Neutrinos, Dark Sectors, and Cosmological Tensions

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Why ν DM interactions? (cosmo)

- **A Tale of Two Relics**

The Cosmic Neutrino Background (CνB) and Dark Matter (DM) are both abundant primordial relics. We observe their profound gravitational impact (though neither is directly detected). It is natural to ask about their potential connections beyond gravity.

- **Tensions**

Cosmological data (ΛCDM + DESI + CMB) bounds $\Sigma m_\nu < 0.055$ eV, contradicting lab oscillation bounds $\Sigma m_\nu > 0.058$ eV. Reconciling tensions in standard ΛCDM pushes the preferred neutrino mass to unphysical, negative values ($\Sigma m_\nu < 0$).

→ J. Lesgourgues talk

- **Observable Impacts**

ν DM interactions can alter neutrino free-streaming and collisional damping. This leaves testable imprints on the CMB and suppresses the matter power spectrum P(k), offering a playground to testing the interactions in cosmology.

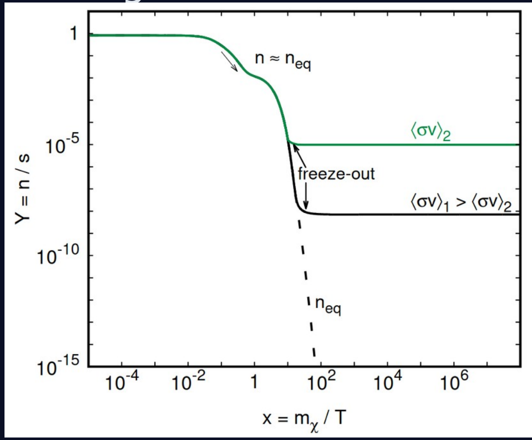
Why ν DM interactions? (particles)

- **Natural Window to New Physics**

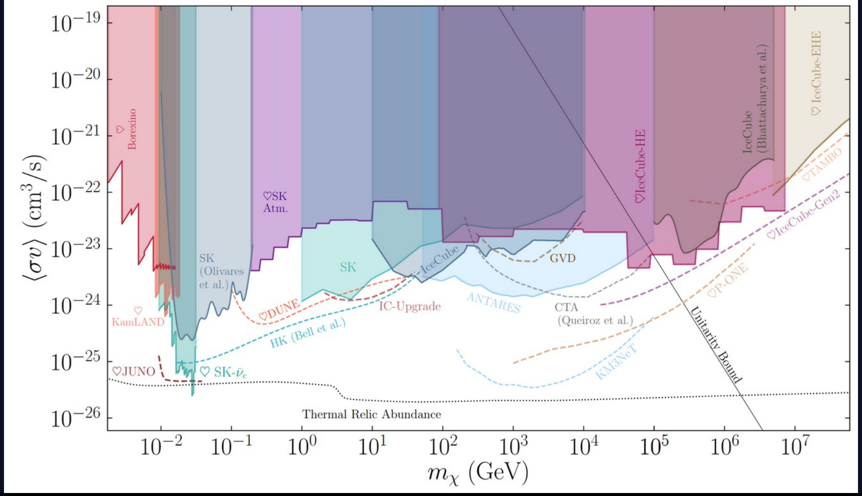
Neutrino oscillations are guaranteed Beyond Standard Model (BSM) physics. Because they already require a new physics sector, they serve as the most natural portal to the Dark Sector.

- **Saving Thermal Dark Matter**

The "WIMP Miracle" is under immense pressure from null results in direct detection and colliders. ν DM portals can successfully mediate the thermal production of DM in the early universe while evading standard nuclear recoil bounds.



L. Roszkowski, E.M. Sessolo, ST, 1707.06277 (Rept.Prog.Phys.)



C.A. Arguelles etal, 1912.09486 (Rev.Mod.Phys)

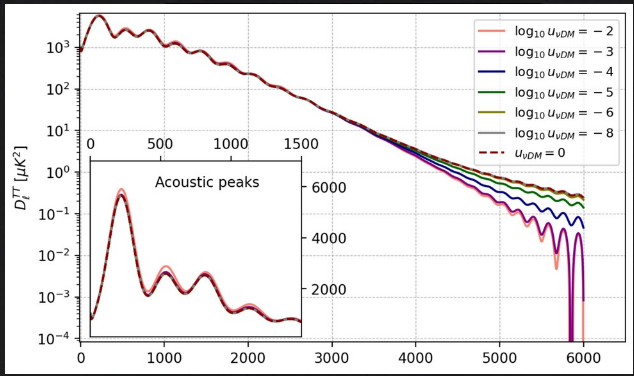
Cosmological signatures of interactions are visible in lensing and high CMB

CMB

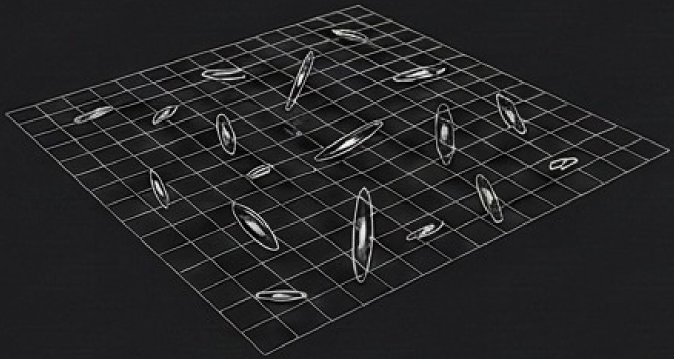
Neutrino Drag

Dark matter trapped in oscillations forces phase shifts in the acoustic spectrum and damping in the high-ℓ tail.

P. Brax etal, 2303.16895 (MNRAS: Letters)



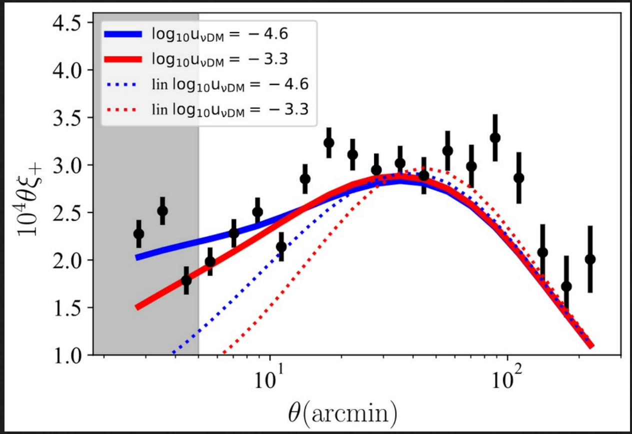
LSS/Lensing



MPS suppression -- impact on cosmic shear

Probed by weak-lensing surveys.
Sensitive to non-linear scales.

L. Zu etal, 2501.13785 (Nat. Astronomy)



P. Brax, C.v..d. Bruck, E. Di Valentino, W. Giare, ST etal, 2303.16895 (MNRAS: Letters)
P. Brax, C.v..d. Bruck, E. Di Valentino, W. Giare, ST etal, 2305.01383 (PDU)

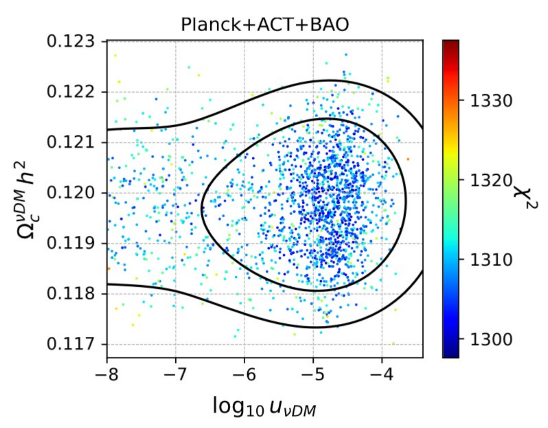
Cosmological data (previous)

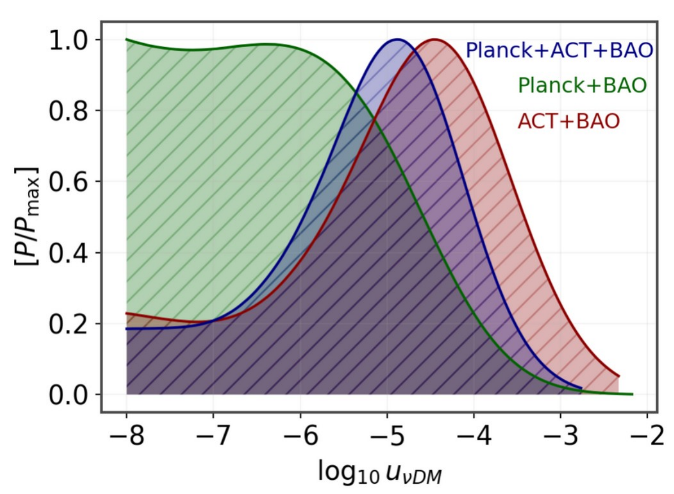
- Simplifying assumption: $u_{\nu\,\mathrm{DM}}$ = const
- Planck + ACT DR4 + BOSS DR12
- Mild preference ~1σ
- Consistent with previous Lyman-α hints

D.C. Hooper, M. Lucca, 2110.04024 (PRD)

- Further hints (including ACT DR6 lensing, SPT-3G & ν mass)

W. Giare, A. Gomez-Valent, E. Di Valentino, C.v.d. Bruck, 2311.09116, (PRD)

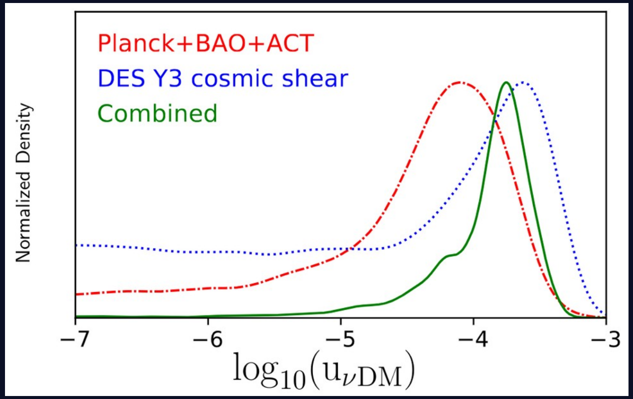


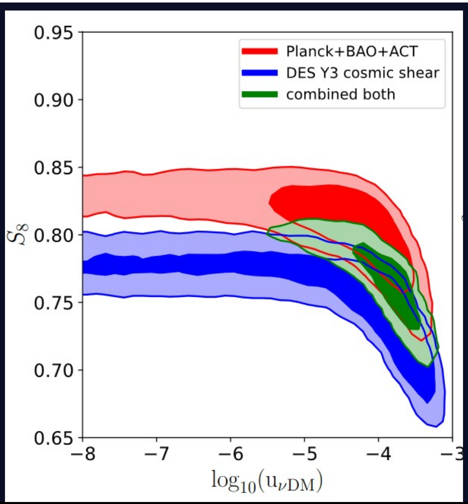


L. Zu etal, 2501.13785 (Nat. Astr.)

Cosmological data (previous 2)

- Simplifying assumption: $u_{\nu\,DM}$ = const
- Planck + ACT DR4 + BOSS DR12 + DES Y3
- Non-linear scales treated with emulation (N-body grid)
- Combined preference ~3σ



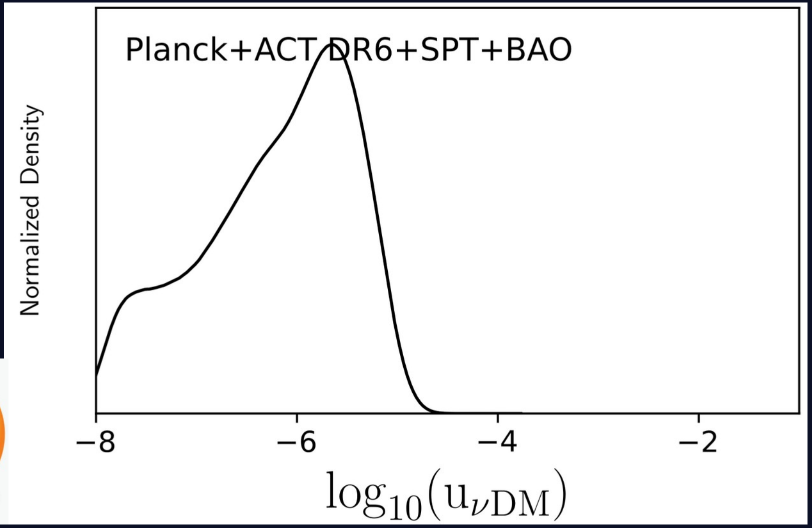


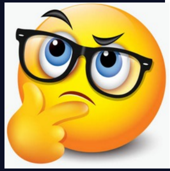
Cosmological data (update)

- Planck + ACT DR6 + SPT + DESI BAO DR2
- Combined preference for non-vanishing $u_{\nu\,DM}$ ~2σ

Persistent preference for
$u_{\nu\,DM} \sim 10^{-6}$ - 10^{-5} ?

Preliminary (credit: L. Zu)



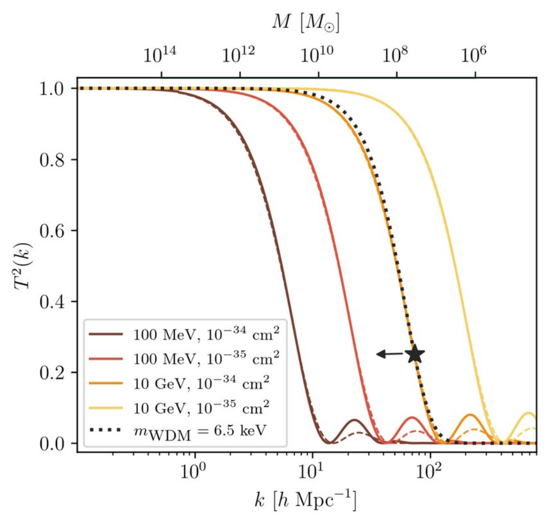


Bounds on ν DM

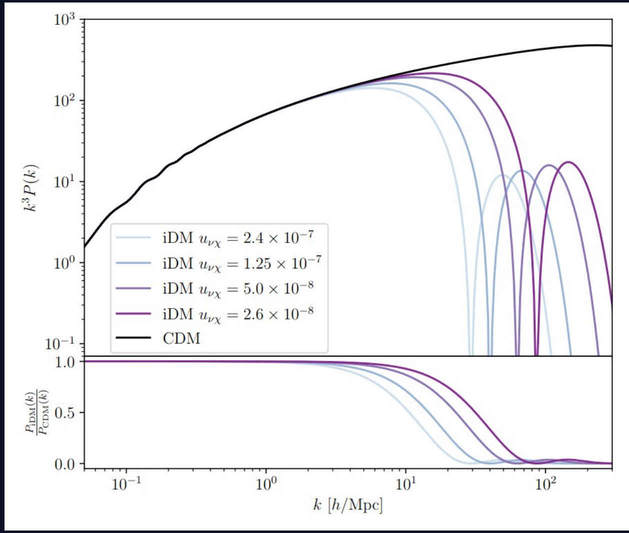
- Strong constraints from other cosmological and astrophysical bounds

- Constant $u_{\nu DM}$ ~< 10^{-8}

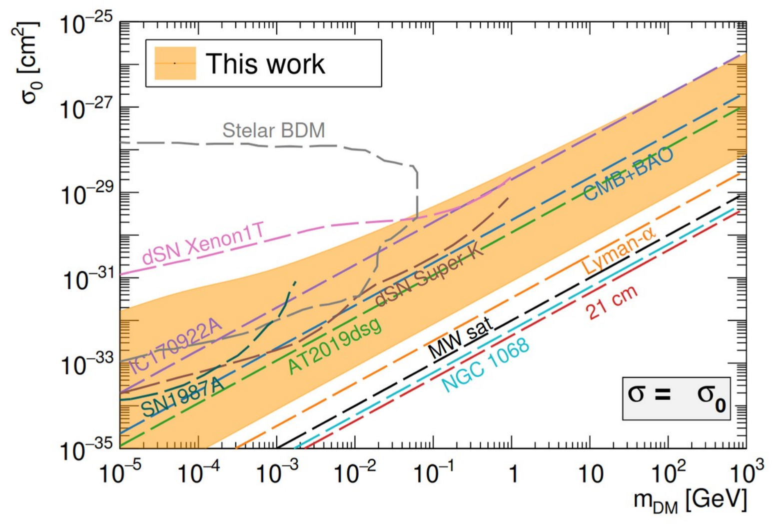
MW satellites: W. Crumrine etal, 2406.19458



Lyman-α: M.R. Mosbech etal, 2607.15020

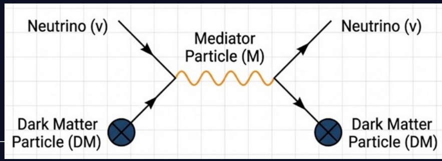


Astro: G.D. Zapata etal, 2503.03823 (JCAP)



A. Olivares-Del Campo etal, 1711.05283 (PRD)

Particle physics perspective (EFT)



$y = (s - m_{\rm DM}^2)/m_{\rm DM}^2 \simeq 2E_\nu/m_{\rm DM}$

Scenario	Lagrangian $(\mathcal{L}_{\rm int})$	$\sigma v_{\rm r}$	$\sigma_{\rm el}$
Complex DM, Dirac mediator	$-g\chi\bar{N}_{\rm R}\nu_{\rm L} + {\rm h.c.}$	$\frac{g^4}{12\pi}\frac{m_{\rm DM}^2}{(m_{\rm DM}^2+m_{\rm N}^2)^2}v_{\rm c.m.}^2$	$\frac{g^4}{32\pi}\frac{m_{\rm DM}^2y^2}{(m_{\rm N}^2-m_{\rm DM}^2)^2}$
Real DM, Dirac mediator		$\frac{4g^4}{15\pi}\frac{m_{\rm DM}^6}{(m_{\rm DM}^2+m_{\rm N}^2)^4}v_{\rm c.m.}^4$	$\frac{g^4}{8\pi}\frac{m_{\rm DM}^6y^4}{(m_{\rm N}^2-m_{\rm DM}^2)^4}$
Complex DM, Majorana mediator		$\frac{g^4}{16\pi}\frac{m_{\rm N}^2}{(m_{\rm DM}^2+m_{\rm N}^2)^2}$	$\frac{g^4}{32\pi}\frac{m_{\rm DM}^2y^2}{(m_{\rm N}^2-m_{\rm DM}^2)^2}$
Real DM, Majorana mediator		$\frac{g^4}{4\pi}\frac{m_{\rm N}^2}{(m_{\rm DM}^2+m_{\rm N}^2)^2}$	$\frac{g^4}{8\pi}\frac{m_{\rm DM}^6y^4}{(m_{\rm N}^2-m_{\rm DM}^2)^4}$
Dirac DM, Scalar mediator	$-g\bar{\chi}_{\rm R}\nu_{\rm L}\phi + {\rm h.c.}$	$\frac{g^4}{32\pi}\frac{m_{\rm DM}^2}{(m_{\rm DM}^2+m_\phi^2)^2}$	$\frac{g^4}{32\pi}\frac{m_{\rm DM}^2y^2}{(m_{\rm DM}^2-m_\phi^2)^2}$
Majorana DM, Scalar mediator		$\frac{g^4}{12\pi}\frac{m_{\rm DM}^2}{(m_{\rm DM}^2+m_\phi^2)^2}v_{\rm c.m.}^2$	$\frac{g^4}{16\pi}\frac{m_{\rm DM}^2y^2}{(m_{\rm DM}^2-m_\phi^2)^2}$
Vector DM, Dirac mediator	$-g\bar{N}_{\rm L}\gamma^\mu\chi_\mu\nu_{\rm L} + {\rm h.c.}$	$\frac{2g^4}{9\pi}\frac{m_{\rm DM}^2}{(m_{\rm DM}^2+m_{\rm N}^2)^2}$	$\frac{g^4}{4\pi}\frac{m_{\rm DM}^2y^2}{(m_{\rm DM}^2-m_{\rm N}^2)^2}$
Vector DM, Majorana mediator		$\frac{g^4}{6\pi}\frac{m_{\rm N}^2}{(m_{\rm DM}^2+m_{\rm N}^2)^2}$	
Complex DM, Vector mediator	$-g_\chi Z'^\mu((\partial_\mu\chi)\chi^\dagger - (\partial_\mu\chi)^\dagger\chi) - g_\nu\bar{\nu}_L\gamma^\mu Z'_\mu\nu_{\rm L}$	$\frac{g_\chi^2g_\nu^2}{3\pi}\frac{m_{\rm DM}^2}{(4m_{\rm DM}^2-m_{Z'}^2)^2}v_{\rm c.m.}^2$	$\frac{g_\chi^2g_\nu^2}{8\pi}\frac{m_{\rm DM}^2y^2}{m_{Z'}^4}$
Dirac DM, Vector mediator	$-g_{\chi_{\rm L}}\bar{\chi}_{\rm L}\gamma^\mu Z'_\mu\chi_{\rm L} - g_{\chi_{\rm R}}\bar{\chi}_{\rm R}\gamma^\mu Z'_\mu\chi_{\rm R} - g_\nu\bar{\nu}_L\gamma^\mu Z'_\mu\nu_{\rm L}$	$\frac{g_\chi^2g_\nu^2}{2\pi}\frac{m_{\rm DM}^2}{(4m_{\rm DM}^2-m_{Z'}^2)^2}$	$\frac{g_\chi^2g_\nu^2}{8\pi}\frac{m_{\rm DM}^2y^2}{m_{Z'}^4}$
Majorana DM, Vector mediator	$-\frac{g_\chi}{2}\bar{\chi}\gamma^\mu Z'_\mu\gamma^5\chi - g_\nu\bar{\nu}_L\gamma^\mu Z'_\mu\nu_{\rm L}$	$\frac{g_\chi^2g_\nu^2}{12\pi}\frac{m_{\rm DM}^2}{(4m_{\rm DM}^2-m_{Z'}^2)^2}v_{\rm c.m.}^2$	$\frac{3g_\chi^2g_\nu^2}{32\pi}\frac{m_{\rm DM}^2y^2}{m_{Z'}^4}$
Vector DM, Vector mediator	$-g_\chi\frac{1}{2}\chi^\mu\partial_\mu\chi^\nu Z'_\nu + {\rm h.c.} - g_\nu\bar{\nu}_L\gamma^\mu Z'_\mu\nu_{\rm L}$	$\frac{g_\chi^2g_\nu^2}{\pi}\frac{m_{\rm DM}^2}{(4m_{\rm DM}^2-m_{Z'}^2)^2}v_{\rm c.m.}^2$	$\frac{g_\chi^2g_\nu^2}{8\pi}\frac{m_{\rm DM}^2y^2}{m_{Z'}^4}$

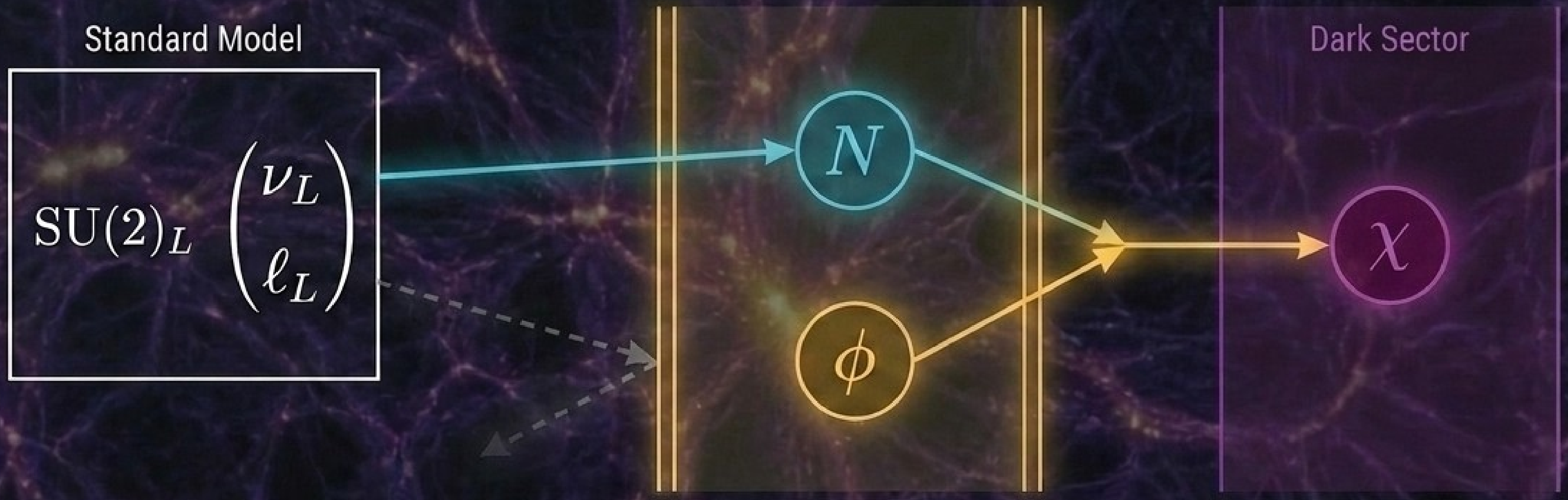
$\sim T^2$

$\sim T^4$

The Neutrino-Dark matter portal

B. Bertoni, etal, 1412.3113
B. Batell, etal, 1709.07001
P. Brax, etal (with ST), 2305.01383

$$\mathcal{L} \supset -\lambda_\ell \,(\bar{L}_\ell \,\hat{H})\, N_R - \phi\bar{\chi}\,(y_L\, N_L + y_R\, N_R) + \text{h.c.}$$



Theoretical Barrier: Gauge invariance typically forces new neutrino physics to couple with electrons and muons (strong constraints).

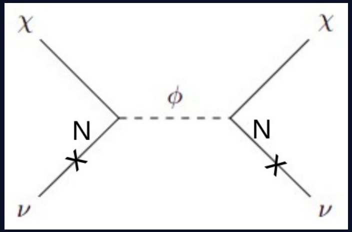
Sample solution: Neutrinophilic portal with heavy mediators (N, ϕ) preserves large ν DM couplings, remaining invisible to quarks and charged leptons.

Recent review on large ν DM effective couplings: K. S. Babu, P. S. Bhupal Dev, Anil Thapa, 2512.25035

P. Brax, etal (with ST), 2305.01383

Neutrino-DM cross section plateau

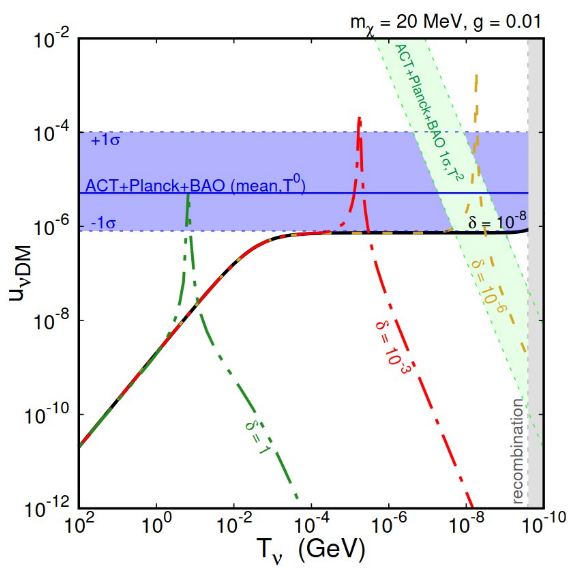
$$\mathcal{L} \supset -\lambda_\ell \left(\bar{L}_\ell \hat{H}\right) N_R - \phi \bar{\chi} \left(y_L N_L + y_R N_R\right) + \text{h.c.}$$



- Focus on s channel only (for simplicity)

$$\sigma_s = \frac{g^4}{16\pi\left(1 + 2E_\nu/m_\chi\right)} \frac{E_\nu^2}{\left(m_\phi^2 - m_\chi^2 - 2m_\chi E_\nu\right)^2 + m_\phi^2 \Gamma_\phi^2}$$

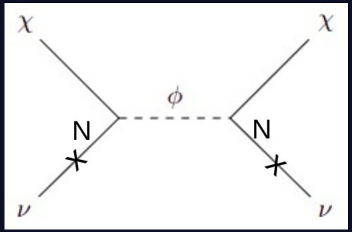
- Mass degenerate limit: mediator and DM masses nearly indentical
- Relevant energy regime is $E_\nu << m_\chi$
- but not too low energy such that the ϕ decay width is negligible
- Cross section plateau $\sigma_s \approx \dfrac{g^4}{64\pi m_\chi^2}$



P. Brax, etal (with ST), 2305.01383

Neutrino-DM cross section resonance peak

$$\mathcal{L} \supset -\lambda_\ell \, (\bar{L}_\ell \, \hat{H}) \, N_R - \phi \bar{\chi} \, (y_L \, N_L + y_R \, N_R) + \text{h.c.}$$



- Focus on s channel only (for simplicity)

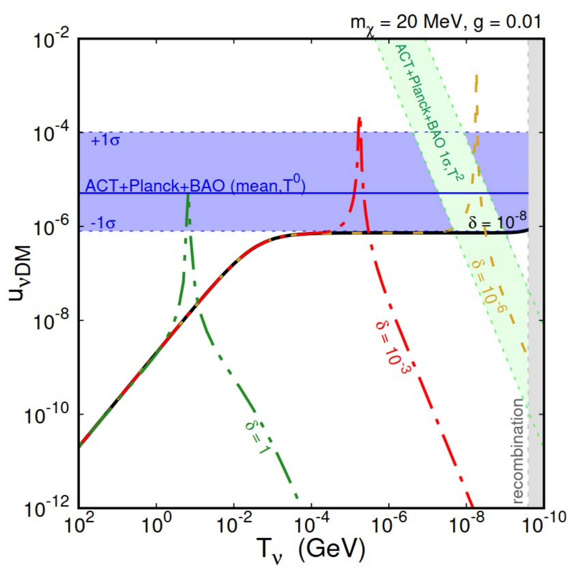
$$\sigma_s = \frac{g^4}{16\pi \, (1 + 2E_\nu/m_\chi)} \frac{E_\nu^2}{\left(m_\phi^2 - m_\chi^2 - 2m_\chi E_\nu\right)^2 + m_\phi^2 \Gamma_\phi^2}$$

- Resonant incident neutrino energy $E_\nu^{\rm res} = \frac{m_\phi^2 - m_\chi^2}{2m_\chi} \ll m_\chi.$

- Pole dominated by a narrow ϕ decay width prop. to g^4

- Cross section peak $\sigma_s^{\rm peak} = \frac{8\pi}{m_\chi^2 (1 - m_\chi^2/m_\phi^2)^2}$

- Unitarity cap $\sigma_{\rm unit} = \frac{4\pi}{p_{\rm cm}^2}$

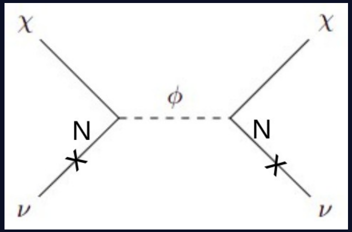


Constant $u_{\nu\,\mathrm{DM}}$ close to recomb. => resonance

P. Brax, etal (with ST), 2305.01383

Neutrino-DM cross section resonance peak

$$\mathcal{L} \supset -\lambda_\ell \, (\bar{L}_\ell \, \hat{H}) \, N_R - \phi \bar{\chi} \, (y_L \, N_L + y_R \, N_R) + \mathrm{h.c.}$$



- Focus on s channel only (for simplicity)

$$\sigma_s = \frac{g^4}{16\pi \, (1 + 2E_\nu / m_\chi)} \frac{E_\nu^2}{\left(m_\phi^2 - m_\chi^2 - 2 m_\chi E_\nu\right)^2 + m_\phi^2 \Gamma_\phi^2}$$

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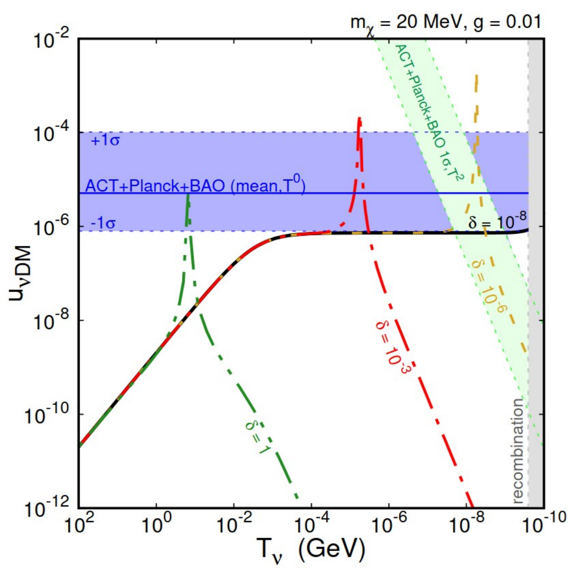
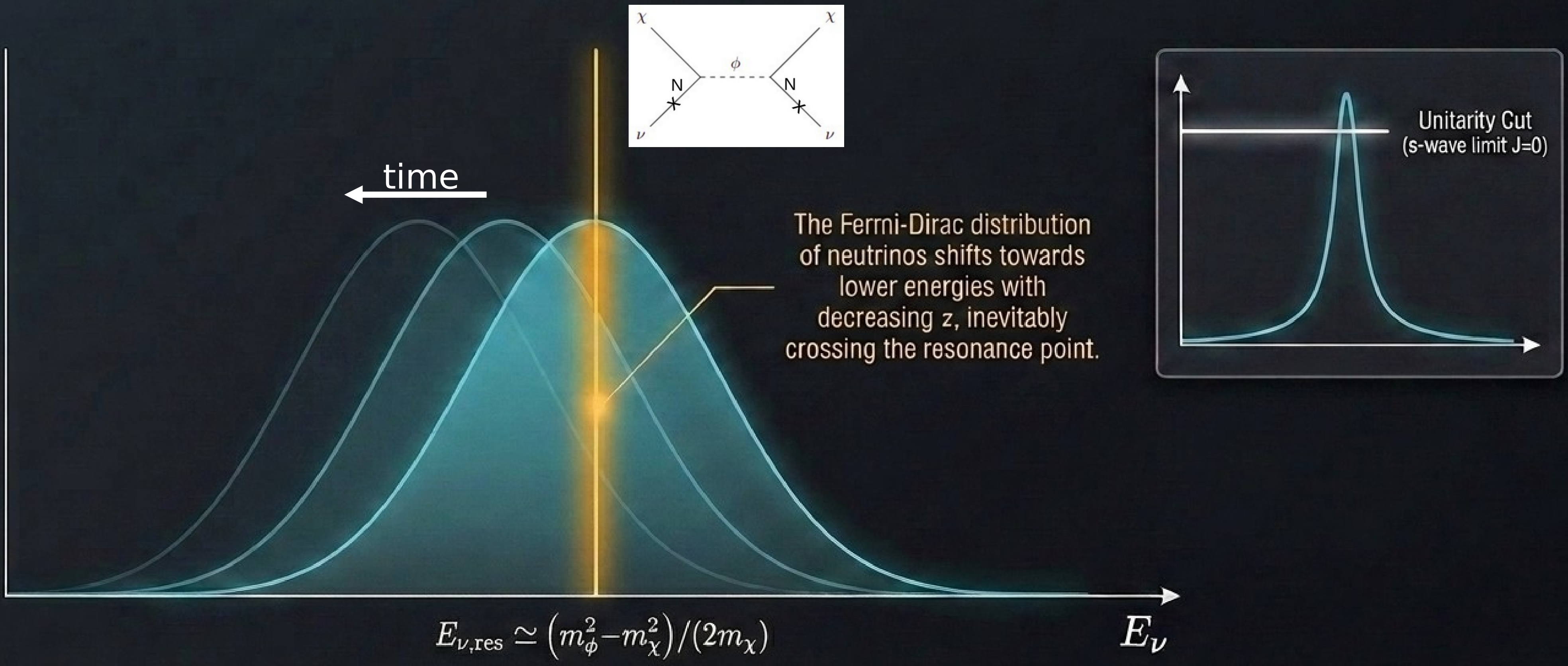


Resonant νDM interactions

ST, L. Zu, 2505.20396



Neutrino-DM resonance in cosmology

- Modified evolution of fluid velocity divergence

$$\dot{\theta}_\chi = k^2\psi - \mathcal{H}\theta_\chi - K_\chi\,\dot{\mu}_\chi\,(\theta_\chi - \theta_\nu)$$

- Momentum transfer (ETHOS): microphysical resonance thermally broadened when the momentum transfer kernel is convoluted with the (unperturbed) neutrino Fermi-Dirac distribution

$$\dot{\mu}_\chi = \frac{a\,n_\chi}{128\,\pi^3\,m_\chi^2\,(\rho_\nu/\eta_\nu)}\int_0^\infty dp\,p^4\left(-\frac{\partial f_\nu^{(0)}}{\partial p}\right)A_{0-1}(p)$$

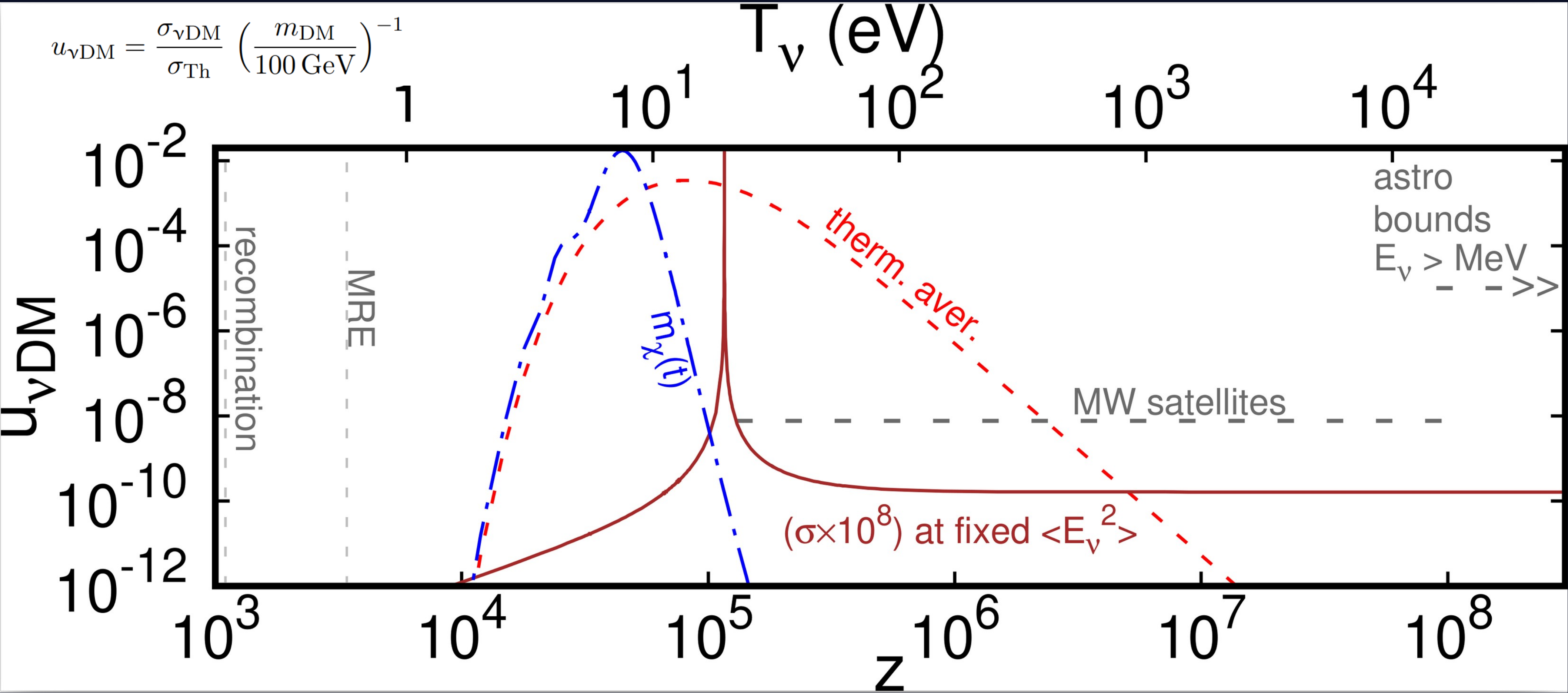
$$A_l(p) = \frac{1}{2}\int_{-1}^{1} d\mu\;P_l(\mu)\left(\frac{1}{\eta_{\rm DM}\,\eta_\nu}\,|\mathcal{M}_{\nu\rm DM}|^2\right)\Bigg|_{\substack{t=2p^2(\mu-1)\\ s=m_{\rm DM}^2+2\,m_{\rm DM}\,p}}$$

- This enhances the ν DM cross section across a broad redshift range

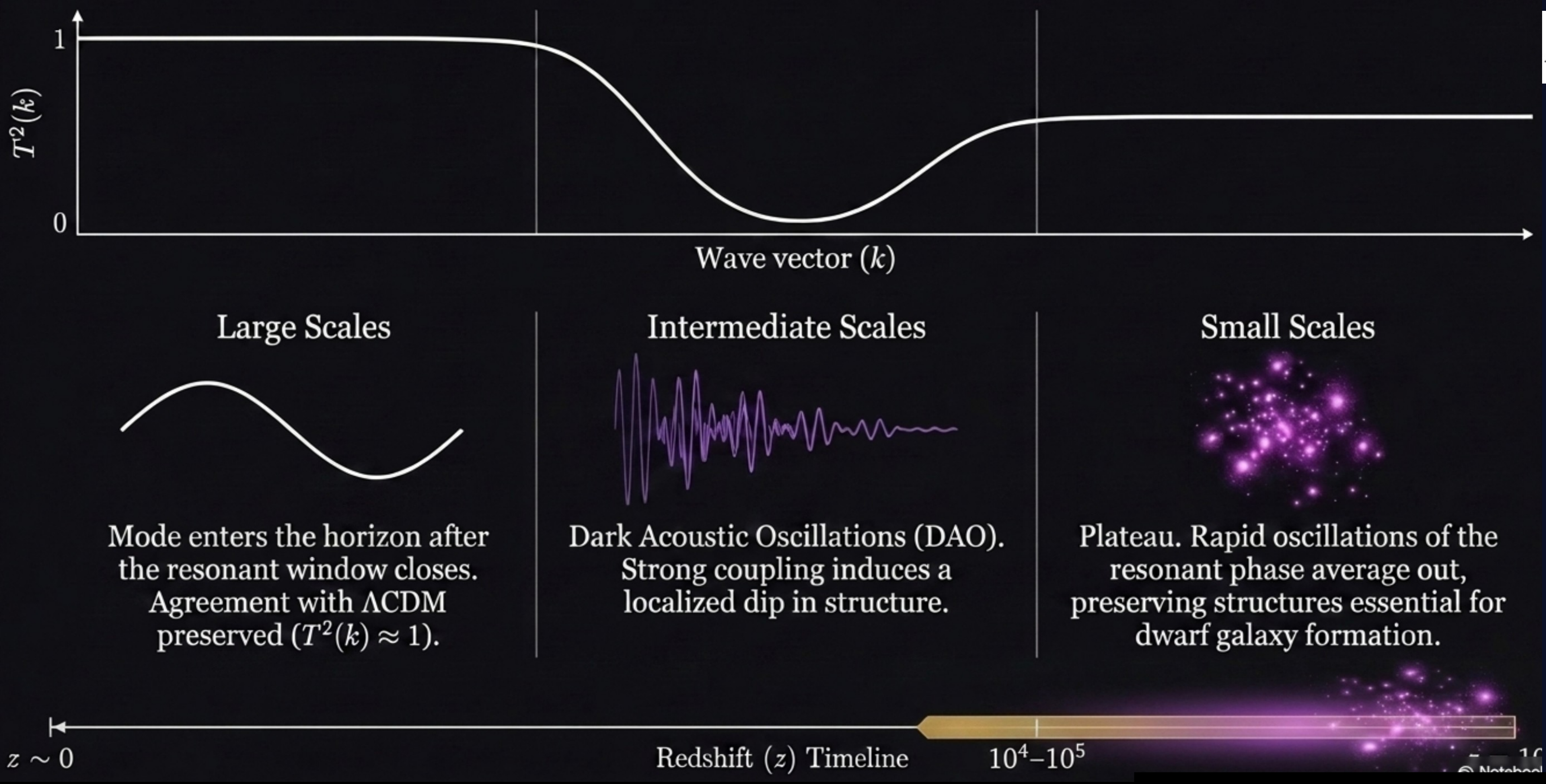
ST, L. Zu, 2505.20396

Redshift-dependent ν DM

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



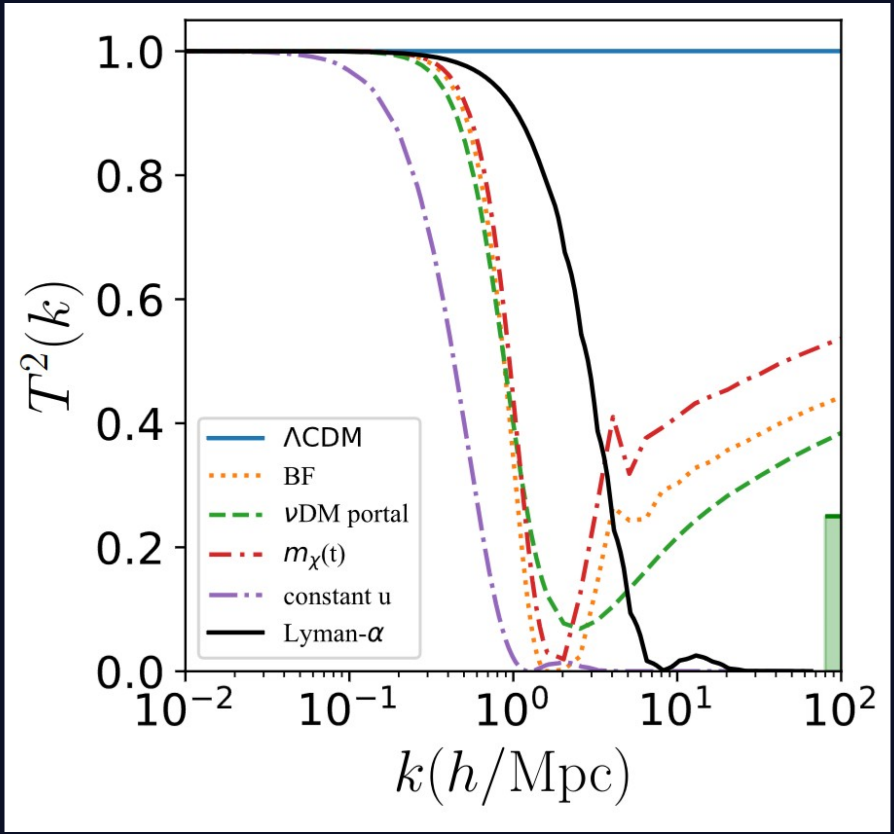
Scale-selective suppression of MPS

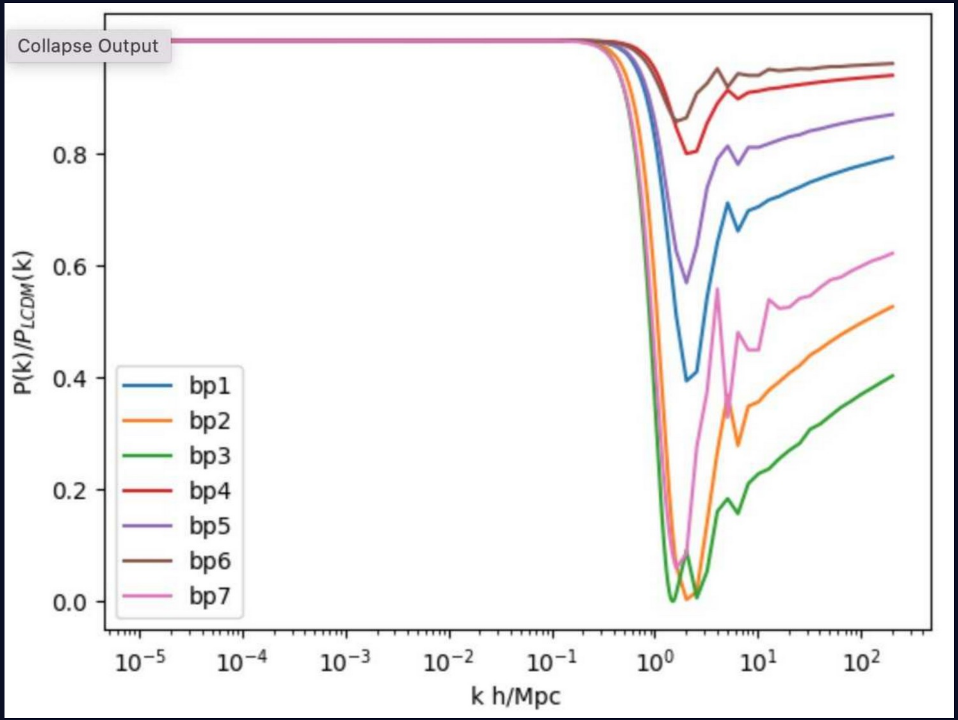


$$I = \int_{\Delta z} \Gamma d\tau$$

$$\Gamma = K_\chi \dot{\mu}_\chi$$

Scale-selective suppression of MPS (2)





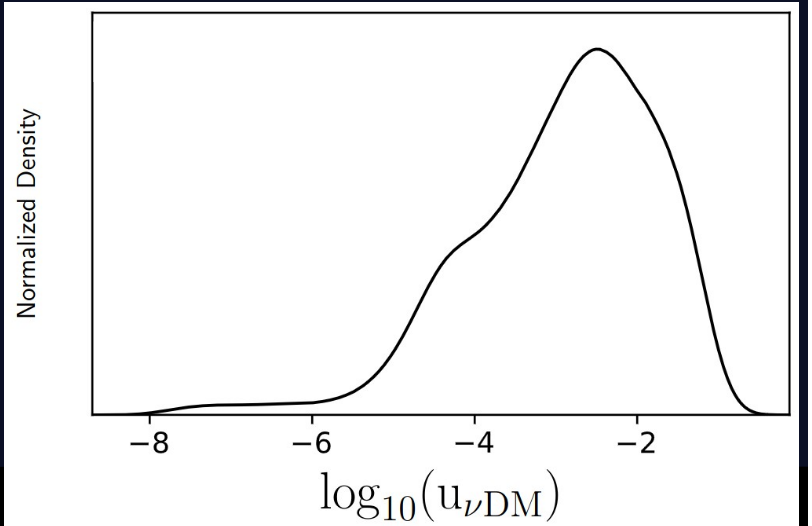
ST, L. Zu, 2505.20396

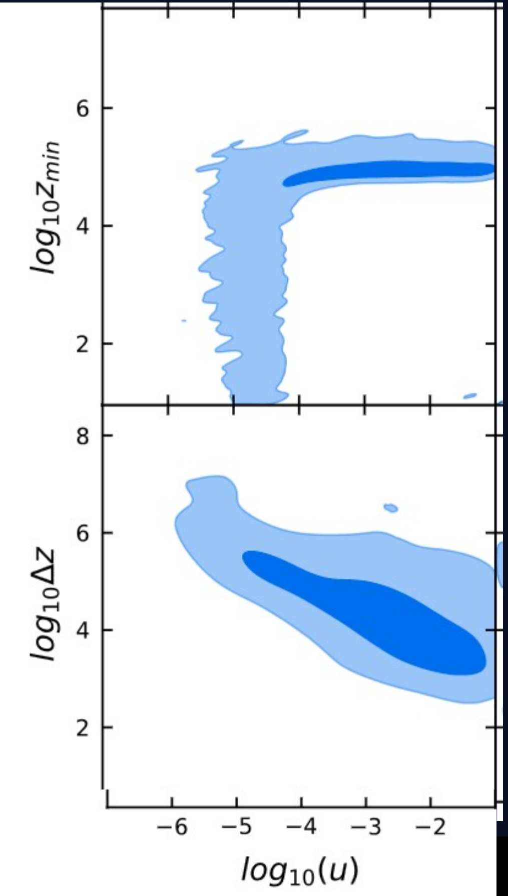
Cosmological data (update)

- Redshift-enhanced scenario $[z_{min}, z_{min} + \Delta z]$
- Planck + ACT DR6 + SPT + DESI BAO DR2 + KiDS-Legacy
- Combined preference for non-vanishing $u_{\nu DM}$ ~3σ
- Preferred cosmological epoch of enhancement $z \sim 10^5$
- Similar χ^2 fit obtained for specific resonant ν DM benchmarks
- Two important points:

— more realistic than a simple constant cross section

— more flexibility to avoid bounds at different scales



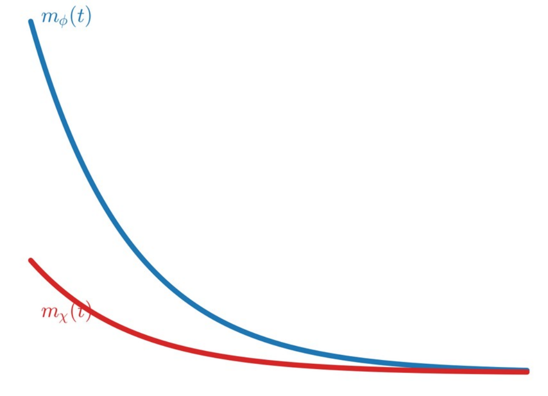


Small mass degeneracy in the dark sector

- Symmetry: small mass splitting could be symmetry protected (e.g., same (super)multiplets)
- Radiative corrections → fine-tuning of model parameters
- ”Dynamical mass degeneracy” via a coupling to an underlying scalar field
- Example: rolling (quintessence) field

P. Agrawal, G. Obied, C. Vafa, 1906.08261 (PRD)

$$m(\phi) = m_0 \exp[-\tilde{c}\,(\phi - \phi_0)]$$



- Multiple other examples (talks: Anne Davis, Carsten van de Bruck, …)
- **Resonances in the dark sector – a tool to reveal tiny mass variations over time/redshift due to an underlying scalar evolution**
- **below MeV mass variations can be relevant for “bare masses” of order GeV or so**

Toy model – even more localized ν DM

- Quadratic potential

$$V(\varphi) = \frac{1}{2} m_\varphi^2 \varphi^2$$

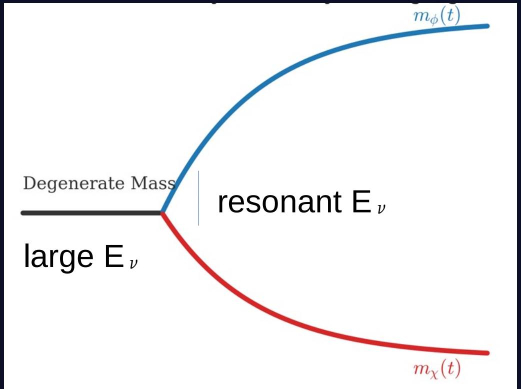
- Field-dependent mass

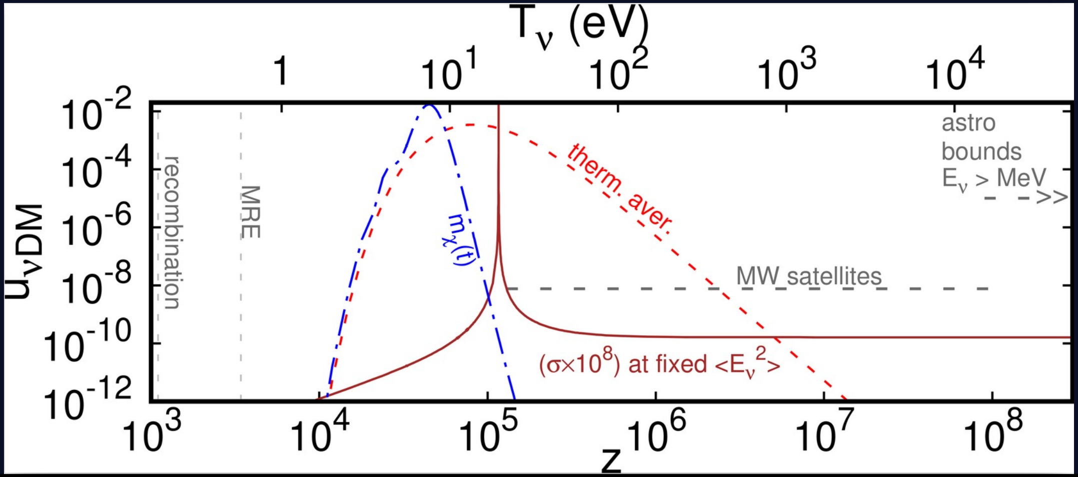
$$m_\chi(\varphi) = m_\chi(0)\left(1 + \frac{1}{2} g_\varphi \varphi^2\right)$$

- Field evolution in the RD epoch (oscillations)

$$\varphi(t) = \phi_i \left(\frac{2}{m_\varphi t}\right)^{1/4} \Gamma(5/4) J_{1/4}(m_\varphi t)$$

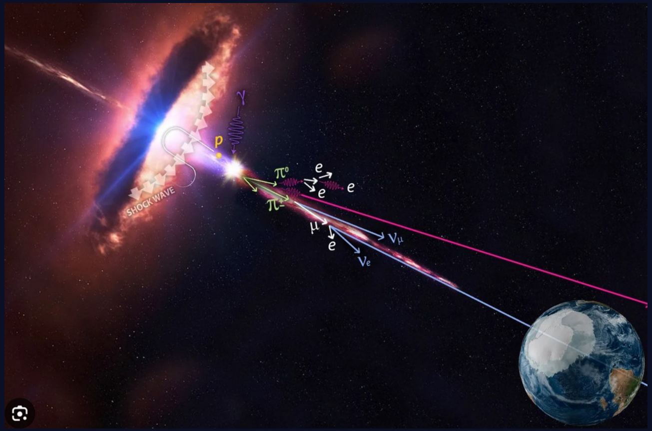
- Scalar mass ~ 10^{-23} eV
- Yields a similar χ^2 fit to previous best-fits



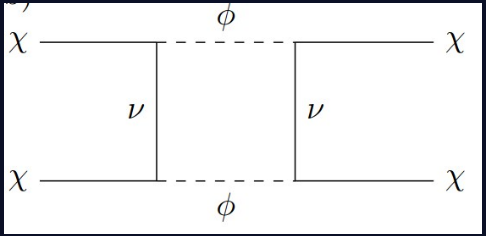


Other tests of small mass splittings & ν DM

- GeV range: high-energy astrophysical neutrinos, traversing through a DM spike (host galaxy)
- MeV range: supernovae neutrinos traversing through a DM halo – flux atteunation a specific energies (resonance)



- Below MeV – challenging –> cosmology to the rescue
- Independent bounds on heavy sterile neutrino states N and on DM annihilations into ν ν
- Possible impact on the small-scale structure through DM self-scatterings



Further effects

- Neutrino damping at a resonance

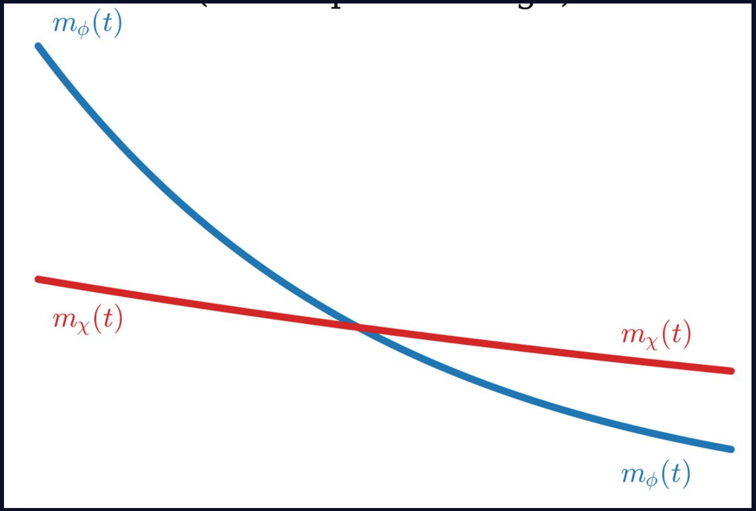
At the resonance peak, neutrino free-streaming will be damped for a short period
Might ease additional ΔN_{eff} produced at earlier times
Similar discussion in the context of Majoron

M. Escudero, S. J. Witte, 1909.04044, 2103.03249

- Dark matter changing identity

In the mass degenerate regime in the dark sector,
underlying scalar field evolution and coupling to matter
can change the identity of DM particle at a certain redshift

- New “heavier” state will decay into the “new” lighter one
and slightly reheat the universe by emitting associated rad. (ν)



- We may loose connection between present day DM annihilation and relic density

Summary

- Neutrino-DM interactions – still exciting opportunity
- Hints in high-multipole CMB & weak lensing,…
- but bounds from Lyman-α, small scales, astro…
- Modeling with a constant ν DM interaction close to recombination naturally leads to:
  — compressed spectra in the dark sector
  — resonant effects on the cross section that enhance interactions in certain periods
- Coupling to background scalar field and mass variation – opportunity to reveal field dynamics
- Potential interesting effects: neutrino damping at specific redshift, DM identity change, ….