Neutrinos: from past surprises to current puzzles

13 April 2022

GGI Tea Break

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HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Horizon2020

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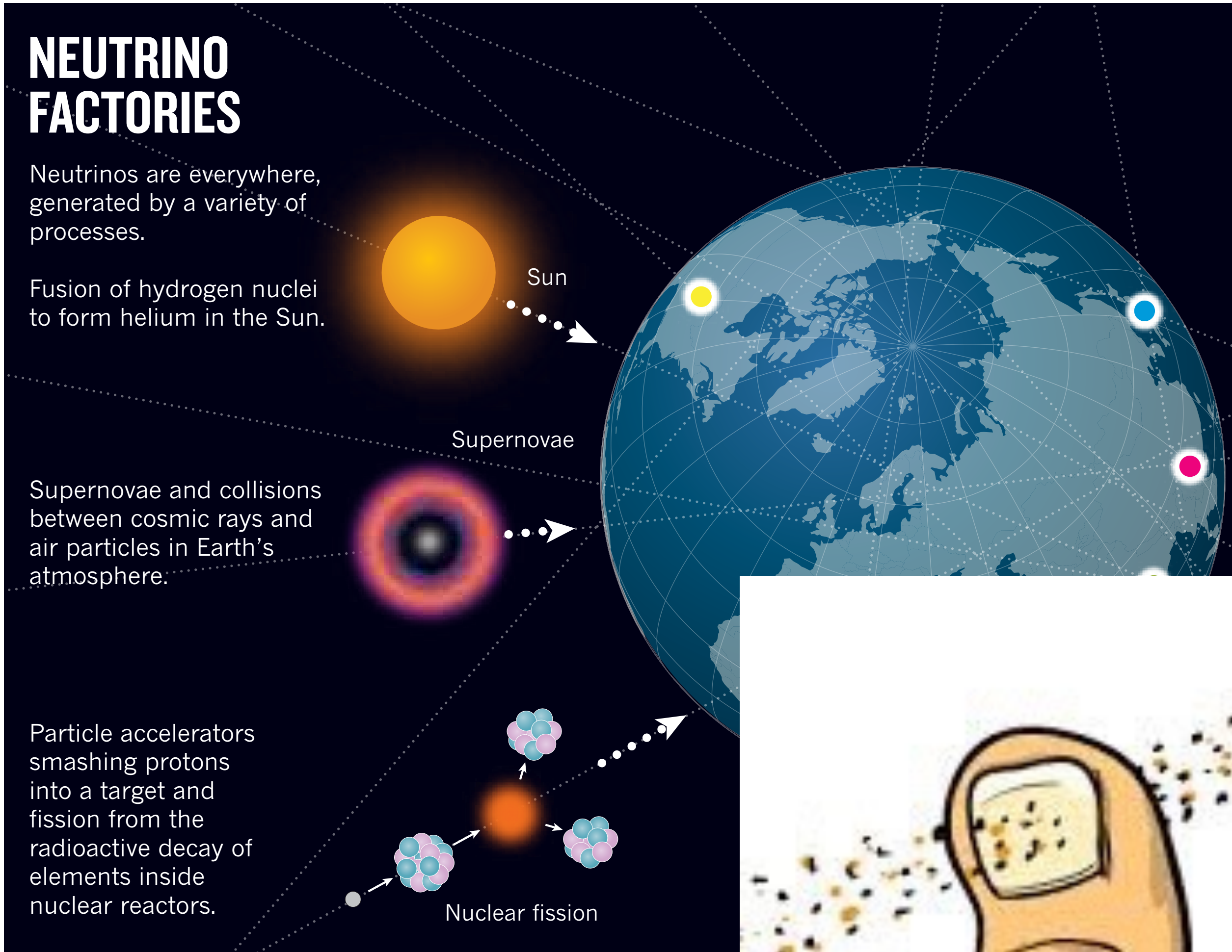
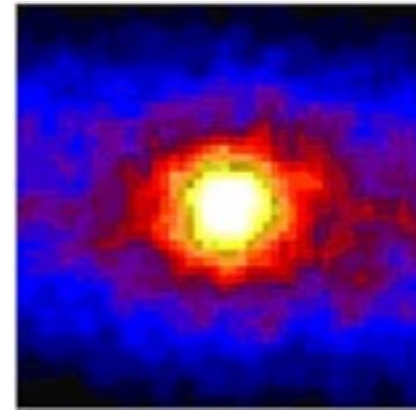
Neutrinos are all around and through us.



@Nature, 2015



@Super-Kamiokande

Neutrinoscope

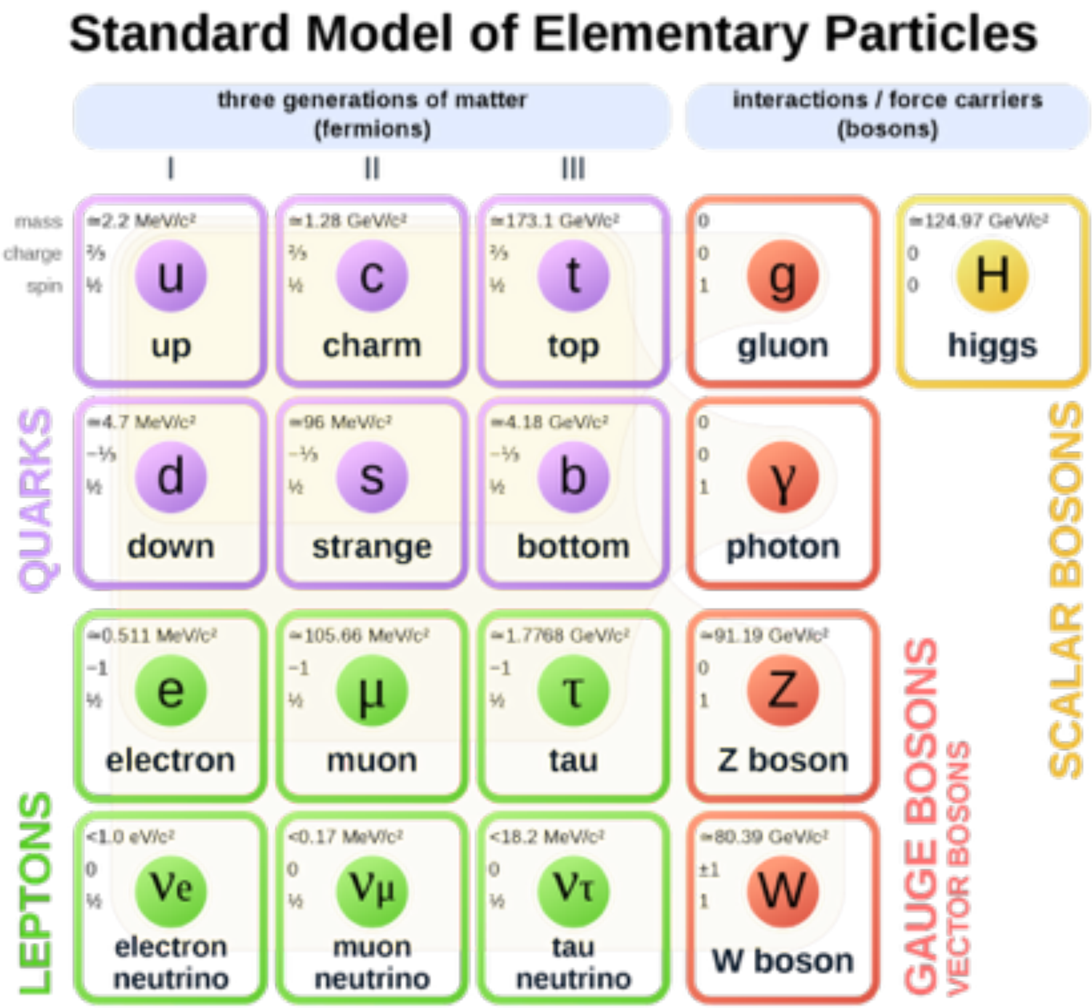
Neutrinoscope is a free App for iPhone and iPad developed by Cambridge Consultants and Durham University. It allows to visualise the neutrinos as they are around us.

Why are neutrinos interesting?

- Neutrino masses imply new physics BSM. Their origin is a necessary ingredient for the newSM.
- The least know of all SM fermions (a window on the BSM?): portal to dark sectors.
- Their nature (and the mass) is related to the fundamental symmetries of nature (lepton number?, link with proton decay).
- The most abundant of all fermions in the Universe with strong impact of its evolution.
- Neutrino mass models can explain the baryon asymmetry of the Universe.

Neutrinos in the SM

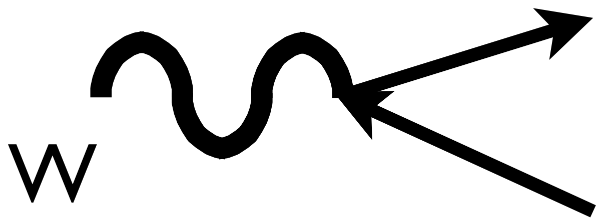
Neutrinos are the lightest and most elusive of all the known elementary particles.



- Neutrinos in the SM are described by Weyl spinors with left chirality ($P_L=1-\gamma_5/2$).

- They come in doublets with the charged leptons.

- Neutrinos come in 3 flavours, corresponding to each of the charged leptons.



They have charge current (CC) and neutral current (NC) interactions

$$\mathcal{L}_{\rm SM} = -\frac{g}{\sqrt{2}} \sum_{\alpha=e,\mu,\tau} \overline{\nu}_{\alpha L} \gamma^{\mu} \ell_{\alpha L} W_{\mu} - \frac{g}{2\cos\theta_W} \sum_{\alpha=e,\mu,\tau} \overline{\nu}_{\alpha L} \gamma^{\mu} \nu_{\alpha L} Z_{\mu} + \text{h.c.}$$

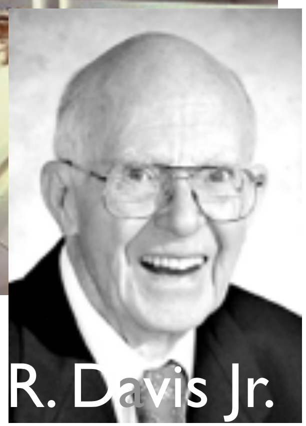
- They carry lepton number, $U(1)_{\rm lepton}$

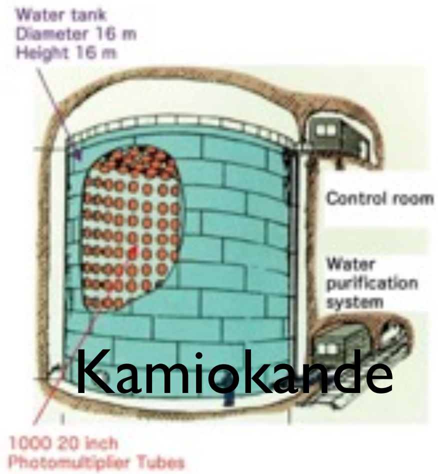
$$\ell \overset{U(1)_{\rm lepton}}{\rightarrow} e^{i\alpha} \ell \qquad \nu_L \overset{U(1)_{\rm lepton}}{\rightarrow} e^{i\alpha} \nu_L$$

Neutrino oscillations: a quantum mechanical phenomenon

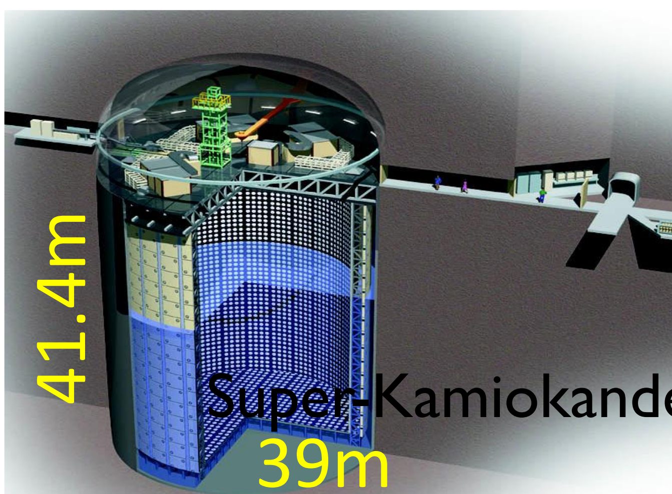
Astrophysical neutrinos, produced in the **Sun, Supernova** and in the **atmosphere, were studied and presented anomalies.**

The Homes take experi ment.





Nobel prize in 2002



Nobel Prize in Physics 2015

What was going on?

The first idea of neutrino oscillations
forward by B. Pontecorvo in 1957.

In a SM interaction a neutrino of one type (electron, muon or tau) is produced. While travelling it changes its “flavour” and can even become another type of neutrino.

Neutrino mixing

Mixing is described by the *Pontecorvo-Maki-Nakagawa-Sakata* matrix:

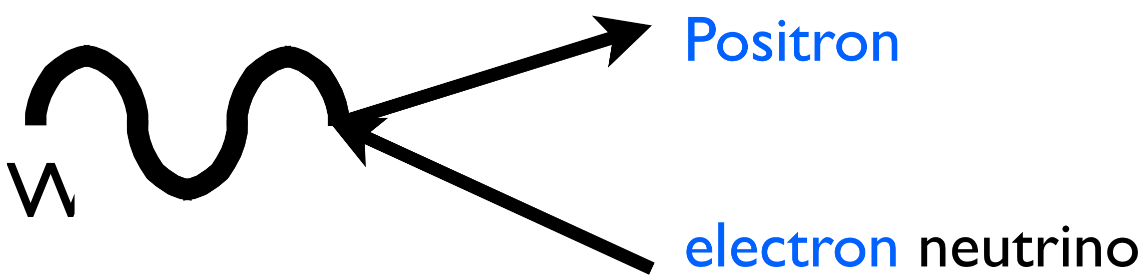
$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i$$

Flavour field (α) — Mass field (i)

which enters in the CC interactions

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \sum_{k\alpha} \left(U^*_{\alpha k} \bar{\nu}_{kL} \gamma^\rho l_{\alpha L} W_\rho + \mathrm{h.c.} \right)$$

This implies that with an electron a superposition of different neutrino mass eigenstates is involved.



$$= \sum_i U^*_{ei} \nu_i$$

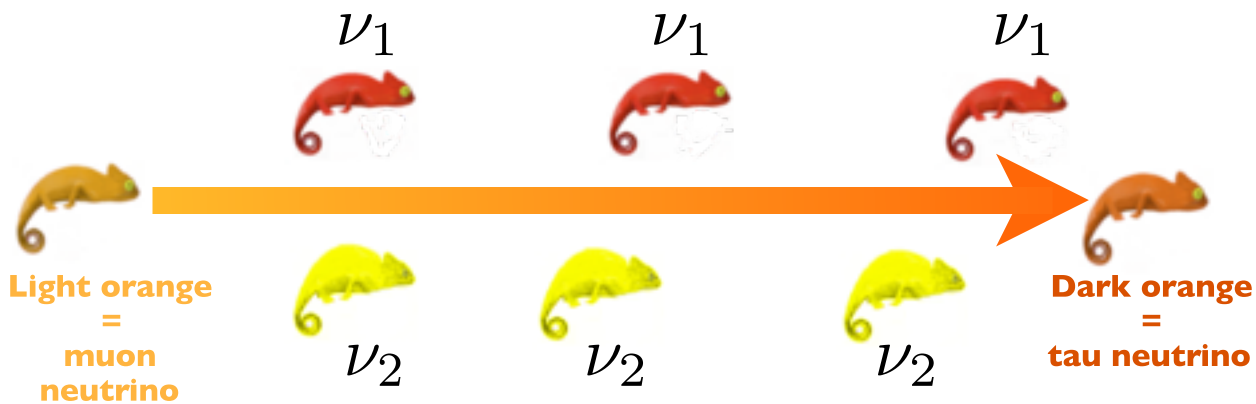
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}$$

For antineutrinos, $U \rightarrow U^*$

CP-conservation requires U is real $\Rightarrow \delta = 0, \pi$

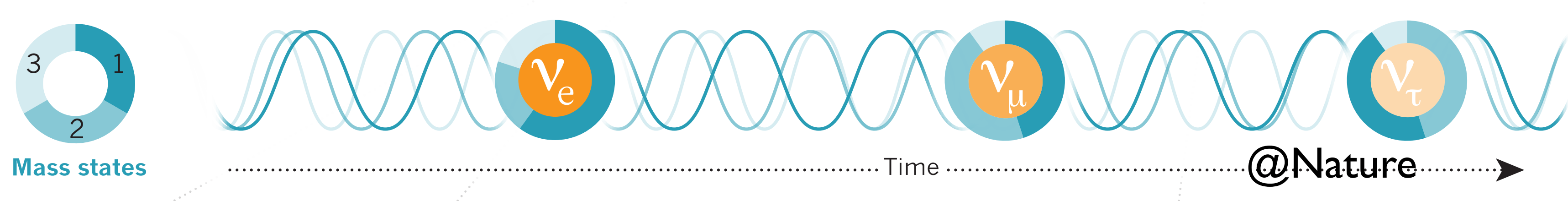
It is useful to express the CP violating effects in a rephrasing invariant manner (Jarlskog invariant):

$$J \equiv \Im[U_{\mu 3} U_{e2} U^*_{\mu 2} U^*_{e3}] = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$



A flavour neutrino is a superposition of different mass states. If their mass is different, then they will evolve in time differently and later their combination can correspond to a different type of neutrino.

This is an eminently quantomechanical effect, similar to other observed ones, such as spin precession. It has an oscillatory behaviour.



Let's assume that at t=0 a muon neutrino is produced

$$|\nu, t=0\rangle = |\nu_\mu\rangle = \sum_i U^*_{\mu i} |\nu_i\rangle$$

The time-evolution is given by the solution of the Schroedinger equation with free Hamiltonian:

$$|\nu, t\rangle = \sum_i U^*_{\mu i} e^{-iE_i t} |\nu_i\rangle$$

In the same-momentum approximation:

$$E_1 = \sqrt{p^2 + m_1^2} \quad E_2 = \sqrt{p^2 + m_2^2} \quad E_3 = \sqrt{p^2 + m_3^2}$$

Note: other derivations are also valid (same E formalism, etc).

At detection one projects over the flavour state as these are the states which are involved in the interactions. The probability of oscillation is

$$
\begin{aligned}
P(\nu_\mu \to \nu_\tau) &= |\langle \nu_\tau | \nu, t\rangle|^2 \\
&= \left| \sum_{ij} U^*_{\mu i} U_{\tau j} e^{-iE_i t} \langle \nu_j | \nu_i \rangle \right|^2 \\
&= \left| \sum_{i} U^*_{\mu i} U_{\tau i} e^{-iE_i t} \right|^2
\end{aligned}
$$

Typically, neutrinos are very relativistic: $E_i \simeq p + \frac{m_i^2}{2p}$

$$
\begin{aligned}
&= \left| \sum_{i} U^*_{\mu i} U_{\tau i} e^{-i \frac{m_i^2}{2E} t} \right|^2 \\
&= \left| \sum_{i} U^*_{\mu i} U_{\tau i} e^{-i \frac{m_i^2 - m_1^2}{2E} t} \right|^2
\end{aligned}
$$

Δm^2_{i1}

Implications of the existence of neutrino oscillations

The oscillation probability implies that

$$P(\nu_\alpha \to \nu_\beta) \quad = \quad \left| \sum_i U^*_{\alpha 1} U_{\beta 1} e^{-i \frac{\Delta m^2_{i1}}{2E} L} \right|^2$$

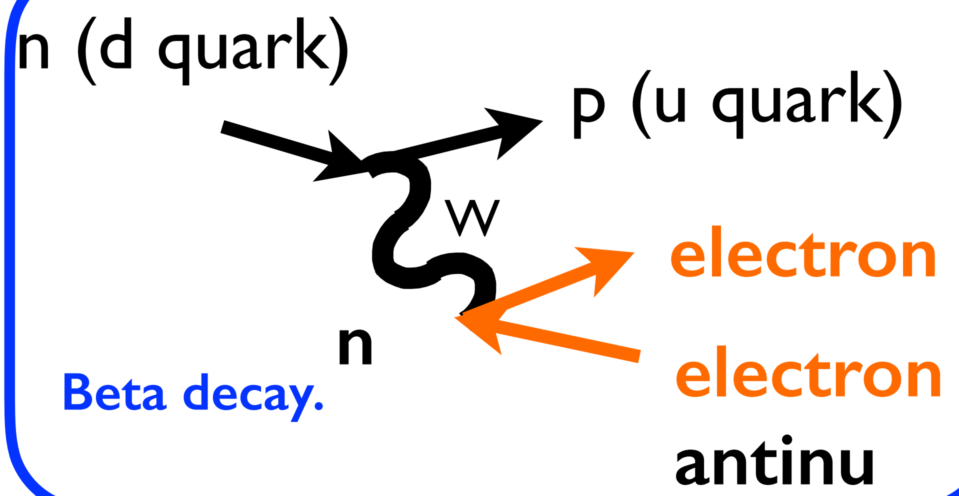
- **neutrinos have mass** (as the different components of the initial state need to propagate with different phases)

- **neutrinos mix** (as U needs not be the identity. If they do not mix the flavour eigenstates are also eigenstates of the propagation Hamiltonian and they do not evolve)

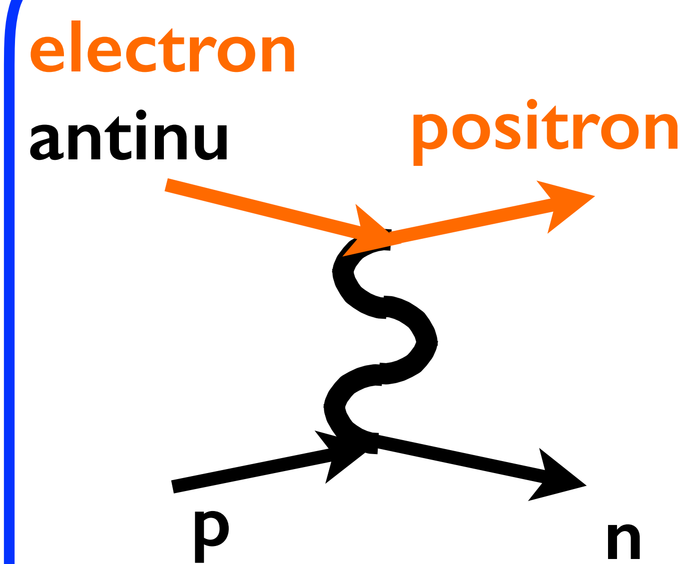
Current knowledge of neutrino properties

Neutrinos oscillations in experiments

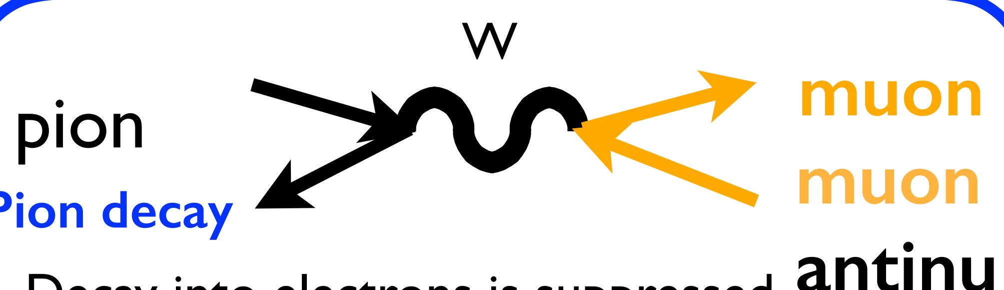
In CC (NC) SU(2) interactions, the W boson (Z boson) are exchanged leading to the production and detection of neutrinos.



Beta decay.

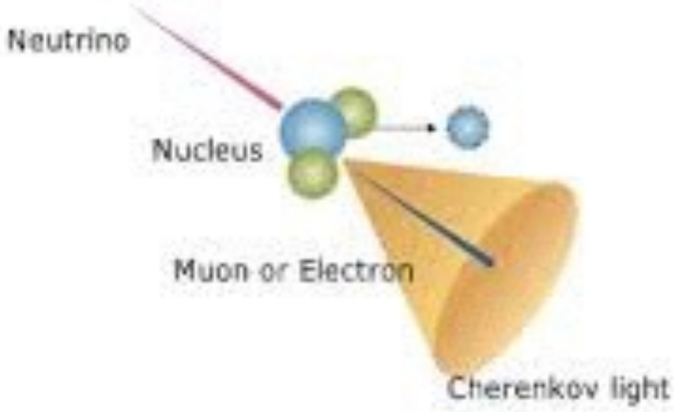


Inverse Beta decay.

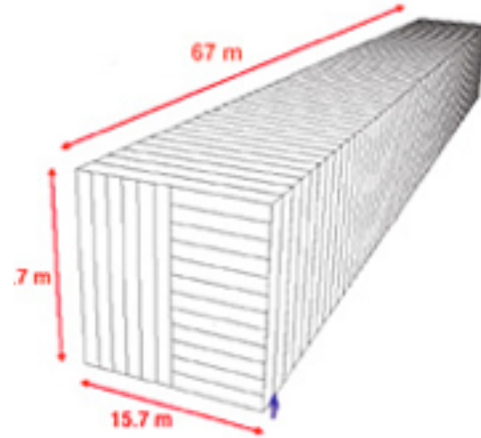


Pion decay

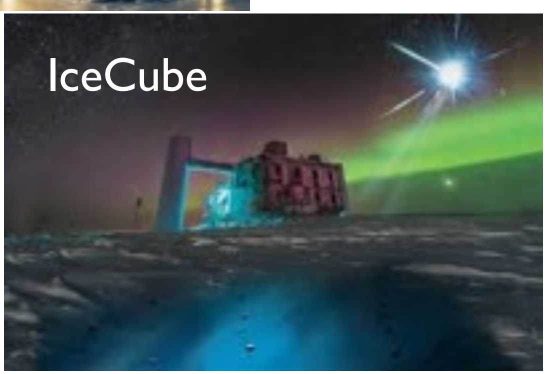
Decay into electrons is suppressed.

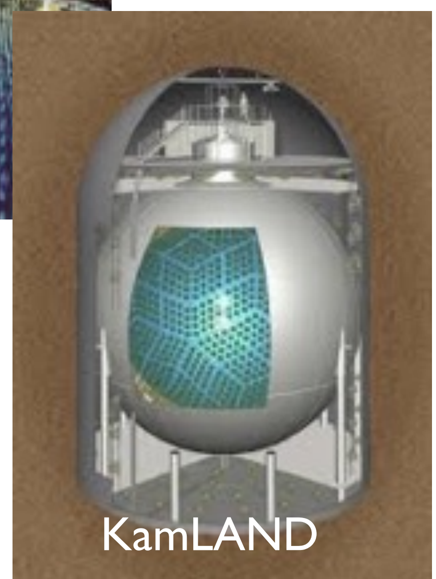


Credit: Super-Kamiokande



NOvA

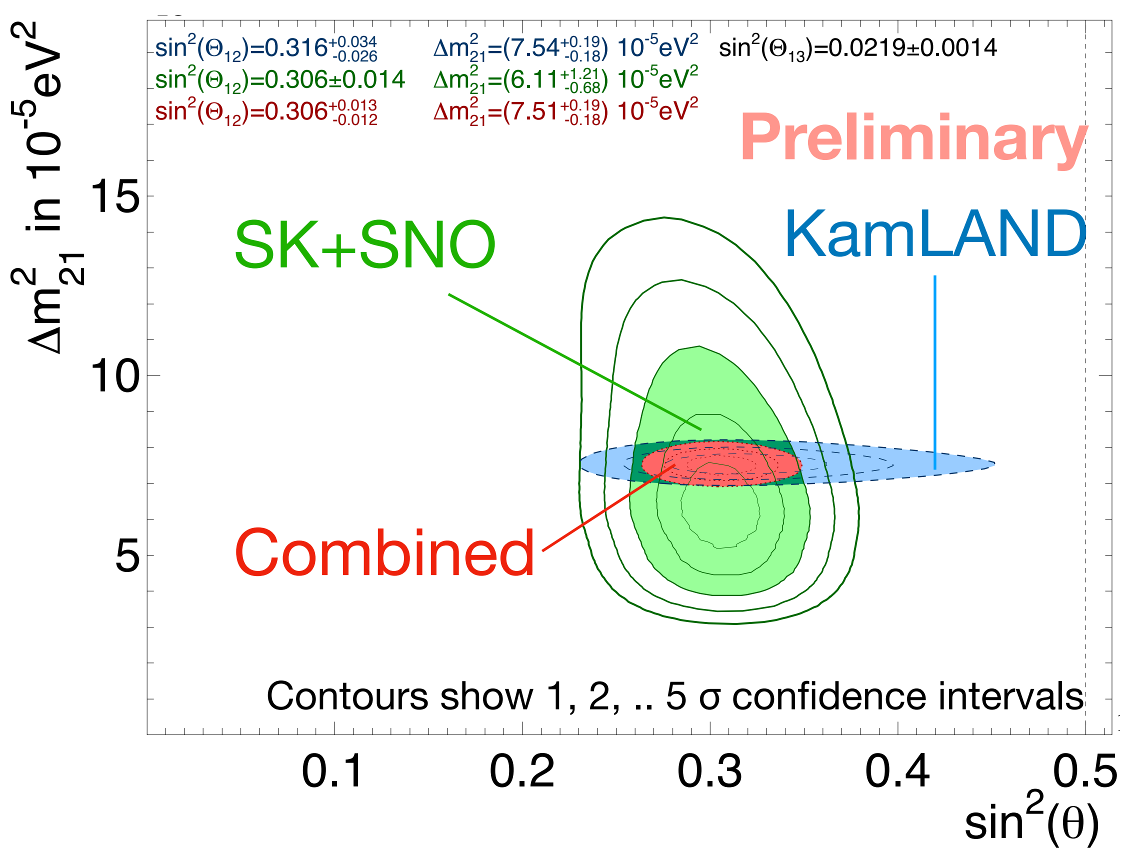




Neutrino experiments

Solar neutrinos:
E~0.1-10 MeV
matter effects

LBL Reactor neutrinos exp:
E~3 MeV,
L~100 Km



Y. Nakajima, for
Super-Kamiokande,
Neutrino 2020

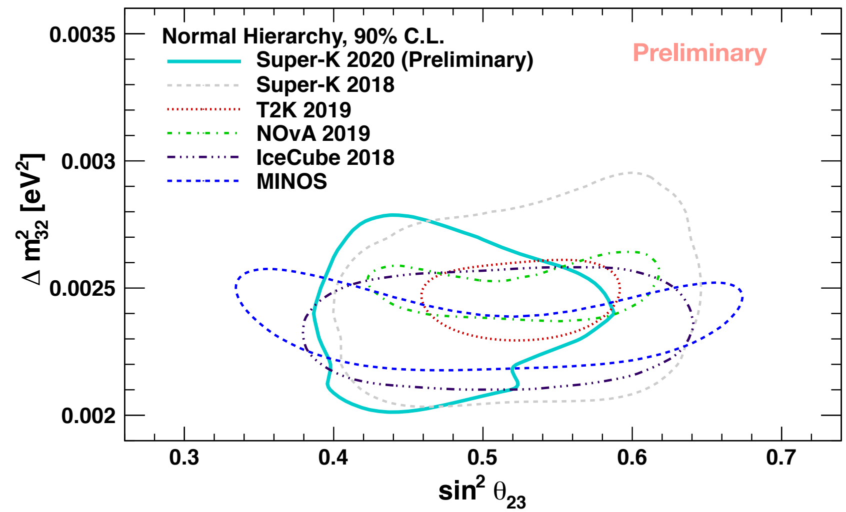
Neutrino experiments

SBL Reactor neutrino exp:
E~3 MeV,
L~1 Km

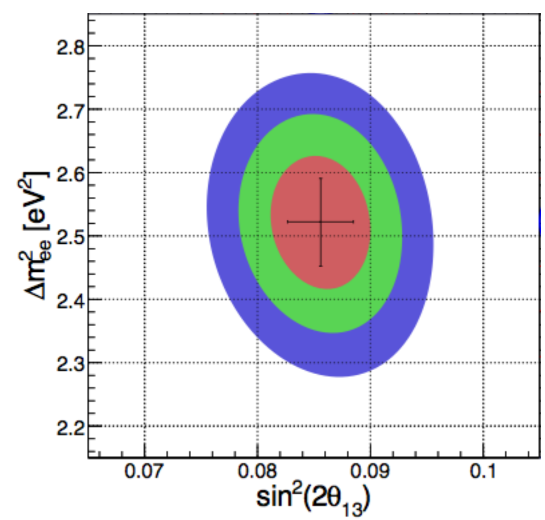
Atmospheric neutrinos:
E~100 MeV-100GeV,
L~10-10000 Km

Accelerator neutrinos:
E~500 MeV-few GeV,
L~295-1300 Km

Δm^2_{32} vs $\sin^2\theta_{23}$ constraints



Y. Nakajima, for Super-Kamiokande, Neutrino 2020



Days Bay coll., PRL 121 (2018)

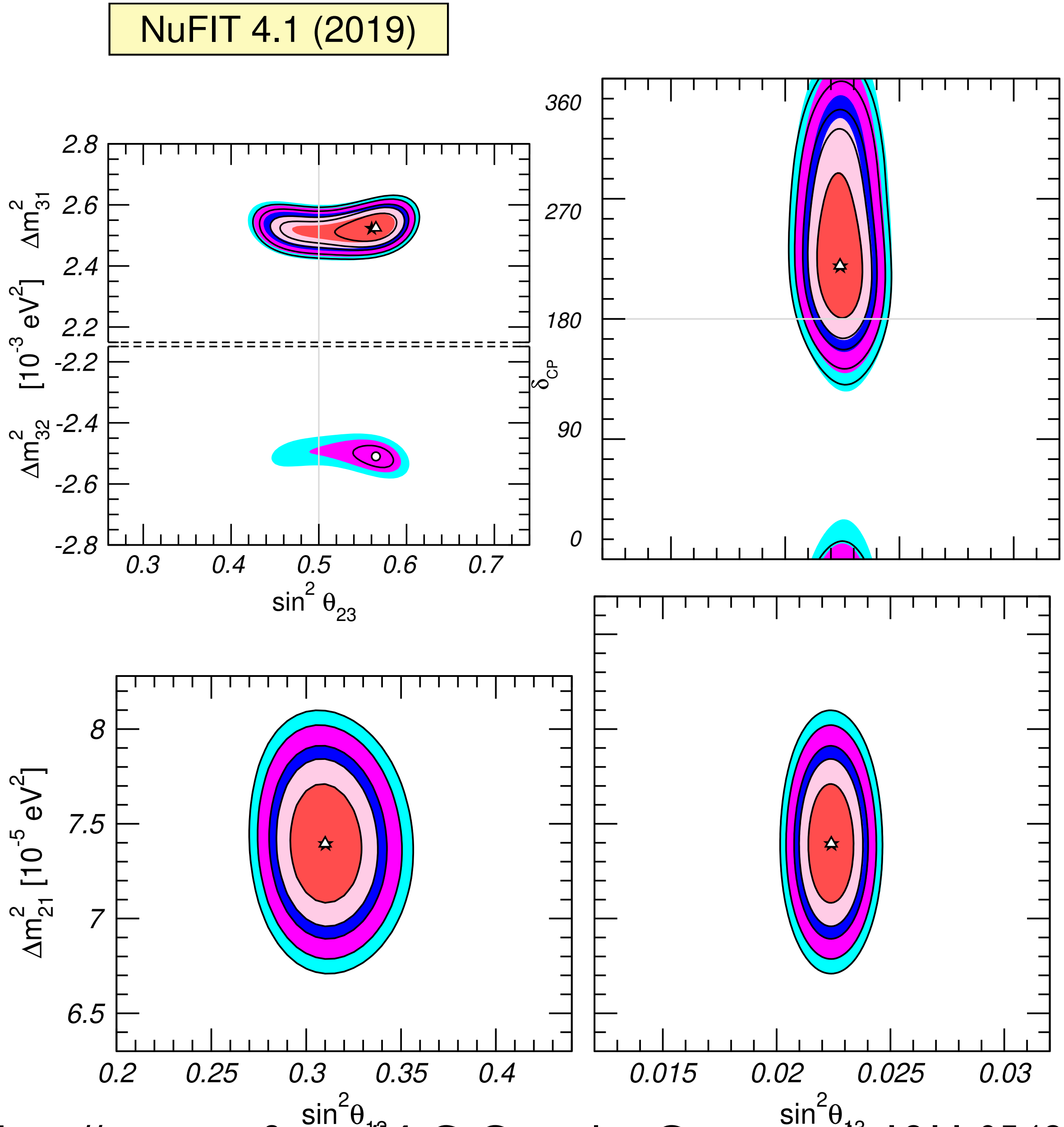
Current status of neutrino parameters

NuFIT 5.1 (2021)

without SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$

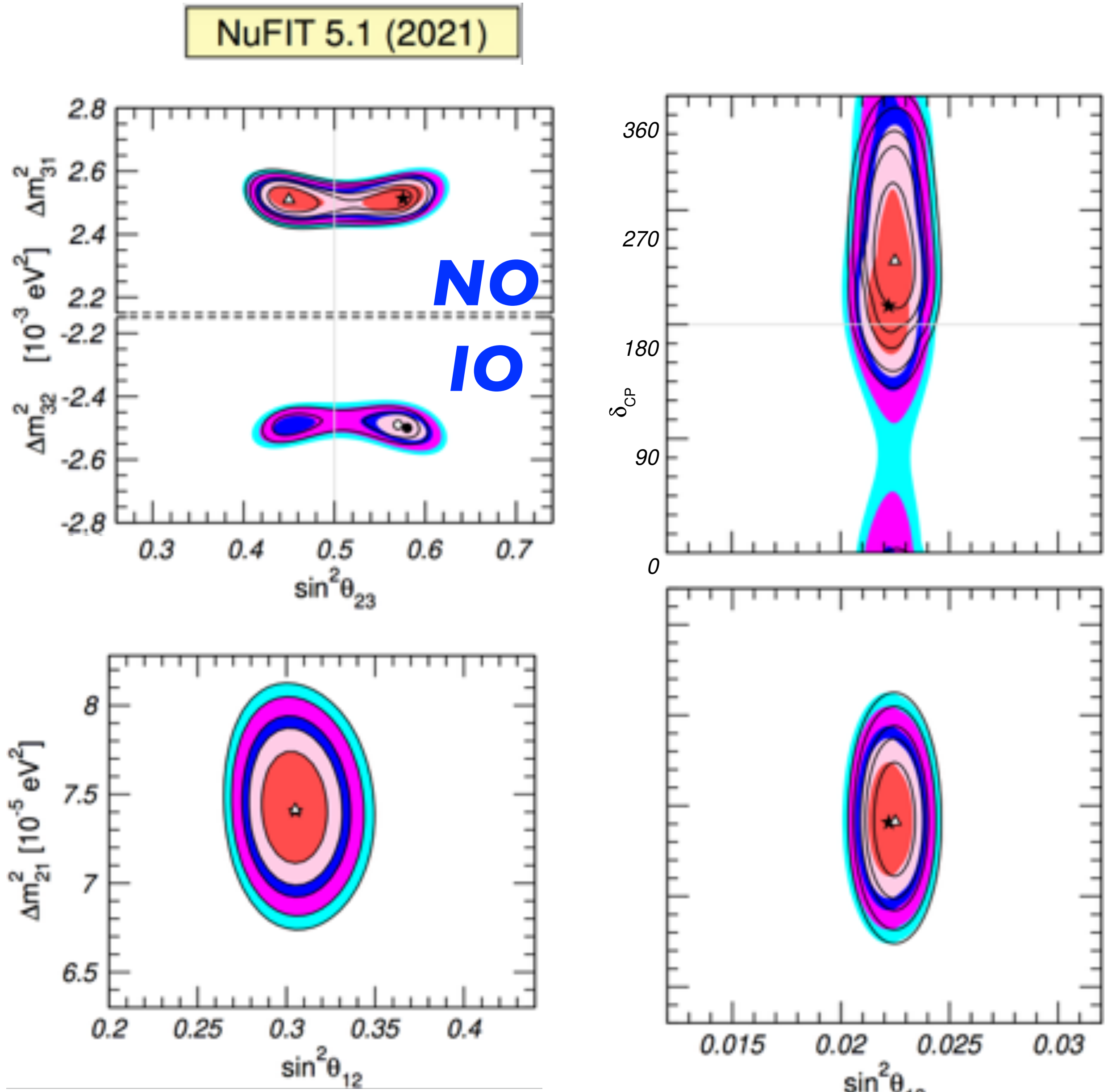
M. C. Gonzalez-Garcia et al., 2007.14792

Neutrino properties after July 2019



http://www.nu-fit.org/ M. C. Gonzalez-Garcia et al., 1811.05487

Neutrino properties as of October 2021

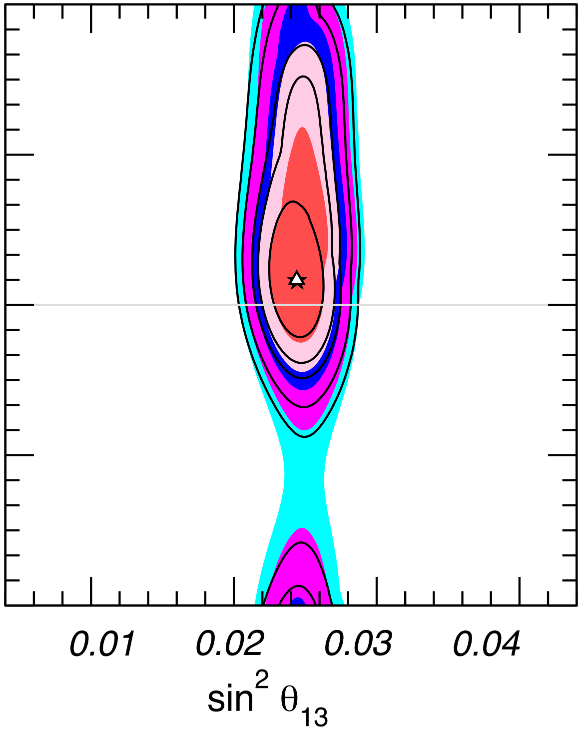


Current status:

- 2 mass squared differences
- 3 sizable mixing angles,
- mild hints of CPV
- mild indications in favour of NO

http://www.nu-fit.org/ M. C. Gonzalez-Garcia et al., 2007.14792

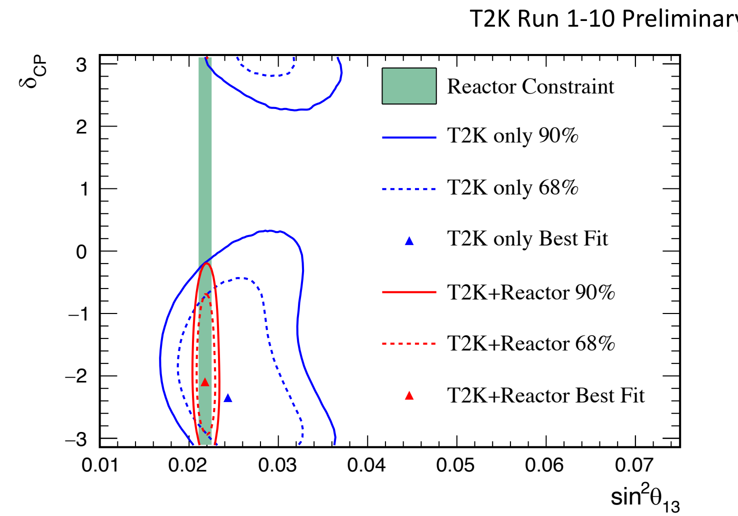
Current Hints for CP violation?

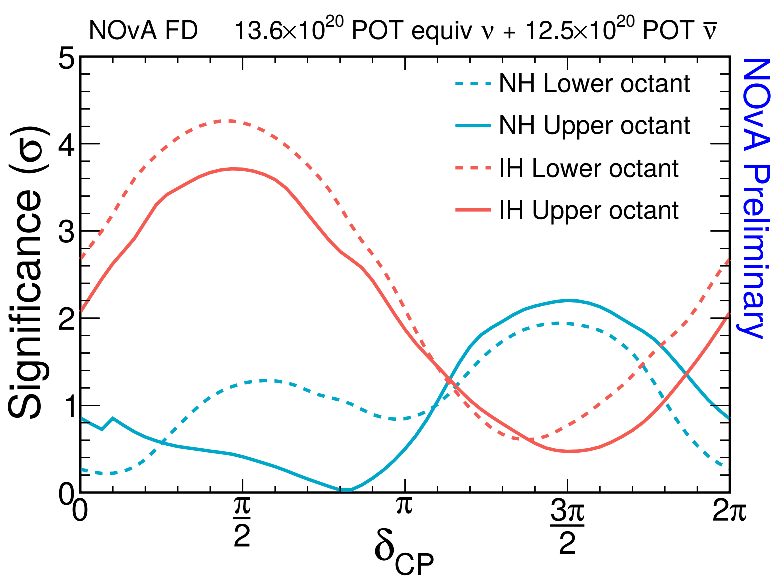


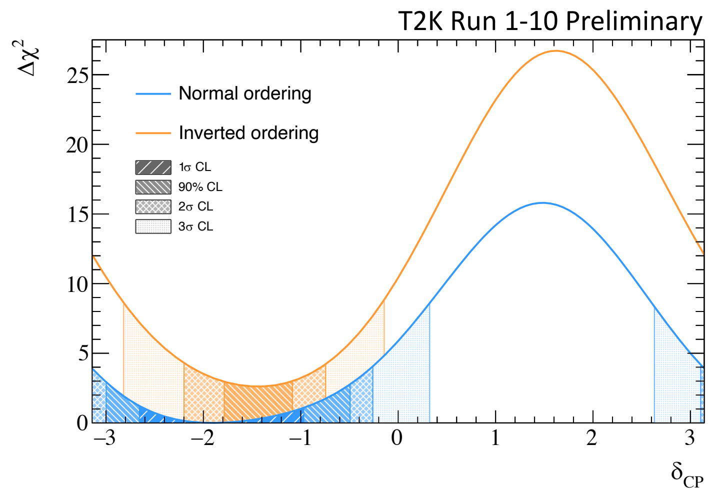
M. C. Gonzalez-Garcia et al., NuFit, 2007.14792

P. Dunne, for T2K, Neutrino 2020

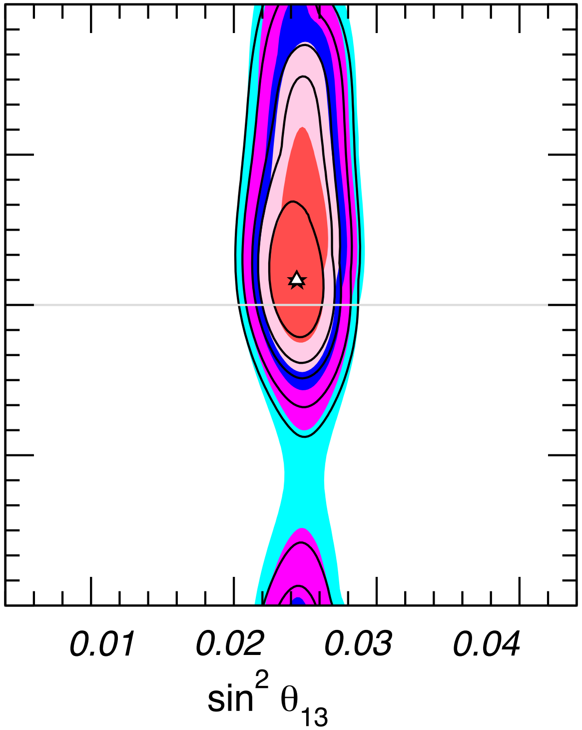
A. Himmel, for NOvA, Neutrino 2020





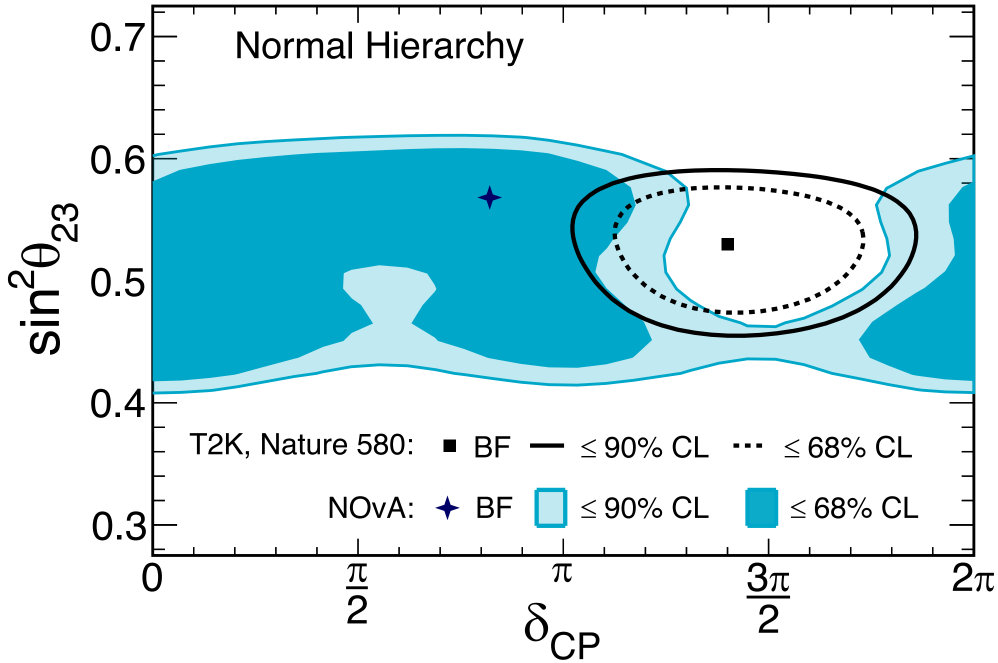


Current Hints for CP violation?



NOvA coll., 2108.08219

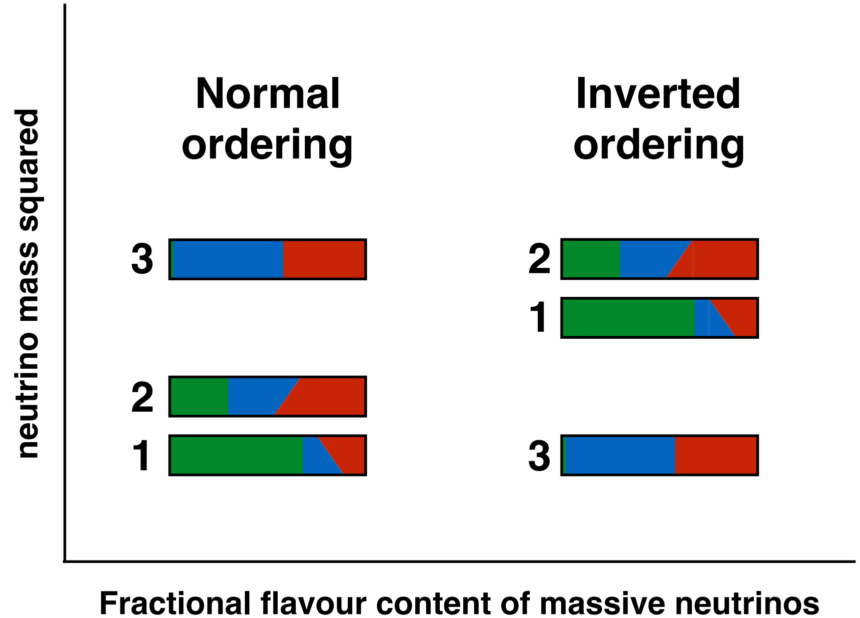
M. C. Gonzalez-Garcia et al., NuFit, 2007.14792



Some mild preference for CP-violation, mainly due to combining T2K (NOvA) with reactor neutrino data. Significance for NO decreased to about 1.6 sigma (2.7 sigma with inclusion of SK atm data).

Neutrino masses

$\Delta m_{\rm s}^2 \ll \Delta m_{\rm A}^2$ implies at least 3 massive neutrinos.



Using

$$m_2 = \sqrt{m_2^2} = \sqrt{m_2^2 \pm m_1^2} = \sqrt{m_1^2 + \Delta m_{21}^2}$$

we can express the masses in terms of MO and $m_{\rm MIN}$:

$$m_1 = m_{\rm min}$$
$$m_2 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm sol}^2}$$
$$m_3 = \sqrt{m_{\rm min}^2 + \Delta m_{\rm A}^2 + \Delta m_{\rm sol}^2/2}$$

$$m_3 = m_{\rm min}$$
$$m_1 = \sqrt{m_{\rm min}^2 + |\Delta m_{\rm A}^2| - \Delta m_{\rm sol}^2/2}$$
$$m_1 = \sqrt{m_{\rm min}^2 + |\Delta m_{\rm A}^2| + \Delta m_{\rm sol}^2/2}$$

What do we still need to know?

- **What is the nature of neutrinos? Dirac vs Majorana?**
- **What are the values of the masses?** Absolute scale (KATRIN, ...?) and the ordering.
- **Is there CP-violation?** Its discovery in the next generation of LBL depends on the value of delta.
- **What are the precise values of mixing angles?** Do they suggest an underlying pattern?
- **Is the standard picture correct?** Are there NSI? Sterile neutrinos? Other effects?

	2020	2025	2030	2035
LBL osc.	T2K NOvA	LBNF-DUNE T2HK (T2HKK)		ESSnuSB?, nufactory?
SBL osc.	SBL reactor,... MicroBooNE SBN	LBNF-DUNE ND T2HK ND ???		
Other osc.	SK, Borexino, LBL detectors JUNO	DUNE HK		Theia???
Direct mass	KATRIN	Project 8		
DBD0nu	KamLAND-Zen GERDA CUORE LEGEND-200 NEXT-100, nEXO...	LEGEND-1000 CUPID NEXT-HD, PANDAX...		Next-next gen?
UHE	IceCube IceCubeGen2 ORCA, KM3Net			

Neutrino nature

Neutrinos can be **Majorana or Dirac** particles. In the SM only neutrinos can be Majorana as they are neutral.

Majorana condition $\nu = C\bar{\nu}^T$

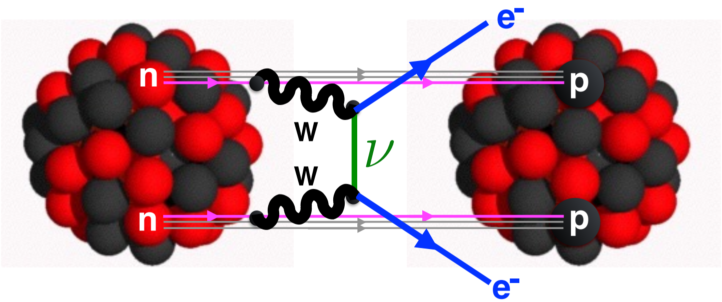
The **nature** of neutrinos is linked to the conservation of **Lepton number (L).**

- This is crucial information to unveil the **Physics BSM: with or without L-conservation**? Lepton number violation is a necessary condition for **Leptogenesis**.

- Tests of LNV:
  - At low energy, neutrinoless double beta decay,
  - LNV tau and meson decays, collider searches.

Neutrinoless double beta decay

Neutrinoless double beta decay, (A, Z) → (A, Z+2) + 2e, will test the nature of neutrinos.



SP, CERN Courier, Jul 2016

The half-life time depends on neutrino properties

$$(T^{1/2}_{0\nu})^{-1} \propto |M_{NME}|^2 |m_{\beta\beta}|^2$$

- The effective Majorana mass parameter:

$$|m_{\beta\beta}| \equiv | m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha_{21}} + m_3 |U_{e3}|^2 e^{i\alpha_{31}} |$$

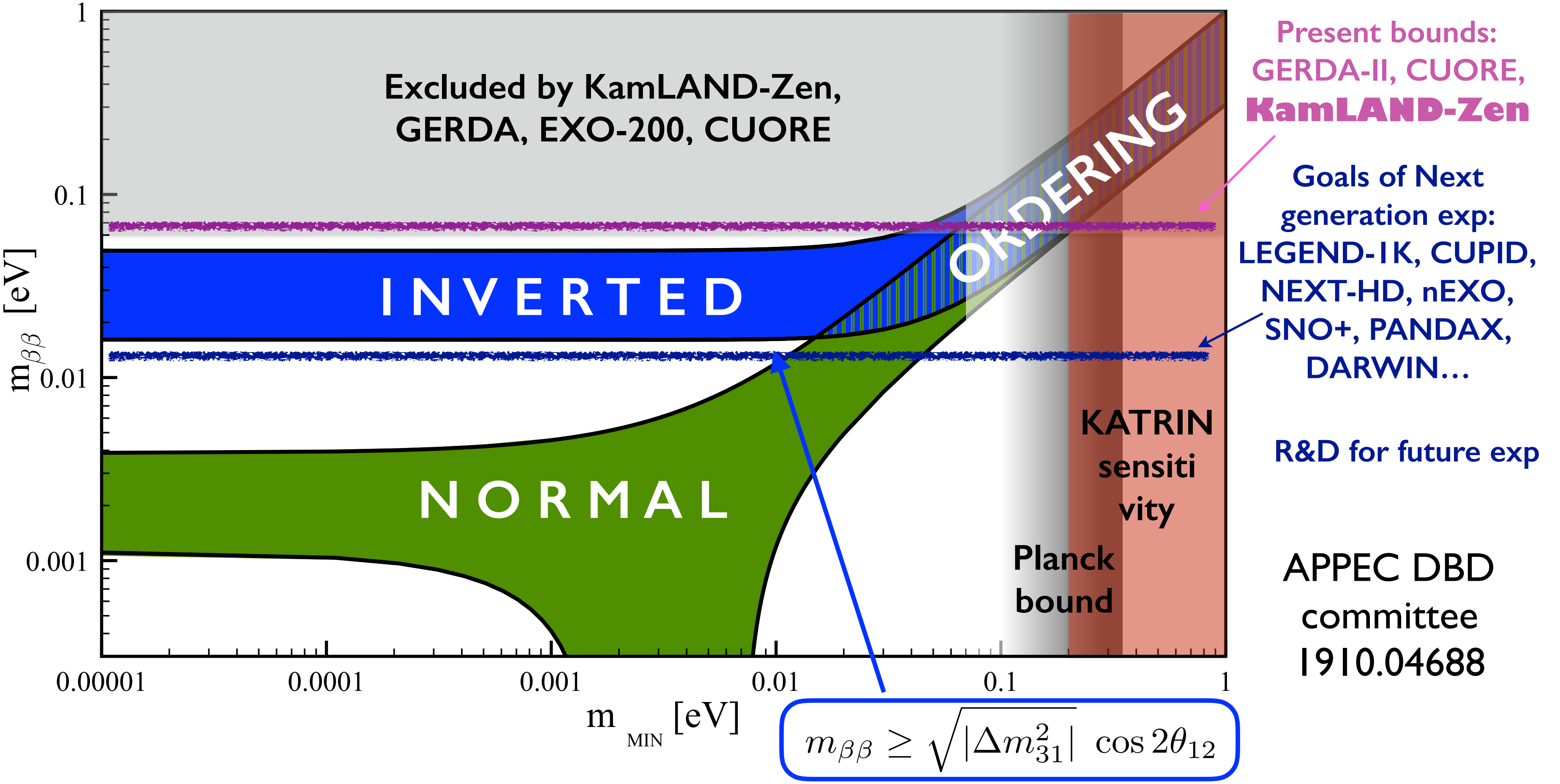
Mixing angles (known)

CPV phases (unknown)

- $|M_{NME}|$ are the nuclear matrix elements

Predictions for betabeta decay

The predictions for m_{bb} depend on the neutrino masses:



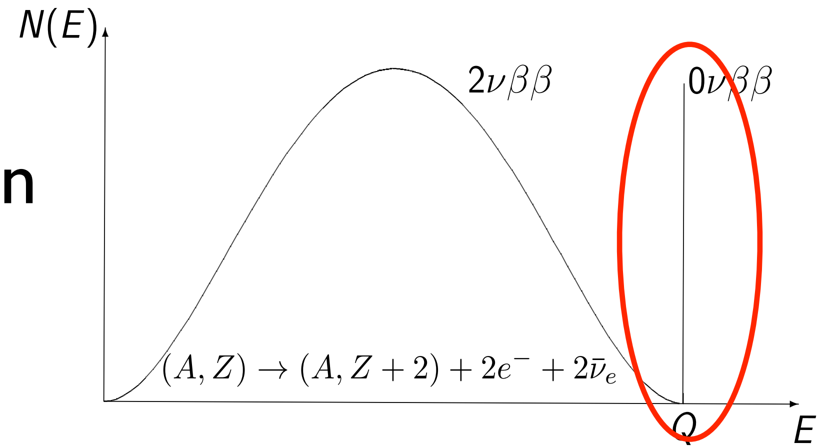
APPEC DBD committee 1910.04688

Wide experimental program which is ongoing. The next generation is well into planning and R&D for future.

A positive signal would indicate L violation!

Experimental searches of betabeta decay

Neutrinoless double beta decay can be tested in nuclei in which single beta decay is kinematically forbidden (^{76}Ge, ^{100}Mo, ^{130}Te, ^{136}Xe…).
It is a very rare process:



$$T_{0\nu} \propto \sqrt{\frac{M\ t}{B\ \Delta E}}$$

ton-scale

<1% at Q_{bb}

<1 cts/yr/ton/ROI

News

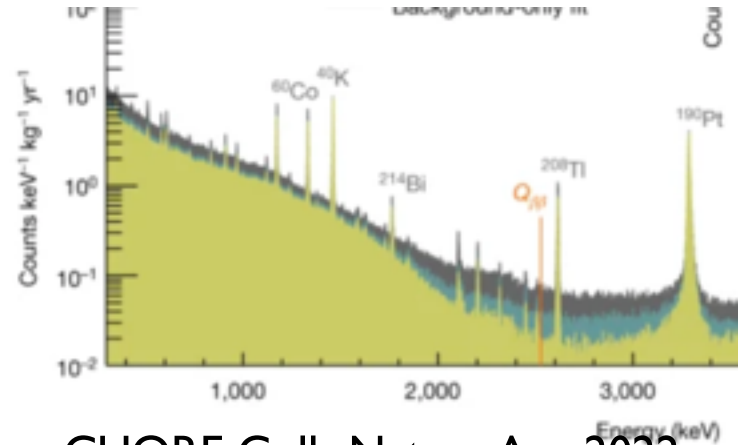
Roman ingots to shield particle detector

Lead from ancient shipwreck will line Italian neutrino experiment.

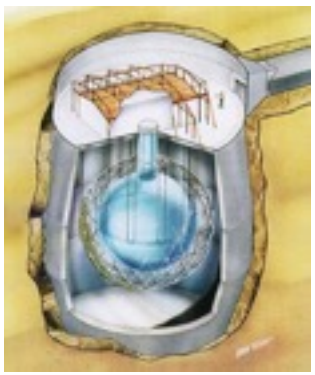
KamLAND-Zen Loaded LSc with 380 kg ^{136}Xe, $T_{1/2} > 1.07 \times 10^{26}$ yrs (90% C.L.), $m_{bb} <$ 61-165 meV

CUORE ^{130}Te, ~206 kg, $T_{1/2} > 2.9 \times 10^{25}$ yrs

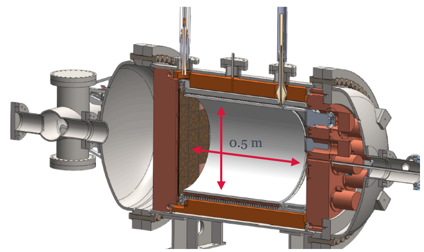
Also, EXO-200, GERDA, MAJORANA



CUORE Coll., Nature Apr 2022



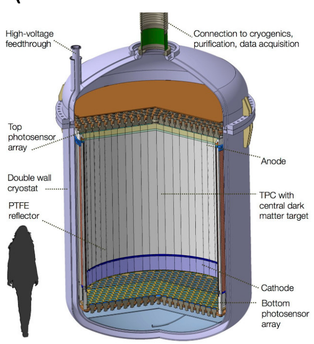
SNO+

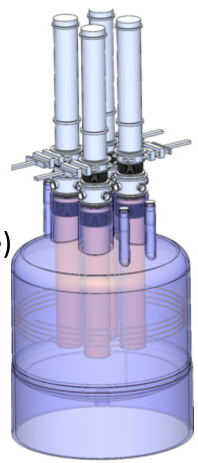


NEXT-HD

nEXO

40 t liquid Xe TPC
(with 8.9% ^{136}Xe → 3.6 t of ^{136}Xe)

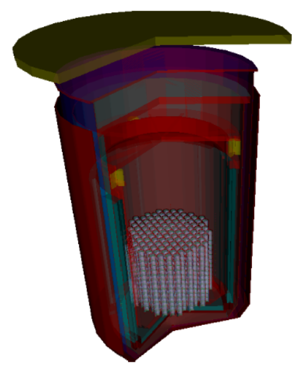




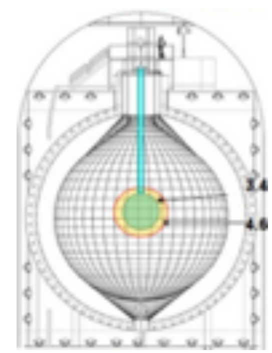
LEGEND

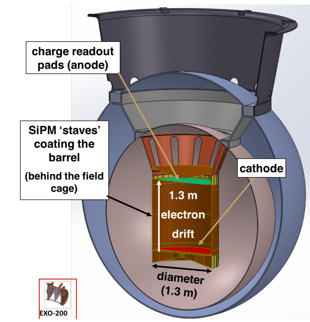
Large Enriched Germanium Experiment for Neutrinoless ββ Decay

DARWIN



CUPID





5 ton LSc Xe

KamLAND2-Zen

HPXe: PANDAX-III

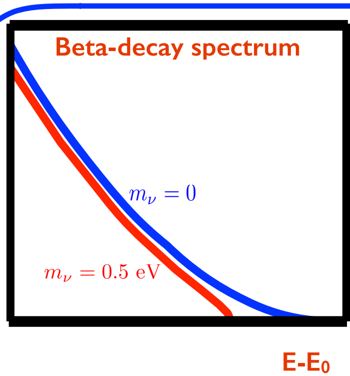
Bolometers: AMoRE

The ultimate goal of next generation is m_{bb}~15-20 meV.

Measuring neutrino masses

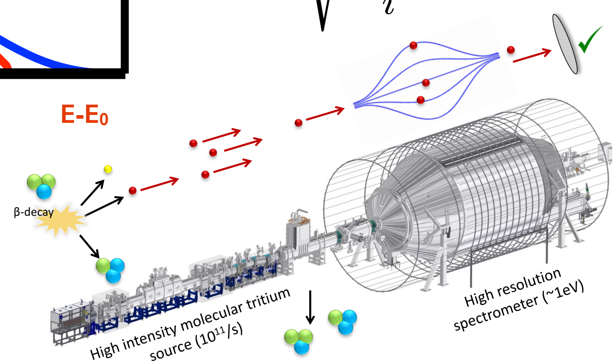
- Absolute mass scale.

Beta decay

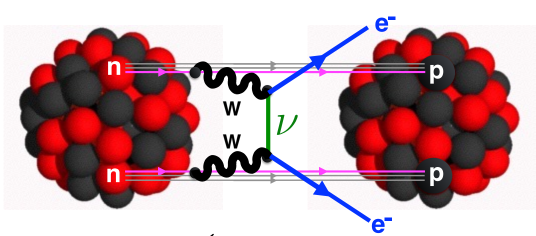


$$m_\beta \equiv \sqrt{\sum_i U_{ei}^2 m_i^2}$$

KATRIN

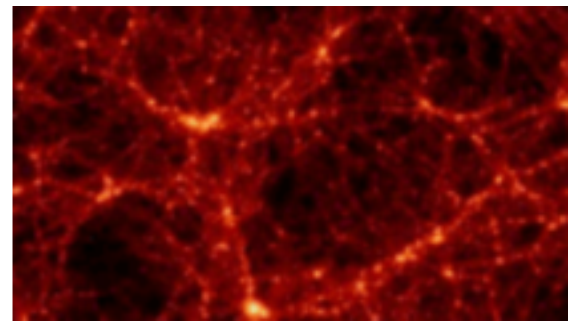


Neutrinoless dbeta decay

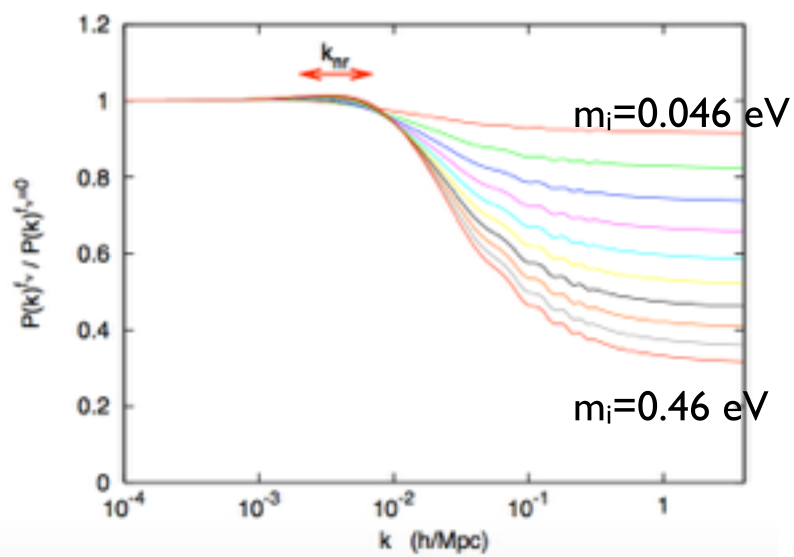


$$m_{\beta\beta} = f(m_i, \alpha_{21}, \alpha_{31}, \delta)$$

Cosmology



$$\sum_i m_i$$



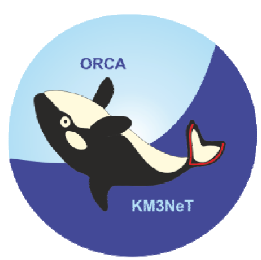
J. Lesgourgues, S. Pastor, Phys. Rep. 429

Neutrino mass ordering

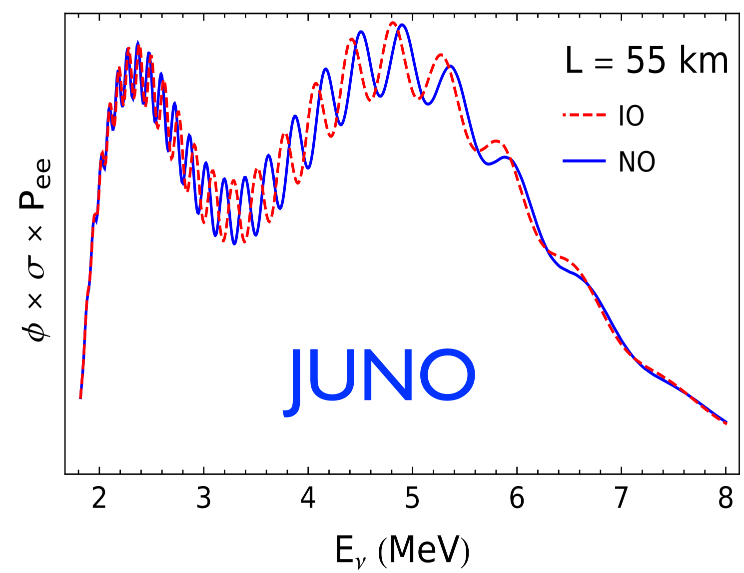
- Mass ordering via neutrino oscillation in matter or in vacuum (JUNO). Discovery expected within 10 years thanks to relatively large θ_{13}.

Atm neutrinos

Exploit the matter effects in Earth. Without detector magnetisation, require large mass (multi Mton) and excellent angular and energy resolution (ORCA, IceCube Gen 2, HK, INO).



Long baseline neutrino oscillation experiments



P. Coloma and SP, World Scientific

Petcov, Piai, hep-ph/0112074

JUNO uses a 20kton LSc detector and reactor nus. Excellent energy resolution is needed. Due to start in 2023.

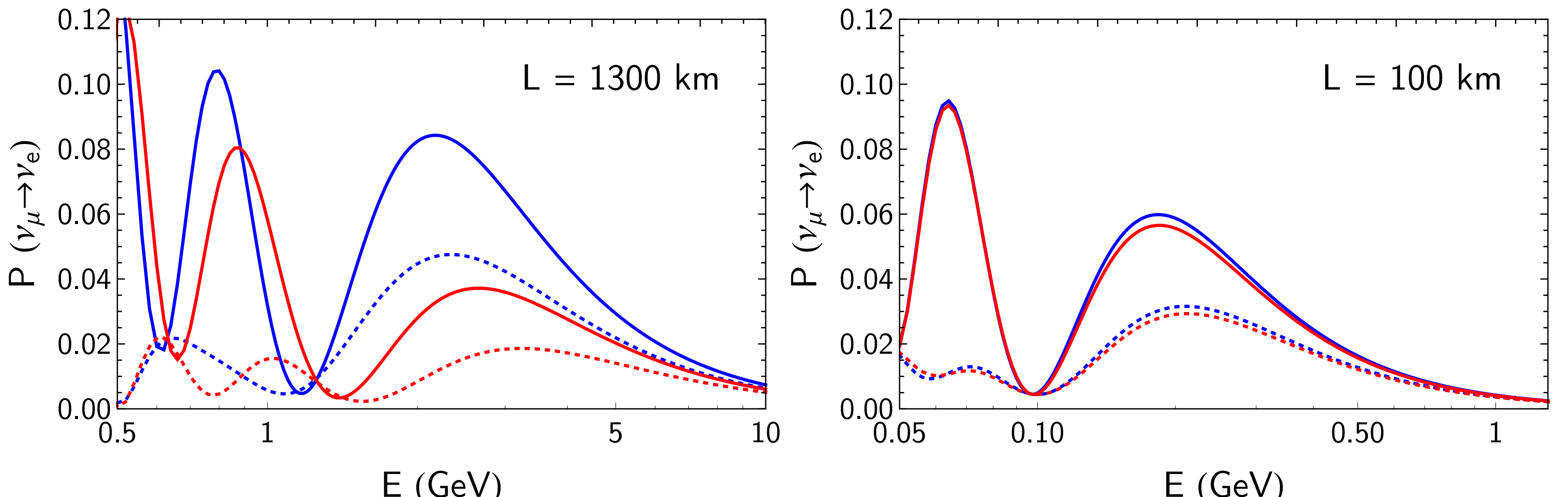
Long baseline oscillations: mass ordering and CPV

Long baseline neutrino oscillation experiments (T2K, NOvA, DUNE, T2HK) study the subdominant channels

A. Cervera et al., hep-ph/0002108;
K. Asano, H. Minakata, 1103.4387;
S. K. Agarwalla et al., 1302.6773...

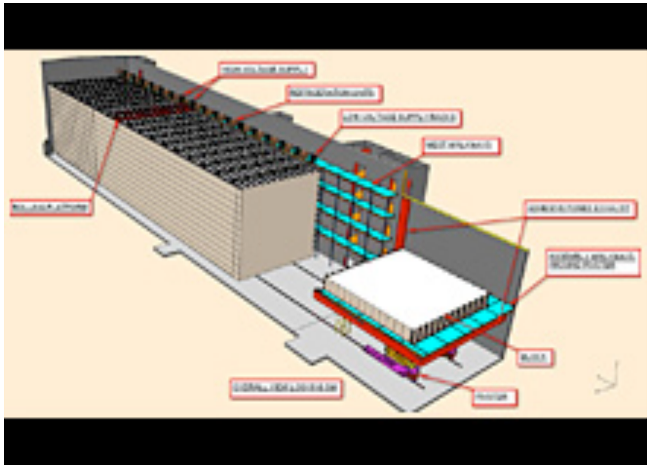
$$P_{\mu e} \simeq 4 c_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta_{31} L}{4E}$$
$$+ \sin 2\theta_{12} \sin 2\theta_{23} s_{13} \frac{\Delta_{21} L}{2E} \sin \frac{(1-r_A)\Delta_{31} L}{4E} \cos\left(\delta - \frac{\Delta_{31} L}{4E}\right)$$
$$+ s_{23}^2 \sin^2 2\theta_{12} \frac{\Delta_{21}^2 L^2}{16 E^2} - 4 c_{23}^2 s_{13}^4 \sin^2 \frac{(1-r_A)\Delta_{31} L}{4E}$$

$$\Delta_{31} \equiv \Delta m_{31}^2/(2E_\nu)$$
$$r_A \simeq \frac{\sqrt{2} G_F N_e}{\Delta m_{31}^2/(2E_\nu)}$$



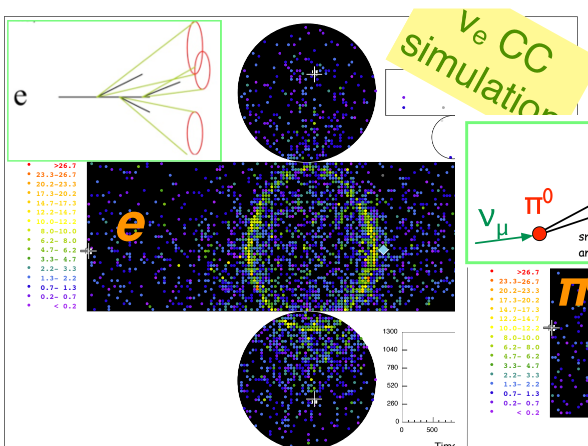
P. Coloma and SP, World Scientific

Present/Future LBL exp



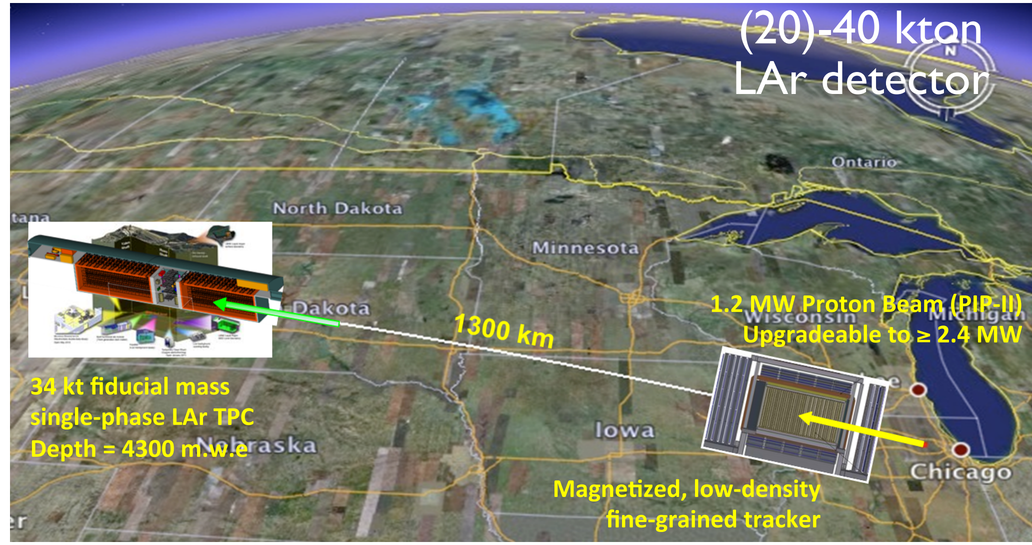
NOvA: 810 km off-axis
~14 kton plastic scintillator detector

T2K: 295 km off-axis
~22.5 kton WC detector

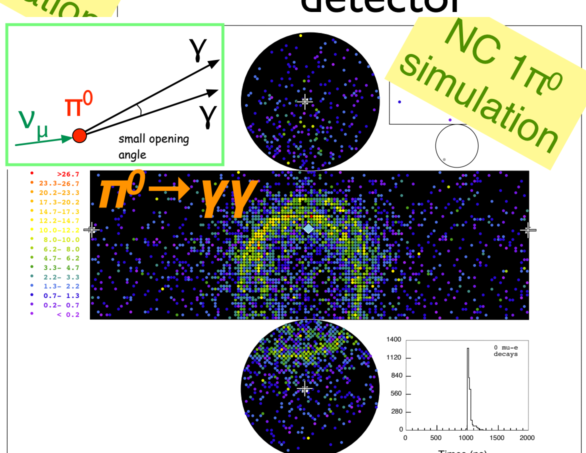


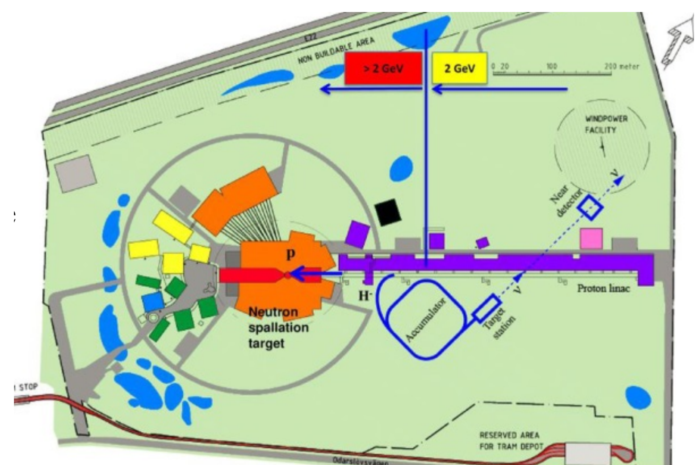
M. Shiozawa, for T2HK coll., NuPhys 2014

DUNE: 1300 km on-axis
(20)-40 kton LAr detector



T2HK: 295 km off-axis
~1 Mton WC detector

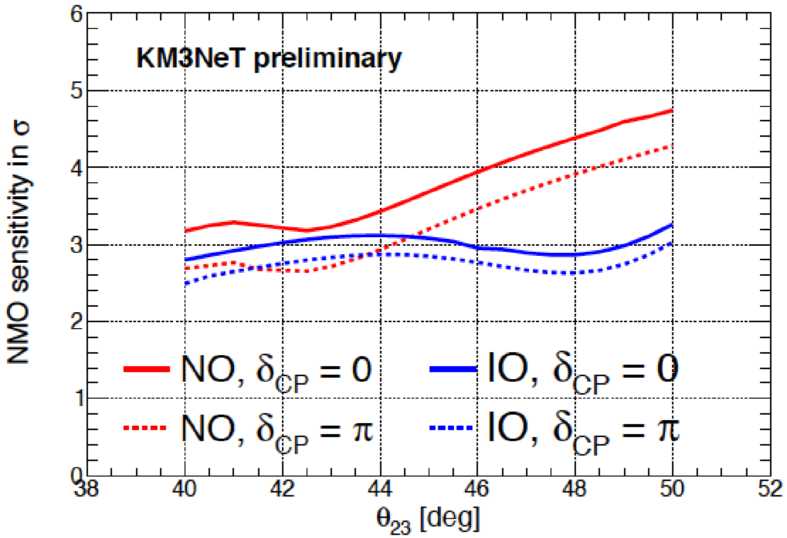




~1 BEuros for the neutrino facility including detector

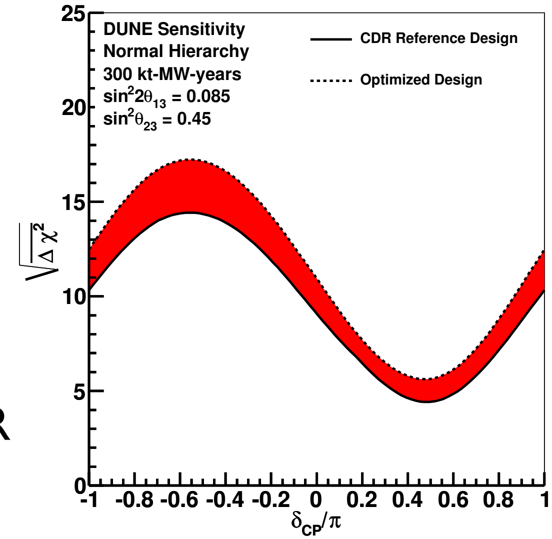
ESSnuSB: 300-500 km
~0.5 Mton WC detector
second oscillation maximum

Mass ordering and CPV sensitivity

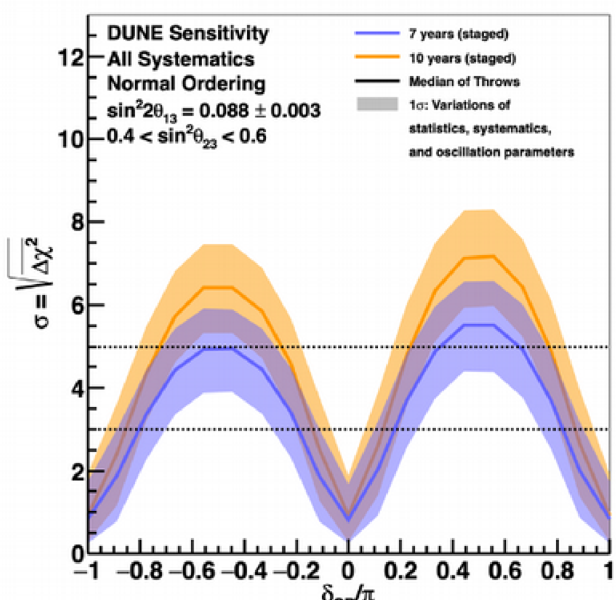


KM3Net, ORCA Coll., 2004.05004

DUNE CDR

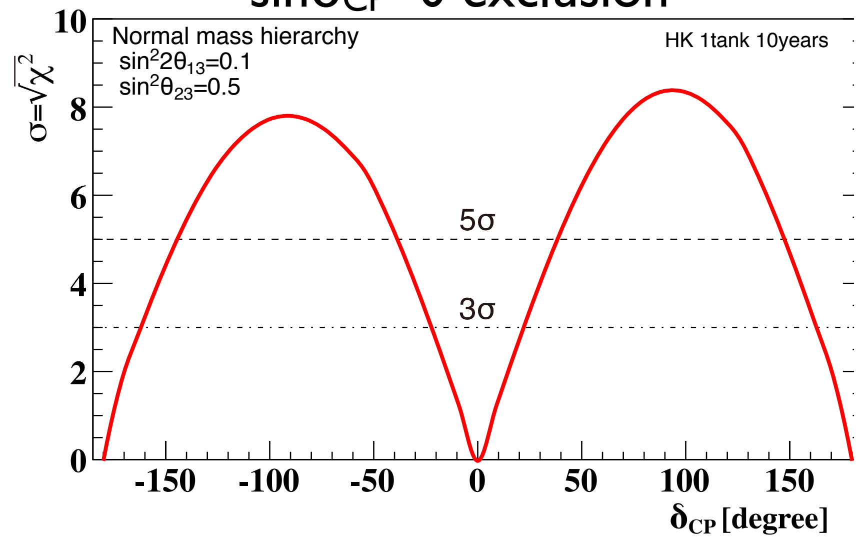


True Normal Ordering



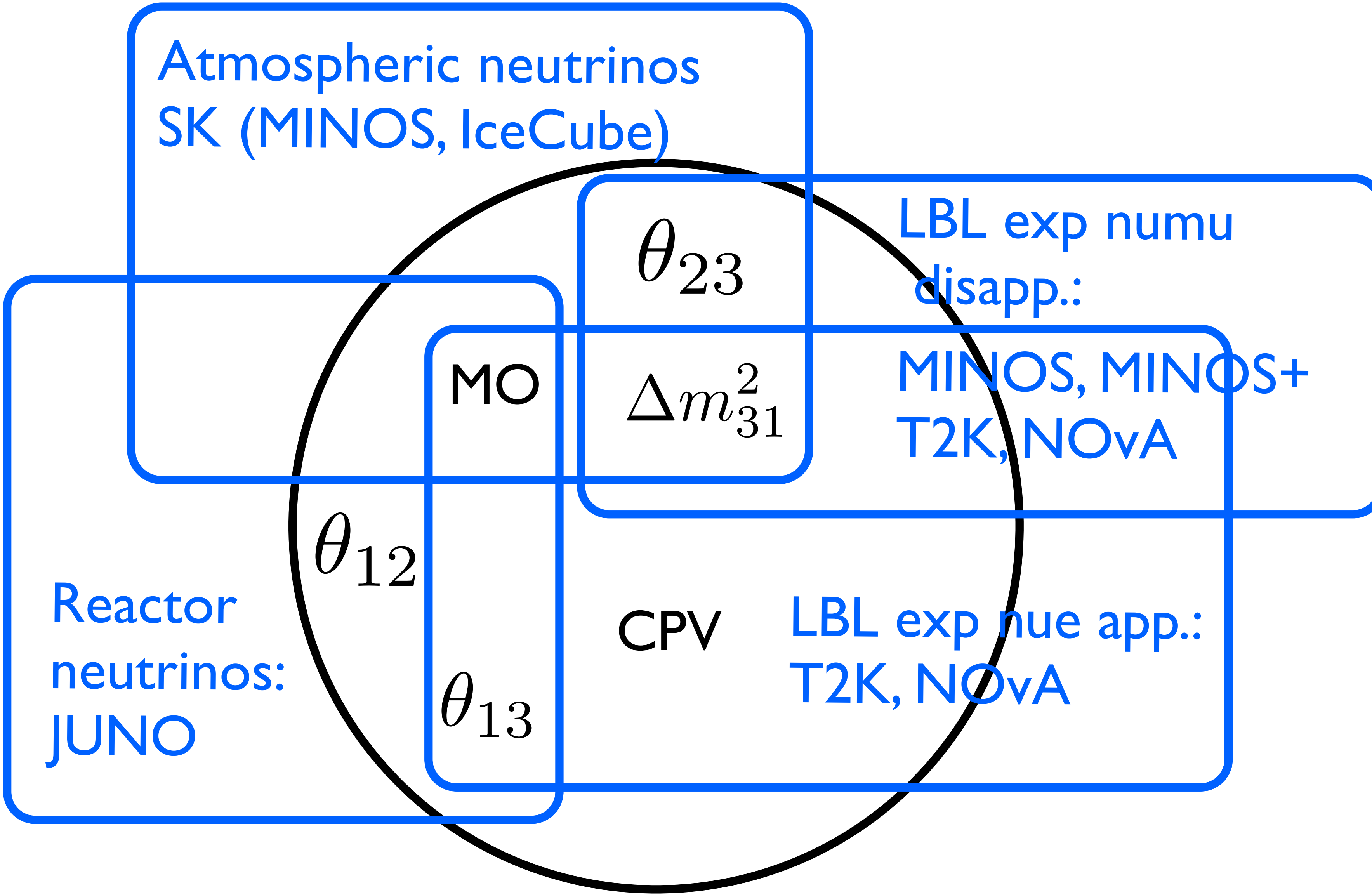
M. Mooney, for DUNE, Neutrino 2020

$\sin\delta_{CP}=0$ exclusion



M. Shiozawa, for HK, Neutrino 2018

Measurement of oscillation parameters



Also: Tests of standard neutrino paradigm

Beyond 3-neutrino mixing?

Sterile neutrinos

Sterile neutrinos: hypothetical neutral fermionic singlets of the Standard Model.

Generically they mix with the light neutrinos:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U_{4\times 4} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$

Flavour state

Massive state

Nearly-sterile neutrino, commonly called sterile neutrino

$$\mathcal{L} = \cdots + \bar{\ell}_L U_{\ell 4} \gamma_\mu \nu_{4,L} W^\mu + \mathrm{NC} + \mathrm{h.c.}$$

Adding sterile neutrinos to the Standard Model is a minimal extension BSM.

- Theory remains anomaly free.

- Can give origin to neutrino masses and explain their smallness (at least in some cases).

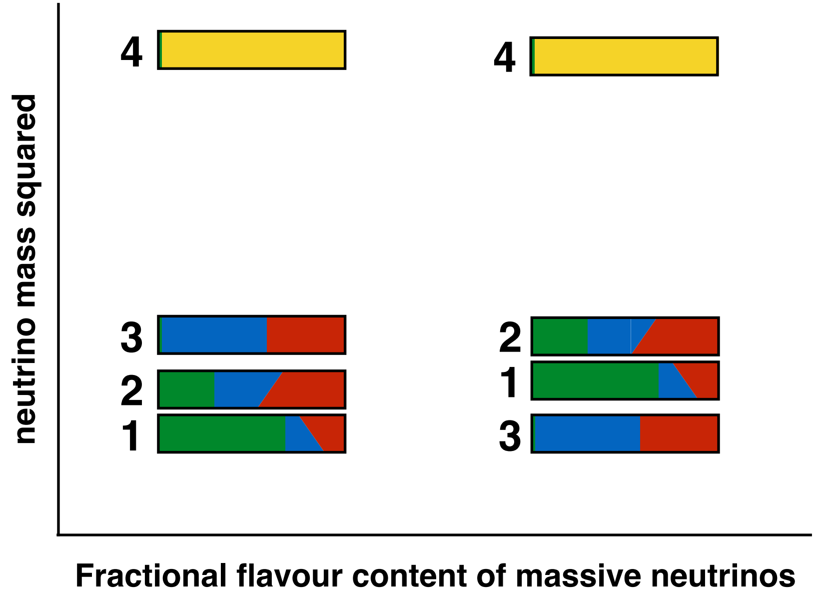
- GUT theories embedding L-R symmetries, e.g. SU(4), SO(10),... predict their existence.

- There is no unique motivation for choosing one mass scale instead of another (except for a naturalness principle: setting their mass to zero restores the lepton number symmetry).

Light (nearly-)sterile neutrinos

$\Delta m_{\rm s}^2 \ll \Delta m_{\rm A}^2$ implies at least 3 massive neutrinos.

$\Delta m_s^2 \ll \Delta m_A^2 \ll \Delta m_{41}^2$ implies at least 4 massive nus.



Appearance oscillation probability at short baselines:

$$P(\nu_\alpha \to \nu_\beta) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 \frac{\Delta m_{41}^2 L}{4E}$$

Oscillation disappearance probability:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4|U_{\alpha 4}|^2 (1 - |U_{\alpha 4}|^2) \sin^2 \frac{\Delta m_{41}^2 L}{4E}$$

Neutrino oscillation appearance channel

There are hints beyond standard 3 neutrino mixing.

LSND, nucl-ex/9605002

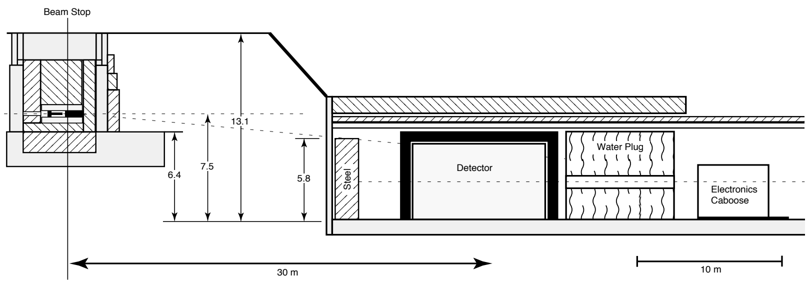
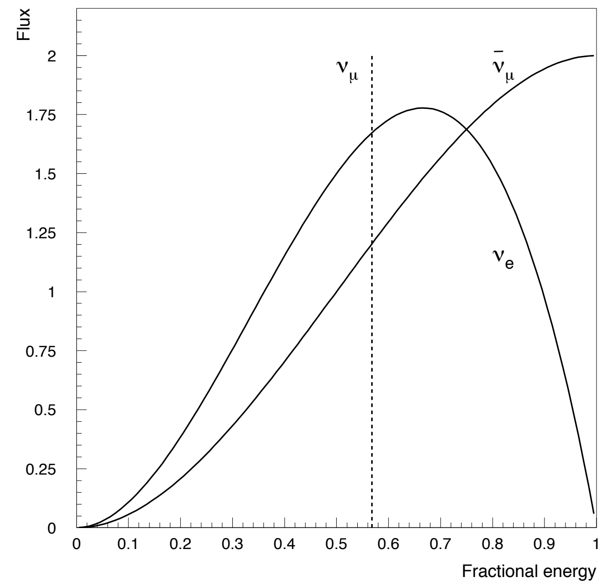


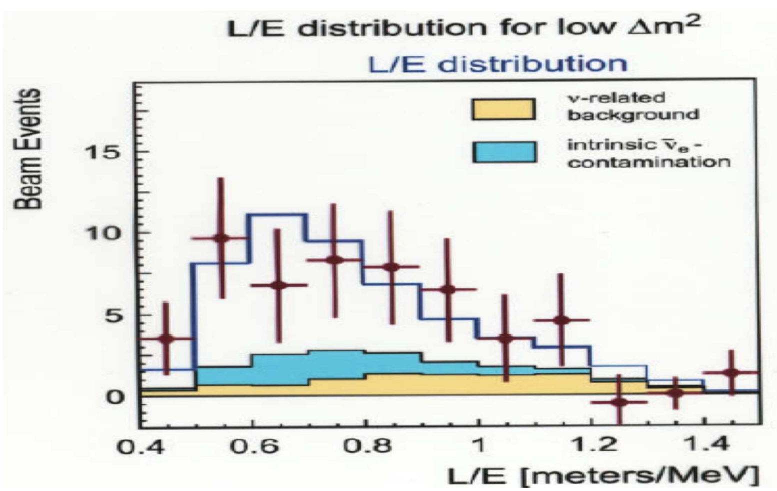
FIG. 1. Detector enclosure and target area configuration, elevation view

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad ,$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

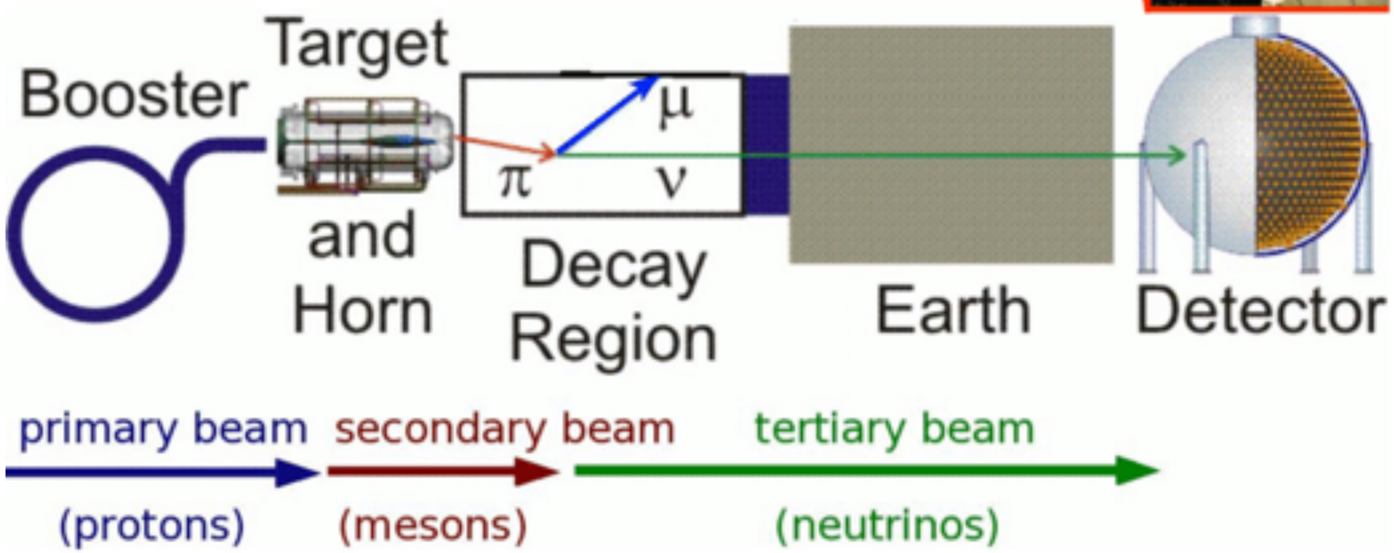


LSND, PRL81 (1998) 1774



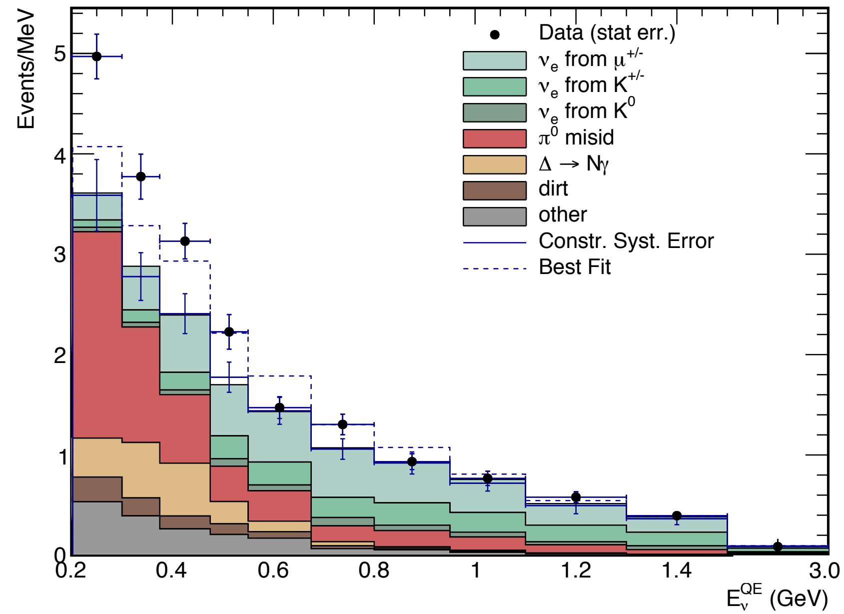
LSND reported the appearance of electron anti-neutrinos (inverse beta decay) at short distance (~30 m) from muon decays (DAR). A 3.8 sigma effect, not confirmed by KARMEN.

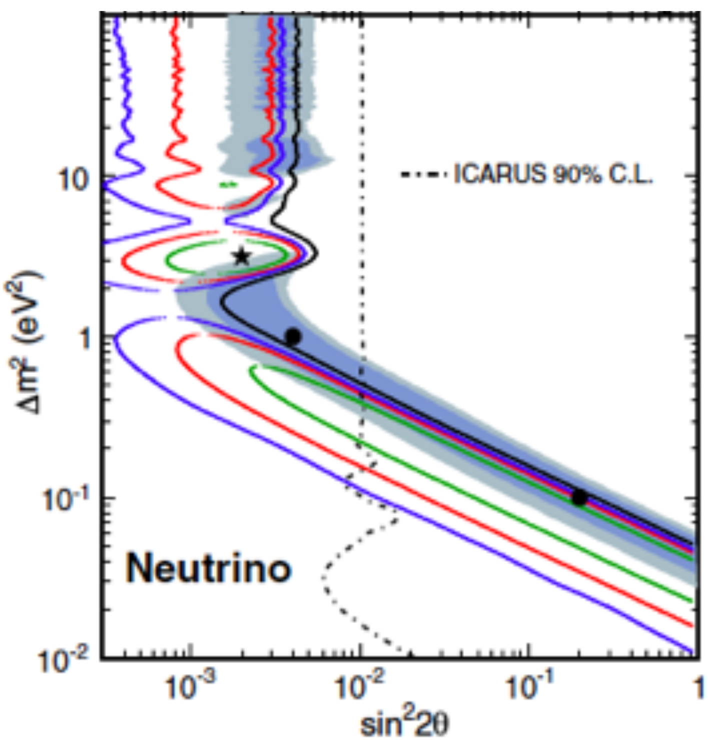
MiniBooNE was designed to test the LSND results. <E>~700 MeV and L~500 m. It found an excess of events at low energy.

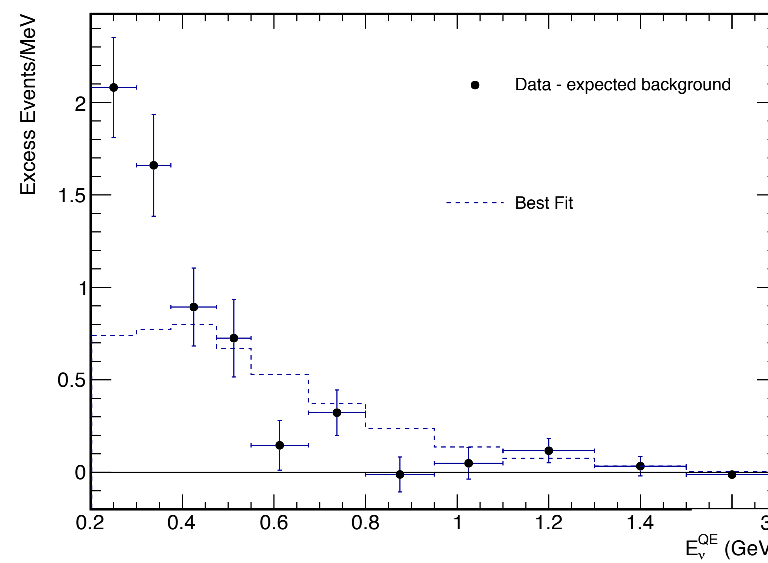


MiniBooNE reports a low-E excess which has increased in significance over time (3.6σ -> 4.7σ -> 4.8σ).

MiniBooNE Coll., PRL 121 (2018)



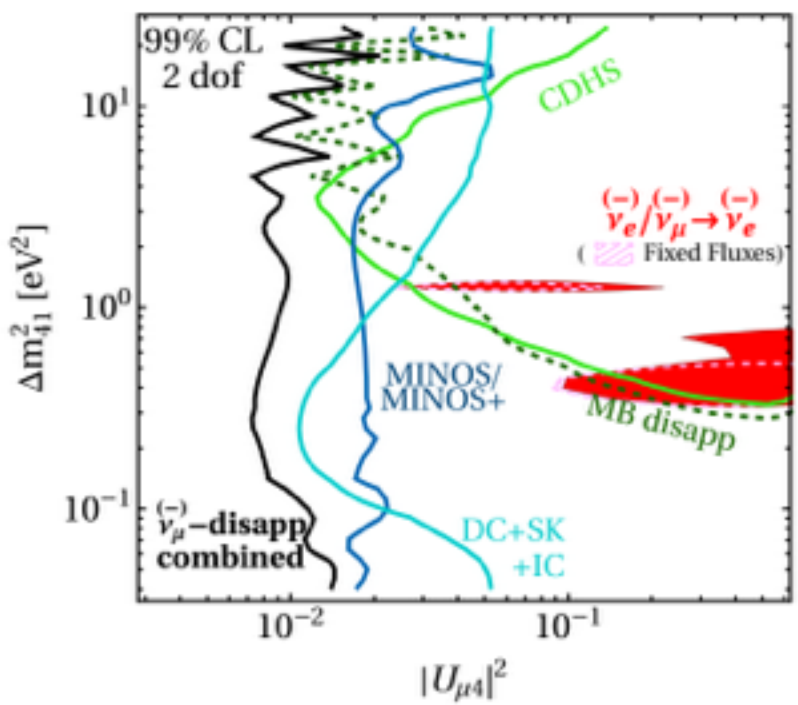




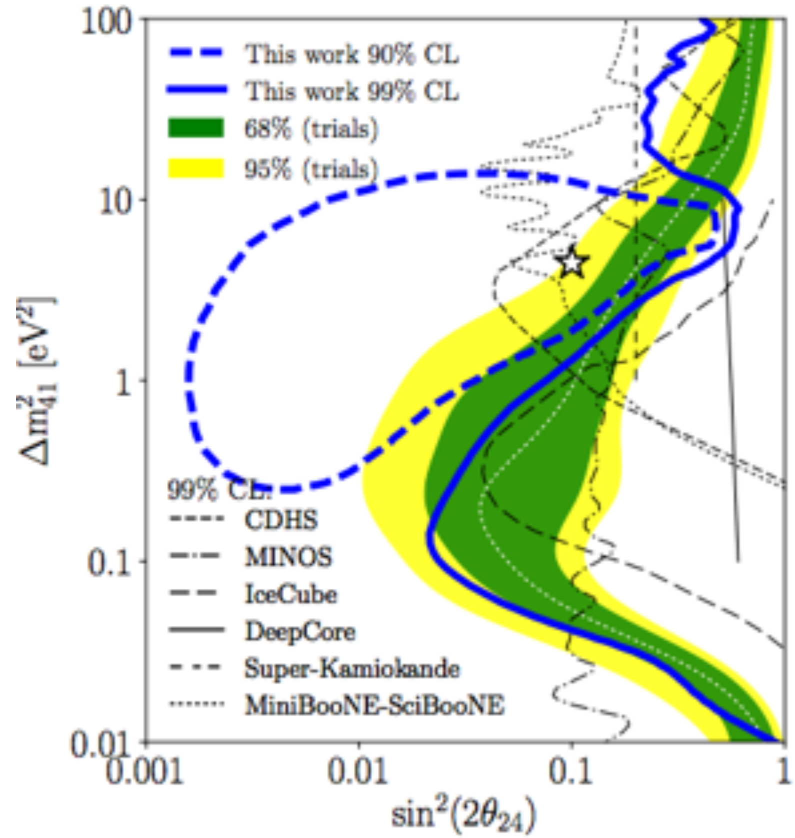
MiniBooNE Coll., 2006.16883

Muon neutrino disappearance channel

Muon neutrino disappearance studies have reported no hints but only strong bounds: IceCube (possible hint?), CDHS, MiniBooNE, SK, DeepCore, NOvA, MINOS/MINOS+.



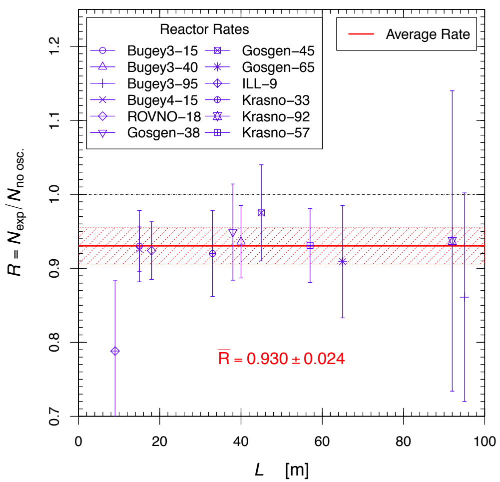
A. Dentler et al., 1803.10661



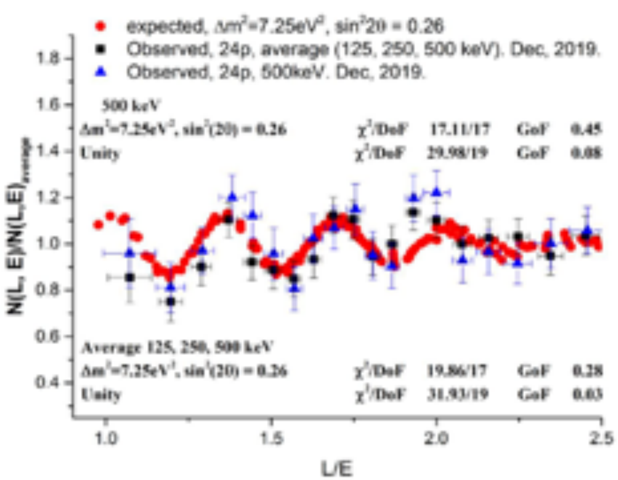
IceCube Coll., PRL 2020

Very short baseline experiments

Reactor anomaly: A deficit of electron antineutrino events. Experiments with very short baselines have been designed to test these anomalies in controlled conditions.



Mention et al., 2011. See also Muller et al., PRC 832011; Huber et al, PRC84 2011. And Sinev, 1103.2452; Ciuffoli et al., JHEP 12 2012; Zhang et al., PRD87 2013; Ivanov et al., 1306.1995.



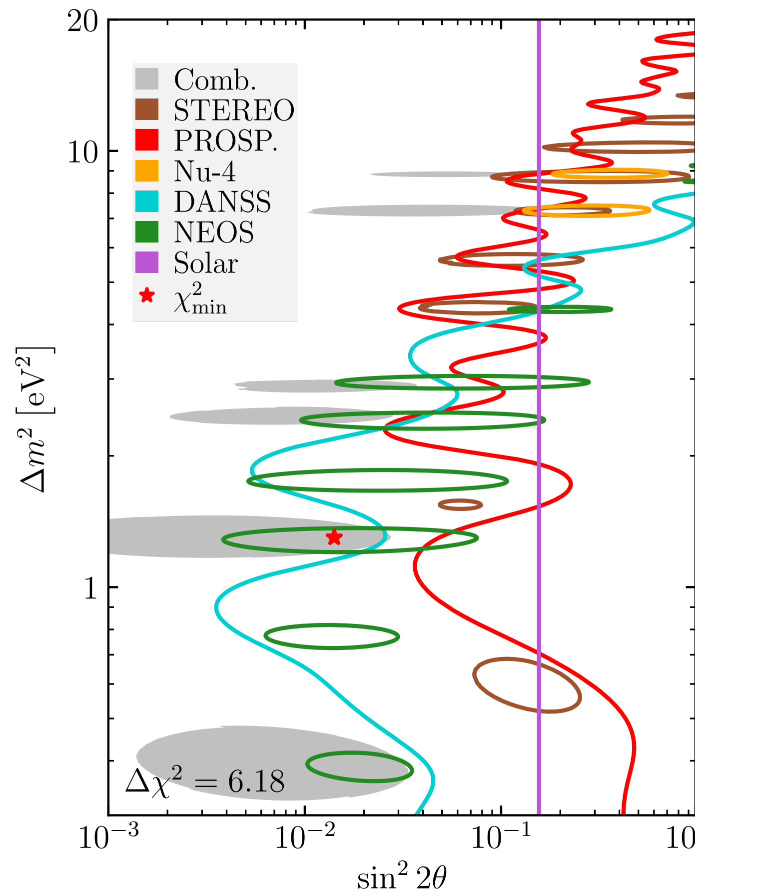
Neutrino4 Coll., 2005.05301

RENO +NEOS

PROSPECT

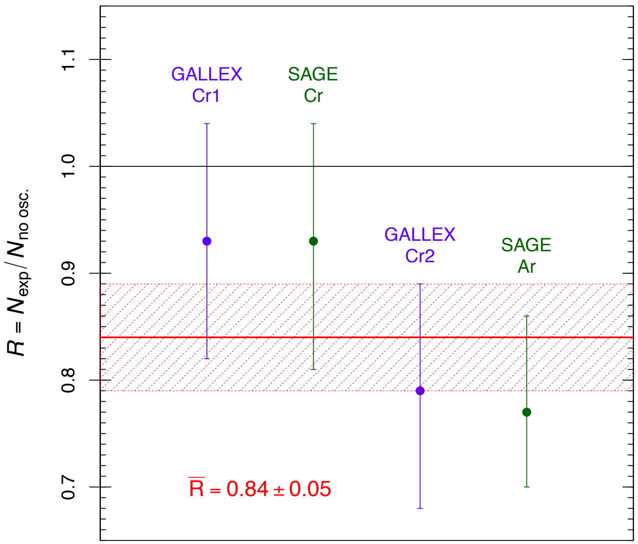
STEREO

DANSS Coll., 1911.10140

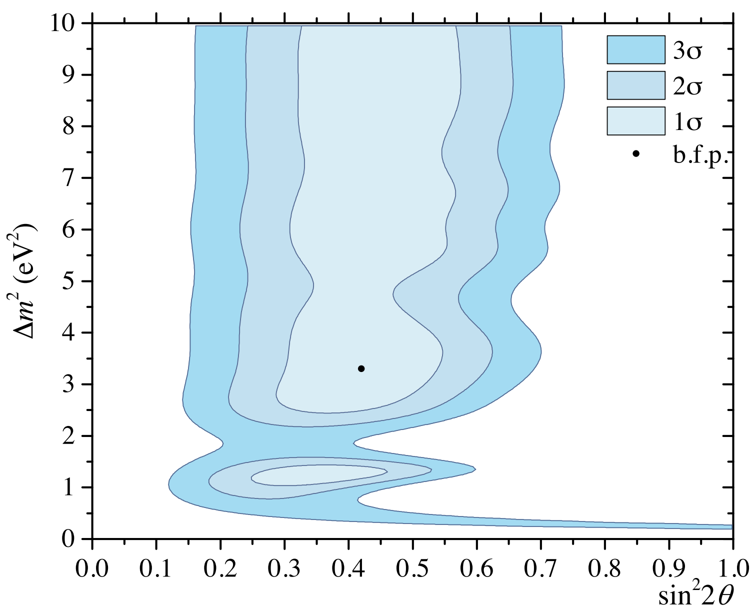


J. Berryman et al., 2111.12530

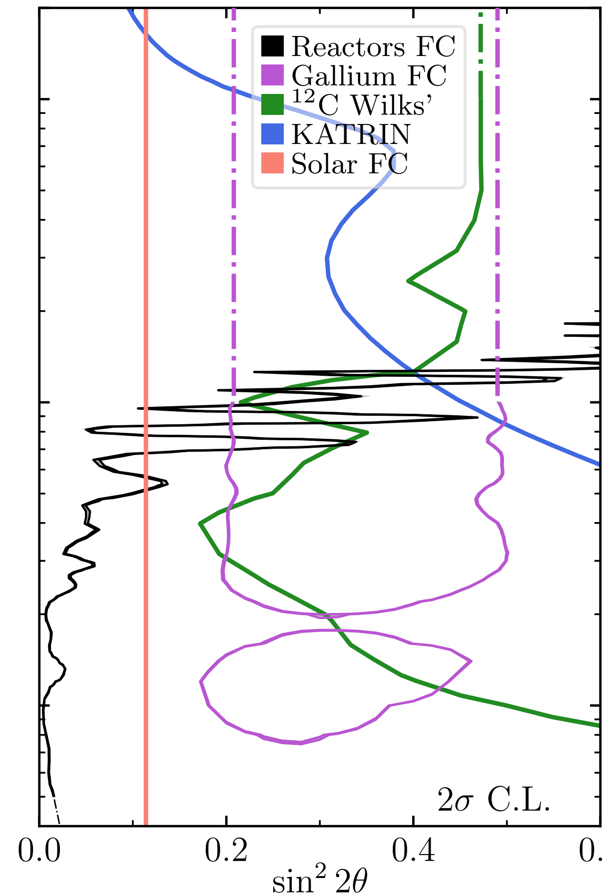
Gallium anomaly:



Frekers et al., PLB 706 2011. See also SAGE 2006, 2009; Laveder et al., NPPS 2007, MPLA 2007, PRD 2008, PRC 2011, PRD 2012.



BEST, 2201.07364



J. Berryman et al., 2111.12530

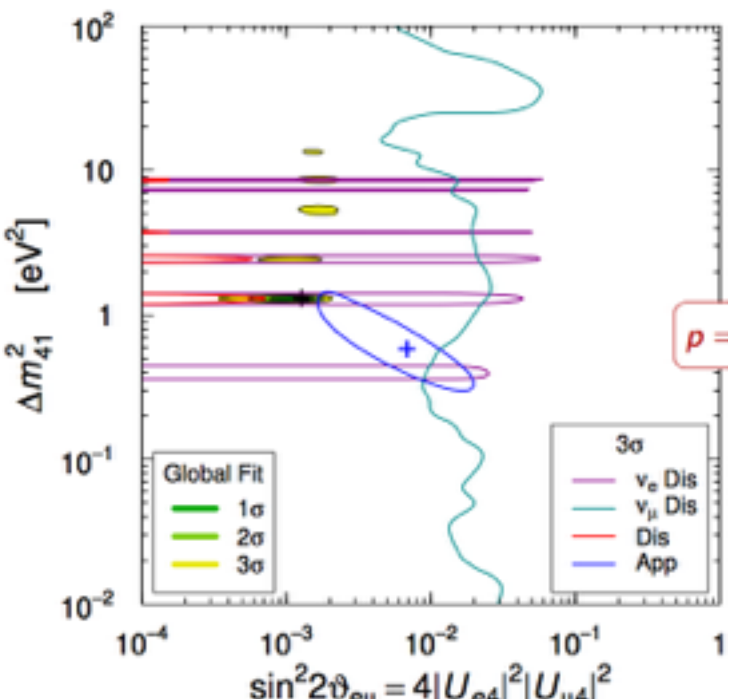
There are anomalies in the electron neutrino sector. A coherent picture has not yet emerged.

Explained by oscillation disappearance:

$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2) \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

Appearance experiments require mixing both with electron neutrinos and muon neutrinos: Tension.

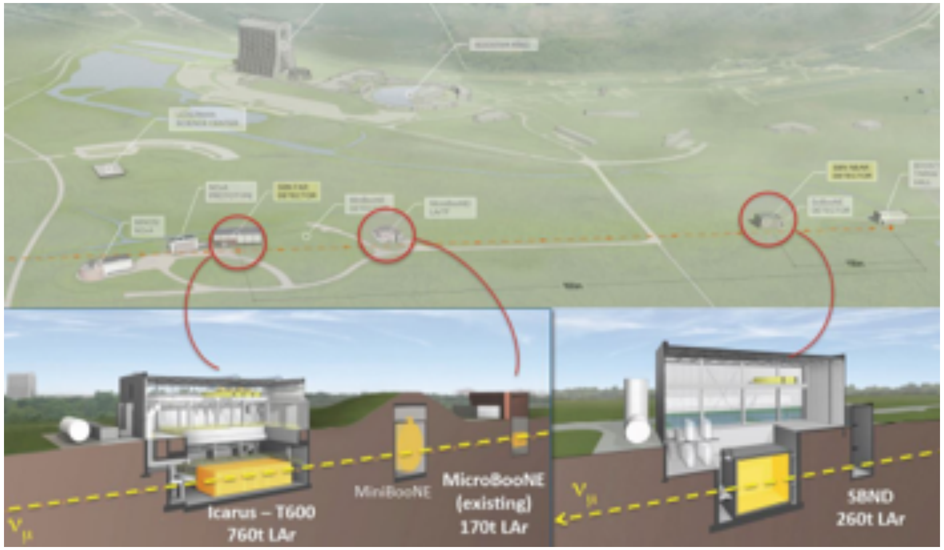
$$P(\nu_\alpha \to \nu_\beta) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 \frac{\Delta m^2_{41} L}{4E}$$



My take: The situation is still rather uncertain. Possibly the appearance results are not due to oscillations??? Major implications for cosmology.

Gariazzo et al., in preparation, TAUP 2021,
See also Gariazzo et al., JHEP 1706 (2017)

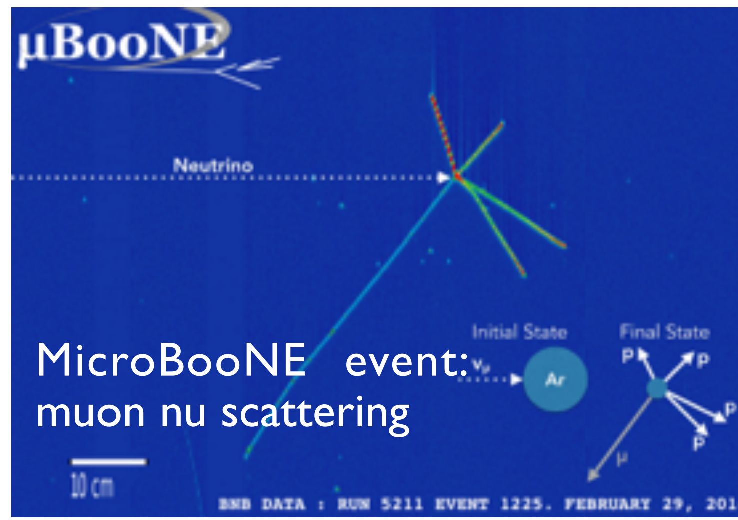
MicroBooNE and SBN at Fermilab



They use accelerator neutrino experiments with L~100-600m and E~700-800 MeV.

https://www.bo.infn.it/gruppo2/sbn-it/

MicroBooNE detector



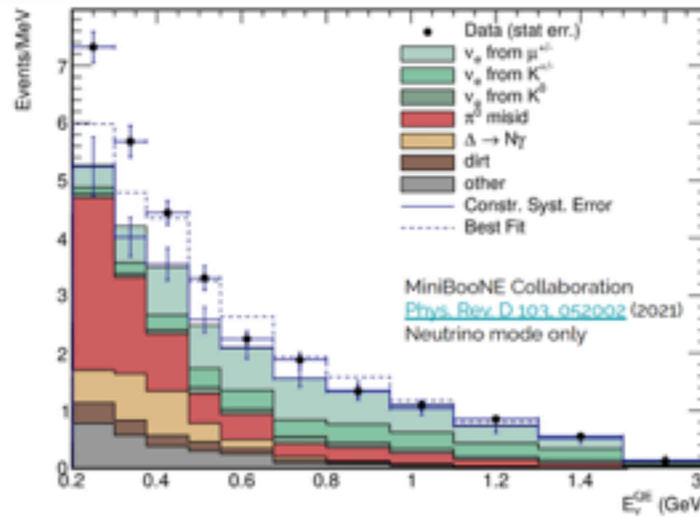
Accelerator neutrino experiments should provide the definitive answer and can check both the appearance and disappearance channels.

First results from MicroBooNE.
- - Is the MiniBooNE LEE is due to SM photons?

Electrons? **Or Photons?**

Several sources of photons in MiniBooNE backgrounds:

- NC π^0 Mis... MEASURED IN-SITU
- Dirt (event... om outside de... BEAM TIMING

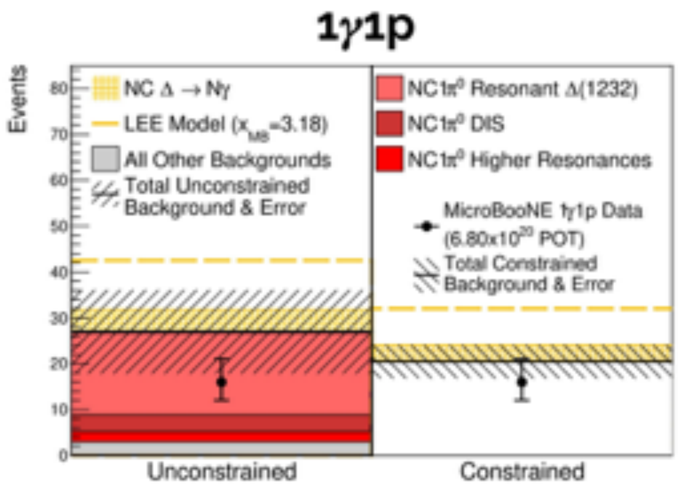


- NC $\Delta \to N\gamma$ (Neutral Current Δ radiative decay)

NC $\Delta \to N\gamma$ is a source of photons **not constrained directly** by the MiniBooNE experiment; rather, the rate was predicted by using the measured NC π^0 and **assuming a theoretical branching fraction** for the radiative decay.

M. Ross-Lonergan's talk at Fermilab, 04/10/2021

First results from MicroBooNE.
- Is the MiniBooNE LEE is due to SM photons?



1γ1p

Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \to N\gamma$	+ 4.88
LEE ($x_{MB} = 3.18$)	+ 15.5

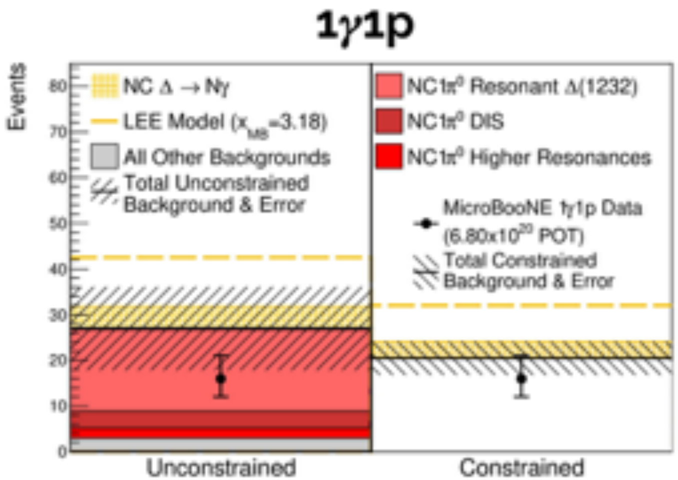
16
Data Events Observed

My take: Most likely not.

M. Ross-Lonergan's talk at Fermilab, 04/10/2021

MicroBooNE Coll., 2110.00409

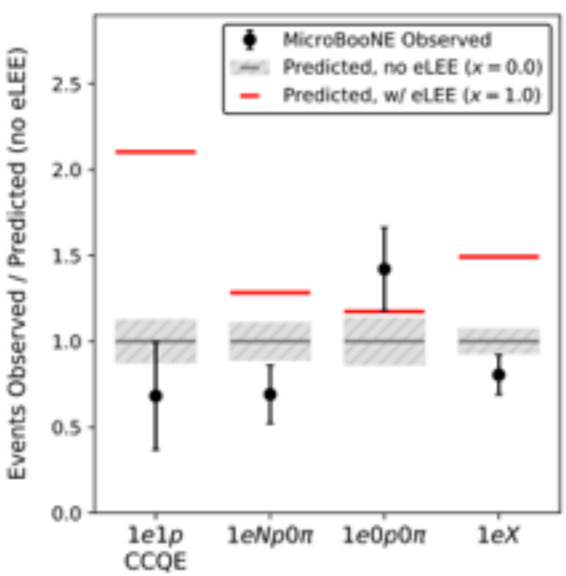
First results from MicroBooNE.
- Is the MiniBooNE LEE is due to SM photons?



My take:
Most likely not.

MicroBooNE Coll., 2110.00409

- Is the MiniBooNE LEE is due to electrons?



Electrons would come from nu_e scattering, and would signal neutrino oscillations.

My take: Most likely not.

My interpretation:

- MB LEE is not due to SM Delta photons.
- MicroBooNE results also strongly disfavour a neutrino oscillation explanation. This is compatible with the BEST and other electron neutrino disappearance anomalies.

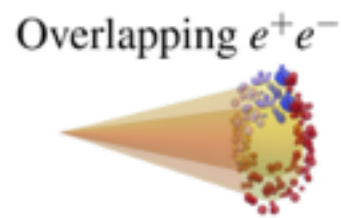
Then, what is the MiniBooNE LEE due to?

BSM explanations for MB LEE

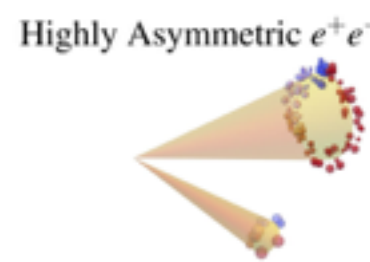
Due to the WC nature of MB, single electrons can be mimicked by photons and by electron-positron pairs (if overlapping or asymmetric).

Electrons? Or Photons? .....Or Neither?

Rich phenomenology developing in recent years around the possibility of the MiniBooNE excess being due to **e^+e^- pairs from decays of new exotic particles.**



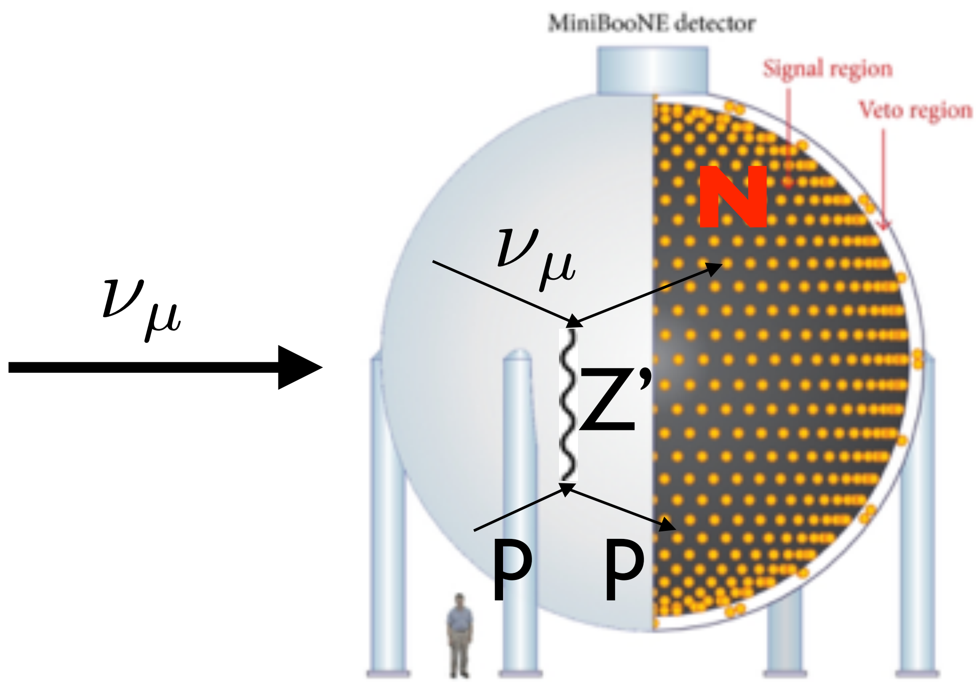
- Decays of **new dark gauge bosons** (Z')
  - E. Bertuzzo, S. Jana, P. A.N. Machado, R.Zukanovich Funchal Phys.Rev.Lett. 121 24, 241801(2018)
  - P. Ballett, S. Pascoli, M. RL Phys. Rev. D 99, 071701 (2019)
  - A. Abdullahi, M. Hostert, S.Pascoli Phys.Lett.B 820 136531(2021)
- General **Extended higgs sectors + Decay**
  - B. Dutta, S. Ghosh, T. Li Phys. Rev. D 102, 055017 (2020)
  - W. Abdallah, R. Gandhi, S. Roy Phys. Rev. D 104, 055028 (2021)
- Decays of **leptophilic axion-like** particles
  - C. V. Chang, C. Chen, S. Ho, S. Tseng Phys. Rev. D 104, 015030 (2021)

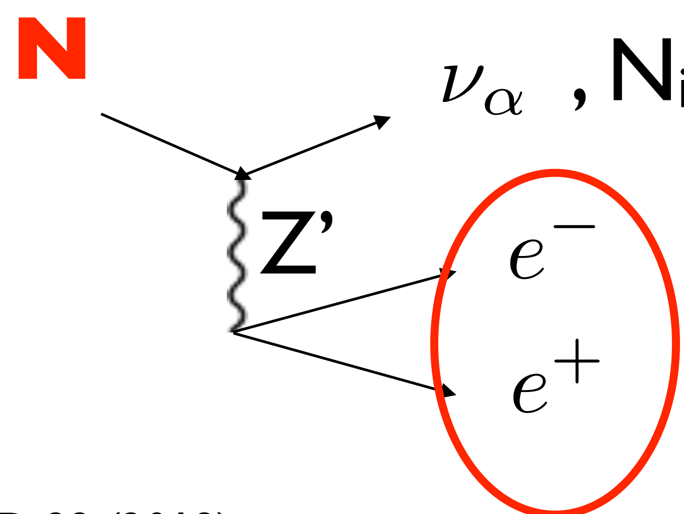


M. Ross-Lonergan's talk at Fermilab, 04/10/2021

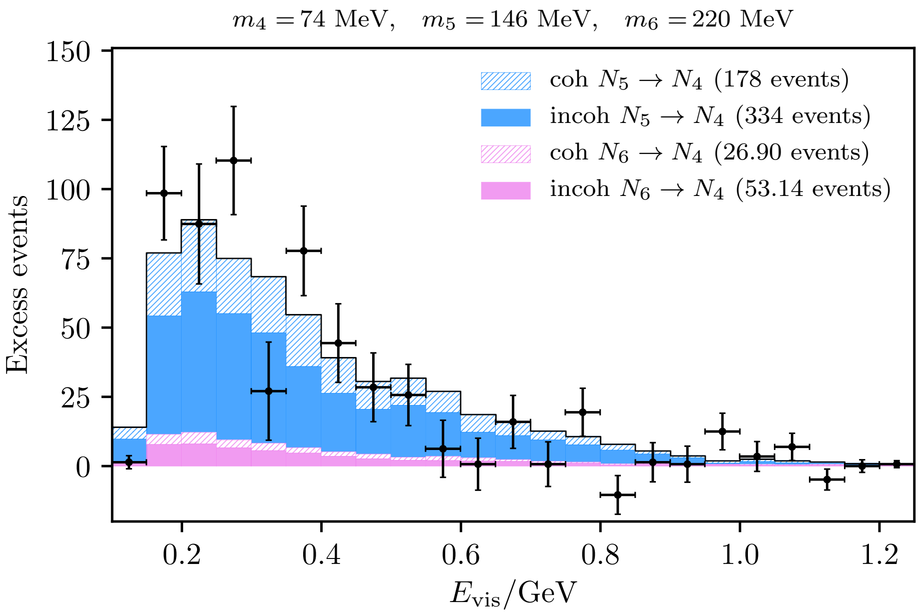
A viable explanation of the MiniBooNE low-E excess is provided by the up-scattering of an HNL N in the detector and its decay into ee nu.

It builds on a decay explanation of MiniBooNE by S. Gnineko, PRL 103 (2009). A similar analysis appeared at the same time but with light Z' by E. Bertuzzo et al., PRL 121 (2018).



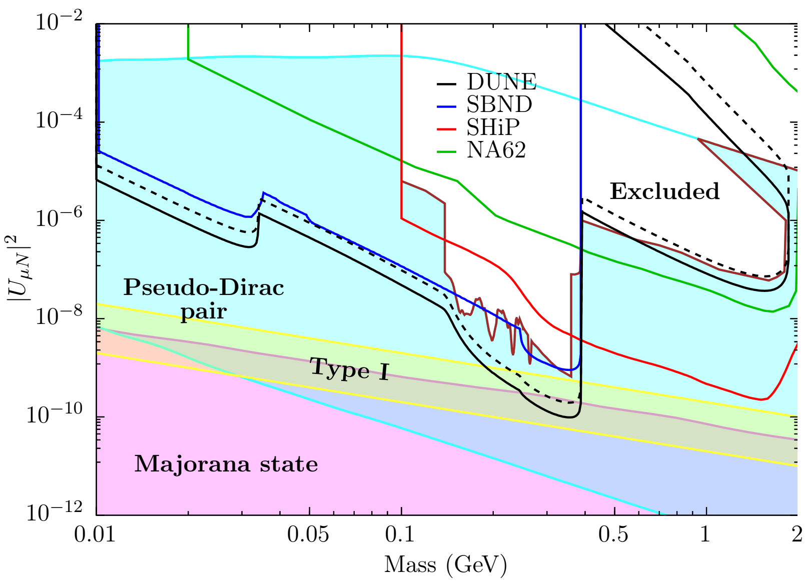


P. Ballett, S. Pascoli, M. Ross-Lonergan, PRD 99 (2019)



A. Abdullahi, M. Hostert, SP, 2007.11813

In a dark sector extension of the SM (U(1)' with associated dark photon and 3 heavy neutrinos (for anomaly cancellation) the decay HNL decays to ee can be very fast explaining the data.



Ballett, Boschi, SP, 1905.00284

Bounds change if additional interactions are allowed, e.g. dark forces (HNL can decay invisibly or semivisibly).

A host of other signatures

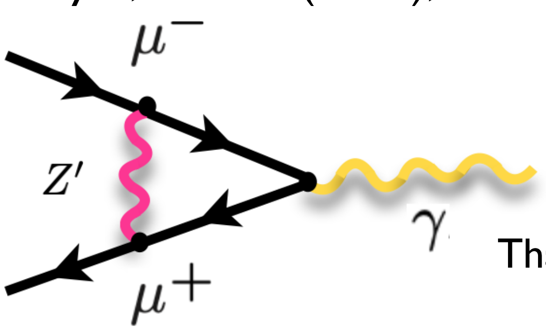
There is a longstanding discrepancy between the measured value of a_μ and the theoretical prediction, at 3.8 sigma.

For the most recent analysis, see Keshavarzi, Marciano, Passera, Sirlin.

$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{th} = (274 \pm 73) \times 10^{-11}$$

Kinetic mixing and light Z' can explain the anomaly,…

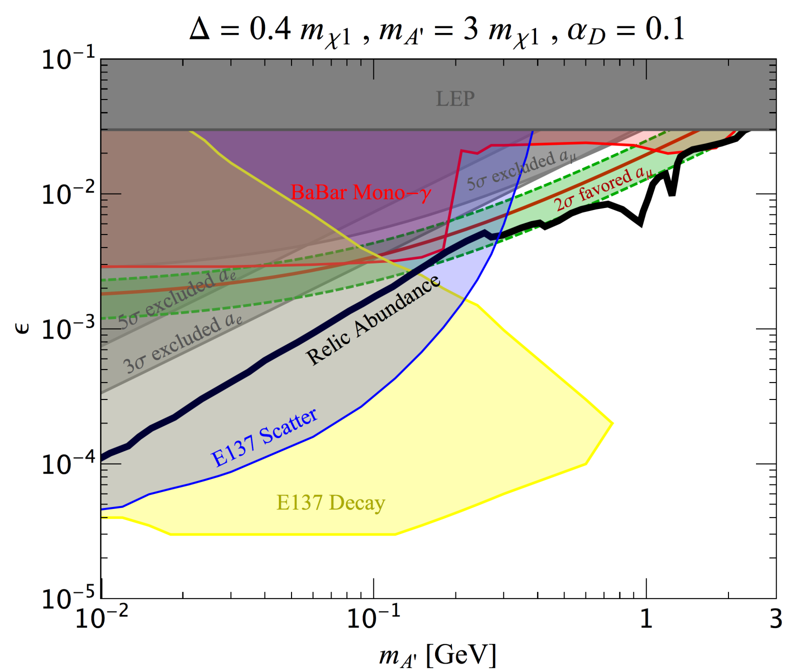
P. Fayet, PRD75 (2007), M. Pospelov, PRD80 (2009)



Thanks to A. Abdullahi

as far as Z' decays mainly semi-visibly (Z'->N N and N decay fast).

A. Abdullahi, M. Hostert, SP, 2007.11813



G. Mohlabeng, PRD99 (2019)

If this is true, what does it imply?

G. de Jode, 1593

Neutrinos as a window to Dark sectors???

The dark or hidden sector indicate extensions of the SM that are below the electroweak scale.

The dark sector interacts with SM via so-called portals:

Portal	Coupling
Dark Photon, A'	$-\frac{\varepsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Axion-like particles, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
Dark Higgs, S	$(\mu S + \lambda_{\rm HS} S^2) H^\dagger H$
Heavy Neutral Lepton, N	$y_N L H N$
milicharged particle, χ	$\epsilon A^\mu \bar{\chi} \gamma_\mu \chi$

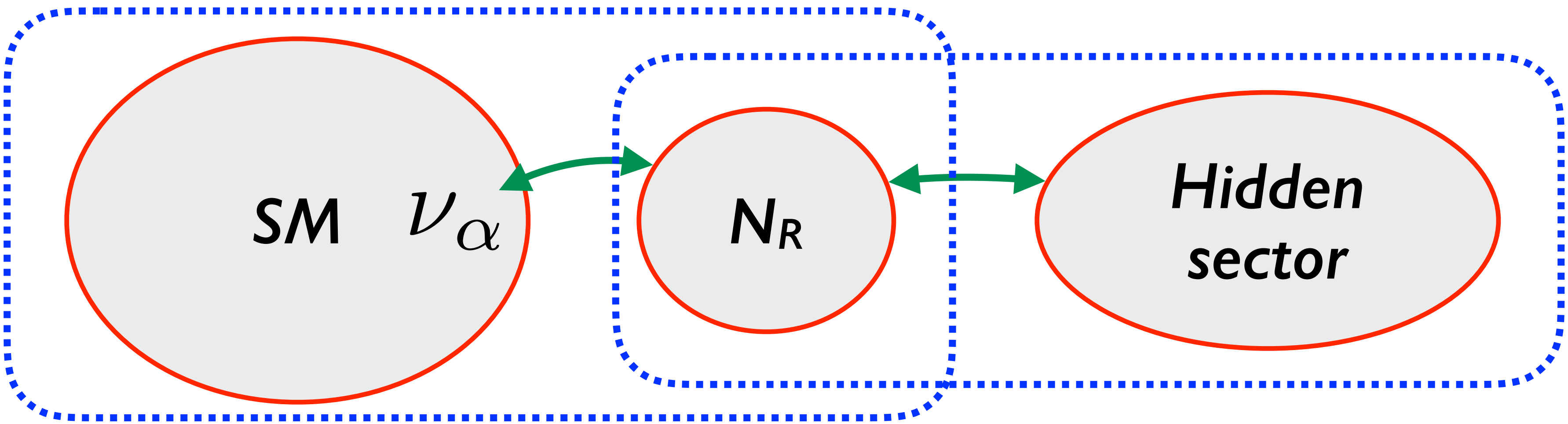
FIPs report, 2102.12143

The neutrino portal

The dark sector can interact with SM via an sterile neutrino NR, being neutral, which couples to both:

neutrino portal

$$\bar{L} \cdot H N_R \quad (+ ... \overline{N_R} N_S)$$



After EW and U(1)' breaking, the active, sterile and dark neutrinos mix. Neutrinos can interact with the new sector (including DM). Neutrino experiments can play a key role in its exploration. Major implications for cosmology.

Conclusions

Neutrinos are the most elusive and mysterious of the known particles. Neutrino masses only particle physics evidence BSM.

Current status: precise knowledge of most of neutrino properties. Key questions open (nature, CPV) due to be answered in the next decade. Thriving experimental programme.

Surprises in store? MiniBooNE LEE remains a puzzle. New MicroBooNE results point away from sterile neutrinos. Neutrino4 and BEST anomalies?

Are neutrinos pointing towards a new understanding of particles: dark sector?