

XVI NExT Ph.D. Workshop – Cosener's House 24-26 August 2026

3 lectures on:

Neutrino Physics and Particle Cosmology

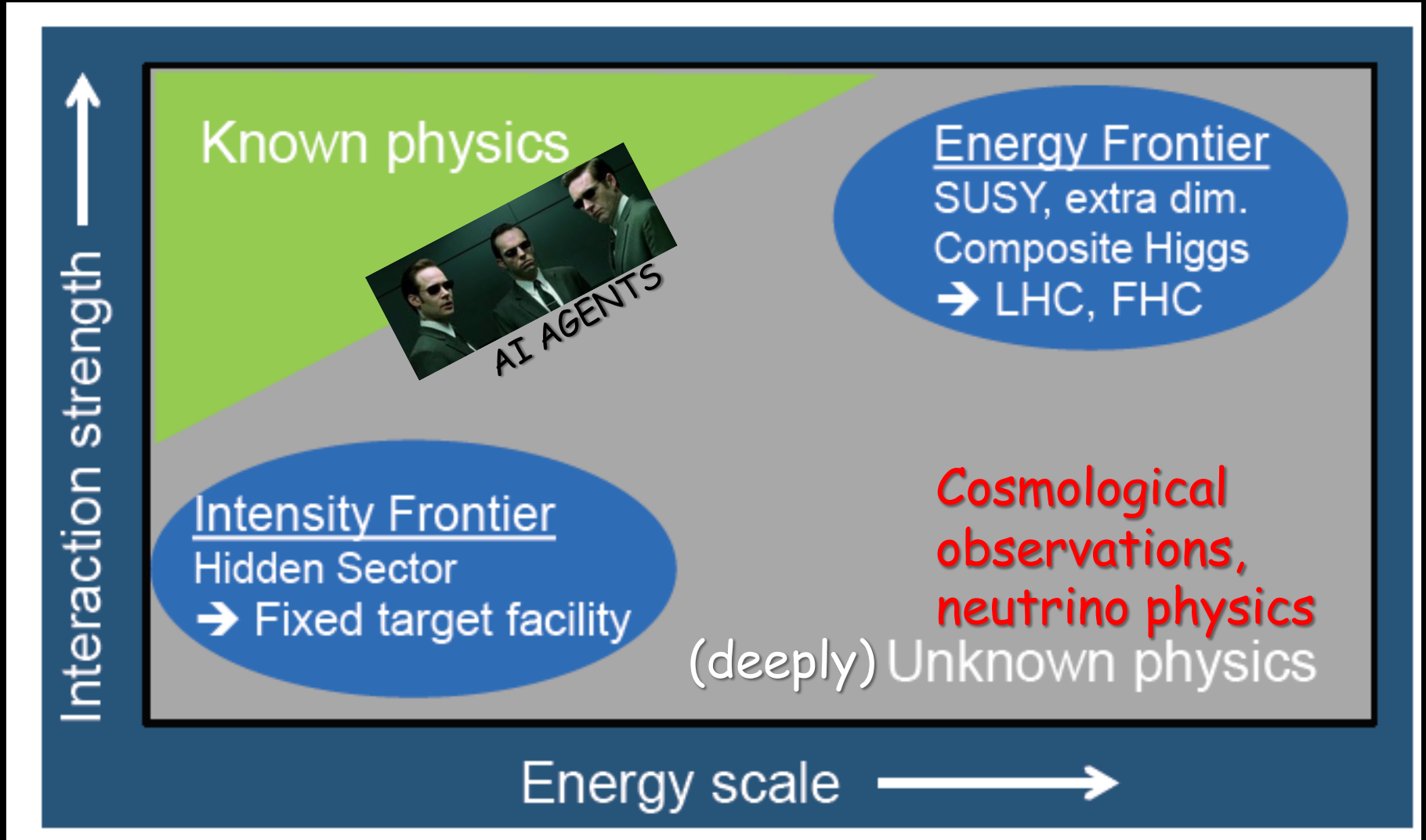
Pasquale Di Bari

(<http://www.hep.phys.soton.ac.uk/~pdb1d08/teaching.html>)



New frontiers

(SHIP proposal, 1504.04855)



Plan

- 1) Neutrinos
- 2) Cosmology
- 3) Neutrino cosmology

Lecture I

Neutrino Physics

- Neutrinos in the Standard Model
- Neutrino mixing and oscillations
- Models of neutrino masses and mixing
- Neutrino-less double beta decay
- Neutrino astronomy

References

- Carlo Giunti and Chung W. Kim, *Fundamentals of Neutrino Physics and Astrophysics*, Oxford University Press (2007).
- M.C. Gonzalez-Garcia, Michele Maltoni, *Phenomenology with massive neutrinos*, *Physics Reports* 460 (2008) 1-129, *arXiv:0704.1800*;
- W. Buchmüller, *Neutrinos, Grand Unification and Leptogenesis*, *hep-ph/0204288*
- S.F. King, *Neutrino mass*, *arXiv:0712.1750*;
- P. Di Bari, *An introduction to leptogenesis and neutrino properties*, *Contemp. Phys* 53 (2012) n.4 315-338, *arXiv:1206.3168*;
- G. Altarelli and F. Feruglio, *Phenomenology of neutrino masses and mixing*, *hep-ph 0306265*.
- S.F. King, *Unified Models of Neutrinos, Flavour and CP violation*, *1701.04413*
- F. Feruglio and A. Romanino, *Neutrino Flavour Symmetries* *1912.06028*
-more specialistic ones in the slides

Nobel Prizes awarded in Neutrino

Theoretical predictions

Physics

Experimental discoveries
awarded with the Nobel Prize



Wolfgang Pauli



Enrico Fermi



Hans Bethe



Rudolf Peierls



Frederick Reines

1995

for the detection
of the neutrino
(in 1956 with Clyde Cowan)

"Mr. Neutrino"



Bruno Pontecorvo



Leon Lederman



Melvin Schwartz



Jack Steinberger

1988
(discovery
of muon
neutrino
in 1962)



Bruno Pontecorvo



John Bahcall



Moisey Markov



Donald Perkins



Raymond Davis



Masatoshi Koshiha

2002

For pioneering contributions
to astrophysics, in particular
for the detection of
cosmic neutrinos



Bruno Pontecorvo



Valery Gribov



Ziro Maki



Masami Nakagawa



Shoichi Sakata



Takaaki Kajita



Arthur B. McDonald

2015

For the discovery of
neutrino oscillations,
which shows that neutrinos
have mass

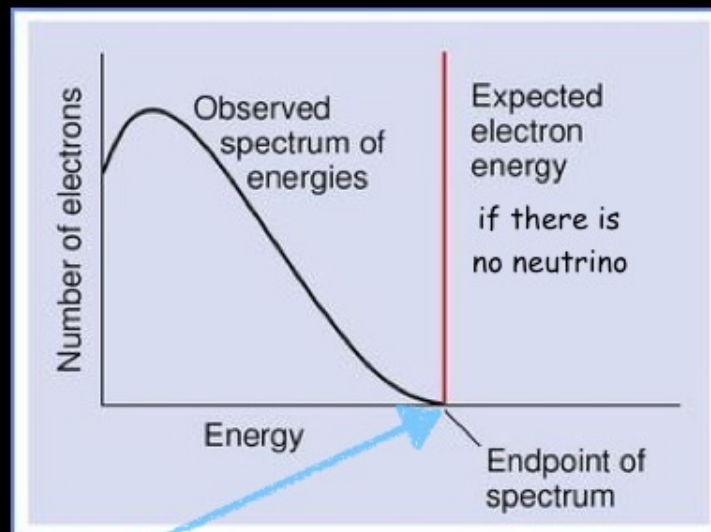


Neutrino as a "desperate remedy"

Wolfgang Pauli, 1930

$$\beta^- \text{ decay: } X(Z, N) \rightarrow Y(Z+1, N-1) + e^- + \bar{\nu}_e$$

(simplest case: $n \rightarrow p + e^- + \bar{\nu}_e$)



$$K_Y = \frac{p^2}{2m_Y} \lll E_e + E_{\nu_e}$$

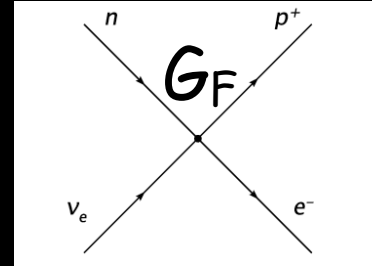
$$E_0 = M_X - M_Y$$

Neutrinos: elusive particles

"I have done a terrible thing, I postulated a particle that can never be detected" (Pauli, 1930)



4-fermion theory of
weak interactions
(Fermi, 1934)



Fermi constant
 $G_F \sim 10^{-5} \text{ GeV}^{-2}$



$$\sigma_{\nu_e + n \rightarrow p + e^-} \sim G_F^2 s \sim 10^{-43} \text{ cm}^2$$

(Bethe, Heitler 1934) (for comparison: $\sigma_{\gamma + p \rightarrow \gamma + p} \sim 10^{-25} \text{ cm}^2$)

A neutrino with MeV energy has a mean free path in steel of about 10 lightyears!

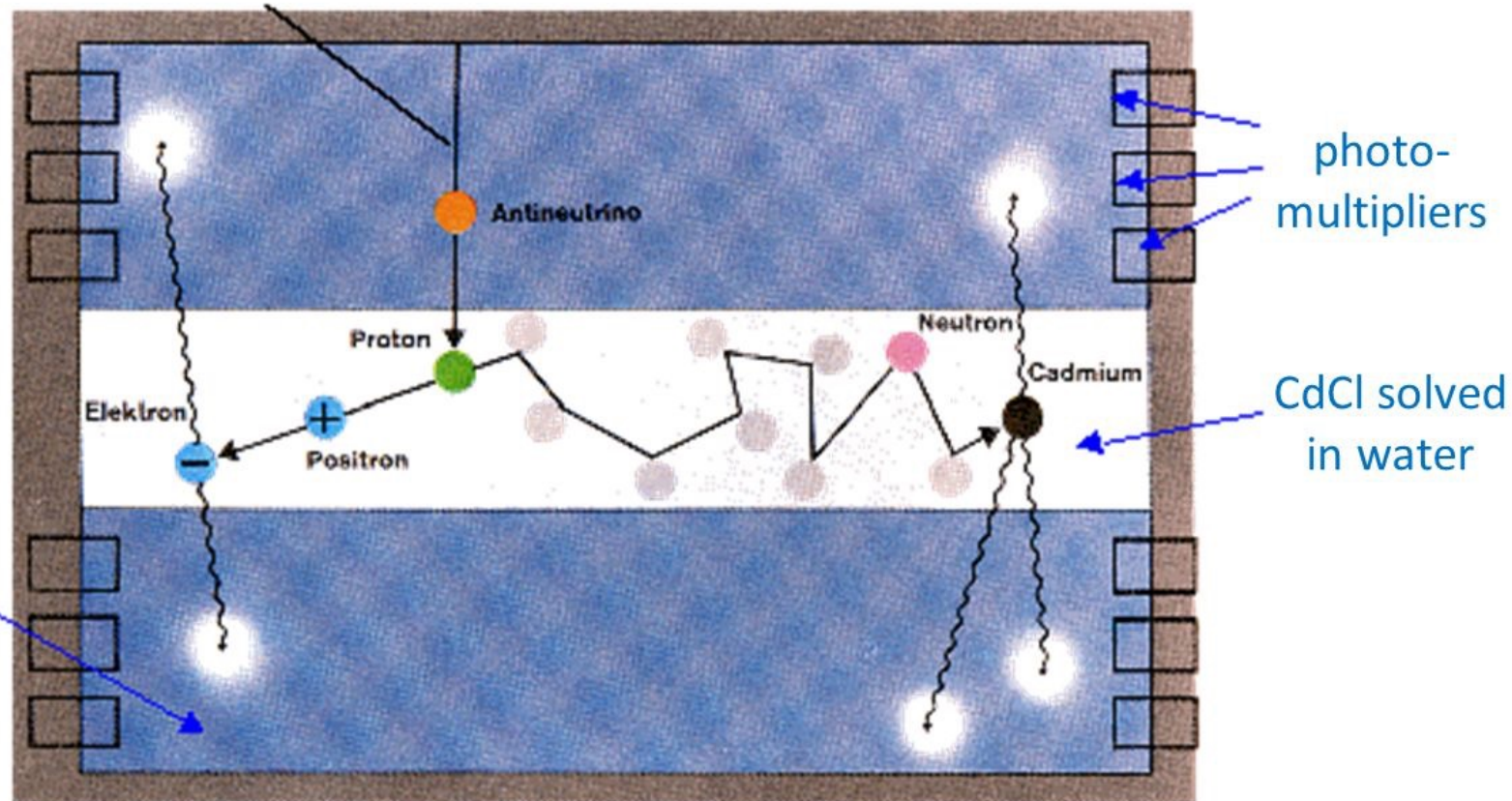
But with intense fluxes in nuclear reactors Cowan and Reines (1956) managed to detect finally the (electron) neutrino in inverse beta decay: $\bar{\nu}_e + p \rightarrow n + e^+$

On the other hand the reaction $\bar{\nu}_e + n \rightarrow p + e^-$ was NOT observed (Davis 1956)

$\Rightarrow$ LEPTON NUMBER IS CONSERVED:

$$L(\nu_e) = L(e^-) = +1 \qquad L(\bar{\nu}_e) = L(e^+) = -1$$

Savannah River experiment: the principle



Neutrinos have flavour!

Why do we not observe $\mu \rightarrow e + \gamma$?

The idea of "lepton flavour" was introduced: **muonic and electronic lepton numbers are separately conserved**

This has been extended to neutrinos carrying lepton flavour of the same kind of the charged leptons in a way that flavour lepton number are conserved.

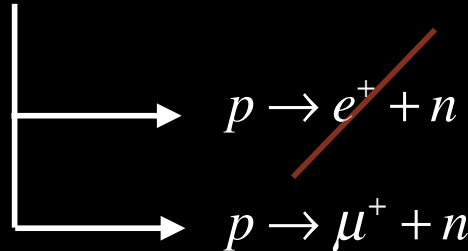
Example: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

$L_\mu = +1 \quad L_e = +1 \quad L_e = -1 \quad L_\mu = +1$



Brookhaven experiment (1962):

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$



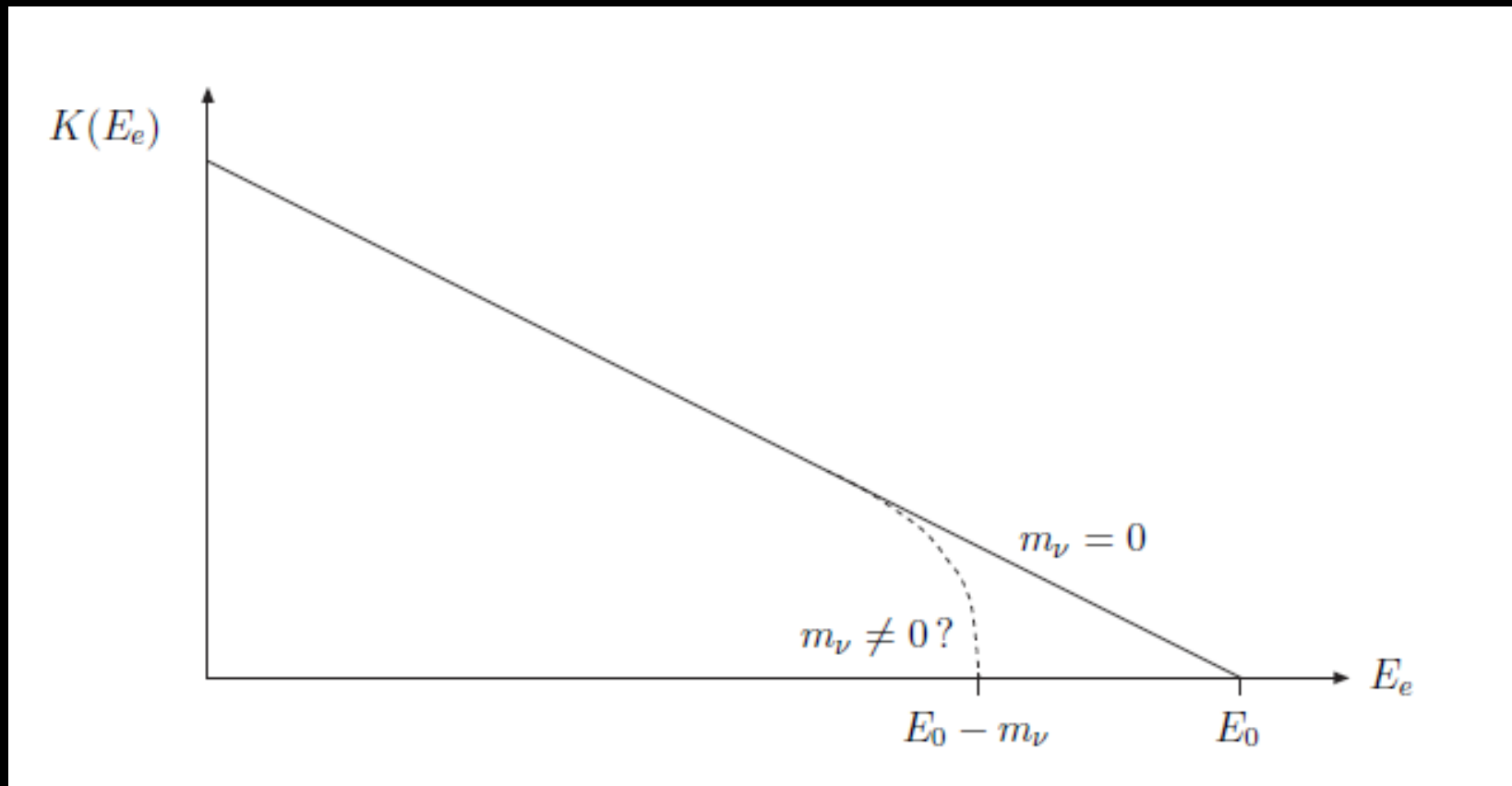
NOT OBSERVED !

$$\nu_e \neq \nu_\mu \neq \nu_\tau$$

$$\bar{\nu}_e \neq \bar{\nu}_\mu \neq \bar{\nu}_\tau$$

Kinematic upper bound on (electron) neutrino mass

Tritium beta decay: Kurie plot



Problem n. 1

$$\frac{dN_e(E_e)}{dE_e} = F(\vec{Z}, E_e) \cdot \overbrace{\sqrt{E_e^{-2} - m_e^2}}^{=P_e} \cdot (E_0 - E_e) \cdot$$

$$\cdot \sqrt{(E_0 - E_e)^2 - m_{\nu_e}^2}$$

$$E_0 = M_x - M_y = E_e + E_\nu + K_y$$

Kurie function:

$$K(E_e, m_{\nu_e}) = \left[\frac{dN_e / dE_e}{F(\vec{Z}, E_e) \cdot P_e E_e} \right]^{1/2}$$

KATRIN (KARlsruhe TRitium Neutrino experiment)



The weight is approximately 200 tons !

After the leak tests the tank was ready to be shipped. There is a slight problem of transportability from Deggendorf to Karlsruhe: The tank is too big for motorways, and the canal between the rivers Rhine and Danube has to be ruled out, too. Thus, instead of a journey of about 400 km, the spectrometer has to travel nearly 9000 km as indicated in the map





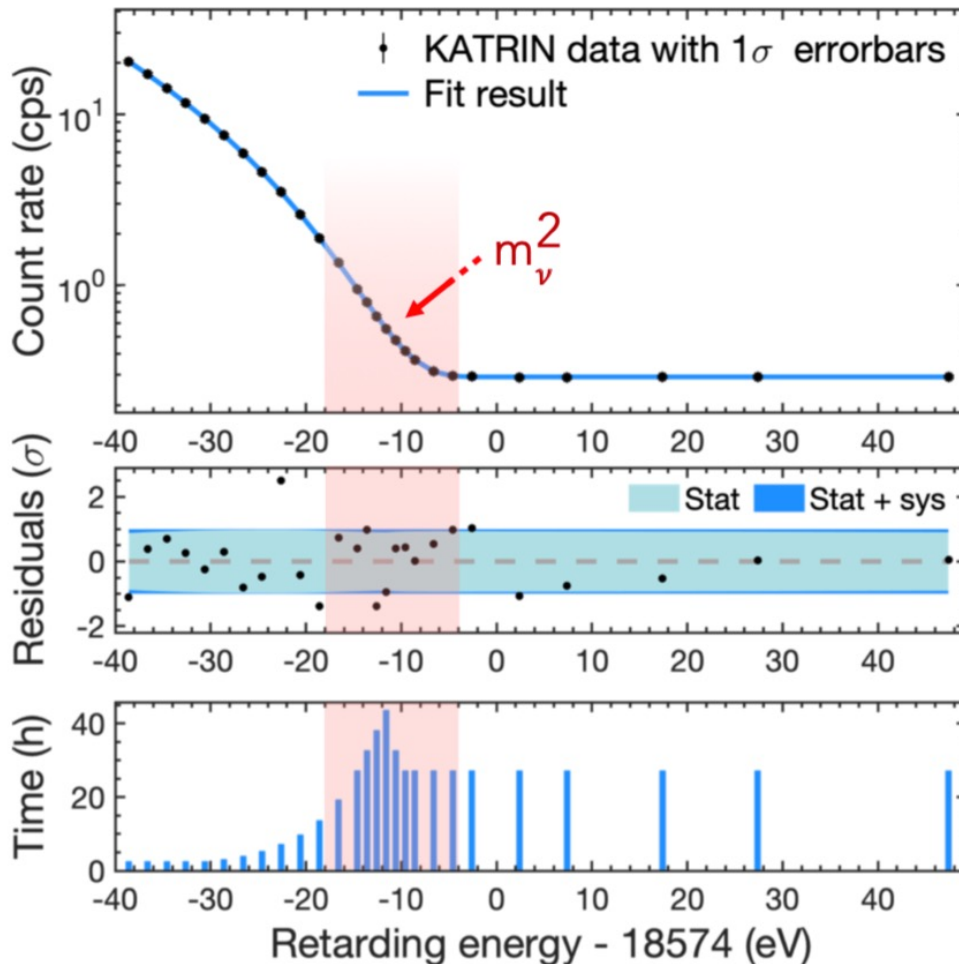
The First KATRIN Neutrino Mass Result

KATRIN Symposium, KIT, 16/09/2019

Thierry Lasserre (CEA & SFB1258)

On behalf the KATRIN collaboration

Neutrino Mass Inference



- 2 million of events
- 4 free parameters: background, tritium activity, E_0 , m_ν^2
- excellent goodness-of-fit: p-value = 0.56
- Neutrino mass best fit

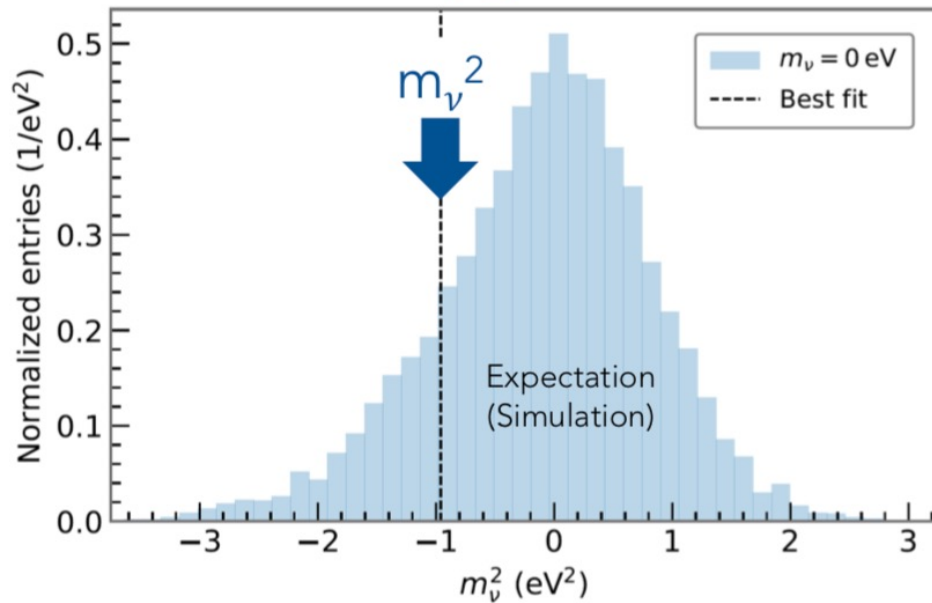
$$m_\nu^2 = -1.0^{+0.9}_{-1.1} \text{ eV}^2$$

- Uncertainties dominated by statistical fluctuations (0.97 eV²)

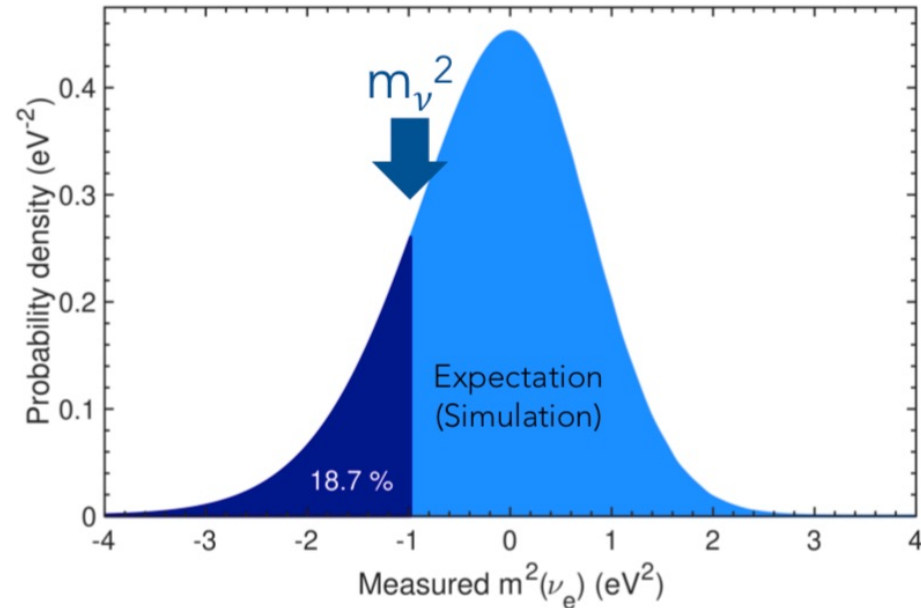
Actual Result Compared to Expectation



MC-Propagation Method



Covariance Matrix Method

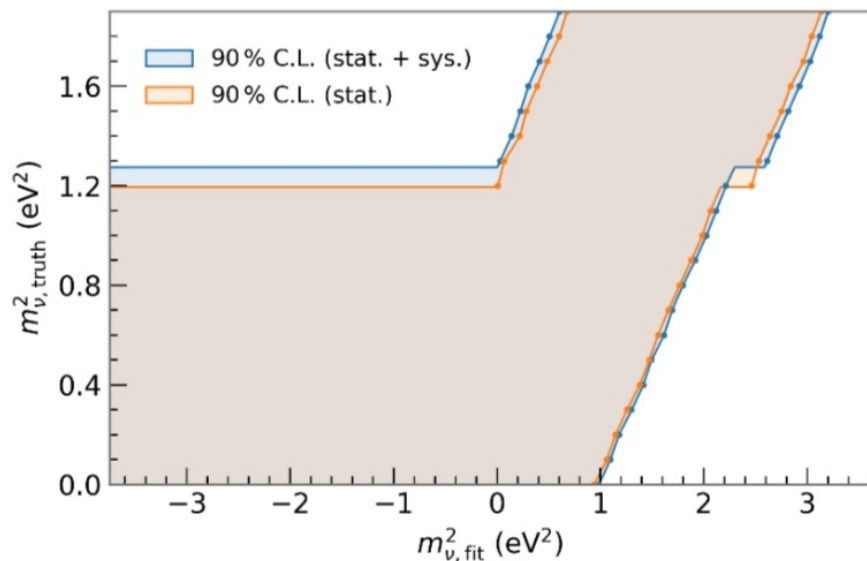


Best-fit m_ν^2 is fully consistent with our expectations
(1σ statistical fluctuation)

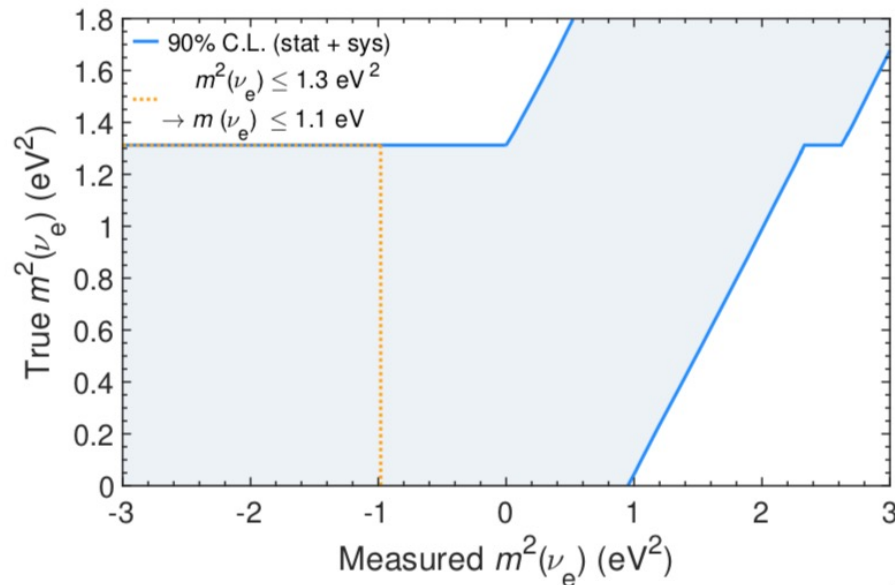
Conservative Upper Limit on the Neutrino Mass



MC-Propagation Method



Covariance Matrix Method



Lokhov-Tkachov - Phys. Part. Nuclei 46, 347 (2015)

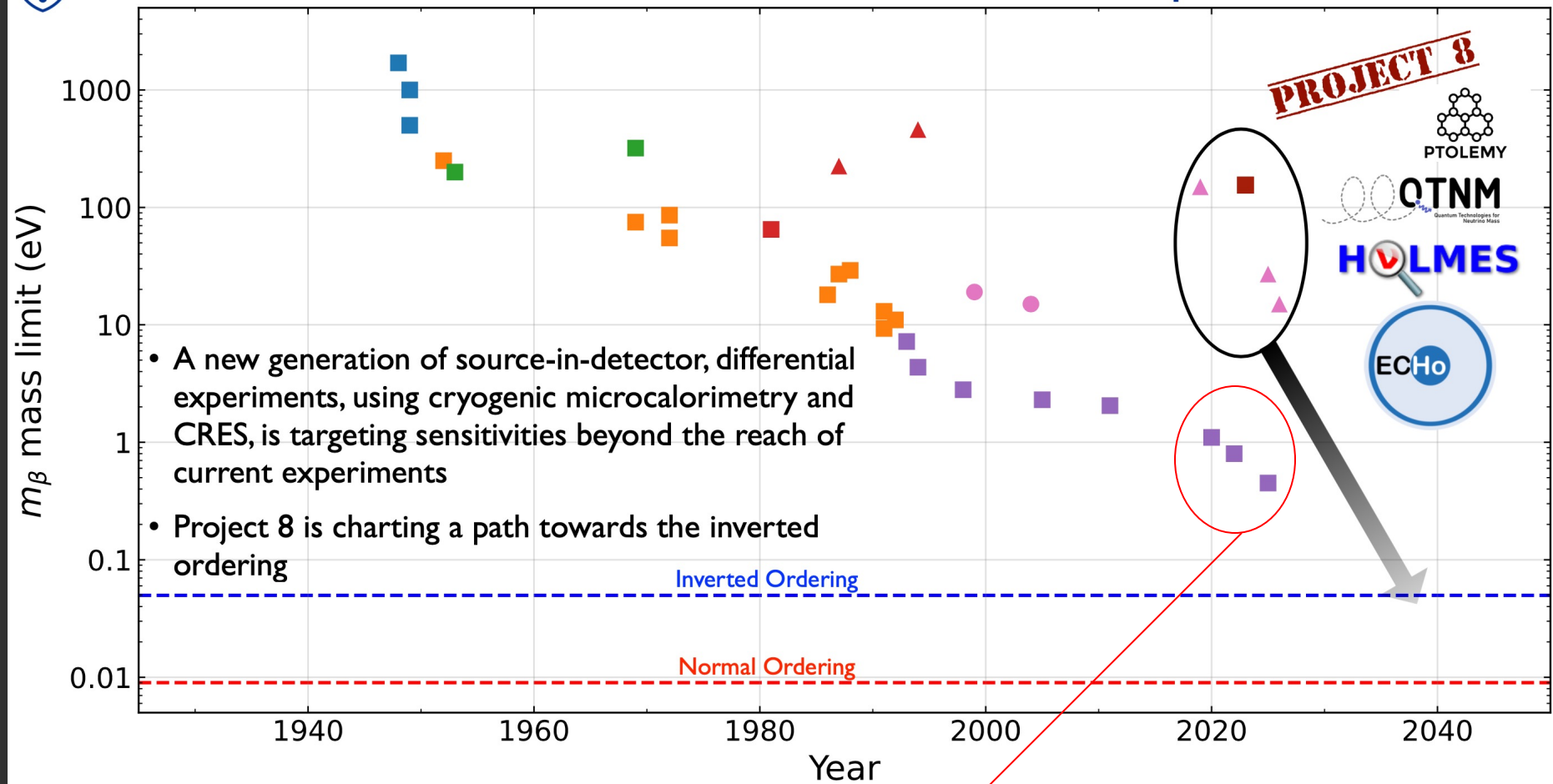
0.8 eV

$m_\nu < 1.1 \text{ eV}$ at 90% CL (Lokhov-Tkachov)

T. Lasserre – KIT – 16/09/2019

World Best Direct Neutrino Mass Measurement

The Path Forward for Direct Neutrino Mass Experiments



KATRIN 2406.13516 : $m_{ee} < 0.45$ eV (90% C.L.)

Electron neutrinos and anti-neutrinos are also produced in muon decays

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e, \quad (1.12)$$

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e, \quad (1.13)$$

and as a subdominant mode in pion decays

$$\pi^+ \rightarrow e^+ + \nu_e, \quad (1.14)$$

$$\pi^- \rightarrow e^- + \bar{\nu}_e, \quad (1.15)$$

and in some other processes.

Muon and tauon neutrinos

Muon neutrinos and antineutrinos are produced in muon decays and in pion decays as well in some other processes. They have a great importance in the recent neutrino physics history, since, as we will see, neutrino oscillations have been first discovered from atmospheric muon neutrinos disappearance in 1998 by the SuperKamiokande experiment.

Tauon neutrinos are produced in $\tau^\pm$ decays and they have been detected for the first time in 2000 by the DONUT experiment in the charged current processes $\nu_\tau(\bar{\nu}_\tau) + N \rightarrow \tau^\mp + X$. This same reaction has been used in the OPERA detector at Gran Sasso laboratory to prove $\nu_\mu \rightarrow \nu_\tau$ oscillations by τ appearance.

Like for the electron neutrino mass, there are also much looser kinematic upper bounds on the muon and on the tauon neutrino masses. The most stringent upper on the muon neutrino mass has been placed by an experiment at the PSI from kinematic analysis of the pion decay $\pi^+ \rightarrow \mu^+ + \nu_\mu$, obtaining

$$m_{\nu_\mu} < 170 \text{ keV (90\%CL)} \quad (1.16)$$

From the study of τ decays

$$\tau^- \rightarrow 2\pi^- + \pi^+ + \nu_\tau, \quad \tau^- \rightarrow 3\pi^- + 2\pi^+ + \nu_\tau (+\pi^0), \quad (1.17)$$

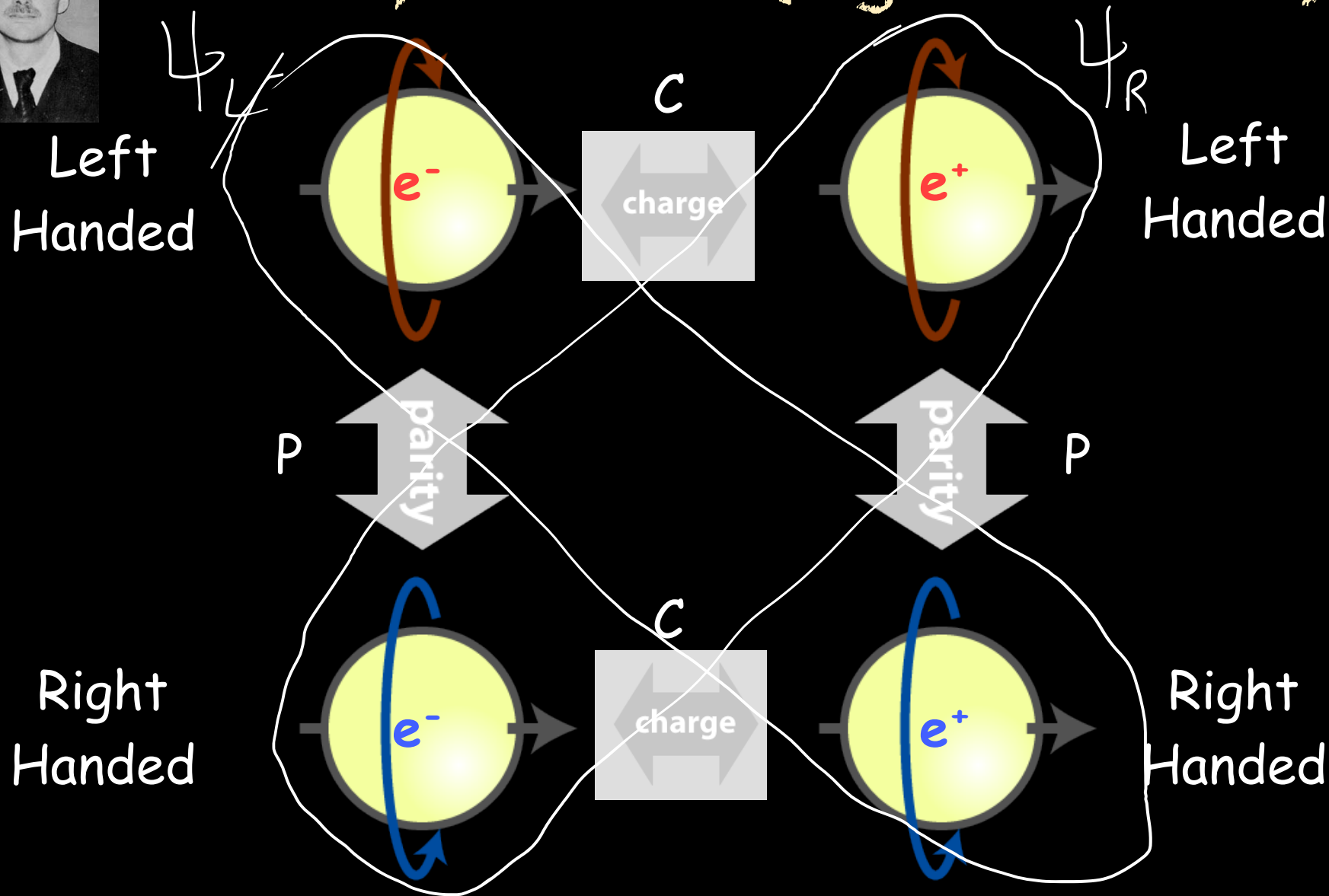
the ALEPH experiment has placed the most stringent upper bound on the tau neutrino mass,

$$m_{\nu_\tau} < 18.2 \text{ MeV (95\%CL)}. \quad (1.18)$$

Neutrinos in the SM



Dirac fermions (e.g. electrons)



The Dirac equation can be recast in terms of the chiral components as (**problem 4**)

$$i \not{\partial} \psi_R = m \psi_L, \quad (1.64)$$

$$i \not{\partial} \psi_L = m \psi_R. \quad (1.65)$$

In the limit of zero mass $m = 0$, the dynamics of the chiral components decouples and they obey the *Weyl equations*,

$$i \not{\partial} \psi_R = 0, \quad (1.66)$$

$$i \not{\partial} \psi_L = 0. \quad (1.67)$$

Notice that the names LH and RH originate from the fact that for relativistic particles chirality almost coincides with the usual LH and RH helicity eigenstates and in the limit $m \rightarrow 0$ they exactly coincide (**problem 5**).

Matter contents of the SM		$SU(3)_C \times SU(2)_L \times U(1)_Y$		
$L_L(1, 2, -\frac{1}{2})$	$Q_L(3, 2, \frac{1}{6})$	$E_R(1, 1, -1)$	$U_R(3, 1, \frac{2}{3})$	$D_R(3, 1, -\frac{1}{3})$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	e_R	u_R	d_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c \\ s \end{pmatrix}_L$	μ_R	c_R	s_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t \\ b \end{pmatrix}_L$	τ_R	t_R	b_R

Gell-Mann -Nishijima relation

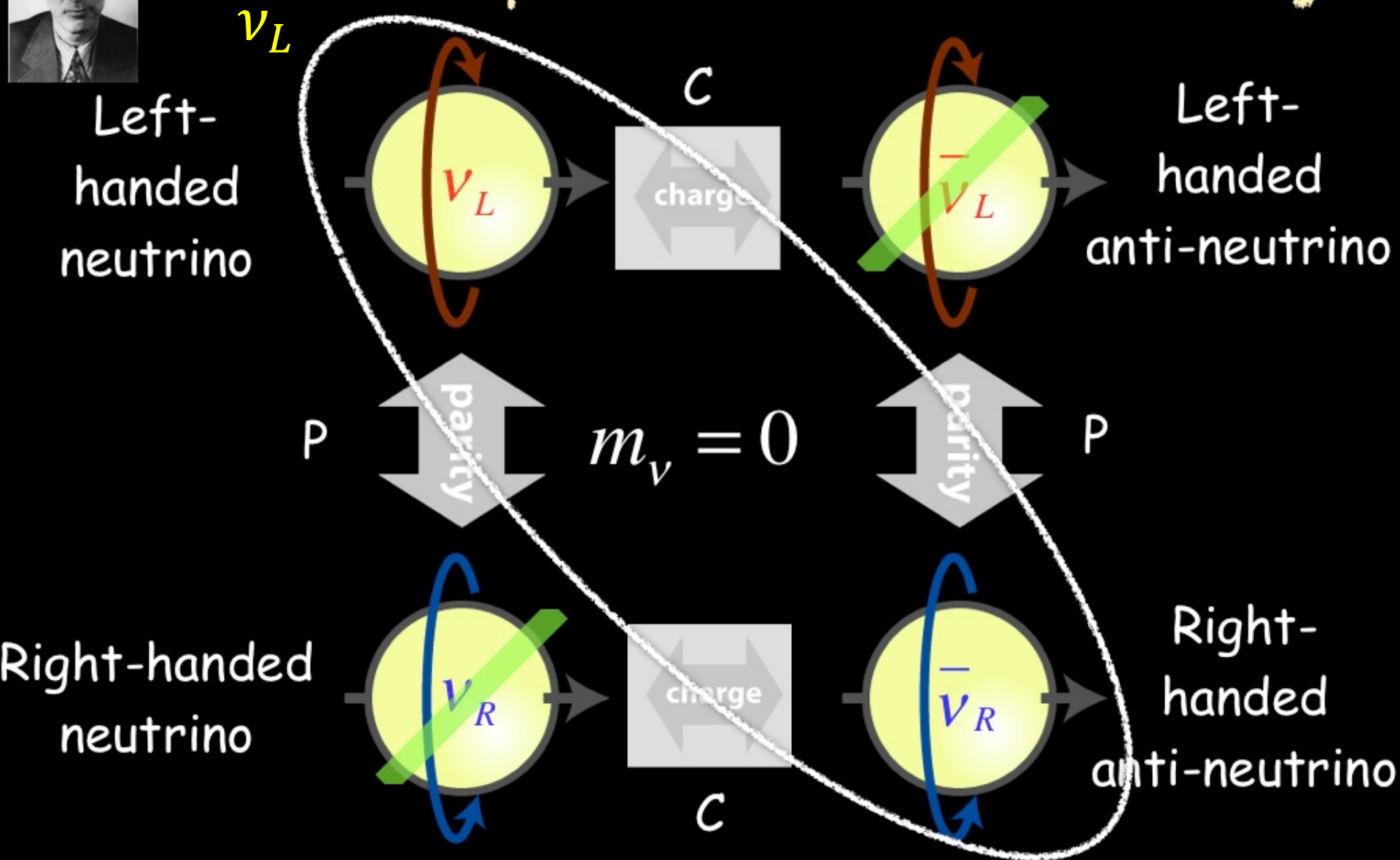
$$Q_{\text{em}} = T_3 + Y$$

where Y is the $U(1)_Y$ hypercharge, the RH neutrinos $\nu_{R\alpha}$ carry no $SU(2)_L \times U(1)_Y$ quantum numbers and this implies that:

- In the SM, by definition, there are no RH neutrino fields and (as we will show) this implies that neutrinos are strictly massless; therefore, neutrinos are described by the phenomenological two-component neutrino theory (Landau, Lee and Yang, Salam) where neutrinos are described by Weyl LH fields and parity is violated. Therefore, SM neutrinos obey just one Weyl equation (the second in Eq. (1.66)).
- Neutrinos detected experimentally, produced by weak interactions, are purely LH (helicity) states and the anti-neutrinos are purely RH (helicity) states;
- The existence of RH neutrinos could be inferred only indirectly through the existence of neutrino masses, though notice that neutrino masses do not necessarily imply the existence of RH neutrinos.⁸⁹



Two-component neutrino theory



Neutrino interactions

$$\mathcal{L}_{W\ell\nu} = \frac{e}{\sqrt{2}\sin\theta_W} [W_+^\mu J_{-\mu}^{\text{lept}} + W_-^\mu J_{+\mu}^{\text{lept}}],$$

Charged current

$$\mathcal{L}_{W\ell\nu} = \frac{e}{\sqrt{2}\sin\theta_W} [W_+^\mu J_{-\mu}^{\text{lept}} + W_-^\mu J_{+\mu}^{\text{lept}}],$$

Universal coupling to Z boson

$$\mathcal{L}_{Z\nu\bar{\nu}} = \frac{e}{2\cos\theta_W\sin\theta_W} Z^\mu [J_\mu^{NC}]_\nu,$$

Neutral current

$$[J_\mu^{NC}]_\nu = \sum_{i'=1,\dots,N_\nu} \bar{\nu}_{Li'} \gamma_\mu \nu_{Li'},$$

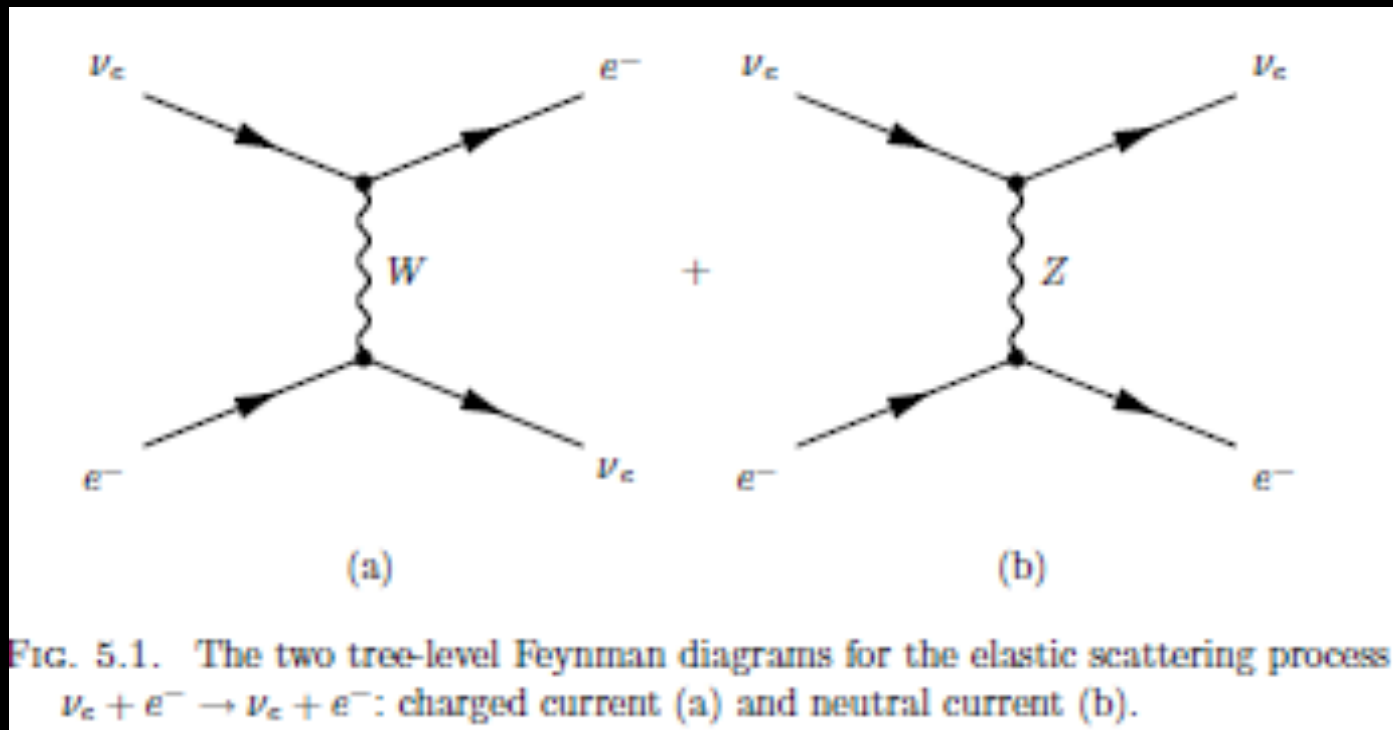


FIG. 5.1. The two tree-level Feynman diagrams for the elastic scattering process $\nu_e + e^- \rightarrow \nu_e + e^-$: charged current (a) and neutral current (b).

Number of neutrino species from the invisible Z decay width

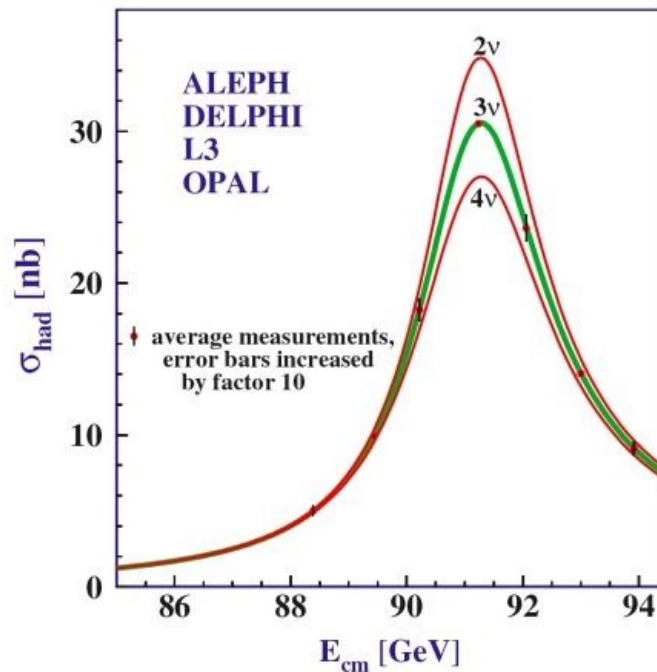
$$\Gamma_{\text{tot}} = \Gamma_{\text{had}} + 3\Gamma_{\text{ch.lep.}} + \Gamma_{\text{inv}}, \quad (1.108)$$

where Γ_{inv} is the so-called invisible decay width that is very simply related to the number of neutrino species

$$\Gamma_{\text{inv}} = N_\nu \Gamma_\nu. \quad (1.109)$$

LEP has measured very accurately Γ_{had} , $\Gamma_{\text{ch.lep.}}$ and Γ_{tot} from a fit of the Z -line shape for $e^+e^- \rightarrow \mu^+\mu^-$ and into hadrons finding (*see in the slide the measurement of σ_{had}*) in a final combined analysis [12]

$$N_\nu = \frac{\Gamma_{\text{tot}} - \Gamma_{\text{had}} - 3\Gamma_{\text{chlep}}}{\Gamma_\nu} = 2.9840 \pm 0.0082, \quad (1.110)$$



Neutrino mixing

Neutrino mixing

neutrino weak eigenfields $\leftarrow \nu_\alpha = \sum_{i=1,2,3} U_{\alpha i} \nu_i \rightarrow$ Neutrino mass eigenfields

Leptonic or PMNS mixing matrix

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle$$

$$c_{ij} \equiv \cos \theta_{ij}$$

$$s_{ij} \equiv \sin \theta_{ij}$$

Parameterisation of the leptonic mixing matrix

$$U = \begin{pmatrix} c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i\delta} \\ -s_{12} c_{23} - c_{12} s_{23} s_{13} e^{i\delta} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i\delta} & s_{23} c_{13} \\ s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i\delta} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i\delta} & c_{23} c_{13} \end{pmatrix} \cdot \text{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1)$$

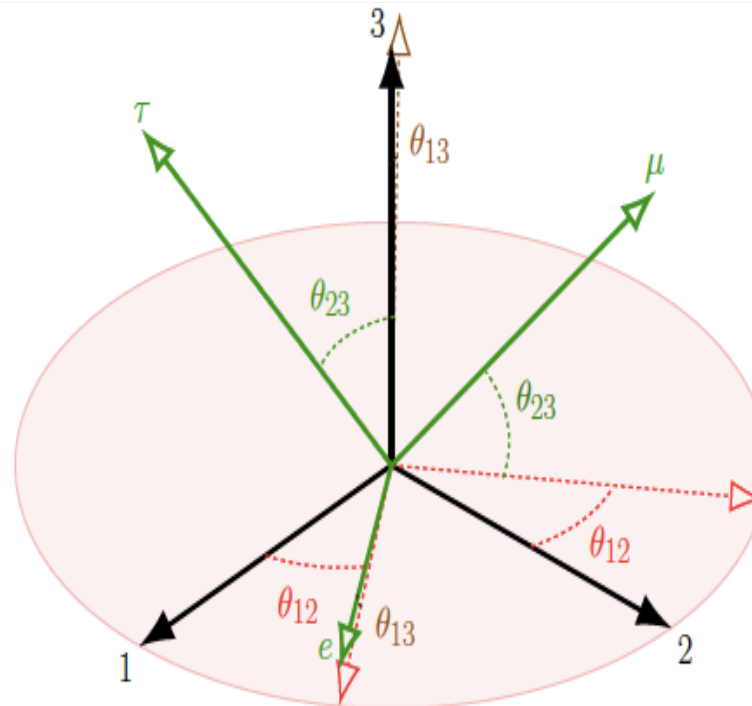
Notice that the leptonic mixing matrix can be recast in the form $U = V P$, where

$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad (2.6)$$

and

$$P = \text{diag} (e^{i\alpha_1}, e^{i\alpha_2}, 1) . \quad (2.7)$$

In the absence of phases this would be the usual parameterisation of a rotation matrix (i.e., an orthogonal matrix) in terms of Euler angles. Therefore, the three mixing angles should be regarded as Euler angles (show slide). The rotation matrices provide a representation of $SO(3)$, while unitary matrices in the form Eq. (2.20) provide a useful representation of $SU(3)$.



Neutrino oscillations in vacuum

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle, \quad (\alpha = e, \mu, \tau; i = 1, 2, 3)$$

Consider now an ultra-relativistic neutrino state produced at the time $t = 0$ in the flavour α described by the ket $|\nu_\alpha(0)\rangle \equiv |\nu_\alpha\rangle$. At the time t (at distance $\ell \simeq ct$ from the place of production) it will have evolved as

$$|\nu_\alpha(t)\rangle = \sum_i U_{\alpha i}^* |\nu_i(t)\rangle, \quad (2.9)$$

and it will have an (oscillation) probability $P_{\alpha\beta}(t) \equiv |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2$ to be detected as a β neutrino in the CC interaction

$$\nu_\alpha(t) + N \rightarrow \beta + N', \quad (2.10)$$

where β is a charged lepton.

- The probability $P_{\alpha\neq\beta}$ is called *appearance probability* (of the flavour β) ;
- The probability $P_{\alpha\alpha}$ is called *survival probability* (of the flavour α);
- Finally the quantity $\sum_{\beta\neq\alpha} P_{\alpha\beta}$ is called *disappearance probability* (of the flavour α) and of course $\sum_{\beta\neq\alpha} P_{\alpha\beta} = 1 - P_{\alpha\alpha}$.

Neutrino oscillation probability

The oscillation probability can be expressed in terms of the mass eigenstates,

$$P_{\alpha\beta}(t) \equiv |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \left| \sum_{i,j} U_{\alpha i}^* U_{\beta j} \langle \nu_j | \nu_i(t) \rangle \right|^2. \quad (2.11)$$

If we now use the standard plane wave approximation

$$|\nu_i(t)\rangle = e^{-i E_i t} |\nu_i(0)\rangle, \quad (2.12)$$

the ultra-relativistic approximation

$$E_i = \sqrt{|\vec{p}|^2 + m_i^2} \simeq |\vec{p}| + \frac{m_i^2}{2 |\vec{p}|} \quad (2.13)$$

and the orthonormality condition $\langle \nu_i | \nu_j \rangle = \delta_{ij}$, we get finally the following expression for the transition probability in vacuum (**problem 3**)

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4 \sum_{i < j}^{1,3} \text{Re}[U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}] \sin^2 \left(\pi \frac{\ell}{\ell_{ij}^0} \right) + 2 \sum_{i < j}^{1,3} \text{Im}[U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}] \sin \left(2 \pi \frac{\ell}{\ell_{ij}^0} \right),$$

where

$$\ell_{ij}^0 \equiv \frac{4\pi E}{\Delta m_{ij}^2} \simeq 2.48 \text{ km} \frac{E/\text{GeV}}{\Delta m_{ij}^2/\text{eV}^2}, \quad \Delta m_{ij}^2 \equiv m_j^2 - m_i^2, \quad (2.15)$$

are the oscillation lengths and mass squared differences in vacuum and we defined $E \equiv |\vec{p}|$.

Factorization of the PMNS matrix

$$\begin{aligned}
 U_{\alpha i} &= \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\
 &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}
 \end{aligned}$$

Atmospheric, LB

Reactors, Accel., LB
CP violating phase

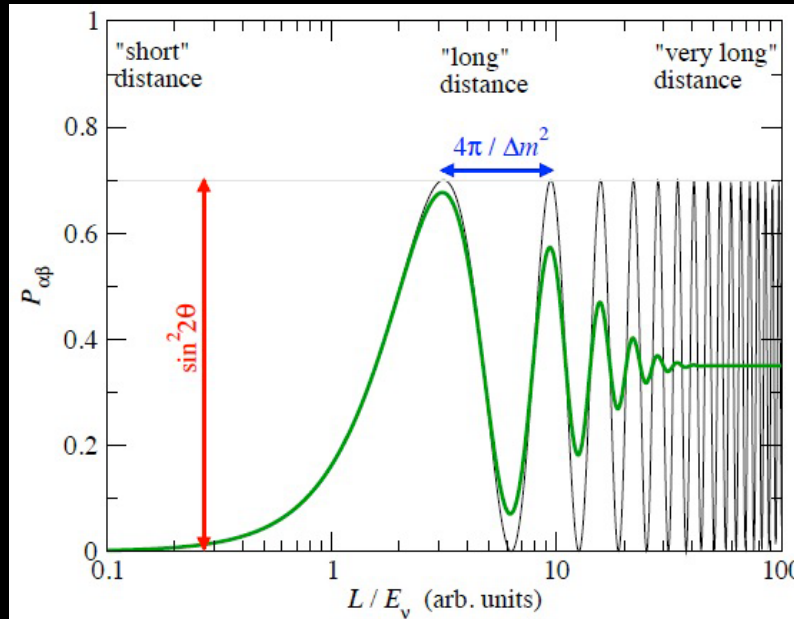
Solar, Reactors

$\beta\beta 0\nu$ decay

Within a three-neutrino mixing framework different experimental observations get connected and CP violation is possible. Historically first studies were done within a two neutrino mixing description since in the approximation of vanishing θ_{13} 'solar' and 'atmospheric' mixing decouple. This approximation was justified by the CHOOZ upper bound (1999): $\theta_{13} \lesssim 13^\circ (3\sigma)$

Some insight

$$P_{\nu_e \rightarrow \nu_e} = 1 - \sin^2 2\theta \times \sin^2 \left[\frac{(m_2^2 - m_1^2)L}{4E} \right]$$



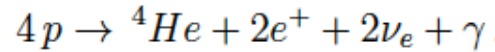
At least 1 neutrino has to be massive since for exactly massless particles travelling at the speed of light, there cannot be any time scale associated to propagation because of "time dilation" that freezes any dynamics. For example in the u.r. limit a decaying particle does not decay! It is a consequence of Special Relativity



John Bahcall

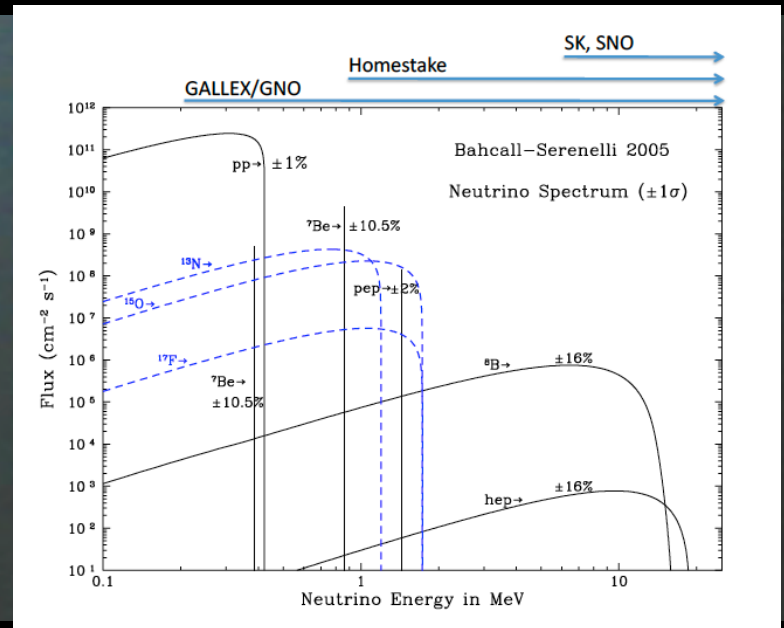
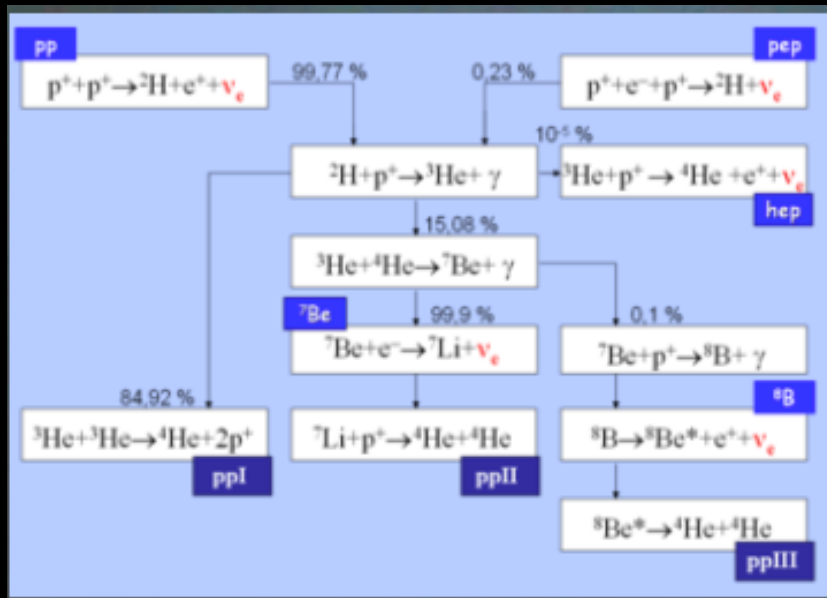
The solar standard model

Neutrinos are produced inside the Sun, on average:



$$\langle E_{\nu_e} \rangle \simeq 0.6 \text{ MeV}$$

More precisely:

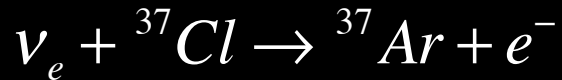




Missing neutrinos!

Raymond Davis

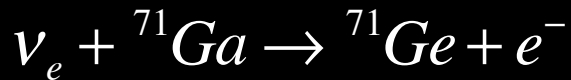
Homestake experiment (final results in 1998):



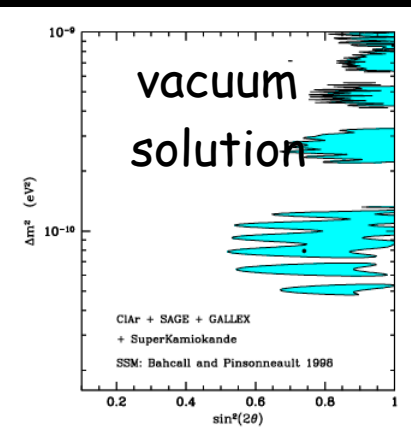
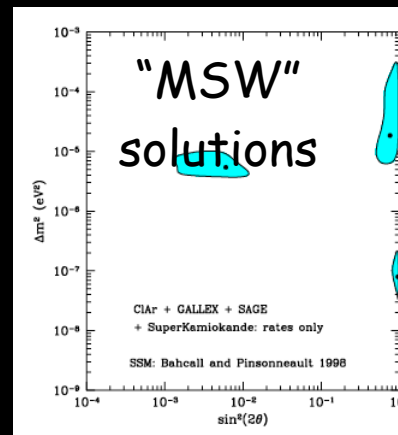
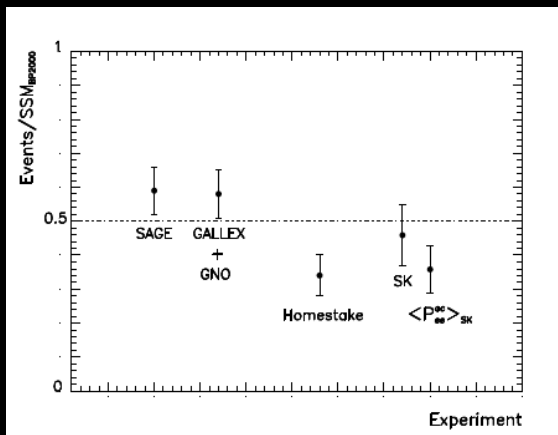
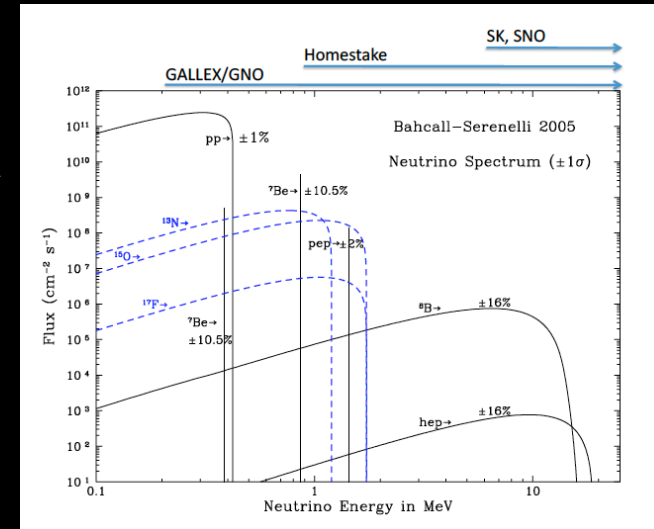
final solar neutrino rate : $2.56 \pm 0.16(\text{stat}) \pm 0.16(\text{sys}) \text{SNU}$

theoretical prediction: $8.5 \pm 0.9 \text{SNU}$

GALLEX/GNO experiment:



final solar neutrino rate $\sim 50\%$ predicted



How to pin down the right solution? How to be sure the Solar Model is correct?

Two neutrino mixing and oscillations

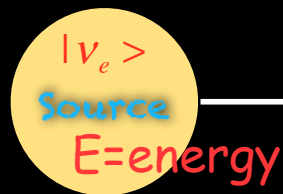


flavour eigenstates

mass eigenstates
with masses
 m_1 and m_2

$$\begin{aligned} | \nu_e \rangle &= \cos \theta | \nu_1 \rangle + \sin \theta | \nu_2 \rangle \\ | \nu_{\mu+\tau} \rangle &= -\sin \theta | \nu_1 \rangle + \cos \theta | \nu_2 \rangle \end{aligned}$$

2 neutrino oscillations



L

Detector

appearance
probability

$$P_{\nu_e \rightarrow \nu_{\mu+\tau}} = \sin^2 2\theta \times \sin^2 \left[\frac{(m_2^2 - m_1^2)L}{4E} \right] \approx \sin^2 2\theta \times \sin^2 \left(1.27 \frac{\Delta m^2 [eV^2] L [km]}{E [MeV]} \right)$$

disappearance
probability

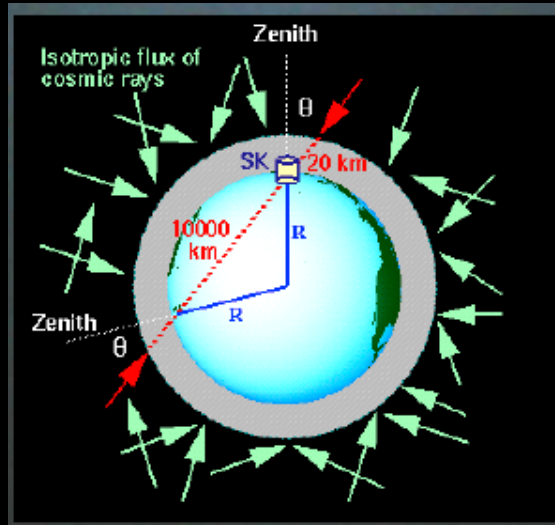
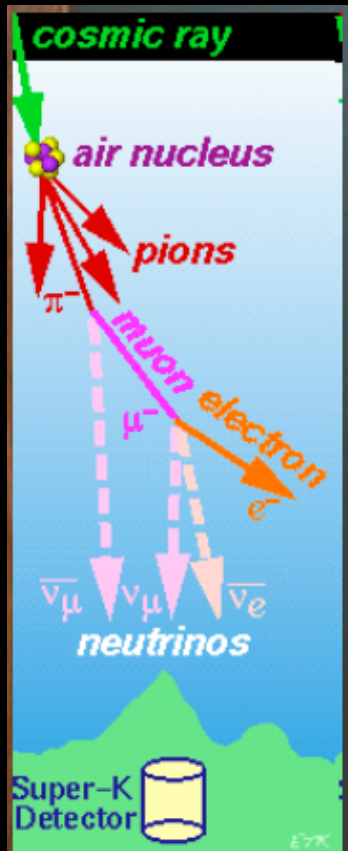
$$P_{\nu_e \rightarrow \nu_e} = 1 - P_{\nu_e \rightarrow \nu_{\mu+\tau}}$$

(Gribov-Pontecorvo 1969)

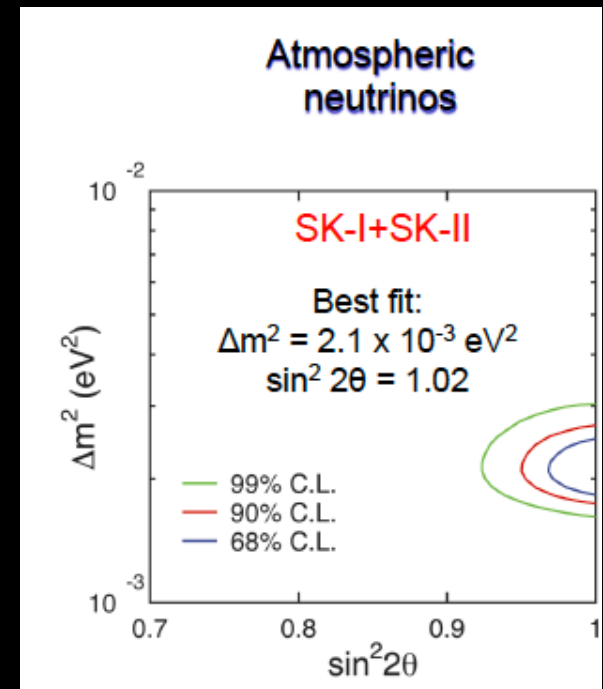
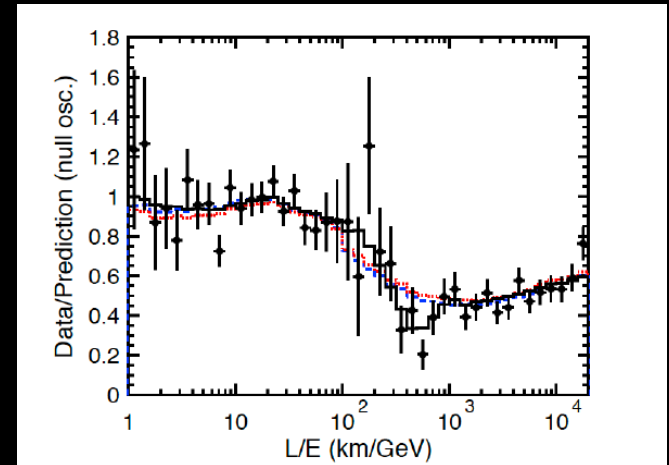


Takaaki Kajita

Atmospheric neutrinos

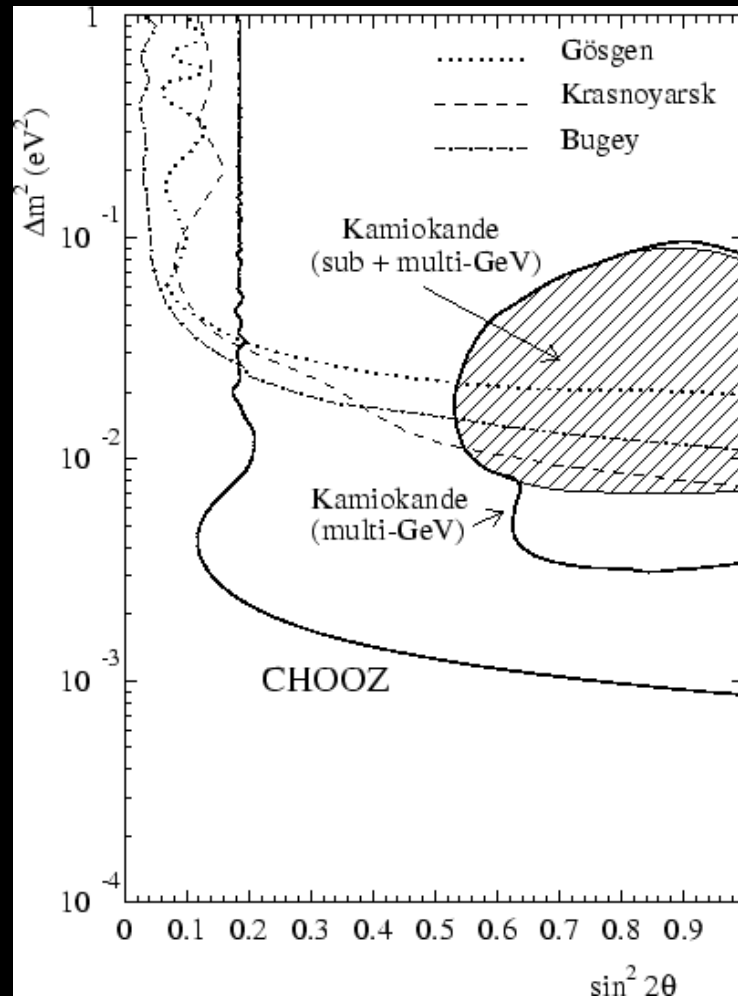


SK results on atmospheric neutrinos support the conclusion that muon neutrinos are converted into tauon neutrinos with approximately maximal mixing

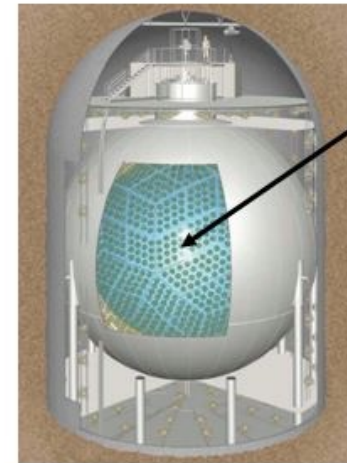


Determination of θ_{13}

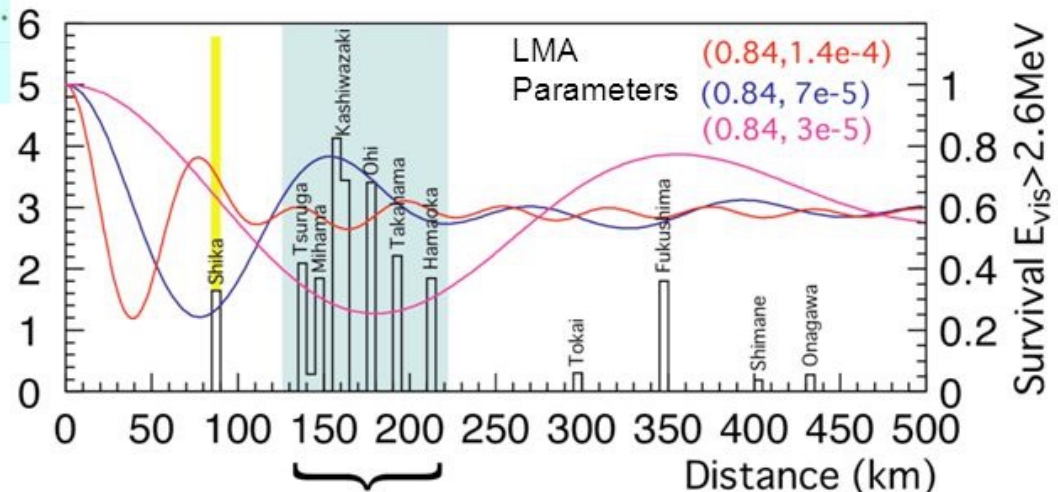
The CHOOZ upper bound



The KamLAND Experiment



1000ton LS
1879 PMT's



80% of total contribution comes from 130~220km distance

A first hint: Combining solar neutrino data with Kamland (longbaseline reactor neutrinos)

Hints of $\theta_{13} > 0$ from global neutrino data analysis

G.L. Fogli^{1,2}, E. Lisi², A. Marrone^{1,2}, A. Palazzo³, and A.M. Rotunno^{1,2}

Phys.Rev.Lett. 101 (2008) 141801

2

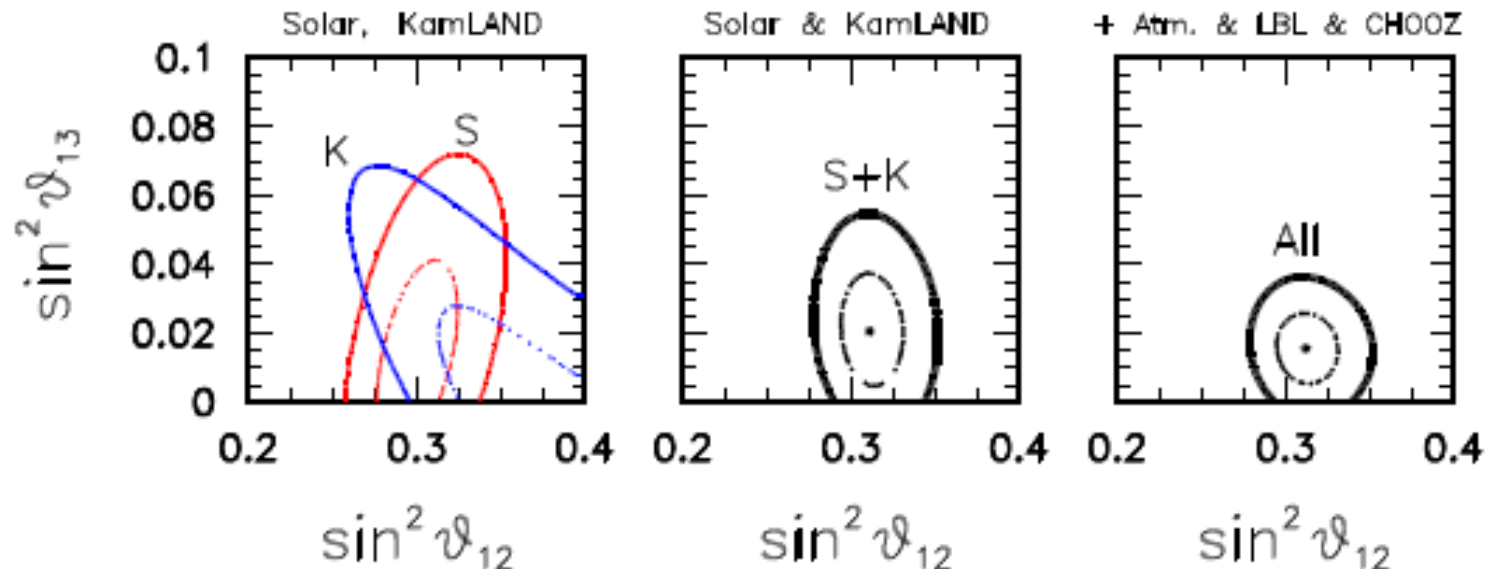


FIG. 1: Allowed regions in the plane $(\sin^2 \theta_{12}, \sin^2 \theta_{13})$: contours at 1σ (dotted) and 2σ (solid). Left and middle panels: solar (S) and KamLAND (K) data, both separately (left) and in combination (middle). In the left panel, the S contours are obtained by marginalizing the δm^2 parameter as constrained by KamLAND. Right panel: All data.

Short baseline reactor neutrino experiments: Daya Bay

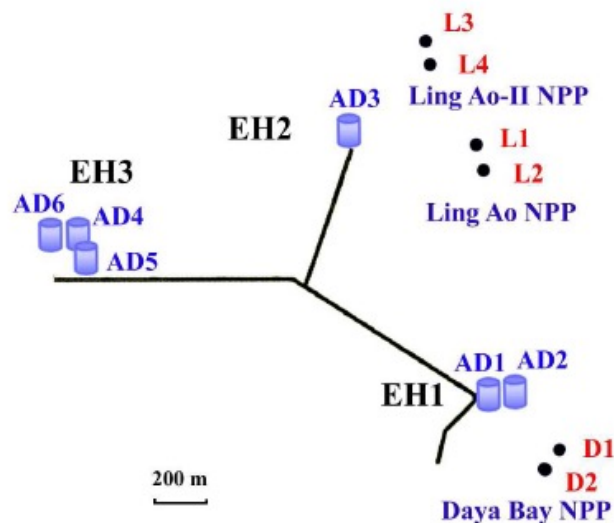
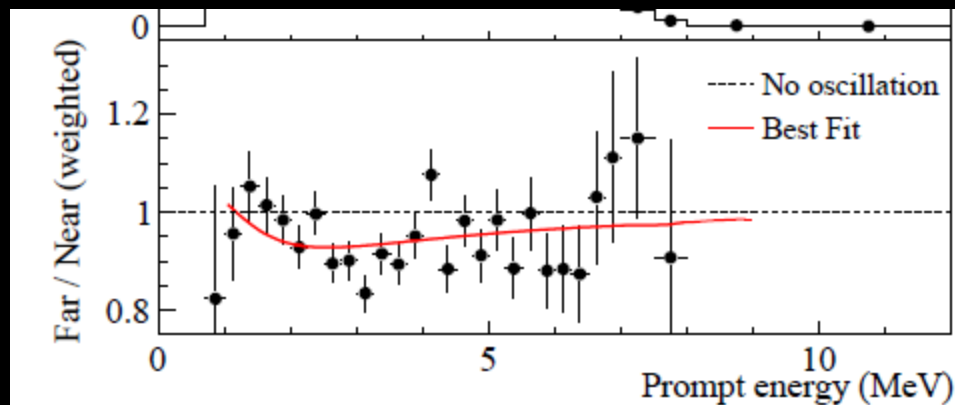
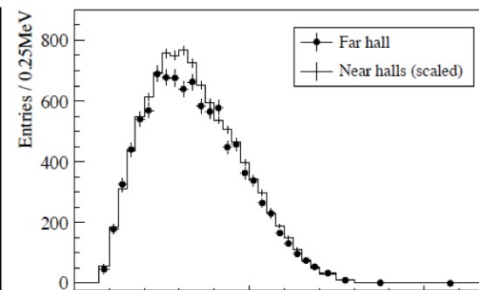
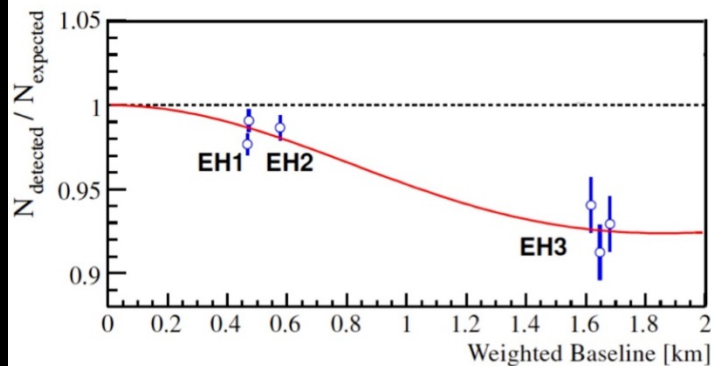


FIG. 1. Layout of the Daya Bay experiment. The dots represent reactors, labeled as D1, D2, L1, L2, L3 and L4. Six ADs, AD1–AD6, are installed in three EHs.



$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$



Reno

$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat.}) \pm 0.019(\text{syst.}).$$

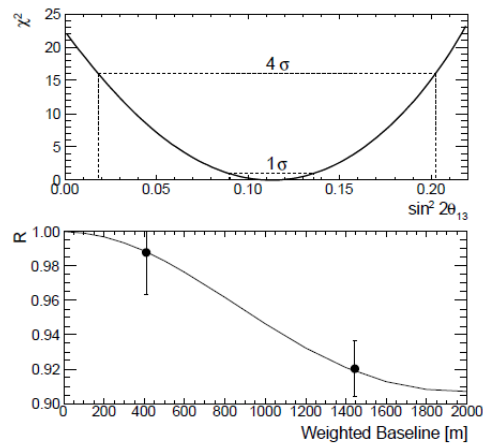
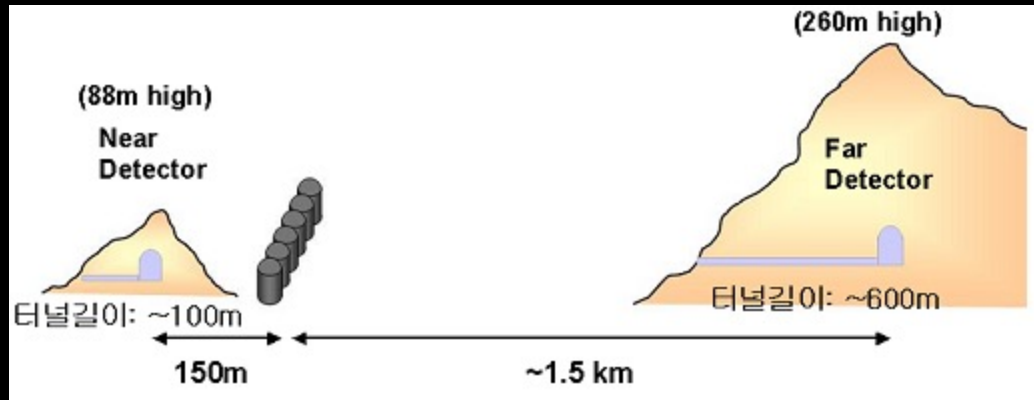


FIG. 3. The χ^2 distribution as a function of $\sin^2 2\theta_{13}$. Bottom: Ratio of the measured reactor neutrino events relative to the expected with no oscillation. The curve represents the oscillation survival probability at the best fit, as a function of the flux-weighted baselines.

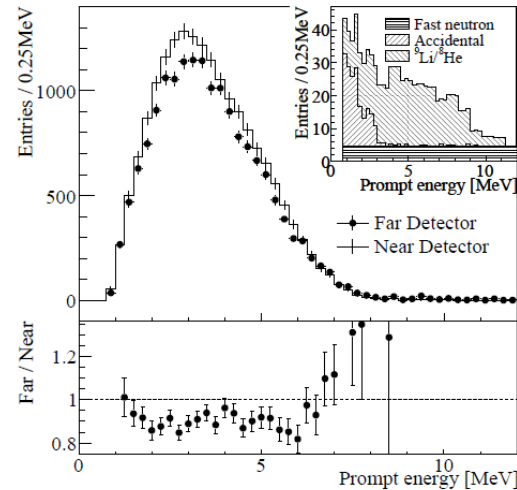
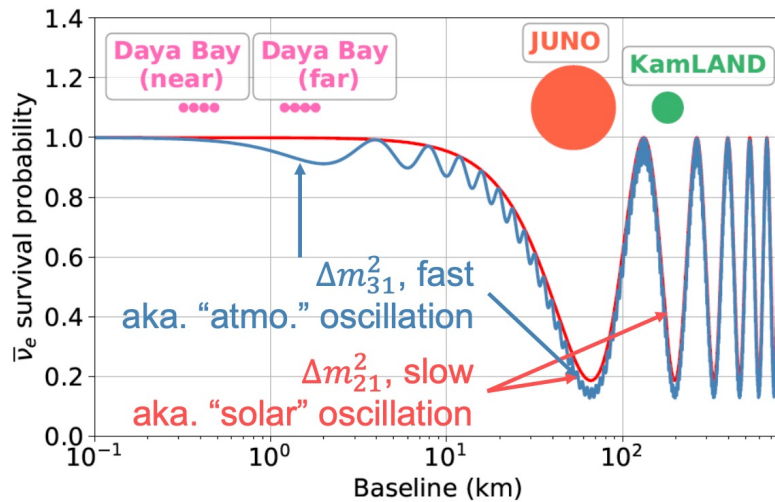


FIG. 4. Observed spectrum of the prompt signals in the far detector compared with the non-oscillation predictions from the measurements in the near detector. The backgrounds shown in the inset are subtracted for the far spectrum. The background fraction is 5.5% (2.7%) for far (near) detector. Errors are statistical uncertainties only. Bottom: The ratio of the measured spectrum of far detector to the non-oscillation prediction.

Neutrino Oscillation at JUNO



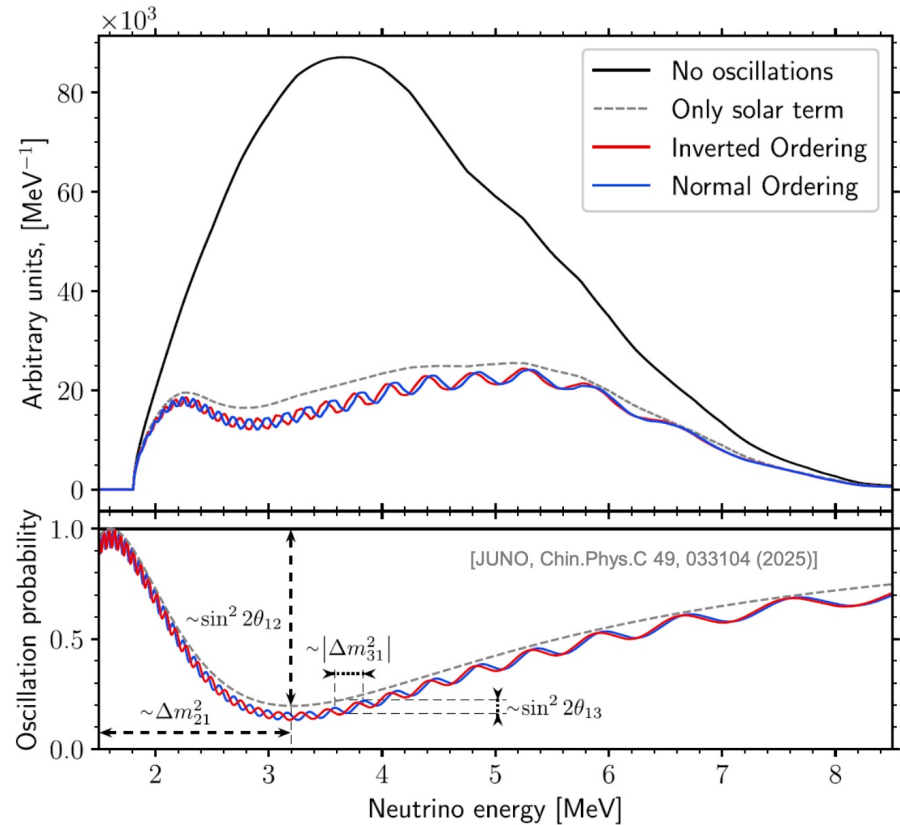
$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21})$$

$$P_{31} = \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31})$$

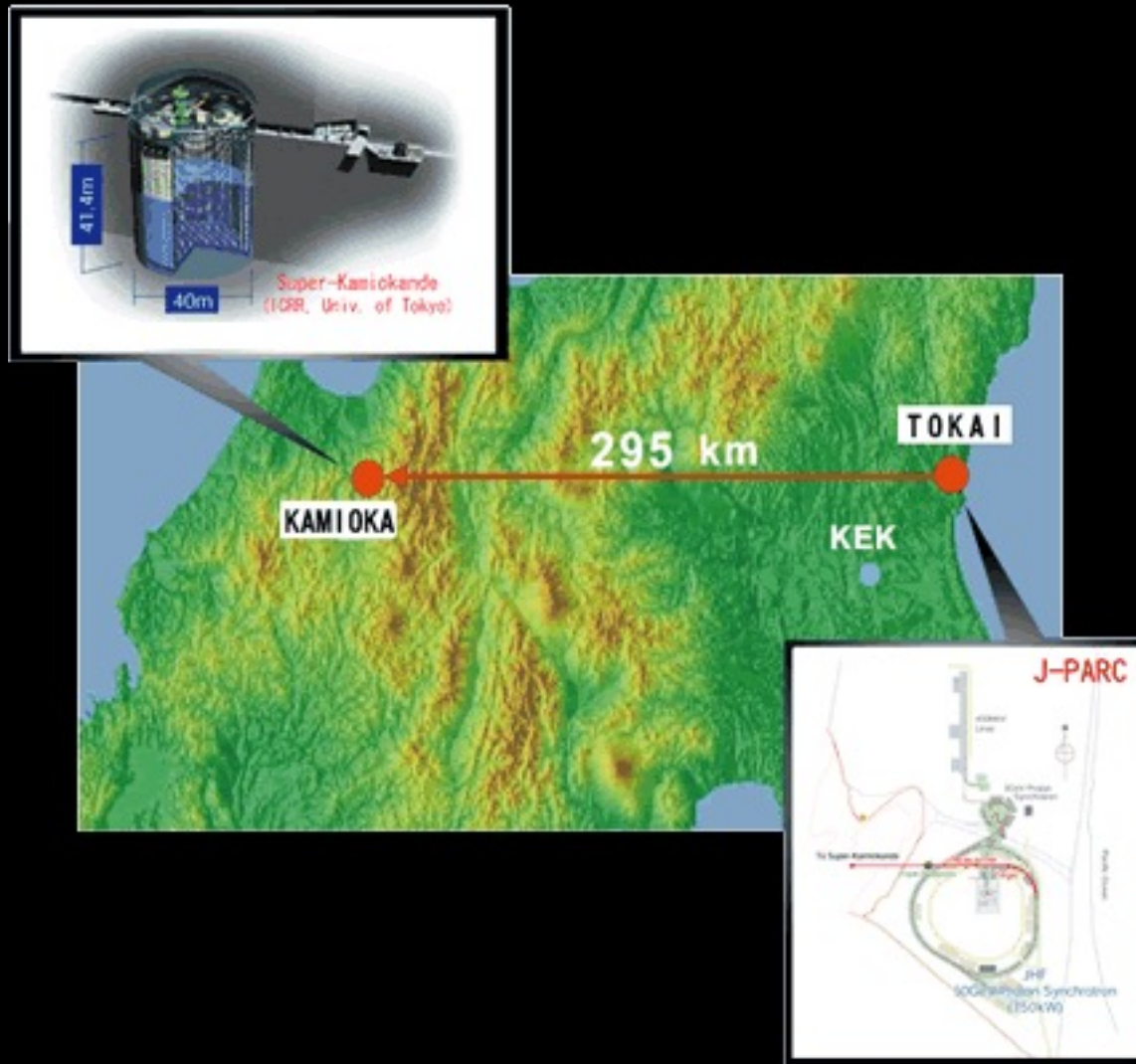
$$P_{32} = \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})$$

S. Petcov and Piai, Phys. Lett. B 553, 94-106 (2002)
 J. Learned et al., PRD 78(2008)071302
 L. Zhan, Y. Wang et al., PRD 78(2008)111103

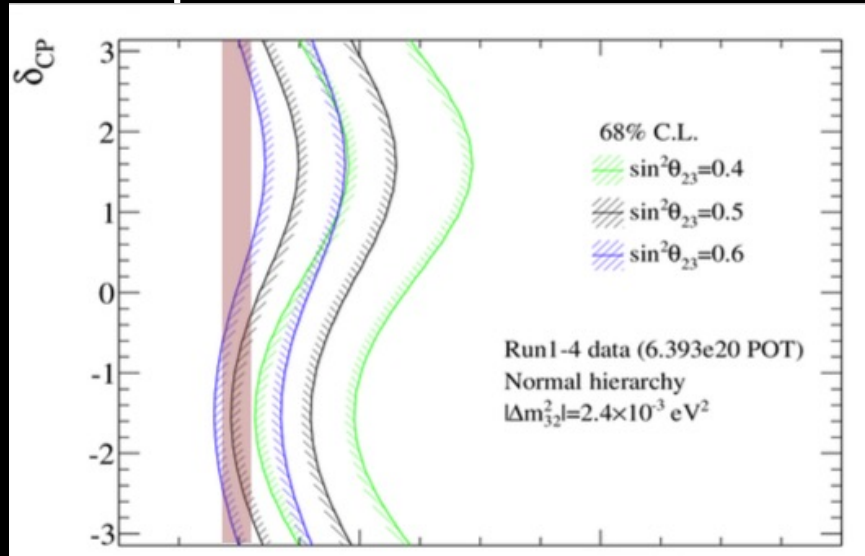


JUNO's main goal: Neutrino Mass Ordering

Long baseline accelerator experiment: T2K

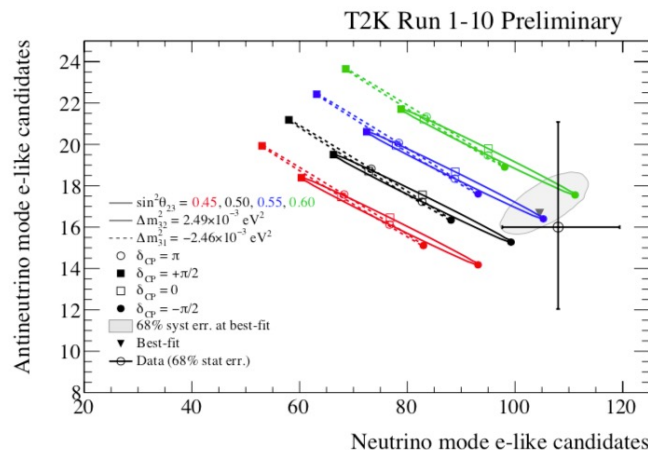


Long baseline experiments: T2K measurement of δ



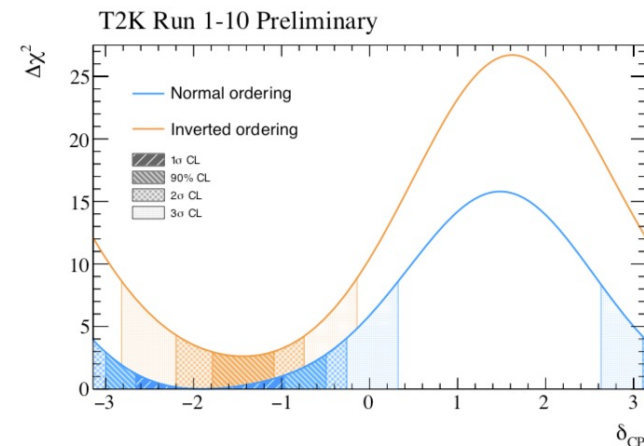
δ_{CP} measurement

NuFact2021



PMNS best-fit around maximal CP-violation

Weak preference for normal ordering



Large region excluded at 3 σ

CP-conservation (0, π) excluded at 90%

Largest $\Delta \chi^2$ change seen in any of our

Matter effects

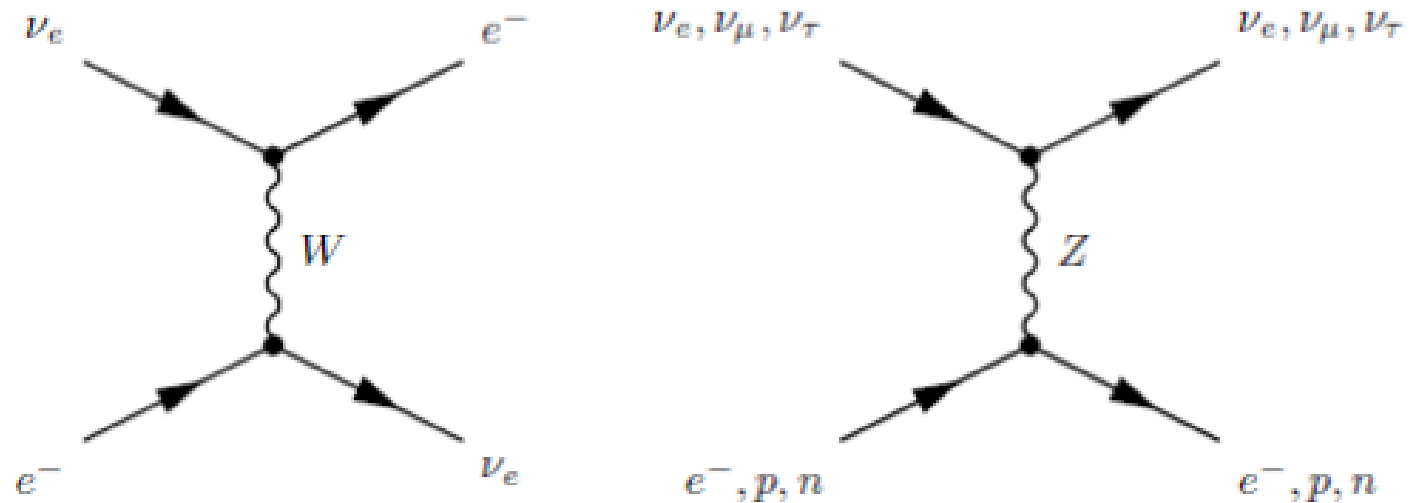


FIG. 9.1. Feynman diagrams of the coherent forward elastic scattering processes that generate the CC potential V_{CC} through W exchange and the NC potential V_{NC} through Z exchange.

Matter effects

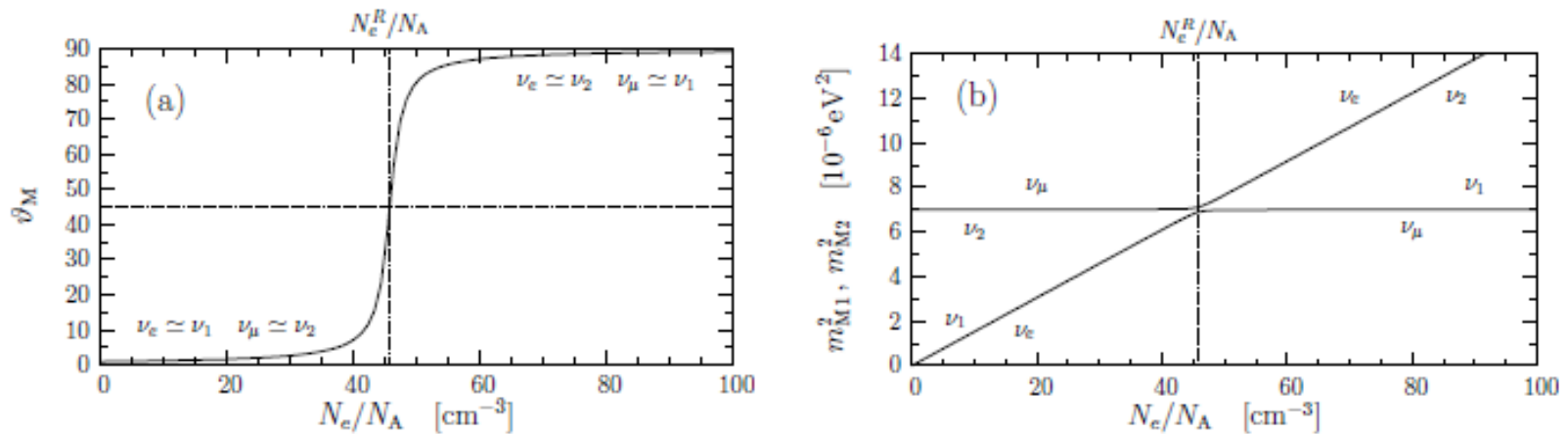


FIG. 9.2. Effective mixing angle ϑ_M (a) and the effective squared-masses m_{M1}^2 , m_{M2}^2 (b) in matter as functions of the electron number density N_e divided by the Avogadro's number N_A , for $m_1 = 0$, $\Delta m^2 = 7 \times 10^{-6} \text{eV}^2$, $\sin^2 2\vartheta = 10^{-3}$ and $E = 1 \text{MeV}$. $N_e^R \equiv \Delta m^2 \cos 2\vartheta / 2\sqrt{2}EG_F$ is the electron number density at the resonance, where $\vartheta_M = 45^\circ$.

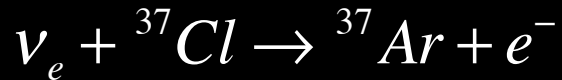
They are crucial to fully explain solar neutrinos



Missing neutrinos!

Raymond Davis

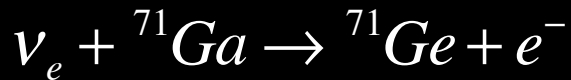
Homestake experiment (final results in 1998):



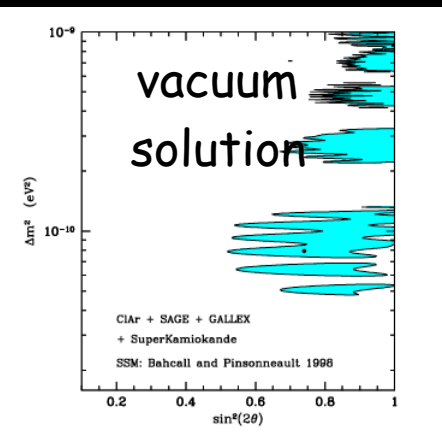
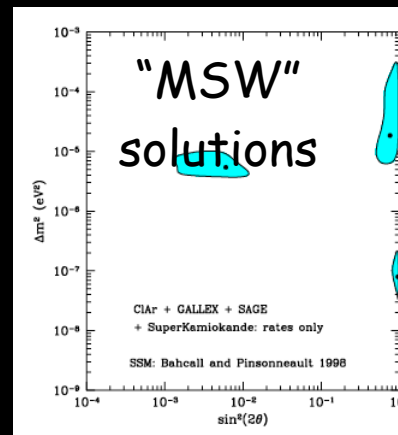
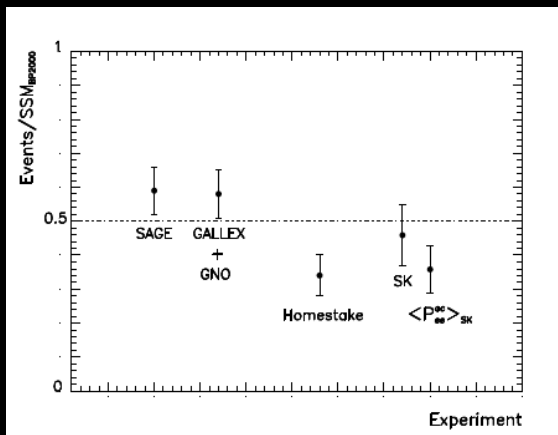
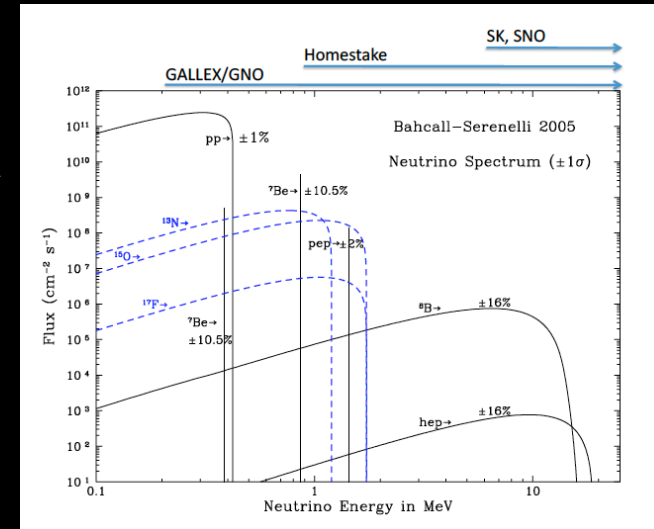
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GALLEX/GNO experiment:



final solar neutrino rate $\sim 50\%$ predicted

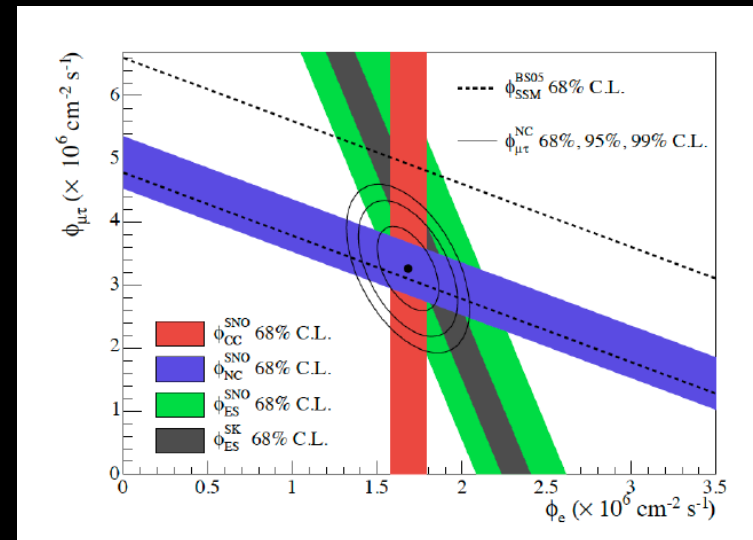
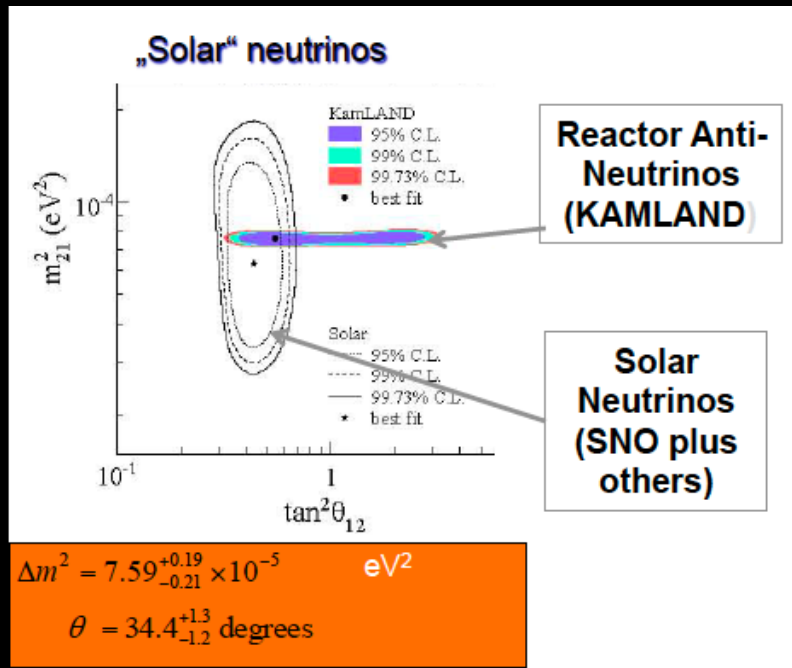
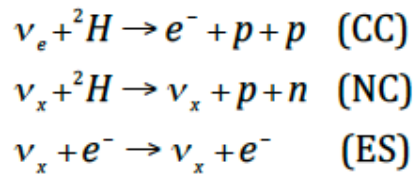
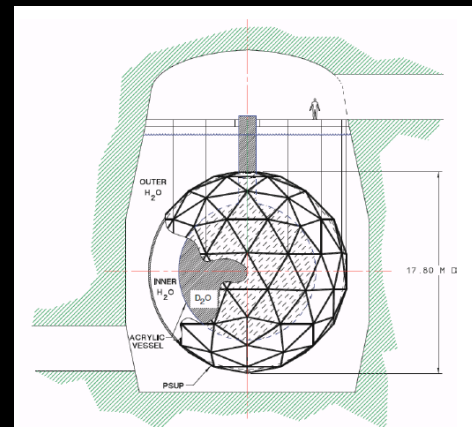


How to pin down the right solution? How to be sure the Solar Model is correct?



SNO Experiment

1000ton of ultra-pure heavy water (D_2O)
in an acrylic 12m diameter sphere



Solar electron neutrino do not oscillate
travelling from the Sun to the Earth but are
“converted” inside the Sun!

Notice that also that $\Delta m^2 > 0$

Comprehensive measurement of pp -chain solar neutrinos

The Borexino Collaboration

Nature **562**, 505–510(2018) | [Cite this article](#)

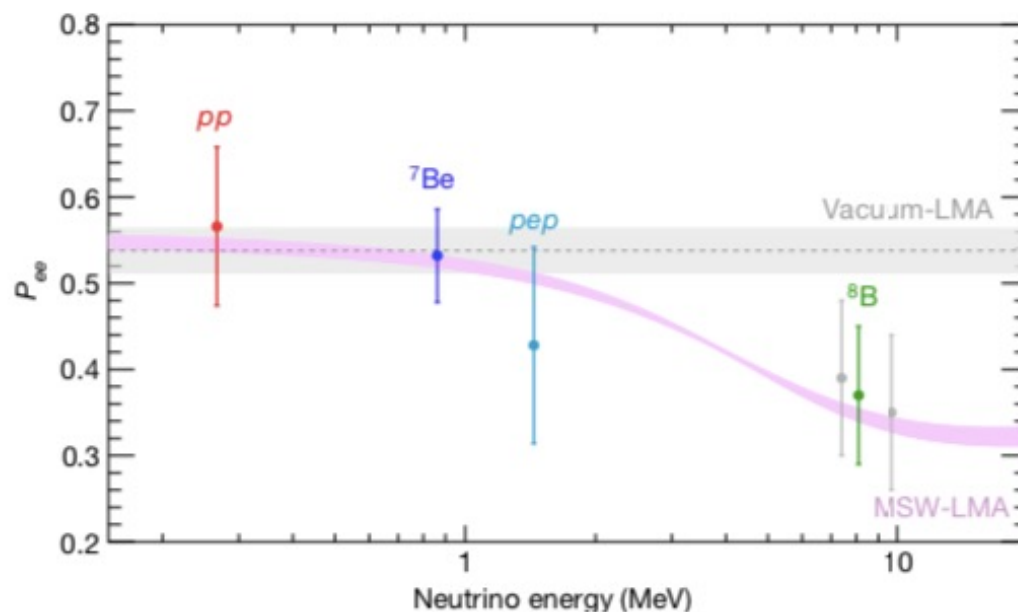


Fig. 3 | Electron neutrino survival probability P_{ee} as a function of neutrino energy. The pink band is the $\pm 1\sigma$ prediction of MSW-LMA with oscillation parameters determined from ref. ¹⁹. The grey band is the vacuum-LMA case with oscillation parameters determined from refs ^{38,39}. Data points represent the Borexino results for pp (red), ${}^7\text{Be}$ (blue), pep (cyan) and ${}^8\text{B}$ (green for the HER range, and grey for the separate HER-I and HER-II sub-ranges), assuming HZ-SSM. ${}^8\text{B}$ and pp data points are set at the mean energy of neutrinos that produce scattered electrons above the detection threshold. The error bars include experimental and theoretical uncertainties.

Matter effects in long baseline accelerator experiments

$$\left. \begin{aligned} P(\nu_\mu \rightarrow \nu_e) &= x^2 f^2 + 2xyfg(\cos \delta \cos \Delta - \sin \delta \sin \Delta) + y^2 g^2 \\ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) &= x^2 \bar{f}^2 + 2xy\bar{f}g(\cos \delta \cos \Delta + \sin \delta \sin \Delta) + y^2 g^2 \end{aligned} \right\} \Delta m_{31}^2 > 0$$

$$\left. \begin{aligned} P(\nu_\mu \rightarrow \nu_e) &= x^2 \bar{f}^2 - 2xy\bar{f}g(\cos \delta \cos \Delta + \sin \delta \sin \Delta) + y^2 g^2 \\ P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) &= x^2 f^2 - 2xyfg(\cos \delta \cos \Delta - \sin \delta \sin \Delta) + y^2 g^2 \end{aligned} \right\} \Delta m_{31}^2 < 0$$

$$\Delta = 1.27 \left| \Delta m_{31}^2 \right| \frac{L}{E}$$

$$x = 2s_{23}s_{13}c_{13}$$

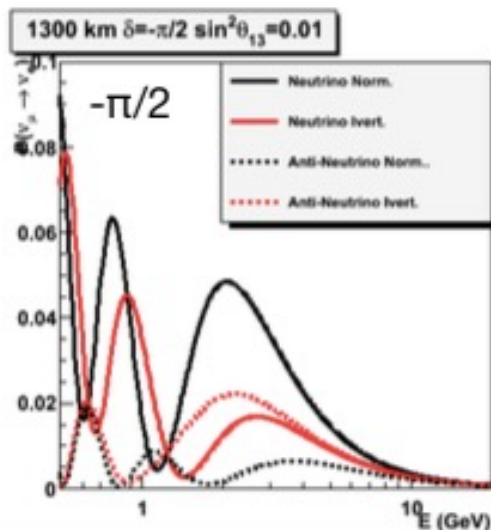
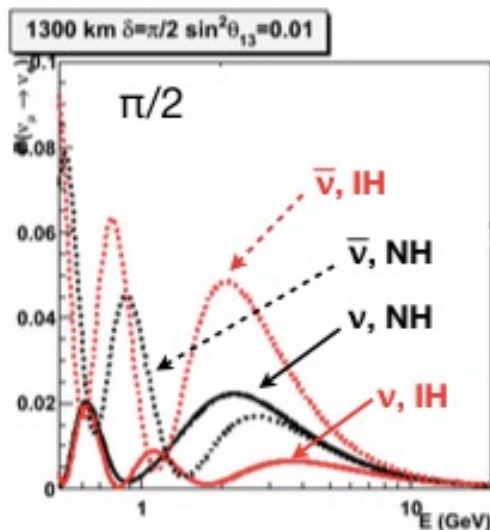
$$f, \bar{f} = \frac{\sin[(1 \mp \hat{A})\Delta]}{(1 \mp \hat{A})}$$

$$\hat{A} = |A / \Delta m_{31}^2|$$

$$y = 2\alpha \cdot c_{23}s_{12}c_{12}$$

$$g = \frac{\sin(\hat{A}\Delta)}{\hat{A}} = \Delta(\hat{A} = 0)$$

$$\alpha = |\Delta m_{21}^2 / \Delta m_{31}^2|$$



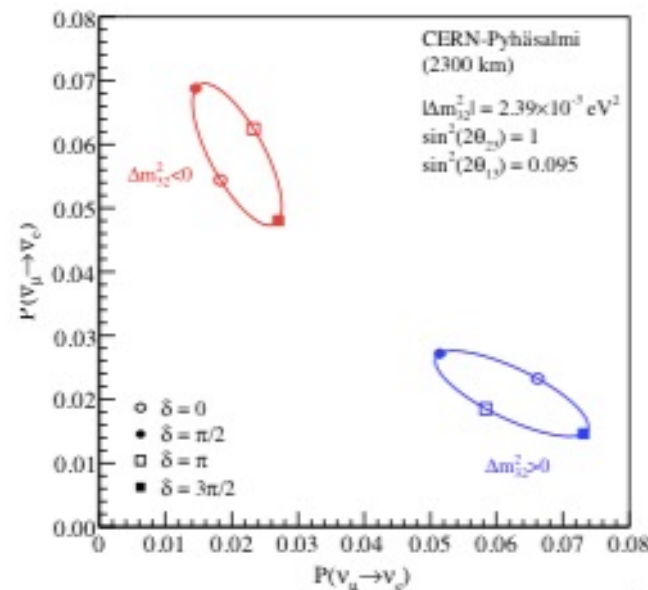
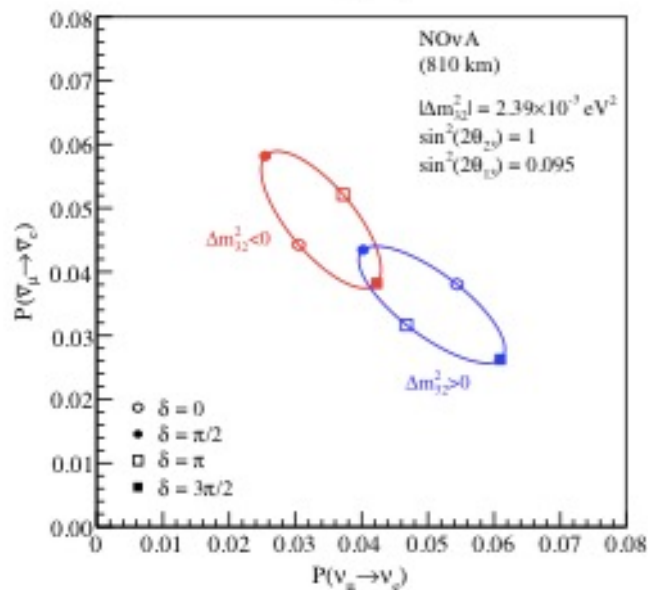
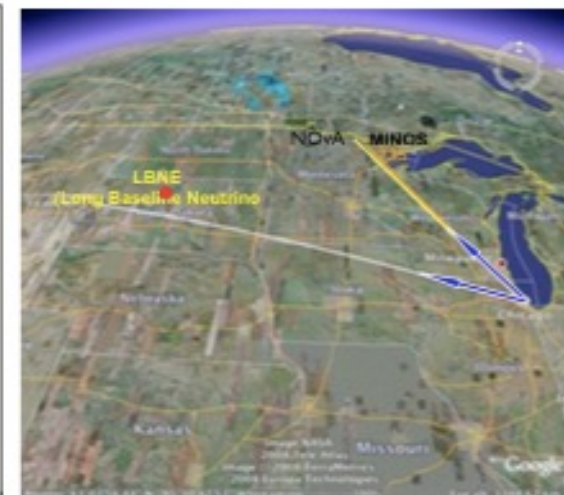
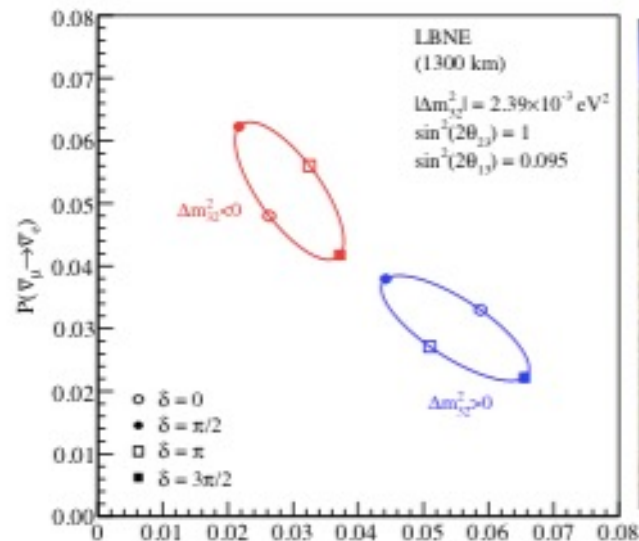
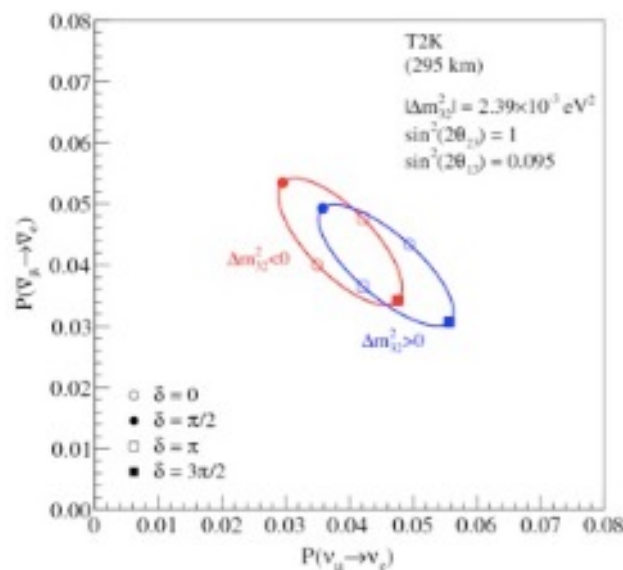
• Complicated Formula

- Interference of all oscillation parameters, in particular CP.
- Resolve the CP degeneracy by comparing appearance probability between neutrinos and antineutrinos

• Clear signal with the optimized energy and distance

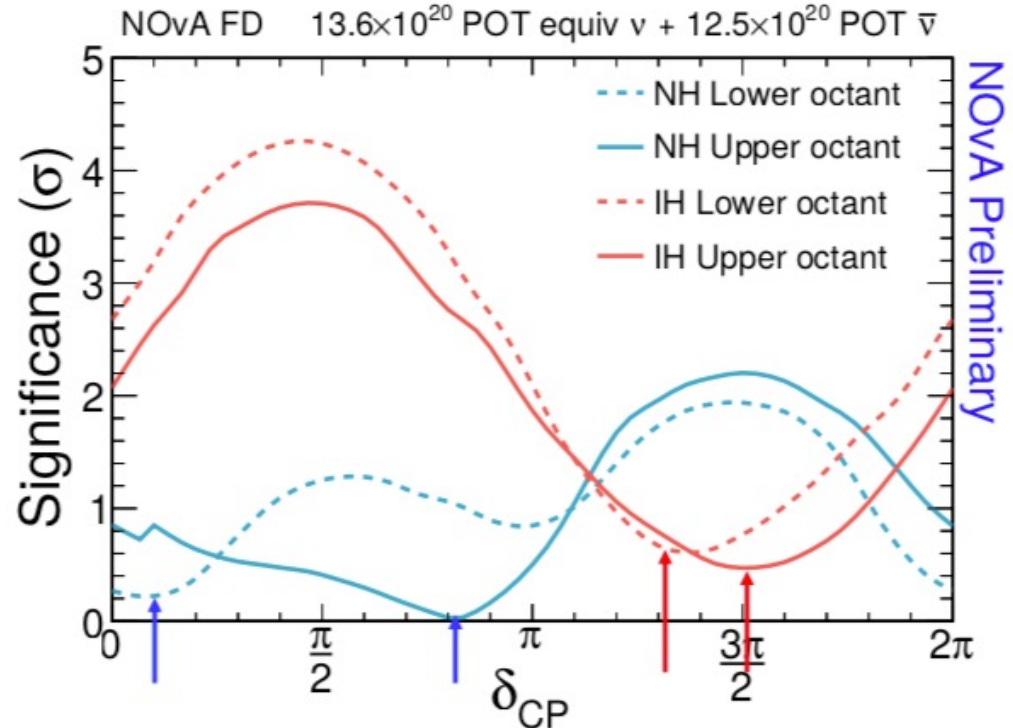
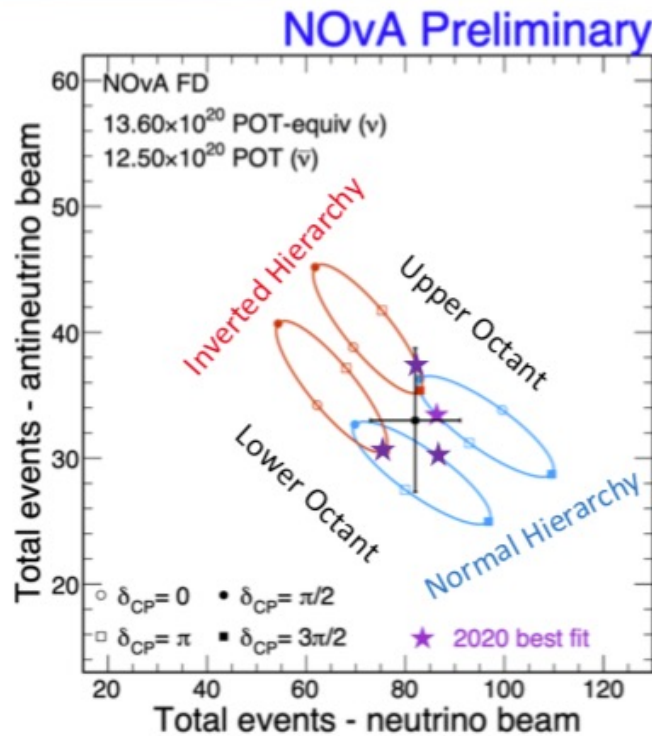
- large MH dependence through matter effect.

Long baseline experiments



NOvA experiment

28



- We see no strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$
- Disfavor hierarchy- δ combinations which would produce that asymmetry
- Consistent with hierarchy-octant- δ combinations which include some “cancellation.”
 - Since such options exist for both octants and hierarchies, results show no strong preferences.

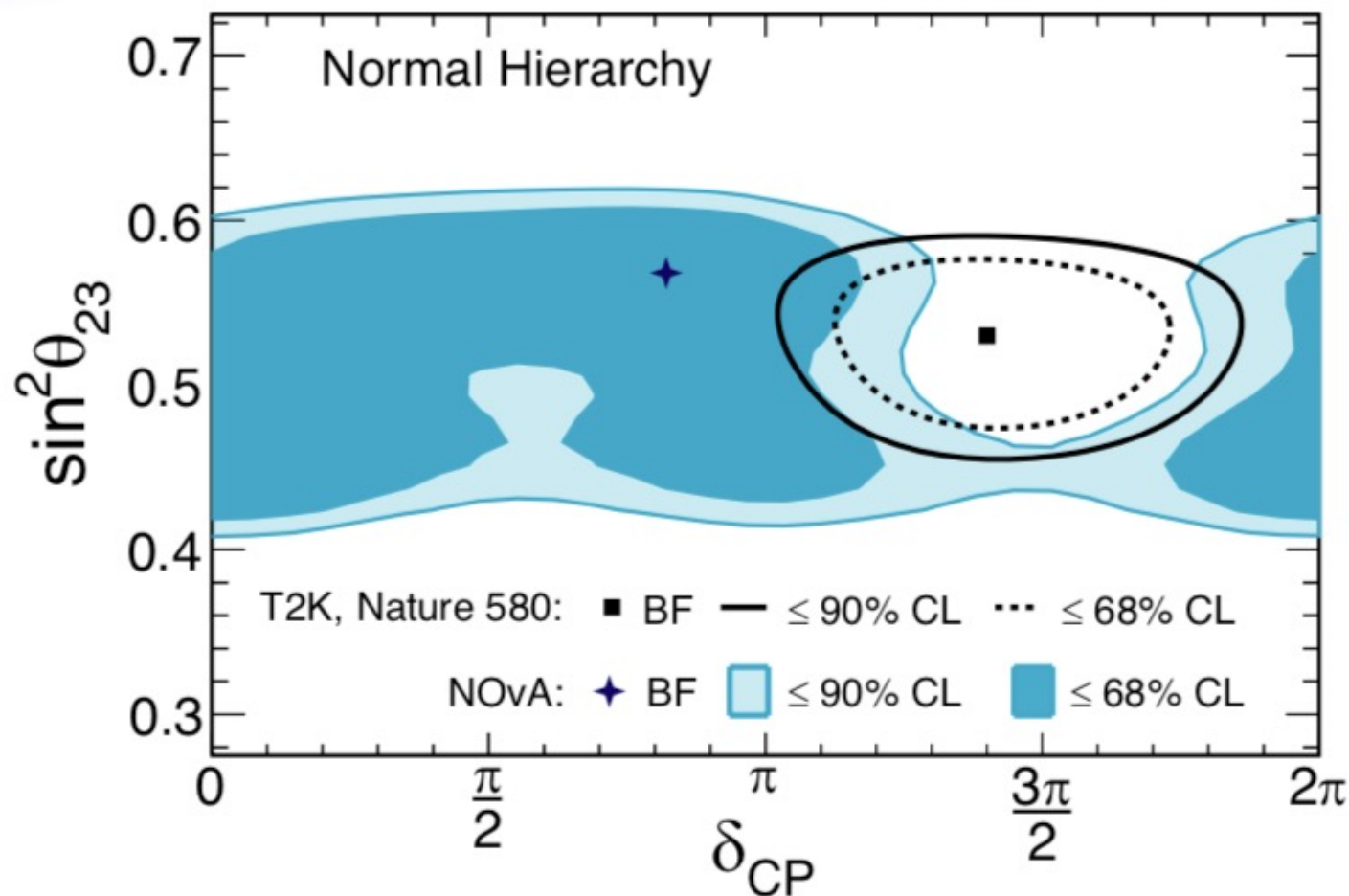
Exclude IH $\delta = \pi/2$ at $>3\sigma$
 Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$

Prefer...

Normal Hierarchy at	1.0 σ
Upper Octant at	1.2 σ

Comparison to T2K

NOvA Preliminary



- Clear tension with T2K's preferred region.
- Quantifying consistency requires a joint fit of the data from the two experiments, which is already in the works.
 - Semi-annual workshops, regular joint group meetings, and a signed joint agreement.

Neutrino mixing parameters:

$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\sigma} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\sigma} \end{pmatrix}$$

PDG :

$$\alpha_{31} = 2(\sigma - \rho)$$

$$\alpha_{21} = -2\rho$$

Atmospheric, LB

Reactors, LB
(CP violation)

Solar, Reactors

$\beta\beta 0\nu$ decay

$$c_{ij} \equiv \cos\theta_{ij}, \quad s_{ij} \equiv \sin\theta_{ij}$$

3 σ ranges (NO)

$$\theta_{12} = [31.63^\circ, 35.95^\circ]$$

$$\theta_{13} = [8.19^\circ, 8.89^\circ]$$

$$\theta_{23} = [41.3^\circ, 49.9^\circ]$$

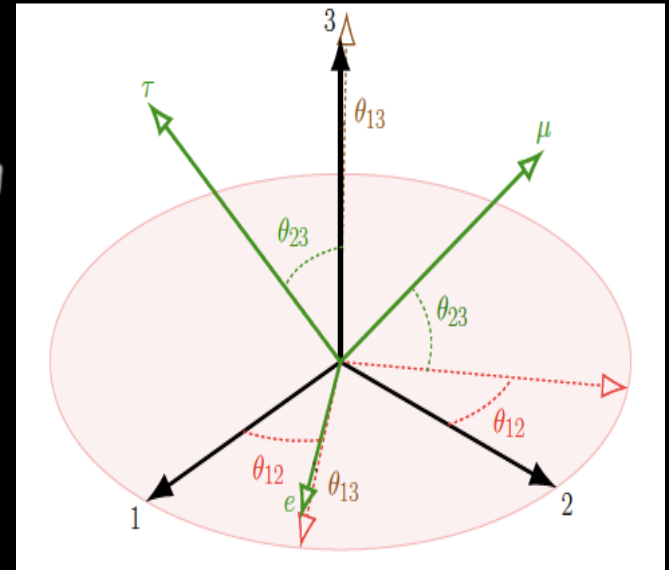
$$\delta = [-236^\circ, 4^\circ]$$

$$\rho, \sigma = [0^\circ, 360^\circ]$$

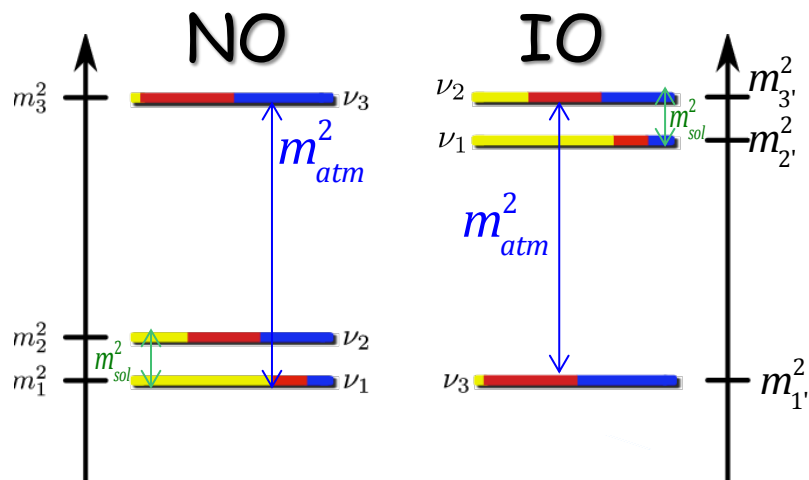
(vfit v6.1 November 2025,
with SK atm. data, including
new JUNO results)

NO favoured over IO:

$$\Delta\chi^2(\text{IO-NO}) = 9.41$$



Neutrino masses ($m_1 < m_2 < m_3$)



$$NO: m_2 = \sqrt{m_1^2 + m_{sol}^2}, \quad m_3 = \sqrt{m_1^2 + m_{atm}^2}$$

$$IO: m_2 = \sqrt{m_1^2 + m_{atm}^2 - m_{sol}^2}, \quad m_3 = \sqrt{m_1^2 + m_{atm}^2}$$

$$m_{sol} = (8.6 \pm 0.1) \text{ meV}$$

$$m_{atm} = (50.0 \pm 0.3) \text{ meV}$$

Lower bound on neutrino masses (NO)

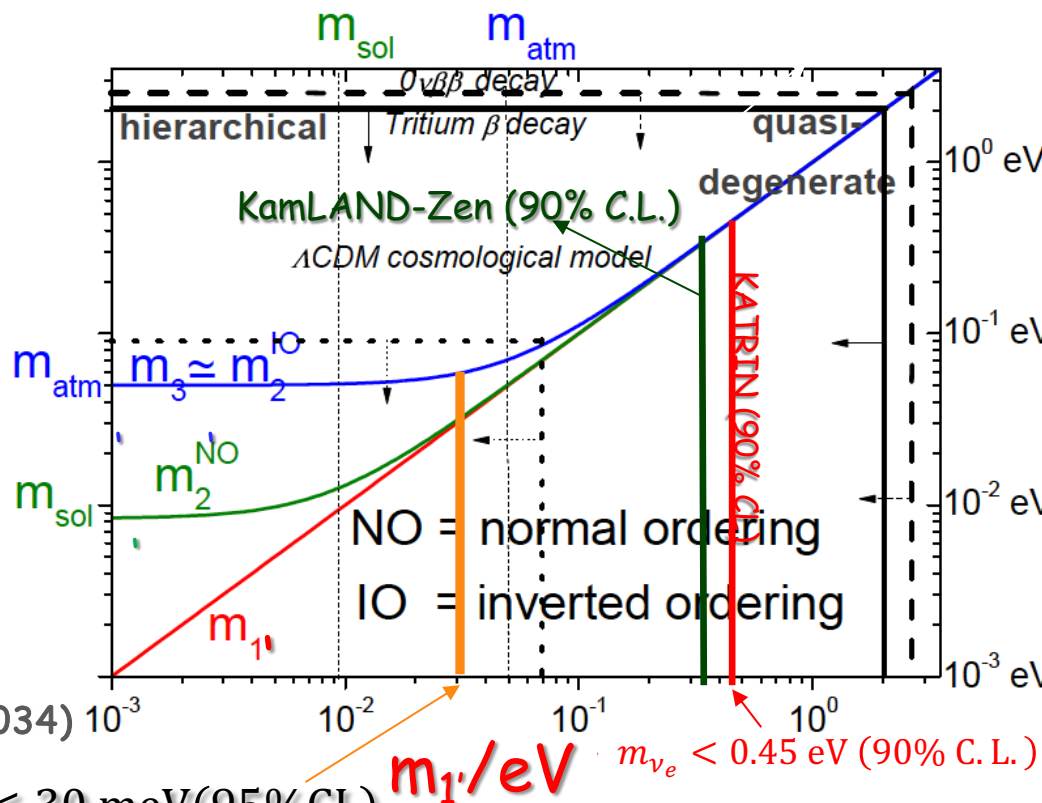
$$\Rightarrow \sum m_i \gtrsim 58 \text{ meV (95\%CL)}$$

For IO it would be much more stringent:

$$\sum m_i \gtrsim 98 \text{ meV (95\%CL)}$$

Cosmological upper bound (Planck 2023, 2309.10034)

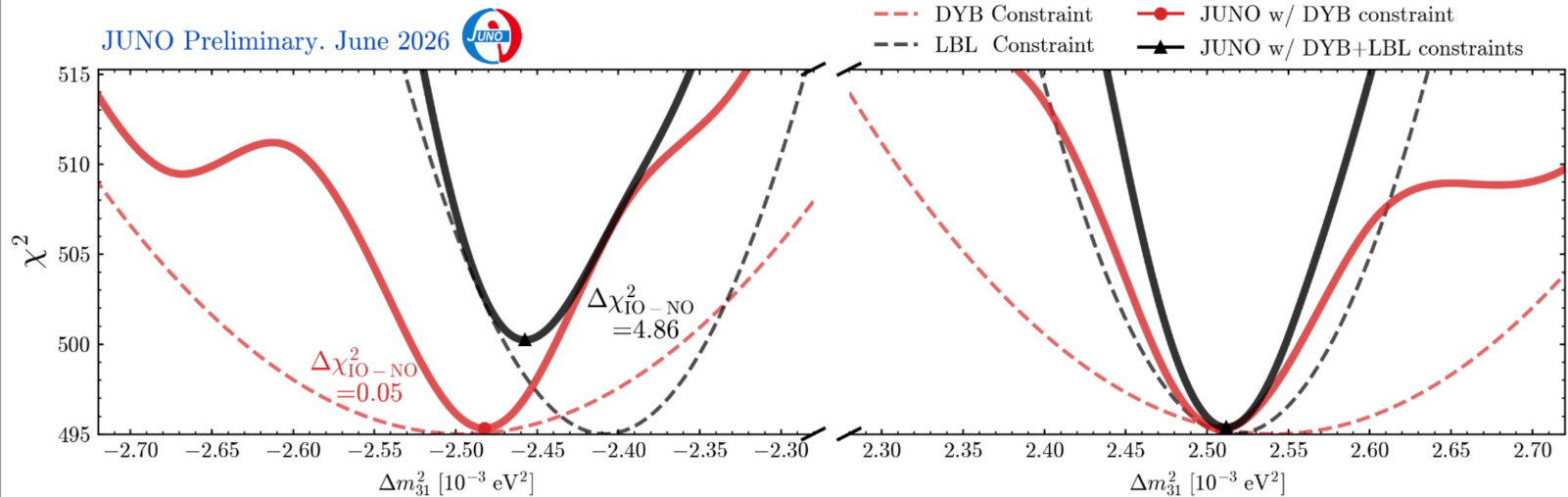
$$\sum m_i \lesssim 0.11 \text{ eV (95\%CL)} \Rightarrow \text{for NO: } m_1 < 30 \text{ meV (95\%CL)}$$



JUNO: MASS ORDERING DETERMINATION

JUNO First Measurement of Δm_{31}^2

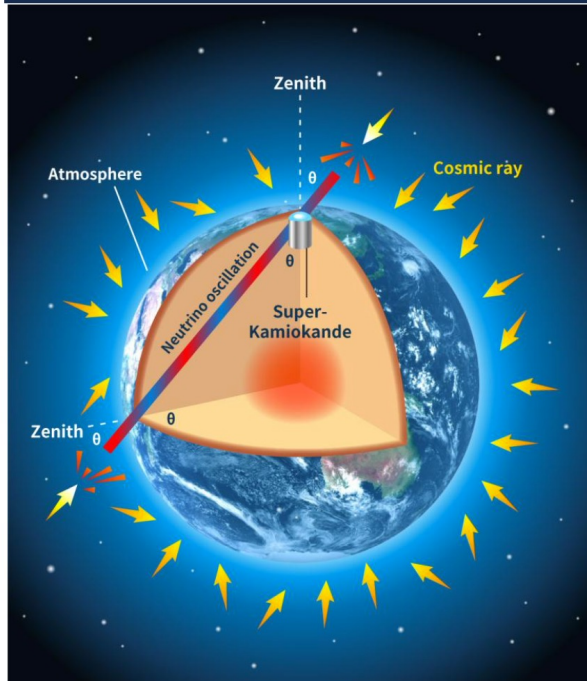
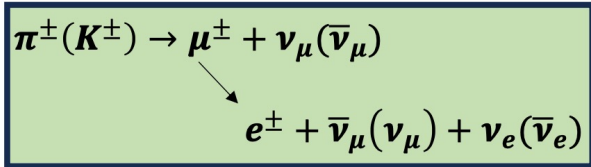
- Δm_{31}^2 from reactor and accelerator neutrinos should align at the right mass ordering [1]
- Adopt the NuFit-LBL results from [2]: normal mass ordering is favored at $\Delta\chi^2 = 4.86$



[1] H. Nunokawa, S. Parke and R.Z. Funchal, Phys. Rev. D 72 (2005) 013009; Y. F. Li et al., Phys. Rev. D 88, 013008 (2013)

[2] NuFIT 6.0 (JHEP 12 (2024) 216 [arXiv:2410.05380]), www.nu-fit.org and M. Maltoni private communication

Atmospheric Neutrinos

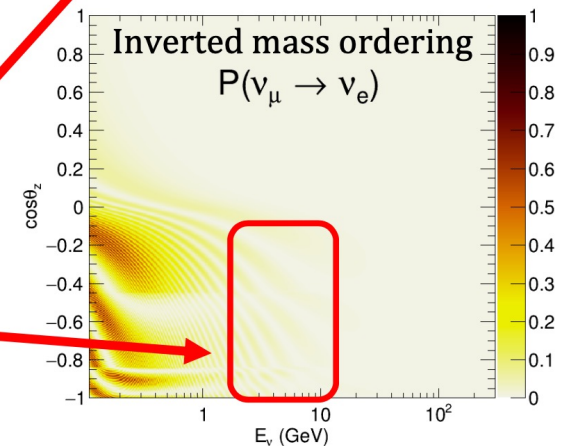
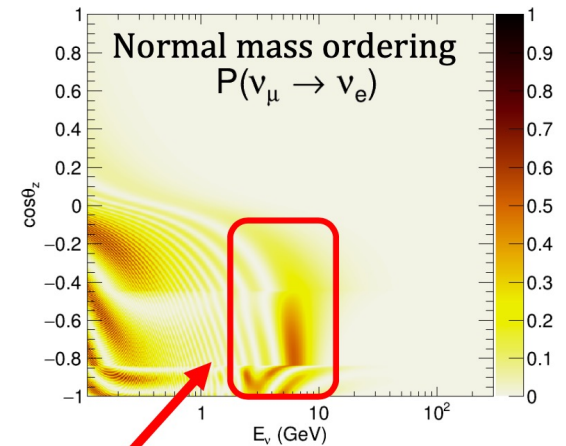


From cosmic-ray interactions in atmosphere

- Baseline: 10 km - 13,000 km
 - Energy: MeV - TeV
- Detected via charged-current interactions

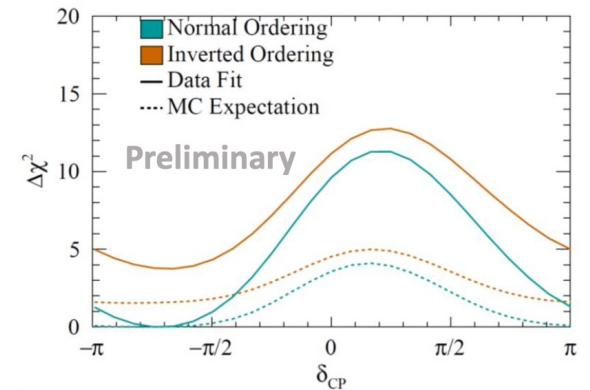
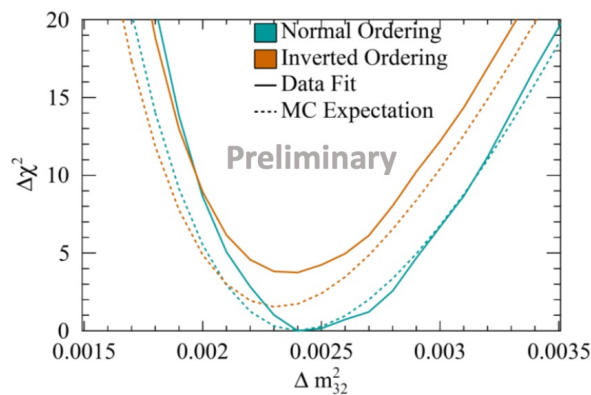
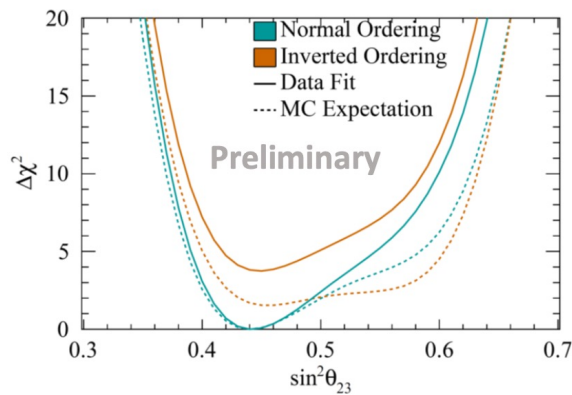
Oscillation measurements:

- ν_μ disappearance
 - Δm_{32}^2
 - $\sin^2 \theta_{23}$
- ν_e appearance
 - Mass-ordering
 - CP phase δ



SK I-VI Oscillation Parameter Measurement

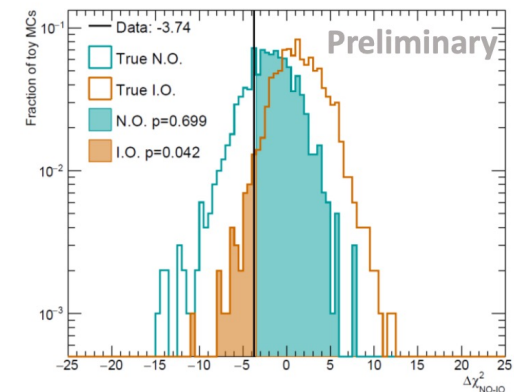
Poster by Ben Jargowsky, #225



	Previous study (SK I-V)	This study (SK I-VI)
$\sin^2 \theta_{32}$	0.45	0.44
$\Delta m_{32}^2 [10^{-3} \text{ eV}^2]$	2.40	2.40
$\Delta \chi_{IO-NO}^2$	5.69	3.69
δ_{CP}	$-\pi/2$	$-3\pi/4$

- Favors **lower octant** at $\sim 1\sigma$
- Smaller $\sin^2 \theta_{32}$ results in less sensitivity to mass ordering
- Roughly same δ_{CP} allowed region
- Favors **normal ordering**

Toy experiments show a **rejection of inverted ordering at $86\% \approx 1.08\sigma$** (CL_s method)



* $\sin^2 \theta_{13}$ prior: 0.0220 ± 0.0007

**Results of MO and δ_{CP} exceed sensitivity

L/E Oscillation Measurement

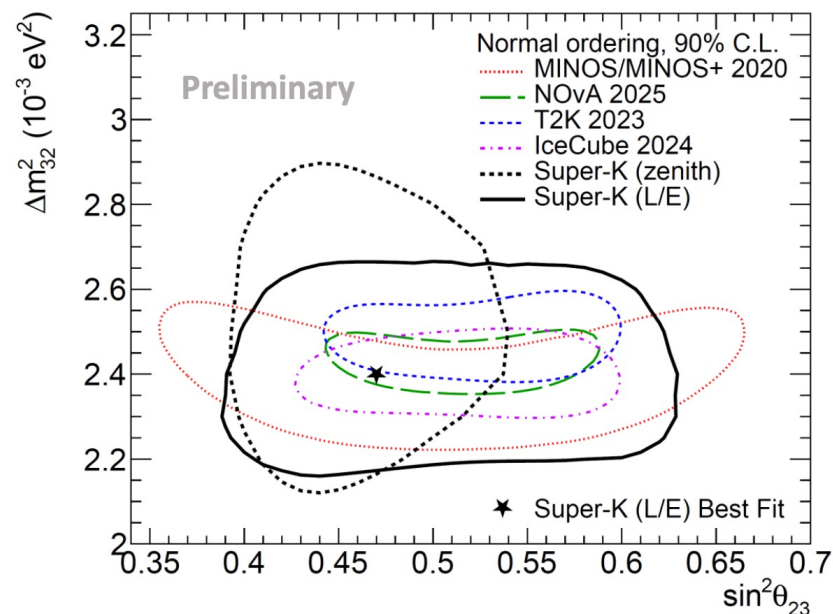
Poster by Mariusz Girgus, #230

Update from 2024 results:

- Introduced a **new BDT classifier to separate partially contained (PC) stopping/through-going events**
- **Increased high resolution PC events by 10%** in the oscillation region $((L/E)_{\text{rec}} > 100 \text{ km/GeV})$

L/E analysis sets a stronger constraint on Δm_{32}^2

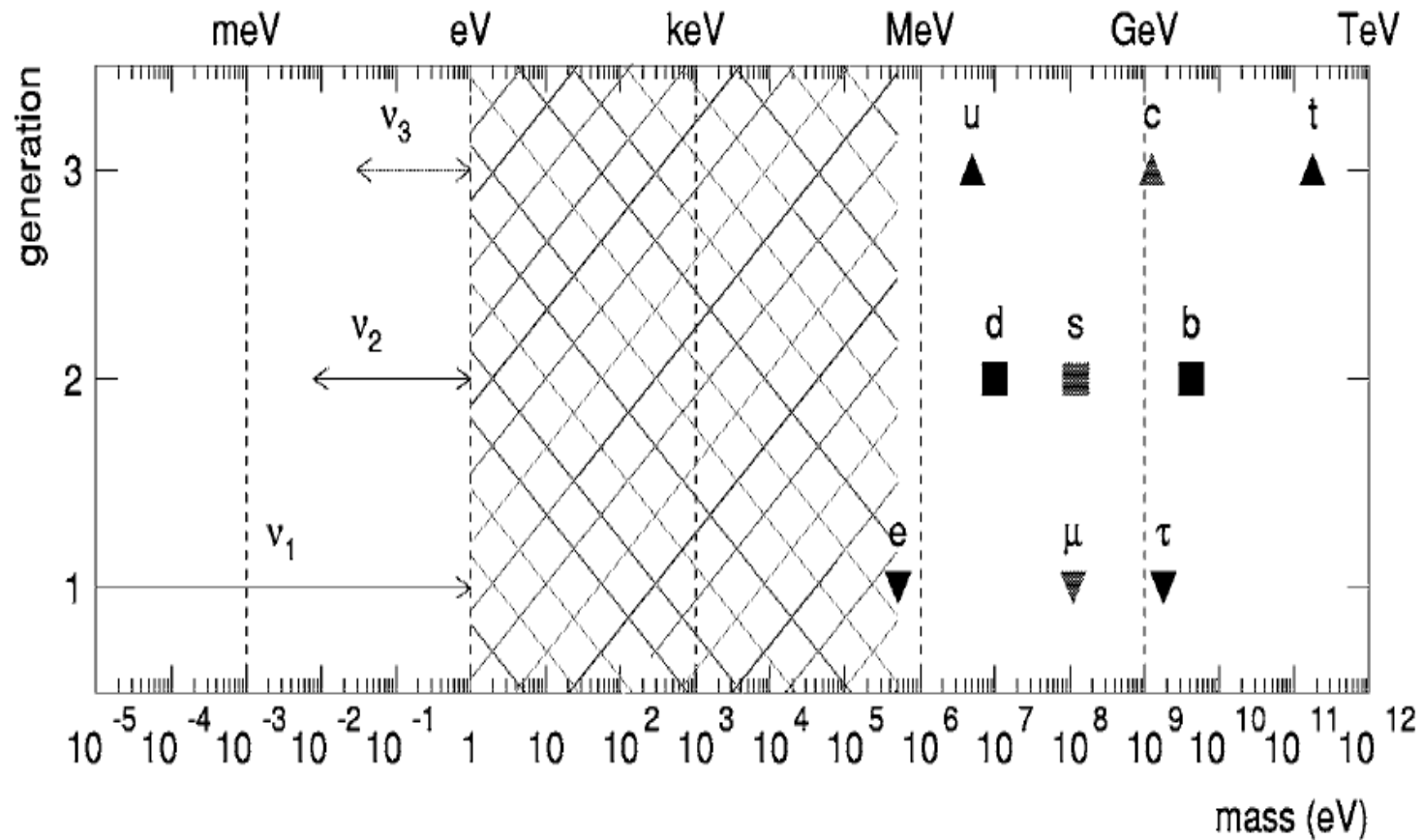
- high resolution sample **preserves the oscillatory pattern** that would otherwise be averaged out in zenith-angle analysis
- lose power to determine θ_{23} octant because ν_e samples are not included



L/E data fit contour assuming NO, in comparison with zenith angle data fit, and other experimental results

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 1.5$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
IC23 without SK atmospheric data	$\sin^2 \theta_{12}$	$0.3088^{+0.0067}_{-0.0066}$	$0.2893 \rightarrow 0.3295$	$0.3088^{+0.0067}_{-0.0066}$	$0.2893 \rightarrow 0.3295$
	$\theta_{12}/^\circ$	$33.76^{+0.42}_{-0.41}$	$32.54 \rightarrow 35.03$	$33.76^{+0.42}_{-0.41}$	$32.54 \rightarrow 35.03$
	$\sin^2 \theta_{23}$	$0.470^{+0.017}_{-0.014}$	$0.432 \rightarrow 0.587$	$0.555^{+0.013}_{-0.016}$	$0.437 \rightarrow 0.590$
	$\theta_{23}/^\circ$	$43.27^{+1.0}_{-0.82}$	$41.11 \rightarrow 50.02$	$48.15^{+0.75}_{-0.92}$	$41.40 \rightarrow 50.21$
	$\sin^2 \theta_{13}$	$0.02249^{+0.00057}_{-0.00057}$	$0.02070 \rightarrow 0.02420$	$0.02261^{+0.00056}_{-0.00056}$	$0.02091 \rightarrow 0.02433$
	$\theta_{13}/^\circ$	$8.62^{+0.11}_{-0.11}$	$8.27 \rightarrow 8.95$	$8.65^{+0.11}_{-0.11}$	$8.31 \rightarrow 8.97$
	$\delta_{\text{CP}}/^\circ$	207^{+23}_{-20}	$114 \rightarrow 405$	283^{+24}_{-28}	$202 \rightarrow 347$
	$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.537^{+0.094}_{-0.10}$	$7.236 \rightarrow 7.823$	$7.537^{+0.094}_{-0.10}$	$7.236 \rightarrow 7.822$
	$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.521^{+0.026}_{-0.018}$	$+2.454 \rightarrow +2.592$	$-2.500^{+0.024}_{-0.023}$	$-2.569 \rightarrow -2.430$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 5.9$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
IC24 with SK atmospheric data	$\sin^2 \theta_{12}$	$0.3088^{+0.0067}_{-0.0066}$	$0.2893 \rightarrow 0.3295$	$0.3088^{+0.0067}_{-0.0066}$	$0.2893 \rightarrow 0.3295$
	$\theta_{12}/^\circ$	$33.76^{+0.42}_{-0.41}$	$32.54 \rightarrow 35.03$	$33.76^{+0.42}_{-0.41}$	$32.54 \rightarrow 35.03$
	$\sin^2 \theta_{23}$	$0.470^{+0.017}_{-0.014}$	$0.435 \rightarrow 0.584$	$0.550^{+0.013}_{-0.016}$	$0.439 \rightarrow 0.584$
	$\theta_{23}/^\circ$	$43.29^{+0.96}_{-0.79}$	$41.27 \rightarrow 49.86$	$47.90^{+0.73}_{-0.92}$	$41.51 \rightarrow 49.83$
	$\sin^2 \theta_{13}$	$0.02248^{+0.00055}_{-0.00059}$	$0.02064 \rightarrow 0.02418$	$0.02262^{+0.00057}_{-0.00056}$	$0.02093 \rightarrow 0.02441$
	$\theta_{13}/^\circ$	$8.62^{+0.11}_{-0.11}$	$8.26 \rightarrow 8.95$	$8.65^{+0.11}_{-0.11}$	$8.32 \rightarrow 8.99$
	$\delta_{\text{CP}}/^\circ$	212^{+26}_{-36}	$125 \rightarrow 365$	274^{+22}_{-25}	$203 \rightarrow 335$
	$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.537^{+0.094}_{-0.10}$	$7.236 \rightarrow 7.823$	$7.537^{+0.094}_{-0.10}$	$7.236 \rightarrow 7.822$
	$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.511^{+0.021}_{-0.020}$	$+2.450 \rightarrow +2.576$	$-2.483^{+0.020}_{-0.020}$	$-2.547 \rightarrow -2.421$

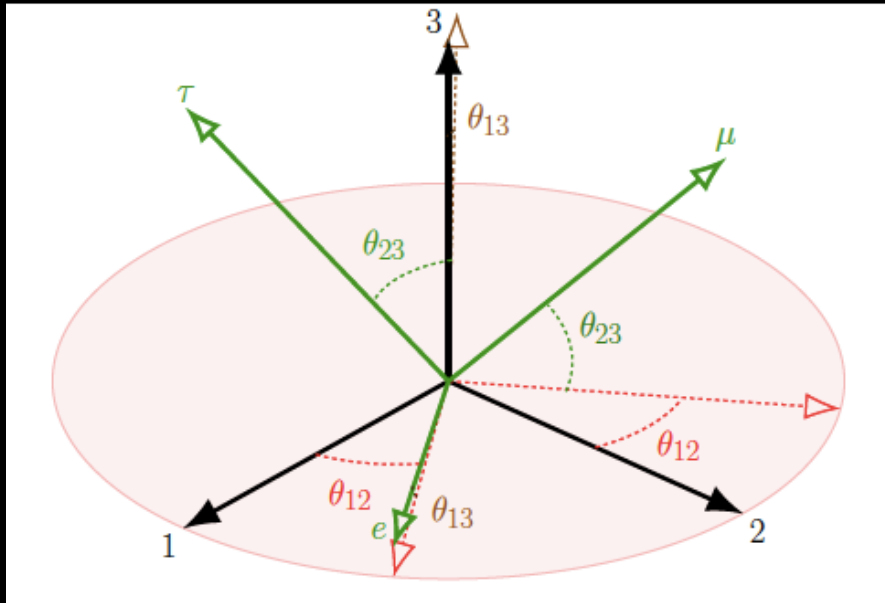
1) much lighter than all other fermions:



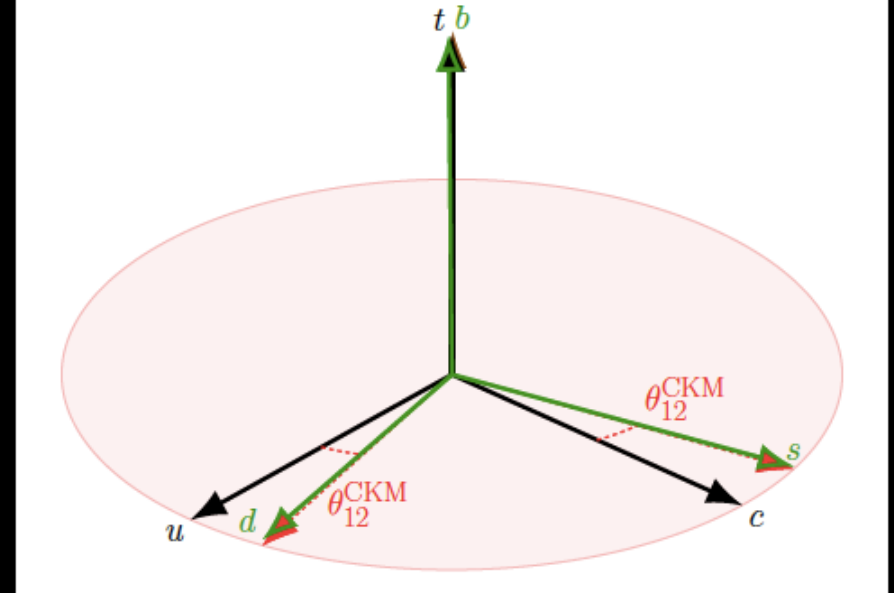
2) neutral $\Rightarrow$ Majorana mass terms are possible

Leptonic mixing angles are much larger than quark mixing angles

lepton flavour space



quark flavour space

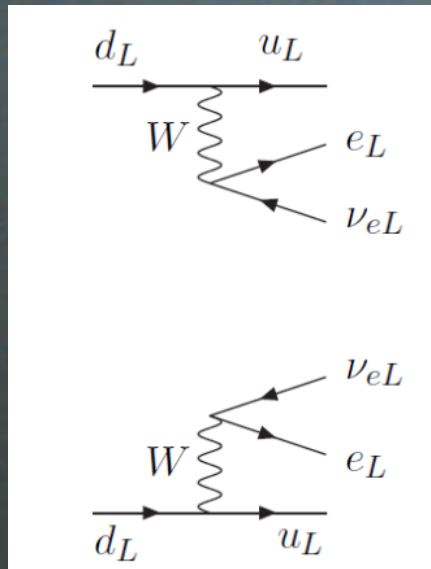


- Cosmological puzzles?
- Why not a Majorana mass term as well?

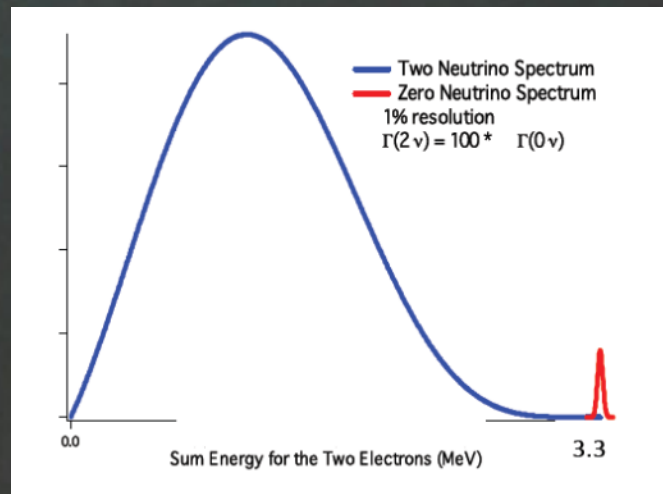
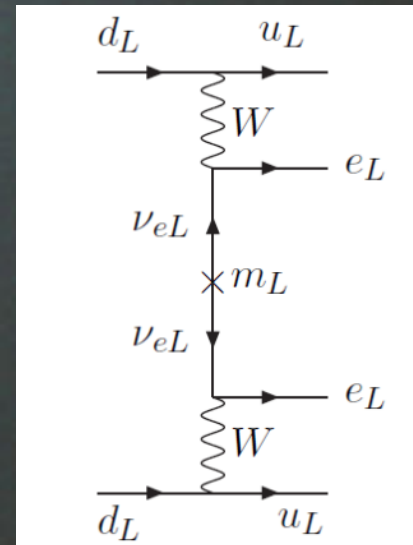
Neutrinoless double beta decay

Double beta decay

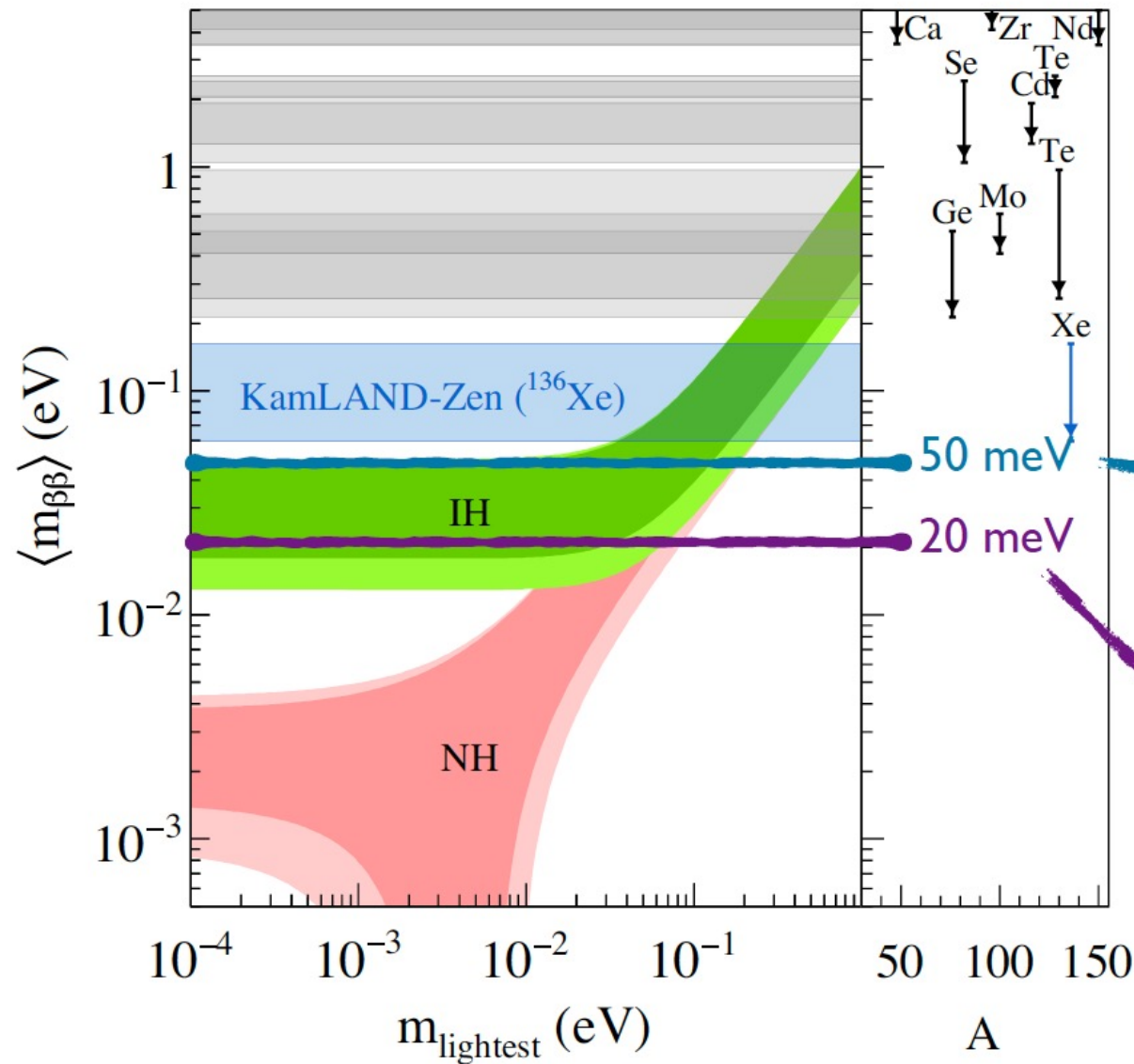
$2\beta 2\nu$ decay



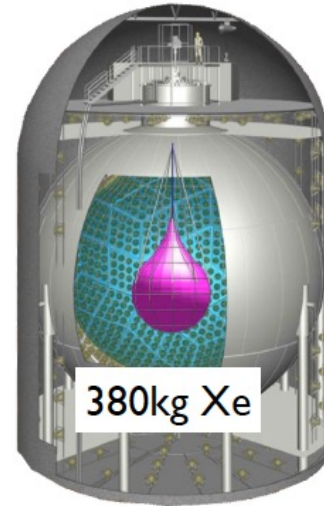
$2\beta 0\nu$ decay



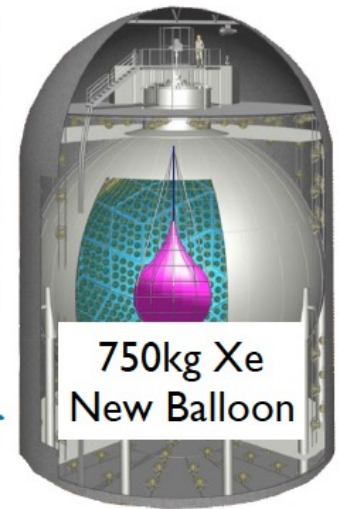
Future Goals



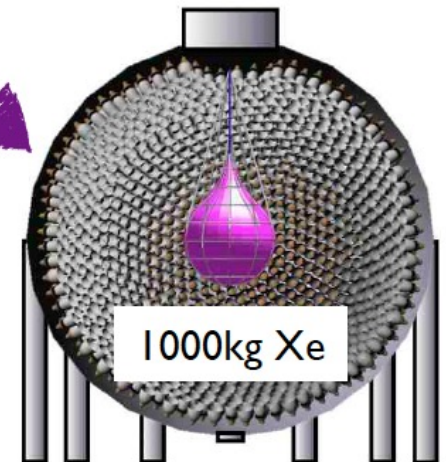
KamLAND-Zen 400



KamLAND-Zen 800



KamLAND2-Zen



Neutrino Astronomy

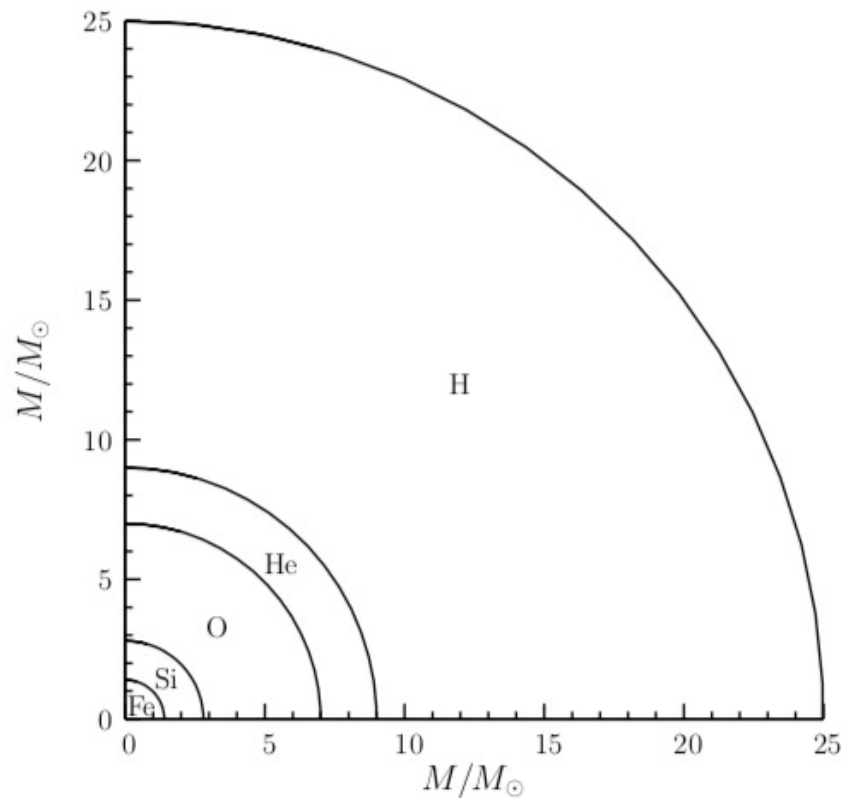


FIG. 15.6. Onion-like interior structure of a Population I star of $25 M_{\odot}$ just before the onset of collapse (see Ref. [1025]). Fe represents assorted iron-peak elements: ^{48}Ca , ^{50}Ti , ^{54}Fe , ^{56}Fe , ^{58}Fe , ^{66}Ni . The Si shell contains less abundant amounts of S, O, Ar, Ca, the O shell contains less abundant amounts of Ne, C, Mg, Si, the He shell contains less abundant amounts of C, Ne, O, and the H shell contains less abundant amounts of He, Ne, O, N, C.

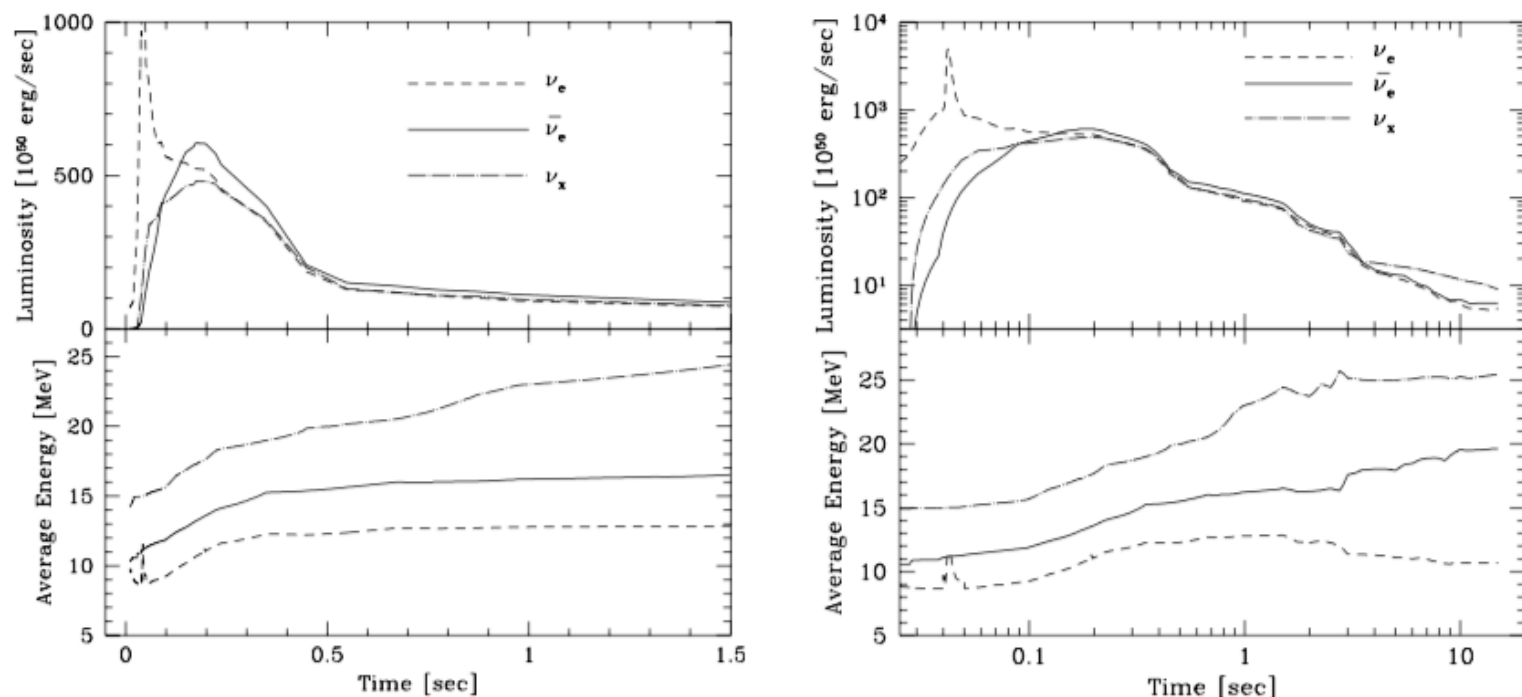


FIG. 15.7. Time evolution of neutrino luminosity and average energy obtained with the numerical SN model in Ref. [1021]. The time starts at the onset of collapse. The left panel shows the early phase in a linear time coordinate. The right panel shows the time evolution until about 10 s after the onset of collapse using a logarithmic time coordinate. The dashed lines are for ν_e , the solid lines for $\bar{\nu}_e$, and the dot-dashed lines for $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$, which are collectively denoted by ν_x . The neutronization burst is visible as a peak of luminosity and energy of electron neutrinos, which happens 40–50 msec after the onset of collapse.

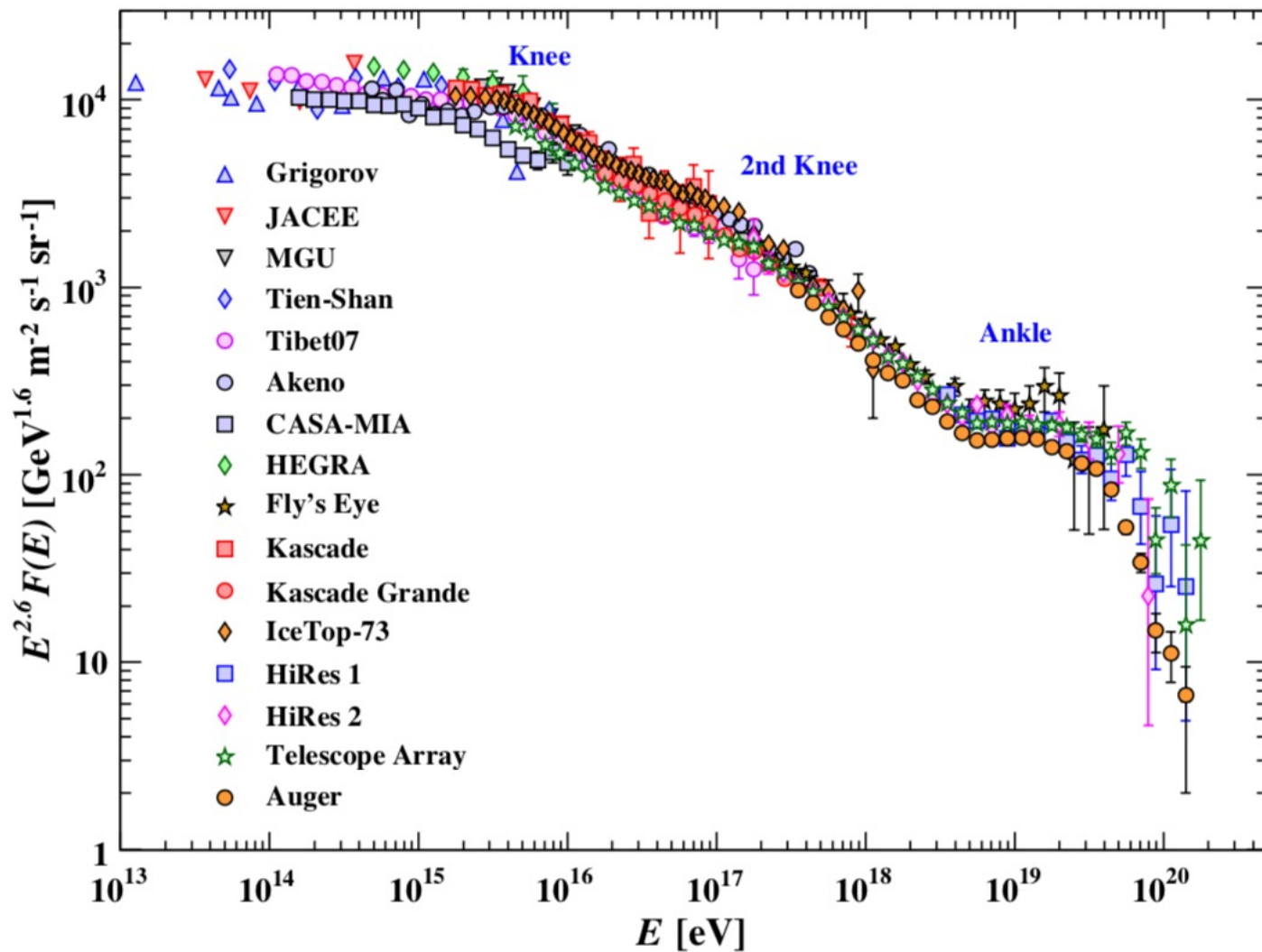


Figure 29.8: The all-particle spectrum as a function of E (energy-per-nucleus) from air shower measurements [91–106].

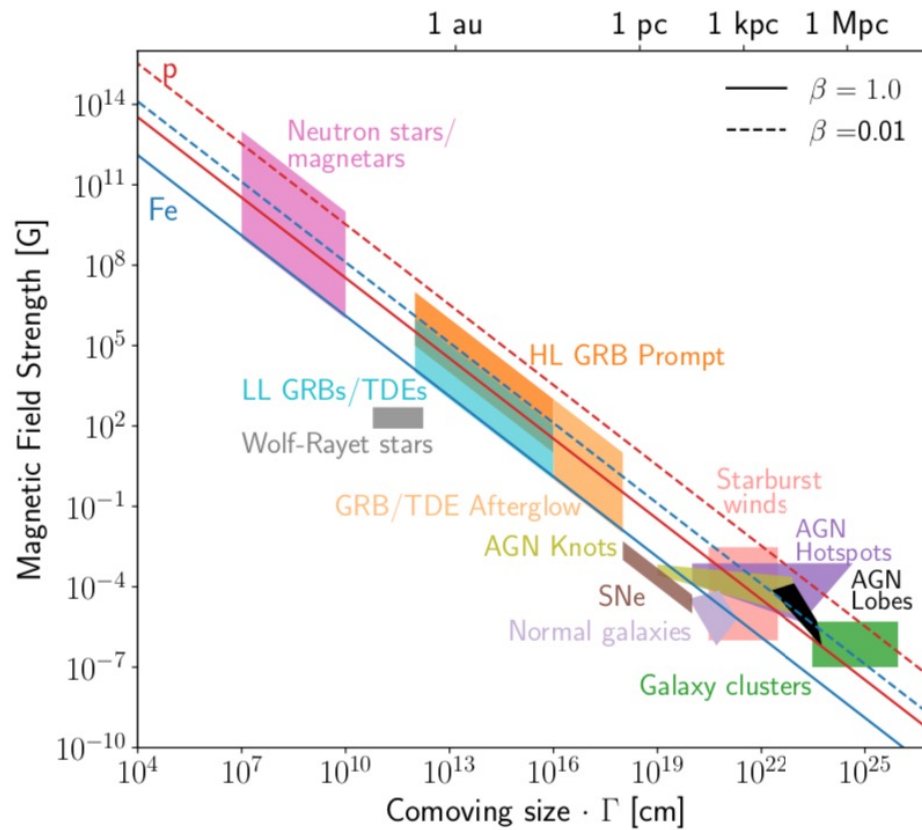


Figure 10. Hillas diagram. Source classes are shown as function of their characteristic size, R , and magnetic field strength, B , in the ideal, Bohm limit, where $\eta = 1$. Quoted values of B are in the comoving frame of the source. The abscissa gives R , the radius from the engine, which is equal to comoving size of the source times the Lorentz factor of the flow, Γ . Solid (dashed) lines indicate the BR product beyond which confinement of protons (red) and iron (blue) nuclei with energy 10^{20} eV are possible for outflows with velocity, $\beta_{\text{sh}} = 1$ ($\beta_{\text{sh}} = 0.01$). Inferred values of B and R for low-luminosity gamma-ray bursts (LL GRBs) and high-luminosity GRBs (HL GRBs) are from [128, 129]. For tidal disruption events they are based on the prototypical jetted-TDE Swift J1644+57 [130–132], for starburst galaxies and normal galaxies they were estimated in [133]. Inferred values of B and R for AGN lobes, hotspots, and knots, were presented in [134] and summarized in [127]. For galaxy clusters, we used the inferred value range from [127]. Inferred B and R values for supernovae were collected from [135–137] and for Wolf-Rayet stars from [138]. For neutron stars and magnetars the quoted values of B , and R correspond to the expected UHECR acceleration sites in [139–141]. *F. Oikonomou and K. Murase for this review.*

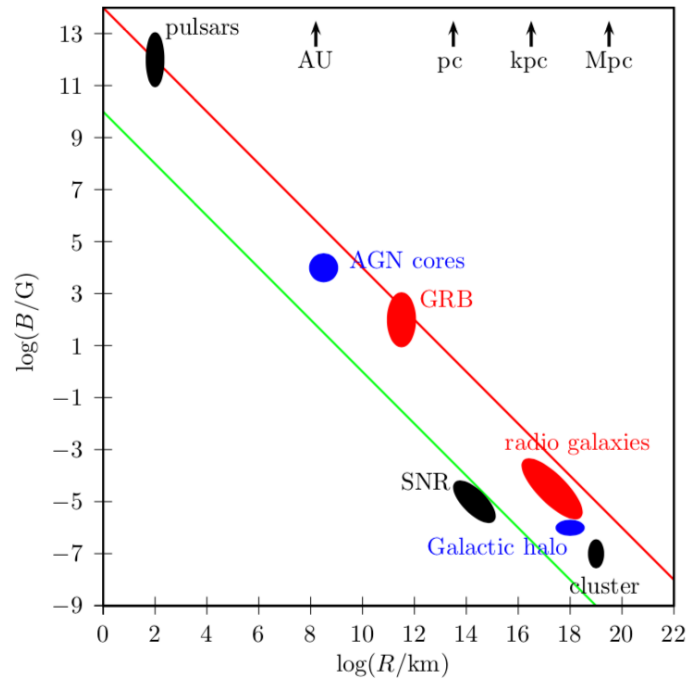
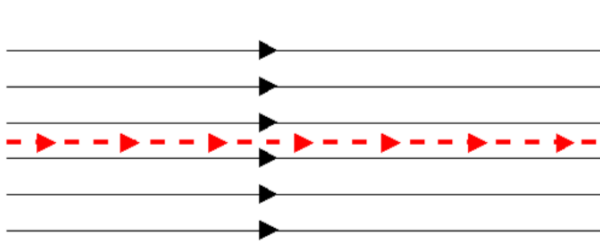
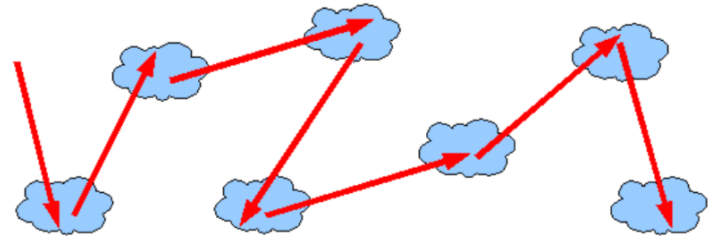


Fig. 2: Hillas plot. Sources above the top (red) line are able to accelerate protons up to 10^{21} eV, while sources above the bottom (green) line are able to accelerate iron up to 10^{20} eV. Figure reproduced from Ref. [12]

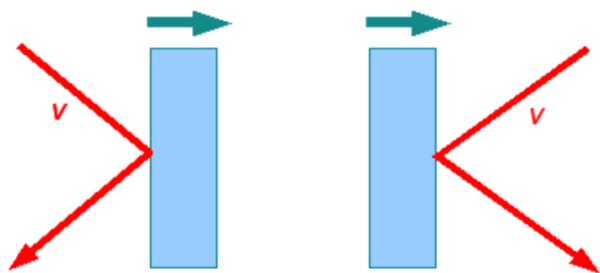


(a)



(b)

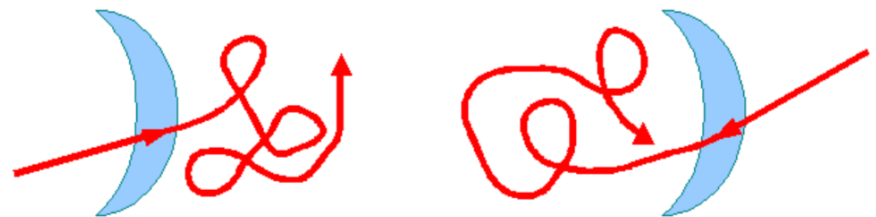
Fig. 4: (a) One-shot acceleration. (b) Diffusive shock acceleration



following
collision

head-on
collision

(a)



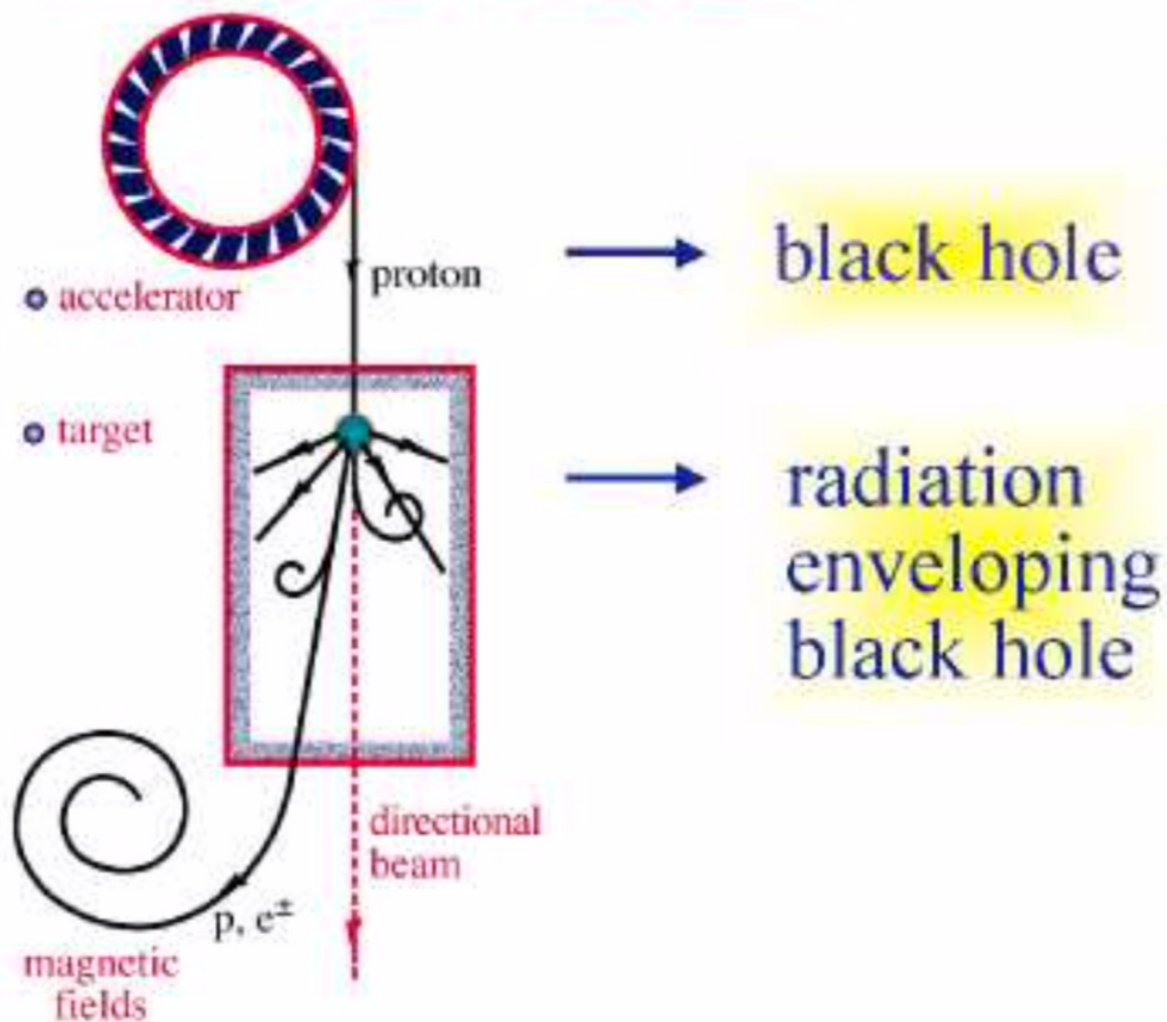
downstream → upstream

downstream ← upstream

(b)

Fig. 5: (a) Second-order Fermi acceleration. (b) First-order Fermi acceleration.

NEUTRINO BEAMS: HEAVEN & EARTH



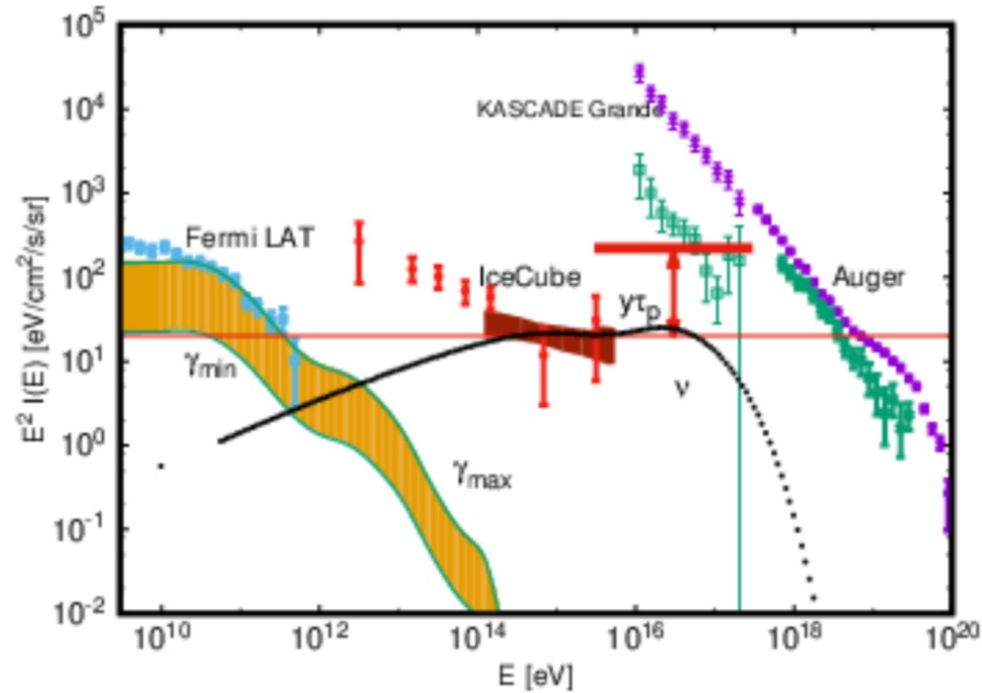


Figure 6: Expected secondary photon and neutrino fluxes from UHECR sources compared to the EGRB measured by Fermi-LAT, diffuse neutrino flux by IceCube and the all-particle and proton fluxes by KASCADE Grande and PAO. The neutrino flux example shown as thin dotted line is from Ref. [13]; adapted from Ref. [36].

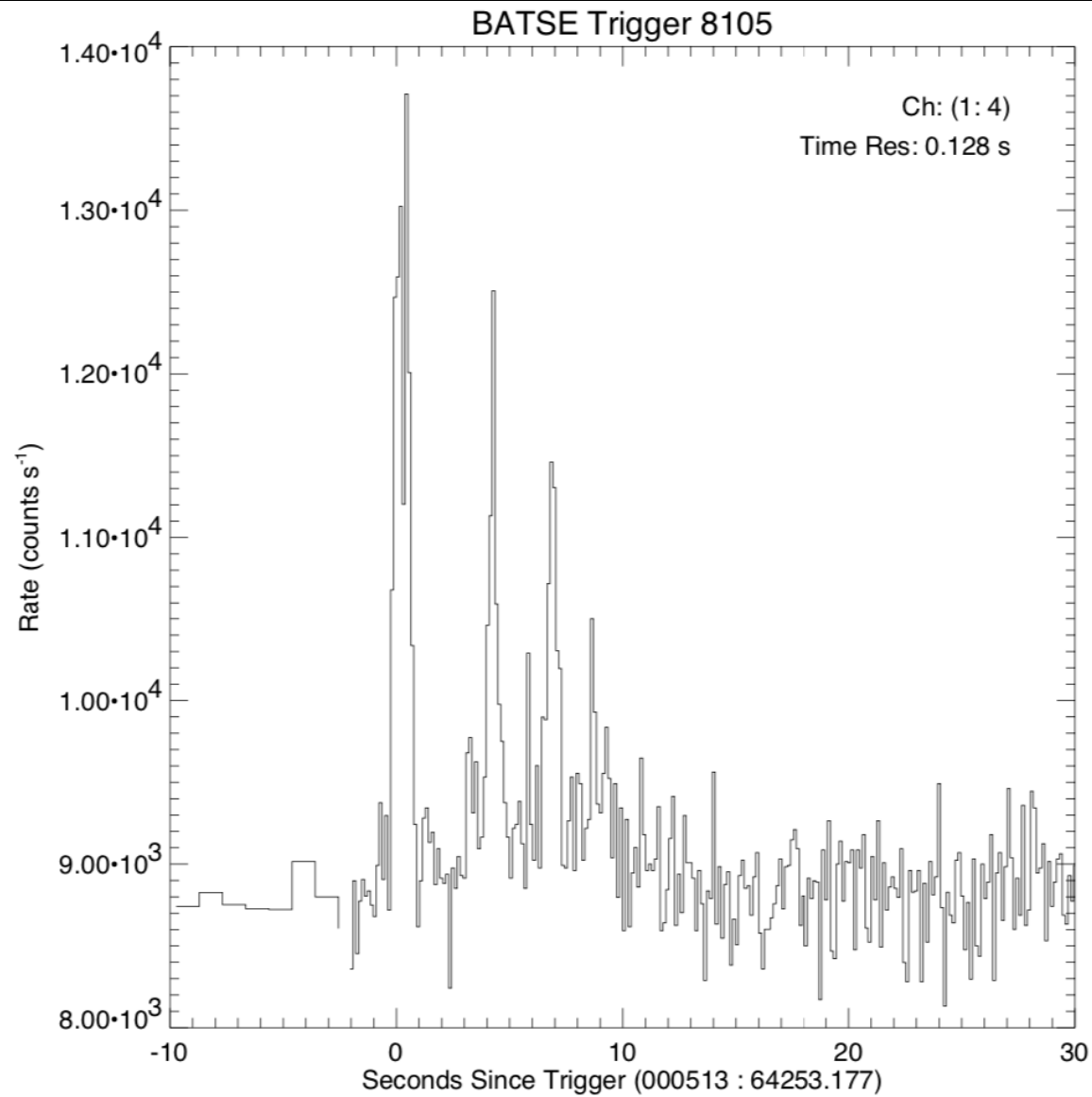


FIG. 16: An example of the temporal structure of a GRB as recorded by BATSE [145]. Note the two time scales: a duration of several seconds and a fluctuation time scale of a fraction of a second.

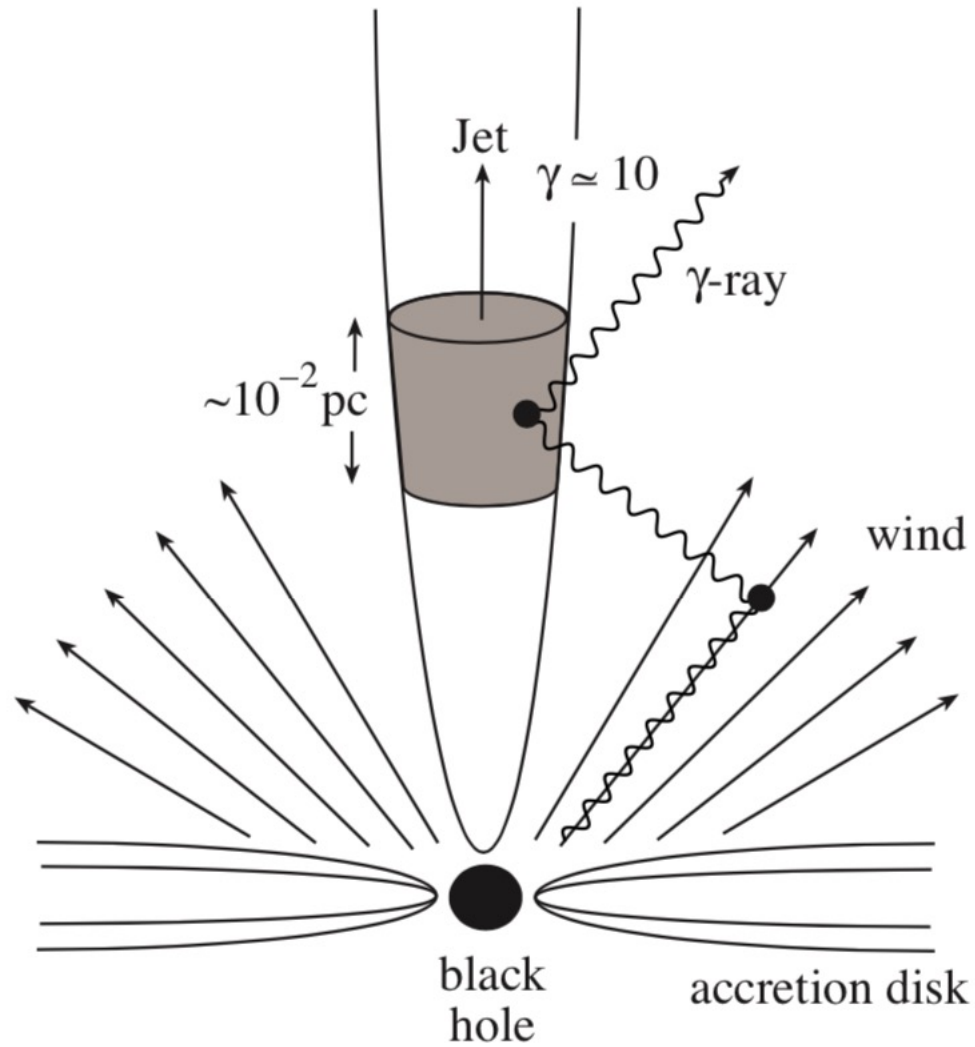


FIG. 18: Diagram of Blazar Kinematics

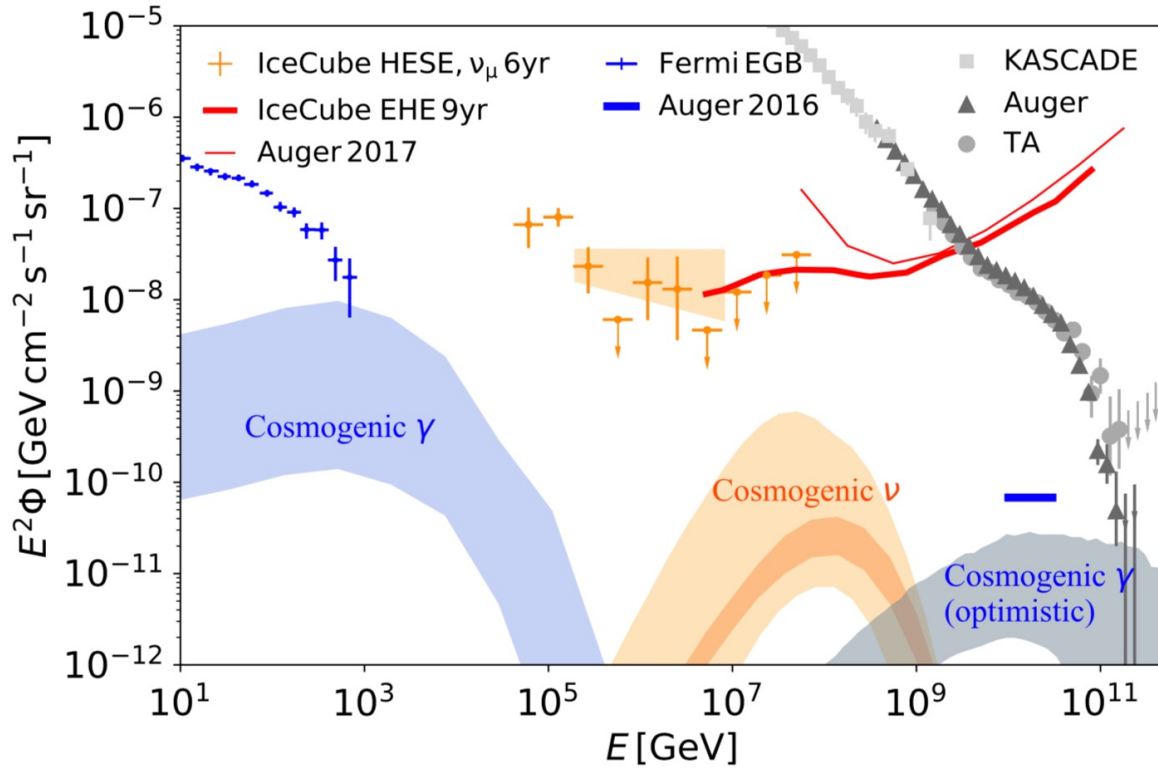


Figure 6. *Left:* Cosmogenic photon (blue) and neutrino (orange) fluxes for models that fit the Auger data including spectrum and composition [65]. Specifically, the dark orange band corresponds to a best-fit model with 99% CL, and the light orange band covers the AGN, star-formation rate (SFR), and gamma-ray burst (GRB) models for fits at 90% CL [65]. In more optimistic models that assume a larger maximum energy $R_{\text{max}} \sim 10^{20.5}$ eV, a second photon bump appears at 1-10 EeV as indicated by the grey shaded area [74]. In comparison, we show the fluxes of the six-year high-energy starting events (HESE, orange data points) [76], six-year muon neutrino events (orange shaded region)[77], nine-year extreme-high-energy (EHE) 90% upper limit [71] measured by IceCube (thick red curve), and the 90% upper limit provided by Auger with data from 1 Jan 04 - 31 Mar 17 (thin red curve, [72]), as well as the extragalactic gamma-ray background observed by *Fermi*-LAT [80, 84], and the differential limit of UHE photons in the bin of 10-30 EeV by Auger [75]. For reference, we also show the cosmic-ray spectra measured by KASCADE, Auger, and TA [35, 78, 79]. *K. Fang for this review.* *Right:* Upper limits on the integral photon flux obtained with the Auger surface detector (Auger SD 2015) [82], a hybrid analysis of nine years of Auger data (Auger Hybrid 2016) [75], and the Telescope Array surface detector (TA SD 2018) [83]. The shaded regions give the predicted cosmogenic photon flux assuming a pure proton (GZK p) and pure iron (GZK Fe) UHECR composition of reference [81]. *F. Oikonomou for this review.*

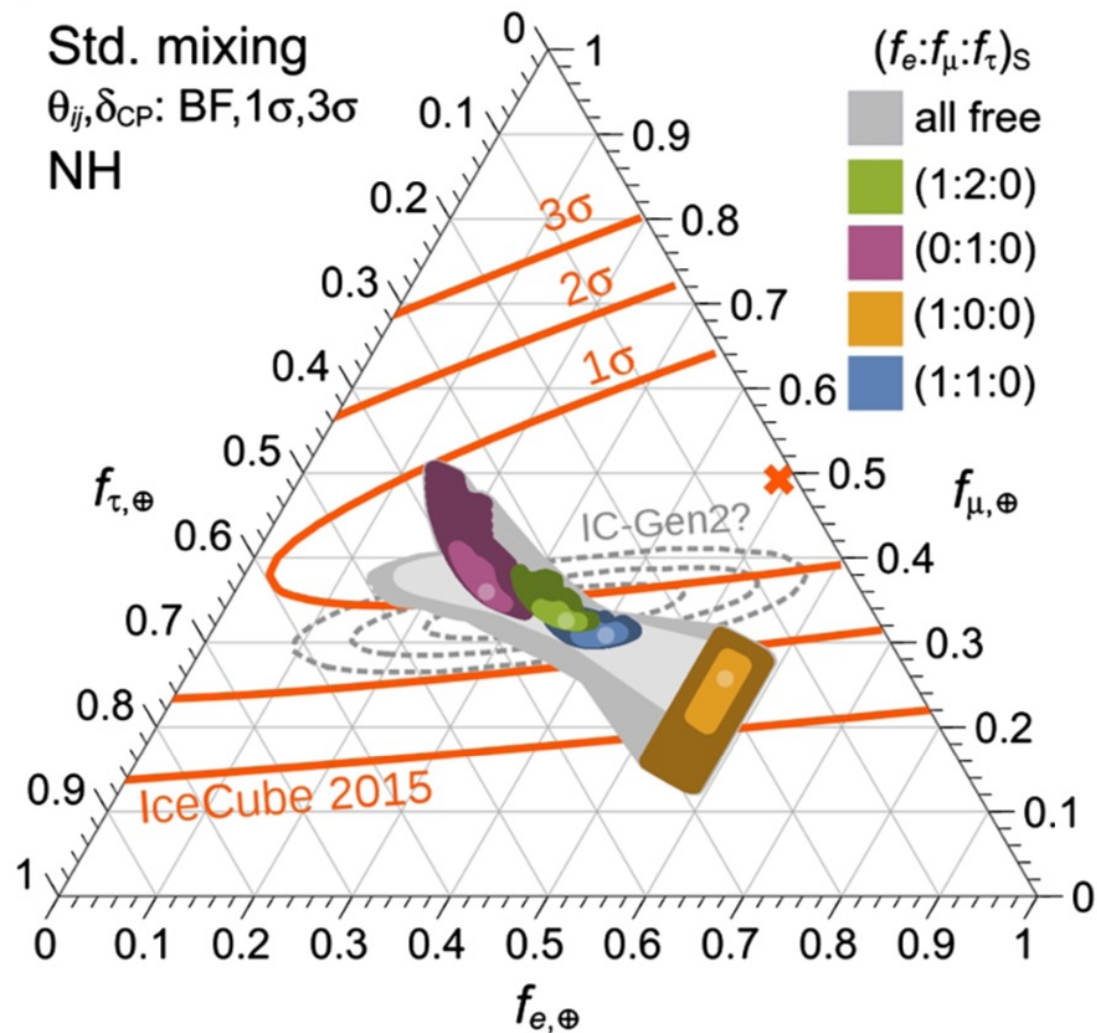


FIG. 3 (color online). Allowed flavor ratios at Earth for different choices of source ratios, assuming standard mixing. Projected 1σ , 2σ , and 3σ exclusion curves from IceCube-Gen2 are included for comparison (gray, dotted); see main text.

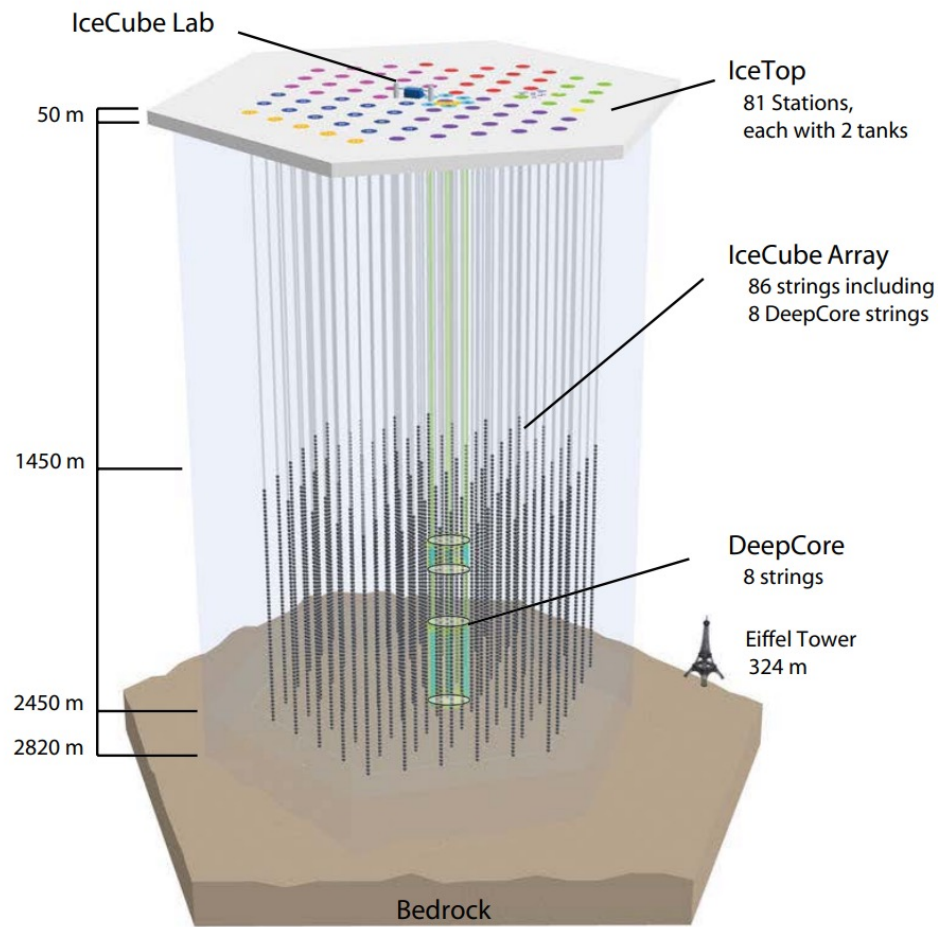


Figure 1: The IceCube Detector with its components DeepCore and IceTop.

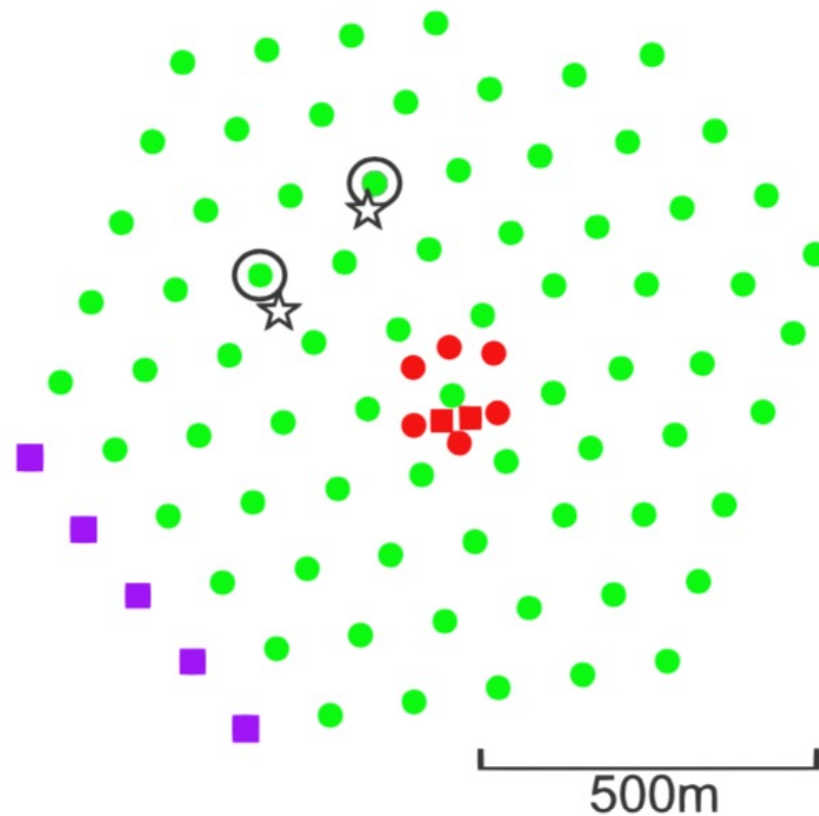
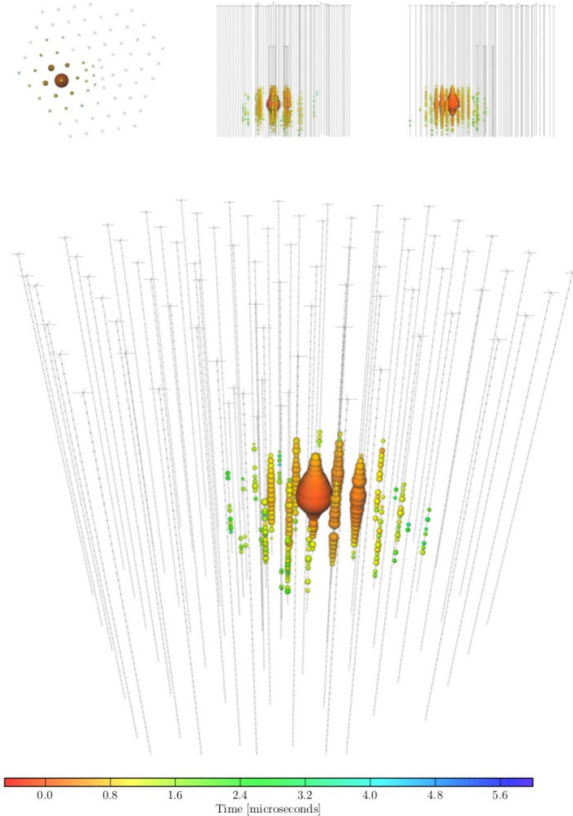


FIG. 1. Surface view of the full IceCube detector layout. Filled marks represent the positions of the IceCube strings. Red marks are the DeepCore strings. Squares represent the strings that did not exist in the IC79 configuration. Open circles are the positions of the closest strings to the observed two cascade events. Stars are their reconstructed vertex positions.

Shower

19

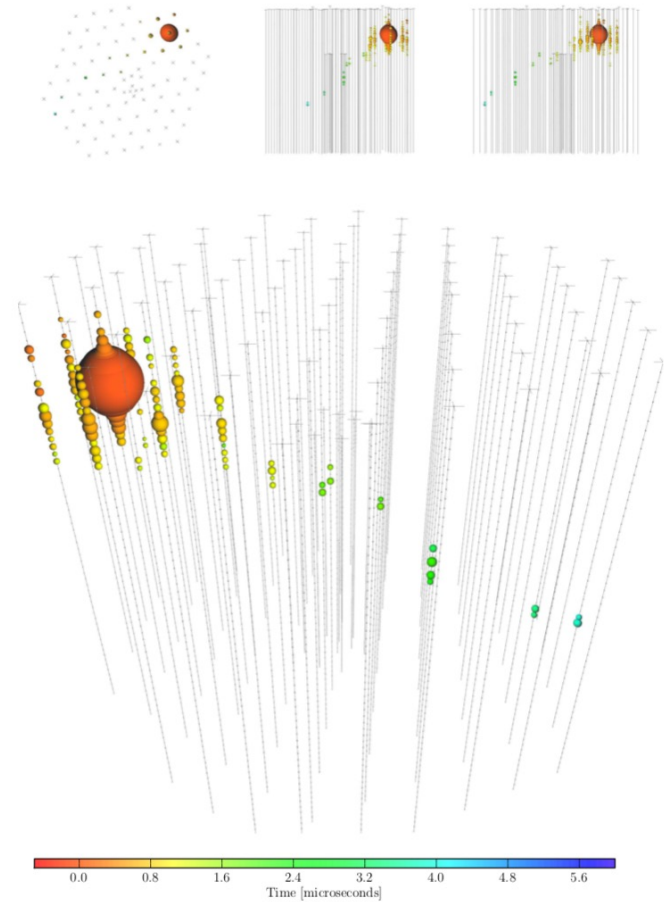
EVENT 9



Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$63.2^{+7.1}_{-8.0}$	55685.6629638	33.6	151.3	16.5	Shower

Track

EVENT 18



Deposited Energy (TeV)	Time (MJD)	Declination (deg.)	RA (deg.)	Med. Ang. Resolution (deg.)	Topology
$31.5^{+4.6}_{-3.3}$	55923.5318175	-24.8	345.6	$\lesssim 1.3$	Track

From *Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector*, Science 342 (2013), 1242856 [arXiv:1311.5238 [astro-ph.HE]].

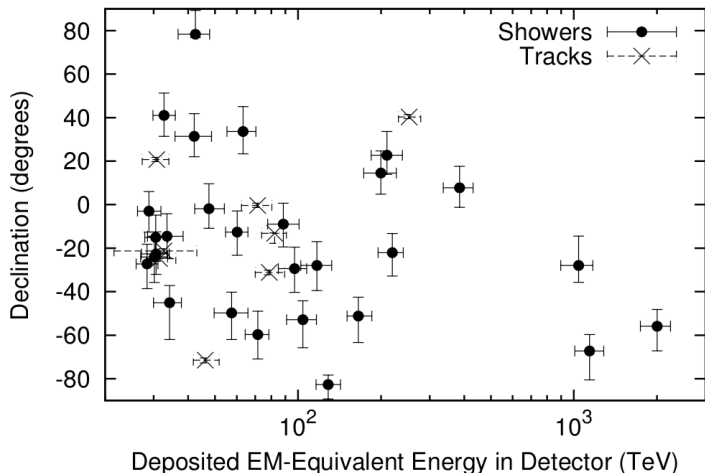


FIG. 1. Arrival angles and deposited energies of the events. Cosmic ray muon background would appear as low-energy track events in the southern sky (bottom). Atmospheric neutrino backgrounds would appear primarily in the northern sky (top), also at low energies and predominantly as tracks. The attenuation of high energy neutrinos in the Earth is visible in the top right of the figure. One event, a pair of coincident unrelated cosmic ray muons, is excluded from this plot. A tabular version of these data, including additional information such as event times, can be found in the online supplement [29].

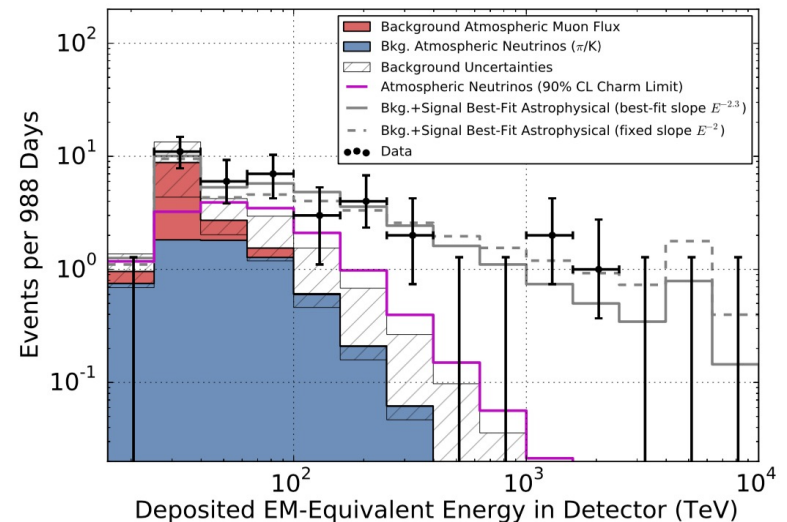


FIG. 2. Deposited energies of observed events with predictions. The hashed region shows uncertainties on the sum of all backgrounds. Muons (red) are computed from simulation to overcome statistical limitations in our background measurement and scaled to match the total measured background rate. Atmospheric neutrinos and uncertainties thereon are derived from previous measurements of both the π/K and charm components of the atmospheric ν_μ spectrum [9]. A gap larger than the one between 400 and 1000 TeV appears in 43% of realizations of the best-fit continuous spectrum.

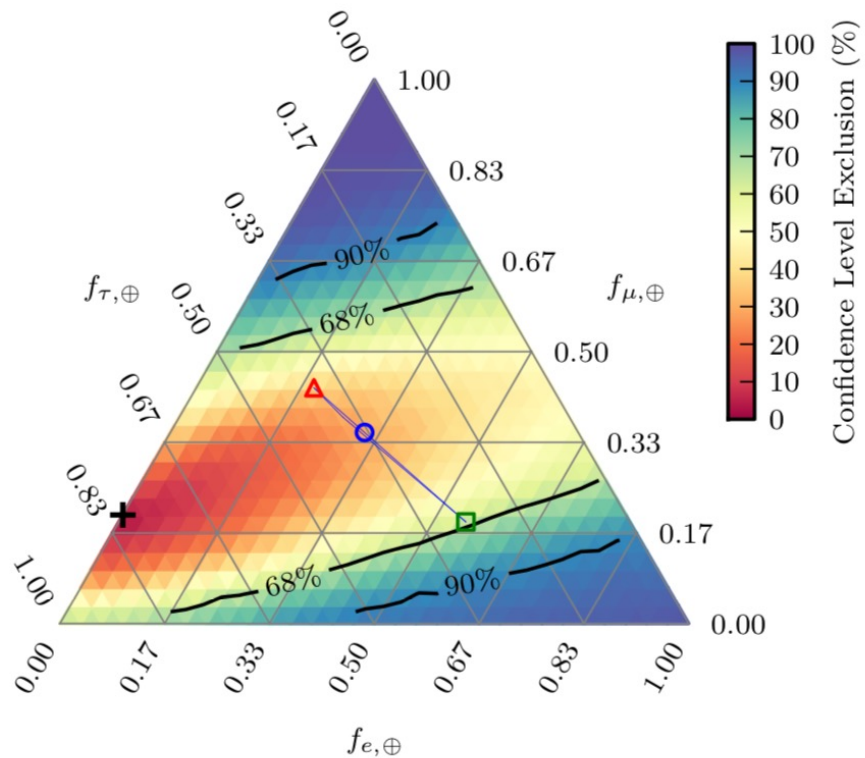


FIG. 3. The exclusion regions for astrophysical flavor ratios $(f_e : f_\mu : f_\tau)_\oplus$ at Earth. The labels for each flavor refer to the correspondingly tilted lines of the triangle. Averaged neutrino oscillations map the flavor ratio at sources to points within the extremely narrow blue triangle. The $\approx (1 : 1 : 1)_\oplus$ composition at Earth, resulting from a $(1 : 2 : 0)_S$ source composition, is marked with a blue circle. The compositions at Earth resulting from source compositions of $(0 : 1 : 0)_S$ and $(1 : 0 : 0)_S$ are marked with a red triangle and green square, respectively. Though the best-fit composition at Earth (black cross) is $(0 : 0.2 : 0.8)_\oplus$, the limits are consistent with all compositions possible under averaged oscillations.