New Constraints on Neutrino-Dark Matter Interactions

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w/ Doojin Kim, Deepak Sathyan, Kuver Sinha & Yongchao Zhang, 2407.abcde

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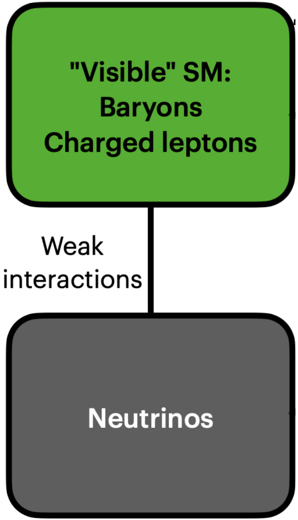
Connecting Two Mostly Unknown Sectors



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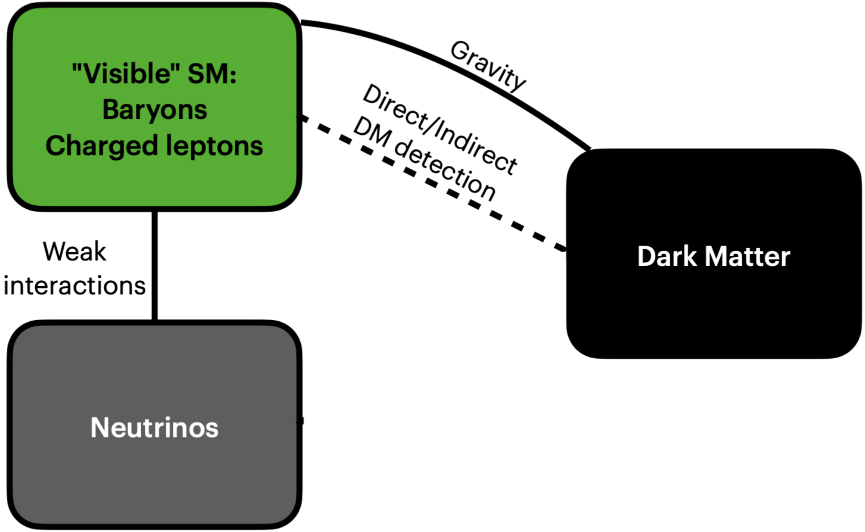

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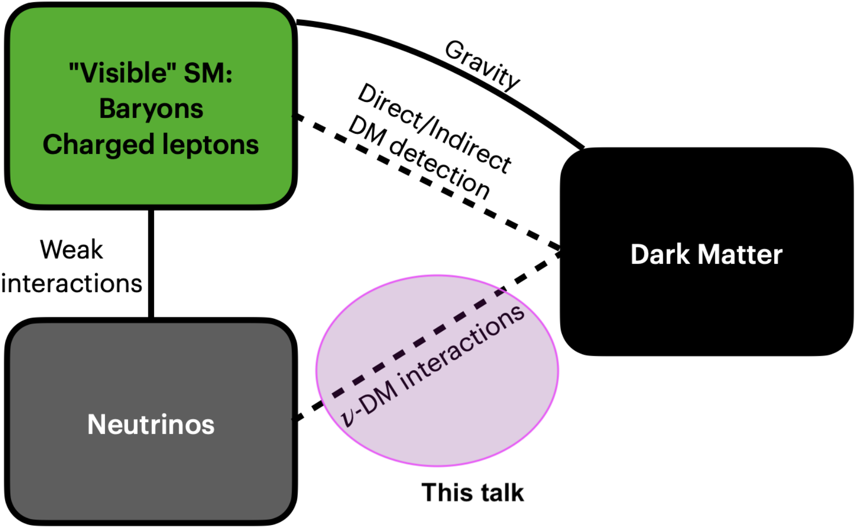

How to Observe ν-DM Interactions

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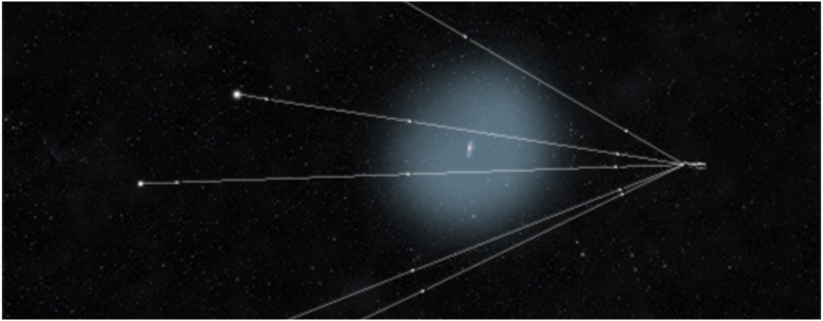
- Large number density $\Longrightarrow$ **Light DM**.
- Large neutrino travel distance through DM halo $\Longrightarrow$ **Astrophysical/cosmological sources**.



Existing Constraints

- **Cosmological:**
  - BBN and CMB [Serpico, Raffelt '04; Bœhm, Dolan, McCabe '13; Escudero '18; Giovanetti, Schmaltz, Weiner '24]
  - Collisional damping [Bœhm, Fayet, Schaeffer '00; Bertoni, Ipek, McKeen, Nelson '14; Akita, Ando '23; Heston, Horiuchi, Shirai '24]
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  - SN1987A and future galactic SN [Mangano et al ’06; Fayet, Hooper, Sigl ’06]
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- **Lab constraints?** Answer is YES and can be most stringent.

Setting the Scale

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DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Hyper-K

JUNO

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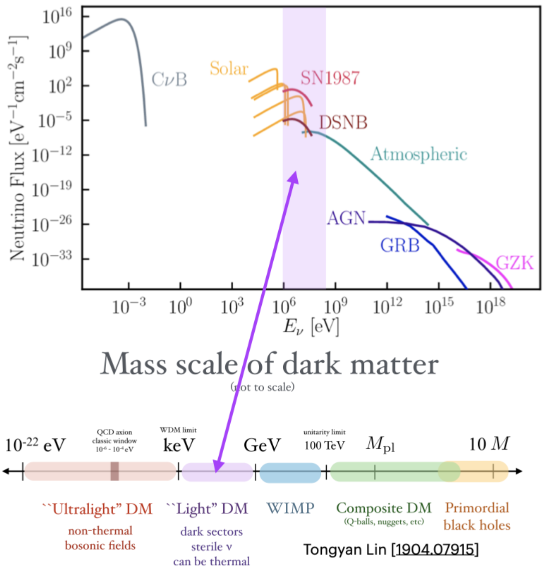

Modeling ν-DM Interactions

- Simplified EFT approach.
  [Olivares-Del Campo, Bœhm, Palomares-Ruiz, Pascoli, 1711.05283;
  Blennow, Fernandez-Martinez, Olivares-Del Campo, Pascoli, Rosauro-Alcaraz, Titov, 1903.00006]
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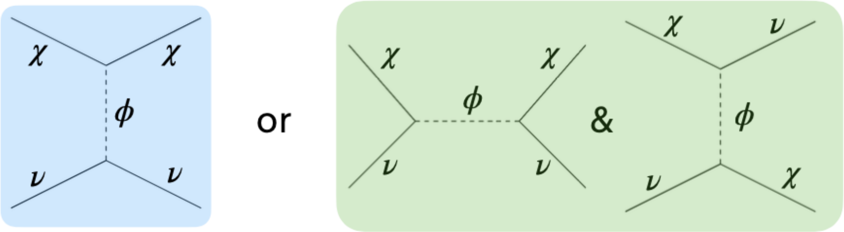
- Categorize models into DM and mediator types: Scalar, fermion, vector.
- Secondary categorization: t-channel or s and u channel ν-DM scatterings, depending on the mediator type.



Only free parameters: DM and mediator masses and couplings.

Cross Sections

- We computed differential cross sections analytically and *exactly*.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = \frac{1}{8\pi}\frac{E_\nu'^2}{4m_\chi^2 E_\nu^2}\sum_{\text{spins}}\overline{|\mathcal{M}|^2}\,,$$

$$\text{where}\quad \frac{1}{E_\nu'} = \frac{1}{E_\nu} + \frac{1-\cos\theta}{m_\chi}\,.$$

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- Previous literature incomplete/inconsistent. E.g. scalar mediator case:

scenario	Lagrangian	channels	amp. sq.	[54]	[32]
complex scalar †	(2.7)	t	(2.8)	–	✓
Dirac fermion	(2.9)	DM-ν: u	(2.10)	✓*	–
		DM-$\bar{\nu}$: s	(2.11)	–	–
Majorana fermion	(2.9)	s, u	(2.12)	✗	–
Dirac fermion †	(2.13)	t	(2.14)	–	✓
complex vector †	(2.15)	t	(2.16)	–	–

[32]: Argüelles, Kheirandish, Vincent,1703.00451;

[54]: Olivares-Del Campo, Bœhm, Palomares-Ruiz, Pascoli, 1711.05283.

Bounds on ν-DM Interactions

- Included three categories of (updated) bounds on ν-DM interactions:
  - **Cosmological:** BBN, CMB, **Collisional Damping**, Relic Density.
  - **Astrophysical:** **SN1987A**, SIDM.
  - **Laboratory:** $0\nu\beta\beta$, **Invisible Z decay**, **Pion and Kaon decays**.

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- Here we show one example scenario:

Dirac fermion DM, (pseudo)scalar mediator.

$$-\mathcal{L} = \phi\bar{\nu}\left(g_{\nu\,s} + i g_{\nu\,p}\gamma_5\right)\nu + \phi\bar{\chi}\left(g_{\chi\,s} + i g_{\chi\,p}\gamma_5\right)\chi\,.$$

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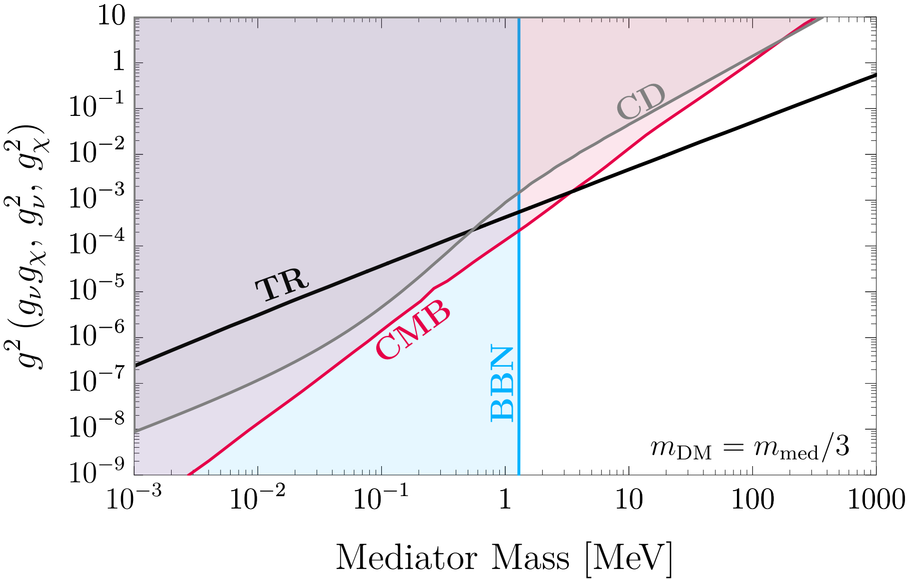
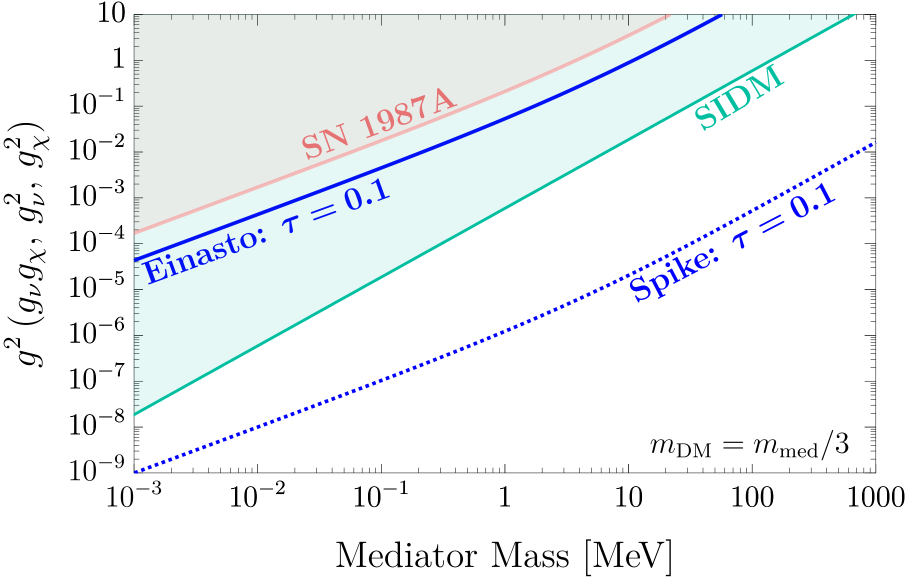
$$\sum_{\text{spins}} |\mathcal{M}|^2 = 4\left(g_{\nu\,s}^2 + g_{\nu\,p}^2\right)\frac{t\left[g_{\chi\,s}^2(t-4m^2) + g_{\chi\,p}^2 t\right]}{(t-m_\phi)^2}\,,$$

where $t = -2E_\nu E'_\nu(1-\cos\theta)$.

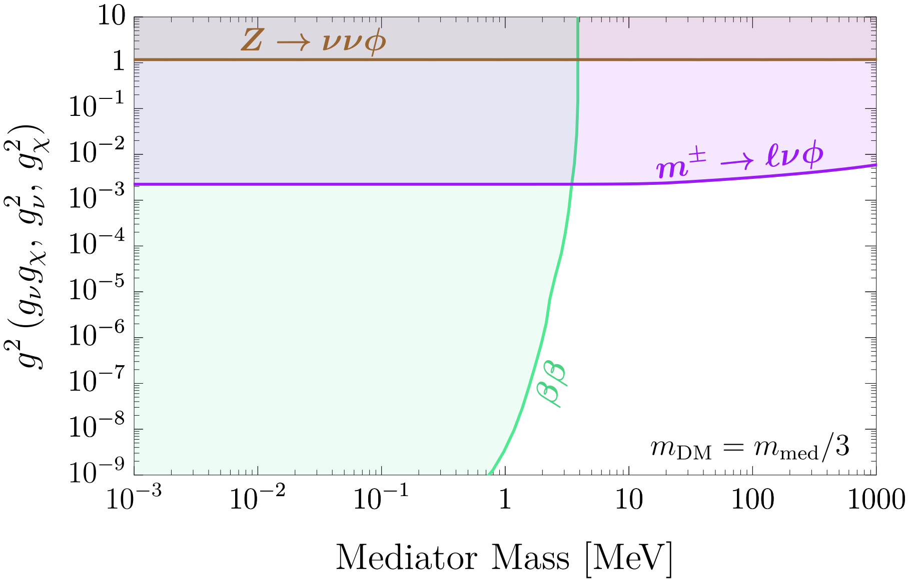
Cosmological Bounds



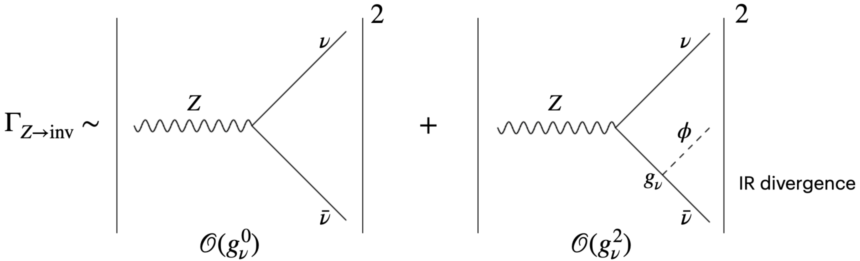
Astrophysical Bounds



Laboratory Bounds



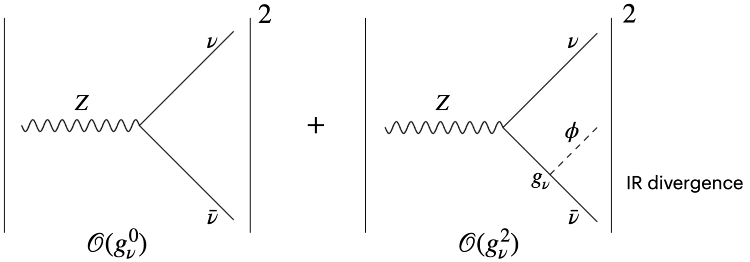
Updated Z Decay Constraints



[Berryman, de Gouvêa, Kelly, Zhang ’18; de Gouvêa, BD, Dutta, Ghosh, Han, Zhang ’19]

Updated Z Decay Constraints

$\Gamma_{Z\to \text{inv}} \sim$



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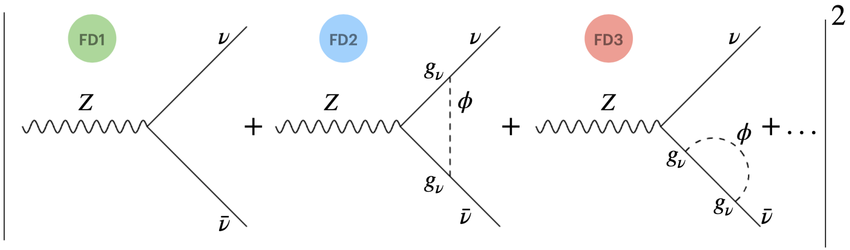

Interference terms FD1 FD2 and FD1 FD3 are $\mathcal{O}(g_\nu^2)$, like tree level $Z \to \nu\nu\phi$

[BD, Kim, Sathyan, Sinha, Zhang (to appear)]

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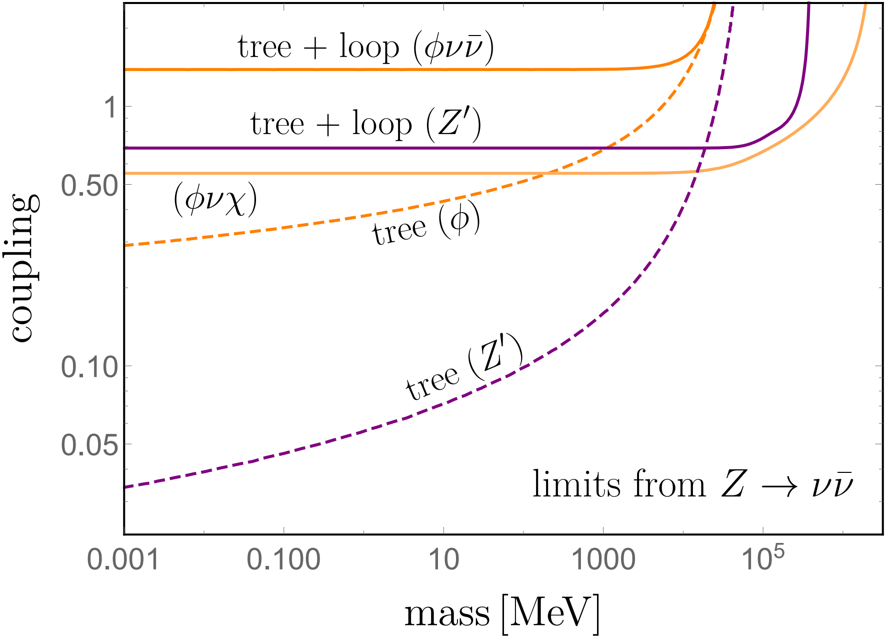
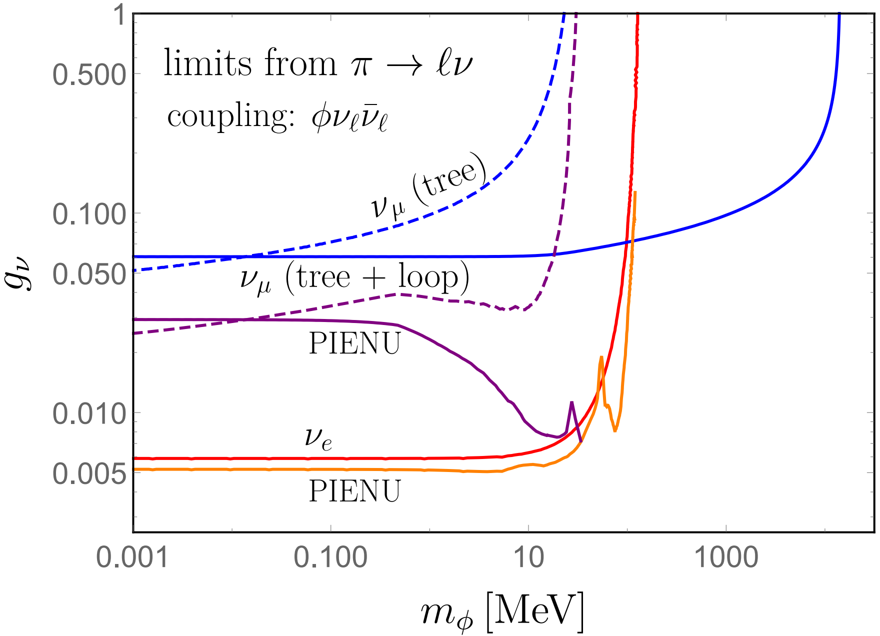
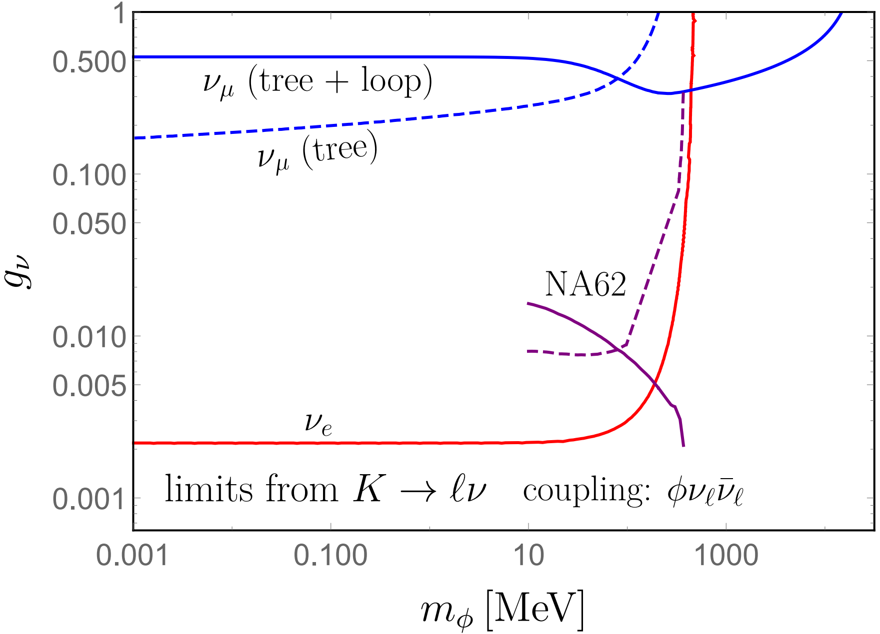


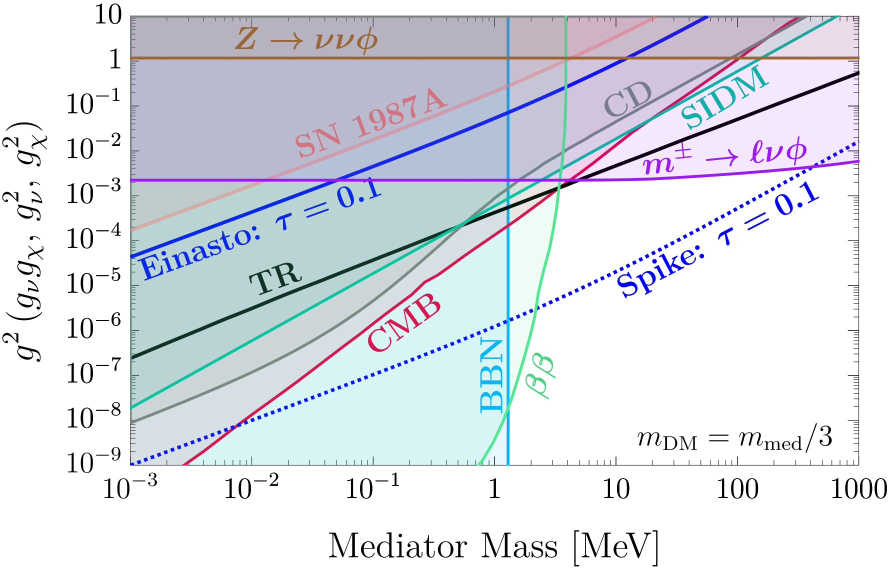
Updated Pion Decay Constraints



Updated Kaon Decay Constraints



Combined ν-DM Constraints



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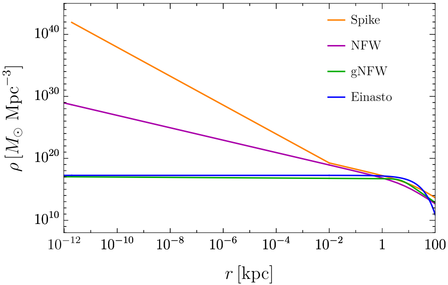

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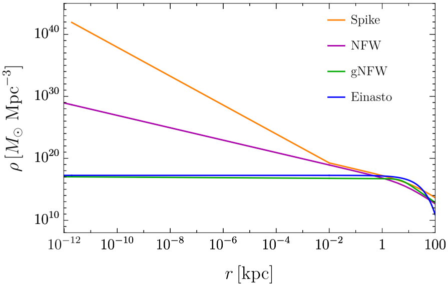
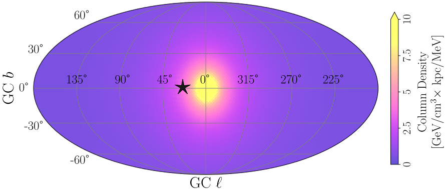
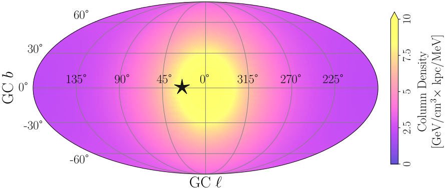
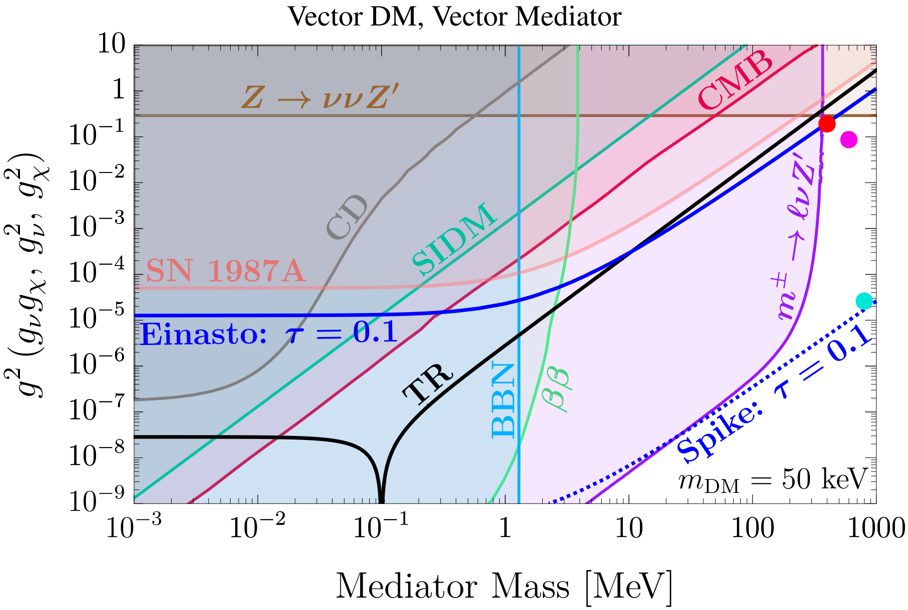






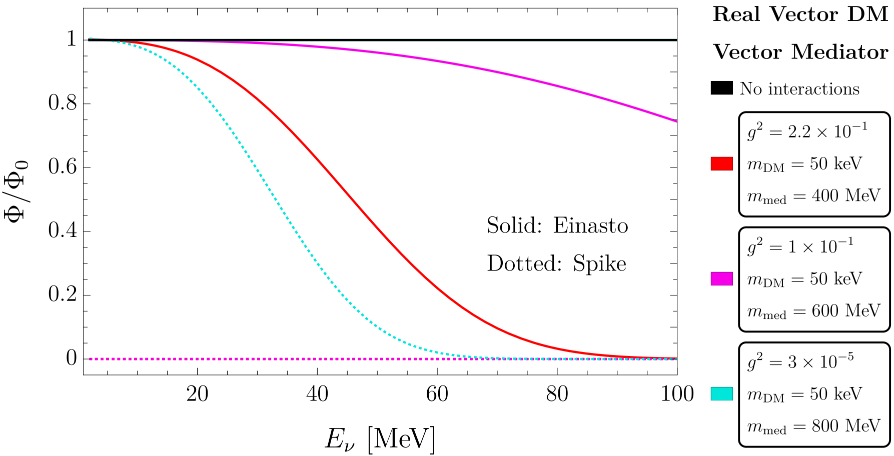
Assume a supernova at $s = 10$ kpc. Near the galactic center would be best.

Best Case Scenario for Local Supernova

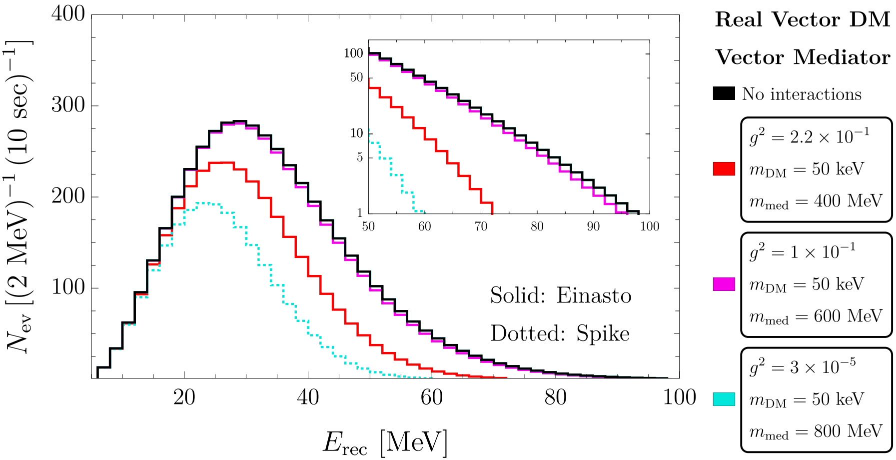


Flux Attenuation

$$\frac{d\Phi(E,\tau)}{d\eta} = -\sigma(E)\Phi(E,\eta) + \int_E^\infty d\tilde{E}\,\frac{d\sigma(\tilde{E},E)}{dE}\Phi(\tilde{E},\eta)$$

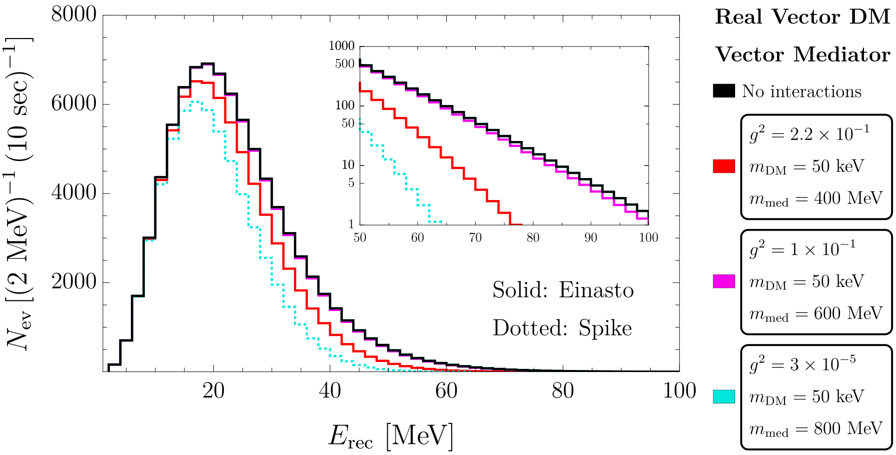


Event Rate at DUNE



Using Warren20 SN neutrino spectrum [Warren, Couch, O'Connor, Morozova, 1912.03328]

Event Rate at Hyper-K



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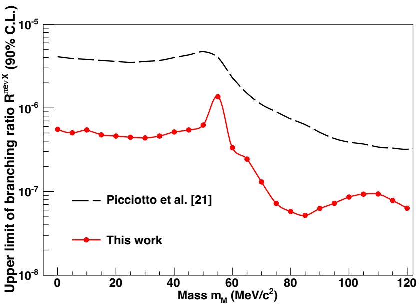
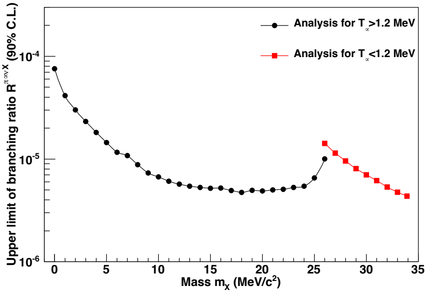
Conclusions

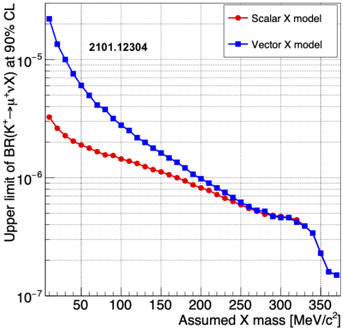
- There exist strong constraints on neutrino-DM interactions from cosmology, astrophysics and lab experiments.
- Must not be overlooked while considering future detection prospects of ν-DM interactions.
- We updated some of these constraints, especially those from Z decay and meson decays, taking into account the one-loop correction.
- Identified benchmarks which pass all constraints and can still give a detectable effect in future neutrino experiments.
- Waiting for the next galactic supernova!

PIENU and NA62





[PIENU, 2101.07381]



[NA62, 2101.12304]

Cancellation of IR Divergence in Meson Decay

$$\Gamma^{\rm tree}(\mathsf{M} \to \ell + \chi + \phi) = \frac{G_F^2 m_{\mathsf{M}}^3 f_{\mathsf{M}}^2 |V|^2 g_\nu^2}{128\pi^3} f(x_{\phi\mathsf{M}},\, x_{\ell\mathsf{M}})\,, \tag{1}$$

$$f(x_1,\, x_2) \simeq -x_2(1 + 2x_2 - x_2^2)\text{arctanh}\frac{1 - x_2}{1 + x_2} + \frac{1}{6}(1 - x_2)$$
$$\times\Big[2 - 4x_2(4 - 5x_2) - 3x_2(1 - x_2)\Big(2\log x_1 + \log 2x_2 - 4\log(1 - x_2)\Big)\Big]$$

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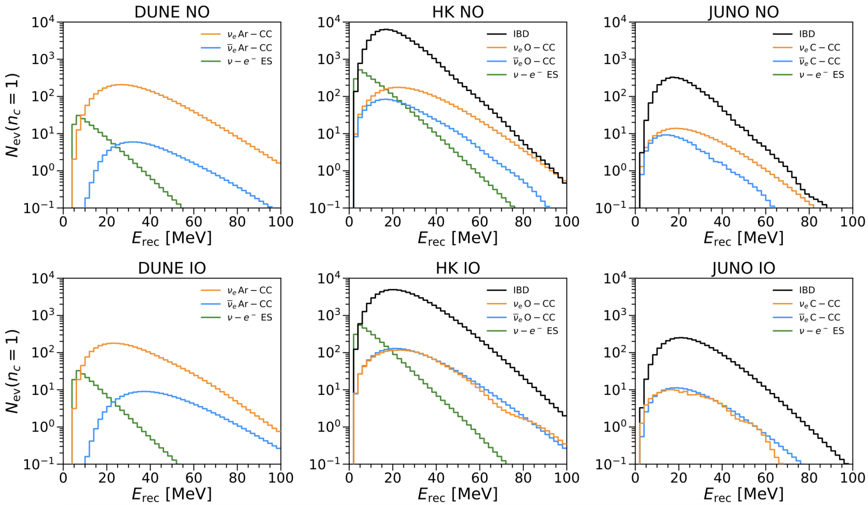
$$\Gamma^{\rm int.}(\mathsf{M} \to \ell + \nu) = \frac{G_F^2 m_{\mathsf{M}} m_\ell^2 f_{\mathsf{M}}^2 |V|^2 g_\nu^2}{128\pi^3} f^{\rm loop}(x_{\phi \mathsf{M}},\, x_{\ell \mathsf{M}},\, x_{\chi \mathsf{M}})\,. \tag{2}$$

$$f^{\rm loop}(x_1,\, x_2,\, x_3) = \frac{1}{4(x_1-x_3)^2}\Big[x_1^2(5+2\log 4\pi)$$
$$+x_3^2\left(7+2\log\frac{16\pi^2 x_1}{x_3}\right) - 4x_1x_3(3+2\log 4\pi)$$
$$-2(x_1-x_3)^2\log x_1(1-x_2)^2\Big]\,.$$

The IR divergent part $x_{\ell \mathsf{M}}(1-x_{\ell \mathsf{M}})^2 \log x_{\phi \mathsf{M}}$ cancels between (1) & (2).

Event Distributions (No Attenuation Case)



[Hajjar, Mena, Palomares-Ruiz, 2303.09369]