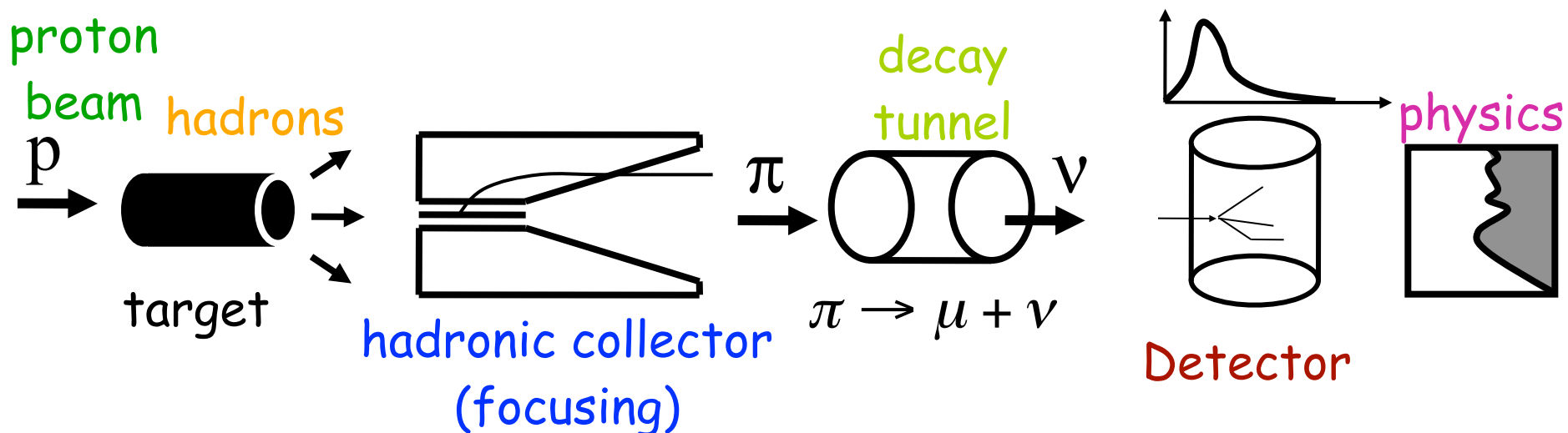


How can we produce a neutrino beam?

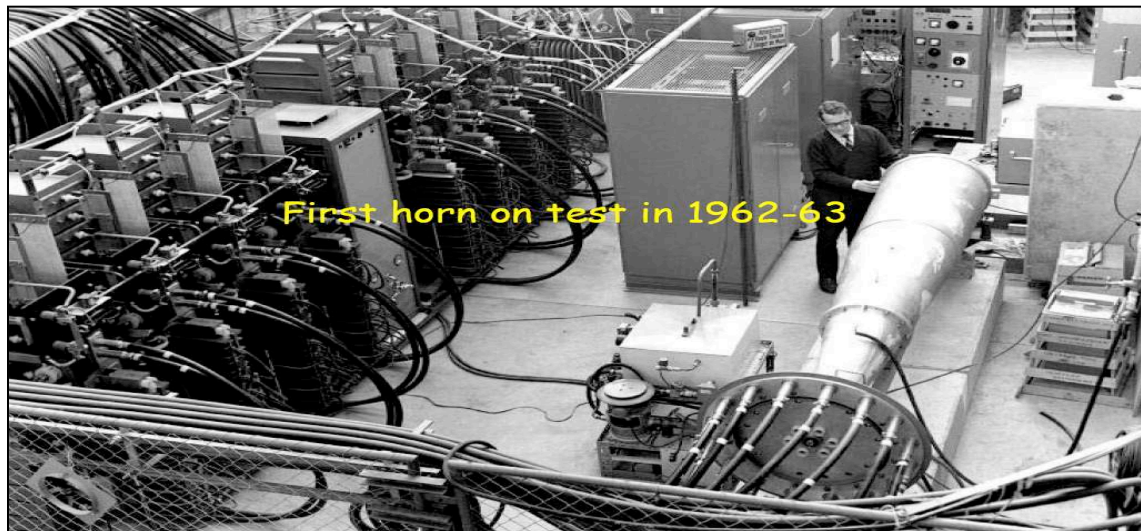


- adjustable proton energy,
- adjustable distance between the production point and the detector,
- neutrino type choice (neutrinos or anti-neutrinos),
- but as usually, the neutrino energy is not well defined...

Hadronic Collector

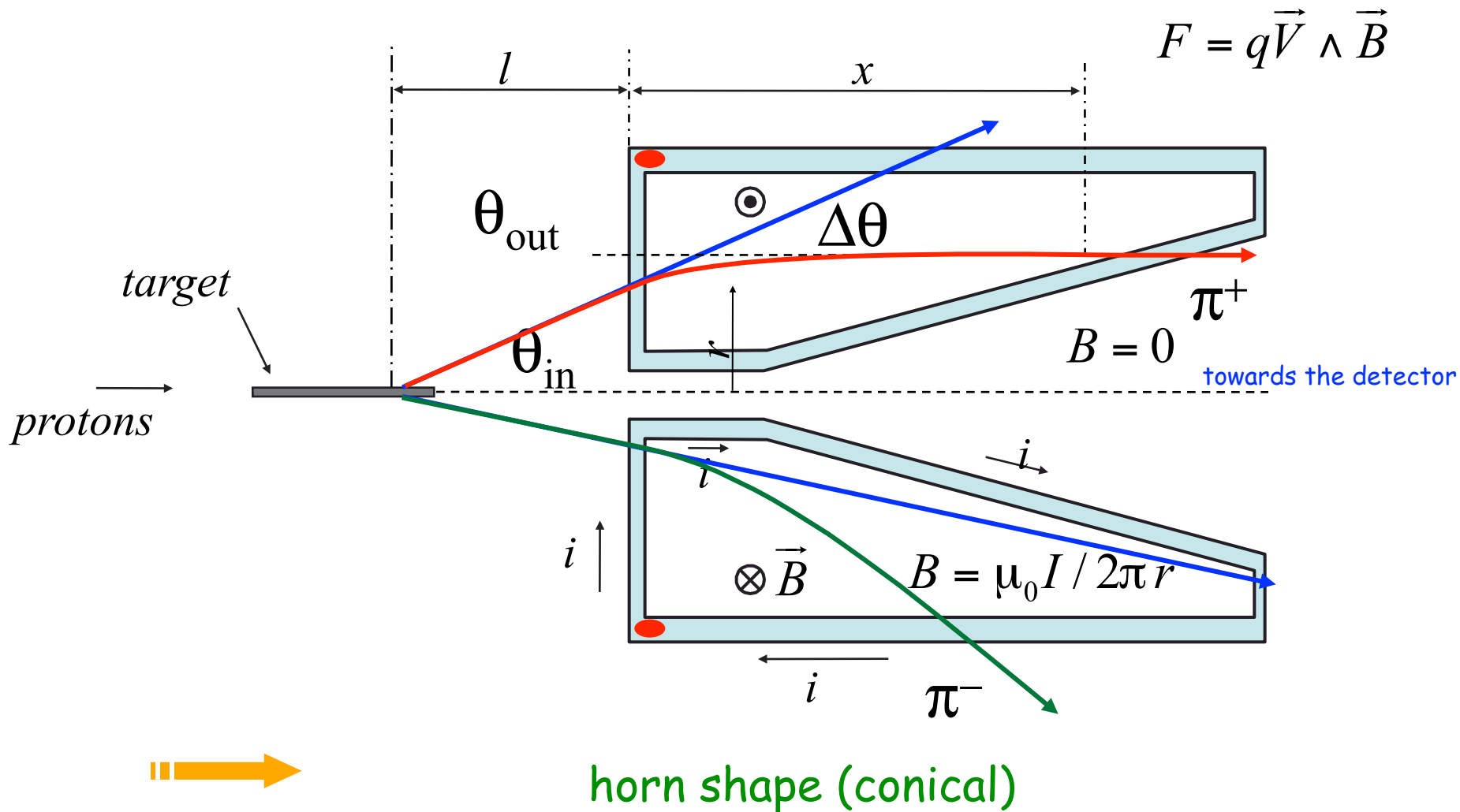


magnetic horn

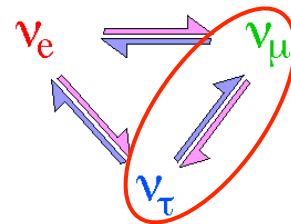


First horn on test in 1962-63

Hadronic Collector



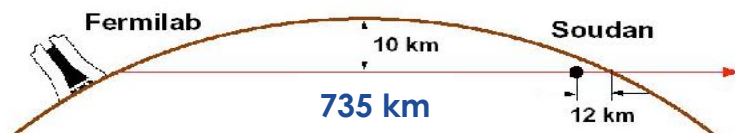
Long Base Line Experiments to well measure the “atmospheric” parameters



MINOS
experiment
(disappearance)



OPERA experiment
(appearance)



1 kton – 100 m deep



5.4 kton – 714 m deep

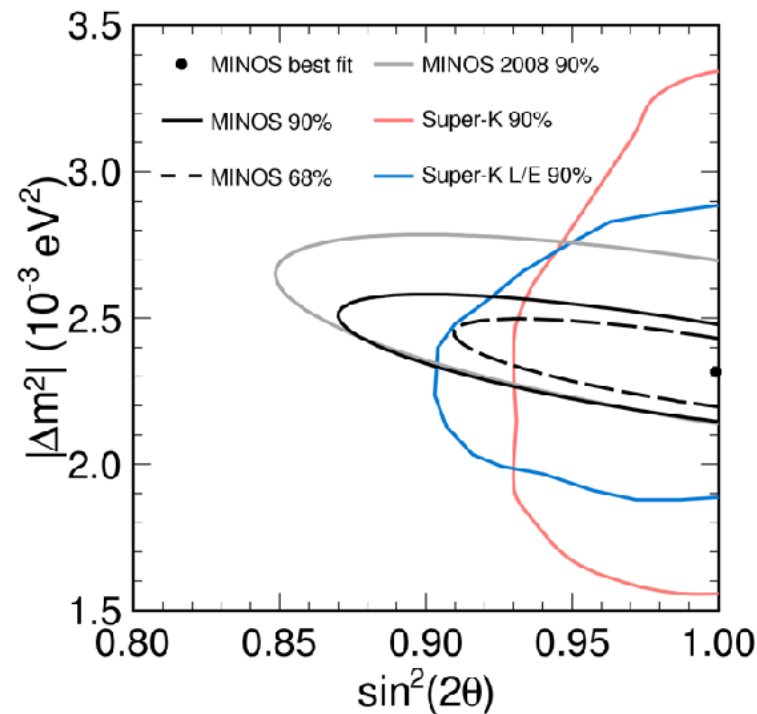
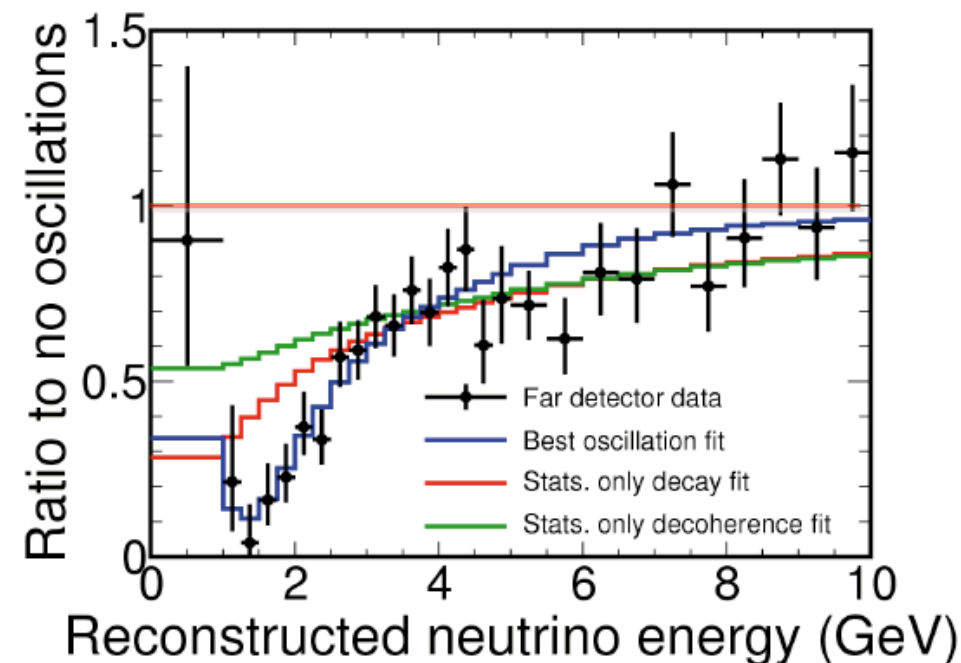
2005-2016



2007-2012

MINOS Experiment

(Main Injector Neutrino Oscillation Search)



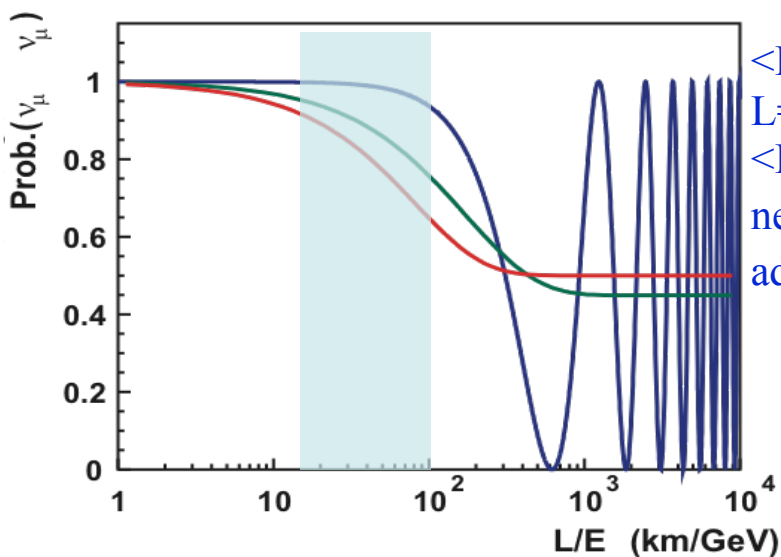
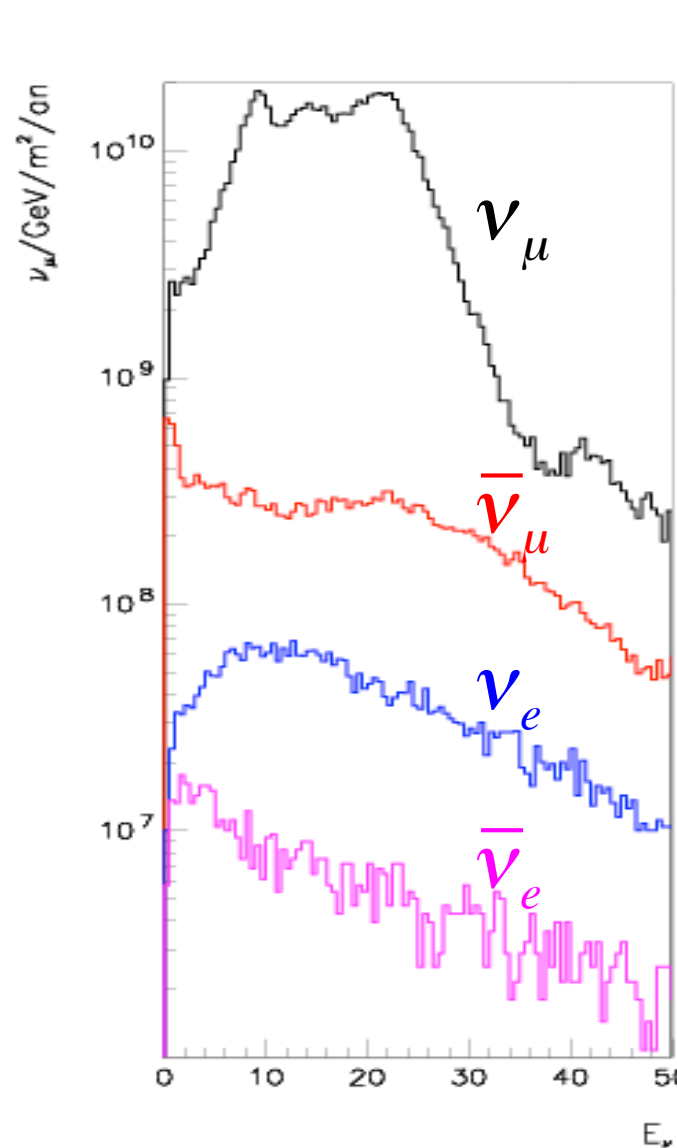
$$|\Delta m^2| = 2.32^{+0.12}_{-0.08} \times 10^{-3} \text{ eV}^2$$

$$\sin^2 2\theta > 0.90 \text{ (90\%CL)}$$

7.25×10^{20} POT

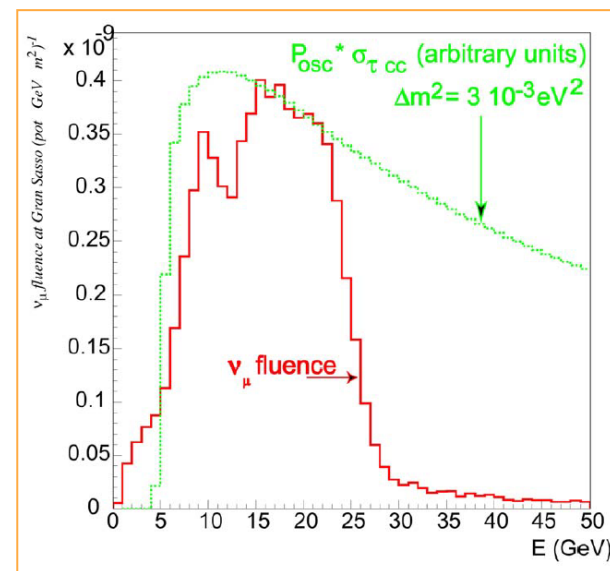
(protons On the Target)

CNGS Oscillations



$\langle E_\nu \rangle \sim 17 \text{ GeV}$ ($E_{\text{CM}} \gg m_\tau$),
 $L = 732 \text{ km}$
 $\langle L/E \rangle \sim 43$
 neutrinos ν_μ beam well
 adapted for ν_τ appearance

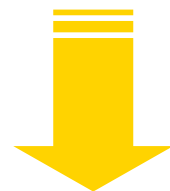
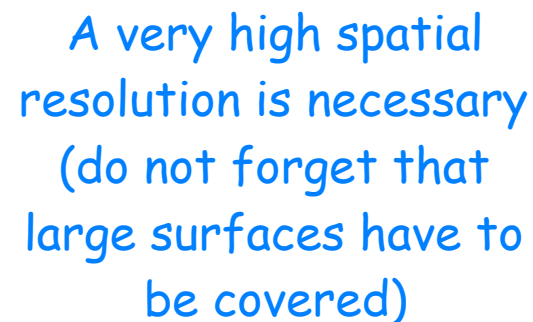
very small
 beam
 contamination



Sensitivity: $\Delta m^2 = 1.6 - 4.0 \cdot 10^{-3} \text{ eV}^2$



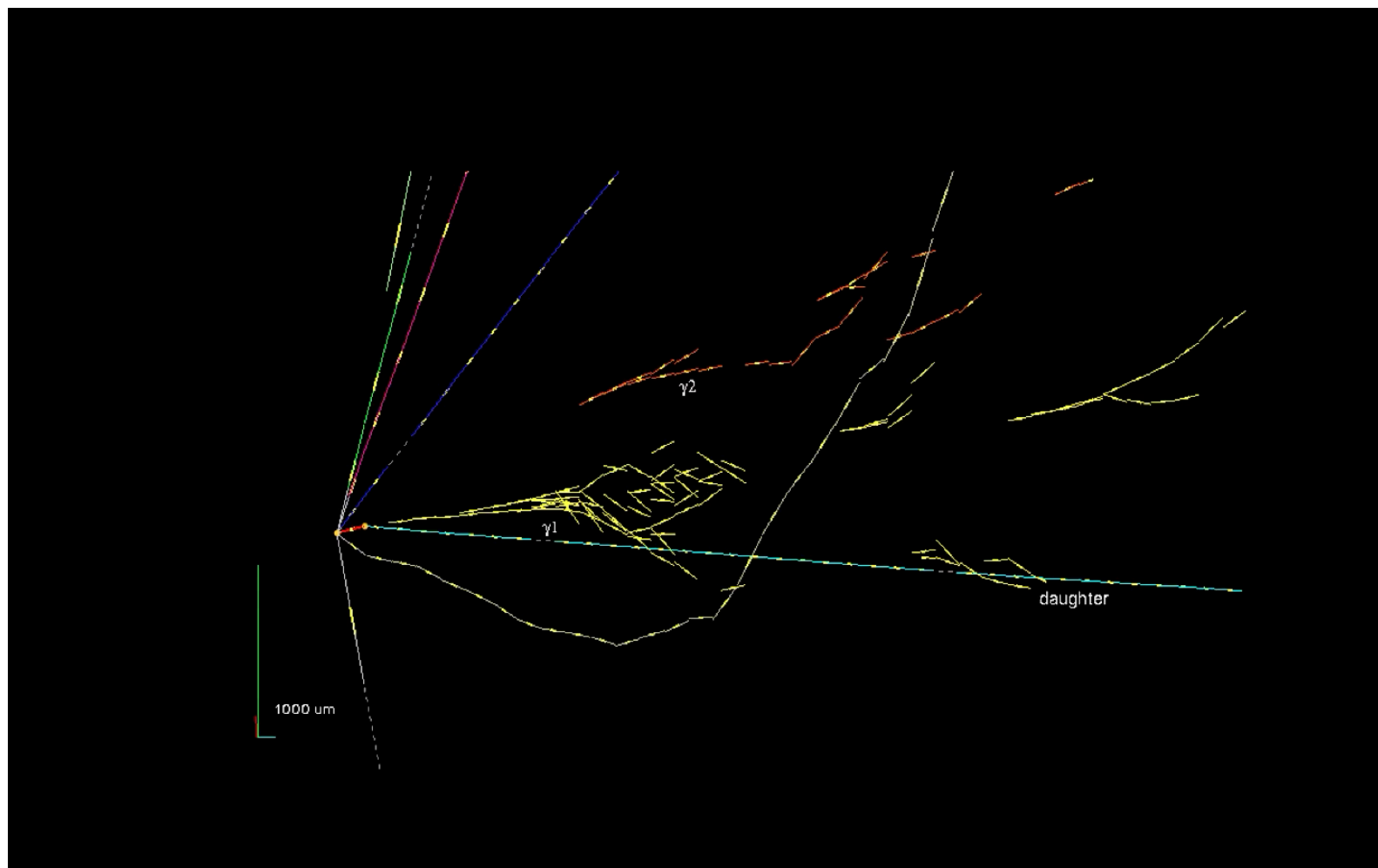
~ 15 grains/ $50\text{ }\mu\text{m}$



Nuclear Emulsions (photographic)



The first ν_τ candidate event



candidate: $\tau \rightarrow \underbrace{\pi^- \pi^0}_{\rho^-} \bar{\nu}_\tau$

Finally, 10 candidates with 5.2σ C. L.

Present measurements

$$\Delta m_{32}^2 = |2.52| \pm 0.04 \times 10^{-3} \text{ eV}^2$$

$$\Delta m_{21}^2 = 7.50_{-0.17}^{+0.19} \times 10^{-5} \text{ eV}^2$$

$$\sin^2 \theta_{23} = 0.441_{-0.021}^{+0.027} \quad (\sim 41.6^\circ) \text{ or } 0.587_{-0.024}^{+0.020}$$

$$\sin^2 \theta_{12} = 0.306_{-0.012}^{+0.012} \quad (\sim 33.6^\circ)$$

$$\sin^2 \theta_{13} \leq 0.046 \quad (< 12.4^\circ)$$

up to 2011

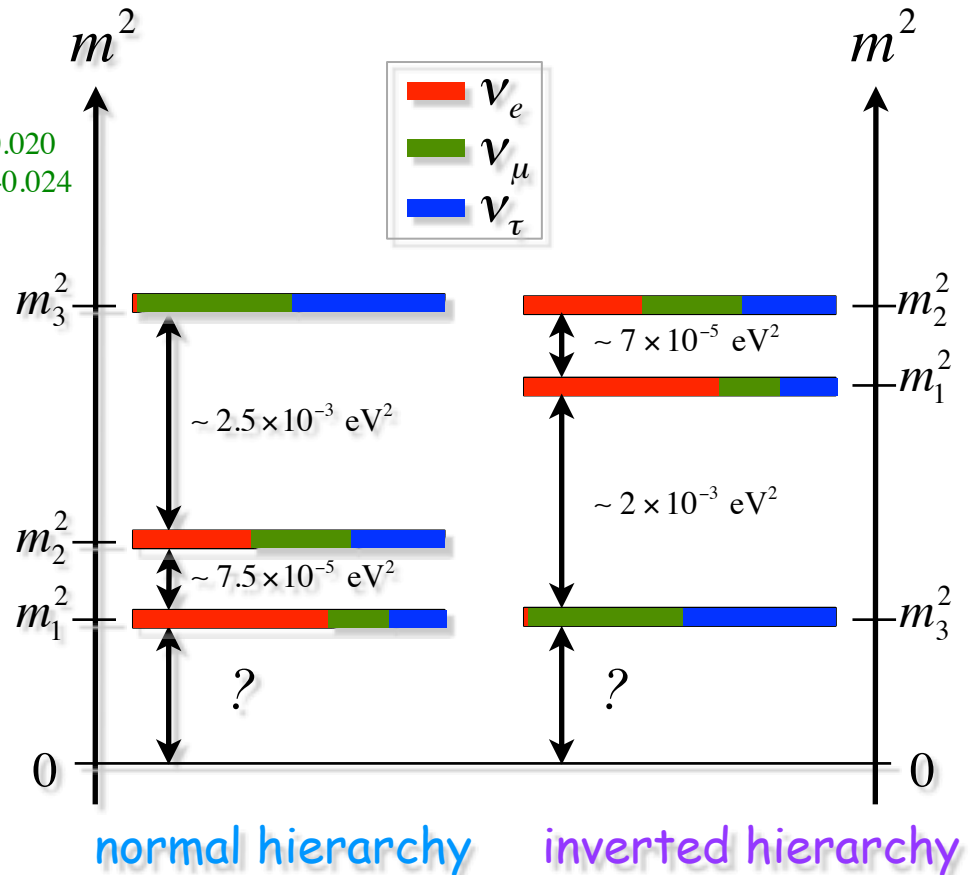
We can then write:

$$\Delta m_{13} \approx \Delta m_{23} \equiv \Delta m$$

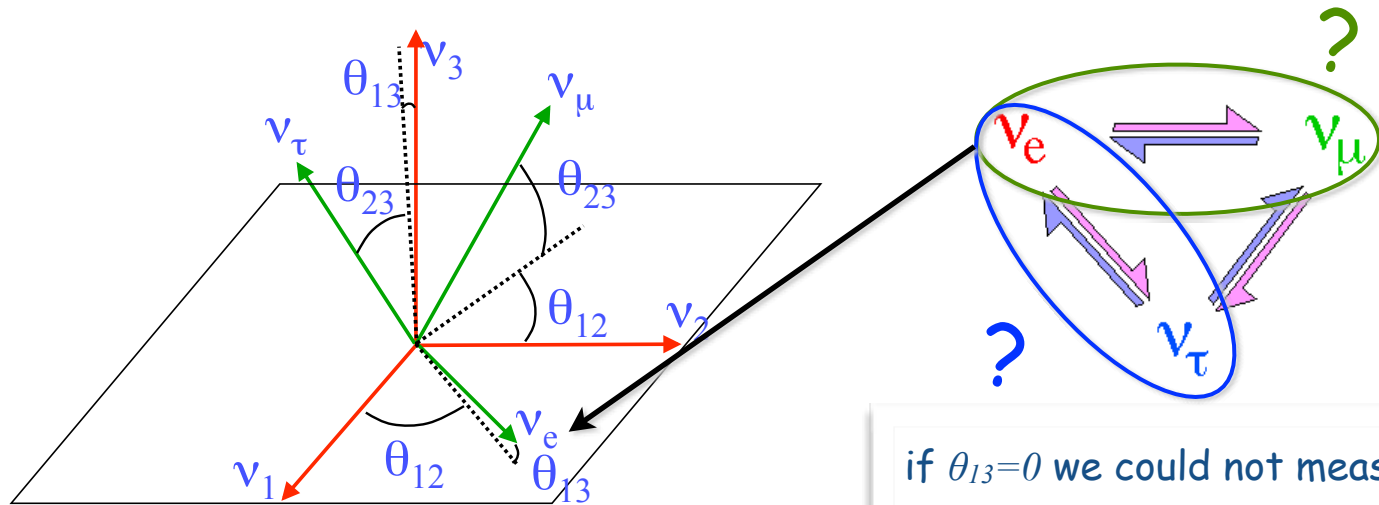
$$\Delta m_{12} \equiv \delta m$$

$$\Delta m \gg \delta m$$

δ_{CP} can be considered unknown



The θ_{13} hunting

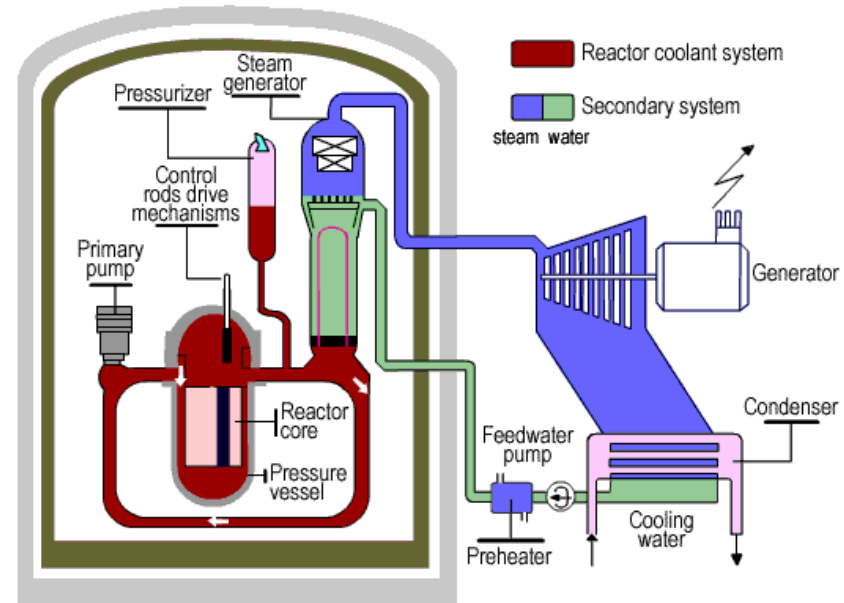
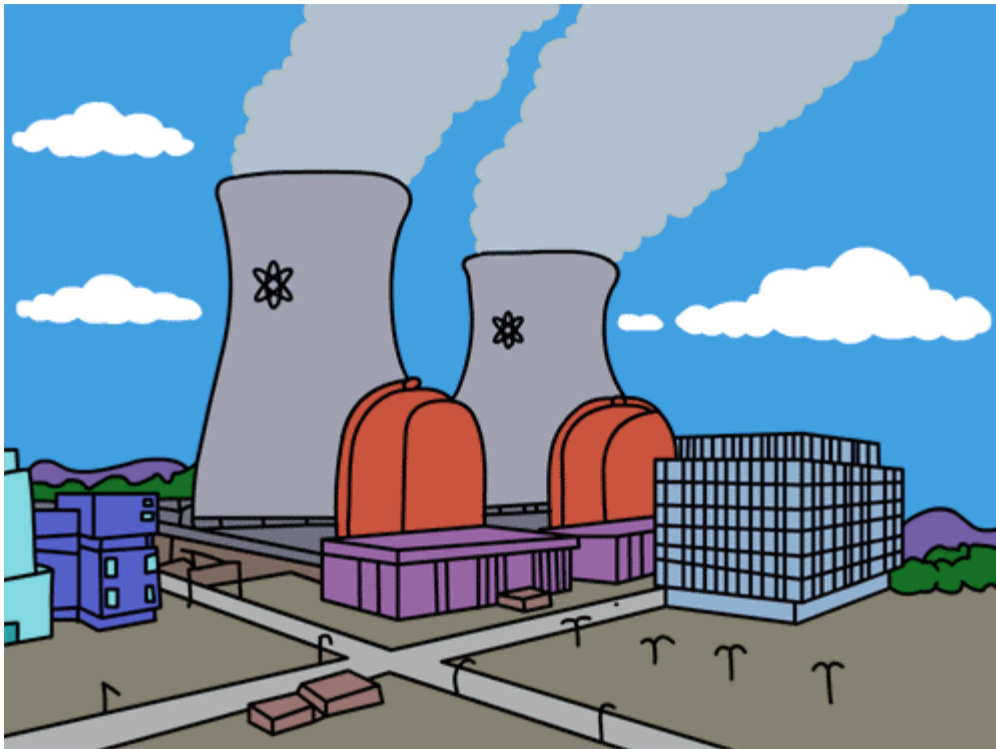


if $\theta_{13}=0$ we could not measure
CP violation

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{rotation around } x\text{-axis with angle } \theta_{23}} \cdot \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{rotation around } y\text{-axis with angle } \theta_{13}} \cdot \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{rotation around } z\text{-axis with angle } \theta_{12}}$$

atmospheric,
accelerators
reactors
solar,
reactors

Nuclear Reactors as neutrino source

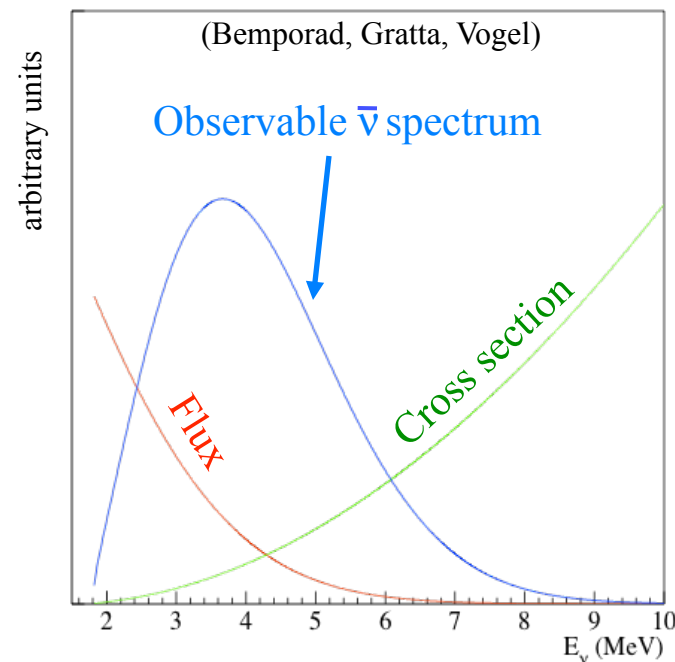


Nuclear Reactors as neutrino source

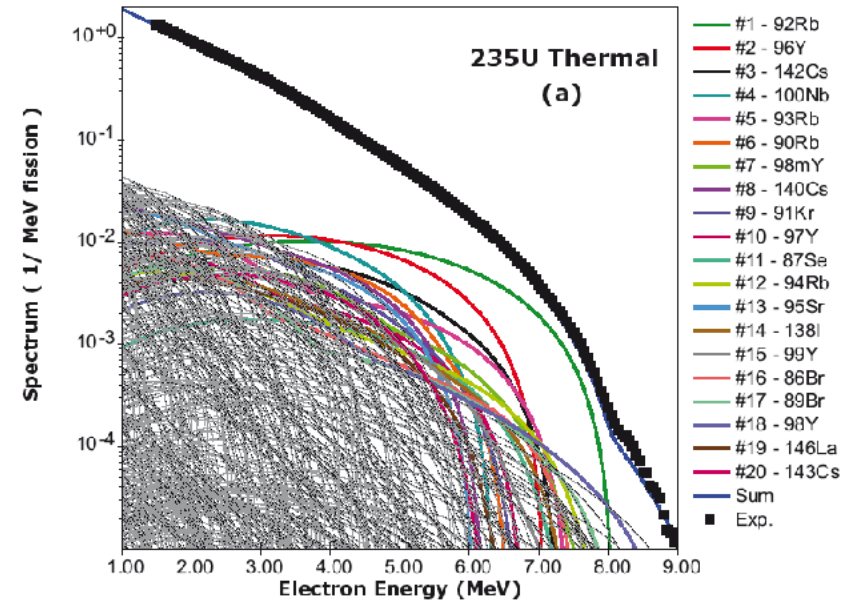
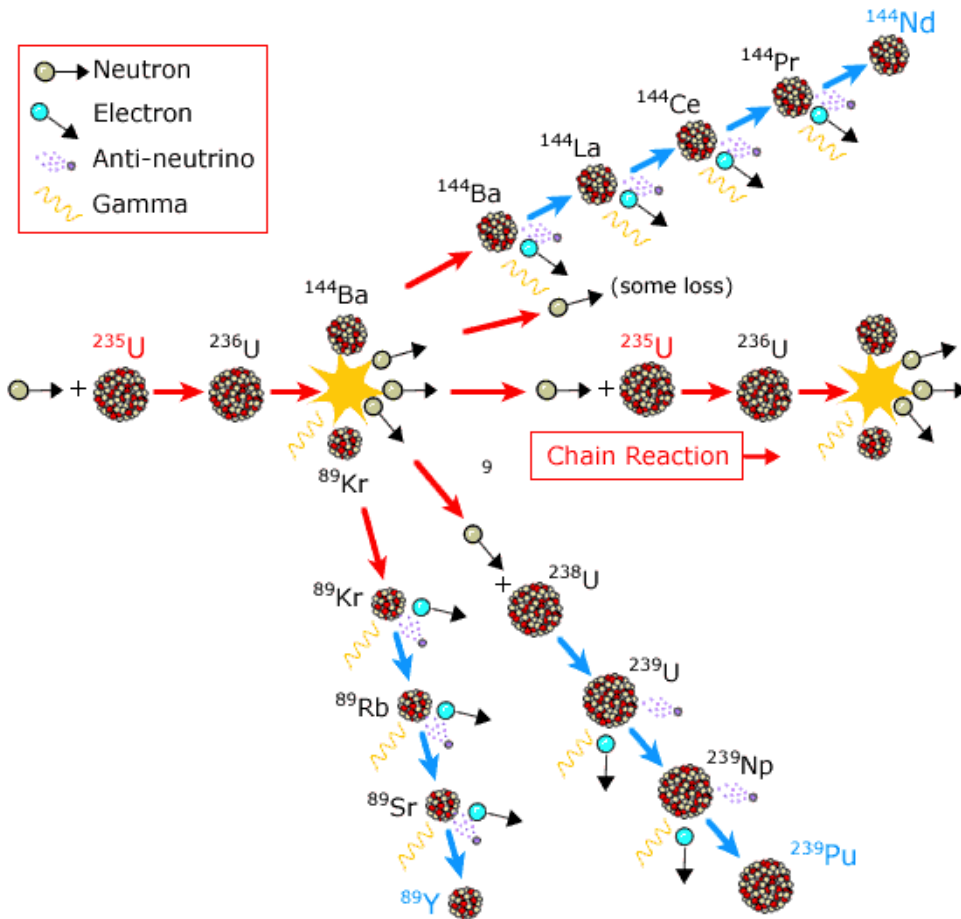
- Nuclear reactors are a very intense electron anti-neutrino source (β decay of neutron rich fission fragments).
- Each fission releases an energy of ~ 200 MeV and generates ~ 6 electron anti-neutrinos. For a typical commercial reactor (3 GW thermal energy):

$$3 \text{ GW} \approx 2 \times 10^{21} \text{ MeV/s} \rightarrow 6 \times 10^{20} \bar{\nu}_e/\text{s}$$

- Observable neutrino energy spectrum =
neutrino flux * cross section.
- The spectrum has a maximum at ~ 3.7 MeV.

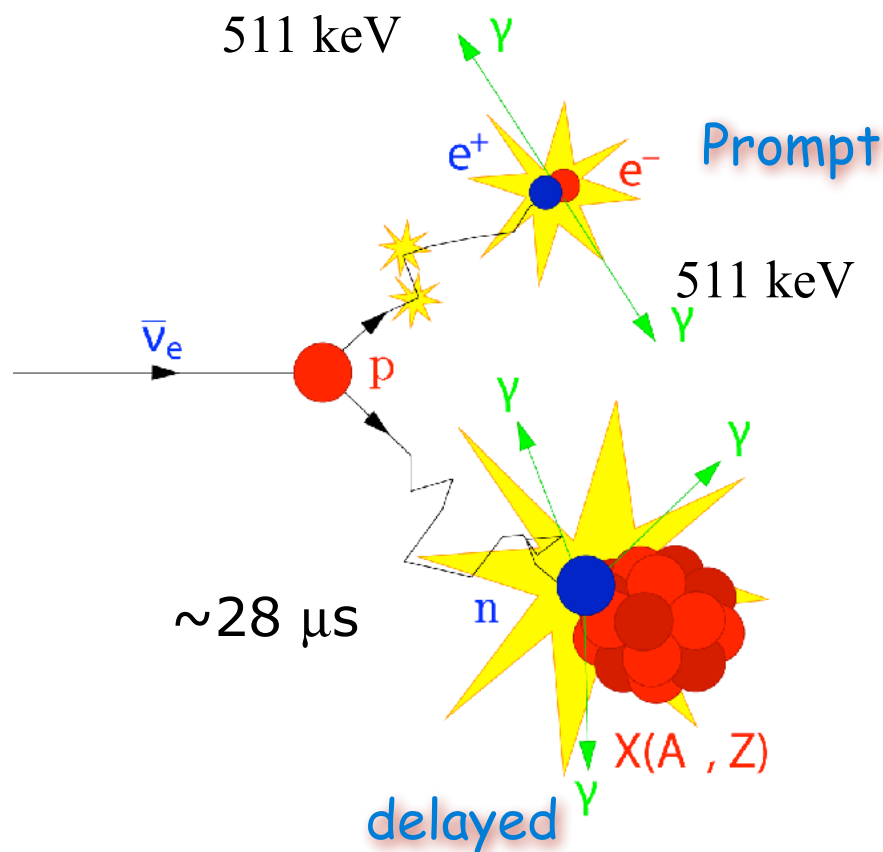
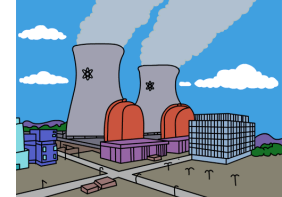


Nuclear Reactors as neutrino source



Not so easy to calculate the neutrino spectrum...

Inverse β decay (IBD) and detection mode



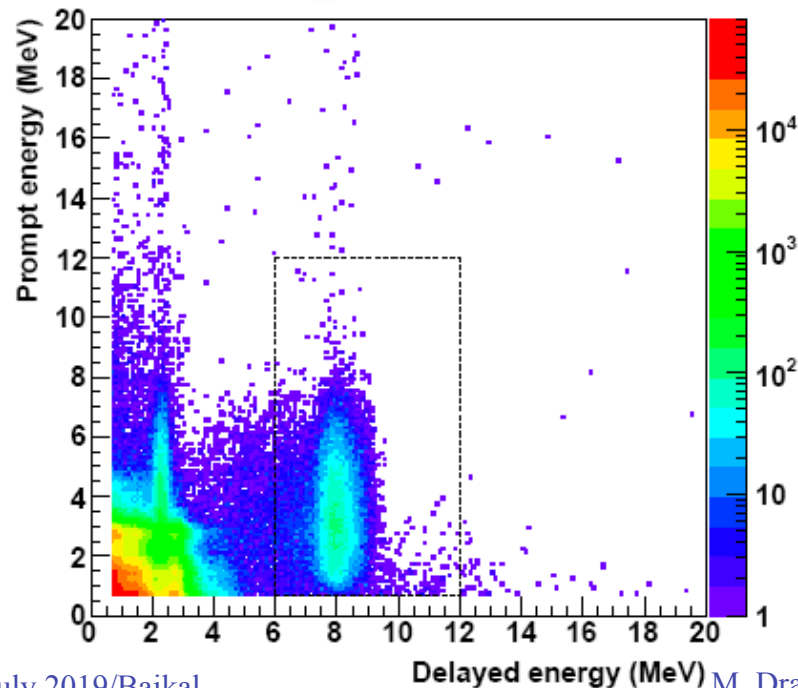
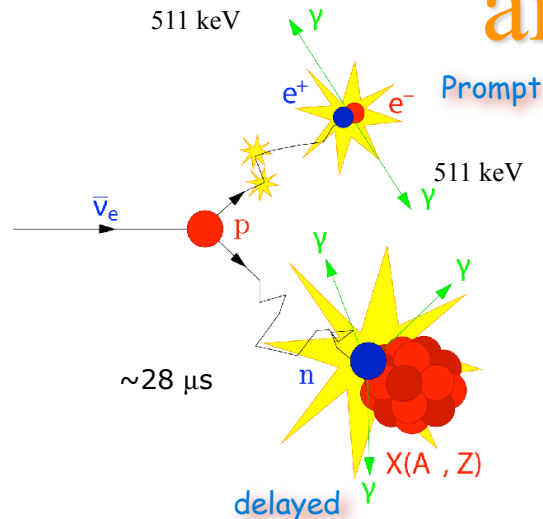
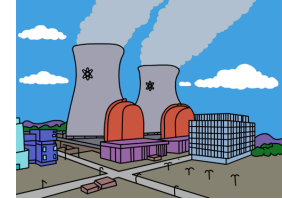
- In a pure scintillator the neutron will be captured by hydrogen:



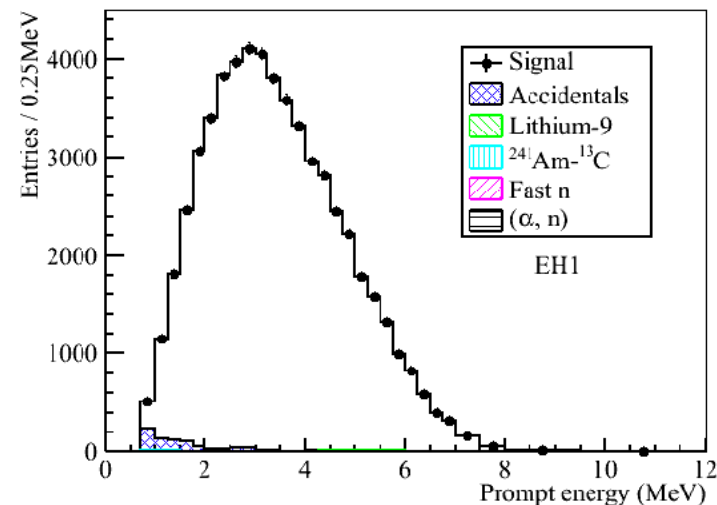
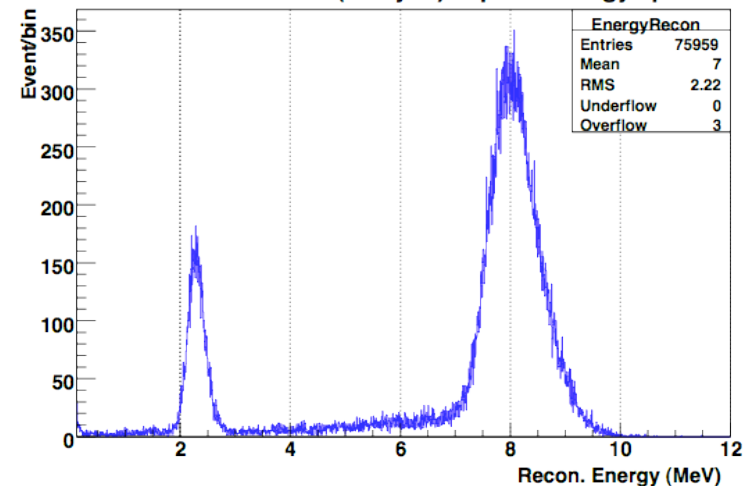
- Very often the scintillator is doped with gadolinium that increase the capture probability and liberates more γ 's:



Inverse β decay (IBD) and detection mode



reconstructed neutron (delayed) capture energy spectrum

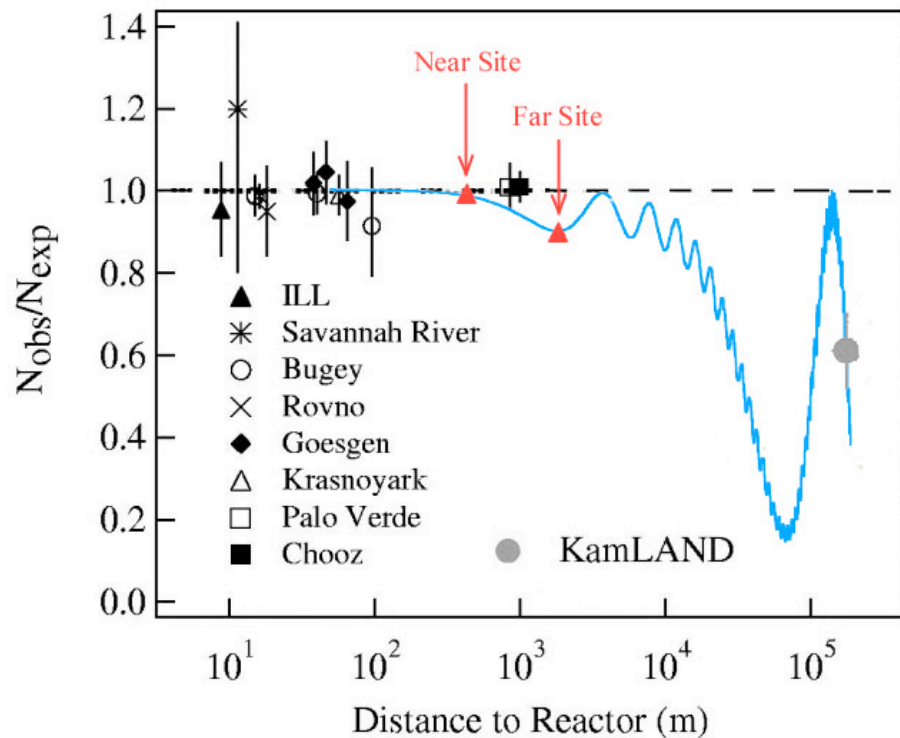
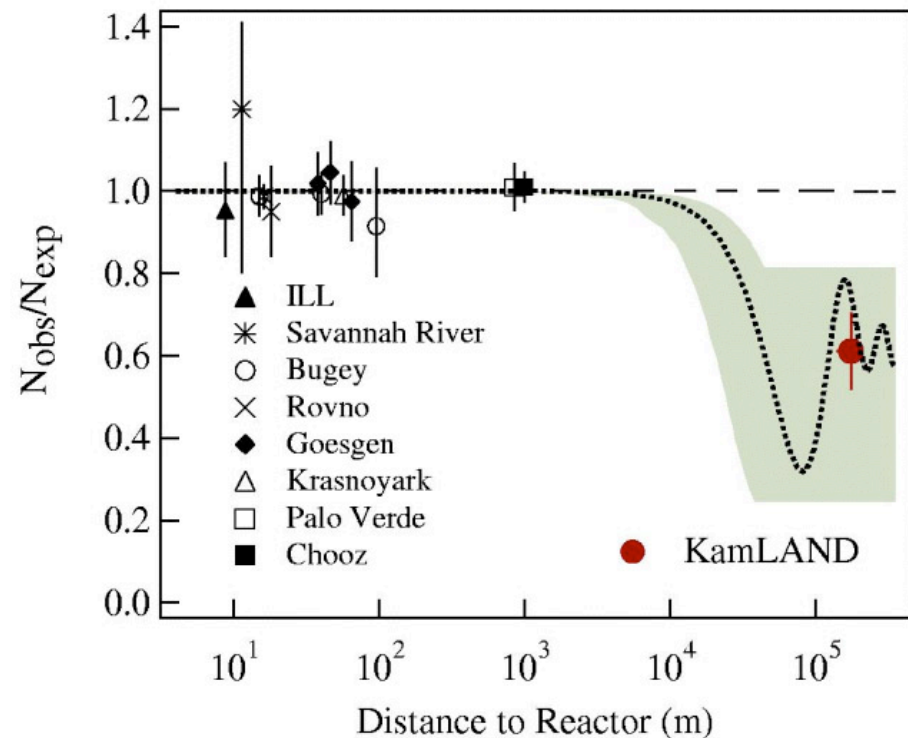


The θ_{13} hunting

(up to 2012)

disappearance of electron neutrinos

For $\theta_{13} \sim 10^\circ$



Actually, we have almost neglected θ_{13} on this figure

Due to “large” uncertainties, up to 2011:

$$\sin^2 \theta_{13} \leq 0.046 \quad (<12.4^\circ)$$

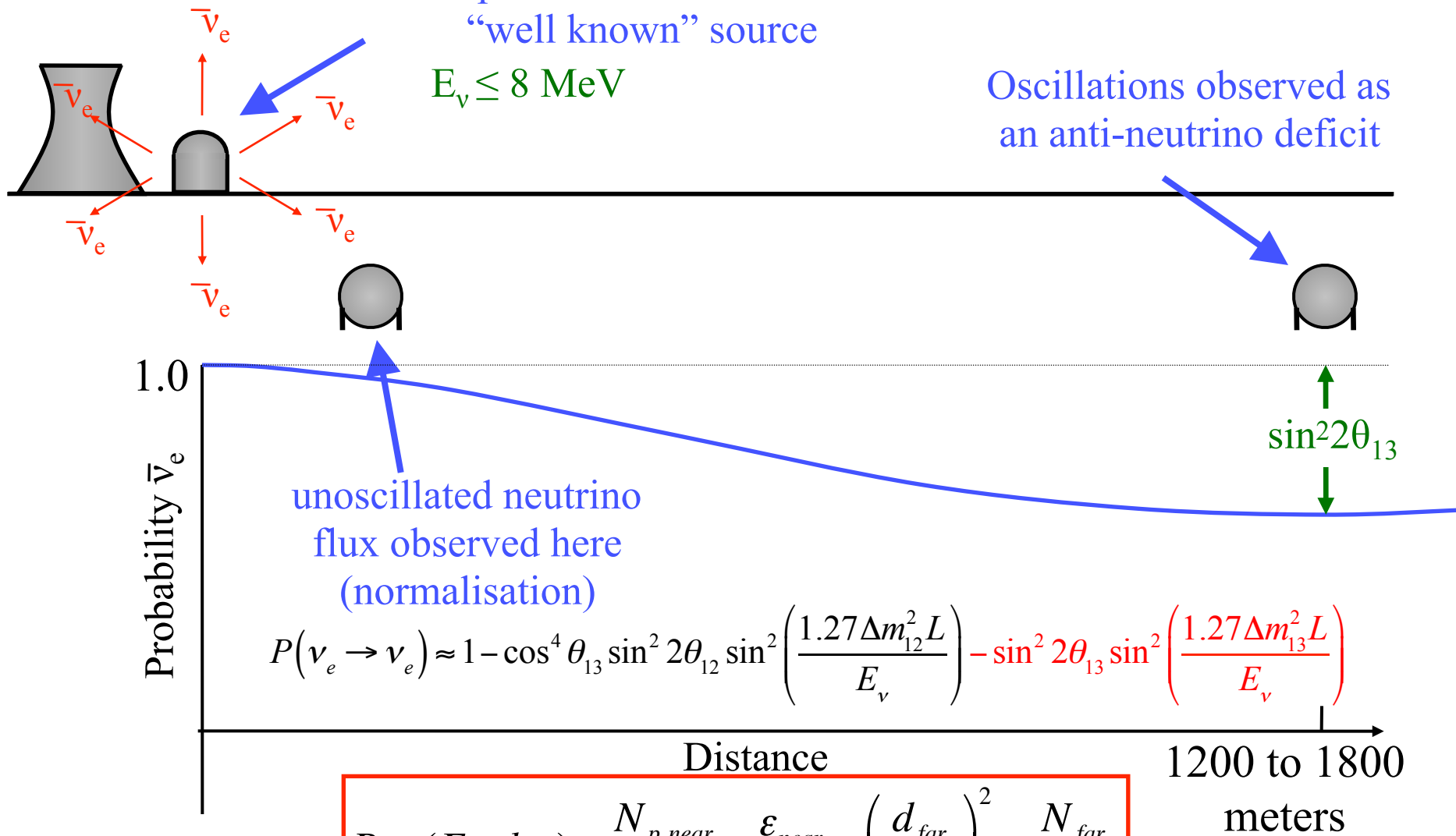
$\sin^2 2\theta_{13}$ and the reactor experiments

isotropic electron anti-neutrino

“well known” source

$$E_\nu \leq 8 \text{ MeV}$$

Oscillations observed as
an anti-neutrino deficit



$$P_{\text{surv.}}(E_\nu, d_{\text{far}}) = \frac{N_{p,\text{near}}}{N_{p,\text{far}}} \times \frac{\varepsilon_{\text{near}}}{\varepsilon_{\text{far}}} \times \left(\frac{d_{\text{far}}}{d_{\text{near}}} \right)^2 \times \frac{N_{\text{far}}}{N_{\text{near}}}$$

$= 1!!$ $= 1!!$

New generation reactor experiments



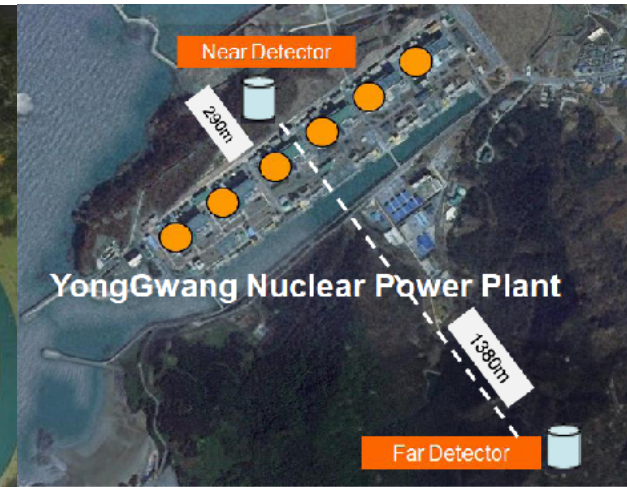
Daya Bay
(China)



Double Chooz
(France)



RENO
(South Korea)



	Luminosity in 3 years (ton·GW·y)	Overburden near/far (mwe)	Expected sensitivity	Start of data taking
Daya Bay	4200	270/950	<0.01	August 2011
Double Chooz	210	80/300	0.02~0.03	April 2011
RENO	740	90/440	~0.02	August 2011

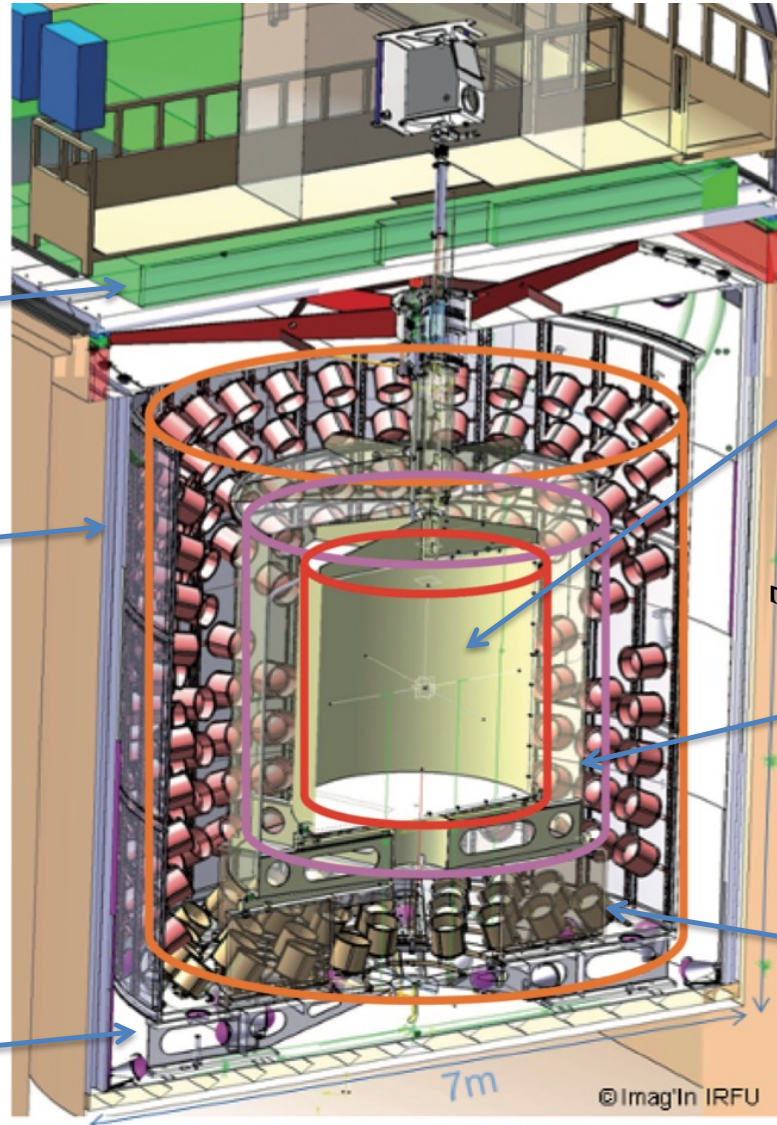
Reactor neutrino detectors



Outer Veto
(plastic scintillator)

Shielding
(15 cm steel)

Inner Veto
(liquid scintillator)
78 (8") PMTs



Target ($r=1.2$ m)
• acrylic vessel (8 mm)
• 8.3 tons Gd-scintillator

Gamma Catcher ($r=0.55$ m)
• scintillator



θ_{13} is “large” !!!

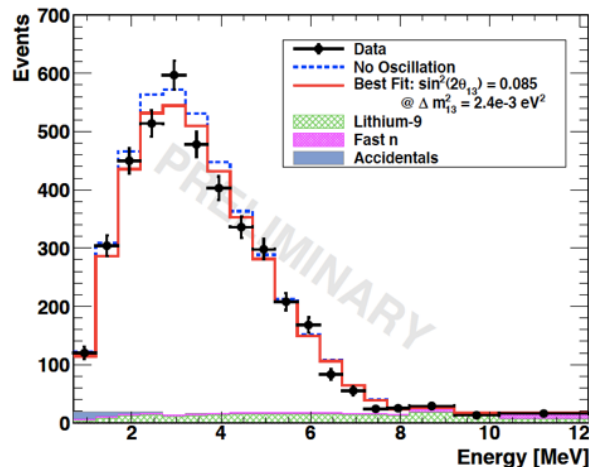
The reactor experiments have
discovered the $1 \rightarrow 3$ oscillation

Daya Bay
(March 2012)

RENO
(April 2012)

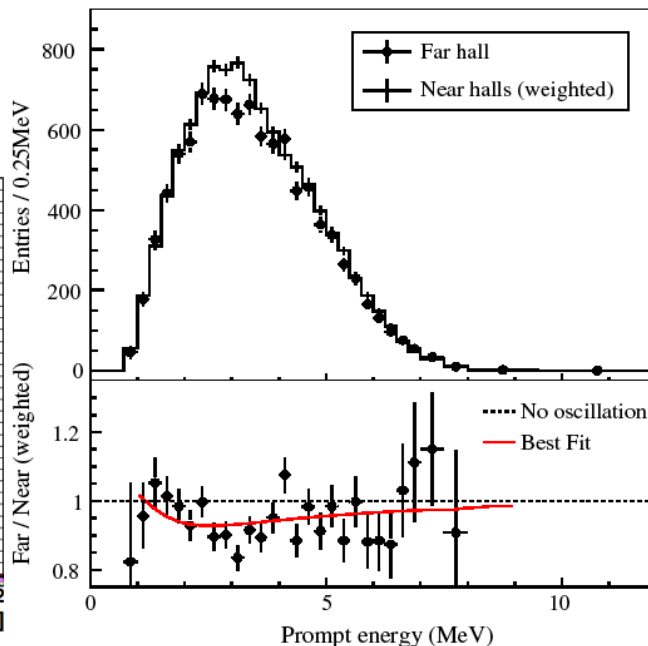
Double Chooz
(Nov. 2011)

Phys.Rev.Lett. 108, 171803 (2012), 1203.1669.



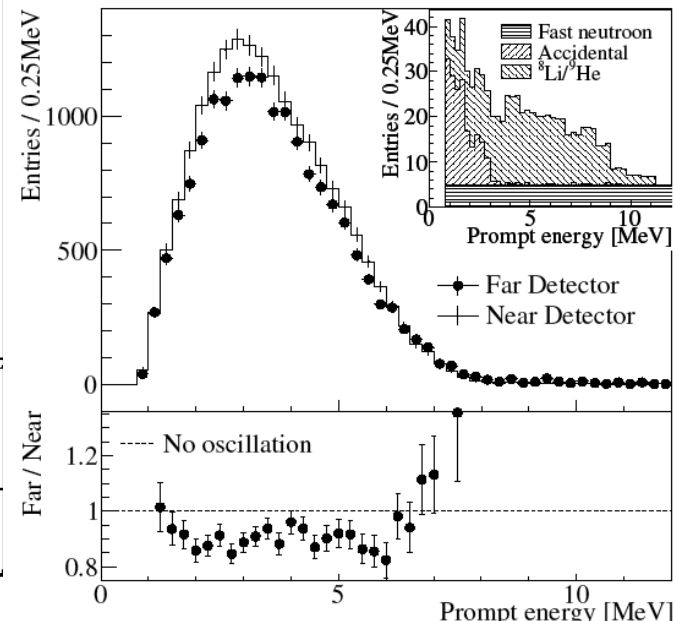
$$\sin^2(2\theta_{13}) = 0.085 \pm 0.029(\text{stat}) \pm 0.042(\text{syst})$$

Phys.Rev. D86, 052008 (2012), 1207.6632.



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

Phys.Rev.Lett. 108, 191802 (2012), 1204.0626.



$$\sin^2 2\theta_{13} = 0.103 \pm 0.013(\text{stat.}) \pm 0.011(\text{syst.})$$

- the future "long baseline" projects must readjust their parameters...
- now, the name of the game is neutrino **mass hierarchy** and **CP violation**.

→ $\theta_{13} > 0$ →

(C.L. > 5 σ by Daya Bay)

Open Questions

- Mass hierarchy: normal or inverted?
- **CP Violation in the leptonic sector?**
- Are neutrinos their own anti-particle (Dirac or Majorana)?
- How many neutrino families? Are there sterile neutrinos?
- What is the absolute neutrino mass scale?
- **What is the neutrino rôle in the Universe evolution?**

Matter/antimatter asymmetry in the Universe

At the very beginning of the Universe:

10,000,000,001

matter

10,000,000,000

antimatter

Matter/antimatter asymmetry in the Universe

annihilation:

• + radiation

matter



what we see around us today...

Baryon Asymmetry in the Universe (BAU)

CP Violating Observables

$$\begin{aligned}
 P_{\nu_{\mu} \rightarrow \nu_e (\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e)} = & s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{\tilde{B}_{\mp}} \right)^2 \sin^2 \left(\frac{\tilde{B}_{\mp} L}{2} \right) && \text{atmospheric} \\
 & + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A} \right)^2 \sin^2 \left(\frac{AL}{2} \right) && \text{solar} \\
 & + \tilde{J} \frac{\Delta_{12}}{A} \frac{\Delta_{13}}{\tilde{B}_{\mp}} \sin \left(\frac{AL}{2} \right) \sin \left(\frac{\tilde{B}_{\mp} L}{2} \right) \cos \left(\pm \delta_{CP} - \frac{\Delta_{13} L}{2} \right) && \begin{array}{l} \text{interference} \\ \text{CP violating} \end{array}
 \end{aligned}$$

$$\tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}, \quad \Delta_{ij} \equiv \frac{\Delta m_{ij}^2}{2E_{\nu}}, \quad \tilde{B}_{\mp} \equiv |A \mp \Delta_{13}|, \quad A = \sqrt{2} G_F N_e$$

$$\mathcal{A} = \frac{P_{\nu_{\mu} \rightarrow \nu_e} - P_{\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e}}{P_{\nu_{\mu} \rightarrow \nu_e} + P_{\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e}}$$

$\neq 0 \Rightarrow$ CP Violation

be careful, matter effects also
create asymmetry

matter effect

$\Rightarrow$ accessibility to
 mass hierarchy
 $\Rightarrow$ long baseline

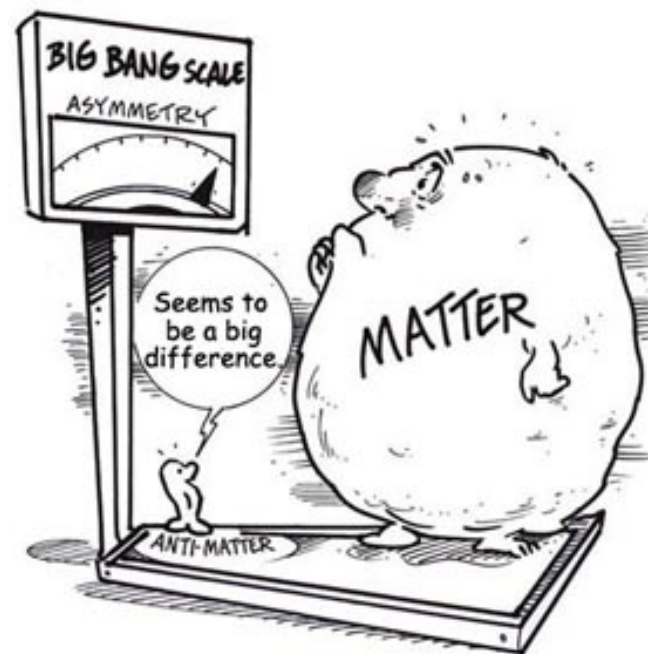


δ_{CP} and Matter-antimatter asymmetry magnitude

$$\begin{aligned}
 A_{\alpha\beta}^{CP} &= P(\nu_{\alpha} \rightarrow \nu_{\beta}) - P(\bar{\nu}_{\alpha} \rightarrow \bar{\nu}_{\beta}) \\
 &= J_{CP}^{PMNS} \cdot \sin\delta_{CP}
 \end{aligned}$$

with: $J_{CP}^{PMNS} \sim 3 \times 10^{-3}$ (Jarlskog invariant)

(for hadrons: $J_{CP}^{CKM} \sim 3 \times 10^{-5}$, not enough even if $\delta_{CP} \sim 70^\circ$)

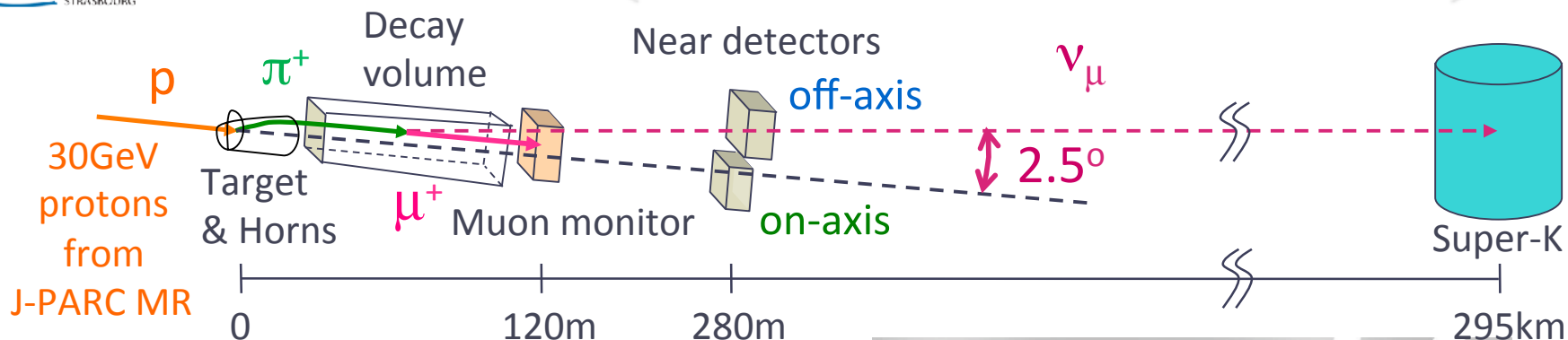


Theoretical models predict that if $|\sin\delta_{CP}| \gtrsim 0.7$ ($45^\circ < \delta_{CP} < 135^\circ$ or $225^\circ < \delta_{CP} < 315^\circ$), it could be enough to explain the observed asymmetry.

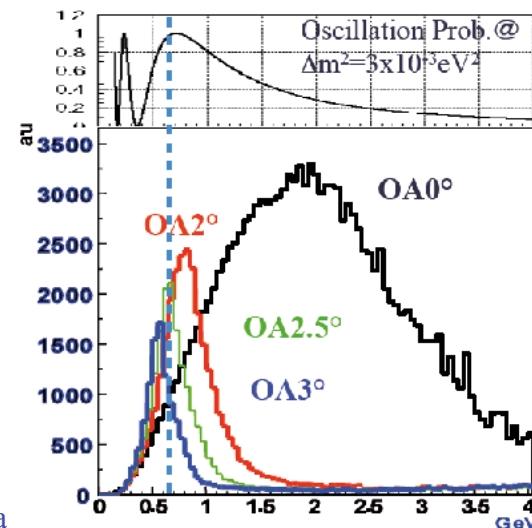
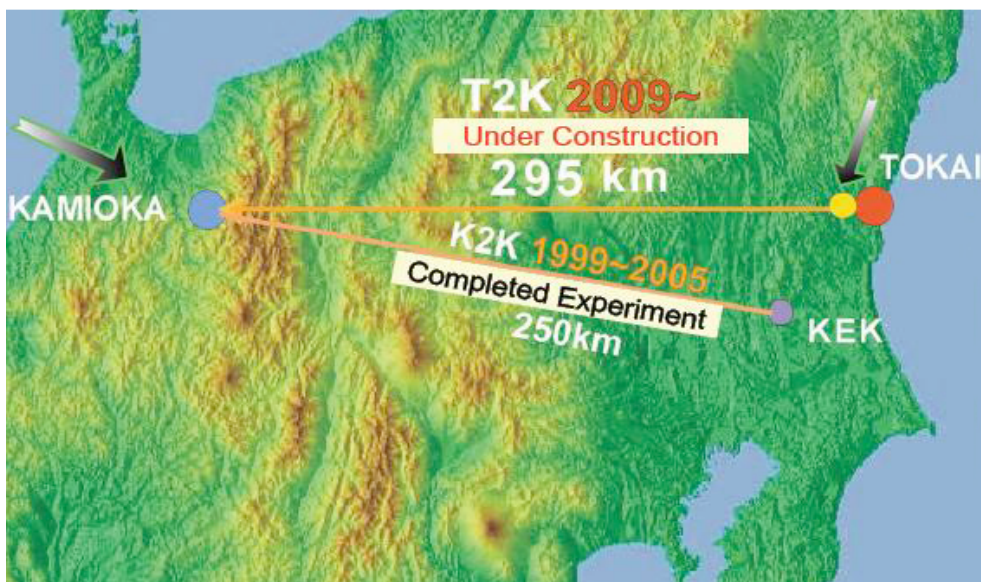
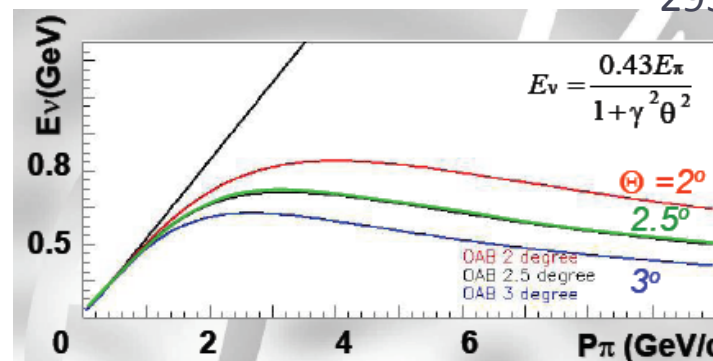
Other sources of CP Violation



T2K (θ_{13} on accelerator)



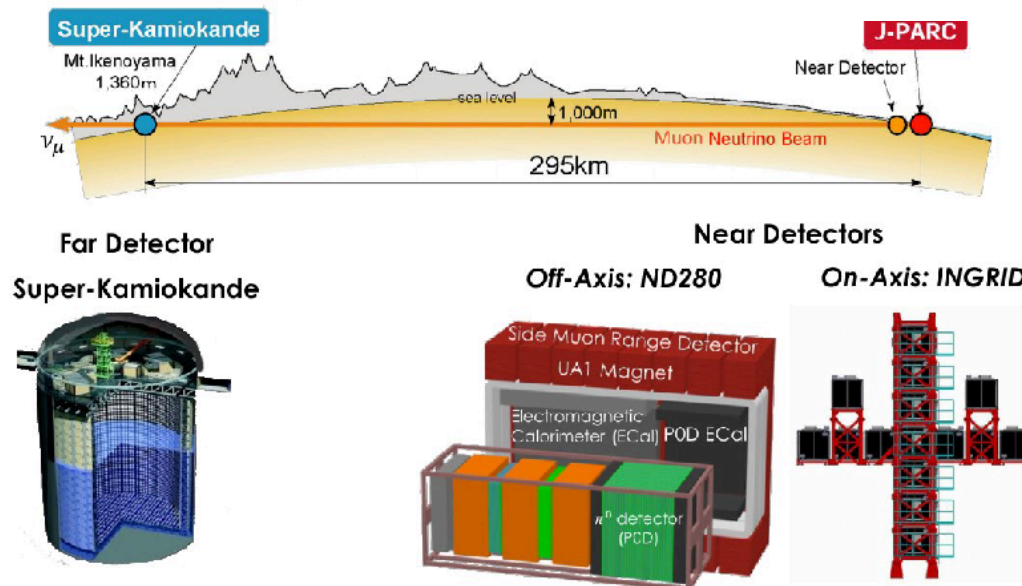
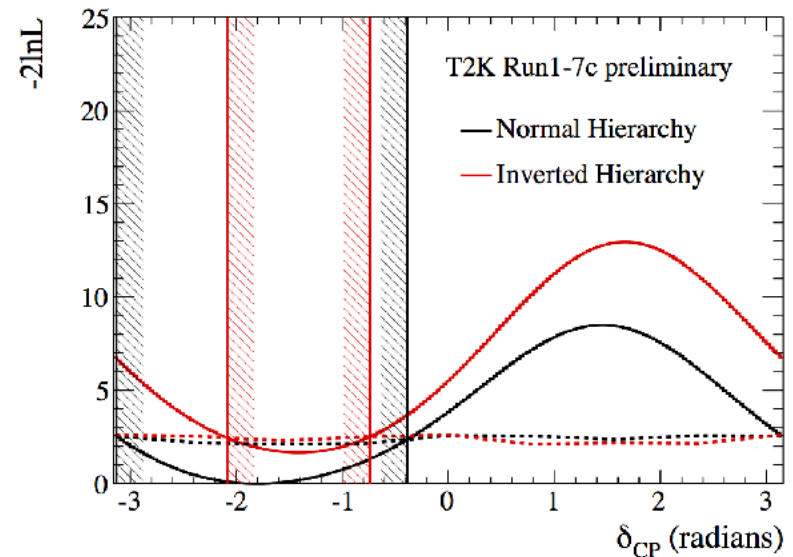
- Very intense proton beam (0.7 MW, 30 GeV)
- **Off-axis** (2-3 deg.)
- $\langle E \rangle 0.7 \text{ GeV}$



Present and Future Projects



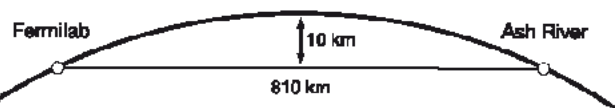
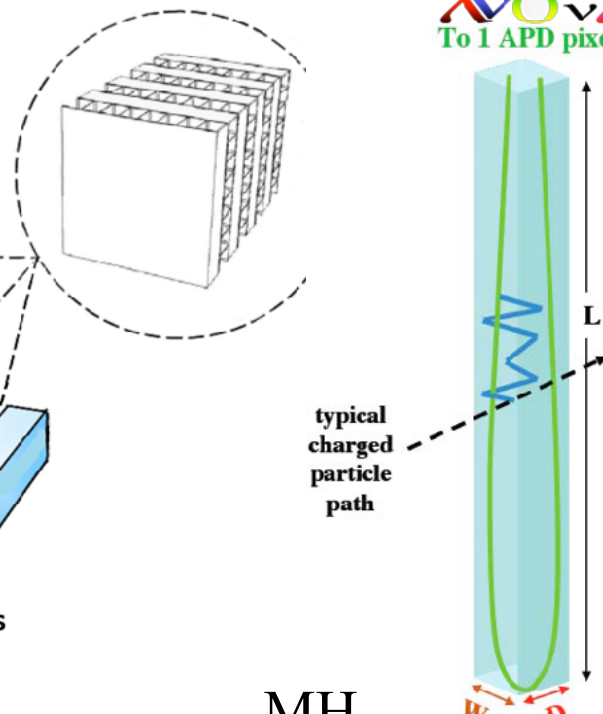
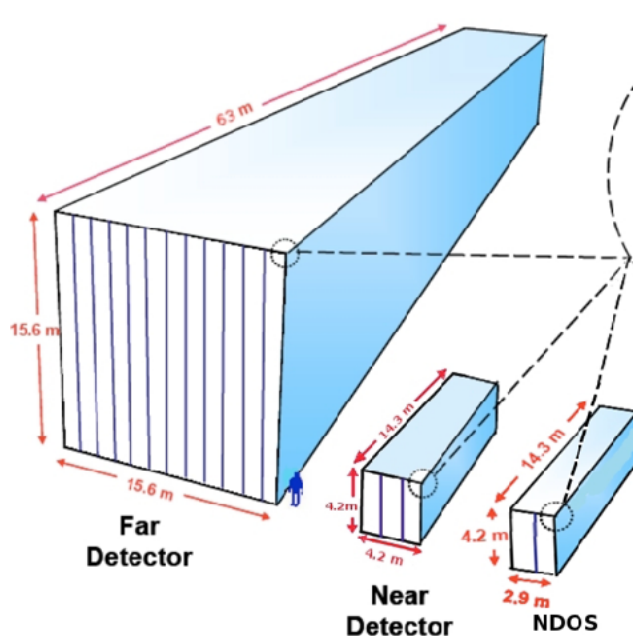
- T2K increases its statistics.
- Increase of the beam power.
- A slight preference for $\delta_{CP} \sim -90^\circ$ and NH but not enough to conclude.



Present and Future Projects



NOvA
To 1 APD pixel

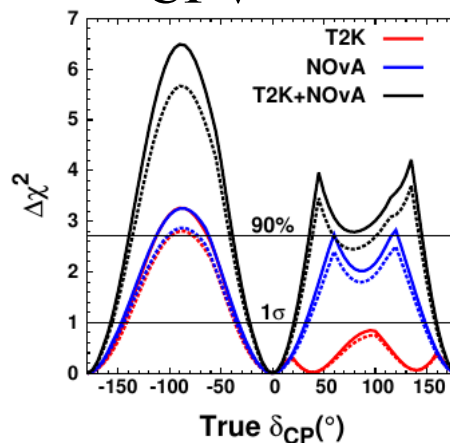


Goal:

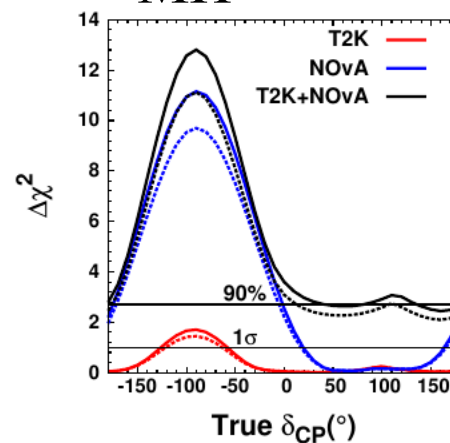
- Determination of mass hierarchy.
- Observation of CP violation.
- Improve the $\sin^2 2\theta_{23}$ measurement.

they must be
very lucky...

CPV

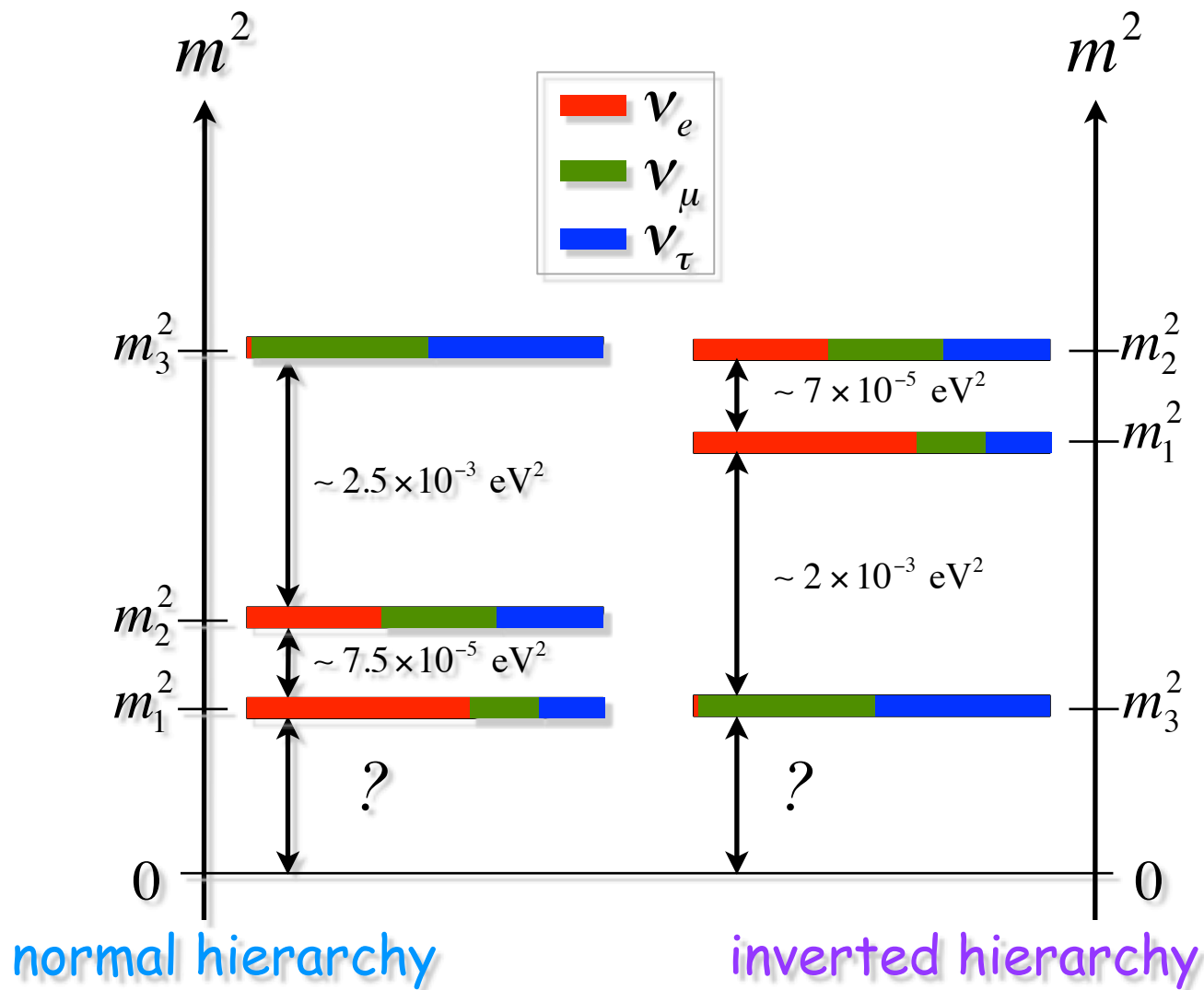


MH



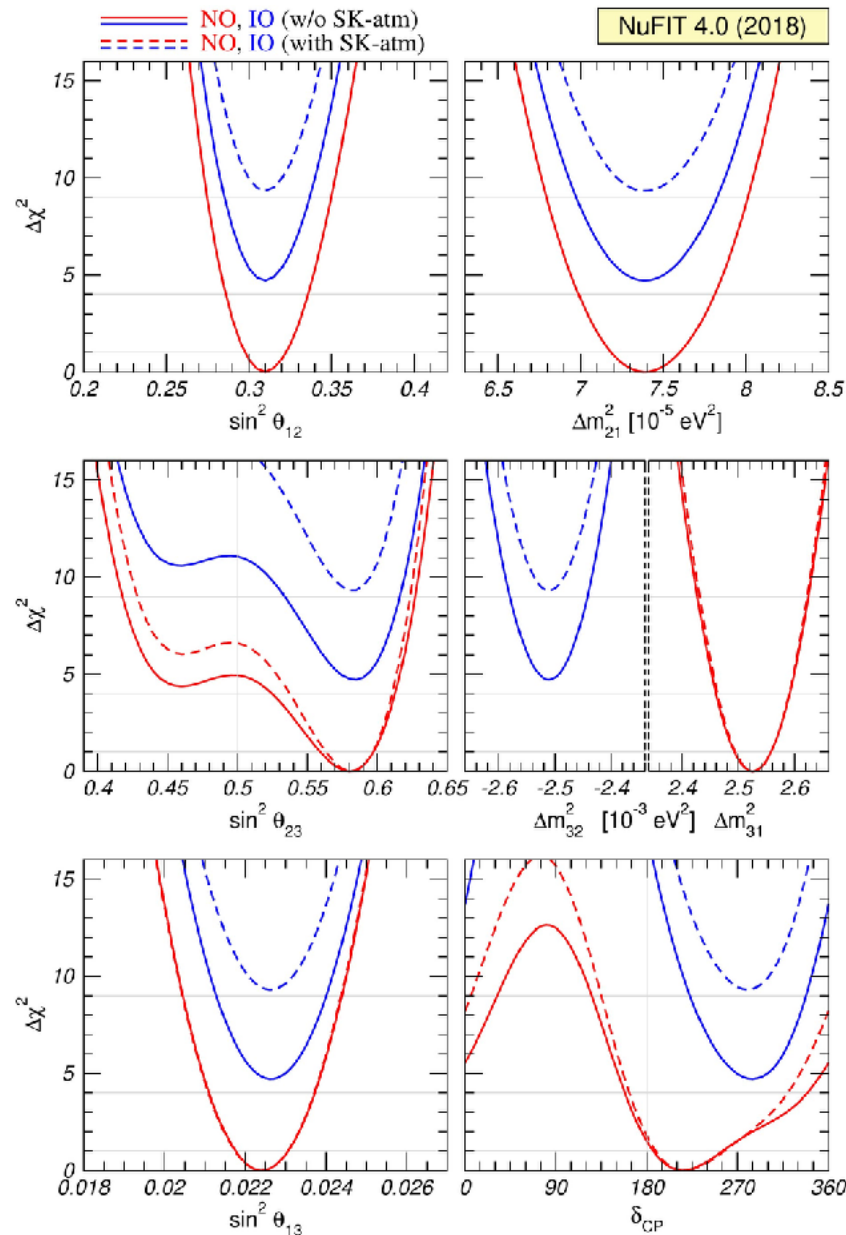
Mass Hierarchy

Projects under construction or preparation

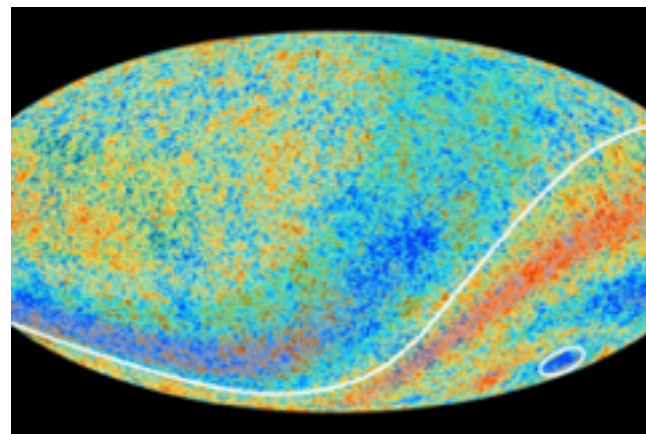
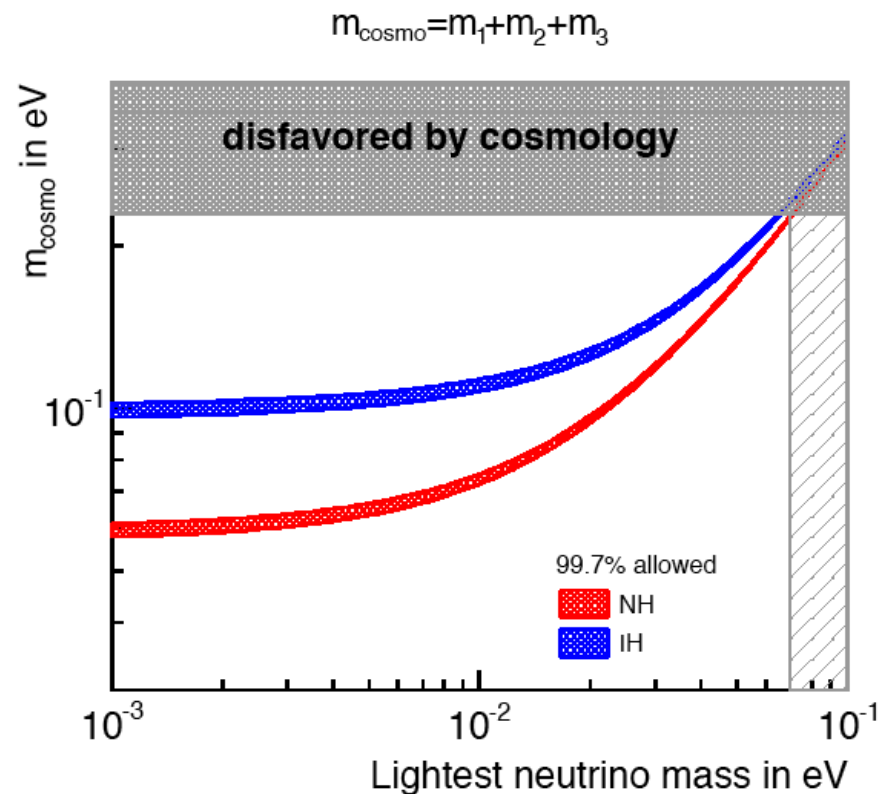


Why to measure MH?

- The oscillation parameter values (slightly or strongly) depend on the mass hierarchy and this avoids precision measurements and checks of the unitarity of the mixing matrix.
- This also significantly reduces the CPV discovery performance of future projects.
- Reject many theoretical models.
- ...



MH and cosmology



from cosmology

if $m_{\text{cosmo}} < 0.1 \text{ eV} \Rightarrow \text{NH}$

$$m_{\text{cosmos}} = \begin{cases} m_L + \sqrt{m_L^2 + \Delta m_{21}^2} + \sqrt{m_L^2 + |\Delta m_{31}^2|} & \text{(Normal Hierarchy)} \\ m_L + \sqrt{m_L^2 + |\Delta m_{32}^2|} + \sqrt{m_L^2 + |\Delta m_{31}^2|} & \text{(Inverted Hierarchy)} \end{cases}$$

JUNO

(Jiangmen Underground Neutrino Observatory)



$$P_{ee}(L/E) = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(\Delta m_{21}^2 \cdot \frac{L}{4E} \right)$$

$$- \sin^2 2\theta_{13} \sin^2 \left(\left| \Delta m_{31}^2 \right| \cdot \frac{L}{4E} \right)$$

$$- \sin^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 \left(\Delta m_{21}^2 \cdot \frac{L}{4E} \right) \cdot \cos \left(2 \left| \Delta m_{31}^2 \right| \cdot \frac{L}{4E} \right)$$

$$\pm \frac{\sin^2 \theta_{12}}{2} \sin^2 2\theta_{13} \sin \left(2 \Delta m_{21}^2 \cdot \frac{L}{4E} \right) \cdot \sin \left(2 \left| \Delta m_{31}^2 \right| \cdot \frac{L}{4E} \right)$$

- no δ_{CP} dependence
- matter effect negligible

$$\Delta m_{31}^2 \equiv \begin{cases} m_3^2 - m_1^2 > 0 \text{ (NH)} \\ m_3^2 - m_1^2 < 0 \text{ (IH)} \end{cases}$$

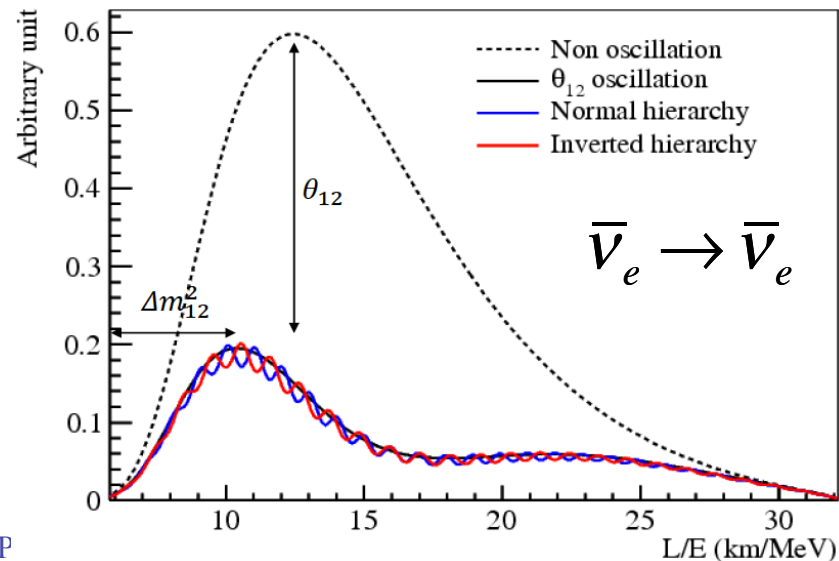
Shift in energy spectrum of $\sim$

$$\Delta m_{21}^2 / \Delta m_{31}^2 \sim 3\%$$



An energy resolution of $\sim 3\%$

(for $E \sim 1$ MeV) is needed

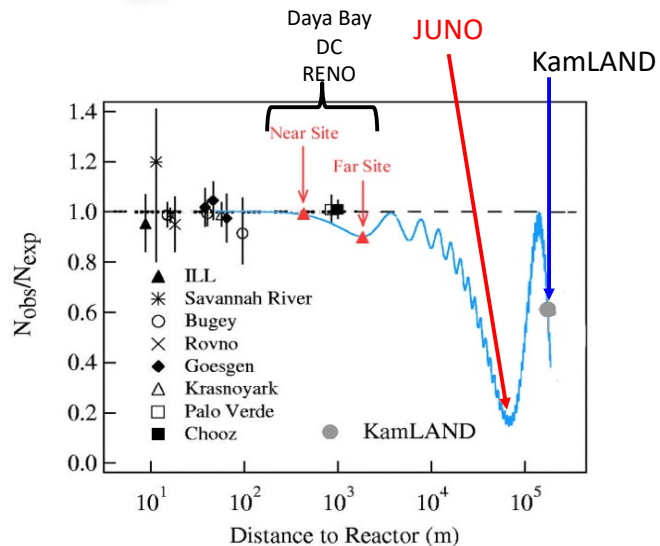


JUNO

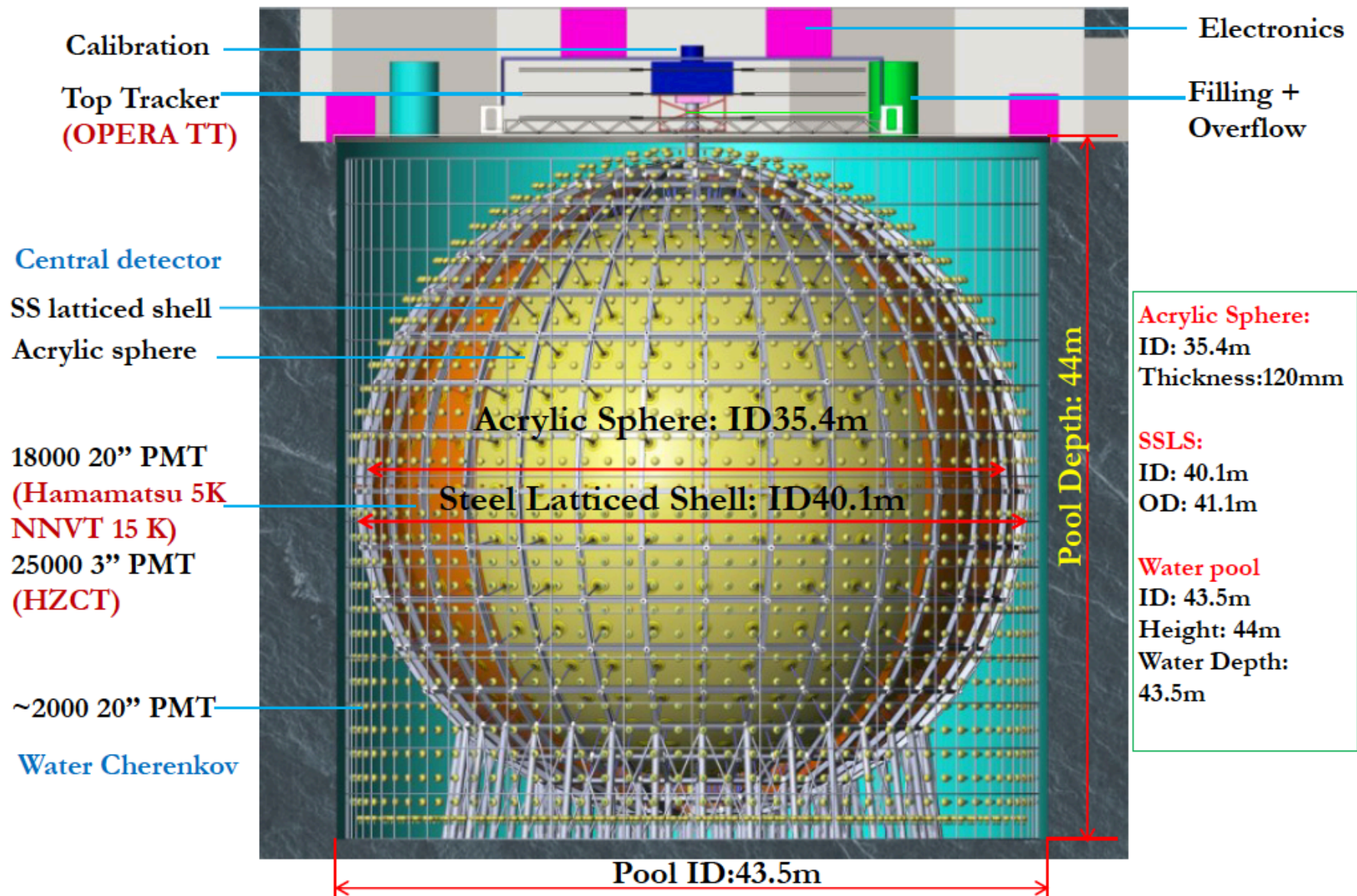
(Jiangmen Underground Neutrino Observatory)

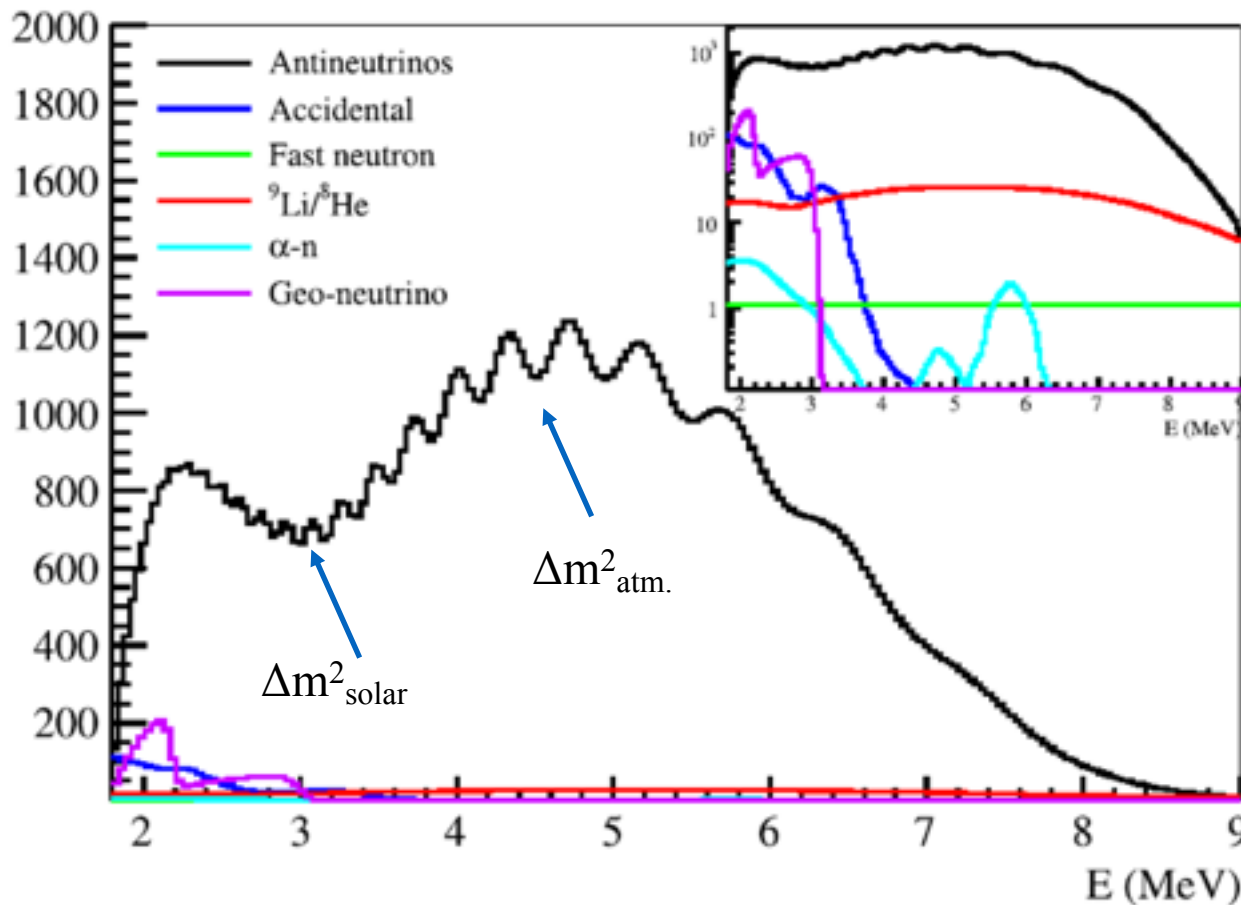


- Very rich physics program:
 - Reactor neutrinos
 - mass hierarchy
 - precise measurement of the oscillation parameters
 - Supernovæ neutrinos
 - Geo-neutrinos
 - Solar Neutrinos
 - Atmospheric neutrinos



	Current	JUNO
Δm^2_{21}	$\sim 2.3\%$	$\sim 0.6\%$
Δm^2_{13}	$\sim 4\%$	$\sim 0.5\%$
$\sin^2\theta_{12}$	$\sim 6\%$	$\sim 0.7\%$

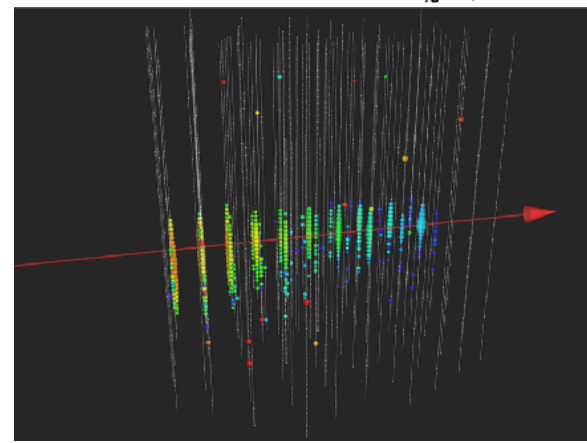
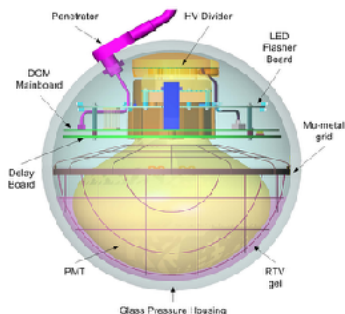
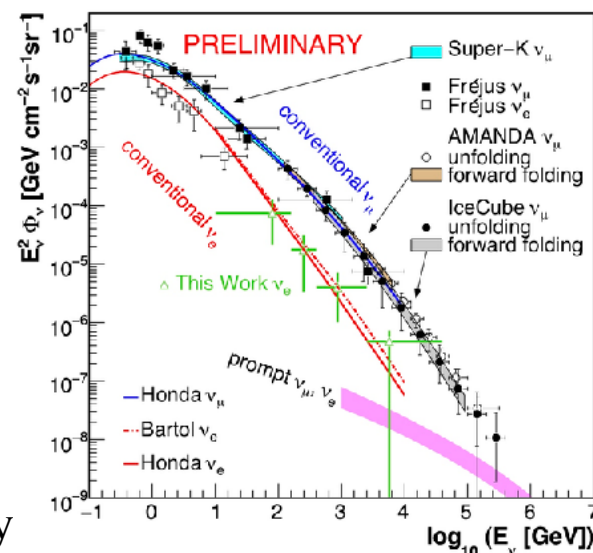
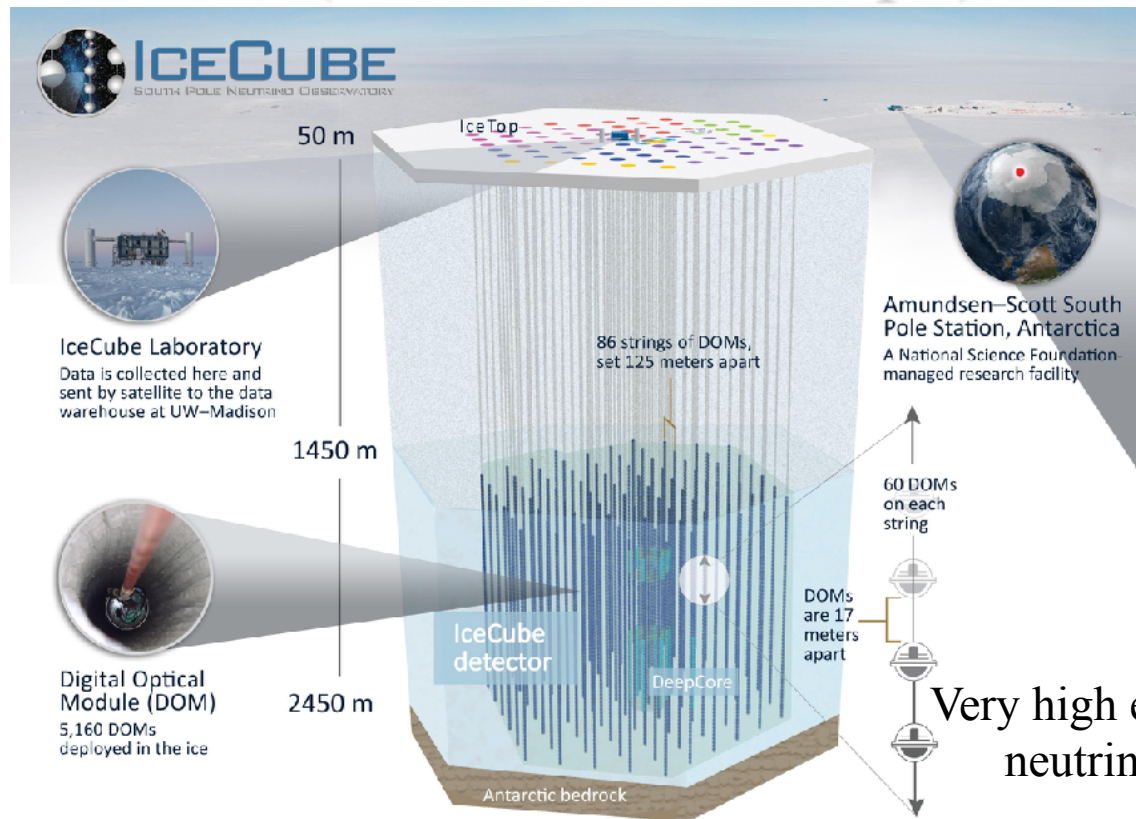




(JUNO Yellow Book; J. of Phys. G: Nucl. Part. Phys. 43 (2016) 030401)

$$\frac{\sigma_E}{E}(\%) \sim \sqrt{0.7^2 + \frac{2.6^2}{E} + \frac{0.85^2}{E^2}}$$

IceCube (neutrino telescope)

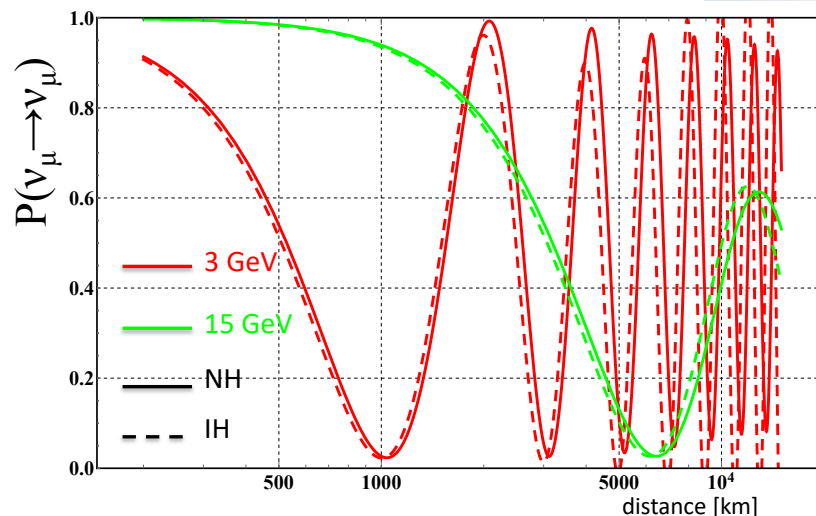
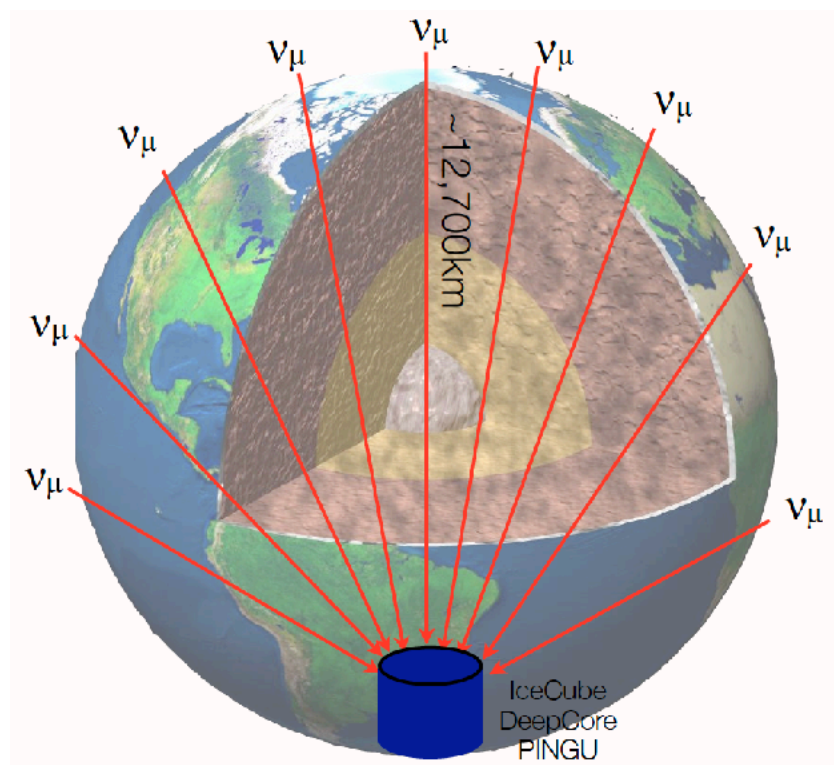


IceCube/PINGU

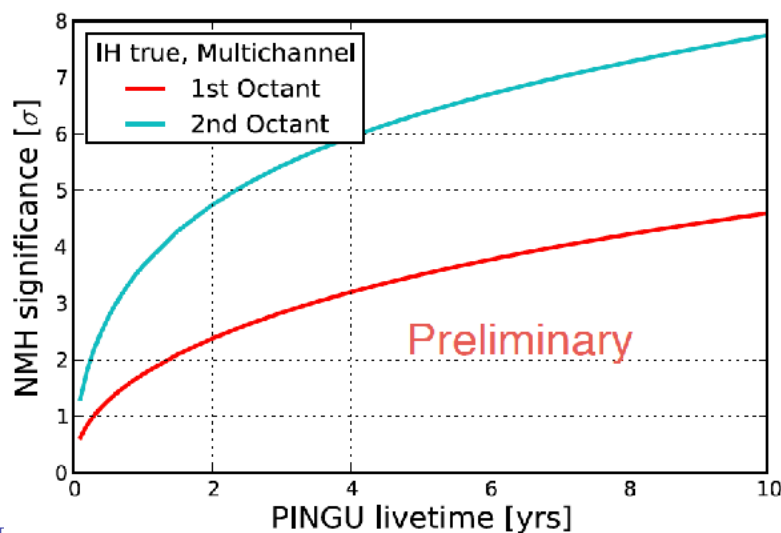
(Precision IceCube Next Generation Upgrade)



Neutrino mass hierarchy using
atmospheric neutrinos

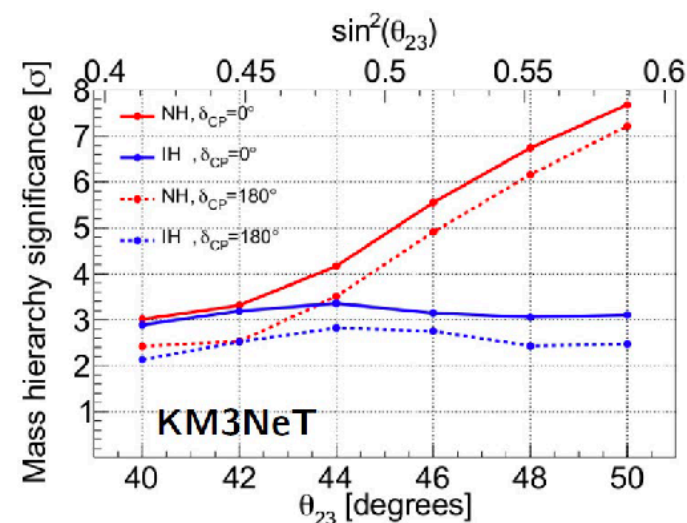
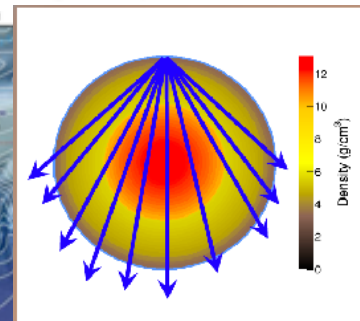
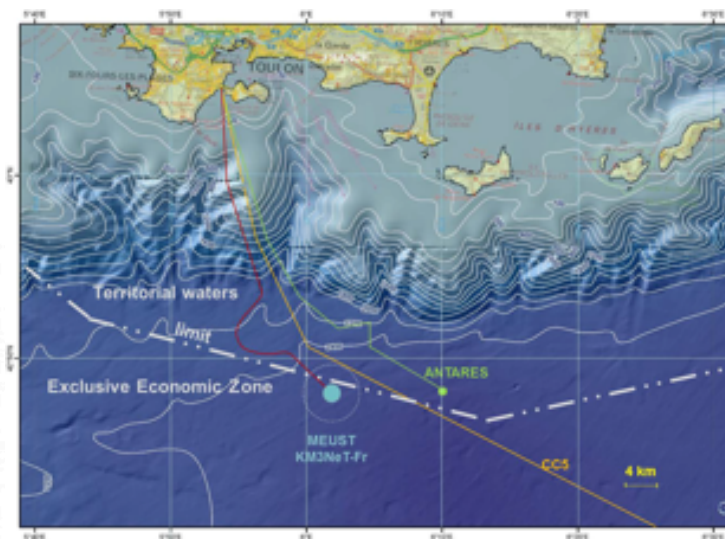
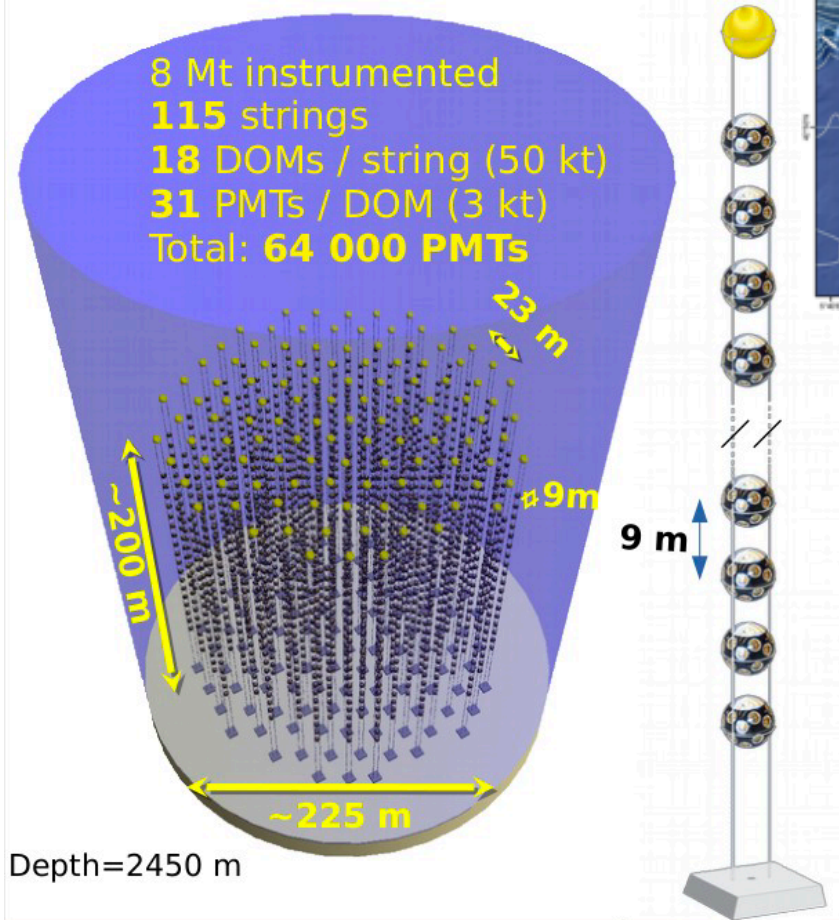


Using neutrinos from 3-15 GeV



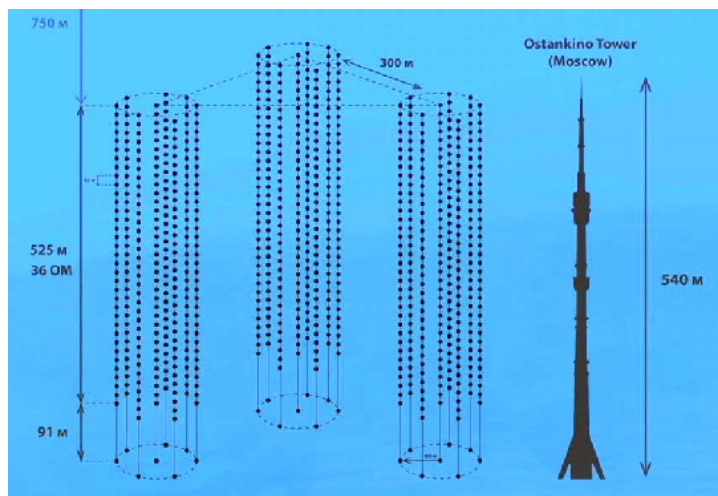
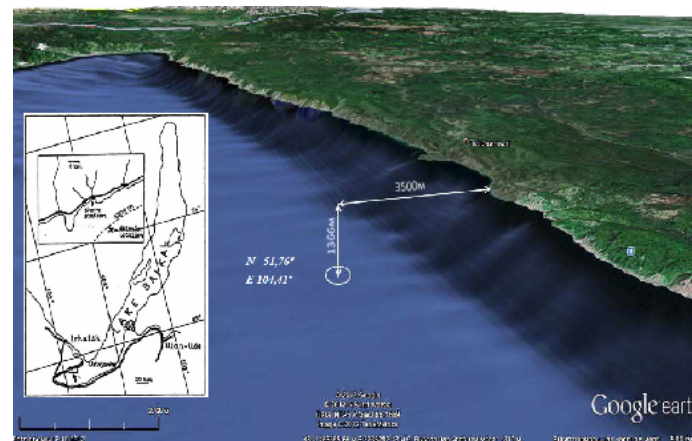
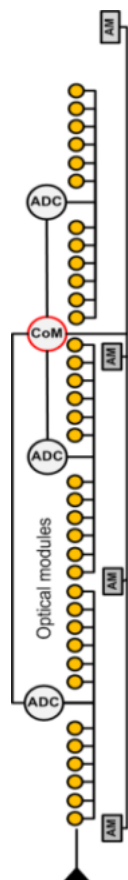
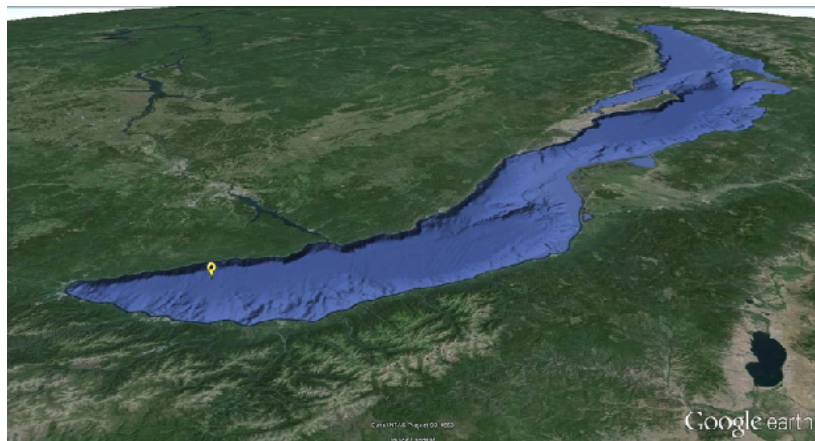


- MH with atm. ν
- partially approved



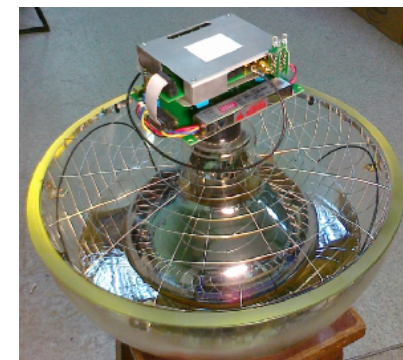
Baikal-GVD

(Gigaton Volume Detector in Lake Baikal)



Year	2016	2017	2018	2019	2020	2021
Nb. of clusters	1	2	3	5	7	9
Nb. of OMs	288	576	864	1440	2016	2592

3D array, 10^4 photodetectors
Eff. volume $\sim 1.5 \text{ km}^3$



PINGU/JUNO combination

