

Journées prospectives du LLR

L'expérience neutrino JUNO et la hiérarchie des masses

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Outline

- Neutrino Oscillation formalism
- Neutrino mass hierarchy
 - Importance this measurement
 - Present neutrino oscillation experiments
 - Future projects
- JUNO experiment
- Conclusions



2015 NOBEL PRIZE
in Physics

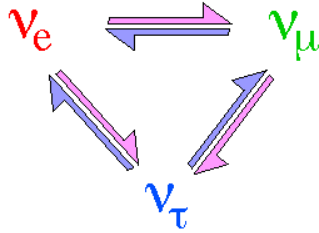


NEUTRINO OSCILLATIONS
The discovery of these oscillations shows that neutrinos have mass.



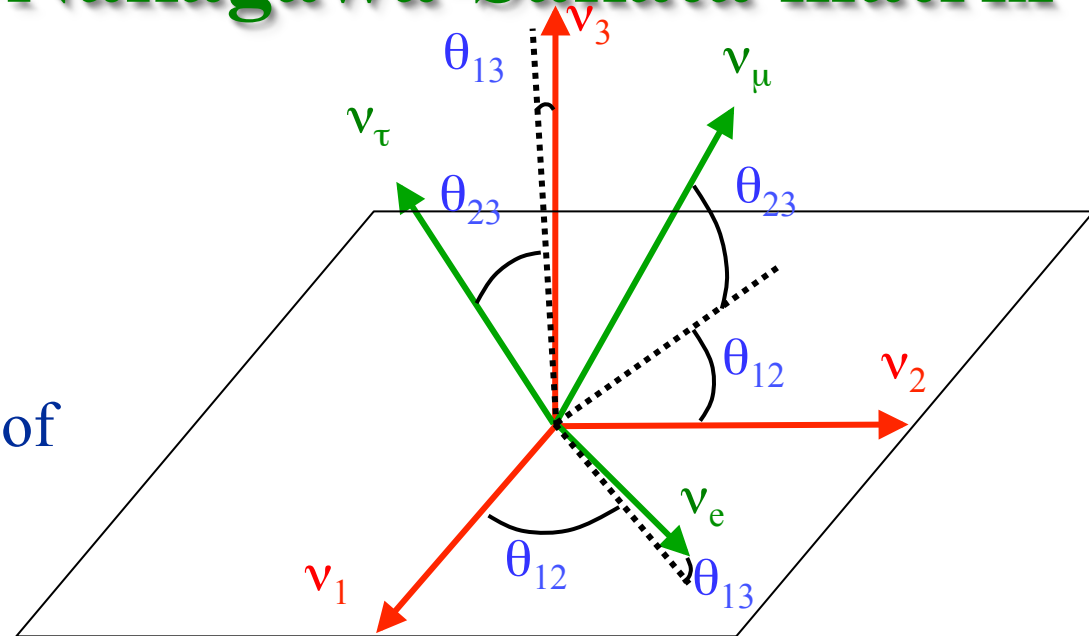
Illustration: © Johan Jarnefeldt/The Royal Swedish Academy of Sciences

Pontecorvo-Maki-Nakagawa-Sakata matrix



Usual parametrization (in case of Dirac neutrinos):

$$U_{\alpha i} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$



with $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$

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

atmospheric,
accelerators

reactors,
accelerators
CP violation

solar,
reactors

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

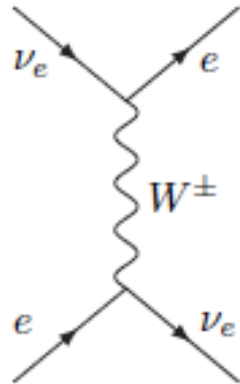
How neutrinos propagate through matter?

(Mikheyev-Smirnov-Wolfenstein effect)

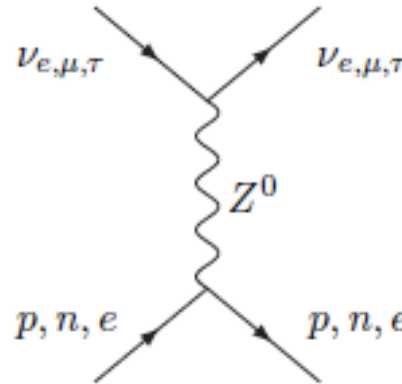
$$| \nu_j(t) \rangle = e^{-iHt/\hbar} | \nu_j(0) \rangle$$

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

only for
electron
neutrinos



CC



NC

in "ordinary" matter

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

with: $a = 2EV_{CC} = 2\sqrt{2}EG_F N_e \approx 7.56 \times 10^{-5} \text{ eV}^2 \left(\frac{\rho}{\text{g/cm}^3} \right) \left(\frac{E}{\text{GeV}} \right)$ ($\rho \sim 3 \text{ g/cm}^3$ for earth crust)

Probability as a function of mixing angles

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

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

$$\Delta m_{ij}^2 = m_j^2 - m_i^2 \quad (3 \text{ mass differences but only 2 are independent})$$

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

replace: $U \rightarrow U^*$

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

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



CP violation
(never observed up
to now)

if this term $\neq 0$

Present measurements

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

$$\Delta m_{21}^2 = (7.50 \pm 0.19) \times 10^{-5} \text{ eV}^2$$

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

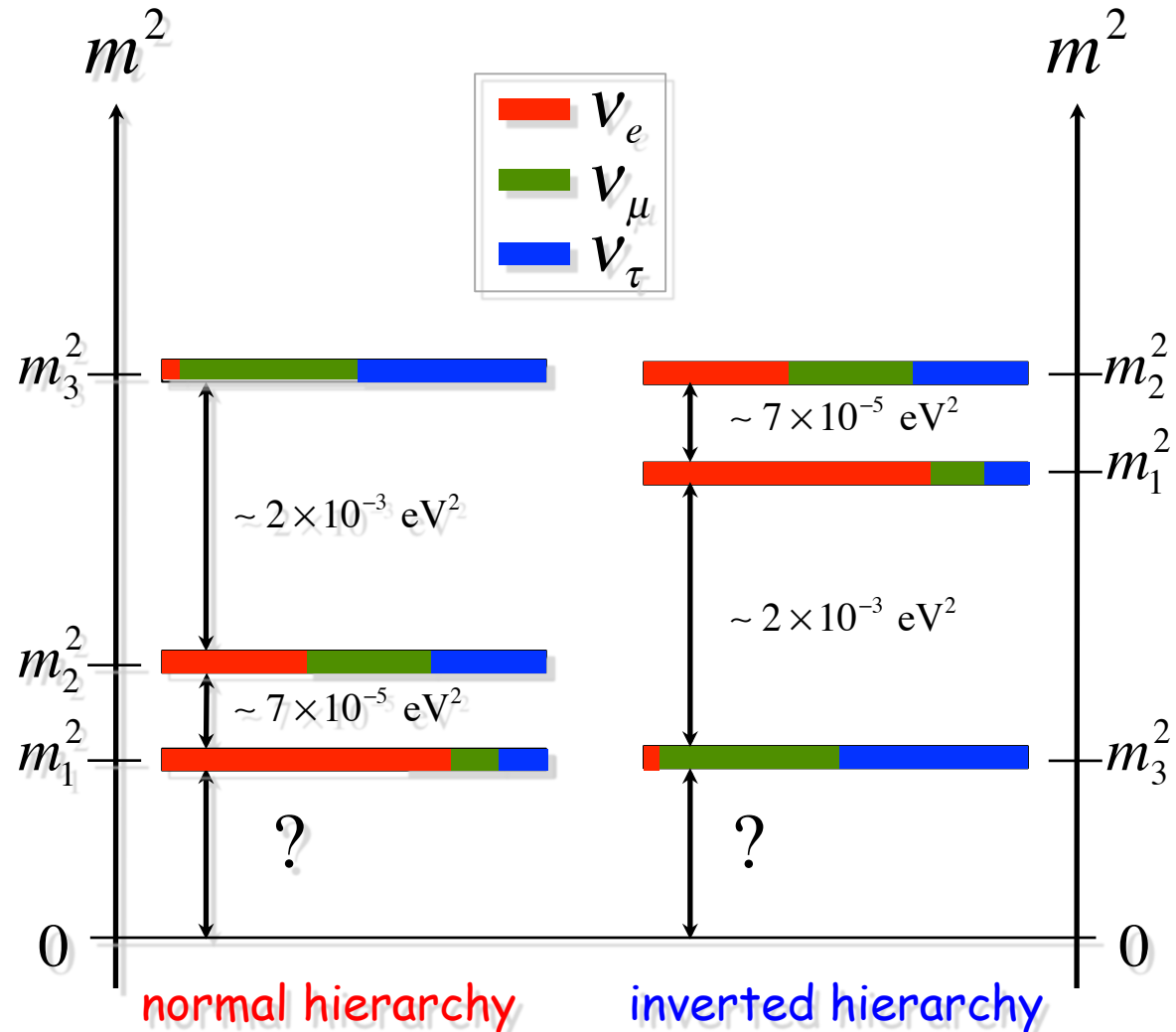
$$|\Delta m_{31}^2| = (2.46 \pm_{-0.05}^{+0.05}) \times 10^{-3} \text{ eV}^2$$

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

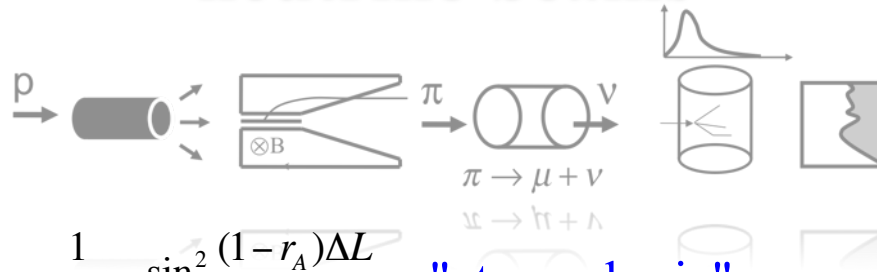
$$\theta_{13} = 8.4^\circ \pm 0.3^\circ \text{ (from DB)}$$

oscillation observed in 2012

~(almost) no information on δ_{CP}



Oscillation probability neutrino beams



$$P_{\nu_\mu \rightarrow \nu_e (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \simeq 4s_{23}^2 s_{13}^2 \frac{1}{(1-r_A)^2} \sin^2 \frac{(1-r_A)\Delta L}{2} \quad \text{"atmospheric"}$$

$$+ 8J_r \frac{r_\Delta}{r_A(1-r_A)} \cos\left(\delta_{CP} - \frac{\Delta L}{2}\right) \sin \frac{r_A \Delta L}{2} \sin \frac{(1-r_A)\Delta L}{2} \quad \text{"interference"}$$

$$+ 4c_{23}^2 c_{12}^2 s_{12}^2 \left(\frac{r_\Delta}{r_A}\right)^2 \sin^2 \frac{r_A \Delta L}{2} \quad \text{"solar"}$$

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

- for antimatter: $\delta_{CP} \rightarrow -\delta_{CP}$ and $a \rightarrow -a$
 - **fake matter/antimatter asymetry due to matter effect**
 - for NH: $\Delta m_{31}^2 \rightarrow |\Delta m_{31}^2|$
 - for IH: $\Delta m_{31}^2 \rightarrow -|\Delta m_{31}^2|$
- δ_{CP} dependence,
 - sizable matter effect for long baselines

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

Oscillation probability

reactor neutrinos



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

with:

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

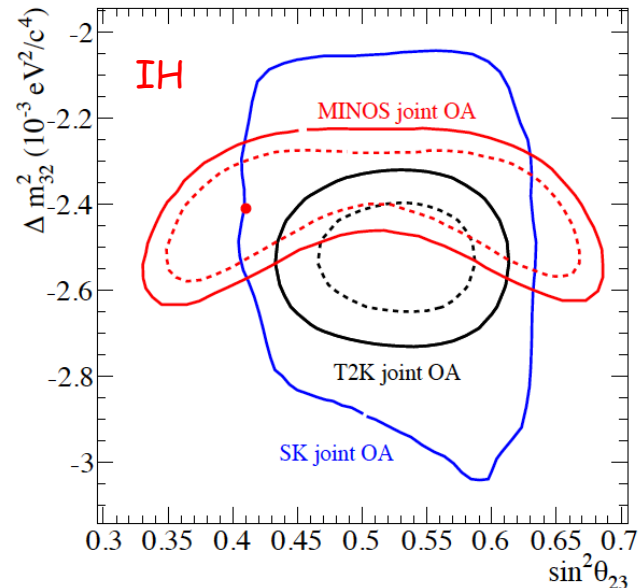
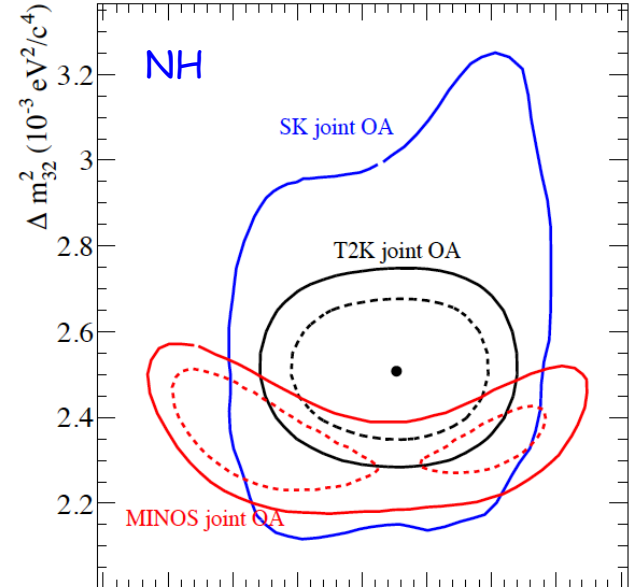
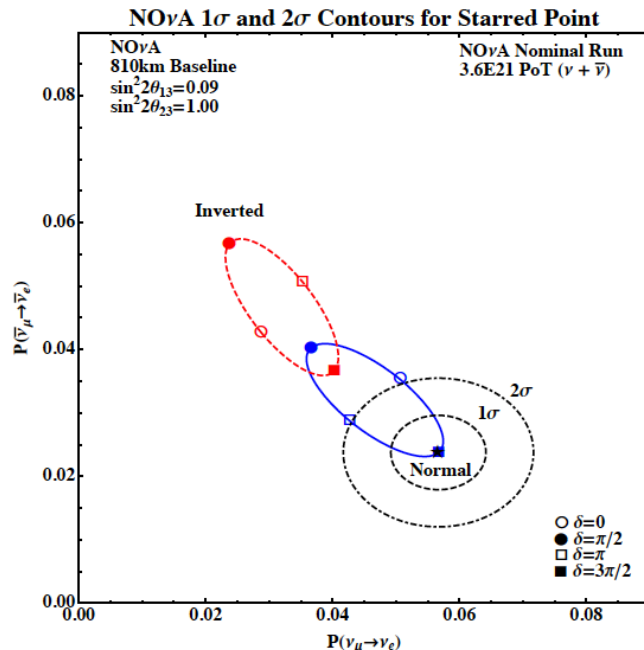


- Mass hierarchy measurement possible, thanks to the relatively large θ_{13} value
- no δ_{CP} dependence
- matter effect negligible

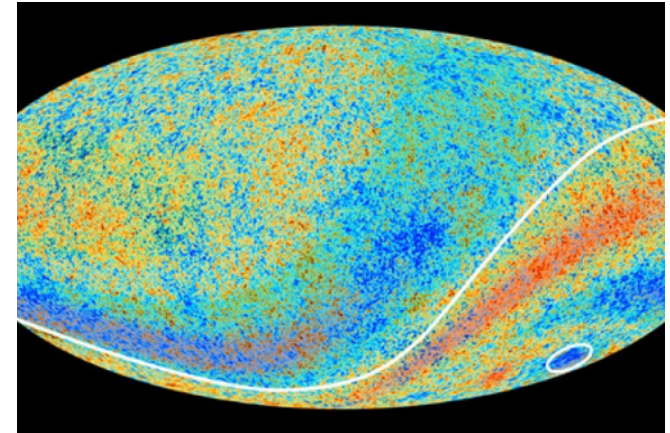
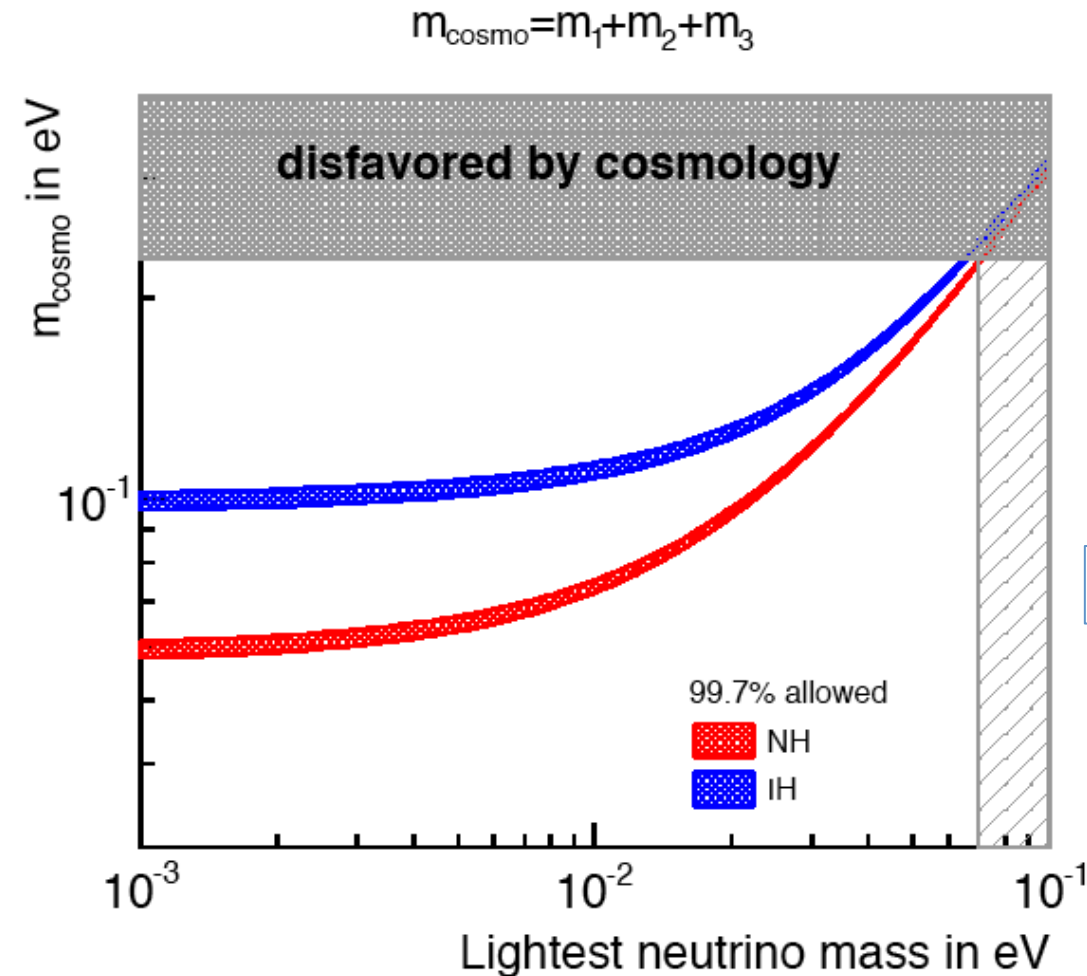
Why to measure MH?

arXiv:1507.08134

- 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



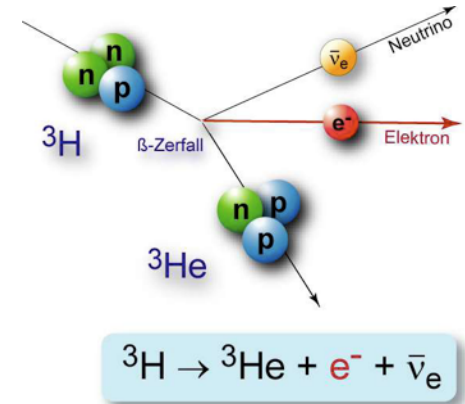
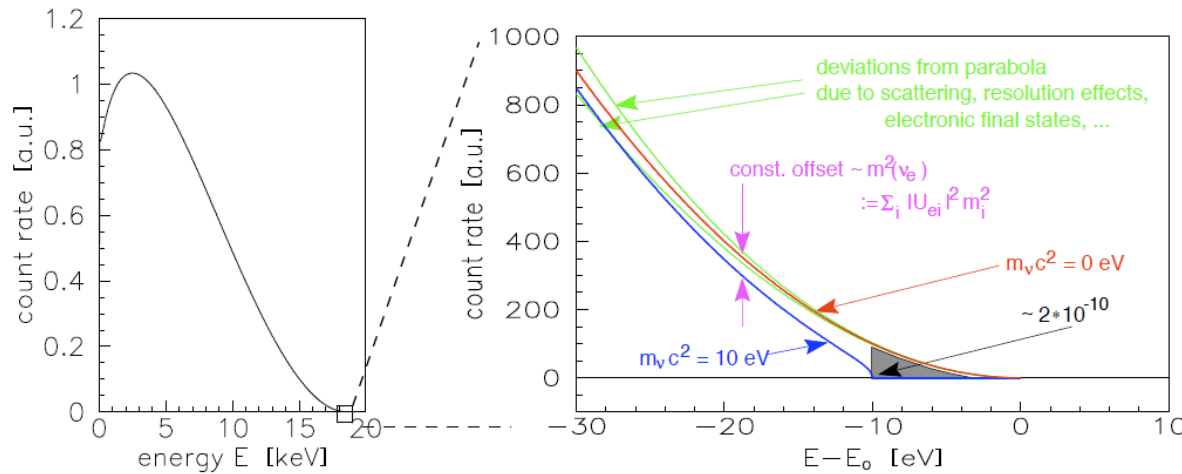
from cosmology

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

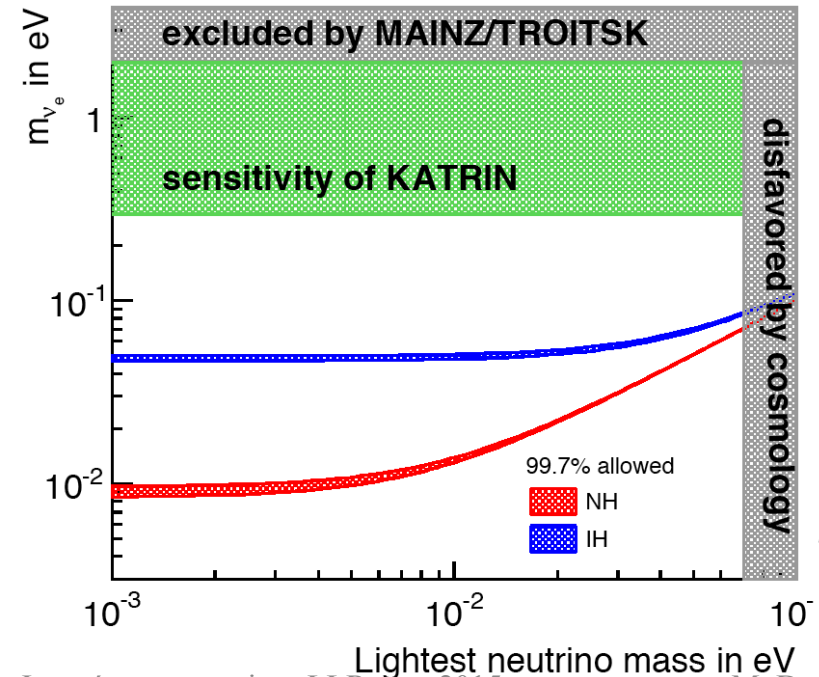
arXiv:1505.01891
(3 σ uncertainty on all mixing parameters)

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

MH and direct neutrino mass measurements



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



from direct mass measurements

if $m_{\nu_e} < 0.05$ eV $\Rightarrow$ NH

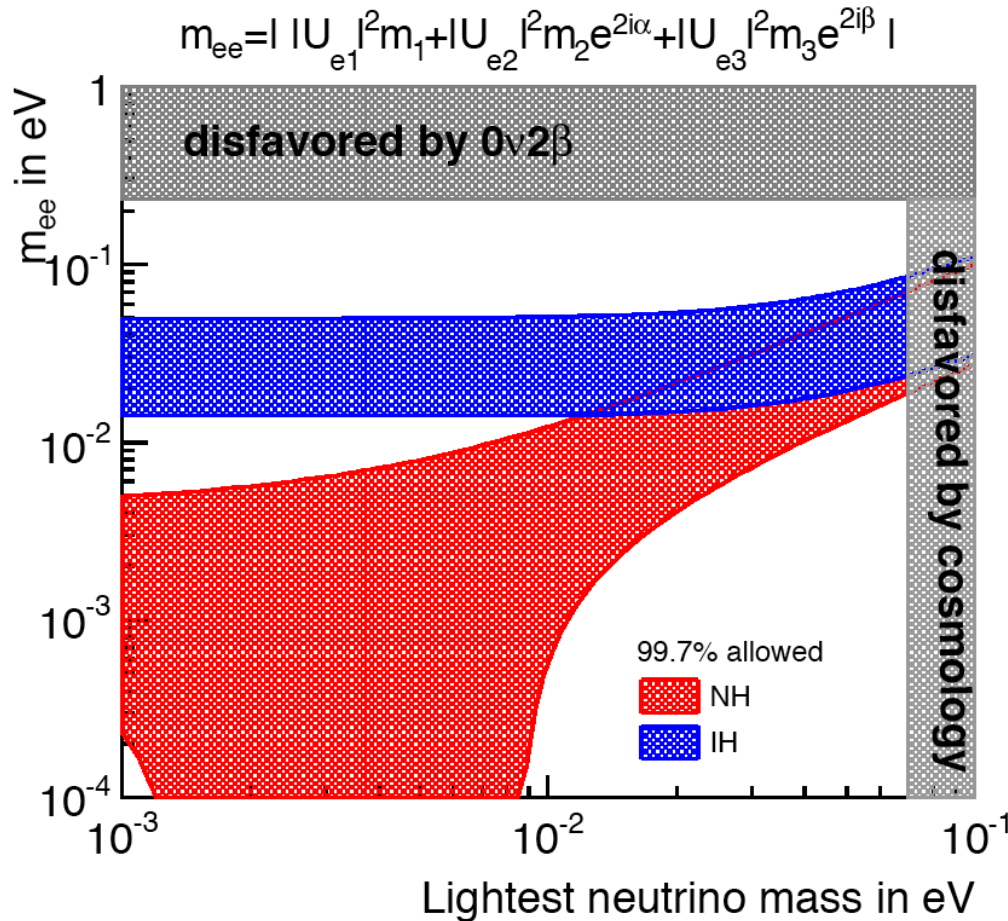
arXiv:1505.01891

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

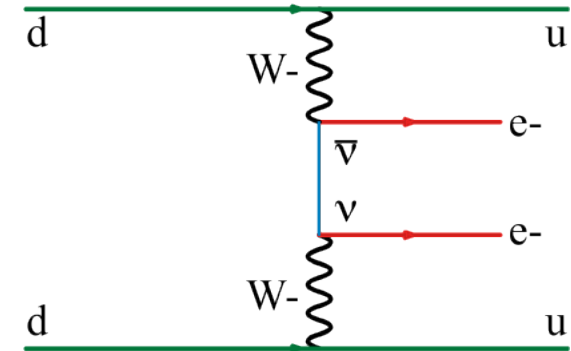
Lightest neutrino mass in eV

MH and neutrinoless Double Beta Decay

arXiv:1505.01891



from double beta decay (Dirac or Majorana particles)

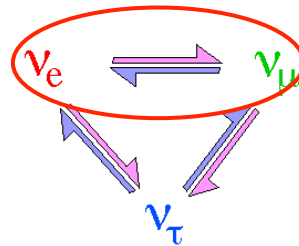
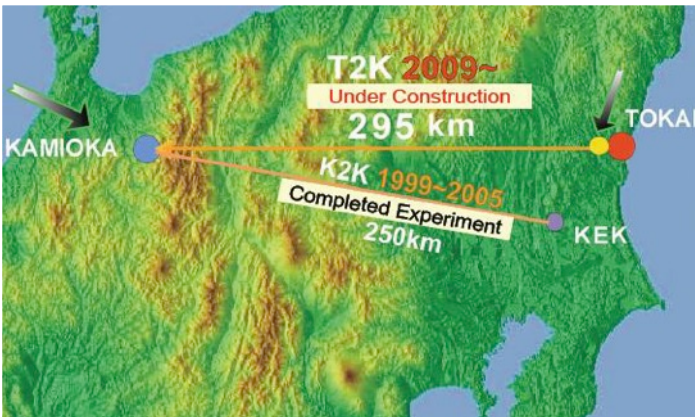


- if $m_{ee} > 0.015 \text{ eV} \Rightarrow \text{IH} \Rightarrow$ future Double Beta Decay experiments could observe neutrinoless DBD (Majorana neutrinos)
- else, if NH, possibly hard time for DBD experiments.

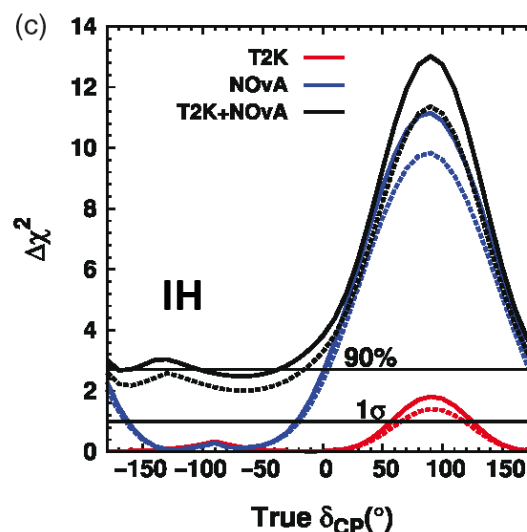
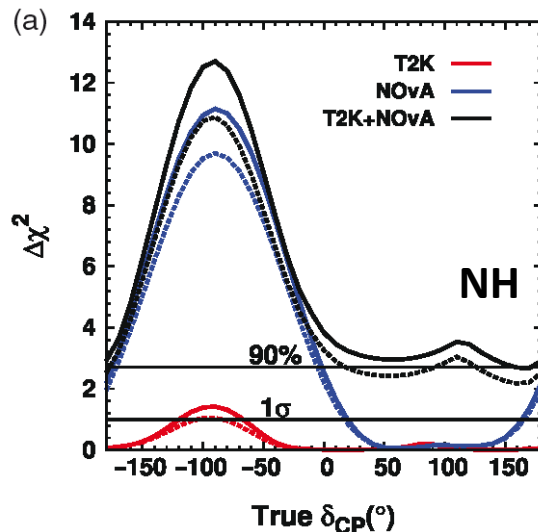
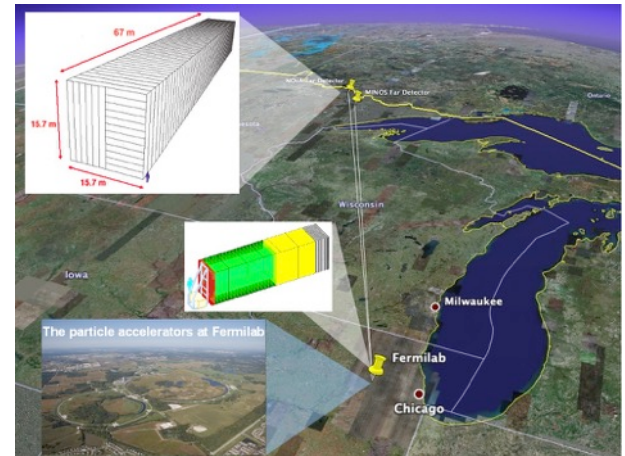
$$m_{ee}^2 = \begin{cases} (c_{12}^2 c_{13}^2 m_L^2 + c_{13}^2 s_{12}^2 \sqrt{m_L^2 + \Delta m_{21}^2} \cos 2\alpha + s_{13}^2 \sqrt{m_L^2 + |\Delta m_{31}^2|} \cos 2\beta)^2 + \\ (c_{13}^2 s_{12}^2 \sqrt{m_L^2 + \Delta m_{21}^2} \sin 2\alpha + s_{13}^2 \sqrt{m_L^2 + |\Delta m_{31}^2|} \sin 2\beta)^2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

Present accelerator neutrino oscillation facilities in the world

JPARC beam and T2K experiment
(appearance/disappearance, off-axis,
 $E_\nu \sim 0.6$ GeV, $L=295$ km)



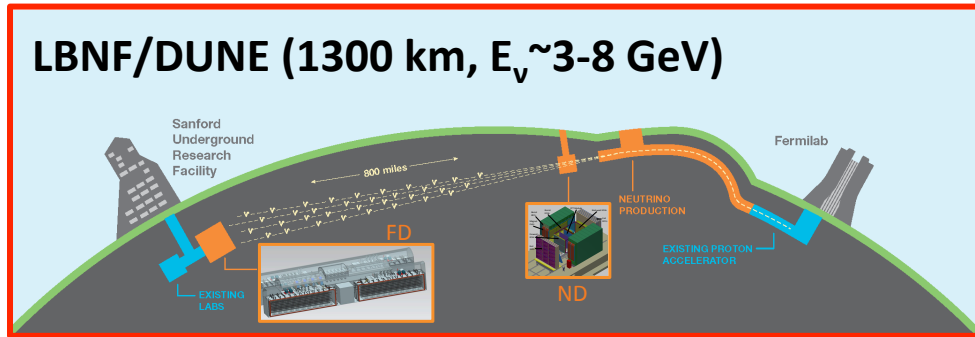
NOvA, same beam than MINOS,
off-axis, $E_\nu \sim 2$ GeV, $L=810$ km.



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

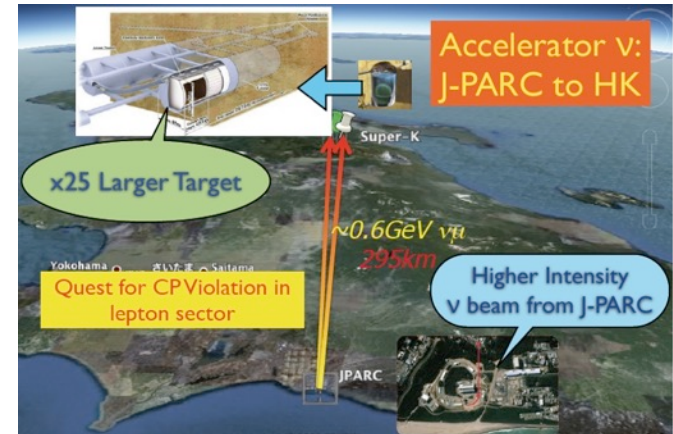
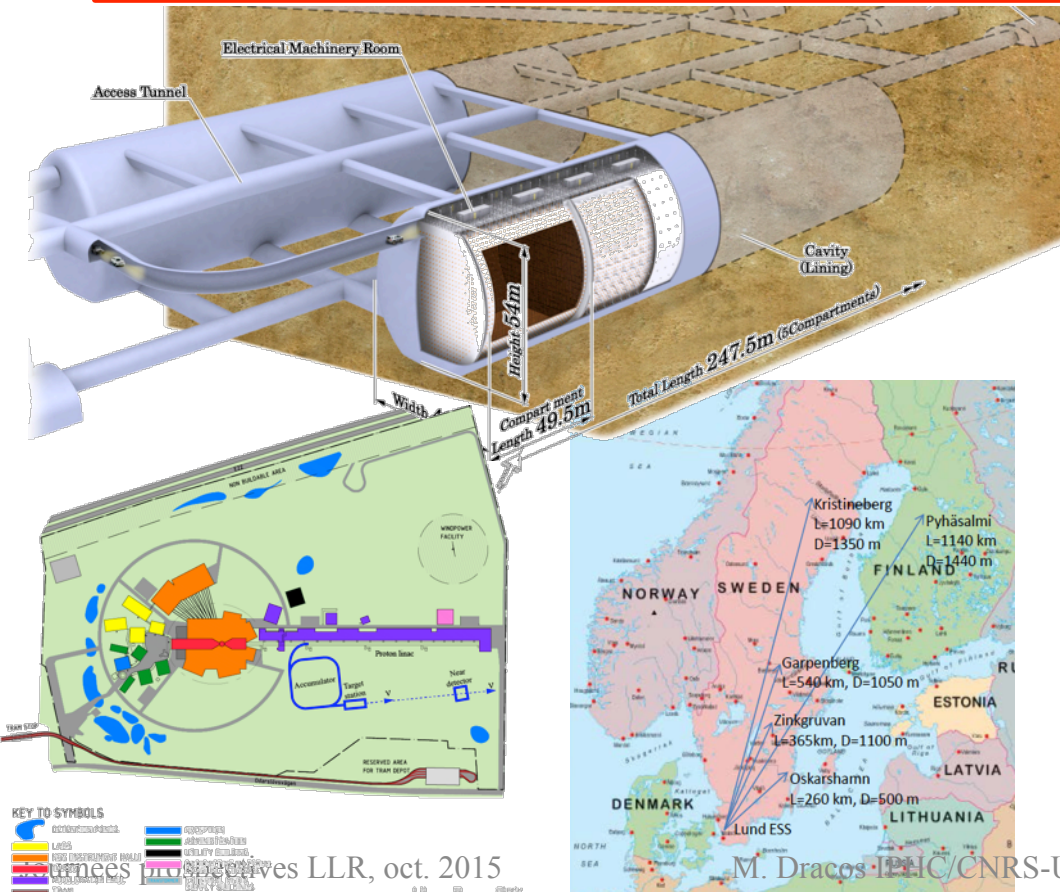
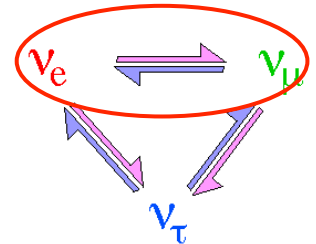
Future neutrino acceleration projects

(approved or not, >2025?)



DUNE

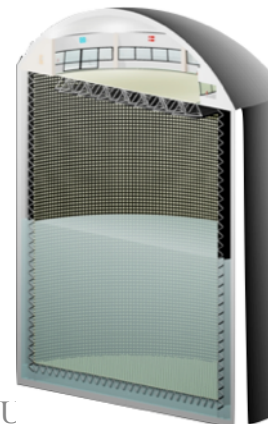
LAr



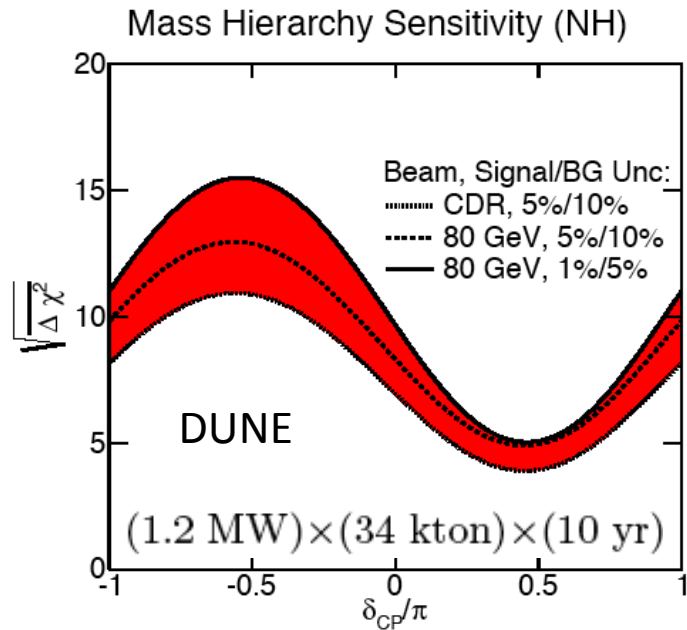
HyperK (295 km, $E_\nu \sim 0.6$ GeV)

Water Cherenkov

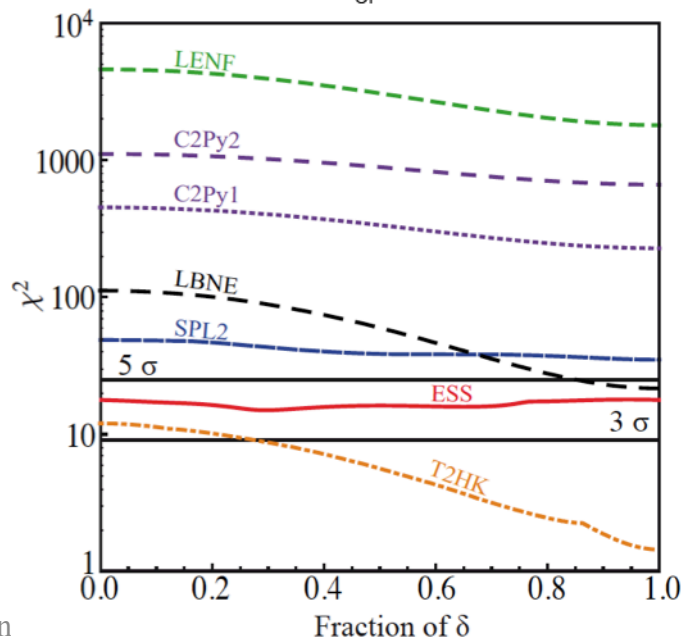
ESSvSB (540 km, $E_\nu \sim 0.4$ GeV, 5MW, ~ 500 kt)



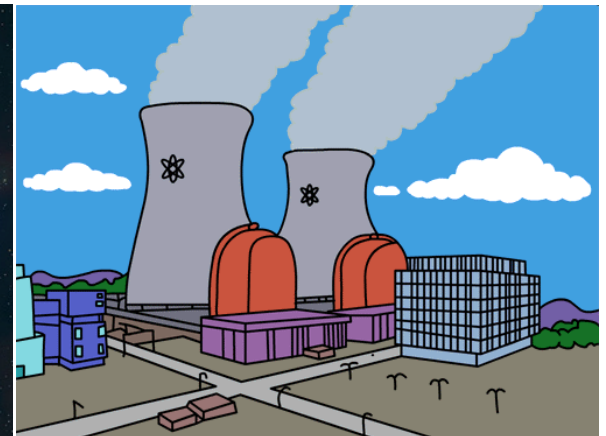
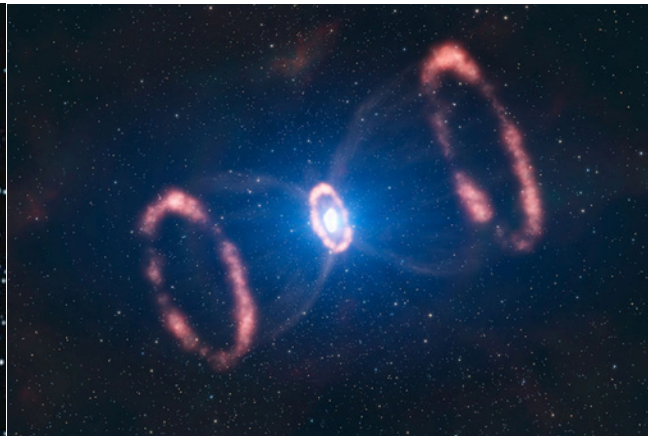
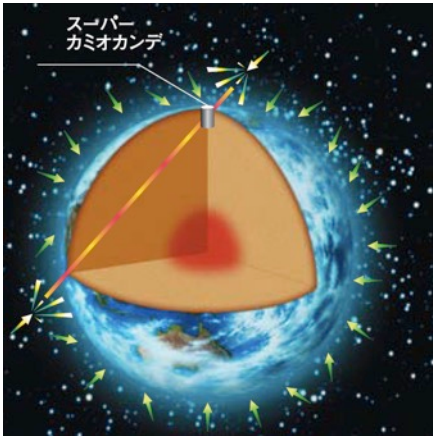
Future neutrino acceleration projects



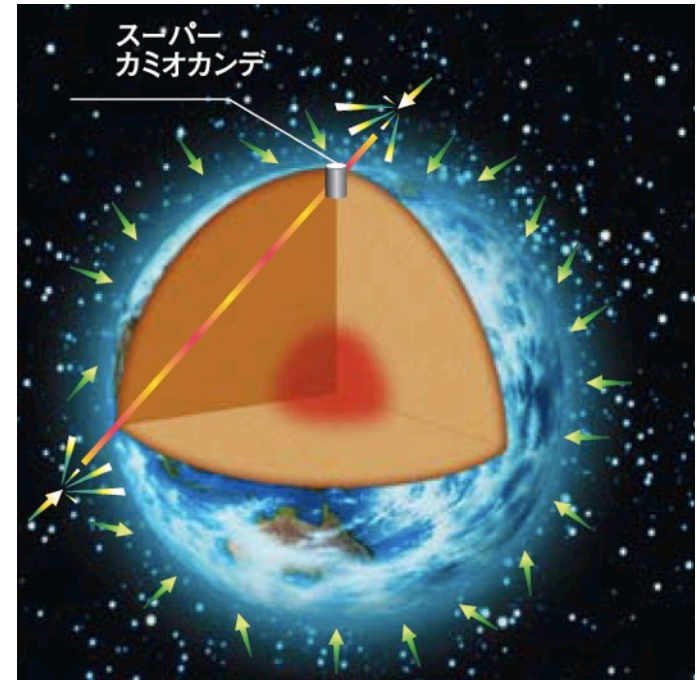
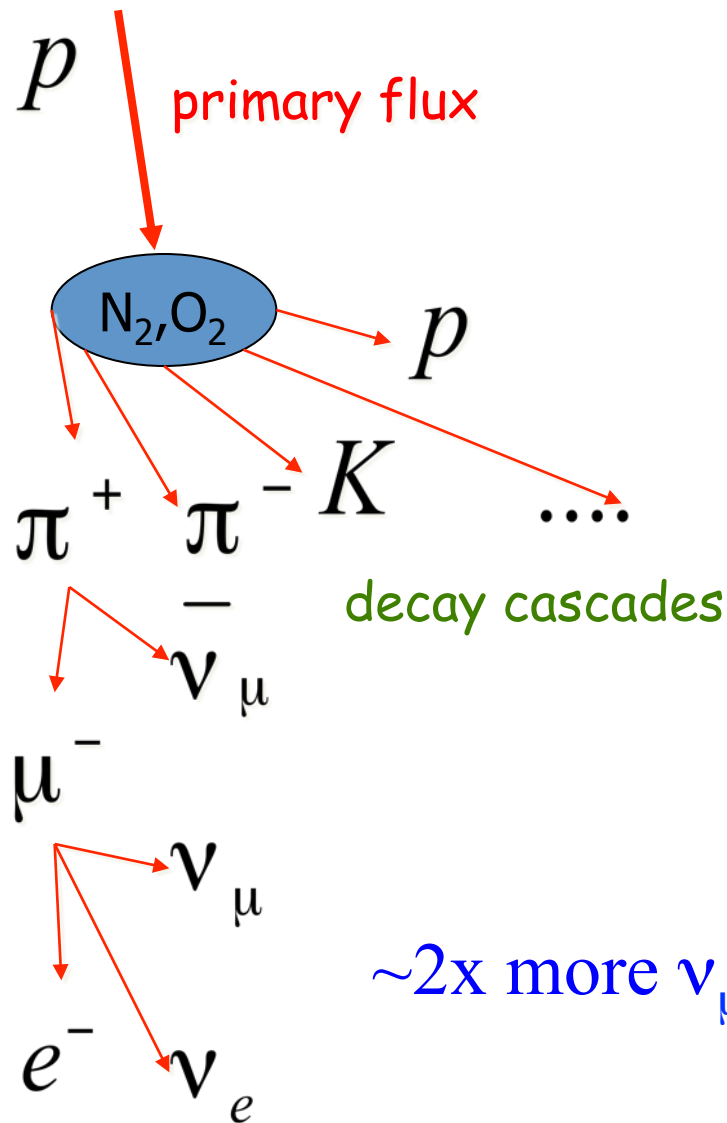
Very long baseline experiments are better for MH determination



Future neutrino non-acceleration projects (approved or not)



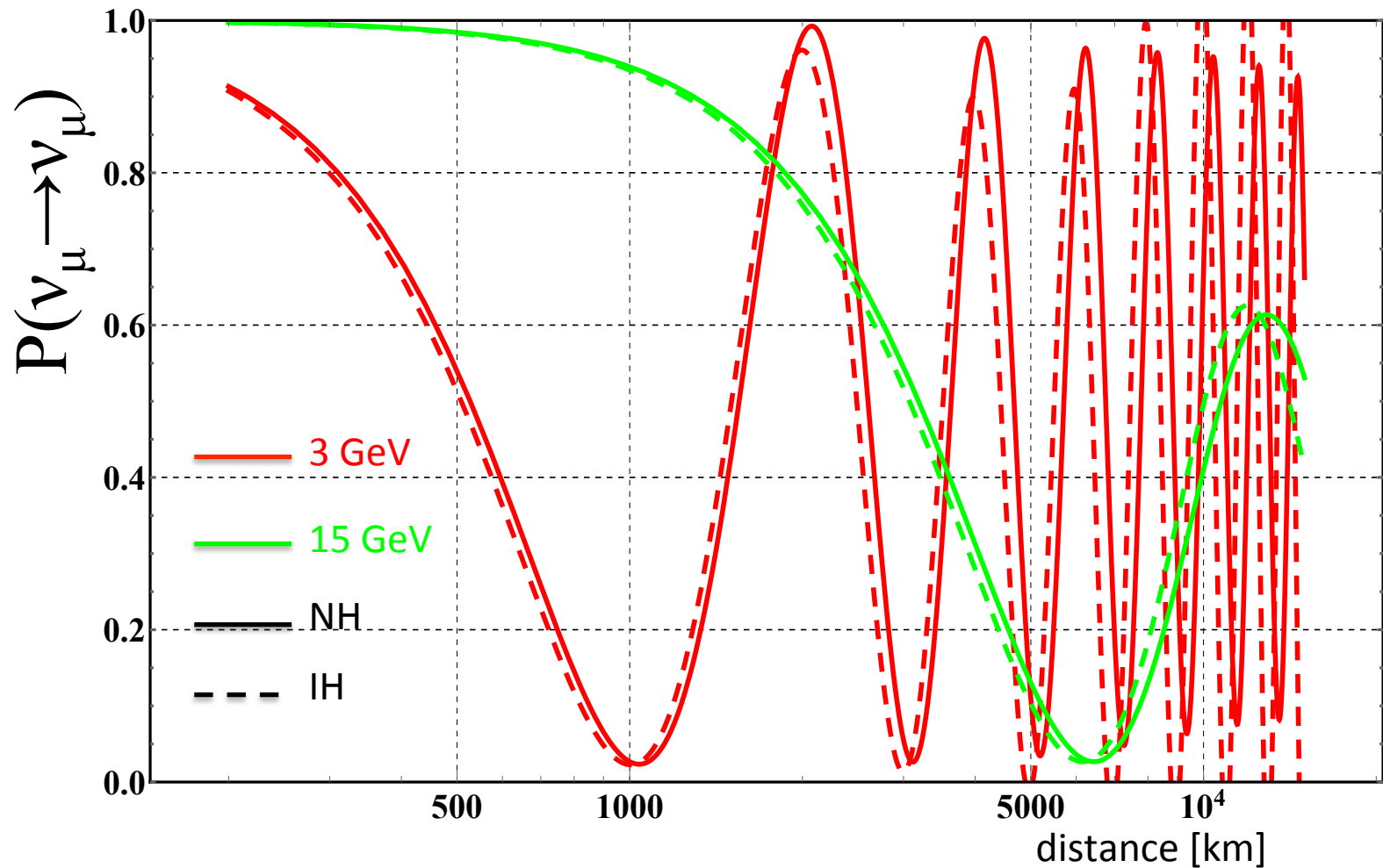
Using atmospheric neutrinos



neutrinos arrive from all directions

Atmospheric neutrinos

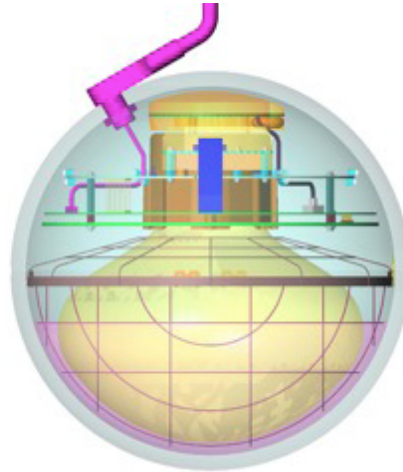
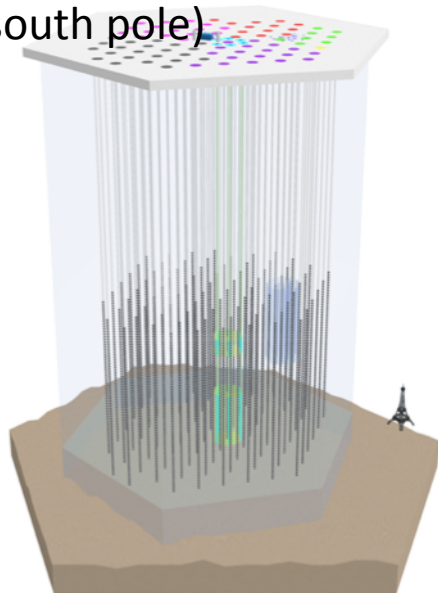
integrate all neutrinos between 3 and 15 GeV



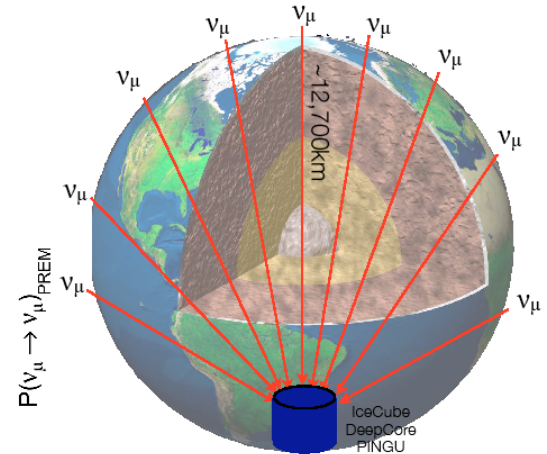
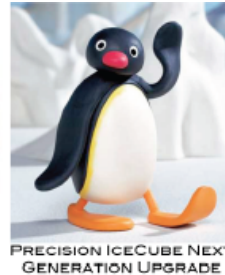
Large Water Cherenkov detectors

(neutrino mass hierarchy)

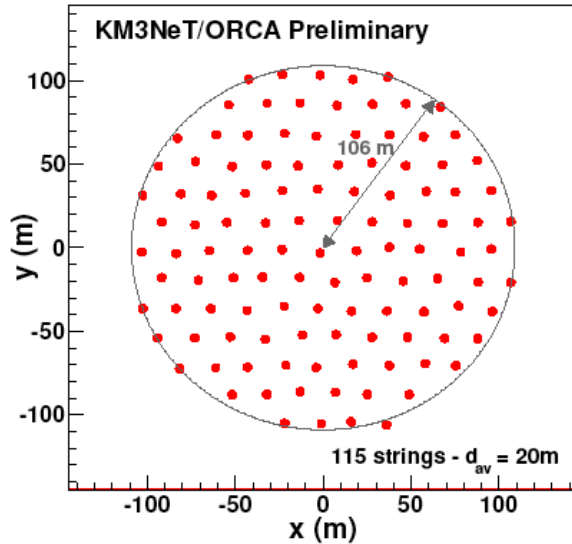
ICE Cube
(south pole)



PINGU



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

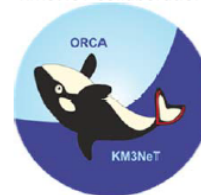


115 strings each carrying 18 DOMs



ORCA

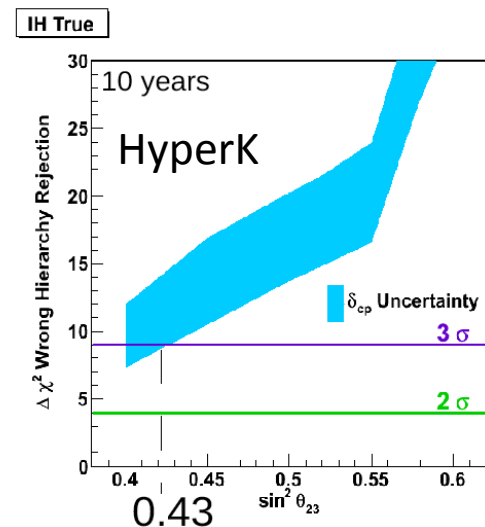
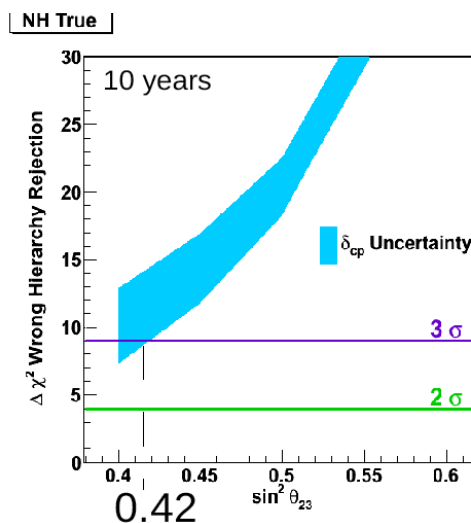
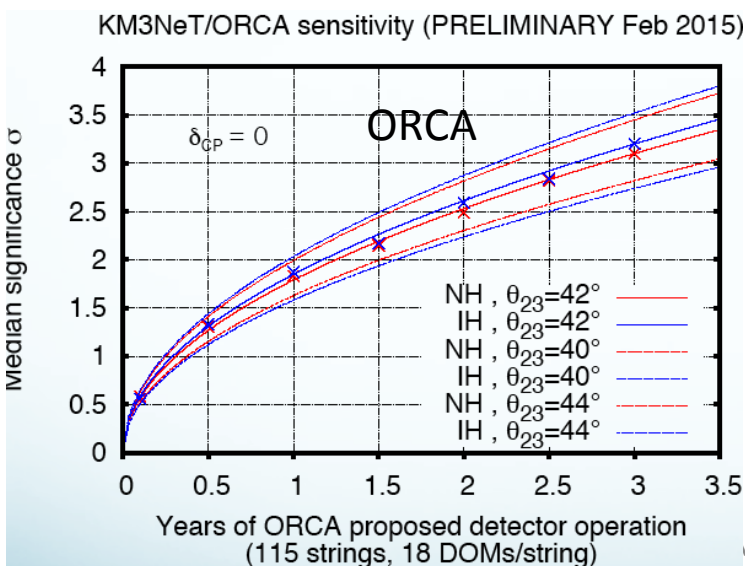
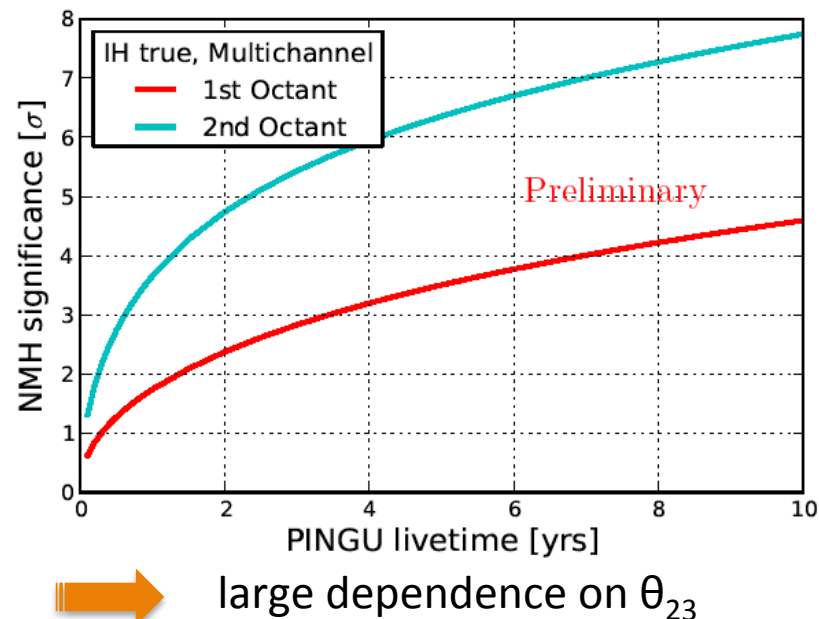
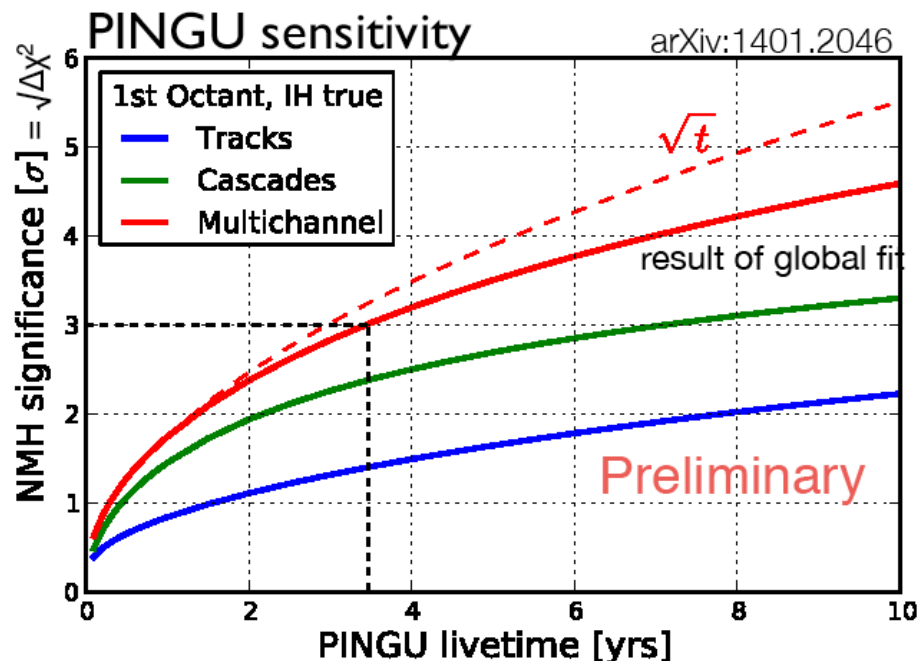
KM3NeT Collaboration



Mediterranean see



Future neutrino non-acceleration projects



Reactors are back...

(mass hierarchy)



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



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

- no δ_{CP} dependence
- matter effect negligible

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

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

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

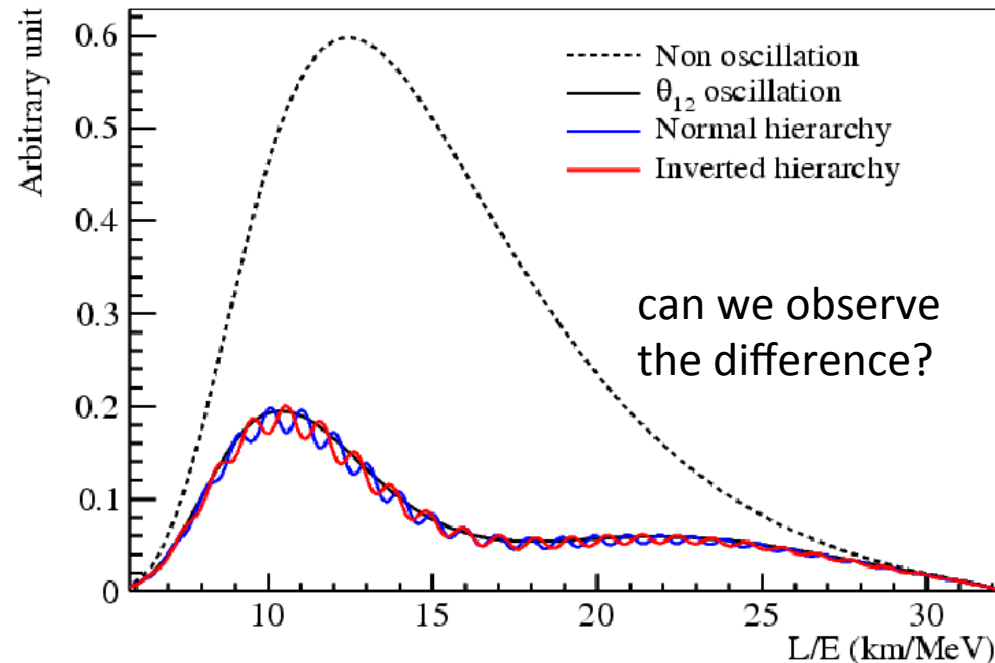
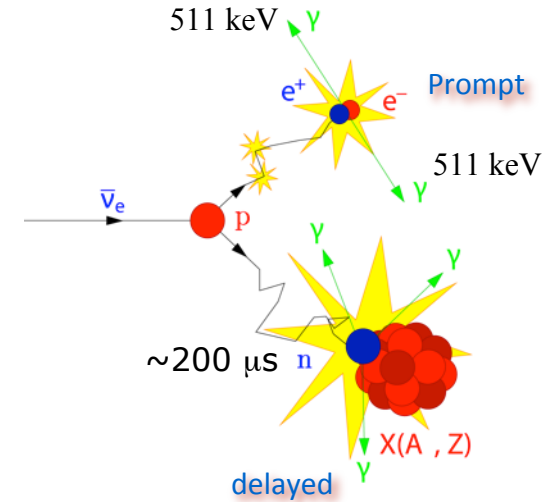
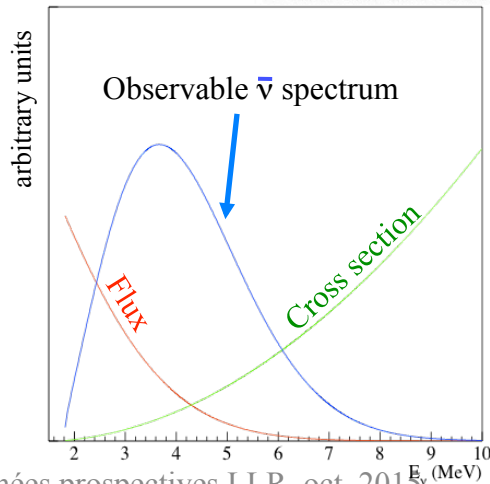
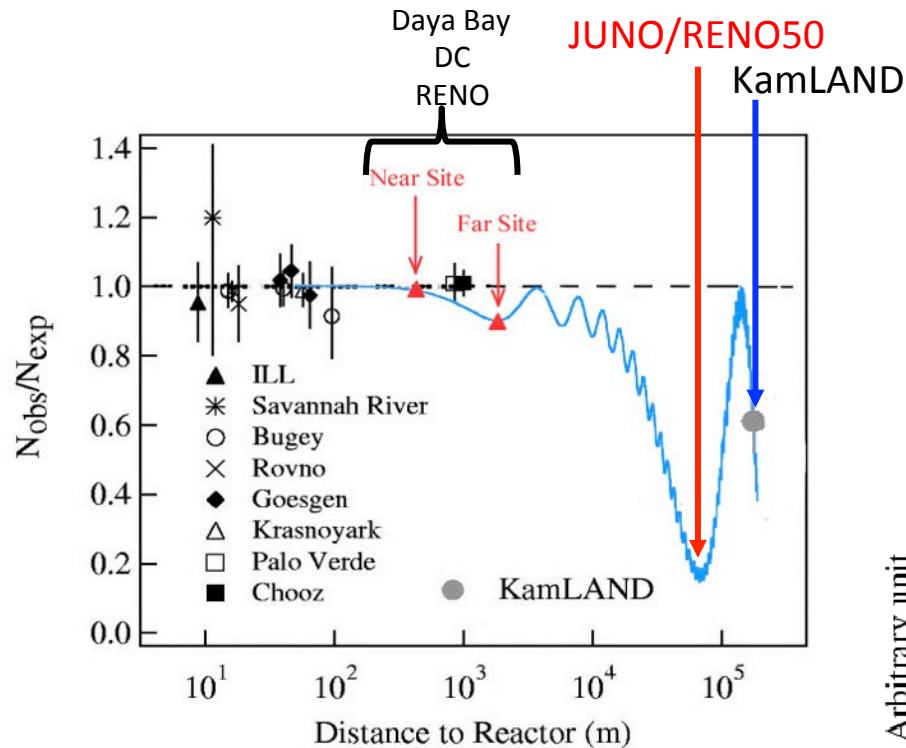


$= (2n-1)\pi/2 \Rightarrow \text{max. sens.}$
 $= n\pi \Rightarrow \text{non sensitivity}$

with:

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

Reactor neutrino spectrum



Energy resolution

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

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

$$\left(\frac{\sigma_E}{E}\right)^2 = \underbrace{\frac{a^2}{E}}_{\text{stat. (N}_{pe})} + \underbrace{b^2}_{\text{syst. (non-uniformities, energy leaks...)}} + \underbrace{\frac{c^2}{E^2}}_{\text{noise}}$$

Measured spectrum (without background):

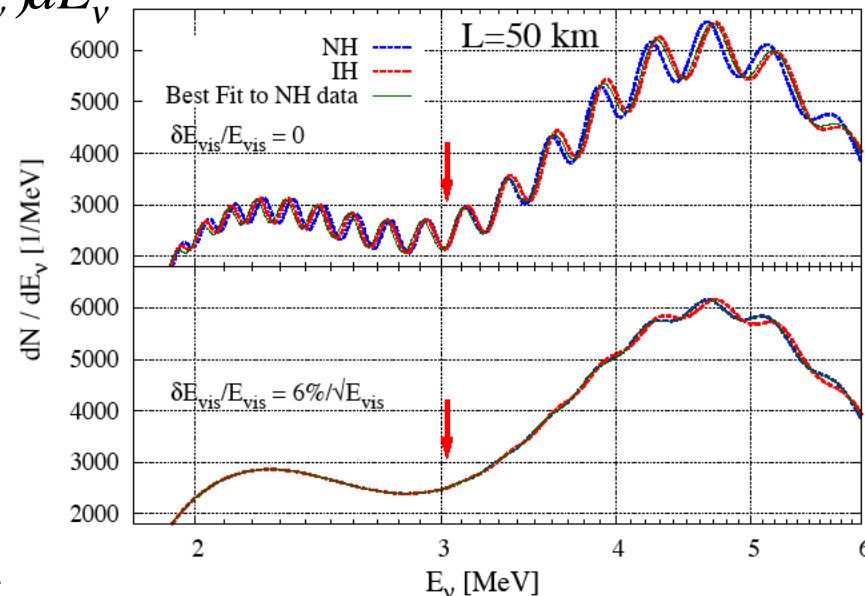
$$N(E_m) = \int R(E_v, E_m) \phi(E_v) \cdot \sigma(E_v) \cdot P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}(E_v) dE_v$$

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

JHEP 1305 (2013) 131



Spectral analysis

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

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

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

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

Discriminant variables:

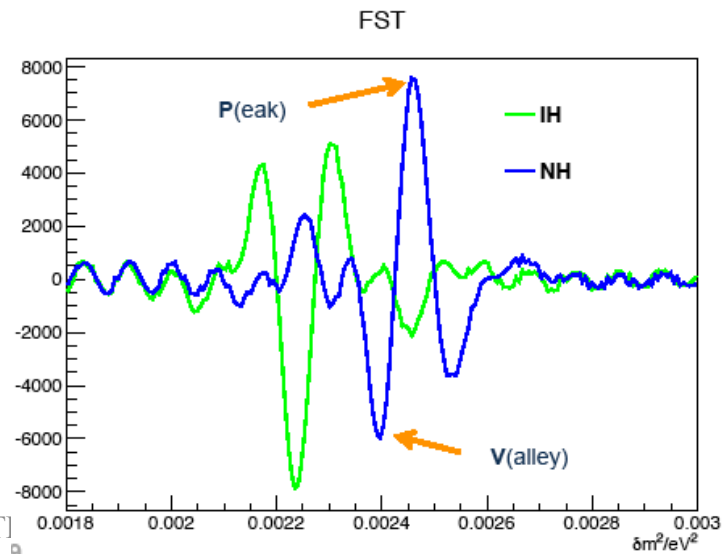
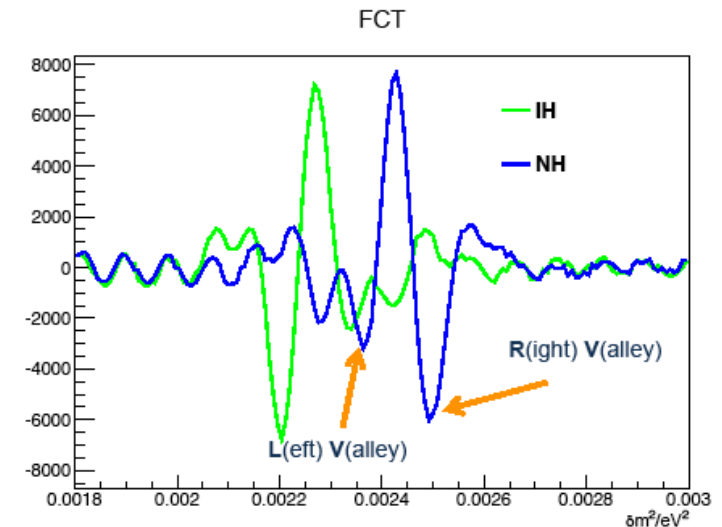
$$RL = \frac{RV - LV}{RV + LV} \quad (\text{for FCT})$$

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

$$RL > 0 \text{ and } PV > 0 \rightarrow \text{NH}$$

$$RL < 0 \text{ and } PV < 0 \rightarrow \text{IH}$$

Statistical test of RL+PV

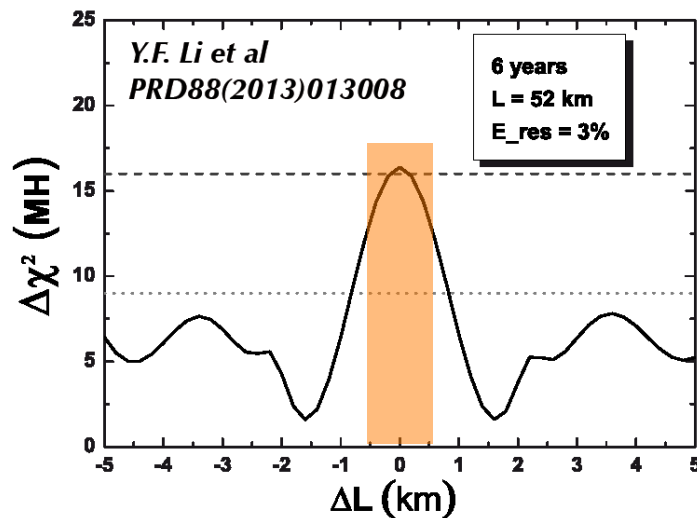


Reactor performance

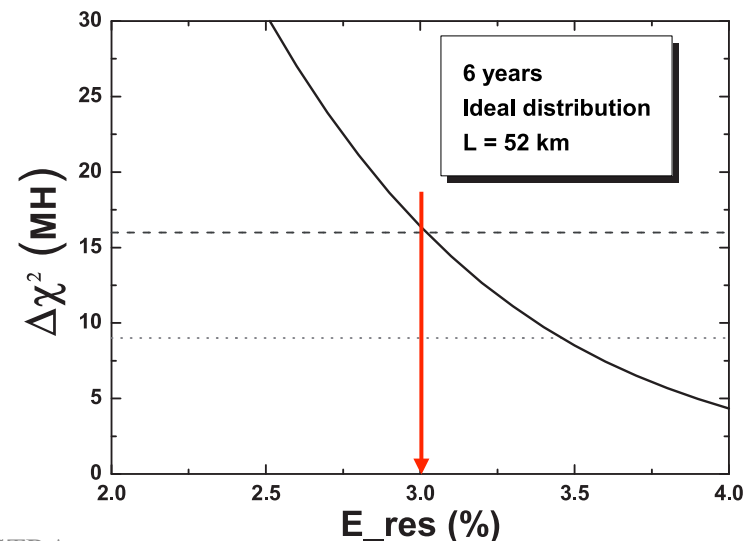
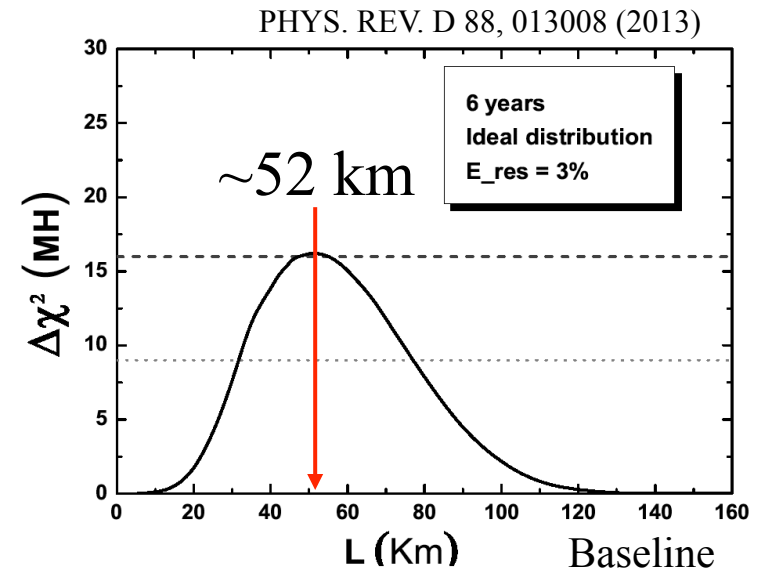
Conditions:

- 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

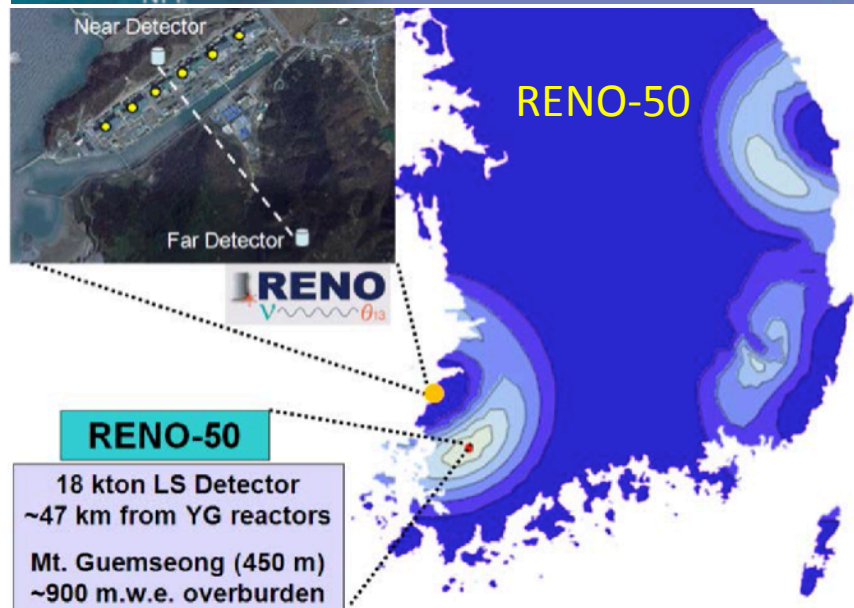
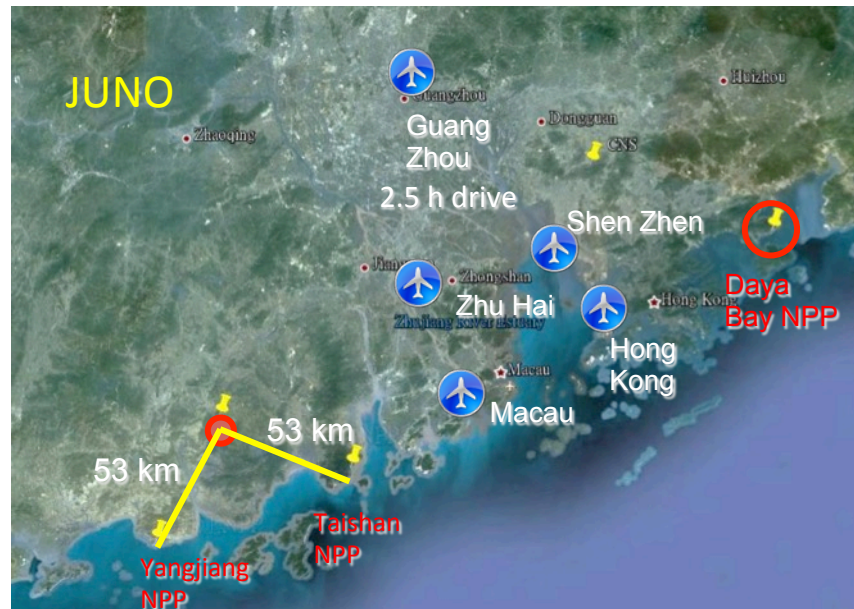
➡ **significance: 3 – 4 σ**



acceptable uncertainty on the distance: ± 500 m



JUNO/RENO-50



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

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

Kaiping,
Jiang Men city,
Guangdong Province



Experimental site



竖井, 入口高程130m,
底高程-451.00m, 深581m

斜井, $L=1340m$, $i=42.6\%$

竖井平段, $L=300m$, $i=3.0\%$

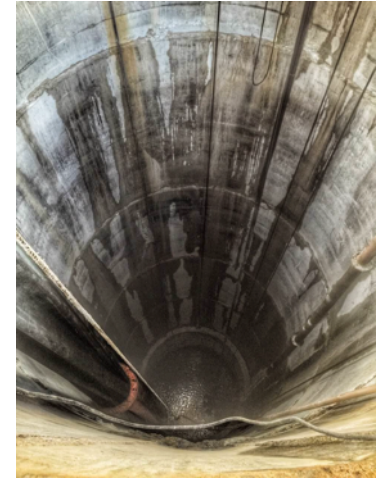
实验厅
268.80
-460.00

斜井平段, $L=85m$, $i=0.3\%$

花岗岩范围

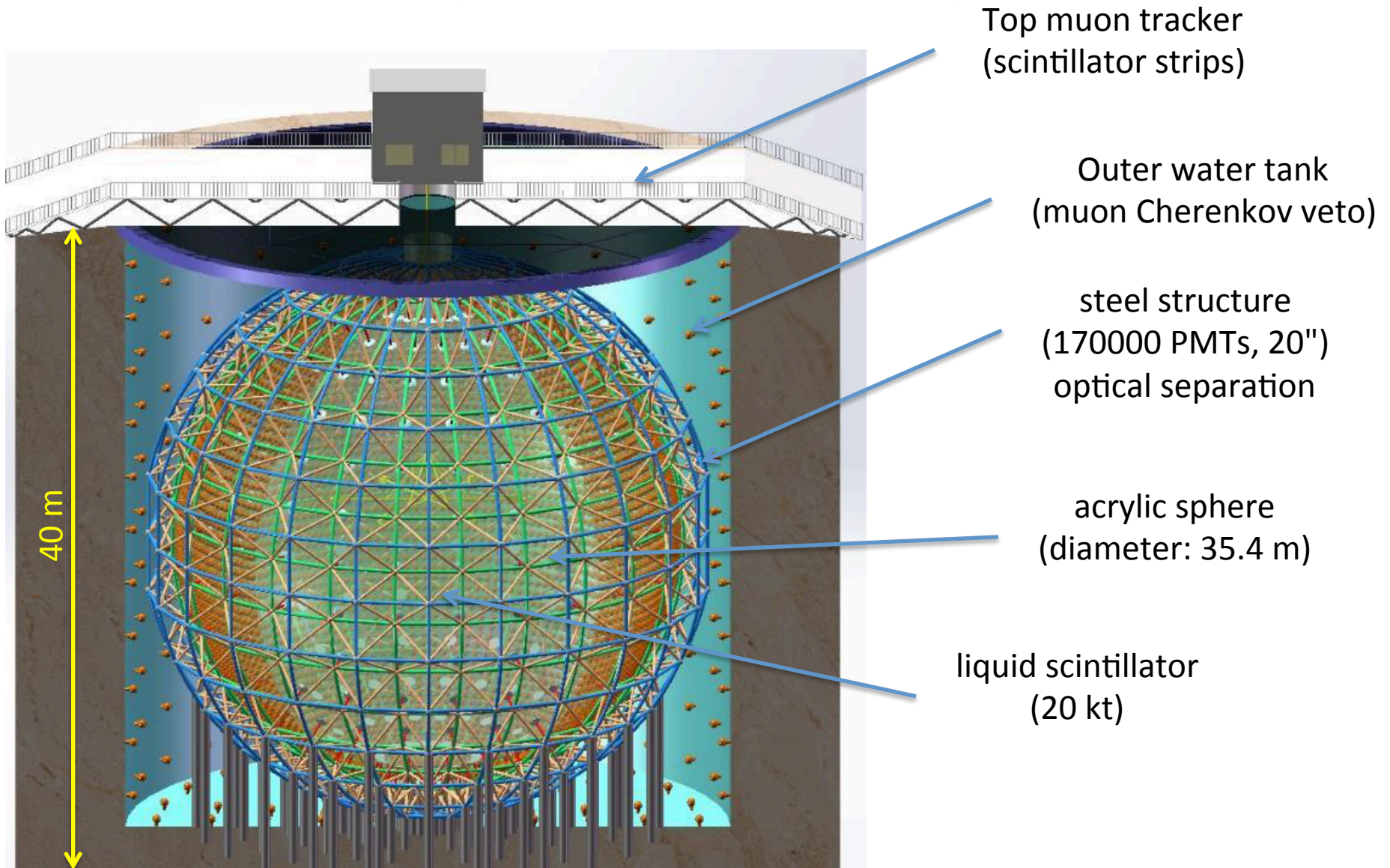


Ground breaking ceremony (January 2015)



JUNO detector

(JUNO CDR: arXiv:1508.07166)



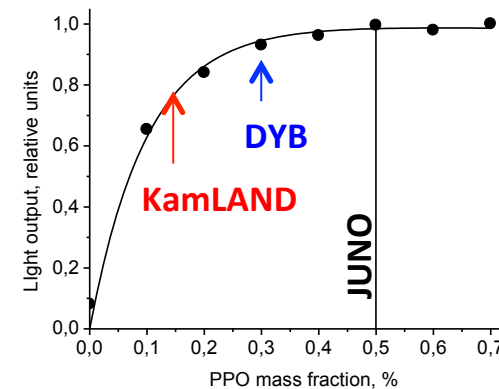
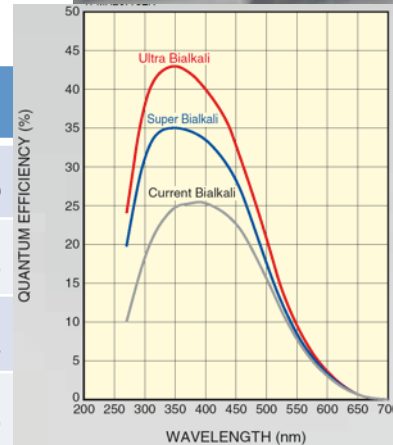
High energy resolution

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



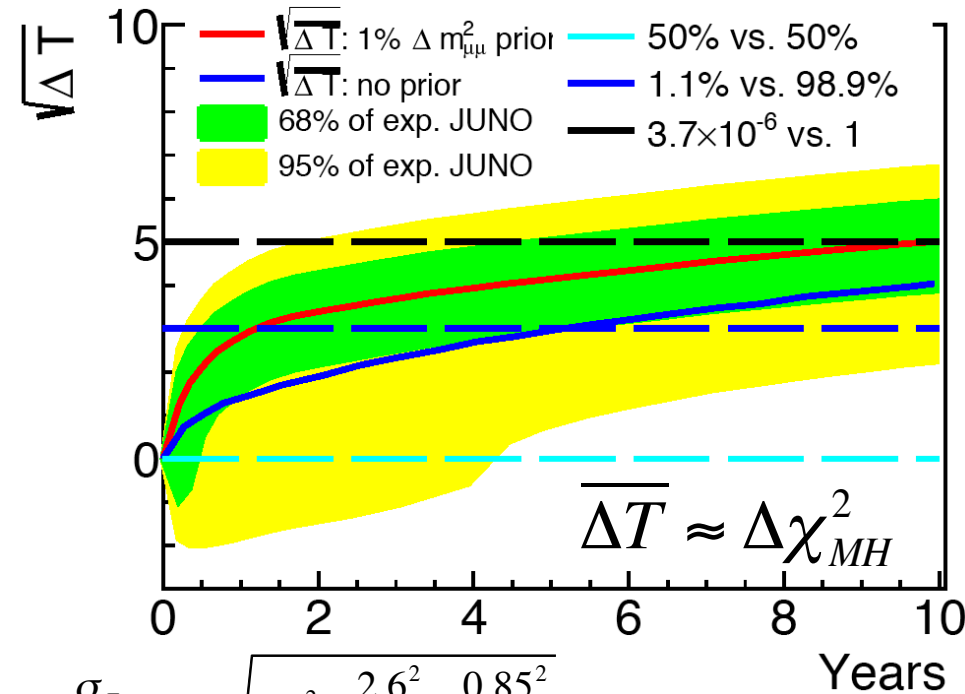
	KamLAND	BOREXINO	JUNO
LS mass	1 kt	0.5 kt	20 kt
Energy Resolution	6%/√E	5%/√E	3%/√E
Light yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

Performance

(JUNO Yellow Book, arXiv:1507.05613)

PRD 88 013008 (2013)

JUNO sensitivity (Y.F. Li et al.)



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

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

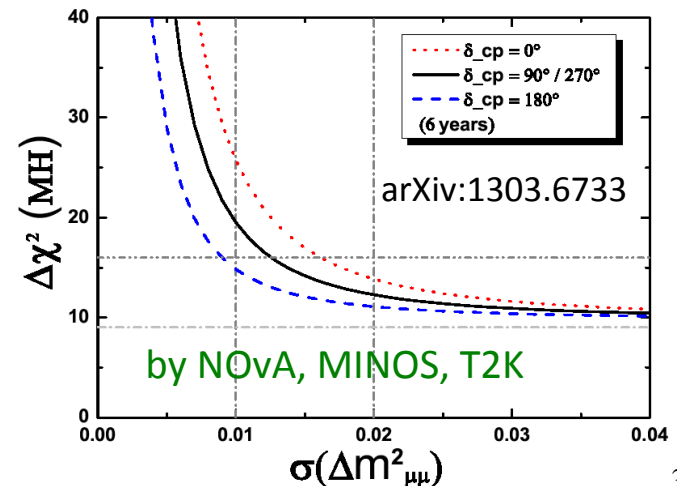
$$\Delta m_{\mu\mu}^2 \simeq \sin^2 \theta_{12} \Delta m_{31}^2 + \cos^2 \theta_{12} \Delta m_{32}^2 + \sin 2\theta_{12} \sin \theta_{13} \tan \theta_{23} \cos \delta \Delta m_{21}^2,$$

Inputs

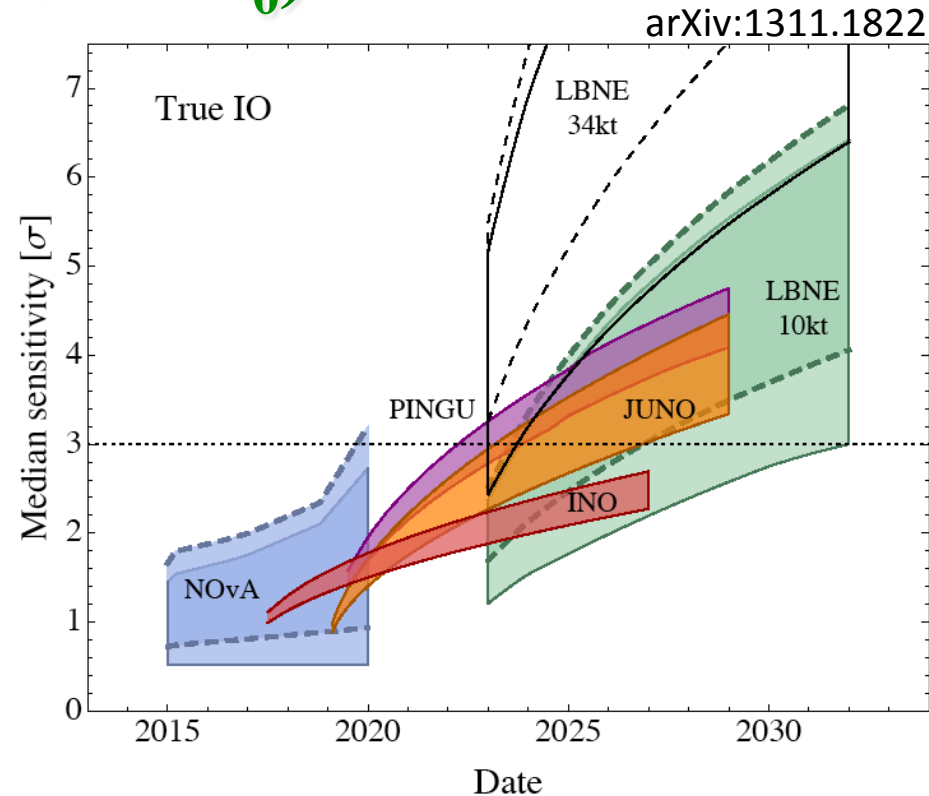
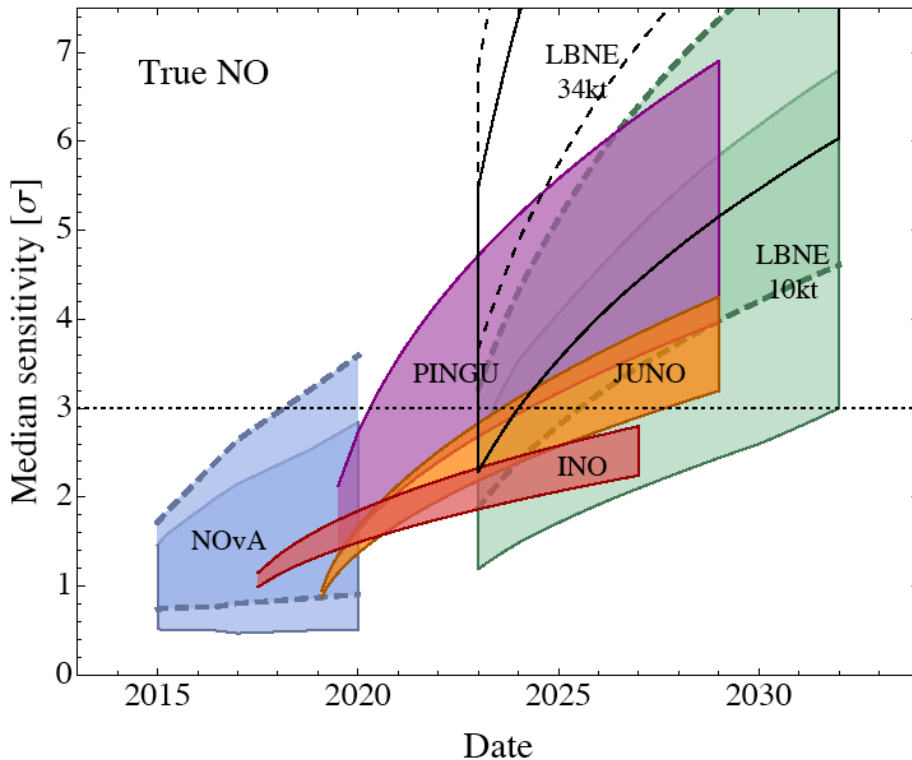
- 100 kevents (6 years)
- 3% @ 1 MeV energy resolution
- 1% energy scale uncertainty
- realistic backgrounds

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



Comparisons and complementarities (big unknown: t_0)



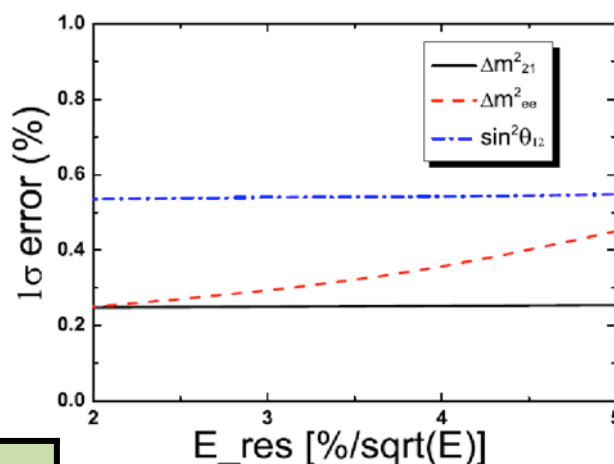
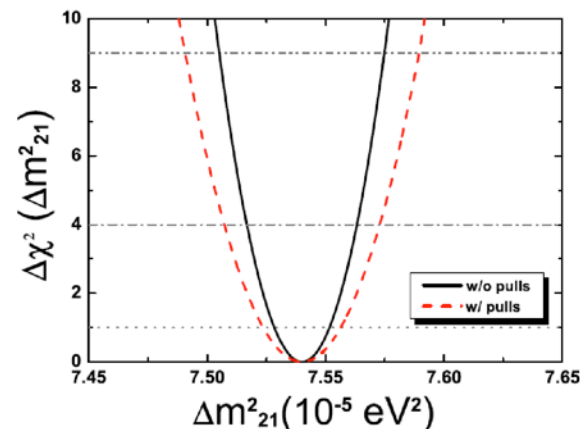
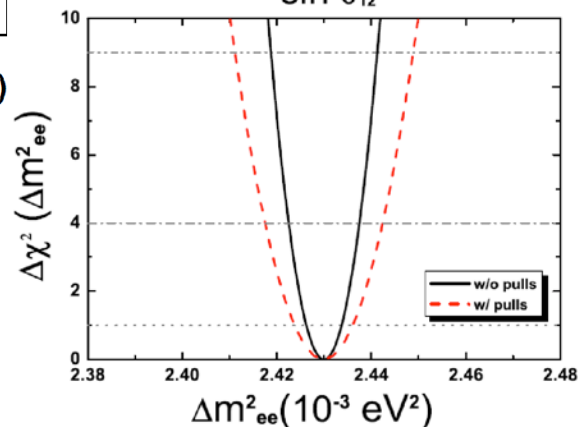
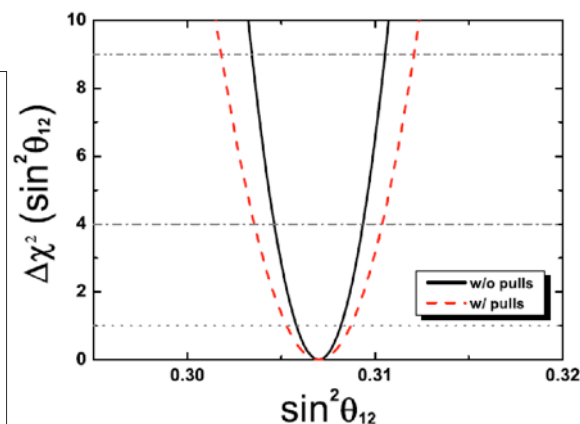
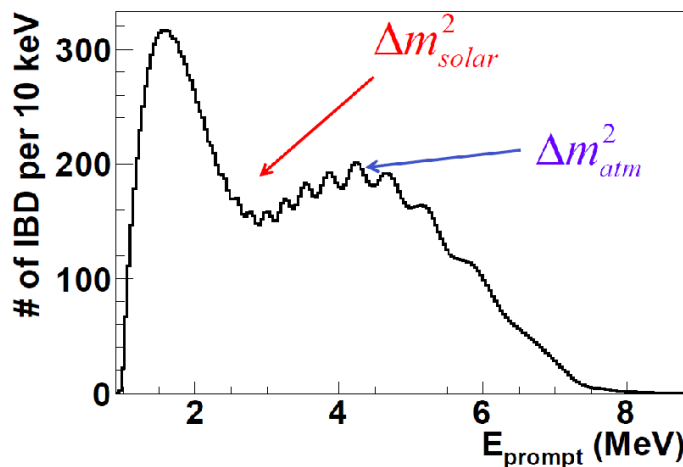
- width of bands due to:
 - δ_{CP} (for NOvA and LBNE)
 - $40^\circ < \theta_{23} < 50^\circ$ (for INO and PINGU)
 - $3.0\% \sqrt{(1 \text{ MeV/E})} < \sigma_E < 3.5\% \sqrt{(1 \text{ MeV/E})}$

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

Oscillation parameters

(precision measurements)

JUNO 100k IBD Events



better precision than for
CKM matrix elements

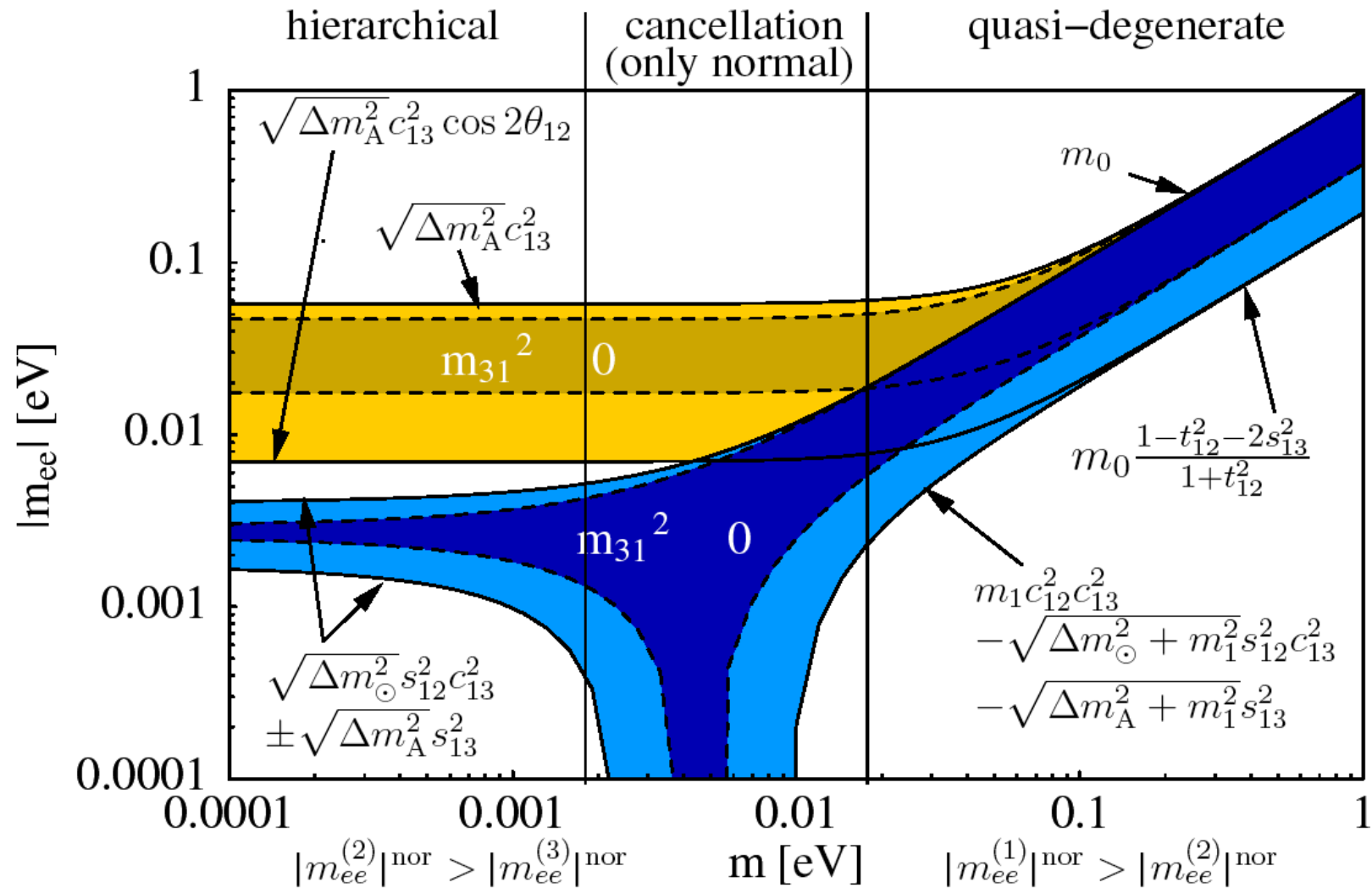
Dracos IPHC/CNRS-UNISTRA

- 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!

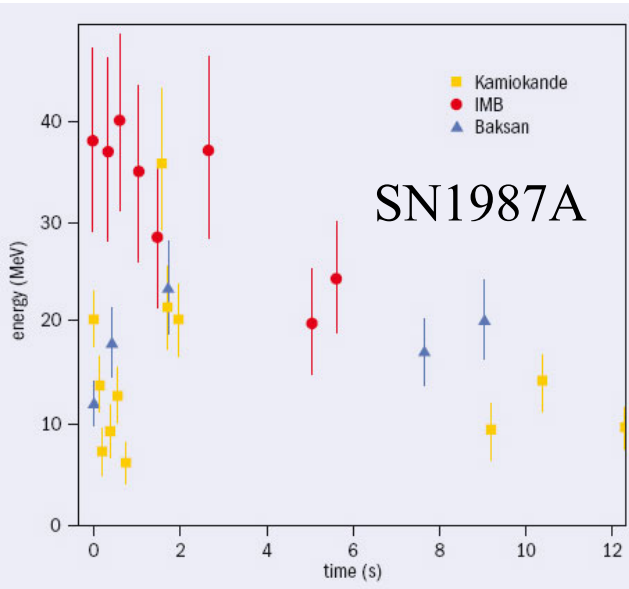
	Current	JUNO
Δm^2_{21}	$\sim 3\%$	$\sim 0.6\%$
Δm^2_{32}	$\sim 4\%$	$\sim 0.5\%$
$\sin^2\theta_{12}$	$\sim 7\%$	$\sim 0.7\%$

Double beta decay

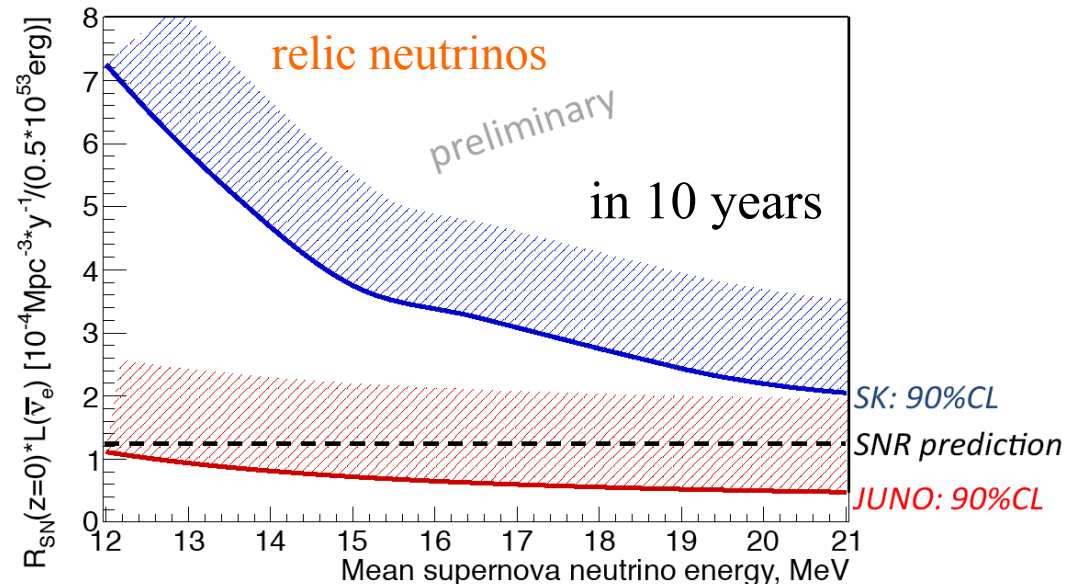
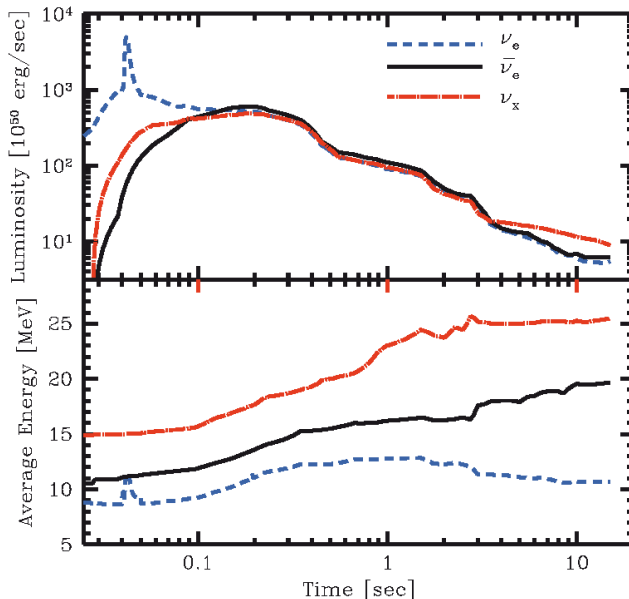
PHYSICAL REVIEW D **73**, 053005 (2006)



Supernovae explosions

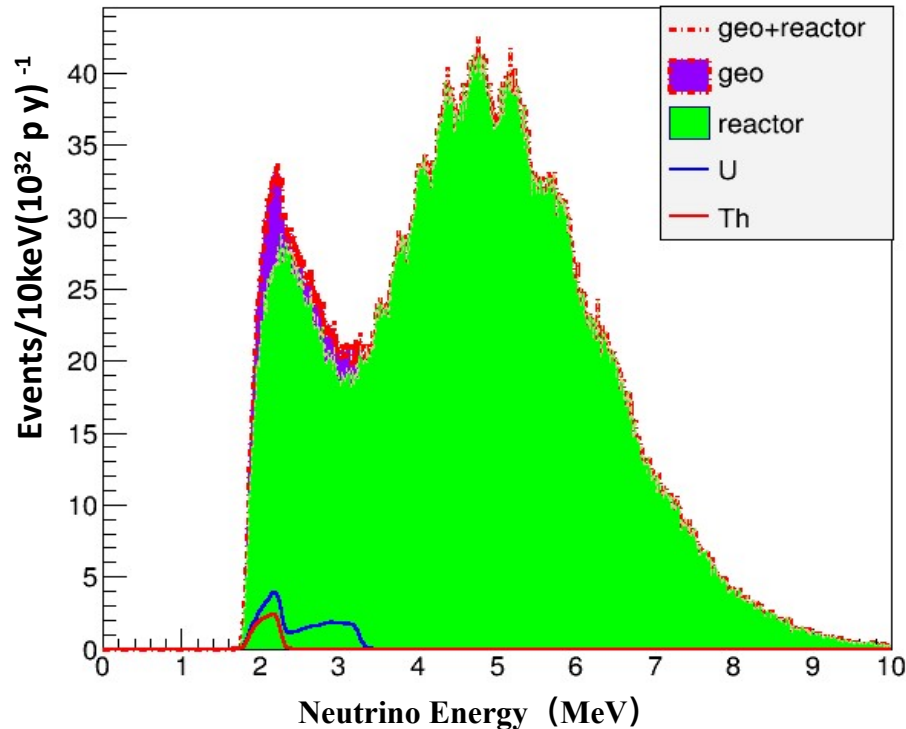


- 5000 ν will be detected by JUNO if explosion at 10 kpc (centre of our galaxy)
 - energy spectrum
 - time distribution
- better understanding of the explosion mechanisms
- detection of relic neutrinos produced by previous explosions



Geo-neutrinos in JUNO

JUNO $\sim 700/\text{year}$
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

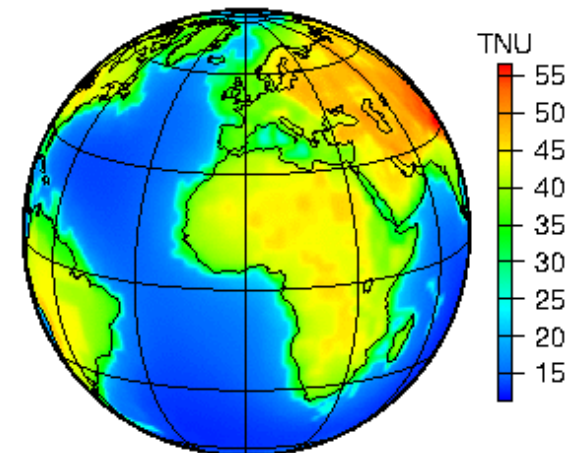
large background from reactors

Aim: $xx \pm 10\%$ (stat.) $\pm 10\%$ (syst.)

1.8-3.4 MeV

Reactor Neutrinos: $14 \pm 0.14/\text{day}$

Geo-neutrinos $2 \pm 0.5/\text{day}$



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

JUNO schedule

First get-together meeting

Funding(2013-2014) review approved



Geological survey and preliminary civil design



1st 20" MCP-PMT

Collaboration formed

Groundbreaking Ceremony (10 Jan. 2015)



2013

Kaiping Neutrino Research Center established

2014

Civil/infrastructure construction bidding

Funding from CAS: "Strategic Leading Science & Technology Programme" approved (~CD1)

Yangjiang NPP started to build the last two cores

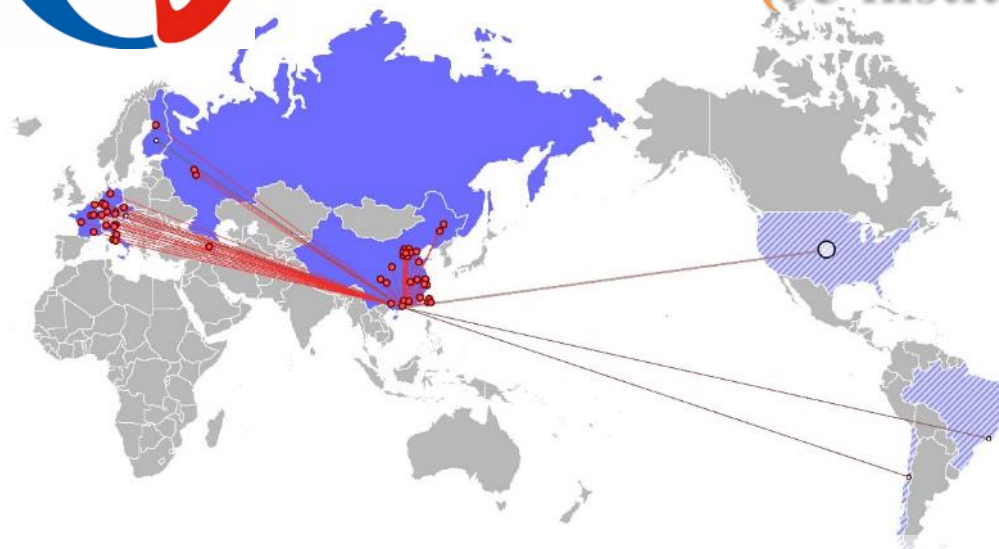
Civil design approved

- Civil construction: 2015-2017
- Detector component production: 2016-2017
- PMT production: 2016-2019
- Detector assembly & installation: 2018-2019
- Filling & data taking: 2020



JUNO Collaboration

(55 institutes)



Asia (28)

BNU	Nanjing U	SYSU
CAGS	Nankai U	Tsinghua U.
CQ U	Natl. CT U	UCAS
CIAE	Natl. Taiwan U	USTC
DGUT	Natl. United U	Wuhan U
ECUST	NCEPU	Wuyi U
Guangxi U	Pekin U	Xiamen U
HIT	Shandong U	Xi'an JTU
IHEP	Shanghai JTU	
Jilin U	Sichuan U	

Europe (24)

America (3)

U. Maryland (phys.)
U. Maryland (geo.)
PCUC Chile

Observers

US institutions
HEPHY Vienna
PUC Brazil
U.F. ABC Brasil
Jyvaskyla U.
MSU Moscow

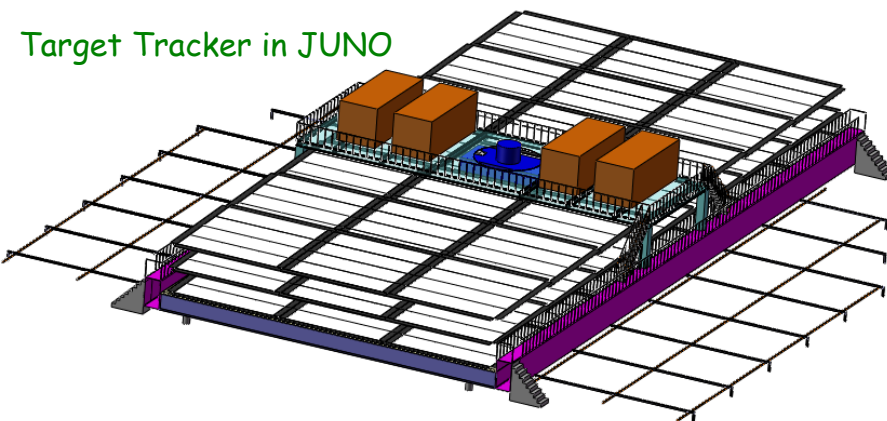
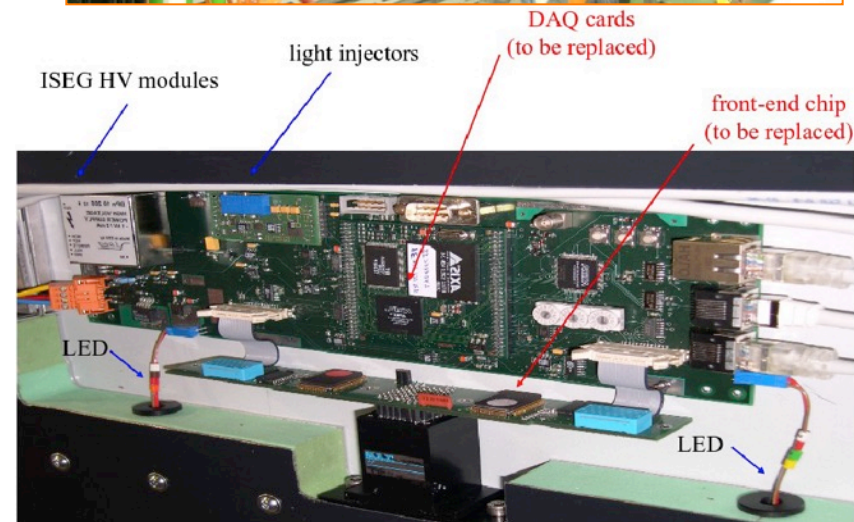
APC Paris	INR Moscow
U. Libre de Bruxelles	IPHC Strasbourg
Charles U.	JINR
CPPM Marseille	LLR Paris
FZ Julich	RWTH Aachen U.
INFN-Frascati	Subatech Nantes
INFN-Ferrara	TUM
INFN-Milano	U. Hamburg
INFN-Milano Bicocca	U. Mainz
INFN-Padova	U. Oulu
INFN-Perugia	U. Tuebingen
INFN-Roma 3	YPI Armenia



French contributions to JUNO

5 French institutes are involved in JUNO:
APC, IPHC, LLR, CPPM, SUBATECH

- Veto: installation of the OPERA Target Tracker on top of JUNO detector
 - cosmogenic background study and evaluation.
- DAQ and electronics of the JUNO central detector.
- Radon background.
- Option "small PMTs" for better calorimetry.
- Data simulation and analysis.



Conclusions

- Two last neutrino oscillation parameters to measure:
 - observation of a possible CP violation in the lepton sector using conventional neutrino beams.
 - neutrino Mass Hierarchy determination.
- Present projects (mainly NOvA) 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
 - Strong French participation
 - Rich physics program (accurate measurement of neutrino oscillation parameters, supernova neutrinos, geo-neutrinos, etc.).

Backup

		Start	end	condition
1	Underground lab construction	2015.1.1	2017.12.27	
2	Water pool cleaning and CD construction preparation	2017.12.28	2018.2.23	1
3	CD & water pool equipment installation	2018.4.2	2018.11.30	2
4	PMT base(& to be sealed electronics) design finalized	2015.1.1	2016.9.30	
5	PMT base production and aging test	2016.10.1	2017.6.30	4
6	PMT bidding	2015.7.1	2015.12.31	
7	PMT mass production	2016.1.1	2018.8.31	6
8	PMT testing	2017.4.4	2018.11.30	
9	PMT potting and testing	2017.7.1	2018.11.30	5
10	CD & VETO PMT installation	2018.12.3	2019.2.28	
11	Readout electronics design finalized	2017.1.2	2017.5.31	
12	Readout electronics mass production	2017.6.1	2018.3.30	11
13	Readout electronics testing and aging	2018.4.1	2018.11.29	12
14	Readout electronics installation	2018.9.28	2019.2.28	
15	CD & water pool cleaning	2019.4.1	2019.4.30	
16	Water pool cover is placed	2019.5.1	2019.5.2	15
17	TTS supporting structure installation	2018.12.3	2018.12.21	16
18	TTS installation	2019.5.1	2019.7.30	17
19	AD & VETO water filling	2019.5.3	2019.7.2	18
20	LS filling	2019.7.3	2019.10.2	19
21	Test run	2019.11.5	2020.1.2	20

Background

IBD~60/day

Singles

Event Type	Raw rate	Reduction
Radioactivity (in FV <17.2m)	0.4 Hz (PMTs) 2.2 Hz (LS) 3.7 Hz (acrylic) 0.2 Hz (support) 1.3 Hz (Rn) ~ 0.03 (rock)	Use low radioactivity PMTs; LS raw material purification (w/o distillation after LS production)
Cosmogenic isotopes (delayed)	340/day	
Spallation neutron	1.8 Hz	

IBD bkg

Accidentals	~410/day	→ 1.1 /day w/ prompt-delayed distance $R_{p-d} < 1.5m$. Negligible.
Fast neutron	0.01/day	0.01/day ($\sigma=100\%$)
$^9\text{Li}/^8\text{He}$	80/day	1.8/day after muon veto ($\sigma=20\%$)
(a, n)	3.8/day (acrylic) 0.2/day (balloon)	→ 0.05 /day (acrylic), FV cut ($\sigma=50\%$) → negligible (balloon), FV cut

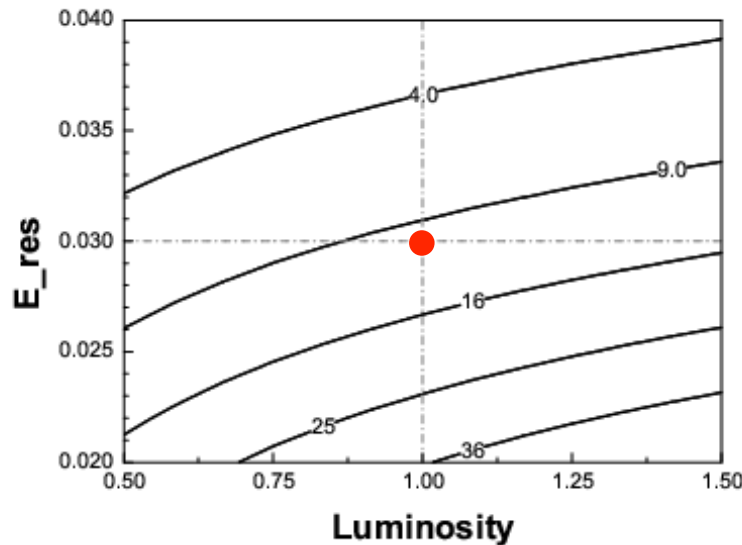
Risques

Si les 3% de résolution en énergie ne sont pas atteints?



Augmenter la prise de données.

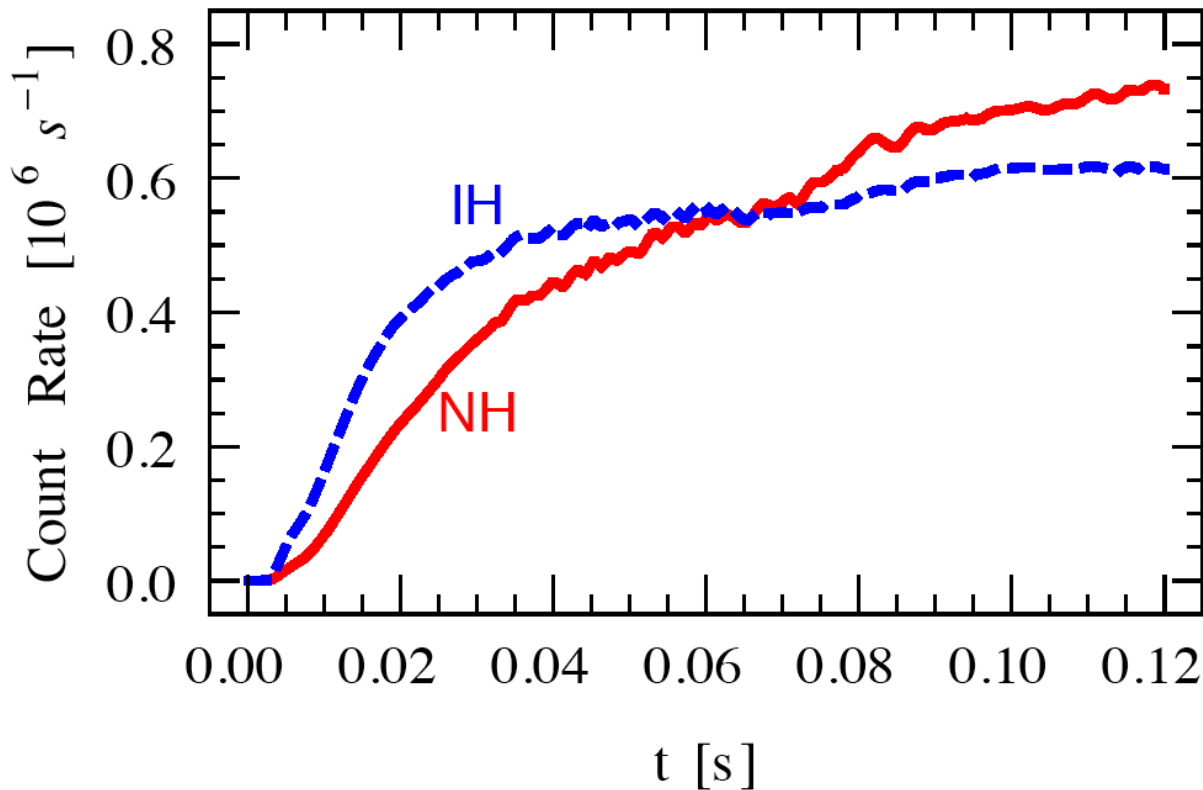
De toute façon l'expérience ne va pas s'arrêter à 6 ans (SK tourne depuis 1996).



100 kev.
(6 ans)

9 ans

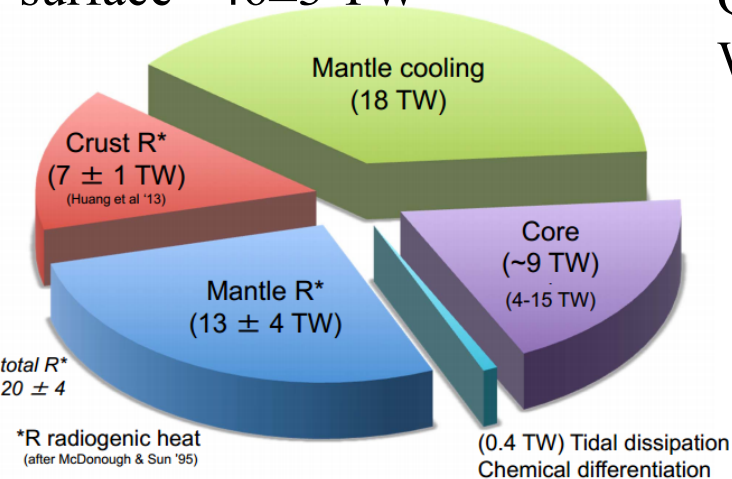
Mass Hierarchy and Supernova explosions



arXiv:1111.4483

Detection of Geo-neutrinos

Heating at the earth
surface $\sim 46 \pm 3$ TW



Radiogenic contribution at the earth surface.

Quantity of U and Th in the mantle.

What is it hidden in the centre of the earth?

Decay	$E_{\max}$ [MeV]	Q [MeV]	$Q - \langle E_{\nu} \rangle$ [MeV]
$^{238}\text{U} \rightarrow ^{206}\text{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e$	3.25	51.7	47.6
$^{232}\text{Th} \rightarrow ^{208}\text{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e$	2.25	42.7	40.4
$^{40}\text{K} \rightarrow ^{40}\text{Ca} + e^- + \bar{\nu}_e$ (89%)	1.311	1.311	0.59
$^{40}\text{K} + e^- \rightarrow ^{40}\text{Ar} + e^- + \nu_e$ (11%)	0.044	1.505	1.461

$$N_{\text{geo}} = 116 \pm 28 (10\text{y})$$

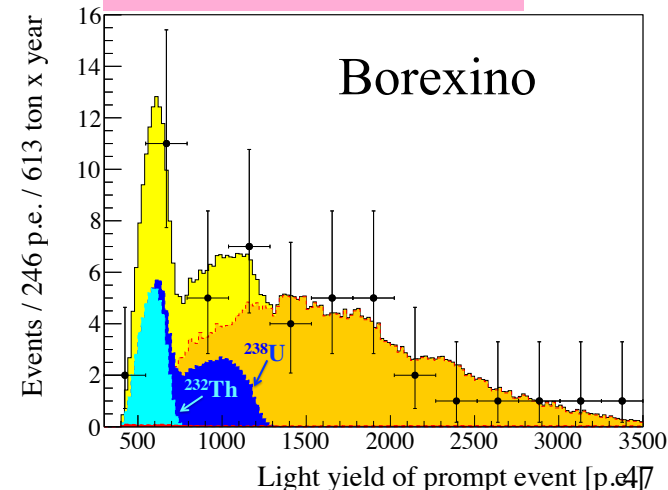
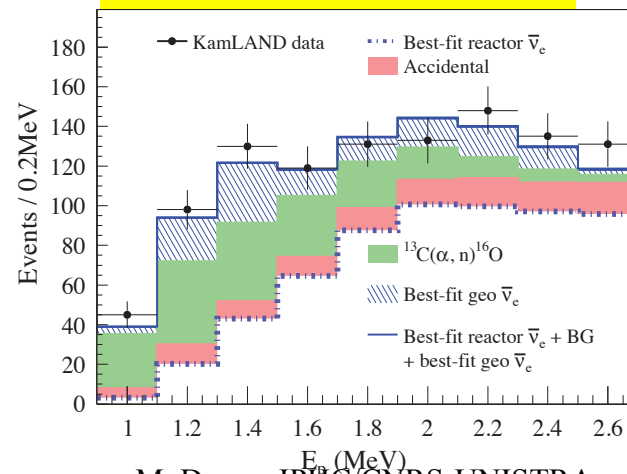
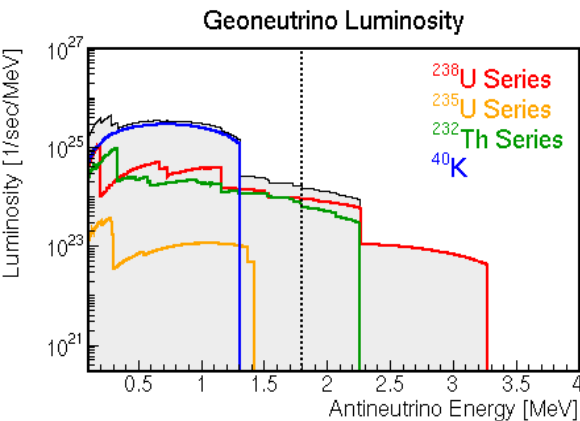
$$S_{\text{geo}} = 28 \pm 6.7 \text{ TNU}$$

$$B/S = 0.24$$

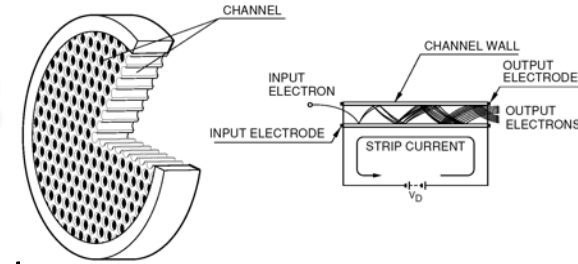
$$N_{\text{geo}} = 14.3 \pm 4.4 (5\text{y})$$

$$S_{\text{geo}} = 38.8 \pm 12.0 \text{ TNU}$$

$$B/S = 0.31$$

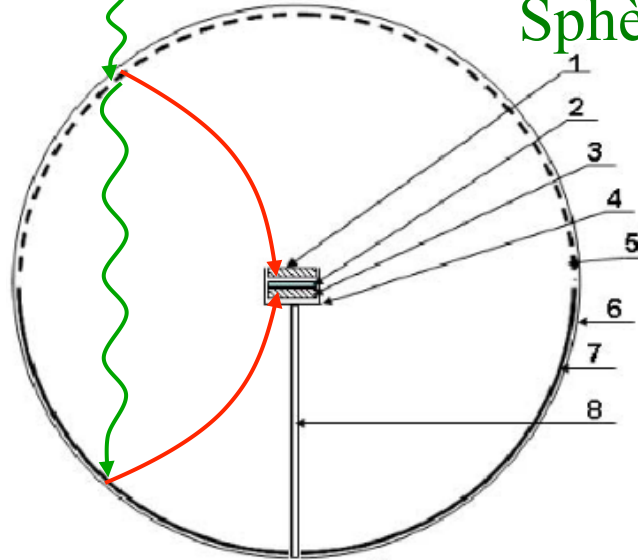
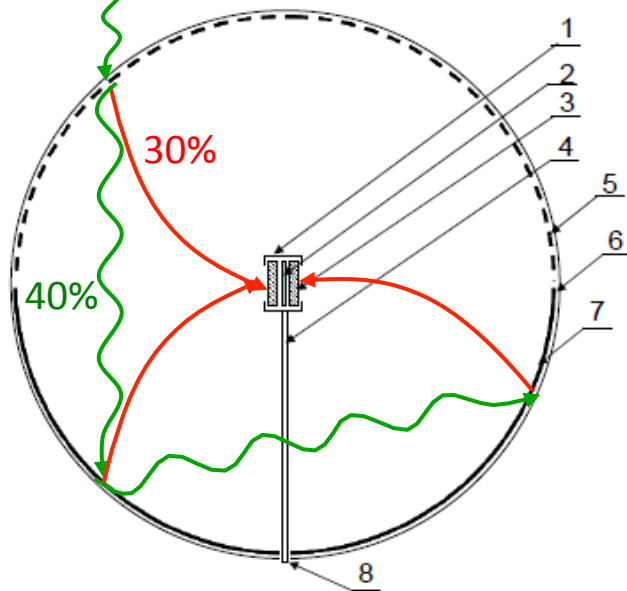


Photodetectors

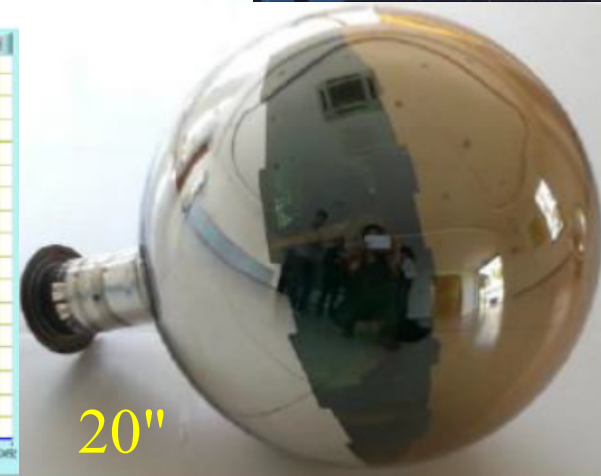
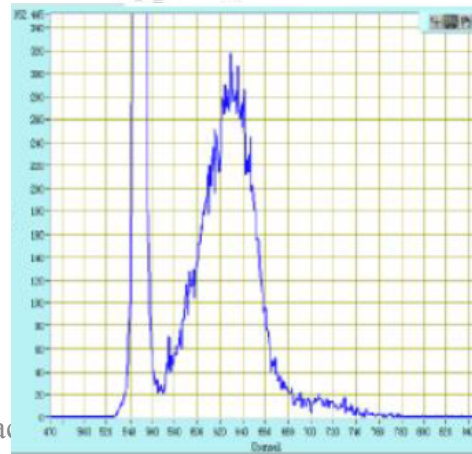


Nouveau type de PMT: MCP (remplacement des dynodes)

MicroChannel Plates
Sphère entièrement active



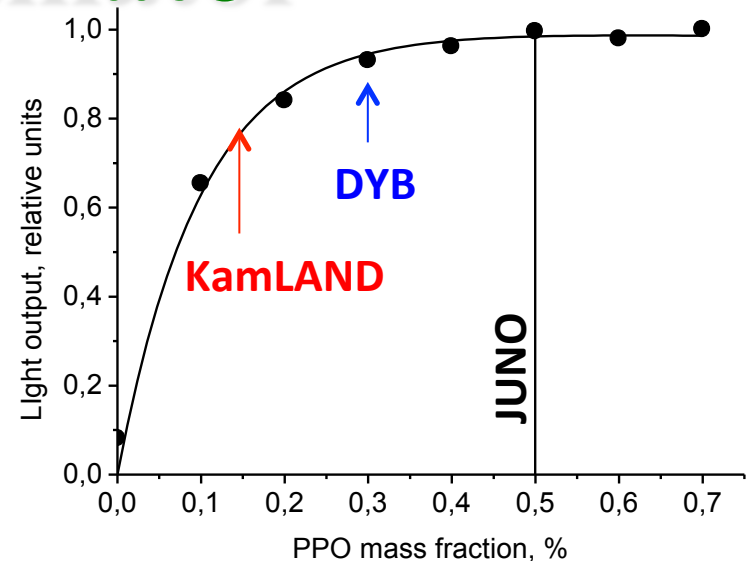
1. Insulated trestle table
2. Anode
3. MCP module
4. Bracket of the cables
5. Transmission Photocathode
6. Glass shell
7. Reflection Photocathode
8. Glass joint



Efficacité quantique: 30%
Transmission du verre: 40%
Efficacité de collection: 70%

Liquid scintillator

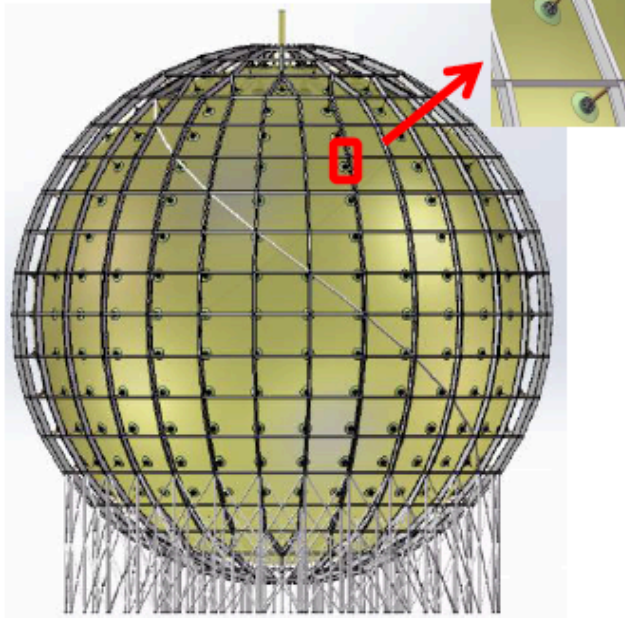
- **Baseline:**
LAB+PPO+bisMSB (without Gd)
- **Improvement of the light yield**
 - **Optimisation of the fluor concentration**
- **Improvement of the transmission**
 - **Solvent: LAB**
 - improvement of the production process
 - **Handling/purification**
 - distillation, filtration, water extraction, N₂ separation, ...
- **Radioactivity reduction**
 - **less critical due to Gd absence**
 - **Singles < 3 Hz (> 0.7 MeV), if ⁴⁰K/U/Th < 10⁻¹⁵ g/g (preliminary)**



Linear Alky Benzene (LAB)	Atte. Length @ 430 nm
RAW	14.2 m
Vacuum distillation	19.5 m
SiO ₂ column	18.6 m
Al ₂ O ₃ column	22.3 m
LAB from Nanjing, Raw	20 m
Al ₂ O ₃ column	25 m

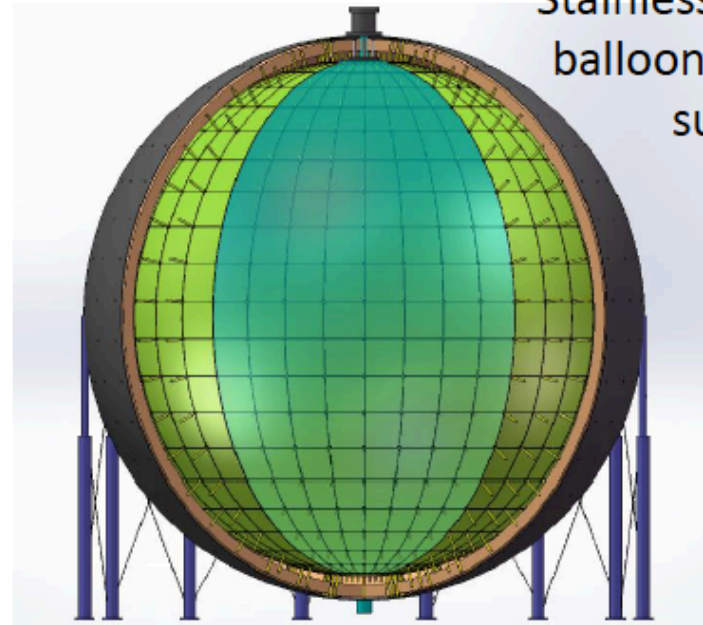
JUNO detector

Acrylic
sphere + steel
space truss



Acrylic option ✓

Stainless-steel tank +
balloon with acrylic
support



Balloon option ✗

- Physics performances
- **Engineering feasibility/reliability**
- Schedule
- Cost
- Risks



Long term stability
Earthquake: 0.1g
Temperature fluctuation
Material/background
Compatible with Liquids
Calibration system
Circulation interface

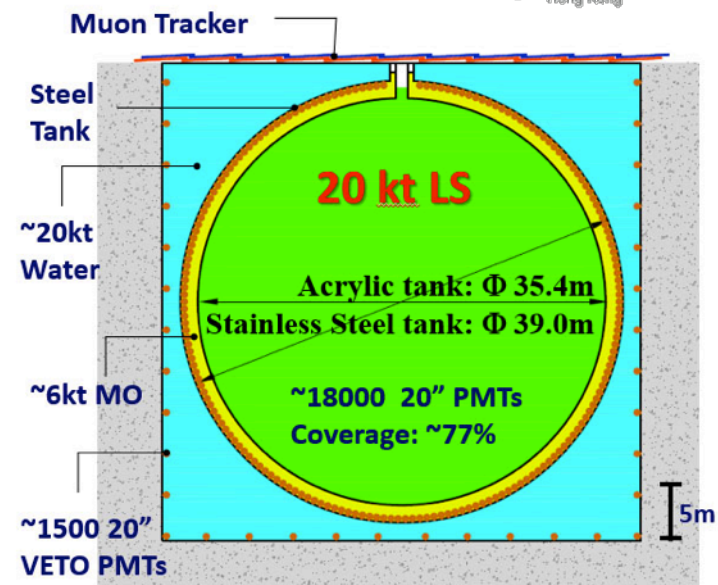
.....



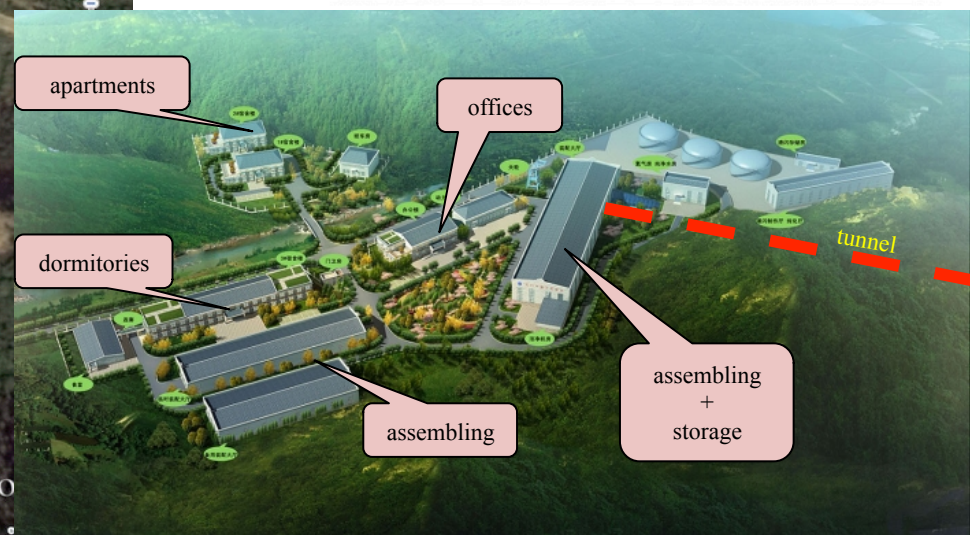
JUNO (55 institutes) (under construction)



data by 2020: 26.6 GW

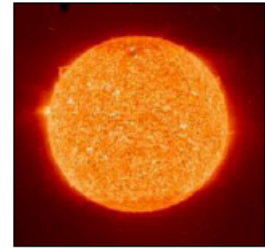


Overburden ~ 700 m

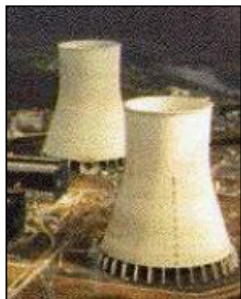


Rates

Supernova ν
 $\sim 5\text{k}$ in 10s for 10kpc



Solar ν
 $(10\text{s}-1000\text{s})/\text{day}$

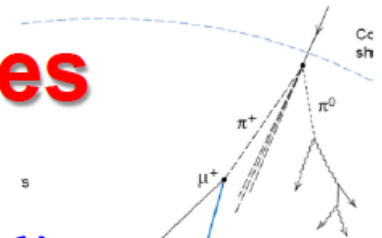


reactor ν , $\sim 60/\text{day}$

36 GW, 53 km

Neutrino Rates

Atmospheric ν
several/day



700 m

Cosmic muons
 $\sim 250\text{k}/\text{day}$

0.003 Hz/m²

215 GeV

10% multiple-muon

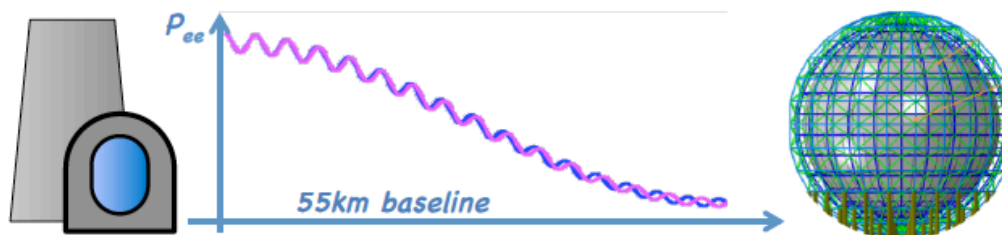
Geo-neutrinos
1-2/day



Performance

Nominal setup for JUNO

- reactor power: 36 GW
- detector mass: 20 kt
- live time: 6 yrs
- IBD efficiency: 80%



	Stat.	Core dist.	DYB & HZ	Shape	B/S (stat.)	B/S (shape)	$ \Delta m^2_{\mu\mu} $
Size	52.5km	± 0.5 km	215/265km	1%	6.3%	0.4%	1%
$\Delta\chi^2$	+16	-3	-1.7	-1	-0.6	-0.1	+8

nominal value
(statistics only)

distance deviation
of individual cores

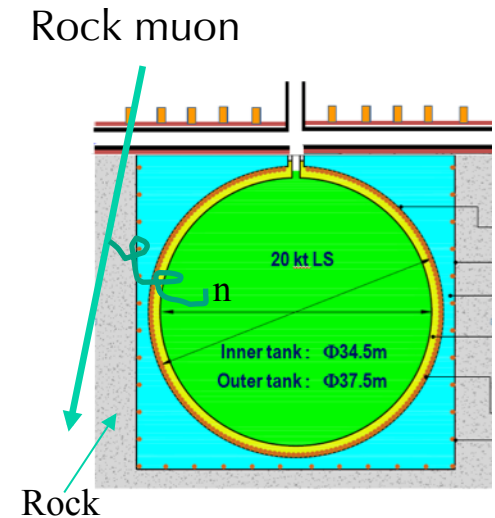
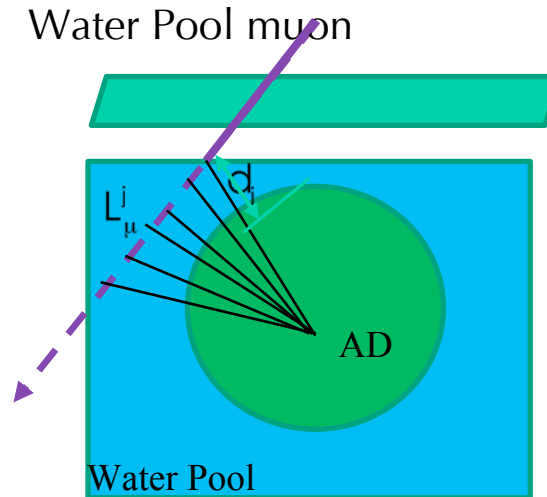
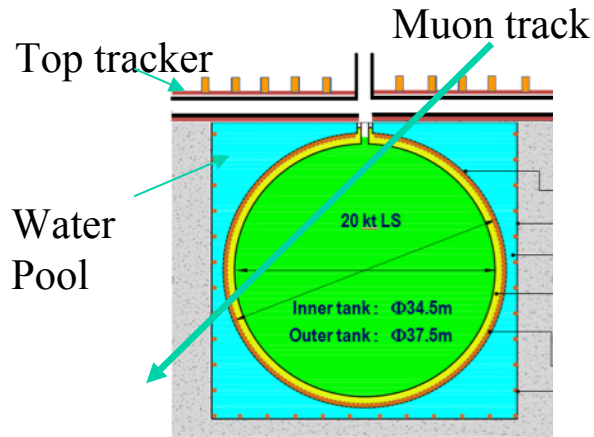
BG signal from
nearby NPPs

uncertainty on
spectral shape of
reactor signal

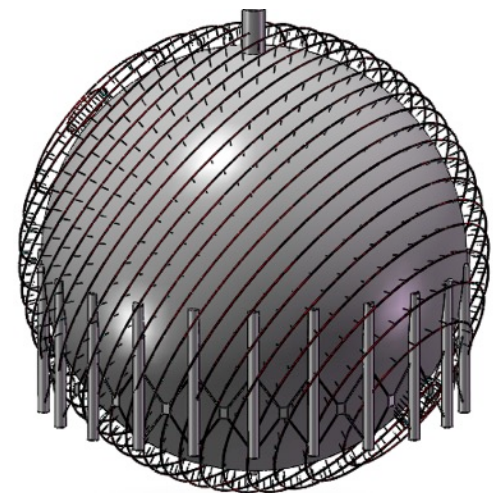
background
uncertainties
rate/shape

precision
measurements
of ν_μ oscillations

Veto system

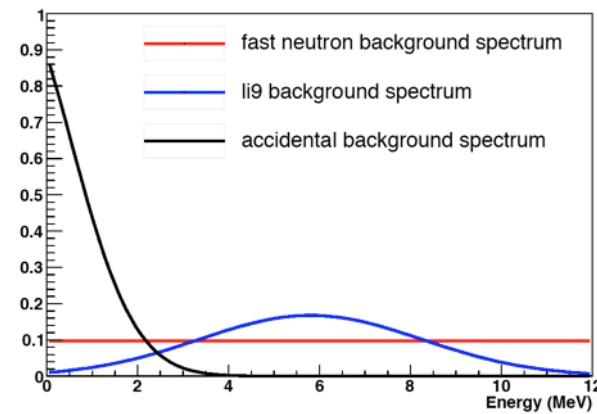
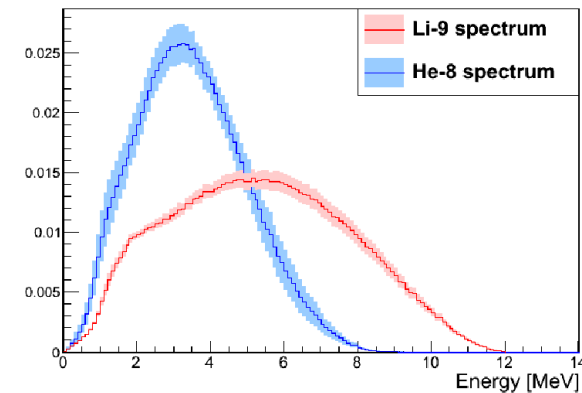
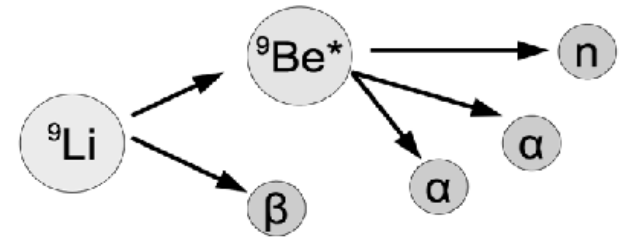


- Veto is not just a veto. Besides radioactive background shielding, we also need tracking information to better understand and remove cosmogenic backgrounds
 - The main body is the water Cherenkov detector
 - OPERA scintillator calorimeters will be moved to JUNO as the Top Tracker (TT)
- Earth magnetic field compensation coils are being designed together with the veto system design
- Radon removal, control and monitoring are under study

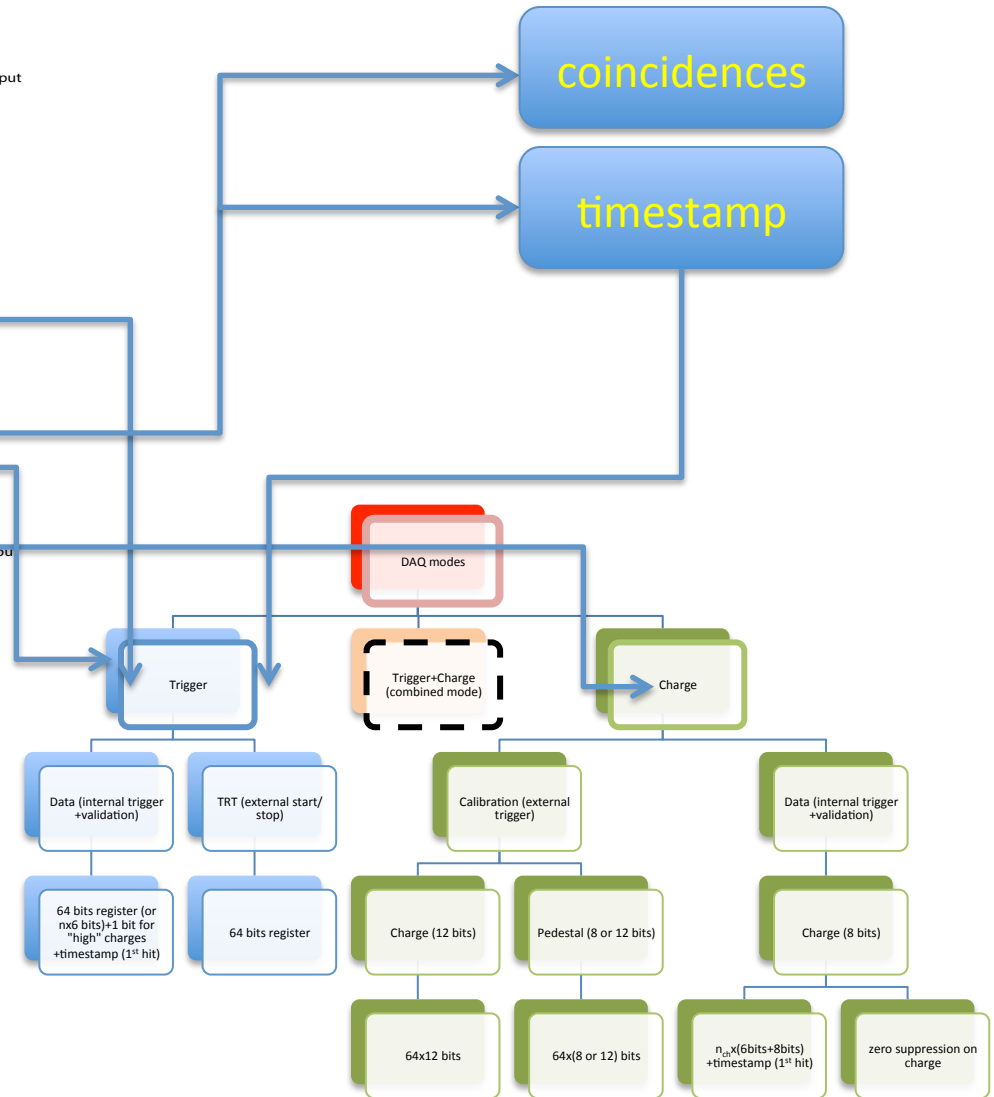
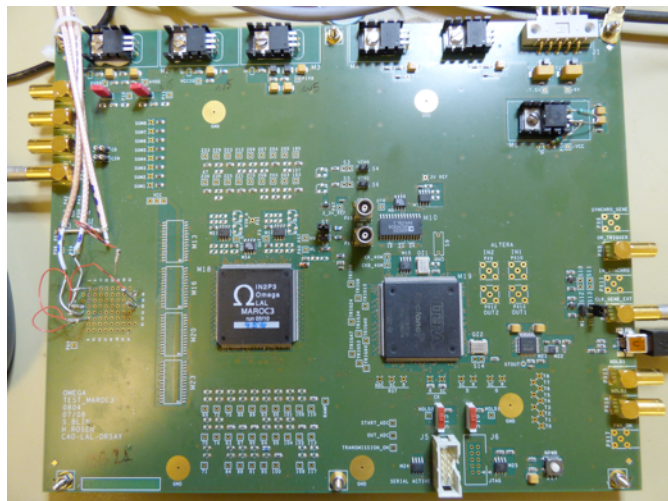
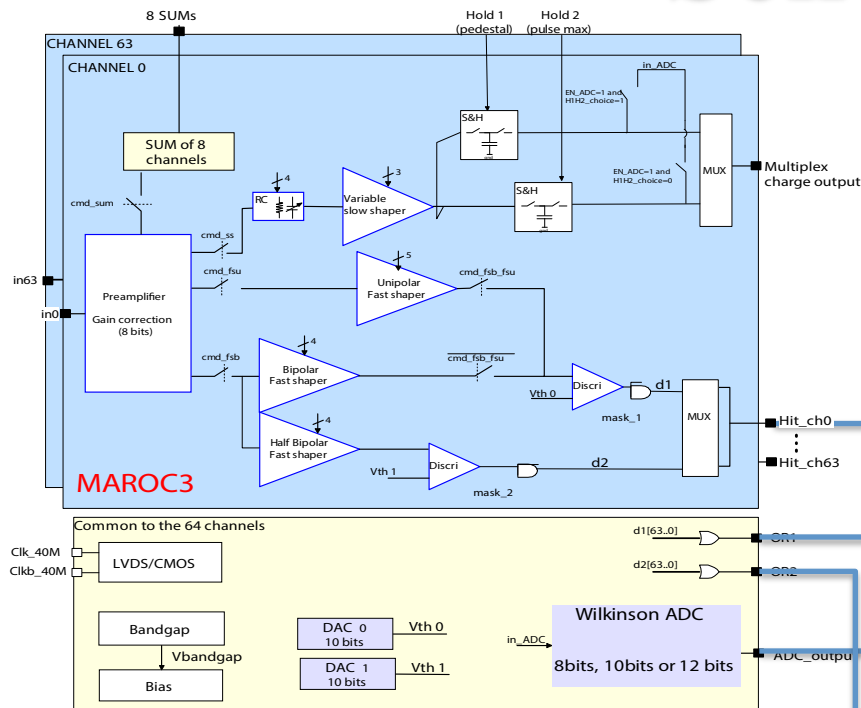


Role of the Top Tracker

- Act as veto around the covered surfaces (impossible to cover all surface around the central detector, 40x40 m²).
- Study the production of ${}^9\text{Li}/{}^8\text{He}$ produced by the muons crossing the central detector or the areas around.
- Study the production of **fast neutrons** produced in the surrounding rock.
- Precise measurement of the spectra of these backgrounds.
- Define the cuts to apply to reduce these backgrounds.
- Introduce all measured parameters in the simulation.
- Better estimation of the systematic errors induced by this background.

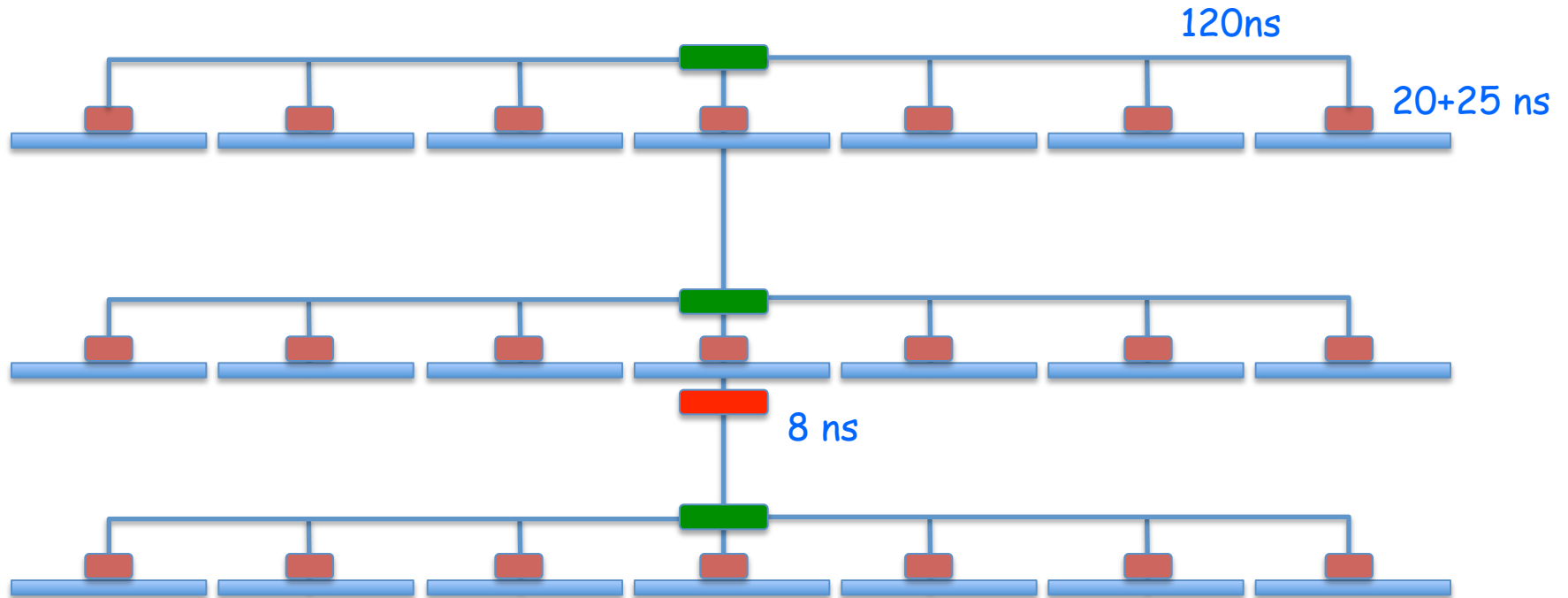


Schematics



Hardware Coincidences

x-y coincidences on 3 layers (in a time window of 100 ns)

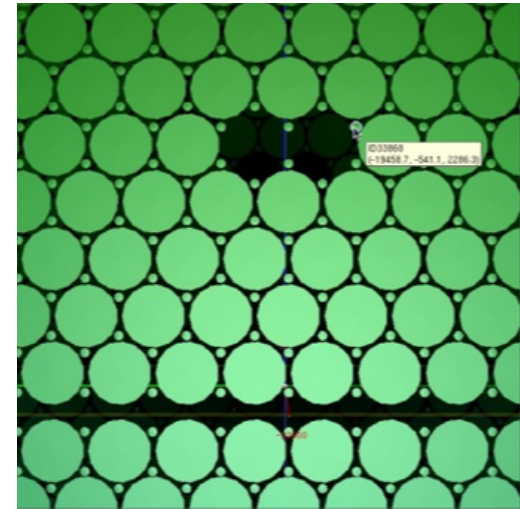
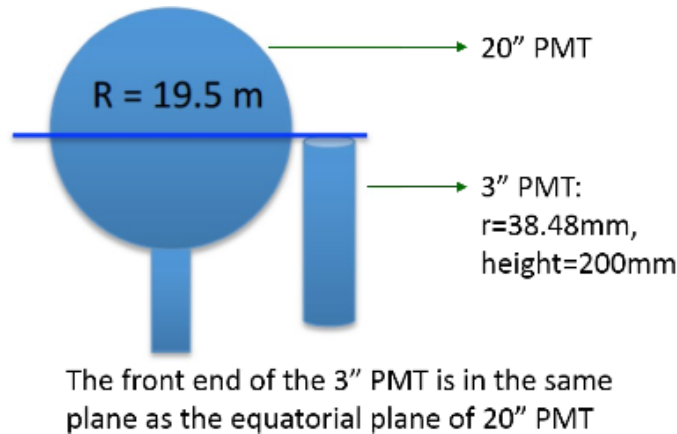


total for 3 layers' coincidence: $(25+20)+120+8+120+8 + 3 \times 50 < 600$ ns

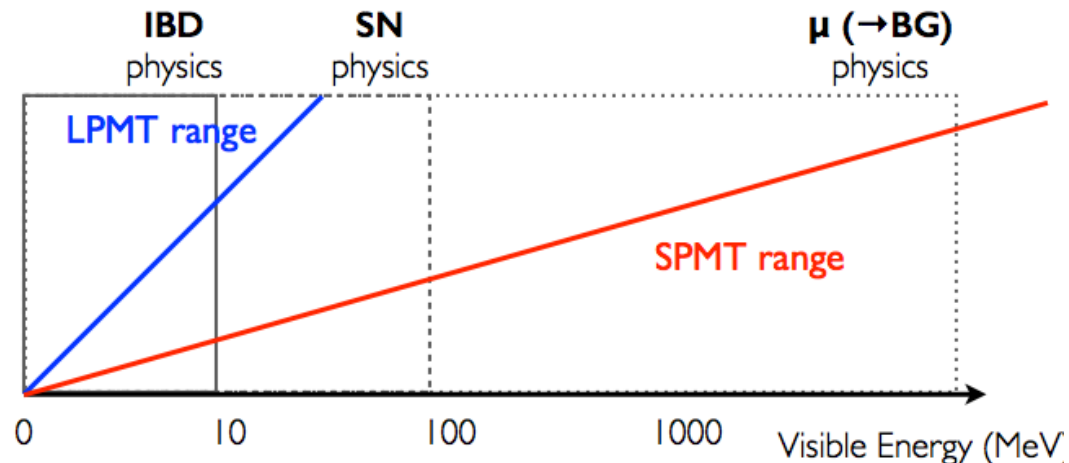
delay in the 3 boxes

Double calorimetry

- Small PMTs (SPMT) are cheaper and faster in time response ($<1\text{ns}$), lower noise and higher QExCE
- Adding 3" PMTs in the gaps: ~ 2 SPMTs for every large PMT (LPMT)
 - increase the photocathode coverage by $\sim 1\%$
 - improve the central detector muon reconstruction resolution
 - avoid high rate supernova neutrino pile-up (if very near)
 - increase the dynamic range and global trigger



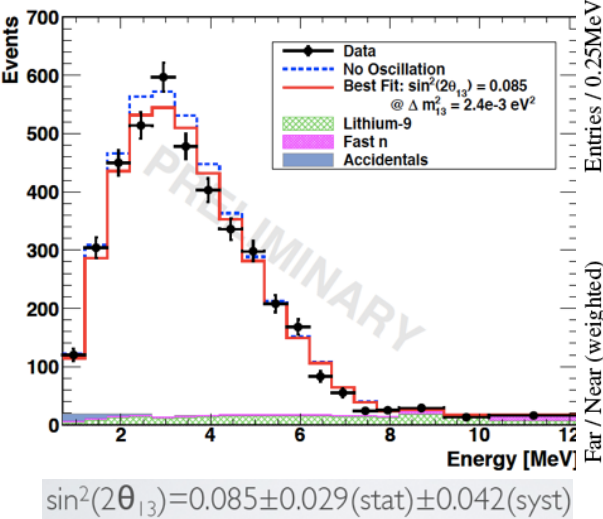
Complementary Roles by sPMTs and LPMTs



θ_{13} is large!!!

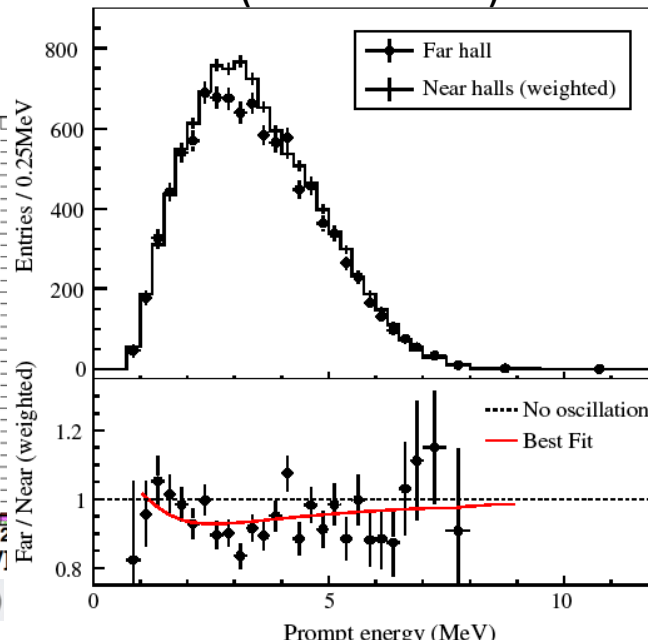
reactor experiments discovery
of the $1 \rightarrow 3$ oscillation

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



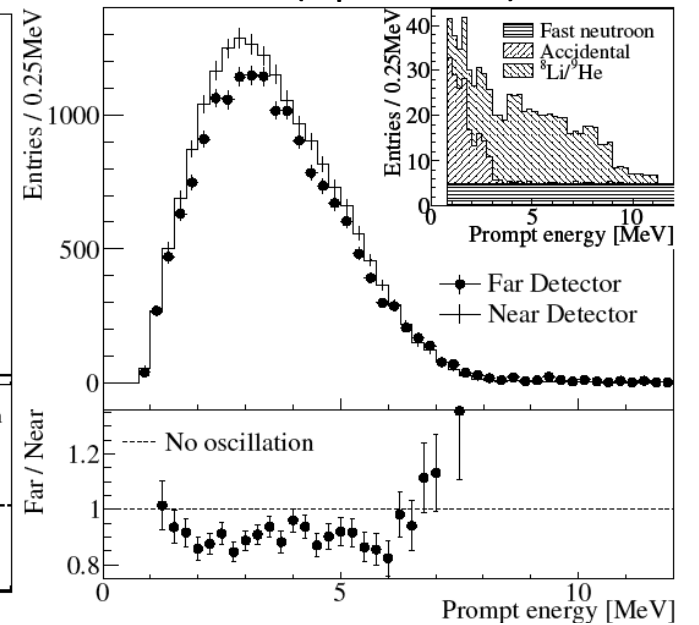
$$\sin^2(2\theta_{13}) = 0.085 \pm 0.029(\text{stat}) \pm 0.042(\text{syst})$$

Daya Bay
(March 2012)



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

RENO
(April 2012)

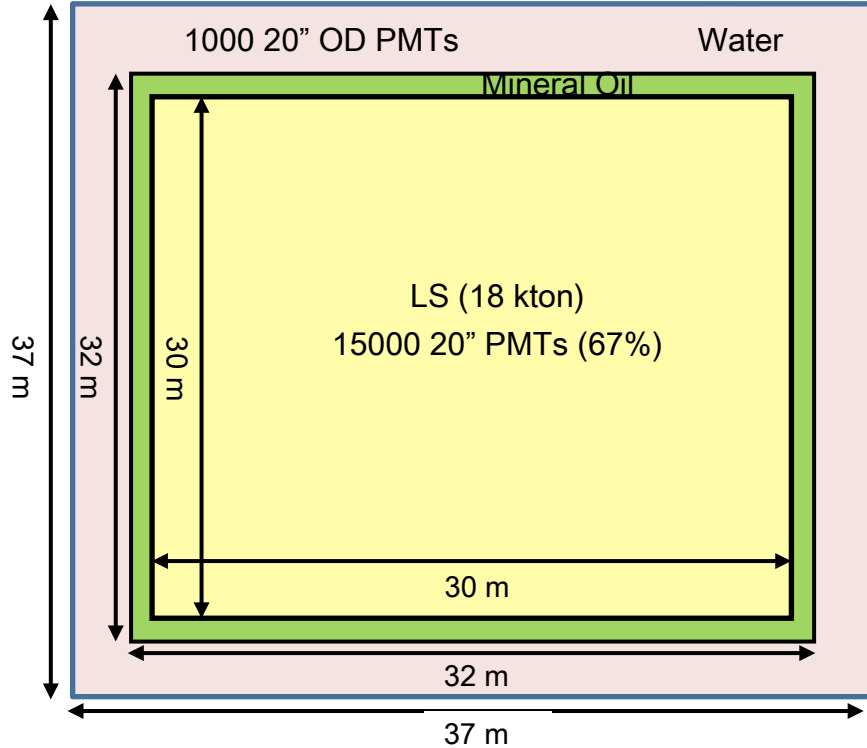


$$\sin^2 2\theta_{13} = 0.103 \pm 0.013(\text{stat.}) \pm 0.011(\text{syst.})$$

$\theta_{13} > 0$ (C.L. $> 5 \sigma$)

proposed LBL beam facilities had to be readjusted...
now, the name of the game is MH and CPV

RENO-50



- 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

