Prospects of JUNO

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Institute of High Energy Physics, Beijing

On behalf of the JUNO collaboration

"Prospects of Neutrino Physics" at Kavli IPMU

2019/04/11

Jiangmen Underground Neutrino Observatory

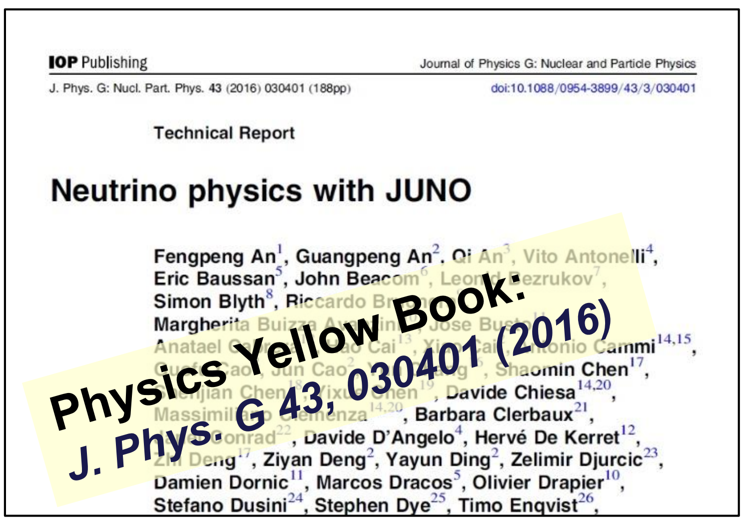
JUNO： a multipurpose neutrino experiment

Project

- 20 kton liquid scintillator,
  3%@1MeV energy resolution,
  700 m underground
- Approved in **2013**, construction started in **2015**, operation in **2021**

Physics

- Determine mass hierarchy
- Precision measurement of oscillation parameters
- Astronomical and geo- ν
- Proton decay and exotics



IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. 43 (2016) 030401 (188pp) — doi:10.1088/0954-3899/43/3/030401

Technical Report

Neutrino physics with JUNO

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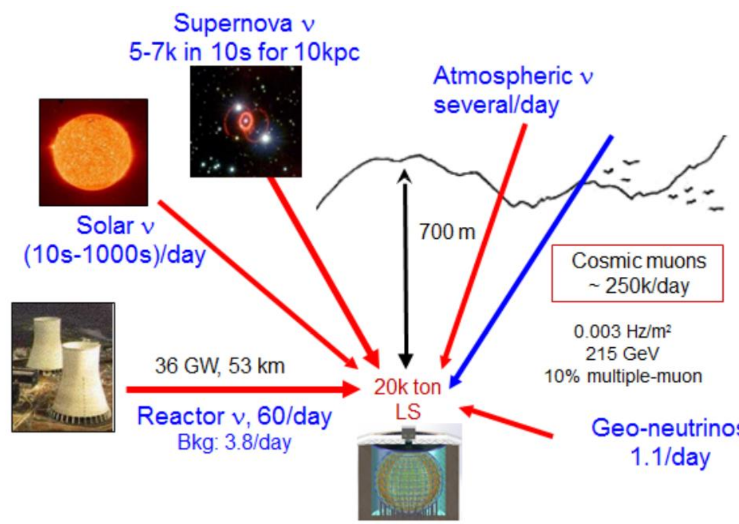
Physics Yellow Book:
J. Phys. G 43, 030401 (2016)



Location

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

Yangjiang NPP

Taishan NPP

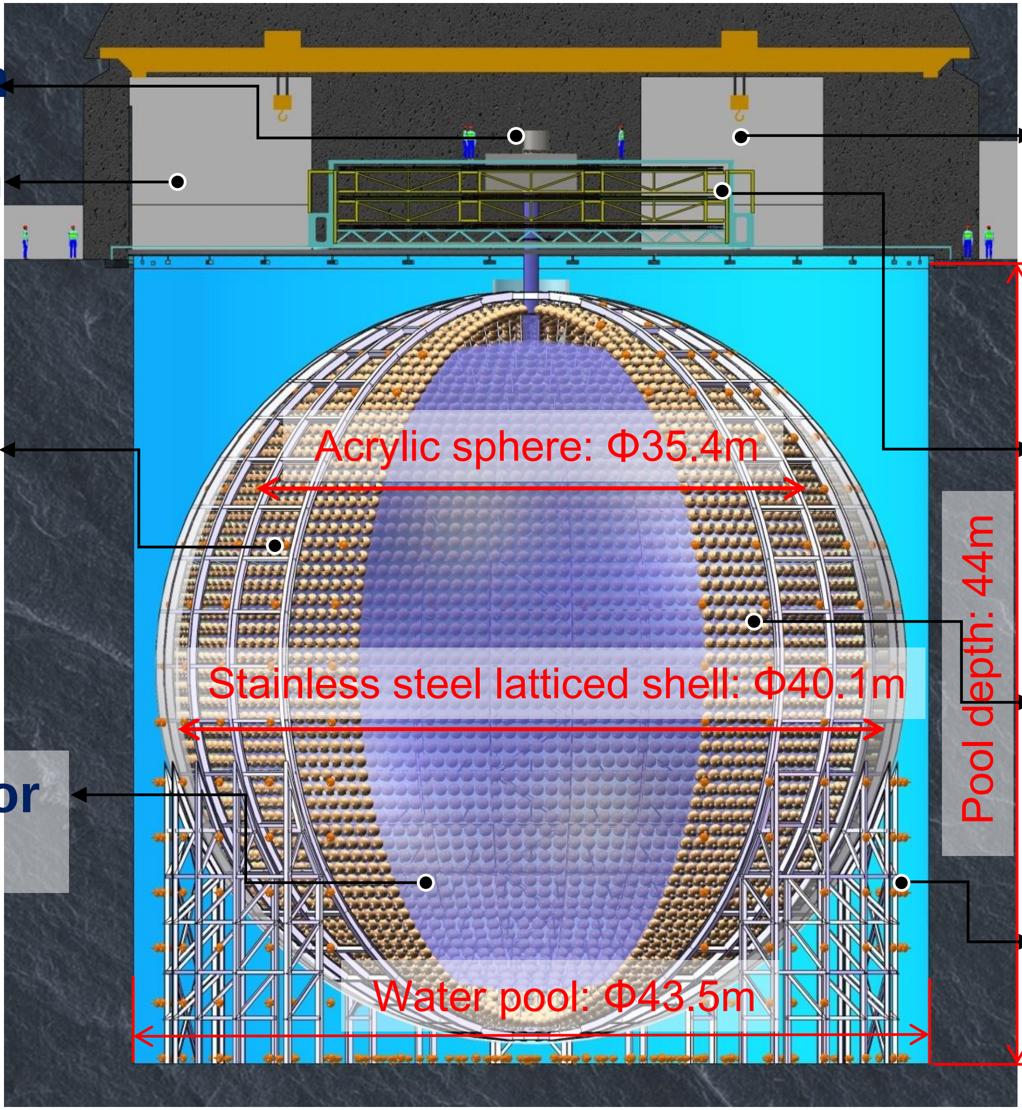
JUNO detector

Calibration room

Pure water room

Central detector
SS latticed shell
Acrylic sphere

Liquid scintillator
20 kton



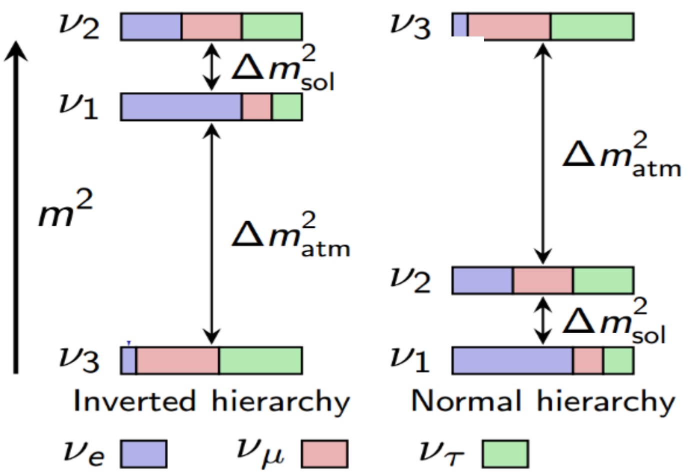
LS Filling room

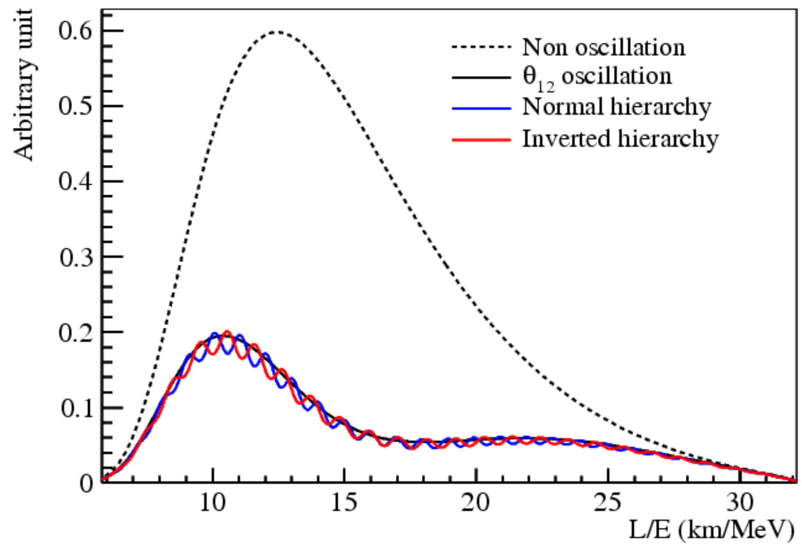
Top Tracker

PMT
~18,000 20” PMTs
+ ~25,000 3” PMTs:
coverage ~77.5%

Water Cherenkov
35 kton pure water
2,000 20” veto PMTs

Neutrino Mass Hierarchy (MH)





- Disappearance of reactor electron antineutrinos at ~60 km: interference between Δm^2_{31} and Δm^2_{32}
- Very unique approach, independent on θ_{23} and CP phase
- Key: energy resolution

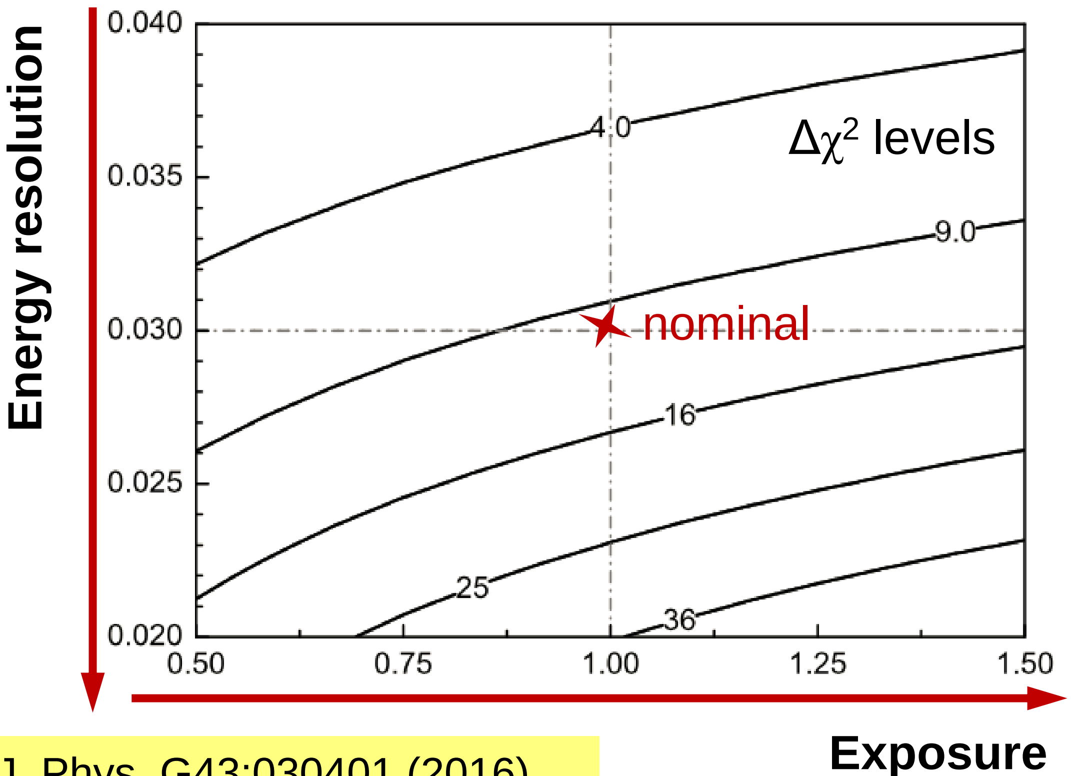
$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

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

Sensitivity to MH

$$\chi^2_{\rm REA} = \sum_{i=1}^{N_{\rm bin}} \frac{[M_i - T_i(1 + \sum_k \alpha_{ik}\epsilon_k)]^2}{M_i} + \sum_k \frac{\epsilon_k^2}{\sigma_k^2}$$

$$\Delta\chi^2_{\rm MH} = |\chi^2_{\rm min}(\rm N) - \chi^2_{\rm min}(\rm I)|$$



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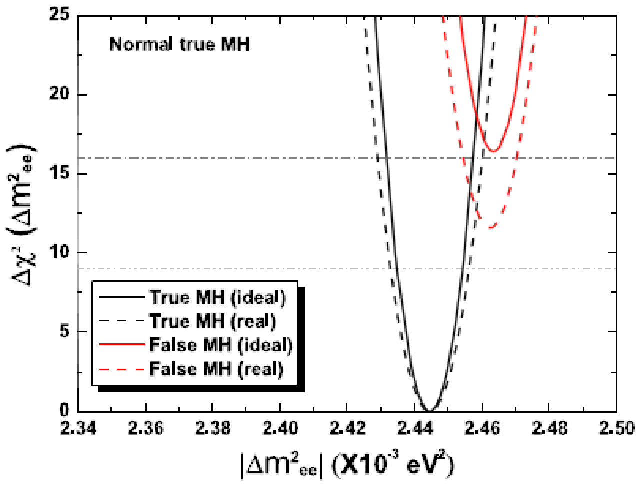
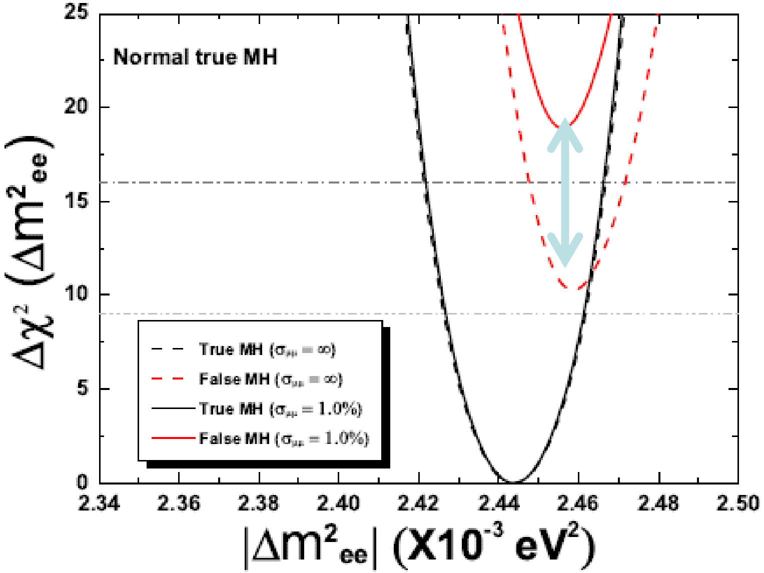
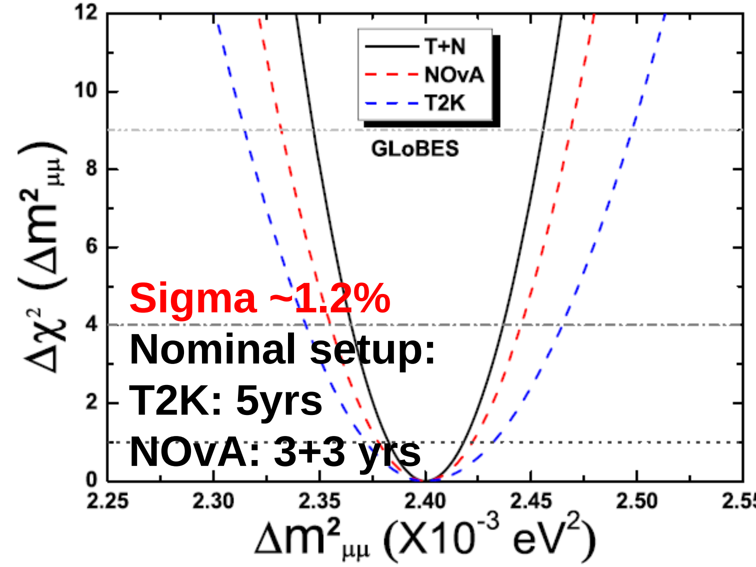


	Size	$\Delta\chi^2_{MH}$
Ideal	52.5 km	+16
Core distr.	Real	-3
DYB & HZ [1)]	Real	-1.7
Spectral Shape	1%	-1
B/S [2)] (rate)	6.3%	-0.6
B/S (shape)	0.4%	-0.1

1) Daya Bay & Huizhou
2) Background to Signal

Sensitivity improvement from $\Delta m^2_{\mu\mu}$





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

JUNO **NOvA+T2K** **Mass Hierarchy** **CP-violating Phase**

- **$\nu_\mu \rightarrow \nu_e$ (appearance) channel can directly determine the MH**
- **T2K+NOvA: $|\Delta m^2_{\mu\mu}|$~ 1%**
- **Combining T2K+NOvA (both disappearance and appearance) with JUNO: 4-σ to 5-σ or better.**

Energy resolution: photon statistics

- Energy resolution: $\Delta m^2_{21}/\Delta m^2_{32}$ < 3%/√E ➔ 1200 p.e./MeV

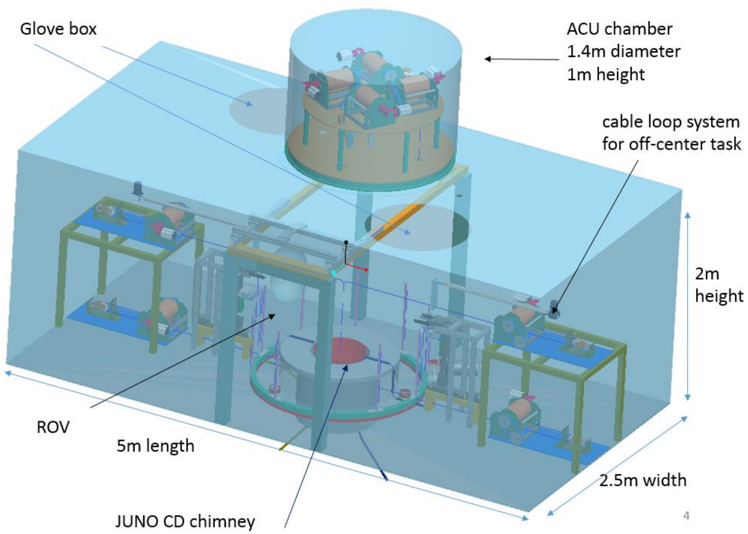
	KamLAND	JUNO
LS mass	**~1 kt**	**20 kt**
Light yield	**250 p.e./MeV**	**1200 p.e./MeV**

- **LS Attenuation length/Diameter:**
- **15m/16m → 30m/34m** **×0.9** ➔ **0.6**
- **LS light yield (1.5g/l PPO → 5g/l PPO)**
- **30%→ 45%** **× 1.5**
- **Photocathode coverage : 34% → ~ 80%** **× 2.3**
- **High QE*CE "PMT":**
  - ⇨ **KamLAND 25%*60% = 15%**
  - **New PMT 40%*60% = 24%** **× 1.6** ➔ **2.0**

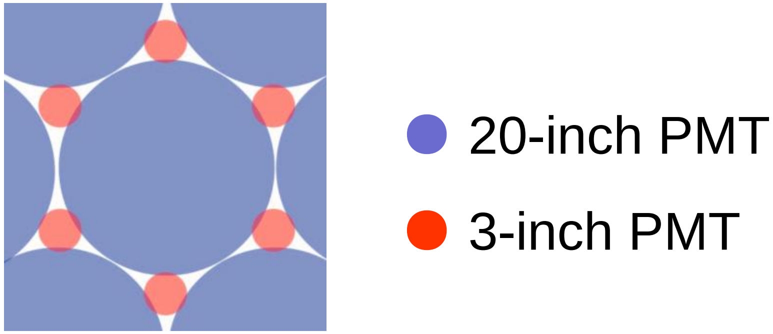
TOTAL: × ~ 5 - 6

Energy resolution: calibration

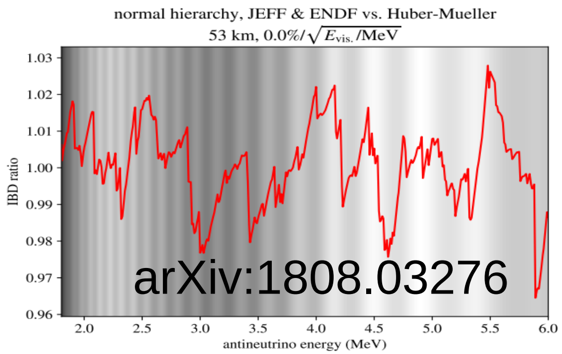
- 1200 p.e.→2.89% stat. fluctuation. Room for systematics: <1%. Calibration is critical!
- Detector energy response: non-uniformity and non-linearity
  - Routinely Source into LS by
    - ACU: at central axis
    - Rope loop: a plane
  - Source into Guided tube
  - “sub-marine”: anywhere in the LS
- Single channel charge response
  - Suppression of over-shoot and Flash-ADC readout
  - Double-calorimetry: measure energy via “photon counting”

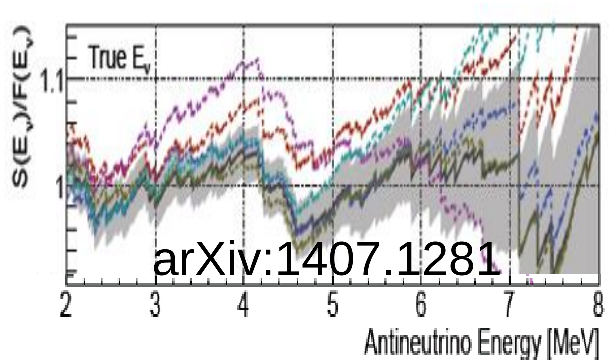


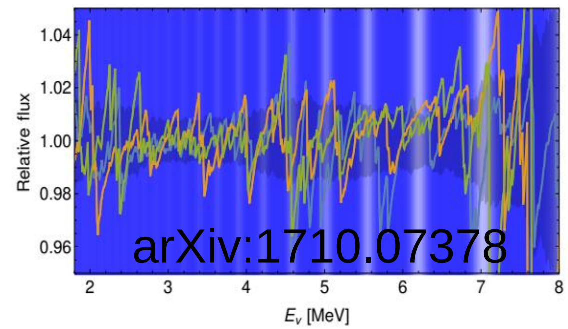
Redundant calibration system



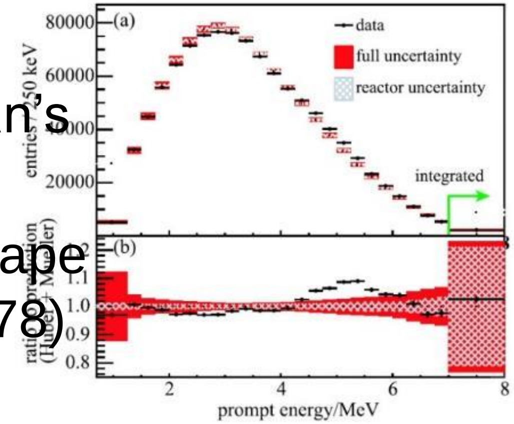
Impact of fine structure to JUNO







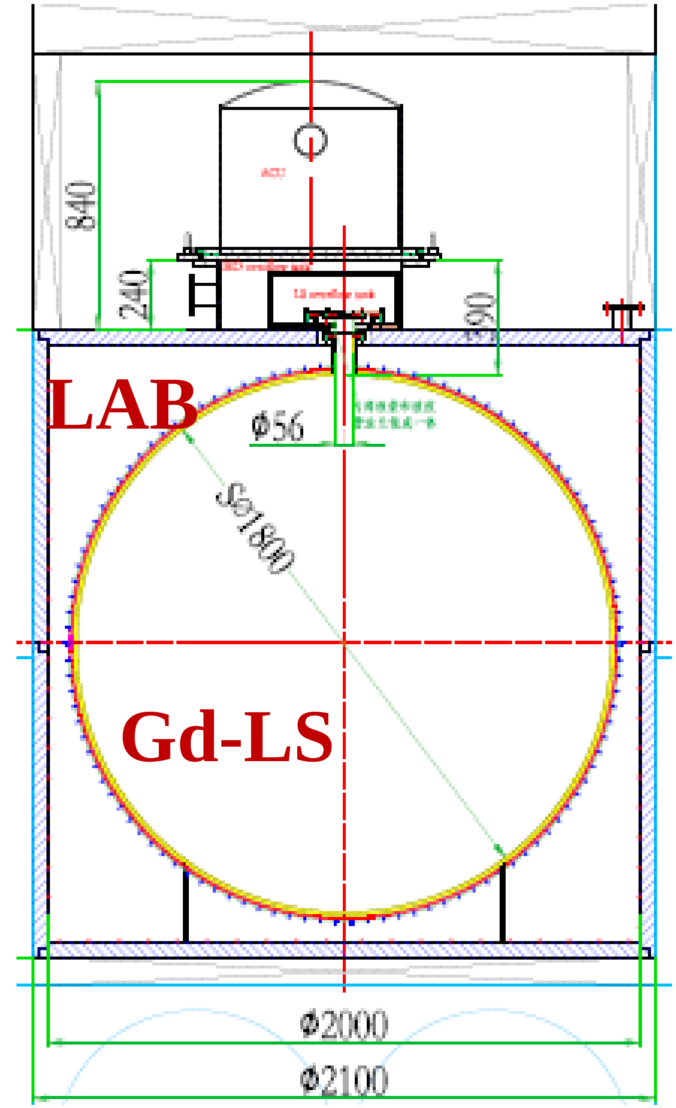
- Large scale fine structure: constrained by Daya Bay
- Known fine structure does not hurt JUNO, e.g. Xin Qian's calculation (JUNO-doc-503)
- Unknown fine structure (5% bin-to-bin uncorrelated shape uncertainty) has larger impact (Huber, arXiv:1710.07378)



- Taishan Antineutrino Observatory (TAO), a ton-level, high energy resolution LS detector at 30 m from the core, a satellite exp. of JUNO.
- Measure reactor neutrino spectrum w/ sub-percent E resolution ($1.5\%/\sqrt{E}$). Provide model-independent reference spectrum for JUNO

JUNO-TAO Detector Concept

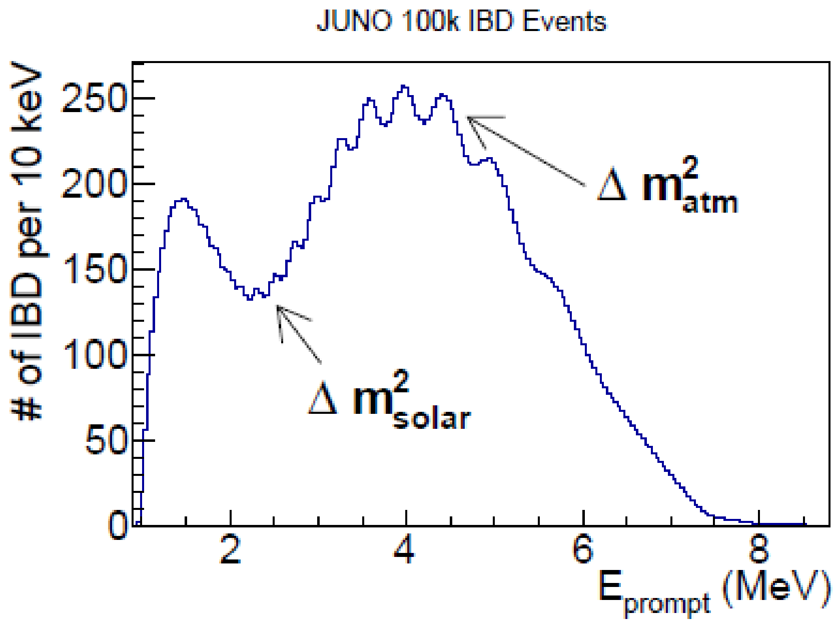
- 2.6 ton Gd-LS in a spherical vessel
  - 1-ton FV, 4000 v's/day
- 10 m^2 SiPM of 50% PDE
  Operate at -50℃
- From Inner to Outside
  - Gd-LS working at -50℃
  - SiPM and support
  - Cryogenic vessel
  - 1~1.5 m water or HDPE shielding
  - Muon veto
- Laboratory in a basement at -10 m, 30-35 m from Taishan core (4.6 GW)
- Plan to be online in 2020



Precision Measurement

Current precision

	Δm^2_{21}	$\|\Delta m^2_{31}\|$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	δ
Dominant Exps.	KamLAND	T2K	SNO+SK	Daya Bay	NOνA	T2K
Individual 1σ	2.4%	2.6%	4.5%	3.4%	5.2%	70%
Nu-FIT 4.0	2.4%	1.3%	4.0%	2.9%	3.8%	16%

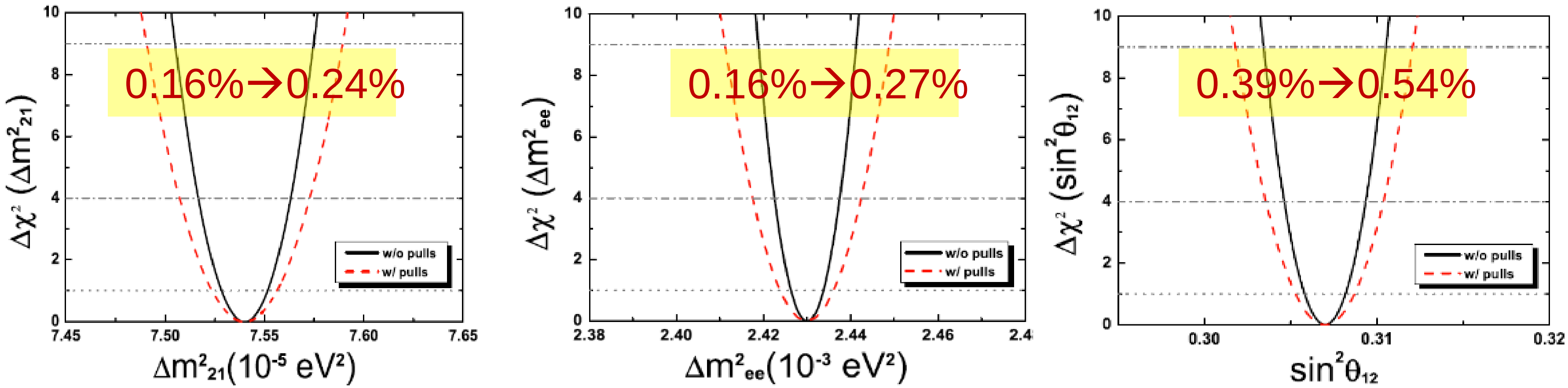


JUNO: First experiment to measure solar and atmospheric mass splitting simultaneously. <1% precision to θ_{12}, Δm^2_{21} and Δm^2_{31} (Δm^2_{32}).

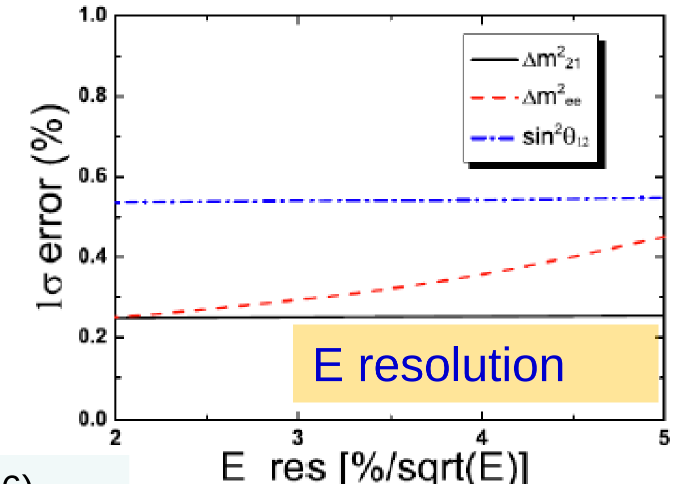
Precision Measurement

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

Correlation among parameters



	Statistics	+BG, +1% bin-to-bin +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%**



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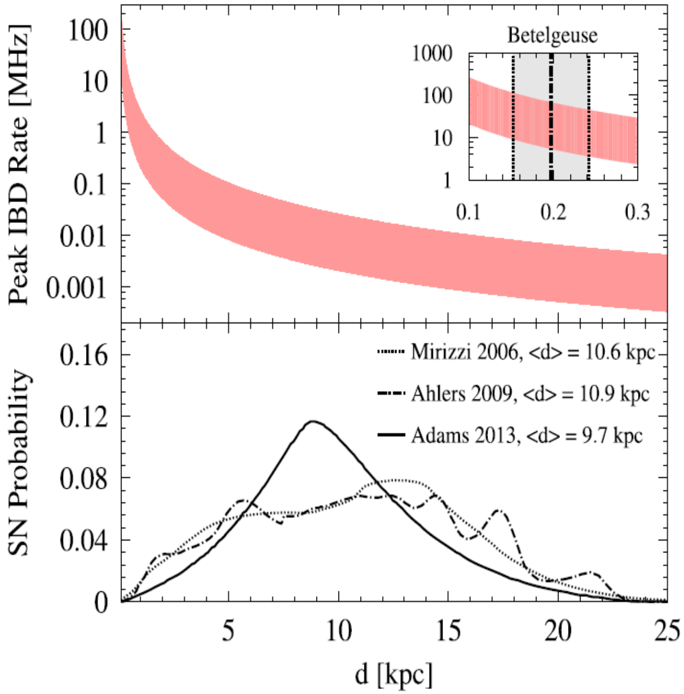
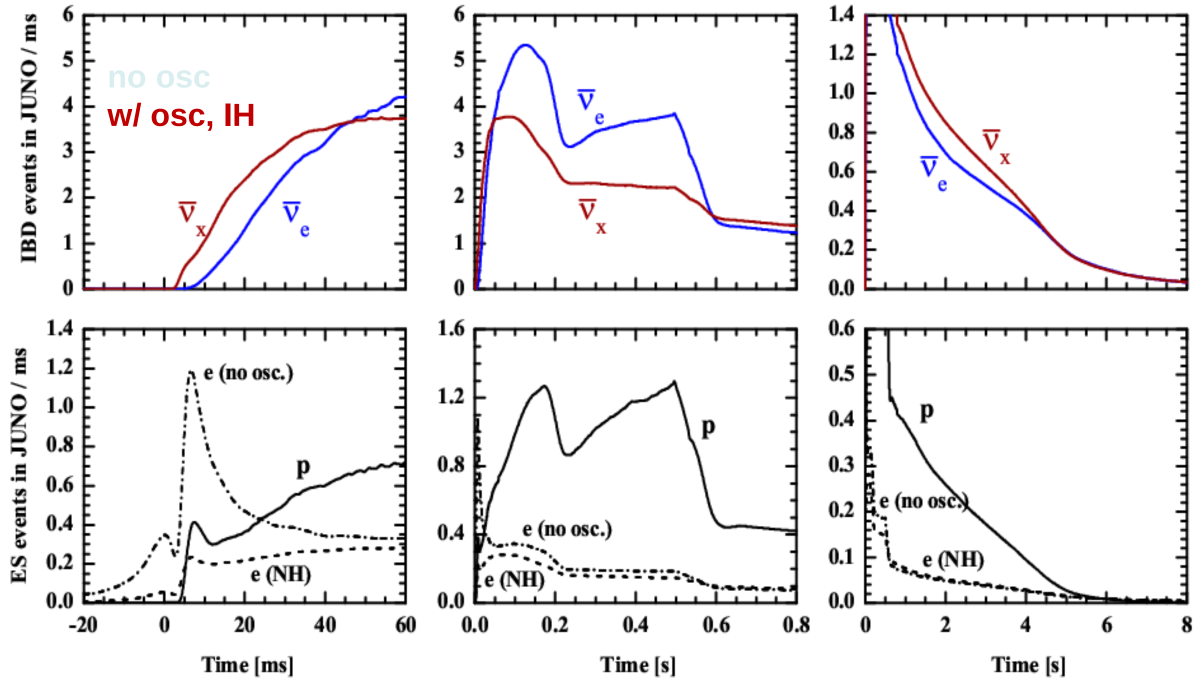
Supernova Burst Neutrinos



Burst **Accretion** **Cooling**

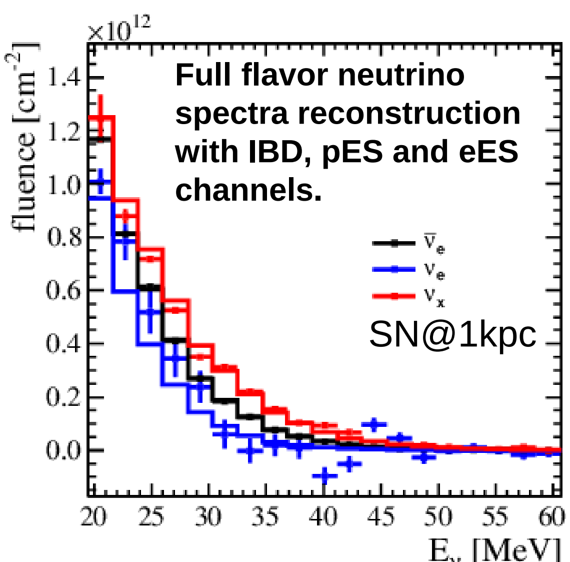


SN@10kpc, w/ 1D simulations from Garching group
The delayed neutrino-driven mechanism of CCSN

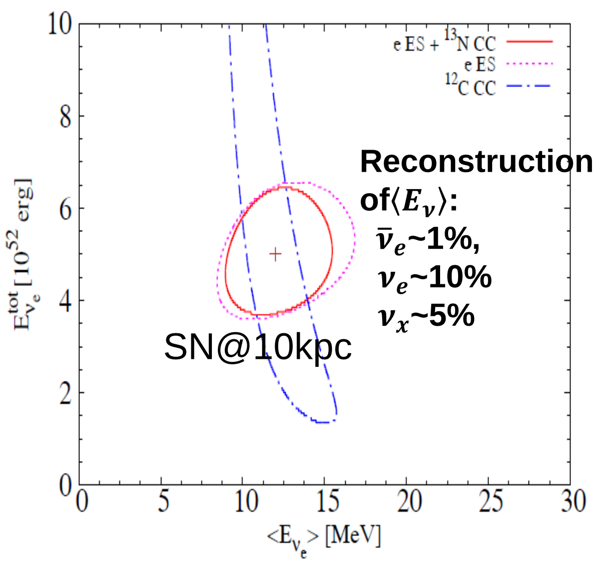
- Galactic CCSN rate~**3 per century**
- **Real-time** detection of SN burst neutrinos, international SN alert, e.g. **SNEWS**
- **Almost background free**, since SN burst neutrinos last for ~10 s

Detection of SN neutrinos

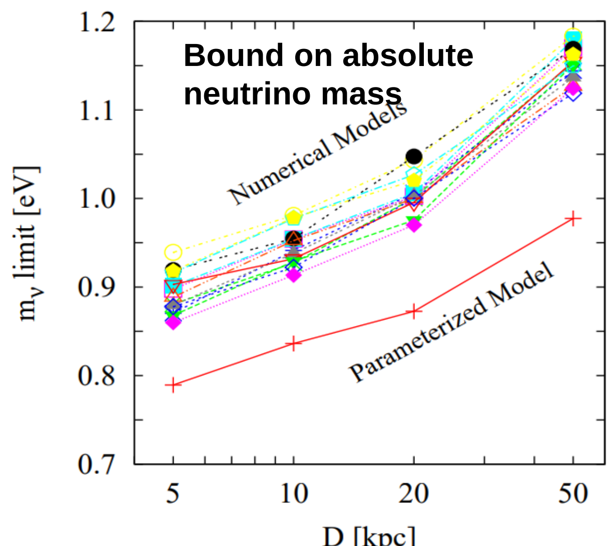
- **Full flavor** detection and **low threshold energy** ~0.2 MeV in LS
- **IBD** is **the golden channel**, ~5000 events for SN@10 kpc
- Especially **the pES channel** can provide us more information about $\boldsymbol{\nu_x}$, better than other type of detectors, e.g. WC, LAr-TPC detectors
- **PSD method** to distinguish events from eES and pES
- Implications of SN neutrinos for particle physics and astrophysics



Phys. Rev. D 97, 063014

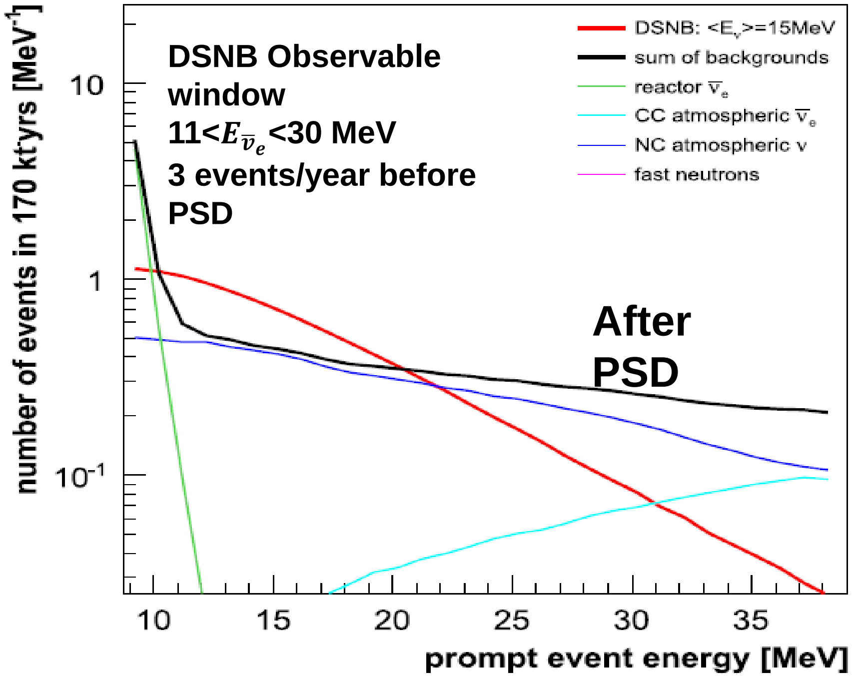


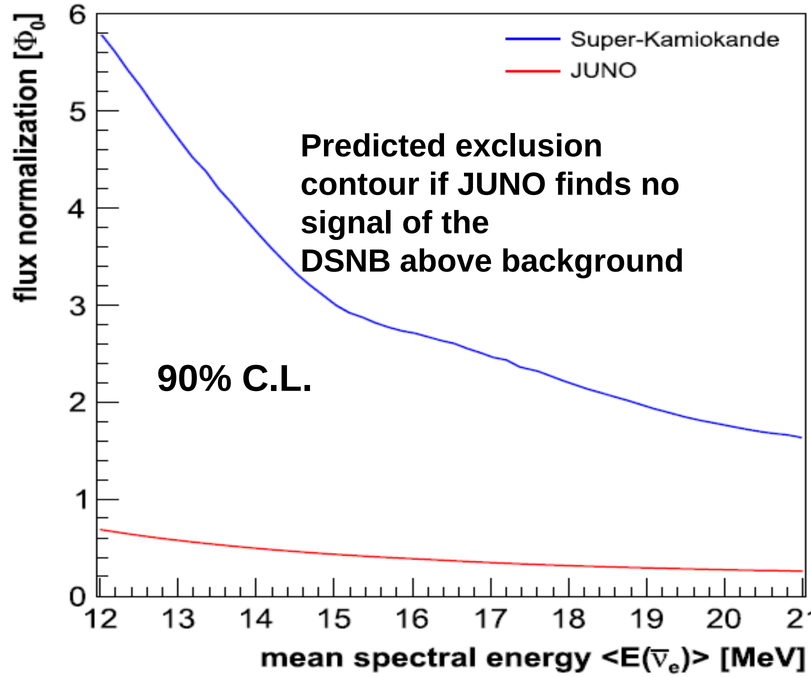
Phys. Rev. D 94, 023006



JCAP 15',1412.7418

Diffused Supernova Neutrino Background



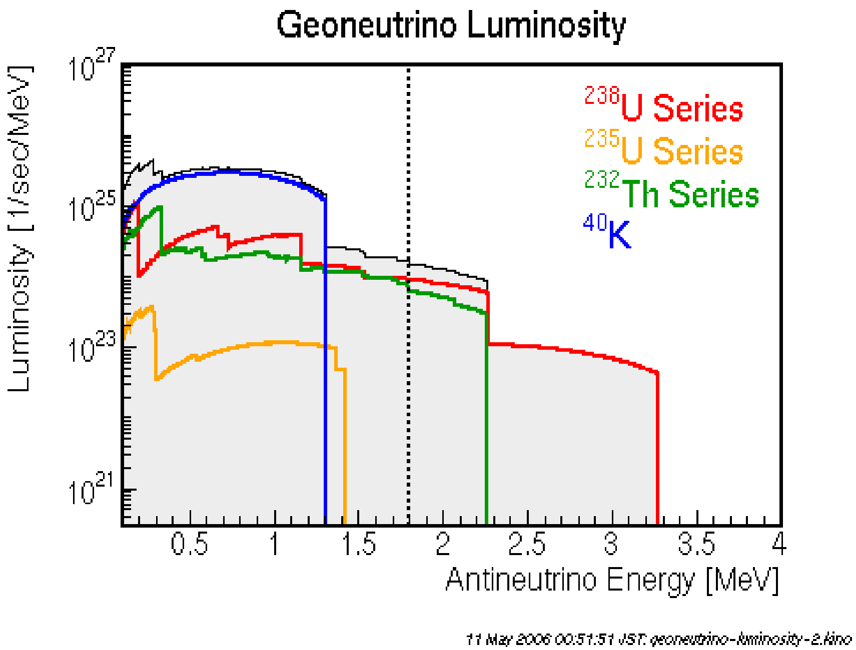


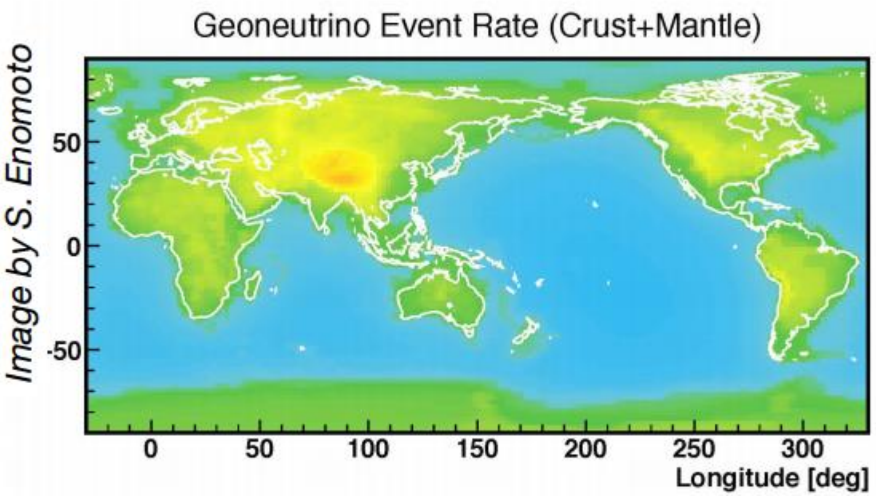
- DSNB rate: approx. **10 core collapse/sec** in the visible universe
- Provide information of star formation rate, ν emission from average CCSNe and BHs.
- **PSD** to suppress background, mainly **atmospheric neutrinos**
- The expected **detection significance~3σ** after 10 years of data taking in JUNO, with $\langle E_{\bar{\nu}_e} \rangle$~15 MeV, bkg systematic uncertainty ~20%

Geo-neutrino physics

- Geo-neutrino as a tool to explore the composition of the Earth and to estimate the amount of radiogenic power driving the Earth's engine.

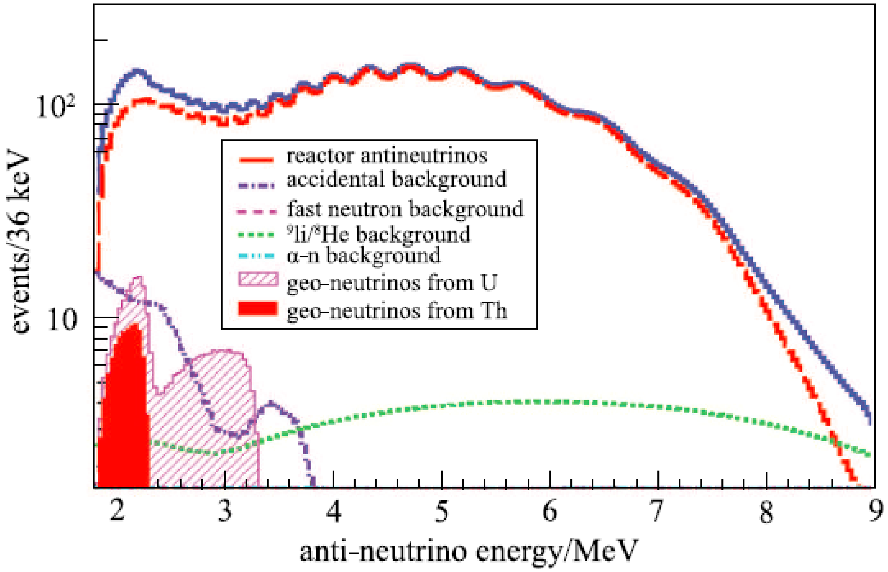
$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6\beta^- + 6\bar{\nu}_e$$
$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4\beta^- + 4\bar{\nu}_e$$
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \beta^- + \bar{\nu}_e$$

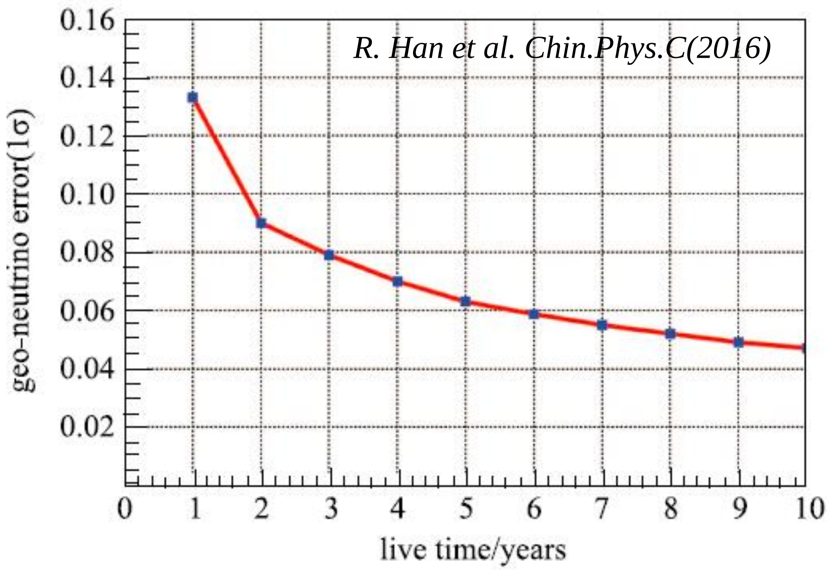




- The detector can only get the total contribution from crust and mantle.
- With a 3-D crust model, mantle neutrino fluxes can be extracted.

Geo-neutrino at JUNO

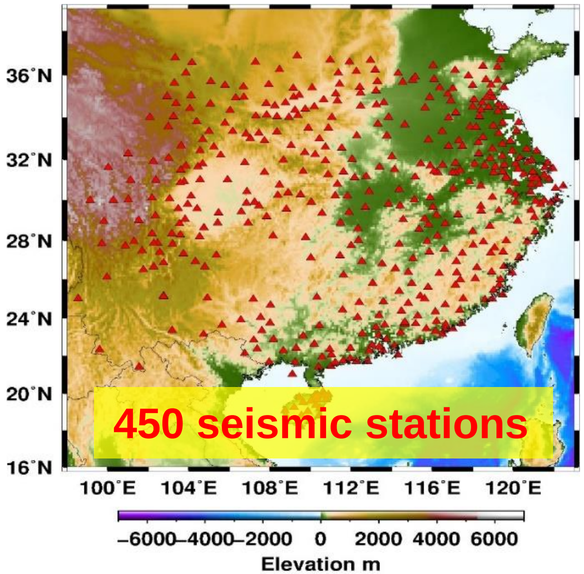


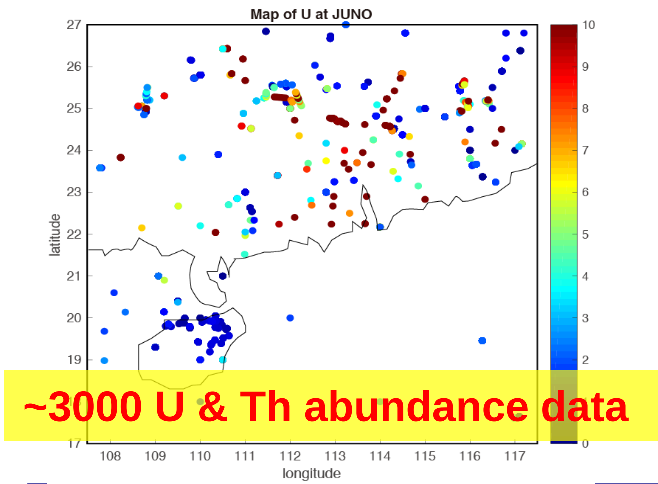


- 400-500 IBD/year, larger than all the accumulated geo-neutrino events before. Challenge: reactor background, ~40 times larger
- With 10 years: total uncertainty reach 5%
- Measure U/Th ratio at percent level
- A local refined crust model is required to get information of Mantle

A Local Crust Model for JUNO

arXiv:1903.11871



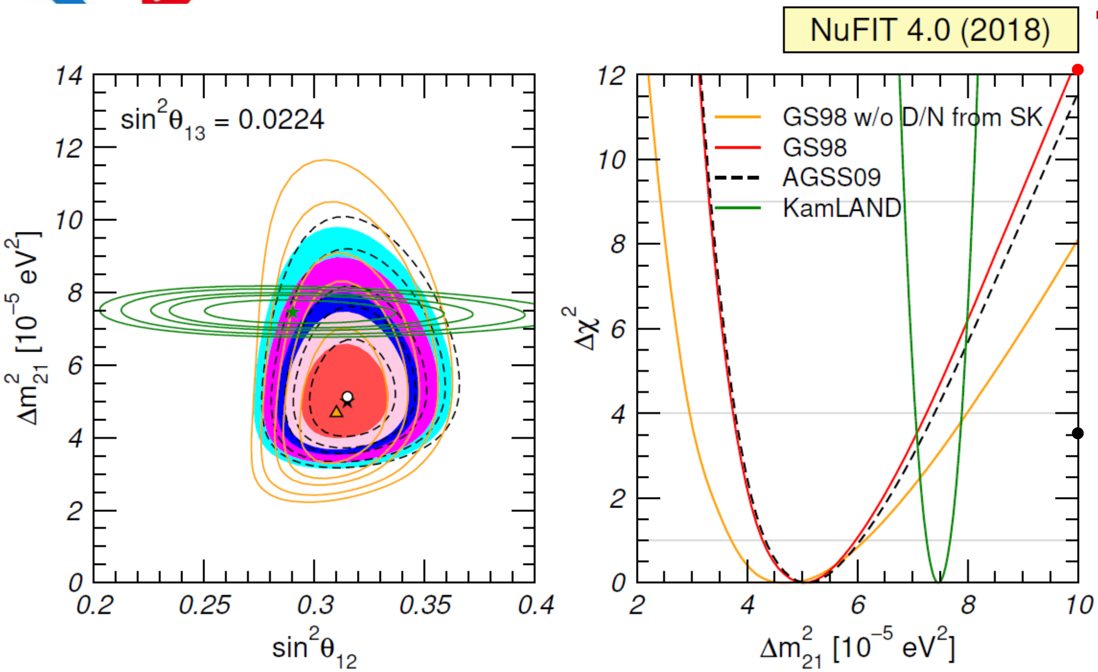


Done by an interdisciplinary group of geo- and particle physics scientists.

		$S_U \pm \sigma$	$S_{Th} \pm \sigma$	$S_{U+Th} \pm \sigma$
Upper Crust	Top Layer	$10.5^{+0.7}_{-0.7}$	$3.2^{+0.3}_{-0.3}$	$13.8^{+0.8}_{-0.7}$
	Basement	$8.1^{+3.7}_{-7.0}$	$2.6^{+1.1}_{-1.8}$	$11.0^{+5.9}_{-3.9}$
Middle Crust		1.7 ± 1.0	0.4 ± 0.3	2.1 ± 1.1
Lower Crust		$1.9^{+1.3}_{-3.8}$	$0.8^{+5.7}_{-0.7}$	$1.7^{+4.0}_{-1.2}$
Oceanic Crust		0.2 ± 0.05	0.1 ± 0.01	0.3 ± 0.05
Total	**Unit: TNU**	21.3 ± 4.0	6.6 ± 1.3	28.5 ± 4.5

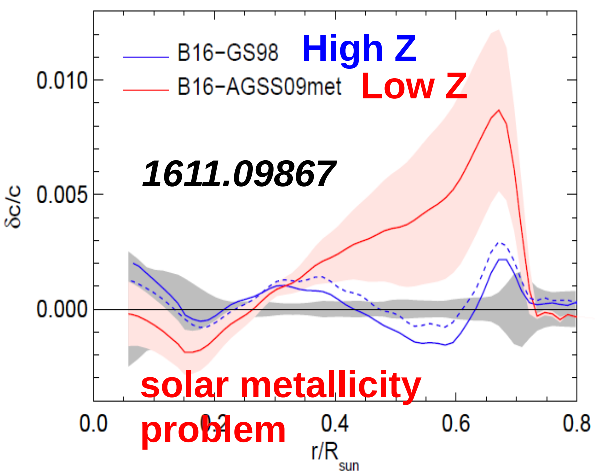
- Research area: around 500 km × 500 km
- Seismic station data give the structure and density of the local crust. Rock samples represent U/Th abundance distributions.
- This result (28.5 TNU) is 30% larger than the prediction using the global model.
- Difference means particular geo-scientific importance!

Solar neutrinos physics



A mild tension between solar & reactor measurements in Δm^2_{21}, which is due to the absence of upturn in the ^{8}B solar neutrino measurement (as well as too large day-night asymmetry).

A new low-threshold ^{8}B solar neutrino measurement would be desirable to test the tension, and possible new physics if any.

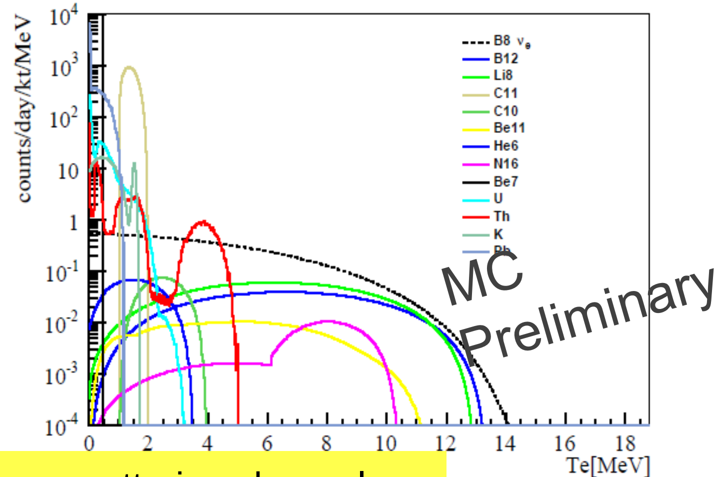


Flux	B16-GS98	B16-AGSS09met	Solar[a]
$\Phi(pp)$	$5.98(1 \pm 0.006)$	$6.03(1 \pm 0.005)$	$5.97^{(1+0.006)}_{(1-0.005)}$
$\Phi(pep)$	$1.44(1 \pm 0.01)$	$1.46(1 \pm 0.009)$	$1.45^{(1+0.009)}_{(1-0.009)}$
$\Phi(hep)$	$7.98(1 \pm 0.30)$	$8.25(1 \pm 0.30)$	$19^{(1+0.63)}_{(1-0.47)}$
$\Phi(^7Be)$	$4.93(1 \pm 0.06)$	$4.50(1 \pm 0.06)$	$4.80^{(1+0.050)}_{(1-0.046)}$
$\Phi(^8B)$	$5.46(1 \pm 0.12)$	$4.50(1 \pm 0.12)$	$5.16^{(1+0.025)}_{(1-0.017)}$
$\Phi(^{13}N)$	$2.78(1 \pm 0.15)$	$2.04(1 \pm 0.14)$	≤ 13.7
$\Phi(^{15}O)$	$2.05(1 \pm 0.17)$	$1.44(1 \pm 0.16)$	≤ 2.8
$\Phi(^{17}F)$	$5.29(1 \pm 0.20)$	$3.26(1 \pm 0.18)$	≤ 85

- Both the CNO neutrinos and ^{8}B neutrinos are important to test the metallicity problem, in order to break the degeneracy from the SSM parameters (e.g., opacity).

Solar neutrinos at JUNO

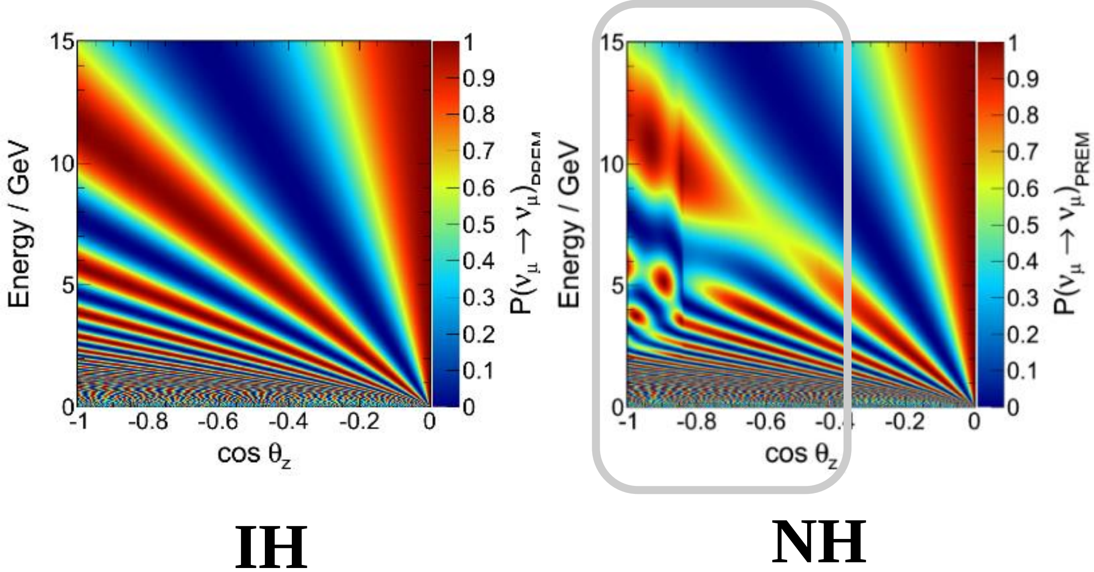
- Very large volume: high statistics and self-shielding of external gamma background with fiducial volume
  - LS radioactivity: **10^{-15} g/g** (baseline), **10^{-17} g/g** (solar phase)
- Very good energy solution (3%@1 MeV): precision energy spectrum measurement
- Overburden is not high: cosmogenic background is a challenge
  - Better muon tracking and veto approach



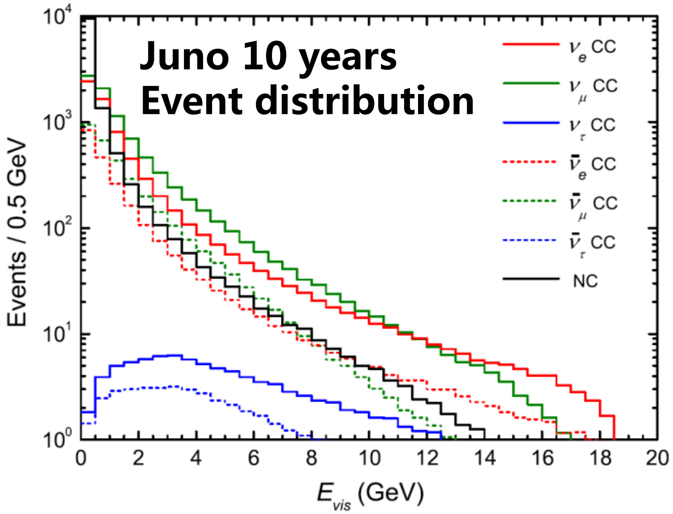
v-e scattering channel

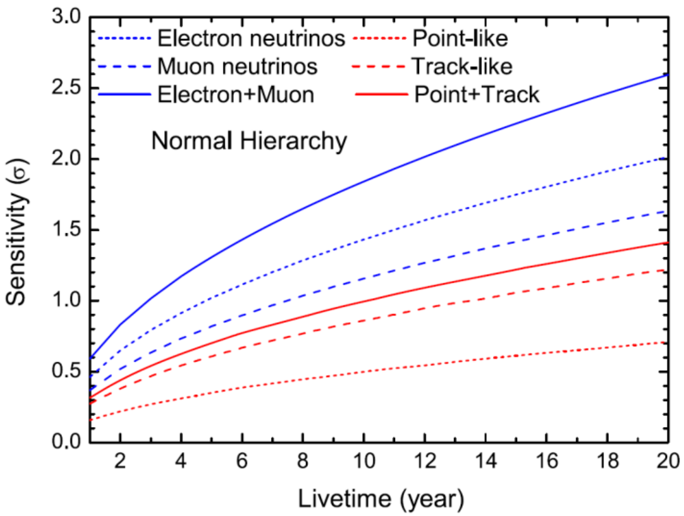
- Solar oscillation measurement with ^{8}B ν: measure up-turn and test the tension of Δm^2_{21} in a single detector
  - Electron kinetic energy spectrum as low as 2 MeV (ν+e → ν+e)
  - Day-night asymmetry
  - ν_e-^{13}C charged-current channel (E_{th}~2.2 MeV) [for the first time]

Atmospheric neutrinos



- **Sensitive to MH and $\boldsymbol{\theta_{23}}$**
- MH determination via matter effect
- Complementary to MH via reactor neutrinos
- 1-2σ for 10 years data taking
- θ_{23} accuracy of 6 deg



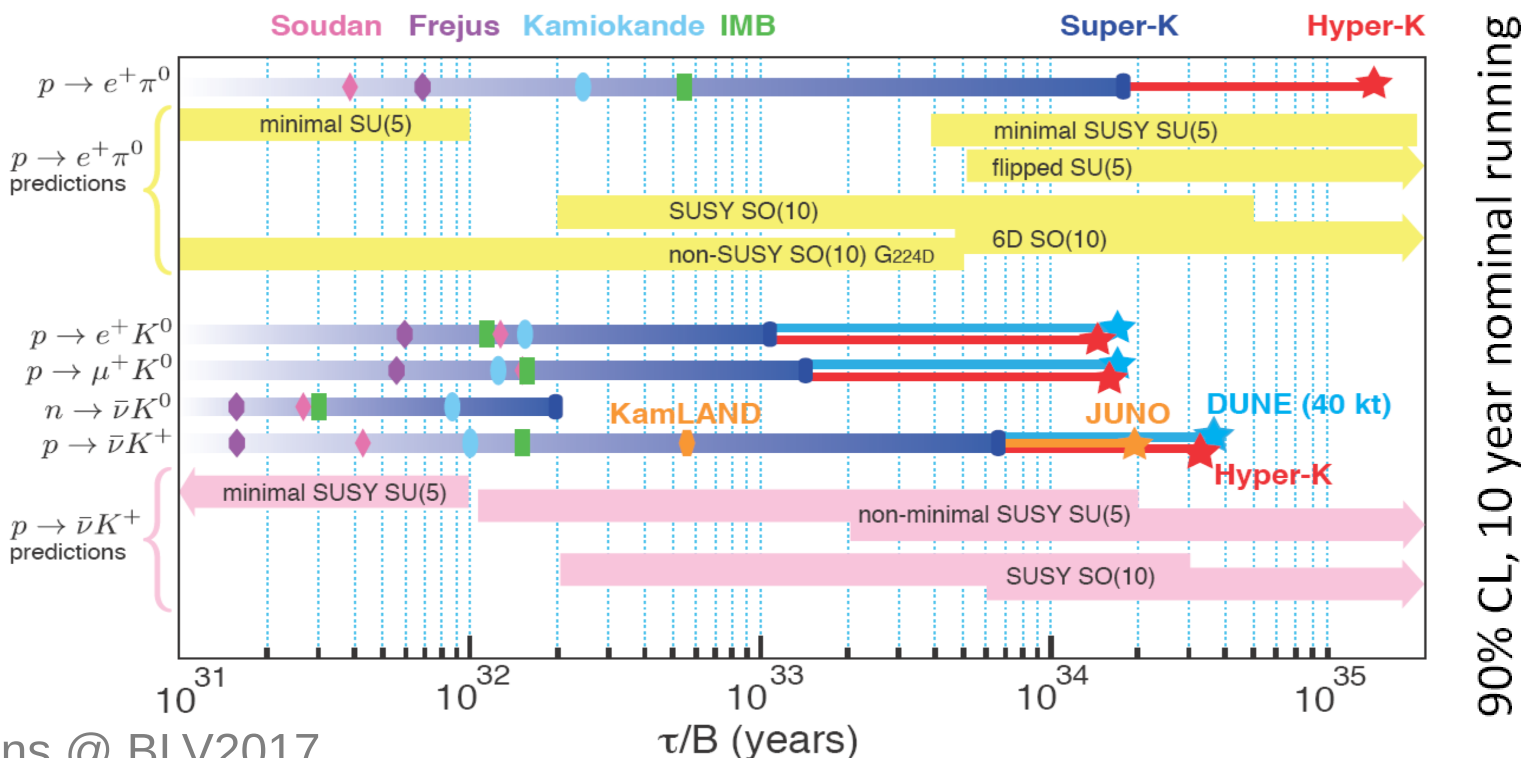


Nucleon Decay

Grand Unified Theories (GUT): e.g. SU(5), SO(10) , SUSY GUTs

- Single coupling constant, Charge quantization, etc
- Nucleon decay ➔ 1. $p \to e^{+} + \pi^{0}$

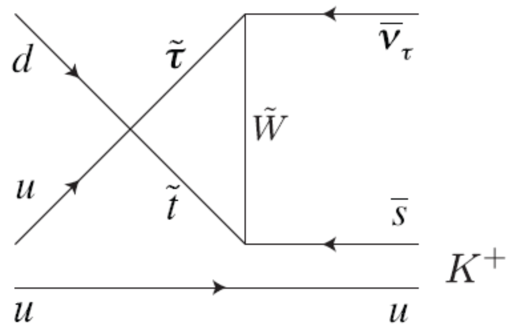
  2. $p \to \overline{\nu} + K^{+}$, SUSY GUTs

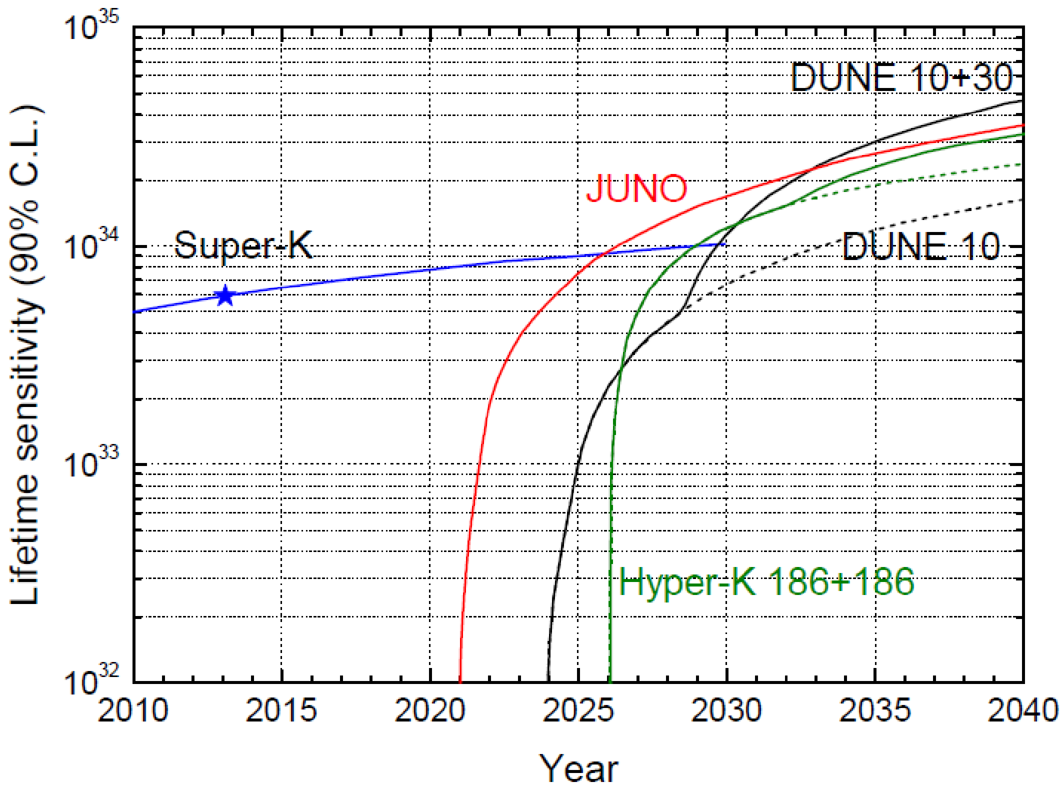


Ed Kearns @ BLV2017

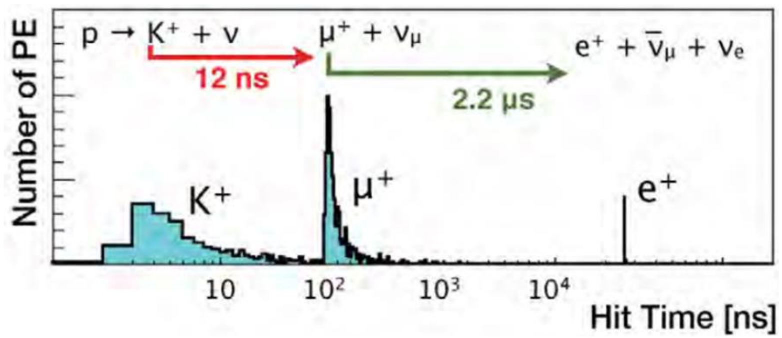
Search $p \to \bar{\nu} K^+$ in JUNO

Search $p \to \bar{\nu} K^+$ in JUNO:





Triple coincidence signals:



1st: $T_{K^+} = 105$ **MeV** $\to \tau_{K^+} = 12.38$ **ns**

2nd: $T_{\mu^+} = 152$ MeV$/E_{\pi^+\pi^0} = 494$ **MeV**

3rd: $2.2\mu s \to$ **Michel electron**

$\varepsilon \approx 65\%$

Multi-variate analysis tools are being developed for S/B discrimination.

Prospect of JUNO physics

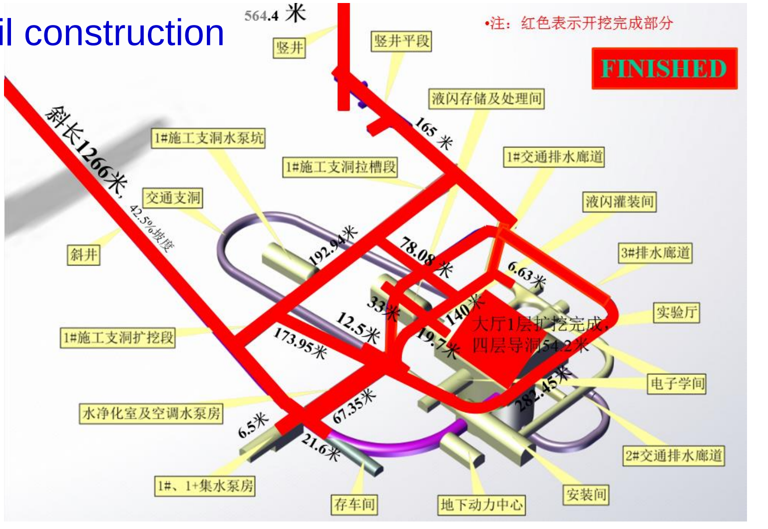
- JUNO is a multipurpose neutrino experiment
- Reactor antineutrinos
  - Determine neutrino mass hierarchy in a unique way, 3σ (4σ with $\Delta m^2_{\mu\mu}$) with 6 years data
  - Measure 3 of oscillation parameters at sub-percent level, first exp. to measure solar and atm. mass splitting simultaneously
- Neutrinos from astrophysical sources: sun, earth, supernova burst, DSNB …
- Nucleon decay and atmospheric neutrinos
- Neutrino-less double beta-decays as an upgrade plan

Prospect of JUNO project

- **Civil construction**: reached 700 m underground, exp. hall to be started
- **Central detector**: production of acrylic panels and stainless steel truss will start soon
- **PMT system**: receive 13,000 20-inch PMTs and 12,000 3-inch PMTs
- **Veto system**: top tracker delivered, water Cherenkov design completed
- **Liquid scintillator**: recipe optimized, pilot plant test nearly complete
- **Electronics**: all underwater, finalizing design, mass production starts soon

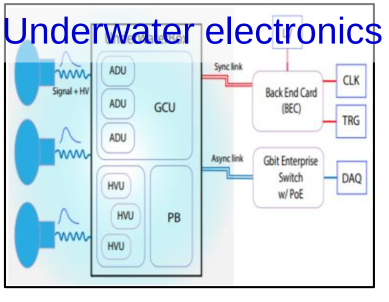
- **Operation by the end of 2021**

Civil construction




CD 1:12 prototype


PMT testing

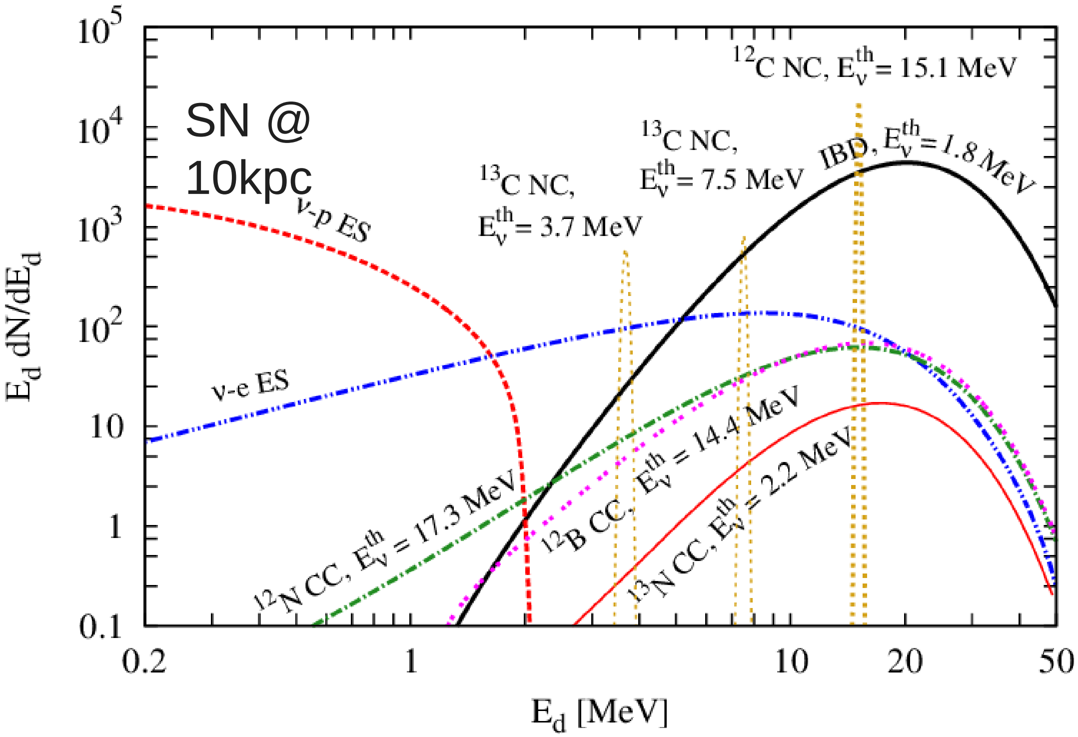


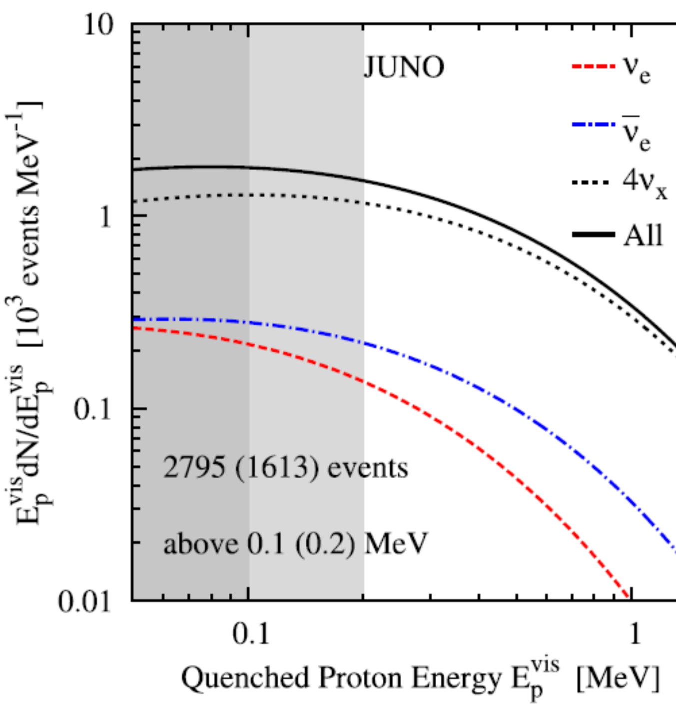
Underwater electronics


LS pilot project

backup

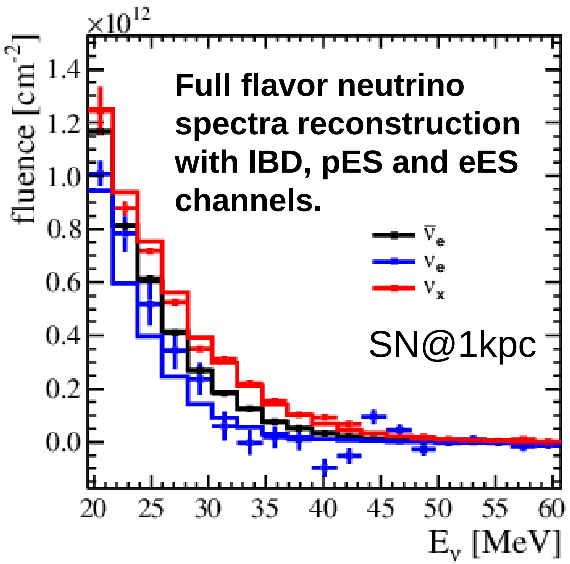
Detection of SN neutrinos



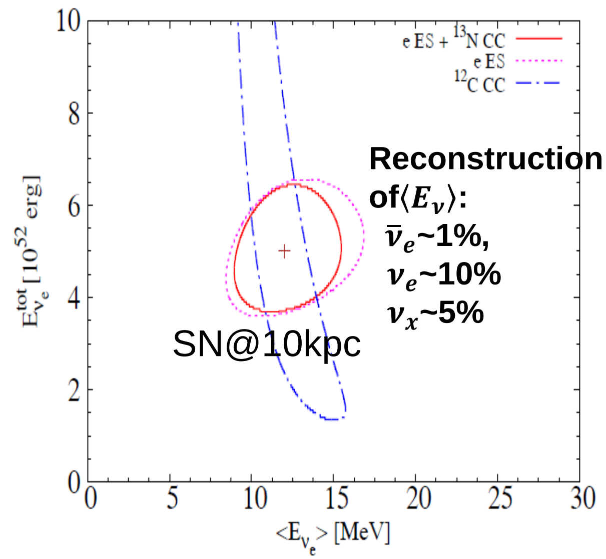


- **Full flavor** detection and **low threshold energy** ~0.2 MeV in LS
- **IBD** is **the golden channel**, ~5000 events for SN@10 kpc
- Especially **the pES channel** can provide us more information about $\boldsymbol{\nu_x}$, better than other type of detectors, e.g. WC, LAr-TPC detectors
- **PSD method** to distinguish events from eES and pES

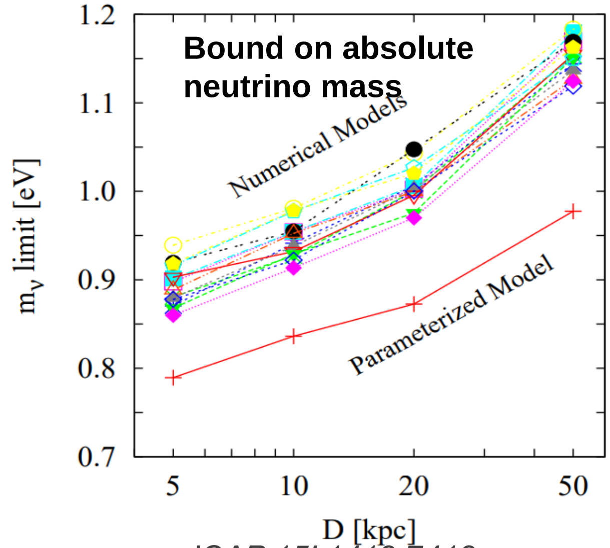
Physics implications of SN neutrinos



Phys. Rev. D 97, 063014



Phys. Rev. D 94, 023006



JCAP 15',1412.7418

For particle physics:

- Bound on absolute neutrino mass
- Discriminate Mass hierarchy of neutrinos?
- Collective neutrino oscillation?
- …

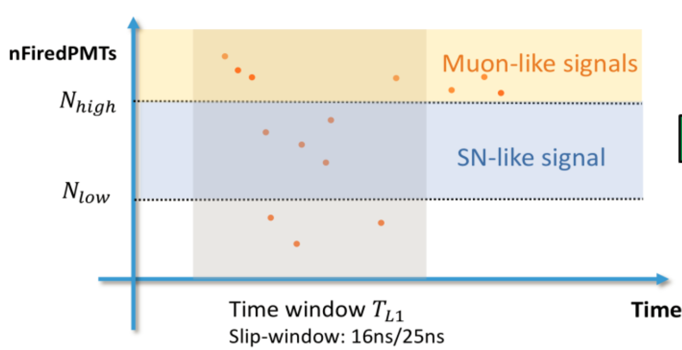
For astrophysics:

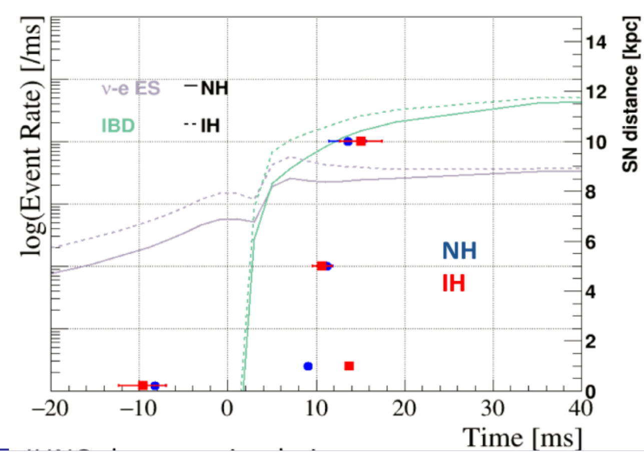
- Locating SN
- Coincidence with Gravitational wave
- SN nucleosynthesis
- Conditions of SN explosion
- …

Potentials for multimessengers

- A comprehensive trigger and DAQ strategy to maximize the potentials on multi-messengers
  - Supernova Burst Neutrinos
  - Low energy events accompanied with astrophysical events

Data taking mode	Trigger type	Energy range
Physics	Global Trigger	>0.2 MeV
Supernova Burst	Self-trigger	All above-threshold SPE waveforms during the SN explosion
‘Multi-messenger’	Stream out hits’ timestamps; Software trigger afterwards	Full capability in <0.2 MeV region

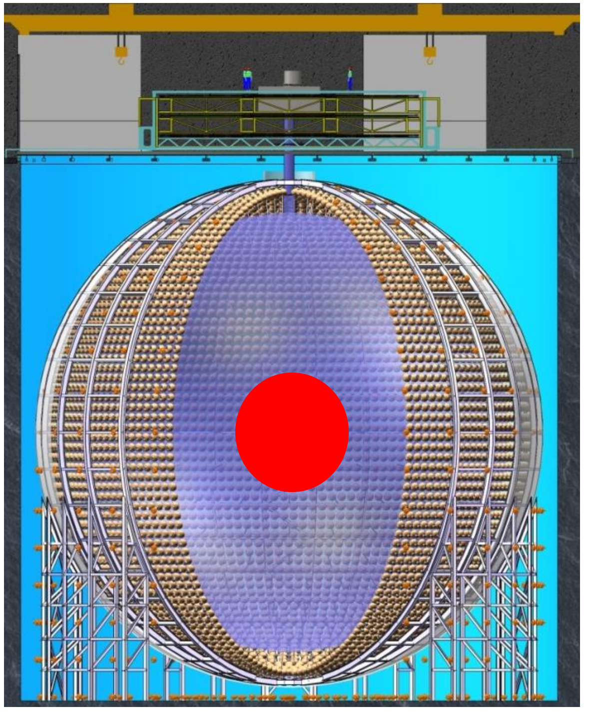




Future: Double beta-decays

- Once MH measurement is mostly completed(~2030), the detector can be upgraded for ββ-decays, in addition to existing capabilities
- Cosmogenic backgrounds can be removed by a cut of LS volume along the muon track for seconds

	Isotopes	Mass(t)	$<m_{\beta\beta}>$,meV
nEXO	^{136}Xe	5	7-22
GERDA/Majorana ->LEGEND-1000	^{76}Ge	1	10-40
SNO+	^{130}Te	8	19-46
KamLAND-Zen	^{136}Xe	1	~20
CUORE->CUPID	^{130}Te->^{100}Mo	0.3	6-20
JUNO-ββ	^{136}Xe	50	4-12



Insert a balloon filled with ^{136}Xe-loaded LS(or ^{130}Te) into the JUNO detector

Zhao et al., arXiv: 1610.07143, CPC 41（2017）5