中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

Neutrino Physics In China

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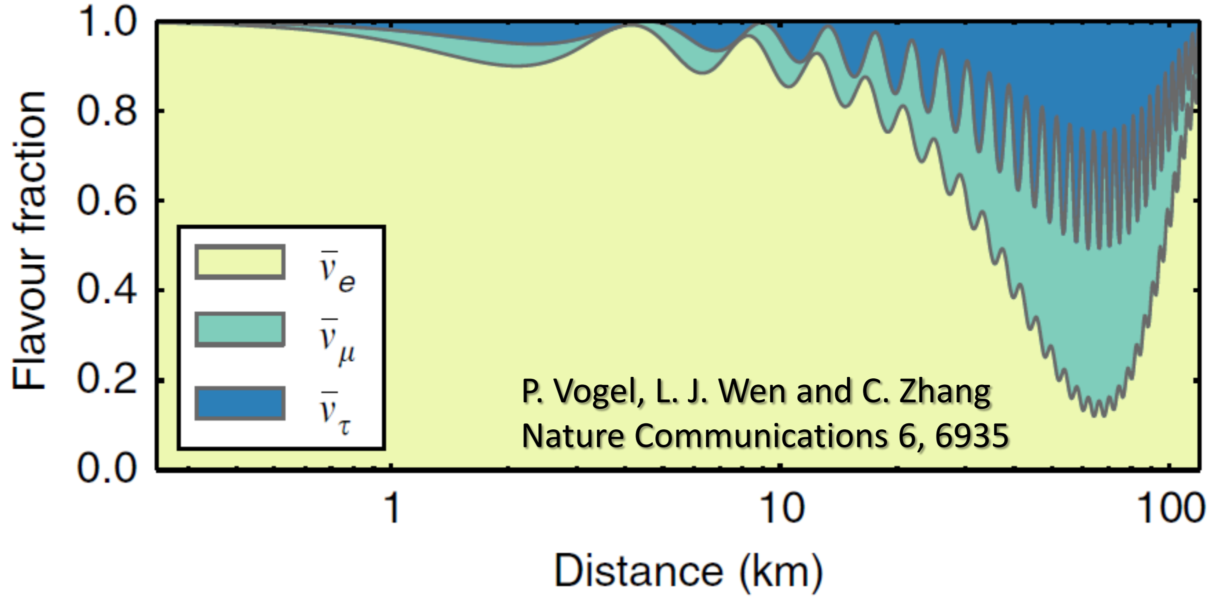
53rd Course: THE FUTURE OF OUR PHYSICS INCLUDING NEW FRONTIERS,
Erice, 24 June – 3 July 2015

Neutrino Oscillation studies with reactors

- **In a simple 2-ν framework**

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

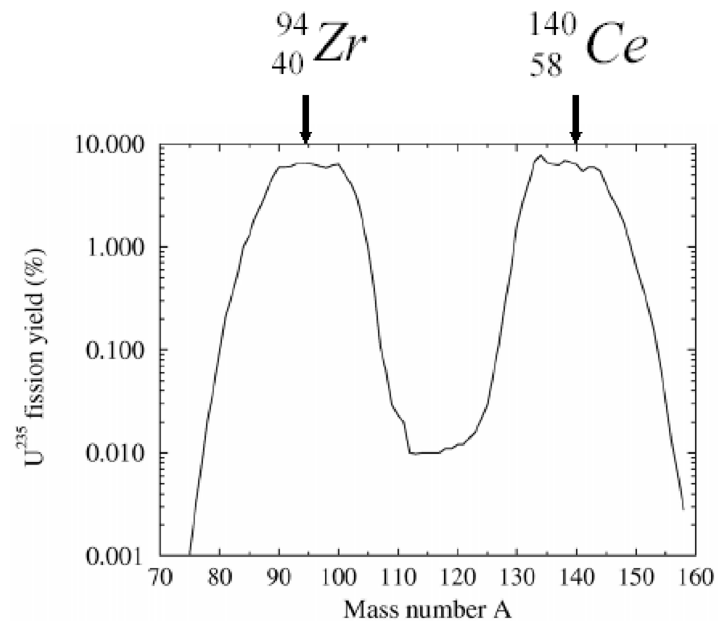
$$P(\nu_e \to \nu_\alpha) = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$



- **A brief history of reactor neutrino experiments**
  - Discovery: **50's – 60's Reines**
  - Early search for oscillation: **70's-80's Reines, ILL,**
  - Atmospheric neutrino oscillation**: 90's Palo Verde, Chooz**
  - Solar neutrino oscillation: **00's KamLAND**
  - Small θ_{13}: **10's Daya Bay, Double Chooz, RENO**

Reactor $\bar{\nu}$

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$



Neutrino Flux

$$\mathbf{S}(E_\nu) = \frac{W_{th}}{\sum_i \left(\frac{f_i}{F}\right) \cdot e_i} \sum_i \left(\frac{f_i}{F}\right) \cdot S_i\,(E_\nu)$$

$$W_{th} = \sum_i f_i e_i \;, \qquad F = \sum_i f_i$$

E_ν: Neutrino energy

$S_i(E_\nu)$: Neutrino energy spectra/f, ~6 ν/fission

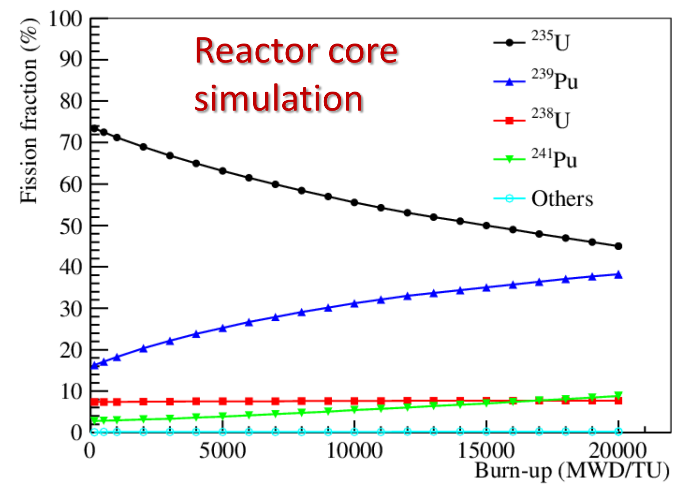
W_{th}: Reactor thermal power

(f_i/F): Fission fraction

f_i: Fission rate of isotope i

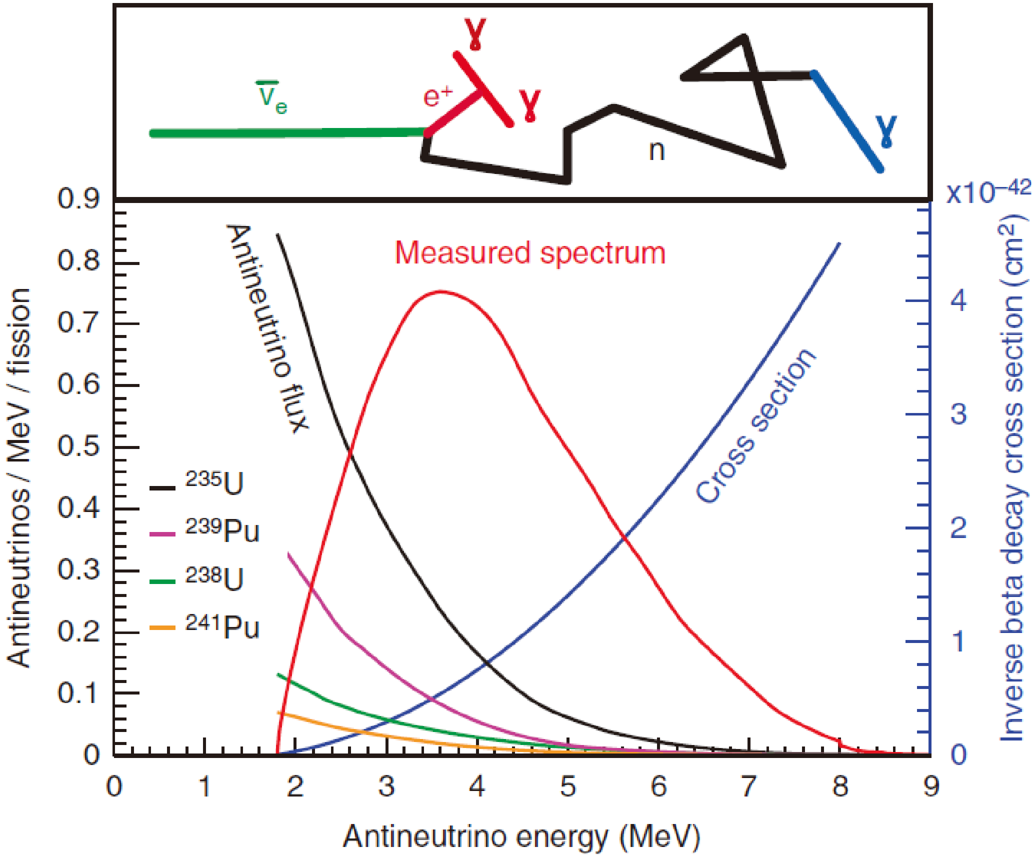
e_i: Energy release per fission, ~200 MeV/fission

- Neutrino flux of a commercial reactor with 3 GW_{th} : **~6×10^{20} ν/s**
- Distinguishing correlated and un-correlated errors is important



Reactor $\bar{\nu}$ Detection

- Detection via Inverse-β reaction $\bar{\nu}_e + p \rightarrow e^+ + n$



τ ≈ 180 μs
or 28 μs (0.1% Gd)

n + p → d + γ (2.2 MeV)
n + Gd → Gd* + γ (8 MeV)

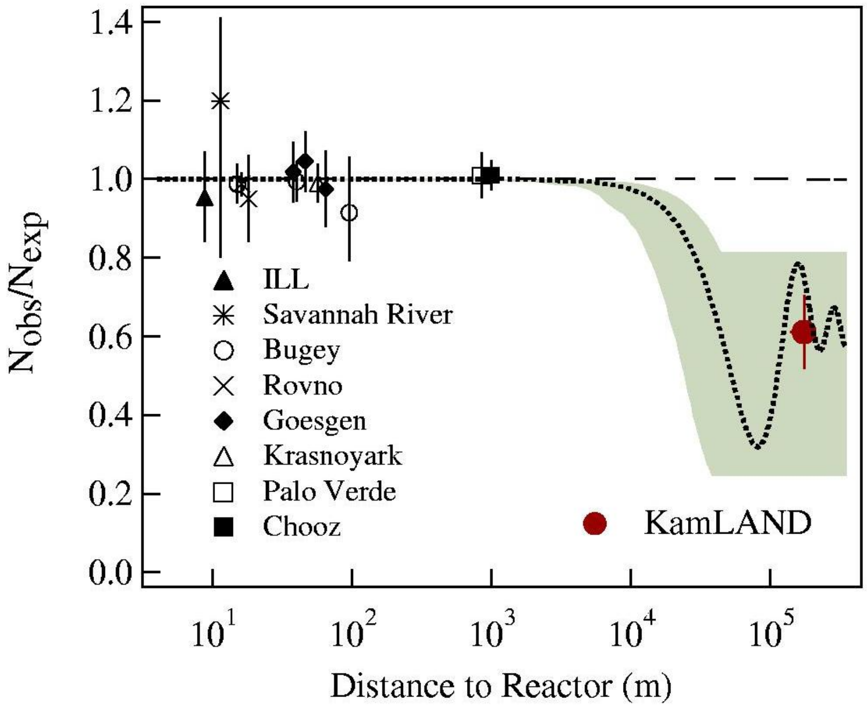
Neutrino Event: coincidence in time, space and energy

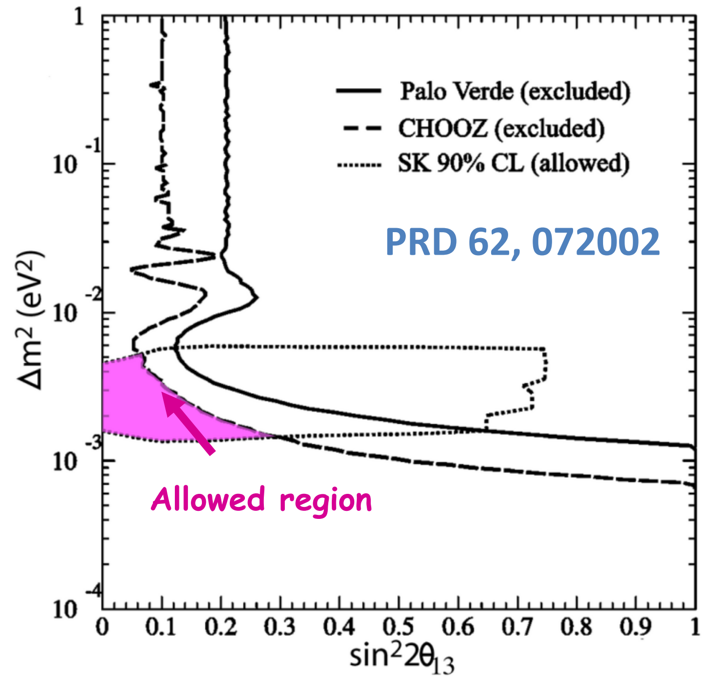
Neutrino energy:

$$E_{\bar{\nu}} \simeq T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

10-40 keV (T_n)   ***1.8 MeV:*** **Threshold**

Early Experiments





Palo Verde & Chooz: no signal

$\sin^2 2\theta_{13} < 0.12$ @ 90%C.L.

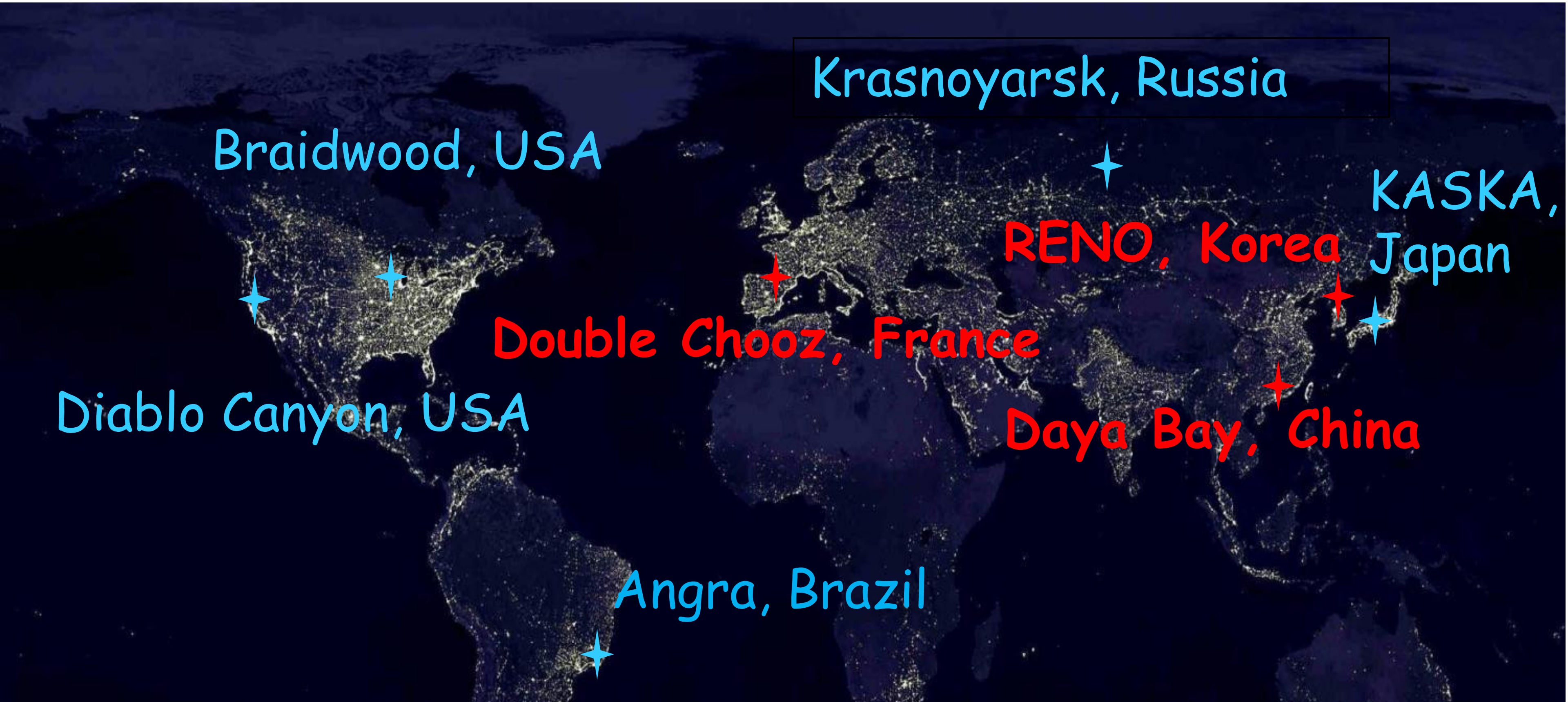
if $\Delta m^2_{23} = 0.0024\ eV^2$

Major sources of uncertainties:

- Reactor related ~2%
- Detector related ~2%
- Background 1~3%

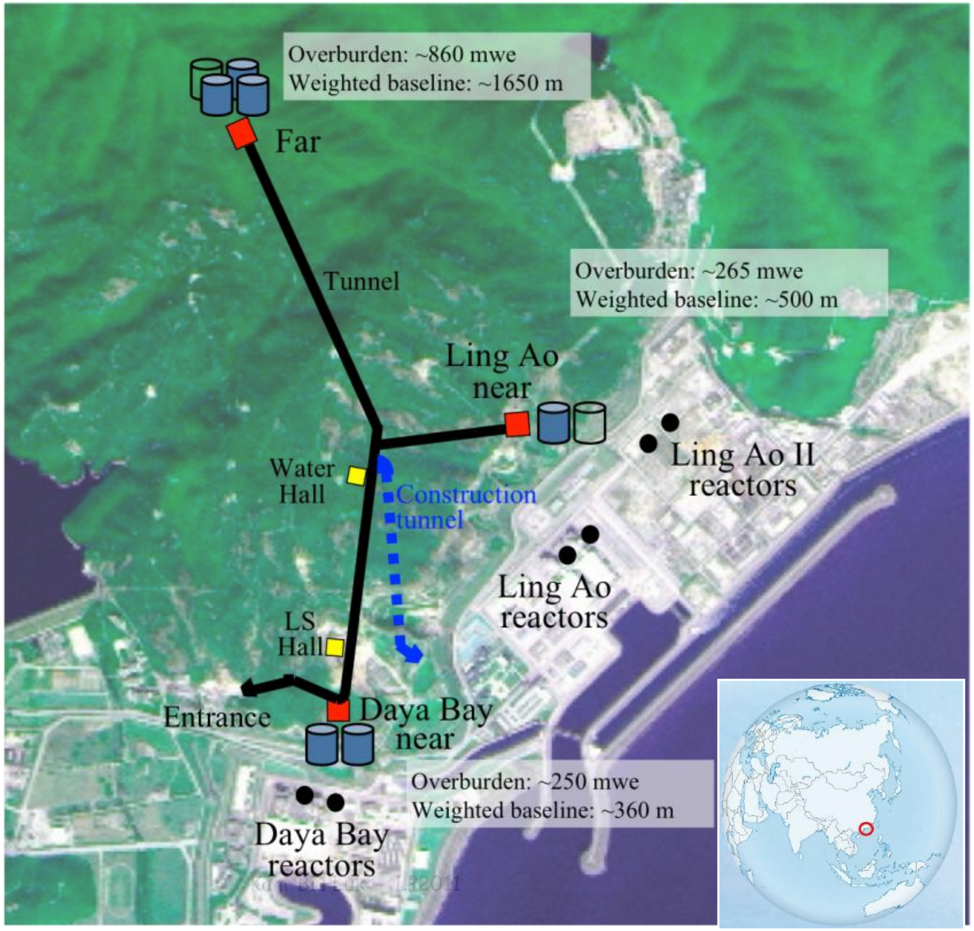
Near-far relative measurement was proposed (Mikaelyan and Sinev, hep-ex/9908047) to reduce the uncertainties from reactor and detector

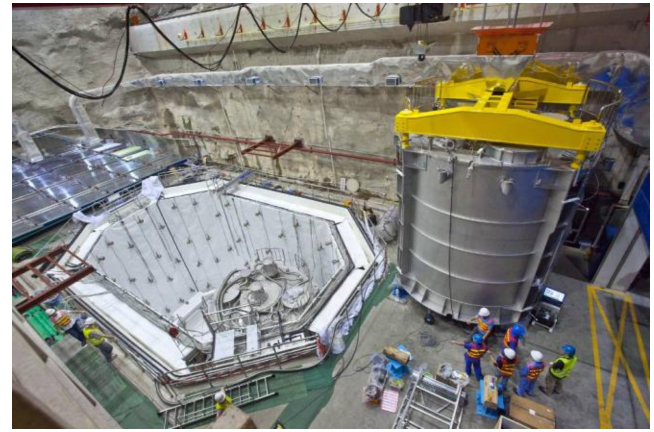
Reactor Proposals for θ_{13}

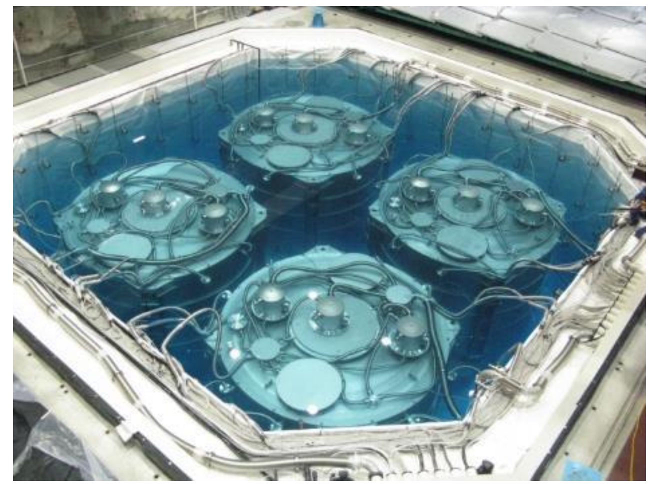


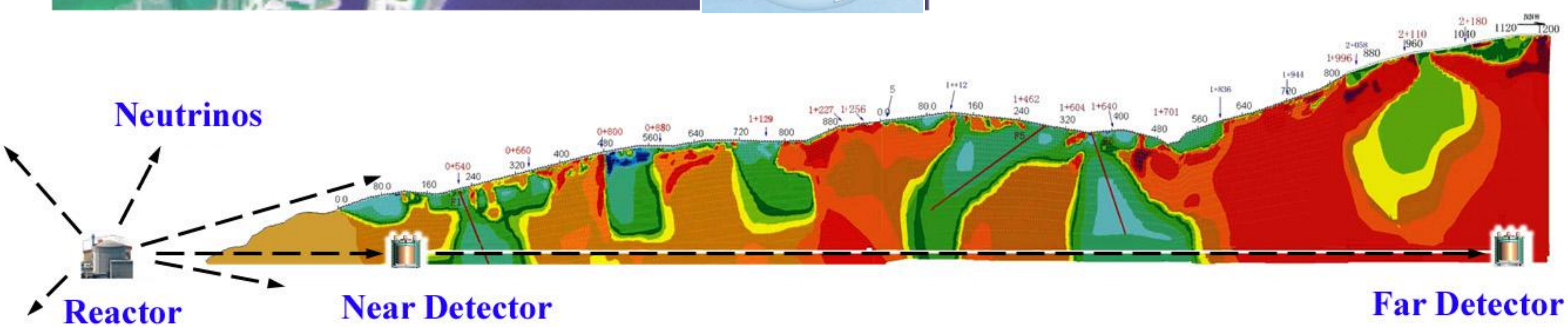
- **Daya Bay was proposed in 2003, the start point of Neutrino Program in China.**
- **3 of the 8 proposals are constructed.**

Daya Bay Scheme



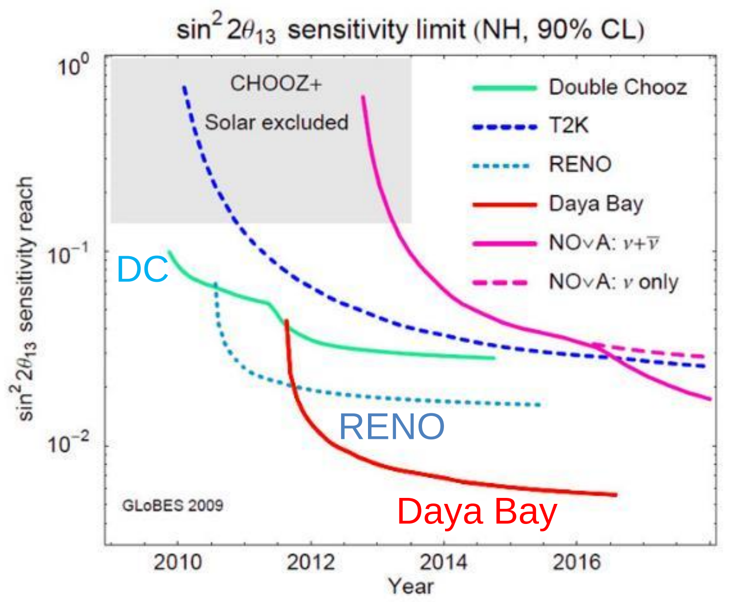






The Best Site for θ_{13}

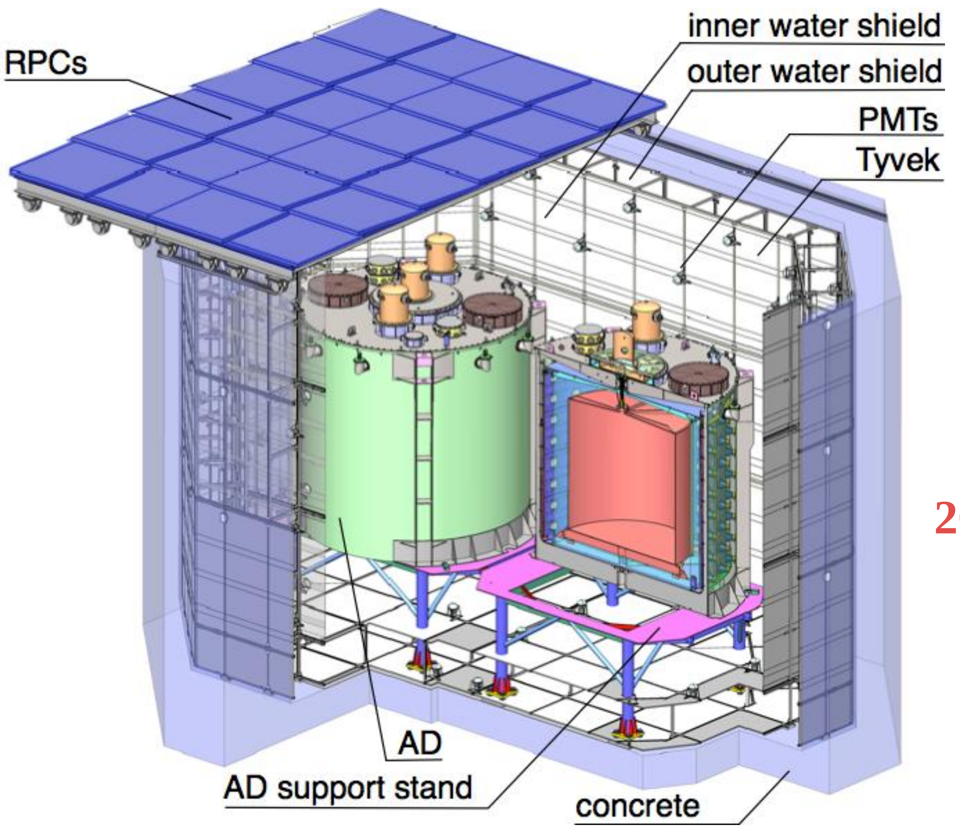
- Powerful reactor complex (Top 5)
- Close to mountains → enough shielding
- Luminosity 5-20 times of DC and RENO
- Featured design → side-by-side calibration (2-4 ADs at each site) → actual relative det. error 0.2% **/√N**,
- Discovered an unexpectedly large θ_{13} in Mar. 2012.

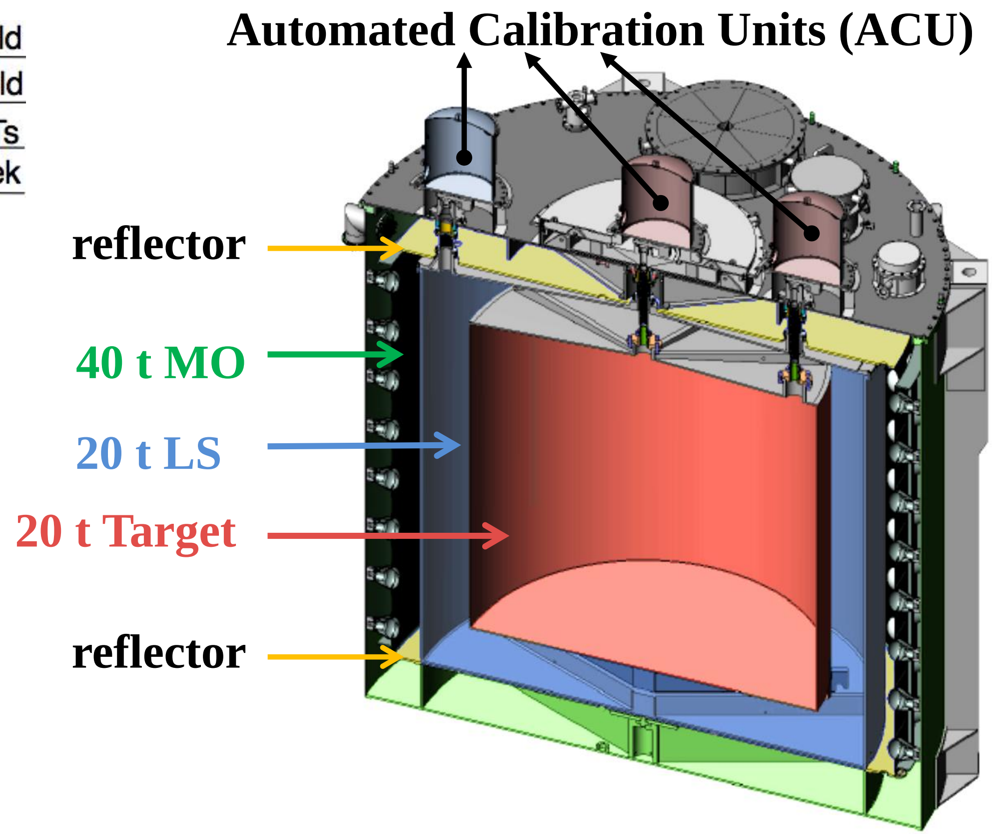


Huber et al. JHEP 0911:044, 2009

Designs	Luminosity (ton·GW)	Detector Systematics	Overburden (near/far, mwe)	Sensitivity (3y, 90%CL)
Daya Bay	1400	0.38%/√N	250 / 860	~ 0.008
Double Chooz (France)	70	0.6%	120 / 300	~ 0.03
RENO (Korea)	260	0.5%	120 / 450	~ 0.02

The Daya Bay Detectors

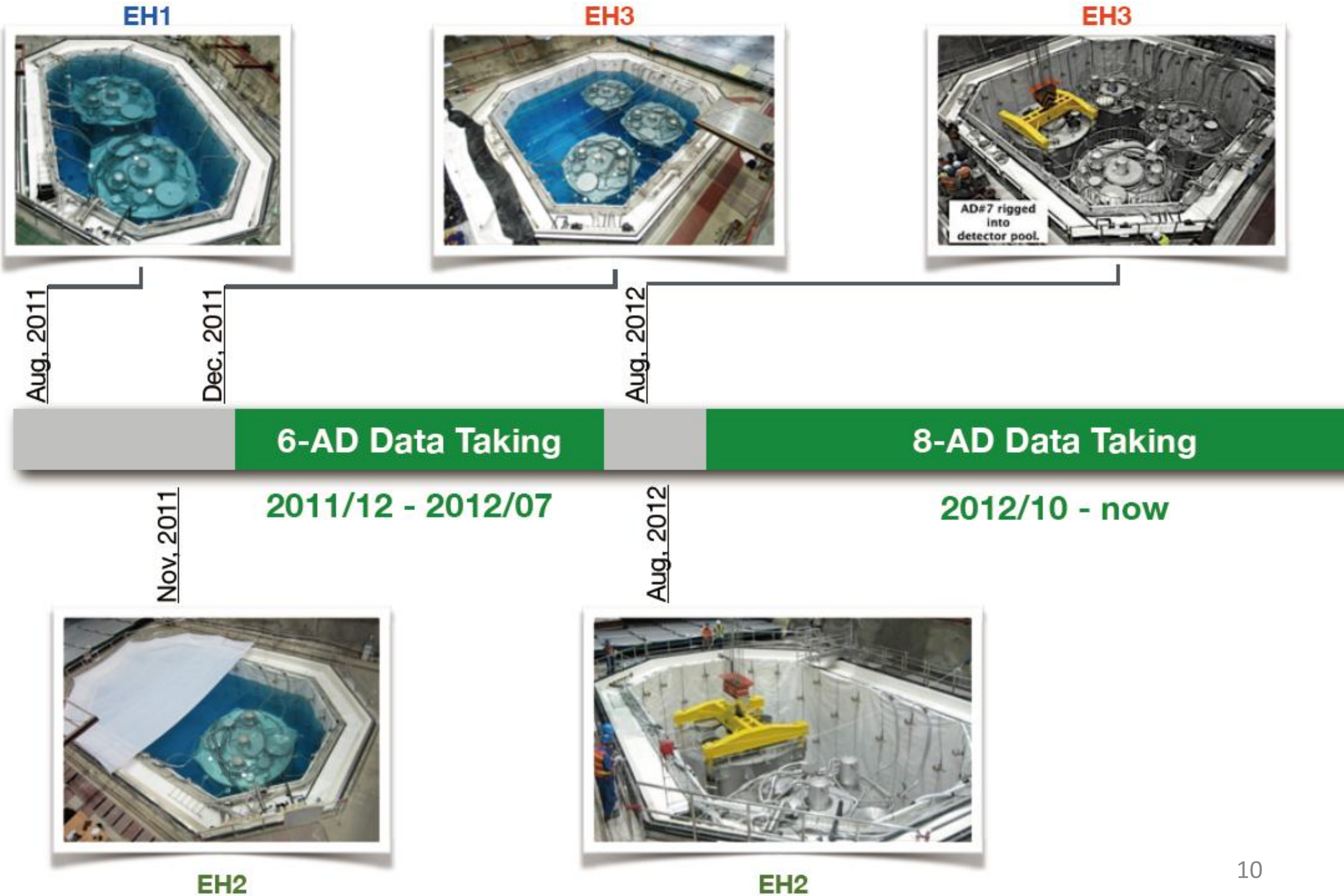




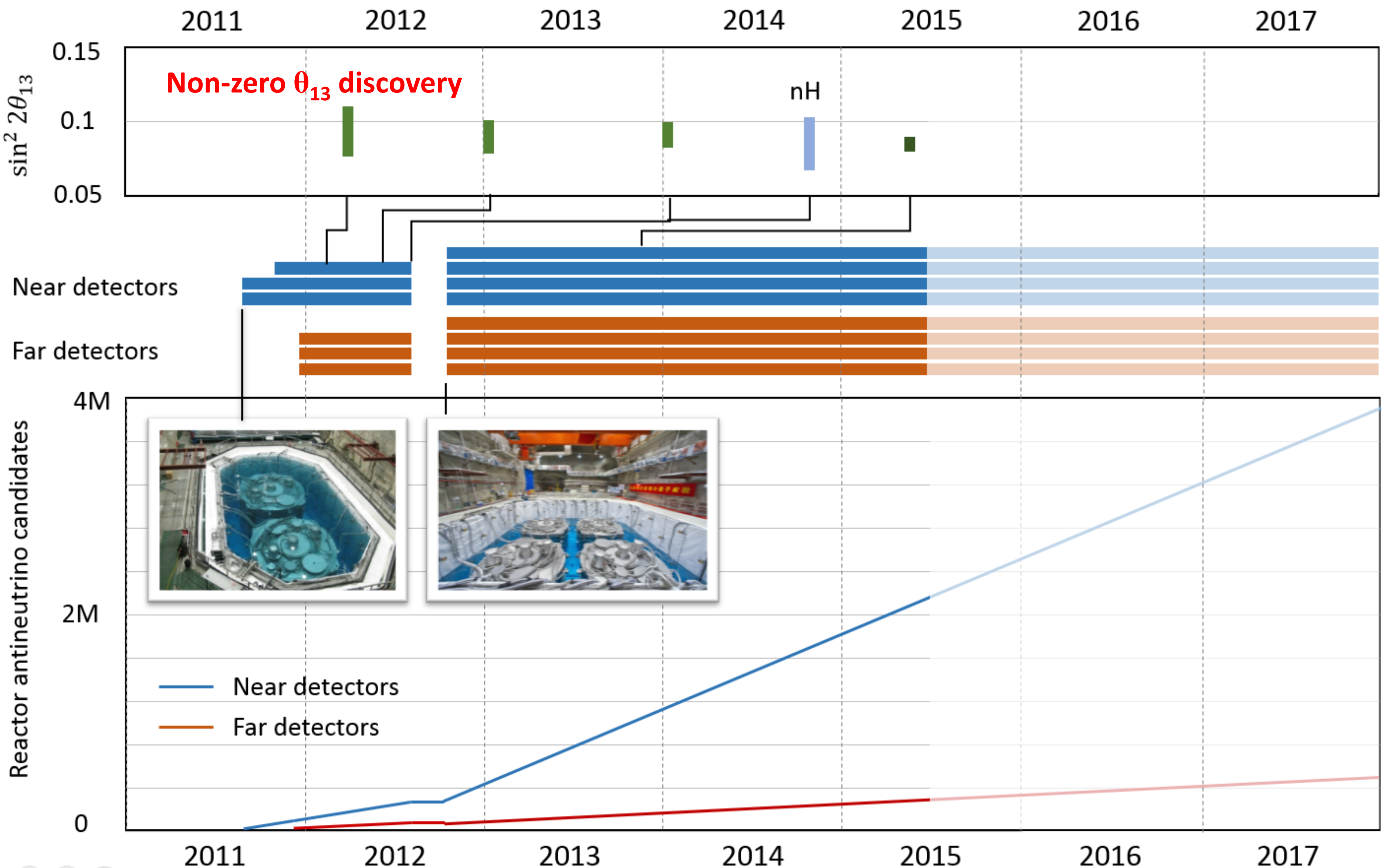
- Multiple AD modules at each site to check Uncorr. Syst. Err.
  - Far: 4 modules， near: 2 modules
- Multiple muon detectors to reduce veto eff. uncertainties
  - Water Cherenkov： 2 layers
  - RPC： 4 layers at the top + telescopes

Redundancy !!!

Installation Timeline



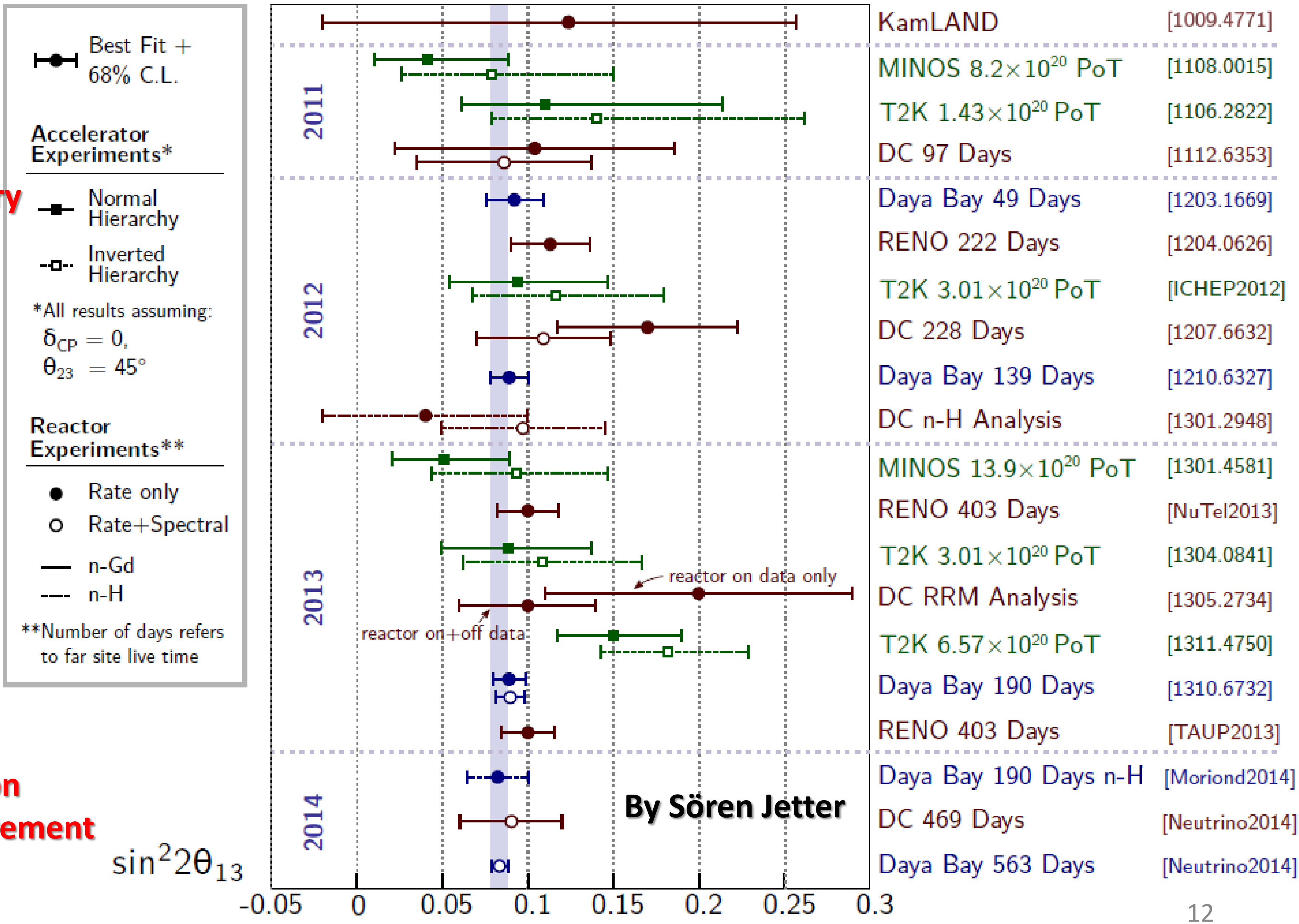
Operation History



Global Picture of θ_{13}

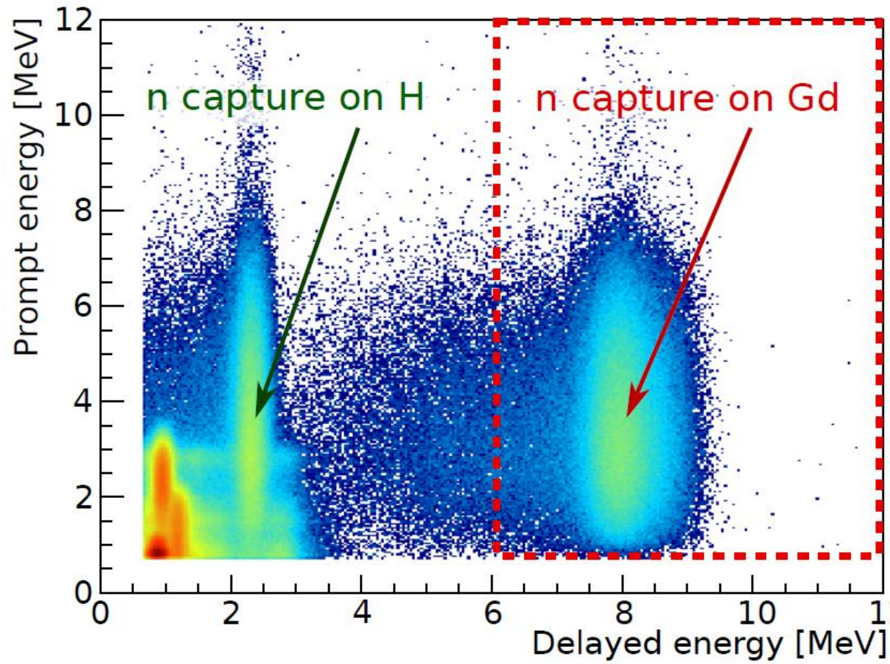
Discovery

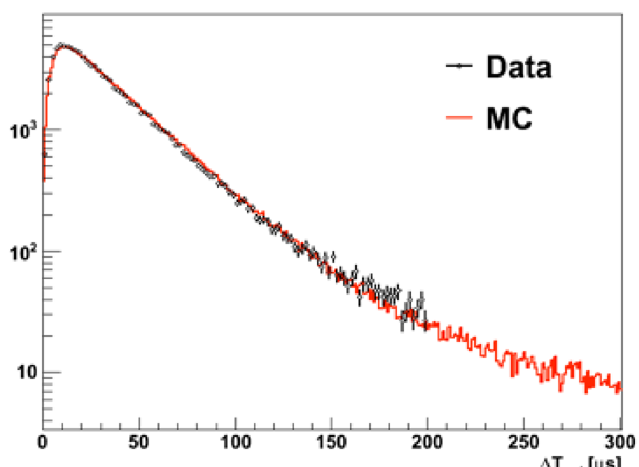
Precision Measurement



Antineutrino Candidates Selection

- Reject PMT flashers
- Coincidence in energy and time
  - Energy: 0.7 MeV < Ep < 12.0 MeV, 6.0 MeV < Ed < 12.0 MeV
  - Time: 1 μs < $\Delta t_{p\text{-}d}$ < 200 μs
  - Multiplicity cut: only select isolated candidate pairs
- Muon Veto:
  - Water pool muon: reject 0.6 ms
  - AD muon (>20 MeV): reject 1 ms
  - AD shower muon (>2.5 GeV): reject 1 s

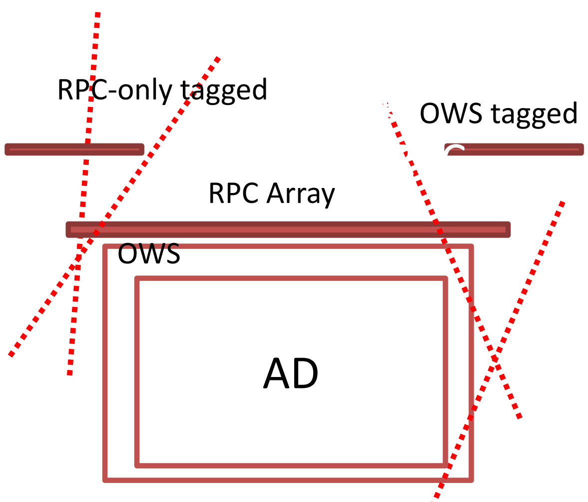


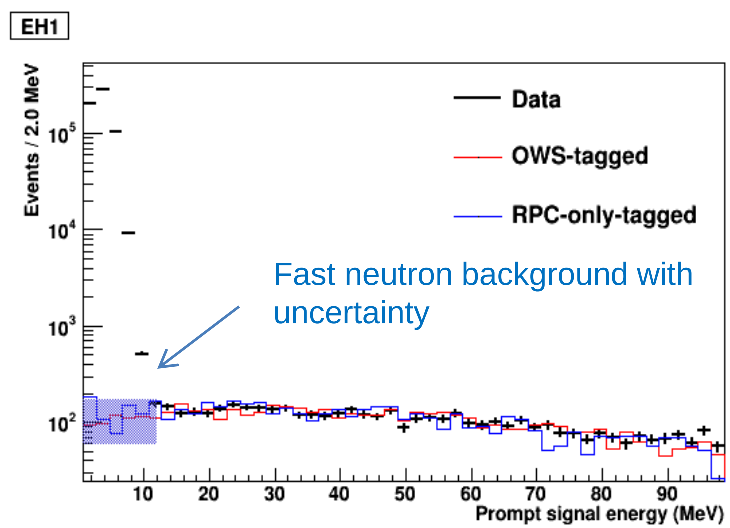


	Efficiency	Correlated Uncertainty	Uncorrelated Uncertainty
Target protons		0.47%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.12%
Prompt energy cut	99.81%	0.10%	0.01%
Capture time cut	98.70%	0.12%	0.01%
Gd capture ratio	84.2%	0.95%	0.10%
Spill-in correction	104.9%	1.50%	0.02%
Combined	80.6%	2.1%	0.2%

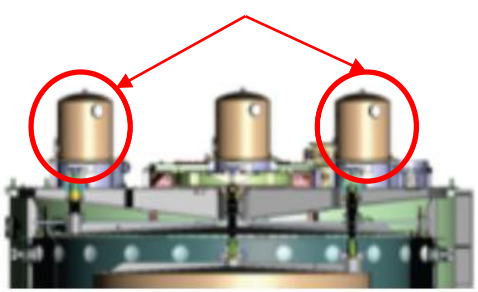
Backgrounds

Background	Near	Far	Uncertainty	Method	Improvement
Accidentals	1.4%	2.3%	Negligible	Statistically calculated from uncorrelated singles	Extend to larger data set
$^{9}Li/^{8}He$	**0.4%**	**0.4%**	**~50%**	Measured with after-muon events	Extend to larger data set
Fast neutron	0.1%	0.1%	~30%	Measured from RPC+OWS tagged muon events	Model independent measurement
AmC source	0.03%	0.2%	~50%	MC benchmarked with single gamma and strong AmC source	Two sources are taken out in Far site ADs
Alpha-n	0.01%	0.1%	~50%	Calculated from measured radioactivity	Reassess systematics





Take out two AmC sources

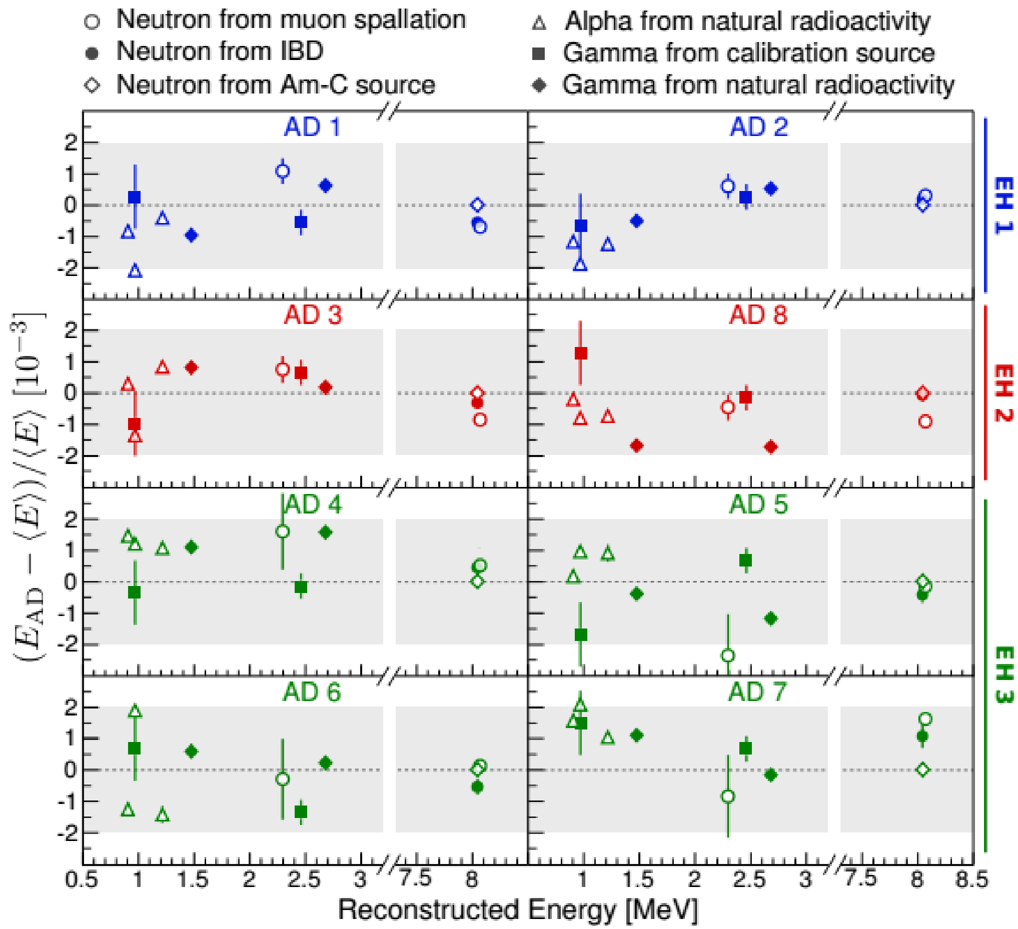


Unique feature: Side-by-side comparison

- Relative energy scale: **< 0.2% variation** in reconstructed energy between ADs
- Improved from 0.35% in 2013 which was between six detectors.

Calibration source:

Auto Calibration Unit: ^{60}Co, ^{68}Ge, AmC Spallation: nGd, nH
Gamma: ^{40}K, ^{208}Tl
Alpha: ^{212}Po, ^{214}Po, ^{216}Po



Unique feature: Side-by-side comparison

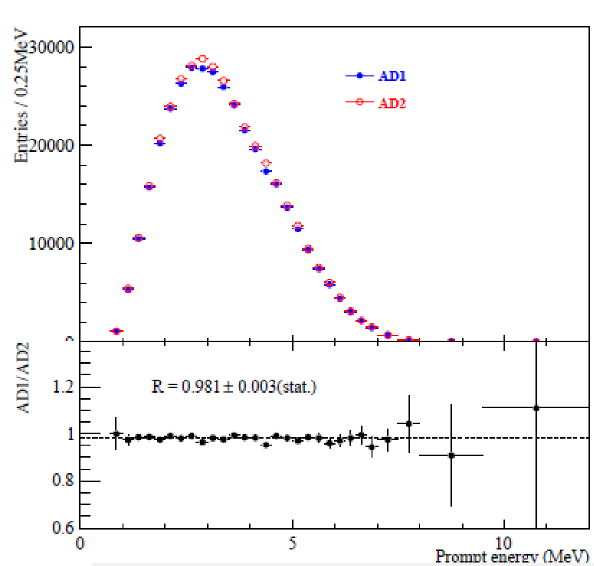
EH1

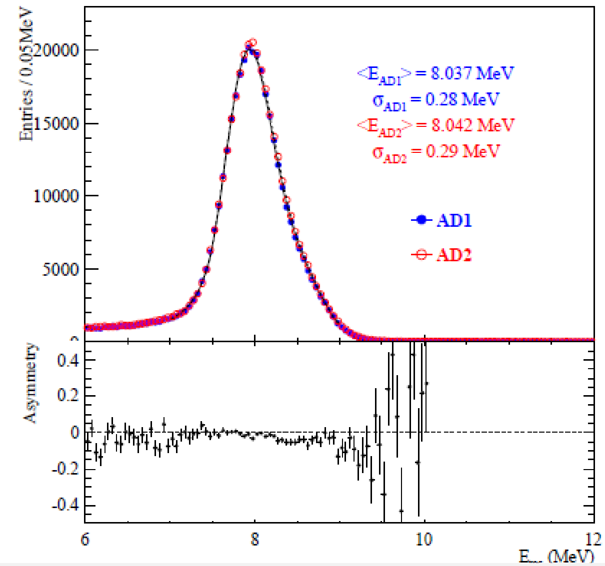
AD1/AD2 (6+8AD data)
Expected: 0.982
Measured: 0.981±0.004

This check shows that systematic errors are under control, and will determine the final systematic error

AD3/AD8 (8AD data)
Expected: 1.012
Measured: 1.019±0.004

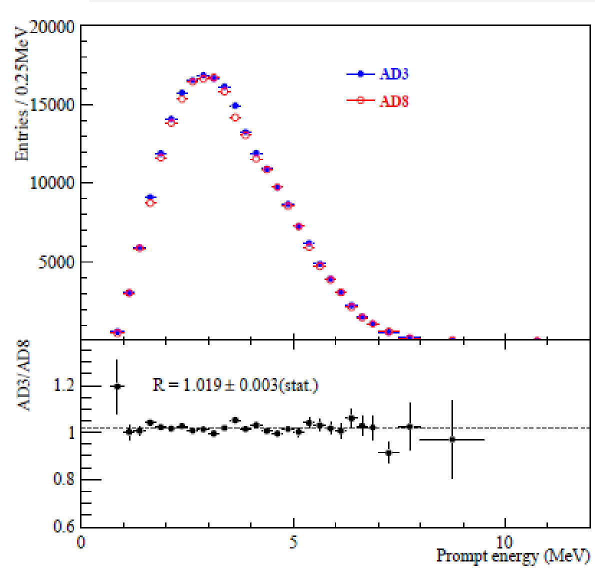
EH2

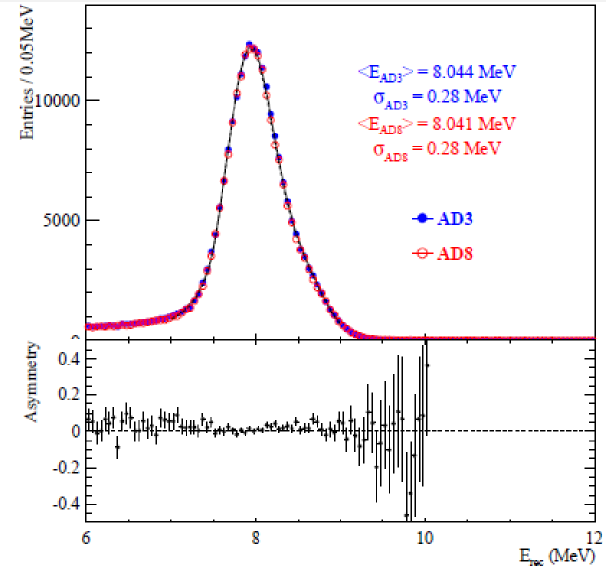




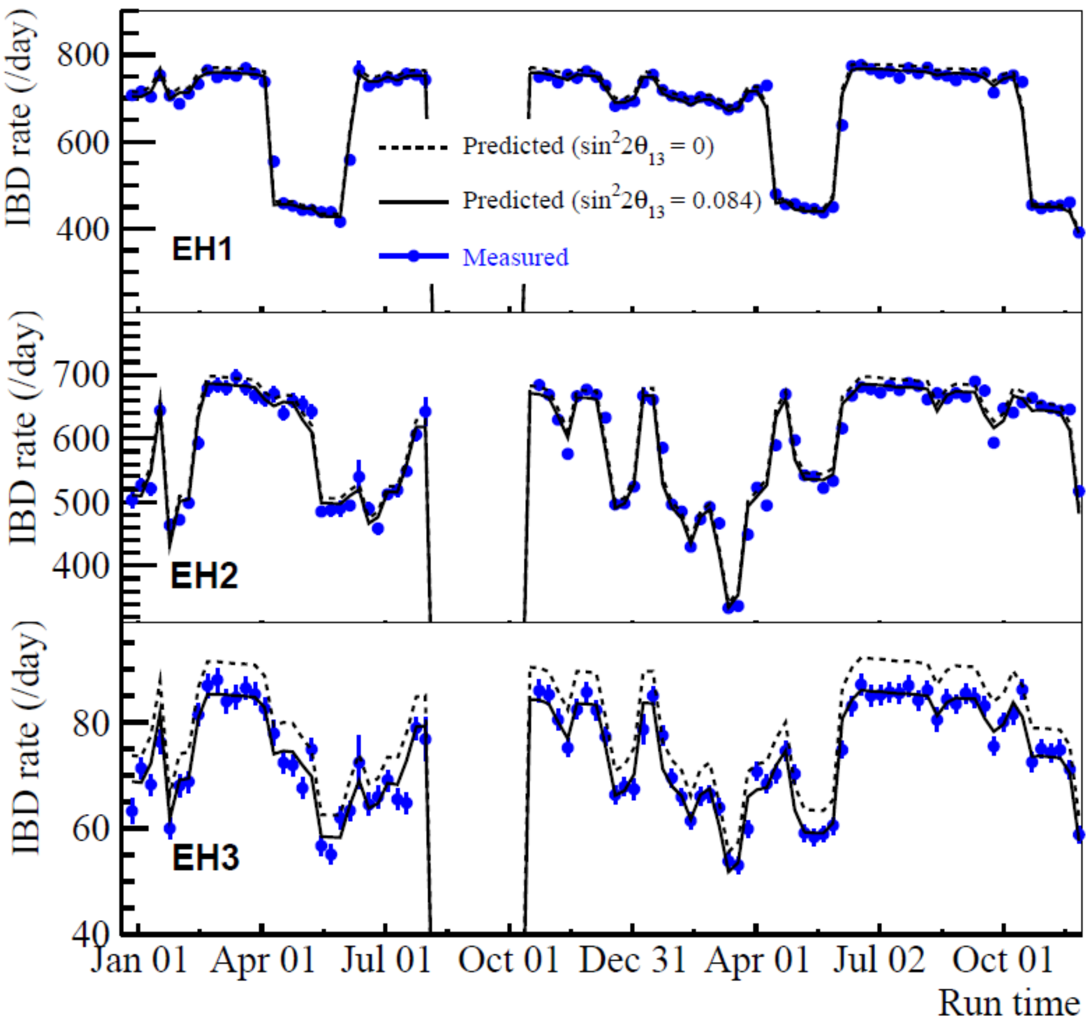
Positron Spectrum

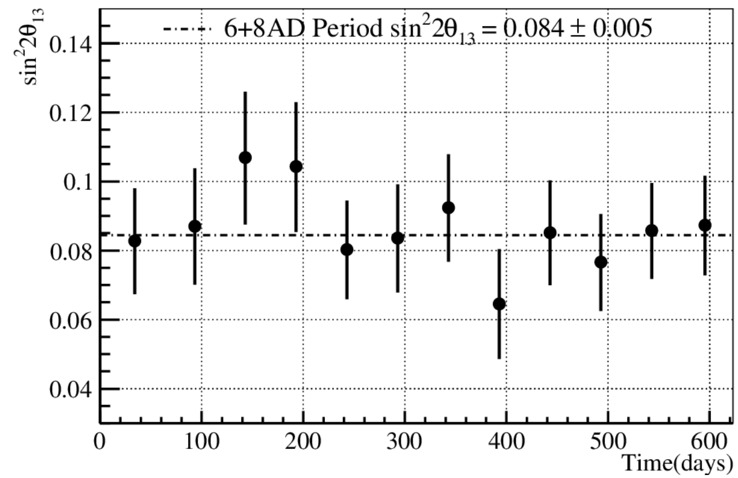
Neutron Capture Spectrum





Time variation of rate deficit

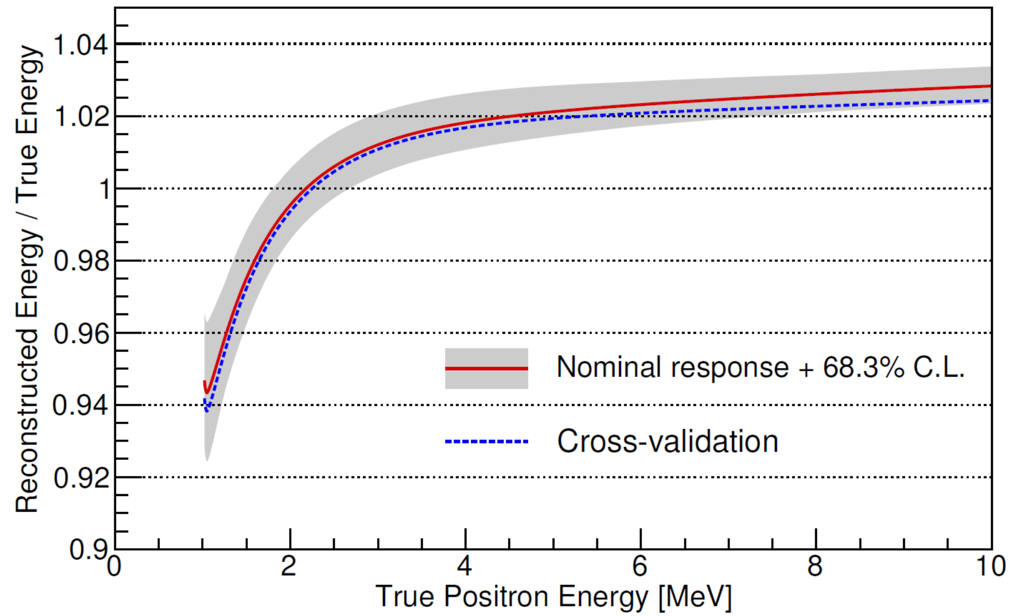




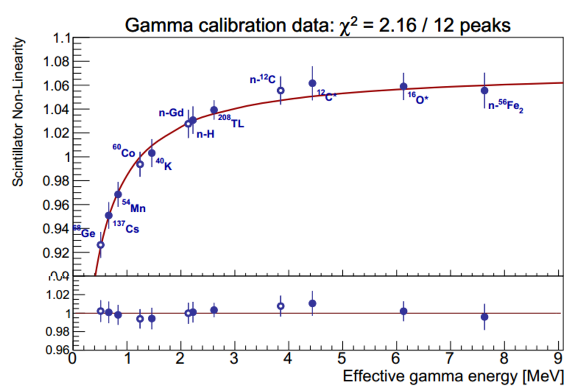
- IBD rate highly correlated with reactor prediction
- Consistent rate deficit as a function of time

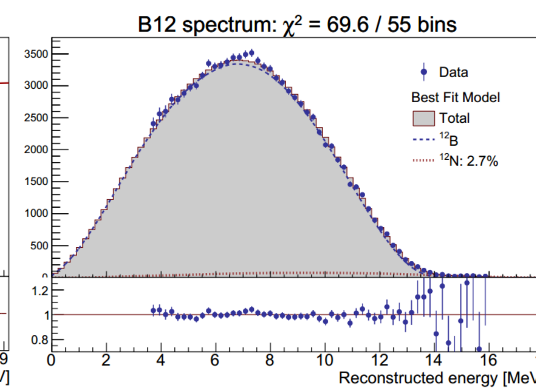
Detector energy response model

- Non-linear energy response in Liquid scintillator
  - Quenching, known as Birks' law *(particle-, E- dep.)*
  - Cerenkov *(particle-, E- dep.)*
  - Electronics *(E- dep, modeled based on MC and signle channel FADC measurement)*



- **Nominal model**: fit to mono-energetic gamma lines and ^{12}B beta-decay spectrum
- **Cross-validation model**: fit to ^{208}Th, ^{212}Bi, ^{214}Bi beta-decay spectrum, Michel electron
- Uncertainty **<1%** above 2MeV



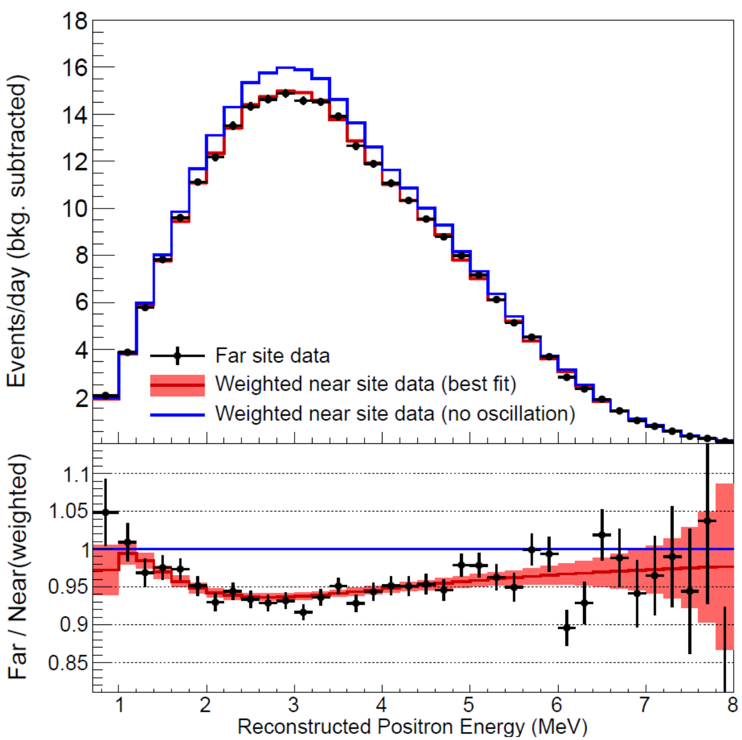


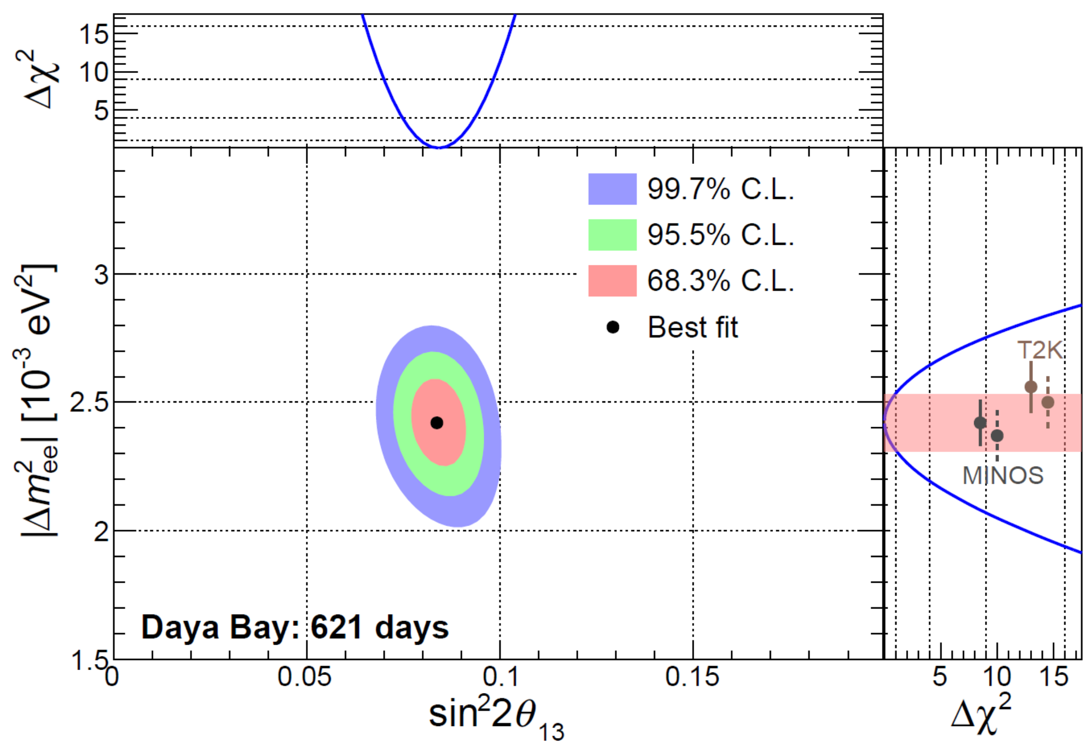
Oscillation analysis

- Far/near relative measurement
- Observed data highly consistent with oscillation interpretation
- Precision of $\sin^2 2\theta_{13}$: **10% → 6%**
- Precision of $|\Delta m^2_{ee}|$: **8% → 4%**

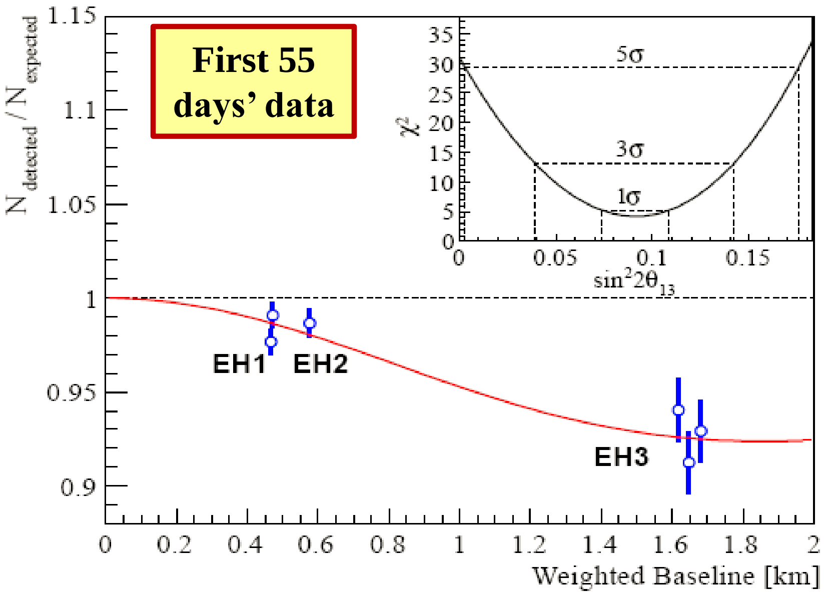
$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$
$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3}\,\mathrm{eV}^2$$

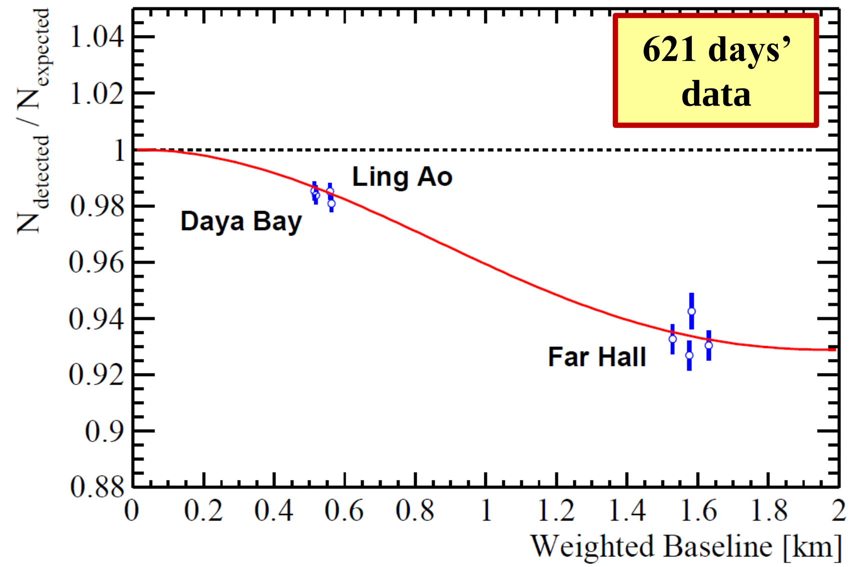
arXiv:1505.03456

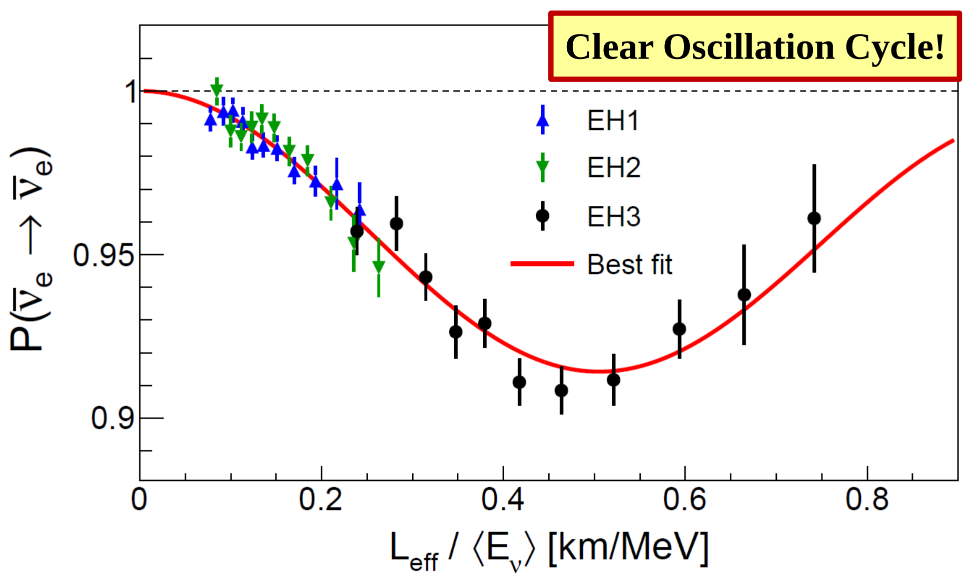




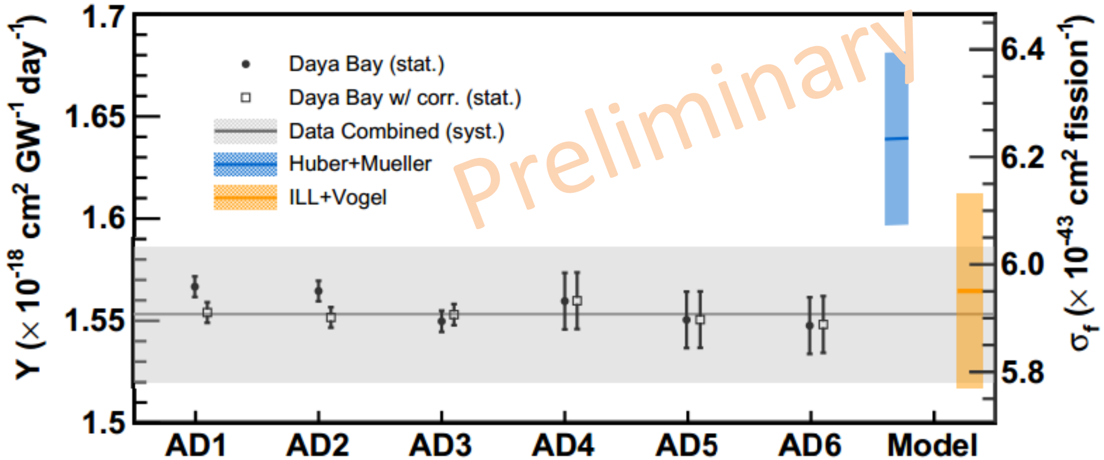
Oscillation



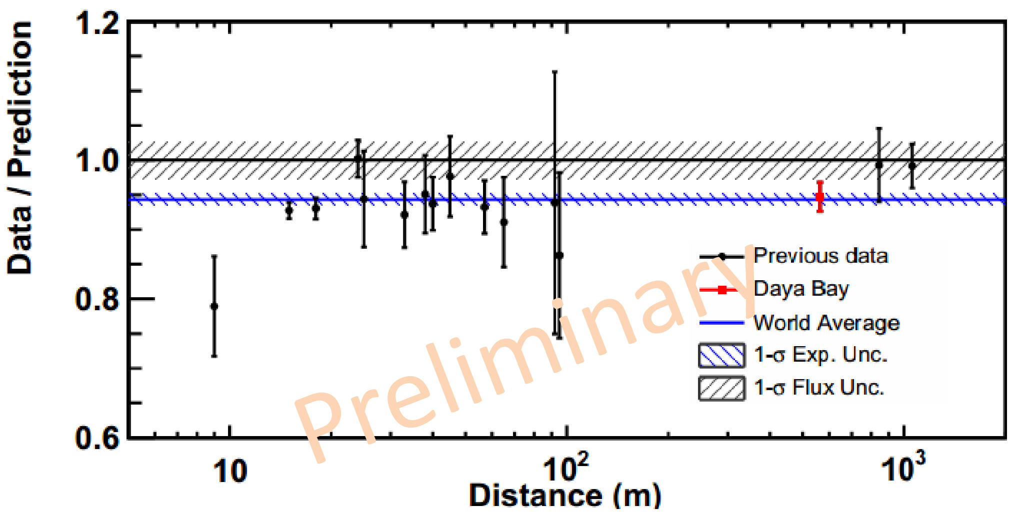




Reactor Neutrino Flux measured @ DYB



Measured IBD events (background subtracted) in each detector are normalized to *cm²/GW/day* (***Y_0***) and *cm²/fission* (***σ_f***).



Global comparison of measurement and prediction (Huber+Mueller)

Daya Bay's reactor antineutrino flux measurement is consistent with previous short baseline experiments.

3-AD (near sites) measurement

$Y_0 = 1.553 \times 10^{-18}$

$\sigma_f = 5.934 \times 10^{-43}$

Compare to flux model

Data/Prediction (Huber+Mueller)

0.947 ± 0.022

Data/Prediction (ILL+Vogel)

0.992 ± 0.023

Effective baseline (near sites)

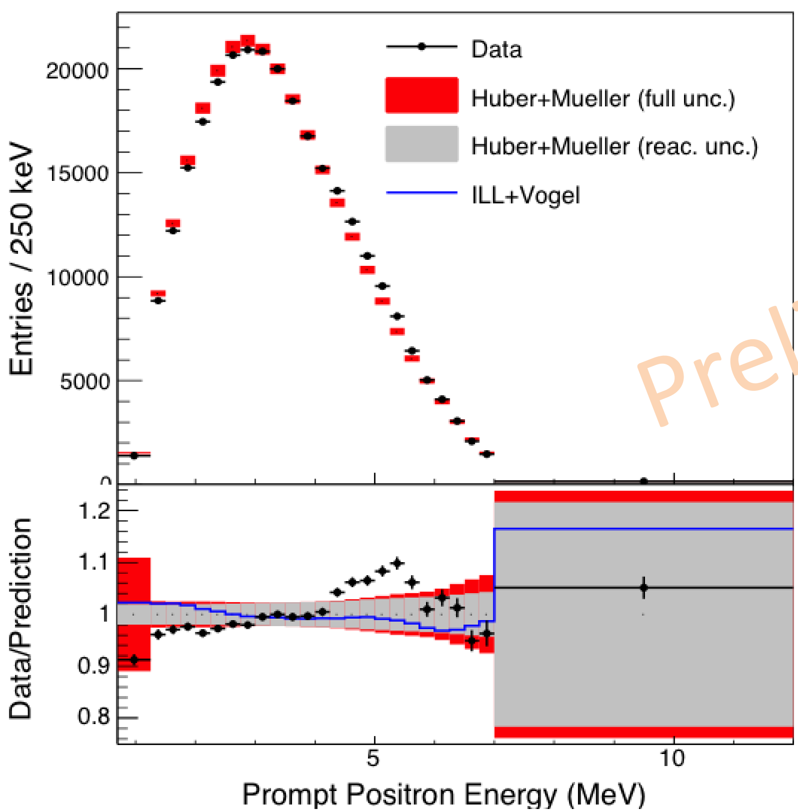
L_{eff} = 573m

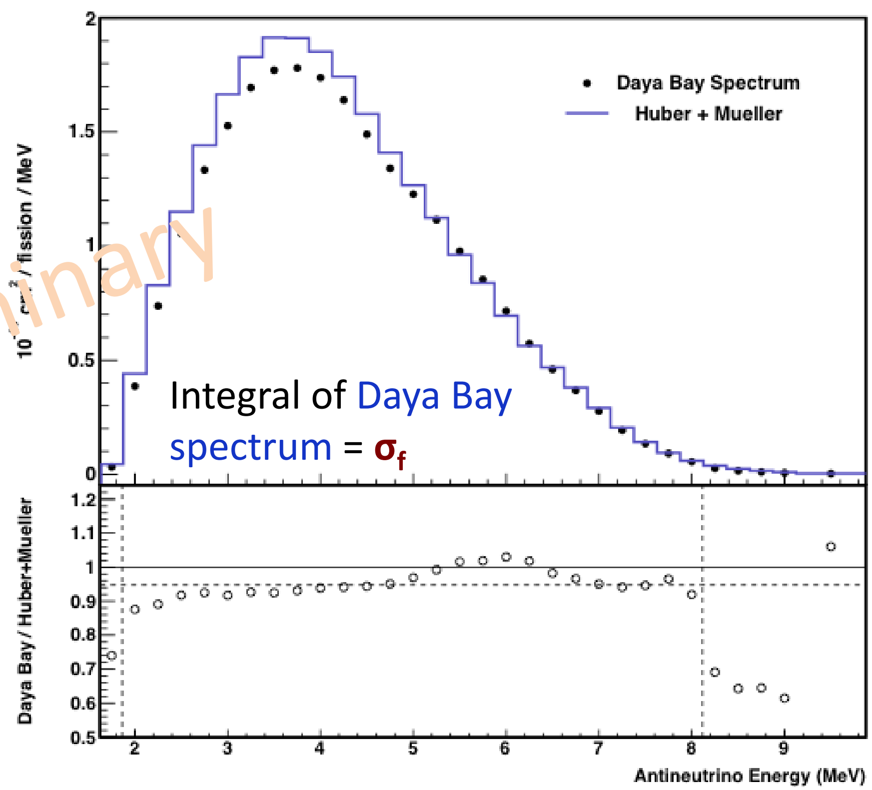
Effective fission fractions α_k

^{235}U	^{238}U	^{239}Pu	^{241}Pu
0.586	0.076	0.288	0.050

Reactor antineutrino spectrum

- Absolute positron spectral shape is NOT consistent with the prediction. A bump is observed in 4-6 MeV (~4σ discrepancy).
- Extract a generic observable reactor antineutrino spectrum by removing the detector response





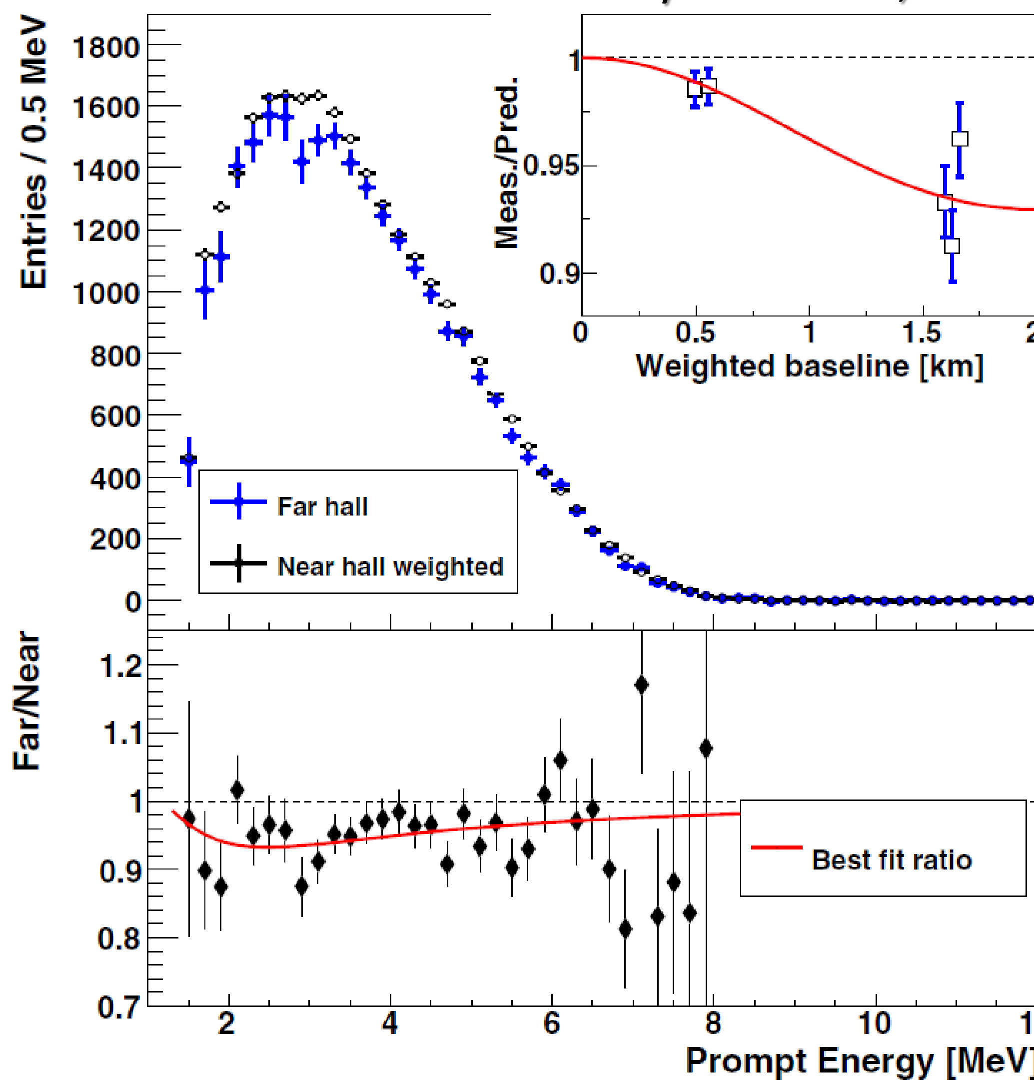
Independent θ_{13} measurement with nH

- **Key features**: independent statistics, different systematics
- **Challenges**: high accidental background because of longer capture time and lower delayed energy
- **Strategy**: raise prompt energy cut (>1.5MeV) and require prompt to delay distance cut (<0.5m)
- **Oscillation analysis** of rate deficit using 217 days of 6AD data

$$\sin^2 2\theta_{13} = 0.083 \pm 0.018$$

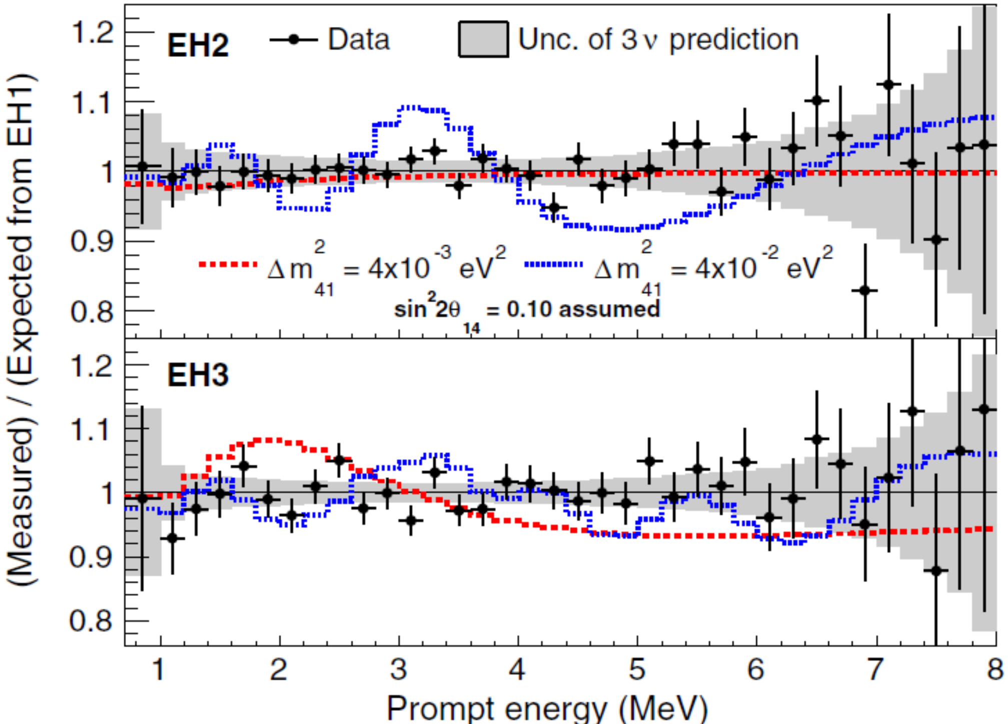
- **Spectral analysis** in progress

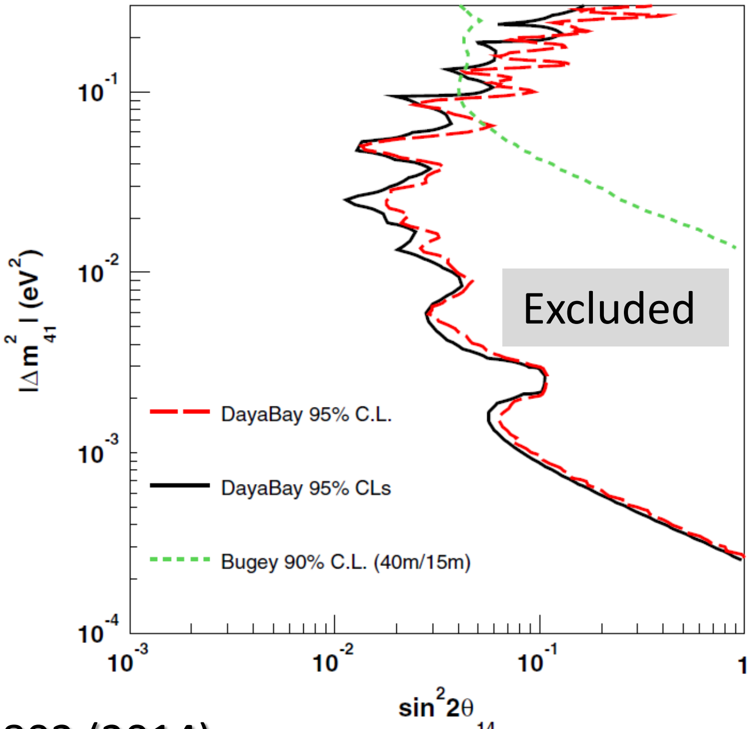
Phys. Rev. D 90, 071101



Search for light sterile neutrinos

- An unique opportunity for sterile neutrino searches
  - Sterile neutrino would introduce additional oscillation mode
  - Relative measurement at multiple baselines: EH1 (~350m), EH2 (~500m), EH3 (~1600m)
- Oscillation analysis
  - No significant signal observed, consistent with 3-flavor neutrino oscillation.
  - Set most stringent limit at 10^{-3} eV^2 < Δm^2_{41} < 0.1 eV^2





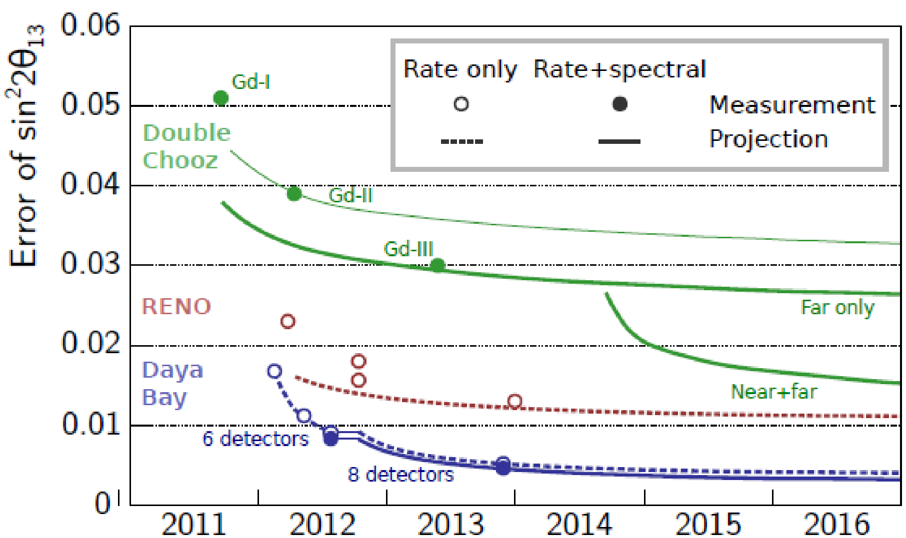
PRL 113, 141802 (2014)

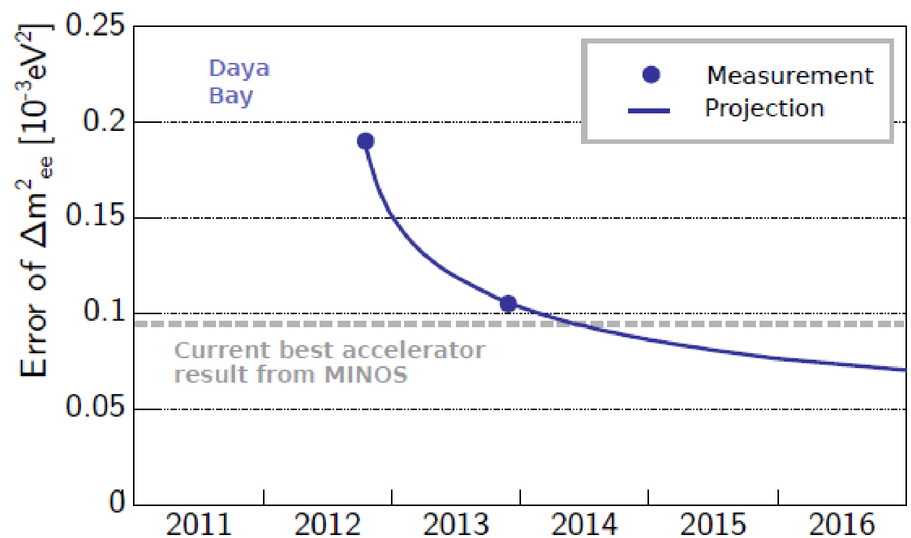
Daya Bay Summary

- Daya Bay updated reactor antineutrino analysis with the **full detector configuration**
  - Most precision measurement of $\sin^2 2\theta_{13}$: **6%**
  - Most precision measurement of $\left|\Delta m^2_{ee}\right|$ in the electron antineutrino disappearance channel: **4%**
- Precision measurement on reactor antineutrino flux and spectrum
  - **Flux** is **consistent** with previous short baseline experiments
  - **Spectrum** is **NOT consistent** with prediction at **4σ** level in 4-6 MeV (5-7 MeV) positron (antineutrino) energy region
- Confirmed reactor antineutrino disappearance and measured $\sin^2 2\theta_{13}$ **independently** with nH sample
- Set **new limit** to light sterile neutrinos

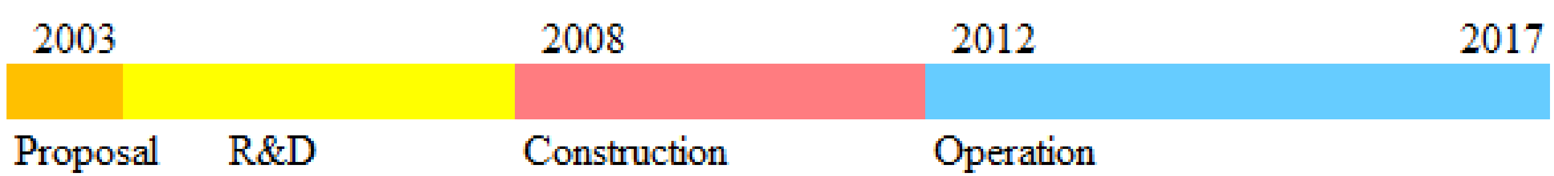
Projected Future

- Daya Bay will run to **2017**. Measuring $\sin^2 2\theta_{13}$ to ~3% precision, the best in tens of years.
- Most precise direct measurement of $|\Delta m^2_{ee}|$, better than $|\Delta m^2_{\mu\mu}|$ from accelerator exp. The most precise reactor neutrino spectrum, and …

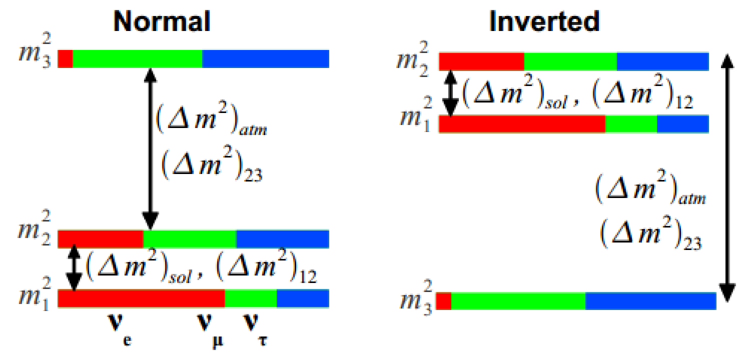




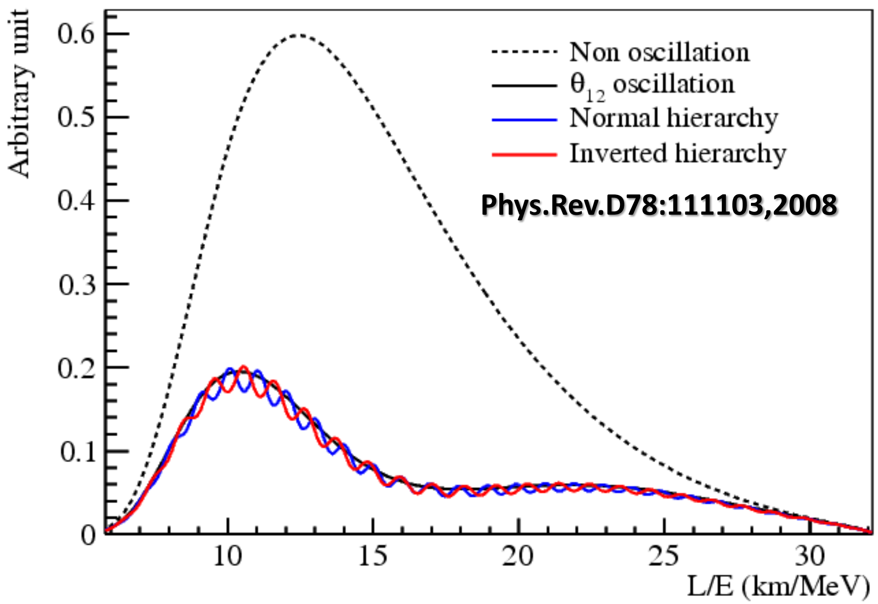
Sören Jetter @ Tau 2014



Neutrino Mass Hierarchy



- Large θ_{13} open doors to MH
  - Exploit L/E spectrum with reactors
    - ➢ Precision energy spectrum measurement
    - ➢ Look for interference between solar- and atmospheric-oscillations → relative measurement



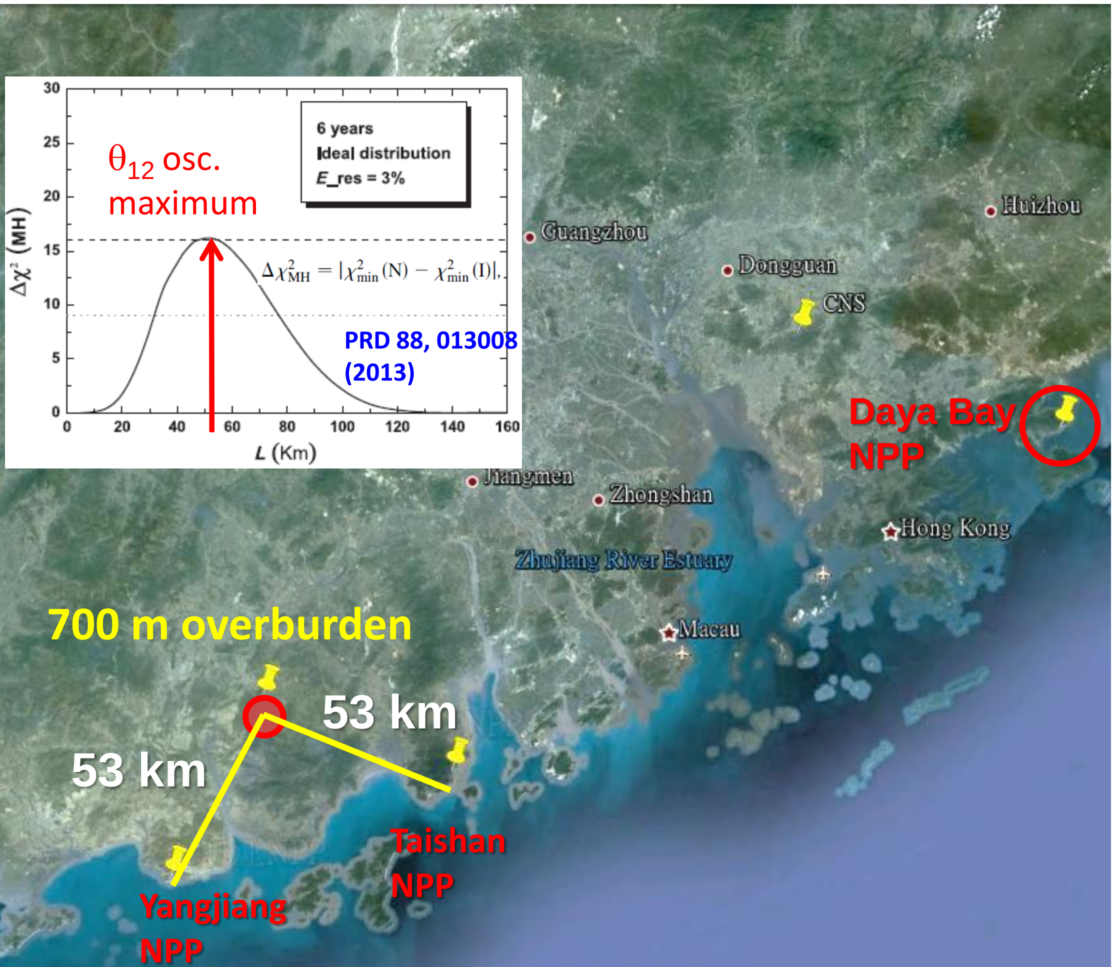
$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})
\end{aligned}
$$

S.T. Petcov et al., PLB533(2002)94
S.Choubey et al., PRD68(2003)113006
J. Learned et al., PRD78, 071302 (2008)
L. Zhan, Y. Wang, J. Cao, L. Wen, PRD78:111103, 2008, PRD79:073007, 2009
J. Learned et al., arXiv:0810.2580
…

Independent on CP phase and θ_{23} (Acc. & Atm. do)
Energy Resolution is the key

JUNO Experiment

- Jiangmen Underground Neutrino Observatory
- Primary goals: mass hierarchy and precision meas.
  - 20 kton LS detector, 3%/$\sqrt{E}$ energy resolution
- Proposed in 2008, approved in Feb.2013



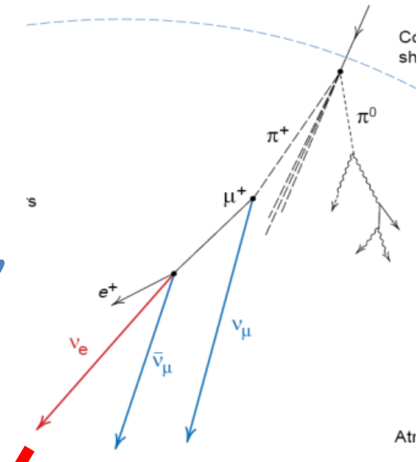
- Rich Physics
  - Mass hierarchy
  - Precision measurement of mixing parameters
  - Supernova neutrinos
  - Geo-neutrinos
  - Solar neutrinos
  - Sterile neutrinos
  - Atmospheric neutrinos
  - Exotic searches

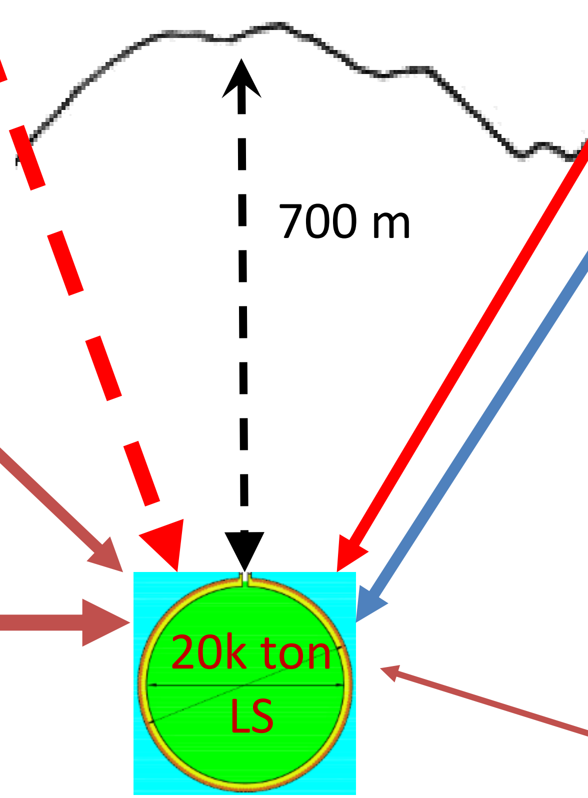
Neutrino Rates

Supernova ν
~ 5k in 10s for 10kpc

Solar ν
(10s-1000s)/day

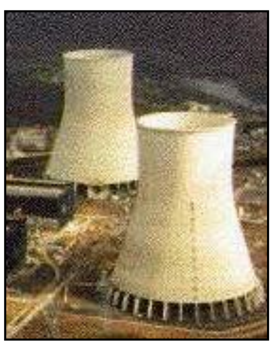
Atmospheric ν
several/day





Cosmic muons
~ 250k/day

0.003 Hz/m^2
215 GeV
10% multiple-muon

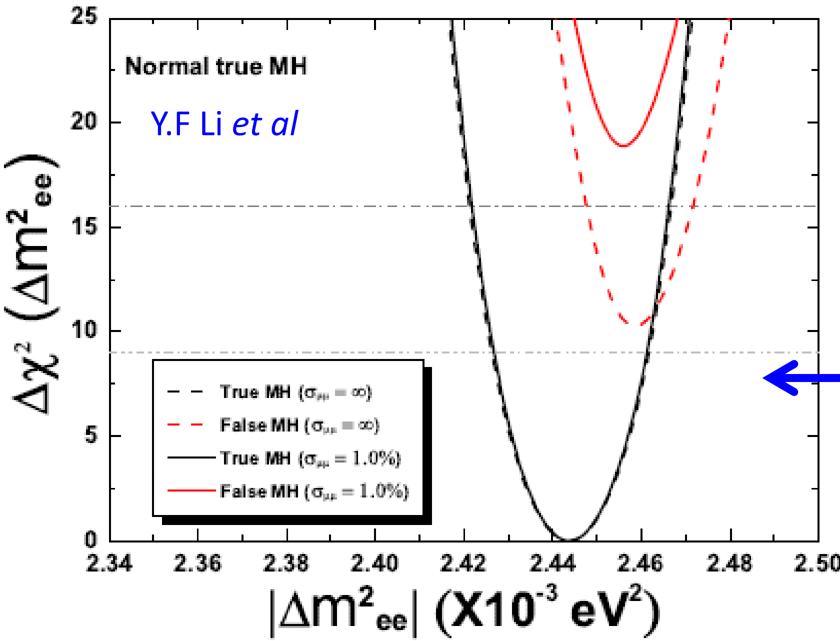


36 GW, 53 km

reactor ν, ~ 60/day

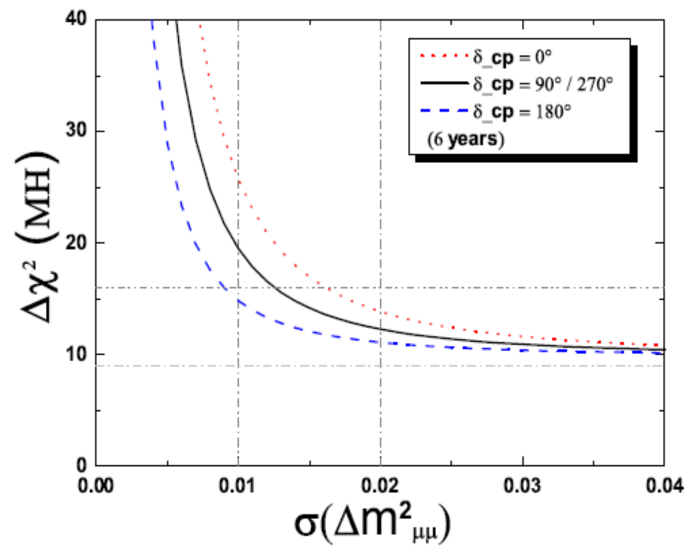
Geo-neutrinos
1-2/day

Sensitivity on MH



JUNO **MH sensitivity with 6 years' data:**

Ref: Y.F Li et al, PRD 88, 013008 (2013)	**Relative Meas.**	[a] **Use absolute Δm^2**
Ideal case	4σ	5σ
[b] **Realistic case**	3σ	4σ

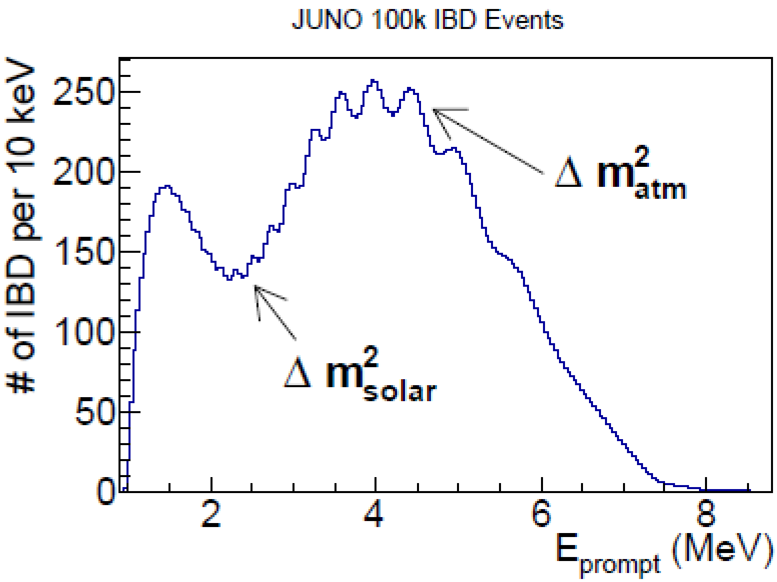


[a] If accelerator experiments, e.g NOvA, T2K, can measure $\Delta M^2_{\mu\mu}$ to ~1% level

[b] Take into account multiple reactor cores, uncertainties from energy non-linearity, etc

	Ideal	Core distr.	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Real	1%	4.5%	0.3%	1%
$\Delta\chi^2_{MH}$	+16	−4	−1	−0.5	−0.1	+8

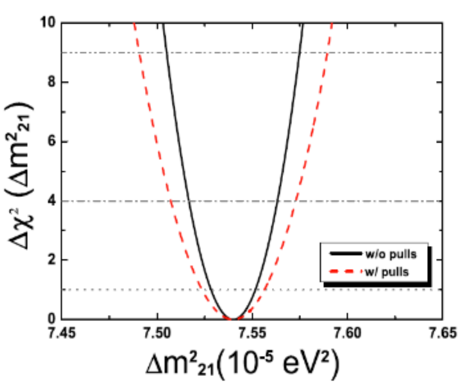
Precision Measurement



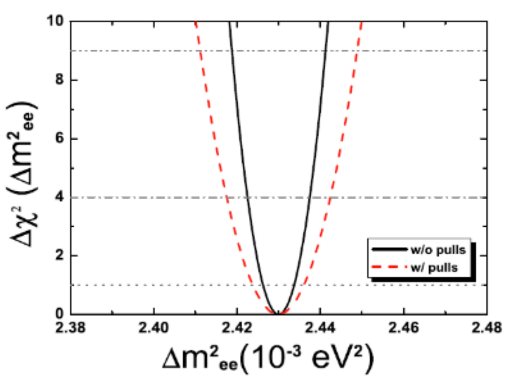
Probing the unitarity of U_{PMNS} to ~1%

more precise than CKM matrix elements !

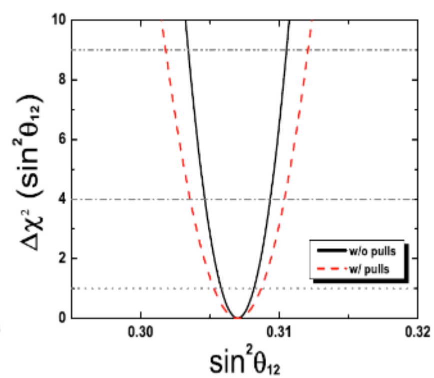
	Statistics	+BG +1% b2b +1% EScale +1% EnonL
$\sin^2\theta_{12}$	0.54%	0.67%
Δm^2_{21}	0.24%	0.59%
Δm^2_{ee}	0.27%	0.44%



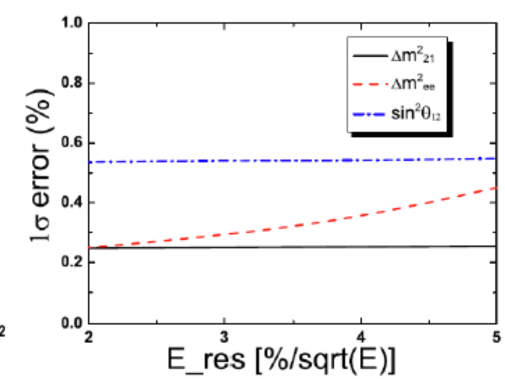
0.16%→0.24%



0.16%→0.27%



0.39%→0.54%

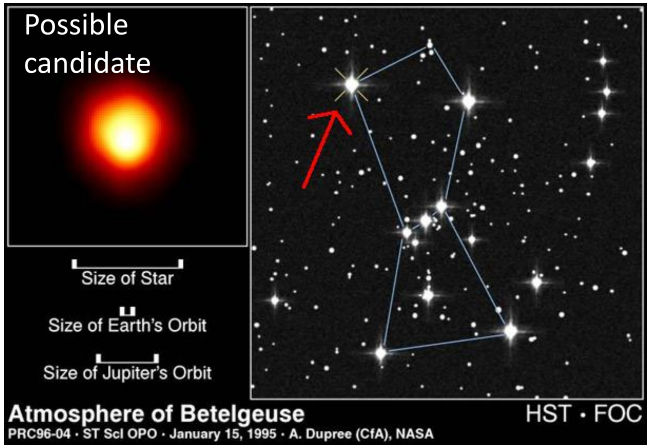


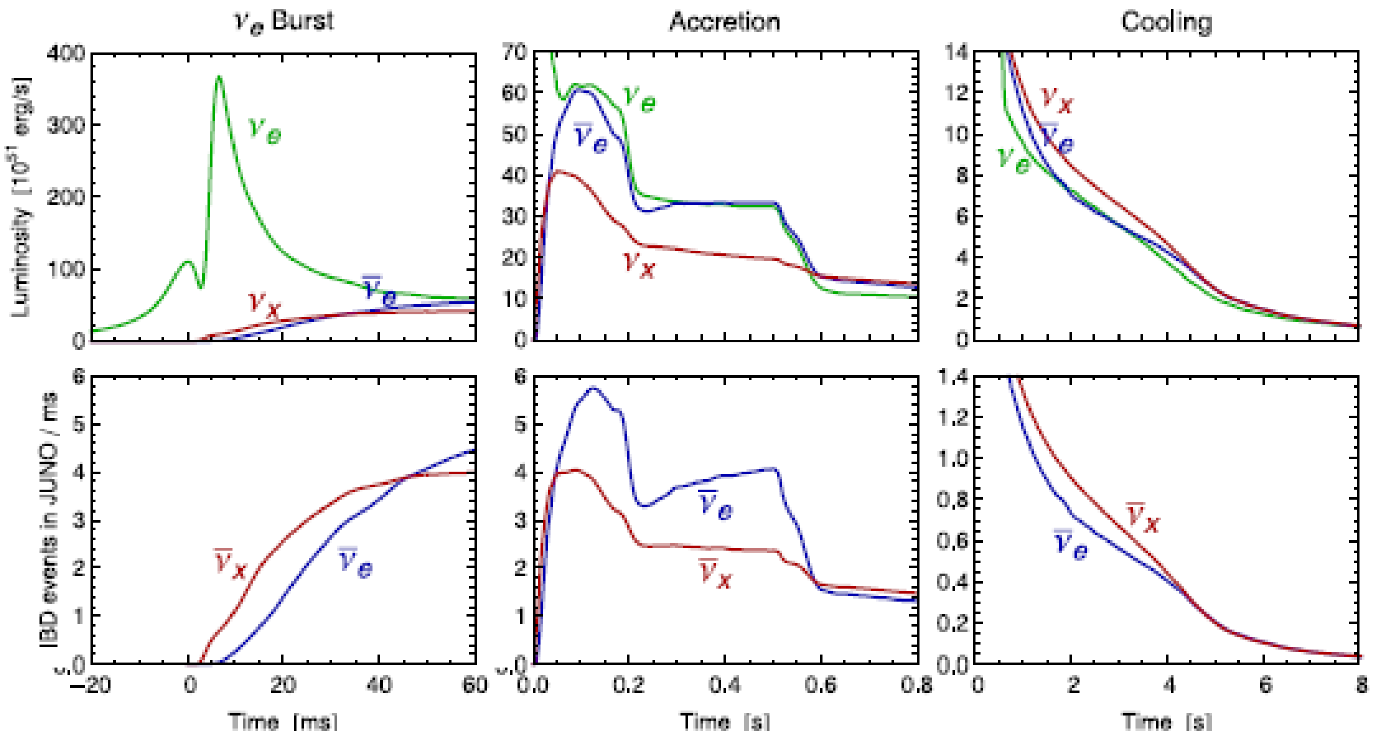
E resolution

Correlation among parameters

Supernova neutrinos

- **<20 events observed so far**
- **Typical galactic SN assumptions:**
  - 10 kpc galactic distance (our Galaxy center)
  - 3×10^{53} erg
  - L_ν the same for all types





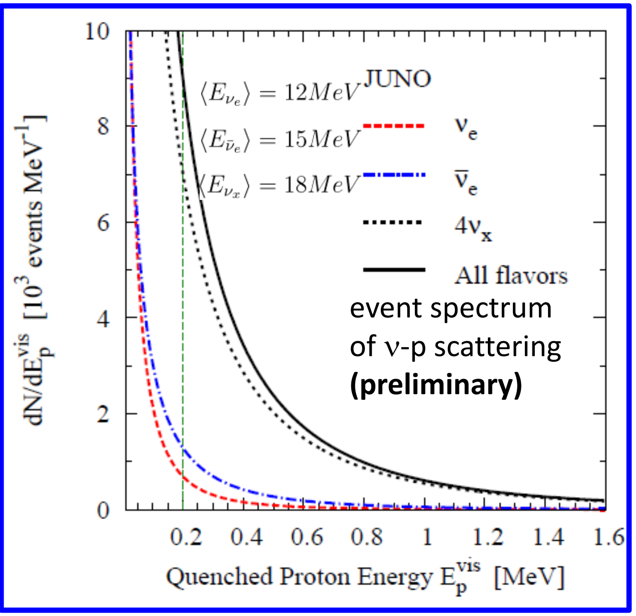
Supernova neutrinos in Giant LS detector

Giant LS detector →
Measure energy spectra & fluxes of almost all types of neutrinos

e.G Estimated numbers of neutrino events in JUNO (preliminary)

Typical galactic SN assumptions:
10 kpc galactic distance, 3×10^{53} erg, L_ν the same for all types

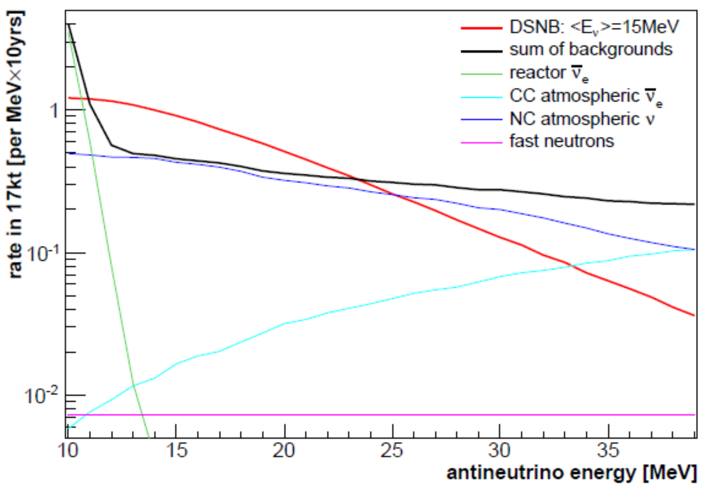
Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	6.0×10^2	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	NC	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}C \to \nu + {}^{12}C^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}C \to e^- + {}^{12}N$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}C \to e^+ + {}^{12}B$	CC	6.0×10^1	1.1×10^2	1.6×10^2

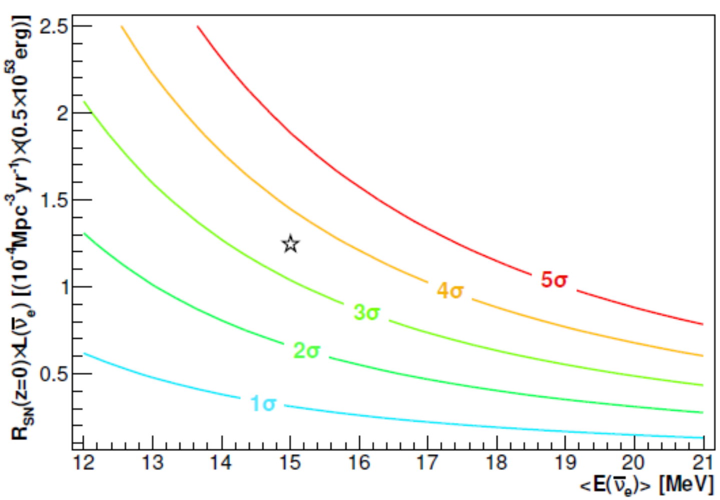


Correlated events. Better detection in LS than in Water

- ν mass: < 0.83±0.24 eV at 95% CL *(arXiv:1412.7418)*
- Locating the SN: ~9°

Diffuse Supernova Neutrino





- **DSNB: Past core-collapse events**
  - Cosmic star-formation rate
  - Core-collapse neutrino spectrum
  - Rate of failed SNe

Item		Rate (no PSD)	PSD efficiency	Rate (PSD)
Signal	$\langle E_{\bar{\nu}_e}\rangle = 12\,\mathrm{MeV}$	12.2	$\varepsilon_\nu = 50\,\%$	6.1
	$\langle E_{\bar{\nu}_e}\rangle = 15\,\mathrm{MeV}$	25.4		12.7
	$\langle E_{\bar{\nu}_e}\rangle = 18\,\mathrm{MeV}$	42.4		21.2
	$\langle E_{\bar{\nu}_e}\rangle = 21\,\mathrm{MeV}$	61.2		30.8
Background	reactor $\bar{\nu}_e$	1.6	$\varepsilon_\nu = 50\,\%$	0.8
	atm. CC	1.5	$\varepsilon_\nu = 50\,\%$	0.8
	atm. NC	716	$\varepsilon_{\mathrm{NC}} = 1.1\,\%$	7.5
	fast neutrons	12	$\varepsilon_{\mathrm{FN}} = 1.3\,\%$	0.15
	Σ			9.2

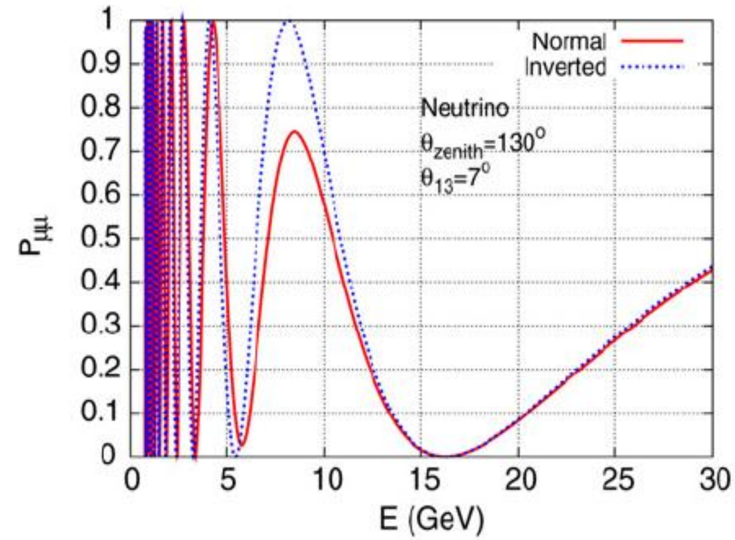
10 Years' sensitivity

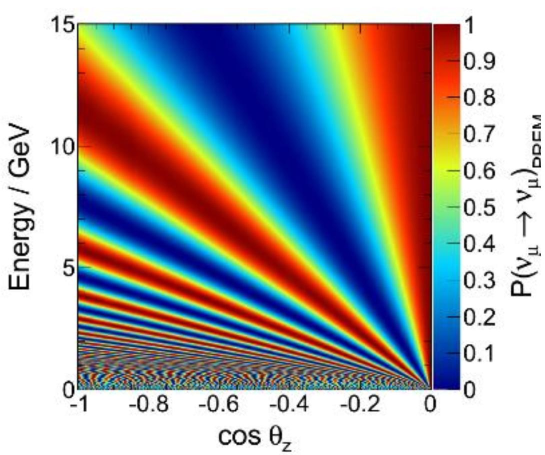
Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e}\rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	$1.7\,\sigma$	$1.9\,\sigma$	$1.5\,\sigma$	$1.7\,\sigma$
15 MeV	$3.3\,\sigma$	$3.5\,\sigma$	$3.0\,\sigma$	$3.2\,\sigma$
18 MeV	$5.1\,\sigma$	$5.4\,\sigma$	$4.6\,\sigma$	$4.7\,\sigma$
21 MeV	$6.9\,\sigma$	$7.3\,\sigma$	$6.2\,\sigma$	$6.4\,\sigma$

Mass Hierarchy from Atmospheric

- **Due to matter effect, oscillation probability of atmospheric muon neutrino when passin[g] the Earth depends on mass hierarchy**

- **JUNO will have 1-2 σ sensitivity**
  - Measure both lepton and hadron energy
  - Good tracking and energy resolution





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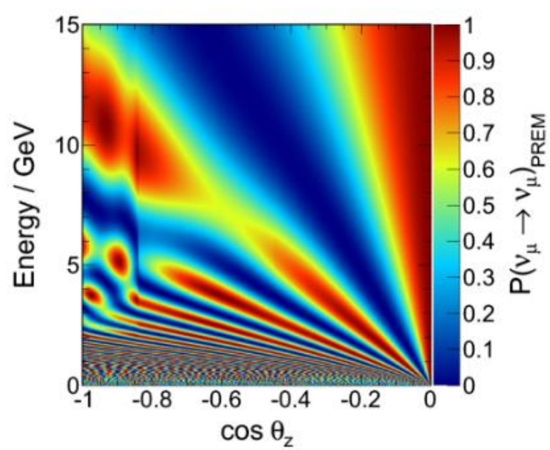

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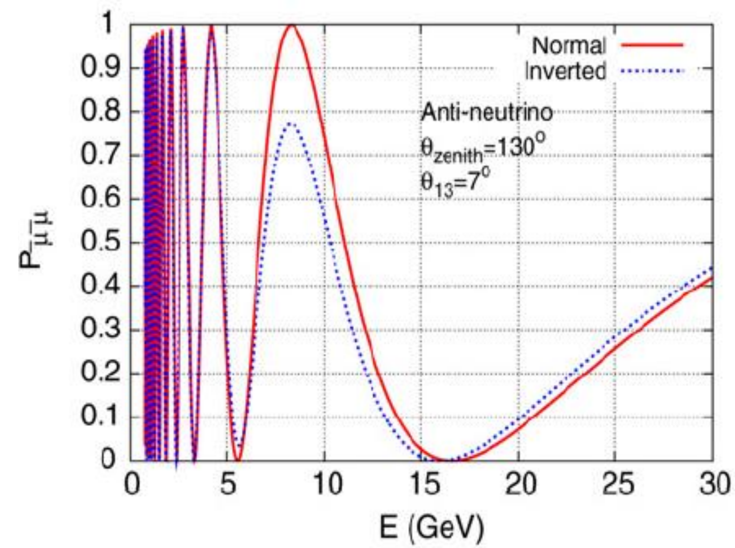
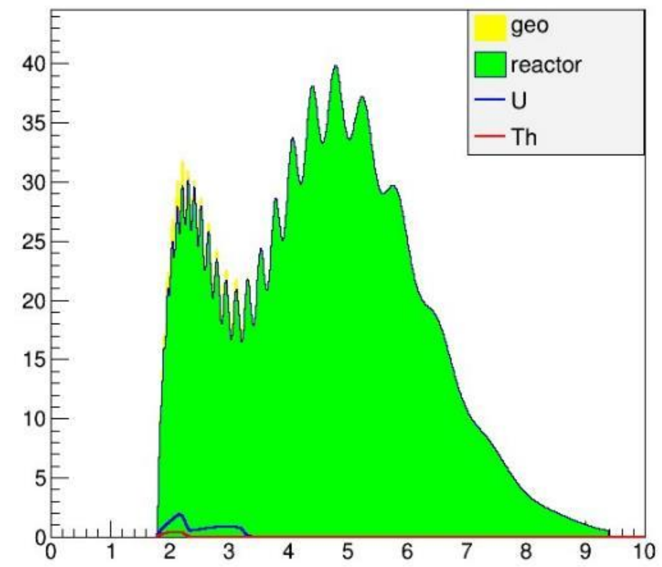


Geo-neutrinos

- **Current results**
  - **KamLAND: 30±7 TNU *(PRD 88 (2013) 033001)***
  - **Borexino: 38.8±12.2 TNU *(PLB 722 (2013) 295)***
  - **Statistics dominant**
- **Desire to reach an error of 3 TNU**
- **JUNO: ×20 statistics**
  - Huge reactor neutrino backgrounds
  - Need accurate reactor spectra



Source	Events/year
Geoneutrinos	408 ± 60
U chain	311 ± 55
Th chain	92 ± 37
Reactors	16100 ± 900
Fast neutrons	3.65 ± 3.65
^{9}Li - ^{8}He	657 ± 130
$^{13}C(\alpha, n)^{16}O$	18.2 ± 9.1
Accidental coincidences	401 ± 4

Combined shape fit of geo-ν and reactor-ν

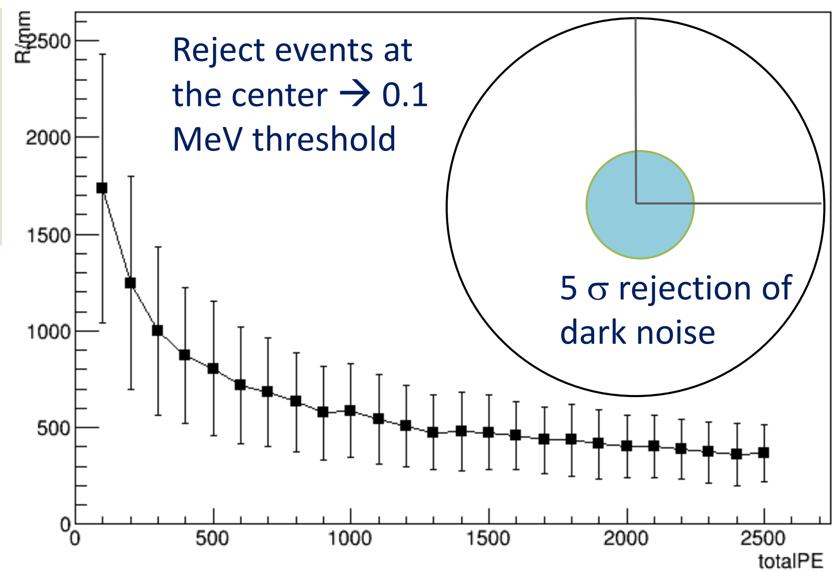
	Best fit	1 y	3 y	5 y	10 y
U+Th fix ratio	0.96	17%	10%	8%	6%
U (free)	1.03	32%	19%	15%	11%
Th (free)	0.80	66%	37%	30%	21%

Solar and other Physics

- Solar neutrino
  - Metallicity? Vacuum oscillation to MSW?
  - ^7Be and ^8B at JUNO
  - Threshold
  - Backgrounds

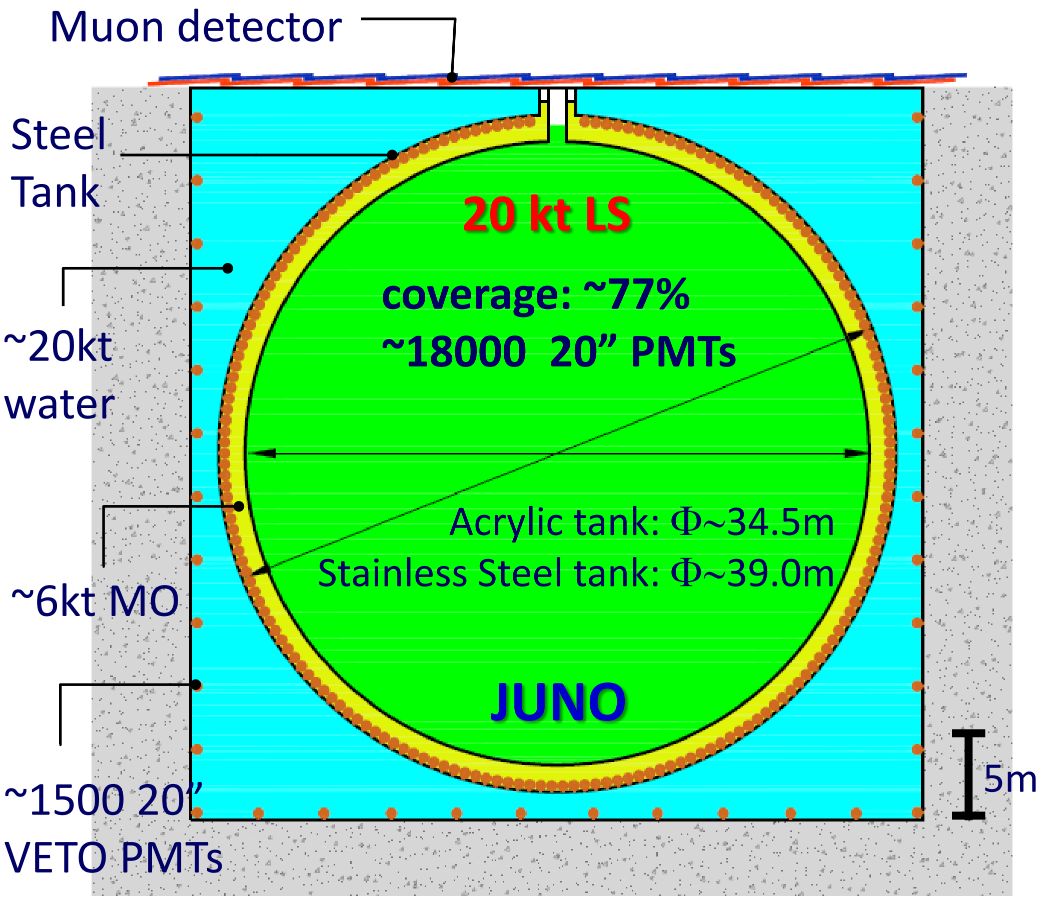
Source	Rate [cpd/1kt]
pp	1337
^7Be [line 0.384 MeV]	19
^7Be [line 0.862 MeV]	475
pep	28
^8B	4.5
^{13}N	25
^{15}O	28
^{17}F	0.7

Liquid Scintillator	^{238}U	^{232}Th	K40	Pb210 (Rn222)	Ref.
No Distillation	10^{-15}	10^{-15}	10^{-16}	$1.4 \cdot 10^{-22}$	Borexino CTF, KamLAND
After Distillation	10^{-17}	10^{-17}	10^{-18}	10^{-24}	



- Sterile ν, Indirect dark matter, Nucleon decay, etc.

Challenge: high-precision, giant LS detector



- **Important factors**
  - **High transparency Liquid Scintillator**
  - **High QE PMT**
  - **Energy scale uncertainty**

	KamLAND	JUNO
LS mass	~1 kt	20 kt
Energy Resolution	$6\%/\sqrt{E}$	~$3\%/\sqrt{E}$
Light yield	250 p.e./MeV	1200 p.e./MeV

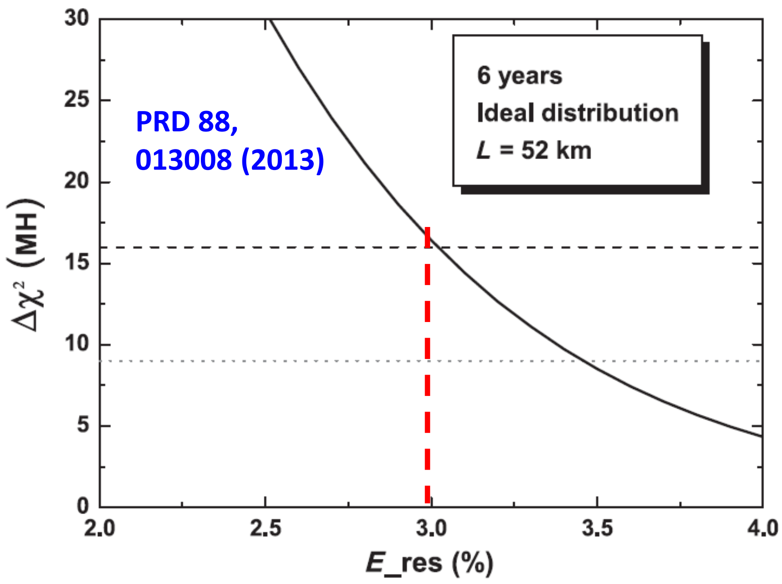
Requirements on Energy Resolution

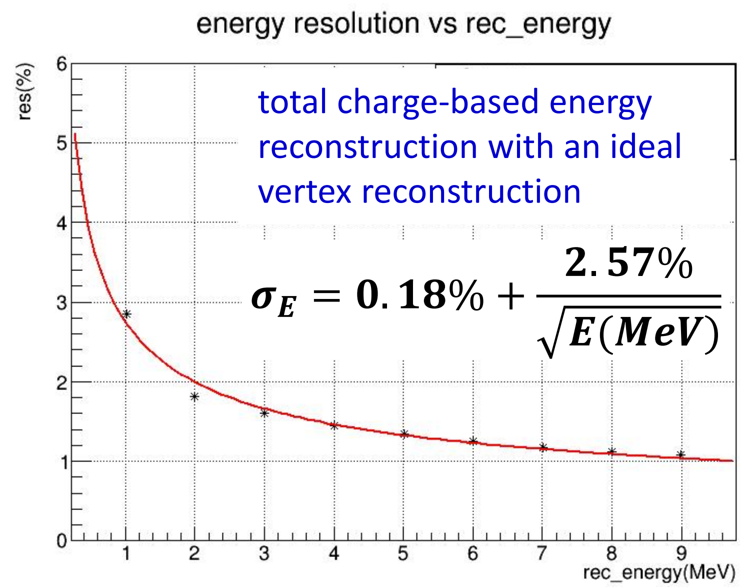
- **$3\%/\sqrt{E}$ energy resolution**
- **Take JUNO MC as example**
  - Based on DYB MC
  - JUNO Geometry
  - 77% photocathode coverage (KamLAND: ~34%)
  - High QE PMT, QE_{max}: 25% → 35%
  - LS attenuation length (1 m-tube measurement @ 430nm)

from 15 m
= absorption 30 m + Rayleigh scattering 30 m

to 20 m
= absorption 60 m + Rayleigh scattering 30 m

The Highlighted parameters are input to MC





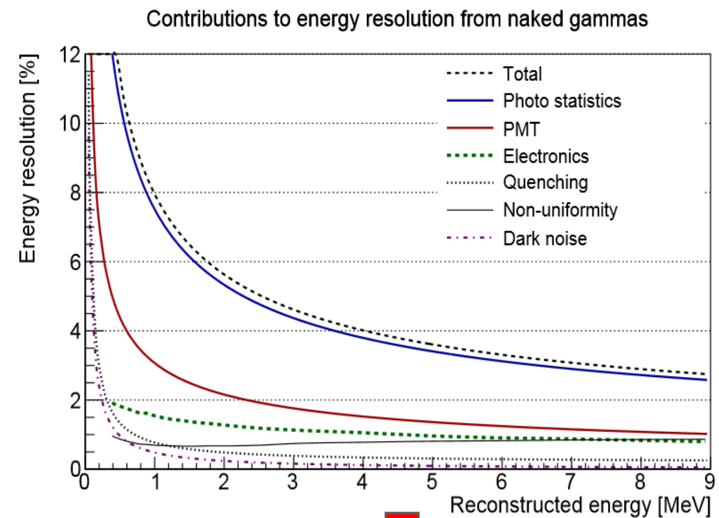
Beyond Photo-statistics

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

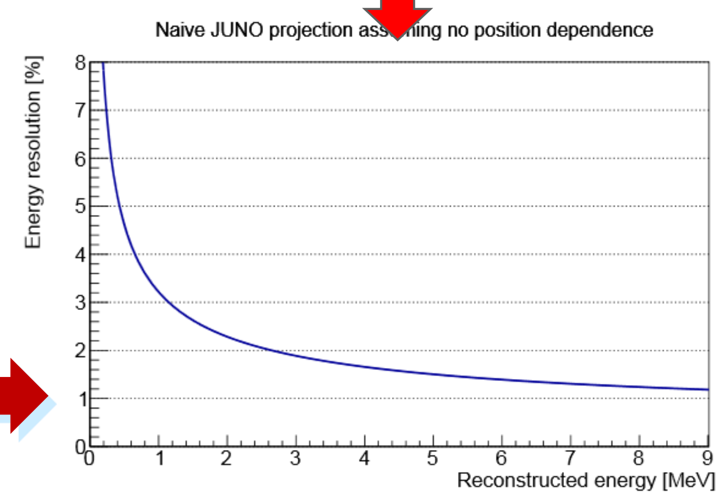
Impact to MH sensitivity

$$\simeq \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{1.6\,b}{\sqrt{E}}\right)^2 + \left(\frac{c}{1.6\,\sqrt{E}}\right)^2}$$

- **Generic form of E resolution**
  - **a: stochastic term**
  - **b: constant term**
  - **c: noise term**



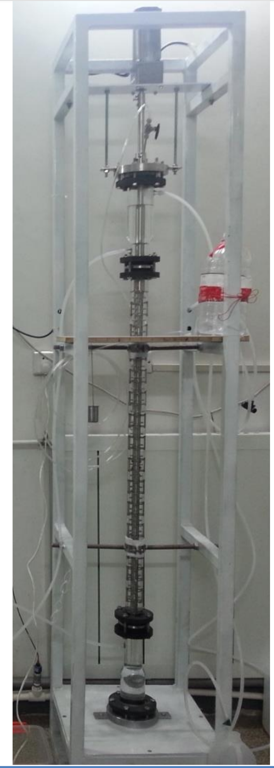
- Data validated Full MC (DYB&DC)
- Noise term dominated by PMT dark noise
- Constant term
  - Residual non-uniformity
  - Flaws in readout electronics
  - Artifacts from resolution plotting
- No JUNO show stopper found in DYB model



Liquid Scintillator in JUNO

- **Current choice:**

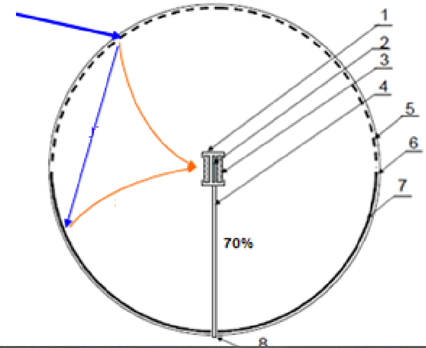
  LAB+PPO+bisMSB (no Gd-loading)
- **Increase light yield**
  - **Optimization of fluors concentration**
- **Increase transparency**
  - **Good raw solvent LAB**
    - **Improve production processes: cutting of components, using Dodecane instead of MO, improving catalyst, etc**
  - **Online handling/purification**
    - **Distillation, Filtration, Water extraction, Nitrogen stripping, …**
- **Reduce radioactivity**
  - **Less risk, since no Gd**
  - **Singles<3Hz (above 0.7MeV), if $^{40}K/U/Th < 10^{-15}$ g/g (preliminary)**

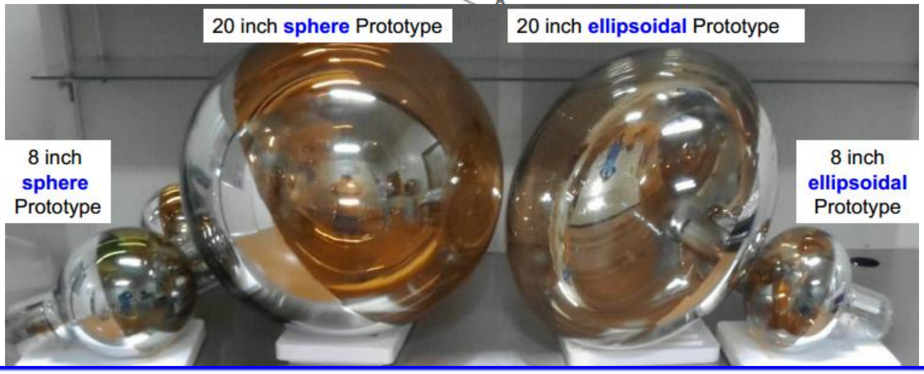


Linear Alky Benzene (LAB)	Atte. Length @ 430 nm
RAW (specially made)	14.2 m
Vacuum distillation	19.5 m
SiO_2 coloum	18.6 m
Al_2O_3 coloum	25 m

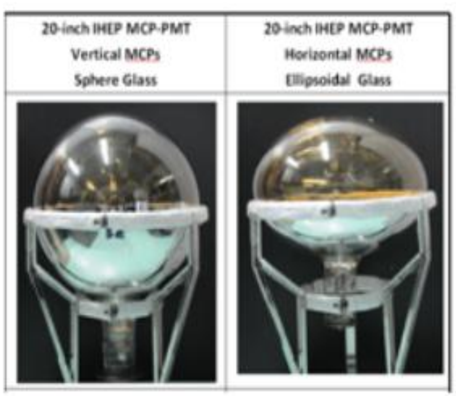
High QE PMT Effort in JUNO

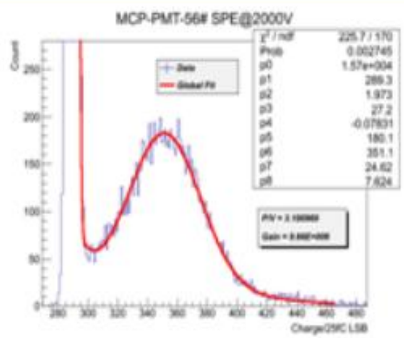
- High QE 20” PMTs under development:
  - A new design using MCP: 4π collection
- MCP-PMT development:
  - Technical issues mostly resolved
  - Successful 8” prototypes
  - A few 20” prototypes
- Alternative options: Hamamatsu or Photonics



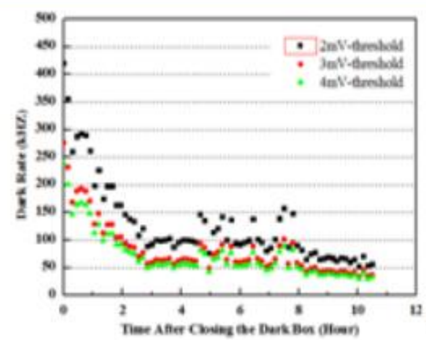


The 20 inch Prototypes

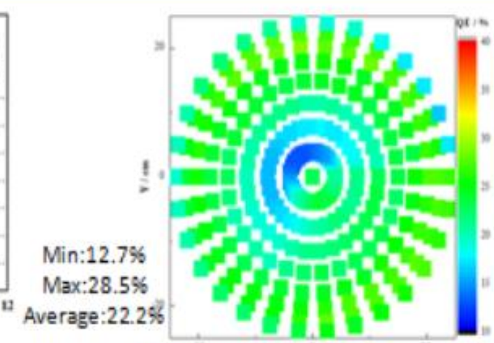




Single photo-electron spectrum



The dark count

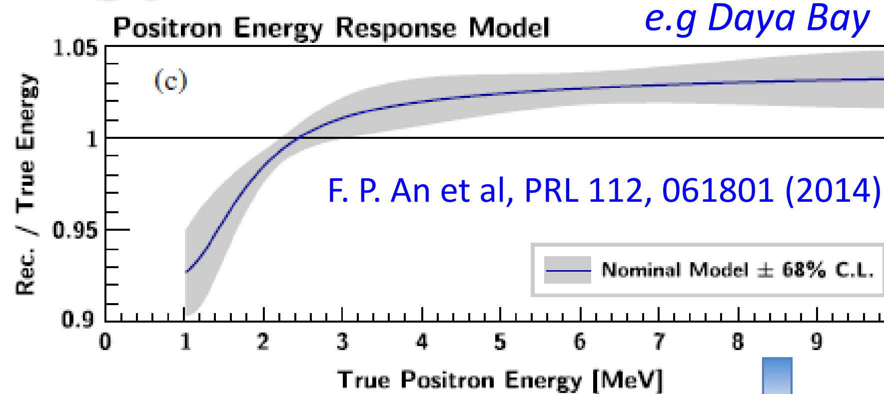


The Photocathode Uniformity

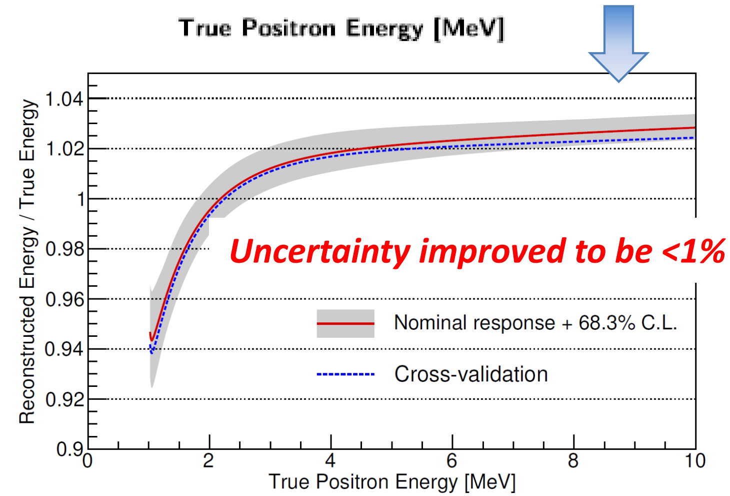
	HV	Gain	QE@410nm	P/V	Rise Time	Fall Time	Dark rate @1E7 (0.25PE)
20”-51#	2000V	~1E7	22%	~3	~1.2ns	~15ns	~50kHz

Absolute Energy scale

e.g Daya Bay

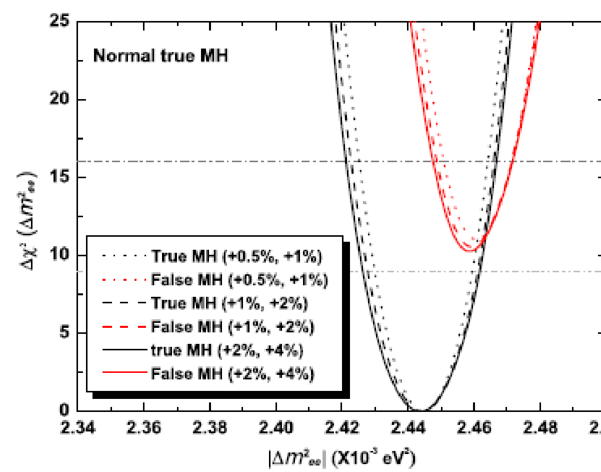


- **Energy non-linearity correction is crucial to spectrum shape analysis**



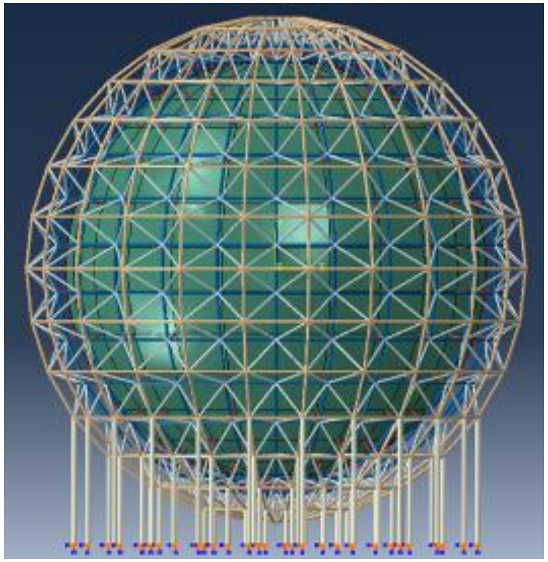
- **If imperfect correction, particular residual non-linearity shape can fake the oscillation pattern with a wrong MH** ***(X.Qian et al, PRD 87, 033005 (2013))***
  → Challenge: understand energy scale better than 1%

- **Self-calibration of the spectrum: multiple oscillation peaks can provide good constraints to non-linearity → possibly mitigate the requirement to be <2%**



Y.F.Li et al, PRD 88, 013008 (2013)

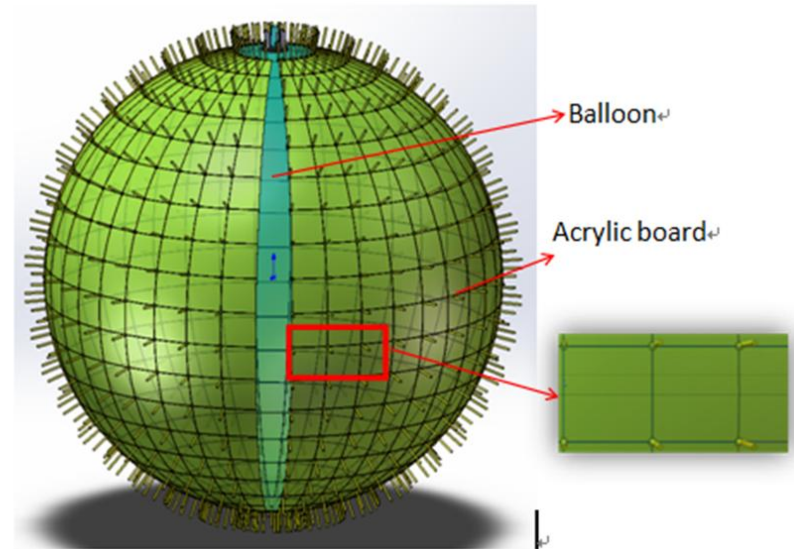
JUNO Central Detector



Acrylic Sphere option:
acrylic tank(D~35m) + SS structure

Target: 20 kt LS

ν_e signal event rate:
~60/day



Balloon option:
SS tank(D~38m) + acrylic structure + balloon

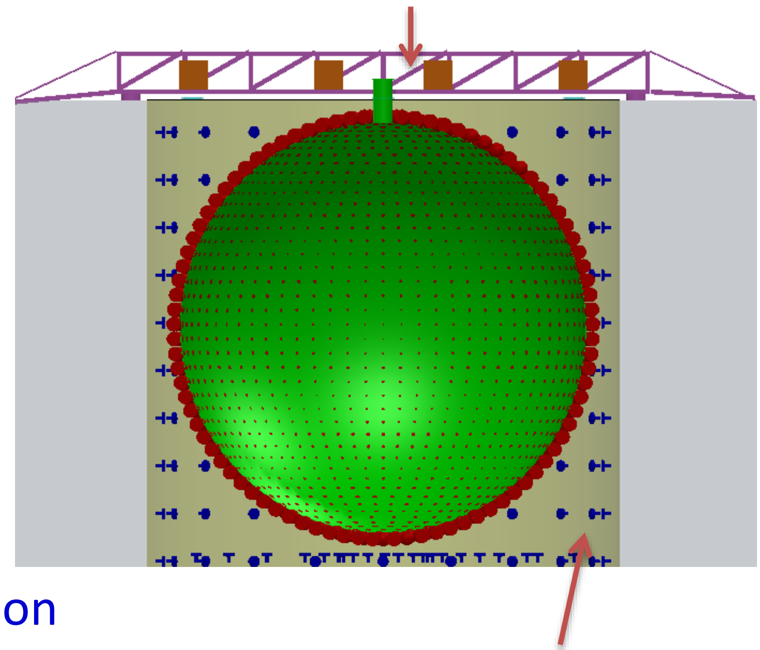
- **Issues:**
  - Engineering: mechanics, safety, lifetime, …
  - Physics: cleanness, light collection, …
  - Assembly & installation
- **Design & prototyping underway**

Veto Detectors

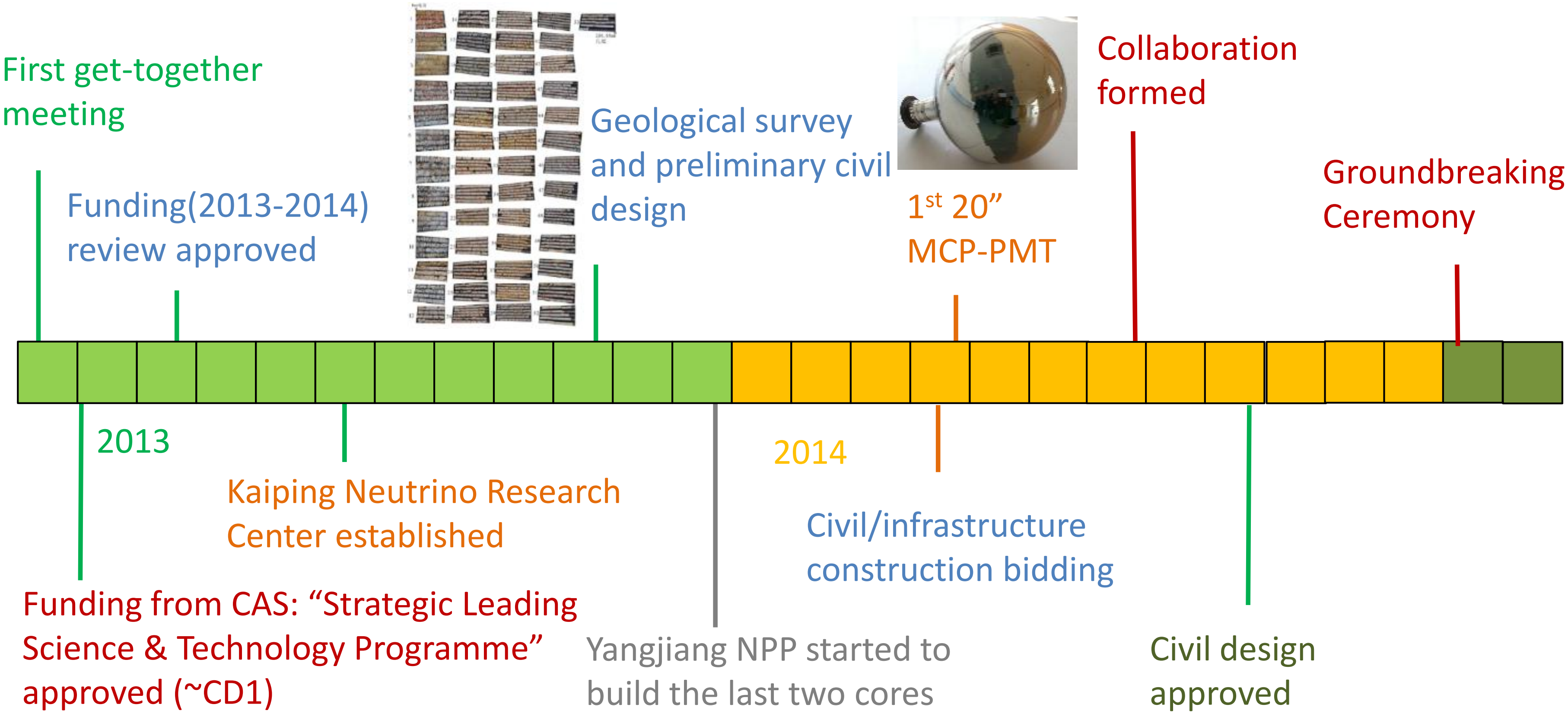
- Cosmic muon flux
  - Overburden：~700 m
  - Muon rate：0.0031 Hz/m^2
  - Average energy：214 GeV
- Water Cherenkov Detector
  - At least 2 m water shielding
  - ~1500 20”PMTs
  - 20~30 kton pure water
  - Similar technology as Daya Bay (99.8% efficiency)
- Top muon tracker
  - Muon track for cosmogenic bkg rejection
  - Decommissioned OPERA plastic scintillator
  - Possibly w/ RPC

Muon multiplicity at JUNO

Multiplicity	1	2	3	4	5	6
Fraction	89.6%	7.7%	1.8%	0.6%	0.3%	0.07%



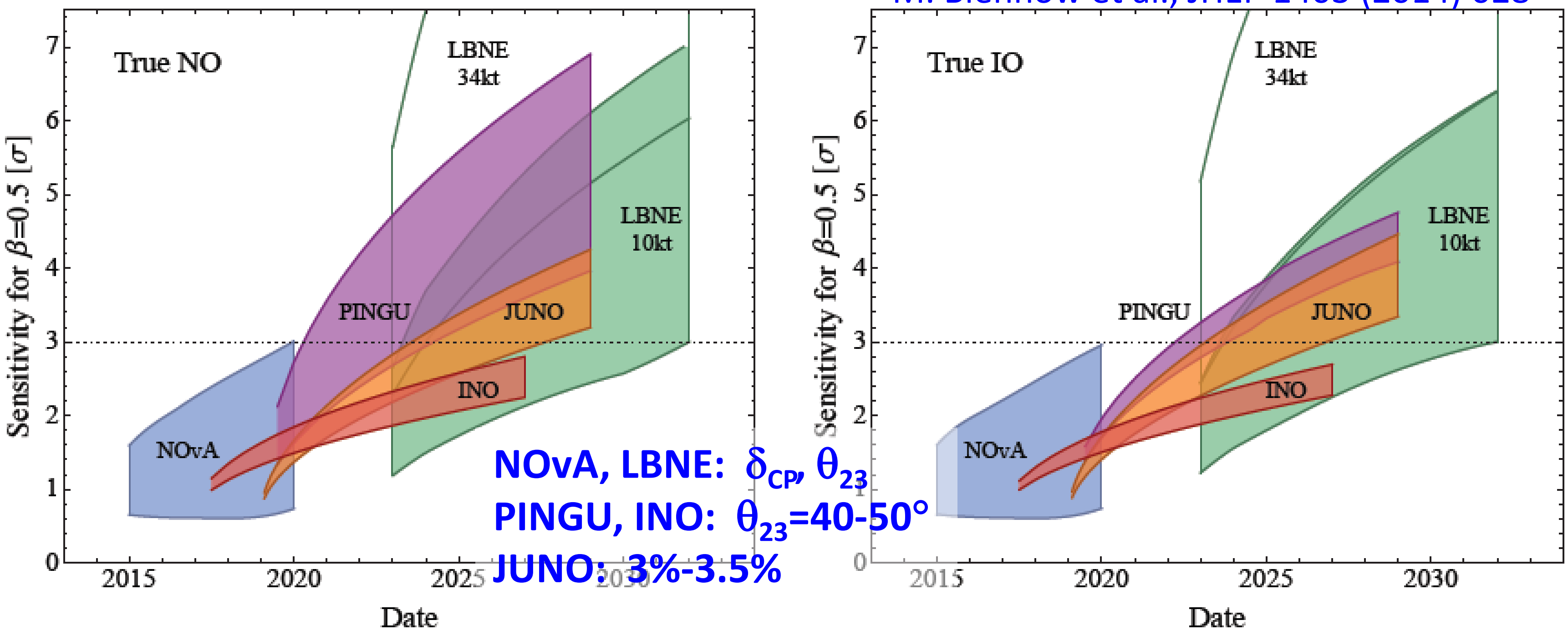
Project Plan and Progresses



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

Other Experiments/Proposals For MH

M. Blennow et al., JHEP 1403 (2014) 028



NOvA, LBNE: δ_{CP}, θ_{23}

PINGU, INO: θ_{23}=40-50°

JUNO: 3%-3.5%

Δm^2_{31} and Δm^2_{32} Interference (ϕ)	Δm^2_{ee} and $\Delta m^2_{\mu\mu}$ difference	Matter Effect

Reactor

atmospheric

JUNO: Competitive in schedule and Complementary in physics

- Has chance to be the first to determine MH
- Precise Δm_{31}^2, θ_{12}, Δm_{21}^2, Geo-, solar, supernovae, …, neutrinos

Measurement of CP

ν_μ-ν_e oscillations in a 3 ν scheme

$$p(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\frac{\Delta m_{13}^2 L}{4E} \times \left[1 \pm \frac{2a}{\Delta m_{13}^2}(1-2s_{13}^2)\right] \quad \theta_{13}\ \text{driven}$$

$$+\ 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{12}^2 L}{4E} \quad \text{CPeven}$$

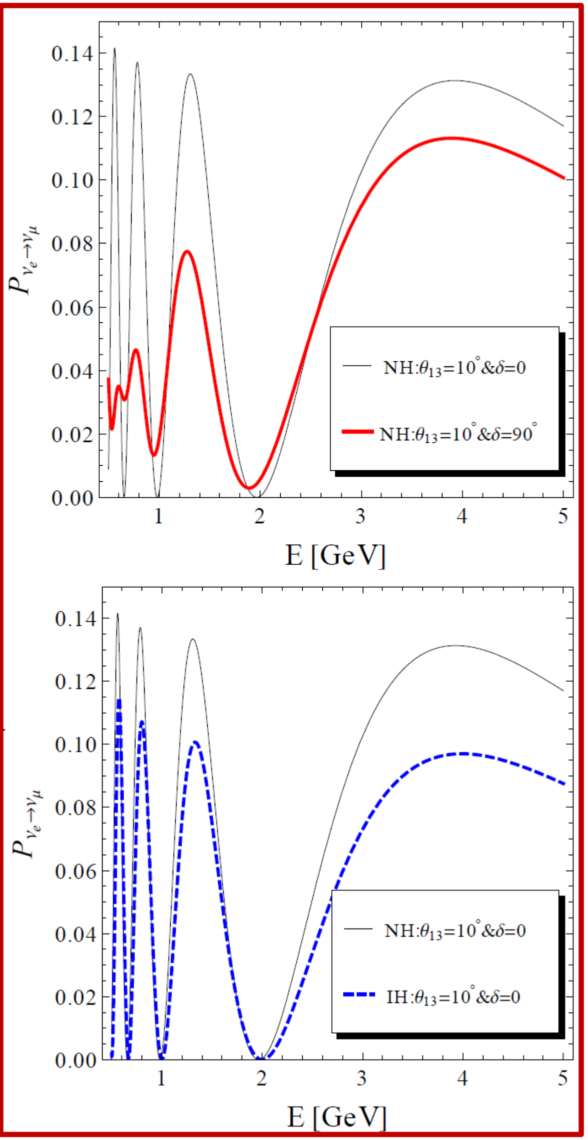
$$\mp\ 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{12}^2 L}{4E} \quad \text{CPodd}$$

$$+\ 4s_{12}^2c_{13}^2\{c_{13}^2c_{23}^2 + s_{12}^2s_{23}^2s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\}\sin\frac{\Delta m_{12}^2 L}{4E} \quad \text{solar driven}$$

$$\mp\ 8c_{12}^2s_{13}^2s_{23}^2\cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\frac{aL}{4E}(1-2s_{13}^2) \quad \text{matter effect (CP odd)}$$

- **Qualitatively…**
  - θ_{13} controls the amplitude
  - CP is a low energy effect
  - MH is determined in the high energy part

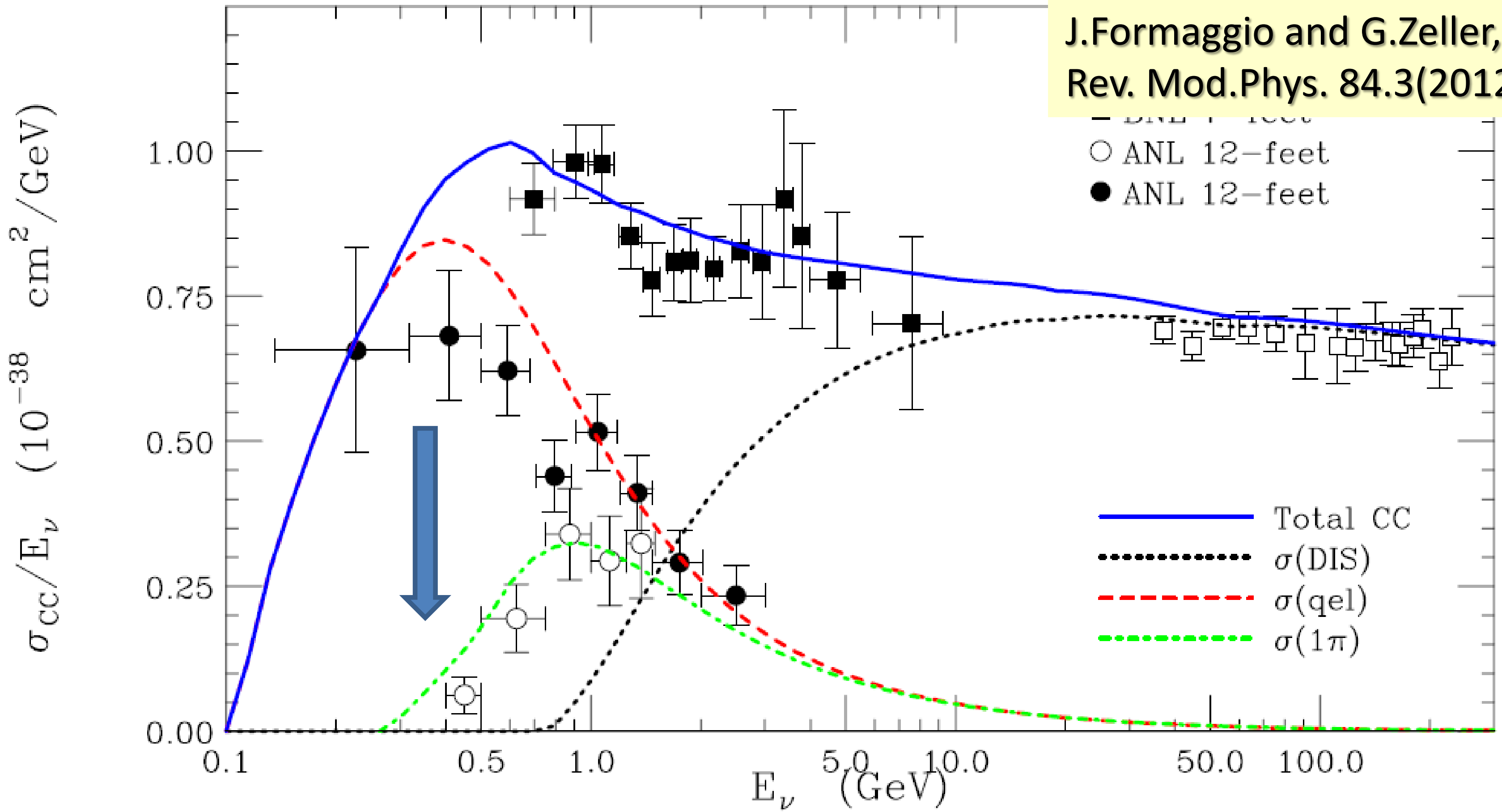
e.g at L=1500km



- **Methods**
  - Compare $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ (CP violation)
  - Measure $\nu_\mu \to \nu_e$ appearance (absolute measurement)
  - Compare $\nu_\mu \to \nu_e$ and $\nu_e \to \nu_\mu$ (T violation)

How low is the best for CP ?

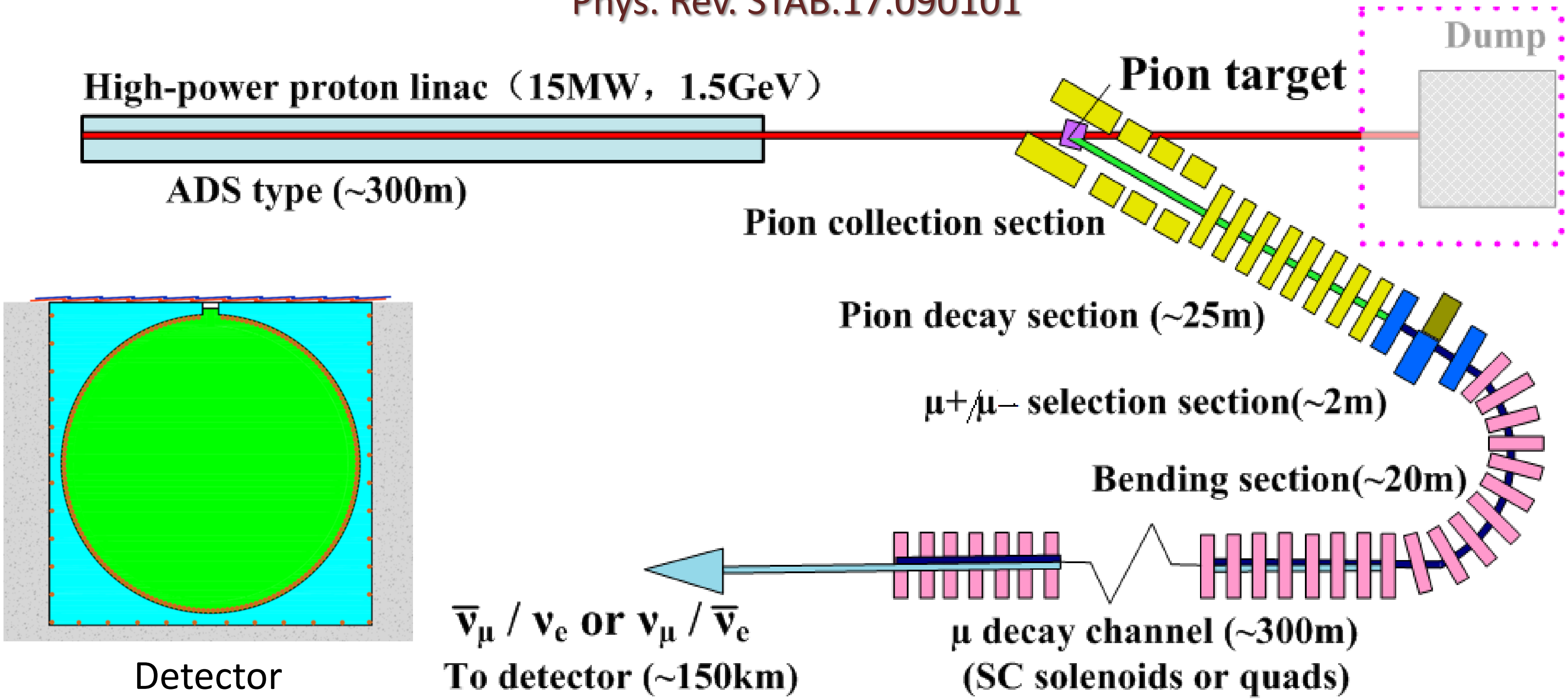
- **Below in-elastic threshold: ~ 300 MeV → baseline = 150 km**
  - **Such a threshold is similar for CC/NC & ν/νbar**
- **Although we loose statistics due to the lower cross section, but we have less systematics by being π^0 free**



J.Formaggio and G.Zeller, Rev. Mod.Phys. 84.3(2012)1307

MOMENT: Muon-decay medium-baseline neutrino beam facility

Phys. Rev. STAB.17.090101



- Neutrinos from muon decay
- Proton LINAC for ADS ~15 MW
- Energy: 300 MeV/150 km

Neutrinos after the target/collection/decay: ~ 10^{21} ν/year

Beam and Detector

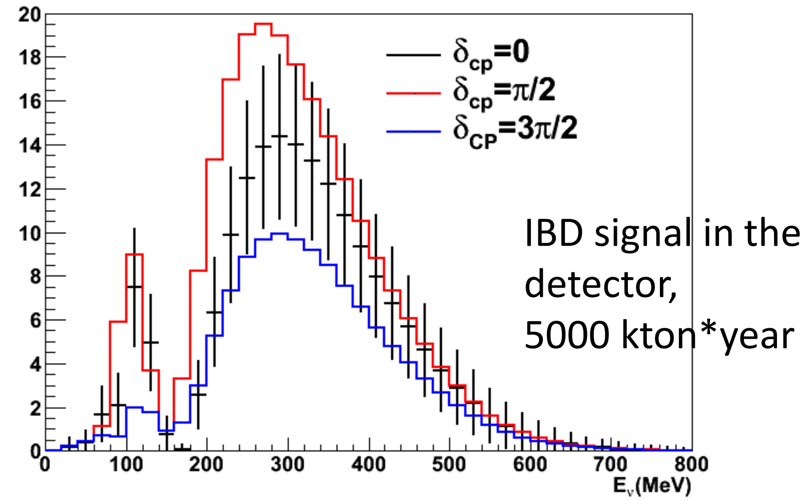
- **μ decay**

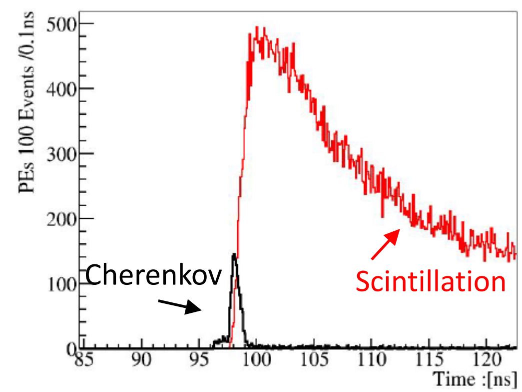
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$\nu_e \rightarrow \nu_\mu$, $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

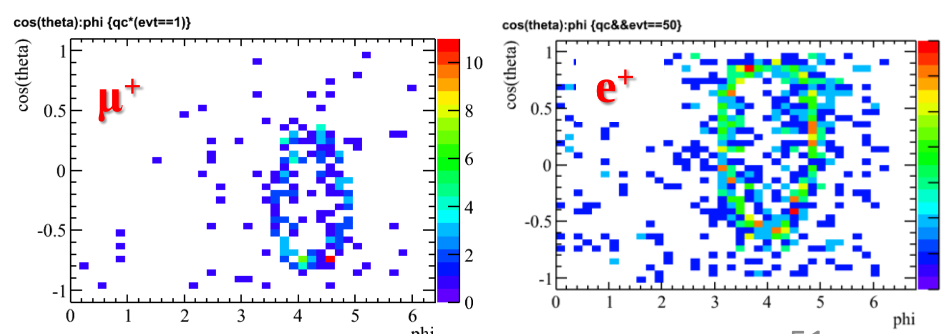
$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$, $\nu_\mu \rightarrow \nu_e$





- **Requirement to the detector**
  - **Flavor sensitive (e/μ identification):** water Cherenkov detector; liquid Argon; **liquid scintillator (challenge)**
  - **Charge sensitive (Neutrino/anti-neutrino identification):** magnetized detector, liquid scintillator or Gd-doped water for IBD
  - **NC/CC sensitive (NC background rejection):** negligible at low energies



MC: 100 MeV kinetic energy

Another option with MOMENT

- **Muon decay-at-rest (DAR)**
  - High efficiency of neutrino production: no focusing, decay pipe, charge separation …
  - No ν_μ CC contamination
  - Lower energy, shorter baseline -> lower matter effect
  - Known spectrum

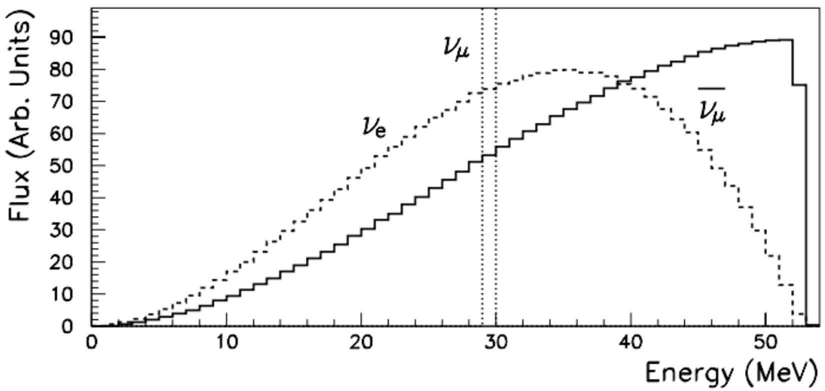
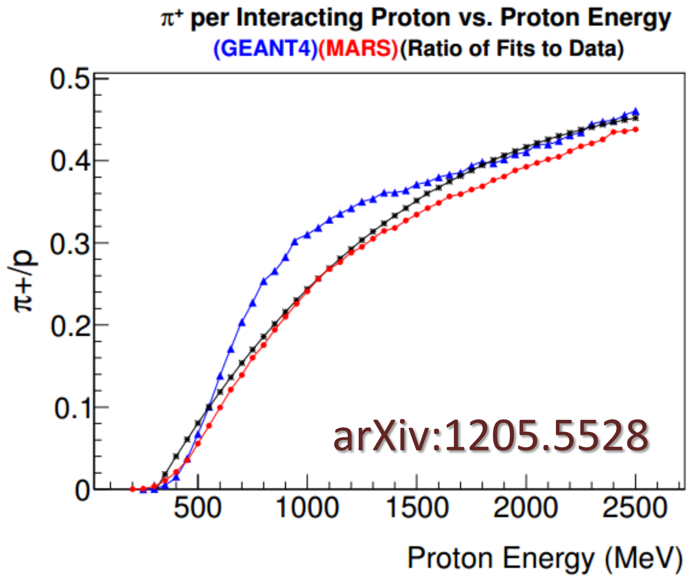
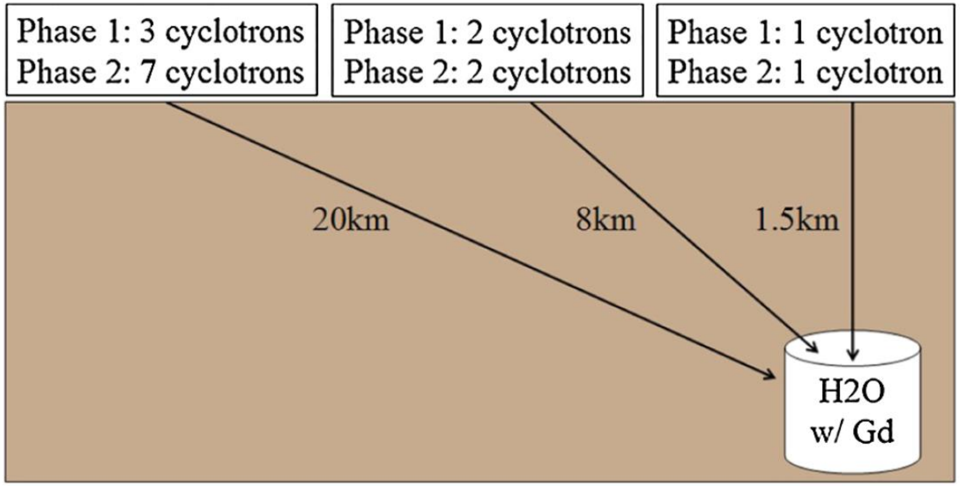


Figure: DAR neutrino fluxes in arbitrary units.

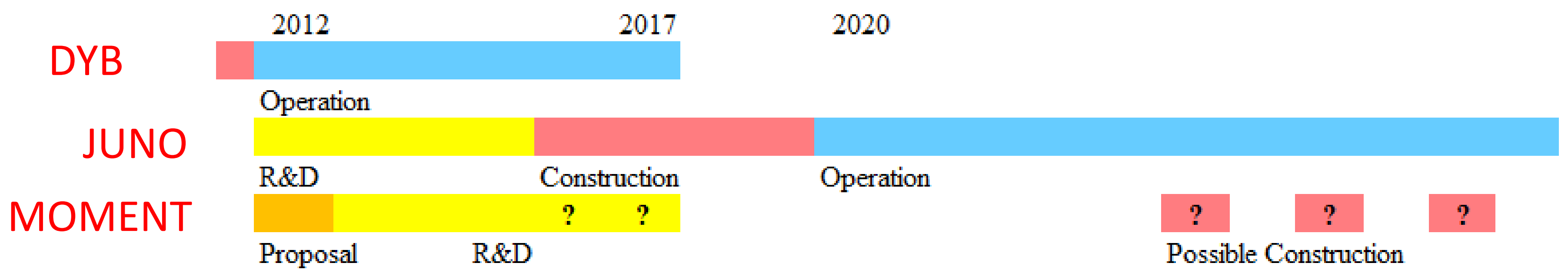




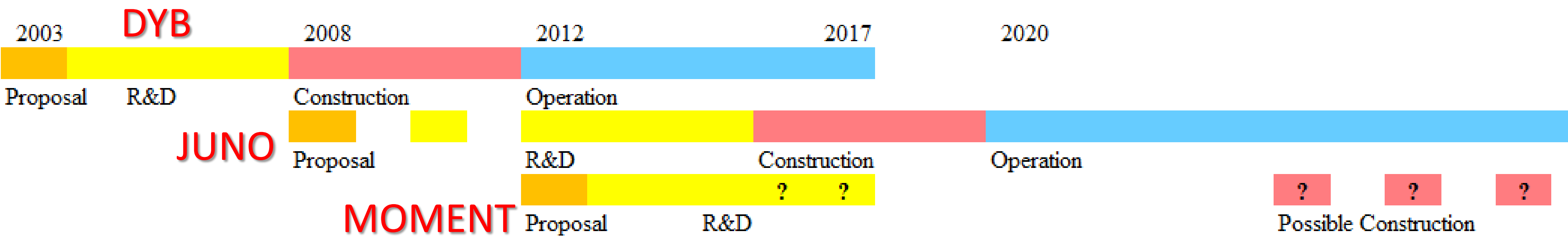
Concept of DAEδALUS, PRL 104, 141802 (2010)

How Serious Are We on MOMENT?

- Design study by a team of ~10. A new idea worthy to study.
- Progress of ADS proton LINAC? Will China build CEPC?
- What's the physics, after DUNE and Hyper-K?
- If there is physics, will a neutrino factory be built?
- The same team also collaborate in LBNF (Targetry & decay beam window) and is in close contact with NuFact and ESSnu.



Summary



- **Daya Bay** is the best site for θ_{13} measurement. It is the start point of neutrino program in China (2003).
- **JUNO** has a rich and very attractive physics program. It will take data in 2020. As a reactor experiment, it is complementary to T2K, NOvA, LBNE, Hyper-K, PINGU, INO, etc.
- Design study for **MOMENT**. Will consider it in a world-wide picture.
- Due to lack of manpower, China has only a little involvement in other neutrino programs (LBNF, EXO)

Thanks!