Exercises

	Hand out	Hand in	Discussion
Exercise 1	Wed 19.2.	Wed 26.2.	Fri 28.2.
Exercise 2	Wed 26.2.	Fri 6.3.	Fri 13.3.
Exercise 3	Fri 6.3.	Fri 20.3.	Fri 27.3.
Exercise 4	Fri 20.3.	Fri 3.4.	Fri 24.4.
Exercise 5	Fri 3.4.	Fri 1.5.	Fri 8.5.
Exercise 6	Fri 1.5.	Fri 15.5.	Fri 22.5.

Praktikum

- Discussion on Fri 29.5. 13:00-15:45

Addendum: Neutrino oscillation length

This lecture:

$$L_{osc} = \frac{4\pi E}{\Delta m^2}$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(\pi\frac{L}{L_{osc}})$$

Martin & Shaw, „Particle Physics“, Chapter 2:

$$L_{osc} = \frac{4E}{\Delta m^2}$$

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2(\frac{L}{L_{osc}})$$

PHY213 Kern- und Teilchenphysik II
(FS 2020)

Intensity Frontier: Neutrino physics

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Overview

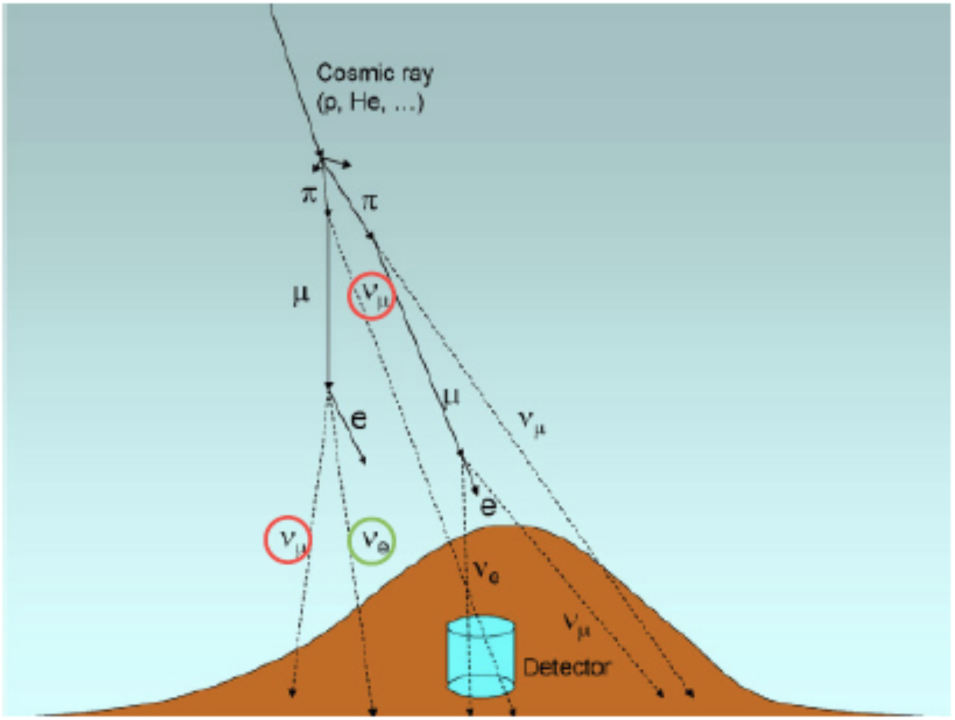
- Atmospheric neutrinos
- Identification with flavor
- Mass hierarchy
- Current status of measurements
- Experimental techniques
  - Sources
  - Reactor experiments
  - Accelerator experiments

Atmospheric neutrinos

- High-energy cosmic rays interact in the upper part of the Earth's atmosphere
- The cosmic rays (~86% protons) mostly interact hadronically giving showers of mainly pions
- Subsequent decay of pions and muons:

$$\pi^+ \rightarrow \mu^+ \nu_\mu \qquad \pi^- \rightarrow \mu^- \overline{\nu}_\mu$$
$$\hookrightarrow e^+ \nu_e \overline{\nu}_\mu \qquad \hookrightarrow e^- \overline{\nu}_e \nu_\mu$$

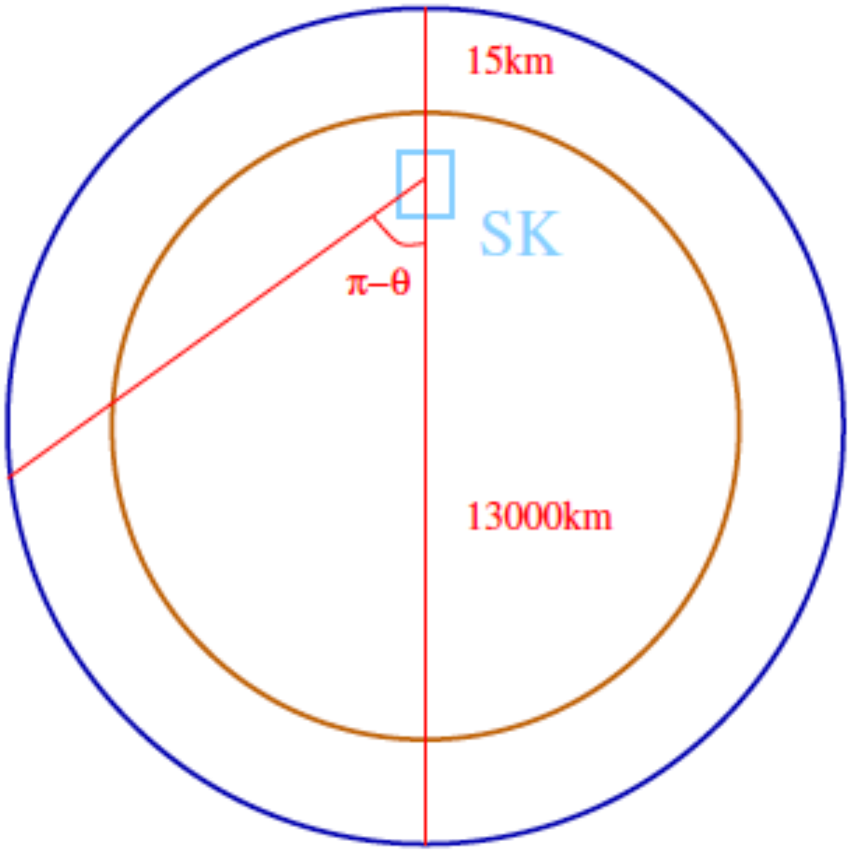
- Producing neutrinos with $E_\nu \sim 100$ MeV – 1 TeV
- Expected ratio is $\nu_\mu : \nu_e \sim 2 : 1$
- However, observed lower ratio (ν_μ deficit)



Atmospheric neutrino oscillations

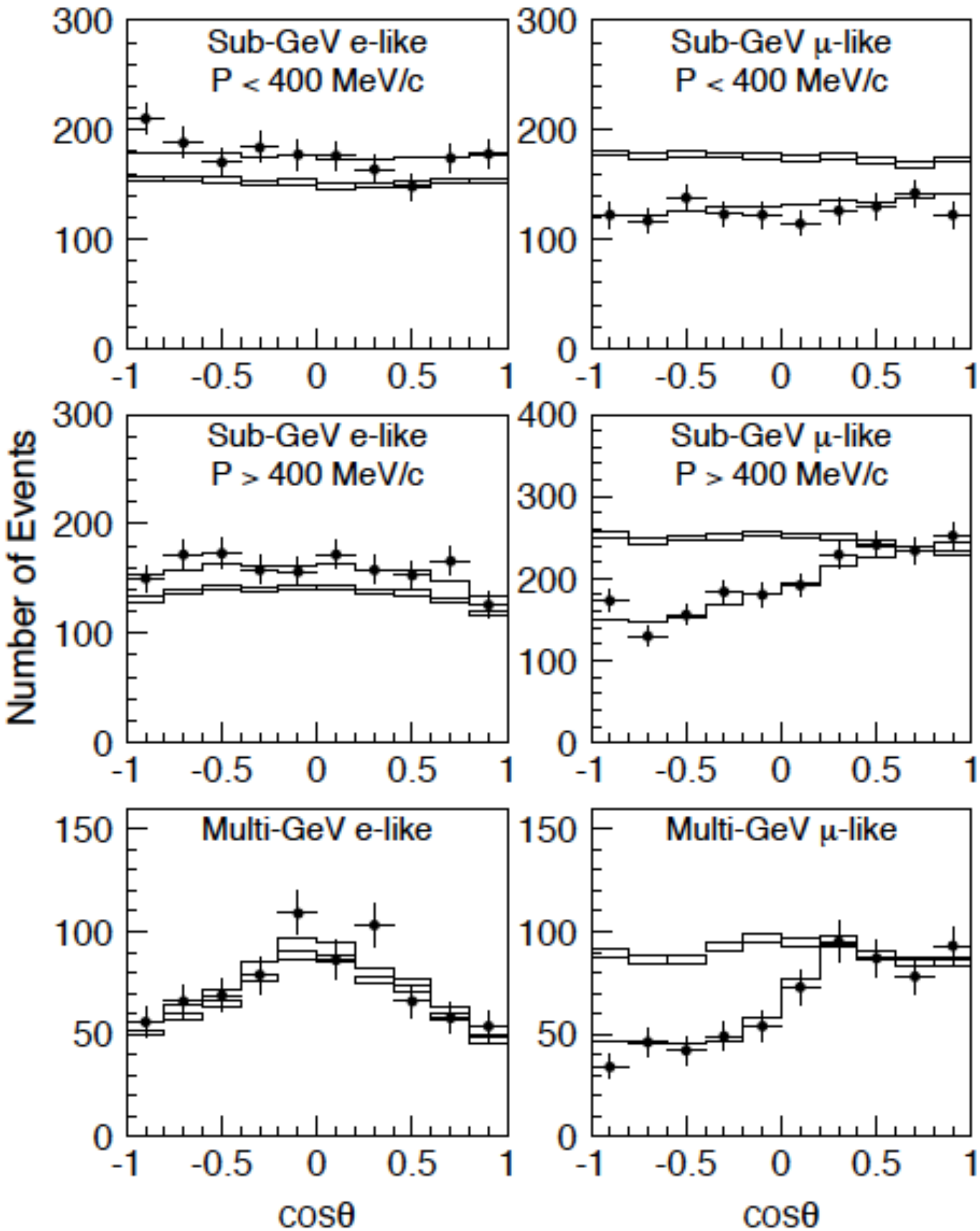
- Atmospheric neutrinos are an ideal source to look for neutrino oscillations → E_ν/L spans several orders of magnitude

- E_ν ~ 100 MeV – 1 TeV
- L ~ 10 – 10^4 km



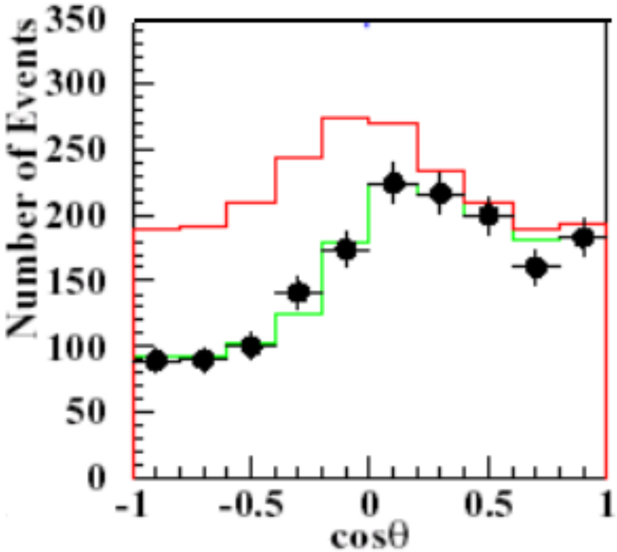
Atmospheric neutrino oscillations

- SuperKamiokande experiment clarified origin of atmospheric ν_μ deficit
  - Experiment can separate ν_μ and ν_e and measure direction of outgoing lepton
  - Measured flux for different energies
- Results
  - ν_e in rough agreement with predictions
  - Strong evidence for disappearance of ν_μ coming from below
  - Consistent with $\nu_\mu \rightarrow \nu_\tau$ oscillations (ν_τ below detection threshold)

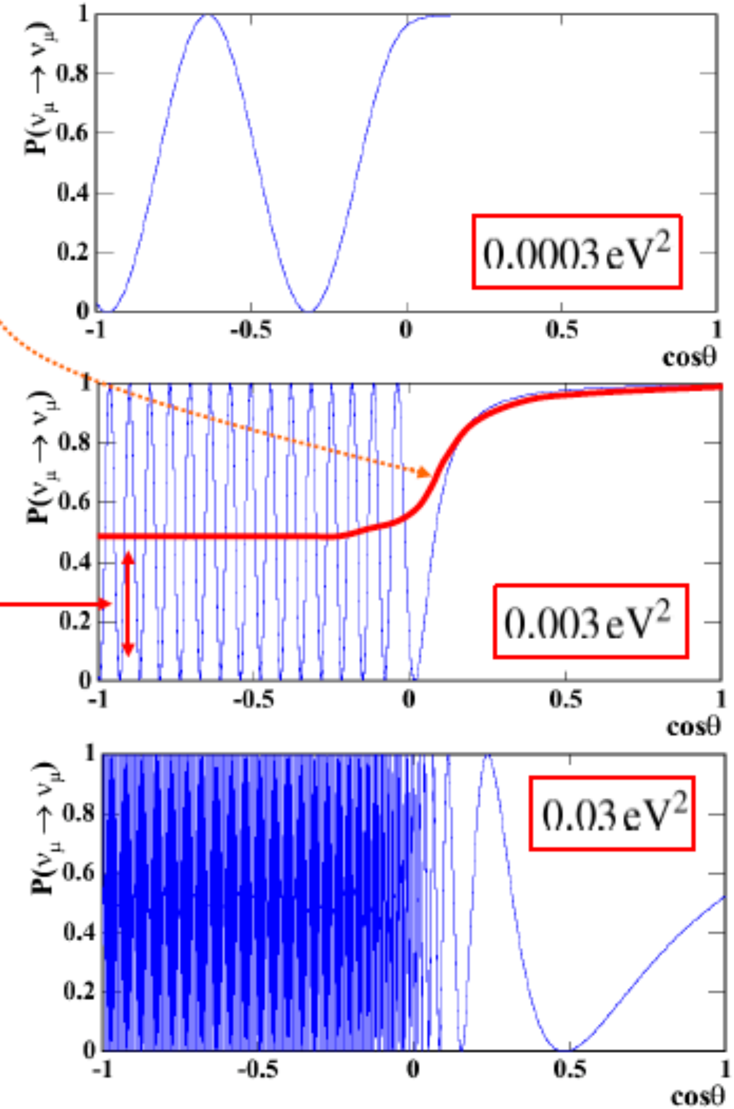


Atmospheric neutrino oscillations

- Measure muon direction and energy not neutrino direction/energy
- Don′t have E/θ resolution to see oscillations
- Oscillations "smeared" out in data
- Compare data to predictions for $|\Delta m^2|$



$$1 - \tfrac{1}{2}\sin^2 2\theta$$



★ Data consistent with:

$$\boxed{\begin{aligned} |\Delta m^2_{\mathrm{atmos}}| &\approx 0.0025\,\mathrm{eV}^2 \\ \sin^2 2\theta_{\mathrm{atmos}} &\approx 1 \end{aligned}}$$

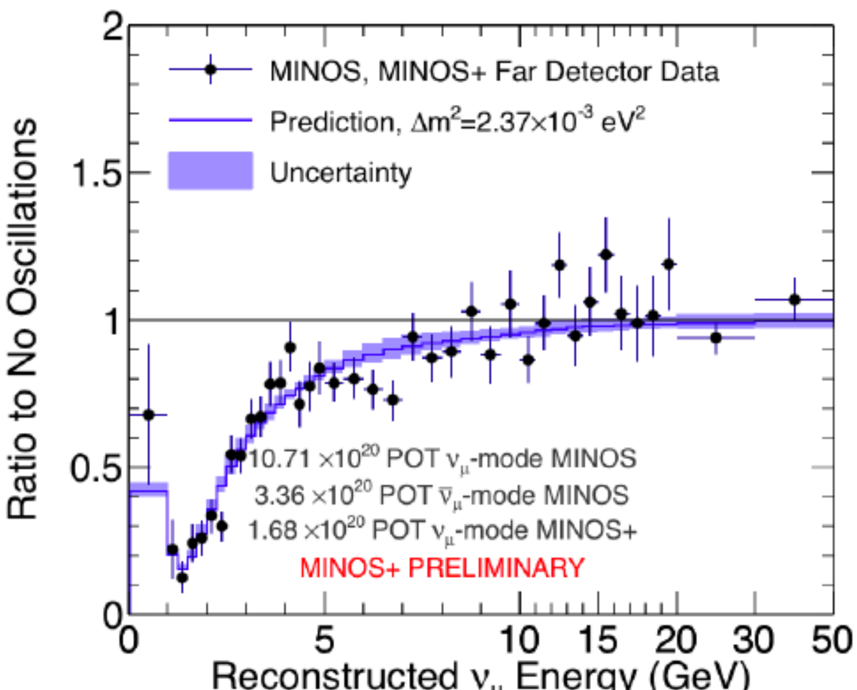
Confirmation by accelerator neutrinos

- Atmospheric neutrino oscillations confirmed by long-baseline accelerator neutrino experiments

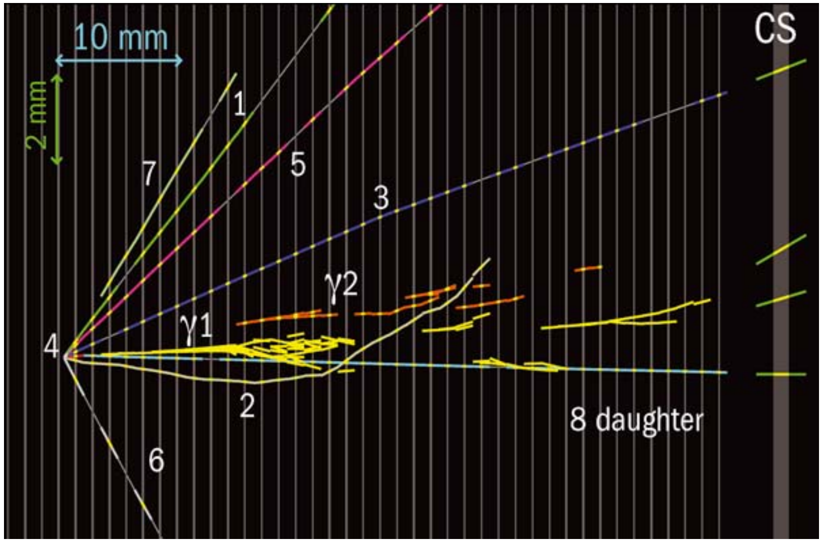
$$\Delta m^2_{\rm atm} = 2.5 \times 10^{-3} eV^2$$

$$|\Delta m^2_{\rm atm}| \sim \frac{\mathcal{O}(GeV)}{\mathcal{O}(1000km)}$$

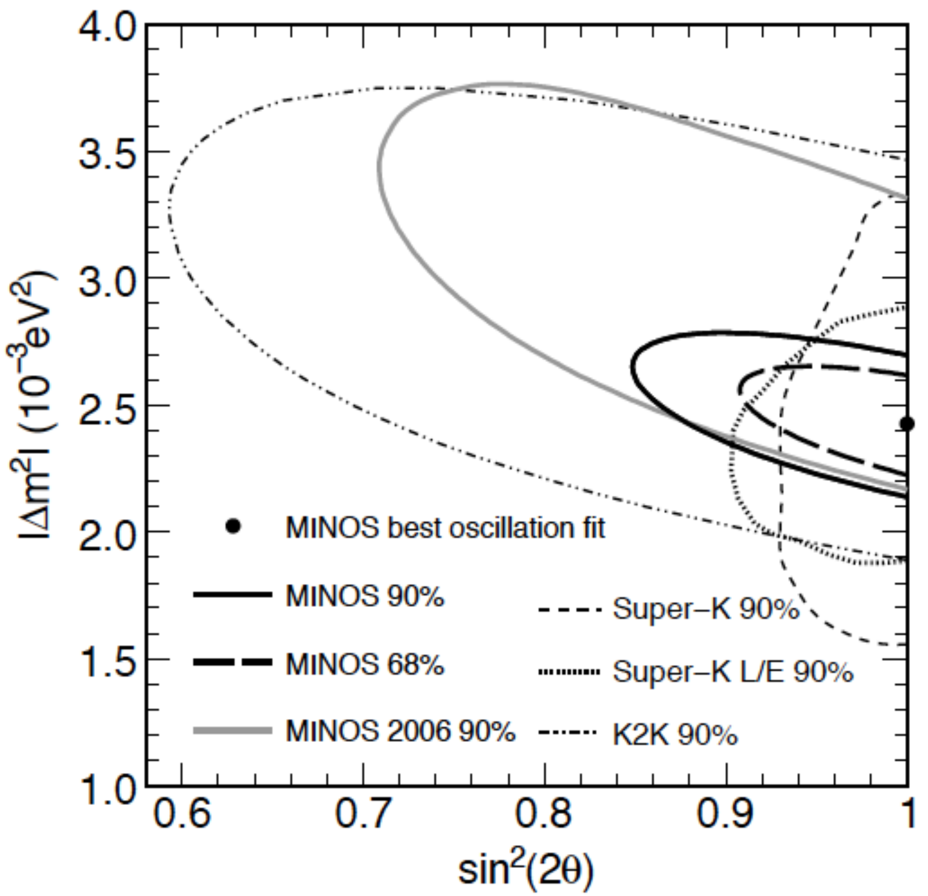
- ν_μ disappearance first measured by MINOS (Fermilab, L=730km) and K2K (JPARC, L=235km)
- ν_τ appearance measured by OPERA (CERN/LNGS, L=730km)



OPERA 2010



Measurement of Δm_{23} and θ_{23}



$$\boxed{\theta_{23} = (38 - 50)^{\circ}(3\sigma)}$$

→ Which octant? Is q_{23} smaller or larger than 45^0?

$$\boxed{|\Delta m^2_{32}| \approx (2.5 \pm 0.4) \times 10^{-3}\mathrm{eV}^2}$$

Identification with flavors

- Have two distinct Δm^2 related to solar and atmospheric oscillation frequencies

$$\underbrace{|\Delta m^2_{\text{solar}}|}_{\sim 8\cdot 10^{-5}\ \text{eV}^2} \ll \underbrace{|\Delta m^2_{\text{atmos}}|}_{\sim 2.5\cdot 10^{-3}\ \text{eV}^2}$$

- Conventional assignment to mass eigenstates

$$\Delta m^2_{23} = m^2_3 - m^2_2 \equiv \Delta m^2_{atm}$$
$$\Delta m^2_{12} = m^2_2 - m^2_1 \equiv \Delta m^2_{sol}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{23}(\theta_{23})U_{13}(\theta_{13},\delta)U_{12}(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Decoupling as 2 flavor mixing

- Three flavor mixing phenomena decouple to 2 flavor mixing phenomena since $\Delta m_{atmos} >> \Delta m_{solar}$ and θ_{13} small
- For athmospheric neutrino oscillations:

$$E_\nu/L \sim |\Delta m^2_{\mathrm{atmos}}| \quad \rightarrow \quad \sin\left(\frac{\Delta m^2_{\mathrm{solar}} L}{4E_\nu}\right) \sim \frac{\Delta m^2_{\mathrm{solar}} L}{4E_\nu} \sim 0$$

$$\theta_{13} \rightarrow 0$$

$$P(\nu_e \rightarrow \nu_\mu) = s^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right) = 0$$

$$P(\nu_e \rightarrow \nu_\tau) = c^2_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right) = 0$$

$$P(\nu_\mu \rightarrow \nu_\tau) = c^4_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right) = \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right)$$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23}}{4E} L\right) = 1$$

- Described by 2x2 mixing with mixing parameters:

$$(\Delta m^2_{23}, \theta_{23}) = (\Delta m^2_{atm}, \theta_{atm})$$

Decoupling as 2 flavor mixing

- Three flavor mixing phenomena decouple to 2 flavor mixing phenomena since Δm_{atmos} >> Δm_{solar} and θ_{13} small
- For solar neutrino oscillations:

$E_\nu / L \sim \left|\Delta m^2_{\text{solar}}\right|$ → Atmospheric oscillations too rapid and get averaged out

$\theta_{13} \to 0$

$$P(\nu_e \to \nu_e) = P(\bar{\nu}_e \to \bar{\nu}_e) \simeq \overset{1}{c^4_{13}} \left(1 - \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{12} L}{4E_\nu}\right)\right) + \overset{0}{s^4_{13}}$$

- Described by 2x2 mixing with mixing parameters:

$$(\Delta m^2_{12}, \theta_{12}) = (\Delta m^2_{\text{sol}}, \theta_{\text{sol}})$$

- Note: measurement of $\theta_{13} \sim 9^0$ → get sizeable corrections

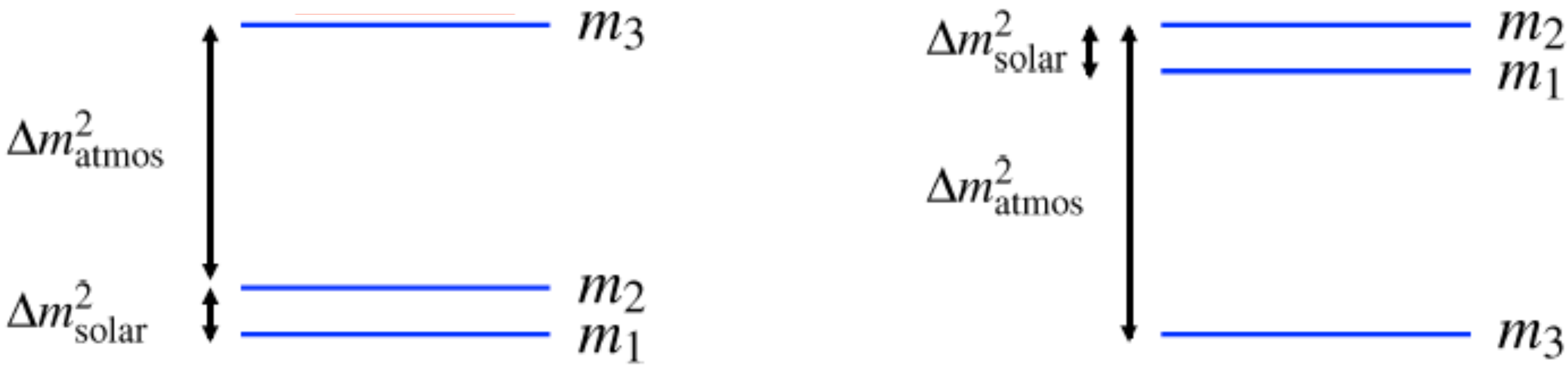
Mass hierarchy

- Results of neutrino oscillations determine $|\Delta m^2_{ji}| = |m^2_j - m^2_i|$
- Two distinct and very different mass scales

$$|\Delta m^2|_{\text{atmos}} \sim 2.5 \times 10^{-3}\,\text{eV}^2$$
$$|\Delta m^2|_{\text{solar}} \sim 8 \times 10^{-5}\,\text{eV}^2$$

- Two possible assignments of mass hierarchy:

Normal hierarchy | **Inverted hierarchy**

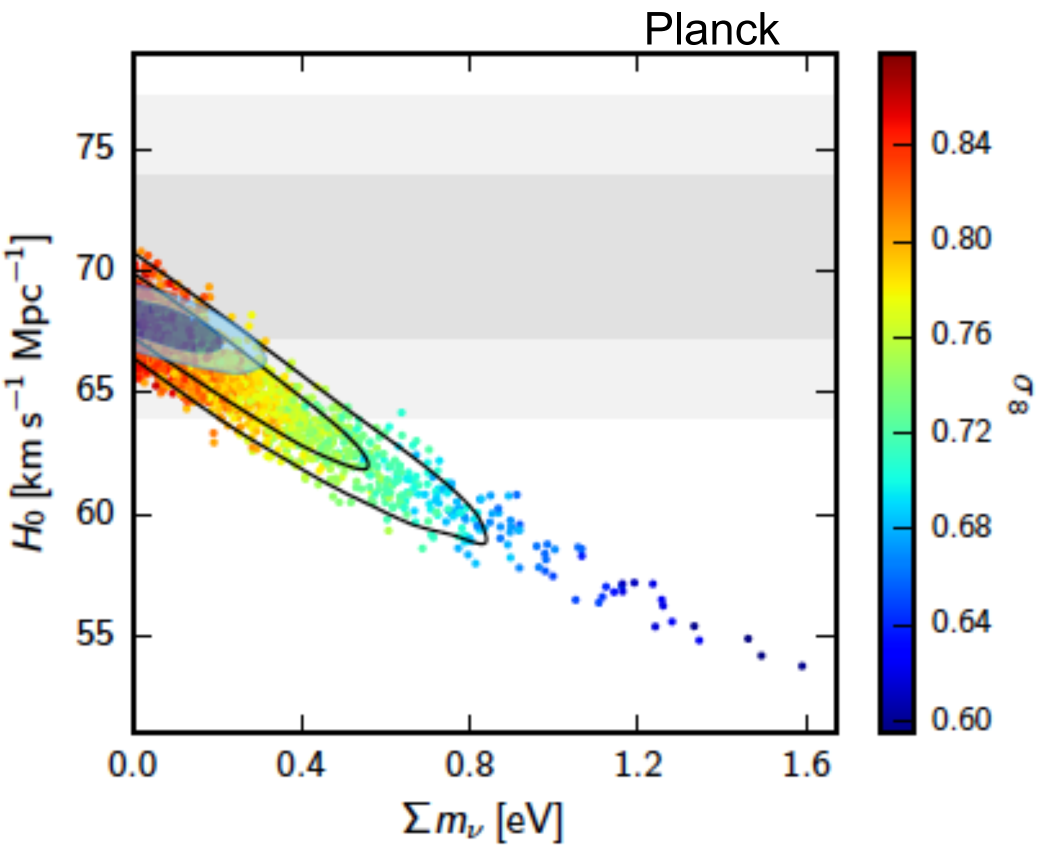


- In both cases:

$$\Delta m^2_{21} \sim 8 \times 10^{-5}\,\text{eV}^2 \quad \text{(solar)}$$
$$|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\,\text{eV}^2 \quad \text{(atmospheric)}$$

Constraints on neutrino masses

- Neutrino oscillations cannot provide information about absolute mass scales
- Best sensitivity to sum of neutrino masses coming from cosmology (CMB temperature power spectrum, galaxy structure formation)



Measurement of mixing parameters

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

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

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

atmospheric, accelerator **accelerator, reactor** **solar, reactor**

3 mixing angles, 2 squared mass difference, 1 complex phase (δ_{CP})

3 Flavour states

3 Mass states
$m_1 \neq m_2 \neq m_3$

more than15 years of experimental efforts

Parameters		Experiment	signal
$\lvert\Delta m_{21}\rvert^2 = \lvert m^2{}_2 - m^2{}_1\rvert$	ϑ_{12}	solar and reactor	$P(\nu_e \to \nu_{\mu,\tau})$
$\lvert\Delta m_{32}\rvert^2 = \lvert m^2{}_3 - m^2{}_2\rvert$	ϑ_{23}	atmospheric and accelerator	$P(\nu_\mu \to \nu_\mu)$ & $P(\nu_\mu \to \nu_\tau)$
	ϑ_{13}	reactor and accelerator	$P(\nu_\mu \to \nu_e)$ & $P(\bar{\nu}_e \to \bar{\nu}_e)$
	δ_{CP}	accelerator	$P(\nu_\mu \to \nu_e)$

Knowns and unknowns

$$\theta_{12} = 33.6 \pm 0.8^{o}$$

$$\Delta m^2_{21} = +(7.5 \pm 0.2) \times 10^{-5} \mathrm{eV}^2$$

Solar parameters

$P(\nu_e \to \nu_{\mu,\tau})$ SNO , SK, BOREXINO, GALLEX, SAGE..

$P(\bar{\nu}_e \to \bar{\nu}_e)$ KamLAND

$$\theta_{23} = (38 - 50)^{o} (3\sigma)$$ → Octant?

$$|\Delta m^2_{32}| \approx (2.5 \pm 0.4) \times 10^{-3} \mathrm{eV}^2$$

→ Mass hierarchy?

Atmospheric parameters

$P(\nu_\mu \to \nu_\mu)$ Kamiokande, SK, IMB, K2K, MINOS, T2K, NOvA

$P(\nu_\mu \to \nu_\tau)$ (Opera)

$$\theta_{13} = 8.4 \pm 0.2^{o}$$

$P(\bar{\nu}_e \to \bar{\nu}_e)$ Daya-Bay, RENO, Double Chooz

$P(\nu_\mu \to \nu_e)$ T2K, NOvA

$$\delta_{CP} = [0, 2\pi]$$ → CP violation?

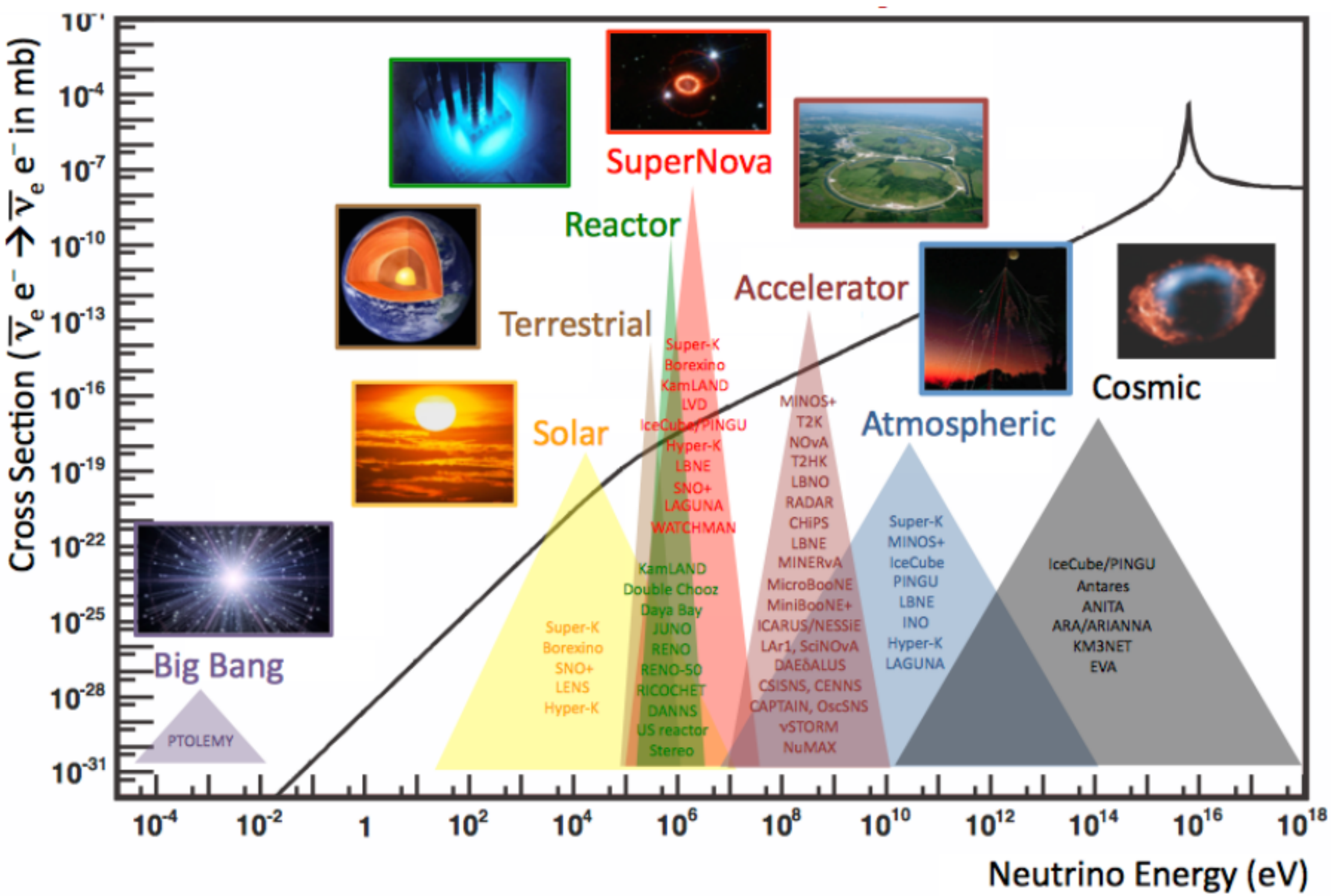
T2K, NOvA

→ New phenomena?

Neutrino physics experiments

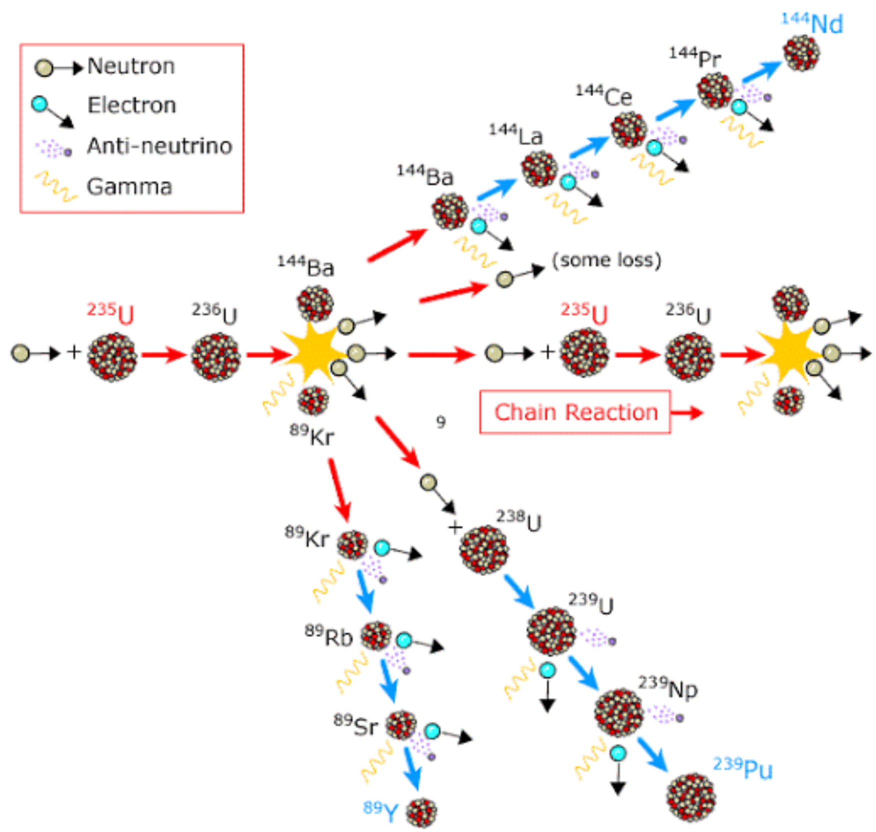
Sources of neutrinos

- Neutrinos are everywhere:
  - Energy spectrum covers 20 orders of magnitude
  - Second most abundant particles in the universe

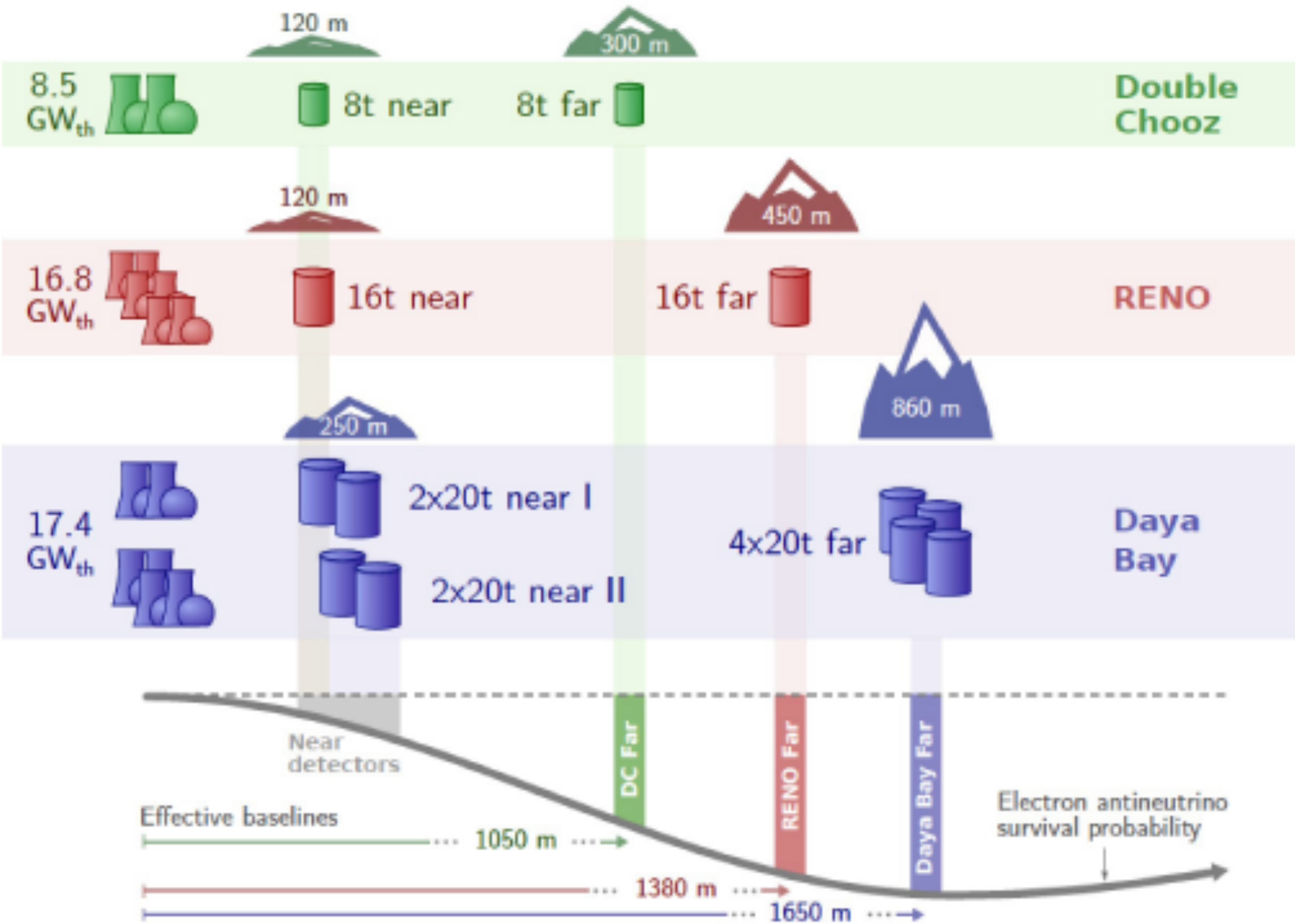


Artificial sources: Reactor neutrinos

- Intense flux of anti-ν, produced "for free" by nuclear power plants E_ν ~ MeV
  - Used for first observations of neutrinos (Reines & Cowan)
  - anti-ν from β-decay of fission products, flux estimated by the fraction of isotopes that are fissioning at a given time and the reactor power
  - Average flux 10^{20} anti-ν_e per second



Reactor neutrino experiments

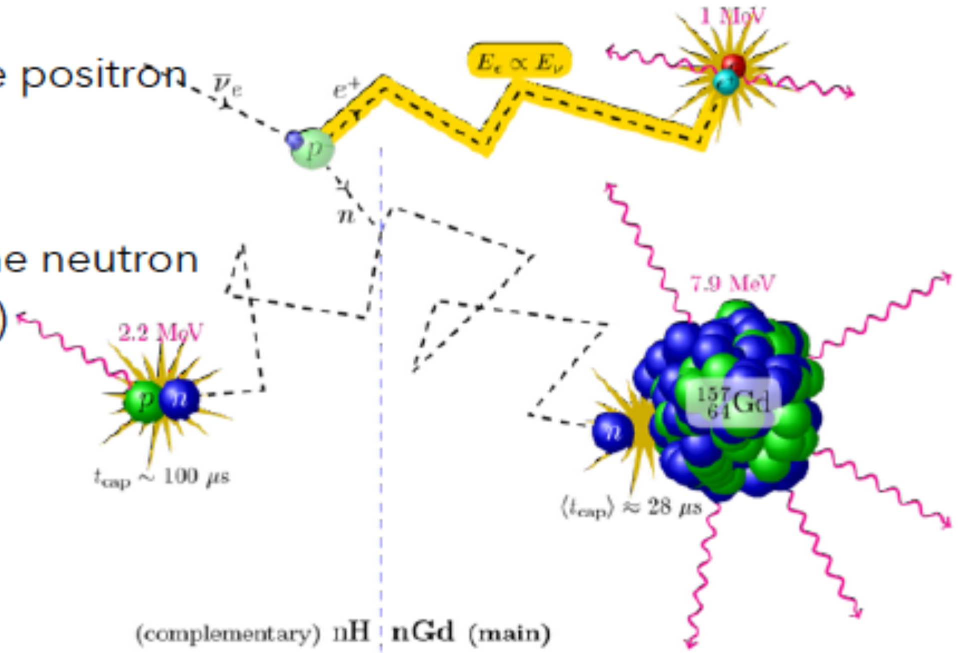


Detectors for reactor neutrino experiments

- Anti-neutrinos detected via inverse ß- decay (IBD)

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

- search for 2 signal coincidence:
  - instantaneous annihilation of the positron (**prompt signal**)
  - thermalisation and capture of the neutron after some time (**delayed signal**)

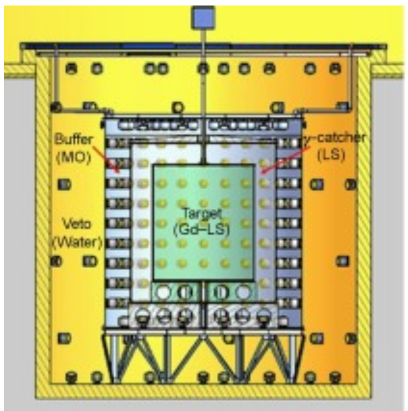


E_{Thr} for anti-neutrinos 1.8 MeV

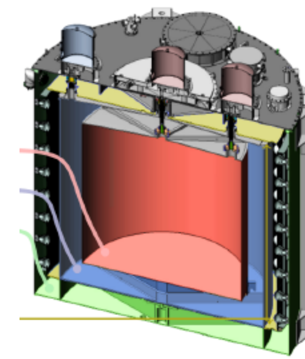
Detectors for reactor neutrino experiments

- Reactor experiments (Daya-Bay, RENO and Double Chooz) have similar design and strategy: detection of inverse β-decay in liquid scintillator doped with Gd

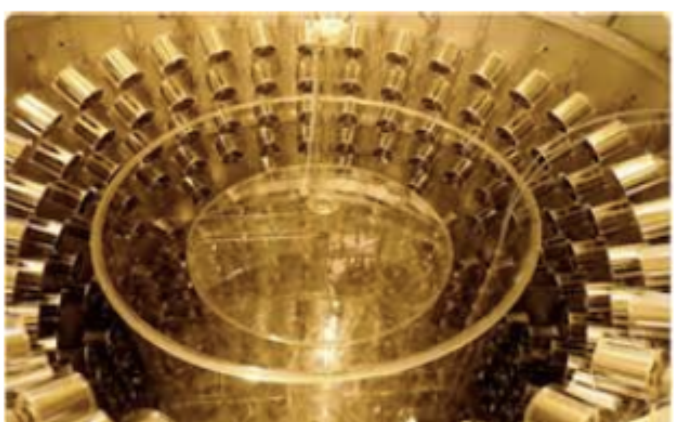
RENO



Daya Bay



Double Chooz detector

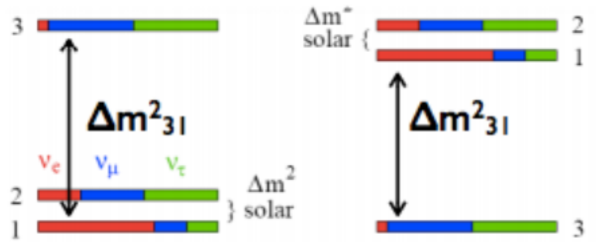


Measurements with reactor neutrinos

- Measurement of anti-ν_e disappearance

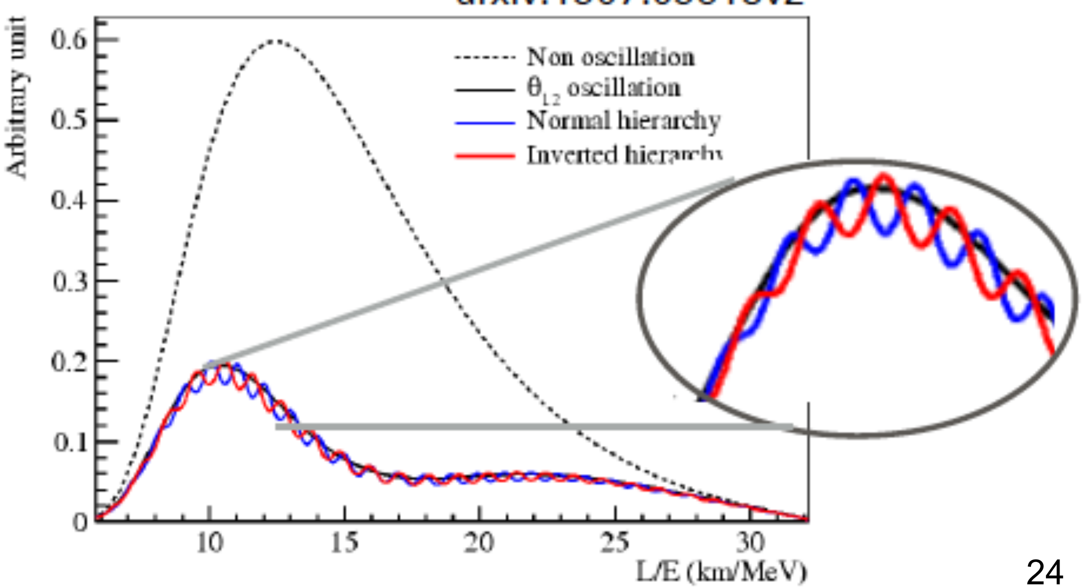
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \boxed{\cos^4\theta_{13}} \sin^2 2\theta_{12} \sin^2\Delta_{21} - \sin^2 2\theta_{13} \left(\cos^2\theta_{12} \sin^2\Delta_{31} + \sin^2\theta_{12} \sin^2\Delta_{32}\right)$$

- Sensitivity to θ_{13}
- No sensitivity to δ_{CP}



- Sensitivity to mass hierarchy through oscillation interference → spectral distortion (3% effect for medium baseline experiments)

arxiv:1507.05613v2

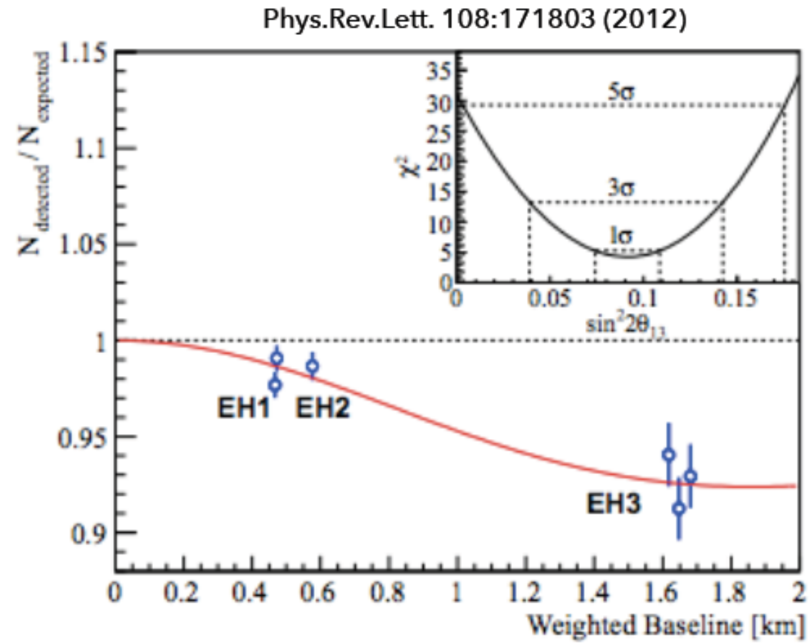


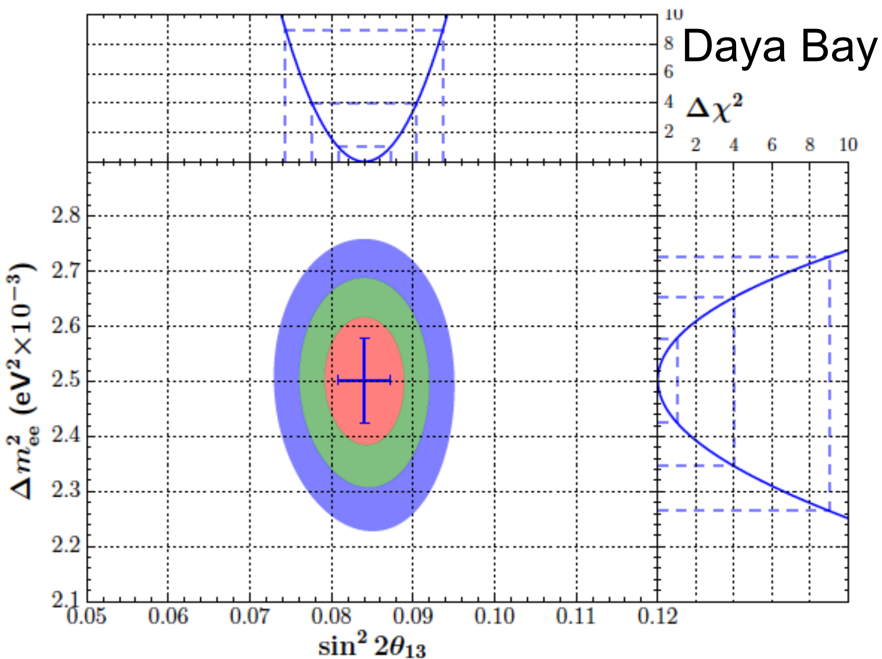
Measurements of θ_{13}

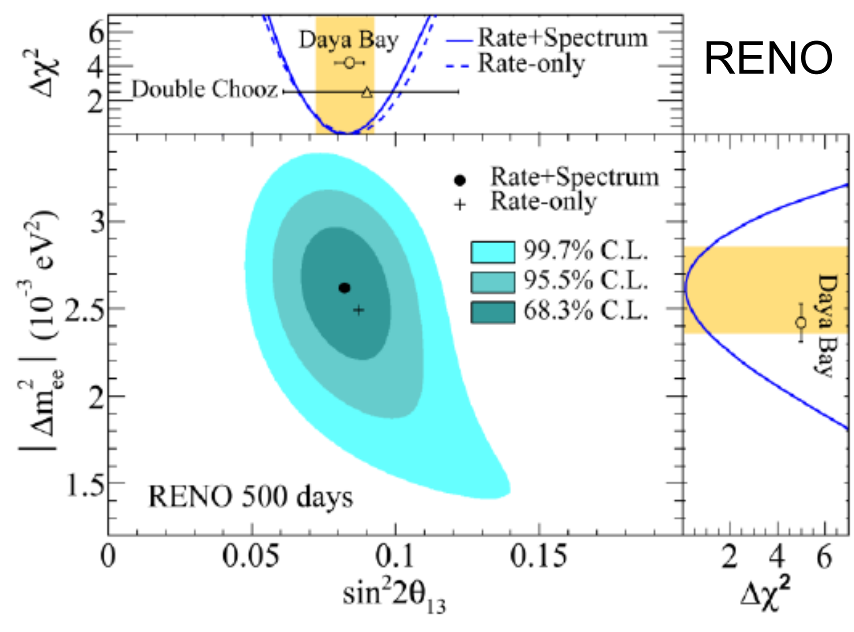
- Daya Bay (March 2012):

$\theta_{13} \neq 0$ with a significance of 5.2σ

- Since then more precise measurement and measurements by RENO and Double Chooz

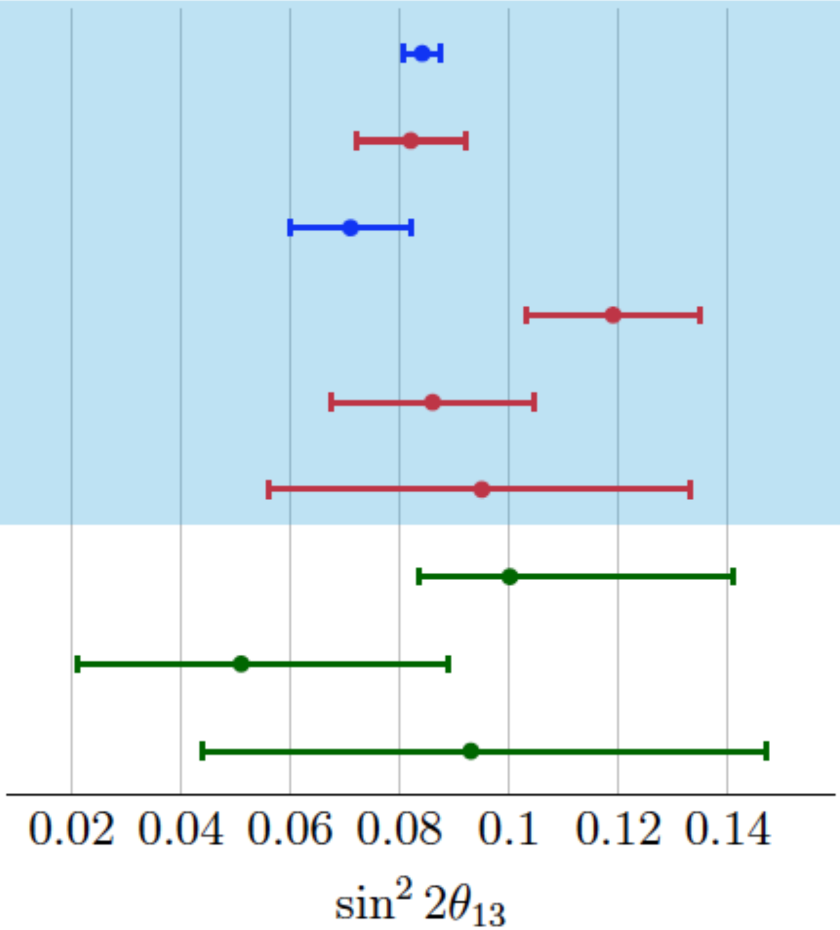






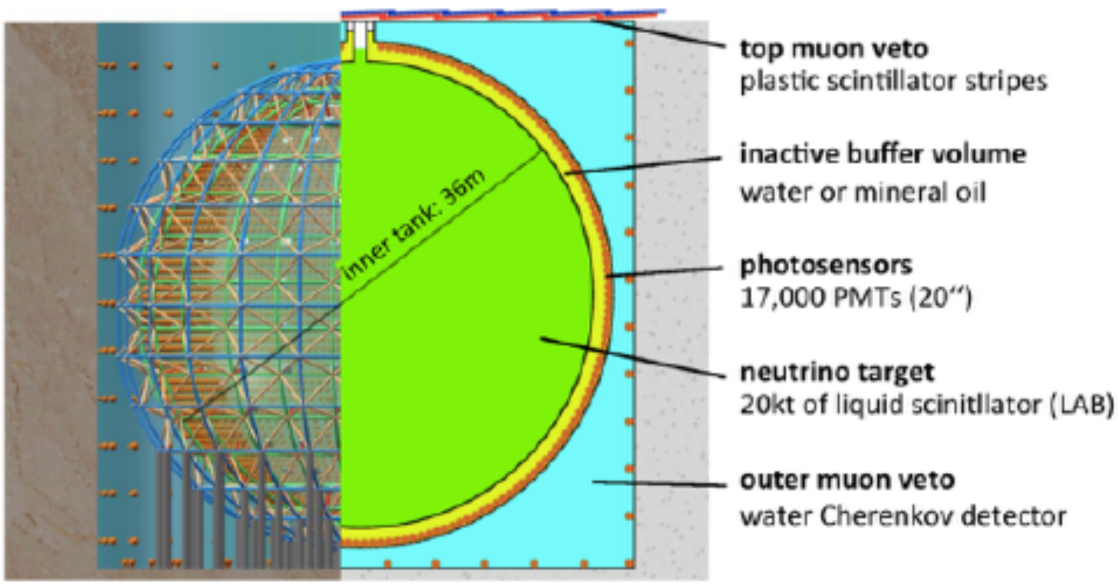
Summary of measurements of θ_{13}

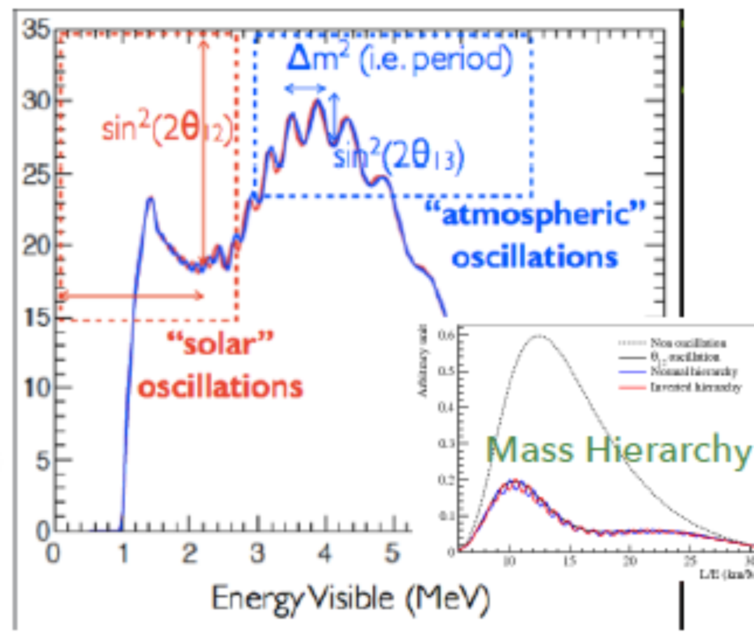
Experiment		Value
Daya Bay	nGd	0.0841 ± 0.0033
RENO	nGd	0.082 ± 0.010
Daya Bay	nH	0.071 ± 0.011
D-CHOOZ	nGd+nH	0.119 ± 0.016
RENO	nH	0.086 ± 0.019
D-CHOOZ	nH	$0.095^{+0.038}_{-0.039}$
T2K		$0.100^{+0.041}_{-0.017}$
MINOS	NH	$0.051^{+0.038}_{-0.030}$
MINOS	IH	$0.093^{+0.054}_{-0.049}$



JUNO

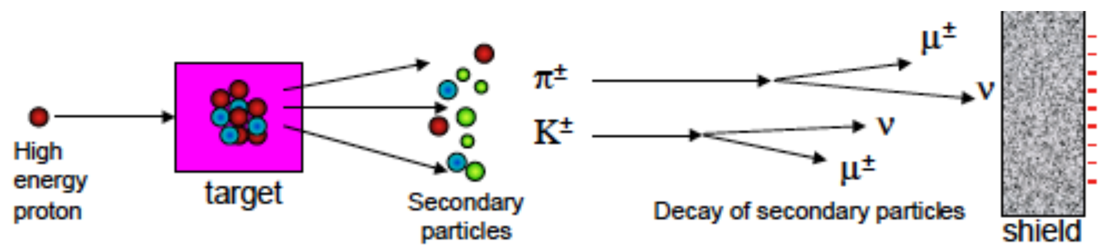
- JUNO: New reactor experiment in China: anti-ν_e from Daya Bay power plant
- 20 kton of liquid scintillator with wide physics program
- MH determination towards oscillation interference
  - big challenge in calorimetry! Need energy resolution better than 3% ($\delta m^2/\Delta m^2$ ~3%)
- Data taking foreseen for > 2021

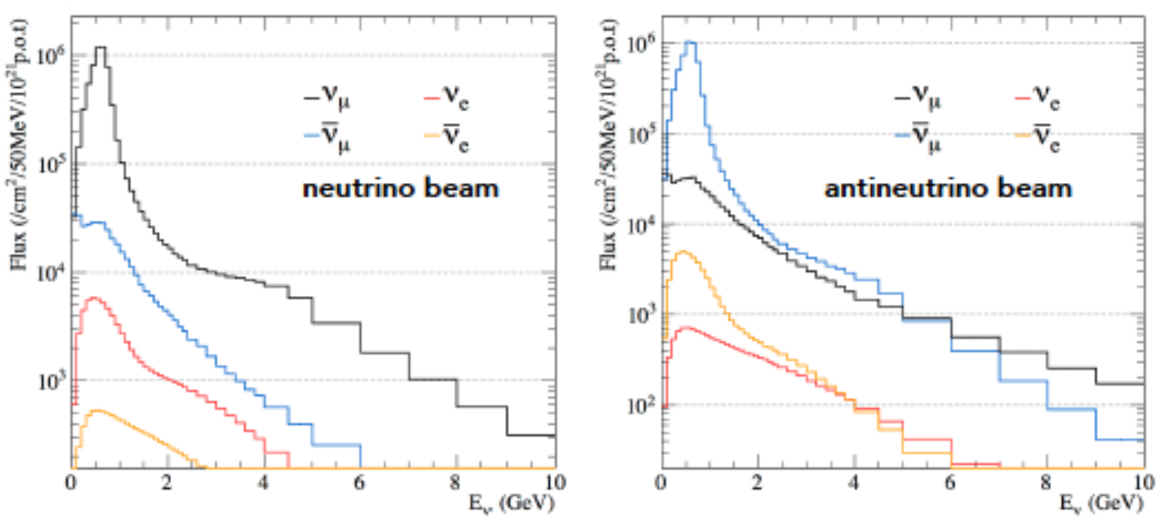




Artificial sources: Accelerator neutrinos

- First accelerator neutrinos by Lederman, Schwartz and Steinberger (1962) with $E_\nu \sim 1$ GeV
- Same principle in modern experiments, better technique (focusing magnets)
- Possibility to produce both ν_μ and anti-ν_μ beams
  - with some contamination of other ν and anti-ν flavors



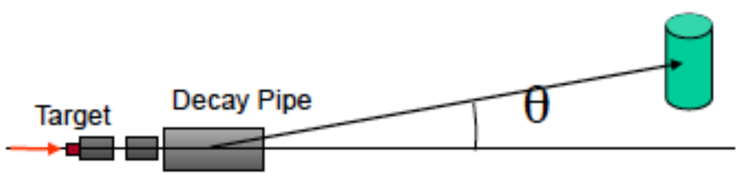


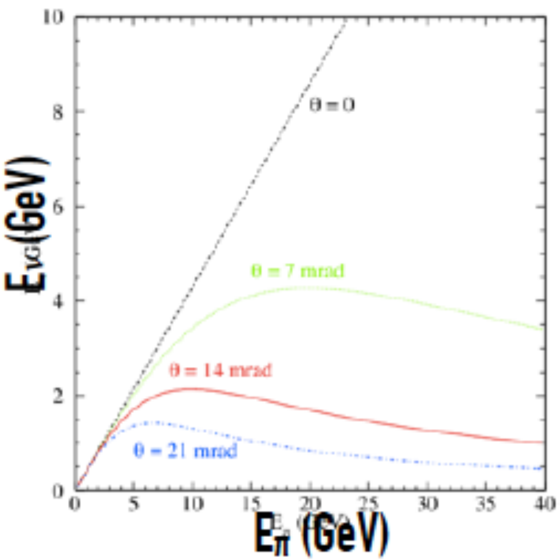
T2K flux at Super-Kamiokande

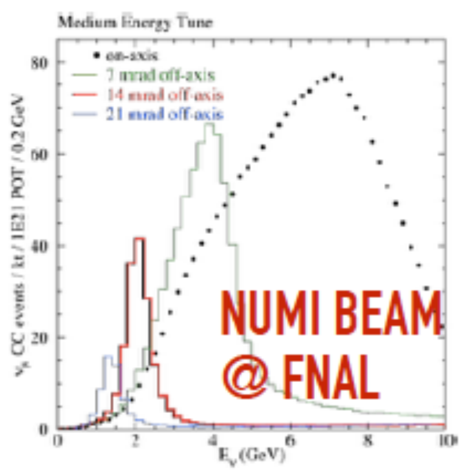
PRL 116, 181801 (2016)

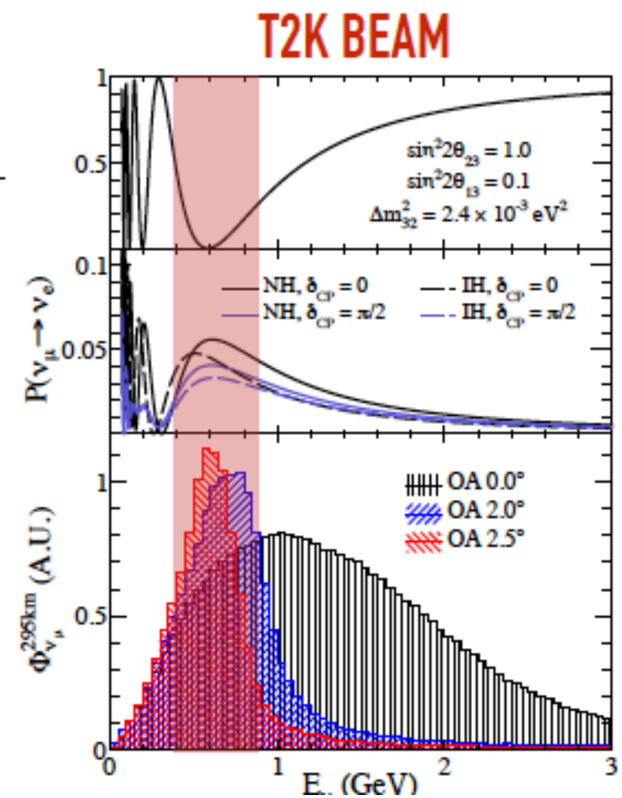
Accelerator neutrinos: Off-axis technique

- Off-axis technique foresees detectors not aligned with the center of the neutrino flux, but shifted by some degrees
- Narrower energy spectrum at “low” energies
- Dependency from parent hadron energy removed
- Technique adopted by T2K and NOvA









Desirable features for neutrino detectors

- Low energy threshold
  - Low-energy neutrinos or secondary particles can be detected and studied
- Good angular resolution
  - Particles direction accurately reconstructed – direction of neutrinos inferred from measured direction of charged leptons
- Good particle identification
  - Discrimination of flavors e/μ/τ crucial for oscillation measurements
- Good energy resolution
  - Measurement of neutrino energy crucial for extraction of oscillation parameters
- Good time resolution
  - Time evolution of transient signals important for background rejection
- Charge identification
  - Discrimination between leptons and anti-leptons important for oscillation measurements, in particular δ_{CP}

➢ Not possible to have all of these features in one detector

➢ Need to select most appropriate technology according to the aim of the experiment

Detection of ν_e with radiochemical sources

- Very first approach to study solar neutrinos (Davis-Pontecervo)
- Production of radioactive isotopes
- ^{37}Ar and ^{71}Ga are extracted chemically and counted by their decay products
  - No information about neutrino energy or direction

$$\nu_e + Ga^{71} \rightarrow Ge^{37} + e^-$$

E_{th} = 233 keV

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

E_{th} = 814 keV

GALLEX (1991-1997)
LNGS Italy

615 tons of cleaning fluid C_2Cl4
Expected 1.5 Ar atoms/day

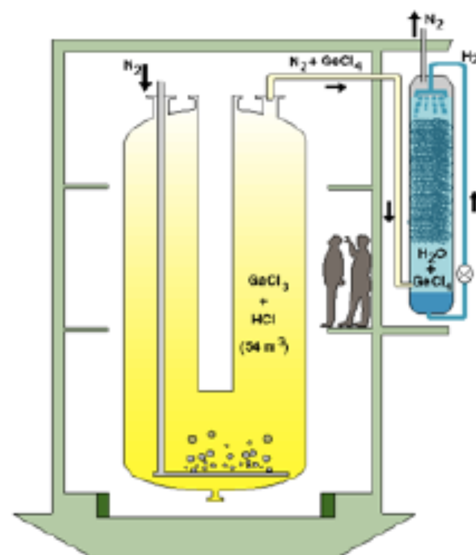


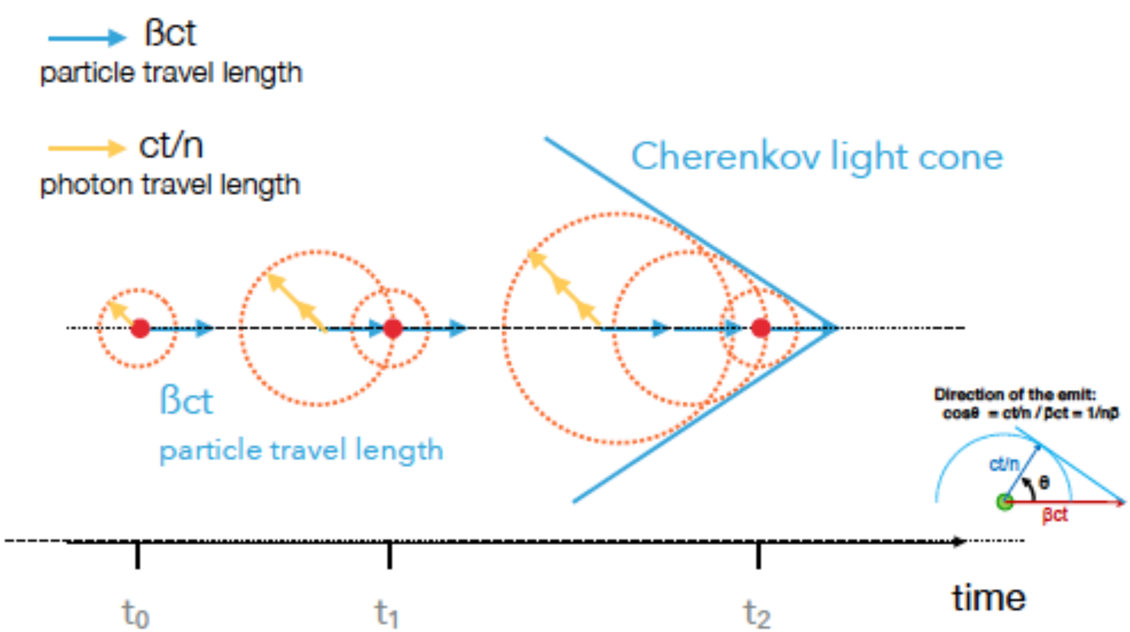
image courtesy of BNL

Davis experiment (1960's)
Homestake mine, South Dakota
(same as DUNE!)

615 tons of cleaning fluid C_2Cl4
Expected 1.5 Ar atoms/day

Cherenkov radiation

- Presence of neutrino inferred from presence of charged lepton
  - Coherent emission of light from passage of charged particle through medium, if speed of particle is larger than the speed of light in the medium
- Threshold for emitting Cherenkov radiation depends on mass of the particle



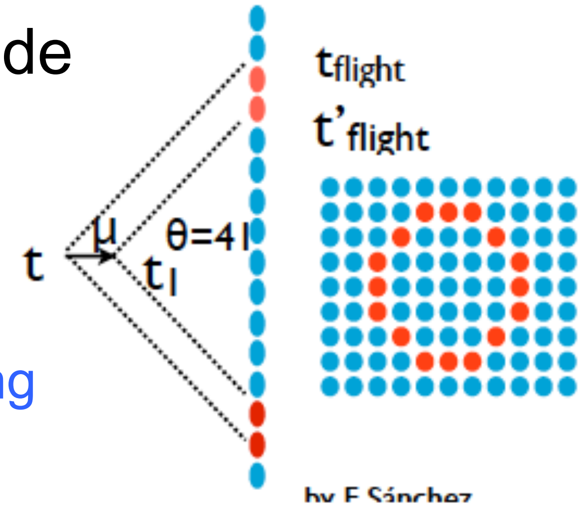
$$\beta > 1/n \simeq 0.75 \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}} \simeq 1.5$$

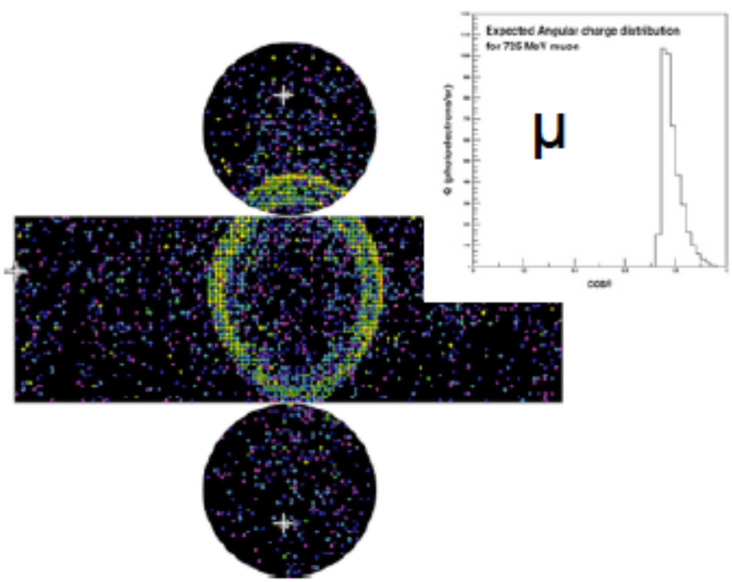
$$E_{Thr} = \gamma m c^2$$

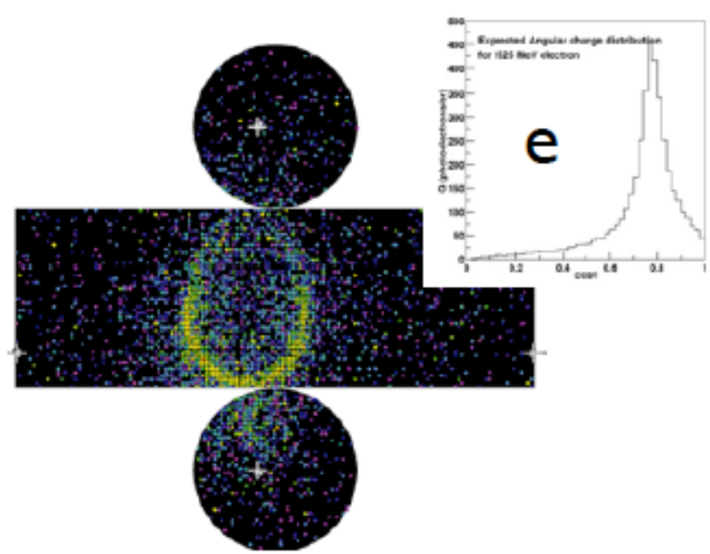
particle	E_{thr}
electrons	0.755 MeV
muons	160.3 MeV
pions	211.7 MeV
protons	1407 MeV

Particle identification

- Angular distribution of Cherenkov photons along the primary particle direction provide key to particle identification
- e/μ discrimination
  - Muons: sharp and clear ring
  - Electrons: fuzzy ring due to multiple scattering and showering



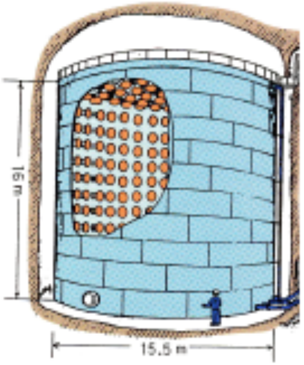


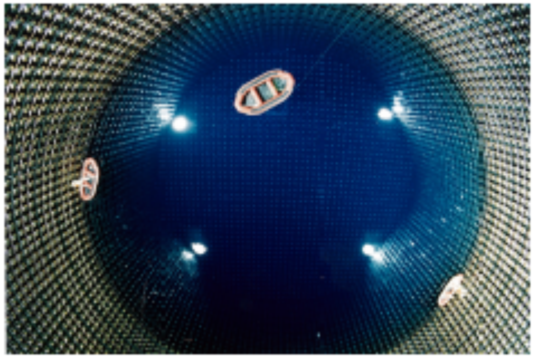


Examples of Cherenkov detectors

Kamiokande (1983-1996)

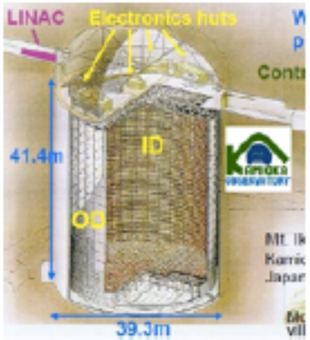
- Nucleon decay experiment
- 4.5ktons of ultra pure water
- 984 (ID) + 123 (OD) PMTs (20-25% coverage)
- **discovery of oscillations with atmospheric neutrinos**

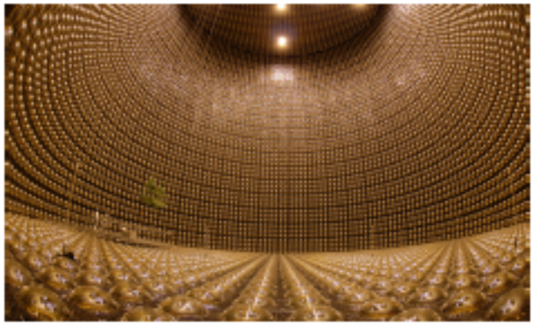




Super-Kamiokande (1996-today)

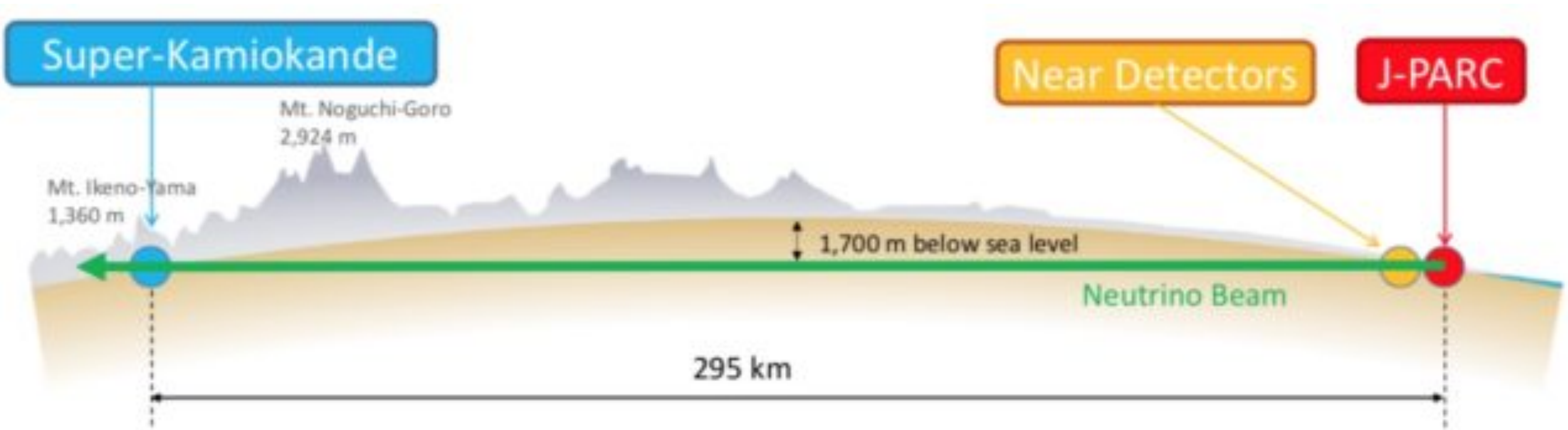
- atmospheric neutrinos experiment + FD for the T2K experiment
- 50ktons of ultra pure water
- 11k (ID) + 2k (OD) PMTs (40% coverage)





T2K: Accelerator neutrinos (since 2010)

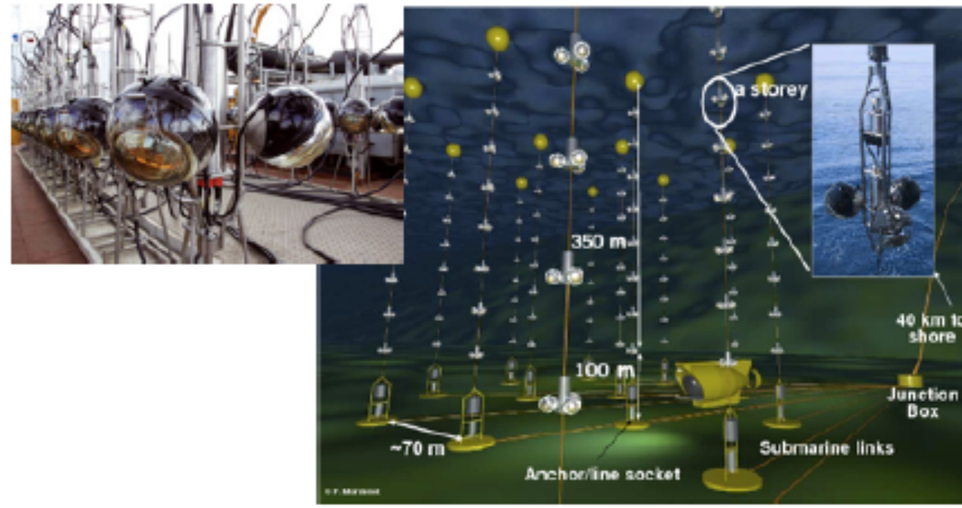
- T2K (Tokai to Kamioka): neutrino beams produced at JPARC
- Two near detectors at 280m from target
  - One to measure beam direction and intensity
  - Other (off-axis) to measured cross section, flux and flavor composition
- Then beam reaches SuperKamiokande after 295km
- Measurements of ν_μ disappearance
- First measurement of ν_e appearance

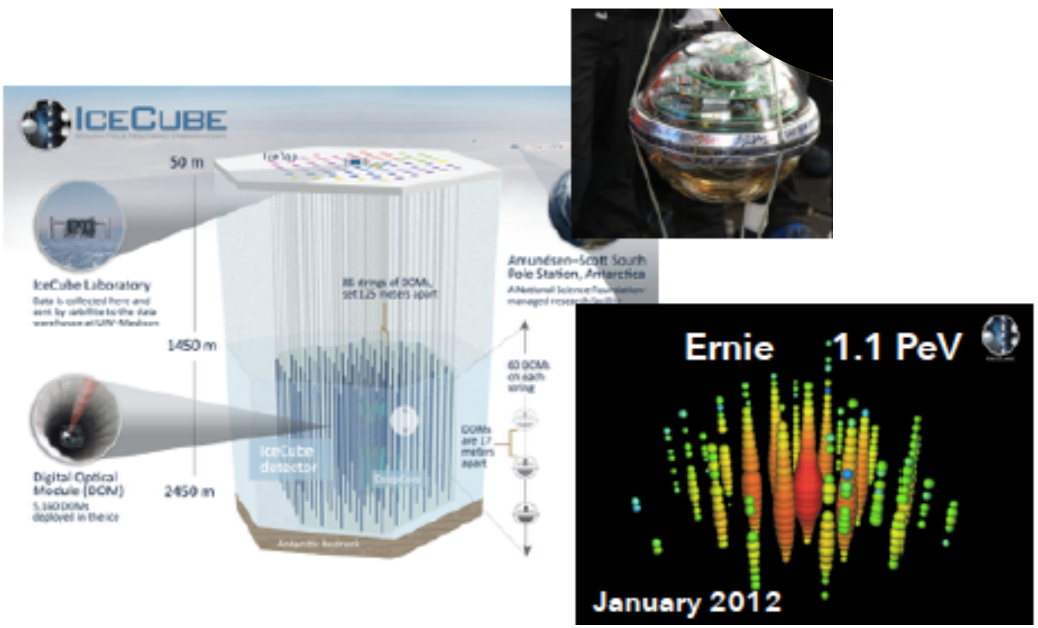


Examples of Cherenkov detectors

Antares (2008-2017)

- 12 separate vertical strings 350m long
- 75 optical modules each
- E_ν 10^{10} - 10^{14} eV
- astro-particle physics



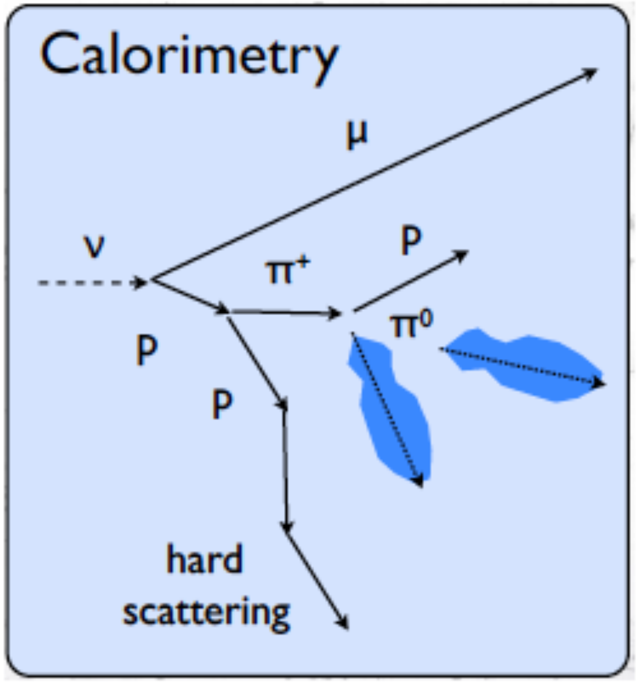


IceCube (2011 - today)

- cubic-kilometer particle detector made of Antarctic Ice
- 5,160 digital optical modules (DOMs) attached in vertical string frozen in 86 boreholes (in-ice detector)
- beginning of searches for cosmogenic neutrino interactions

Tracking Calorimetry

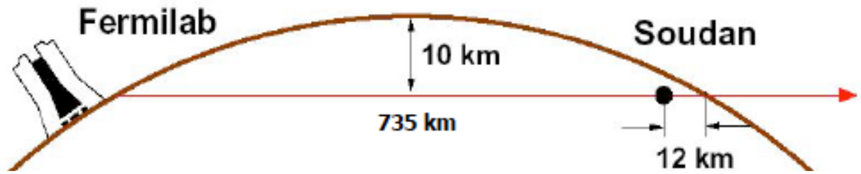
- Aim to detect and reconstruct all particles from neutrino interaction
- Two main types
  - Alternating detector layers
  - Monolithic (single volume detector)
- If magnetized
  - Charge determination → ν or anti-ν
  - Momentum from curvature of charged particle tracks



$$E_\nu = E_{lepton} + E_{had}$$

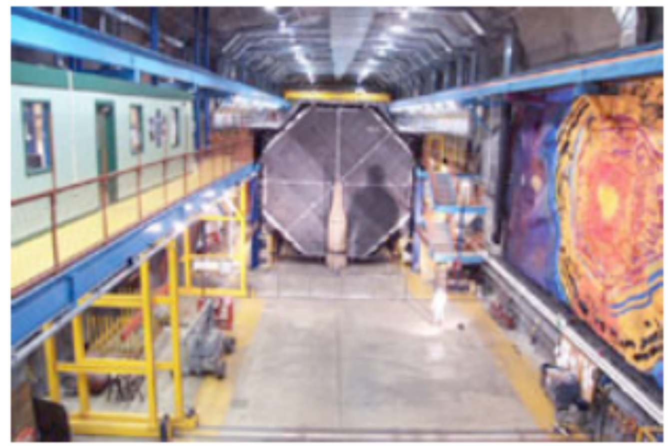
Tracking Calorimetry: MINOS (2003-2016)

- 120 GeV proton beam at Fermilab, $\langle E_\nu \rangle \sim 3$ GeV
- Near detector at 1km, far detector at Soudan mine at 735km



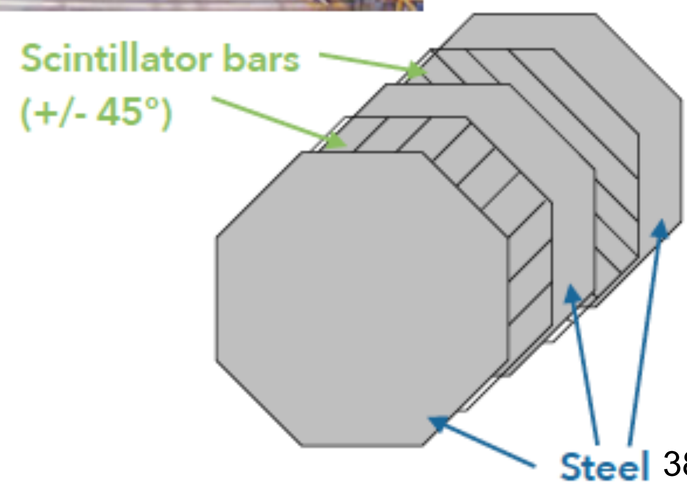
First measurement of ν_μ disappearance

1kton



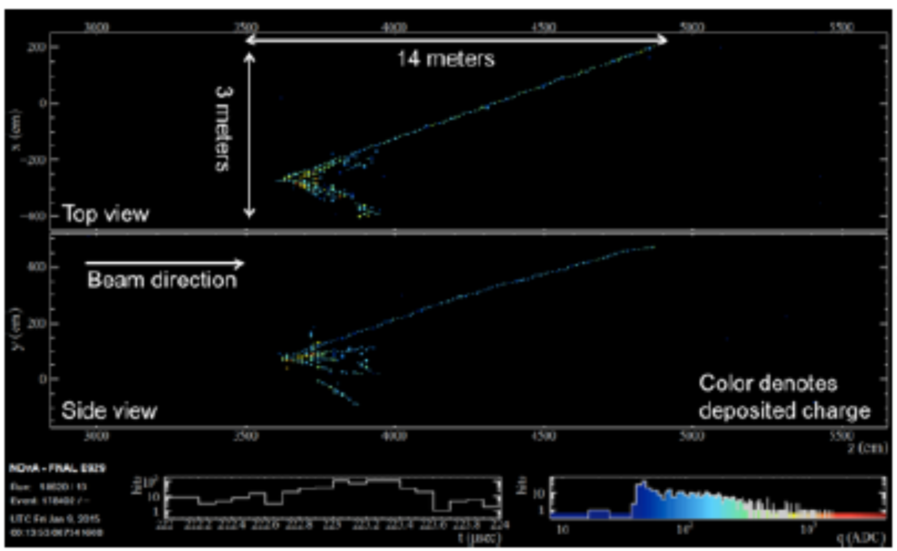
5.4kton

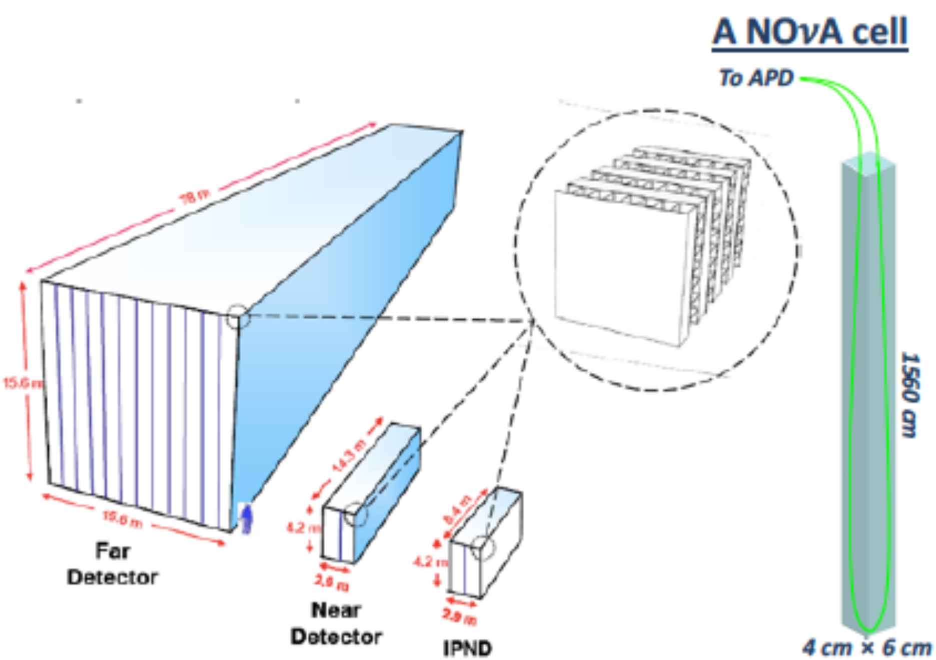
- Magnetized (1.3T) steel/scintillator sampling calorimeter/tracking
  - 2.54cm steel absorbers $\sim 1.4 X_0$
  - 1 cm thick plastic scintillator bars with orthogonal direction in alternating layers



Tracking Calorimetry: NOvA (since 2014)

- 120 GeV proton beam at Fermilab, $\langle E_\nu \rangle \sim 3$ GeV
- Far detector at Soudan mine at 735km
- Uses off-axis technique
- 385'000 high refracting plastic PVC cells filled with liquid scintillators
- Energy deposited by incoming particles collected by wavelength shifting fibers

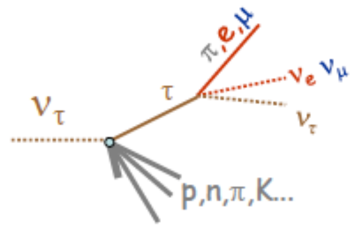


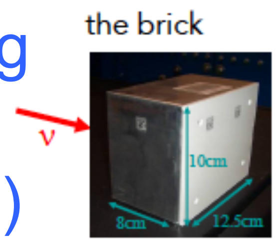


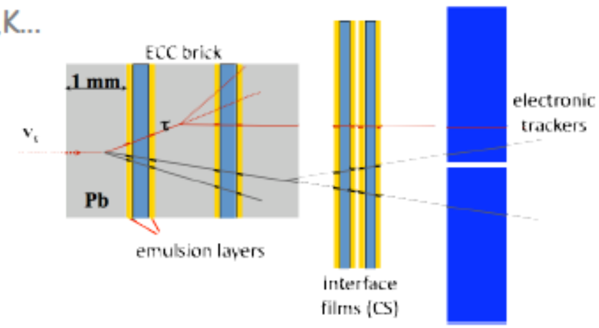
Tracking Calorimetry: OPERA (2008-2012)

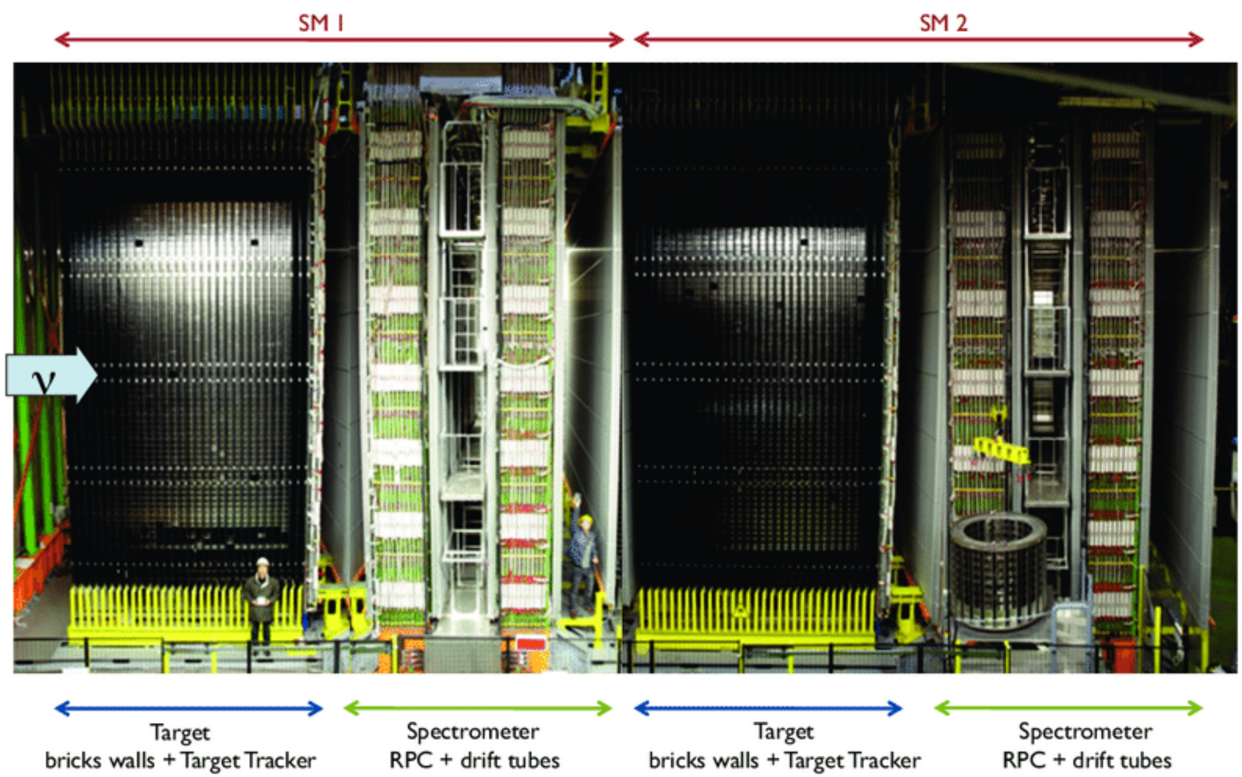
- Optimized for reconstruction of ν_τ interactions
- $<E_\nu>$ ~ 17 GeV
- Modular structure alternating lead sheets and emulsion films (1.25 kton target mass)

First measurement of ν_τ appearance









Measurements at accelerator experiments

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \sim\ & \boxed{\sin^2 2\theta_{13}} \times \boxed{\sin^2\theta_{23}} && \times \boxed{\frac{\sin^2[(1-x)\Delta]}{(1-x)^2}} \\
& \boxed{-\alpha \sin\delta} \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} && \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& +\alpha\cos\delta \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} && \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& +\mathcal{O}(\alpha^2)
\end{aligned}
$$

matter effects

$$
\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad \boxed{x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}}
$$

M. Freund, Phys.Rev. D64 (2001) 053003

- Sensitivity to θ_{23}
- Sensitivity to θ_{13} as reactor measurement have determined that θ_{13} is not too small
- Measurement of δ_{CP} only possible at accelerator experiments
- Sensitivity to mass hierarchy due to matter effects

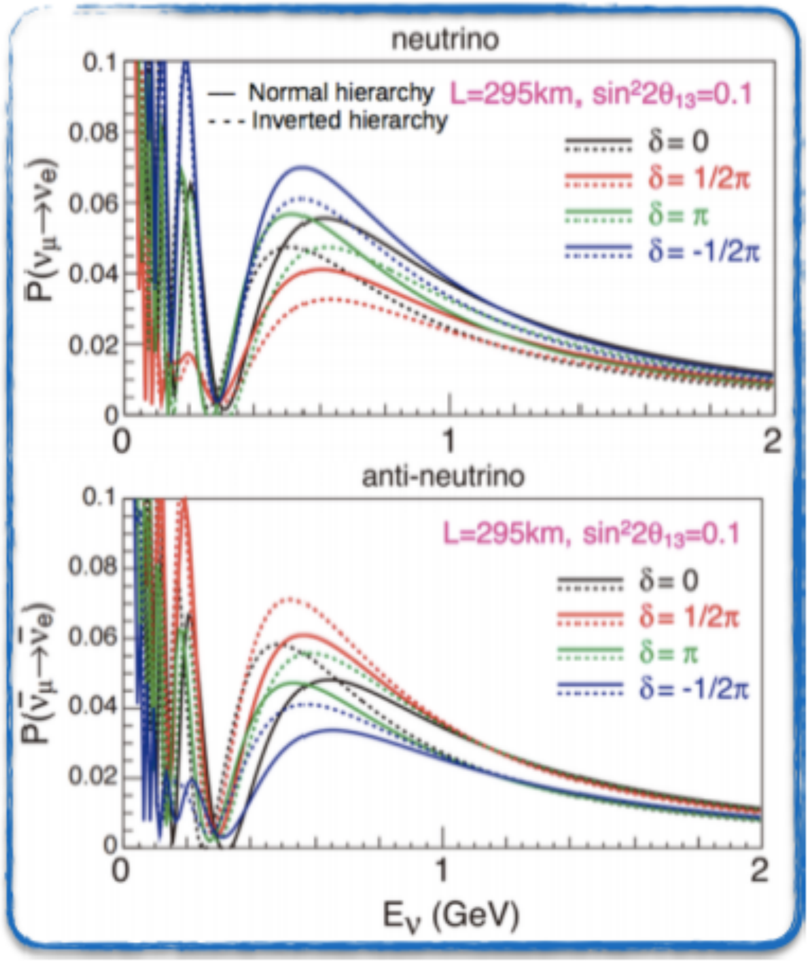
Measurement of δ_{CP}

- Measurement is (in principle) simple: looking for different behavior between neutrino and anti-neutrino oscillations

e.g. if $\delta_{CP} =$:

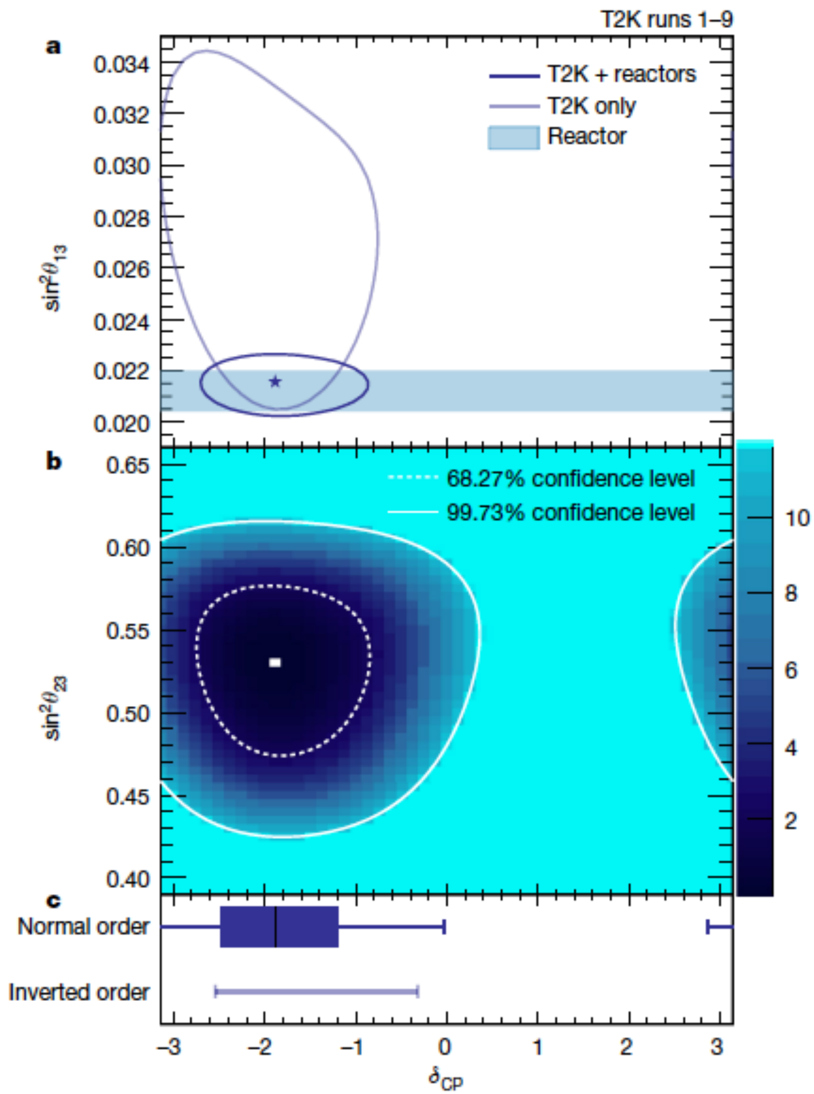
- $0, \pi$: no CP violation $P(\nu_\mu \to \nu_e) = P(\overline{\nu_\mu} \to \overline{\nu_e})$
- $-\pi/2$: enhance $P(\nu_\mu \to \nu_e)$ suppress $P(\overline{\nu_\mu} \to \overline{\nu_e})$
- $+\pi/2$: suppress $P(\nu_\mu \to \nu_e)$ enhance $P(\overline{\nu_\mu} \to \overline{\nu_e})$

- Complicated by matter effects
- Complicated by beam contamination
- Dependence on θ_{13}



Measurement of δ_{CP}

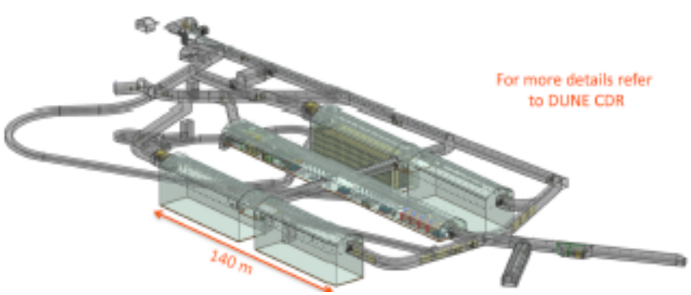
- T2K results published this month exclude CP conservation at 95% confidence level *Nature* **volume 580**, pages 339–344(2020)



Future accelerator-based experiments

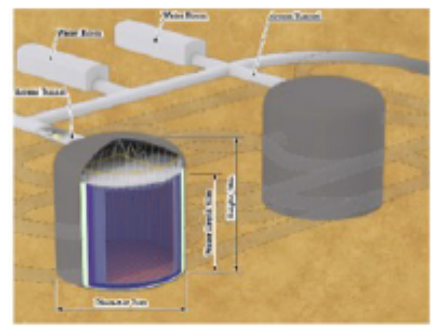
DUNE

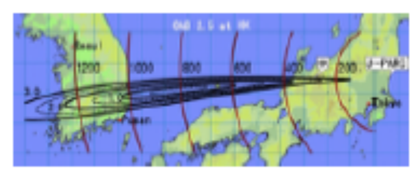
- 4 modules Liquid Ar-TPC ~10kton each
- SURF, Homestake mine (US) ~2400mwe
- On-axis beam from Fermilab (1.2-2.4 MW)
- baseline ~**1300km**
- $\langle E_\nu \rangle$ ~**3GeV**



HYPER-KAMIOKANDE

- 2 water Cherenkov of ~260 ton each
- Tochibora, near Kamioka (Japan),~1750mwe
- Off-axis beam from Tokai (1.3 MW)
- baseline ~**300km** (1100km if T2HKK)
- $\langle E_\nu \rangle$ ~**0.6GeV**





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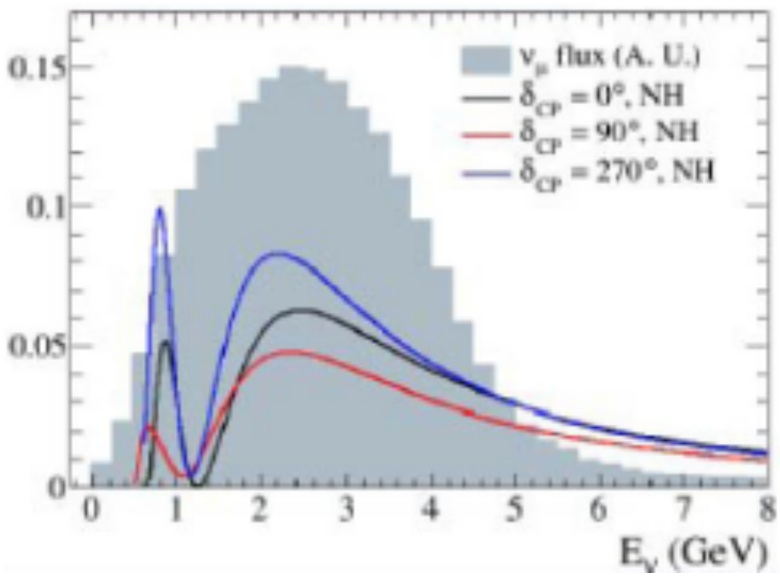
- baseline ~**1300km**
- <E_ν> ~**3GeV**



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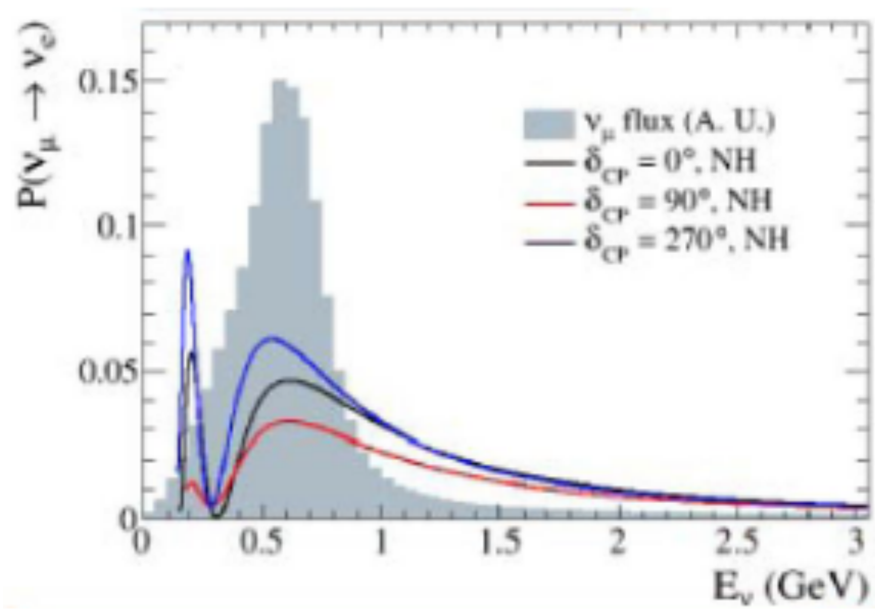
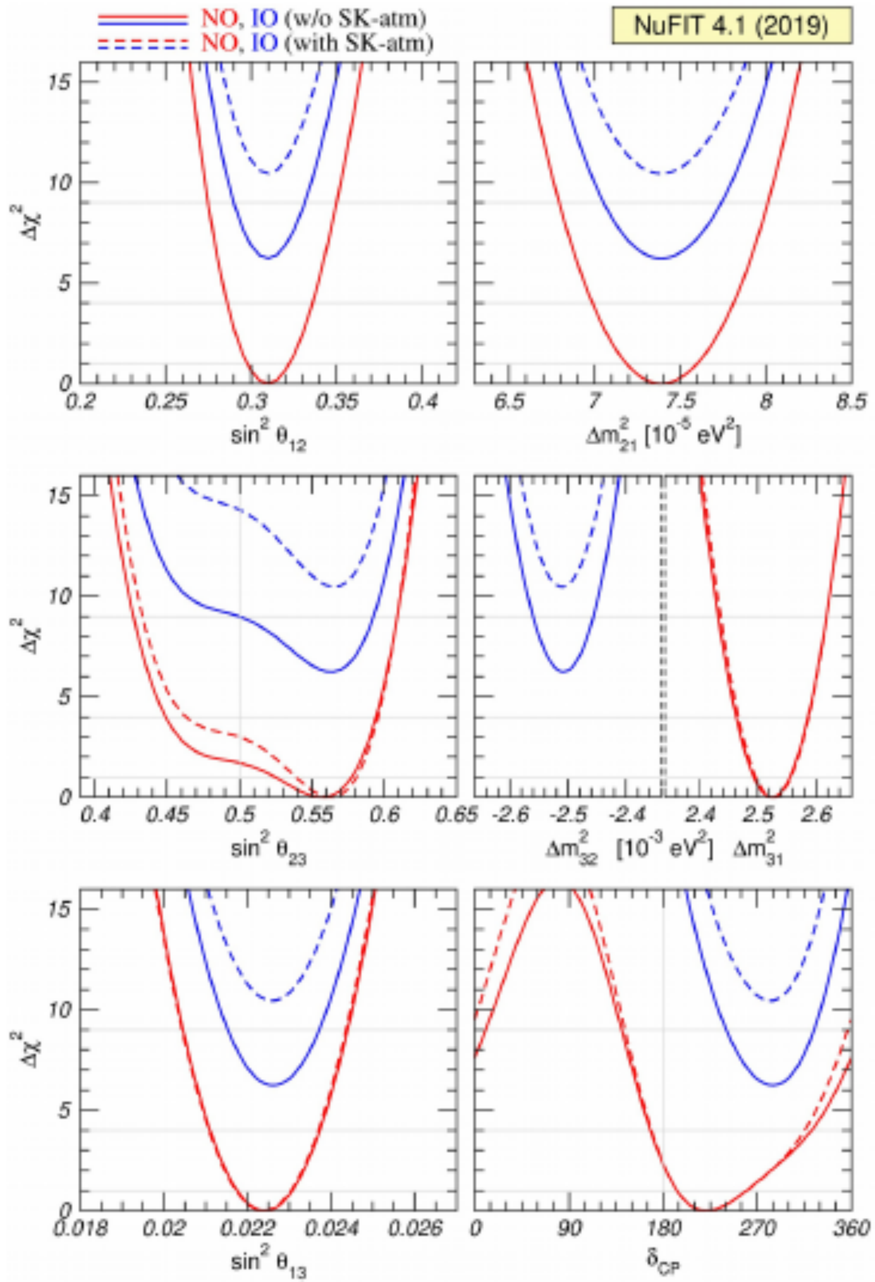


Summary of 3 flavor neutrino oscillation measurements

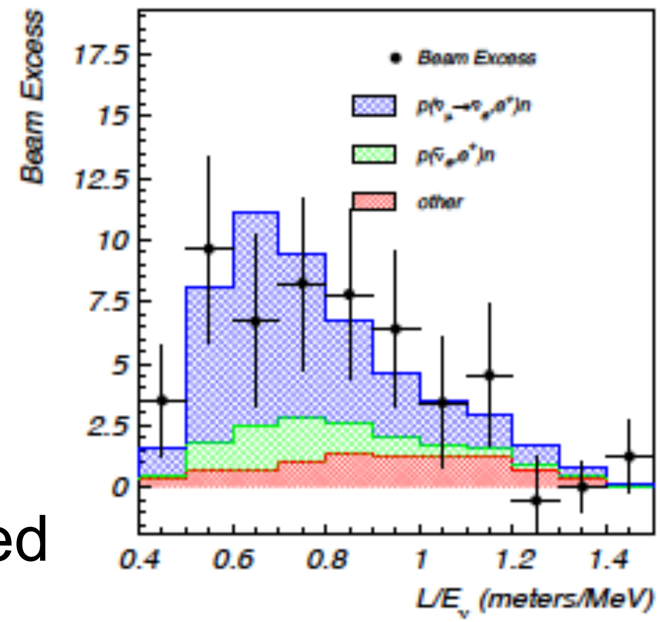
- Complementary and consistent measurements of three mixing angles and two mass[2] differences using solar, atmospheric, reactor and accelerator neutrinos
- Improved measurement of θ_{23}, determination of mass hierarchy and search for CP violation in lepton sector being addressed by current and future experiments



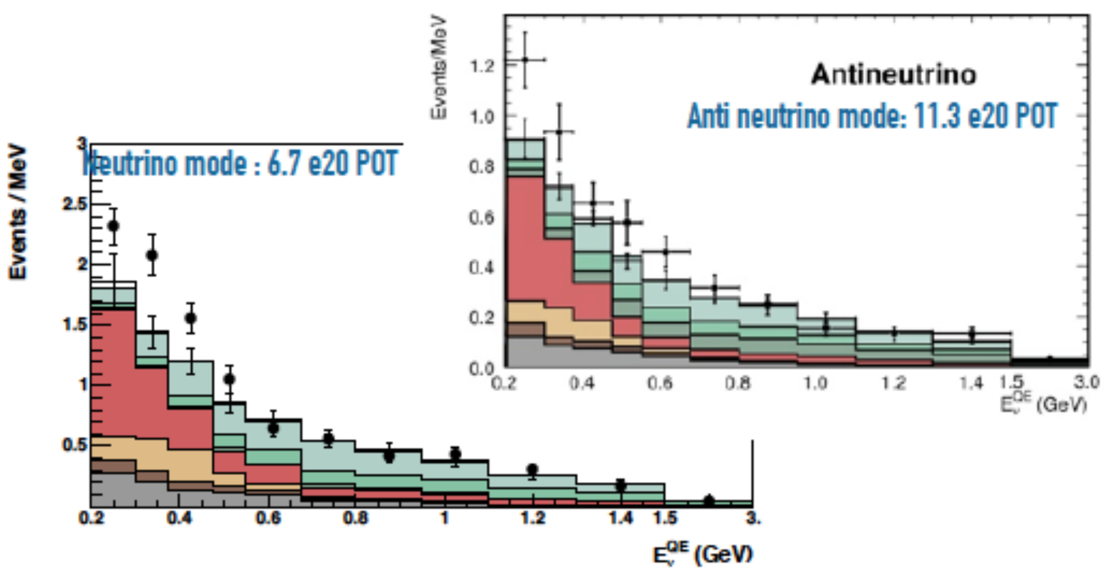
LSND anomaly

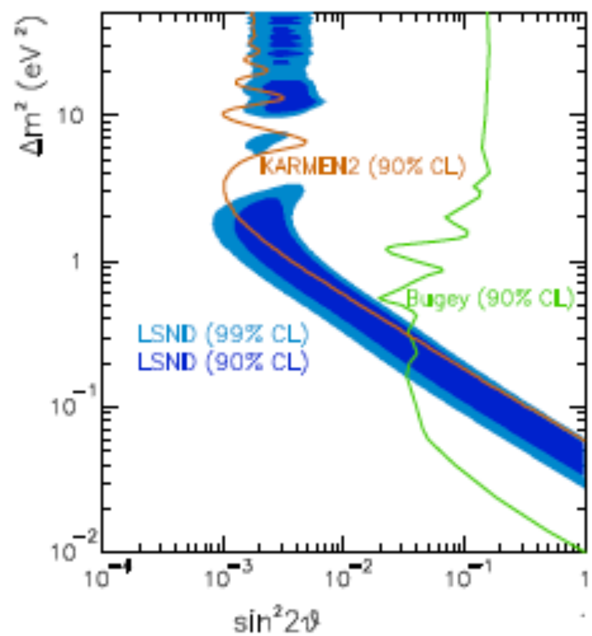
- LSND (1993-1998) with L/E ~ m/MeV observed excess in appearance of $\bar{\nu}_e$ from $\bar{\nu}_\mu$ beam

→ Compatible with oscillations with $\Delta m^2 \sim 0.2$ eV (>> Δm^2_{atmo}, Δm^2_{solar})



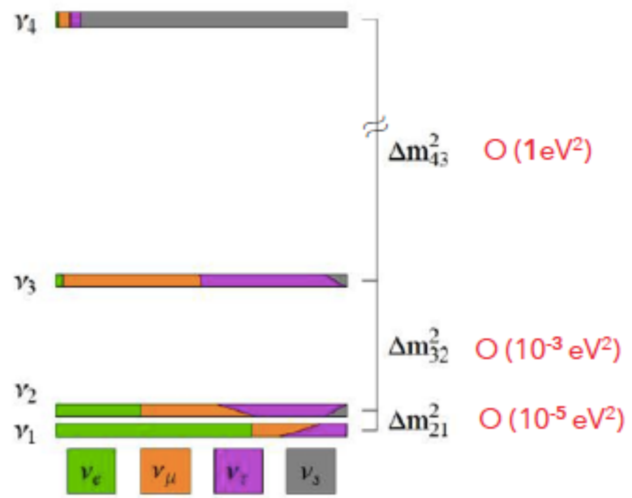
- Large regions of phase space excluded by KARMEN and Bugey
- Excess seen by MiniBooNE





Interpretation as sterile neutrino

- Considering the 3+1 model. Because of the large mass splitting (1eV^2), the other neutrino masses appear degenerate
  - $\Delta m^2_{41} \approx \Delta m^2_{43} \approx \Delta m^2_{24}$
  - approximation to 2 neutrino flavour-mixing



$$P^{SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2$$

$$P^{SBL}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

ν_e DIS
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

ν_μ DIS
$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu 4}|^2$

$\nu_\mu \to \nu_e$ APP
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$
[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]

Addressing the anomaly

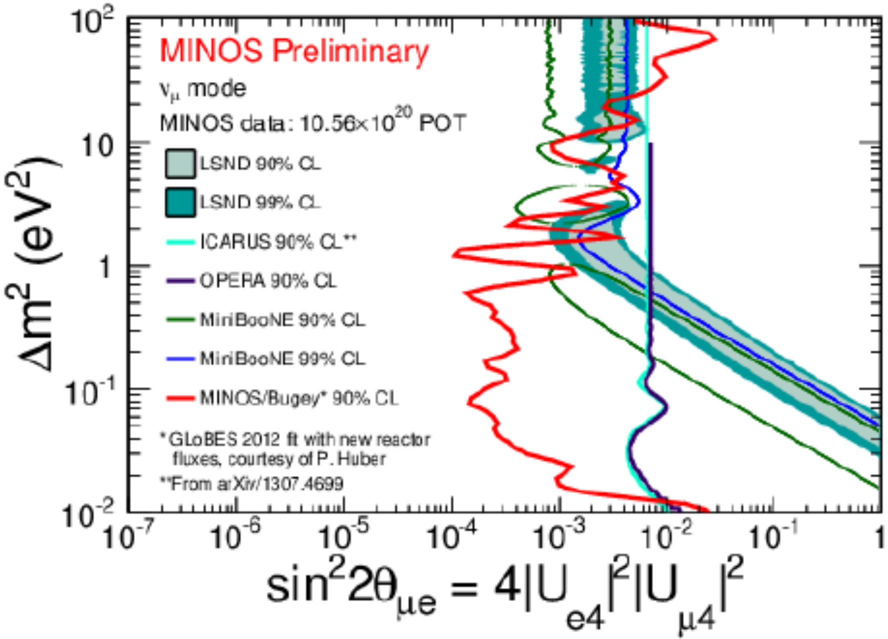
ν_e DIS:

- Almost all short baseline reactor neutrino experiments show deficits in measured neutrino flux

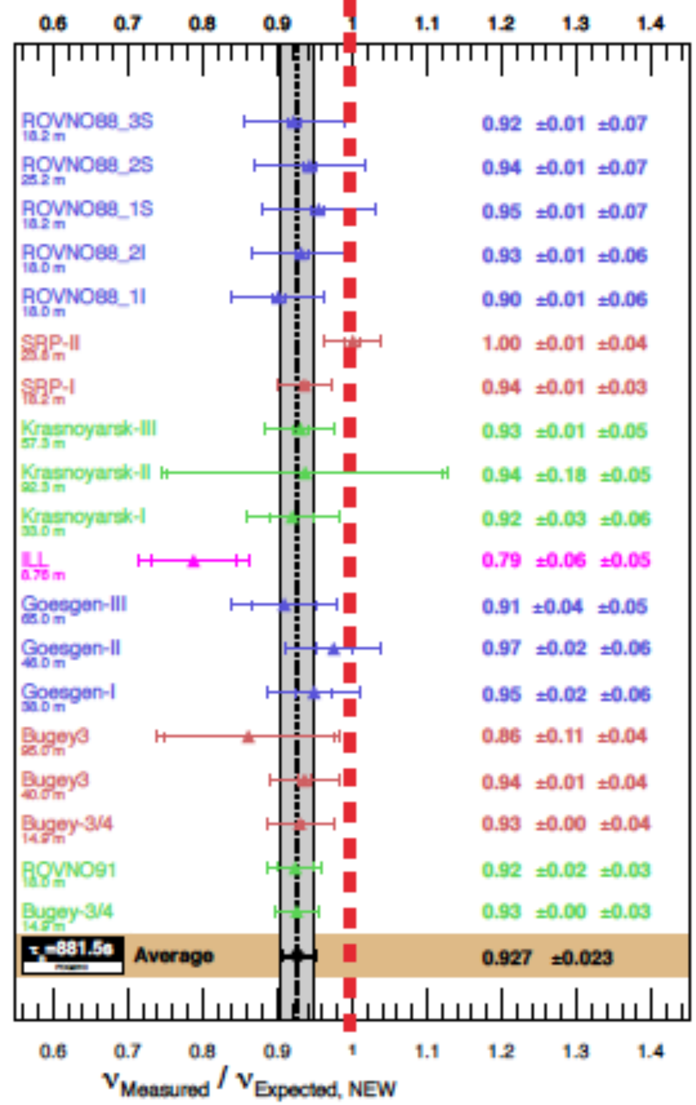
ν_μ DIS:

- No anomaly seen at accelerator experiments

→ To be followed



Phys. Rev. D 83, 073006



$R_{avg} = 0.927 \pm 0.023$

References

- CERN Academic training lectures, ”Neutrinos”, March 2017: Pilar Hernandez and Stefania Bordoni https://indico.cern.ch/event/610409/

- Lecture notes Pilar Hernandez “Neutrino physics” https://arxiv.org/abs/1708.01046

- Nico Serra, KTII lecture, 2017

- Stefania Ricciardi, Lecture notes on neutrino oscillations in matter, 2013