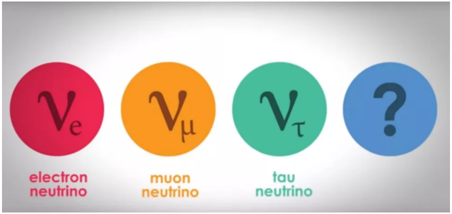
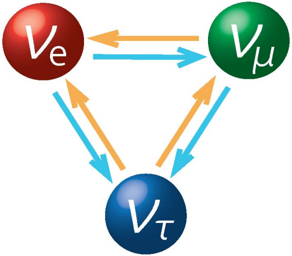
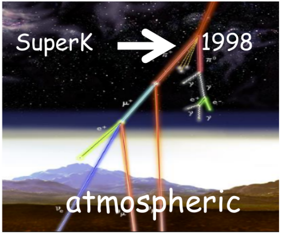
Neutrino Theory - Main Issues

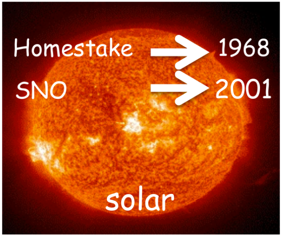


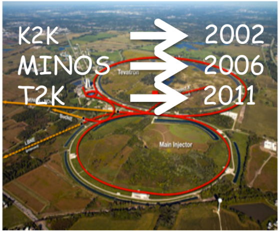


Vedran Brdar (CERN–TH)

Neutrino Oscillations



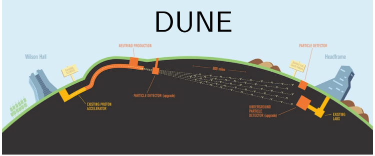


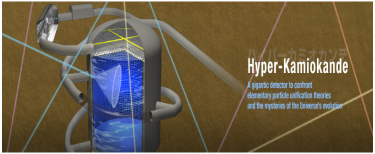


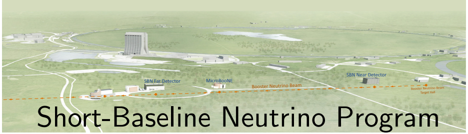
$$P_{\alpha\beta} = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

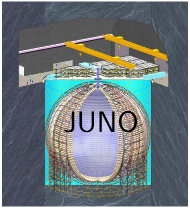
(Some of the) Open Questions

- 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?

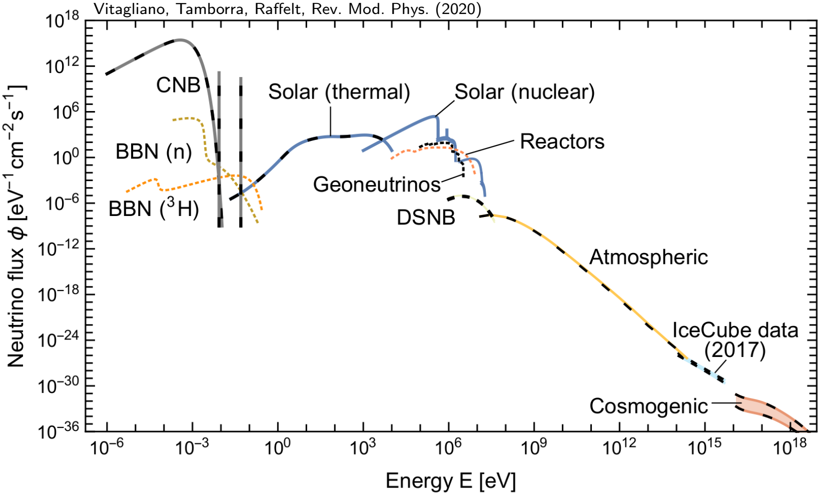




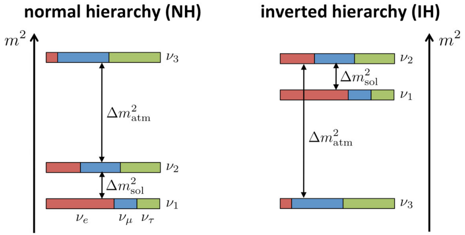




Grand Unified Neutrino Spectrum at Earth



Neutrino Mass Ordering

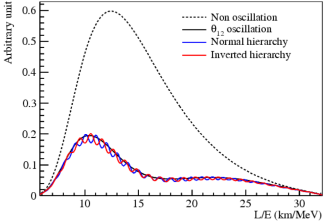


NuFIT, 2007.14792

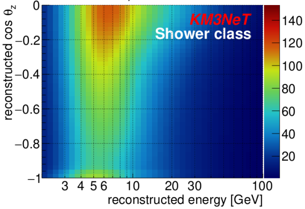
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$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

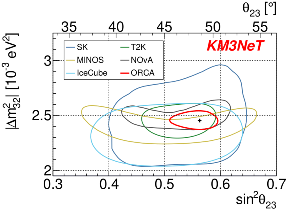
- vacuum, $E_\nu \sim$ MeV
- matter effects, $E_\nu \gtrsim$ GeV

JUNO, 2103.09885

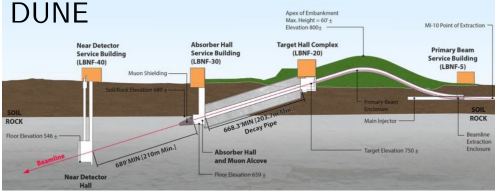


KM3NeT, 2103.09885

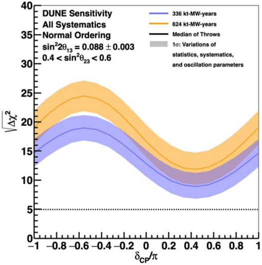




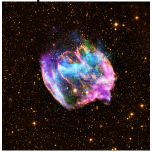
Neutrino Mass Ordering



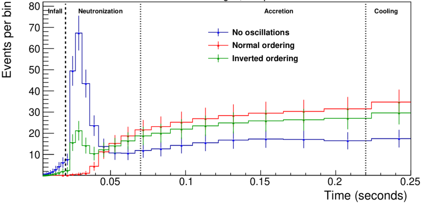
DUNE, EPJC 2020



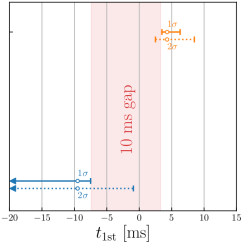
Supernovae



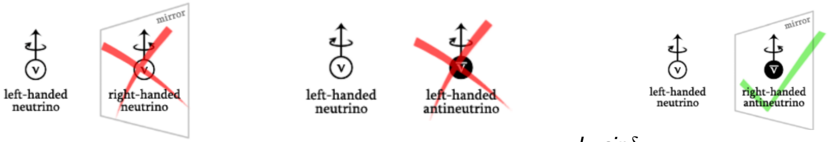
Scholberg, 1707.06384 40 kton argon, 10 kpc



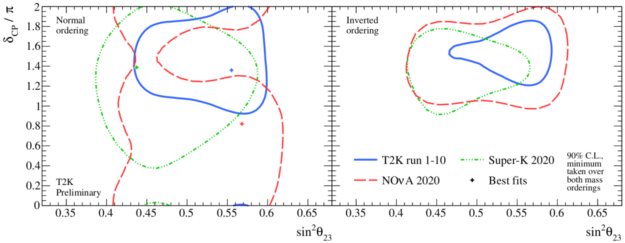
VB, Xu, JCAP 2022

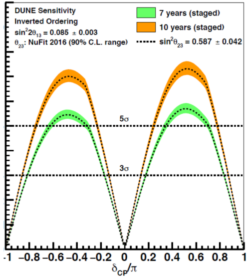


CP Violation in Lepton Sector



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

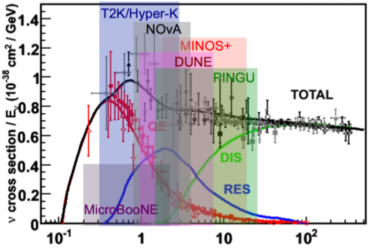




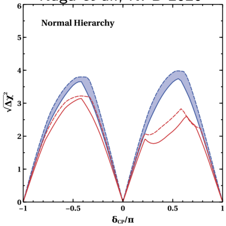
Prerequisites for the Discovery

- Reduction of ν-nucleus cross section uncertainties

G. Zeller

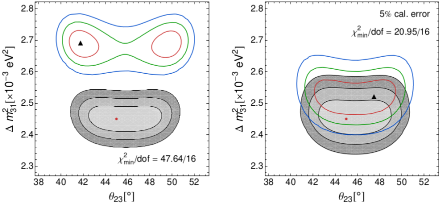


Nagu et al., NPB 2020

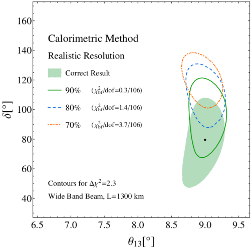


- Reconstruction of neutrino energy

Coloma et al., 1311.4506

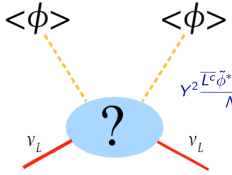


Ankowski et al., 1507.08561



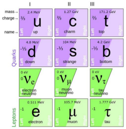
Is the Neutrino its own Antiparticle?

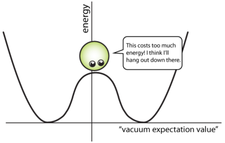
Majorana



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

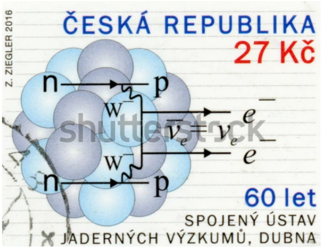
Dirac

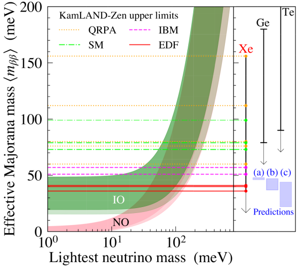




$y\bar{\psi}_L \phi \psi_R \Rightarrow m_\nu = y\langle\phi\rangle \Rightarrow y \sim 10^{-12}$

$0\nu 2\beta$ Decay



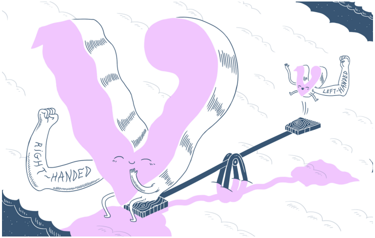


$\Gamma_{0\nu 2\beta} \propto G_F^4 |\tilde{M}_{0\nu 2\beta}|^2 \left|\sum U_{ej}^2 m_j\right|^2 p_e^2$

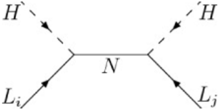
Theory Challenge:
Matrix Elements

Neutrino Mass

Type-I Seesaw



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

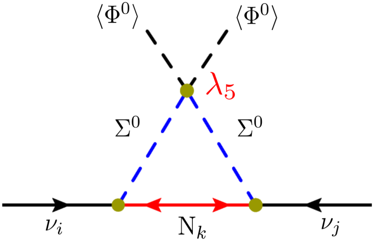


$$m_\nu = -M_D M_R^{-1} M_D^T$$

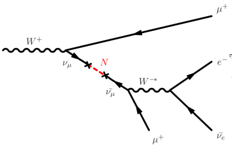
Scotogenic Model

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

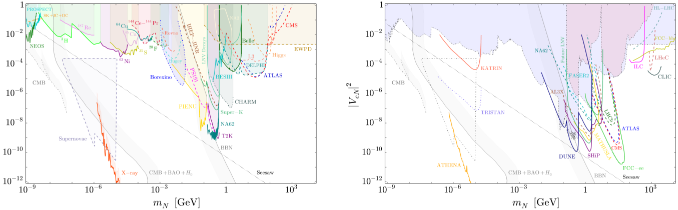
Ma (2006)



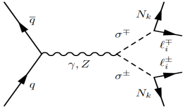
Probing the Low Scale Origin of Neutrino Mass

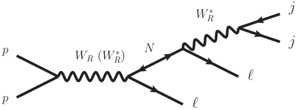


Bolton et al., JHEP 2020

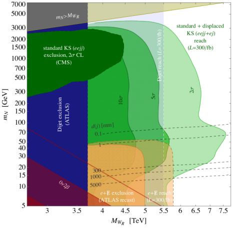


- for type-I Seesaw, $V_{\alpha N} \sim 10^{-6}\sqrt{100\,\text{GeV}/M_R} \Rightarrow$ not testable
- remedy: inverse seesaw, new interactions of N...

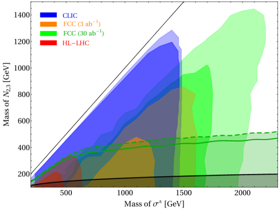




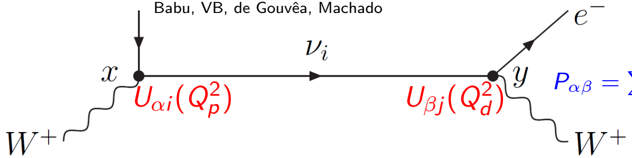
Nemevšek et al, PRD 2018



Baumholzer et al, JHEP 2020



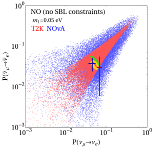
Babu, VB, de Gouvêa, Machado



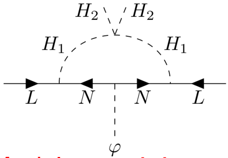
$$P_{\alpha\beta} = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}\, e^{-i\frac{m_j^2 - m_k^2}{2|\vec{p}|}L}$$

Energy dependence of oscillation parameters:

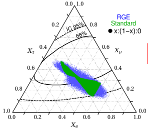
- propagating neutrino is on shell ($Q^2 = p_\nu^2 = m_\nu^2 \approx 0$) $\rightarrow$ m_i in formula is the mass at $\sqrt{Q^2} = m_i$
- at production, contribution to the amplitude should be Lorentz invariant; in the rest frame of decaying pion $E = m_\pi \rightarrow U_{\alpha i} = U_{\alpha i}(Q_p^2 = m_\pi^2)$
- at detection site we take $U_{\beta i}(Q_d^2)$ where Q_d^2 is Mandelstam t which has no dependence on m_π^2



T2K
NOvA



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



IceCube

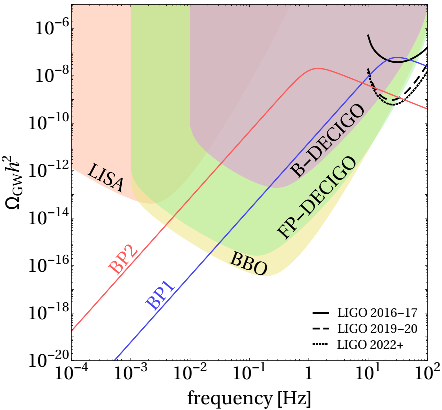
Model containing light new particles

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

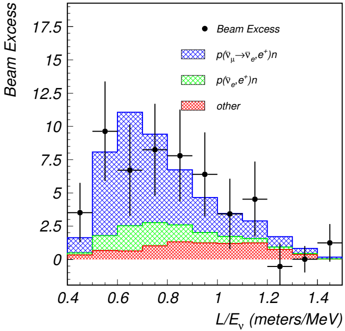
Probing the High Scale Origin of Neutrino Mass

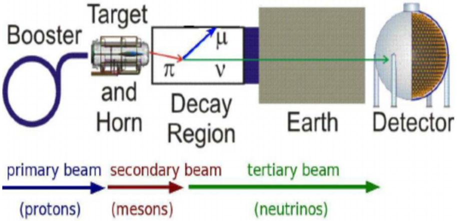
- GW detectors as a window to unexplored seesaw scales
- testing $M_N \lesssim 10^8$ GeV in models featuring first-order phase transition
  (for GW from topological defects, e.g. cosmic strings GUT scale can be probed)

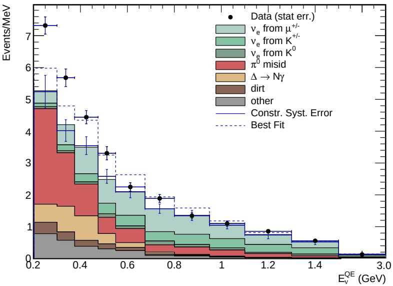
VB, Helmboldt, Kubo, JCAP 2019



Anomalies: LSND and MiniBooNE



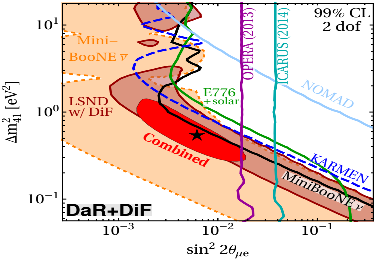




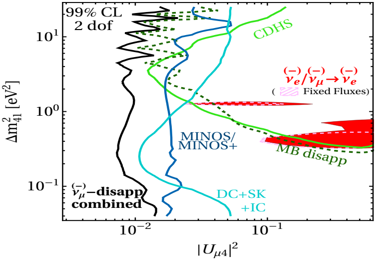
- LSND: $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam from stopped pion source ($> 3\sigma$) at $L/E \sim 1\text{km GeV}^{-1}$
- MiniBooNE: reports electron-like event excess (4.8σ)
- in combination with LSND 6.1σ

eV-scale Sterile Neutrino as an 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

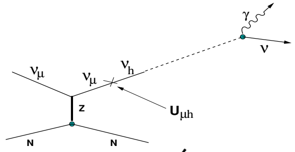


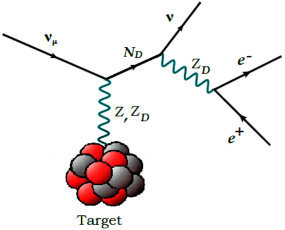
- while ν_e appearance data supports eV-scale ν_s explanation of LSND and MiniBooNE, ν_μ disappearance data puts such solution in strong tension

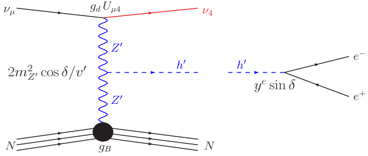
Non-oscillatory Explanations of MiniBooNE Anomaly

- 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	$\mu^+ \rightarrow$ anti-ν_e		
Lorentz violation	Sidereal time variation		
Dark neutrinos	Upscattering to $N \rightarrow \nu\, e^+e^-$		
Dipole portal	Upscattering to $N \rightarrow \nu\, \gamma$		
(3+1) + vis-ν decay	DIF of $\nu_s \rightarrow \nu_e$		
(3+1) + vis decay	DIF of $N \rightarrow \nu\, \gamma$		
Dark sectors: dark matter	Upscattering to $\chi' \rightarrow \chi\, e^+e^-$		
Dark sectors: (pseudo)-scalar	Forward scattering to γ		





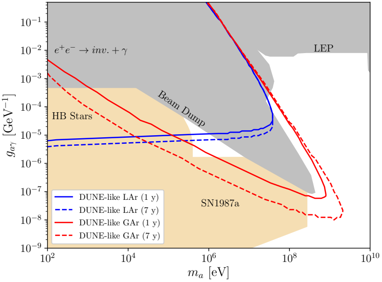


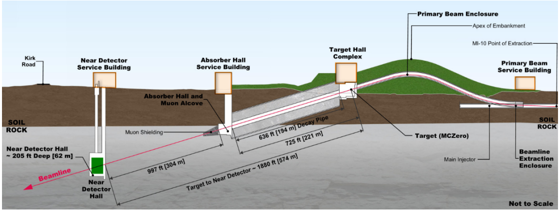
Beyond Neutrino Mass, Beyond Anomalies

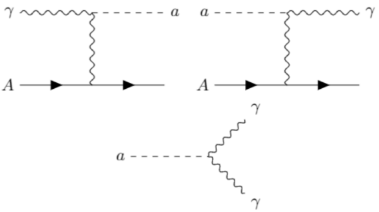
from Jae Yu (Snowmass 2021)

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

VB et al. PRL 2021

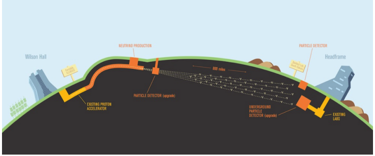


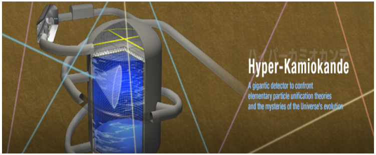




Summary. Quo Vadis, Neutrino?

- 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!