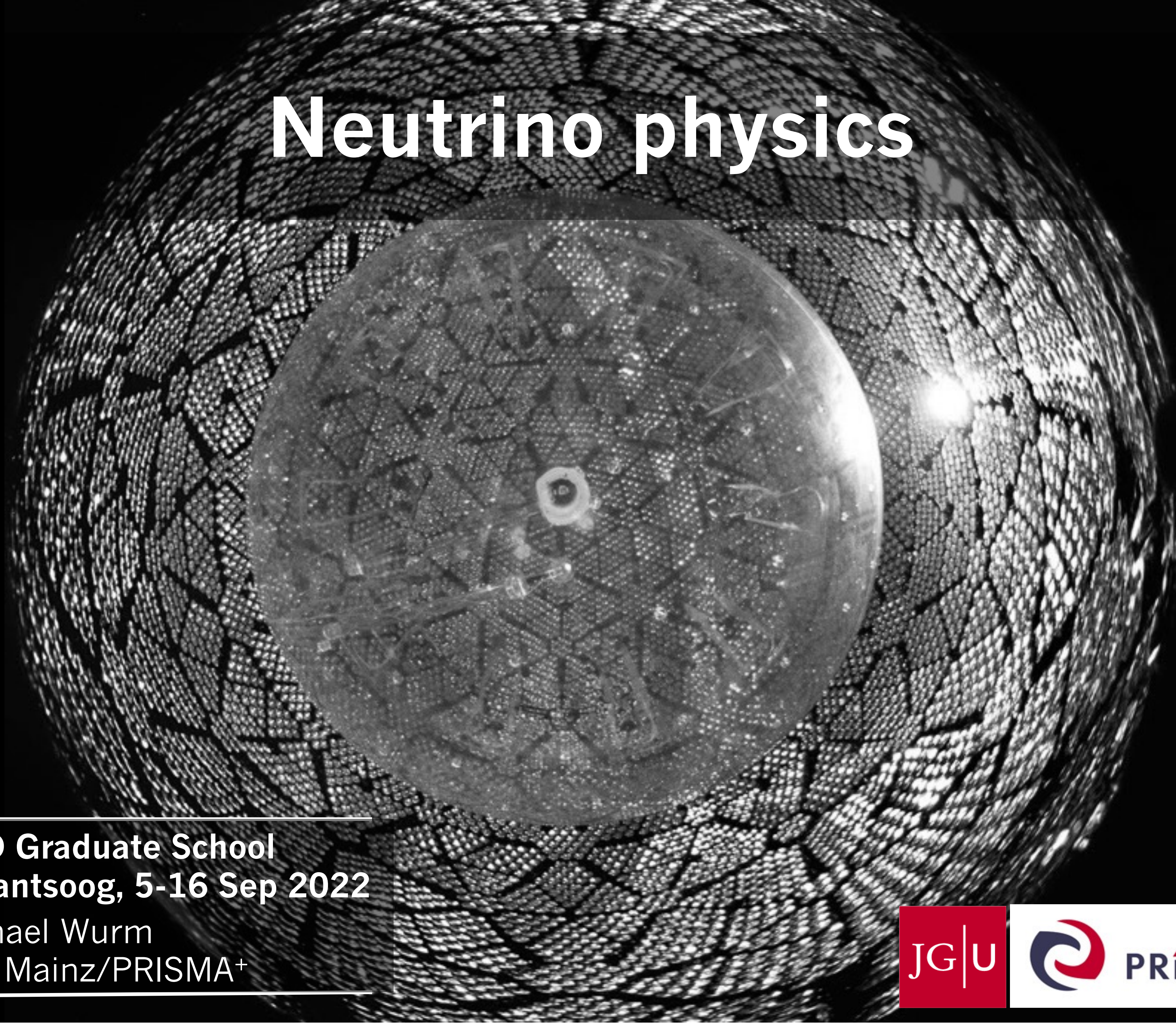
Neutrino physics

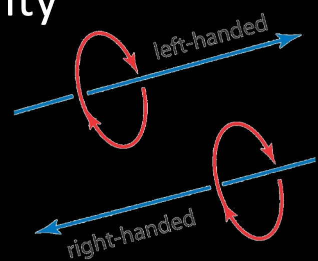


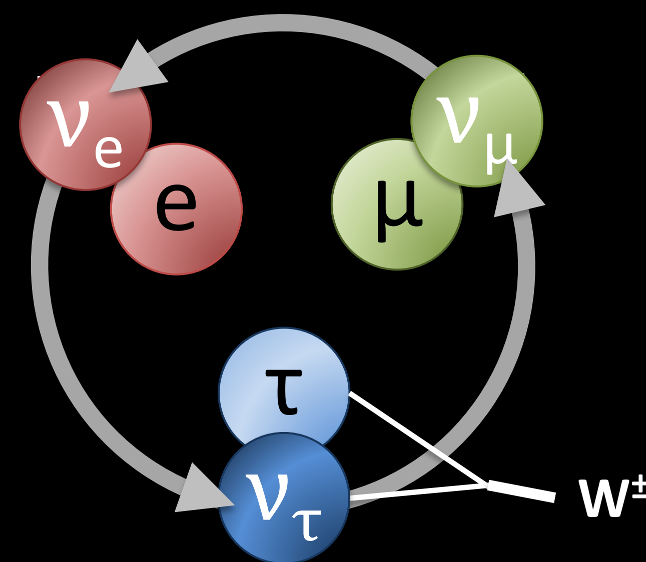
BND Graduate School
Callantsoog, 5-16 Sep 2022

Michael Wurm
JGU Mainz/PRISMA$^+$

Neutrinos in a nut-shell

- Neutrinos are fermions. → spin ½$\hbar$
- no electric or color charge → no bound states
- **but:** weak charge → nuclear & weak decays
- virtually but not completely massless → (almost?) no gravitational effect
  [$\Sigma m_\nu < 0.23\mathrm{eV} \approx 5\mathrm{x}10^{-7}\, m_e$]
- **three kinds (flavors) of neutrinos** are produced/absorbed in weak interactions along with e^-, μ^-, τ^- → $\nu_e - \nu_\mu - \nu_\tau$
- **each neutrino has (is?) its antiparticle:** same properties but different chirality
  - neutrinos = left-handed
  - antineutrinos = right-handed

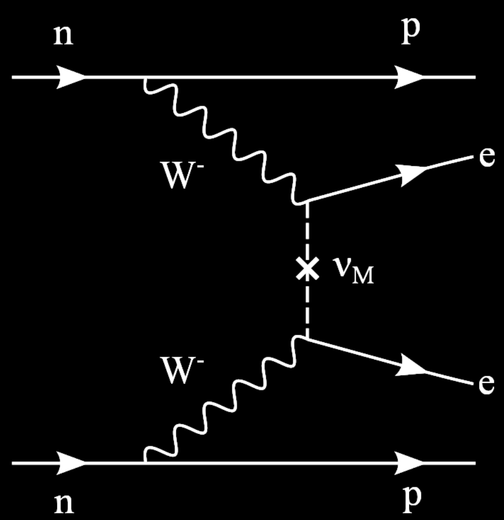


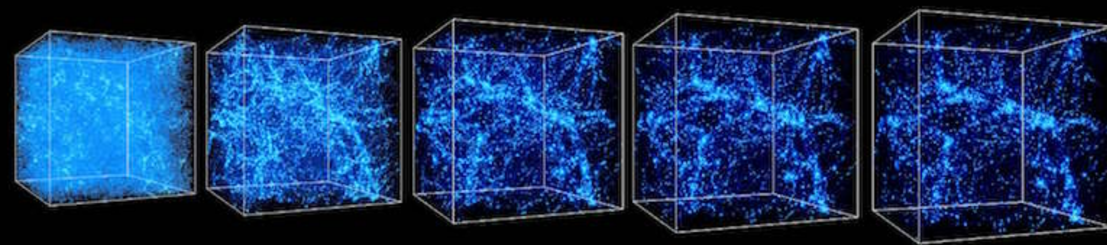


- **flavor and mass eigenstates are different**
  → neutrino oscillations

The many uses of the neutrino ...

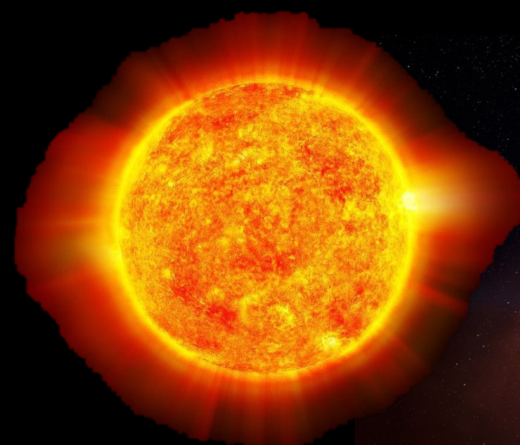
→ Gateway to particle physics
- weak interaction
- flavor physics
- mass generation
- BSM physics

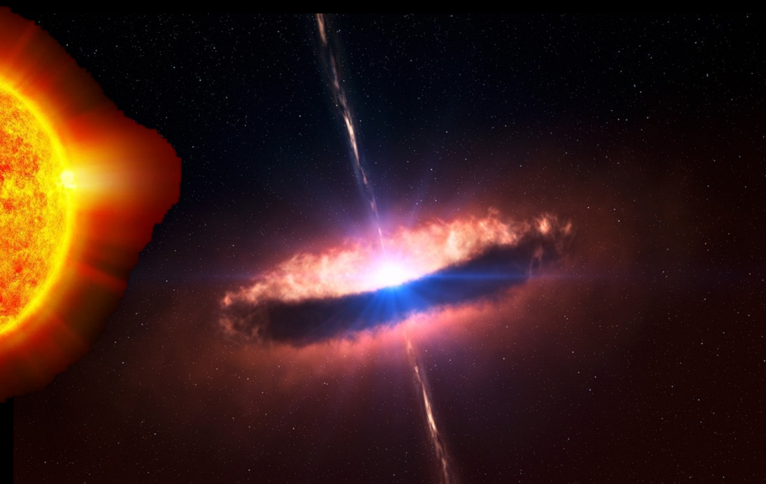




→ Impact on cosmology
- (hot?) dark matter
- structure formation
- nucleosynthesis

→ Probes in astronomy
- stellar physics
- black hole formation
- cosmic accelerators

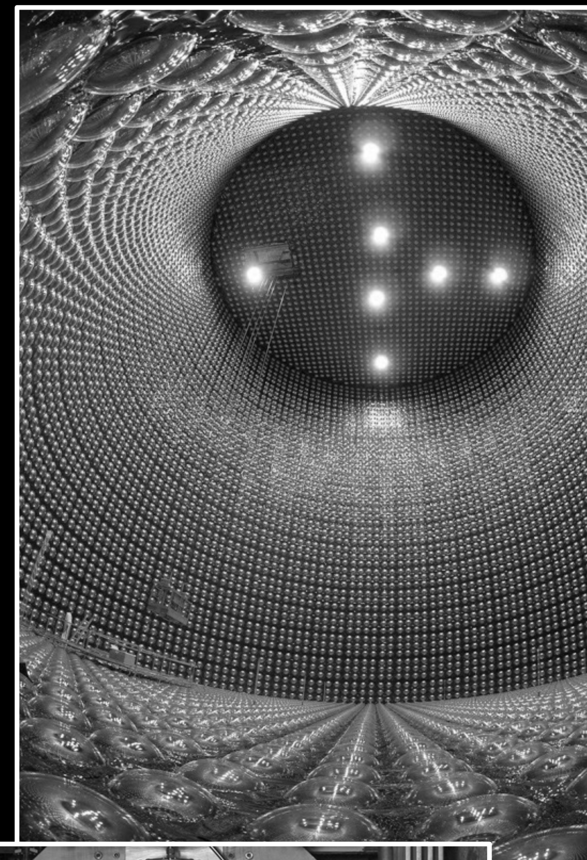


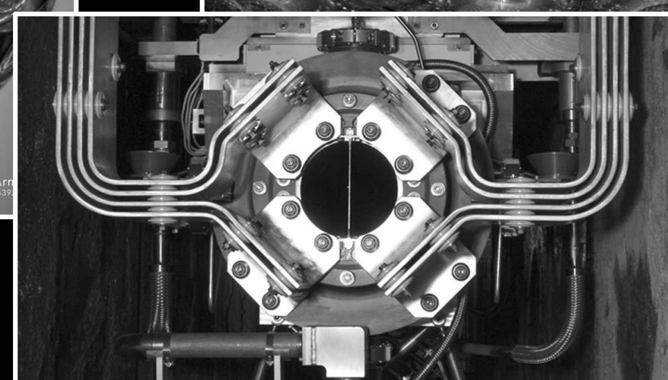


Contents of these lectures

focused to neutrino oscillations:

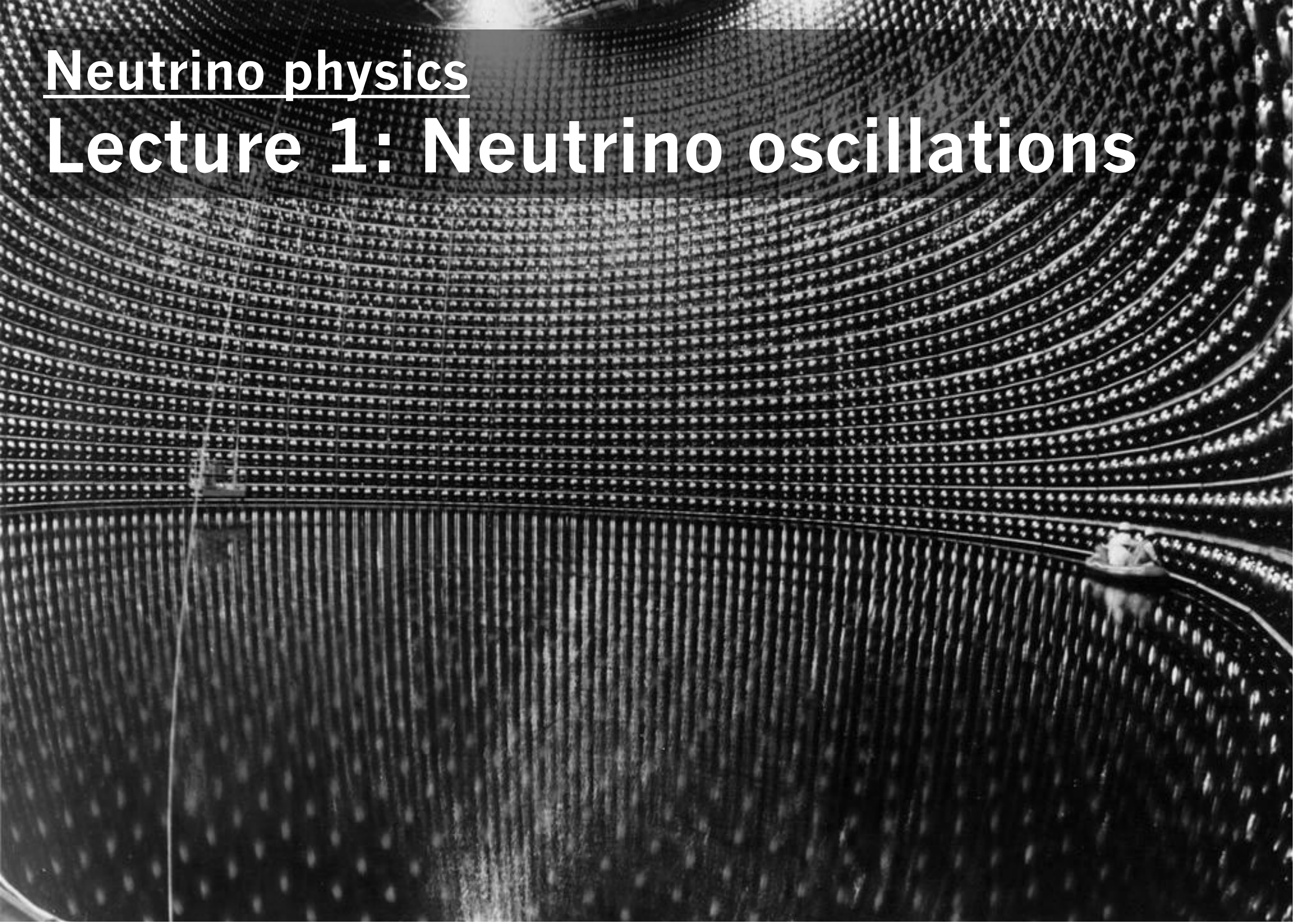
- Lecture 1: **Neutrino oscillations**
  from first hints to discovery and current day
  - Lecture 2: **Neutrino masses**
    absolute mass, Majorana mass, mass ordering
    - Lecture 3: **Astrophysical neutrinos**
      Sun, Supernovae and cosmic accelerators





Neutrino physics

Lecture 1: Neutrino oscillations



Neutrino oscillations

- **What is the oscillation mechanism?**
  - standard vacuum oscillations
  - oscillations in matter → MSW effect
- **How do oscillation experiments work?**
  - discovery: from Solar Neutrino Puzzle to SNO
  - detecting flavor conversion/oscillation patterns
  - example: long-baseline neutrino oscillations

Pontecorvo – The ‘inventor’ of ν oscillations

1957

“… the neutrino may be a particle mixture and ... there is a possibility of real transitions neutrino to antineutrino in vacuum, provided that the lepton (neutrino) charge is not conserved.”

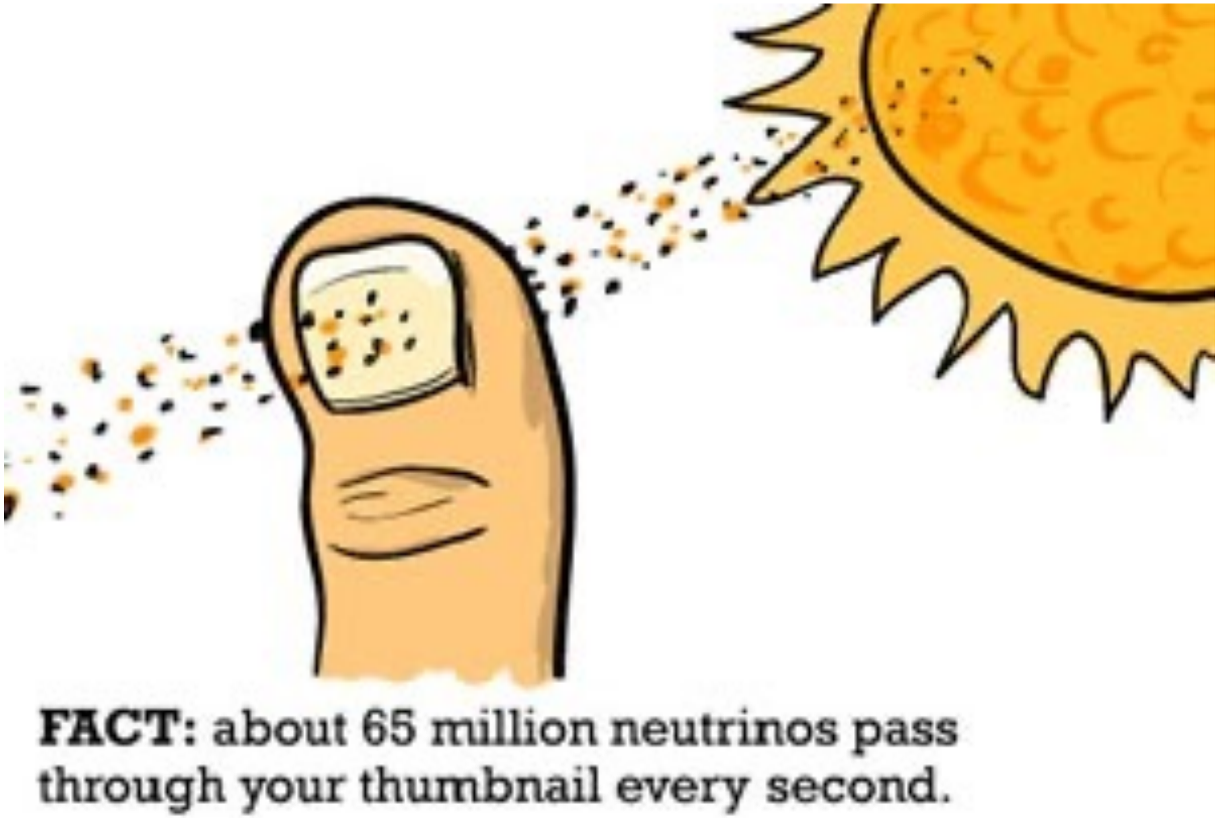
1968

“If the lepton charge is not an exactly conserved quantum number, and the neutrino mass is different from zero, oscillations similar to those in K^0 beams become possible in neutrino beams.”

“From an observational point of view the ideal object is the sun.“

Neutrinos from the Sun

from Learn Something New Every Day:
http://www.lsned.com/neutrino/

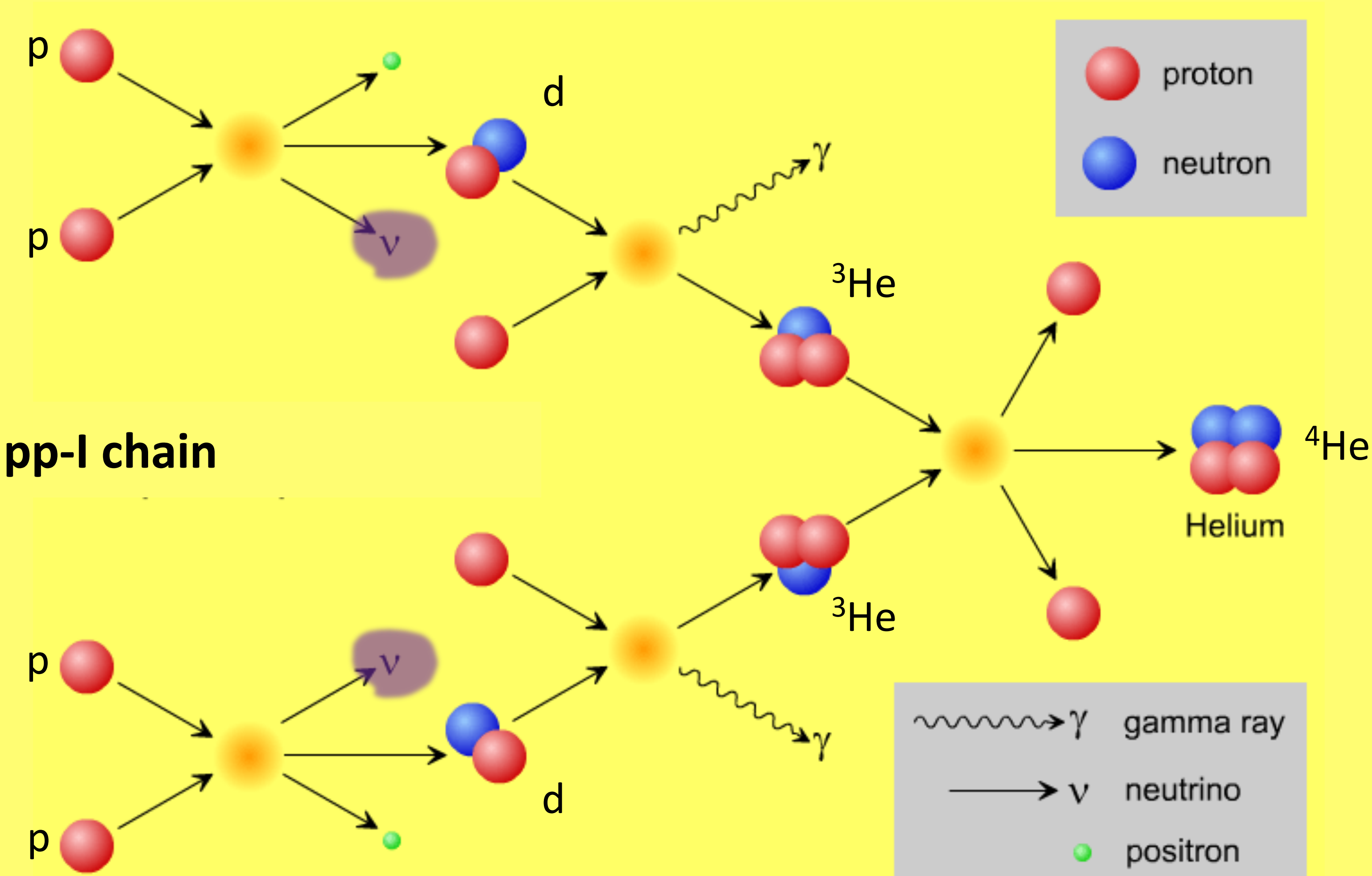


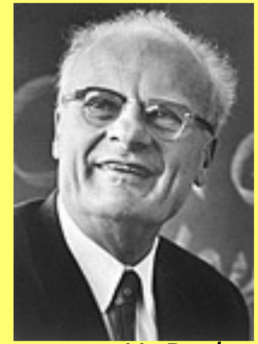
Neutrinos from the Sun

from Learn Something New Every Day:
http://www.lsned.com/neutrino/

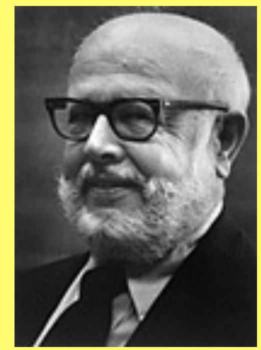
Hydrogen burning in the Sun

Net fusion reaction: $4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_e$ [+26.7 MeV]



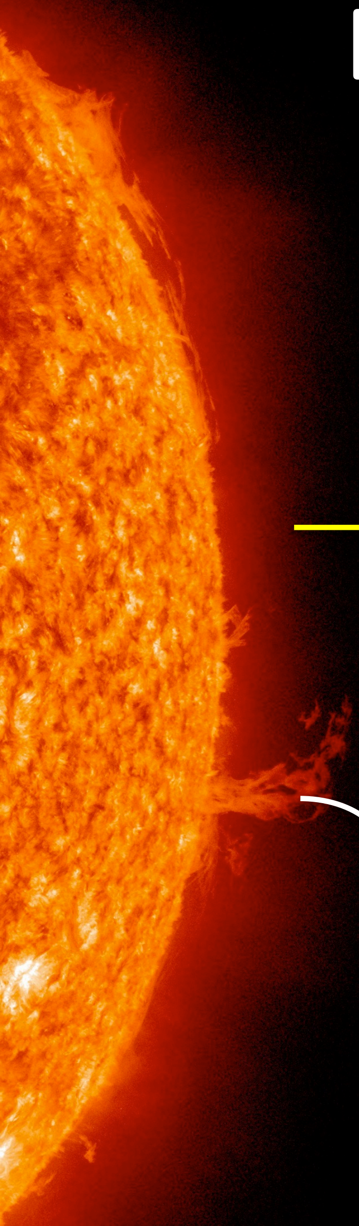


H. Bethe



W. Fowler

Expected solar neutrino flux



electromagnetic luminosity

$L_\odot = 3.85\text{x}10^{26}$ W

→ γ

ν

neutrino luminosity

$L_\nu \approx 2\%\ L_\odot$

flux at Earth

$\Phi_\gamma \approx 4\text{x}10^{21}$ /m²s

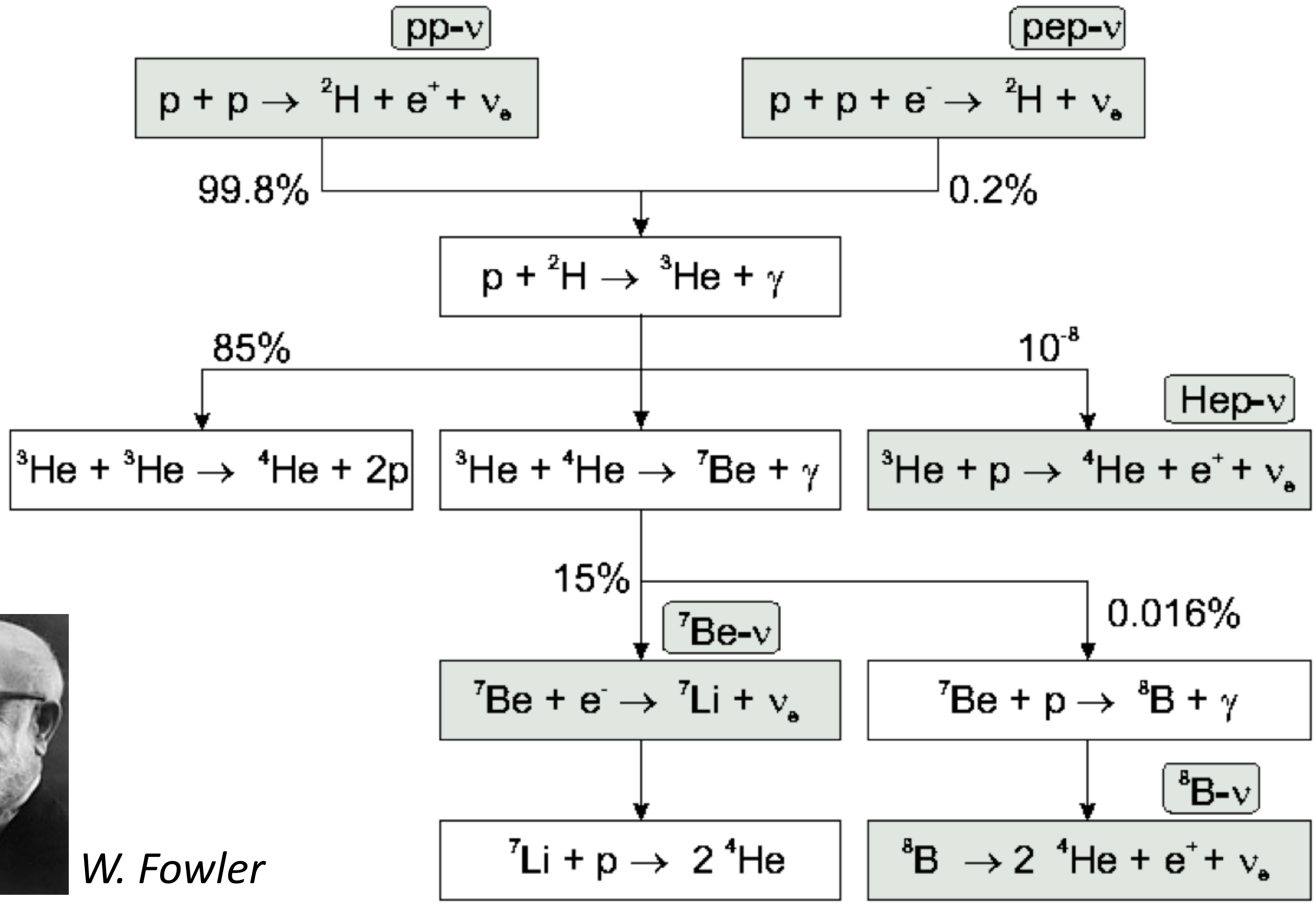
$\rightarrow S_\gamma = 1367$ W/m²

$$\Phi_\nu = \frac{S_\gamma}{Q_{4p\rightarrow\mathrm{He}}} \times 2$$

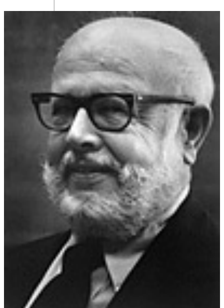
$\approx 6.6\text{x}10^{14}$ /m²s

Overview of the solar pp-chain

Net fusion reaction: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e$ [+26.7 MeV]



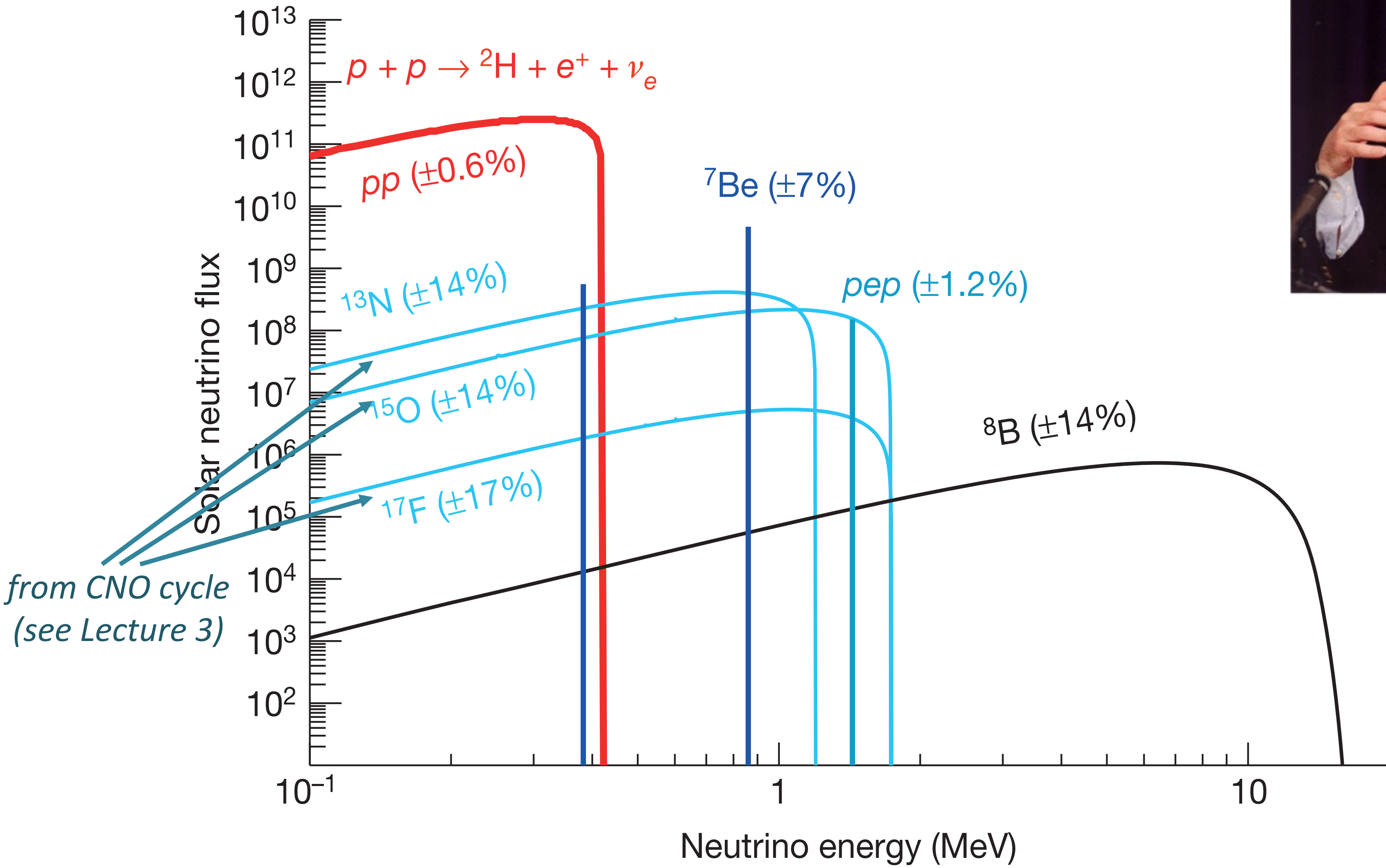
H. Bethe

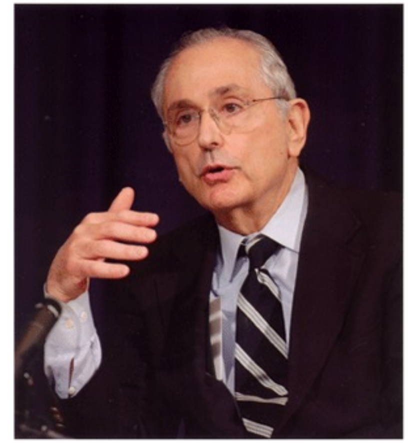


W. Fowler

Solar neutrino spectrum

based on **Standard Solar Model (SSM)** by John Bahcall

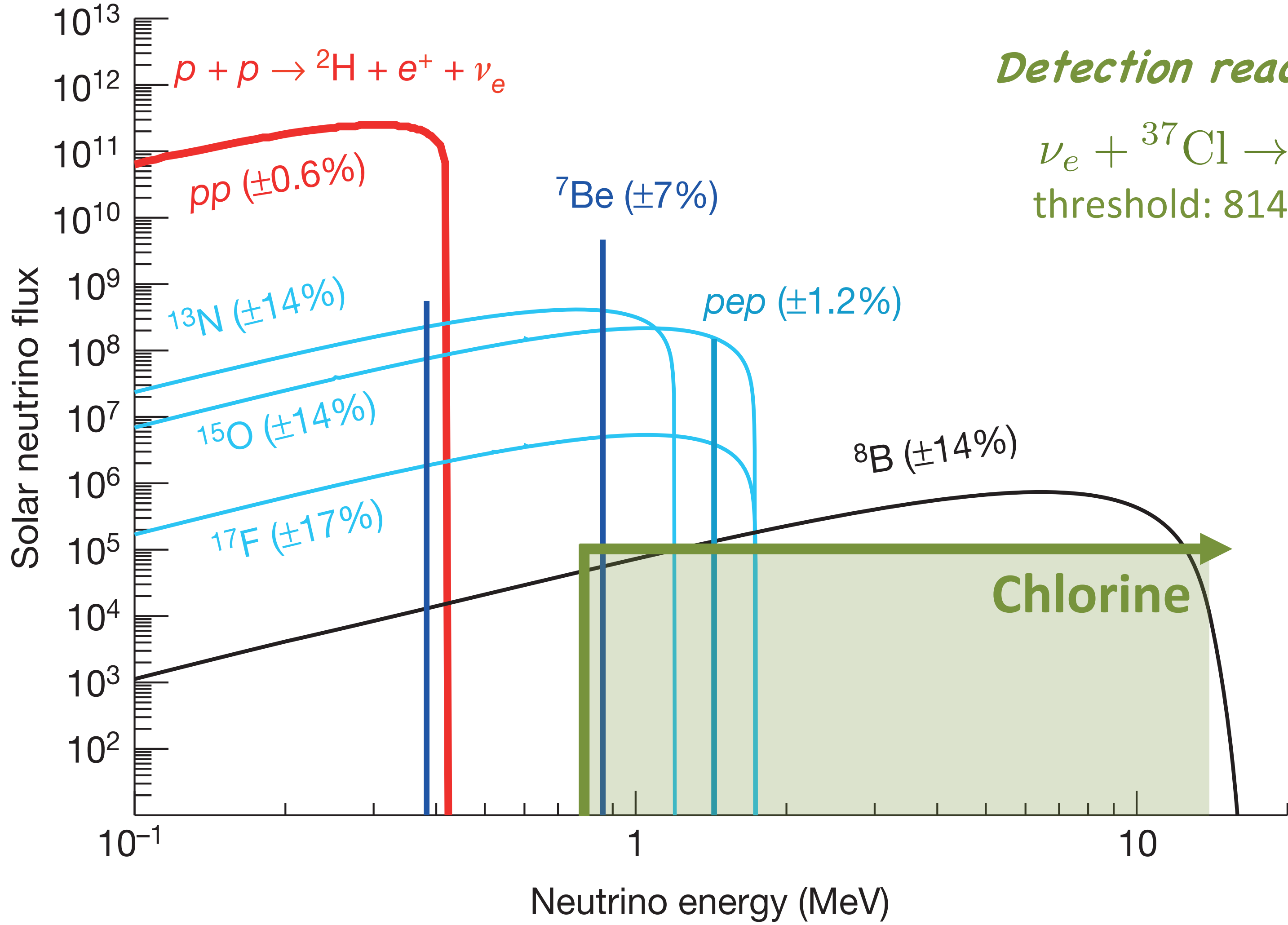




John N. Bahcall
(1934 – 2005)

Solar neutrino detection with ^{37}Cl

based on **Standard Solar Model (SSM)** by John Bahcall



Detection reaction

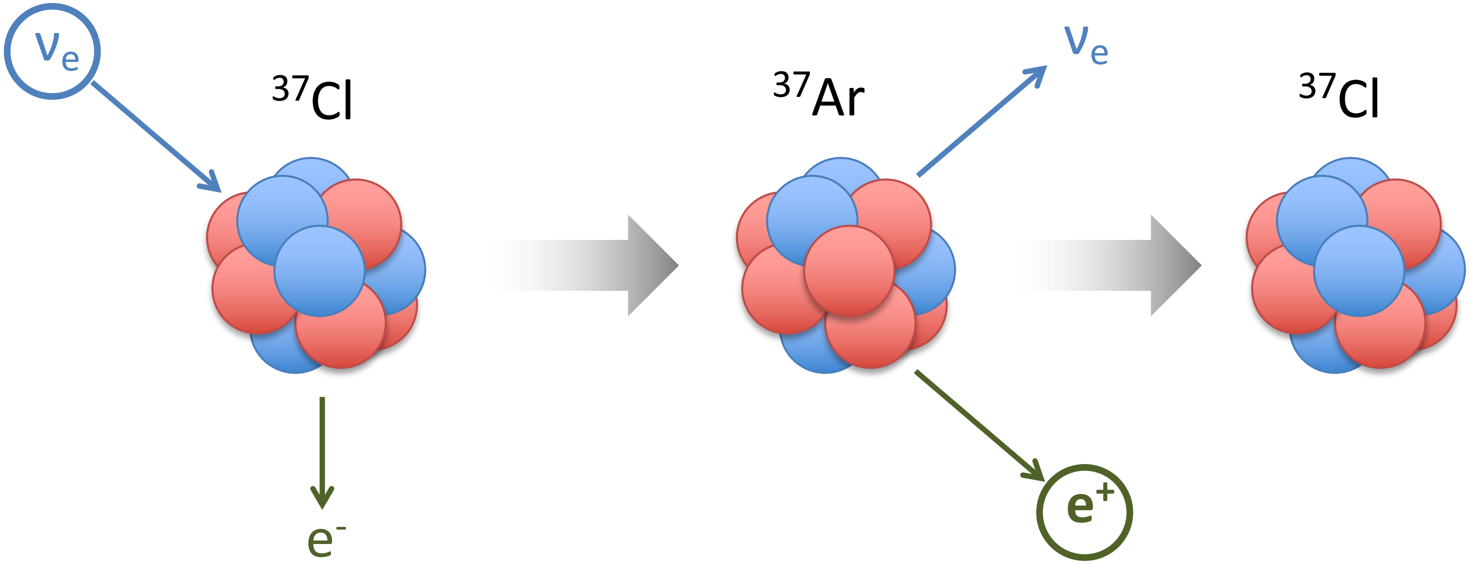
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

threshold: 814 keV

The Davis experiment

- **Location:** Homestake mine (US)
  - depth: 1478 m
  - avoids conversion of ^{37}Cl to ^{37}Ar by cosmic rays
- **Target material:**
  - perchloroethylene
  - 615 tons of C_2Cl_4
  - ~6×10^{30} atoms of ^{37}Cl

Detection mechanism



Neutrino reaction:

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

reaction threshold: 814 keV

→ mainly ^{7}Be and ^{8}B neutrinos

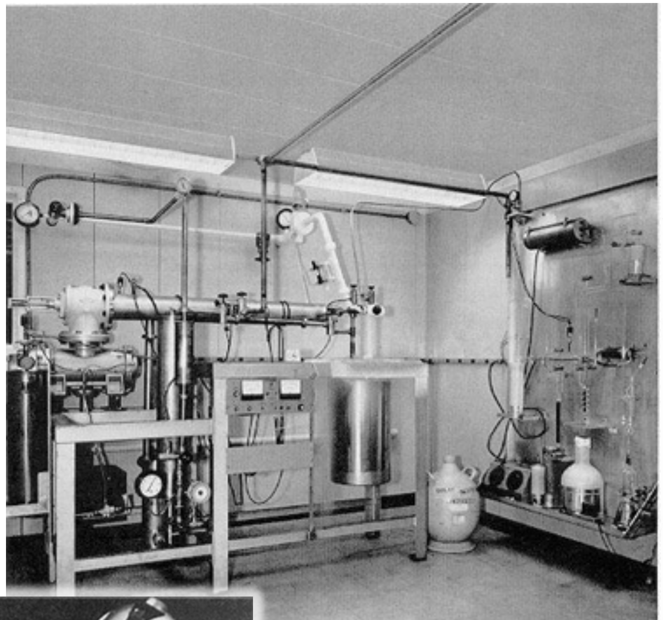
→ SSM-predicted rate: ~1.5 d^{-1}

Rate measurement:

– every few weeks, chemical extraction of ^{37}Ar from the tank

– detection of β^+ re-decays of ^{37}Ar ($T_{1/2}$=35d) in counting tubes

Argon extraction from Chlorine tank



Ray Davis:
“Mostly plumbing“

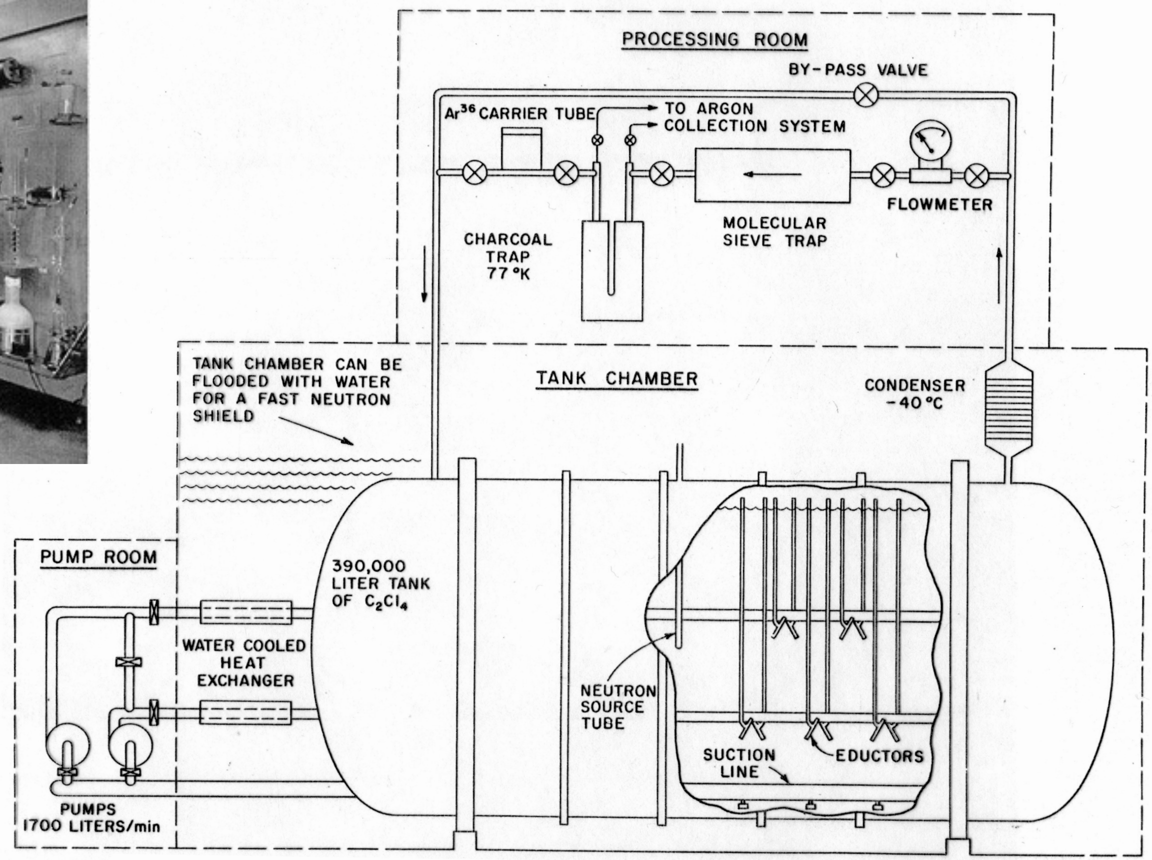
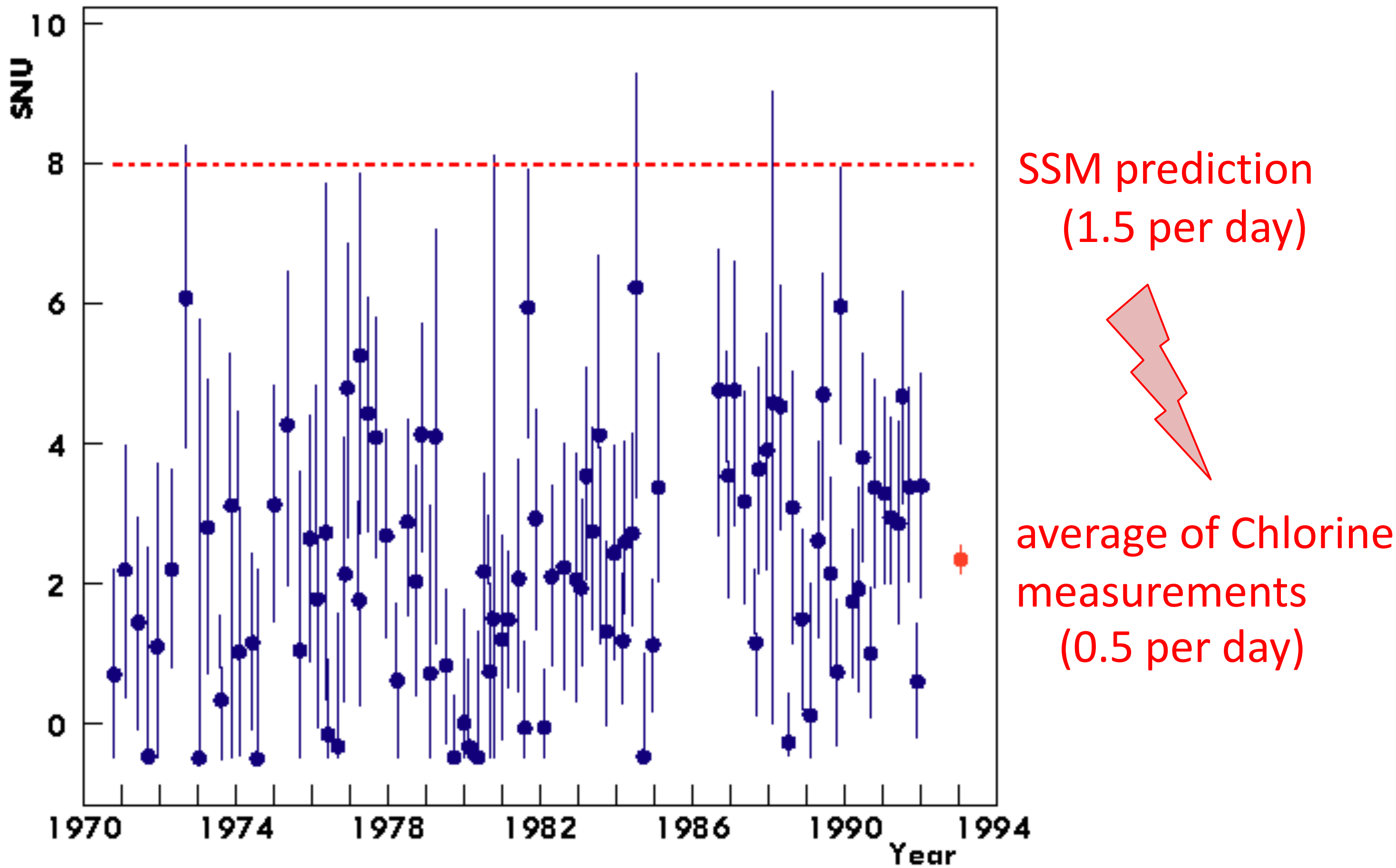


Figure 2.3. Schematic drawing of the argon recovery system. The pump-eductor system forces helium gas through the tetrachloroethylene liquid and provides the helium gas flow through the argon collection system.

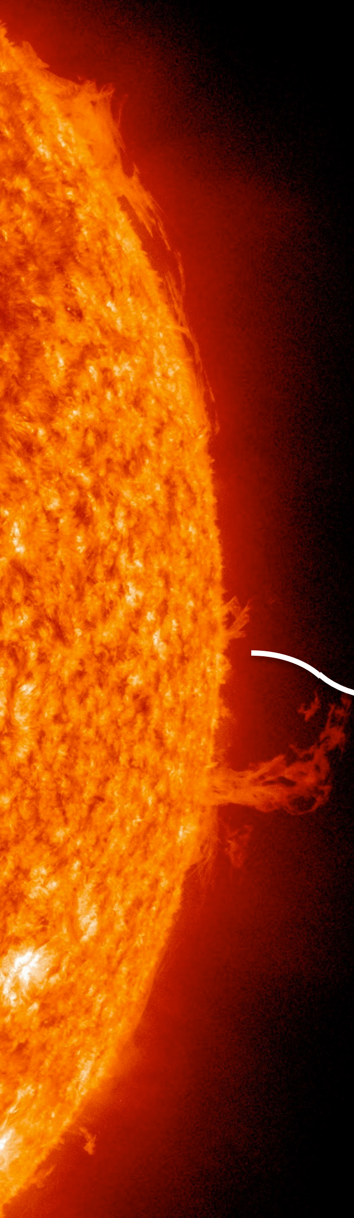
Homestake solar neutrino result



SNU = solar neutrino unit

1 reaction per 10^{36} target atoms and second

Birth of the solar neutrino puzzle



?

ν

$\Phi_{obs} \approx {}^{1}/_{3}\ \Phi_{SSM}$

Proposed explanations

- *the experiment is wrong*
- *the solar model is wrong*
- *the neutrinos are wrong*

LECTURE QUIZ

Question 1

How many solar neutrinos are passing through your thumbnail every second?

X : 60 thousand

Y : 60 million

Z : 60 billion

Note down the **first letter** of the solution word.

Neutrino masses and mixing

QM: For massive neutrinos (m_ν<0.23eV) with differing masses,

- the three neutrino **flavor-eigenstates**
  (taking part in weak interactions)

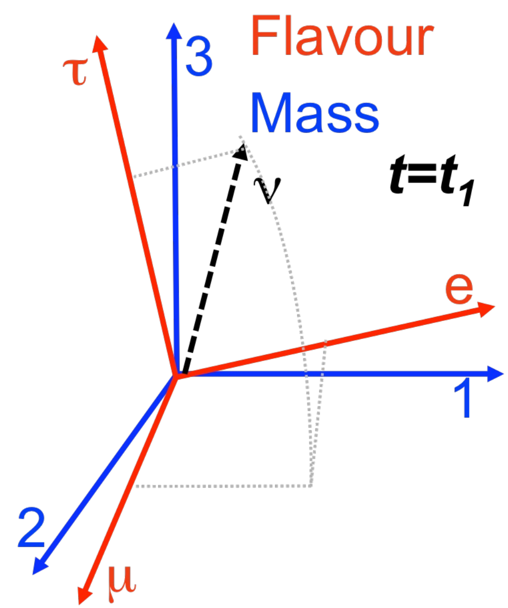
  can be a **superposition** of

- the three **mass-eigenstates**
  (propagating through space)

- The relative fractions of mass in flavor states (and vice versa) are described by a **3x3-mixing matrix**

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

flavor-states ***mass-states***



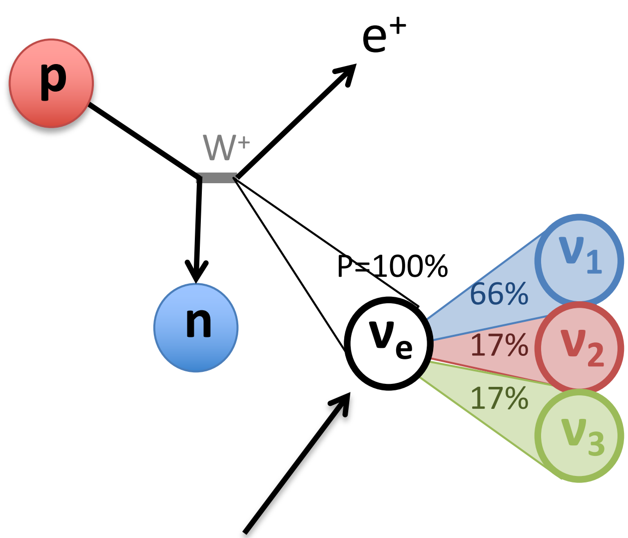
PMNS-mixing matrix *corresponds to a 3D-rotation between flavor and mass eigenspaces*

→ cf. CKM-matrix in quark-sector

Neutrino masses and mixing

ν production

e.g. β⁺-decay



Weak interaction creates neutrino in **flavor-eigenstate**.

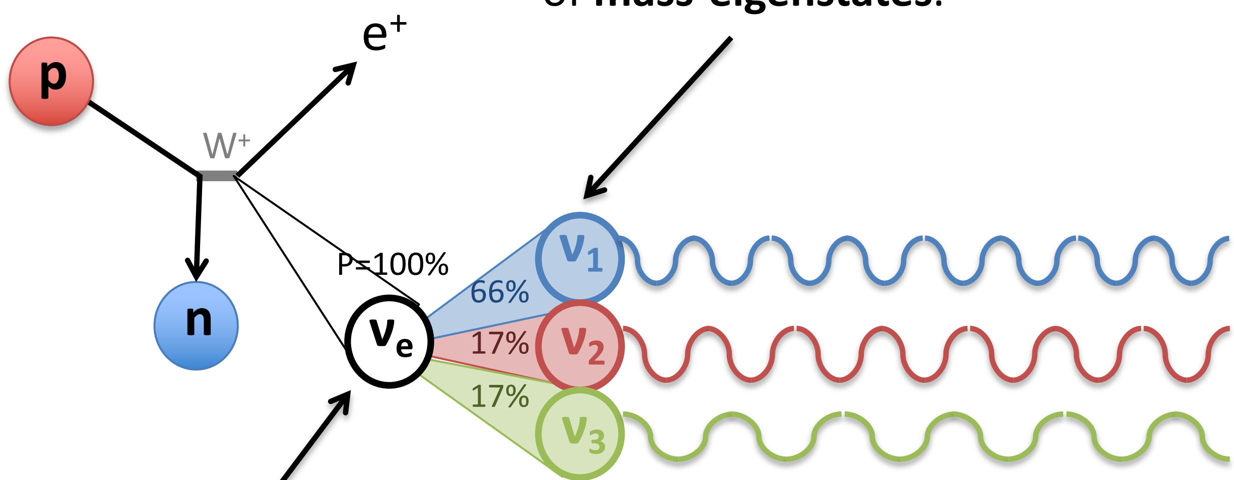
Neutrino masses and mixing

ν production

e.g. β⁺-decay

ν propagation

as coherent superposition of **mass-eigenstates**.



Weak interaction creates neutrino in **flavor-eigenstate**.

Different masses create a **phase difference** over time.

Neutrino masses and mixing

ν production

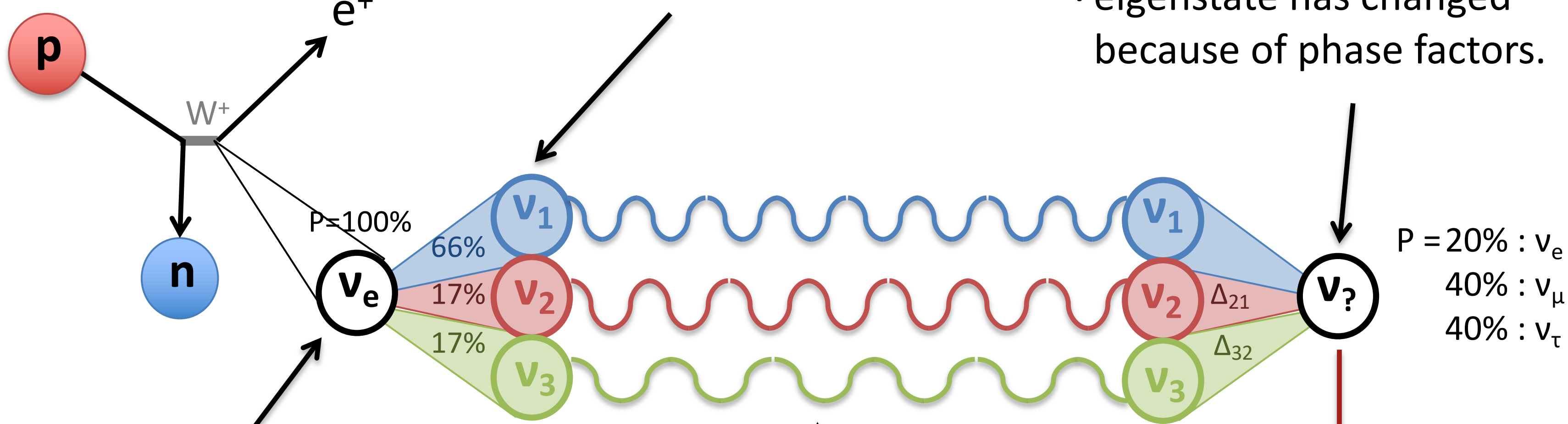
e.g. β⁺-decay

ν propagation

as coherent superposition of **mass-eigenstates**.

ν detection

as **flavor-eigenstate**: Superposition of mass eigenstate has changed because of phase factors.

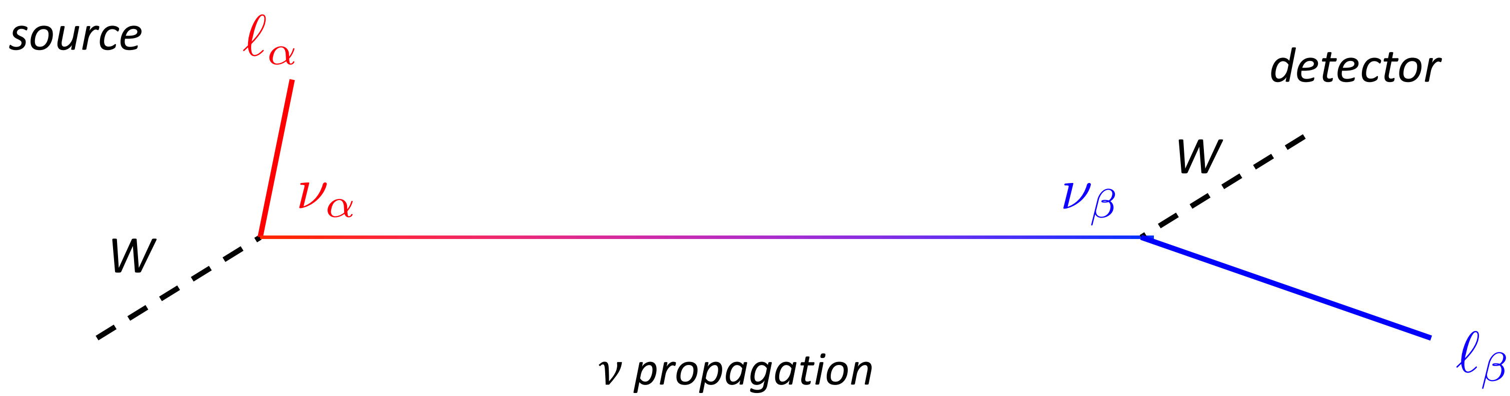


Weak interaction creates neutrino in **flavor-eigenstate**.

Different masses create a **phase difference** over time.

*Finite probability to detect a different **neutrino-flavor**!*

Neutrino oscillations



$|\nu_\alpha\rangle = U_{\alpha i}|\nu_i\rangle$ $\qquad$ $e^{-i(E_i t - p_i x)}$ $\qquad$ $|\nu_\beta\rangle = U^*_{\beta i}|\nu_i\rangle$

- propagation for $p_i = p,\ m_i \ll E$ $\qquad E_i = \sqrt{m_i^2 + p^2} = p + \frac{m_i^2}{2p} = E + \frac{m_i^2}{2E}$
- amplitude: $\qquad \mathcal{A}_{\nu_a \to \nu_\beta} = \langle \nu_\beta | \mathrm{propagation} | \nu_\alpha \rangle = \sum_i U_{\beta i} U^*_{\alpha i} e^{-i\left(\frac{m_i^2}{2E}\right)L}$
- probability: $\qquad P_{\nu_a \to \nu_\beta} = |\mathcal{A}_{\nu_a \to \nu_\beta}|^2 = \sum_{i,j} U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j} e^{-i\left(\frac{m_i^2 - m_j^2}{2E}\right)L}$

Solar neutrinos: Two-flavor approximation

2x2 mixing:

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

flavor states *mass states*

Oscillation probability:

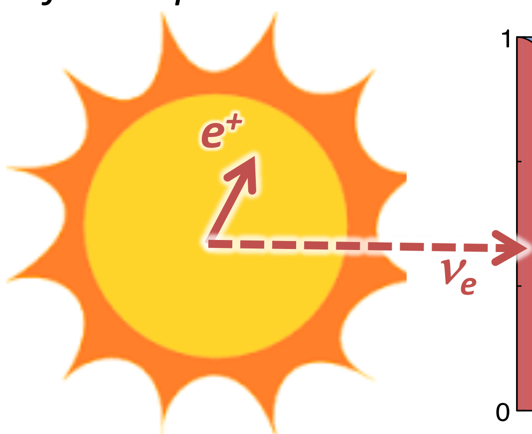
$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

baseline-over-energy

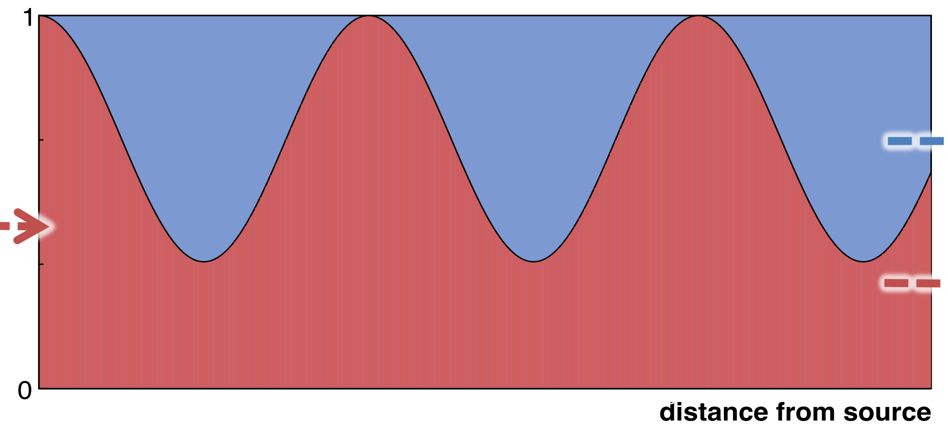
oscillation amplitude

oscillation frequency/length

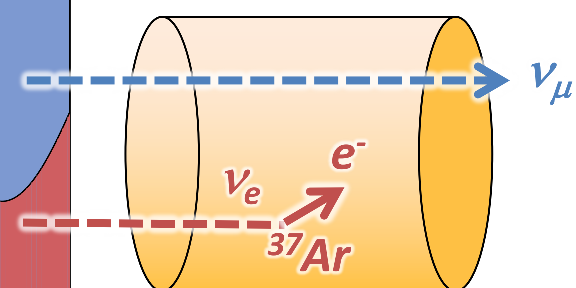
electron neutrinos created in solar fusion processes



neutrinos propagate → oscillate
partial flavor transition ν_e → ν_μ



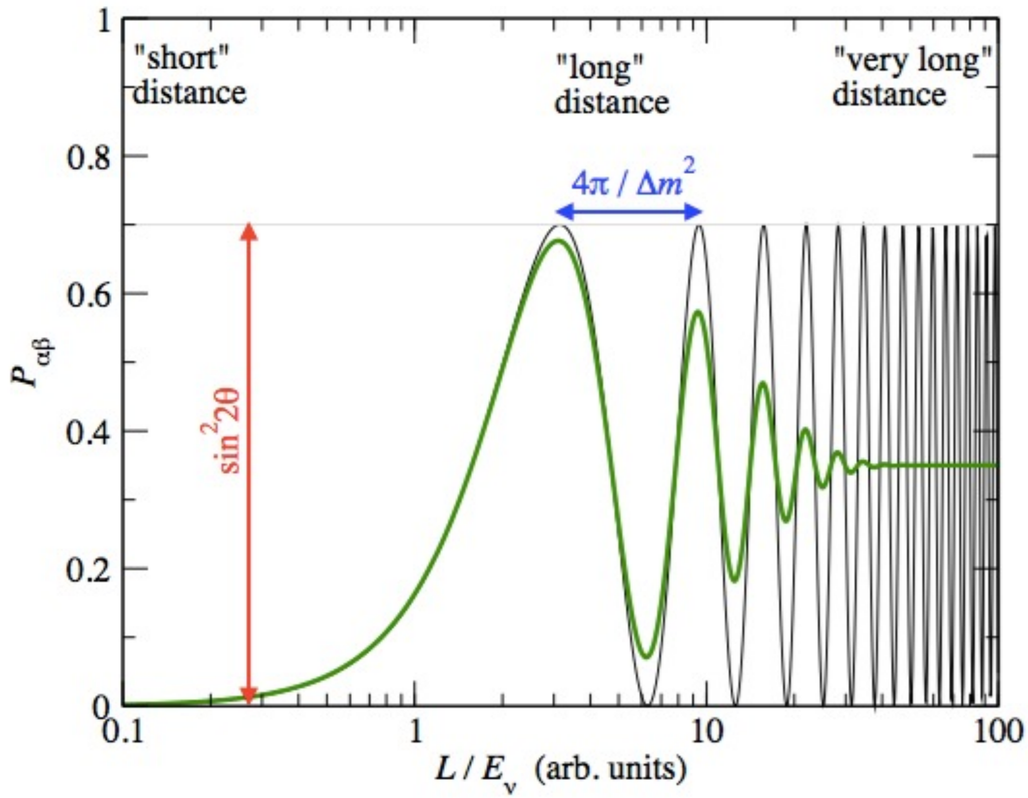
detectors only sensitive to electron neutrinos



→ **rate deficit!**

Oscillation pattern

oscillation length
*is given by **4π/Δm²***



detector resolution and
wave packet decoherence
averages out pattern
for large distances

$\rightarrow P_{ee} = 1 - \frac{1}{2}\sin^2(2\theta_{12})$

oscillation amplitude
*depends on **sin²2ϑ***

oscillation phase** depends on **L/E:

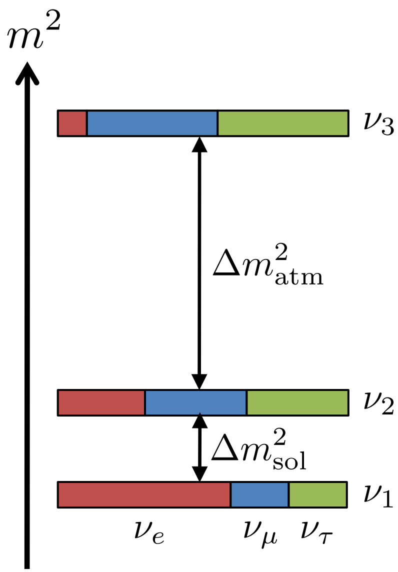
$$\rightarrow P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

Three-flavor mixing

$$\mathbf{U_{3\times 3}} = \mathbf{U}_{\mathrm{PMNS}}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\mathbf{U_{3\times 3}} = \mathbf{U}_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor states | *atmospheric mixing* | *reactor mixing & CP violation* | *solar mixing* | *mass states*



mixing angles : $c_{ij} = \cos\theta_{ij}, \;\; s_{ij} = \sin\theta_{ij}$

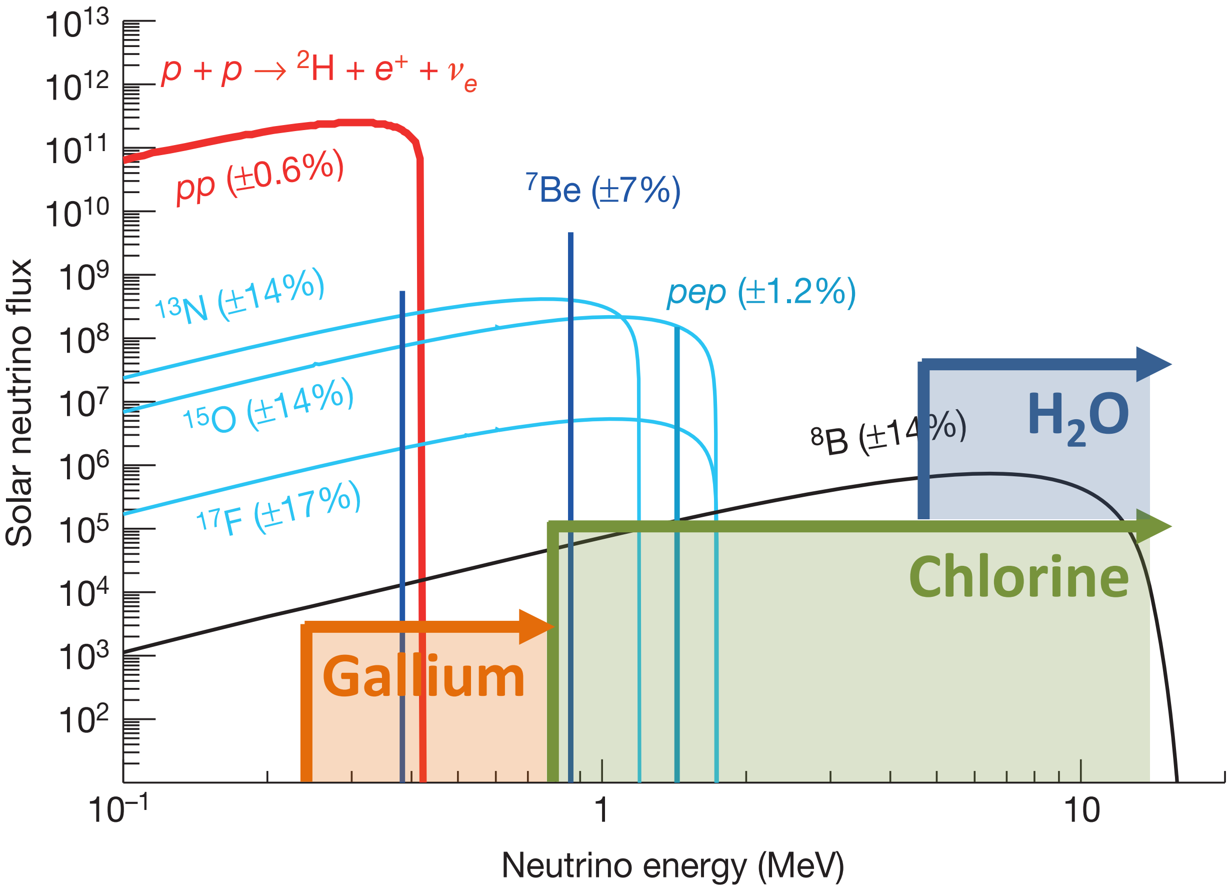
CP violating phase : δ

mass squared differences :

- $\Delta m^2_{\mathrm{sol}} = \Delta m^2_{21}$
- $\Delta m^2_{\mathrm{atm}} = \Delta m^2_{32} \approx \Delta m^2_{31}$

Solar neutrino experiments of the 80/90's

further confirmation of the solar neutrino deficit:



Gallex/GNO + SAGE

- detection reaction:
  $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$
- threshold: 233 keV
  → pp measurement

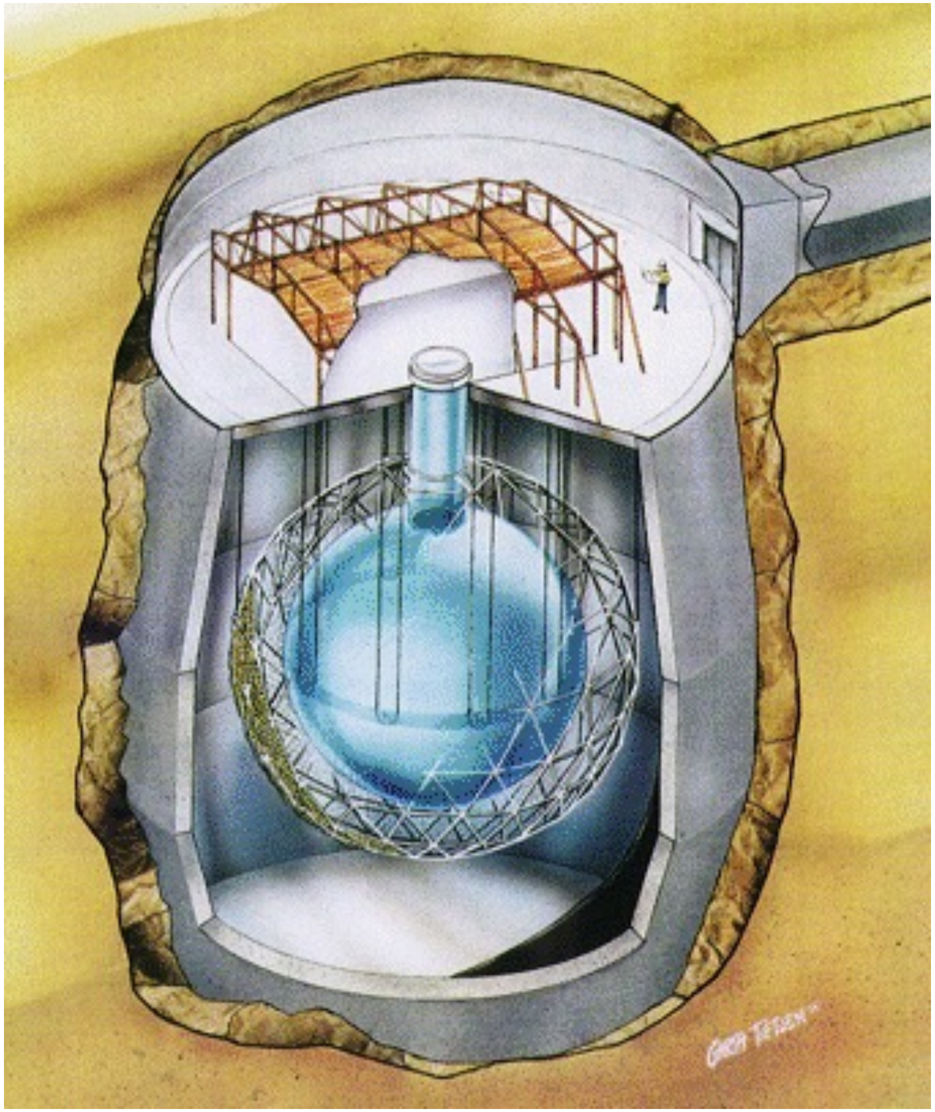
→ 50 % deficit observed

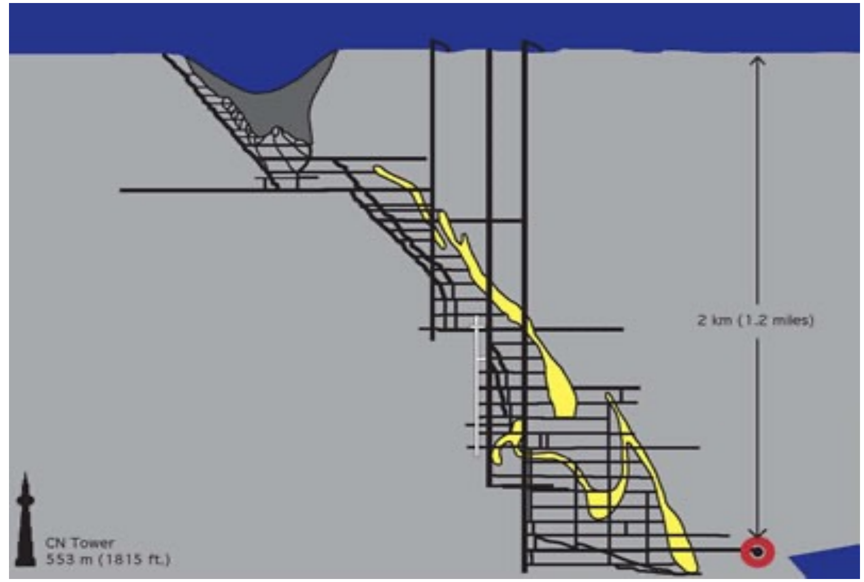
(Super-)Kamiokande

- detection reaction:
- threshold: ~5 MeV
  → only ^{8}B neutrinos

→ 70 % deficit observed

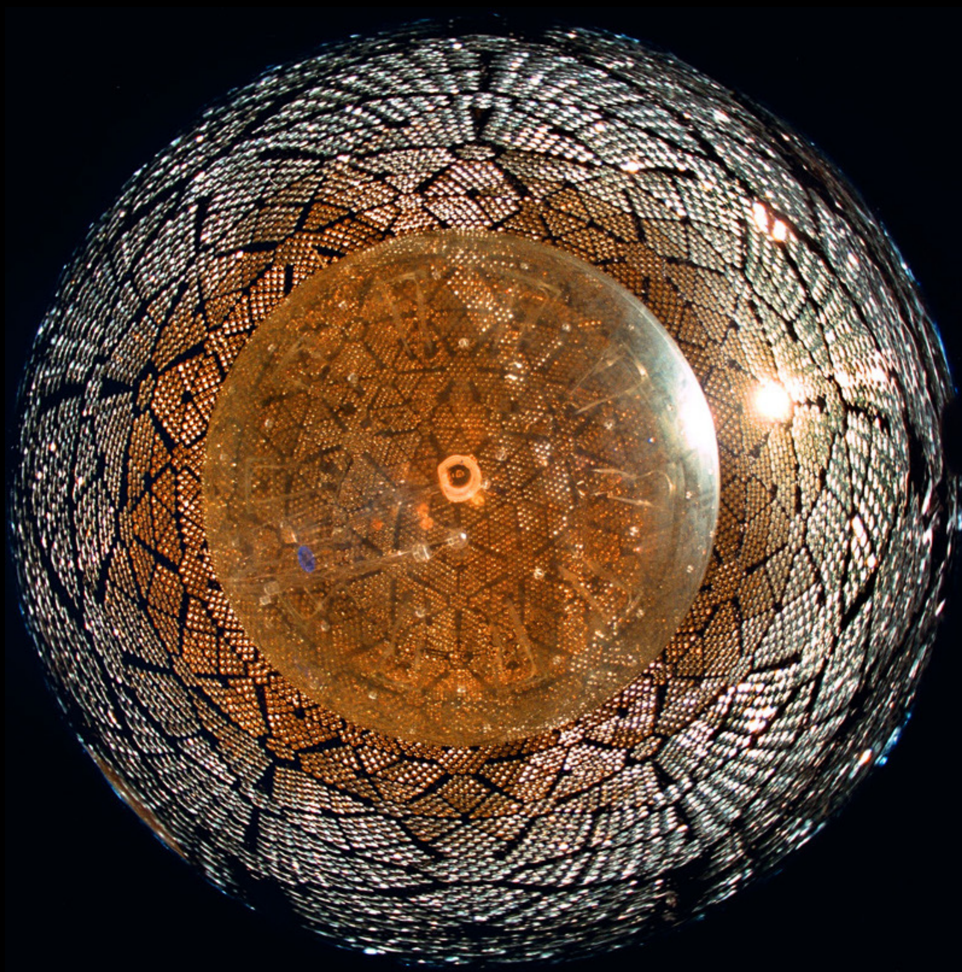
Sudbury Neutrino Observatory (SNO)



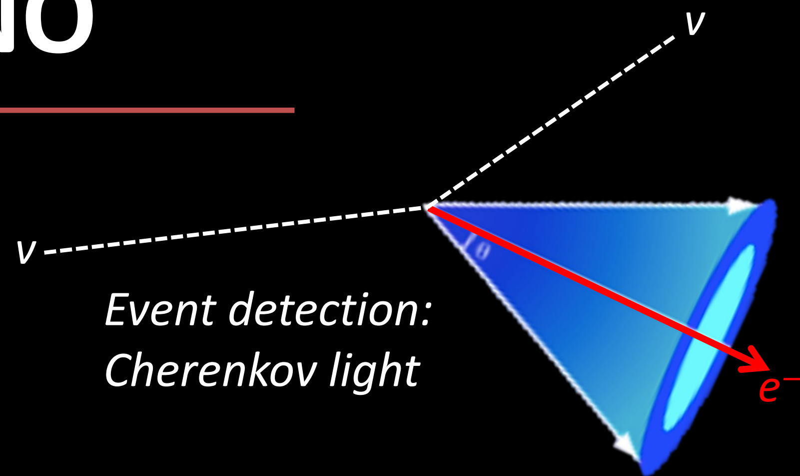


- **Water Cherenkov detector**
  Underground water tank to measure neutrino interactions by final-state charged particles
- **Location:** Sudbury mine
  depth: 2000 m → 6000 mwe
- **Target mass:** 1 kt of D_2O

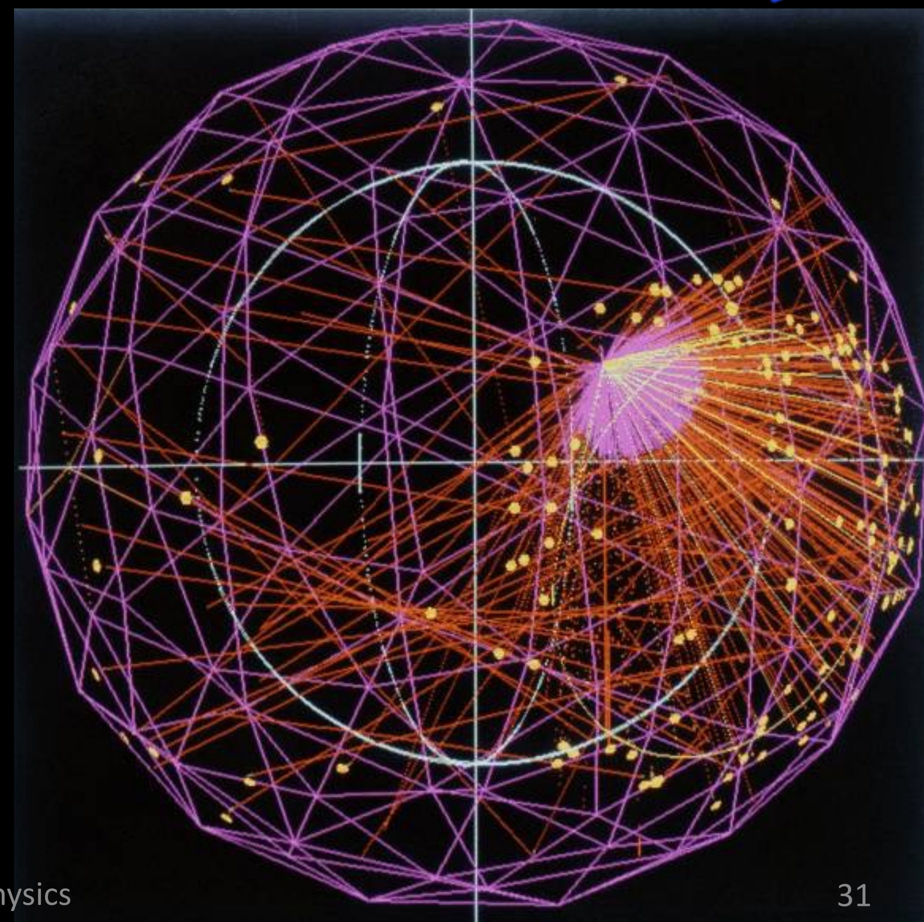
Neutrino detection in SNO



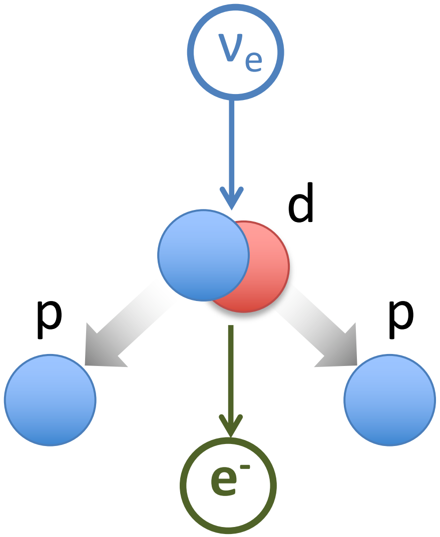
10,000 photomultiplier tubes



Event detection: Cherenkov light



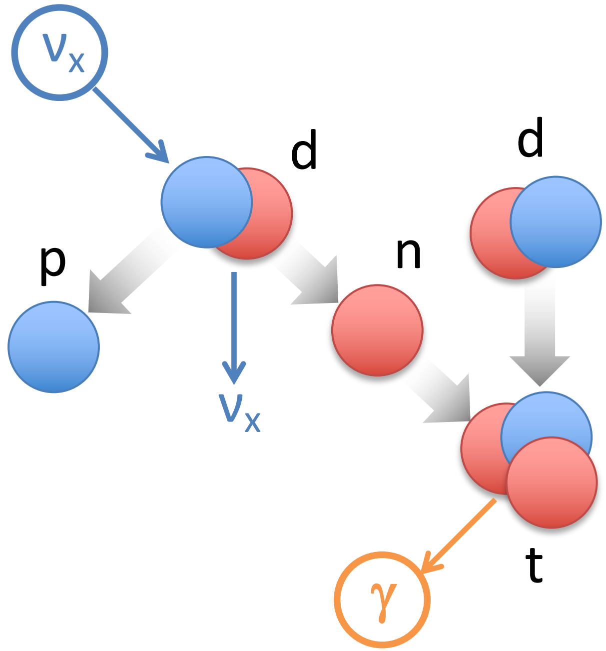
Detection reactions in heavy water



(CC) on deuterons

$$\nu_e + d \rightarrow p + p + e^-$$

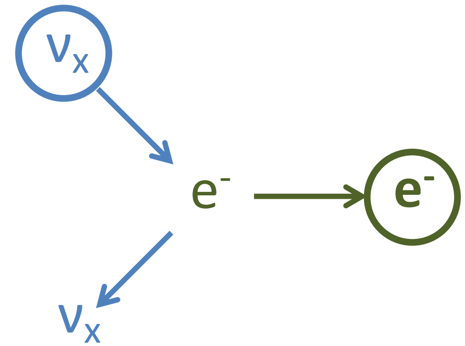
– sensitive only to ν_e



(NC) on deuterons

$$\nu_x + d \rightarrow p + n + \nu_x$$

– sensitive to all flavors



elastic scattering on electrons (ES)

$$\nu_x + e^- \rightarrow e^- + \nu_x$$

– mostly ν_e, but also $\nu_{\mu,\tau}$

→ determine **total neutrino flux (all flavors)** and **ν_e-flux** separately

2002: SNO result on flavor conversion

The fluxes measured via the three channels were:

$$\left.\begin{array}{l} \boxed{\Phi_{CC} = 1.76 \pm 0.11} \\ \Phi_{ES} = 2.39 \pm 0.27 \\ \boxed{\Phi_{NC} = 5.09 \pm 0.62} \end{array}\right\} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

The Standard Solar Model prediction for ^{8}B-ν's is:

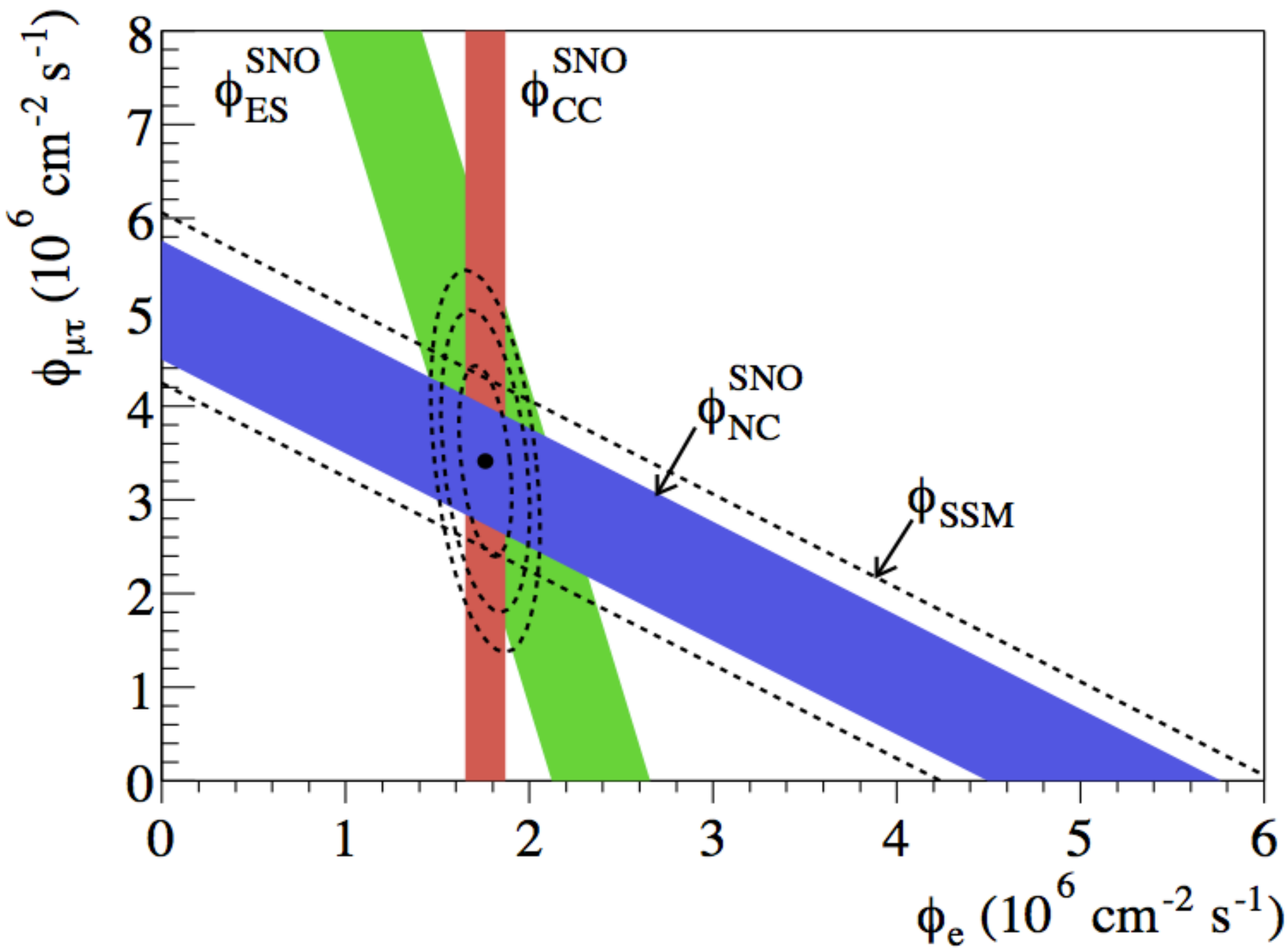
$$\boxed{\Phi_{SSM} = \left(5.05^{+1.01}_{-0.81}\right)} \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$$

$\rightarrow$ The survival probability for ν_e measured in (CC) channel is $\boxed{P_{ee} \approx 35\,\%.}$

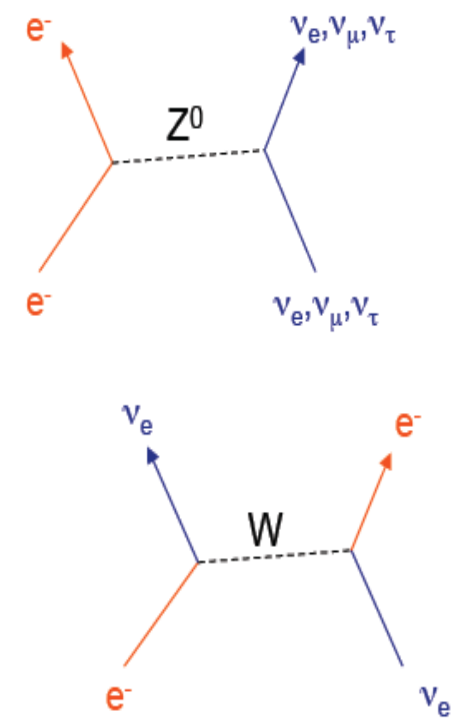
$\rightarrow$ The overall neutrino flux of (NC) corresponds to the SSM prediction as ν_e converted to $\nu_{\mu,\tau}$ still contribute to the (NC) rate.

→ total flux (all flavors) as predicted by SSM, ν_e flux suppressed by oscillations

SNO result – self-consistency check



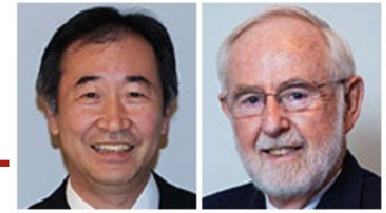
Elastic scattering (ES):

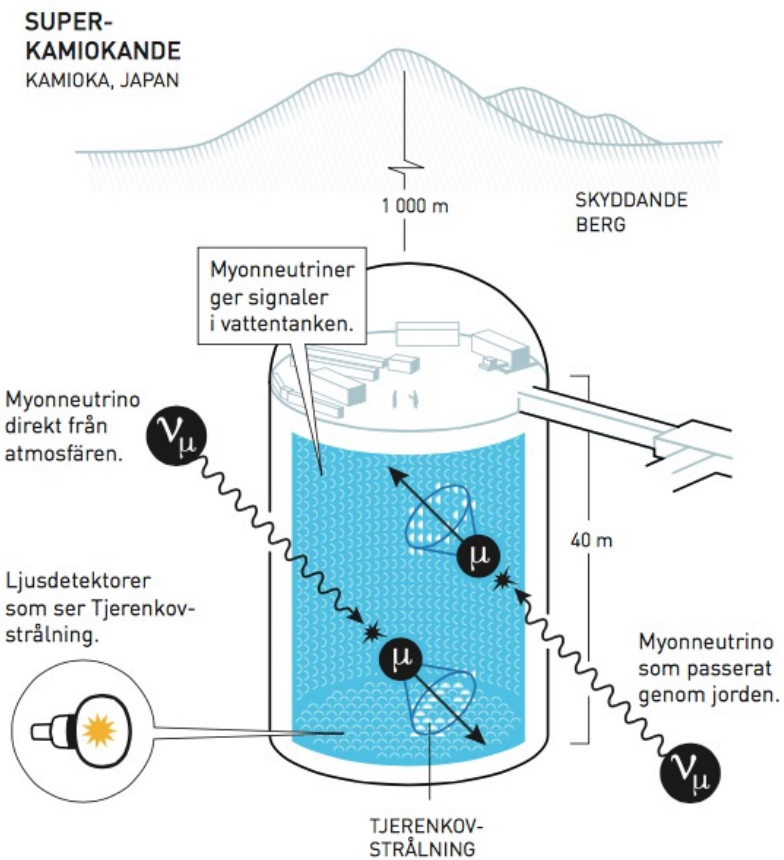


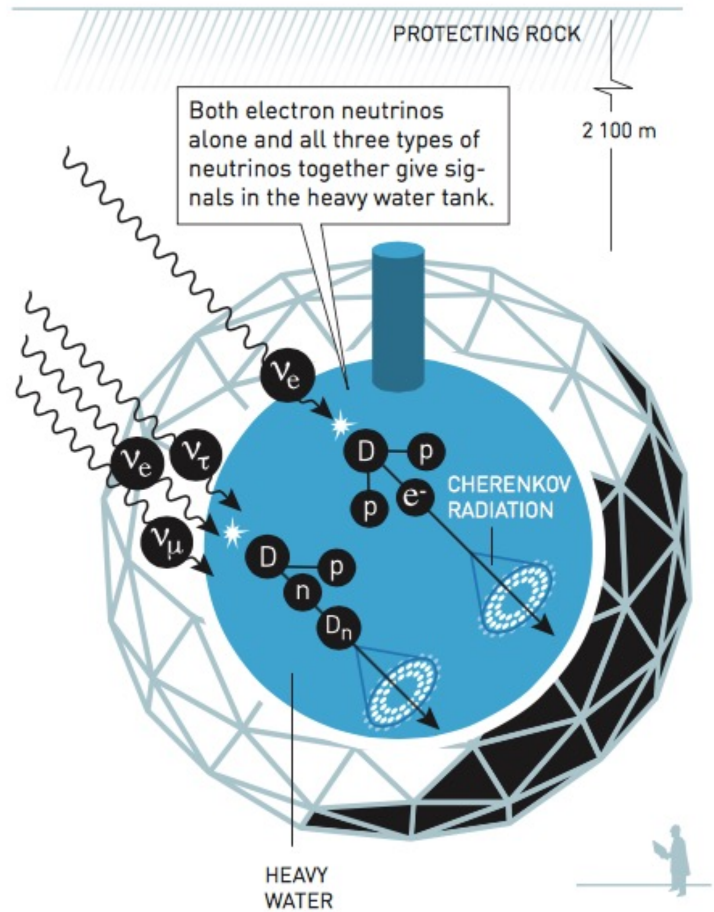
→ Larger cross-section for electron neutrinos

all three measurements are mutually consistent → **neutrinos change flavor!**

Nobel Prize in Physics 2015







→ ν_μ disappear with the correct L/E dependence of oscillations

+

→ ν_e disappear and re-appear as $\nu_{\mu,\tau}$

→ ν's undergo flavor oscillations!

→ at least 2 ν states have mass!

SNO result and neutrino oscillations?

SNO result

The fluxes measured via the three channels were:

$$\left.\begin{array}{l} \Phi_{\mathrm{CC}} = 1.76 \pm 0.11 \\ \boxed{\Phi_{\mathrm{ES}} = 2.39 \pm 0.27} \\ \boxed{\Phi_{\mathrm{NC}} = 5.09 \pm 0.62} \end{array}\right\} \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

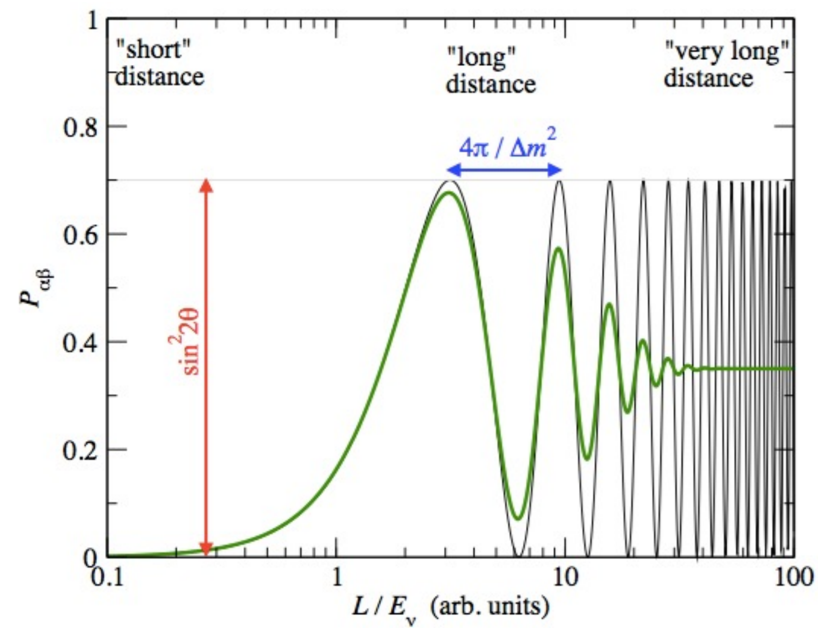
The Standard Solar Model prediction for ^{8}B-ν's is:

$$\boxed{\Phi_{\mathrm{SSM}} = \left(5.05^{+1.01}_{-0.81}\right)} \times 10^6\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

→ The survival probability for ν_e measured in (CC) channel is $\boxed{P_{ee} \approx 35\,\%.}$

→ oscillation amplitude $P_{e\mu} \geq 65\%$

Transition probability



→ for distance Sun—Earth, oscillations average out

$P_{e\mu} = ½ \sin^2 2\theta \overset{!}{<} 0.5$

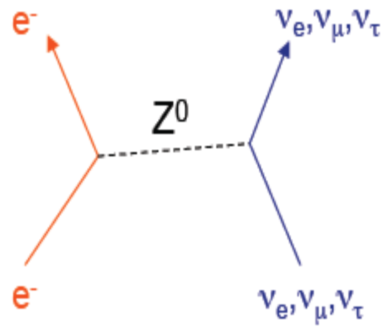
→ high conversion probability in SNO needs solar matter effect

Matter effect on neutrino oscillations

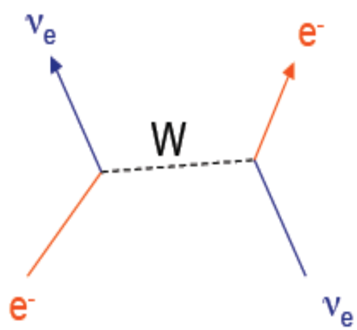
a.k.a. the MSW-effect (1985)

Forward-scattering of ν's in matter:

- NC the same for all flavors



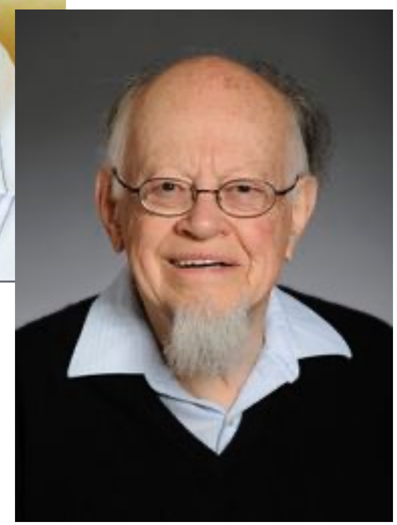
- CC on electrons only for ν_e



→ ν_e pick up an effective mass

Mikheyev

Smirnov



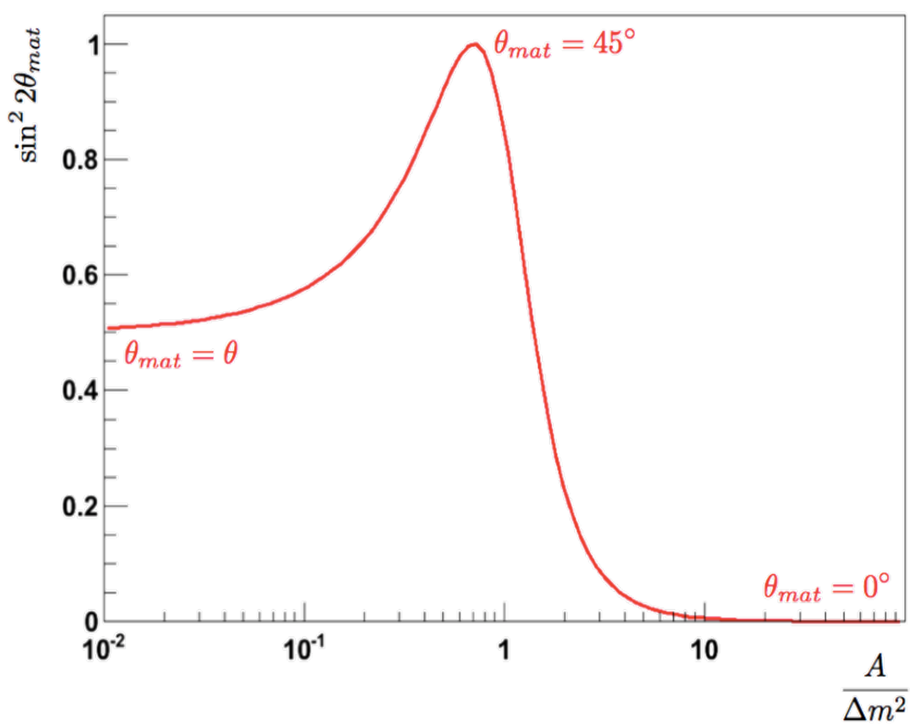
Wolfenstein

Oscillation parameters in matter

→ Modified mass-squared difference and mixing angle in matter:

$$\Delta m^2_{\rm mat} = \left(m_2^{\rm mat}\right)^2 - \left(m_1^{\rm mat}\right)^2 = \Delta m^2 \sqrt{\left(\frac{A}{\Delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta}$$

$$\sin^2\left(2\theta_{\rm mat}\right) = \frac{\sin^2 2\theta}{\left(\frac{A}{\Delta m^2} - \cos 2\theta\right)^2 + \sin^2 2\theta}$$



$\frac{A}{\Delta m^2} = 0$ vacuum: no matter effects
$\Delta m^2_{\rm mat} = \Delta m^2$ and $\theta_{\rm mat} = \theta$

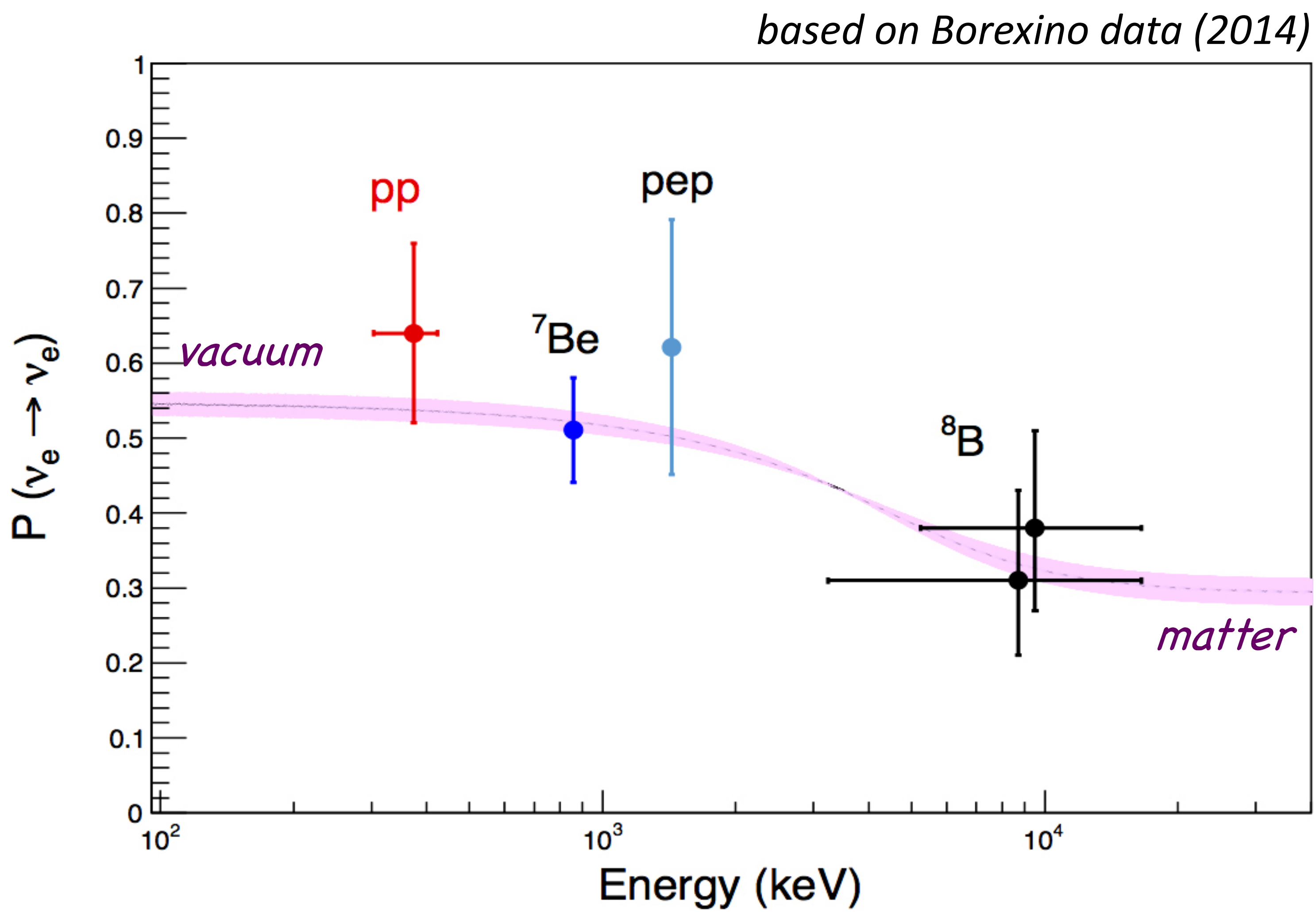
$\frac{A}{\Delta m^2} = \cos 2\theta$ resonance, maximum mixing
$\sin^2 2\theta_{\rm mat} = 1,\ \theta_{\rm mat} = 45°$

resonance condition:
$N_e E = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2} G_{\rm F}}$

$\frac{A}{\Delta m^2} \gg 1$ oscillation amplitude suppressed by $(A/\Delta m^2)^2$

→ full flavor conversion is possible if weak matter potential matches resonance condition!

Energy dependence of solar ν oscillations



mixing angle from SNO/Super-K data on ^{8}B-ν's: $P_{ee} = \sin^2\theta_{12}$ → $\theta_{12} \approx 33°$

LECTURE QUIZ

Question 2

What variables does the oscillation phase depend on?

U : energy and mixing angle

V : mixing angle and distance

W : distance and energy

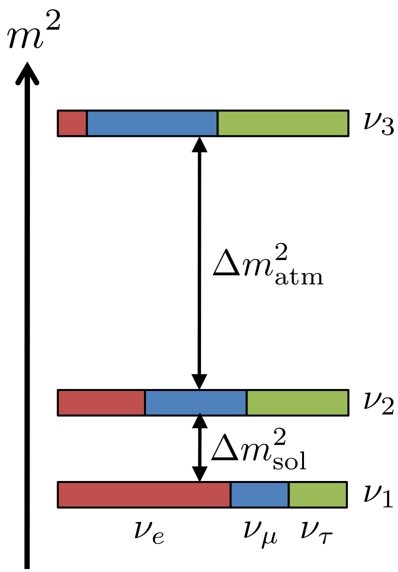
Note down the **7th** letter of the solution word.

Three-flavor mixing in 2022

$$\mathbf{U_{3\times 3}} = \mathbf{U}_{\mathrm{PMNS}}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\mathbf{U}_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

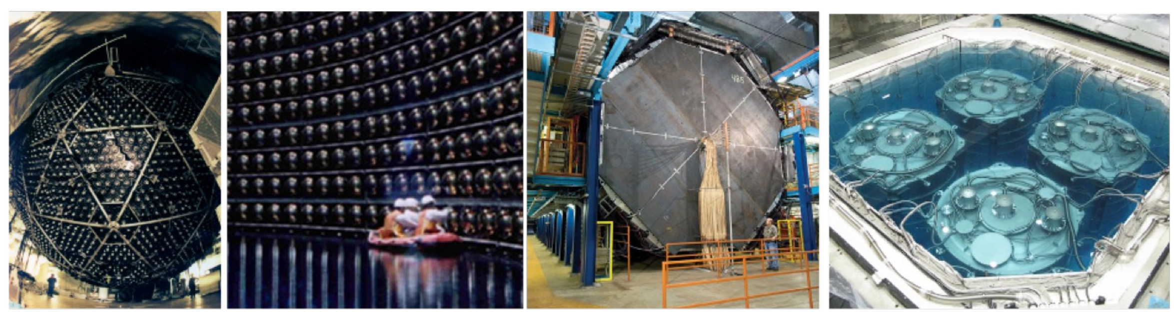
flavor states | ***atmospheric mixing*** (maximum: 45°?) | ***reactor mixing & CP violation*** (small θ_{13}=8.4°, $\delta = -\frac{\pi}{2}$?) | ***solar mixing*** (large 33°) | ***mass states***



normal ordering

mass squared differences → oscillation frequencies

- $\Delta m^2_{\mathrm{sol}} = \Delta m^2_{21}$ → KamLAND+solar: $+8\times10^{-5}$ eV^2
- $\Delta m^2_{\mathrm{atm}} = \Delta m^2_{32} \approx \Delta m^2_{31}$ → SK+acc+reactor: $\pm2.5\times10^{-3}$ eV^2

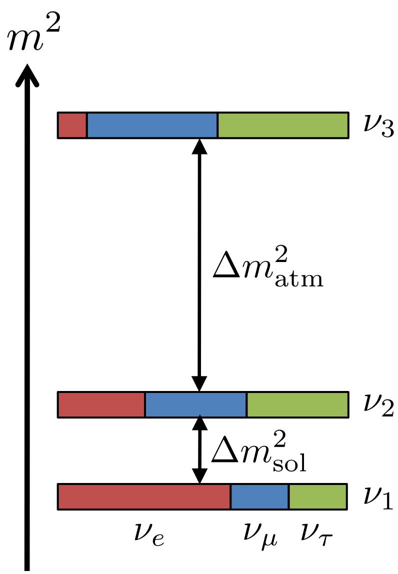


What parameters are still unknown?

$$\mathbf{U_{3\times 3}} = \mathbf{U}_{\mathrm{PMNS}}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

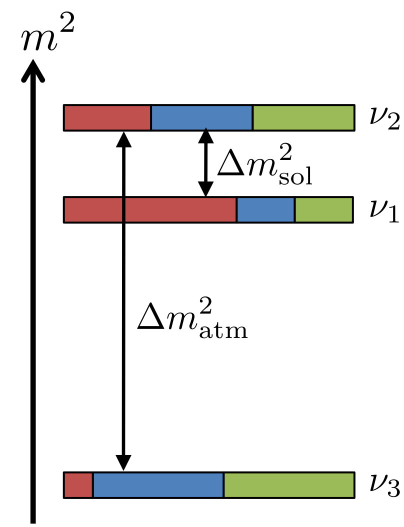
flavor states | ***atmospheric mixing*** (maximum: 45°?) | ***reactor mixing & CP violation*** (small θ_{13}=8.4°, $\delta = -\frac{\pi}{2}$?) | ***solar mixing*** (large 33°) | ***mass states***



normal ordering

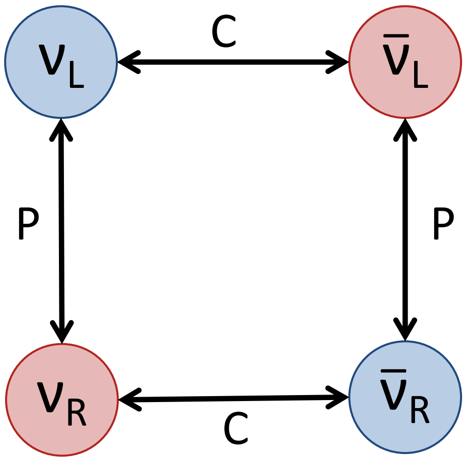
Open issues

- **octant of θ_{23} ($\lessgtr$45°)**
- value of **CP-phase**
- **mass ordering** (sign of Δm^2_{32})
- are there more than 3 light neutrino states?



inverted ordering

Effects of the leptonic CP phase



→ **Neutrinos** themselves violate both P and C-parities.

→ **In oscillations:**

CP conservation: $P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

CP violation: $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

but $P(\nu_\alpha \to \nu_\beta) = P(\bar{\nu}_\beta \to \bar{\nu}_\alpha)$ **CPT**

Full three-flavor oscillation probability:

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta}$$

$$-4\sum_{i<j} \mathrm{Re}\left[U_{\alpha i}U^*_{\alpha j}U^*_{\beta i}U_{\beta j}\right] \sin^2\left[\frac{\Delta m^2_{ji}}{4E}L\right]$$

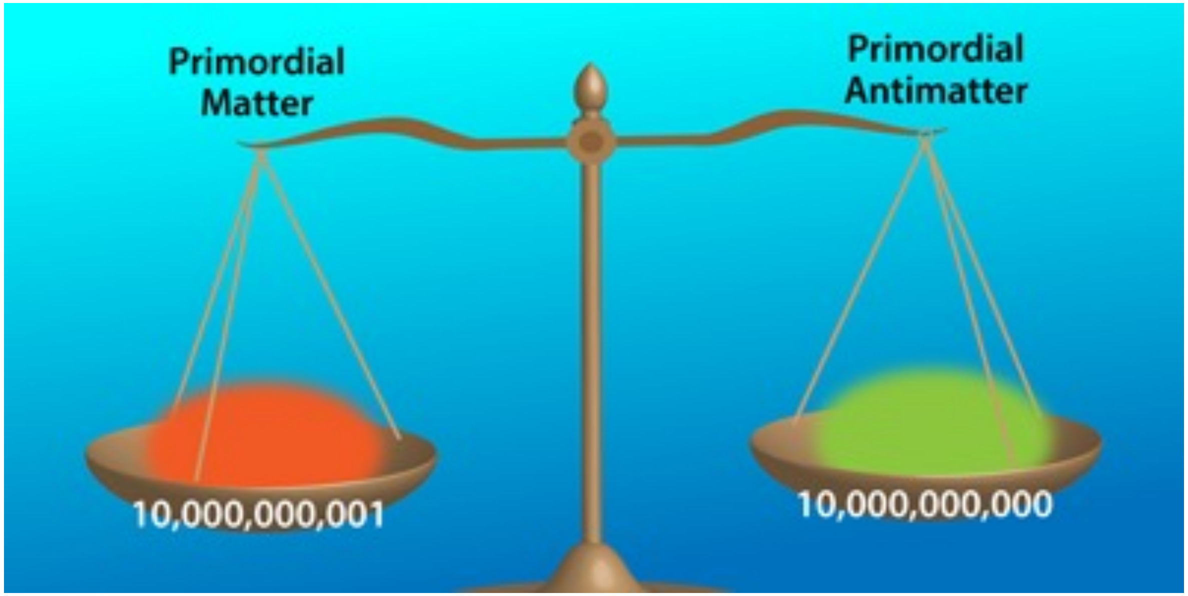
same for neutrinos and antineutrinos
→ **conserves CP-symmetry**
→ flavor disapperance & appearance

$$+2\sum_{i<j} \mathrm{Im}\left[U_{\alpha i}U^*_{\alpha j}U^*_{\beta i}U_{\beta j}\right] \sin\left[\frac{\Delta m^2_{ji}}{2E}L\right]$$

different for neutrinos and antineutrinos
→ **violates CP-symmetry**
→ only **appearance** oscillations!

CP violation

... is one of the three preconditions of creating matter-antimatter asymmetry:



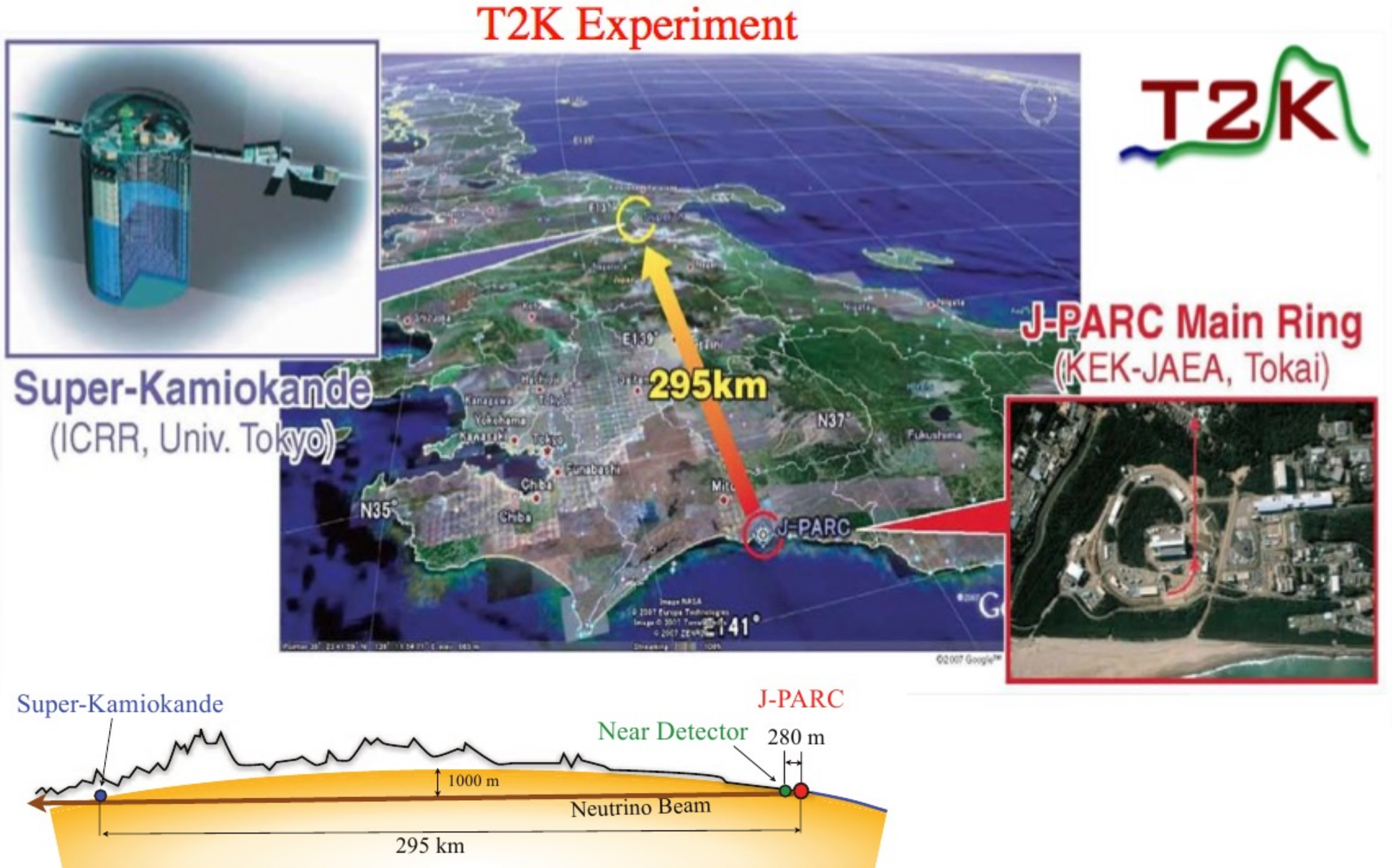
→ matter access is tiny, but CP violation in the quark sector is not sufficient

CP violation in neutrino oscillations opens the door for **leptonic CP violation**

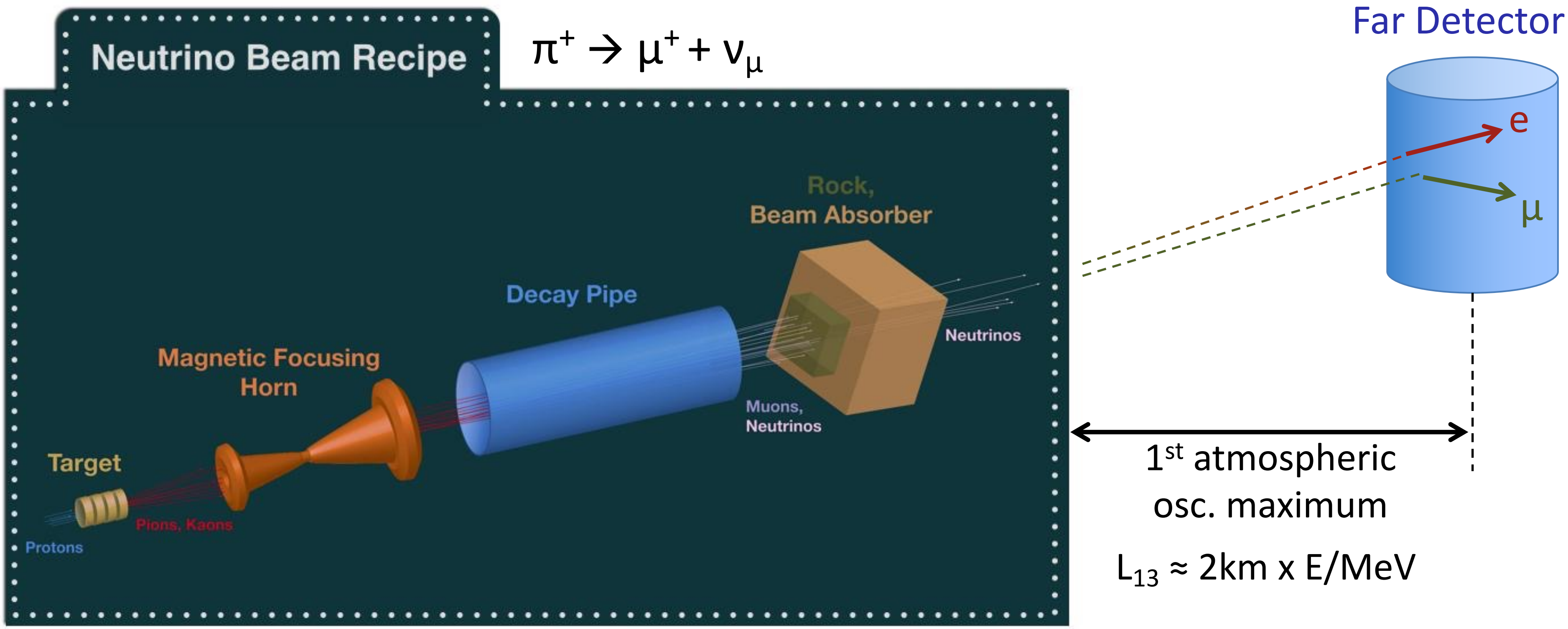
→ can still be 1000x larger than in the quark sector

→ **Leptogenesis:** Leptonic CP asymmetry can be transferred to baryon sector

T2K: Tokai-to-Kamioka



Long-baseline ν_μ beam experiments



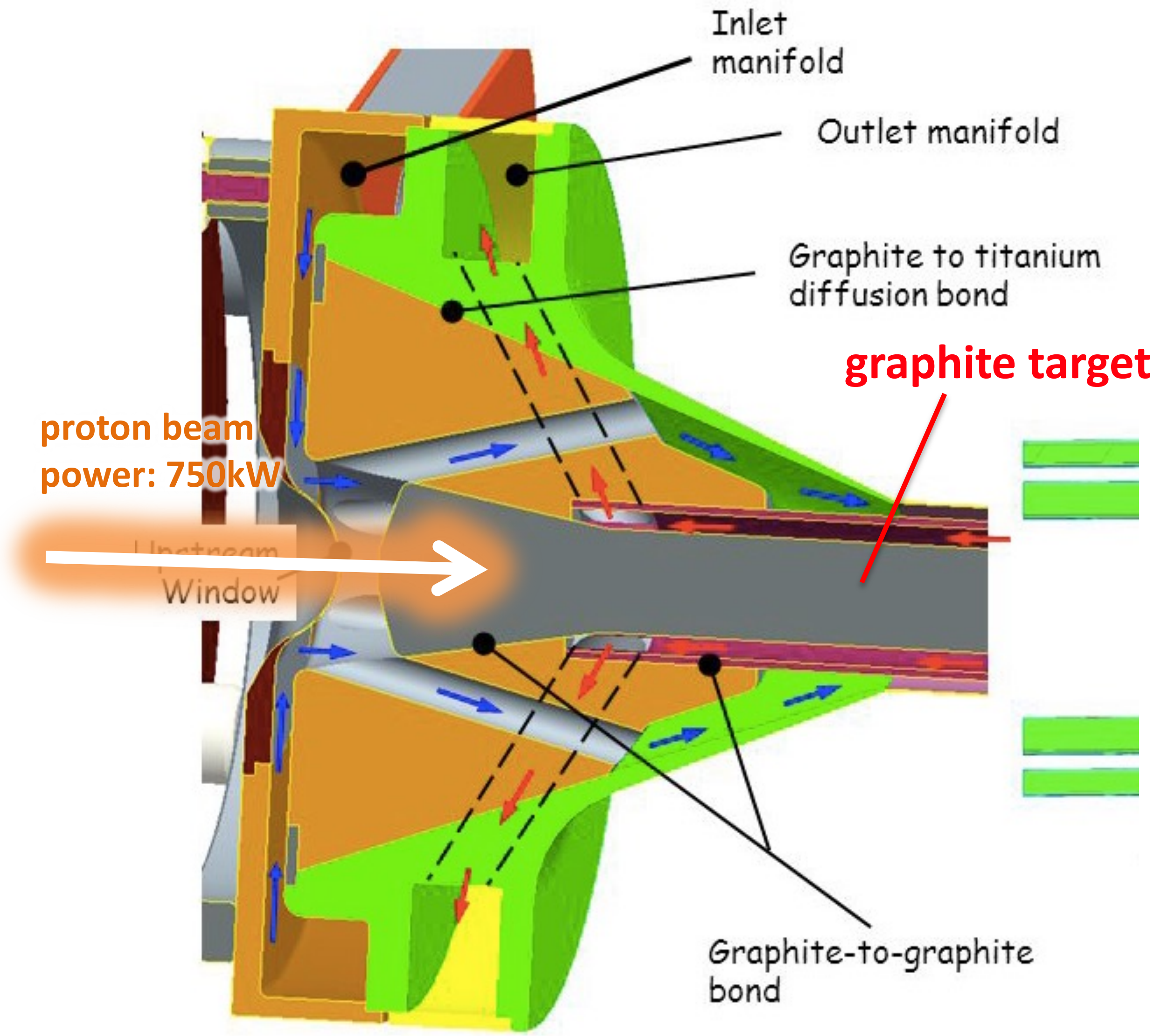
Search modes:

- Disappearance oscillations: $\nu_\mu \rightarrow \nu_\mu$ $\rightarrow$ $\theta_{23}, \Delta m^2_{32}$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32}}{4E}\right)$$

- **Appearance oscillations:** $\nu_\mu \rightarrow \nu_e$ $\rightarrow$ θ_{13}, δ_{CP}

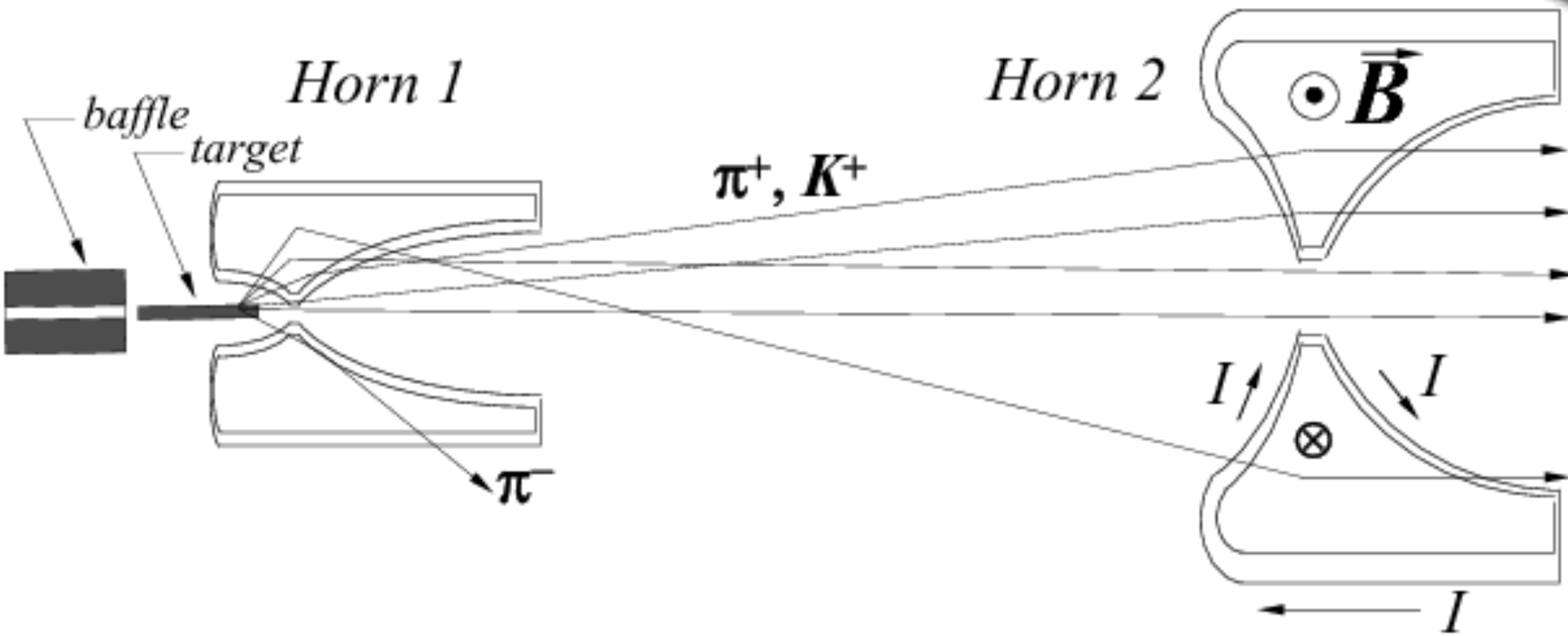
Neutrino target



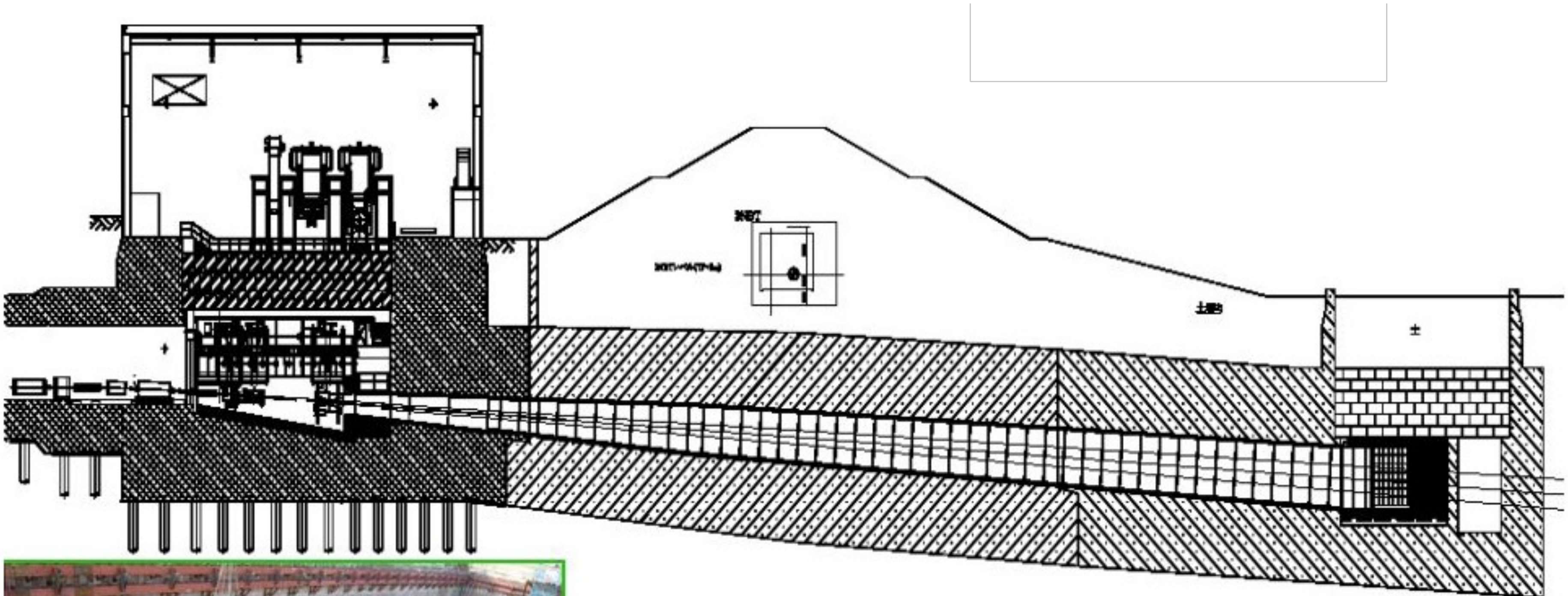
- production of charged pions (and kaons) by interactions of protons on carbon
- light material favors higher-energy pions
- pions are beamed in forward direction
- beams are typically pulsed → BG reduction

Focussing horns

- magnetic fields improve forward-focussing of pions
- de-selects other particles (especially wrong-sign pions)



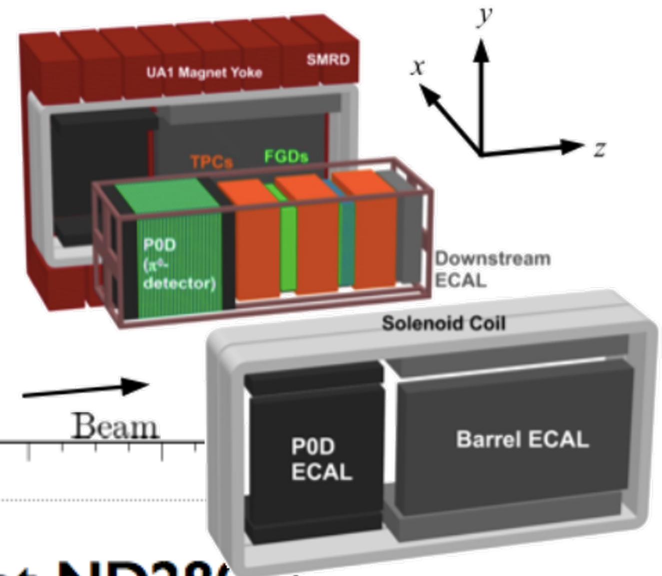
Inclined decay pipe

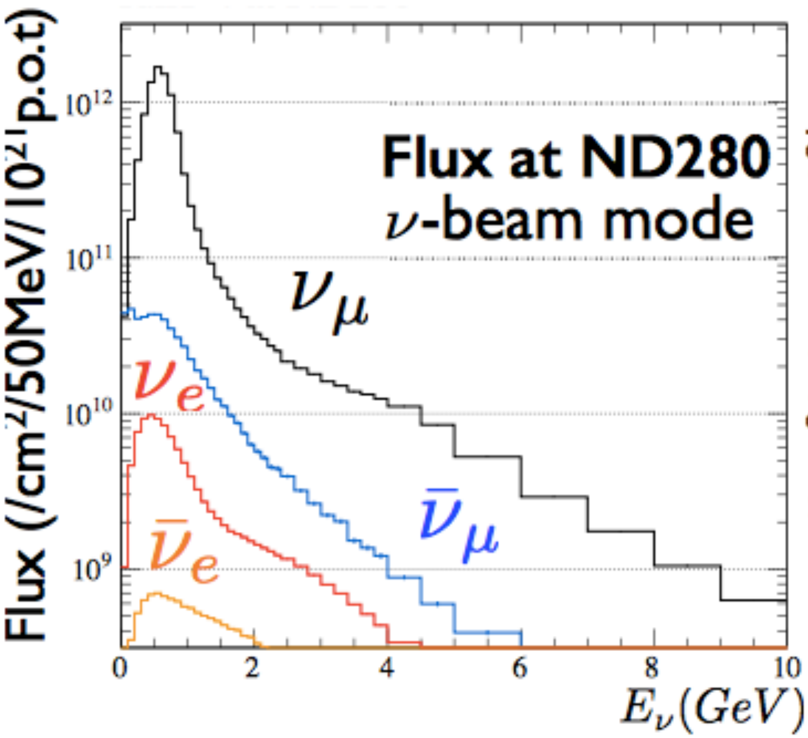


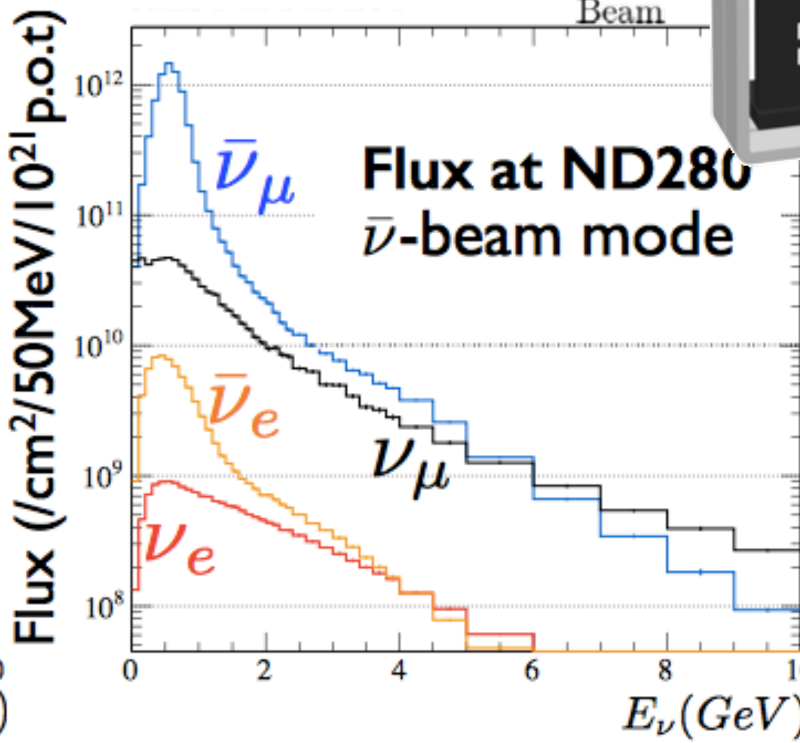
- evacuated pipe for $\pi^+ \to \mu^+ + \nu_\mu$ *(neutrino mode)*
- try to balance pion and muon decay not wanted: $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$
- tunnel has to be inclined to compensate curvature of Earth surface → expensive!!

T2K Near Detectors for ν spectrum

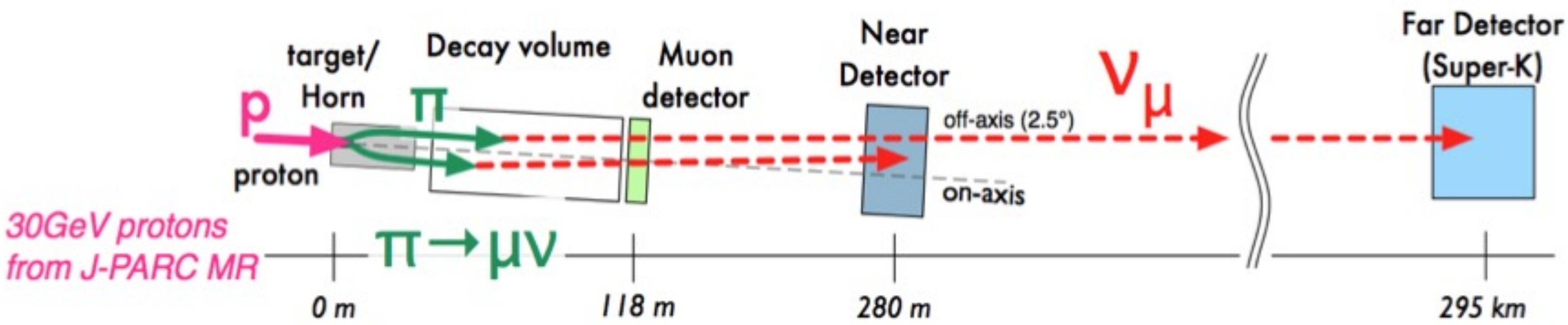
- some intrinsic beam contamination with ν_e flavor
- polarity of beam horn switched to obtain $\bar{\nu}_\mu$-beam
- near detector (ND280) to measure beam direction and composition, cross-sections ... (reduce systematics)

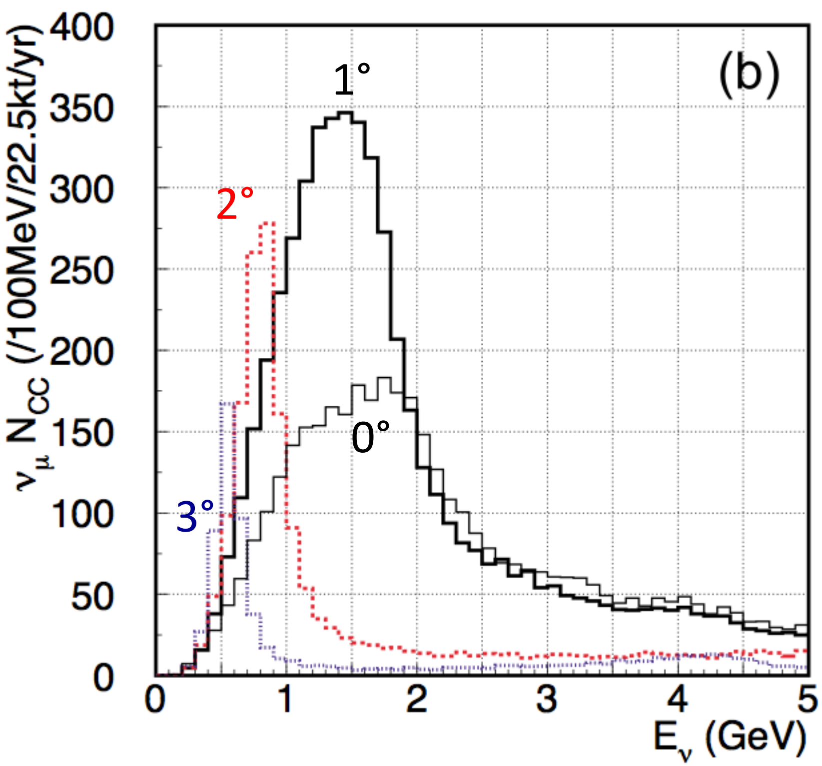






T2K: Off-axis beam





ν_μ-beam energy spectrum

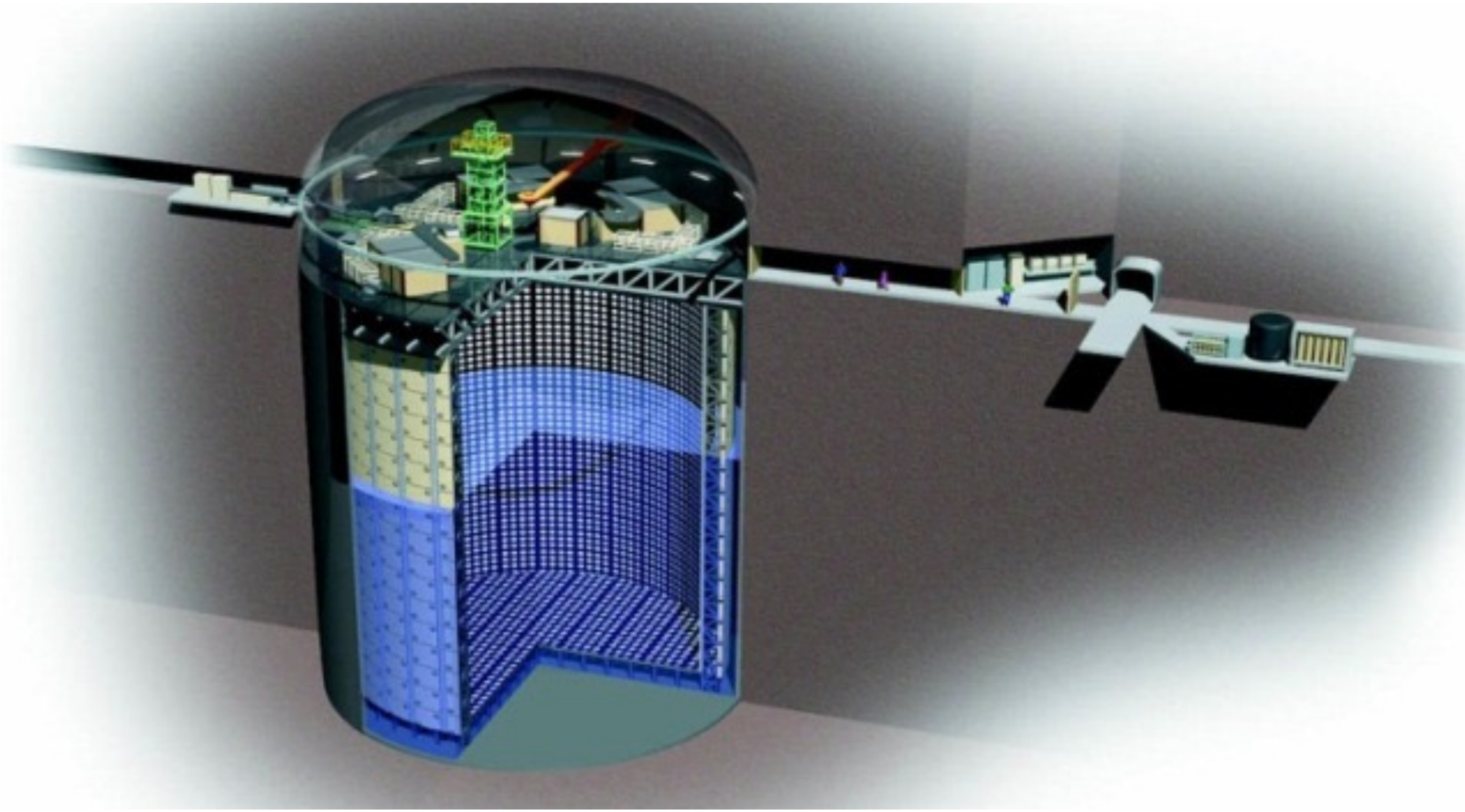
- on-axis: wide-band beam
- off-axis: narrower beam spectrum, increased peak intensity

→ increased event rate at correct L/E

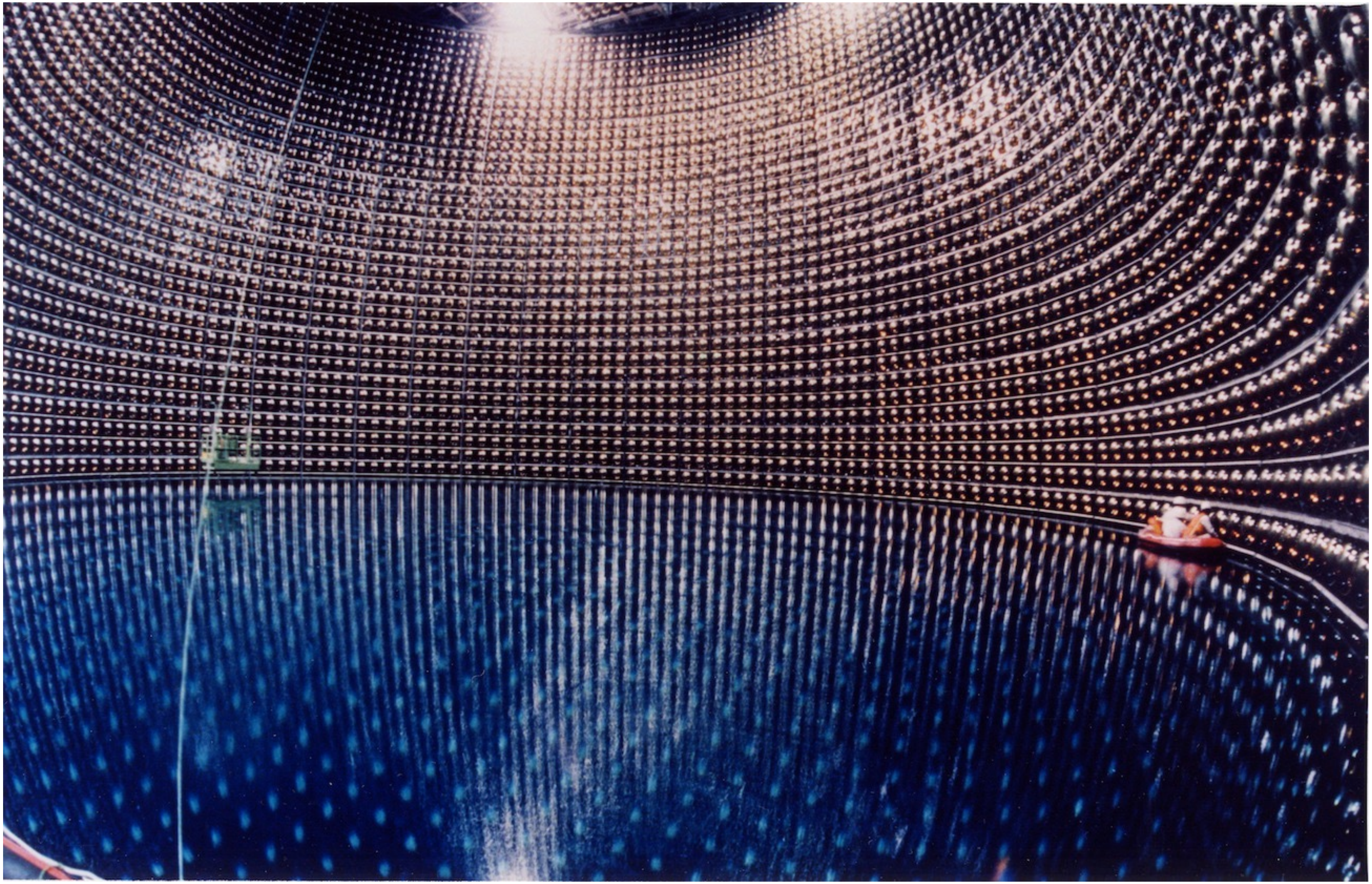
→ less high-energy background

Super-Kamiokande experiment

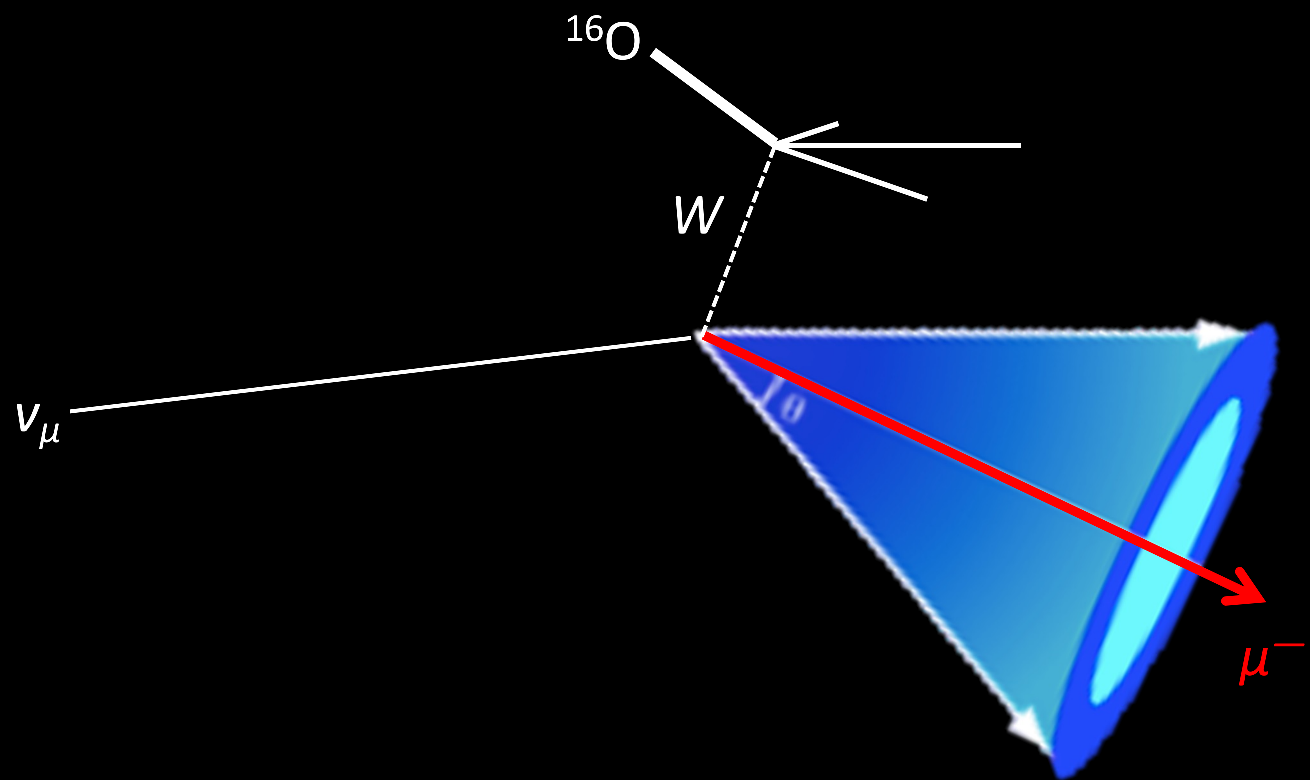
dimensions: 45m x 45m – target mass: 50 kton – light readout: 11,200 20''-PMTs



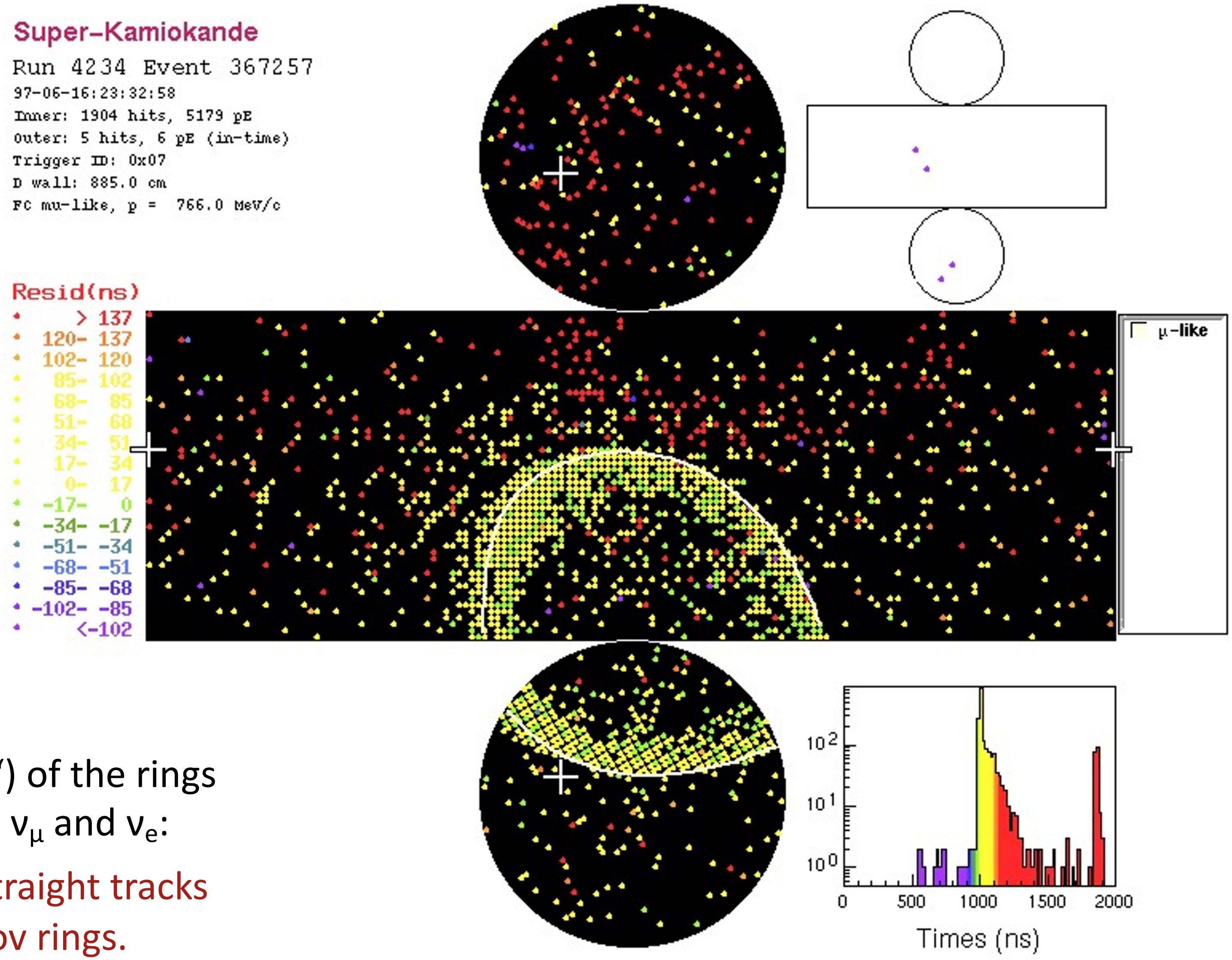
Super-Kamiokande during filling



Neutrino detection by Cherenkov effect



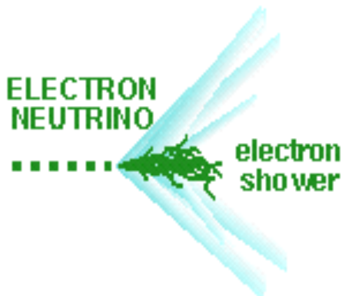
Muon (neutrino) signal

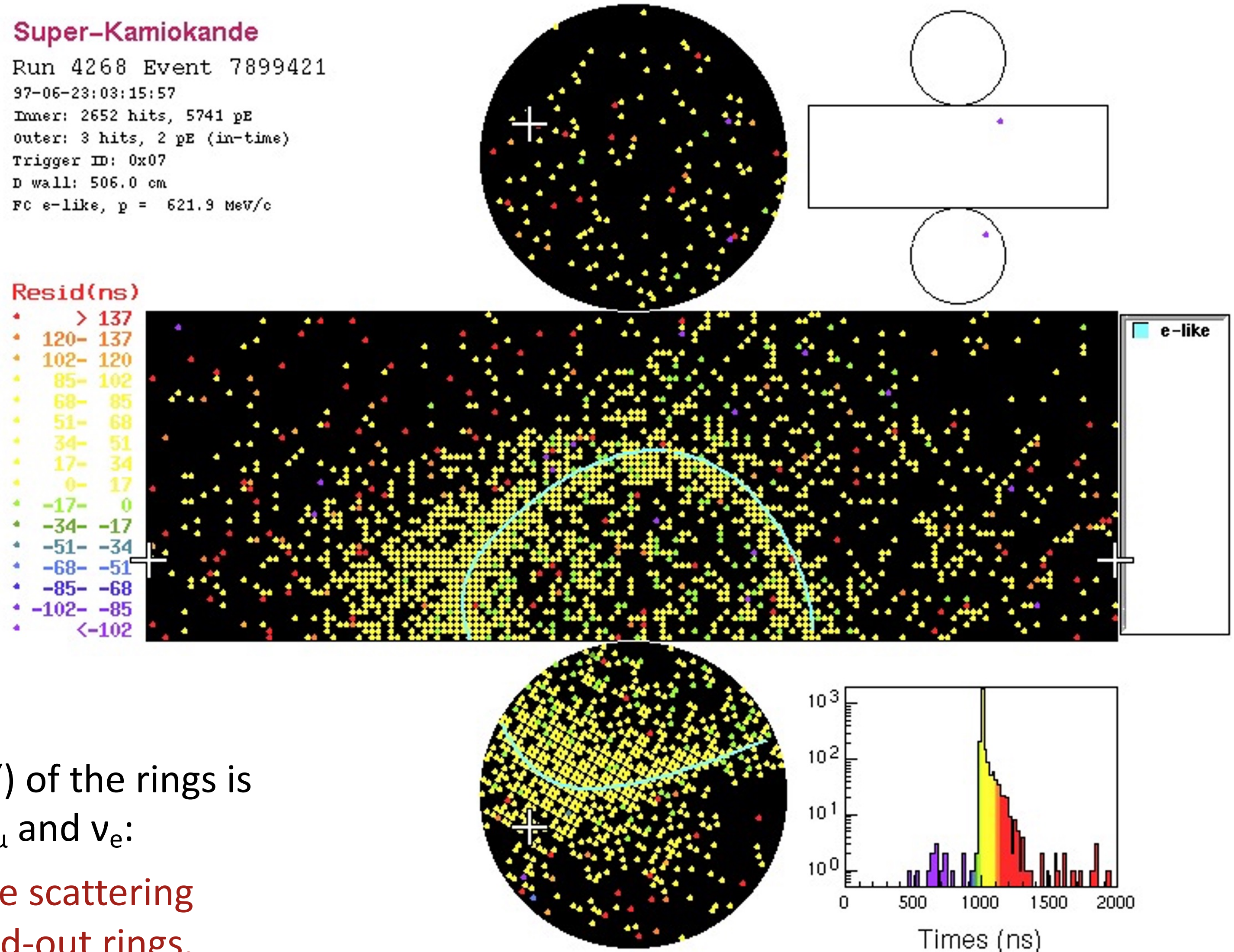


The shape ("fuzziness") of the rings is used to discriminate ν_μ and ν_e:

→ μ's produce long, straight tracks and sharp Cherenkov rings.

Electron (neutrino) signal





The shape ("fuzziness") of the rings is used to discriminate ν_μ and ν_e:

→ e's undergo multiple scattering and produce washed-out rings.

$\nu_\mu \rightarrow \nu_e$ oscillation probability

good approximation for 1st atmospheric oscillation maximum

Oscillation probability for ν_e appearance
in a ν_μ neutrino beam:

$$P_{\mu e(\bar{\mu}\bar{e})} = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\left(\frac{B_\pm L}{2}\right)$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right)$$
$$+J\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_\pm}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{B_\pm L}{2}\right)\cos\left(\mp\delta - \frac{\Delta_{13}L}{2}\right)$$

$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu} \qquad B_\pm = |A \pm \Delta_{13}| \qquad A = \sqrt{2}G_F N_e$$

$\nu_\mu \rightarrow \nu_e$ oscillation probability

Oscillation probability for ν_e appearance
in a ν_μ neutrino beam:

atmospheric oscillations

$$P_{\mu e(\bar{\mu}\bar{e})} = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\left(\frac{B_\pm L}{2}\right)$$

solar oscillations

$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right) \approx 0$$

$$+J\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_\pm}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{B_\pm L}{2}\right)\cos\left(\mp\delta - \frac{\Delta_{13}L}{2}\right)$$

neutrino-antineutrino asymmetry term

$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu} \qquad B_\pm = |A \pm \Delta_{13}| \qquad A = \sqrt{2}G_F N_e$$

$\nu_\mu \rightarrow \nu_e$ oscillation probability

Oscillation probability for ν_e appearance
in a ν_μ neutrino beam:

atmospheric oscillations

$$P_{\mu e(\bar{\mu}\bar{e})} = \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2\left(\frac{B_\pm L}{2}\right)$$

solar oscillations

$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{12}}{A}\right)^2 \sin^2\left(\frac{AL}{2}\right) \approx 0$$

leptonic CP violation

$$+J\frac{\Delta_{12}}{A}\frac{\Delta_{13}}{B_\pm}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{B_\pm L}{2}\right)\cos\left(\mp\delta - \frac{\Delta_{13}L}{2}\right)$$

neutrino-antineutrino asymmetry term

$$J = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}$$

$$\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E_\nu} \qquad B_\pm = |A \pm \Delta_{13}| \qquad A = \sqrt{2}G_F N_e$$

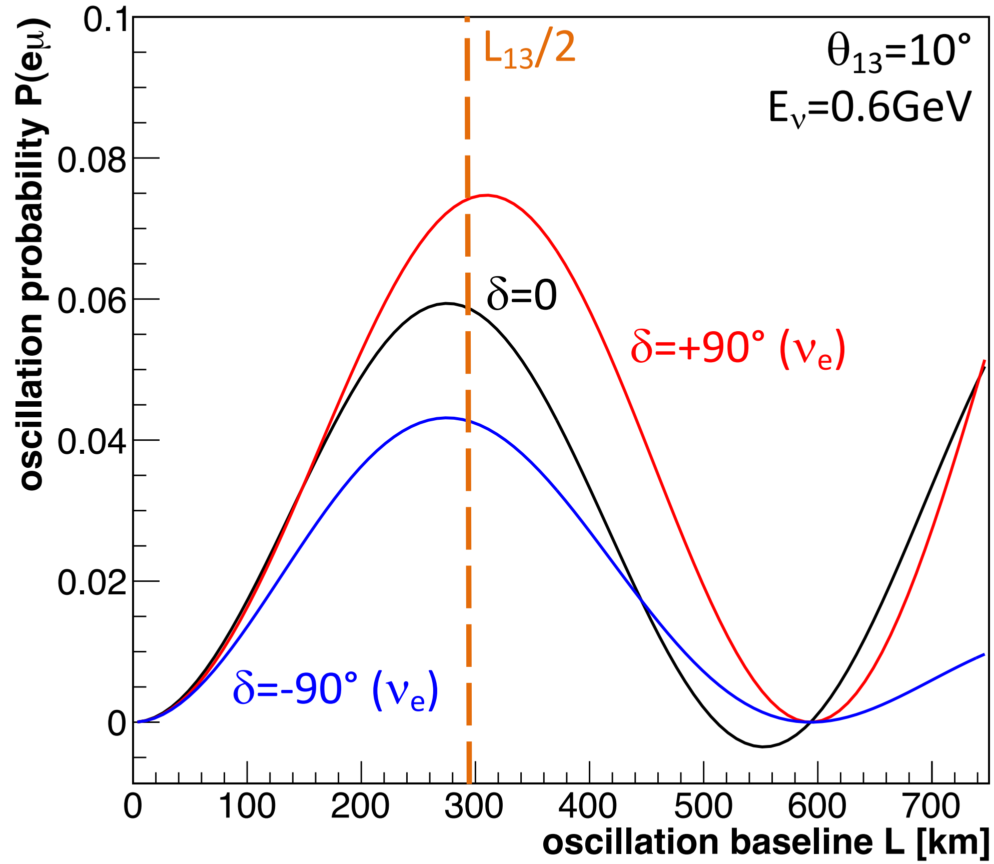
Short-baseline ν_e appearance probability

Effective oscillation probability

$$P_{\mu e} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right) + h.o.f.(\theta_{ij},\Delta m^2_{ij})\cdot\cos(\mp\delta)$$

→ term with CP phase shifts amplitude and position of 1st oscillation maximum

→ neutrinos and antineutrino shifts are inverted



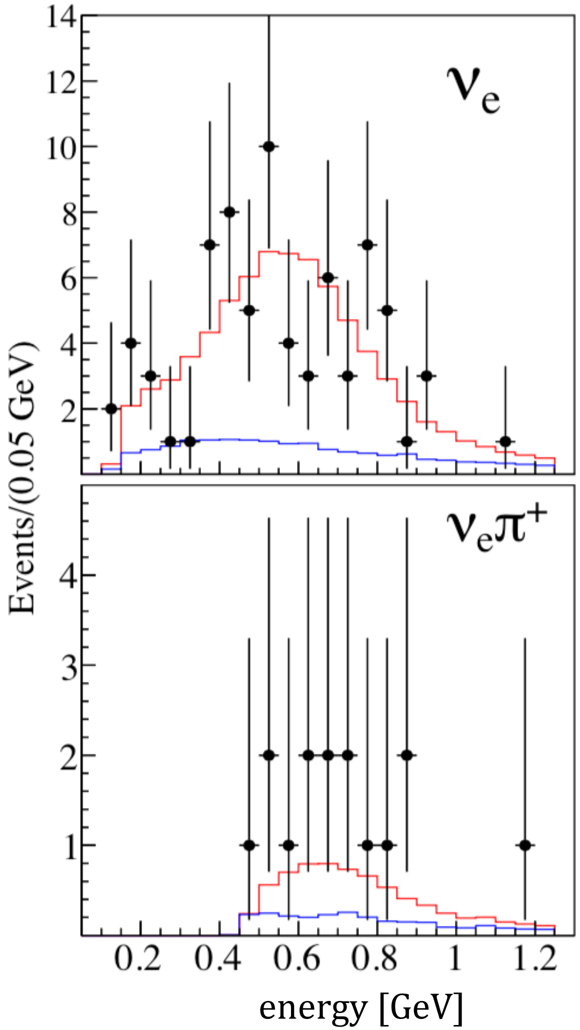
T2K results on $\nu_\mu \rightarrow \nu_e$ appearance

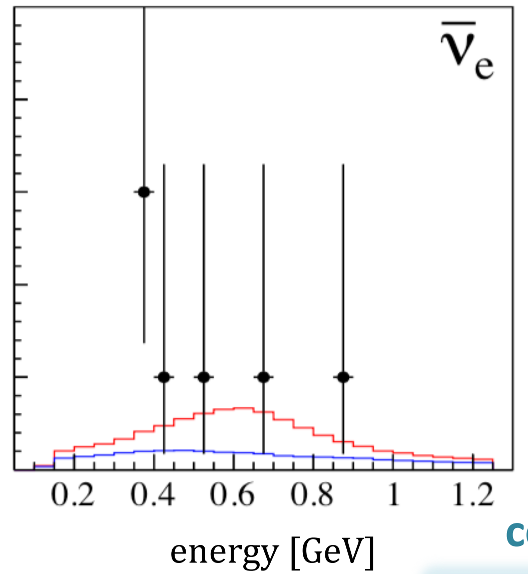
neutrino mode

antineutrino mode

CC-QE

CC-1π





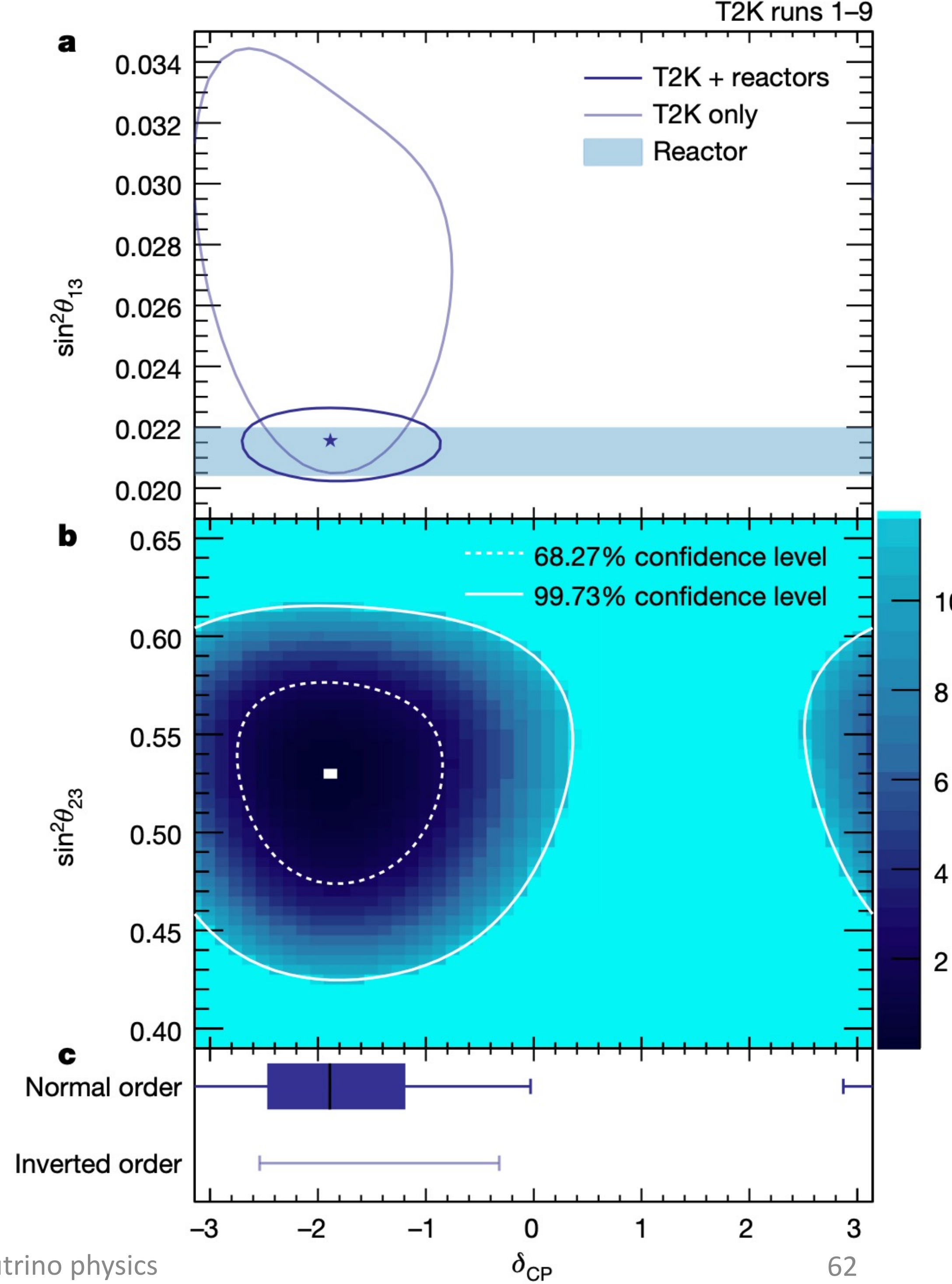
data points
oscillation signal
background

comparison to rate predictions:

	δ_{CP}	ν_e CCQE	ν_eCC $1\pi^+$	$\bar{\nu}_e$ CCQE
	$-\pi/2$	73.5	6.9	7.9
Normal	0	61.4	6.0	9.0
ordering	$\pi/2$	49.9	4.9	10.0
	π	61.9	5.8	8.9
	$-\pi/2$	64.9	6.2	8.5
Inverted	0	54.4	5.1	9.8
ordering	$\pi/2$	43.5	4.3	10.9
	π	54.0	5.3	9.7
Observed		74	15	7

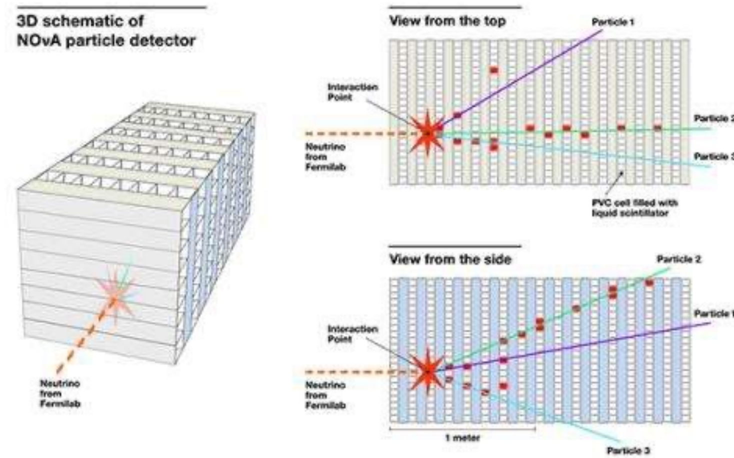
T2K results on θ_{13} and δ_{CP}

- order 3σ preference for **negative non-zero value of δ_{CP}**
- **result on θ_{13}** favors larger value than reactor experiments
- **normal ordering** preferred over interted ordering (1-2σ)



Future experiments for CP-phase

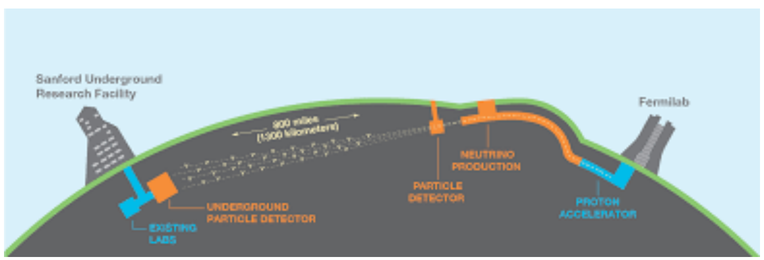
- **running projects:**
  - T2K: J-PARC → Super-Kamiokande (285 km)
  - NOvA: Fermilab → Soudan (800 km)

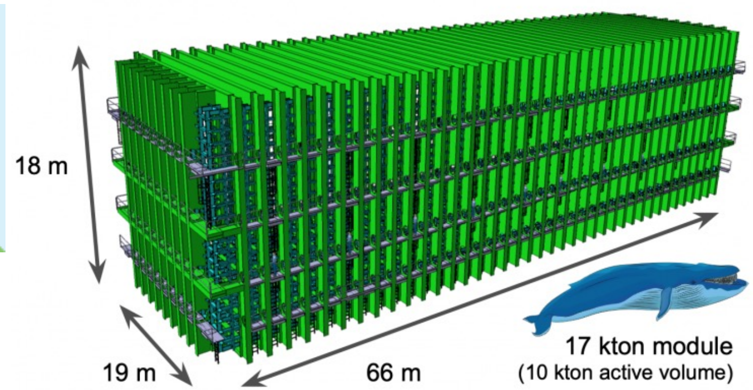


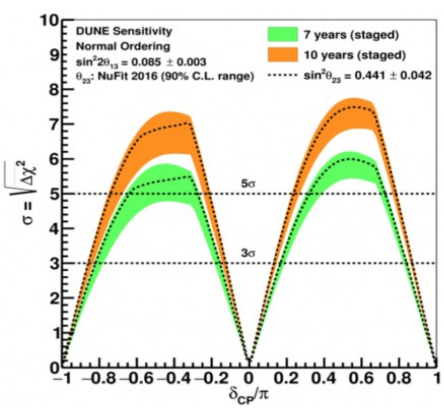
NOvA

- **future projects:**
  - LBNF/DUNE: Fermilab → Homestake (1300 km)
  - T2HK: J-PARC → Hyper-Kamiokande (285 km)
  - ESS-SB: Lund → ? (360/450 km)

DUNE







LECTURE QUIZ

Question 3

What property of the Cherenkov signals does Super-Kamiokande use for electron/muon discrimination?

A: ring fuzziness

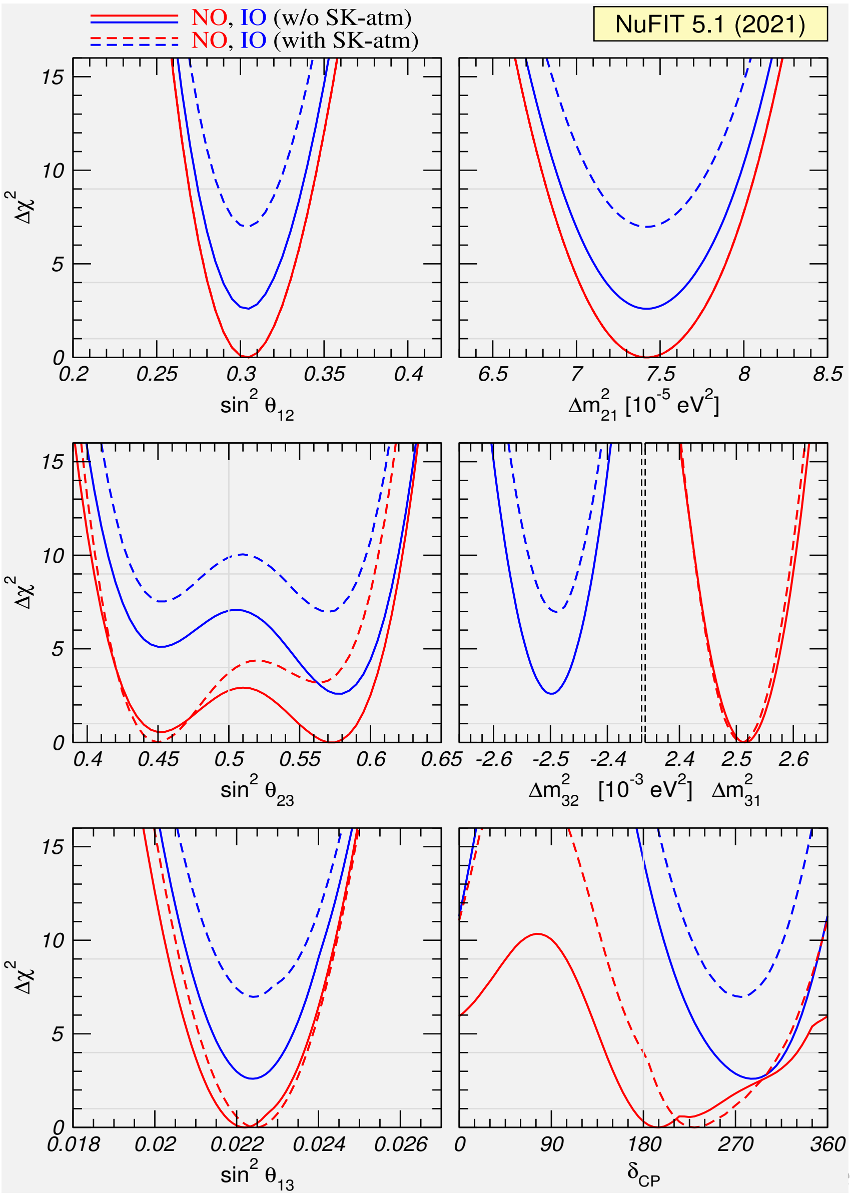
B : number of rings

C : ring brightness

Note down the **eighth** letter of the solution word.

Current best values of oscillation parameters

NO – Normal Ordering, IO – Inverted Ordering



1σ uncertainties

- Δm^2_{21} 2.8%
- Δm^2_{32} 1.1%
- $\sin^2\theta_{12}$ 4.3%
- $\sin^2\theta_{13}$ 2.9%
- $\sin^2\theta_{23}$ 3.6%

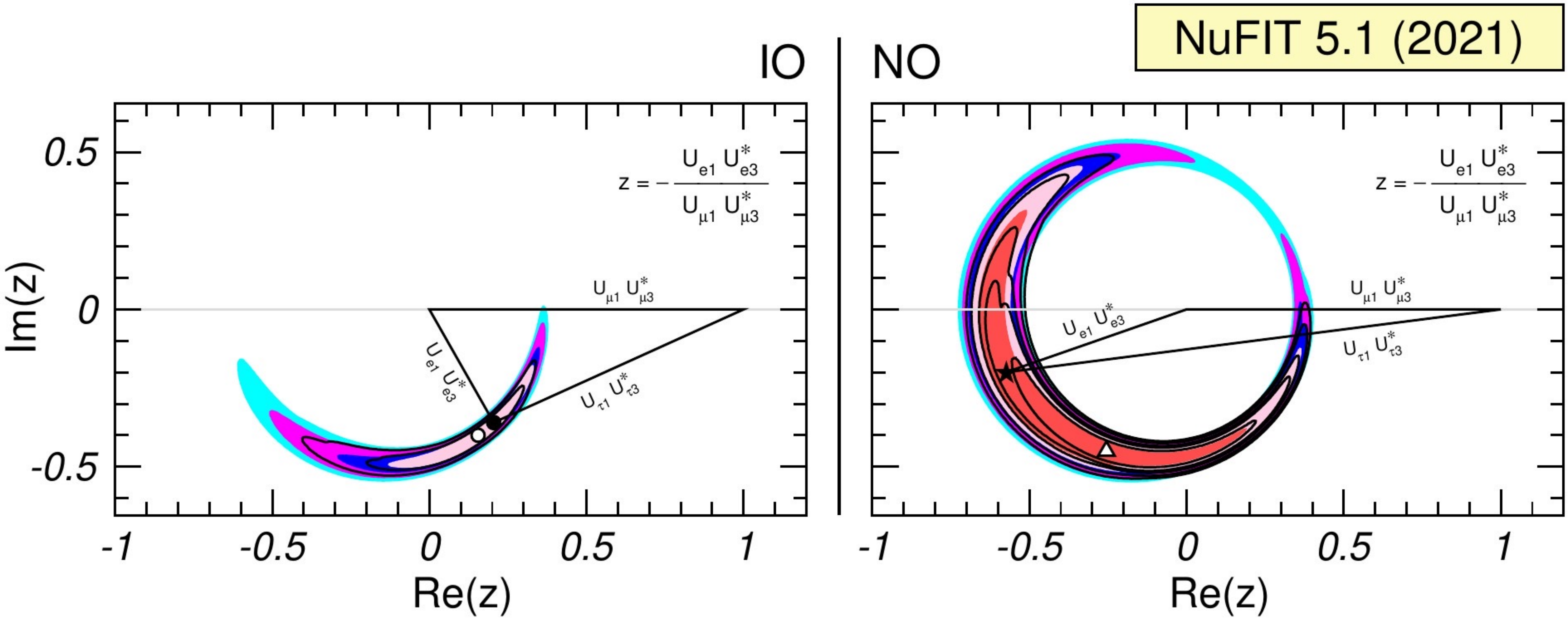
NuFit 5.1
(assuming normal mass hierarchy)

→ all angles & Δm^2's determined

→ large & well-known value of θ_{13}:
- simplifies future osc. experiments
- indication for non-zero $\delta \approx -90°$

→ other unknowns
- no preference for octant of θ_{23}
- mass hierarchy unknown

Leptonic unitarity triangle

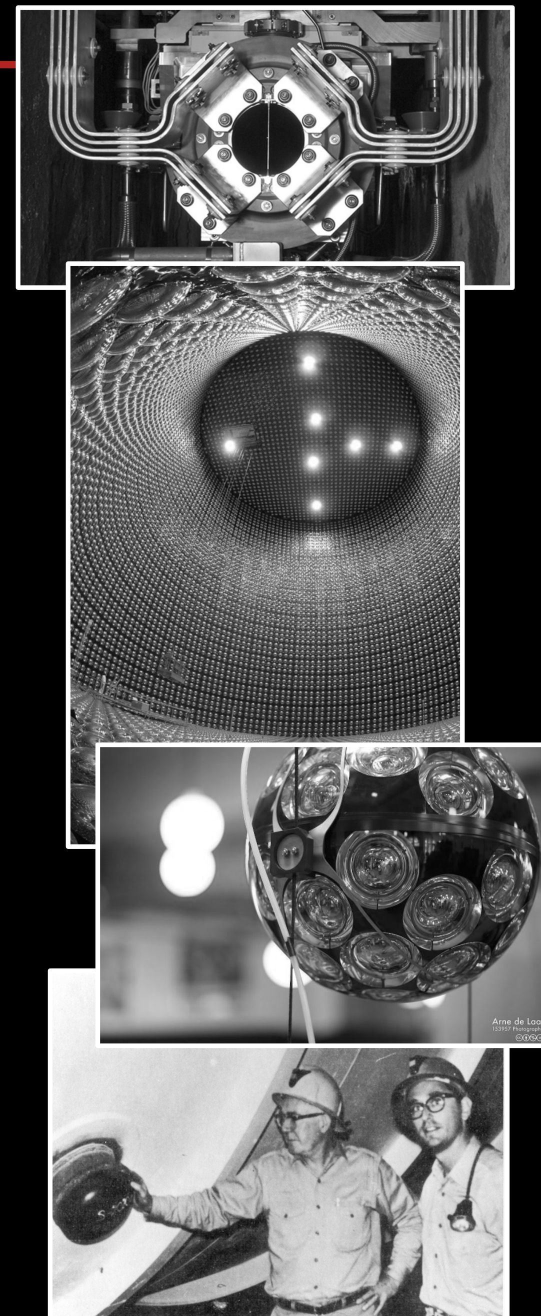


Unitarity triangle based on the 1st and 3rd column of PMNS matrix

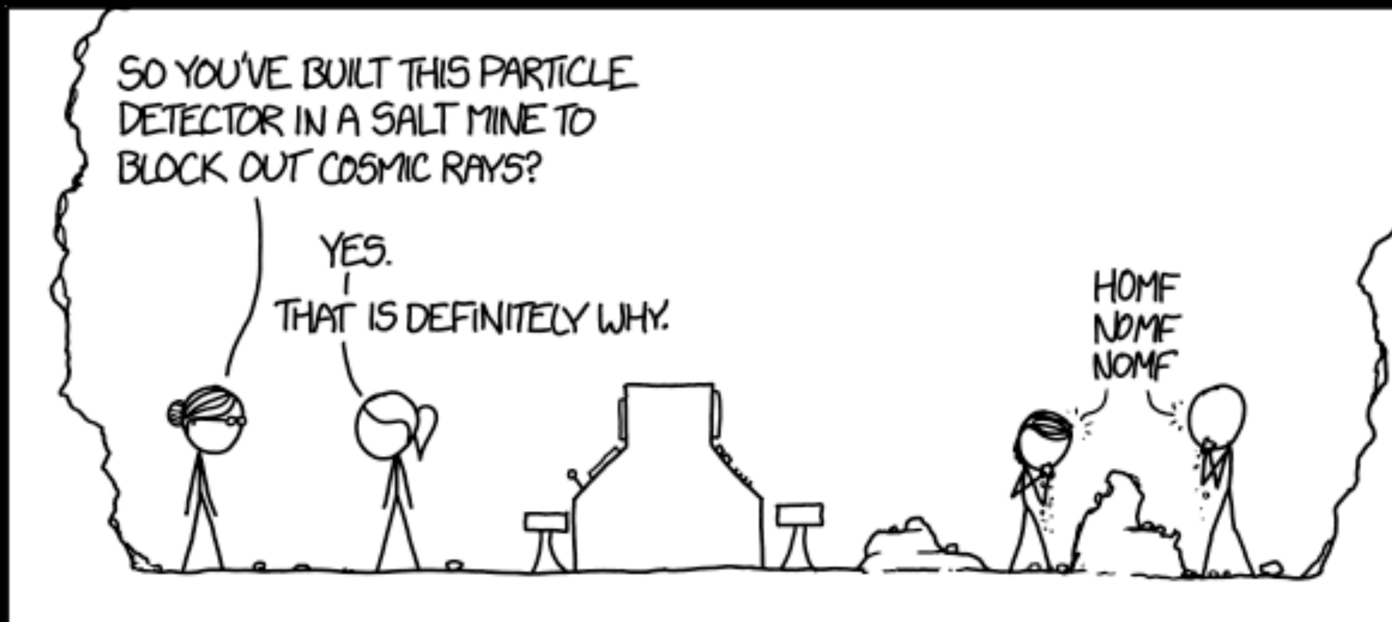
- unitarity is assumed (not yet a test of unitarity!)
- still far from the knowledge we have on UT in quark sector

Summary of Lecture 1

- **Neutrinos** feature properties unlike all other constituents of the Standard Model of particle physics.
- The discovery of **neutrino flavor oscillations** explains anomalies as the Solar Neutrino Problem
- They prove as well that **neutrinos have non-zero mass** → first extension of the original Standard Model.
- Unlike the quark sector, **neutrino mixing is** a **large** effect.
- Current **oscillation experi**ments investigate **CP-violating phase δ_{CP}** and the **mass ordering** (see next Lecture).



Thanks for your attention!



Questions?

Projections for next-generation experiments

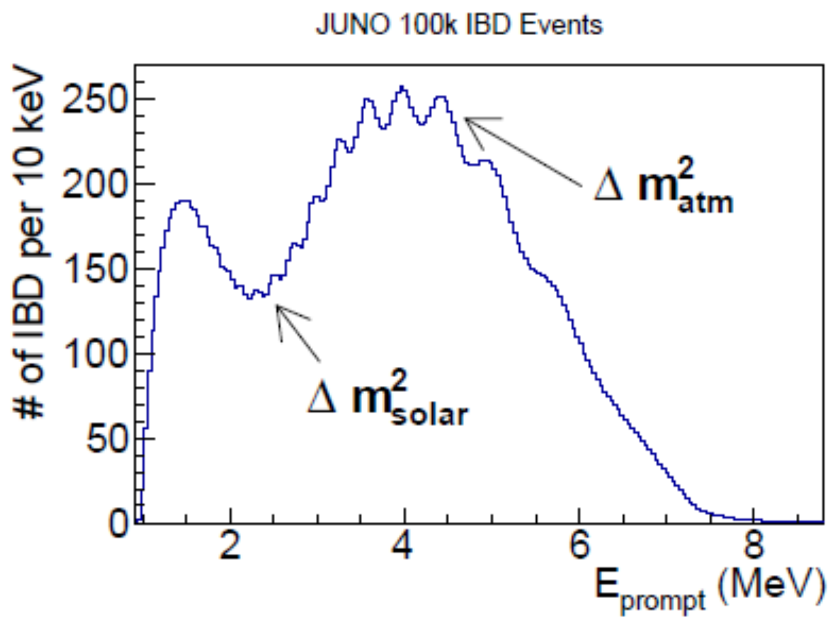
oscillation parameters	2015 precision	2025? precision
$\sin^2\theta_{12}$	5.4 %	0.67%
$\sin^2\theta_{23}$	~10 %	~7 %
$\sin^2 2\theta_{13}$	5.8 %	~3%
Δm^2_{21}	2.6 %	0.59%
$\lvert\Delta m^2_{ee}\rvert$	2.6 %	0.44%

+ inputs from other experiments

JUNO

atm., LBL

DB+DC+RENO



→ **substantial increase in precision**

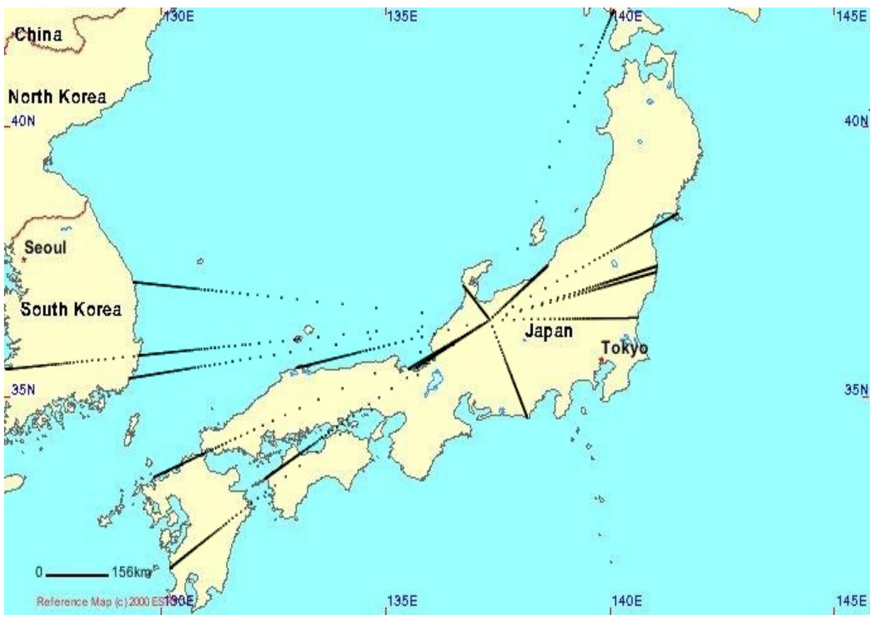
- will be comparable to present CKM matrix
- are there more than three neutrino flavors?

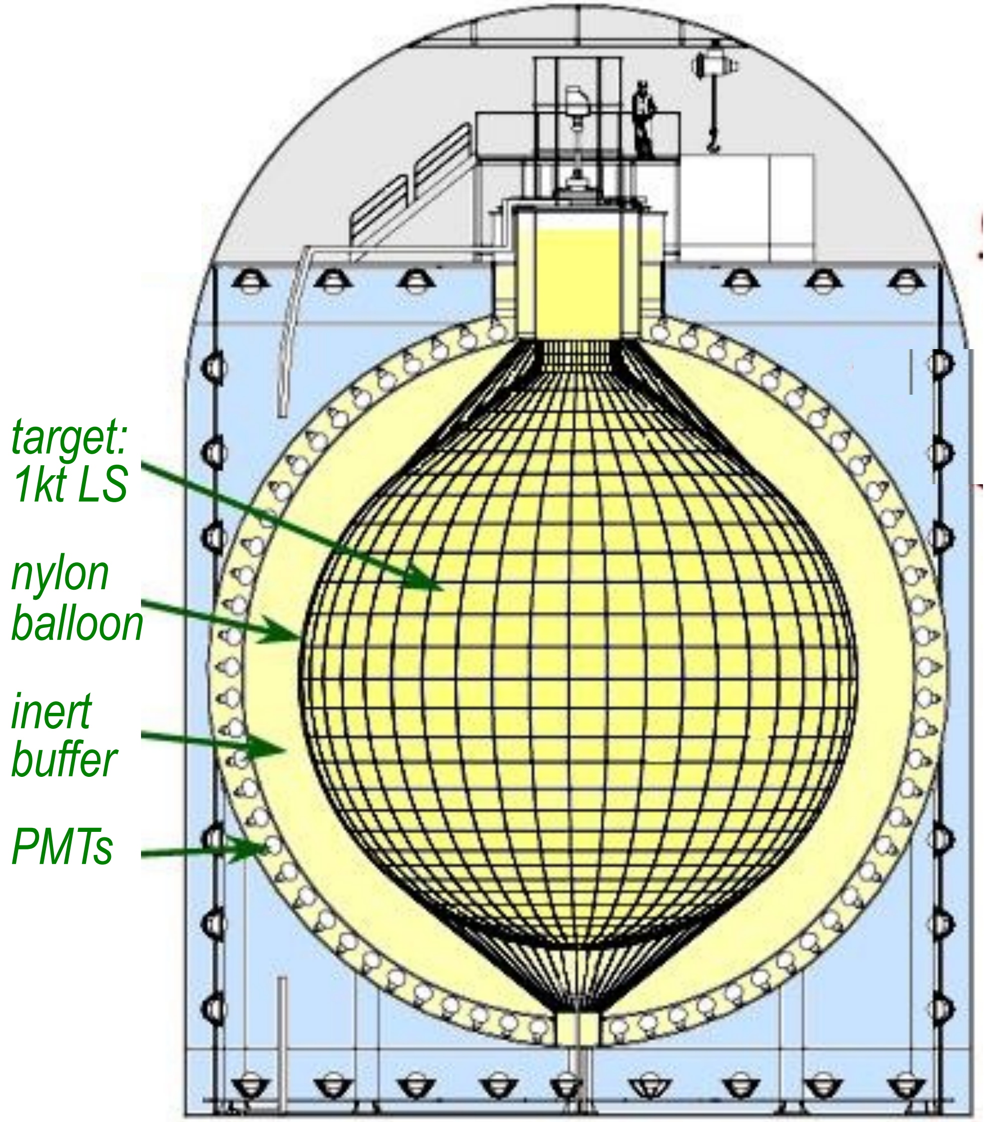
KamLAND: Long-baseline reactor $\bar{\nu}_e$ oscillations

KamLAND detector @ Kamioka

- large detector: 1kt of liquid scintillator at Kamioka mine
- most Japanese reactors at ~200km baseline

→ sensitive to oscillations via solar parameters $\boldsymbol{\theta_{12}, \Delta m^2_{21}}$

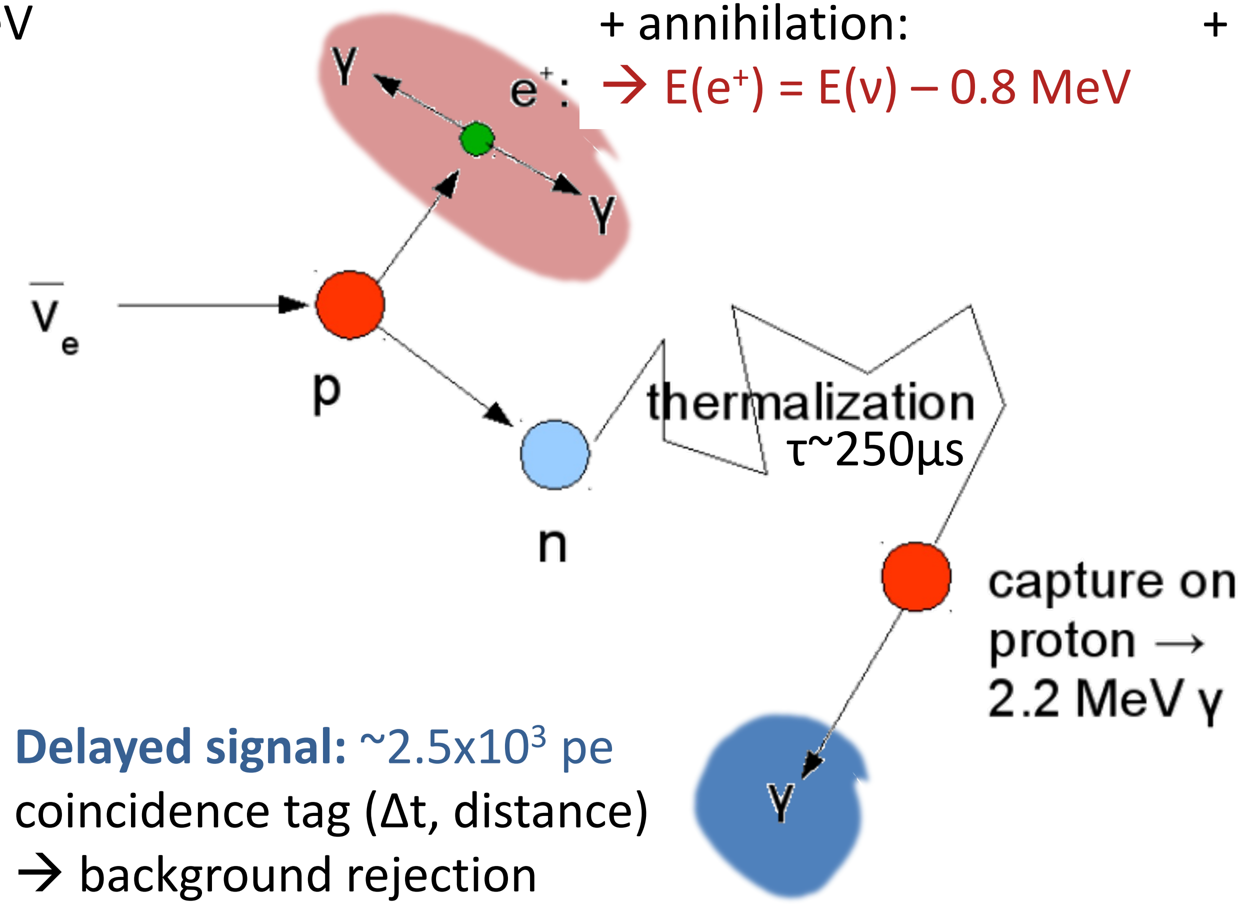




KamLAND: $\bar{\nu}_e$ detection

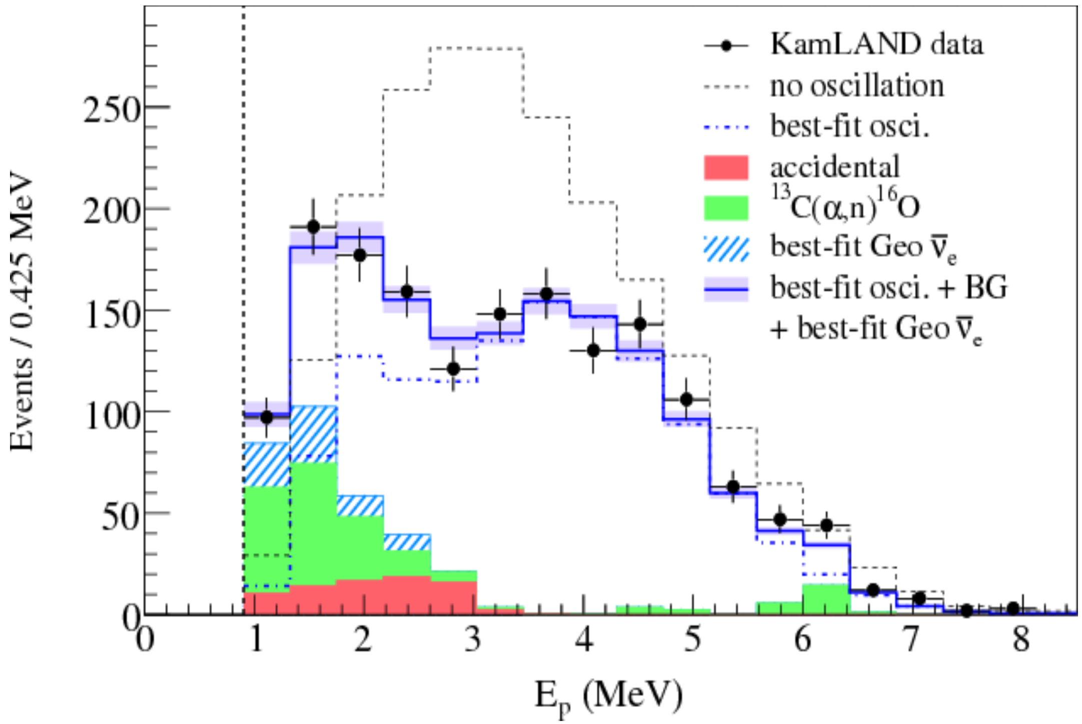
Threshold:
$Q = m(n)+m(e^+)-m(p)$
$= 1.8$ MeV

Prompt signal: 10^{3-4} pe
Kinetic energy of positron: $E(\nu) - Q$
+ annihilation: $+ 2m(e^{\pm})$
→ $E(e^+) = E(\nu) - 0.8$ MeV



Delayed signal: ~$2.5\text{x}10^3$ pe
coincidence tag (Δt, distance)
→ background rejection

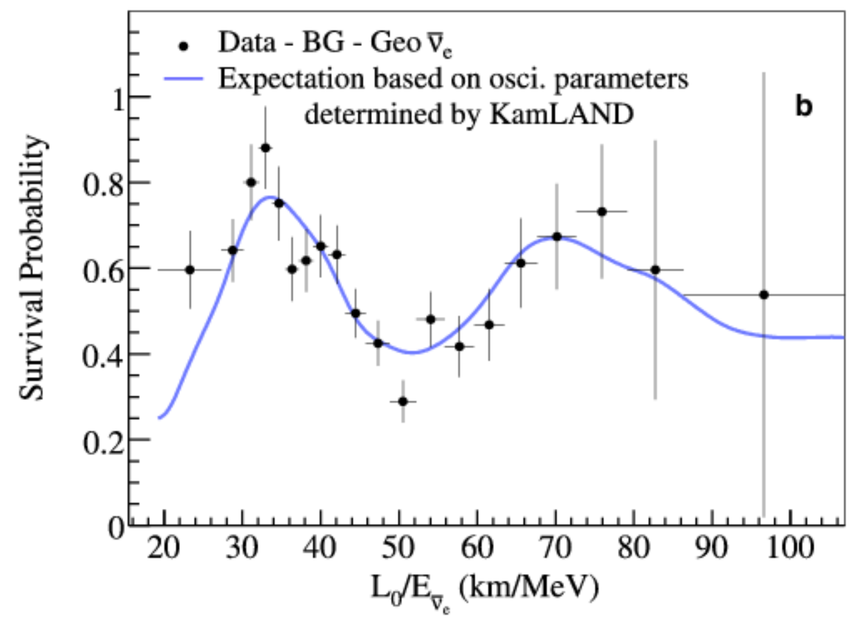
KamLAND result



two-flavor oscillations:

$$P = \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

oscillation in L/E representation

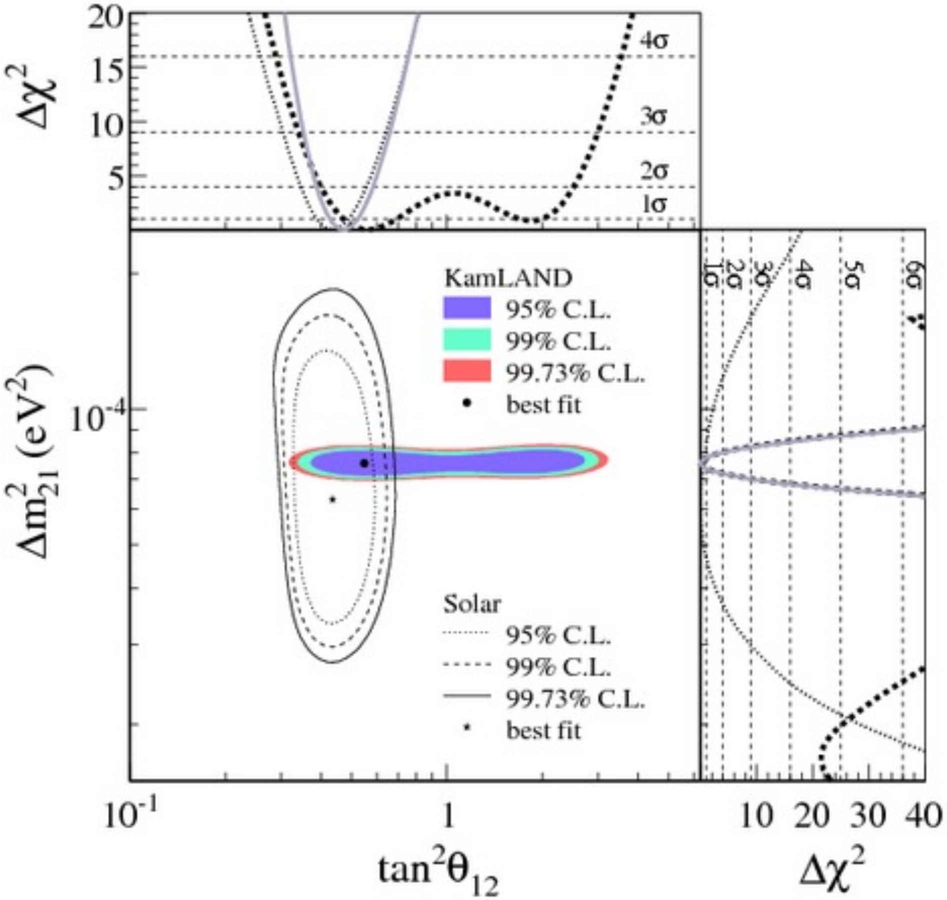


Prompt event energy spectrum

- large rate deficit found
- signature of the L/E dependence of oscillation probability

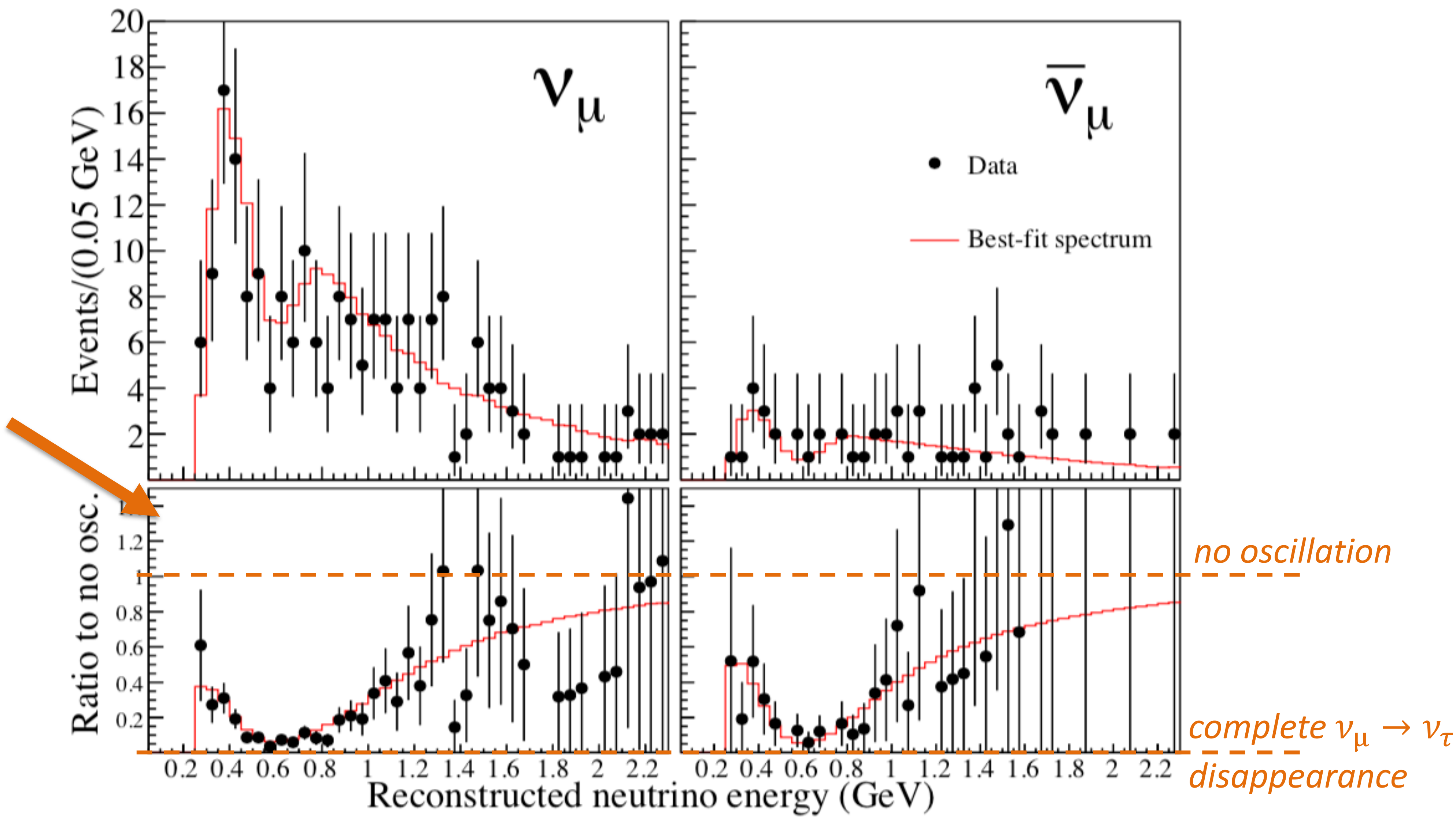
Combined KamLAND and solar ν data

best-fit oscillation parameters

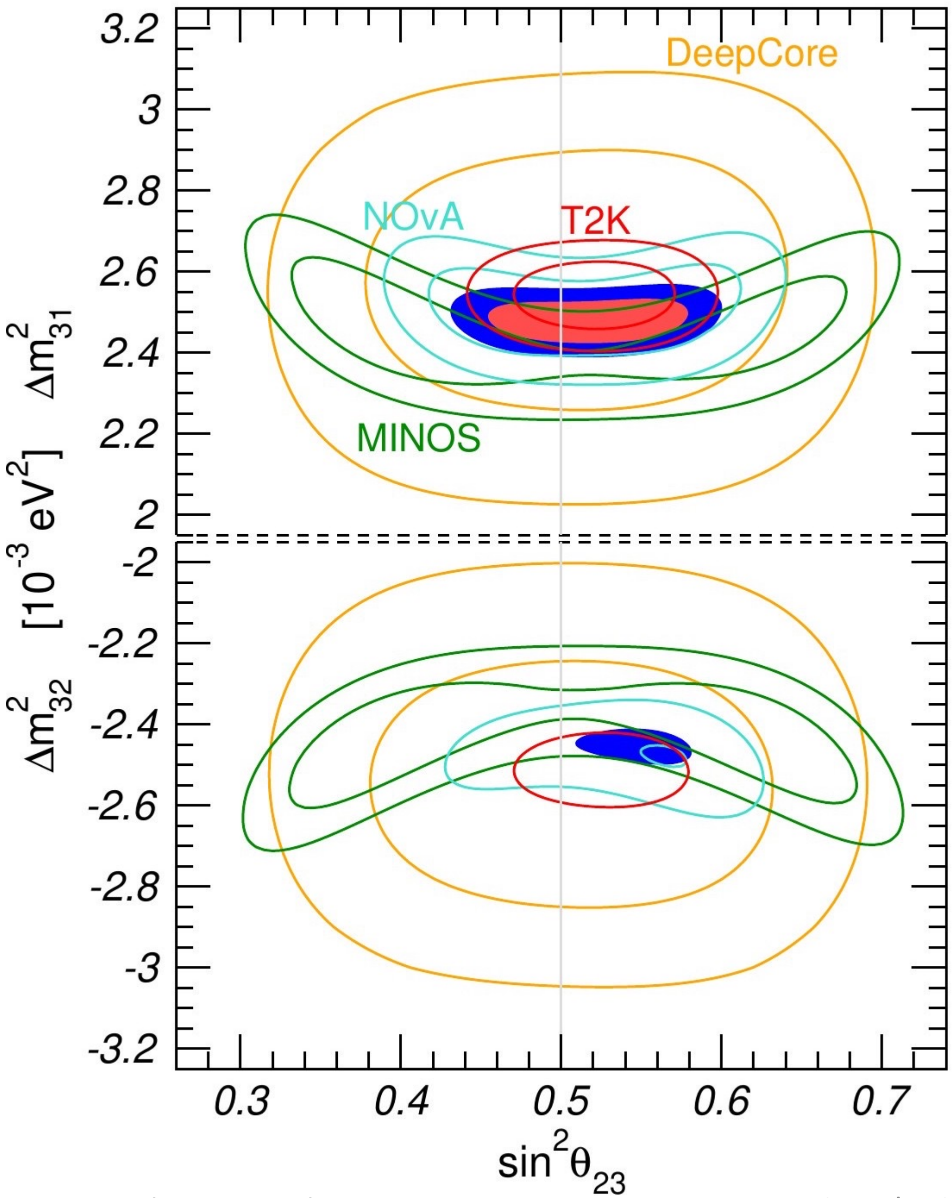


- solar neutrino data more sensitive on mixing angle
- KamLAND data determines Δm^2

2018: T2K result on ν_μ disappearance



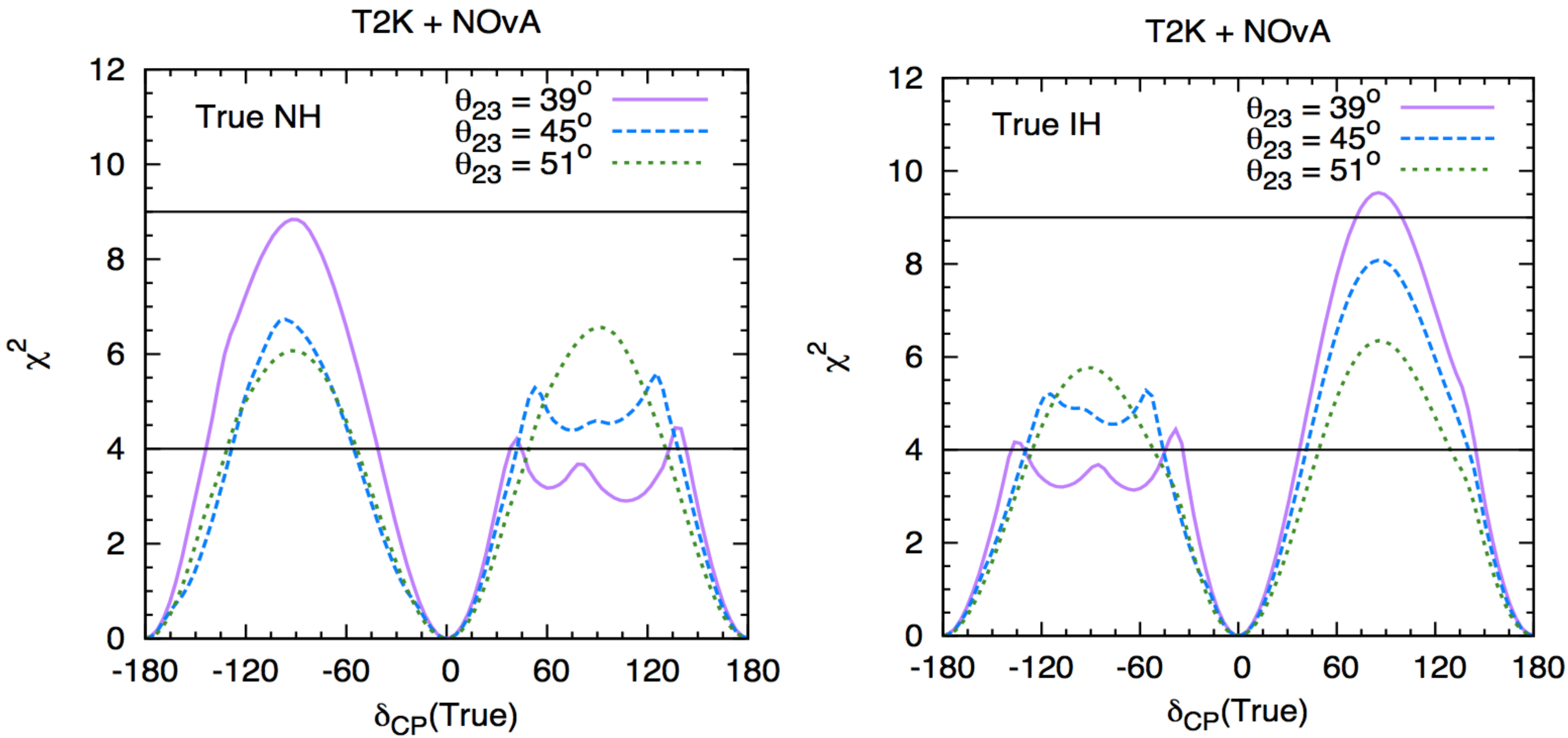
Data on atmospheric ν_μ oscillations



NuFit 3.2
(assuming normal mass hierarchy)

T2K+NovA median sensitivity for non-zero δ_{CP}

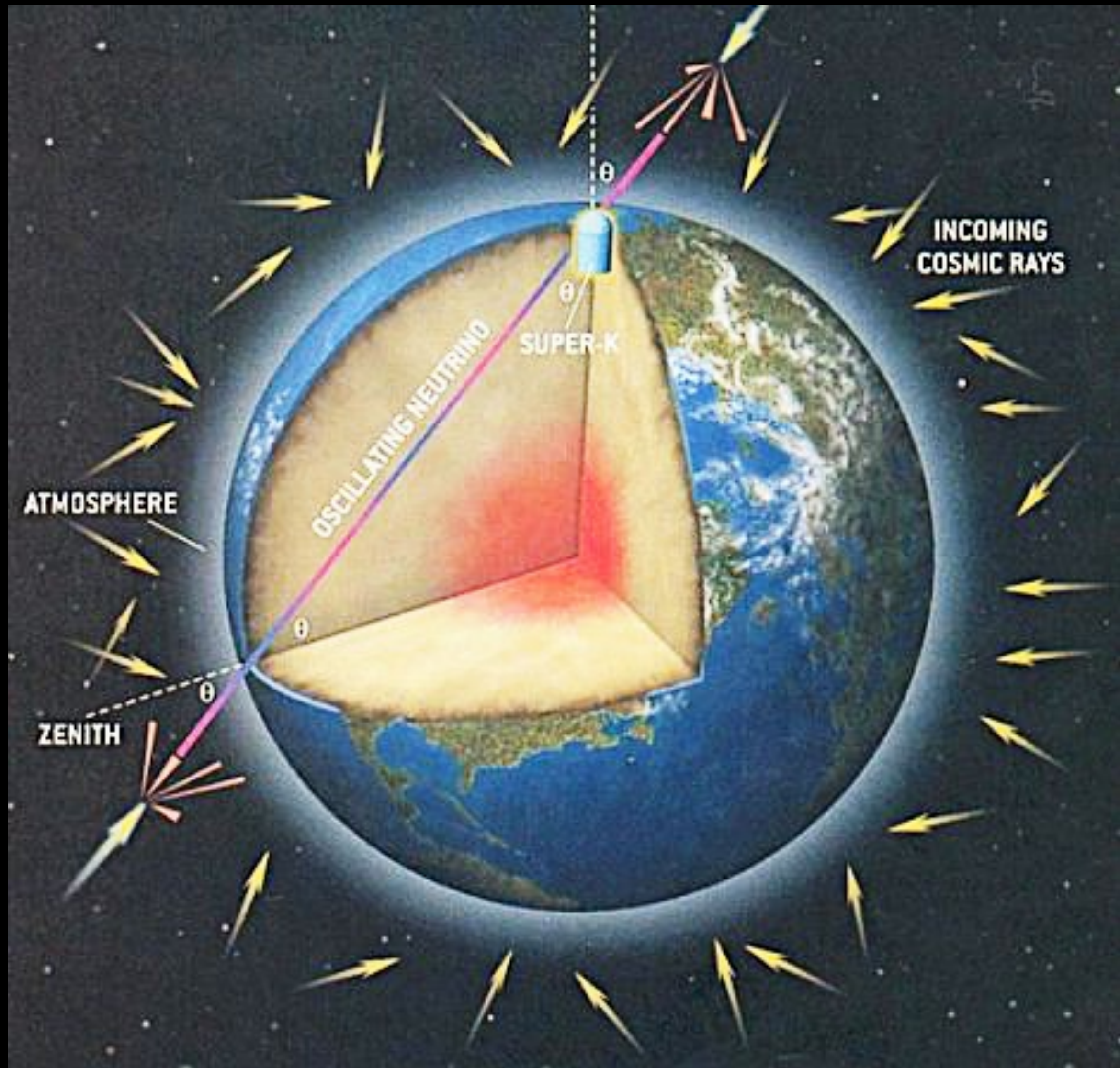
arXiv:1306.2500



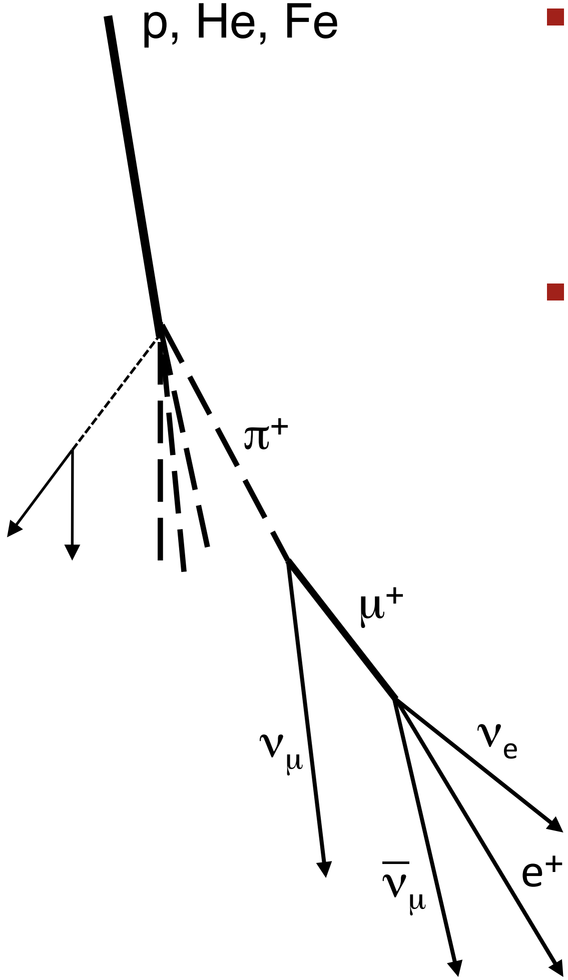
sensitivity for non-zero CP phase depends on:

- true value of δ_{CP}, octant of θ_{23} and **mass ordering** (8-fold degeneracy)
- significance of current results profits from the maximum (?) CP phase oberserved

Atmospheric neutrinos



Atmoshperic neutrino production



- High-energy cosmic rays collide with nitrogen in the Earth's atmosphere

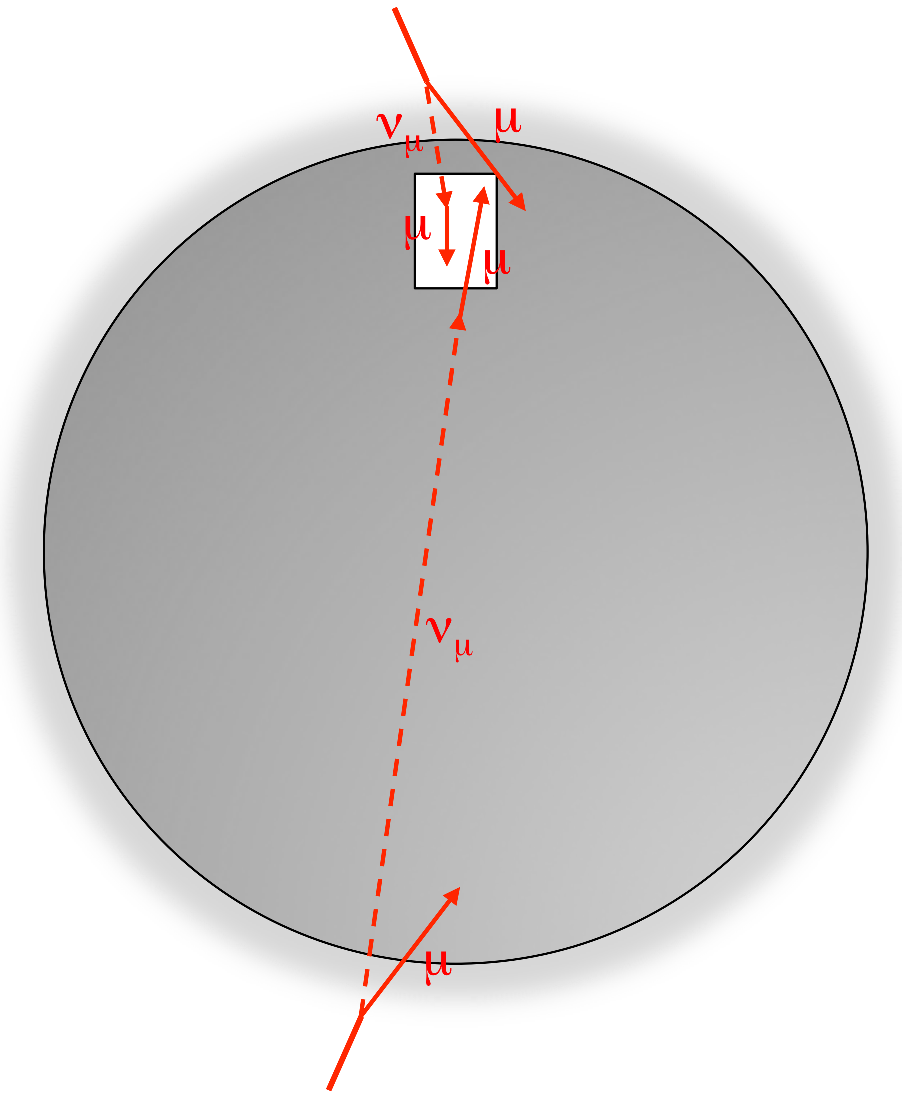
$$p + N \rightarrow p + N' + \pi, K...$$

- Charged mesons decay into neutrinos:

$$\begin{aligned} \pi^+, K^+ \quad &\rightarrow \quad \mu^+ \nu_\mu \\ &\qquad \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \\ \pi^-, K^- \quad &\rightarrow \quad \mu^- \bar{\nu}_\mu \\ &\qquad \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \end{aligned}$$

→ **Flavor ratio:**
At GeV energies, the expected ratio of ν_μ to ν_e is $R_{th} = 2$.

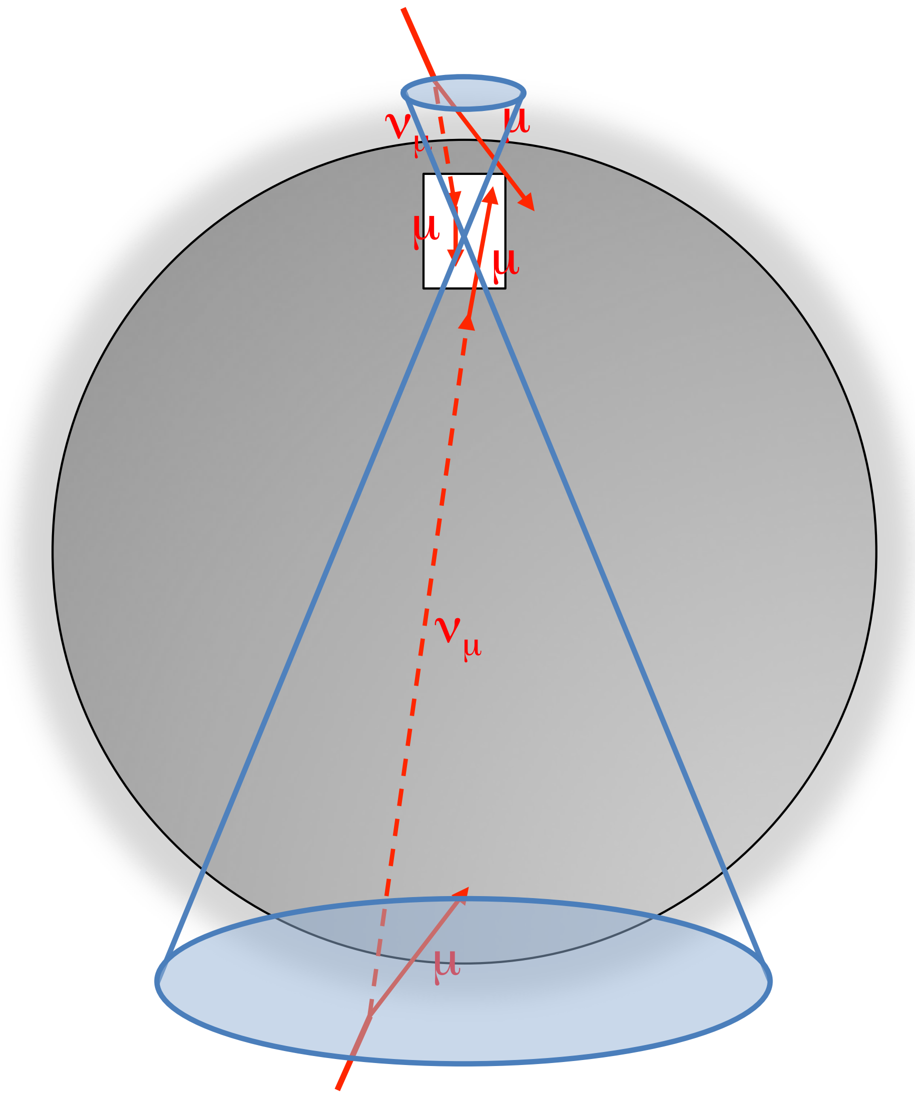
Angular distribution of atmospheric ν's



- Neutrinos are the only particles to cross the Earth from the antipodes.
- Arrival direction described by zenith angle:

  cosθ = +1 for zenith
  cosθ = -1 for nadir

Angular distribution of atmospheric ν's



- Neutrinos are the only particles to cross the Earth from the antipodes.
- Arrival direction described by zenith angle:

  cosθ = +1 for zenith
  cosθ = -1 for nadir

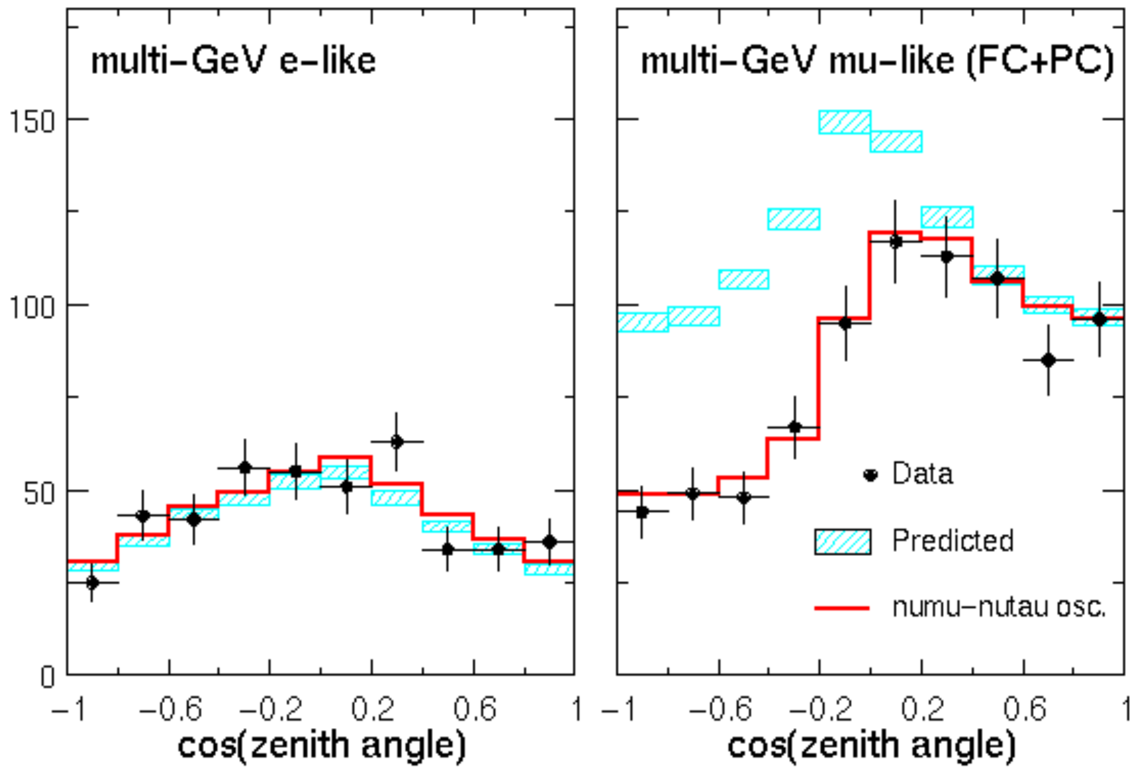
→ In first approximation, the atmospheric ν flux should be independent of the zenith angle θ.

1998: Super-Kamiokande result

- At **low neutrino energies**, the measured ratio R_{exp} of $\nu_\mu : \nu_e$ was lower than the expectation:

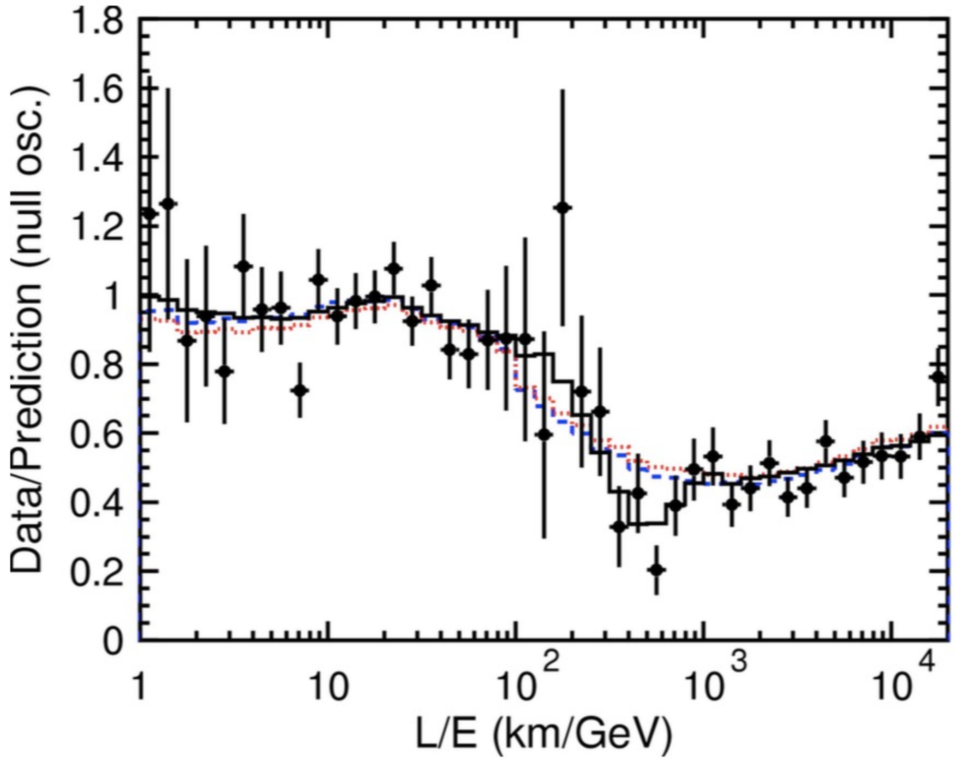
$$R_{\rm exp}/R_{\rm th} = 0.63 \pm 0.03_{stat} \pm 0.05_{syst}$$

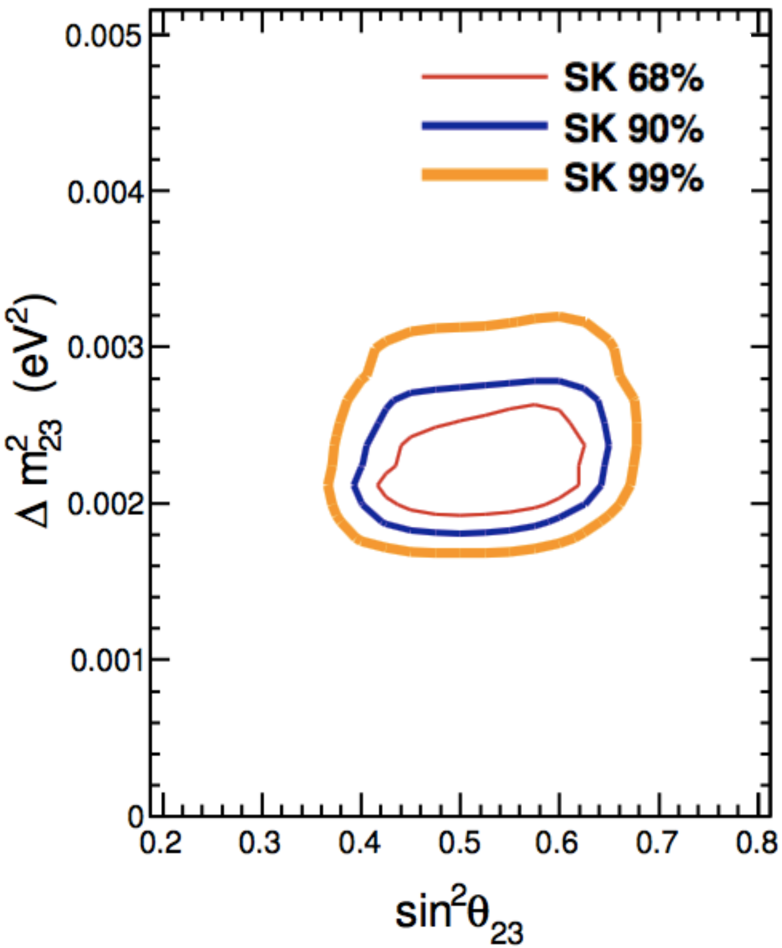
- At **high neutrino energies**, asymmetry in angular distribution



- down-going (cosθ=1): baseline: ~20 km
  → no oscillations
- up-going (cosθ=-1): baseline ≤ 13,000 km
  → ν_μ disappearance
- no ν_e excess observed:
  → $\nu_\mu \rightarrow \nu_\tau$ (?)
- surprise: large amplitude!
  → today: $\theta_{23} \approx 45°$

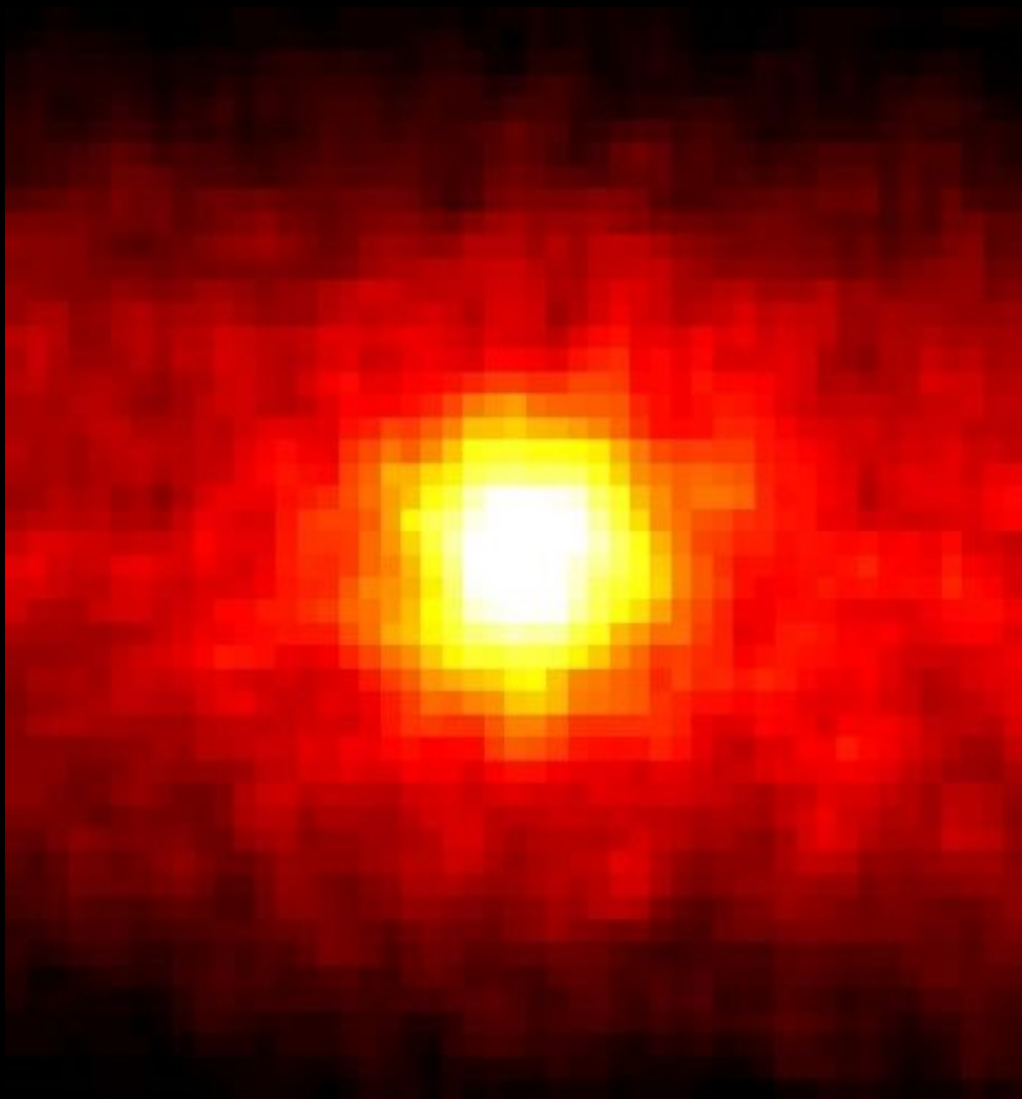
Later SK data on atmospheric ν's

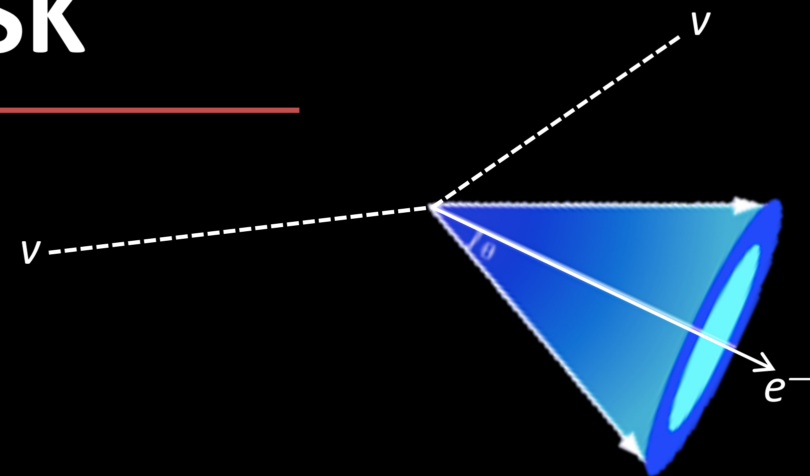




- oscillation-like L/E structure found
- evidence (4.6σ) for ν_τ-appearance in the detector
- still unclear whether $\sin^2 2\theta_{23}<1$ ($\theta_{23}\neq45°$)

Solar neutrino signal in SK





Elastic neutrino-electron scattering