A Dark Side of Neutrino Masses

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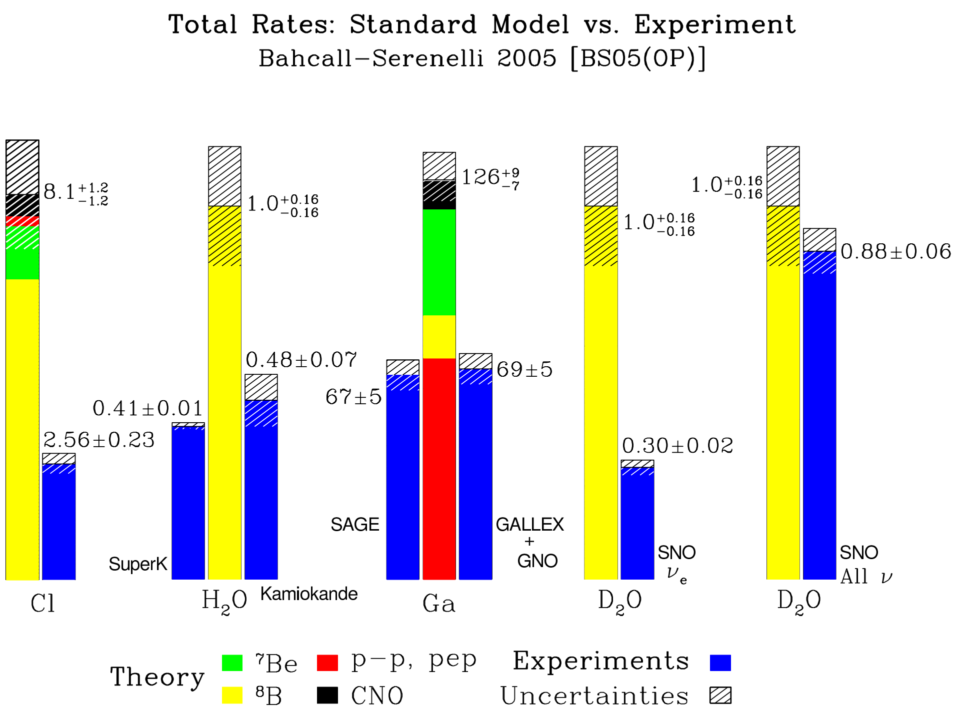
arXiv: 1412.2027 with Frank Deppisch

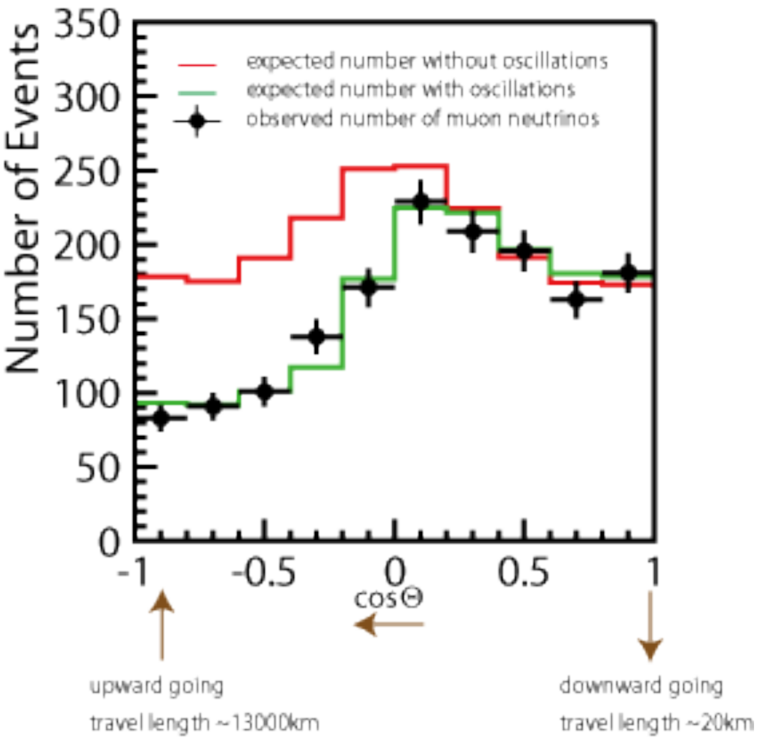
The key question

- Can we "predict" the DM mass given the neutrino mass?

Outline

- Brief discussion on evidences of the neutrino mass and the DM existence
- Effective Lagrangian to connect the DM and neutrino mass
- A UV-complete toy model
- Conclusions and outlook

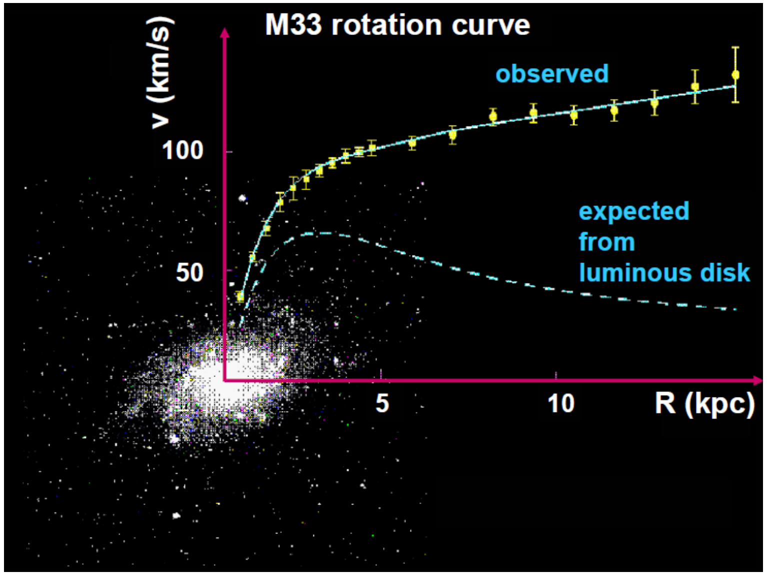


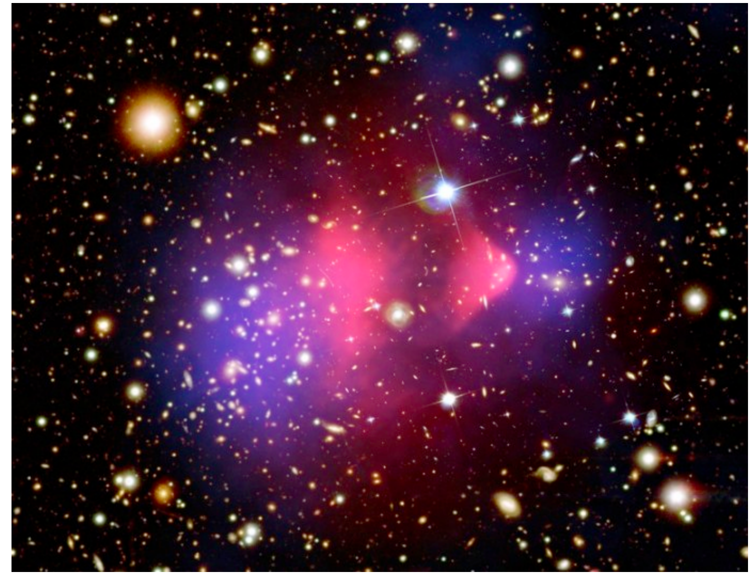


http://www.sns.ias.edu/~jnb/

http://www-sk.icrr.u-tokyo.ac.jp/sk/physics/atmnu-e.html

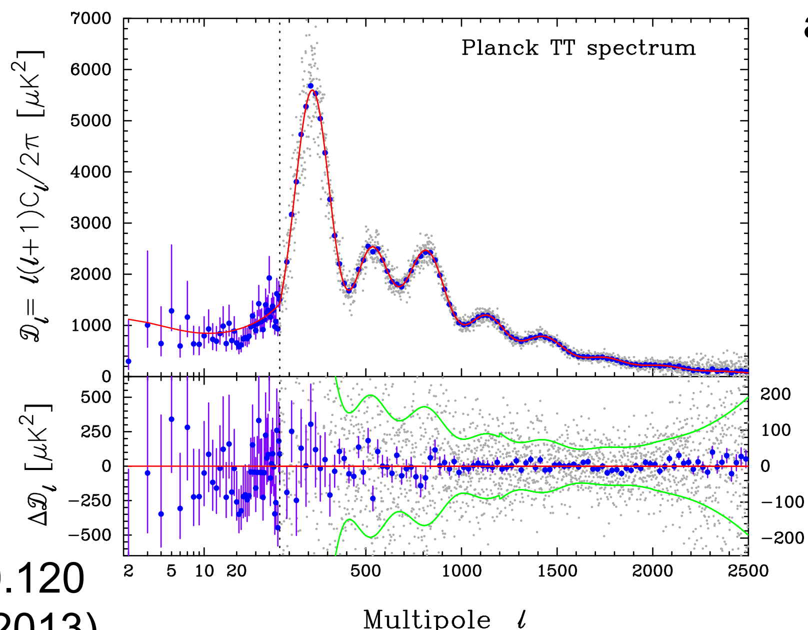
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$



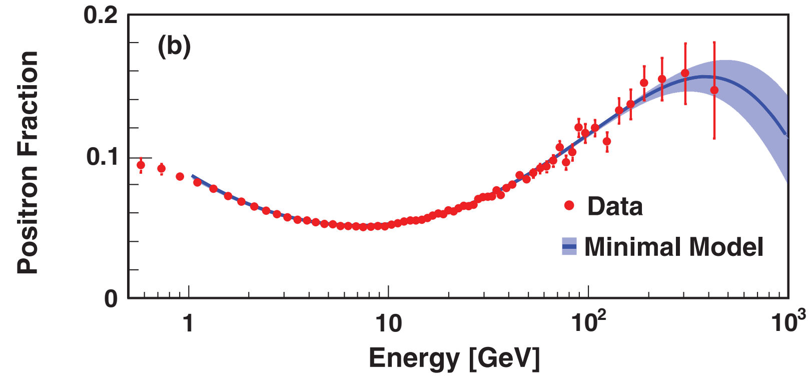


Rocky Kolb Lecture 07/2005

Clowe et al, ApJ, 648:L109 http://apod.nasa.gov/apod/ap060824.html



$\Omega_{DM}h^2$=0.120
Planck(2013)



DM? Pulsars?
AMS02(2014)

Effective Lagrangian

- Here, we propose a very simple idea to connect the DM and neutrino mass.
- We start with an effective operator (Weyl-spinor notation) connecting the Majorana DM particle (χ) and the standard model (SM) neutrino (ν):

$$\mathcal{L} \supset \frac{\chi\chi\nu\nu}{\Lambda^2} + h.c.,$$

- As shown below, the scale Λ is actually lower than the electroweak (EW) scale, which justifies explicit SU(2) breaking in the effective operator.

Effective Lagrangian

- To realize this effective operator, one can involve a scalar Φ which links DM to the SM sector:

$$\mathcal{L} \supset c_2 \, \Phi \chi \chi + \frac{\Phi^* LHLH}{\Lambda_*^2} + h.c..$$

Where L is the SM lepton doublet while H is the Higgs doublet.

- After integrating out Φ, one obtain the effective DM-neutrino operator: $\mathcal{L} \supset \frac{\chi\chi\nu\nu}{\Lambda^2} + h.c.,$
- The Lepton number (L) assignment is: L(χ)=-1, L(Φ)=2 and L(L)=1 such that lepton is conserved in the effective Lagrangian.

Effective Lagrangian

- In the context of effective language, the only lepton number violation (LNV) comes from the Majorana DM mass term:

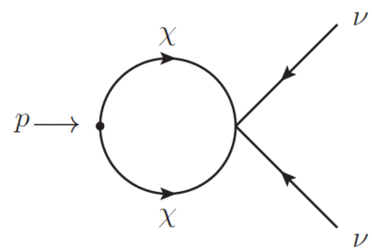
$$\mathcal{L} \supset \frac{1}{2} m_\chi \chi\chi + h.c.$$

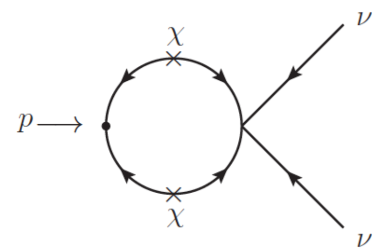
- The DM mass could result from some hidden sector, which does not couple to the SM sector directly but only via DM.
- Therefore, one has a direct connect between the DM and neutrino mass because the neutrino Majorana mass term $m_\nu \nu\nu$ requires LNV, which is zero if m_χ=0.

Effective Lagrangian

- By contracting two χs, the neutrino receives a radiative mass

$$m_\nu = \frac{m_\chi^3}{2\pi^2\Lambda^2}\left(6\ln\frac{m_\chi}{\mu} - 1\right)$$





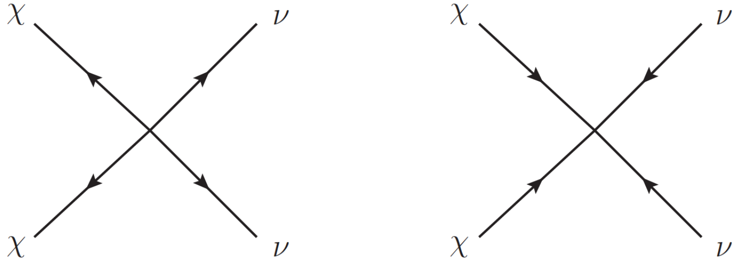
- We use the dimensional regularization scheme with the modified minimum subtraction that can be justified if the underlying UV-complete theory has exactly the same DM-loop diagram.

Effective Lagrangian

- The DM-neutrino effective operator determines the DM annihilation cross section:

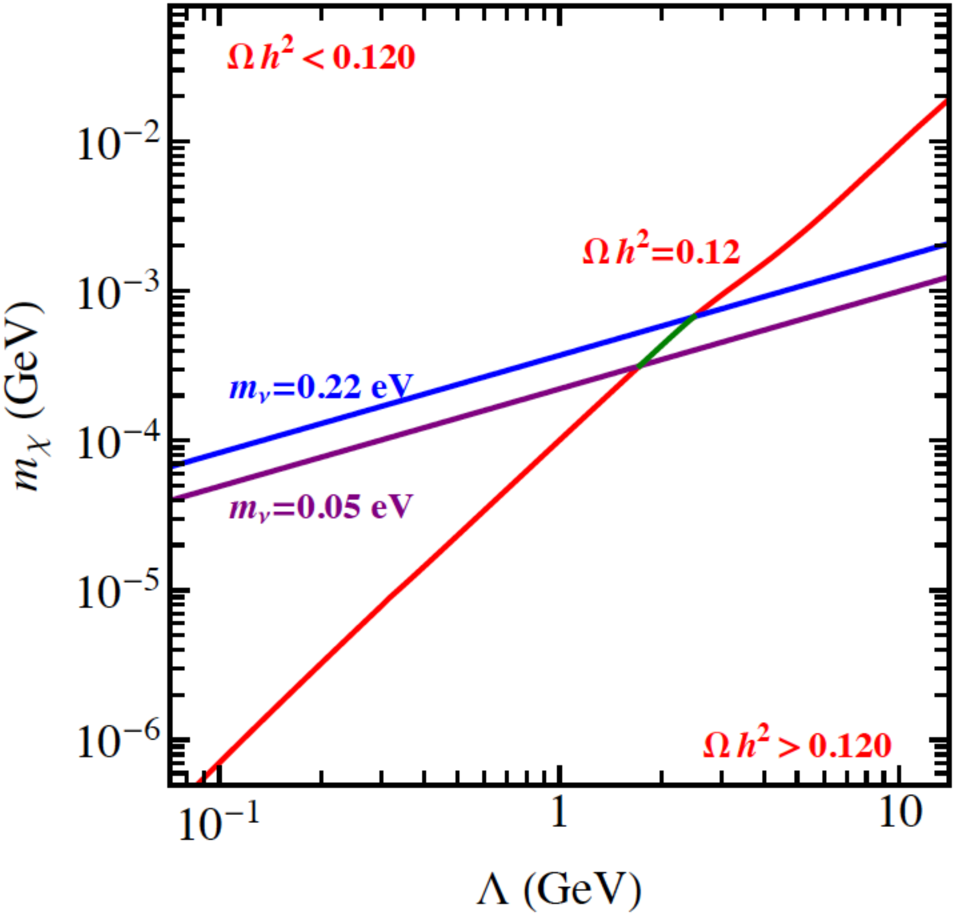
$$\sigma v_{\mathrm{rel}} = \frac{m_\chi^2}{\pi \Lambda^4}\left(1 + \frac{1}{2} v_{\mathrm{rel}}^2\right)$$

- There are two contributions from opposite chiralities



- The interference between opposite chiralities is nearly zero due to the very small neutrino mass.

Effective Lagrangian



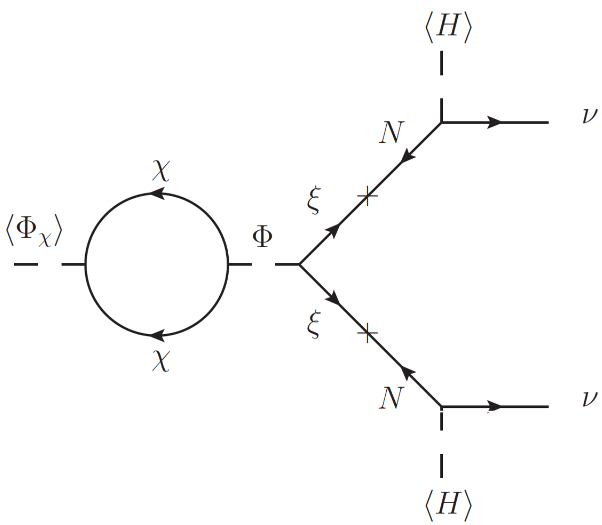
- There are two unknown parameters in the operator, m_χ and Λ.
- They are completely determined, given the DM relic abundance and neutrino mass.
- For demonstration, we only study one neutrino flavor, the heaviest active neutrino, with the mass of 0.05 eV to 0.2 eV (PDG and Planck data).

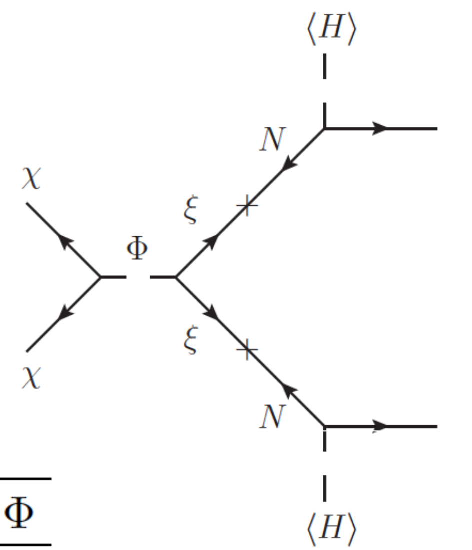
$$m_\chi \approx 0.4\ \mathrm{MeV}\left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)^{1/2}\left(\frac{\Omega h^2}{0.12}\right)^{1/4}$$

$$\Lambda \approx 1.5\ \mathrm{GeV}\left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right)^{1/4}\left(\frac{\Omega h^2}{0.12}\right)^{3/8}$$

UV-complete Toy Model

$$\mathcal{L} \supset \frac{c_1}{2}\left(\Phi_\chi + \langle\Phi_\chi\rangle\right)\chi\chi + c_2\Phi\chi\chi + c_3\Phi^*\xi\xi$$
$$+ yLHN - m_{\Phi_\chi}\Phi_\chi\Phi_\chi^* - m_\Phi\Phi\Phi^* - m_N N\xi + h.c.,$$





Field	L	H	N	χ	ξ	Φ_χ	Φ
$[SU(2)_L]_Y$	$2_{-1/2}$	$2_{1/2}$	1_0	1_0	1_0	1_0	1_0
L	1	0	-1	-1	1	2	2
Z_2	+	+	+	−	+	+	+

UV-complete Toy Model

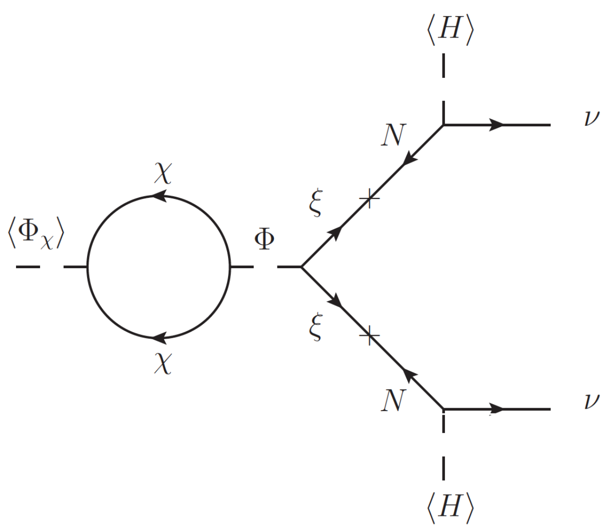
- Φ_χ obtains a vev, that breaks lepton number ($L(\Phi_\chi)=2$) and gives a mass to DM. Then, LNV is passed to ν via DM.
- The scale Λ in the effective operator $\chi\chi\nu\nu/\Lambda^2$ can be obtained by integrating out Φ, ξ, N and replacing H by a vev v:

$$\Lambda = \frac{1}{\sqrt{c_2 c_3}} \frac{m_N m_\Phi}{y v}$$

- Given GeV Λ with y,$c_{2,3}$~1, we have roughly $m_N{}^*m_\Phi$~ O(100 GeV^2). From EW precision test constraints on the active-heavy neutrino mixing, $yv/mN<0.1$, (0803.4008), one has $1<m_N<100$ TeV with 1 MeV$<m_\Phi<0.1$ GeV.

UV-complete Toy Model

- Alternatively, the DM-loop induces a mixing between Φ_χ and Φ and consequently a small vev of Φ is triggered, that gives a small Majorana mass to ξ.



$$\mathcal{L} \supset \frac{c_1}{2}\left(\Phi_\chi + \langle \Phi_\chi \rangle\right)\chi\chi + c_2 \Phi \chi\chi + c_3 \Phi^* \xi\xi + yLHN - m_{\Phi_\chi} \Phi_\chi \Phi_\chi^* - m_\Phi \Phi\Phi^* - m_N N\xi$$

UV-complete Toy Model

- The neutrino mass matrix in the basis of ν, N and ξ reads

$$\begin{pmatrix} 0 & yv & 0 \\ yv & 0 & m_N \\ 0 & m_N & 2\frac{c_2 c_3 \chi\chi}{m_\Phi^2} \end{pmatrix}$$

- Comparing the neutrino mass from the mass matrix diagonalization to the one directly from the effective DM-neutrino operator $\chi\chi\nu\nu/\Lambda^2$, the scale Λ can be inferred.
- In fact, it is a realization of the inverse seesaw proposed by Mohapatra and Valle in 1986.

UV-complete Toy Model

There are two important requirements to achieve the DM and neutrino connection:

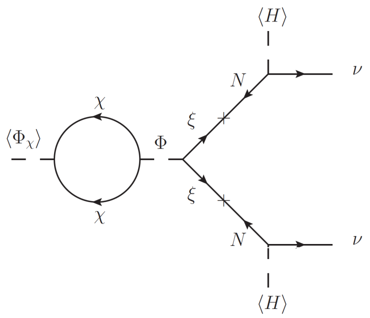
- The LNV comes from the hidden sector which only couples to the SM sector via the DM loop and the LNV source manifests as the DM Majorana mass in the low-energy effective theory.
- The heavy particles that are being integrated do *not* enter the DM-loop that is the distinctive feature of this model from models in the existing literature, rendering the model more predictive.

Conclusions and Outlook

- Here we propose a simple model based on the effective operator $\chi\chi\nu\nu/\Lambda^2$, which connects DM (χ) and neutrino (ν) physics.
- The DM annihilation cross section is determined by the operator.
- The neutrino receives a radiative mass from the contraction on two χs via the DM Majorana mass, which is the only LNV source in the low-energy theory.
- Two unknown parameters in the operator, m_χ and Λ can be completely fixed to be of order MeV and GeV, given the observed DM relic abundance and neutrino mass.

Conclusions and Outlook

- We provide a UV-complete toy model to realize this DM-neutrino connection in the context of the inverse seesaw mechanism.
- The toy model fulfills two important requirements. First, the LNV source arises from the hidden sector, which couples to the SM sector through DM only, i.e., the LNV term manifests as the DM Majorana mass term in the low-energy theory.
- Second, the heavy particles associated with the scale Λ, do not enter the DM-loop.



Conclusions and Outlook

- The model predicts a MeV neutrino flux from S-wave DM annihilations, which could be detectable at neutrino experiments.
- MeV DM will reheat the neutrino sector when it decouples from the thermal bath, i.e., N_ν=4.4 (1207.0497) in conflict with the CMB measurement N_ν=3.15±0.23 (1502.01589).
- The tension might be alleviated by including three neutrino flavors to increase the DM mass above 8 MeV.