A Cosmological Dark Matter Collider Experiment

PASCOS 2021

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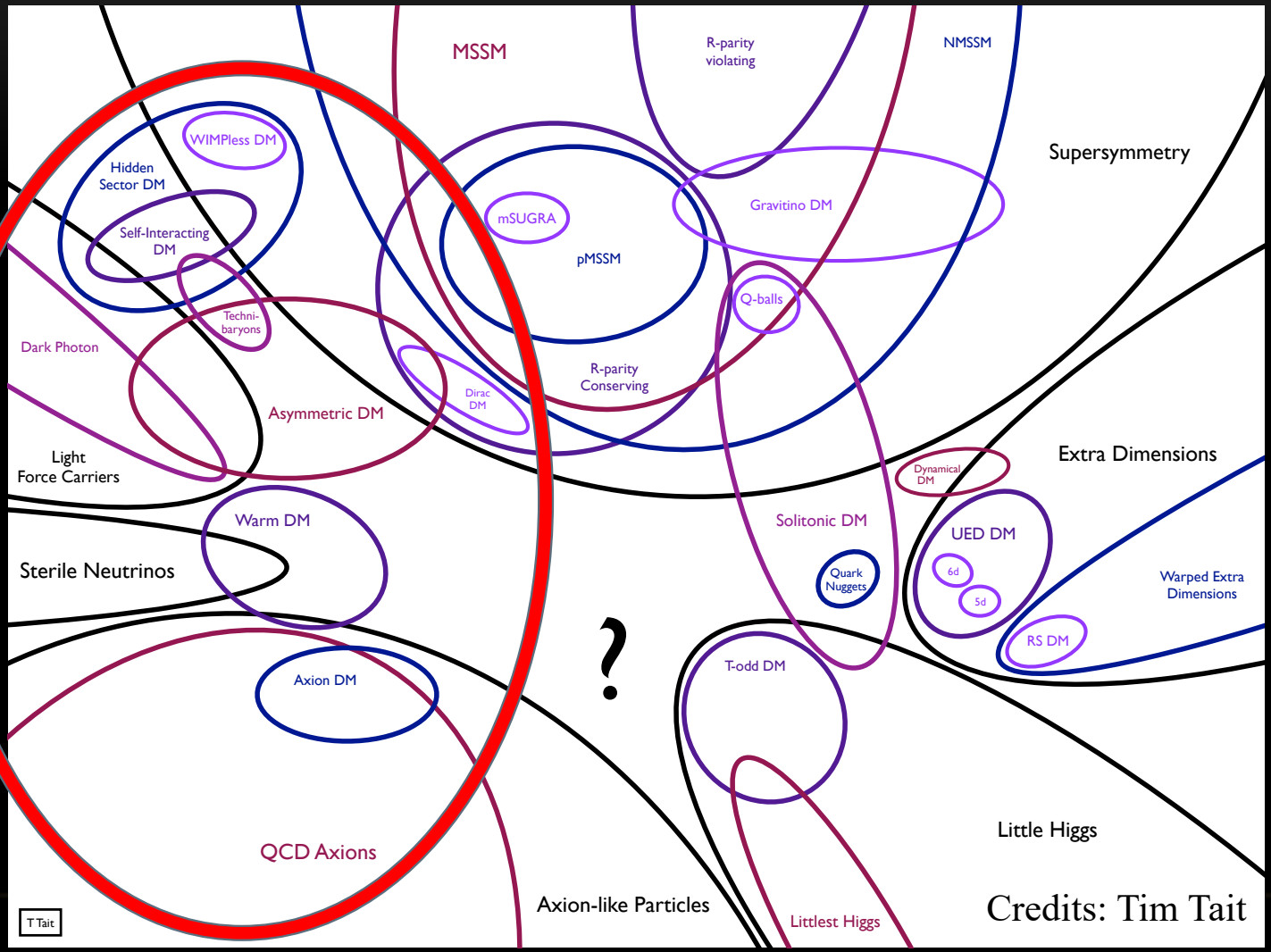
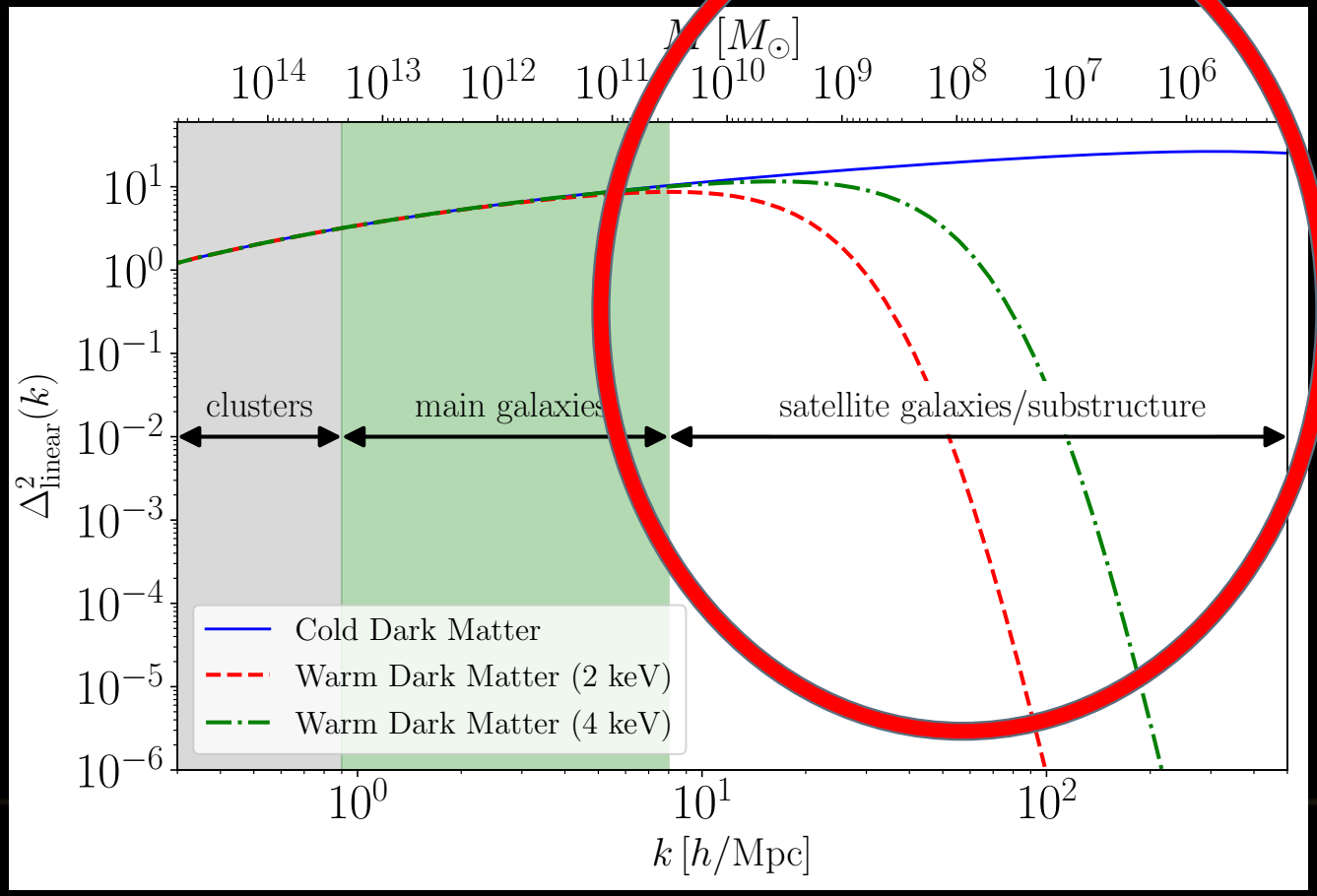
Broad parameter space for dark matter…which one is right??



Focus on small-scale matter power spectrum

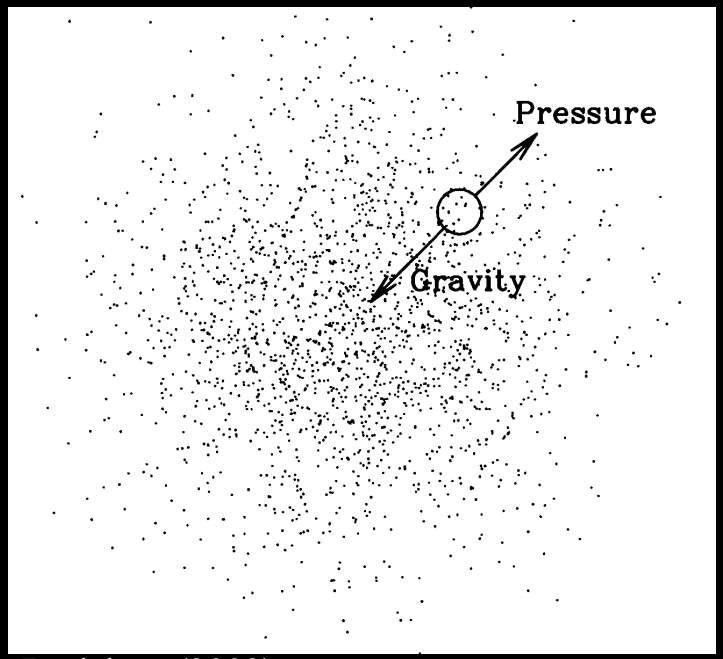
- The matter power spectrum tells us the typical amplitude of matter fluctuations at different scales.



Structure of the power spectrum

- Competition between gravity and pressure determines the shape of the power spectrum

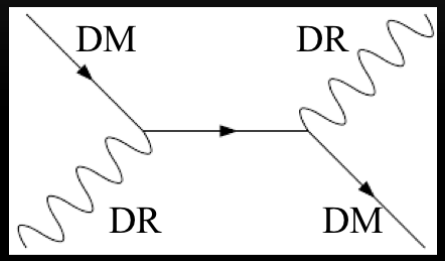
$$P_{\rm m}(k) = T^2_{\rm m}(k) P_\zeta(k)$$

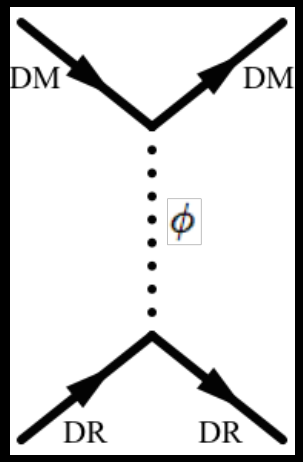


Dodelson (2003)

$$\ddot{\delta} + [\text{Pressure} - \text{Gravity}]\, \delta = 0.$$

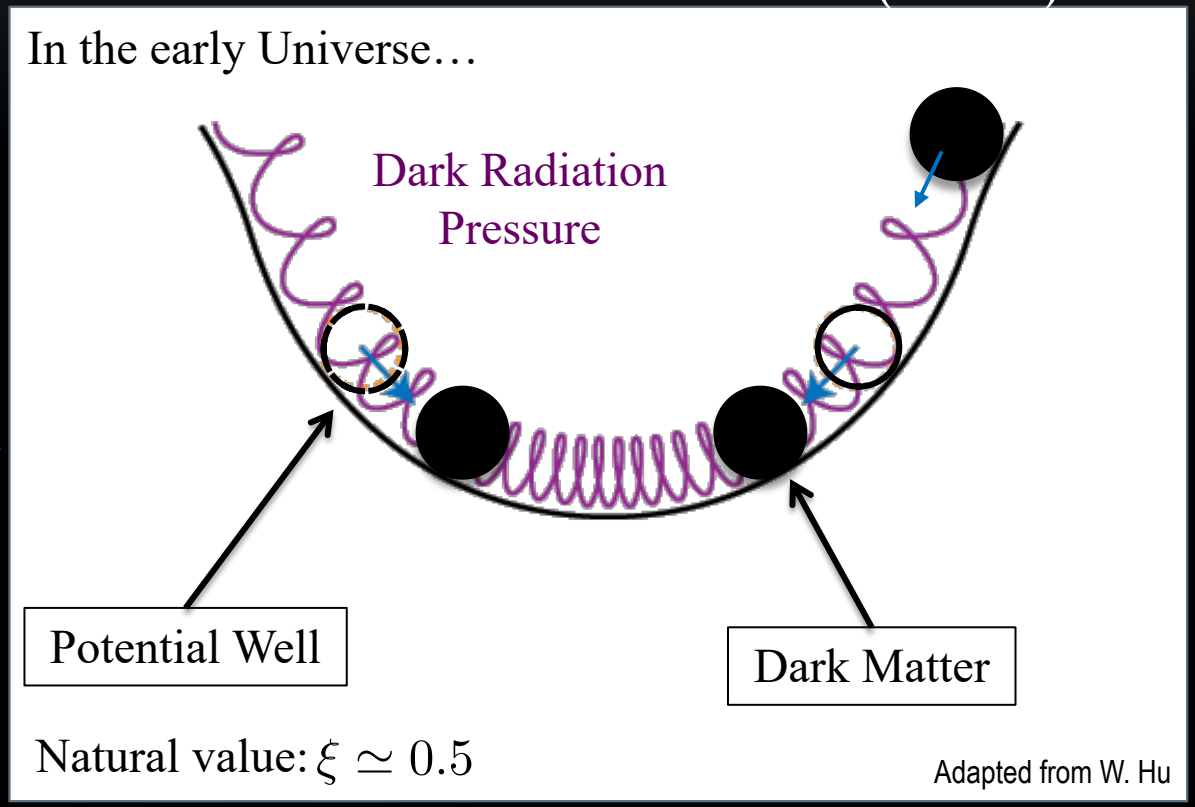
Phenomenology of dark matter-dark radiation (DR) interaction





Cyr-Racine et al. (2016)
Cyr-Racine et al. (2014)
Cyr-Racine & Sigurdson (2013)

Dark acoustic oscillation (DAO)

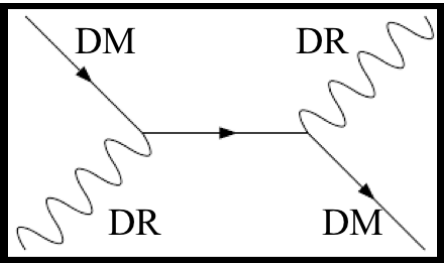


$$\xi \equiv \left(T_D / T_{\rm CMB}\right)\big|_{z=0}$$

Focus: Coupling dark matter to light relativistic species

- Example 1: Dark matter interacting with a massless photon.

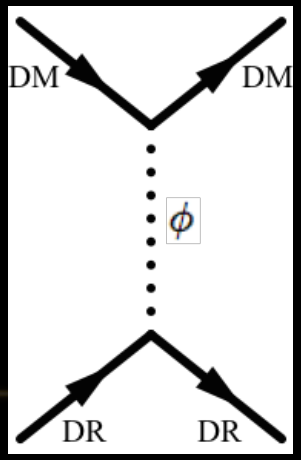
$$\mathcal{L}_{\rm int} = -(D^\mu \chi)^\dagger D_\mu \chi - m_\chi^2 \chi^\dagger \chi, \qquad \text{where} \qquad D_\mu = \partial_\mu - i g_\chi \tilde{A}_\mu.$$



- Example 2: Dark matter interacting with a massless neutrino via a massive mediator.

$$\mathcal{L}_{\rm int} = -g_\chi \phi_\mu \bar{\chi} \gamma^\mu \chi - \frac{1}{2} g_\nu \phi_\mu \bar{\nu}_{\rm s} \gamma^\mu \nu_{\rm s} - \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu - \frac{1}{2} m_\chi \bar{\chi} \chi$$

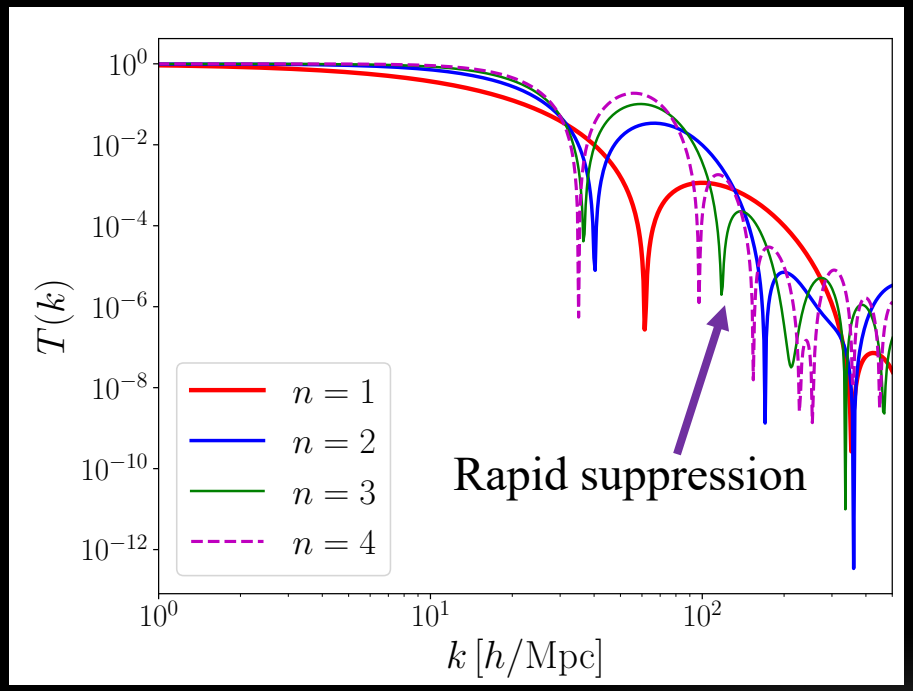
…and many more!



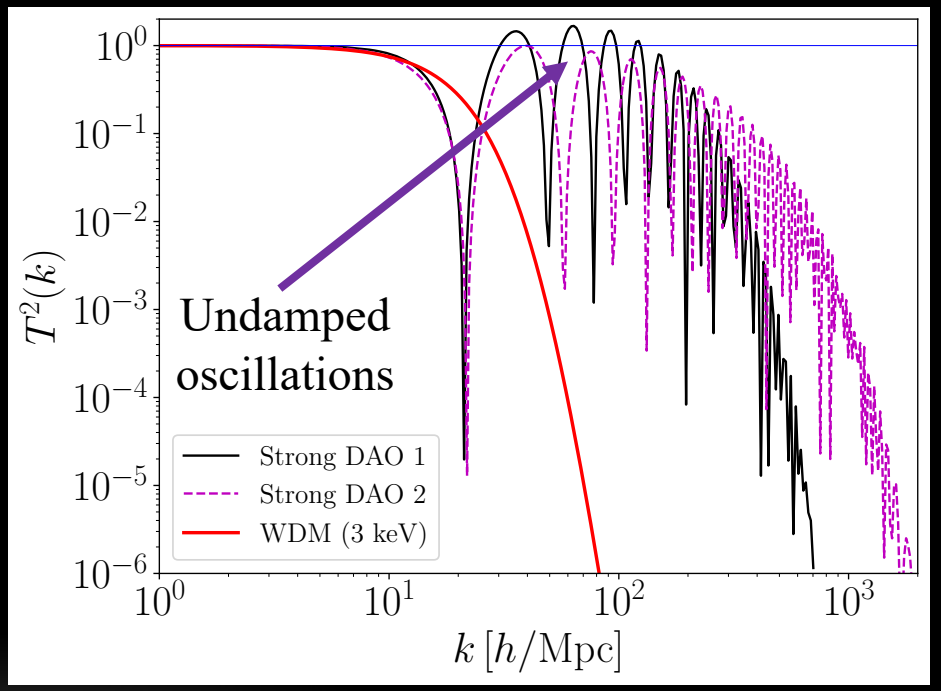
Hofmann et al. 2001; Chen et al. 2001; Bœhm et al. 2002; Green et al. 2004; Bertschinger 2006; Bringmann & Hofmann 2007; van den Aarssen et al. 2012; Cyr-Racine & Sigurdson 2013

Broad diversity of matter power spectrum shapes

Weak DAO



Strong DAO



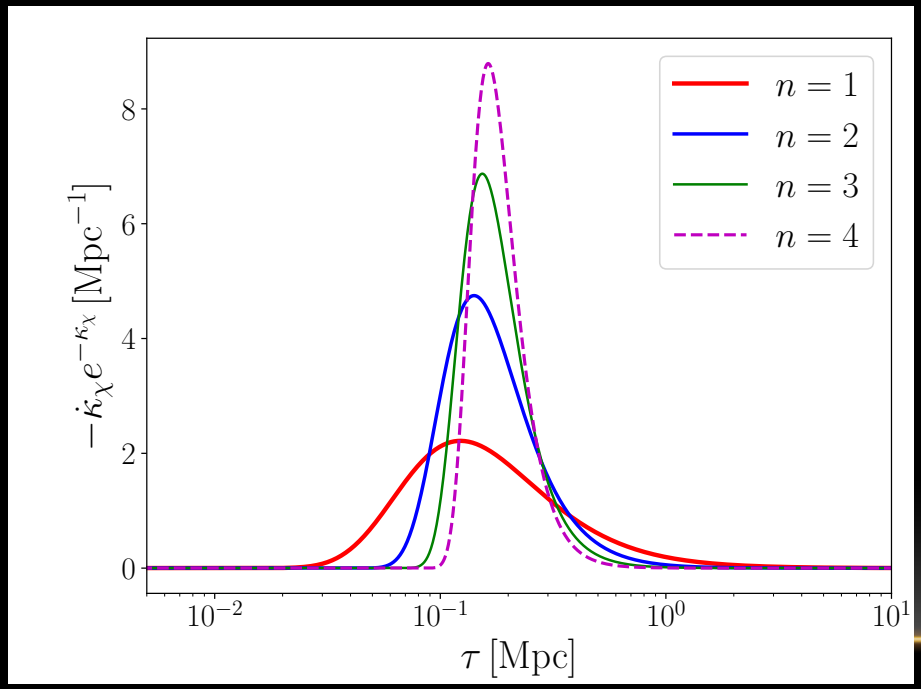
Cyr-Racine et al. (2016)

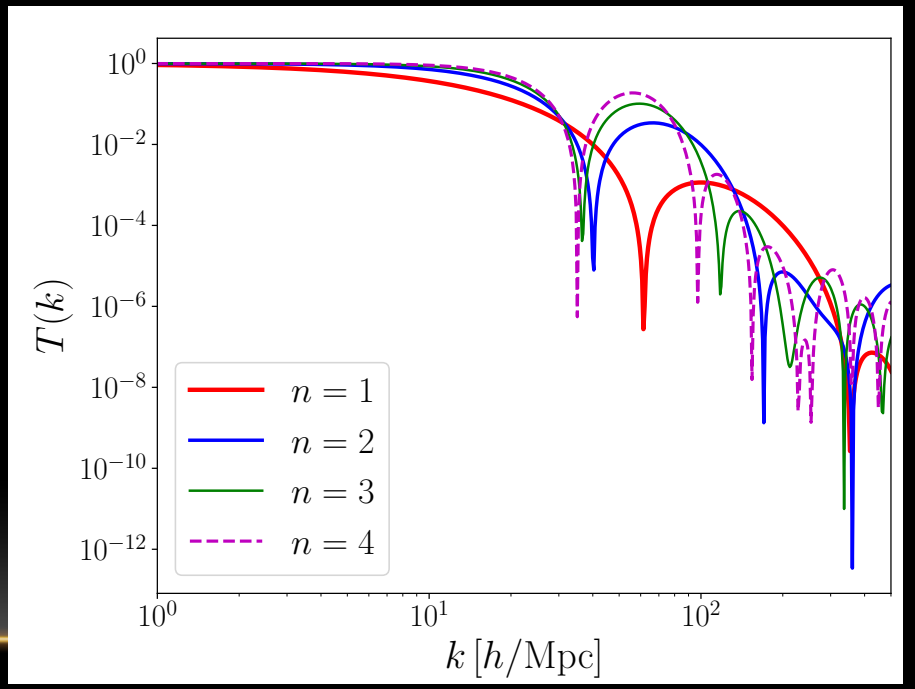
What determines the shape of the matter power spectrum?

DM-DR interaction: The dark matter drag visibility function determines the shape of the transfer function.

$$\dot{\kappa}_\chi = -a\frac{4}{3}\frac{\rho_{\rm DR}}{m_\chi}\langle\sigma_{\rm DM-DR}\rangle \approx -\left(\frac{z}{z_{\rm D}}\right)^{n+1}\mathcal{H}$$

Cyr-Racine et al. (2016)





Important Lesson #1

Dark matter particle collisions with light degrees of freedom at early times imprint a new scale in the matter distribution.

Can we detect its presence?

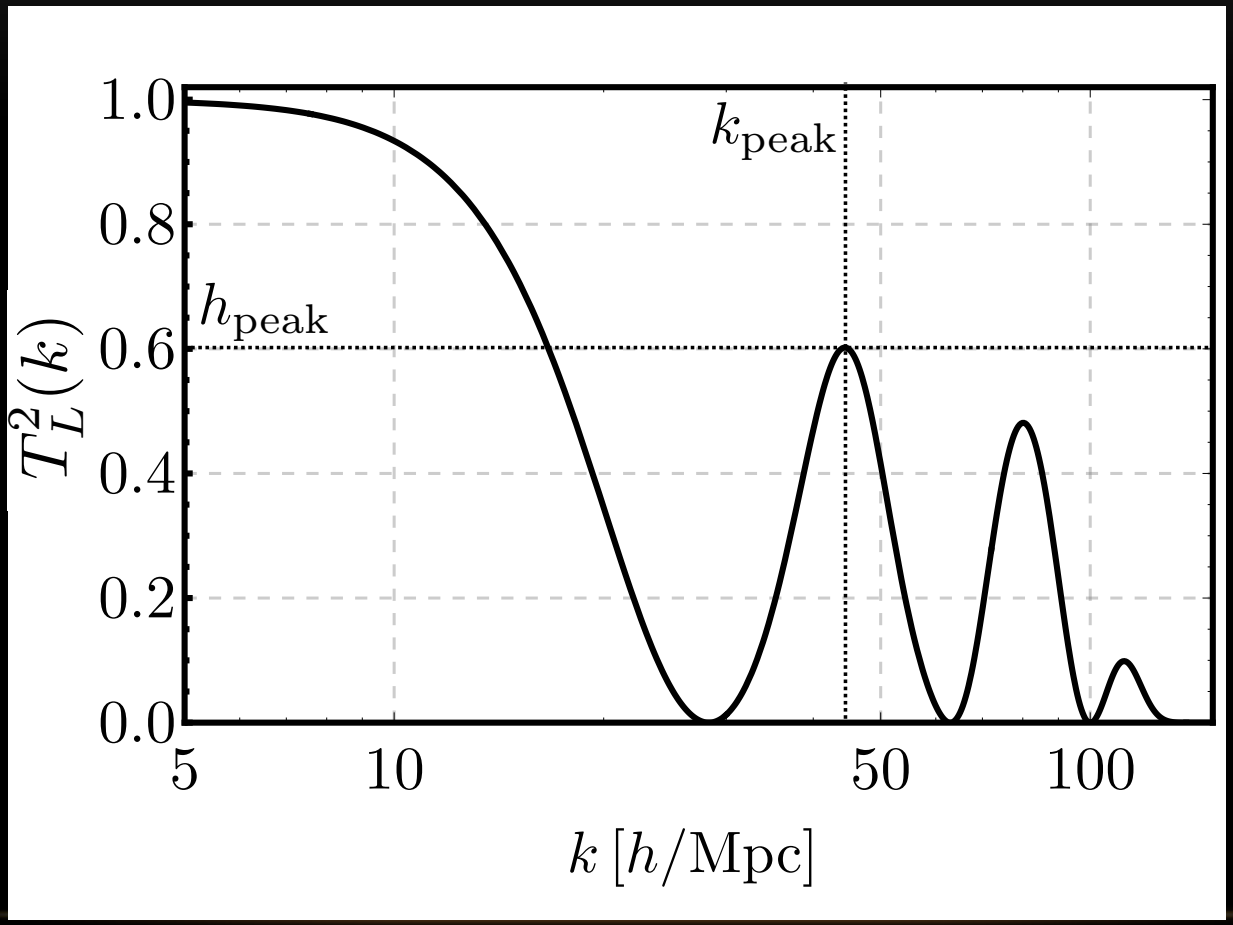
Introducing some notation

- Capture key features of DAOs with two parameters:

Julian Muñoz

Jesús Zavala

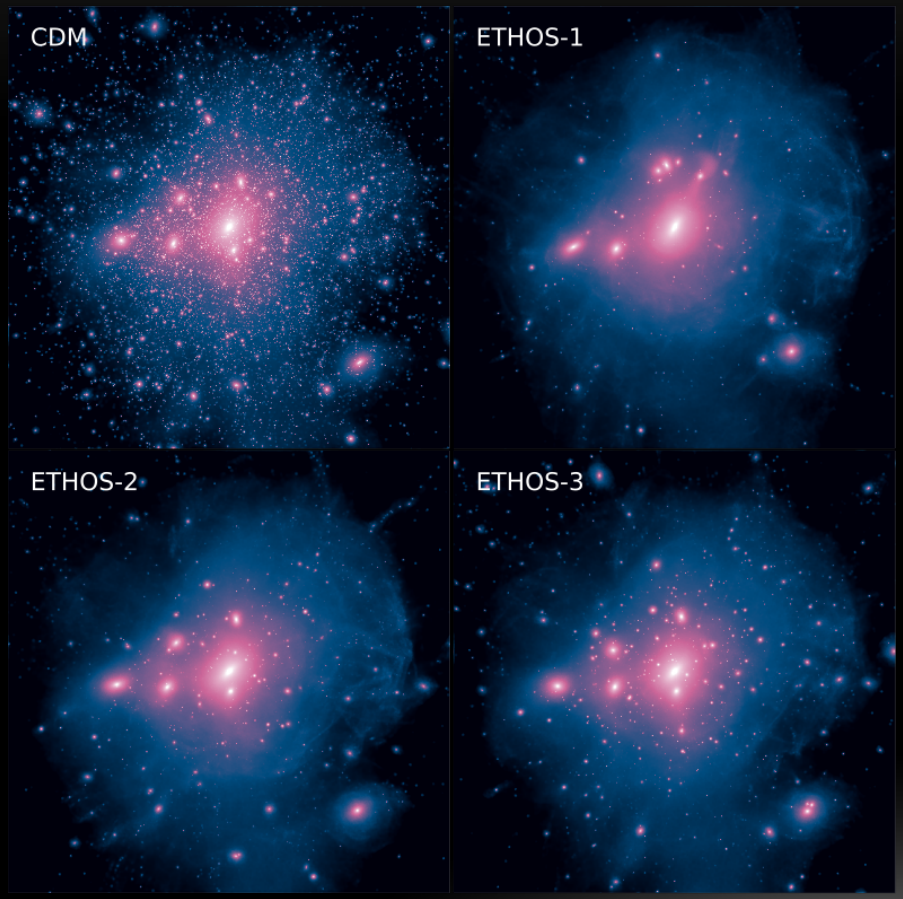
Sebastian Bohr



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

Look at the halo mass function

- Counting halos of different masses



Vogelsberger, Zavala, Cyr-Racine et al. (2016)

Following Press & Schechter:

$$\frac{dn}{d\ln M} = -\frac{1}{2}\bar{\rho}_m \frac{f}{\sigma^2}\frac{d\sigma^2}{dM}$$

$$\sigma^2(M) = \frac{1}{2\pi^2}\int dk k^2 P(k) W^2(k)$$

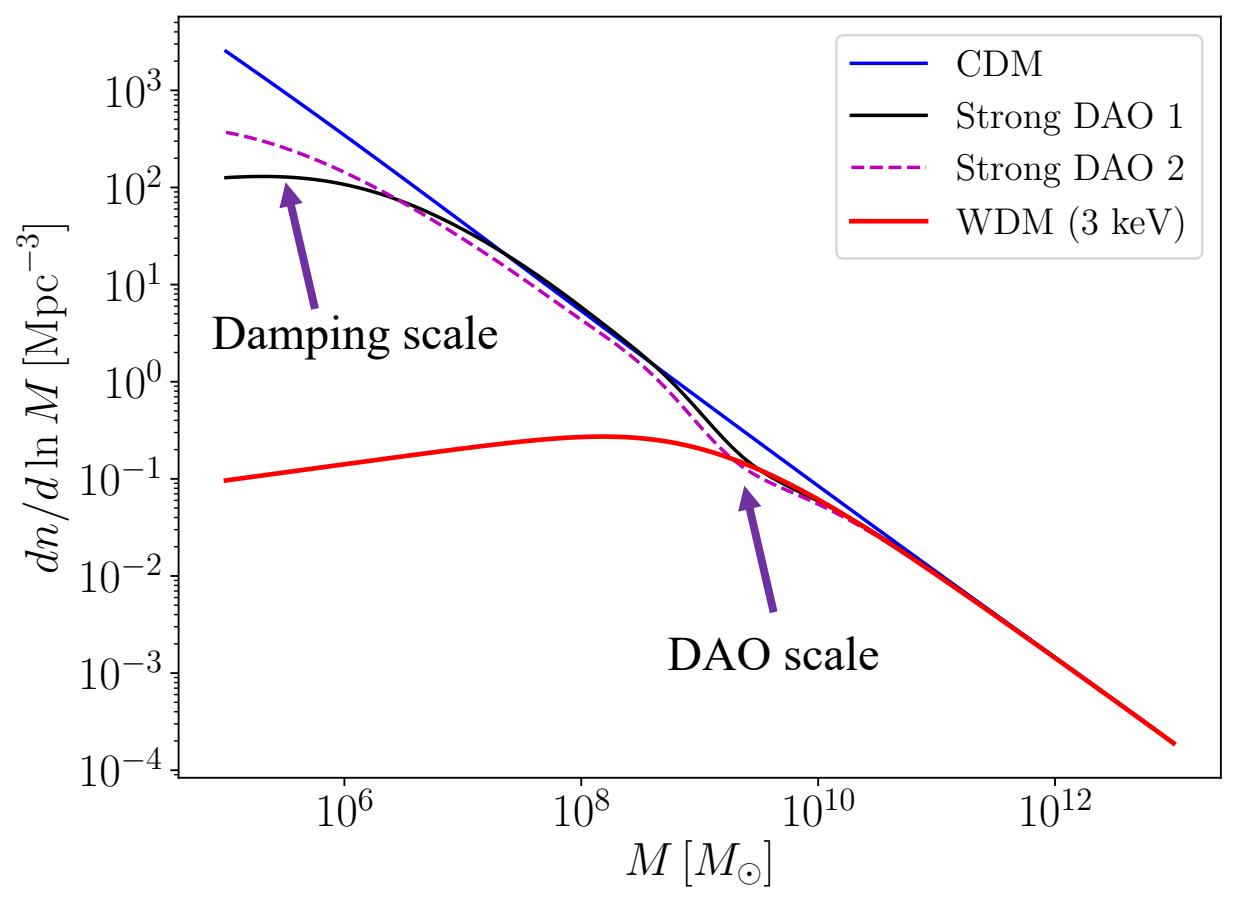
$$f(\nu) = A\sqrt{\frac{2q\nu}{\pi}}(1 + (q\nu)^{-p})\exp\left(-\frac{q\nu}{2}\right)$$

$$\nu = \frac{\delta_c^2}{D^2(z)\sigma^2}$$

Press & Schechter (1974), Bond et al. (1991), Sheth & Tormen (1999)

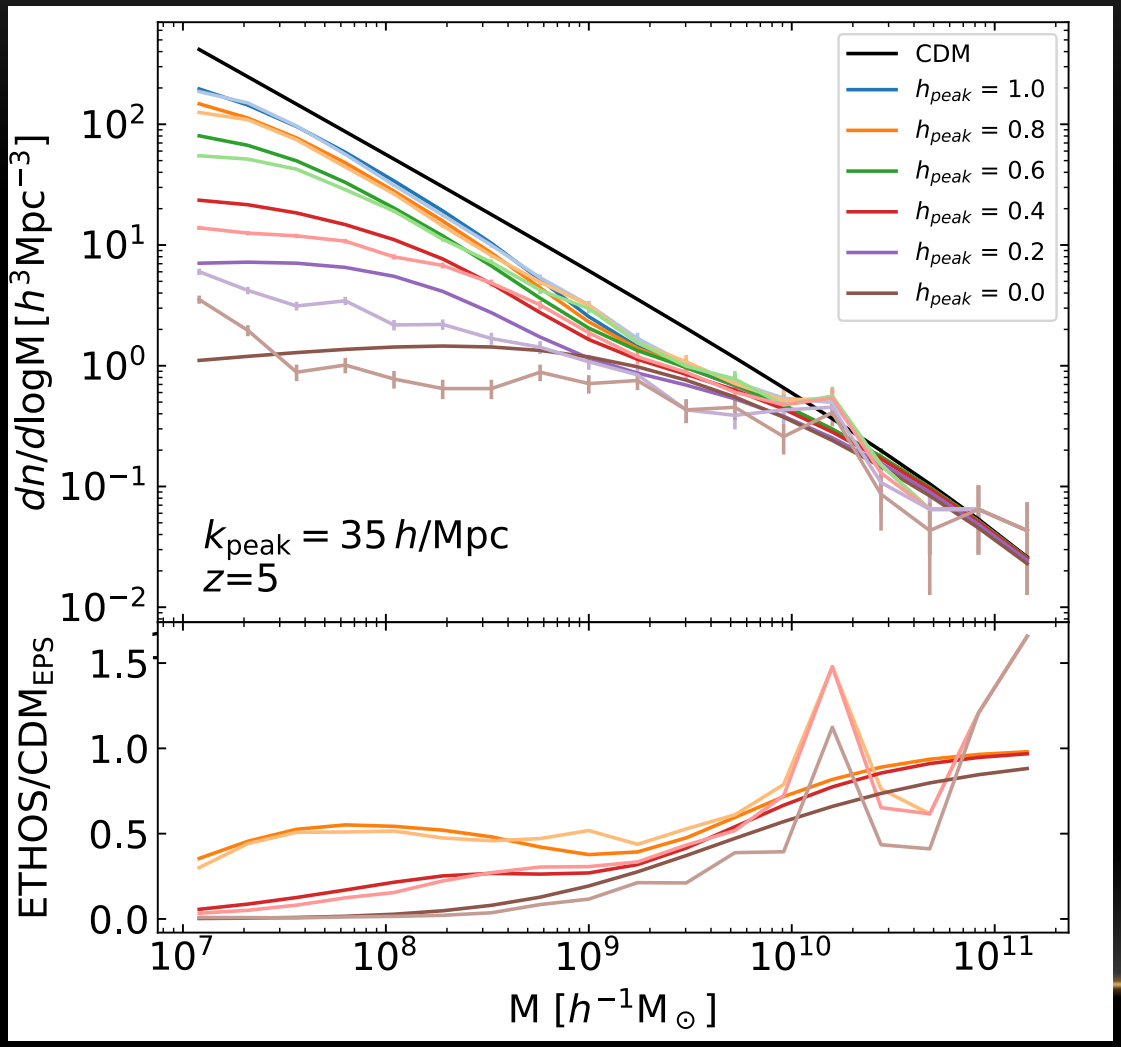
An interesting mass function shape

- DAO: Sowing confusion in the halo mass function!



Halo mass function in the presence of DAOs

- Perform a suite of 50 simulations for a grid of k_{peak} and h_{peak} values



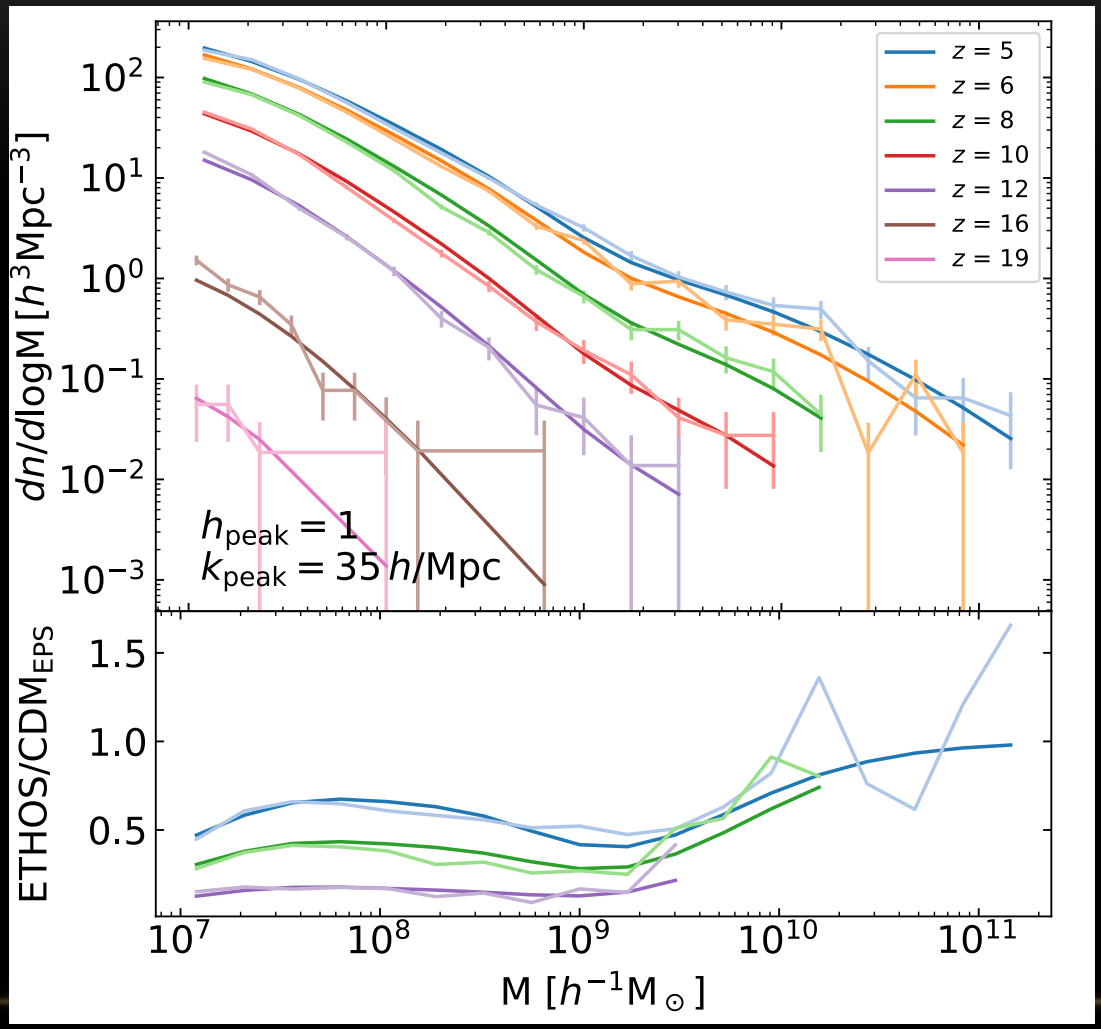
$$\sigma^2(R) = \frac{1}{2\pi^2}\int_0^\infty dk k^2 P(k) \widetilde{W}_R^2(k)$$

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

Bohr , Zavala, Cyr-Racine+ (2021)

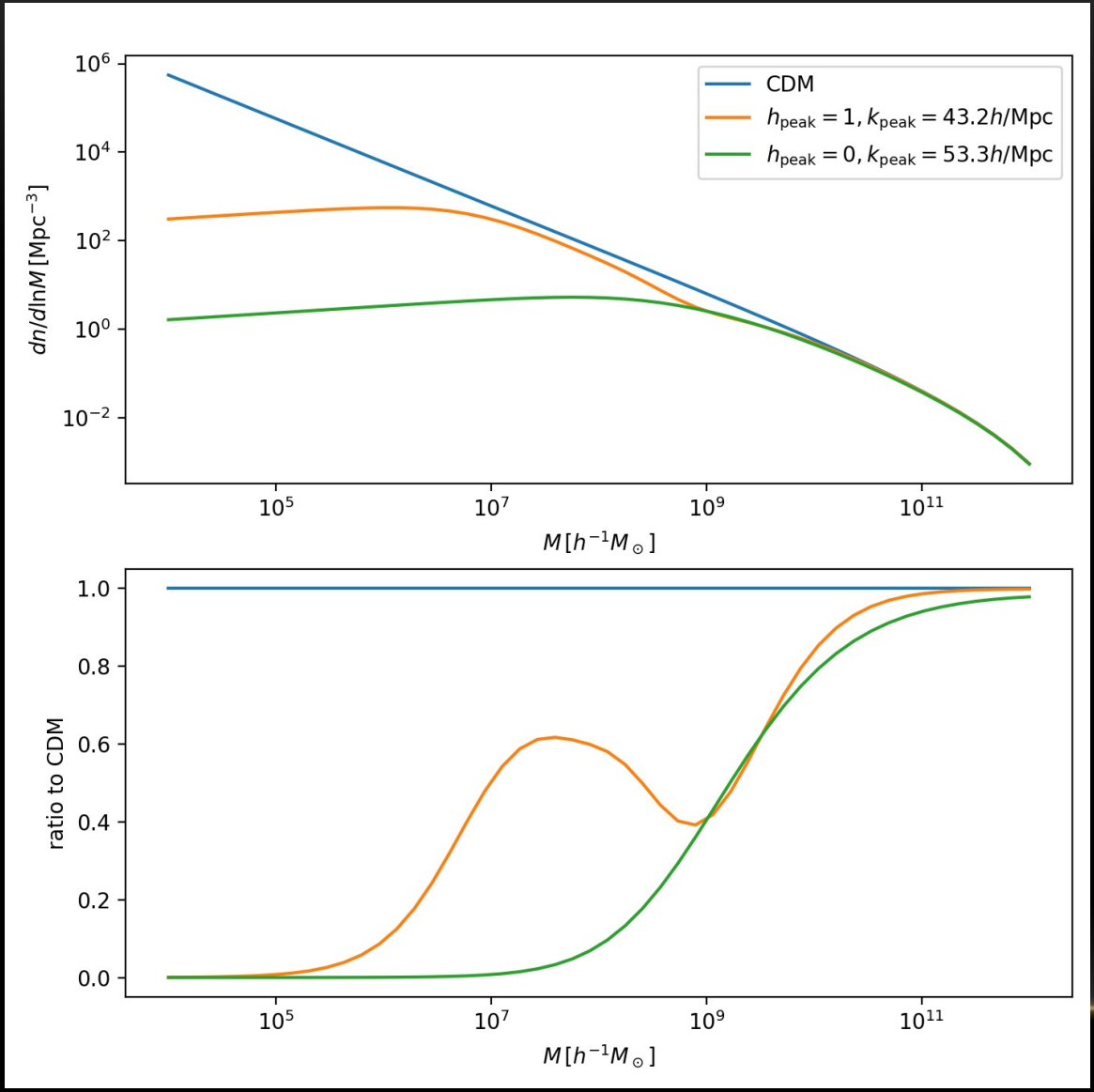
Halo mass function in the presence of DAOs

- Prominence of DAO feature increases with time!



Bohr , Zavala, Cyr-Racine+ (2021)

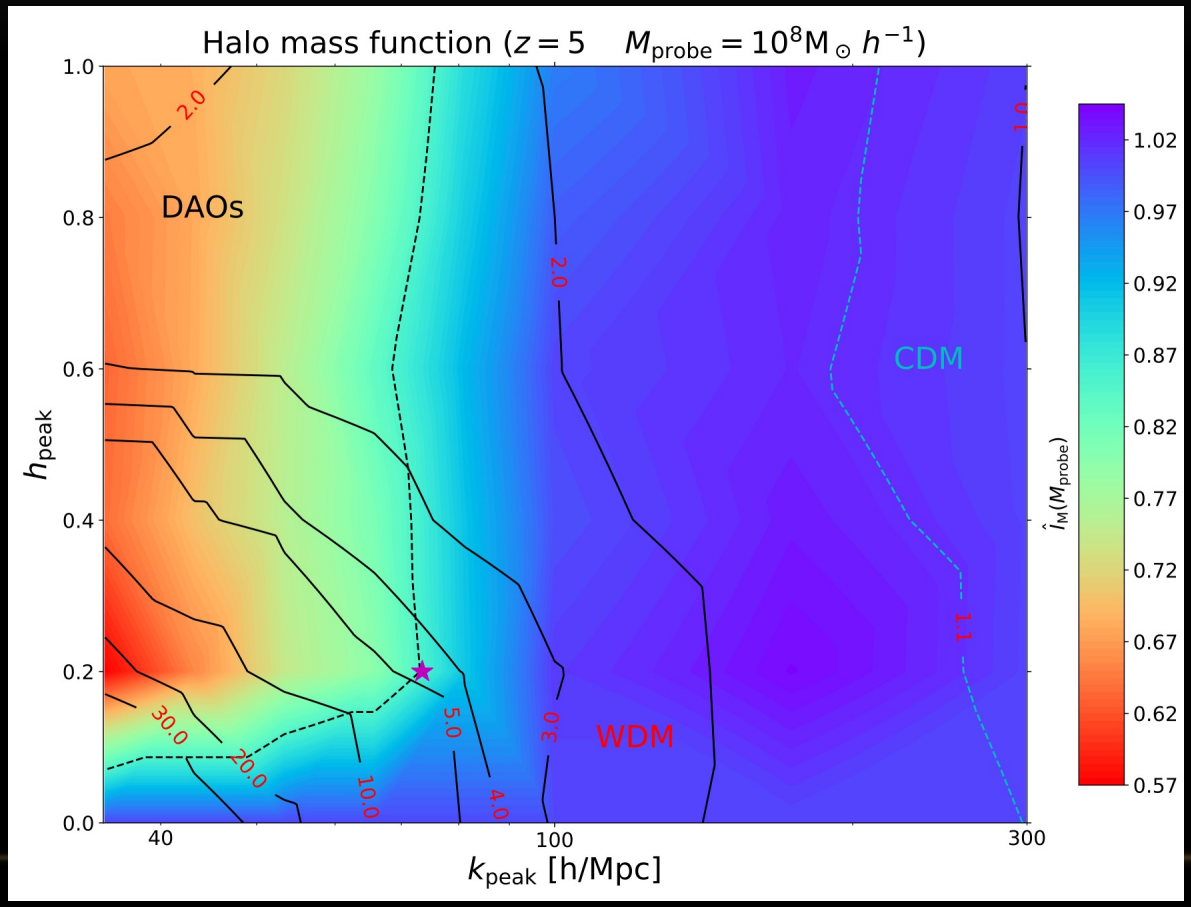
A new feature in the mass function



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

Halo mass function: Better sensitivity to DAOs

- There is a broad range of models that are distinguishable from WDM.



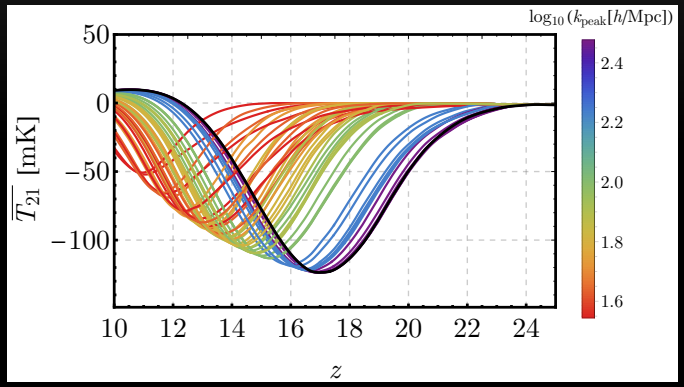
Bohr , Zavala, Cyr-Racine+ (2020)

Important Lesson #2

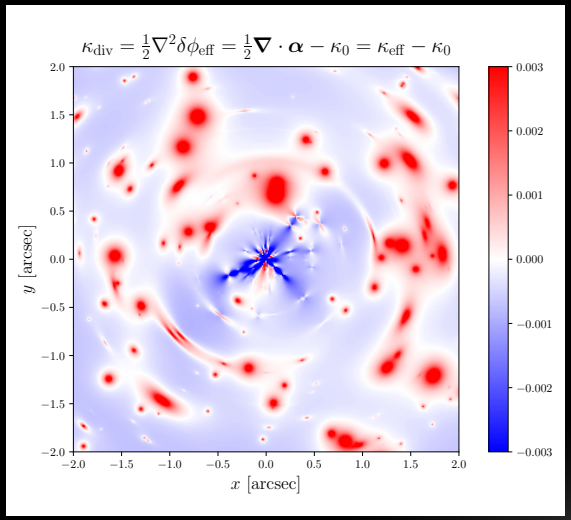
The halo mass function retains memory of dark matter interactions taking place in the early universe.

Applications

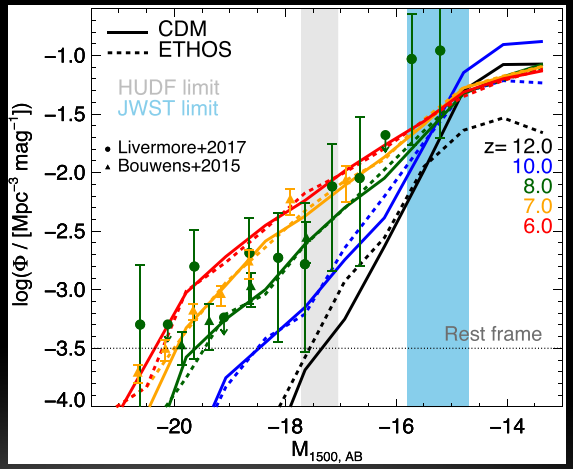
- 21-cm cosmology
- UV Luminosity function
- Substructure Lensing



Muñoz, Bohr, Cyr-Racine + (2021)



Dhanasingham & Cyr-Racine (in prep.)



Lovell et al. (2018)

Conclusions

- DM-DR collisions at early times leave distinct imprints on the linear matter power spectrum.
- While nonlinear evolution tends to erase these imprints, the halo mass function has a much better memory of these effects. A new feature appears in the HMF.
- In the strong DAO case, these predictions can be quite distinct as compared to either WDM or CDM.
- The prominence of the DAO feature in the halo mass function increases with time.

Thank you!

Back-up slides

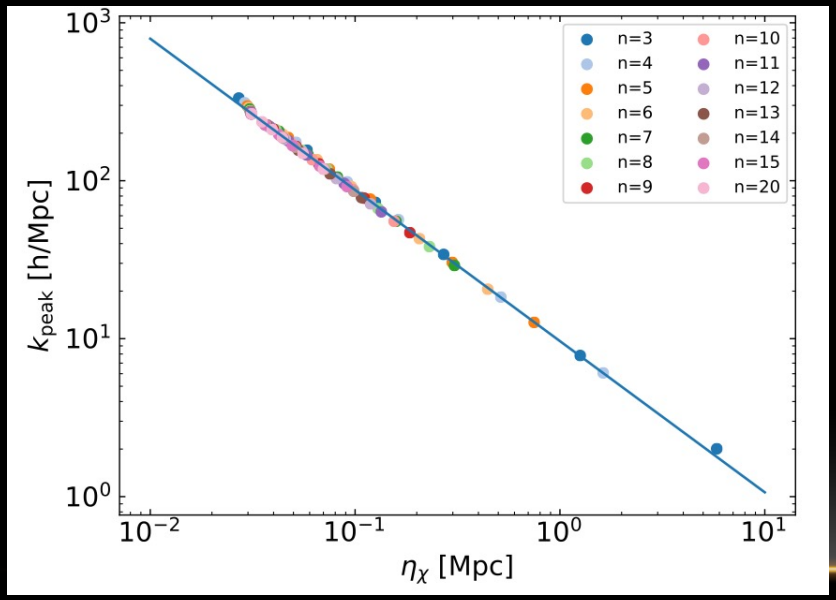
Connection to particle physics

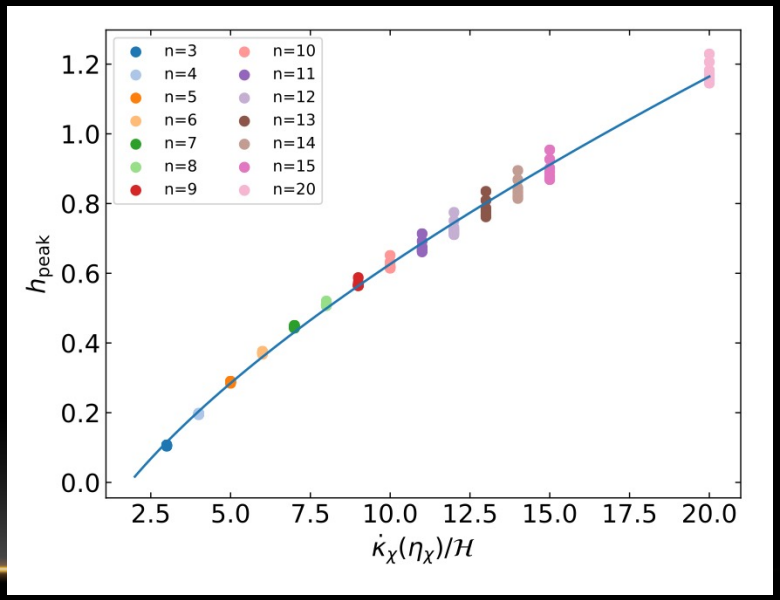
- Clear connection to the particle physics: for an opacity scaling as

$$\dot{\kappa}_\chi \propto a_n (1+z)^{n+1}$$

- Define the time of dark matter decoupling via

$$\int_{\eta_\chi}^{\eta_0} -\dot{\kappa}_\chi d\eta = 1$$





Bohr , Zavala, Cyr-Racine+ (2020)