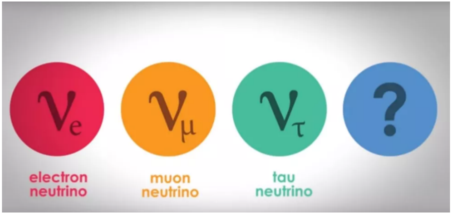
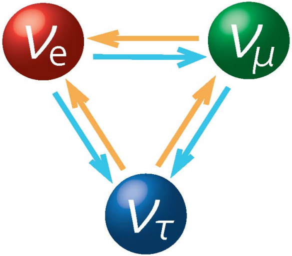
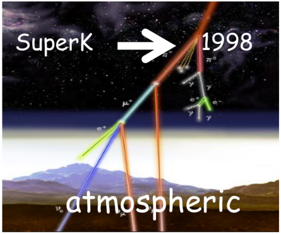
Present Status of Neutrino Physics from a Theory Perspective

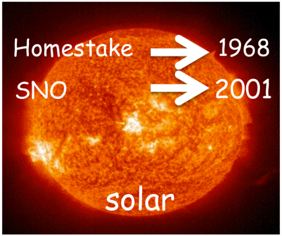


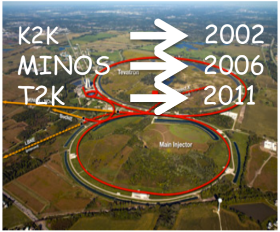


Vedran Brdar (CERN–TH)

Neutrino Oscillations



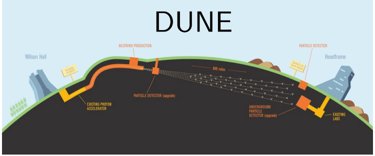


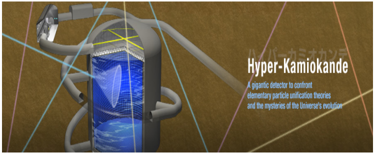


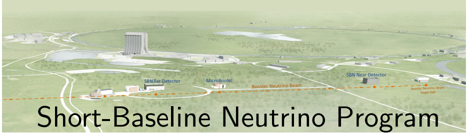
$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

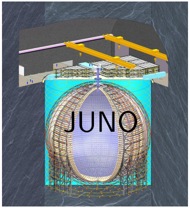
(Some of the) Open Questions

- What is the origin of neutrino mass?
- CP violation in neutrino sector?
- Ordering of neutrino masses?
- Is the neutrino its own antiparticle?
- Absolute neutrino mass scale?
- Sterile neutrinos?

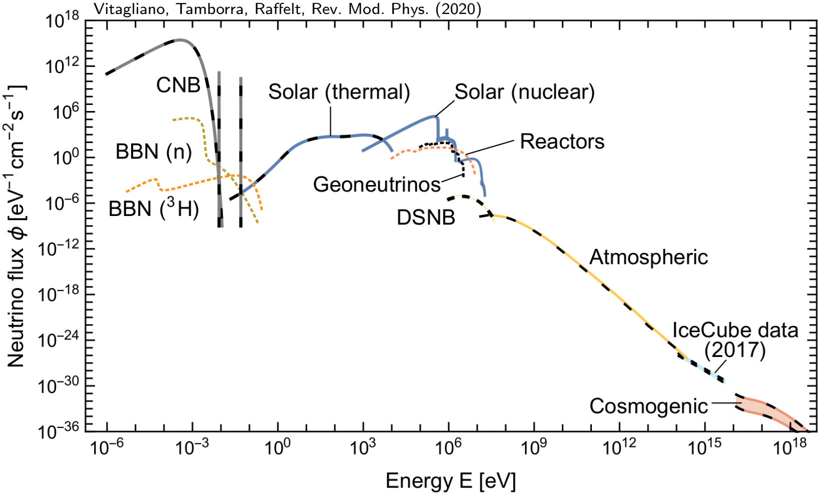




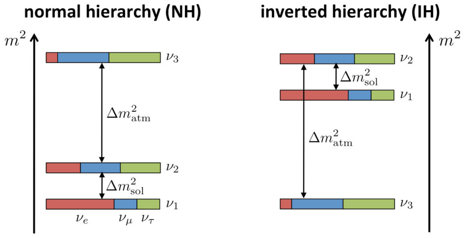




Grand Unified Neutrino Spectrum at Earth



Neutrino Mass Ordering

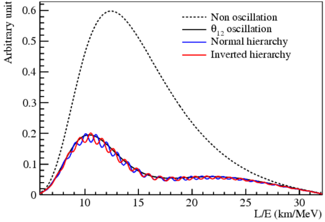


NuFIT, 2007.14792

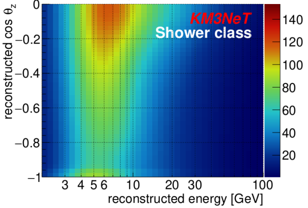
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$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

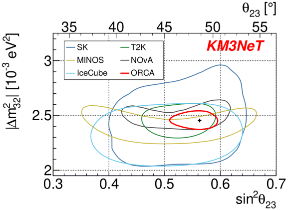
- vacuum, $E_\nu \sim$ MeV
- matter effects, $E_\nu \gtrsim$ GeV

JUNO, 2103.09885

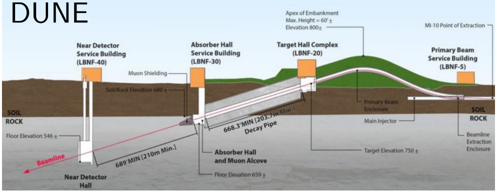


KM3NeT, 2103.09885

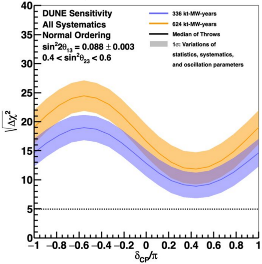




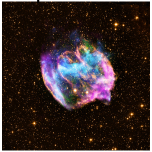
Neutrino Mass Ordering



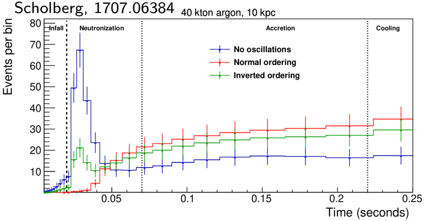
DUNE, EPJC 2020



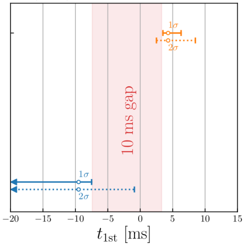
Supernovae



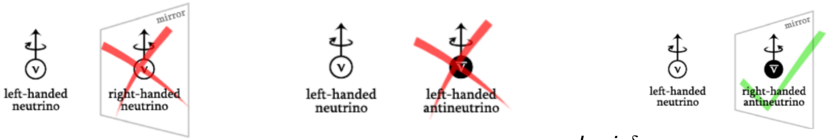
Scholberg, 1707.06384



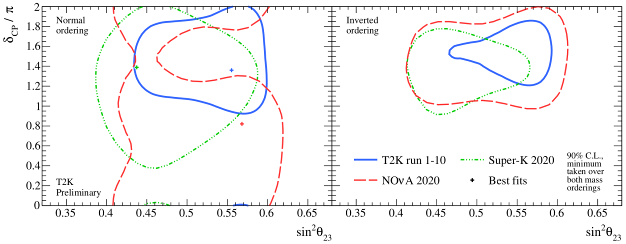
VB, Xu, JCAP 2022

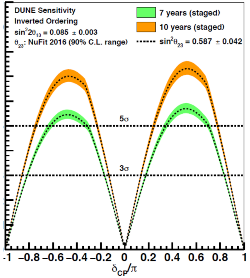


CP Violation in Lepton Sector



$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = \sum_{j\neq k} 2i \overbrace{Im(U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k})}^{J\sim \sin\delta} \; e^{-i\frac{(m_j^2 - m_k^2)L}{2E}}$$



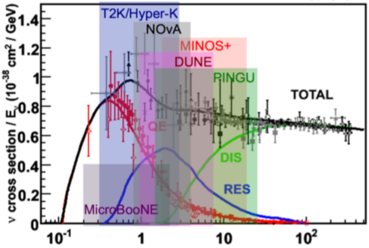


Pan in parallel sessions

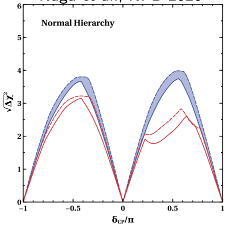
Prerequisites for the Discovery

- Reduction of ν-nucleus cross section uncertainties

G. Zeller

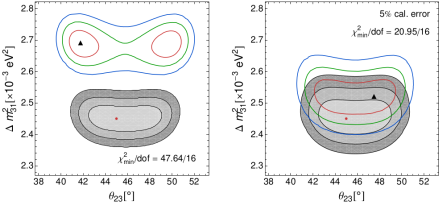


Nagu et al., NPB 2020

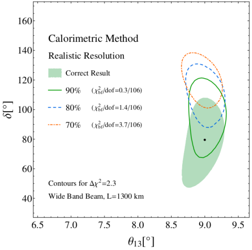


- Reconstruction of neutrino energy

Coloma et al., 1311.4506

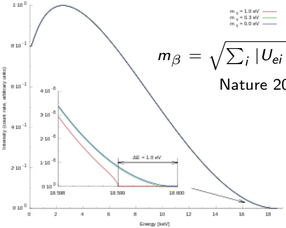


Ankowski et al., 1507.08561



Neutrino Mass Scale?

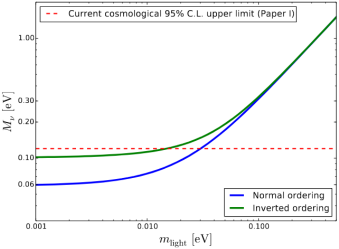
Köllenberger in parallel sessions



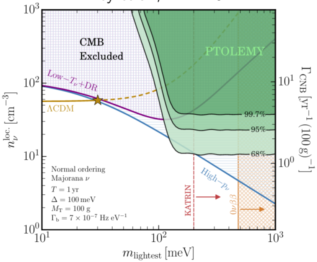
$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < 0.8$ eV

Nature 2022

- Testing non-standard cosmology

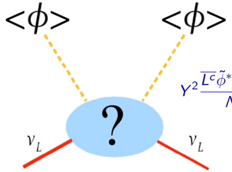


Alvey et al., PRD 2022



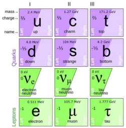
Is the Neutrino its own Antiparticle?

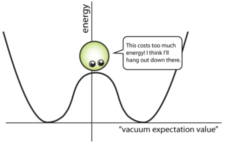
Majorana



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

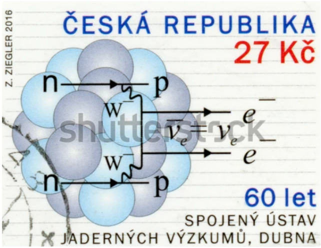
Dirac

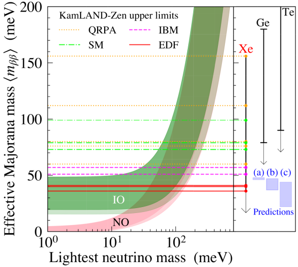




$y\bar{\psi}_L \phi \psi_R \Rightarrow m_\nu = y\langle\phi\rangle \Rightarrow y \sim 10^{-12}$

$0\nu 2\beta$ Decay





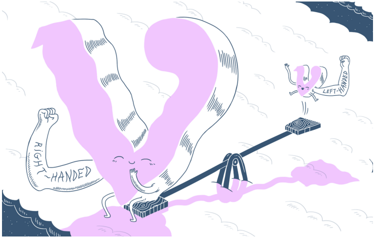
Beretta in parallel sessions

$\Gamma_{0\nu 2\beta} \propto G_F^4 |\tilde{M}_{0\nu 2\beta}|^2 \left|\sum U_{ej}^2 m_j\right|^2 p_e^2$

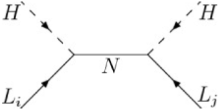
Theory Challenge:
Matrix Elements

Neutrino Mass

Type-I Seesaw



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



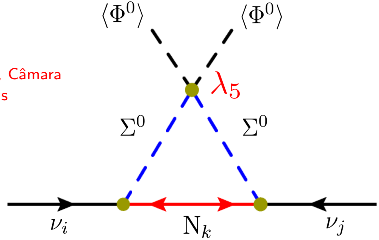
$$m_\nu = -M_D M_R^{-1} M_D^T$$

Scotogenic Model

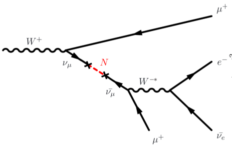
	$SU(2)_L$	$U(1)_Y$	Z_2
Σ	2	1/2	-
N_i	1	0	-
Φ	2	1/2	+
L	2	-1/2	+

Costa, Escribano, Câmara
in parallel sessions

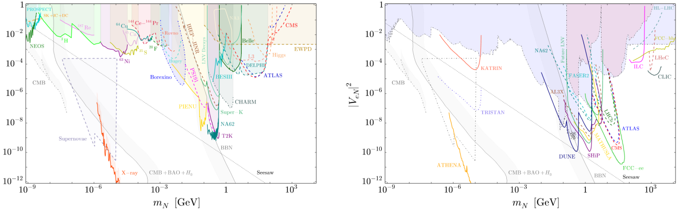
Ma (2006)



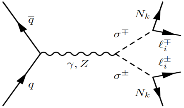
Probing the Low Scale Origin of Neutrino Mass

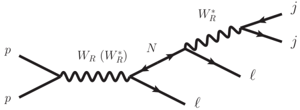


Bolton et al., JHEP 2020

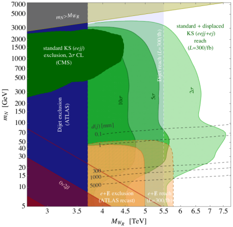


- for type-I Seesaw, $V_{\alpha N} \sim 10^{-6}\sqrt{100\,\text{GeV}/M_R} \Rightarrow$ not testable
- remedy: inverse seesaw, new interactions of N...

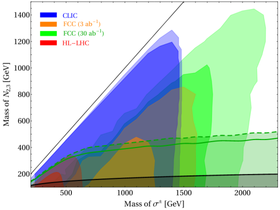




Nemevšek et al, PRD 2018

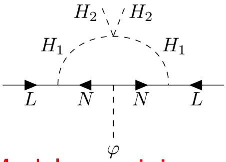


Baumholzer et al, JHEP 2020

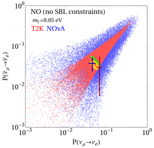


Energy-Dependent Mixing Parameters

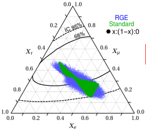
Babu, VB, de Gouvêa, Machado, PRD 2022



$$\Longrightarrow \quad U(Q_p^2) \neq U(Q_d^2) \quad \Longrightarrow$$



T2K
NOvA



IceCube

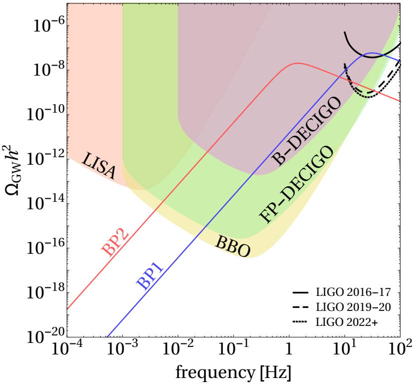
Model containing light new particles

Mismatch between PMNS matrix at Q_p^2 and Q_d^2

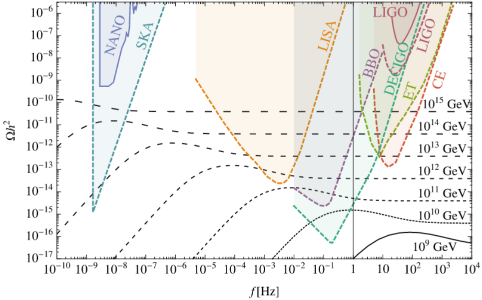
Probing the High Scale Origin of Neutrino Mass

- 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

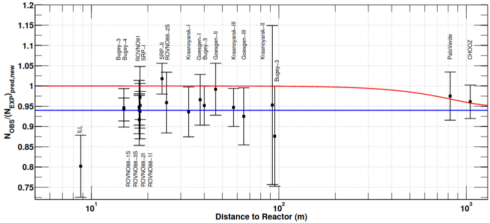


Dror et al., PRL 2020

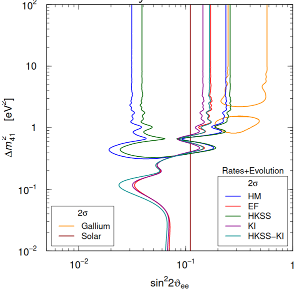


Anomalies: Reactor and Gallium

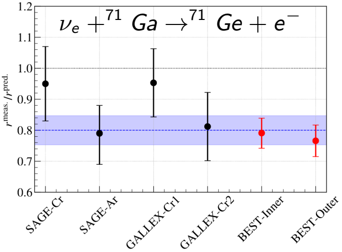
Huber PRC 2011, Mention et al., PRD 2011

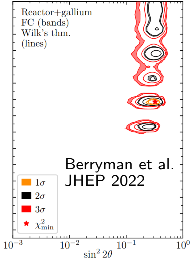


Giunti et al. PLB 2022
see also Berryman et al. JHEP 2022



- reactor anomaly is fading away

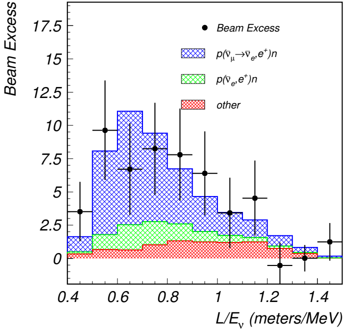


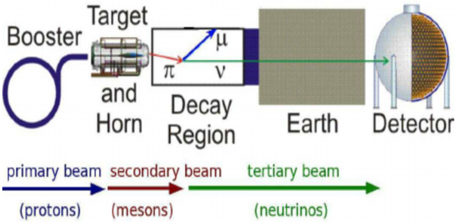


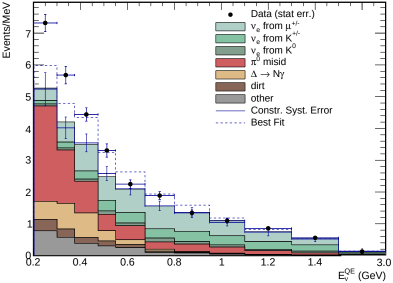
from B. Littlejohn

…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 $L/E \sim 1 \text{km GeV}^{-1}$
- MiniBooNE: reports electron-like event excess (4.8σ)
- in combination with LSND 6.1σ

Standard Model Explanation?

arXiv > hep-ph > arXiv:2109.08157

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High Energy Physics - Phenomenology

[Submitted on 16 Sep 2021 (v1), last revised 17 Jun 2022 (this version, v2)]

An Altarelli Cocktail for the MiniBooNE Anomaly?

Vedran Brdar (Fermilab and Northwestern U), Joachim Kopp (CERN and JGU Mainz)

We critically examine a number of theoretical uncertainties affecting the MiniBooNE short-baseline neutrino oscillation experiment in an attempt to better understand the observed excess of electron-like events. We re-examine the impact of fake charged current quasi-elastic (CCQE) events, the background due to neutral current π^0 production, and the single-photon background. For all processes, we compare the predictions of different event generators (GENIE, GiBUU, NUANCE, and NuWro) and, for GENIE, of different tunes. Where MiniBooNE uses data-driven background predictions, we discuss the uncertainties affecting the relation between the signal sample and the control sample. In the case of the single-photon background, we emphasize the uncertainties in the radiative branching ratios of heavy hadronic resonances. We find that not even a combination of uncertainties in different channels adding up unfavorably (an "Altarelli cocktail") appears to be sufficient to resolve the MiniBooNE anomaly. We finally investigate how modified background predictions affect the fit of a $3+1$ sterile neutrino scenario. We carefully account for full four-flavor oscillations not only in the signal, but also in the background and control samples. We emphasize that because of the strong correlation between MiniBooNE's ν_e and ν_μ samples, a sterile neutrino mixing only with ν_μ is sufficient to explain the anomaly, even though the well-known tension with external constraints on ν_μ disappearance persists.

arXiv > hep-ph > arXiv:2210.08021

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High Energy Physics - Phenomenology

[Submitted on 14 Oct 2022]

More Ingredients for an Altarelli Cocktail at MiniBooNE

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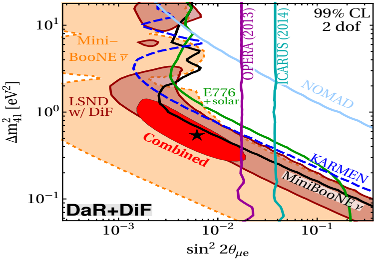
The MiniBooNE excess of low-energy electron-neutrino-like events persists as one of the most significant puzzles in particle physics today and remains the subject of intense experimental and theoretical focus. A key feature of this excess is the inability of the detector to discriminate between electron-like signals and backgrounds due to photons. Besides single photons, this includes also pairs of overlapping and/or highly-asymmetric photons. In this work, we study photon backgrounds in MiniBooNE in depth, first considering a novel single-photon background arising from multi-nucleon scattering with coherently enhanced initial or final state radiation. This class of processes, which we dub "2p2hγ" (two-particle--two-hole + photon) can explain ~ 40 of the ~ 560 excess events observed by MiniBooNE in neutrino mode (positive horn polarity). Second, we consider the background from neutral-current single-π^0 production, where the two photons from $\pi^0 \to \gamma\gamma$ decay are mis-identified as an electron-like shower. We find two significant effects when comparing our results to those of MiniBooNE: first, the impact of limited Monte Carlo statistics may be larger than naively expected due to highly non-Gaussian behavior of the fluctuations. This is an effect that needs to be understood with detailed experimental studies, not least because it may affect future experiments as well. Second, in spite of data-driven background estimation techniques, there is a residual dependence on the Monte Carlo generator used. In tandem, we estimate that when combining all effects the significance of the MiniBooNE neutrino-mode low-energy excess may be reduced from 4.7σ to around 3σ.

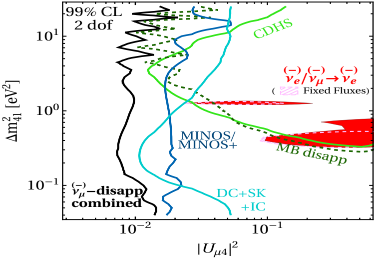
- reducing the significance to $\simeq 3\sigma$

eV-scale Sterile Neutrino Explanation?

- Oscillation maxima for standard oscillations expected at
  - $L/E \sim 500$ km/GeV (from $\Delta m^2_{31} \sim 2.4 \times 10^{-3} \text{eV}^2$)
  - $L/E \sim 15000$ km/GeV (from $\Delta m^2_{21} \sim 7.5 \times 10^{-5} \text{eV}^2$)
- the minimal solution for LSND and MiniBooNE requires an additional mass squared difference $\Delta m^2_{41} \sim 1\,\text{eV}^2$



Kopp et al., arXiv:1803.10661

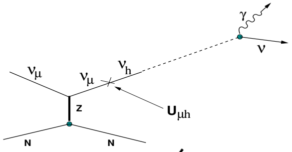


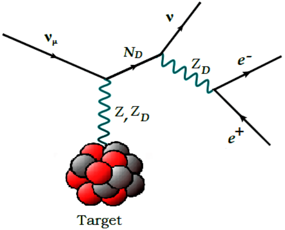
- while ν_e appearance data supports eV-scale ν_s explanation of LSND and MiniBooNE, ν_μ disappearance data puts such solution in strong tension

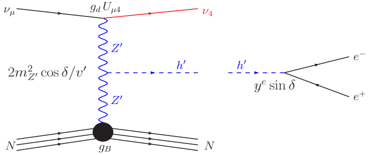
Non-oscillatory Explanations of MiniBooNE Anomaly

- 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 $N \to \nu\, e^+e^-$		
Dipole portal	Upscattering to $N \to \nu\,\gamma$		
(3+1) + vis-ν decay	DIF of $\nu_s \to \nu_e$		
(3+1) + vis decay	DIF of $N \to \nu\,\gamma$		
Dark sectors: dark matter	Upscattering to $\chi' \to \chi\, e^+e^-$		
Dark sectors: (pseudo)-scalar	Forward scattering to γ		







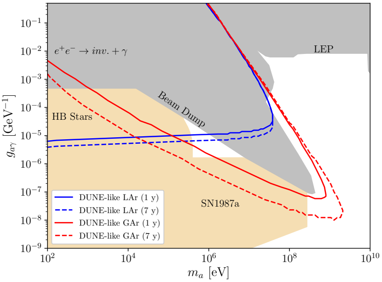
Beyond Neutrino Mass, Beyond Anomalies

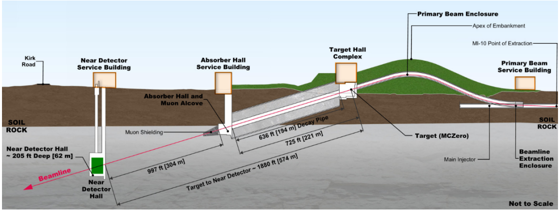
from Jae Yu (Snowmass 2021)

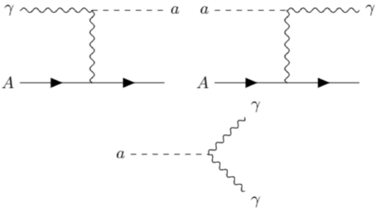
Pulido in parallel sessions

Process	Signatures	Background
ALP	Scattering: γ+e/ γ+N (n) Decay in flight : γγ	ν coherent, NC w/ π^0, ν_e CC w/ π^0, etc
LDM	$\chi e^- \to \chi e^-$, $\chi N \to N'n$	NC w/ π^0, ν_e CC, QE, RES
mCP	Multiple e^- scatterings	ν_e CC w/ π^0
Dark Photon	$A \to e^- e^+$, $\mu^- \mu^+$	ν CC + mis-ID π, Accidental overlap of CC
HNL	$N \to \nu e^- e^+$, $\nu\mu^-\mu^+$, $\nu e\mu$, $\nu\pi^0$, $e\pi$, $\mu\pi$	ν CC + mis-ID π, ν_e CC w/ π^0
ν trident	$\nu \to \nu e^- e^+$, $\nu\mu^-\mu^+$, $\nu e\mu$	$\nu_\mu N \to \nu_\mu \pi N$□ (ν CC)
BDM/ iBDM	$\chi N \to e^- N$	ν coherent, NC w/ π^0, ν_e CC

VB et al. PRL 2021

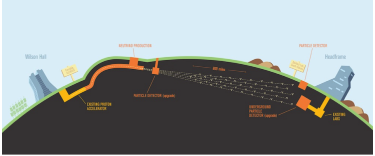


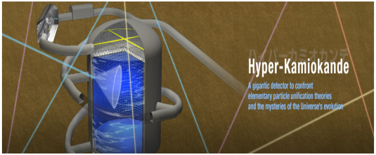




Summary. Quo Vadis, Neutrino?

- Goal for the oscillation physics: CP phase, mass ordering, θ_{23} octant

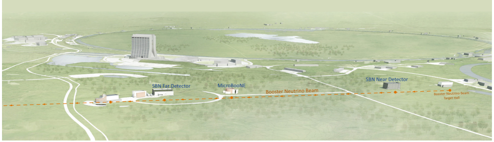




- Theory input: reducing the ν-nucleus cross section uncertainties
- Bonus: Neutrino experiments as a powerful probe of BSM (ALPs...)

- Holy Grail for Neutrino Theory: The Origin of Neutrino Mass
- HL-LHC? Gravitational Waves? New Ideas?

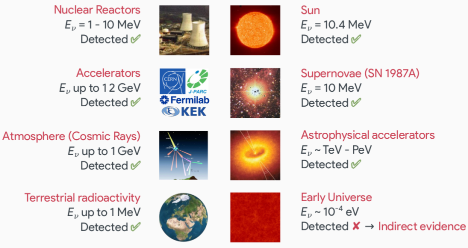
- In the meantime....... Anomalies!



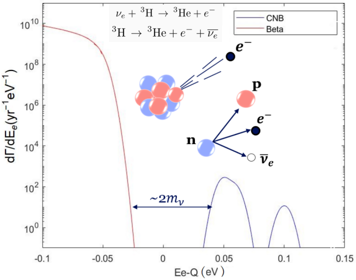
BACKUP

Direct Detection of Cosmic Neutrino Background

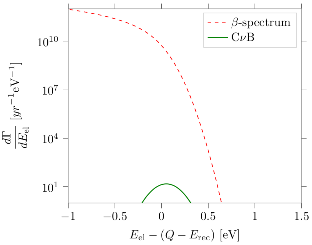
Giachero (2020)



Tan, Cheianov, 2202.07406



- Graphene substrates to hold ^3H at PTOLEMY
- Intrinsic uncertainty in the e^- energy (Cheipesh et al., 2101.10069)



- Heavier nuclei?

VB, Plestid, Rocco, PRC 2022