Lyman-alpha constraints on atomic dark matter from N-body simulations

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aDM - what is it and why?

Atomic dark matter (aDM) and its motivation

- Model
  - hidden U(1) gauge group, dark proton, dark electron, dark photon
  - 5 parameters: $\alpha_D, m_{pD}, m_{eD}, f \equiv \frac{\Omega_{aDM}}{\Omega_{DM}}, \xi \equiv \frac{T_D}{T_{CMB}}\Big|_{z=0}$
  - Lagrangian: $\mathscr{L}_{dark} = \overline{\Psi}(\not{D} + m_p)\Psi_p + \overline{\Psi}_e(\not{D} + m_e)\Psi_e$

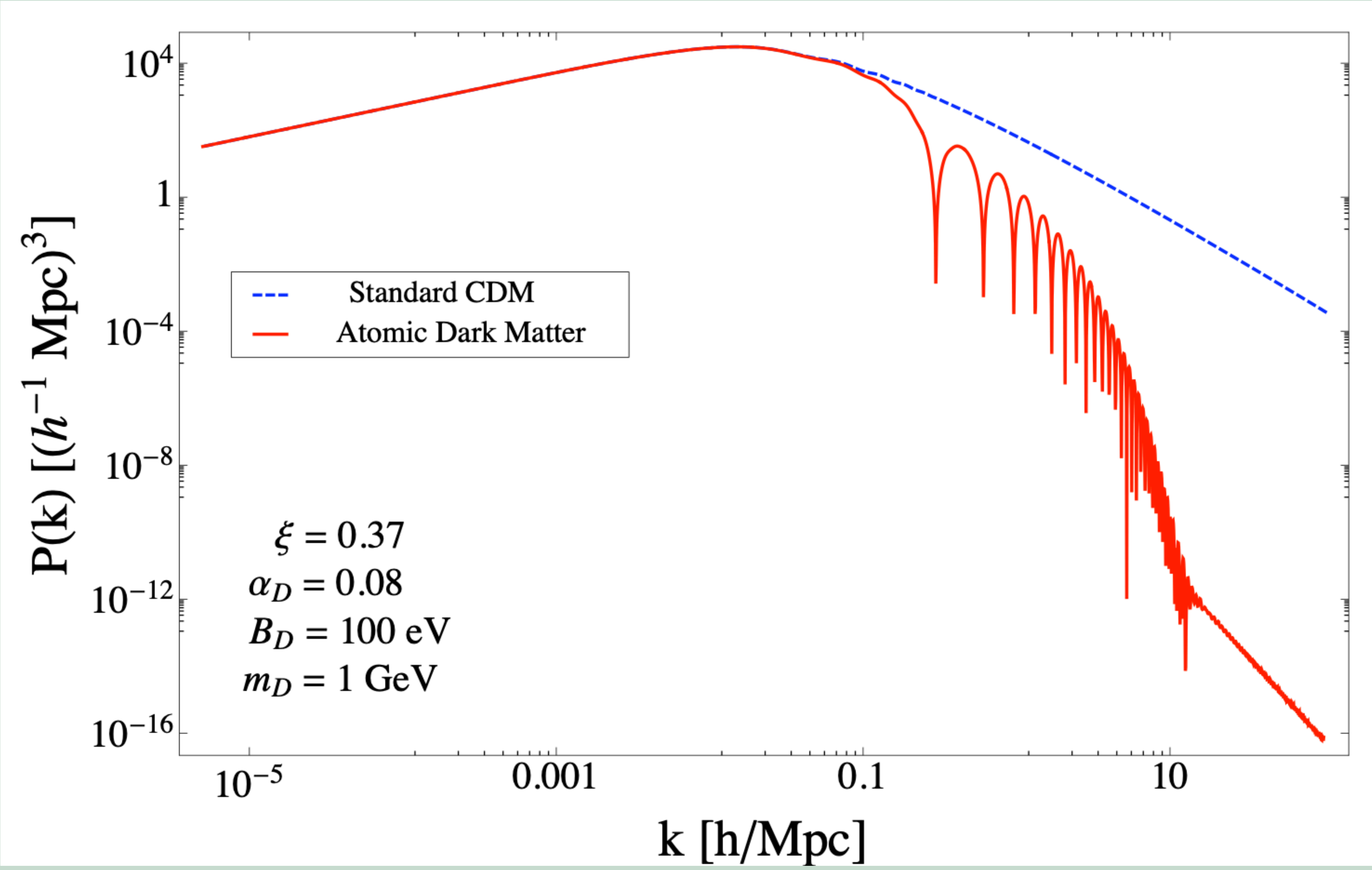
- Theoretical motivation
  - neutral naturalness (Twin Higgs) (2311.06341), similar to SM QED

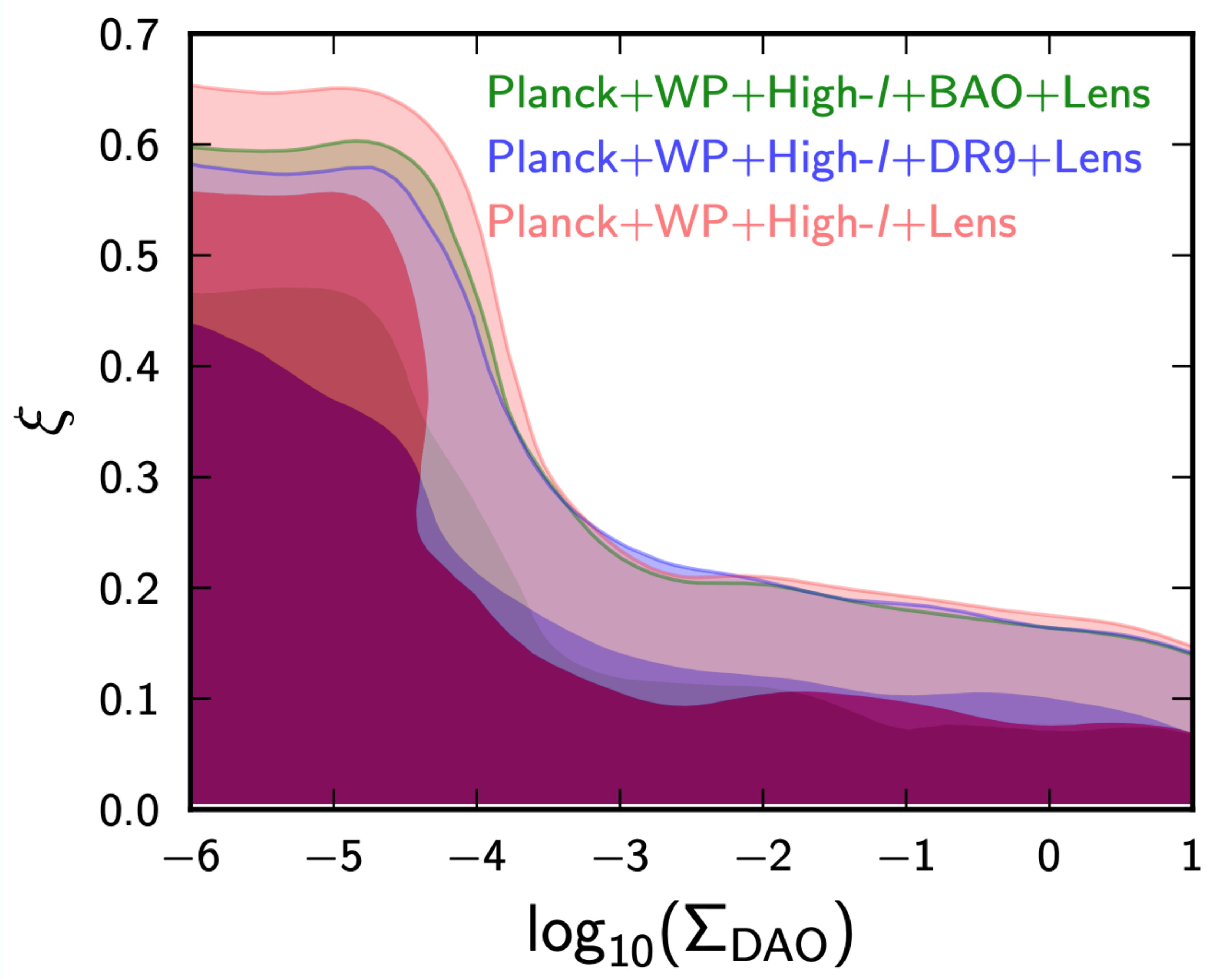
- Observational motivation
  - at cosmological scales: H0 and S8 tensions
  - at galactic scales : under-abundance of low-mass galaxies, core-cusp problem, rotation curves in dwarf galaxies (1504.01437)

aDM - what do we know?

Cosmological bounds on aDM

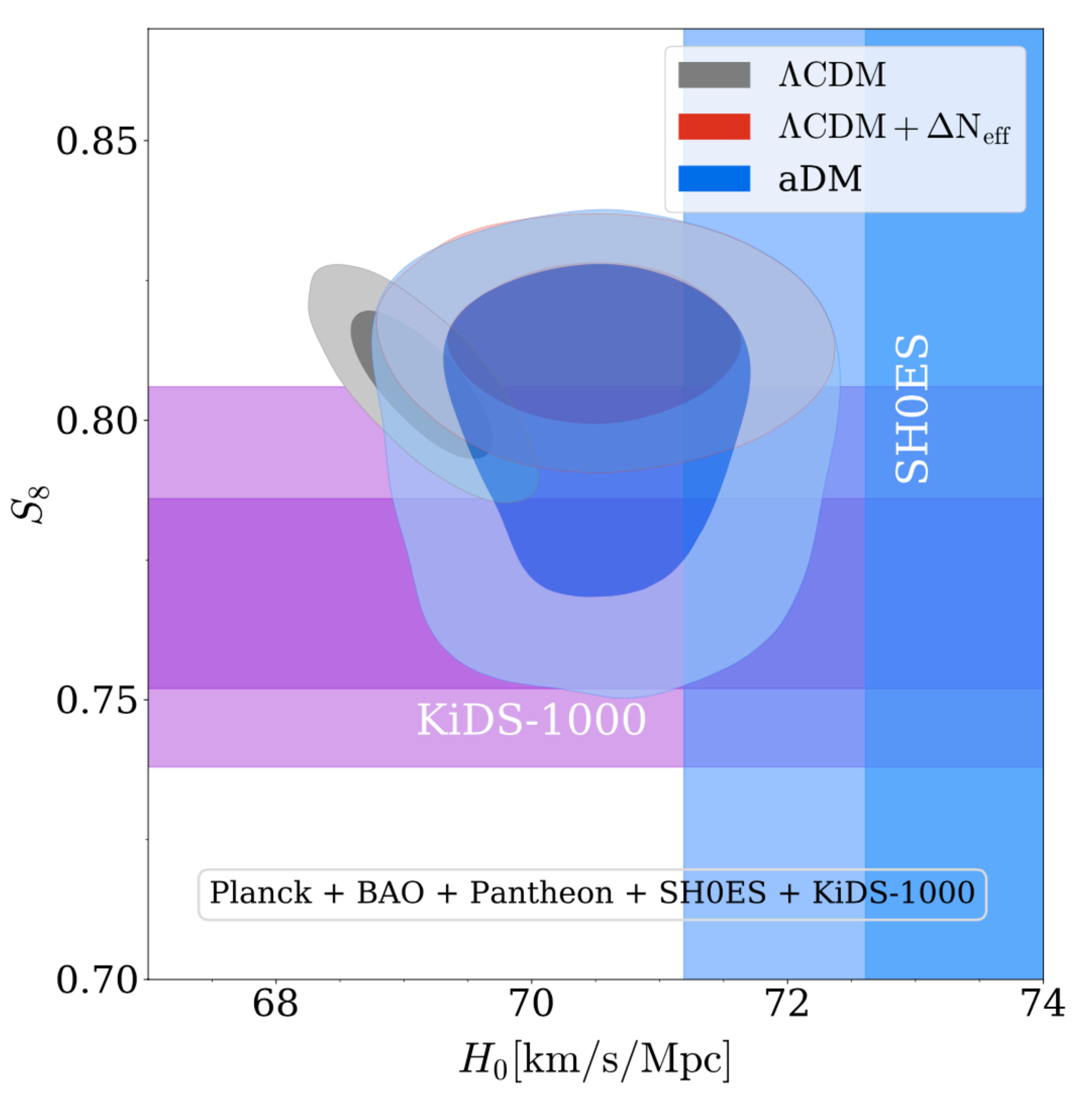
- Dark radiation → ΔN_{eff}
- Dark acoustic oscillations (DAO) → suppression of large scale structure
- Constrained by large scale structure and CMB (1310.3278, 1209.5752)

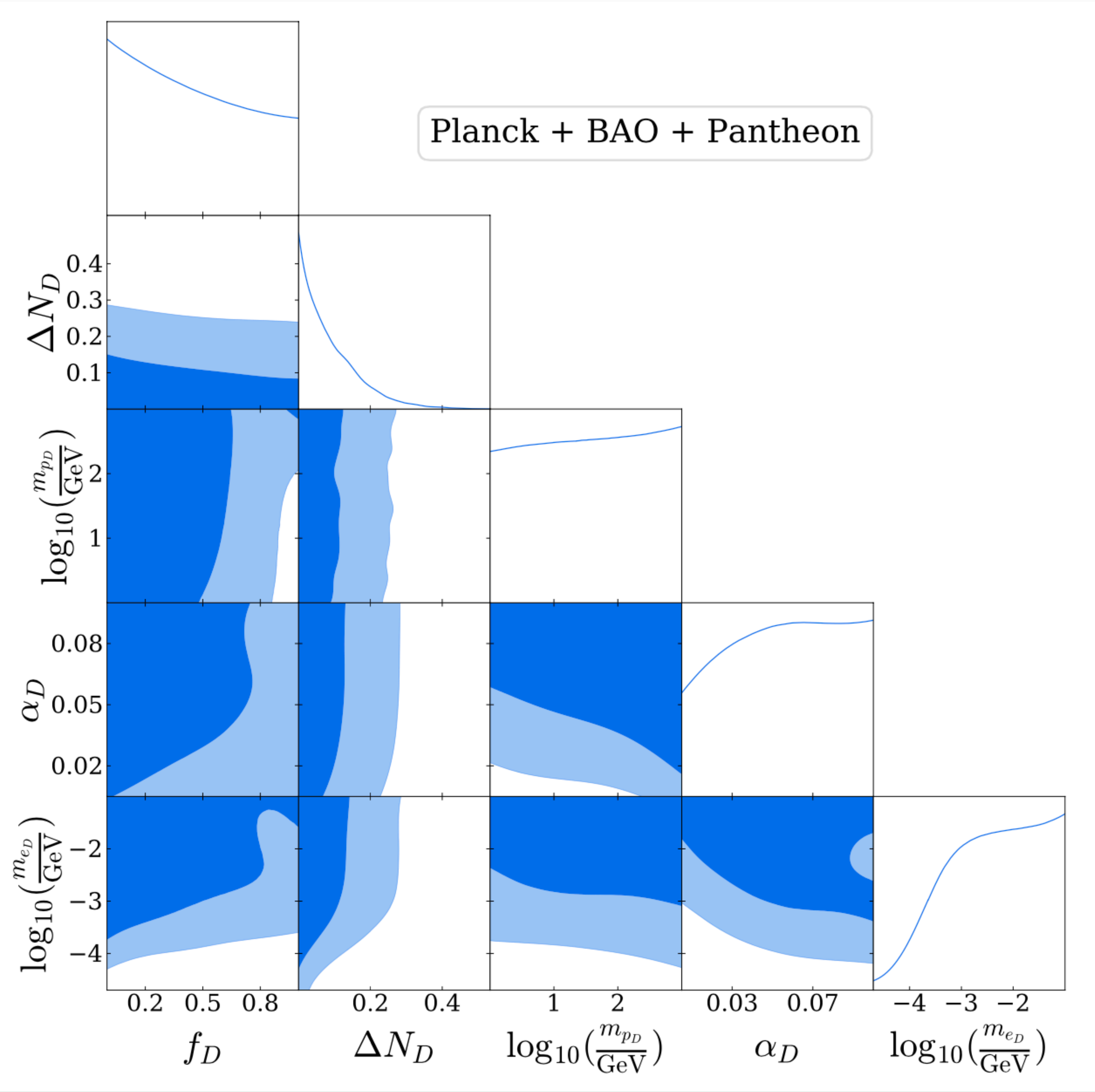




Cosmological bounds on aDM

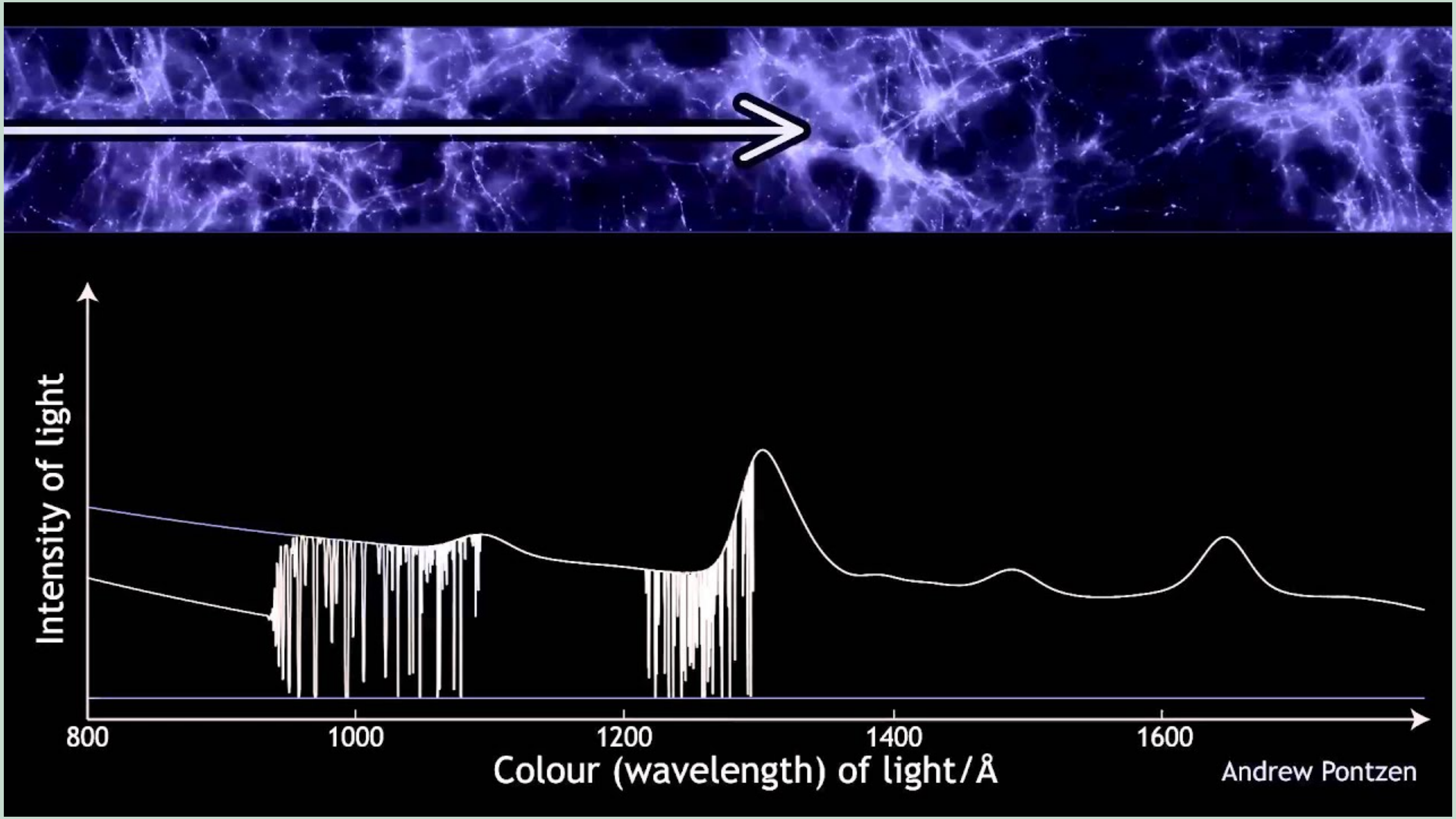
- First comprehensive aDM constraints from CMB (2212.02487)
- CLASS-adm: the Cosmic Linear Anisotropy Solving System modified for aDM





What is Lyman-alpha - how does aDM affect it?

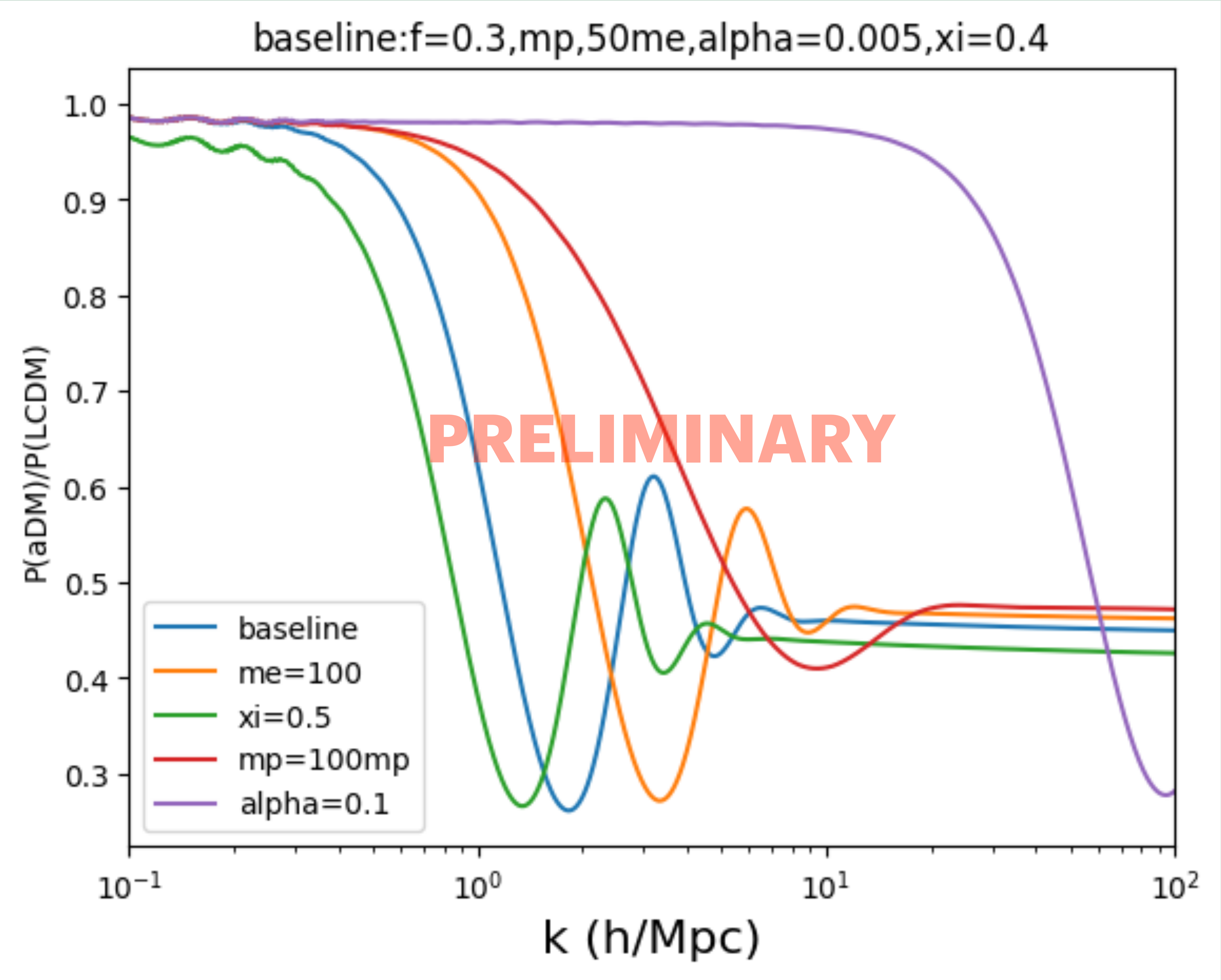
The physics of Lyman-alpha



https://www.youtube.com/watch?v=6Bn7Ka0Tjjw

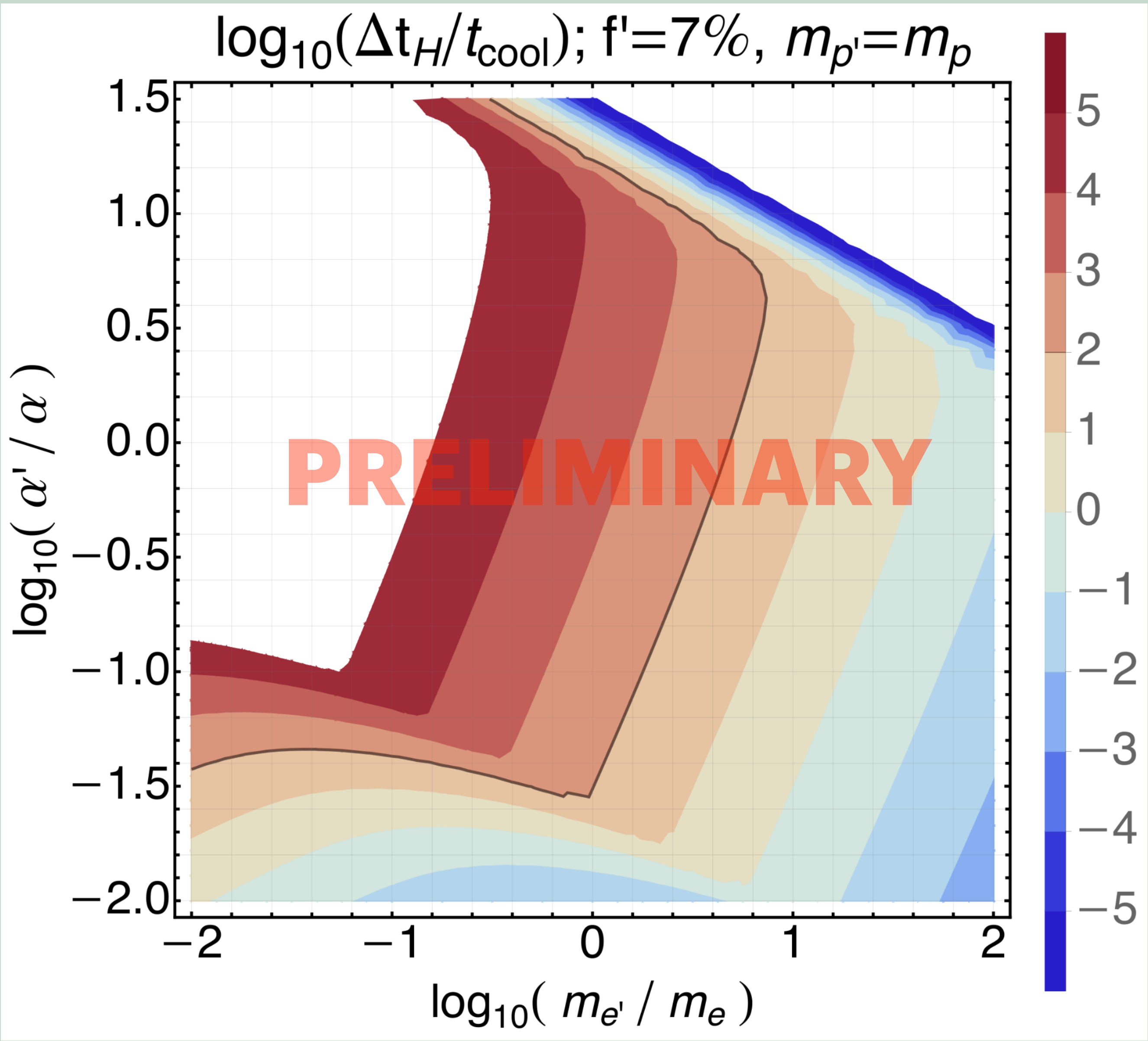
Effects of aDM on Lyman-alpha

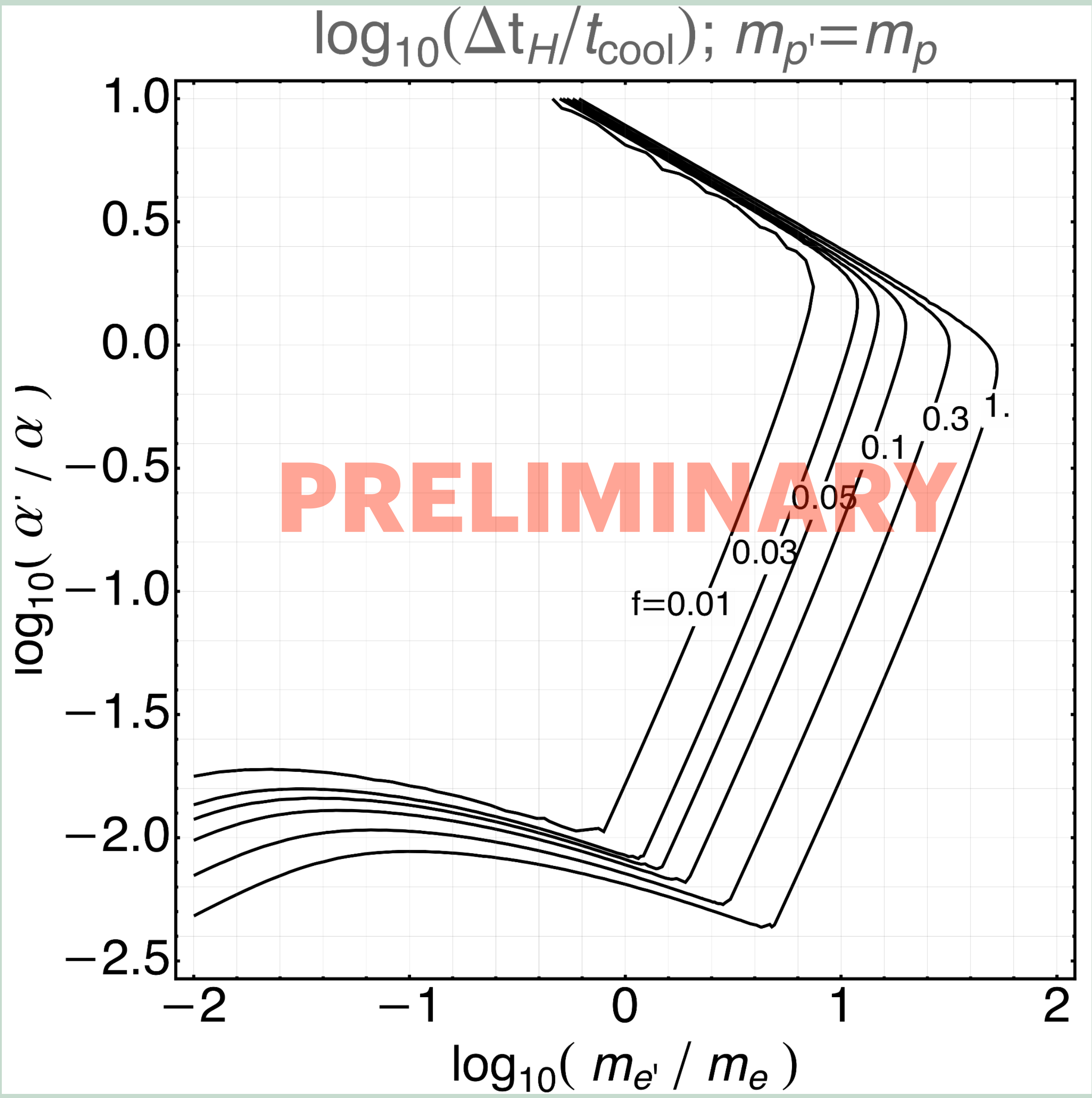
- Structure formation that can be probed by Lyman-alpha
- $T(k) \equiv P(aDM)/P(\Lambda CDM)$



Effects of aDM on Lyman-alpha

- aDM forms clumps and affects star formation -> reionization physics needs to be parametrized
- Take into account of cooling of spherical cow halos over cosmic history -> stronger constraints than only considering cooling rate today
- We want to avoid these regions where aDM cooling is important in order to get new Lyman-alpha constraints as a first pass

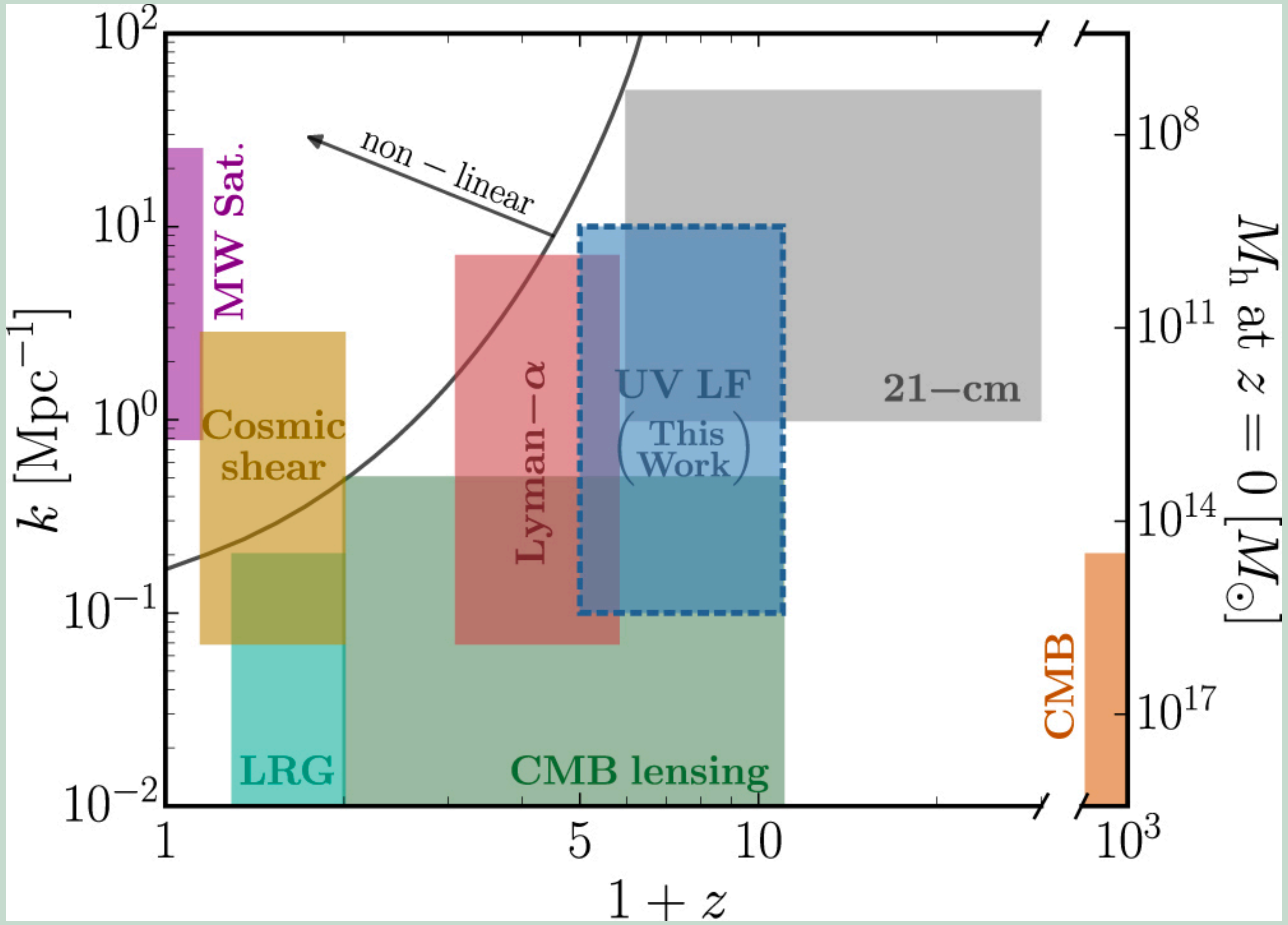




N-body simulations for Lyman-alpha – why we do it

N-body simulation for Lyman-alpha

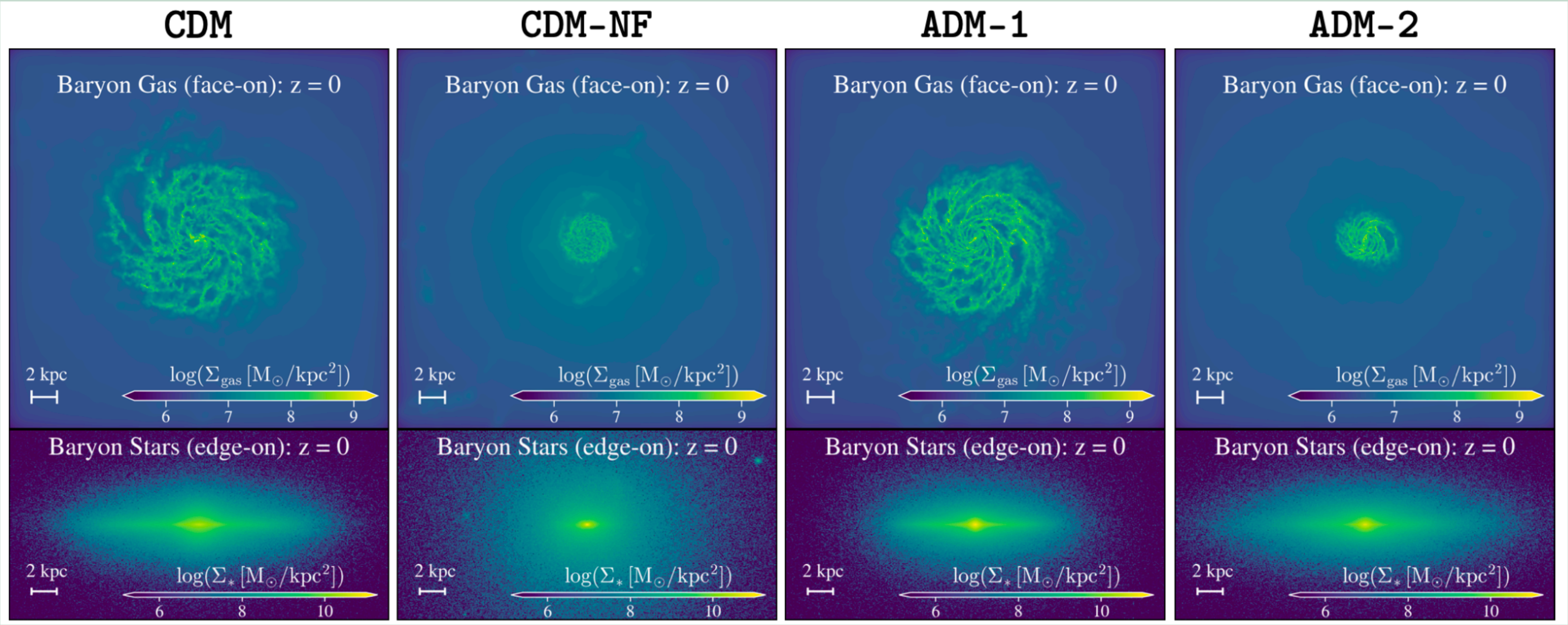
- Existing studies:
  - Cosmo constraints at z~1000, k<~0.1
  - Milky Way simulation at z~1, k~1-10 (2304.09878)

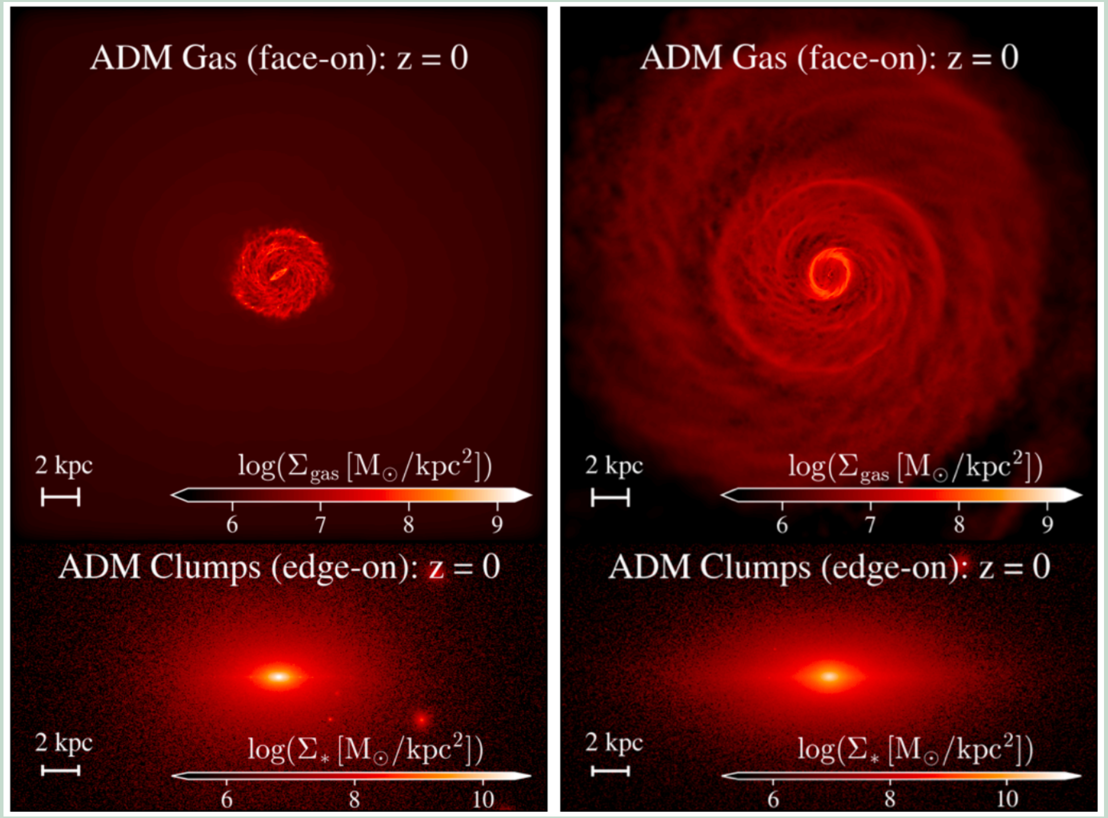


AAS NOVA

N-body simulation for Lyman-alpha

- Existing studies:
  - Cosmo constraints at z~1000, k<~0.1
  - Milky Way zoom in simulation at z~1, k~1-10 (2304.09878)
    - World's first N-body simulation with aDM!
    - MUSIC-adm and GIZMO-adm

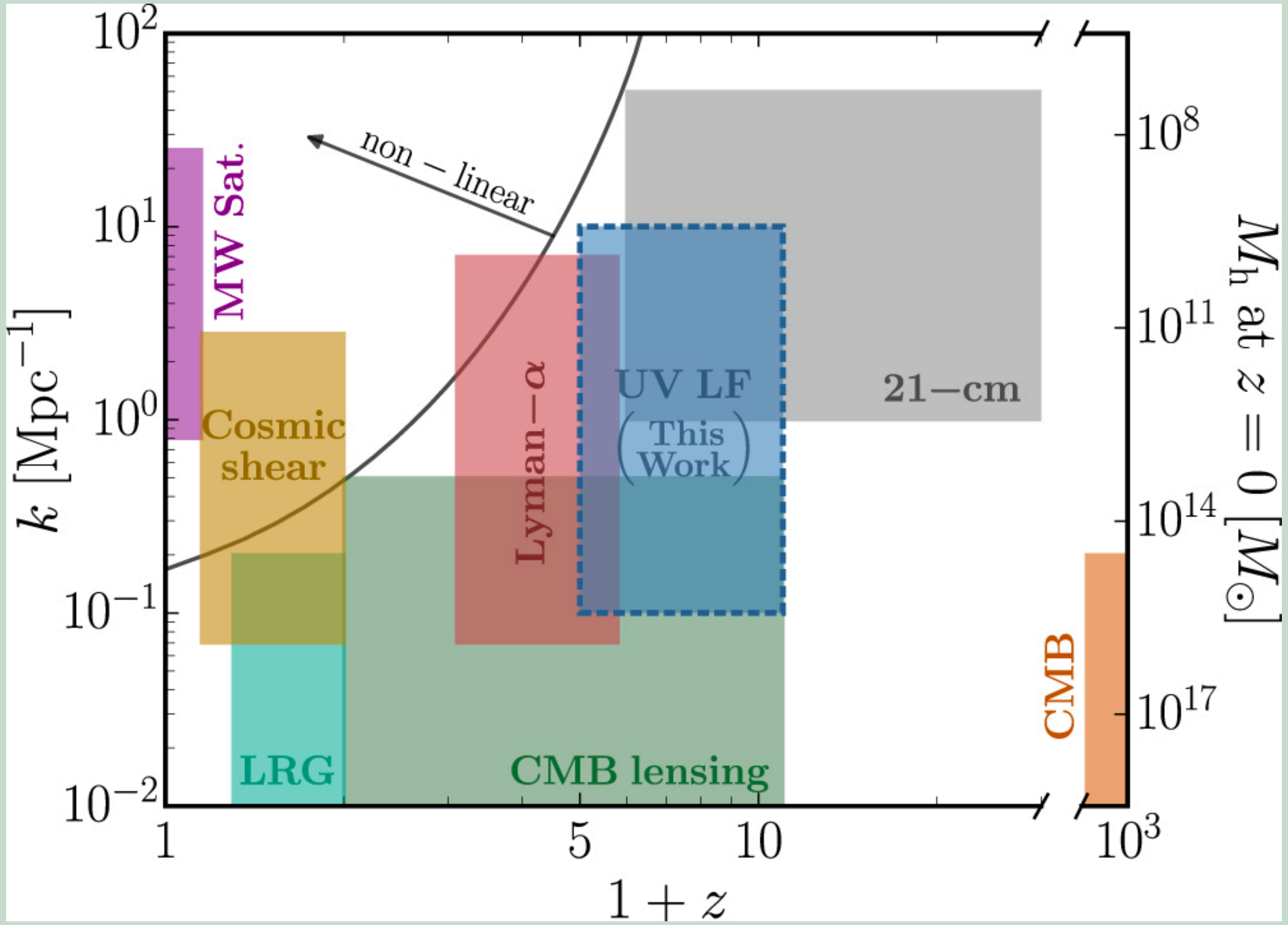




N-body simulation for Lyman-alpha

- Existing studies:
  - Cosmo constraints at z~1000, k<~0.1
  - Milky Way simulation at z~1, k~1-10 (2304.09878)

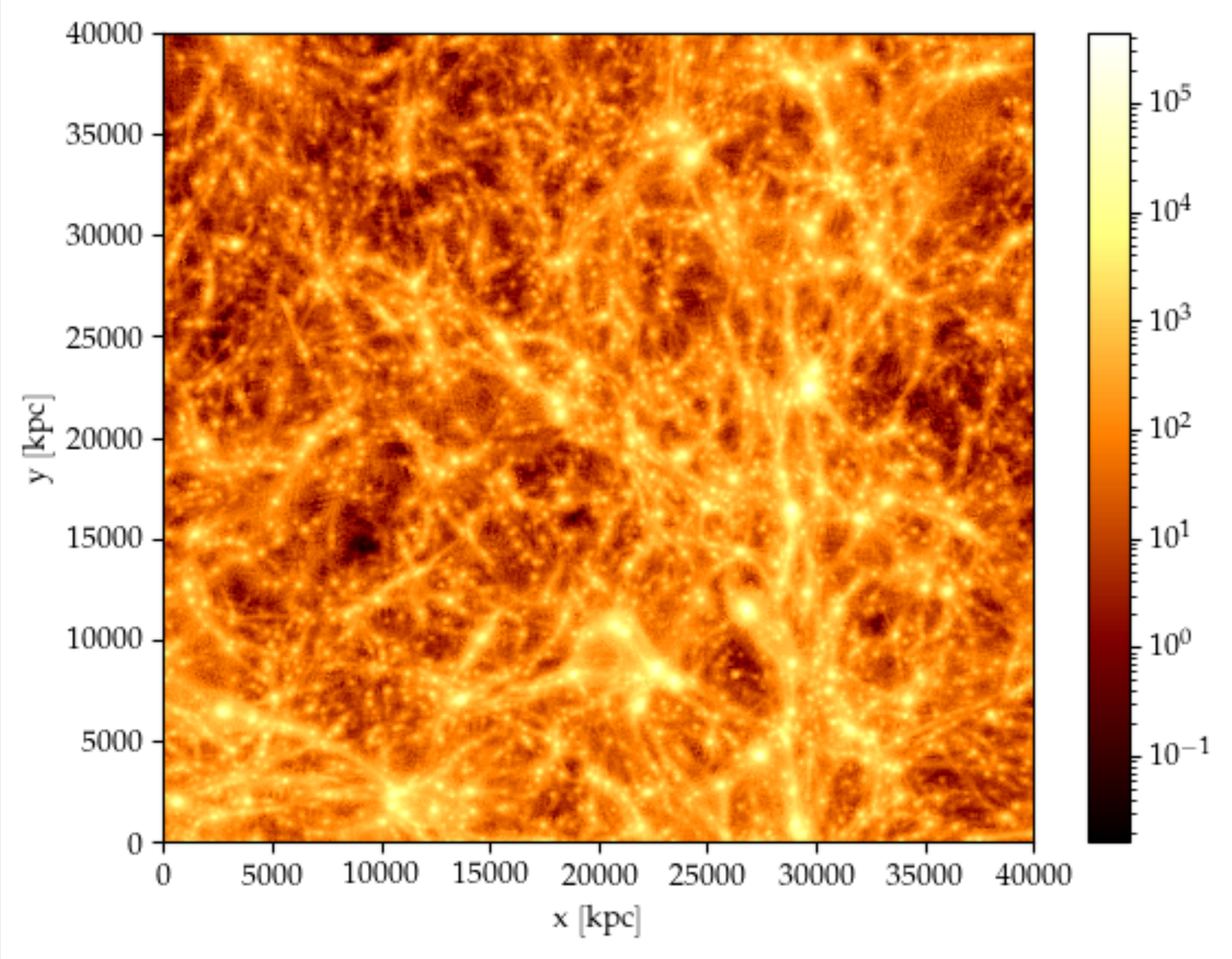
- New study:
  - aDM N-body sim for Lyman-alpha



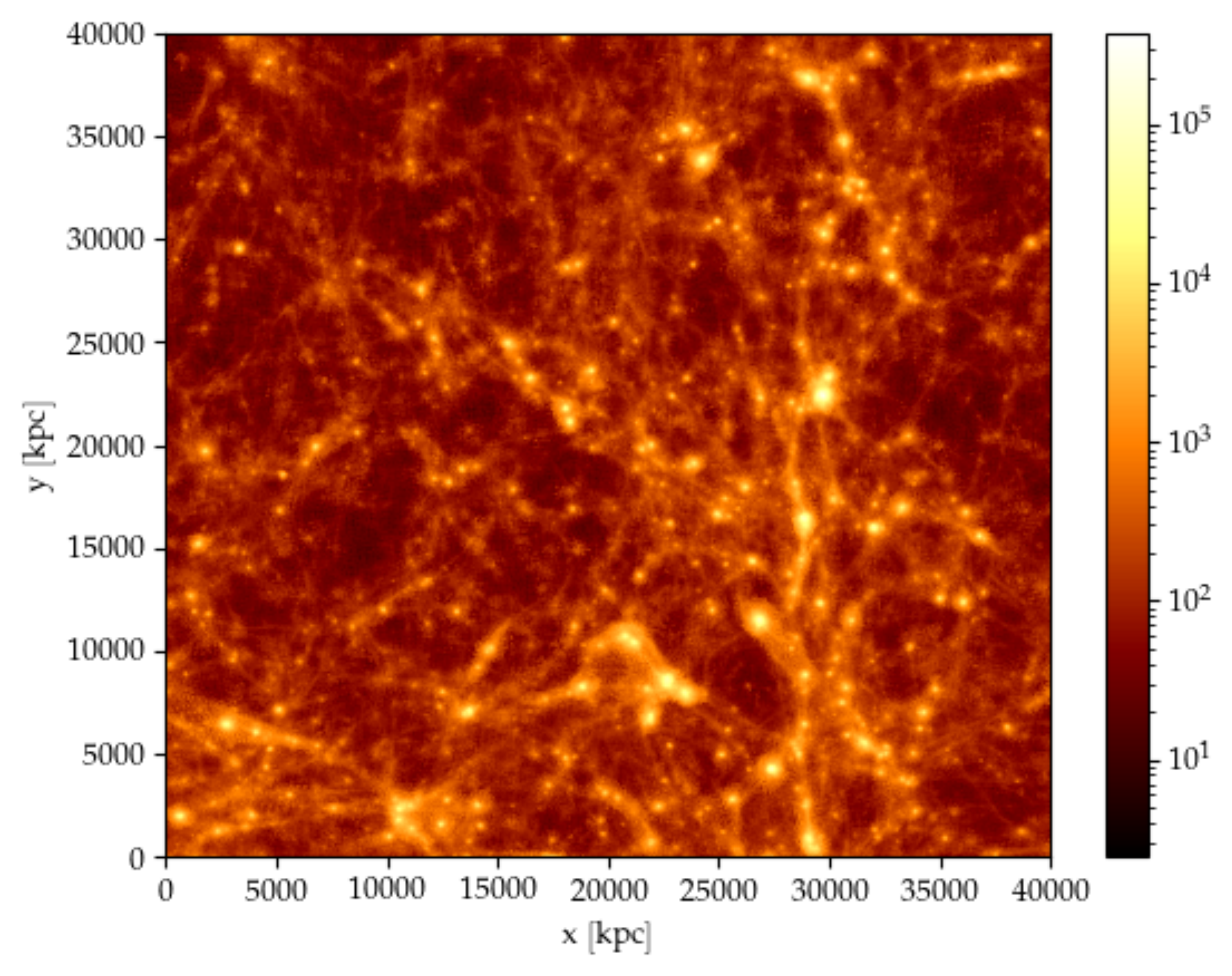
AAS NOVA

N-body simulation for Lyman-alpha

- World's first full cosmo N-body sim with aDM!
- Low resolution test run: 2D-histogram of temperature of aDM/baryon gas at z=3



aDM



Baryon

N-body simulation for Lyman-alpha - how we do it

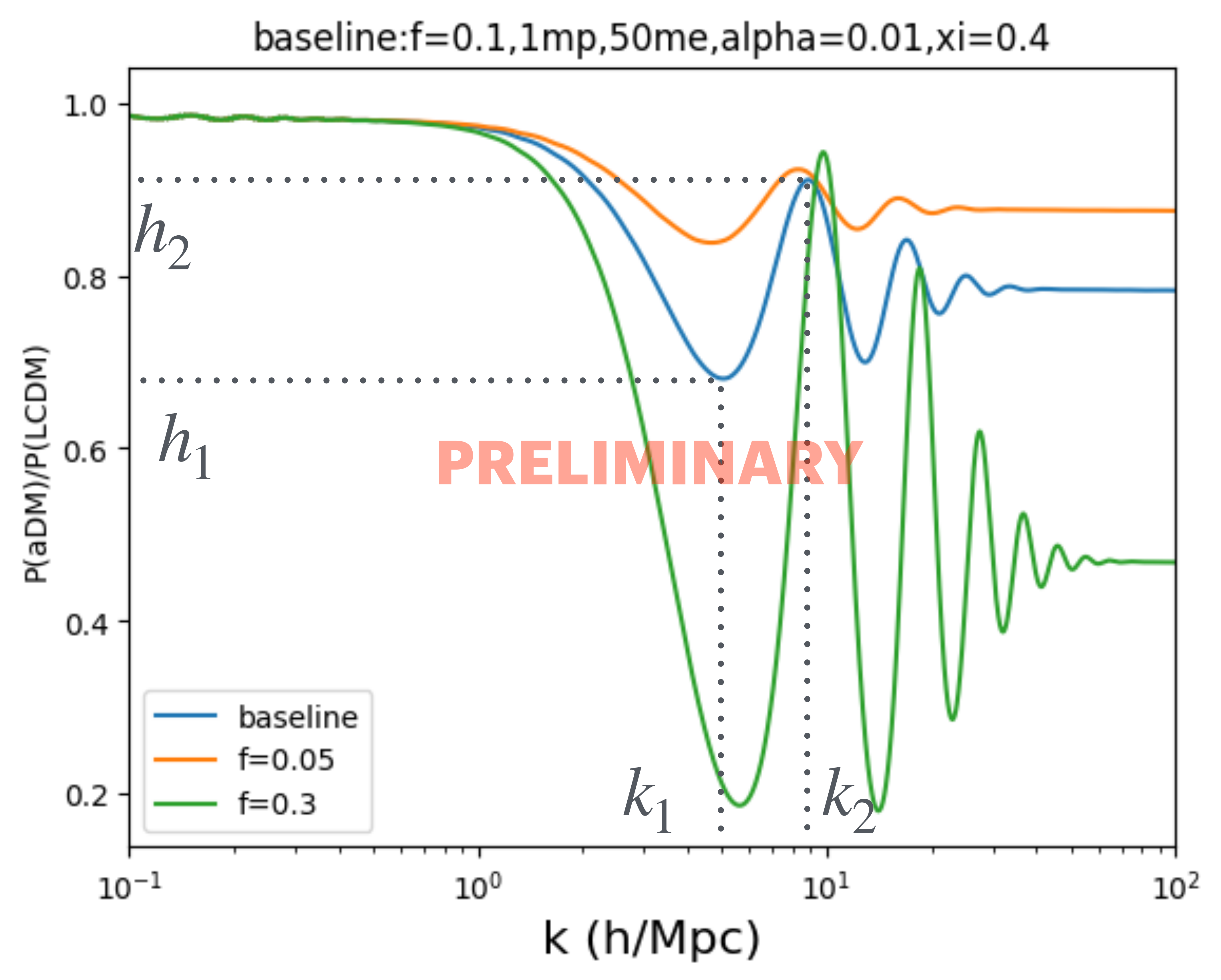
N-body simulation for Lyman-alpha - how we do it

- Toolbox: CLASS-adm, MUSIC-adm, GIZMO-adm, fakespectra
- N-body simulations are very expensive!!!
- Machine learning sampler:
  - feed a small set of “training simulations” to the Bayesian emulator → emulator is optimized and selects a new point in the parameter space → emulator is re-optimized with new training set and selects another point → repeat until convergence (2007.13751)
- Acquisition function = exploitation term + exploration term
- Desired outcome: New aDM constraints from Lyman-alpha

Current Status

Degeneracy in the parameter space

- Can we already find degeneracies in the very first step? (CLASS output at z=99)
- 5D parameter space, but transfer functions can be characterized by k_1, h_1 and h_2



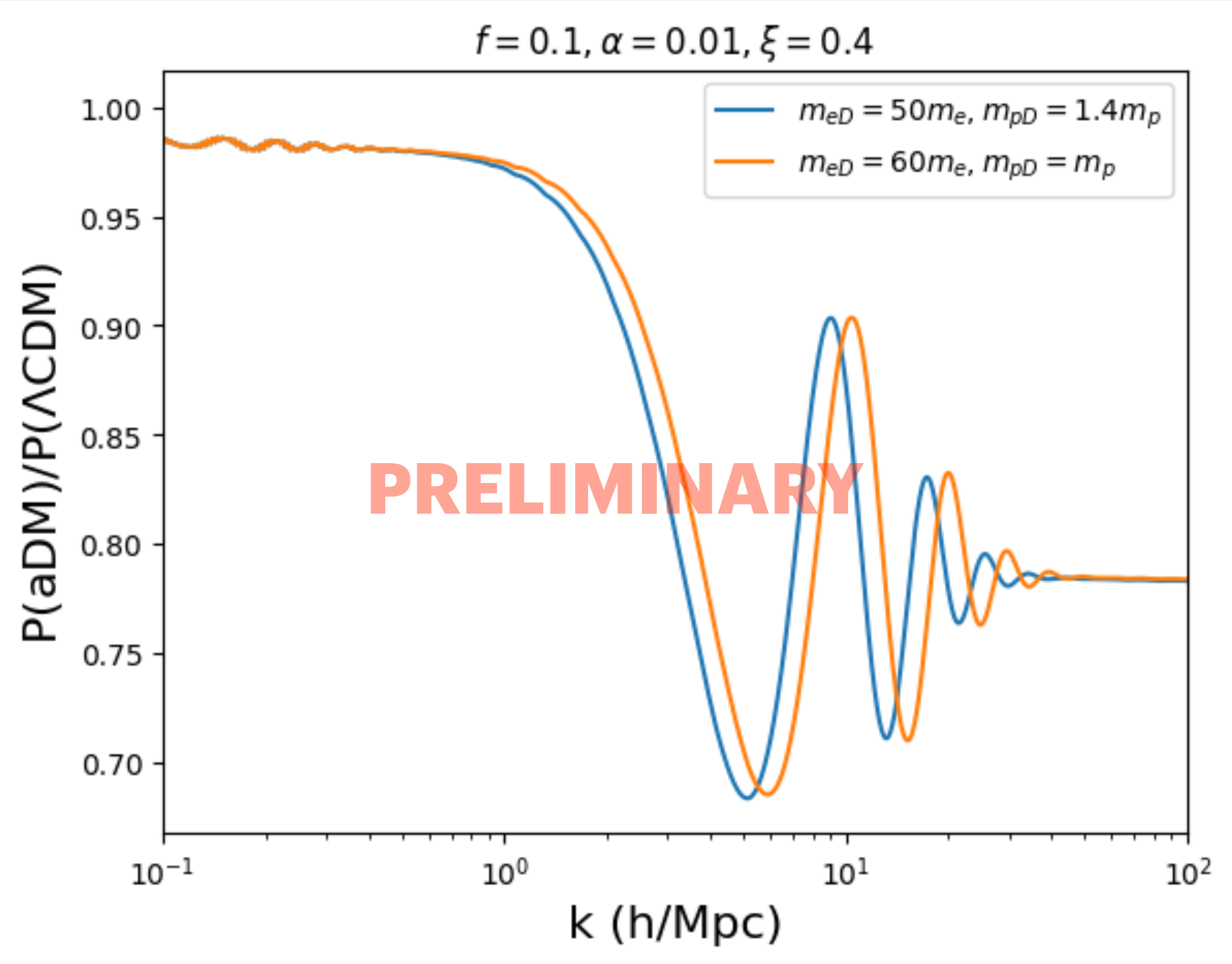
k_2/k_1 constant

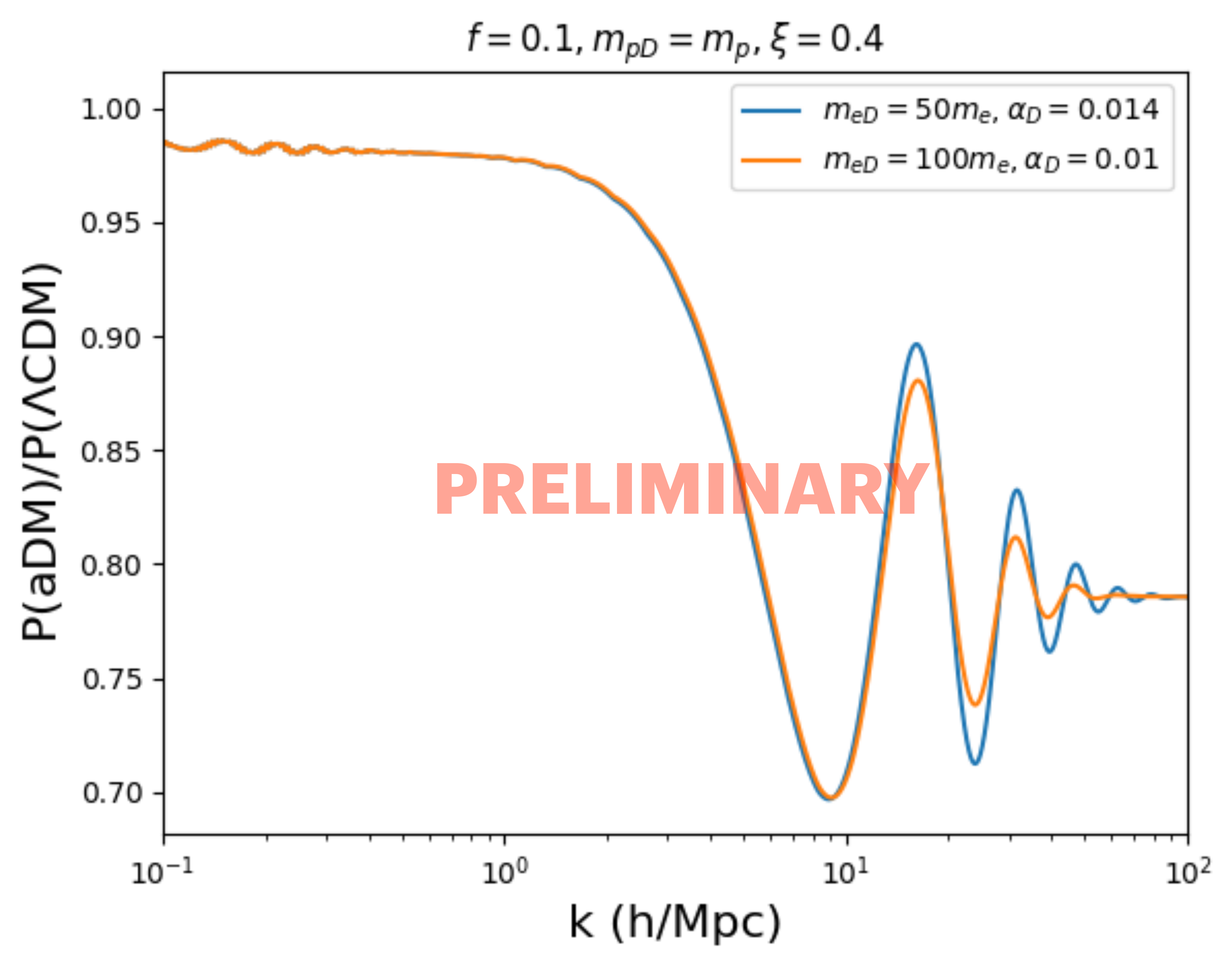
Sound speed

Decoupling time

Degeneracy in the parameter space

- coarse CLASS scans at z=99 -> found degeneracies in parameter space $(m_{eD}, m_{pD}, \alpha_D)$





Degeneracy in the parameter space

- Want to map aDM parameters to k_1, h_1 and h_2
- Opacity:
  - Compton scattering (dominates in most cases)
  - Rayleigh scattering (can dominate after recombination for large alpha or small mpD)
  - Photonionization
- Dark recombination: $T_D/B_D \sim \xi/(\alpha_D^2 m_{eD})$
- Kinetic decoupling time?

Reduces 5D problem to 3D
Makes N-body simulation possible!
Simulations are now in progress

Conclusion

- aDM motivated by naturalness, cosmology and astrophysics
- Tools for aDM N-body simulations have been developed
- Lyman-alpha can place new constraints on aDM
- Simulations are expensive! Three solutions:
    1. Avoid regions where aDM cools and affects star formation
    2. Sample the parameter space with optimized Bayesian emulator
    3. Reduce dimension of parameter space from 5D to 3D

aDM cooling

- Different parameters lead to different dark recombination, Bremsstrahlung and collisional processes
- Dark molecular cooling not considered because it involves dense regions below our resolution
- No dark neutrons so no dark helium