New Insight on Neutrino Dark Matter Interactions from Small-Scale CMB Observations

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

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DARK MATTER – NEUTRINO INTERACTIONS

● appear naturally if dark matter (DM) coupled to weak gauge bosons or otherwise to $SU(2)_L$ lepton doublet, but…

● ...typically couplings to charged leptons dominate pheno (especially for electrons)

Can DM-ν couplings determine DM phenomenology?

EXAMPLE 1: non-universal couplings to charged leptons,
e.g., $U(1)_{L\mu-L\tau}$ gauge boson portal to DM

- light DM and Z' → self-interactions J. Heeck, A. Thapa, 2202.08854
- H_0 tension, $(g-2)_\mu$ anomaly
- still couplings to muons dominate pheno: tridents, ...

EXAMPLE 2: (sterile) neutrino portal to DM

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \overline{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \overline{N}\left(i\partial\!\!\!/ - m_N\right)N + \partial_\mu S^* \partial^\mu S$$
$$- \left[\lambda_\alpha \overline{L_\alpha}\tilde{H} N_R + \overline{\chi}\left(y_L N_L + y_R N_R\right) S + \text{h.c.}\right]$$
$$- \mu_S^2 |S|^2 - \lambda_S |S|^4 - \lambda_{SH} |S|^2 H^\dagger H \,,$$

B. Bertoni, etal, 1412.3113
B. Batell, etal, 1709.07001
M. Blennov, etal, 1903.00006

DARK MATTER – NEUTRINO INTERACTIONS & CMB

- CMB plays an essential role in establishing DM role in the evolution of the Universe

- Non-interacting cold DM

fast & slow modes of perturbation
Baryon-photon and DM effectively self-gravitating until the drag epoch

- Neutrinos contribute to fast (baryon-photon) modes

- In the presence of DM-neutrino interactions:

– DM takes part in oscillations R.J. Wilkinson, etal, 1401.7597
→ gravitational boost & enhanced CMB peaks

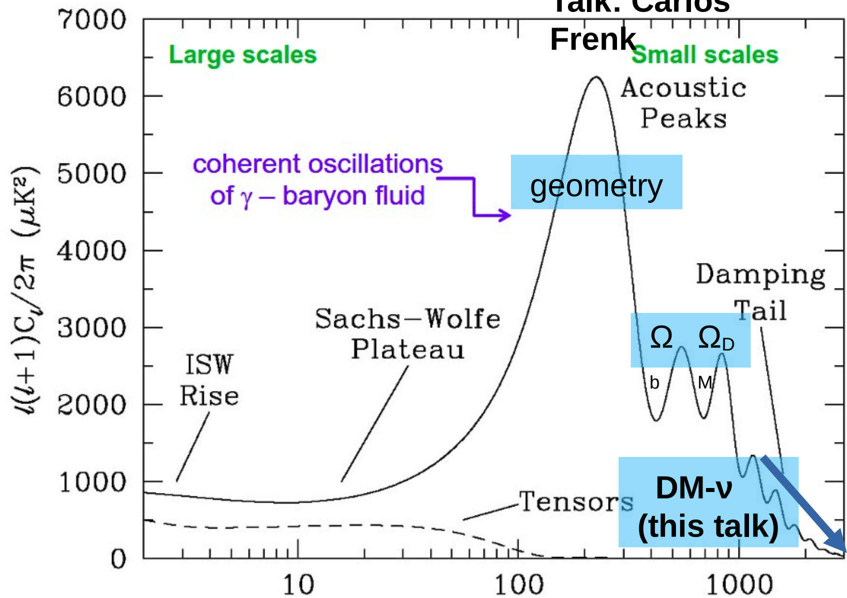
G. Magano, etal 0606190
– DM-ν interactions could affect ν free streaming
→ stronger clustering & enhanced CMB peak

– DM has a lower sound speed P. Serra, etal, 0911.4411
→ drag effect, CMB peaks shifted

and more…

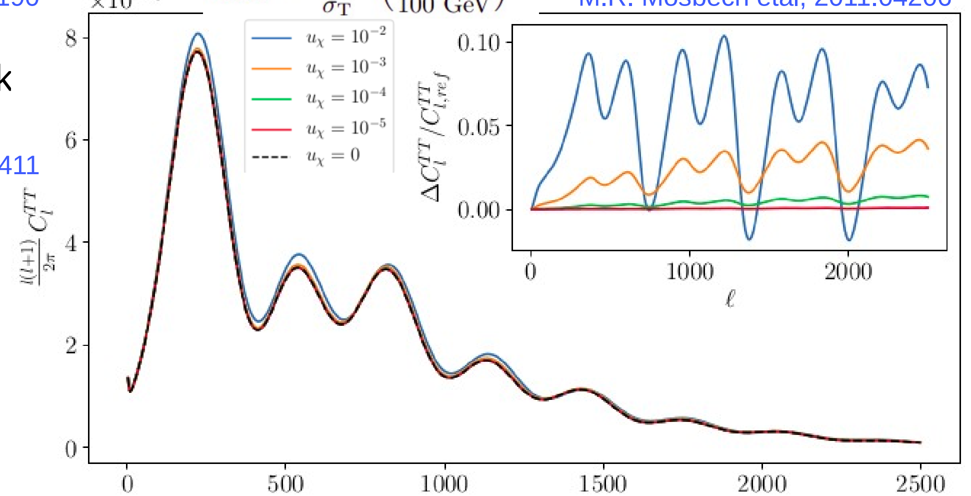
- Visible effects at low multipoles => **bounds**

Talk: Carlos Frenk



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

M.R. Mosbech etal, 2011.04206



SMALL-SCALE CMB

- Diffusion damping of CMB peaks at small scales

- Difficulties in probing this regime due to foreground, etc.

- Atacama Cosmology Telescope (ACT)
  – tool for high-multipole CMB measurements

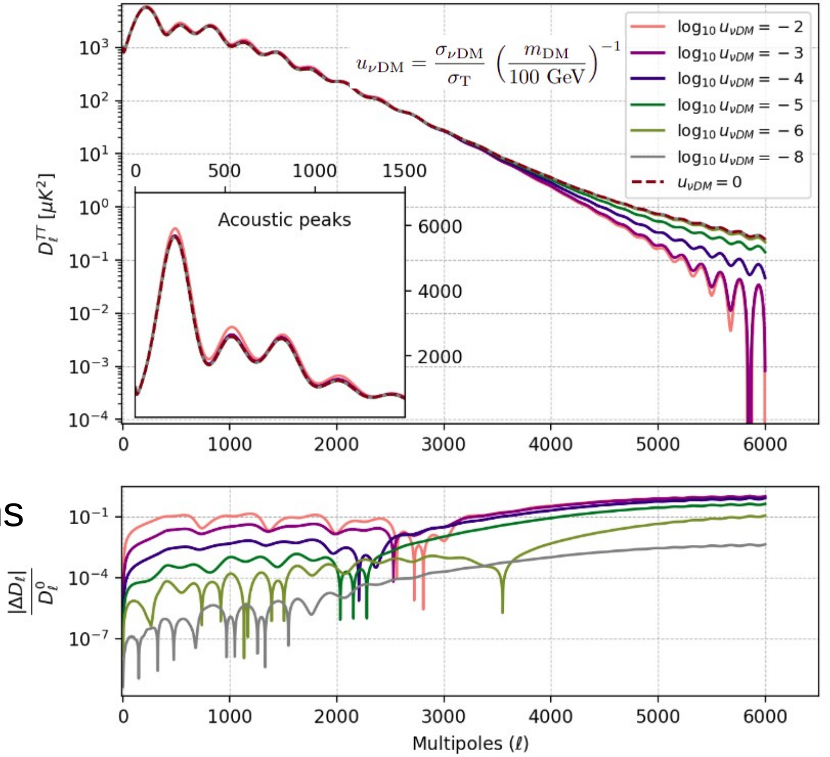
- DM-ν interactions:

  – suppression of high-multipole peaks at few % level

  – negligible effect at low multipoles for $u_{\nu DM} < 10^{-5}$

- Similar effect in the temperature (TT) & polarization (EE) distributions

- Future surveys can further improve: CMB-S4, ...



High-multipole CMB data = new window to study DM-ν interactions

CURRENT DATA & ANALYSIS

DATA

- **Planck** 2018

temperature & polarization
1907.12875, 1807.06209, 1807.06205

lensing
1807.06210

- Atacama Cosmology Telescope (**ACT**)

temp. & polar. DR4 2007.07289

- Baryon Acoustic Oscillations (**BAO**) & Redshift Space Distortions

BOSS DR12 1208.0022

ANALYSIS

- (modified) CLASS + DM-ν

1104.2933, 1903.00540, 2011.04206

- Sampling:
COBAYA (with CosmoMC)

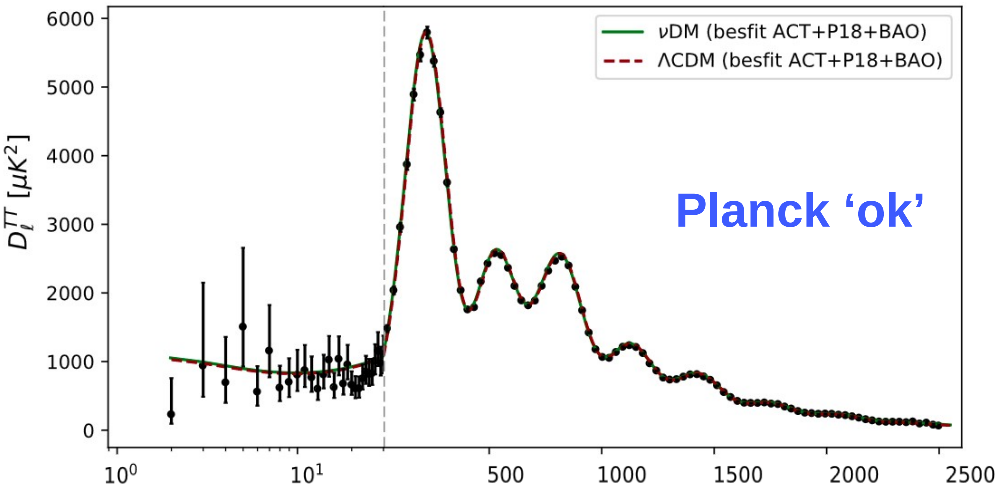
2005.05290, 0205436, 1304.4473

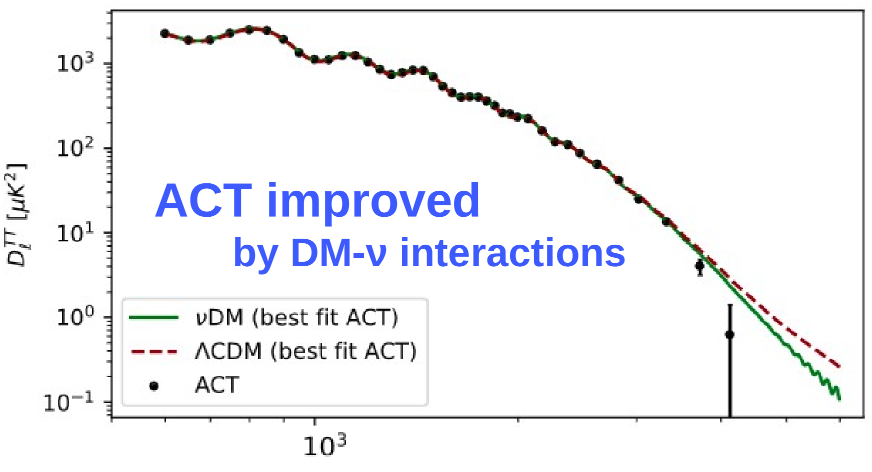
- Adding ACT:
  - weaker bounds on $u_{\nu DM}$
  - non-zero coupling preferred

	Parameter	$\sigma_{\nu DM} \sim T^0$
	$\Omega_b h^2$	$[0.005\,,\,0.1]$
	$\Omega_c^{\nu DM} h^2$	$[0.005\,,\,0.1]$
	$100\,\theta_{MC}$	$[0.5\,,\,10]$
	τ	$[0.01\,,\,0.8]$
	$\log(10^{10} A_S)$	$[1.61\,,\,3.91]$
	n_s	$[0.8\,,\,1.2]$
	N_{eff}	$[0\,,\,10]$
DM-ν	$\log_{10} u_{\nu DM}$	$[-8\,,\,-1]$

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

σ_T – Thomson scat.





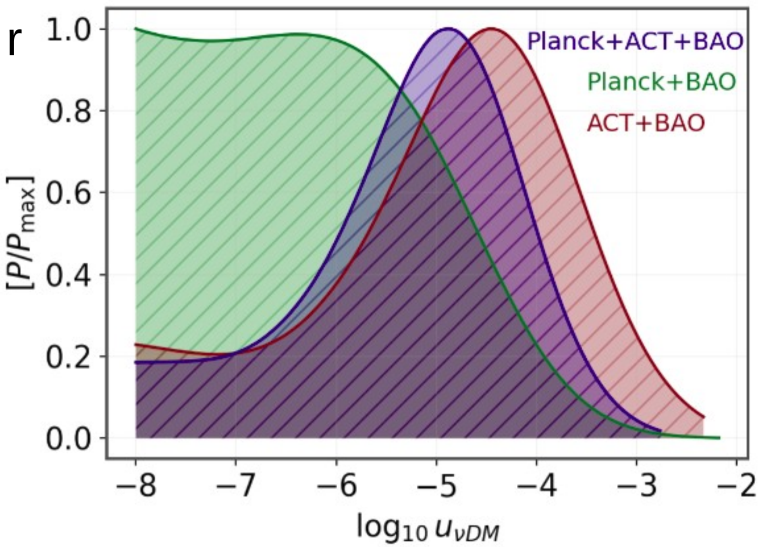
PREFERENCE: NON-ZERO DM-ν COUPLING

$\sigma_{\nu DM} \sim T^0$

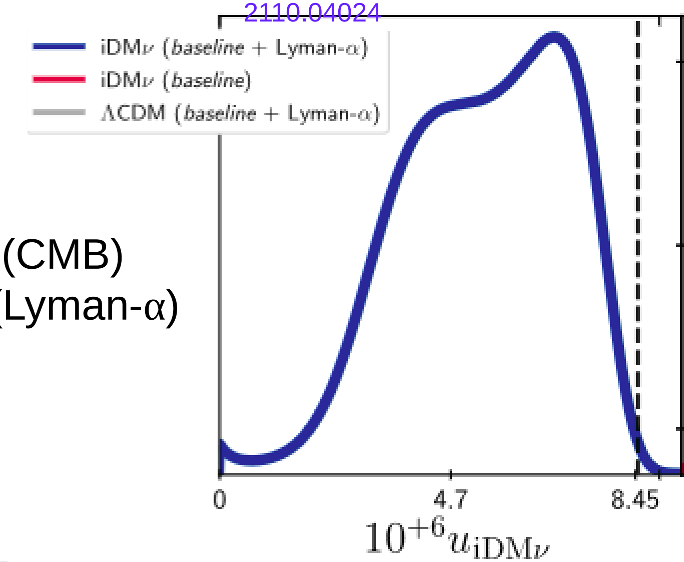
CMB (this work)

Hints from **Lyman-α**

Posterior



D.C. Hopper, M. Lucca, 2110.04024



$\mathrm{Log}_{10}\, u_{\nu DM} = -5.20^{+1.20}_{-0.74}$ (CMB)

$-5.42^{+0.17}_{-0.08}$ (Lyman-α)

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

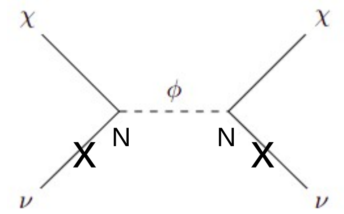
Parameter	Planck	Planck + BAO	ACT	ACT + BAO	ACT + Planck + BAO
$\Omega_b h^2$	0.02239 ± 0.00015	0.02239 ± 0.00013	0.02153 ± 0.00030	0.02154 ± 0.00030	0.02236 ± 0.00012
$\Omega_c^{\nu DM} h^2$	0.1196 ± 0.0012	0.11958 ± 0.00093	0.1185 ± 0.0039	0.1198 ± 0.0015	0.11975 ± 0.00097
$100\theta_s$	1.04193 ± 0.00030	1.04191 ± 0.00028	1.04337 ± 0.00069	1.04321 ± 0.00063	1.04206 ± 0.00026
τ_{reio}	0.0528 ± 0.0074	0.0524 ± 0.0072	0.064 ± 0.015	0.062 ± 0.014	0.0563 ± 0.0064
$\log(10^{10} A_s)$	3.039 ± 0.014	3.038 ± 0.014	3.049 ± 0.030	3.047 ± 0.030	3.053 ± 0.013
n_s	0.9642 ± 0.0044	0.9642 ± 0.0038	1.004 ± 0.016	1.001 ± 0.014	0.9678 ± 0.0036
$log_{10} u_{\nu DM}$	$< -4.42\ (< -3.95)$	$< -4.46\ (< -4.39)$	$-5.08^{+1.5}_{-0.98}\ (< -3.74)$	$-4.86^{+1.5}_{-0.83}\ (< -3.70)$	$-5.20^{+1.2}_{-0.74}\ (< -4.17)$
H_0	$68.03 \pm 0.55\ (68.0^{+1.1}_{-1.1})$	$68.05 \pm 0.42\ (68.05^{+0.81}_{-0.82})$	$68.2 \pm 1.6\ (68.2^{+3.3}_{-3.3})$	$67.66 \pm 0.58\ (67.7^{+1.1}_{-1.2})$	$68.01 \pm 0.43\ (68.01^{+0.83}_{-0.85})$
σ_8	$0.806^{+0.013}_{-0.0097}\ (0.806^{+0.024}_{-0.028})$	$0.807^{+0.011}_{-0.0084}\ (0.807^{+0.020}_{-0.021})$	$0.823^{+0.025}_{-0.021}\ (0.823^{+0.046}_{-0.050})$	$0.821^{+0.025}_{-0.020}\ (0.821^{+0.044}_{-0.050})$	$0.820^{+0.011}_{-0.0093}\ (0.820^{+0.021}_{-0.023})$
$\ln BF$	-3.74	-2.48	-0.194	-0.156	0.525

B. Bertoni, etal, 1412.3113
B. Batell, etal, 1709.07001
M. Blennov, etal, 1903.00006

SAMPLE MODEL – STERILE NEUTRINO PORTAL

- Fermionic χ DM coupled to a new scalar ϕ and (heavy) sterile neutrino N

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



- Mixing with the active neutrino (dominant with ν_τ)

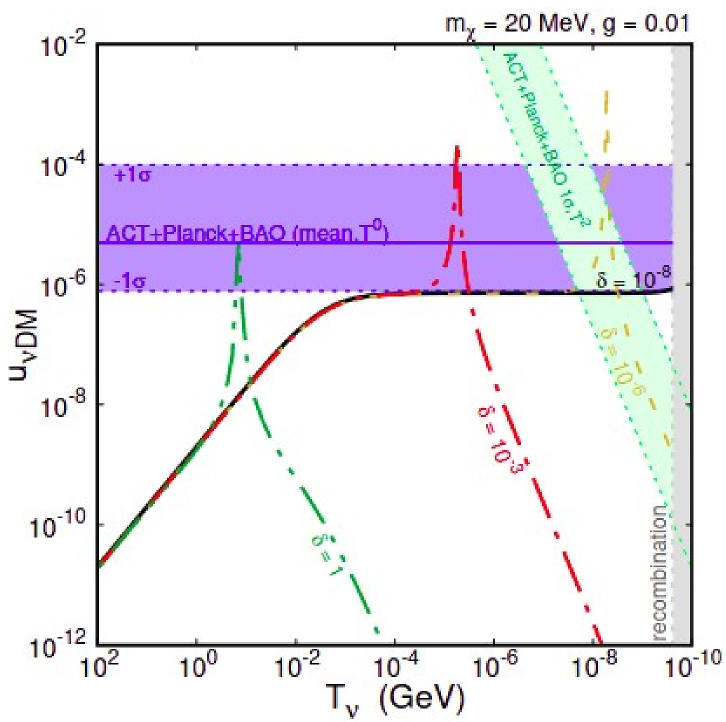
$$\mathcal{L} \supset -\lambda\,(\bar{L}\,\tilde{H})\,N_R,$$

$$\sigma_{\chi\nu} \simeq (10^{-34}\,\text{cm}^2)\left(\frac{g}{0.01}\right)^4\left(\frac{20\text{ MeV}}{m_\chi}\right)^2$$
$$\times\left[1 + 0.075\left(\frac{m_\chi}{20\text{ MeV}}\right)^2\left(\frac{T_{\text{rec.}}}{T_\nu}\right)^2\left(\frac{\delta}{10^{-8}}\right)^2\right]$$

- **For small mass splittings DM-ν cross section ~ T^0**

$\delta = (m_\phi - m_\chi)/m_\chi$. << 1

for a range of temperatures



- For lower temperatures, σ grows, resonance ϕ production

- At even lower temperatures, $\sigma \sim T^2 / m_\chi^4$

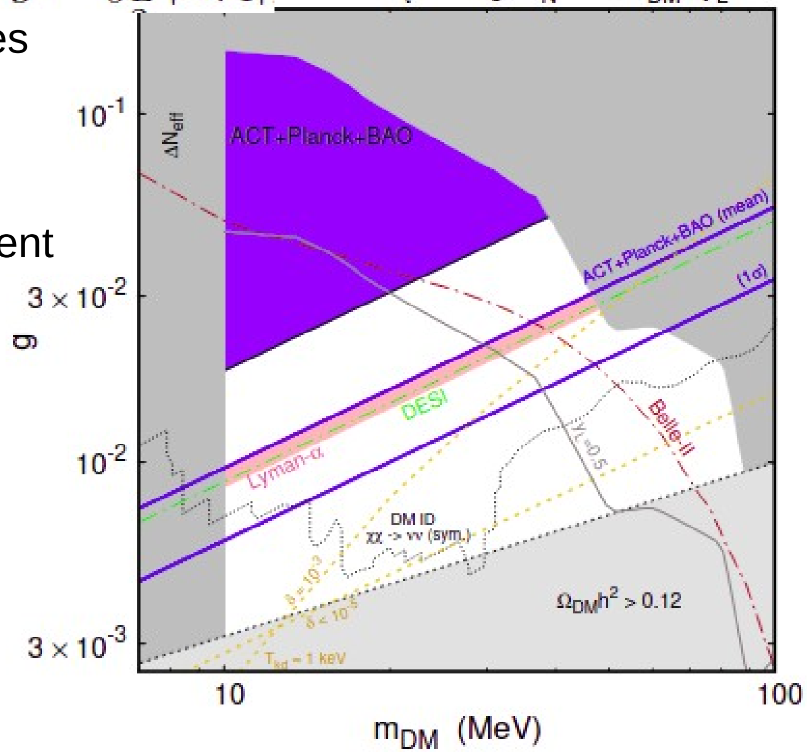
$$\sigma_{\chi\nu} \simeq (10^{-52}\,\text{cm}^2)\left(\frac{g}{0.1}\right)^4\left(\frac{100\text{ MeV}}{m_\phi}\right)^4\left(\frac{T}{T_0}\right)^2$$

- At high temperatures, $\sigma \sim 1/T^2$ helps avoiding atrophysical bounds from blazars, etc.

FITTING THE DATA

● The model can accommodate the data
& avoid exclusion bounds from accelerator-based searches

$$g = y_L\,|U_{\tau 4}|$$



● For the DM mass ~ tens of MeV

● DM relic density requires, e.g., asymmetric DM component

● This also helps avoiding DM ID bounds from χχ → νν

● Future probes: DESI, Belle-II (τ decays)

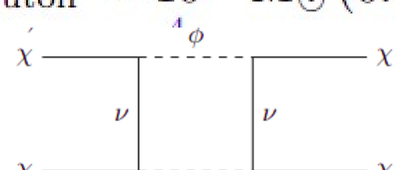
CHALLENGES OF THE TOY MODEL:

● Mass degeneracy requires fine-tuning
& can be radiatively unstable via $\lambda_{\phi H}|\phi|^2|H|^2$

● Low neutrino kinetic decoupling temperature

$$T_{kd}\Big|_{m_\phi \simeq m_\chi} \simeq (0.12\ \mathrm{keV}) \left(\frac{0.01}{g}\right)^2 \left(\frac{m_\chi}{20\ \mathrm{MeV}}\right)^{3/2} \rightarrow M_{\rm cutoff} \sim 10^{11}\, M_\odot\, (0.1\ \mathrm{keV}/T_{kd})^3$$

● Possible DM (too) strong self-interactions



POSSIBLE SOLUTIONS: fraction of DM interacts strongly with νs; increase the mass splitting δ

CONCLUSIONS

- CMB observations are crucial for our understanding of dark matter
- small-scale CMB measurements with few % accuracy open a new window to study DM interactions with neutrinos
- preference for non-zero DM-ν coupling in the high-multipole ACT data & agreement with low-multipole Planck data + BAO & RSD
- Similar earlier hints from Lyman-α
- We modeled this for the effectively temperature-independent cross section (T^0), but the preference is also found for the T^2 case
- Toy model: sterile neutrino portal to DM
- Can accommodate the data but careful checking of other effects needed (cutoff scale, DM self-interactions...)
- Future data: ACT, CMB-S4, DESI, … + accelerator-based bounds on sterile neutrinos

THANK YOU !