Probing Dark Matter–Neutrino interactions in Cosmology

Markus R. Mosbech

News from the Dark 10, September 10, Montpellier

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

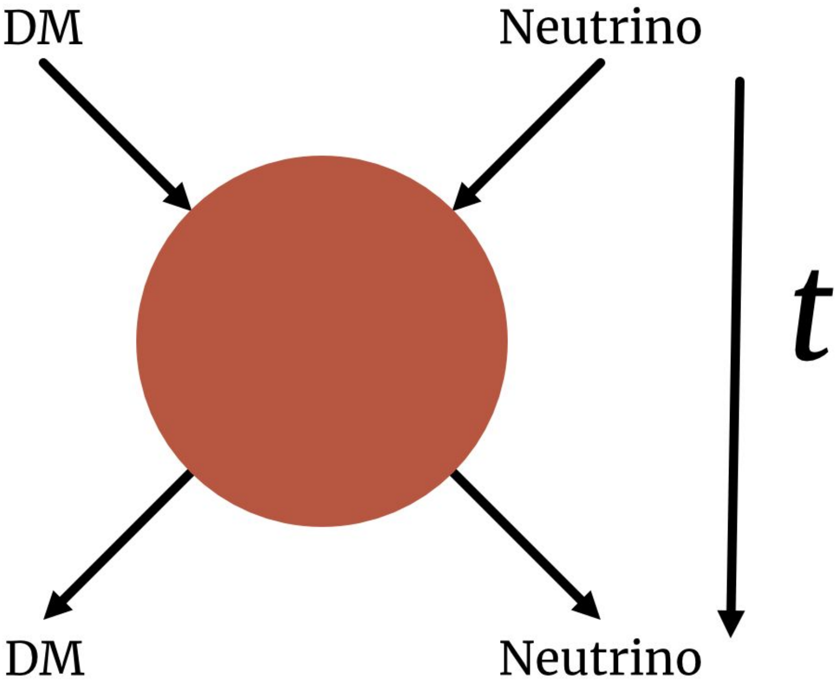
Observational “motivations”:

- 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
- Original implementation of massless neutrino approx. by Stadler et al. arXiv:1903.00540
- Implementation for massive neutrinos by Mosbech et al. arXiv: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

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

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

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

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

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

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

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

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

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

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

Mangano et al. arXiv:astro-ph/0606190
Serra et al. arXiv:0911.4411
Wilkinson et al. arXiv:1401.7597
Di Valentino et al. arXiv:1710.02559
Stadler et al. arXiv:1903.00540

The massive hierarchy

- Introduces p2/E2 factor
- More complex to evolve due to neutrino mass
- Slightly smaller effect for equal interaction strength

$$\frac{\partial \Psi_1}{\partial \tau} = [...] - C_\chi \frac{v_\chi E_\nu(p)}{3 f^{(0)}(p)} \frac{df^{(0)}(p)}{dp} - C_\chi \Psi_1 \ ,$$
$$\frac{\partial \Psi_2}{\partial \tau} = [...] - \frac{9}{10} C_\chi \Psi_2 \ ,$$
$$\frac{\partial \Psi_l}{\partial \tau} = [...] - C_\chi \Psi_l, \quad l \geq 3 \ ,$$

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

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

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

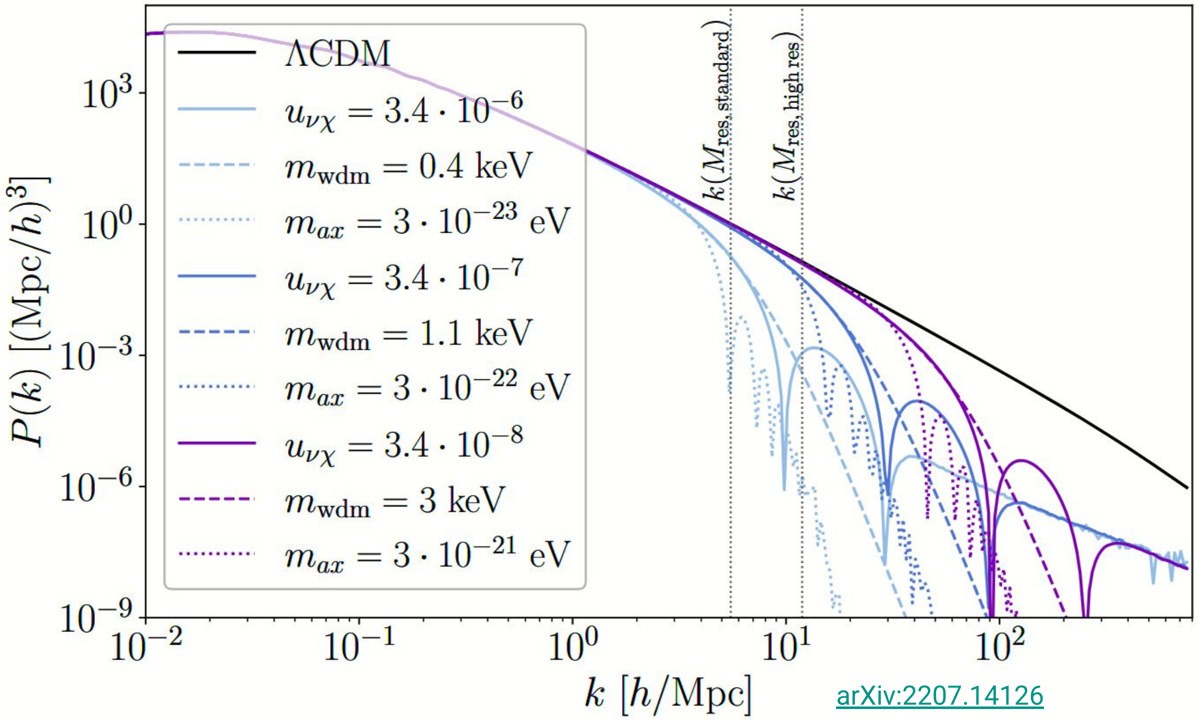
arXiv:2011.04206

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



arXiv:2207.14126

In the non-linear universe

Quick back of the envelope calculation:

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

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

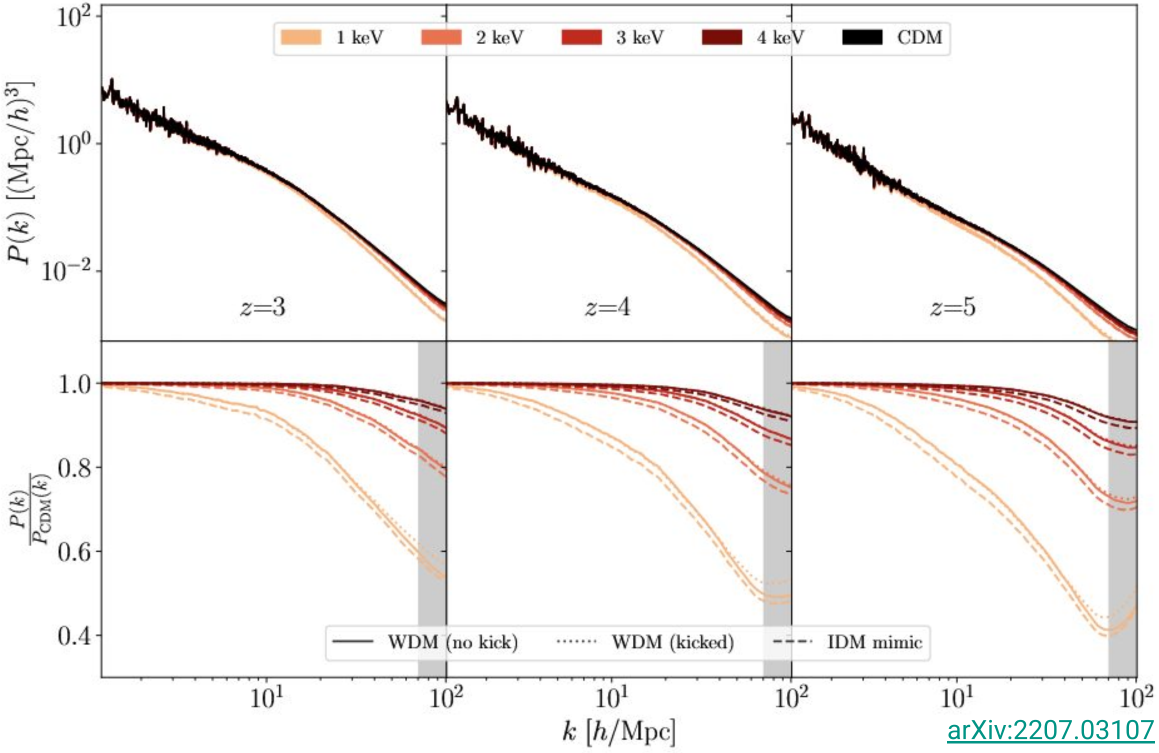
Neutrino non-linear growth much smaller than this
⇒ DM always unaffected after global decoupling

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

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

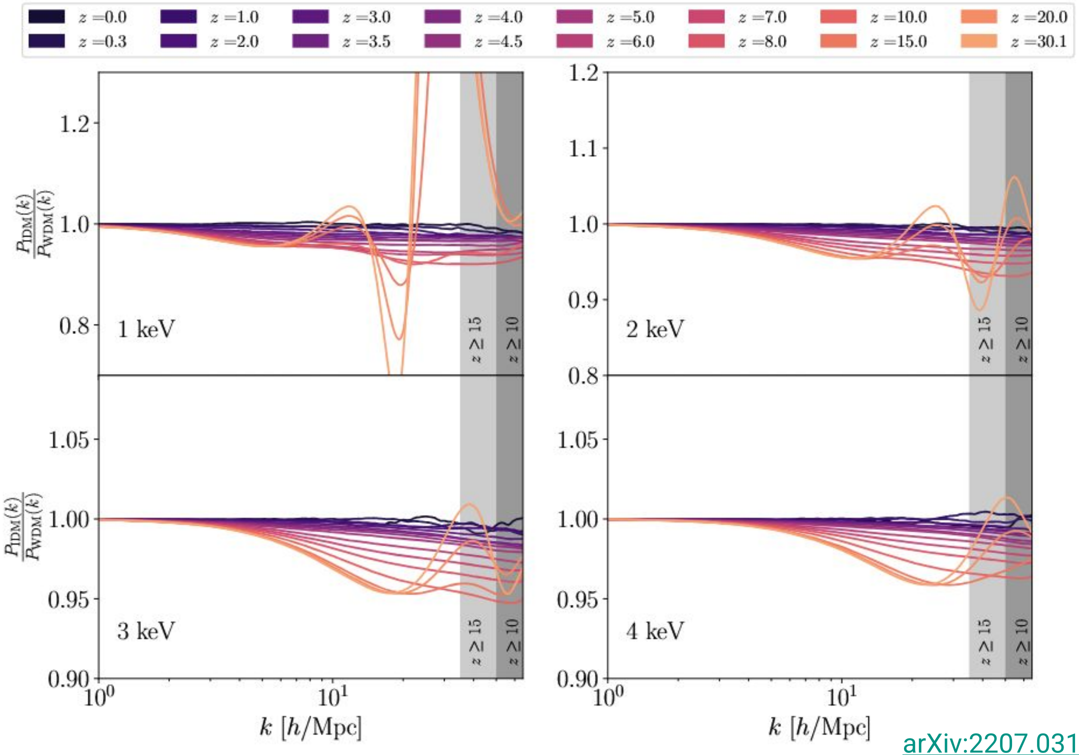
Exception: Cross-sections with non-trivial temperature dependence.

Uniqueness of (non-linear) signature



arXiv:2207.03107

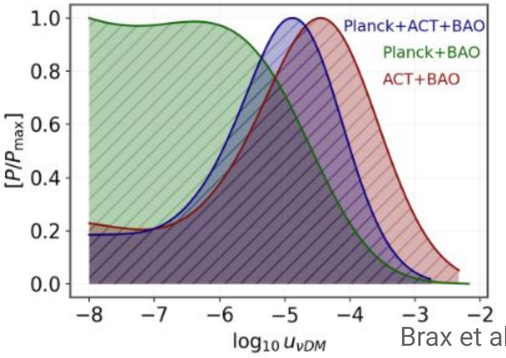
Uniqueness of (non-linear) signature



arXiv:2207.03107

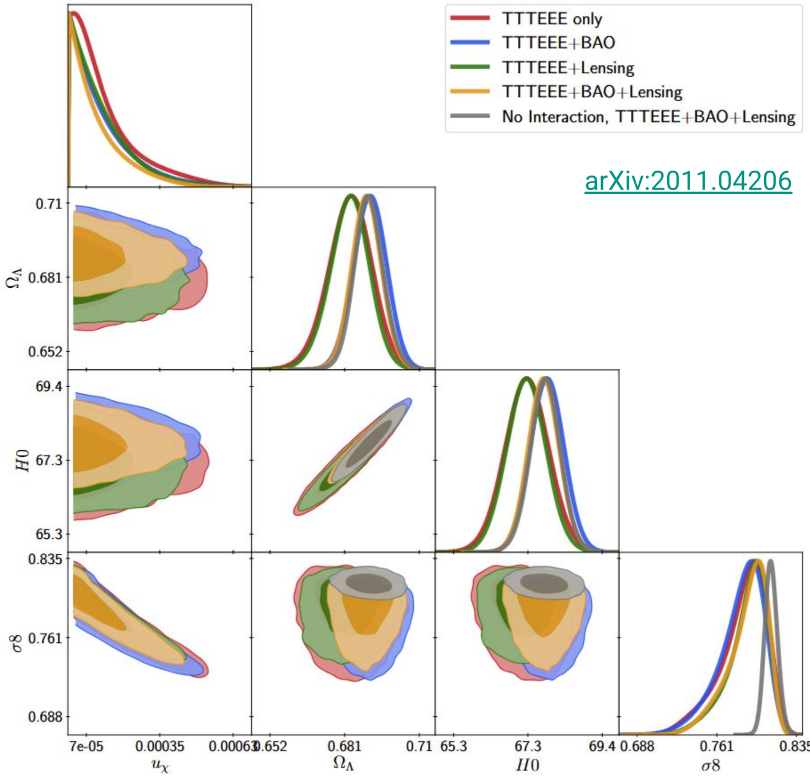
Observational status: CMB+BAO

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



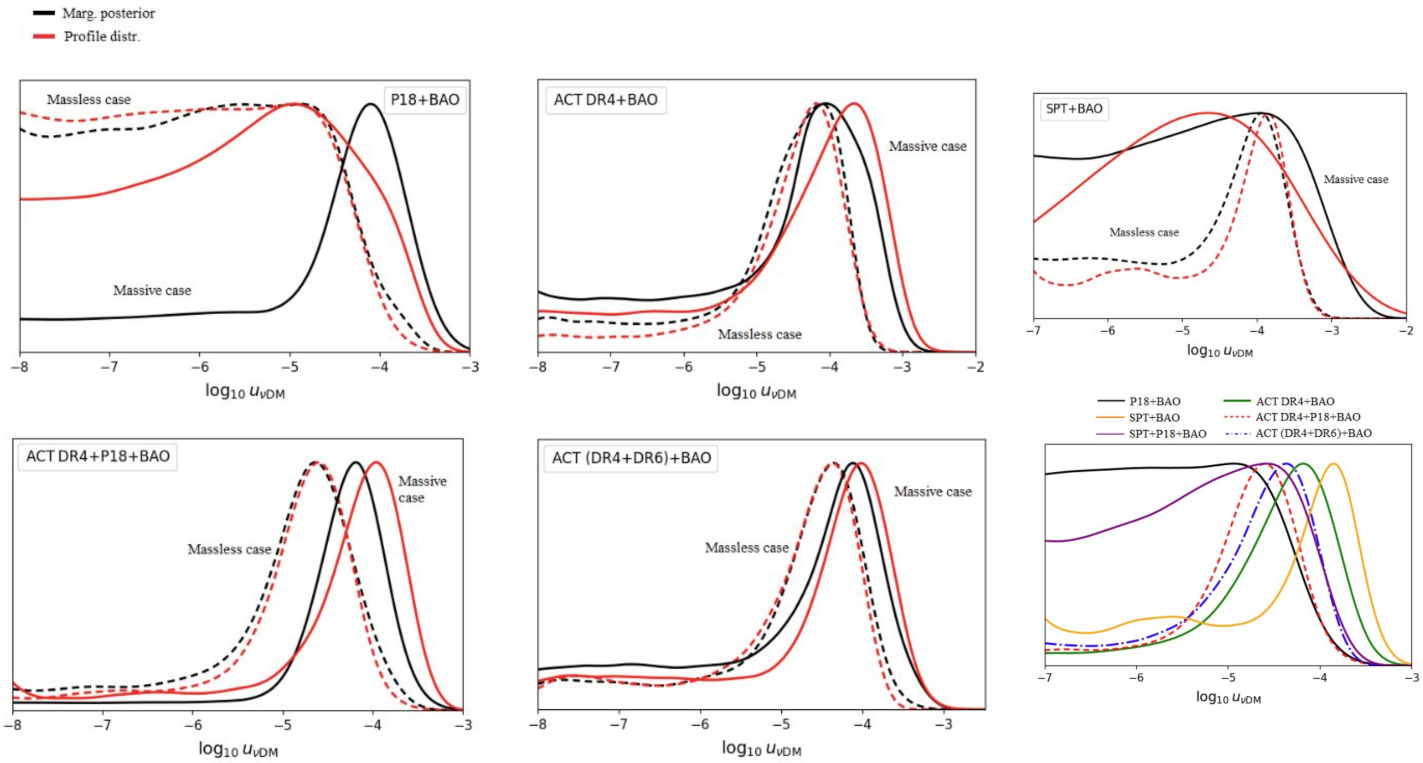
Brax et al. arXiv:2303.16895
+ arXiv:2305.01383

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



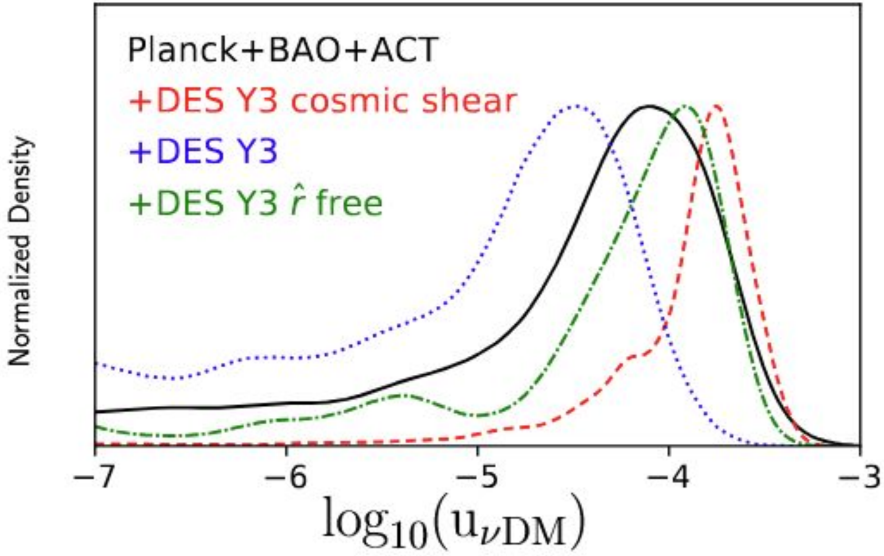
arXiv:2011.04206

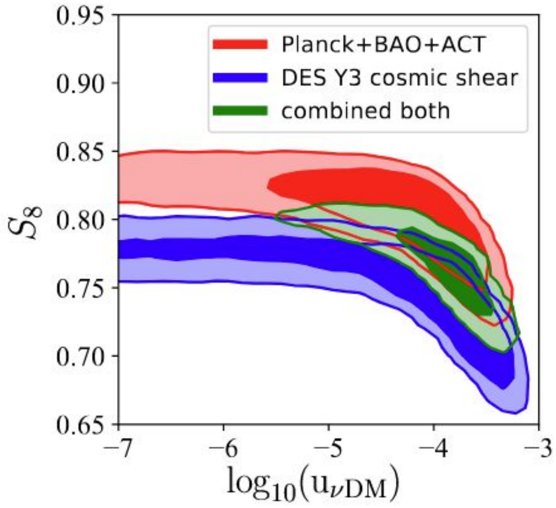
Observational status: CMB+BAO



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

Observational status: CMB+LSS

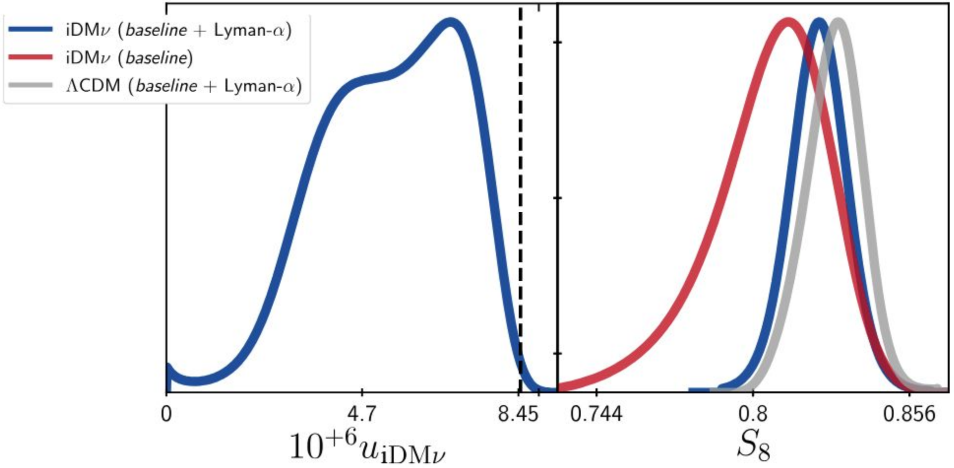


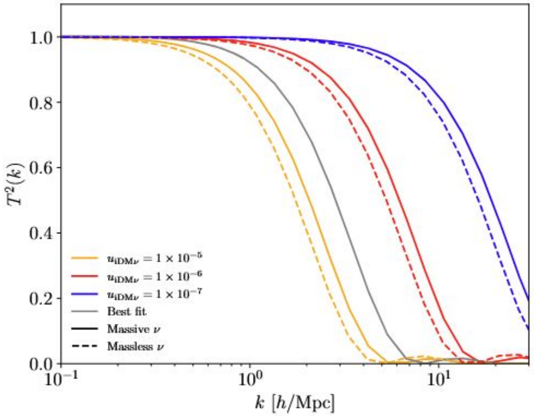


Zu et al. arXiv:2501.13785

See also Trojanowski & Zu arXiv:2505.20396
(enhanced interaction in narrow redshift range)

Observational status: CMB+Lyman-α





Hooper & Lucca
arXiv:2110.04024

Lyman-α = HIRES/MIKE

Observational status: Milky-Way Satellites

Semi-analytical subhalo model, Akita & Ando arXiv:2305.01913

Validated against Dark Matter-Dark Radiation simulations

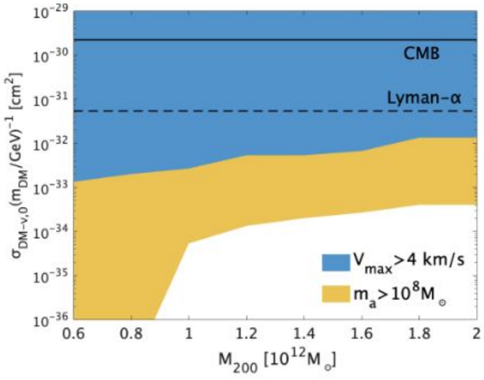
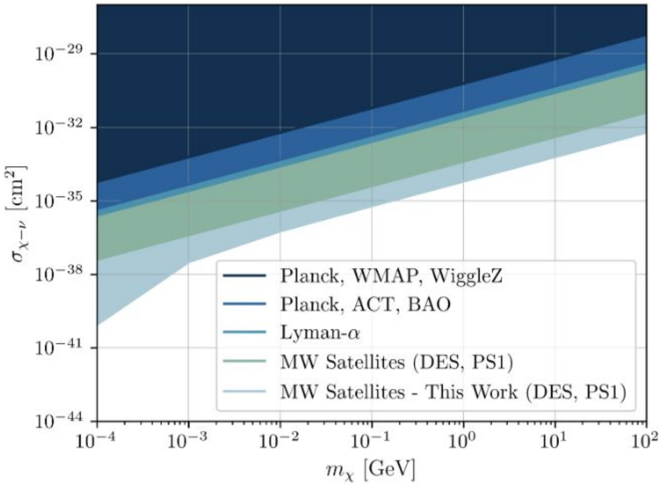


Figure 3: Constraints on the DM-neutrino cross section as $\sigma_{\mathrm{DM}-\nu,0}$ = const at 95 CL as a function of the Milky-Way mass considering the kinematics data of 94 Milky-Way satellites with $V_{\max} > 4$ km/s (blue) as well as the data of 270 Milky-Way satellites imposing the satellite 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

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



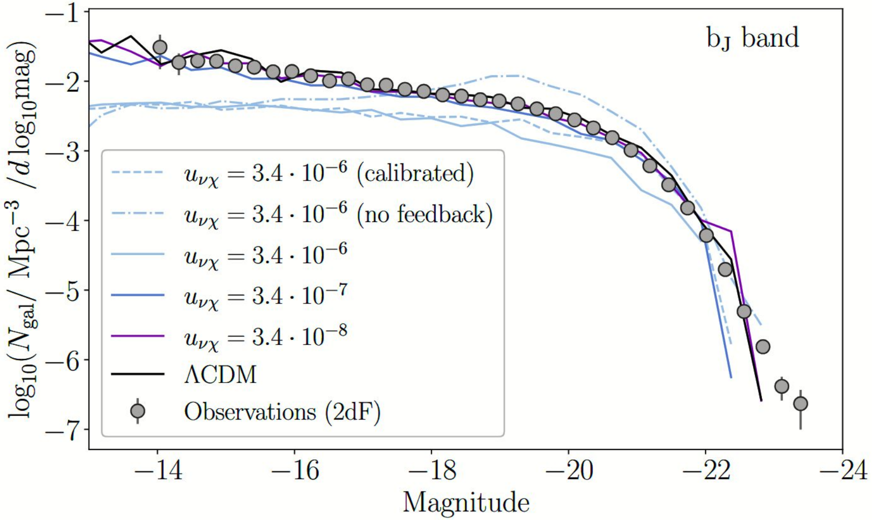
Observational status: Galaxy Population

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
⇒ results are robust

arXiv:2207.14126

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



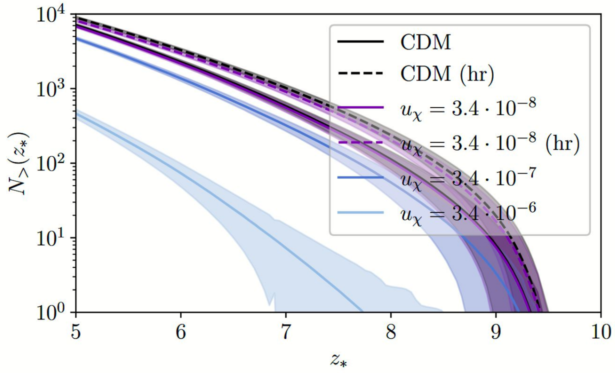
Observational status: Gravitational waves

Computed from galaxy model with stellar population evolution models.

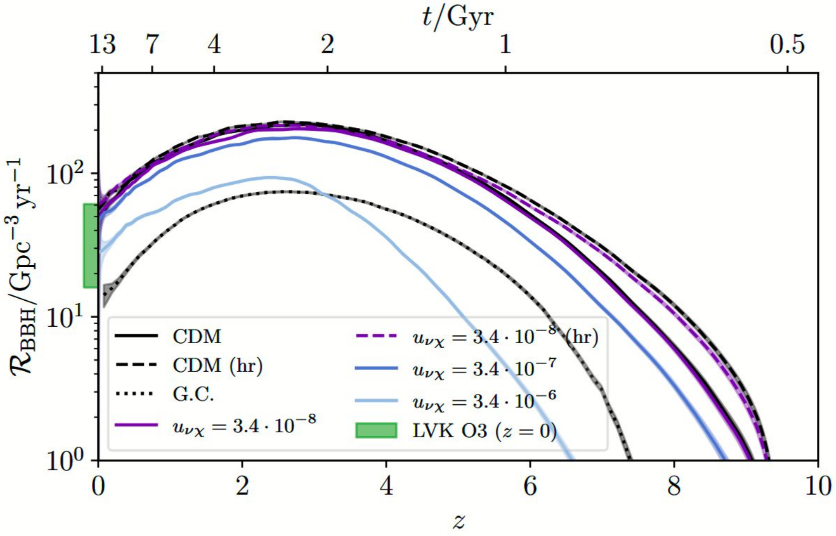
Subject to another layer of modeling uncertainty

Currently no limit.

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



arXiv:2207.14126



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
- $u_{\nu X} \lesssim 5.5 \cdot 10^{-7}$ Dey et al. arXiv:2207.02451 (Bound from 50% reionization at z=8)

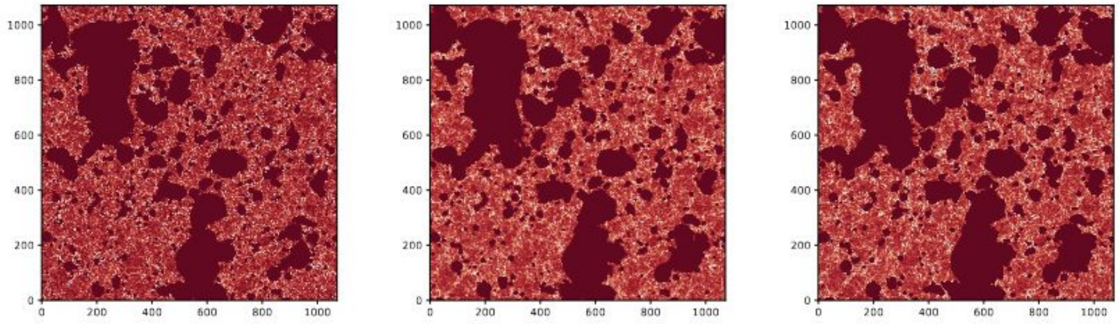


Figure 3. HI map: Two dimensional section of the simulated HI map at $z = 8.0$ generated from 2144^3 grid size of the simulation box. The above figures are for $u = 0$, $N_{\rm ion} = 24$; $u = 8.8 \times 10^{-8}$, $N_{\rm ion} = 300$ and $u = 6.6 \times 10^{-7}$, $N_{\rm ion} = 500$, units along x and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

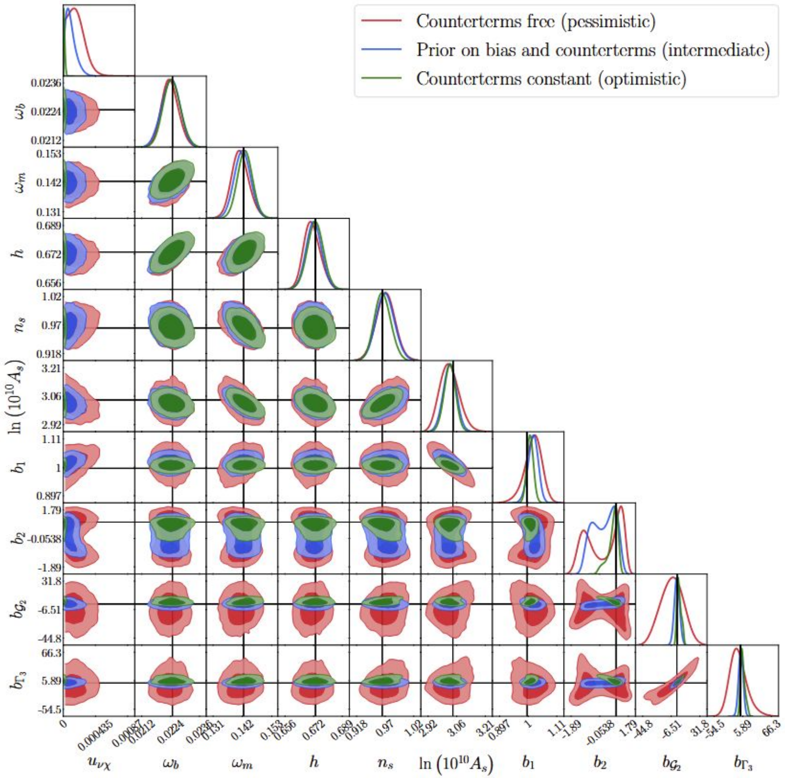
Forecasts: Galaxy Clustering with EFTofLSS

Massless approx. fully consistent with EFTofLSS

Preliminary validation against sims completed

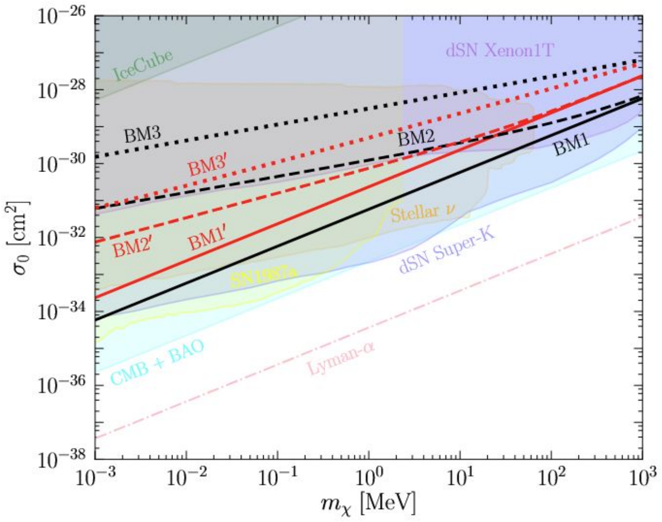
Constraining power strongly dependent on nuisance parameter treatment.

	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



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

Comprehensive overview Dev et al. arXiv: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 ΛCDM?
- Is the particle physics always self-consistent? (check recent work Dev et al. arXiv:2507.01000)

Where do we go from here?

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