Neutrino masses and oscillations

Tests of the Standard Model of Particle Physics II, SS 2020

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(updates by Dr. M. Spalla)

Neutrino (ν) masses and oscillation

- In the Standard Model, neutrinos are massless
  - ν only left-handed ($\bar{\nu}$ only right handed)
    - ➤right handed ν do not participate in the weak interaction

- Neutrino oscillation:
  - first observed in 1998
  - imply that neutrino must have nonzero mass
  - as well as violation of lepton flavour conservation, as for quarks

	Mass	m measurements	Discovery
ν_e	< 2 eV	Mainz / Troitsk	Cowan, Reines 1956 (inverse β decay)
ν_μ	< 190 keV	PSI Zürich	Ledermann, Schwartz, Steinberger 1962
ν_τ	< 18.2 MeV	ALEPH (LEP)	DONUT Experiment (FNAL) 2001

Neutrino (ν) masses and oscillation

- Since neutrinos are electrically neutral, they can be either *Dirac spinors* or *Majorana spinors*
  - Dirac neutrinos:
    - 4 component Dirac spinors: $(\nu_L^D, \overline{\nu}_R^D; \nu_R^D, \overline{\nu}_L^D)$
    - With:

$$\overline{\nu}_R^D = \mathrm{CPT}(\nu_L^D)\ ,\quad \overline{\nu}_L^D = \mathrm{CPT}(\nu_R^D)$$

  - Majorana neutrinos:
    - 2 component Majorana spinors: $(\nu_L^M; \nu_R^M)$
    - <u>Majorana neutrinos are their own antiparticle:</u>

$$\overline{\nu}_R^M = \mathrm{CPT}(\nu_L^M) \equiv \nu_R\ ,\quad \overline{\nu}_L^M = \mathrm{CPT}(\nu_R^M) \equiv \nu_L$$

- Which of the two occurs in nature is yet to be clarified experimentally

- The very low value of the neutrino mass is also yet to be theoretically explained

Mechanism of ν oscillation

- The same argument discussed for quarks also holds for neutrino
  - From interaction with Higgs field

- ν mass eigenstates ≠ ν weak eigenstates
  - Mass matrix is non-diagonal on the weak eigenstates basis
    - ➢Same applies to charged leptons, known to have nonzero (and very different) masses

- It follows that weak transitions exist between mass states in different generations: ν mixing
  - Time oscillation between mixing states as for neutral mesons
    - ➢First: Bruno Pontecorvo, Moscow 1958

Mechanism of ν oscillation

- As for quarks, both up-type (neutral) and down-type (charged) lepton weak eigenstates are connected to the mass eigenstates by a unitary transform

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_L = U_u \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_L = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_L$$

$$\nu_i \ (i = 1, ..., 3) \qquad \nu_\alpha \ (\alpha = e, \mu, \tau), \quad \Rightarrow \quad \begin{cases} \nu_i = \sum_\alpha U^*_{\alpha i} \, \nu_\alpha \, ; \ \ \bar{\nu}_i = \sum_\alpha U_{\alpha i} \, \bar{\nu}_\alpha \, ; \\ \nu_\alpha = \sum_i U_{\alpha i} \, \nu_i \, ; \ \ \bar{\nu}_\alpha = \sum_i U^*_{\alpha i} \, \bar{\nu}_i \, . \end{cases}$$

Mechanism of ν oscillation

- U_u is the Pontecorvo-Maki-Nakagawa-Sakata mixing matrix:

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

$$\cdot \begin{pmatrix} e^{i\phi_1} & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Independent parameters:
  - **3** mixing angles: $\theta_{ij}\ (i,j = 1,2,3; i > j),$ $\quad c_{ij} = \cos\theta_{ij} > 0,\ s_{ij} = \sin\theta_{ij} > 0,$
  - **1** CP-violating phase: $e^{i\delta}$
  - **2** Majorana phases: $\phi_1\ ,\ \phi_2$ $\quad (\nu^M \equiv \overline{\nu}^M$ for Majorana neutrino$)$
    - ➤Majorana phases play no role in oscillation

Mechanism of ν oscillation

- Time evolution of weak eigenstate:

$$\nu_i(t) = e^{-iE_it}\nu_i(0)\ ,$$

  - In the limit $|\vec{p}| \gg m_i$ (ν have very small masses)

$$\mathrm{E_i} = \sqrt{\mathrm{\vec{p}^2 + m_i^2}} \overset{\mathrm{m_i \ll |\vec{p}|}}{\approx} |\mathrm{\vec{p}}| + \frac{1}{2}\frac{\mathrm{m_i^2}}{|\mathrm{\vec{p}}|} \overset{|\mathrm{\vec{p}}| \approx \mathrm{E}_\nu}{\approx} \mathrm{E}_\nu + \frac{1}{2}\frac{\mathrm{m_i^2}}{\mathrm{E}_\nu}.$$

- We can then derive the time evolution of a weak eigenstate:

$$\nu(0) = |\nu_\alpha> = \sum_i U_{\alpha i}\nu_i(0)\ ,$$

$$\Rightarrow \quad \nu(t) = \sum_i U_{\alpha i} e^{-iE_it}\nu_i(0) = \sum_i \sum_\beta U_{\alpha i} U^*_{\beta i} e^{-iE_it}\nu_\beta\ .$$

Mechanism of ν oscillation

- From $\nu(t)$ time evolution, the transition probability from weak state α to weak state β can be derived:

$$\mathcal{P}(\nu_\alpha \to \nu_\beta; t) = |<\nu_\beta|\nu(t)>|^2$$
$$= \sum_i |U_{\alpha i} U^*_{\beta_i}|^2 + 2\mathcal{R}e \sum_{i,j(j>i)} U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} e^{-i\Delta_{ij}},$$

  - Where ($L = ct$):

$$\Delta_{\rm ij} = ({\rm E_i} - {\rm E_j}){\rm t} \approx \frac{\rm m_i^2 - m_j^2}{\rm 2E}{\rm t} =: \frac{1}{2}\Delta {\rm m_{ij}^2}\frac{\rm L}{\rm E}.$$

- Nonzero oscillation means nonzero $\Delta m_{ij}^2 = m_i^2 - m_j^2$
  - The ν masses are not all identical and cannot be all = 0
    - ➤Otherwise the mass matrix would have been a multiple of $\mathbb{I}$ and there wouldn't have been any mixing

Mechanism of ν oscillation

- Simplest case: mixing between two generations
  - 1 parameter: mixing angle θ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

- Transition probabilities:

$$\begin{aligned} \mathcal{P}(\nu_e \to \nu_e) &= \mathcal{P}(\nu_\mu \to \nu_\mu) = \mathcal{P}(\bar{\nu}_e \to \bar{\nu}_e) = \mathcal{P}(\bar{\nu}_\mu \to \bar{\nu}_\mu) \\ &= 1 - \sin^2 2\theta \sin^2 \frac{\Delta}{2} \\ \mathcal{P}(\nu_e \to \nu_\mu) &= \mathcal{P}(\nu_\mu \to \nu_e) = \mathcal{P}(\bar{\nu}_e \to \bar{\nu}_\mu) = \mathcal{P}(\bar{\nu}_\mu \to \bar{\nu}_e) \\ &= \sin^2 2\theta \sin^2 \frac{\Delta}{2} = 1 - \mathcal{P}(\nu_e \to \nu_e), \end{aligned}$$

With: $\Delta = \frac{\Delta m^2}{2}\frac{L}{E}$ $\Rightarrow$ Oscillation length: $L_0 = \frac{4\pi E}{\delta m^2}.$

Mechanism of ν oscillation

- Simple case of 2 families

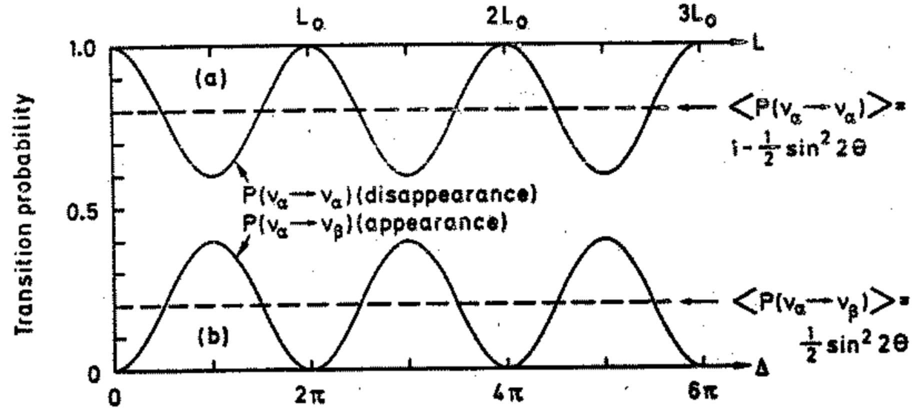
$$\mathcal{P}(\nu_e \to \nu_e) = \mathcal{P}(\nu_\mu \to \nu_\mu) = \mathcal{P}(\bar{\nu}_e \to \bar{\nu}_e) = \mathcal{P}(\bar{\nu}_\mu \to \bar{\nu}_\mu)$$
$$= 1 - \sin^2 2\theta \sin^2 \frac{\Delta}{2}$$
$$\mathcal{P}(\nu_e \to \nu_\mu) = \mathcal{P}(\nu_\mu \to \nu_e) = \mathcal{P}(\bar{\nu}_e \to \bar{\nu}_\mu) = \mathcal{P}(\bar{\nu}_\mu \to \bar{\nu}_e)$$
$$= \sin^2 2\theta \sin^2 \frac{\Delta}{2} = 1 - \mathcal{P}(\nu_e \to \nu_e),$$

$$\Delta = \frac{\Delta m^2}{2} \frac{L}{E}$$

- Transition probabilities depend on 2 parameters:
  - oscillation amplitude: $\sin^2 2\theta$
  - oscillation frequency: $\Delta m^2 / 2E_\nu$
- For 3 generations, complex mixing matrix U_u parametrised as for CKM
  - CP violation becomes possible: $\mathcal{P}(\nu_e \to \nu_\mu) \neq \mathcal{P}(\overline{\nu}_e \to \overline{\nu}_\mu)$
    - But CPT requires that: $\mathcal{P}(\nu_e \to \nu_\mu) \equiv \mathcal{P}(\overline{\nu}_\mu \to \overline{\nu}_e)$

Sensitivity to ν oscillation

$$L_0 = \frac{4\pi E}{\delta m^2}.$$

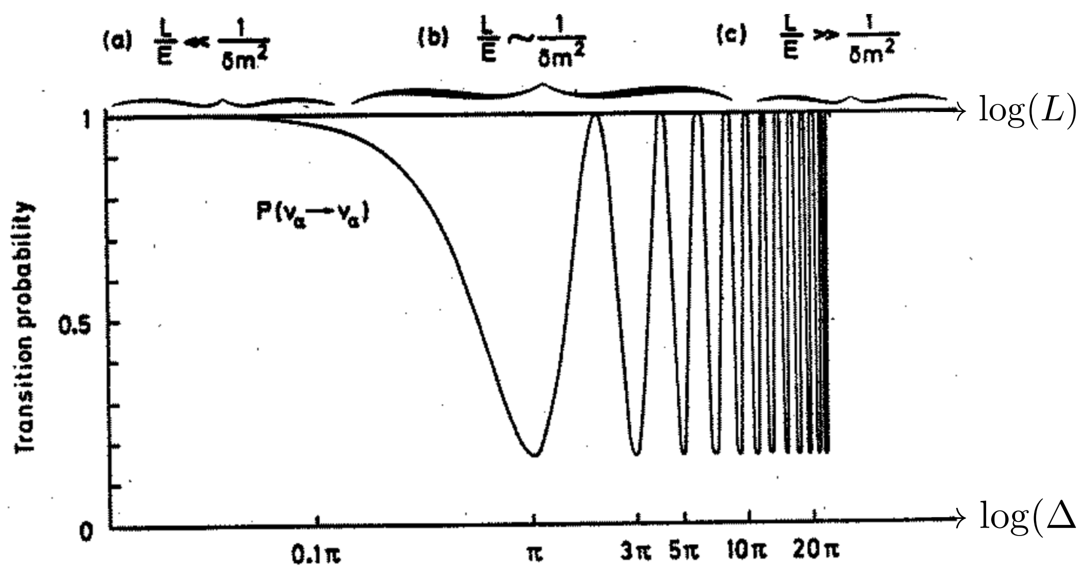


$$\Delta = \frac{\delta m^2}{2}\frac{L}{E}$$

- Sensitivity to a given δm^2 depends on *L/E*
  - i.e. the energy of the produced ν and the distance between source and detector

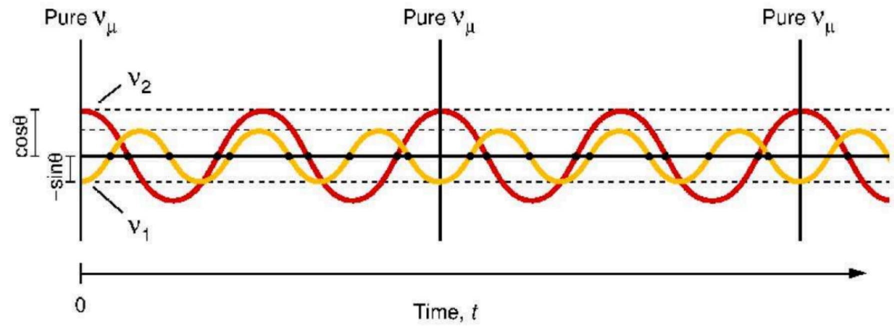
- Optimal sensitivity when the oscillation frequency is neither too large nor too small:

$$\frac{L}{E} \sim \frac{1}{\delta m^2}$$



Note about charged leptons

- Oscillation is a pure quantum mechanical effect: coherent superposition of ν mass eigenstates



- It is visible only because momentum resolution doesn't allow us to resolve the mass eigenstates
  - i.e. the oscillation length L_0 is long enough

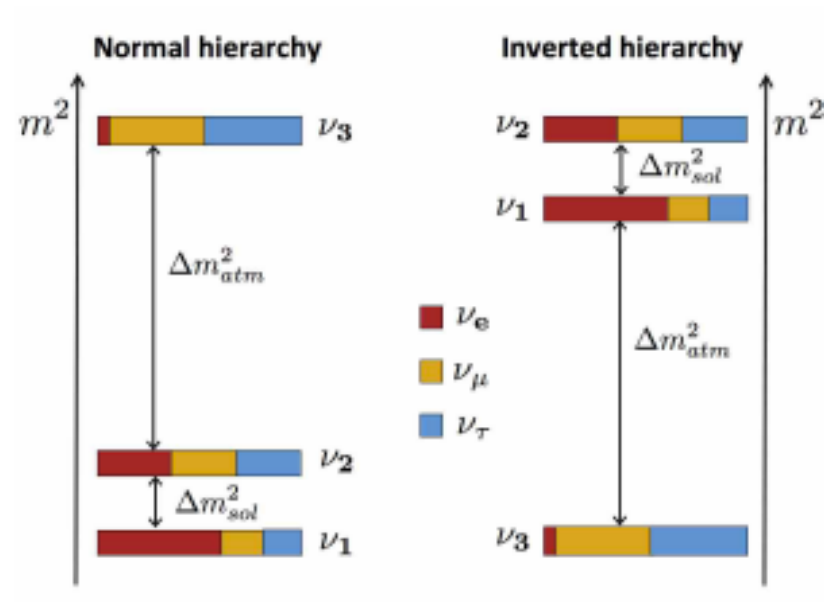
$$L_0 = \frac{4\pi E}{\delta m^2}.$$

- In charged leptons and quarks, masses can be resolved and the effect is disrupted
  - To resolve the mass states, it must be: $\Delta p < |p_i - p_j|$
  - Hence L_0 is smaller than spatial resolution:

$$\Delta x > \frac{1}{\Delta p} > \frac{1}{|p_i - p_j|} \approx \frac{2E}{|m_i^2 - m_j^2|} \approx L_0^{ij},$$

What can we learn from ν oscillation?

- ν mass differences: ordering of the ν_i mass states
  - The absolute scale of ν mass cannot be measured from oscillation: direct measurement needed



- Mixing angles
  - Built a 'unitarity triangle' for leptons
- CP violating phase: CP violation in lepton mixing?

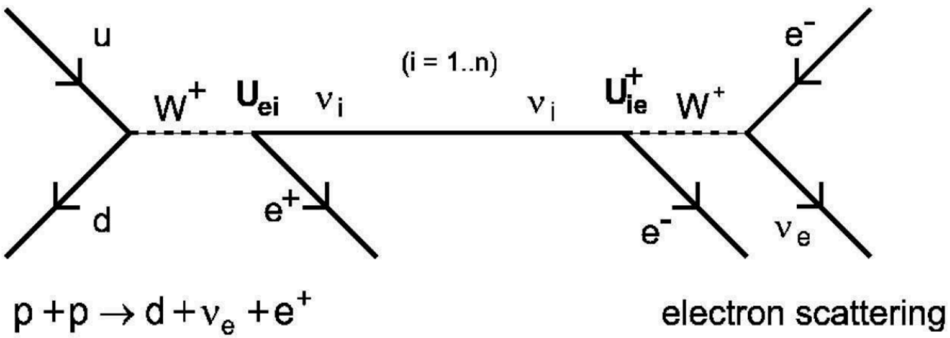
Search for ν oscillation

- Typical ν experiment
  - A source creates ν of a specific flavour ν_α in a given energy range, at *t=0*
  - A detector then measures the flavour components of the ν flux at time *t=L/c*:

$$\nu(t) = \sum_{i,\beta} U_{\alpha i} U^*_{\beta i} e^{-iE_i t} |\nu_\beta >$$

    - as well as the neutrino's energy
  - The distance *L* between source and detector tuned in order to be sensitive to the δm^2 of interest

Example:



- Two classes of experiments: appearance and disappearance experiments

Disappearance experiments

- Detector sensitive to same flavour as produced in the source
- Measuring the ν_α flux (ν rate / detector area) in the detector as a function of ν energy

- Survival probability: $\mathcal{P}(\nu_\alpha \to \nu_\alpha; L)$
  - equivalent to measuring the probability of oscillation into any other flavour eigenstate

$$\mathcal{P}(\nu_\alpha \to \nu_X \neq \nu_\alpha; L) \equiv 1 - \mathcal{P}(\nu_\alpha \to \nu_\alpha; L)$$

- Requires:
  - precise knowledge of the source or
  - measurements at multiple distances

Appearance experiments

- Detection of a different flavour than that generated at the source

- Measures the probability of appearance of a specific flavour

$$\mathcal{P}(\nu_\alpha \to \nu_\beta; L).$$

- Requires
  - low contamination of the source with ν_β or
  - precise knowledge of source flavour composition

Sensitivity to ν oscillation

- The fundamental parameter is the oscillation frequency
  - For each oscillation component

$$S := \sin^2 \frac{\Delta}{2} = \sin^2 \left[\frac{\Delta m^2}{4} \frac{L}{E} \right]$$

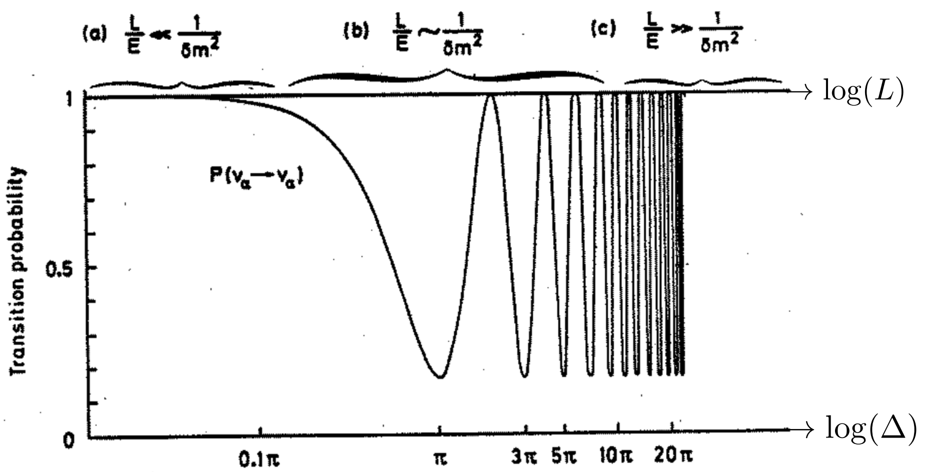
- Three ranges can be considered:

1. $L/_E \ll 4/_{\Delta m^2}$

(or $L \ll L_0 = {}^{4\pi E}/_{\Delta m^2}$)

$$\Rightarrow \quad S \approx 0$$

- No sensitivity to oscillation



Sensitivity to ν oscillation

2. $^{L}/_{E} \geq {^{4}/_{\Delta m^2}}$
   - At sensitivity threshold: *condition on* minimum Δm^2 the experiment is sensitive to (given *L* and *E*)

$$\Delta m^2_{\rm min} \approx \frac{E\ [\rm MeV]}{L\ [\rm m]}\ \rm eV^2$$

   - Large *L* and low *E* improve sensitivity to small Δm^2
     - But ν flux decreases with distance (isotropic, divergent beam)

3. $^{L}/_{E} \gg {^{4}/_{\Delta m^2}}$ (or $L \ll L_0$)
   - High frequency: many oscillations between source and detector
   - $^{L}/_{E}$ must be measured very precisely to resolve oscillations
   - Otherwise it is only possible to observe average transition probability
     - i.e. measure θ but not Δm^2

$$< \mathcal{P}(\alpha \rightarrow \beta \neq \alpha) > \ = \ \frac{1}{2}\sin^2\theta$$

- <u>$^{L}/_{E}$ determines the mass range to which the experiment is sensitive</u>
  - i.e. basic parameter in order to decide what experiment should be built to test a given Δm^2 region

Types of ν sources

Experiment		L (m)	E (MeV)	$\lvert\Delta m^2\rvert$ (eV^2)	Produced flavour
Solar		10^{10}	1	10^{-10}	ν_e
Atmospheric		$10^4 - 10^7$	10^2–10^5	$10^{-1} - 10^{-4}$	$\nu_\mu, \overline{\nu}_\mu, \nu_e, \overline{\nu}_e$
Reactor	SBL	$10^2 - 10^3$	1	$10^{-2} - 10^{-3}$	$\overline{\nu}_e$
	LBL	$10^4 - 10^5$		$10^{-4} - 10^{-5}$	
Accelerator	SBL	10^2	10^3–10^4	> 0.1	$\nu_\mu, \overline{\nu}_\mu$
	LBL	$10^5 - 10^6$	$10^3 - 10^4$	$10^{-2} - 10^{-3}$	

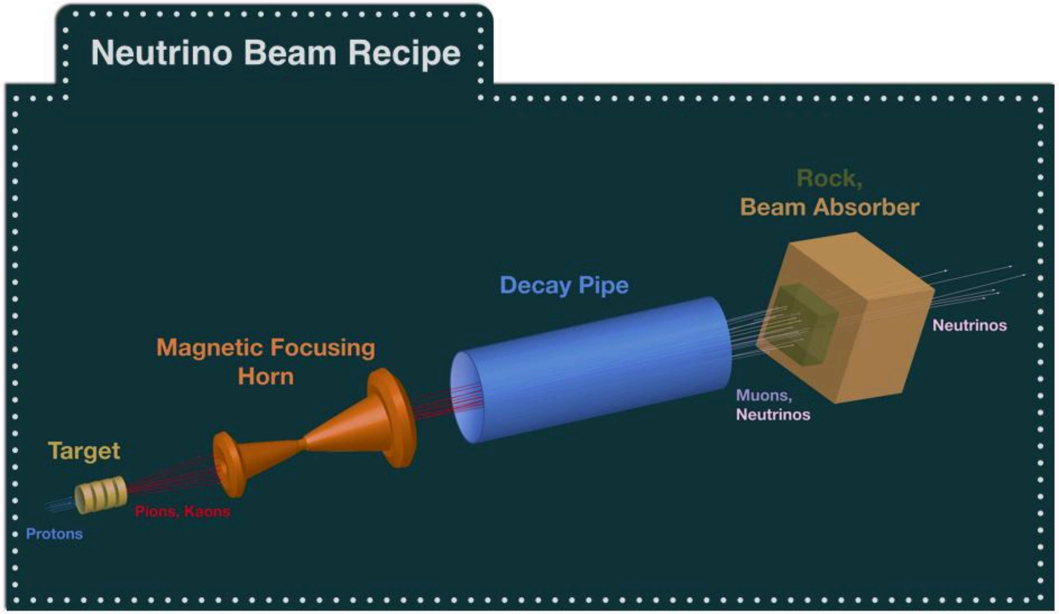
SBL = short baseline, LBL = long baseline (see next)

- Neutrinos from supernovas have also been measured, but they are used as messengers for astronomy research rather then for studying neutrino properties

Neutrino beams

- Nuclear reactors: ν from β decays in the fission process
  - Produces low energy $\bar{\nu}_e$
  - Needs detailed knowledge of neutrino flux produced by the reactor (many decay chains involved)

- Accelerators:
  - proton beam on fixed target
  - interaction with nuclei in target produces π,K
  - ν from π,K *weak decays*
  - Produces $\nu_\mu, \bar{\nu}_\mu$, energy can be tuned



Neutrino beams: detection

- Detection method: mostly inverse β decay

$$\Rightarrow \quad \overline{\nu_e} + p \rightarrow e^+ + n$$

- Decay products then detected through
  - electron-positron annihilation: $e^+e^- \rightarrow \gamma\gamma$ (Prompt photon)
  - neutron capture: $n + p \rightarrow d + \gamma$ (2.2 MeV) $\quad n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma$ (8 MeV)
    - Often use Gadolidium (Gd) for high neutron capture efficiency
  - Photons can the be detected

$$\Rightarrow \quad \nu_{e,\mu.\tau} + N \rightarrow (e^-, \mu^-, \tau^-) + \text{ Hadrons}$$

- Then detect charged lepton (e.g. through Cherenkov light)
  - Charged leptons retains ν direction and energy (forward scattering)

- For better precision, two detectors are often used (multi-detector):
  - One near the source, to measure the produced flux
  - One at distance, to detect oscillations

Neutrino beams: measurements

- <u>Reactors</u>:
  - Only disappearance measurements
    - ➢Direct detection of ν_μ , ν_τ from oscillation is not possible due to low energy: under threshold for producing a μ/τ
  - $\bar{\nu}_e$ disappearance: address $\nu_e \longrightarrow \nu_\tau / \nu_\mu$ oscillation (same as solar neutrinos)

- <u>Accelerators</u>:
  - ν_μ disappearance, ν_τ/ν_e appearance
  - can verify $\nu_\mu \longrightarrow \nu_\tau$ oscillation observed in atmospheric neutrino (see next)
  - and target $\nu_\mu \longrightarrow \nu_e$ observation

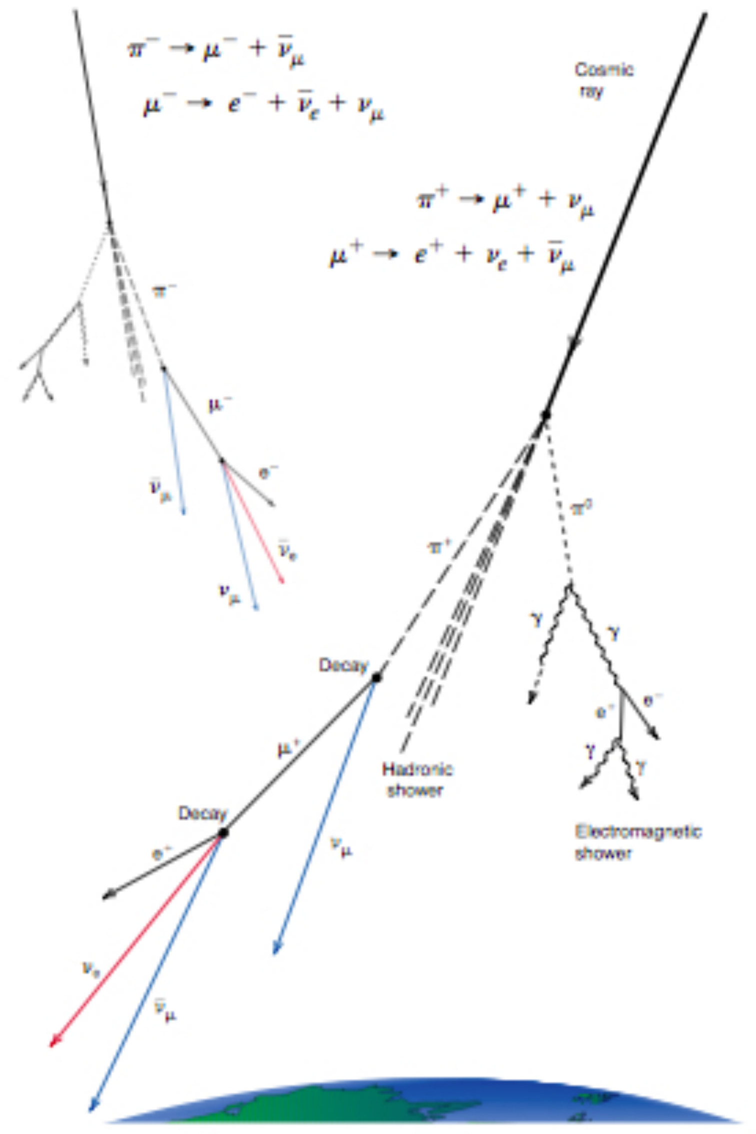
Neutrino beams: long baseline vs short baseline

- Two categories:
  - Short baseline: distance between source and detector up to 100-1000 m
  - Long baseline: distance between source and detector > 100 Km

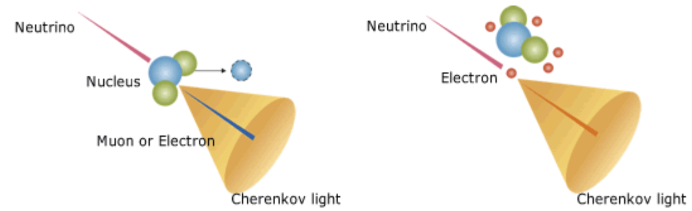
- Designed to address different ranges in Δm^2
  - For instance: $\Delta m^2 = \mathcal{O}(10^{-3})$ eV (observed in atmospheric neutrinos)
    - ➤First oscillation maximum at $L/E \sim 500\ \mathrm{km}/\mathrm{GeV}$
    - ➤e.g. accelerator neutrinos produced at $\sim$ GeV → need $L \sim 10^3$ Km

Atmospheric neutrinos

- Cosmic radiation (~99% protons) interacts with atoms in the atmosphere
  - Produces particle showers: π, K produce ν by decaying weakly
- Oscillation observed for the first time in atmospheric ν by Superkamiokande experiment
  - 1998

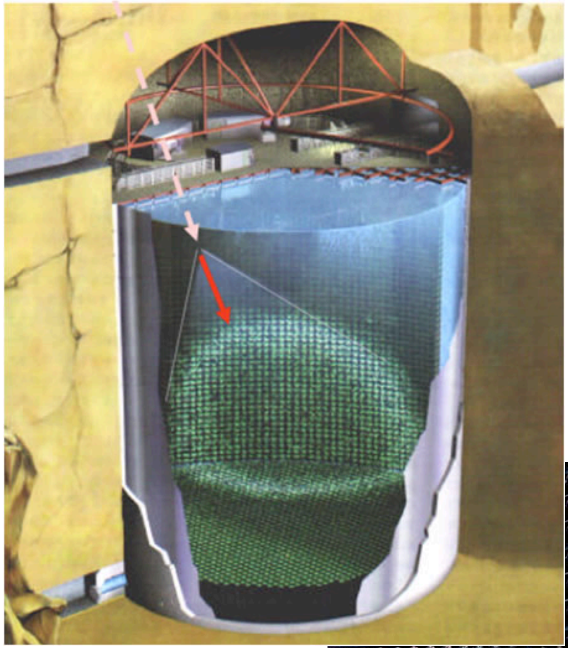


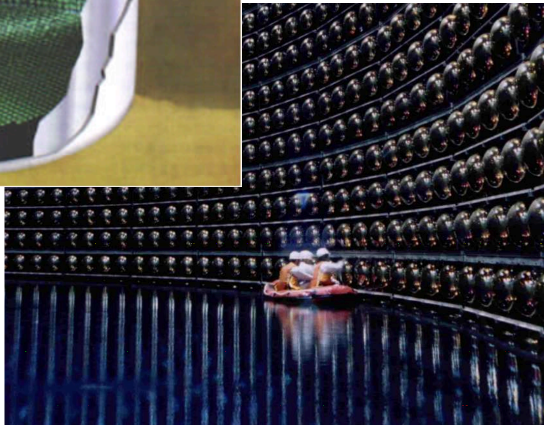
Superkamiokande experiment



The generated charged particle emits the Cherenkov light.

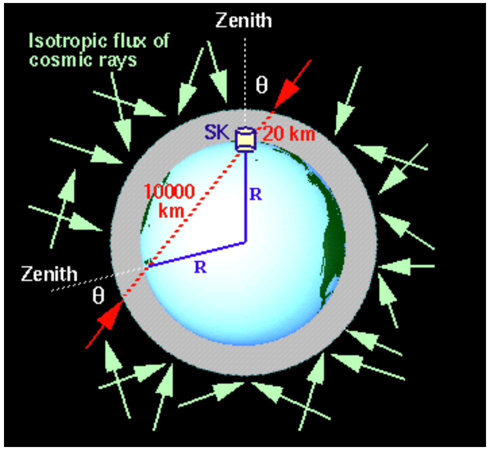
- 5000 ton water tank, 1000 m underground in Kamioka mine, Japan
- Neutrinos detection:
  - interaction with electron or nucleus in the water (inverse β decay)
- Instrumented with photomultipliers
  - collects Cherenkov light from (from inverse β decay)
    - Direction of charged particles used to determine direction of incoming neutrino
  - Cherenkov rings allow to distinguish e, μ, τ:
    - Can determine neutrino flavour





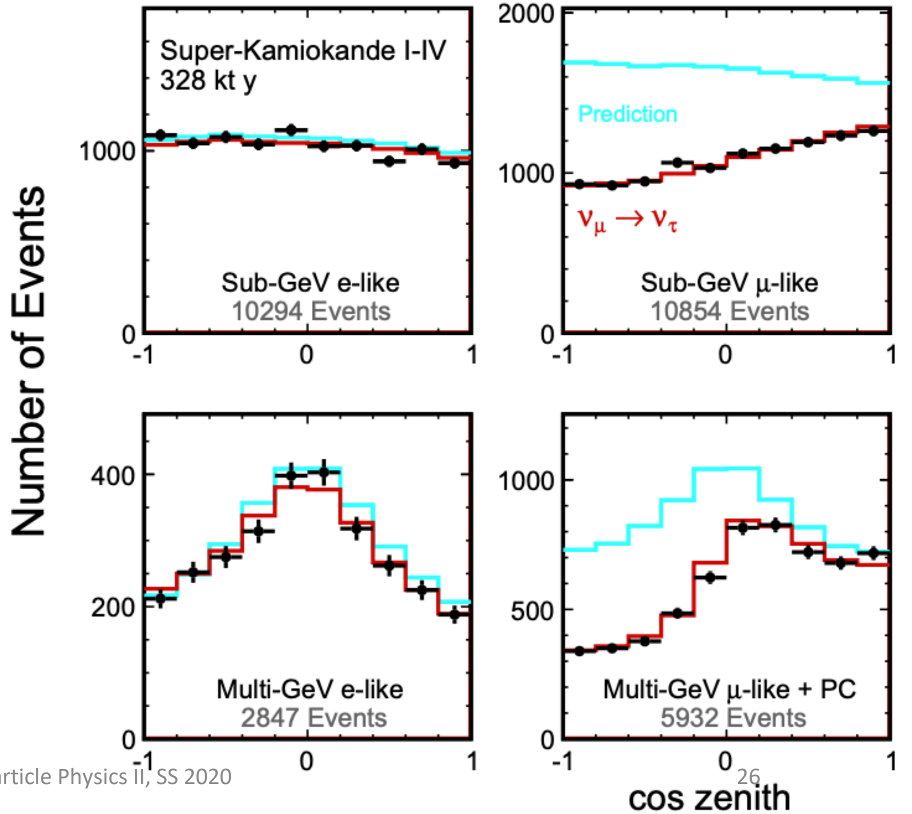
Atmospheric ν oscillations

- Superkamiokande: deficit of ν_μ ($\bar{\nu}_\mu$) with respect to ν_e ($\bar{\nu}_e$) coming from below
  - zenith angle proportional to travel length
- Explained by ν oscillation ($\nu_\mu \to \nu_\tau$ or $\nu_\mu \to \nu_e$) while passing through the globe (L_0 = 10^4 km)
- Later also measured ν_τ appearance (4.6σ)
  - Very difficult due to:
    - high threshold for inverse β decay (large τ mass)
    - short τ lifetime



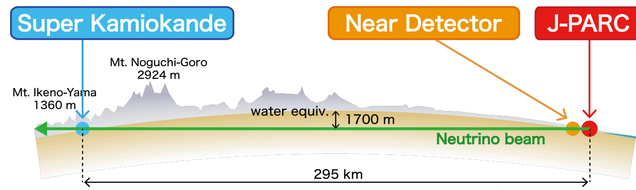
e-like events: no oscillation

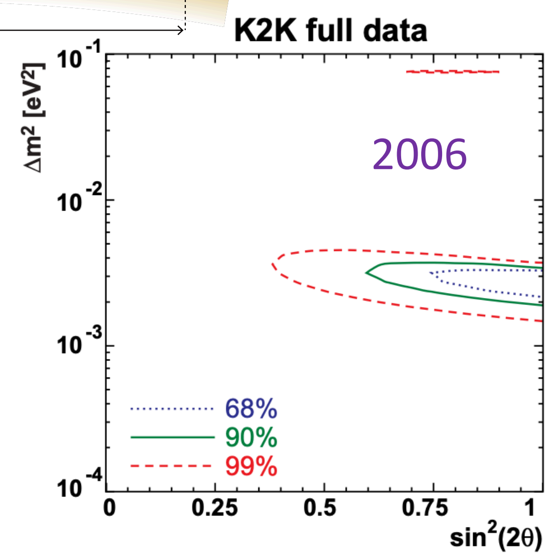
μ-like events: oscillation observed



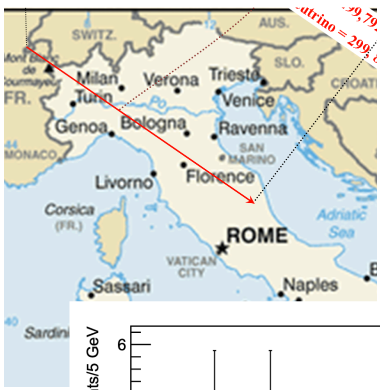
Confirmation from long baseline accelerators

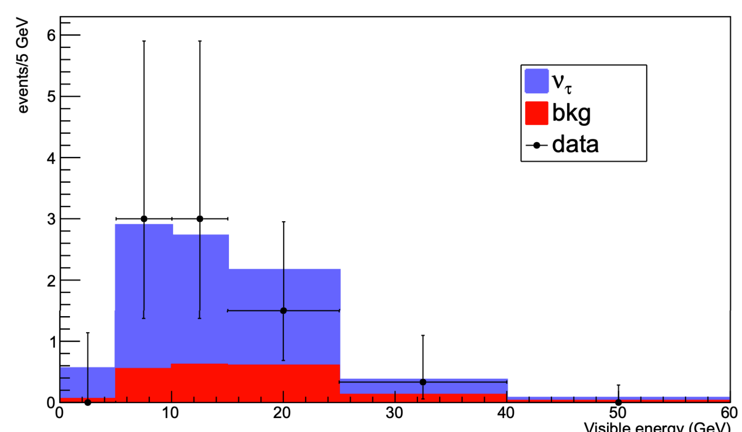
- K2K
  - beam from KEK accelerator to Superkamiokande detector (L=250 km)
  - First confirmation of ν_μ disappearance outside atmospheric neutrinos (2006)





- $\nu_\mu \longrightarrow \nu_\tau$ appearance confirmed by OPERA
  - Beam from CERN to Gran Sasso Laboratories (L=730 km)
  - Emulsion+lead target
- $\nu_\mu \longrightarrow \nu_e$ appearance observed by MINOS, T2K, NOvA (see later)





https://arxiv.org/pdf/1804.04912.pdf (OPERA, 2018)

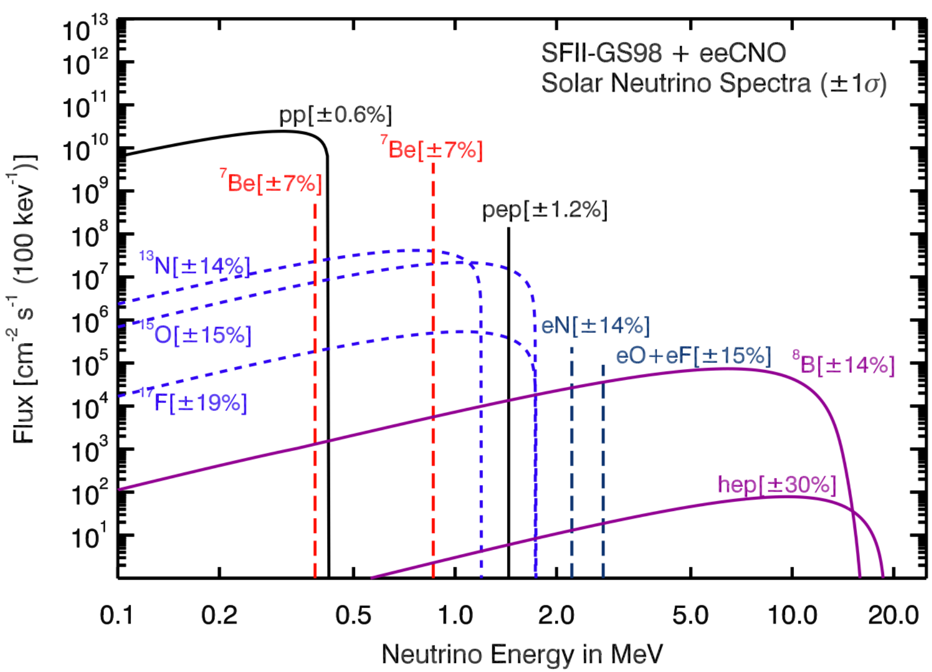
Solar neutrinos

- ν_e produced by thermonuclear fusions in the Sun nucleus
- Solar models predict about 98% of ν produced by the pp-cycle
  - It results in:

$$4p + 2e^- \rightarrow He^4 + 2\nu_e + 26.73\ \mathrm{MeV}$$

$$\Rightarrow \langle E_\nu \rangle = 0.59\ \mathrm{MeV}$$

  - Remaining 1.6% produced by CNO and Bethe-Weizsäcker cyles



Solar neutrinos

- Two main experimental goals with solar ν

1. Test the Solar Model
   - Predicts the temperature distribution in the Sun, which determines the fusion reactions taking place, hence the flux and energy of neutrinos
     - Expected ν flux from the Sun: $1.87 \cdot 10^{38}$ s^{-1}
     - Expected ν flux density on Earth: $6.6 \cdot 10^{10}$ cm^{-2} s^{-1}

   ➤ ν offer direct, almost instantaneous information about fusion process
     - photons take about 10^6 years to get from the center to the surface, due to strong interaction with solar matter

   - Models in good agreement with measured oscillation excitations opf the Sun (heliosismology)
2. Search for ν oscillations
   - Good search conditions:
     - ➤ very low ν energy ($\sim$ eV)
     - ➤ very long travel length (10^5 km in Sun matter + 10^8 in vacuum)

$$\Longrightarrow \Delta m^2_{\text{min}} \approx \frac{E_\nu[\text{MeV}]}{L[\text{m}]}\ \text{eV}^2 \approx 10^{-12}\ \text{eV}^2.$$

Solar ν detection

- Two detection methods:
  1) Radiochemical measurements
  2) Real-time measurements

Table 14.2: List of solar neutrino experiments

	Name	Target material	Energy threshold (MeV)	Mass (ton)	Years
(1)	Homestake	C_2Cl_4	0.814	615	1970–1994
(1)	SAGE	Ga	0.233	50	1989–
(1)	GALLEX	$GaCl_3$	0.233	100 [30.3 for Ga]	1991–1997
(1)	GNO	$GaCl_3$	0.233	100 [30.3 for Ga]	1998–2003
(2)	Kamiokande	H_2O	6.5	3,000	1987–1995
(2)	Super-Kamiokande (**)	H_2O	3.5	50,000	1996–
(2)	SNO	D_2O	3.5	1,000	1999–2006
(2)	KamLAND	Liquid scintillator	0.5/5.5	1,000	2001–2007
(2)	Borexino	Liquid scintillator	0.19	300	2007–

From: http://pdg.lbl.gov/2019/reviews/rpp2019-rev-neutrino-mixing.pdf

(**) Same detector often works with multiple ν sources

Solar ν detection: radiochemical measurements

- ν captured via inverse β decay of target nuclei

$$\nu_e + B(Z) \;\rightarrow\; C(Z+1) + e^-$$

$$(\nu_e + n \;\rightarrow\; p + e^-)$$

- Detected through decay of the new nuclei *C* by electron capture
  - Photons or Auger electrons are emitted, which can be detected with a proportional chamber.

$$C(Z+1) + e^- \rightarrow B(Z) + \nu_e$$

- Detector then consists of a huge tank filled with *B*
  - Targets of choice: Cl^{37} and Ga^{71}
    - ➢ Half life of *C* must be neither too short nor too long
  - They have different thresholds for ν capture, hence sensitive to different parts of the solar ν spectrum

Solar ν detection: real-time measurements

- Use the reactions
  a) Elastic scattering: $\nu_\alpha e^- \rightarrow \nu_\alpha e^-$
    - The scattered electron indicates the energy and direction of the incident ν (forward scattering)
    - Used by e.g. (Super-) Kamiokande, SNO, Borexino

  b) ν capture by deuteron (reaction rate 10 times larger than elastic scattering)
    - Two processes:

$$(1)\ \nu_e + d \rightarrow e^- + 2\,p$$ → ν capture, $E_\nu > 1.442$ MeV

$$(2)\ \nu_\alpha + d \rightarrow \nu_\alpha + p + n$$ → d spallation, $E_\nu > 2.226$ MeV

    - By comparing measurements, information on neutrino flux ratio ν_α / ν_e
    - SNO (Sudbury Neutrino Observatory), Canada: 1000 ton D_2O

The solar ν deficit in summary

- Homestake experiment (1970-1994, see next)
  - Using the reaction: $\nu_e + Cl^{37} \rightarrow Ar^{37} + e^-$
  - Found only ~50% of ν_e expected from Solar Model

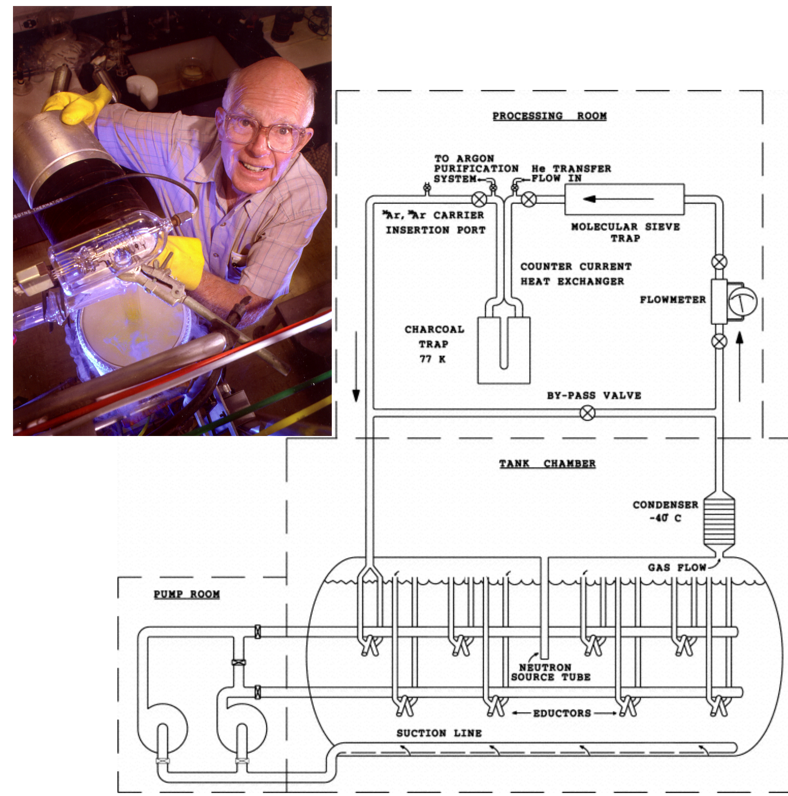
- Confirmed by SAGE and Gallex
  - Using: $\nu_e + Ga^{71} \rightarrow Ge^{71} + e^-$
    - ➢Different E_ν threshold → Different region of the spectrum
- And by (Super-) Kamiokande
  - With: $\nu_\alpha e^- \rightarrow \nu_\alpha e^-$
    - ➢ $\sigma(\nu_{\mu,\tau} e^-) \approx \frac{1}{6} \cdot \sigma(\nu_e e^-)$

- Explanation: neutrino oscillation in matter (Sun) are different than in vacuum
  - Resonant amplification through the Mikheyev-Smirnov-Wolfenstein (MSW) effect: different scattering of ν_e and ν_μ in solar matter with decreasing density
    - ➢2002 Nobel prize to R. Davis (Homestake) und M. Koshiba (Kamiokande).

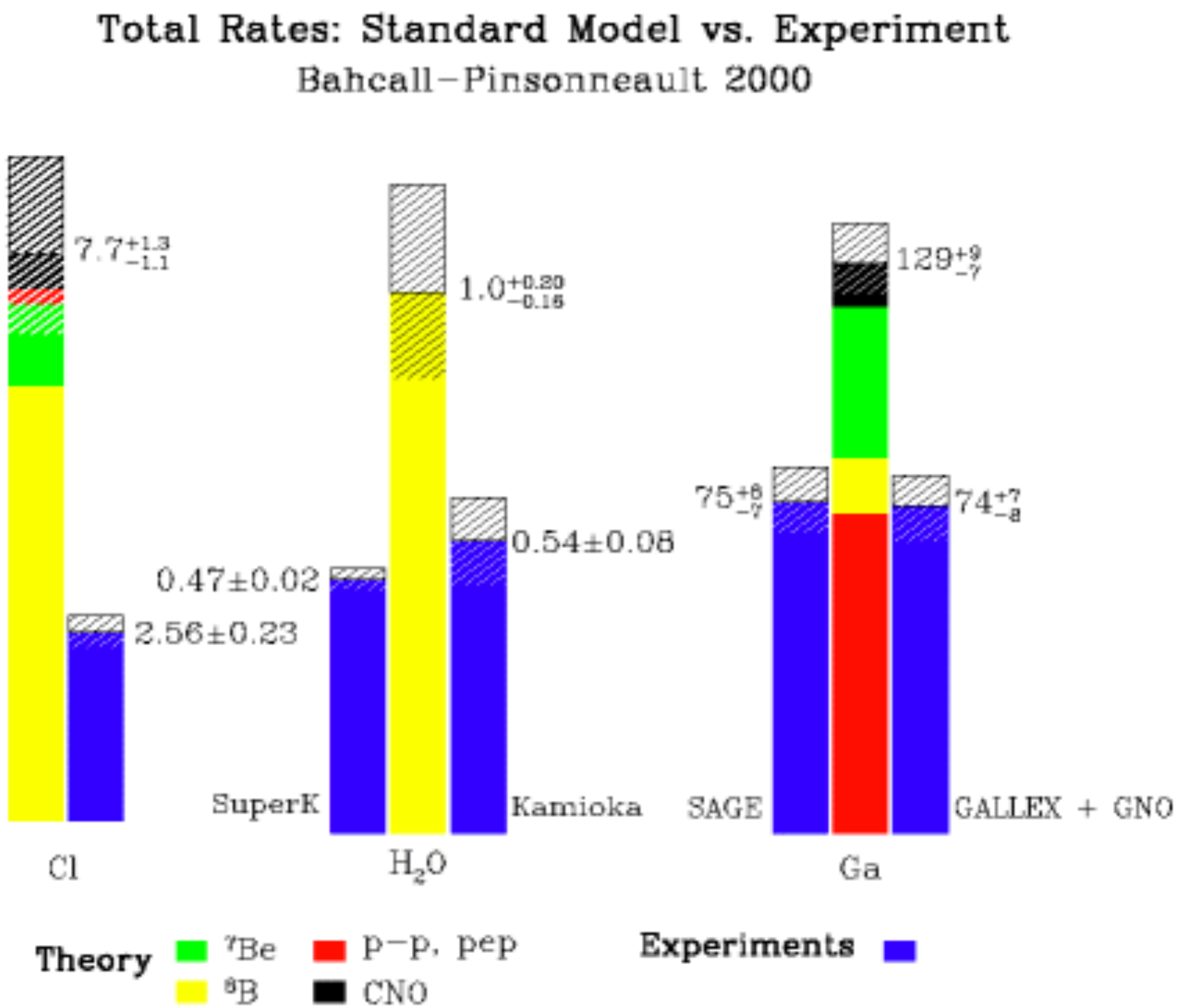
Solar ν deficit: Homestake

- Homestake experiment (R. Davis, Jr. and collaborators)
- About 615 ton of C_2Cl_4
  - In a gold mine in South Dakota
- Method:
  - Exposed for 60-70 days until equilibrium between ν capture and decay (half life: 34.8 days) is reached
  - Chemically extract Ar^{37} (together with known amount of stable Ar^{36}) and introduce it into low-background proportional chamber
  - Reaction rate determined by counting Auger electrons from Ar^{37} decay

$$\nu_e + Cl^{37} \rightarrow Ar^{37} + e^-$$

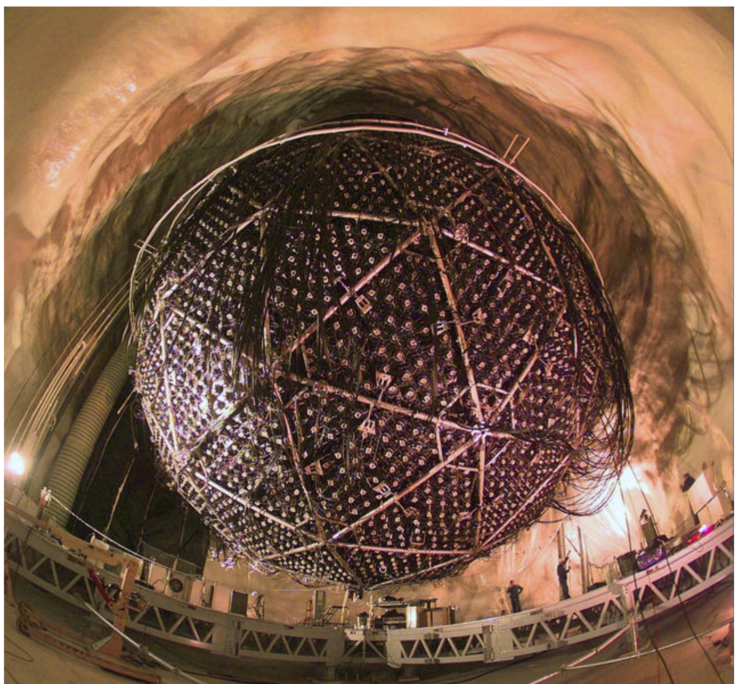


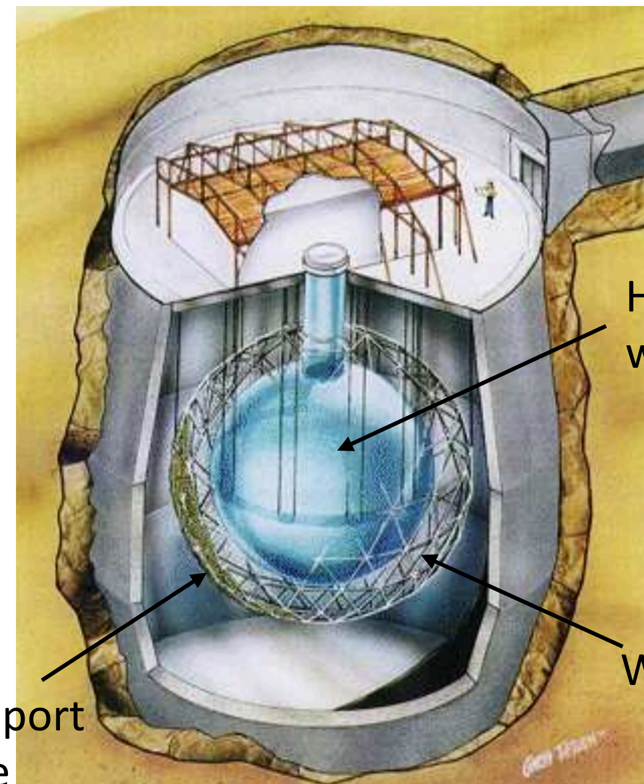
Solar ν deficit: data



Oscillation hypothesis confirmed by SNO

- SNO (Sudbury Neutrino Observatory), Canada:
  - 1000 ton D_2O in spherical vessel, surrounded by H_2O shield
  - Instrumented with photomultipliers (PMTs) to detect Cherenkov light in both D_2O and H_2O

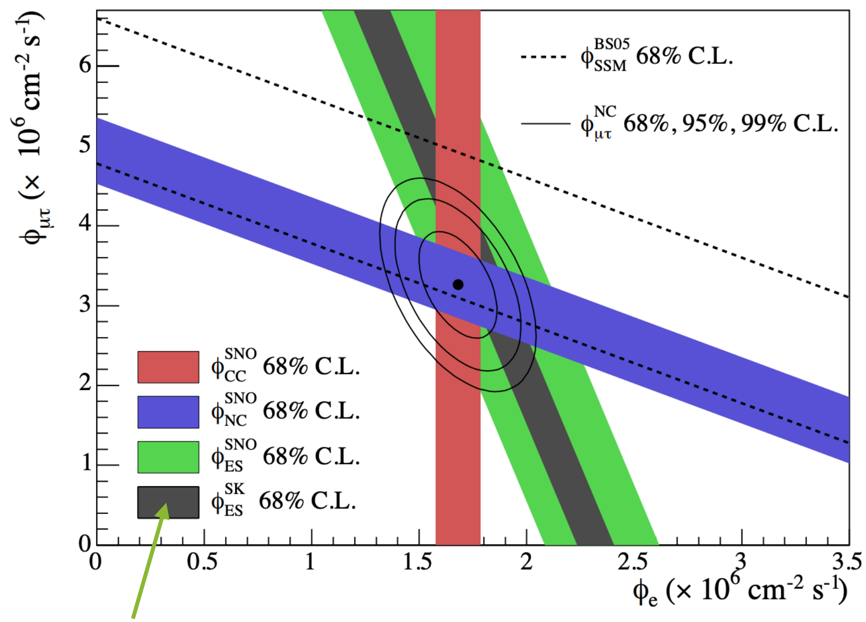




Oscillation hypothesis confirmed by SNO

- 3 simultaneous measurements
  - ν capture: $\nu_e + d \rightarrow e^- + p + p.$
    - only ν_e are detected (charged current)
    - deficit is observed
  - *d* spallation: $\nu_\alpha + d \rightarrow \nu_\alpha + p + n$
    - all flavours interact with the same cross section
    - NO deficit is observed (not sensitive to oscillation)
  - elastic scattering: $\nu_\alpha e^- \rightarrow \nu_\alpha e^-$
    - all flavour interact, but with different cross section ($\sigma_{\nu_e} \sim \frac{1}{6}\sigma_{\nu_\mu+\nu_\tau}$)
- Provides model independent test
- ν_e oscillations confirmed in 2002 by long-baseline reactor experiments (KamLAND, see later)

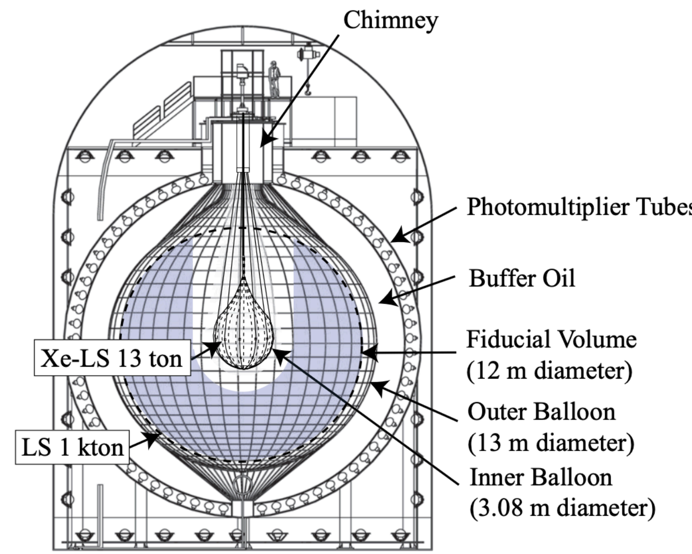
$$\Phi_{CC} = \Phi_e$$
$$\Phi_{ES} = \Phi_e + \frac{1}{6}\,\Phi_{\mu\tau}$$
$$\Phi_{NC} = \Phi_e + \Phi_{\mu\tau}$$



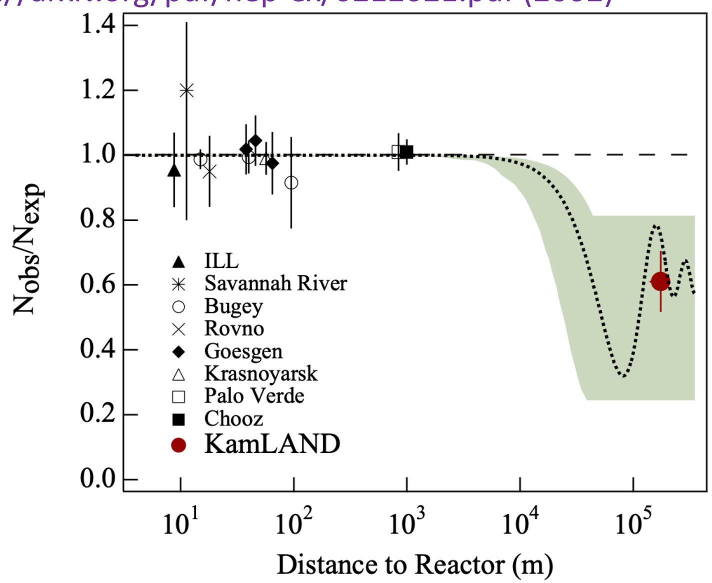
Superkamiokande measurement

Confirmation from reactor neutrino

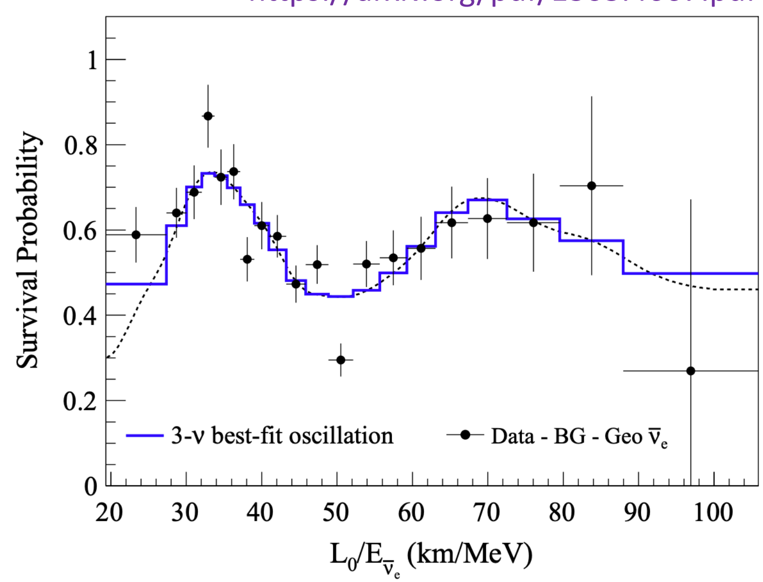
- KamLAND experiment
  - 1000 ton of ultra-pure liquid scintillator in spherical baloon
  - $\bar{\nu}_e$ flux from multiple reactors in Japan and Korea
  - Average distance: 180 km
- In 2002 showed evidence of $\bar{\nu}_e$ disappearance
  - Deficit in agreement with solar model
  - Also in agreement with observations from reactor experiments at shorter distance



https://arxiv.org/pdf/hep-ex/0212021.pdf (2002)



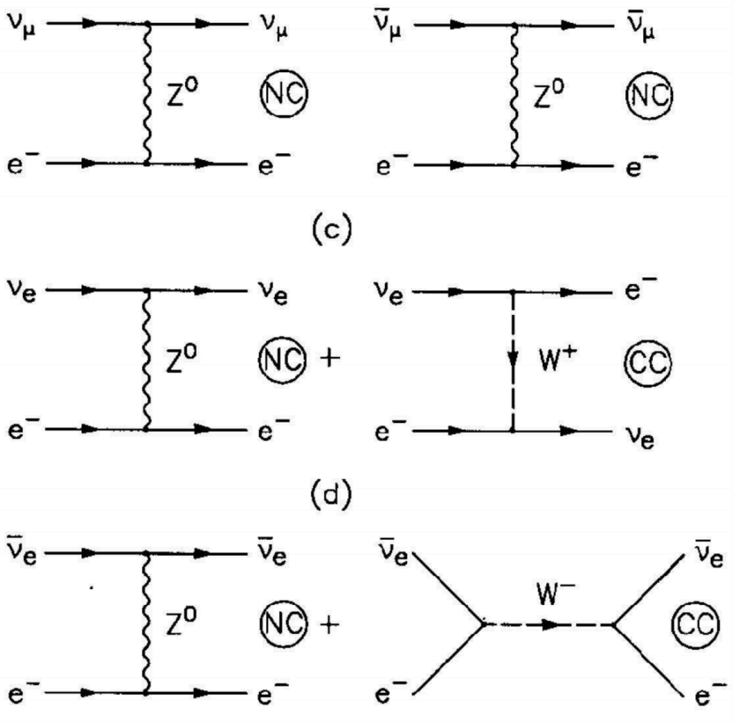
https://arxiv.org/pdf/1303.4667.pdf (2013)



Deficit explanation: neutrino oscillation in matter

- Oscillation in matter has different frequency and amplitude than in vacuum
  - First examined by Wolfenstein in 1978
  - Mikheyev and Smirnov, 1985
- Today, the preferred explanation for solar ν deficit

- At low energies, matter is almost transparent to neutrinos
  - Only elastic forward scattering occurs
- Can define an effective refraction index for ν in matter
  - Analog to elastic scattering of light in glass
- Weak interaction with electrons has different cross sections for ν_e and ν_μ/ν_τ
  - Implies different effective refraction indexes: $n_\mu \neq n_e$



ν oscillation in matter: example with two families

- Assuming constant *E* (constant phase factor in wave function), the free neutrino Hamiltonian is approximately:

$$H = E + \frac{M^2}{2E} \longrightarrow H = \frac{M^2}{2E}.$$

- Taking mixing into account, one can write *H* as mass operator in vacuum.
  - In the mass eigenstate basis:

$$H^{(i)} = \frac{1}{2E}\begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix}$$

  - And in flavour eigenstate basis:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}}_{=U} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$H^{(\alpha)} = \frac{1}{2E}\begin{pmatrix} m_e^2 & m_{e\mu}^2 \\ m_{e\mu}^2 & m_\mu^2 \end{pmatrix} = U H^{(i)} U^\dagger$$

ν oscillation in matter: example with two families

- Expanding $H^{(\alpha)}$:

$$
\begin{aligned}
H^{(\alpha)} &= \frac{1}{2E}\begin{pmatrix} m_1^2\cos^2\theta + m_2^2\sin^2\theta & (m_2^2-m_1^2)\sin\theta\cos\theta \\ (m_2^2-m_1^2)\sin\theta\cos\theta & m_1^2\sin^2\theta + m_2^2\cos^2\theta \end{pmatrix} \\
&\equiv \frac{1}{4E}(m_1^2+m_2^2)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\
&+ \frac{1}{4E}\underbrace{(m_2^2-m_1^2)}_{=\Delta m^2=:D}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix}
\end{aligned}
$$

- The mass eigenvalues are then:

$$m_{1,2} = \frac{1}{2}\left[(m_e+m_\mu) \mp \sqrt{(m_\mu-m_e)^2+4m_{e\mu}^2}\right]$$

  - With:

$$\tan 2\theta = \frac{2m_{e\mu}}{m_\mu - m_e}.$$

ν oscillation in matter: example with two families

- In matter, weak interaction of ν with e adds effective potential to the Hamiltonian
  - Diagonal in flavour states:

$$V_{\alpha\beta}^{(\alpha)} = < \nu_\alpha e^- | H_{WW} | \nu_\alpha e^- > \delta_{\alpha\beta},$$

$$H \longrightarrow H_m = H + V = \frac{M^2}{2E} + V \quad \Leftrightarrow \quad V^{(\alpha)} = \begin{pmatrix} V_e & 0 \\ 0 & V_\mu \end{pmatrix}$$

- With global phase transform on the flavour states:

$$|\nu_\alpha > \rightarrow e^{iV_\mu t} |\nu_\alpha > \quad \Rightarrow \quad V^{(\alpha)} = \begin{pmatrix} V_e - V_\mu & 0 \\ 0 & 0 \end{pmatrix} =: \frac{1}{2E} \begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix}$$

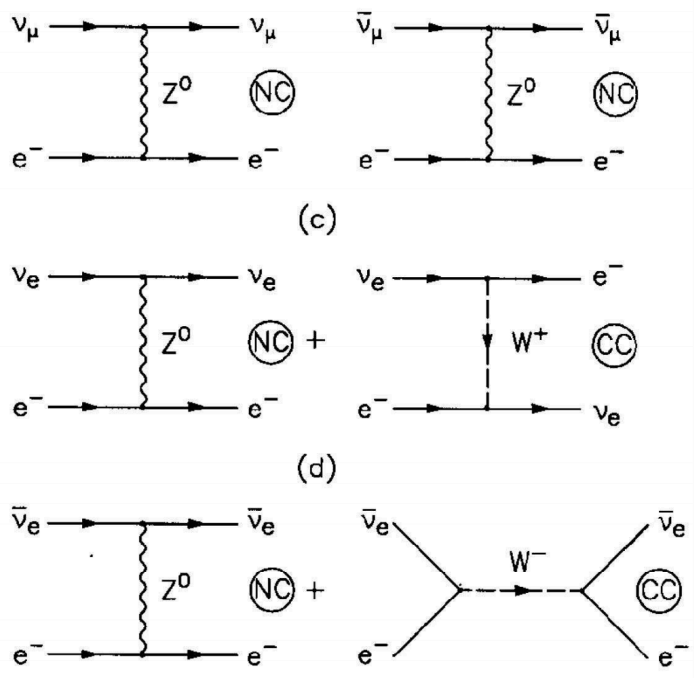
ν oscillation in matter: example with two families

- The difference between ν_e and ν_μ interaction is due to contribution from charged interaction

$$V_e - V_\mu =< \nu_\alpha e^- | H_{WW}^{CC} | \nu_\alpha e^- > \equiv \frac{A}{2E} = \sqrt{2} G_F N_e$$

  - With:

$$\begin{aligned} A &= 2\sqrt{2} G_F E N_e = 2\sqrt{2} G_F E \frac{Y_e \rho}{m_N} \\ &= 1.52 \cdot 10^{-7} \cdot E[\text{MeV}] \cdot Y_e \rho [\text{g/cm}^3] \text{ eV}^2 \end{aligned}$$



$$\begin{aligned} G_F &= \text{Fermi constant for weak } WW = 1.1664 \cdot 10^{-5} \text{ GeV}^{-2} \\ N_e &= \frac{Y_e \rho}{m_N} = \text{electron density in matter} \\ Y_e &= \text{number of electrons/nucleons} \\ \rho &= \text{matter mass density} \\ m_N &= \text{nucleon mass} \approx m_p = 938 \text{ MeV} \end{aligned}$$

➤ On average (expecially for sun matter)

$$N_e \approx N_p \approx N_n \Rightarrow Y_e \approx \frac{1}{2}$$

ν oscillation in matter: example with two families

- The hamiltonian in matter then becomes
  - For the flavour eigenstates:

$$
\begin{aligned}
H_m^{(\alpha)} &= H^{(\alpha)} + \frac{1}{2E}\begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix} \\
&= \frac{1}{2E}\begin{pmatrix} m_e^2 + A & m_{e\mu}^2 \\ m_{e\mu}^2 & m_\mu^2 \end{pmatrix} \\
&= \frac{1}{4E}(m_1^2 + m_2^2 + A)\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \\
&+ \frac{1}{4E}\begin{pmatrix} A - D\cos 2\theta & D\sin 2\theta \\ D\sin 2\theta & -A + D\cos 2\theta \end{pmatrix}
\end{aligned}
$$

ν oscillation in matter: example with two families

- The Hamiltonian in vacuum mass eigenstates can then be derived:

$$
\begin{aligned}
H_m^{(i)} &= U^\dagger H_m^{(\alpha)} U = H^{(i)} + \frac{1}{2E} U^\dagger \begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix} U \\
&= \frac{1}{2E} \begin{pmatrix} m_1^2 + A\cos^2\theta & A\sin\theta\cos\theta \\ A\sin\theta\cos\theta & m_2^2 + A\sin^2\theta \end{pmatrix},
\end{aligned}
$$

- Not any more diagonal in (ν_1, ν_2)
  - we now have $\nu_1 \leftrightarrow \nu_2$ transitions due to weak interactions with the matter
  - mass eigenstates in matter: $(\nu_{1m}, \nu_{2m}) \neq (\nu_1, \nu_2)$

ν oscillation in matter: example with two families

- Mass eigenstates in matter: (ν_{1m} , ν_{2m}) obtained by diagonalizing the Hamiltonian operator in the flavour representation

$$U_m^\dagger H_m^{(\alpha)} U_m = H_m^{(i)} = \frac{1}{2E} M_m^{(i)2} := \frac{1}{2E} \begin{pmatrix} m_{1m}^2 & 0 \\ 0 & m_{2m}^2 \end{pmatrix}$$

  - Where U_m is the mixing matrix in matter:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m & \cos\theta_m \end{pmatrix}}_{=U_m} \cdot \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix},$$

- One can then compute the mass eigenvalues in matter, as well as the mixing angle θ_m:

$$m_{1,2m}^2 = \frac{1}{2}\left[(m_1^2+m_2^2+A) \mp \sqrt{(A - D\cos 2\theta)^2 + D^2 \sin^2 2\theta}\right]$$

$$\tan 2\theta_m(A/D) = \frac{2D\sin 2\theta}{-A + D\cos 2\theta - A + D\cos 2\theta} = \frac{\sin 2\theta}{\cos 2\theta - \frac{A}{D}}$$

ν oscillation in matter: example with two families

- From the expressions for $m_{1,2m}$ and θ_m one can derive the oscillation parameters in matter
  - As a function of those in vacuum

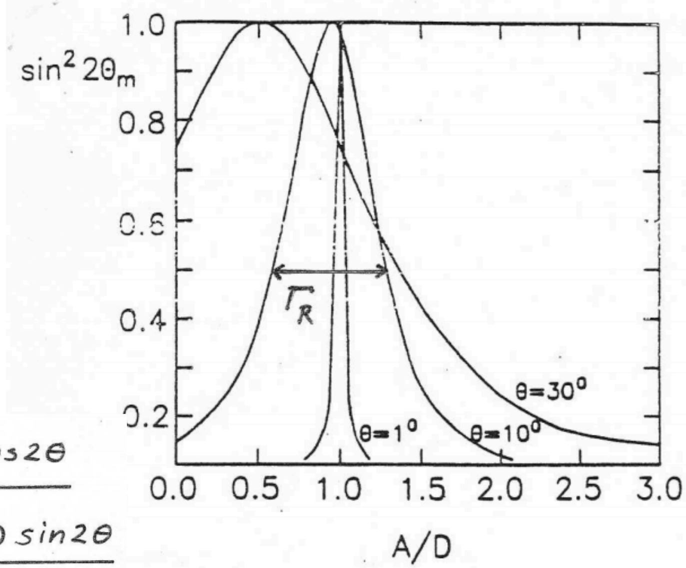
- Mass slitting:

$$D_m \equiv m^2_{2m} - m^2_{1m} = D\sqrt{(\frac{A}{D} - \cos 2\theta)^2 + \sin^2 2\theta} \; > 0$$

- Oscillation amplitude is a resonance curve as a function of *A/D*:

$$\sin^2 2\theta_m(A/D) = \frac{\tan^2 2\theta_m}{1 + \tan^2 2\theta_m} =$$

$$= \frac{\sin 2\theta}{(\frac{A}{D} - cos2\theta)^2 + \sin^2 2\theta} \, ,$$



$\left(\frac{A}{D}\right)_R = \cos 2\theta$

$\Gamma_R = 2D \sin 2\theta$

ν oscillation in matter: example with two families

- Survival and transition probabilities then are:

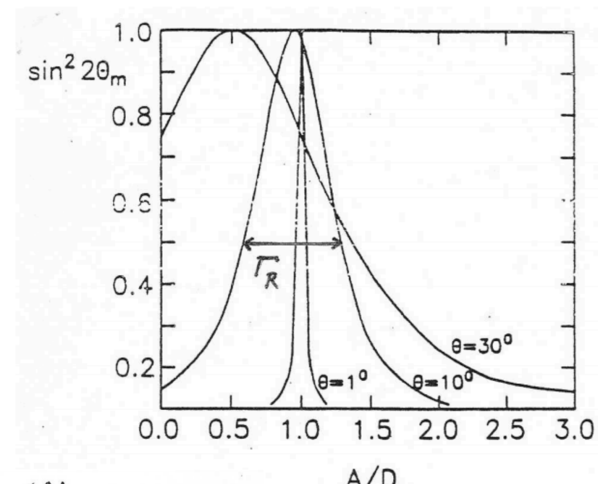
$$\mathcal{P}(\nu_e \to \nu_e) = 1 - \sin^2 2\theta_m \sin^2 \frac{\Delta_m}{2}$$

$$\mathcal{P}(\nu_e \to \nu_\mu) = \sin^2 2\theta_m \sin^2 \frac{\Delta_m}{2}$$

$$\Delta_m := \frac{D_m}{2}\frac{L}{E}$$

- Maximal amplitude for θ_m=45°
  - Can be reached for any θ, when the A/D ratio is:

$$\frac{A}{D} = \frac{2\sqrt{2}G_F E N_e}{\Delta m^2}$$



$\left(\frac{A}{D}\right)_R = \cos 2\theta$

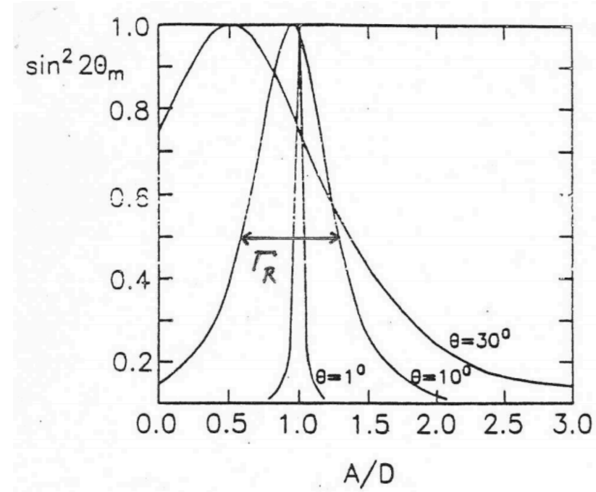
$\Gamma_R = 2D \sin 2\theta$

- For $\bar{\nu}$: $A \to -A$
  - Solar neutrinos must be ν and not $\bar{\nu}$

Mikheyev-Smirnov-Wolfenstein Effect

- Resonance in oscillation amplitude, as a function of *A/D*
  - Depends on density N_e, neutrino energy and vacuum oscillation parameters
  - Resonance at:

$$A = A_R = D\cos 2\theta,$$



$\left(\frac{A}{D}\right)_R = \cos 2\theta$

$\Gamma_R = 2D\sin 2\theta$

- In the sun, matter density changes along ν path
  - mass eigenstates split as a function of $A \sim N_e$, for given ν energy

- At the sun centre: $\rho = 150\ \text{g/cm}^3,\ Y_e = 0.7,$ $\quad N_{e0} = \rho Y_e / m_N.$
  - Density then decreases as a function of radius

$$N_e(R) = N_{e0} e^{-10.5 R/R_\odot}. \qquad R_\odot = 7 \cdot 10^8$$

Mikheyev-Smirnov-Wolfenstein Effect

- 3 regimes

1. Sun nucleus, large N_e:

$$\frac{A}{D} \gg 1 \;\Rightarrow\; A > A_R$$
$$\Longrightarrow \quad \sin^2 2\theta_m \approx \frac{\sin^2 2\theta}{(A/D)^2} \approx 0$$
$$\Longrightarrow \quad \theta_m = 90^\circ$$
$$\Longrightarrow \quad D_m \approx A$$

- Oscillation suppressed
- Neutrino states at the source:

$$|\nu_{1m}> \approx -|\nu_\mu> \qquad |\nu_{2m}> \approx |\nu_e>$$

$$m^2_{1m} \approx m^2_2 \qquad m^2_{2m} \approx A$$

With:

$$m_{1,2m} \approx \tfrac{1}{2}[m_1^2 + m_2^2 + A \mp (A - D)]$$

$$D = m_2^2 - m_1^2 > 0 \qquad A > 0$$

Mikheyev-Smirnov-Wolfenstein Effect

- 3 regimes

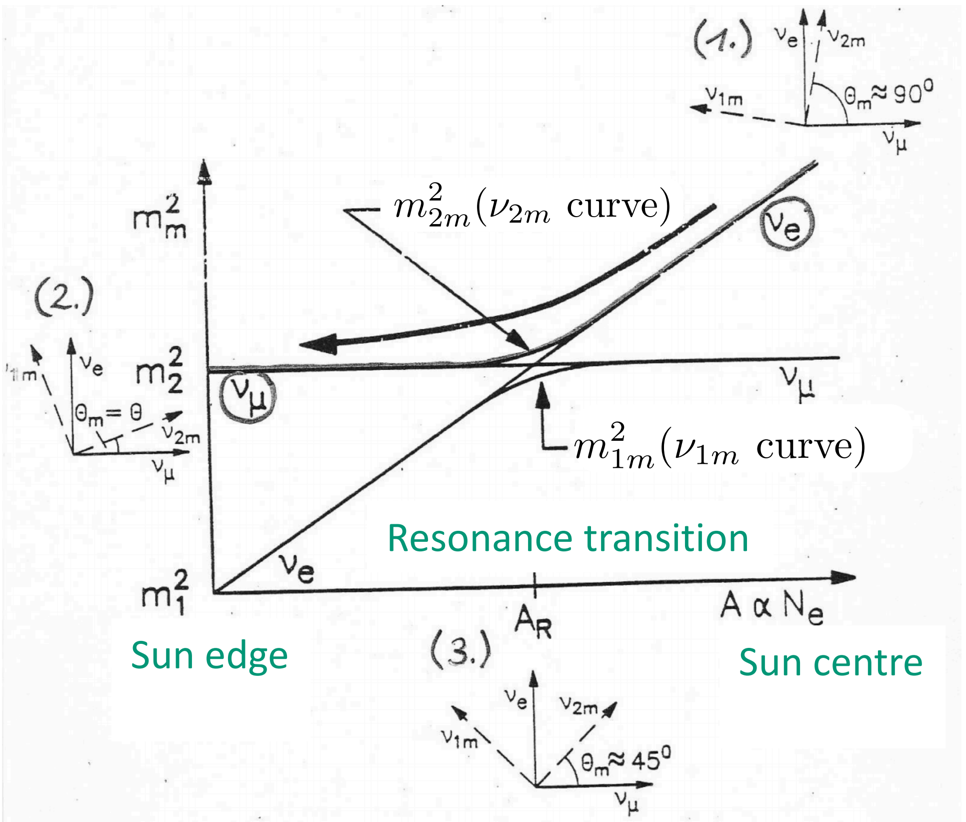
3. Resonance transition during transit through sun
   - Continuous density change between 1. and 2.
   - At resonance:
     - Amplitude is maximal
     - Mass splitting is maximal

$\Rightarrow$ 'Flavour flip'

- Neutrino states at resonance:

$$|\nu_{1m}>=\frac{1}{\sqrt{2}}(|\nu_e>+|\nu_\mu>)$$
$$|\nu_{2m}>=\frac{1}{\sqrt{2}}(|\nu_e>-|\nu_\mu>)$$

$$m^2_{1m}\approx m^2_{2m}$$
$$m^2_1\approx m^2_2$$

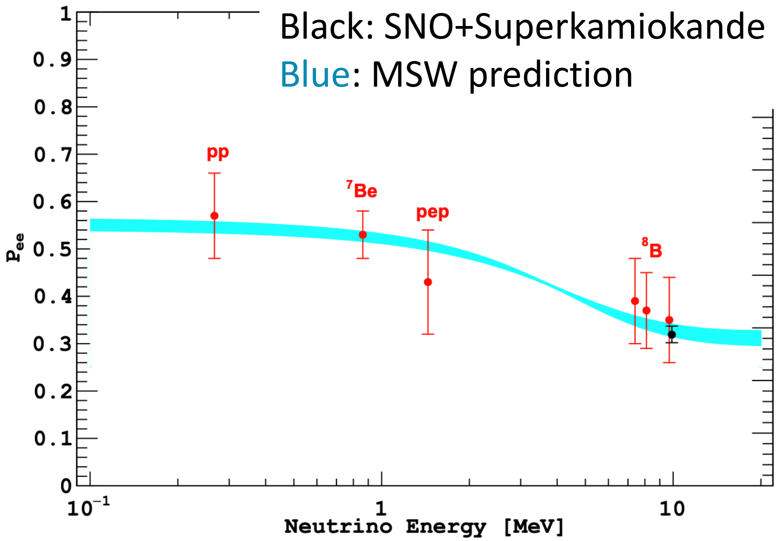


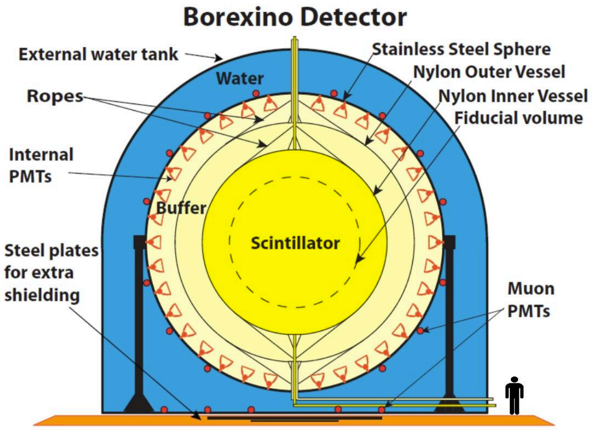
Deficit explanation: neutrino oscillation in matter

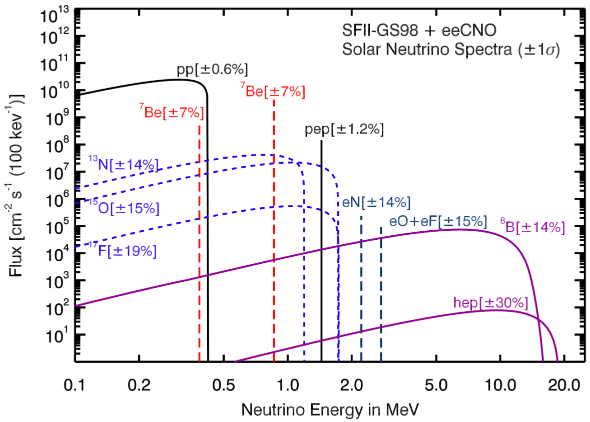
- Observed deficit in solar ν_e consistent with oscillation in solar matter.
  - No evidence of further oscillation in vacuum.

- Confirmation with measurements at multiple ν energies by Borexino experiment (Gran Sasso Laboratories, Italy)
  - Borexino:
    - 300 ton of liquid scintillator
    - 0.19 MeV energy threshold, 5% energy resolution at 1 MeV
    - Allows to distinguish ν from different points of the solar ν spectrum

Red: Borexino measurements
Black: SNO+Superkamiokande
Blue: MSW prediction







State of the art: what do we know about neutrinos?

Table 14.6: Experiments contributing to the present determination of the oscillation parameters.

Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}, $\lvert\Delta m^2_{31,32}\rvert$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\lvert\Delta m^2_{31,32}\rvert$, θ_{13},$\delta_{\rm CP}$
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\lvert\Delta m^2_{31,32}\rvert$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	$\delta_{\rm CP}$	θ_{13} , θ_{23}

http://pdg.lbl.gov/2019/reviews/rpp2019-rev-neutrino-mixing.pdf

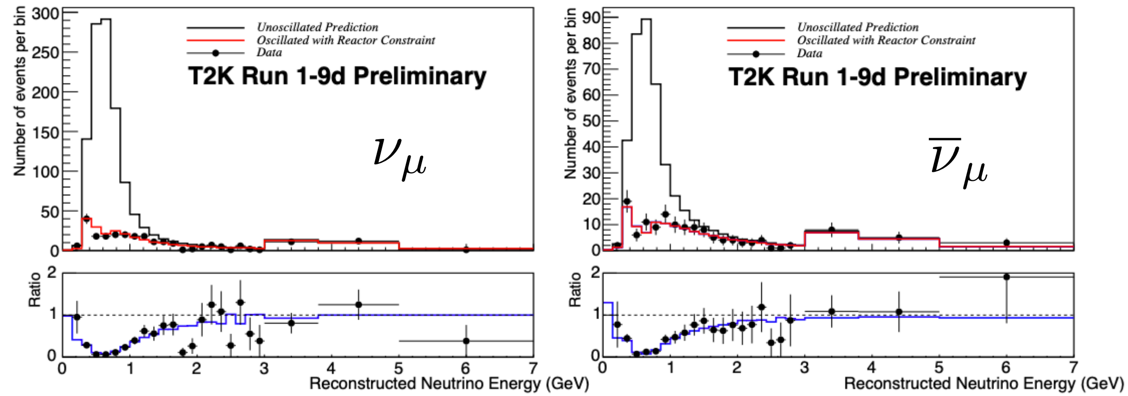
ν_μ oscillation

- Atmospheric neutrino:
  - Disappearing ν_μ
  - Appearing ν_τ

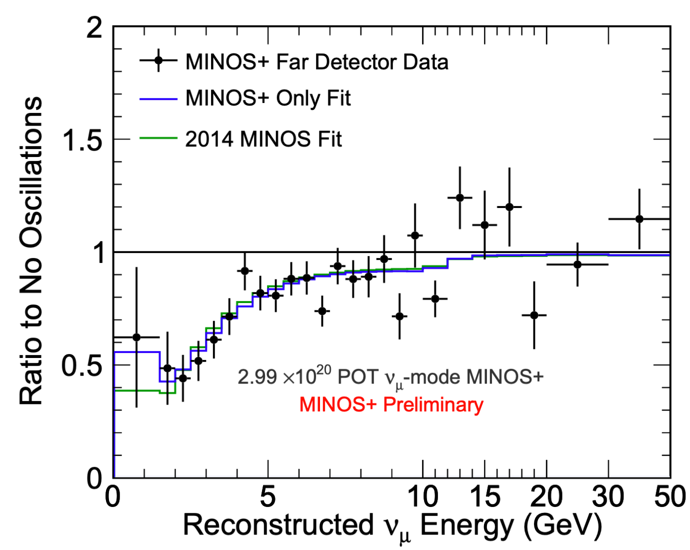
- Long baseline accelerator:
  - Disappearing ν_μ
  - Appearing ν_τ
  - Appearing ν_e

Latest long baseline accelerator neutrino experiments

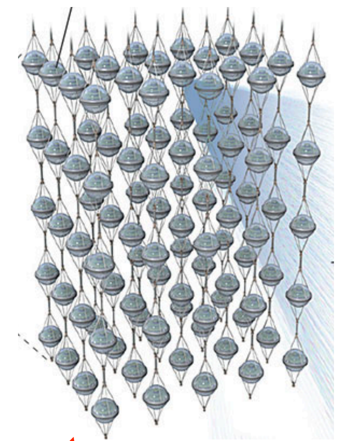
- T2K (started operations in 2010)
  - New high-intensity beam, on Superkamiokande detector
  - Tuned on the first maximum of oscillation probability ($\Delta m^2 = 2.5 \cdot 10^{-3}$ eV)



- MINOS/MINOS+
  - beam from Fermilab to Soudan mine (L=735 km)
  - Iron+scintillator tracking calorimeter in magnetic field
- NOvA (started in 2014)
  - beam from Fermilab to Ash River, Minnesota (L=810 km)
  - tracking calorimeter: planes of polyvinyl chloride cells filled with liquid scintillator

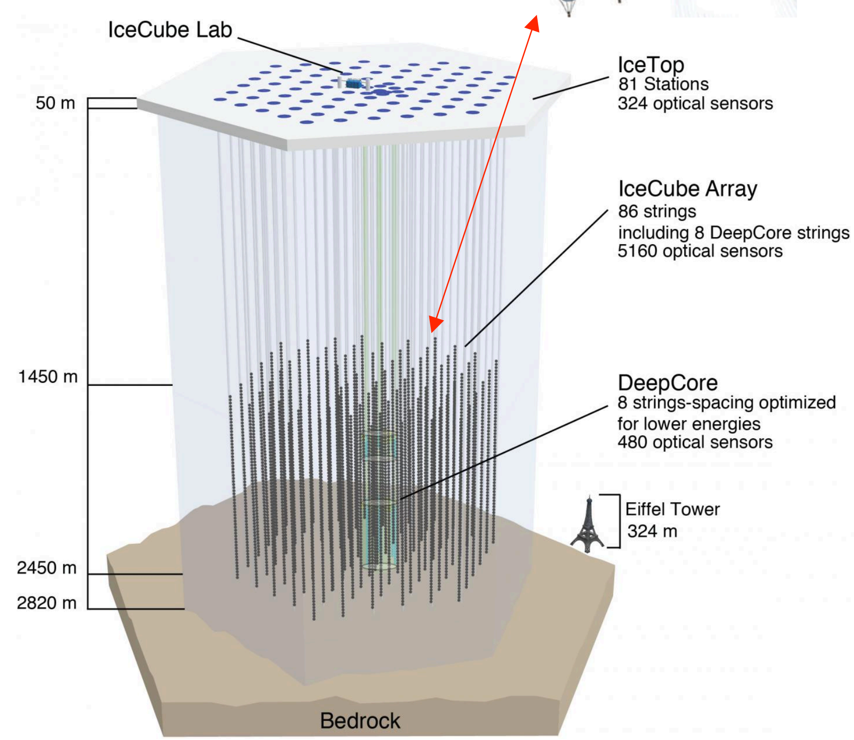


Other atmospheric ν measurements



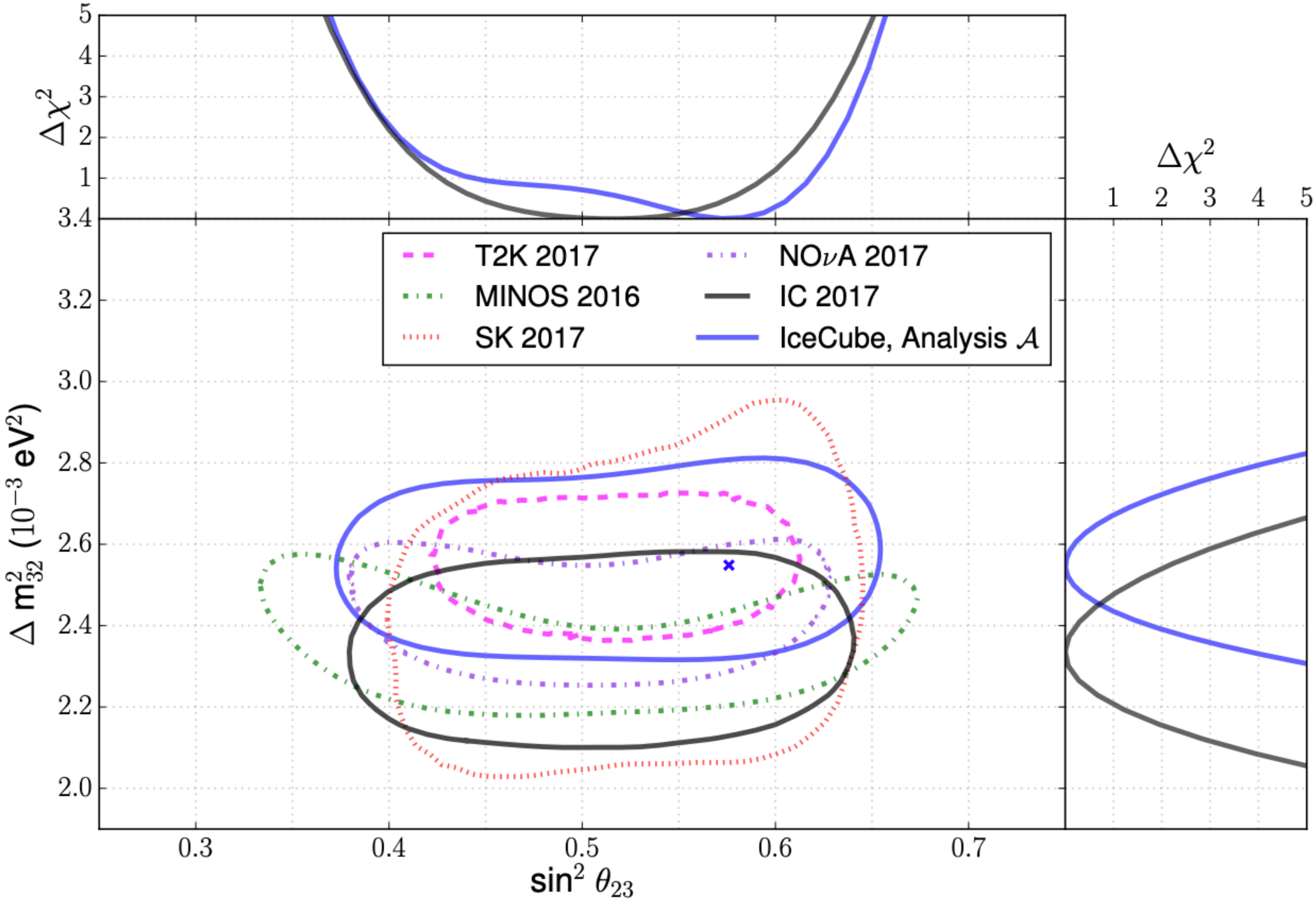
- Atmospheric ν_μ oscillations confirmed by
  - MACRO (Gran Sasso, Italy),
  - Soudan2 (Soudan Underground Mine, Minnesota)
  - ANTARES (Marseille, France) / IceCube (South Pole)

- <u>ANTARES / IceCube</u>
  - Cherenkov detector: strings of photomultipliers inside natural body of water
    - ANTARES: in deep Mediterranean sea, near Marseille, France
    - IceCube (currently in operation): in polar ice-cap, close to geographical South Pole
  - Primarily dedicated to neutrino astronomy
    - neutrinos from supernovas
  - Also sensitive to atmospheric neutrinos



Measuring Δm_{23}

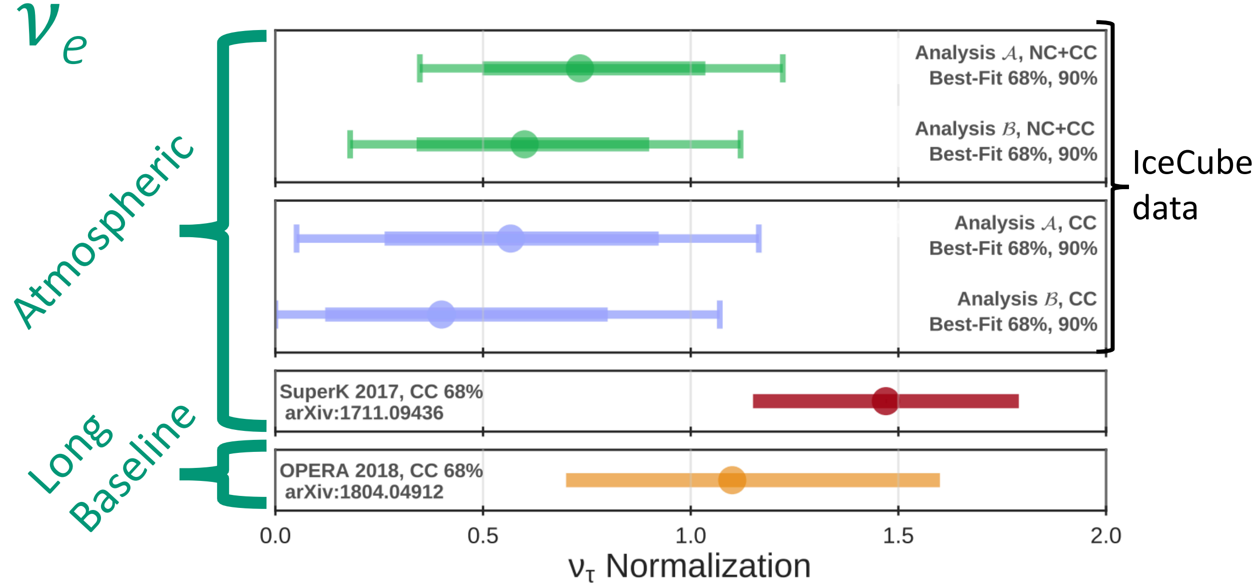
arXiv:1901.05366 [hep-ex] (2019)



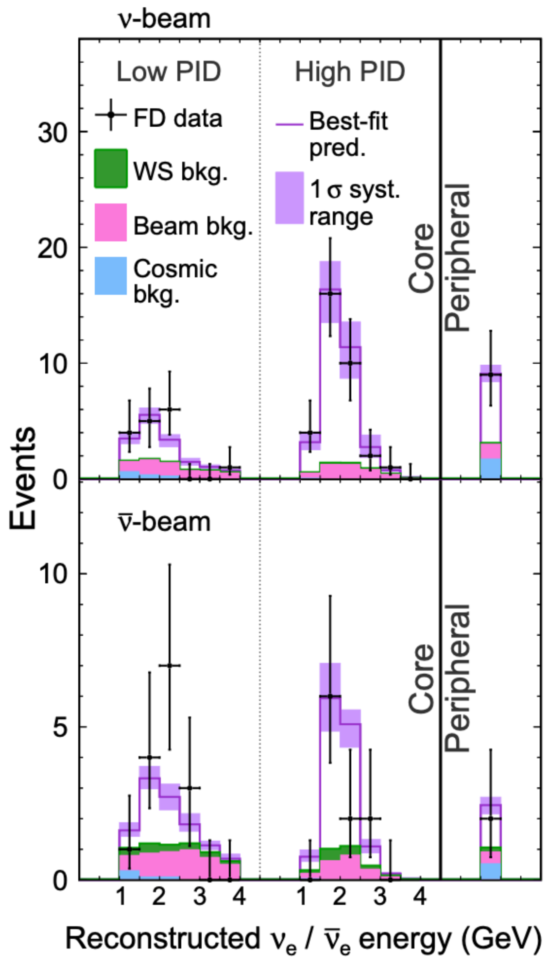
➢ 'ν_τ Normalization' = 1 means standard neutrino oscillation

Appearing ν_τ / ν_e

$$\nu_\mu \rightarrow \nu_\tau \Rightarrow$$



arXiv:1901.05366 [hep-ex] (2019)



$$\Leftarrow \nu_\mu \rightarrow \nu_e$$

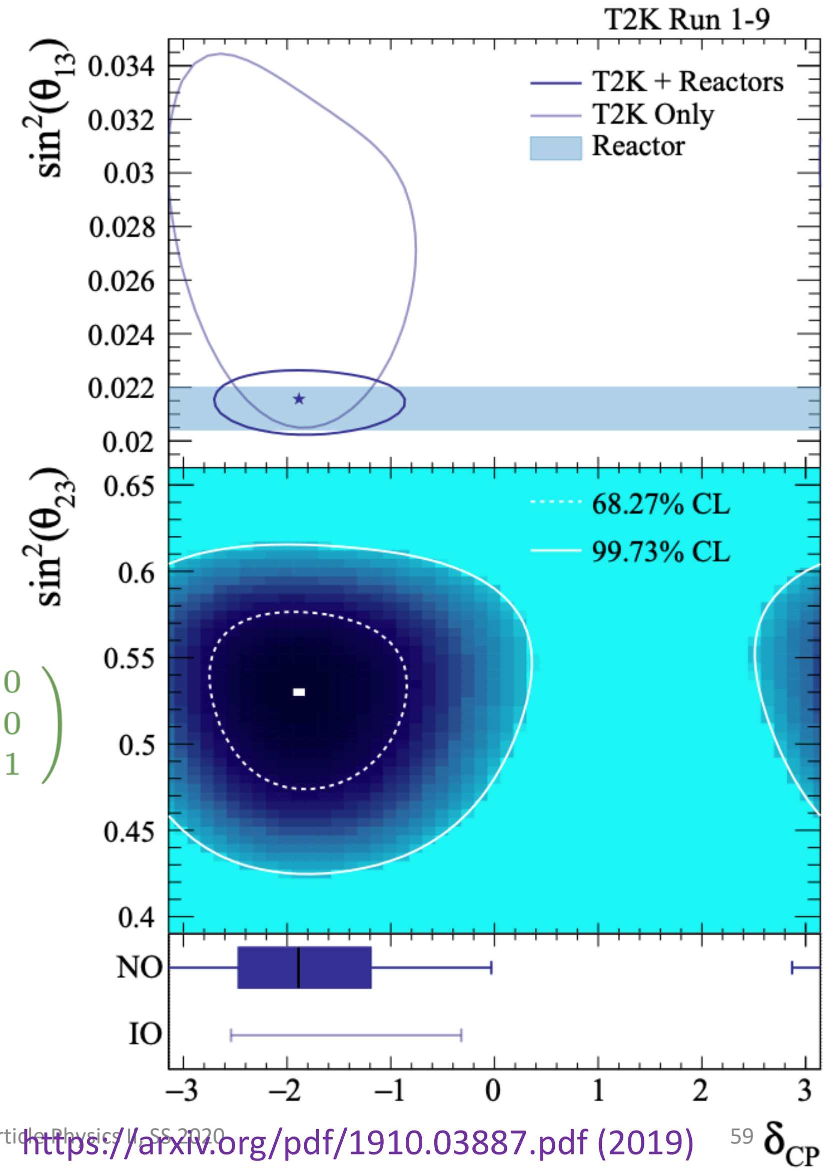
- First indication by T2K in 2011
  - 7σ in 2014
- From 2016 also confirmed by NoVA

NoVA, 2019 (arXiv:1906.04907)

First evidence of CP violations

- T2K:
- 2σ evidence of non-zero δ_{CP}
  - CP-violating phase
- We are starting to probe CP violation in leptons

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\phi_1} & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



https://arxiv.org/pdf/1910.03887.pdf (2019)

ν_e oscillation

- Solar neutrino (discussed before)
- Long baseline reactors (KamLAND, discussed before)

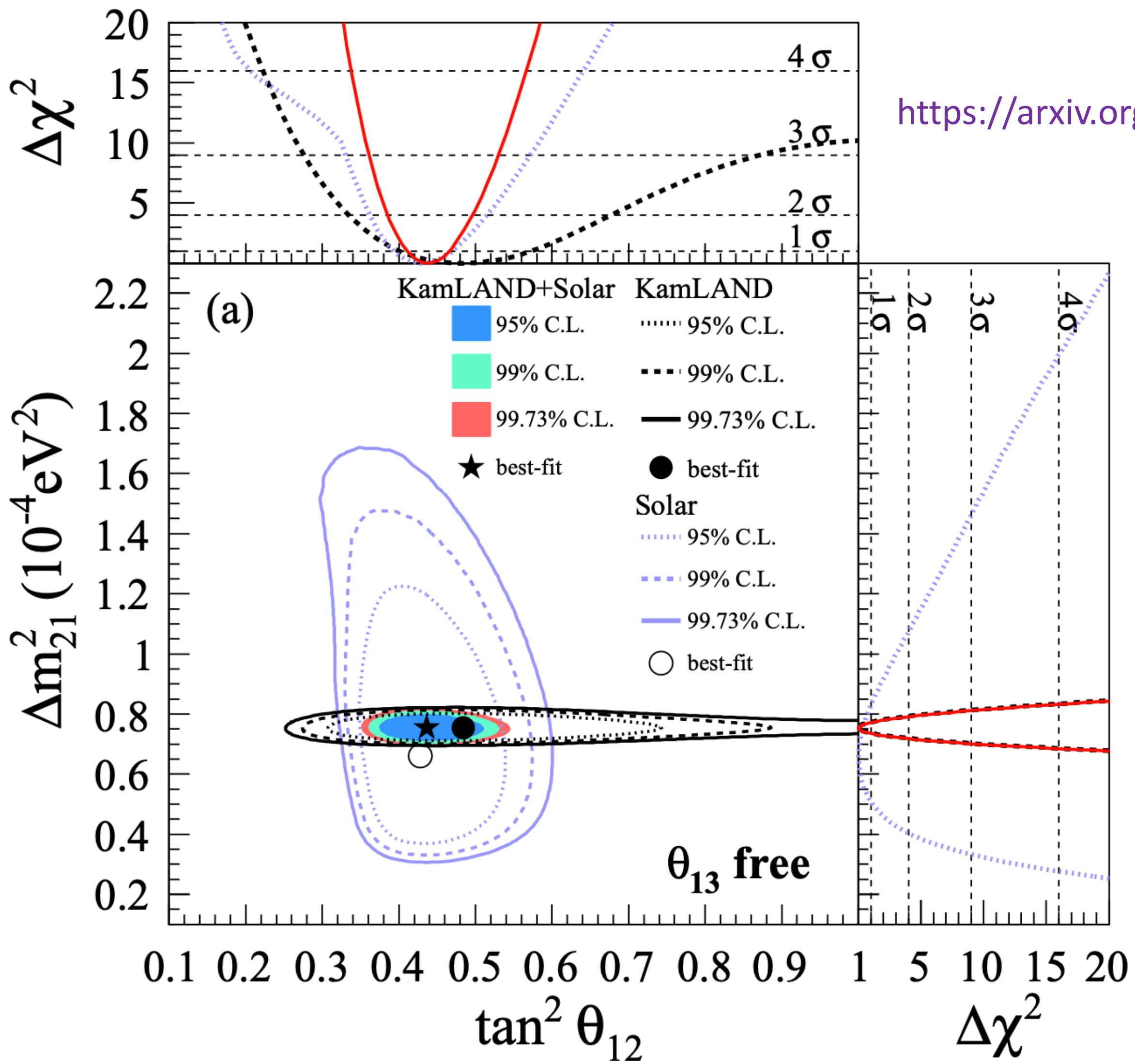
→ $\Delta m_{12}, \theta_{12}$

- Medium baseline reactors (Daya-Bay, Reno, D-Chooz: see later)

→ θ_{13}

Measuring Δm_{23}

https://arxiv.org/pdf/1303.4667.pdf

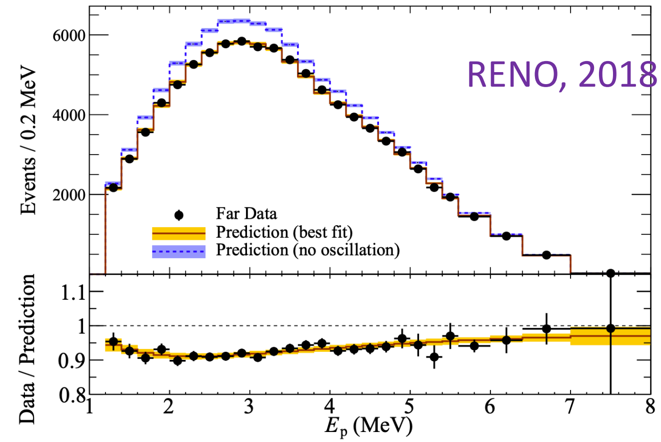


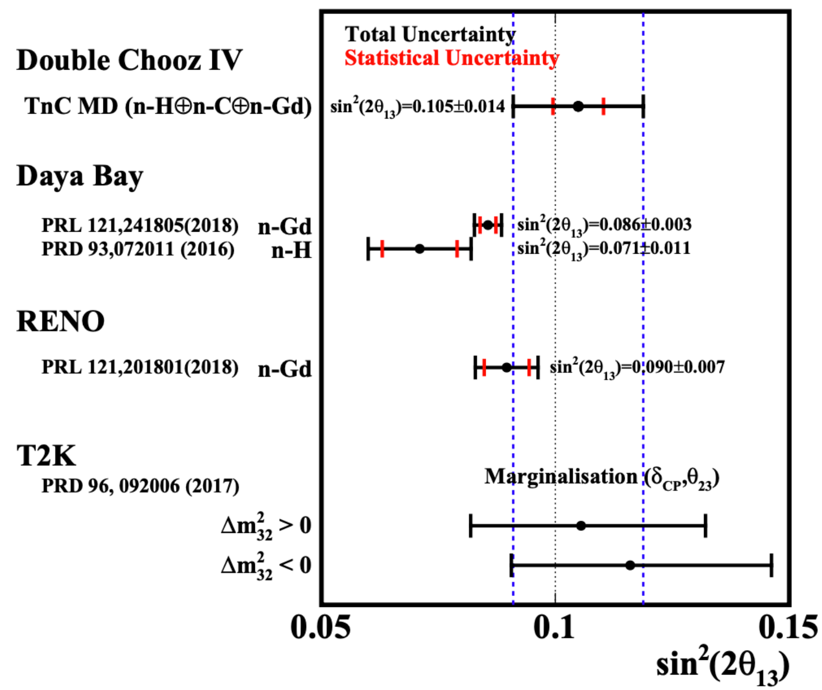
Measuring θ_{13}: reactor experiments

- $L \sim 1$ km: can measure $\sin^2(2\theta_{13})$ from $\bar{\nu}_e$ disappearance

- First searches in the 90's (CHOOZ, Palo Verde)
- Measurements at Double CHOOZ, Daya-Bay, RENO
  - All started in 2011, first results in 2012
- Double detector (near-far) to go below limits set by previous experiments
  - Double CHOOZ (France): liquid scintillator
  - Daya-Bay (China), RENO (Korea): Cherenkov detector

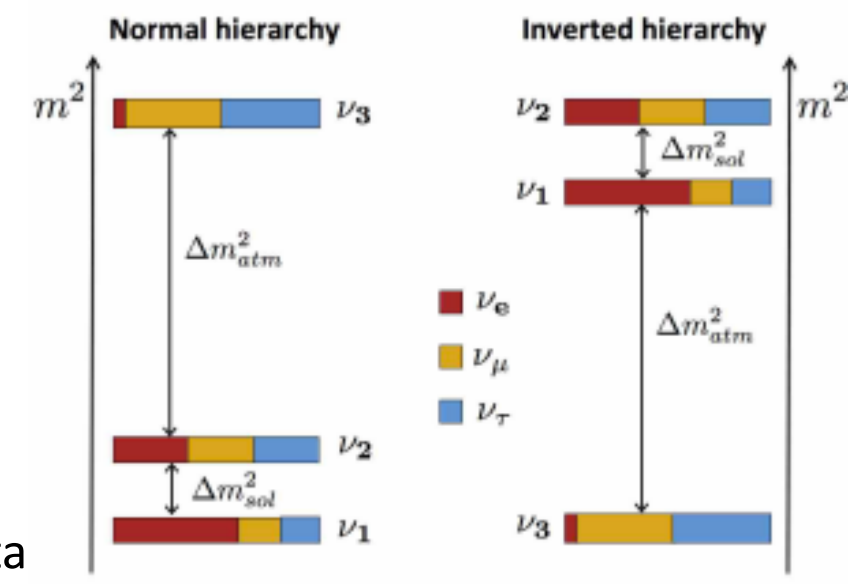
- Some $\sim 1\sigma$ tension between the measurements





Interpreting the results

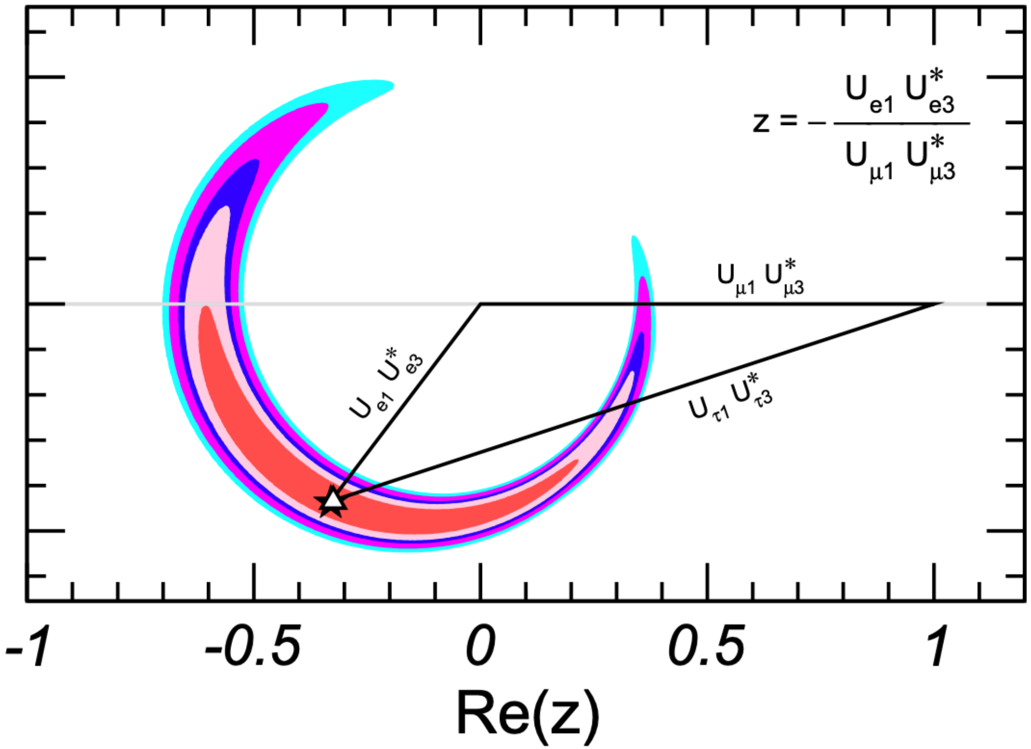
- To fully determine which is the ordering of the 3 mass eigenstates, we need 6 parameters
  - 2 Δm
  - 3 mixing angles
  - 1 CP phase
- Experiments in general are in agreement with one another
- Two scenarios compatible with the data we have
  - Normal hierarchy vs Inverted hierarchy
- We are missing (or not known with enough precision): θ_{23}, δ_{CP}



Interpreting the results: leptonic unitarity triangle

- Results available can be used to build a 'leptonic unitarity triangle', in the same way as for the quarks
  - Hints at nonzero area: CP violation occurs
  - But still compatible with CP conservation within 1-2 σ

http://pdg.lbl.gov/2019/reviews/rpp2019-rev-neutrino-mixing.pdf (2019)



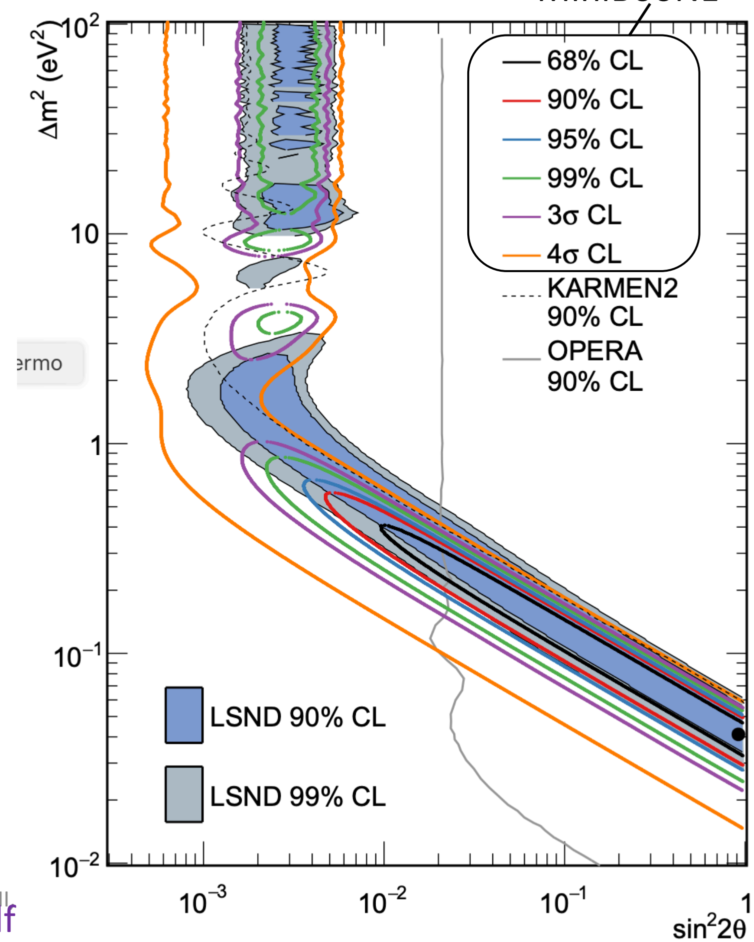
Anomalies: short distance $\nu_\mu \rightarrow \nu_e$

- ○ LSND experiment: ν from 780 MeV p-LINAC at Los Alamos (*L=30* m)
  - Search for $\nu_\mu \longrightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) oscillation
  - Observed excess compatible with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance
- ○ KARMEN experiment: ν from 800 MeV proton accelerator at RAL, London (*L=28* m)
  - No $\bar{\nu}_e$ excess observed, excludes parameter area favoured by LSND
- ○ MiniBooNE: ν from Fermilab Booster beamline
  - Same parameter region as LSND
  - Observes both ν_e and $\bar{\nu}_e$ excess at 4.7σ

- ○ To be further investigated with multi-detector experiments (in preparation)
  - ➤ LSND and MiniBooNE were single-detector experiments
  - e.g.
    - ➤ SBN program, Fermilab
    - ➤ JSNS[2] experiment, JPARK (Japan)

Note:
- ➤ T2K: L/E ~ 500 m/MeV
- ➤ Here: L/E ~ 1 m/MeV

Not the same effect!



MiniBooNE analysis, 2018
https://arxiv.org/pdf/1805.12028.pdf

- Neutrino oscillation still a quite open field

- Vast variety of new experiment planned for upcoming years

Neutrino mass direct measurements

- Neutrino oscillation can only tell the difference between neutrino masses
- For the absolute scale, a direct measurement is needed

- ν_e : measure end point of e energy spectrum from tritium β decay (see later)

- ν_μ: muon pulse measurement in weak π decay (PSI, Zürich) $\pi^+ \to \mu^+ \nu_\mu$
  - masses of μ and π known very well from energy levels of pionic atoms and muon magnetic moment

$$\mathrm{sum}_i m_i |U_{\mu i}|^2 < 190\ keV,$$

- ν_τ: end point of hadron invariant mass in hadronic τ decays:

$$m_{\nu_\tau} = m_\tau - \mathrm{Max}(m_{\mathrm{Hadronen}})$$

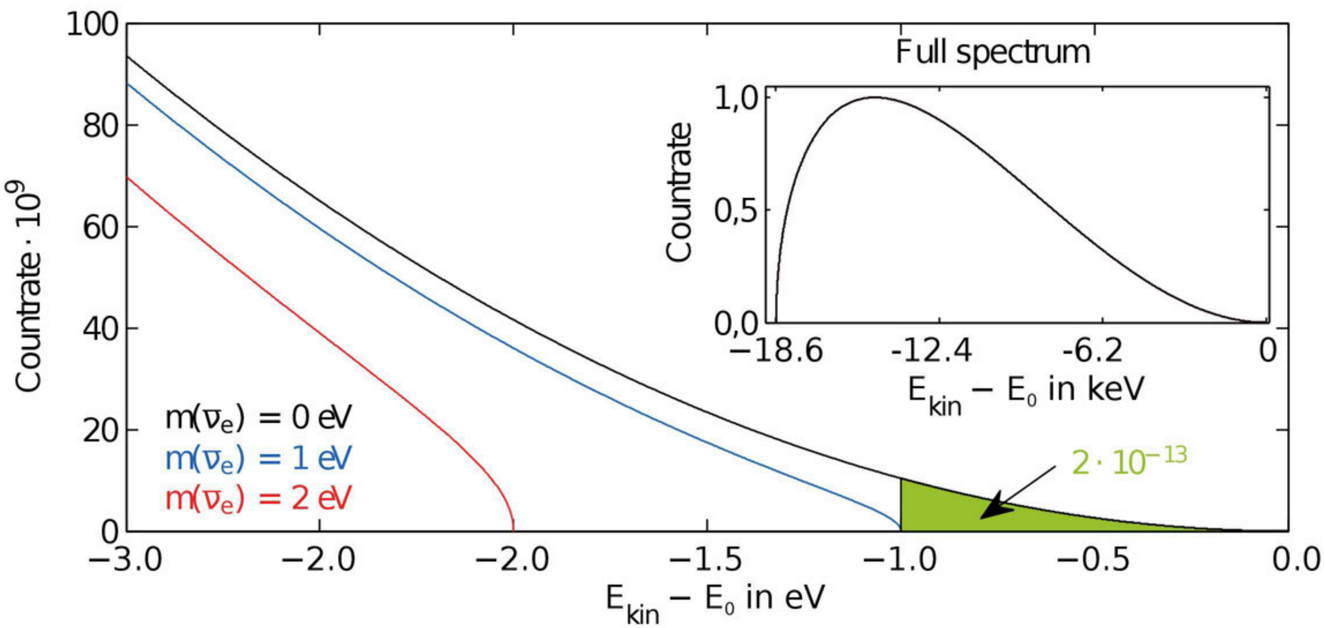
  - m_τ known precisely from e^+e^- storage rings (BES, Beijing)
  - Best results from ALEPH, at LEP

$$\mathrm{sum}_i m_i |U_{\tau i}|^2 < 18.2\ MeV.$$

ν_e mass measurement

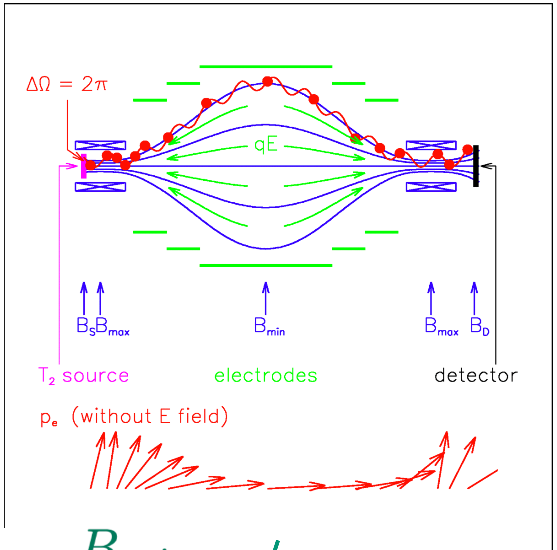
- Measure end point of *e* energy spectrum from tritium β decay

$$H^3 \rightarrow He^3 + e^- + \overline{\nu}_e$$

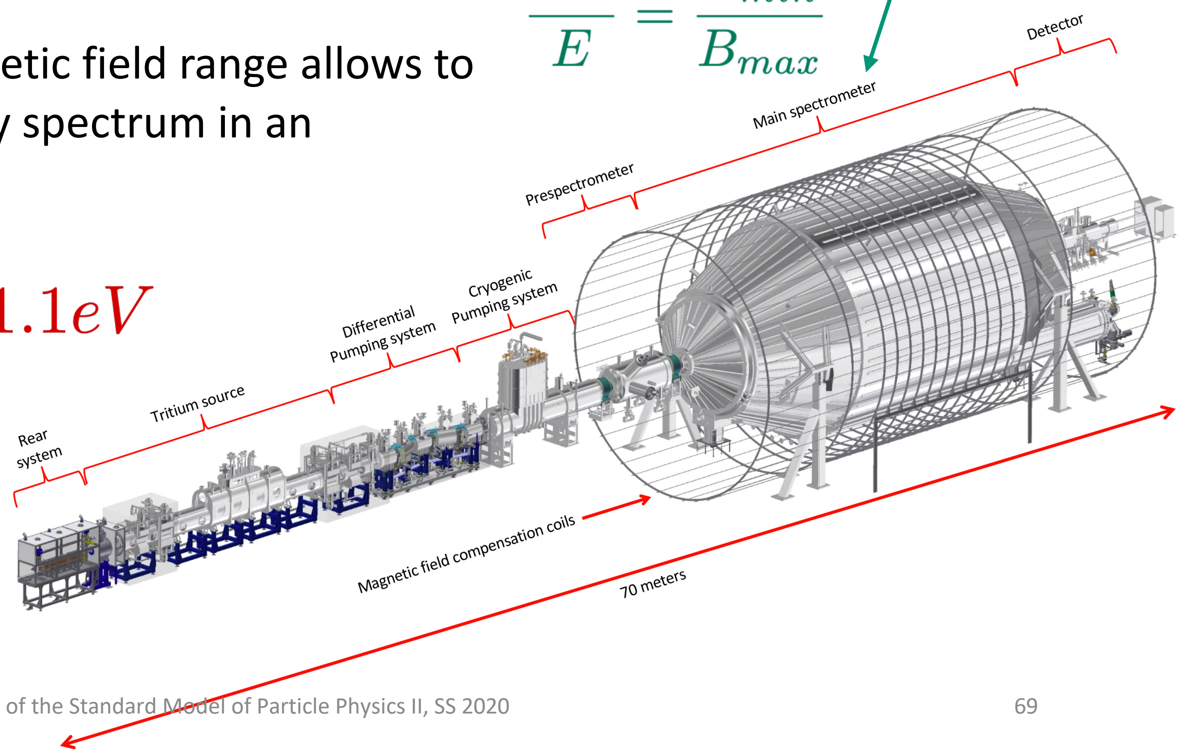


ν_e mass measurement

- Magnet spectrometers:
  - First experiments: Mainz, Troitsk
  - Best limit from KATRIN experiment (Karlsruhe)
  - Magnetic field selects only electrons with high enough energy
    - ➤ By varying the magnetic field range allows to measure the β decay spectrum in an integrating mode



$$\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$$



$$\text{sum}_i m_i |U_{ei}|^2 < 1.1eV$$

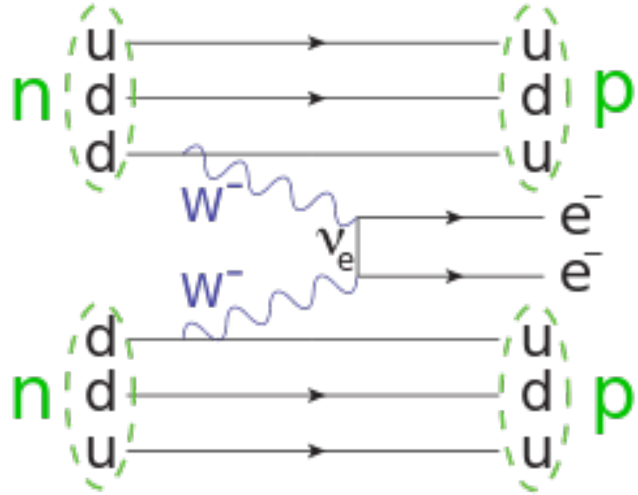
Majorana neutrinos?

- If neutrinos are (massive) Majorana particles ($\bar{\nu} = \nu$)
  - Neutrinoless double β decay must occur
  - Half life proportional to ν mass squared

- Signature: sum of electron energies equal to *Q-value* from nuclear transition
  - Ultra-low background experiments, large source mass needed

$$T_{1/2}^{0\nu} \sim |<m_{ee}>|^2$$

$$<m_{ee}> = \sum_i m_i U_{ei}^2$$



Majorana neutrinos?

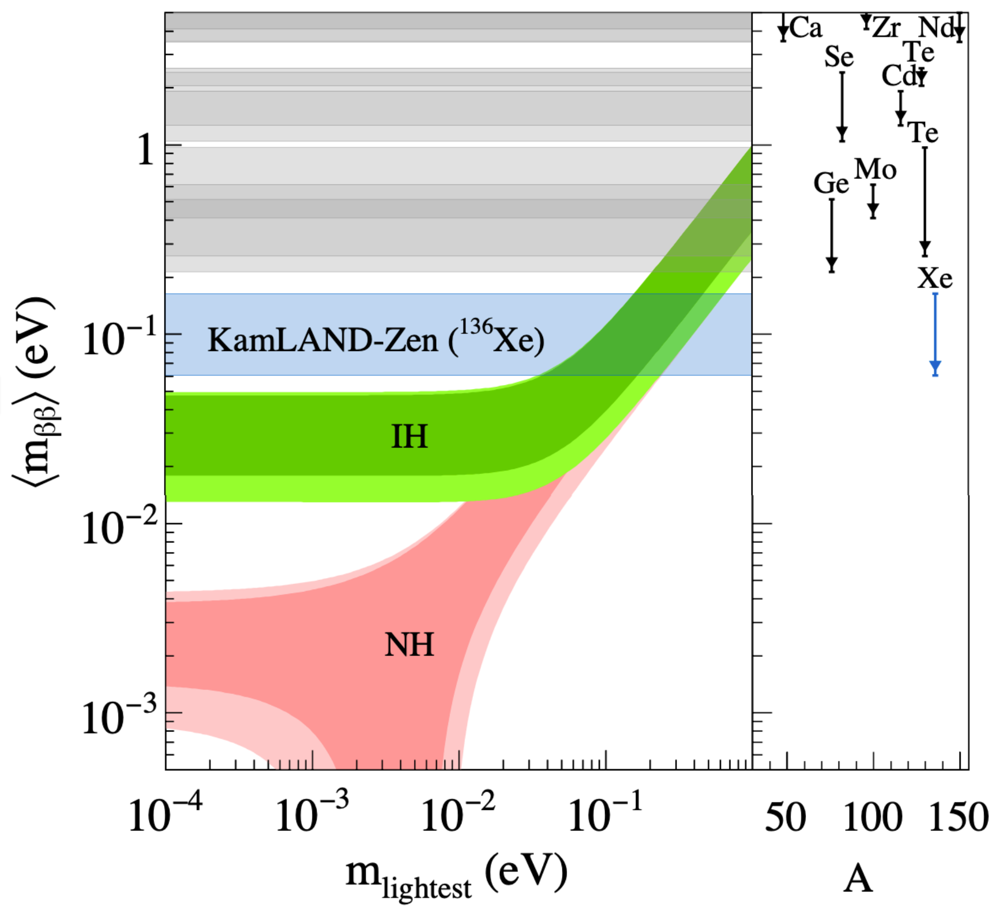
- Multiple techiniques used

- Ultra-pure Germanium detector (ionization detector)
  - Enriched in ^{76}Ge
  - GERDA, Majorana demonstrator

- Liquid scintillator detector: use existing detector, by adding β source
  - KamLAND-Zen: add balloon with Xenon enriched in ^{136}Xe
  - Currently gets the strongest bound: $T^{0\nu}_{1/2} > 1.07 \times 10^{26}$
  - SNO+: similar idea

- Other experiments (some, in preparation) use time projection chambers, or bolometric detectors

ν_e mass: results summary



IH: inverted hierarchy
NH: normal hierarchy