Neutrino electromagnetic properties and non-standard interactions in the light of the XENON1T excess

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Snowmass 2021: Neutrino Properties Mini Workshop, August 12, 2020

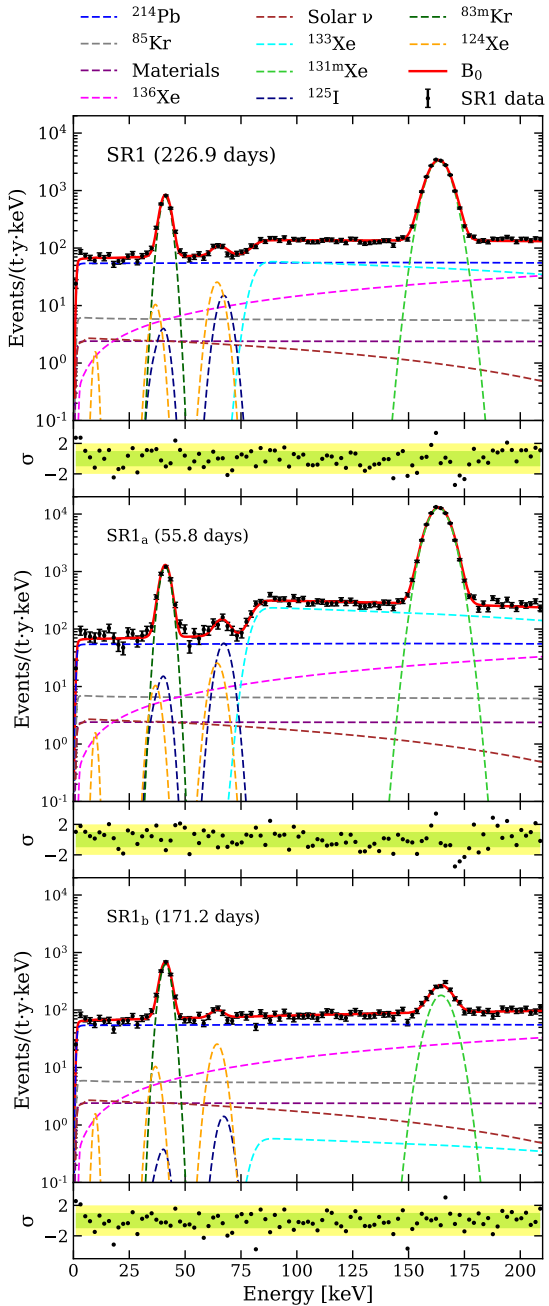
talk based on:

2006.12457 [hep-ph]: in collab. with D. Aristizabal Sierra, V. De Romeri, L.J. Flores
2007.01765 [hep-ph]: in collab. with O. Miranda, M. Tórtola, J. Valle

Outline

1. The XENON1T excess
   - possible explanations
   - solar neutrino background
2. Non-Standard Interactions
   - light vector mediators
   - scalar, pseudoscalar mediators
   - Z' kinetic mixing
3. Electromagnetic neutrino properties
   - Neutrino transition magnetic moments
     - new limits from XENON1T
   - other probes
4. Summary

Observed signal @ XENON1T



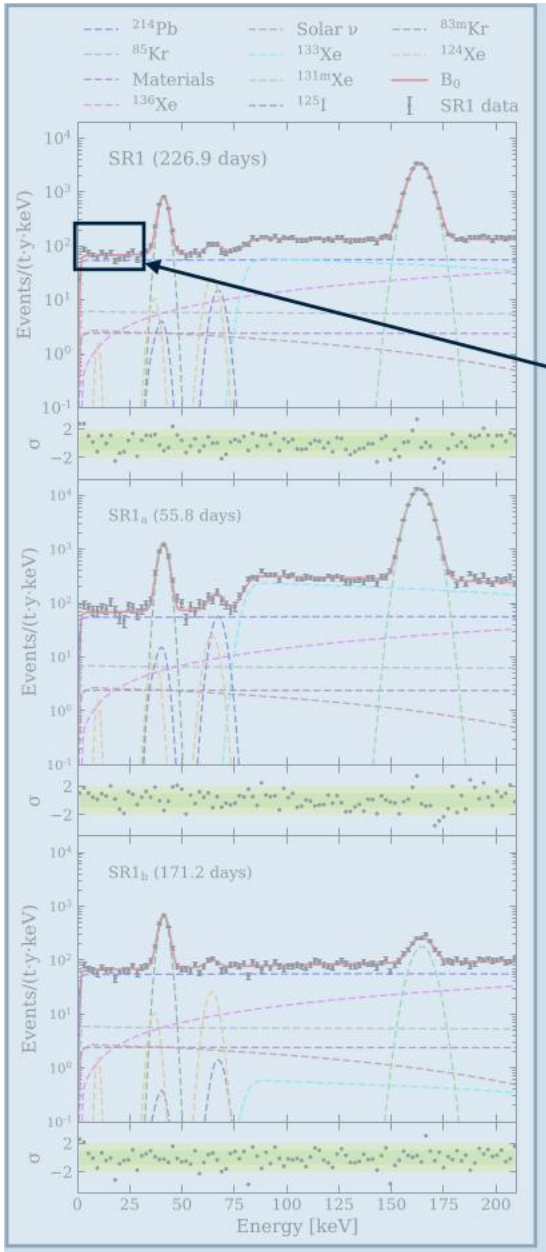
- SR1 live time: 226.9 days
- Region of Interest: 1-210 keV
- Detector mass: 1042 kg
- Exposure: 0.65 ton.yr

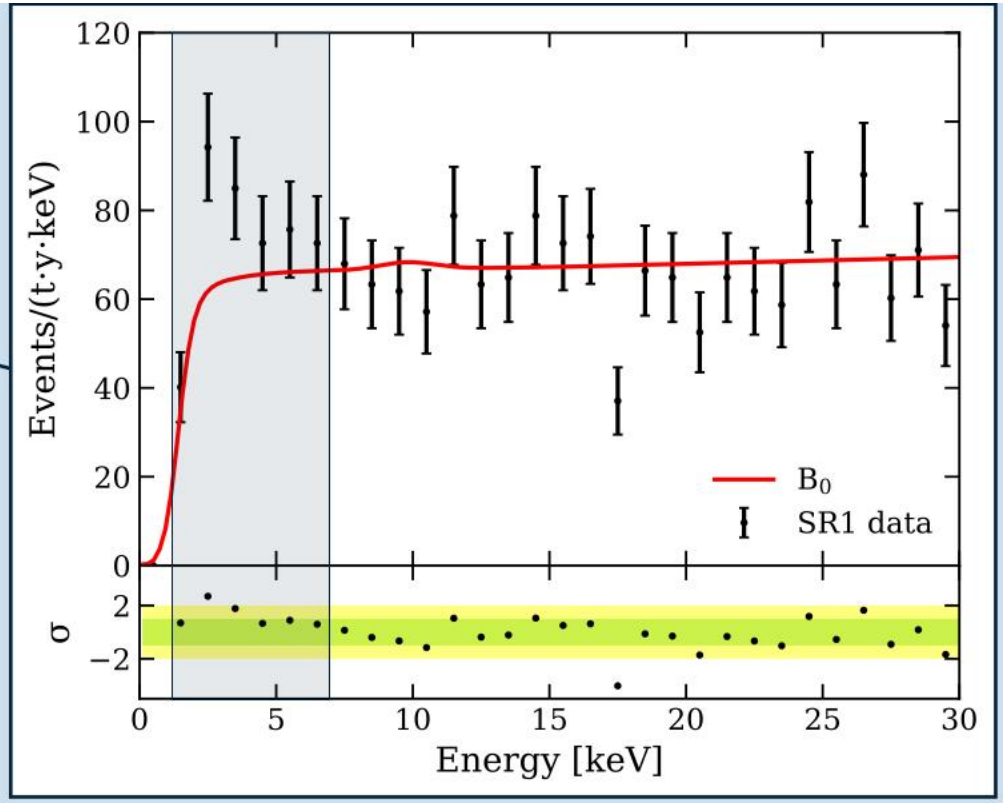
No.	Component	Expected Events	Fitted Events
i	^{214}Pb	(3450, 8530)	7480 ± 160
ii	^{85}Kr	890 ± 150	773 ± 80
iii	Materials	323 (fixed)	323 (fixed)
iv	^{136}Xe	2120 ± 210	2150 ± 120
v	Solar neutrino	220.7 ± 6.6	220.8 ± 4.7
vi	^{133}Xe	3900 ± 410	4009 ± 85
vii	^{131m}Xe	23760 ± 640	24270 ± 150
	^{125}I (K)	79 ± 33	67 ± 12
viii	^{125}I (L)	15.3 ± 6.5	13.1 ± 2.3
	^{125}I (M)	3.4 ± 1.5	2.94 ± 0.50
ix	^{83m}Kr	2500 ± 250	2671 ± 53
	^{124}Xe (KK)	125 ± 50	113 ± 24
x	^{124}Xe (KL)	38 ± 15	34.0 ± 7.3
	^{124}Xe (LL)	2.8 ± 1.1	2.56 ± 0.55

TABLE I. Summary of components in the background model B_0 with expected and fitted number of events in the 0.65 tonne-year exposure of SR1. Both numbers are within the (1, 210) keV ROI and before efficiency correction. See text for details on the various components.

[XENON Collaboration, arXiv:2006.09721]

Zoom in the low energy bump





Excess between 1-7 keV

285 *events observed*

vs.

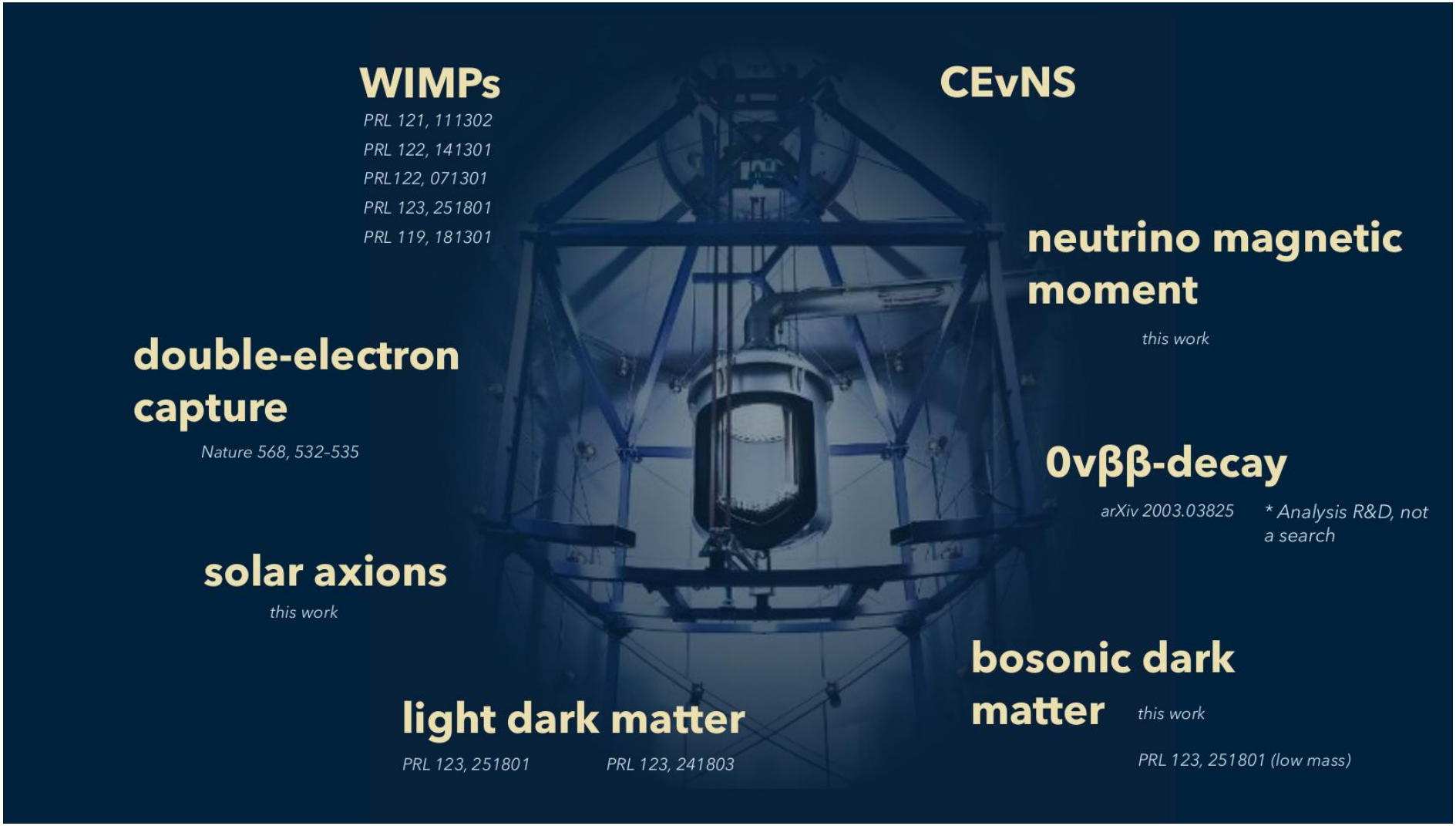
232 (+/- 15) *events expected (from best-fit)*

Would be a ***3.5σ*** *fluctuation*

(naive estimate – we use likelihood ratio tests for main analysis)

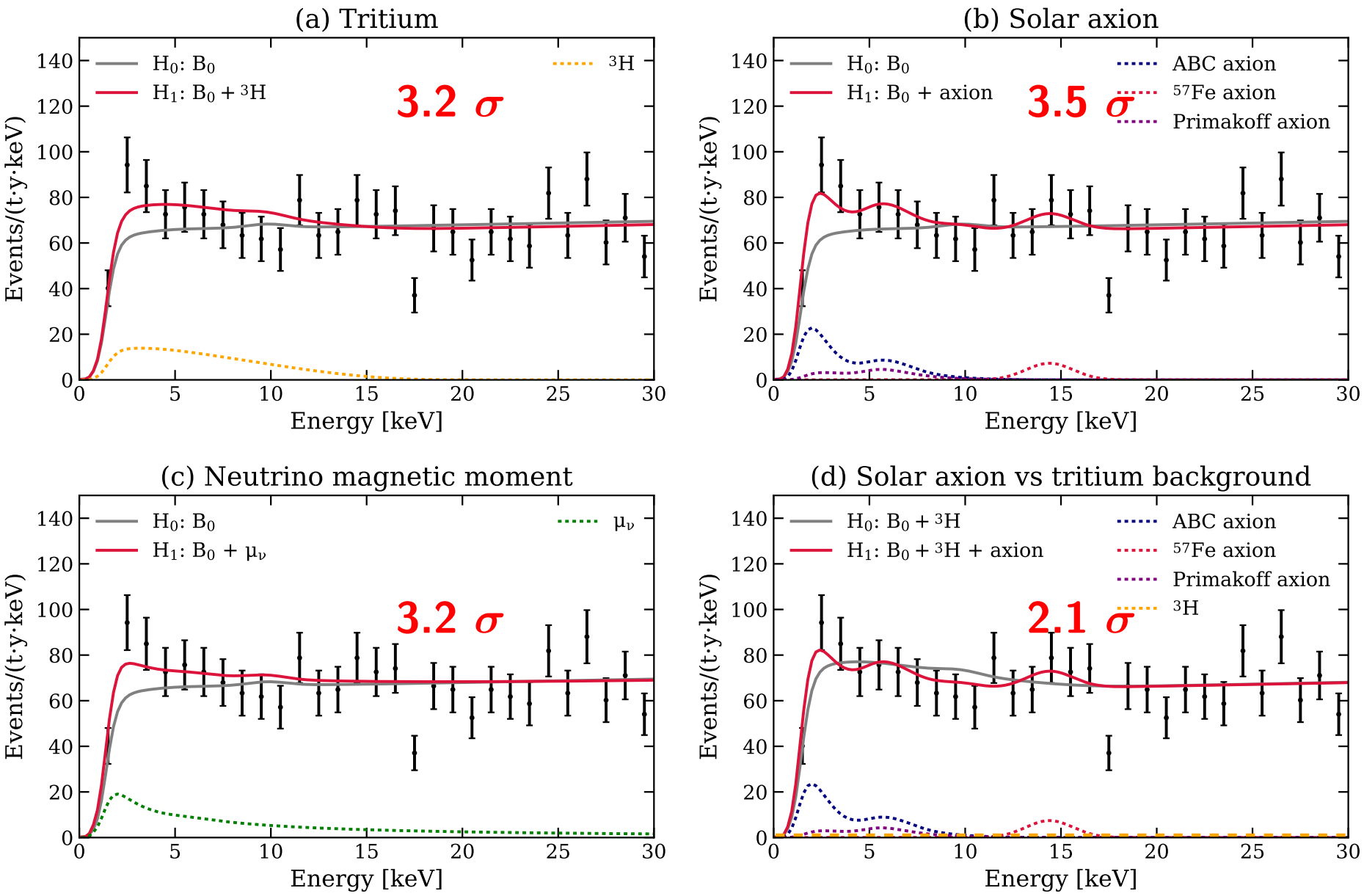
[XENON Collaboration, arXiv:2006.09721], slide taken from Evan Shockley: LNGS Webinar June 17th, 2020

Physics accessible @XENON1T



taken from Evan Shockley, Chicago U.: see the recording

XENON1T results



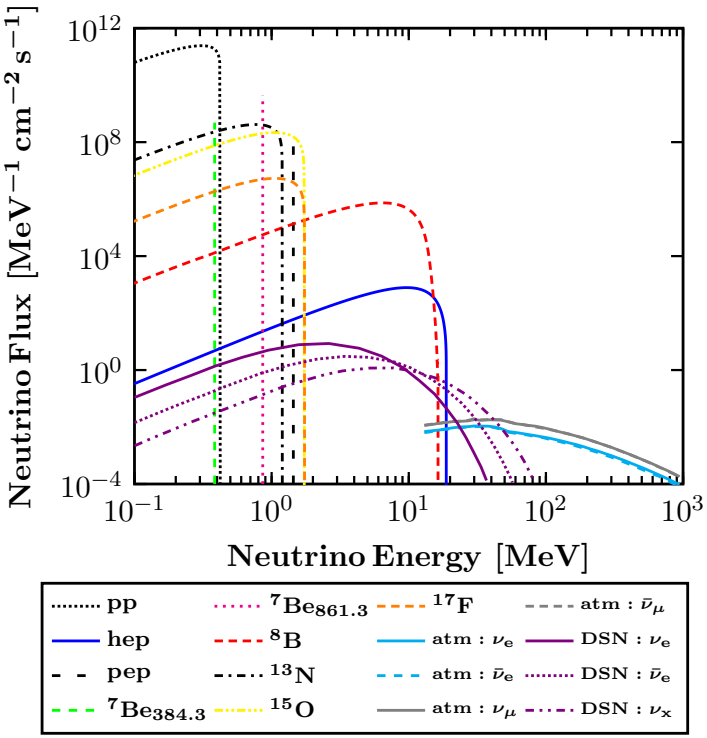
[XENON Collaboration, arXiv:2006.09721]

Neutrino backgrounds to dark matter searches

- Solar neutrinos
  W. C. Haxton, R. G. Hamish Robertson, and A. M. Serenelli, Ann. Rev. Astron. Astrophys. **51** (2013), 21
- Low-energy Atmospheric neutrinos (FLUKA simulations)
  G. Battistoni, A. Ferrari, T. Montaruli, and P. R. Sala, Astropart. Phys. **23** (2005) 526
- Diffuse Supernova neutrinos S. Horiuchi, J. F. Beacom, and E. Dwek, Phys. Rev. **D79** (2009) 083013

type	$E_{\nu_{\max}}$ [MeV]	flux [$\mathrm{cm^{-2}s^{-1}}$]
pp	0.423	$(5.98 \pm 0.006) \times 10^{10}$
pep	1.440	$(1.44 \pm 0.012) \times 10^{8}$
hep	18.784	$(8.04 \pm 1.30) \times 10^{3}$
$^{7}\mathrm{Be_{low}}$	0.3843	$(4.84 \pm 0.48) \times 10^{8}$
$^{7}\mathrm{Be_{high}}$	0.8613	$(4.35 \pm 0.35) \times 10^{9}$
$^{8}\mathrm{B}$	16.360	$(5.58 \pm 0.14) \times 10^{6}$
$^{13}\mathrm{N}$	1.199	$(2.97 \pm 0.14) \times 10^{8}$
$^{15}\mathrm{O}$	1.732	$(2.23 \pm 0.15) \times 10^{8}$
$^{17}\mathrm{F}$	1.740	$(5.52 \pm 0.17) \times 10^{6}$

Solar neutrino fluxes and uncertainties in the framework of the employed high metallicity SSM



Relevant neutrino backgrounds @XENON1T

- Solar neutrinos
  W. C. Haxton, R. G. Hamish Robertson, and A. M. Serenelli, Ann. Rev. Astron. Astrophys. **51** (2013), 21
- Low-energy Atmospheric neutrinos (FLUKA simulations)
  G. Battistoni, A. Ferrari, T. Montaruli, and P. R. Sala, Astropart. Phys. **23** (2005) 526
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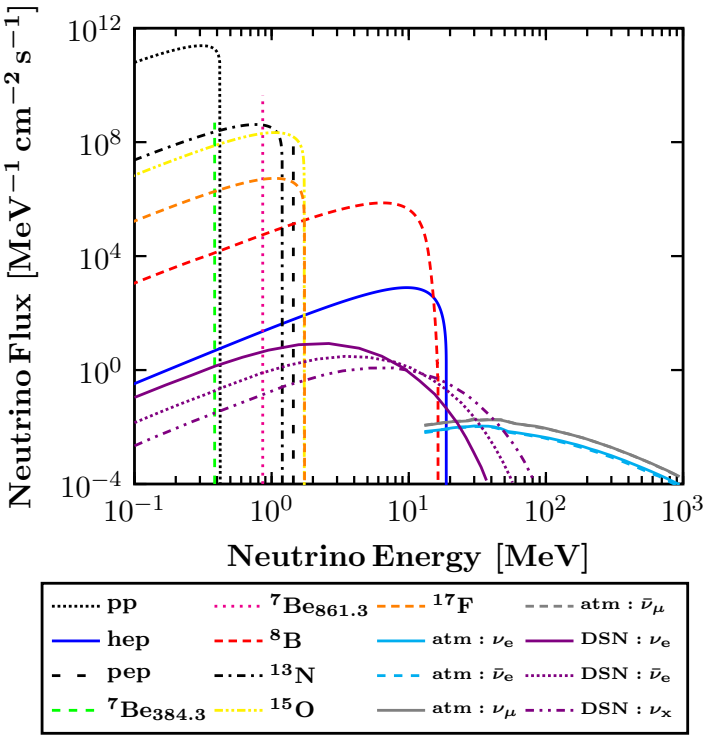
Given the ROI @XENON1T
only *pp* and $^{7}\mathrm{Be_{low}}$ are relevant



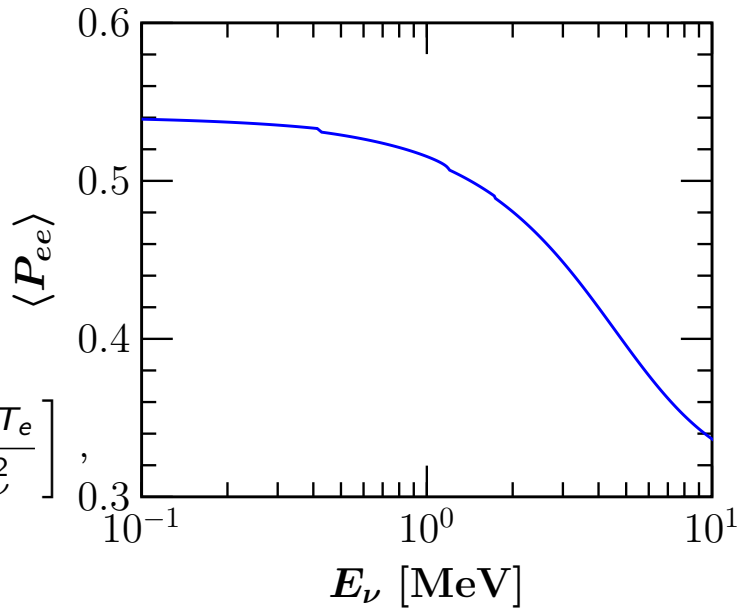
Neutrino-electron scattering

SM detection cross section

[Vogel, Engel.: PRD 39 [1989] 3378

$$\left[\frac{d\sigma_\nu(E_\nu, T_e)}{dT_e}\right]_{\rm SM} = \frac{d\sigma_{\nu_e}}{dT_e} P_{ee}(E_\nu) + \frac{d\sigma_{\nu_{\mu,\tau}}}{dT_e}[1 - P_{ee}(E_\nu)]\,,$$

Averaged survival probability



$\nu_e - e$ scattering (CC+NC)

$$\left(\frac{d\sigma_{\nu_e}}{dT_e}\right)_{\rm SM} = \frac{2G_F^2 m_e}{\pi}\left[(g_L+1)^2 + g_R^2\left(1-\frac{T_e}{E_\nu}\right)^2 - (g_L+1)g_R\frac{m_e T_e}{E_\nu^2}\right]\,,$$

$\nu_{\mu,\tau} - e$ scattering (NC)

$$\left(\frac{d\sigma_{\nu_{\mu,\tau}}}{dT_e}\right)_{\rm SM} = \frac{2G_F^2 m_e}{\pi}\left[g_L^2 + g_R^2\left(1-\frac{T_e}{E_\nu}\right)^2 - g_L g_R\frac{m_e T_e}{E_\nu^2}\right]\,.$$

with

$$g_L = -1/2 + \sin^2\theta_W\,,$$
$$g_R = \sin^2\theta_W\,.$$

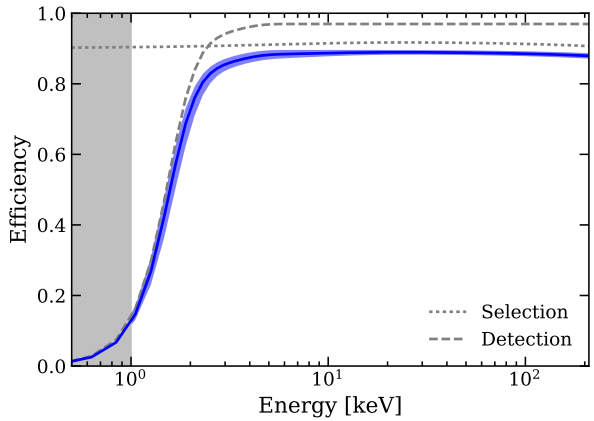
- two-flavor approximation
- BS05 Standard Solar Model

Simulating the solar neutrino event rate

Event rate as a function of the reconstructed recoil energy E_{rec}

$$\left[\frac{dN}{dE_{rec}}\right]_{\rm SM} = \varepsilon(E_{rec})\, N_T \sum_x \int_{T_e^{\rm min}}^{T_e^{\rm max}} \int_{E_\nu^{\rm min}}^{E_\nu^{\rm max}} \frac{d\phi_x}{dE_\nu} \left[\frac{d\sigma_\nu(E_\nu, T_e)}{dT_e}\right]_{\rm SM} \mathcal{G}(E_{rec}, T_e)\, dE_\nu\, dT_e,$$

Detector efficiency $\varepsilon(E_{rec})$



Detector resolution $\mathcal{G}(E_{rec}, T_e)$

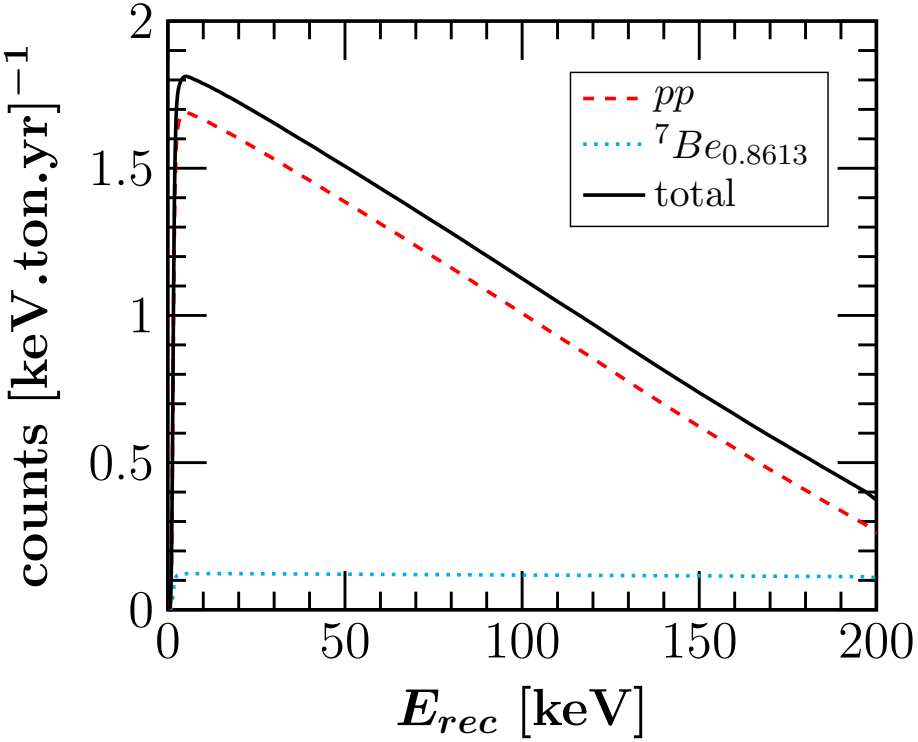
approximated as a Gaussian with

$\sigma/E_{rec} = (31.71/\sqrt{E_{rec}\,[\mathrm{keV}]} + 0.15)\%$

[XENON Collaboration, arXiv:2006.09721]

Expected SM event rate

[Aristizabal, De Romeri, Flores, Papoulias: arXiv 2006.12457]



- dominated by pp neutrinos in the ROI

New Light vector mediators (LVM) @XENON1T

Assume a new LVM with mass m_V, coupled to neutrinos and electrons

- the cross section reads

$$\left(\frac{d\sigma}{dT_e}\right)_{SM+Z'} = \frac{m_e G_F^2}{4\pi}\left[g_2^2 + g_1^2\left(1-\frac{E_r}{E_\nu}\right)^2 - g_1 g_2 \frac{m_e E_r}{E_\nu^2}\right]$$

- the couplings $g_{1,2}$ account for SM + LVM contributions

$$g_{1,2} = g_{1,2}^{\mathrm{SM}} + a_{1,2} + \frac{b_{1,2}}{G_F(2m_e E_r + m_V^2)} \ .$$

[Lindner, Queiroz, Rodejohann, Xu: arXiv 1803.00060]

- the SM couplings read

$$g_1^{\mathrm{SM}} = -2\sqrt{2}s_W^2 \ , \qquad g_2^{\mathrm{SM}} = \sqrt{2}(1-2s_W^2) - 2\sqrt{2} \qquad \text{(present for } \nu_e \text{ only)}$$

Assuming suppressed kinetic and mass mixing:

$$a_1 = a_2 = 0 \ , \quad b_1 = -\frac{1}{4}Q_\nu^L Q_\ell^R g_V^2 \ , \quad b_2 = -\frac{1}{4}Q_\nu^L Q_\ell^L g_V^2 \ ,$$

- g_V is the coupling associated to the new vector boson
- charge choices are determined by anomaly cancellation [Campos et al.: arXiv 1705.05388]
- here we take: $Q_\nu^L = Q_\ell^R = Q_\ell^L = -1$ ($U_{\text{B-L}}$ case).

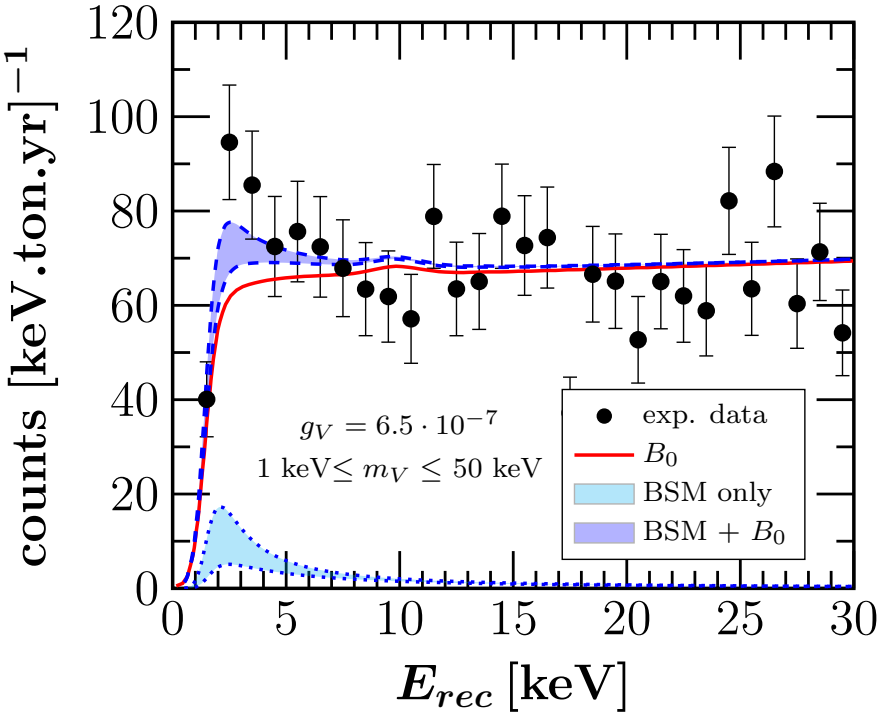
The SM limit is recovered as

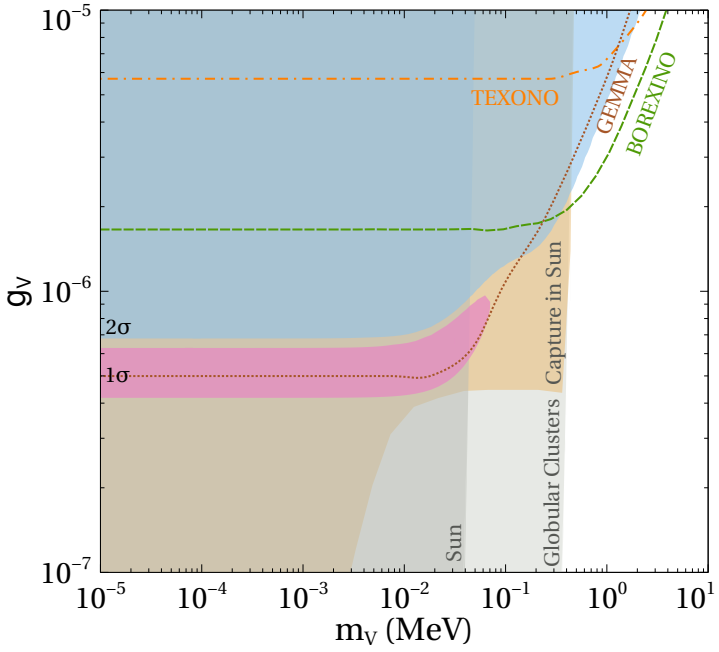
$$\frac{d\sigma_{\mathrm{SM}}}{dT_e} = \left(\left.\frac{d\sigma}{dT_e}\right|_{a_i=b_i=0}\right)_{\mathrm{SM+LVM}} \ .$$

Probing LVM in the light of XENON1T data

Fitting the XENON1T data [Aristizabal, De Romeri, Flores, Papoulias: arXiv 2006.12457]

$$\chi^2 = \sum_{a=1}^{29} \frac{1}{\sigma_a^2} \left[\left(\frac{dR^{V+B_0}}{dE_{rec}} \right)_a - \left(\frac{dR^{\rm Exp}}{dE_{rec}} \right)_a \right]^2 .$$

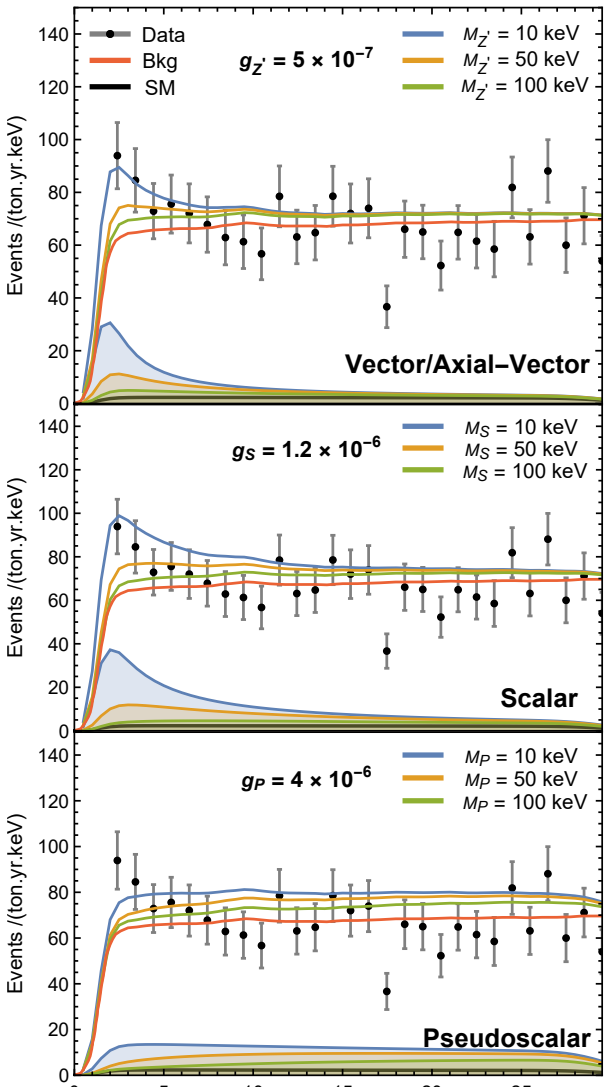




- conflict with lab- and astro-limits?

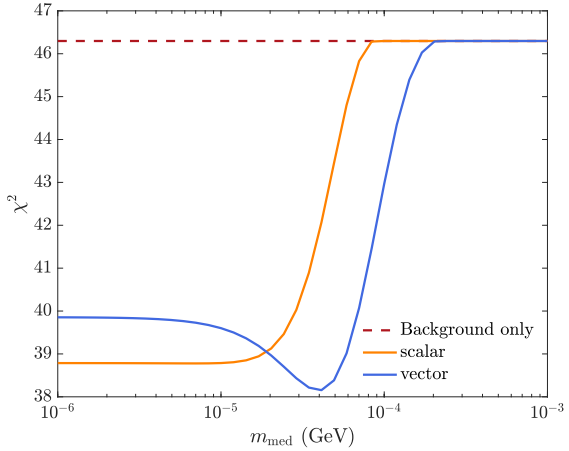
Scalar and pseudoscalar mediators

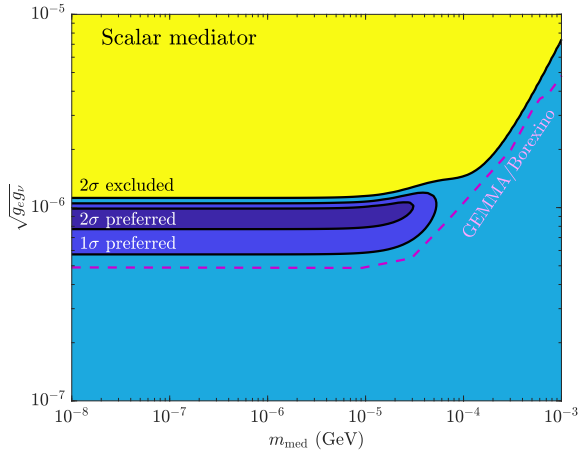
[Khan: arXiv 2006.12887]



$$\left(\frac{d\sigma_{\nu_\alpha e}}{dE_r}\right)_P = \left(\frac{g_P^4}{8\pi(2m_eE_r + m_P)^2}\right)\frac{m_eE_r^2}{E_\nu^2}$$

[Boehm et al.: arXiv 2006.12887]





- Scalar mediator (with mass m_ϕ) and scalar couplings

$$\mathcal{L} \supset (g_\nu\, \phi\bar{\nu}_R\nu_L + h.c.) + \phi\bar{\ell}g_l\ell \qquad (5)$$

$$\frac{d\sigma_{\nu e}}{dE_R} - \frac{d\sigma_{\nu e}^{\rm SM}}{dE_R} = \frac{g_\nu^2 g_e^2 E_R m_e^2}{4\pi E_\nu^2\left(2E_R m_e + m_\phi^2\right)^2}\,. \qquad (6)$$

Active/Sterile neutrino-electron scattering via Z'

- NSI can arise due to kinetic mixing of Z' with photons
- term $L \supset -(\epsilon/4)F_{\mu\nu}Z'^{\mu\nu} \Rightarrow \epsilon(q^2 - q_\mu q_\nu)/m_{Z'}^2$ in the $\nu - e$ scat. amplitude

$\mathcal{L} \supset g\bar{\nu}\gamma_\mu \nu Z'^\mu$	$\frac{d\sigma}{dE_R} = \frac{\alpha g^2 \epsilon^2 m_e}{4(2E_R m_e + m_{Z'}^2)^2}\left[1 + \left(1 - \frac{E_R}{E_\nu}\right)^2 - \frac{m_e E_R}{E_\nu^2}\right]$
$\mathcal{L} \supset g_d\, \bar{\nu}\sigma_{\mu\nu}\nu Z'^{\mu\nu}$	$\frac{d\sigma}{dE_R} = \frac{\alpha g_d^2 \epsilon^2 m_e^2 E_R(E_\nu - E_R)}{E_\nu(2E_R m_e + m_{Z'}^2)^2}$
$\mathcal{L} \supset g\bar{\nu}\gamma_\mu N Z'^\mu$	$\frac{d\sigma}{dE_R} = \frac{\alpha g^2 \epsilon^2}{4E_\nu^2(2E_R m_e + m_{Z'}^2)^2}\Big[4m_e E_\nu^2 - m_e m_N^2 - 2E_R(2m_e^2 - m_N^2 - 2m_e E_R) - 2E_\nu(m_N^2 + 2m_e E_R)\Big],$
$\mathcal{L} \supset g_d\, \bar{\nu}\sigma_{\mu\nu} N Z'^{\mu\nu}$	$\frac{d\sigma}{dE_R} = \frac{\alpha g_d^2 \epsilon^2 m_e^2}{(2E_R m_e + m_{Z'}^2)^2}\Big[E_R - \frac{E_R^2}{E_\nu} - \frac{m_N^2 E_R}{2E_\nu m_e}\left(1 - \frac{E_R}{2E_\nu} + \frac{m_e}{2E_\nu}\right) + \frac{m_N^4(E_R - m_e)}{8E_\nu^2 E_R^2 m_e^2}\Big],$
$\mathcal{L} \supset g\bar{N}\gamma_\mu N Z'^\mu$	$\frac{d\sigma}{dE_R} = \frac{\alpha g^2 \epsilon^2 \sin^2\theta}{4E_\nu^2(2E_R m_e + m_{Z'}^2)^2}\Big[2m_e E_\nu^2 - 2m_e E_\nu E_R - E_R(m_e^2 + m_N^2 - m_e E_R)\Big].$

[Karmakar, Pandey: arXiv 2007.11892]

Electromagnetic neutrino properties

The Electromagnetic neutrino-electron cross section reads

[Vogel, Engel.: PRD 39 [1989] 3378

$$\left(\frac{d\sigma}{dT_e}\right)_{\mathrm{EM}} = \frac{\pi a_{\mathrm{EM}}^2 \mu_\nu^2}{m_e^2}\left(\frac{1 - T_e/E_\nu}{T_e}\right) .$$

- can be dominant for sub-keV threshold experiments
- may lead to detectable distortions of the recoil spectrum

The helicity preserving SM cross section adds incoherently with the helicity-violating EM cross section

$$\left(\frac{d\sigma}{dT_e}\right)_{\mathrm{tot}} = \left(\frac{d\sigma}{dT_e}\right)_{\mathrm{SM}} + \left(\frac{d\sigma}{dT_e}\right)_{\mathrm{EM}}$$

μ_ν^2 is the effective neutrino magnetic moment (NMM) in the mass basis relevant to a given neutrino beam [talk by O.Miranda]

- Experimental measurements usually constrain some process-dependent effective parameter combination
- needs to be expressed in terms of fundamental parameters (TMMs + CP phases + mixing-angles)
- Even in the case of laboratory neutrino experiments, where the initial neutrino flux is fixed

The neutrino transition magnetic moment (TMM) matrix

... recalling O. Miranda's talk..

The magnetic moment matrix λ ($\tilde{\lambda}$) in the flavor (mass) basis reads

[Tórtola: PoS AHEP 2003 (2003)]

$$\lambda = \begin{pmatrix} 0 & \Lambda_\tau & -\Lambda_\mu \\ -\Lambda_\tau & 0 & \Lambda_e \\ \Lambda_\mu & -\Lambda_e & 0 \end{pmatrix}, \qquad \tilde{\lambda} = \begin{pmatrix} 0 & \Lambda_3 & -\Lambda_2 \\ -\Lambda_3 & 0 & \Lambda_1 \\ \Lambda_2 & -\Lambda_1 & 0 \end{pmatrix}$$

- the definition $\lambda_{\alpha\beta} = \varepsilon_{\alpha\beta\gamma}\Lambda_\gamma$ has been introduced,
- the neutrino TMMs are represented by the complex parameters

$$\Lambda_\alpha = |\Lambda_\alpha| e^{i\zeta_\alpha}, \qquad \Lambda_i = |\Lambda_i| e^{i\zeta_i}$$

three complex or six real parameters (3 moduli + 3 phases)

Effective NMM relevant to solar neutrino detection

NMM in the mass basis is known to be

$$\left(\mu^M_{\nu,\text{eff}}\right)^2(L,E_\nu) = \sum_j \left| \sum_i U^*_{\alpha i} e^{-i\,\Delta m^2_{ij} L/2E_\nu}\,\tilde{\lambda}_{ij} \right|^2$$

- neutrino mixing and oscillations between the source and detection considered
- Λ_i: entries of the transition magnetic moment matrix with $\lambda_{\alpha\beta} = \varepsilon_{\alpha\beta\gamma}\Lambda_\gamma$

For solar neutrinos (mass basis) [Cañas et al.: PLB 753 (2016)]

$$(\mu^M_{\nu,\,\text{sol}})^2 = |\mathbf{\Lambda}|^2 - c^2_{13}|\Lambda_2|^2 + (c^2_{13}-1)|\Lambda_3|^2 + c^2_{13}P^{2\nu}_{e1}(|\Lambda_2|^2 - |\Lambda_1|^2)$$

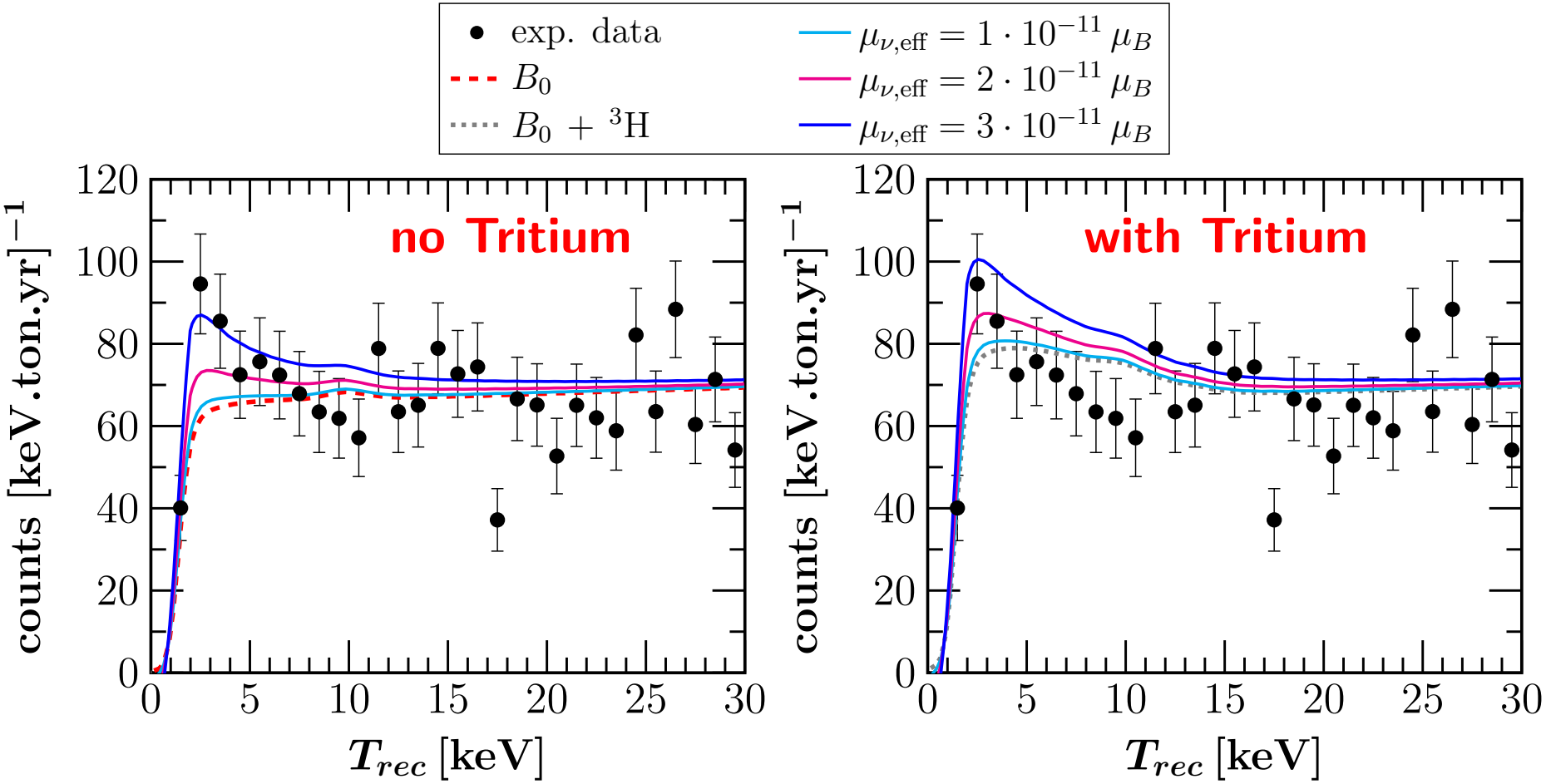
- solar electron neutrinos undergo flavor oscillations arriving to the detector as an incoherent admixture of mass eigenstates (no phase dependence)
- the oscillation probabilities from ν_e to mass eigenstates ν_i are approximated

$$P^{3\nu}_{e3} = \sin^2\theta_{13}, \quad P^{3\nu}_{e1} = \cos^2\theta_{13}P^{2\nu}_{e1}, \quad P^{3\nu}_{e2} = \cos^2\theta_{13}P^{2\nu}_{e2},$$

with the unitarity condition, $P^{2\nu}_{e1} + P^{2\nu}_{e2} = 1$

Impact of NMM @XENON1T

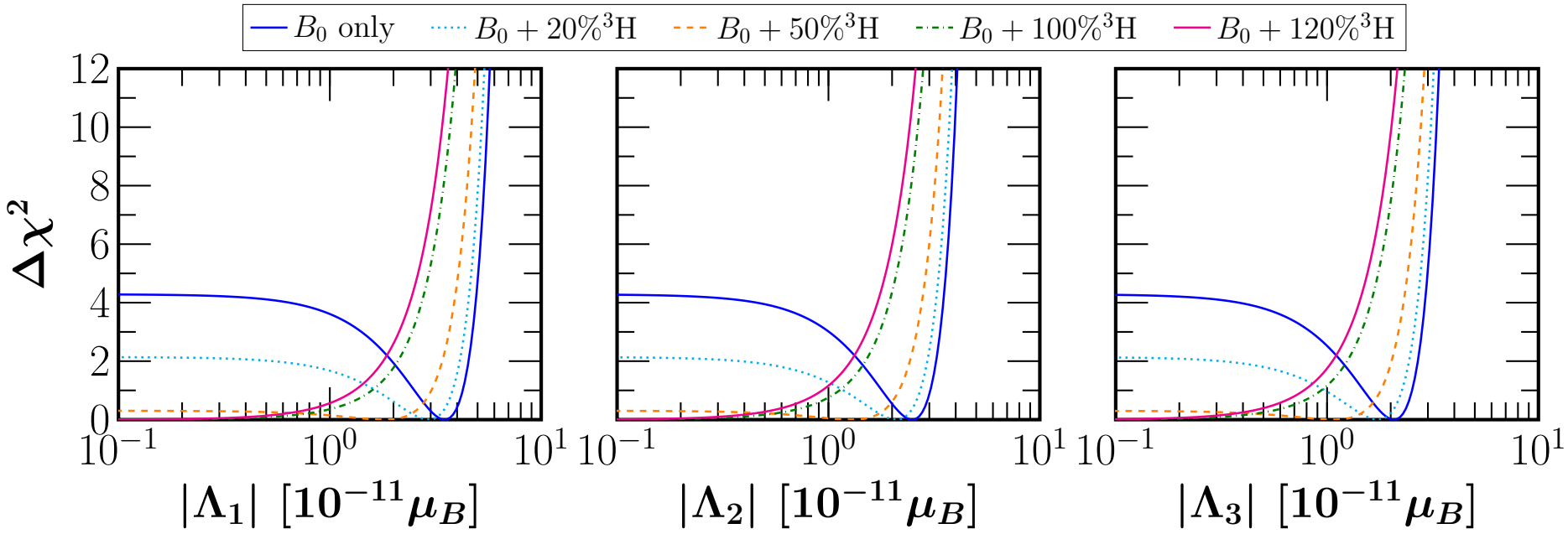
Explore cases w/o tritium background



[Miranda, Papoulias, Tórtola, Valle: arXiv 2007.01765]

Probing transition magnetic moments @XENON1T

Explore cases with arbitrary tritium background

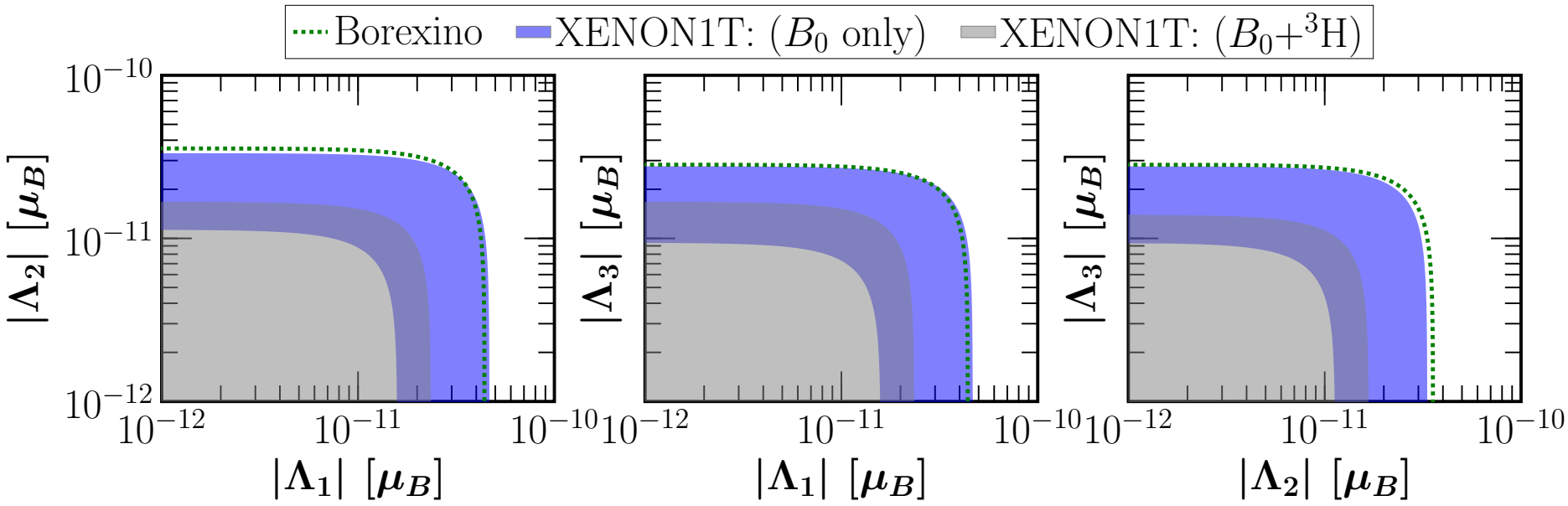


- B_0 only: leads to a positive signal at 90% C.L
- when ^{3}H is considered: TMM significance diminishes

[Miranda, Papoulias, Tórtola, Valle: arXiv 2007.01765]

Comparing with other constraints

Explore cases w/o tritium background



	$\lvert\Lambda_1\rvert\,[10^{-11}\mu_B]$	$\lvert\Lambda_2\rvert\,[10^{-11}\mu_B]$	$\lvert\Lambda_3\rvert\,[10^{-11}\mu_B]$
Borexino [16]	< 4.4	< 3.6	< 2.8
XENON1T (B_0 only)	(1.5–4.7)	(1.1–3.3)	(0.9–2.8)
XENON1T (B_0 + ^{3}H)	< 2.4	< 1.7	< 1.4

TABLE I: 90% C.L. limits and allowed ranges for the TMM matrix elements $|\Lambda_i|$ obtained from Borexino and the recent XENON1T data under different background assumptions.

[Miranda, Papoulias, Tórtola, Valle: arXiv 2007.01765]

Evading constraints from astrophysics

- NMM strengths required to explain the XENON1T are: $\mu_\nu \sim \text{few} \cdot 10^{-11} \mu_B$
- RG branch of globular clusters leads to $\mu_\nu \lesssim \text{few} \cdot 10^{-12} \mu_B$

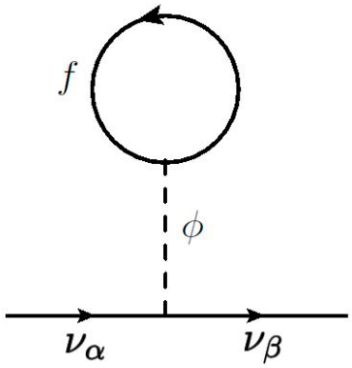
[Viaux et al.: PRL 111 (2013) 231301]

[talk by A. Studenikin]

Proposed mechanisms to evade astro-limits

- active-to-sterile neutrino dipole portal: $L \subset d(\bar{\nu}\sigma_{\mu\nu}F^{\mu\nu}N) + h.c.$
  $N \to \nu + \gamma$ (decay length longer than the detector)

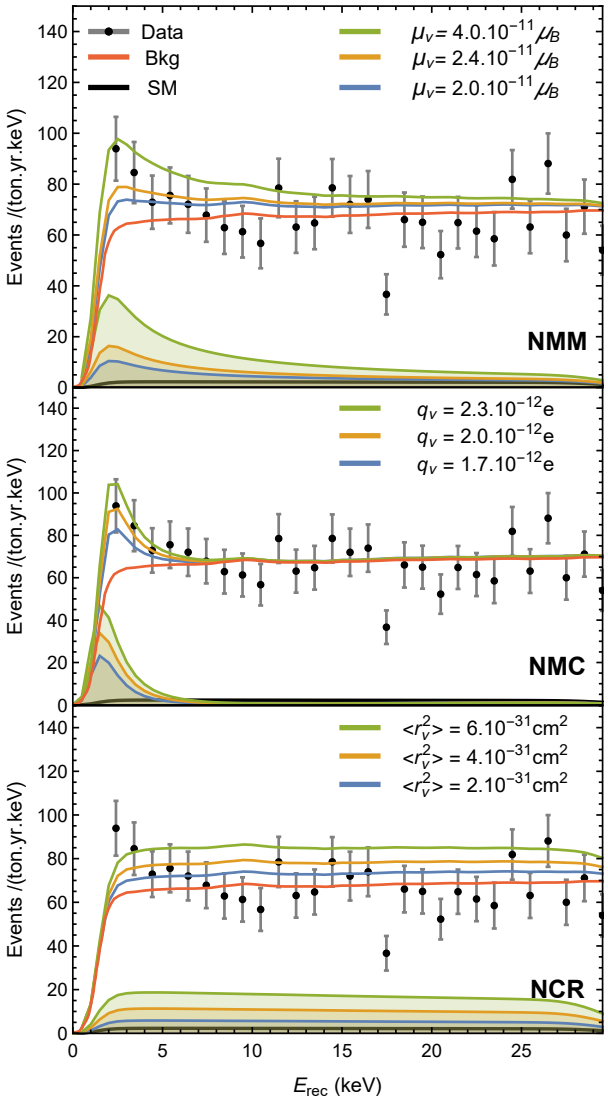
  [Shoemaker, Tsai, Wyenberg: arXiv 2007.05513]
- Majorana neutrino interactions with a light scalar, which also couples to fermion f [Babu, Jana, Lindner: arXiv 2007.04291]



neutrinos would acquire a medium-dependent mass, which may exceed the core temperature of the star, thus preventing plasmon decay kinematically

More on neutrino electromagnetic properties

[Khan: arXiv 2006.12887]



Flavor	$\mu_\nu[\times 10^{-11}\mu_B]$	$\langle r_\nu^2\rangle$ $[\times 10^{-32}\mathrm{cm}^2]$	q_ν $[\times 10^{-12}e]$	a_ν $[\times 10^{-30}\mathrm{cm}^2]$
ν_e (XENON1T)	$[1.4, 2.9]$	$[-93,\ 56\ ]$	$[2.2,\ 2.8\ ]$	$[\ -0.32, 1.2]$
ν_μ(XENON1T)	≤ 1.3	$[-88,\ 92\ ]$	$[-0.7,\ 0.7\ ]$	$[-1.24, 1.24]$
ν_τ(XENON1T)	≤ 1.4	$[-80,\ 82\ ]$	$[-0.63,\ 0.63\ ]$	$[-1.1, 1.1]$
ν_e (Others)	≤ 3.9 (Borexino) ≤ 110 (LAMPF) ≤ 11 (Super-K) ≤ 7.4 (TEXONO) ≤ 2.9 (GEMMA)	$[0.82,\ 1.27]$ (Solar) $[-5.94,\ 8.28]$ (LSND) $[-4.2,\ 6.6]$ (TEXONO)	≤ 1.5 (Reactor)	–
ν_μ(Others)	≤ 5.8 (Borexino) ≤ 68 (LSND) ≤ 74 (LAMPF)[7]	$[-9,\ 31]$ (Solar) ≤ 1.2 (CHARM-II) $[-4.2,\ 0.48]$ (TEXONO)	–	–
ν_τ(Others)	≤ 5.8 (Borexino) $\leq 3.9\times 10^4$ (DONUT)	$[-9,\ 31]$ (Solar)	$\leq 3\times 10^8$ (Beam dump)	–

TABLE I. 90% C.L. bounds on neutrino magnetic moment, charge radius, millicharge and anapole moment from XENON1T and other laboratory experiments. For comparison with astrophysical constraints see ref. [28] and for COHERENT see refs. [29, 30]. Apart from Borexino [26] and solar [46], bounds from all other experiments were taken from tables of ref. [28].

The SM coupling is modified

- neutrino charge radius (NCR)
- neutrino milli-charge (NMC),
- neutrino anapole moment

$$\tilde{g}_V = g_V + \frac{\sqrt{2}\pi\alpha}{G_F}\left(\frac{\langle r_{\nu_\alpha}^2\rangle}{3} - \frac{q_{\nu_\alpha}}{m_e E_r} - \frac{a_{\nu_\alpha}}{18 G_F}\right).$$

$$g_V = -1/2 + \sin^2\theta_W$$

Summary

Non-standard interactions

- XENON1T data offer a new probe to study novel mediators
- light vector mediators fully excluded at 1σ by astrophysics
- competing with laboratory experiments
- future measurements (like XENONnT, etc.) will tell us more

Electromagnetic neutrinos

- discussed the effective μ_ν formalism in terms of fundamental parameters relevant to solar neutrinos
- XENON1T shares the best current limit on NMM with Borexino
- tritium background can modify the sensitivity
- results already of the order of $10^{-11}\mu_B$
- future experiments (like XENONnT etc.) are expected to improve down to $10^{-12}\mu_B$ and probe astro-limits

... *Dark Matter experiments are excellent sites to explore BSM neutrino physics*

Thank you for your attention !

Acknowledgments

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Extras

Electromagnetic neutrino vertex (spin component)

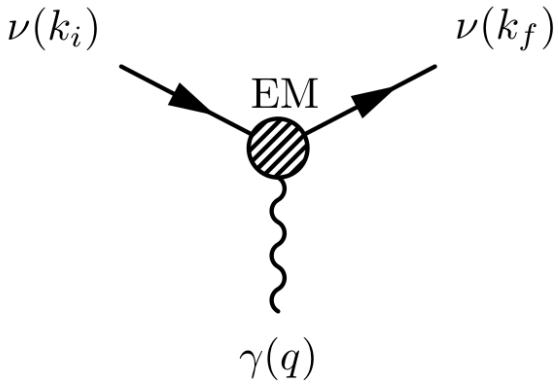
Dirac neutrinos: $H_{\mathrm{EM}}^{\mathrm{D}} = \frac{1}{2}\bar{\nu}_R \lambda \sigma^{\alpha\beta} \nu_L F_{\alpha\beta} + \mathrm{h.c.}$

- $\lambda = \mu - i\epsilon$ is an arbitrary complex matrix
- $\mu = \mu^\dagger$ and $\epsilon = \epsilon^\dagger$.

Majorana neutrinos: $H_{\mathrm{EM}}^{\mathrm{M}} = -\frac{1}{4}\nu_L^{\mathsf{T}} C^{-1} \lambda \sigma^{\alpha\beta} \nu_L F_{\alpha\beta} + \mathrm{h.c.}$

- $\lambda = \mu - i\epsilon$: antisymmetric complex matrix ($\lambda_{\alpha\beta} = -\lambda_{\beta\alpha}$)
- $\mu^{\mathsf{T}} = -\mu$ and $\epsilon^{\mathsf{T}} = -\epsilon$ are two imaginary matrices.
- three complex or six real parameters are required

In contrast to the Dirac case, vanishing diagonal moments are implied for Majorana neutrinos, $\mu_{ii}^{\mathrm{M}} = \epsilon_{ii}^{\mathrm{M}} = 0$.



[Schechter, Valle: PRD 24 (1981), PRD 25 (1982)]

Effective neutrino magnetic moment @ experiments

Is expressed in terms of the neutrino magnetic moment matrix and the amplitudes of positive and negative helicity states 3−vectors $\mathfrak{a}_+$ and $\mathfrak{a}_-$,

- In the flavor basis one finds [Grimus, Schwetz: Nucl. Phys. B587 (2000)]

$$\left(\mu_\nu^F\right)^2 = \mathfrak{a}_-^\dagger \lambda^\dagger \lambda \mathfrak{a}_- + \mathfrak{a}_+^\dagger \lambda \lambda^\dagger \mathfrak{a}_+ \,,$$

Introducing the transformations (U is the lepton mixing matrix)

$$\tilde{\mathfrak{a}}_- = U^\dagger \mathfrak{a}_-, \qquad \tilde{\mathfrak{a}}_+ = U^\mathsf{T} \mathfrak{a}_+, \qquad \tilde{\lambda} = U^\mathsf{T} \lambda U \,,$$

- In the mass basis reads

$$\left(\mu_\nu^M\right)^2 = \tilde{\mathfrak{a}}_-^\dagger \tilde{\lambda}^\dagger \tilde{\lambda} \tilde{\mathfrak{a}}_- + \tilde{\mathfrak{a}}_+^\dagger \tilde{\lambda} \tilde{\lambda}^\dagger \tilde{\mathfrak{a}}_+$$