Neutrino Experiments

(Sorry, only a small fraction of experiments)

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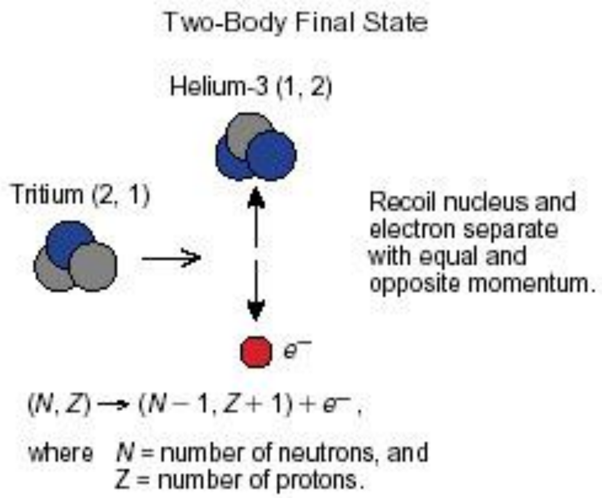
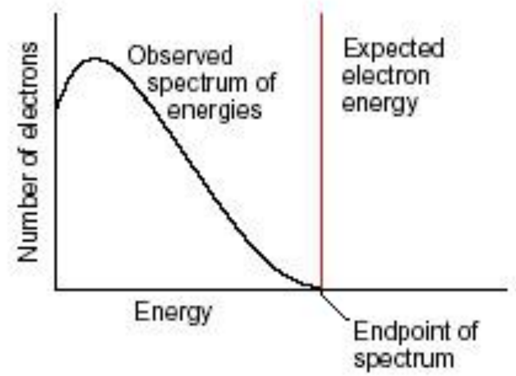
Hypothesis

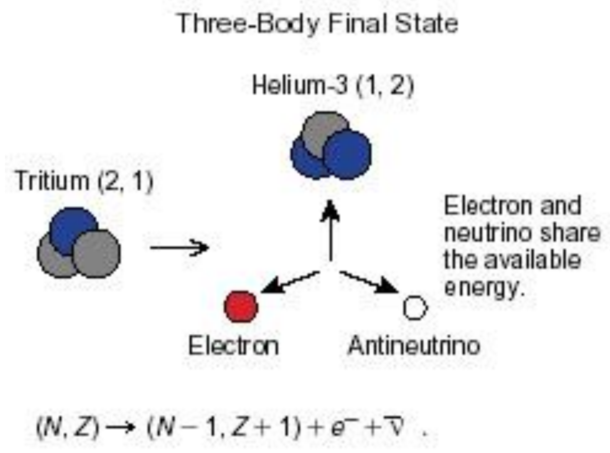
In 1930, Pauli postulated a particle to solve the crisis of conservation of energy in β decay. It should has tiny mass, neutral, barely interact with matter.

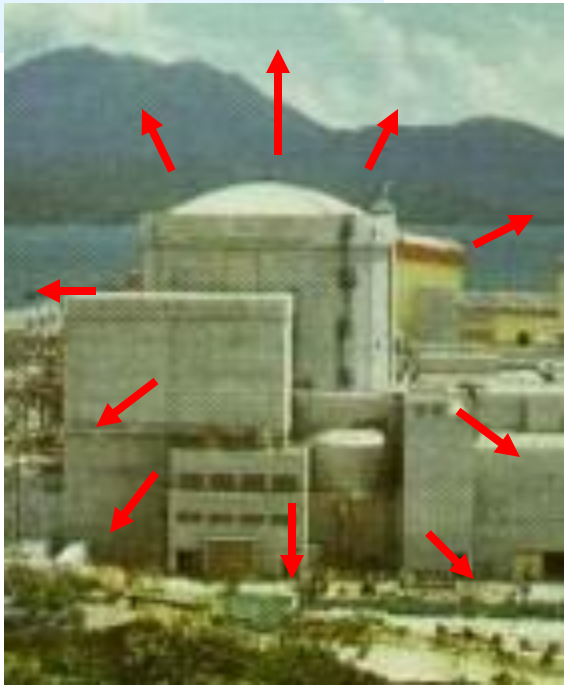
Wolfgang Pauli

"I have done a terrible thing. I have postulated a particle that cannot be detected." -- Puali



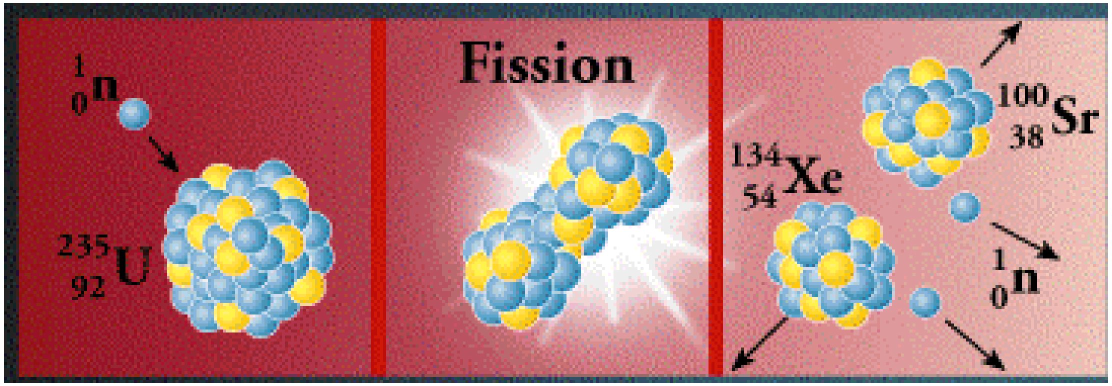






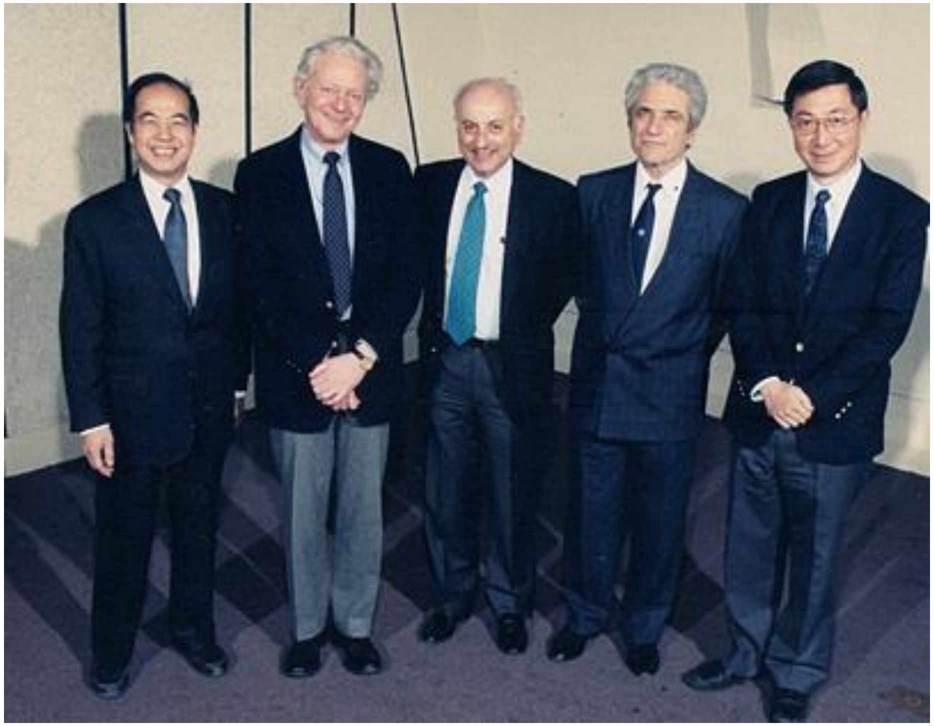
Discovery of Neutrino

- 26 years later, Cowan and Reines discovered neutrinos using reactor. (Nobel Prize in 1995)
- Each fission releases 6 electron antineutrinos. Six reactors in Daya Bay (17.4GW) release 3.5×10^{21} neutrinos per second.

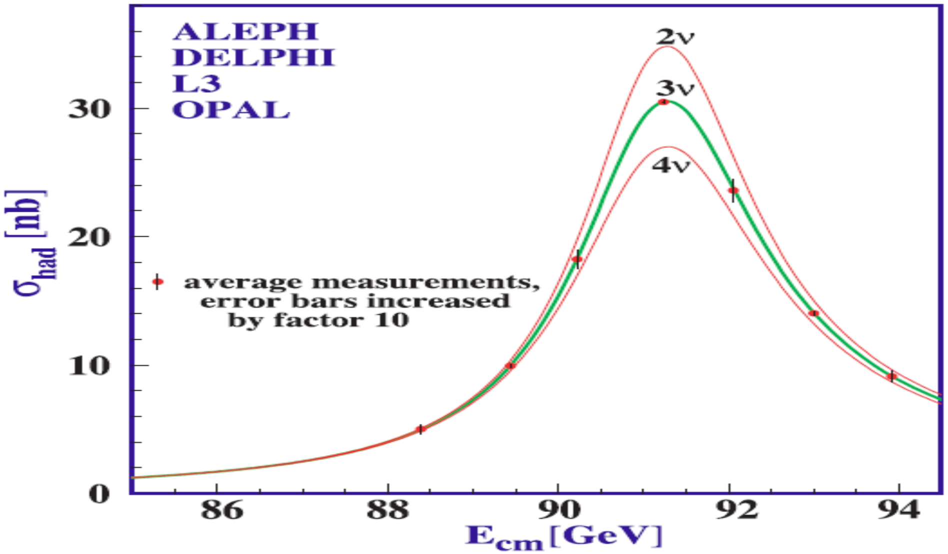


Discovery of the 2^{nd} and 3^{rd} neutrinos

- **Evidence for a second type of neutrino came in 1962, Leon Lederman, Jack Steinberger, and Melvin Schwartz (Nobel Prize in 1988)**

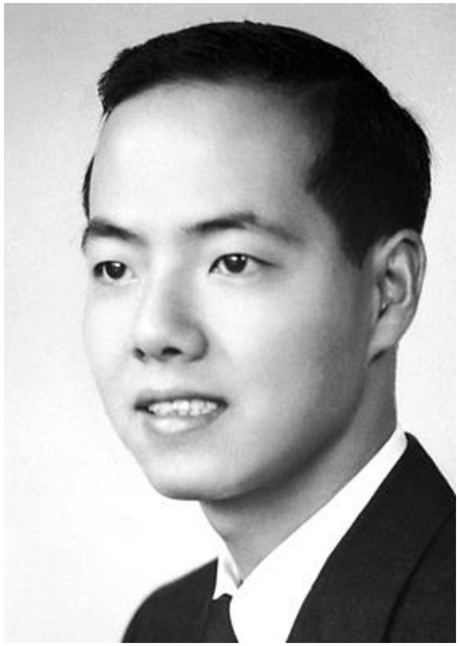
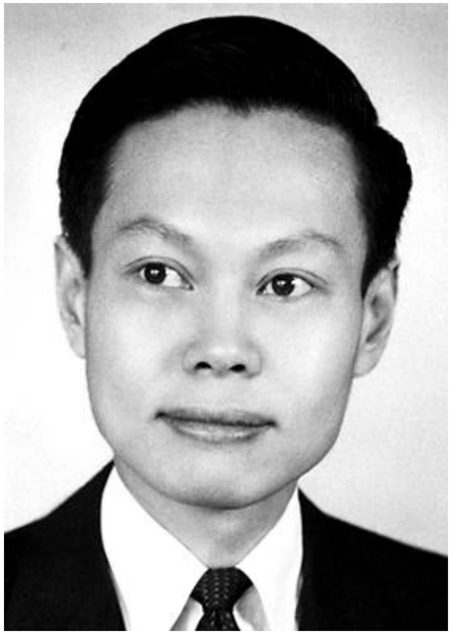


- **In 1989, experiments at CERN proved that there exists exactly 3 neutrino**



- **In 2000, DONUT at Fermilab found the τ neutrino.**

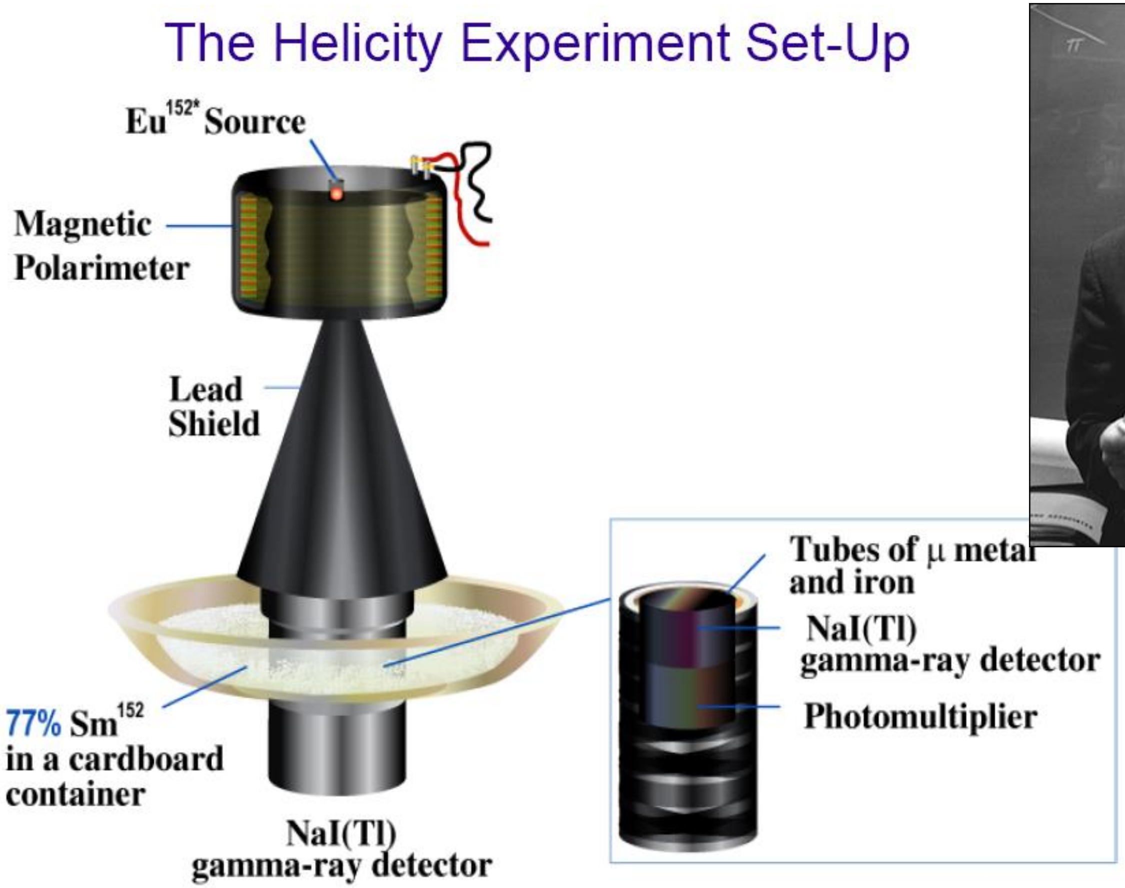
Does Neutrino has mass?

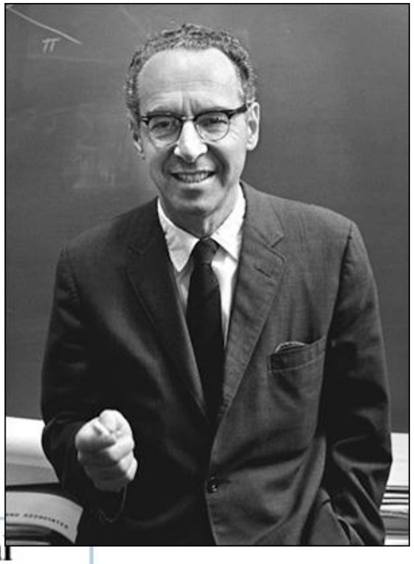



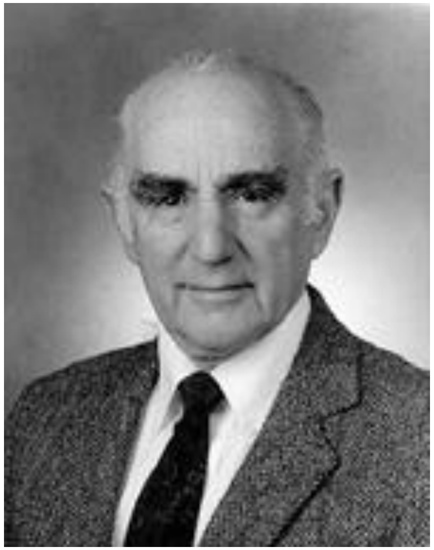

- **In 1956, T.D. Lee and C.N. Yang proposed Parity violation in weak interaction.**
- **In 1957, C.S. Wu proved it experimentally. Maximum violation.**
- **Lee and Yang: V-A theory of weak interaction, inherited by Standard Model**
- **Maximum violation → Only left-handed neutrino exist → neutrino is massless in Standard Model**

Left-handed Neutrino

- **In 1958, Goldhaber-Grodzins-Sunyar experiment proved the neutrino is left-handed.**



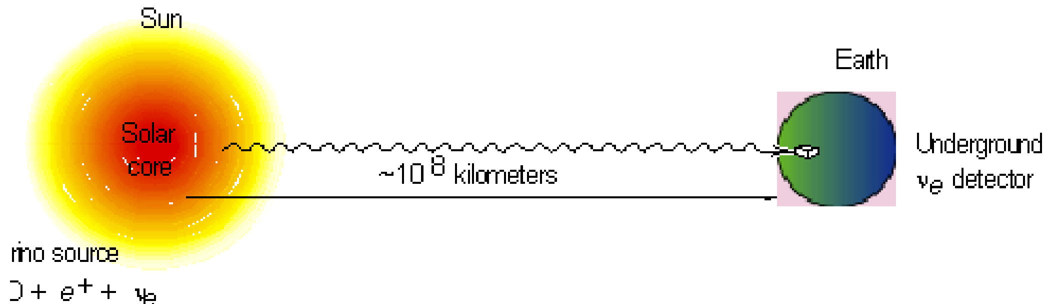




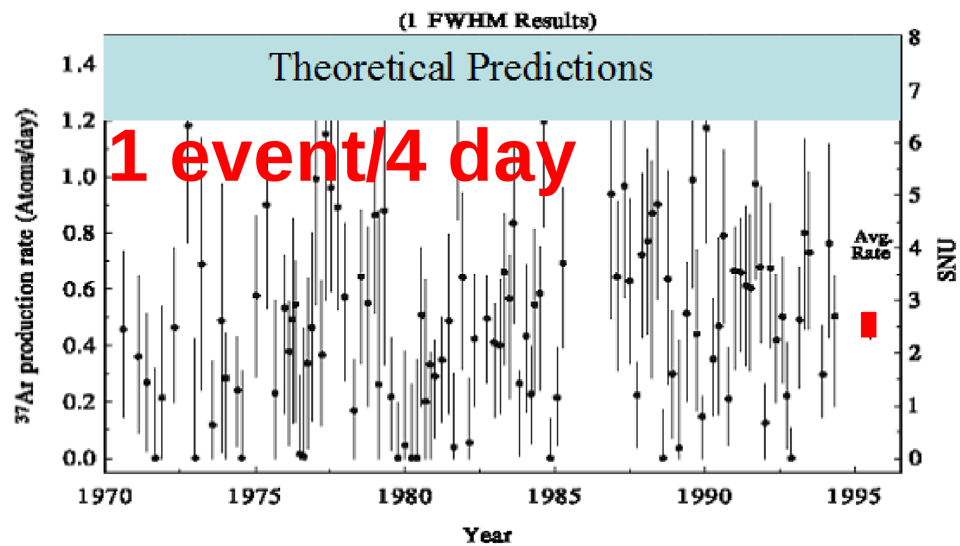
neutrino has mass → there should be right-handed neutrino but not observed yet.
Possible observation: 0νββ

Solar Neutrino Puzzle

- Every second there are **60 billion** solar neutrinos fall on 1 cm^2 area on the Earth.
- In 1968, Homestake found that observed solar neutrino rate is only 1/3 of expected.



$$\nu + {}^{37}Cl \rightarrow {}^{37}Ar + e$$

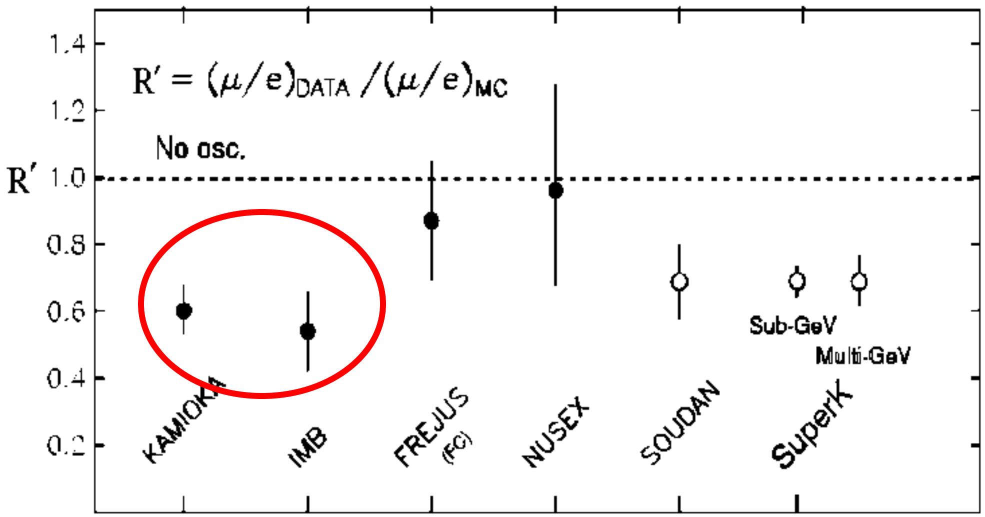


Davis, Nobel Prize in 2002

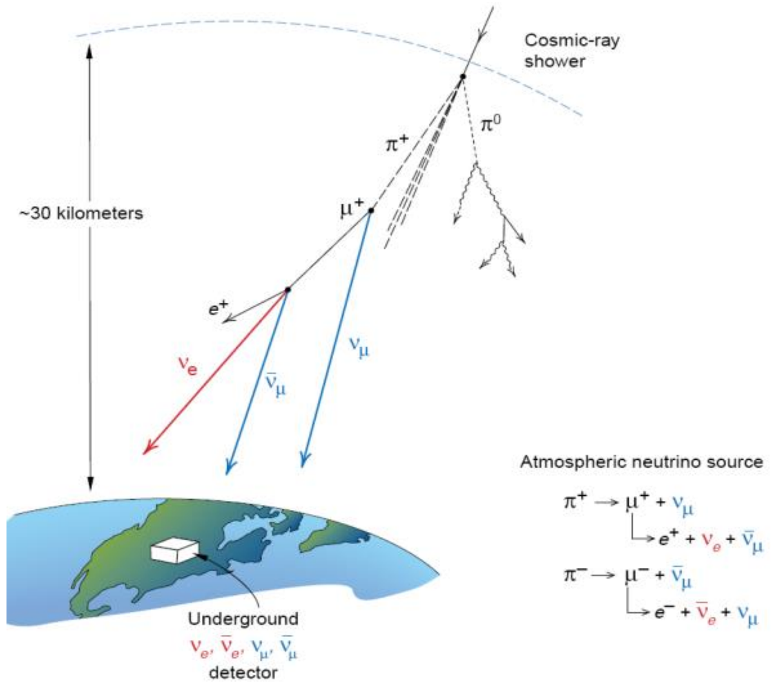
Neutrino Oscillation

- **In 1957, Pontecovo proposed neutrino oscillation, if neutrino has tiny mass, and there are different kind of neutrinos.**
- **Is solar neutrino puzzle due to oscillation when flying from the Sun to the Earth?**
- **Vacuum oscillation assumption need fine-tuning. Different experiments are not consistent.**
- **In 1978, Wolfenstein noticed that oscillation effect will be impacted by the electron neutrino scattering in matter.**
- **In 1986, Mikheyev and Smirnov used this idea to explain the solar neutrino problem. (MSW effect/matter effect)**

Atmospheric Neutrino Anomaly



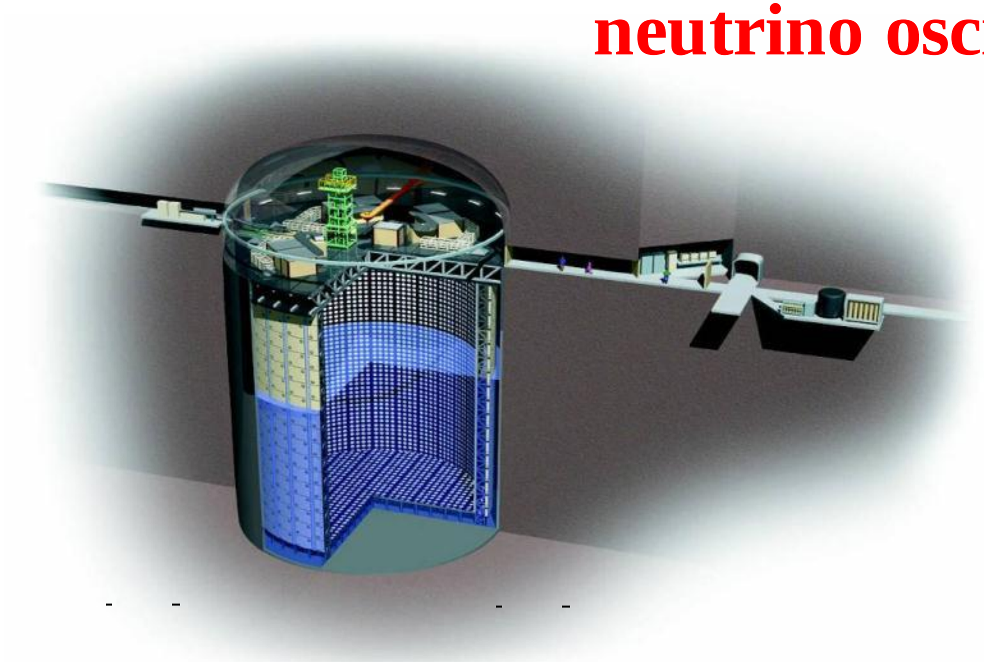
Kamiokande and IMB experiments found atmospheric neutrinos are less than expected.

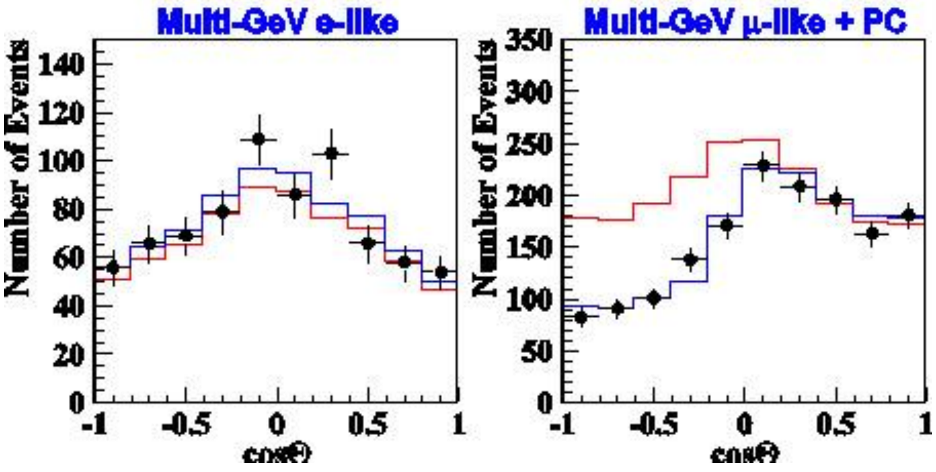


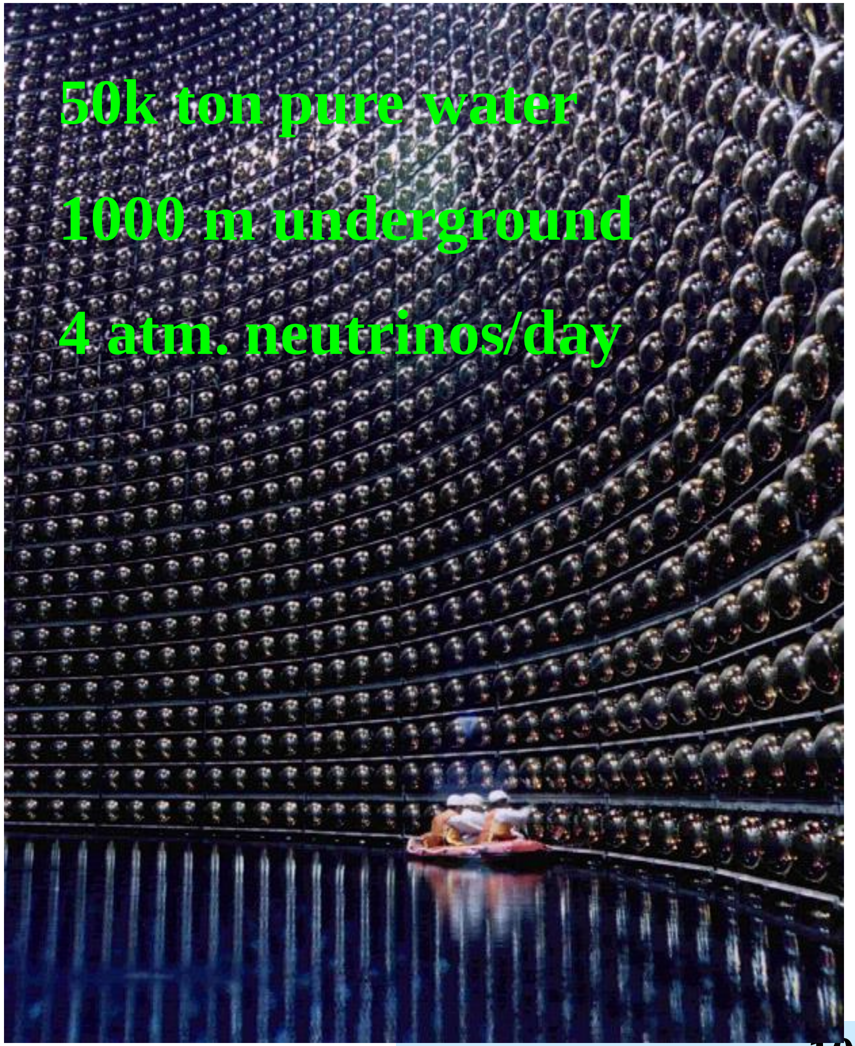
Koshiba, Nobel Prize in 2002

Discovery of Neutrino Oscillation

In 1998, Super-Kamiokande discovered atmospheric neutrino oscillation!







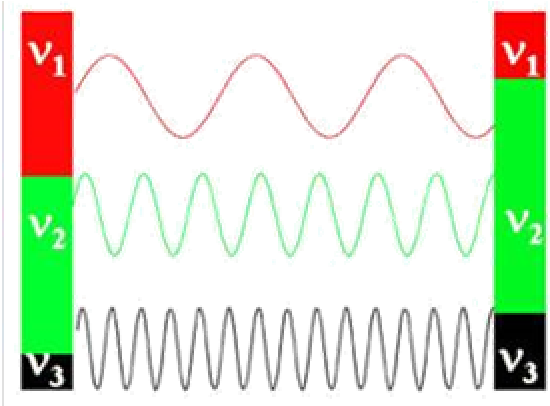
Neutrino Oscillation

Weak Eigen state

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

Mass Eigen state

$|\nu_e\rangle =$

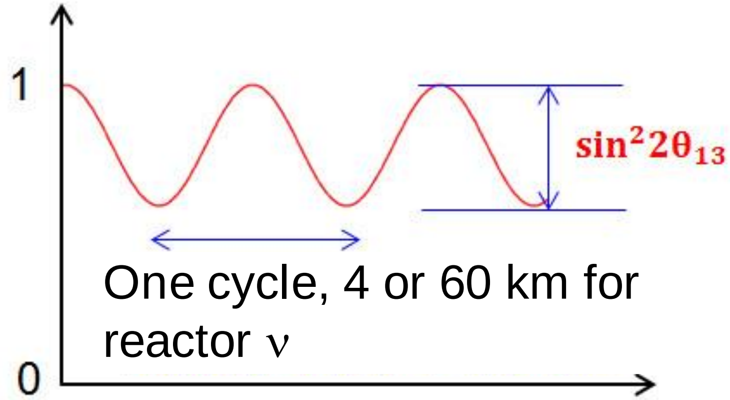


$= c_1|\nu_e\rangle + c_2|\nu_\mu\rangle + c_3|\nu_\tau\rangle$

Distance / Neutrino Energy

$$P_{sur} \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(1.27 \cdot \Delta m^2_{31} \cdot \frac{L}{E}\right)$$

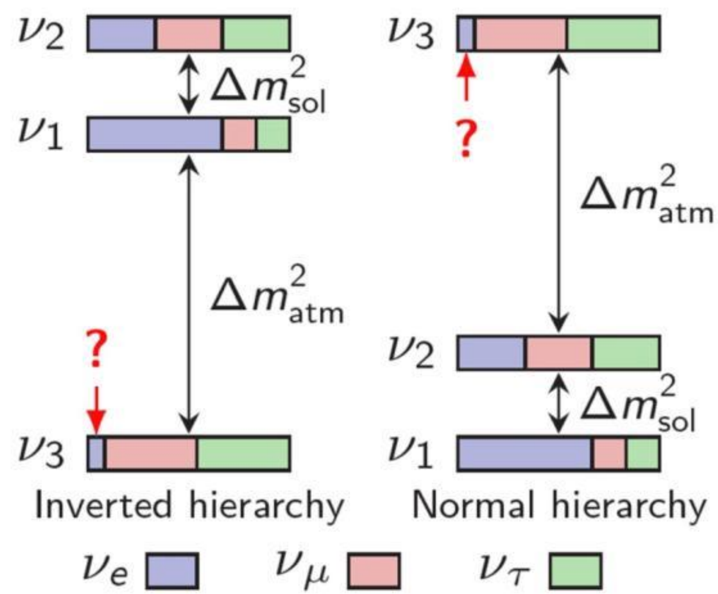
Amplitude   Frequency



Six parameters of Oscillation

In a 3-ν framework

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



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

$\theta_{23} \sim 45°$
Atmospheric
Accelerator

$\theta_{13} \sim 9°$
Reactor
Accelerator

$\theta_{12} \sim 34°$
Solar
Reactor

0νββ

Confirmation from Solar ν： SNO

D_2O, water Cherenkov detector

Charged-Current (CC)

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

Ee~Eν, ~isotropic

$\Rightarrow \nu_e$

Neutral-Current (NC)

$$\nu_x + d \longrightarrow \nu_x + n + p$$

$$n + d \rightarrow t + \gamma \,,\; E_\gamma = 6.25\ \text{MeV}$$

$$\nu_x = \nu_e + \nu_\mu + \nu_\tau \Leftarrow$$

Elastic Scattering (ES)

$$\nu_x + e^- \longrightarrow \nu_x + e^-$$

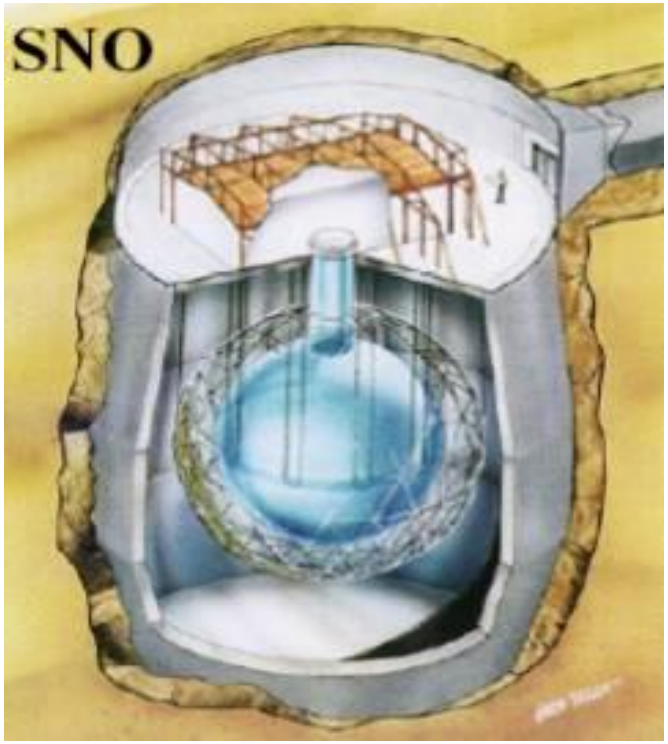
Forward Peaking

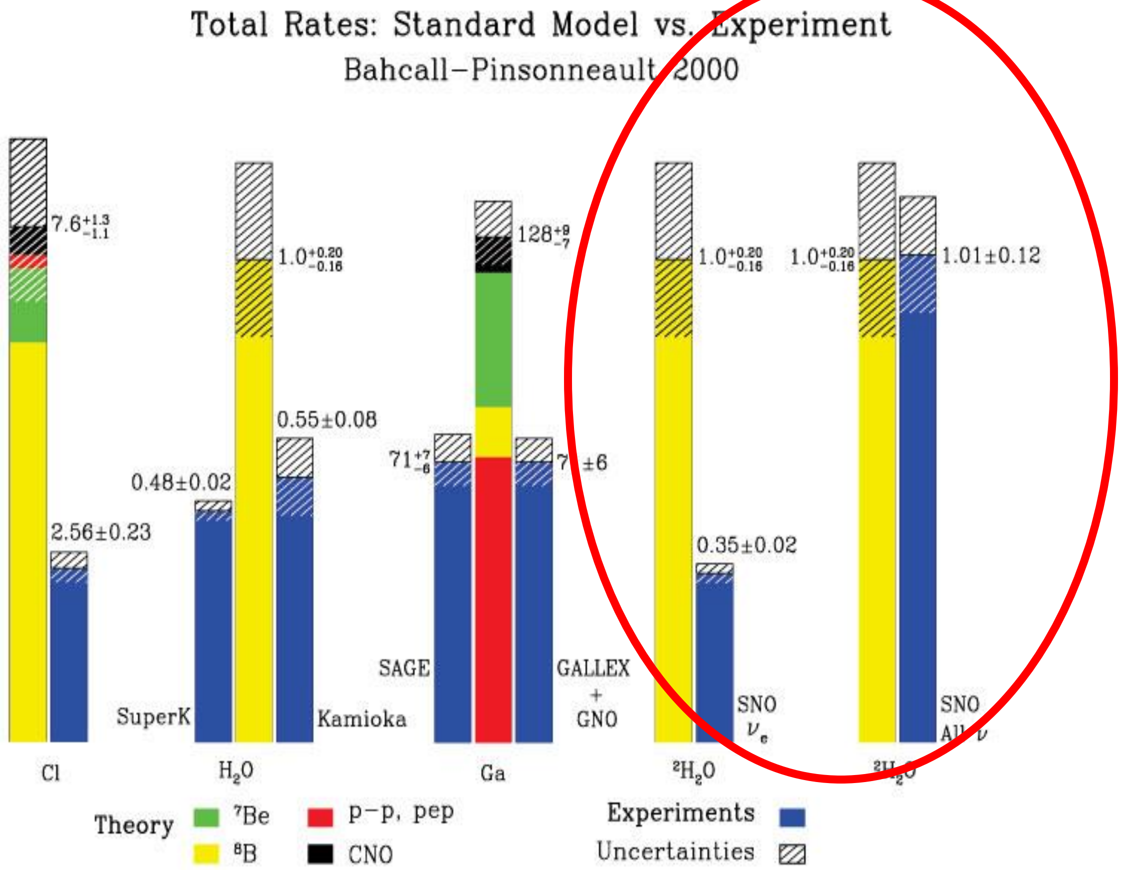
$Z^0, W^\pm$

$$\Rightarrow \nu_x = \nu_e + (\nu_\mu + \nu_\tau)/6$$

Confirmation from Solar ν

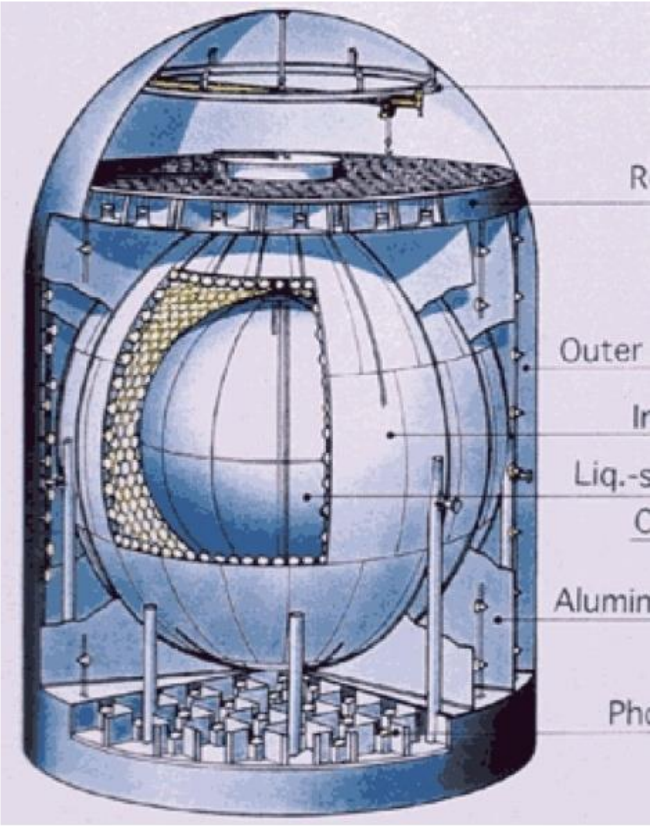
- **In 2001, SNO experiment confirmed solar neutrino oscillation unambiguously, by detecting 3 reactions simultaneously. Electron neutrinos (solar) do disappear, but total number is the same.**

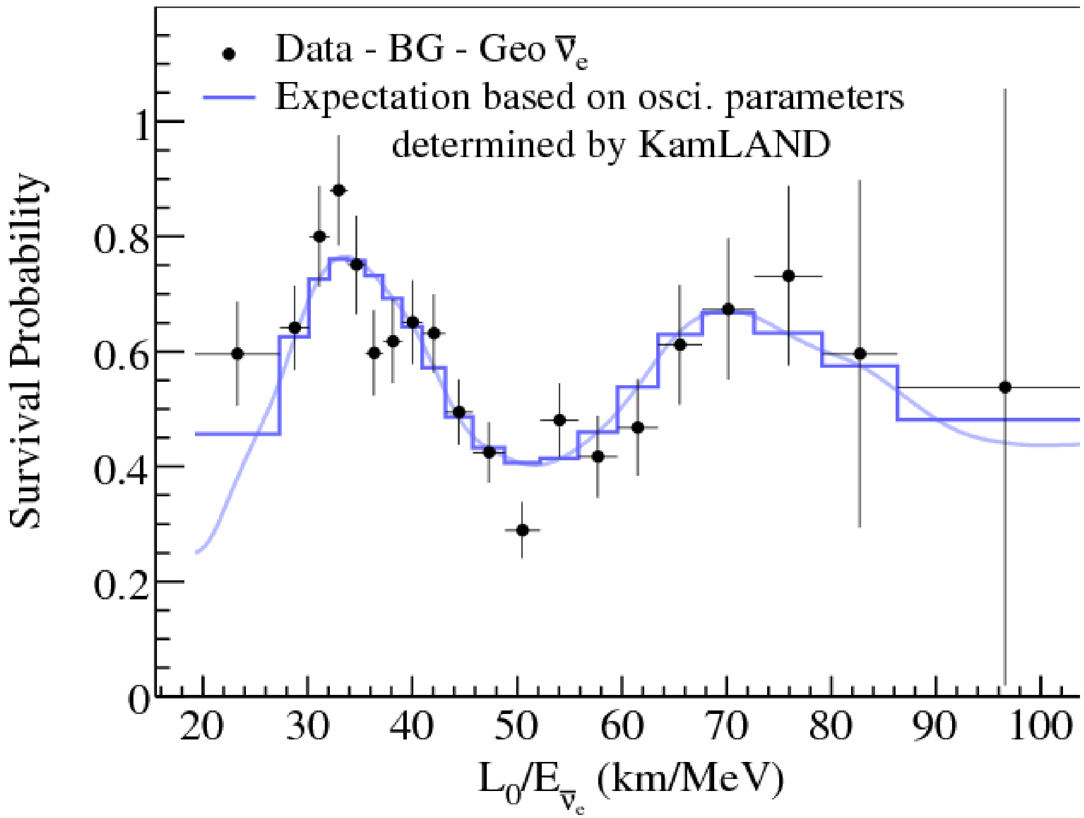




Confirmation from Reactor ν

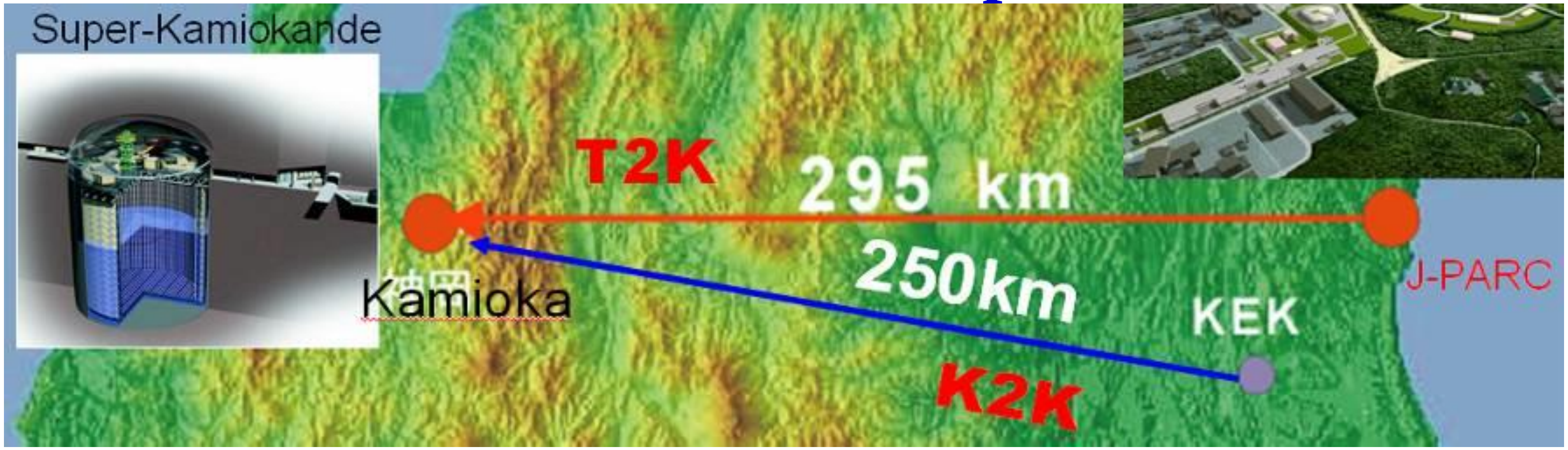
- **In 2002, KamLAND confirmed the oscillation using reactor neutrinos. (Solar oscillation mode)**

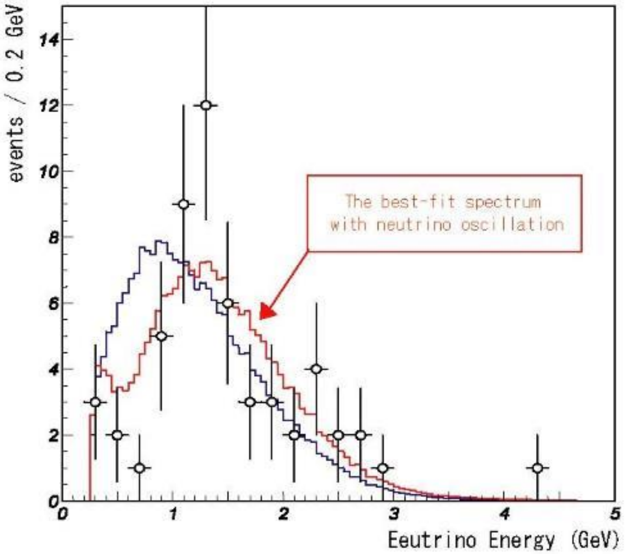




Confirmation from Accelerator ν

- **In 2003, K2K experiment confirmed the oscillation with accelerator (atmospheric model). The 1st accelerator neutrino experiment.**

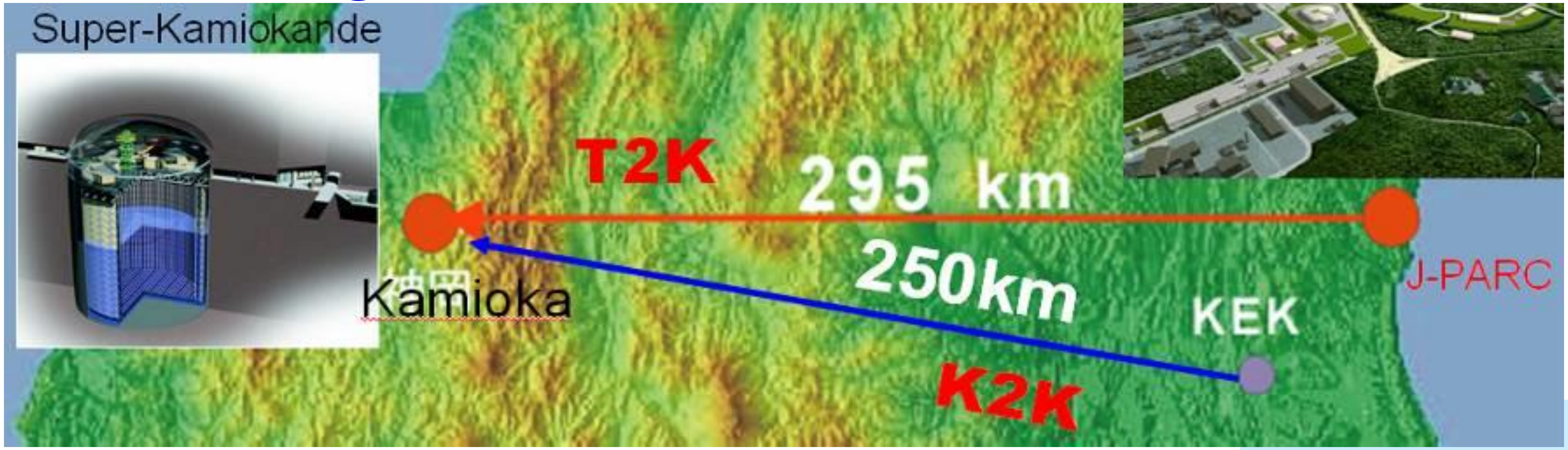




Event rate: 2.9σ
Spectrum: 2.5 σ
Total: 3.9 σ

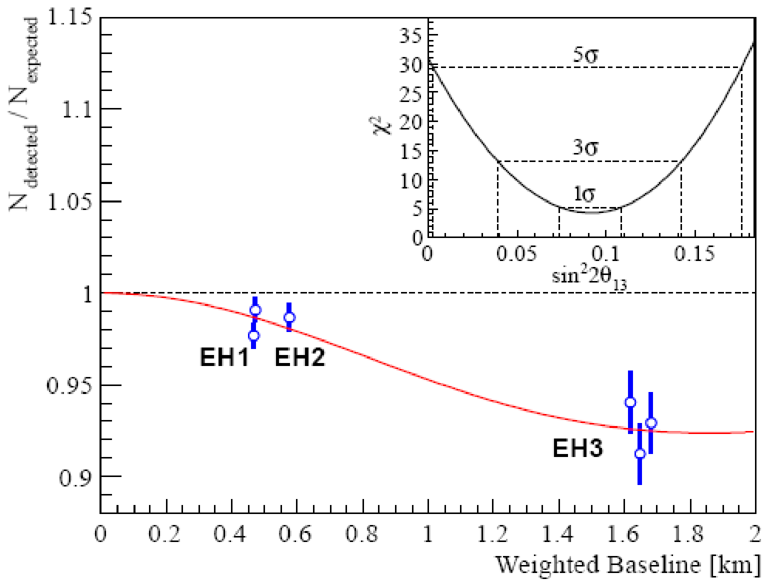
Mixing angle θ_{13}

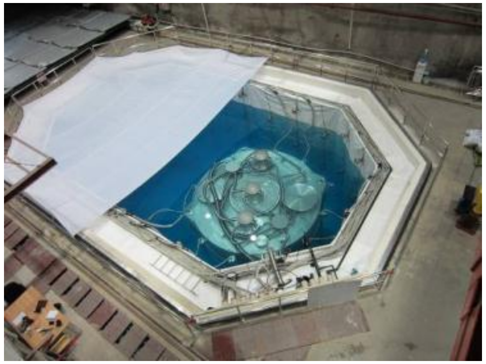
- **Solar mode (solar and reactor experiments) measured** Δm^2_{21}, $\sin^2 2\theta_{21}$
- **Atmospheric model (atmospheric and accelerator experiments) measured** $|\Delta m^2_{32}|$, $\sin^2 2\theta_{32}$
- **Three generations of neutrino need 6 oscillation parameters.** θ_{13}, δ_{CP}, **and mass hierarchy unknown.**
- **Reactor experiments CHOOZ and Palo Verde didn't observe oscillation:** $\sin^2 2\theta_{13}<0.17$
- **In 2011, T2K found the indication (2.5 σ) of** $\nu_\mu \rightarrow \nu_e$, θ_{13} **could be large.**

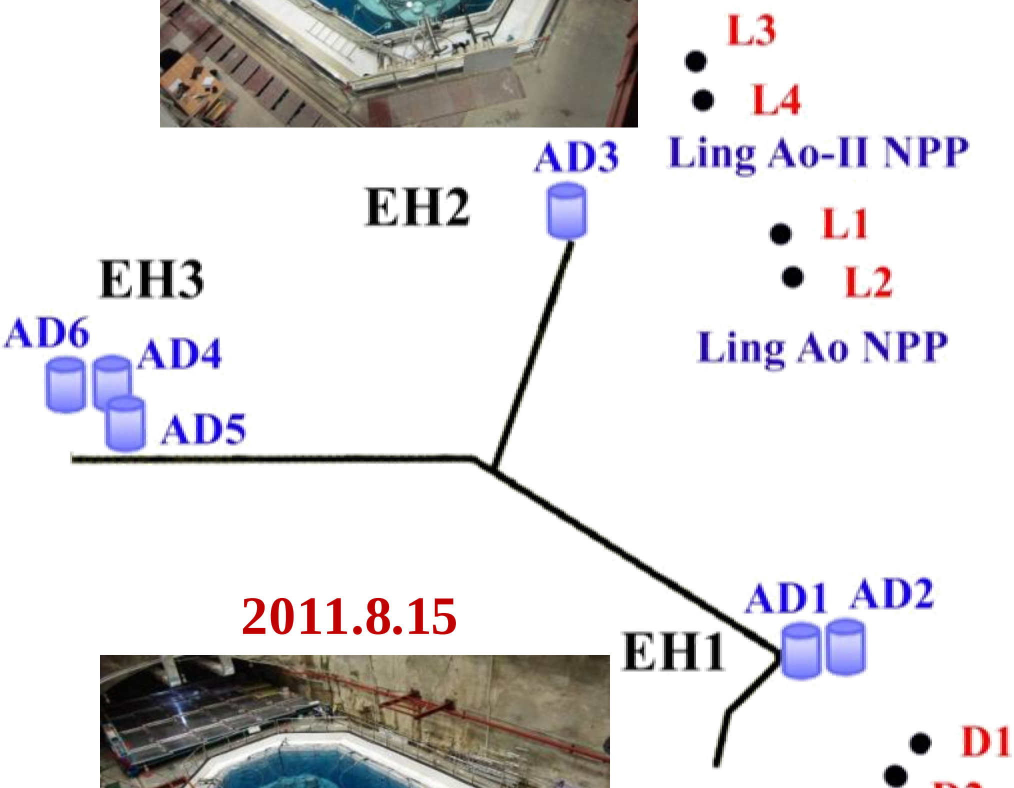


Daya Bay in 2012: θ_{13} is large

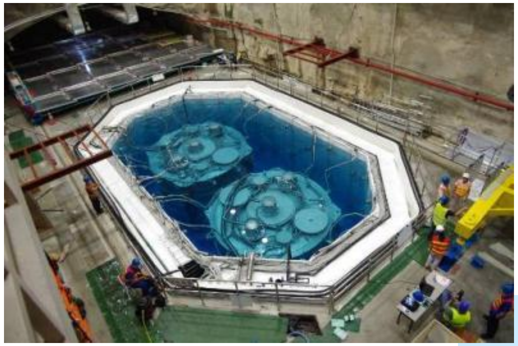
$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$$







2011.8.15



Neutrino Puzzles

- **Neutrino Oscillation**
  - **Mass hierarchy: Which neutrino is the lightest?**
  - **CP violation: Mystery of the missing antimatter**
  - **Octant of θ_{23}**
- **The absolute neutrino mass?**
  - **β decay; $0\nu\beta\beta$; cosmology**
- **Is neutrino its own anti-particle?**
  - **Dirac or Majorana ($0\nu\beta\beta$)**
- **Is there sterile neutrino(s)?**

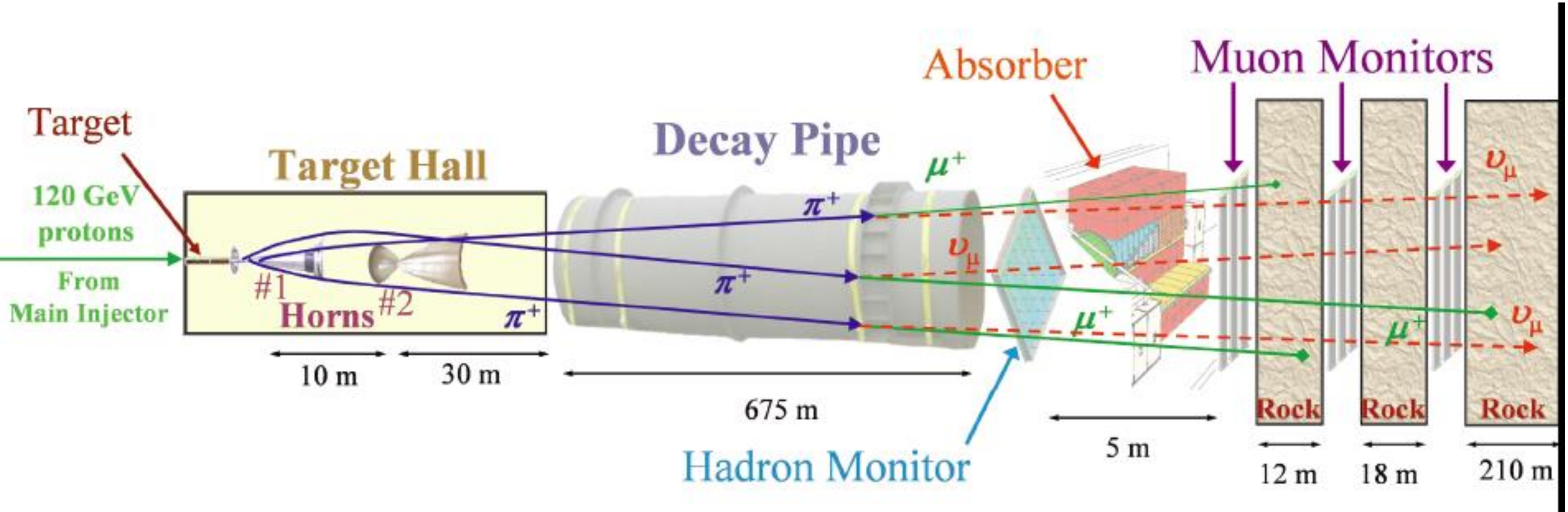
… …

- **Neutrinos as probes**
  - **Nucleon structure and QCD;**
  - **Solar ν; supernovae ν; ultra-high energy ν; big bang ν**
  - **geo-ν;**

Next Goals in Oscillation

- **Mass Hierarchy.**
  - ⇨ **Long baseline accelerator experiment (>1000 km)**
  - ⇨ **Atmospheric experiment (better if charge identified).**
  - ⇨ **Reactor experiment, via P_{31} and P_{32} interference.**
  - ⇨ **All are challenging. Need > 10 k ton detector.**
- **CP phase.**
  - ⇨ **By accelerator experiment. Measuring the asymmetry between neutrino and antineutrino oscillation.**
  - ⇨ **Atmospheric has certain sensitivity**
- **θ_{23} Octant, also by accelerator and atmospheric**
- **Sterile neutrino.**
  - ⇨ **Short baseline accelerator experiments**
  - ⇨ **Short baseline reactor experiments**
  - ⇨ **Source experiments**

Accelerator Neutrinos



- **Conventional beam**

$$\pi^- \to \mu^- + \bar{\nu}_\mu \qquad K \to \mu + \nu_\mu$$

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \mu \to e + \bar{\nu}_\mu + \nu_e$$

- **Muon beam under R&D (ν factory, MOMENT)**

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

Accelerator Neutrinos

	Past	Running	Planned
Japan	K2K	T2K	Hyper-K
Fermilab		MINOS(+) NOvA	LBNE(F)
CERN	ICRUS OPERA		LBNO?

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

$\nu_\mu \rightarrow \nu_e$

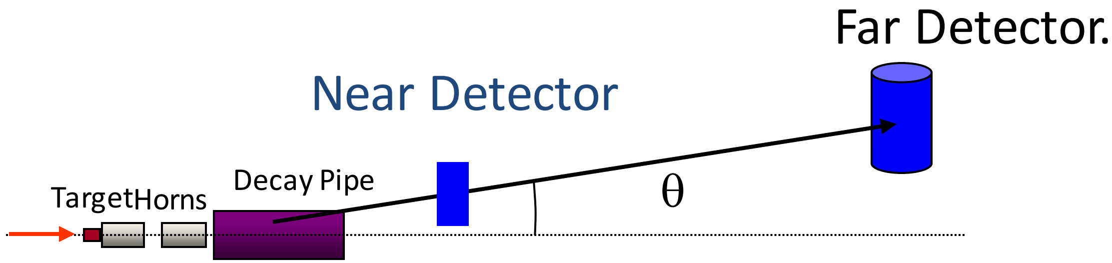
$\nu_\mu \rightarrow \nu_\tau$

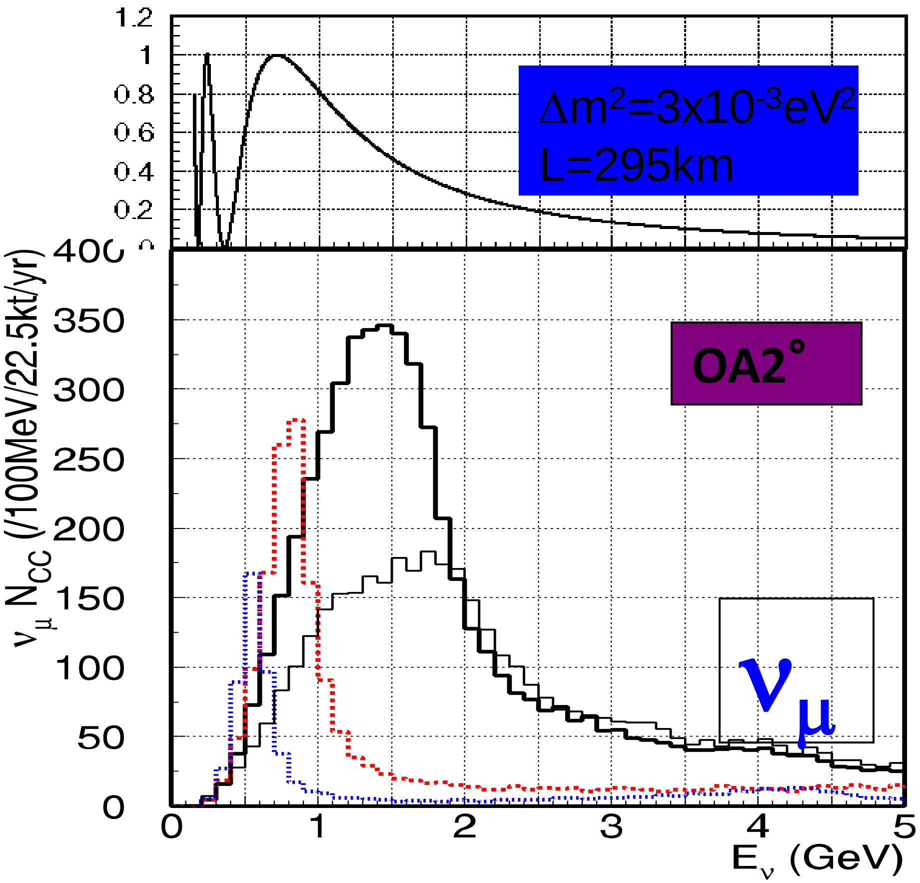
$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) = & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \\ & + 8c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin \Delta_{31} [\cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta] \sin \Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 s_{12}^2 \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} \\ & + 4c_{13}^2 s_{12}^2 [c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta] \sin^2 \Delta_{21} \\ & - 8c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2) \frac{aL}{4E_\nu} \sin \Delta_{31} \left[\cos \Delta_{32} - \frac{\sin \Delta_{31}}{\Delta_{31}} \right] . \end{aligned}$$

- **Short-baseline such as MiniBooNE**

Neutrino beam: Off-Axis

an Idea from BNL (TRIUMF):

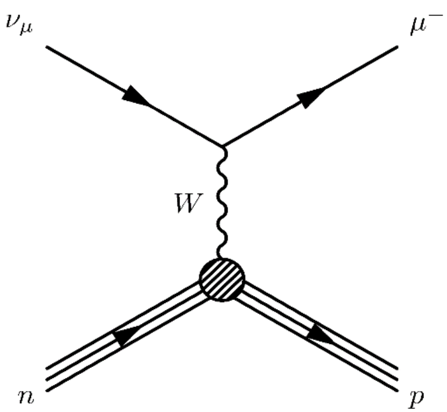




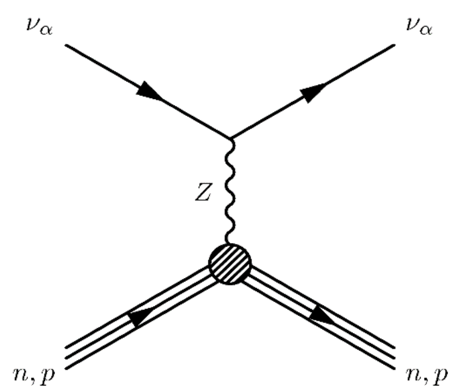
- ***Pros –***
  - *Increases flux on osc. max.*
  - *Reduces high-E tail, and thus NC backgrounds*
  - *Reduces ν_e contamination from K and μ decay*
- ***Cons –***
  - *Complicates disappearance measurement*
  - *Increases near/far differences*
  - *Have to know angle!*

Detection

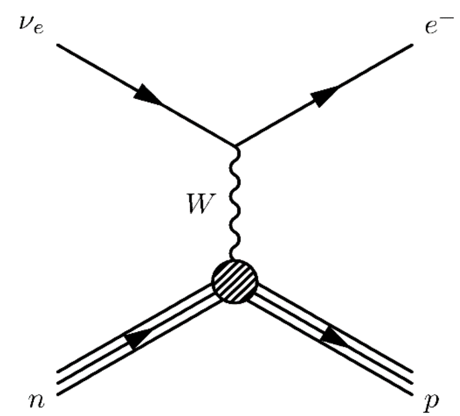
ν_μ CC Event

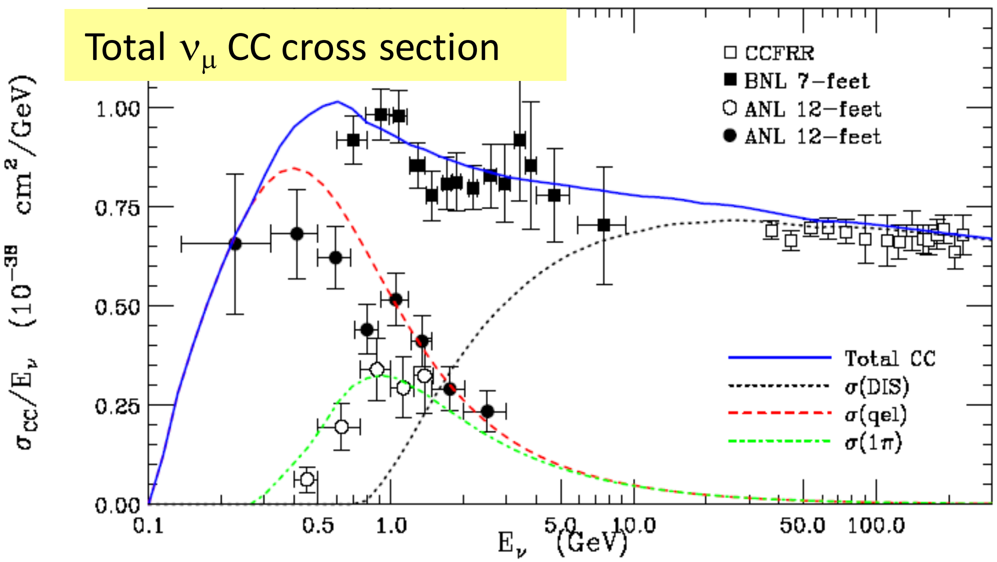


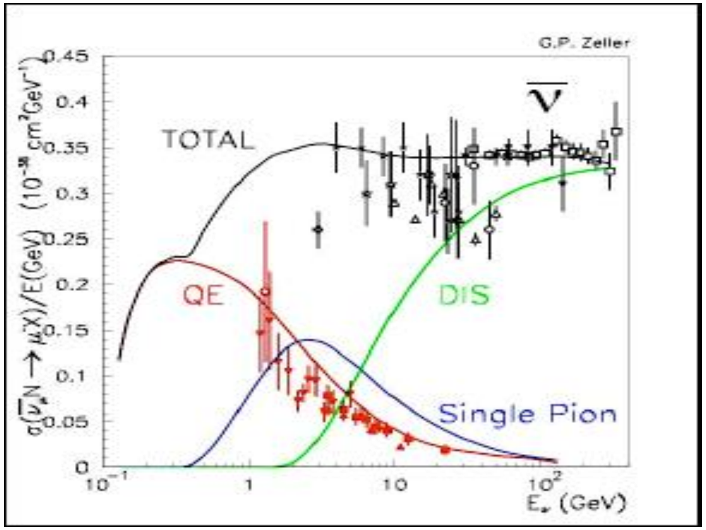
NC Event



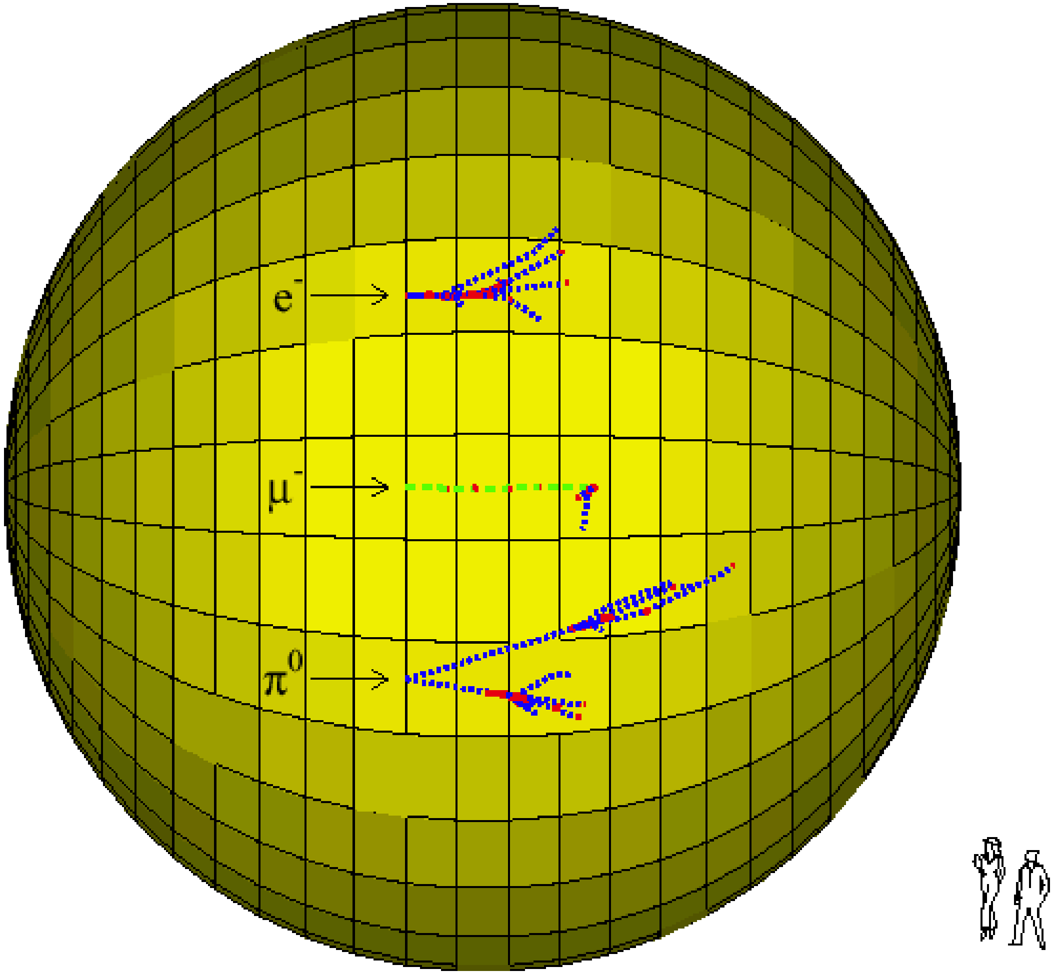
ν_e CC Event

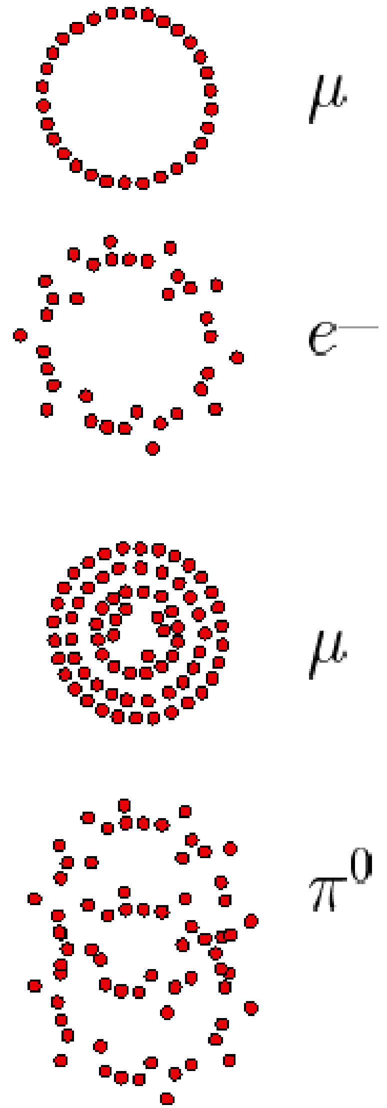






Particle Identification

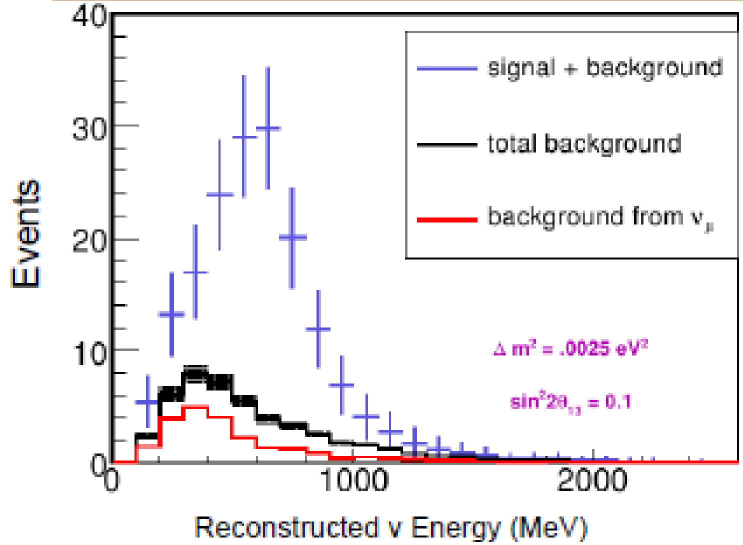




e.g. MiniBooNE

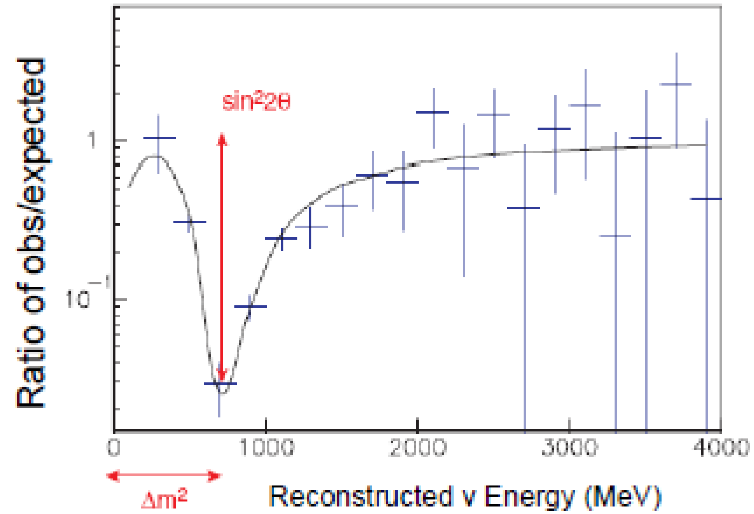
Appearance

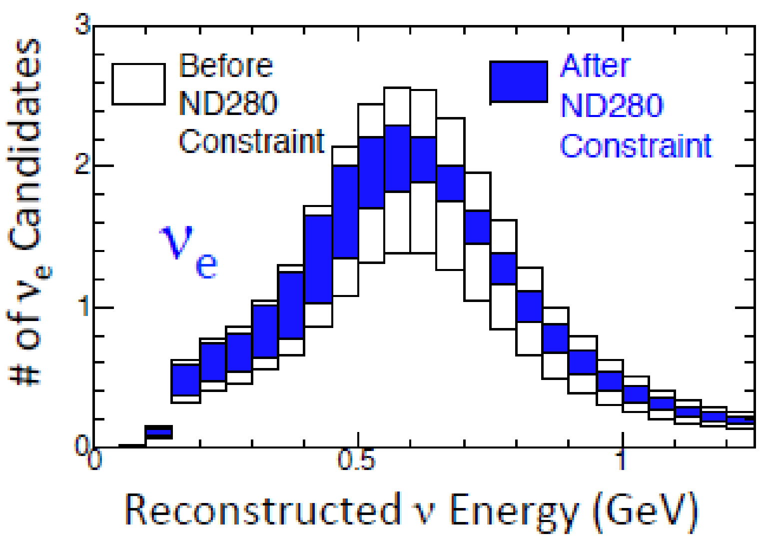
ν_e appearance: determine θ_{13} constrain δ_{CP}

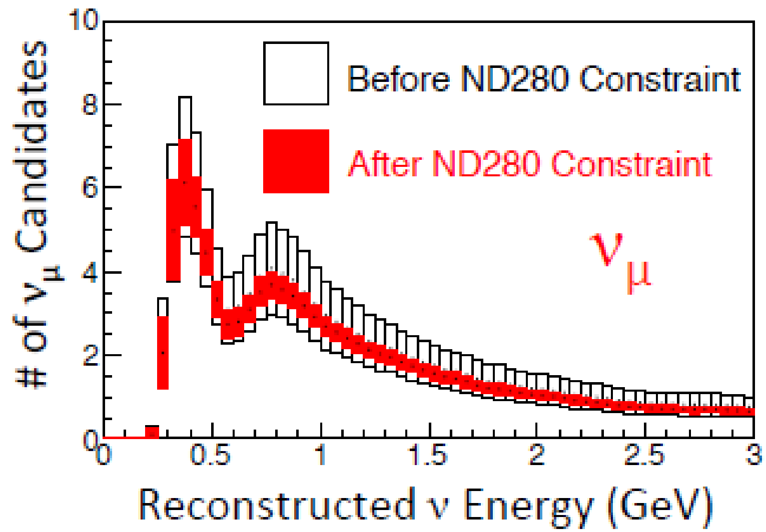


Disappearance:

ν_μ disappearance: determine θ_{23} and Δm^2_{32}







2011：Indication from T2K

- We reported new results on $\nu_\mu \rightarrow \nu_e$ oscillation analysis based on 1.43×10^{20} p.o.t. (2% exposure of T2K's goal)
  - The expected number of events is 1.5 ± 0.3 ($\sin^2 2\theta_{13} = 0$)
  - 6 candidate events are observed
  - Under $\theta_{13}=0$ hypothesis, the probability to observe 6 or more candidate events is 0.007 (equivalent to 2.5σ significance)
  - $0.03\ (0.04) < \sin^2 2\theta_{13} < 0.28\ (0.34)$ at 90% C.L. for normal (inverted) hierarchy
    (assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

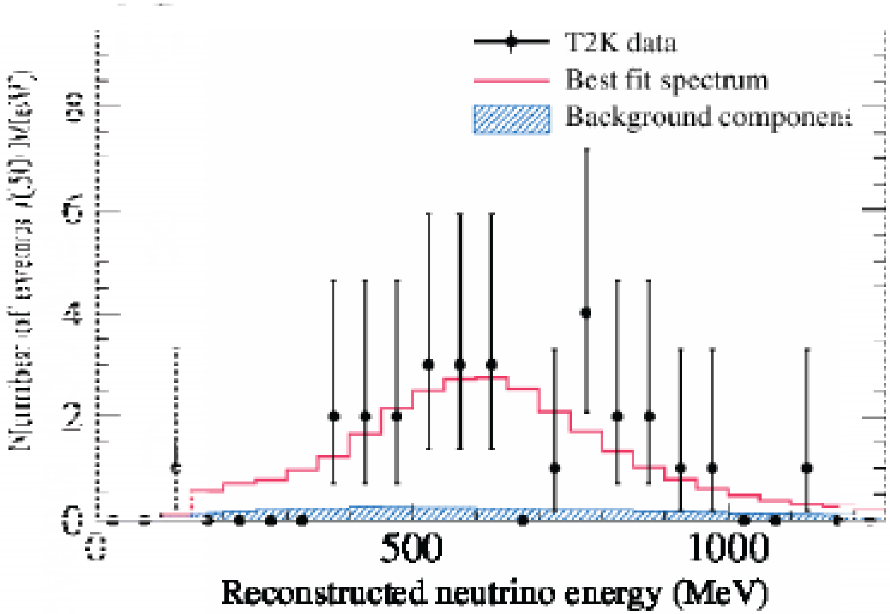
Indication of ν_e appearance

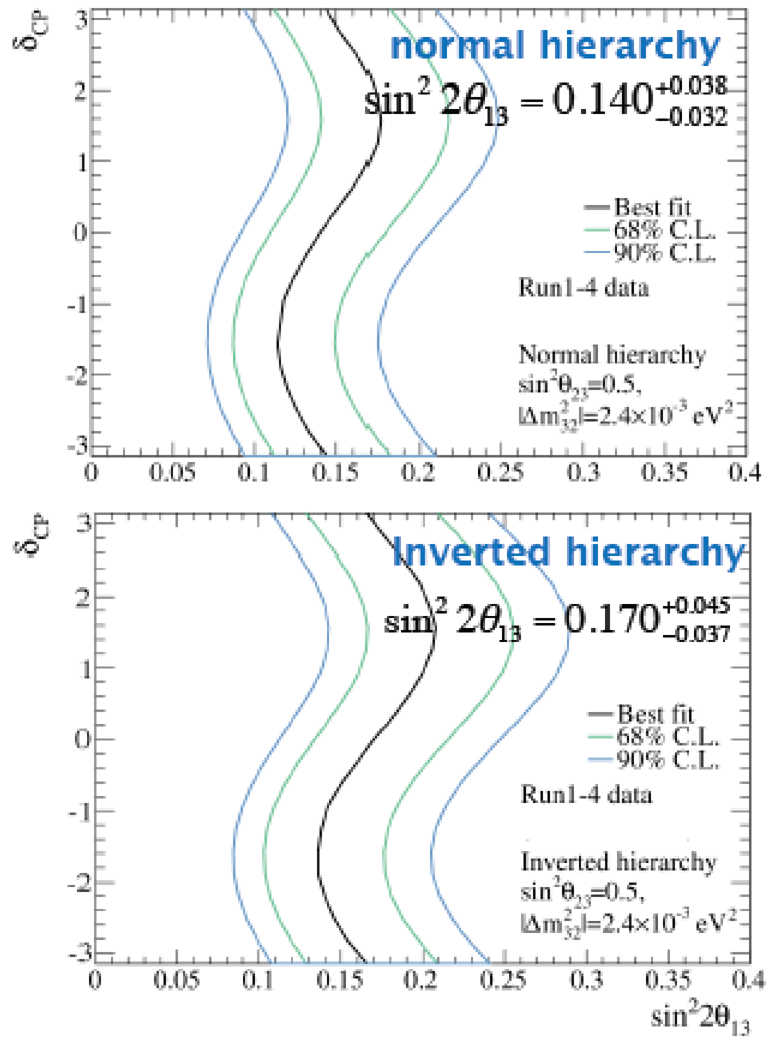
submitted to PRL

- Resume experiment as soon as possible and improve analysis method to conclude ν_e appearance phenomenon
- ν_μ disappearance result with 1.43×10^{20} p.o.t. data will be reported this summer

Phys. Rev. Lett. 112, 061802 (2014)

T2K observation of ν_e Appearance





4.92 ± 0.55 events expected background

28 events observed

21.6 events expected @ $\sin^2 2\theta_{13}$= 0.1

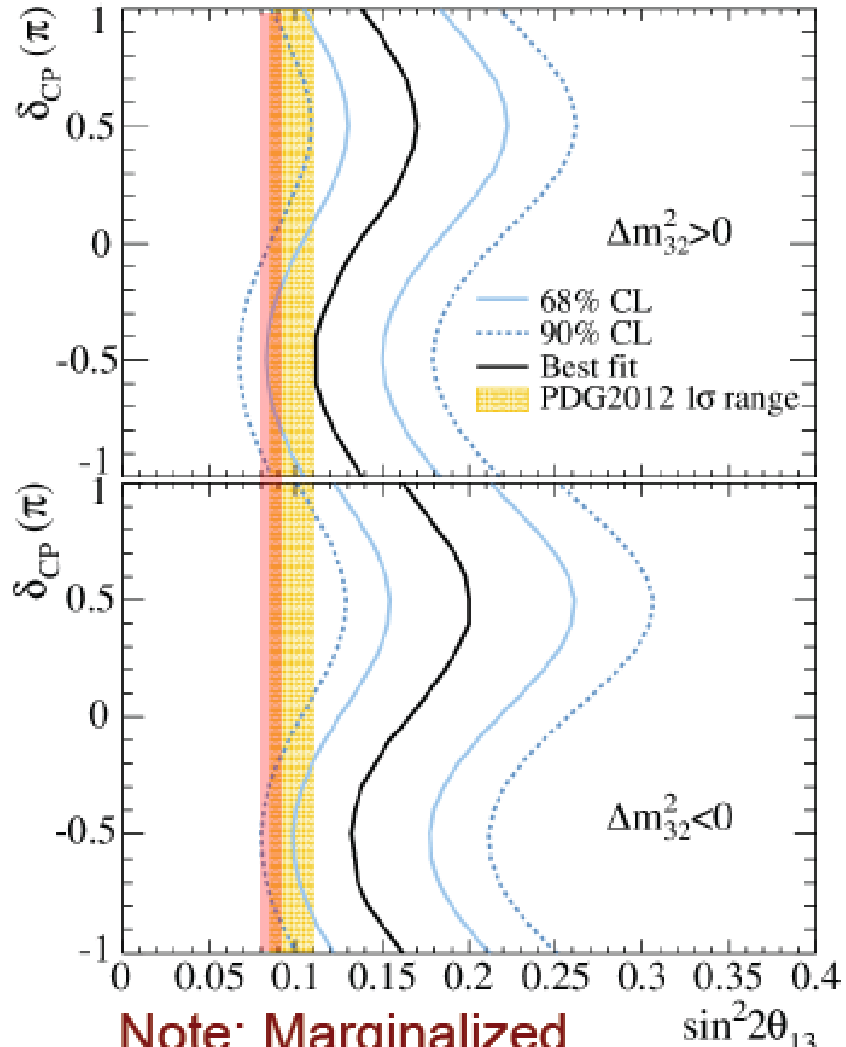
δ_{CP}= 0, $\sin^2\theta_{23}$= 0.5

7.3 σ significance for non-zero θ_{13}

First ever observation (>5σ) of an explicit ν appearance channel

Let's think about these regions!

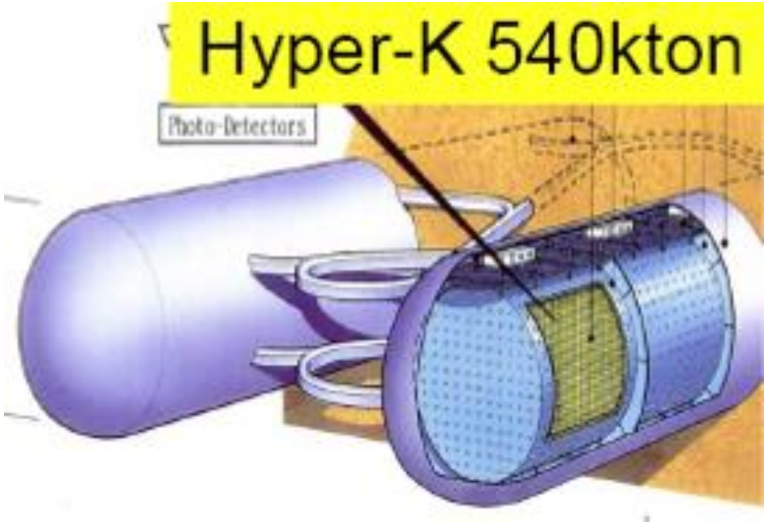
- Comparing with the external reactor constraint the best overlap is for the normal hierarchy with $\delta_{cp}=-\pi/2$.
- This is a **lucky point**!
- You also need to increase the θ_{23} mixing angle to account for the number of observed events.



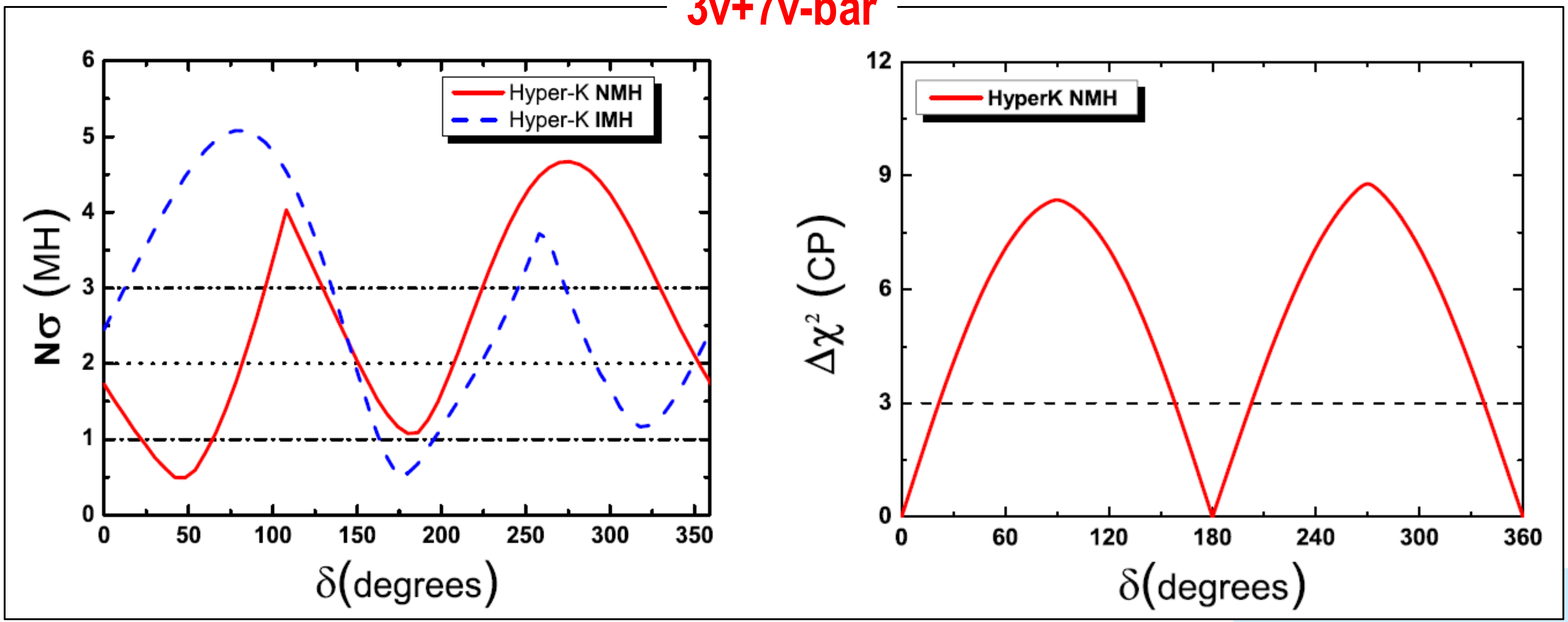
Note: Marginalized over θ_{23} and Δm^2_{32}

Hyper-K

- **1Mt water Cherenkov**
- **J-PARC beam, 0.2 – 2 MW**
  - ⇨ **And atmospheric neutrinos**
- **Detector Construction: 2015**
- **Operation: 2022**

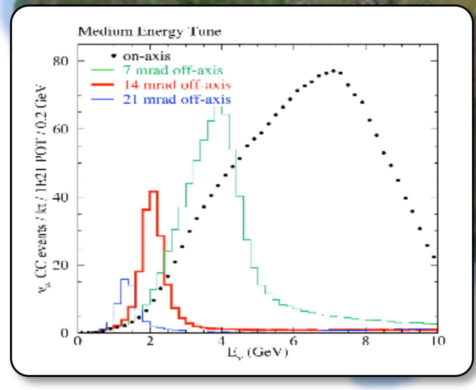


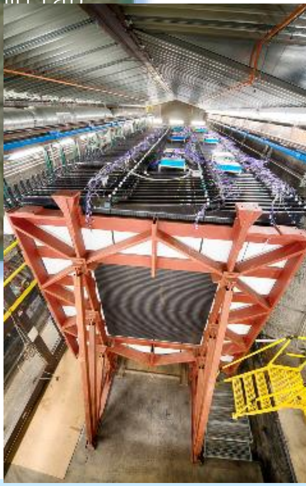
3ν+7ν-bar



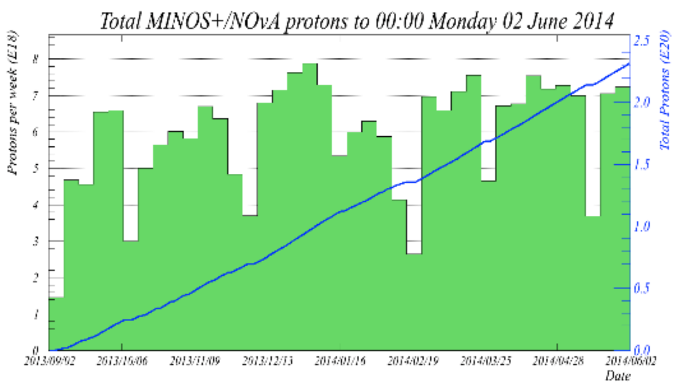
NOνA

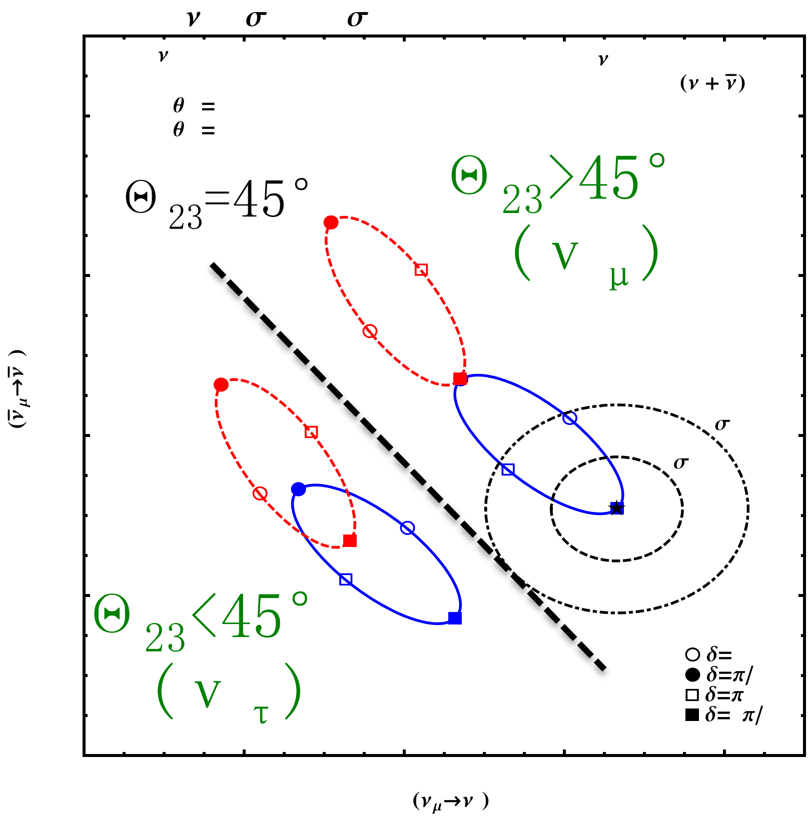
- measurements of the $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\mu$ for both ν and $\bar{\nu}$
- 14 kt *totally active*, liquid scintillator , surface detector
- Optimized as a highly segmented low Z calorimeter/range stack
- Tuned to:
  - ⇨ Reconstruct EM showers
  - ⇨ Measure μ track momenta
  - ⇨ Identify interaction vertices and nuclear recoils

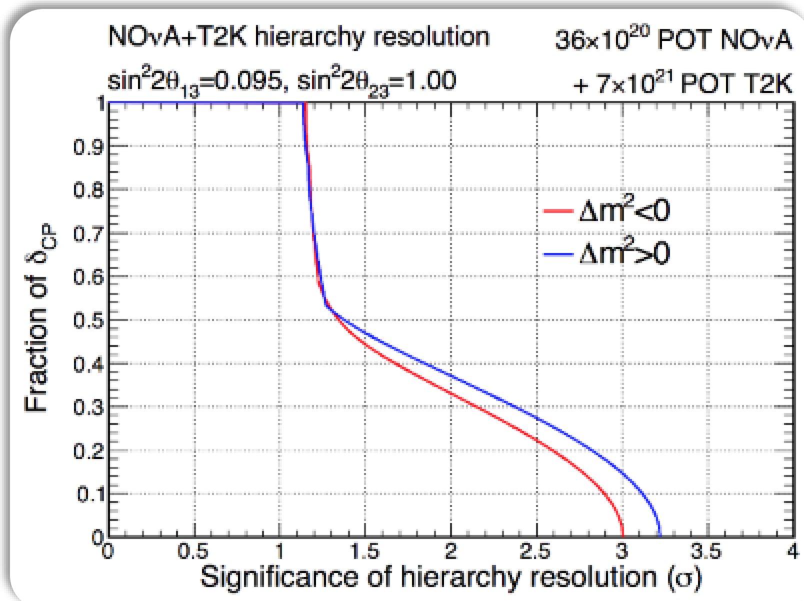


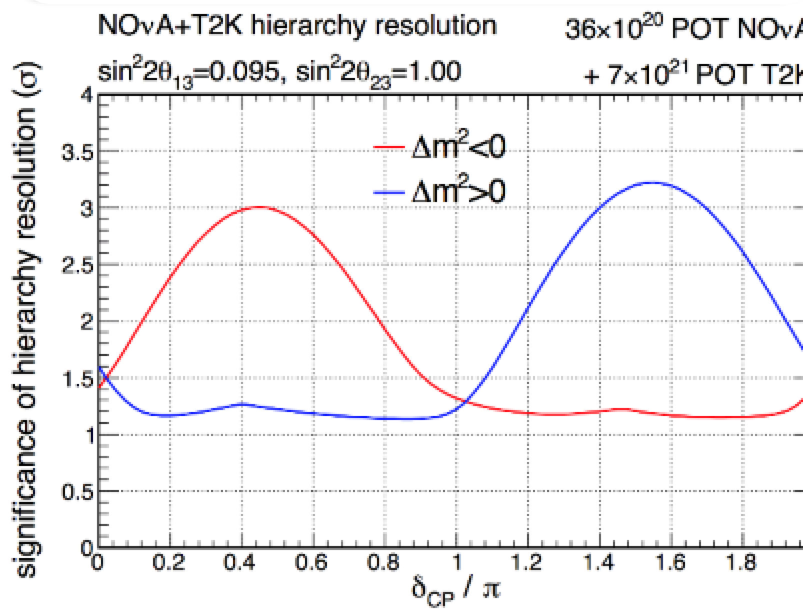


NOvA- Mass Hierarchy



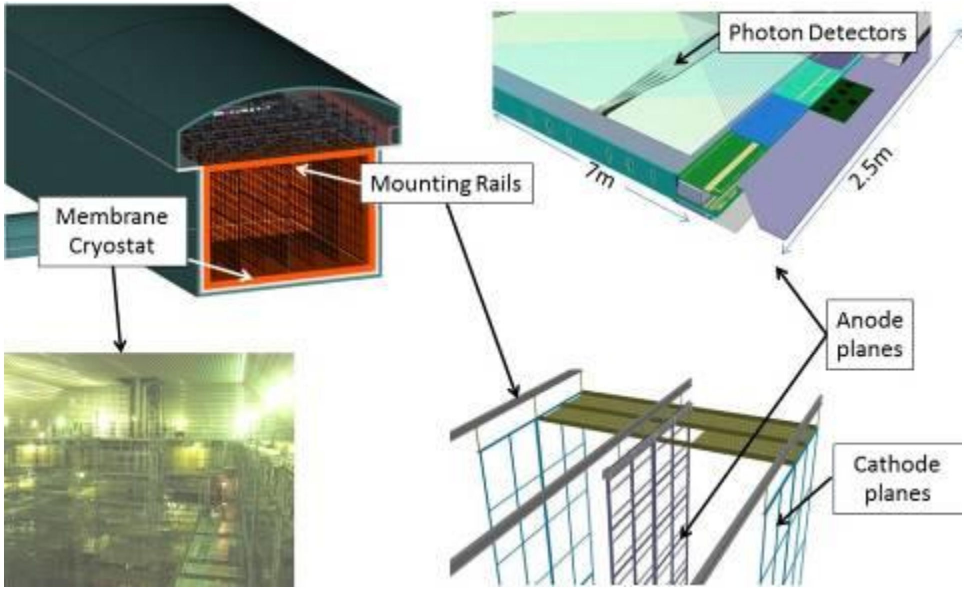




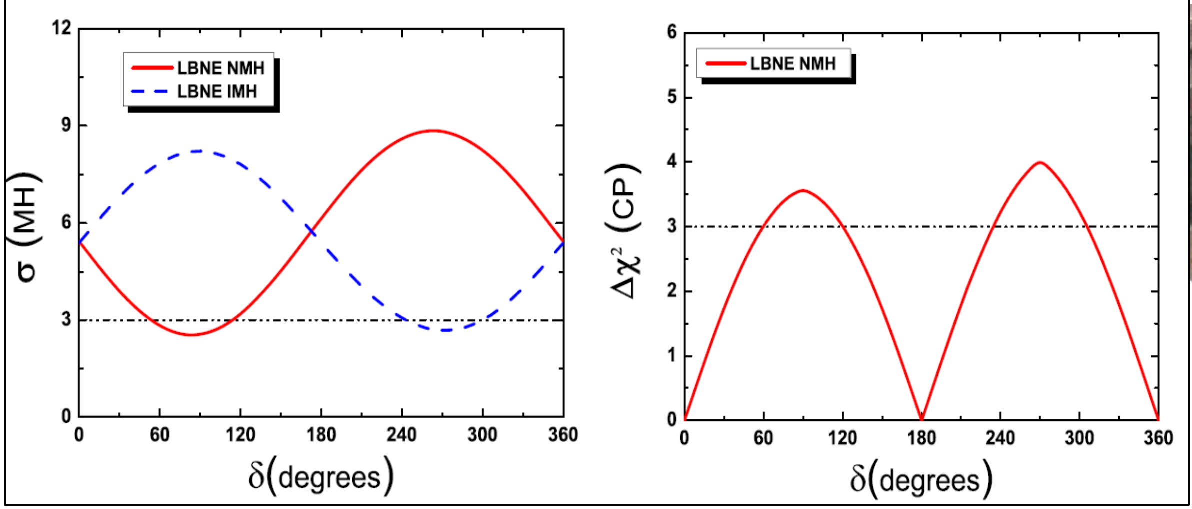


LBNE(F)

- 10 kt (34 kt) LAr on surface (underground)
- FermiLab NUMI beam, 0.7 MW
- Detector Construction: 2014
- CD1 approved
- Operation: 2022?



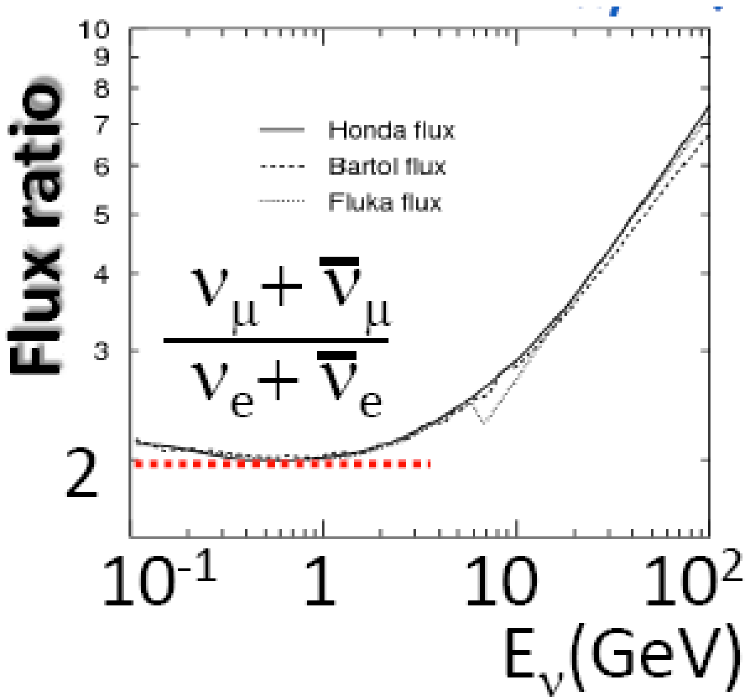
5ν +5ν-bar

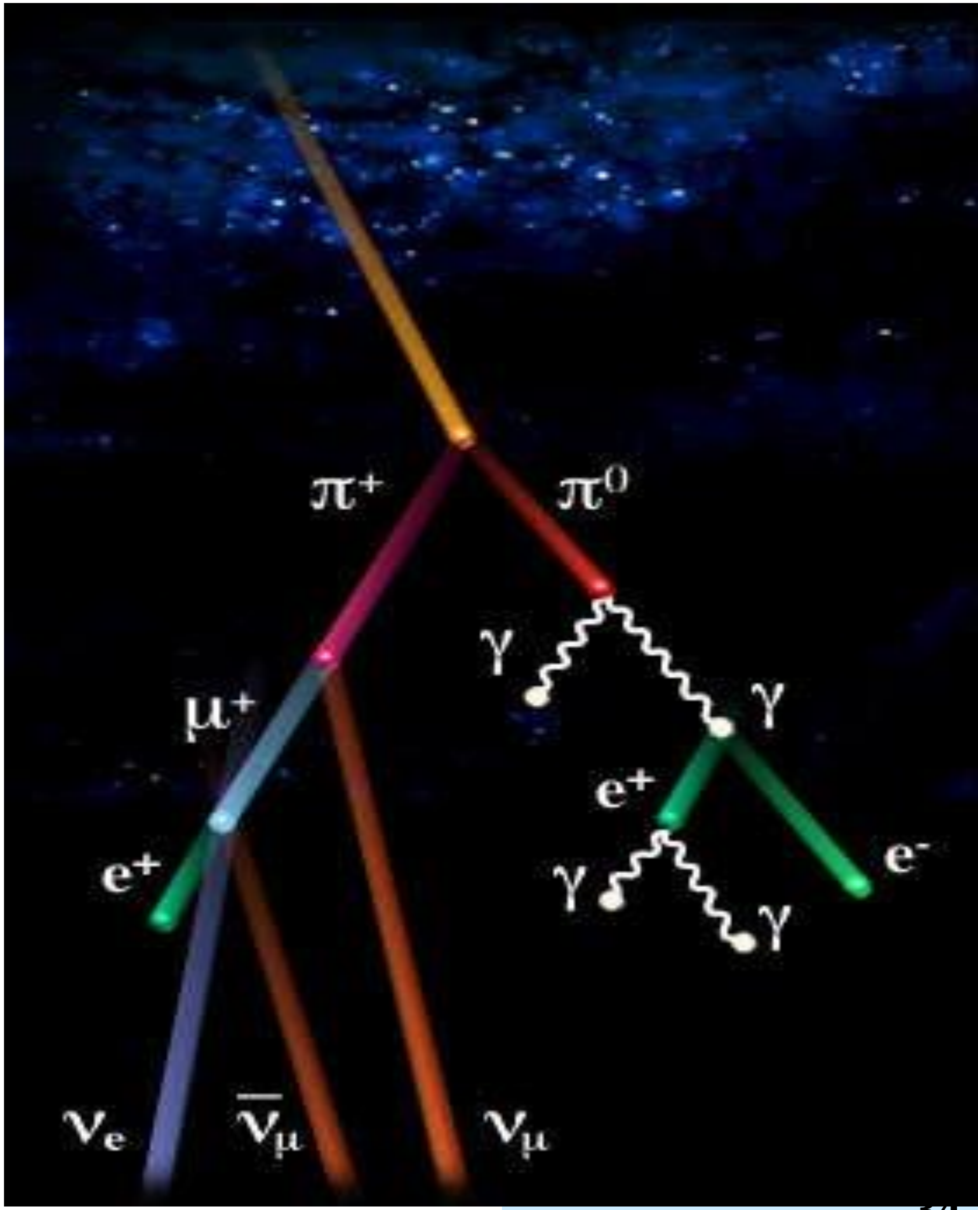


Atmospheric neutrinos

$\nu_\mu/\nu_e \approx 2$ at low energies

$\nu_\mu/\nu_e > 2$ at high energies since fewer μ decays





History of Super-Kamiokande

96	97	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13

phase-I
4.1years
91.7ktyr

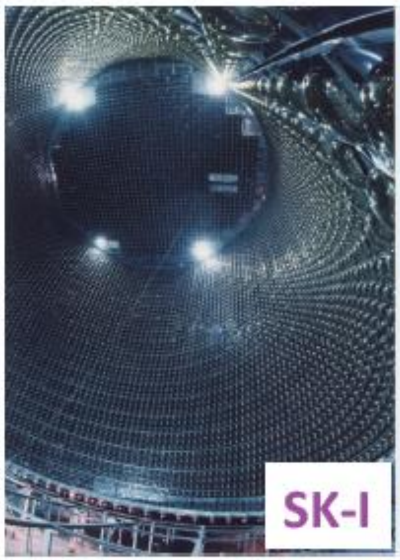
phase-II
2.2years
49.2ktyr

phase-III
1.4years
31.9ktyr

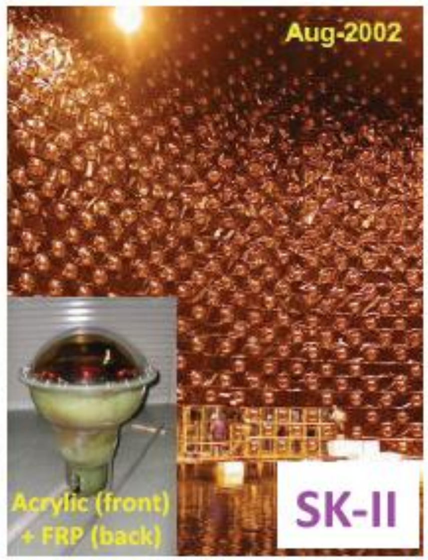
phase-IV
4.9years
109ktyr

M. Shiozawa

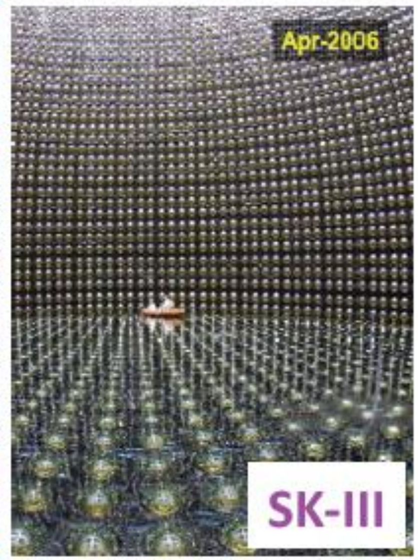
Super-K total 13years or 282 kton×years



11,146 ID PMTs (40% coverage)



5,182 ID PMTs (19% coverage)



11,129 ID PMTs (40% coverage)

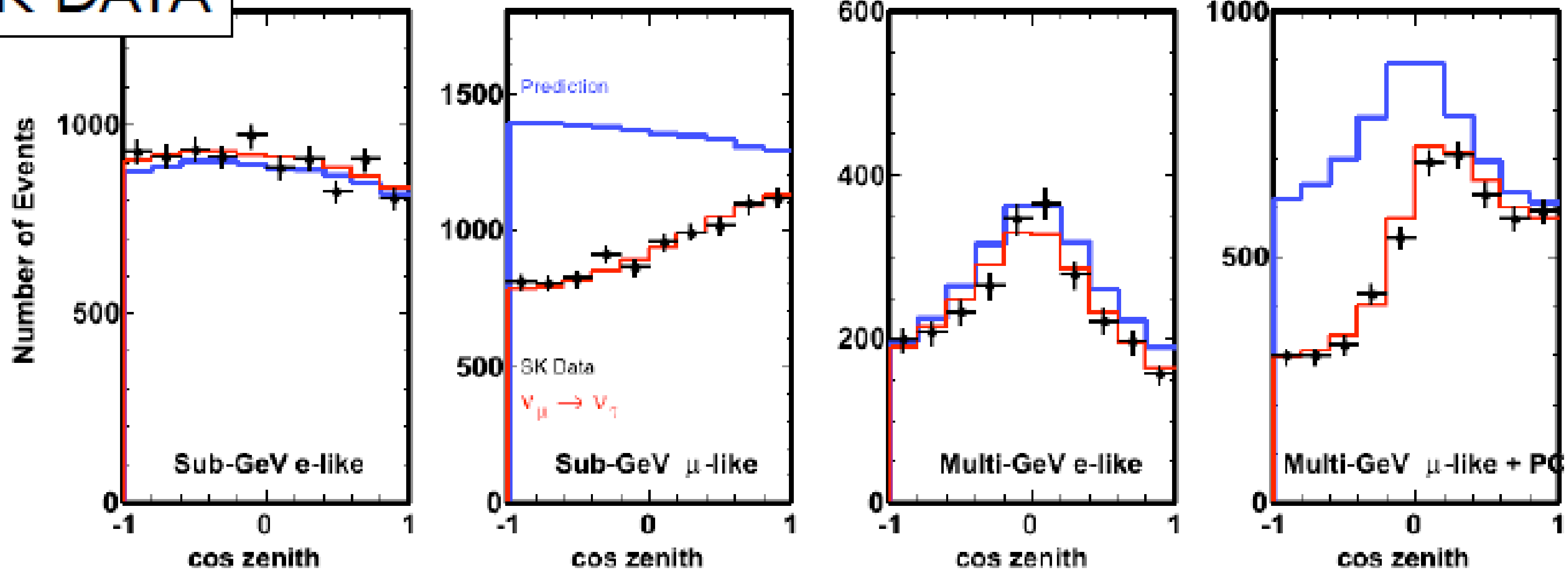
Electronics Upgrade

Energy Threshold	SK-I	SK-II	SK-III	SK-IV
(Total energy)	5.0 MeV	7.0 MeV	5.0 MeV	< 4.0 MeV
(Kinetic energy)	~4.5 MeV	~6.5 MeV	~4.5 MeV	<~3.5 MeV

Target

Prediction
$\nu_\mu \rightarrow \nu_\tau$
SK DATA

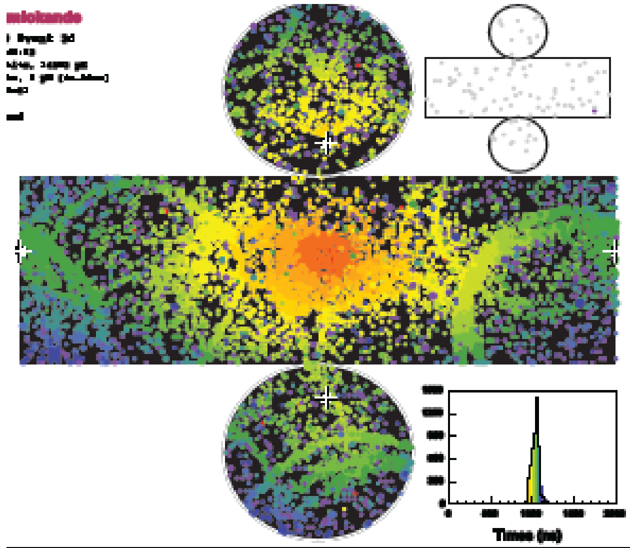
ν's oscillation studies in Super-K



- Dominant effect is ν_μ disappearance **(discovered in 1998)**
- Further studies on sub-dominant effects
  - ν_τ appearance **(established in 2013)**
- Full three flavor analysis
  - ν_e and ν_μ flux change to extract information on mass hierarchy, δ_{CP}, θ_{23} and Δm^2_{32}
- Test of non-standard models

Evidence for τ neutrino appearance

Published in PRL 110, 181802 (2013)

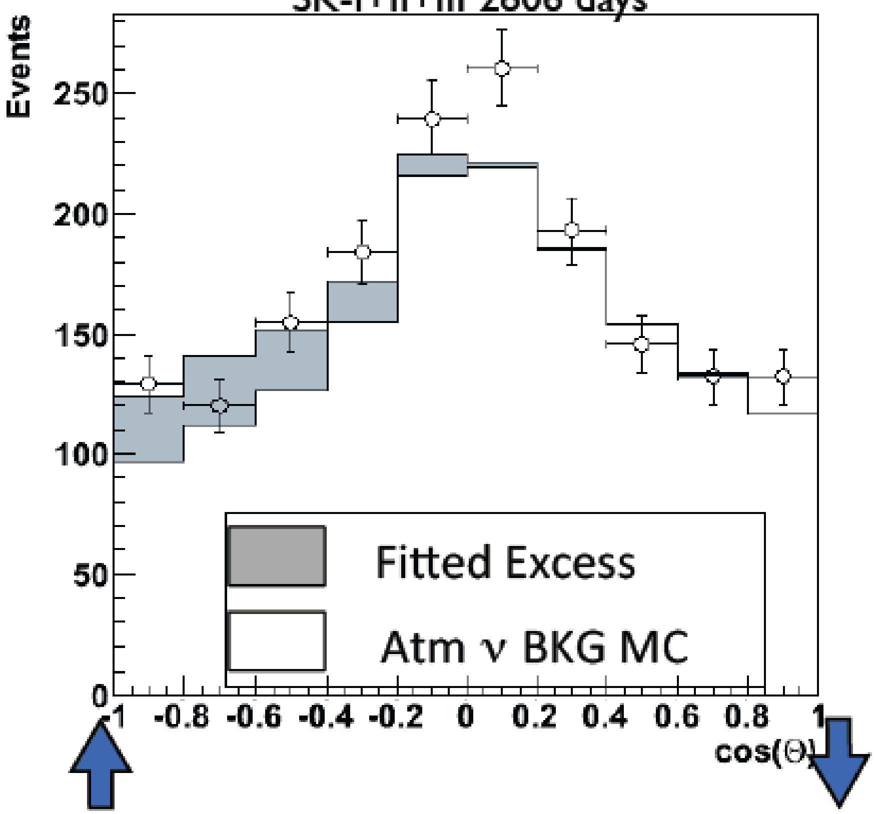


Neural network to enhance events consistent with hadronic decays of τ

$N_\tau^{DATA}/N_\tau^{exp} = 1.42 \pm 0.35(\text{stat}) {}^{+0.14}_{-0.12}(\text{syst})$

3.8σ significance for null τ

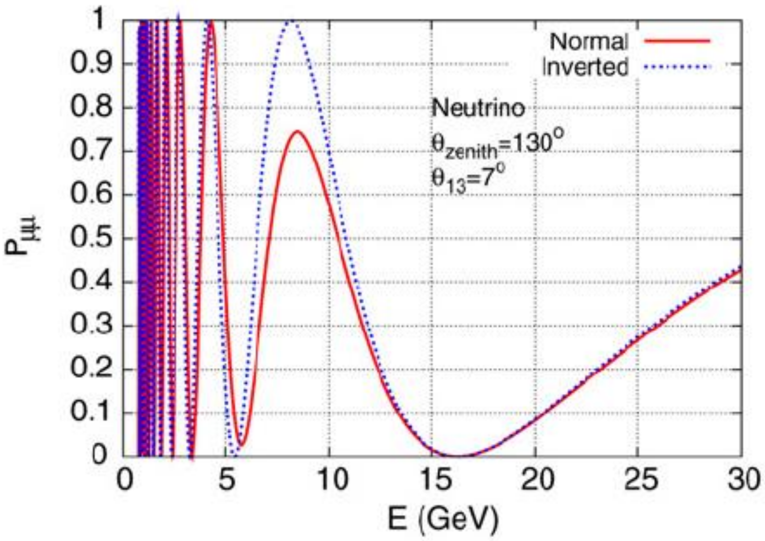
Zenith Distribution of τ-like events

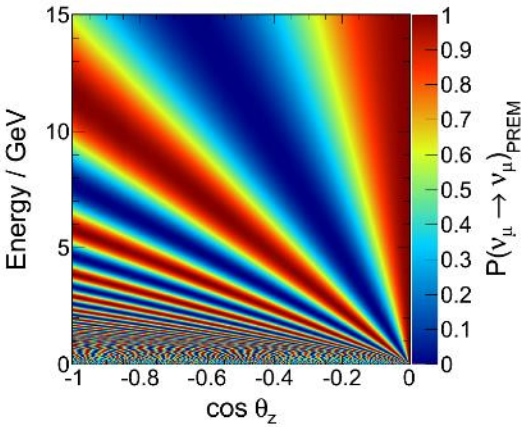


$\nu_\mu \rightarrow \nu_\tau$ channel has been confirmed by τ identification

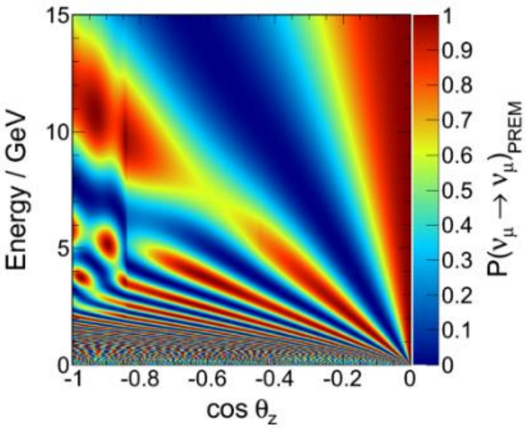
Mass Hierarchy from Atmospheric

- **Due to matter effect, oscillation probability of atmospheric muon neutrino when passing the Earth depends on mass hierarchy**
- **If can't do PID, most of the effec will cancel, but the residual effec still can distinguish the MH**
- **7 GeV**

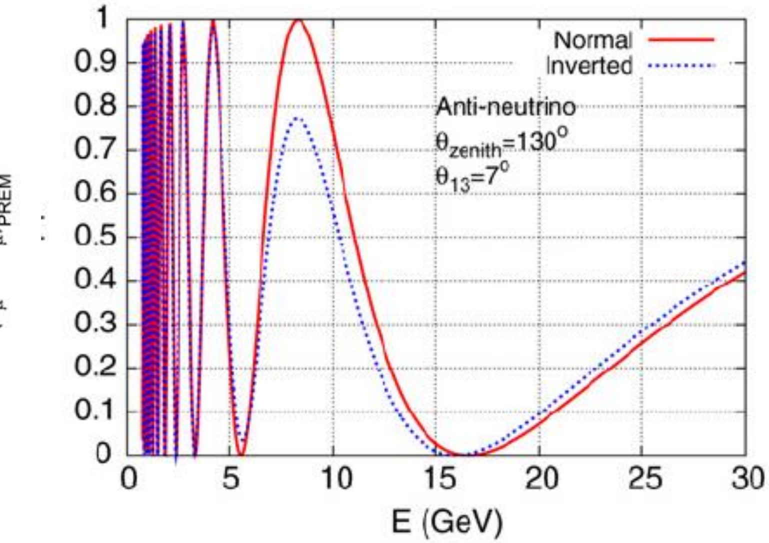




IH

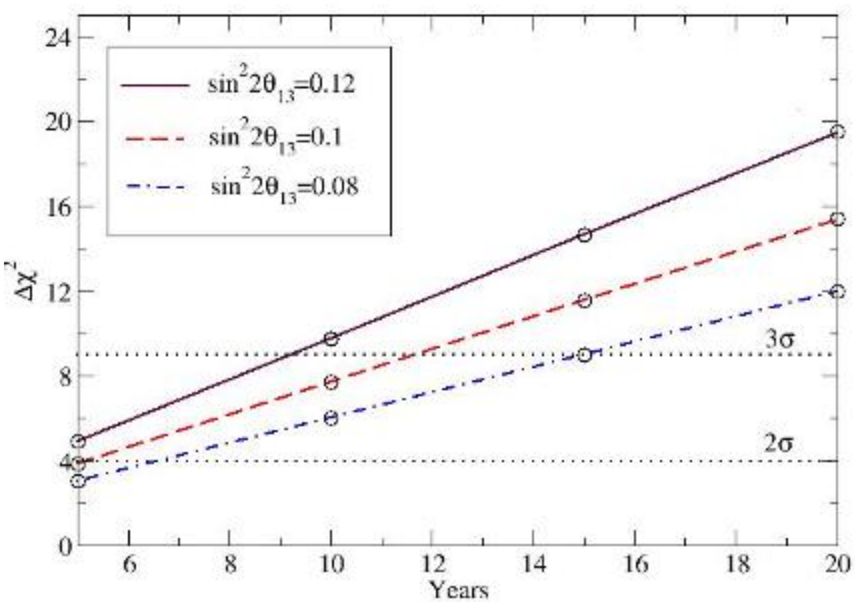


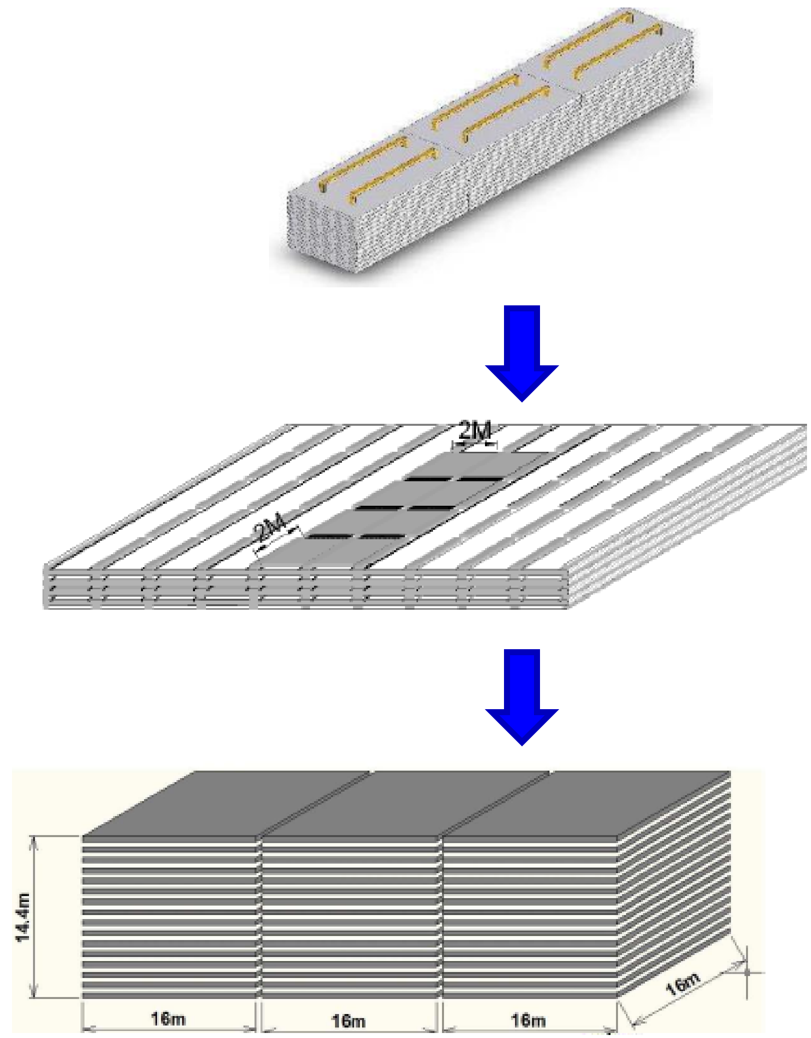
NH



INO

- Atmospheric neutrino
- 50kt Iron-calorimeter
- Construction: 2012-2017
- Operation: 2018
- 3 s in ~2030

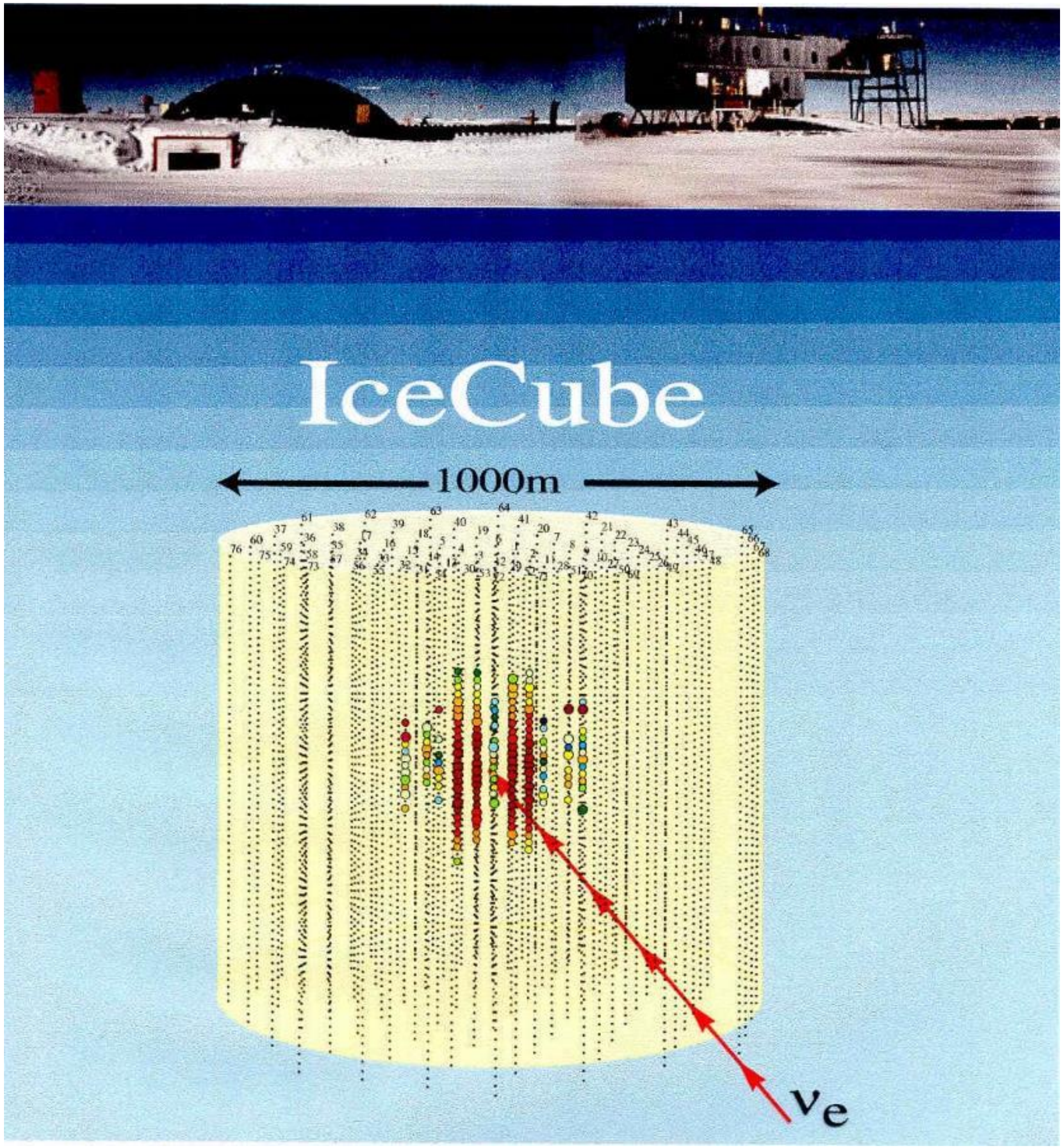


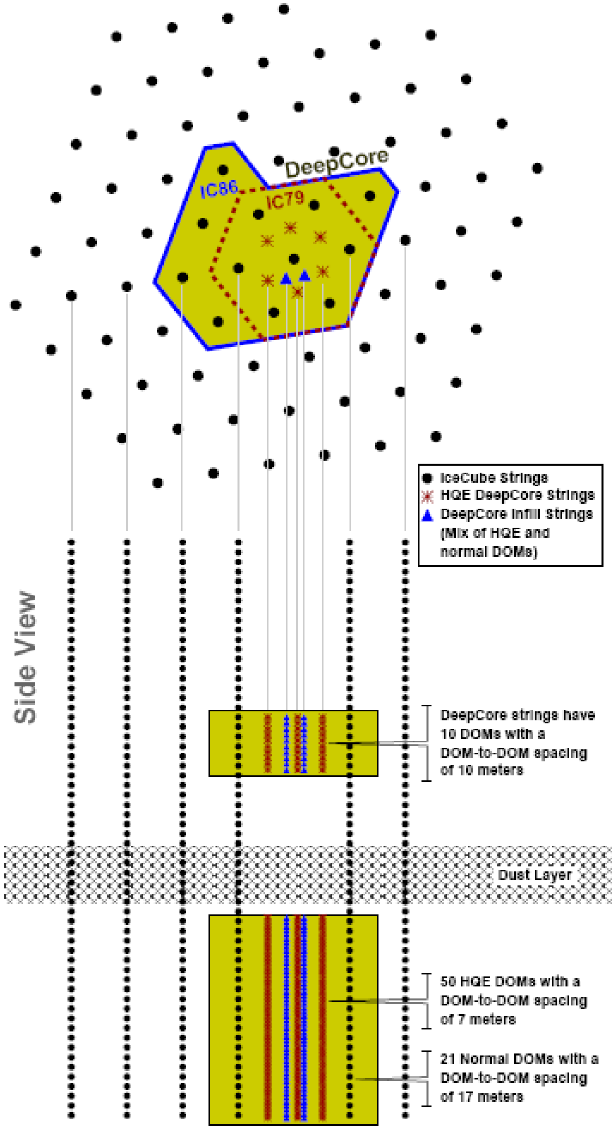


three 17kt modules,
each 16×16×14.4m³
150 iron plates, each 5.6 cm thick

PINGU

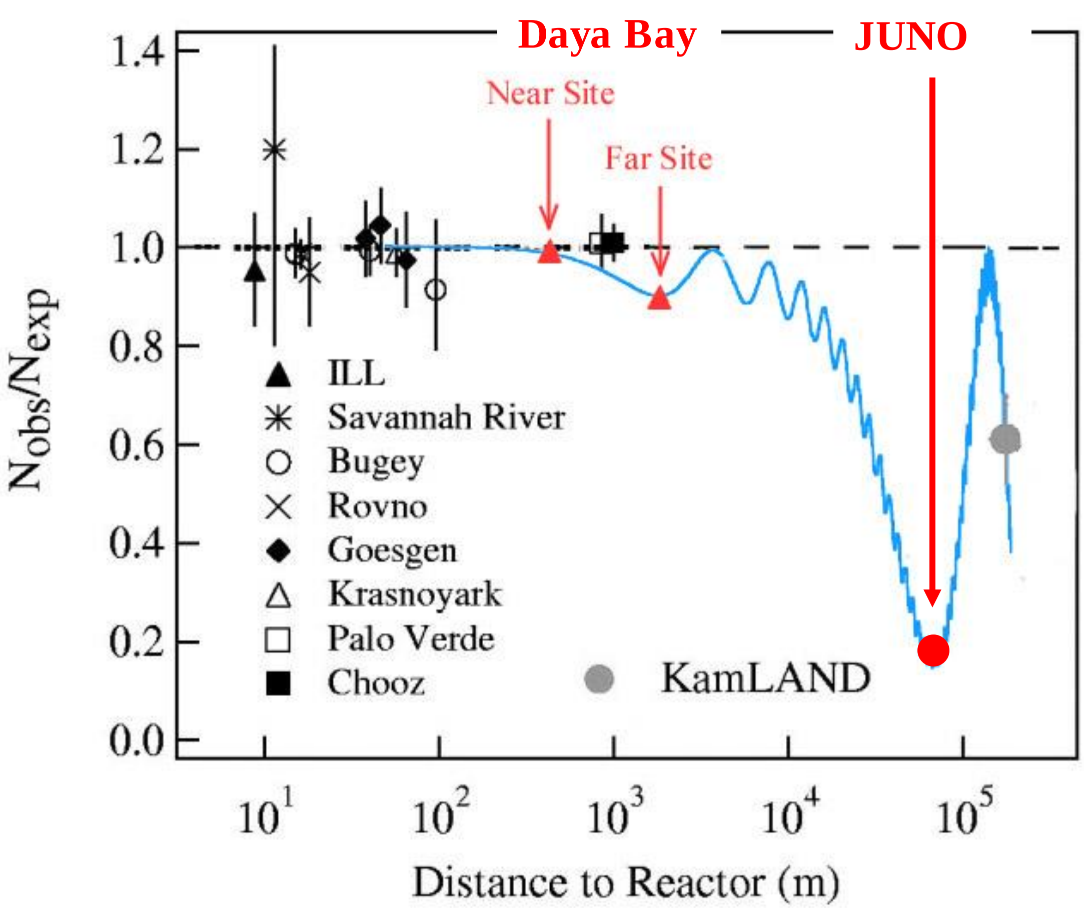
- Phased Icecube Next Generation Upgrade





The JUNO Experiment

- Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, approved in Feb. 2013. ~ 300 M$.



- 20 kton LS detector
- 3% energy resolution
- Rich physics possibilities
  - ⇨ Reactor neutrino for Mass hierarchy and precision measurement of oscillation parameters
  - ⇨ Supernovae neutrino
  - ⇨ Geoneutrino
  - ⇨ Solar neutrino
  - ⇨ Sterile neutrino
  - ⇨ Atmospheric neutrino
  - ⇨ Exotic searches

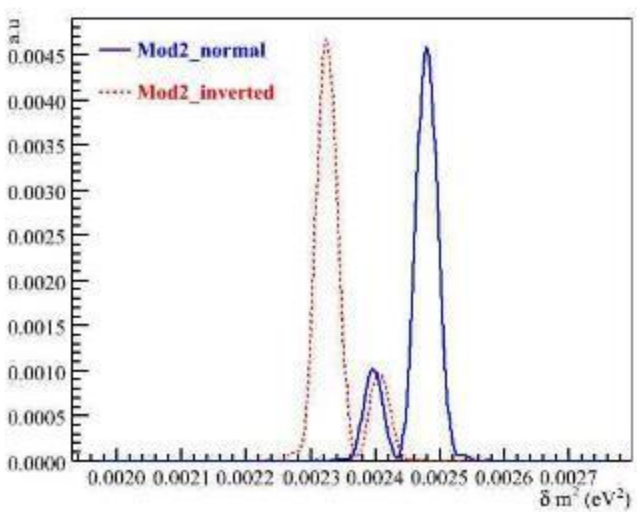
Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011; by J. Cao at Nutel 2009, NuTurn 2012 ;
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103, 2008; PRD79:073007,2009

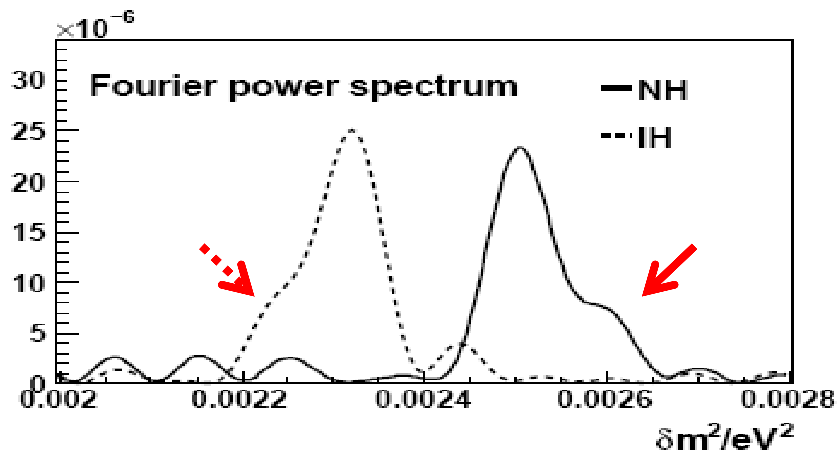
Interference: Relative Measurement

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

$$
\begin{aligned}
P_{21} &= 0.81\ \sin^2\Delta_{21} \\
P_{31} &= 0.7 \times \sin^2 2\theta_{13} \times \sin^2\Delta_{31} \\
P_{32} &= 0.3 \times \sin^2 2\theta_{13} \times \sin^2\Delta_{32}
\end{aligned}
$$

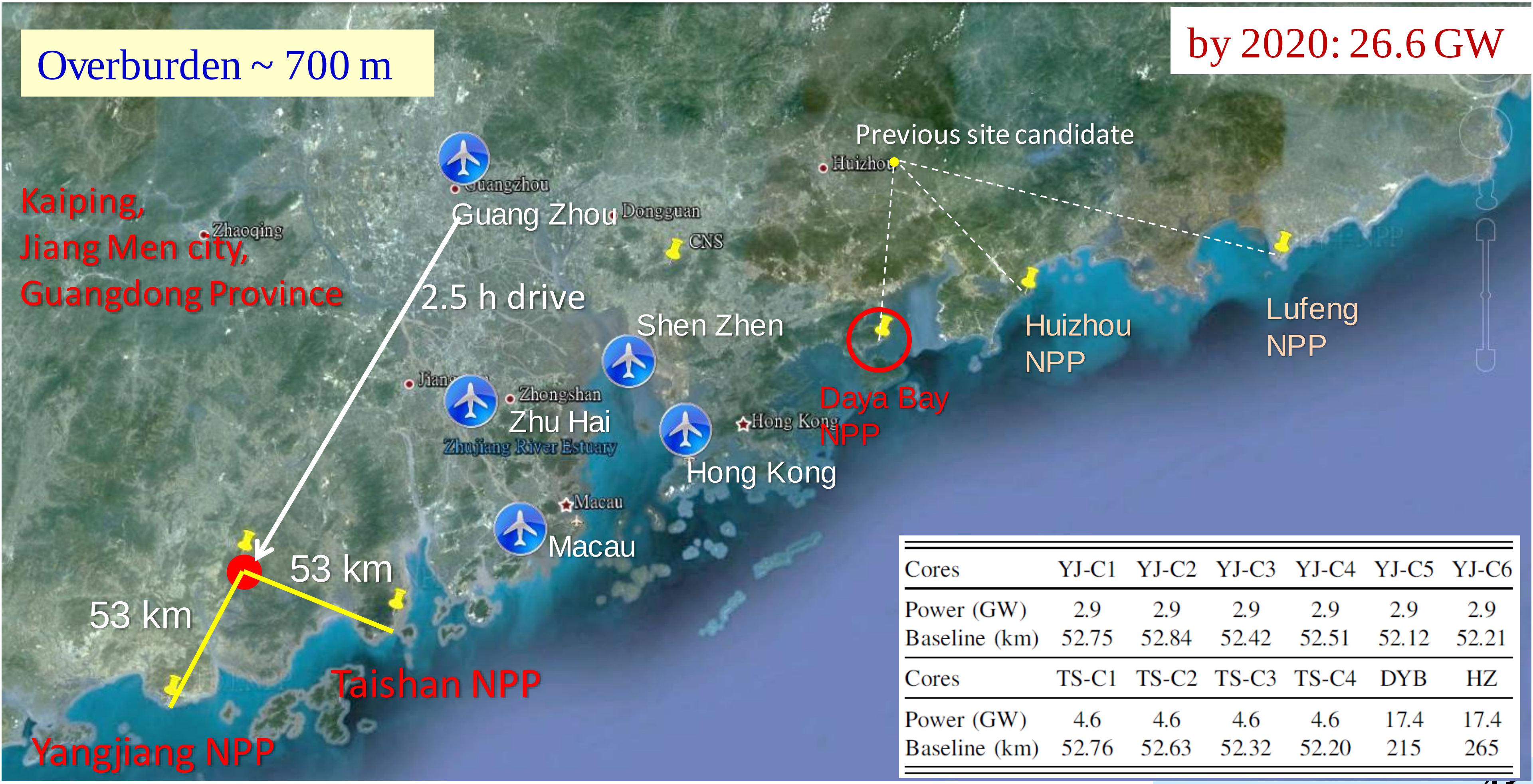
- **The relative larger (0.7) oscillation and smaller (0.3) oscillation, which one is slightly (1/30) faster?**
- **Take Δm^2_{32} as reference, after a Fourier transformation**
  - ⇨ **NH: $\Delta m^2_{31} > \Delta m^2_{32}$, Δm^2_{31} peak at the right of Δm^2_{32}**
  - ⇨ **IH: $\Delta m^2_{31} < \Delta m^2_{32}$, Δm^2_{31} peak at the left of Δm^2_{32}**





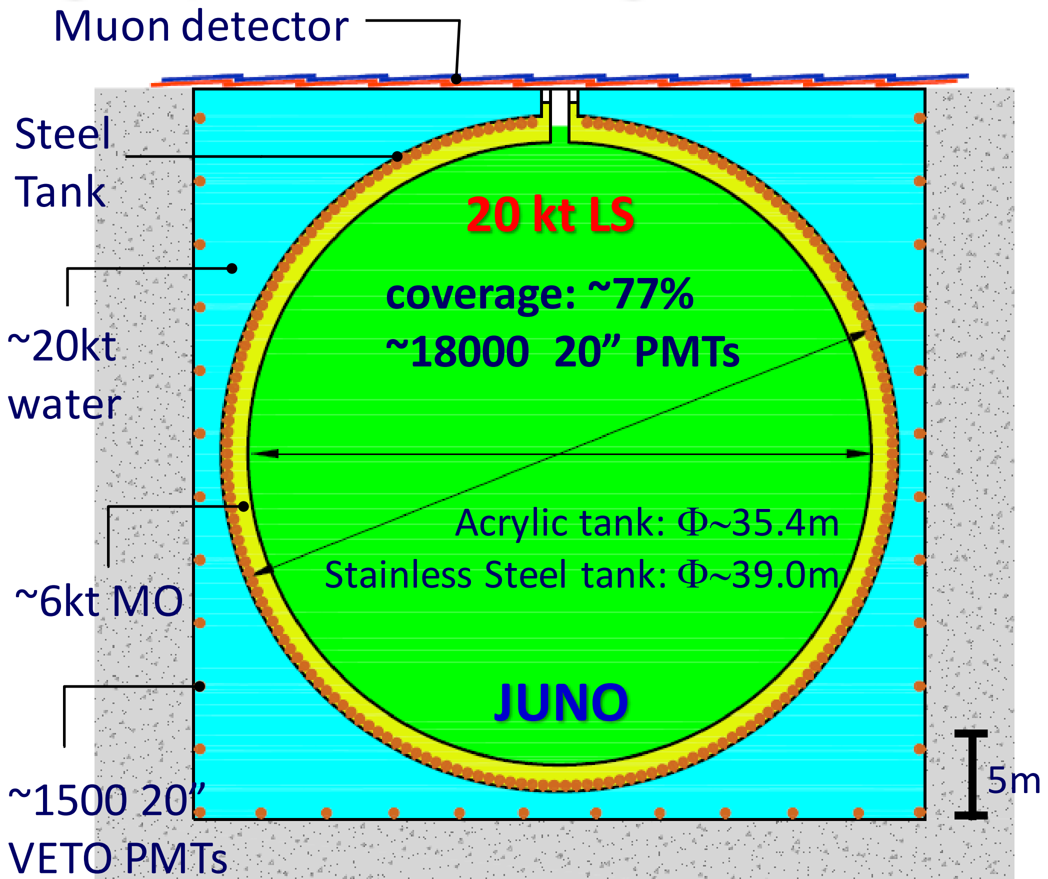
Location of JUNO

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



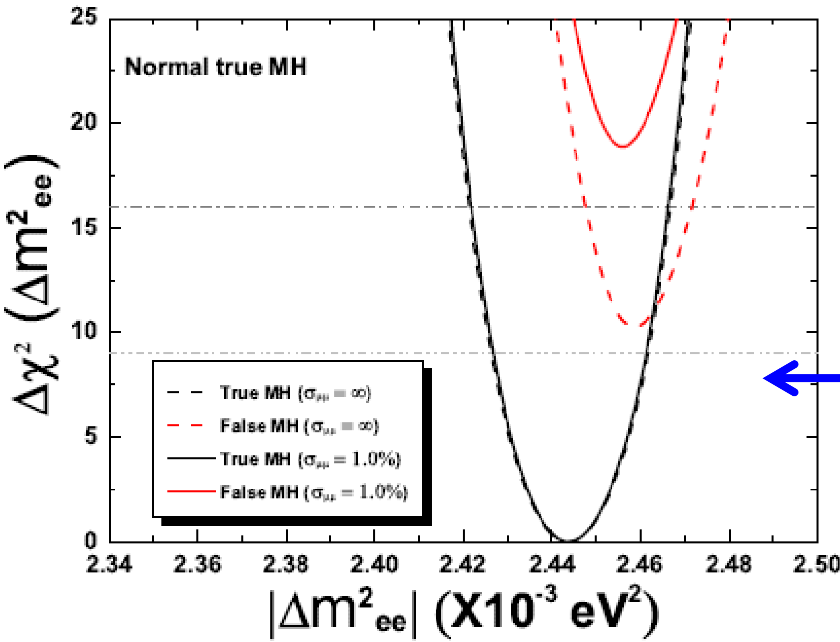
Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

High-precision, giant LS detector



	KamLAND	BOREXINO	JUNO
LS mass	1 kt	0.5 kt	20 kt
Energy Resolution	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

Sensitivity on MH and mixing parameters



JUNO **MH sensitivity with 6 years' data:**

Ref: Y.F Li et al, PRD 88, 013008 (2013)	**Relative Meas.**	**[a] Use absolute Δm^2**
Ideal case	4σ	5σ
[b] Realistic case	3σ	4σ

(a) If accelerator experiments, e.g NOvA, T2K, can measure $\Delta m^2_{\mu\mu}$ to ~1% level

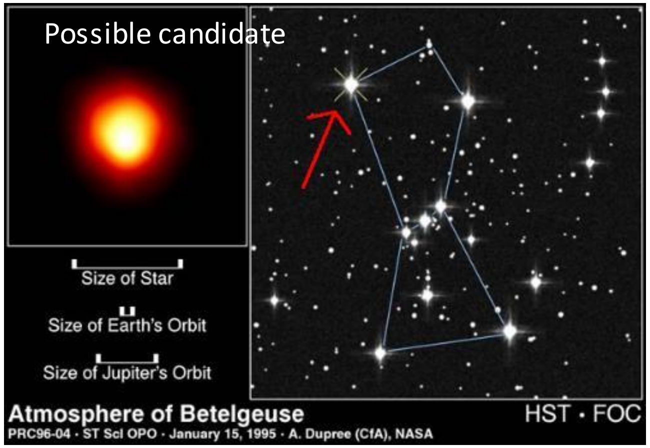
(b) Take into account multiple reactor cores, uncertainties from energy non-linearity, etc

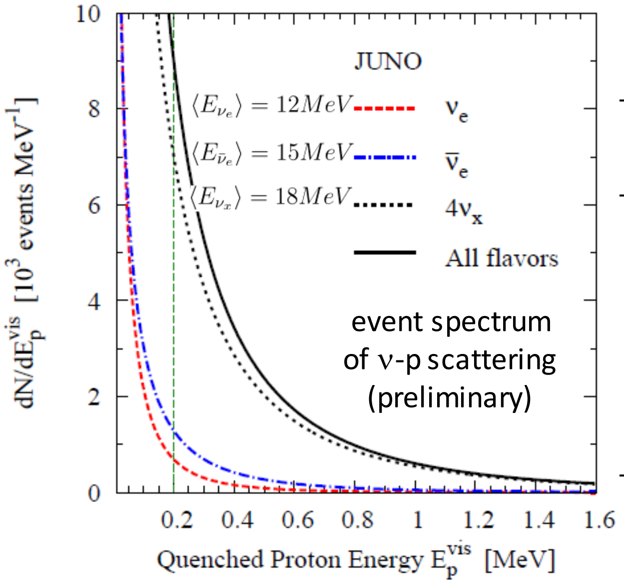
	Current	**JUNO**
Δm^2_{12}	~3%	~0.5%
Δm^2_{23}	~4%	~0.6%
$\sin^2\theta_{12}$	~7%	~0.7%
$\sin^2\theta_{23}$	~15%	N/A
$\sin^2\theta_{13}$	~6% → ~4%	~ 15%

Probing the unitarity of U_{PMNS} to ~1% more precise than CKM matrix elements !

Supernova Neutrinos

- Less than 20 events observed so far
- Assumptions:
  - ⇨ Distance: 10 kpc (our Galaxy center)
  - ⇨ Energy: 3×10^{53} erg
  - ⇨ L_ν the same for all types





Estimated numbers of neutrino events in JUNO (preliminary)

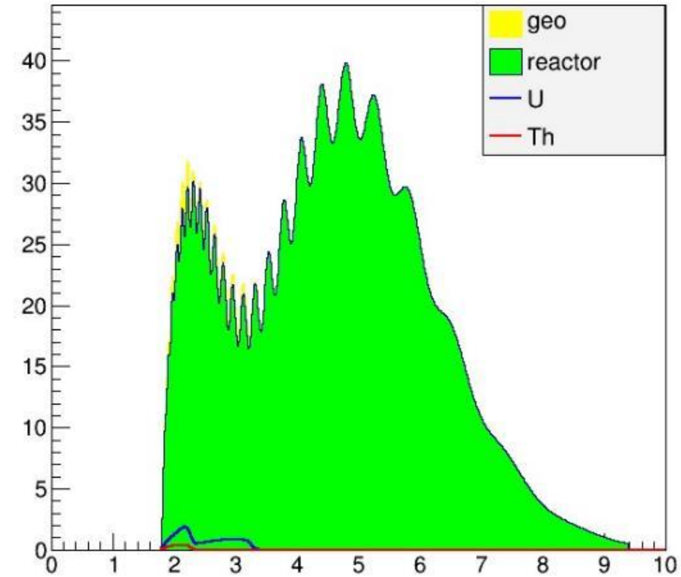
Channel	Type	Events for different $\langle E_\nu\rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	NC	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \to \nu + {}^{12}C^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}C \to e^- + {}^{12}N$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$	CC	6.0×10^1	1.1×10^2	1.6×10^2

LS detector vs. Water Cerenkov detectors: much better detection to these correlated events

→ Measure energy spectra & fluxes of almost all types of neutrinos

Other Physics

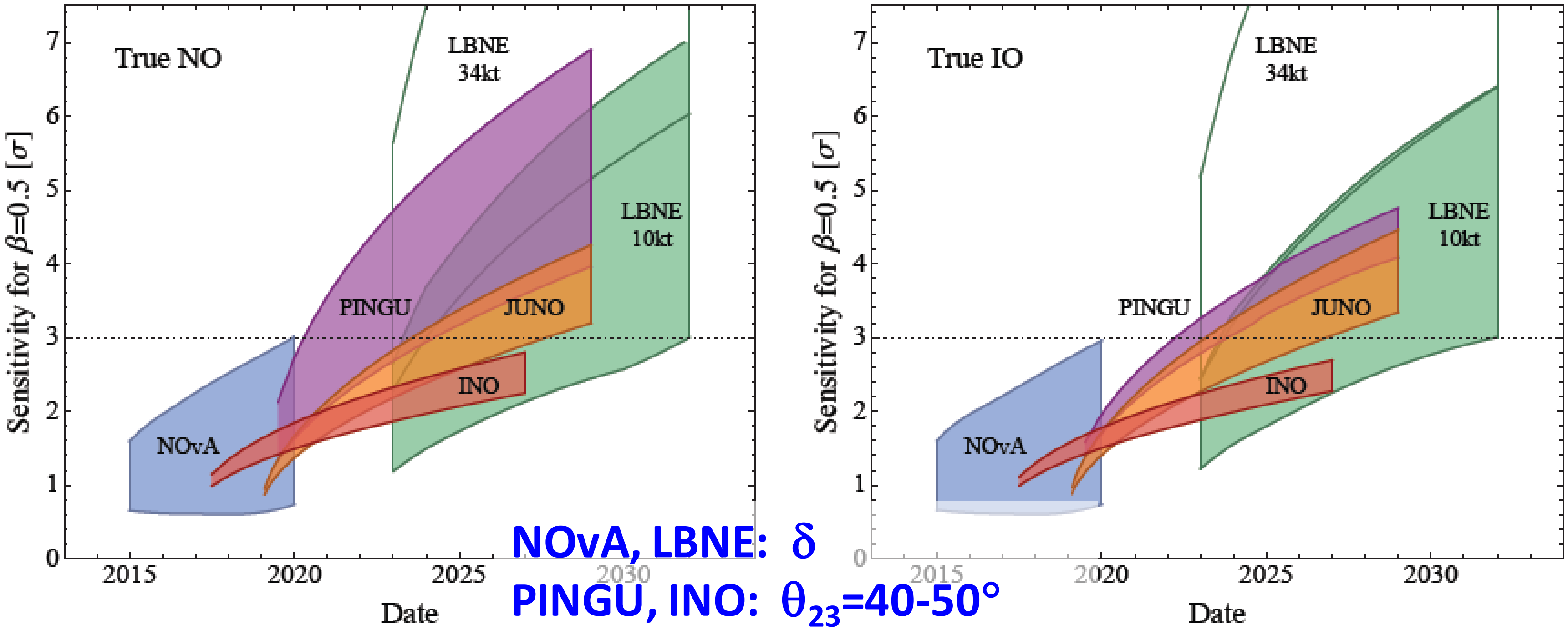
- **Geo-neutrinos**
  - ⇨ Current results
    KamLAND: 30±7 TNU *(PRD 88 (2013) 033001)*
    Borexino: 38.8±12.2 TNU *(PLB 722 (2013) 295)*
    Statistics dominant
  - ⇨ Desire to reach an error of 3 TNU
  - ⇨ JUNO: ×10 statistics
    - Huge reactor neutrino backgrounds
    - Expectation: ~36±10%±10%



- **Solar neutrino**
  - ⇨ Metallicity? Vacuum oscillation to MSW?
  - ⇨ need LS purification, low threshold
  - ⇨ background handling (radioactivity, cosmogenic)
- **Atmospheric neutrino**
  - ⇨ measure ν energy instead of leptons' in LS. ~ 2σ for MH in 10 years
- **Diffuse supernovae ν, Sterile ν, Indirect dark matter, Nucleon decay, etc.**

Experiments/Proposals for MH

M. Blennow et al., JHEP 1403 (2014) 028



NOvA, LBNE: δ
PINGU, INO: θ_{23}=40-50°
JUNO: 3%-3.5%

JUNO: Competitive in schedule and Complementary in physics

- ⇨ Have chance to be the first to determine MH
- ⇨ Independent of the CP phase and θ_{23} (Acc. and Atm. do)
- ⇨ Combining with other experiments can significantly improve the sensitivity
- ⇨ Well established liquid scintillator detector technology

Neutrino Mass

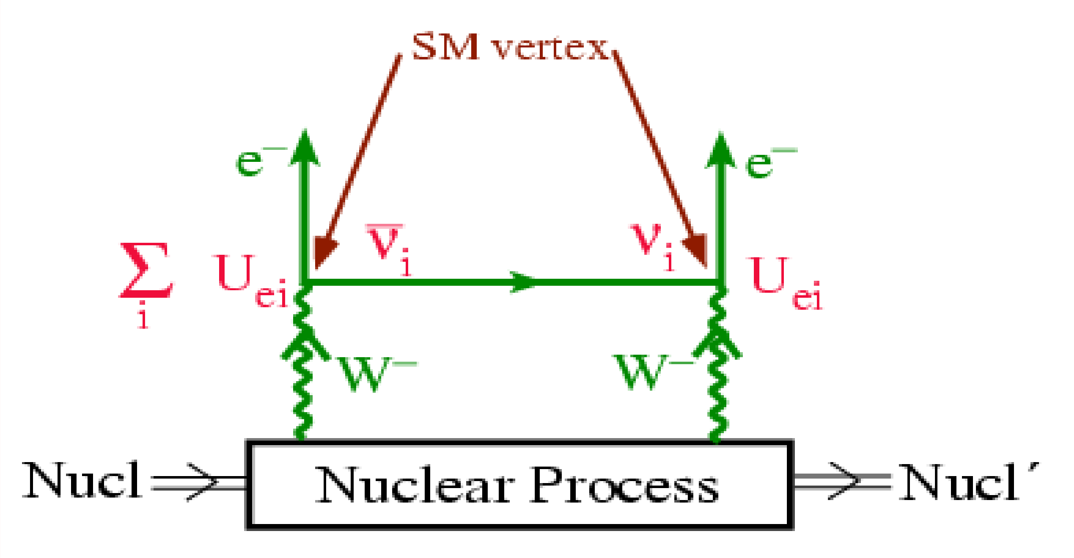
Three ways to determine the absolute mass

1) 0νββ decay

$$\langle m \rangle_{ee} = \sum_i (m_i V_{ei}^2)$$

2) β decay

$$\langle m \rangle_{e} = \sqrt{\sum_i (m_i^2 \, |V_{ei}|^2)}$$



3) Cosmology

And Supernovae?

non-oscillation parameter	probed by	experimental limit at 99% CL	99% CL range normal hierarchy	99% CL range inverted hierarchy
ee-entry of m	$0\nu2\beta$	$m_{ee} < 0.39\,h$ eV	$(1.1 \div 4.5)$ meV	$(12 \div 57)$ meV
$(m^\dagger m)_{ee}^{1/2}$	β-decay	$m_{\nu_e} < 2.1$ eV	$(4.6 \div 10)$ meV	$(42 \div 57)$ meV
$m_1 + m_2 + m_3$	cosmology	$m_{\rm cosmo} \lesssim 0.5$ eV	$(51 \div 66)$ meV	$(83 \div 114)$ meV

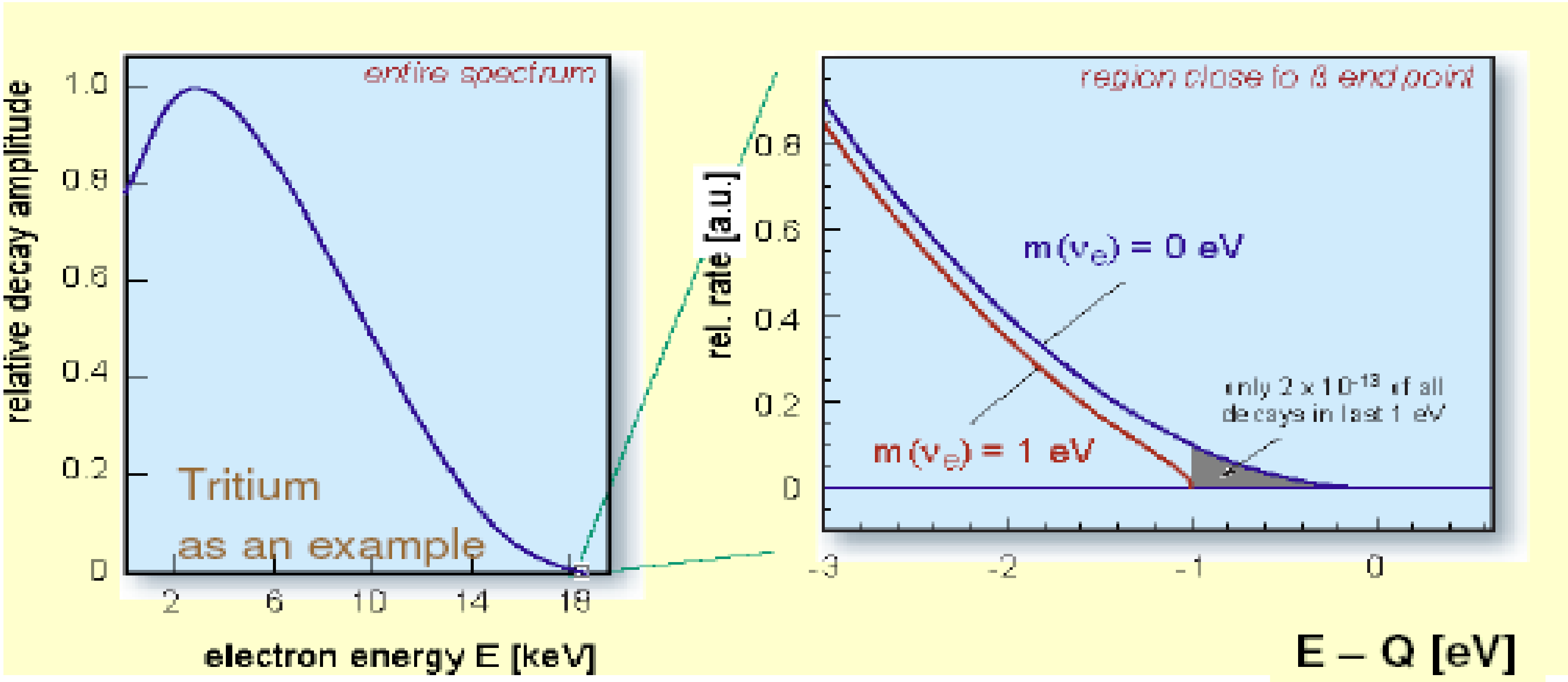
Direct Measurement: Kurie plot

- **Nuclear β decay:**

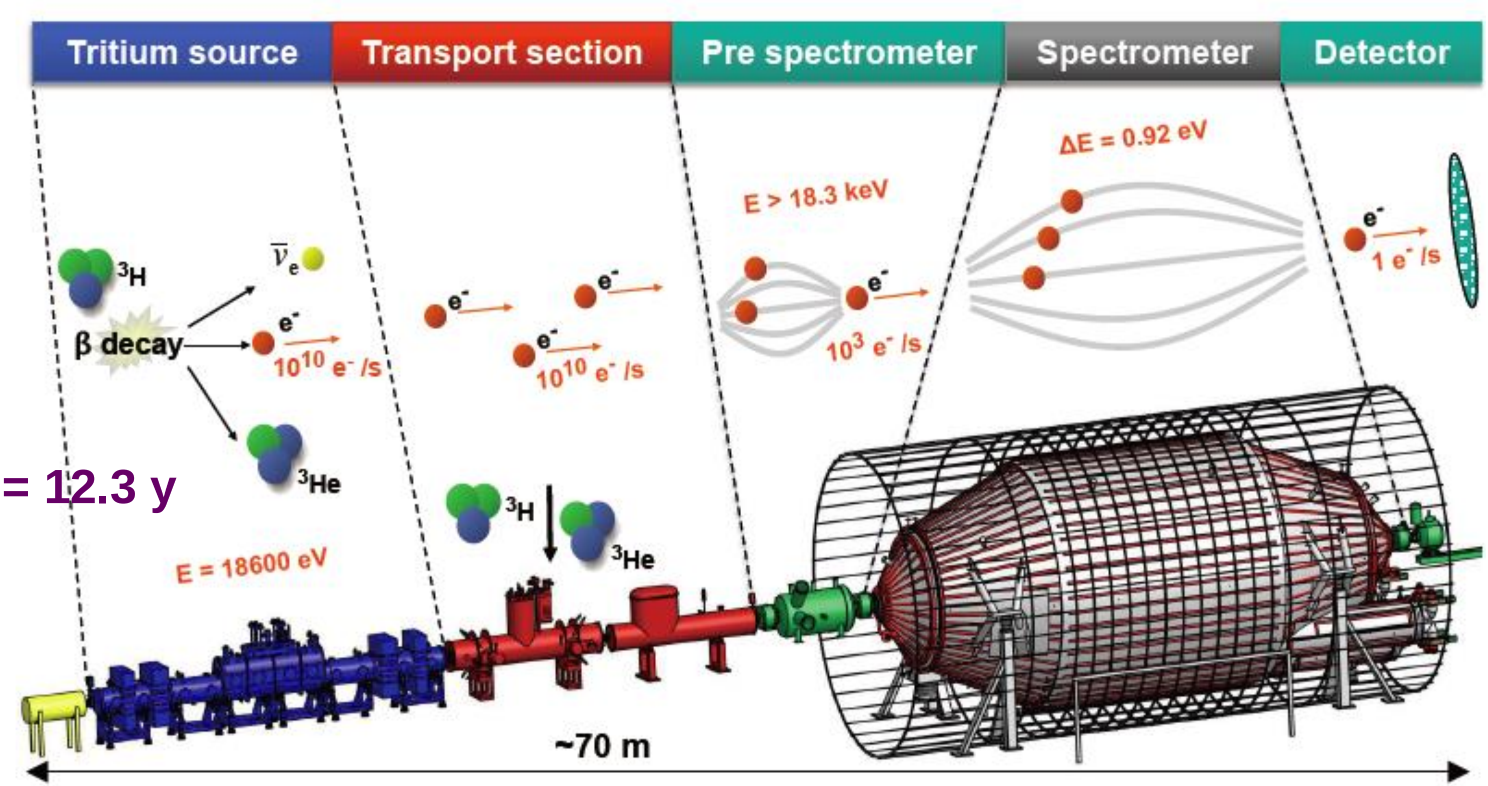
$$\frac{d\Gamma_i}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E,Z) \cdot \theta(E_0 - E - m_i)$$

(ν– mass)²

- **Neutrino mass determination: E0 & shape**



Katrin experiment



$T_{1/2}$ = 12.3 y

Magnetic Adiabatic Collimation + Electrostatic Filter

A large spectrometer:
Sensitivity increase with area
Low statistics for relevant events
Resolution: ~ 1 eV

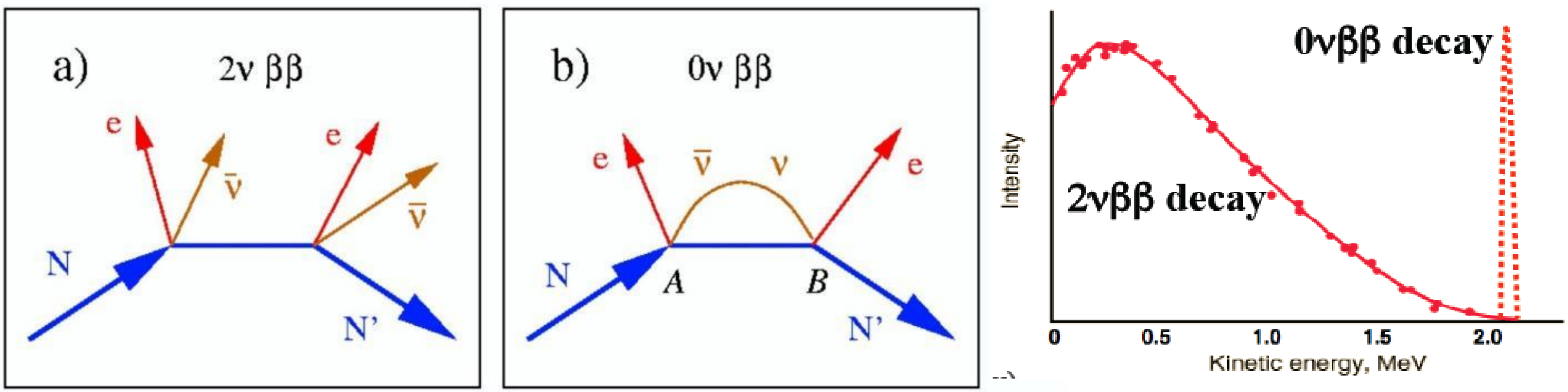
Sensitivity @ 90%CL:
m(ν) < 0.2 eV
Last such exp. ?

ββ-decays: two modes

2ν mode: a conventional 2nd order process in nuclear physics

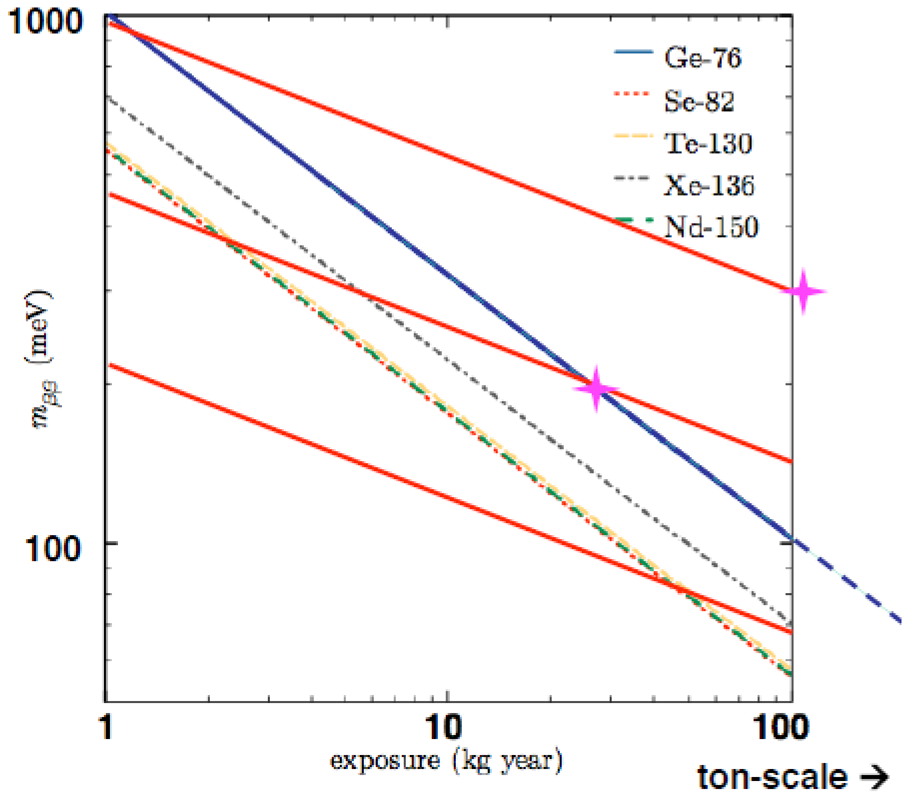
0ν mode: a hypothetical process can happen only if:
- $M_\nu \neq 0$
- $\overline{\nu} = \nu$

Since helicity has to "flip"



- 2ν mode ββ decays would have a half lives in excess of 10^{20} years
- **A second order process, Only if the first order beta decay is forbidden**
- **Experimental observation of 2νββ–decays in 1980'**

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z) \left|M_{0\nu}\right|^2 m^2_{\beta\beta}$$



$$m_{\beta\beta} = \left|\sum_i U^2_{ei}\, m_i\right|$$

- **Without Background**

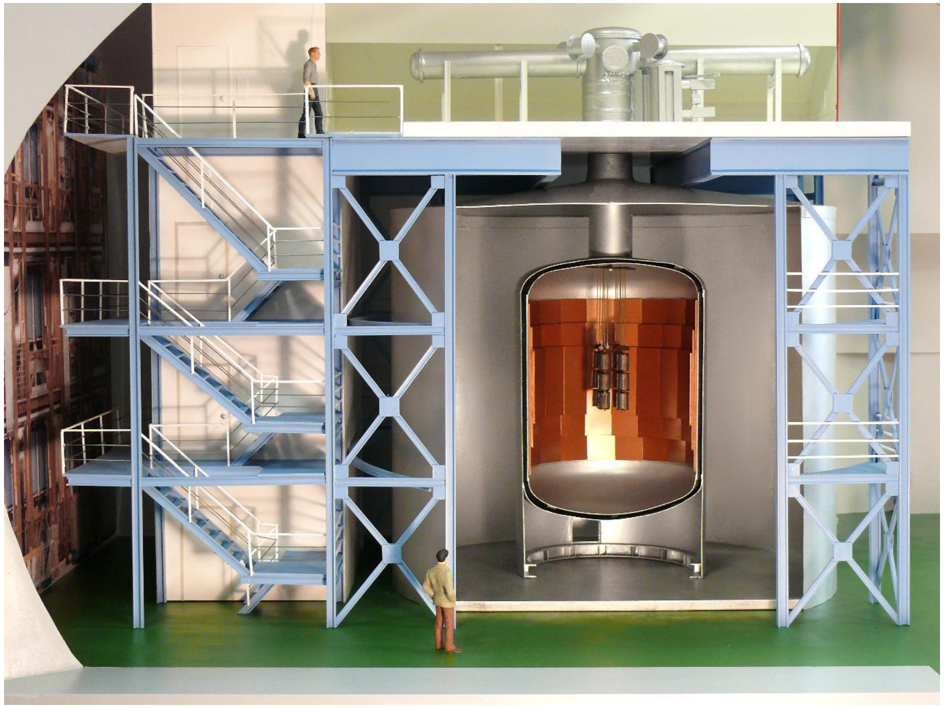
$$m_{\beta\beta} = K_1 \sqrt{\frac{N}{\varepsilon M t}}$$

- **With Background**

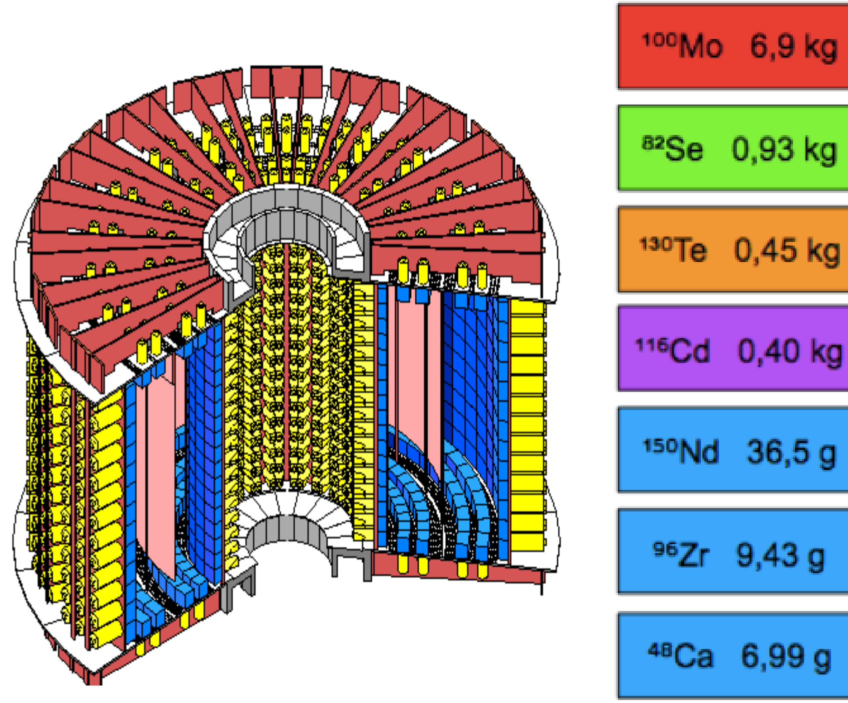
$$m_{\beta\beta} = K_2\ \sqrt{1/\varepsilon}\ \left(\frac{c\,\Delta E}{Mt}\right)^{1/4}$$

M. Lindner

Some Experiments



Gerda in Gran Sasso

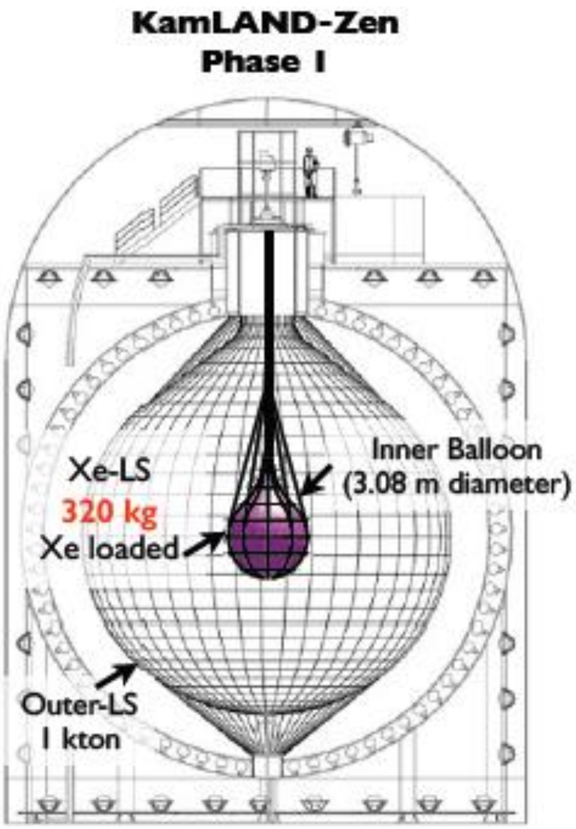


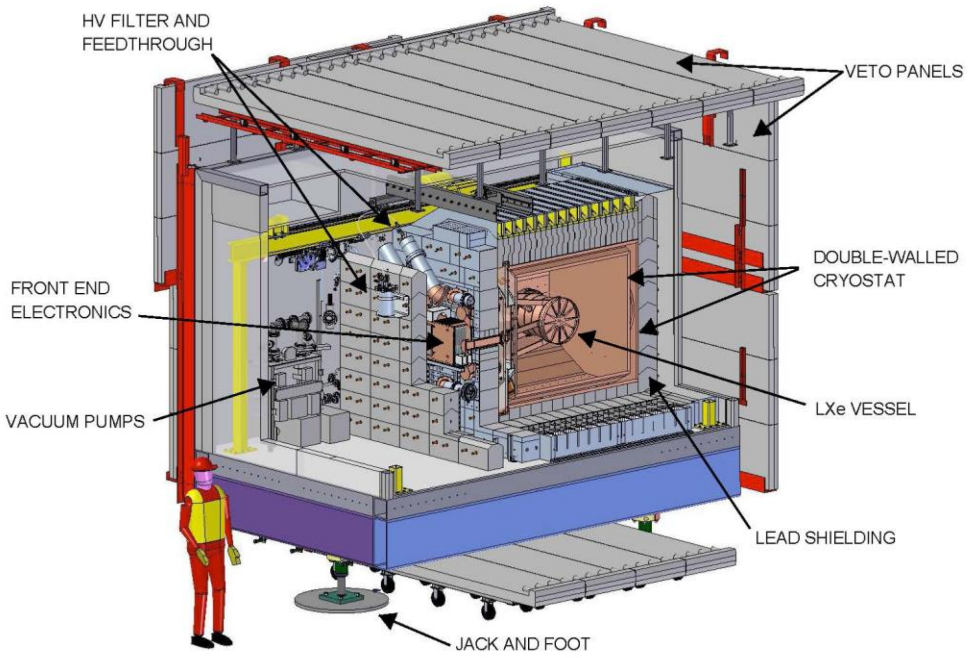
NEMO-3 in Frejus

- **Exposure 21.6 kg × yr**
- **Half-life limit**
- **$T_{1/2}(0\nu)>2.1\times10^{25}$ yr (90% CL)**

- **^{100}Mo Exposure 34.3 kg × yr**
- **Half-life limit**
- **$T_{1/2}(0\nu) >1.1\times10^{24}$ yr (90% CL)**
- **$\langle m_{\beta\beta}\rangle < 0.33 – 0.87$ eV**

Some Experiments





KamLAND-zen

- **320 kg Xe**
- **Half-life limit**

$T_{1/2}(0\nu) > 2.6\times10^{25}$ yr (90% CL)

- **$\langle m_{\beta\beta}\rangle < 0.33 – 0.87$ eV**

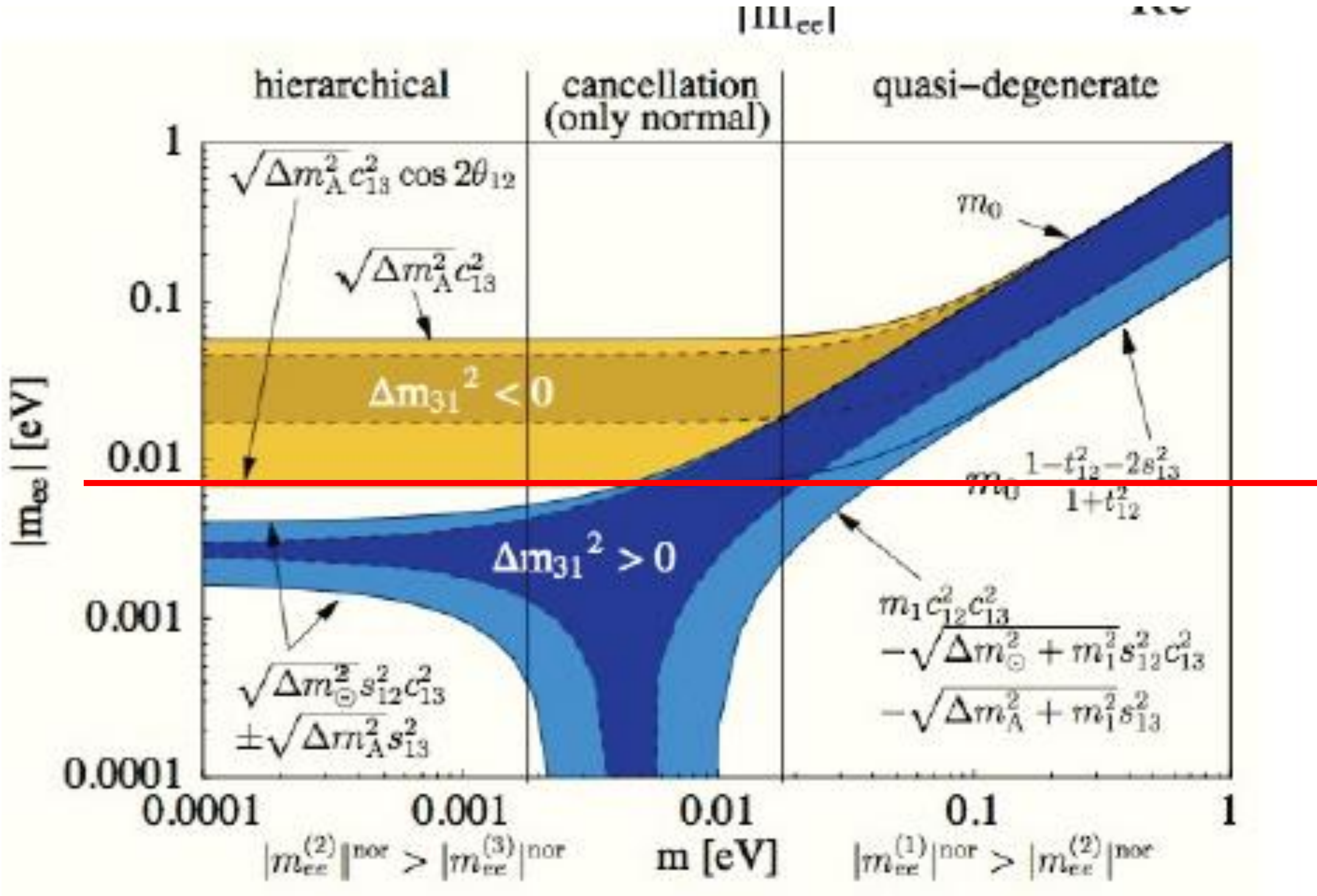
EXO-200: 200 kg

$$T_{1/2}^{0\nu\beta\beta} > 1.1\cdot10^{25}\ yr$$ **(90% CL)**

$\langle m\rangle_{\beta\beta} < 190 – 450$ meV

nEXO: 5 ton, Ba^{++} tag

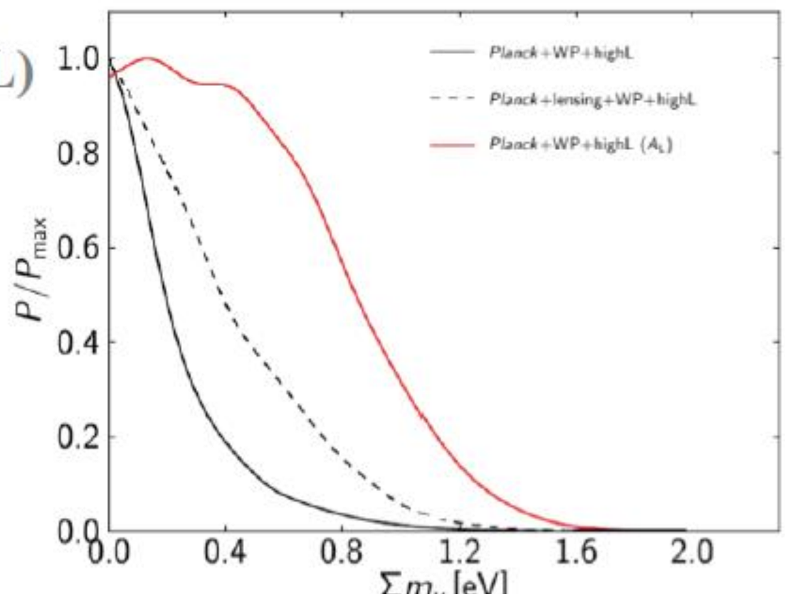
Mass Hierarchy and 0νββ



Neutrino mass and Neff from cosmology

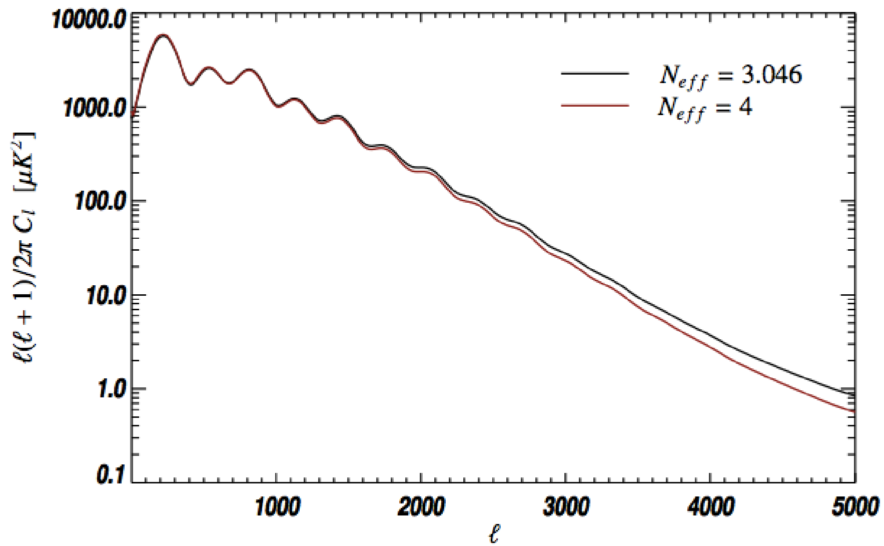
- **Planck+WP+high *l***
  $\Sigma m_\nu < 0.66$ eV (95%CL)
- **+ lensing**
  $\Sigma m_\nu < 0.85$ eV
- **+ BAO**
  $\Sigma m_\nu < 0.23$ eV

[Planck 2013 results.XVI.]



$$N_{\rm eff} = 3.32 \pm 0.27 \ (68\% CL)$$

$$\sum m_\nu < 0.28 \text{ eV} \ (95\% CL)$$



Summary: Neutrino Puzzles

- Neutrino oscillation well established by many exp.
  - ⇨ We have measured 4.5 parameters out of 6
  - ⇨ Mass hierarchy should be able to know in 10-15 years.
  - ⇨ CP violation may be determined in 15-20 years?
- Neutrino mass can be directly measured to >0.2 eV, New tech could improve the limit to 0.1 eV but hard to improve further.
- If we see $0\nu\beta\beta$ decay, very likely neutrino is Majorana particle. New physics must exist. Current planned experiments could exclude $0\nu\beta\beta$ if mass hierarchy is normal, but can't if MH is inverted.
- Is there sterile neutrino? (accelerator, reactor, source …)