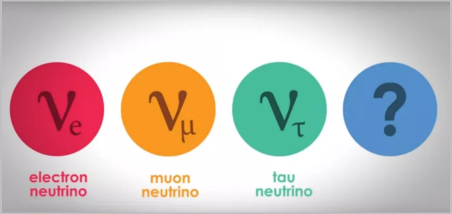
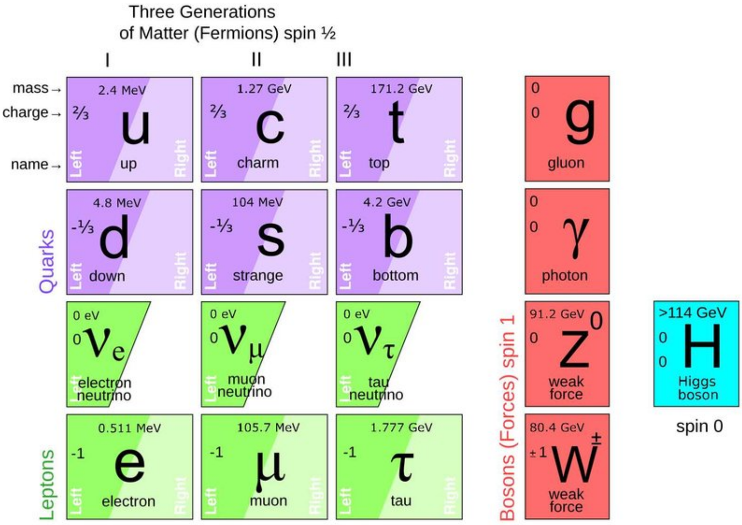
Sterile Neutrino Searches Across the Scales



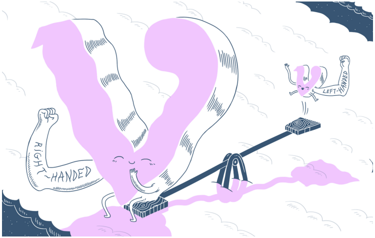
Vedran Brdar (CERN–TH)

Standard Model

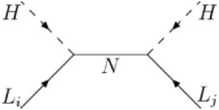


Neutrino Mass Generation

Type-I Seesaw



Minkowski, Mohapatra, Senjanović,
Gell-Mann, Ramond, Slansky, Yanagida



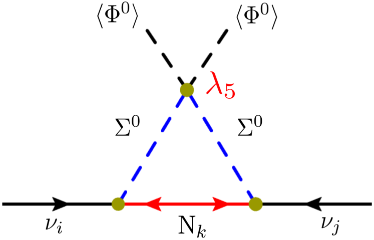
$$\mathcal{M} = \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$

$$m_\nu = -M_D M_R^{-1} M_D^T$$
$$\theta = M_D / M_R$$

Scotogenic Model

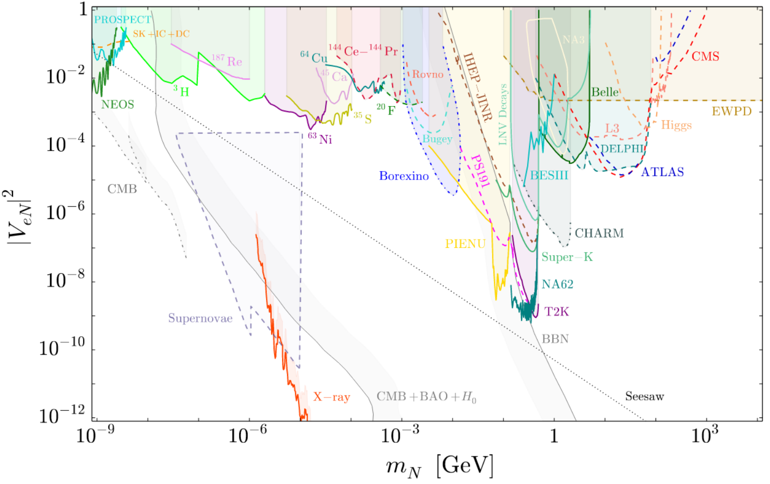
	$SU(2)_L$	$U(1)_Y$	Z_2
Σ	2	1/2	-
N_i	1	0	-
Φ	2	1/2	+
L	2	-1/2	+

Ma (2006)



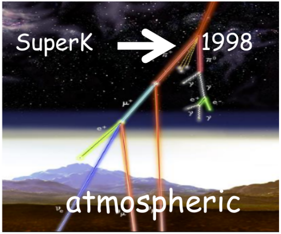
Sterile Neutrino Searches Across The Scales

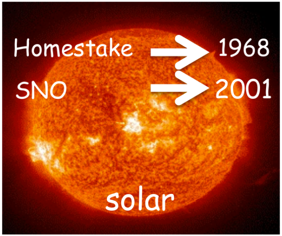
Bolton et al., JHEP 2020

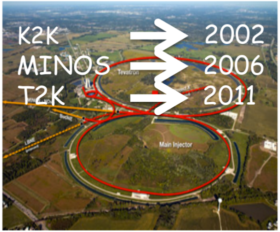


eV-scale ν_s

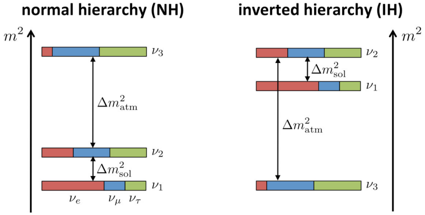
Neutrino Oscillations





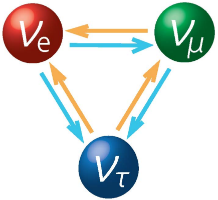


Standard Three Flavor Picture



NuFIT, 2007.14792

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{\rm CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$



$$P_{\alpha\beta} = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}\, e^{-i\frac{m_j^2 - m_k^2}{2E}L}$$

2 flavors:

$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2 L}{E} \frac{[\mathrm{eV}^2][\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

- neutrinos are massive particles

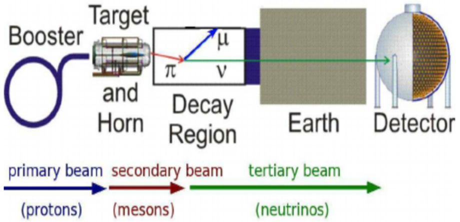
3+1 model with eV-scale sterile neutrino

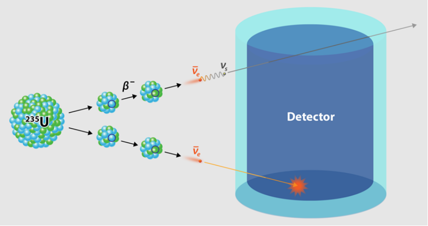
$$U^{4\text{flavor}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$P_{ee} = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2) \times \sin^2\left(\frac{(m_4^2 - m_1^2)L}{4E}\right)$$

$$P_{\mu\mu} = 1 - 4|U_{\mu 4}|^2(1 - |U_{\mu 4}|^2) \times \sin^2\left(\frac{(m_4^2 - m_1^2)L}{4E}\right)$$

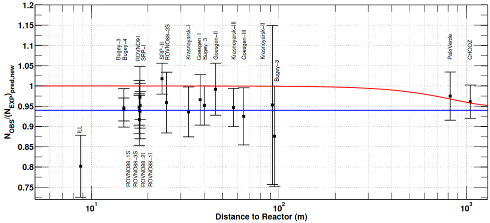
$$P_{\mu e} = 4|U_{\mu 4} U_{e4}|^2 \times \sin^2\left(\frac{(m_4^2 - m_1^2)L}{4E}\right)$$



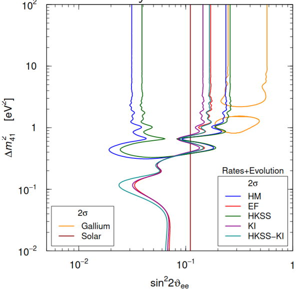


Anomalies: Reactor and Gallium

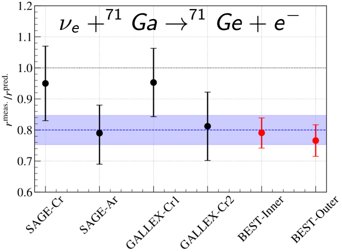
Huber PRC 2011, Mention et al., PRD 2011

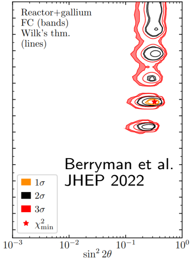


Giunti et al. PLB 2022
see also Berryman et al. JHEP 2022



- reactor anomaly is fading away

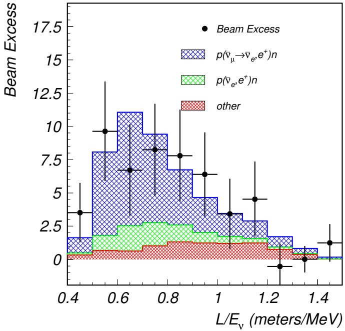


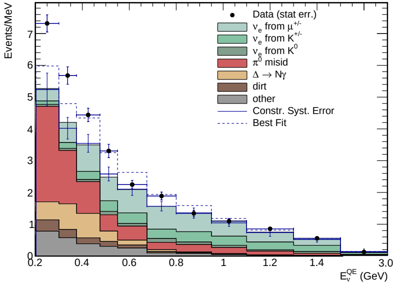


from B. Littlejohn

…did we actually get a full pour??

Anomalies: LSND and MiniBooNE





- LSND: $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam from stopped pion source ($> 3\sigma$) at $L/E \sim 1\mathrm{km\,GeV}^{-1}$ (arXiv:hep-ex/0104049)
- MiniBooNE: reports electron-like event excess (4.8σ) (arXiv:0812.2243, 1805.12028, 2006.16883)
- in combination with LSND 6.1σ

Nuclear Physics Uncertainties?

- large nuclear and hadronic physics uncertainties in ν-nucleus scattering
- MiniBooNE used not-so-recent MC event generator for background studies

Generator	Tune	Ref.	Comments
NUANCE	–	[40]	the generator used by MiniBooNE
GiBUU	–	[42]	theory-driven generator
NuWro	–	[41]	
GENIE	G18_01a_02_11a	[39, 44]	GENIE baseline tune; see [44] for naming conventions
	G18_01b_02_11a		different FSI implementation compared to G18_01a_02_11a
	G18_02a_02_11a		updated res./coh. scattering models compared to G18_01a_02_11a
	G18_02b_02_11a		updated res./coh. scattering models and different FSI
	G18_10a_02_11a		theory-driven configuration; similar to G18_02a
	G18_10b_02_11a		theory-driven configuration; similar to G18_02b

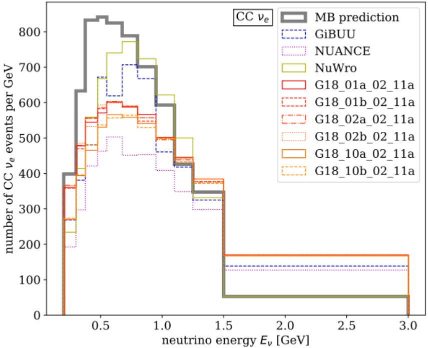
Relevant Channels

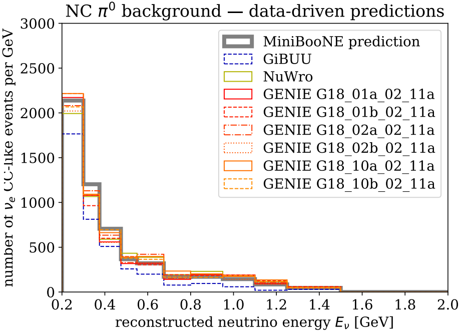
$$\nu_e + N \rightarrow e^- + N'$$

$$\nu + N \rightarrow \nu + N + \pi^0(\gamma\gamma)$$

$$\nu + N \rightarrow \nu + \Delta \rightarrow \nu + N\gamma$$

VB, Kopp PRD (2022)

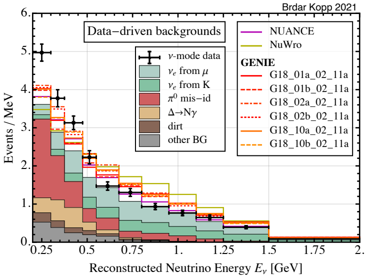


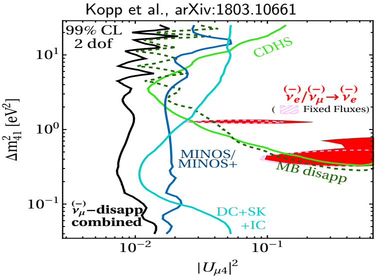


New Physics?

data-driven backgrounds

Generator	Tune	Δm^2_{41}	$\sin^2 2\theta_{\mu e}$	$\lvert U_{\mu 4}\rvert^2$	χ^2/dof	$\Delta\chi^2_{\text{no osc.}}$	Significance
MB official		0.25	0.01	0.062	12.0	19.1	4.0σ
NUANCE	–	0.32	0.0079	0.051	12.3	19.3	4.0σ
NuWro	–	3.2	0.0016	0.040	13.3	12.7	3.1σ
GENIE	G18_01a_02_11a	0.79	0.00020	0.14	12.2	23.3	4.4σ
	G18_01b_02_11a	0.79	0.0001	0.12	12.2	15.5	3.5σ
	G18_02a_02_11a	0.13	0.063	0.18	12.2	19.2	4.0σ
	G18_02b_02_11a	0.13	0.050	0.20	12.3	16.9	3.7σ
	G18_10a_02_11a	0.25	0.016	0.062	12.3	15.1	3.5σ
	G18_10b_02_11a	0.40	0.013	0.016	12.1	19.5	4.0σ

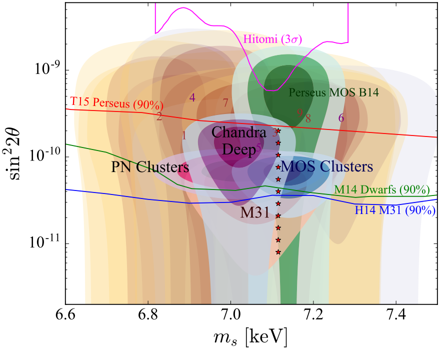


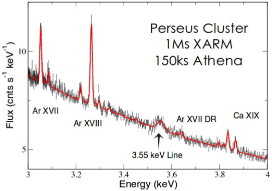


keV-scale ν_s

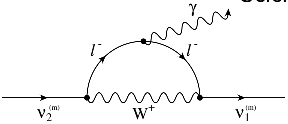
keV-scale Sterile Neutrino Dark Matter

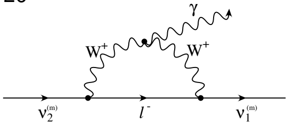
K. Abazajian, arXiv:1705.01837





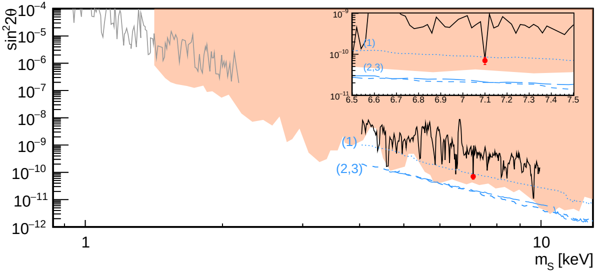
- revival in 2014
- hints for DM from stacked clusters (Bulbul et al. 1402.2301), Perseus and M31 (Boyarski et al. 1402.4119)
- (Cappelluti et al., 1701.07932) – Deep Field search using Chandra satellite
- opposite claims... Jeltema, Profumo 1408.1699, Potassium contribution
- 1608.04751, charge exchance
- Dessert et al., 1812.06976, Science '20





Final answer coming soon?

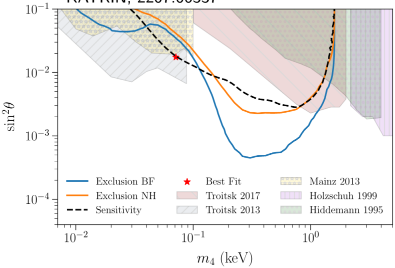
- Micro-X: A Sounding Rocket Dark Matter Search (1506.05519)



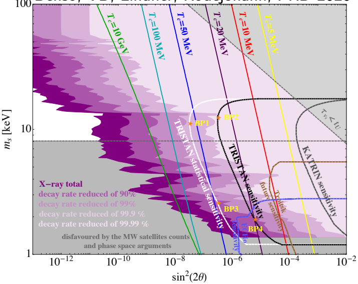
- energy resolution ~ 3 eV
- launched in August '22

Northwestern University

KATRIN, 2207.06337



Benso, VB, Lindner, Rodejohann, PRD 2020



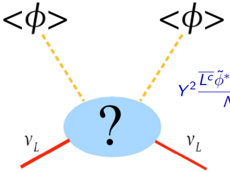
- KATRIN will reach $\sin^2 2\theta \sim 10^{-7}$
- DM in this region of parameter space?

- (i) Multicomponent DM or
  change ν_s decay rate
- (ii) lower T_{RH} to suppress production

heavier ν_s

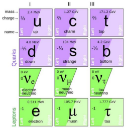
$0\nu2\beta$ Decay and Sterile Neutrinos

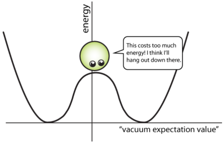
Majorana



$$Y^2 \frac{\overline{L^c}\tilde{\phi}^* \tilde{\phi}^\dagger L}{\Lambda} \longrightarrow m_\nu \sim Y^2 \frac{\langle\phi\rangle^2}{\Lambda}$$

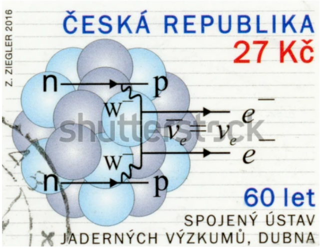
Dirac





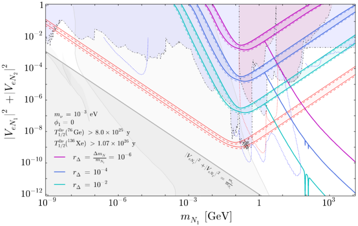
$$y\bar{\psi}_L\phi\psi_R \Rightarrow m_\nu = y\langle\phi\rangle \Rightarrow y \sim 10^{-12}$$

$0\nu2\beta$ Decay

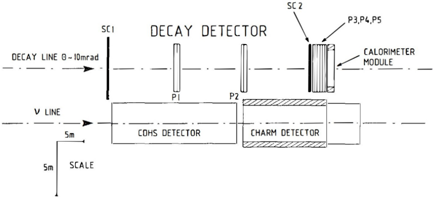


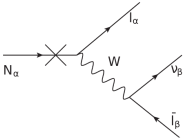
$$|m_{\beta\beta}| = \left| m_1|U_{e1}|^2 e^{i\theta_1} + m_2|U_{e2}|^2 e^{i\theta_2} + m_3|U_{e3}|^2 e^{i\theta_3} + \left(\frac{m_4}{1 - m_4^2/p^2}\right)|U_{e4}|^2 e^{i\theta_4} \right|$$

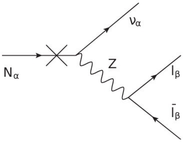
Bolton et al., JHEP 2020, see also Dekens et al. JHEP 2020



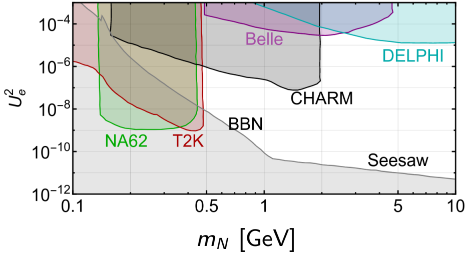
GeV-scale searches: CHARM Experiment as an Example



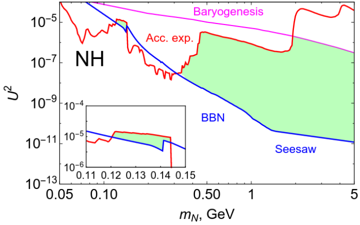




Boiarska et al. PRD 2021

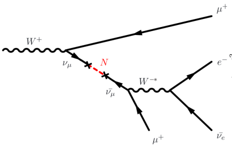


Bondarenko et al. JHEP 2021

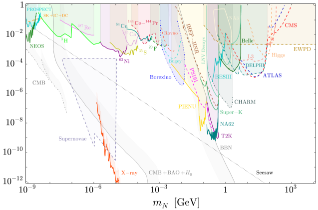


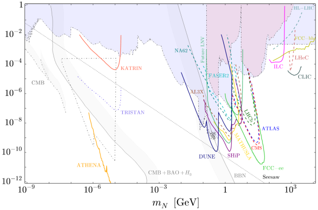
see Juraj's talk on Leptogenesis on Friday

Probing the Low Scale Origin of Neutrino Mass

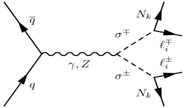


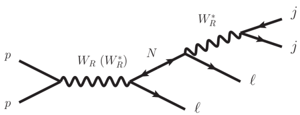
Bolton et al., JHEP 2020



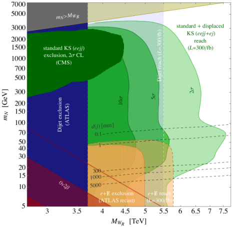


- for type-I Seesaw, $V_{\alpha N} \sim 10^{-6}\sqrt{100\,\text{GeV}/M_R} \Rightarrow$ not testable
- remedy: inverse seesaw, new interactions of N...

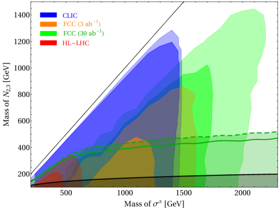




Nemevšek et al, PRD 2018



Baumholzer et al, JHEP 2020

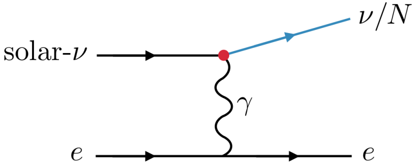


Transition Magnetic Moments

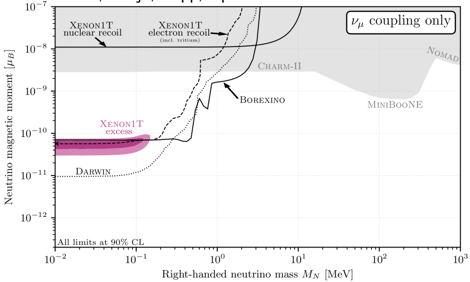
$$\mathcal{L}_\mu = \frac{\mu_\nu^\alpha}{2} F_{\mu\nu}\, \bar{\nu}_L^\alpha \sigma^{\mu\nu} N_R + \text{h.c.}$$

$$\frac{dR}{dE_r} = N_T \epsilon(E_r) \int_{E_\nu^{\text{min}}} \mathrm{d}E_\nu \frac{\mathrm{d}\Phi}{\mathrm{d}E_\nu} \frac{\mathrm{d}\sigma}{\mathrm{d}E_r}$$

- scattering targets
- solar neutrino flux
- cross-sections for scattering via magnetic moment operator



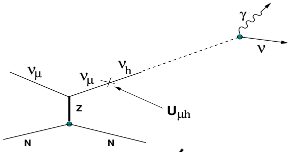
VB, Greljo, Kopp, Opferkuch JCAP 2021

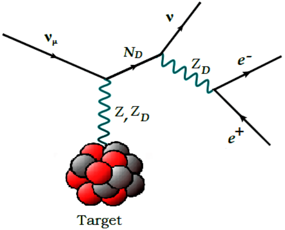


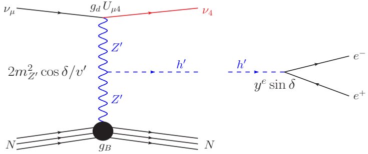
Non-oscillatory Explanations of MiniBooNE Anomaly

- single shower events can be produced by e, γ, collimated e^+e^- and $\gamma\gamma$

Model	U. Signature	LSND	MB
3+1	Oscillations		
(3+1) + inv-ν decay	Damped oscillations		
(3+1) + NSI	Modified matter effects		
Anomalous matter	Resonant appearance		
Large extra dim	Osc with related freqs.		
LNV in μ decays	$\mu^+ \to$ anti-ν_e		
Lorentz violation	Sidereal time variation		
Dark neutrinos	Upscattering to N → ν e^+e^-		
Dipole portal	Upscattering to N → ν γ		
(3+1) + vis-ν decay	DIF of $\nu_s \to \nu_e$		
(3+1) + vis decay	DIF of N → ν γ		
Dark sectors: dark matter	Upscattering to $\chi' \to \chi\, e^+e^-$		
Dark sectors: (pseudo)-scalar	Forward scattering to γ		



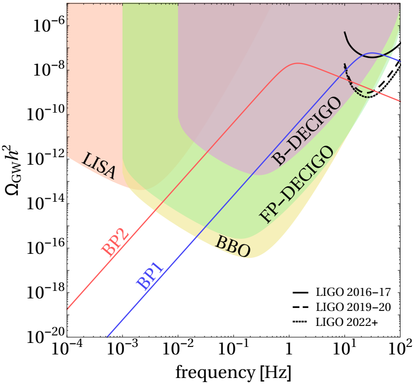




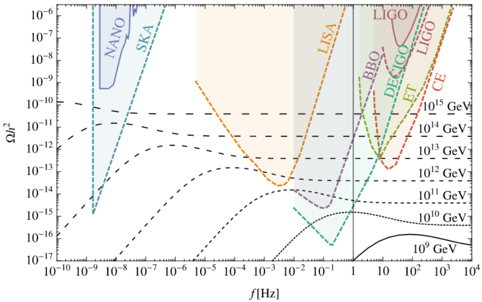
Probing Heavy Sterile Neutrinos

- GW detectors as a window to unexplored seesaw scales
- testing $M_N \lesssim 10^8$ GeV in models featuring first-order phase transition and $M_N \lesssim$ GUT from topological defects, e.g. cosmic strings

VB, Helmboldt, Kubo, JCAP 2019



Dror et al., PRL 2020



Summary

- Sterile neutrino is a well-motivated extension of the Standard Model
- Sterile neutrinos can explain the origin of Neutrino mass, Dark Matter and Baryon Asymmetry of the Universe
- There is a number of complementary sources for producing these hypothetical particles: terrestrial experiments, cosmology, stars...
- Probes: neutrino oscillations, decay of ν_s to SM states, decay of SM states to ν_s, production in scattering