Neutrino oscillation experiments

ISAPP School
„Neutrinos and Dark Matter"
KIT/Bad Liebenzell, 20 Sep 2024

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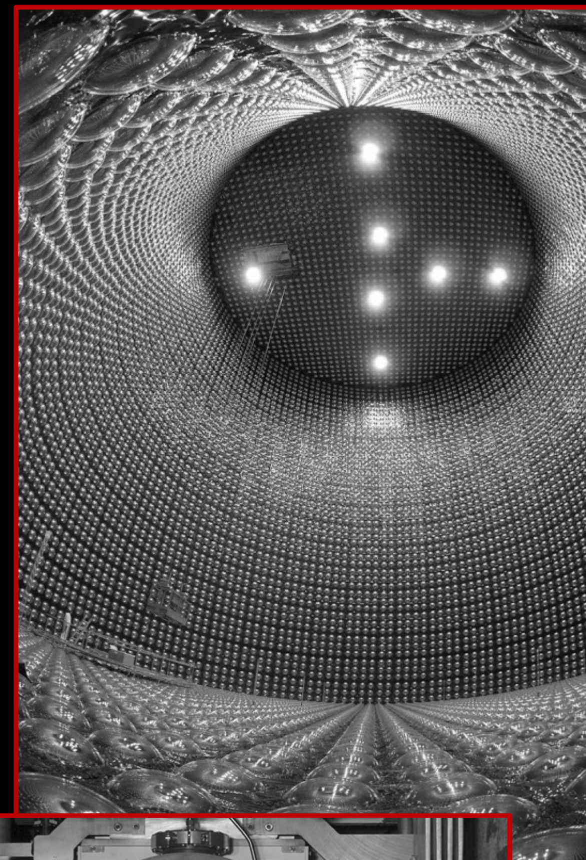
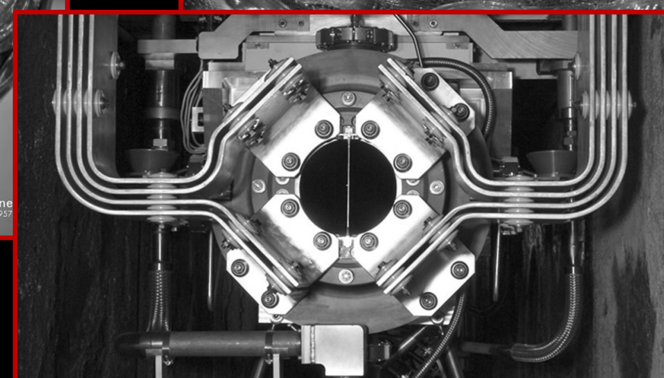
JGU Mainz/PRISMA$^+$

Contents of this talk

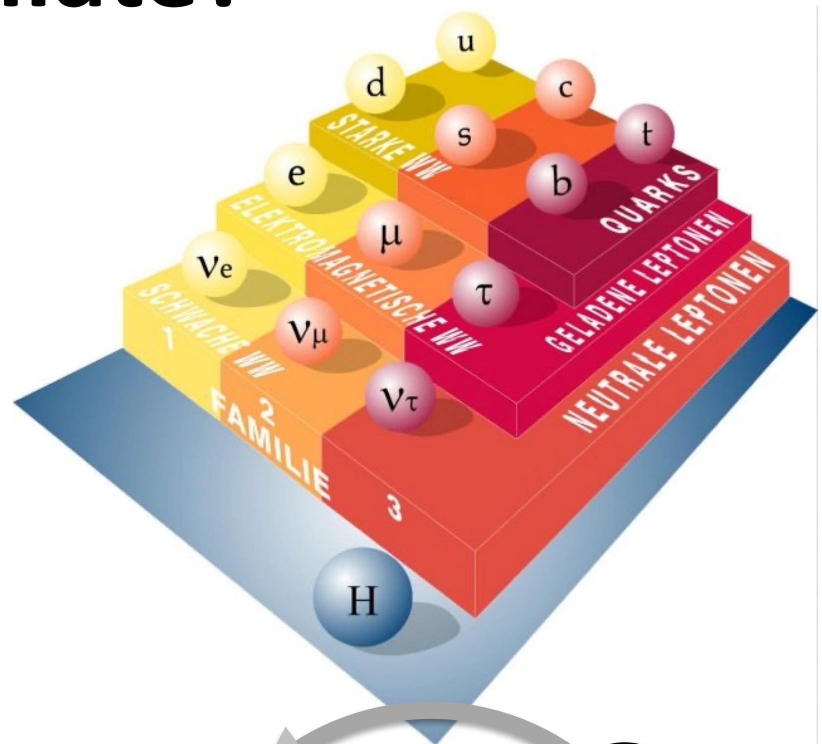
- Neutrino oscillations in a nut-shell
- Discovery of neutrino oscillations
- Current knowledge on oscillation parameters
- Two ways to order neutrino masses
- Accelerator neutrinos and CP violation

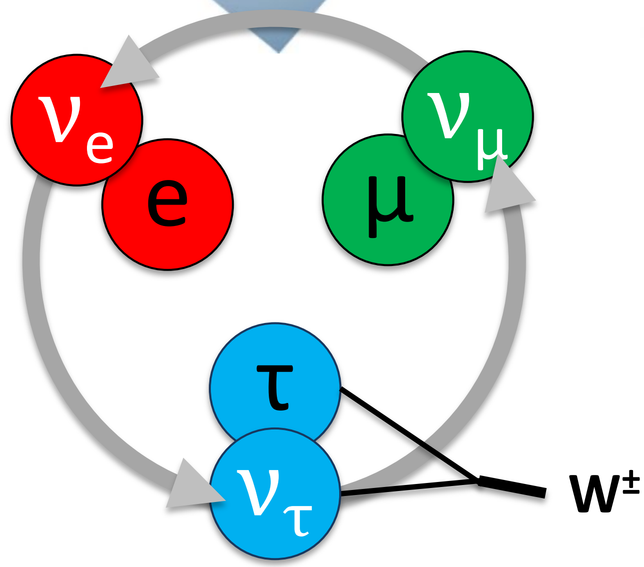




Why can neutrinos oscillate?

- Neutrinos appear in three families
- Neutrinos appear to be massless
  → upper limit: $m_\beta < 0.5$ eV
- Participate only in weak interactions
  → only left-handed neutrinos or right-handed antineutrinos
  → assumed mass-less in the Standard Model (mostly for convenience)
- but IF they have tiny masses mass and flavor eigenstates can be different (rotated)
- IF so, eigenstates will interfere while propagating → neutrino oscillations





Neutrino masses and mixing

QM: For massive neutrinos with different masses,

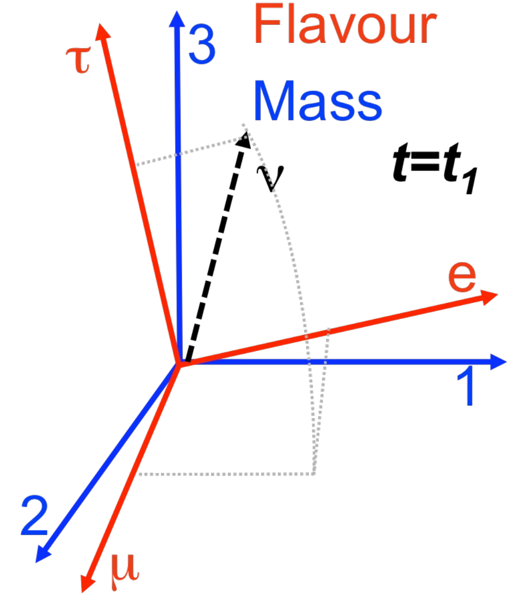
- the three neutrino **flavor-eigenstates**
  (taking part in weak interactions)

can be a **superposition** of

- the three **mass-eigenstates**
  (propagating through space)
- The relative fractions of mass in flavor states are described by a **3x3-mixing matrix**

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

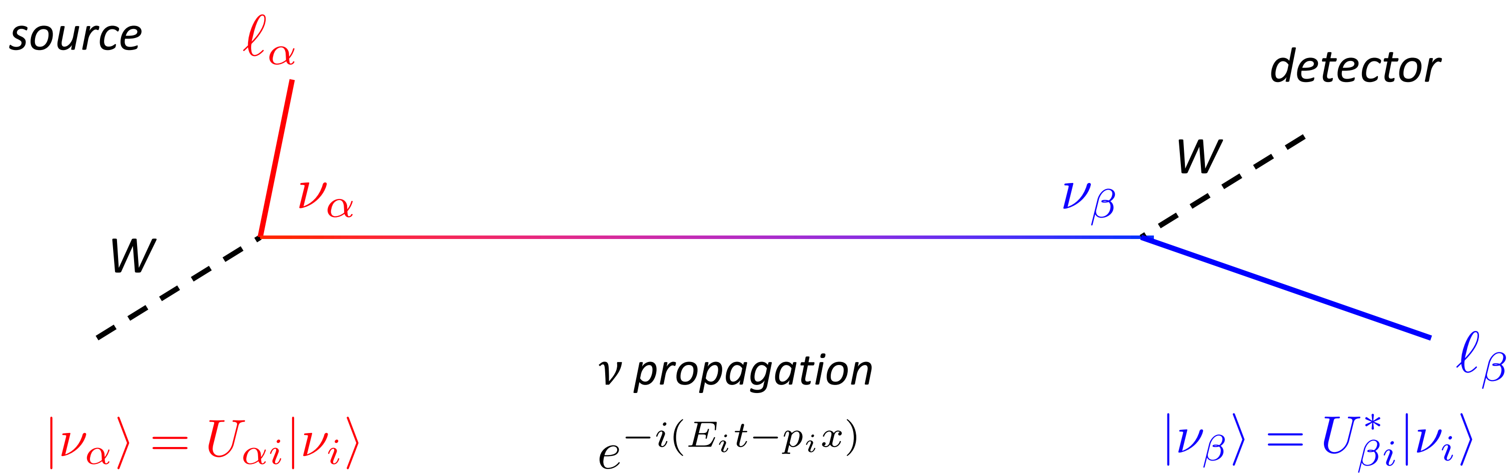
flavor-states ***mass-states***



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

→ cf. CKM-matrix in quark-sector

Neutrino oscillation formalism



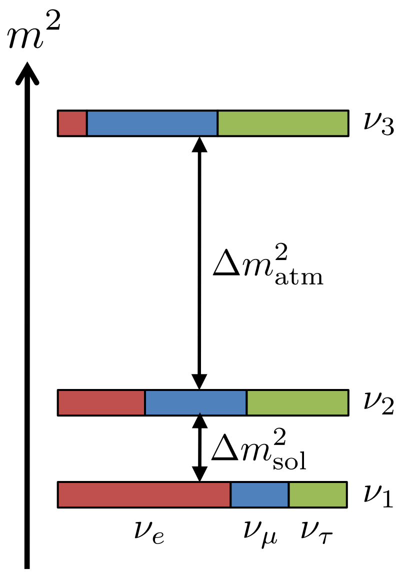
- propagation for $p_i = p,\ m_i \ll E$ $$E_i = \sqrt{m_i^2 + p^2} = p + \frac{m_i^2}{2p} = E + \frac{m_i^2}{2E}$$
- amplitude: $$\mathcal{A}_{\nu_a \to \nu_\beta} = \langle \nu_\beta | \mathrm{propagation} | \nu_\alpha \rangle = \sum_i U_{\beta i} U^*_{\alpha i} e^{-i\left(\frac{m_i^2}{2E}\right)L}$$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

Parametrization of three-flavor mixing

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

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

flavor states | *atmospheric mixing* | *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 :

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

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.”

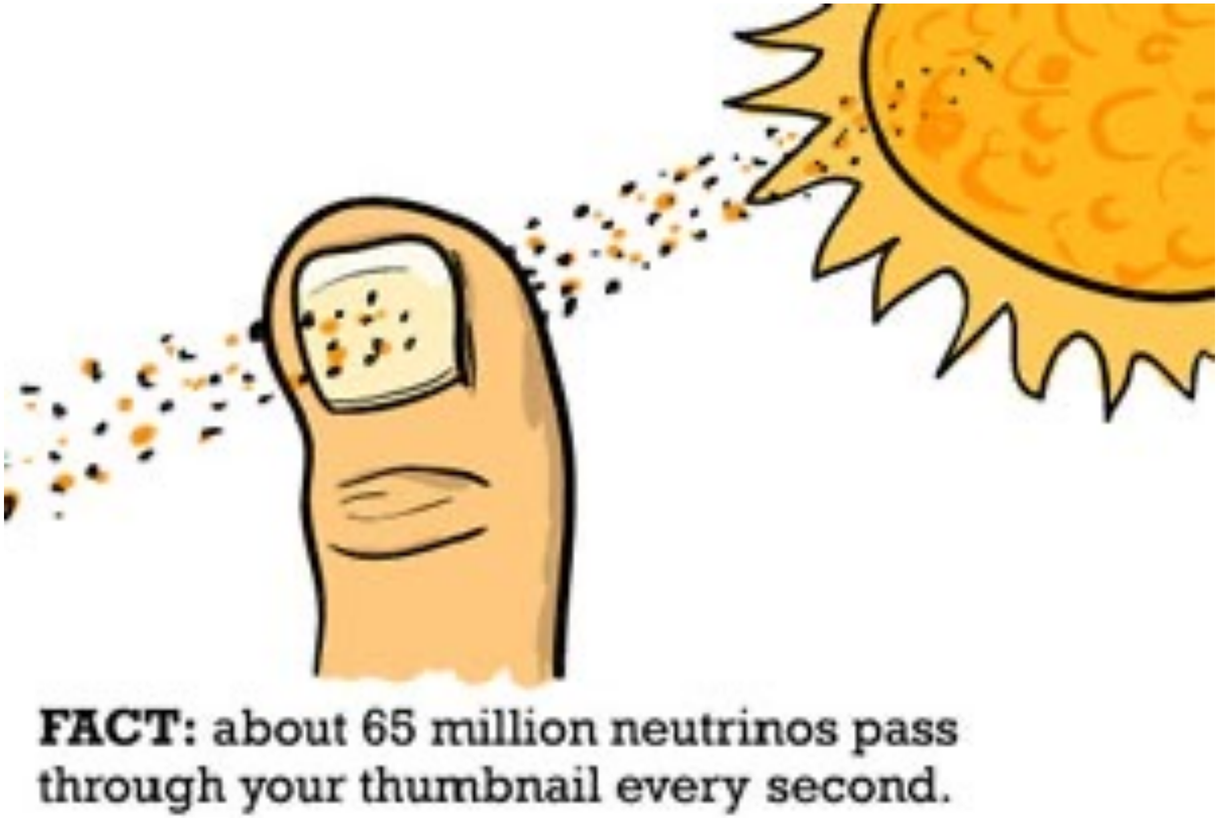
1968

“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:
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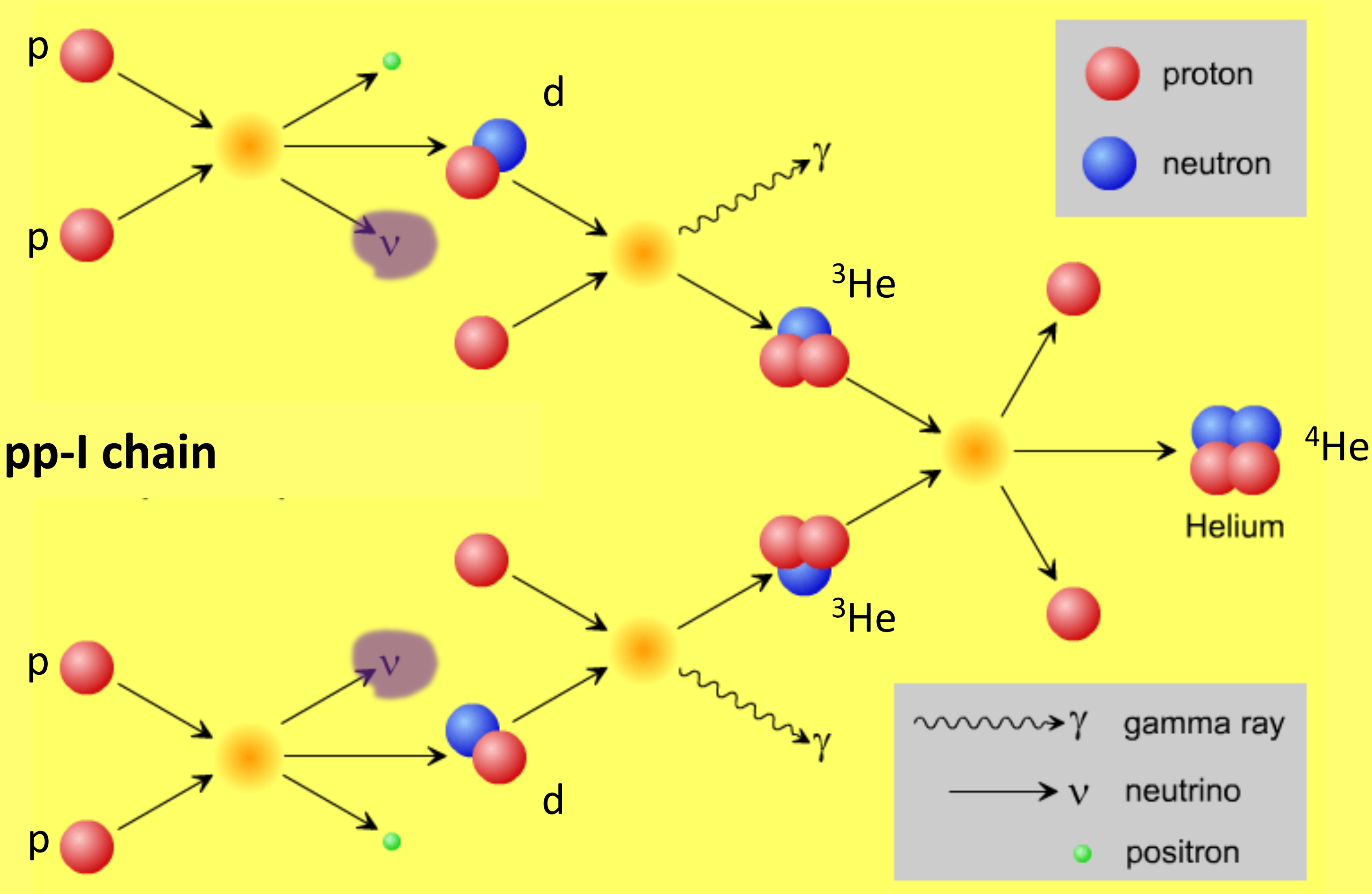
Hydrogen burning in the Sun

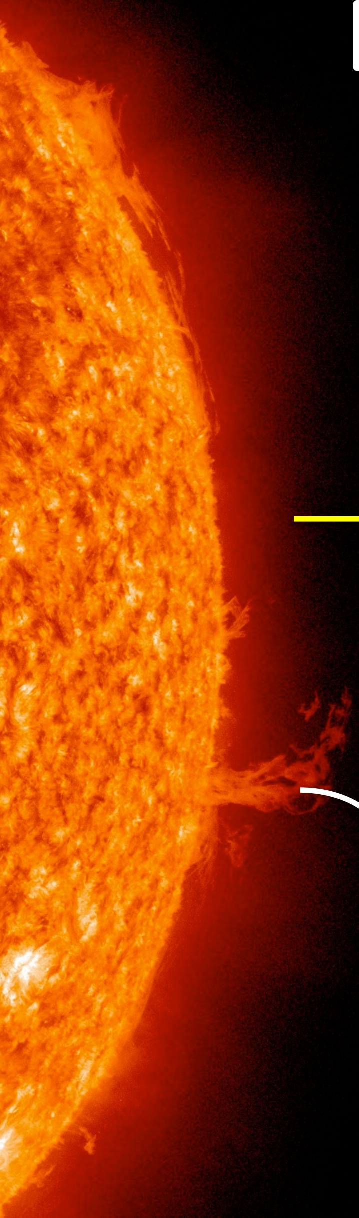
Net fusion reaction: $4p \rightarrow {}^4He + 2e^+ + 2\nu_e$ [+26.7 MeV]



H. Bethe

W. Fowler

Expected solar neutrino flux



electromagnetic luminosity

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

→ γ

ν

neutrino luminosity

$L_{\nu} \approx 2\% \, L_{\odot}$

flux at Earth

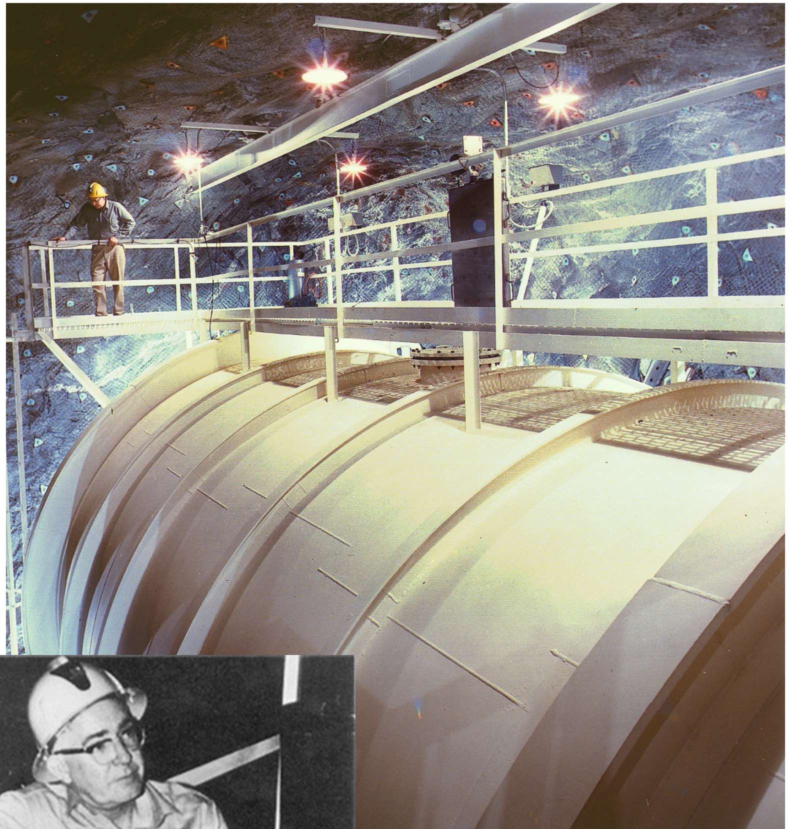
$\Phi_{\gamma} \approx 4 \times 10^{21}$ /m²s

$\to S_{\gamma} = 1367$ W/m²

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

$\approx 6.6 \times 10^{14}$ /m²s

First detection of solar neutrinos: Davis



Ray Davis Jr.

- Location: Homestake mine (US)
- Depth: 1478 m
- Target material: 615 tons of C_2Cl_4
  → ca. 6×10^{30} atoms of ^{37}Cl
- Detection reaction:

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

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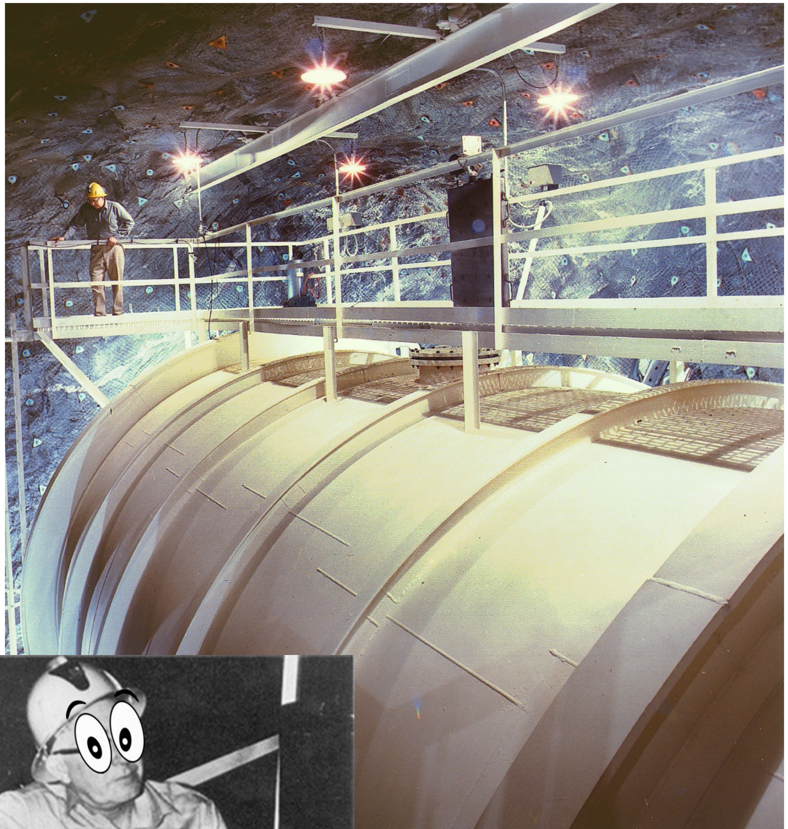

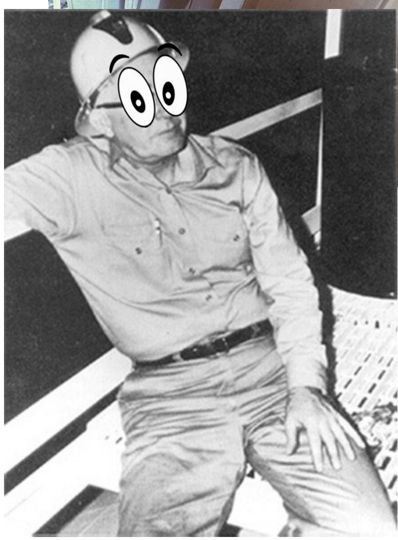

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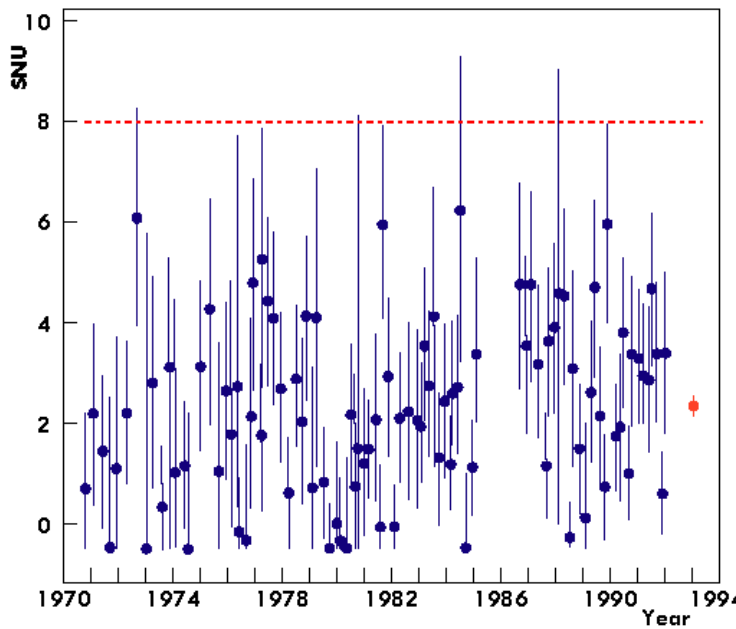
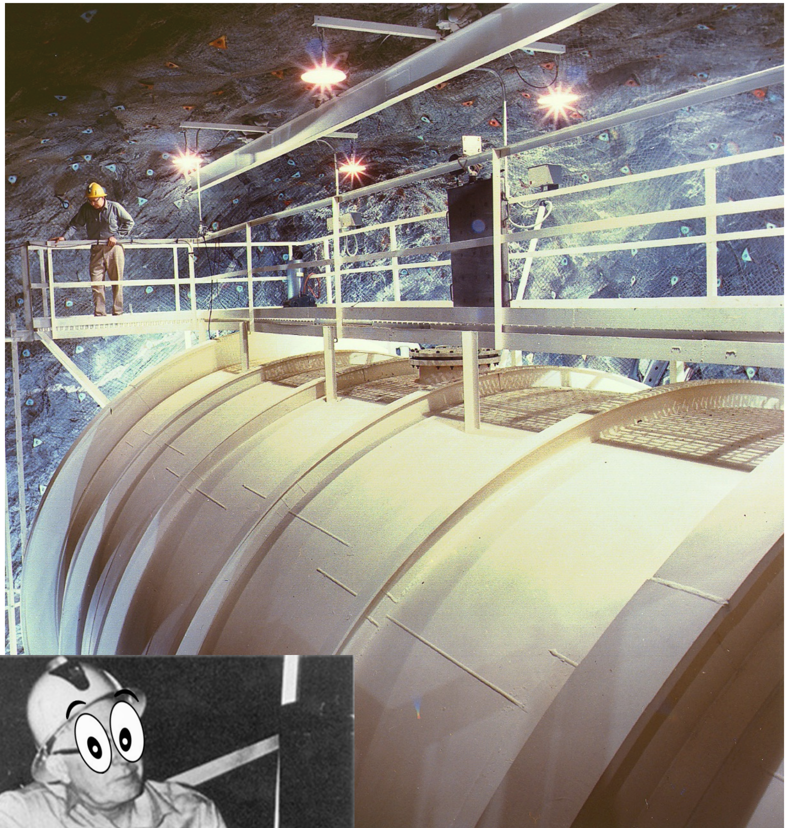


SSM expectation:
1.5 per day

average of
detected rate:
0.5 per day

First detection of solar neutrinos: Davis



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

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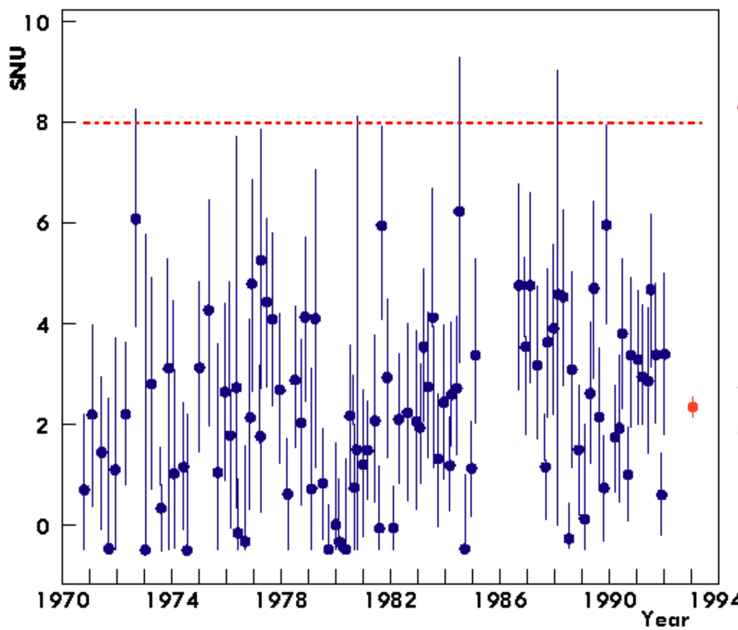


SSM expectation:
1.5 per day

average of detected rate:
0.5 per day

Solar neutrinos: Two-flavor approximation

2x2 mixing:

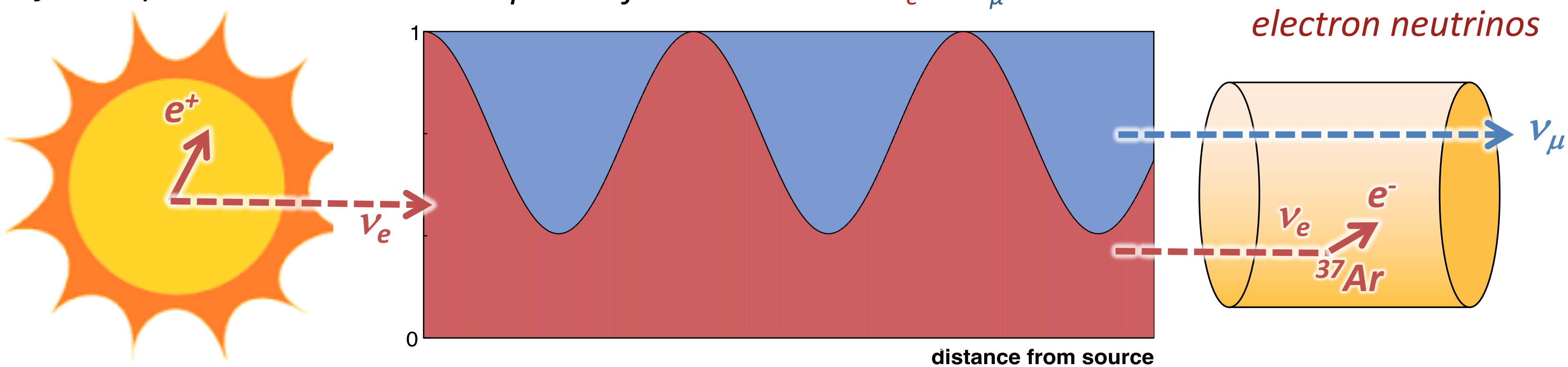
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

flavor states — *mass states*

Oscillation probability:

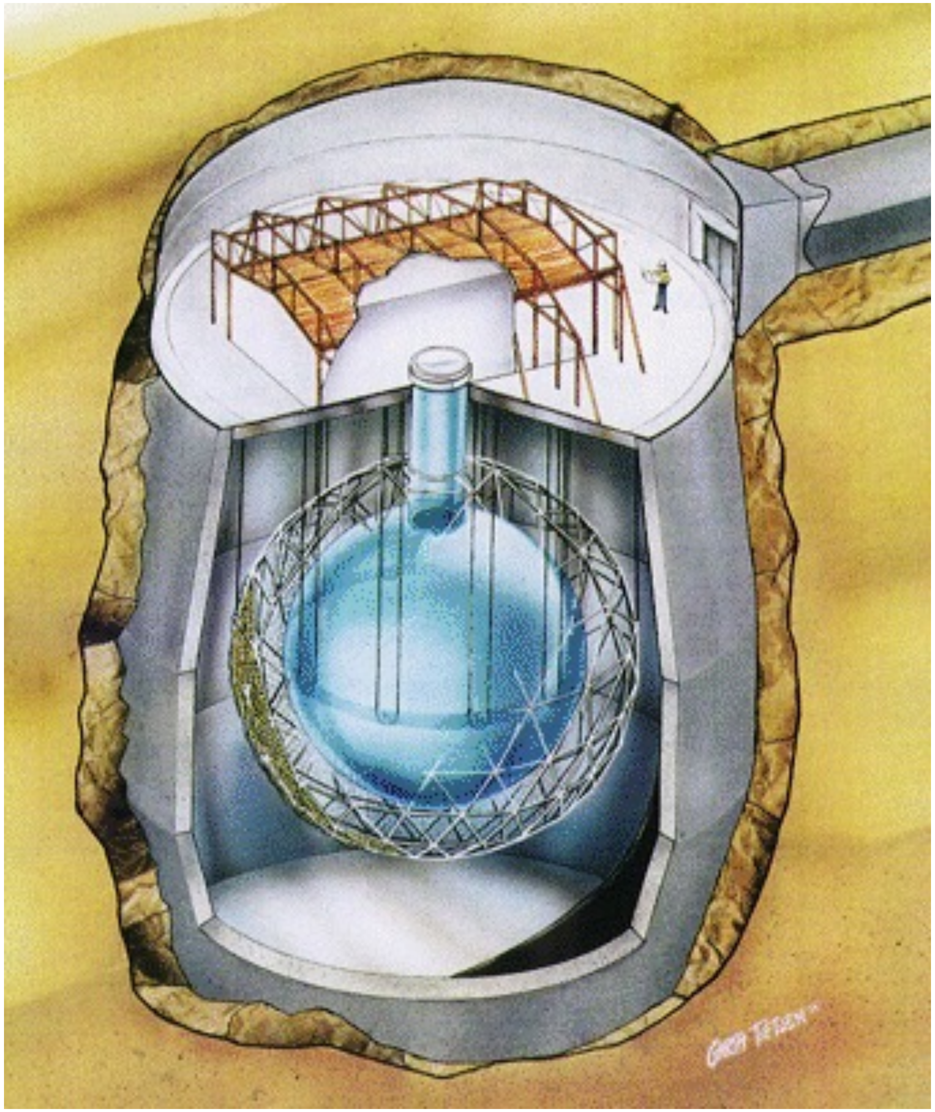
$$P(\nu_e \to \nu_e) = 1 - \sin^2(2\theta_{12}) \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

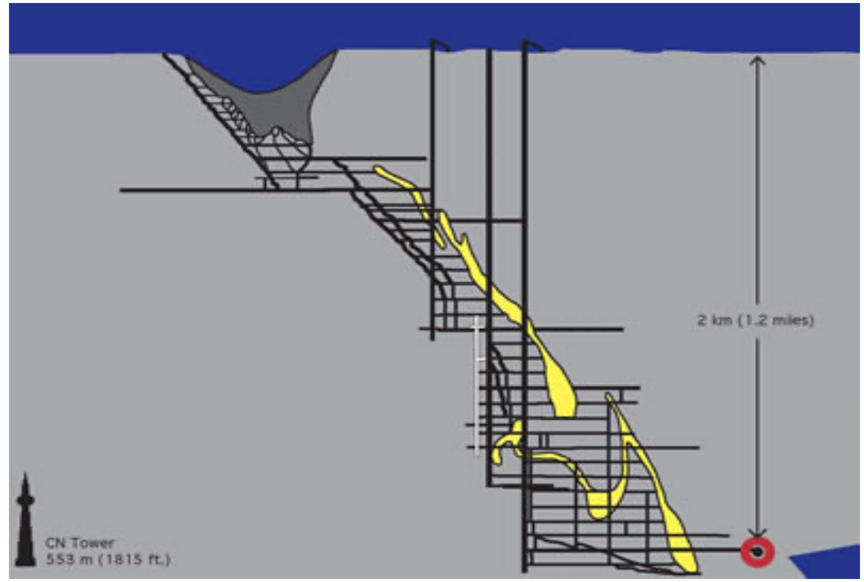
oscillation amplitude — *oscillation frequency/length* — *baseline-over-energy*



→ **observation of rate deficit!! but how to prove it is flavor oscillations?**

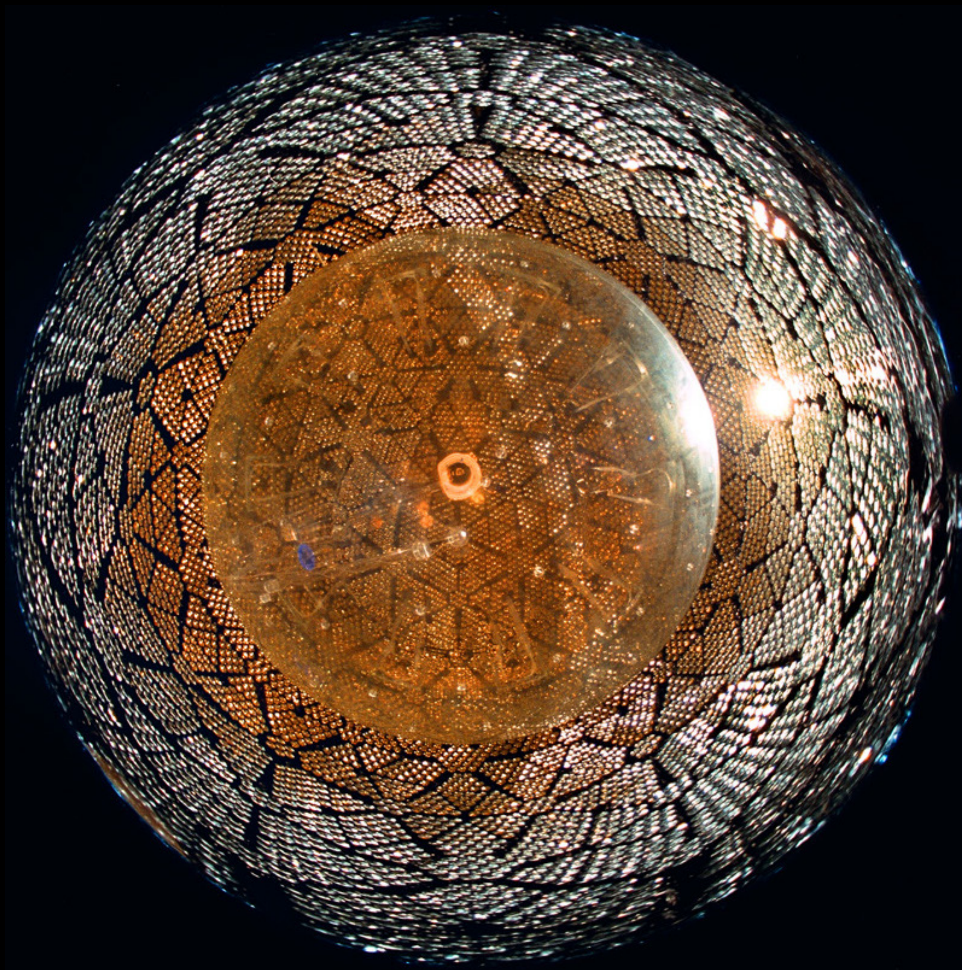
Sudbury Neutrino Observatory (SNO)



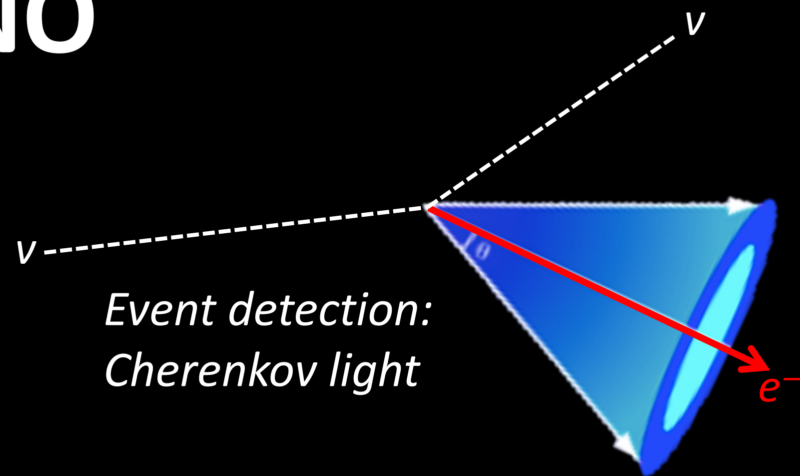


- **Water Cherenkov detector**
  Underground water tank to measure neutrino interactions by final-state charged particles
- **Location:** Sudbury mine
  depth: 2000 m → 6000 mwe
- **Target mass:** 1 kt of D_2O

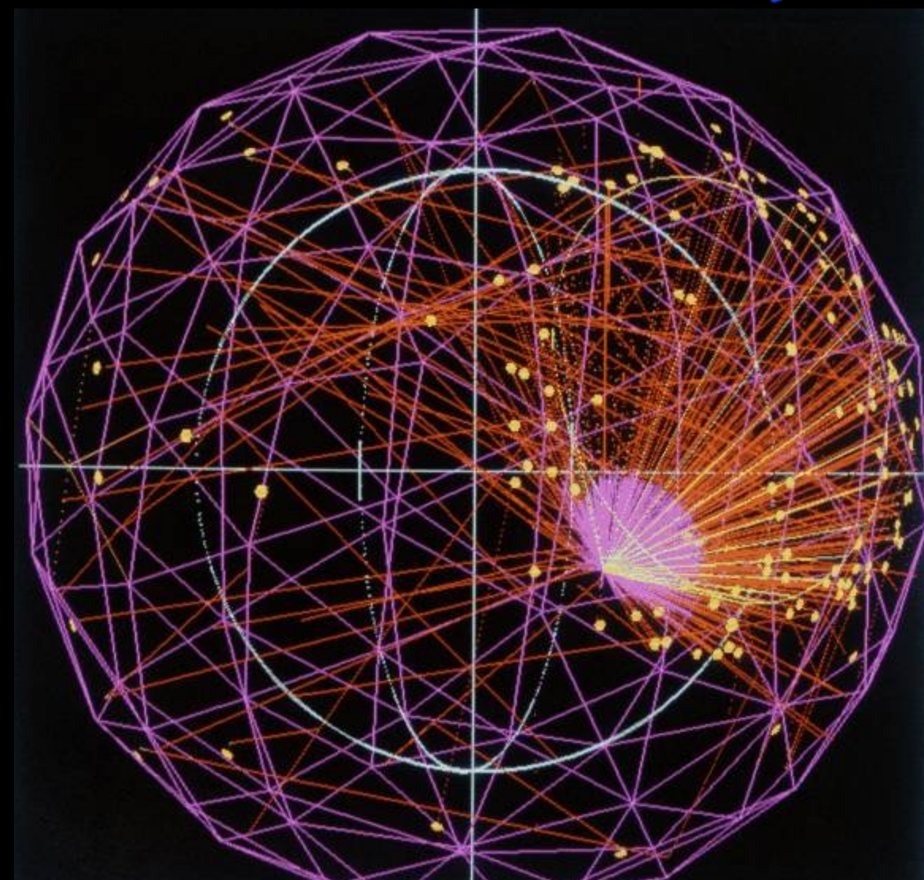
Neutrino detection in SNO



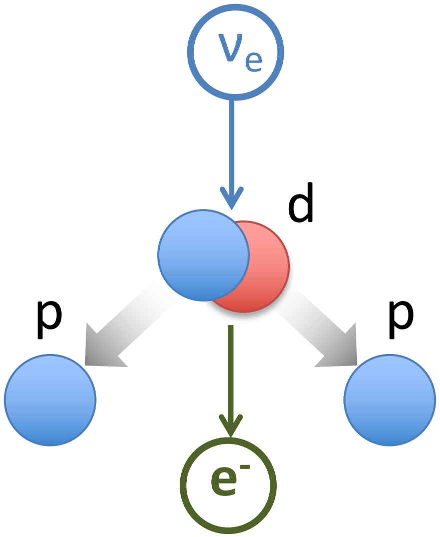
10,000 photomultiplier tubes

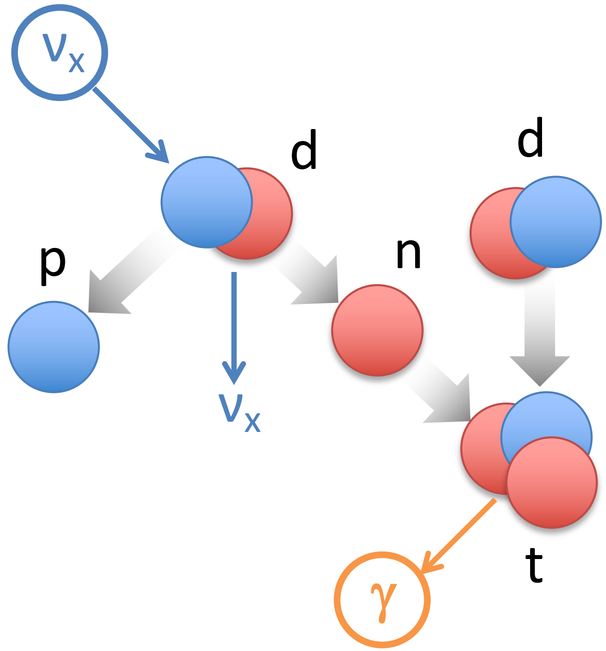


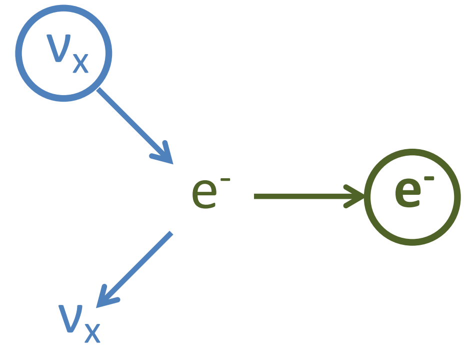
Event detection: Cherenkov light



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:

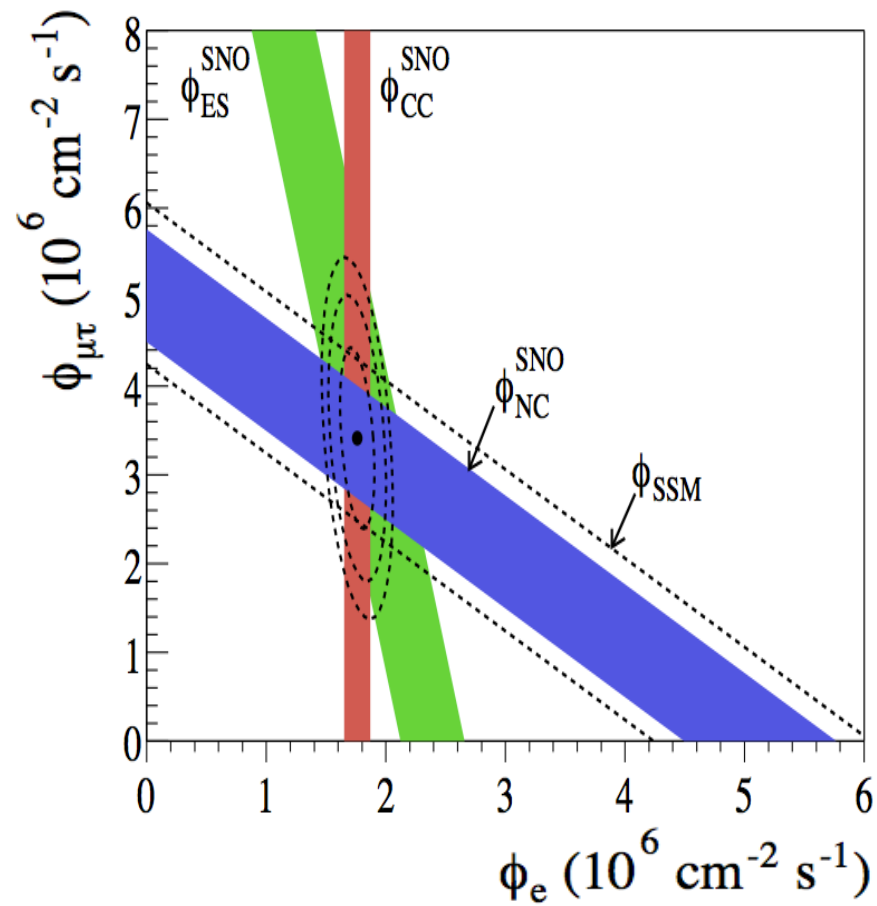
$$\left.\begin{array}{l}\Phi_{\rm CC} = 1.76 \pm 0.11 \\ \Phi_{\rm ES} = 2.39 \pm 0.27 \\ \Phi_{\rm NC} = 5.09 \pm 0.62\end{array}\right\} \times 10^6 \ {\rm cm}^{-2}{\rm s}^{-1}$$

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

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

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

→ 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
→ cross-check: elastic scattering (mostly ν_e)

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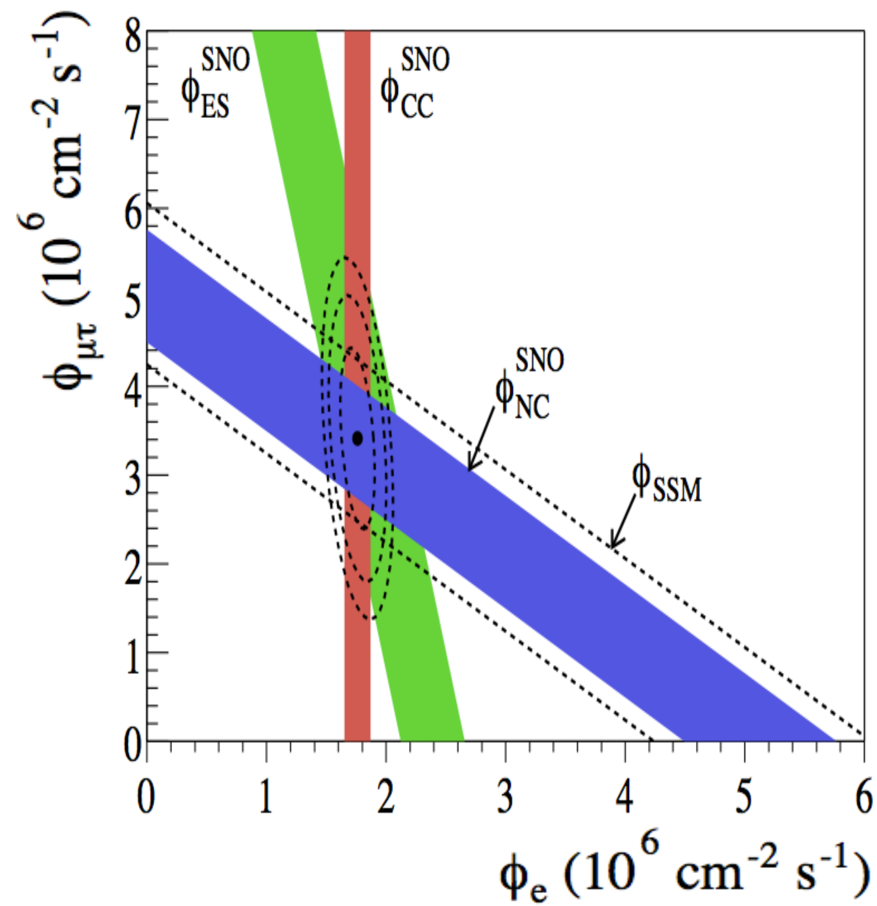


→ total flux (all flavors) as predicted by SSM
→ ν_e flux suppressed by oscillations
→ cross-check: elastic scattering (mostly ν_e)

but:
SNO proves only flavor conversion
what about the oscillation pattern?

LECTURE QUIZ

Question 1

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

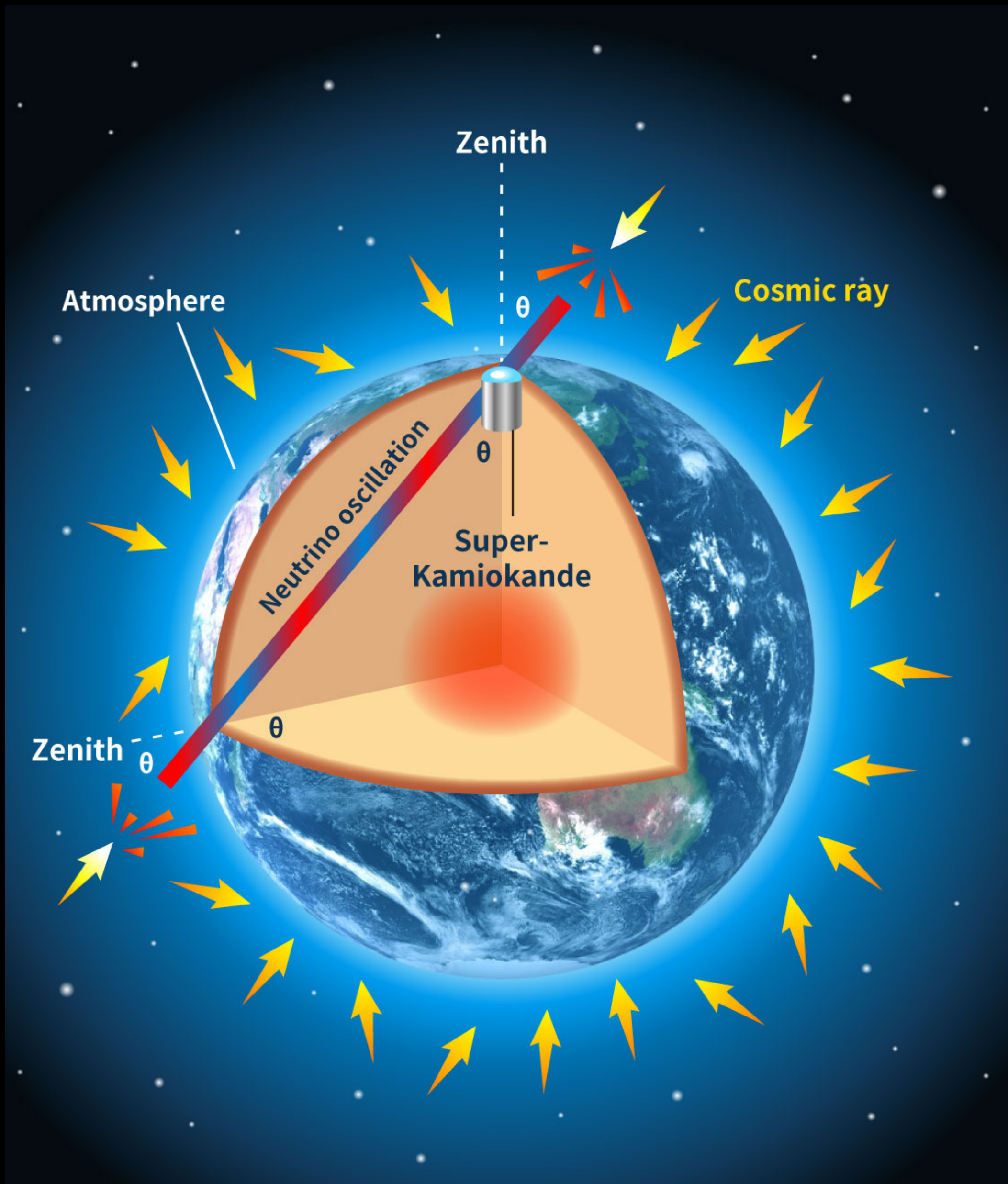
B : 60 thousand

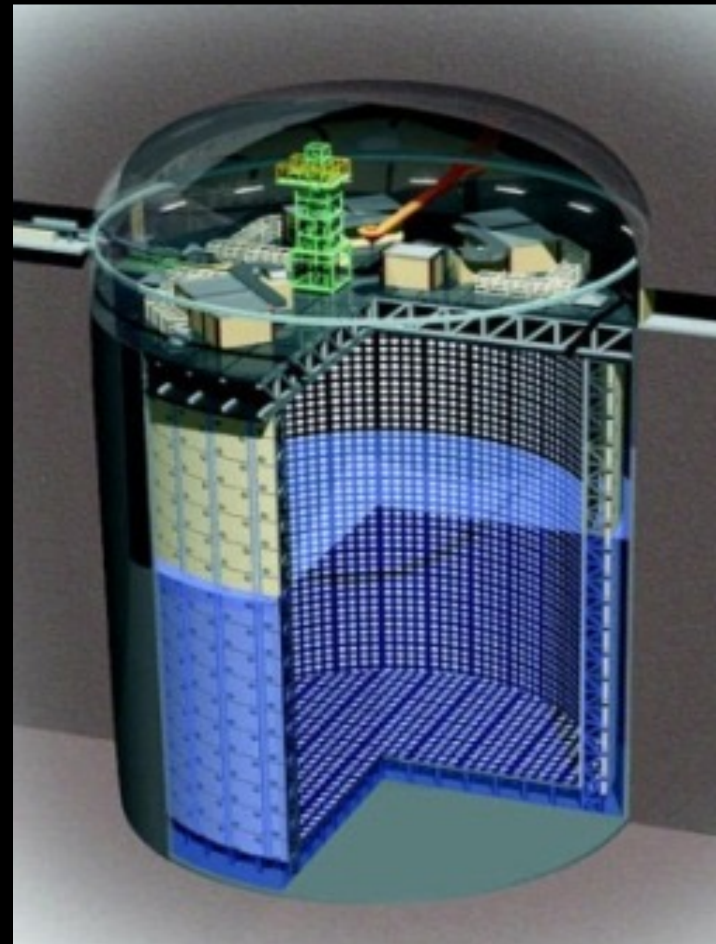
C : 60 million

D : 60 billion

Note down the **letter** in front of the solution.

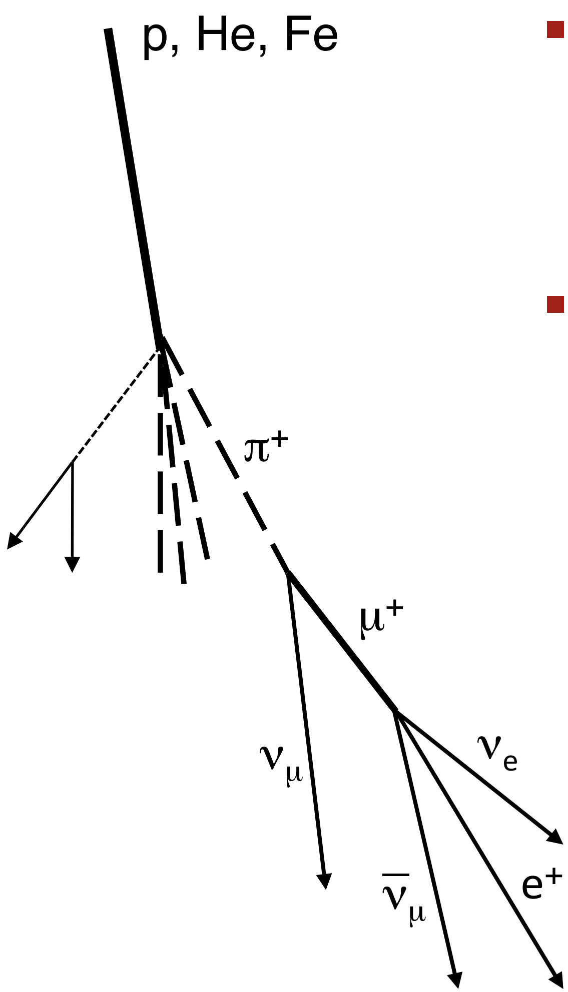
Atmospheric ν's in Super-Kamiokande





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

Atmoshperic neutrino production



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

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

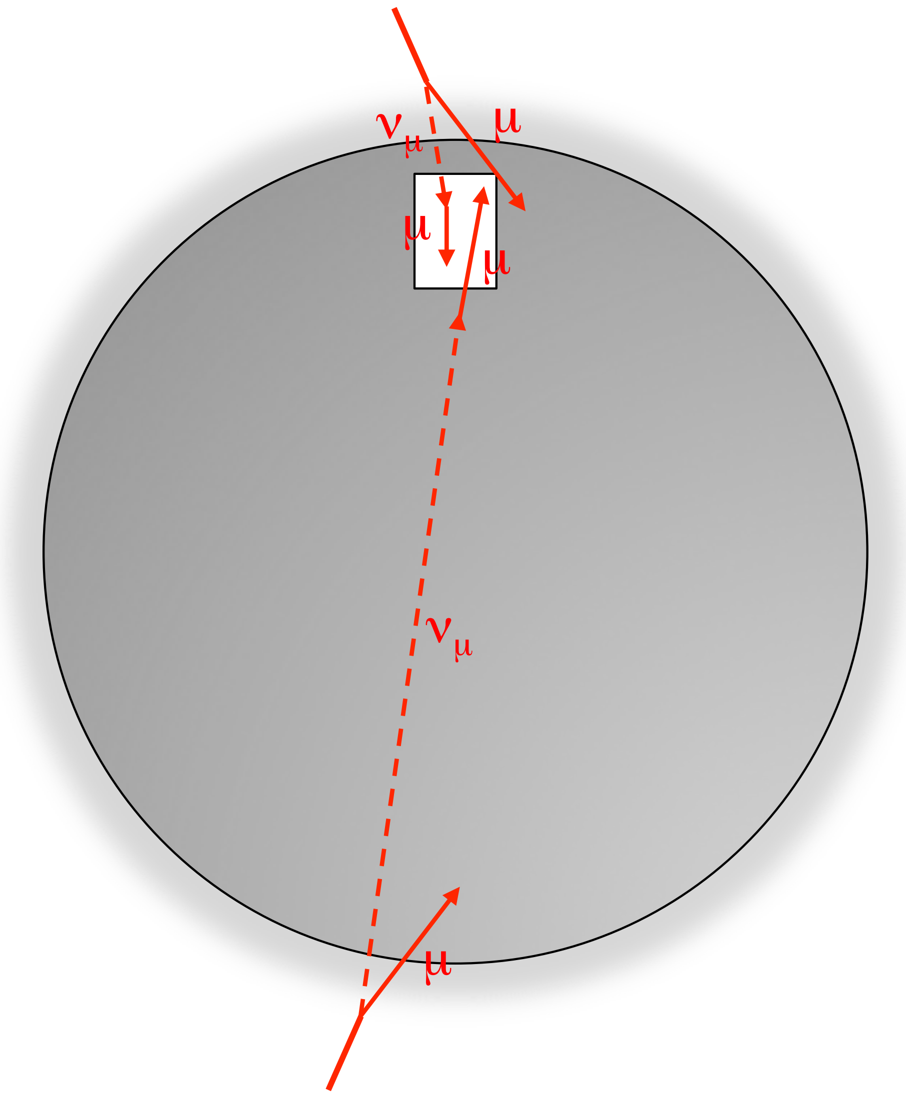
- Charged mesons decay into neutrinos:

$$\pi^+, K^+ \rightarrow \mu^+ \nu_\mu$$
$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\pi^-, K^- \rightarrow \mu^- \bar{\nu}_\mu$$
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

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

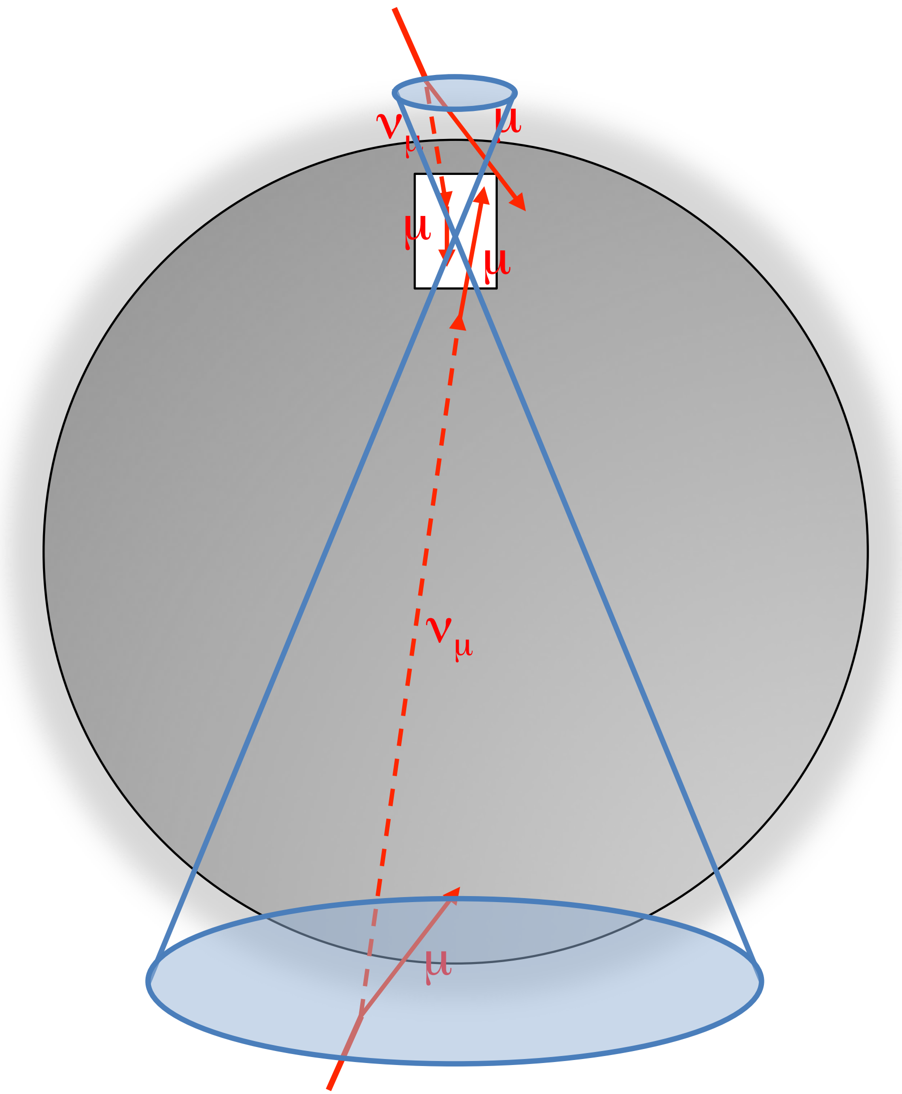
Angular distribution of atmospheric ν's



- 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

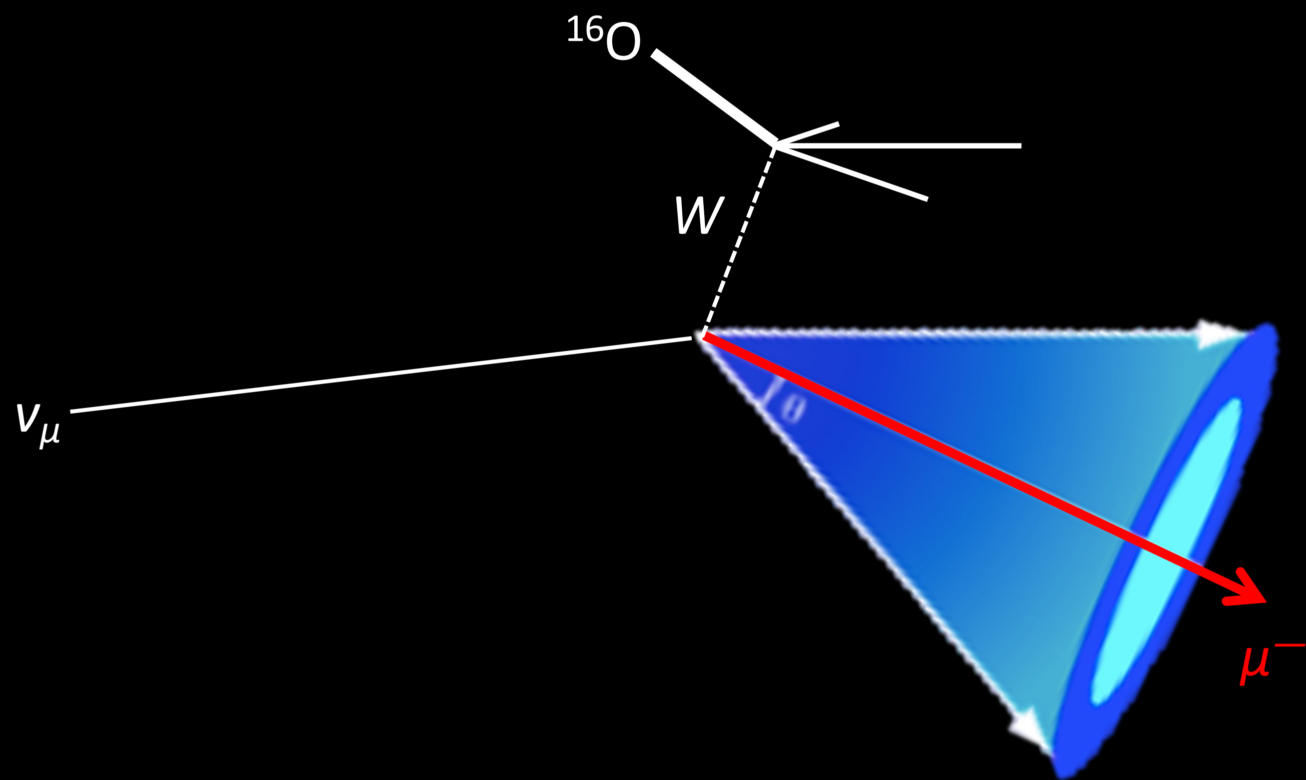


- Neutrinos are the only particles to cross the Earth from the antipodes.
- Arrival direction described by zenith angle:

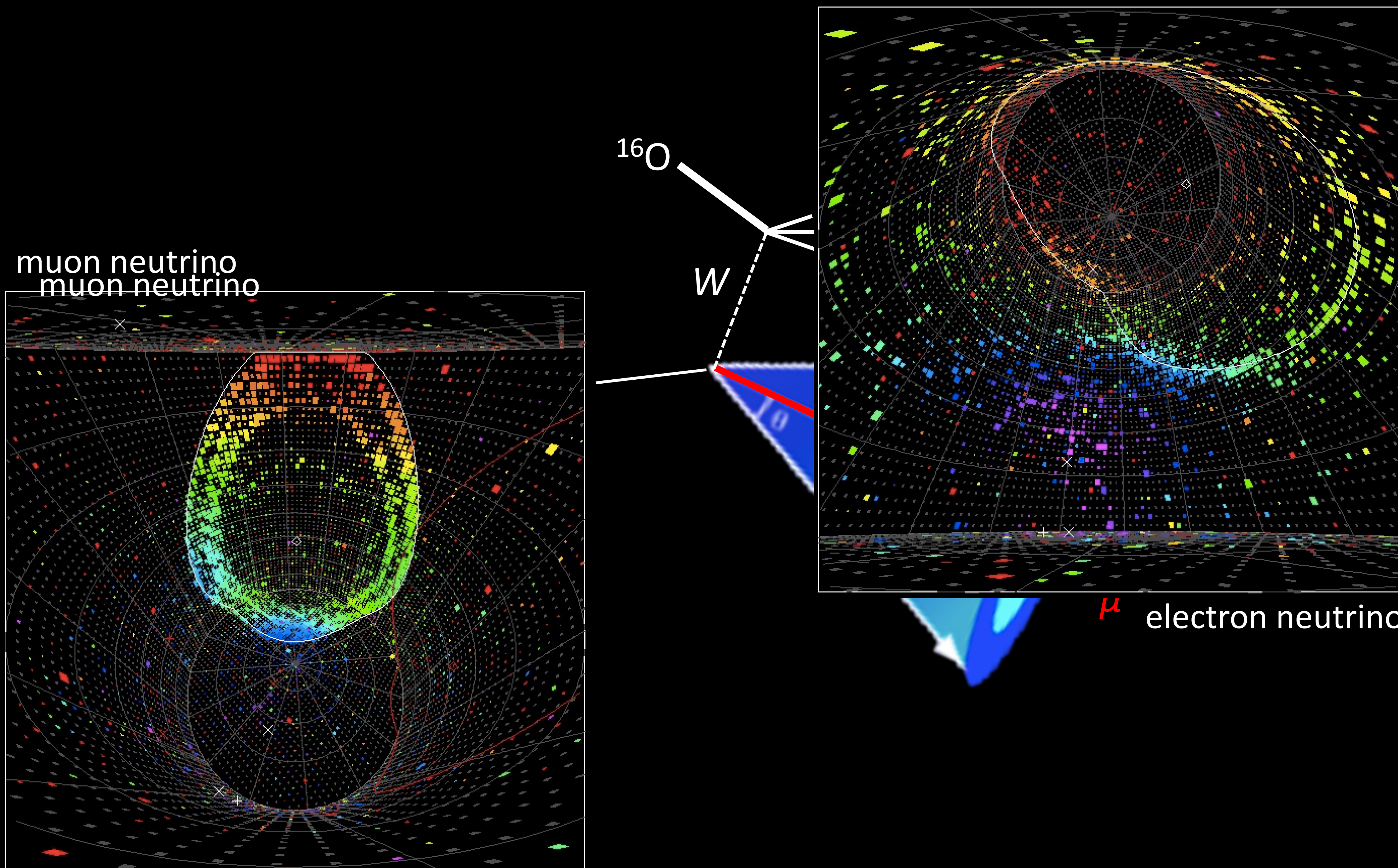
  cosθ = +1 for zenith
  cosθ = -1 for nadir

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

Neutrino detection by Cherenkov effect



Flavor identification by ring *fuzziness*

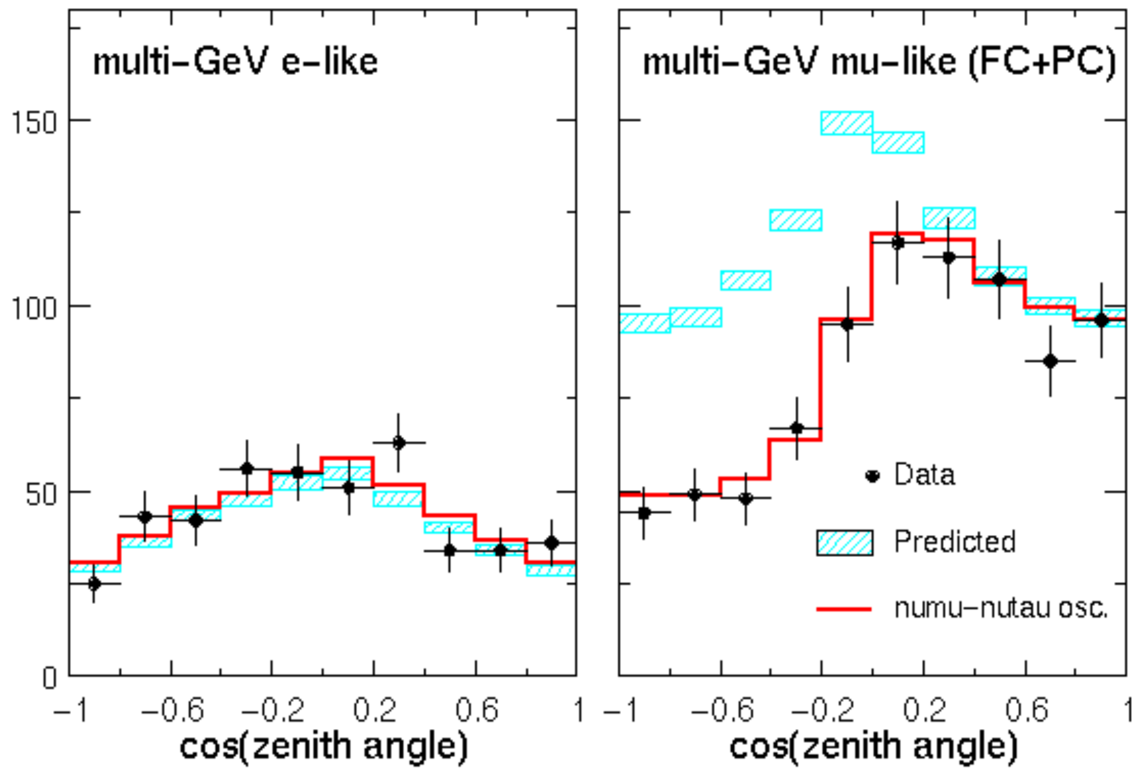


1998: Super-Kamiokande result

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

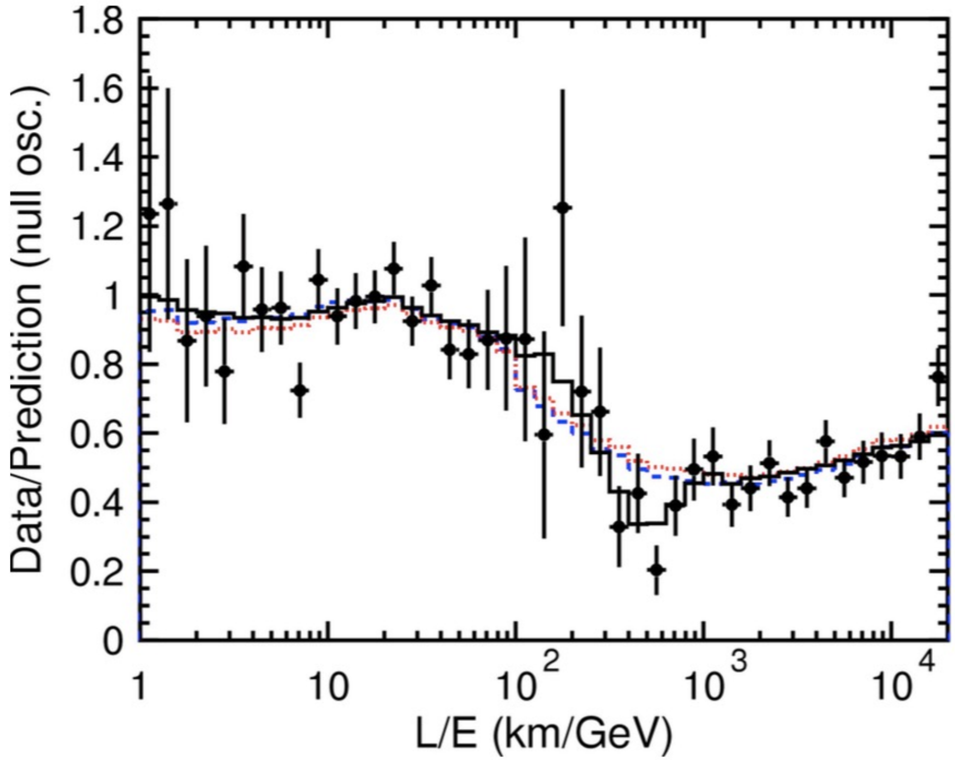
$$R_{\rm exp}/R_{\rm th} = 0.63 \pm 0.03_{stat} \pm 0.05_{syst}$$

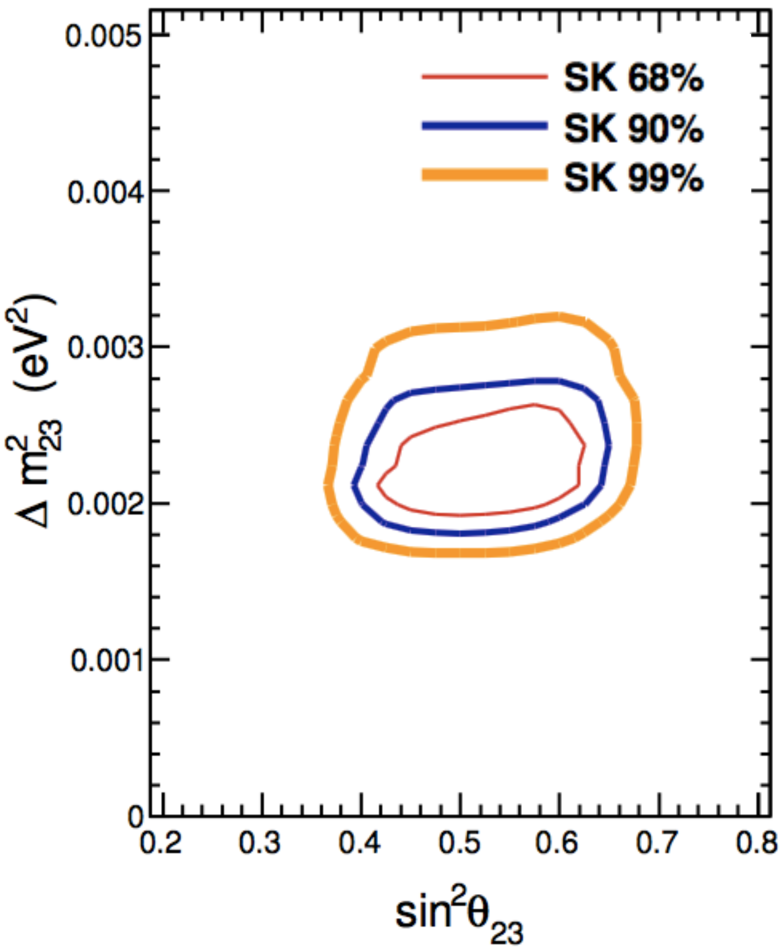
- At **high neutrino energies**, asymmetry in angular distribution



- 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: → oscillations are $\nu_\mu \rightarrow \nu_\tau$
- surprise: large amplitude! → today: $\theta_{23} \approx 45°$

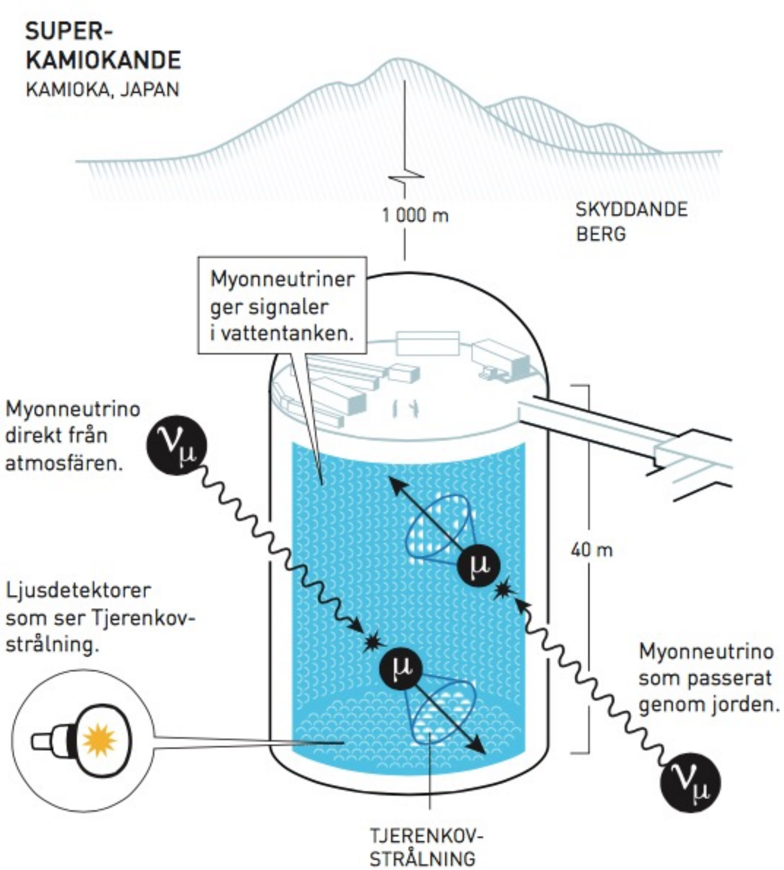
Later SK data on atmospheric ν's



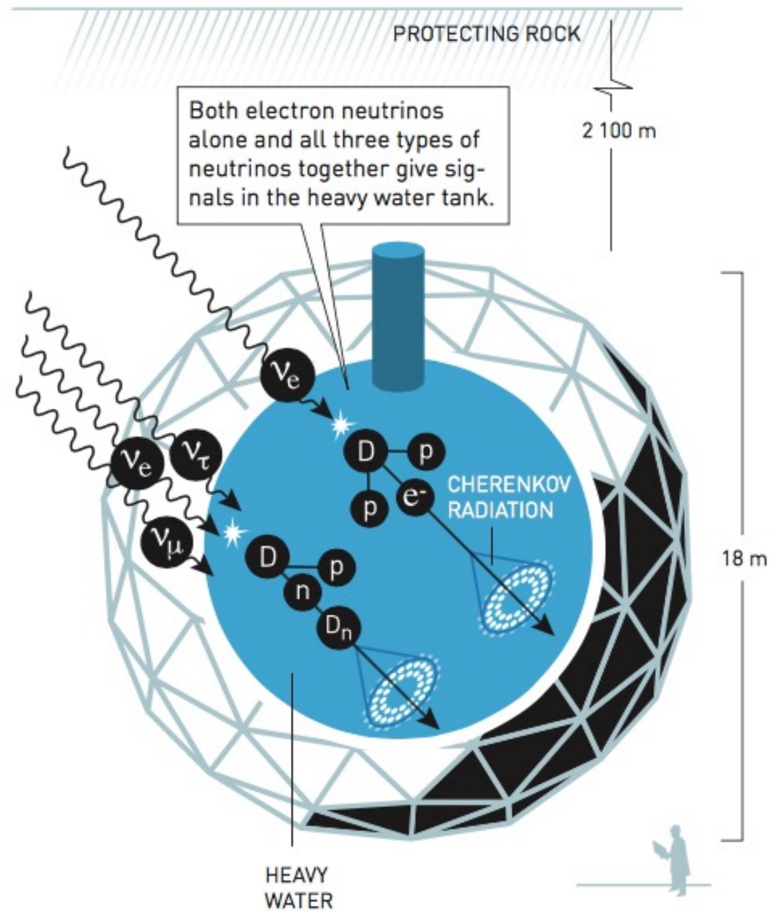


- oscillation-like L/E structure found
- evidence (4.6σ) for ν_τ-appearance in the detector
- still unclear whether $\sin^2 2\theta_{23}<1$ ($\theta_{23}\neq45°$)

Nobel Prize in Physics 2015



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



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

→ neutrinos undergo **flavor oscillations** and at least 2 **neutrino states have mass!**

LECTURE QUIZ

Question 2

What is the expected ratio of electron to muon neutrinos created by pion decay in the Earth‘s atmosphere (i.e. without oscillations)?

G) 2:1

H) 1:1

I) 1:2

Current Status of Neutrino Oscillations

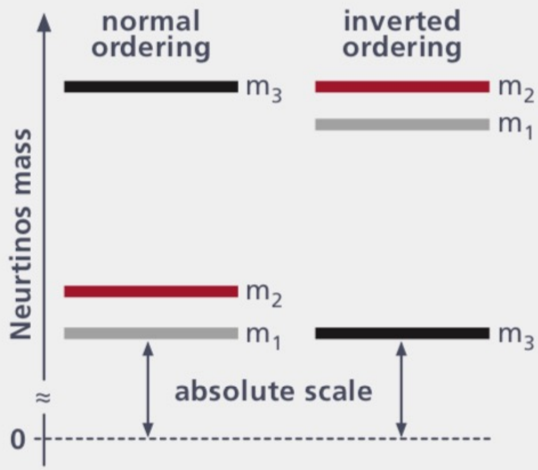
Mixing angles

PMNS mixing matrix $U_{3\times3}$ → 3 mixing angles + CP phase

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

Mass splittings

- **Squared mass differences**
  → oscillation frequencies
- **Absolute mass scale**
  not constrained by oscillations



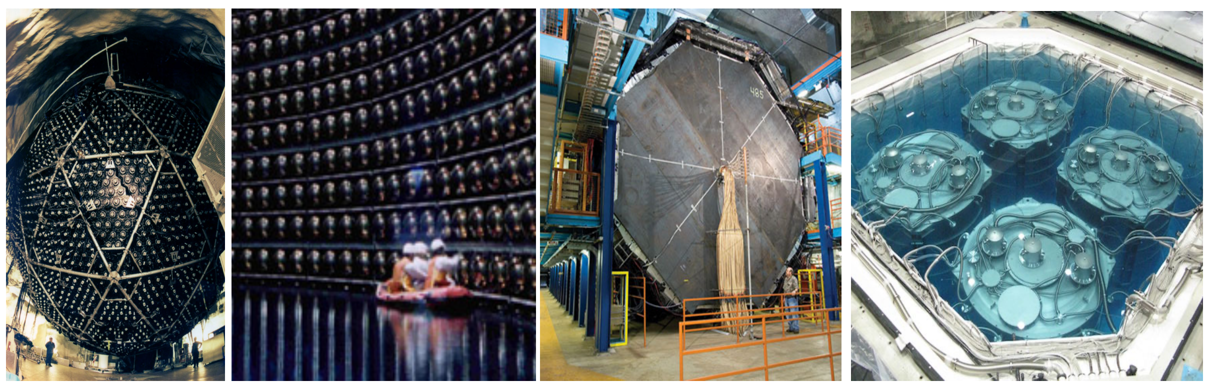
Mixing angles (NMO, 1σ unc.)

- $\theta_{12} = 33.7° \pm 0.7°$
- $\theta_{23} = 49.1°\,^{+1.3°}_{-1.0°}$
- $\theta_{13} = 8.5° \pm 0.1°$

Mass splittings (NMO, 1σ unc.)

- $\Delta m^2_{21} = 7.4 \pm 0.2 \times 10^{-5}\,\text{eV}^2$
- $\Delta m^2_{31} = 2.51 \pm 0.03 \times 10^{-3}\,\text{eV}^2$

based on combination of results from solar, reactor, atmospheric, accelerator ... experiments



Open Issues in 3-Flavor Oscillations

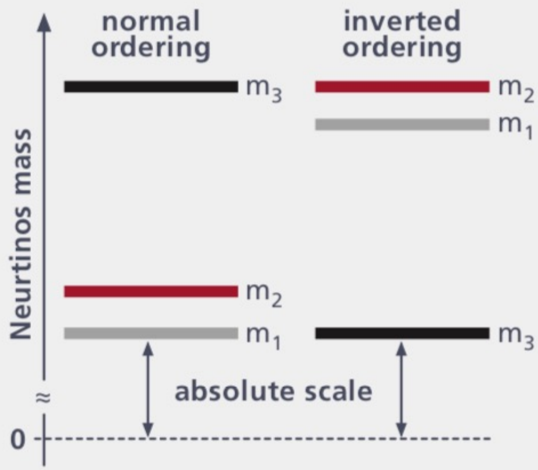
Mixing Angles

PMNS mixing matrix $U_{3\times3}$ → 3 mixing angles + CP phase

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

Mass Splittings

- **Squared mass differences** → oscillation frequencies
- **Absolute mass scale** not constrained by oscillations



What is the octant of θ_{23}?

Is the **PMNS matrix unitary?**

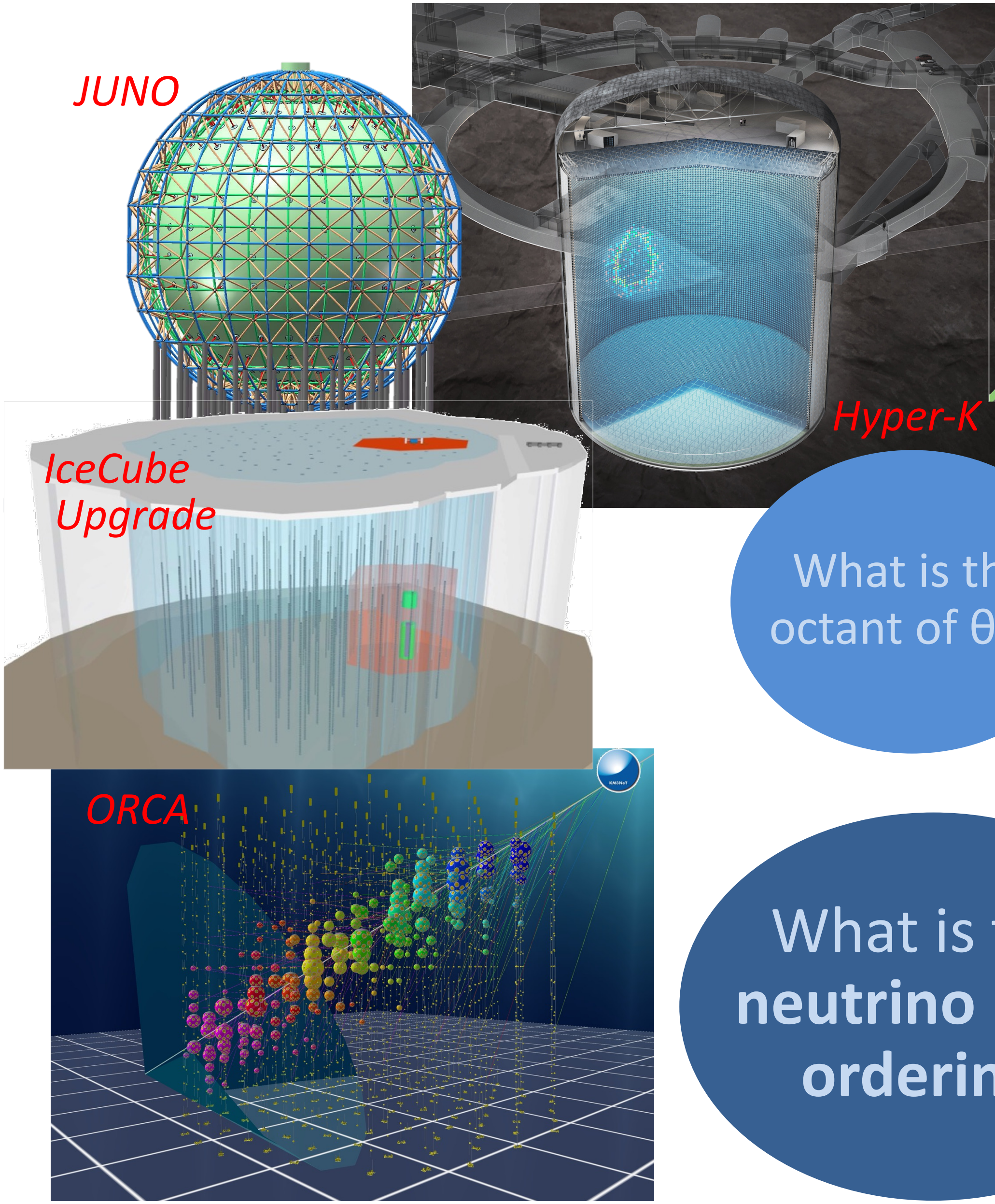
What is the phase δ_{CP} of **leptonic CP violation?**

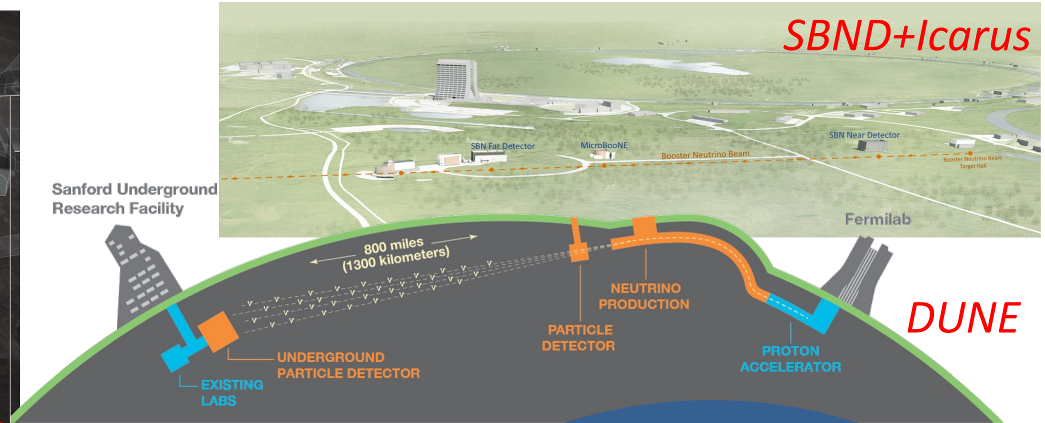
Is it the cause of **baryon asymmetry?**

What is the **neutrino mass ordering?**

Are there additional **sterile neutrinos?**

Upcoming Oscillation Experiments





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Is the **PMNS matrix unitary?**

What is the phase δ_{CP} of **leptonic CP violation?**

Is it the cause of **baryon asymmetry?**

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Are there additional **sterile neutrinos?**

LECTURE QUIZ

Question 3

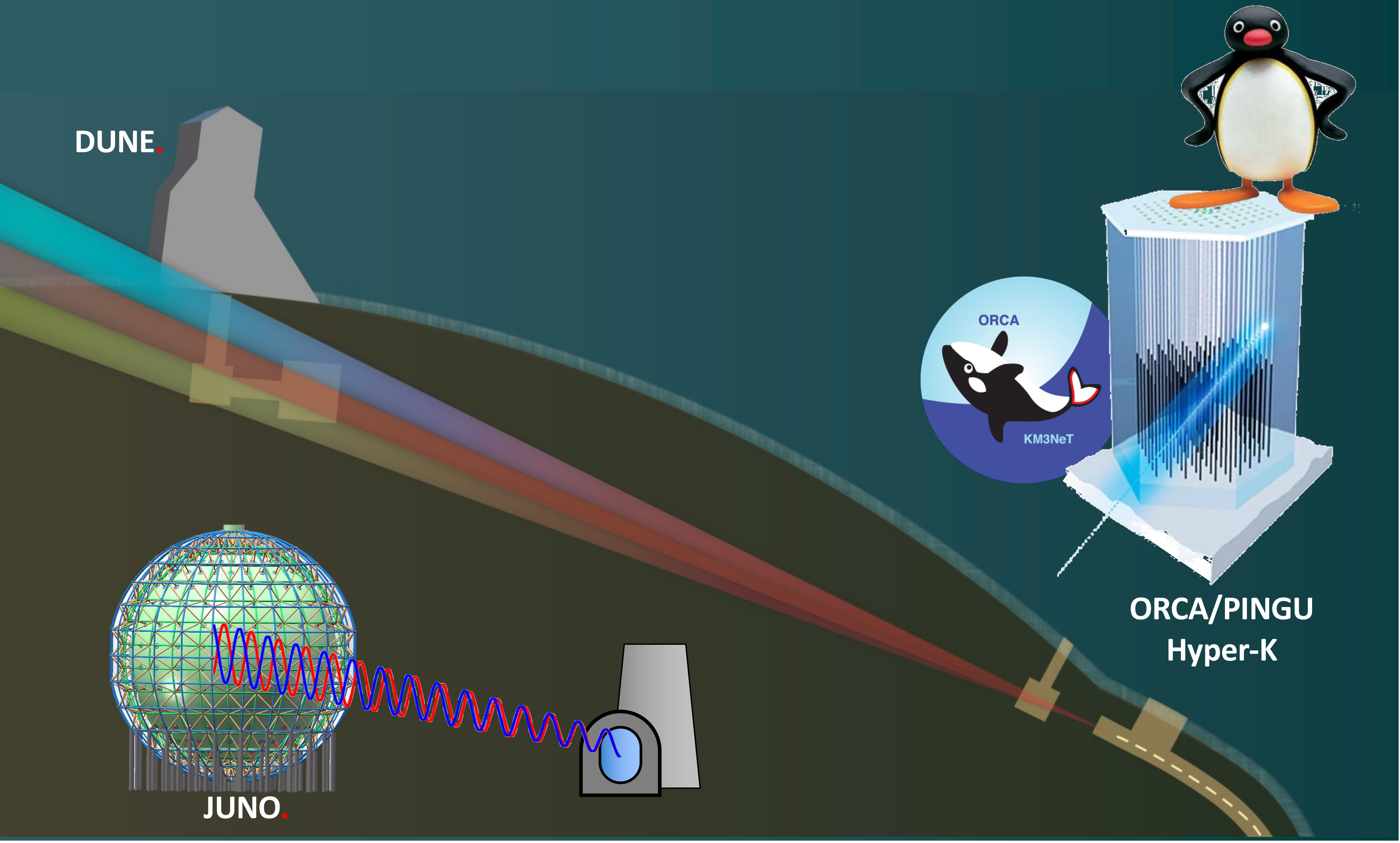
At what precision do we know the neutrino mixing angles?

M : 0.1°

N : 1°

O : 10°

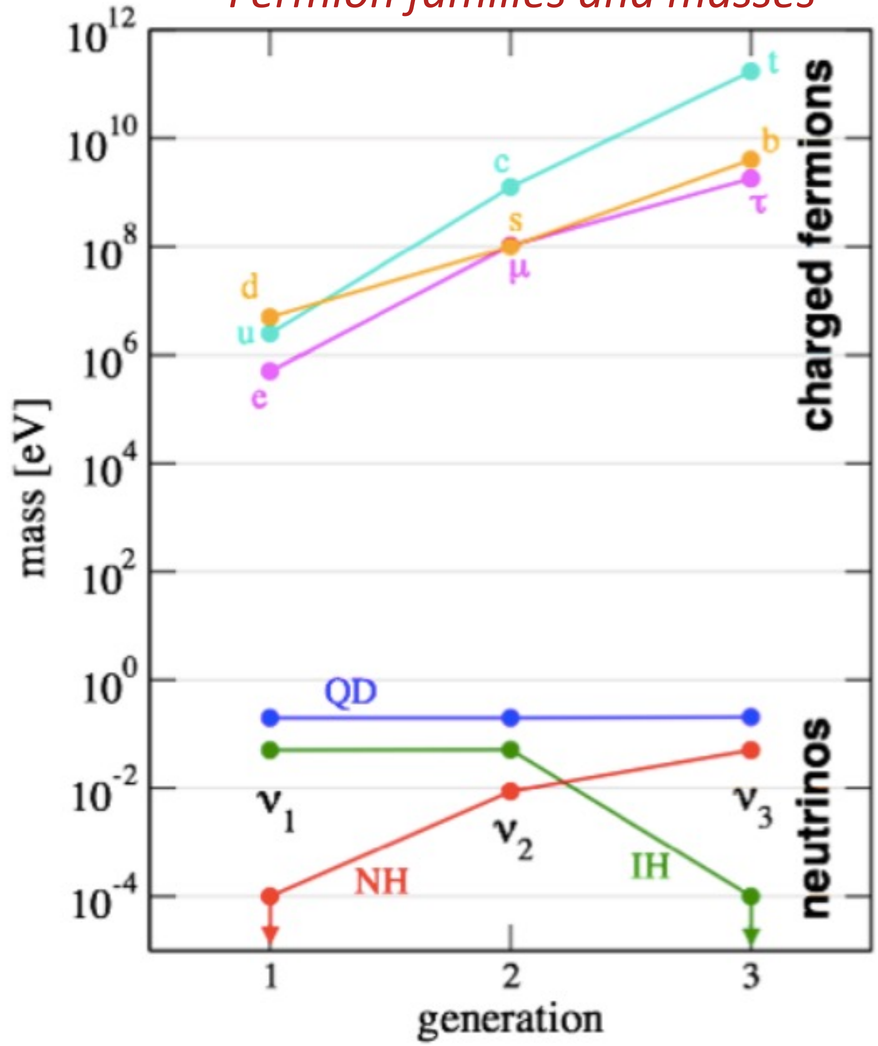
Experiments for Neutrino Mass Ordering



Neutrino Mass Ordering (Hierarchy)

- **Arrangement** of the neutrino masses
  - as in quark sector
    → normal mass ordering (NMO)
  - opposed to it
    → inverted mass ordering (IMO)
  - w/o clear ordering
    → quasi-degenerate (QD)

Fermion families and masses



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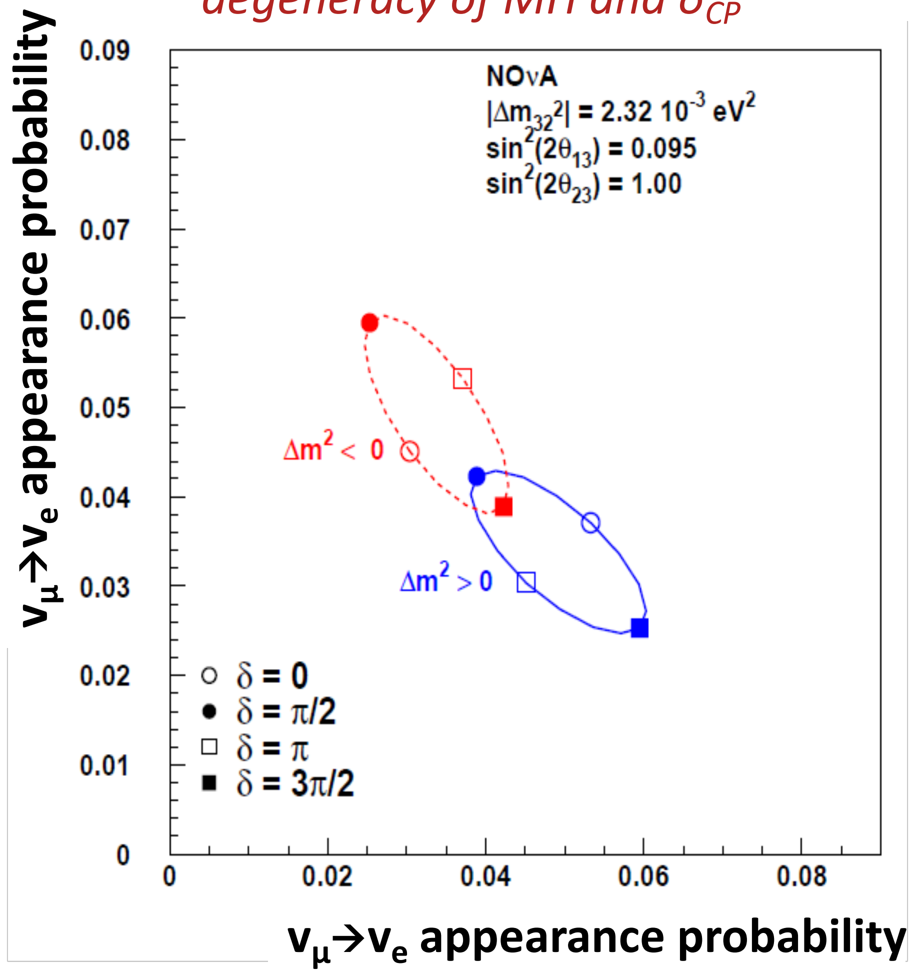
- resolving the **degeneracy in** the interpretation of **δ_{CP} measurements**

long baseline experiments: degeneracy of MH and δ_{CP}



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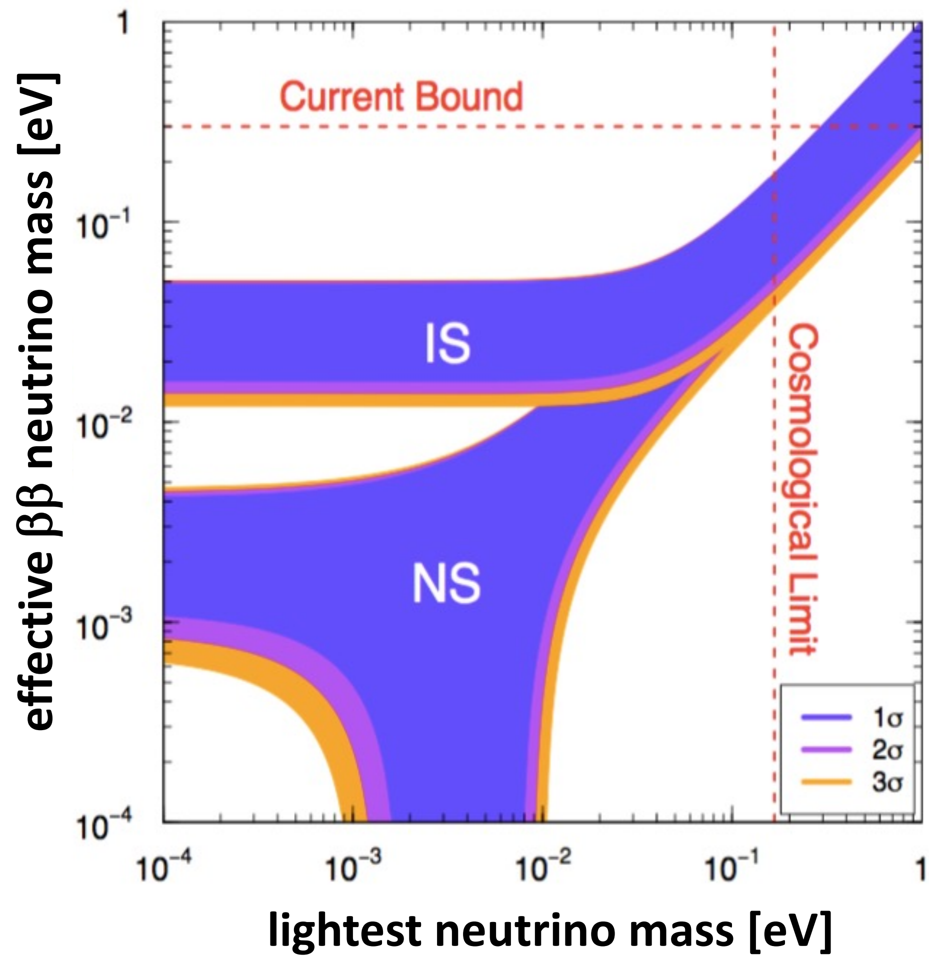
- resolving the **degeneracy in** the interpretation of **δ_{CP} measurements**
- target range for **sensitivity** of **0νββ decay** experiments

Lightest vs. effective ββ neutrino mass



Neutrino Mass Ordering (Hierarchy)

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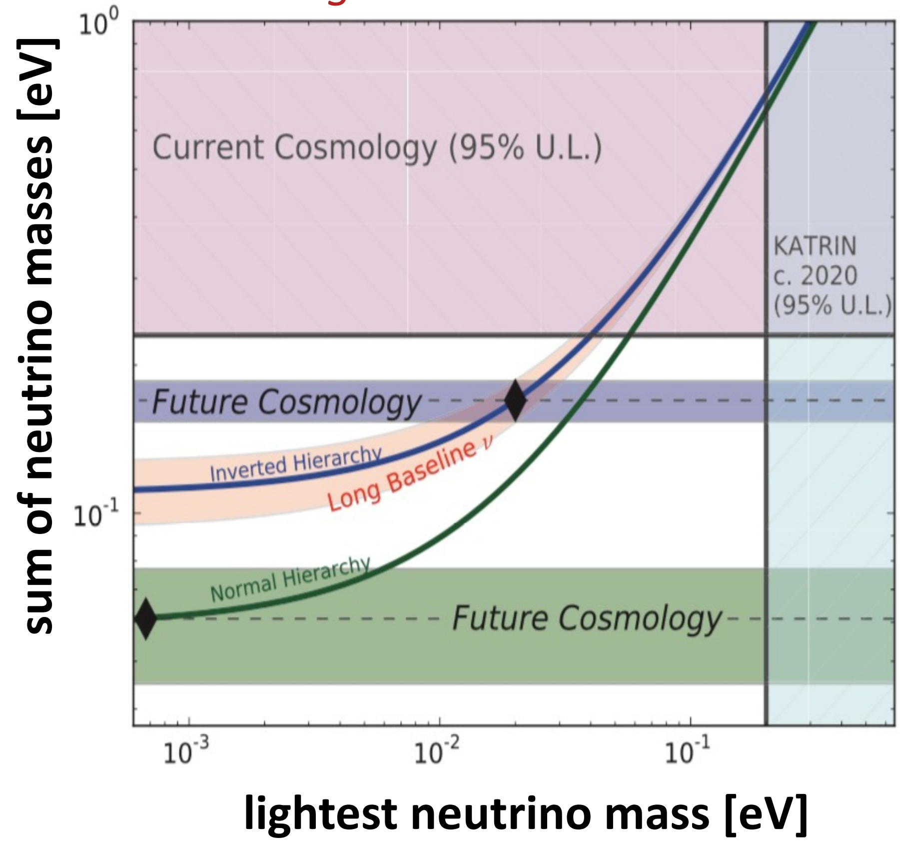
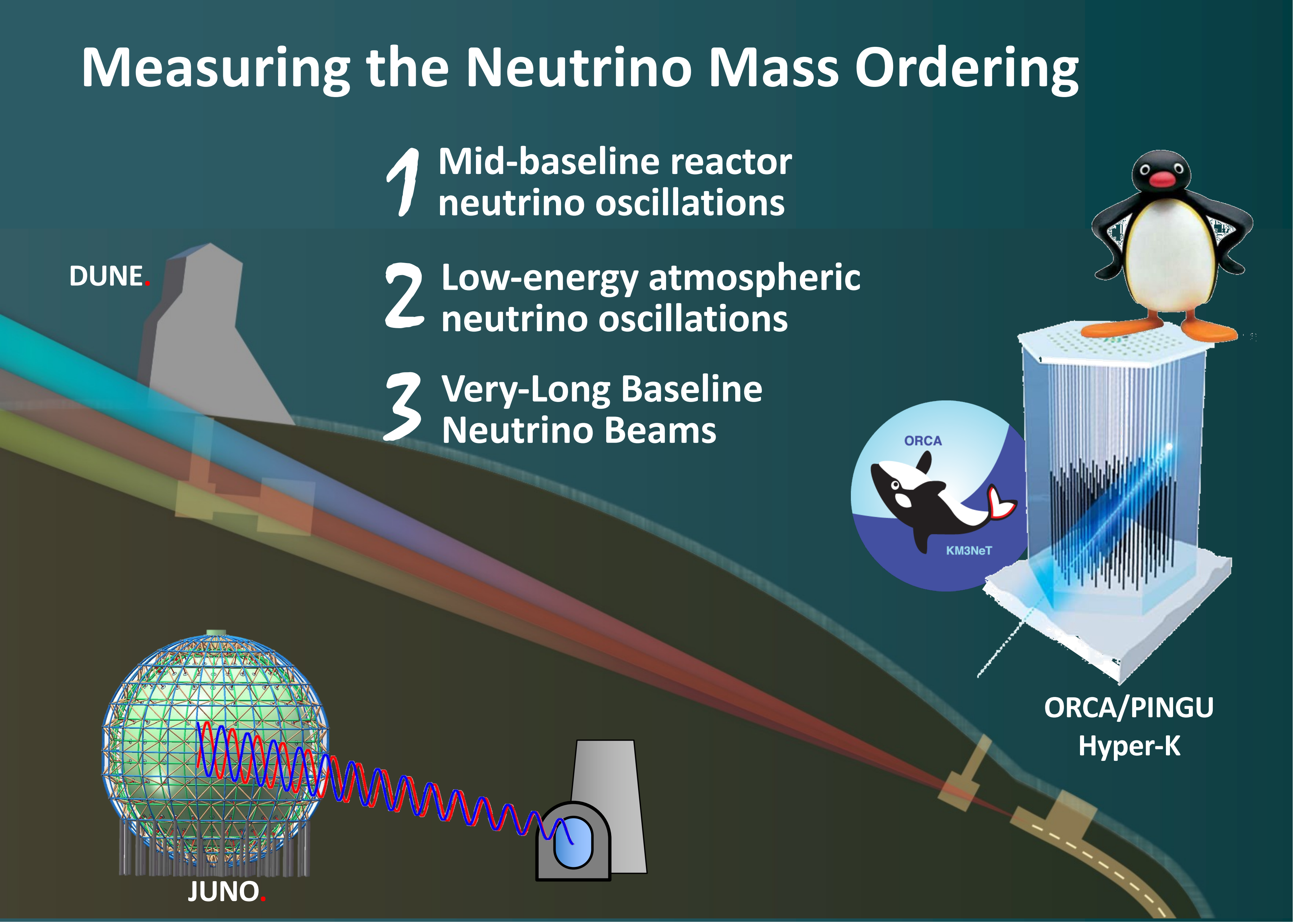
  - w/o clear ordering
    → quasi-degenerate (QD)
- resolving the **degeneracy in** the interpretation of **δ_{CP} measurements**
- target range for **sensitivity** of **0νββ decay** experiments
- combination with **cosmology** to find **lightest neutrino mass**

Cosmological neutrino mass vs. MH

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DUNE.
ORCA
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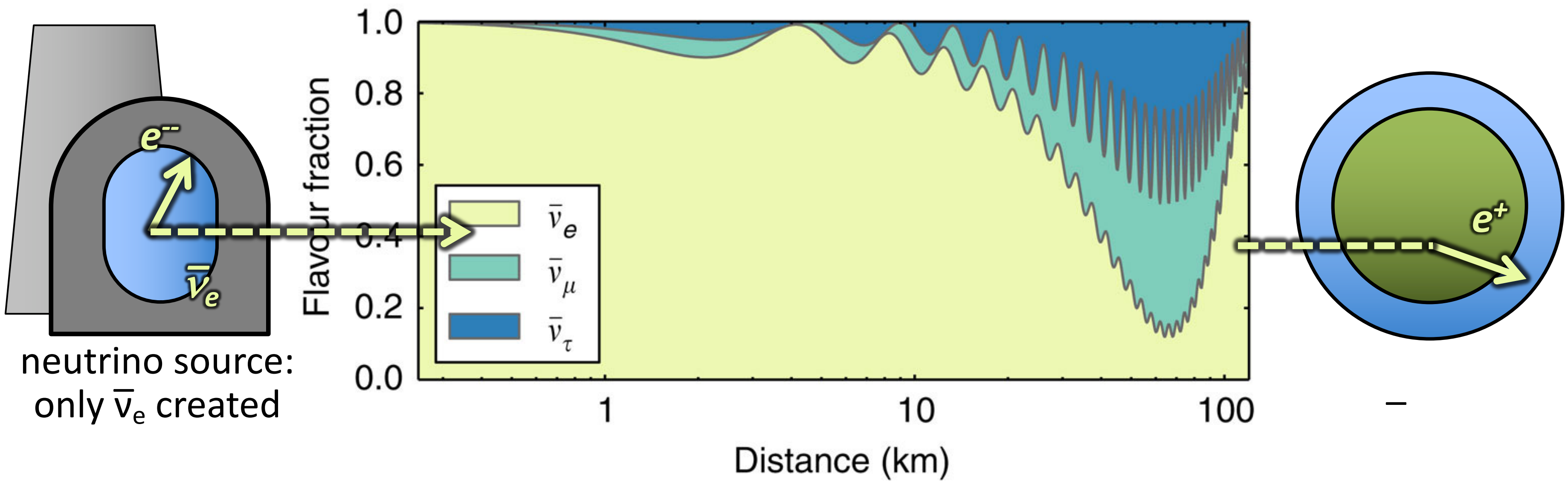
ORCA/PINGU
Hyper-K
JUNO.

Standard oscillations and Δm^2_{ij} values

Common three-flavor reactor electron-antineutrino survival probability:

$$P_{ee} = 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}}{4E}\right) - \sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21}}{4E}\right)$$



→ oscillation parameters are extracted from $\bar{\nu}_e$ **disappearance pattern**

→ due to the $\sin^2$ terms, P_{ee} terms do not depend on sign of Δm^2_{ij}

→ however, the formula above implicitly assumes $\mathbf{\Delta m^2_{31} = \Delta m^2_{32}}$

NMO from reactor $\bar{\nu}_e$ disappearance

Survival probability

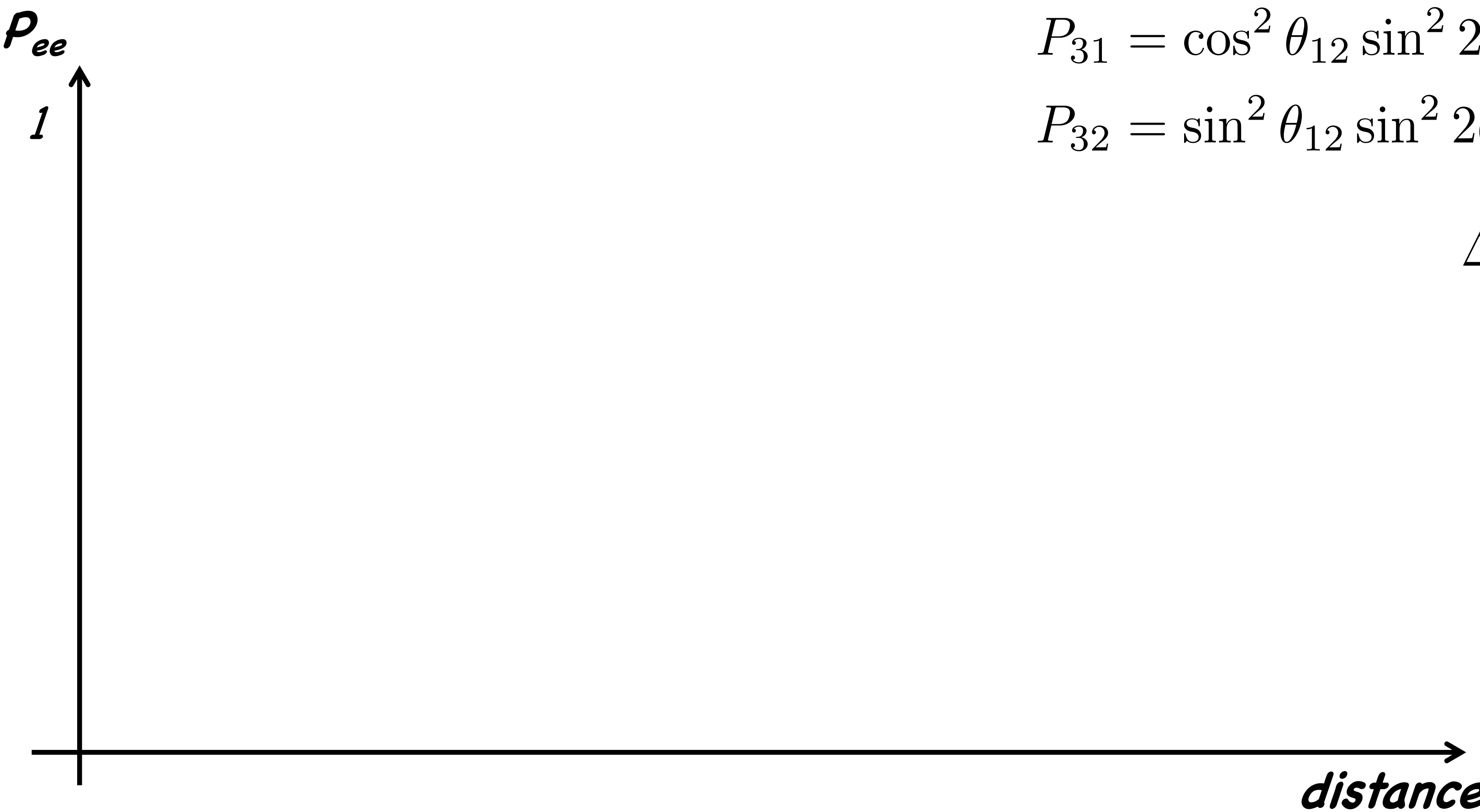
$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

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

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

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

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$



Petcov, Piai, hep-ph/0112074

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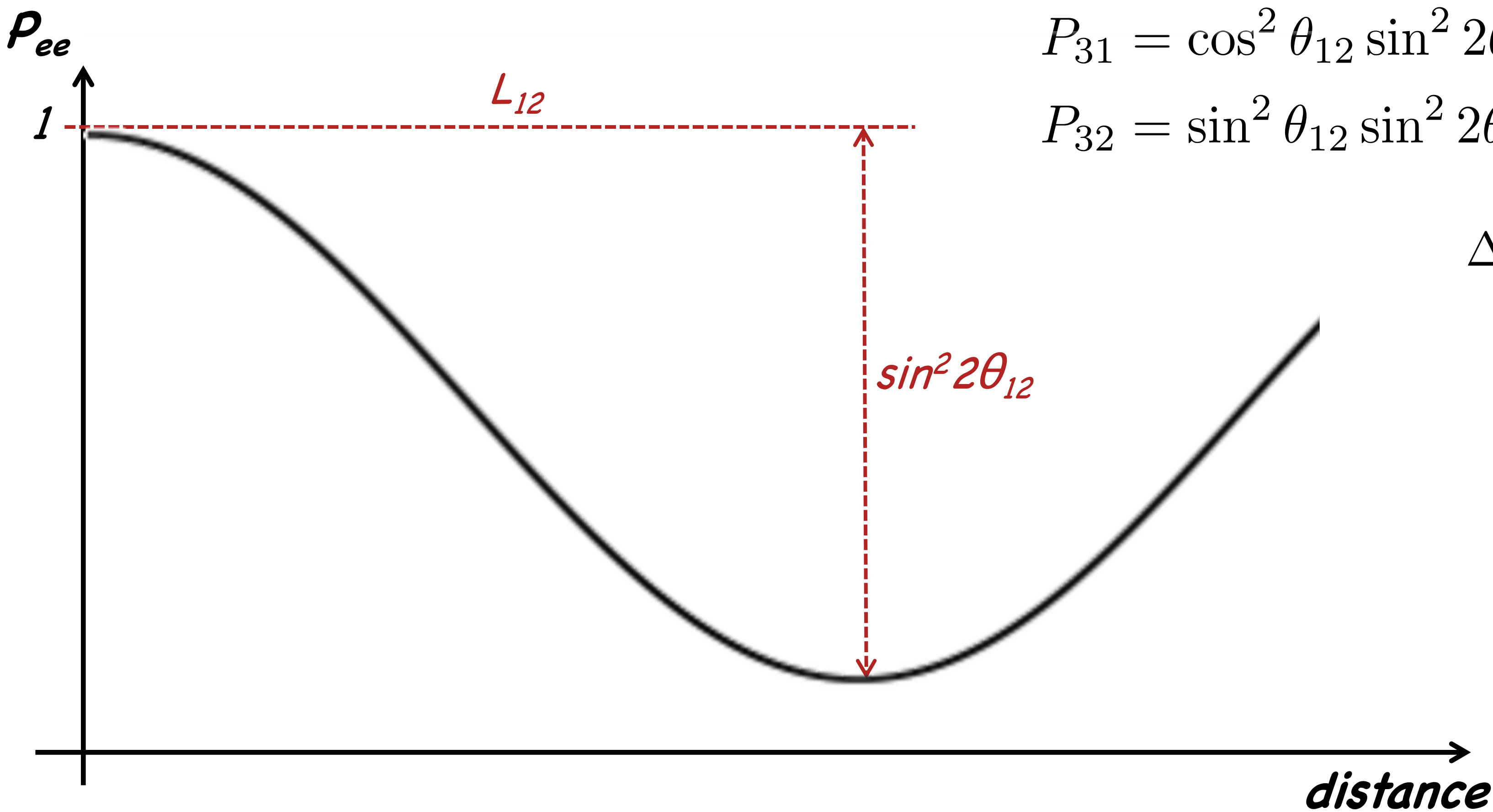

Petcov, Piai, hep-ph/0112074

NMO from reactor $\bar{\nu}_e$ disappearance

→ subdominant oscillation pattern depends on phase terms of P_{31}/P_{32}

→ depends on **relative sizes** of Δm^2_{32} and Δm^2_{31}

Survival probability

$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$

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

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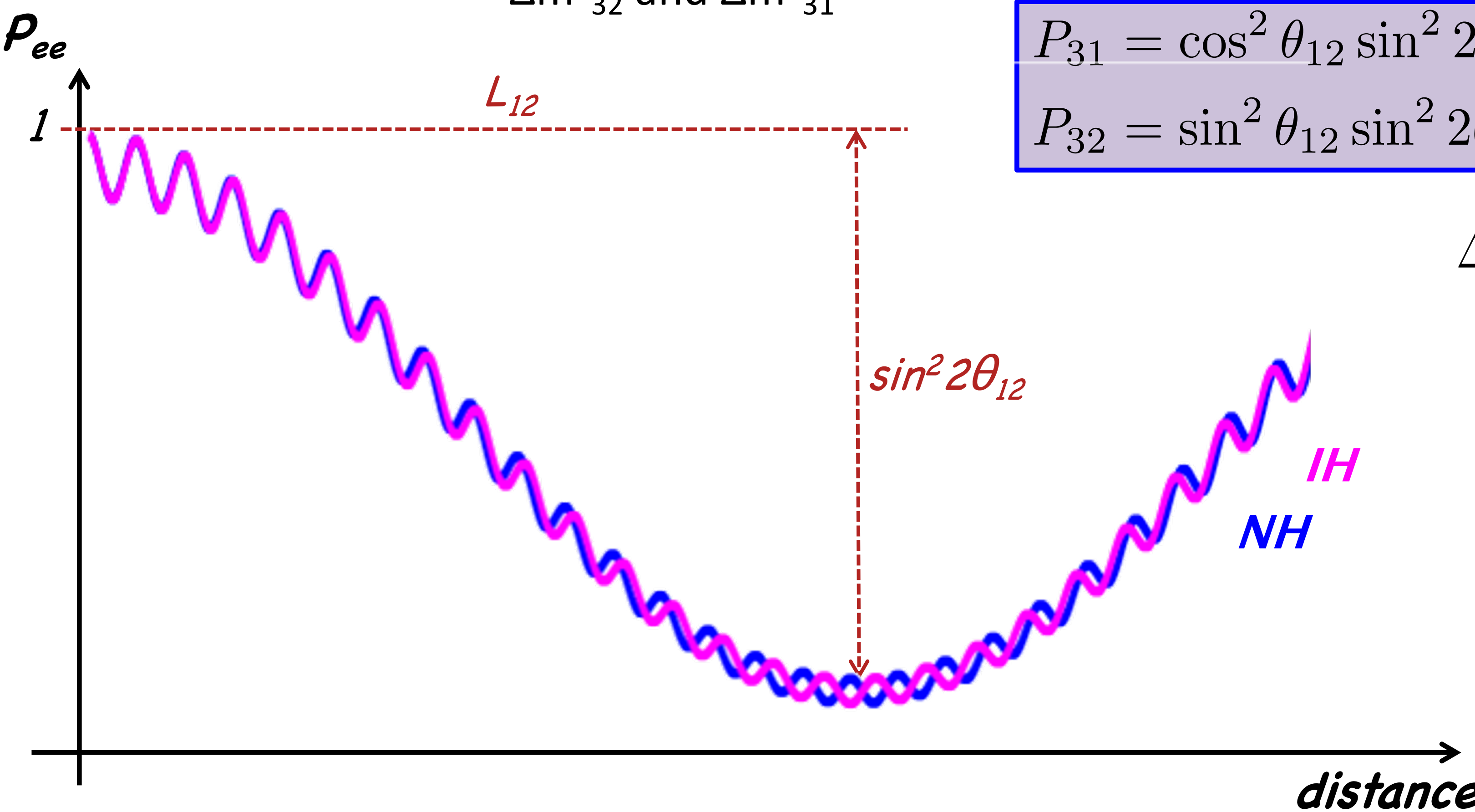
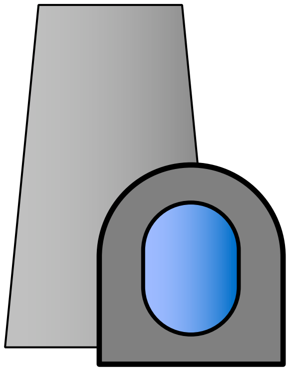
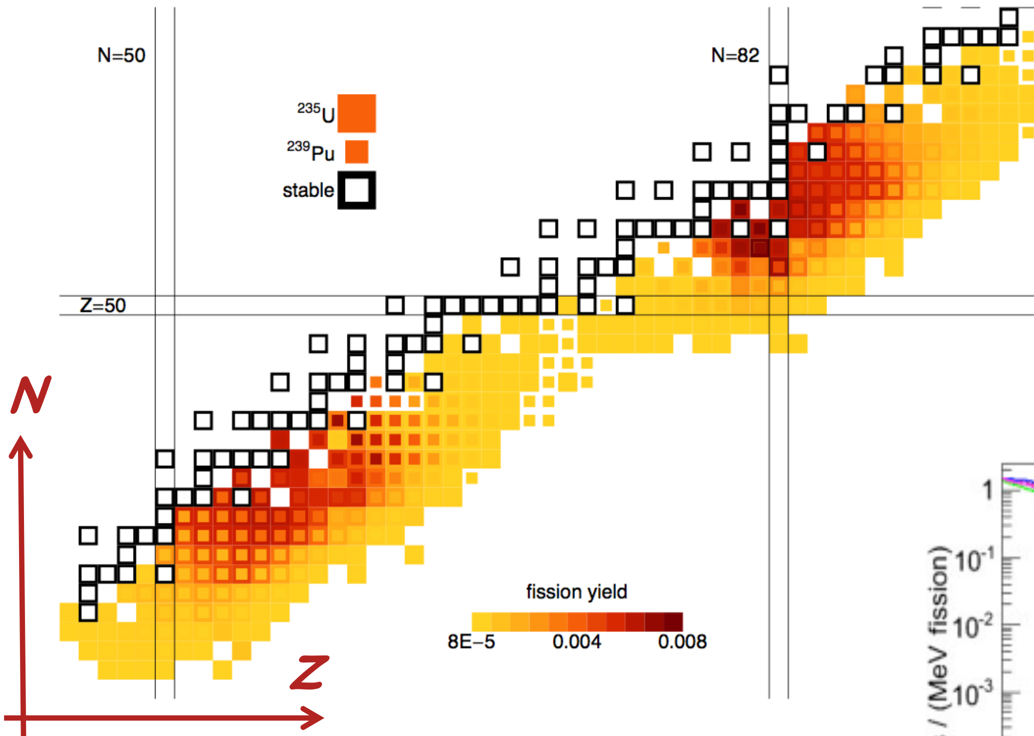


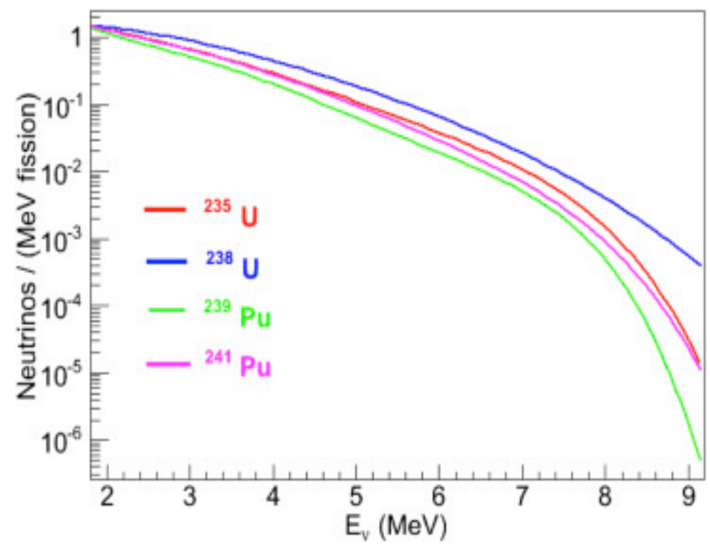
Petcov, Piai, hep-ph/0112074

Nuclear reactors as intense $\bar{\nu}_e$ source



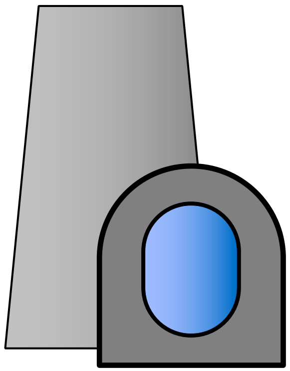
$$n + {}^{235}\mathrm{U} \rightarrow {}^{A}(Z) + {}^{233-A}(92 - Z) + 3n + 200\,\mathrm{MeV}$$

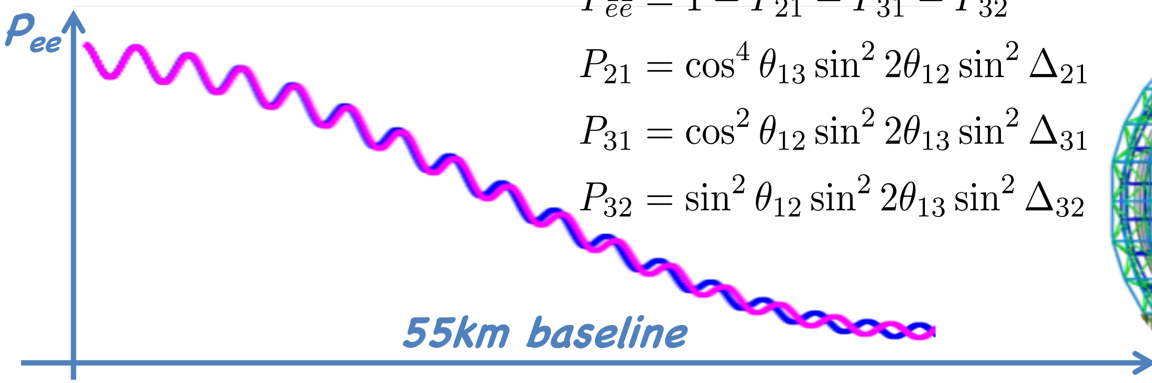




- ν's from β^--decays of neutron-rich fission products
- ~6 $\bar{\nu}_e$'s per fission (200MeV) → **intense! ~10^{20} $\bar{\nu}$/GW$_{th}$**
- **energy spectra:** up to ~8 MeV

Mid-distance $\bar{\nu}_e \rightarrow \bar{\nu}_e$ oscillations





$$P_{\bar{e}\bar{e}} = 1 - P_{21} - P_{31} - P_{32}$$
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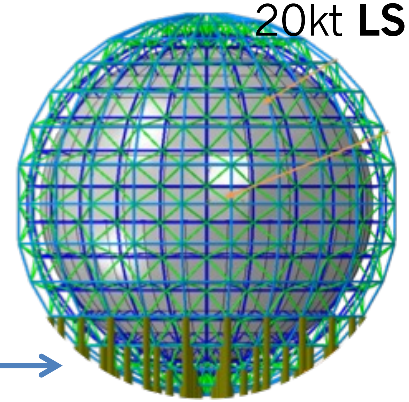

Nuclear reactor(s)
ΣP~30GW

Mid-distance $\bar{\nu}_e \rightarrow \bar{\nu}_e$ oscillations

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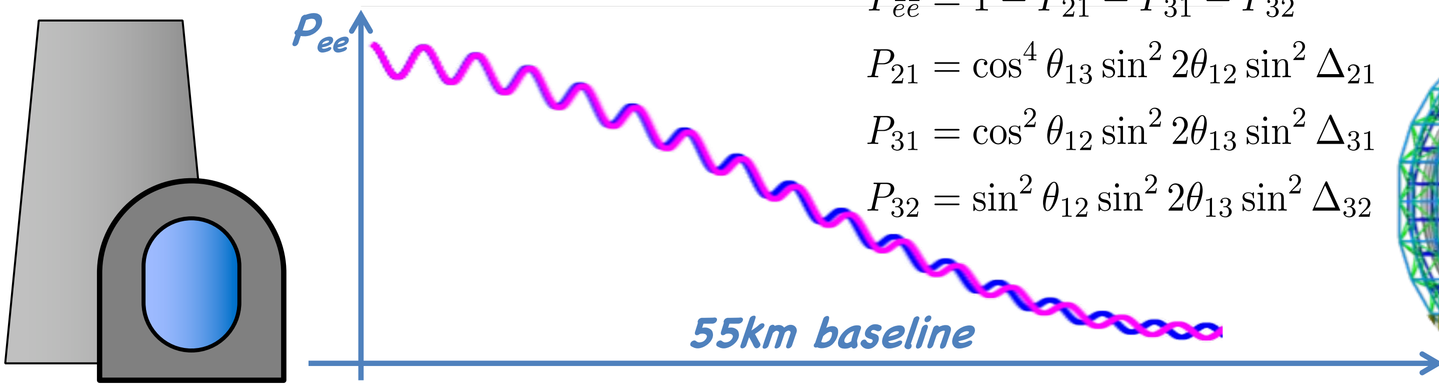
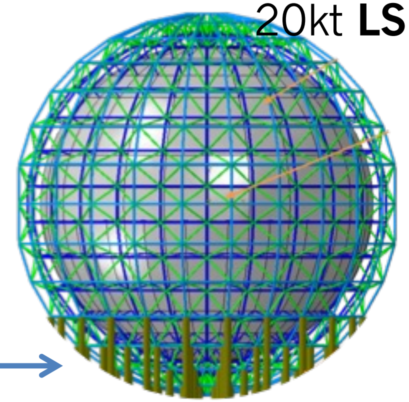
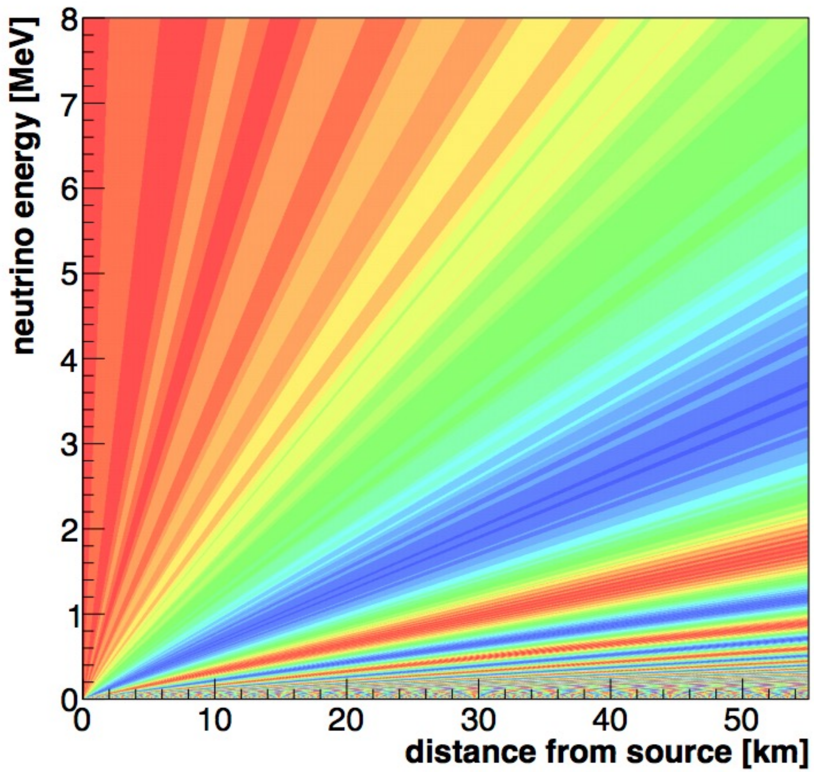


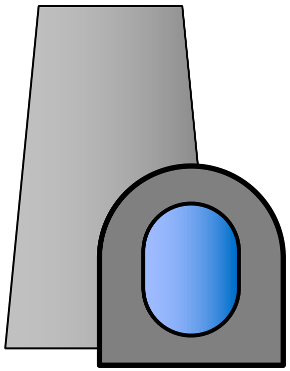


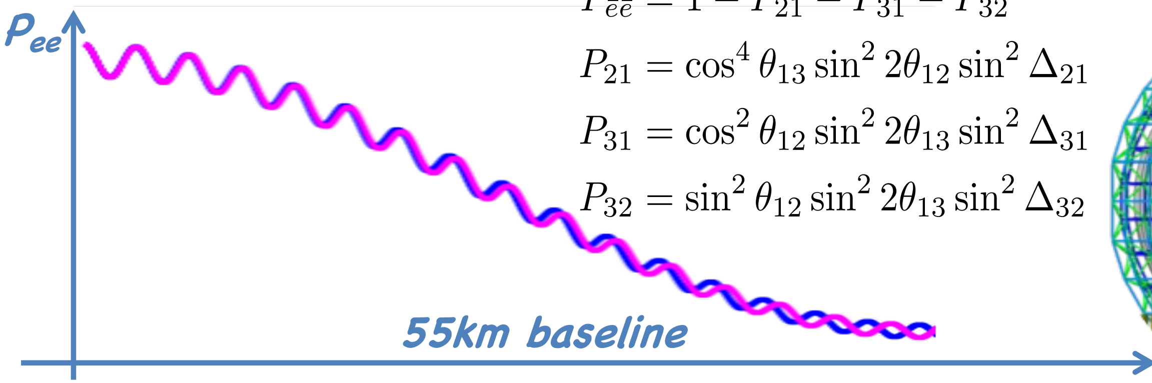
Nuclear reactor(s)
ΣP~30GW

energy range of reactor spectrum



Mid-distance $\bar{\nu}_e \rightarrow \bar{\nu}_e$ oscillations





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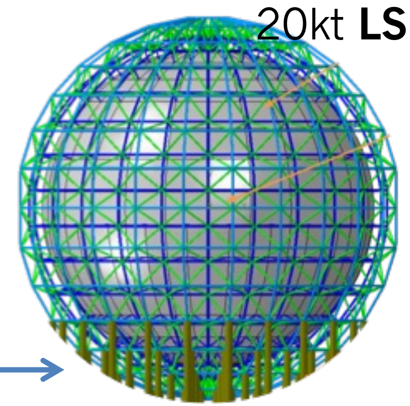

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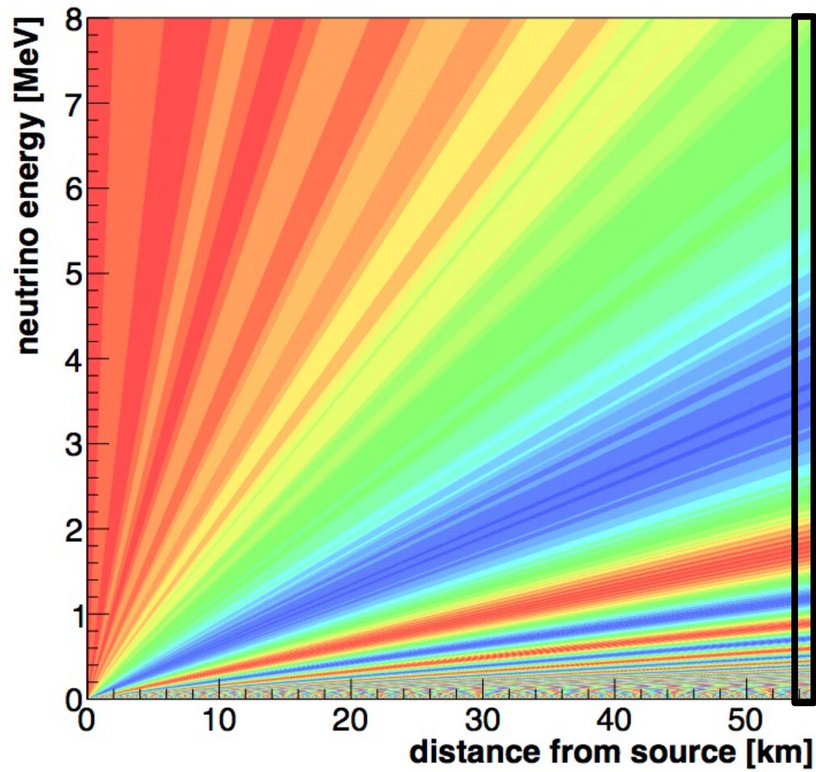
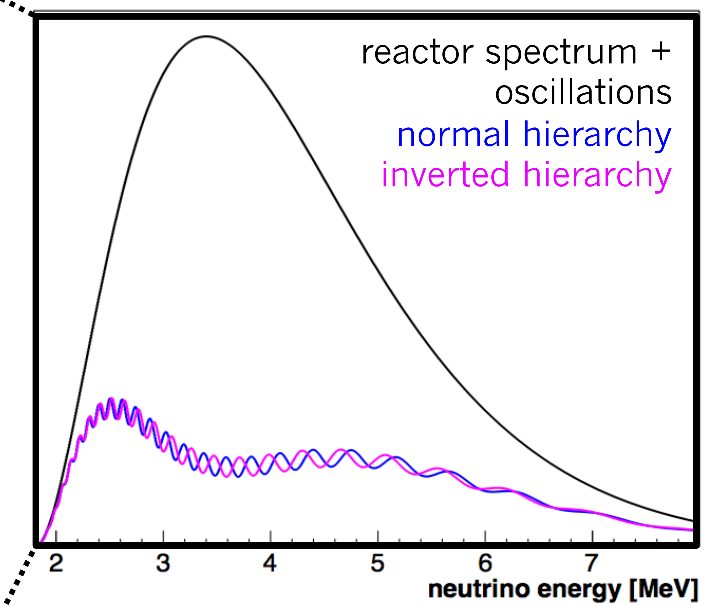




→ MH from position of spectral wiggles!

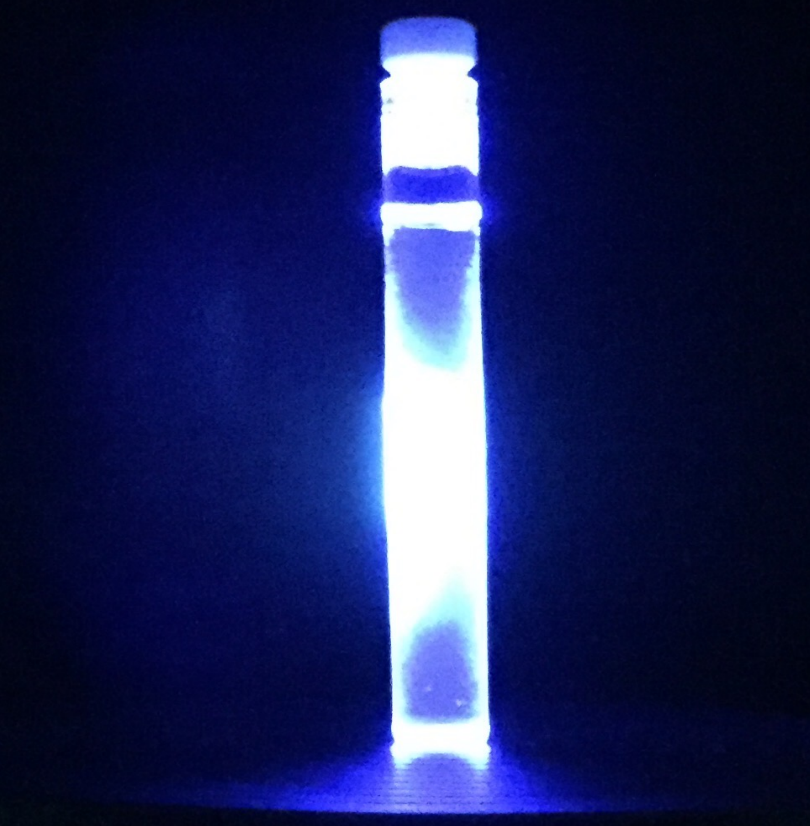
Basic Detector Requirements for JUNO

- reactor antineutrinos at MeV energies
  → **Liquid-scintillator detector**
  → Detection by inverse beta decay

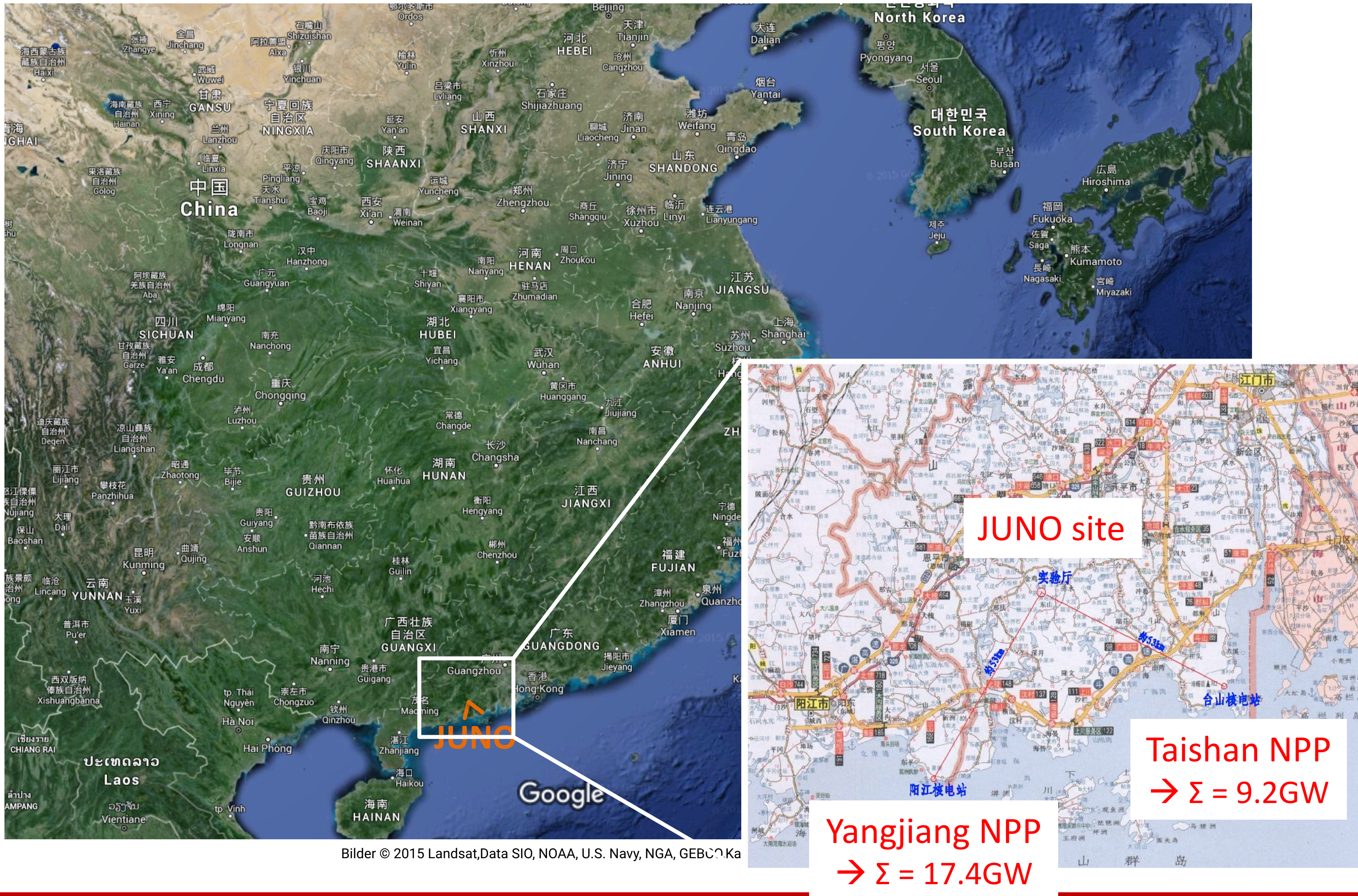
- signature in position of spectral wiggles
  → **~3% energy resolution** at 1 MeV
  → photoelectron yield: **~1,100 pe/MeV**

- large distance to source and high-statistics measurement
  → large target mass: **20 kilotons of LAB**

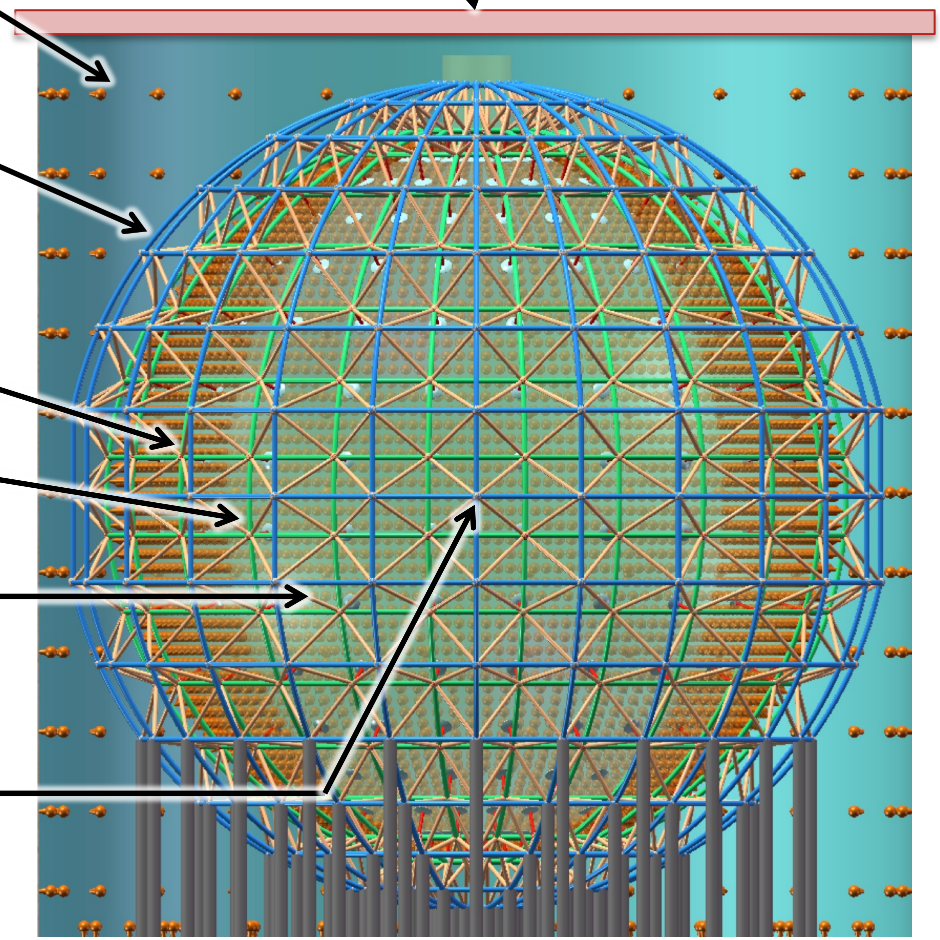
- cosmogenic background
  → rock overburden of **~600 m**



Experimental Setup of JUNO



JUNO Detector Layout

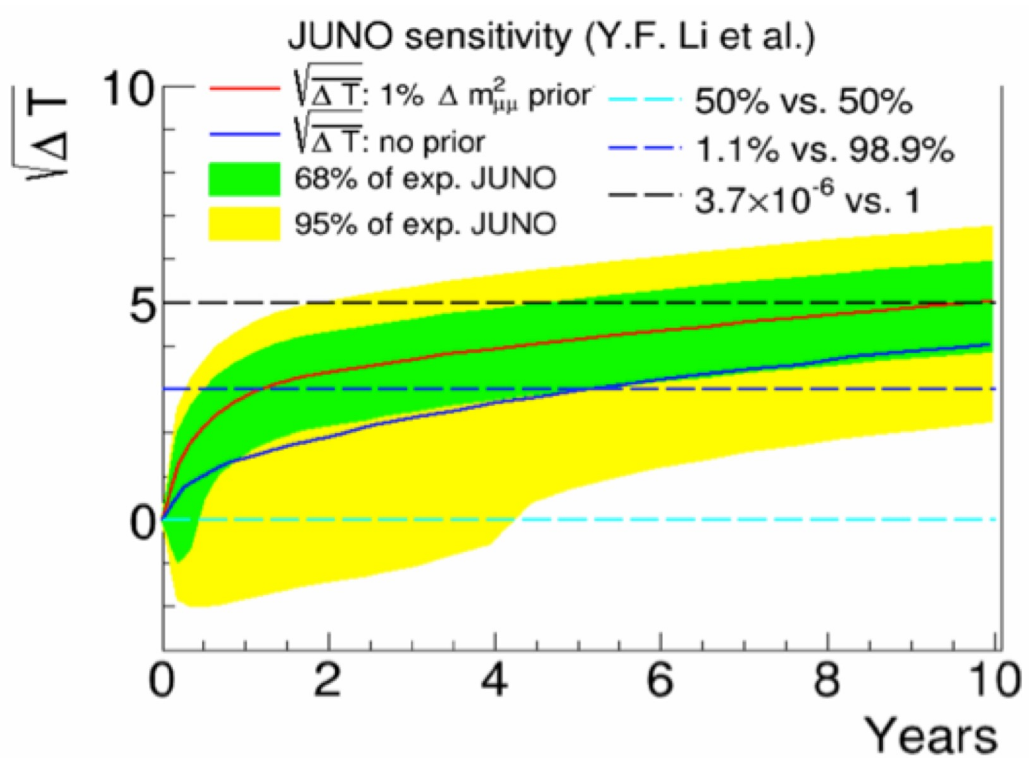


600m below ground

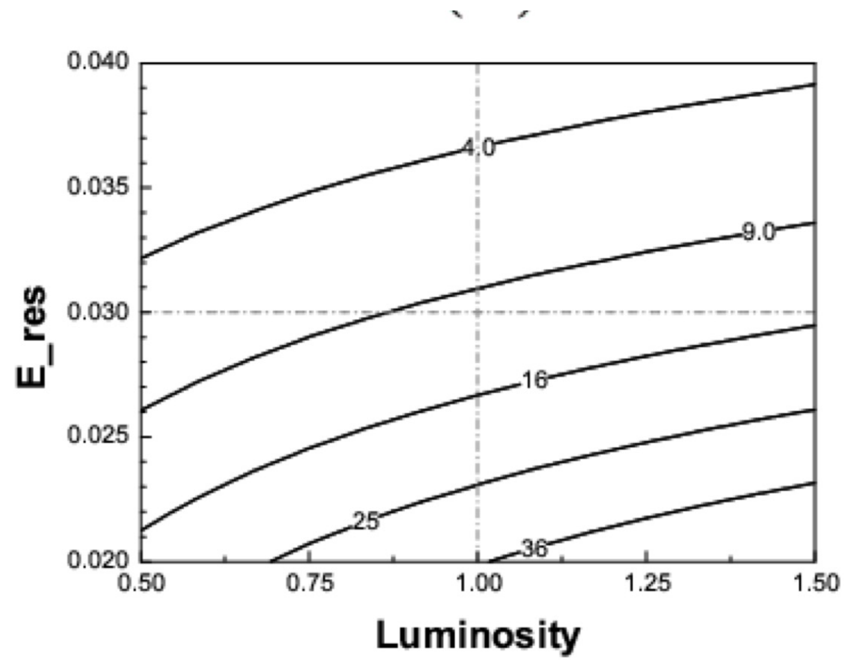
JUNO: Current Status

JUNO Sensitivity

- sensitivity to NMO: about 6 years (10^5 events) to reach 3σ
- depends strongly on energy resolution and energy scale linearity
- combination with existing experiments increases sensitivity to 4σ after 6 years



NMO sensitivity over time



sensitivity as function of energy resolution/exposure

LECTURE QUIZ

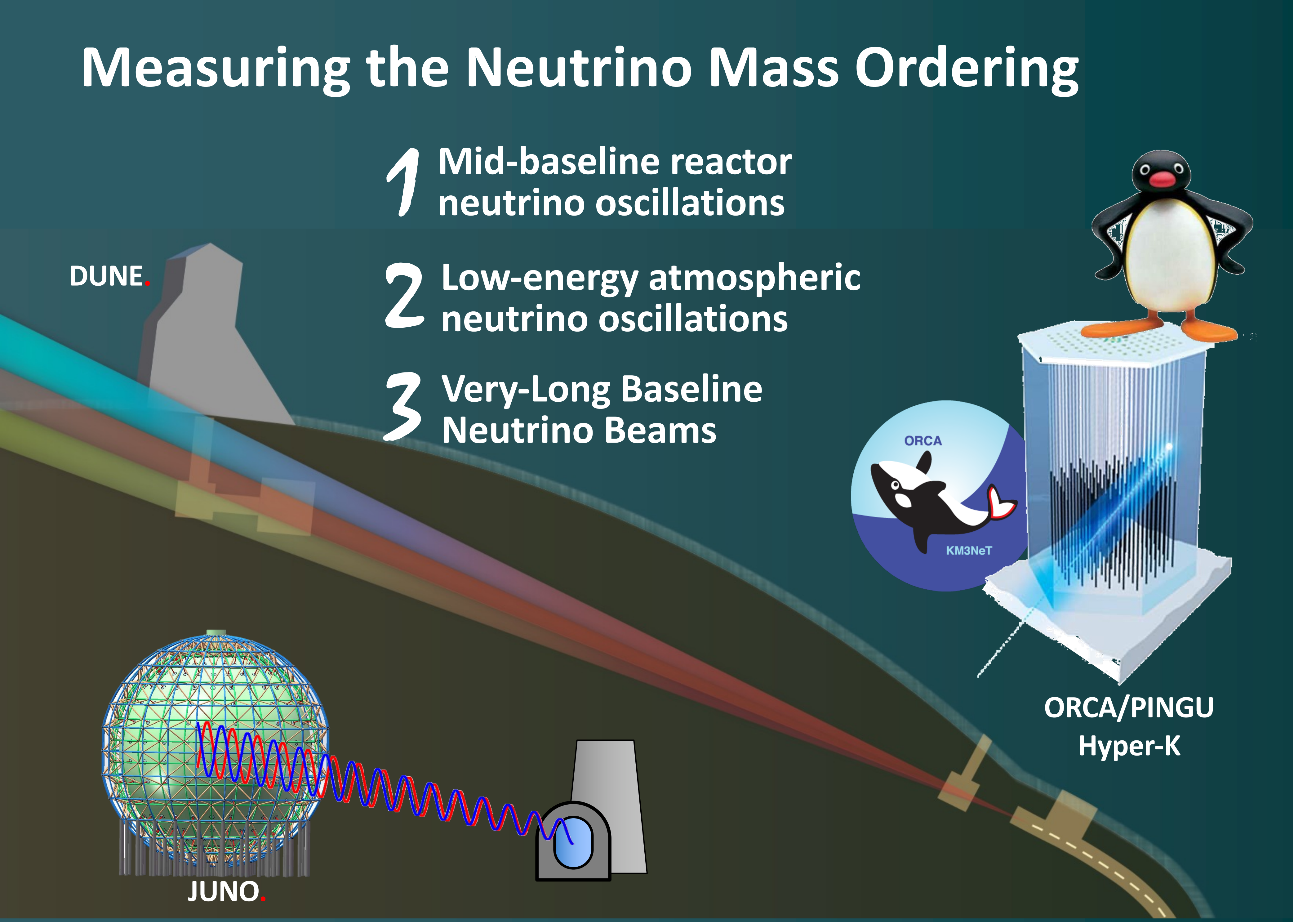
Question 4

How large is the scintillator target mass to be deployed in JUNO?

L : 200 tons

M : 2 kt

N : 20 kt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ORCA
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ORCA/PINGU
Hyper-K
JUNO.

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

good approximation for 1st atmospheric oscillation maximum

Oscillation probability for ν_e appearance
in a ν_μ neutrino beam:

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

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

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

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

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

$\nu_\mu \to \nu_e$ 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

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

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$\nu_\mu \rightarrow \nu_e$ oscillation probability: CP violation

Oscillation probability for ν_e appearance
in a ν_μ neutrino beam:

atmospheric oscillations

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leptonic CP violation

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

Oscillation probability for ν_e appearance
in a ν_μ neutrino beam:

effects of weak matter potential

atmospheric oscillations → T2K

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

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

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

weak matter potential A

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

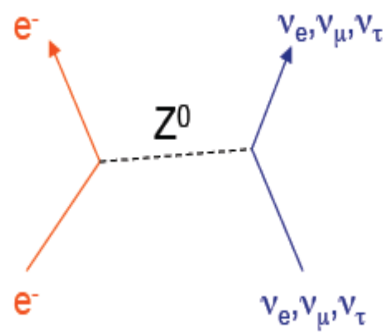
$\nu \leftrightarrow \bar{\nu}$ asymmetry if $A \sim \Delta_{13}$!

Matter effect on neutrino oscillations

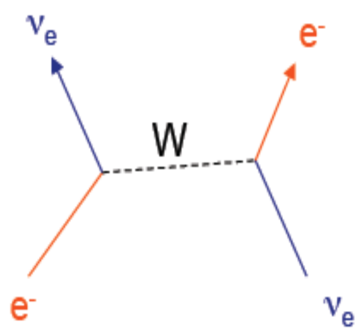
Forward-scattering of ν's in matter:

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

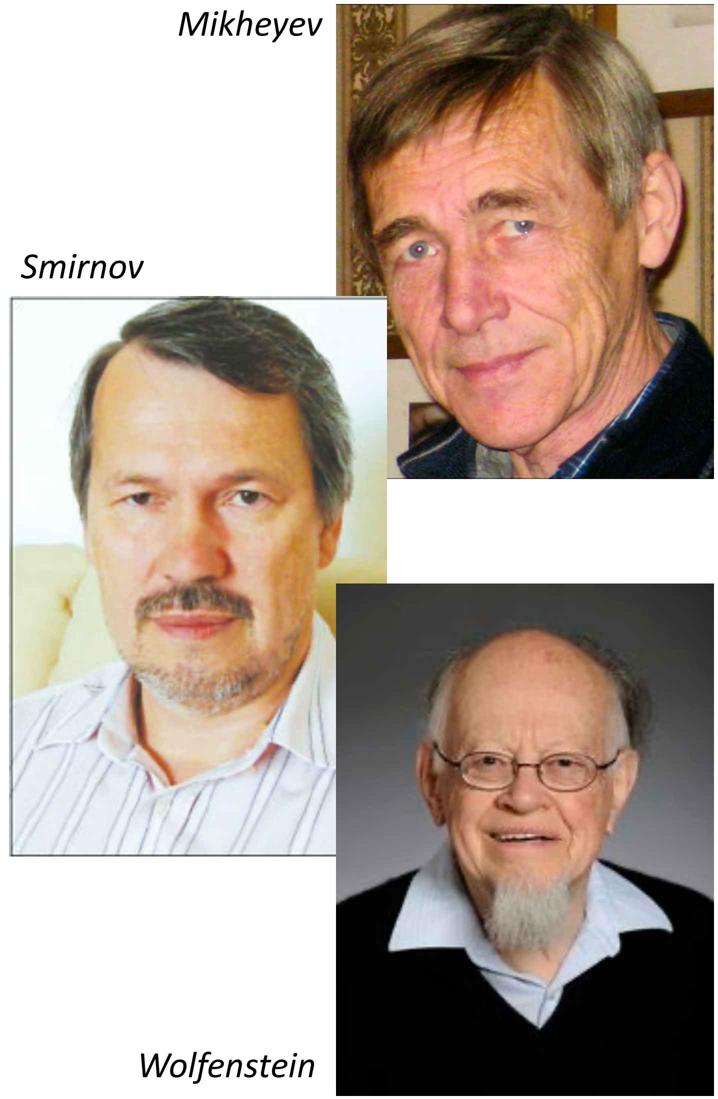
- NC the same for all flavors



- CC on electrons only for ν_e



→ ν_e pick up an effective mass term
→ impact on Δm^2 values AND osc. amplitudes



Mikheyev

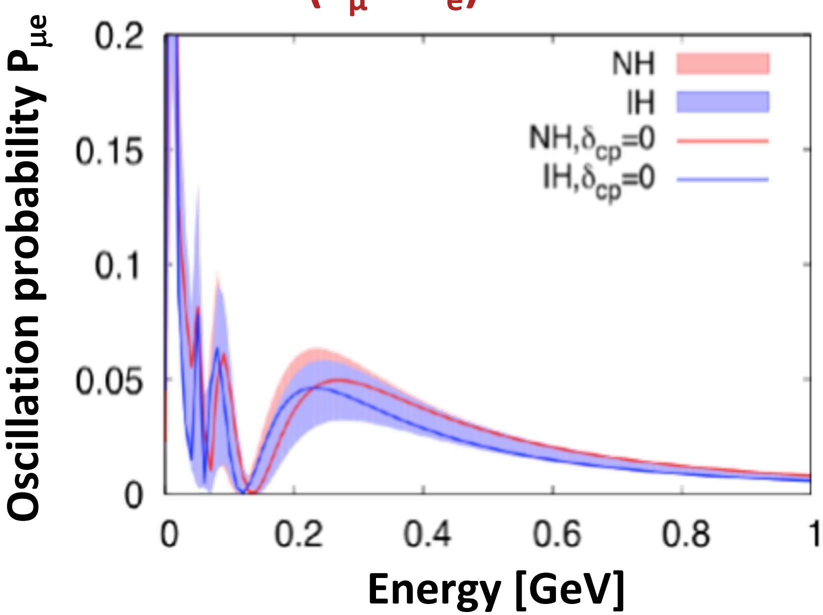
Smirnov

Wolfenstein

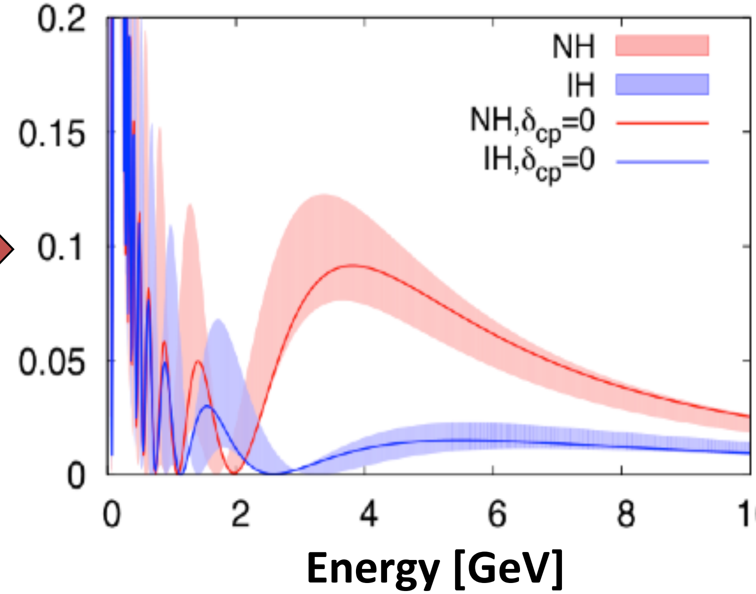
Oscillation spectra at long baselines

- **Oscillation probabilities** differ for $\boldsymbol{\nu_\mu \to \nu_e}$ vs. $\boldsymbol{\nu_\mu \to \nu_e}$
- Enhanced electron-flavor appearance for: neutrinos → normal hierarchy
  antineutrinos → inverted

P($\nu_\mu \to \nu_e$) for 130 km



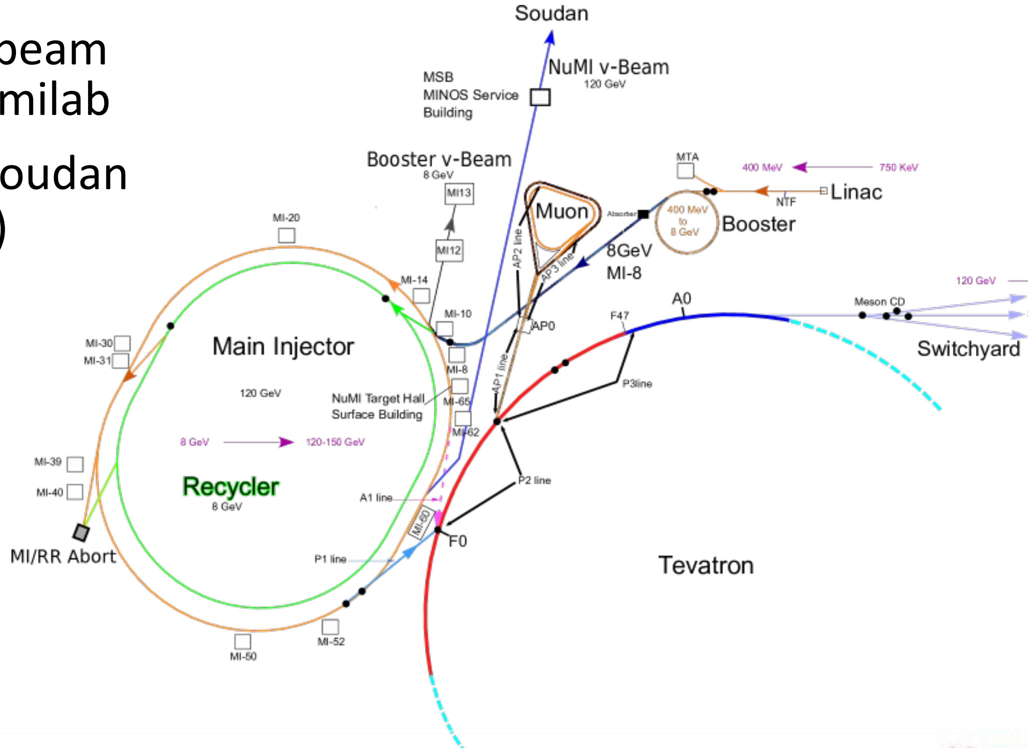
P($\nu_\mu \to \nu_e$) for 2300 km

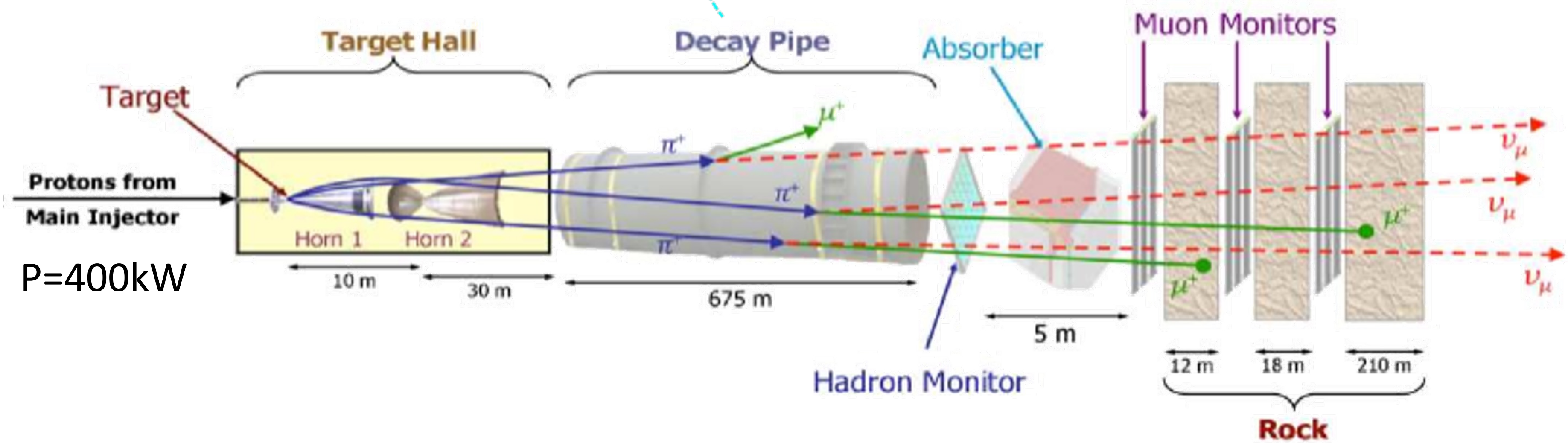


- **Far detector** at first atmospheric oscillation maximum:
  longer baseline → larger energy → larger matter effect!

Long-baseline oscillations with NOvA

- muon neutrino beam produced at Fermilab
- far detector in Soudan mine (Ash River)

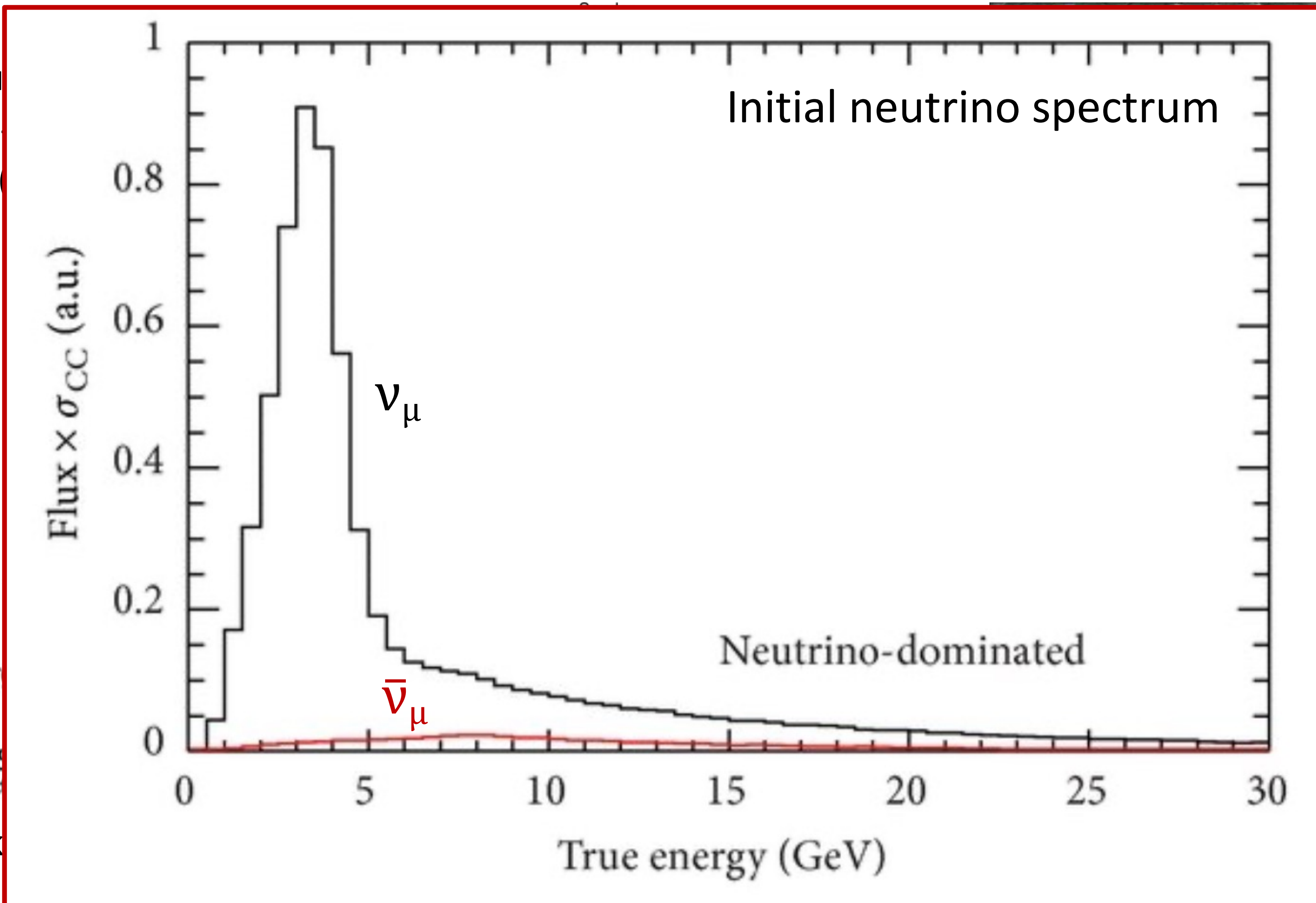


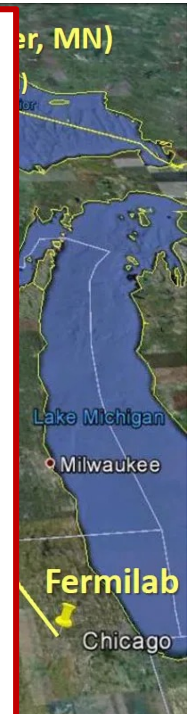


P=400kW

Long-baseline oscillations with NOvA

- muon produ
- far de mine (



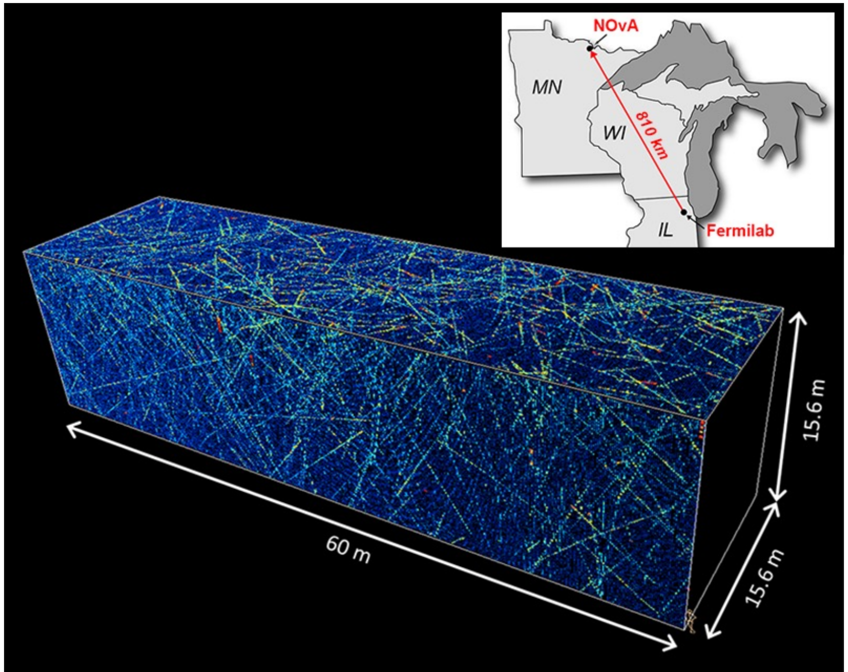


Tar

Protons fr
Main Injec

P=400k

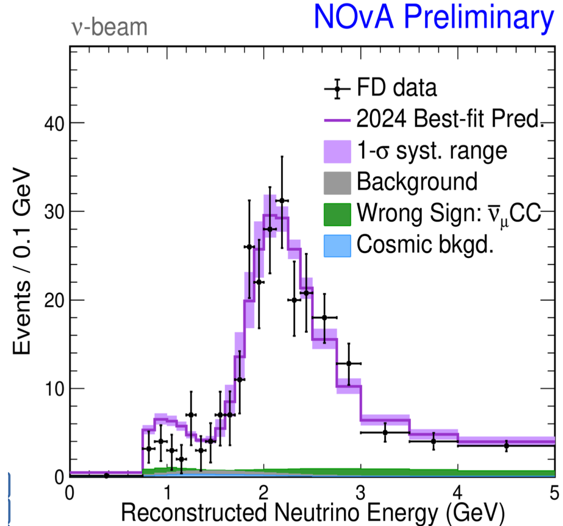
Results from NOvA Experiment



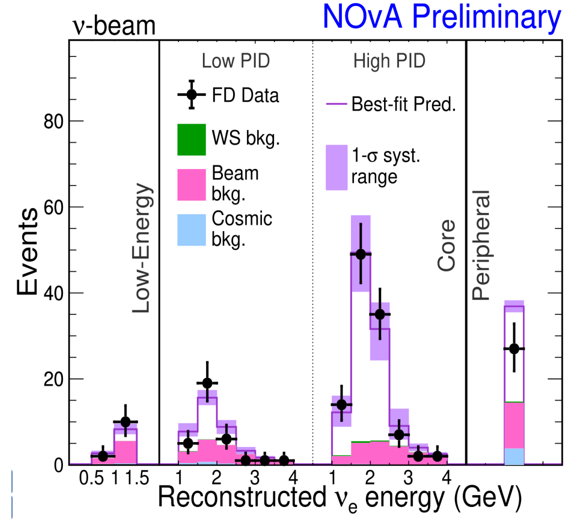
Experimental Layout

- baseline: 810km
- alignment: 16 mrad off-axis
- spectrum: (2±1) GeV
- beam power: 400kW
- detector: 14kt of segmented scintillator
- near detector for cross-sections and spectral comparison

$\nu_\mu \rightarrow \nu_\mu$ disappearance



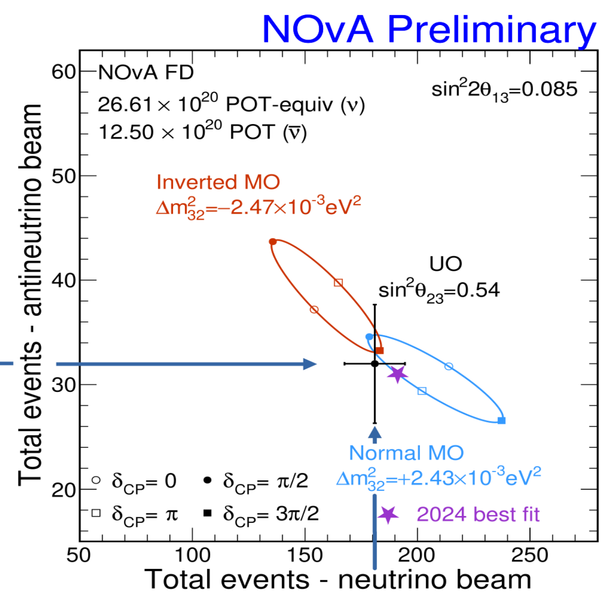
$\nu_\mu \rightarrow \nu_e$ appearance



comparison of neutrino and anti-neutrino modes

$\bar{\nu}_e$ appearance: 32 ev

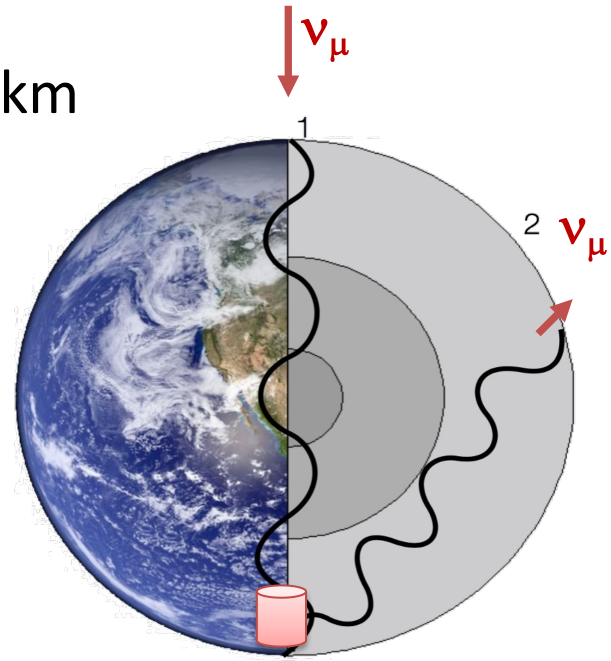
ν_e appearance: 181 ev

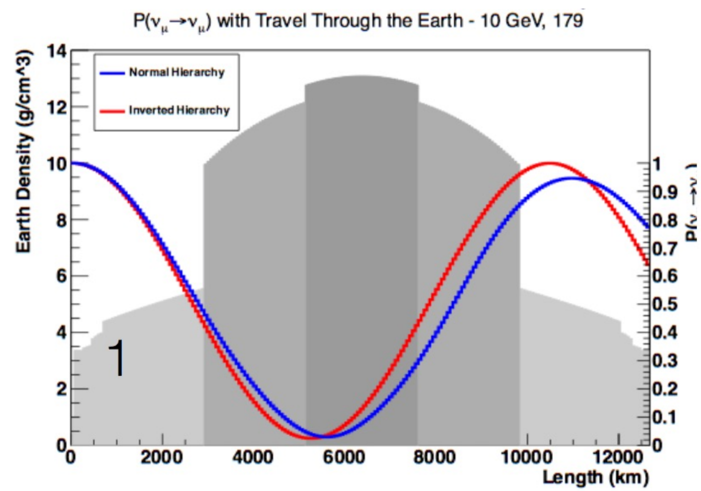


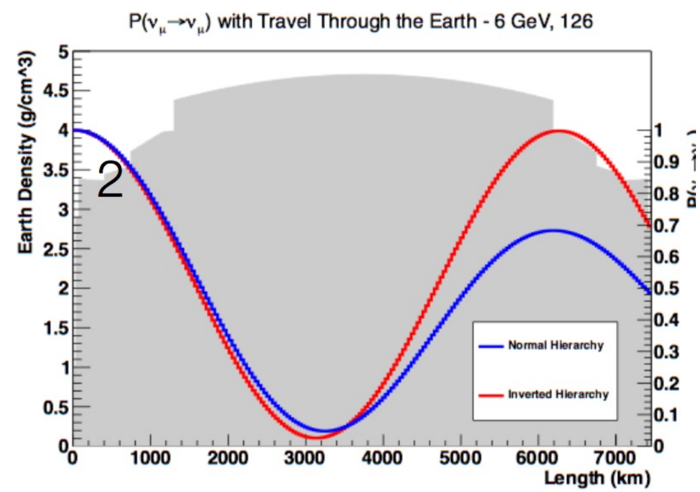
Matter effects and atmospheric neutrinos

Source: Atmospheric μ-neutrinos

- Energies: 2-20 GeV
- Baselines: 20-13000 km
- Matter potential: Earth core & mantle







MH signature

matter effects in

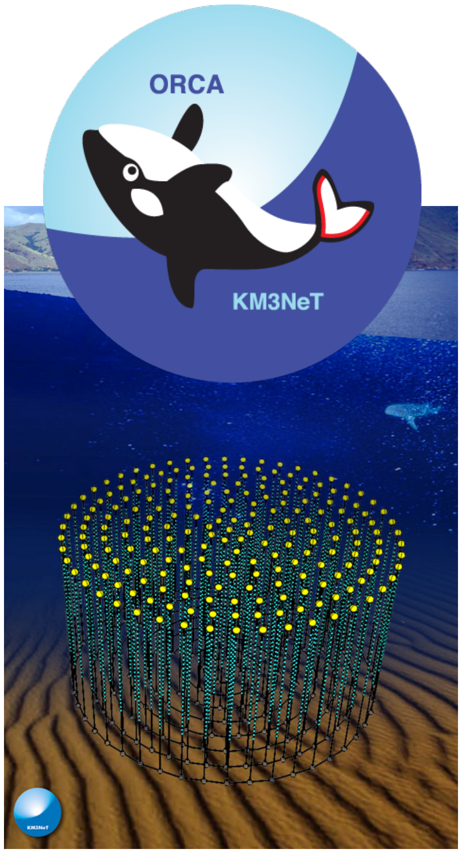
- $\nu_\mu \rightarrow \nu_\mu$ disappearance
- $\nu_\mu \rightarrow \nu_e$ appearance

Detector requirements

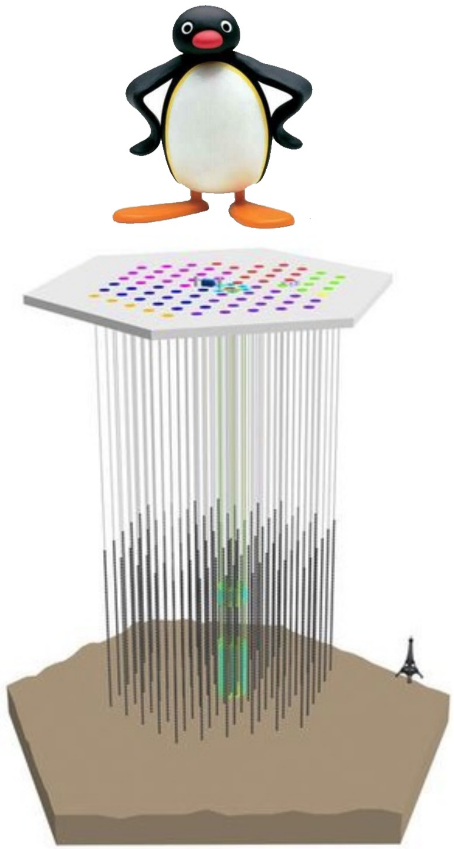
- relatively low energy threshold: O(1GeV)
- good angular resolution
- flavor identification
- nice to have: lepton charge ID ($\nu/\bar{\nu}$)

Upcoming Detectors

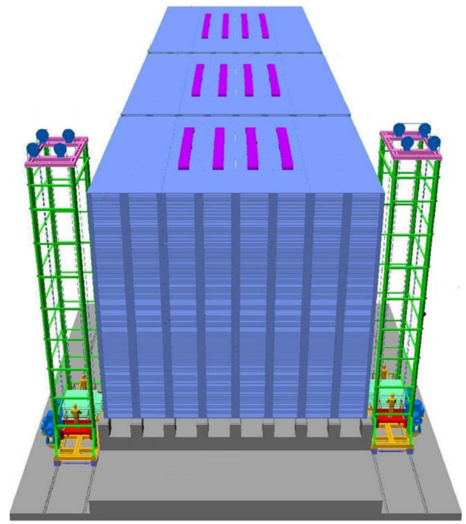
KM3Net ORCA (2025)



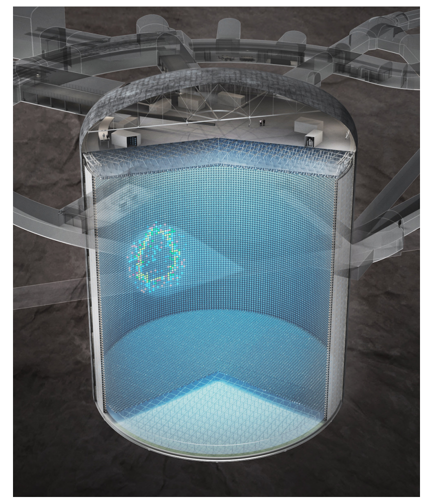
IceCube-Upgrade (2026)



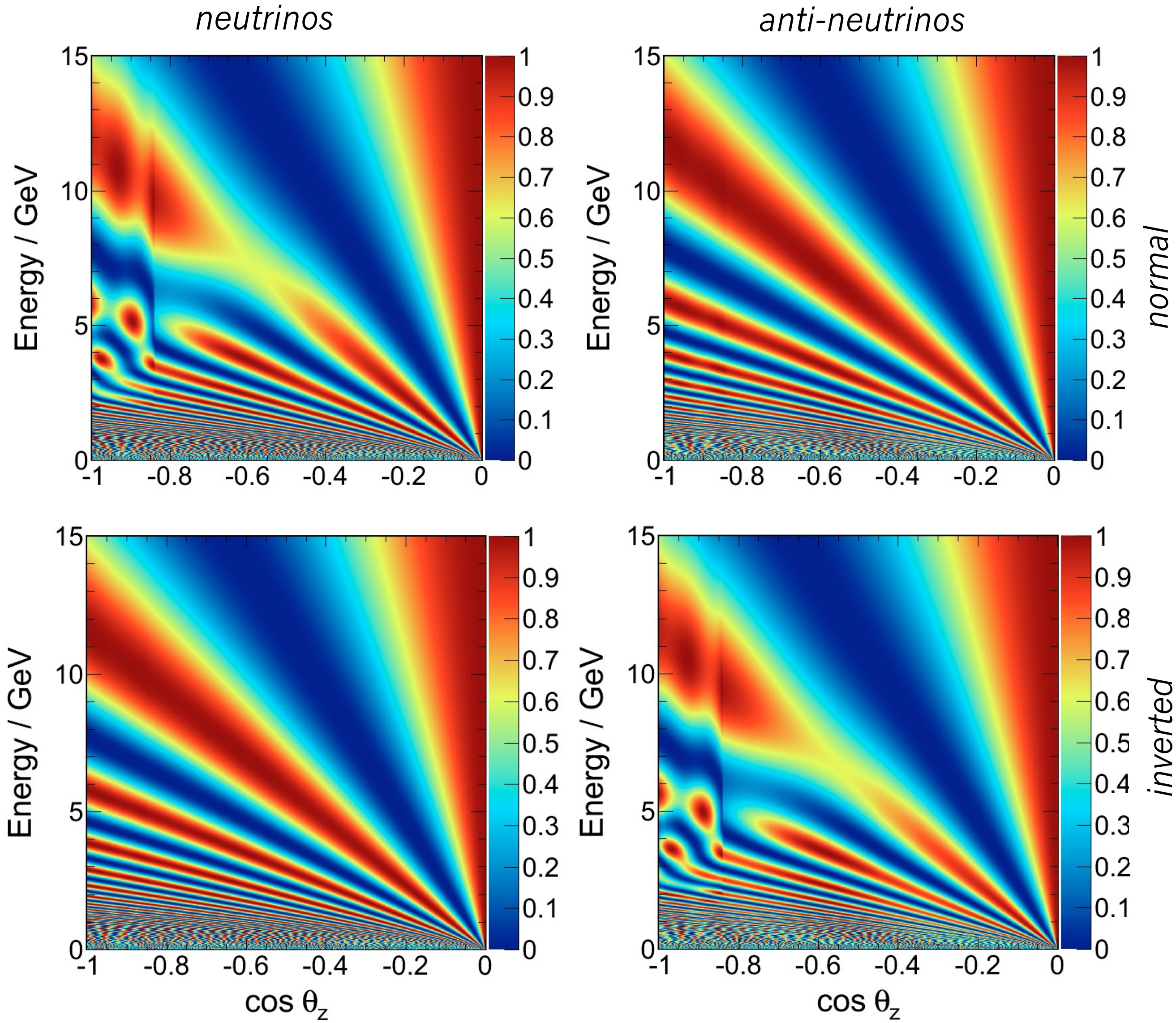
INO (??)



Hyper-Kamiokande (2027)



Matter effects in atmospheric ν oscillations



Signal

- matter effects inverted for NH and IH
- similar flux of ν and $\bar{\nu}$
- detector cannot separate ν and ν events! → combined signal
- **but:** different x-sections $\sigma(\nu N) : \sigma(\bar{\nu}N) \approx 2 : 1$

→ few % effect

Requirements

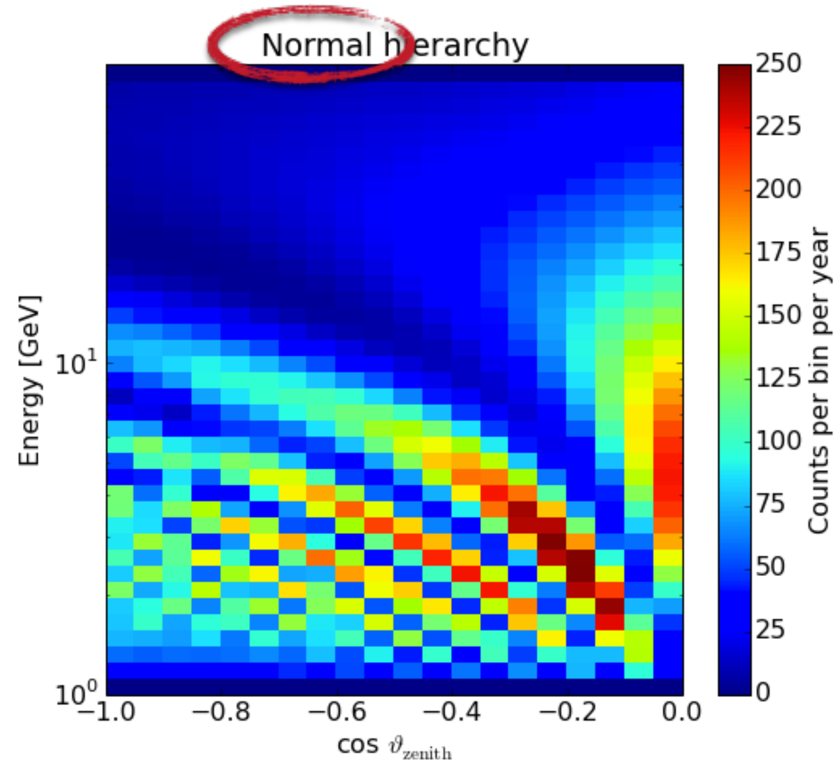
- high statistics
- very good control of systematic effects

plots by Sebastian Böser

Expected signal in PINGU

Event statistics

- ν_μ: 5.0x10^4 yr^{-1}
- ν_e: 3.8x10^4 yr^{-1}

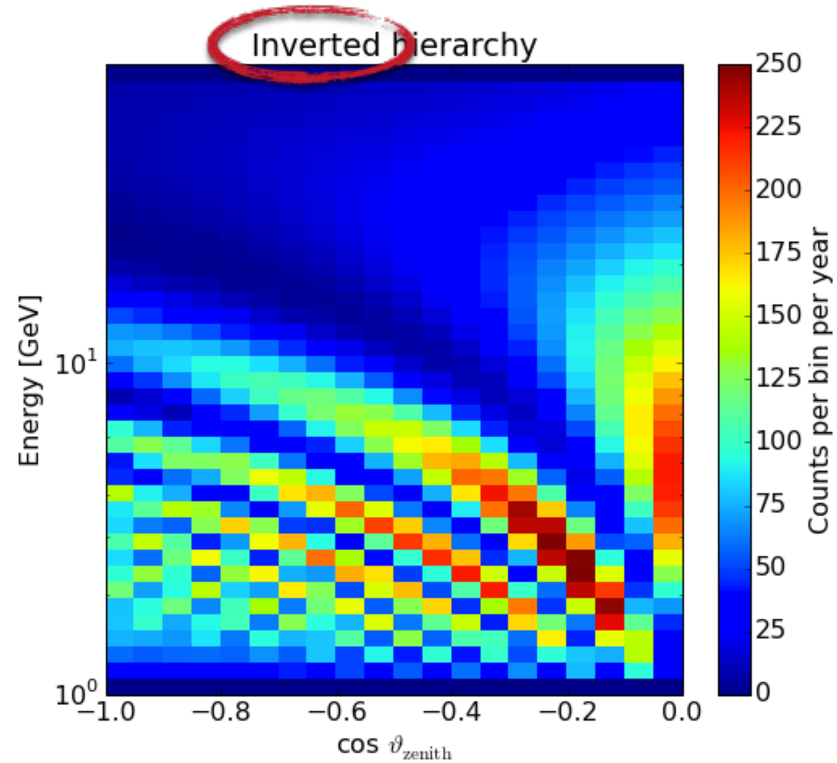


plots by Sebastian Böser

Expected signal in PINGU

Event statistics

- ν_μ: 5.0x10^4 yr^{-1}
- ν_e: 3.8x10^4 yr^{-1}



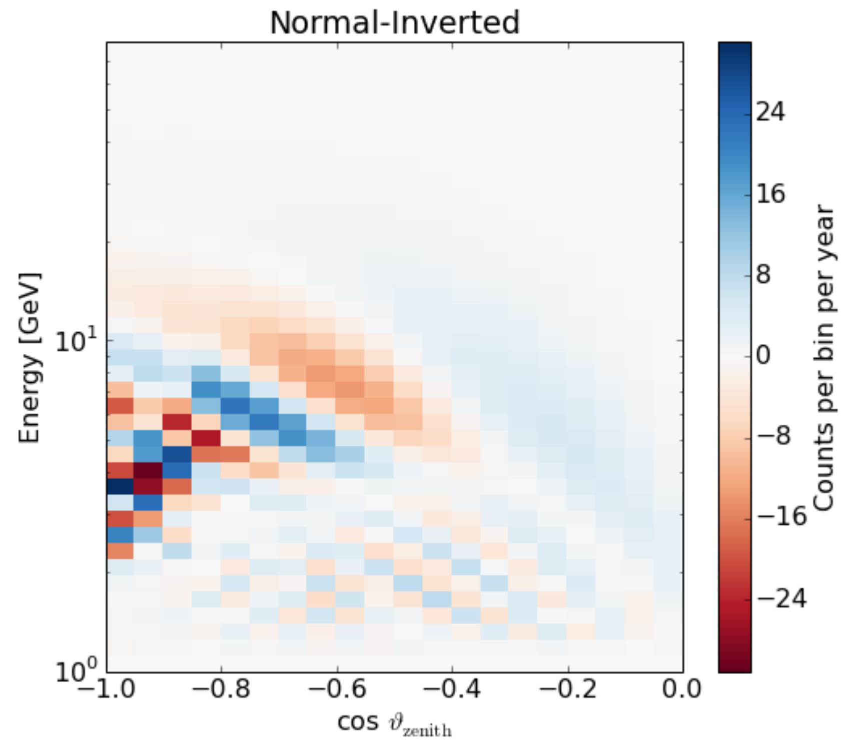
plots by Sebastian Böser

Expected signal in PINGU

Event statistics

- ν_μ: 5.0x10^4 yr^{-1}
- ν_e: 3.8x10^4 yr^{-1}

→ detectable difference



plots by Sebastian Böser

Expected signal in PINGU

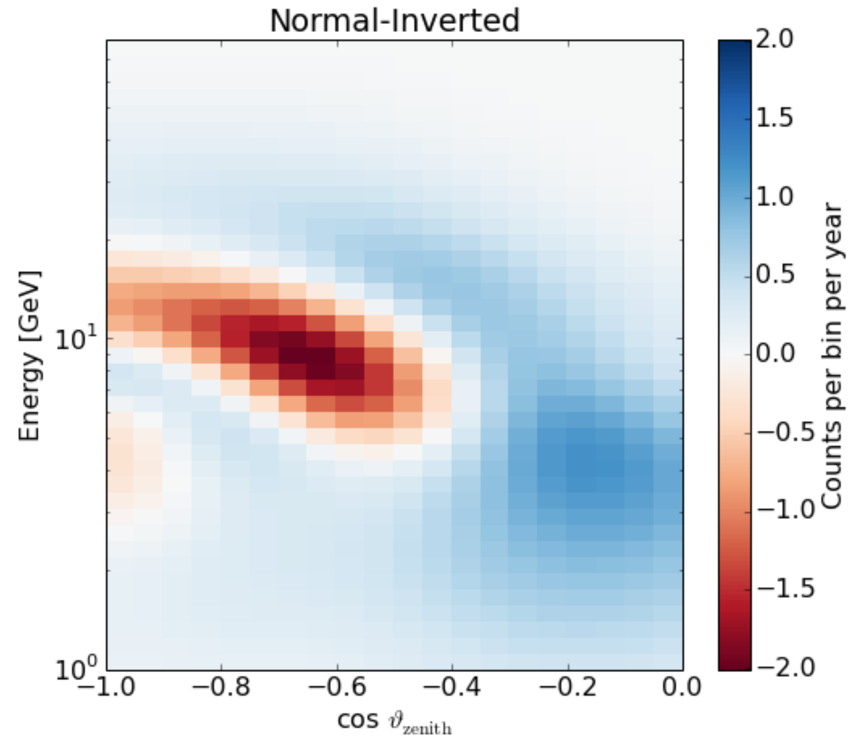
Event statistics

- ν_μ: 5.0x10^4 yr^{-1}
- ν_e: 3.8x10^4 yr^{-1}

→ detectable difference

Detector resolution

- energy resolution: ~20% above 10 GeV
- directional resolution improving with energy



plots by Sebastian Böser

Expected signal in PINGU

Event statistics

- ν_μ: $5.0 \times 10^4\ yr^{-1}$
- ν_e: $3.8 \times 10^4\ yr^{-1}$

→ detectable difference

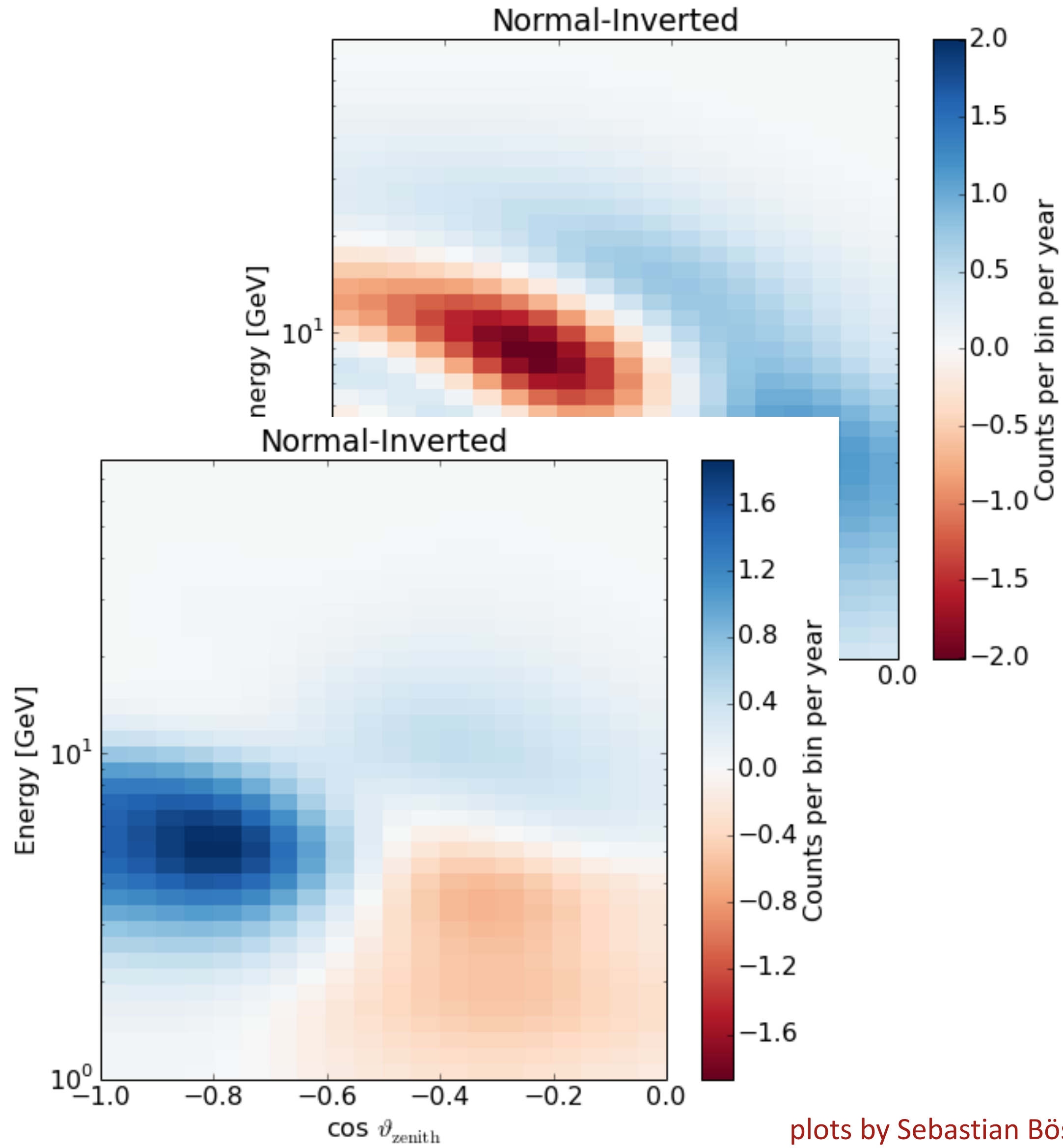
Detector resolution

- energy resolution: ~20% above 10 GeV
- directional resolution improving with energy

Particle identification

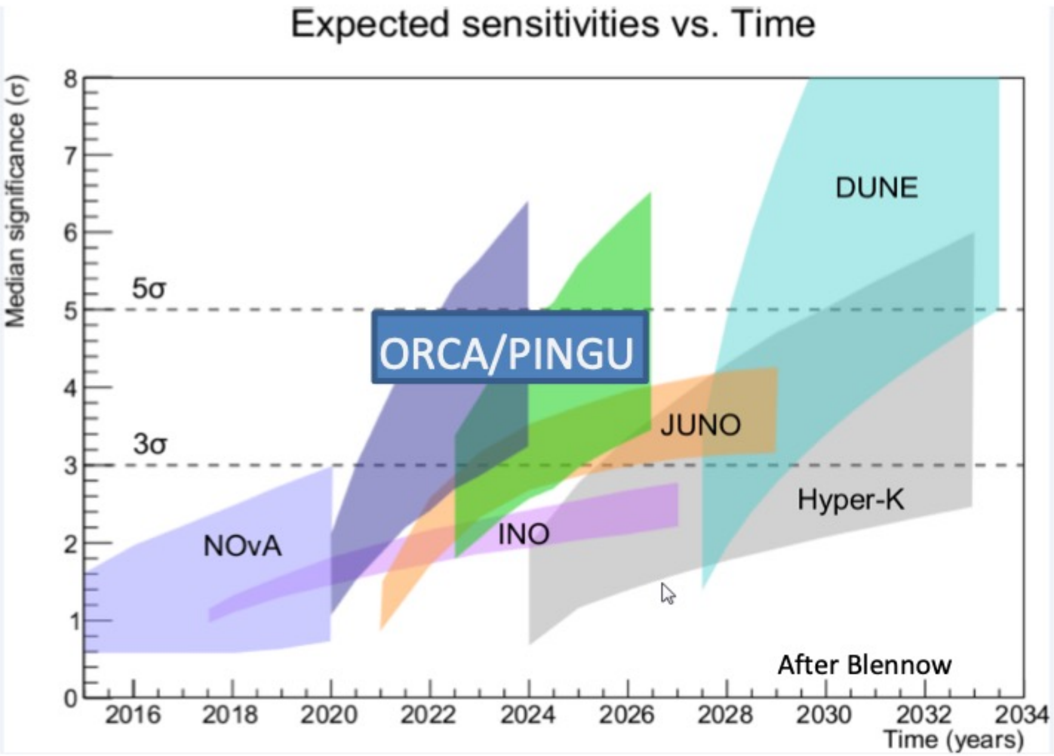
- ν_μ (CC): tracks
- ν_e (CC) + ν_x (NC): cascades

→ distinction of event types



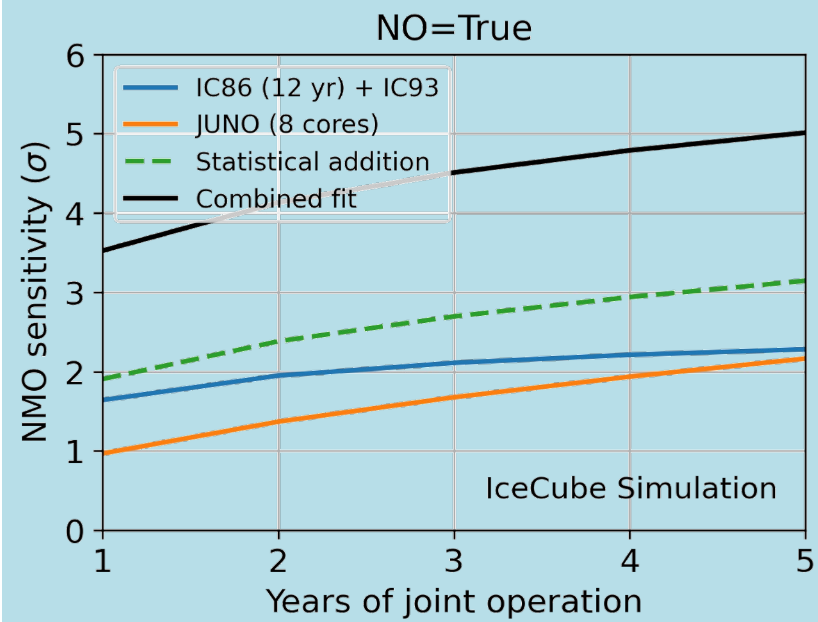
plots by Sebastian Böser

Global NMO sensitivity vs. time



NMO sensitivity depends on

- oscillation parameters, e.g. δ_{CP} for DUNE, θ_{23} for atm. exp.
- detector performance, e.g. energy resolution for JUNO



Note: there is a strong synergy effect between JUNO and any kind of NMO measurement based on matter effects

→ combined sensitivity quickly reaches 5σ discovery range

LECTURE QUIZ

Question 5

What detector technology is used in the NOvA Far Detector?

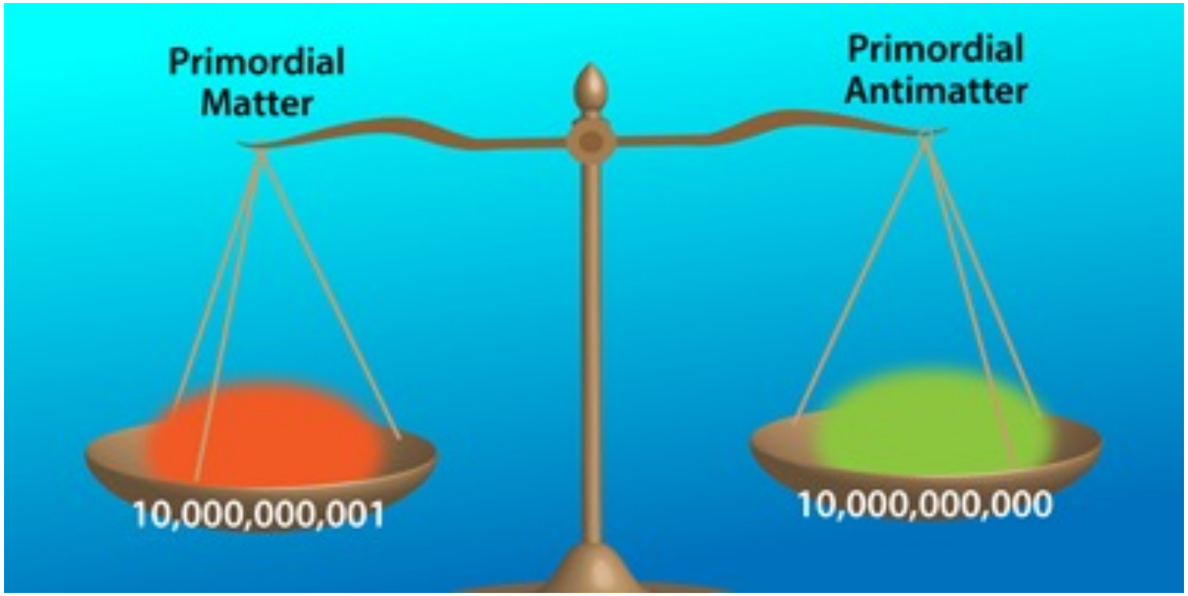
C : Water Cherenkov Detector

D : Liquid Argon Detector

E : Liquid Scintillator Detector

CP violation

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



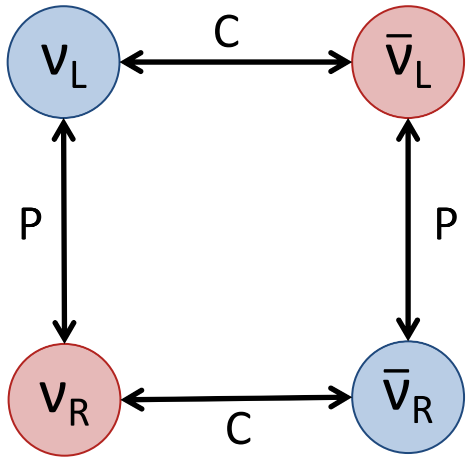
→ matter access is tiny, but CP violation in the quark sector is not sufficient

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

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!

$\nu_\mu \rightarrow \nu_e$ oscillation probability: δ_{CP} vs. NMO

Oscillation probability for ν_e appearance
in a ν_μ neutrino beam:

effects of weak matter potential

atmospheric oscillations → *T2K*

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

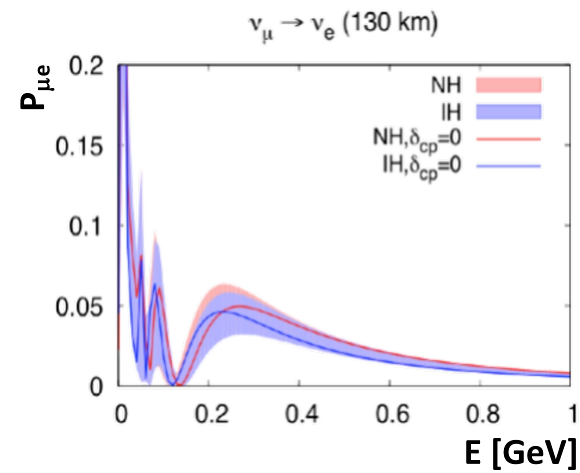
solar oscillations

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

leptonic CP violation

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

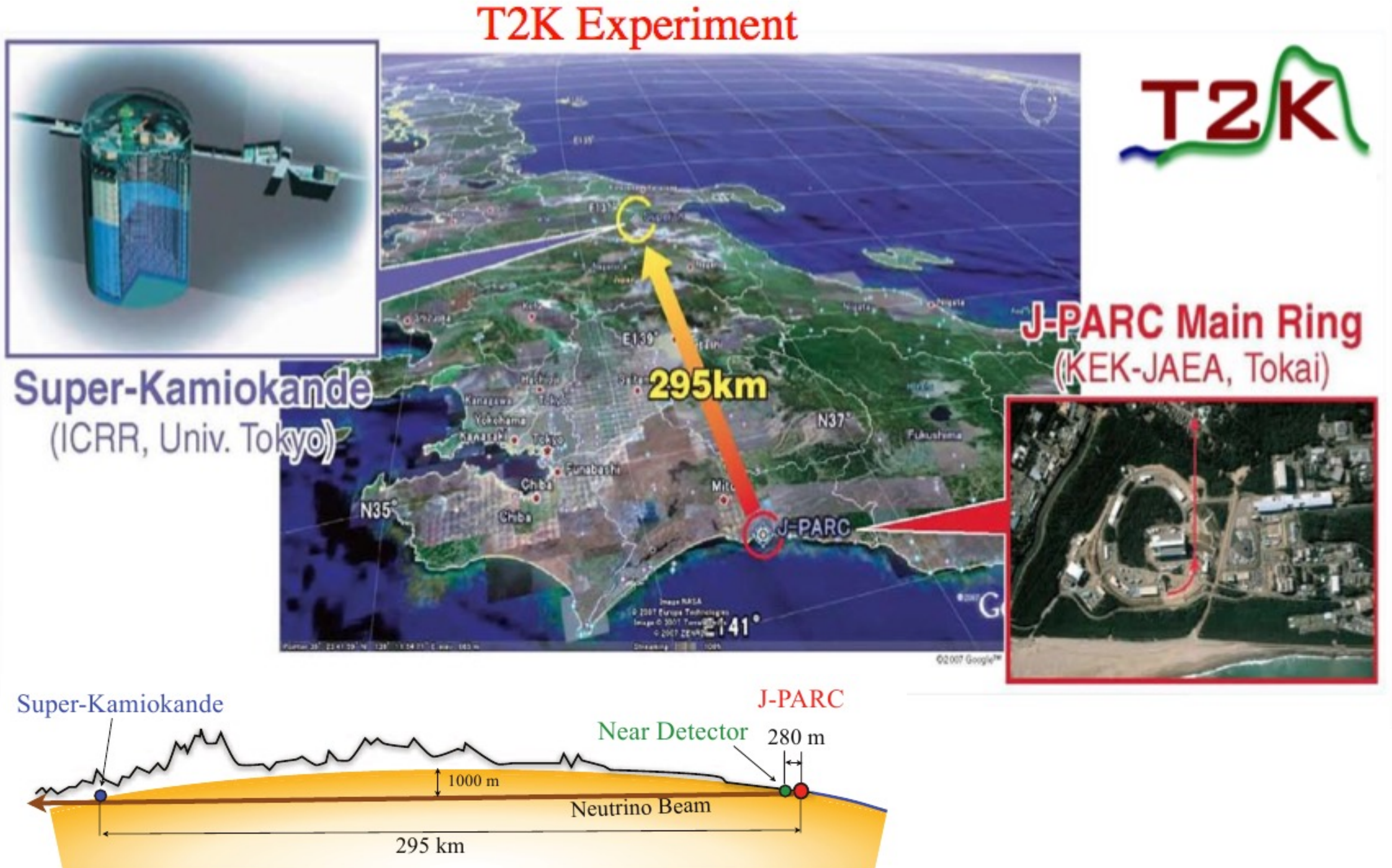
neutrino-ant **P($\nu_\mu \rightarrow \nu_e$) for 130 km** *m*



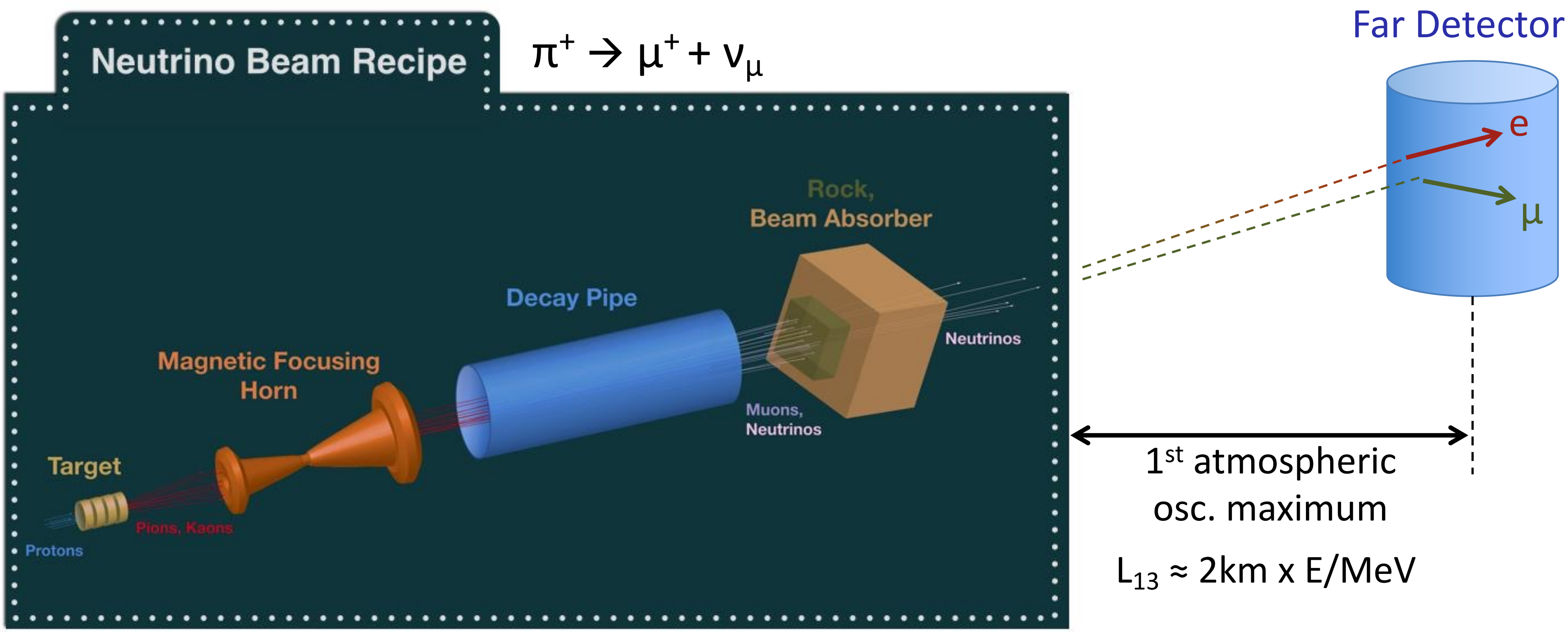
→ matter effects and δ_{CP} both lead to differences in neutrino/antineutrino oscillation probabilities

→ δ_{CP} best measured over short baselines where impact of matter effects is small!

T2K: Tokai-to-Kamioka Experiment



Long-baseline ν_μ beam experiments



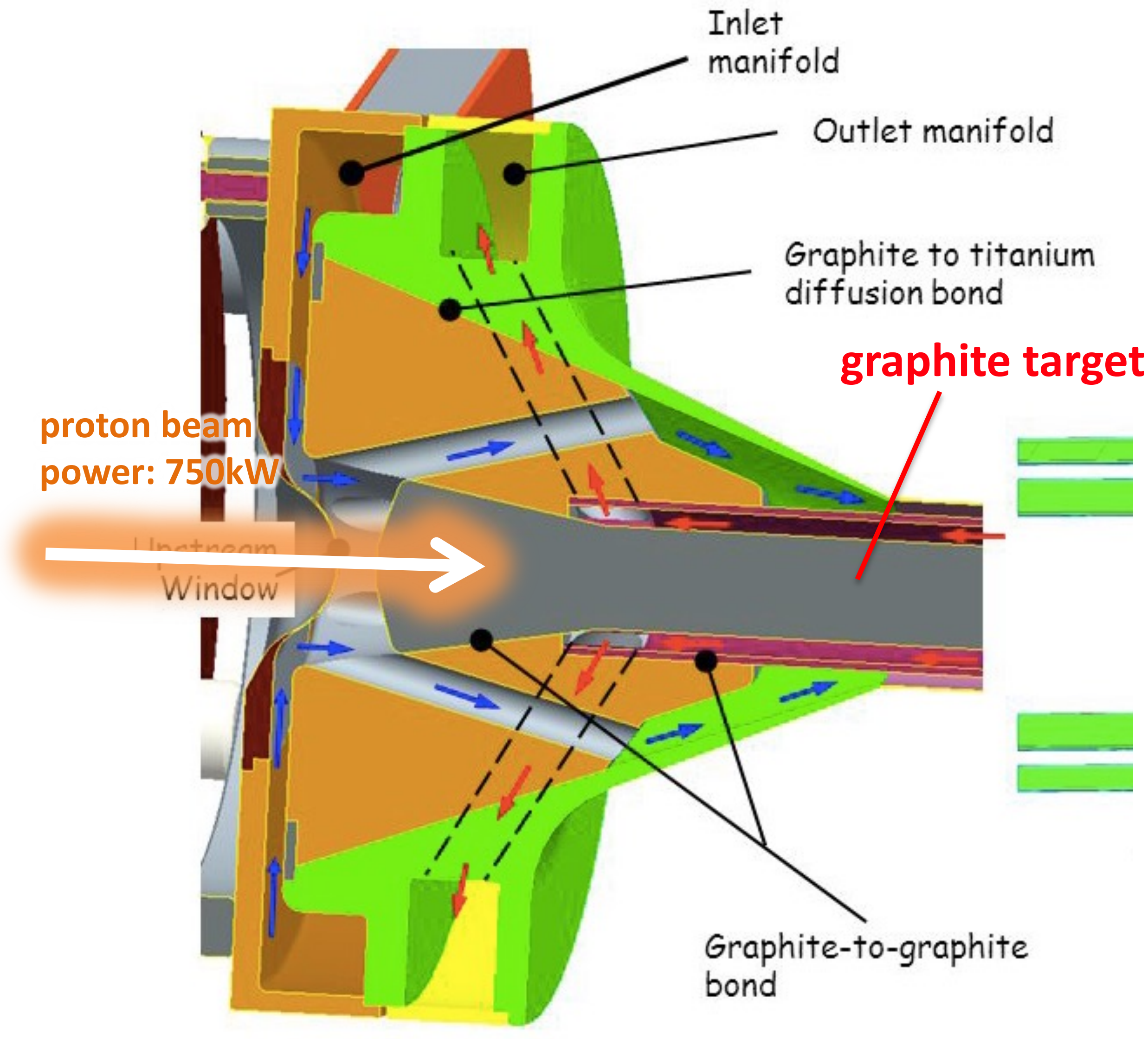
Search modes:

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

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

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

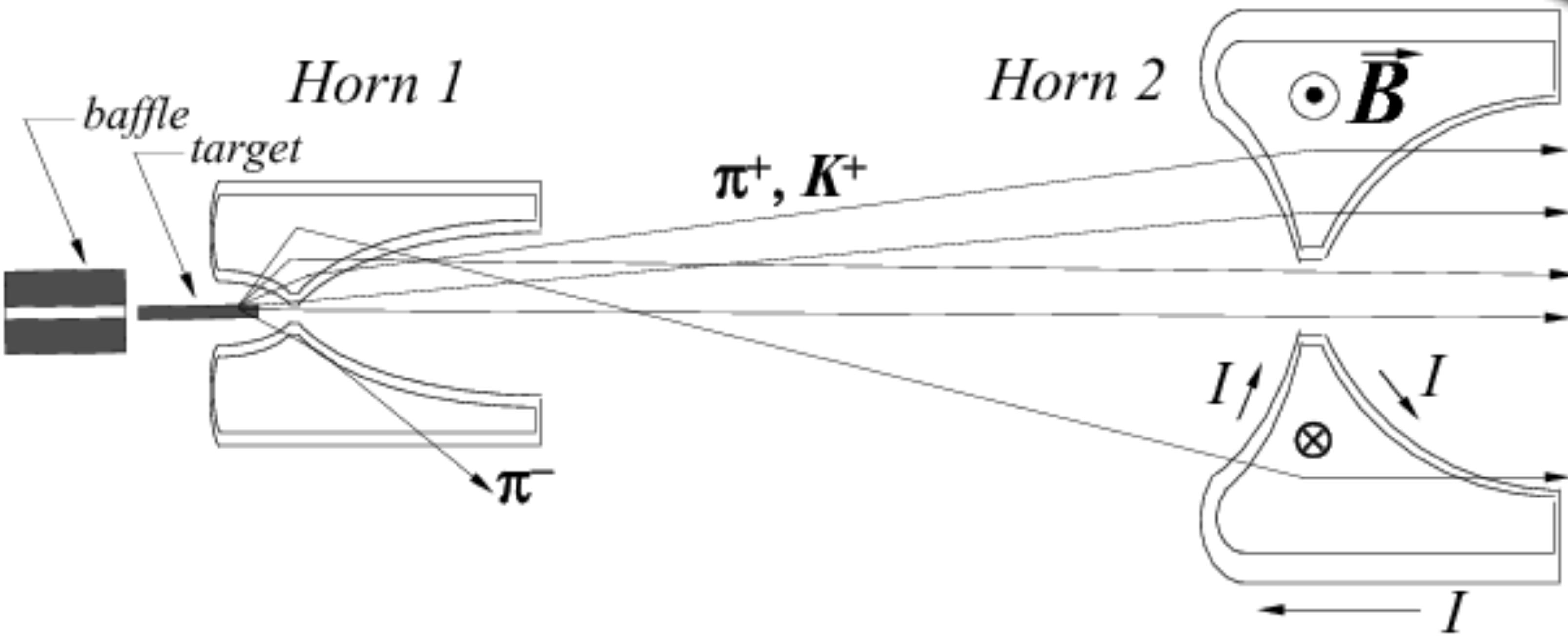
Neutrino target



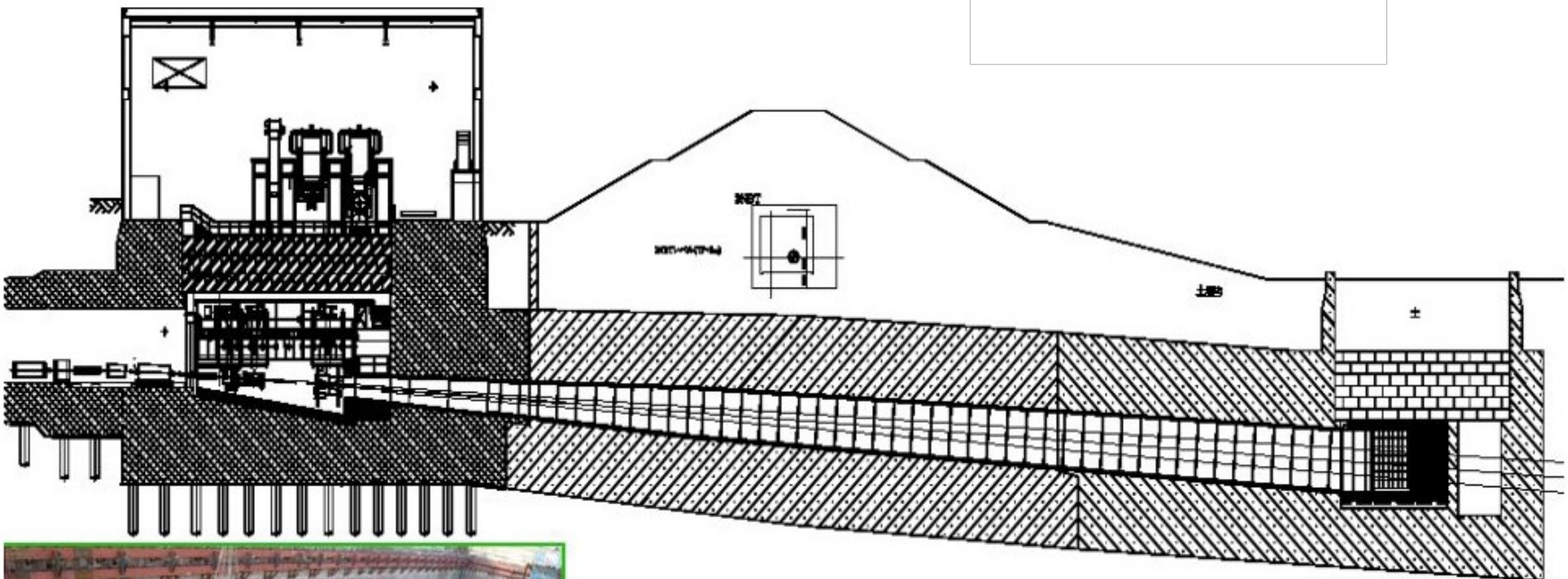
- production of charged pions (and kaons) by interactions of protons on carbon
- light material favors higher-energy pions
- pions are beamed in forward direction
- beams are typically pulsed → BG reduction

Focussing horns

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



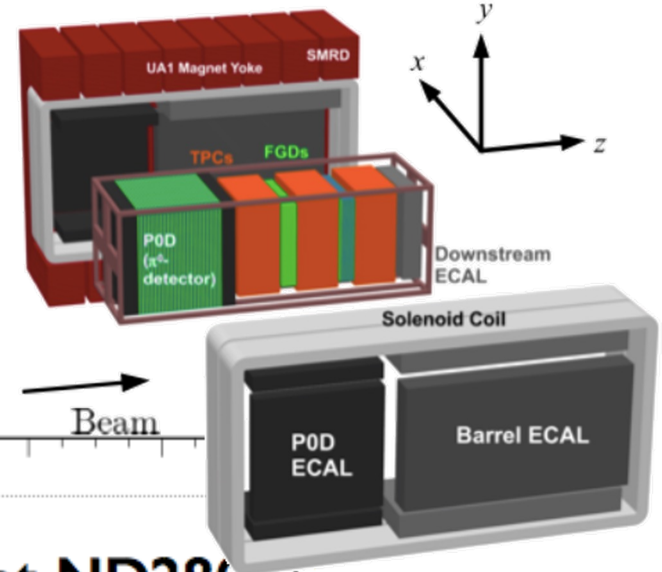
Inclined decay pipe

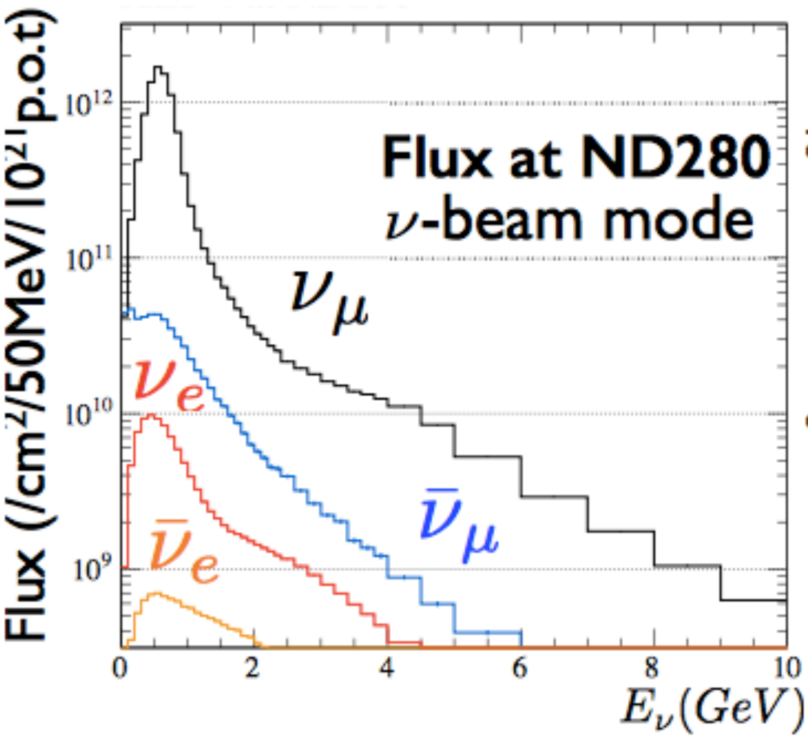


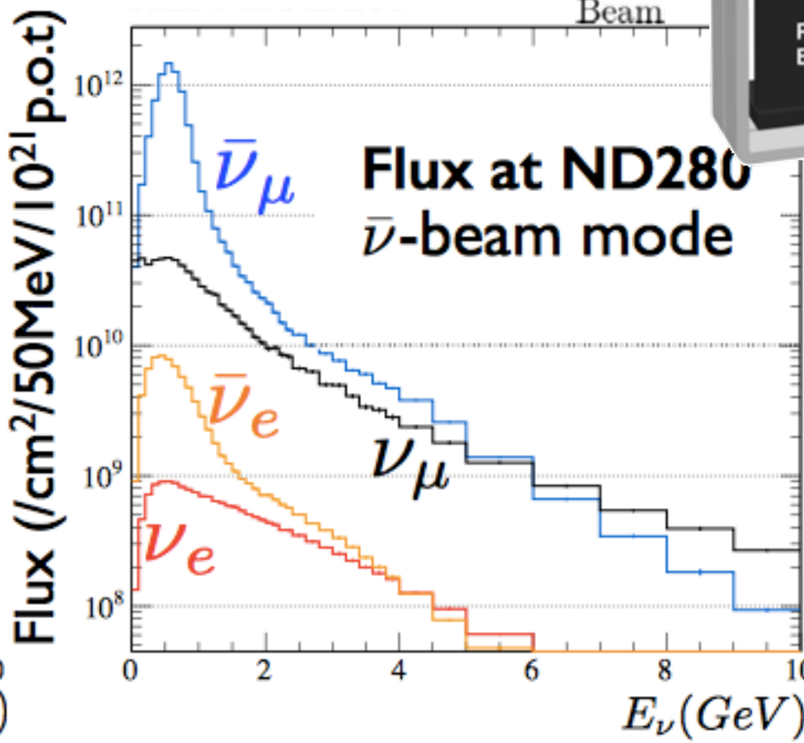
- evacuated pipe for $\pi^+ \rightarrow \mu^+ + \nu_\mu$ *(neutrino mode)*
- try to balance pion and muon decay not wanted: $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
- tunnel has to be inclined to compensate curvature of Earth surface → expensive!!

T2K Near Detectors for ν spectrum

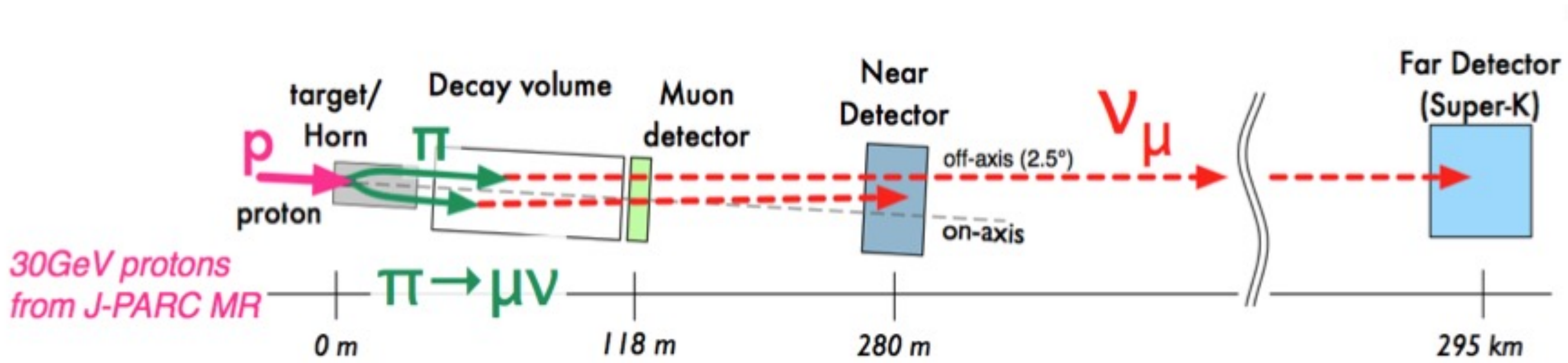
- some intrinsic beam contamination with ν_e flavor
- polarity of beam horn switched to obtain $\bar{\nu}_\mu$-beam
- near detector (ND280) to measure beam direction and composition, cross-sections ... (reduce systematics)

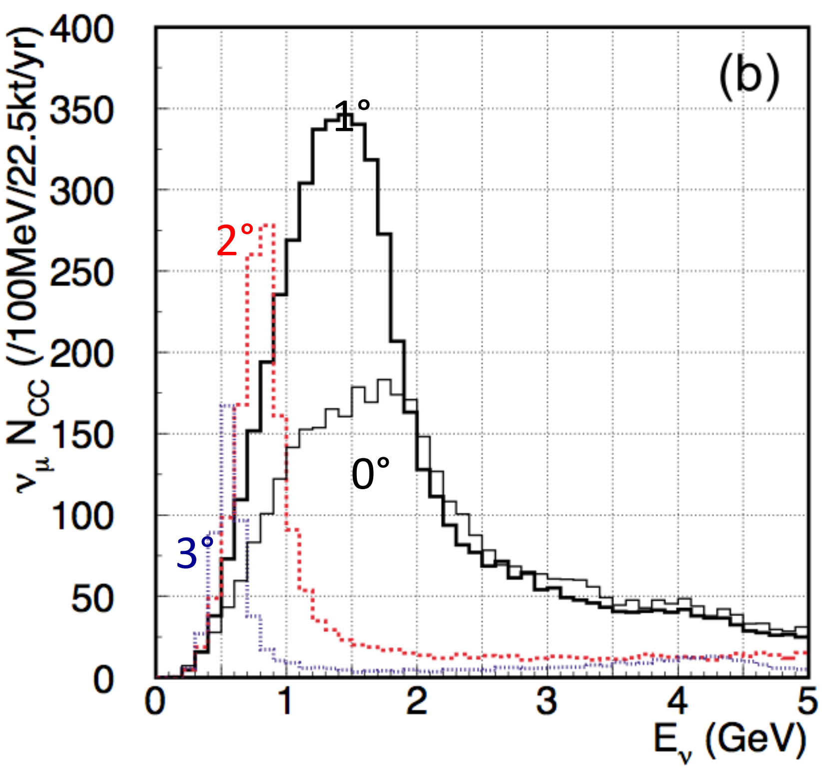






T2K: Off-axis beam





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

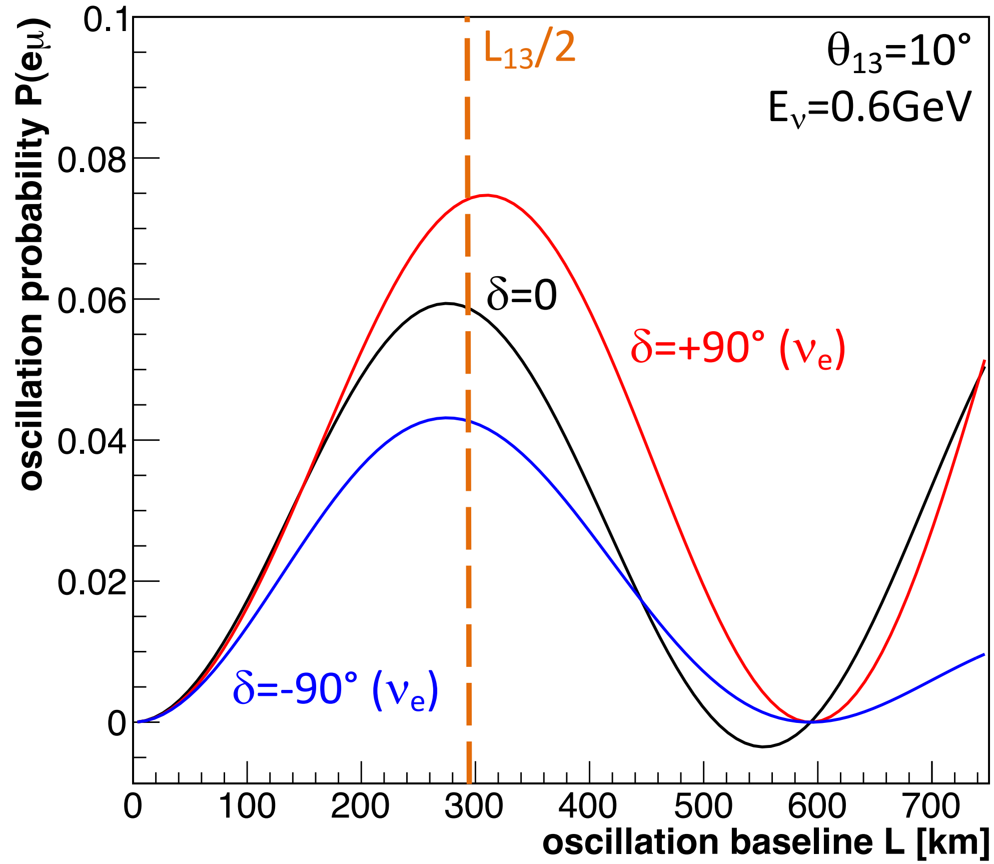
Short-baseline ν_e appearance probability

Effective oscillation probability

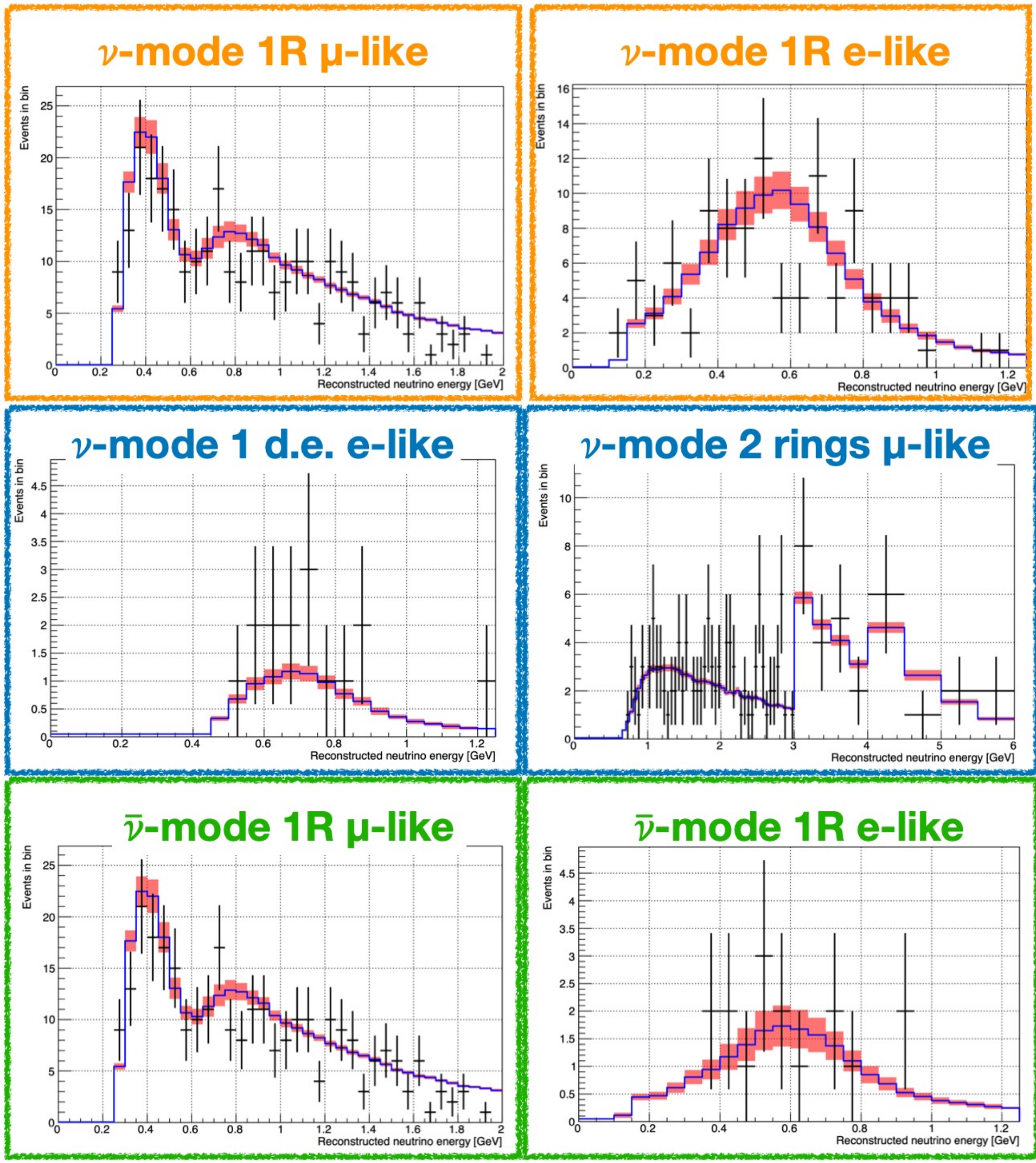
$$P_{\mu e} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$
$$+\, h.o.f.(\theta_{ij}, \Delta m^2_{ij})\cdot\cos(\mp\delta)$$

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

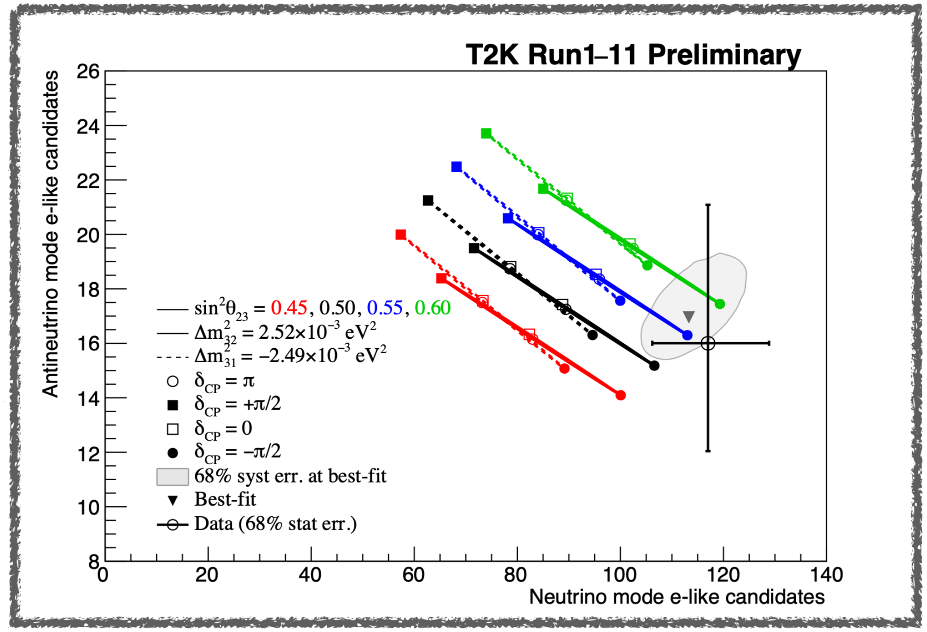
→ neutrinos and antineutrino shifts are inverted

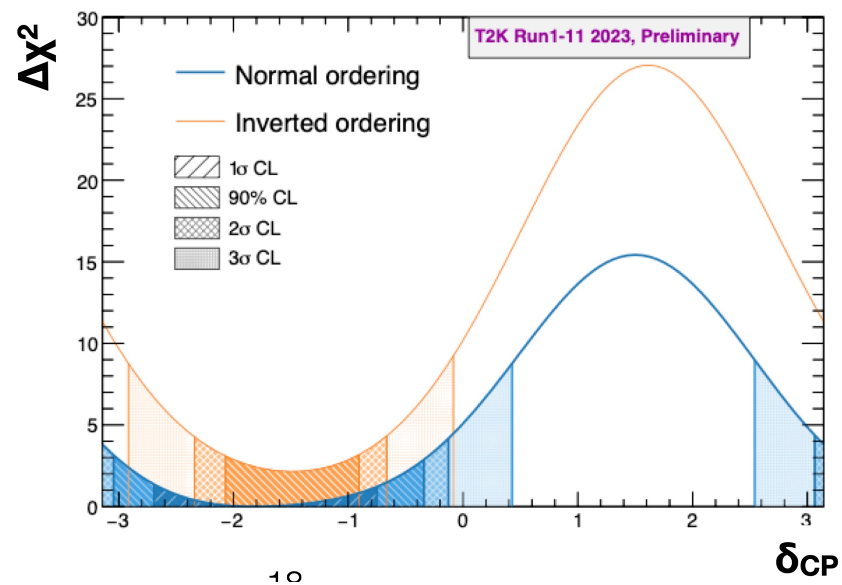


T2K $\nu_\mu \rightarrow \nu_e$ appearance results for δ_{CP}



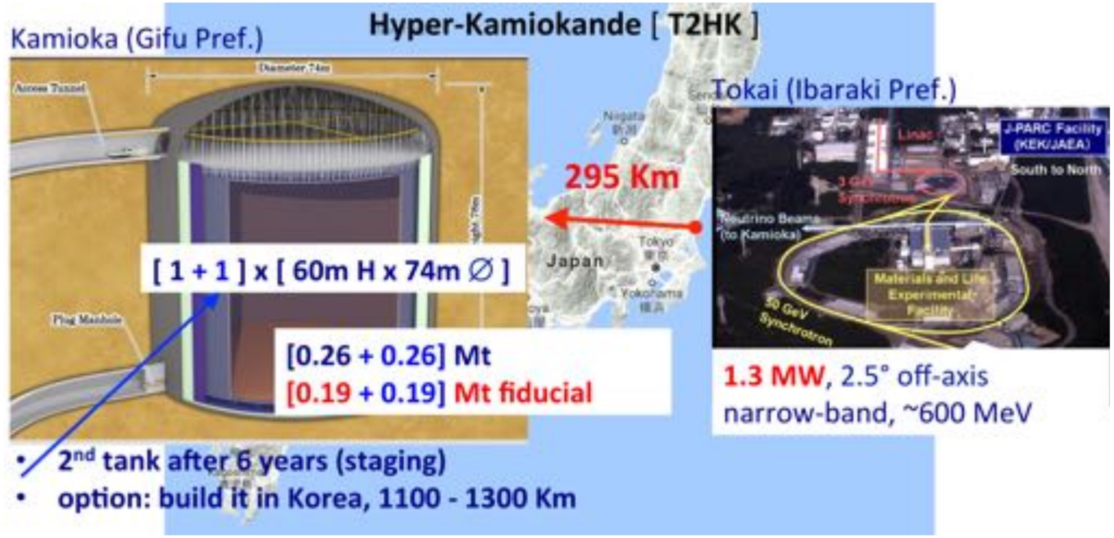
Neutrino24

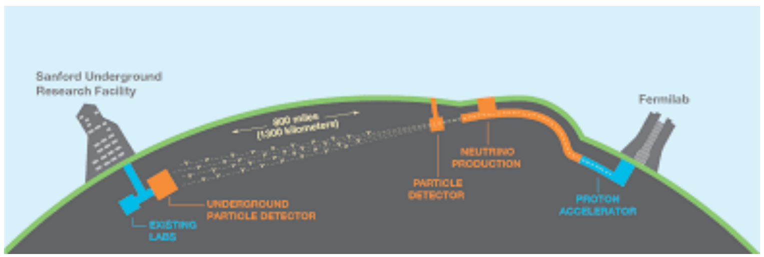


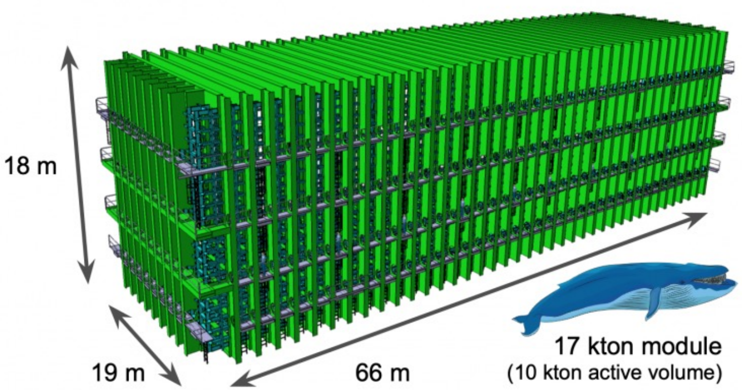


Future experiments for CP-phase

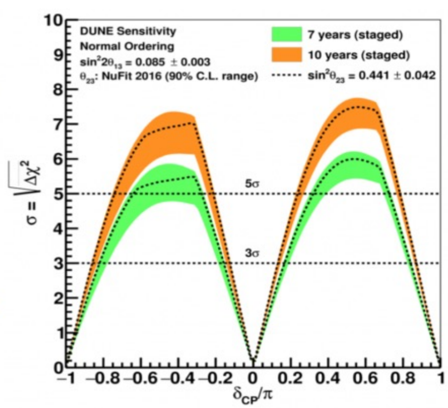
- DUNE: Fermilab → Homestake (1300 km)
- T2HK: Tokai → Kamioka (285 km)
- ESSνSB: Lund → ? (360/450 km)



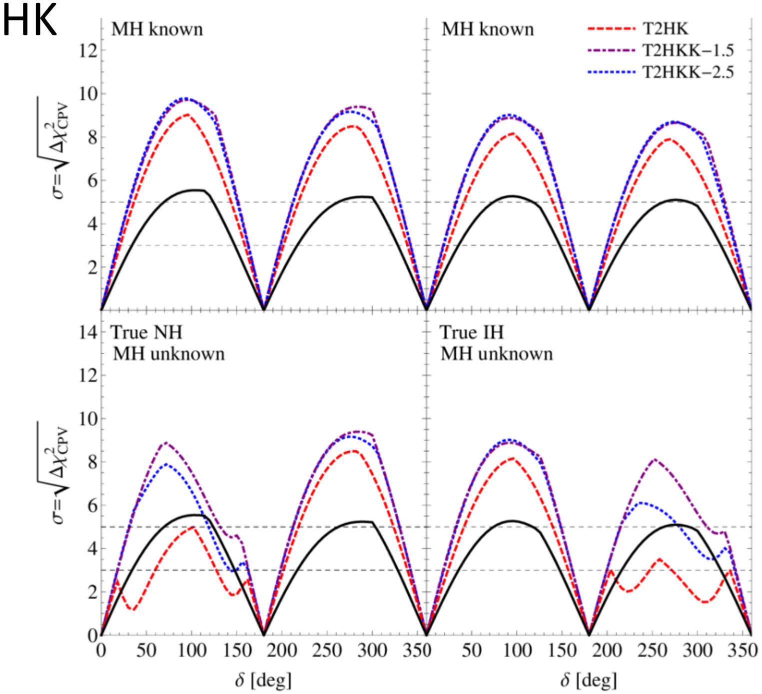




DUNE



T2HK



LECTURE QUIZ

Question 6

What device is used in the T2K beam?

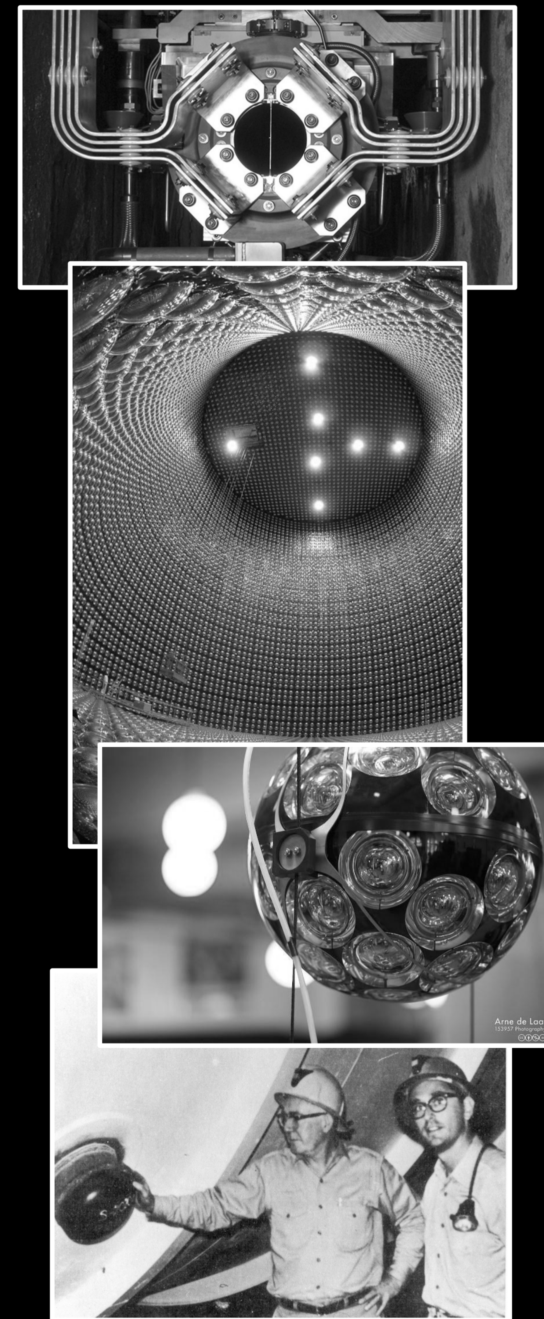
Q : Berillium target

R : Magnetic horn

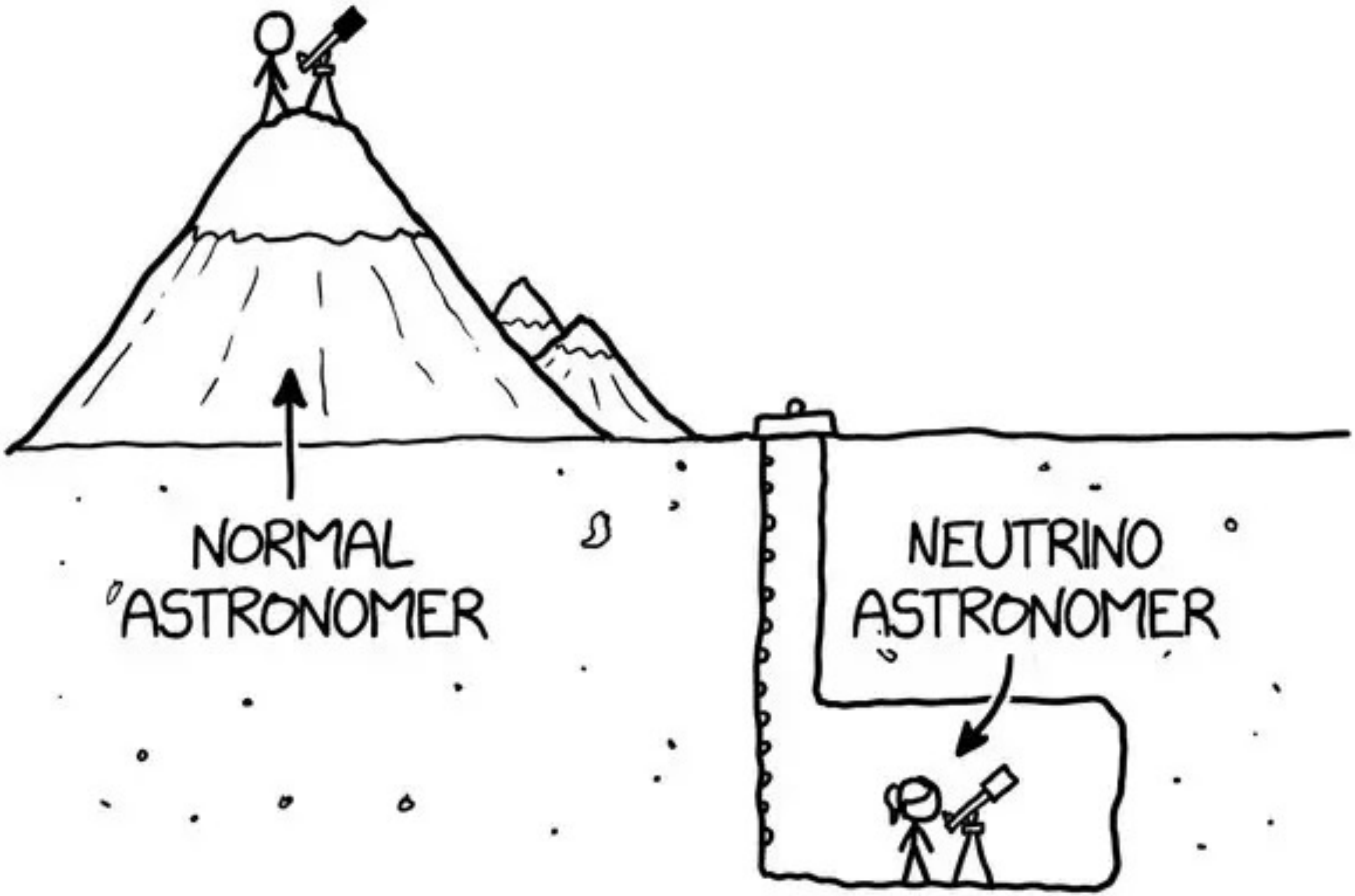
S : Neutrino lense

Summary

- The discovery of neutrino flavor oscillations is the 1st evidence of physics beyond the original Standard Model.
- Historically, natural neutrino sources (e.g. atmospheric, solar ν's) have played a large role in their exploration. Precision experiments often use reactors or beams.
- Basic oscillation parameters (mixing angles, mass splittings) have been measured on few %-level but important ingredients are still missing.
- Upcoming oscillation experiments investigate the neutrino mass ordering (JUNO, ORCA, IC-Upgrade) and CP phase δ_{CP} (T2HK, NovA, DUNE)
- Note: Complementary searches for non-standard oscillations (eV sterile neutrinos) are on-going.



Thanks for your attention!



Questions? Or is it time for _ _ _ _ _ _?