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La hiérarchie de masse des neutrinos

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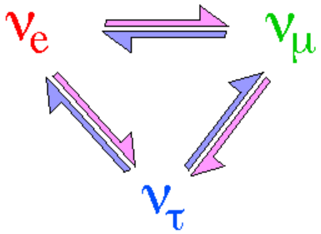
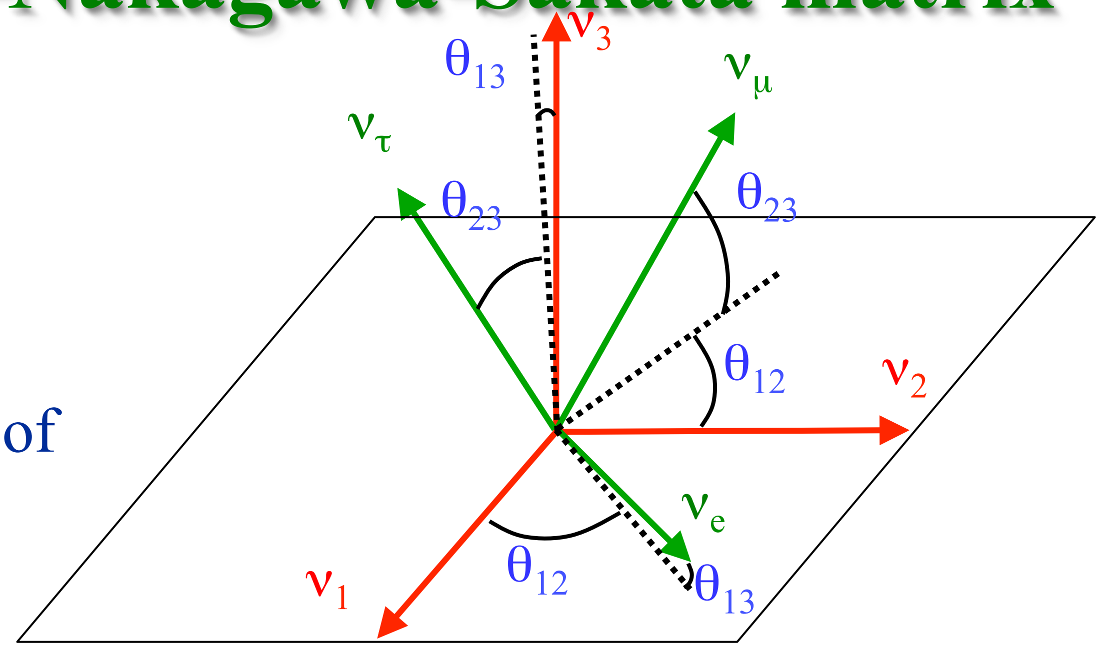
Outline

ν

- Neutrino Oscillation formalism
- Measurement of the last mixing angle θ_{13} and importance for mass hierarchy determination and CP Violation discovery
- Neutrino mass hierarchy
  - Present neutrino oscillation experiments
  - Future projects
- Conclusion

Pontecorvo-Maki-Nakagawa-Sakata matrix





Usual parametrization (in case of Dirac neutrinos):

$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \qquad \text{with } c_{ij} = \cos\theta_{ij} \; and \; s_{ij} = \sin\theta_{ij}$$

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

atmospheric,
accelerators

reactors,
accelerators
CP violation

solar,
reactors

- δ_{CP} for neutrinos
- $-\delta_{CP}$ for anti-neutrinos

How neutrinos propagate through vacuum?

For 3 neutrinos with a well defined mass and energy:

Schrödinger equation:

(H: Hamiltonian)

$$i\frac{d}{dt}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} = H\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

for the mass eigen states

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H_f\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

for the flavour eigen states

$$\left|\nu_j(t)\right\rangle = e^{-iHt/\hbar}\left|\nu_j(0)\right\rangle$$

Solutions of Schrödinger equation

with: $$H_f = UHU^\dagger$$

$$H = \begin{pmatrix} m_1^2 & 0 & 0\\ 0 & m_2^2 & 0\\ 0 & 0 & m_3^2\end{pmatrix}$$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}}_{\text{unitary mixing matrix}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Probability as a function of mixing angles

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\Phi_{ij} + 2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin 2\Phi_{ij}$$

$$\Phi_{ij} = \frac{\Delta m^2_{ij} L}{4E} = 1.27\,\Delta m^2_{ij}\left(\frac{L}{E}\right)$$ (L in km, E in GeV, Δm in eV and $\hbar$c=197 MeV fm)

$\boxed{\Delta m^2_{ij} = m^2_j - m^2_i}$ (3 mass differences but only 2 are independent)

if this term $\neq 0$

To obtain: $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$ CP transformation

replace: $U \to U^*$

or: $\Phi_{ij} \to -\Phi_{ij}$

if: $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

CP violation
(never observed up
to now)

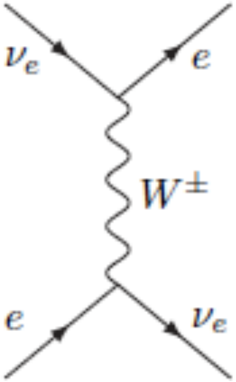
How neutrinos propagate through matter?

(Mikheyev-Smirnov-Wolfenstein effect)

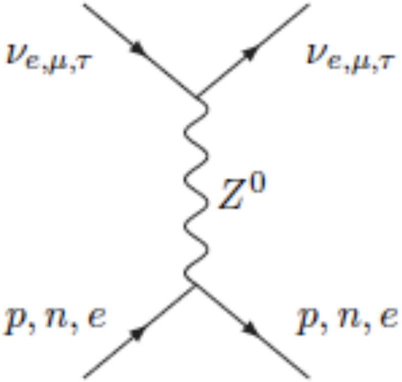
$$\left|\nu_j(t)\right\rangle = e^{-iHt/\hbar}\left|\nu_j(0)\right\rangle$$

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H_f\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

only for electron neutrinos



CC



NC

in "ordinary" matter

$$H_f = UHU^\dagger = \frac{1}{2E}U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{pmatrix}U^\dagger \rightarrow \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m_{21}^2 & 0\\ 0 & 0 & \Delta m_{31}^2\end{pmatrix}U^\dagger + \begin{pmatrix}a & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]$$

with: $a = 2EV_{CC} = 2\sqrt{2}EG_F N_e \approx 7.56\times10^{-5}\,eV^2\left(\frac{\rho}{g/cm^3}\right)\left(\frac{E}{GeV}\right)$

($\rho \sim 3\ g/cm^3$ for earth crust)

Present measurements

$$\theta_{12} = 33.5 \pm 0.8^\circ$$

$$\Delta m^2_{21} = (7.50 \pm 0.19) \times 10^{-5}\ \mathrm{eV}^2$$

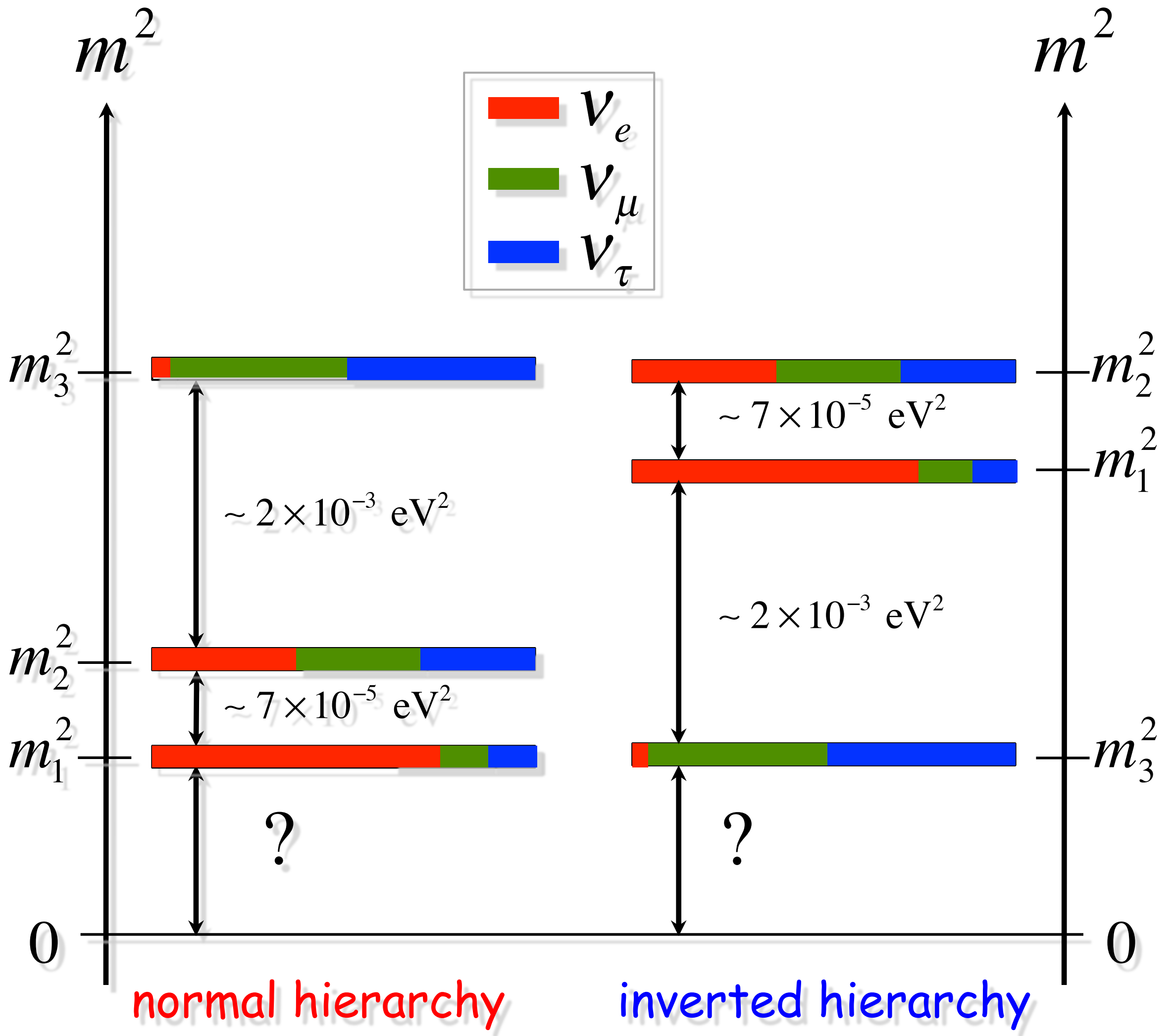
$$\theta_{23} = 42.3^{+3.0}_{-1.6} \text{ or } 49.5^{+1.5}_{-2.2} \text{ deg}.$$

$$\left|\Delta m^2_{31}\right| = (2.46 \pm^{+0.05}_{-0.05}) \times 10^{-3}\ \mathrm{eV}^2$$

[(JHEP 11 (2014) 052 [arXiv:1409.5439])]

$\theta_{13} < 12.4^\circ$, 90% CL
up to recently

~(almost) no information on δ_{CP}



Oscillation probability

(neutrino beams)

$$
\begin{aligned}
P_{\nu_\mu\to\nu_e(\overline{\nu_\mu}\to\overline{\nu_e})} \simeq\ & 4 s_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2}\sin^2\frac{(1-r_A)\Delta L}{2} && \text{"atmospheric"}\\
& +8 J_r \frac{r_\Delta}{r_A(1-r_A)}\cos\left(\delta_{CP}-\frac{\Delta L}{2}\right)\sin\frac{r_A\Delta L}{2}\sin\frac{(1-r_A)\Delta L}{2} && \text{"interference"}\\
& +4 c_{23}^2 c_{12}^2 s_{12}^2\left(\frac{r_\Delta}{r_A}\right)^2\sin^2\frac{r_A\Delta L}{2} && \text{"solar"}
\end{aligned}
$$

$$
J_r \equiv c_{12}s_{12}c_{23}s_{23}s_{13},\ \Delta \equiv \frac{\Delta m_{31}^2}{2E_\nu},\ r_A \equiv \frac{a}{\Delta m_{31}^2},\ r_\Delta \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2},\ a = 2\sqrt{2}G_F N_e E_\nu
$$

matter effect

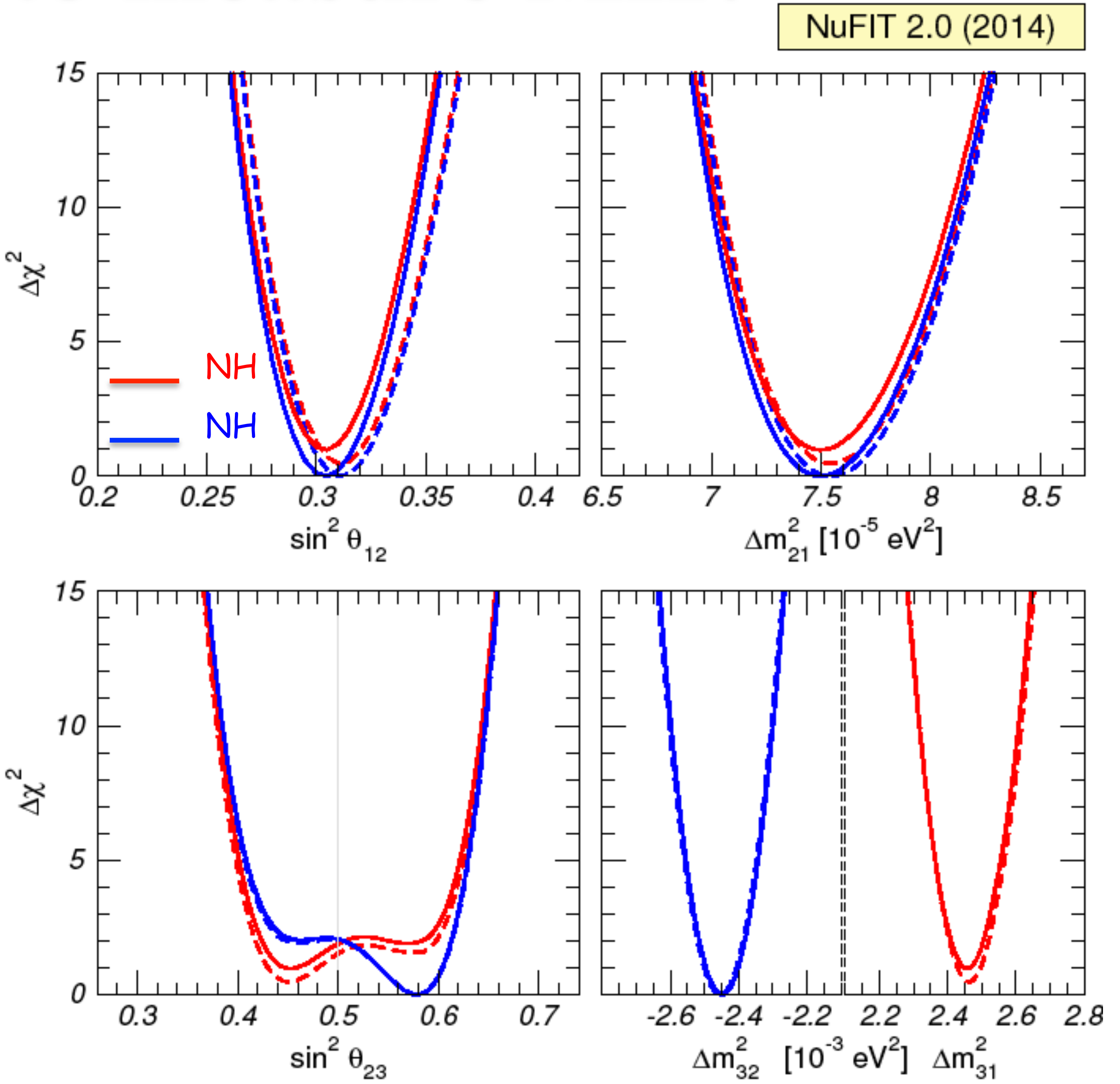
- for antimatter: $\delta_{CP} \to -\delta_{CP}$ and $a \to -a$
- fake matter/antimatter asymetry due to matter effect
- for NH: $\Delta m_{31}^2 \to |\Delta m_{31}^2|$
- for IH: $\Delta m_{31}^2 \to -|\Delta m_{31}^2|$

- δ_{CP} dependence,
- sizable matter effect for long baselines

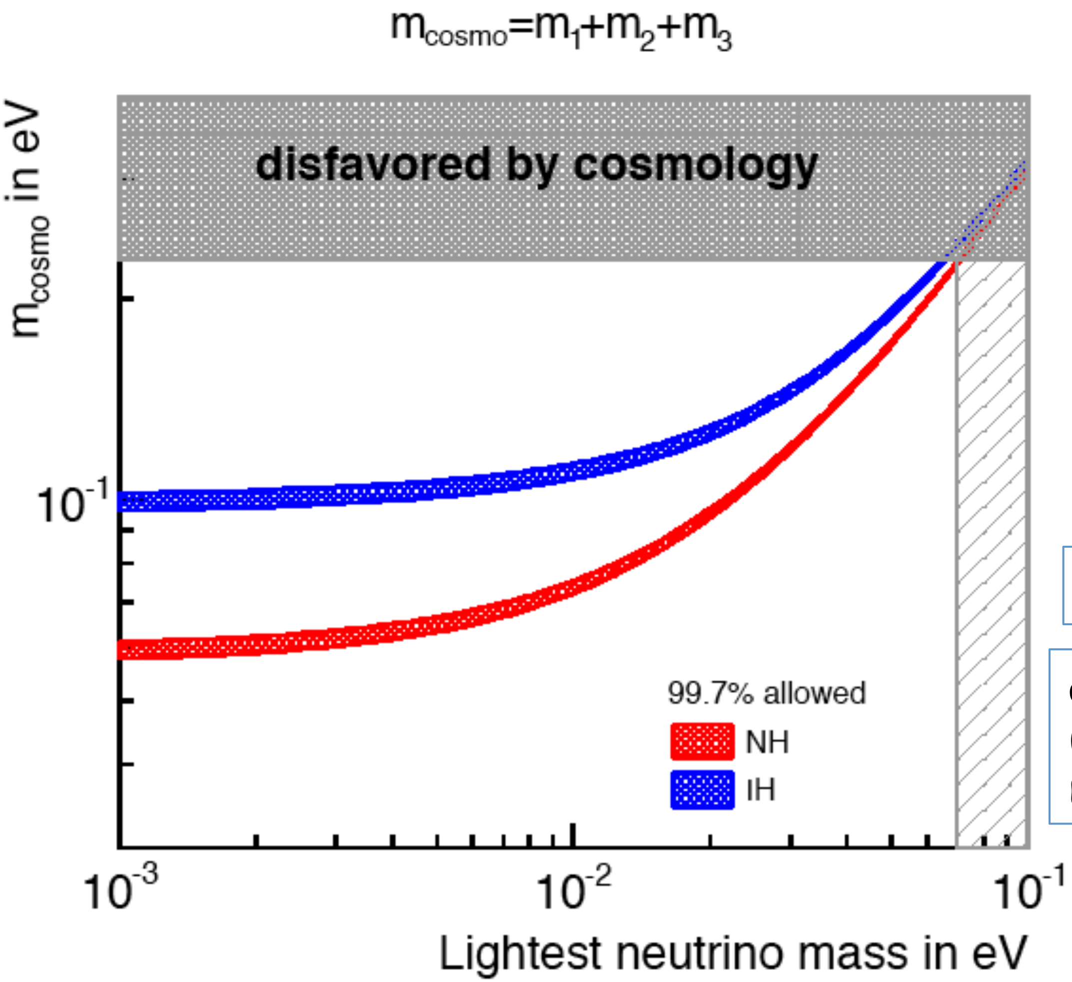
if $\theta_{13}\sim 0$ → oscillation probability not sensitive to δ_{CP} → impossible to observe CP violation in the leptonic sector.

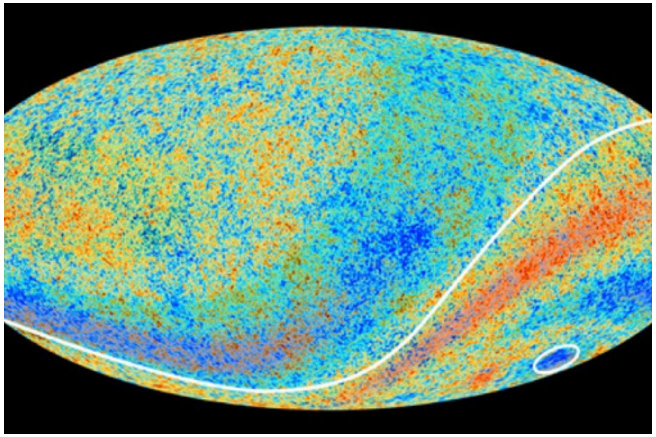
Why to measure MH?

- 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





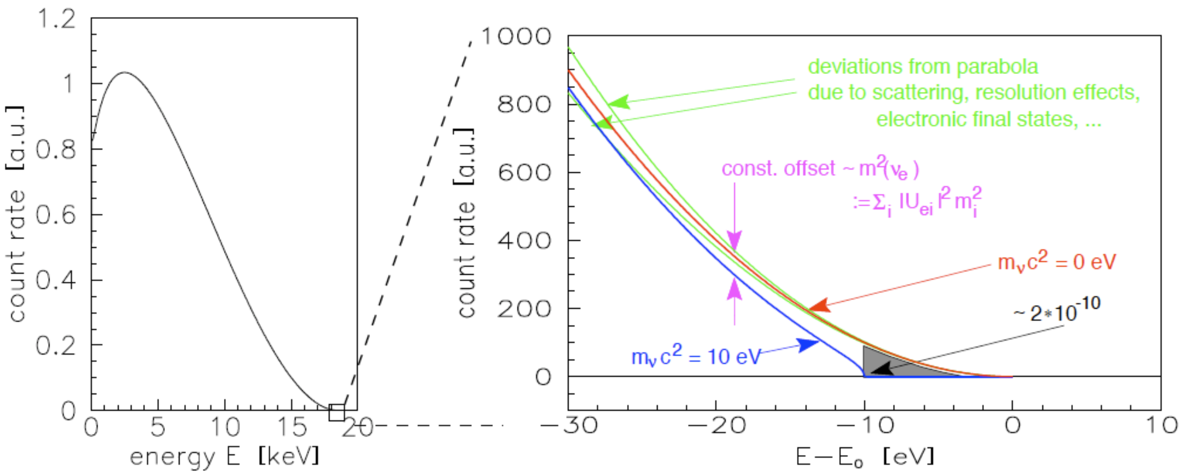
from cosmology

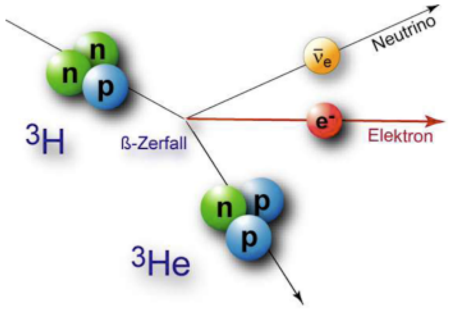
if $m_{cosmo} < 0.1$ eV ⇒ NH

arXiv:1505.01891
(3 σ uncertainty on all
mixing parameters)

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

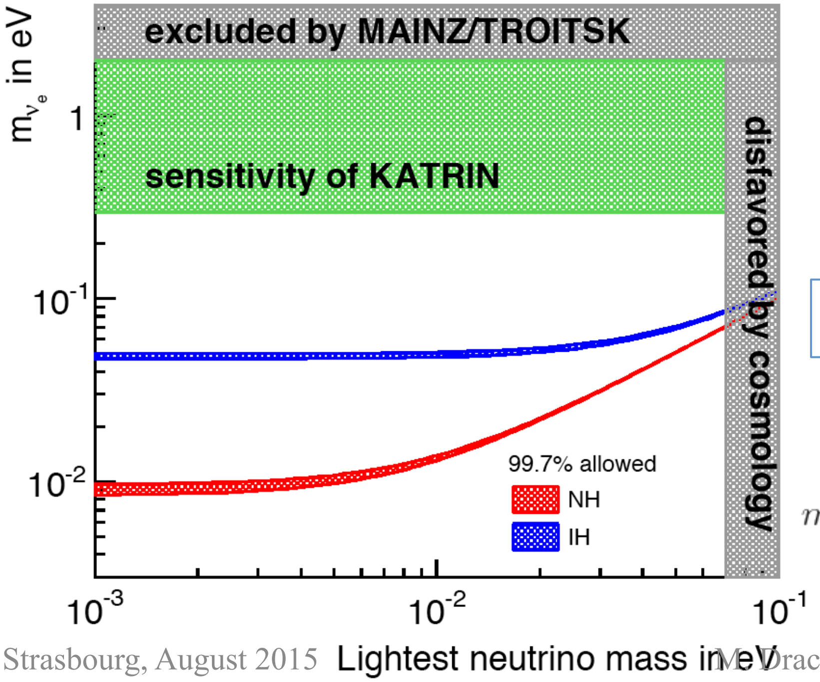
MH and direct neutrino mass measurements





$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$

$m_{\nu_e} = \sqrt{|U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2}$



from direct mass measurements

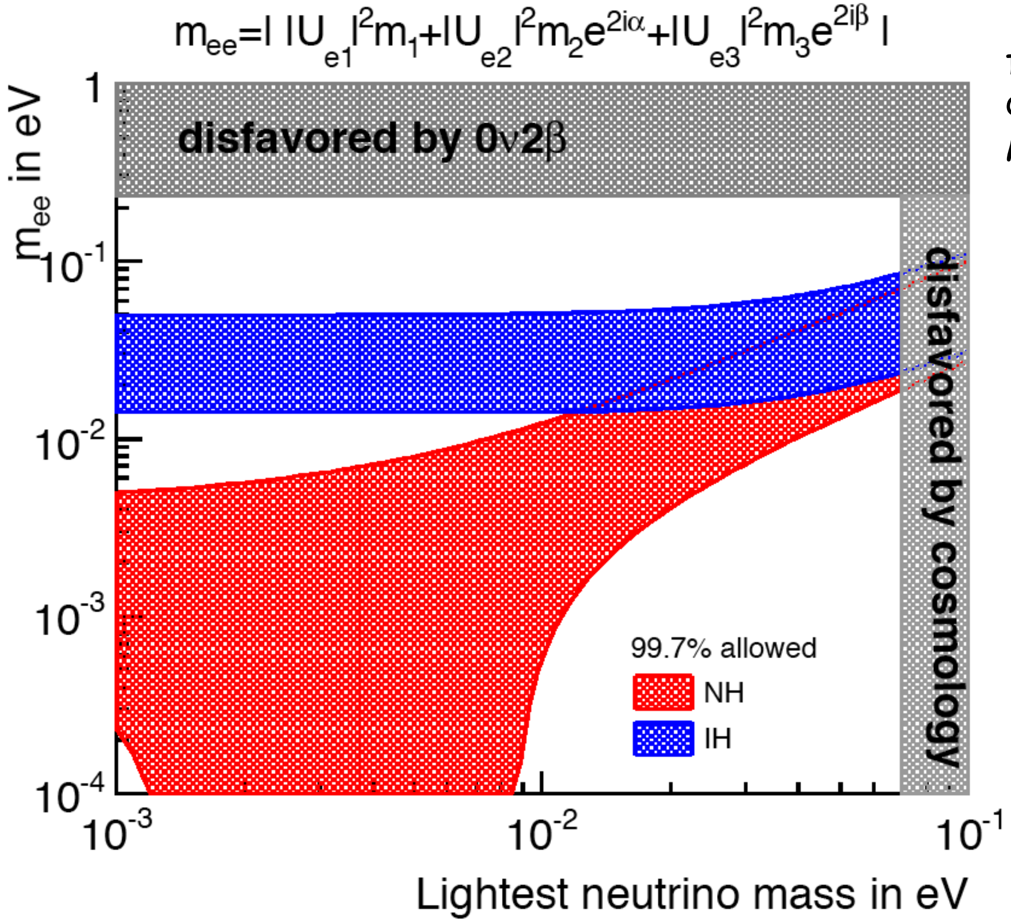
if $m_{\nu e} < 0.05$ eV ⇒ NH

arXiv:1505.01891

$$m_{\nu_e} = \begin{cases} \sqrt{m_L^2 + c_{13}^2 s_{12}^2 \Delta m_{21}^2 + s_{13}^2 |\Delta m_{31}^2|} & \text{(Normal Hierarchy)} \\ \sqrt{m_L^2 + c_{13}^2 c_{12}^2 |\Delta m_{31}^2| + c_{13}^2 s_{12}^2 |\Delta m_{32}^2|} & \text{(Inverted Hierarchy)} \end{cases}$$

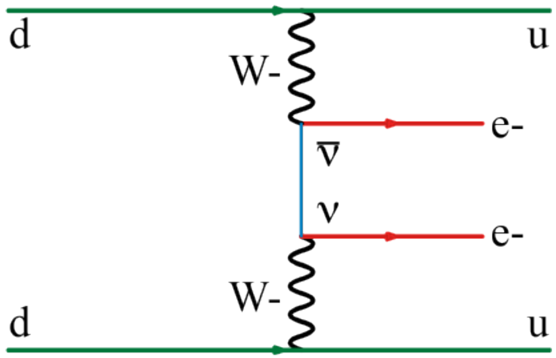
MH and neutrinoless Double Beta Decay

arXiv:1505.01891



$m_{ee}=|\,|U_{e1}|^2 m_1+|U_{e2}|^2 m_2 e^{2i\alpha}+|U_{e3}|^2 m_3 e^{2i\beta}\,|$

from double beta decay (Dirac or Majorana particles)



- if m_{ee} > 0.015 eV ⇒ IH ⇒ future Double Beta Decay experiments could observe neutrinoless DBD (Majorana neutrinos)
- else, if NH, hard time for DBD experiments.

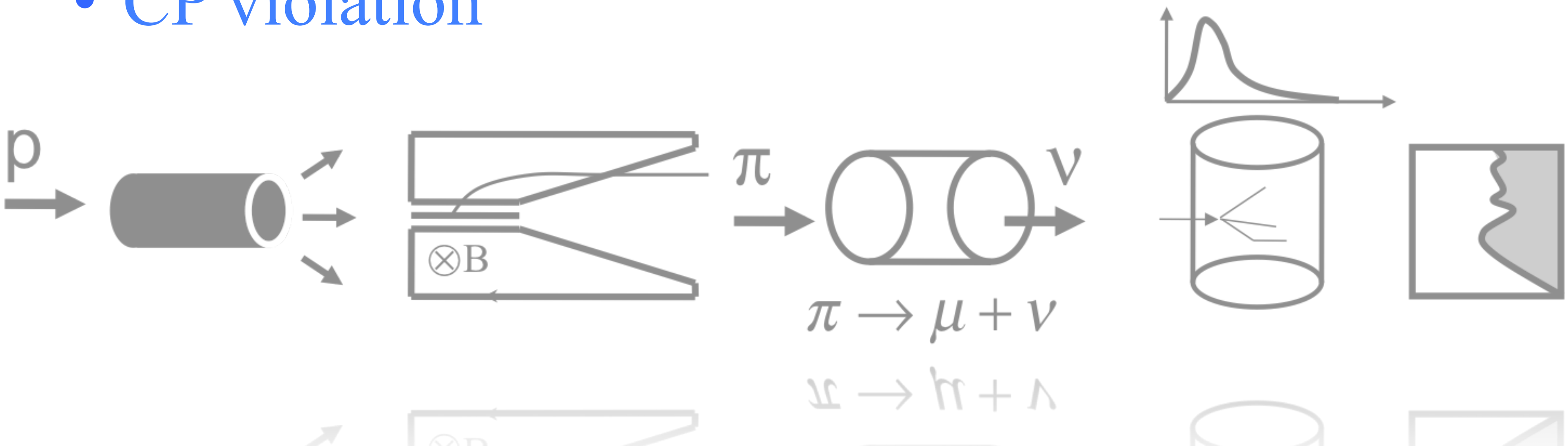
$$m_{ee}^2=\begin{cases}(c_{12}^2c_{13}^2m_L+c_{13}^2s_{12}^2\sqrt{m_L^2+\Delta m_{21}^2}\cos 2\alpha+s_{13}^2\sqrt{m_L^2+|\Delta m_{31}^2|}\cos 2\beta)^2+ & \\ (c_{13}^2s_{12}^2\sqrt{m_L^2+\Delta m_{21}^2}\sin 2\alpha+s_{13}^2\sqrt{m_L^2+|\Delta m_{31}^2|}\sin 2\beta)^2 & \text{(Normal Hierarchy)}\\ (c_{12}^2c_{13}^2\sqrt{m_L^2+|\Delta m_{31}^2|}+c_{13}^2s_{12}^2\sqrt{m_L^2+|\Delta m_{31}^2|}\cos 2\alpha+s_{13}^2m_L\cos 2\beta)^2+ & \\ (c_{13}^2s_{12}^2\sqrt{m_L^2+|\Delta m_{31}^2|}\sin 2\alpha+s_{13}^2m_L\sin 2\beta)^2 & \text{(Inverted Hierarchy)}\end{cases}$$

θ_{13} hunting…

(up to ~2012)

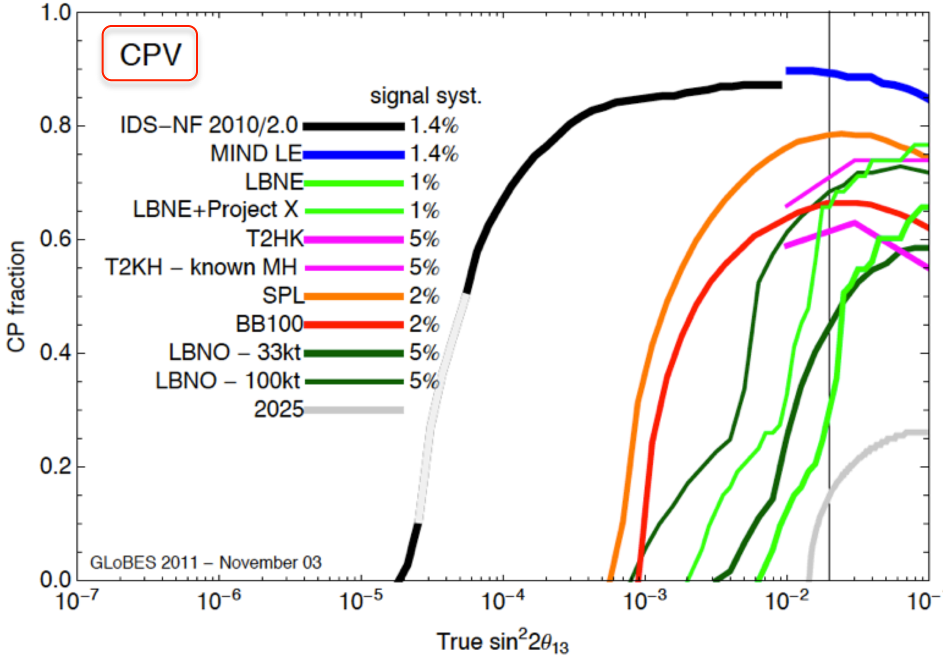
New proposals for neutrino beams to measure:

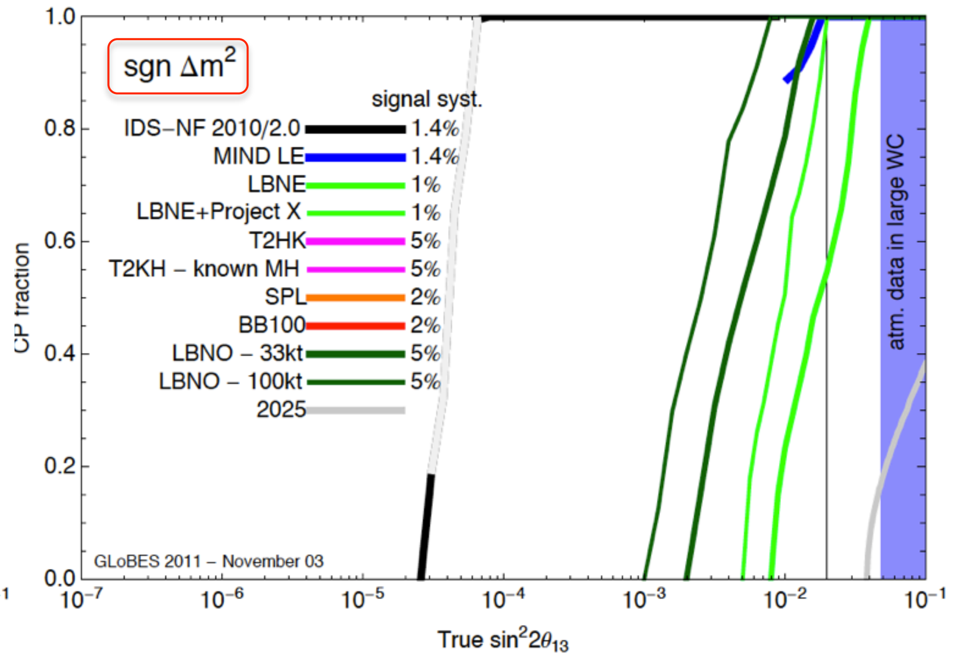
- θ_{13} (as low as possible)
- neutrino mass hierarchy (sign of Δm^2_{13})
- CP violation



(Super Beams, Beta Beams, Neutrino Factory…)

Project Comparison (unknown θ_{13})

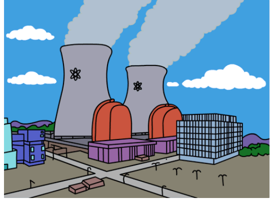




name	baseline	type	mass	power	sec. in year	years	sig. syst.
LBNE	1300	WC/LAr	200/33	0.7MW	2×10^7	5+5	1%
LBNE+ Pro. X	1300	WC/LAr	200/33	2.3MW	2×10^7	5+5	1%
LBNO 33kt	2300	LAr	33	1.7MW	1.7×10^7	5+5	5%
LBNO 100kt	2300	LAr	100	1.7MW	1.7×10^7	5+5	5%
T2HK	295	WC	560	1.66MW	1×10^7	2.1+2.9	5%
SPL	130	WC	440	4MW	1×10^7	2+8	2%
BB100	130	WC	440	1.1×10^{18} Ne 2.9×10^{18} He	1×10^7	5+5	2%
IDS-NF 2.0	4000+7500	MIND	100+50	4MW	1×10^7	5+5	1.4%
MIND LE	2000	MIND	100	4MW	1×10^7	5+5	1.4%

landscape up to 2011

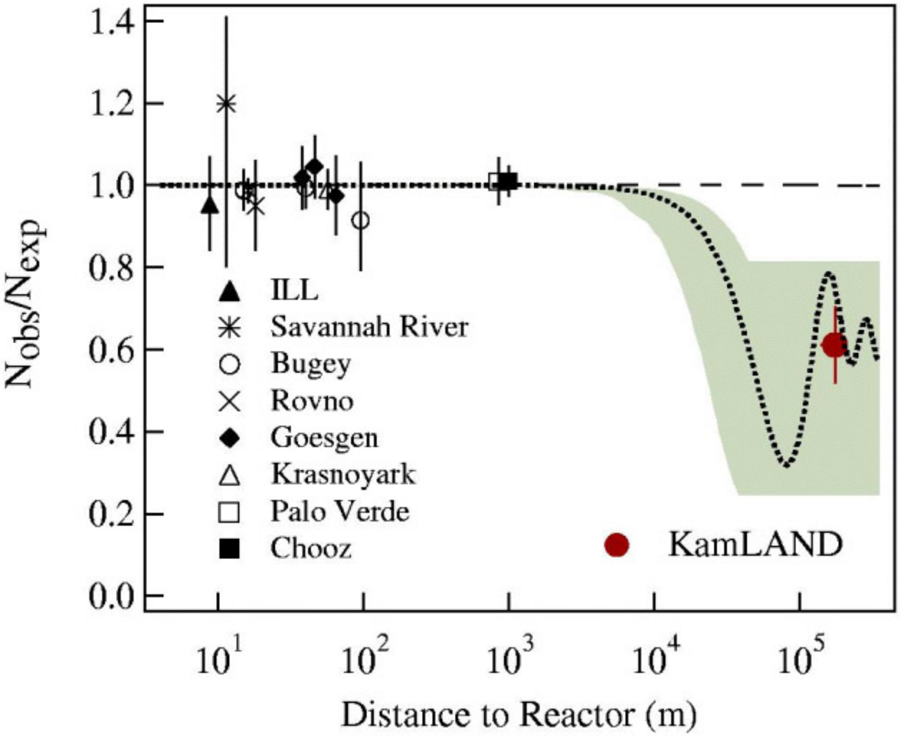
the game:
go as low as possible on θ_{13}

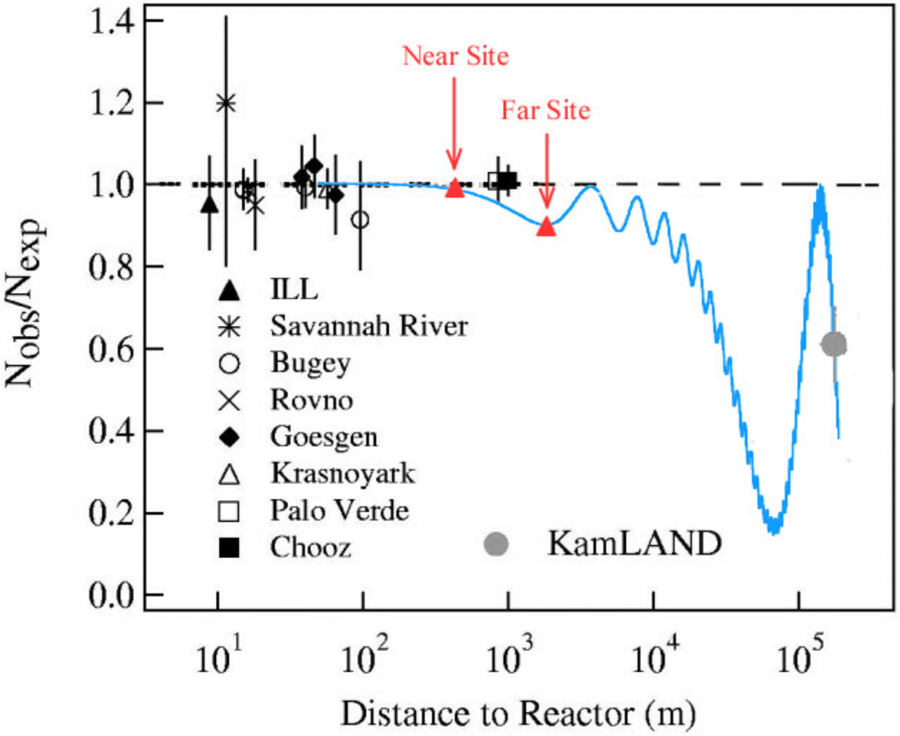


The θ_{13} hunting

(meanwhile, reactor neutrinos)

disappearance of electron anti-neutrinos

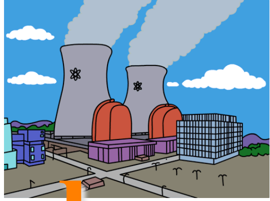


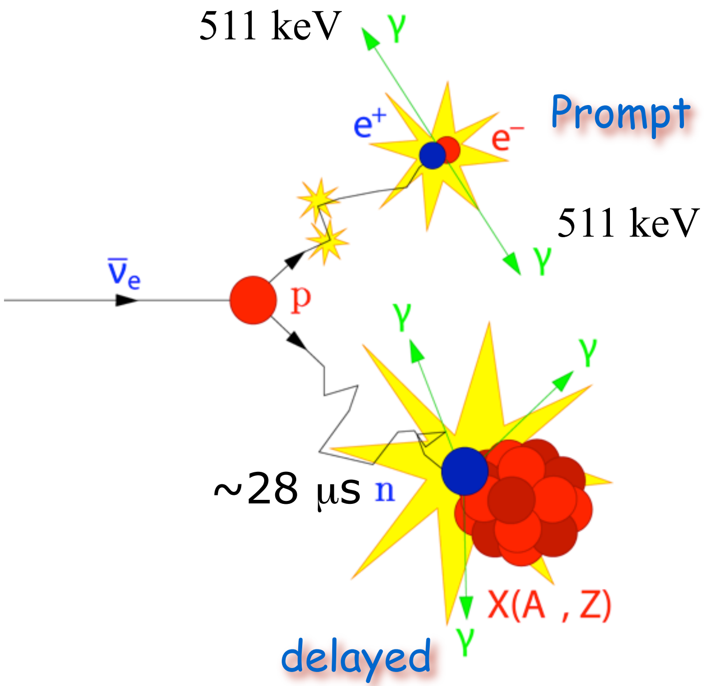


Actually, we have almost neglected θ_{13} on this figure

For $\theta_{13} \sim 10°$

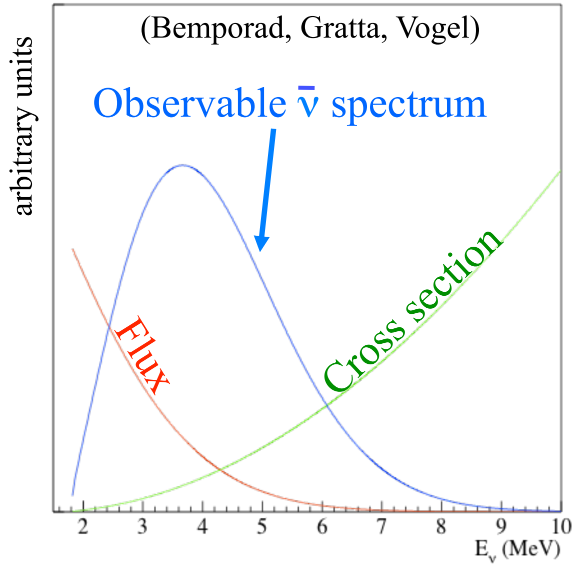
Inverse β decay and reactor neutrino detection mode





$$P\left(\overline{\nu}_e \to \overline{\nu}_e\right) \simeq 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2 \frac{\Delta m_{21}^2 L}{4E} - \sin^2 2\theta_{13}\left[c_{12}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} + s_{12}^2 \sin^2 \frac{\Delta m_{32}^2 L}{4E}\right]$$

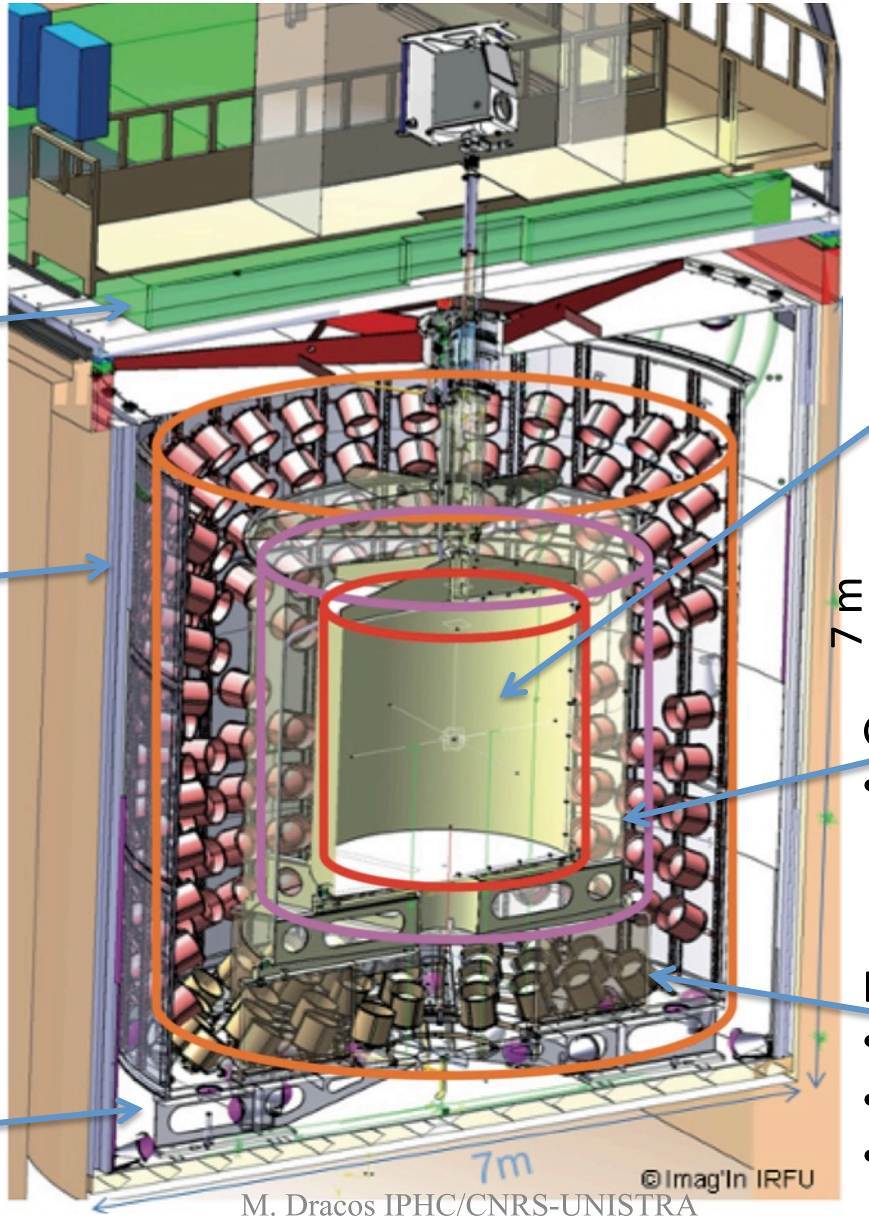
- no δ_{CP} dependence
- matter effect negligible



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

$$3\text{ GW} \approx 2\times10^{21}\text{ MeV/s} \to 6\times10^{20}\ \nu_e\text{/s}$$

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

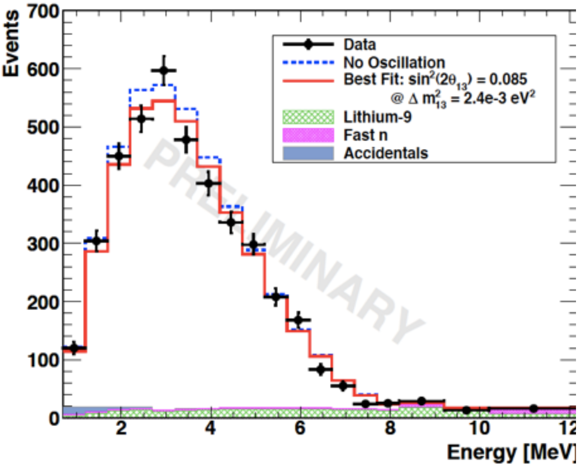
Gamma Catcher (e=0.55 m)
- scintillator

Buffer (e=1.05 m)
- steel (3 mm)
- 80 tons "oil"
- 390 PMTs (10")

θ_{13} is large!!!

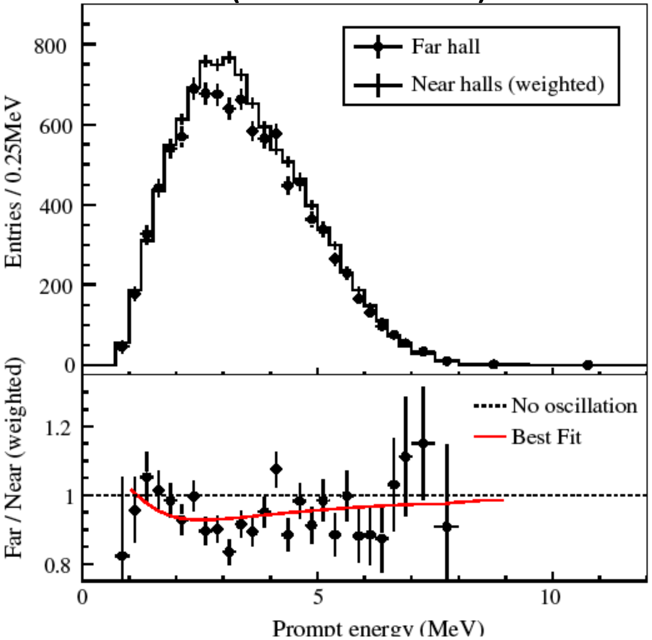
reactor experiments discovery
of the 1→3 oscillation

Double Chooz
with only a far detector
(Nov. 2011)



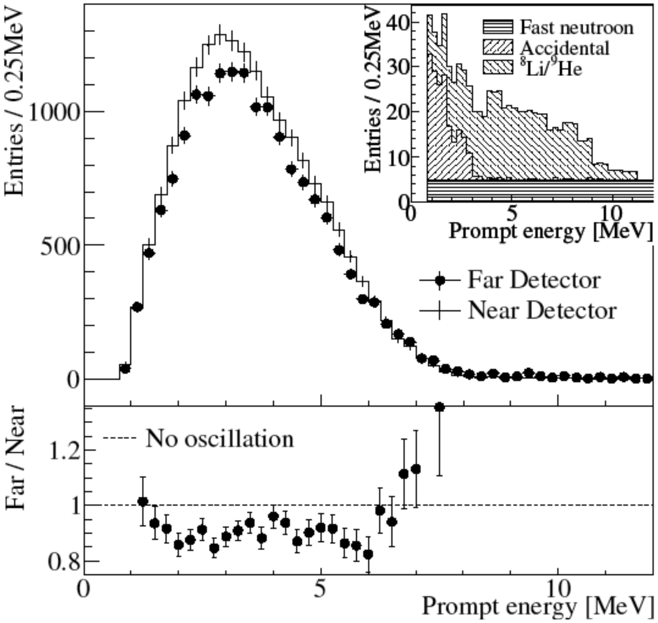
$\sin^2(2\theta_{13})$=0.085±0.029(stat)±0.042(syst)

Daya Bay
(March 2012)



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

RENO
(April 2012)



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

θ_{13}>0 (C.L. > 5 σ) → proposed LBL beam facilities had to be readjusted…
now, the name of the game is MH and CPV

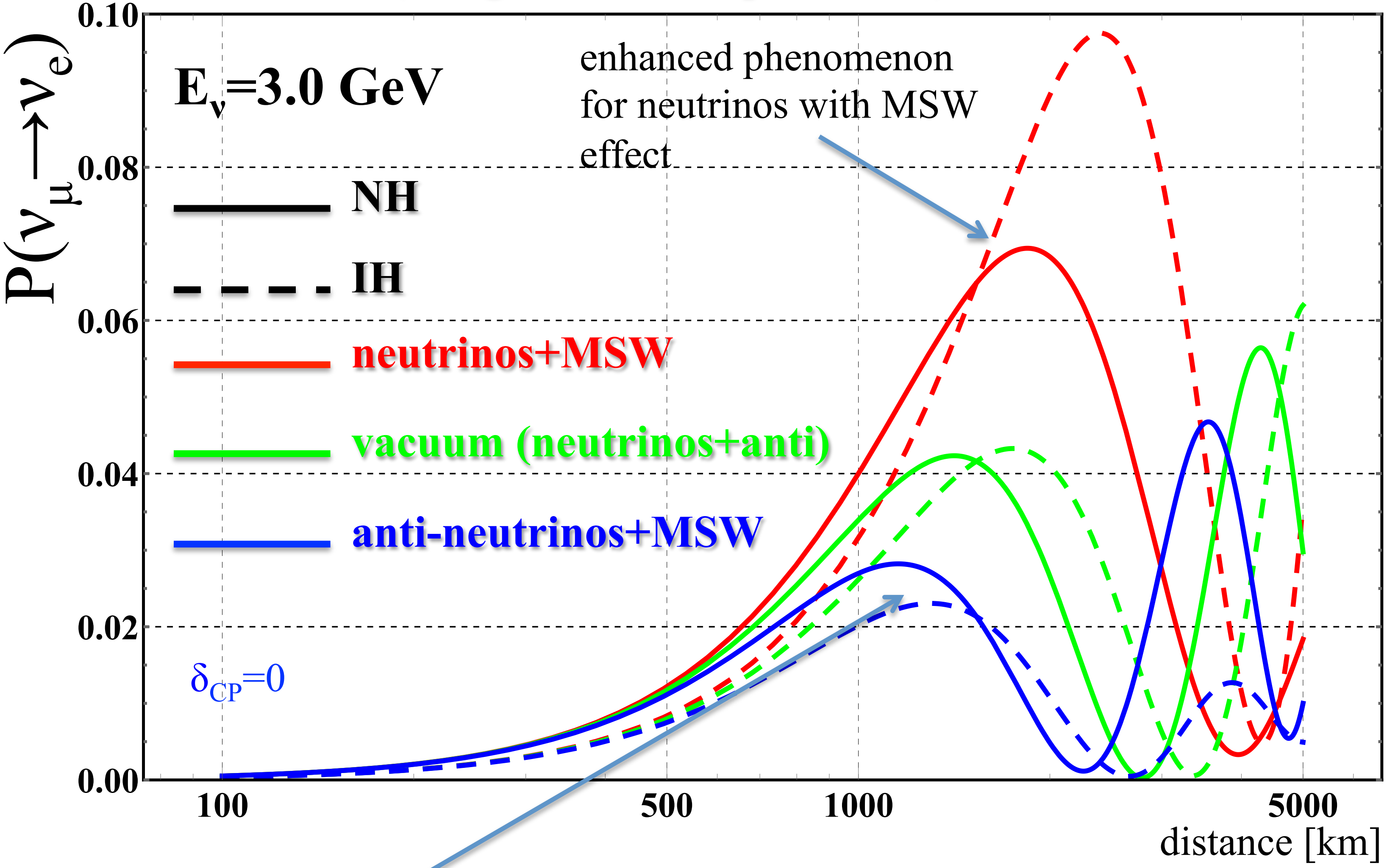
Next steps…

The door is now open for Mass Hierarchy measurement and CP Violation discovery

but, how steep is the slope?

Oscillation probability

(Long Baseline Experiments)



enhanced phenomenon for neutrinos with MSW effect

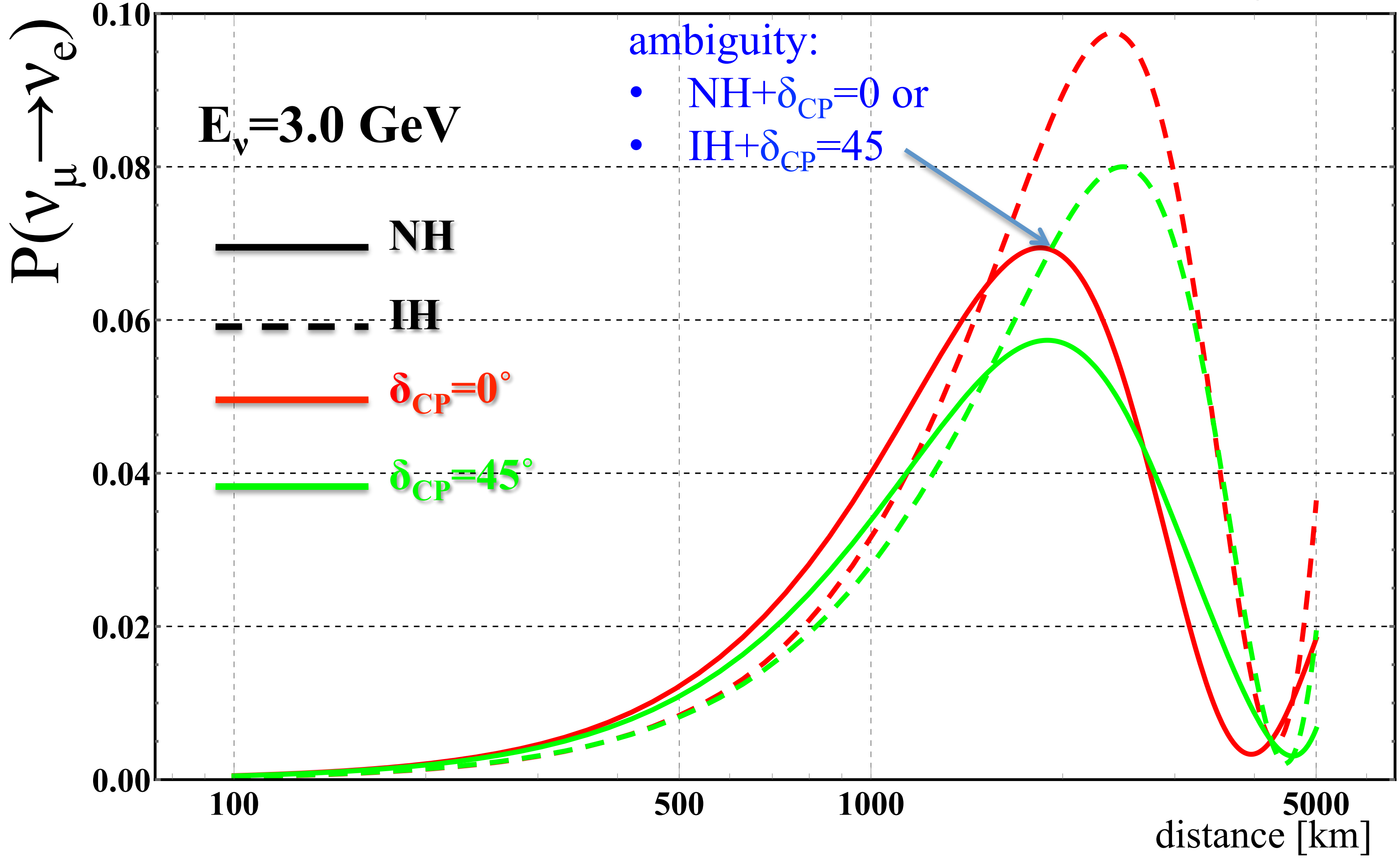
opposite phenomenon for anti-neutrinos

compare neutrino and anti-neutrino oscillations

MSW effect helps to find the right MH

Oscillation probability
(in matter)

be careful with ambiguities

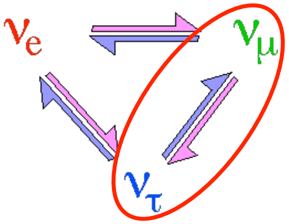


ambiguity:

- NH+δ_{CP}=0 or
- IH+δ_{CP}=45

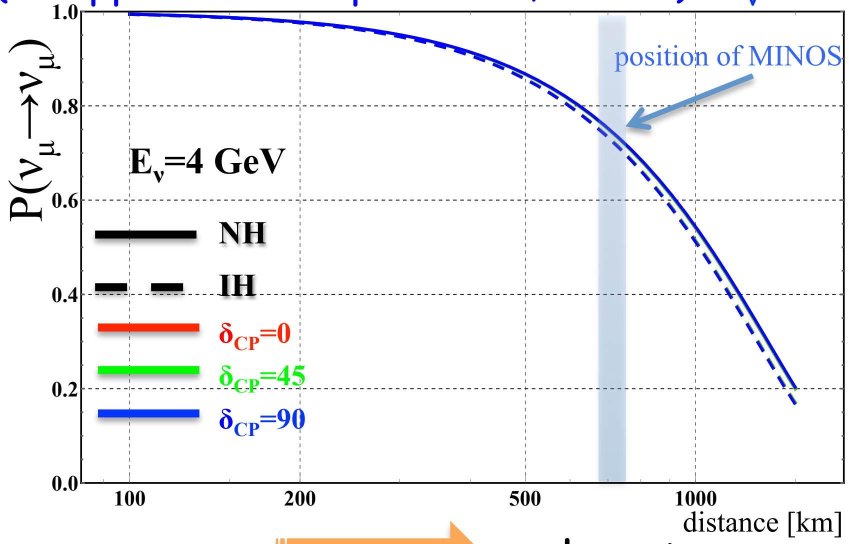
Present accelerator neutrino oscillation facilities

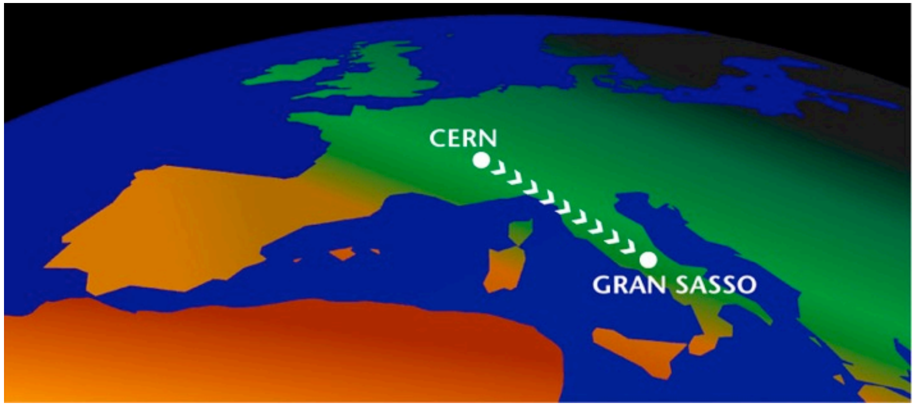
(long baseline)



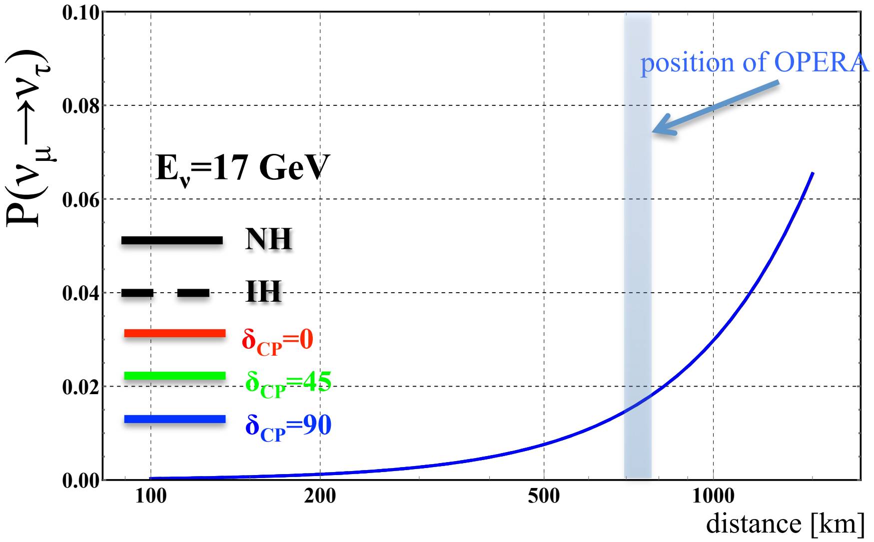
L~732 km

NUMI beam and MINOS experiment (disappearance experiment, 2005-) $\langle E_\nu \rangle$~4 GeV





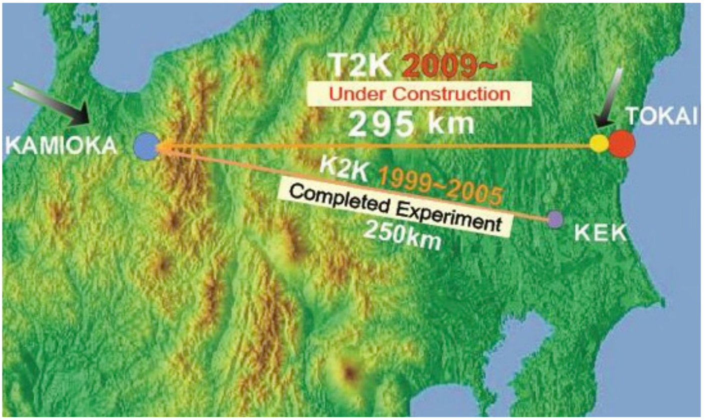
CNGS beam and OPERA (ICARUS) experiment ($\nu_\mu \to \nu_\tau$ appearance experiment, 2008-2012) $\langle E_\nu \rangle$~17 GeV

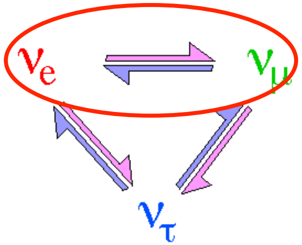


almost no sensitivity to mass hierarchy

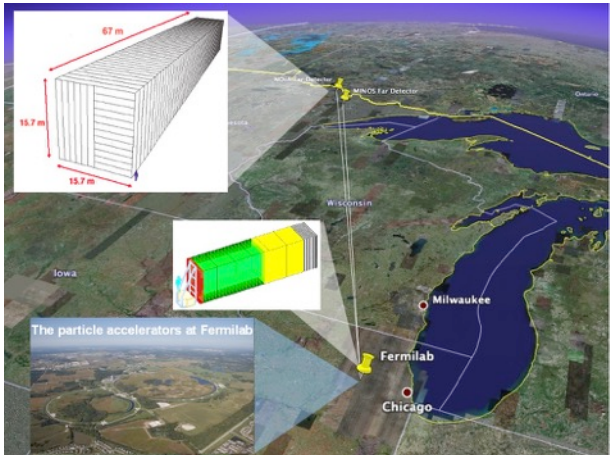
Present accelerator neutrino oscillation facilities in the world

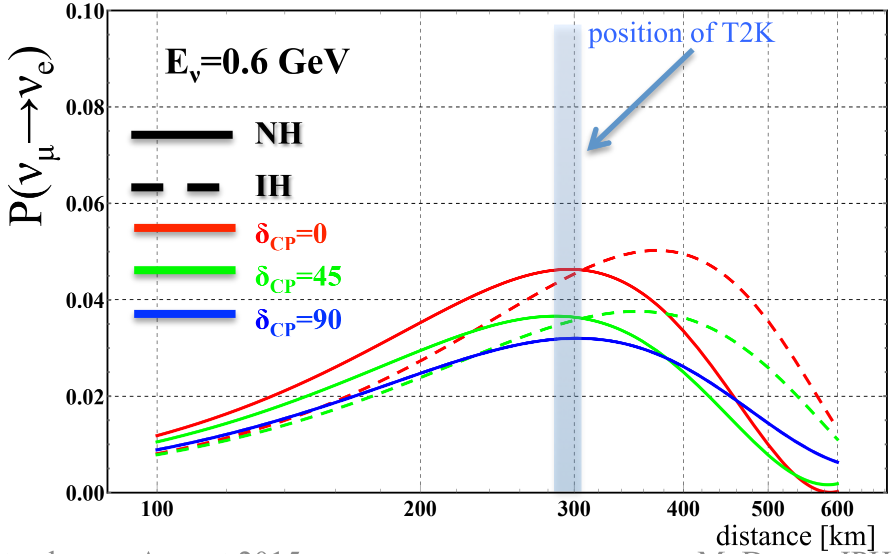
JPARC beam and T2K experiment (appearance/disappearance, off-axis, E_ν~0.6 GeV, L=295 km)

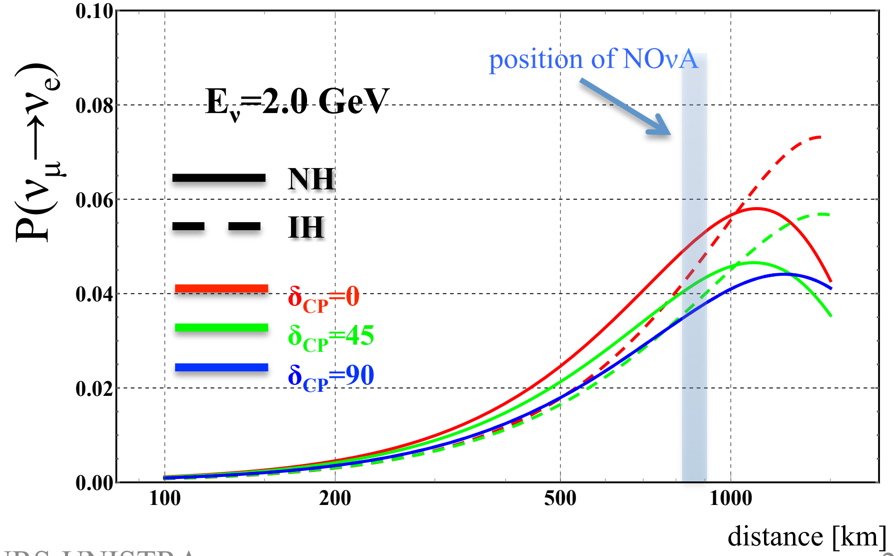




NOvA, same beam than MINOS, off-axis, E_ν~2 GeV, L=810 km.

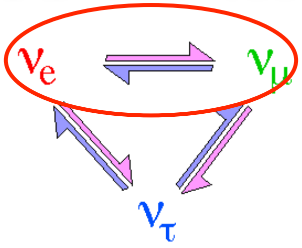




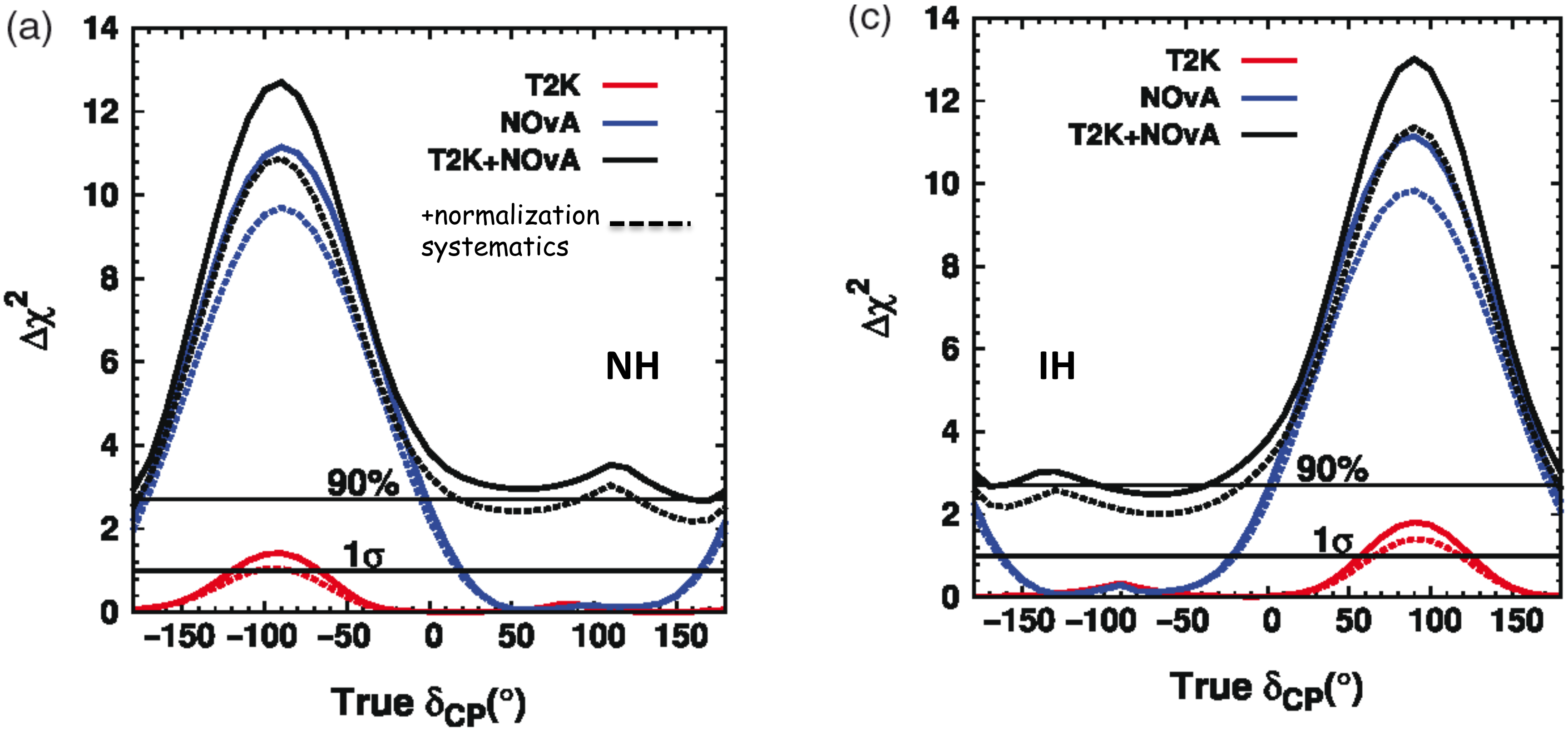


Present accelerator neutrino oscillation facilities in the world

JPARC beam and T2K experiment (appearance/disappearance, off-axis, E_ν~0.6 GeV, L=295 km)



NOvA, same beam than MINOS, off-axis, E_ν~2 GeV, L=810 km.

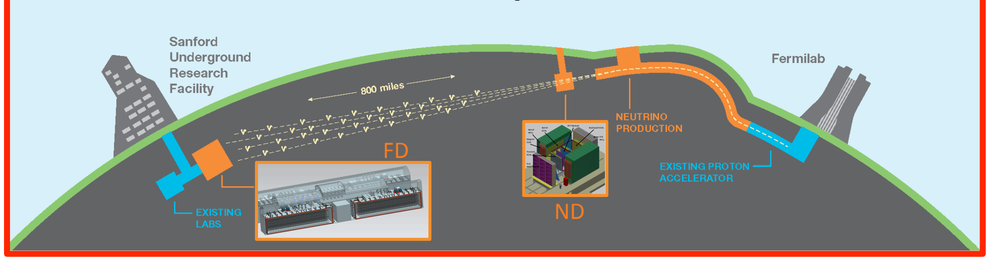


if lucky, NOvA can reach more than 3σ significance (little contribution from T2K)

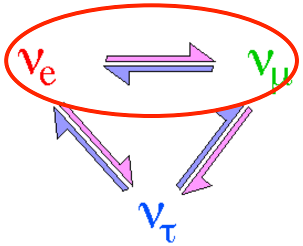
Future neutrino acceleration projects

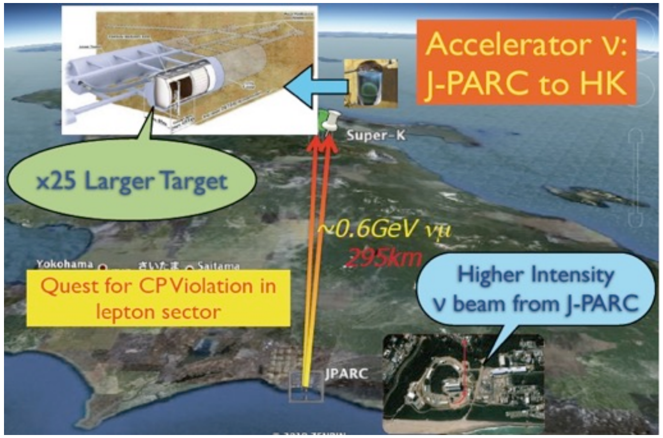
(approved or not)

LBNF/DUNE (1300 km, E_ν~3-8 GeV)

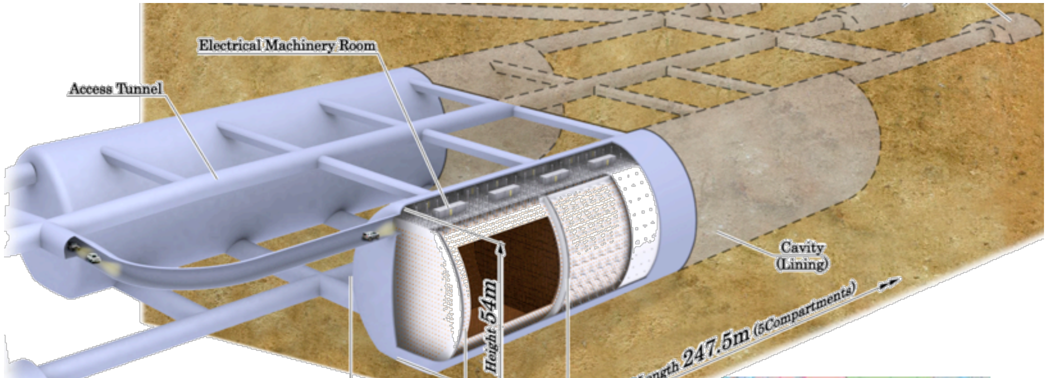


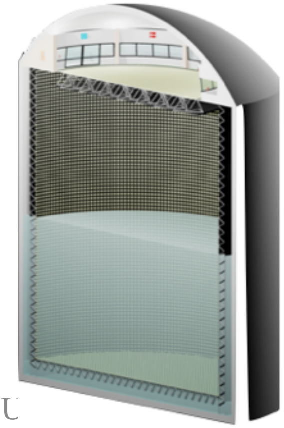
LAr



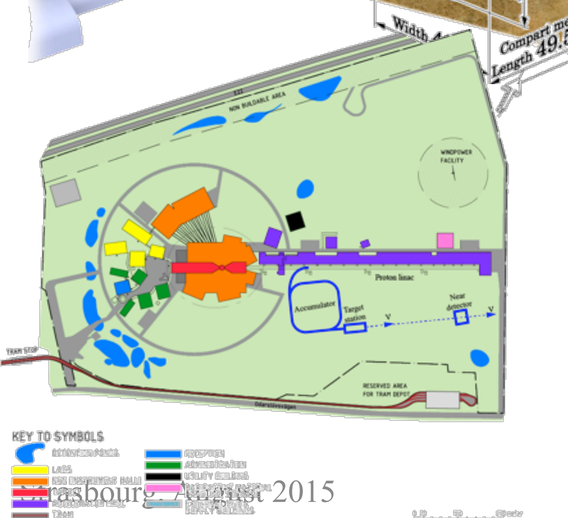


HyperK (295 km, E_ν~0.6 GeV)



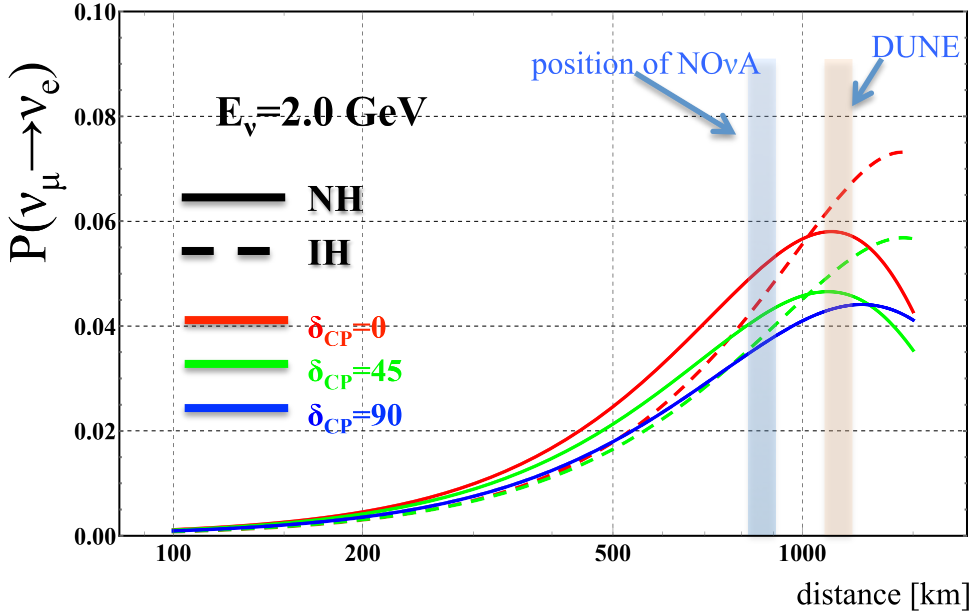


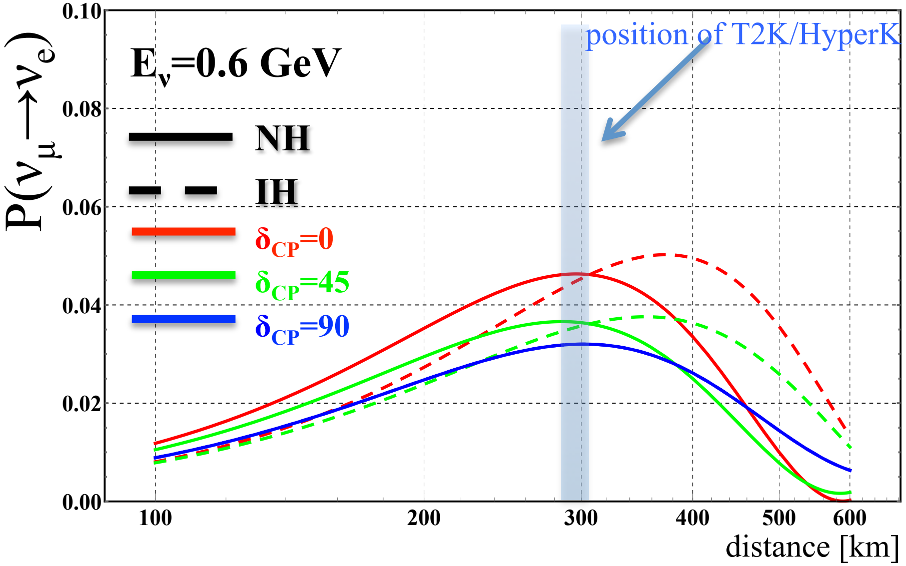
Water Cherenkov

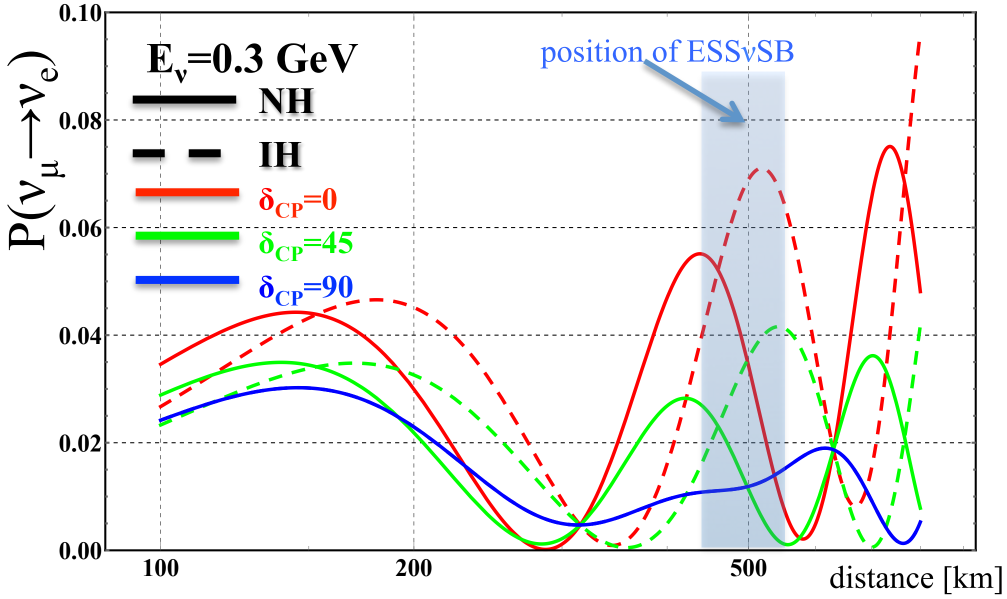


ESSνSB (540 km, E_ν~0.4 GeV, 5MW, ~500 kt)

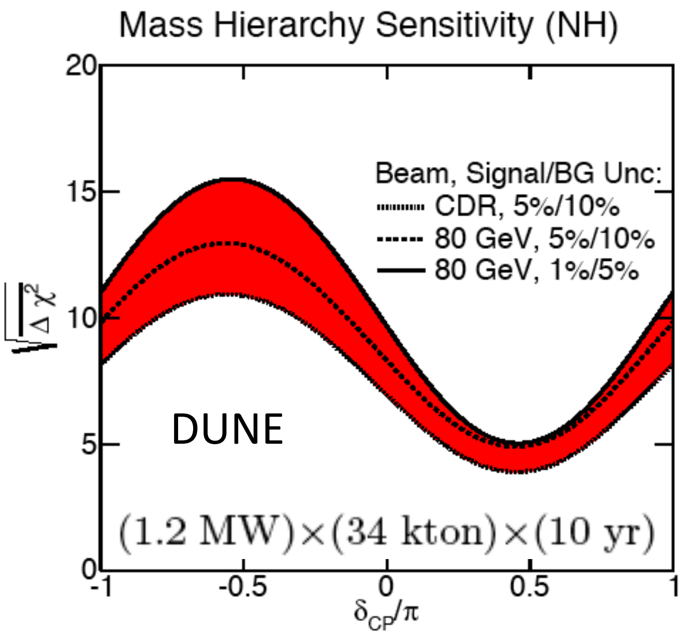
Future neutrino acceleration projects

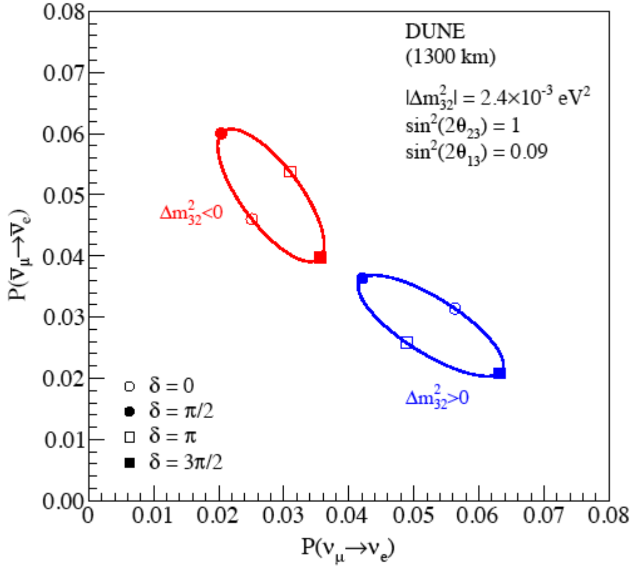


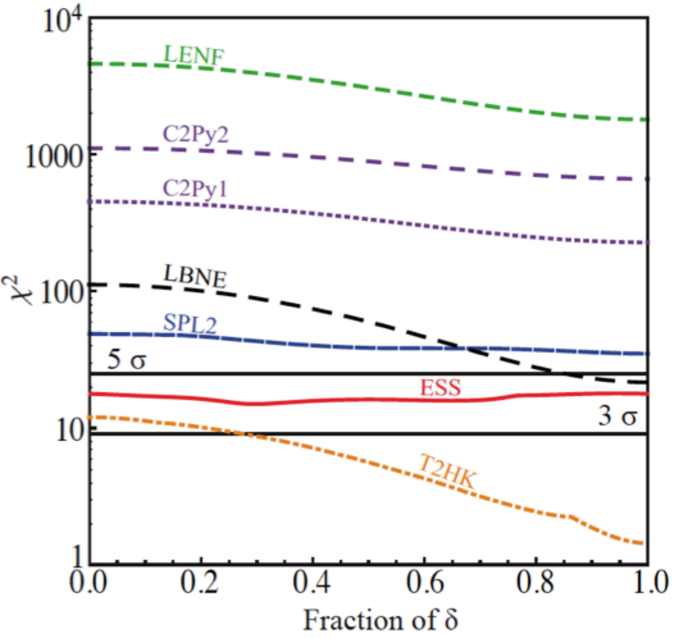




Future neutrino acceleration projects

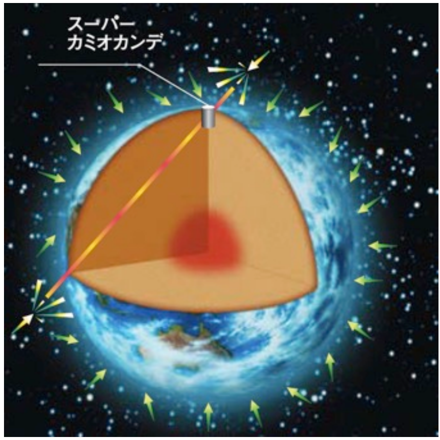


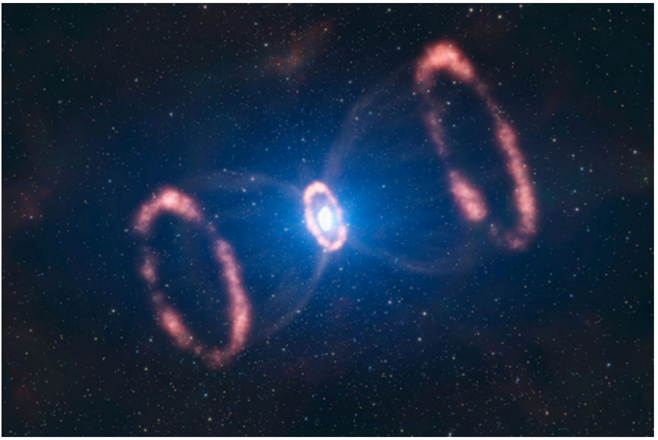


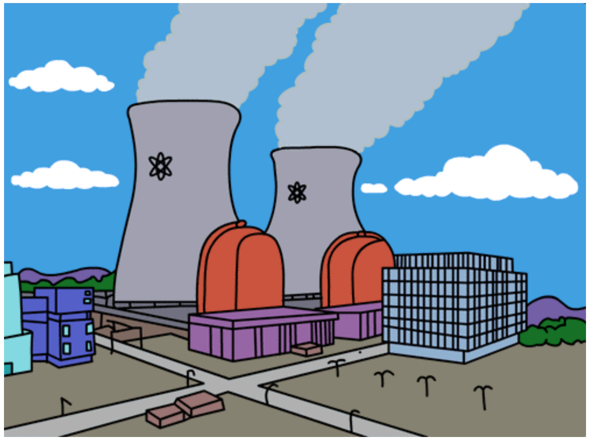


Very long baseline experiments are better for MH determination

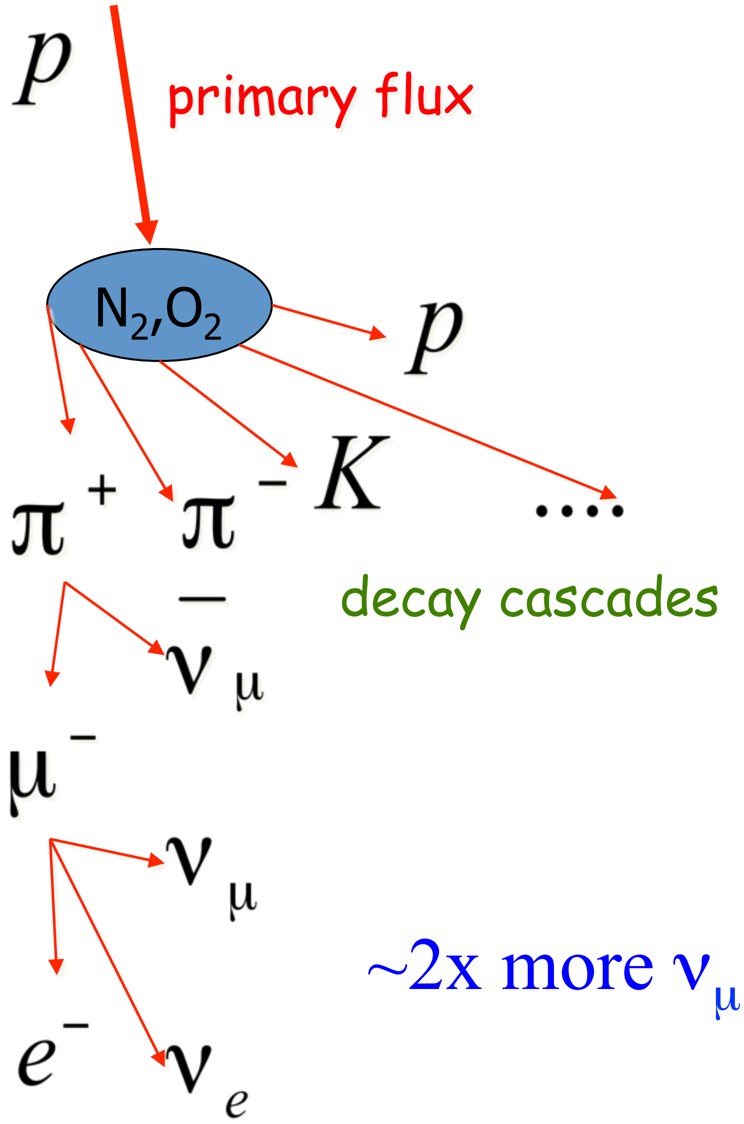
Future neutrino non-acceleration projects (approved or not)







Using atmospheric neutrinos



p

primary flux

N_2,O_2

p

π^+ π^- K ....

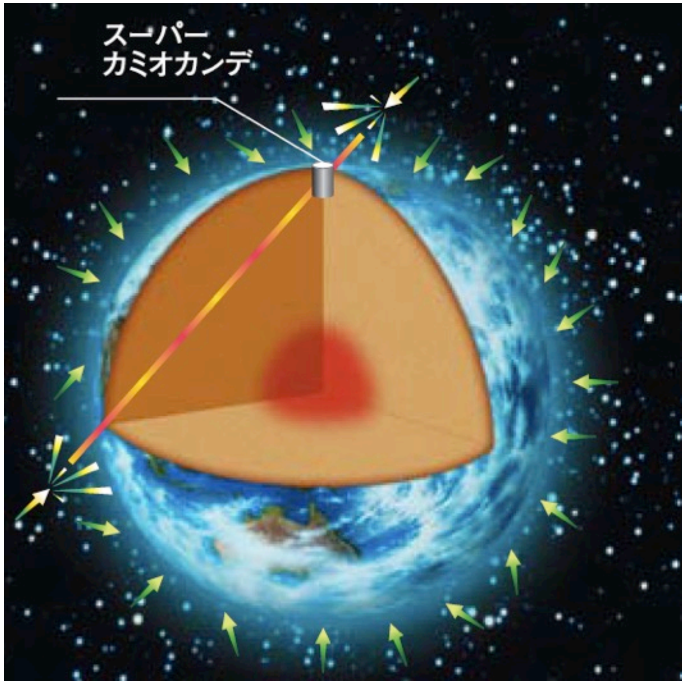
decay cascades

$\bar{\nu}_\mu$

μ^-

ν_μ

e^- ν_e

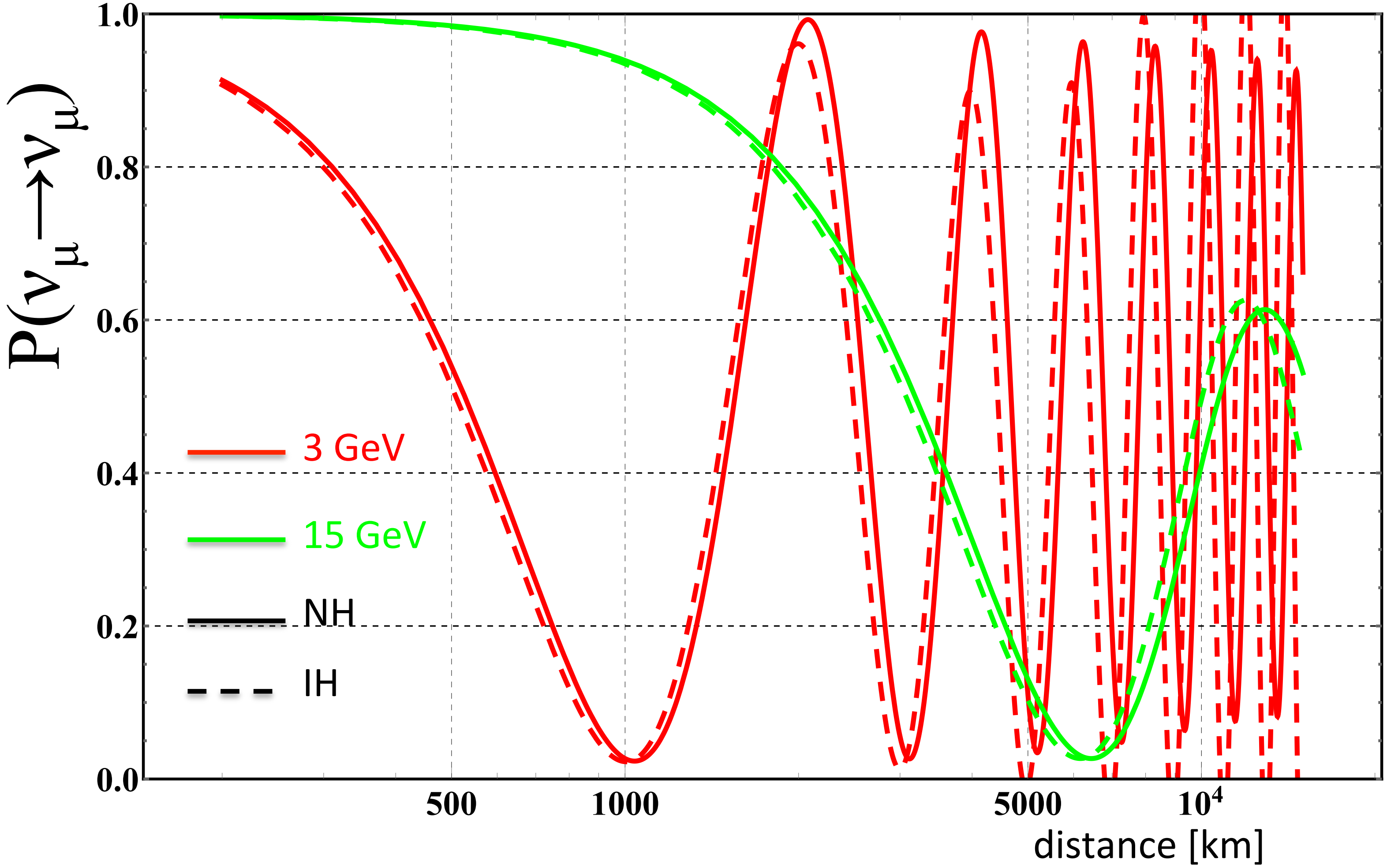


neutrinos arrive from all directions

~2x more ν_μ than ν_e

Atmospheric neutrinos

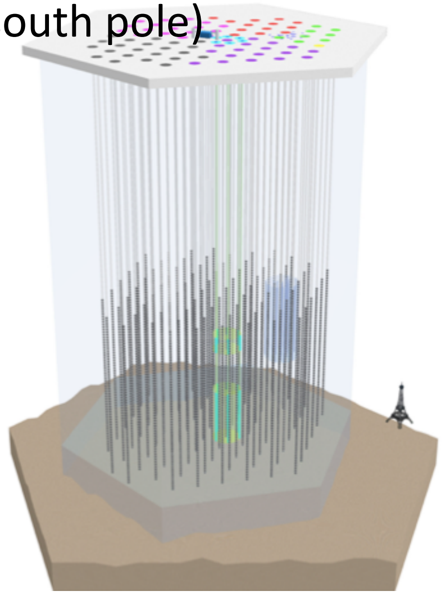
integrate all neutrinos between 3 and 15 GeV

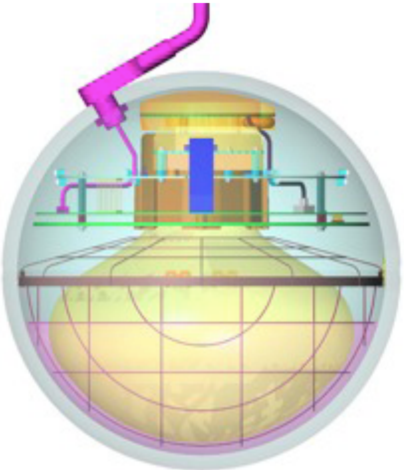


Large Water Cherenkov detectors

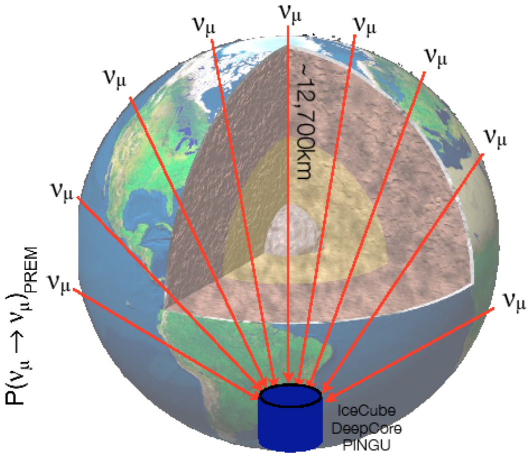
(neutrino mass hierarchy)

ICE Cube
(south pole)

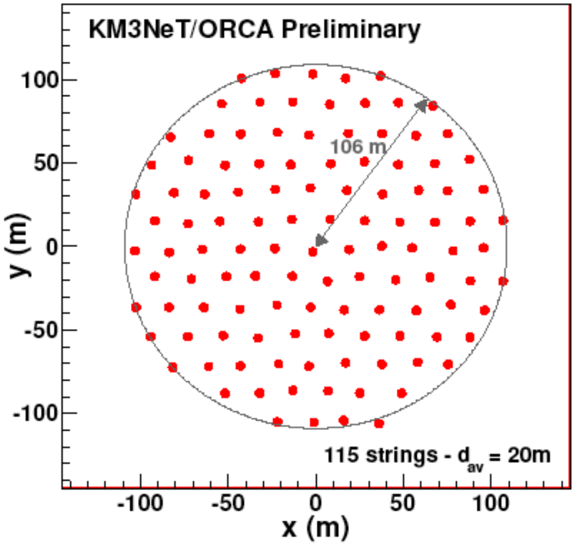




PINGU



- 2-12 GeV neutrinos
- good angular resolution
- good energy resolution

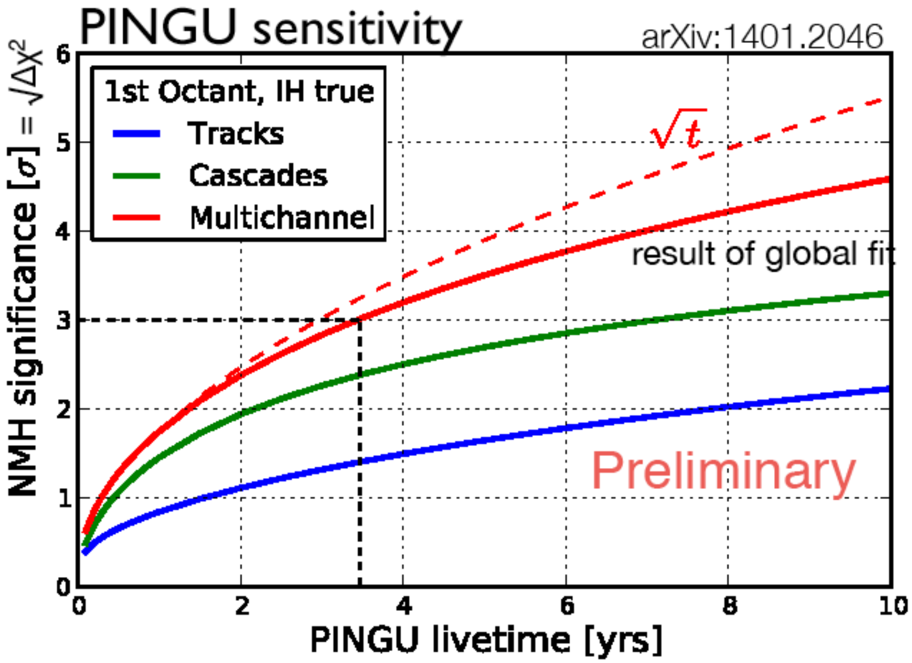


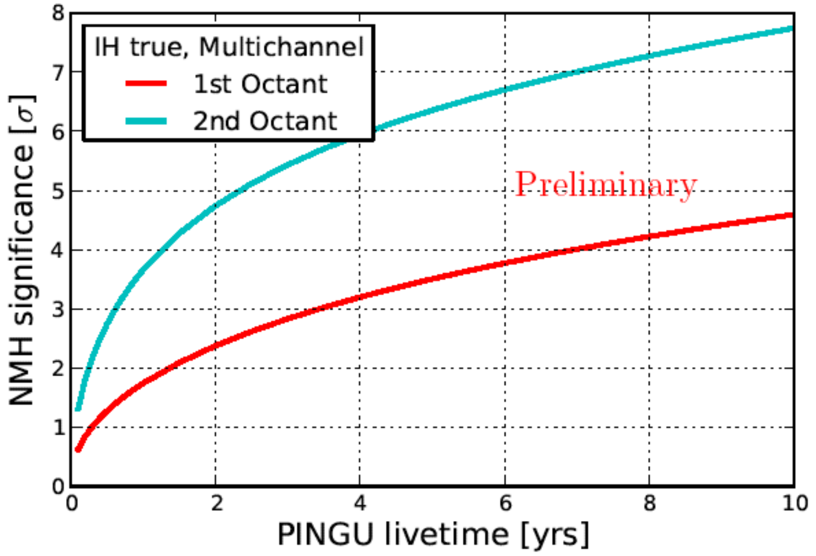
115 strings each carrying 18 DOMs

ORCA
KM3NeT Collaboration

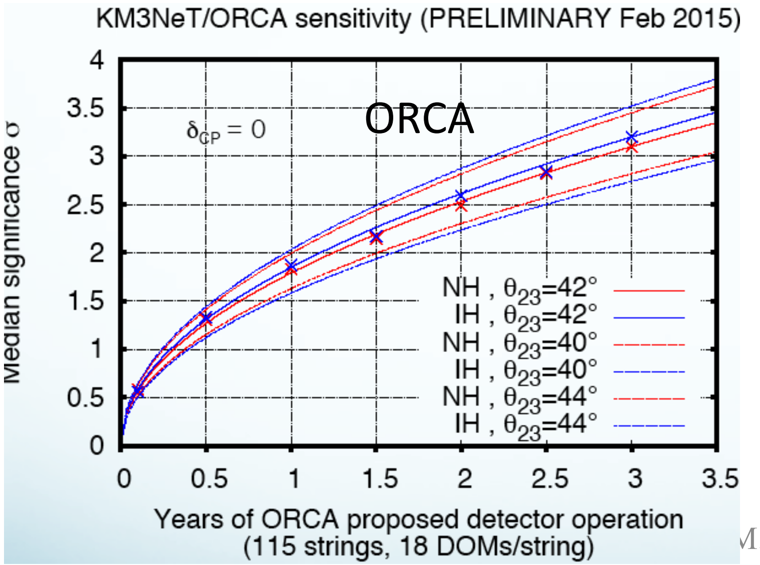
Mediterranean see

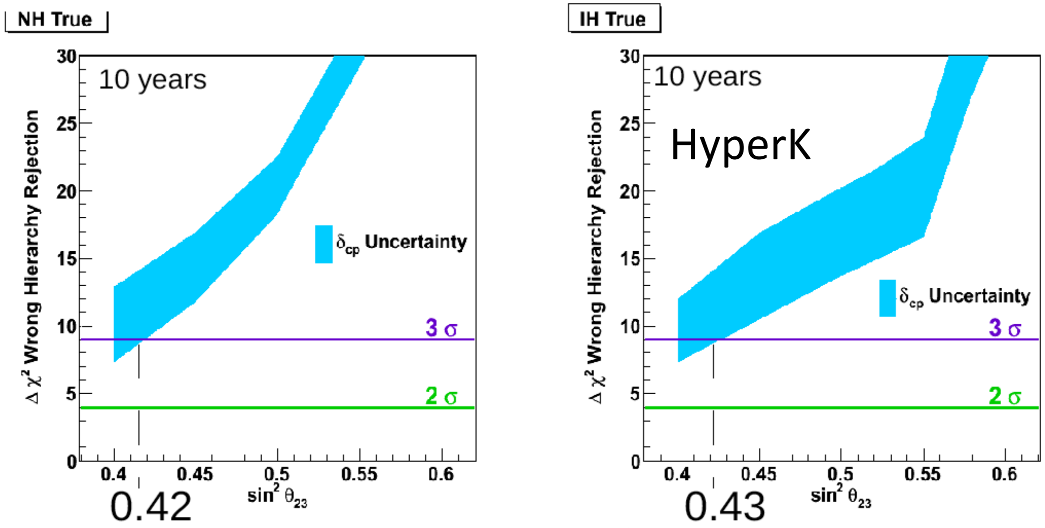
Future neutrino non-acceleration projects





→ large dependence on θ_{23}





using atmospheric neutrinos

Reactors are back…

(mass hierarchy)

$$P\left(\overline{\nu_e} \rightarrow \overline{\nu_e}\right) \simeq 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$

$$- \sin^2 2\theta_{13} \left[c_{12}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} + s_{12}^2 \sin^2 \frac{\Delta m_{32}^2 L}{4E} \right]$$

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

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

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

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

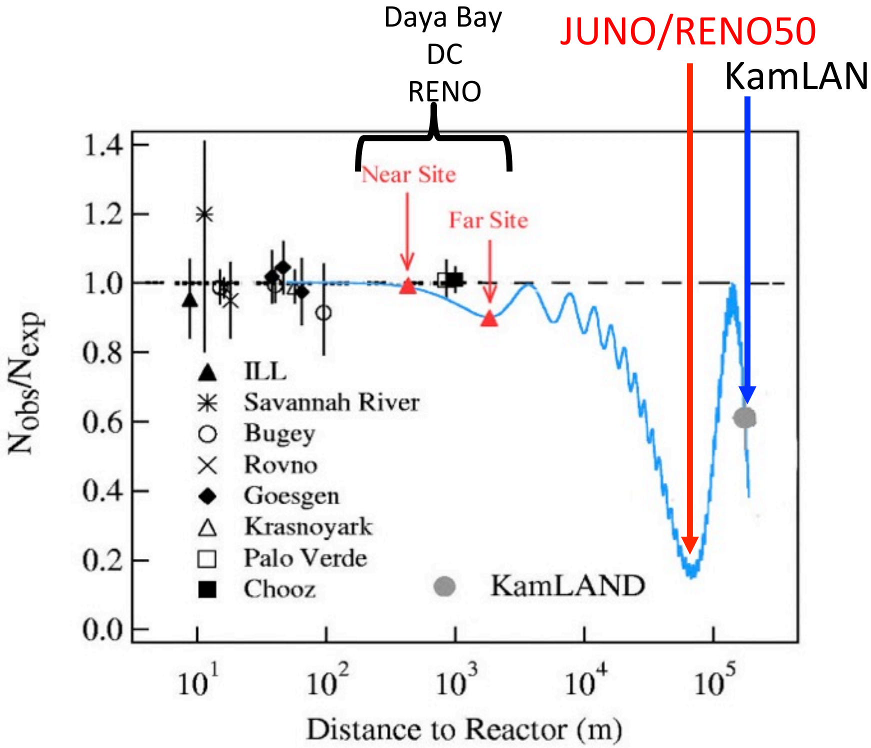
- no δ_{CP} dependence
- matter effect negligible

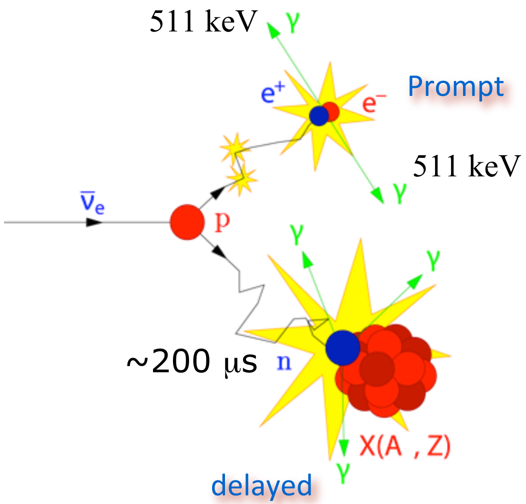
with:

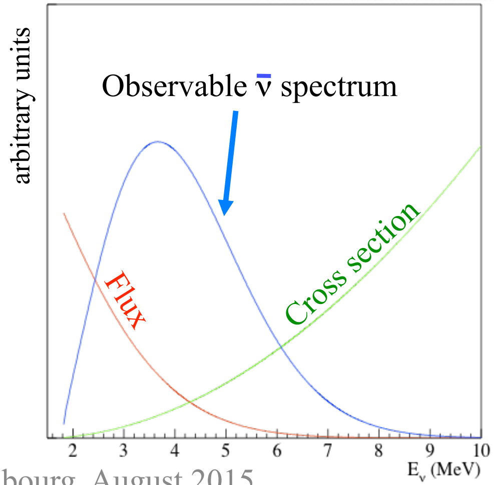
$$\Delta m_{31}^2 \equiv \begin{cases} m_3^2 - m_1^2 > 0 \text{ (NH)} \\ m_3^2 - m_1^2 < 0 \text{ (IH)} \end{cases}$$

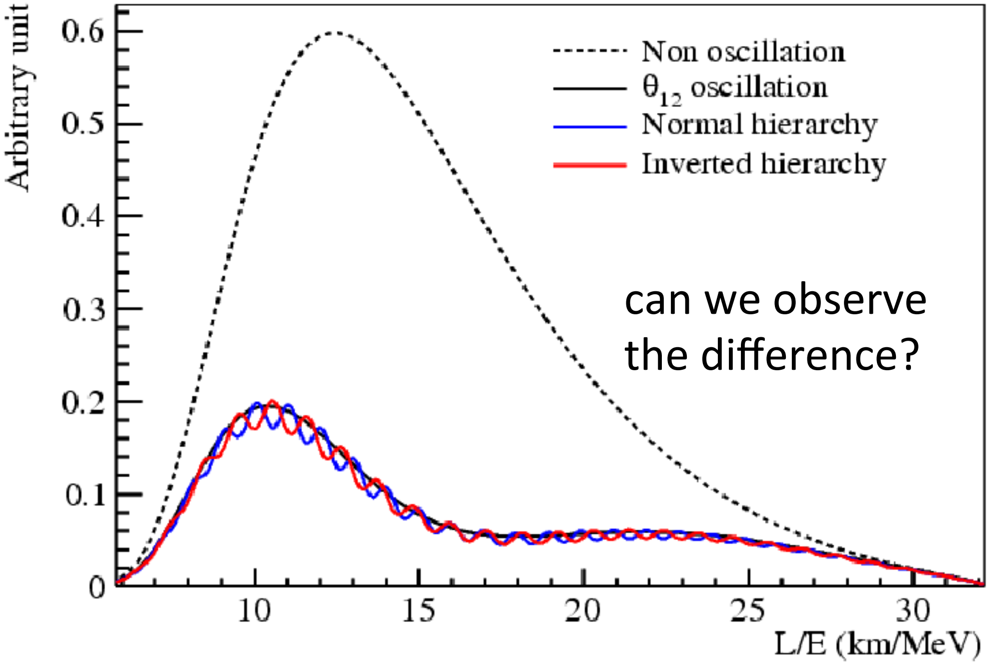
=(2n-1)π/2 ⇒ max. sens.
=nπ ⇒ non sensitivity

Reactor neutrino spectrum









can we observe the difference?

Reactor performance

Conditions:

- Go to the right distance
- Accumulate 100 kIBD (~6 years)
    - ~20 kt detector
- High energy resolution ~3% (at 1 MeV)
    - high PMT coverage (~80%)
    - high PMT Quantum Eff. (~35%)
    - high liquid transparency

significance: 3 – 4 σ

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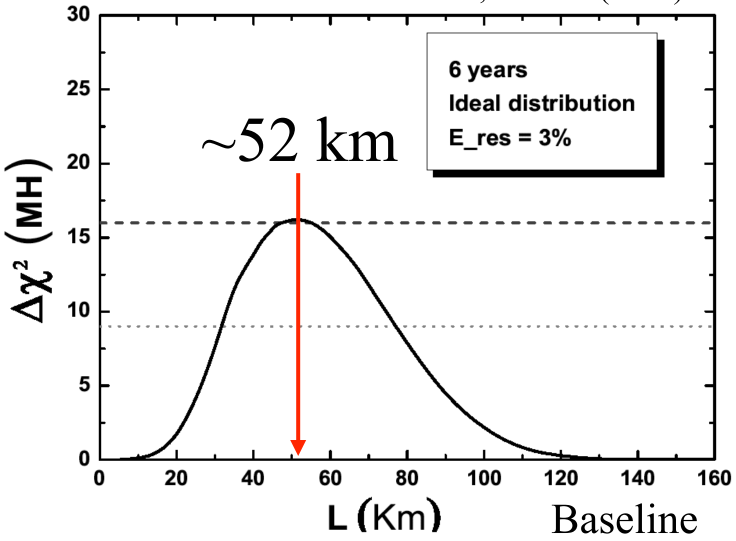
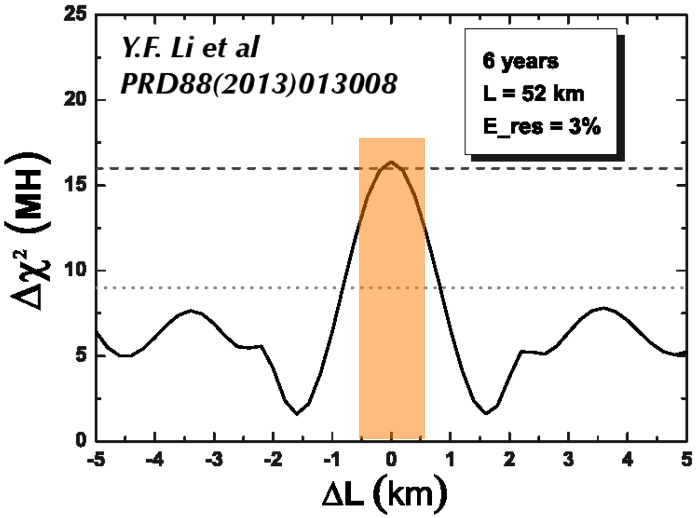
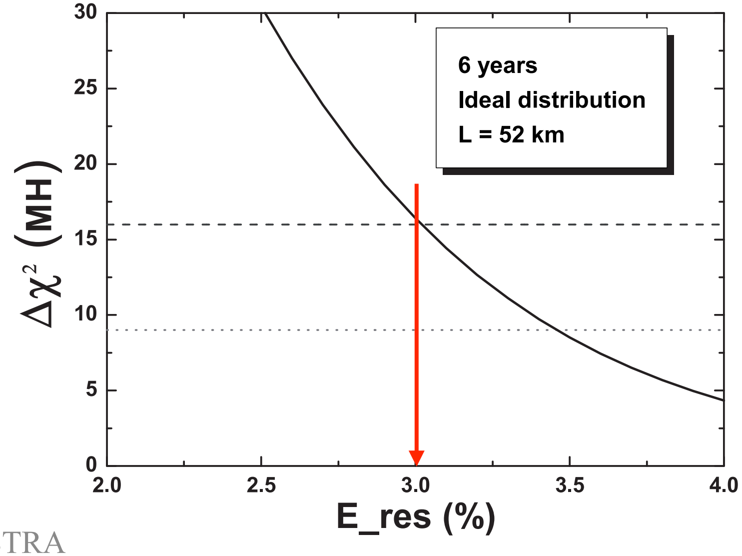
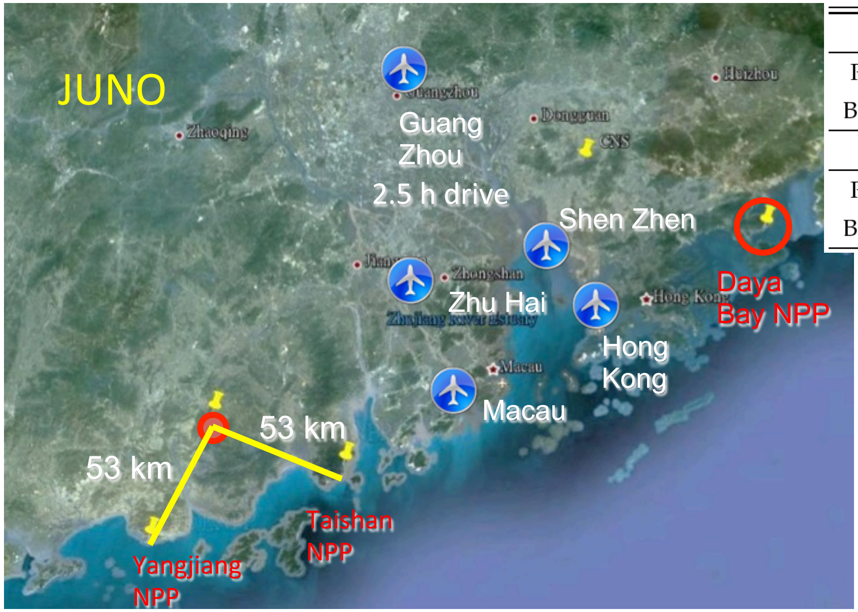




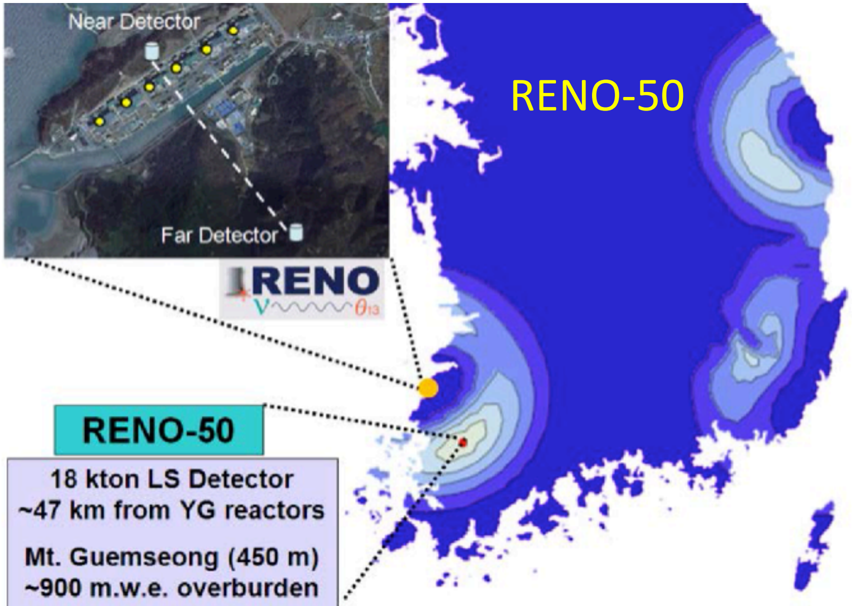
acceptable uncertainty on the distance: ±500 m



JUNO/RENO-50



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

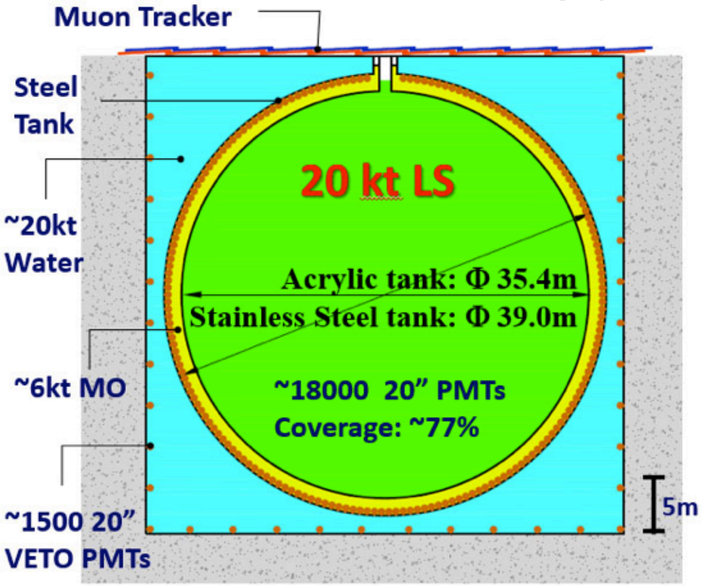


- Rich physics program:
  - Reactor neutrinos
    - Mass Hierarchy
    - precision measurements of oscillation parameters
  - Supernovae neutrinos
  - Geoneutrinos
  - Solar neutrinos
  - Atmospheric neutrinos
  - Exotic searches

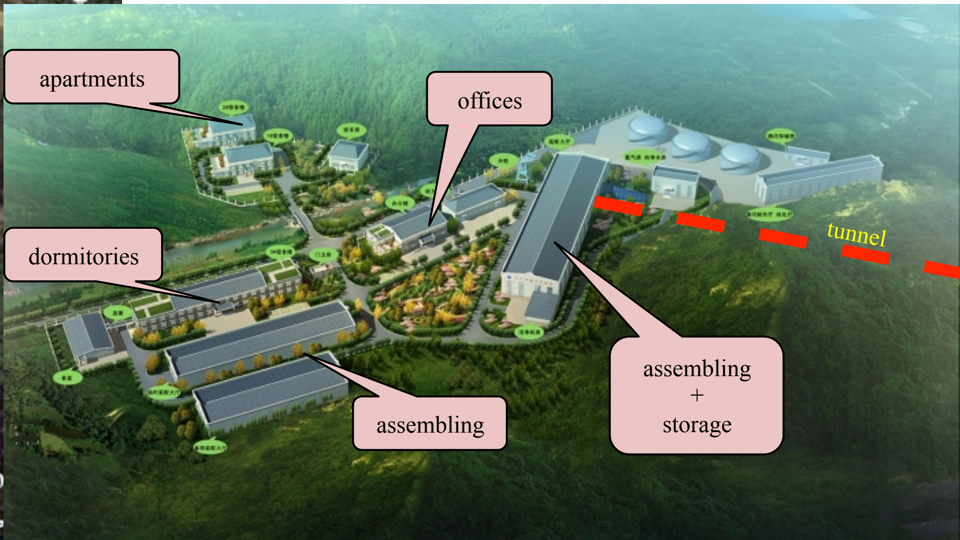
JUNO (55 institutes)

(under construction)

data by 2020: 26.6 GW



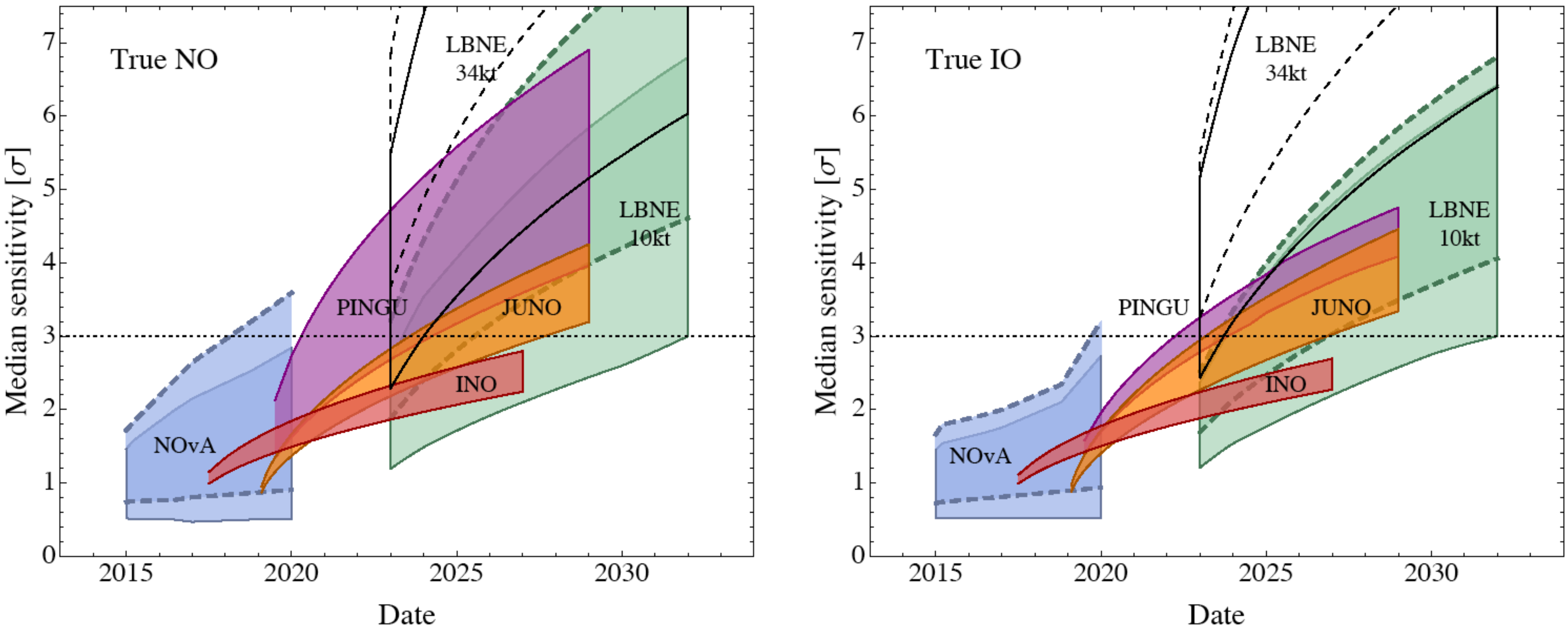
Overburden ~ 700 m



Comparisons and complementarities

(big unknown: t_0)

arXiv:1311.1822



- width of bands due to:
    - δ_{CP} (for NOνA and LBNE)
    - $40^o<\theta_{23}<50^o$ (for INO and PINGU)
    - $3.0\%\sqrt{(1 \text{ MeV}/E)}<\sigma_E<3.5\%\sqrt{(1 \text{ MeV}/E)}$

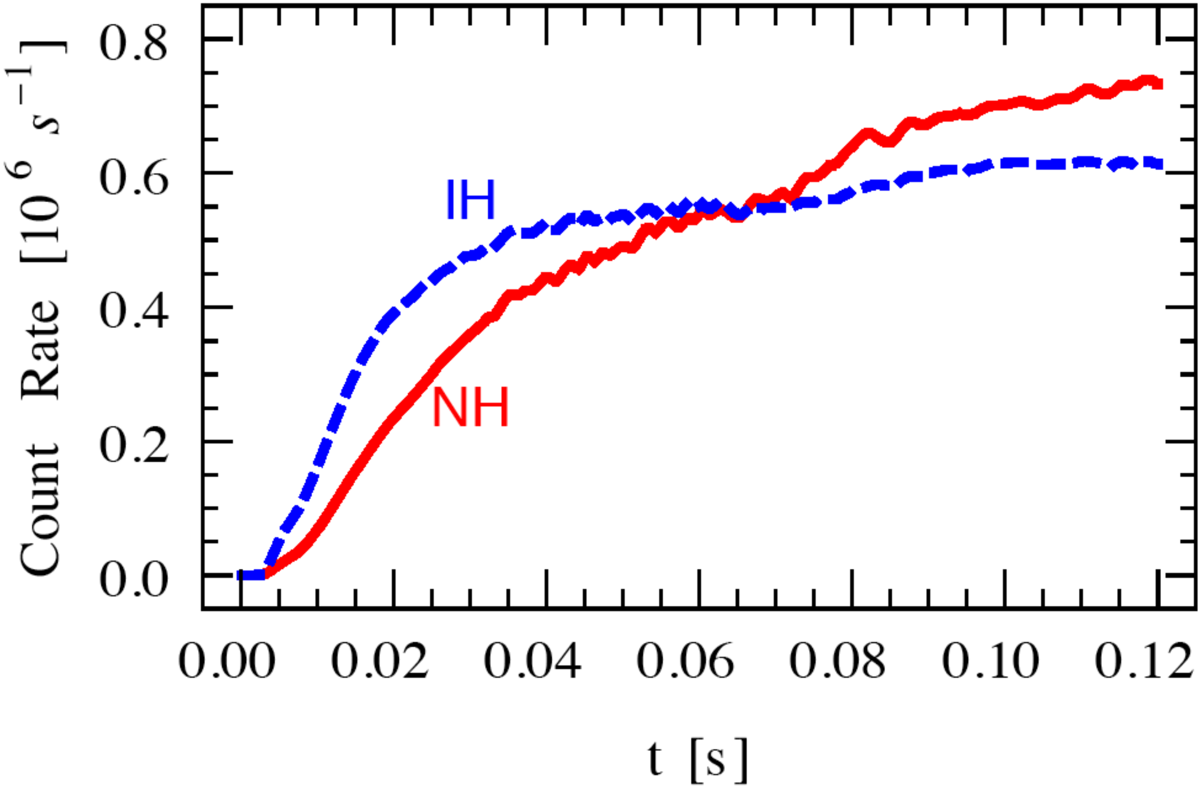
- complementarities:
    - reactors (low energy)
        - LS, antineutrinos
    - LBL (high energy)
        - accelerator and atm. neutrinos
        - LAr, WC, …

Conclusions

- Reactor experiments allowed the θ_{13} measurement and opened now the door to:
  - neutrino Mass Hierarchy determination
  - observation of a possible CP violation in the lepton sector using conventional neutrino beams.
- Present projects (mainly NOνA) will give some indications on MH.
- Atmospheric neutrinos are very useful for MH (projects still to be approved)
- New Medium baseline large volume reactor experiments will very probably solve the Mass Hierarchy problem during the next 10 years:
  - High energy resolution is needed.
  - JUNO:
    - Under construction in China (data by 2020)
  - RENO-50:
    - In R&D phase in S. Korea.
- Accurate measurement of neutrino oscillation parameters.

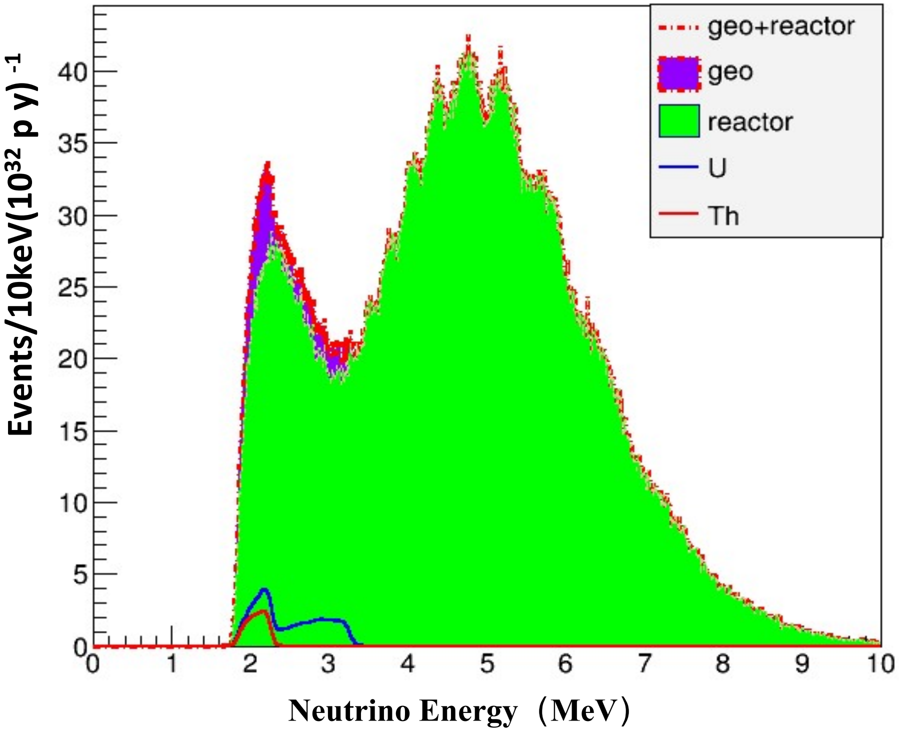
Backup

Mass Hierarchy and Supernova explosions



arXiv:1111.4483

Geo-neutrinos in JUNO



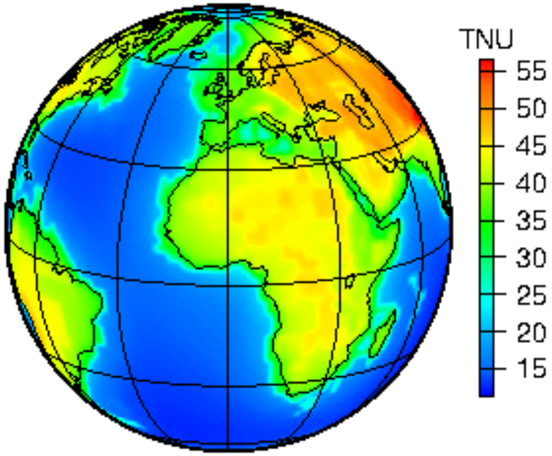
JUNO ~700/year
Kamland 116/10 years
Borexino 14.3/5 years

KamLAND: 30±7 TNU
Borexino: 38.8±12.0 TNU
JUNO:

- reach an uncertainty of 3 TNU
- large background from reactors
- Aim: 37 ±**10% (stat.) ±10% (syst.)**

1.8-3.4MeV

- Reactor Neutrinos: 14±0.14/day
- Geo-neutrinos 2±0.5/day



(TNU ~ number of detected ν/year/kt LS (IBD, 10^{32} p))

Double beta decay

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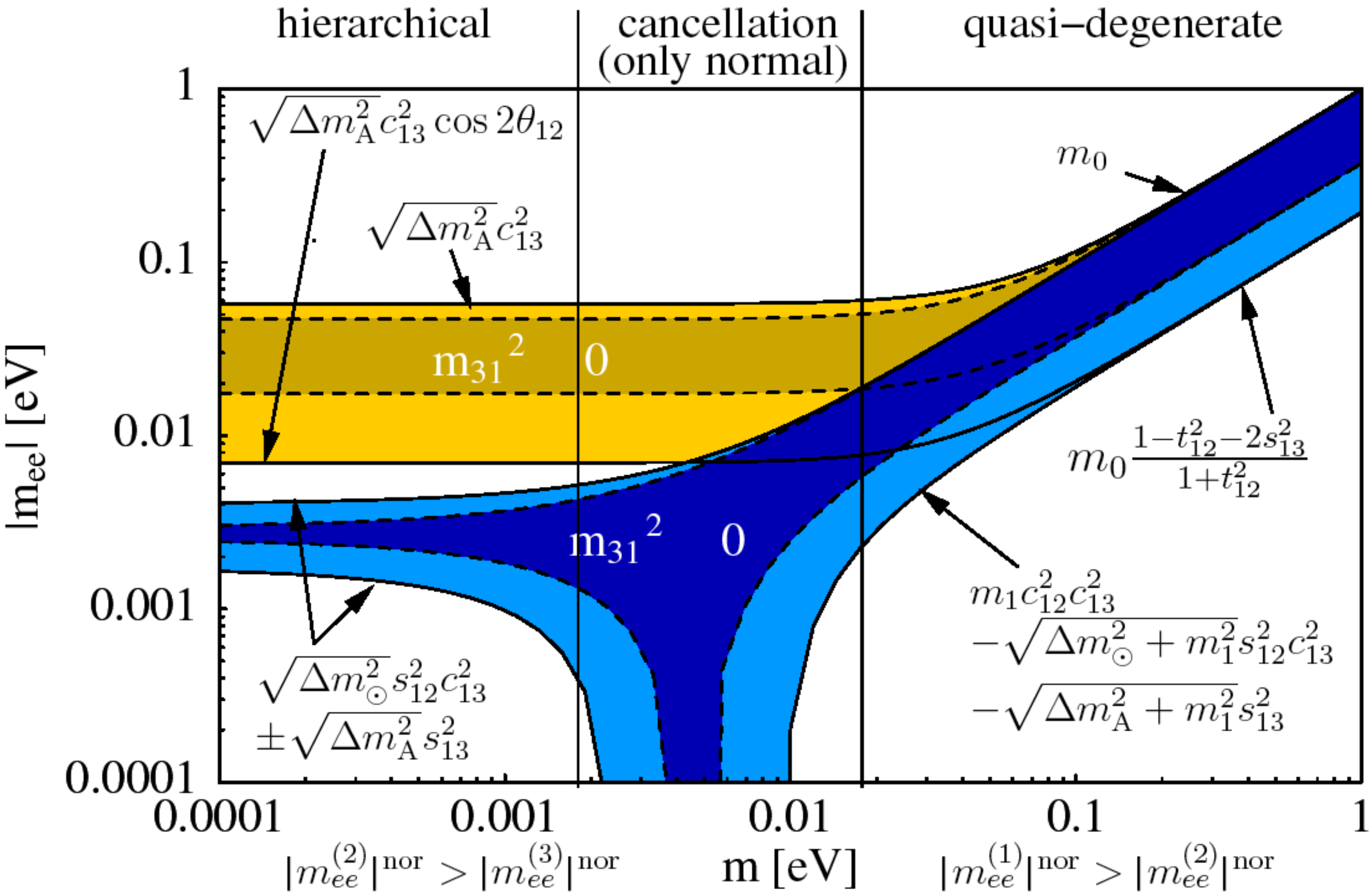
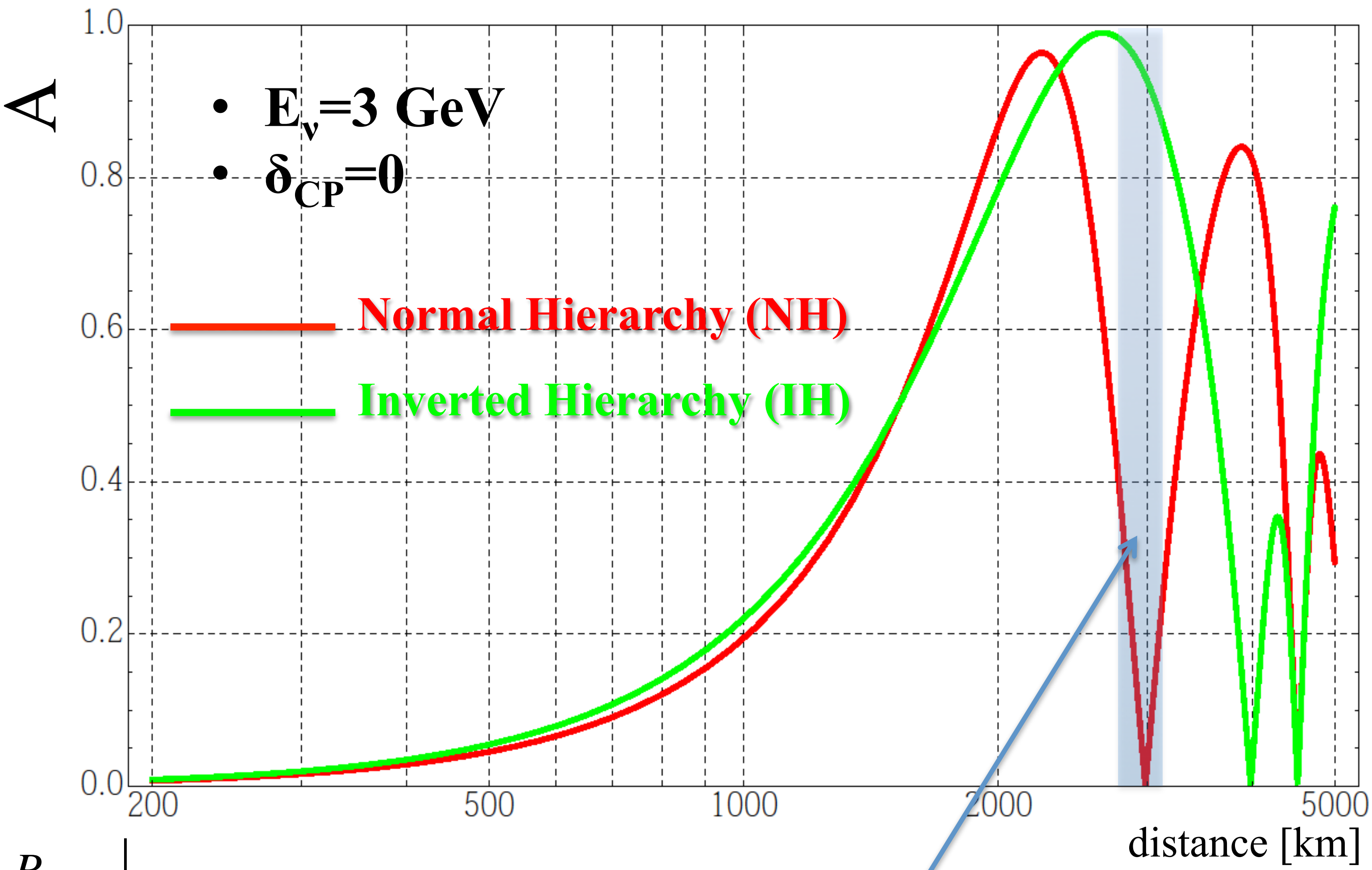


Asymmetry due to matter effects



$$\left| A = \frac{P_{\nu_\mu \to \nu_e} - P_{\overline{\nu_\mu} \to \overline{\nu_e}}}{P_{\nu_\mu \to \nu_e} + P_{\overline{\nu_\mu} \to \overline{\nu_e}}} \right|$$

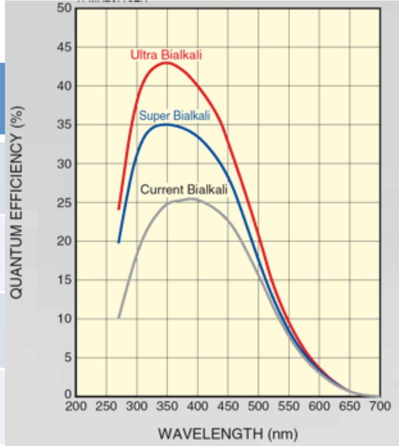
good position to measure MH (LAGUNA-LBNO)

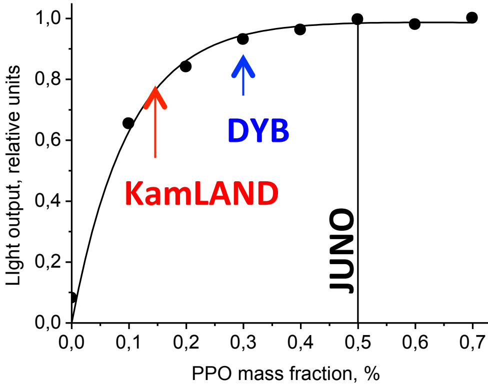
High energy resolution

How to reach the required energy resolution?

- Photocathode coverage: 77% with 20" PMTs
- High PMT QE: ~35%
- Liquid scintillator attenuation length: ~30 m
- High light yield with optimised fluors

	R5912	R5912-100	MCP-PMT
QE@410 nm	25%	35%	25%
Rise time	3 ns	3.4 ns	5 ns
Dark noise	1 kHz	3.5 kHz	2.2 kHz
TTS	5.5 ns	1.5 ns	3.5 ns

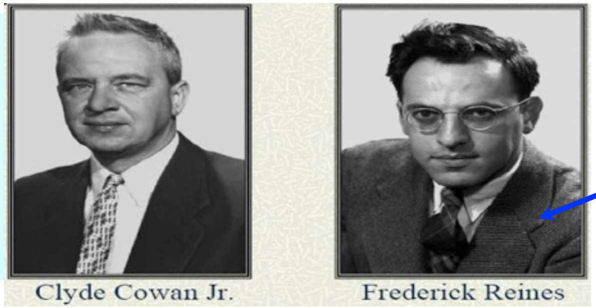




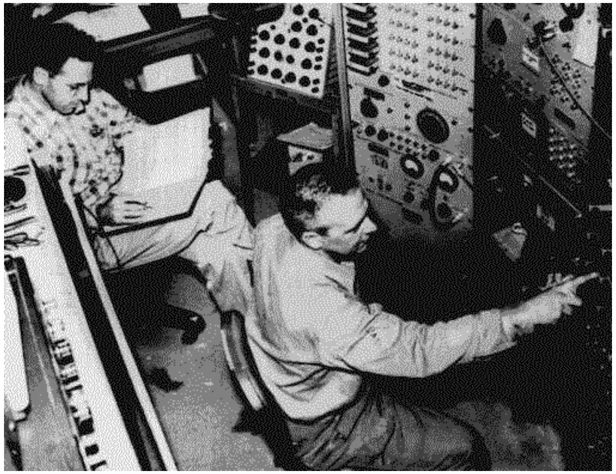
	KamLAND	BOREXINO	JUNO
LS mass	**1 kt**	**0.5 kt**	**20 kt**
Energy Resolution	**6%/√E**	**5%/√E**	**3%/√E**
Light yield	**250 p.e./MeV**	**511 p.e./MeV**	**1200 p.e./MeV**

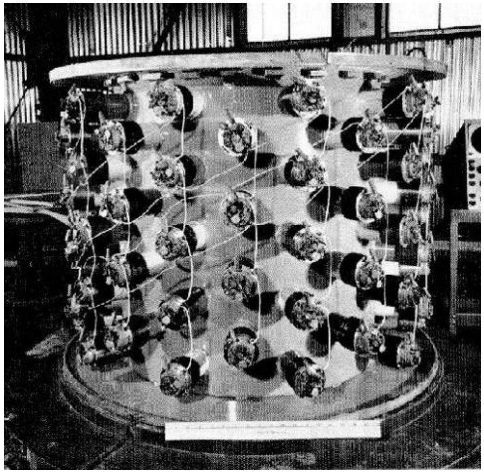
First neutrino detection…

1956: Fred Reines and Clyde Cowan detect the first neutrino interactions near the nuclear reactor of Savannah River at the USA (11 m from the reactor and 12 m underground).

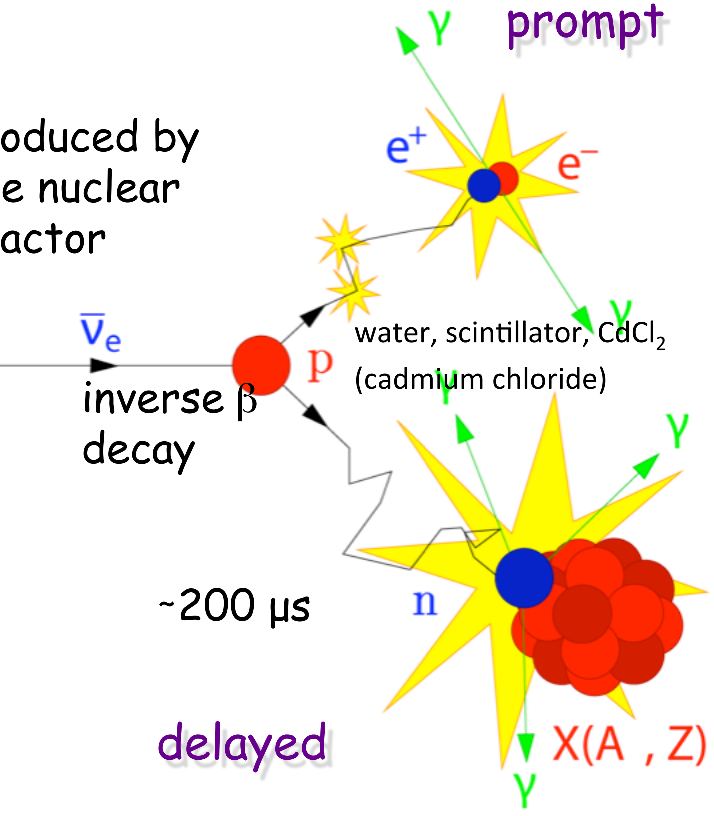


Nobel prize in 1995





about three neutrinos per hour



prompt

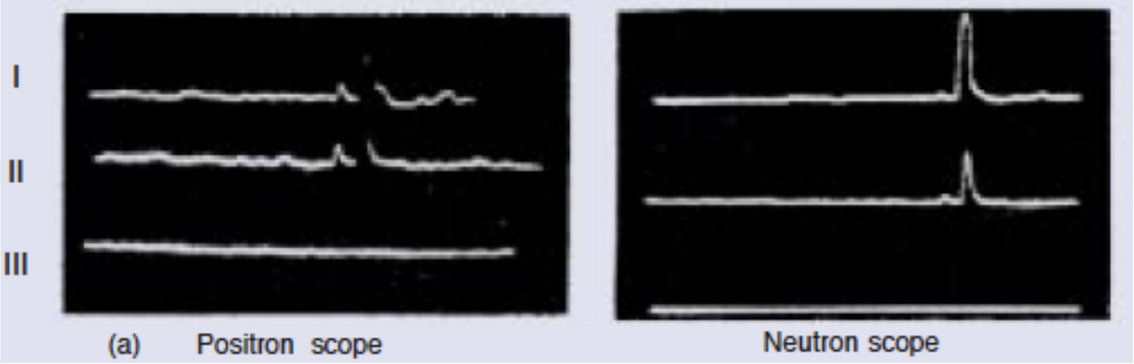
produced by the nuclear reactor

water, scintillator, $CdCl_2$ (cadmium chloride)

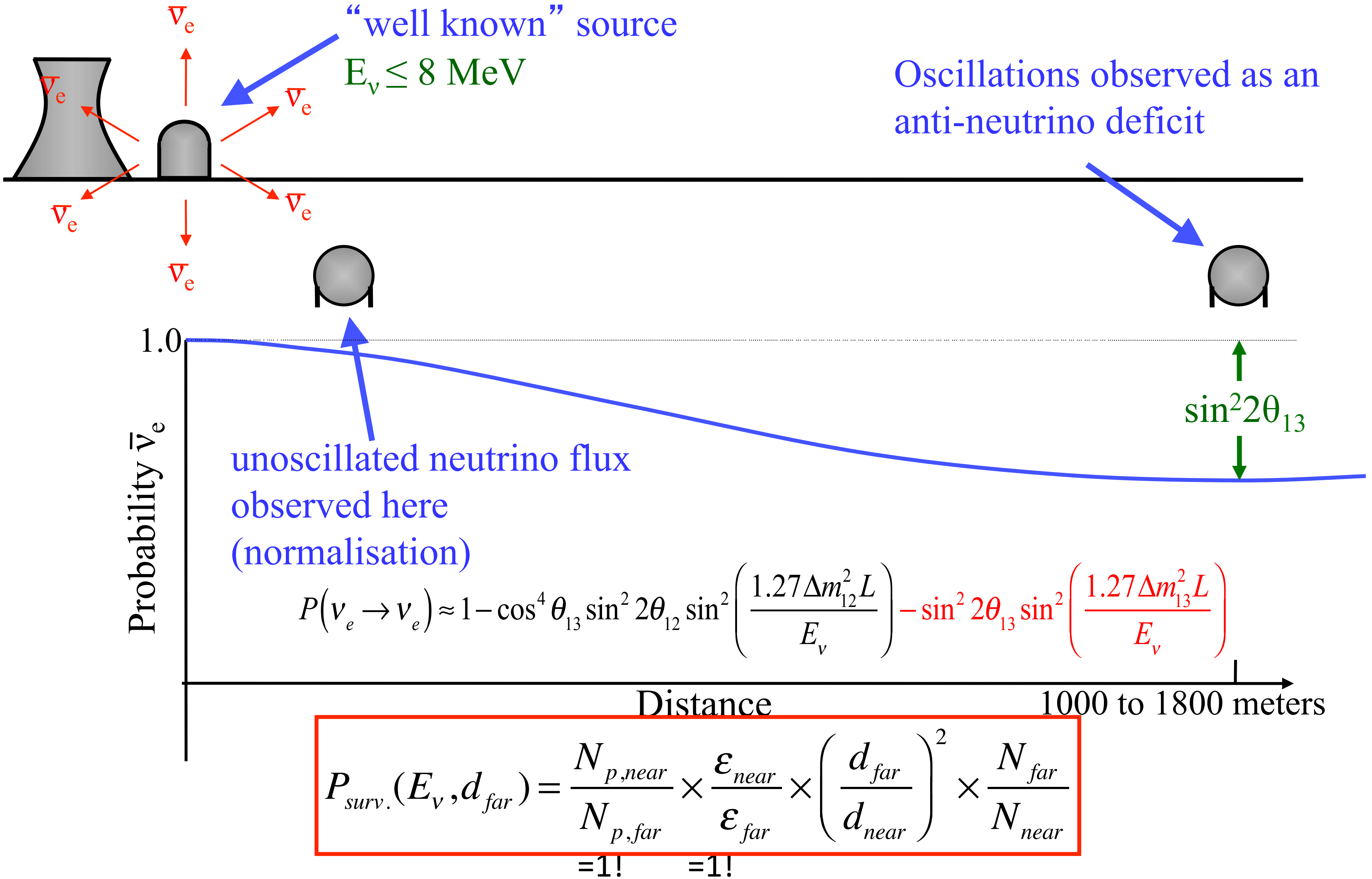
inverse β decay

~200 µs

delayed



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



isotropic electron anti-neutrino
“well known” source
$E_\nu \leq 8$ MeV

Oscillations observed as an
anti-neutrino deficit

unoscillated neutrino flux
observed here
(normalisation)

$$P(\nu_e \to \nu_e) \approx 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{1.27\Delta m_{12}^2 L}{E_\nu}\right) - \sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m_{13}^2 L}{E_\nu}\right)$$

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

=1! =1!

New Reactor Projects ready (2011)

Daya Bay

(China)

Double Chooz

(France)

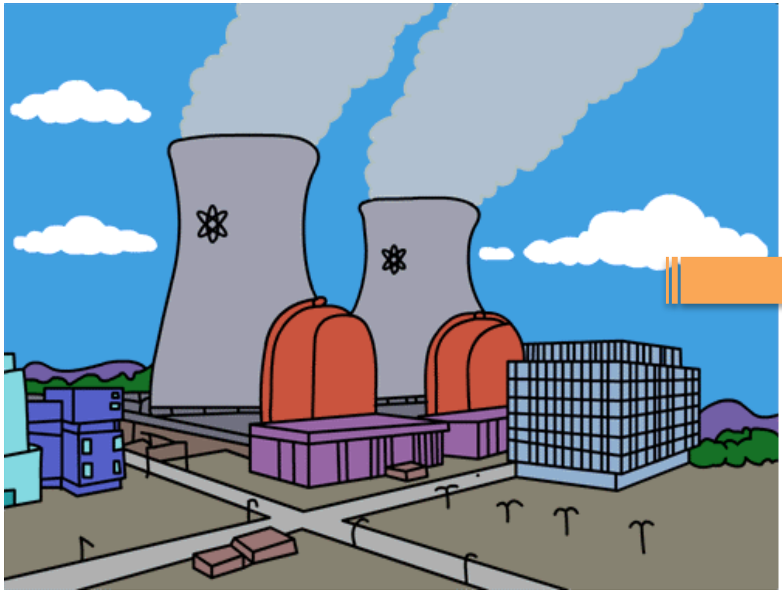
RENO

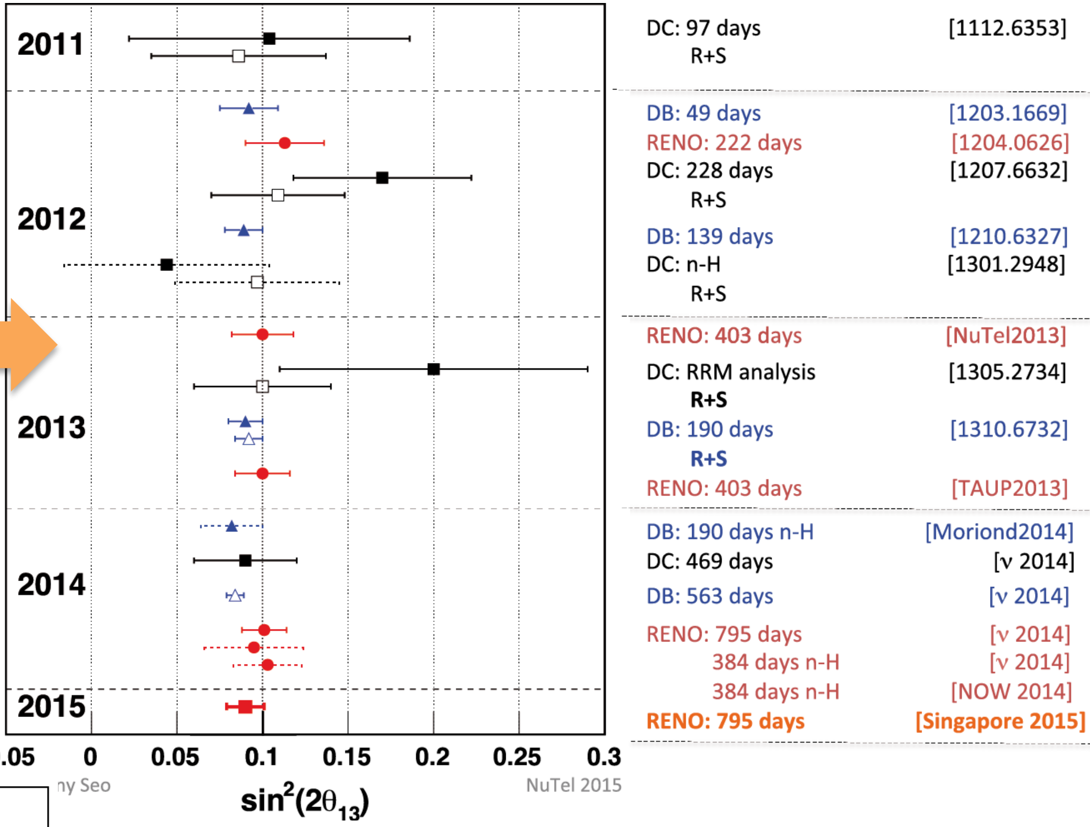
(South Korea)

	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

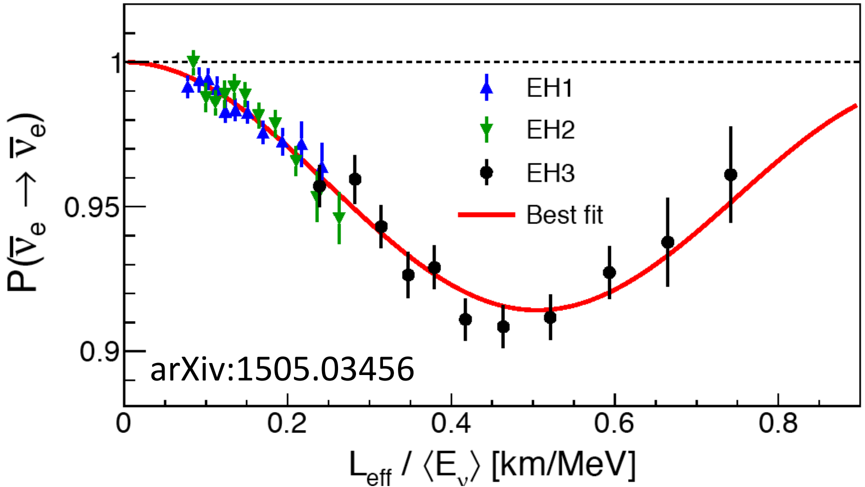
Present results

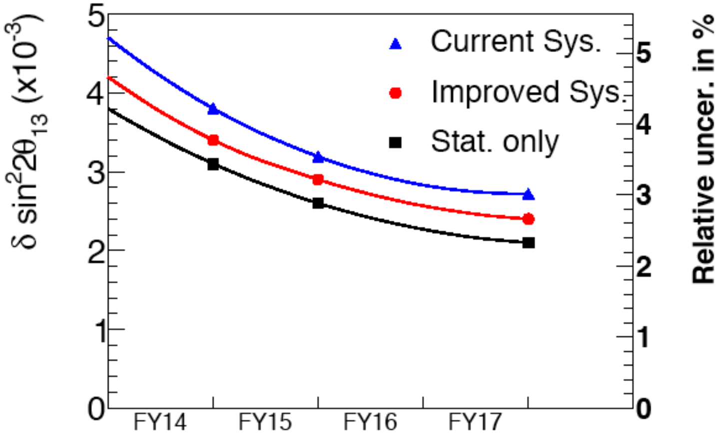
(NuTel2015)





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





Energy resolution

The sensitivity will strongly depend on the energy resolution (E_m: mesured energy)

$$R(E_\nu, E_m) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(E_m - E_\nu)^2}{2\sigma_E^2}}$$

$$\left(\frac{\sigma_E}{E}\right)^2 = \frac{a^2}{E} + b^2 + \frac{c^2}{E^2}$$

stat. (N_{pe})

syst. (non-uniformities, energy leaks…)

noise

Measured spectrum (without background):

$$N(E_m) = \int R(E_\nu, E_m)\phi(E_\nu)\cdot\sigma(E_\nu)\cdot P_{\bar{\nu}_e\to\bar{\nu}_e}(E_\nu)dE_\nu$$

Shift in energy spectrum of $\sim\Delta m_{21}^2/\Delta m_{31}^2\sim 3\%$

⇒

An energy resolution of ~3% (for E~1 MeV) is needed

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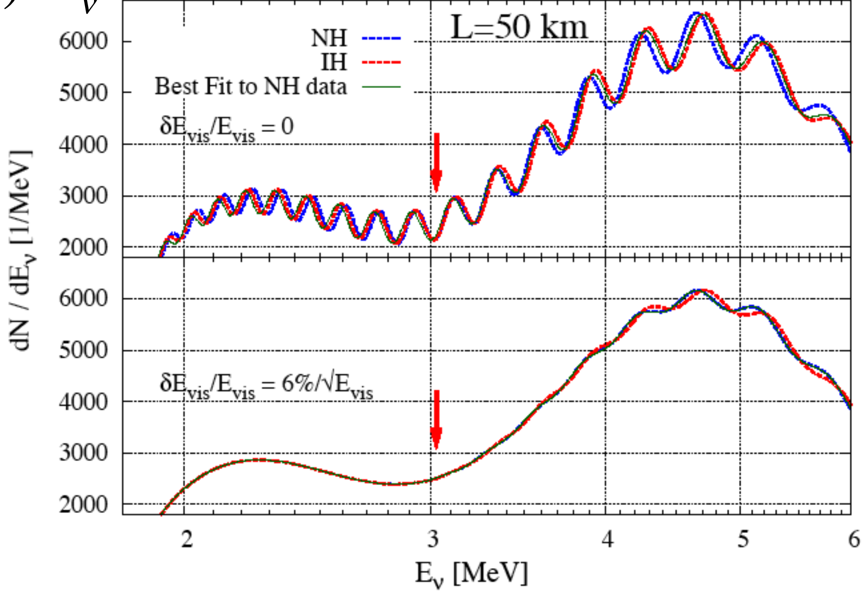


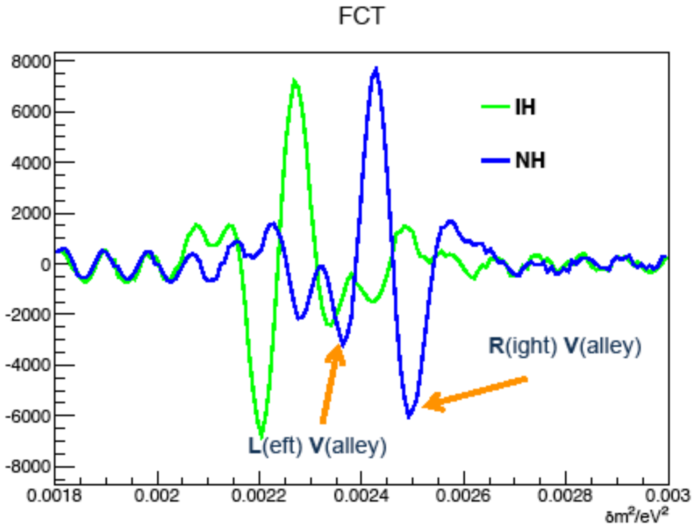
Spectral analysis

PHYS. REV. D 78, 111103(R) (2008)

Fourrier transform of the energy spectrum F(t):
(t=L/E)

$$FCT(\omega) = \int_{t_{\min}}^{t_{\max}} F(t)\cos(\omega t)\,dt$$

$$FST(\omega) = \int_{t_{\min}}^{t_{\max}} F(t)\sin(\omega t)\,dt$$



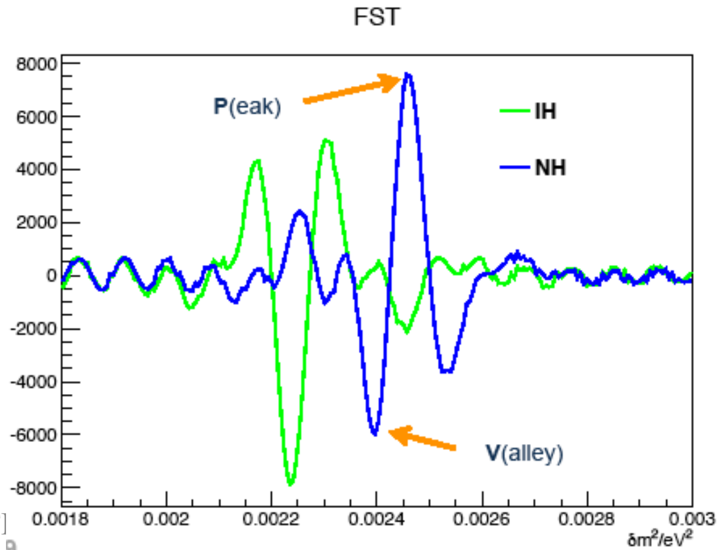
Discriminant variables:

$$RL = \frac{RV - LV}{RV + LV} \quad \text{(for FCT)}$$

$$PV = \frac{P - V}{P + V} \quad \text{(for FST)}$$

RL>0 and PV>0 →NH
RL<0 and PV<0 →IH

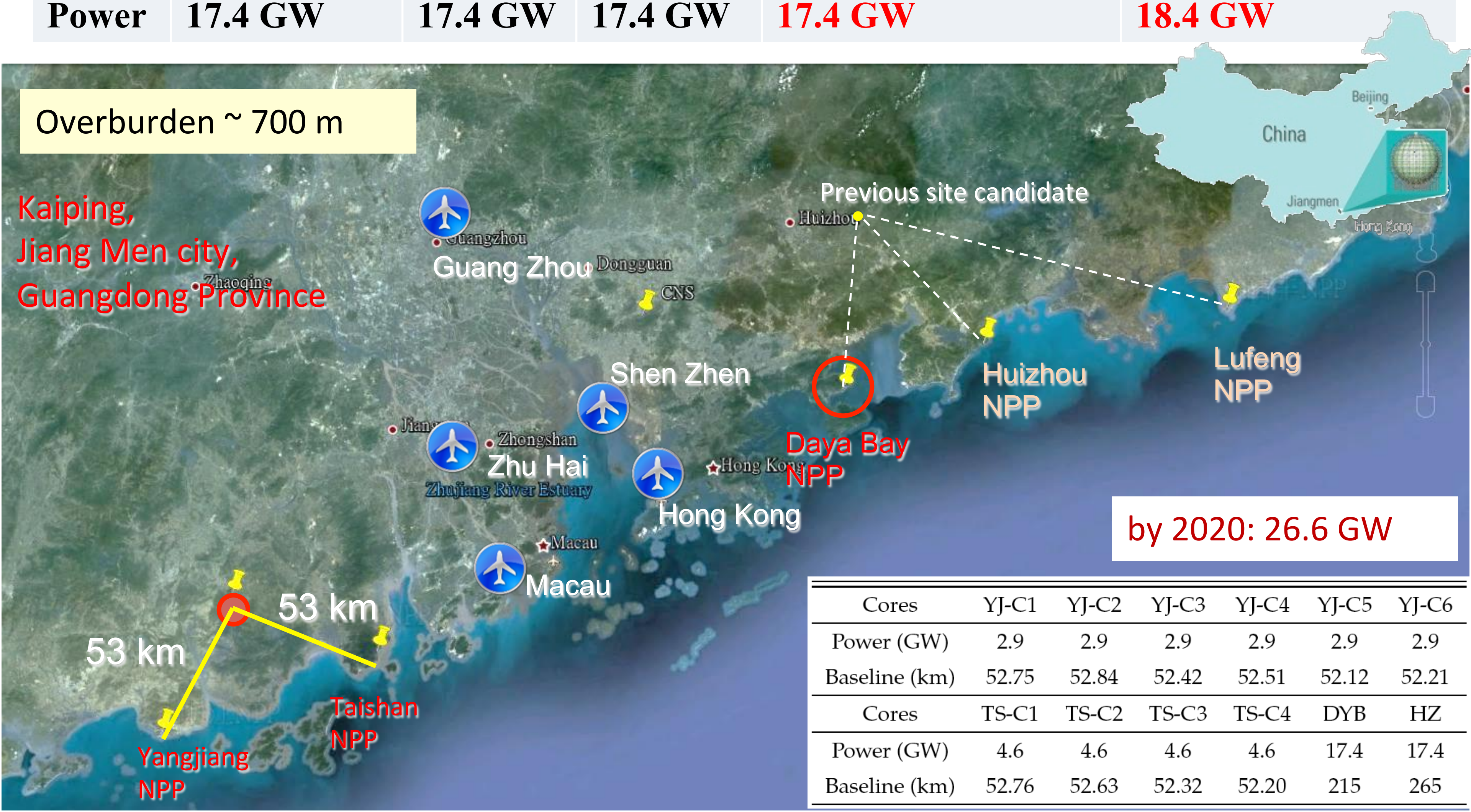
Statistical test of RL+PV



JUNO (55 institutes)

(under construction)

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



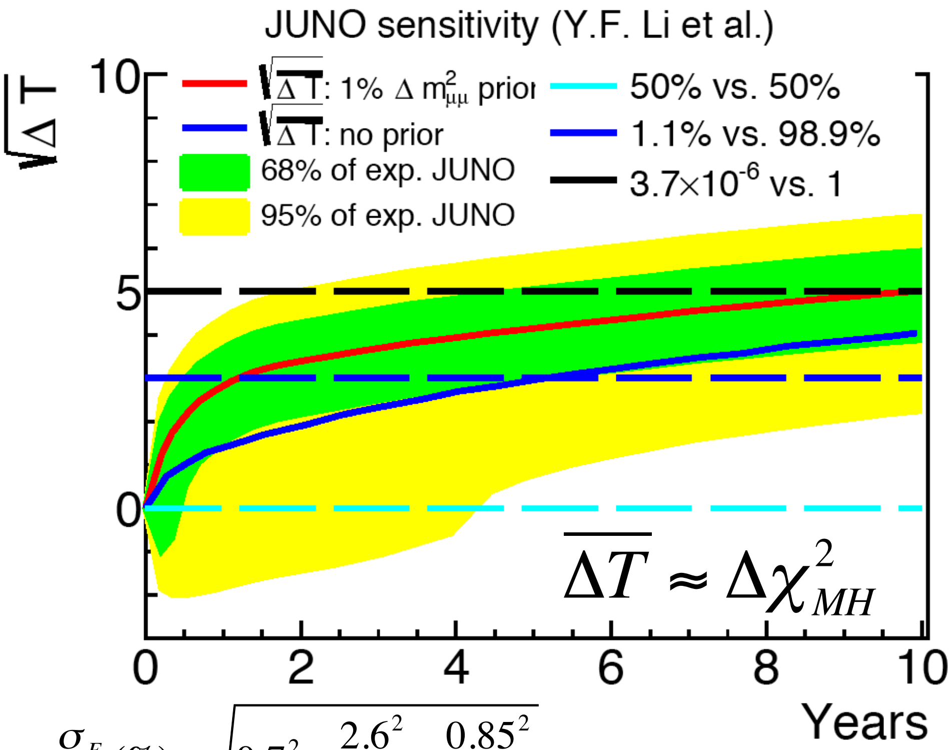
Overburden ~ 700 m

by 2020: 26.6 GW

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

Performance

PRD 88 013008 (2013)



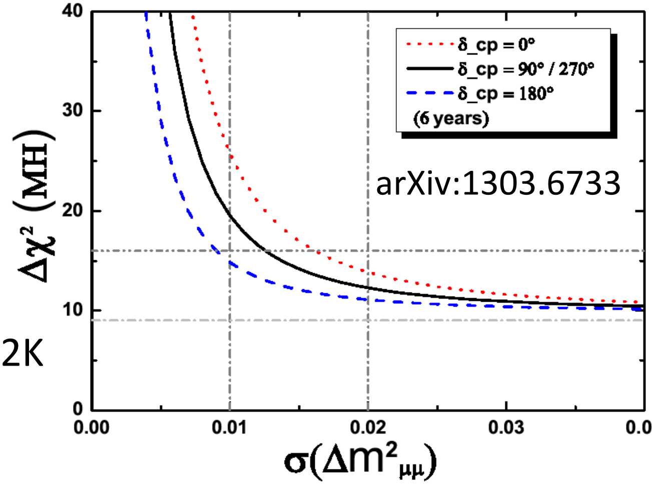
$$\frac{\sigma_E}{E}(\%) \sim \sqrt{0.7^2 + \frac{2.6^2}{E} + \frac{0.85^2}{E^2}}$$

$$\Delta m^2_{ee} \simeq \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32},$$

$$\Delta m^2_{\mu\mu} \simeq \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} + \sin 2\theta_{12}\sin\theta_{13}\tan\theta_{23}\cos\delta\Delta m^2_{21},$$

- Inputs
  - 100 kevents (6 years)
  - 3% @ 1 MeV energy resolution
  - 1% energy scale uncertainty
  - realistic backgrounds
- Sensitivity
  - JUNO only
    - 50% chance to have 3 σ or higher
    - 2.3% chance to have 5 σ or higher
  - JUNO + 1% $\Delta m_{\mu\mu}^2$
    - 84% chance to have 3 σ or higher
    - 16% chance to have 5 σ or higher

by NOvA, MINOS, T2K

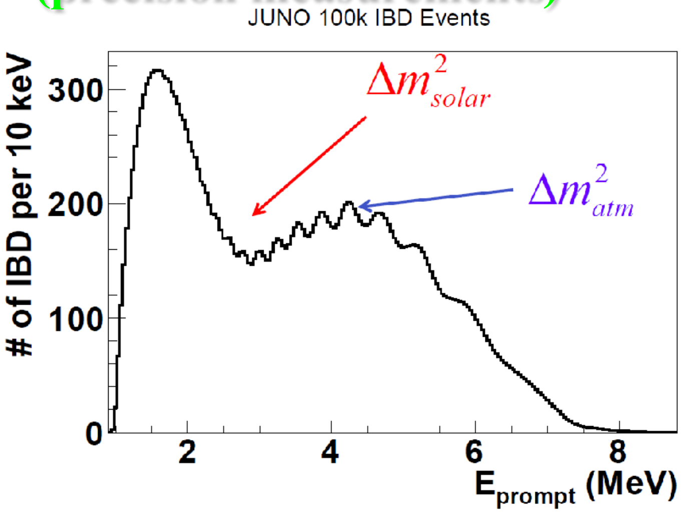


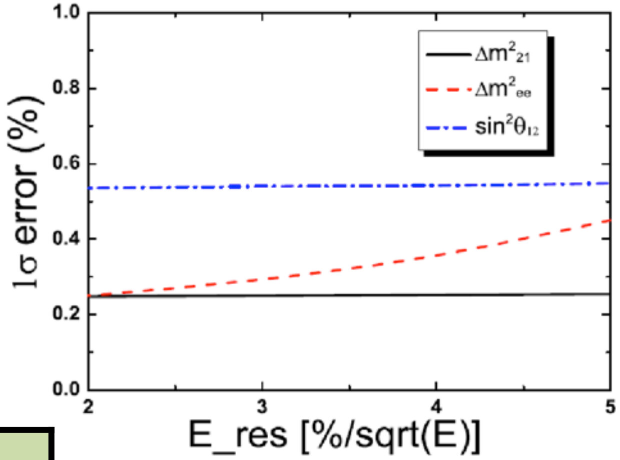
arXiv:1303.6733

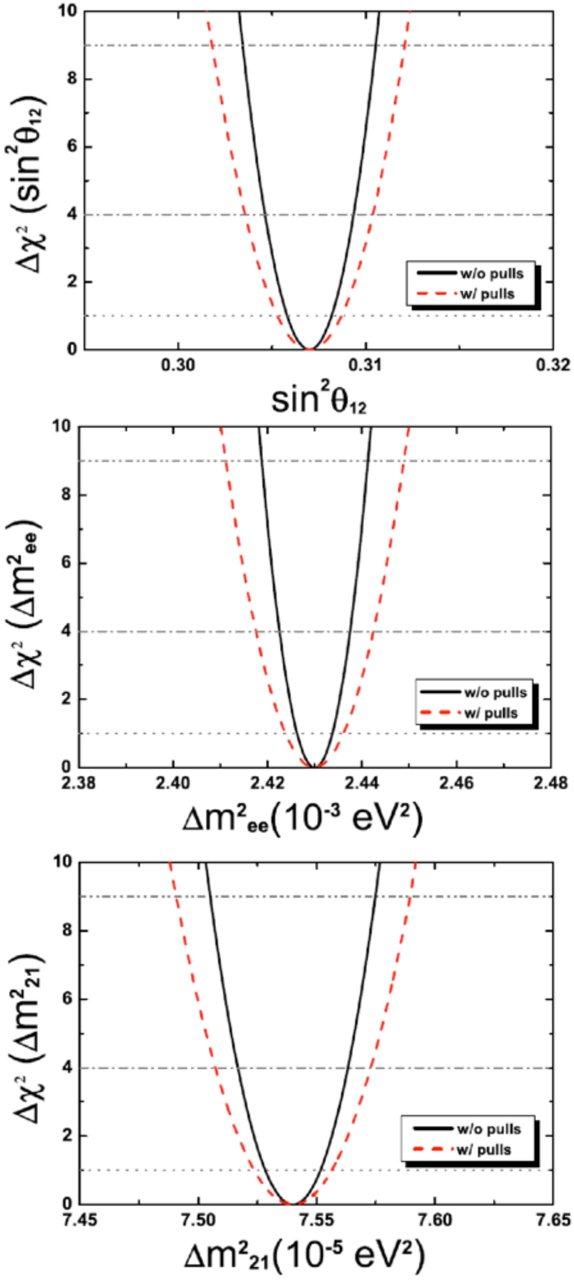
Oscillation parameters

(precision measurements)

- First experiment to observe:
  - simultaneously “solar” and “atmospheric” oscillations
  - more than two cycles of neutrino oscillations
- Complementary to long baseline accelerator program
- Probing the unitarity of U_{PMNS} to the sub-percent level!



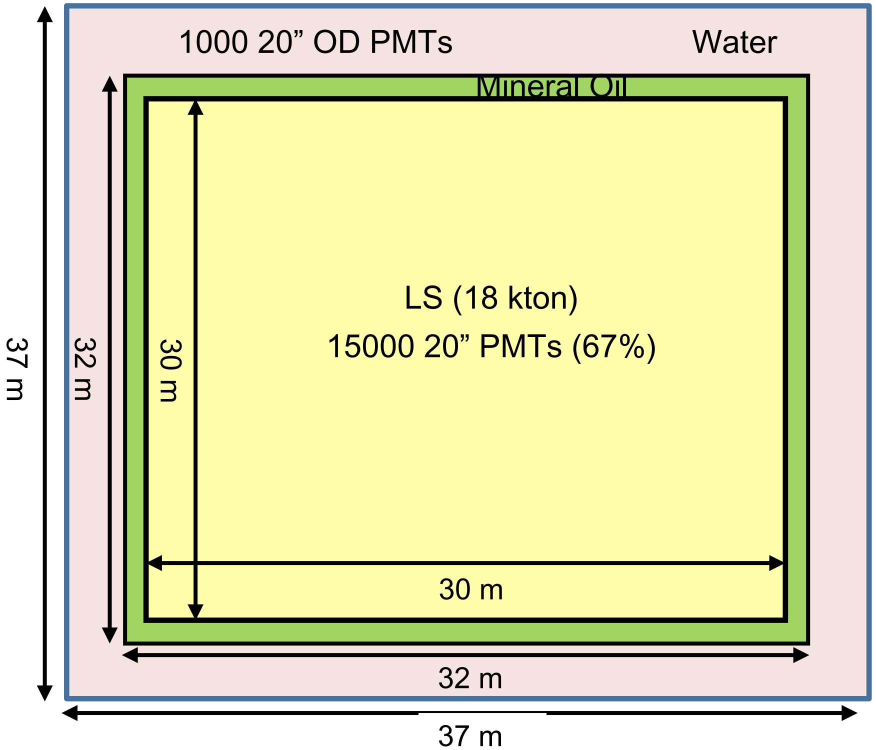




	Current	JUNO
Δm^2_{21}	~3%	~0.6%
Δm^2_{32}	~4%	~0.5%
$\sin^2\theta_{12}$	~7%	~0.7%

better precision than for CKM matrix elements

RENO-50



Mt. GuemSeong
Altitude : 450 m

- 18 kton liquid scintillator underground detector
- 15000 20" PMTs
- R&D funding ($ 2M in 3 years, 2015~2017) given by the Samsung Science & Technology Foundation.
- A proposal has been submitted to obtain construction funding.
- 2015:
  - Group organization
  - Detector simulation & design
  - Geological survey
- 2016 ~ 2017 :
  - Civil engineering for tunnel excavation, Underground facility ready, Structure design,
  - PMT evaluation and order, Preparation for electronics, HV, DAQ & software tools, R&D for liquid scintillator and purification
- 2018 ~ 2020 : Detector construction
- 2021 ~: Data taking & analysis

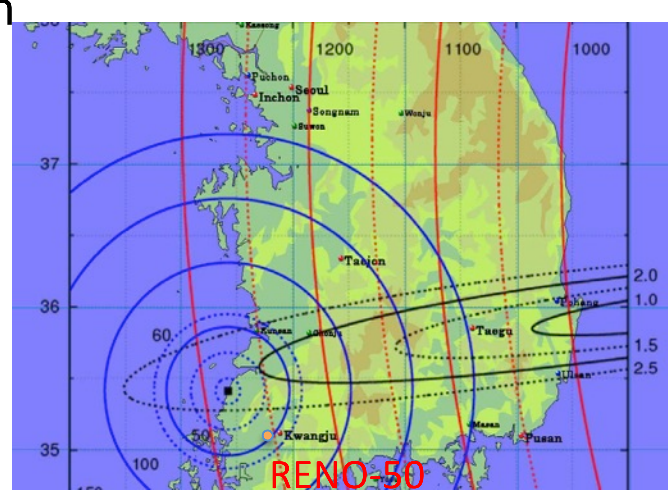
RENO-50 physics

- Determination of neutrino mass hierarchy
  - 3 σ sensitivity from 5 years of data
- Precise measurement of θ_{12}, Δm^2_{21} and Δm^2_{32}

$$\frac{\delta \sin^2\theta_{12}}{\sin^2\theta_{12}} < 1.0\%(1\sigma) \qquad \frac{\delta\Delta m^2{}_{21}}{\Delta m^2{}_{21}} < 1.0\%(1\sigma) \qquad \frac{\delta\Delta m^2{}_{32}}{\Delta m^2{}_{32}} < 1.0\%(1\sigma)$$

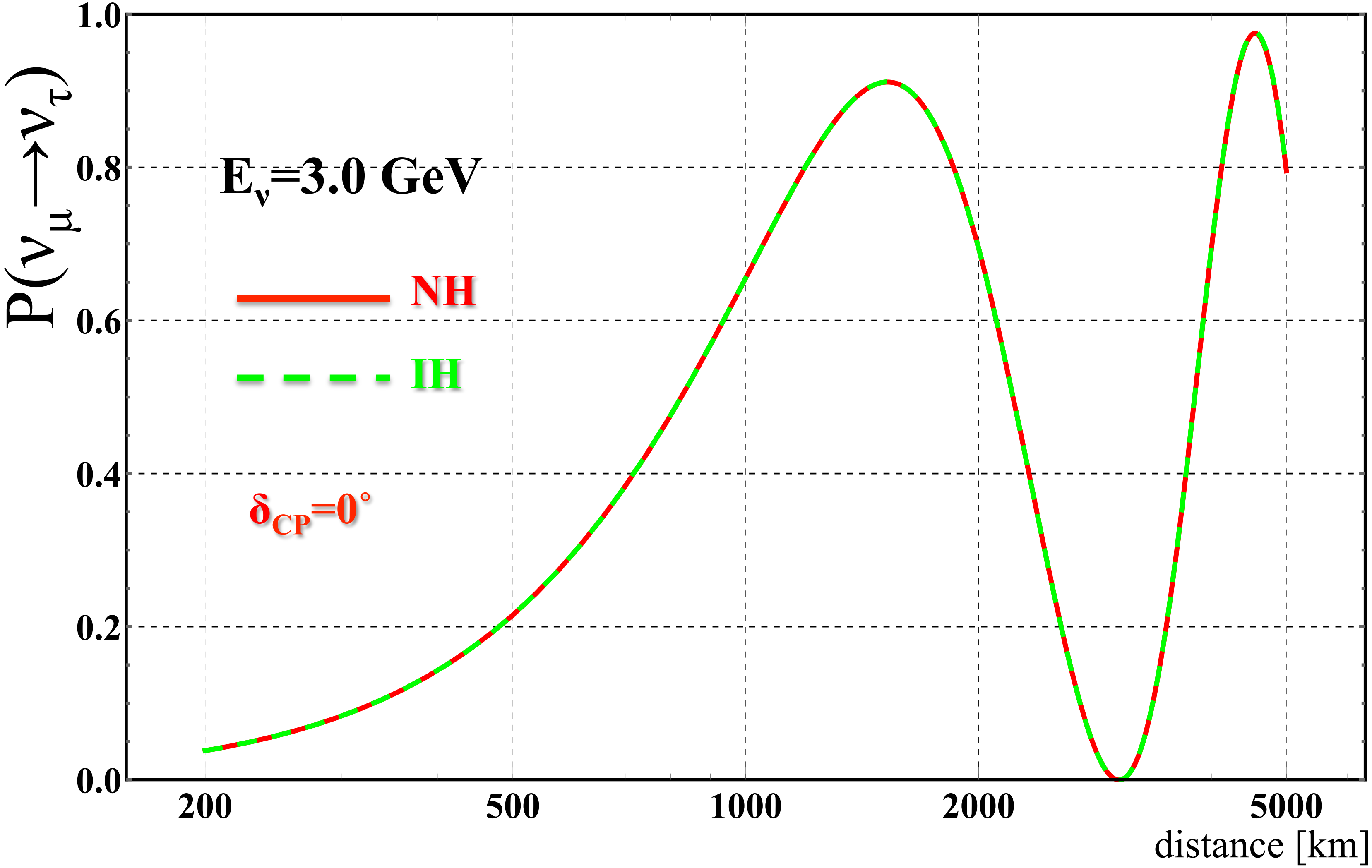
- Neutrino burst from a Supernova in our Galaxy
  - ~5,600 events (@8 kpc)
- Geo-neutrinos : ~ 1,000 geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth
- Solar neutrinos : with ultra low radioactivity
  - MSW effect on neutrino oscillation and solar models

Detection of J-PARC beam (Hyper-K): ~200 events/year



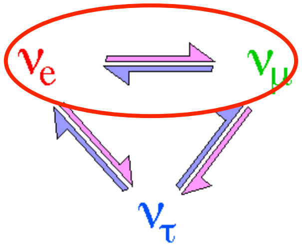
Oscillation probability

(negligible matter effect)

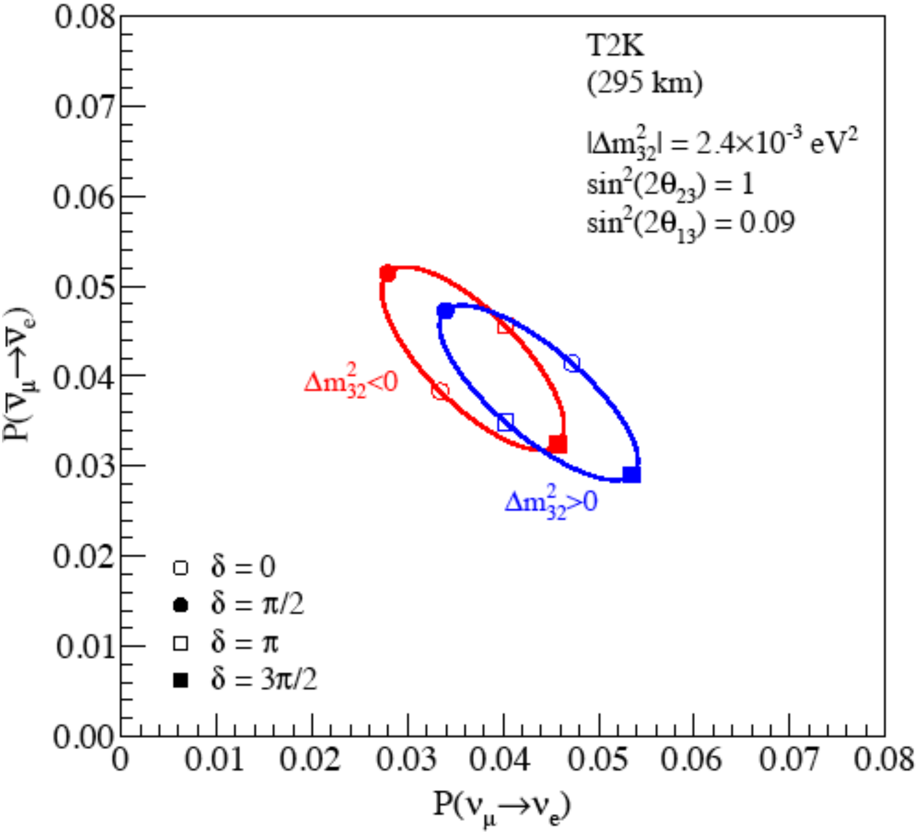


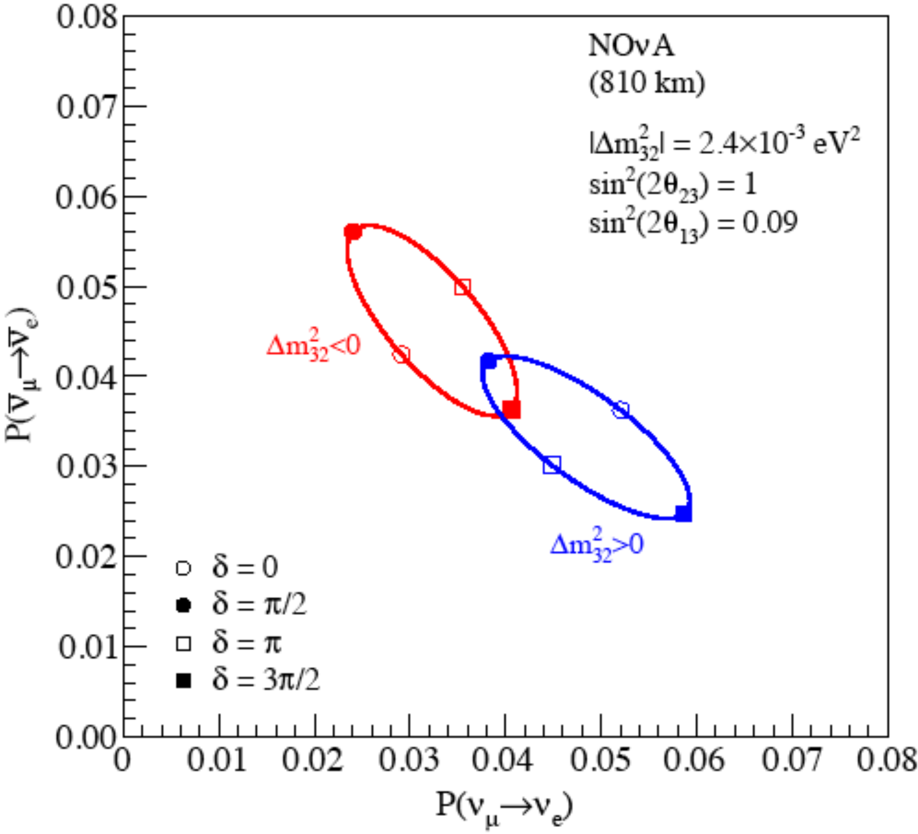
Present accelerator neutrino oscillation facilities in the world

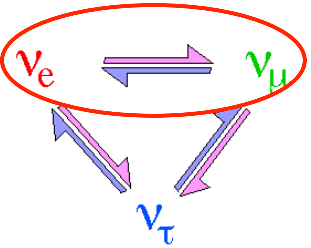
JPARC beam and T2K experiment
(appearance/disappearance, off-axis,
E_ν~0.6 GeV, L=295 km)



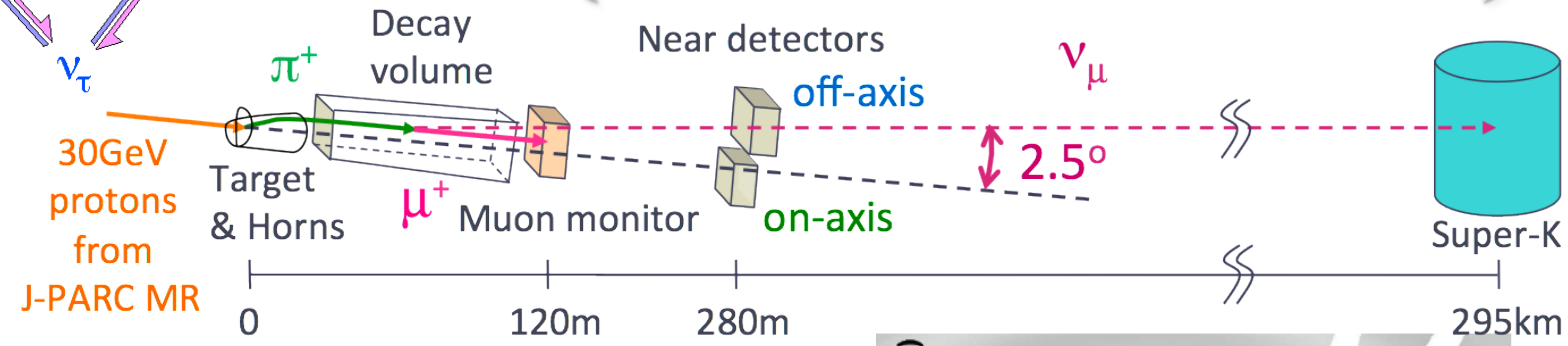
NOvA, same beam than MINOS,
off-axis, E_ν~2 GeV, L=810 km.







T2K (θ_{13} on accelerators)



Very intense proton beam
(0.75 MW nominal power, 30 GeV)
Off-axis (2.5 deg.)
< E > 0.7 GeV