Status and Physics of JUNO

14 Aug 2018, 12:00 (Est) @Hahn N 130, 25'+5'

Xuefeng Ding[1,2] on behalf of JUNO collaboration

1. Gran Sasso Science Institute, L'Aquila, Italy
2. INFN Sezione di Milano, Milan, Italy

The 20th International Workshop on Neutrinos from Accelerators
@ Virginia Tech., Blacksburg, VA, U.S. 12–18 August 2018

Outline

- JUNO overview
- JUNO detectors
- JUNO physics goals and potentials
- Conclusion

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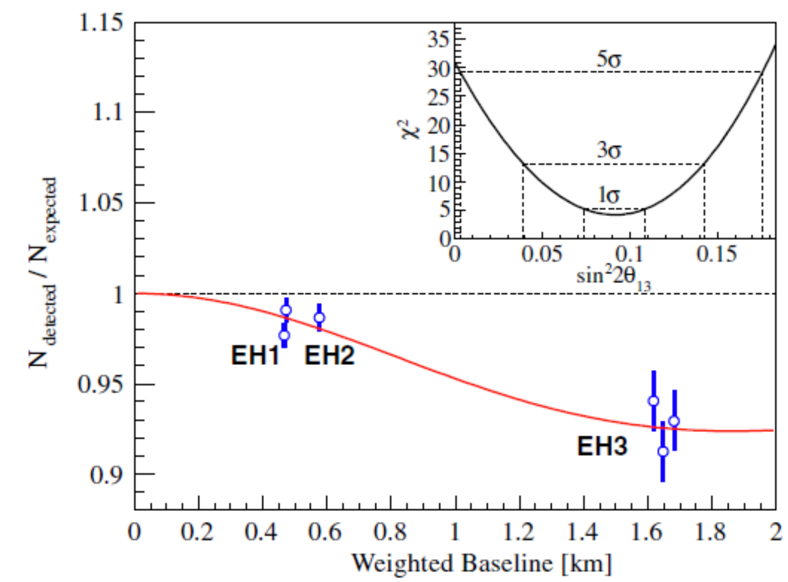
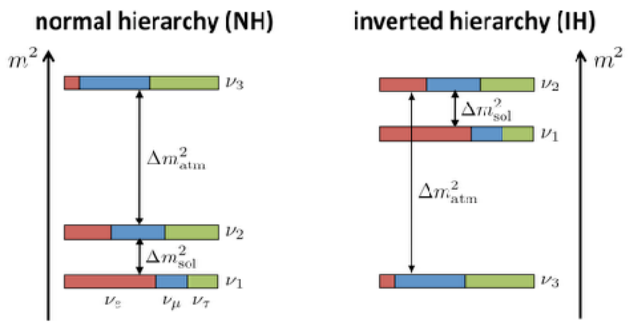
Birth of JUNO: *ν* Mass Ordering

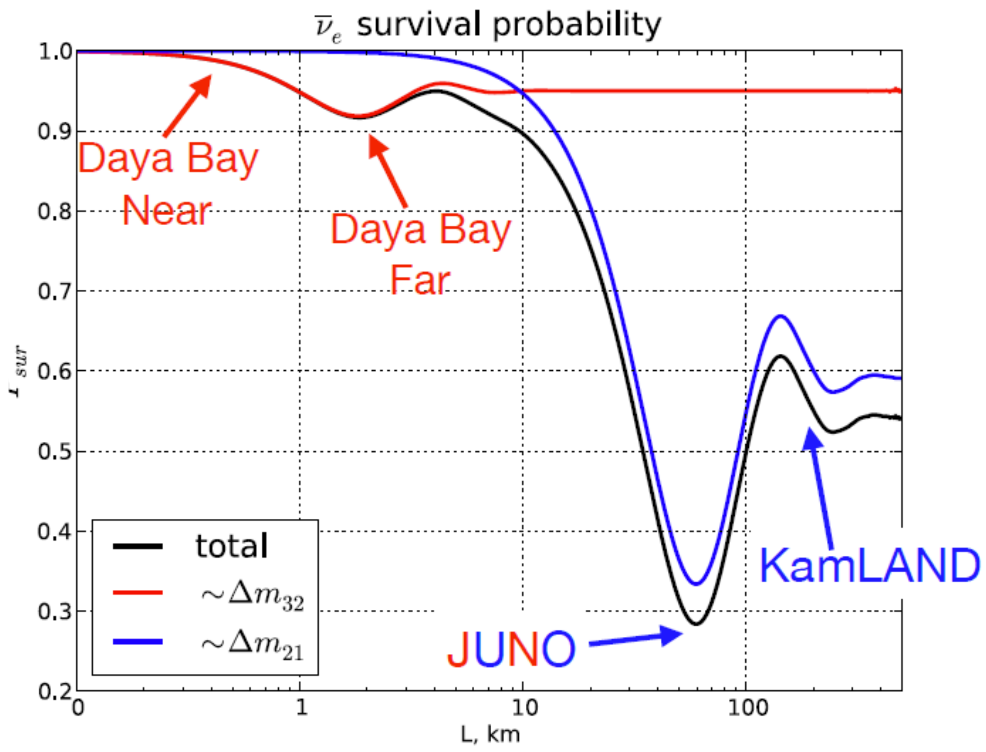
- Petcov and Piai PLB 533, 94-106 (2002);
  Zhan L. et al. PRD (2008) PRD (2009) PRD.78.111103(2008), PRD.79.073007(2009)
  A medium baseline detector would be able to determine Neutrino Mass Hierarchy through vacuum oscillation given non-zero $\sin^2\theta_{13}$
- **2012**: **$\sin^2\theta_{13}$ is large**, opens a door to ***ν*MO**
- **2013**: JUNO **fully funded** to measure *ν*MO

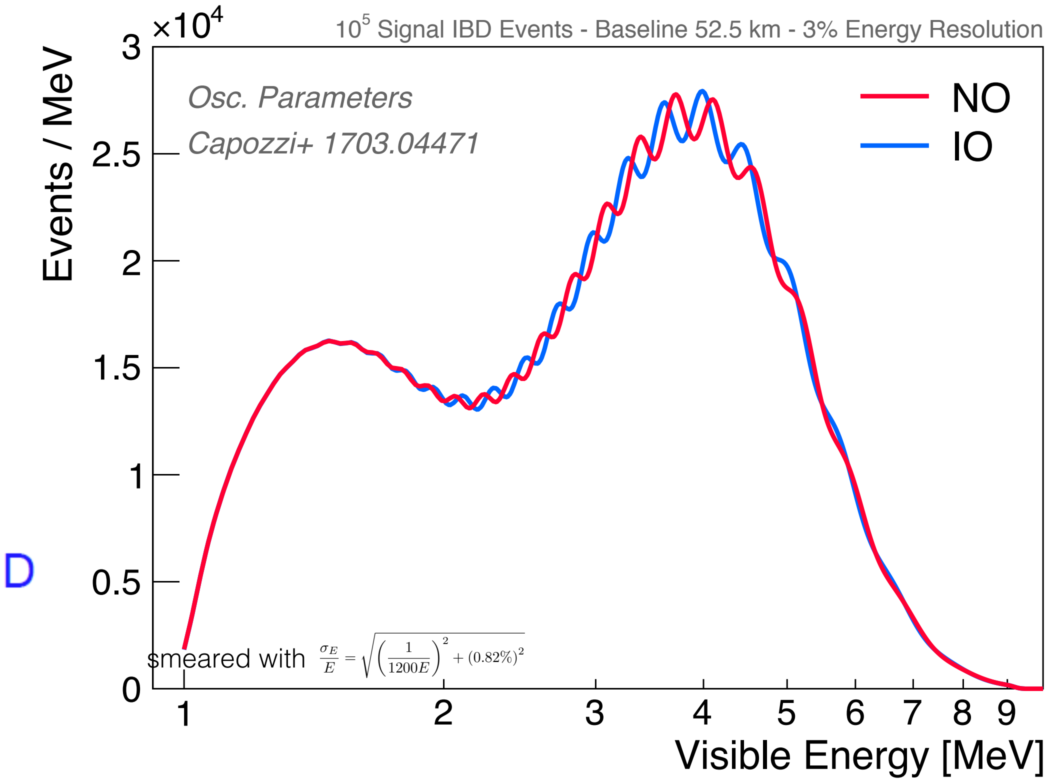


$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat.}) \pm 0.005(\text{syst.})$$

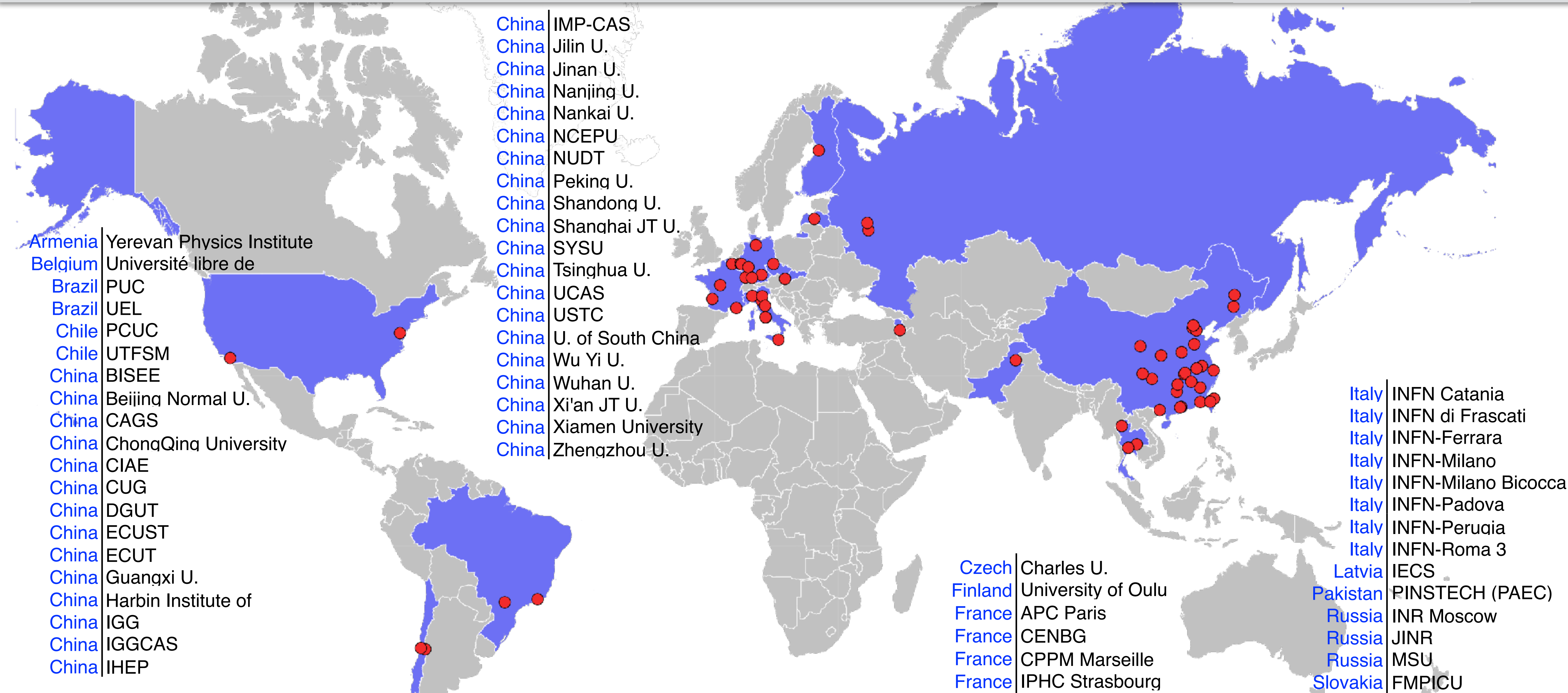
Daya Bay. PRL 108, 171803 (2012)







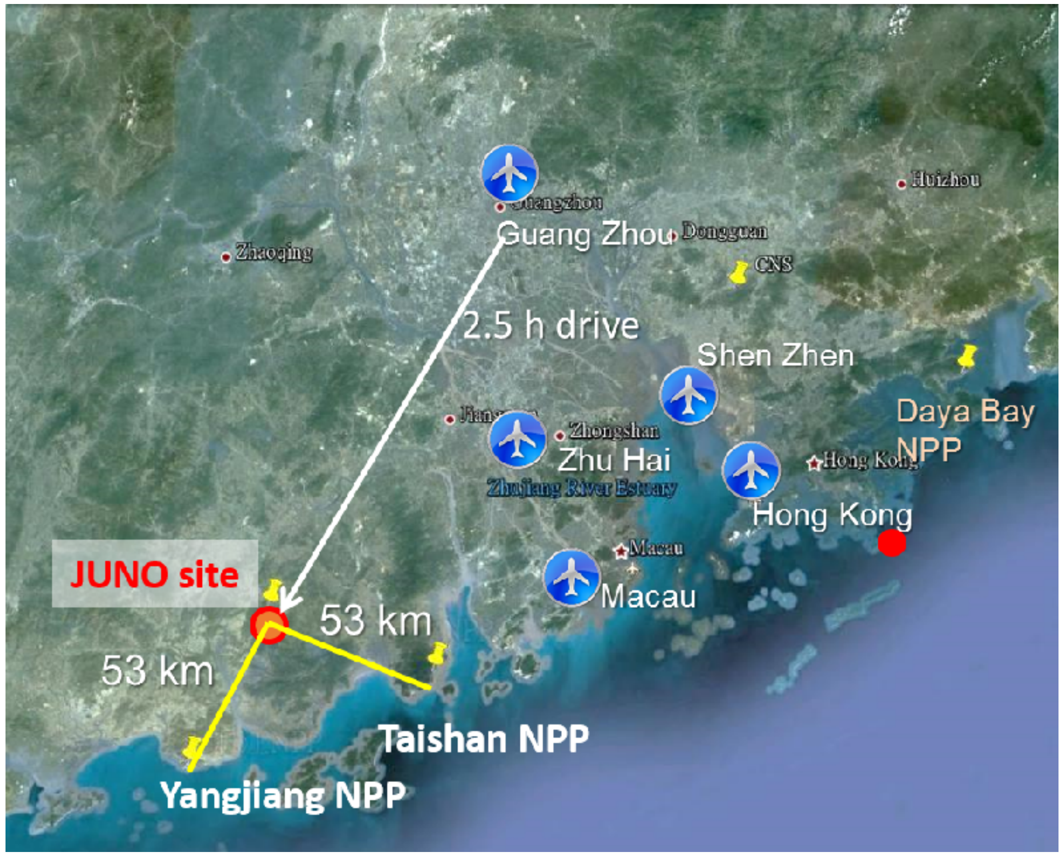
JUNO collaboration



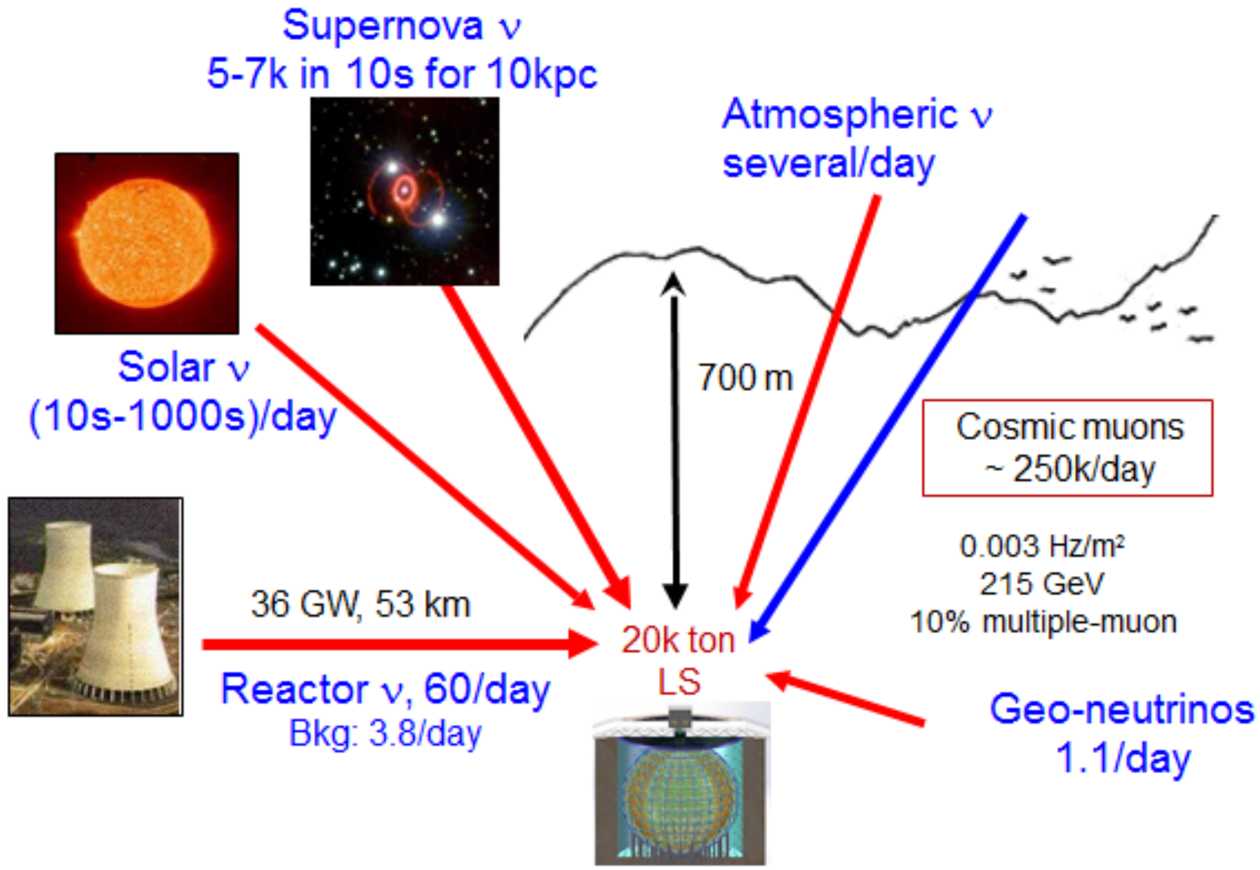
Armenia	Yerevan Physics Institute
Belgium	Université libre de
Brazil	PUC
Brazil	UEL
Chile	PCUC
Chile	UTFSM
China	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
China	CIAE
China	CUG
China	DGUT
China	ECUST
China	ECUT
China	Guangxi U.
China	Harbin Institute of
China	IGG
China	IGGCAS
China	IHEP
China	IMP-CAS
China	Jilin U.
China	Jinan U.
China	Nanjing U.
China	Nankai U.
China	NCEPU
China	NUDT
China	Peking U.
China	Shandong U.
China	Shanghai JT U.
China	SYSU
China	Tsinghua U.
China	UCAS
China	USTC
China	U. of South China
China	Wu Yi U.
China	Wuhan U.
China	Xi'an JT U.
China	Xiamen University
China	Zhengzhou U.
Czech	Charles U.
Finland	University of Oulu
France	APC Paris
France	CENBG
France	CPPM Marseille
France	IPHC Strasbourg
France	Subatech Nantes
German	ZEA FZ Julich
German	RWTH Aachen U.
German	TUM
German	U. Hamburg
German	IKP FZ Jülich
German	U. Mainz
German	U. Tuebingen
Italy	INFN Catania
Italy	INFN di Frascati
Italy	INFN-Ferrara
Italy	INFN-Milano
Italy	INFN-Milano Bicocca
Italy	INFN-Padova
Italy	INFN-Perugia
Italy	INFN-Roma 3
Latvia	IECS
Pakistan	PINSTECH (PAEC)
Russia	INR Moscow
Russia	JINR
Russia	MSU
Slovakia	FMPICU
Taiwan	National Chiao-Tung U.
Taiwan	National Taiwan U.
Taiwan	National United U.
Thailand	NARIT
Thailand	PPRLCU
Thailand	SUT
USA	UMD1
USA	UMD2
USA	UCI

Collaboration established on July 2014

Now 77 institutions ~600 collaborators



- Location: Kaiping, Jiangmen city, Guangdong province, China
- Optimized for determining νMO
- Expect to start data taking on 2021



- Large mass (20 kt)
- Good *E* resolution (3%)
- Rich physics potentials

Outline

- JUNO overview
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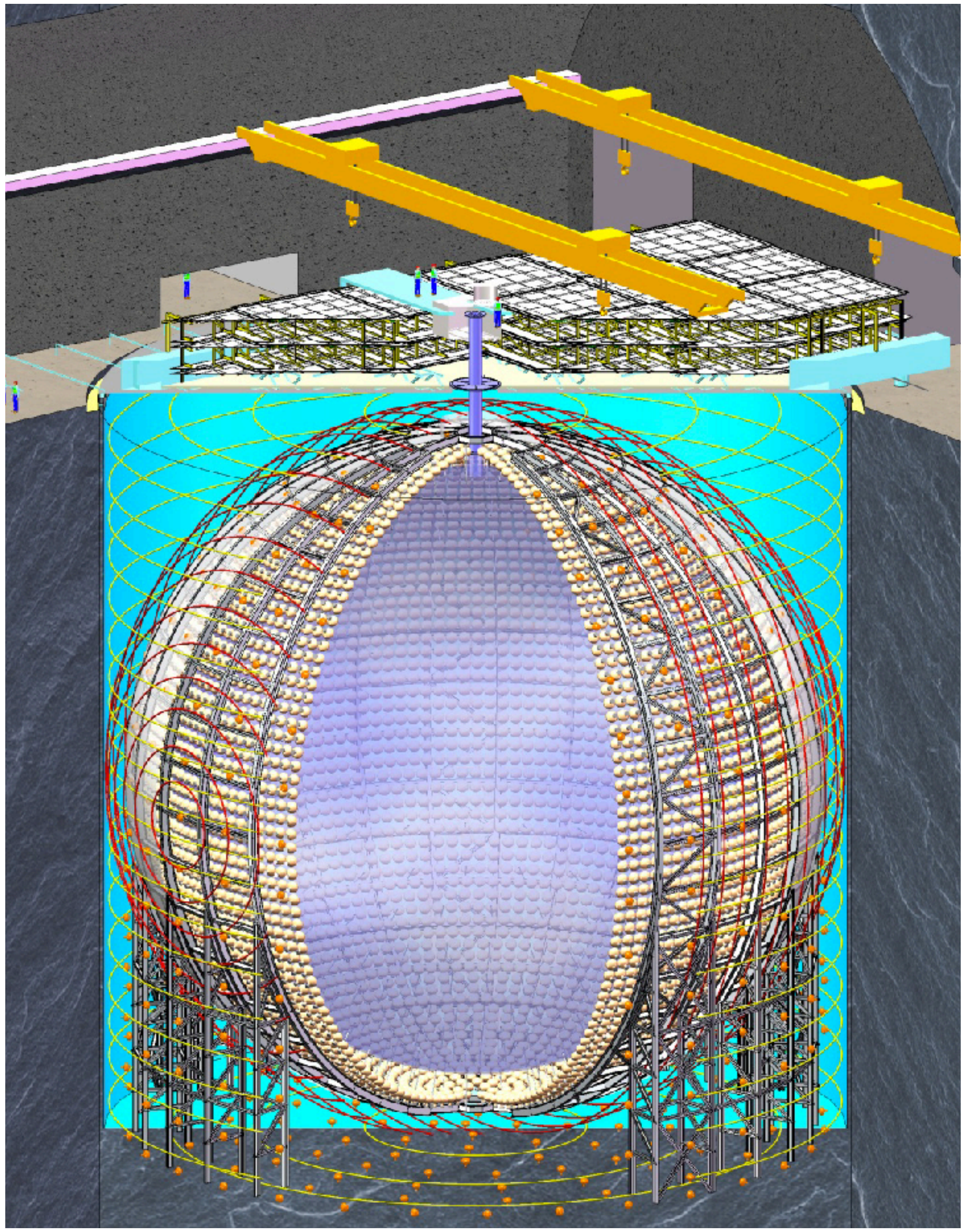
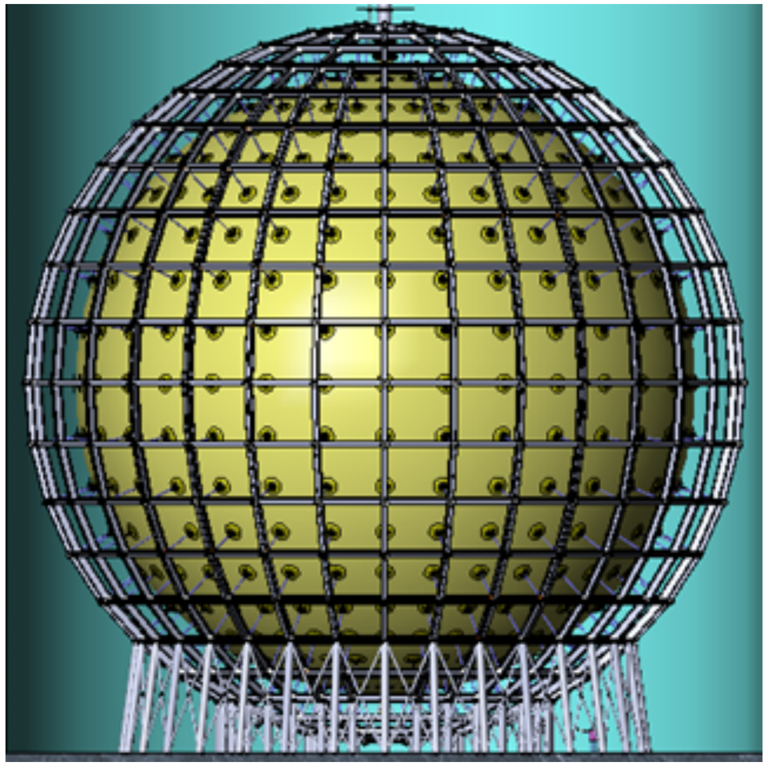
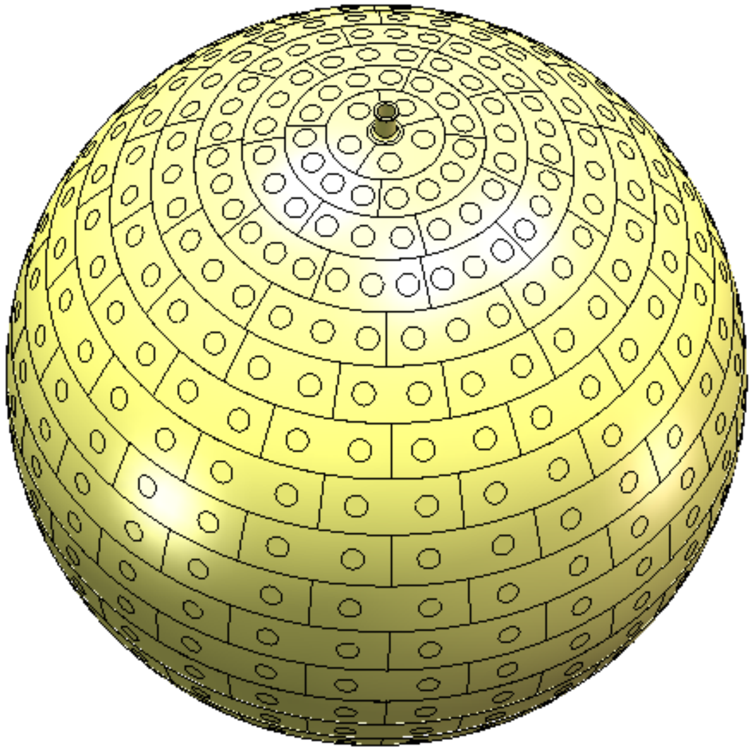
- **Center Detector**
  - Acrylic sphere containing **L**iquid **S**cintillator(LS)
  - PMT in water (18k 20” + 25k 3”)
  - 20 kt LS + 78% photocathode coverage
- **Veto Detector (μ tagger)**
  - Water Cherenkov detector
  - Top tracker
  - For μ tagging and track reconstruction
- **Calibration System**
  - 4 complimentary sub-system
  - Covering various particle type, full energy range and position



Center Detector

- Liquid scintillator based calorimeter
  - Req.: **3% resolution** & **<1% NL precision**
- **SS** supporting **PMTs** + **Acrylic Sphere**(AS)
  - Outside AS: water (shielding PMT/SS γs)
  - Inside AS: LS (scintillation matter)
- Scintillation **photon** detector:
  - 18k 20” PMTs + 25k 3” PMTs
- Electronics:
  - **1 GHz, 14 bit**, 1~4000 p.e. dynamic range





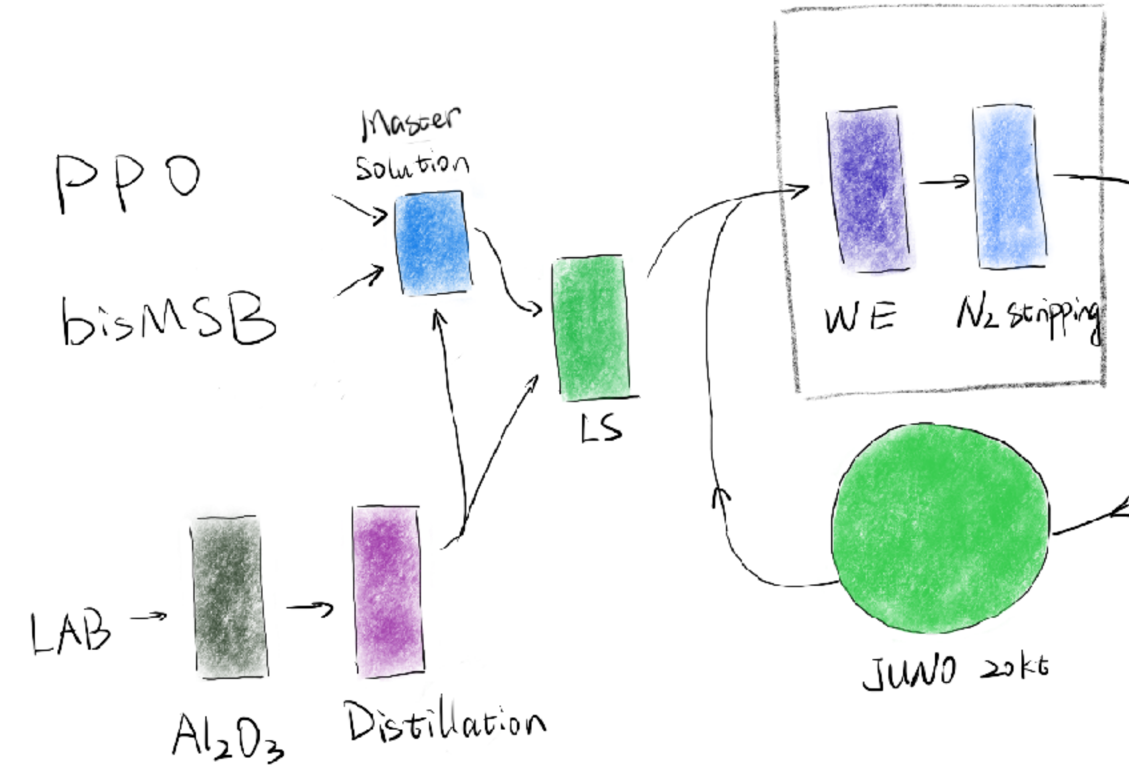
More details see Yuekun’s talk:

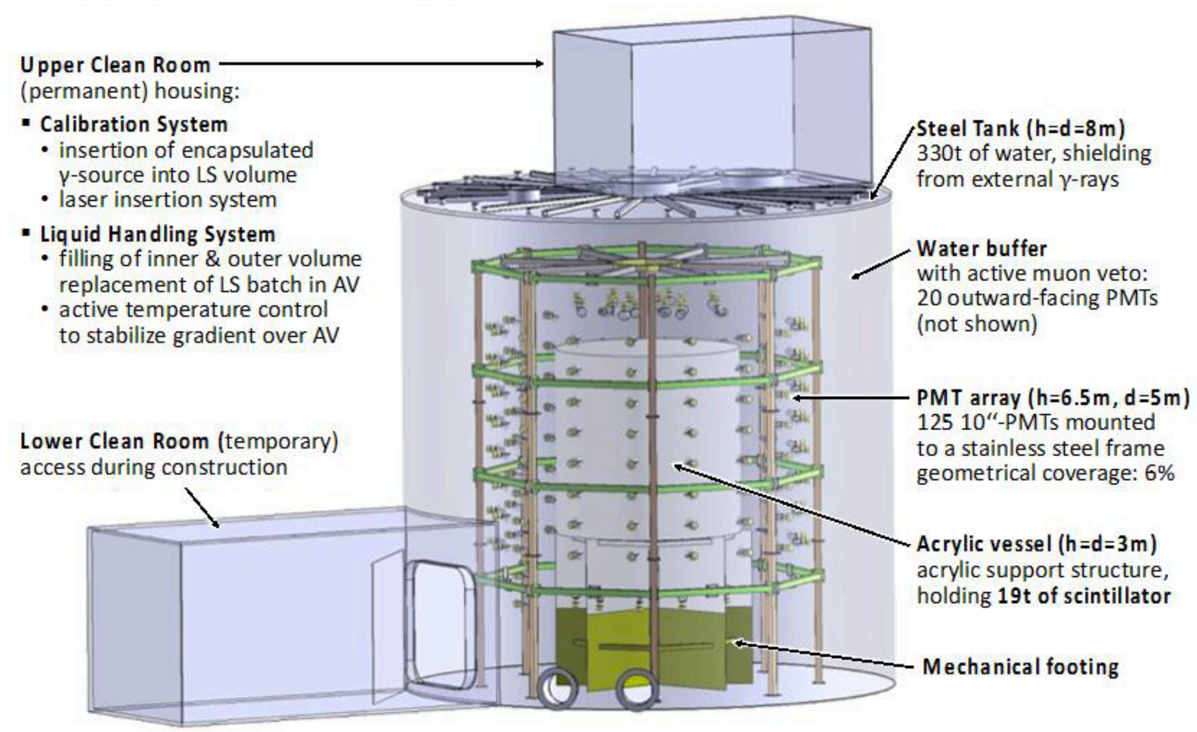
177. The design and research progresses of the Central Detector in JUNO
Prof. Yuekun Heng (IHEP)
13/08/2018, 15:30
WG1 Neutrino oscillatio...

Liquid scintillator

- LAB + 2.5 g/L PPO + **1~3** mg/L bisMSB
- Need good E resolution -> high LY
  - A.L.(LAB)>25 m @ 430 nm

    (measured with long tube)
- Need good radio-purity -> WE, stripping
  - **Prototype** of all plants** **tested at Dayabay AD1** (20t), Result promising.
    - WE* ε ~80%, stripping ε ~96%
- **Monitor LS purity** level quickly
  - **OSIRIS** conceptual design finished
  - 19t LS + 125 10” PMT
  - ^{238}U sensitive: better than 10^{-16} g/g (solar req.) in 24 hours





*WE: Water Extraction
**except PPO mater solution water extraction plant

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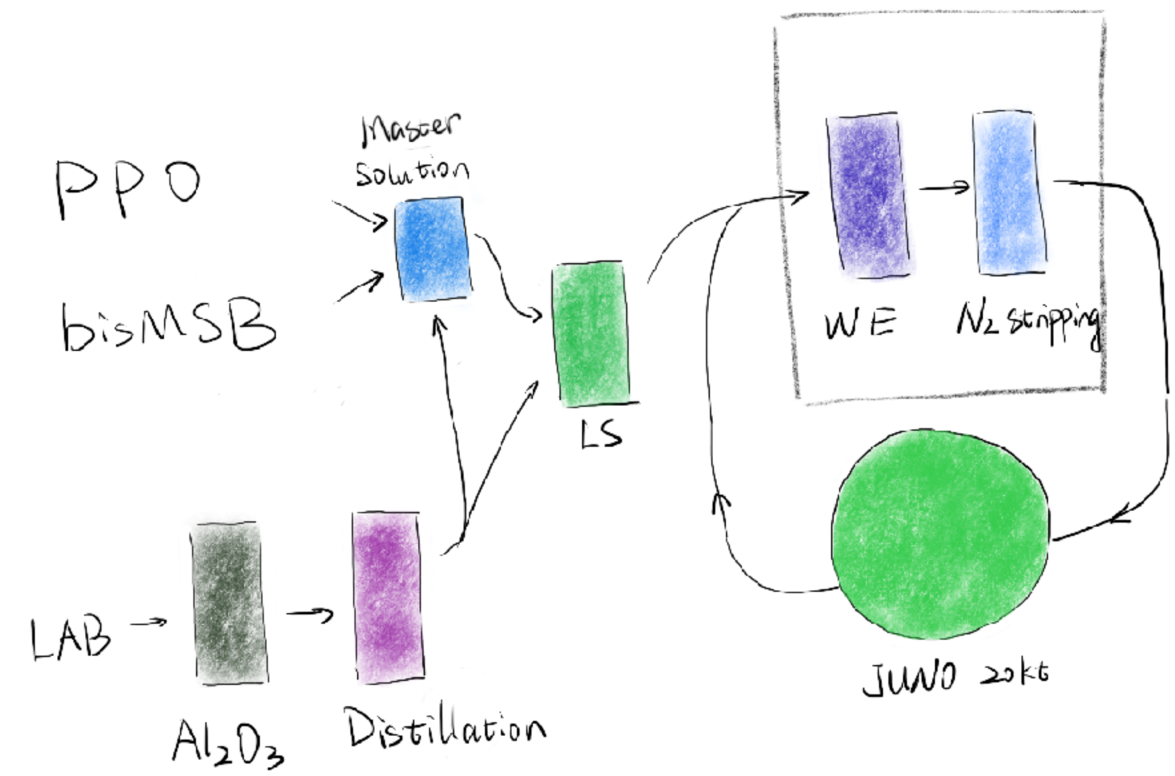
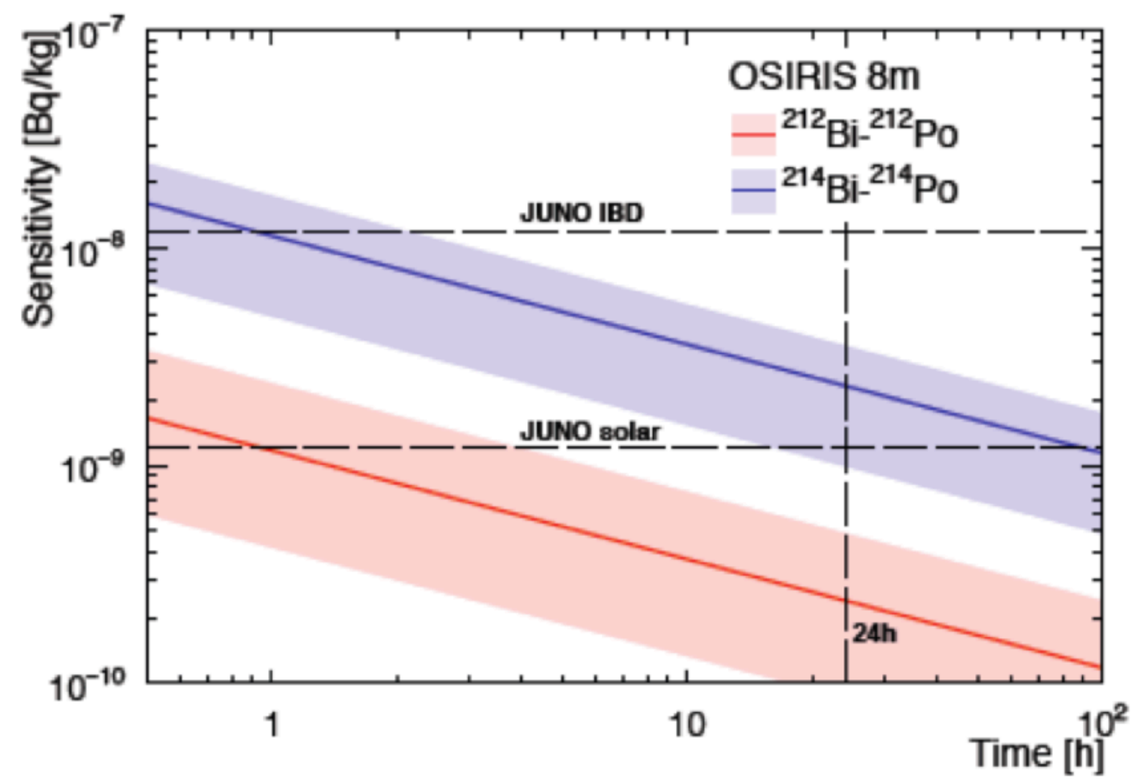


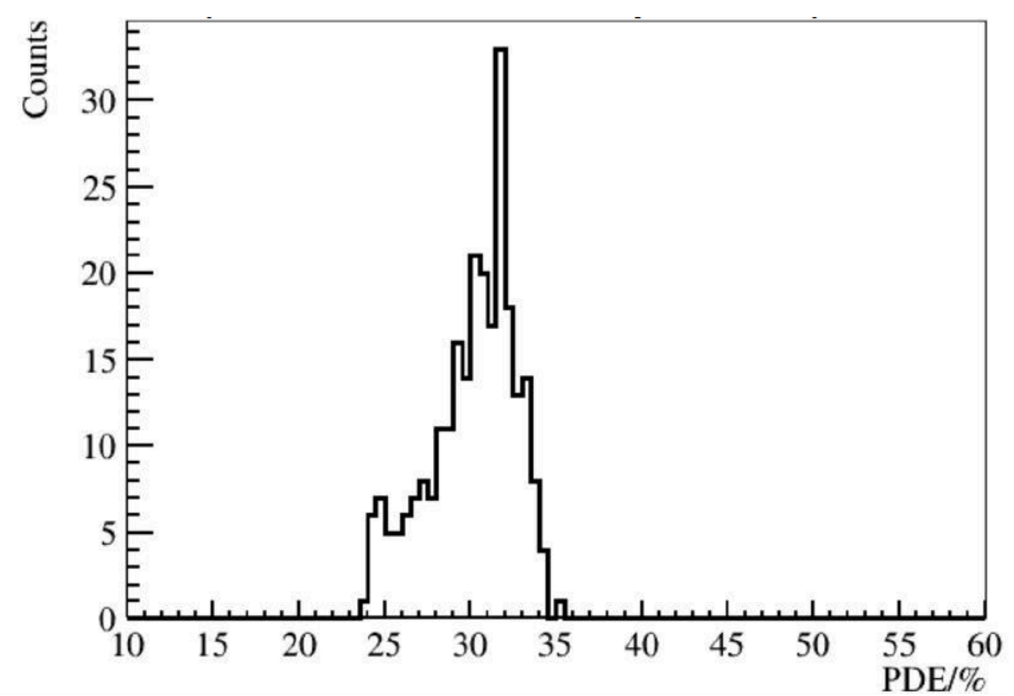


*WE: Water Extraction
**except PPO mater solution water extraction plant

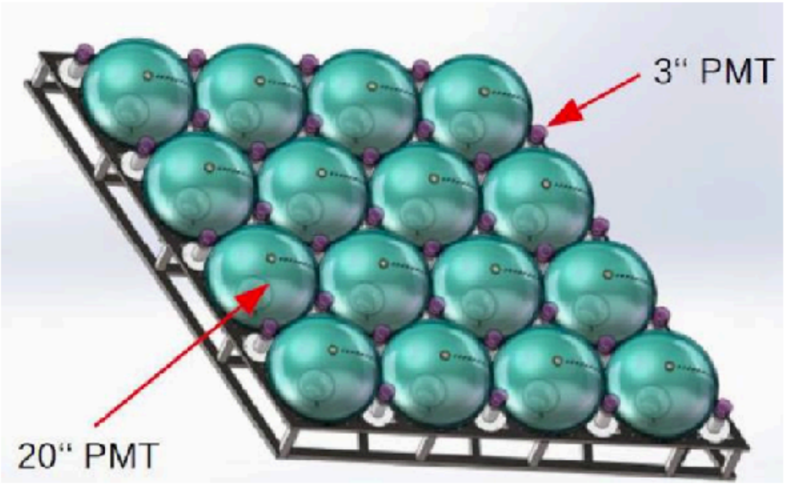
- **15 k MCP-PMT** from NNVT*
- **5k dynode PMT** from Hamamatsu
- ~10 k delivered, >5k tested
- New HQE MCP-PMT this year: **another 10% improvement** in PDE (27%->30%)

Characteristics	unit	MCP-PMT (NNVT)	R12860 (Hamamatsu)
Detection Efficiency (QE*CE)	%	27%	27%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	R~2, F~12	R~5,F~9
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	1, <2	10, < 15
Radioactivity of glass	ppb	238U:50 232Th:50 40K: 20	238U:400 232Th:400 40K: 40

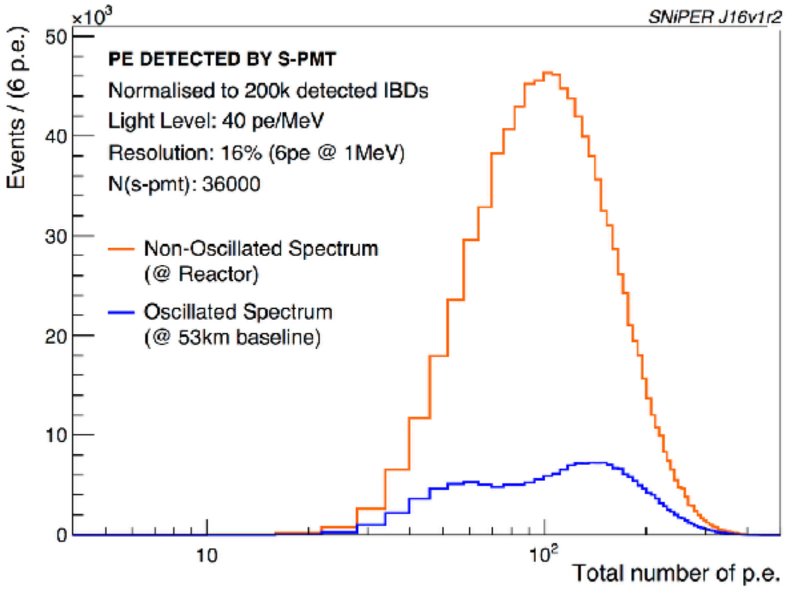
PDE of newly arrived MCP-PMTs



3" PMTs



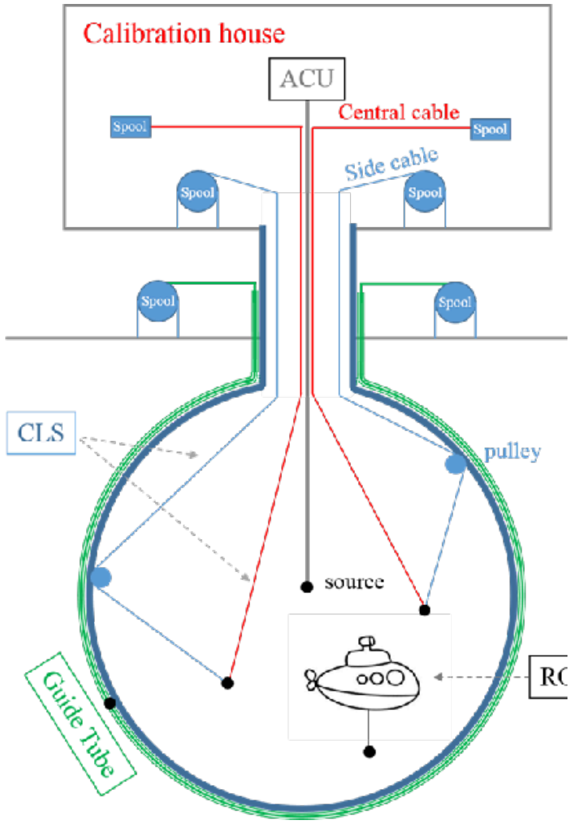
- Why 3" PMTs?
  - Always **photon counting**
    - Calibrate NL of charge reconstruction
    - Reduce non-stochastic resolution term
  - **Increased dynamic range**, helps with large signals (shower μ and thus $^{12}B/^{9}Li/^{8}He$ vetoing)
  - **Similar precision** on $\sin^2\theta_{12}$ Δm_{12}^2 to 20" PMT
  - **Supernova readout complementary**: ensure unbiased energy and rate measurement
- **25k PMTs** contracted to HZC,6k produced, 6k tested. **TTS improved** (5->3.5 ns FWHM) after update in HV divider

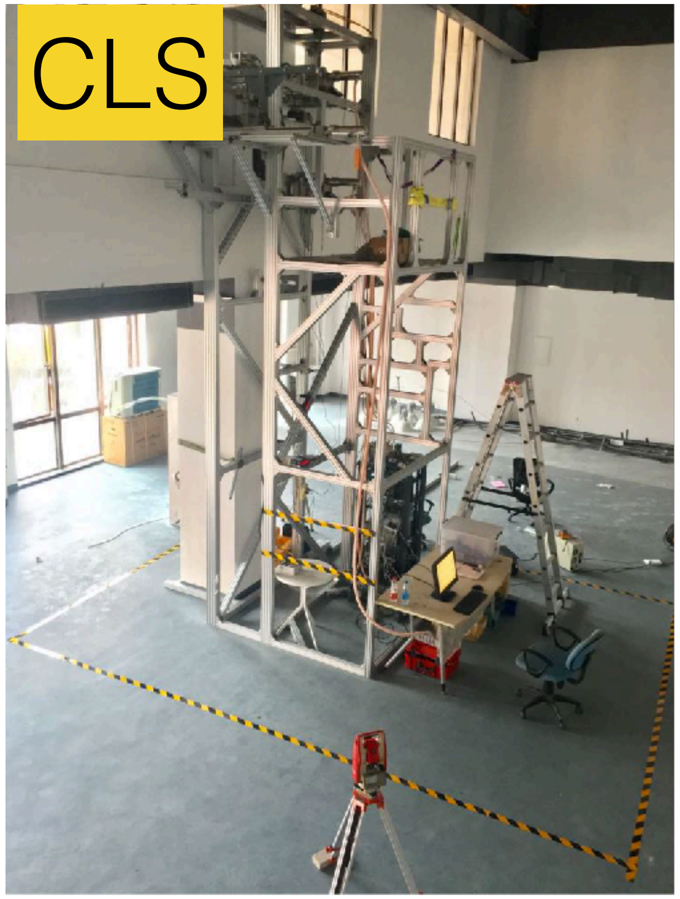


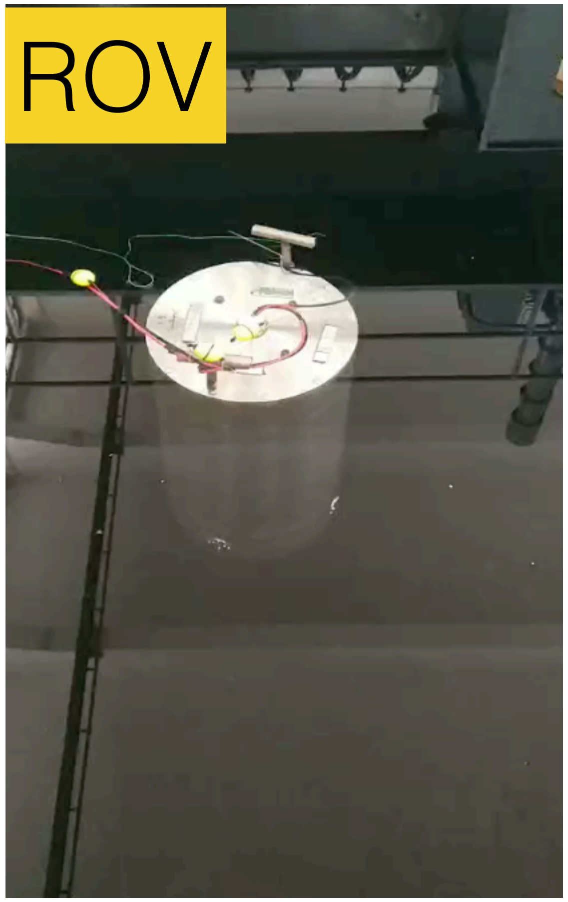
QE 25% , P/V 3.0
SPE resolution 33%
DN 500 Hz,
σTTS **1.5 ns**

Calibration

- 4 complementary systems
  - 1D: ACU (z-axis, weekly)
  - 2D: Cable Loop System + Guid Tube (θ-ϕ)
  - 3D ROV (r-θ-ϕ)
- Full volume positioning, all in good shape

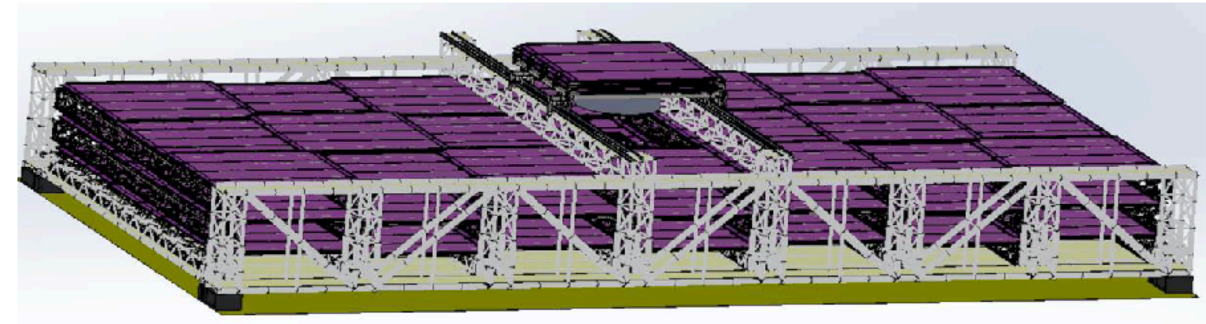


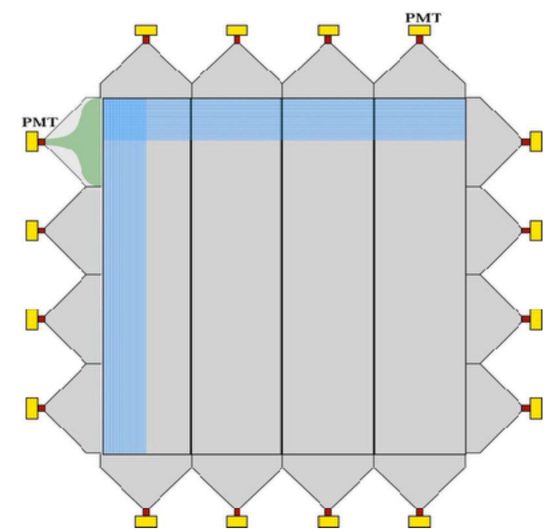


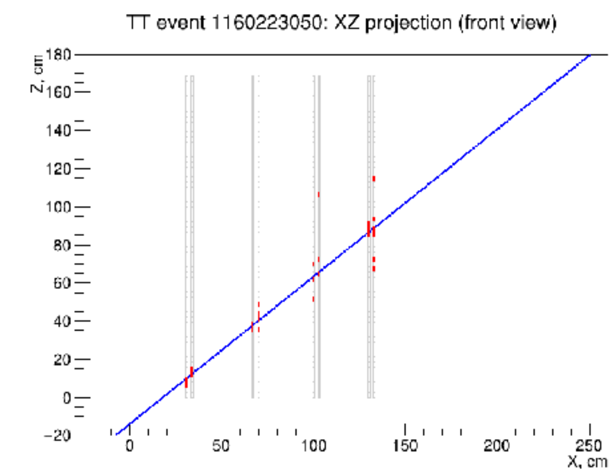


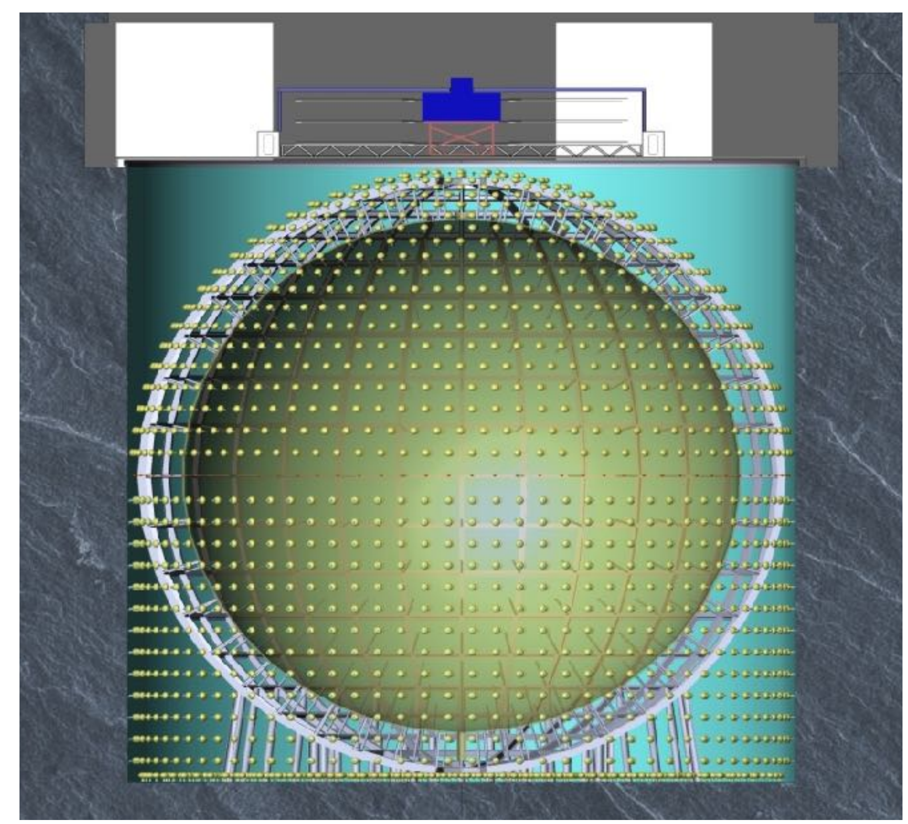
Veto detector

- **Top tracker**: plastic scintillator
  - Precise muon tracking
  - Cover half of the top area
  - x,y readout, 3 layers1.7 m
  - No significant aging observed!
- **Water pool Cherenkov det.**
  - 35 kt ultra-pure water
  - ~2k 20” MCP PMT
  - μ track reconstruction; shield γ from rocks and fast neutrons





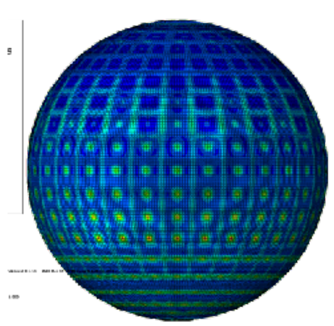




Milestone & schedule

2014:

- International collaboration established
- Start civil construction



2015:

- PMT production line setup
- CD parts R&D

2016:

- Start PMT production
- Start CD parts production

2017:

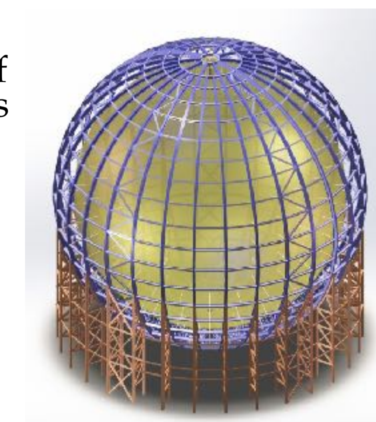
- Start PMT testing
- TT arrived

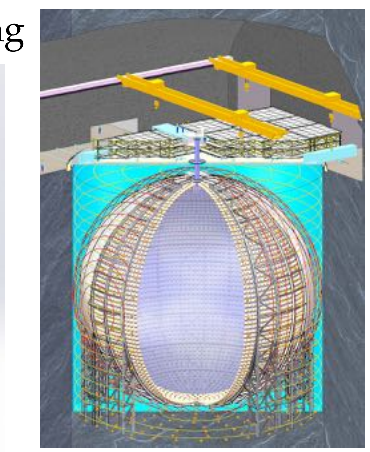
2018:

- PMT potting
- starts Delivery of surface buildings
- Start production of acrylic sphere

2019-2020:

- Electronics production starts
- Civil work and lab preparation Completed
- Detector constructing





2021:

- Detector ready for Data taking!

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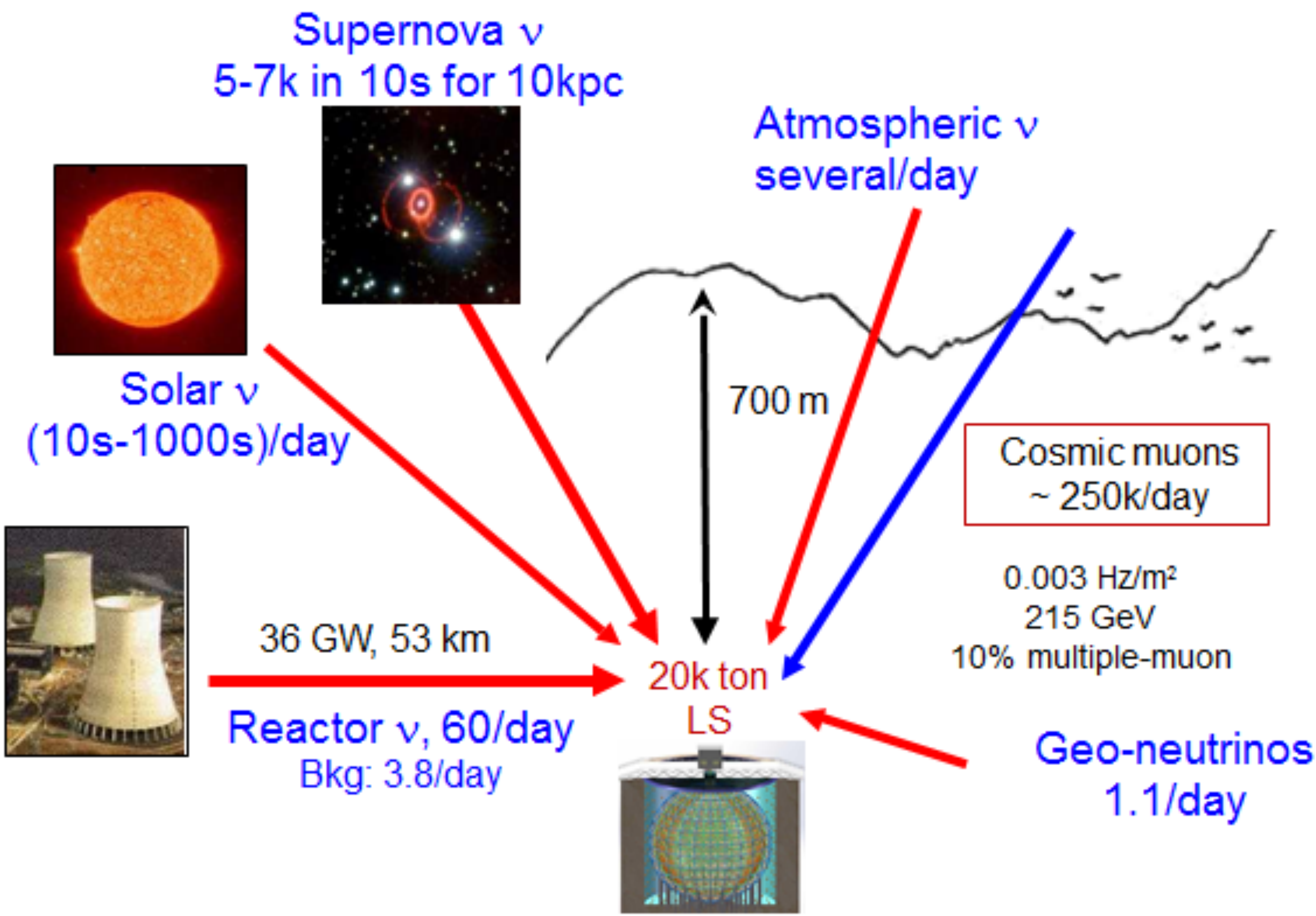

Supernova ν
5-7k in 10s for 10kpc
Atmospheric ν
several/day
Solar ν
(10s-1000s)/day
700 m
Cosmic muons
~ 250k/day
0.003 Hz/m²
215 GeV
10% multiple-muon
36 GW, 53 km
20k ton
LS
Reactor ν, 60/day
Bkg: 3.8/day
Geo-neutrinos
1.1/day

Reactor ν: Neutrino mass ordering

- Medium baseline exp.
- Rely on Vac. Osc. pattern
- Key:
  - **3% resolution,**
  - **<1% NL accuracy**
  - **Good knowledge of reactor ν spectrum**
- Will be improved with constraint from acc. LBL ν on $\Delta m_{\mu\mu}^2$

$$|\Delta m^2_{ee}| - |\Delta m^2_{\mu\mu}| = \pm \Delta m^2_{21} \cdot (\cos(2\theta_{12}) - \sin(2\theta_{12})\sin(\theta_{13})\tan(\theta_{23})\cos(\delta))|$$

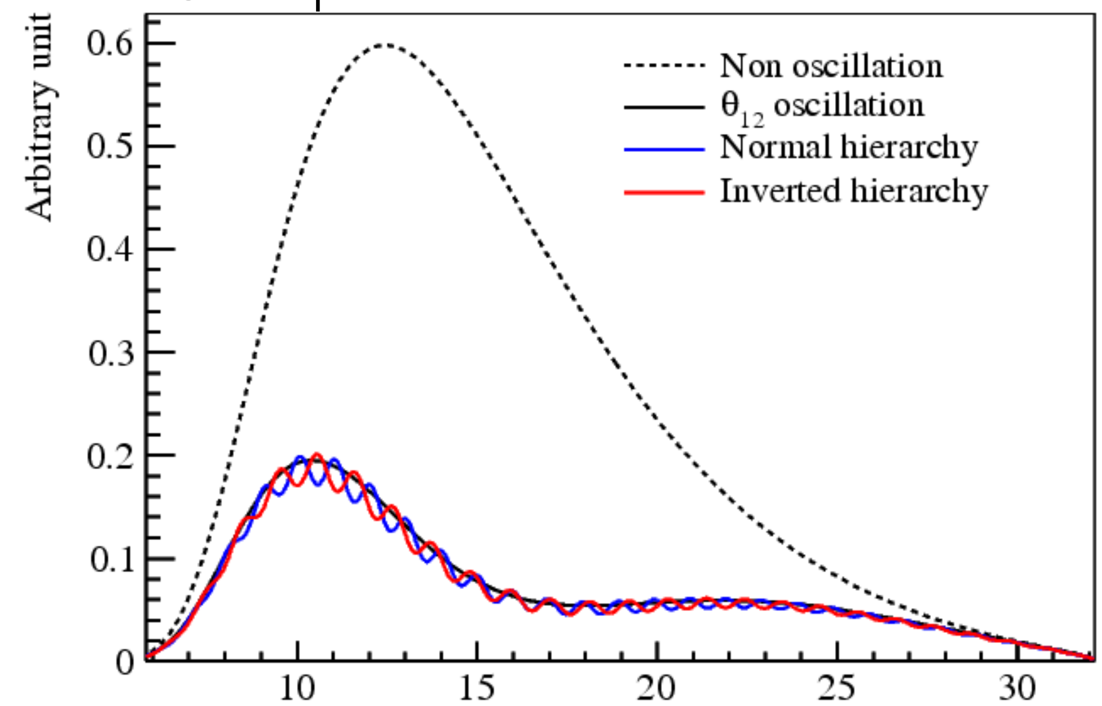
Sign defined by MH

See H. Nunokawa et al, Phys.Rev. D72 (2005) 013009

More details:

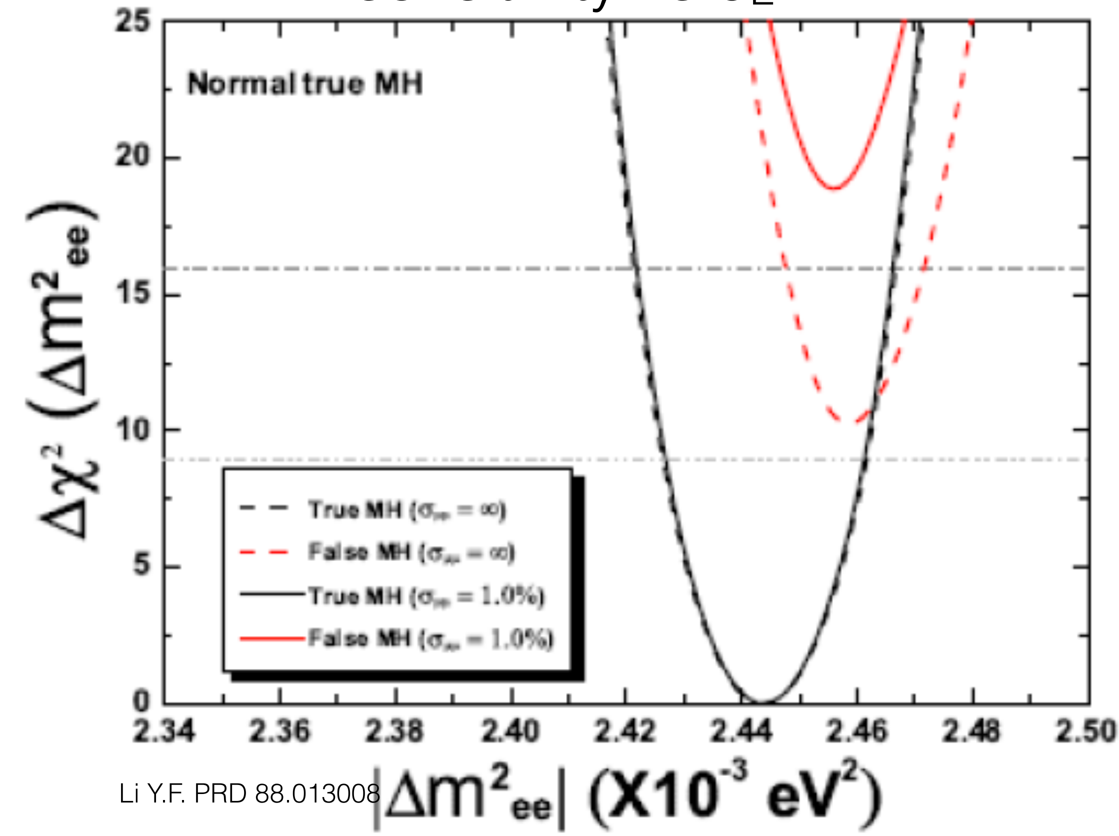
176. JUNO physics
Xuefeng Ding (Gran Sasso Science I...)
13/08/2018, 15:00
WG1 Neutrino oscillatio...

Vec. Osc. patter



Li Y.F. PRD 88.013008

sensitivity vs σ_E



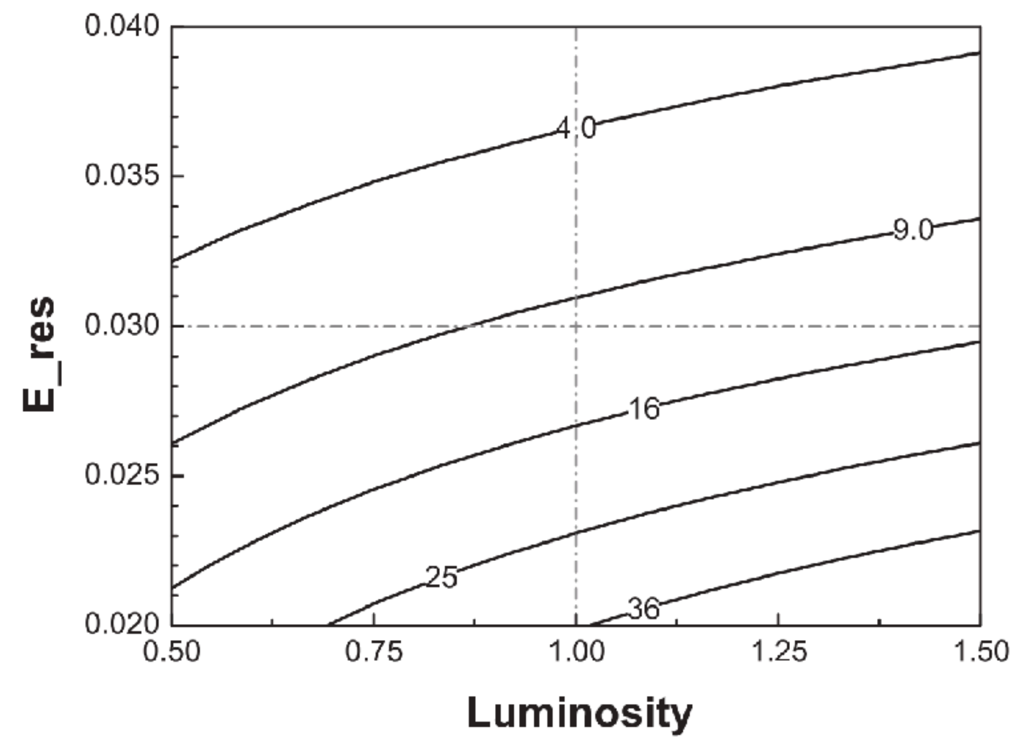
Li Y.F. PRD 88.013008

3% energy resolution

- Small σ_1
  - Transparent LS
  - high PDE PMTs
  - high coverage
- Small σ_2
  - Good energy resolution, small residual non-uniformity
  - Multivariate fit: fit E+xyz

$$\mathrm{Var}[E_{\mathrm{rec.}}] = \sigma_0^2 + \sigma_1^2 \cdot \mu_{E_{\mathrm{rec.}}} + \sigma_2^2 \cdot \mu_{E_{\mathrm{rec.}}}^2$$

- σ_0: dark noise;
- σ_1: single p.e. charge resolution, light yield
- σ_2: history of dE/dx, quenching, residual non-uniformity

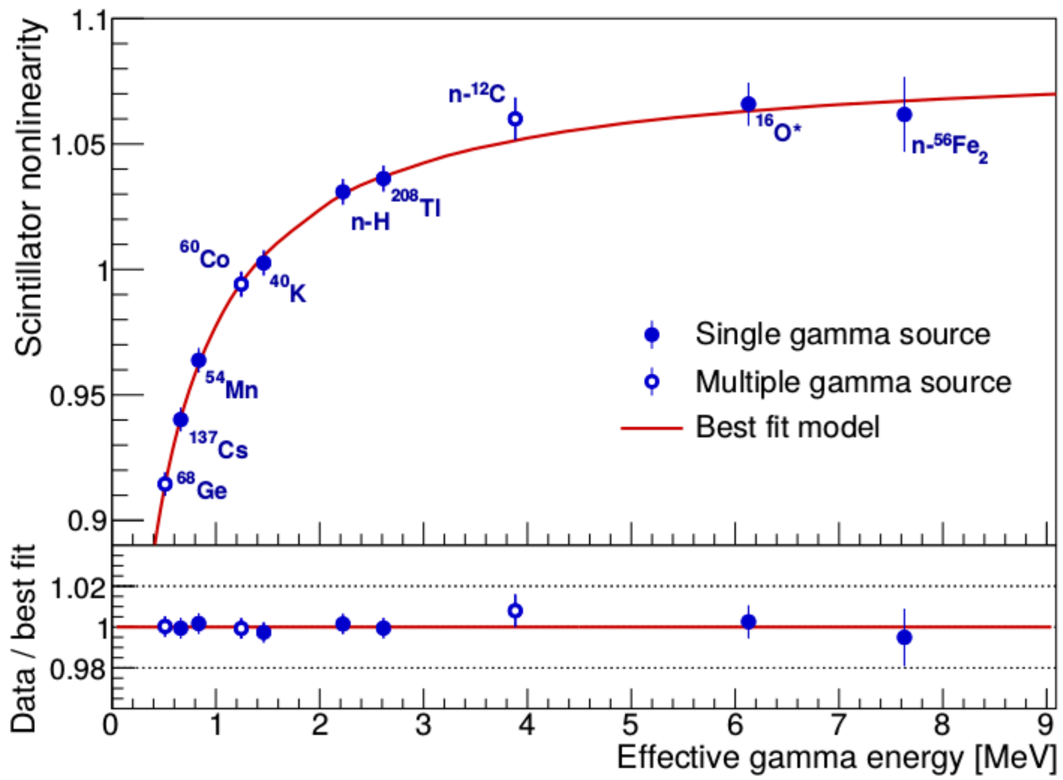


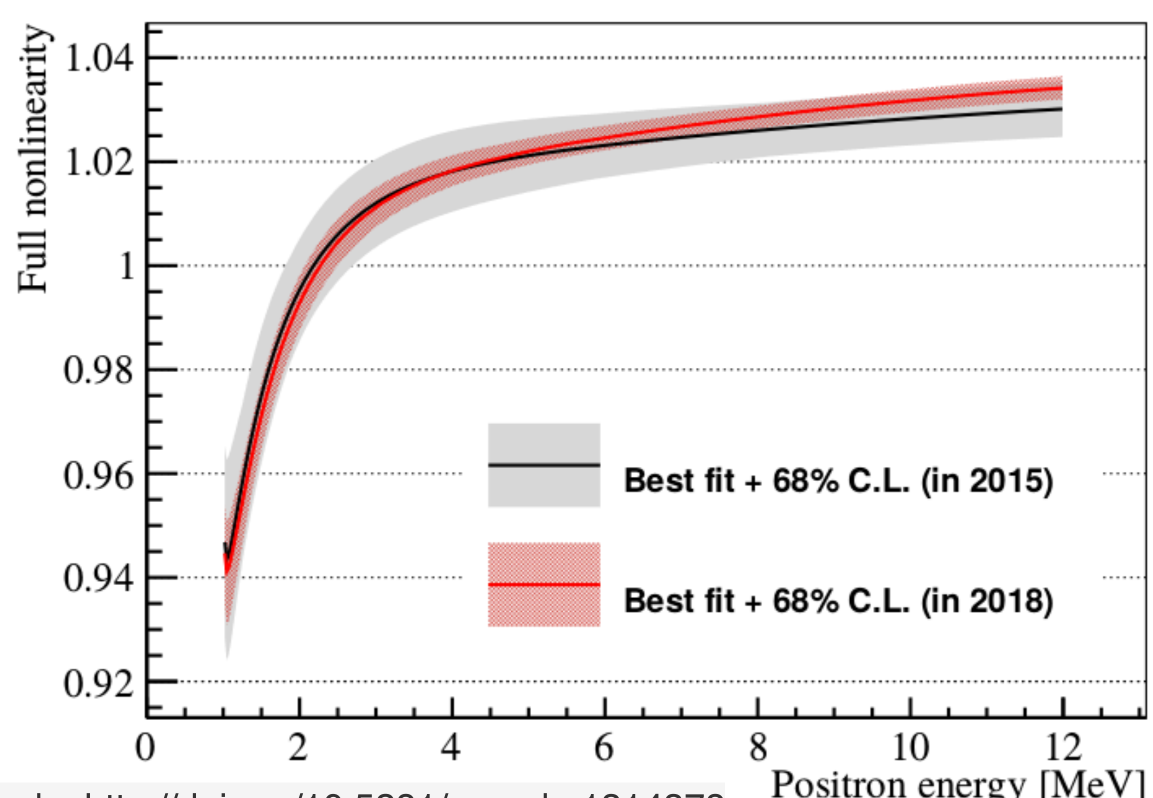
F. An et al., "Neutrino physics with JUNO," 2016 pp. 35

How to achieve <1% NL accuracy

- Answer: Meticulous calibration
  - Different sources, over whole energy range…
- Other experiments already achieved 1% accuracy
  - Daya Bay ~0.5%, Double Chooz 0.74%, Borexino <1% (at low energies), KamLAND 1.4%

DayaBay: achieved 0.5% NL accuracy (ESCAPE 2018)

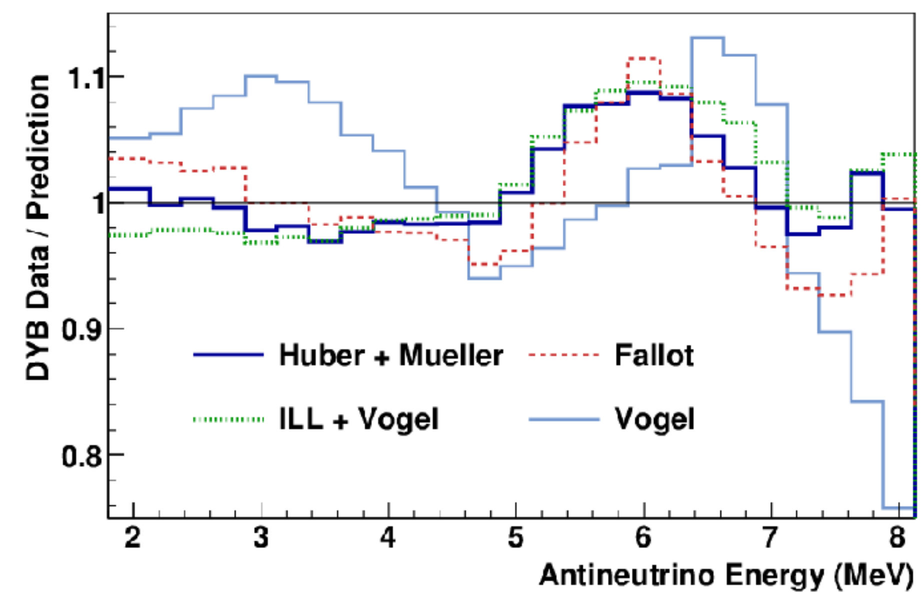




Yu, Zeyuan. (2018, June). Calibration and Energy Scale in Daya Bay. Zenodo. http://doi.org/10.5281/zenodo.1314378

Reactor anti-neutrino spectrum

- Currently the predicted antineutrino spectrum have **discrepancy** with respect to the observed antineutrino spectrum, also has unknown **uncertainty**
- A **high energy resolution** detector can precisely measure the antineutrino spectrum and provide **reference spectrum** for future experiments, e.g., JUNO.
  - Important for JUNO



By An F.P.

Zhan, Liang. (2018, June). Proposal of a Near Detector for JUNO Experiment. ESCAPE 2018

Contribution of shape uncertainty to ***ν*MO** sensitivity

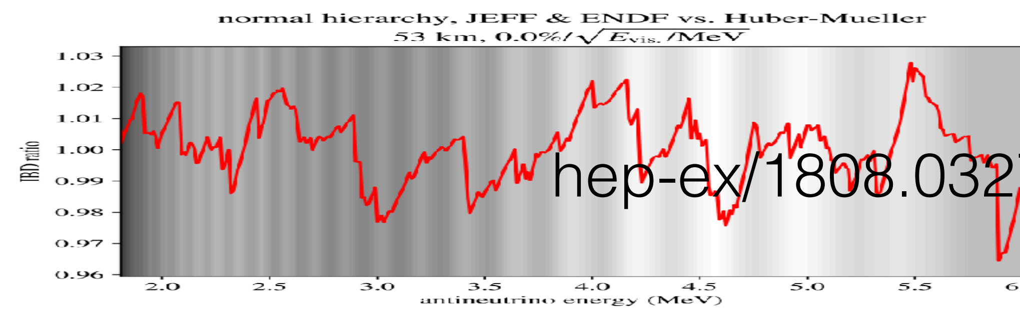
	Stat.	Shape
Size	52.5 km	1%
$\Delta\chi^2_{MH}$	+16	−1

F. An, "Neutrino physics with JUNO," 2016 pp. 35

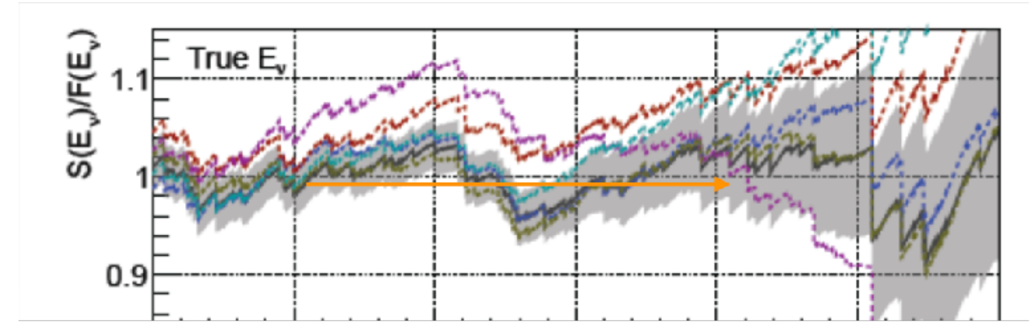
Fine structure of reactor ν spectrum

- **Known fine structure** does not hurt JUNO: Xin Qian took 6 spectra with fine local structure from Dan's ab initio calculation (PRL 114, 012502 (2015)), and fluctuate the spectra in JUNO sensitivity calculation => no major effect
- **Unknown fine structure** (infinite uncertainty) has larger impact (Huber)
  - Do we trust database?
  - Only rely on experiment data
    - infinite uncertainty below exp. E resolution
  - interesting topic: **size of binning**
- Measured spectrum from a high energy resolution **near detector** will constrain the fine structure.

Fine structure

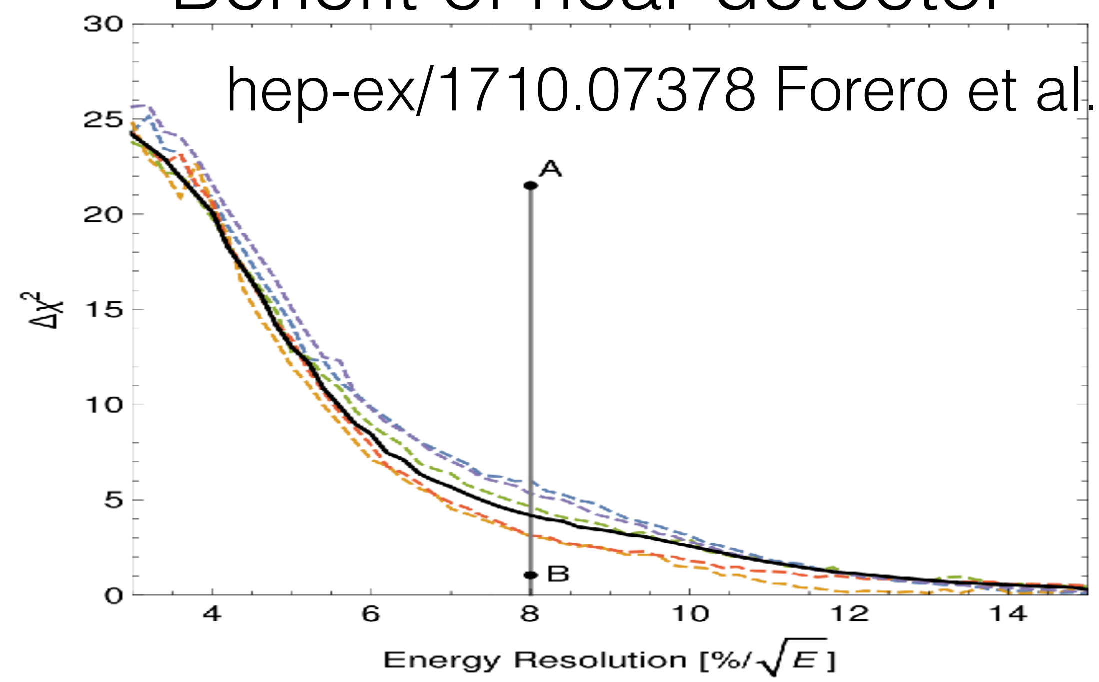


hep-ex/1808.03276



Phys.Rev.Lett. 114 (2015) no.1, 012502

Benefit of near detector

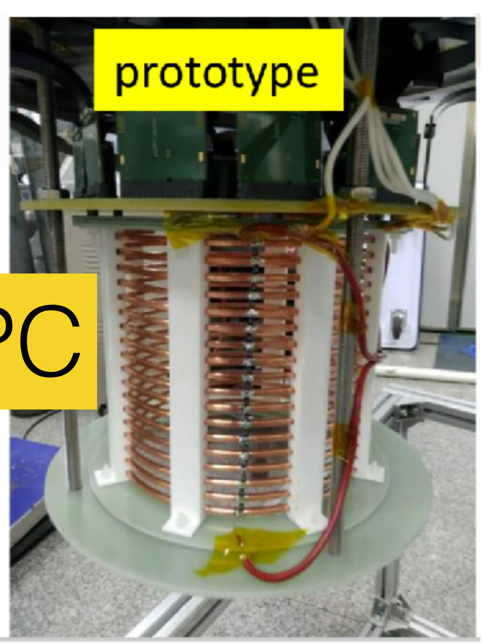


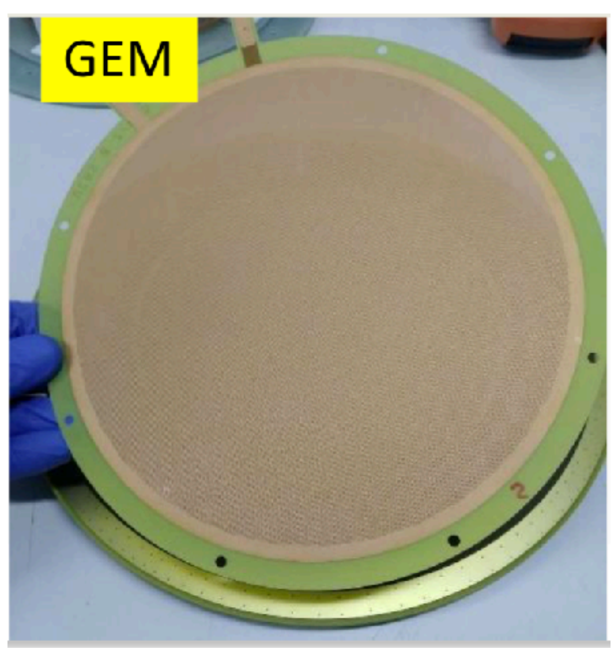
hep-ex/1710.07378 Forero et al.

Near Detector

- Has been investigating since approval of JUNO (2013)
- **gas TPC**
  - independent measurement. no scintillator NL problem
  - under design (~200 kg), prototype already constructed
- **High energy resolution liquid scintillator detector**
  - 1t Gd-LS (FV) 30~50 m baseline, (1~4)x10^6 IBD in 3 yrs
  - 1.7% at 1 MV: 10 m^2SiPM 50% PDE, operate at ~ -50 °C

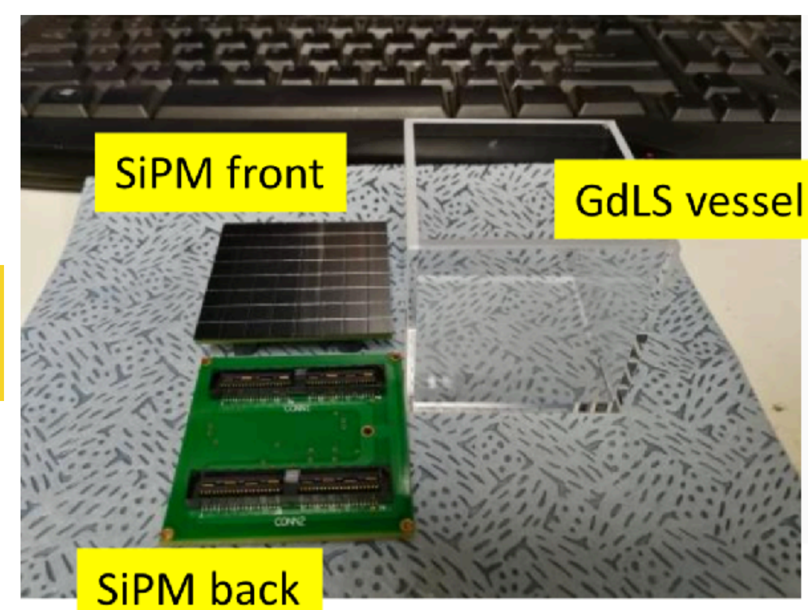
gasTPC





Yan WQ, The Reactor Neutrino Energy Spectrum Measurement with a High Pressure Gas TPC Detector, Neutrino 2018

LS+SiPMT



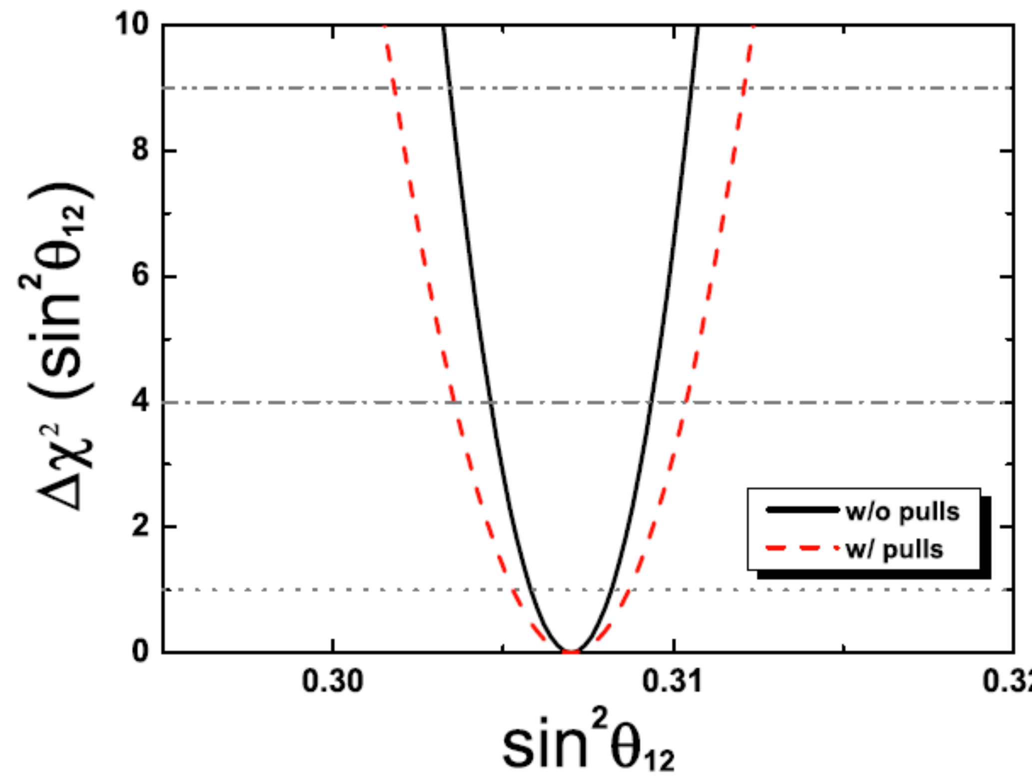
Zhan, Liang. (2018, June). Proposal of a Near Detector for JUNO Experiment. ESCAPE 2018

Precision oscillation par.

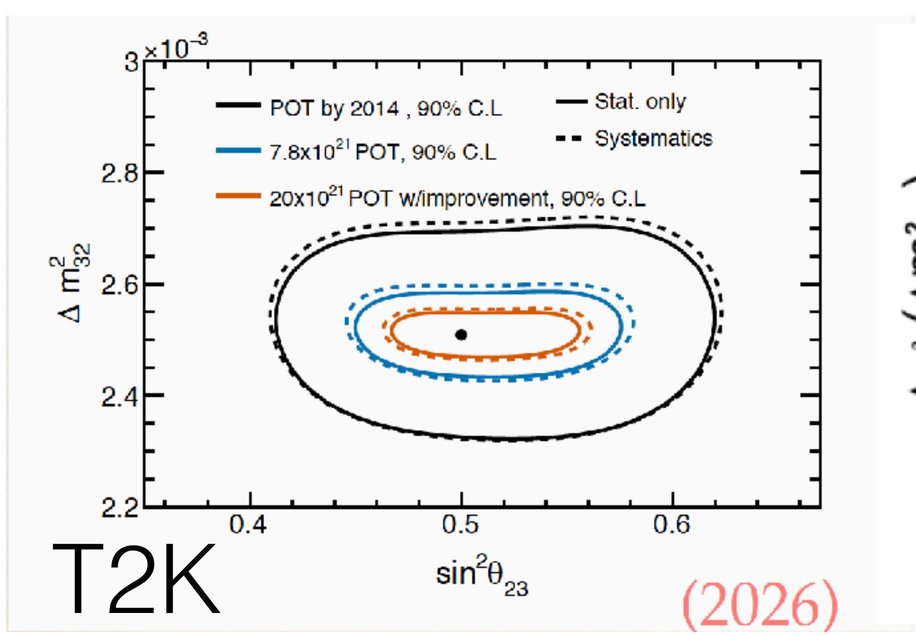
- Improve $\sin^2\theta_{12}$ to 0.7%

  (current 2.2%, mainly KL)
- Improve Δm^2_{21} to 0.6%

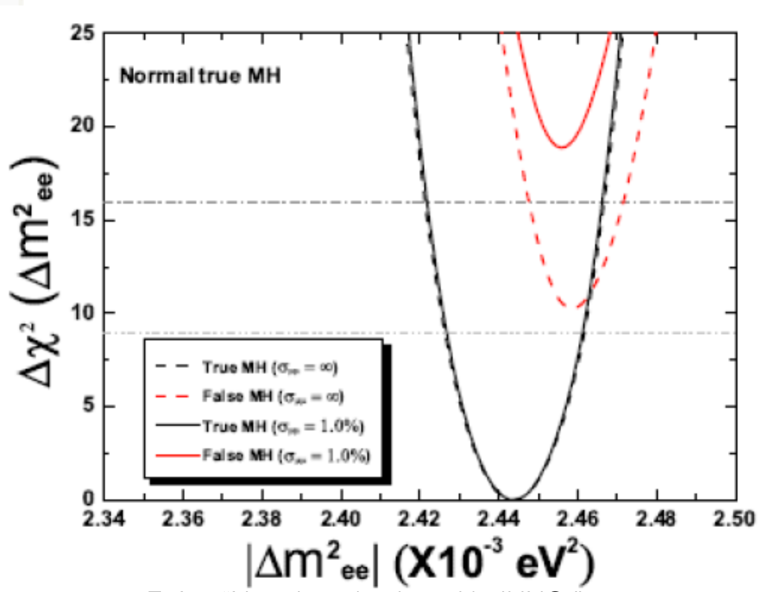
  (current 3.9%, mainly SNO)
- Improve $|\Delta m_{ee}^2|$ (current 1.2%)-> 0.4%
  - by 2026, T2K will reach $|\Delta m_{\mu\mu}^2|$ ~1%



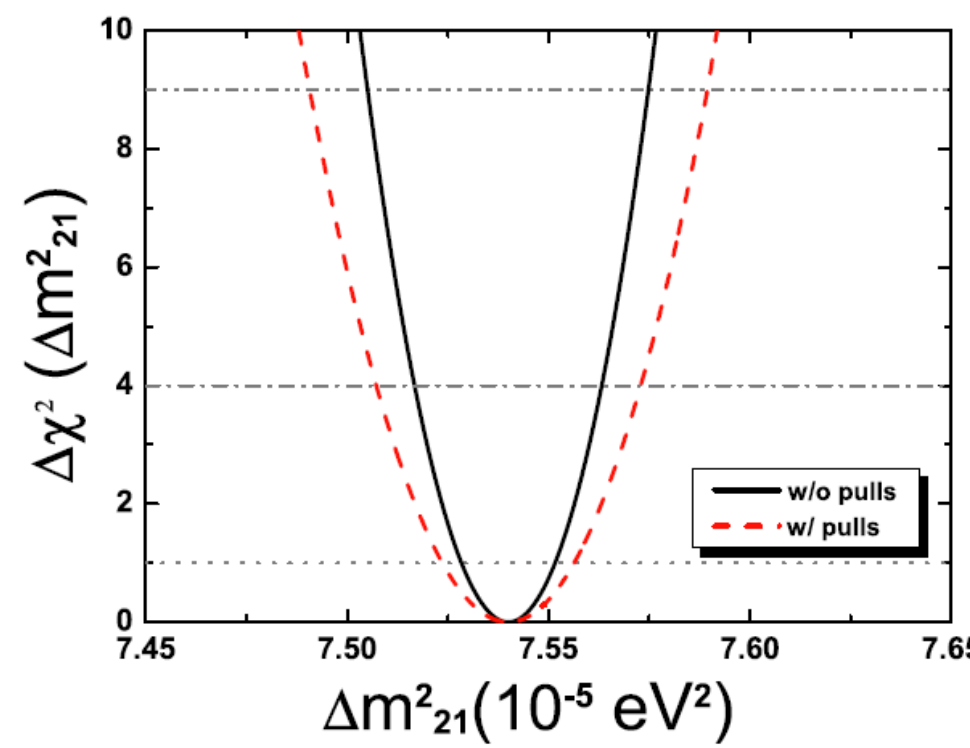
F. An, "Neutrino physics with JUNO," 2016



K. Abe et al., Proposal for an Extended Run of T2K to 20×10[21] POT, 1609.0411



F. An, "Neutrino physics with JUNO," 2016



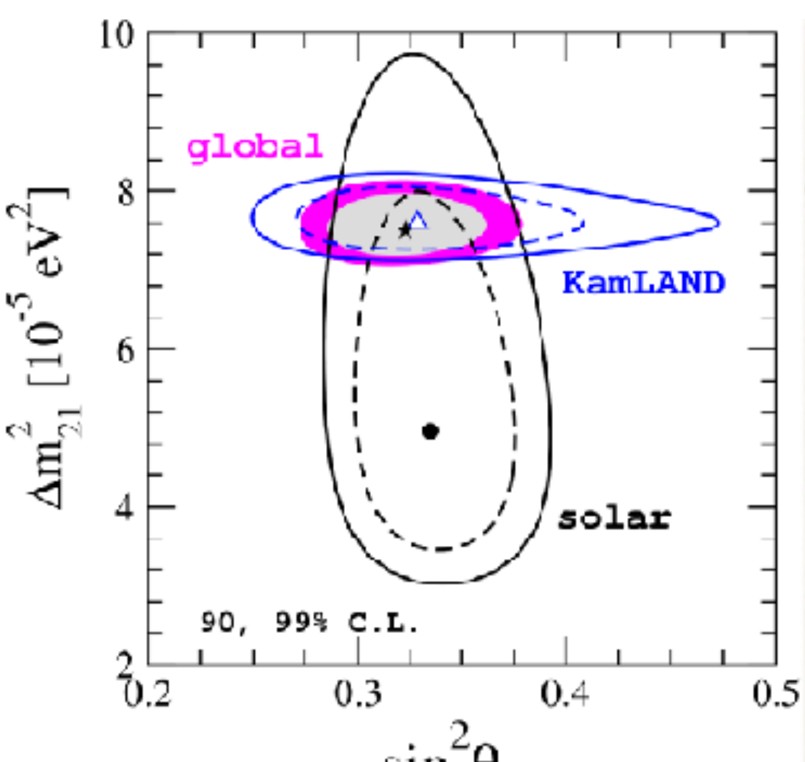
F. An, "Neutrino physics with JUNO," 2016

Solar neutrinos

- Promising WE eff. :good chance to have low LS purity
- **^{8}B: need to suppress cosmogenic ^{10}C to reach 2 MeV threshold**
  - If possible: first exp. in transition zone

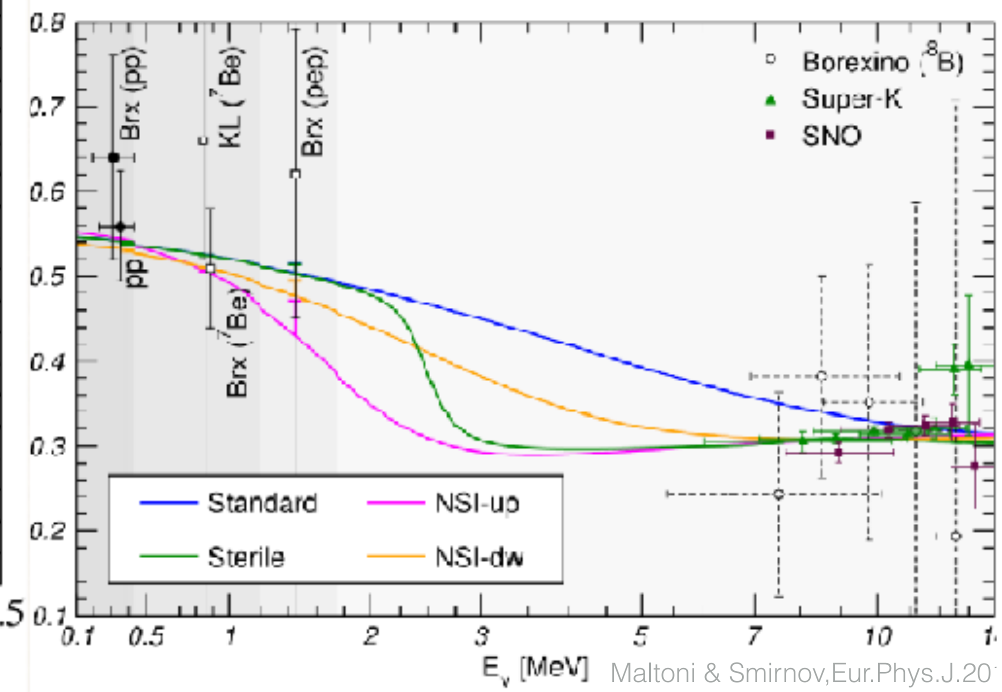
More details:

176. JUNO physics
Xuefeng Ding (Gran Sasso Science I...)
13/08/2018, 15:00
WG1 Neutrino oscillatio...

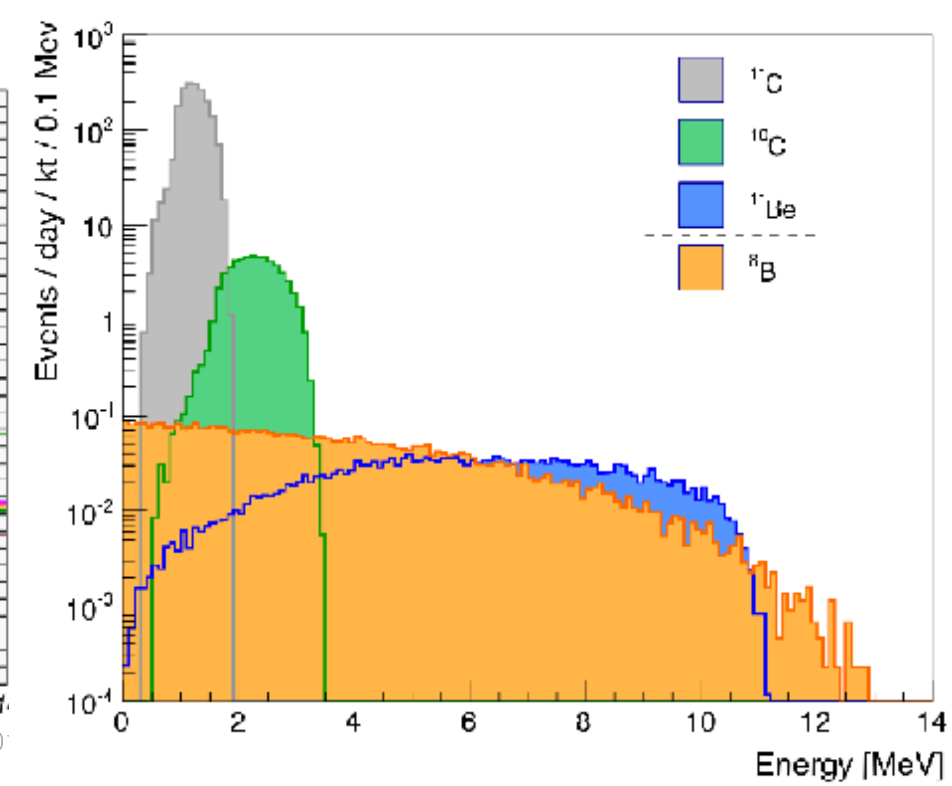


Mariam Tórtola, Neutrino 2018

Various MSW-LMA survival prob.



Maltoni & Smirnov,Eur.Phys.J.20



F. An, "Neutrino physics with JUNO," 2016

Other physics with JUNO

	KamLAND	Borexino	Daya Bay	JUNO
Mass [t]	~1000	~300	~170	20k
LY [p.e./MeV]	250	500	200	1200
E resolution	6%/√E	5%/√E	7.5%/√E	**3%/√E**
E NL accuracy	1.4%	<1%	0.5%	**<1%**

Rich physics program:

- supernova ν
- atm. ν
- Diffusive supernova ν
- geo ν

- proton decay
- Indirect Dark Matter search
- other exotic searches

Outline

- JUNO overview
- JUNO detectors
- JUNO physics goals and potentials
- Conclusion

Conclusion

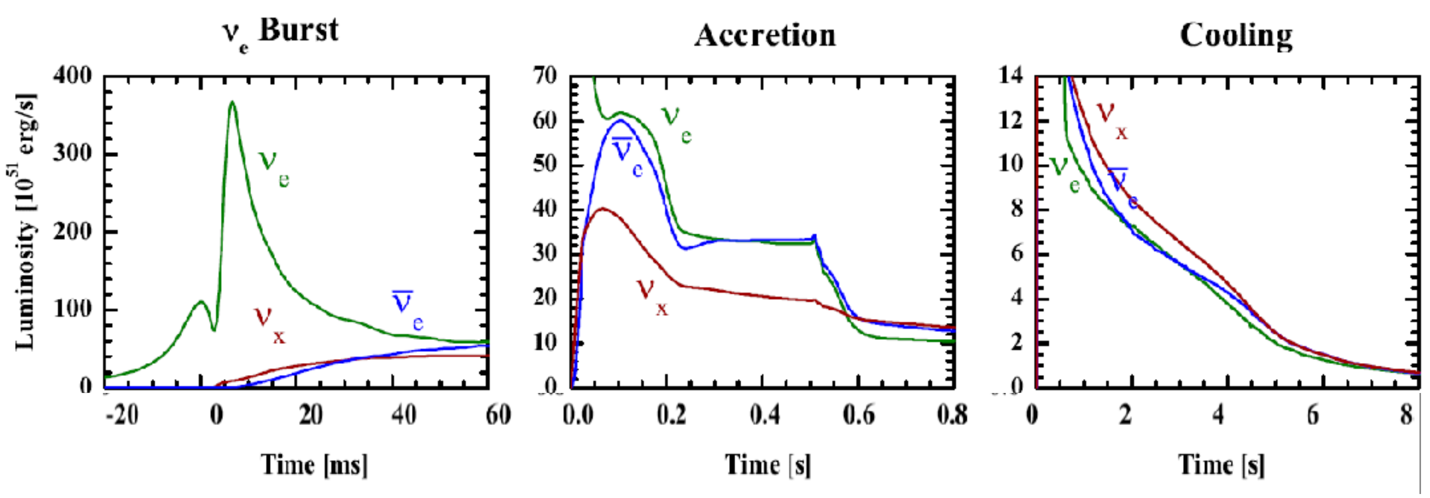
- JUNO detector provides vast opportunities with its **large mass** and **good energy resolution**
- Neutrino Mass Ordering sensitivity in 6 yrs:
  - >3σ. can **reach >4σ with 1% constraint on $\Delta m_{\mu\mu}^2$**
  - Strong synergy with long baseline ν experiment.
- **Sub-percent measurement** of $\sin^2\theta_{12}$ Δm_{12}^2 and Δm_{ee}^2
  - Complementary to long baseline experiment
- **Might reach MSW transition zone**, depending on ^{10}C suppression eff.
- Rich physics programs
- Good project progress
- Expected data taking starting time: **2021**

Backup

- **Advantage**
  - Large statistics
  - ^{12}C related channel
  - Good E resolution
- **Physics potential**
  - test SN model
  - Information about MO
  - Multi-messanger astronomy

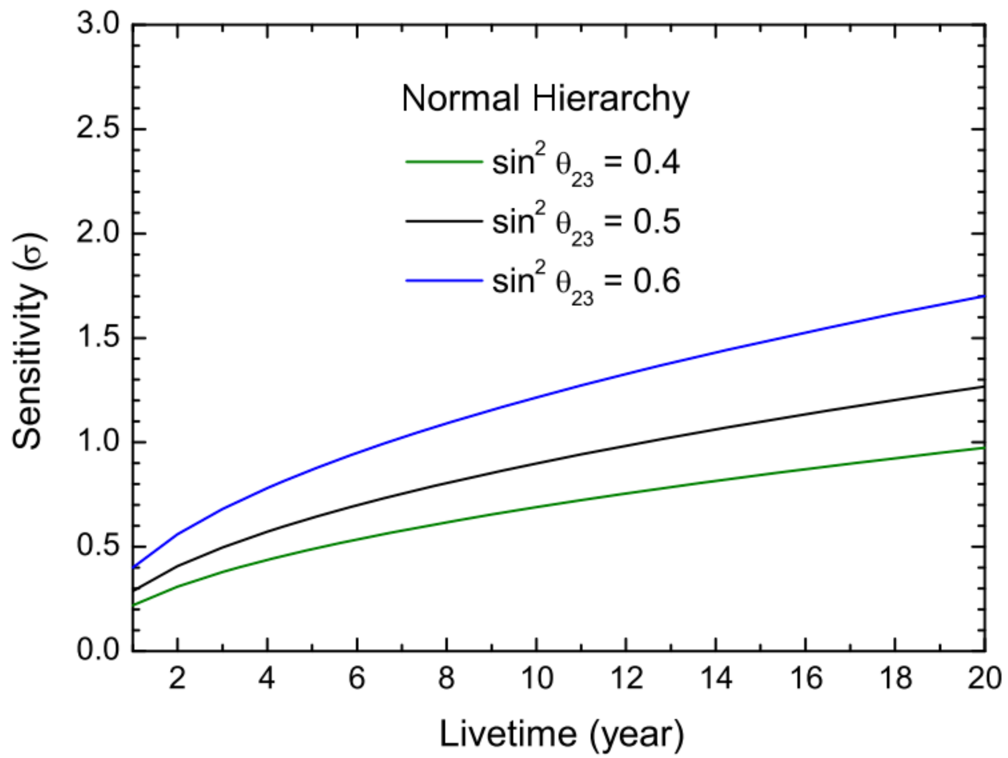
Channel	Type	Events for different $\langle E_\nu \rangle$ values		
		12 MeV	14 MeV	16 MeV
$\overline{\nu}_e + p \to e^+ + n$	CC	4.3×10^3	5.0×10^3	5.7×10^3
$\nu + p \to \nu + p$	NC	0.6×10^3	1.2×10^3	2.0×10^3
$\nu + e \to \nu + e$	ES	3.6×10^2	3.6×10^2	3.6×10^2
$\nu + {}^{12}\mathrm{C} \to \nu + {}^{12}\mathrm{C}^*$	NC	1.7×10^2	3.2×10^2	5.2×10^2
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}$	CC	0.5×10^2	0.9×10^2	1.6×10^2
$\overline{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}$	CC	0.6×10^2	1.1×10^2	1.6×10^2

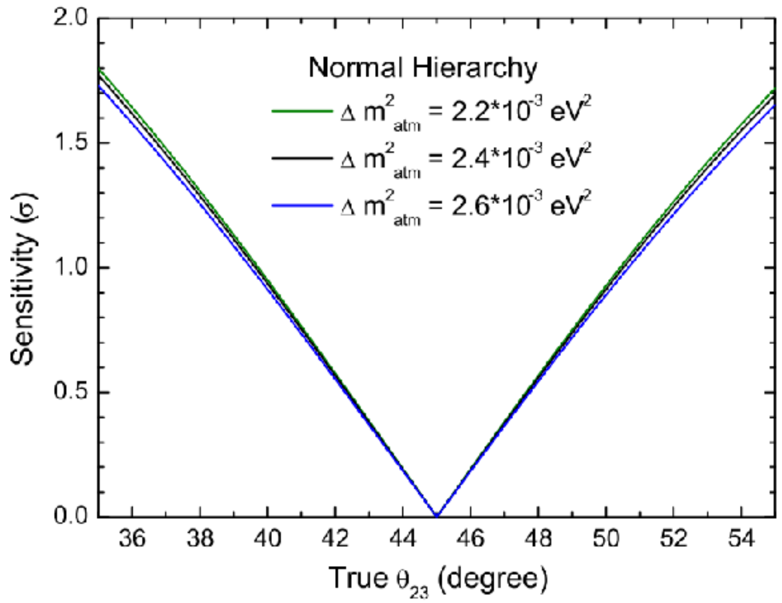
F. An, "Neutrino physics with JUNO," 2016

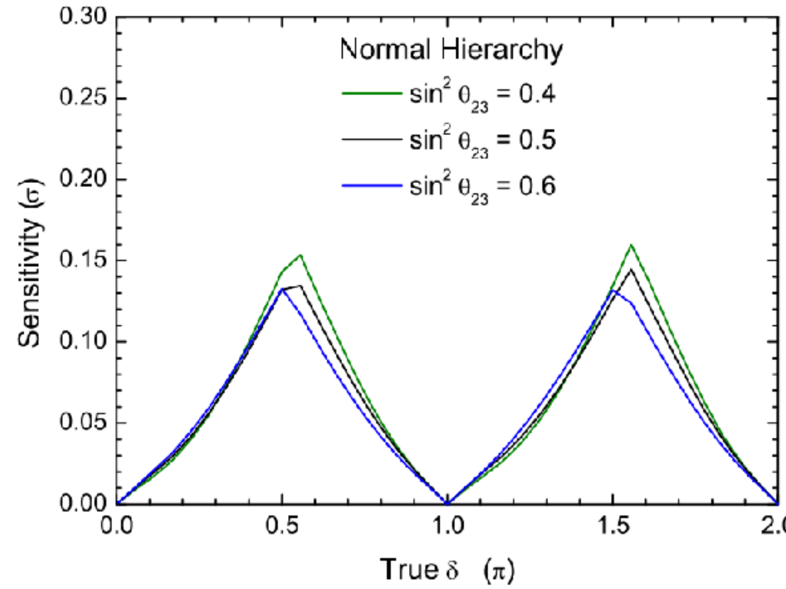


F. An, "Neutrino physics with JUNO," 2016

Atmospheric neutrinos



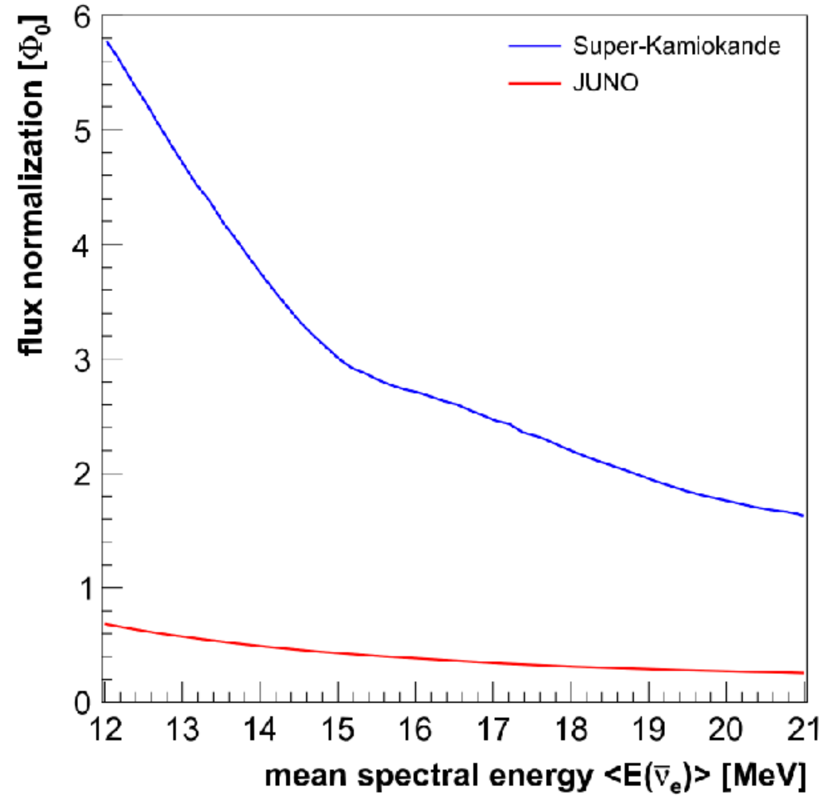




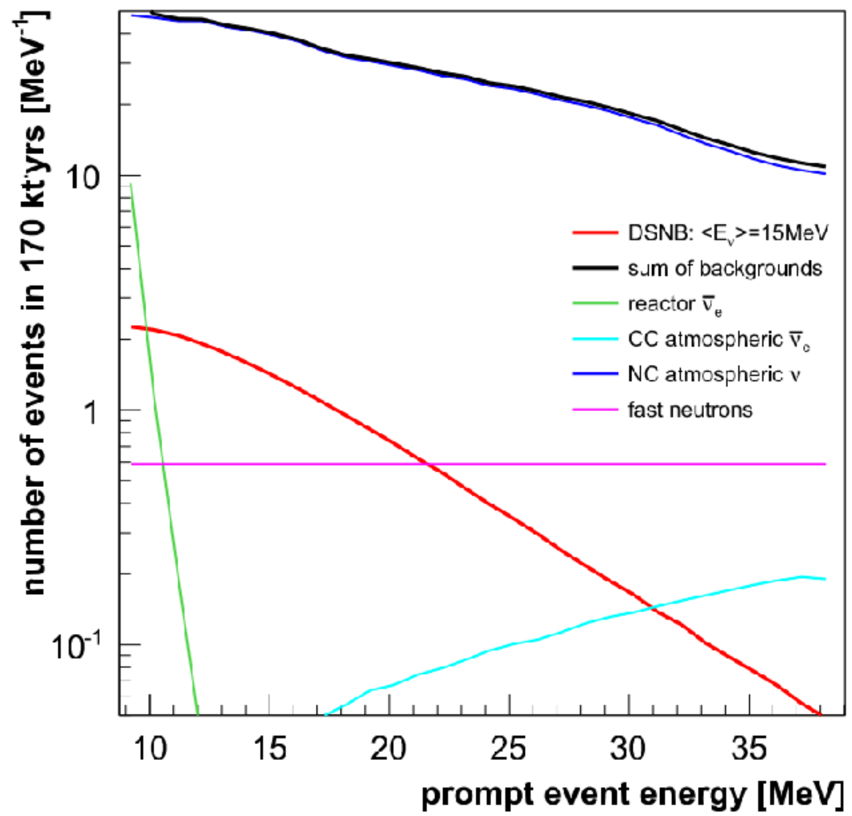
F. An, "Neutrino physics with JUNO," 2016

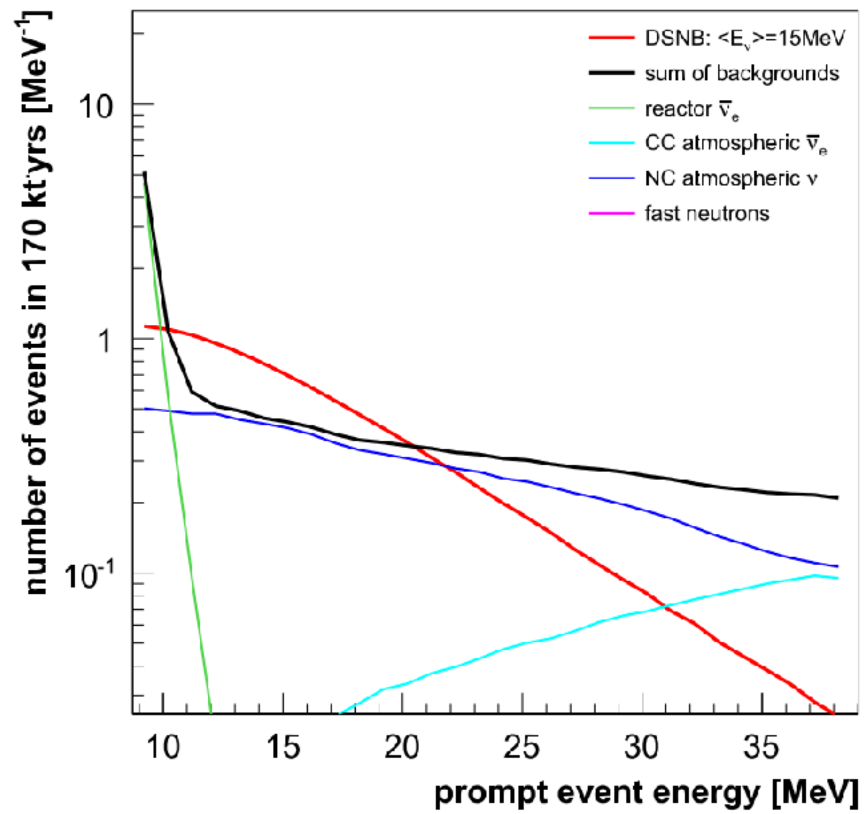
- only better result for MO
- Future plan
  - Particle reconstruction and identification
  - Upward through-going and stopping muon events from atm. ν in rock/WP
  - New physics beyond the SM
    - NSI, Sterile ν, new long range forces etc.

Diffusive SuperNovae Background



F. An, "Neutrino physics with JUNO," 2016





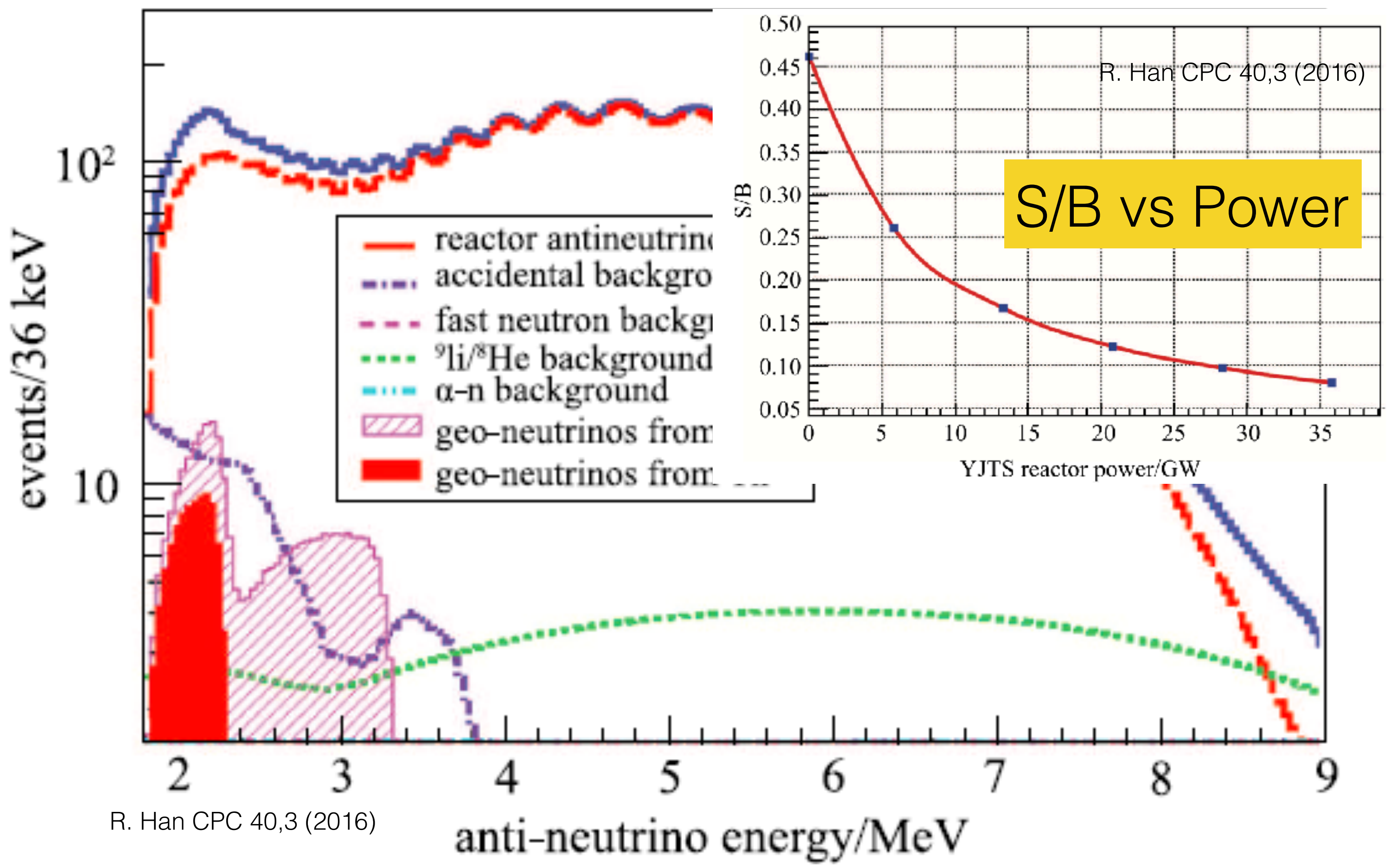
F. An, "Neutrino physics with JUNO," 2016

- IBD signal
- key: PSD for **atm. NC** and **fast neutron (>99%)**
- 10 yrs 0 event -> improve current limit by 10.

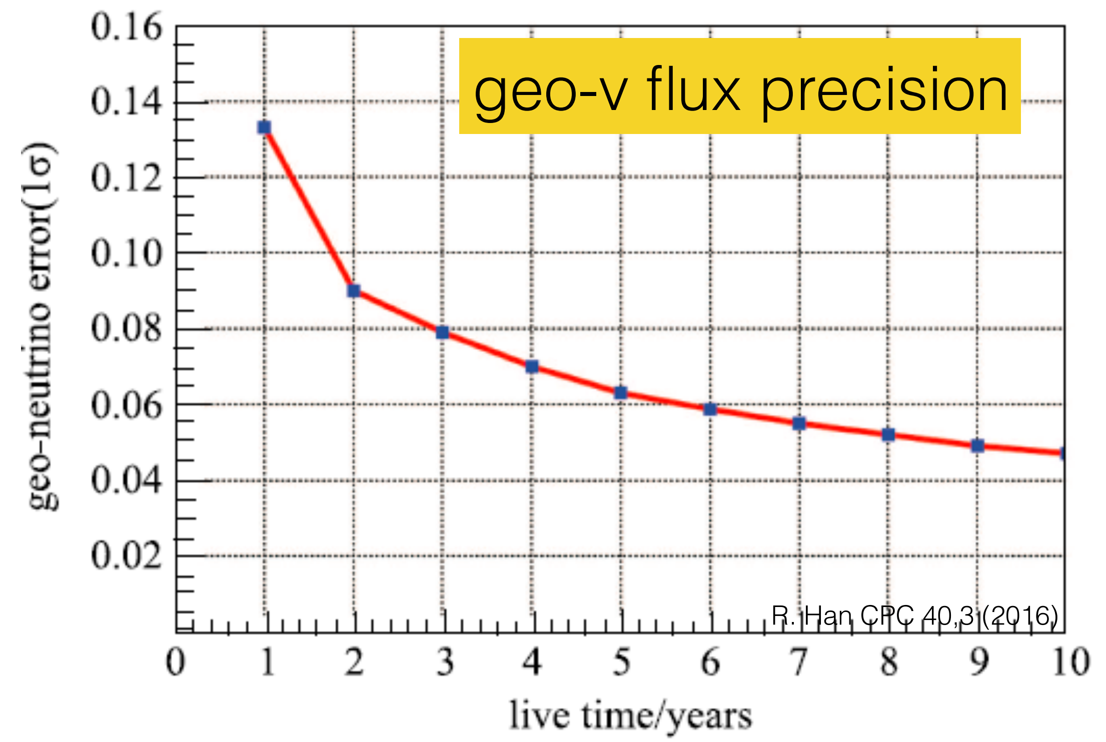
Item		Rate (no PSD)	PSD efficiency	Rate (PSD)
Signal	$\langle E_{\bar{\nu}_e}\rangle = 12$ MeV	13	$\varepsilon_\nu = 50\%$	7
	$\langle E_{\bar{\nu}_e}\rangle = 15$ MeV	23		12
	$\langle E_{\bar{\nu}_e}\rangle = 18$ MeV	33		16
	$\langle E_{\bar{\nu}_e}\rangle = 21$ MeV	39		19
Background	reactor $\bar{\nu}_e$	0.3	$\varepsilon_\nu = 50\%$	0.13
	atm. CC	1.3	$\varepsilon_\nu = 50\%$	0.7
	atm. NC	6×10^2	$\varepsilon_{NC} = 1.1\%$	6.2
	fast neutrons	11	$\varepsilon_{FN} = 1.3\%$	0.14
	Σ			7.1

F. An, "Neutrino physics with JUNO," 2016

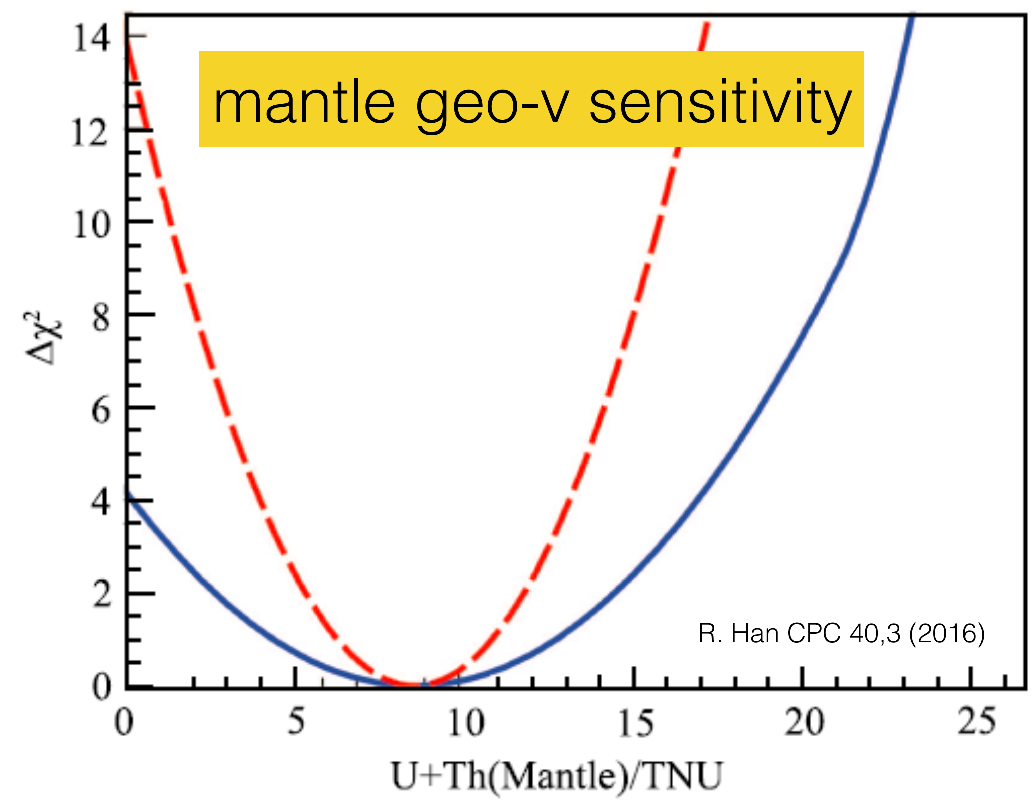
Geo-neutrinos



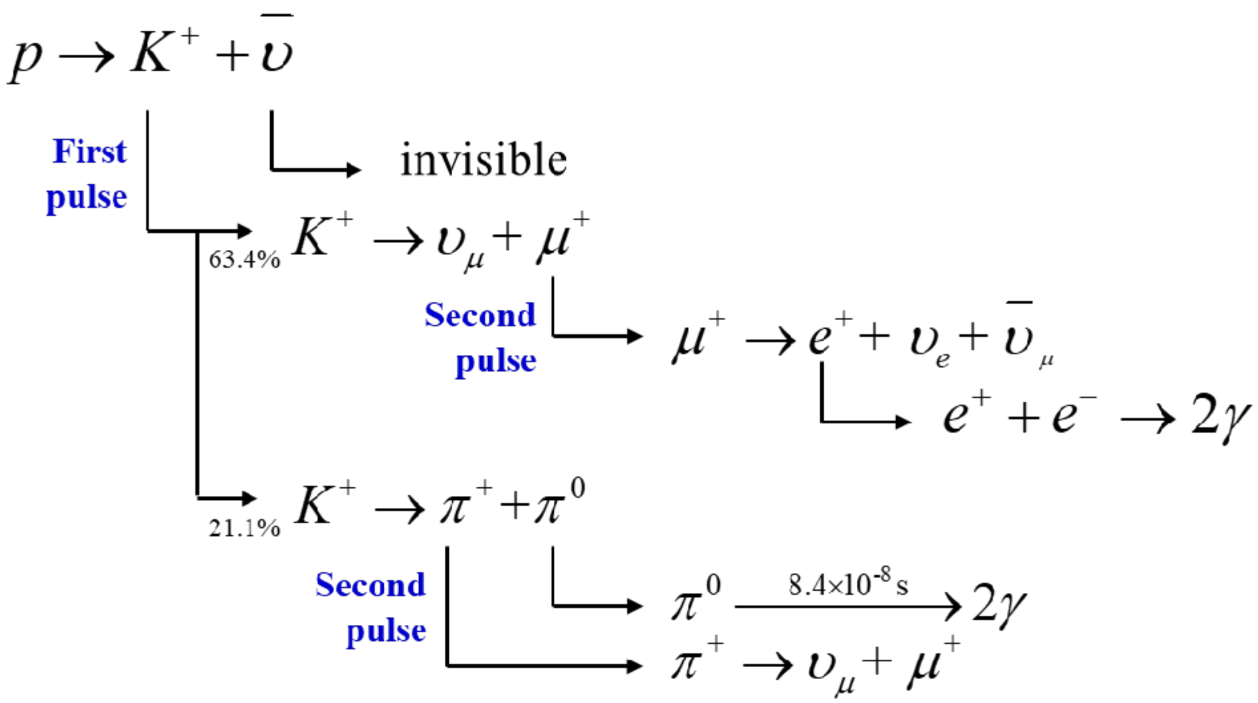
R. Han CPC 40,3 (2016)

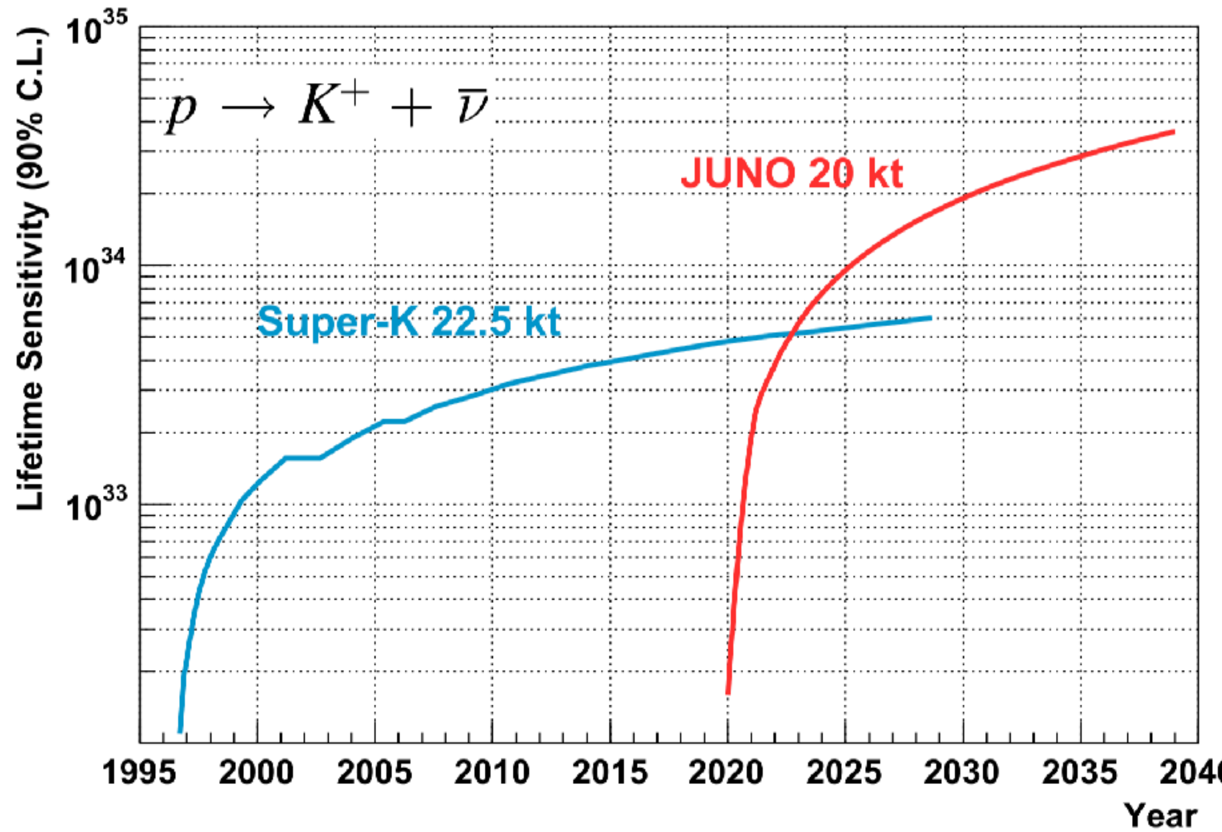


- 10 years 5% $\Phi_{geo\text{-}\nu}$ measurement
- 18%(8%) crust ν model:
  - 2σ(3.7σ) mantle ν detection
  - Help to eliminate various models



Proton decay





Nucleon Decay searches and Indirect Detection of Dark Matter with JUNO, ICHEP2016

- **Signal**: three pulse (K^+, π^+, μ^+)
- **Atm bkg.**
  - Nuclear recoil CC, qeCC
  - two-pulse event: π/K production
- **Sensitivity:**
  - 1.67×10^{34} yrs (90% C.L.) in 10 yrs.