Neutrinos: from past surprises to new puzzles?

21 January 2022

U. Torino

Silvia Pascoli

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

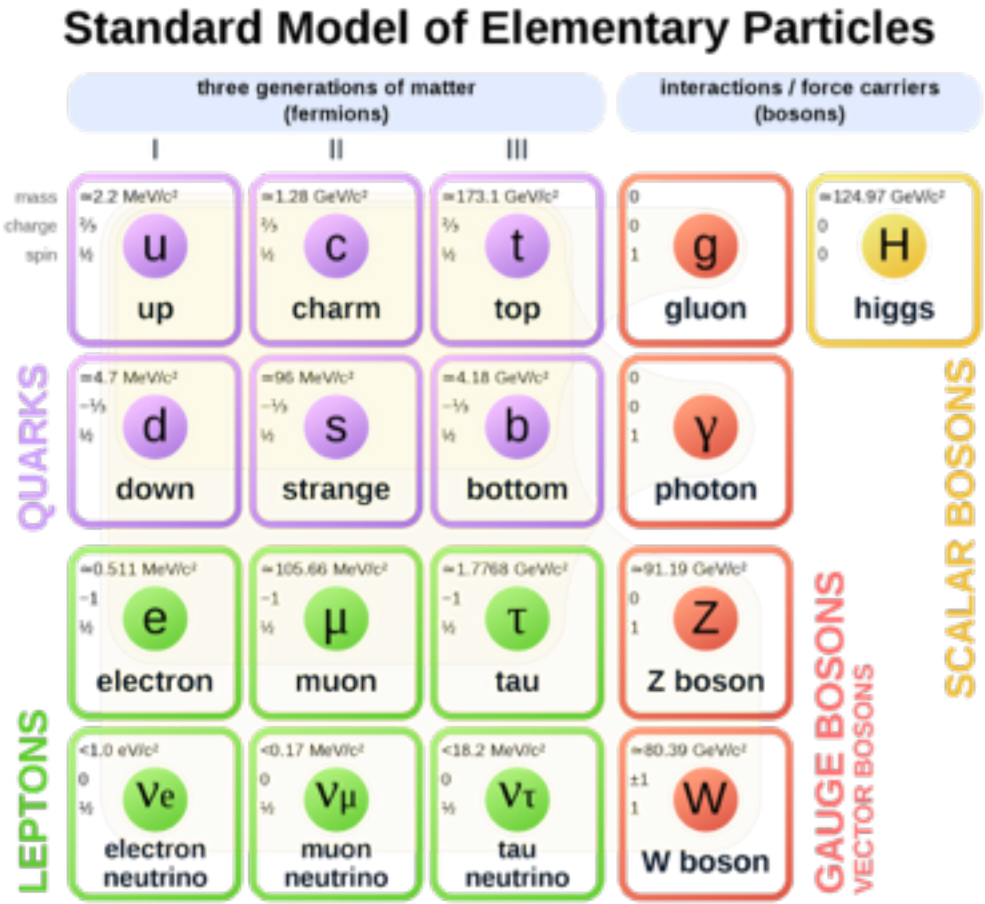
Horizon2020

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

INFN

Neutrinos in the SM

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



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

- Neutrinos in the SM are of only one type (left-handed Weyl spinors) as the right-handed component is not included.

SM is a gauge theory: $SU(3)_c \times SU(2)_L \times U(1)_Y$

Particles	$SU(3)$	$SU(2)_L$	$U(1)_Y$
Leptons			
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L , \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	**1**	**2**	$-1/2$
$e_R\,, \quad \mu_R\,, \quad \tau_R$	**1**	**1**	-1
Quarks			
$\begin{pmatrix} u \\ d \end{pmatrix}_L , \quad \begin{pmatrix} c \\ s \end{pmatrix}_L , \quad \begin{pmatrix} t \\ b \end{pmatrix}_L$	**3**	**2**	$1/6$
$u_R\,, \quad c_R\,, \quad t_R$	**3**	**1**	$2/3$
$d_R\,, \quad s_R\,, \quad b_R$	**3**	**1**	$-1/3$

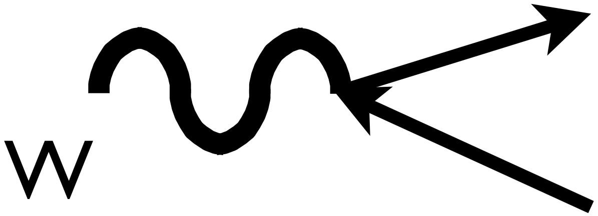
Neutrinos belong to SU(2) doublets and are neutral.

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

$$\ell \xrightarrow{U(1)_{\text{lepton}}} e^{i\alpha}\ell \qquad \nu_L \xrightarrow{U(1)_{\text{lepton}}} e^{i\alpha}\nu_L$$

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

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



W

electron

electron antineutrino

Number of active neutrinos

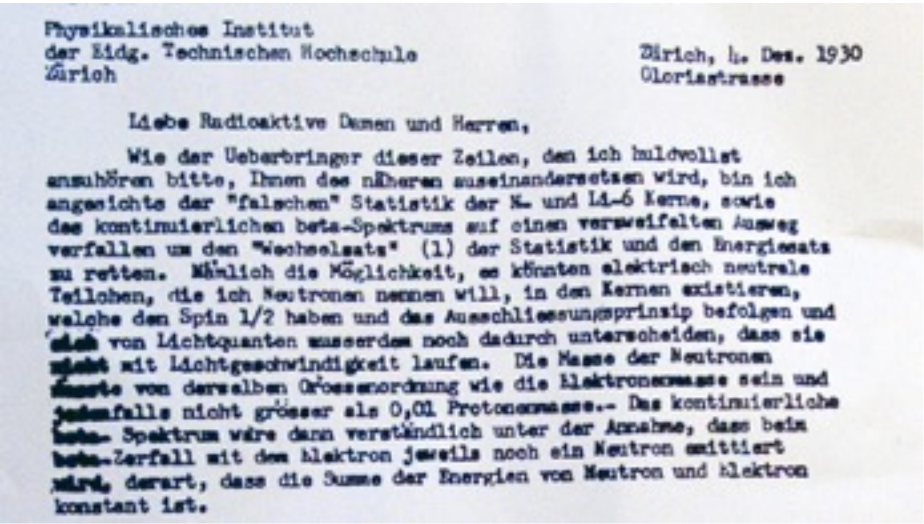
The invisible width of the Z (measured precisely at LEP) restricts the number of active (=interacting) neutrinos to

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

Note: Additional neutrinos can be present but they cannot partake of the SM interactions and are called sterile neutrinos.

A REALLY brief history of our knowledge of neutrinos

The proposal of the “neutrino” was put forward by W. Pauli in 1930. [Pauli Letter Collection, CERN]



Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

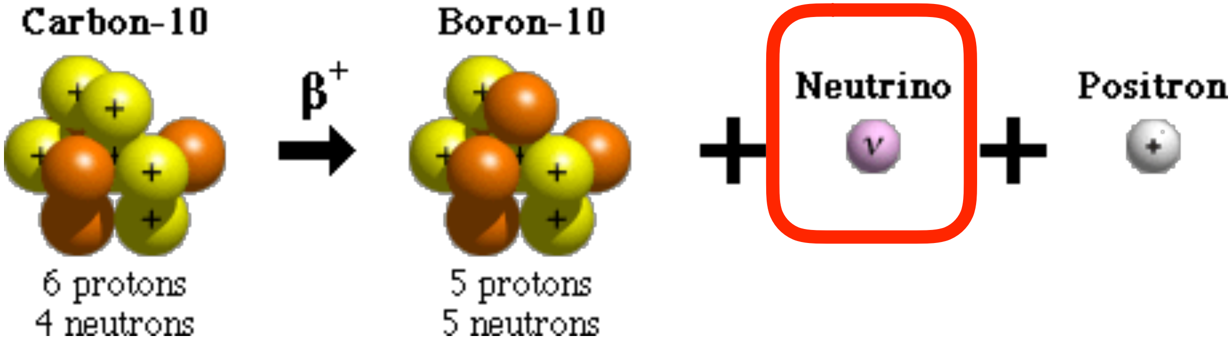
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

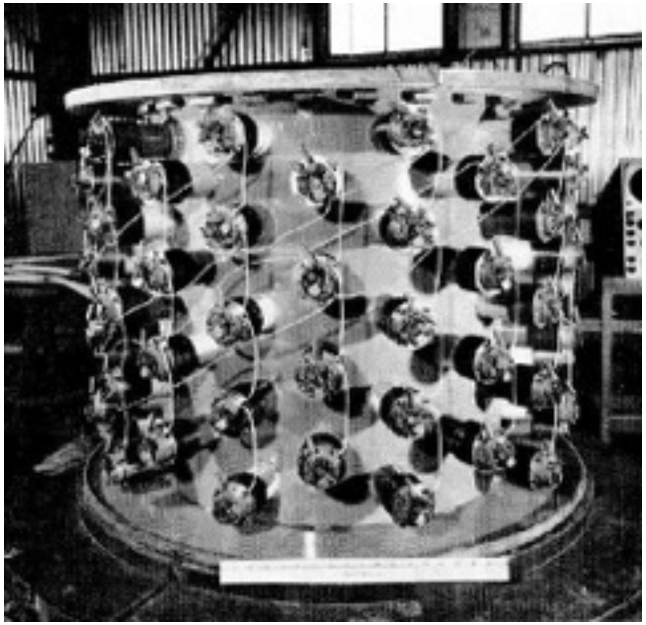
Dear radioactive ladies and gentlemen,

…I have hit upon a desperate remedy to save the … energy theorem. Namely the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons, which have spin 1/2 … The mass of the neutron must be … not larger than 0.01 proton mass. …in β decay a neutron is emitted together with the electron, in such a way that the sum of the energies of neutron and electron is constant.

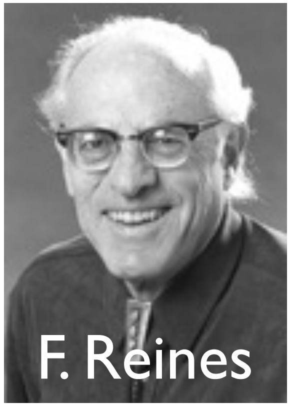


- Fermi, following E. Amaldi, used the name "neutrino" (little neutron) and later proposed the Fermi theory of beta decay.

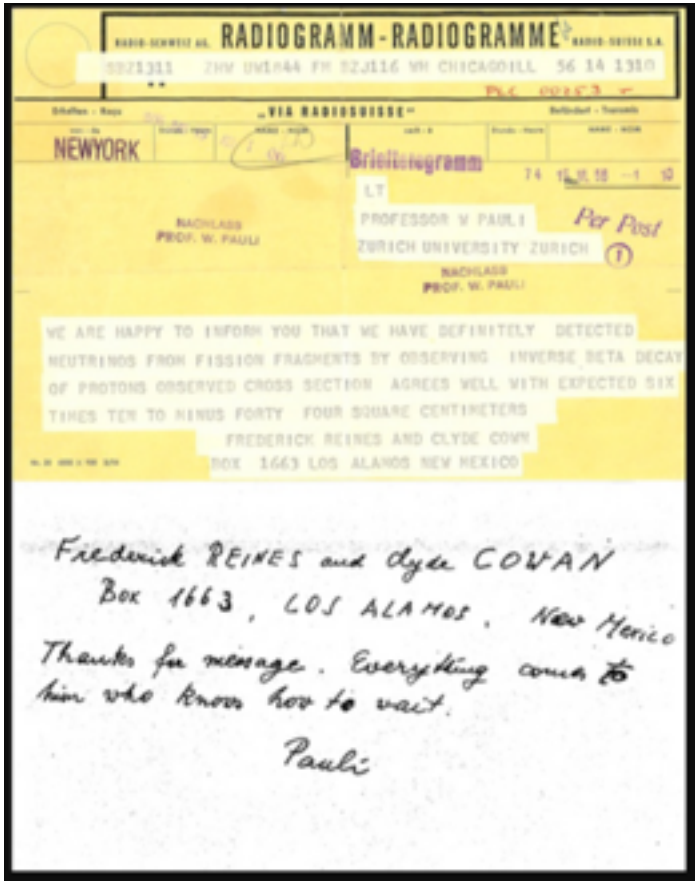
- Reines and Cowan discovered neutrinos in 1956 using inverse beta decay.



Savannah River experiment



The Nobel Prize in Physics 1995



RADIOGRAMM-RADIOGRAMME

VIA RADIOSUISSE

NEWYORK

Brieftelegramm

NACHLASS
PROF. W. PAULI

LT
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH

Per Post

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

FREDERICK REINES AND CLYDE COWAN
BOX 1663 LOS ALAMOS NEW MEXICO

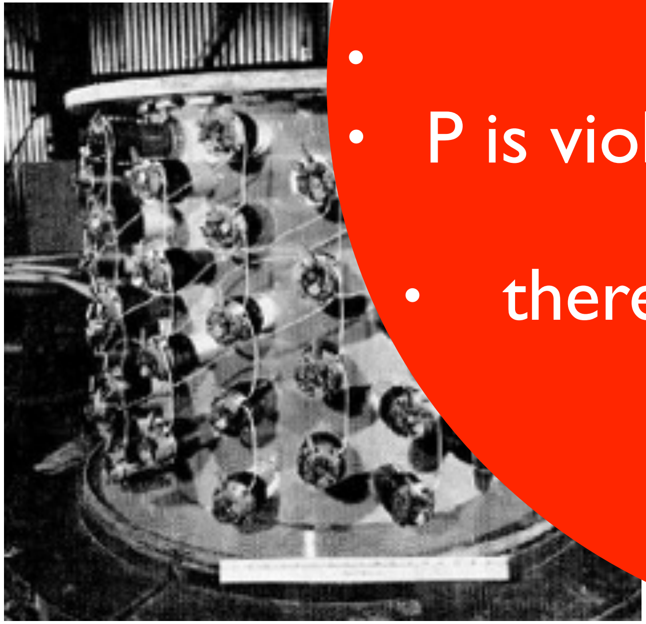
Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico

Thanks for message. Everything comes to him who knows how to wait.

Pauli

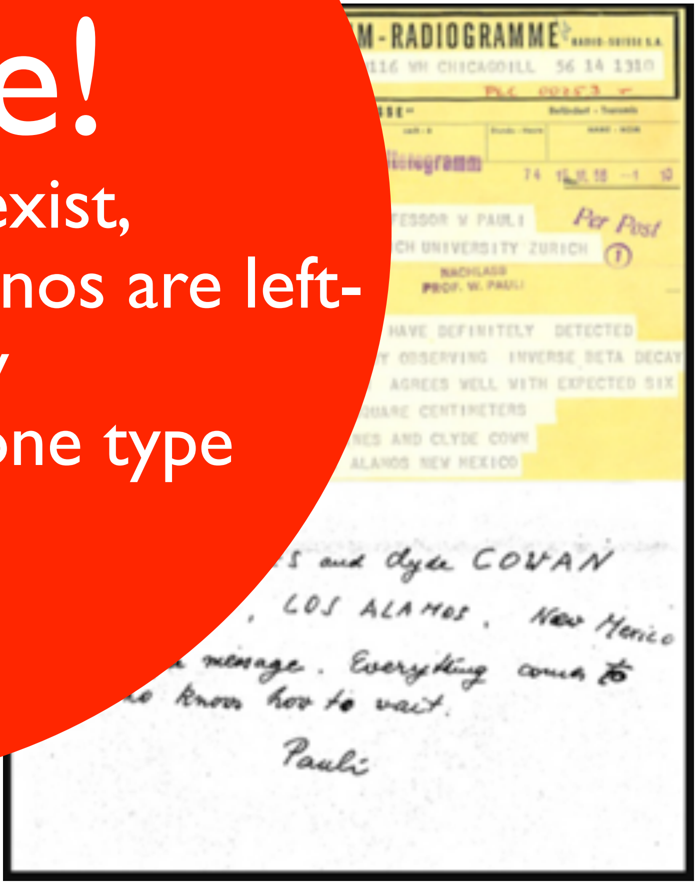
- Fermi, following E. Amaldi, used the name "neutrino" (little neutron) and later proposed the Fermi theory of b

- Reines and C
neutrinos in
beta decay.



Savannah River experiment

1995



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FESSOR W PAULI
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HAVE DEFINITELY DETECTED
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QUARE CENTIMETERS
NES AND CLYDE COWN
ALAMOS NEW MEXICO

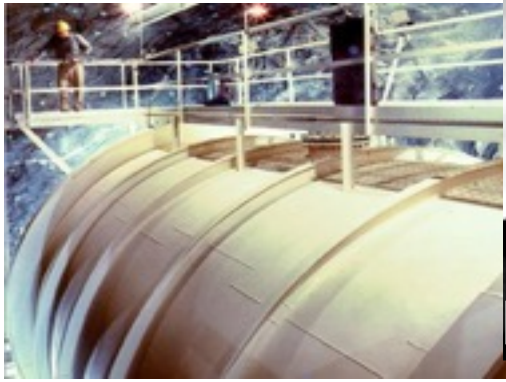
s and Clyde COWAN
, LOS ALAMOS, New Mexico
message. Everything comes to
o knows how to wait.
Pauli

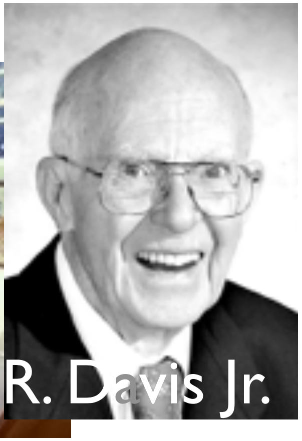
Surprise!

- Neutrinos exist,
- P is violated and neutrinos are left-handed only
- there is more than one type

Searches for **astrophysical neutrinos** (from the Sun, SN and atmosphere) started, reporting anomalies.

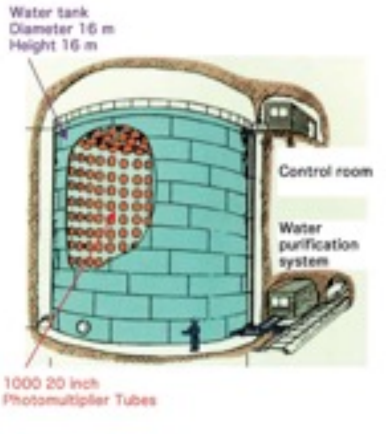
Homestake





R. Davis Jr.

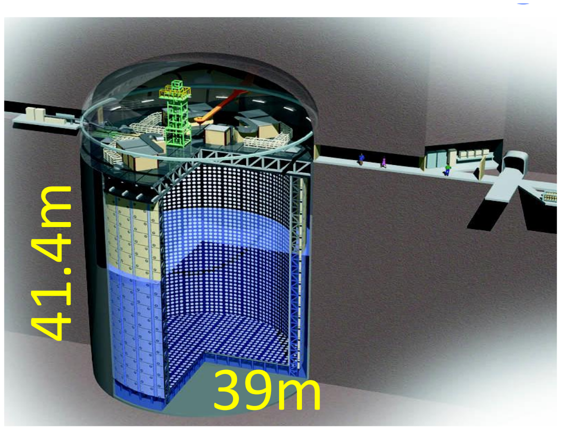
Kamiokande



M. Koshiba

Nobel prize in 2002

This led to the discovery of neutrino oscillations.



Super-Kamiokande

T. Kajita

SNO

A. McDonald

Nobel Prize in Physics 2015

Searches for **astrophysical neutrinos** (from the Sun, SN and atmosphere) started, reporting anomalies.

Homestake

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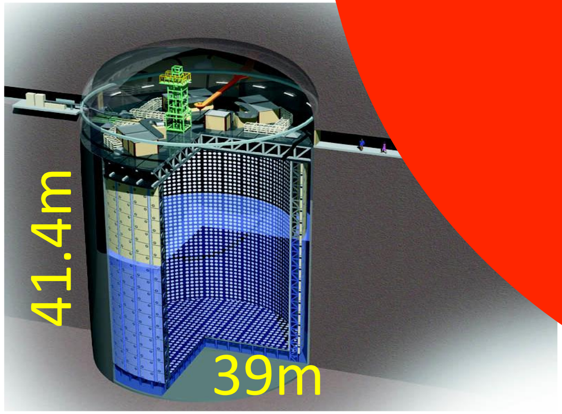
Nobel
prize
in
2002

This

ions.

Surprise!

Neutrinos oscillate



Super-Kamiokande

T. Kaj

SNO

A. McDonald

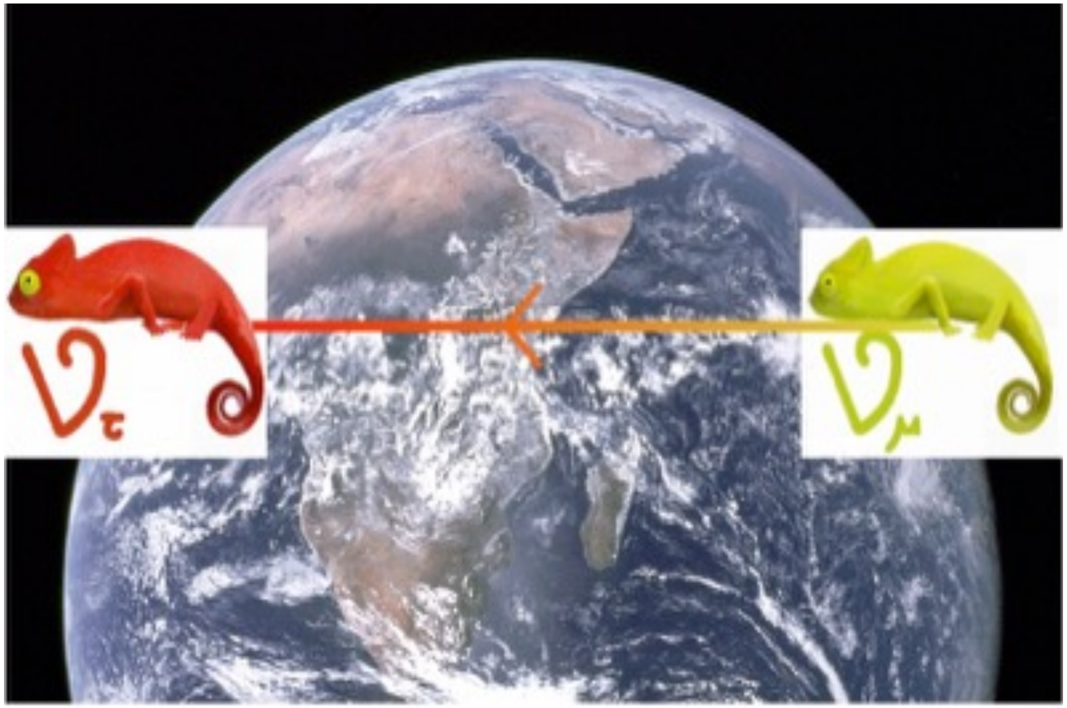
Nobel Prize in
Physics 2015

Neutrino oscillations: a quantum mechanical phenomenon

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

Бруно Понтекорво

Neutrinos can change flavour while traveling. This is an eminently quantomechanical effect, similar to other observed ones, such as spin precession. It has an oscillatory behaviour.



Neutrino mixing

Mixing between two basis (flavour and mass) is described by the *Pontecorvo-Maki-Nakagawa-Sakata* matrix:

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

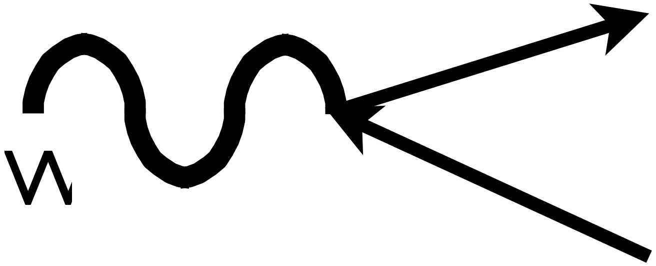
Flavour field

Mass field

which enters in the CC interactions

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

This implies that in an interaction with an electron, the corresponding (anti-)neutrino will be produced, as a superposition of different mass eigenstates.



Positron

electron neutrino $= \sum_{i} U^{*}_{ei} \nu_{i}$

- 2-neutrino mixing matrix depends on 1 angle only. The phases get absorbed in a redefinition of the leptonic fields (a part from 1 Majorana phase).

$$\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

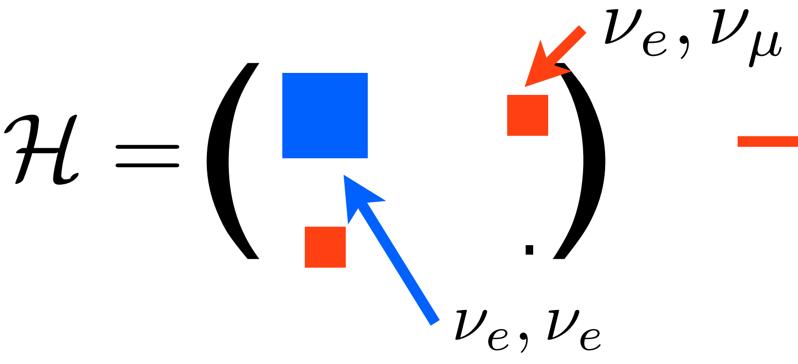
- 3-neutrino mixing matrix has 3 angles and 1(+2) CPV phases (neutrino - antineutrino $U \to U^*$).

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

Let's assume that a muon neutrino is produced

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

The time-evolution is described by the Schroedinger equation with free Hamiltonian:



flavour basis

$$\longrightarrow \quad i\frac{d}{dt}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = \begin{pmatrix}E_1 & 0\\ 0 & E_2\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

mass basis

The solution is

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

At detection one projects over the flavour state. The probability of oscillation is

$$P(\nu_\mu \to \nu_e) = |\langle \nu_\mu | \nu_e \rangle|^2 = \left| \sum_{ij} U^*_{ei} U_{\mu j} e^{-iE_i t} \langle \nu_j | \nu_i \rangle \right|^2$$

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

$$= \left| \sum_i U^*_{ei} U_{\mu i} e^{-i \frac{m_i^2 - m_1^2}{2E} t} \right|^2$$

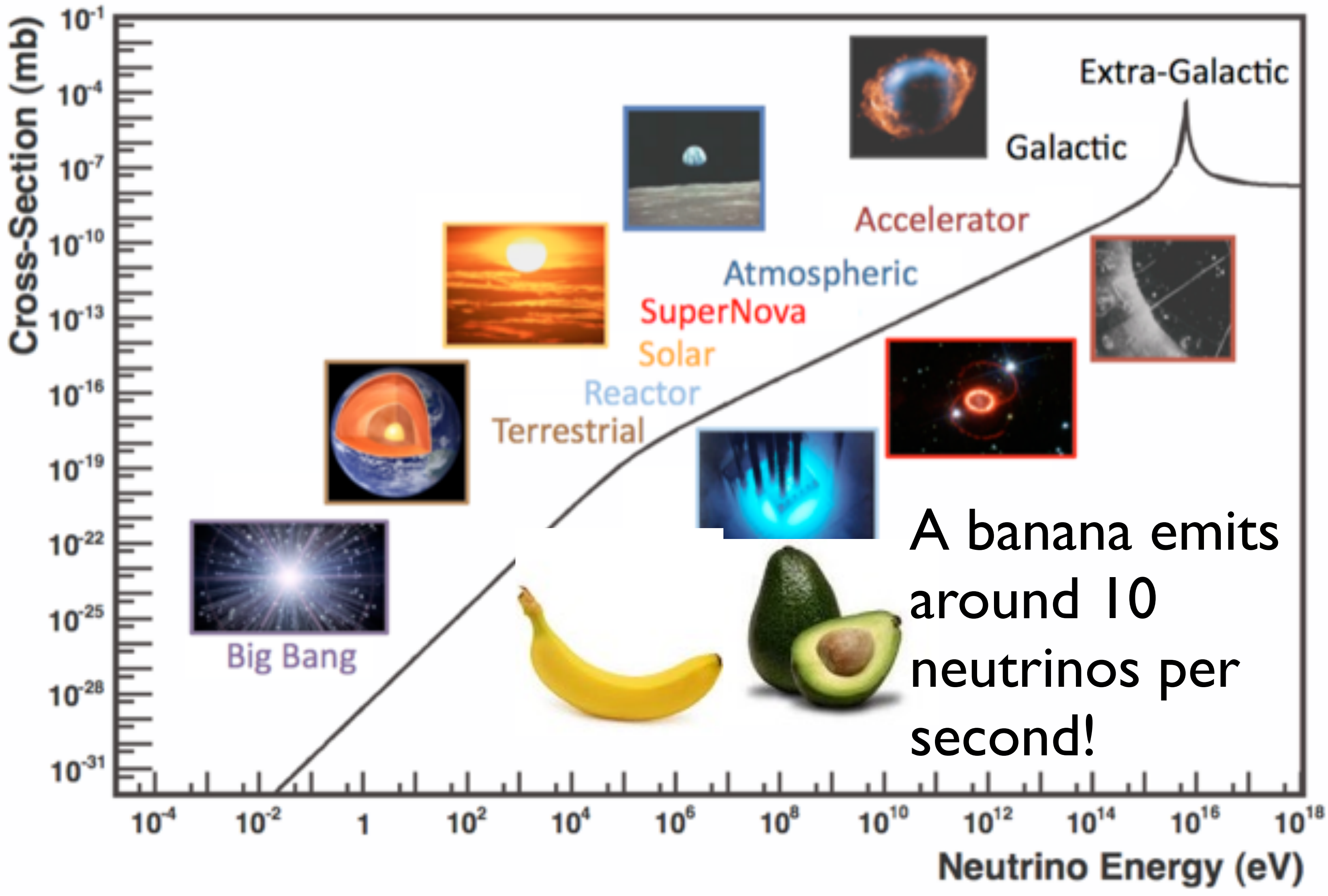
$$\Delta m^2_{i1}$$

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

- **neutrinos have mass** (as the different components of the initial state need to propagate with different phases)
- **neutrinos mix** (If they do not mix the flavour eigenstates are also eigenstates of the propagation Hamiltonian.)

Current knowledge of neutrino properties

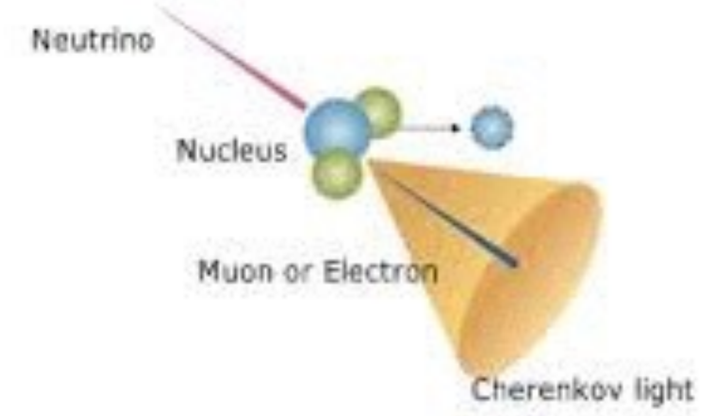
Neutrino sources



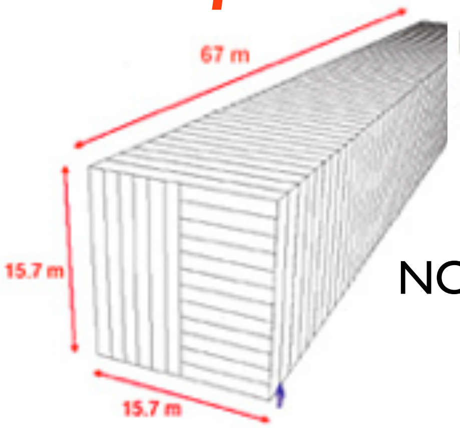
A banana emits around 10 neutrinos per second!

J. Formaggio and S. Zeller, 1305.7513

Current/past experiments



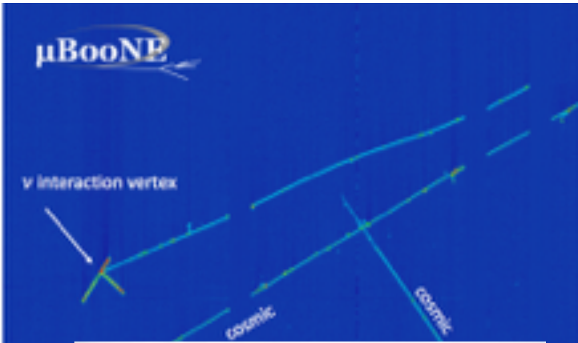
Credit: Super-Kamiokande



NOvA

KamLAND

DayaBay, RENO, DoubleCHOOZ



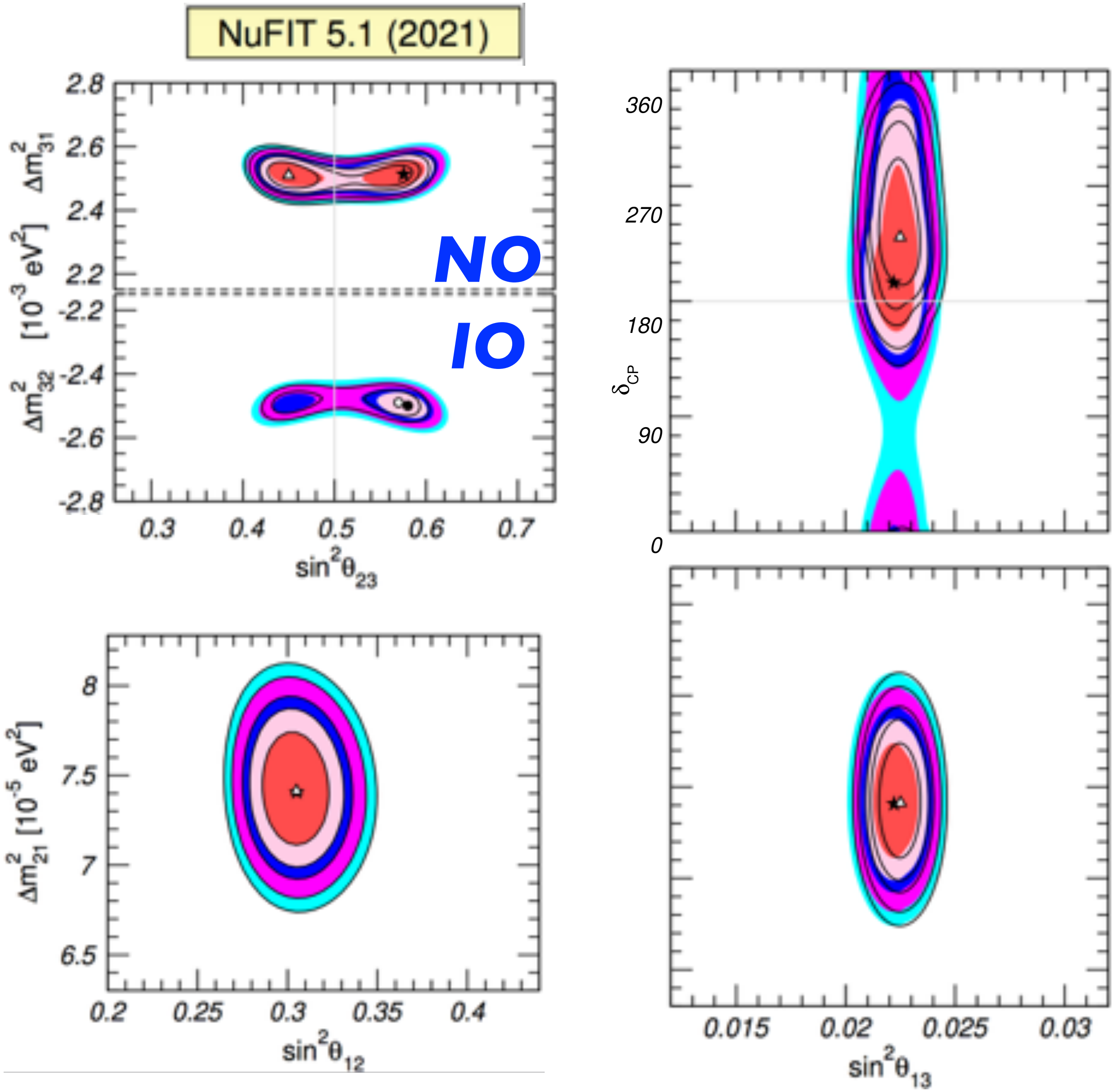
ICARUS

SNO

Super-Kamiokande

T2K

IceCube

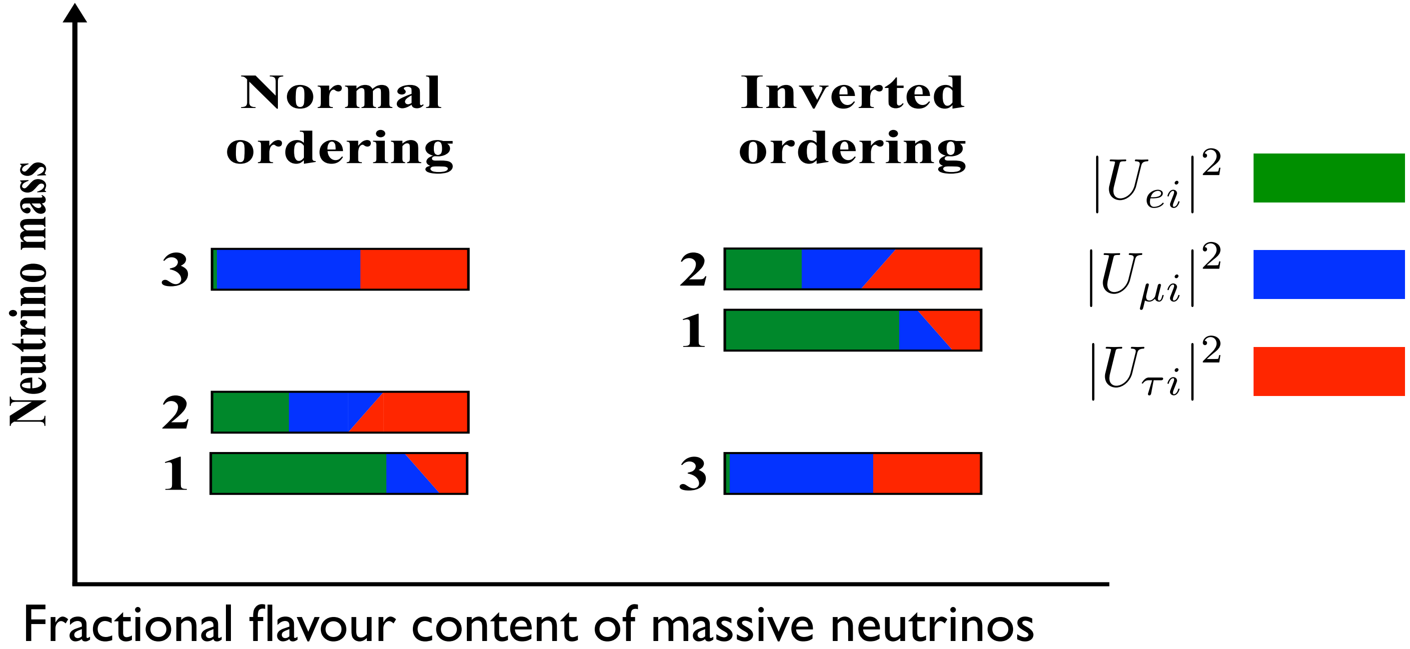


Current status:

- 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

$\Delta m^2_{21} \ll \Delta m^2_{31}$ implies at least 3 massive neutrinos.



$$\begin{aligned} m_1 &= m_{\min} \\ m_2 &= \sqrt{m_{\min} + \Delta m^2_{21}} \\ m_3 &= \sqrt{m_{\min} + \Delta m^2_{31}} \end{aligned}$$

$$\begin{aligned} m_3 &= m_{\min} \\ m_1 &= \sqrt{m_{\min} + |\Delta m^2_{32}| - \Delta m^2_{21}} \\ m_2 &= \sqrt{m_{\min} + |\Delta m^2_{32}|} \end{aligned}$$

- Neutrino masses: ordering and scale unknown. They are much smaller and less hierarchical than charged fermions.
- Possibly large CPV: fundamental question
- Large mixing angles (differently from quark sector).

$\Delta m^2_{21} \ll \Delta m^2_{31}$ implies at least 3 massive neutrinos.

Surprise!

Very small and not-very-hierarchical masses

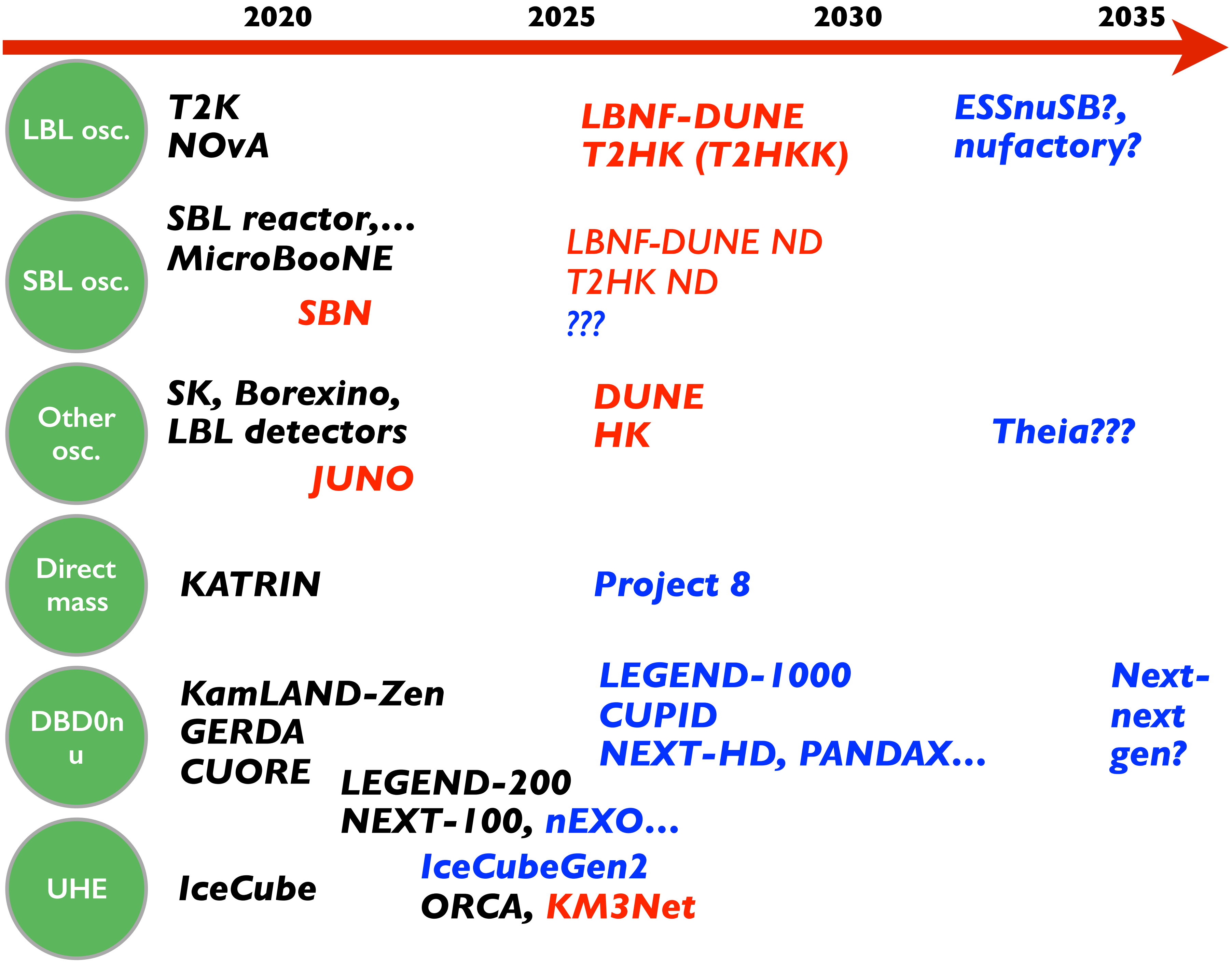
Large mixing angles

- Neutrino ma wn. They are much smaller and arged fermions.
- Possibly large CPV: fund question
- Large mixing angles (differently from quark sector).

Questions for the future

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 and neutrinoless DBD

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

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

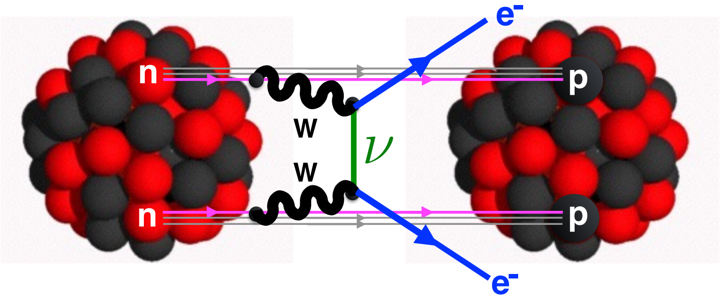
The **nature** of neutrinos is linked to the conservation of **Lepton number (L).**

- 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 ((A,Z) -> (A, Z+2) + 2 e) experiments can proceed via the exchange of massive Majorana 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:

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

Mixing angles (known)

CPV phases (unknown)

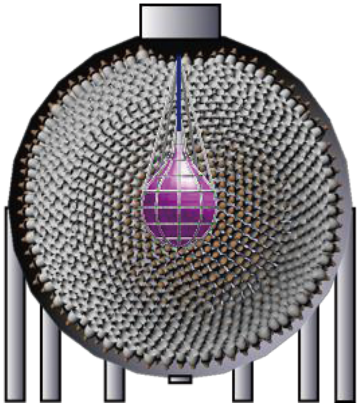
Neutrinoless double beta decay is a very rare process: $T_{1/2} > 10^{26}$ yrs.

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

ton-scale

<1% at Q_{bb}

<1 cts/yr/ton/ROI



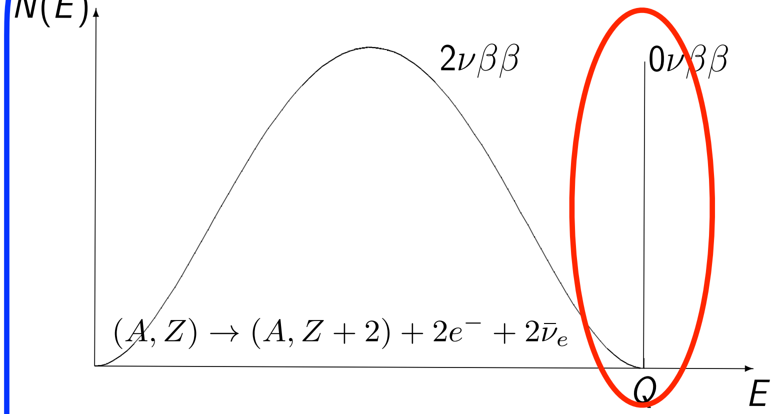
KamLAND-Zen

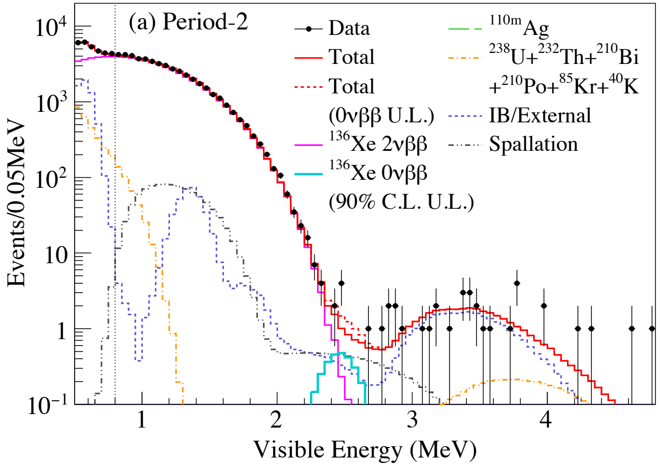
News

Roman ingots to shield particle detector

Lead from ancient shipwreck will line Italian neutrino experiment.

Nature





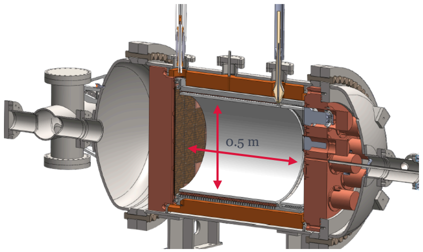
KamLAND-Zen, PRL 117 (2016)

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

EXO-200 ~75 kg LXe TPC, $T_{1/2} > 3.5 \times 10^{25}$ yrs

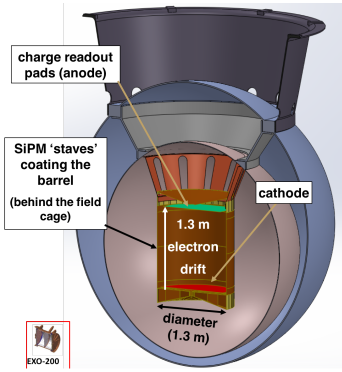
GERDA 31 kg (enriched) ^{76}Ge, $T_{1/2} > 1.8 \times 10^{26}$ yrs
MAJORANA 26.0 kg yrs, $T_{1/2} > 0.27 \times 10^{26}$ yrs

CUORE ^{130}Te, ~206 kg, $T_{1/2} > 2.2 \times 10^{25}$ yrs

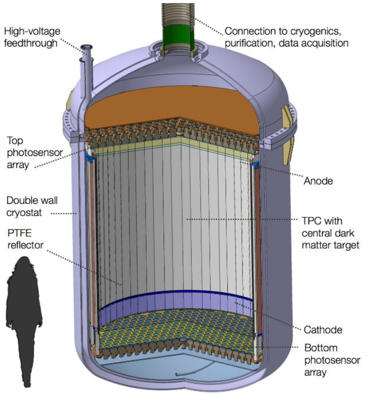


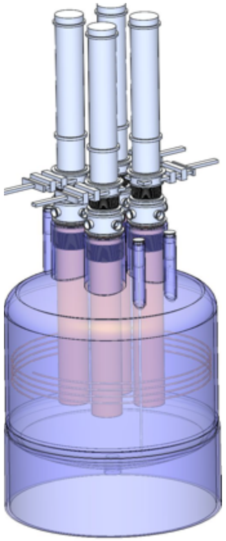
NEXT-HD

nEXO



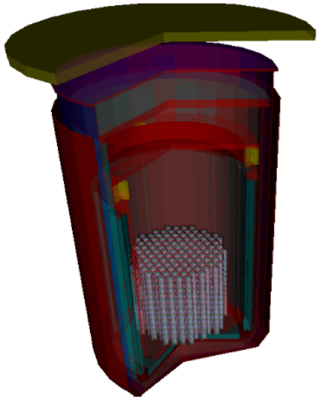
DARWIN

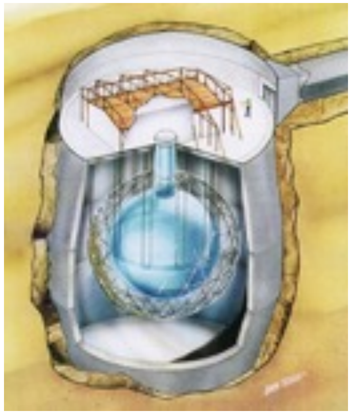


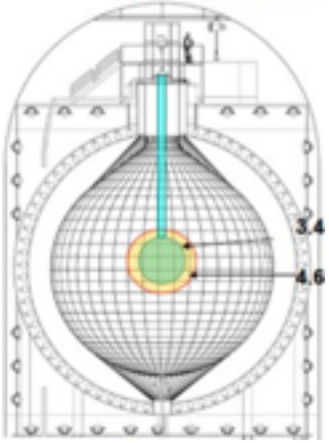


LEGEND Large Enriched Germanium Experiment for Neutrinoless ββ Decay

CUPID







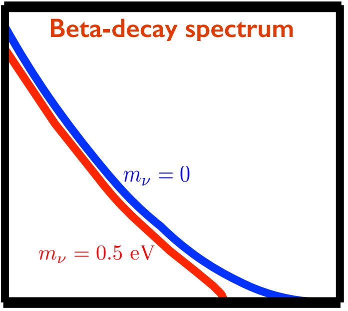
SNO+ **KamLAND2-Zen**

HPXe: PANDAX-III
Bolometers: AMoRE

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

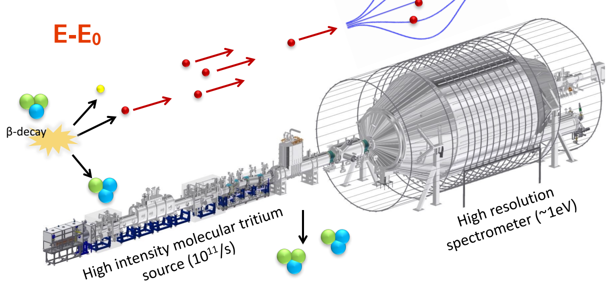
Measuring neutrino masses

- Absolute mass scale.



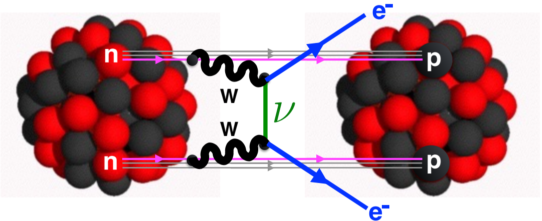
Beta decay

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



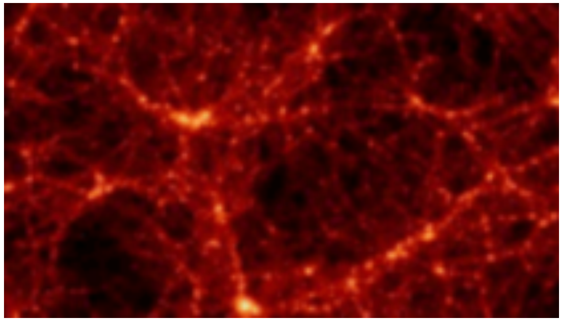
KATRIN

Neutrinoless dbeta decay

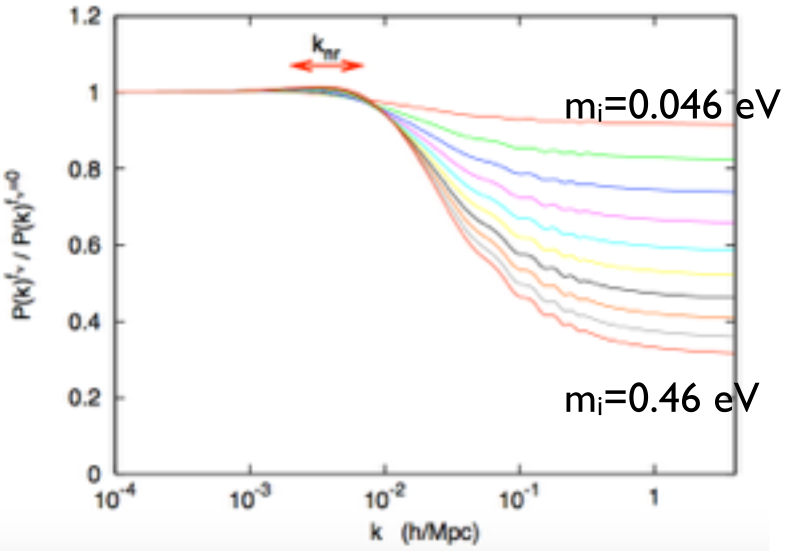


$$m_{\beta\beta} = f(m_i, \alpha_{21}, \alpha_{31}, \delta)$$

Cosmology



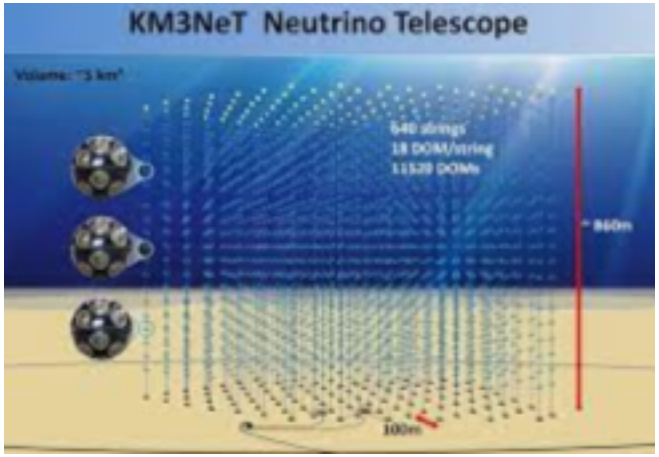
$$\sum_i m_i$$



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

- 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 matter effects in large detectors.

Long baseline neutrino oscillation experiments

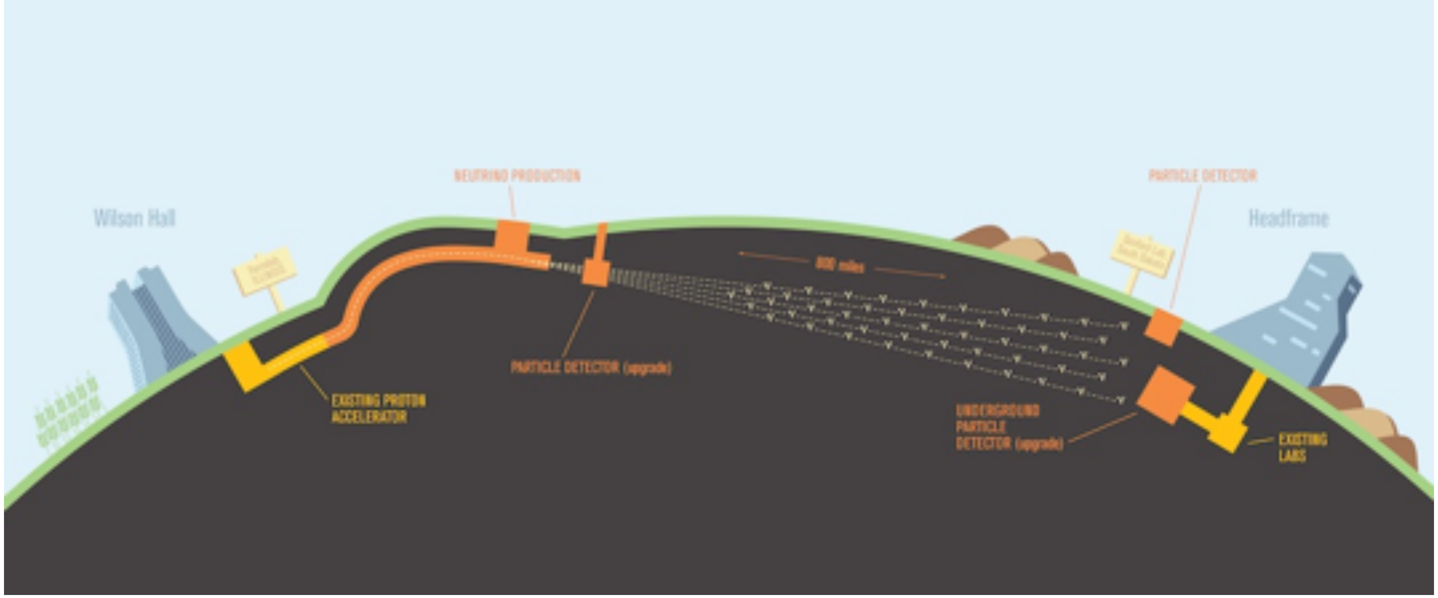
JUNO

JUNO Coll., 2104.02565

JUNO uses a 20kton LSc detector to detect reactor nus at a baseline of ~60 km. Excellent energy resolution is needed. Due to start in 2023.

Long baseline oscillations: mass ordering and CPV

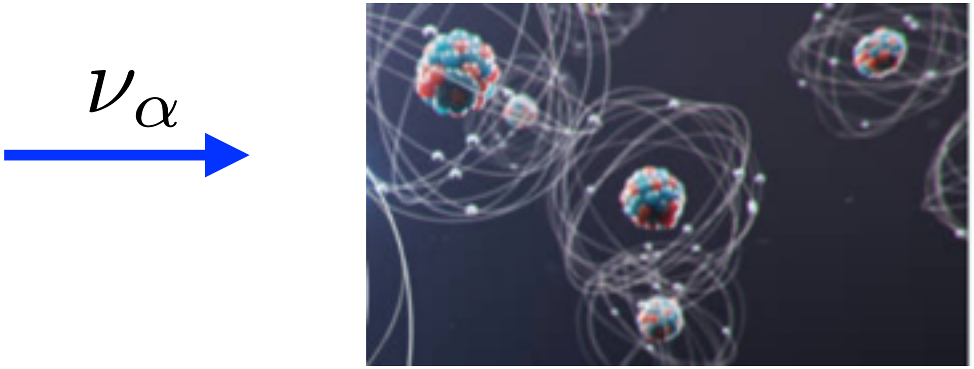
Long baseline neutrino oscillation experiments (T2K, NOvA, DUNE, T2HK) study the subdominant channels muon to electron (anti)neutrino.



Credit: Symmetry magazine

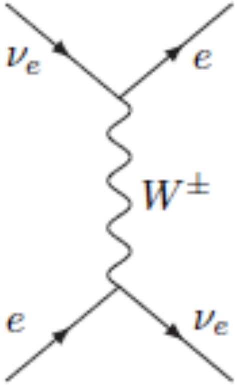
Muon neutrinos are produced in pion decays at accelerator complexes (JPARC, Fermilab) and then travel 100s Km to highly capable very large neutrino detectors.

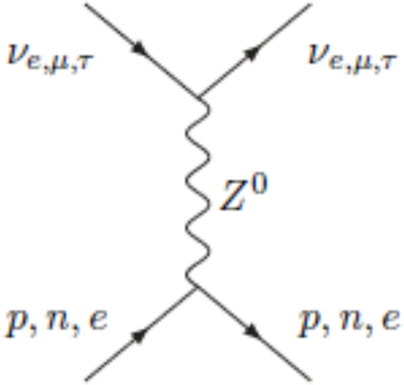
- When neutrinos travel through a medium, e.g. Earth, they interact with the background of e, p and n.



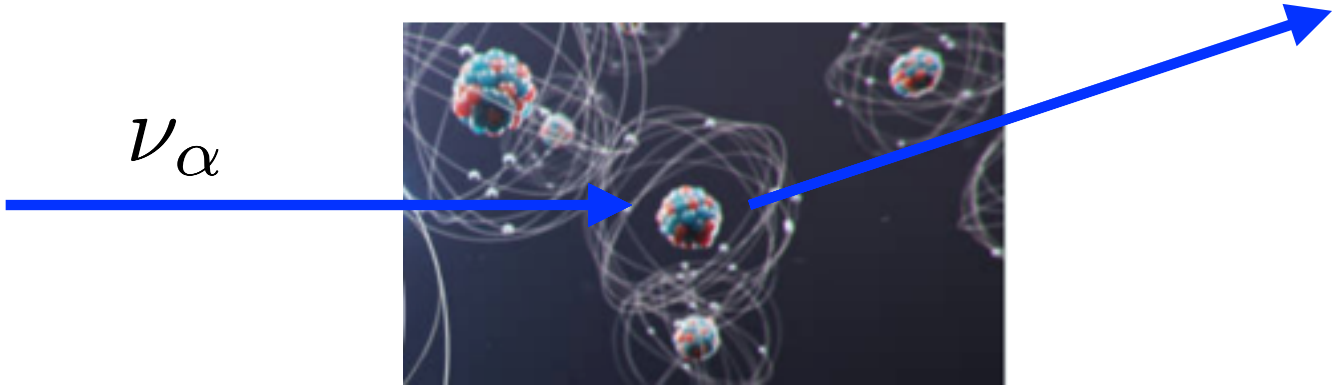
Matter (e, p, n)

via SM processes:



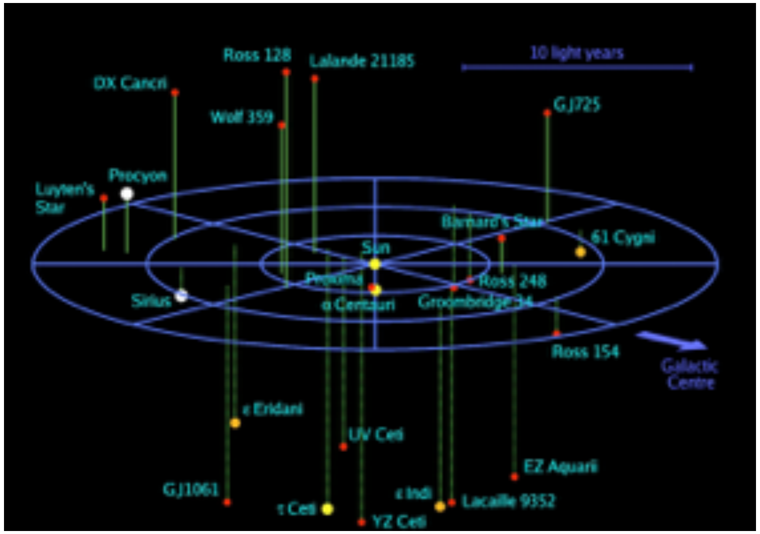


Inelastic scattering in which the neutrino changes direction/energy or converts into a charged lepton is very very very rare.



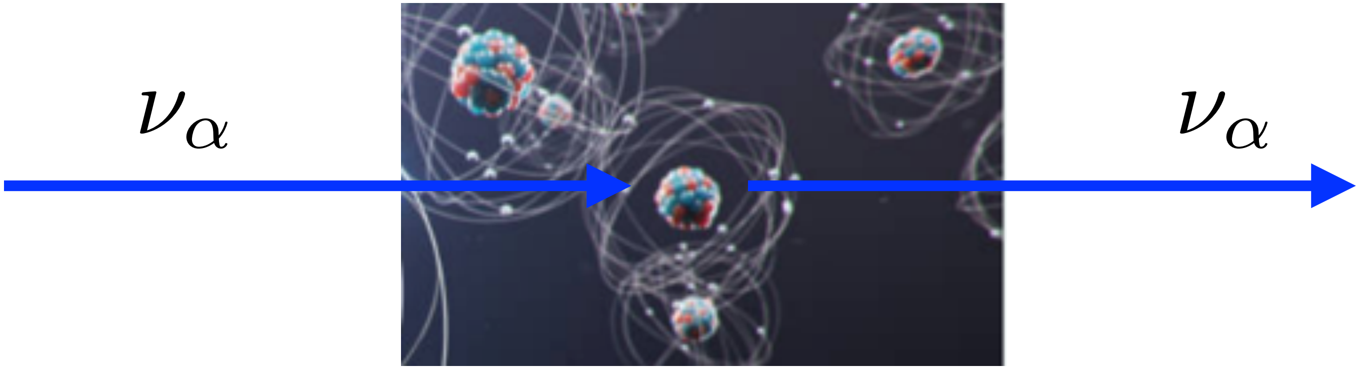
Matter (e, p, n)

At the neutrino energy of beta decays, the average distance before an interaction (mean free path) in water (1 g/cm^3) is d= 200 lightyears!



ESO

Forward elastic scattering gives neutrinos a flavour-diagonal effective mass and affects oscillations.



Matter (e, p, n)

- The background is CP and CPT violating, e.g. the Earth contains only particle and not antiparticles, and the resulting oscillations are CP and CPT violating (therefore, neutrinos and antineutrinos are affected differently).

Effective Hamiltonian

$$\begin{pmatrix} \text{🟦} & \text{🟥} \\ \text{🟥} & \cdot \end{pmatrix}$$

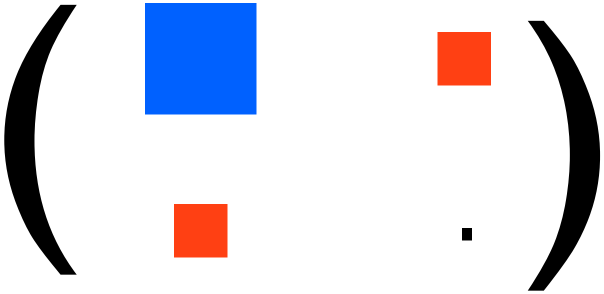
Mixing angle

vacuum

$$\tan 2\theta \sim \frac{2\,\text{🟥}}{\text{🟦}}$$

Effective Hamiltonian

Mixing angle

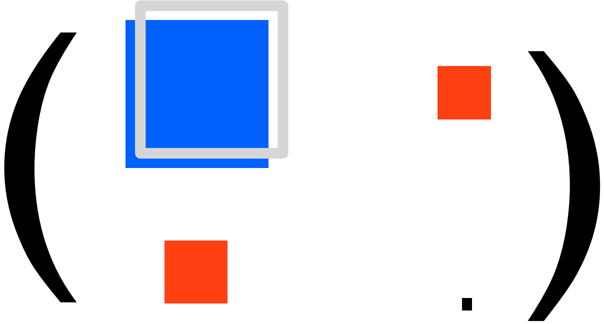


vacuum

$$\tan 2\theta \sim \frac{2\,🟥}{🟦}$$

matter suppression (Sun, SN)

$$\tan 2\theta^M \sim \frac{2\,🟥}{🟦 + 🟩} \ll \tan 2\theta$$



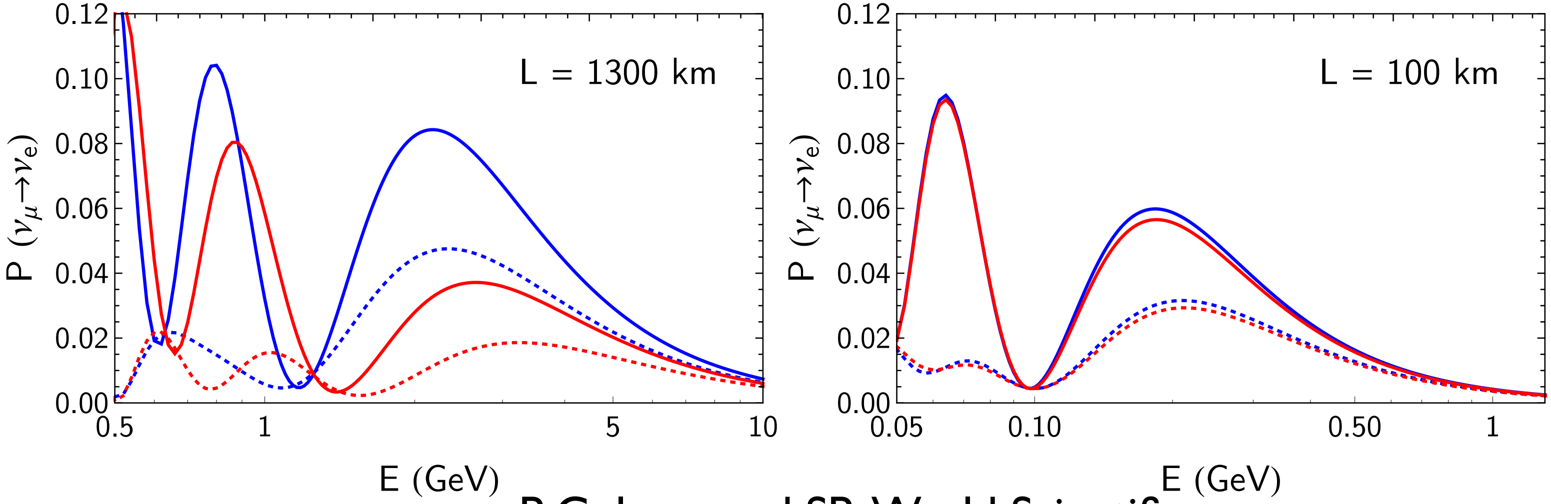
MSW resonance (Sun, SN)

$$\tan 2\theta^M \sim \frac{2\,🟥}{🟦 - ⬜} \sim \infty$$

- Matter effects are described by a potential V in the effective Hamiltonian which determines the time evolution.

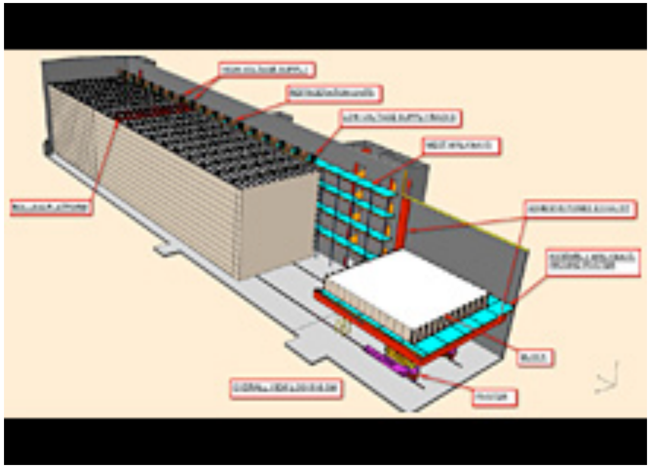
$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos(2\theta) + \boxed{\sqrt{2}G_F N_e} & \frac{\Delta m^2}{4E}\sin(2\theta) \\ \frac{\Delta m^2}{4E}\sin(2\theta) & \frac{\Delta m^2}{4E}\cos(2\theta) \end{pmatrix}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix}$$

- The oscillations can be enhanced or suppressed (depending on the sign of Δm^2 = mass ordering).



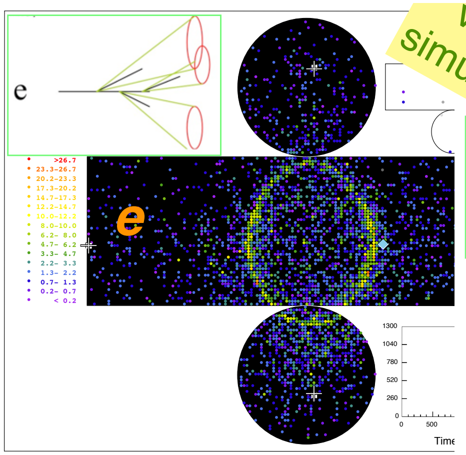
P. Coloma and SP, World Scientific

Present/Future LBL exp



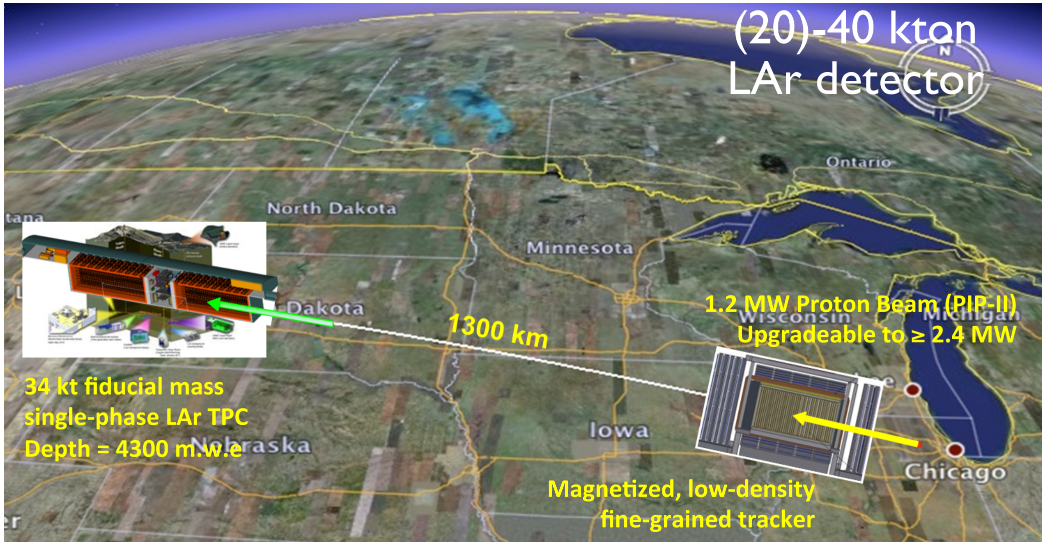
NOvA: 810 km off-axis
~14 kton plastic scintillator detector

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

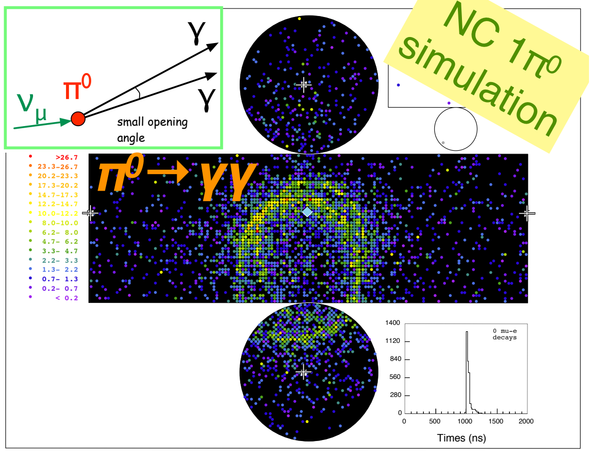


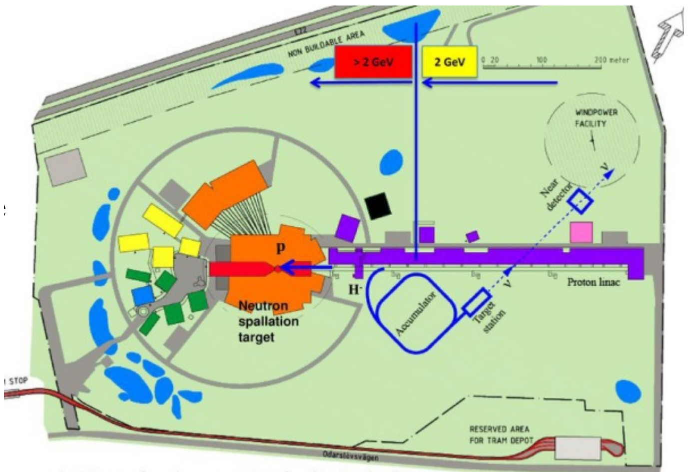
M. Shiozawa, for T2HK coll., NuPhys 2014

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



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



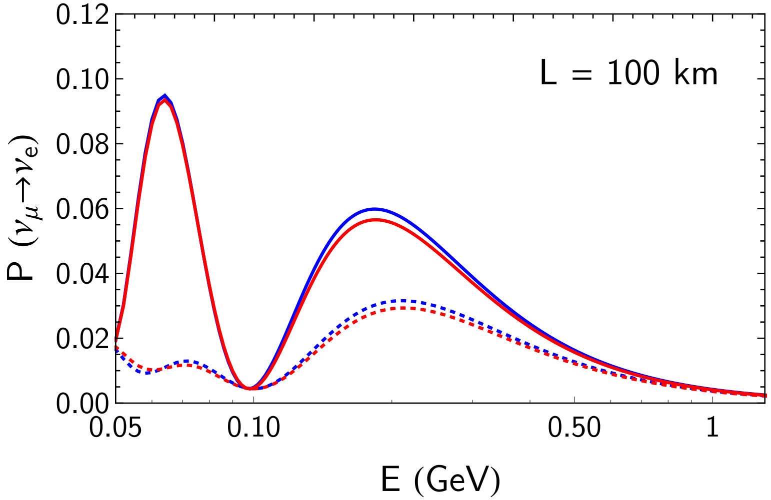


~1 BEuros for the neutrino facility including detector

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

CP-violation in LBL experiments

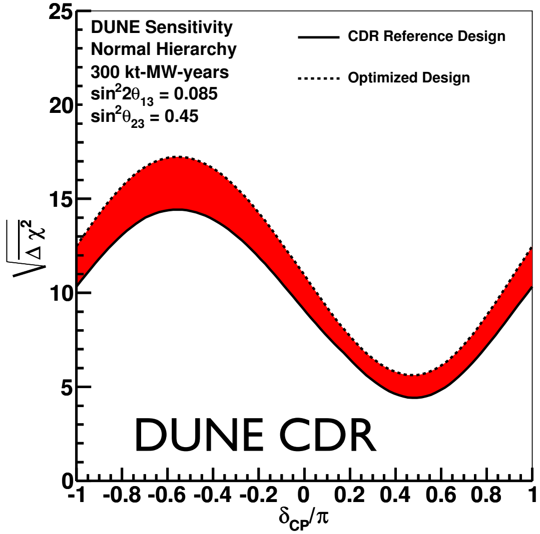
In presence of CP violation (complex mixing matrix U), neutrinos and antineutrinos behave differently.



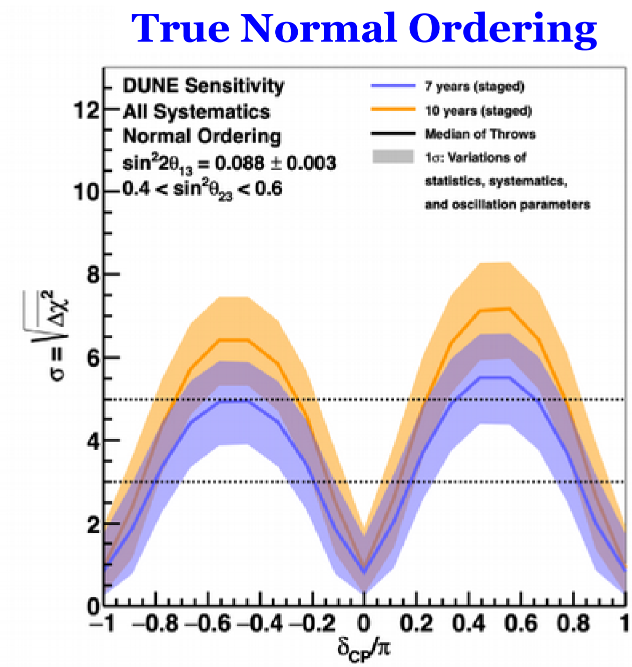
P. Coloma and SP, World Scientific

- By comparing neutrino and antineutrino oscillations one can deduce the presence of leptonic CPV.
- One needs to disentangle true CPV from matter effects.
- CPV effects are more pronounced at low energy.

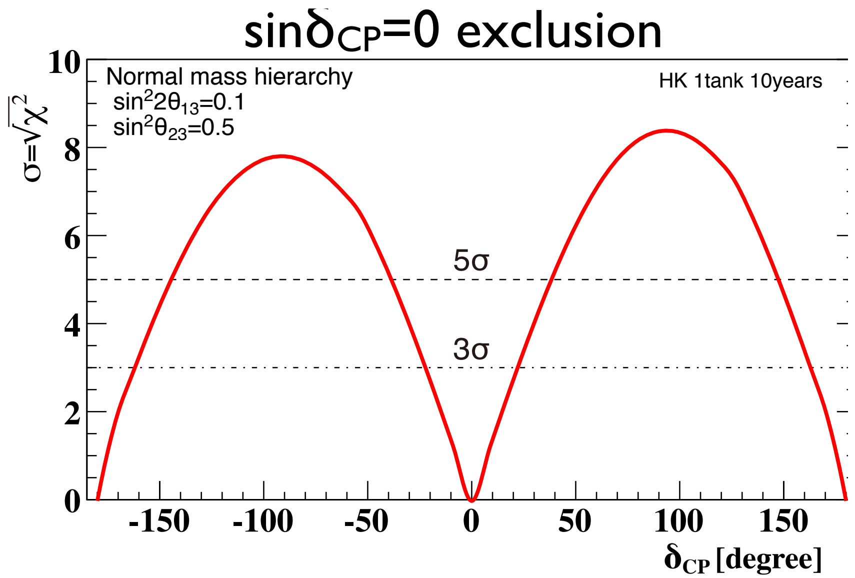
Mass ordering and CPV sensitivity



- The mass ordering will be discovered by the end of the decade by DUNE, with strong indications by ~2025 by JUNO, KM3Net, Atm neutrino exp.
- If CPV is ~ maximal, we will know it in the next ~10-15 years.



04



M. Mooney, for DUNE, Neutrino 2020

M. Shiozawa, for HK, Neutrino 2018

Beyond 3-neutrino mixing?

Anomalies in the neutrino sector

There are hints beyond standard 3 neutrino mixing.

LSND, nucl-ex/9605002

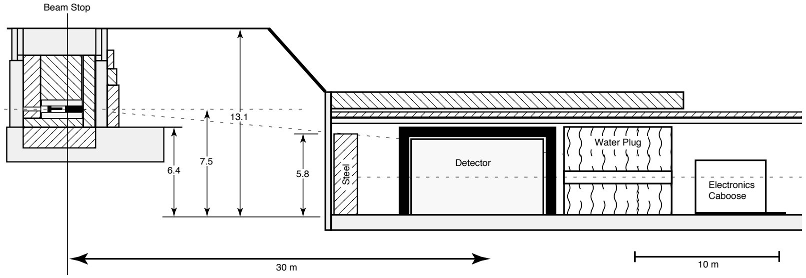
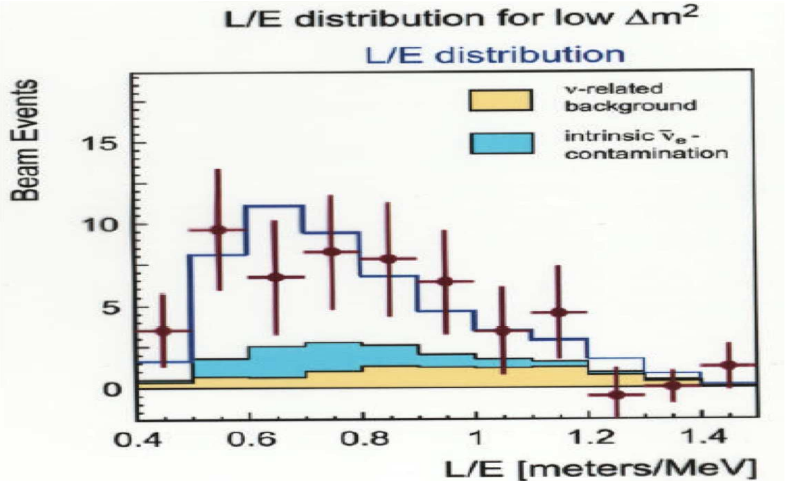


FIG. 1. Detector enclosure and target area configuration, elevation view

LSND, PRL81 (1998) 1774

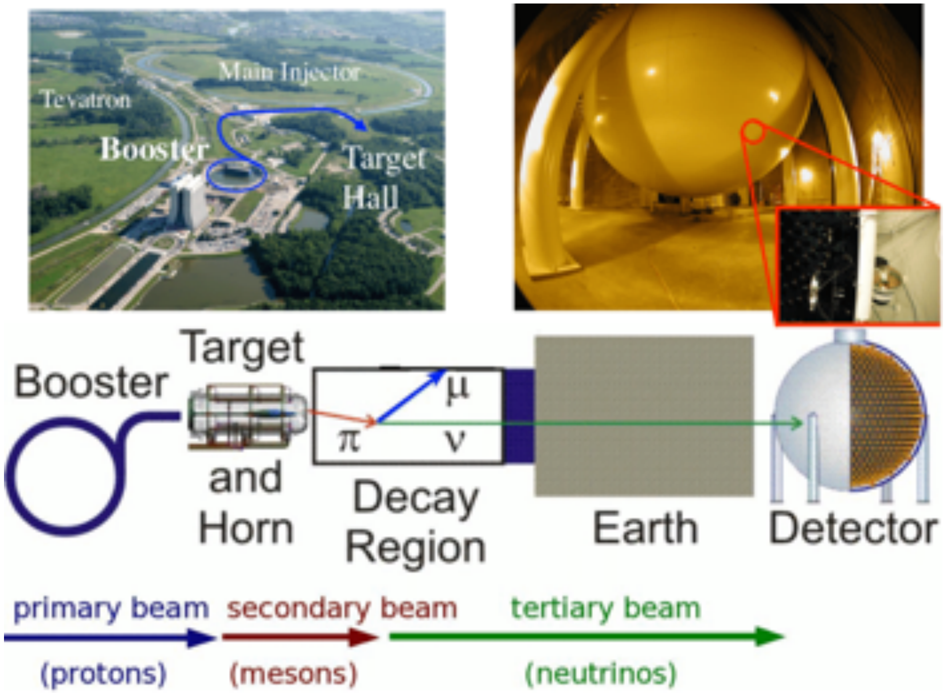


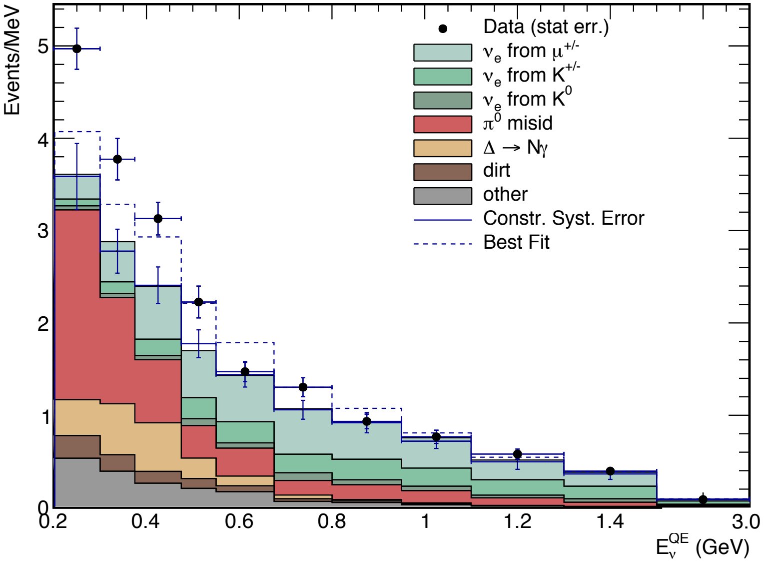
$$\pi^+ \to \mu^+ + \nu_\mu \quad ,$$

$$\mu^+ \to e^+ + \nu_e + \boxed{\bar{\nu}_\mu} \longrightarrow \bar{\nu}_e$$

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.

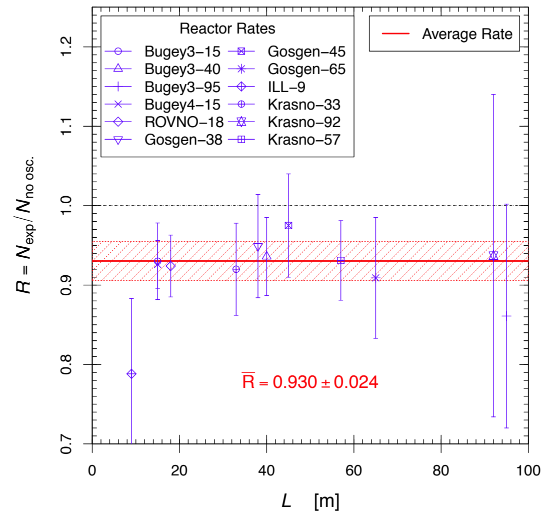
MiniBooNE was designed to test the LSND results. <E>~700 MeV and L~500 m.





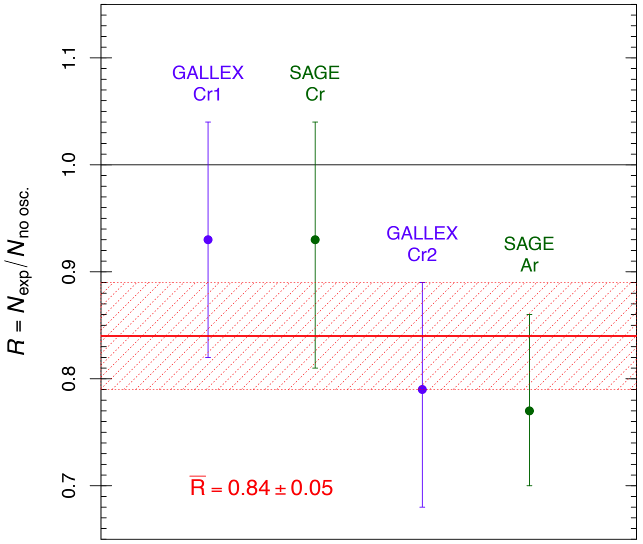
MiniBooNE Coll., PRL 121 (2018)

MiniBooNE reports a low-E excess which has increased in significance over time (3.6σ -> 4.7σ -> 4.8σ) with more data and sophisticated analysis.



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.

Reactor anomaly: A recomputation of the reactor fluxes seems to indicate neutrino disappearance, compatible with oscillations into sterile neutrinos with large masses. Recent results have reduced the significance of these results.



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

Gallium anomaly: The measurement of the fluxes of electron neutrinos in Gallium Radioactive sources reports a value 2.9 sigma away from what expected.

Sterile neutrinos as an explanation?

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 the simplest possible extension BSM.

- Theory remains anomaly free.

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

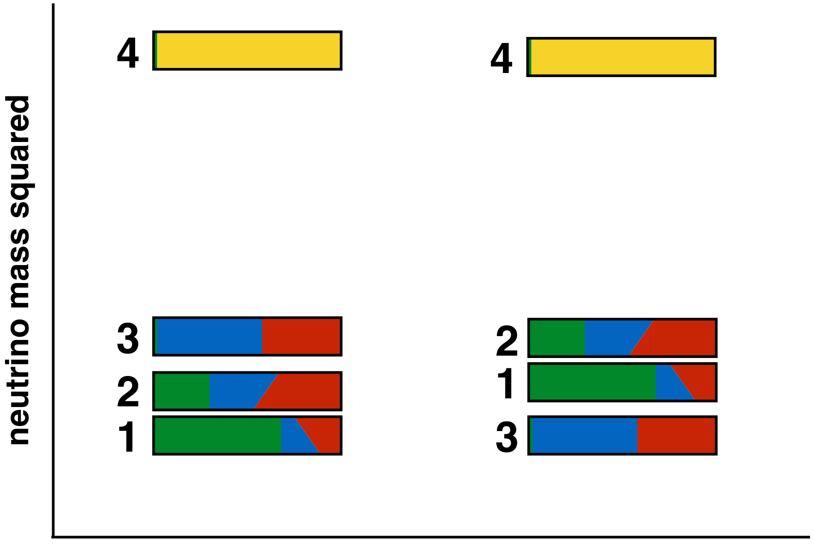
- GUT theories embedding L-R symmetries, e.g. SU(4), SO(10),... predict their existence.

- A part from GUT theories, there is no strong 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

$$\Delta m_s^2 \ll \Delta m_A^2 \ll \Delta m_{41}^2$$

for 4 massive nus.



Fractional flavour content of massive neutrinos

Appearance oscillation probability at short baselines:

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

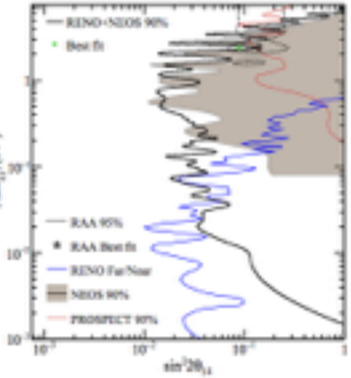
Oscillation disappearance probability:

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

Light sterile neutrino oscillations can explain the appearance data.

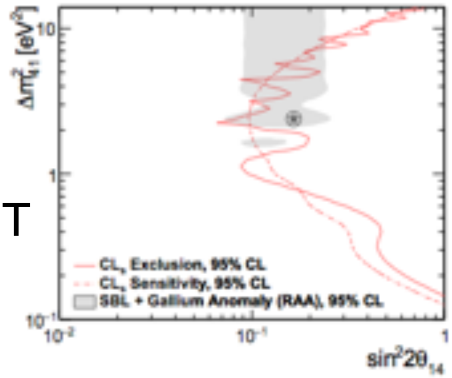
Electron neutrino disappearance

Experiments with very short baselines have been designed to test these anomalies in controlled conditions.

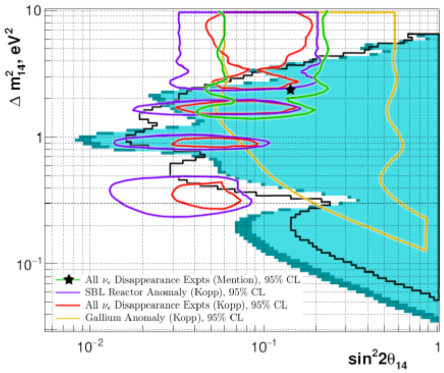


RENO
+NEOS

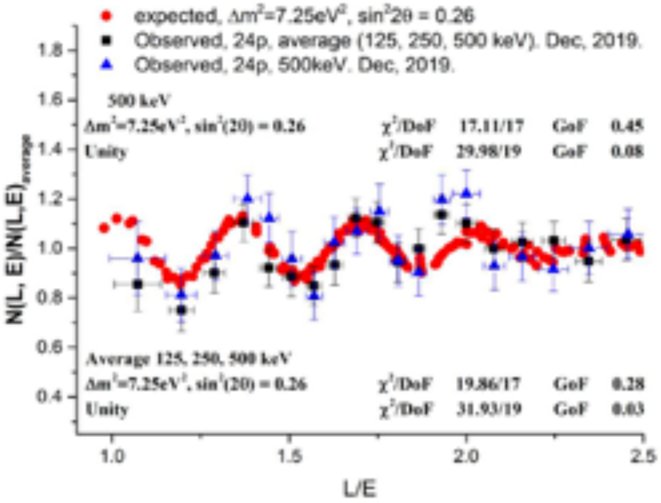
PROSPECT



STEREO

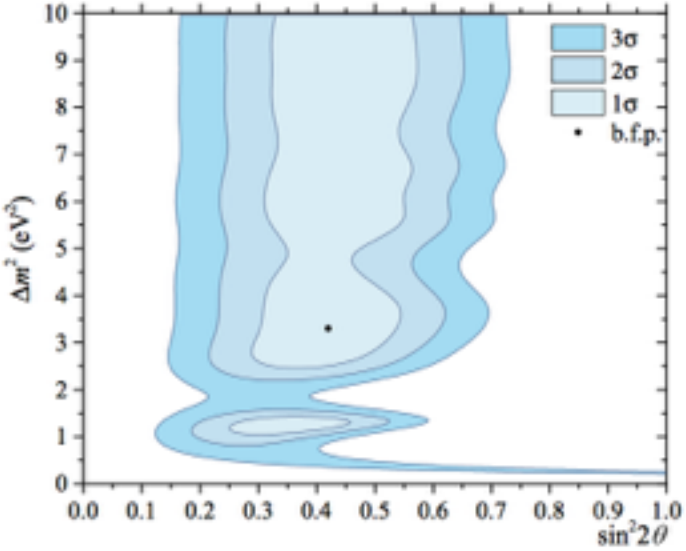


DANSS Coll., 1911.10140

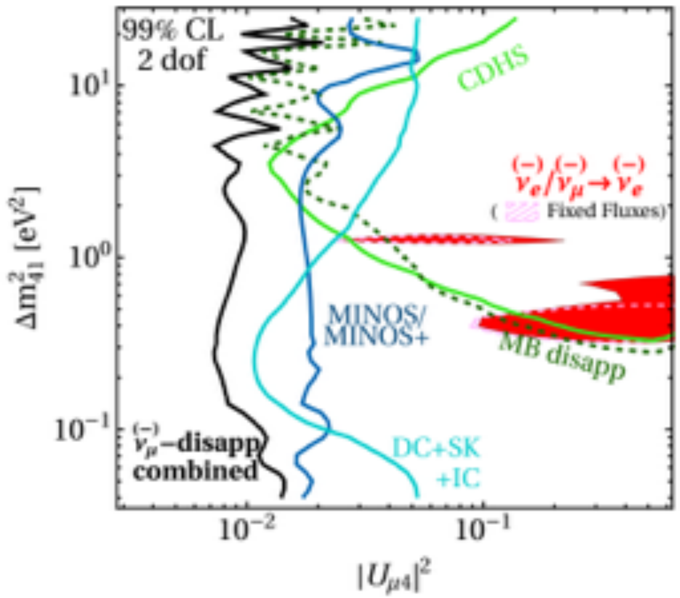


Neutrino4

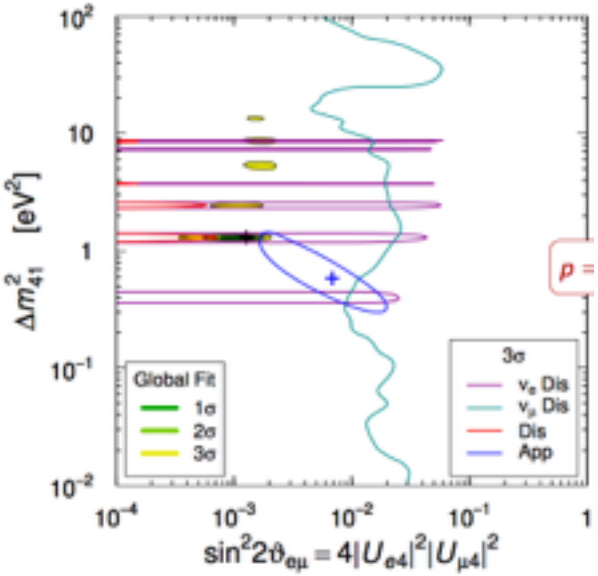
BEST, 2109.11482



But there is a tension with muon neutrino disappearance data.



A. Dentler et al., 1803.10661

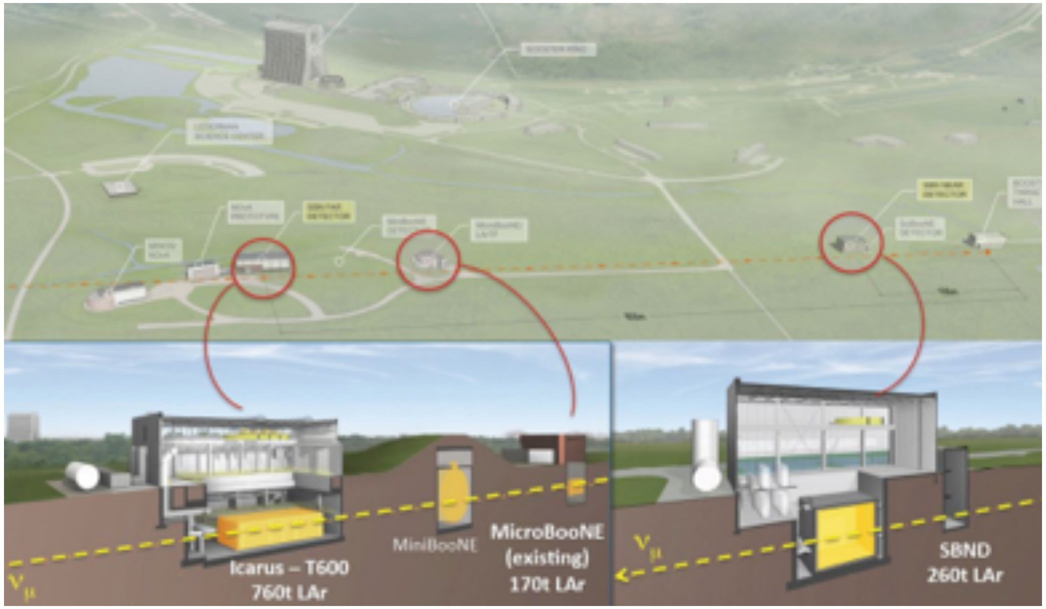


Gariazzo et al., in preparation, TAUP 2021

$$P(\nu_\mu \to \nu_e) = \underbrace{4|U_{e4}|^2|U_{\mu4}|^2}_{\sin^2 2\theta} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$

My take: The situation is still rather uncertain. Probably the appearance results are not due to oscillations. Major tension with cosmology.

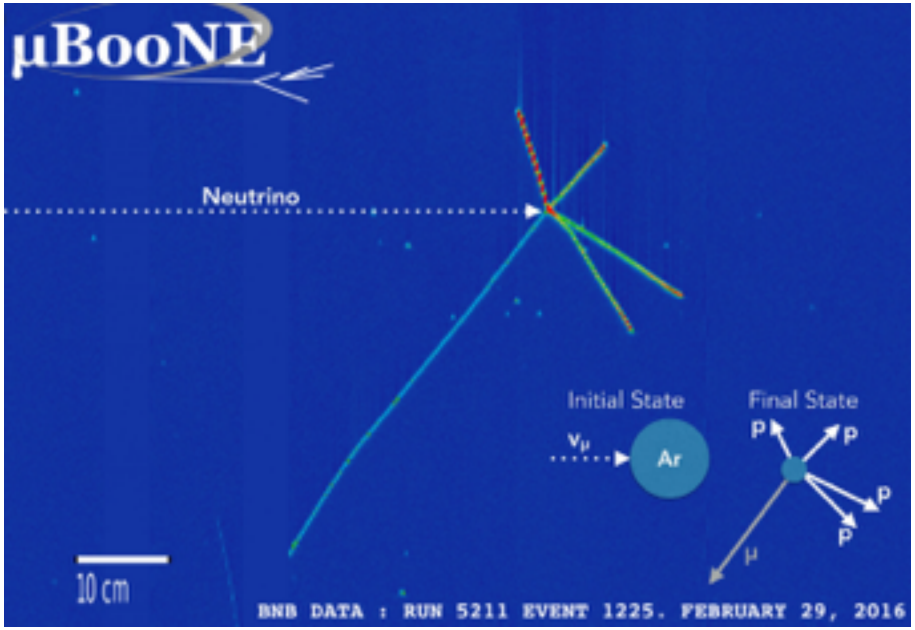
MicroBooNE and SBN at Fermilab



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

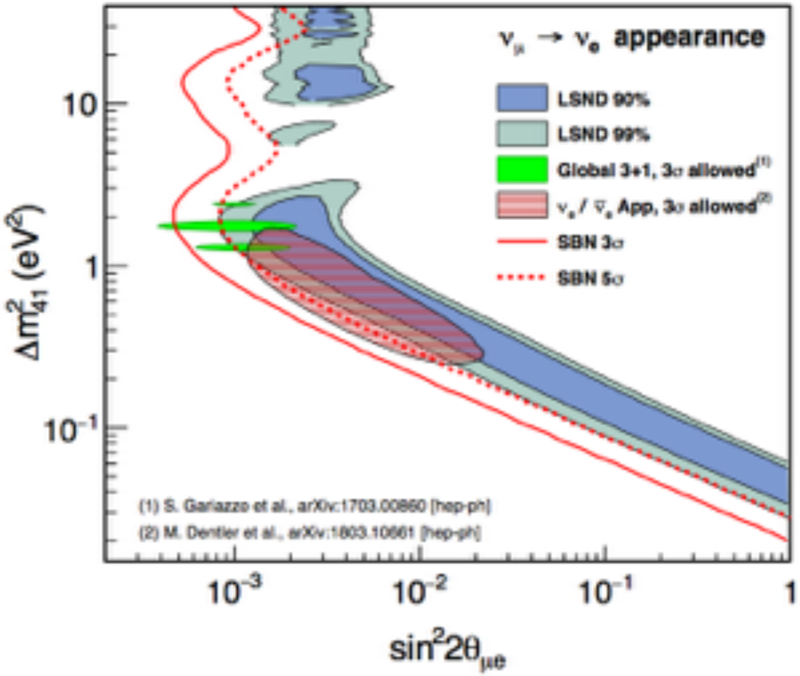
https://www.bo.infn.it/gruppo2/sbn-it/

MicroBooNE detector

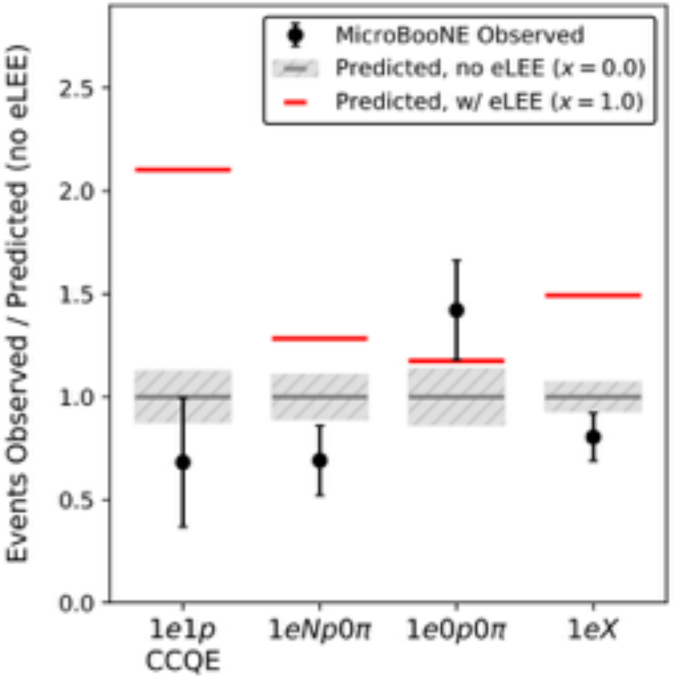


MicroBooNE event: muon neutrino scattering in LAr

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



MicroBooNE Coll., 1903.04608

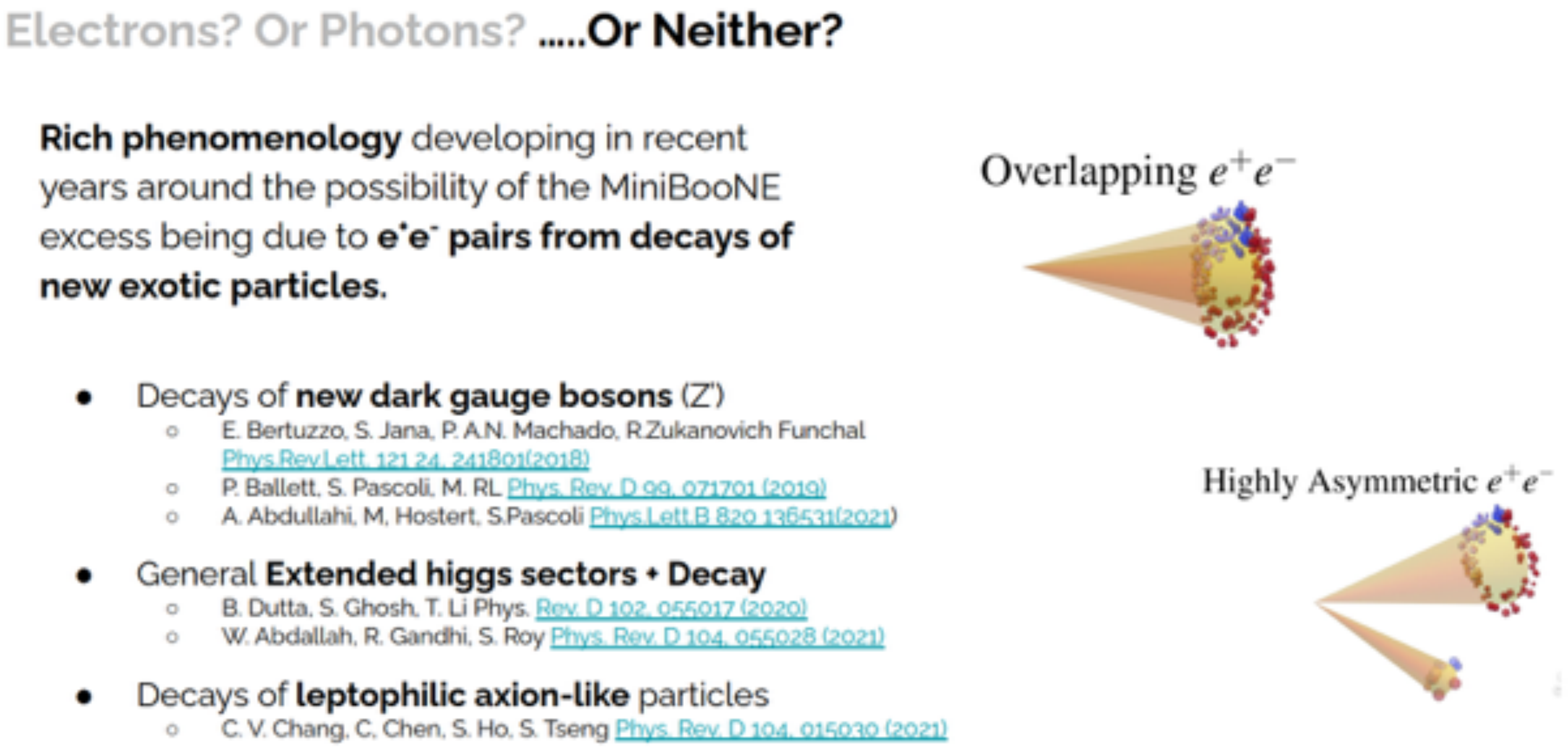


MicroBooNE Coll., 2110.14054

MicroBooNE first results disfavour a neutrino oscillation explanation, as well as some not understood background (Delta single photons).

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)

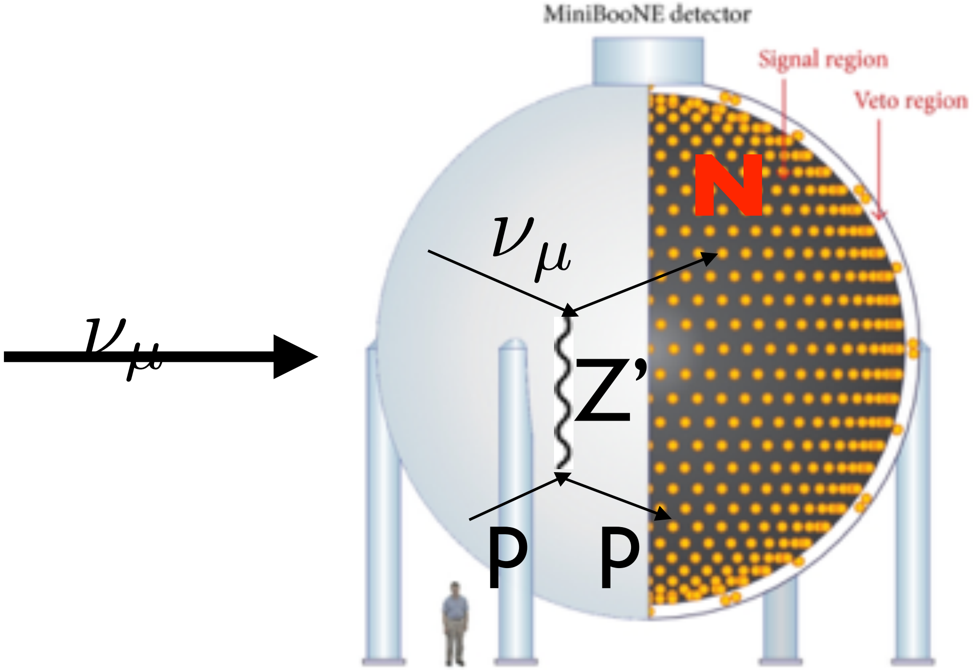
Overlapping e^+e^-

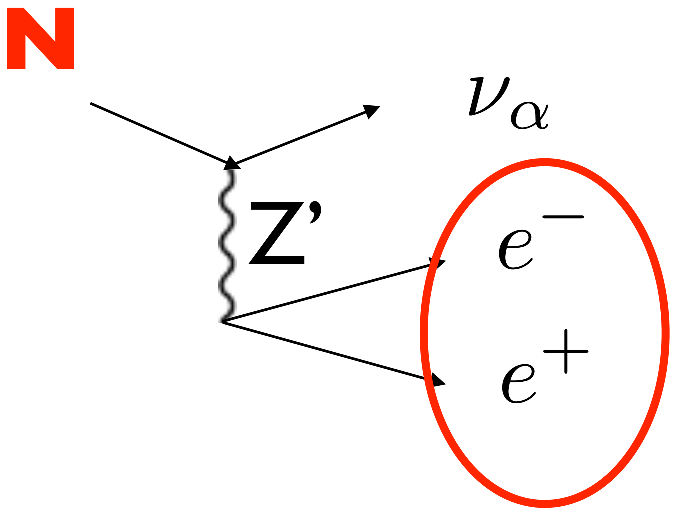
Highly Asymmetric e^+e^-

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).



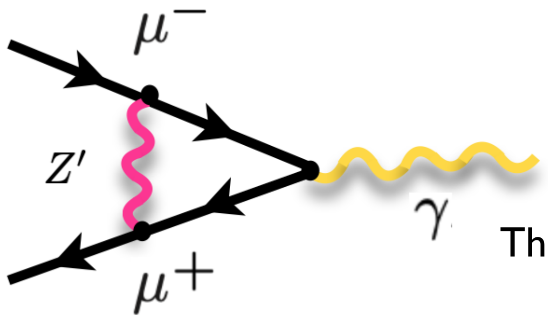


P. Ballett, S. Pascoli, M. Ross-Lonergan, PRD 99 (2019), A. Abdullahi, M. Hostert, SP, 2007.11813

This type of models require a low energy extension of the SM (dark sector) with new gauge or scalar interactions (for the scattering) and new fermions (which need to decay fast).

These models have a distinct phenomenology and could also explain other anomalies, specifically the muon (g-2).

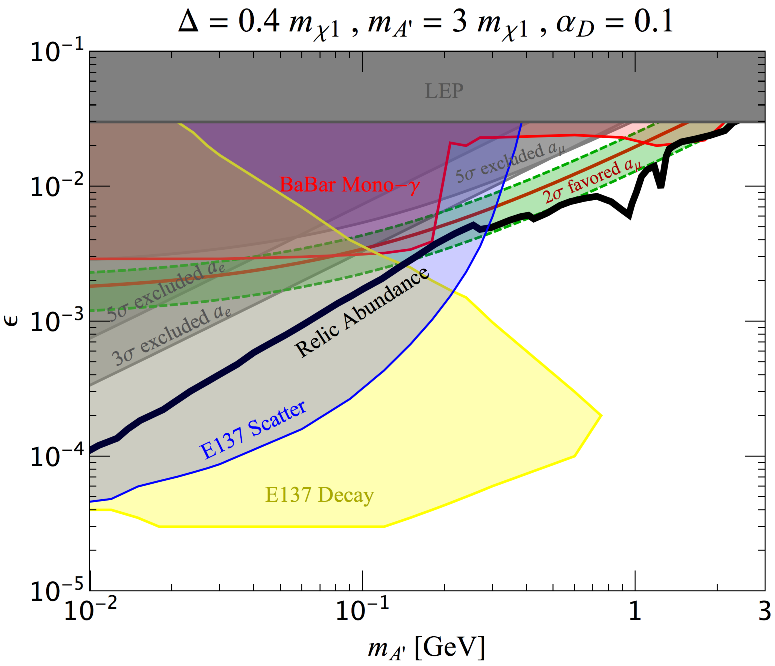
P. Fayet, PRD75 (2007), M. Pospelov, PRD80 (2009)



Thanks to A. Abdullahi

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

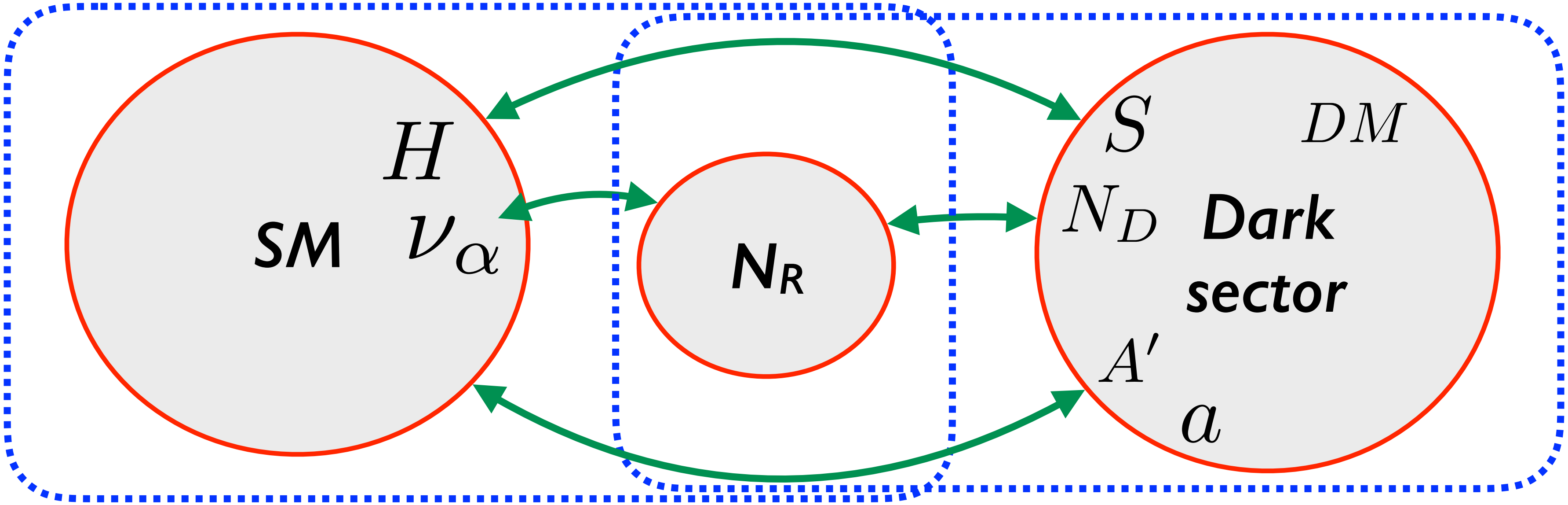
A. Abdullahi, M. Hostert, SP, 2007.11813



G. Mohlabeng, PRD99 (2019)

Neutrinos as a window to Dark sectors???

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



Dark sectors can account for neutrino masses, the baryon asymmetry, dark matter.

This would be a major departure from "traditional" BSM thinking and open a very exciting experimental landscape.

Neutrinos as a window to Dark sectors???

The dark or hidden sect … extensions of the SM that are l … k scale.

Surprise??????

We do not know yet but it would be really a big surprise.

Dark sectors … the baryon

This would be a majo … m “traditional” BSM thinking and open a very exciting experimental landscape.

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, neutrino masses) 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 and interactions: dark sector?

Neutrinoscope

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Cambridge Consultants

★★★★★ 5.0, 7 Ratings

Free

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.