

Probing Dark Matter Particle Physics with Cosmology

Markus R. Mosbech

Theory Seminar, University of Oslo, 11. February 2026

A dark blue diagonal gradient bar that starts from the bottom left and extends towards the top right, covering the lower half of the slide.

Dark Matter: What do we **know**?

- Contributes like matter to the energy budget of the universe
- Clusters like “cold” matter on the scales we have been able to probe
- Accounts for the majority of mass in most collapsed structures
- Very limited coupling to standard model particles, if any
- Limited self-coupling
- At least one stable (or very long-lived) species

The cosmological “standard model”

Six baseline “free” parameters:

- Ω_b : Baryon content
- Ω_{dm} : Dark matter content
- H_0 : Hubble parameter
- A_s : Primordial scalar amplitude
- n_s : Primordial spectrum tilt
- τ : Optical depth to reionization

Implicit “fixed” parameters:

- T_{cmb} : CMB temperature
- N_{eff} : Effective neutrino number

Common extensions:

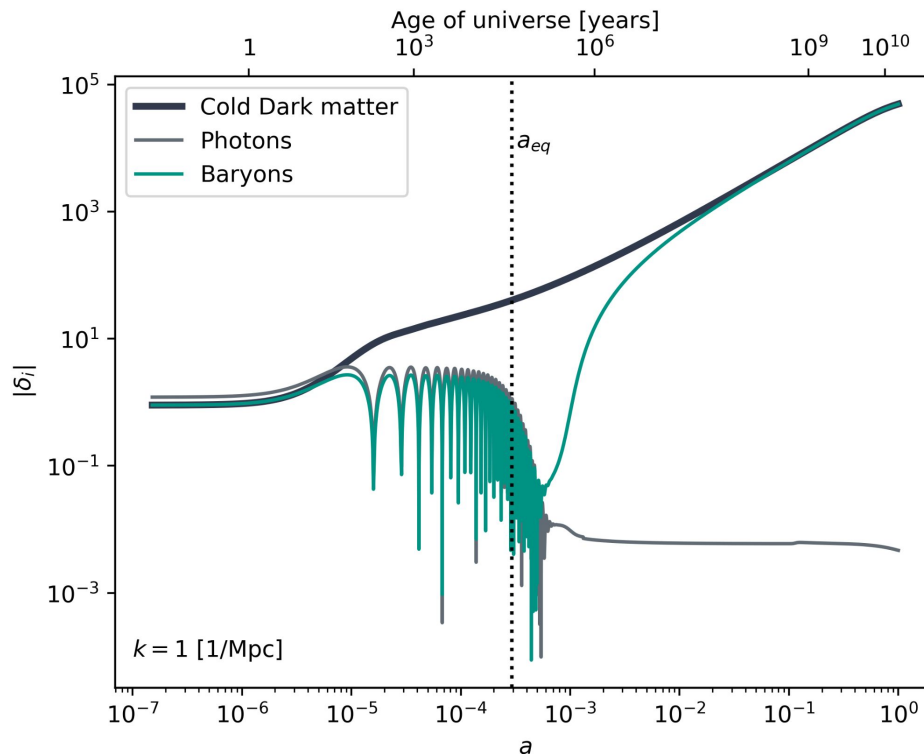
- Ω_k : Curvature
- ΔN_{eff} : Additional ‘dark’ radiation
- M_ν : Neutrino masses
- $w_0 w_a$: Evolving dark energy

The Role of Dark Matter

- Seeds of structure
- Shape of CMB
- Hosts of galaxies

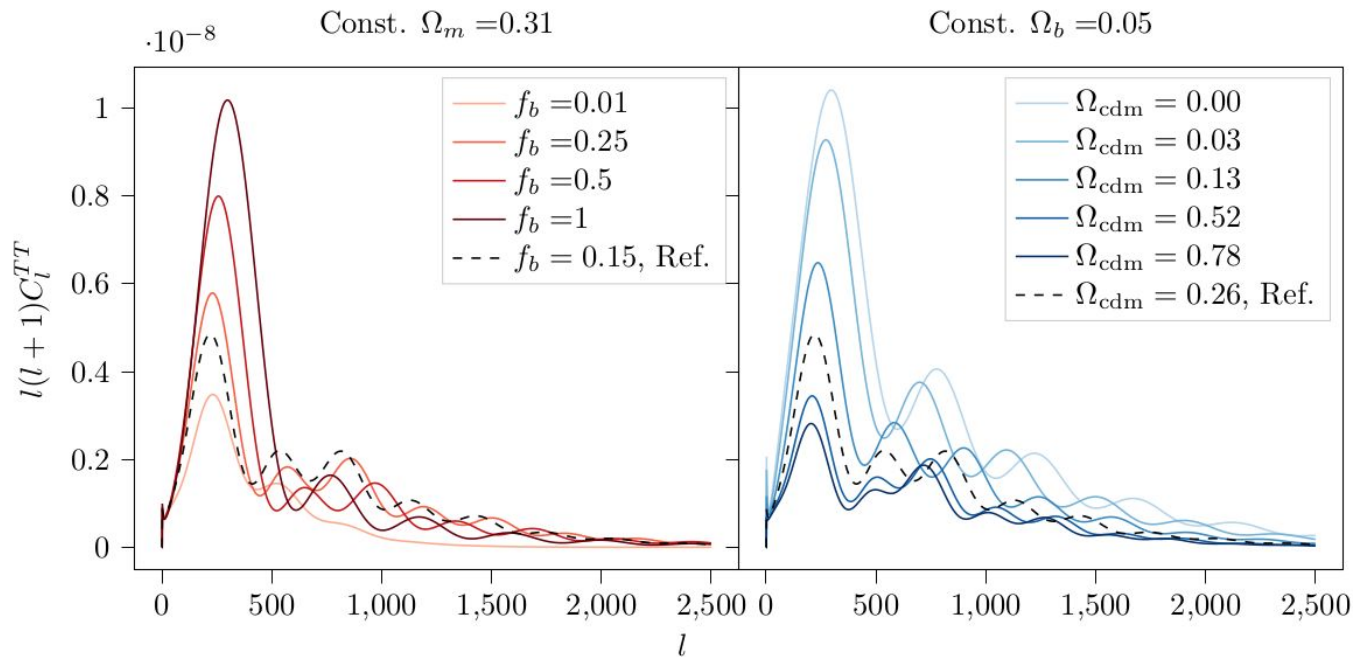
$$\dot{\delta}_{\text{cdm}} = -\theta_{\text{cdm}} + 3\dot{\phi},$$

$$\dot{\theta}_{\text{cdm}} = -\frac{\dot{a}}{a}\theta + k^2\psi.$$



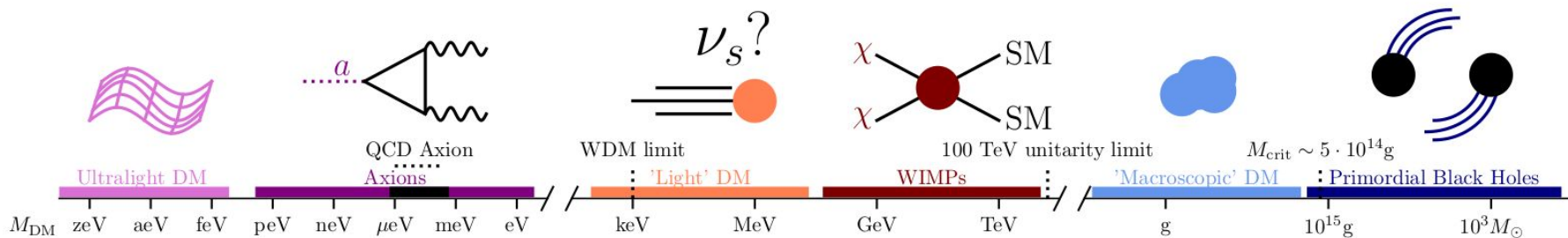
The Role of Dark Matter

- Seeds of structure
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So **what** is Dark Matter?

- CDM is not a “true model” - it is a qualitative description of a type of behaviour
- Cosmology gives us a broad range of integrated observables
- Good at probing general behaviours
- Difficult to probe exact model
- Distinguishing different models with similar signature? Ongoing research!



An example: **DM-neutrino** interactions

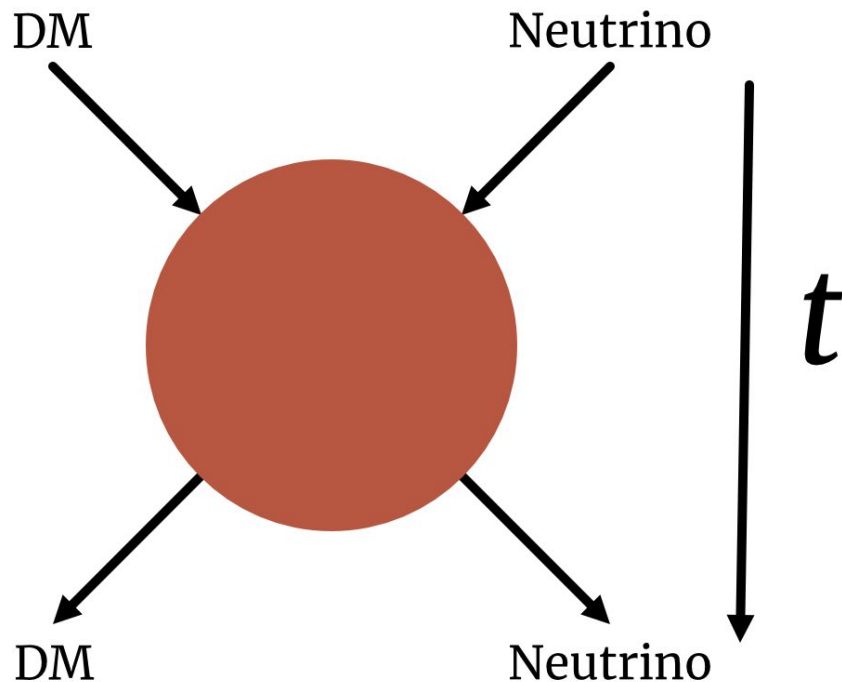
Theoretical motivations:

- Neutrinos not fully understood (neutrino mass)
- Nice to tie DM to something in standard model

Observational “motivations”:

- Hard to probe in laboratory experiments
- Only indirect impact on visible universe
- **Bonus:** hints in data!

The interaction is harder to rule out from other methods: the impact on structure formation is potentially our best probe!



Perturbation equations

- More or less equivalent to interactions with massless dark radiation
- Cheaper to evaluate
- Qualitatively similar to massive case

$$u_{\nu\text{DM},0} = \frac{\sigma_{\nu\text{DM}}}{\sigma_{\text{Th}}} \left(\frac{m_{\text{DM}}}{100 \text{ GeV}} \right)^{-1}$$

$$u_{\nu\text{DM}} = u_{\nu\text{DM},0} \times a^{-n_{\nu\text{DM}}}$$

$$\dot{\kappa}_{\nu\text{DM}} = a n_{\text{DM}} u_{\nu\text{DM}}$$

$$\dot{\delta}_{\text{DM}} = -\theta_{\text{DM}} + 3\dot{\phi},$$

$$\dot{\theta}_{\text{DM}} = k^2 \psi - \mathcal{H} \theta_{\text{DM}} - R \dot{\kappa}_{\nu\text{DM}} (\theta_{\text{DM}} - \theta_{\nu}) .$$

Massive case: Mosbech et al. [arXiv:2011.04206](https://arxiv.org/abs/2011.04206)

$$\dot{\delta}_{\nu} = -\frac{4}{3}\theta_{\nu} + 4\dot{\phi},$$

$$\dot{\theta}_{\nu} = k^2 \left(\frac{\delta_{\nu}}{4} - \sigma_{\nu} \right) + k^2 \psi - \dot{\kappa}_{\nu\text{DM}} (\theta_{\nu} - \theta_{\text{DM}}) ,$$

$$2\dot{\sigma}_{\nu} = \frac{8}{15}\theta_{\nu} - \frac{3}{5}kF_{\nu,3} - \alpha_2 \dot{\kappa}_{\nu\text{DM}} \sigma_{\nu} ,$$

$$\dot{F}_{\nu,l} = \frac{k}{2l+1} [lF_{\nu,l-1} - (l+1)F_{\nu,l+1}] - \alpha_l \dot{\kappa}_{\nu\text{DM}} F_{\nu,l} ,$$

$$\dot{F}_{\nu,l_{\text{max}}} = k \left[F_{\nu,l_{\text{max}}-1} - \frac{l_{\text{max}}+1}{k\tau} F_{\nu,l_{\text{max}}} \right] - \alpha_{l_{\text{max}}} \dot{\kappa}_{\nu\text{DM}} F_{\nu,l_{\text{max}}}$$

Mangano et al. [arXiv:astro-ph/0606190](https://arxiv.org/abs/astro-ph/0606190)

Serra et al. [arXiv:0911.4411](https://arxiv.org/abs/0911.4411)

Wilkinson et al. [arXiv:1401.7597](https://arxiv.org/abs/1401.7597)

Di Valentino et al. [arXiv:1710.02559](https://arxiv.org/abs/1710.02559)

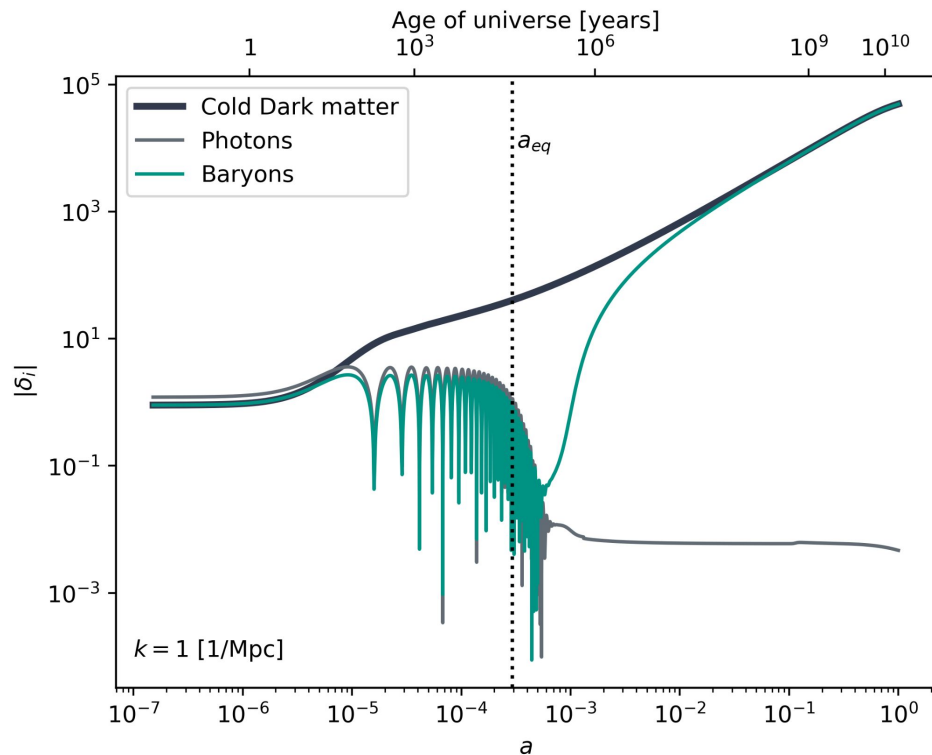
Stadler et al. [arXiv:1903.00540](https://arxiv.org/abs/1903.00540)

Clustering of Cold Dark Matter

- No interactions
- No free-streaming
- Clusters “maximally” under gravity

$$\dot{\delta}_{\text{cdm}} = -\theta_{\text{cdm}} + 3\dot{\phi},$$

$$\dot{\theta}_{\text{cdm}} = -\frac{\dot{a}}{a}\theta + k^2\psi.$$

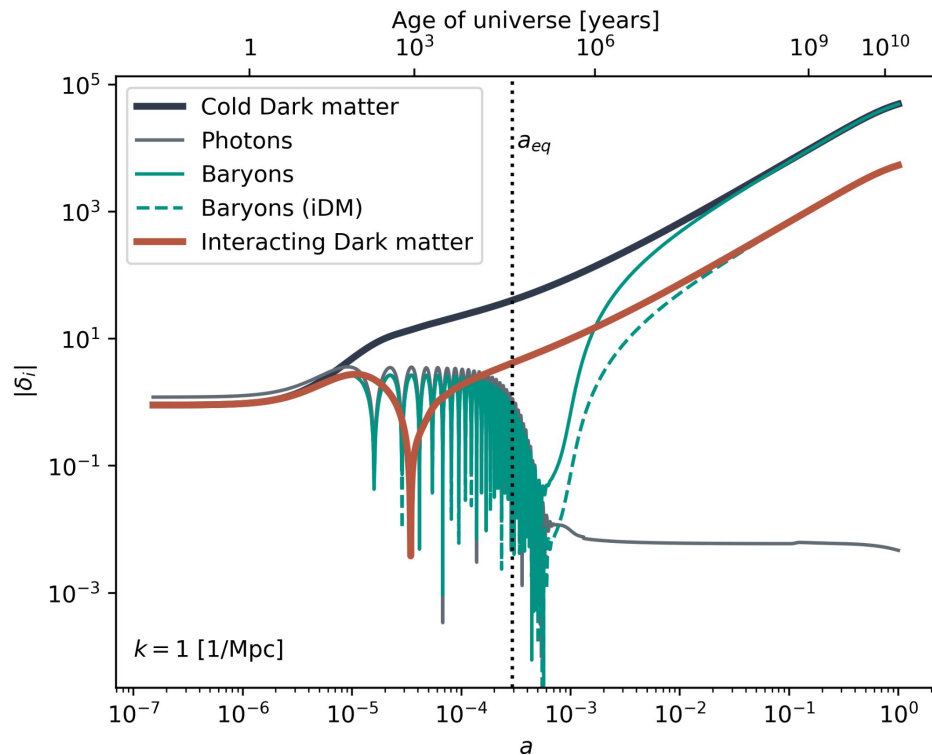


Clustering of **interacting** Dark Matter

- Coupled to non-clustering species
- Clustering delayed $\rightarrow$ suppressed
- Baryons follow suit

$$\dot{\delta}_{\text{DM}} = -\theta_{\text{DM}} + 3\dot{\phi},$$

$$\dot{\theta}_{\text{DM}} = k^2\psi - \mathcal{H}\theta_{\text{DM}} - R\dot{\kappa}_{\text{vDM}}(\theta_{\text{DM}} - \theta_{\text{v}}).$$

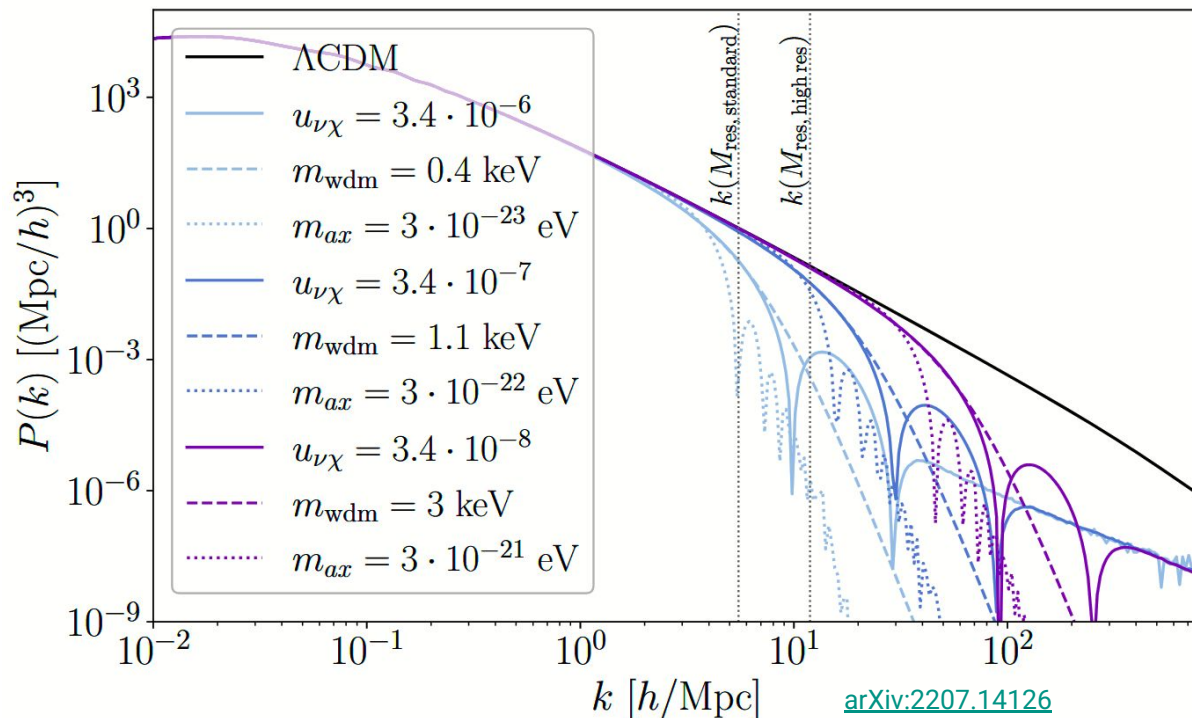


Uniqueness of (linear) signature

- Distinct oscillations
- Similar to other models of DM interacting with relativistic particles

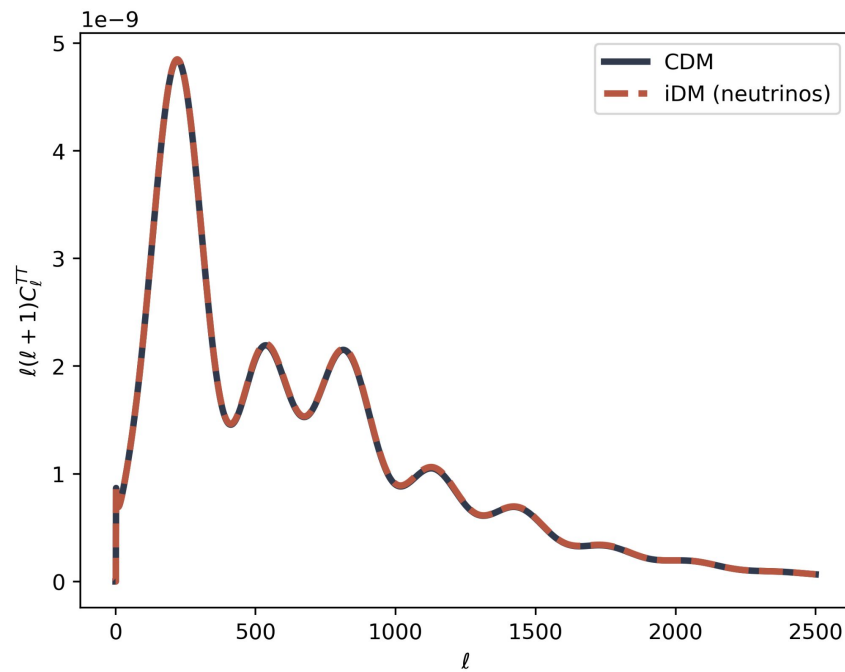
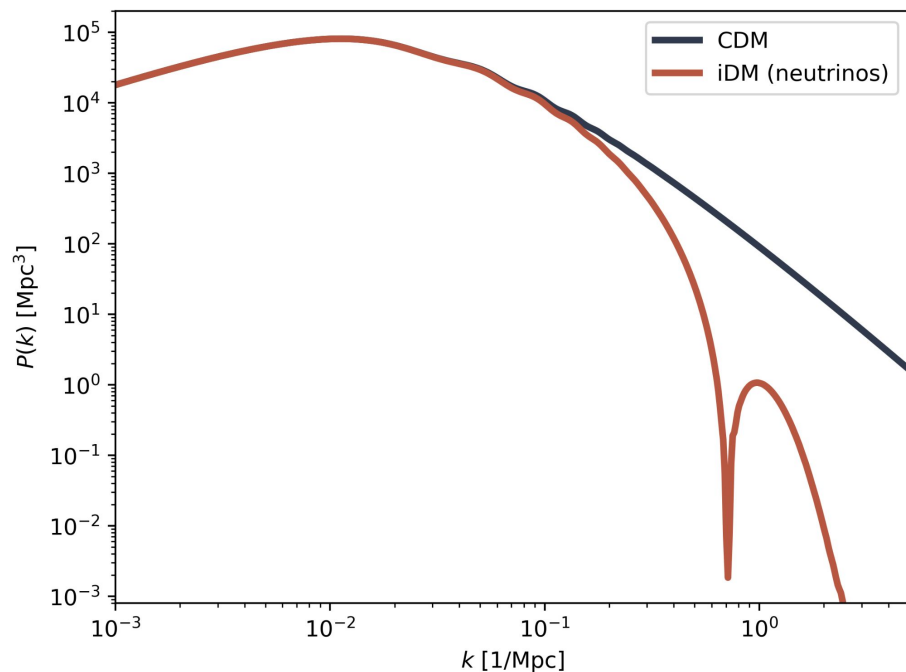
m_{WDM}	$u_{\nu\chi}$	$u_{\gamma\chi}$
1 keV	$8.5 \cdot 10^{-7}$	$4.0 \cdot 10^{-7}$
2 keV	$1.8 \cdot 10^{-7}$	$9.0 \cdot 10^{-8}$
3 keV	$7.0 \cdot 10^{-8}$	$3.5 \cdot 10^{-8}$
4 keV	$3.6 \cdot 10^{-8}$	$1.8 \cdot 10^{-8}$

[arXiv:2207.03107](https://arxiv.org/abs/2207.03107)

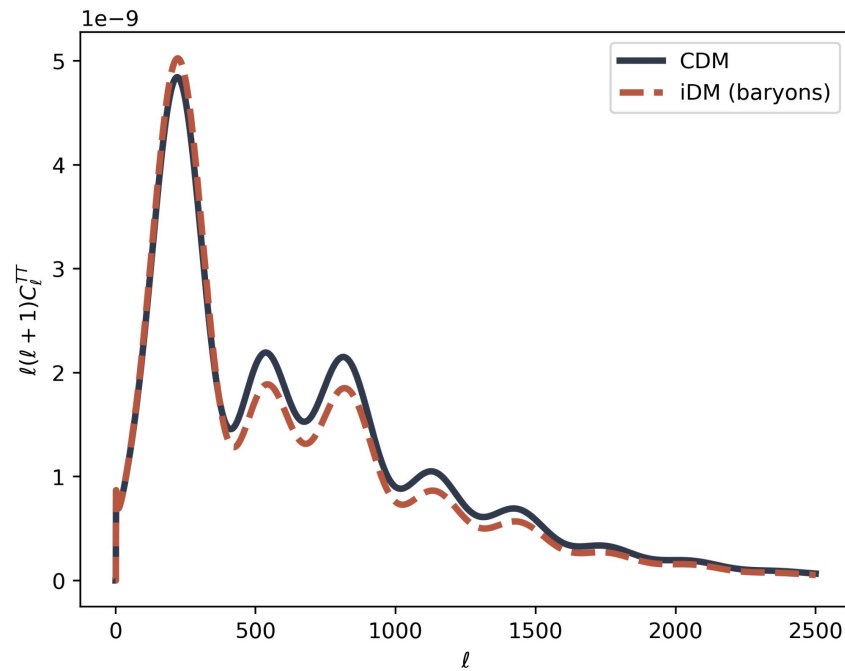
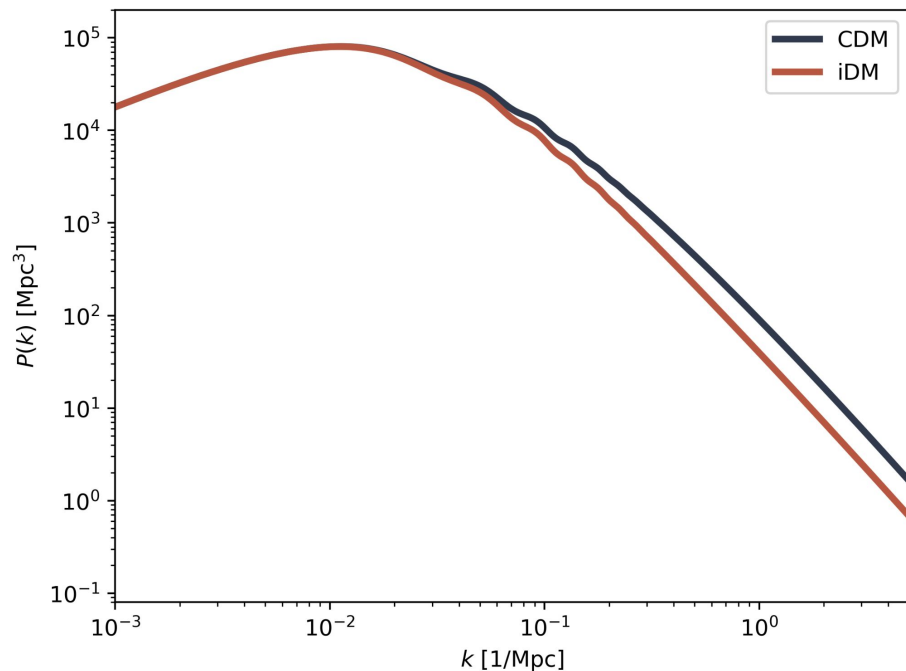


[arXiv:2207.14126](https://arxiv.org/abs/2207.14126)

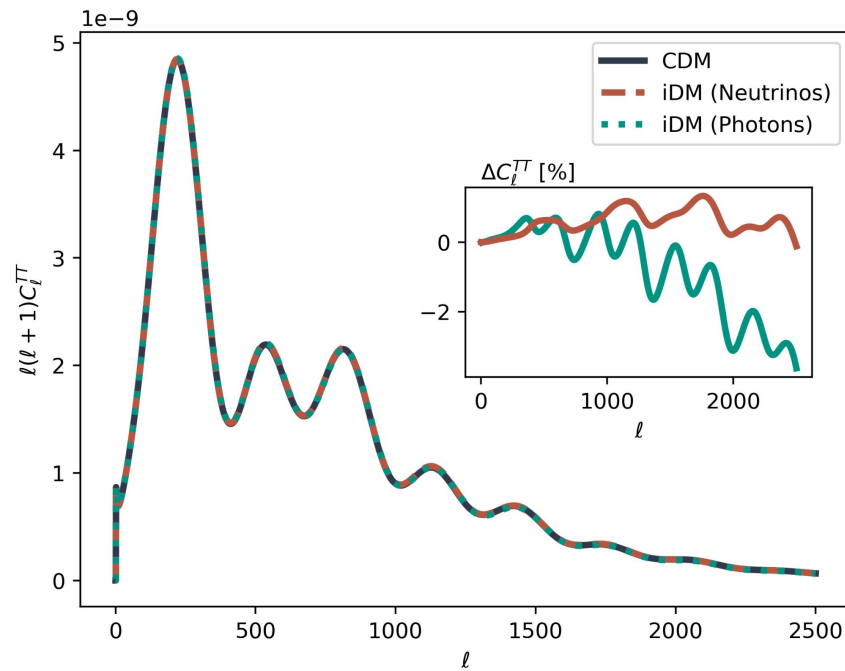
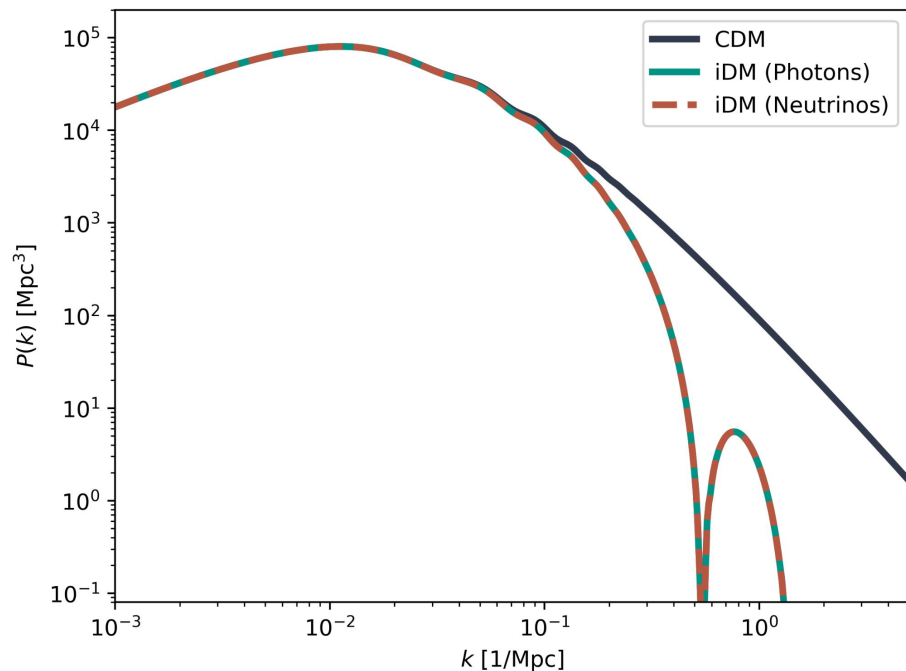
Linear Observables: DM-neutrino interactions



Linear Observables: DM-baryon interactions



Linear Observables: DM-photon interactions



In the **non-linear** universe

Quick back of the envelope calculation:

- Scattering rate of DM $\propto n_\nu$
- Scattering rate of $\nu \propto n_{\text{DM}}$

Conservative assumption: Global DM- ν decoupling before CMB:

- At $z=100$, n factor 1000 smaller
- At $z=10$, n factor 10^6 smaller
- At $z=0$, n factor 10^9 smaller

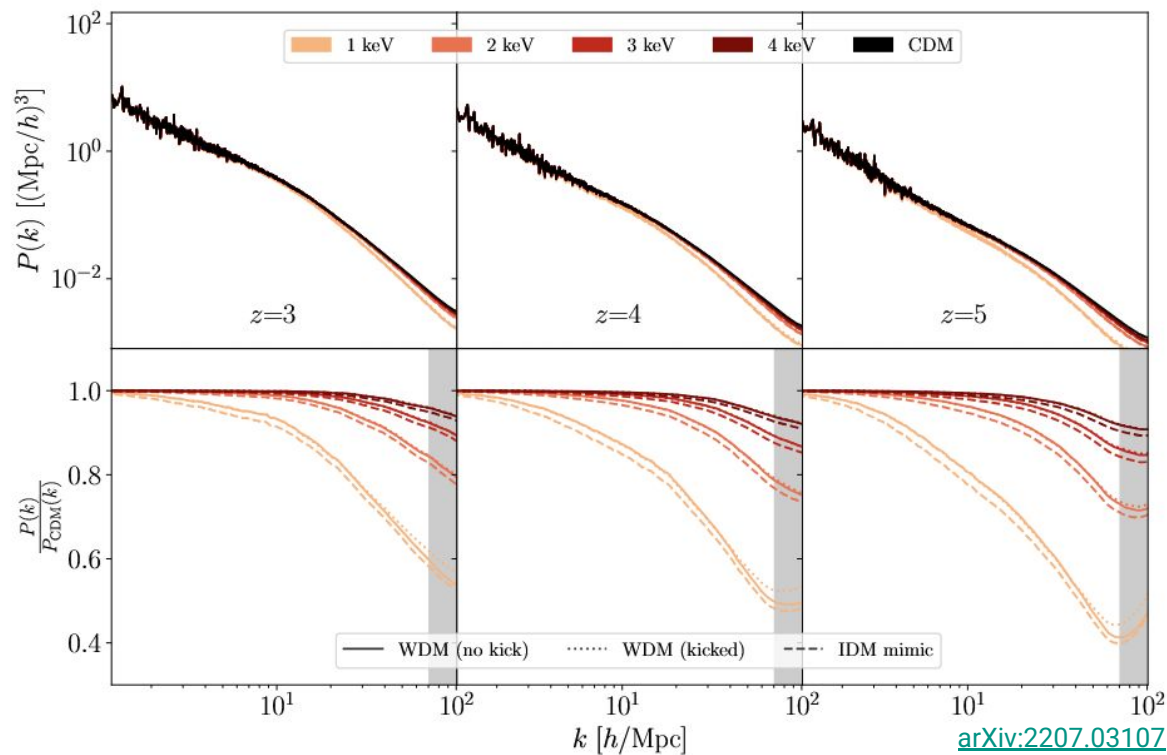
Neutrino non-linear growth much smaller than this
 $\Rightarrow$ **DM always unaffected after global decoupling**

For **massive neutrinos**: further p^2/E^2 suppression.

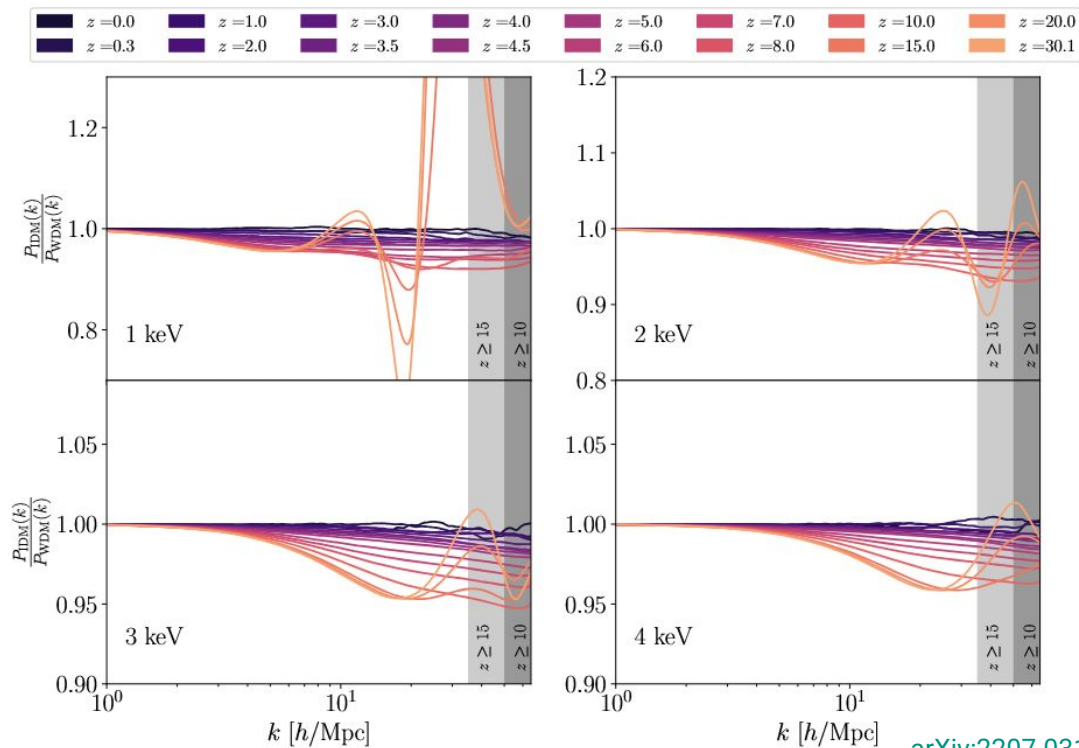
Conclusion: Interactions enter only through linear initial conditions (for DM simulations). Easy to model!

Exception: Cross-sections with non-trivial temperature dependence.

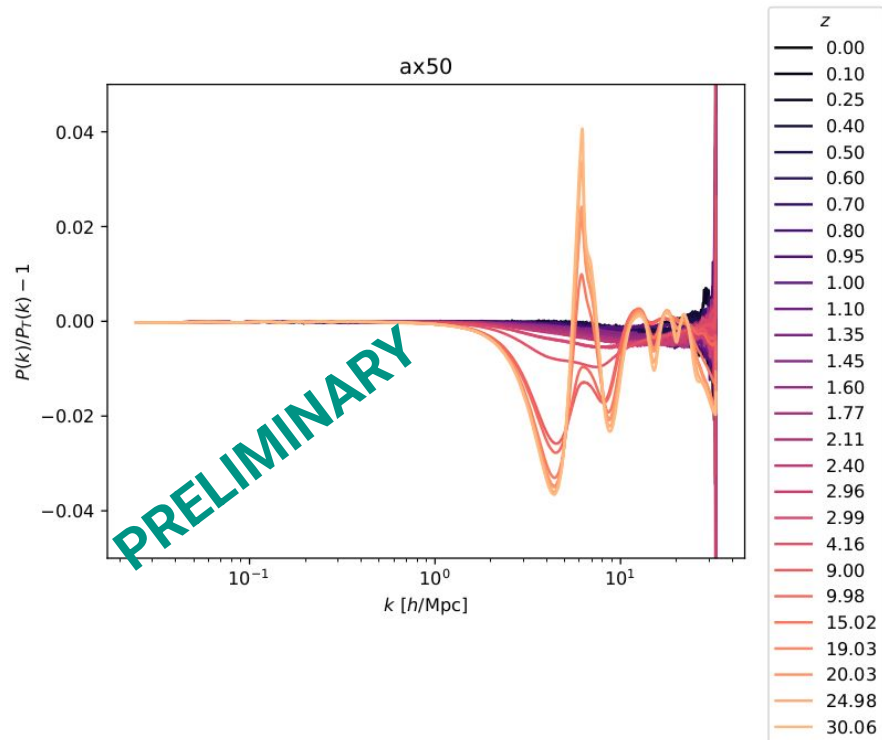
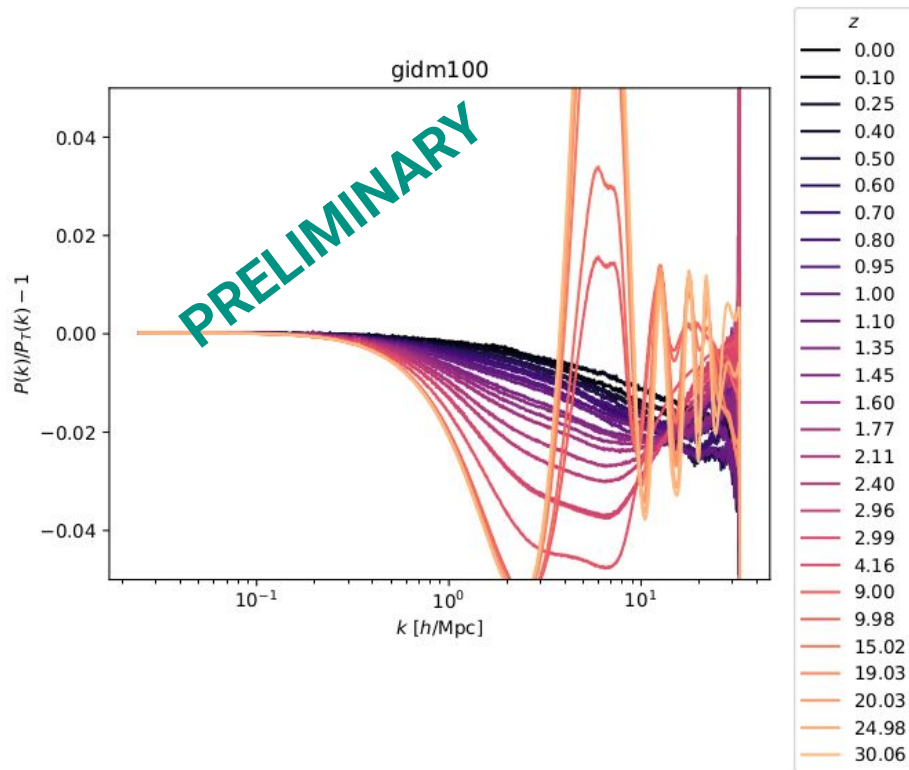
Uniqueness of (non-linear) signature



Uniqueness of (non-linear) signature



Fitting functions: ongoing work



Observational status: CMB+BAO

- Initial analyses: upper limits
 $u \lesssim 3 \cdot 10^{-4}$ (massive case) [2011.04206](#)
 $u \lesssim 5 \cdot 10^{-5}$ (massless case) [1903.00540](#), [1710.02559](#)
- Recent analyses: detection hints
 $u \sim 10^{-6} - 10^{-4}$

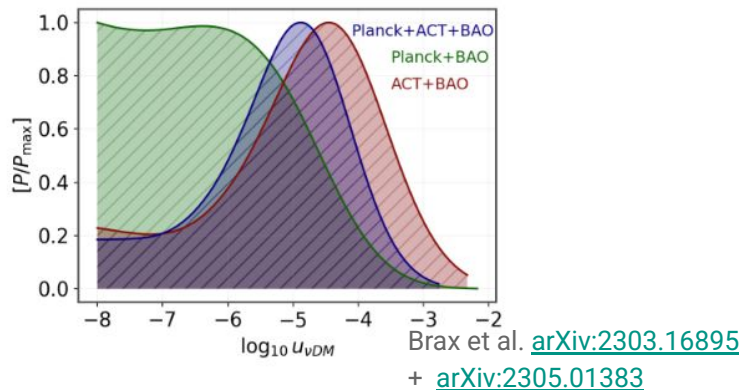
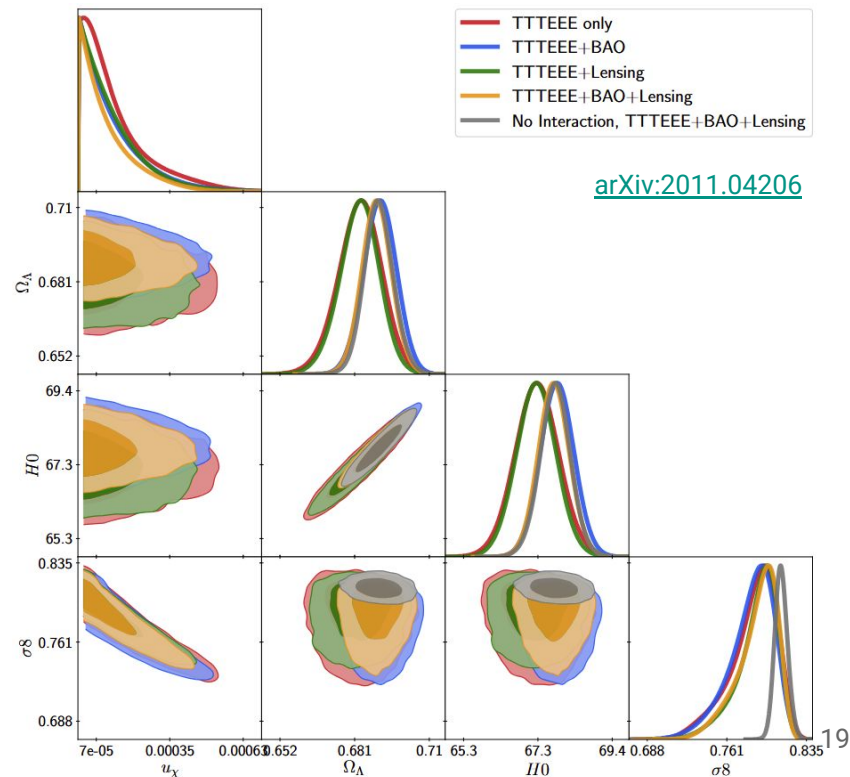
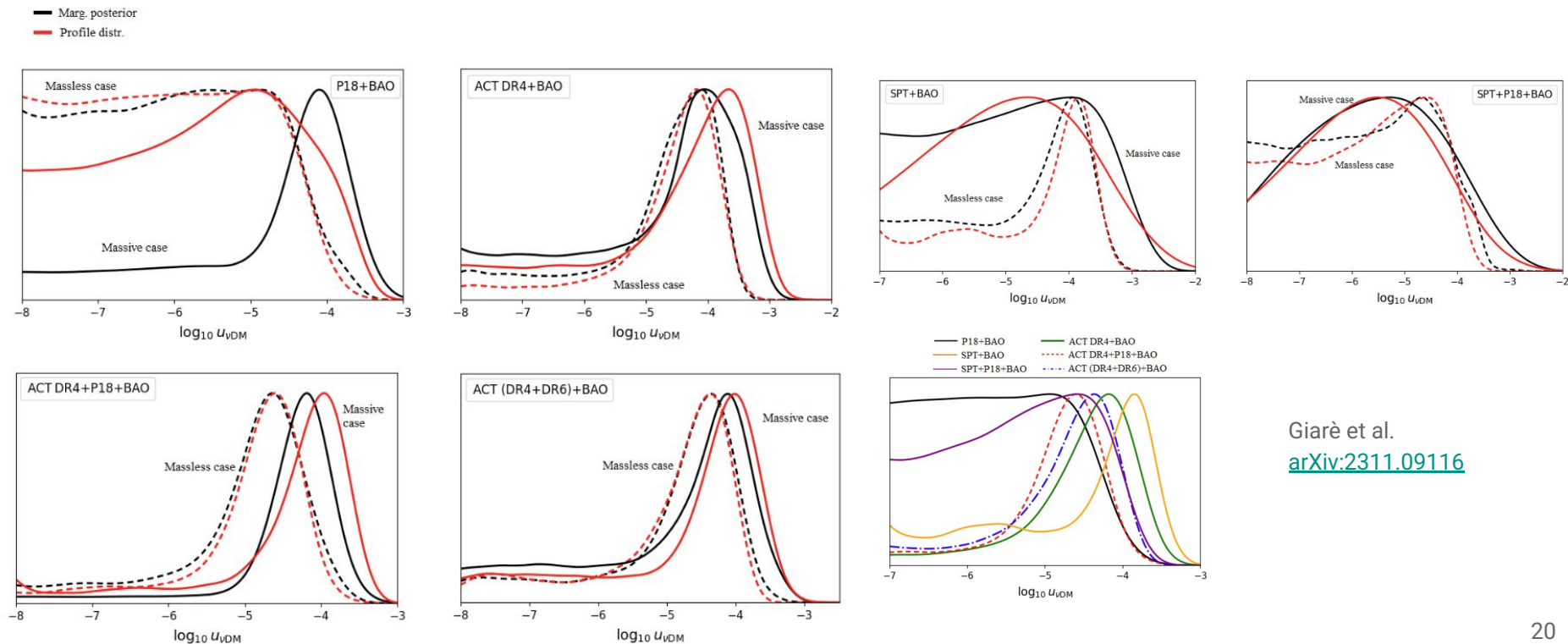


Figure 2. Posterior probability distribution functions for the coupling $\log_{10} u_{\text{vDM}}$ resulting from different combinations of CMB and BAO+RSD measurements.

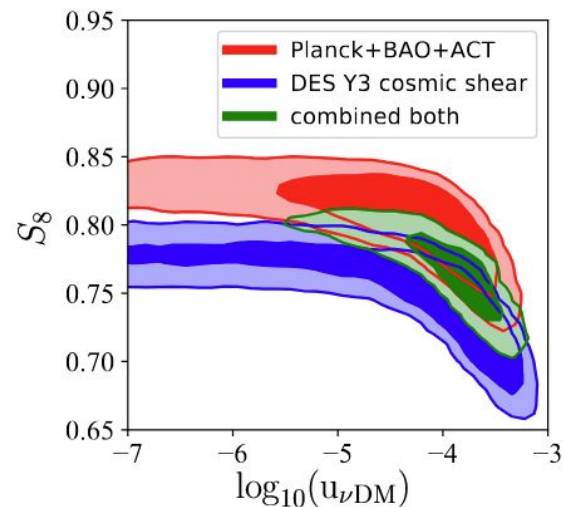
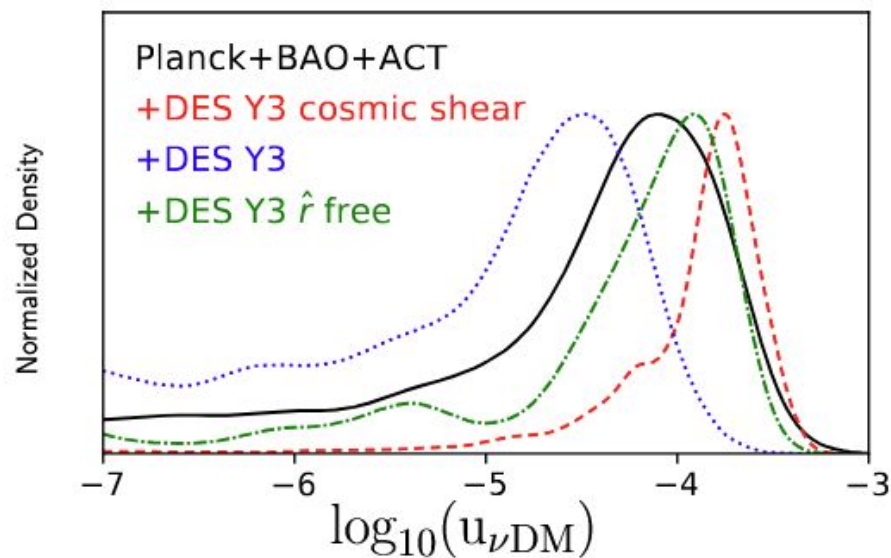


Observational status: CMB+BAO



Giarè et al.
[arXiv:2311.09116](https://arxiv.org/abs/2311.09116)

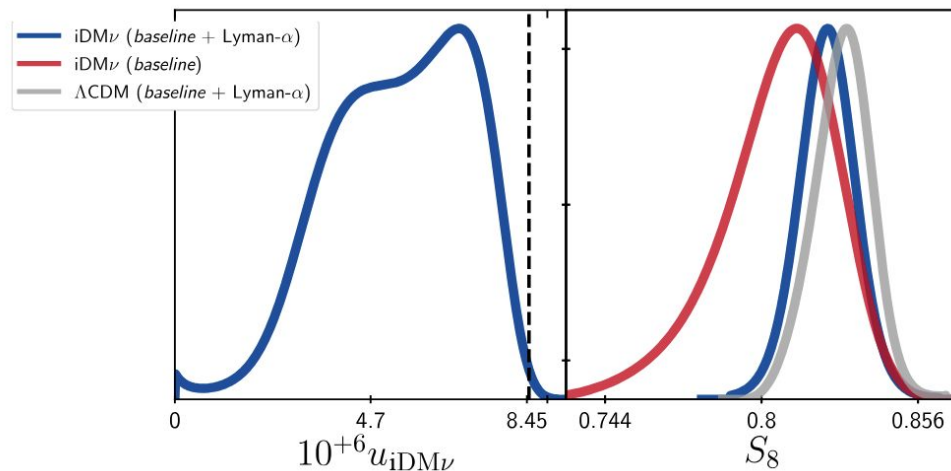
Observational status: CMB+LSS



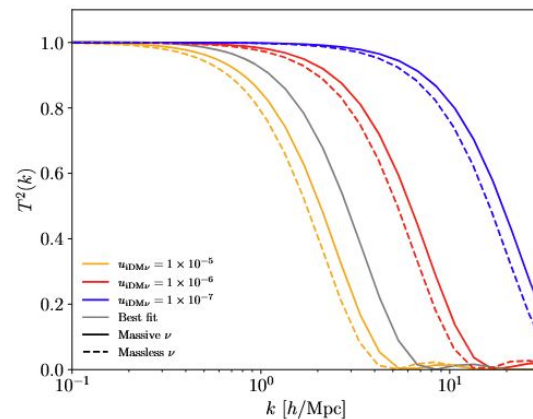
Zu et al. [arXiv:2501.13785](https://arxiv.org/abs/2501.13785)

See also Trojanowski & Zu [arXiv:2505.20396](https://arxiv.org/abs/2505.20396)
(enhanced interaction in narrow redshift range)

Observational status: CMB+Lyman- α

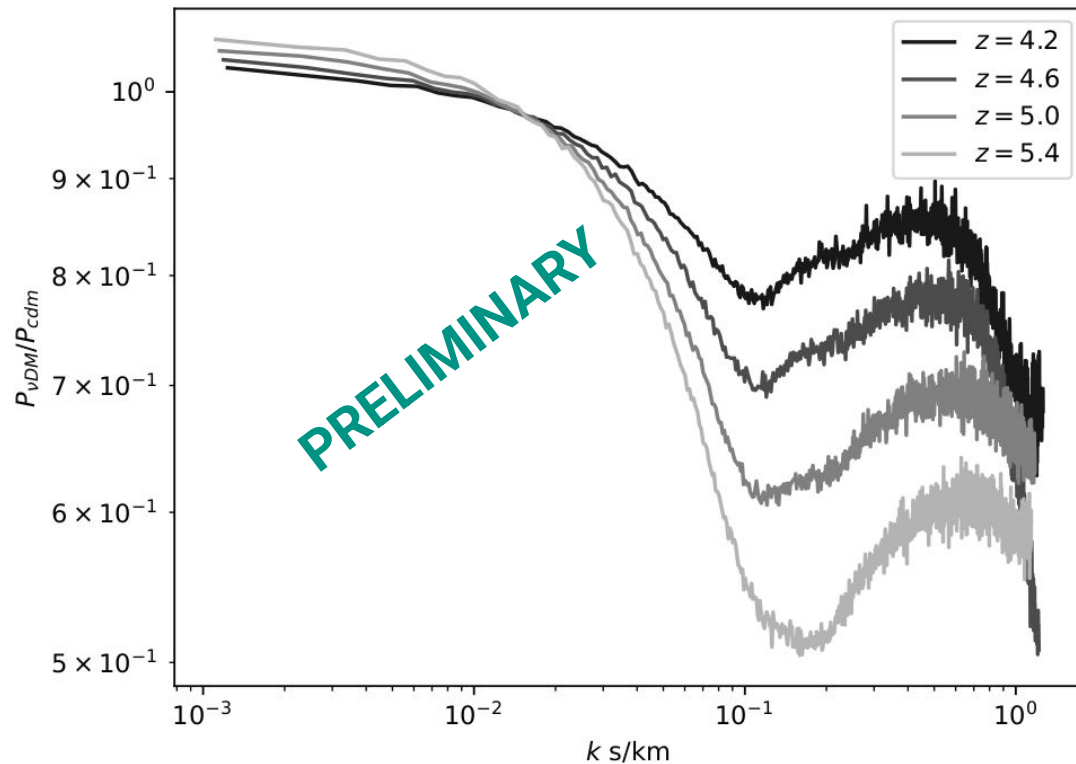


Lyman- α = HIRES/MIKE

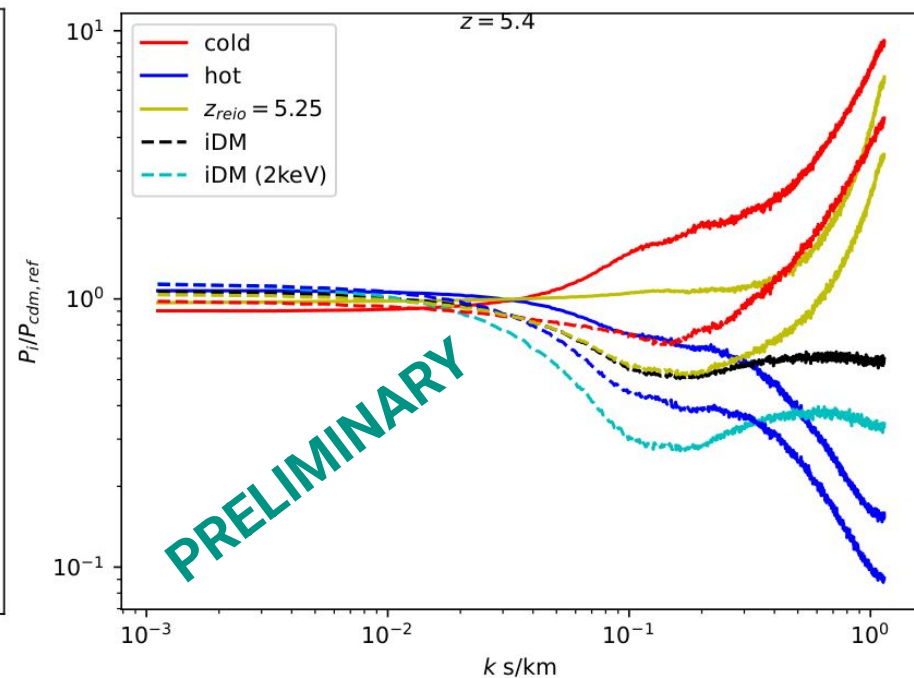
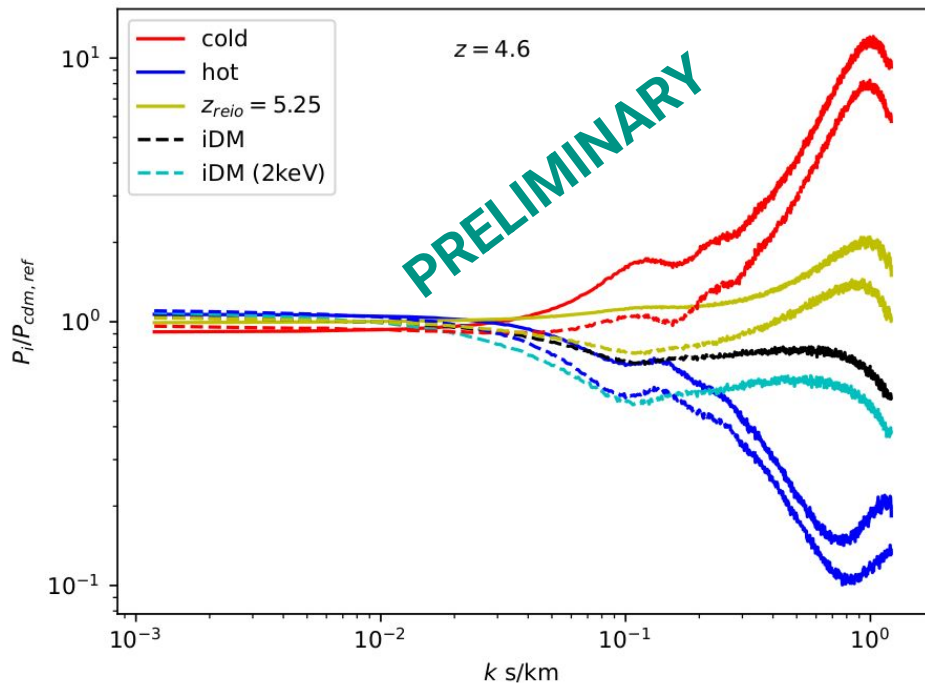


Hooper & Lucca
[arXiv:2110.04024](https://arxiv.org/abs/2110.04024)

Lyman- α : ongoing work



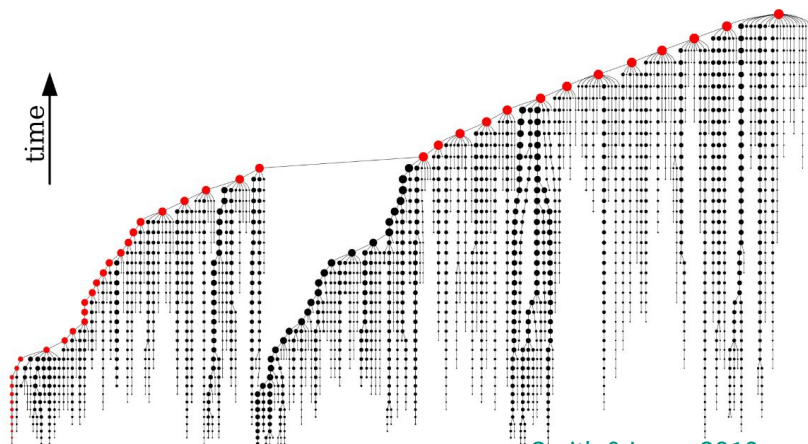
Lyman- α : ongoing work



Observational status: Galaxy Population

Semi-analytical galaxy evolution modeling cannot reproduce galaxy luminosity function with $u \sim 3 \cdot 10^{-6}$

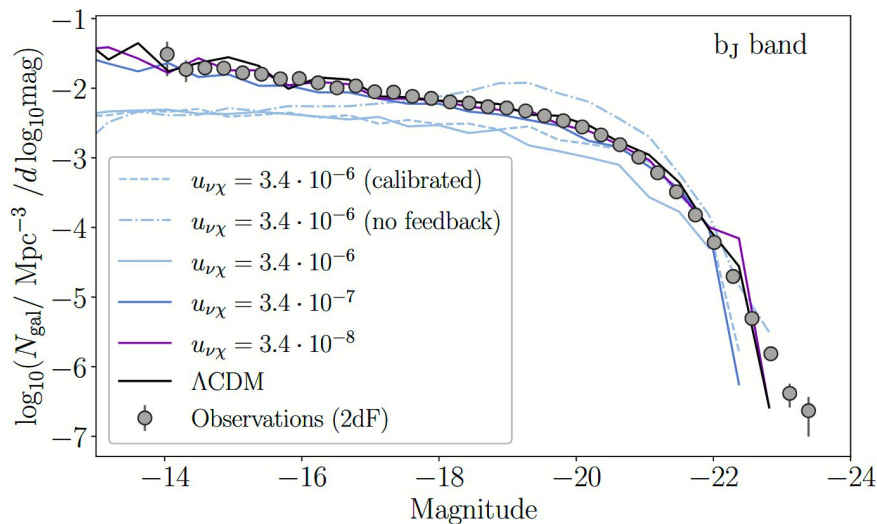
Even with **no** feedback, low-luminosity tail not reproduced
 $\Rightarrow$ results are robust



[Smith & Lang, 2019](#)

[arXiv:2207.14126](#)

$u \lesssim 3 \cdot 10^{-6}$



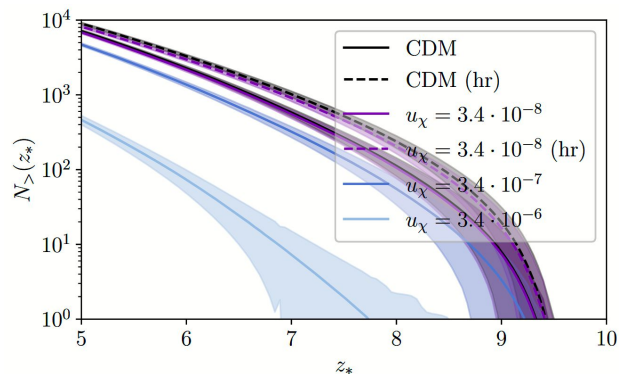
Observational status: Gravitational waves

Computed from galaxy model with stellar population evolution models.

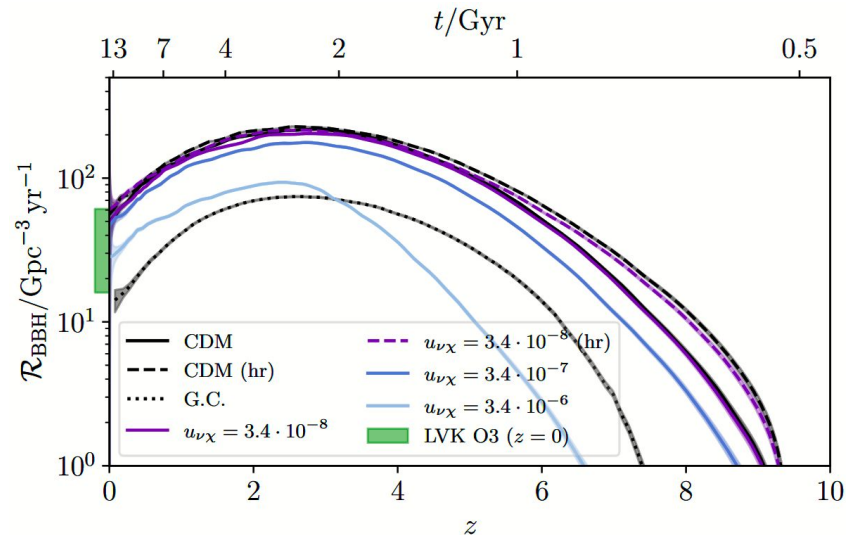
Subject to another layer of modeling uncertainty

Currently no limit.

Forecast potential limits $u \sim 10^{-7}$ (optimistic):



[arXiv:2207.14126](https://arxiv.org/abs/2207.14126)



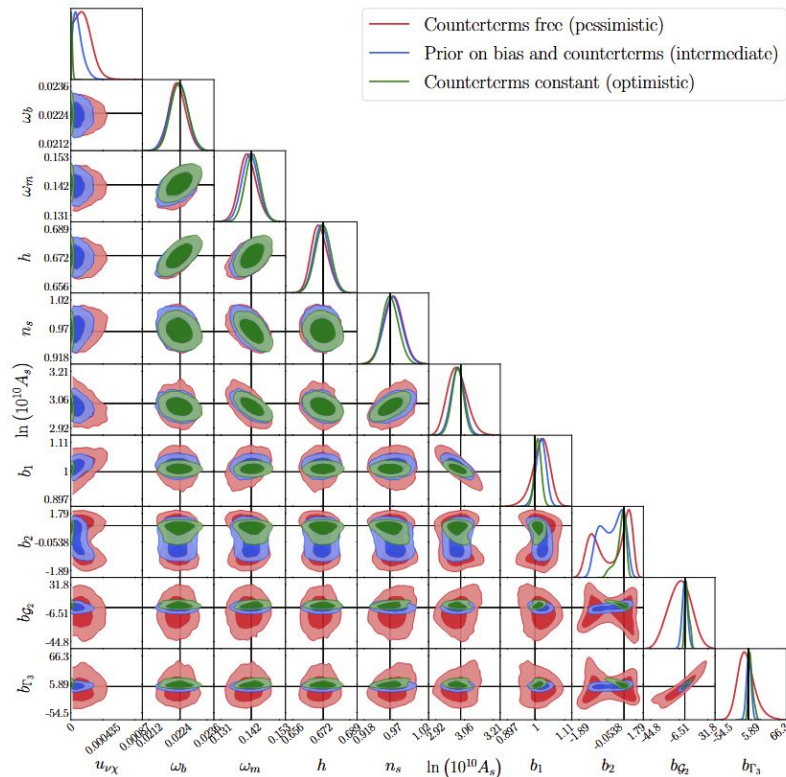
Forecasts: Galaxy Clustering with EFTofLSS

Massless approx. fully consistent with EFTofLSS

Preliminary validation against sims completed

Constraining power strongly dependent on nuisance parameter treatment.

	95% CL upper limit (CDM fid.)
Optimistic	$< 3.49 \times 10^{-5}$
Intermediate	$< 2.48 \times 10^{-4}$
Pessimistic	$< 3.93 \times 10^{-4}$
	Mean $\pm 2\sigma$ (IDM90 fid.)
Optimistic	$6.08^{+4.08}_{-5.23} \times 10^{-5}$
Intermediate	$1.54^{+1.62}_{-1.42} \times 10^{-4}$
Pessimistic	$2.54^{+2.94}_{-2.50} \times 10^{-4}$



Further methods

- Line intensity mapping
- Milky way satellites
- Strong lensing
- Other secondary effects

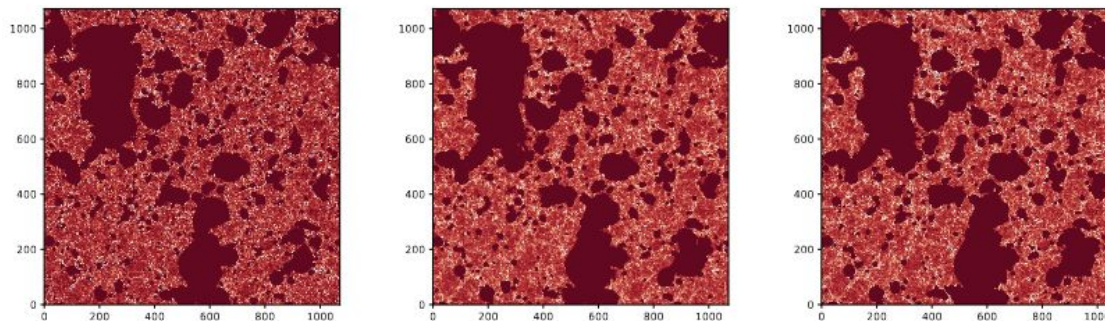
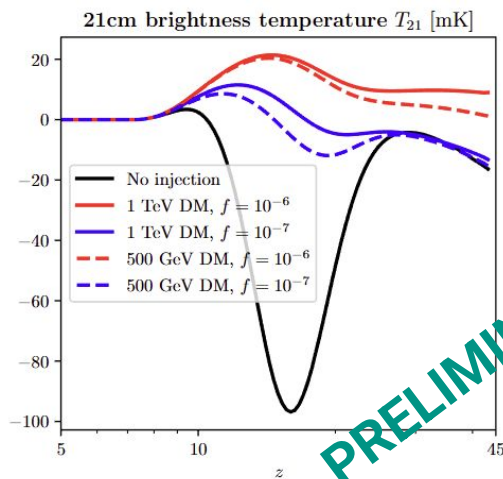
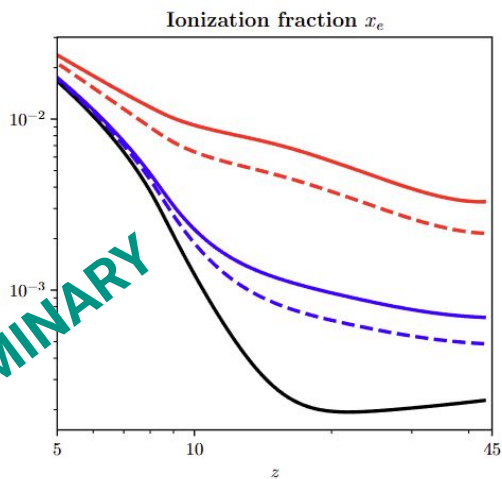
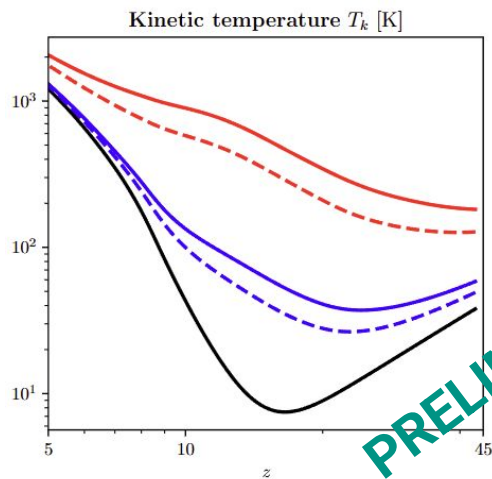


Figure 3. HI map: Two dimensional section of the simulated HI map at $z = 8.0$ generated from 2144^3 grid size of the simulation box. The above figures are for $u = 0$, $N_{\text{ion}} = 24$; $u = 8.8 \times 10^{-8}$, $N_{\text{ion}} = 300$ and $u = 6.6 \times 10^{-7}$, $N_{\text{ion}} = 500$, units along x and y axis are in 0.06 Mpc. Darker shades corresponds to more ionized regions. For all the simulations we have assumed the identical initial random seed.

Dey et al. [arXiv:2207.02451](https://arxiv.org/abs/2207.02451)

Probes **beyond** structure formation

- Decaying dark matter may not leave large imprints on structures - especially subcomponents
- CMB spectral distortions
- Global 21cm Temperature



In Conclusion

- Cosmology is a powerful probe of dark matter models
- Cosmology generally probes qualitative effects rather than direct couplings at the Lagrangian level
- There is potential for even stronger probes as new observatories come online