Constraining Atomic Dark Matter with the high-redshift UV Luminosity Function

Jared Barron

Based on work w/ David Curtin, Mariangela Lisanti, Hongwan Liu, Julian Muñoz, Sandip Roy

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Motivations

Observational

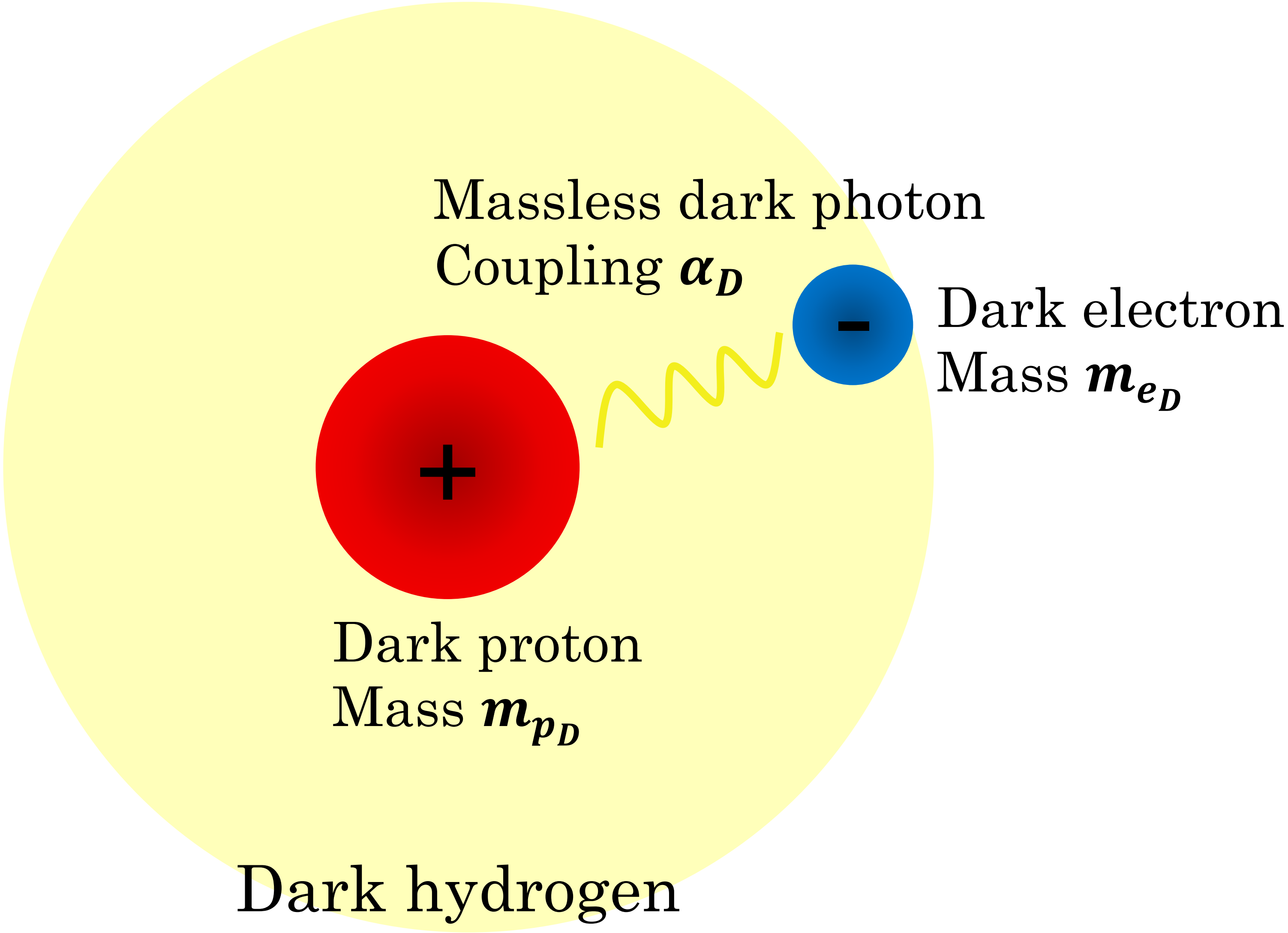
- "Small-scale crises" like diversity problem.
- H_0 and S_8 tensions.
- Dark sector interactions with dark radiation could address these?

Theoretical

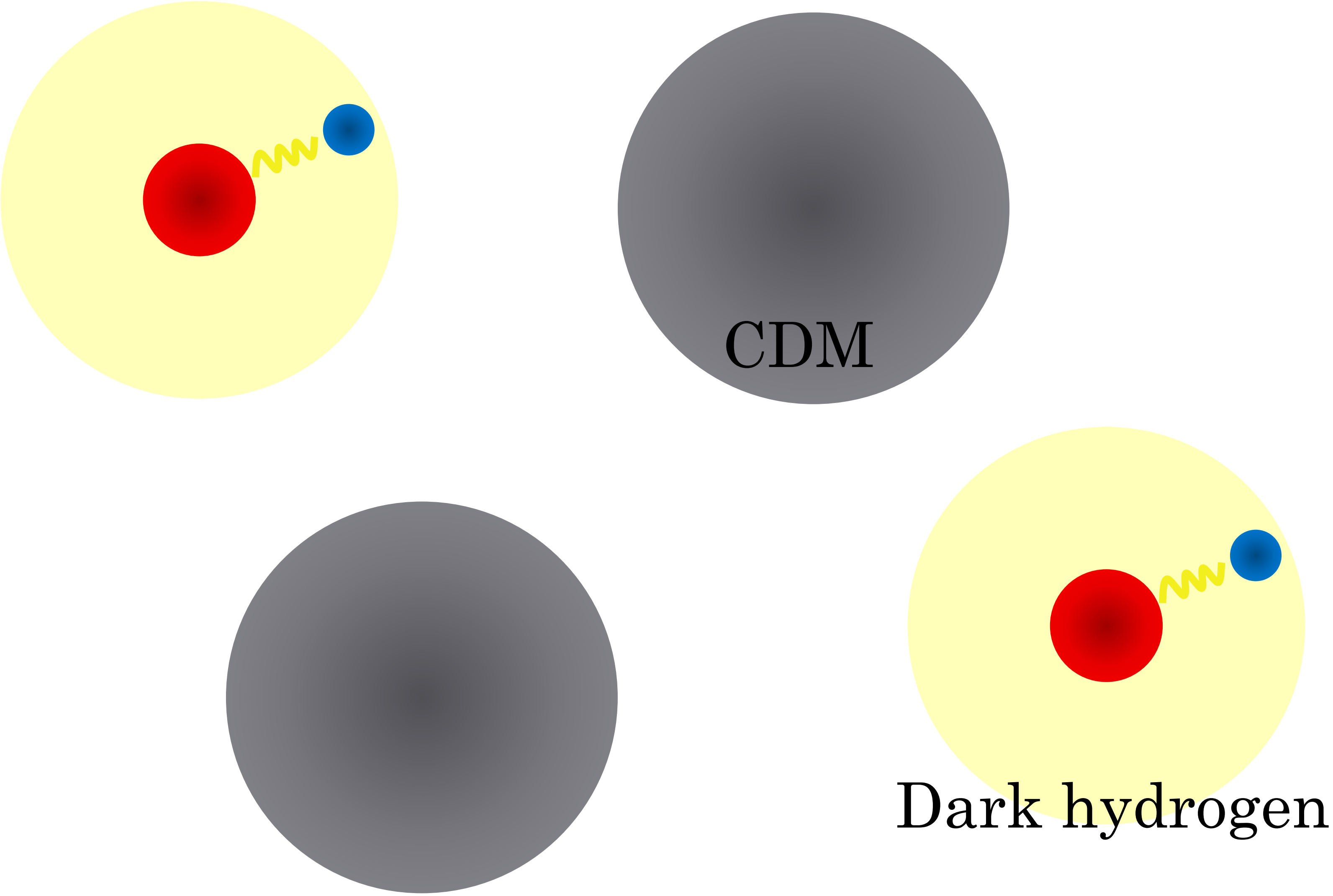
- Hierarchy problem: why is the Higgs boson so light?
- "Neutral naturalness" solutions introduce hidden sector particles.
- Typical example: Twin Higgs.
- Relic abundance of twin protons, electrons, and photons could form a component of dark matter.

(Alonso-Alvarez, Curtin, Rasovic, Yuan 2023)

Atomic Dark Matter



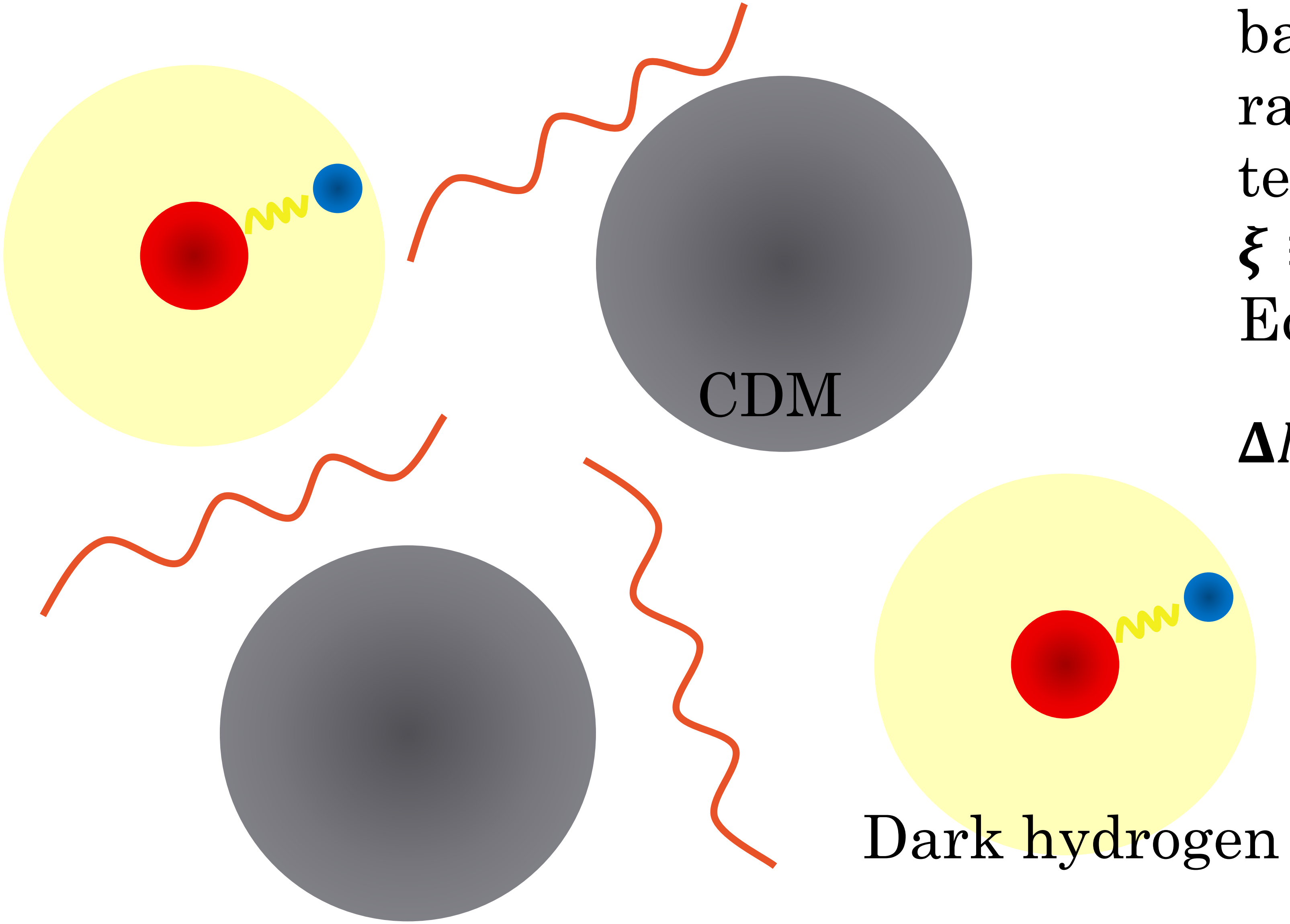
Atomic Dark Matter



Fraction of total dark matter density

$$\mathbf{f_D} \equiv \frac{\Omega_{aDM}}{\Omega_{DM}} \leq 1$$

Atomic Dark Matter



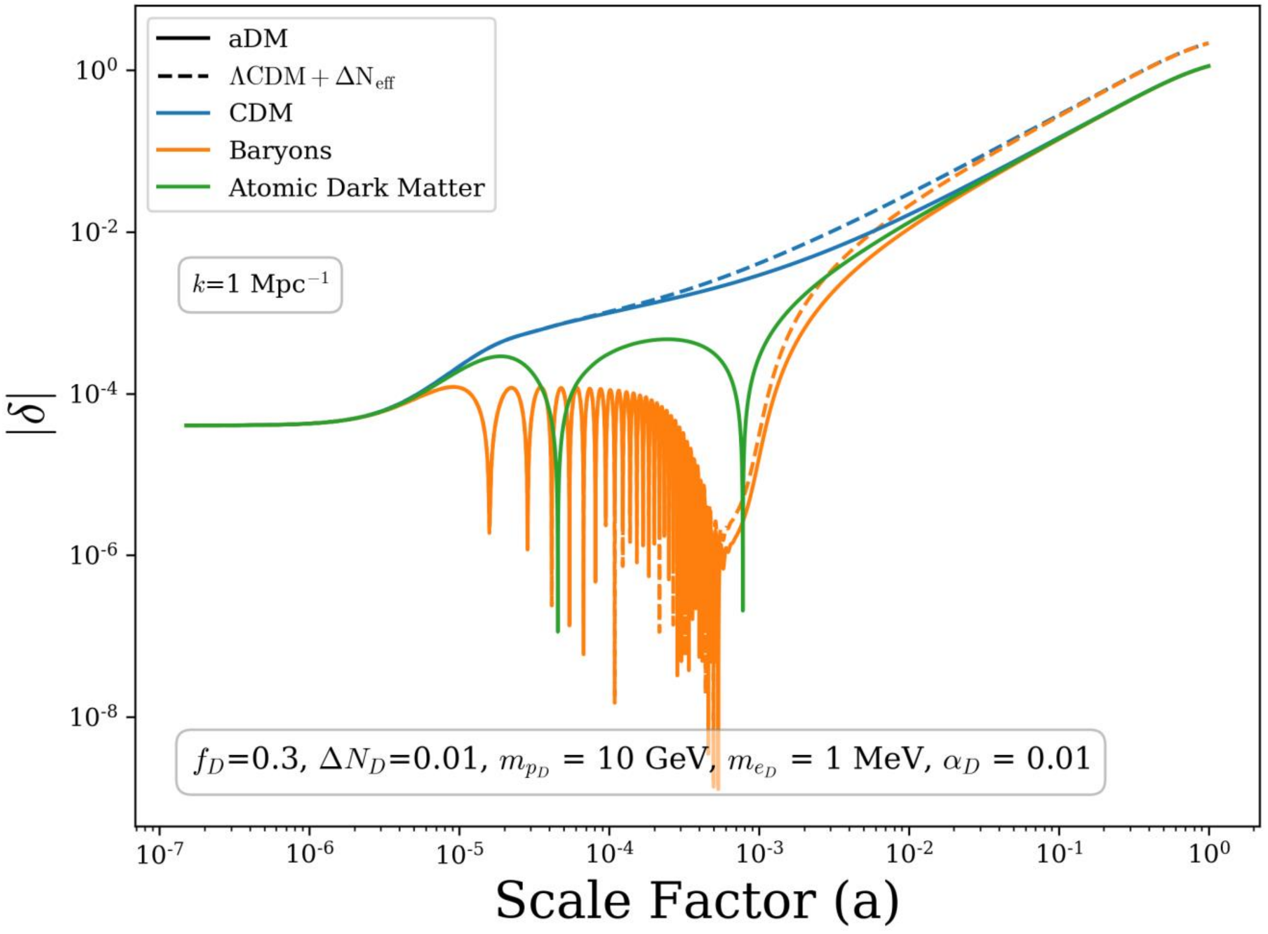
Dark photon background radiation with temperature ratio $\boldsymbol{\xi} \equiv T_D/T_{SM}$. Equivalently,

$$\boldsymbol{\Delta N_D} \equiv \left(\frac{8}{7}\right)\left(\frac{11}{4}\right)^{\frac{4}{3}} \xi^4$$

Cosmology of Atomic Dark Matter

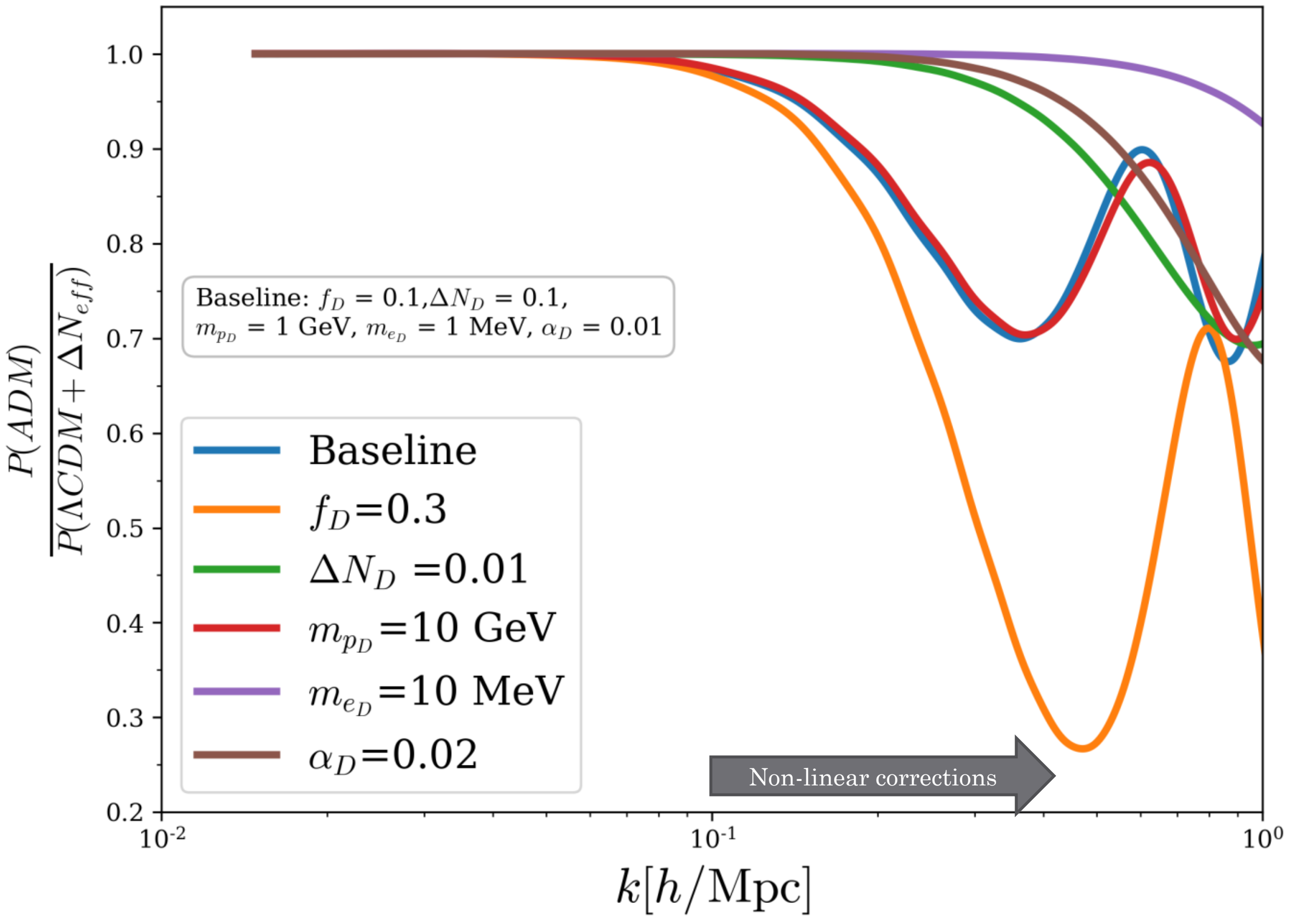
- Early universe: plasma of dark photons, protons, electrons.
- Dark acoustic oscillations (DAOs) due to dark photon pressure support.
- DAOs end when dark hydrogen recombines and decouples from dark CMB.
- Dark sound horizon

$$r_{\rm DAO} \sim \frac{2\pi}{k_{\rm DAO}}$$



Matter Power Spectrum

Suppression and oscillations for k that enter horizon before dark decoupling, $k > k_{\mathrm{DAO}}$.



Matter power spectrum relative to ΛCDM + ΔN_{eff}

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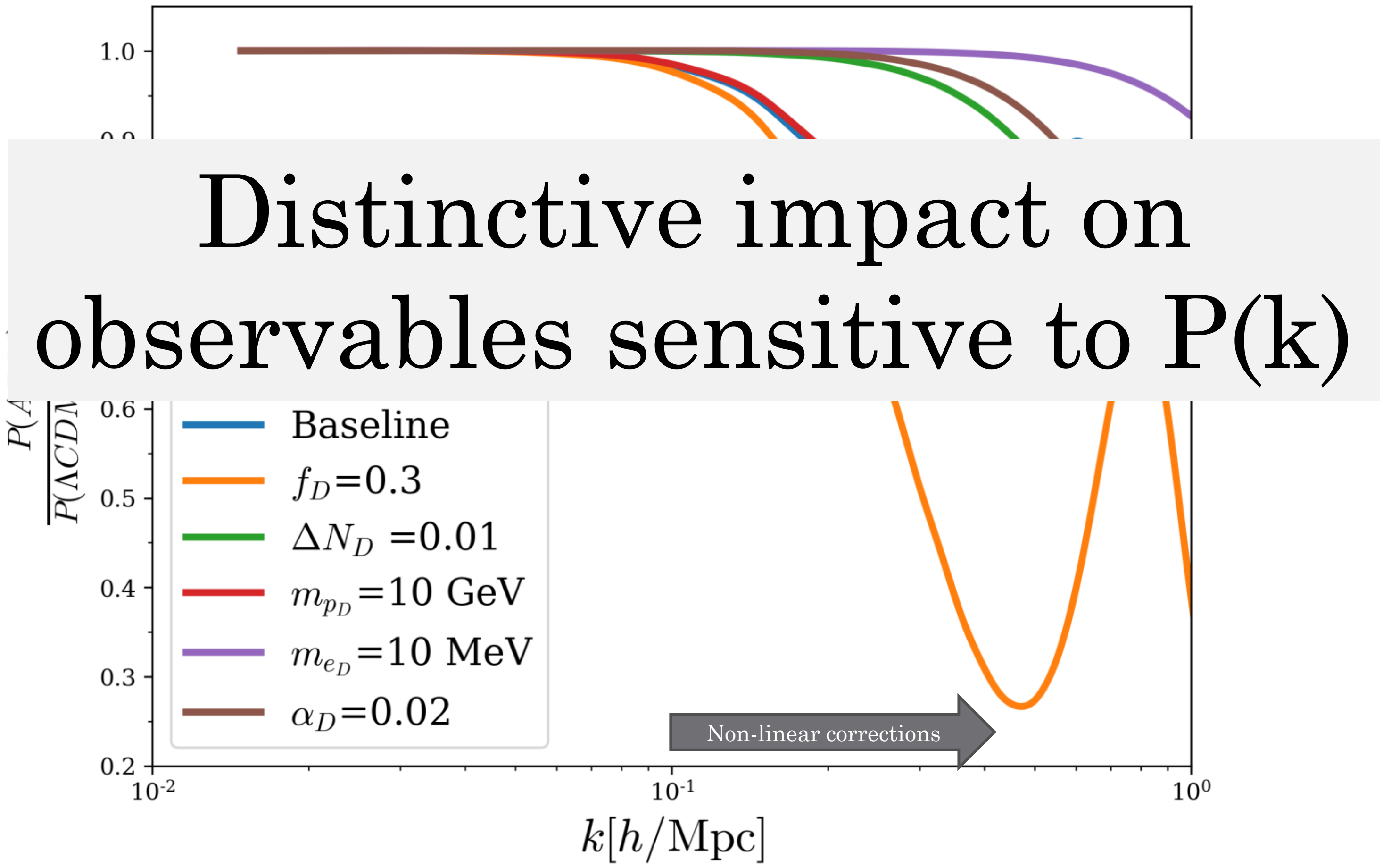

Distinctive impact on observables sensitive to P(k)

Matter power spectrum relative to ΛCDM + ΔN_{eff}

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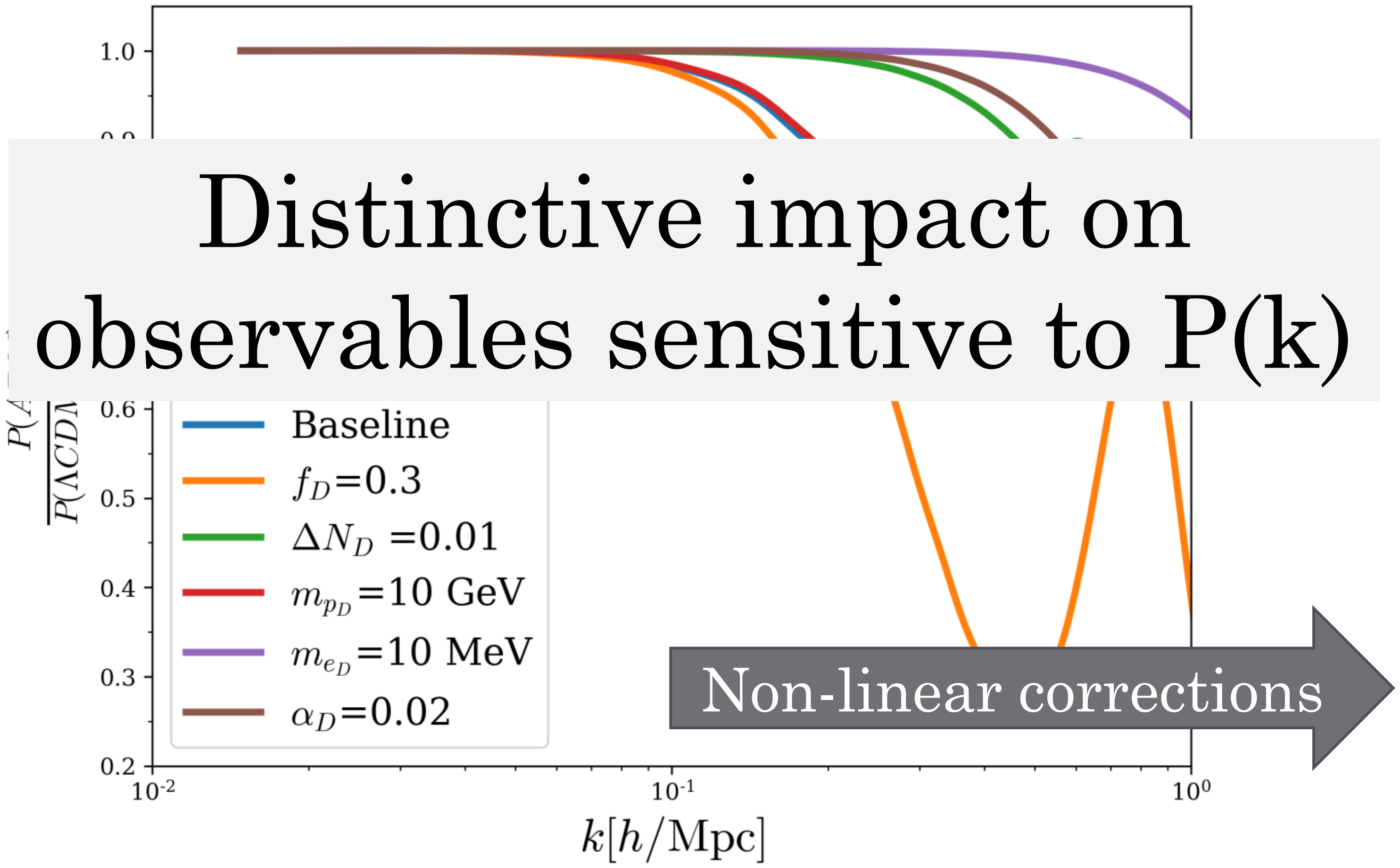

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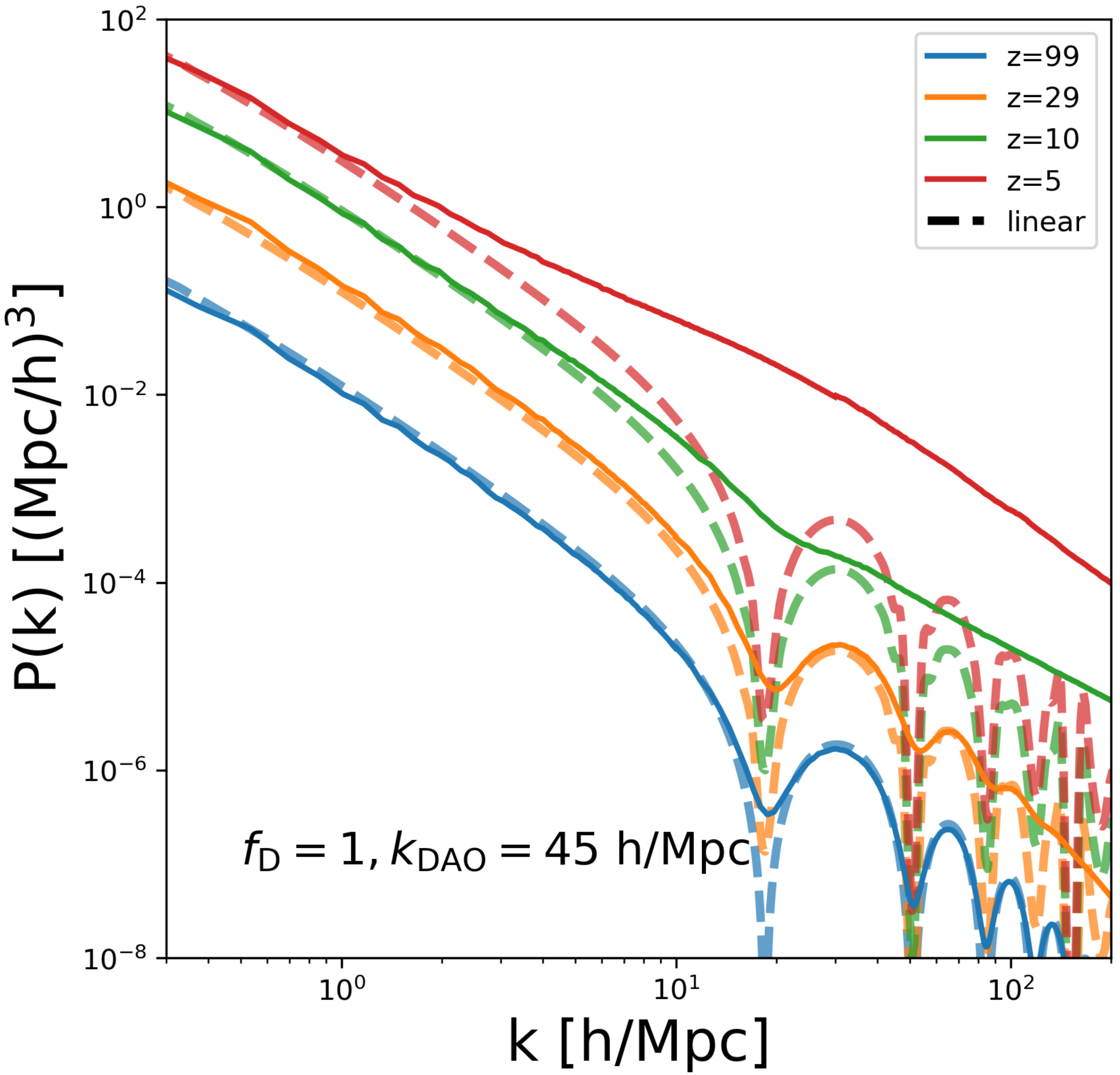
Non-linear evolution



- n-body simulations required to compute non-linear evolution. (Roy et al, 2304.09878)
- DAOs are washed out at low redshifts.
- Power transferred from large to small scales.
- High redshift observables may retain more information about DAOs.

Probing the dark sector with measurements of structure

- CMB (Cyr-Racine and Sigurdson 2013, Bansal, JB, Curtin, Tsai 2023)
- 21-cm cosmology
- High-redshift UV luminosity function
- Lyman-α forest
- Cosmic shear
- And more (especially on galactic scales)

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Decreasing redshift

Require n-body simulations

Probing the dark sector with measurements of structure

- CMB
- 21-cm cosmology

This talk

- High-redshift UV luminosity function
- Lyman-α forest cf. Caleb's talk
- Cosmic shear
- And more (especially on galactic scales)

cf. Sandip's talk

Decreasing redshift

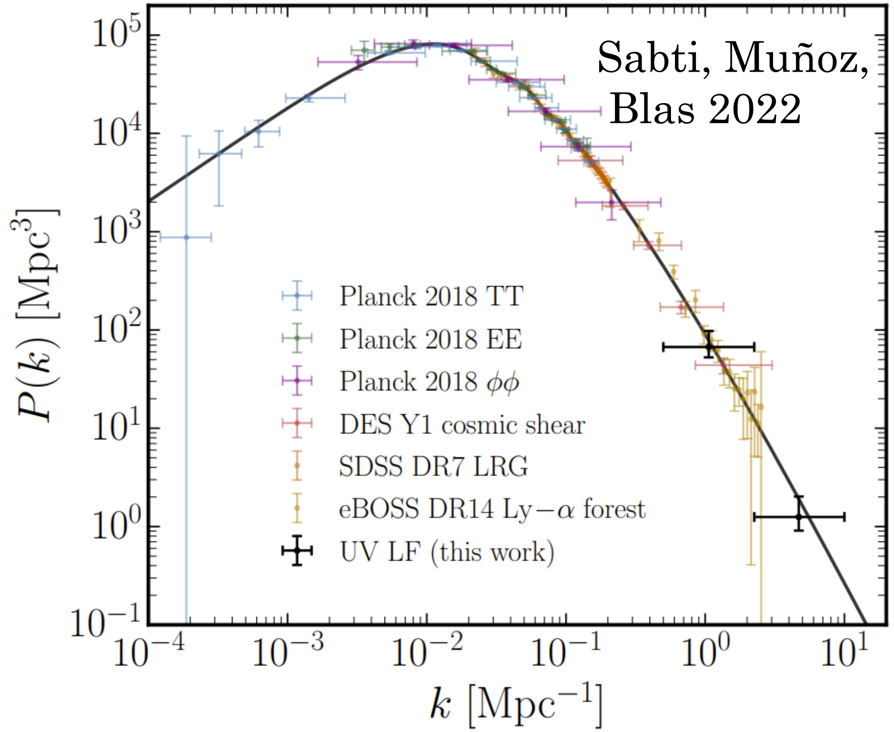
Require n-body simulations

Probing structure with the UVLF

$$\Phi_{UV} = \frac{dn}{dM_h} \times \frac{dM_h}{dM_{UV}}$$

Halo mass function

Halo-galaxy connection

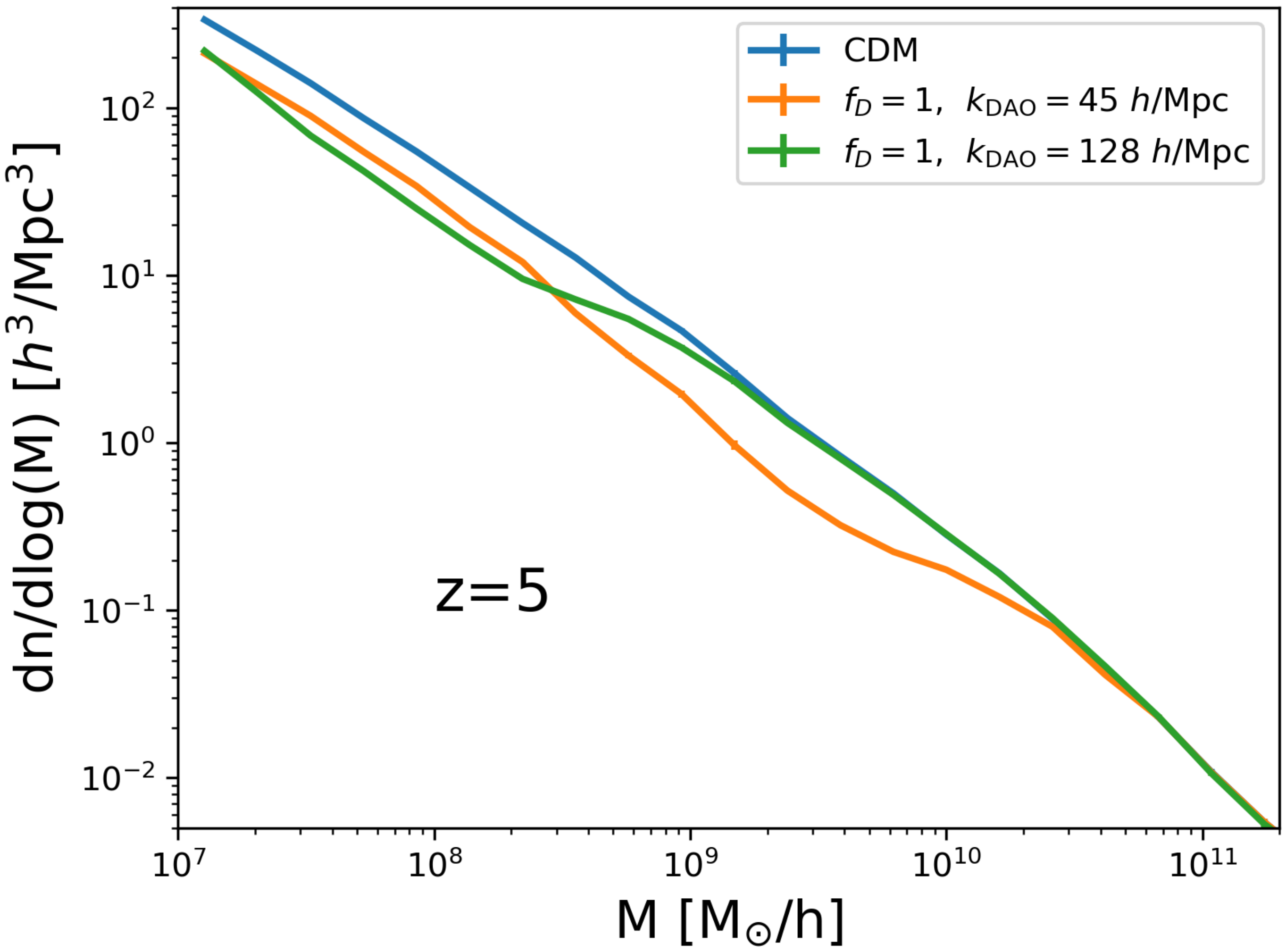


- Halo mass function depends on cosmology – extract from simulation.
- Halo-galaxy connection depends on astrophysics, stellar formation – use Zeus21 code.
- Using HST observations at z=4-10, matter power spectrum has been constrained for $k \sim 1 - 10$ h/Mpc.
- New JWST observations measure the UVLF at $z > 10$.

Halo Mass Function

- HMF from simulation.
- Suppression relative to CDM at low halo mass.
- Suppression goes away as $f_D \to 0$ and pushed to smaller M as k_{DAO} increases.
- HMF from simulation can be used to calibrate Extended Press-Schechter formalism for power spectrum with DAOs.

(Bohr, Zavala, Cyr-Racine, Vogelsberger 2021)

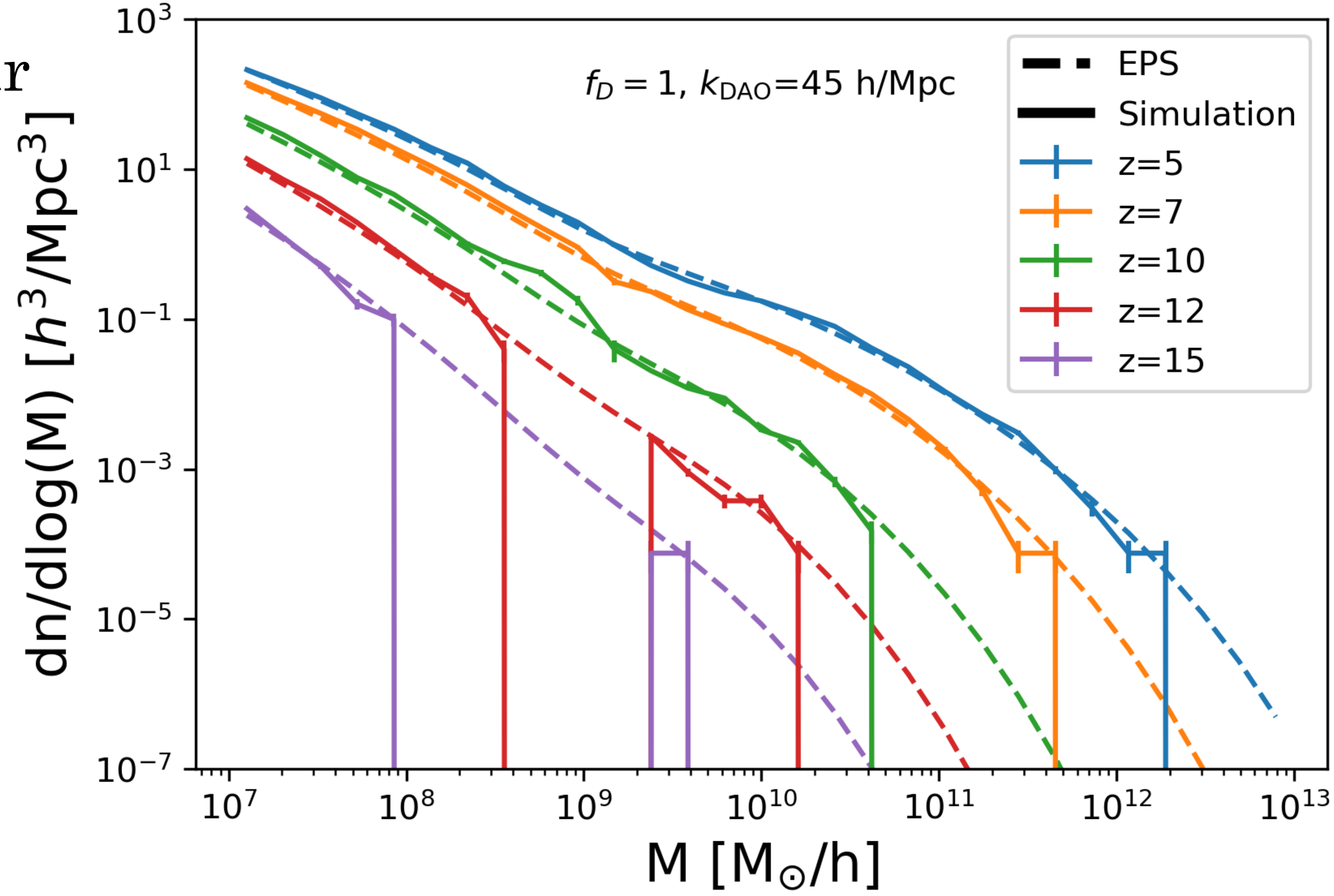


Semi-analytic HMF

$$\widetilde{W}_R^{\mathrm{smooth}}(k) = \frac{1}{1 + \left(\frac{kR}{c_W}\right)^{\beta}},$$

$$f(\nu) = A\sqrt{\frac{2q\nu}{\pi}}\left(1 + (q\nu)^{-p}\right)\exp\left(-\frac{q\nu}{2}\right)$$

- Use extended Press-Schechter formalism to model HMF given linear power spectrum.
- Fit parameters to simulations across redshift and aDM parameter space.
- Obtain semi-analytic HMF, much faster to evaluate than running simulation.



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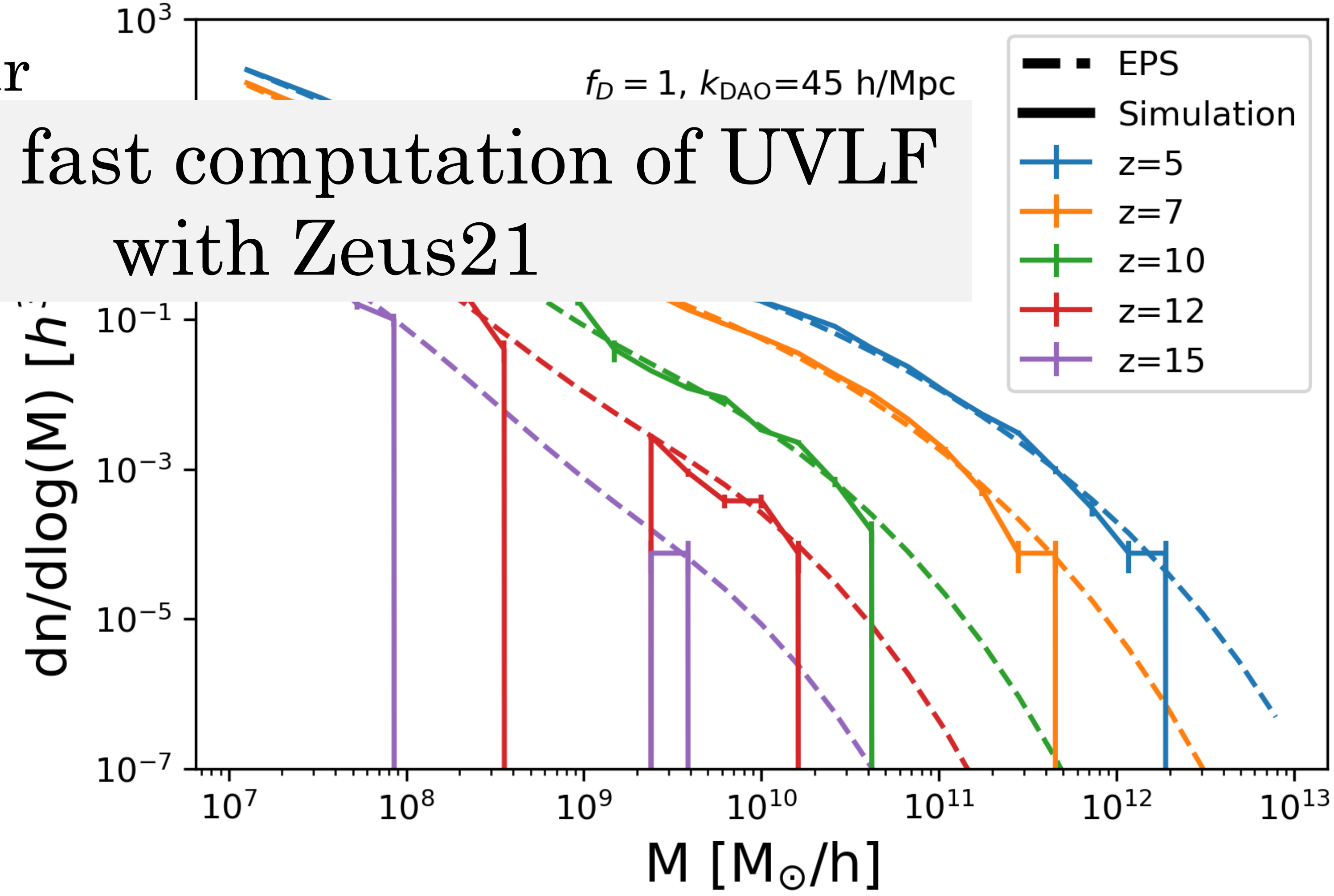
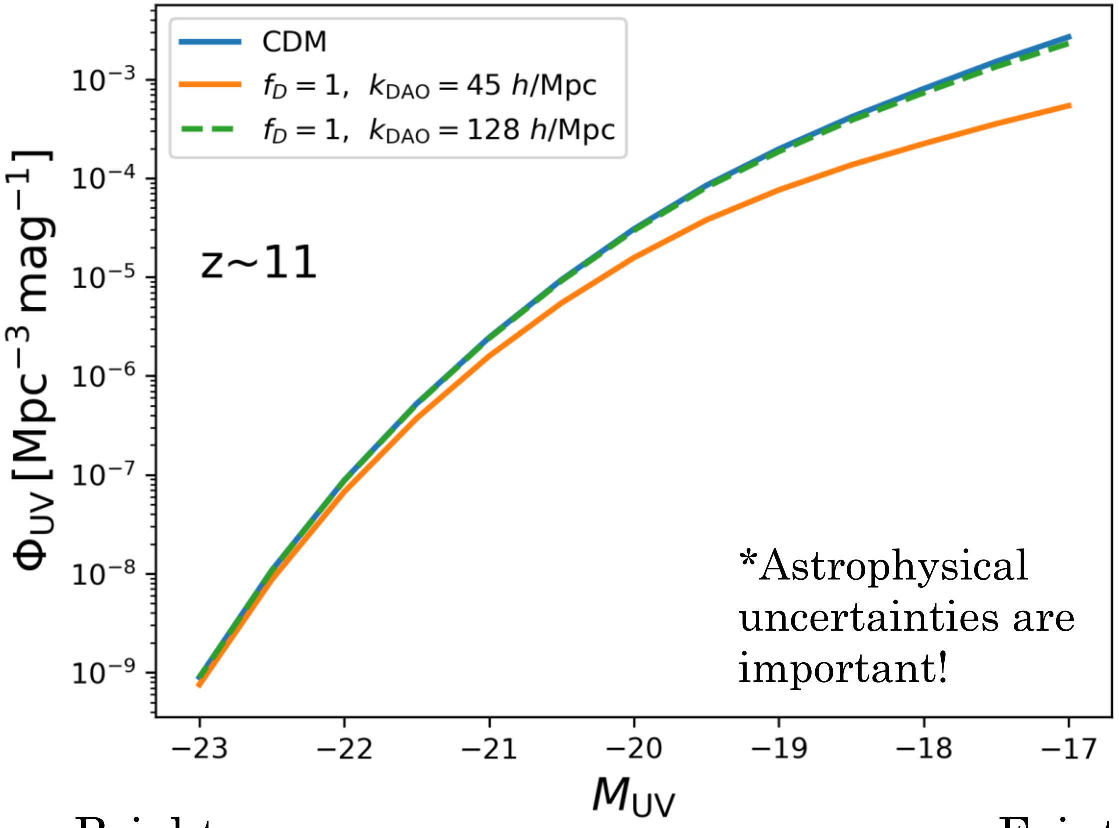


Enables fast computation of UVLF with Zeus21

UV Luminosity Function

UVLF prediction from Press-Schechter HMF

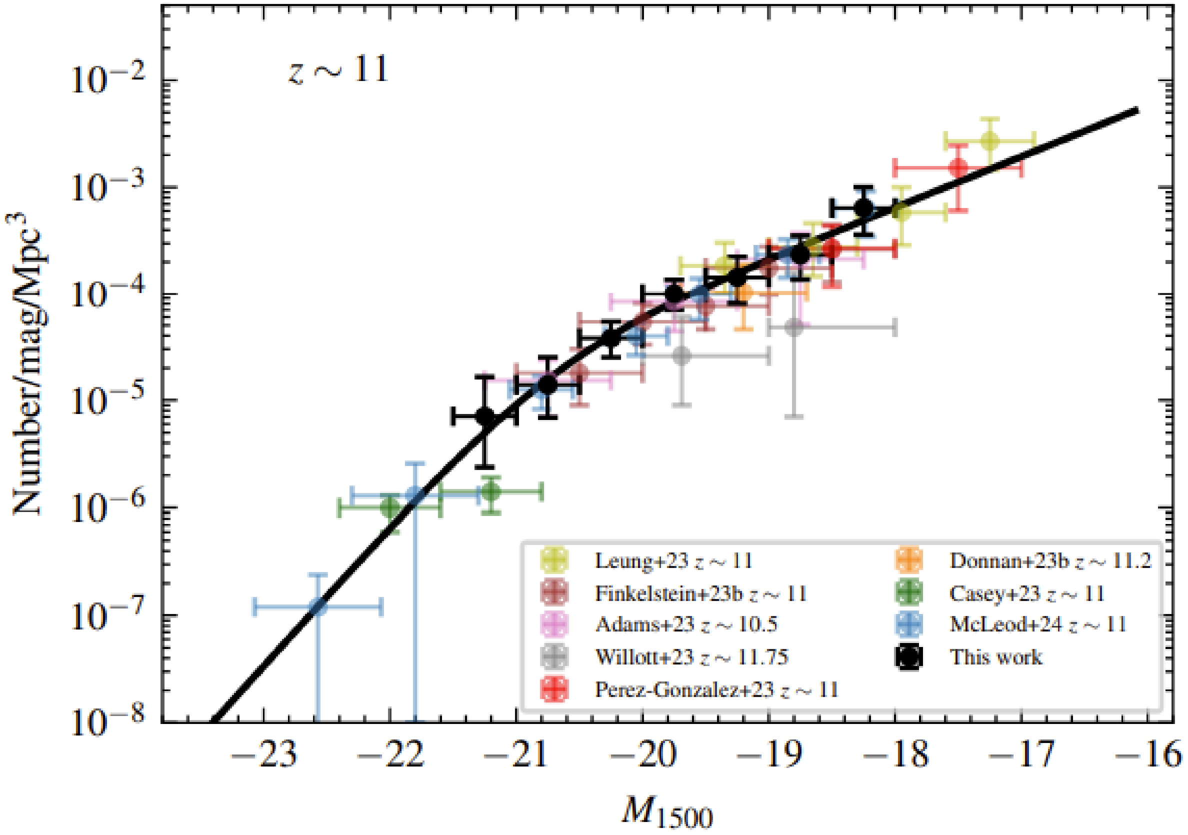


*Astrophysical uncertainties are important!

Bright

Faint

New JWST observations



Donnan et al., 2403.03171

Code: Zeus21, J. Muñoz 2302.08506

UV Luminosity Function

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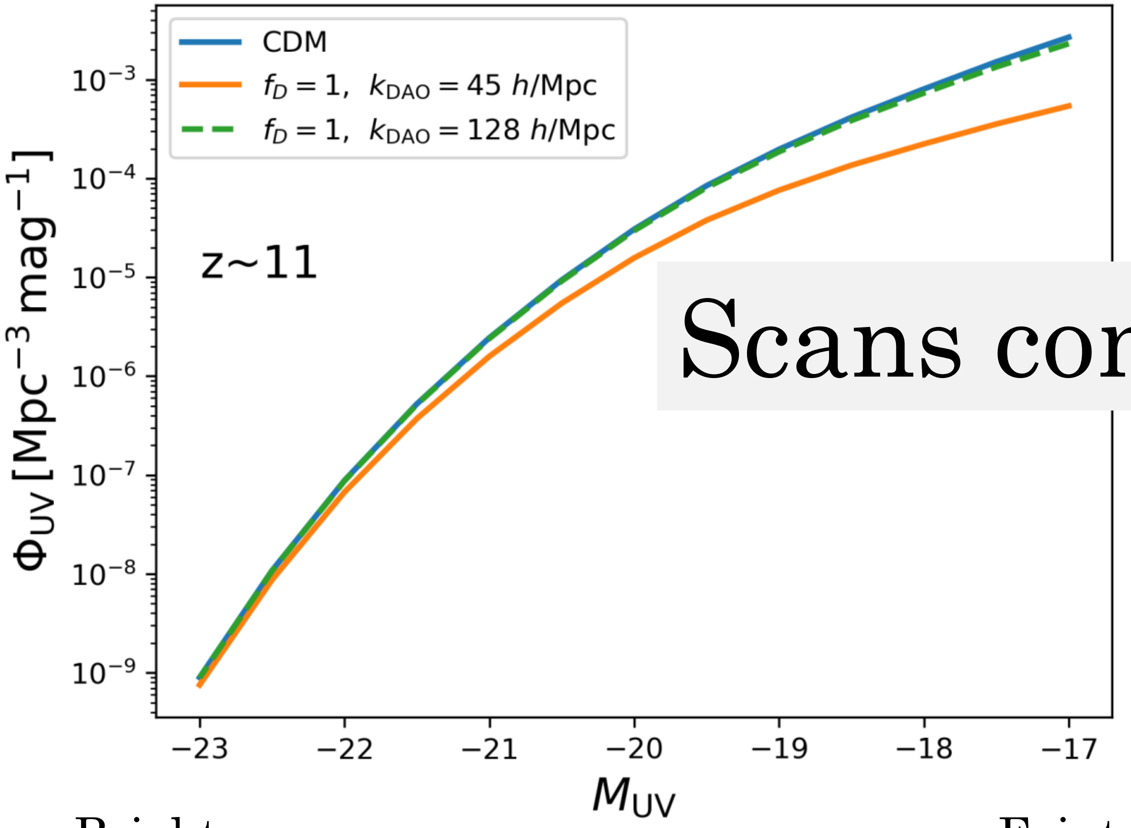

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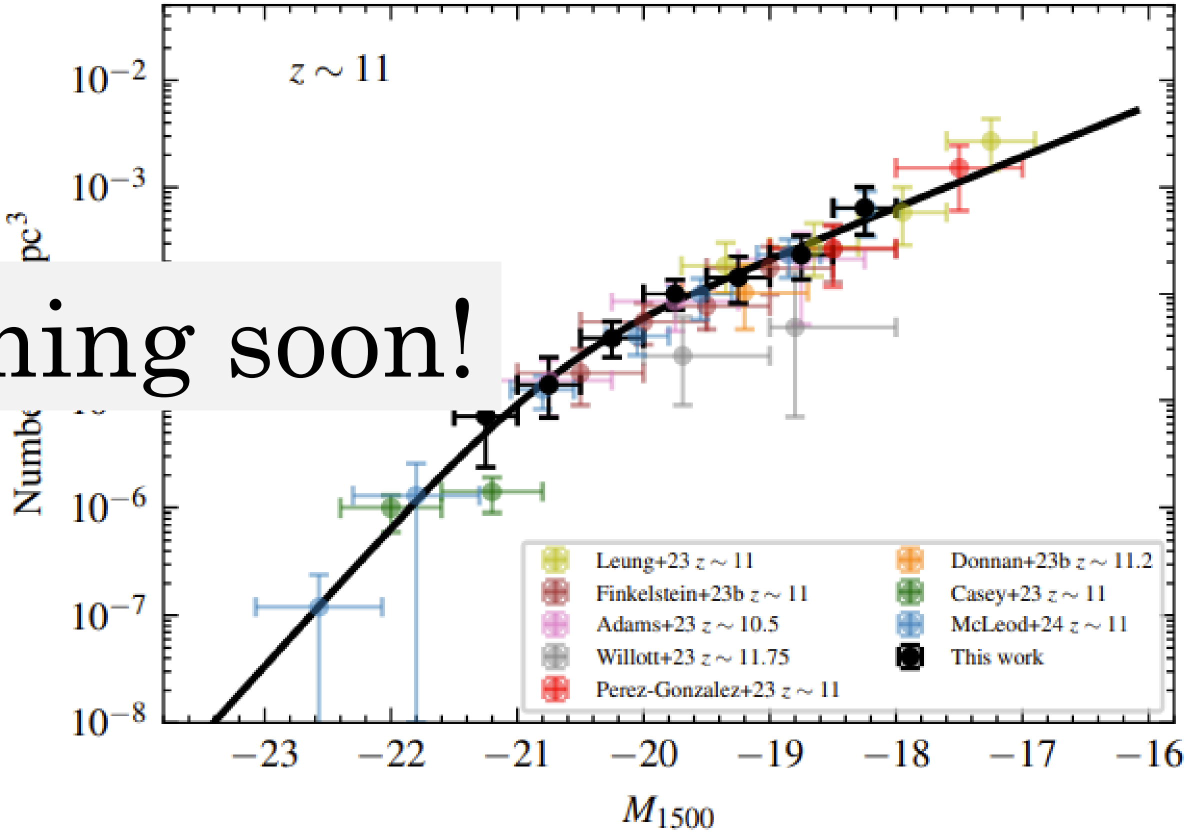

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Scans coming soon!

Code: Zeus21, J. Muñoz 2302.08506

Conclusions

- Atomic dark matter is a well-motivated dark sector model.
- It can dramatically impact the growth of structure.
- To compute these effects on small scales, n-body simulations are required.
- By using the output of those simulations to calibrate an Extended Press-Schechter fit, we can predict observables like the UV luminosity function.
- Existing HST and new JWST data will put new constraints on the aDM parameter space – and other models with DAOs.

Thank you for your attention!