Neutrino Oscillation Experiments

(Necessarily) Selected topics
(i.e., an abbreviated story)

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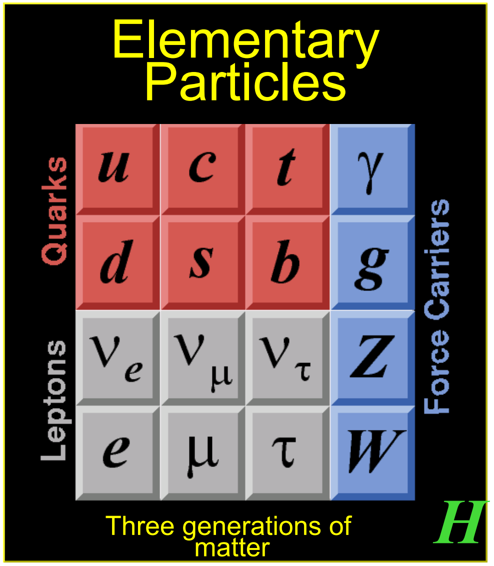
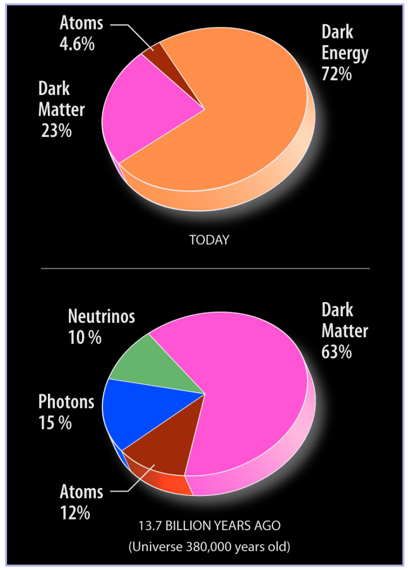
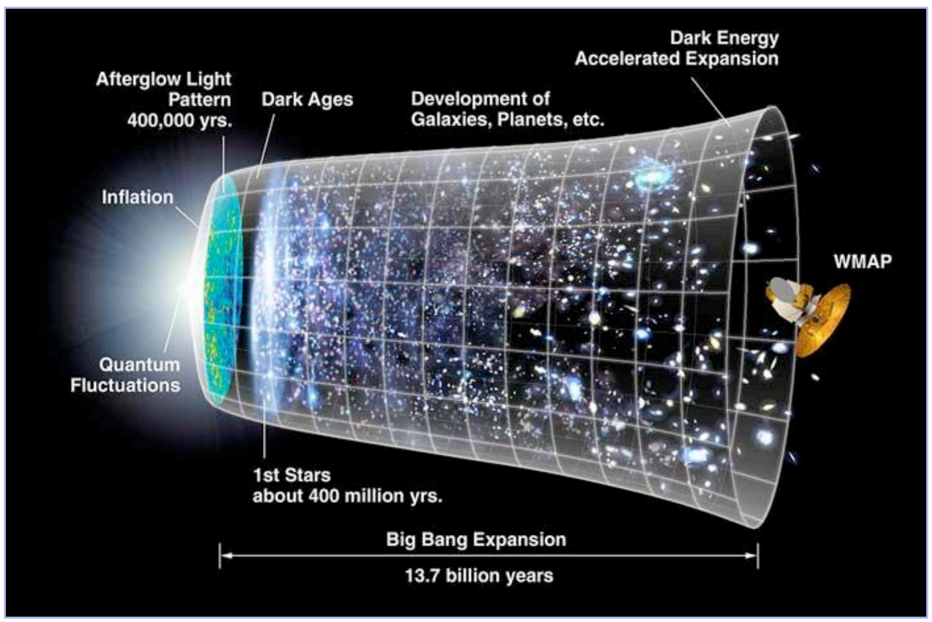
OUTLINE:

- Neutrino puzzles resolved
  - Solar neutrino deficit
  - Atmospheric neutrino anomaly
- Some neutrino oscillations QM
  - A little formalism
  - Approximations and
- 2-ν disappearance
  - Reactor experiments
  - Accelerator experiments
- Precision experiments
- Appearance experiments
- What remains: loooong baselines

The standard view of the Universe







Open questions:

- ✓ Why this structure?
- ✓ Matter-antimatter asymmetry ?
- ✓ What is dark matter ?
- ✓ What is dark energy ?
- ✓ What about gravity?
- ✓ …

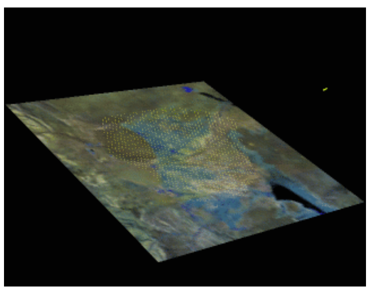
Neutrinos are
“implicated” in answering
most if not all of these questions!

Remarkable "Neutrino Years"
(painted with a broad brush)

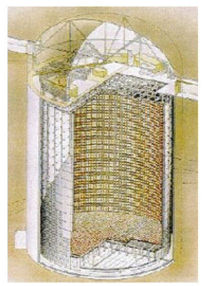
< 1998

- $m_\nu = 0, \qquad \nu = e, \mu, \tau$

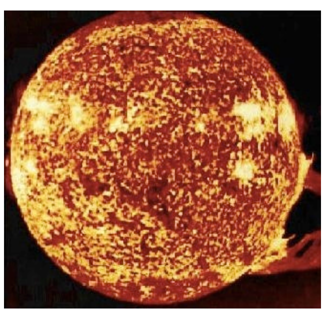
- *atmospheric* neutrinos *anomaly*



$$\frac{N(\nu_\mu)}{N(\nu_e)} \neq 2$$

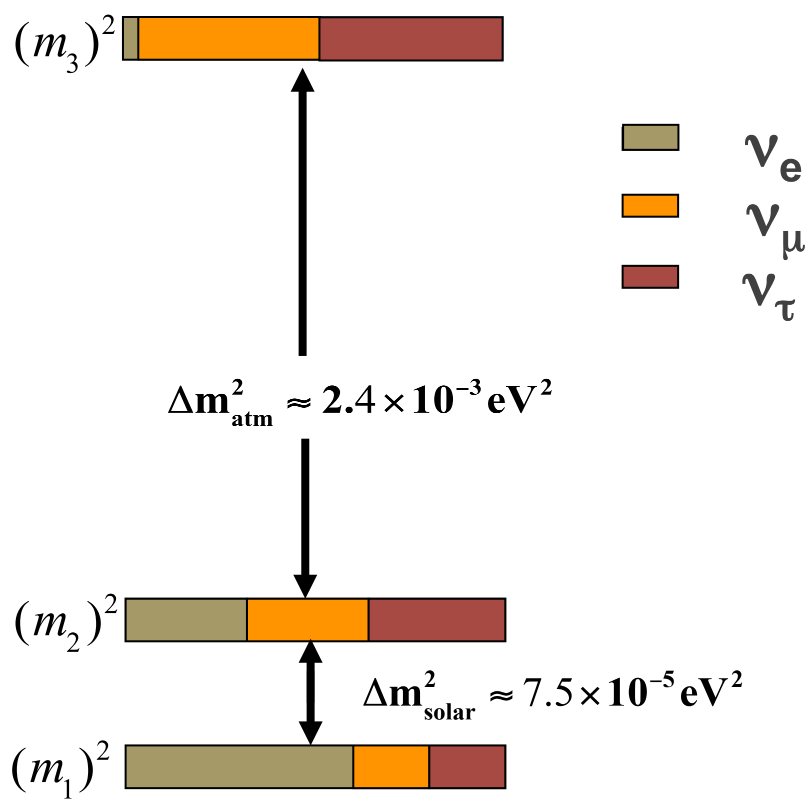


- *solar* neutrinos *deficit*



1998 - 2014

- *neutrino oscillations* $\rightarrow m_\nu \neq 0$
- *measured* Δm^2_{sol} *and* Δm^2_{atm}
- *measured* 3 *out of* 4 *angles*



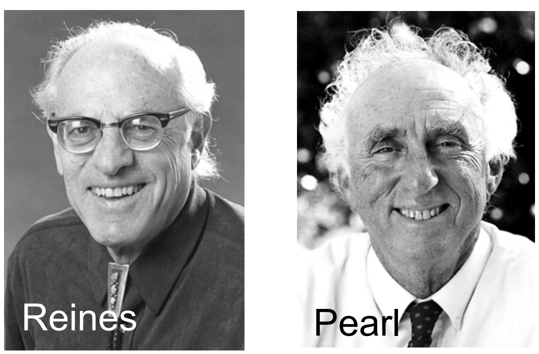
Remarkable "Neutrino Years"

(painted with a broad brush)

< 1998

- $m_\nu = 0, \qquad \nu = e, \mu, \tau$

Nobel 1988



Nobel 1995

1998 - 2014

- *neutrino oscillations* $\rightarrow m_\nu \neq 0$
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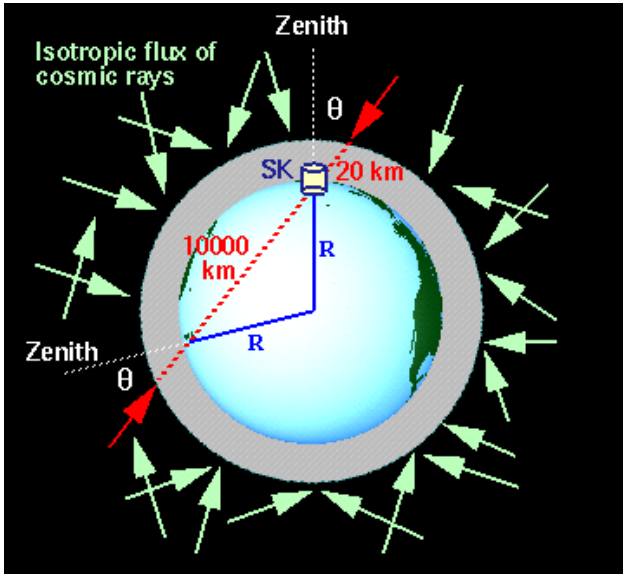
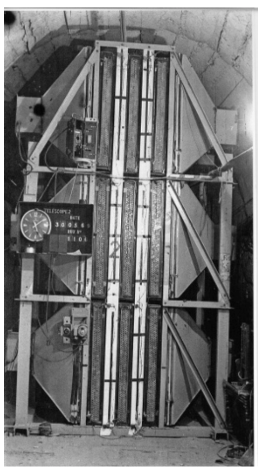
Nobel 2002

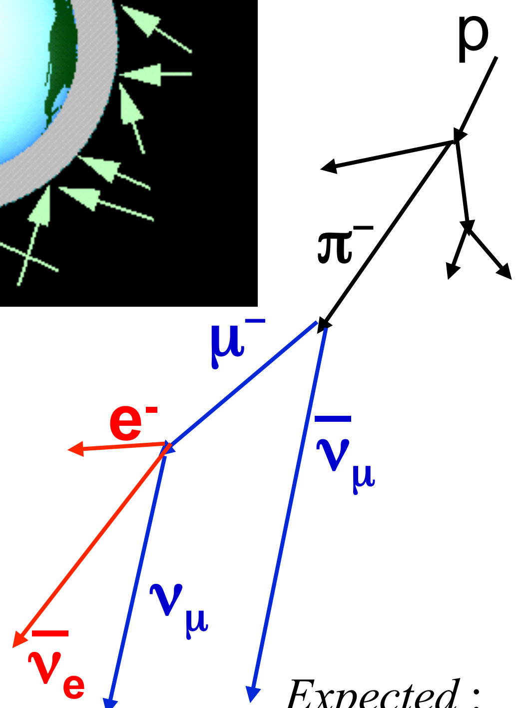
ATMOSPHERIC NEUTRINOS ANOMALY RESOLVED

Atmospheric neutrinos *anomaly* resolved
The advent of LARGE detectors

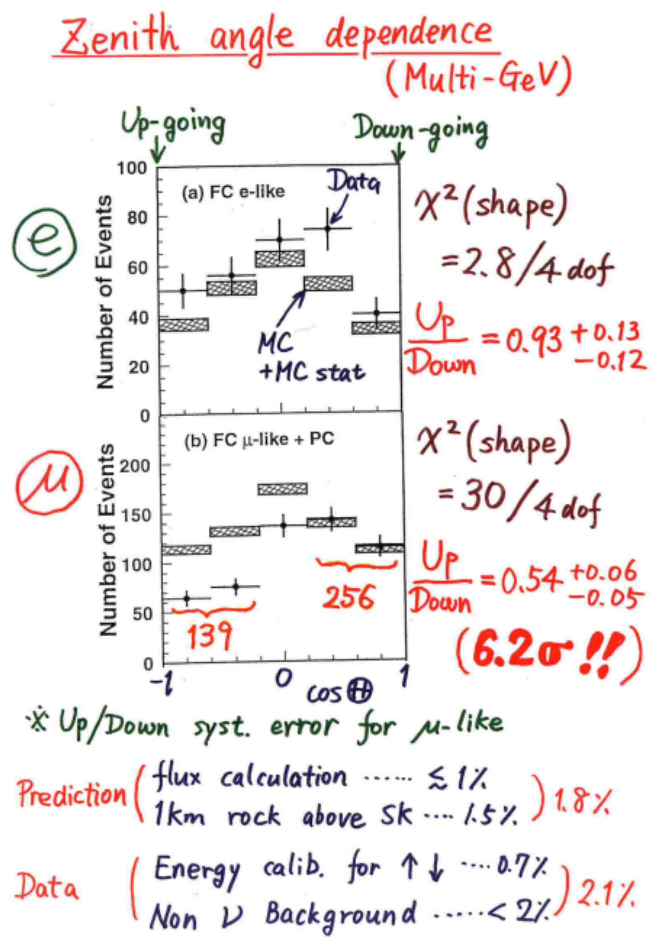




First detection of atmospheric neutrino at Kolar Gold Field in 1965

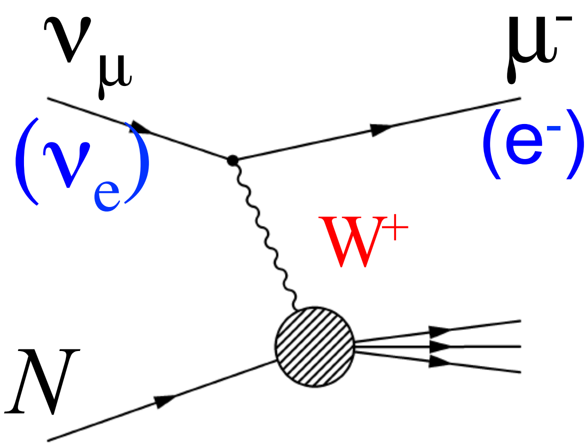


$$\textit{Expected}: \frac{N(\nu_\mu + \bar{\nu}_\mu)}{N(\nu_e + \bar{\nu}_e)} \approx 2$$

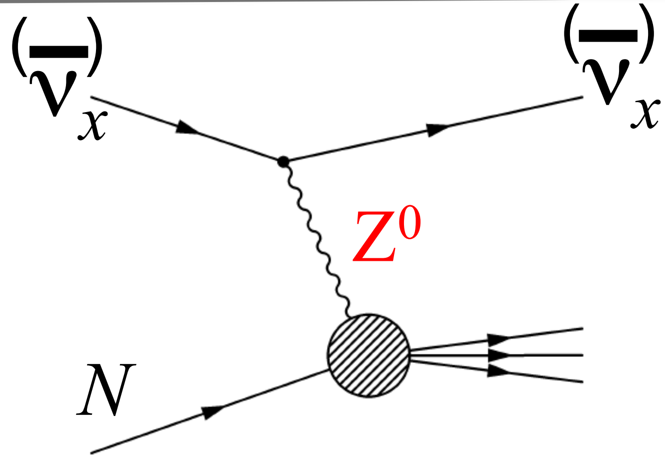


The announcement of the discovery of neutrino oscillations at Neutrino 1998 by T. Kajita

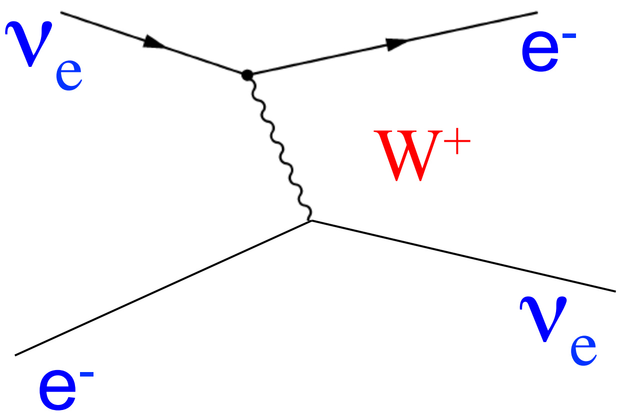
Neutrino Interactions

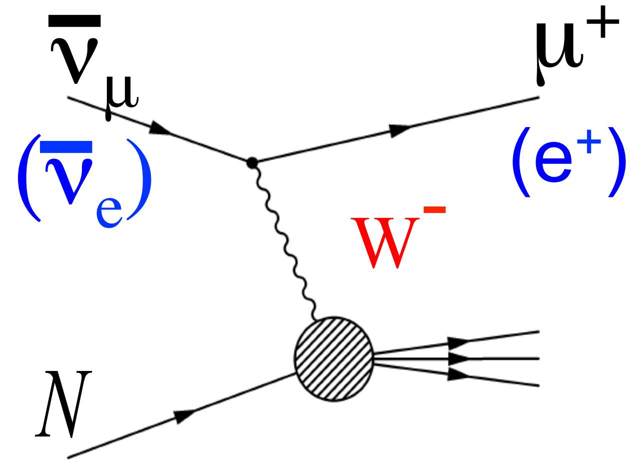


Charged Current



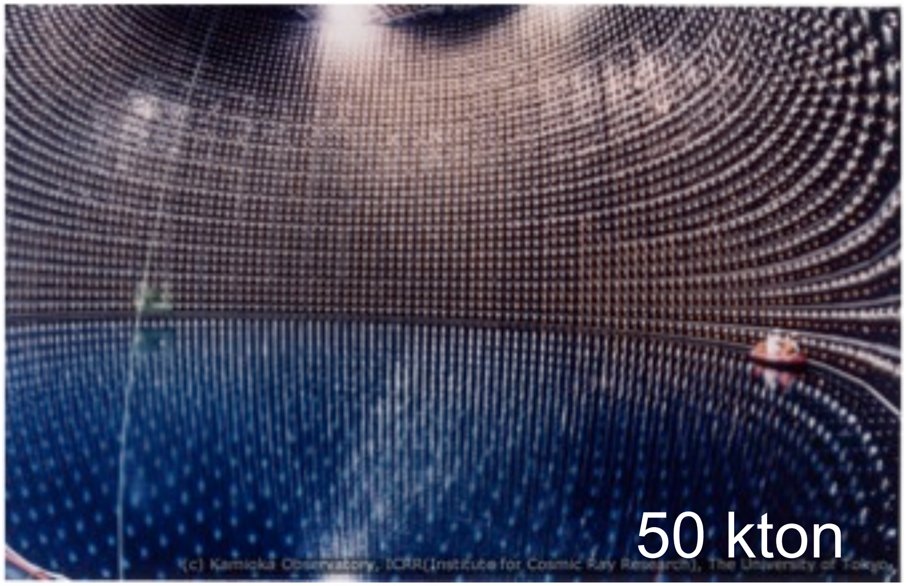
Neutral Current

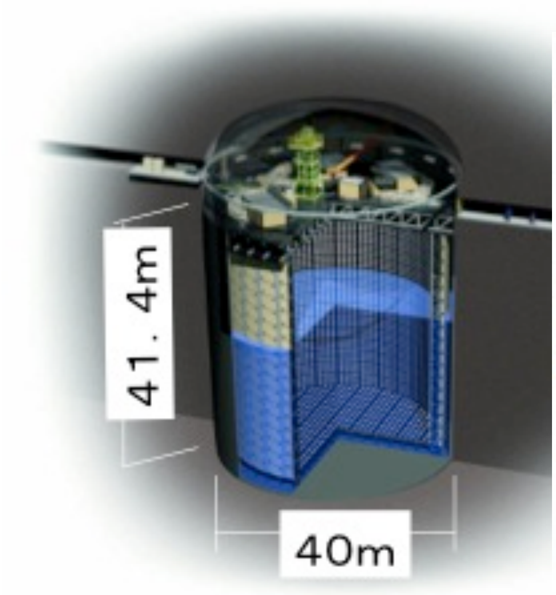




Antineutrino Charged Current

Detecting atmospheric neutrinos: (Underground) SuperKamiokande Experiment

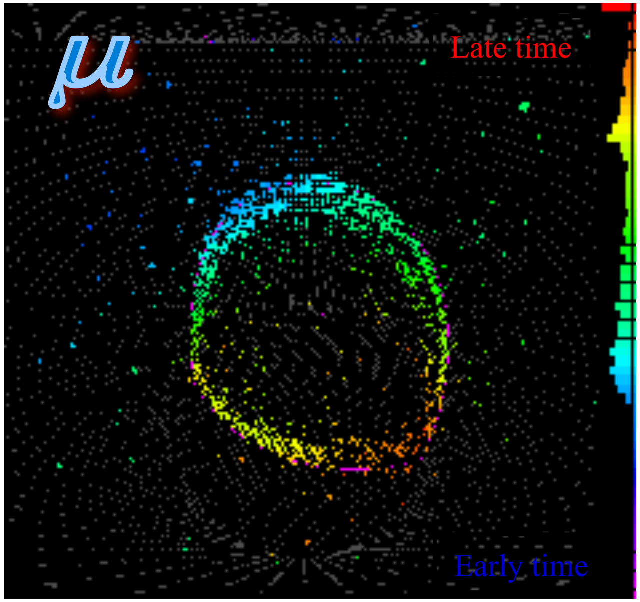


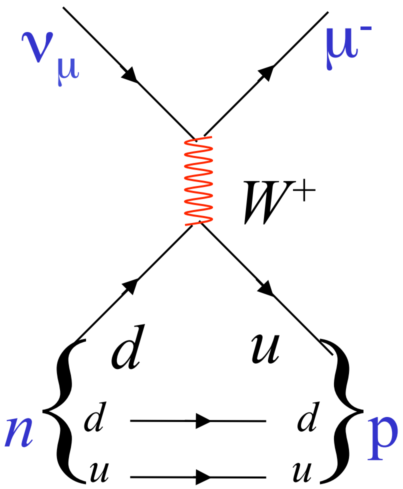


- 50 kton water (22.5 kton fid.vol.)
- 11,146 PMTs +1,885 PMTs
- overburden 2,700 m.w.e.

SuperKamiokande Cherenkov rings

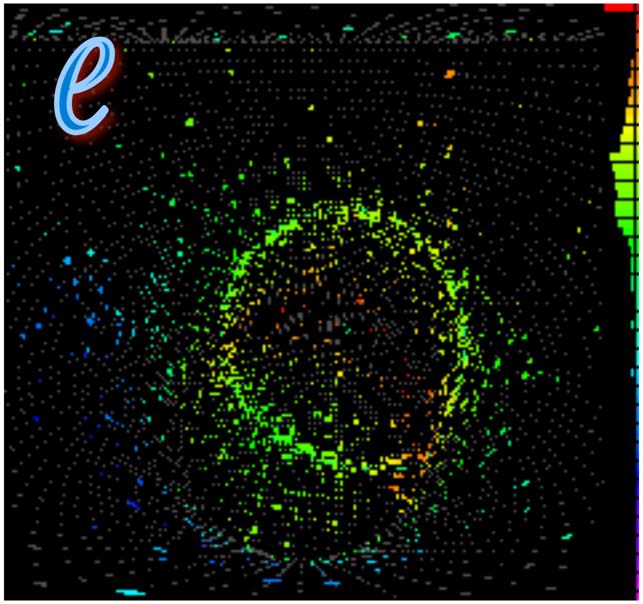
$$\nu_\mu + n \rightarrow p + \mu^-$$

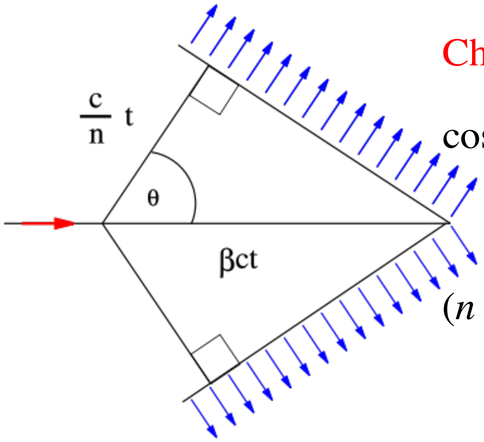




$$\nu_\mu + n \rightarrow p + \mu^-$$

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

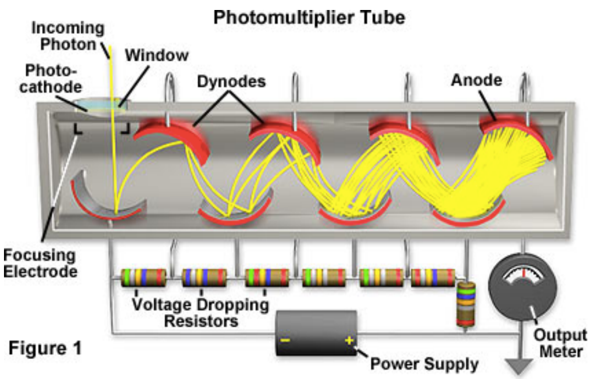




Cherenkov radiation

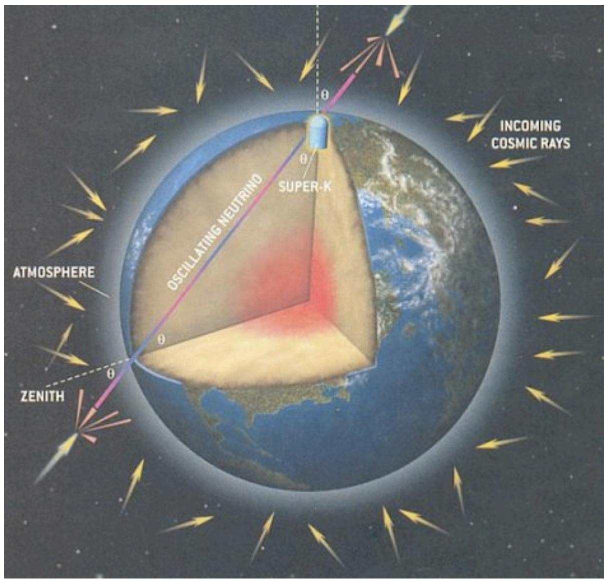
$$\cos\theta_C = \frac{1}{\beta n(\omega)} \quad \text{if} \quad \beta \geq \frac{1}{n}$$

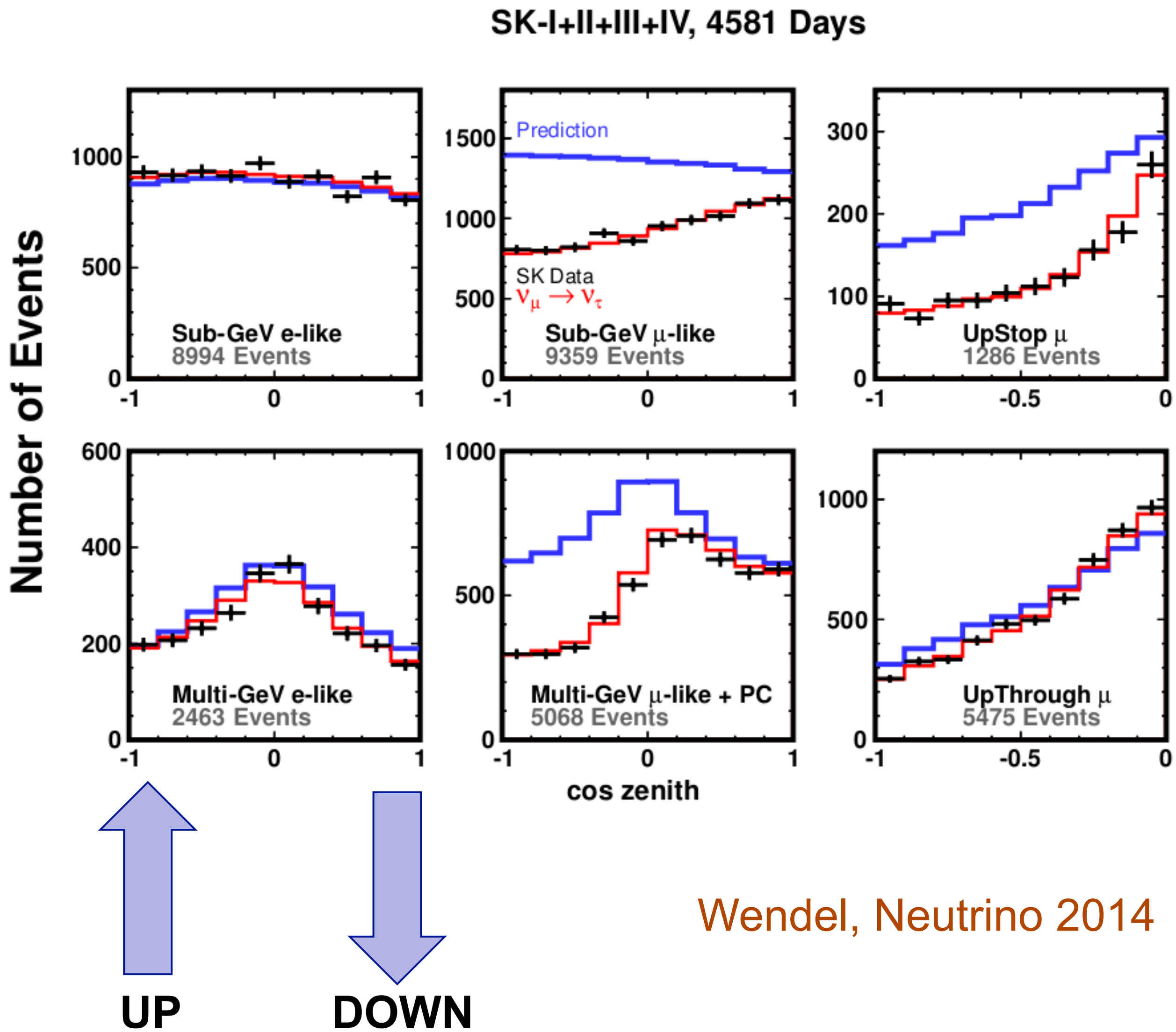
$$(n = \frac{c}{v} \quad \text{and} \quad \beta = \frac{v}{c})$$



16 years later …(lots of statistics)

SK Detector

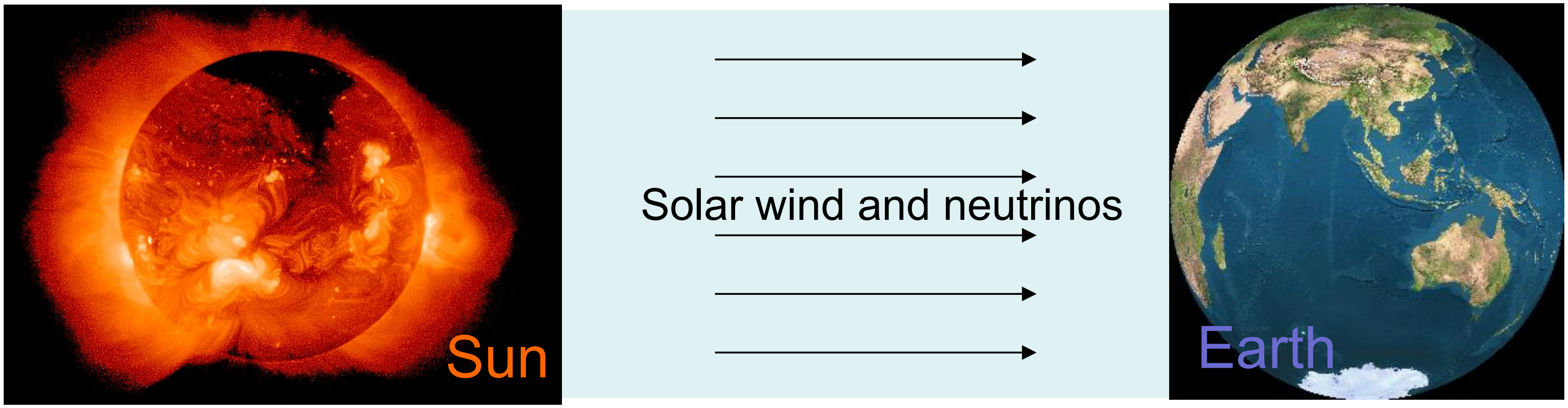


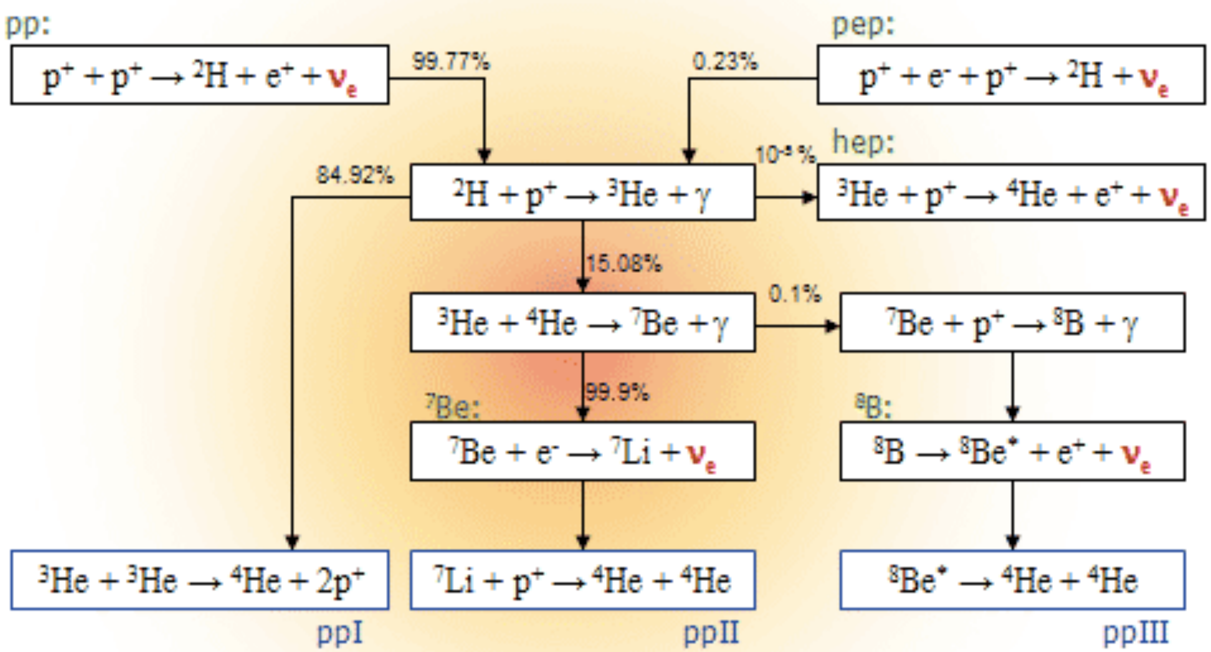


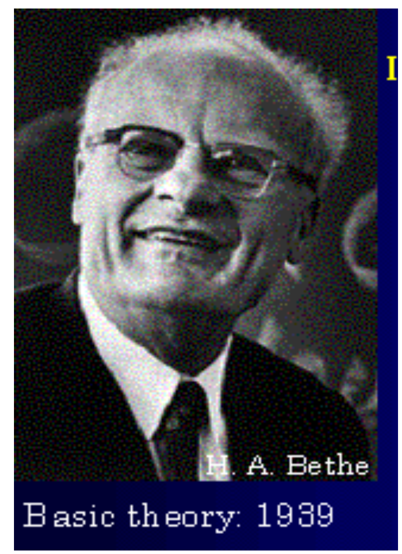
Wendel, Neutrino 2014

SOLAR NEUTRINOS
DEFICIT RESOLVED

Solar neutrinos

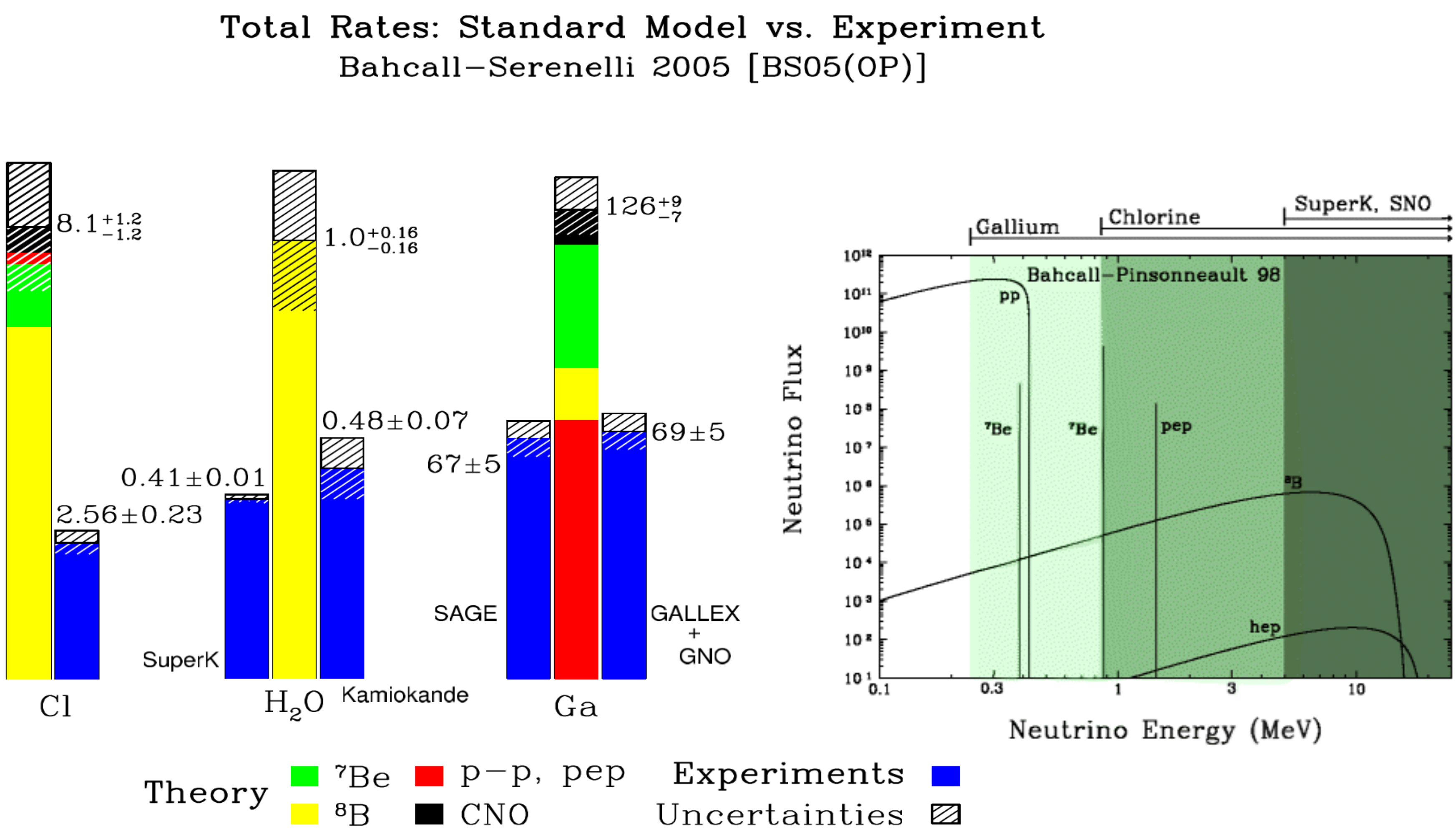




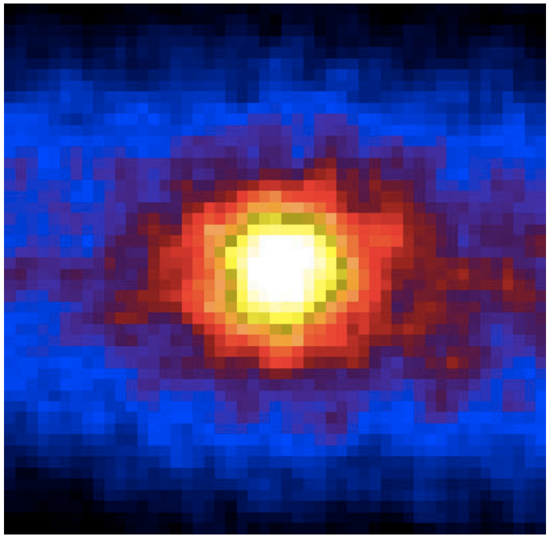


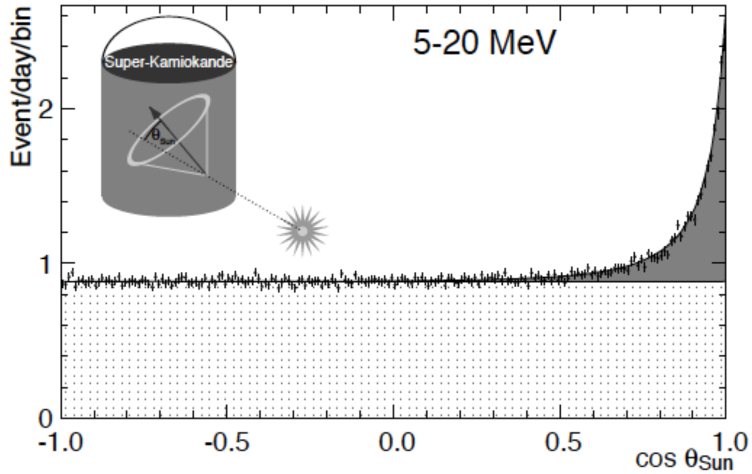
Nobel 1967

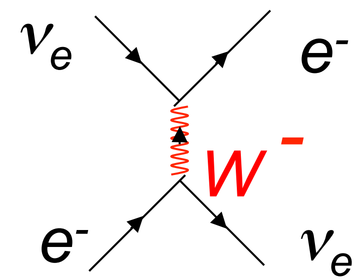
Deficit of solar neutrinos



SuperK – solar events



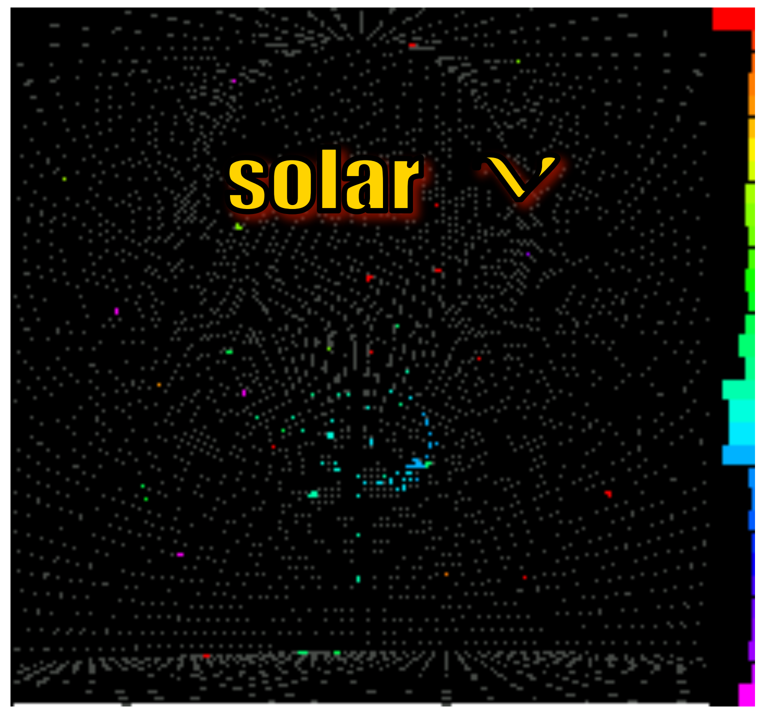




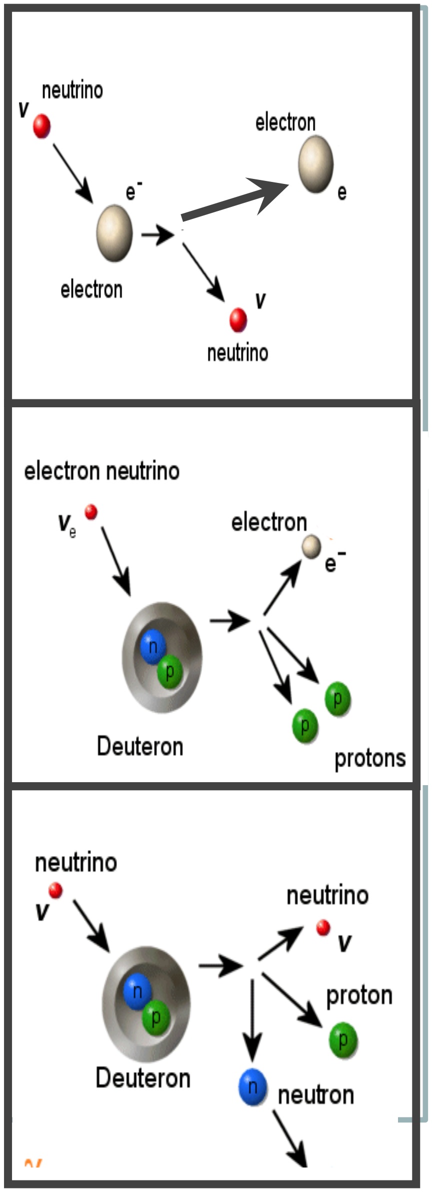
Charged Current (CC)

$$\frac{\text{measured}}{\text{expected}} = 0.465 \pm 0.005(stat)^{+0.015}_{-0.013}(syst)$$

measured << expected



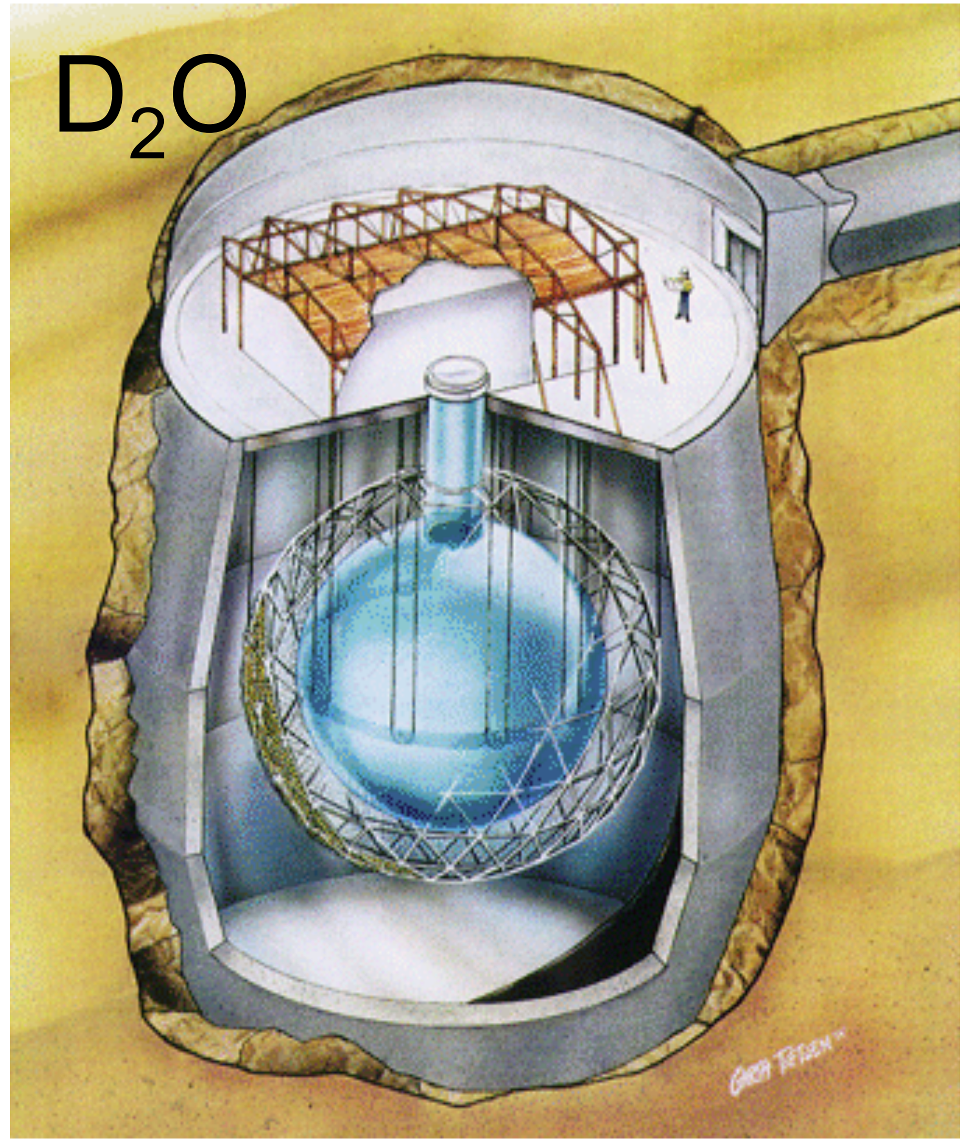
Sudbury Neutrino Observatory (SNO)



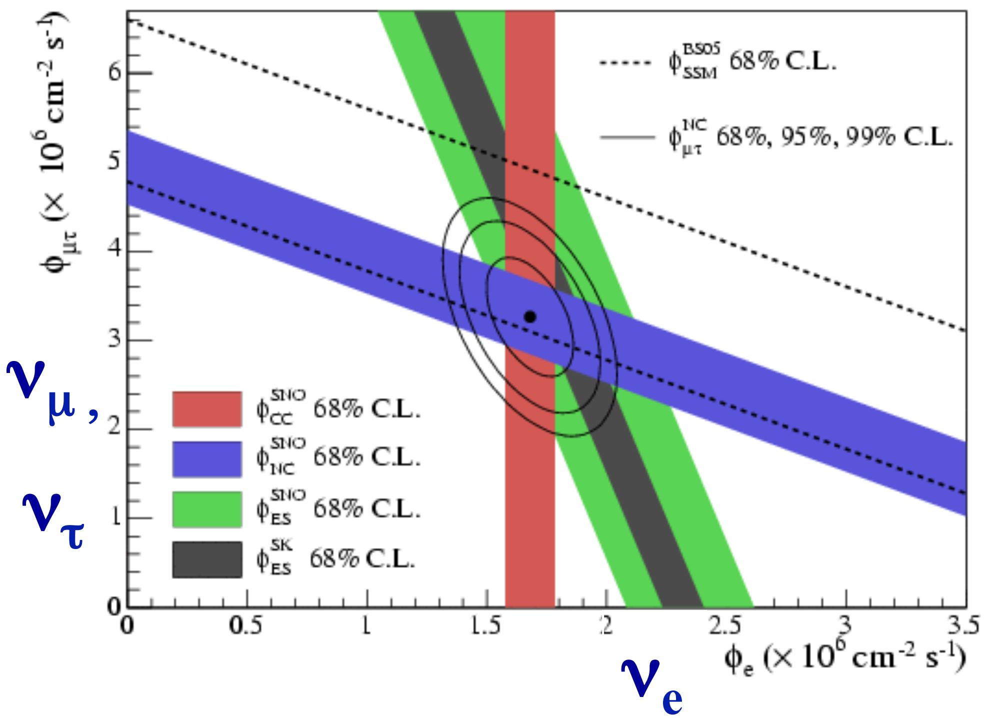
Neutrino-Electron Scattering (ES)

Charged Current (CC)

Neutral Current (NC)



SNO measurements (total solar flux)



$$\phi_{CC} = 1.68 \;{}^{+0.06}_{-0.06}(\text{stat.})^{+0.08}_{-0.09}(\text{syst.})$$

$$\phi_{NC} = 4.94 \;{}^{+0.21}_{-0.21}(\text{stat.})^{+0.38}_{-0.34}(\text{syst.})$$

$$\phi_{ES} = 2.35 \;{}^{+0.22}_{-0.22}(\text{stat.})^{+0.15}_{-0.15}(\text{syst.})$$

(In units of $10^6\,\text{cm}^{-2}\text{s}^{-1}$)

The total flux of active neutrinos is measured independently (NC) and agrees well with solar model.

$$\frac{\varphi_{CC}}{\varphi_{NC}} = 0.34 \pm 0.023(\text{stat.})^{+0.029}_{-0.031}$$

Calculations:

5.82 +- 1.3 (Bahcall *et al.*),

5.31 +- 0.6 (Turck-Chieze *et al.*)

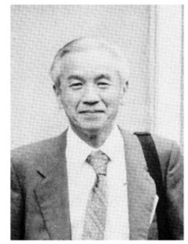
Electron neutrinos are Only about 1/3 of total!

NEUTRINO OSCILLATIONS
SOME QM

Neutrino mixing
The PMNS matrix

Bruno Ponecorvo
1913 — 1993

Ziro Maki
1929 — 2005



Masami Nakagawa
1932 — 2001

Shoichi Sakata
1911 — 1970

Pontecorvo – Maki – Nakagawa - Sakata

Flavor eigenstates

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

Mass eigenstates

so, e.g., : $\nu_e = U_{e1}\nu_1 + U_{e2}\nu_2 + U_{e3}\nu_3$

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle$$

$$|\nu_i\rangle = \sum_{\alpha=e,\mu,\tau} U_{\alpha i} |\nu_\alpha\rangle$$

$|U_{\alpha i}|^2$ = flavor-α fraction of $|\nu_i\rangle$

Neutrino propagation

The state function at birth: $\left|\nu(0,0)\right\rangle \equiv \left|\nu_{\alpha}^{flavor}\right\rangle = \sum_{i=1}^{3} U_{\alpha i}^{*}\left|\nu_{\alpha}^{mass}\right\rangle$

Propagation (plane wave): $\left|\nu(t,\vec{x})\right\rangle = \left|\nu_{\alpha}^{flavor}\right\rangle = \sum_{i=1}^{3} U_{\alpha i}^{*} e^{-ip_i x}\left|\nu_{\alpha}^{mass}\right\rangle$

$$\phi_i \equiv p_i x = E_i t - \vec{p}_i \vec{x}$$

Probability of evolution: $P(\nu_{\alpha} \rightarrow \nu_{\beta}) = \left|\left\langle \nu_{\beta}^{flavor} \middle| \nu(t,\vec{x})\right\rangle\right|^2$

This is heursitic.
Not rigorous!
Should do either
Wave packets or QFT

For ultra-relativistic neutrinos:

$$p_i = \sqrt{E^2 - m_i^2} \approx E - \frac{m_i^2}{2E}$$

$$-\Delta p \equiv p_1 - p_2 = -\frac{\Delta m^2}{2E}$$

$\Rightarrow$

$$P(\nu_{\alpha} \rightarrow \nu_{\beta}; L) = \left|\sum_i U_{\beta i} e^{-i\frac{m_i}{2p}L} U_{\alpha i}^{*}\right|^2$$

Two neutrino case

Transition probability: $P(\nu_\alpha \to \nu_\beta) = \left| \left\langle \nu_\beta^{fl} \middle| \nu(t,x) \right\rangle \right|^2$

Now more explicitly: $P(\nu_\alpha \to \nu_\beta; L) = \left| \sum_i U_{\beta i} e^{-i \frac{m_i}{2p} L} U^*_{\alpha i} \right|^2$

Consider a two component theory: $\mathrm{U} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$

So

$$\left| \nu_\alpha \right\rangle = \cos\theta \left| \nu_1 \right\rangle + \sin\theta \left| \nu_2 \right\rangle$$

$$\left| \nu_\beta \right\rangle = -\sin\theta \left| \nu_1 \right\rangle + \cos\theta \left| \nu_2 \right\rangle$$

$$P(\nu_\alpha \to \nu_\beta; L) = \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2}{4E} L \right)$$

NEUTRINO OSCILLATIONS

EXPERIMENTAL OBSERVATIONS USING NUCLEAR REACTORS

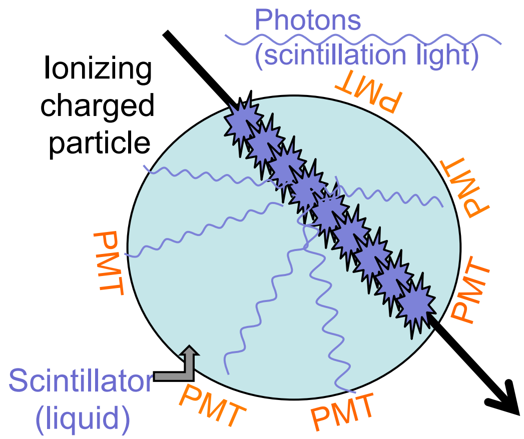
KamLAND

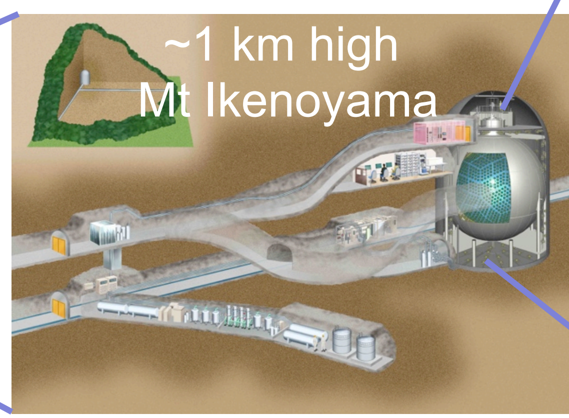
- KamLAND is surrounded by nuclear power plants which produce electron anti-neutrinos.
- 180 km away on average

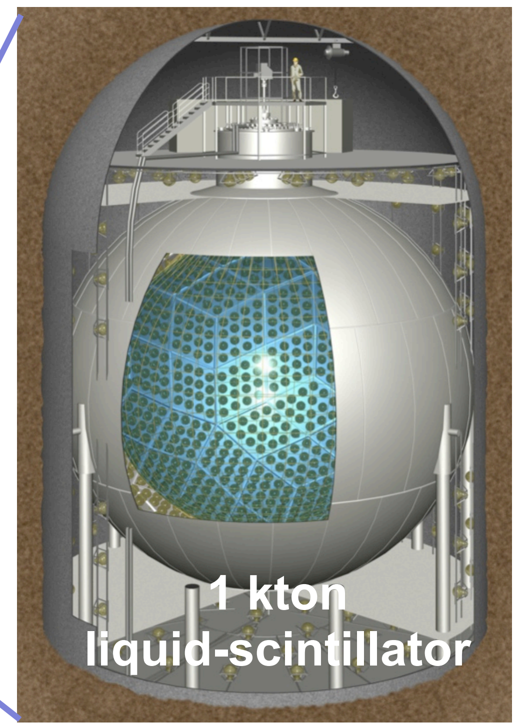
Detecting anti-neutrinos

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad \text{(prompt)}$$

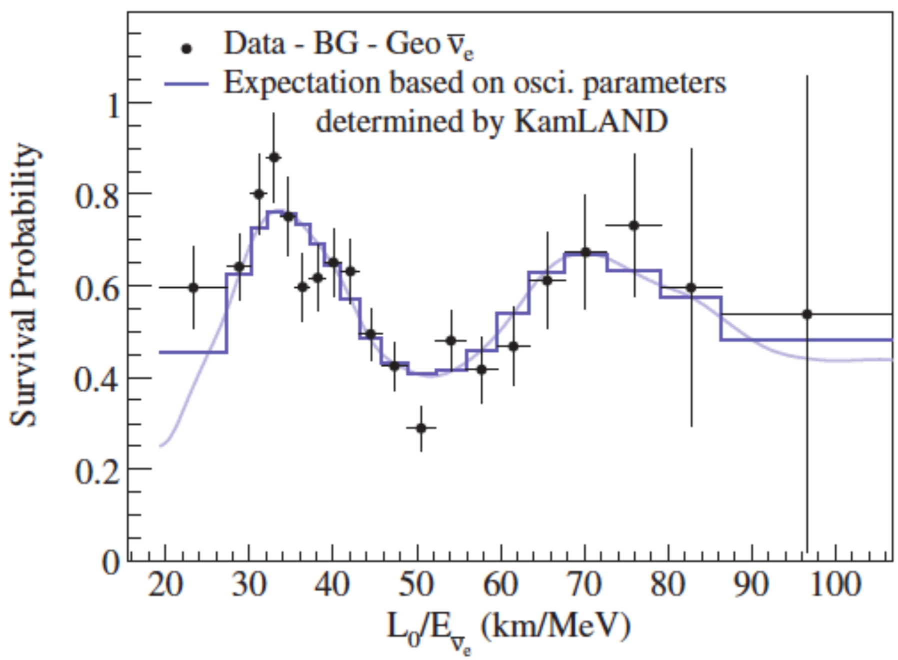
$$n + p \rightarrow d + \gamma(2.2\ MeV) \quad \text{(delayed)}$$

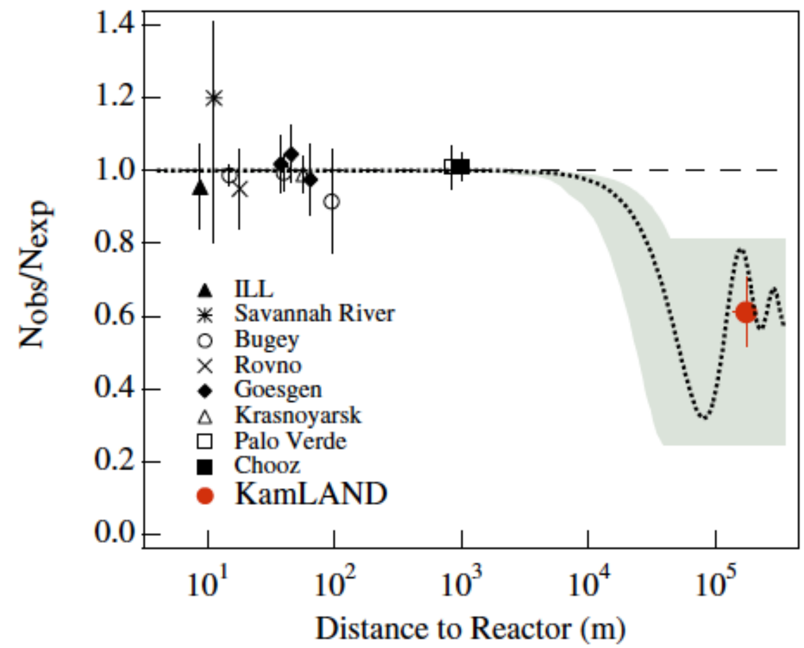






KamLAND results





$$\Delta m_{21}^2 = \left(7.58^{+0.14}_{-0.13}(stat) \pm 0.015(syst)\right) \times 10^{-5} eV^2$$

$$\tan^2\theta_{12} = 0.56^{+0.10}_{-0.07}(stat)^{+0.10}_{-0.06}(syst)$$

NEUTRINO OSCILLATIONS

EXPERIMENTAL OBSERVATIONS USING ACCELERATORS

Two Neutrinos Case

A disappearance experiment

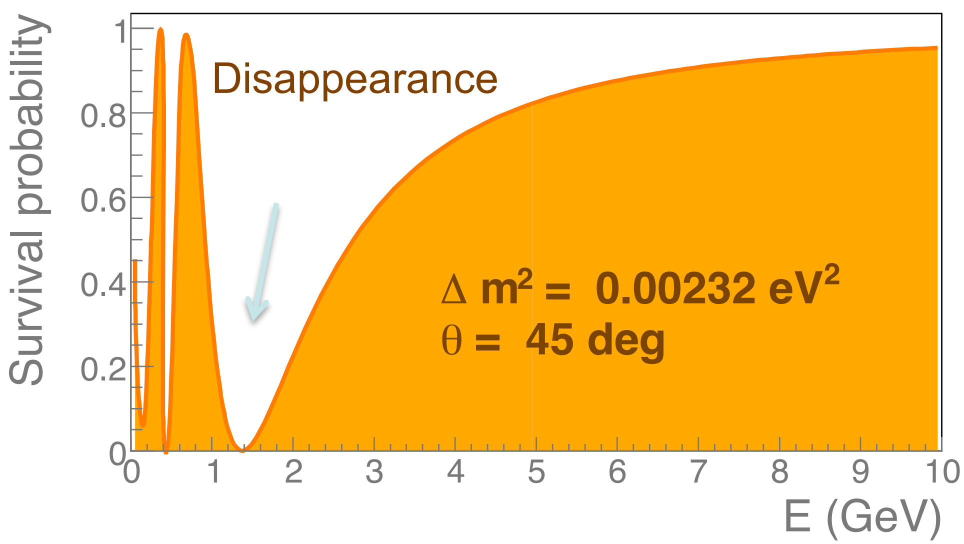
$$P(\nu_\alpha \to \nu_\beta; L) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

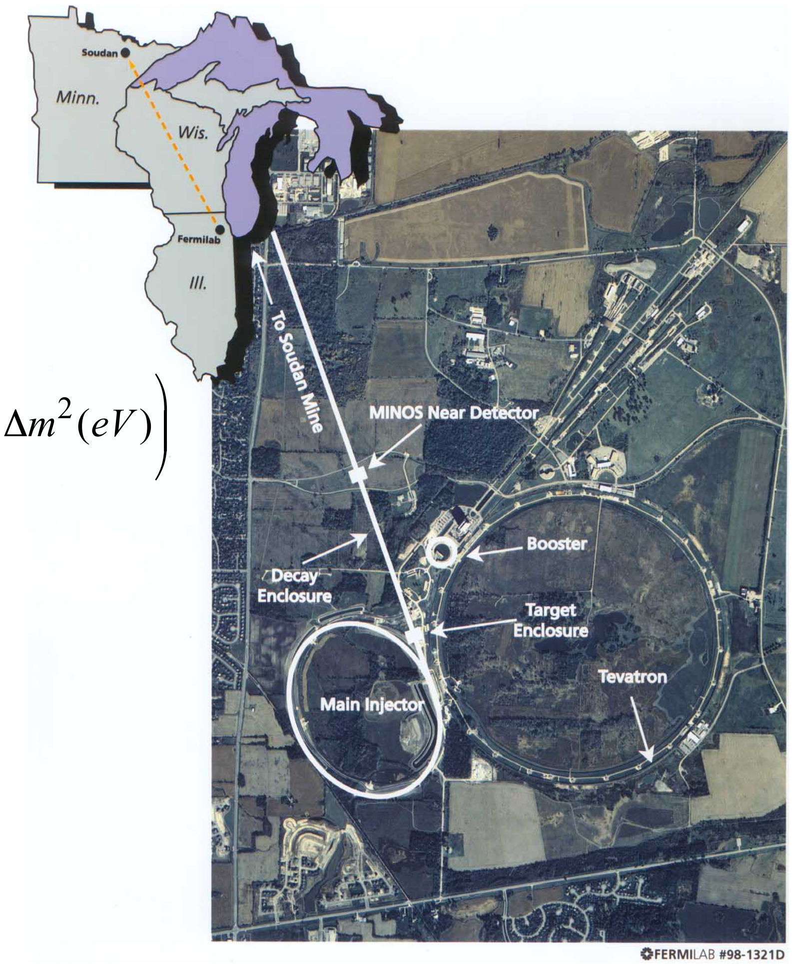
$$P(\nu_\alpha \to \nu_\beta; L) = \sin^2(2\theta)\sin^2\left(1.267\frac{L(km)}{E(GeV)}\Delta m^2(eV)\right)$$

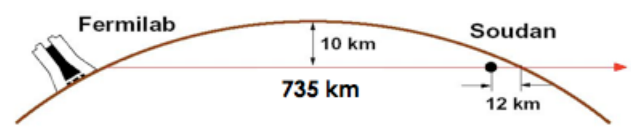
Survival probability:

$$P(\nu_\alpha \to \nu_\alpha; L) = 1 - P(\nu_\alpha \to \nu_\beta; L) = 1 - \sin^2(2\theta)\sin^2\left(1.267\frac{L(km)}{E(GeV)}\Delta m^2(eV)\right)$$

For L = 734 km and $\theta = 45^o$ (MINOS at Fermilab)

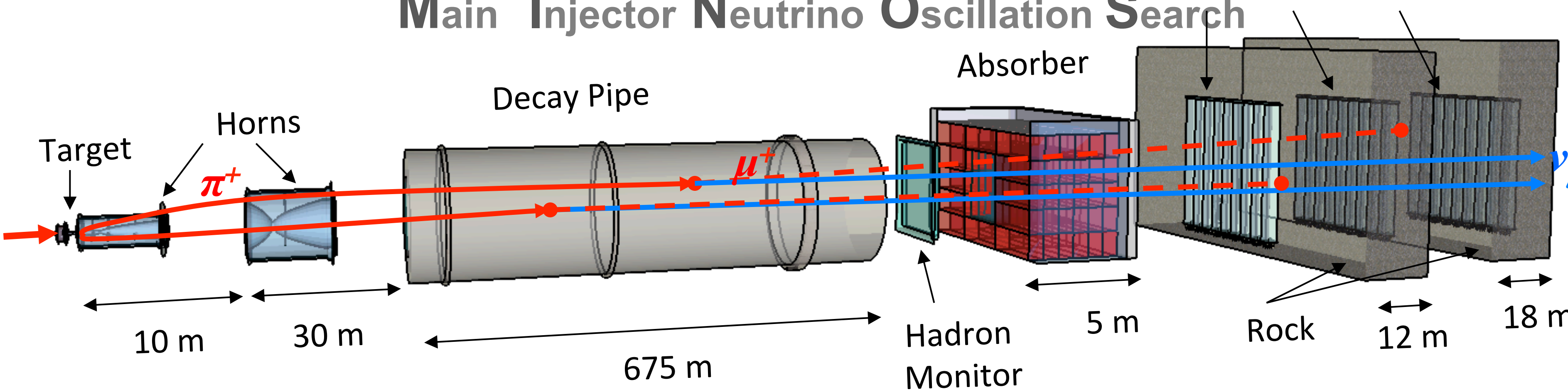






MINOS

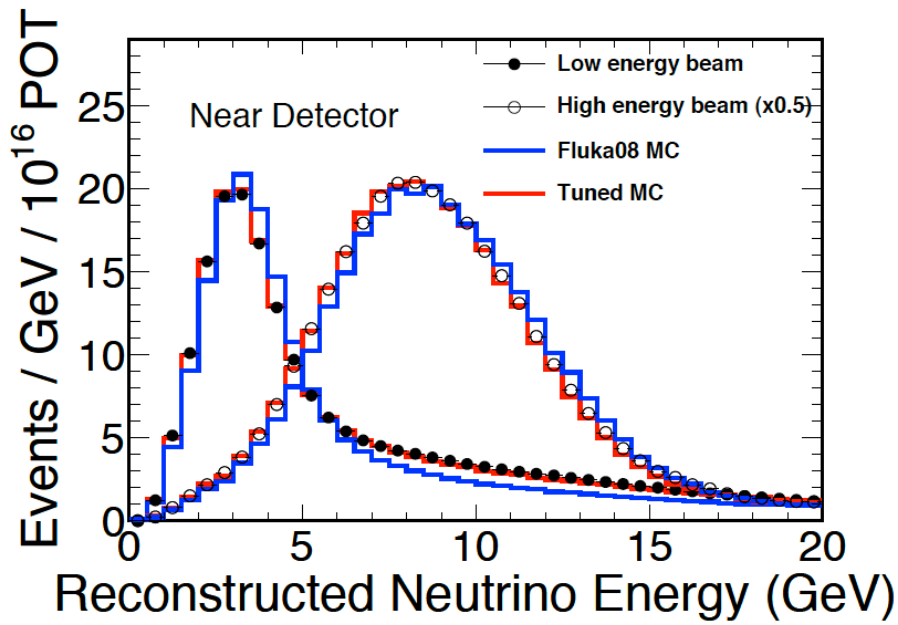
Main Injector Neutrino Oscillation Search



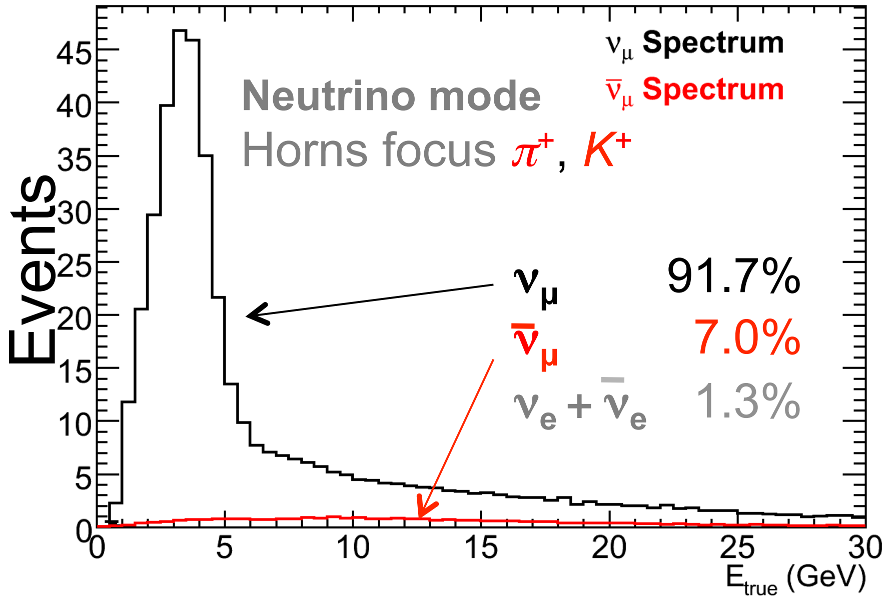
Strategy

- Two functionally similar magnetized detectors

- High intensity, flexible beam
  - ⇨ 3.5×10^{13} protons/pulse (320 kW beam)
  - ⇨ two magnetic horns
  - ⇨ movable target (→ adjustable energy spectrum)

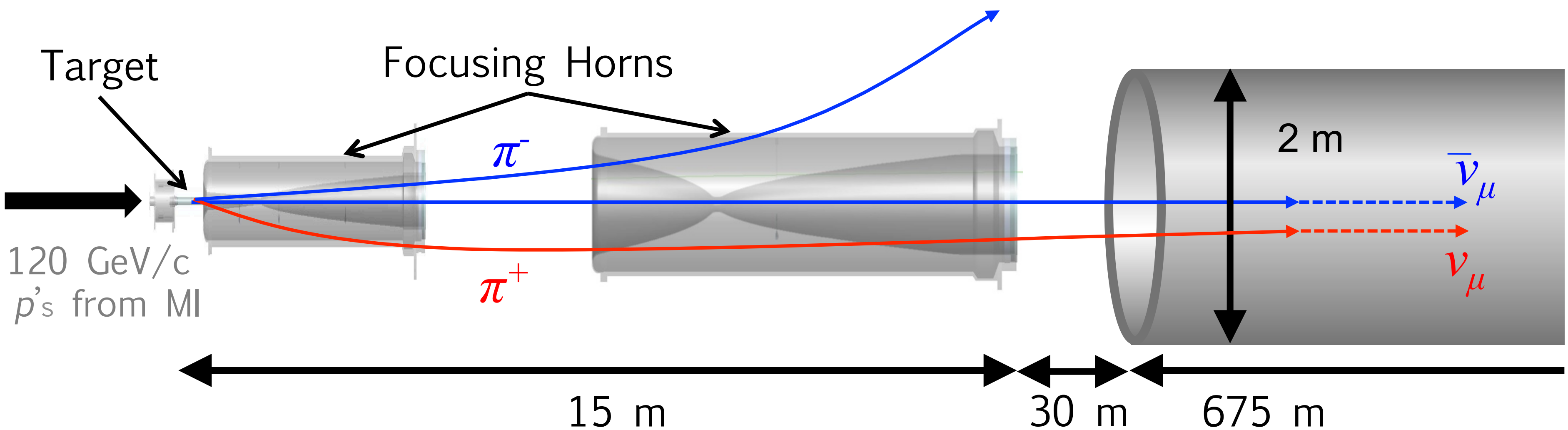


Making a neutrino beam

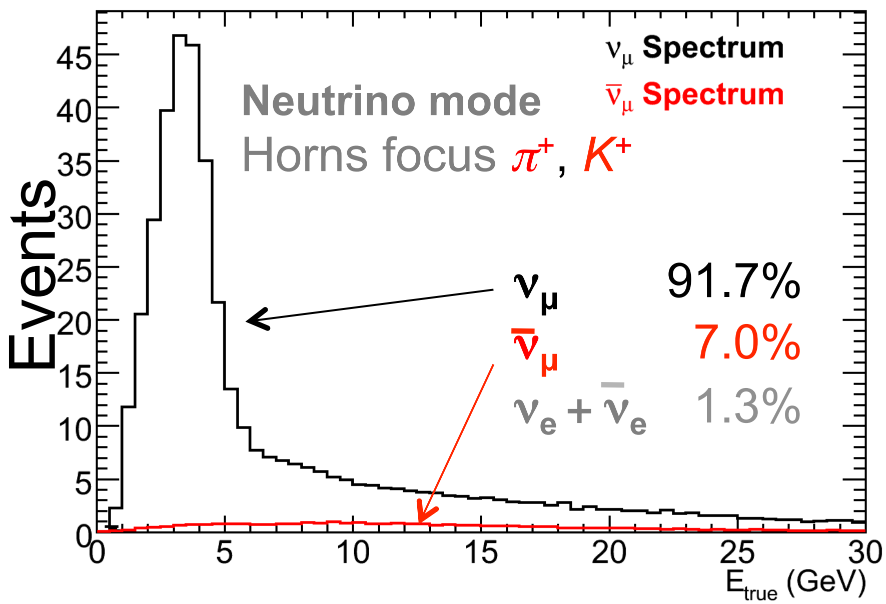


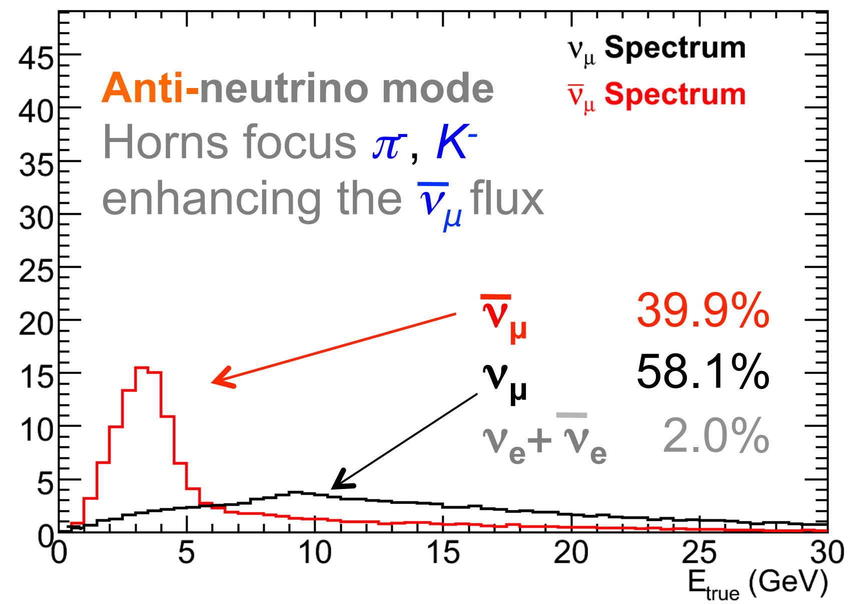
$$E_\nu \approx E_\pi \frac{1 - m_\mu^2 / m_\pi^2}{1 + \gamma^2 \theta^2} \approx \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$

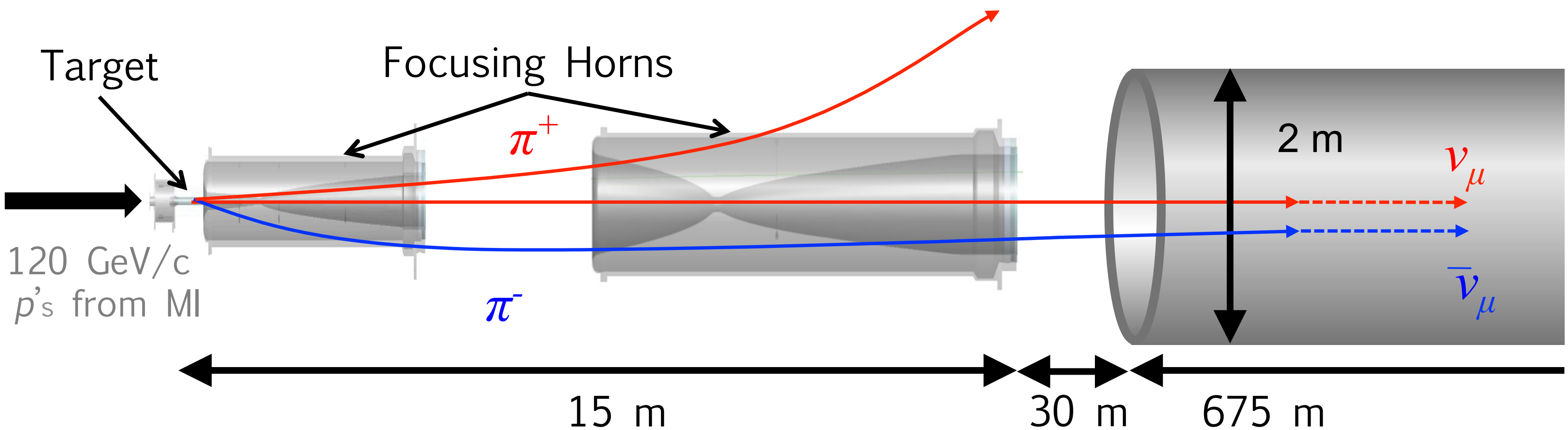
$$\frac{dN}{d\Omega} \approx \frac{1}{4\pi} \left(\frac{2\gamma}{1 + \gamma^2 \theta^2} \right)^2$$



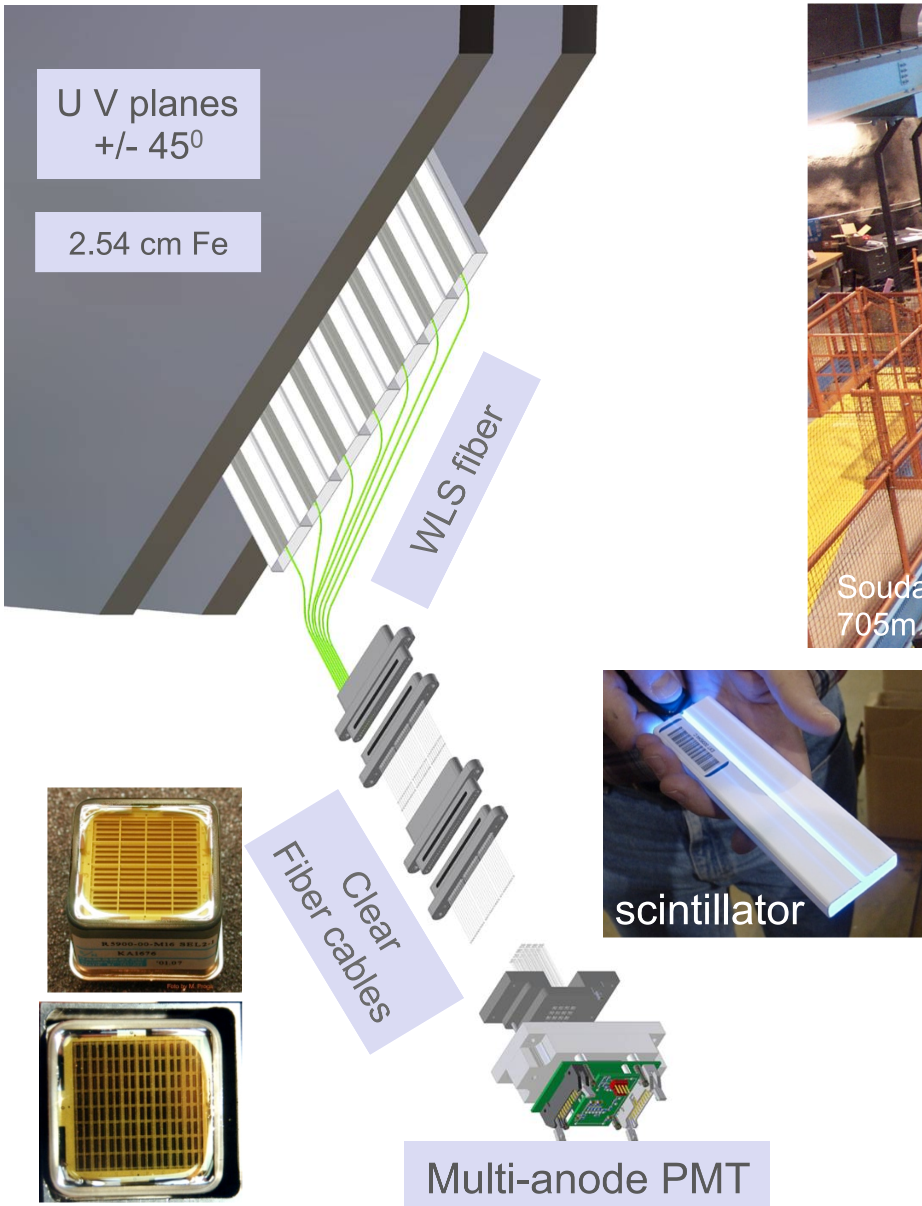
Making an anti-neutrino beam

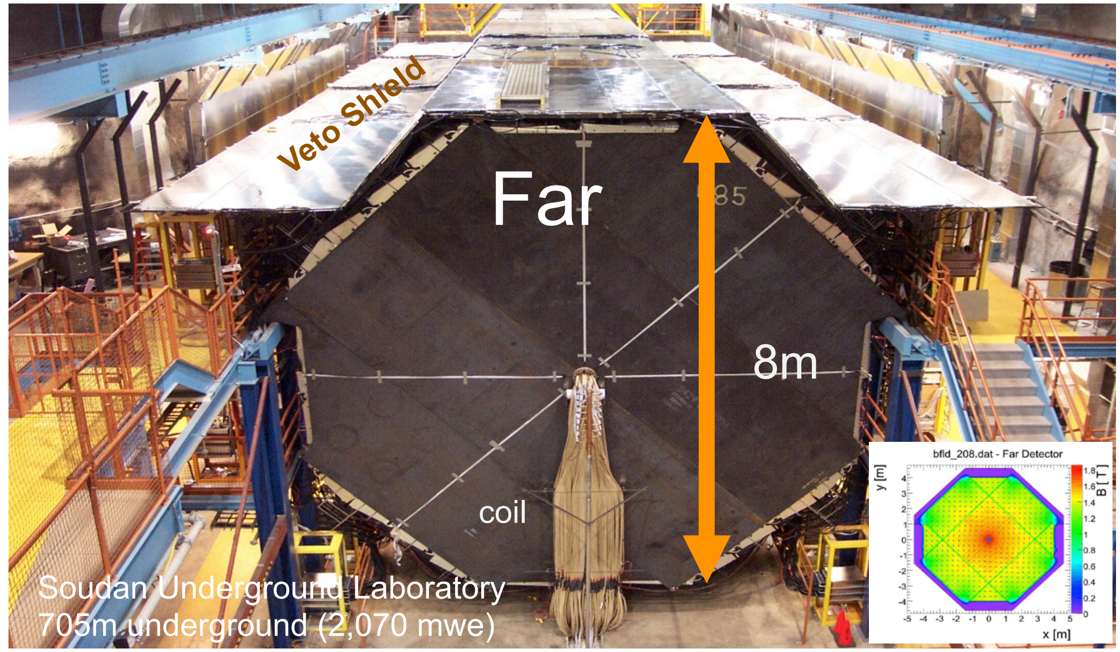


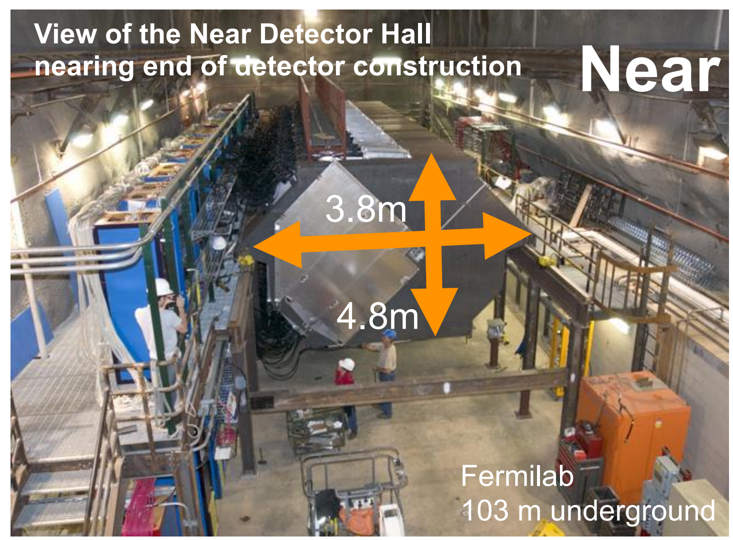




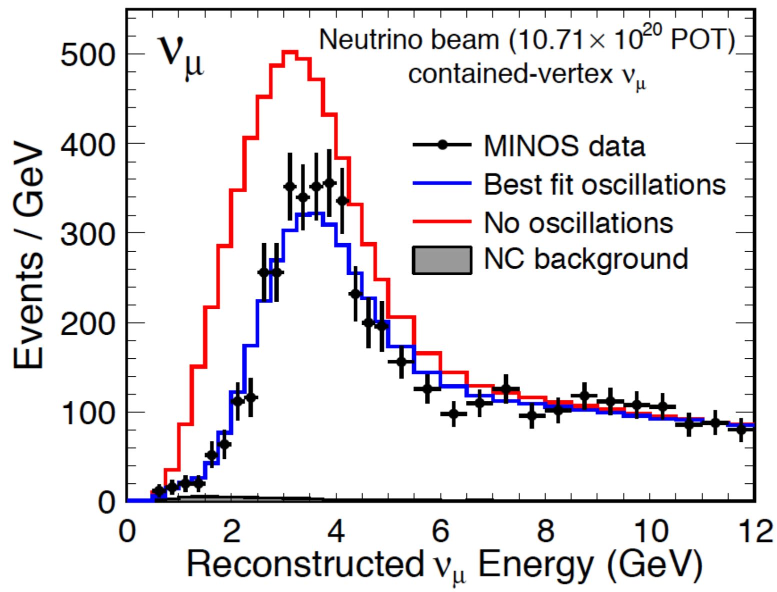
MINOS: Near and Far Detectors

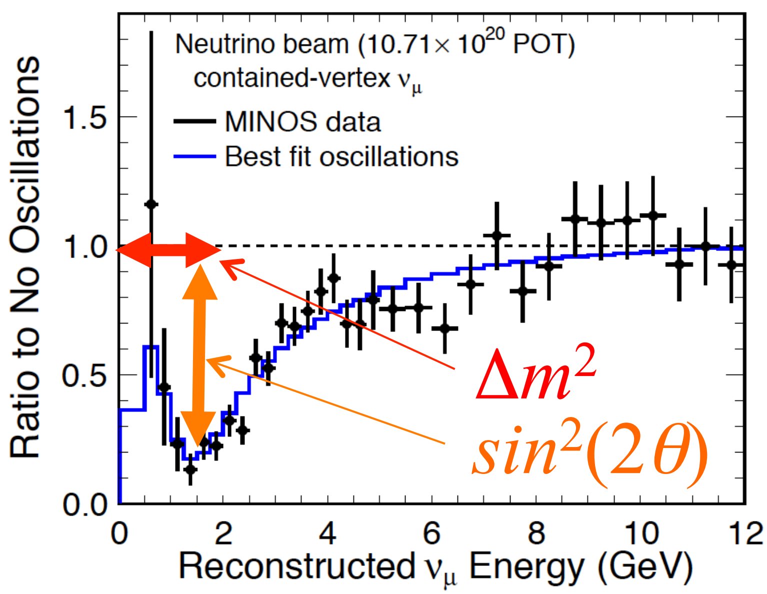






MINOS disappearance results





Survival probability:

$$P(\nu_\mu \to \nu_\mu; L) = 1 - \sin^2(2\theta)\sin^2\left(1.267\frac{L(km)}{E(GeV)}\Delta m^2(eV)\right)$$

For L = 734 km and E= 1-50 *GeV* (MINOS at Fermilab)

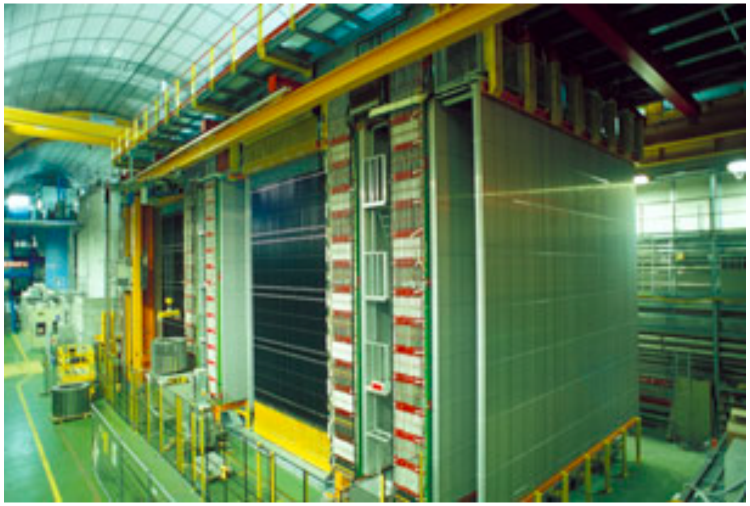
$$\left|\Delta m^2\right| = 2.41^{+0.09}_{-010} \times 10^{-3}\,\mathrm{eV}^2$$

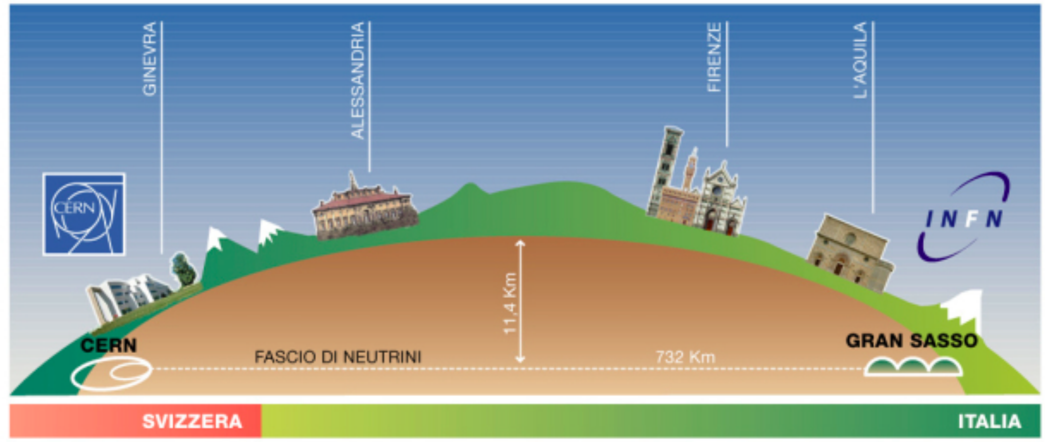
$$\sin^2(2\theta) = 0.950^{+0.035}_{-0.036}$$

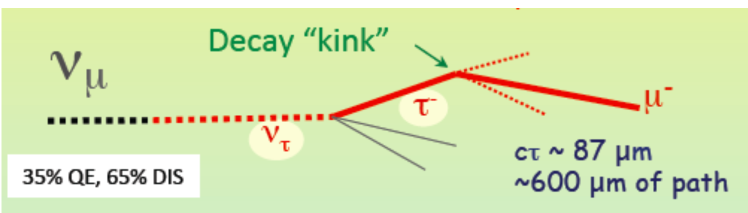
$$\left[\sin^2(2\theta) > 0.890 \quad (90\%\ \mathrm{C.L.})\right]$$

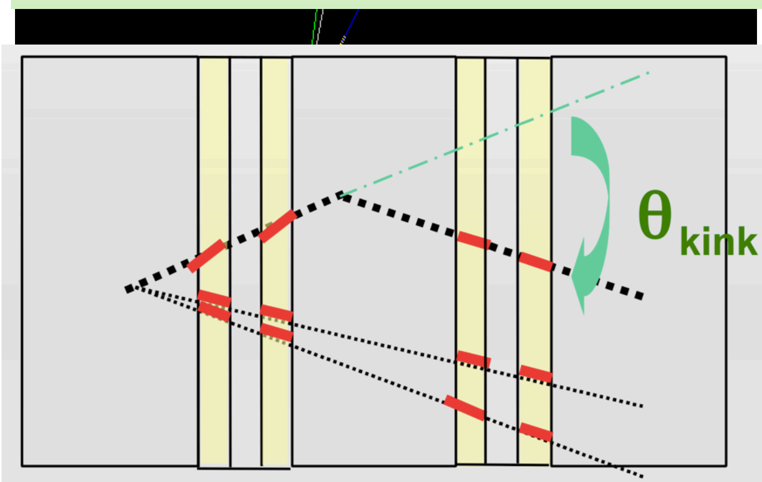
K. Lang, Venice NeuTel'2013

OPERA → ν_τ appearance experiment







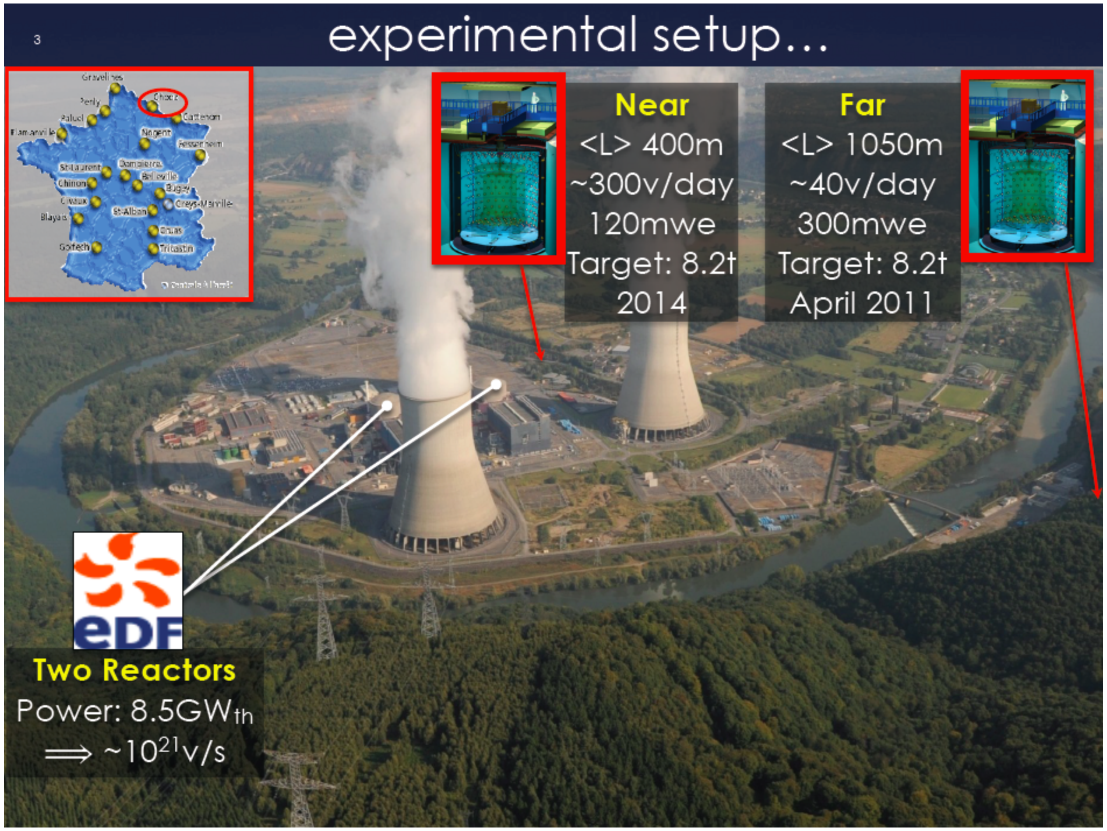


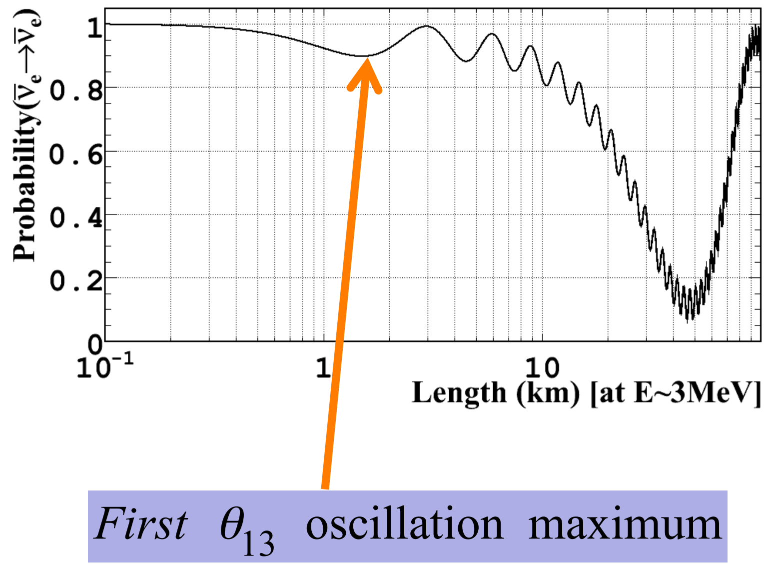
- 5 ν_τ candidates (0.25 ± 0.05 background)
- 5σ exclusion of no $\nu_\mu \to \nu_\tau$ oscillation
- $\Delta m^2_{23} = 3.3 \times 10^{-3} eV^2$ (best fit)

$$\to [2.0 - 5.0] \times 10^{-3} eV^2 @ 90 C.L.$$

See arXiv:1507.01417 for details

From CHOOZ to Double CHOOZ



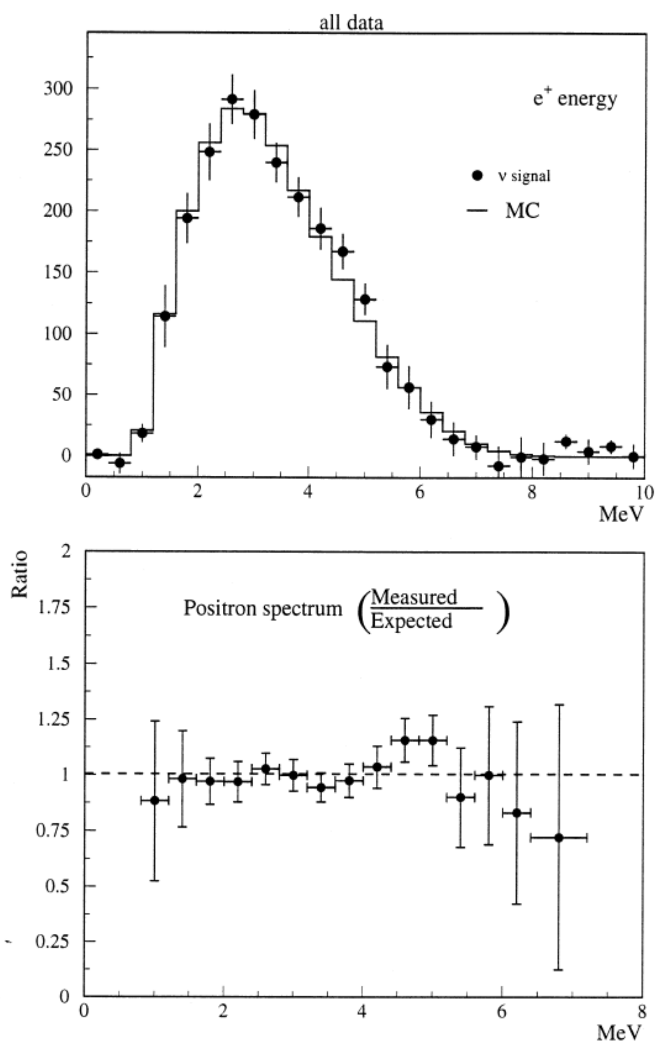


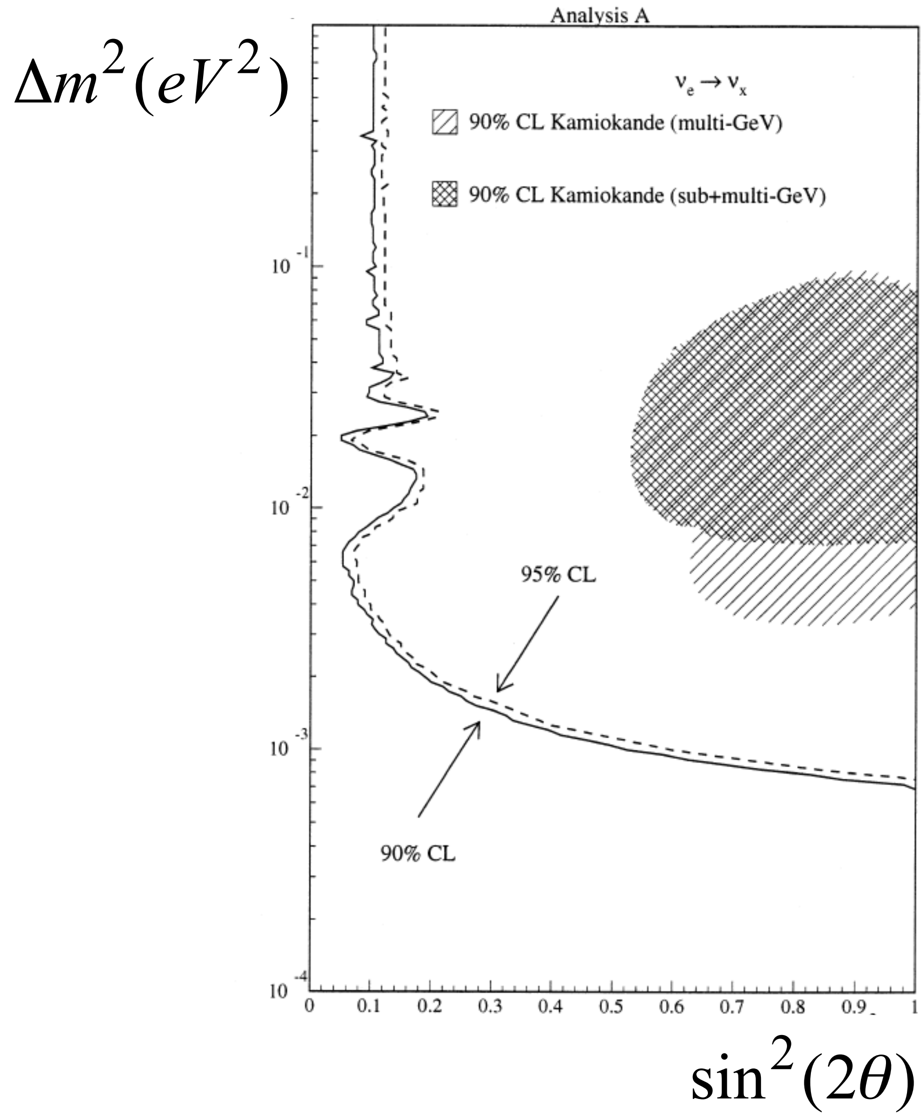
- **Simple 2-flavor oscillation formula is good for L~1 km:**
  - ✓ No matter effects
  - ✓ No parameter degeneracy

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

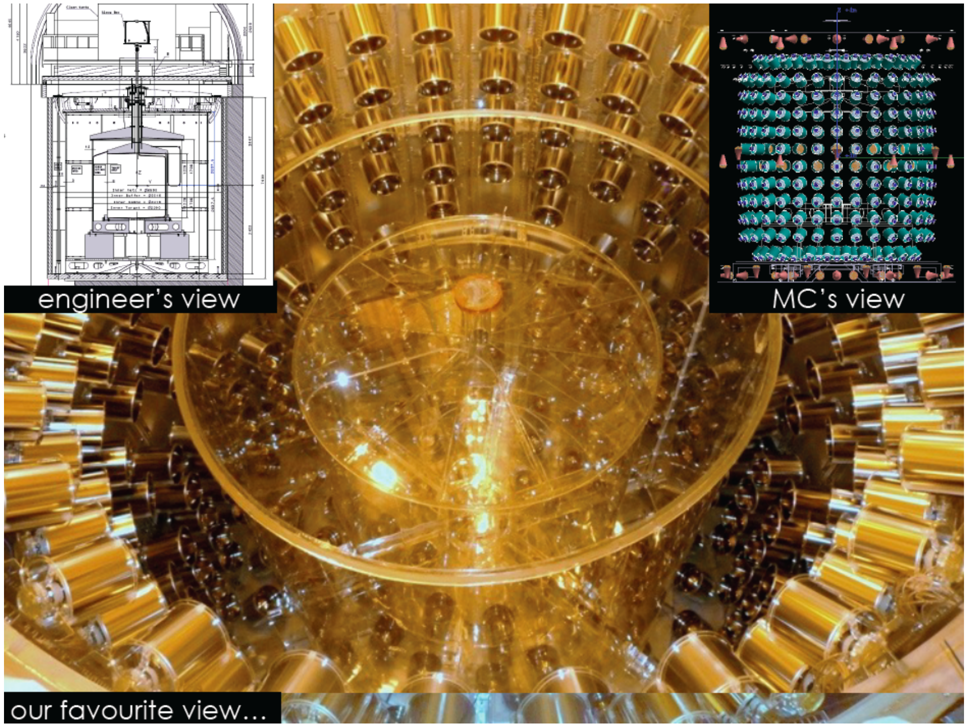
CHOOZ (5 ton detector)

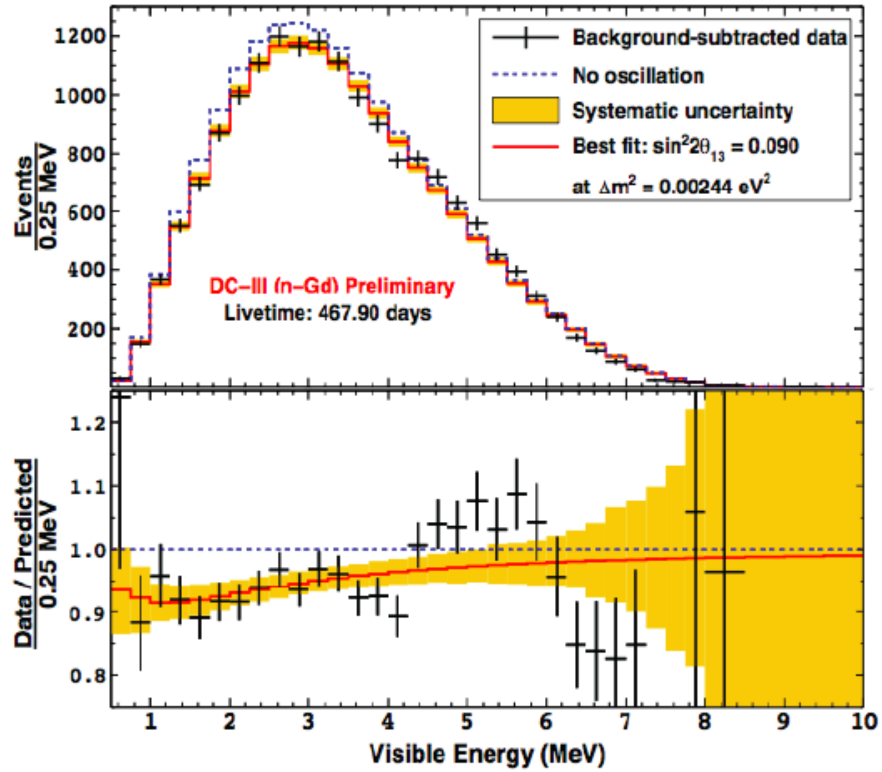
M. Apollonio et al. / Physics Letters B 466 (1999) 415–430





Double CHOOZ 8.2 ton

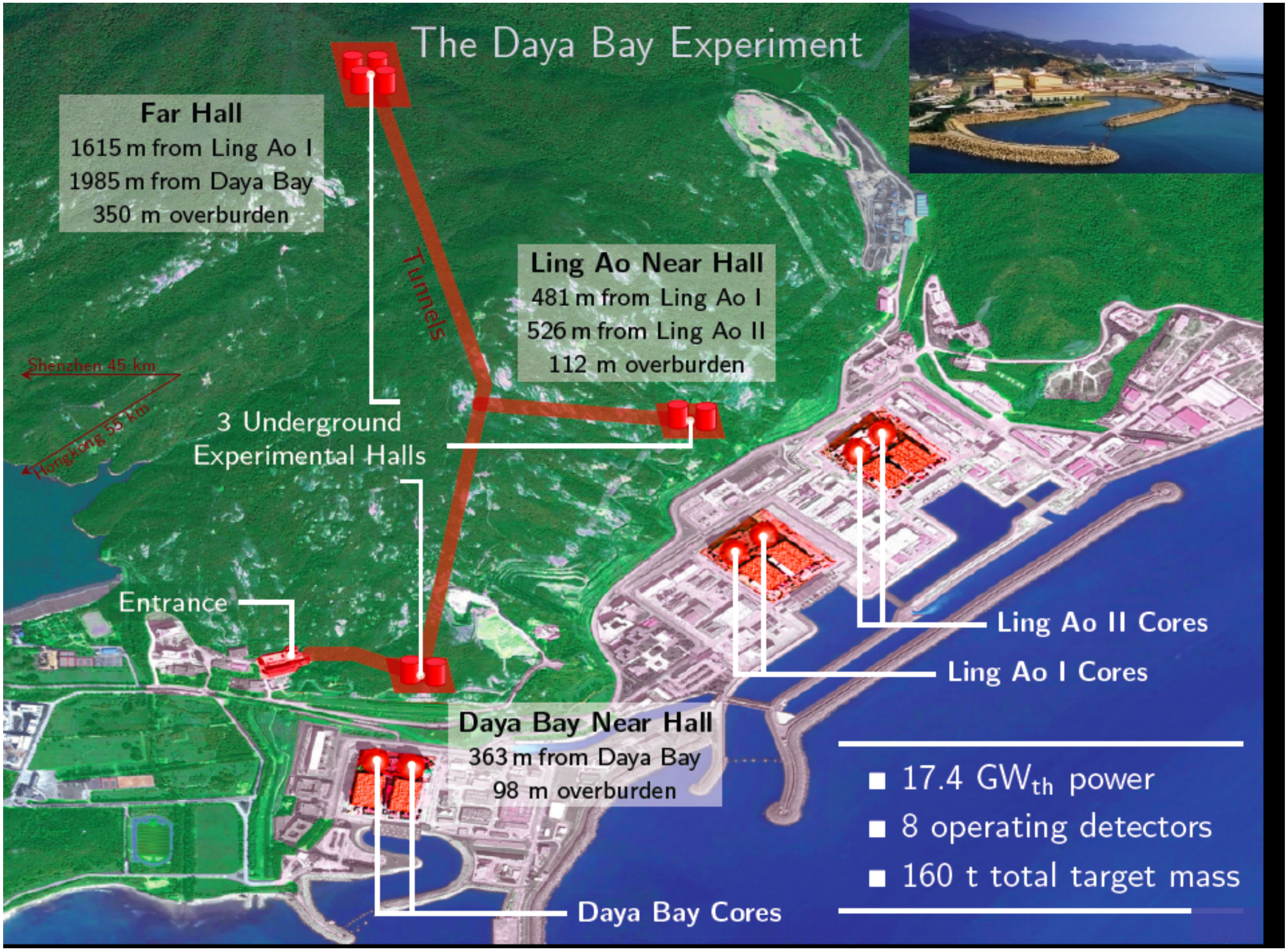




$\sin^2(2\theta_{13}) = (0.09 \pm 0.03)$

Neutrino 2014

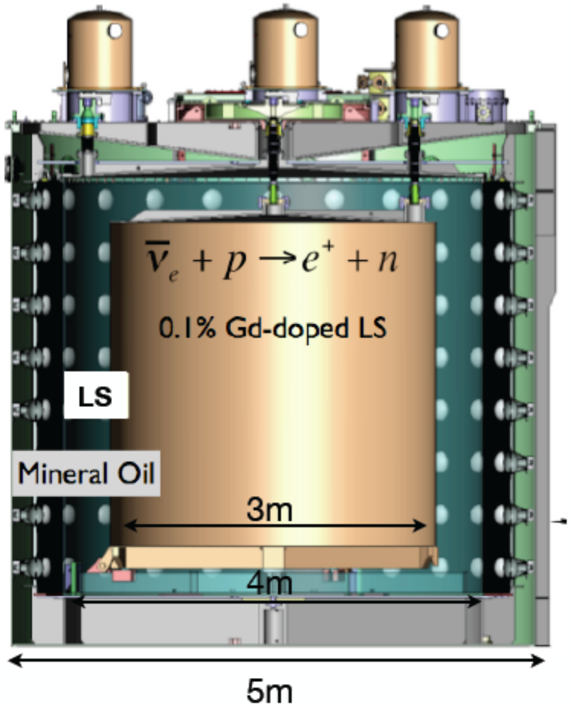
Daya Bay Experiment

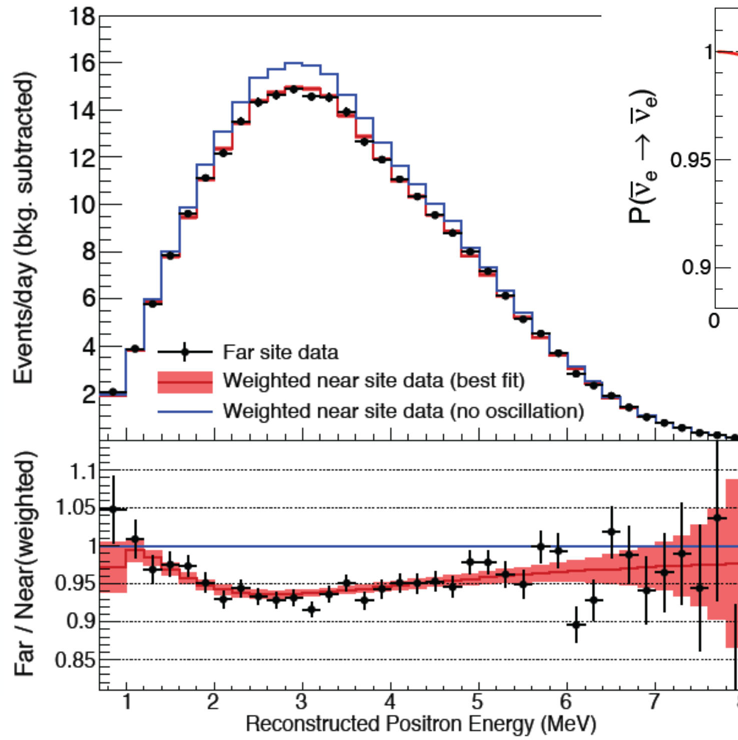


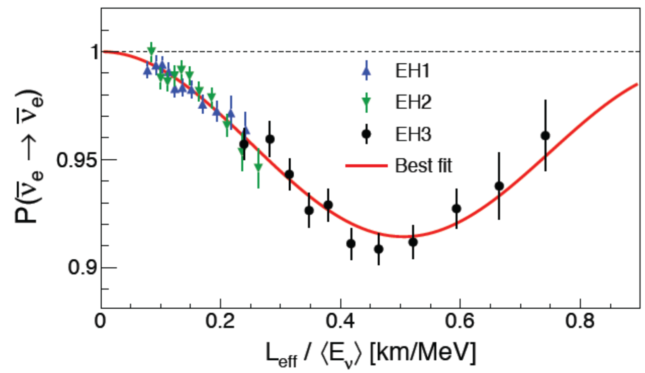
arXiv:1505.03456

Daya Bay: 8 detectors

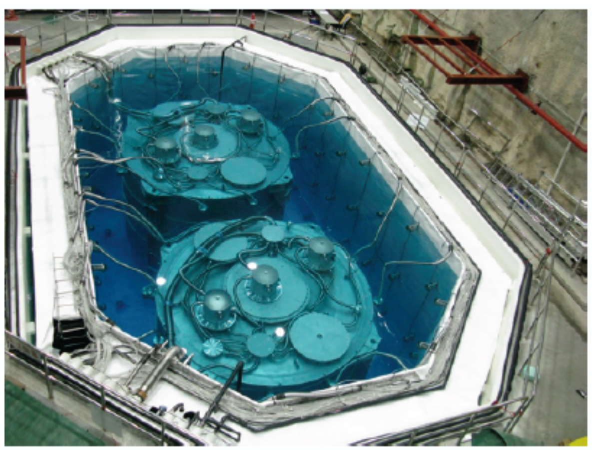
2x20ton + 2x20ton + 4x20ton







404 days with 8-AD
217 days with 6-AD



$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$\left|\Delta m^2_{ee}\right| = (2.42 \pm 0.11) \times 10^{-3} eV^2$$

1. Mixing angle θ_{13} governs overall size of $\bar{\nu}_e$ deficit
2. Effective mass squared difference $|\Delta m^2_{ee}|$ determines deficit dependence on L/E

Short Baseline — Long Baseline

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4 2\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

$$\sin^2\left(\Delta m^2_{ee} \tfrac{L}{4E}\right) \equiv \cos^2\theta_{12} \sin^2\left(\Delta m^2_{31} \tfrac{L}{4E}\right) + \sin^2\theta_{12} \sin^2\left(\Delta m^2_{32} \tfrac{L}{4E}\right)$$

NEUTRINOS OSCILLATIONS
PRECISION ERA
(NEED 3-NEUTRINO FORMALISM AND MATTER EFFECTS)

More on the PMNS matrix

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{CP}} & c_{13}c_{23} \end{pmatrix}$$

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

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

Decomposition:

$$U = \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta_{CP}} \\ & 1 & \\ -s_{13}e^{i\delta_{CP}} & & c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \times M$$

Solar,
LB reactor

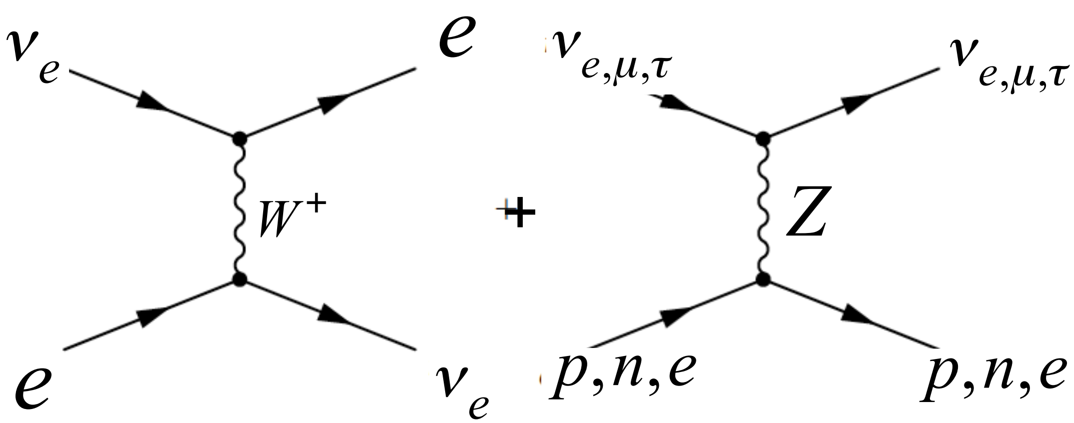
Reactor,
LB accelerators

Reactor,
LB accelerators

Majorana

$$M = \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Neutrinos in matter



Neutrino interactions in matter

This gives an effective potential of electron neutrinos: $V = \sqrt{2}G_F N_e$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix} = \begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + V & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix}\begin{pmatrix}\nu_e \\ \nu_\mu\end{pmatrix}$$

θ_m diagonalizes the Hamiltonian in matter:

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta \cdot \left(\frac{\Delta m^2}{2E}\right)^2}{\left[\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}G_F N_e\right]^2 + \left(\frac{\Delta m^2}{2E}\right)^2 \sin^2 2\theta}$$

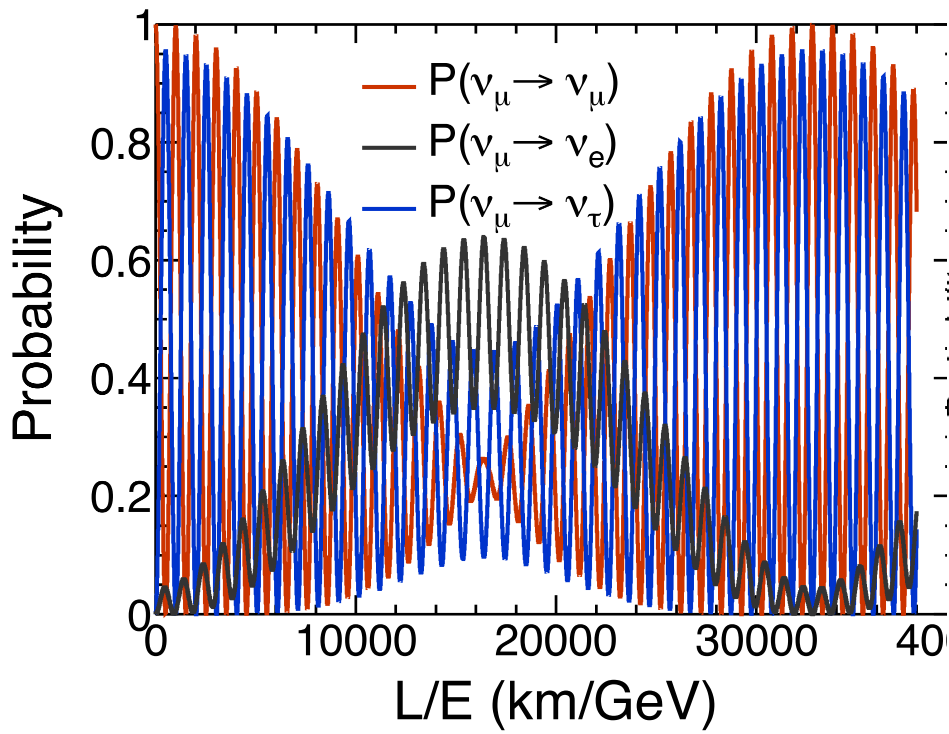
The flavor eigenstates are (in 2ν approx.):

$$|\nu_e\rangle = \cos\theta_m |\nu_{1m}\rangle + \sin\theta_m |\nu_{2m}\rangle$$

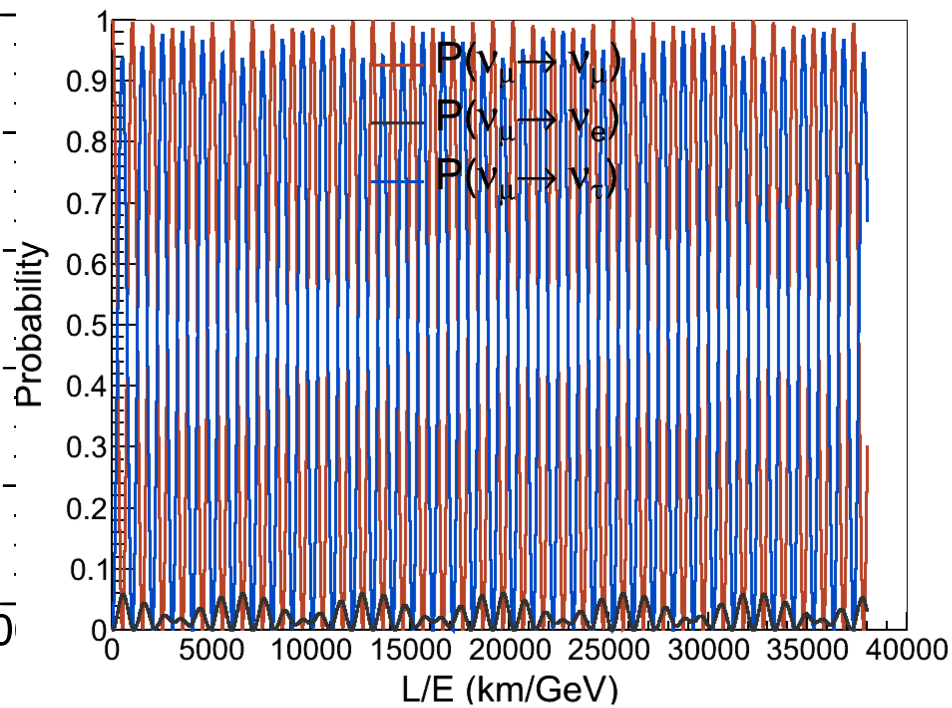
$$|\nu_\mu\rangle = -\sin\theta_m |\nu_{1m}\rangle + \cos\theta_m |\nu_{2m}\rangle$$

Matter does matter

No matter



With matter



Hypothetical example for illustration purposes only!

MINOS disappearance + appearance

$$P(\nu_\mu \to \nu_\mu) = 1 - 4\sin^2\theta_{23}\cos^2\theta_{13}(1-\sin^2\theta_{23}\cos^2\theta_{13})\sin^2\left(\frac{\Delta m^2_{32}L_\nu}{4E_\nu}\right)$$

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2\Delta(1-A)}{(1-A)^2} + \alpha J\cos(\Delta \pm \delta_{CP})\frac{\sin\Delta A}{A}\frac{\sin^2\Delta(1-A)}{(1-A)} + \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2\Delta A}{A^2}$$

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

$$A = \pm 2\sqrt{2}G_F n_e E_\nu/\Delta m^2_{31}$$

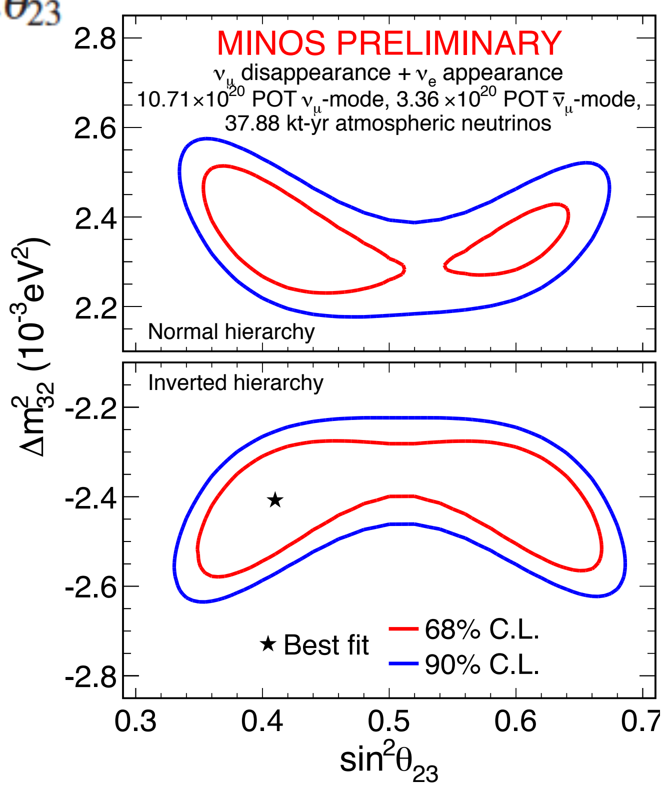
$$\alpha = \Delta m^2_{21}/\Delta m^2_{32} \approx 1/32$$

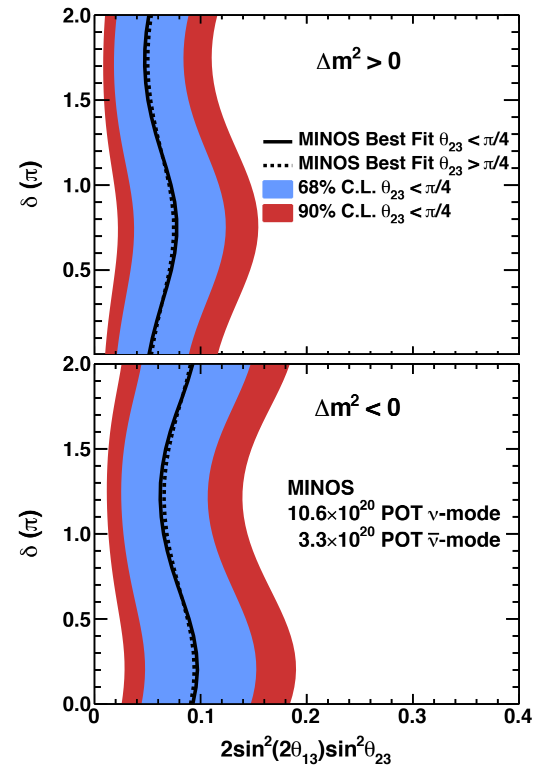
$\left|\Delta m^2_{32}\right| = [2.28 - 2.46]\times 10^{-3} eV^2$ (68%C.L.)

$\sin^2_{23} = 0.35 - 0.65$ (90%C.L.)

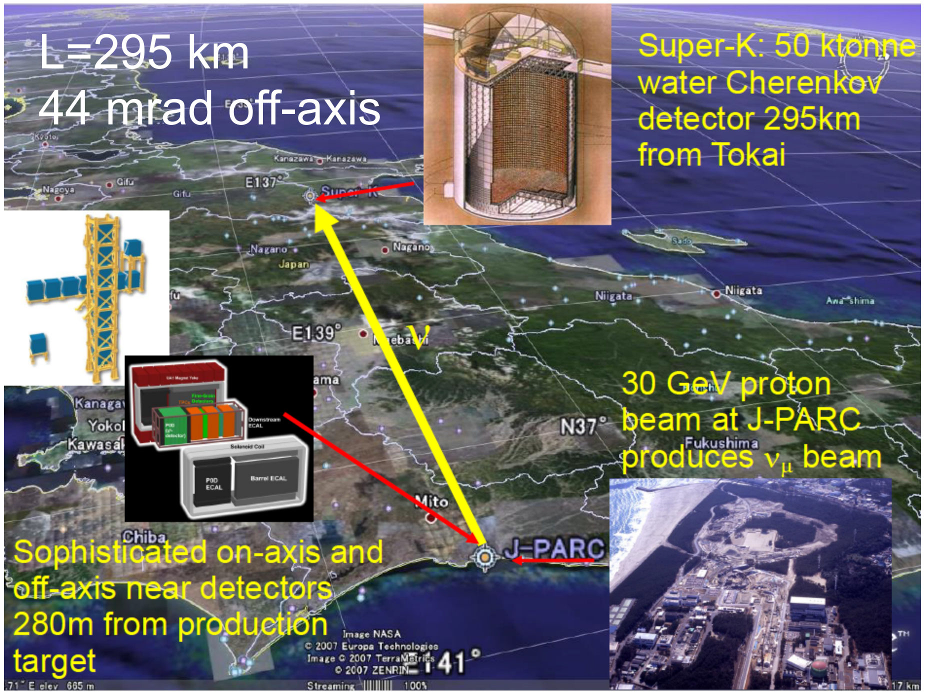
$\left|\Delta m^2_{32}\right| = [2.32 - 2.53]\times 10^{-3} eV^2$ (68%C.L.)

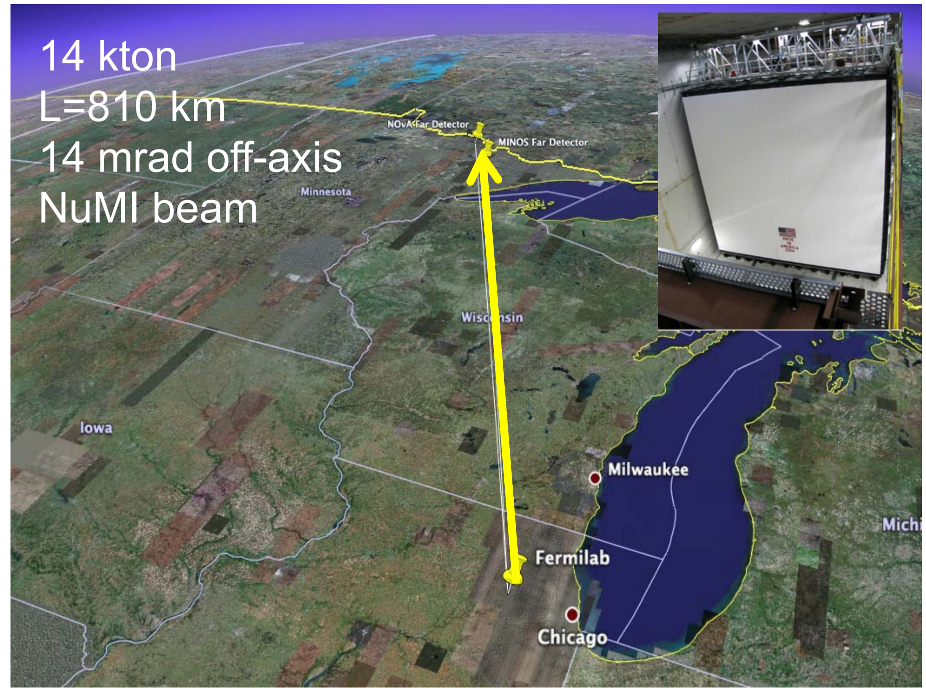
$\sin^2_{23} = 0.34 - 0.67$ (90%C.L.)





T2K vs NOvA

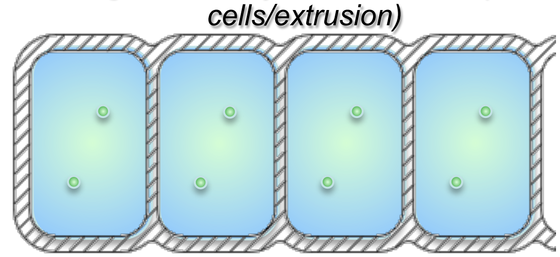




$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1^2)}$$
$$\overset{(+)}{-}\; 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin\Delta$$
$$+\, 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \cos\Delta$$

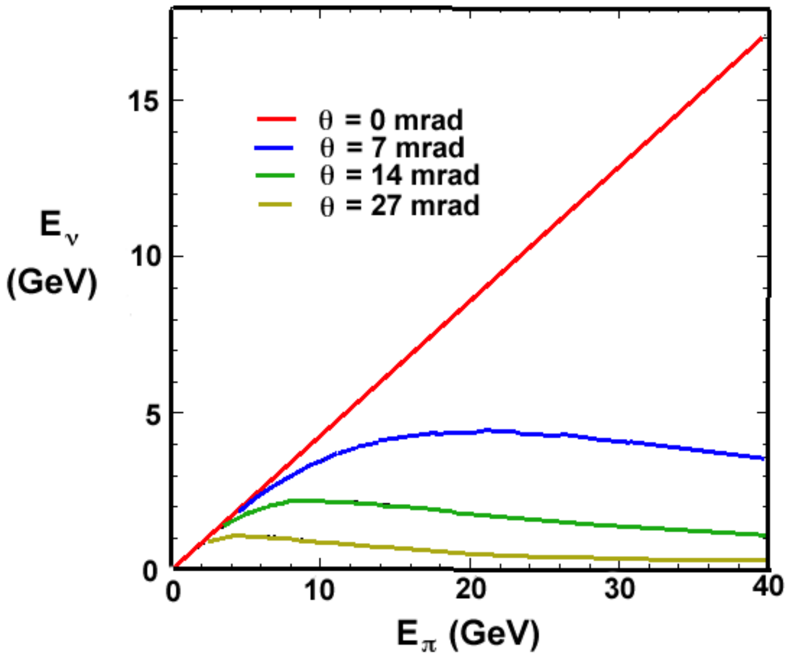
$$\text{Where:} \quad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \Delta m^2_{31} \frac{L}{4E} \qquad A = \overset{(-)}{+} G_f N_e \frac{L}{\sqrt{2}\Delta}$$

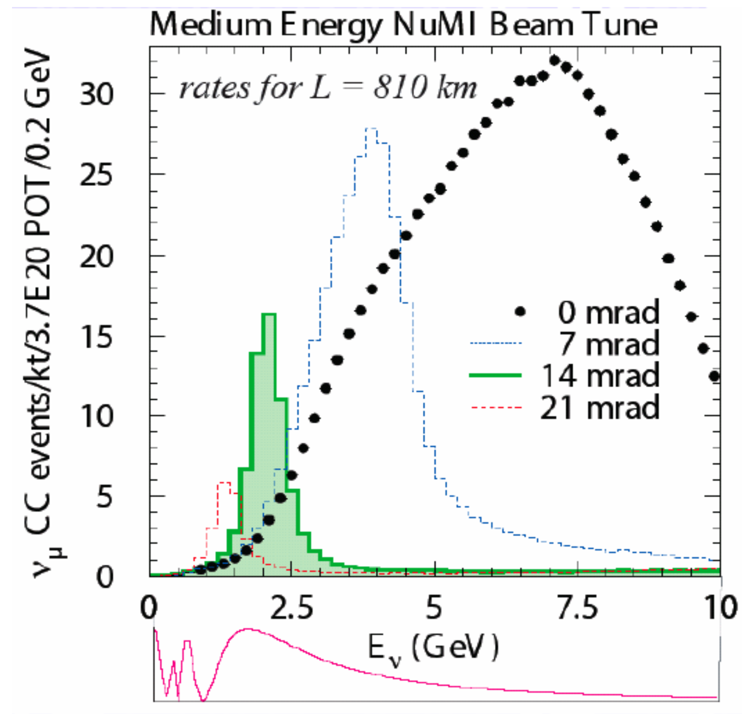
High reflectivity PVC extrusion (16 cells/extrusion)



0.7 mm waveshifting Fiber readout (double end)

The strategy: off-axis NuMI beam





$$E_\nu = E_\pi \frac{1 - \frac{m_\mu^2}{m_\pi^2}}{1 + \gamma^2\theta^2}$$

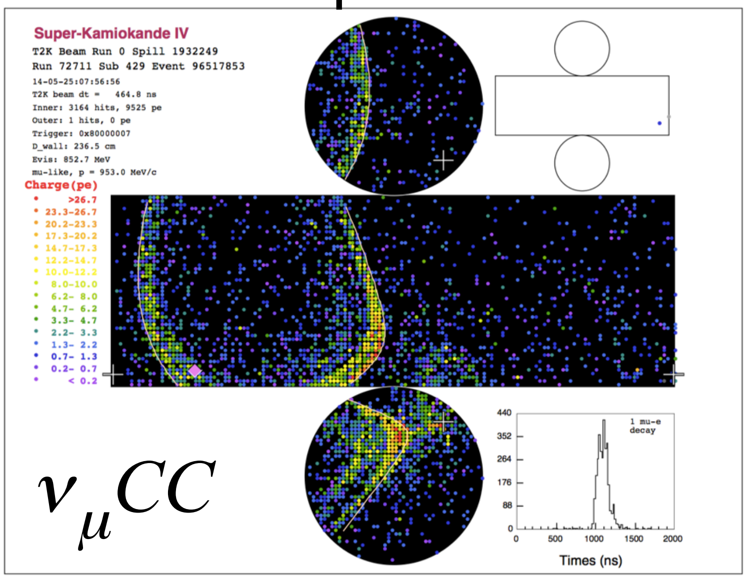
or

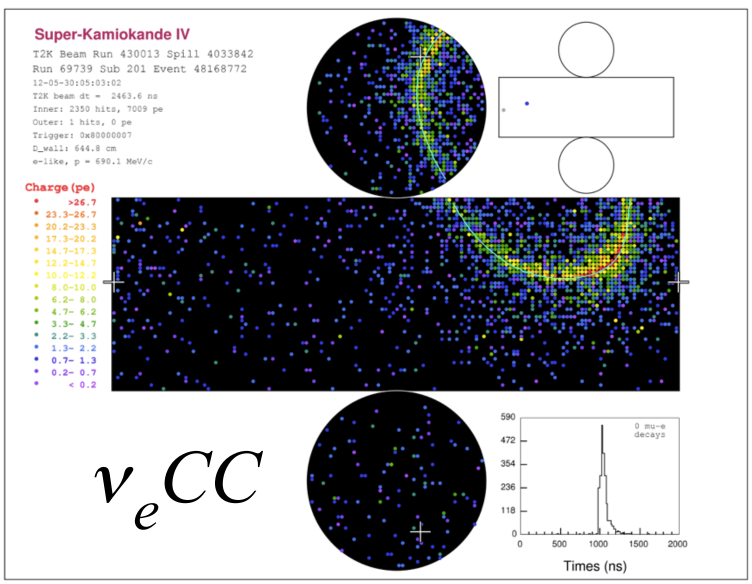
$$E_\nu = \frac{0.43\,\gamma\, m_\pi}{1+\gamma^2\theta^2} = \frac{0.43\, E_\pi}{1+\gamma^2\theta^2}$$

$$\frac{dN}{d\Omega} \approx \frac{1}{4\pi}\left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2$$

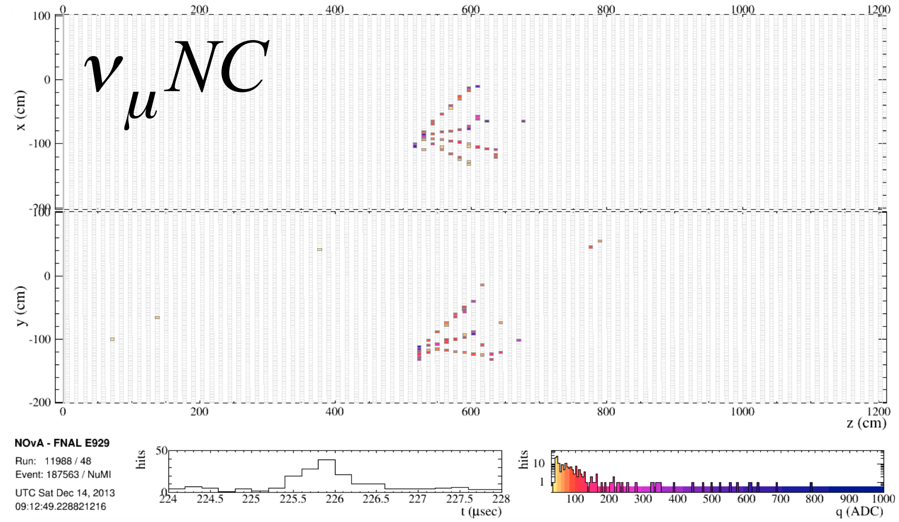
Event displays

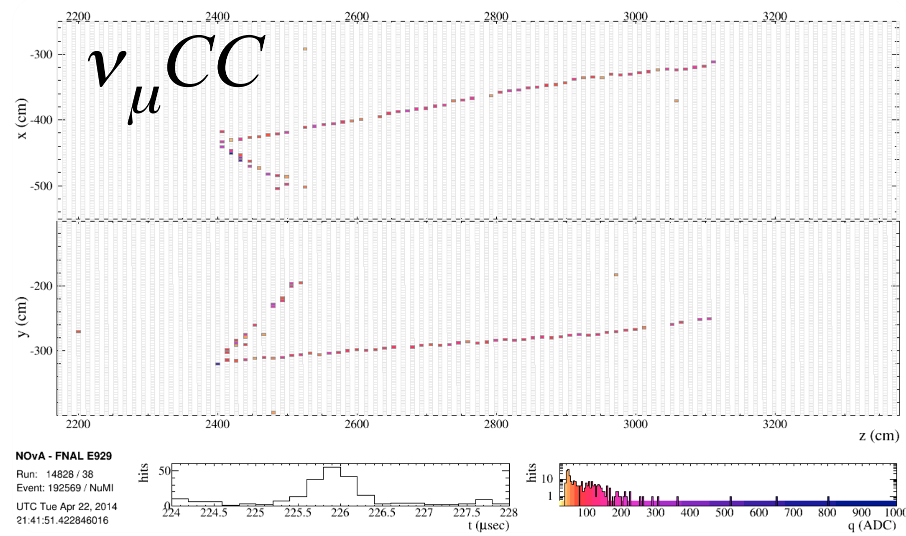
T2K experiment



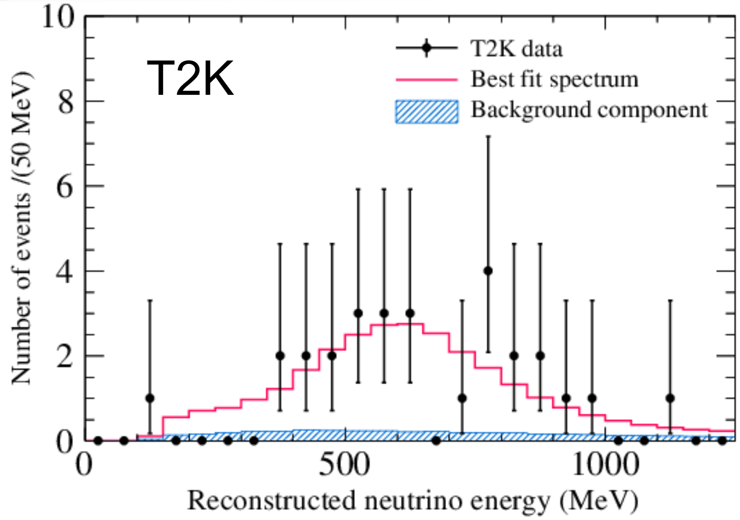


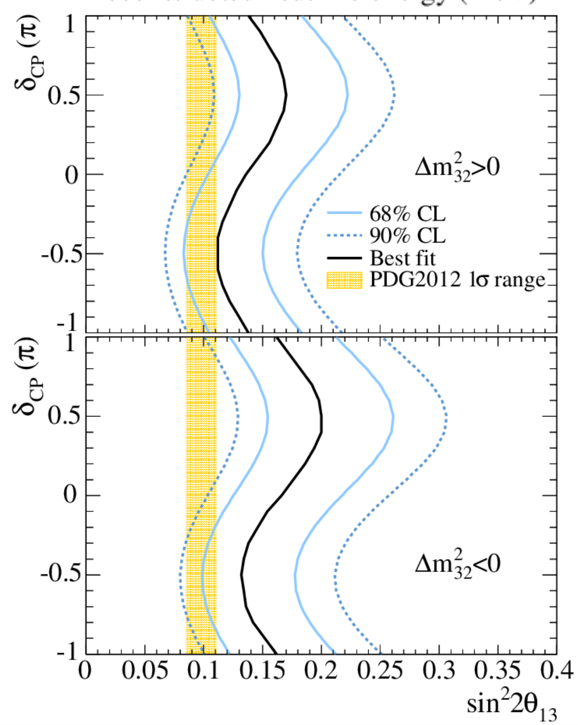
NOvA experiment



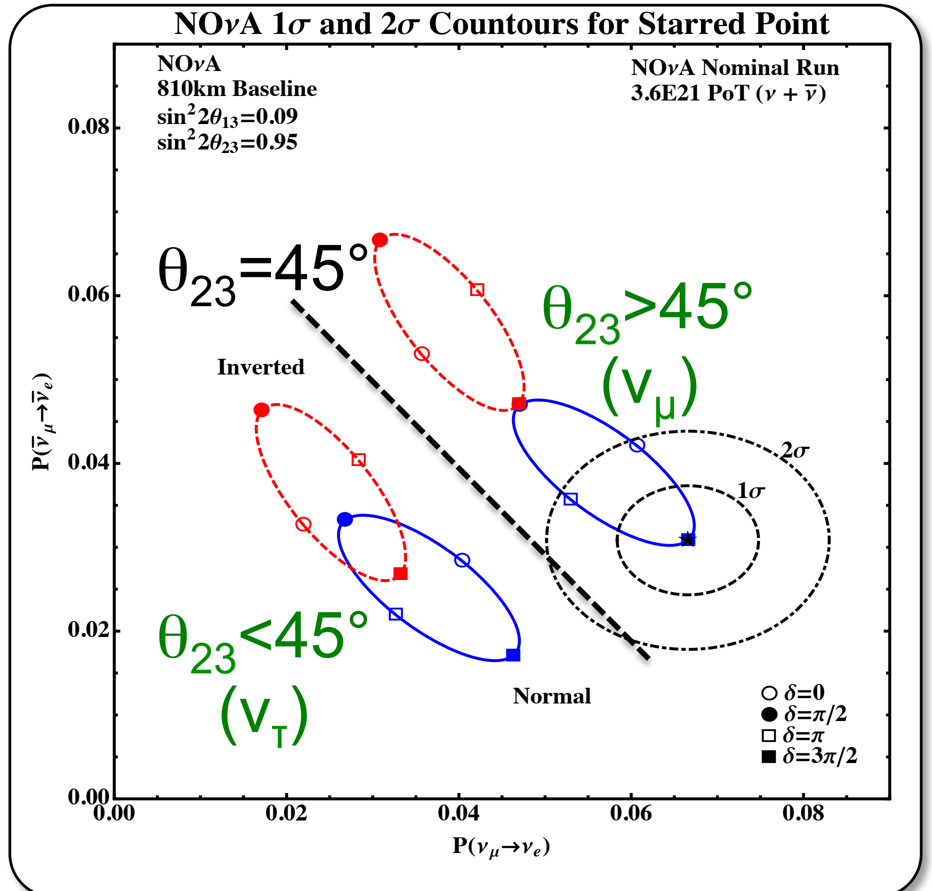


T2K measurements & NOvA starting up





NOvA (results soon)



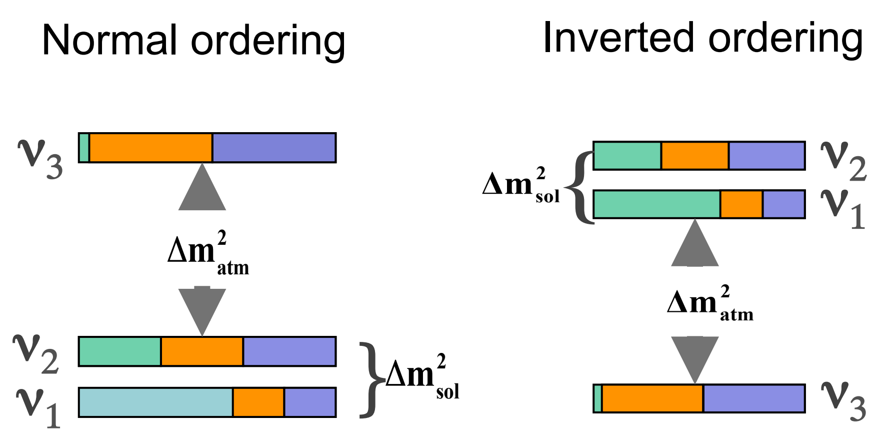
T2K and NOvA @ Neutrino 2014

It's tough to make predictions,
especially about the future.

Yogi Berra
(baseball player)

NEUTRINOS OSCILLATIONS
FUTURE ERA

Future



- **What is left:**
  - ⇨ Mass ordering
  - ⇨ θ_{23} octant
  - ⇨ δ_{CP}
- **If $\theta_{CP} \neq 0$ (CP violation)**
  - ⇨ Major consequences in particle physics and cosmology
  - ⇨ The "holy grail" of neutrino physics (and beyond)
- **What is the nature of neutrinos**
  - ⇨ Majorana
  - ⇨ Dirac
- **Are there sterile neutrinos [LSND and miniBooNE puzzles ("anomalies")]**

Not covered but important

Key formulas

- **Muon-neutrino disappearance**

$$P(\nu_\mu \to \nu_\mu) = 1 - 4\sin^2\theta_{23}\cos^2\theta_{13}(1 - \sin^2\theta_{23}\cos^2\theta_{13})\sin^2\left(\frac{\Delta m^2_{32} L_\nu}{4E_\nu}\right)$$

- **Electron-neutrino appearance**

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2\Delta(1-A)}{(1-A)^2} + \alpha J\cos(\Delta \pm \delta_{CP})\frac{\sin\Delta A}{A}\frac{\sin^2\Delta(1-A)}{(1-A)} + \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2\Delta A}{A^2}$$

$$J = \cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23} \qquad A = \pm 2\sqrt{2}G_F n_e E_\nu/\Delta m^2_{31}$$

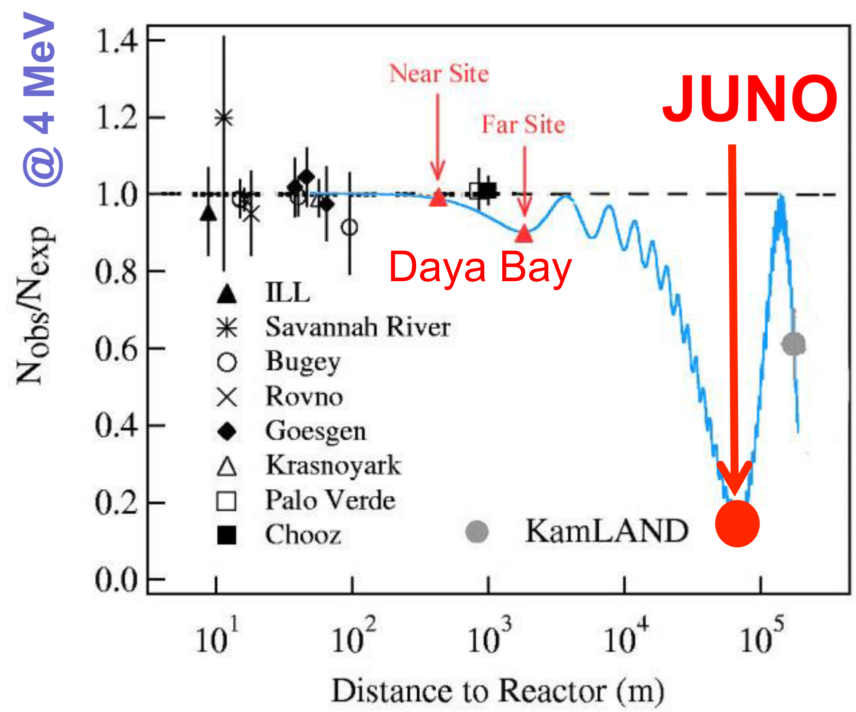
$$\alpha = \Delta m^2_{21}/\Delta m^2_{32} \approx 1/32$$

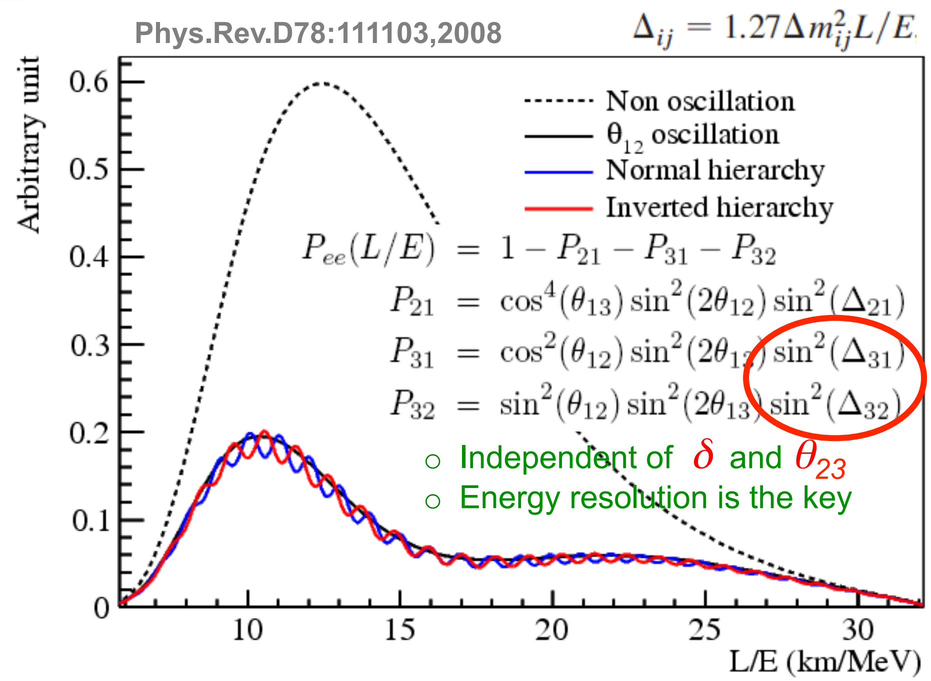
- **Electron-neutrino disappearance**

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

JUNO and RENO 50 – the concept

Jiangmen Underground Neutrino Observatory





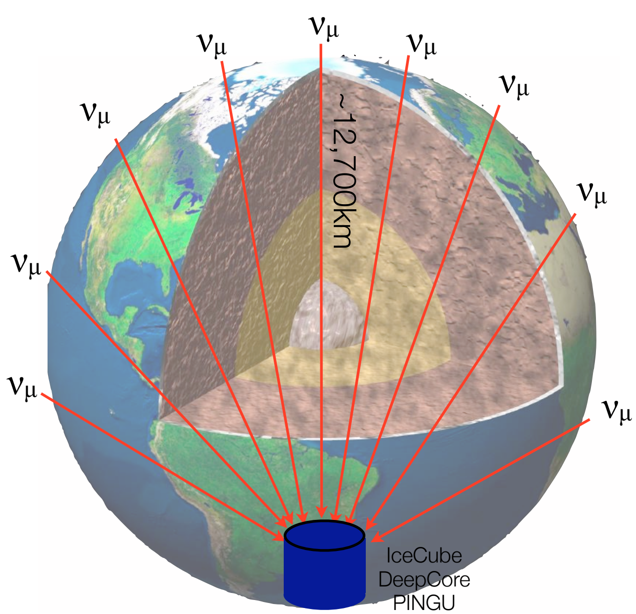
- Interference effect → driven by Δm^2_{32} & Δm^2_{31}
- Need stats → 20 kT Liq. Scint.
- Need resolution → $\sigma_E = 3\% / \sqrt{E(\mathrm{Mev})}$

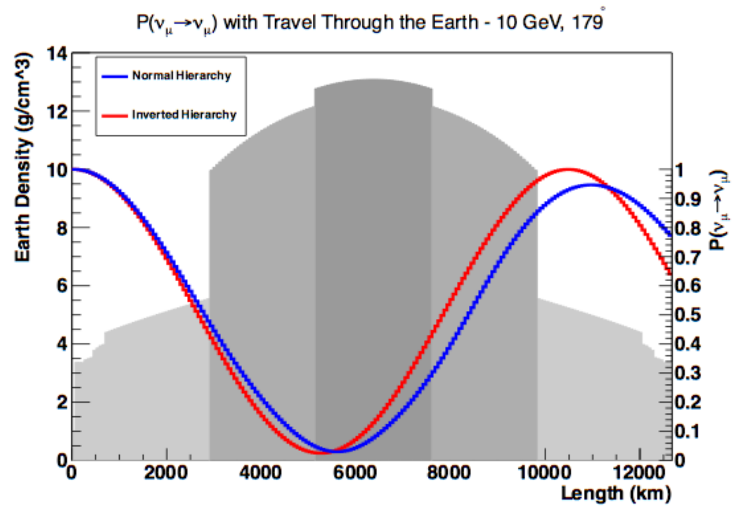
  $\sigma_E = \Delta m^2_{21} / |\Delta m^2_{32}|$
- Need optimum distance --> 53 km
- CR suppression → 700 m overburden

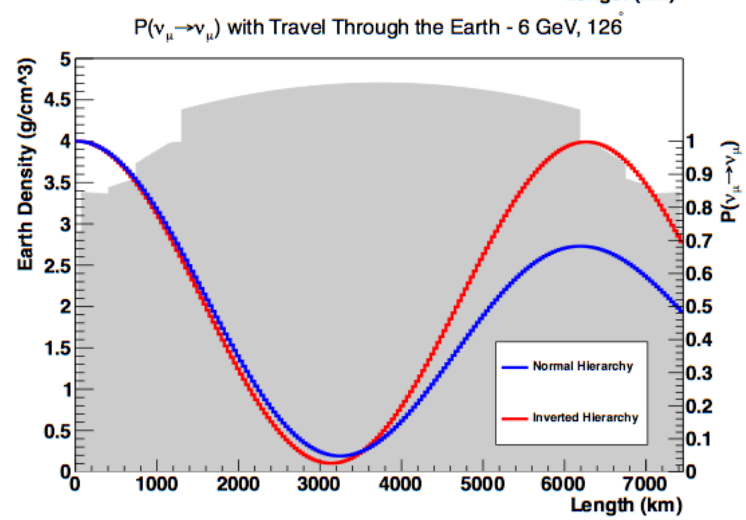
- Rich physics program
  - ⇨ Mass hierarchy
  - ⇨ Sterile neutrinos
  - ⇨ Improve mixing of 4 par.
    - ○ $\sin^2\theta_{12}$, $\sin^2\theta_{13}$ Δm^2_{21} Δm^2_{32}
  - ⇨ Supernovae
  - ⇨ Atmospheric
  - ⇨ Exotics

Atmospheric neutrinos

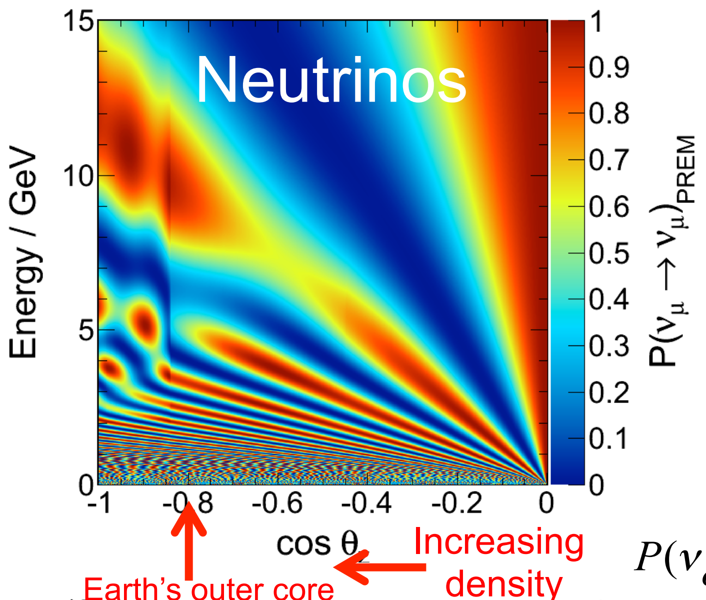
- Exploit atmospheric neutrinos and a large detector
- Determine the neutrino mass ordering ("hierarchy" in old parlance)
- For the normal ordering matter effects enhance (suppress) the transition probability for neutrinos (antineutrinos) and vice versa for the inverted ordering.

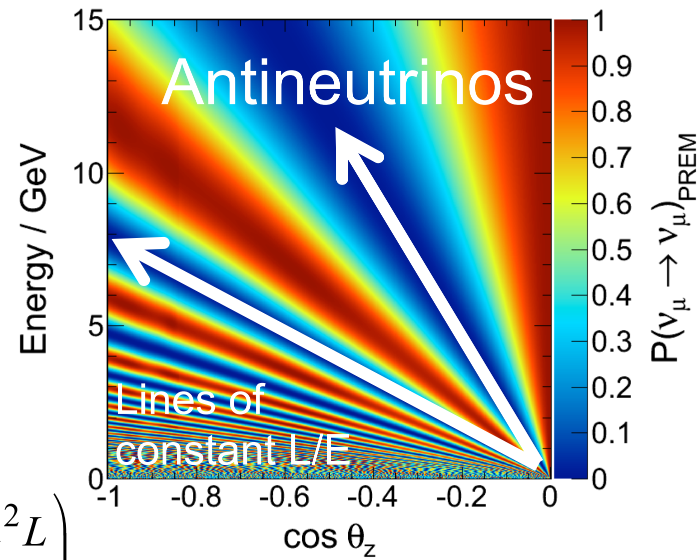






Atmospheric neutrinos oscillograms



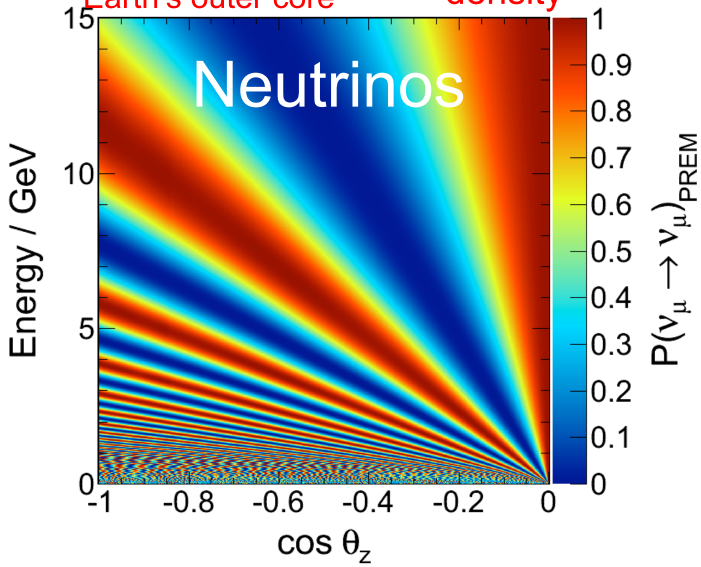


Normal ordering

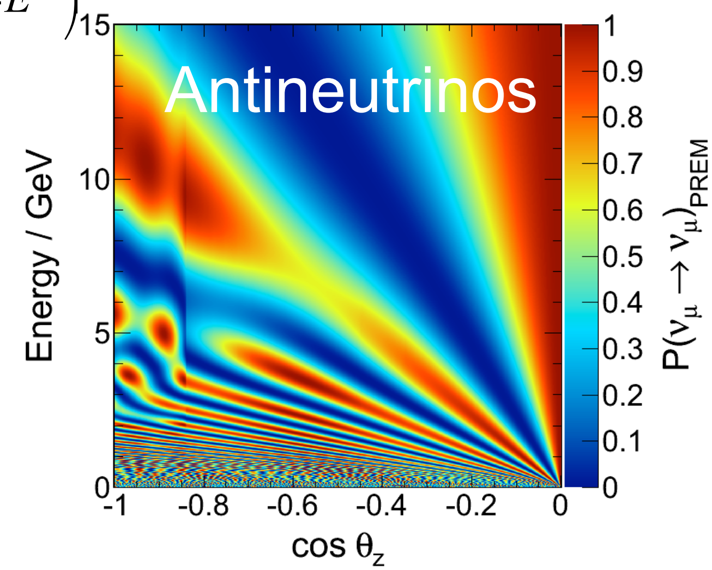
$$\Delta m_{32}^2 = 2.32 \times 10^{-3} \mathrm{eV}^2$$

$$\sin^2(\theta_{23}) = \frac{\pi}{4}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

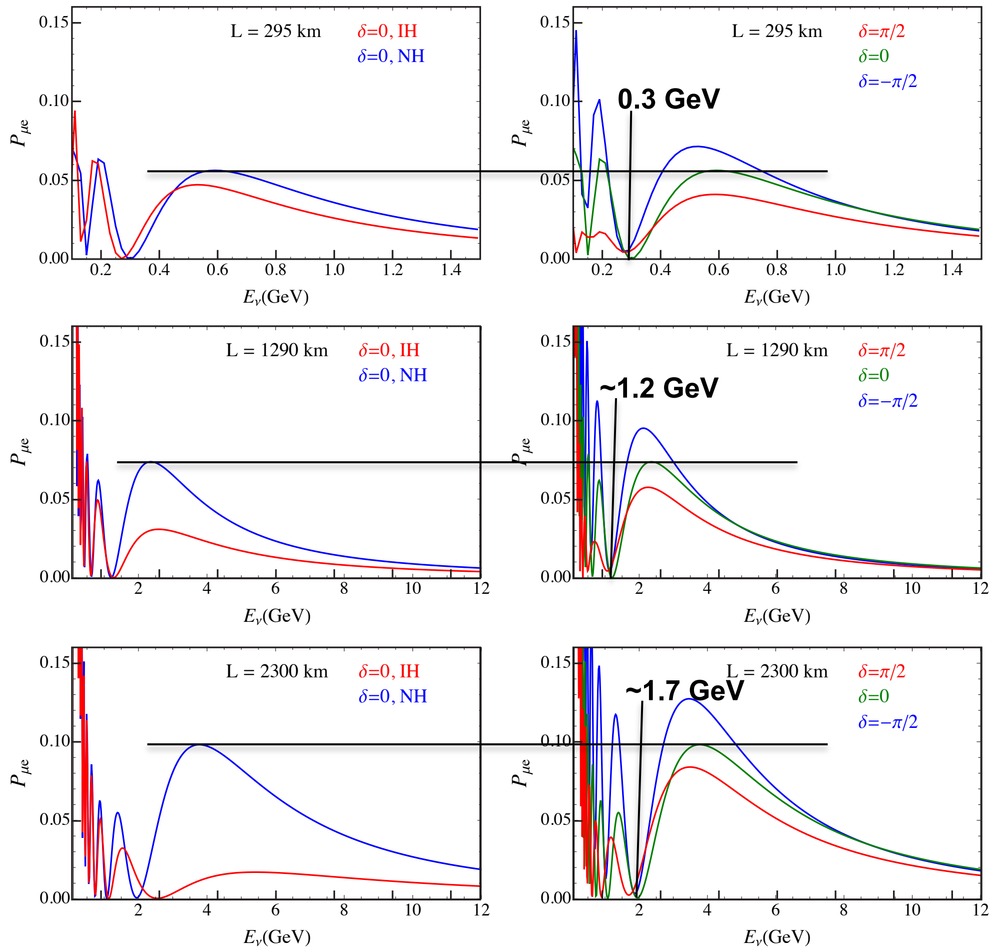


Inverted ordering



Accelerator LBL experiments: MH and CPV

Accelerator long baseline



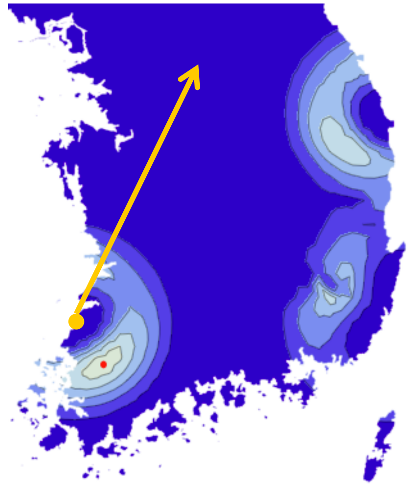
- **Mass hierarchy and CP modulate oscillation probability:**
  - ⇨ Need to measure as a function of *L*/*E* [measure *E* spectrum]
- **MH sensitivity grows with *L* [matter effect]**
- **CP modulation grows with *L*/*E* [measure *E* spectrum]**

Future MH & CPV experiments

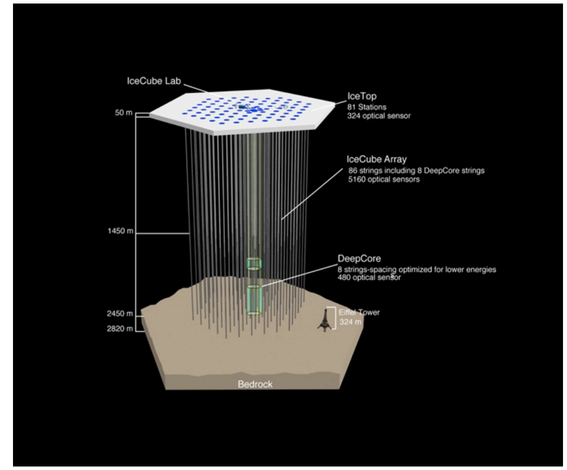
(mass hierarchy and CP violation)

JUNO (L=60 km) - China

RENO (L=60 km) - Korea



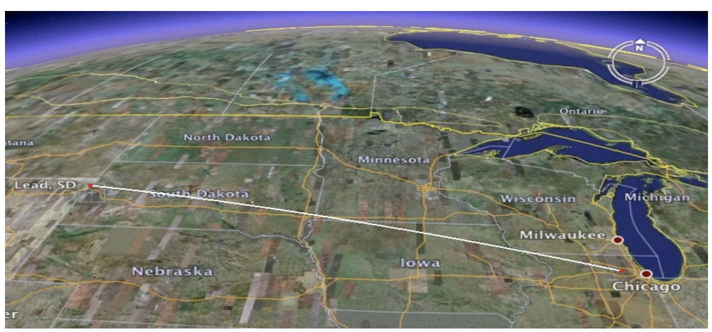
PINGU – South Pole



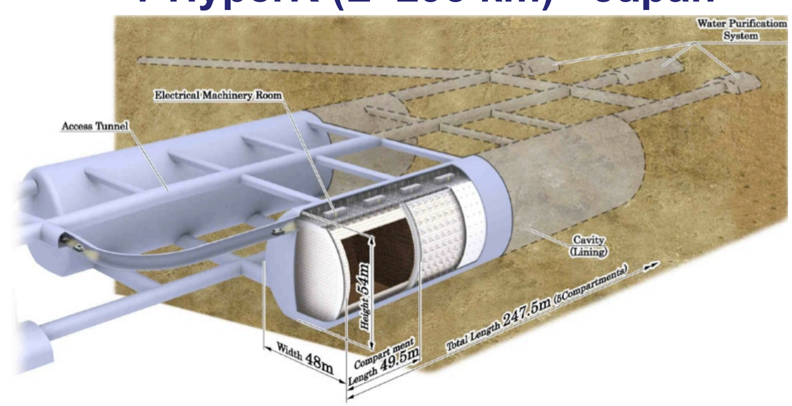
ORCA – Mediterranean

LENO (L=2,300 km) - Eu

LBNF/DUNE (L=1,300 km) - US

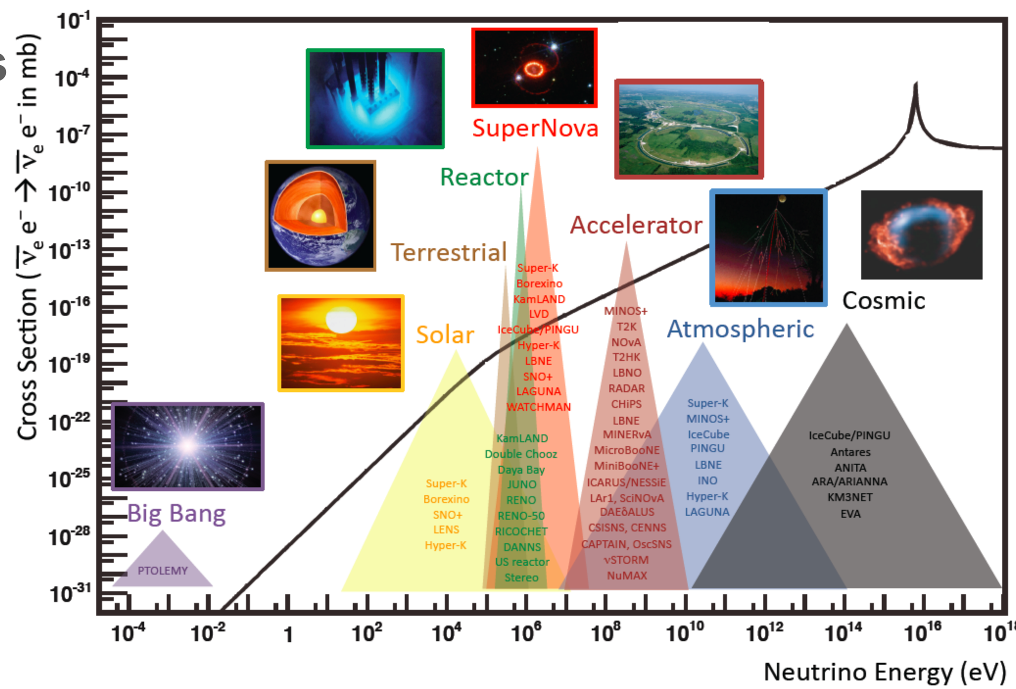


? HyperK (L=295 km) - Japan



Closing remarks (lessons learned ?)

- **In neutrino oscillations physics**
  - ⇨ Build a large detector or two
  - ⇨ Build an intense neutrino source
  - ⇨ Much to do!
- **Be first!**
  - ⇨ No one argues with success!
  - ⇨ Winners take it all!
  - ⇨ Be decisive!



When you come to a fork in the road,
take it!

Yogi Berra
(baseball player)

Don't work on it!
Do it!

Dick Tracy
(fictional character)