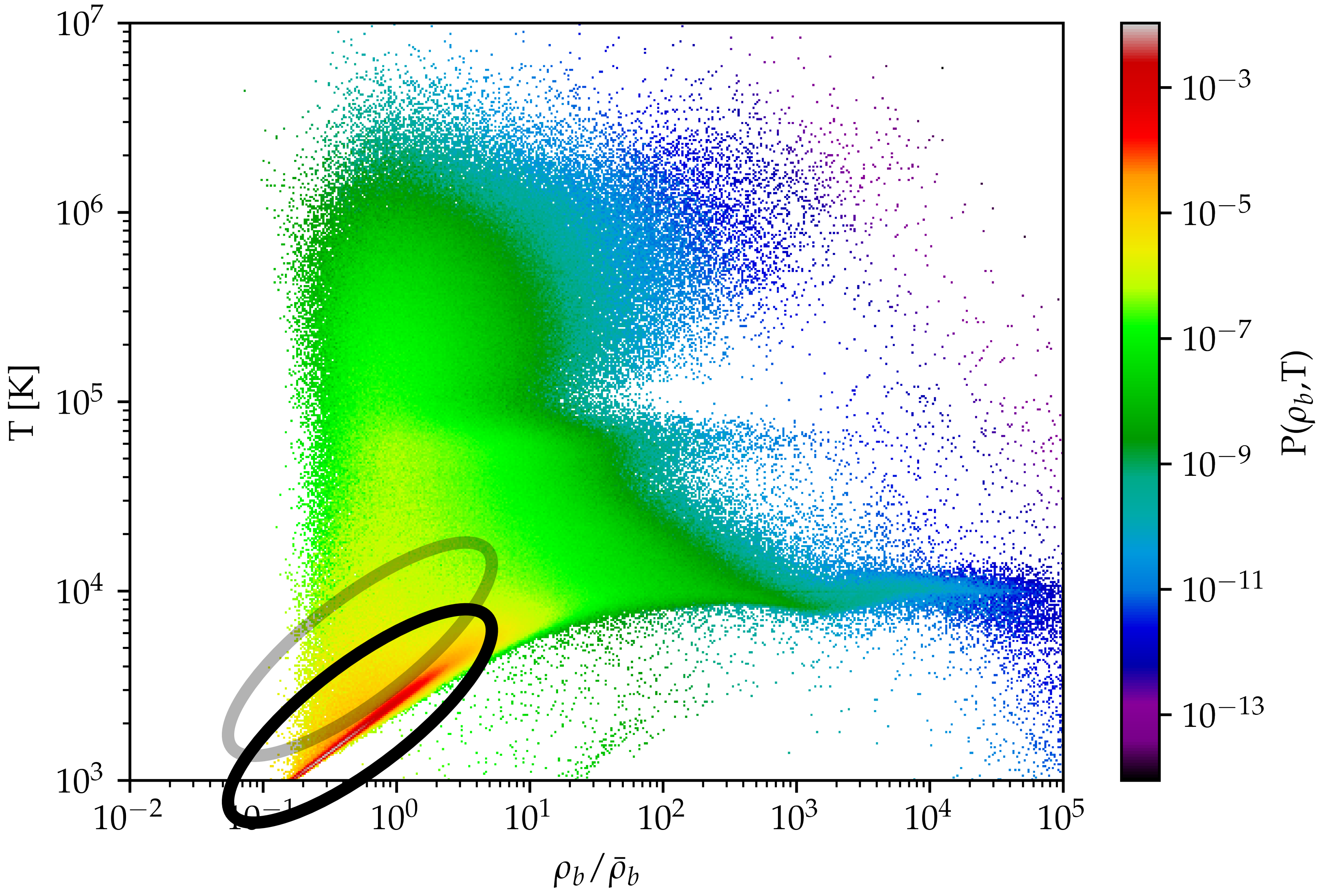
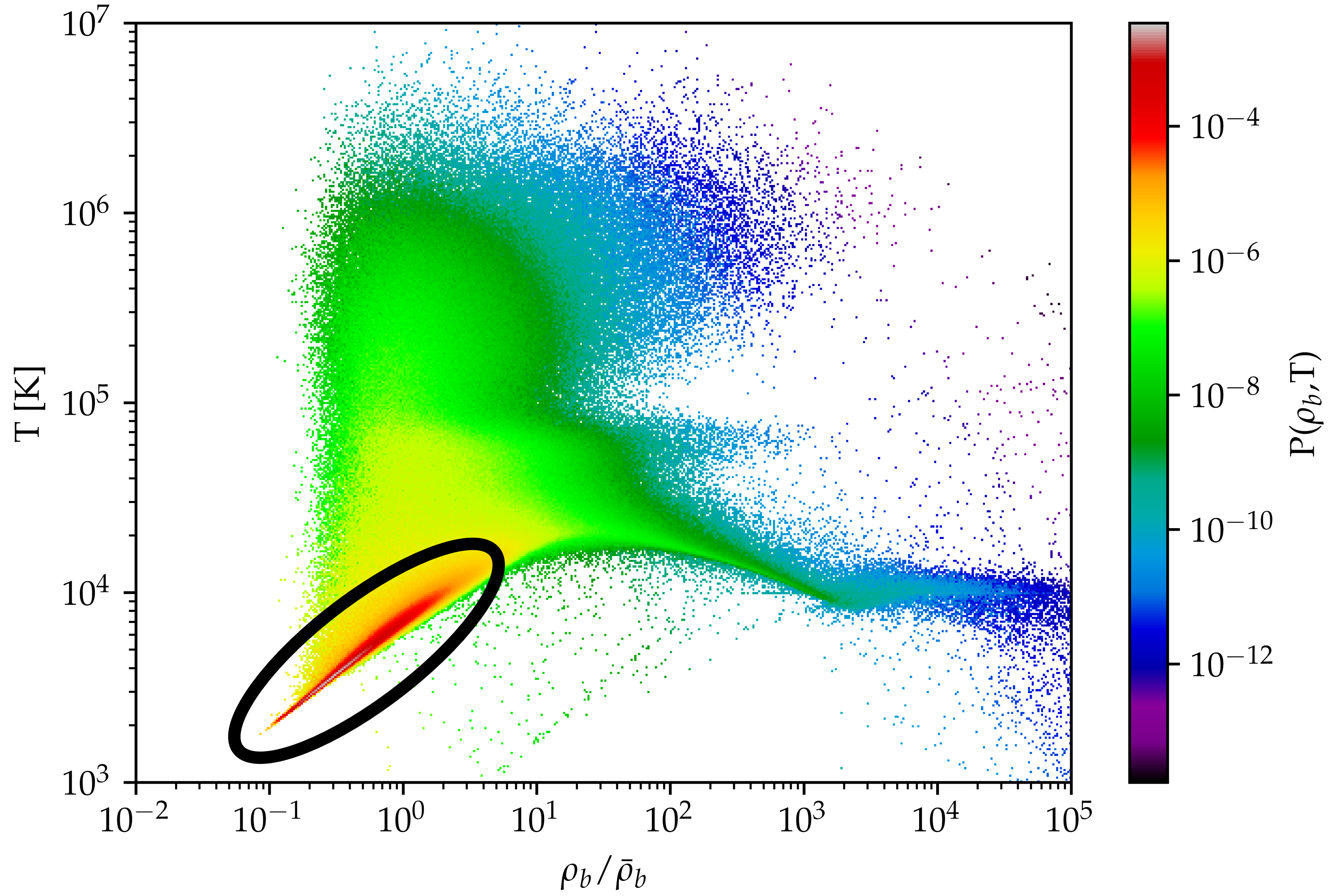


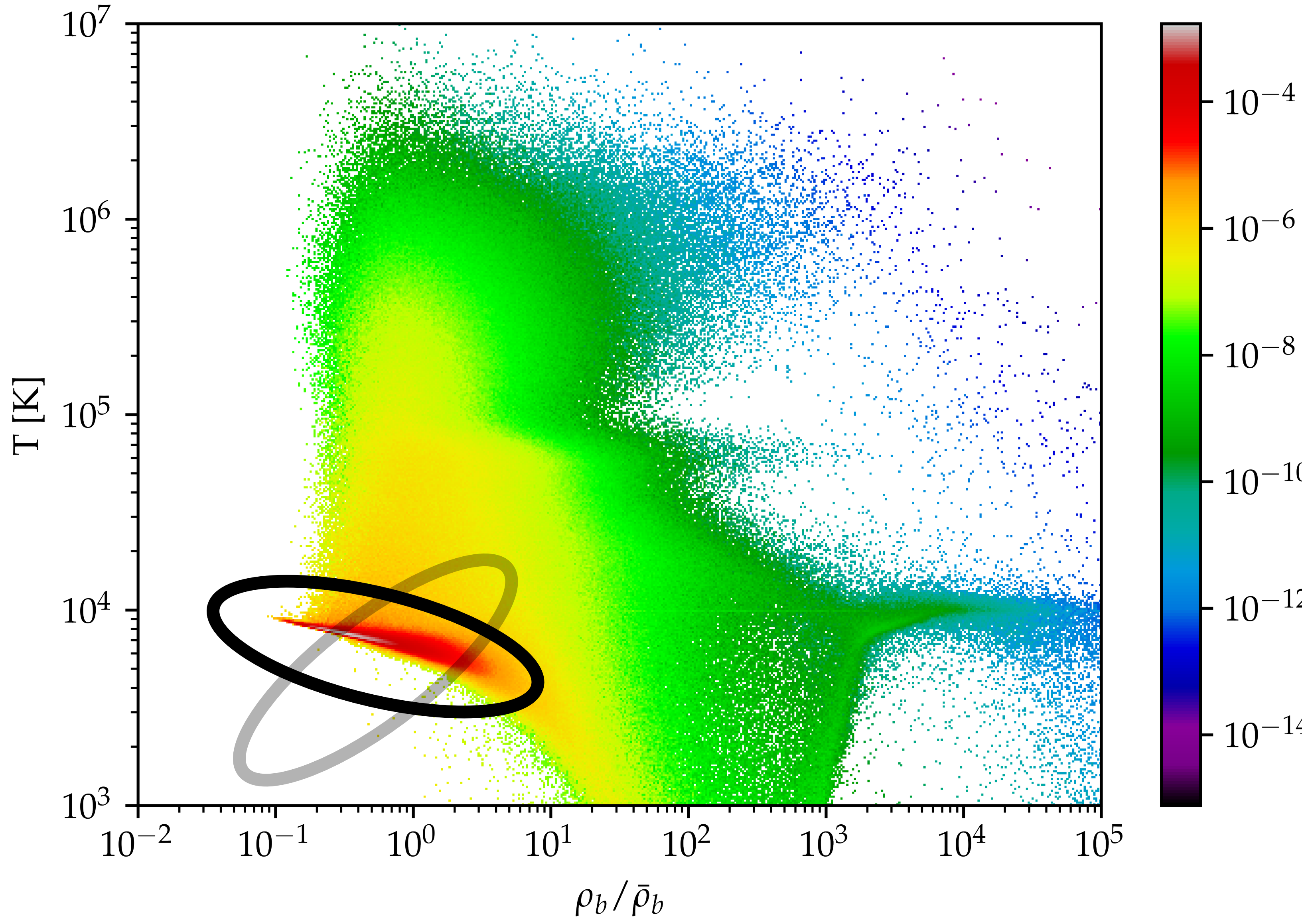
Flux Power Spectra Uncertainties

$H_A \downarrow\downarrow$





$H_S \downarrow\downarrow$



$$\epsilon = H_A * \epsilon_0 * \left(\frac{\rho_b}{\overline{\rho_b}}\right)^{H_S}$$

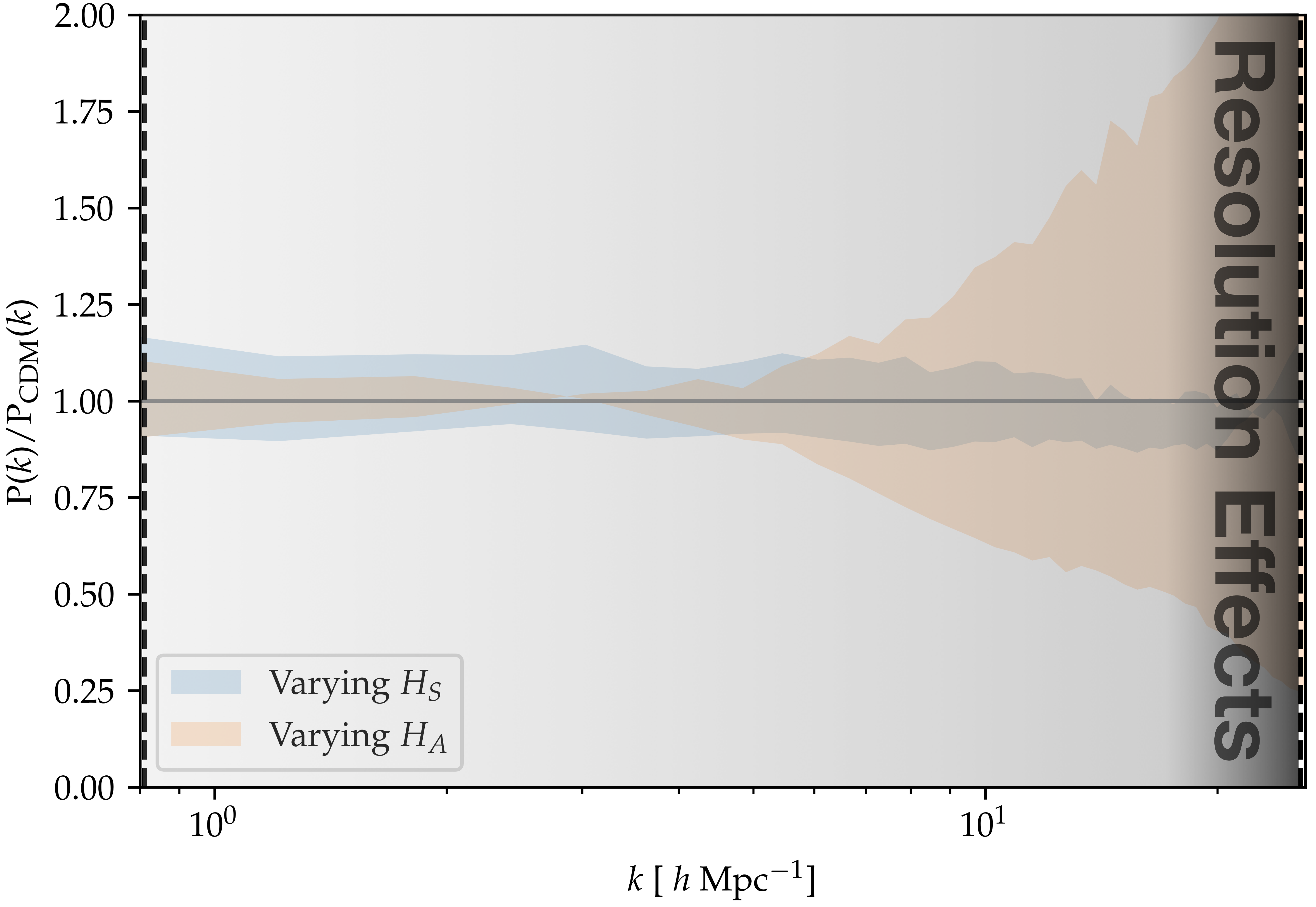
Default heating rate

Nuisance parameters

Flux Power Spectra Uncertainties

IGM uncertainties can cause suppression / enhancement at small scales

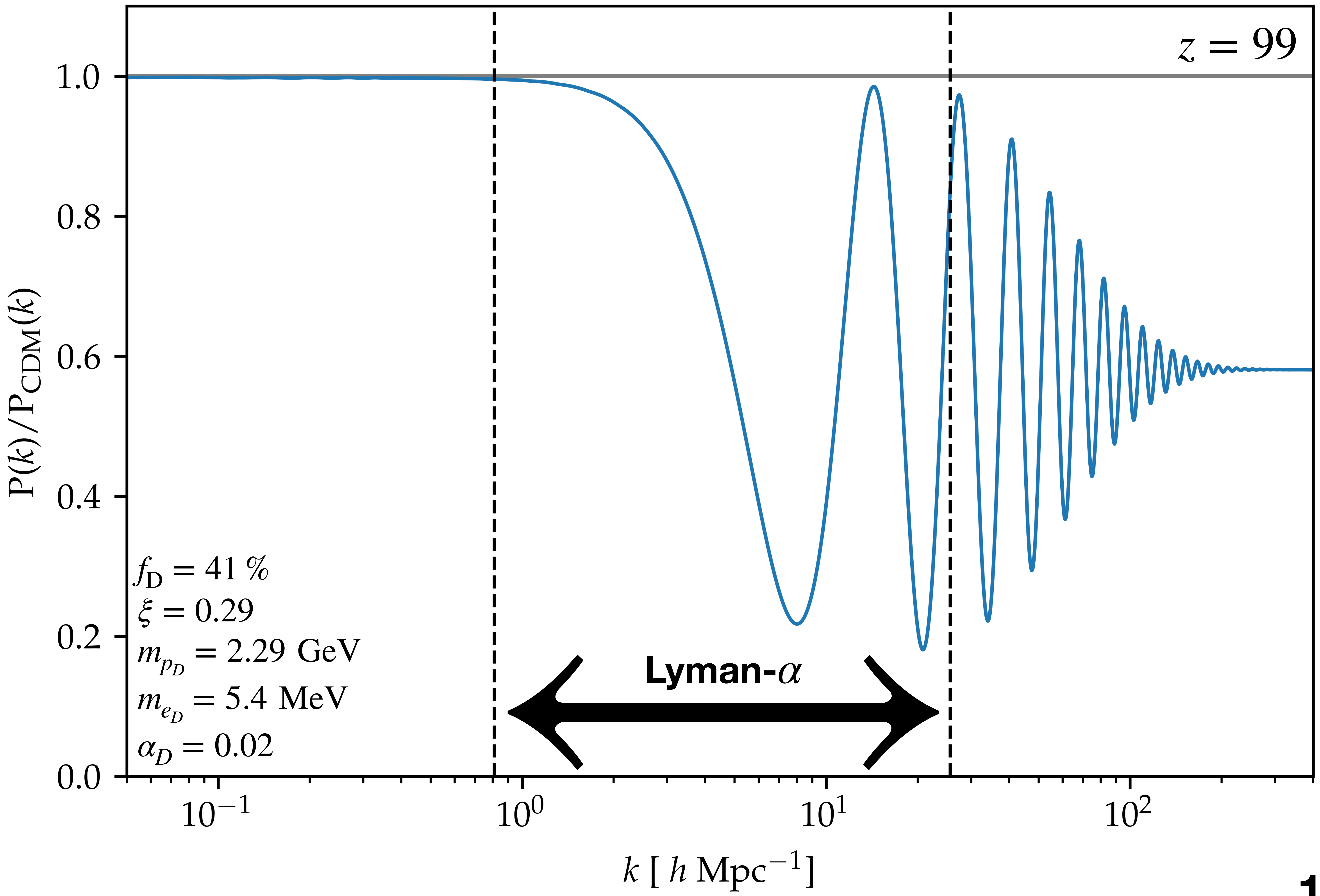
= Need to marginalise over



Can atomic dark matter hide in the forest?

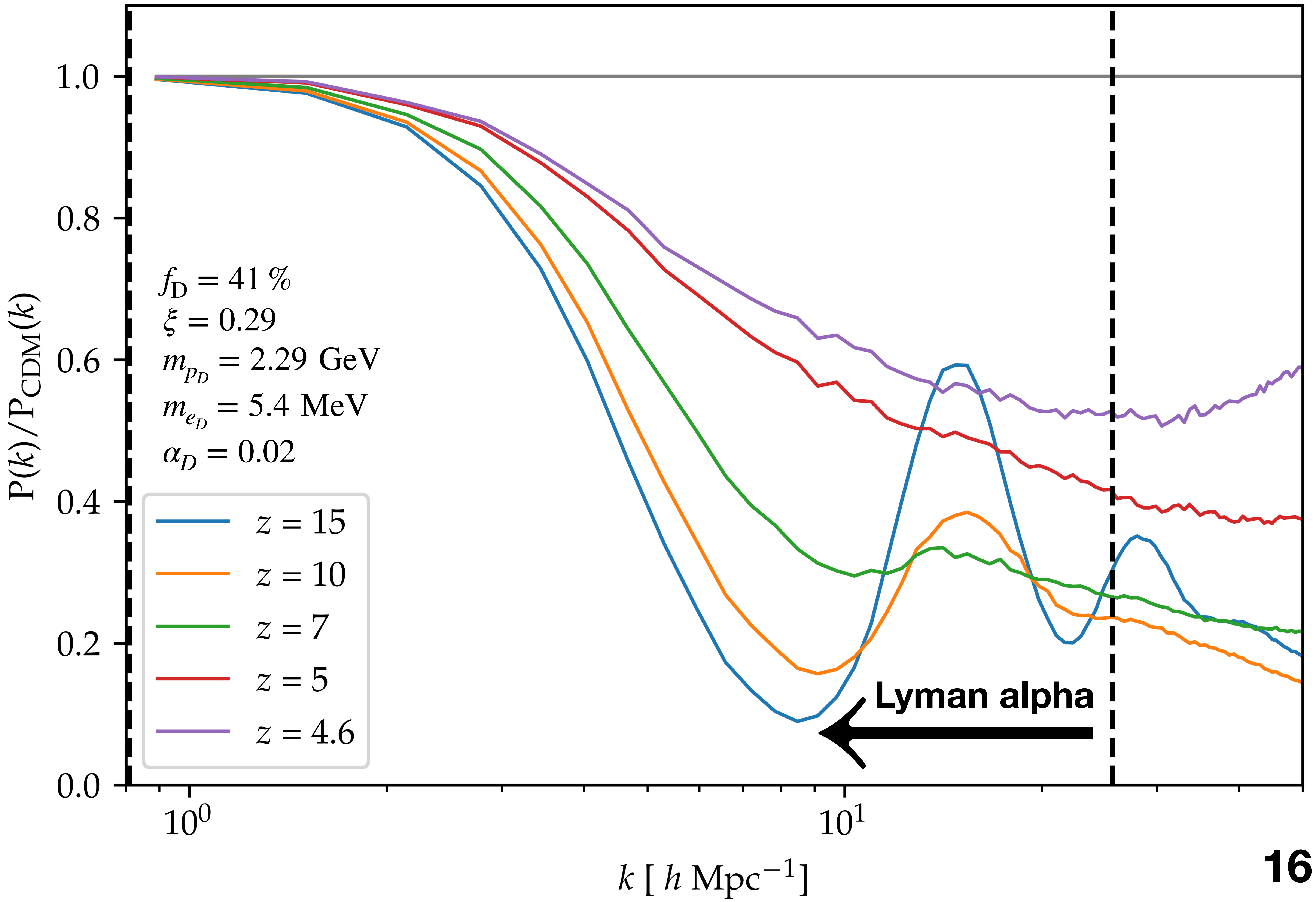
The Lyman-α Range

- **Lyman-α can probe to smaller scales**
- **But still need to evolve matter power spectrum to later redshifts using N-body simulations**



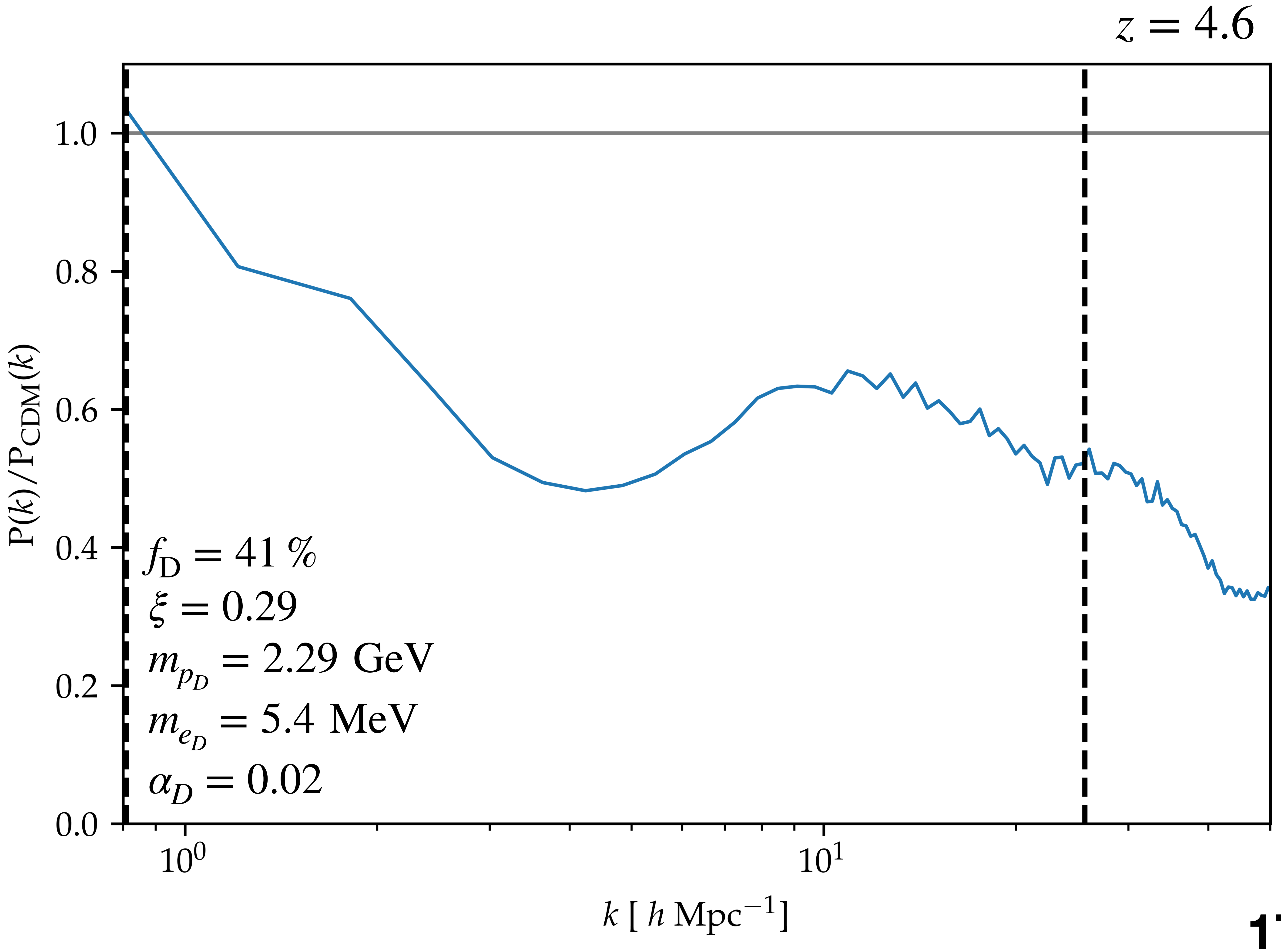
Transfer Function Evolution

- **From simulation snapshots can calculate 3D matter power spectra at various redshifts**
- **Oscillations washout through non-linear evolution, suppression remains for large k**

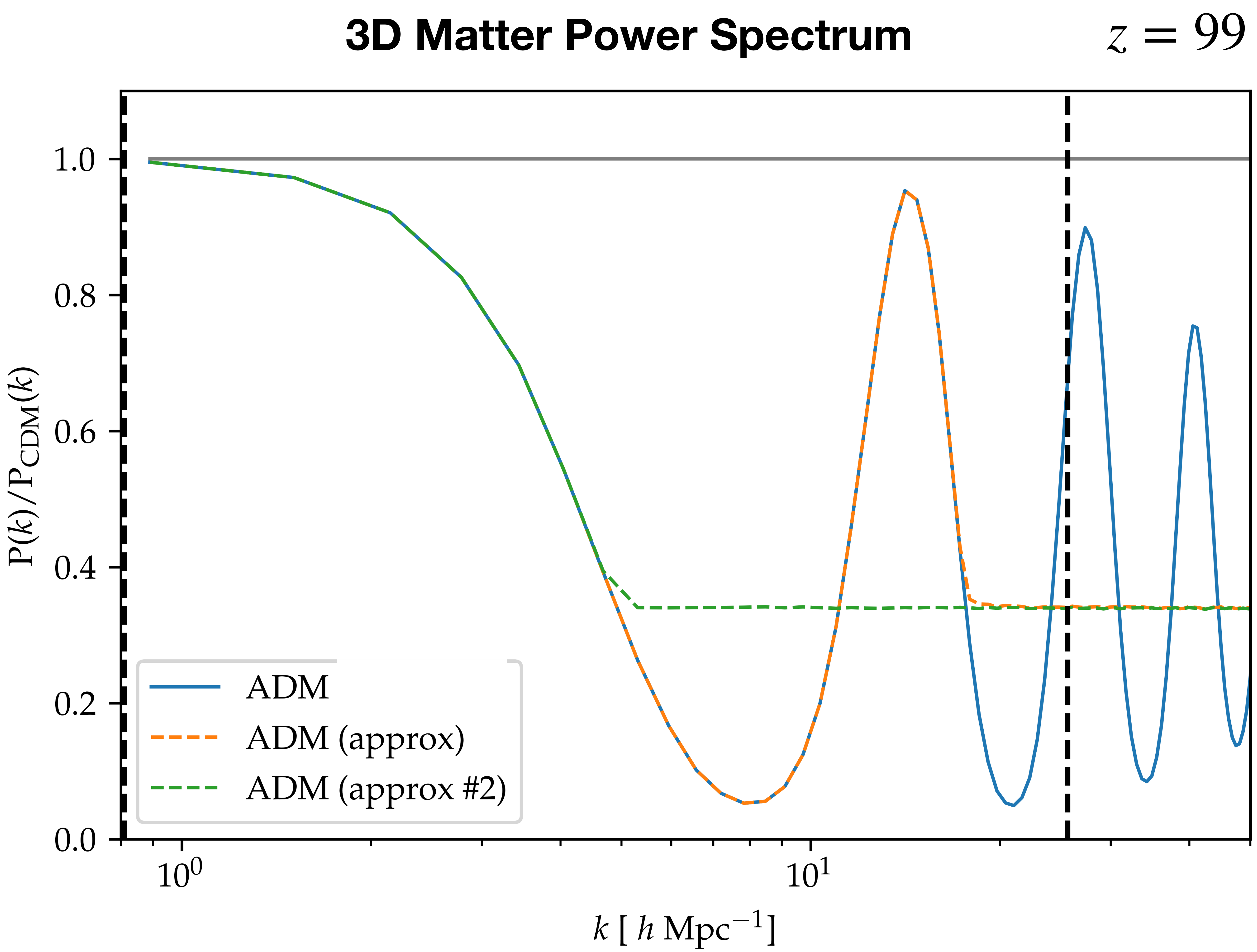


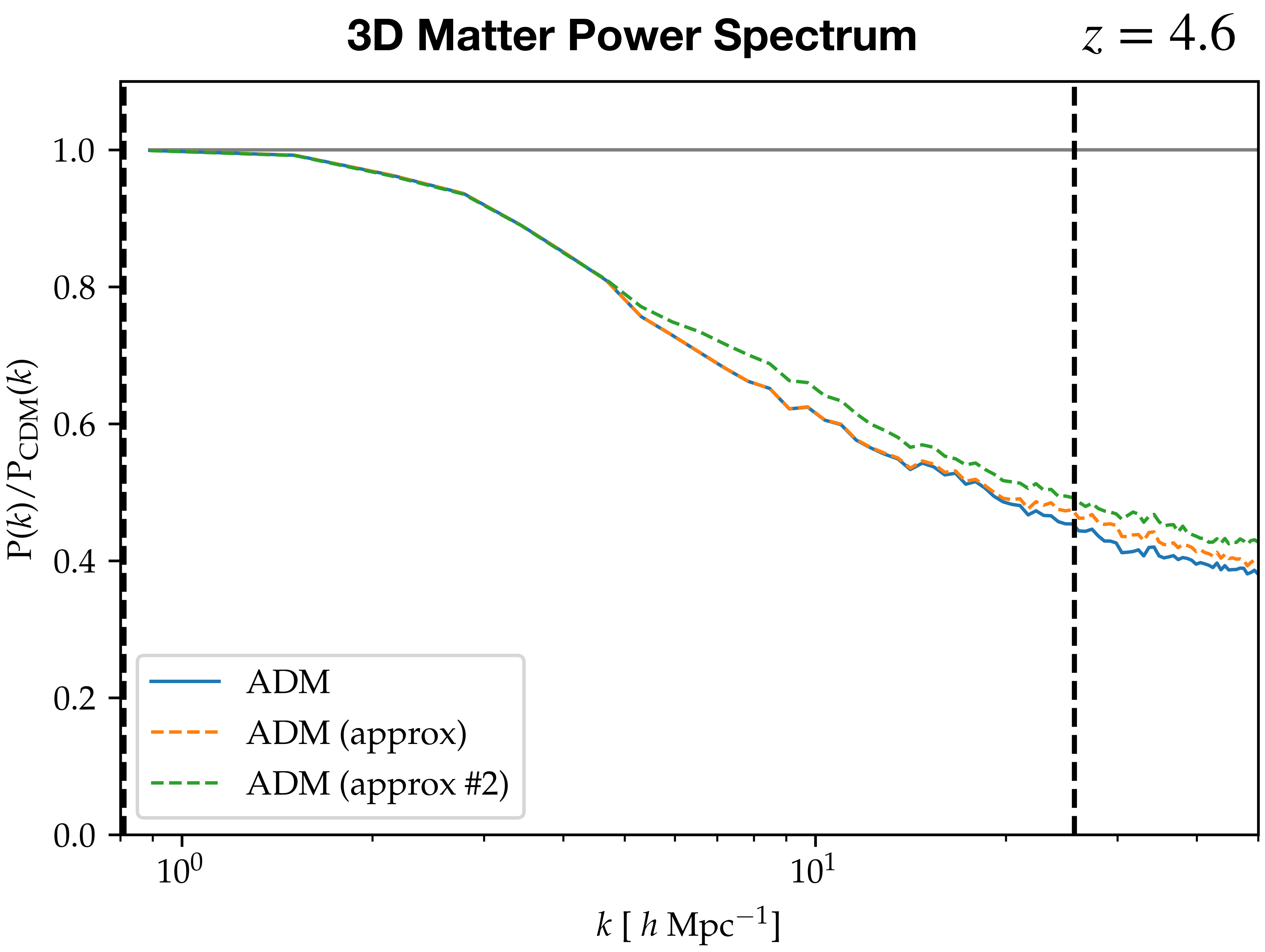
1D Flux Power Spectra

- **1D Flux power spectra calculated using** `fake_spectra` Bird, ascl:1710.012
- **Replicates the actual Lyman-α signal from integrated neutral Hydrogen densities**
- **Appears to retain the DAO oscillation…**



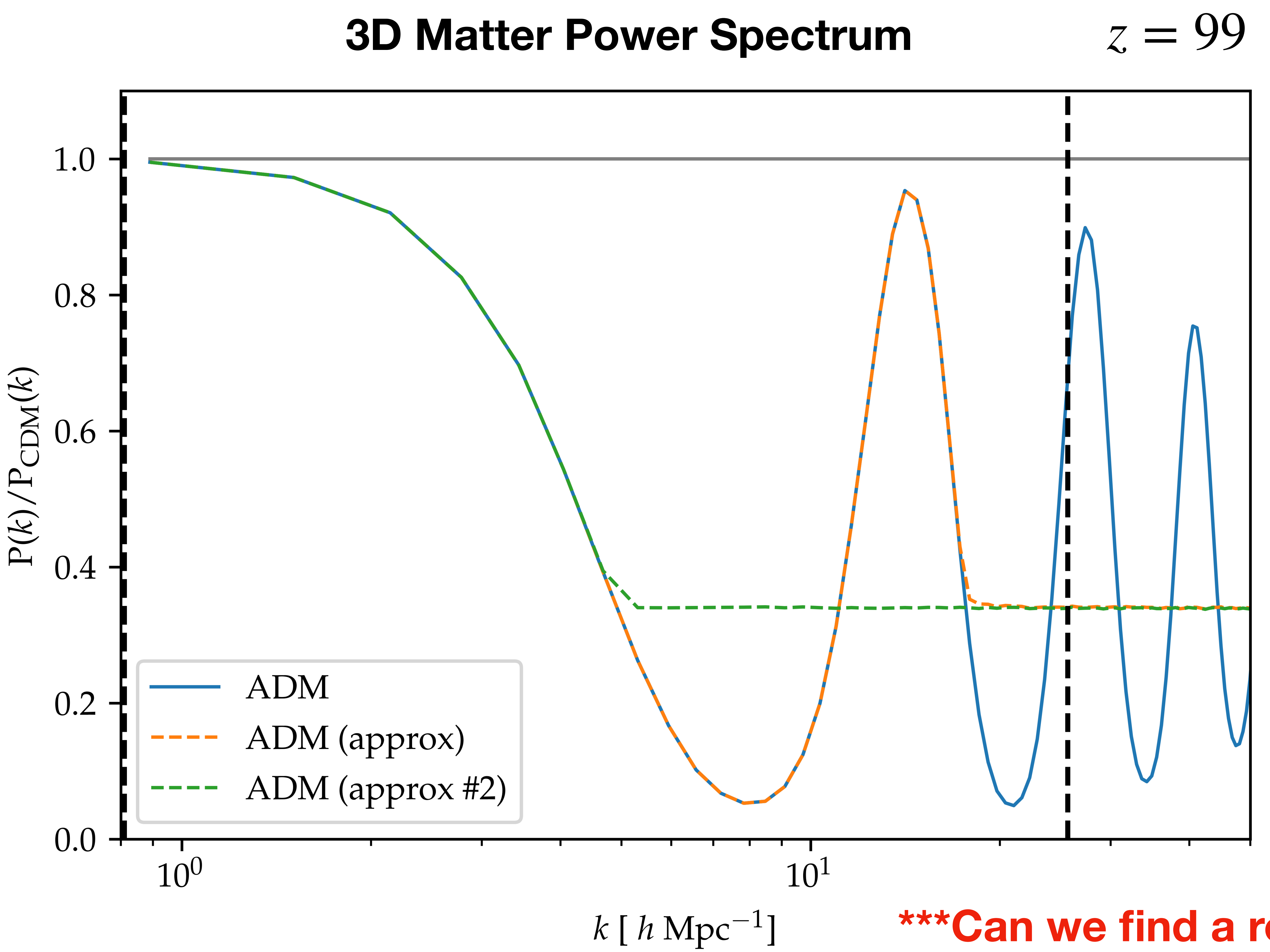
Can Lyman-α see DAOs ?

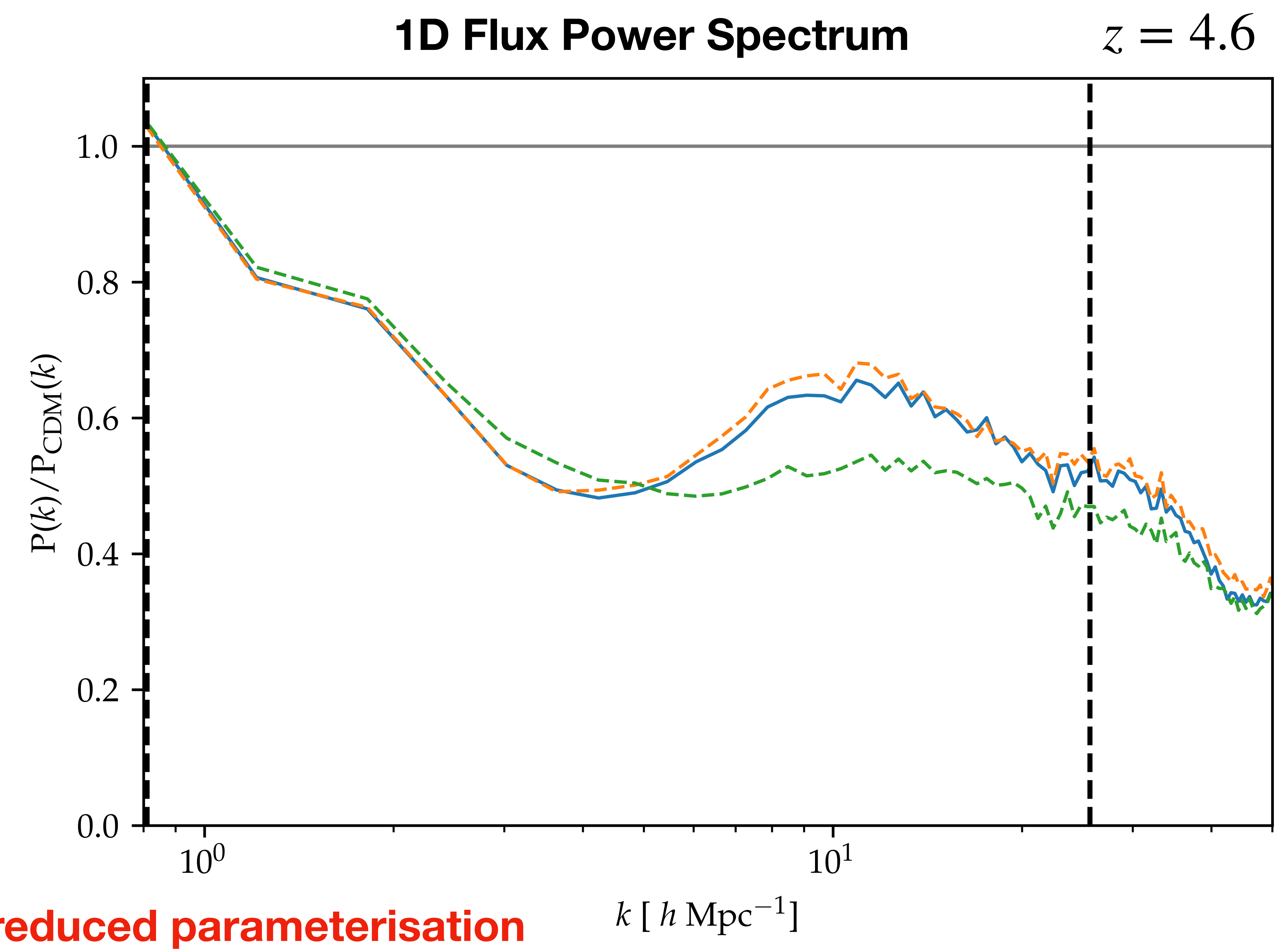




Can Lyman-α see DAOs ?

See also Bose et al., arXiv: 1811.10630



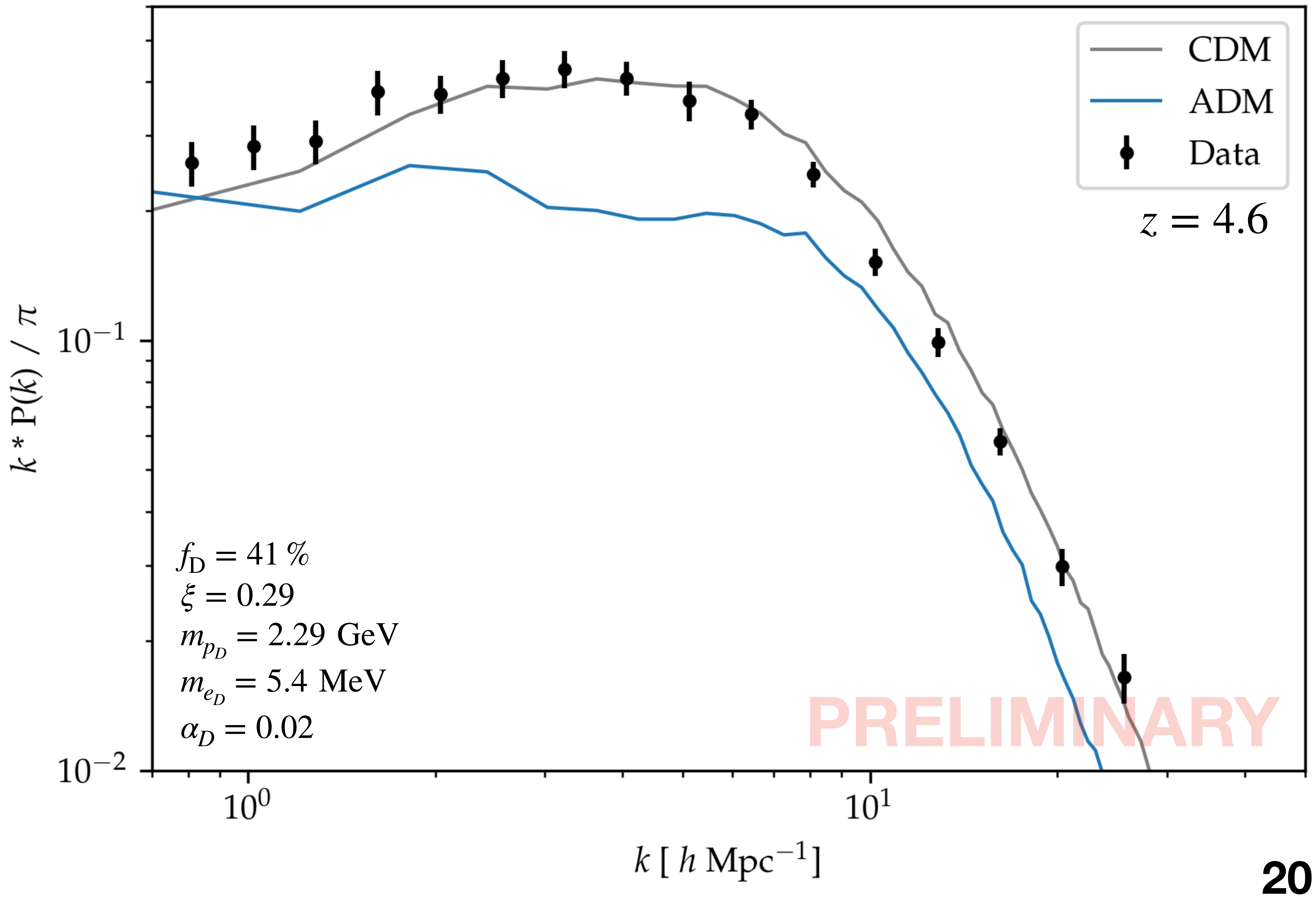


***Can we find a reduced parameterisation for the transfer function?

Full Scan Coming!

- **Compare to data from HIRES and UVES** Boera et al., arXiv: 1809.06980
- **Example of a parameter point while allowed by CMB is excluded by Lyman-α**
- **Will marginalise over IGM and cosmological parameter uncertainties**
- **Will utilise a emulator and Bayesian optimisation to minimise simulations required to converge on allowed parameter region**

Rogers, Peiris, arXiv: 2007.13751



Conclusions:

- **aDM is a model theoretically motivated by both particle and astrophysics**
- **Finishing up preliminary tests, ramping up to resolution / box size tests and eventual full scan**
- **CMB measurements have begun to constrain the aDM parameter space, but the Lyman-α forest will be able to probe smaller scales and further carve away at the allowed parameter space**
- **Additionally, the Lyman-α forest proves to be uniquely sensitive to DAOs even at late redshifts, ideal for aDM constraints**

Supplementary Slides

aDM cooling and Lyman-α