Searching for new physics with neutrino detectors

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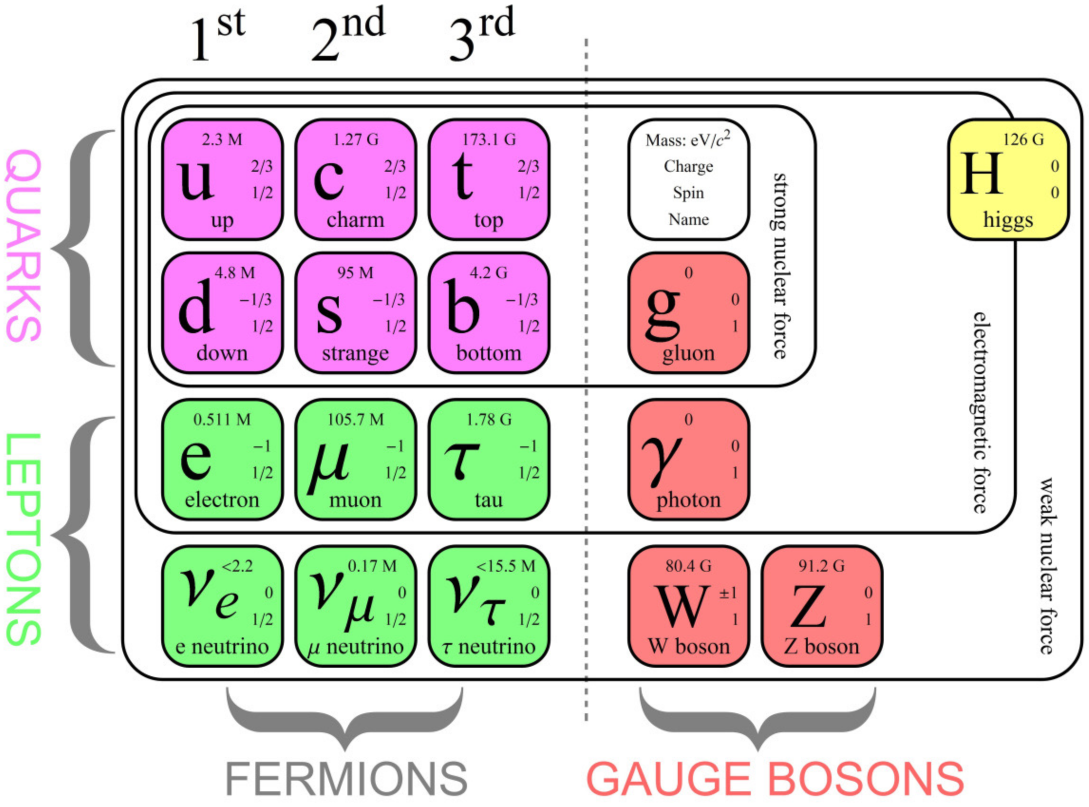
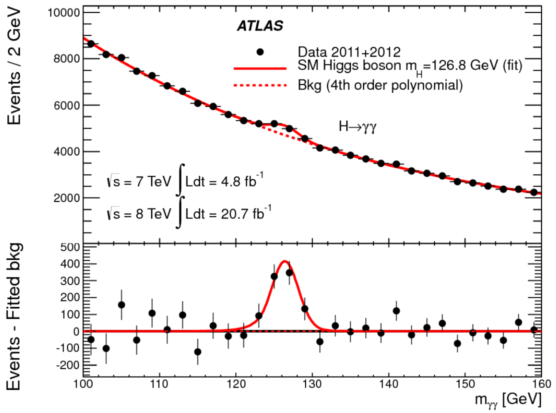
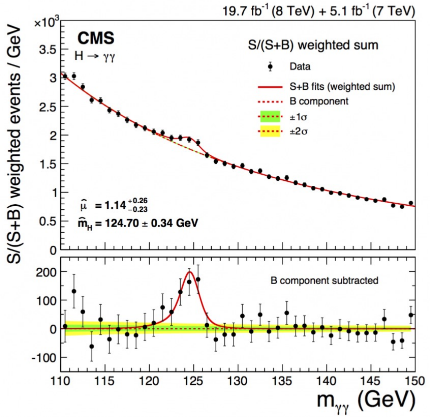
The 4th CCAST workshop on the JUNO related theory and phenomenology:
Astrophysics and Neutrinos

IHEP , April 28-29, 2024

The Standard Model of Particle Physics

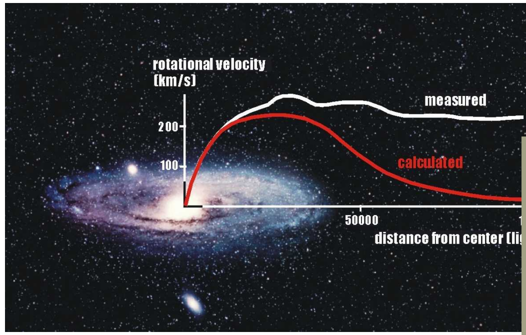


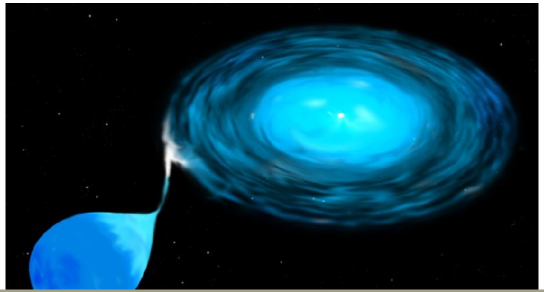


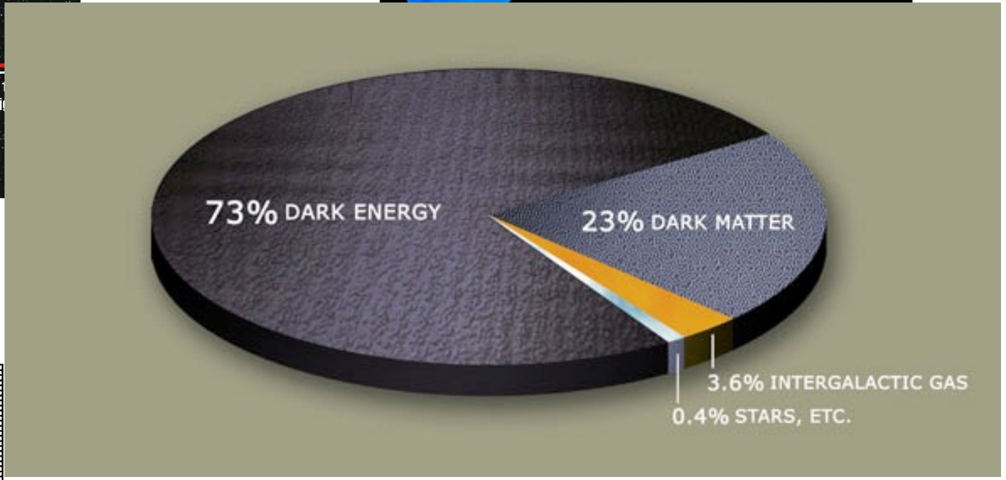


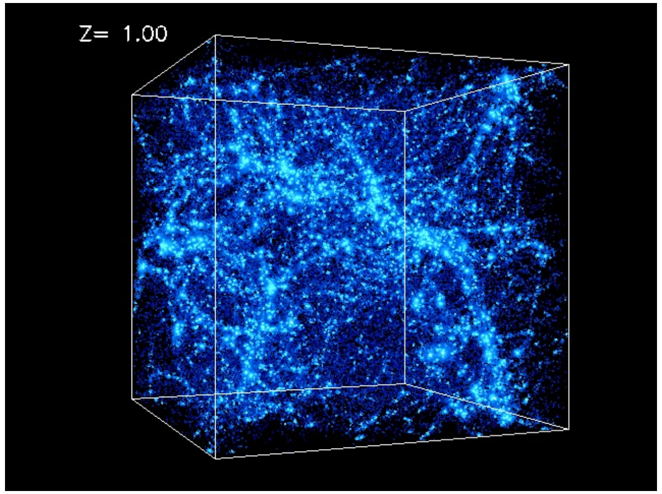
2013

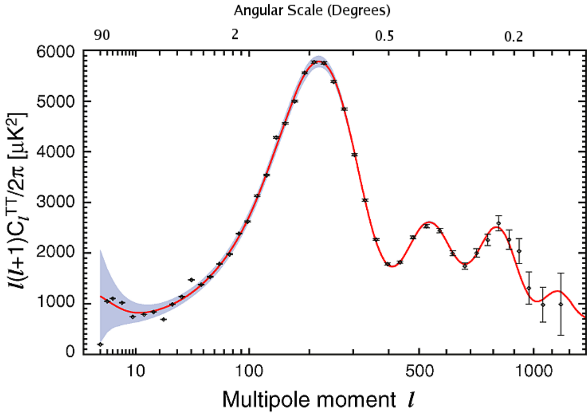
We have plenty of evidences for DM

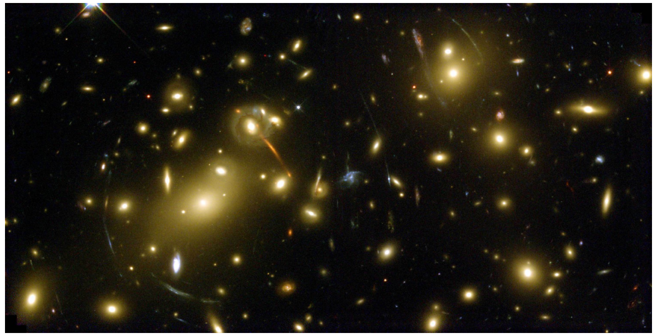




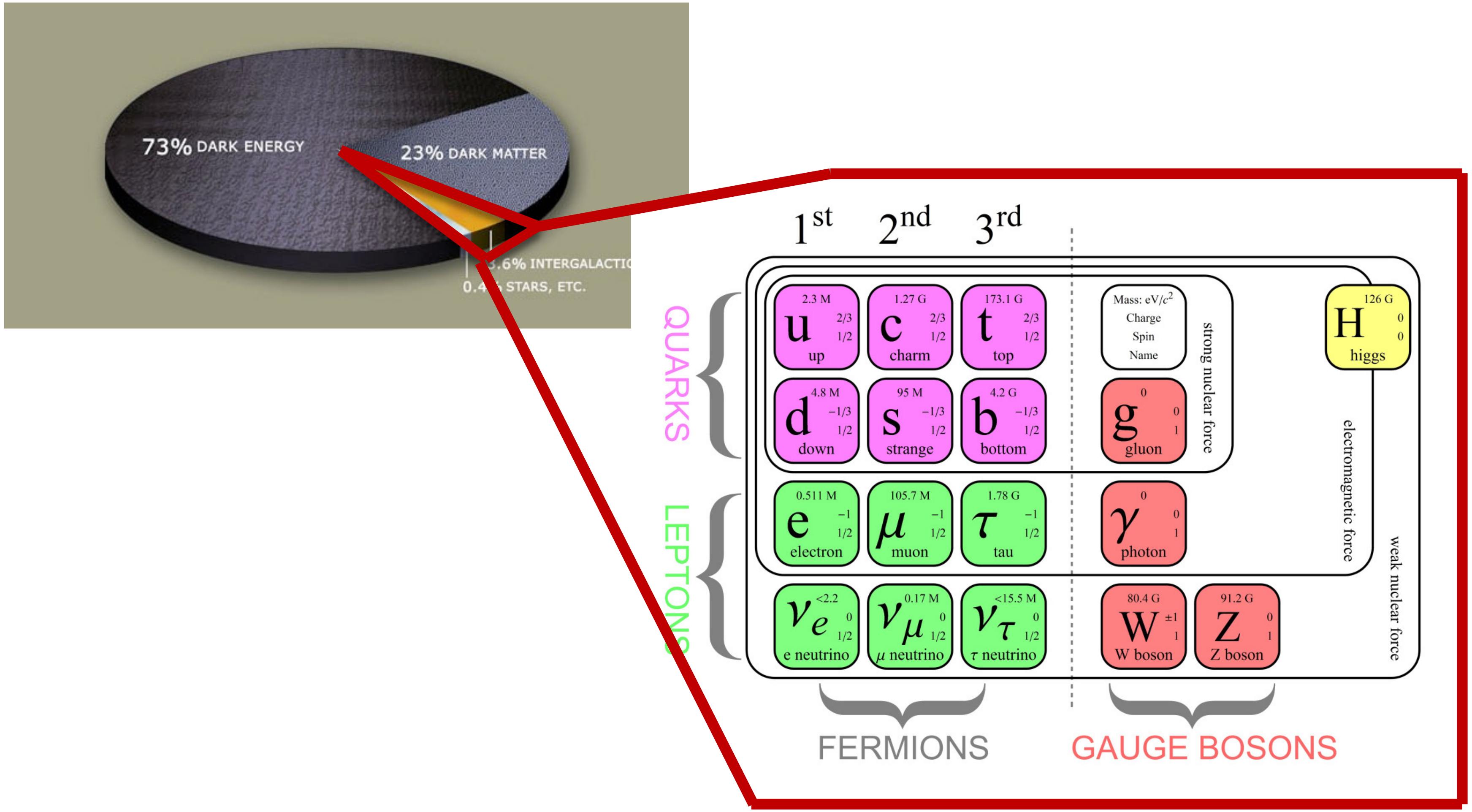






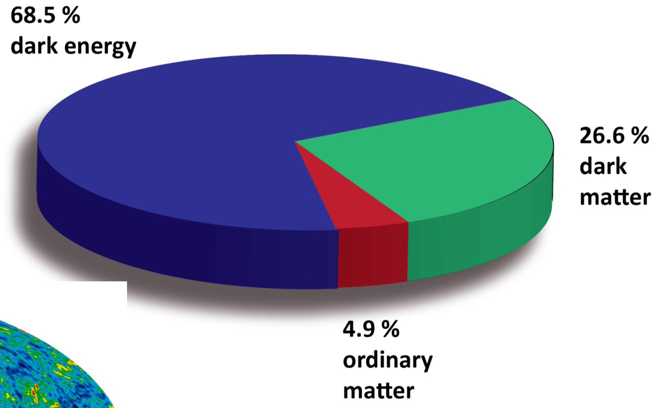


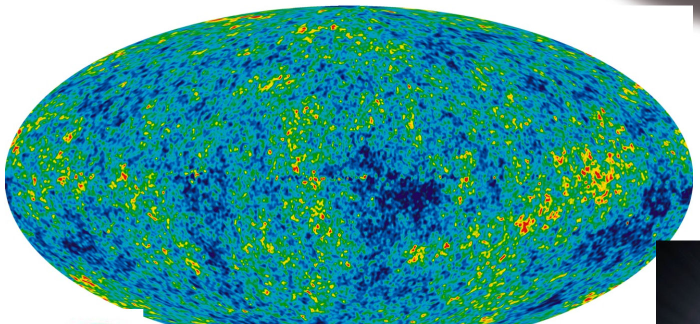
New Physics Beyond the Standard Model



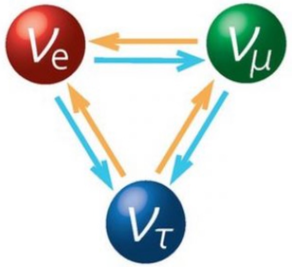
New Physics Beyond the Standard Model

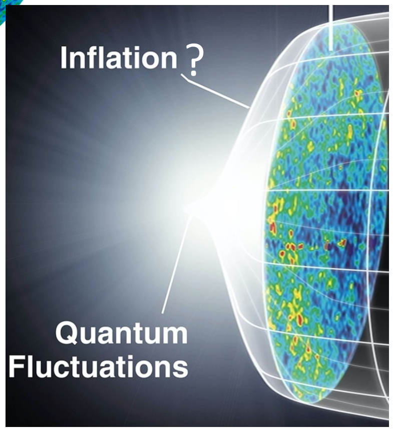
$$\frac{n_B}{n_\gamma} = (6.047 \pm 0.074) \times 10^{-10}$$



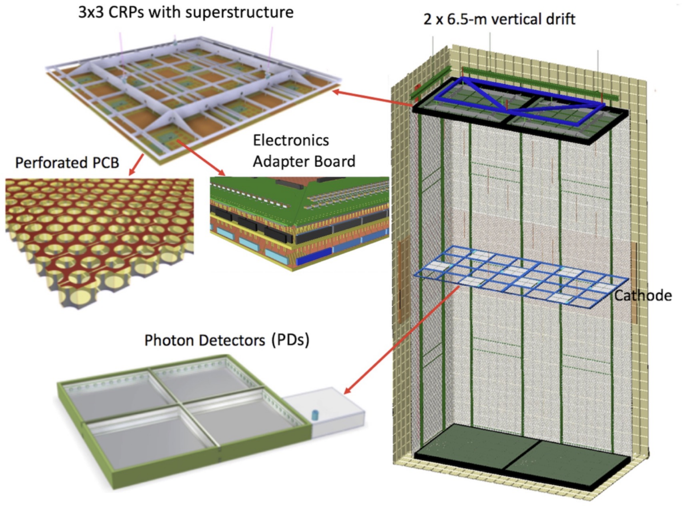


SM





Neutrino detectors



- Noble element detectors
  - Liquid Argon TPCs
  - Liquid and gasesous Xenon detectors
- Photon based neutrino detectors (Cherenkov or scintillation)
  - Water Cherenkov
  - Scintillation
- Low-Threshold Neutrino Detectors
  - Phonon, CCD sensors, HPGe, …

Neutrino experiments

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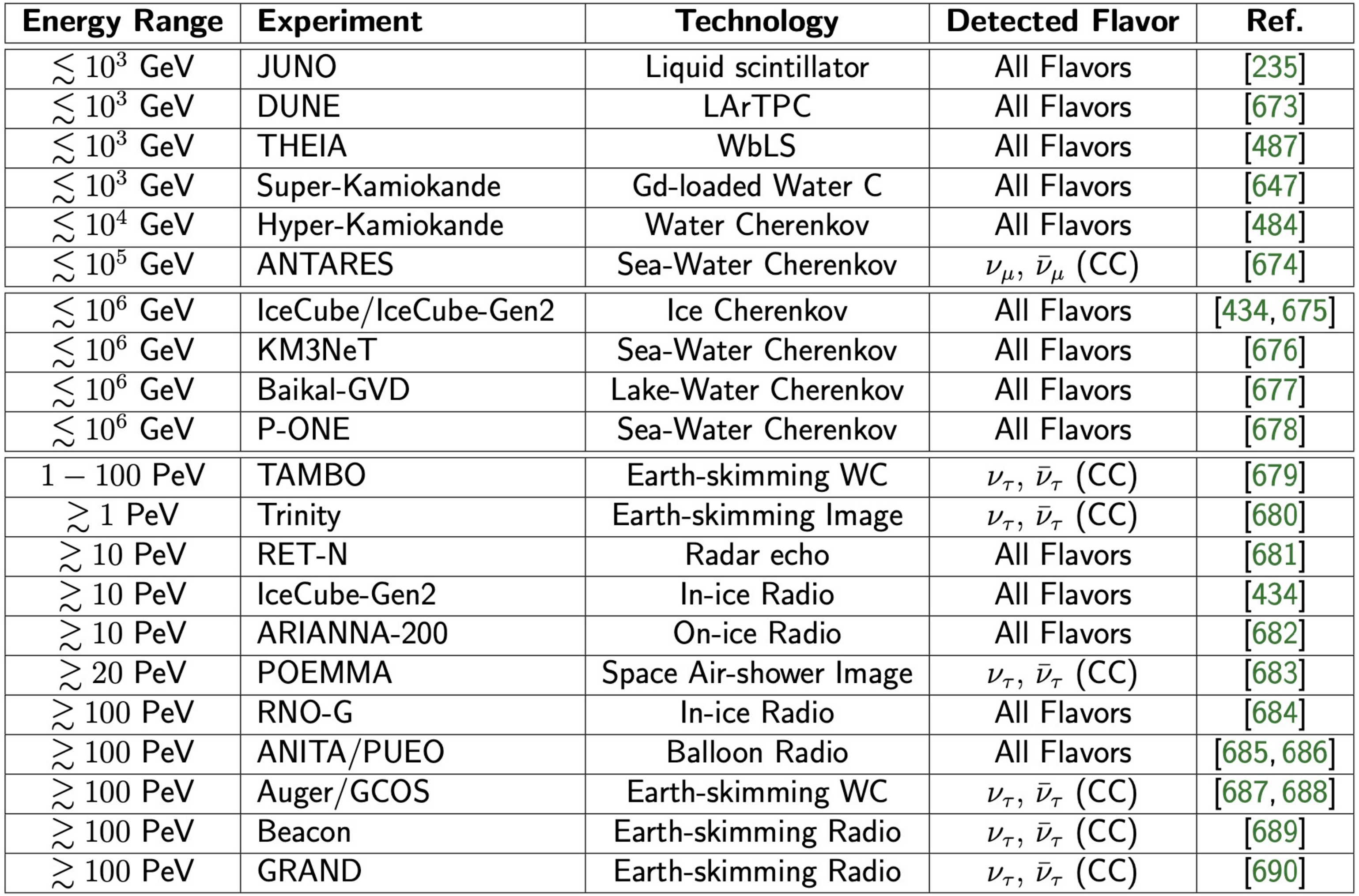


Energy Range	Experiment	Technology	Detected Flavor	Ref.
$\lesssim 10^3$ GeV	JUNO	Liquid scintillator	All Flavors	[235]
$\lesssim 10^3$ GeV	DUNE	LArTPC	All Flavors	[673]
$\lesssim 10^3$ GeV	THEIA	WbLS	All Flavors	[487]
$\lesssim 10^3$ GeV	Super-Kamiokande	Gd-loaded Water C	All Flavors	[647]
$\lesssim 10^4$ GeV	Hyper-Kamiokande	Water Cherenkov	All Flavors	[484]
$\lesssim 10^5$ GeV	ANTARES	Sea-Water Cherenkov	ν_μ, $\bar{\nu}_\mu$ (CC)	[674]
$\lesssim 10^6$ GeV	IceCube/IceCube-Gen2	Ice Cherenkov	All Flavors	[434, 675]
$\lesssim 10^6$ GeV	KM3NeT	Sea-Water Cherenkov	All Flavors	[676]
$\lesssim 10^6$ GeV	Baikal-GVD	Lake-Water Cherenkov	All Flavors	[677]
$\lesssim 10^6$ GeV	P-ONE	Sea-Water Cherenkov	All Flavors	[678]
$1 - 100$ PeV	TAMBO	Earth-skimming WC	ν_τ, $\bar{\nu}_\tau$ (CC)	[679]
$\gtrsim 1$ PeV	Trinity	Earth-skimming Image	ν_τ, $\bar{\nu}_\tau$ (CC)	[680]
$\gtrsim 10$ PeV	RET-N	Radar echo	All Flavors	[681]
$\gtrsim 10$ PeV	IceCube-Gen2	In-ice Radio	All Flavors	[434]
$\gtrsim 10$ PeV	ARIANNA-200	On-ice Radio	All Flavors	[682]
$\gtrsim 20$ PeV	POEMMA	Space Air-shower Image	ν_τ, $\bar{\nu}_\tau$ (CC)	[683]
$\gtrsim 100$ PeV	RNO-G	In-ice Radio	All Flavors	[684]
$\gtrsim 100$ PeV	ANITA/PUEO	Balloon Radio	All Flavors	[685, 686]
$\gtrsim 100$ PeV	Auger/GCOS	Earth-skimming WC	ν_τ, $\bar{\nu}_\tau$ (CC)	[687, 688]
$\gtrsim 100$ PeV	Beacon	Earth-skimming Radio	ν_τ, $\bar{\nu}_\tau$ (CC)	[689]
$\gtrsim 100$ PeV	GRAND	Earth-skimming Radio	ν_τ, $\bar{\nu}_\tau$ (CC)	[690]

New Physics beyond the Standard Model

- New physics related to neutrinos
- Other new physics produced similar signals in neutrino detectors

Information already known about neutrinos

- Masses and mixing angles

$$\theta_{12} = 33.44\ (31.27 - -35.86) \qquad \text{for both mass orderings,}$$

$$\theta_{23} = 49.2\ (39.5 - -52.0)\ (\mathrm{NO}) \qquad \theta_{23} = 49.5\ (39.8 - -52.1)\ (\mathrm{IO}),$$

$$\theta_{13} = 8.57\ (8.20 - 8.97)\ (\mathrm{NO}) \qquad \theta_{13} = 8.60\ (8.24 - 8.98)\ (\mathrm{IO}),$$

$$\sum_{j=1}^{3} m_j \gtrsim 60\ \mathrm{meV}, \quad (\mathrm{NO}),$$

$$\gtrsim 100\ \mathrm{meV}, \quad (\mathrm{IO}).$$

$$m_\beta \equiv \sqrt{\sum_{j=1,2,3} \left|U_{ej}\right|^2 m_j^2} < 0.8\ \mathrm{eV}$$ KATRIN

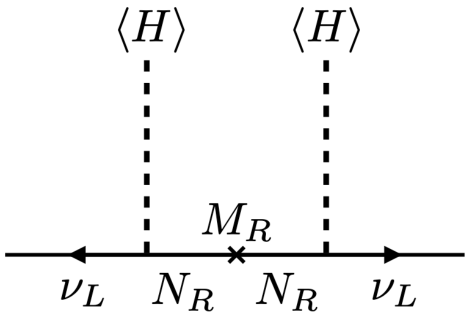
$$\sum_{j=1,2,3} m_j < 0.12\ \mathrm{eV}$$ Cosmology

Neutrino physics beyond SM

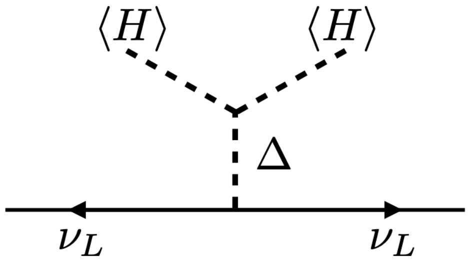
- Heavy neutral lepton searches
- BSM effects on neutrino flavors
- BSM effects on neutrino scattering
- Neutrino interaction with dark matter
- Neutrino self-interaction

Heavy neutral lepton searches

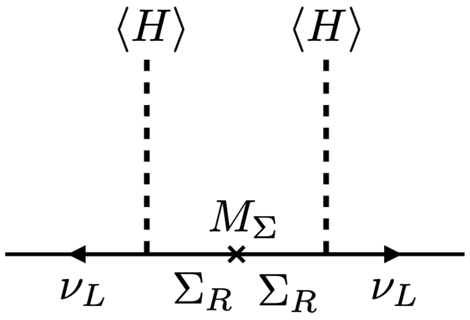
- Origins of neutrino masses



See-saw type I



See-saw type II



See-saw type III

Heavy neutral lepton searches

- Type-I seesaw
  - Mixing angle too small $\theta^2 \sim \frac{m_\nu}{M}$
- Symmetry protected scenarios are invented.

$$\begin{pmatrix} 0 & vY & v\epsilon Y' \\ vY^T & \mu_1 M & M \\ \epsilon v Y'^T & M & \mu_2 M \end{pmatrix}$$

$$m_\nu = v^2 \epsilon \left(Y' M^{-1} Y^T + Y M^{-1} Y'^T \right) - v^2 Y \mu_2 M^{-1} Y^T$$

$$\theta \sim Y v M^{-1}$$

Inverse seesaw when $\epsilon = \mu_1 = 0$

Heavy neutral leptons

- Neutrino minimal standard model   Asaka, Blanchet, Shaposhnikov, hep-ph/0503065

$$\delta\mathcal{L} = \overline{N}_I i\partial_\mu \gamma^\mu N_I - f^\nu_{I\alpha}\,\Phi \overline{N}_I L_\alpha - \frac{M_I}{2}\,\overline{N^c_I} N_I + h.c.$$

N_1 is the dark matter candidate.
N_2 and N_3 are nearly degenerate and in charge of leptogenesis.
N_1 dark matter can be produced through active neutrino mixing (freeze-in).

Beyond the heavy neutral lepton model

- Left-right symmetric models
  - Combination of type-I and type-II seesaw

$$M_\nu = -M_D^T M_N^{-1} M_D + \frac{v_L}{v_R} M_N$$

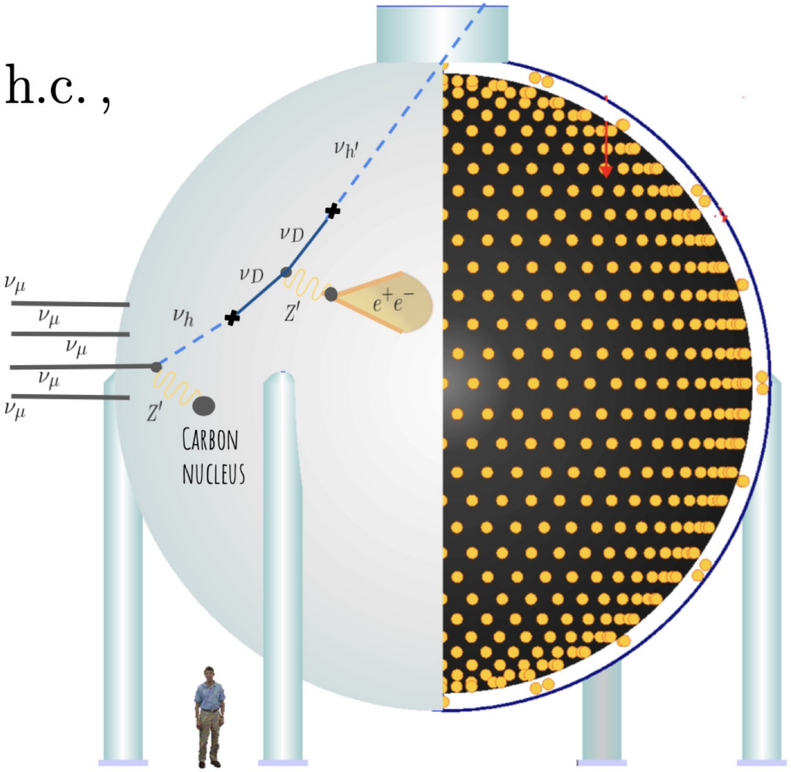
- GUT models
  - Energy scale is too high, and mixing angles between sterile neutrinos and active neutrinos are too small.

Beyond the heavy neutral lepton model

- Dark sector heavy neutral lepton model

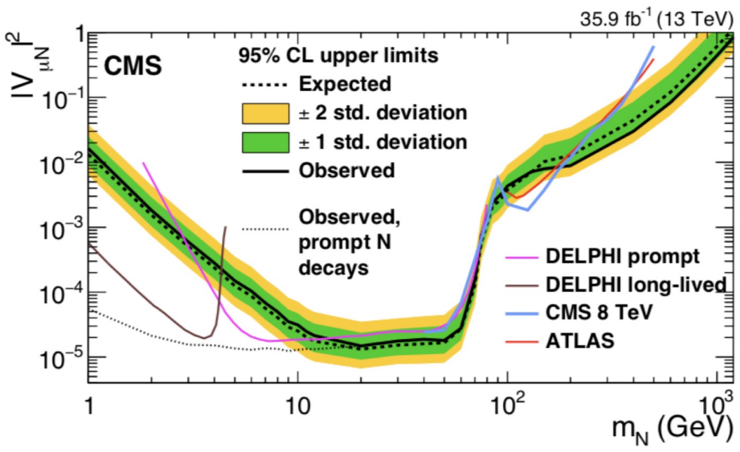
$$\mathcal{O}_{\ell N q_u q_d} = U_{\ell 4} V_{q_u q_d} \, G_F \; [\bar{q}_u \gamma^\mu (1-\gamma_5) q_d] \; \left[\bar{\ell}\gamma_\mu (1-\gamma_5) N\right] + \text{h.c.} \, ,$$

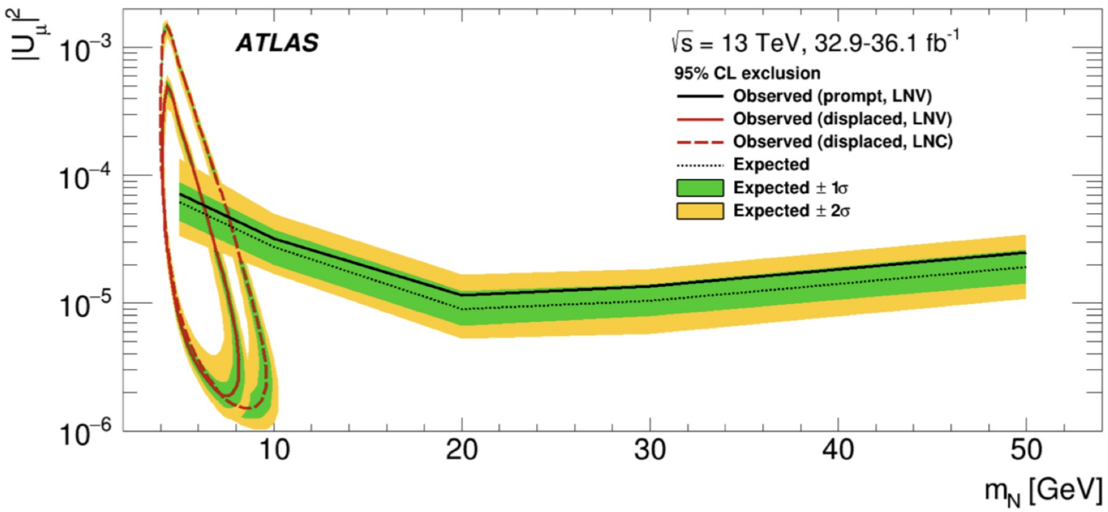
$$\mathcal{O}_{N\nu\gamma} = \frac{1}{\Lambda} \bar{N} \sigma^{\alpha\beta} \nu F_{\alpha\beta}$$

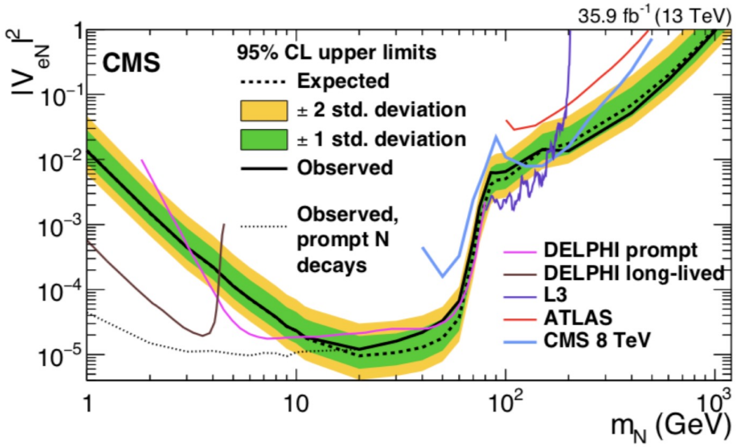


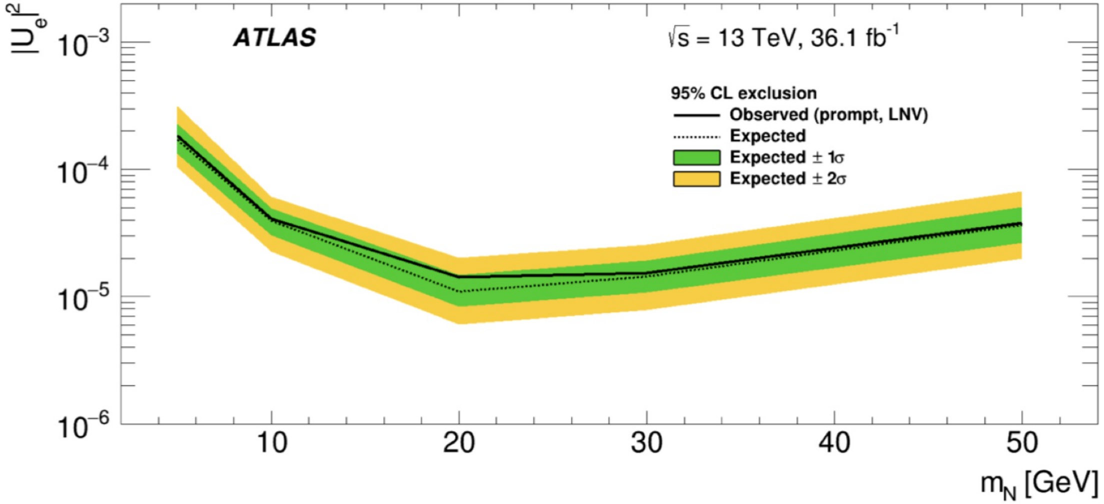
HNL production and decay inside the MiniBooNE detector.

Experimental searches for neutral leptons



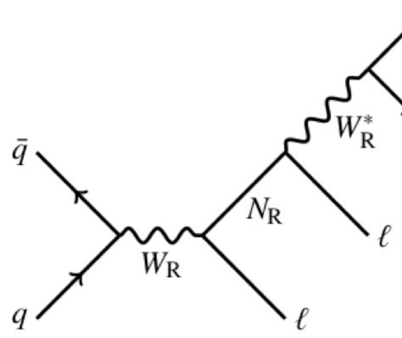




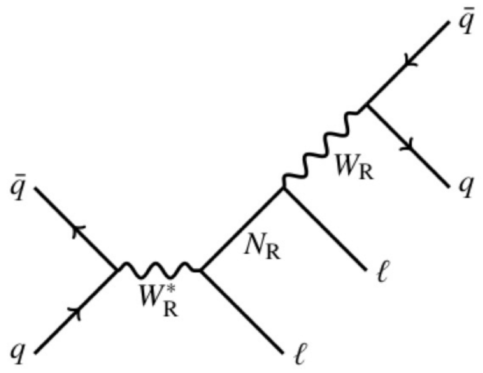


Experimental searches for neutral leptons

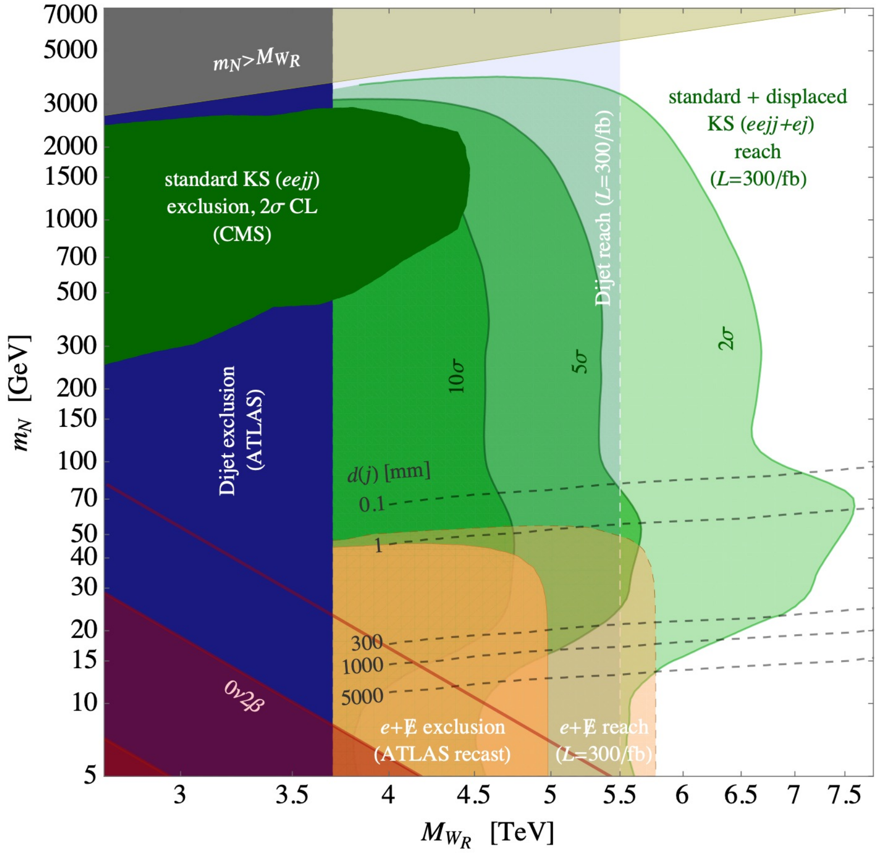
- Things will be different for more complete models



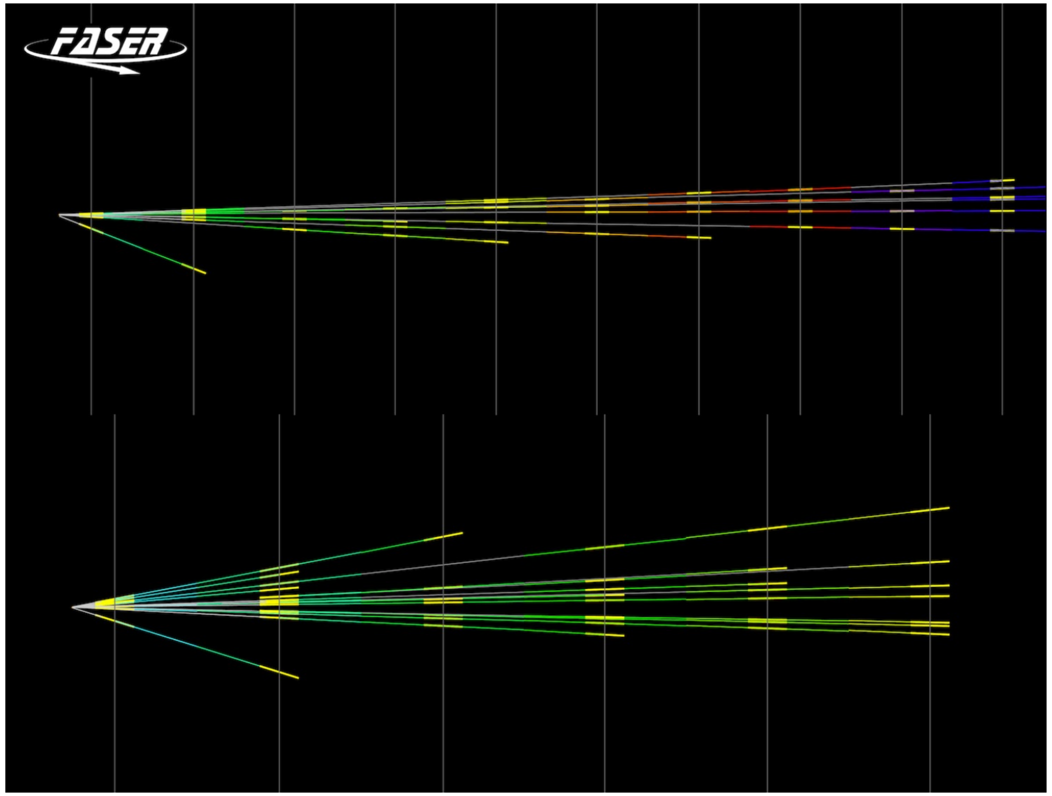
(a)



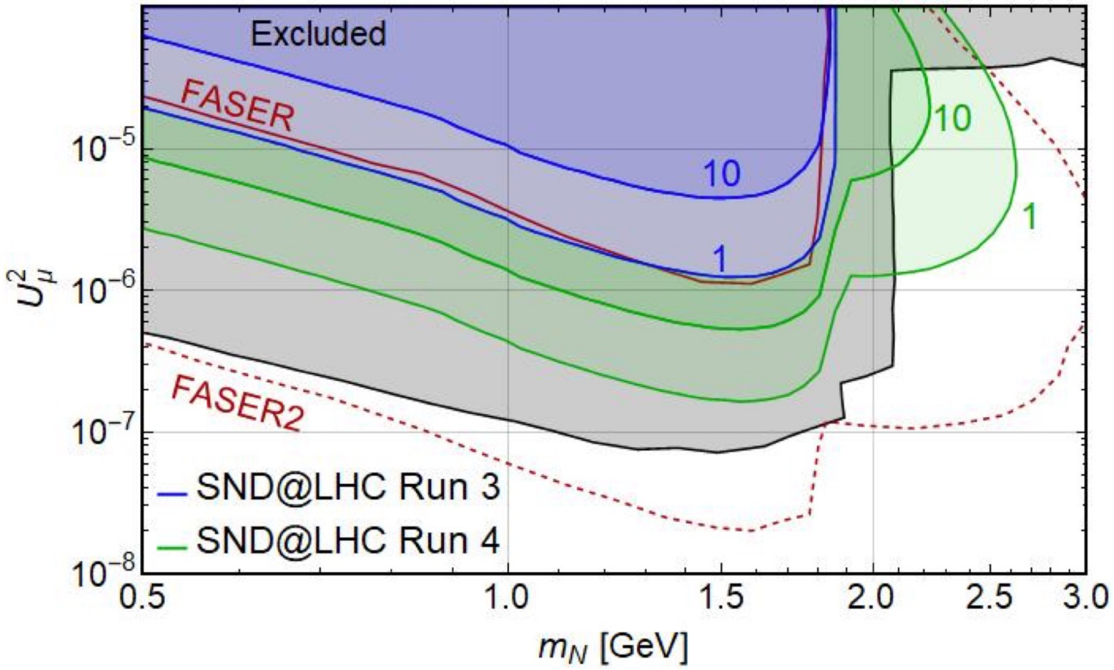
(b)



Faser neutrino detector



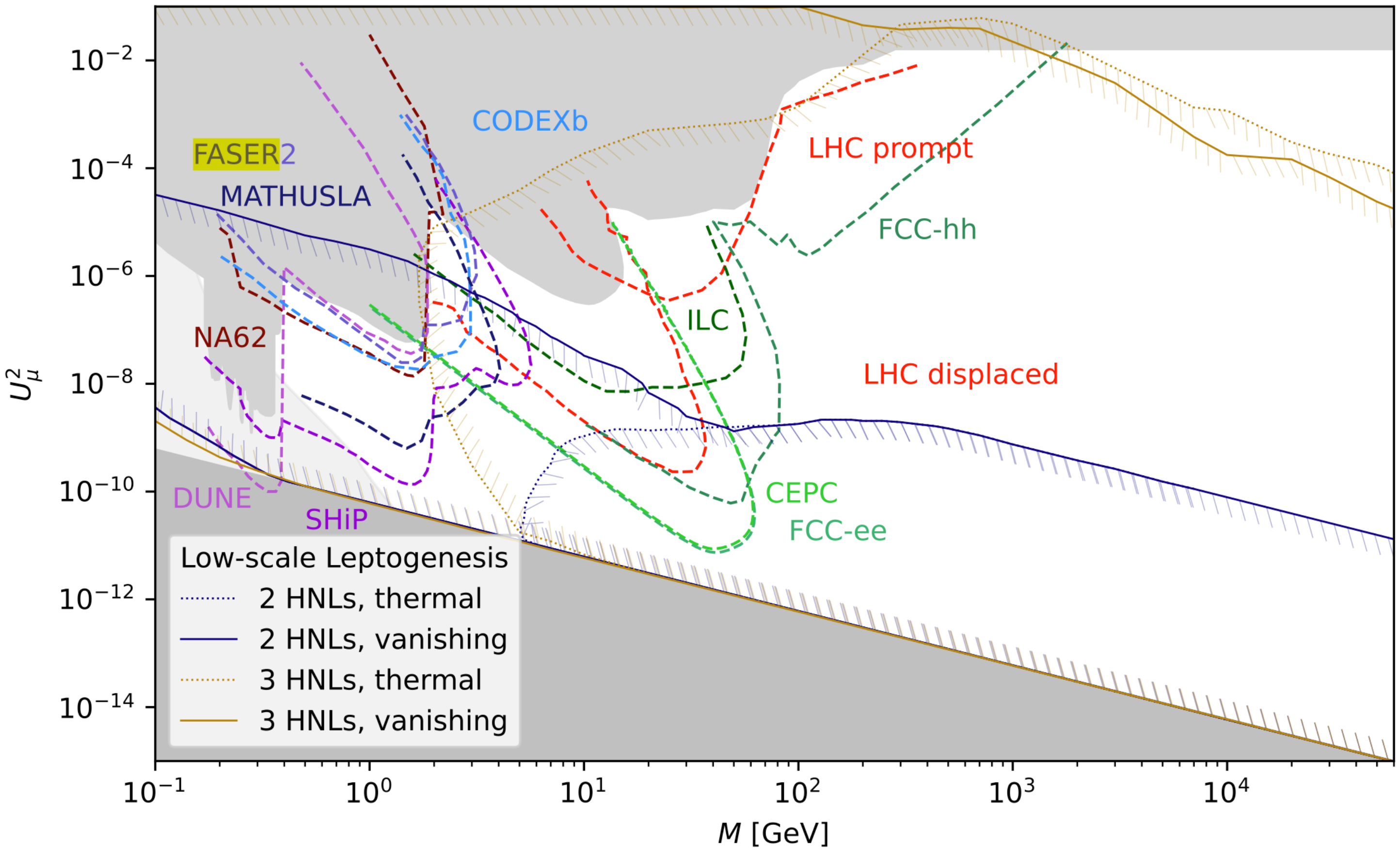
PRL 131 (2023) 3



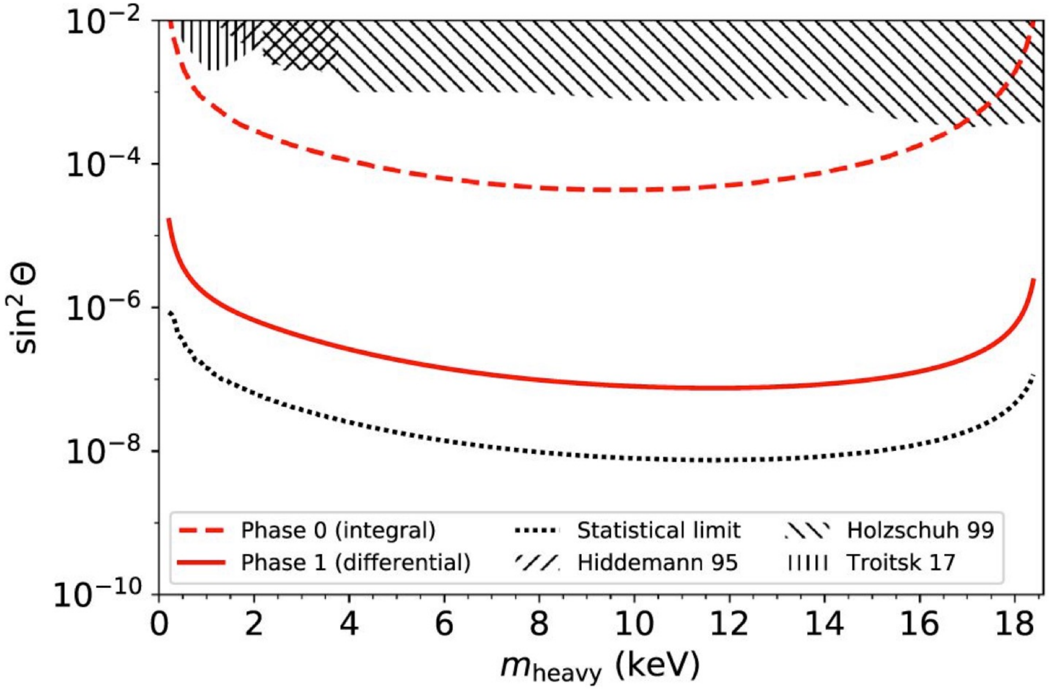
2104.09688

Future colliders

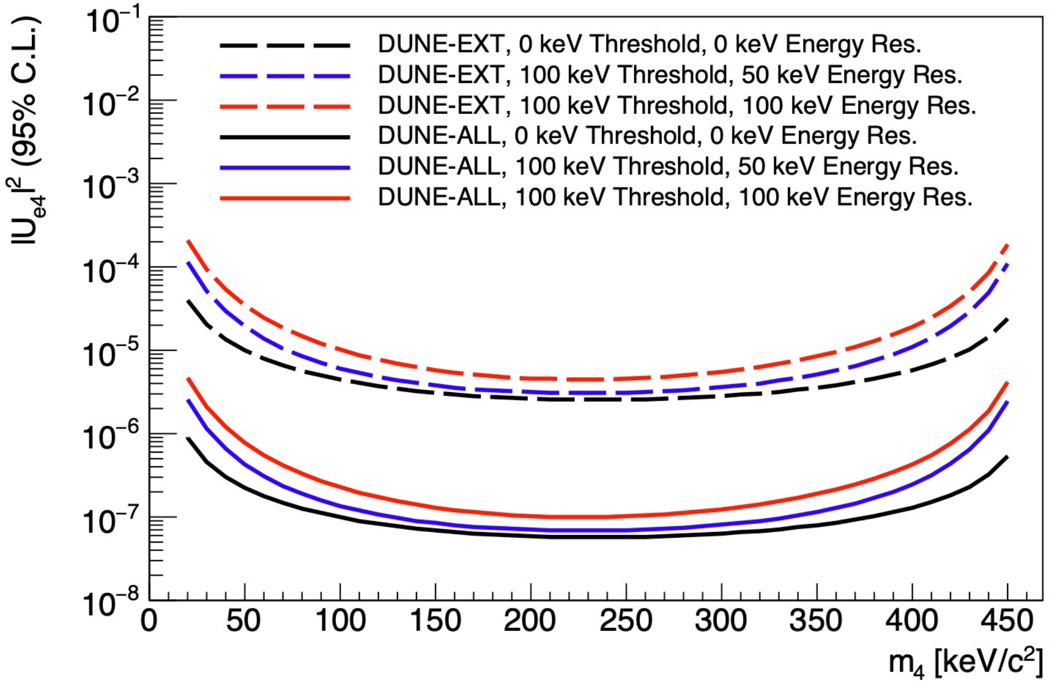
- $Z \rightarrow N\nu$ ($N \rightarrow$ off shell W and Z)



Nuclear decay searches



KATRIN/TRISTAN



DUNE

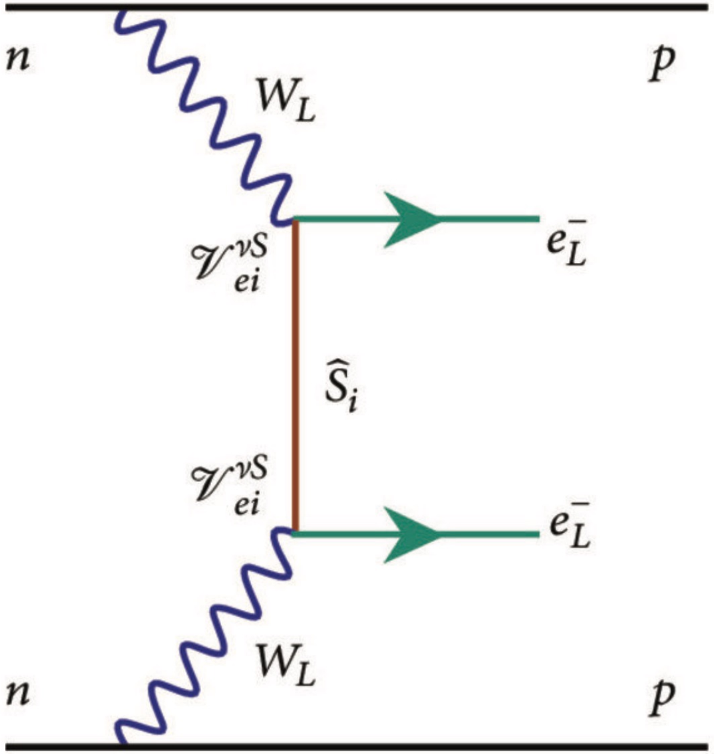
Neutrinoless double beta decay

$$\frac{10^{28}\ \mathrm{yr}}{T^{0\nu}_{1/2}} \approx \left(\frac{|U_{eN}|^2}{10^{-9}} \cdot \frac{1\ \mathrm{GeV}}{m_N}\right)^2$$

For $m_N > 100$ MeV

$$\frac{10^{28}\ \mathrm{yr}}{T^{0\nu}_{1/2}} \approx \left(\frac{|U_{eN}|^2}{10^{-9}} \cdot \frac{m_N}{15\ \mathrm{MeV}}\right)^2$$

For $m_N < 100$ MeV



But it is usually easy to avoid the constraint by tuning U_{eN} to zero.

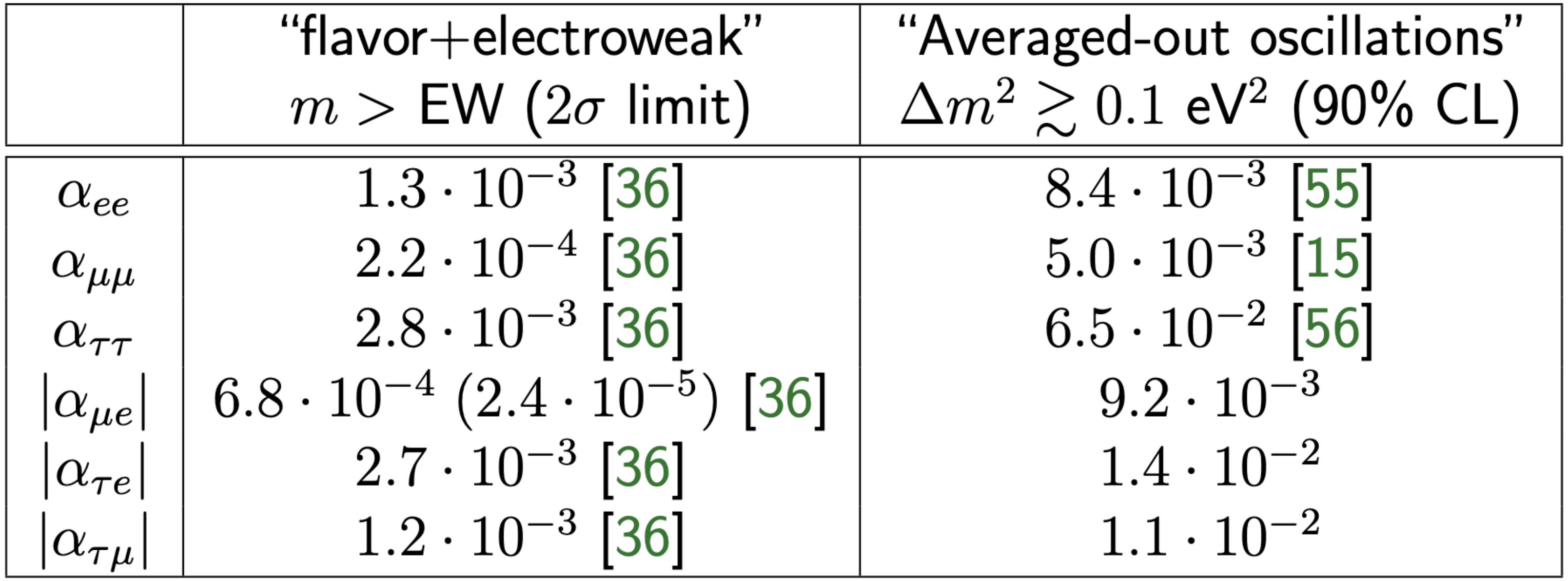
Heavy neutral lepton searches

- Neutrino non-unitary oscillation

$$H = \frac{1}{2E}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} + N^\dagger \begin{pmatrix} V_{\mathrm{CC}} + V_{\mathrm{NC}} & 0 & 0 \\ 0 & V_{\mathrm{NC}} & 0 \\ 0 & 0 & V_{\mathrm{NC}} \end{pmatrix} N$$

- Heavy sterile neutrinos
- Light sterile neutrinos
- Large extra dimension models

$$N = \begin{pmatrix} 1-\alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & 1-\alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & 1-\alpha_{\tau\tau} \end{pmatrix}$$



	"flavor+electroweak" $m >$ EW (2σ limit)	"Averaged-out oscillations" $\Delta m^2 \gtrsim 0.1$ eV^2 (90% CL)
α_{ee}	$1.3 \cdot 10^{-3}$ [36]	$8.4 \cdot 10^{-3}$ [55]
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$ [36]	$5.0 \cdot 10^{-3}$ [15]
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$ [36]	$6.5 \cdot 10^{-2}$ [56]
$\lvert\alpha_{\mu e}\rvert$	$6.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$ [36]	$9.2 \cdot 10^{-3}$
$\lvert\alpha_{\tau e}\rvert$	$2.7 \cdot 10^{-3}$ [36]	$1.4 \cdot 10^{-2}$
$\lvert\alpha_{\tau\mu}\rvert$	$1.2 \cdot 10^{-3}$ [36]	$1.1 \cdot 10^{-2}$

Neutrino self interations

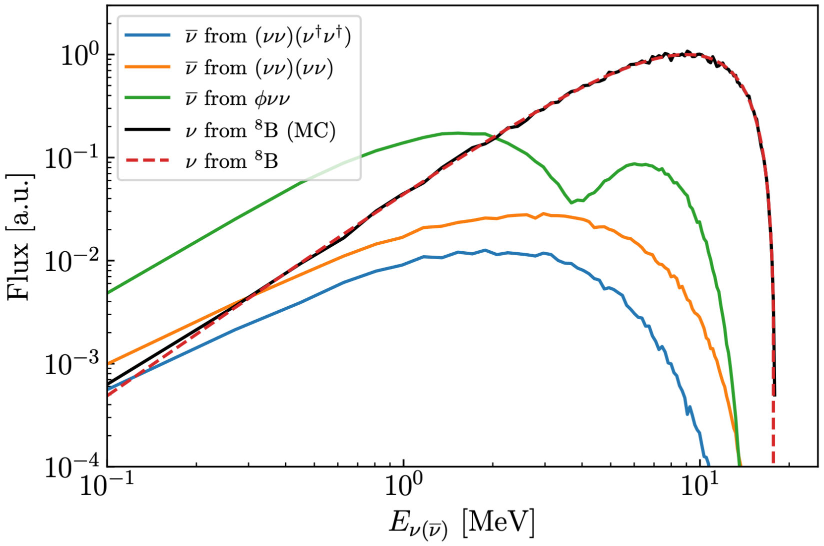
$$\mathcal{L}_S = \frac{1}{\Lambda_S^2}(\nu\nu)(\nu\nu) + \text{h.c.}\,,$$

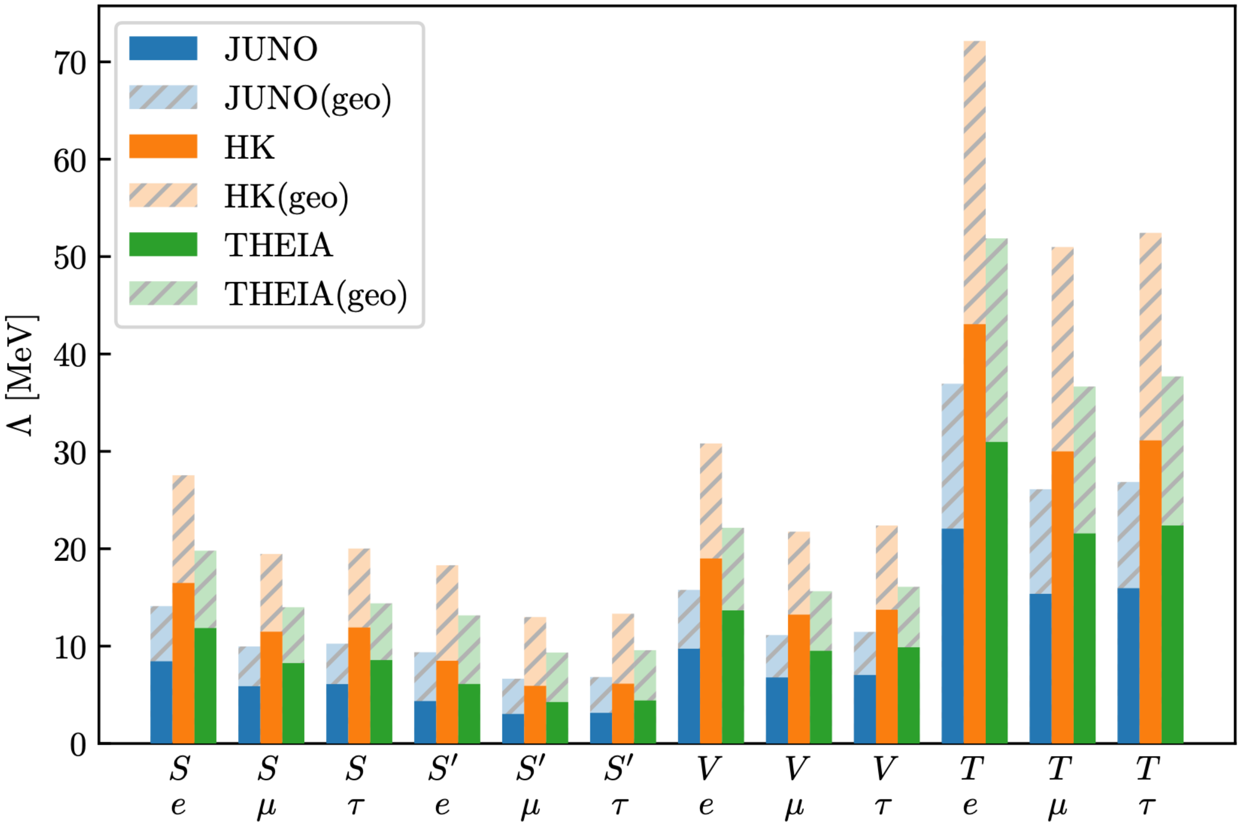
$$\mathcal{L}_{S'} = \frac{1}{\Lambda_{S'}^2}(\nu\nu)(\nu^\dagger\nu^\dagger)\,,$$

$$\mathcal{L}_V = \frac{1}{\Lambda_V^2}(\nu^\dagger\overline{\sigma}^\mu\nu)(\nu^\dagger\overline{\sigma}_\mu\nu)\,,$$

$$\mathcal{L}_{V'} = \frac{1}{\Lambda_{V'}^2}(\nu^\dagger\overline{\sigma}^\mu\nu)(\nu\sigma_\mu\nu^\dagger)\,,$$

$$\mathcal{L}_T = \frac{1}{\Lambda_T^2}(\nu\sigma^{\mu\nu}\nu)(\nu\sigma_{\mu\nu}\nu) + \text{h.c.}$$



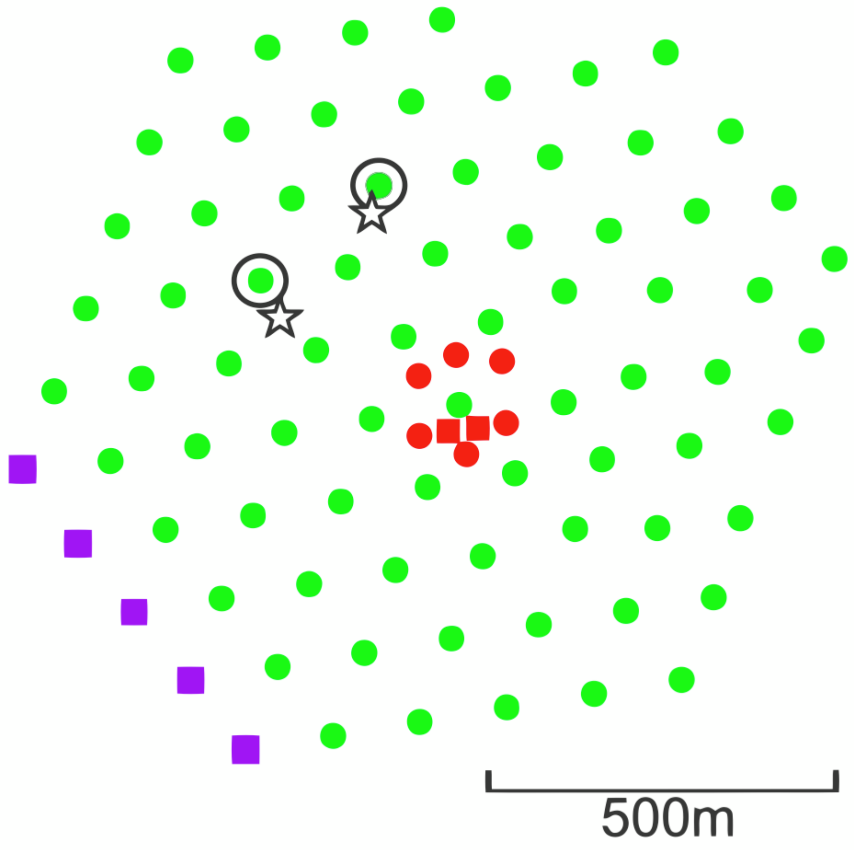


Wu and Xu 2308.15849

Neutrino interaction with dark matter

Snowmass document 2203.10811

- Decay of PeV dark matter into neutrinos: source for IceCube PeV neutrinos events.
- But it can be explained by other SM mechanisms:
    - Produced by AGN
    - Tidal disruption
    - Galactic PeVatron

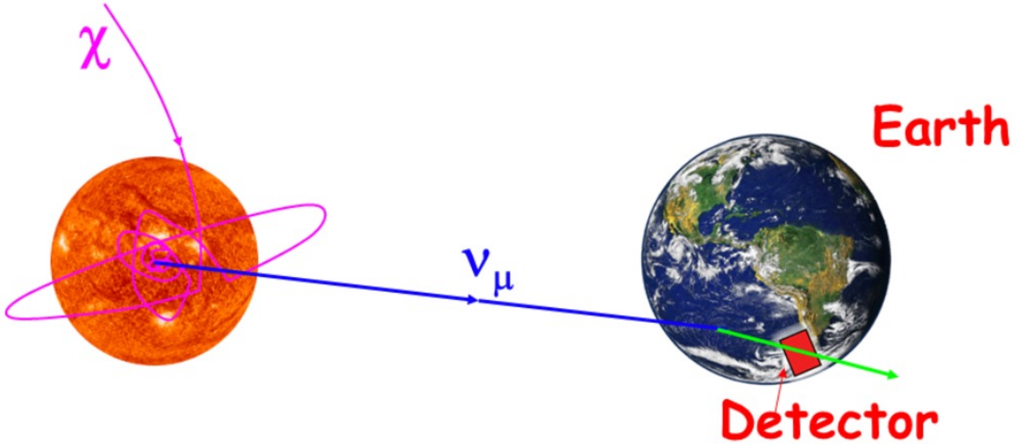


Neutrino interaction with dark matter

Snowmass document 2203.10811

- GeV-TeV WIMP dark matter annihilate into neutrinos at the galactic center, and at the center of stars.
- DM particles collide with nucleus inside the Sun and lose energy, and then be captured by the Sun.
- The accumulated DM particles find their anti-particles to annihilate.
- The neutrinos in the final state will escape and fly to the earth.

$$\Gamma_{\rm ann} = \Gamma_{\rm cap}$$



$$\text{signal} \propto \Gamma_{\rm ann}$$

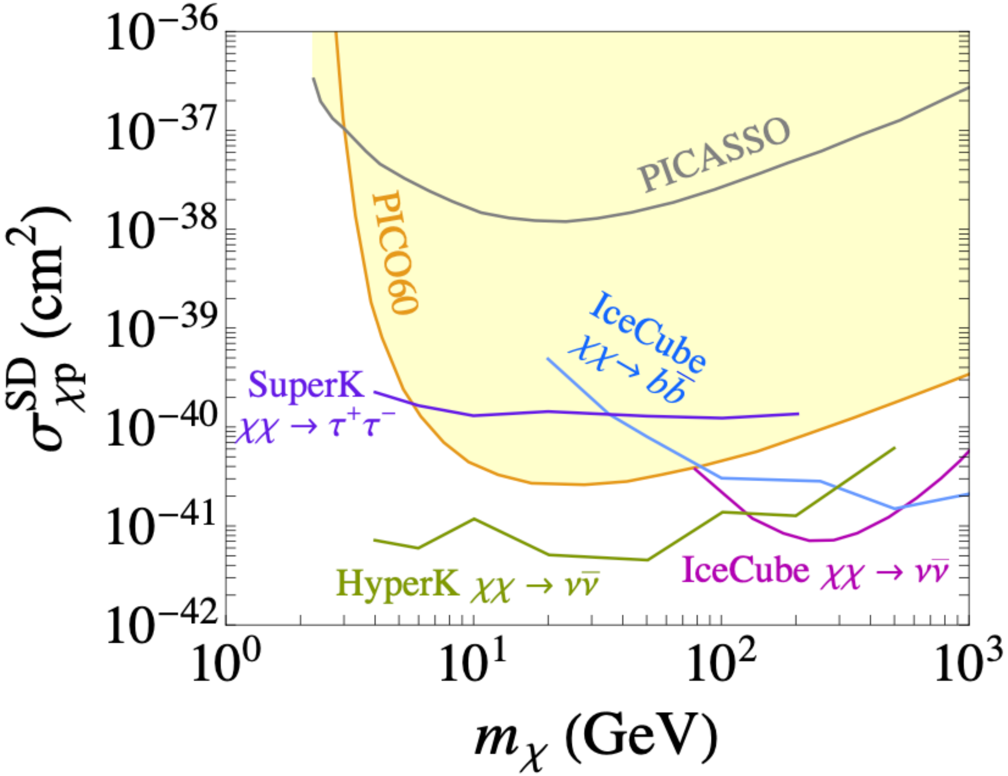
$$\Gamma_{\rm cap} \propto \sigma_{\chi N}$$

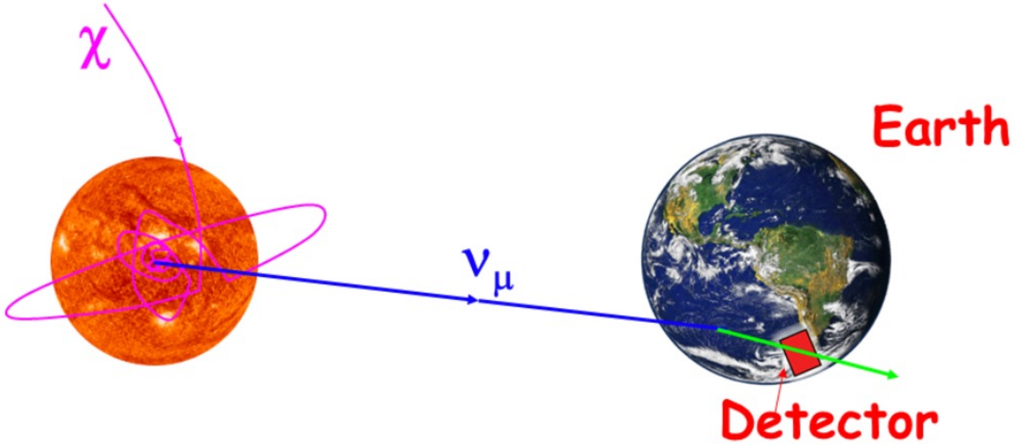
It is $\sigma_{\chi N}$ that gets constrained.

Neutrino interaction with dark matter

Snowmass document 2203.10811

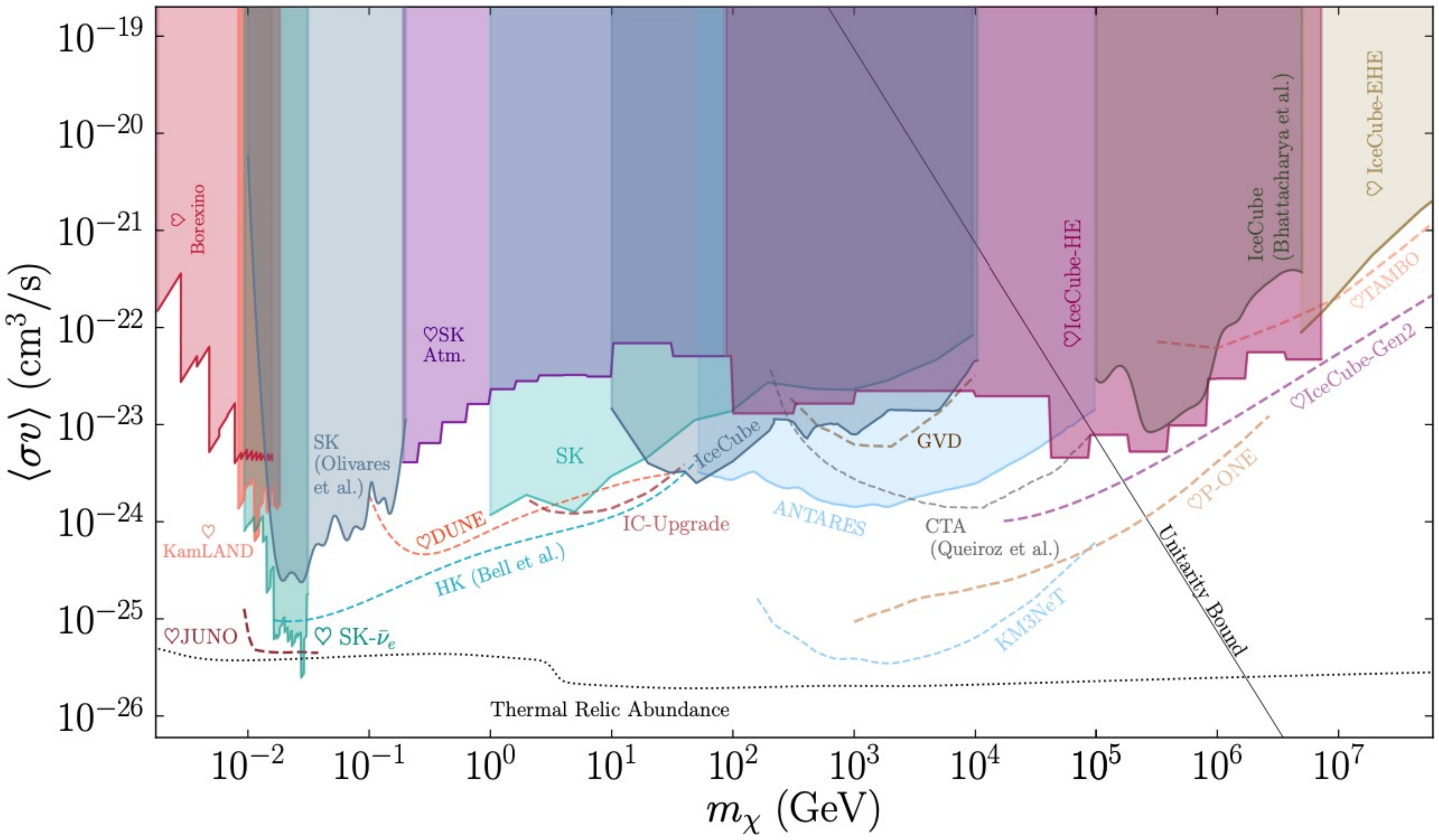
- GeV-TeV WIMP dark matter annihilate into neutrinos at the galactic center, and at the center of stars.





It is competitive for the case of spin-dependent interaction.

DM annihilate into neutrinos at the galactic center



Arguelles et al. Rev.Mod.Phys. 93(3) 035007, 2021

Boosted DM at neutrino detectors

Berger, Cui, Graham, Necib, Petrillo, Stocks, Tsai, Zhao, 1912.05558

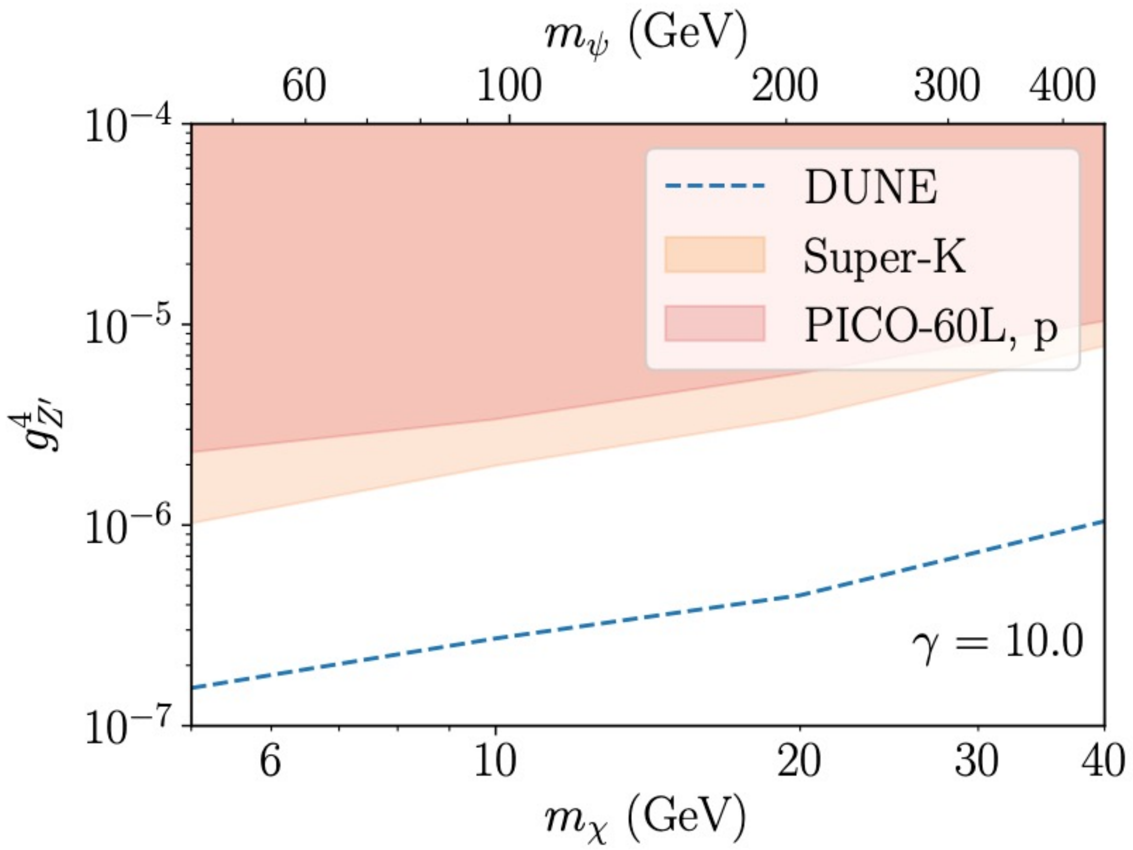
Inside the Sun

$$\psi + \overline{\psi} \to \chi + \overline{\chi}.$$

Inside the detector such as DUNE

$$\chi + N \to \chi + X,$$

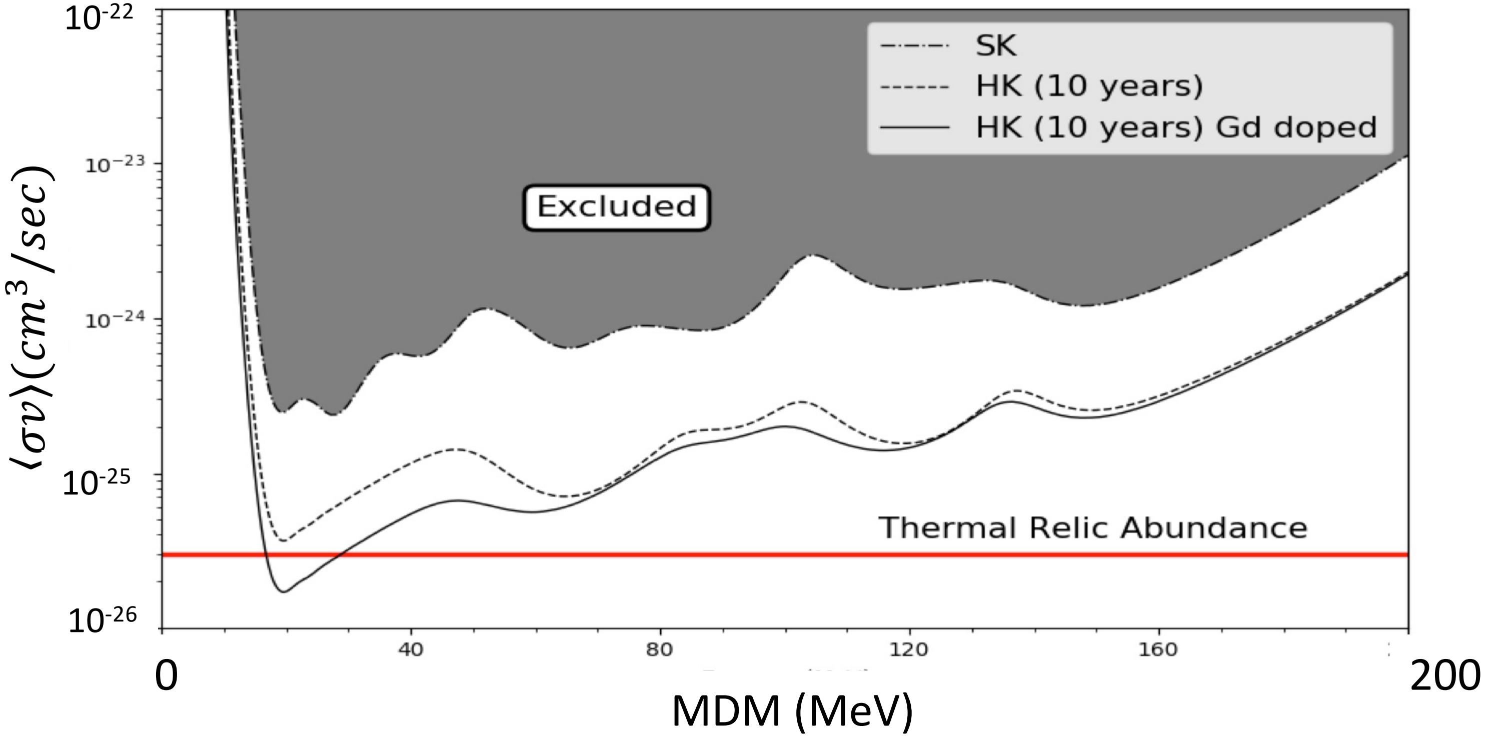
Interaction between *X* and SM particles is mediated by *Z′*.



MeV mass dark matter: annihilation of MeV DM into neutrinos

Snowmass document 2203.10811

- This will lead to monochromatic neutrino flux and can be detected by future experiments



Andŕ es Olivares-Del Campo, Sergio Palomares-Ruiz, Silvia Pascoli, 1805.09830

Neutrino interaction with dark matter

Snowmass document 2203.10811

- Ultralight dark matter: time varying mass of active neutrinos.

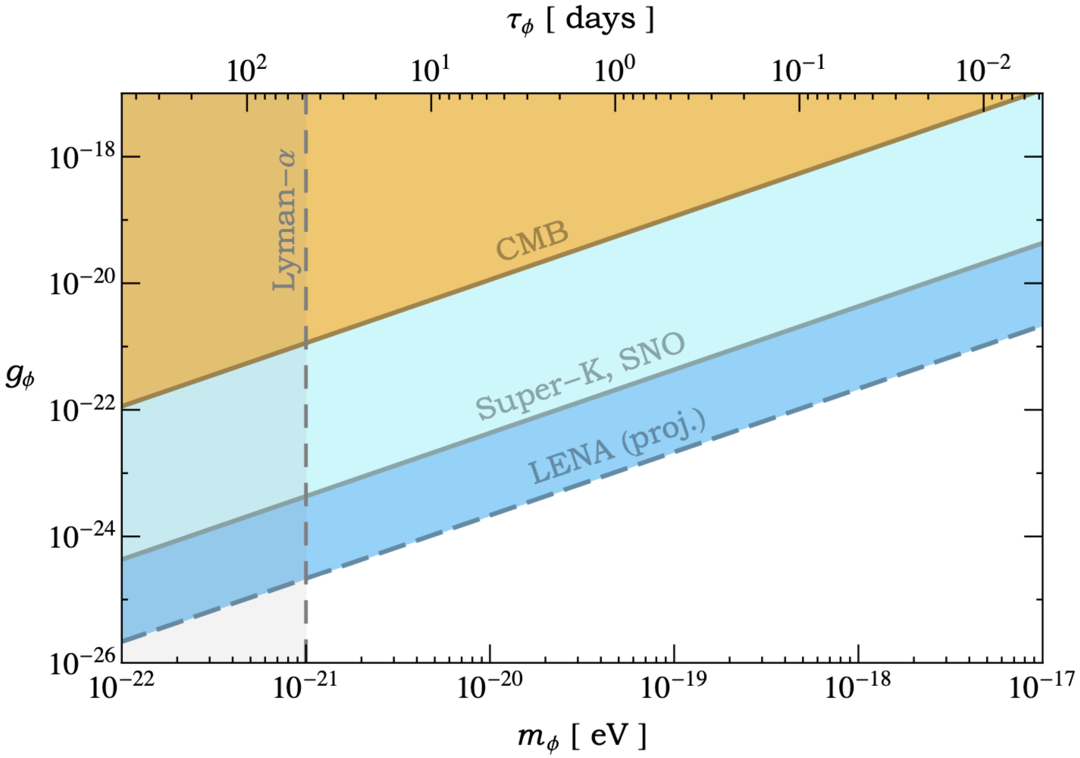
Asher Berlin, 1608.01307

$$-\mathcal{L} \supset \frac{1}{2} m_\phi^2 \phi^2 + \frac{1}{2} m_i \bar{\nu}_i \nu_i + g_\phi \phi \bar{\nu}_1 \nu_2 + \cdots$$

$$\Phi_{\text{eff}} \equiv \Phi \times \left(P_{\nu_e}^{\odot} + \left(1 - P_{\nu_e}^{\odot}\right) \frac{\sigma_{\mu,\tau}}{\sigma_e} \right)$$

$$\Phi_{\text{eff}} = \Phi^{(0)} + \Phi^{(1)} \cos m_\phi t$$

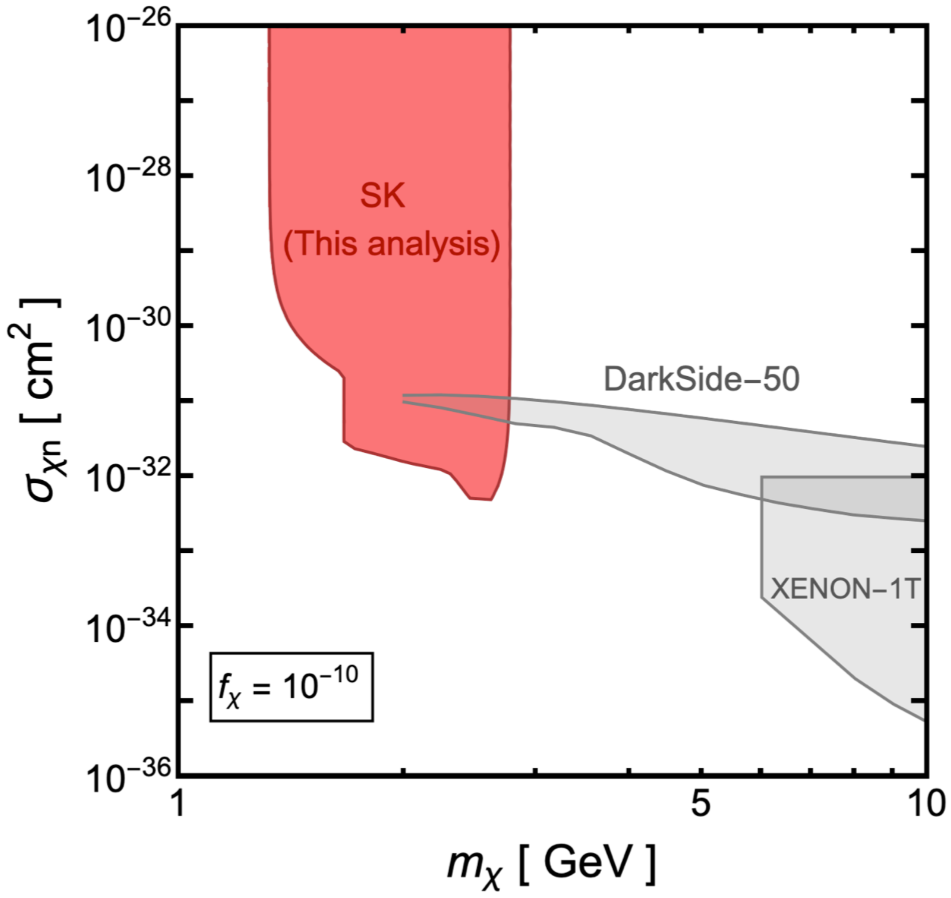
$$\frac{\Phi^{(1)}}{\Phi^{(0)}} \simeq 2 \cot \theta_{12} \frac{g_\phi \sqrt{2 \rho_{\text{DM}}}}{m_\phi \Delta m_{12}}$$



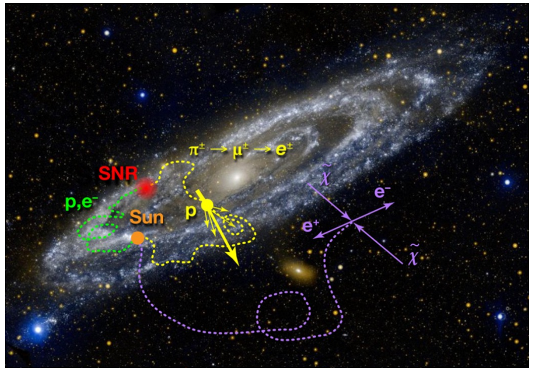
Dark matters annihilate inside neutrino detectors

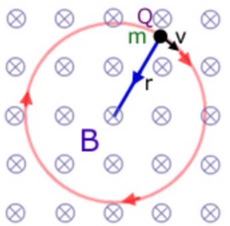
Mckeen, Morrissey, Pospelov, Ramani, ray, 2303.03416 & PRL

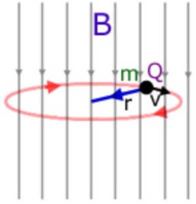
- A small fraction of GeV-ish DM with very large DM-nucleus cross section accumulate inside the Earth.
- DM can find anti-particle to annihilate inside the detector and release GeV scale energy.

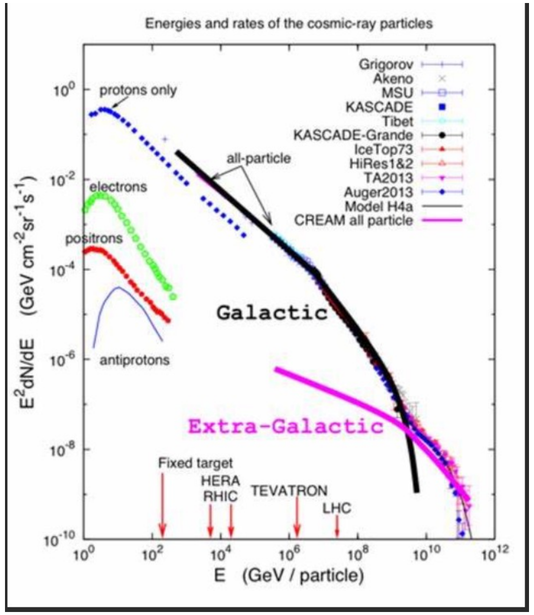


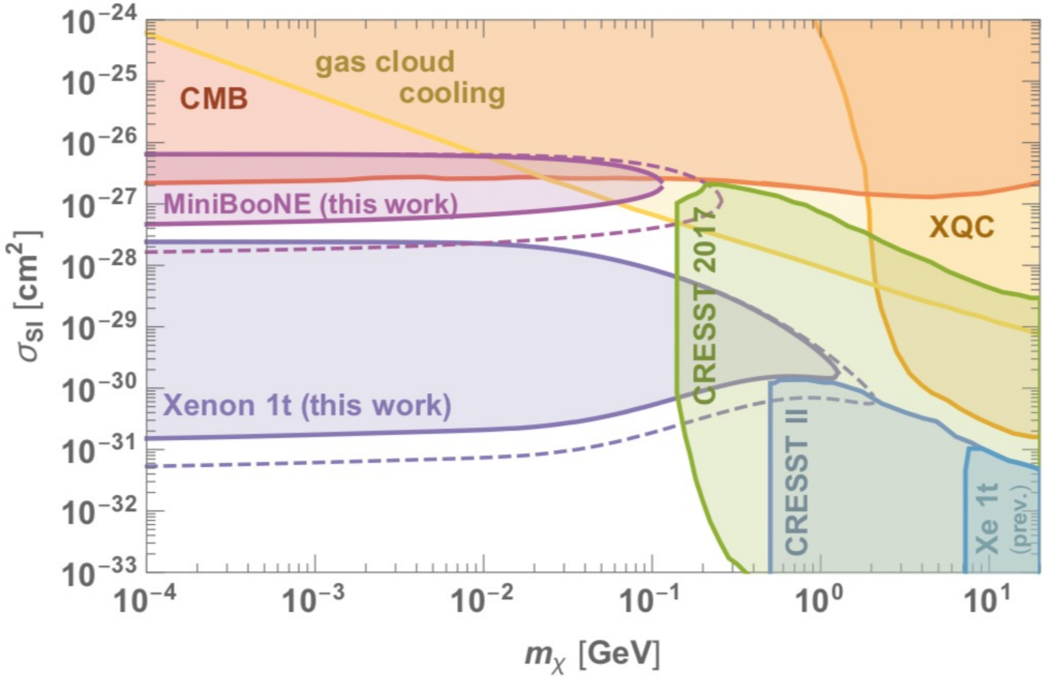
Searching for cosmic ray accelerated DM with neutrino detectors











Bringman and Pospelov, PRL 122 (2019) 171801

Using neutrino detectors to search for charged excited state of dark matter

- DM must be neutron.
- There can be a charged state close to it in the spectrum.
- $(X^0, X^\pm)$

Case A: the spins of X^0 and $X^\pm$ are different

$$\mathrm{spin}(X^0) = \frac{1}{2}\ , \quad \mathrm{spin}(X^-) = 0$$

$$yX^0 e^+ X^- + \mathrm{h.c.}$$

Case B: the spins are the same

$$\mathrm{spin}(X^0) = 0\ , \quad \mathrm{spin}(X^-) = 0\ .$$

$$g_{\mathrm{eff}}(X^0 \partial_\mu X^+ - \partial_\mu X^0 X^+) W^{-\mu}$$

Using neutrino detectors to search for charged excited state of dark matter

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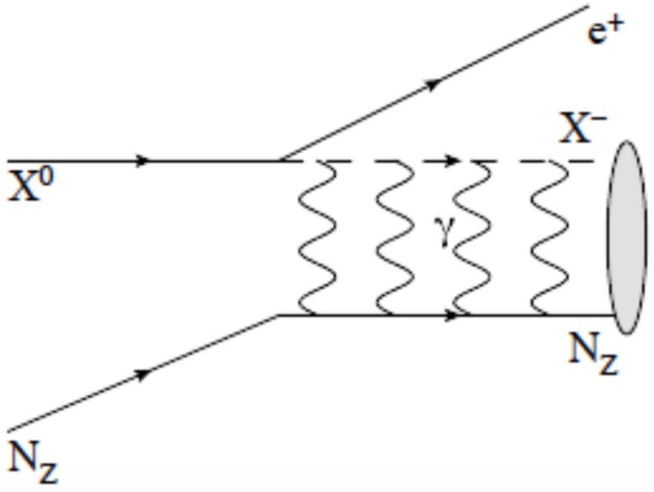

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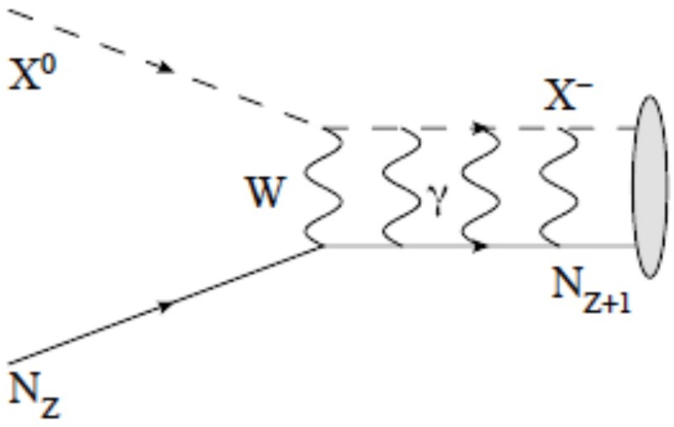


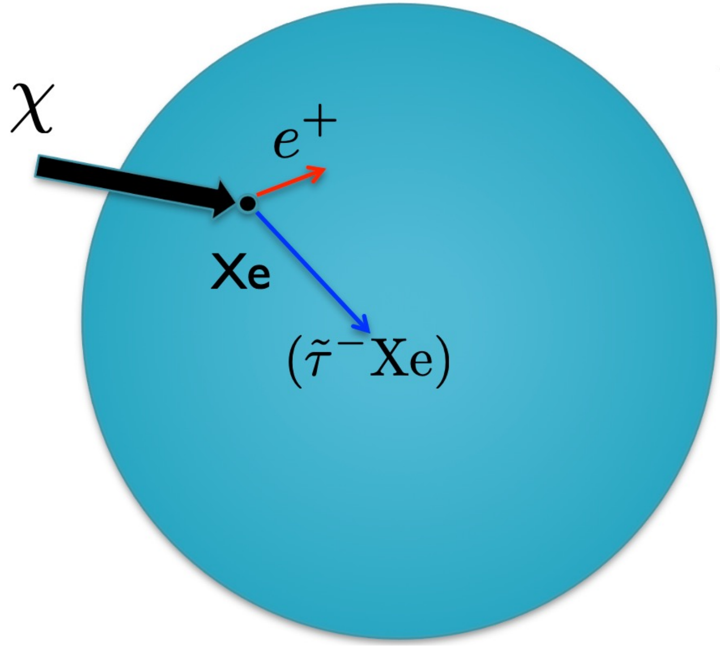
Using neutrino detectors to search for charged excited state of dark matter

- Bound state formation will release binding energy.
- Take Xenon as the target

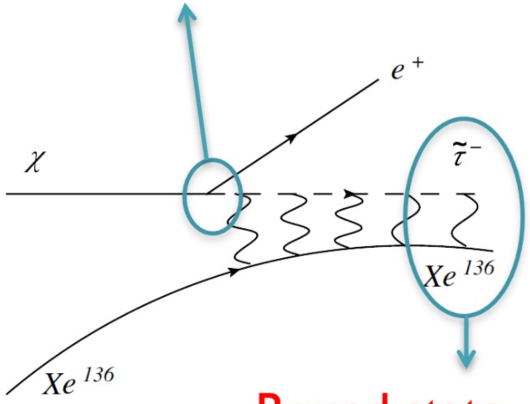
$$X^0 \to \chi$$

$$X^\pm \to \tilde{\tau}$$

A. different spin:



$$\mathcal{L}_{\text{eff}} = y\ \bar{e}\chi\tilde{\tau} + \text{h.c.}$$



Bound state due to QED

$$V(r) = \begin{cases} \frac{1}{2}\frac{Z\alpha}{r_0}\frac{r^2}{r_0^2} - \frac{3}{2}\frac{Z\alpha}{r_0}\ , & r < r_0 \\ -\frac{Z\alpha}{r}\ , & r > r_0 \end{cases}$$

$$E_B^{(0)} \approx \left| \frac{3}{2}\sqrt{\frac{Z\alpha}{r_0^3\mu}} - \frac{3}{2}\frac{Z\alpha}{r_0} \right| \approx 20\ \text{MeV}\ .$$

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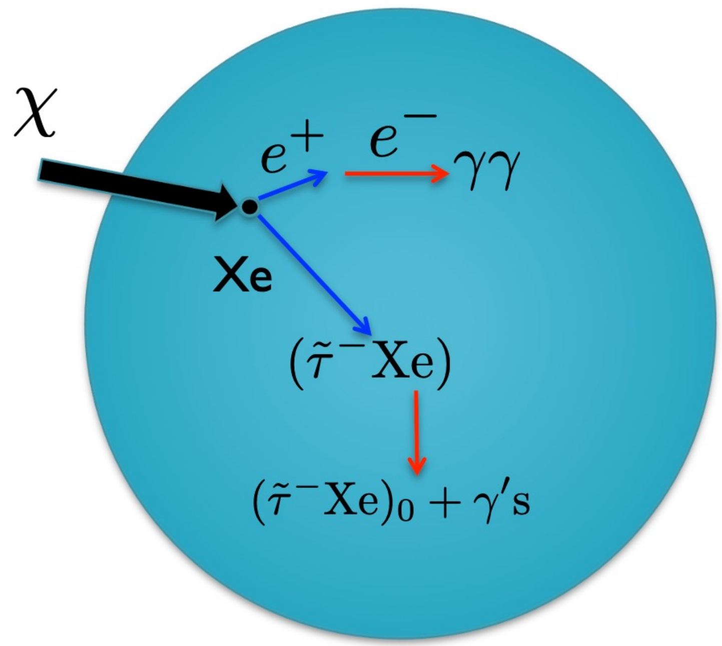

- e$^+$ deposits energy during propagation and then finds an e$^-$ to annihilate into to gammas.
- Excited state decays to ground state by emitting gammas.

$$V(r) = \begin{cases} \frac{1}{2}\frac{Z\alpha}{r_0}\frac{r^2}{r_0^2} - \frac{3}{2}\frac{Z\alpha}{r_0}\,, & r < r_0 \\ -\frac{Z\alpha}{r}\,, & r > r_0 \end{cases}$$

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Using neutrino detectors to search for charged excited state of dark matter

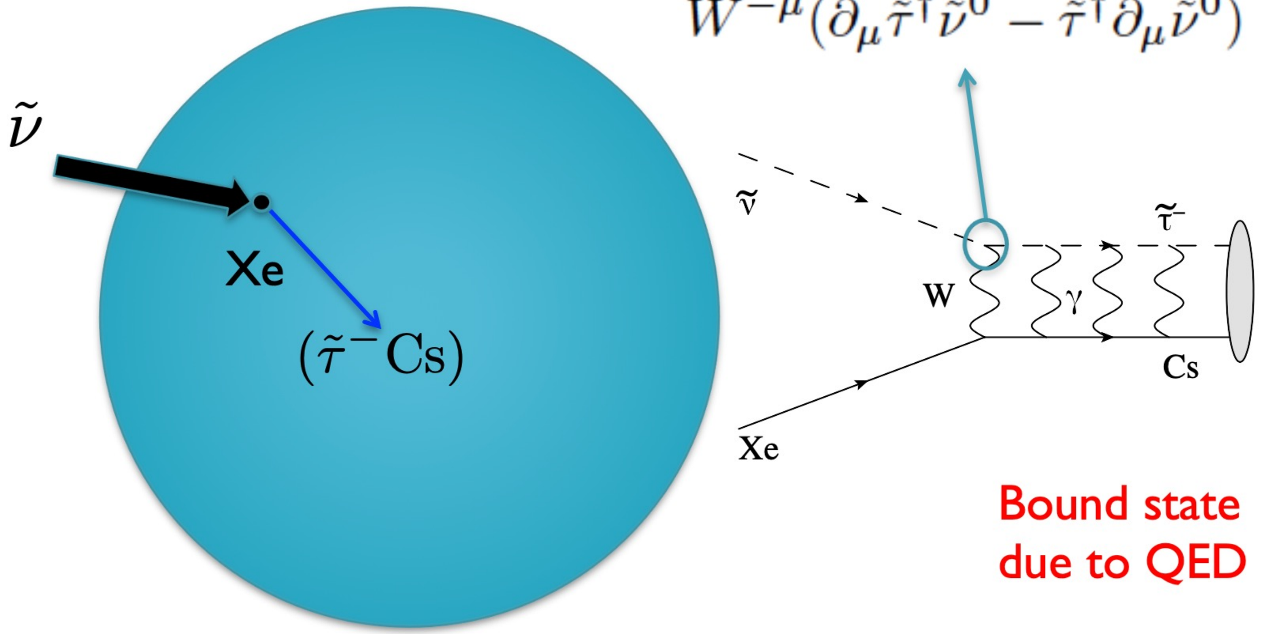
- Bound state formation will release binding energy.
- Take Xenon as the target

$$X^0 \to \tilde{\nu}$$

$$X^\pm \to \tilde{\tau}$$

B. same spin:

$$W^{-\mu}(\partial_\mu \tilde{\tau}^\dagger \tilde{\nu}^0 - \tilde{\tau}^\dagger \partial_\mu \tilde{\nu}^0)$$



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Using neutrino detectors to search for charged excited state of dark matter

- Bound state formation will release binding energy.
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$$X^0 \to \tilde{\nu}$$

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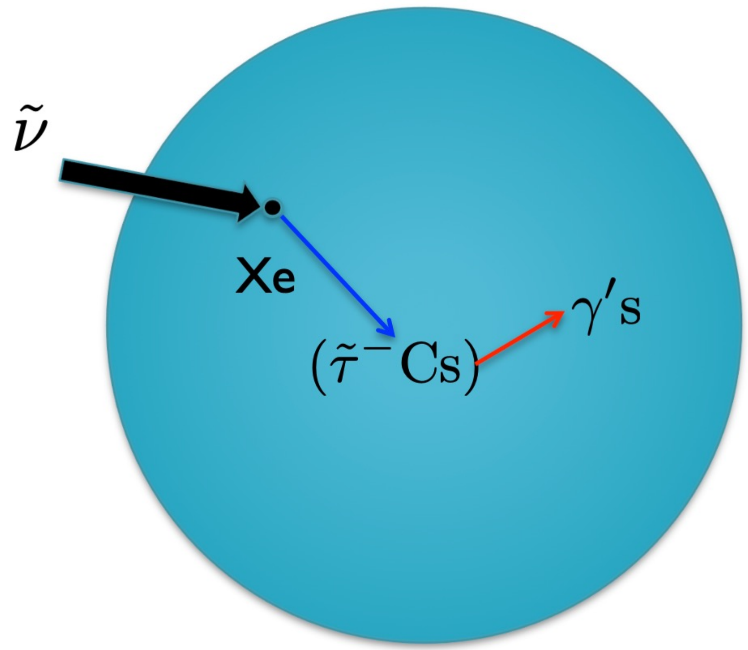

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Using neutrino detectors to search for charged excited state of dark matter

- Energy budget
- Incoming energy: $E_k + E_B$

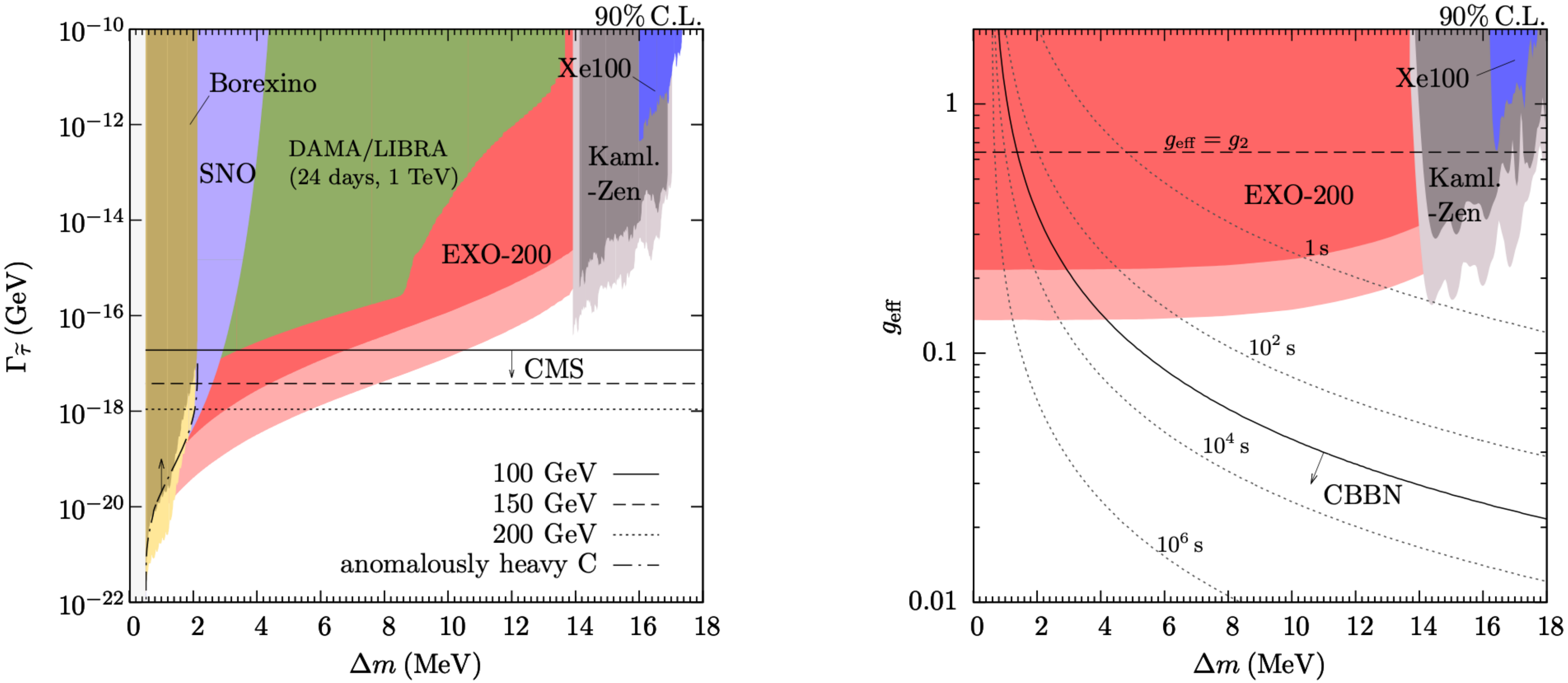
$$E_k \sim \frac{1}{2}\mu v_{\rm DM}^2 \sim O(100)\mathrm{keV}$$

negligible

$$E_{\rm tot} \approx \begin{cases} E_B^{(0)} - \Delta m + m_e & \text{Case A,} \\ E_B^{(0)} - \Delta m + m_Z - m_{Z+1} & \text{Case B.} \end{cases}$$

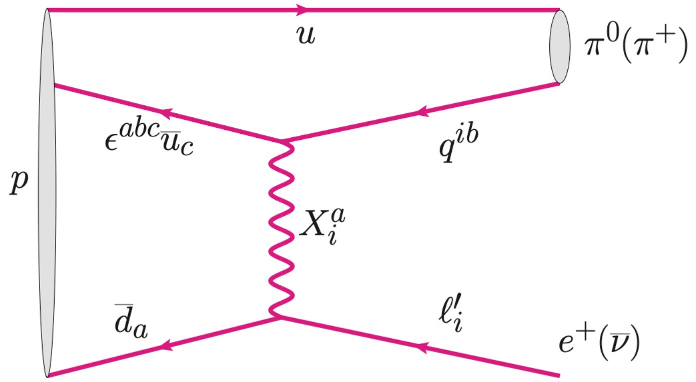
- Total deposit energy is almost single-valued.

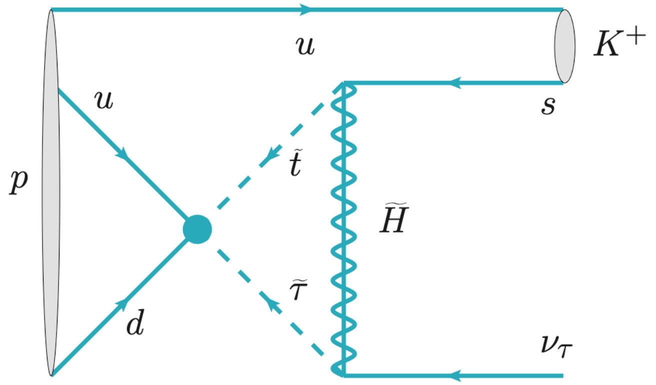
Using neutrino detectors to search for charged excited state of dark matter

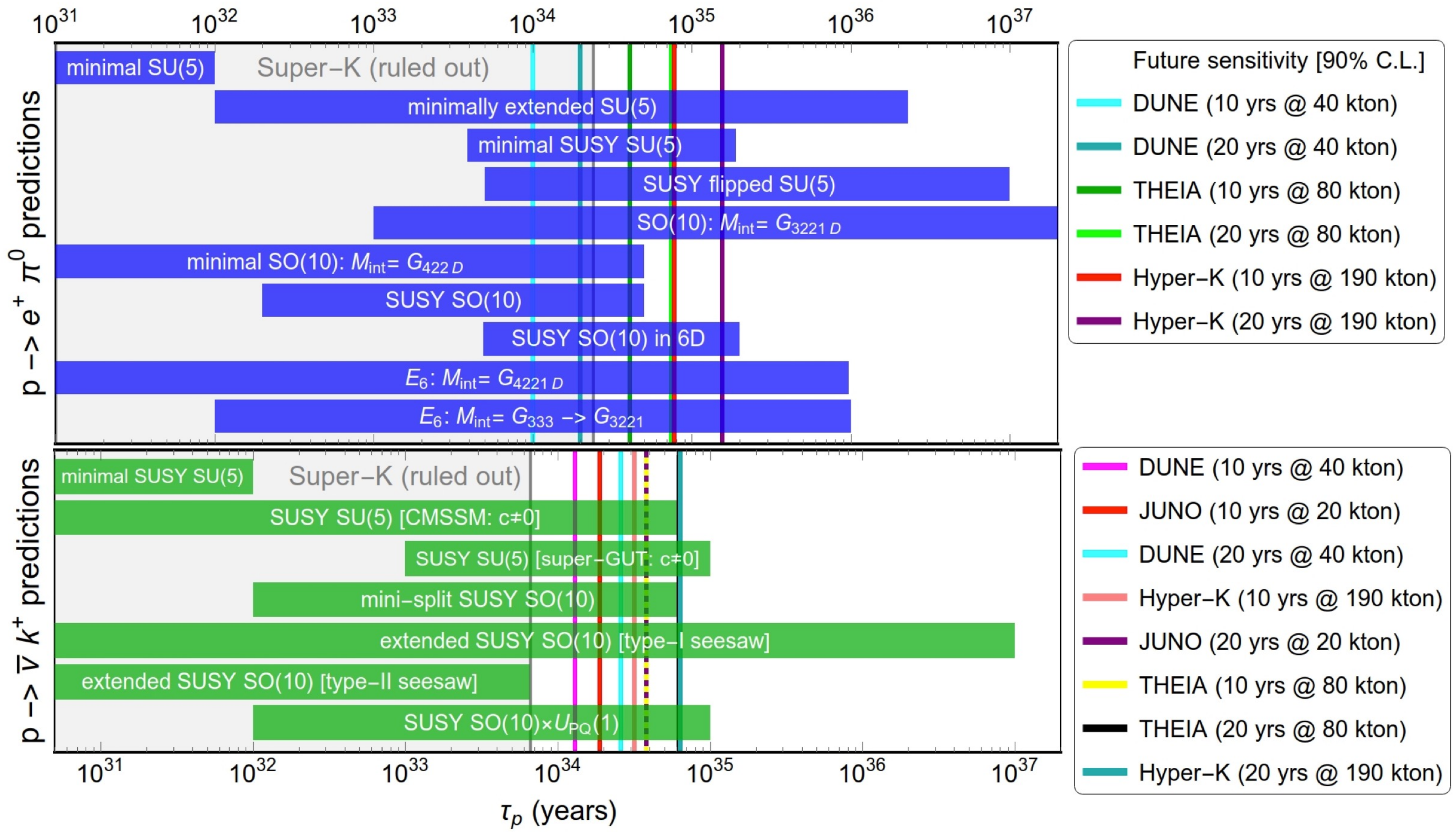


HA, M. Pospelov, J. Pradler, PRL 109 (2012), 251302

Search for baryon number violation using neutrino experiments





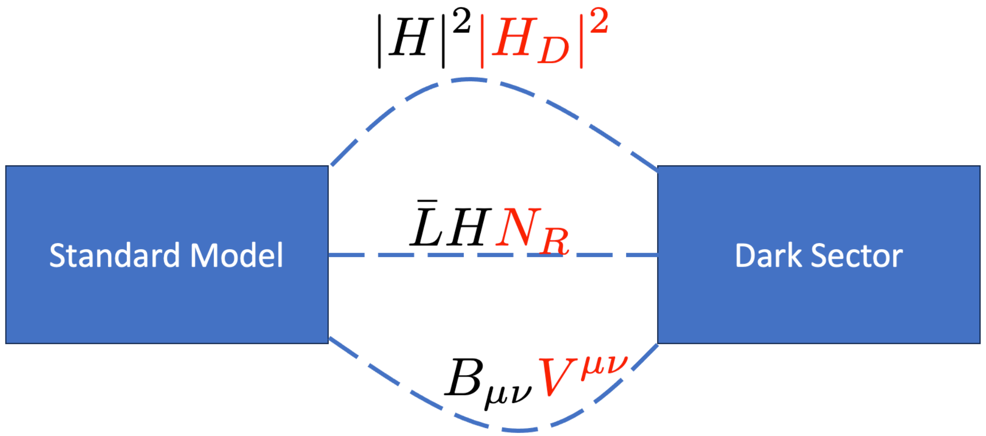


Dark sector study with neutrino beams

2207.06898

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} + \sum_{d=i+j} \frac{1}{\Lambda^{d-4}} \mathcal{O}_i^{\text{SM}} \mathcal{O}_j^{\text{DS}}$$

$$\sum_{d=i+j} \frac{1}{\Lambda^{d-4}} \mathcal{O}_i^{\text{SM}} \mathcal{O}_j^{\text{DS}} = \mathcal{L}_{\text{portals}} + \mathcal{O}(1/\Lambda)$$



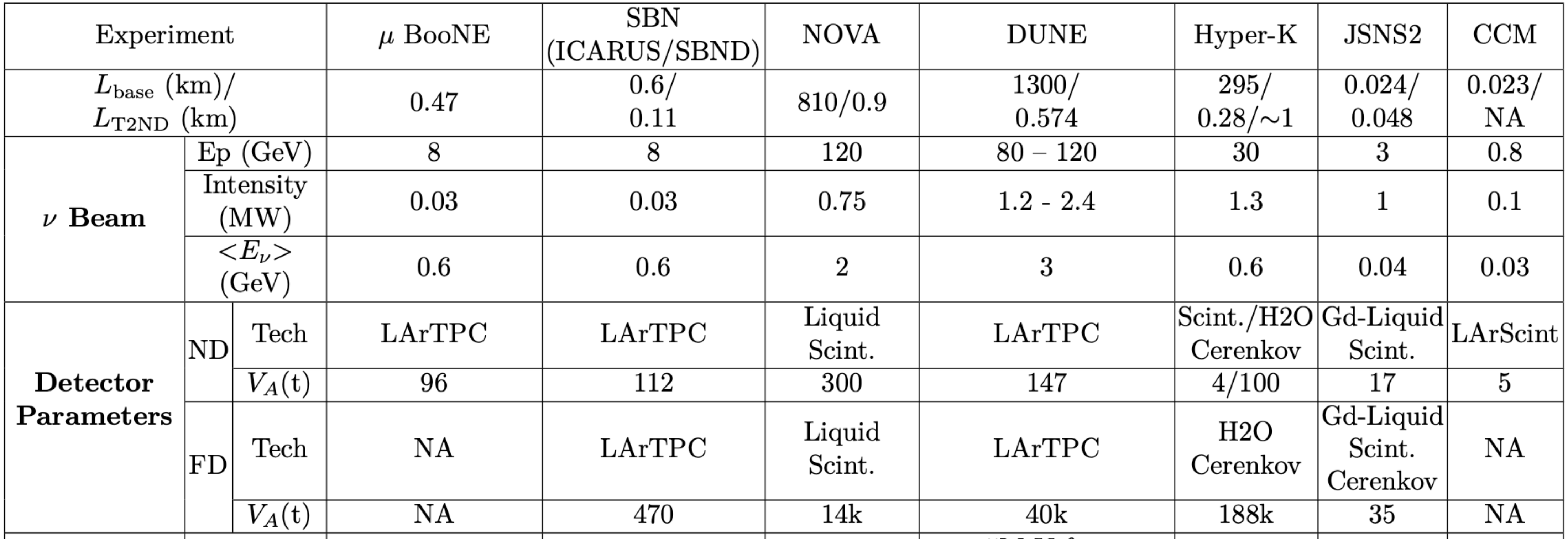
$$\mathcal{L}^{d=4}_{\text{neutrino portal}} = -\sum y_\nu^{\alpha I} (\bar{L}_\alpha H) N_I \longrightarrow -\frac{1}{\sqrt{2}} \sum v y_\nu^{\alpha I} \bar{\nu}_\alpha N_I + \cdots$$

$$\mathcal{L}^{d=3,4}_{\text{Higgs portal}} = -(\mu S + \lambda S^2) H^\dagger H \longrightarrow -\frac{\mu v}{m_h^2 - m_S^2} S J_h + \cdots$$

$$\mathcal{L}^{d=4}_{\text{vector portal}} = -\frac{\epsilon}{2 \cos\theta_W} B_{\mu\nu} F'_{\mu\nu} \longrightarrow \epsilon e A'_\mu J^\mu_{\text{EM}} + \cdots .$$

$$\mathcal{L}_{\text{axion portal}} = \frac{a}{4 f_G} \operatorname{Tr} G^{\mu\nu} \widetilde{G}_{\mu\nu} + \frac{a}{4 f_\gamma} F^{\mu\nu} \widetilde{F}_{\mu\nu} + \frac{1}{f_q} \partial_\mu a \sum_q \bar{q} \gamma^\mu \gamma^5 q + \frac{1}{f_l} \partial_\mu a \sum_l \bar{l} \gamma^\mu \gamma^5 l$$

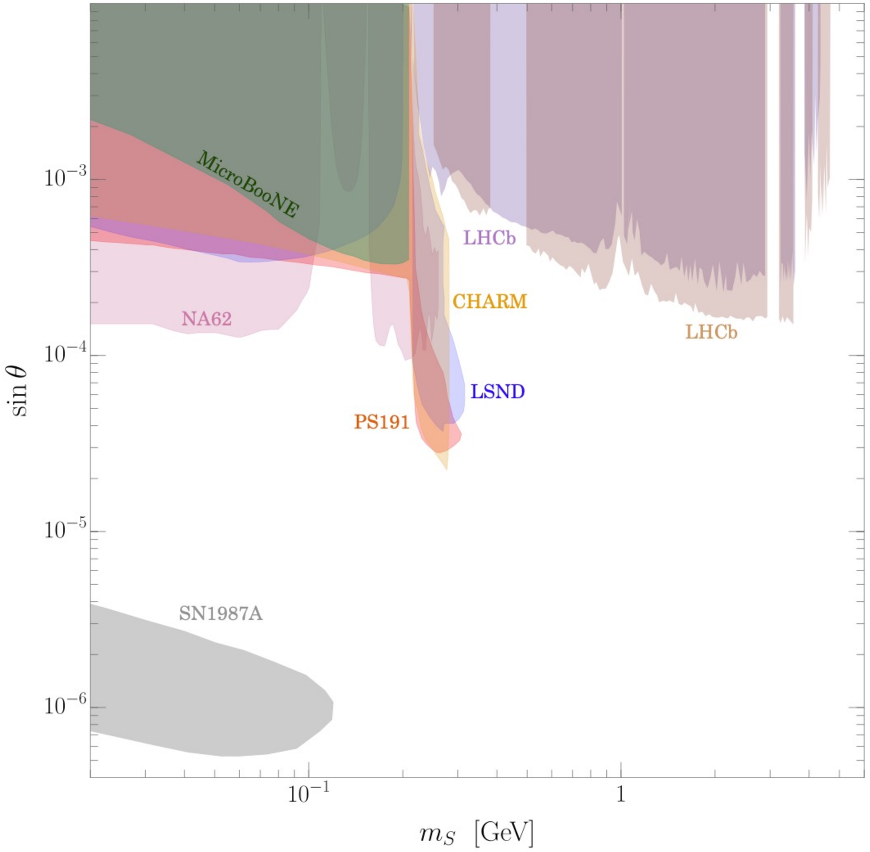
Dark sector study with neutrino beams

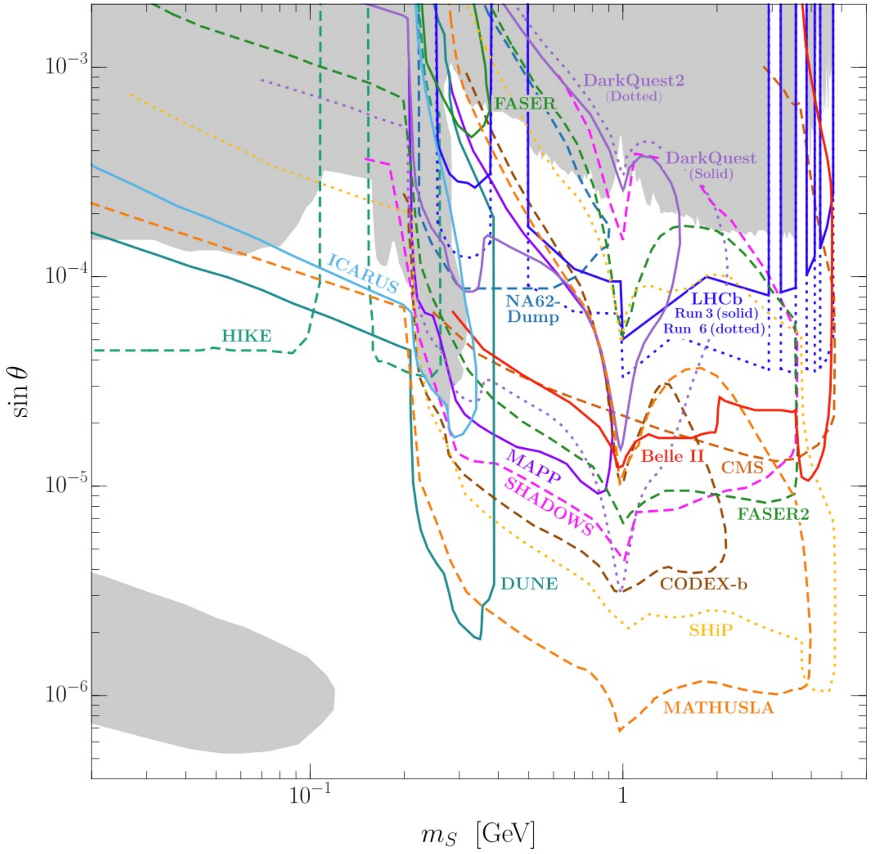


Experiment			μ BooNE	SBN (ICARUS/SBND)	NOVA	DUNE	Hyper-K	JSNS2	CCM
L_{base} (km)/ L_{T2ND} (km)			0.47	0.6/ 0.11	810/0.9	1300/ 0.574	295/ 0.28/$\sim$1	0.024/ 0.048	0.023/ NA
ν **Beam**	Ep (GeV)		8	8	120	80 – 120	30	3	0.8
	Intensity (MW)		0.03	0.03	0.75	1.2 - 2.4	1.3	1	0.1
	$<E_\nu>$ (GeV)		0.6	0.6	2	3	0.6	0.04	0.03
Detector Parameters	ND	Tech	LArTPC	LArTPC	Liquid Scint.	LArTPC	Scint./H2O Cerenkov	Gd-Liquid Scint.	LArScint
		V_A(t)	96	112	300	147	4/100	17	5
	FD	Tech	NA	LArTPC	Liquid Scint.	LArTPC	H2O Cerenkov	Gd-Liquid Scint. Cerenkov	NA
		V_A(t)	NA	470	14k	40k	188k	35	NA

Dark sector study with neutrino beams

- Higgs portal $\mathcal{L} \supset -(AS + \lambda S^2)H^\dagger H$
  - Meson decay, Bremsstrahlung, Drell-Yan



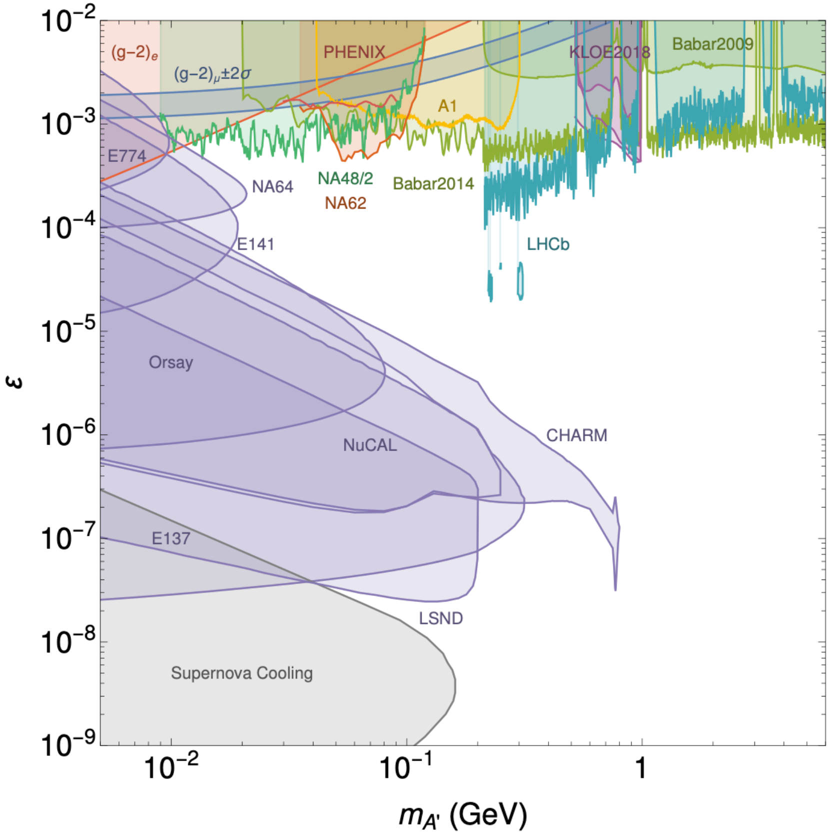


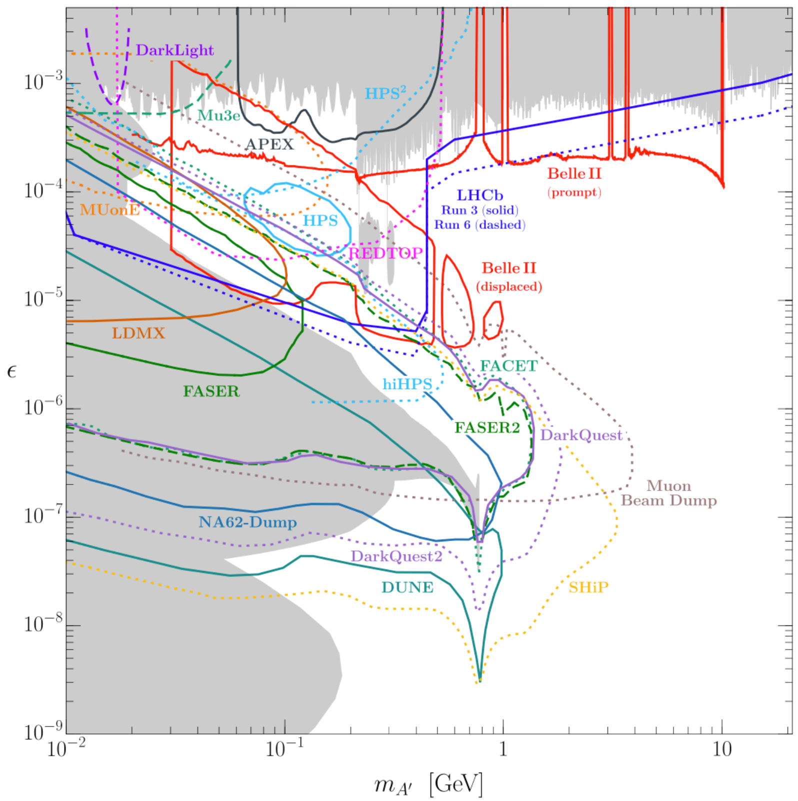
Dark sector study with neutrino beams

- Vector portal

$$\mathcal{L}_{A'} = -\frac{1}{4}A_{\mu\nu}^2 - \frac{\varepsilon}{2\cos\theta_W}A'_{\mu\nu}B^{\mu\nu} - \frac{1}{2}m_{A'}A'_\mu A'^\nu$$

  - Meson decay, Bremsstrahlung, Drell-Yan





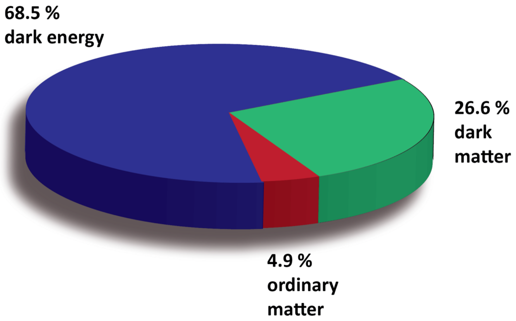
Other possibilities?

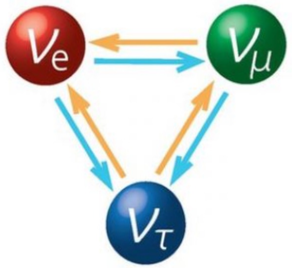
- Neutrino interaction with dark energy?

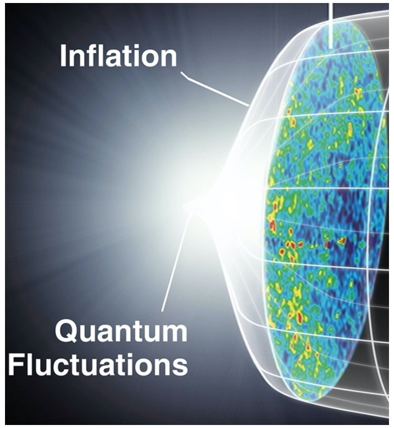
  Yes, there are papers.
- Neutrino connection to inflation?

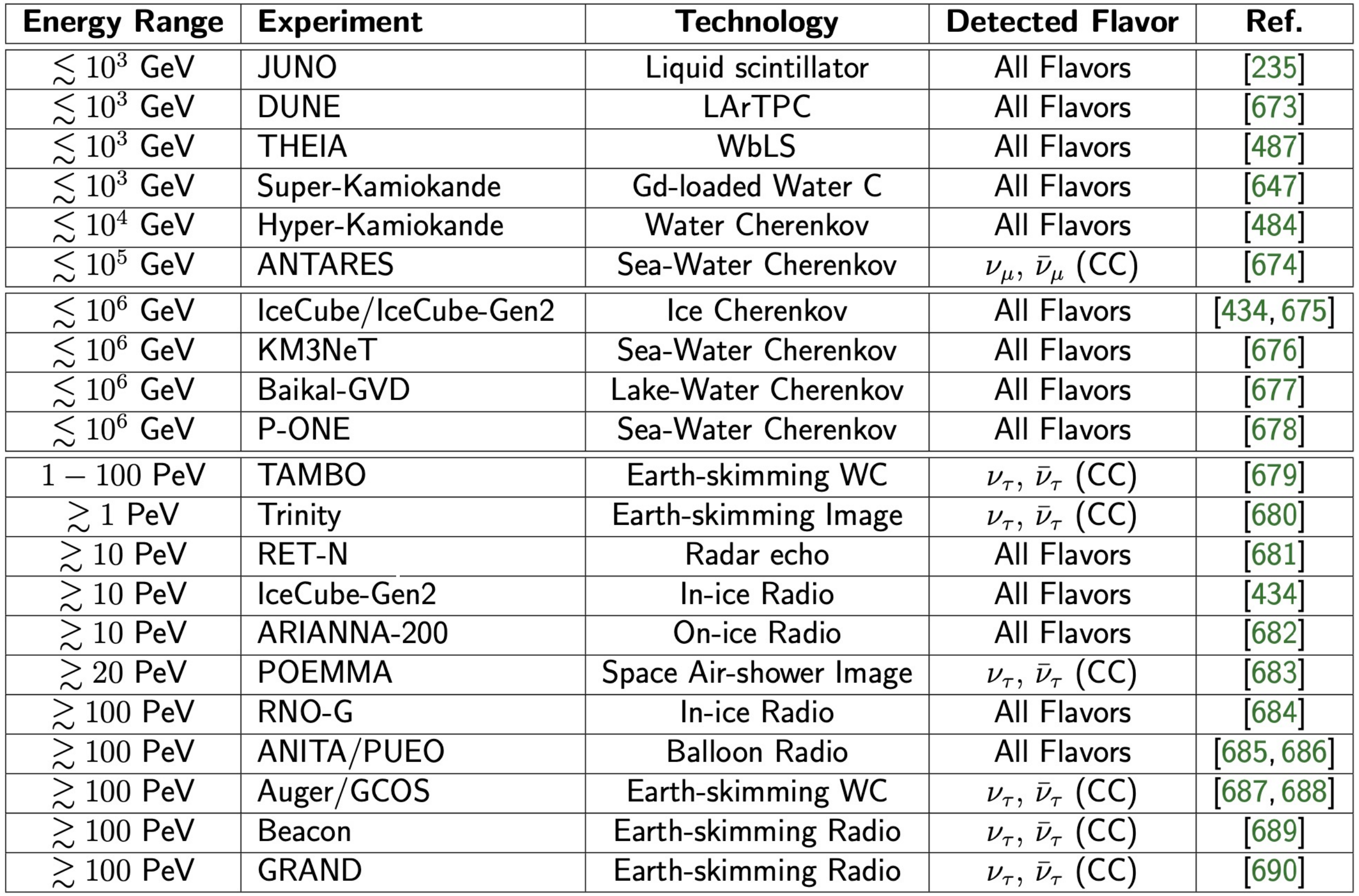
  Can sneutrino be a inflaton candidate?

Summary









Energy Range	Experiment	Technology	Detected Flavor	Ref.
$\lesssim 10^3$ GeV	JUNO	Liquid scintillator	All Flavors	[235]
$\lesssim 10^3$ GeV	DUNE	LArTPC	All Flavors	[673]
$\lesssim 10^3$ GeV	THEIA	WbLS	All Flavors	[487]
$\lesssim 10^3$ GeV	Super-Kamiokande	Gd-loaded Water C	All Flavors	[647]
$\lesssim 10^4$ GeV	Hyper-Kamiokande	Water Cherenkov	All Flavors	[484]
$\lesssim 10^5$ GeV	ANTARES	Sea-Water Cherenkov	ν_μ, $\bar{\nu}_\mu$ (CC)	[674]
$\lesssim 10^6$ GeV	IceCube/IceCube-Gen2	Ice Cherenkov	All Flavors	[434, 675]
$\lesssim 10^6$ GeV	KM3NeT	Sea-Water Cherenkov	All Flavors	[676]
$\lesssim 10^6$ GeV	Baikal-GVD	Lake-Water Cherenkov	All Flavors	[677]
$\lesssim 10^6$ GeV	P-ONE	Sea-Water Cherenkov	All Flavors	[678]
$1 - 100$ PeV	TAMBO	Earth-skimming WC	ν_τ, $\bar{\nu}_\tau$ (CC)	[679]
$\gtrsim 1$ PeV	Trinity	Earth-skimming Image	ν_τ, $\bar{\nu}_\tau$ (CC)	[680]
$\gtrsim 10$ PeV	RET-N	Radar echo	All Flavors	[681]
$\gtrsim 10$ PeV	IceCube-Gen2	In-ice Radio	All Flavors	[434]
$\gtrsim 10$ PeV	ARIANNA-200	On-ice Radio	All Flavors	[682]
$\gtrsim 20$ PeV	POEMMA	Space Air-shower Image	ν_τ, $\bar{\nu}_\tau$ (CC)	[683]
$\gtrsim 100$ PeV	RNO-G	In-ice Radio	All Flavors	[684]
$\gtrsim 100$ PeV	ANITA/PUEO	Balloon Radio	All Flavors	[685, 686]
$\gtrsim 100$ PeV	Auger/GCOS	Earth-skimming WC	ν_τ, $\bar{\nu}_\tau$ (CC)	[687, 688]
$\gtrsim 100$ PeV	Beacon	Earth-skimming Radio	ν_τ, $\bar{\nu}_\tau$ (CC)	[689]
$\gtrsim 100$ PeV	GRAND	Earth-skimming Radio	ν_τ, $\bar{\nu}_\tau$ (CC)	[690]