JUNO: A Multi-purpose Neutrino Observatory

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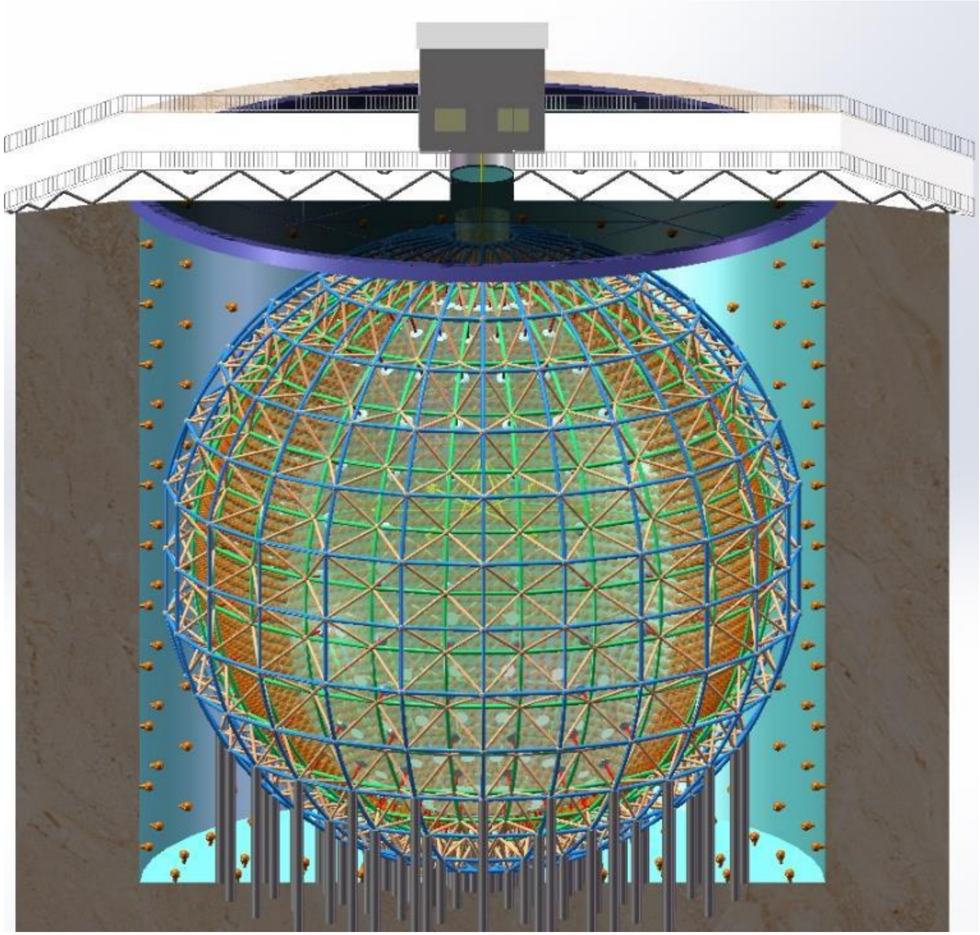
Institute of High Energy Physics

Neutrino Telescopes, Venice, Mar. 2-6, 2015

The JUNO Experiment

- **Jiangmen Underground Neutrino Observatory, a multiple-purpose neutrino experiment, approved in Feb. 2013. ~ 300 M$.**



- **20 kton LS detector**
- **3% energy resolution**
- **700 m underground**
- **Rich physics possibilities**
  - ⇨ **Reactor neutrino for Mass hierarchy and precision measurement of oscillation parameters**
  - ⇨ **Supernovae neutrino**
  - ⇨ **Geoneutrino**
  - ⇨ **Solar neutrino**
  - ⇨ **Atmospheric neutrino**
  - ⇨ **Exotic searches**

Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011; by J. Cao at Nutel 2009, NuTurn 2012 ;
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103, 2008; PRD79:073007,2009

A Slide at NuTel 2009

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If $\sin^2 2\theta_{13}$ is large

A **10k ton detector** at 60km, with **3%/sqrt(E)** energy resolution, can determine the mass hierarchy to 90% C.L. in 5 years.

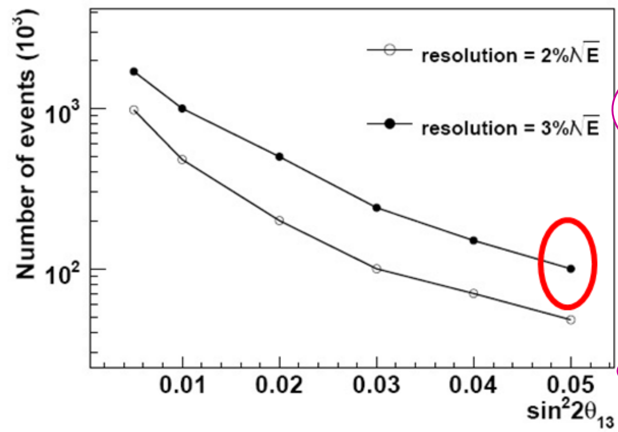


FIG. 6: Requirements to the number of events to determine the mass hierarchy at 90% probability as a function of $\sin^2(2\theta_{13})$.

[arXiv:0901.2976]

Each point represents 500 simulated Exp.

100k events = 10k ton • (2.9GWx8) • (300 days x 5) / (60 km)^2

If we are lucky, $\sin^2 2\theta_{13}$ may be as large as 0.05

neutrino exps were not precise.

8 cores planned @DYB

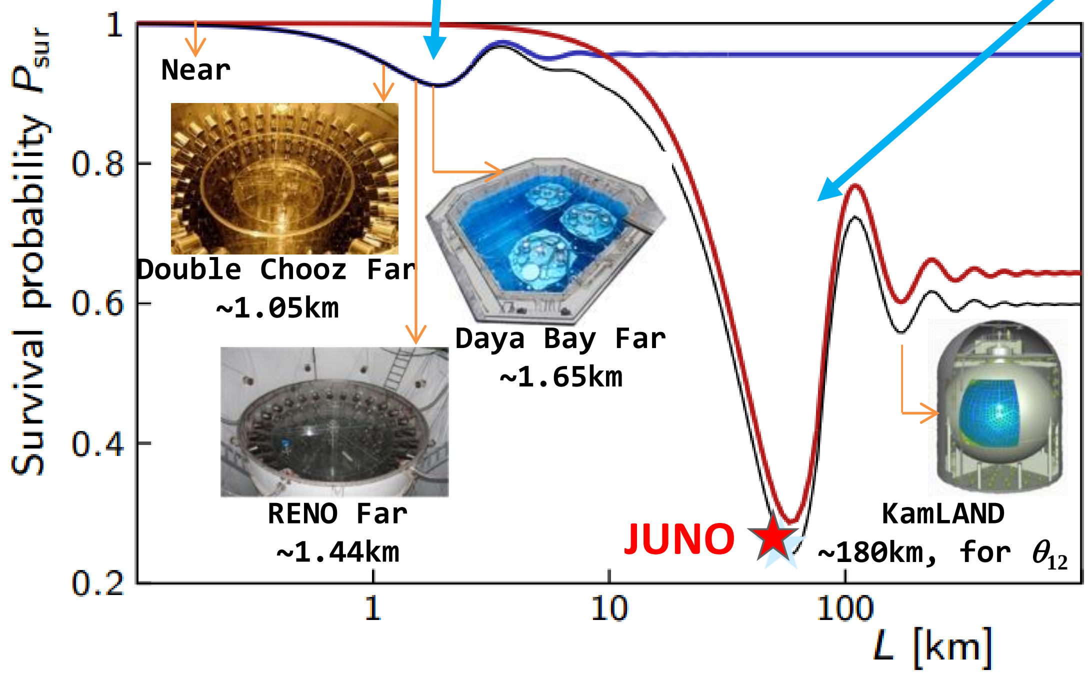
Reactor Neutrinos

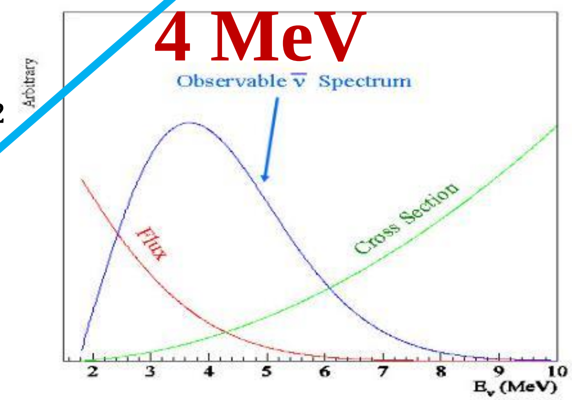
"Disappearance" experiments: $\bar{\nu}_e \rightarrow \bar{\nu}_e$

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right) - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2\left(\Delta m^2_{21} \frac{L}{4E}\right)$$

Another definition:

$$\Delta m^2_{ee} = \cos^2\theta_{12}\,\Delta m^2_{31} + \sin^2\theta_{12}\,\Delta m^2_{32}$$
$$\sim 0.7\Delta m^2_{31} + 0.3\Delta m^2_{32}$$





- Inverse beta decay

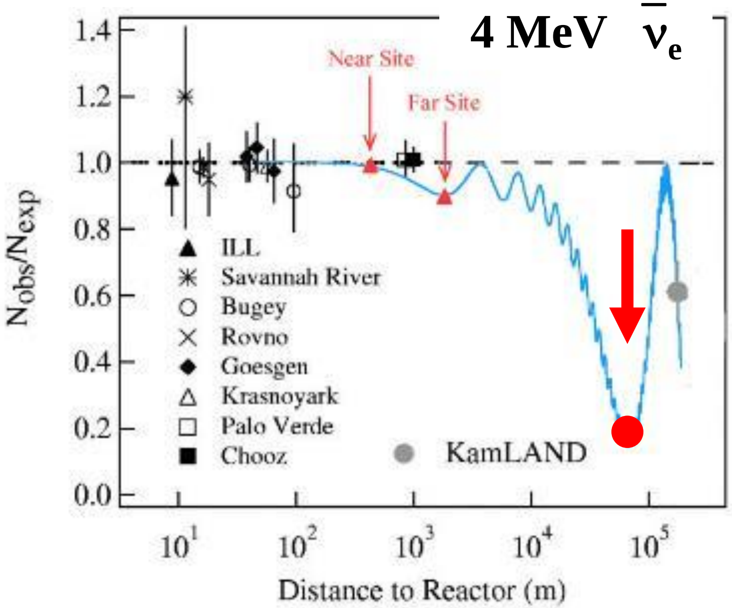
Prompt signal

$$e^+ + e^- \rightarrow 2\gamma$$

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

Capture on H or Gd,
Delayed signal, 2.2 or 8 MeV

Determine MH with Reactors

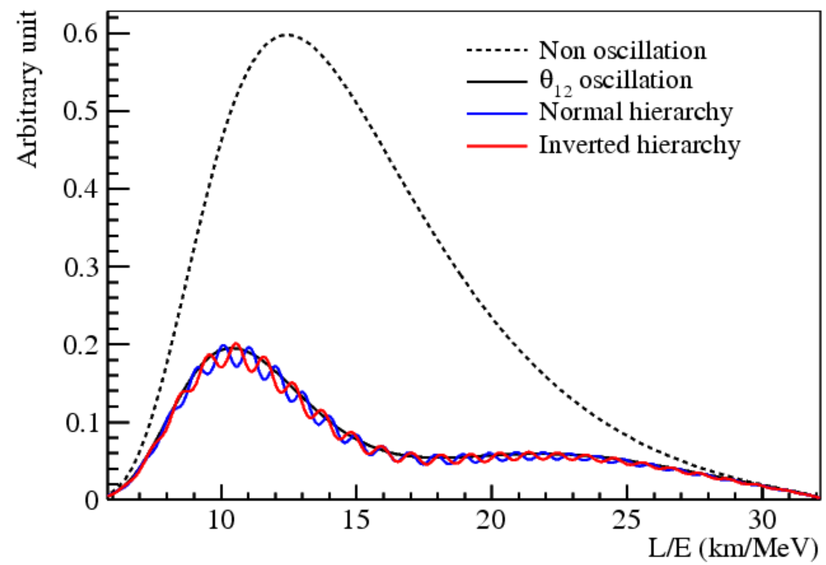


$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

$$
\frac{1}{2}\sin^2 2\theta_{13}\left[1 - \sqrt{1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}}\cos(2|\Delta_{ee}| \pm \phi)\right]
$$

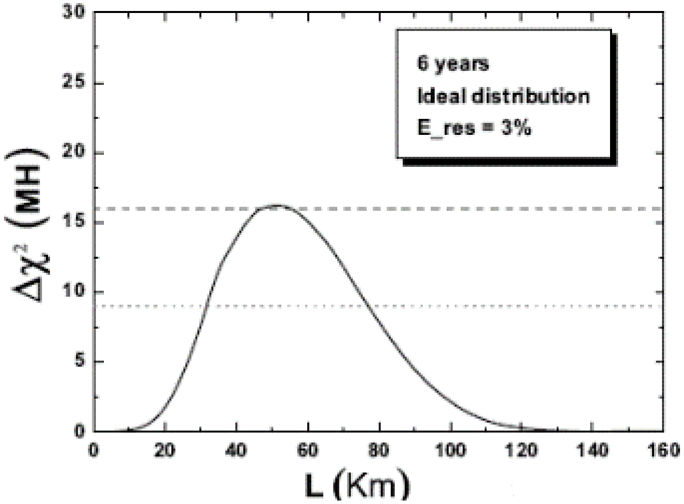
- **A fixed definition Δm^2_{ee}**
- **And an energy related phase shift ϕ**

Precision energy spectrum measurement interference between *P_{31}* and *P_{32}*
→ Relative measurement

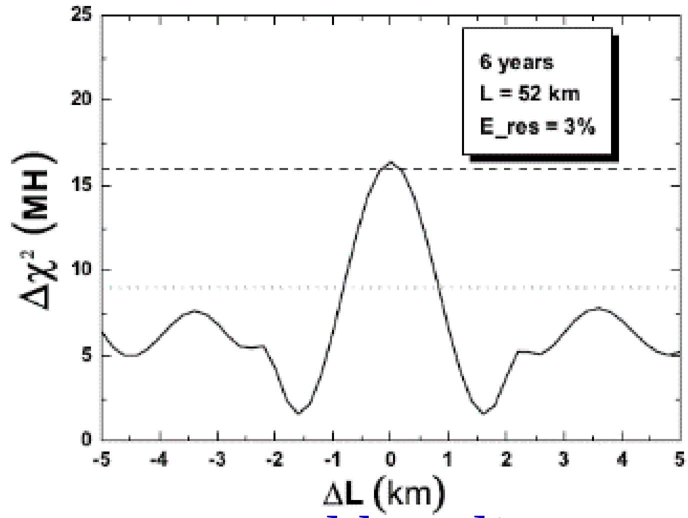


Further improvement with $\Delta m^2_{\mu\mu}$ measurement from accelerator exp.
→ Absolute measurement

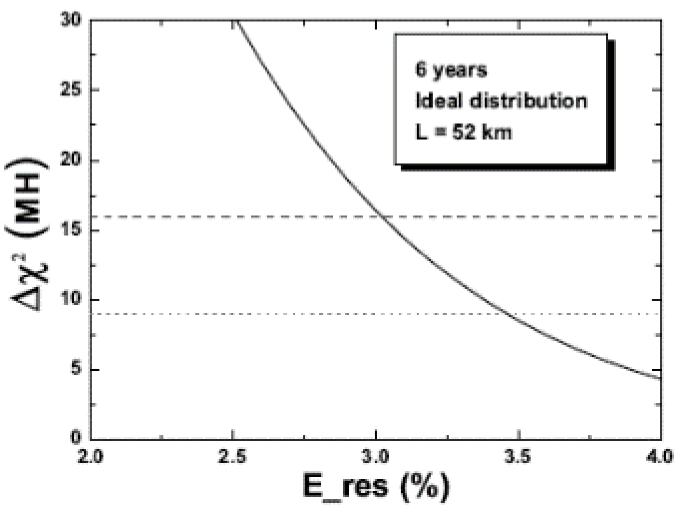
Requirements



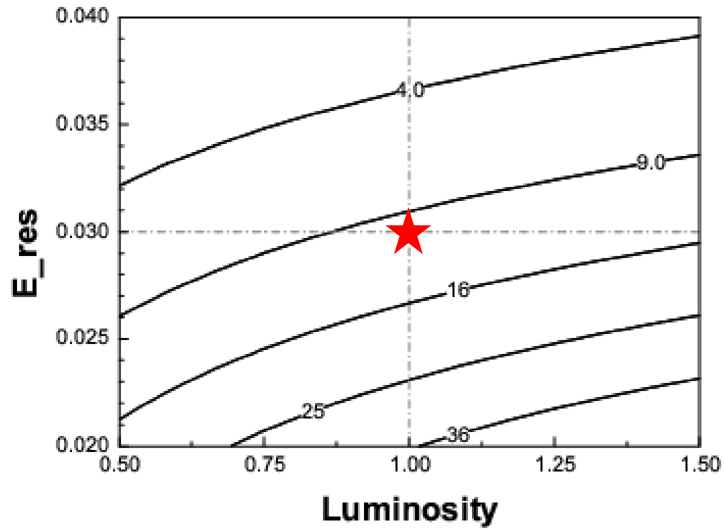
Proper baseline: 45-60 km



Equal baselines



3% Energy resolution



100k events=20 kton×35 GW×6 year

Location of JUNO

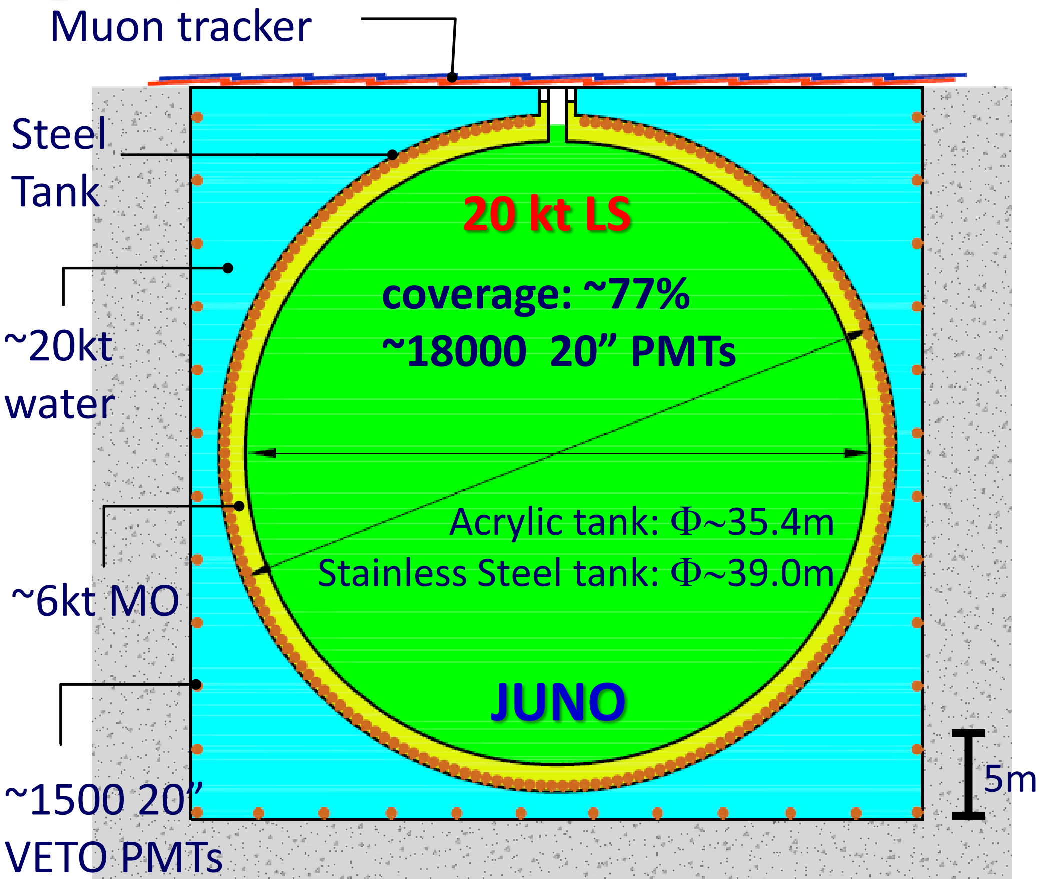
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW

by 2020: 26.6 GW

Overburden ~ 700 m

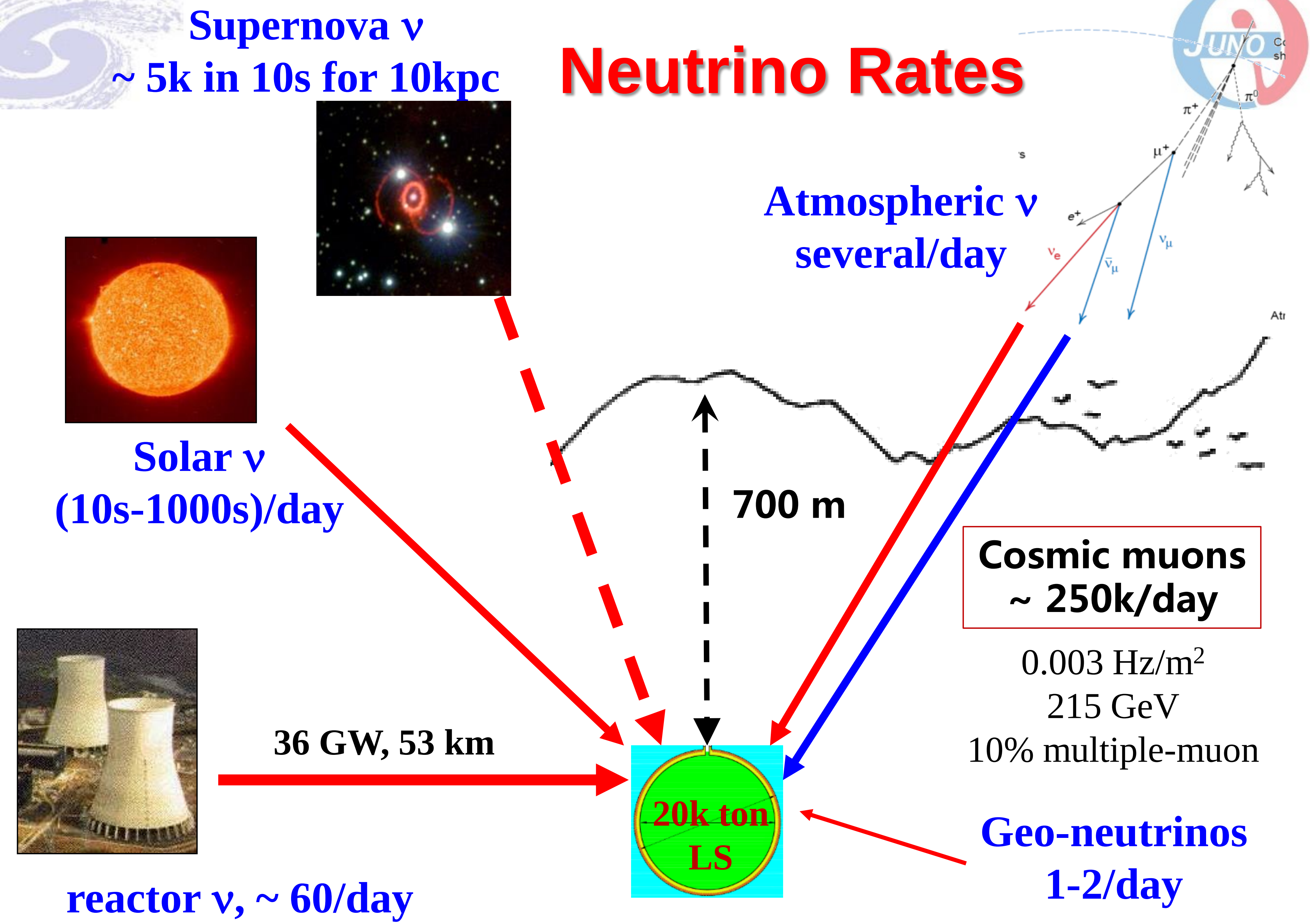
Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline (km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline (km)	52.76	52.63	52.32	52.20	215	265

High-precision, Giant LS detector



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

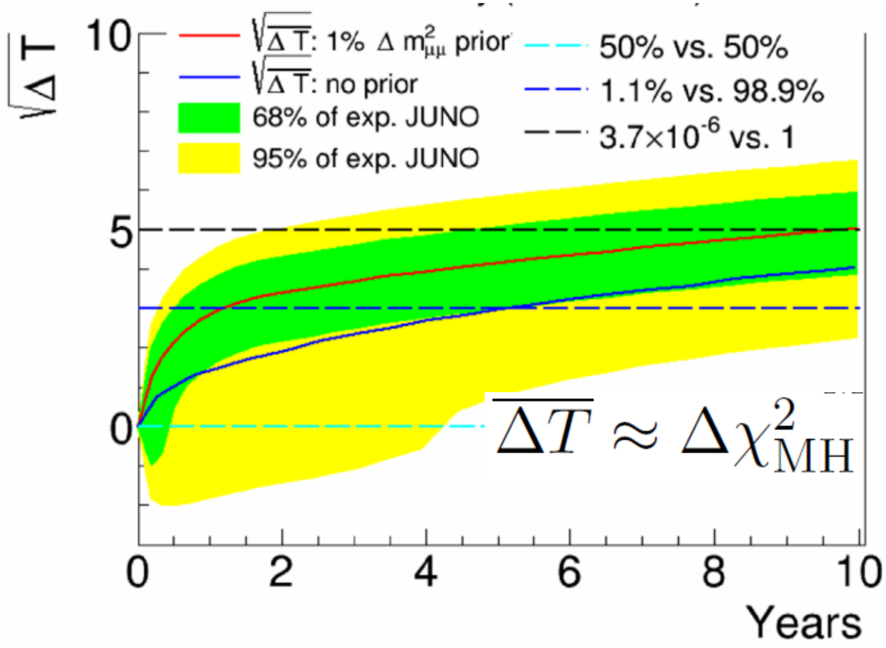
Neutrino Rates

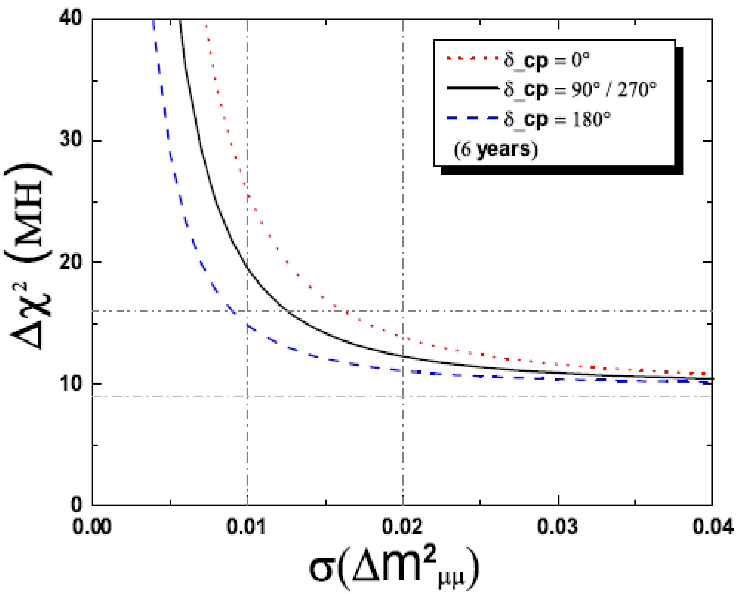


Sensitivity on MH

PRD 88, 013008 (2013)	Relative Meas.	Use absolute Δm^2
Statistics only	4σ	5σ
Realistic case	3σ	4σ

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

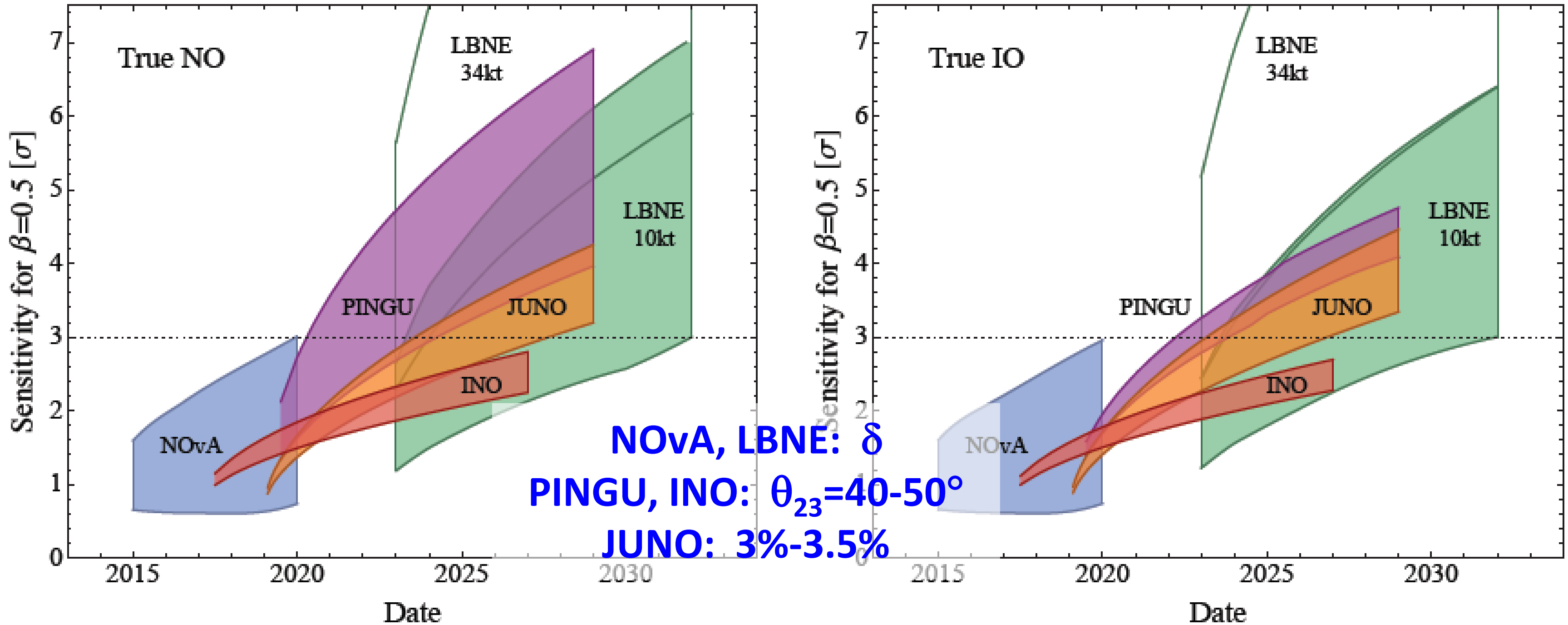




	Ideal	Core distr.	Shape	B/S (stat.)	B/S (shape)	$\lvert\Delta m^2_{\mu\mu}\rvert$
Size	52.5 km	Real	1%	4.5%	0.3%	1%
$\Delta\chi^2_{MH}$	+16	−4	−1	−0.5	−0.1	+8

Other Exp/Proposals for MH

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



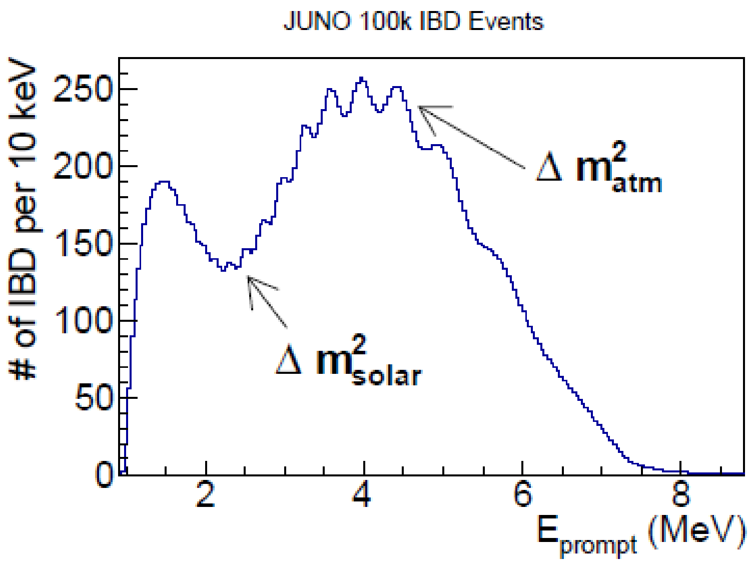
NOvA, LBNE: δ
PINGU, INO: θ_{23}=40-50°
JUNO: 3%-3.5%

JUNO: Competitive in schedule and Complementary in physics

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

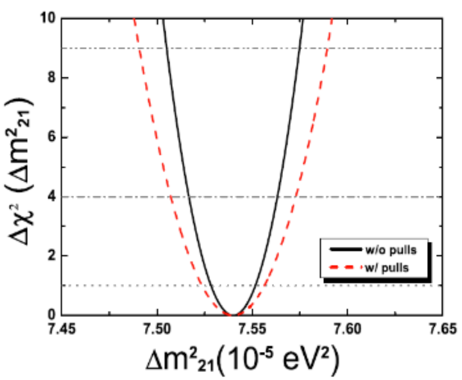
Reactor — **atmospheric** — **Accelerator**

Precision Measurements

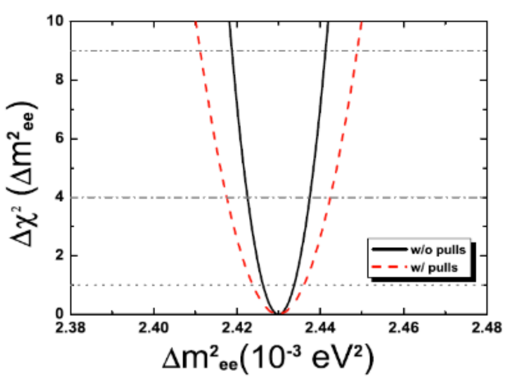


Probing the unitarity of U_{PMNS} to ~1%
more precise than CKM matrix elements !

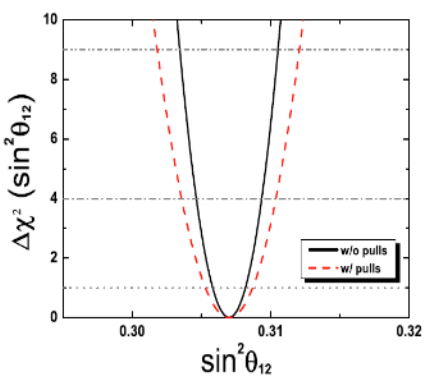
	Statistics	+BG +1% b2b +1% EScale +1% EnonL
$\sin^2\theta_{12}$	0.54%	0.67%
Δm^2_{21}	0.24%	0.59%
Δm^2_{ee}	0.27%	0.44%



0.16%→0.24%

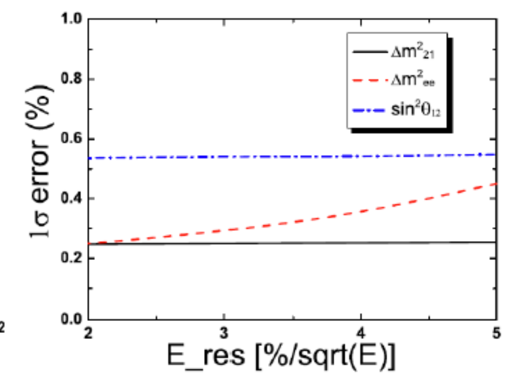


0.16%→0.27%



0.39%→0.54%

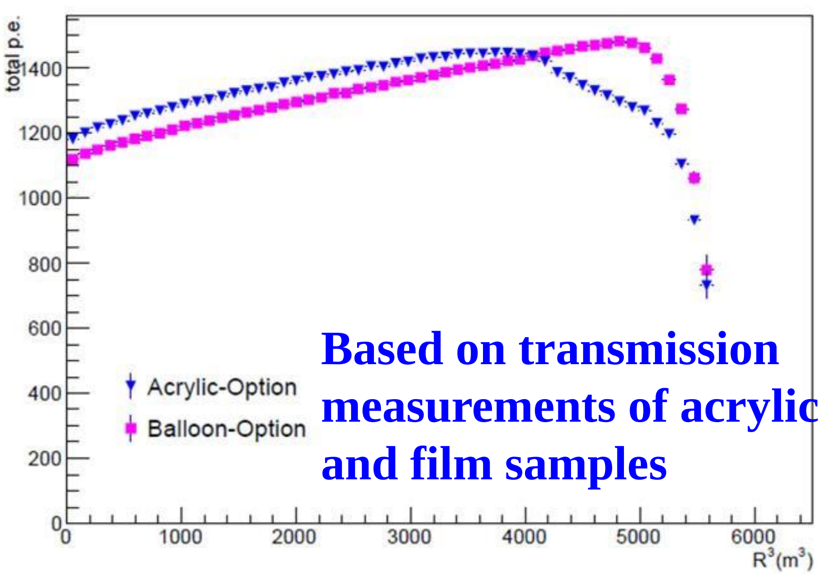
Correlation among parameters



E resolution

Energy Resolution

- **JUNO MC, based on DYB MC (p.e. tuned to data), except**
  - ⇨ **JUNO Geometry and 77% photocathode coverage**
  - ⇨ **High QE PMT: maxQE from 25% -> 35%**
  - ⇨ **LS attenuation length (1 m-tube measurement@430 nm)**
    - **from 15 m = absorption 30 m + Rayleigh scattering 30 m**
    - **to 20 m = absorption 60 m + Rayleigh scattering 30 m**



Photon Statistics

- **1200 p.e./MeV (center) → $2.89\%/\sqrt{E}$**
- **1400 p.e./MeV (edge) → $2.67\%/\sqrt{E}$**

No significant contributions from (Toy MC)

- IBD neutrino recoil, LS non-linearity, vertex smearing, vertex bias, non-uniformity
- PMT QE variation, QE non-uniformity, charge resolution, dark noise
- Electronic noise and non-linearity

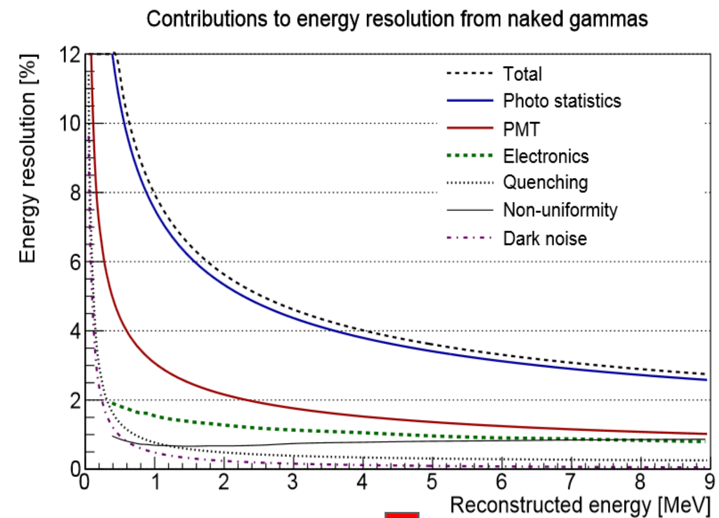
Beyond Photo-statistics

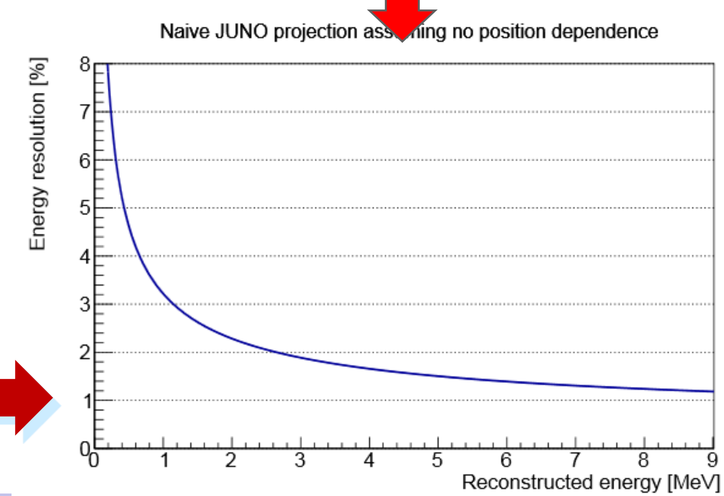
$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

Impact to MH sensitivity

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

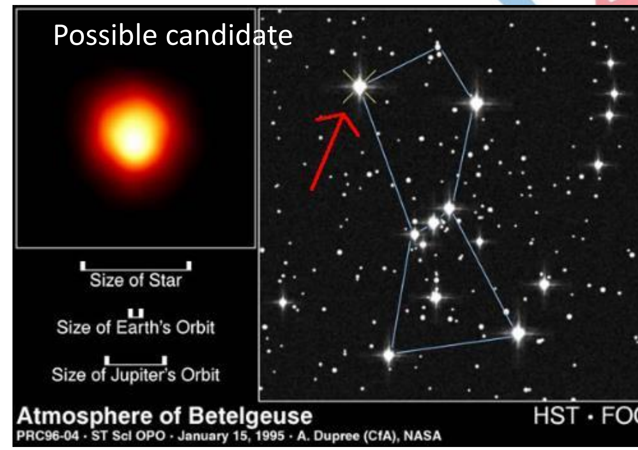
- Generic form of E resolution
  - a: stochastic term
  - b: constant term
  - c: noise term
- Data validated Full MC (DYB&DC)
- Noise term dominated by PMT dark noise
- Constant term
  - Residual non-uniformity
  - Flaws in readout electronics
  - Artifacts from resolution plotting
- No JUNO show stopper found in DYB model

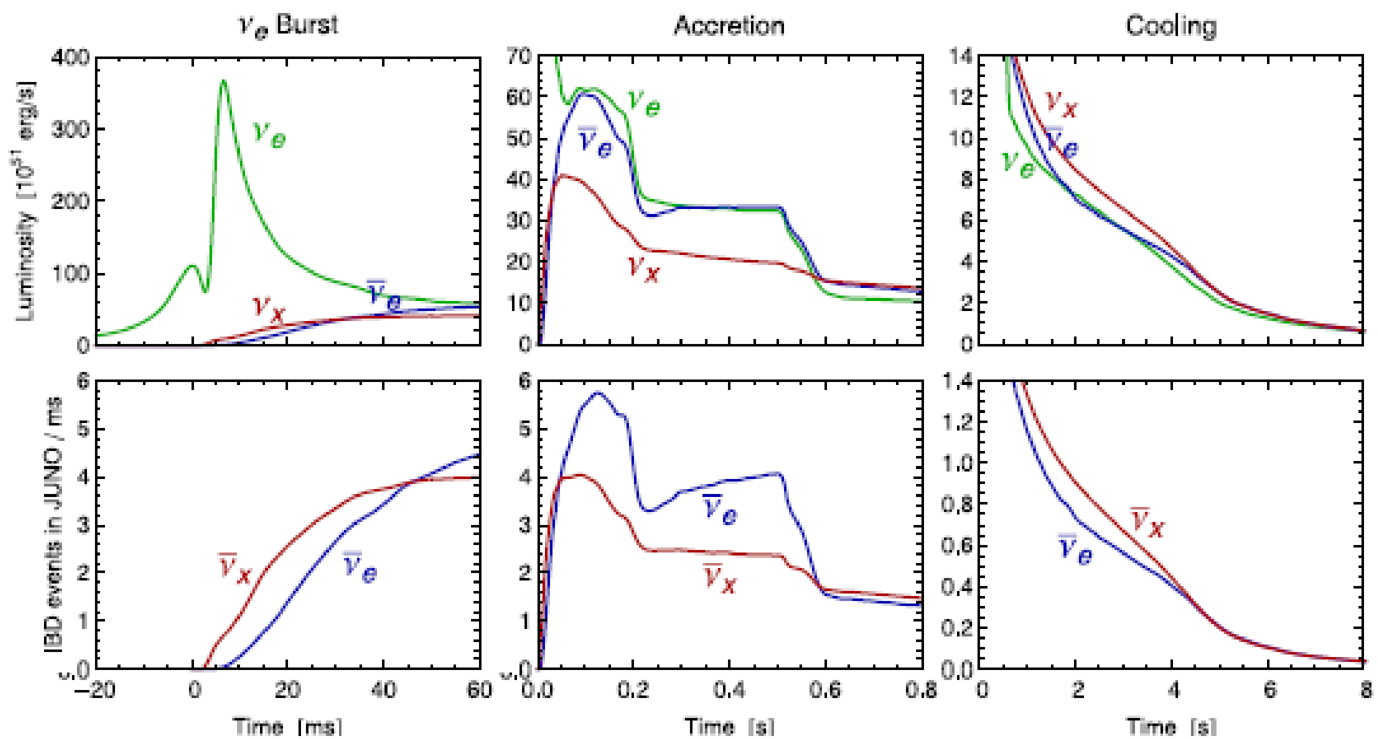




Supernova Neutrinos

- Less than 20 events observed so far
- Assumptions:
  - ⇨ Distance: 10 kpc (our Galaxy center)
  - ⇨ Energy: 3×10^{53} erg
  - ⇨ L_ν the same for all types





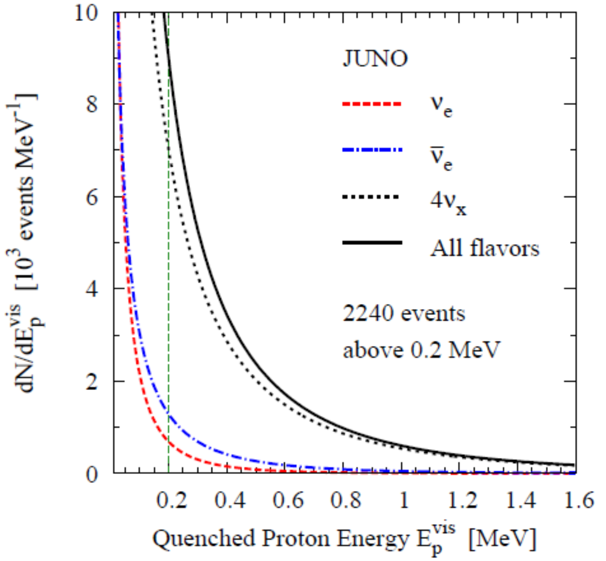
Supernova Neutrinos

Estimated numbers of neutrino events in JUNO

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
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	4.7×10^1	9.4×10^1	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	6.0×10^1	1.1×10^2	1.6×10^2

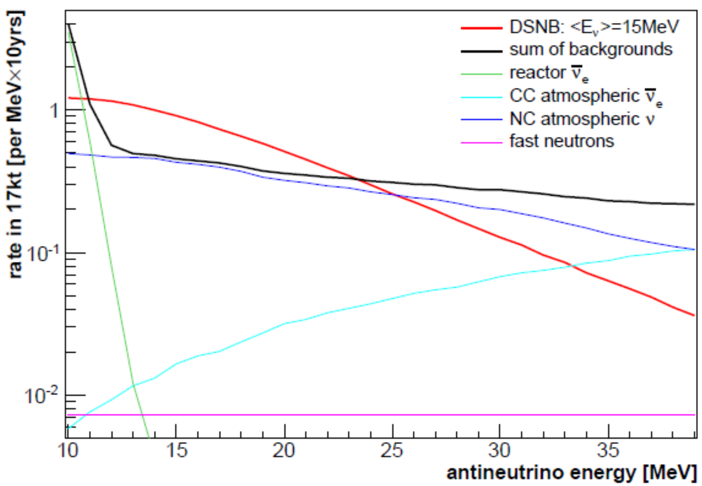
LS detector vs. Water Cerenkov detectors: much better detection to these correlated events

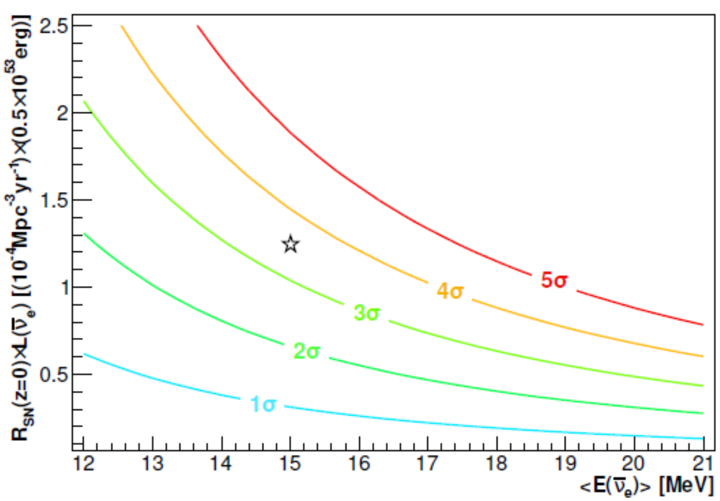
→ Measure energy spectra & fluxes of almost all types of neutrinos



- ν mass: < 0.83±0.24 eV at 95% CL (arXiv:1412.7418)
- Locating the SN: ~9°
- Pre-SN ν (> 1 day)
- SN Nucleosynthesis via ν_x spectra
- Collective ν oscillation
- MH

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

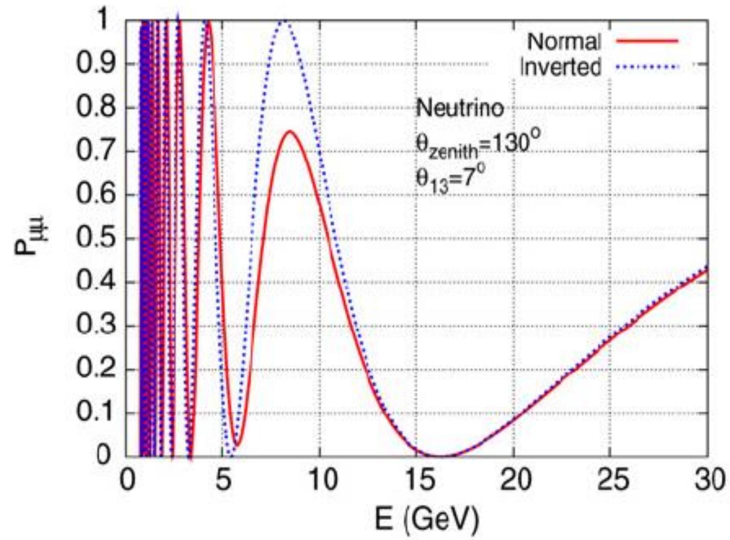
10 Years' sensitivity

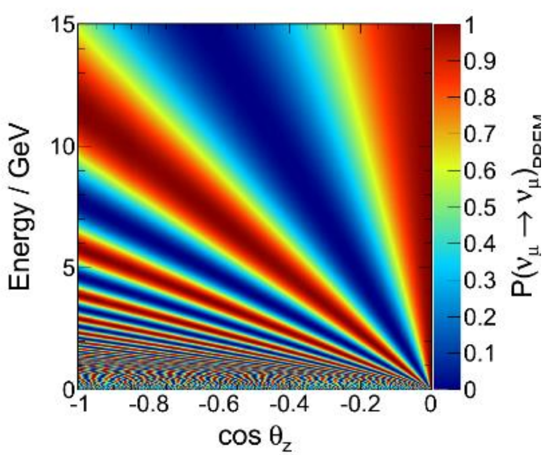
Syst. uncertainty BG	5 %		20 %	
$\langle E_{\bar{\nu}_e}\rangle$	rate only	spectral fit	rate only	spectral fit
12 MeV	$1.7\,\sigma$	$1.9\,\sigma$	$1.5\,\sigma$	$1.7\,\sigma$
15 MeV	$3.3\,\sigma$	$3.5\,\sigma$	$3.0\,\sigma$	$3.2\,\sigma$
18 MeV	$5.1\,\sigma$	$5.4\,\sigma$	$4.6\,\sigma$	$4.7\,\sigma$
21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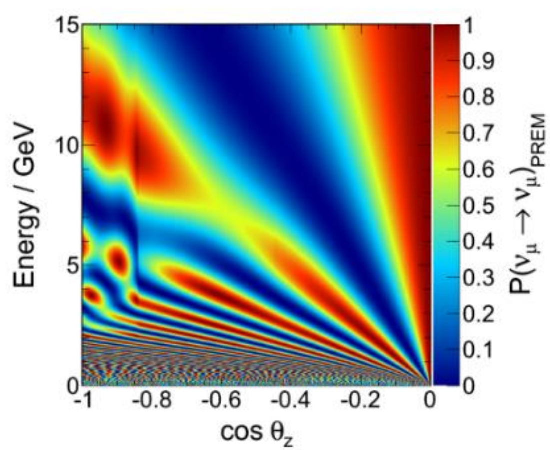

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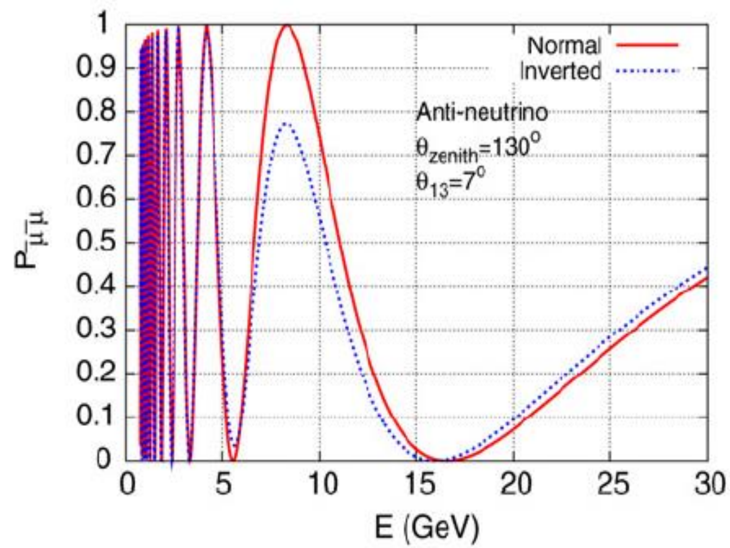


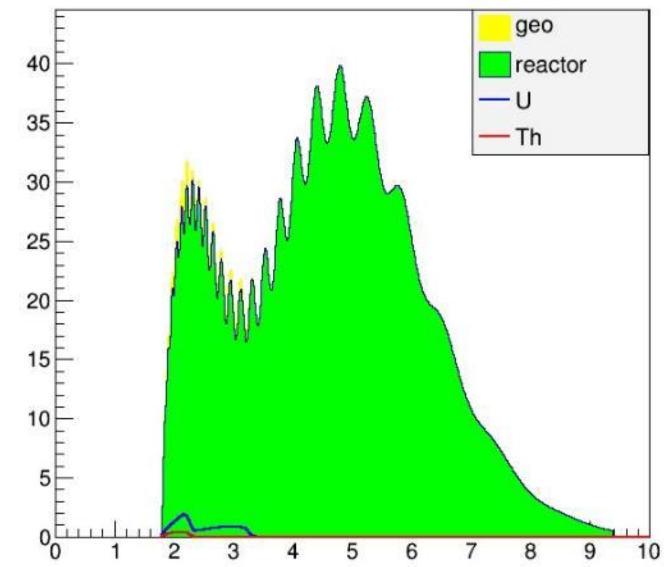
Geo-neutrinos

- **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

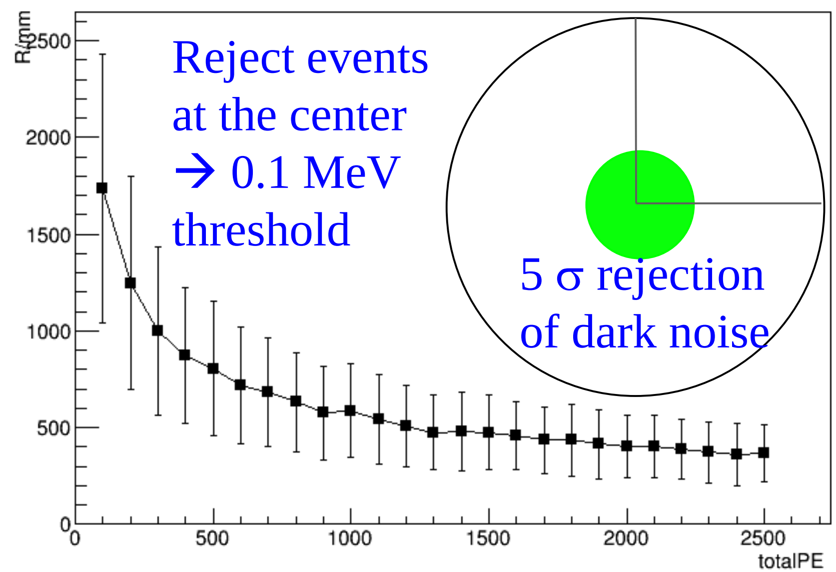
	Best fit	1 y	3 y	5 y	10 y
U+Th fix ratio	0.96	17%	10%	8%	6%
U (free)	1.03	32%	19%	15%	11%
Th (free)	0.80	66%	37%	30%	21%

Solar and other Physics

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

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

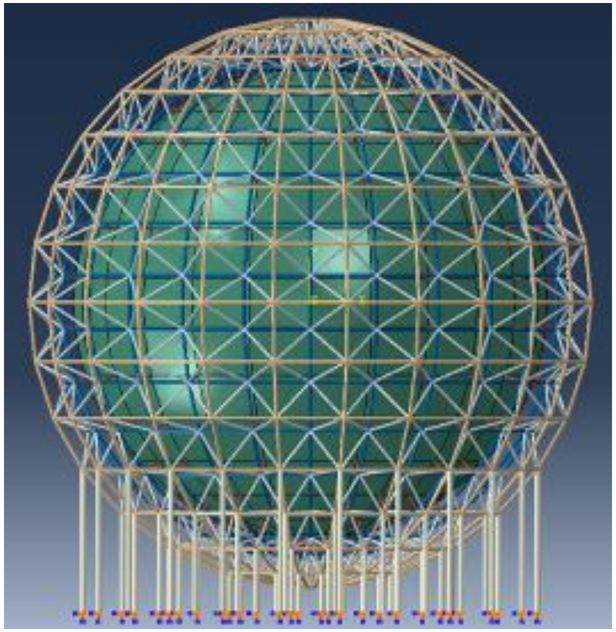
Liquid Scintillator	U238	Th232	K40	Pb210 (Rn222)	Ref.
No Distillation	10^{-15}	10^{-15}	10^{-16}	$1.4\cdot10^{-22}$	Borexino CTF, KamLAND
After Distillation	10^{-17}	10^{-17}	10^{-18}	10^{-24}	

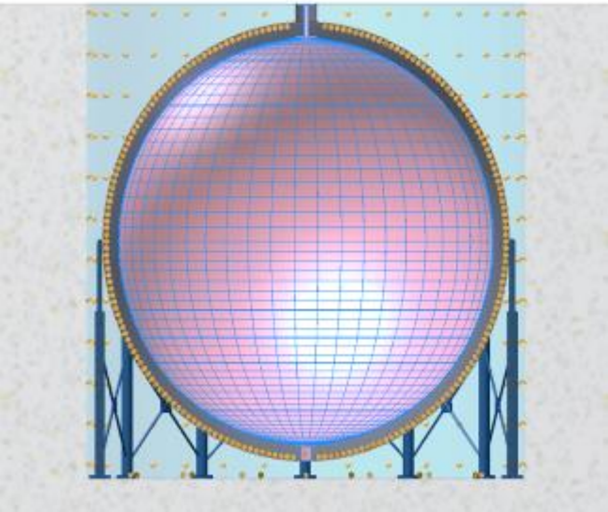


- **Sterile ν, Indirect dark matter, Nucleon decay, etc.**

JUNO Central Detector

- Some basic numbers:
  - Target: 20 kt LS
  - Backgrounds/reactor signal: Accidentals (~10%), $^{9}Li/^{8}He$ (<1%), fast neutrons (<1%)
- A huge detector in a water pool:
  - Default option: acrylic tank (D~35m) + SS truss
  - Alternative option: SS tank (D~39m) + acrylic structure + balloon
- Challenges:
  - Engineering: mechanics, safety, lifetime, …
  - LS: high transparency, low background
  - PMT: high QE, high coverage
- Design & prototyping underway



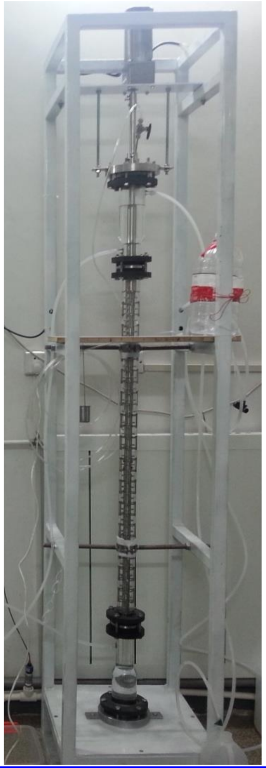


Liquid Scintillator in JUNO

- Recipe

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
  - ⇨ Instrinsic singles < 3Hz (above 0.7MeV), if ^{40}K/U/Th <10^{-15} g/g (TCF)

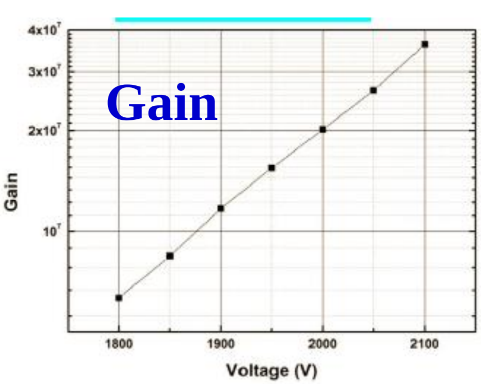


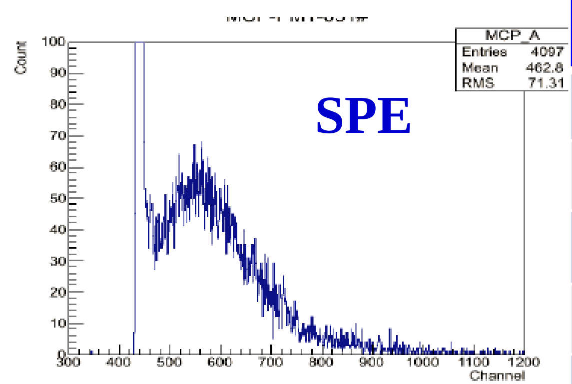
Linear Alky Benzene (LAB)	Atte. Length @ 430 nm
RAW (specially made)	14.2 m
Vacuum distillation	19.5 m
SiO_2 coloum	18.6 m
Al_2O_3 coloum	25 m

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**
  - ⇨ **Many 20” prototypes**
- **Alternative options:** Hamamatsu or Photonics

20” and 8” MCP-PMTs





	R5912	R5912-100	MCP-PMT
QE@410nm	25%	35%	25%
Rise time	3 ns	3.4ns	5ns
Dark noise	1kHz	3.5kHz	2.2kHz
P/V of SPE	>2.5	>2.5	`~2
TTS	5.5ns	1.5 ns	3.5 ns

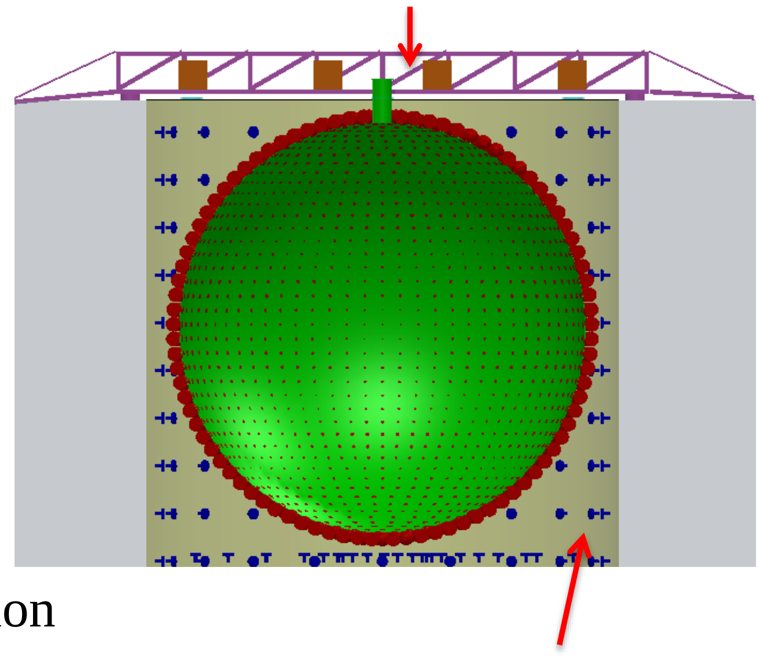
Veto Detectors

- 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%

Top muon tracker



Water Cherenkov Detector

Project Plan and Progresses

First get-together meeting

Funding(2013-2014) review approved

Geological survey and preliminary civil design

1st 20” MCP-PMT

Collaboration formed

Groundbreaking Ceremony

2013

Kaiping Neutrino Research Center established

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

Yangjiang NPP started to build the last two cores

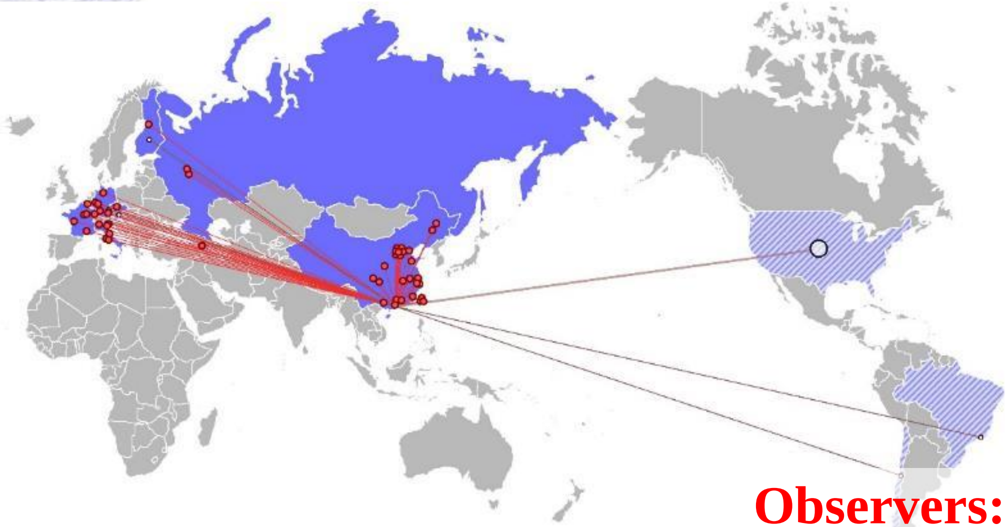
2014

Civil/infrastructure construction bidding

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



Asia (28)

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

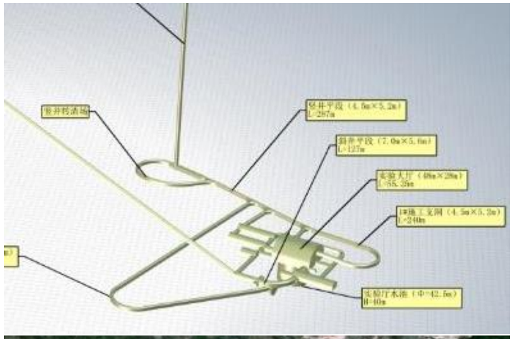
Observers:

US institutions
HEPHY Vienna
PUC Brazil
PCUC Chile
MPP Munich
Jyvaskyla U.

Europe (23)

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

Jan. 10, 2015



600 m vertical shaft
1300-m long tunnel(40% slope)
50-m diameter, 80-m high cavern

Summary

- JUNO was approved in Feb. 2013 w/ ~300 M$ budget
- Very rich physics possibilities
- Preparation proceeds very well
  - ⇨ Detector R&D
  - ⇨ Physics book and CDR in months
  - ⇨ Groundbreaking on Jan.10, 2015. Civil construction will be completed in 3 years.
- A strong international collaboration formed

Thanks!

Background

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