Dark atom effects on the CMB and LSS

PITT PACC Workshop: Atomic Dark Matter
Jan 26-28, 2023

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Coming full circle…

- It's great that these ideas are still of interest!

The Cosmology of Atomic Dark Matter

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(Dated: November 9, 2012)

While, to ensure successful cosmology, dark matter (DM) must kinematically decouple from the standard model plasma very early in the history of the Universe, it can remain coupled to a bath of "dark radiation" until a relatively late epoch. One minimal theory that realizes such a scenario is the Atomic Dark Matter model, in which two fermions oppositely charged under a new U(1) dark force are initially coupled to a thermal bath of "dark photons" but eventually recombine into neutral atom-like bound states and begin forming gravitationally-bound structures. As dark atoms have (dark) atom-sized geometric cross sections, this model also provides an example of self-interacting DM with a velocity-dependent cross section. Delayed kinetic decoupling in this scenario predicts novel DM properties on small scales but retains the success of cold DM on larger scales. We calculate the atomic physics necessary to capture the thermal history of this dark sector and show significant improvements over the standard atomic hydrogen calculation are needed. We solve the Boltzmann equations that govern the evolution of cosmological fluctuations in this model and find in detail the impact of the atomic DM scenario on the matter power spectrum and the cosmic microwave background (CMB). This scenario imprints a new length scale, the Dark-Acoustic-Oscillation (DAO) scale, on the matter density field. This DAO scale shapes the small-scale matter power spectrum and determines the minimal DM halo mass at late times which may be many orders of magnitude larger than in a typical WIMP scenario. This model necessarily includes an extra dark radiation component, which may be favoured by current CMB experiments, and we quantify CMB signatures that distinguish an atomic DM scenario from a standard ΛCDM model containing extra free-streaming particles. We finally discuss the impacts of atomic DM on galactic dynamics and show that these provide the strongest constraints on the model.

arXiv:1209.5752

Constraints on Large-Scale Dark Acoustic Oscillations from Cosmology

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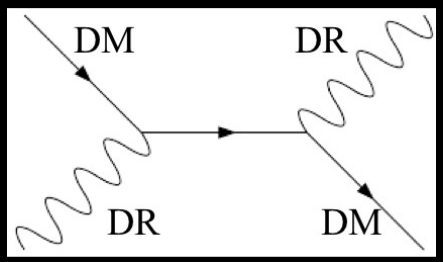
(Dated: February 4, 2014)

If all or a fraction of the dark matter (DM) were coupled to a bath of dark radiation (DR) in the early Universe we expect the combined DM-DR system to give rise to acoustic oscillations of the dark matter until it decouples from the DR. Much like the standard baryon acoustic oscillations, these dark acoustic oscillations (DAO) imprint a characteristic scale, the sound horizon of dark matter, on the matter power spectrum. We compute in detail how the microphysics of the DM-DR interaction affects the clustering of matter in the Universe and show that the DAO physics also gives rise to unique signatures in the temperature and polarization spectra of the cosmic microwave background (CMB). We use cosmological data from the CMB, baryon acoustic oscillations (BAO), and large-scale structure to constrain the possible fraction of interacting DM as well as the strength of its interaction with DR. Like nearly all knowledge we have gleaned about DM since inferring its existence this constraint rests on the betrayal by gravity of the location of otherwise invisible DM. Although our results can be straightforwardly applied to a broad class of models that couple dark matter particles to various light relativistic species, in order to make quantitative predictions, we model the interacting component as dark atoms coupled to a bath of dark photons. We find that linear cosmological data and CMB lensing put strong constraints on existence of DAO features in the CMB and the large-scale structure of the Universe. Interestingly, we find that at most $\sim 5\%$ of all DM can be very strongly interacting with DR. We show that our results are surprisingly constraining for the recently proposed Double-disk DM model, a novel example of how large-scale precision cosmological data can be used to constrain galactic physics and sub-galactic structure.

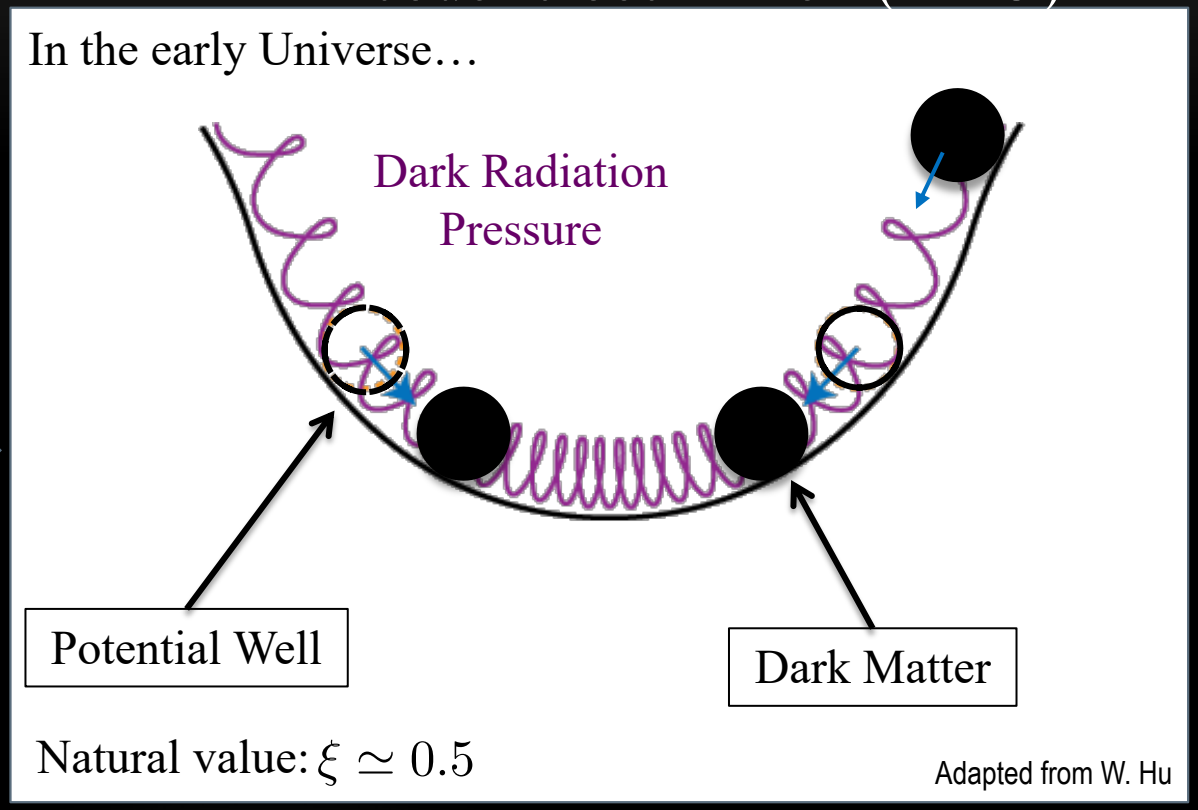
arXiv:1310.3278

Following Goldberg & Hall (1986), Kaplan et al. (2009), Kaplan et al. (2011), and many Robert Foot papers.

Ab initio phenomenology of dark matter-dark radiation (DR) interaction

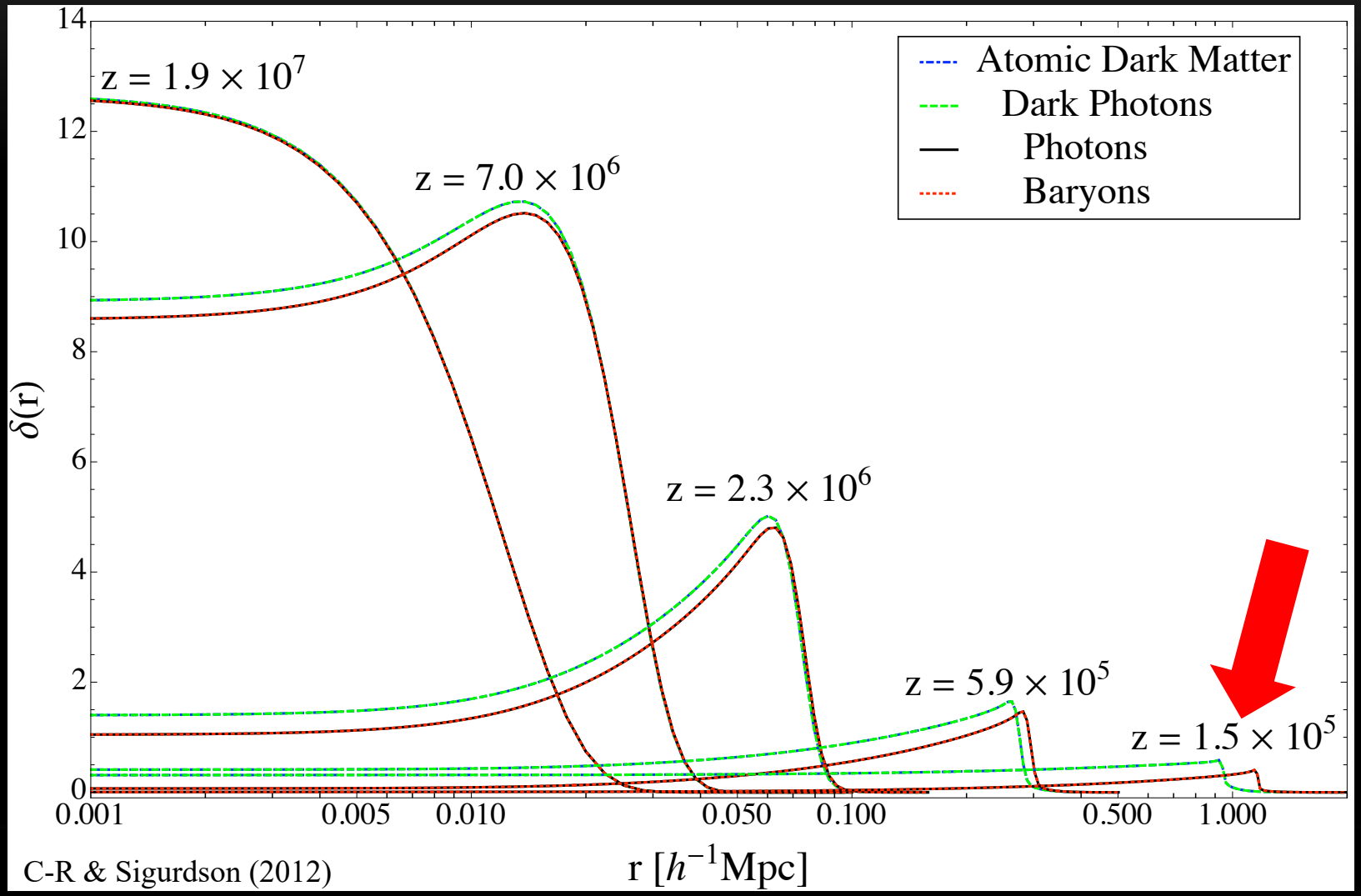


Dark acoustic oscillation (DAO)

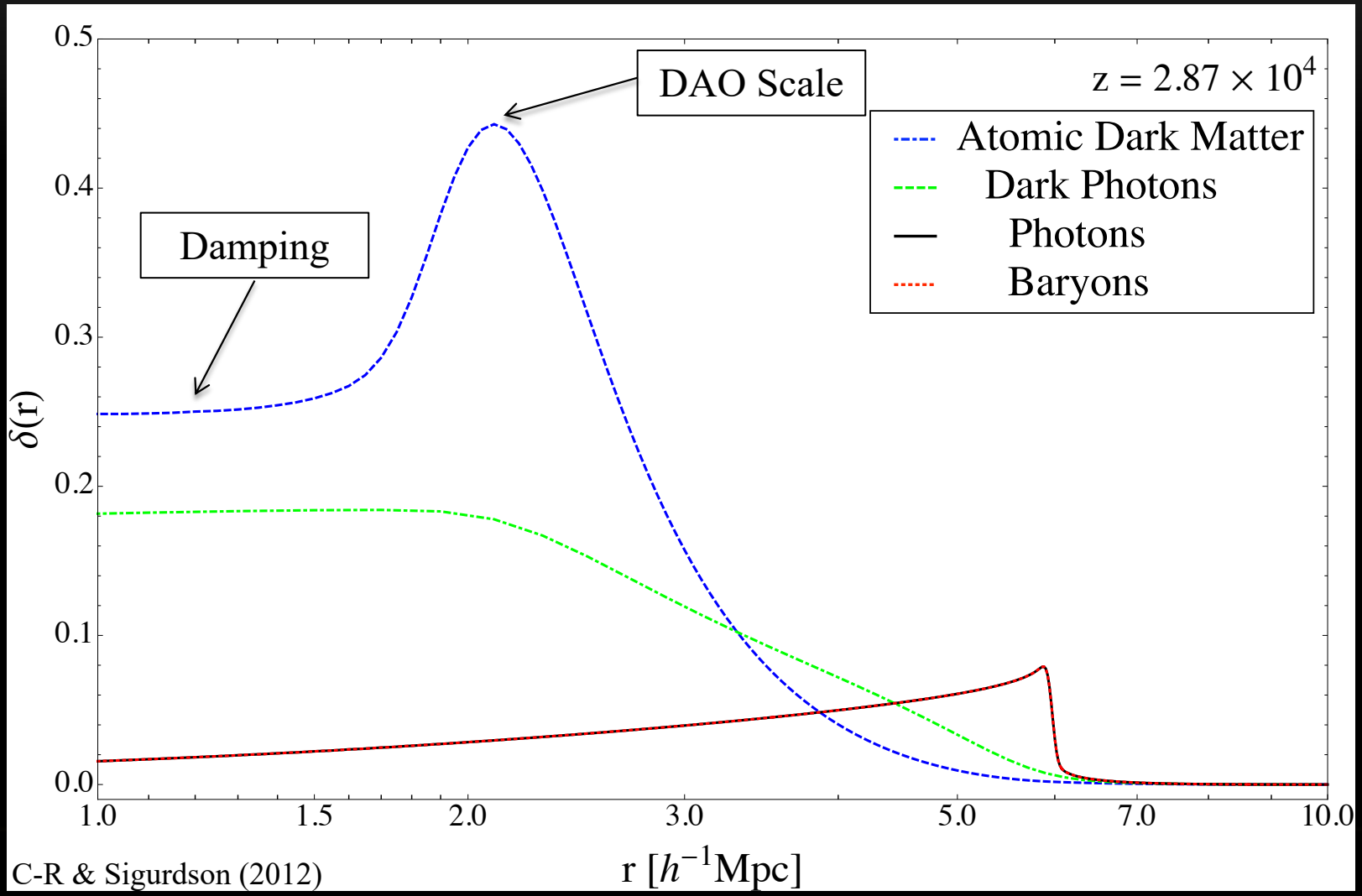


$$\xi \equiv (T_D/T_{\rm CMB})|_{z=0}$$

Phenomenology of dark matter-dark radiation interaction: Sound wave

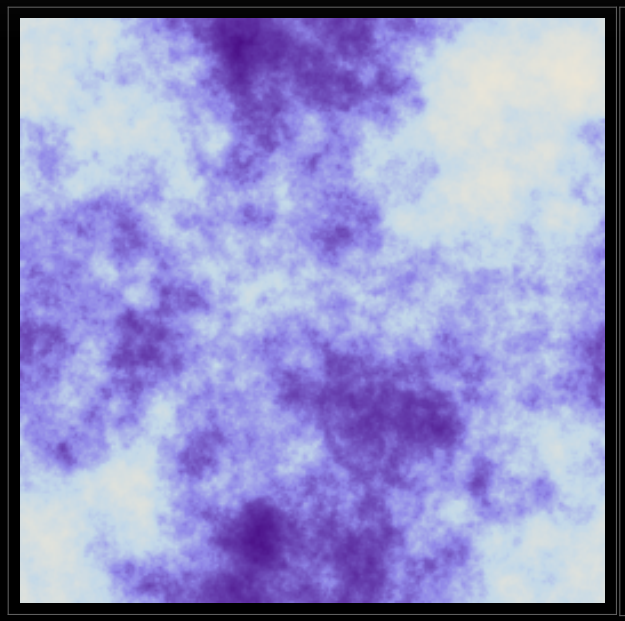


Phenomenology of dark matter-dark radiation interaction: Sound wave

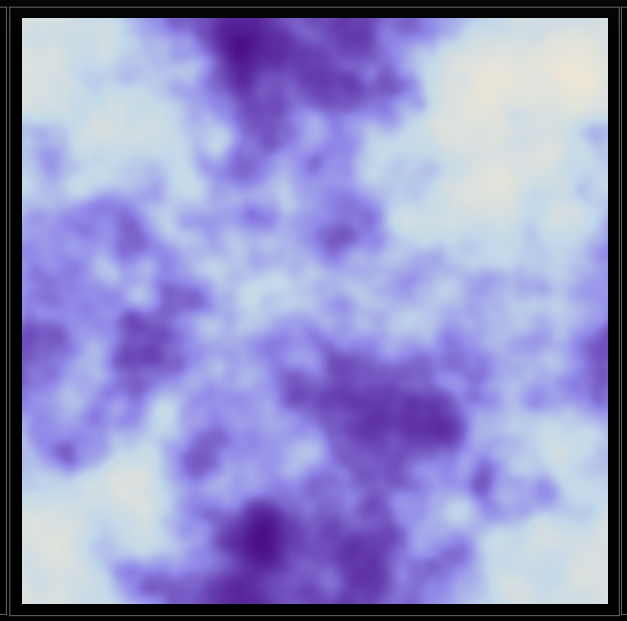


The structure of the dark matter density field is distinctly different

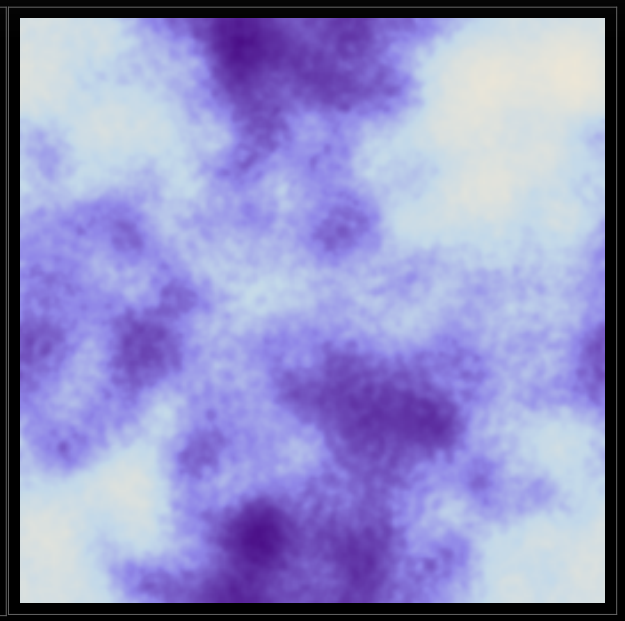
Cold DM



Warm DM

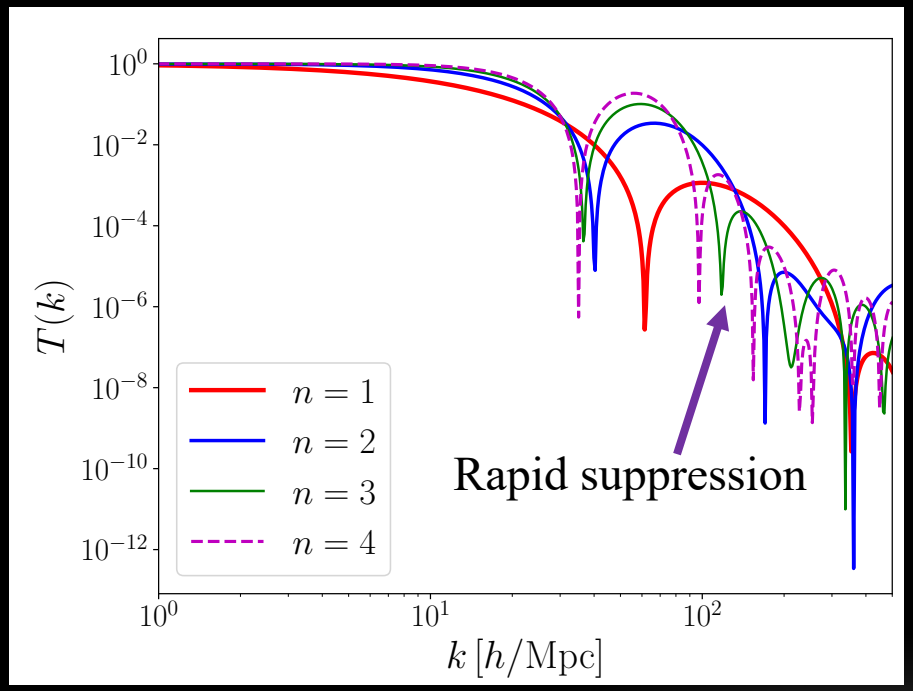


Atomic DM

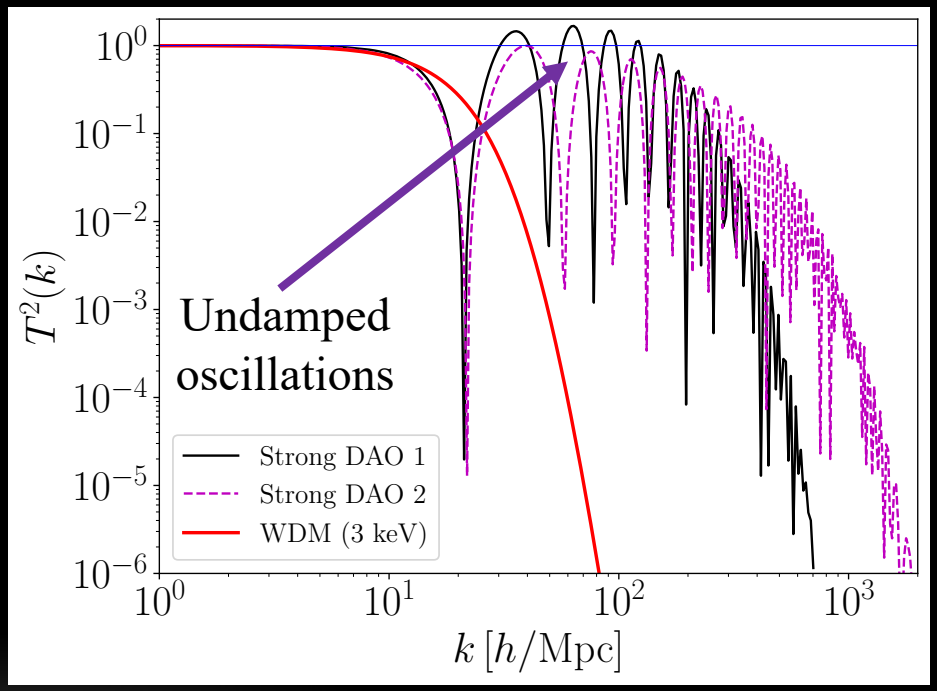


Broad diversity of matter power spectrum shapes across atomic DM parameter space

Weak DAO



Strong DAO: Atomic DM

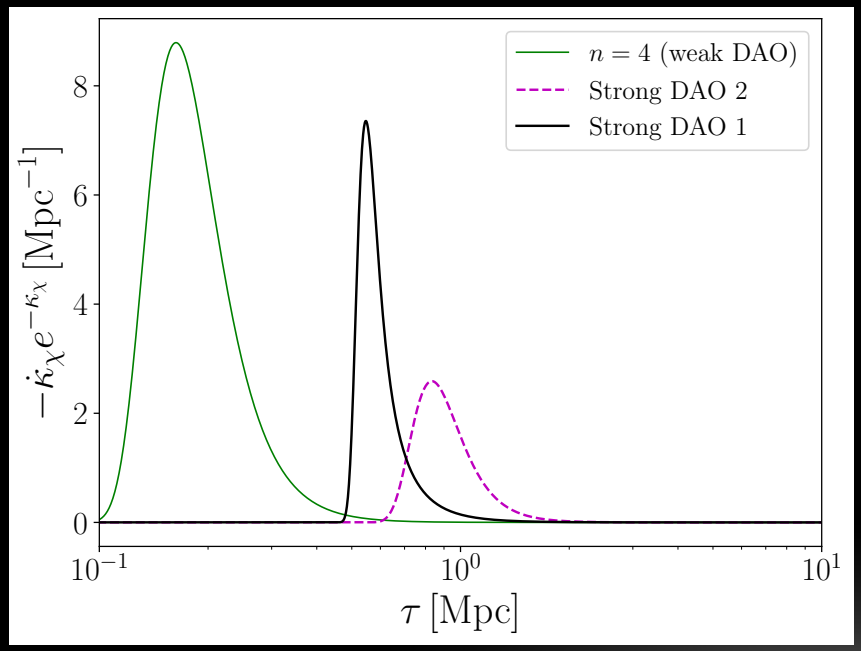


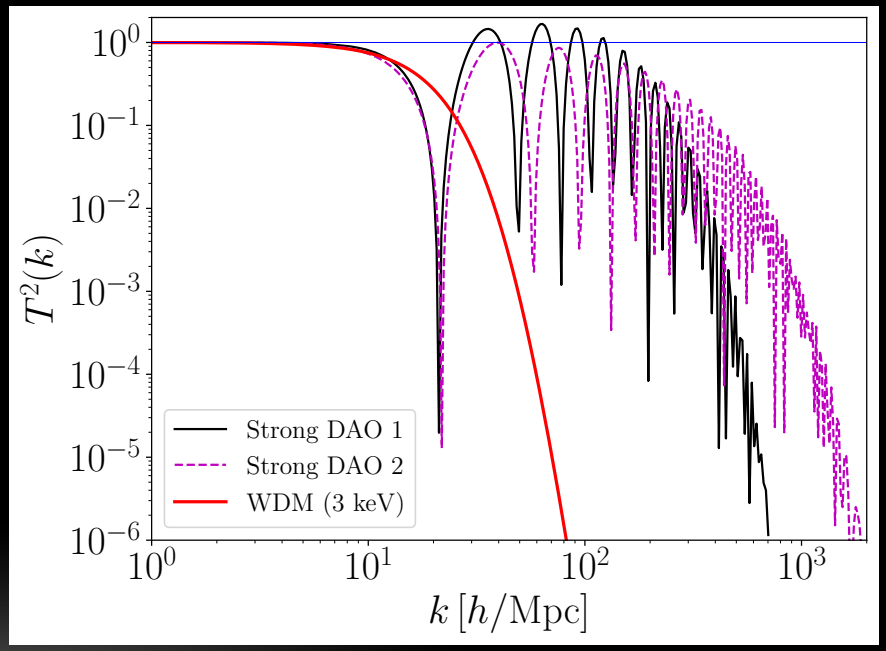
Cyr-Racine et al. (2016)

What determines the shape of the matter power spectrum?

Rapid dark recombination leads to a narrow dark matter drag visibility function => undamped DAOs.

$$\dot{\kappa}_\chi = -a\frac{4}{3}\frac{\rho_{\rm DR}}{m_\chi}\langle\sigma_{\rm DM-DR}\rangle$$

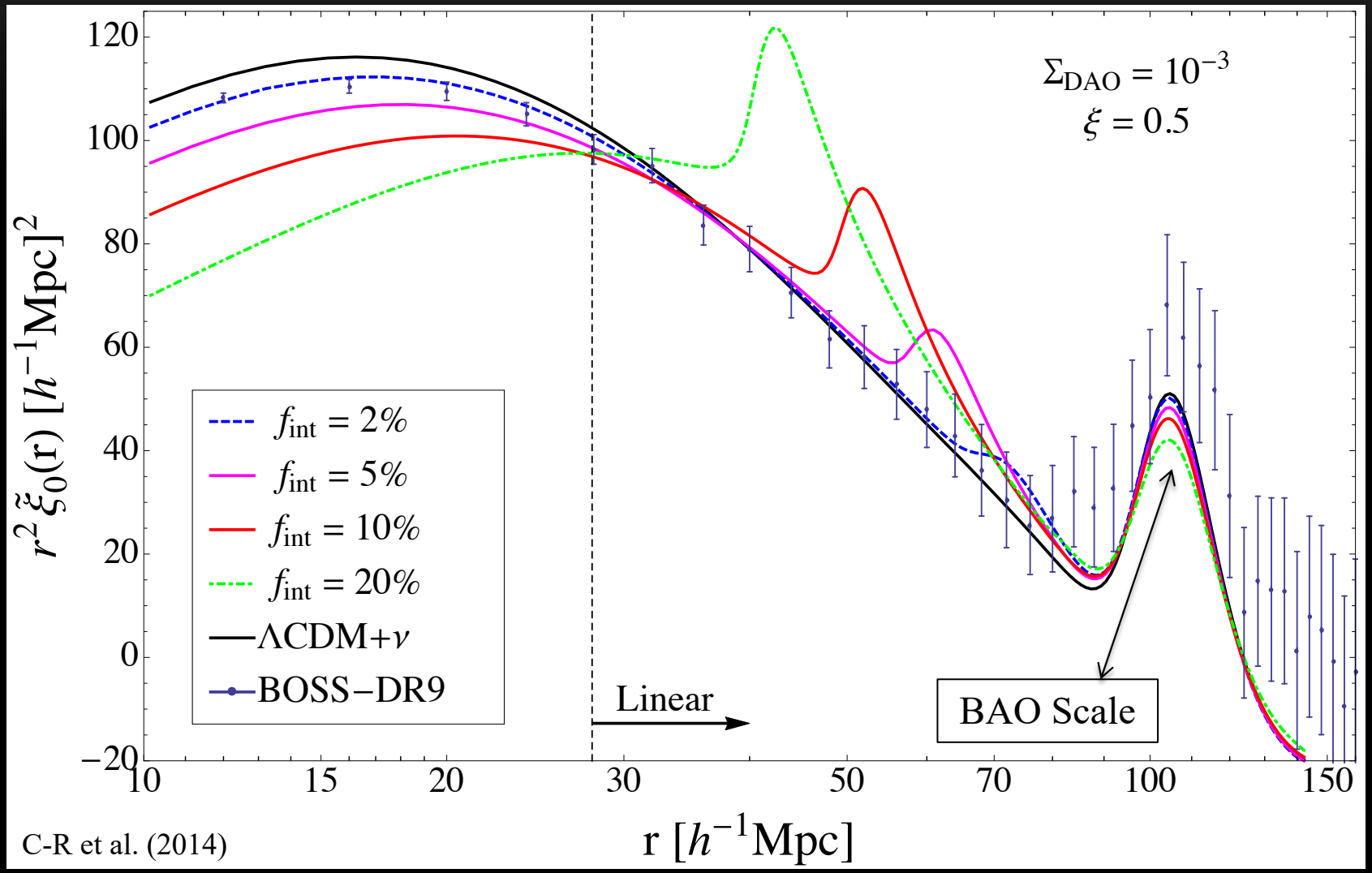




Outline: Observables

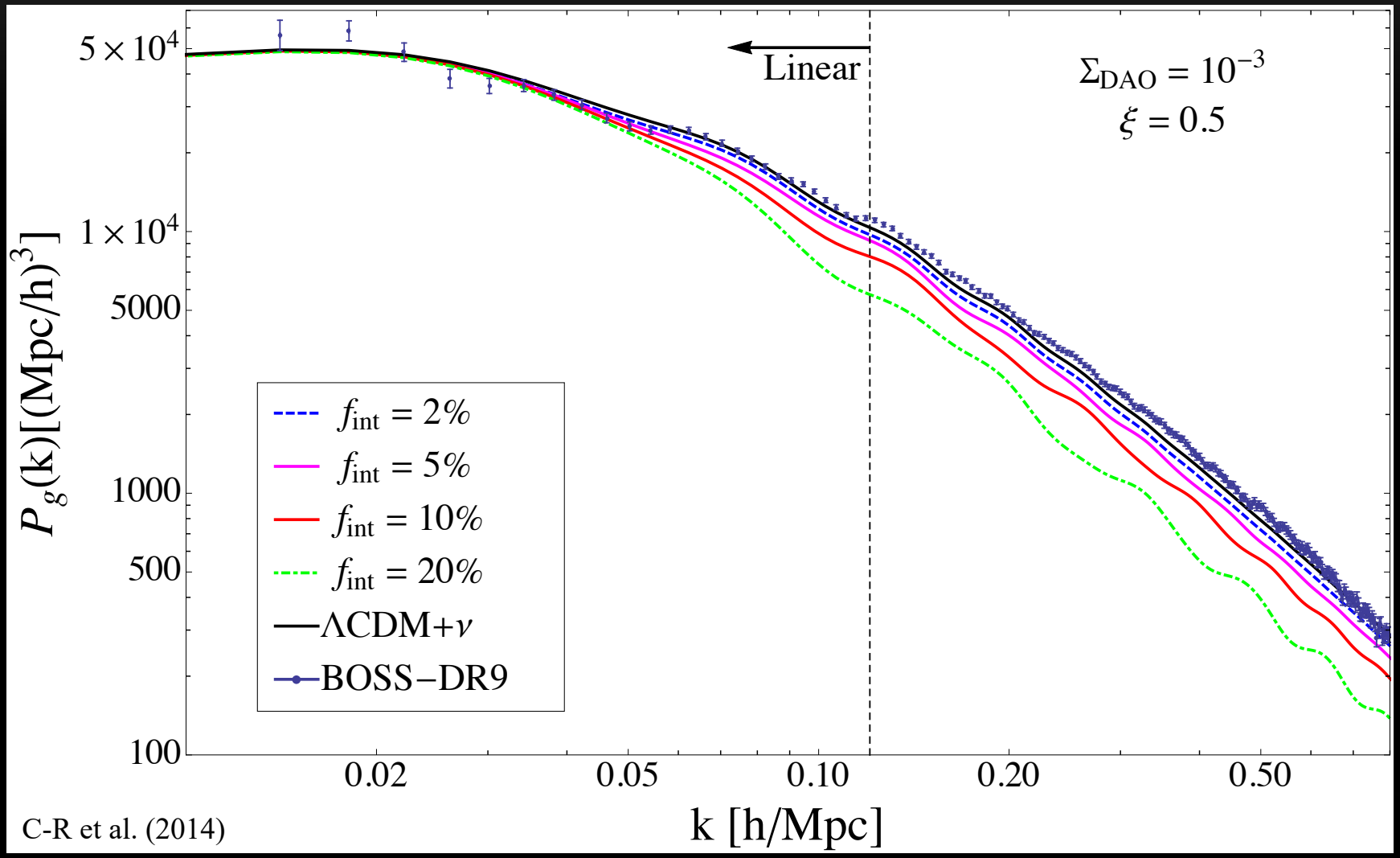
- Linear scales:
  - Large-scale structure (galaxy)
  - CMB/CMB lensing
- Nonlinear scales:
  - Erasure of DAOs
  - Lyman-alpha forest
  - Halo mass function
  - 21-cm

Large-Scale Structure: DAO Scale + Damping



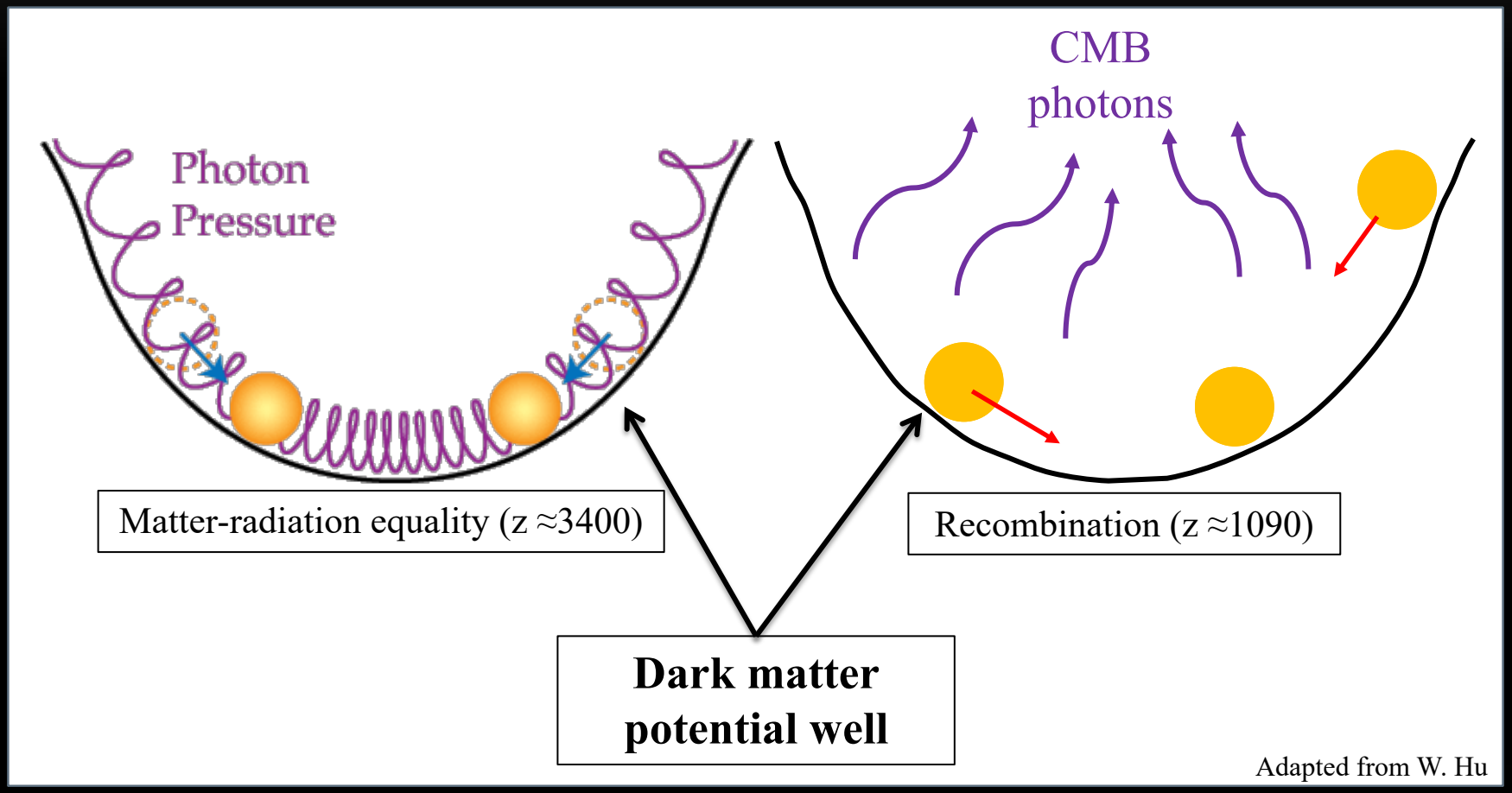
C-R et al. (2014)

Large-Scale Structure: DAO Scale + Damping



C-R et al. (2014)

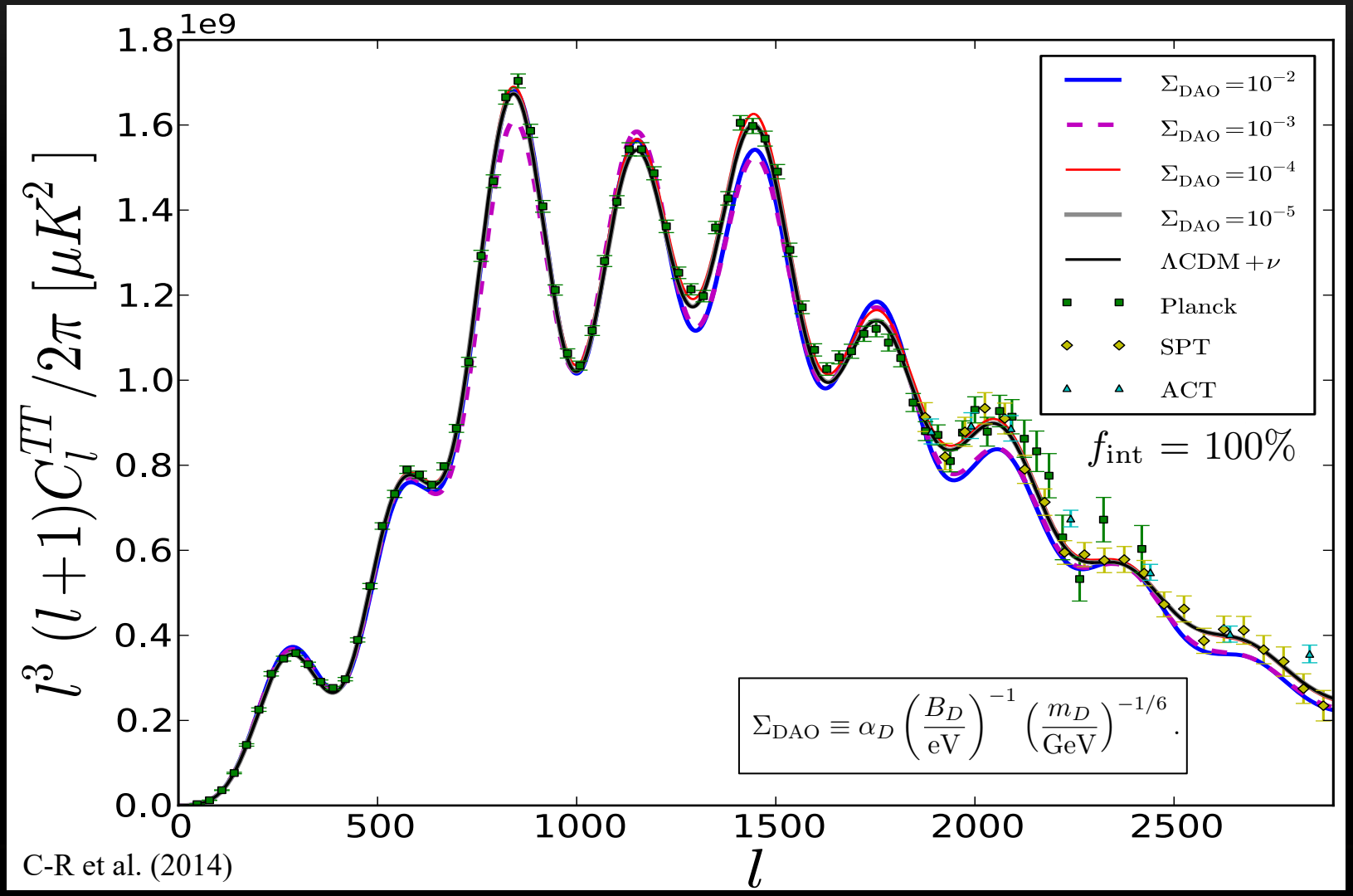
CMB: Dark matter provides gravitational potential wells for baryons to fall into



CMB: Gravitational Effects

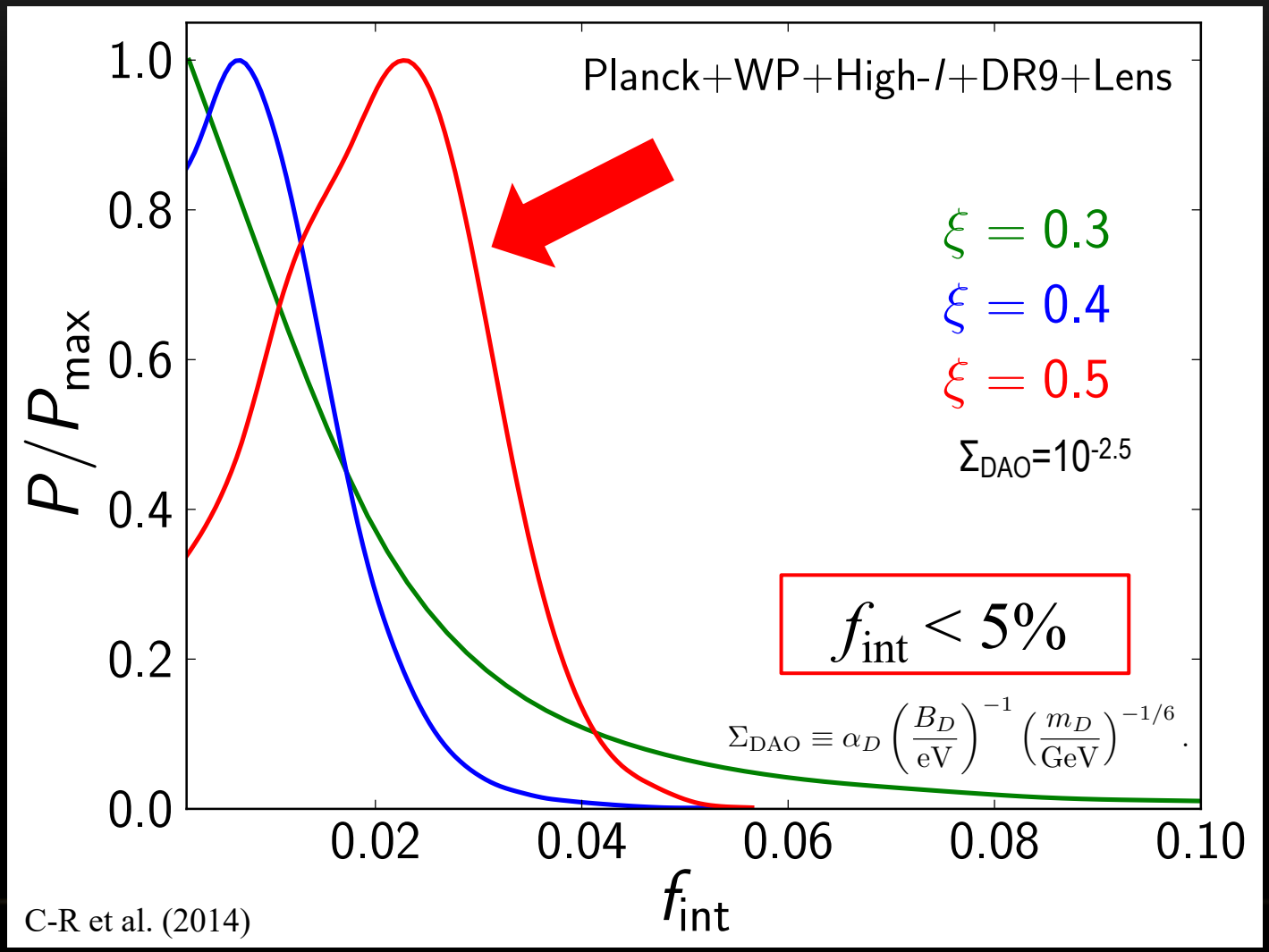
- There are 2 types of effects that can allow us to distinguish an atomic dark matter scenario from ΛCDM:
  - The smoother DM distribution on small scales lead to shallower DM gravitational potentials.
    - Modified ratio of even and odd TT peaks
    - Modified CMB lensing
  - The dark photons are not free-streaming at early time and therefore does not behave like neutrinos.
    - Modified amplitudes and phase in temperature and polarization spectra.
    - Modified shear stress close to CMB last scattering modify TT and EE spectra.
    - Stronger early Integrated Sachs-Wolfe effect .

CMB: lensed TT Spectrum



C-R et al. (2014)

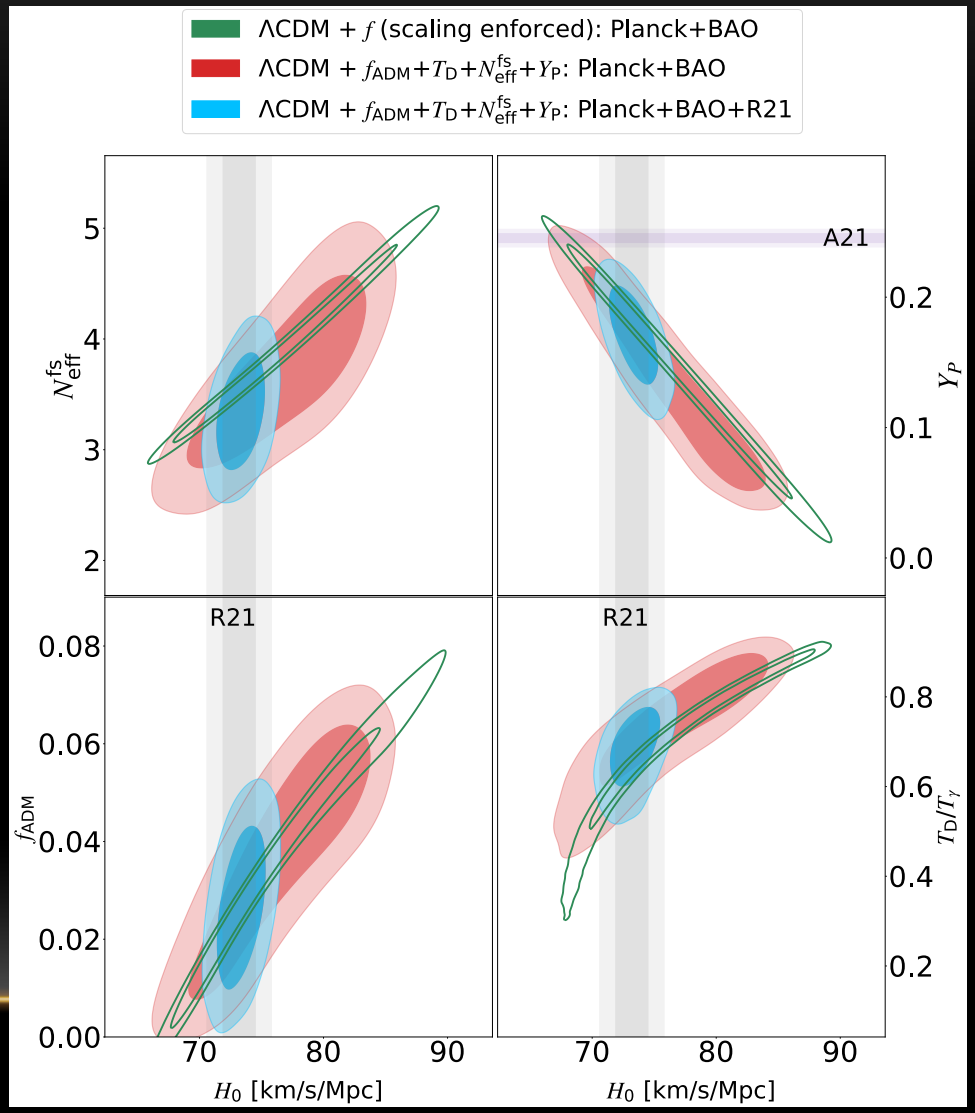
SM-like atomic DM: Allowed Fraction



C-R et al. (2014)

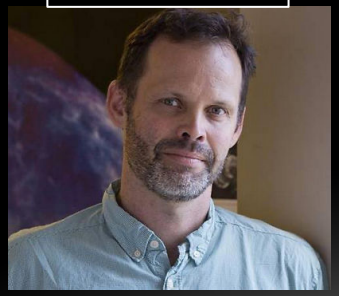
This ~3% fraction of atomic DM came up again recently…

There is a way to "hide" atomic DM in the CMB if one exploits a very specific scaling transformation.



Fei Ge

Lloyd Knox



Cyr-Racine, Ge, Knox, PRL 128, 201301 (2022)

The Free-fall, Amplitude and Thomson (FFAT) scaling

- The CMB power spectra, BAO, and other matter clustering observables are invariant under the scaling transformation:

$$\left\{ \sqrt{G\rho_i} \to \lambda\sqrt{G\rho_i},\ \sigma_{\mathrm{T}} n_{\mathrm{e}} \to \lambda\sigma_{\mathrm{T}} n_{\mathrm{e}},\ A_{\mathrm{s}} \to A_{\mathrm{s}}/\lambda^{n_{\mathrm{s}}-1} \right\}$$

- This specifies a specific direction in cosmological model space where the predicted CMB/BAO observables are automatically invariant: Useful for model building!

Cyr-Racine, Ge, Knox, arXiv: 2107:13000, PRL 128, 201301 (2022)
Ge, Cyr-Racine, Knox, arXiv: 2210:16335

What does FFAT scaling leave invariant?

1. $\sigma_{\mathrm{T}} n_{\mathrm{e}}(z)/H(z)$ → Photon scattering rate over Hubble rate

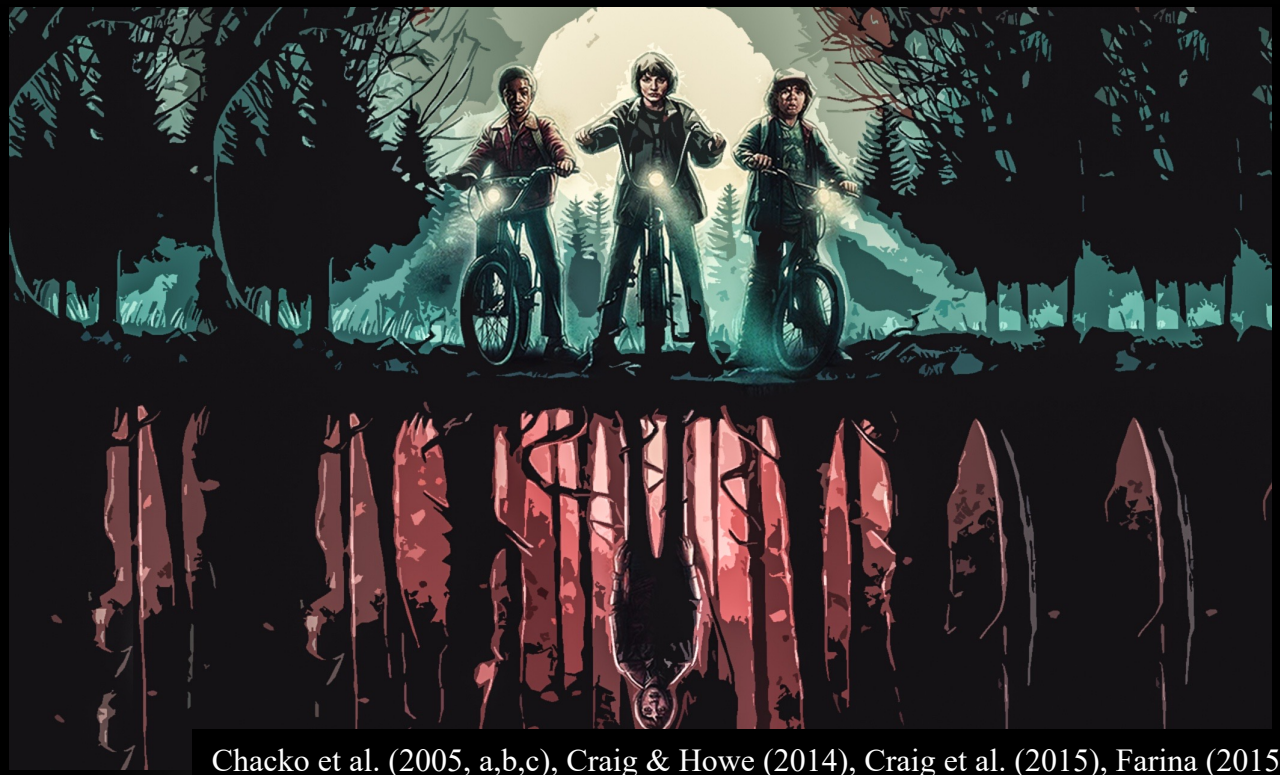
2. $\dfrac{\sqrt{\rho_{\mathrm{rad,fs}}}}{\sqrt{\rho_{\mathrm{rad,fluid}}}}$ → Free-streaming radiation fraction

3. $\dfrac{\sqrt{\rho_{\mathrm{m,pressure}}}}{\sqrt{\rho_{\mathrm{m,pressureless}}}}$ → Clustering matter fraction

4. $\text{recombination rates}/H(z)$ → Recombination rate over Hubble rate

SM-like atomic DM can exploit this scaling transformation

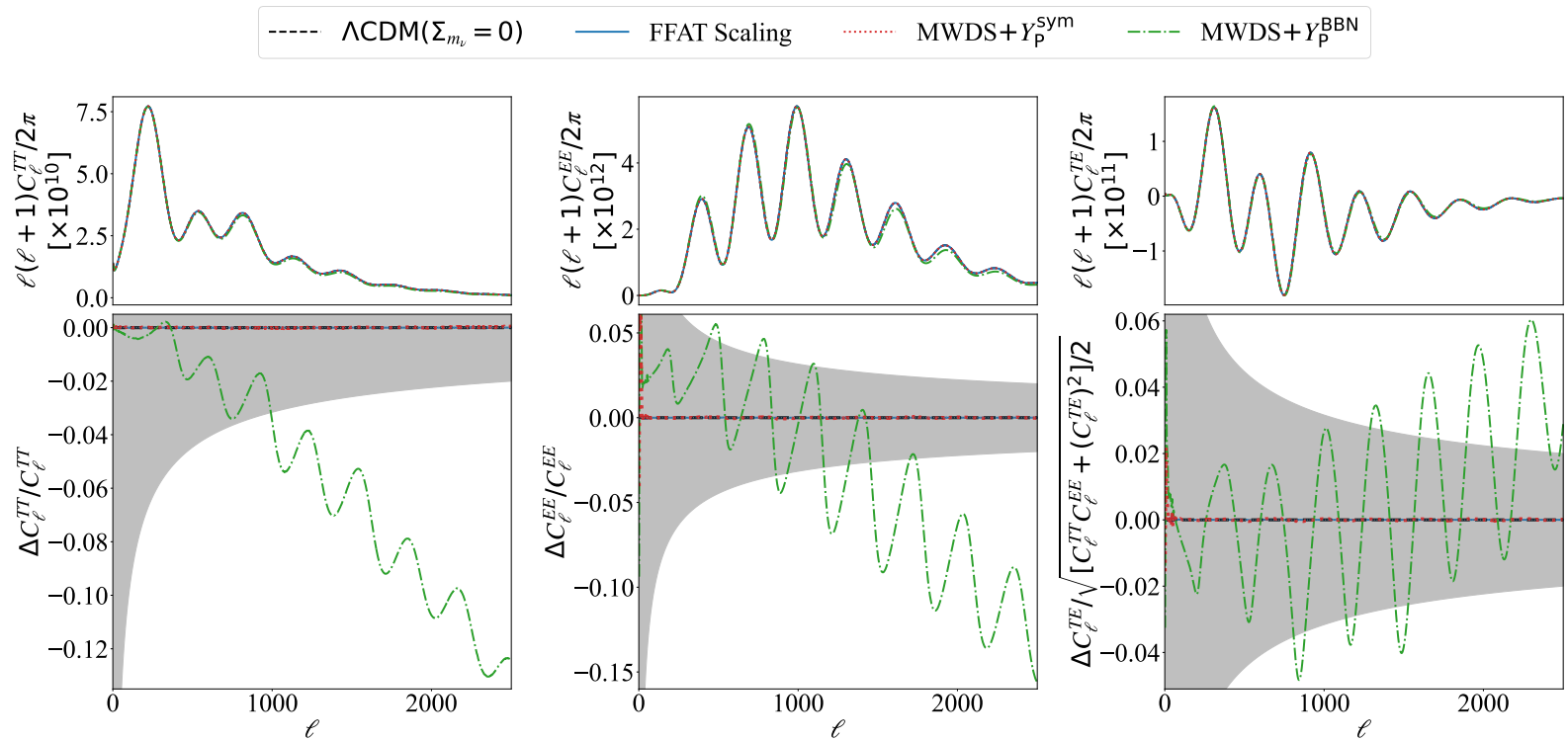
- This might be a way to address the Hubble tension.



Stranger Things

Chacko et al. (2005, a,b,c), Craig & Howe (2014), Craig et al. (2015), Farina (2015), Barbieri et al. (2016), Chacko et al. (2017), Csaki et al. (2017), Hochberg et al. (2017), Harigaya et al. (2017), Ibe et al. (2019), Terning et al. (2019), Curtin & Gryba (2021), Blinov et al. (2021) and many more

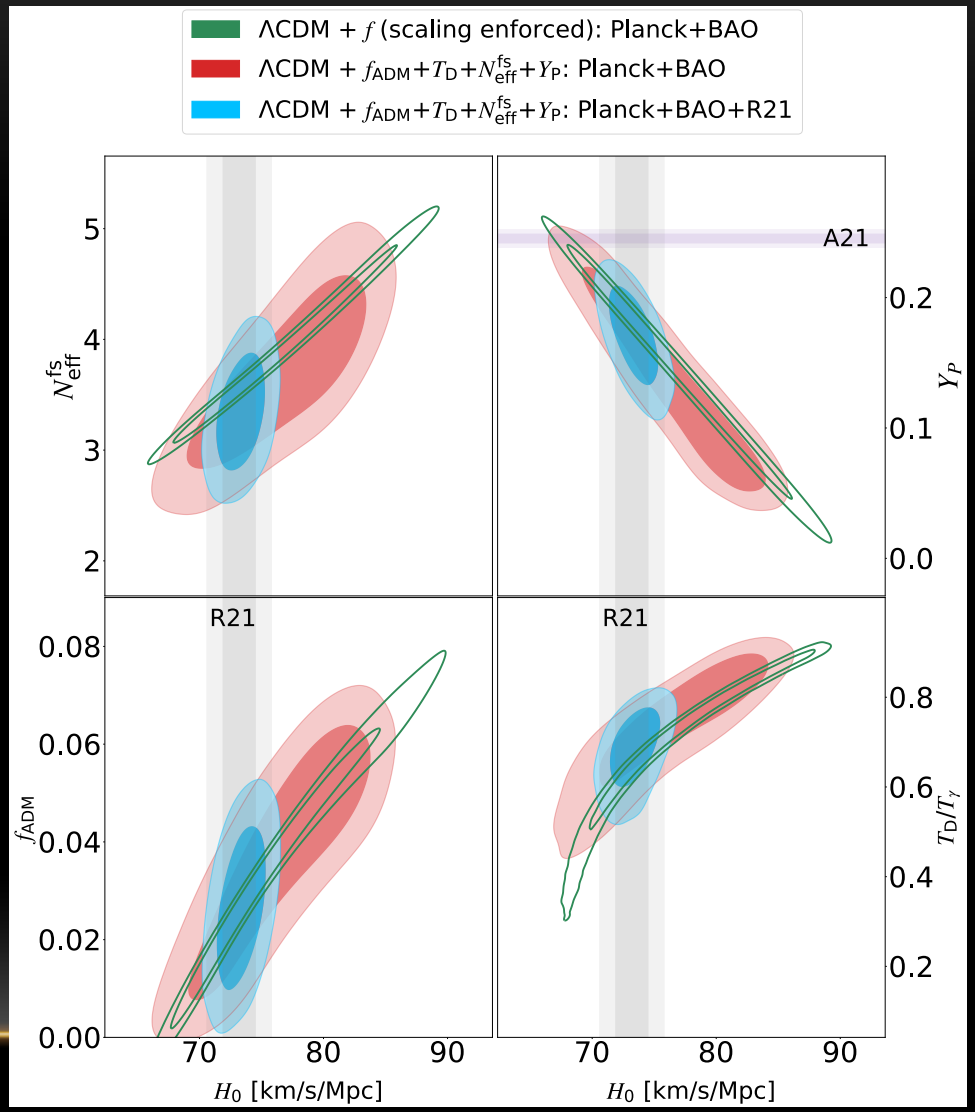
Atomic DM + photon scattering rate adjustment does leave CMB invariant



Ge, Cyr-Racine, Knox, arXiv: 2210:16335

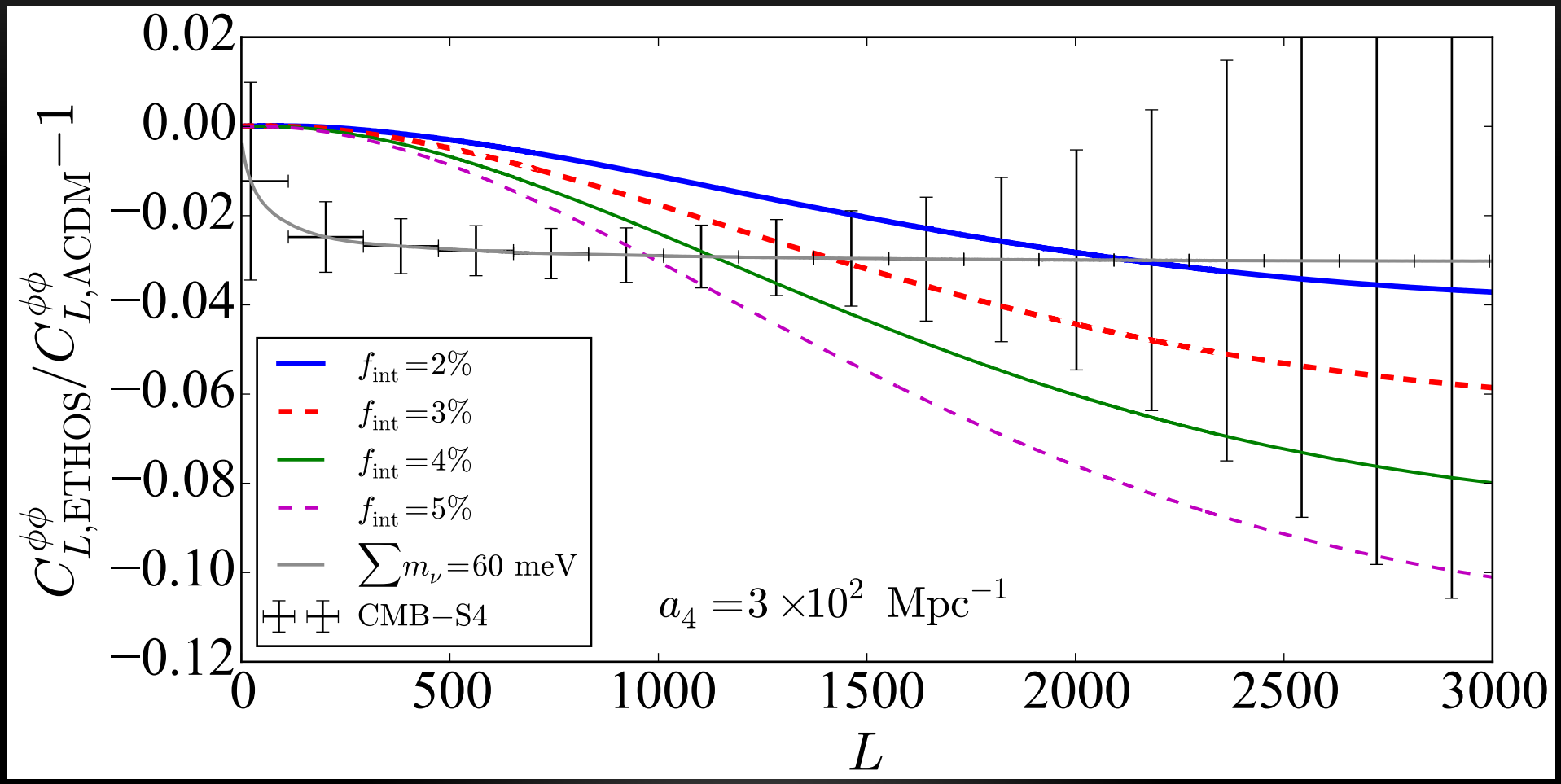
Hubble constant measurements as a calibrator of the dark sector

At face value, the direct Hubble measurements predict ~3% in atomic dark matter, and a dark photon bath with a neutrino-like temperature.



Cyr-Racine, Ge, Knox, PRL 128, 201301 (2022)

Prospects for DM-DR interaction with CMB-S4

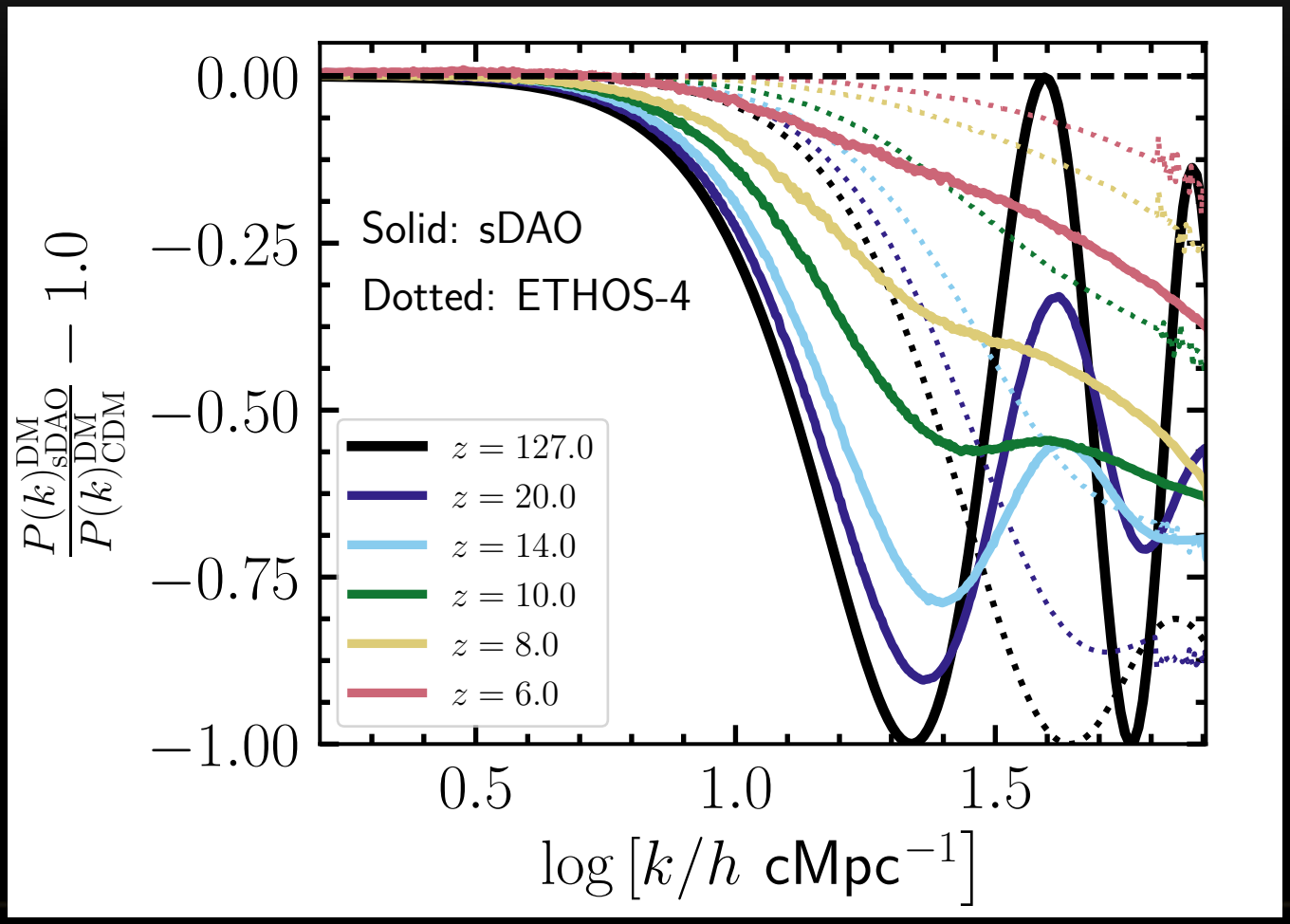


CMB-S4 Science Book

Non-linear scales

First look: Non-linear evolution of DAOs

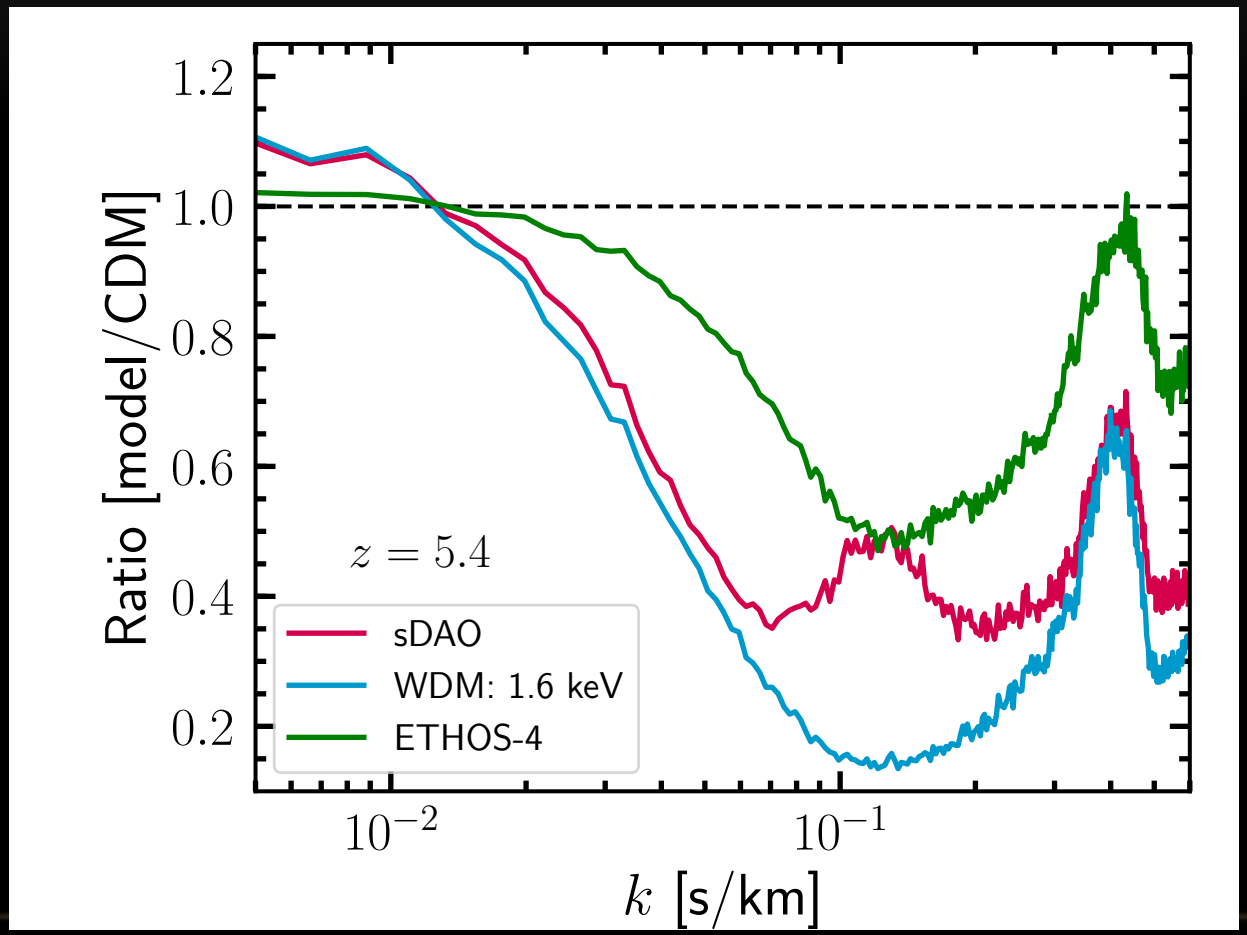
- Mode-coupling erases acoustic oscillations over time



Bose et al. (2019) [See also Schaeffer and Schneider (2021)]

Lyman-alpha: Non-linear evolution of DAOs

- They might survive long-enough to be observed at high redshifts in Lyman-alpha data



Bose et al. (2019)

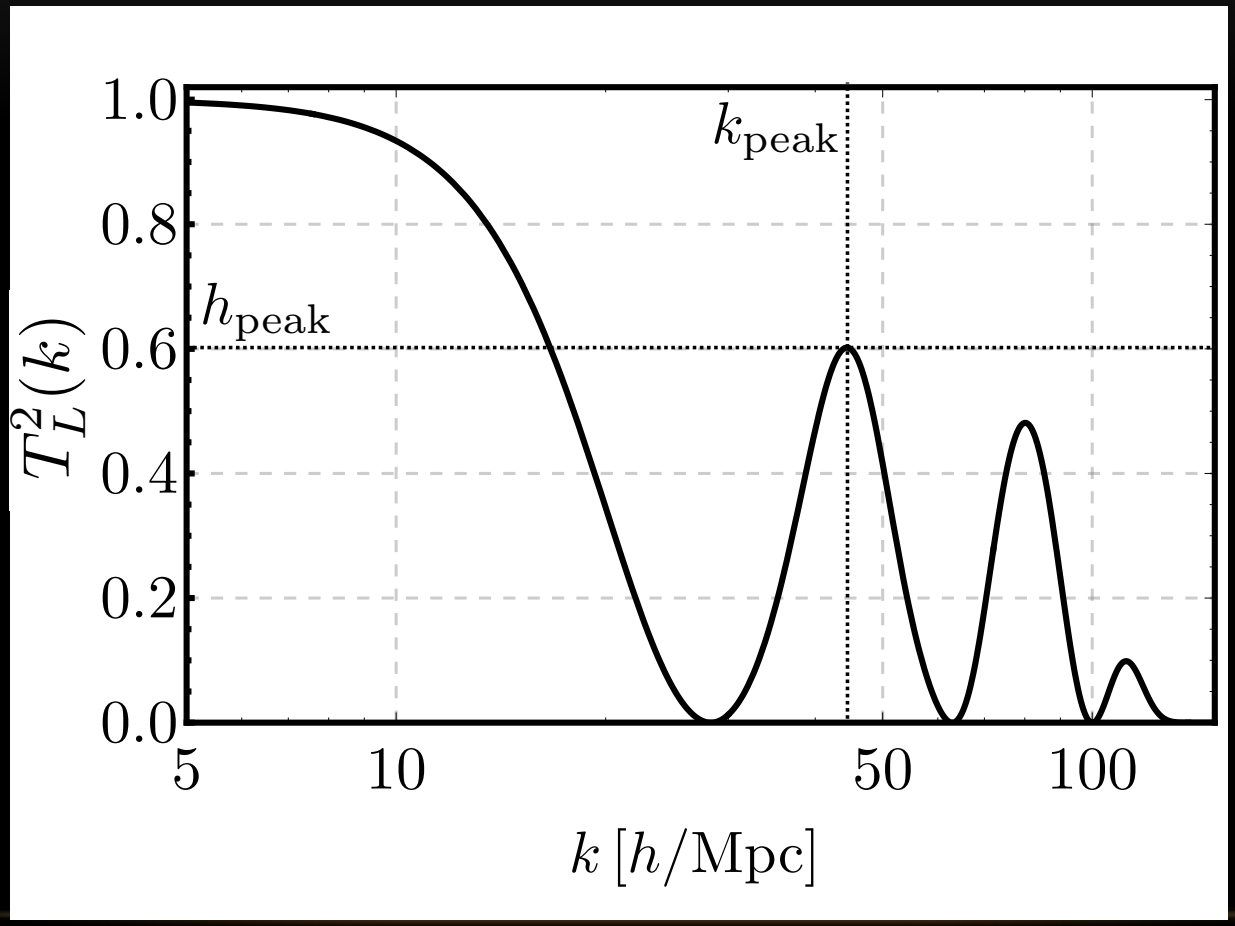
A more systematic approach: Introducing some notation

- Capture key features of DAOs with two parameters:

Julian Muñoz

Jesús Zavala

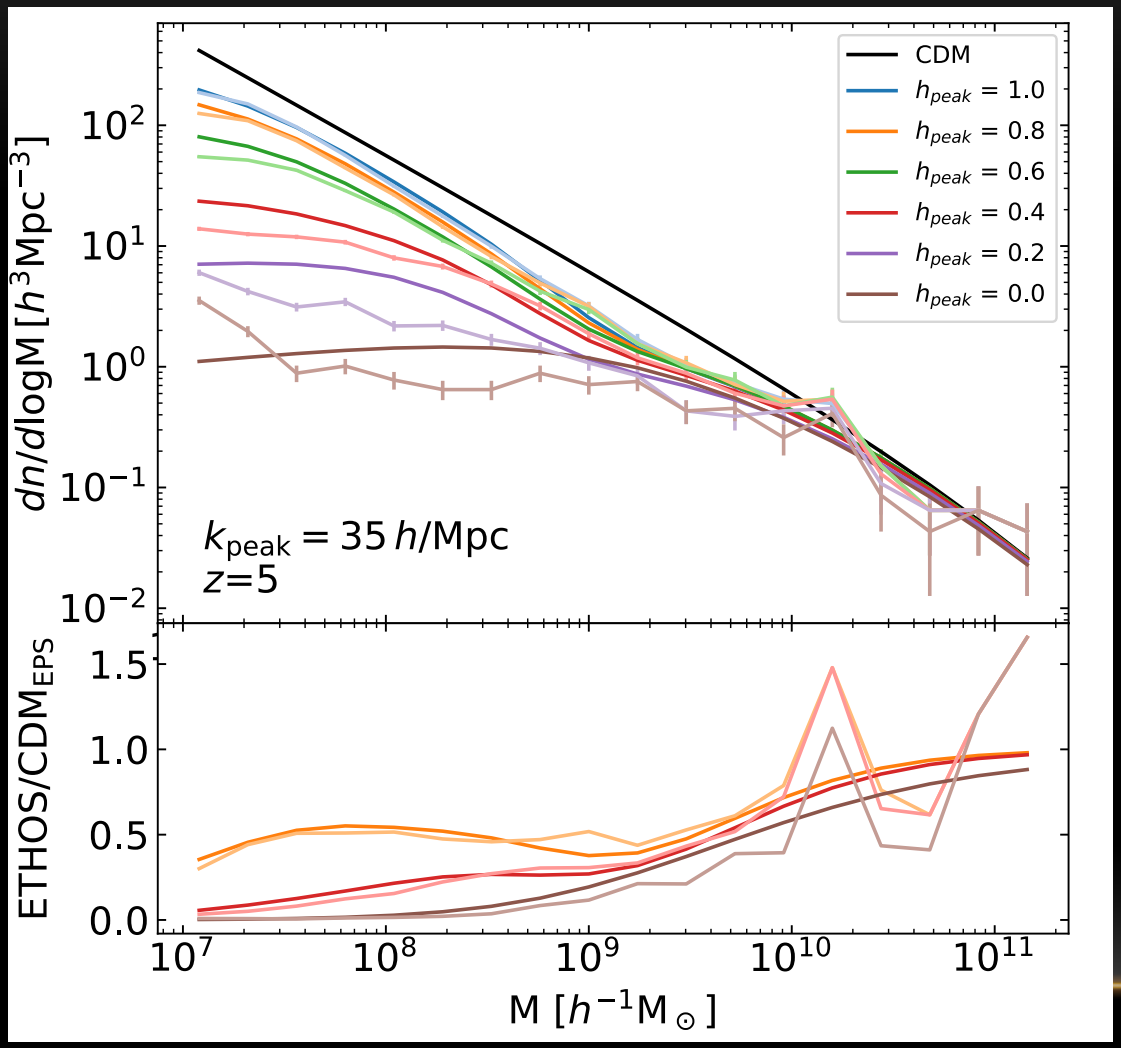
Sebastian Bohr

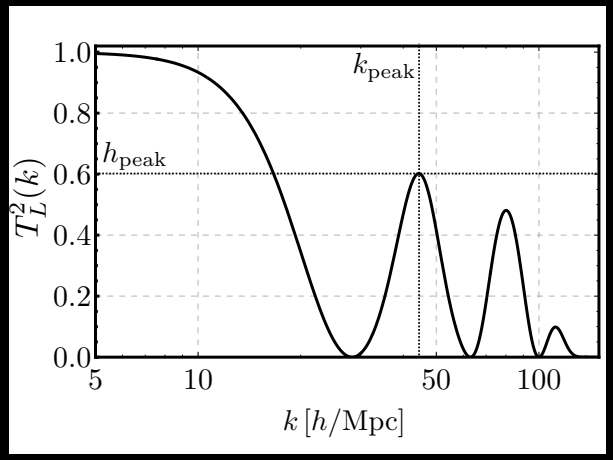


Muñoz, Bohr, Cyr-Racine + (2021),
Bohr , Zavala, Cyr-Racine+ (2020)

Halo mass function in the presence of DAOs

- Halo mass function has a distinct shape than either CDM or WDM



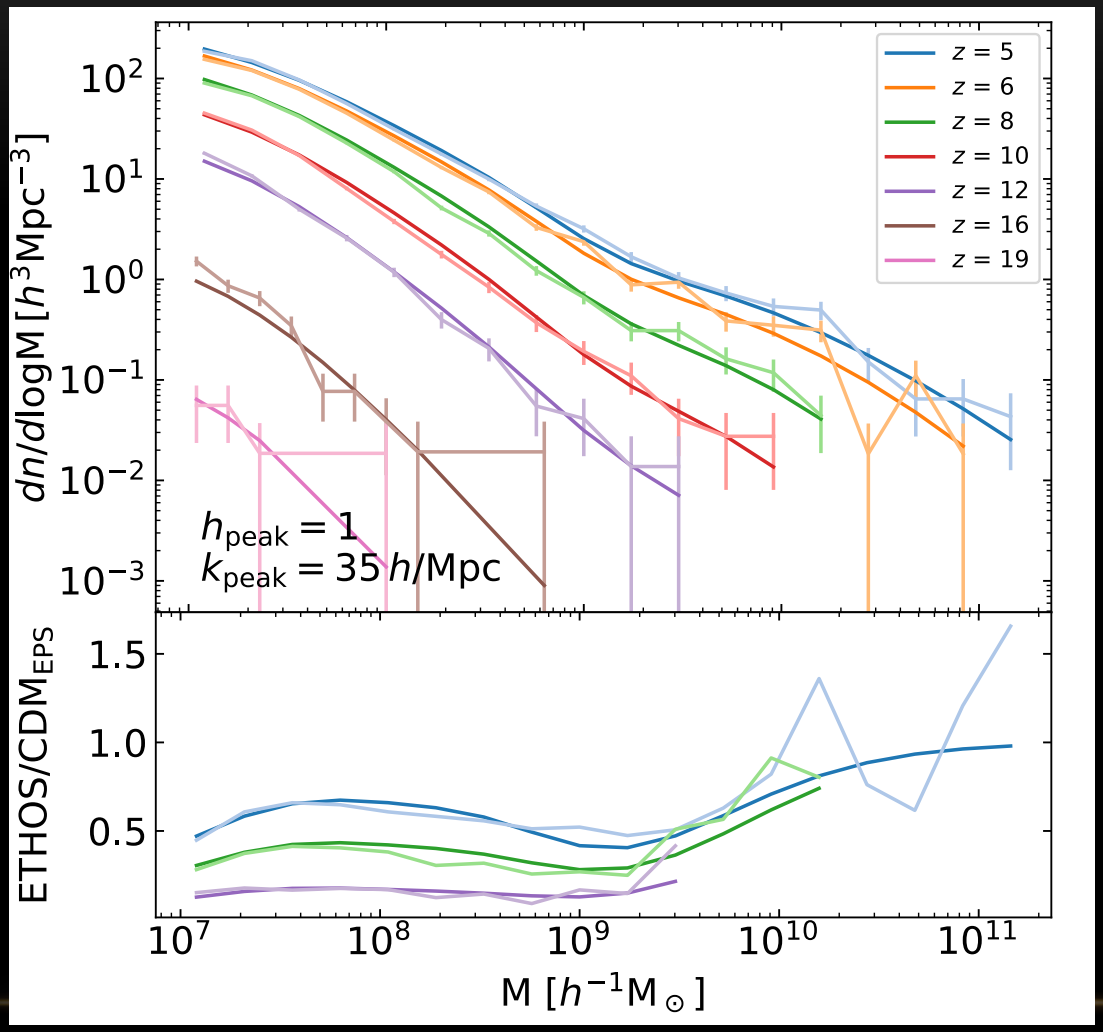


Muñoz, Bohr, Cyr-Racine + (2021)

Bohr , Zavala, Cyr-Racine+ (2021)

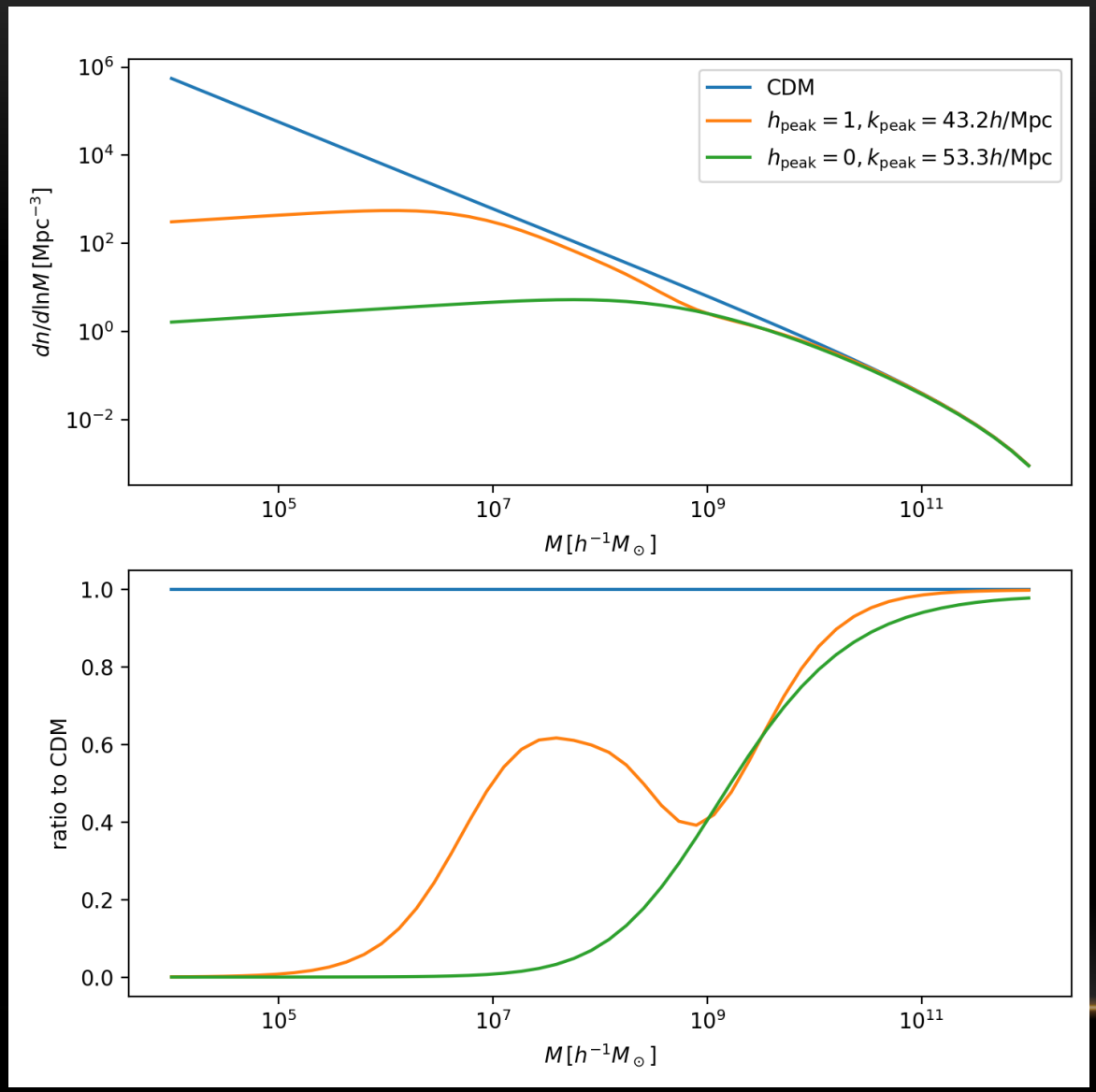
Halo mass function in the presence of DAOs

- We also capture the correct redshift evolution



Bohr , Zavala, Cyr-Racine+ (2021)

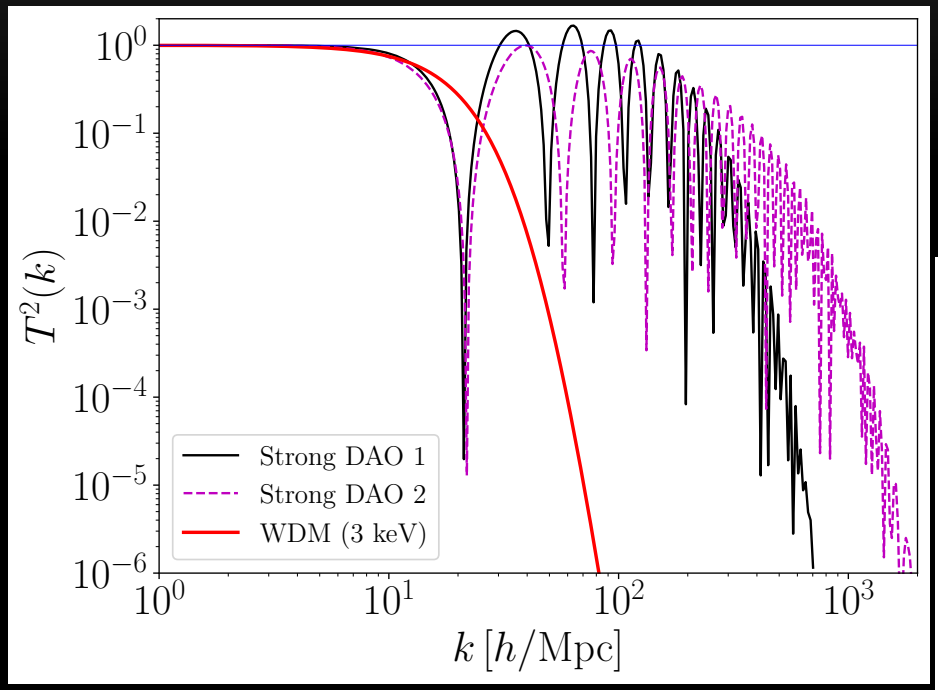
A new feature in the mass function

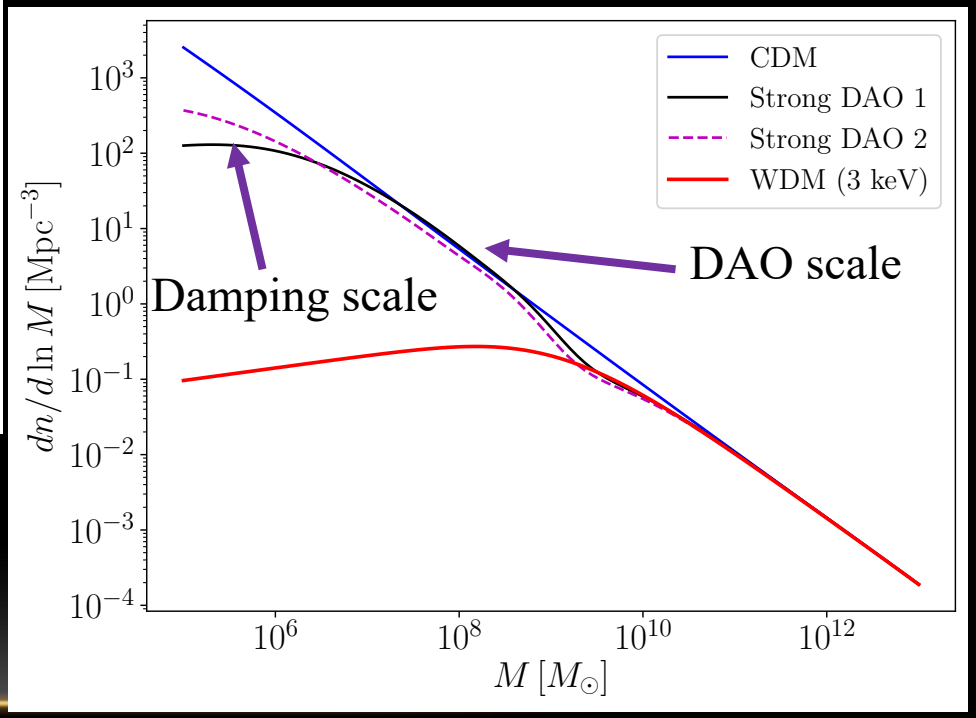


Early-universe scattering between dark matter and a relativistic species introduces a new DAO "feature" in the halo mass function.

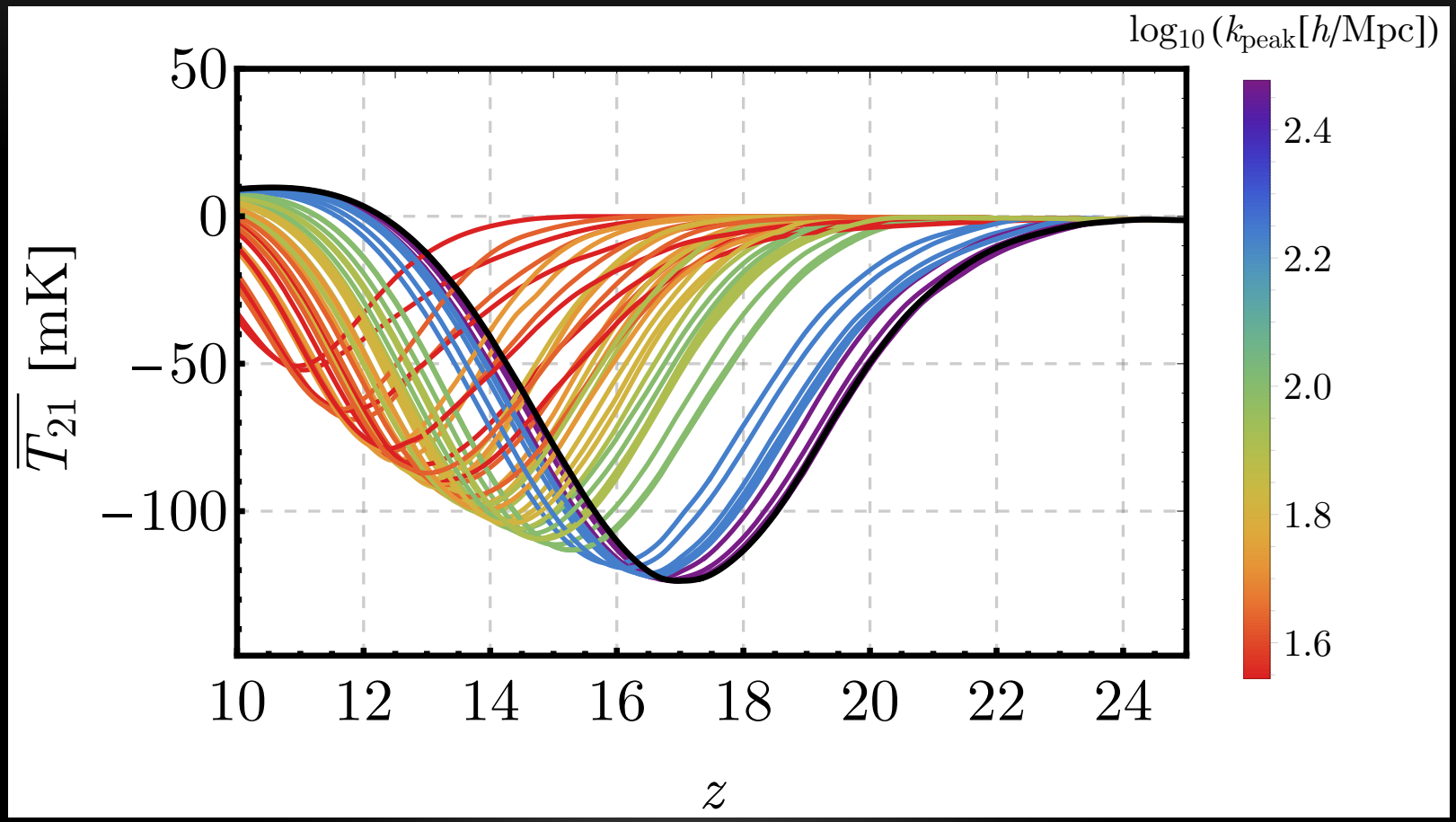
An interesting mass function shape

- DAO: Sowing confusion in the halo mass function!



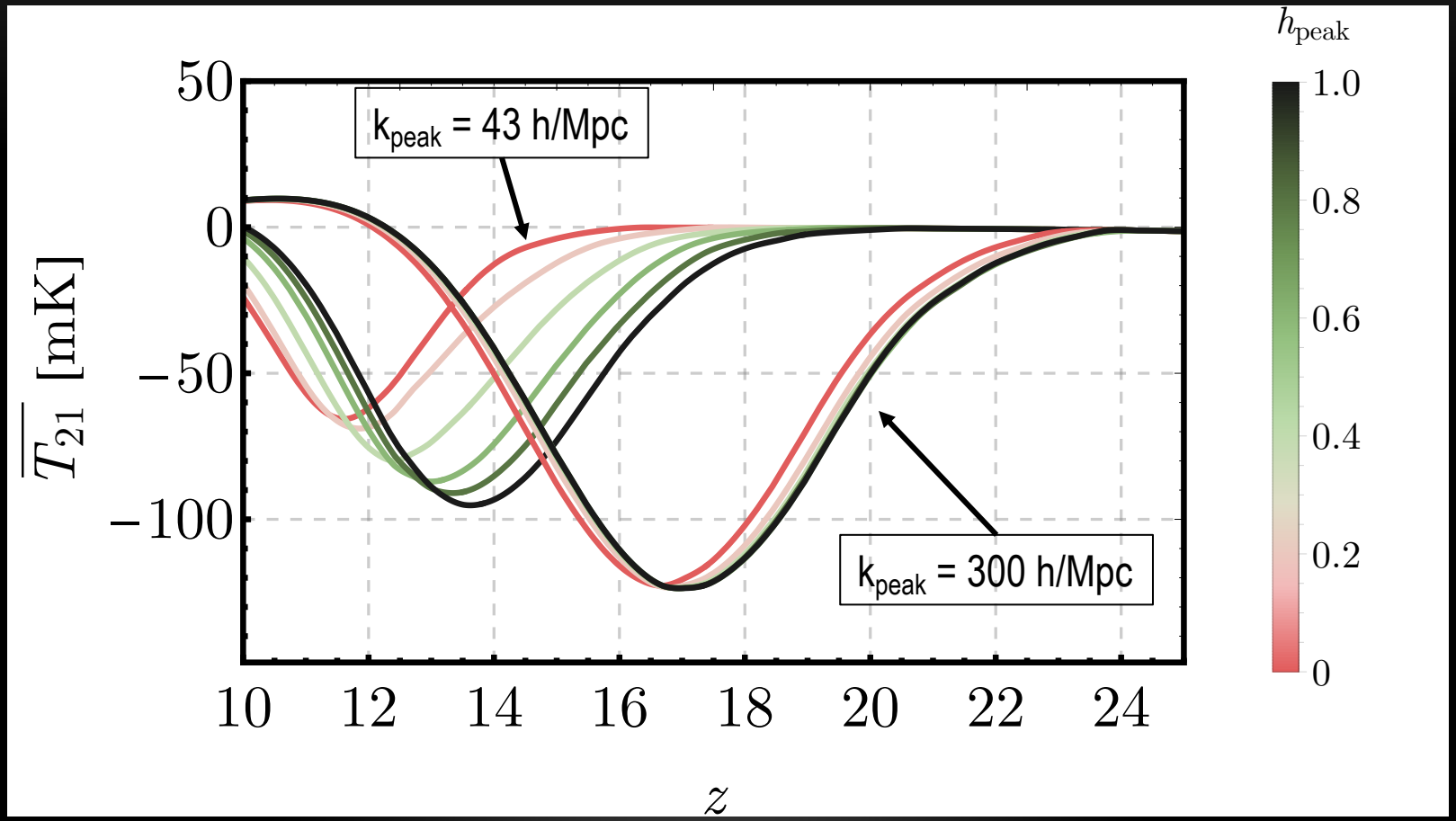


21-cm global signal: Impact of DAOs



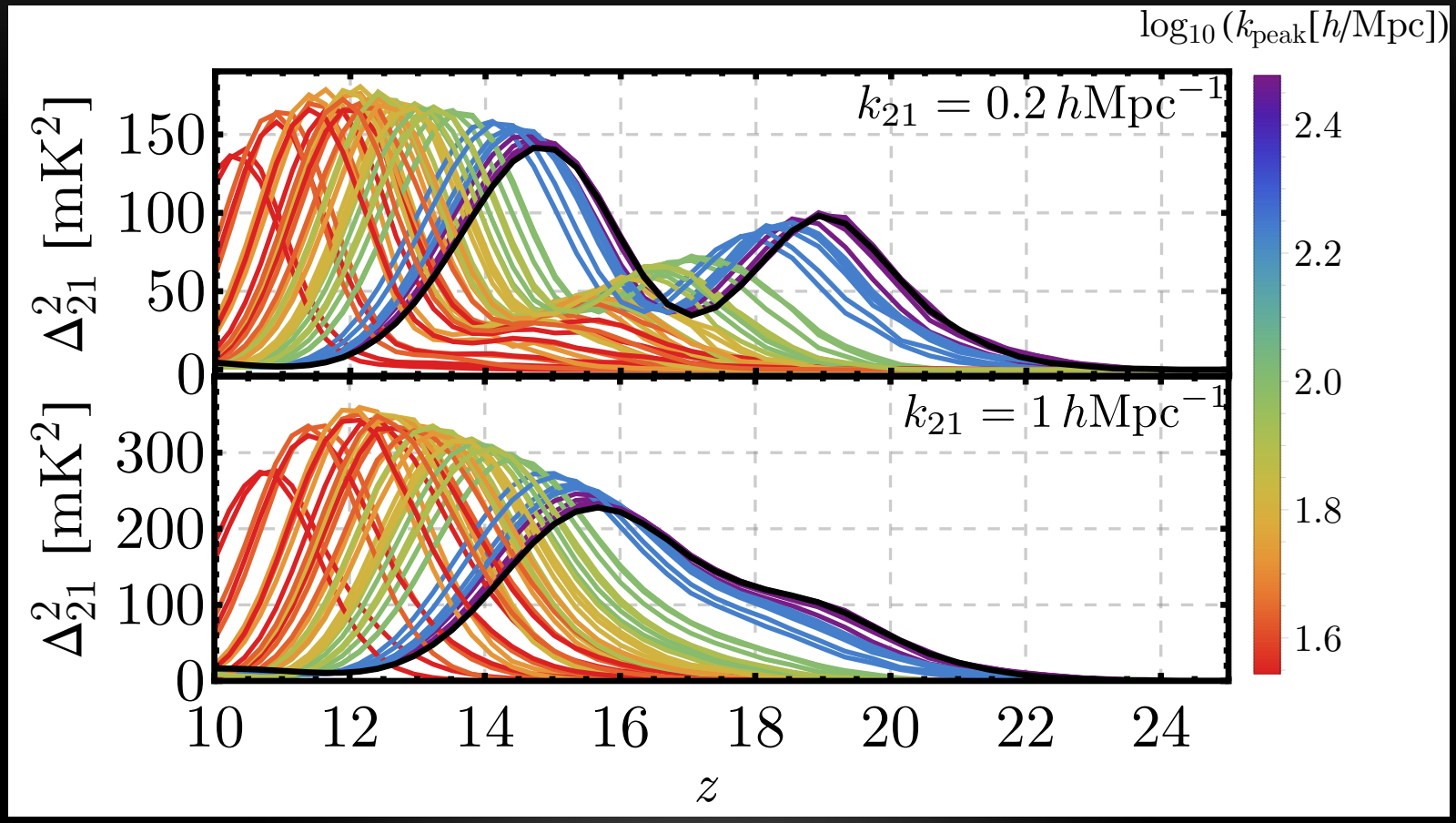
Muñoz, Bohr, Cyr-Racine + (2021)

21-cm global signal: Impact of DAOs



Muñoz, Bohr, Cyr-Racine + (2021)

Even more information contained in the 21-cm fluctuation spectrum



Muñoz, Bohr, Cyr-Racine + (2021)

Conclusions

- It's great to see everyone's interest in atomic DM.
- Focusing only on its ab-initio effects, atomic DM has a rich impact on structure formation => DAOs, damping.
- Shape of DAOs is strongly influenced by the width of the DM drag visibility function.
- Coupled to a mechanism to change the (regular) photon-baryon scattering rate, atomic DM could play a key role in allowing the CMB to be consistent with a high H_0.
- DAOs can leave interesting signatures in Lyman-alpha, the halo mass function, and 21cm (among others)