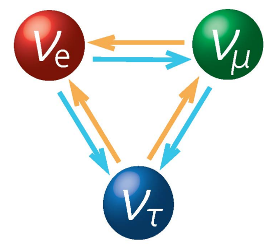
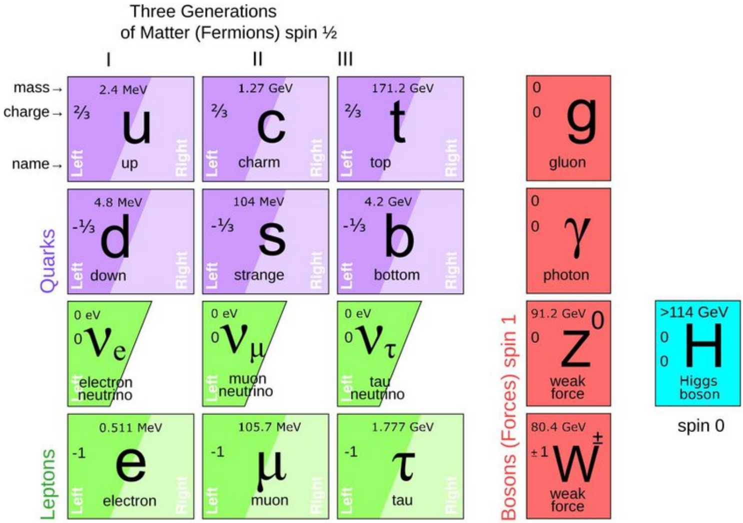
Introduction to Neutrino Physics

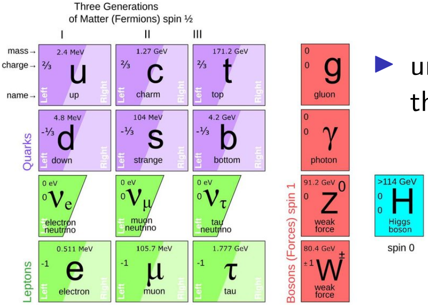


Vedran Brdar (CERN–TH)

Standard Model

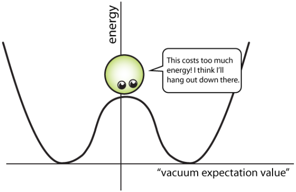


Neutrinos in the Standard Model



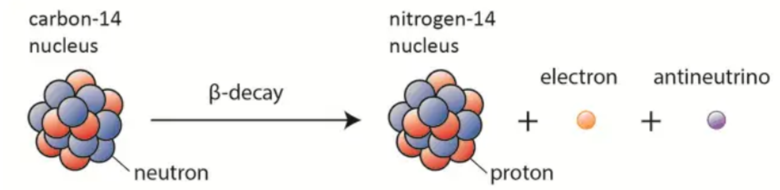
- unlike all other fermions, neutrinos in the Standard Model are only left-handed

$$y\bar{\psi}_L H\psi_R$$

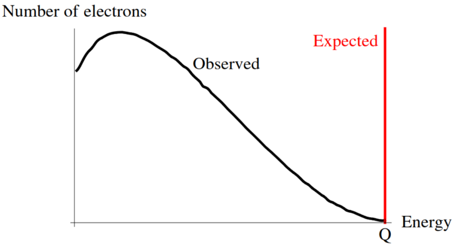


- neutrinos in the Standard Model are massless

First Hint for the Neutrino Existence

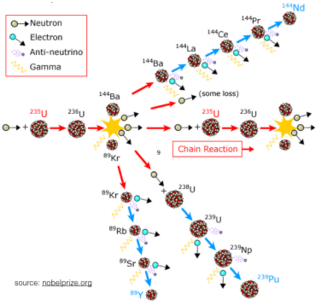


- in β decays, electron was observed to have a continuous rather than a discrete spectrum $\Longrightarrow$ something else was emitted!?

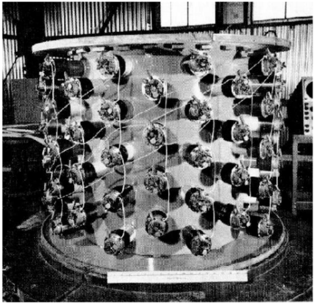


- such a new particle would need to be electrically neutral and interact very weakly $\Longrightarrow$ called neutrino ("the little neutral one" in Italian)

Neutrino Discovery



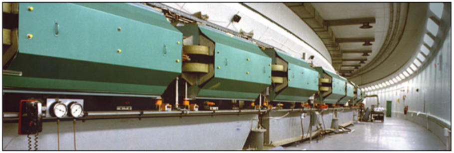
source: nobelprize.org

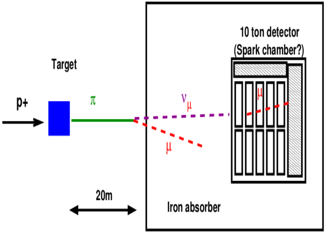


- electron (anti)neutrinos first detected using a nuclear reactor in 1956

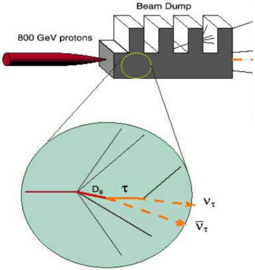
$$(1)\ \bar{\nu}_e\ p \Longrightarrow n\ e^+$$
$$(2)\ e^+\ e^- \Longrightarrow \gamma\ \gamma$$
$$(3)\ n\ {}^{108}Cd \Longrightarrow\ {}^{109}Cd\ \gamma \quad (5\mu s \text{ delayed})$$

Muon and Tau Neutrinos





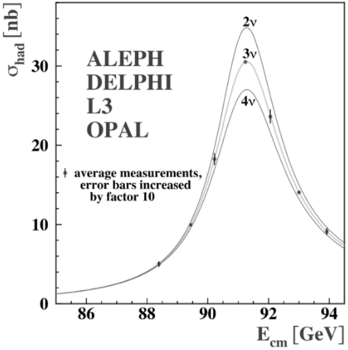
- muon neutrino (ν_μ) discovered at BNL in 1962 via $\nu_\mu n \rightarrow p\mu^-$



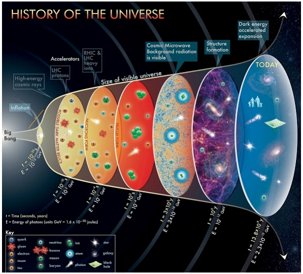
- tau neutrino (ν_τ) discovered by DONUT collaboration at Fermilab in 2000

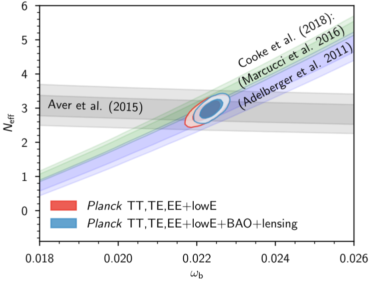
(1) $\nu_\tau \ n \Longrightarrow p \ \tau^-$
(2) τ^- decay to e^- or μ^- or hadrons $+ \ \nu_s$

Number of Neutrino Species



$$N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_{\bar{\nu}\nu}} = 2.984 \pm 0.008$$





The Solar and Atmospheric Neutrino Problem

- Sun produces electron neutrinos: $4p\ 2e^- \rightarrow {}^4\mathrm{He}\ 2\nu_e\ Q$
- Observed number of solar ν_e events at the Homestake experiment was $\sim$ 3 times smaller than expected
- atmospheric neutrinos are produced from collisions of cosmic rays with nuclei in the Earth's atmosphere
- Observed number of atmospheric ν_μ events smaller than expected

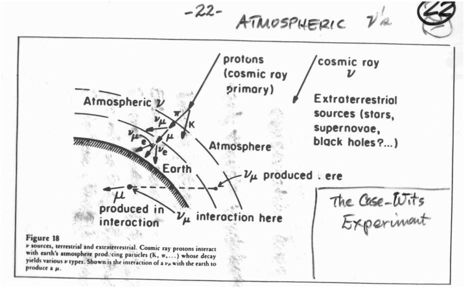
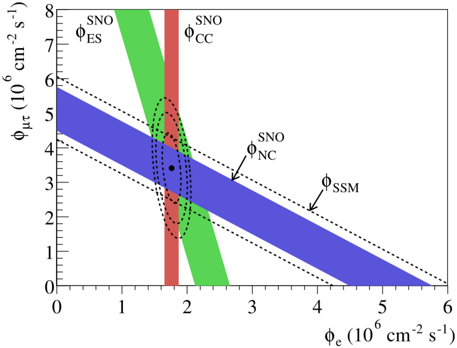
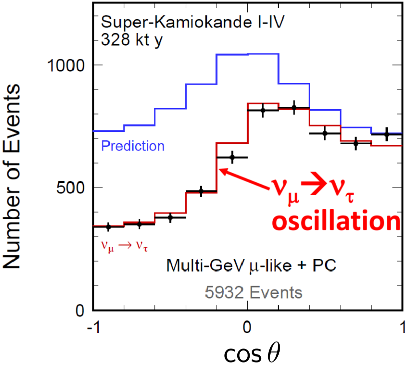


Figure 18
ν sources, terrestrial and extraterrestrial. Cosmic ray protons interact with earth's atmosphere producing particles (K, π, ...) whose decay yields various ν types. Shown is the interaction of a ν_μ with the earth to produce a μ.

Solution: Neutrinos Change Flavor as They Travel





Neutrino Oscillations

$$\nu_\alpha = U_{\alpha i}\ \nu_i$$

$\alpha = e, \mu, \tau$
$i = 1, 2, 3$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

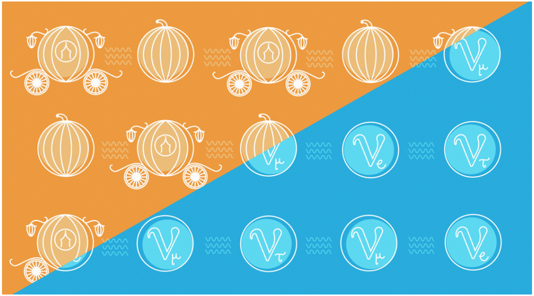
- produce flavor α at the source $|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} |\nu_j\rangle$
- en route to the detector $|\nu_\alpha(T, L)\rangle = \sum_j U^*_{\alpha j}\,\mathrm{Exp}[-iE_j T + ip_j L]\ |\nu_j\rangle$
- detector measures state $\langle\nu_\beta| = \sum_k U_{\beta k} \langle\nu_k|$
- $\mathcal{A} = \langle\nu_\beta|\nu_\alpha(T, L)\rangle = \sum_{j,k} U^*_{\alpha j} U_{\beta k} \mathrm{Exp}[-iE_j T + ip_j L] \overbrace{\langle\nu_k|\nu_j\rangle}^{\delta_{jk}}$

$$P_{\alpha\beta} = |\mathcal{A}|^2 = \sum_{j,k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k}\ \mathrm{Exp}[\frac{-i(m_j^2 - m_k^2)L}{2E}]$$

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

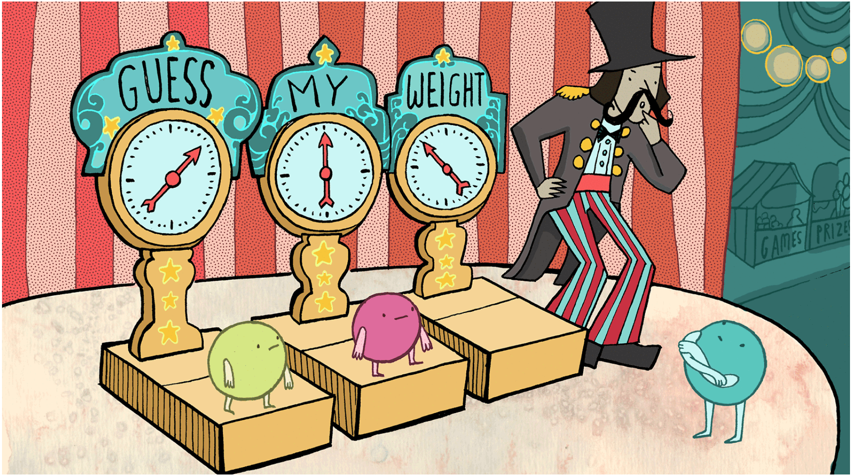
Neutrino Oscillations

credit: Symmetry Magazine

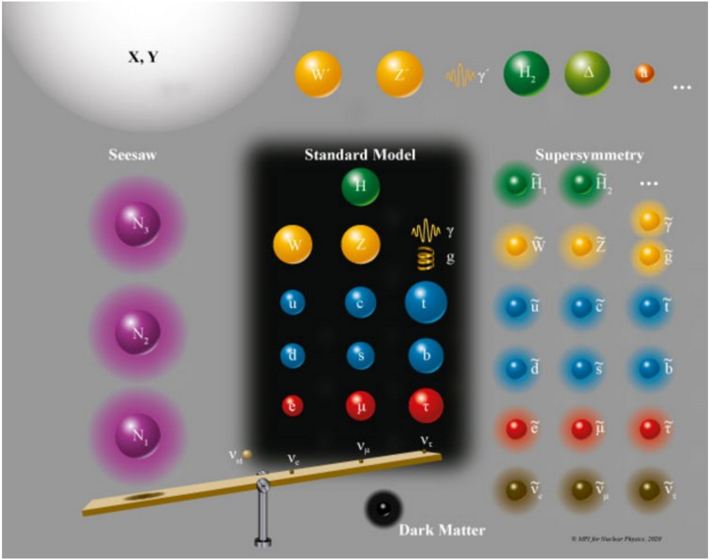


$$P_{\alpha\beta} = \sin^2 2\theta \sin^2(\frac{\Delta m^2 L}{4E})$$

Neutrinos Have Mass

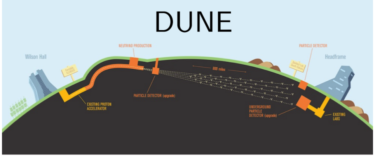


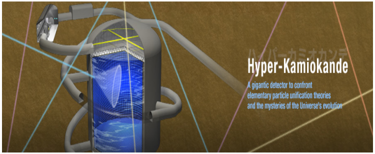
Beyond The Standard Model

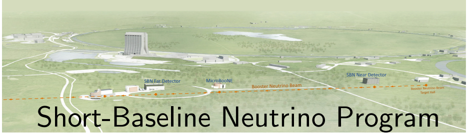


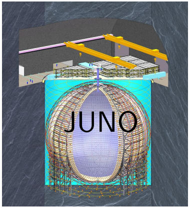
(Some of the) Open Questions

- 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?
- New Physics?



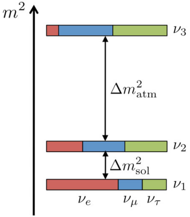


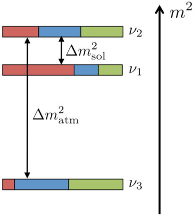




CP violation and neutrino mass ordering?

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


normal hierarchy (NH)

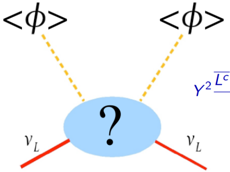

inverted hierarchy (IH)

$$U(\theta_{12}, \theta_{23}, \theta_{13}, \delta)$$

$$\theta_{12} \in [31^\circ, 35^\circ]$$
$$\theta_{23} \in [40^\circ, 52^\circ]$$
$$\theta_{13} \in [8.2^\circ, 9^\circ]$$
$$\delta \in [0, 2\pi]$$

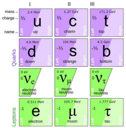
Is the Neutrino its own Antiparticle?

Majorana

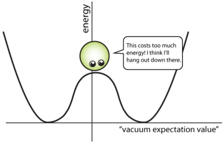


$$Y^2 \frac{\overline{L^c}\tilde{\phi}^* \tilde{\phi}^\dagger L}{\Lambda} \longrightarrow m_\nu \sim Y^2 \frac{\langle\phi\rangle^2}{\Lambda}$$

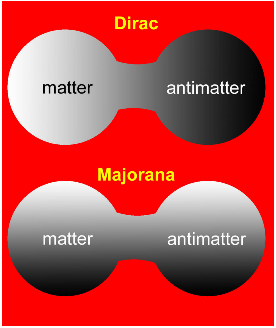
Dirac



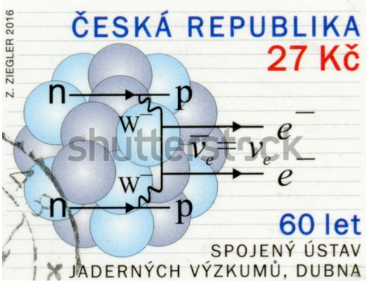
	I	II	III
mass → charge → name →	2.4 MeV ⅔ u up	1.27 GeV ⅔ c charm	171.2 GeV ⅔ t top
Quarks	4.8 MeV -⅓ d down	104 MeV -⅓ s strange	4.2 GeV -⅓ b bottom
	0 eV 0 ν_e electron neutrino	0 eV 0 ν_μ muon neutrino	0 eV 0 ν_τ tau neutrino
Leptons	0.511 MeV -1 e electron	105.7 MeV -1 μ muon	1.777 GeV -1 τ tau



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

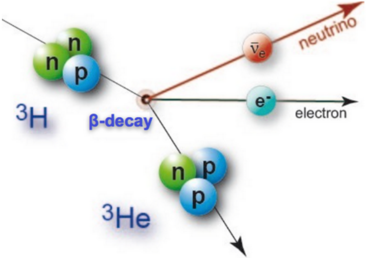


Neutrinoless double beta decay

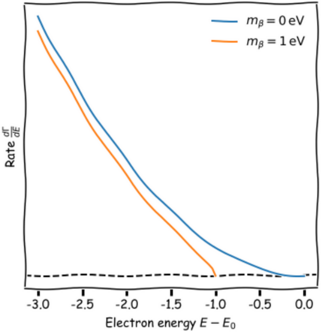


Neutrino Mass Scale?

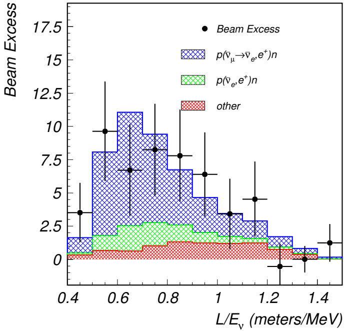
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < 0.8 \text{ eV (Nature 2022)}$$

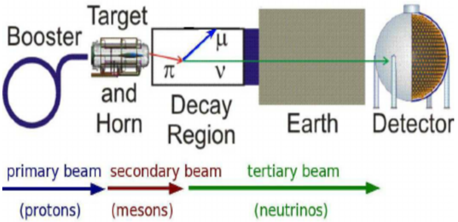


PROJECT 8

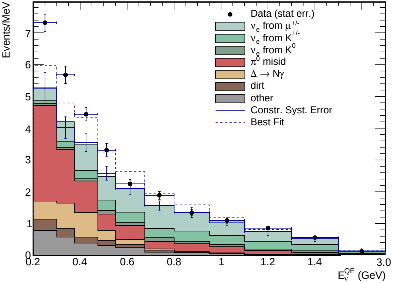


Anomalies: LSND and MiniBooNE





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



eV-scale ν_s for LSND and MiniBooNE Anomalies?

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

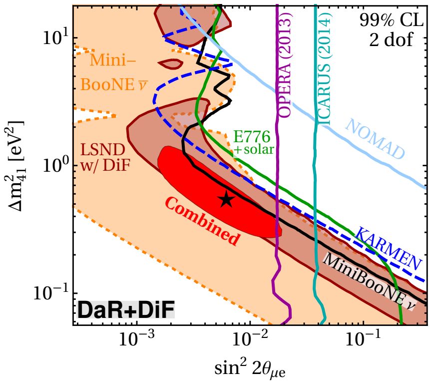
$$U^{\text{4flavor}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

$$\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$$

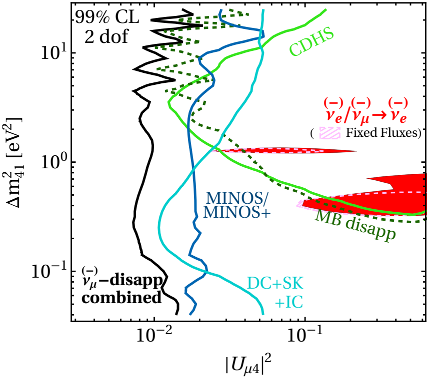
$$P_{\mu e} = 4|U_{\mu 4}U_{e4}|^2 \times \sin^2\left(\frac{(m_4^2 - m_1^2)L}{4E}\right)$$

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

3+1 Model with eV-scale Sterile Neutrino

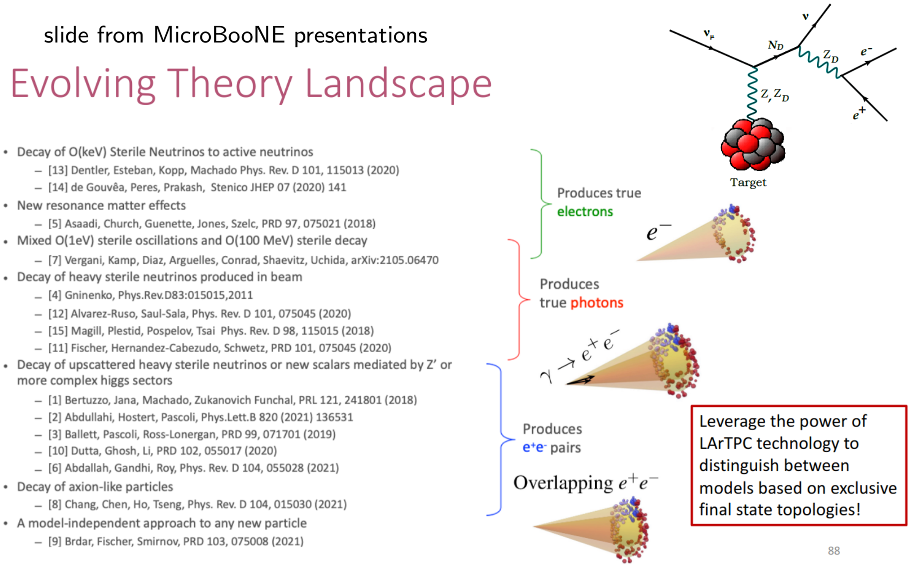


Kopp et al., arXiv:1803.10661



Non-oscillatory Explanations of MiniBooNE Anomaly

slide from MicroBooNE presentations



Evolving Theory Landscape

- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - [13] Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)
  - [14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141
- New resonance matter effects
  - [5] Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
  - [7] Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470
- Decay of heavy sterile neutrinos produced in beam
  - [4] Gninenko, Phys.Rev.D83:015015,2011
  - [12] Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)
  - [15] Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)
  - [11] Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
  - [1] Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)
  - [2] Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531
  - [3] Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)
  - [10] Dutta, Ghosh, Li, PRD 102, 055017 (2020)
  - [6] Abdallah, Gandhi, Roy, Phys. Rev. D 104, 055028 (2021)
- Decay of axion-like particles
  - [8] Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)
- A model-independent approach to any new particle
  - [9] Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)

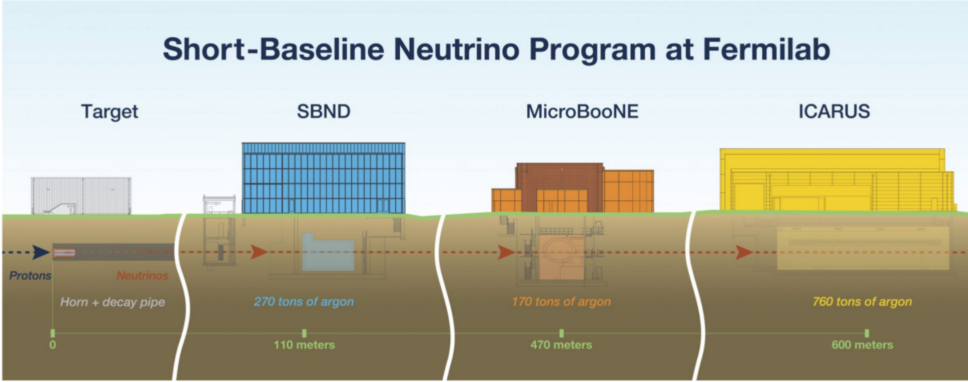
Produces true **electrons**

Produces true **photons**

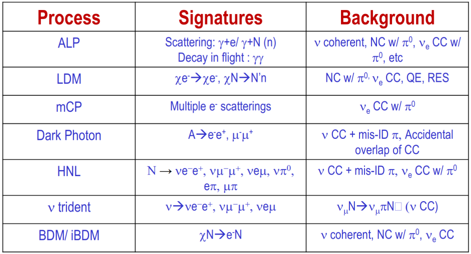
Produces **e^+e^-** pairs

Leverage the power of LArTPC technology to distinguish between models based on exclusive final state topologies!

Short-Baseline Neutrino Program

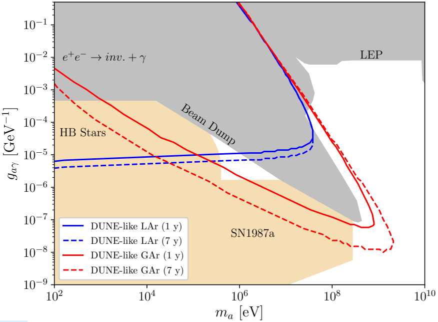


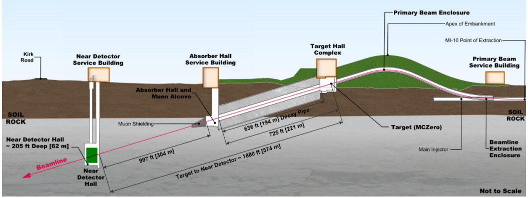
Testing New Physics Beyond Anomalies

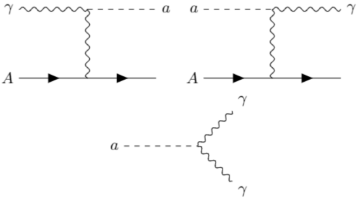


Process	Signatures	Background
ALP	Scattering: γ+e/ γ+N (n) Decay in flight : $\gamma\gamma$	ν coherent, NC w/ π^0, ν_e CC w/ π^0, etc
LDM	$\chi e^- \rightarrow \chi e^-$, $\chi N \rightarrow N'n$	NC w/ π^0, ν_e CC, QE, RES
mCP	Multiple e^- scatterings	ν_e CC w/ π^0
Dark Photon	$A \rightarrow e^-e^+$, $\mu^-\mu^+$	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

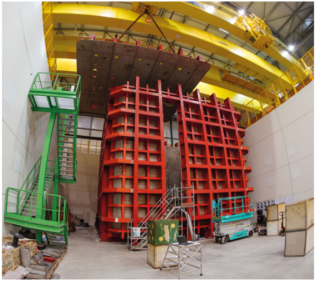
VB et al. PRL 2021

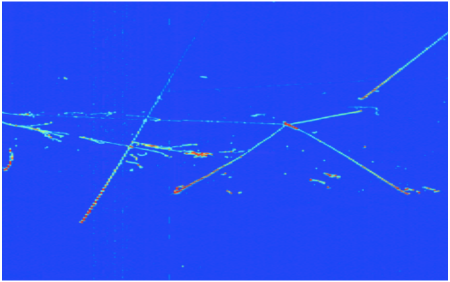


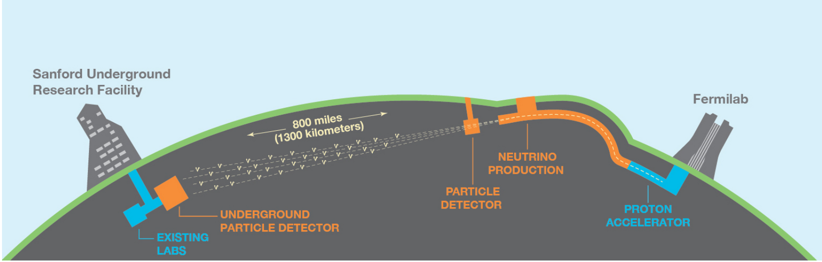




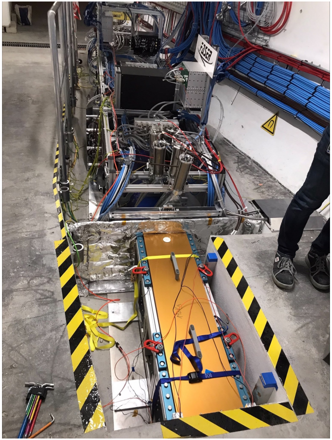
Neutrino Physics at CERN: Proto-DUNE

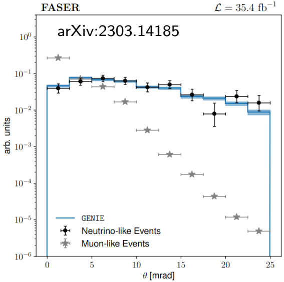






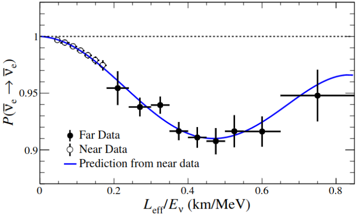
Neutrino Physics at CERN: FASERν and SND@LHC





- the beginning of the field of collider neutrino physics

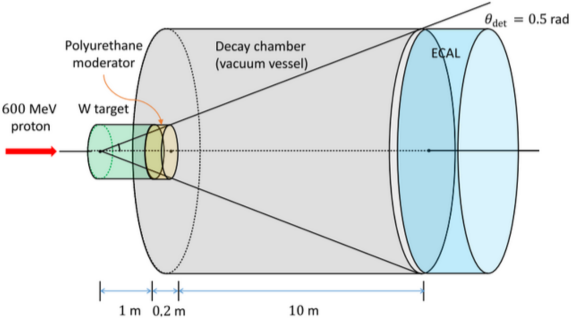
Neutrino Physics and South Korea: RENO



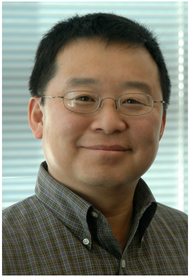
- $\sin^2 2\theta_{13} = 0.0896 \pm 0.0048(\mathrm{stat}) \pm 0.0047(\mathrm{syst})$

Neutrino Physics and South Korea: DAMSA

담사, /dɑːmsɑ/: deep thought, rumination.



DEEP UNDERGROUND NEUTRINO EXPERIMENT

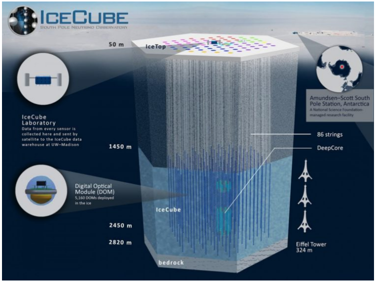


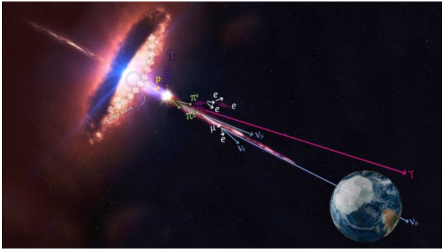
Jaehoon Yu

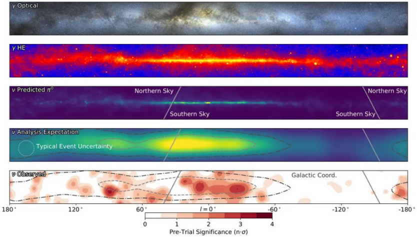
Summary. Quo Vadis, Neutrino?

- The golden age of neutrino experiments is beginning
- Goal for the oscillation physics: CP phase, mass ordering, θ_{23} octant
- Plenty of opportunities for new physics discovery at existing and near future experiments
- Ongoing program for neutrino mass measurements
- Holy Grail for Neutrino Theory: The Origin of Neutrino Mass
- There's more!

Neutrino Astronomy: IceCube

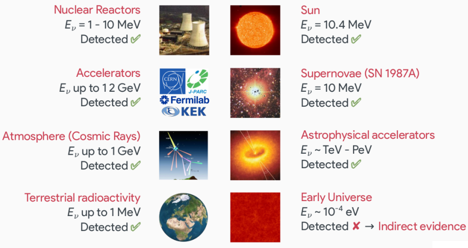






Cosmic Neutrino Background

Giachero (2020)



Nuclear Reactors
E_ν = 1 - 10 MeV
Detected ✓

Accelerators
E_ν up to 12 GeV
Detected ✓

Atmosphere (Cosmic Rays)
E_ν up to 1 GeV
Detected ✓

Terrestrial radioactivity
E_ν up to 1 MeV
Detected ✓

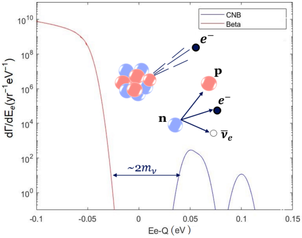
Sun
E_ν = 10.4 MeV
Detected ✓

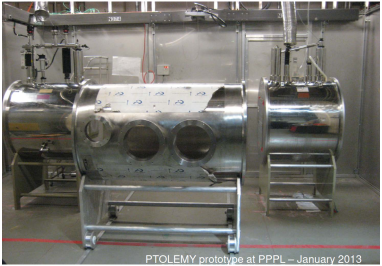
Supernovae (SN 1987A)
E_ν = 10 MeV
Detected ✓

Astrophysical accelerators
E_ν ~ TeV - PeV
Detected ✓

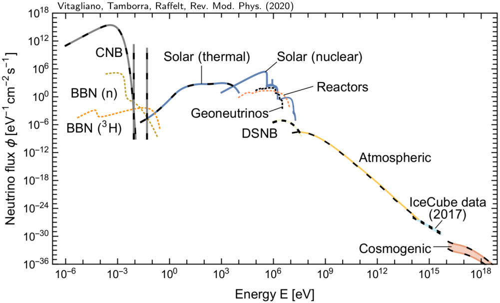
Early Universe
$E_\nu \sim 10^{-4}$ eV
Detected ✘ → Indirect evidence

Tan, Cheianov, 2202.07406





PTOLEMY prototype at PPPL – January 2013



Vitagliano, Tamborra, Raffelt, Rev. Mod. Phys. (2020)