

Probing Dark Matter-Neutrino interactions in Cosmology

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News from the Dark 10, September 10, Montpellier

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Overview

- Motivations
- Numerical treatment
- Status of results
- Outlook

Why neutrinos?

Theoretical motivations:

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

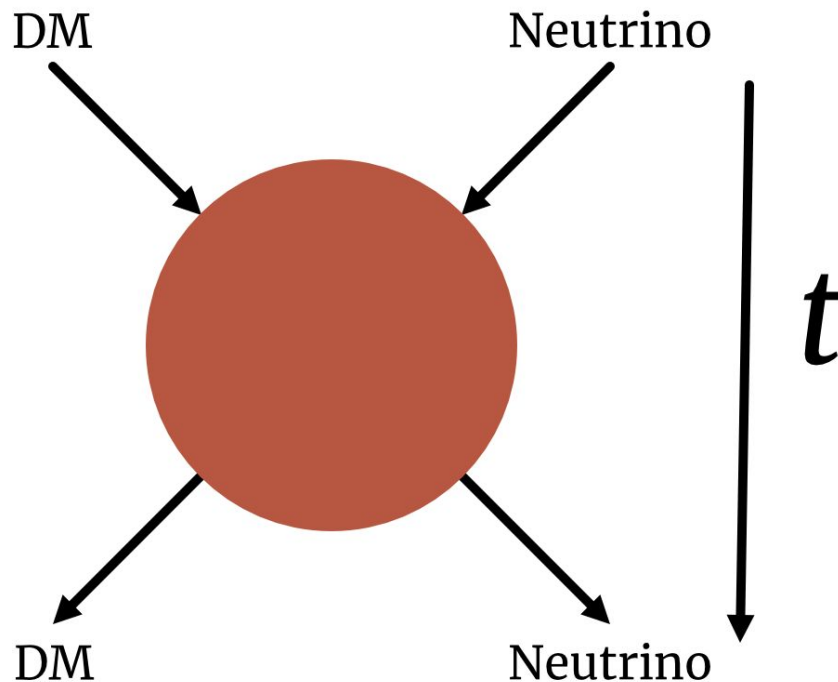
Observational “motivations”:

- 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!

In the **linear** universe

- Usually treated as a Coulomb-like interaction
- Implementation of massless neutrino approx. by Stadler et al. [arXiv:1903.00540](https://arxiv.org/abs/1903.00540)
- Implementation for massive neutrinos by Mosbech et al. [arXiv:2011.04206](https://arxiv.org/abs/2011.04206)
- Constraints mainly from CMB+BAO



The **massless** neutrino approximation

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

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

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

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

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

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

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

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

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

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

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

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)

The massive hierarchy

- Introduces p^2/E^2 factor
- More complex to evolve due to neutrino mass
- Slightly smaller effect for equal interaction strength

$$C_\chi = a u_{\nu\chi} \frac{\sigma_{\text{Th}} \rho_\chi}{100 \text{ GeV}} \frac{p^2}{E_\nu^2}$$

$$K_\chi \equiv \frac{\rho_\nu + P_\nu}{\rho_\chi} = \frac{(1 + w_\nu) \rho_\nu}{\rho_\chi}$$

$$\frac{\partial \Psi_1}{\partial \tau} = [\dots] - C_\chi \frac{v_\chi E_\nu(p)}{3 f^{(0)}(p)} \frac{df^{(0)}(p)}{dp} - C_\chi \Psi_1 ,$$

$$\frac{\partial \Psi_2}{\partial \tau} = [\dots] - \frac{9}{10} C_\chi \Psi_2 ,$$

$$\frac{\partial \Psi_l}{\partial \tau} = [\dots] - C_\chi \Psi_l, \quad l \geq 3 ,$$

$$\begin{aligned} \dot{\theta}_\chi &= [\dots] + K_\chi \frac{3}{4} k \frac{\int p^2 dp p f^{(0)}(p) C_\chi(p) \left(\frac{\theta_\chi E_\nu(p)}{3 k f^{(0)}(p)} \frac{df^{(0)}(p)}{dp} + \Psi_1 \right)}{\int p^2 dp p f^{(0)}(p)} \\ &= [\dots] + K_\chi \dot{\mu}_\chi (\theta_\nu - \theta_\chi) , \end{aligned}$$

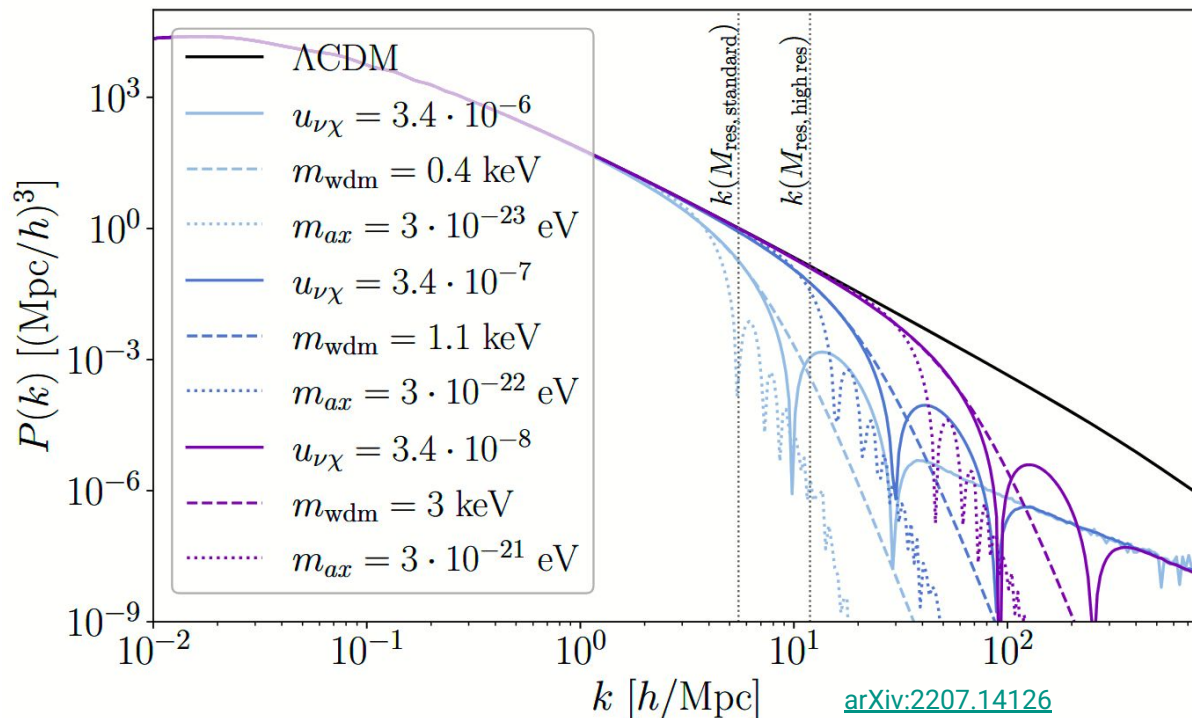
[arXiv:2011.04206](https://arxiv.org/abs/2011.04206)

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)

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

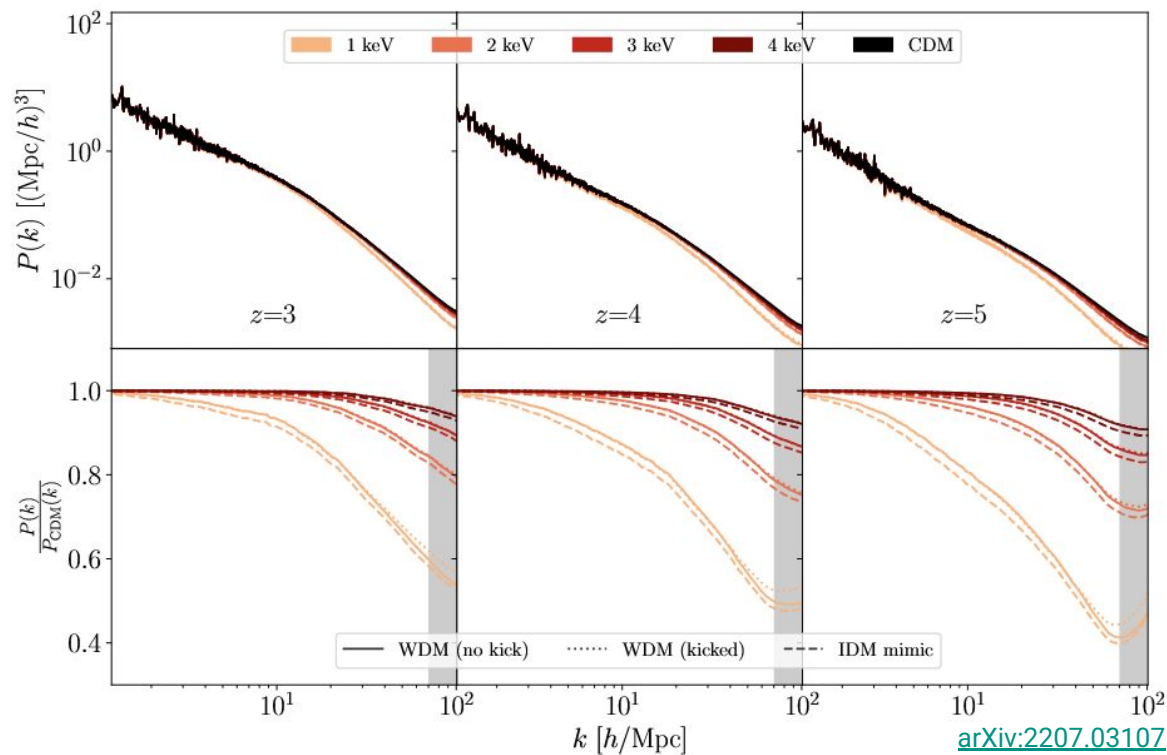
⇒ **DM always unaffected after global decoupling**

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

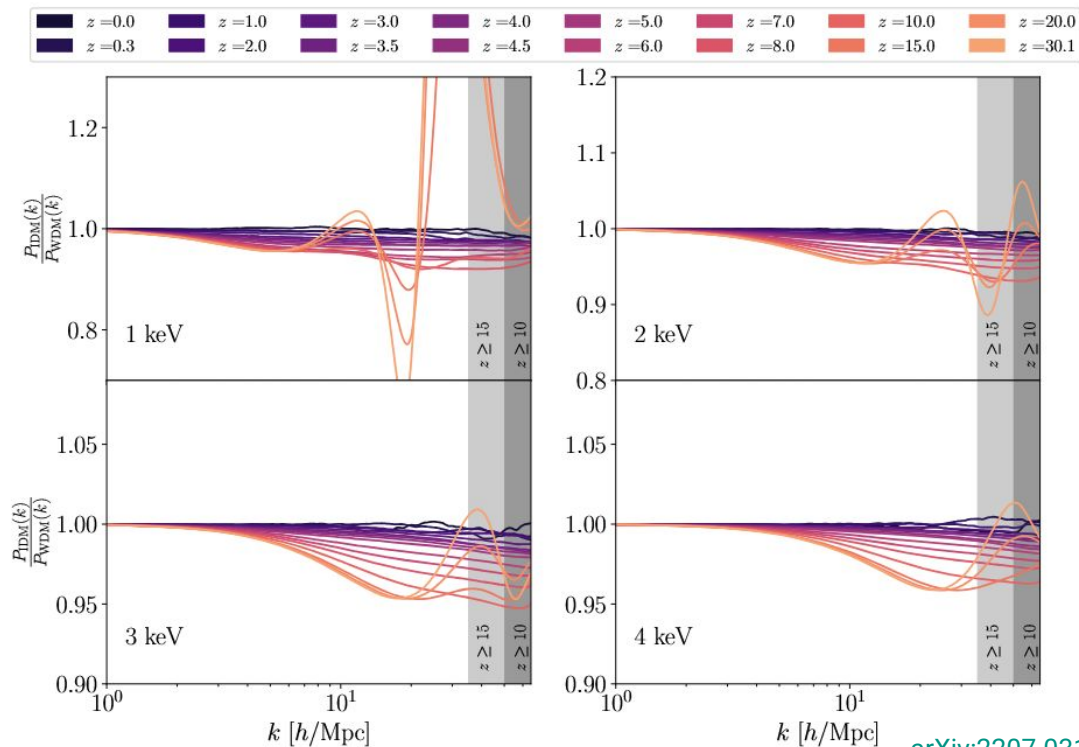
Conclusion: Interactions enter only through linear initial conditions (for DM simulations). Easy to model!

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

Uniqueness of (non-linear) signature



Uniqueness of (non-linear) signature



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
 $u \sim 10^{-6} - 10^{-4}$

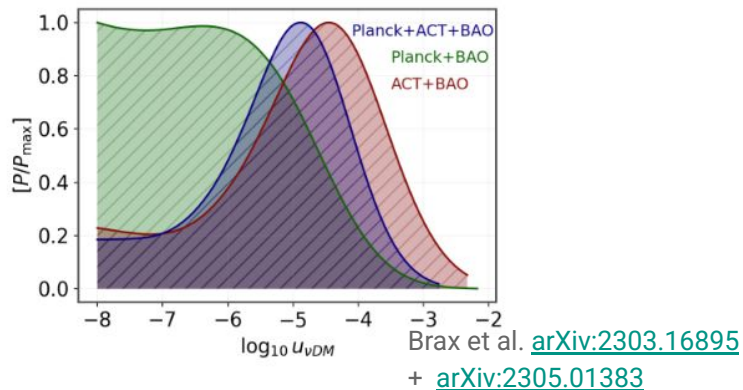
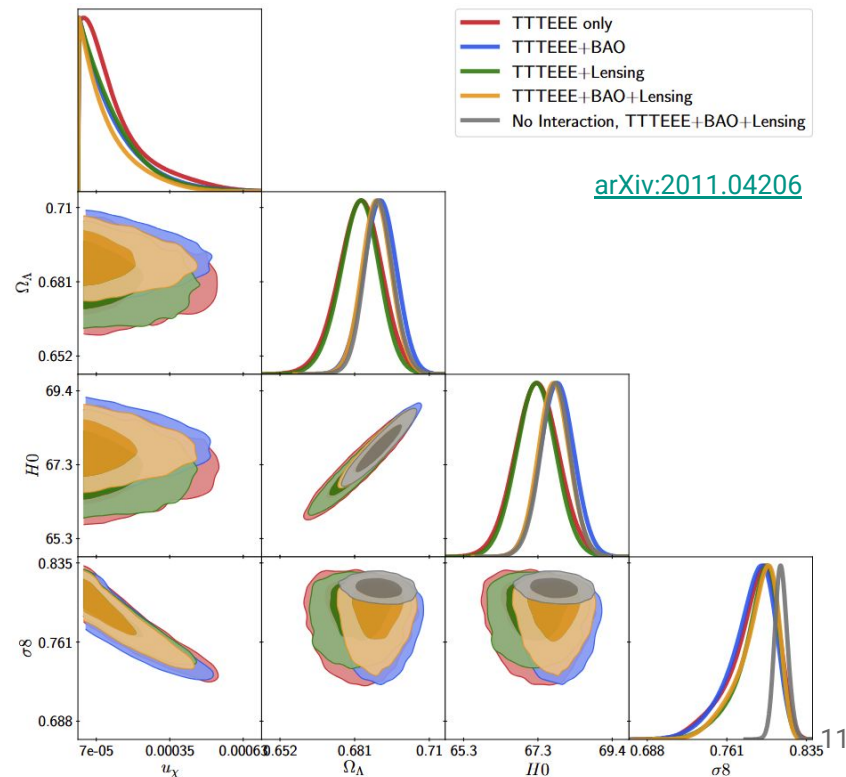
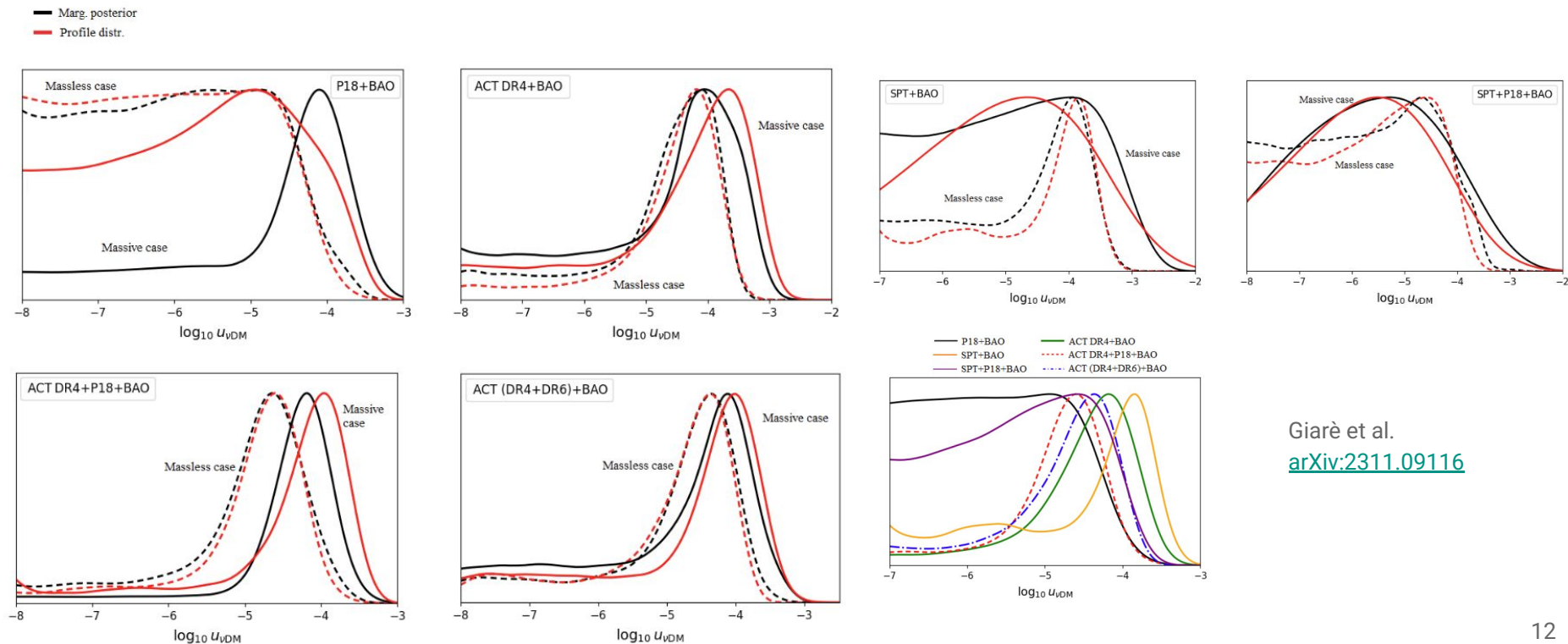


Figure 2. Posterior probability distribution functions for the coupling $\log_{10} u_{\text{vDM}}$ resulting from different combinations of CMB and BAO+RSD measurements.

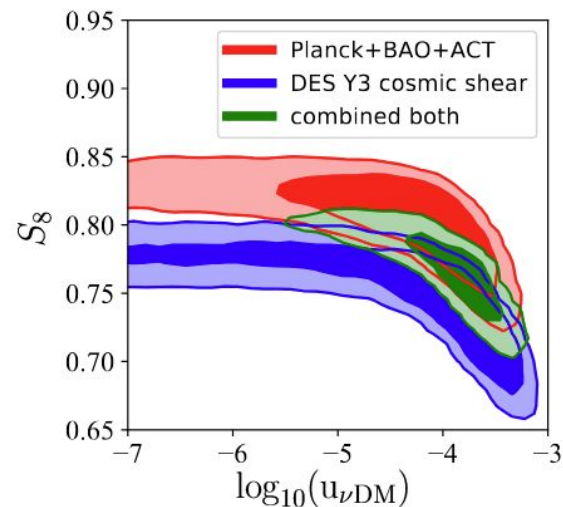
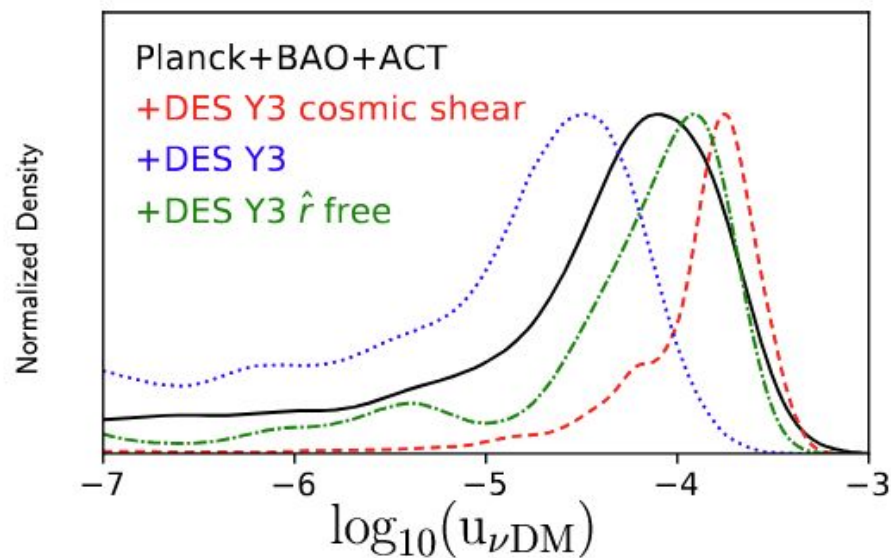


Observational status: CMB+BAO



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

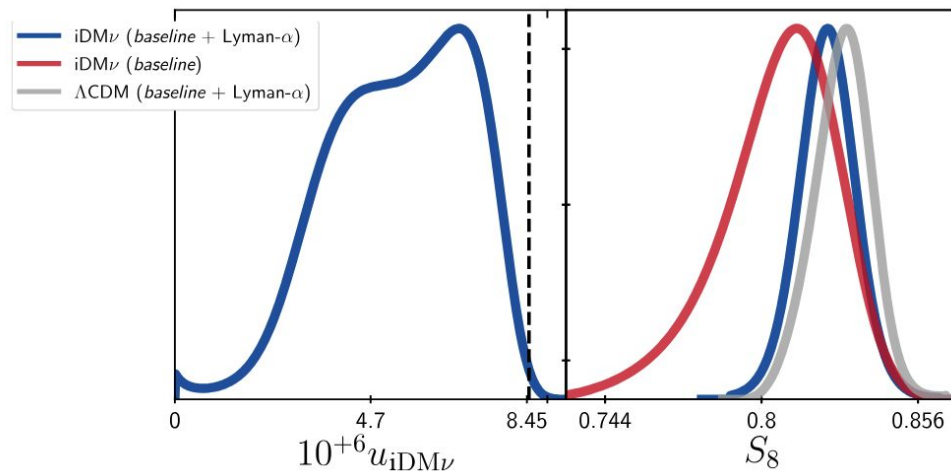
Observational status: CMB+LSS



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)

Observational status: Milky-Way Satellites

Semi-analytical subhalo model, Akita & Ando [arXiv:2305.01913](https://arxiv.org/abs/2305.01913)

Validated against Dark Matter-Dark Radiation simulations

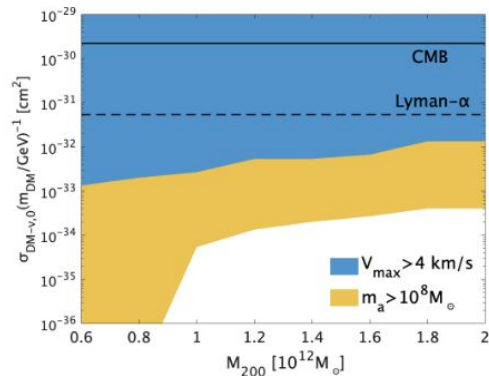
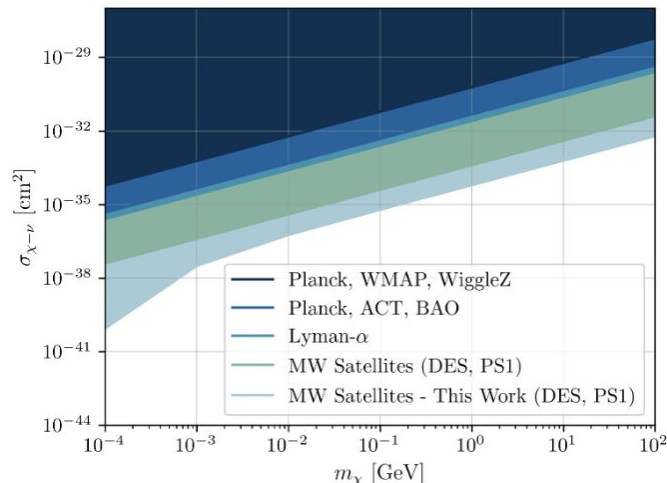


Figure 3: Constraints on the DM-neutrino cross section as $\sigma_{\text{DM}-\nu,0} = \text{const}$ at 95 CL as a function of the Milky-Way mass considering the kinematics data of 94 Milky-Way satellites with $V_{\text{max}} > 4 \text{ km/s}$ (blue) as well as the data of 270 Milky-Way satellites imposing the satellite forming condition of $m_a > 10^8 M_{\odot}$ (yellow). The constraints from CMB (solid line) [23,32] and Lyman- α (dashed line) [34] are shown for comparison.

Mapping to WDM constraints,
Crumrine et al. [arXiv:2406.19458](https://arxiv.org/abs/2406.19458)

$$u \lesssim 3 \cdot 10^{-8}$$



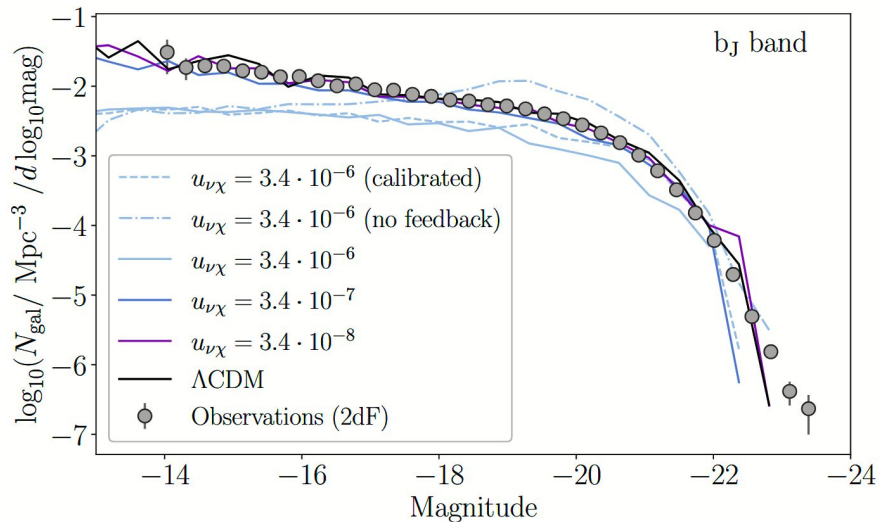
Observational status: Galaxy Population

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

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

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



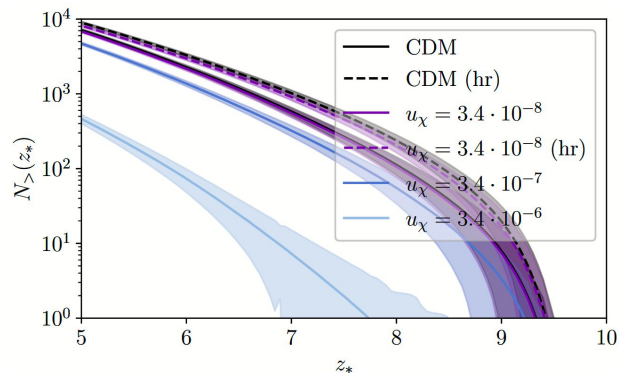
Observational status: Gravitational waves

Computed from galaxy model with stellar population evolution models.

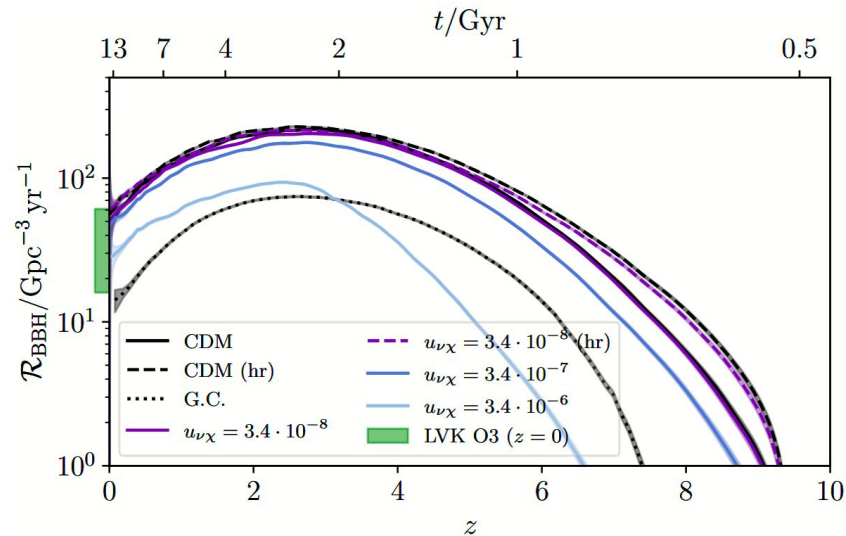
Subject to another layer of modeling uncertainty

Currently no limit.

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



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



Forecasts: 21cm intensity mapping + reionization

21cm line intensity mapping has the potential to be a hugely powerful tool.

- Traces neutral hydrogen
- Can (in principle) probe high redshifts
- Very observationally challenging!

Current SKA **forecast** limits:

- $u_{\nu X} \lesssim 3.6 \cdot 10^{-8}$ (structure bound) [arXiv:2207.03107](https://arxiv.org/abs/2207.03107)
- $u_{\nu X} \lesssim 5.5 \cdot 10^{-7}$ Dey et al. [arXiv:2207.02451](https://arxiv.org/abs/2207.02451)
(Bound from 50% reionization at $z=8$)

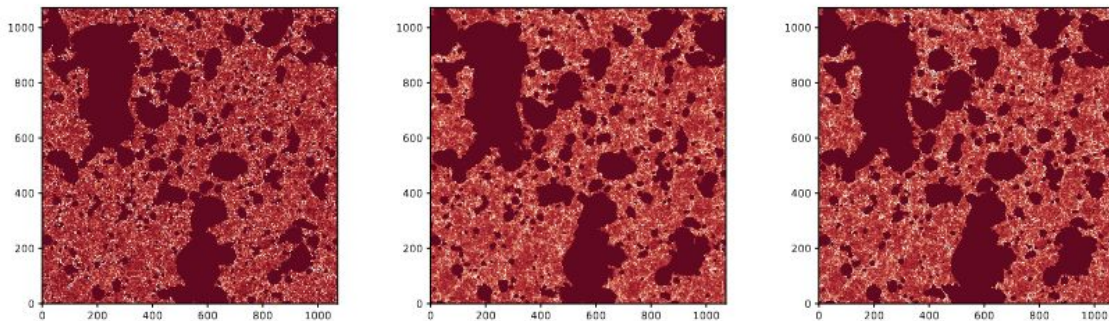


Figure 3. HI map: Two dimensional section of the simulated HI map at $z = 8.0$ generated from 2144^3 grid size of the simulation box. The above figures are for $u = 0$, $N_{\text{ion}} = 24$; $u = 8.8 \times 10^{-8}$, $N_{\text{ion}} = 300$ and $u = 6.6 \times 10^{-7}$, $N_{\text{ion}} = 500$, units 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)

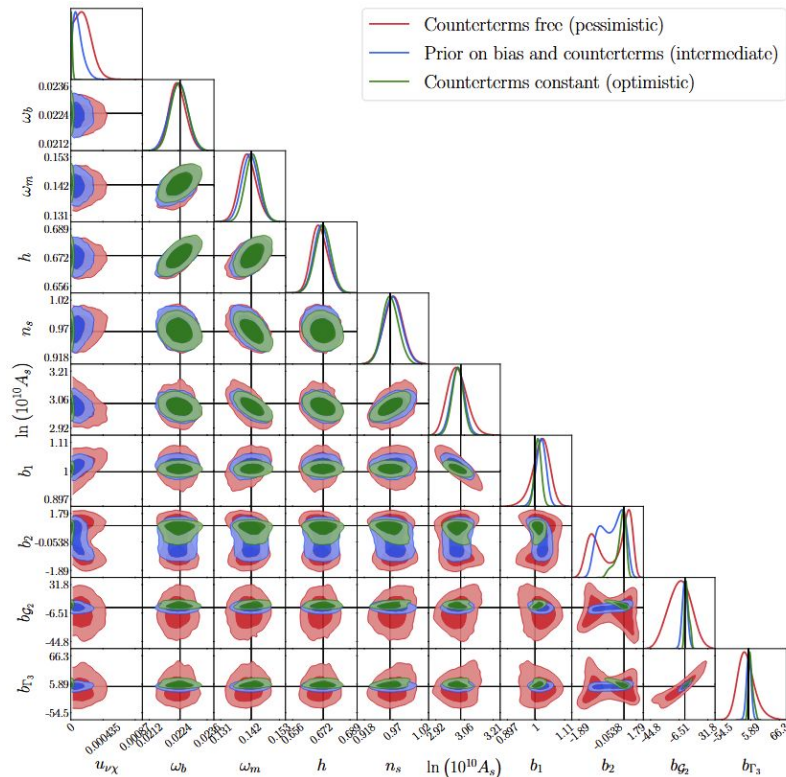
Forecasts: Galaxy Clustering with EFTofLSS

Massless approx. fully consistent with EFTofLSS

Preliminary validation against sims completed

Constraining power strongly dependent on nuisance parameter treatment.

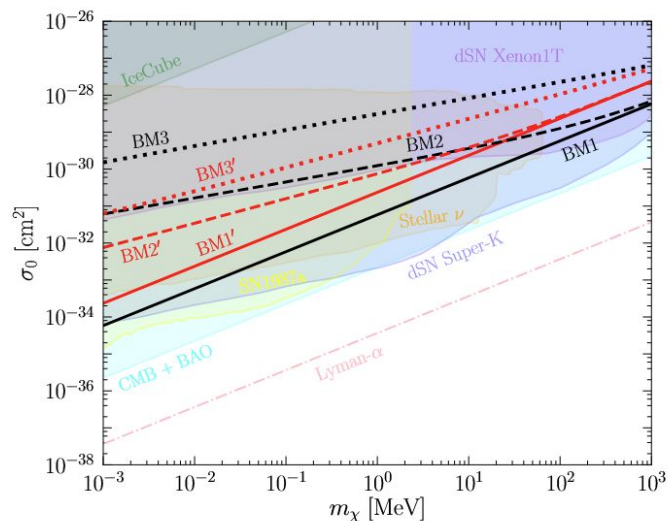
	95% CL upper limit (CDM fid.)
Optimistic	$< 3.49 \times 10^{-5}$
Intermediate	$< 2.48 \times 10^{-4}$
Pessimistic	$< 3.93 \times 10^{-4}$
	Mean $\pm 2\sigma$ (IDM90 fid.)
Optimistic	$6.08^{+4.08}_{-5.23} \times 10^{-5}$
Intermediate	$1.54^{+1.62}_{-1.42} \times 10^{-4}$
Pessimistic	$2.54^{+2.94}_{-2.50}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



Non-cosmology constraints

- E.g. blazar neutrinos + DM spike

Cline et al. [arXiv:2209.02713](https://arxiv.org/abs/2209.02713)



- Supernova 1987A
- Bullet cluster
- High energy neutrinos
- Laboratory limits

Comprehensive overview Dev et al.

[arXiv:2507.01000](https://arxiv.org/abs/2507.01000)

The things “swept under the rug”

- Many of these hints and limits are mutually exclusive!
- Are the mappings always robust?
- Are we using tools calibrated for Λ CDM?
- Is the particle physics always self-consistent?
(check recent work Dev et al. [arXiv:2507.01000](https://arxiv.org/abs/2507.01000))

Where do we go from here?

- More simulations?
- Consistency checks?
- Theoretical model building work?
- New tools?
- New observables?