Neutrino Physics and Beyond at JUNO

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On behalf of the JUNO Collaboration

10th workshop of the FCPPL

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The JUNO

- **JUNO** (Jiangmen Underground Neutrino Observatory): a 20 kton **“multipurpose”** neutrino experiment, under construction near Kaiping (South China).

Oscillation probes

1. Neutrino Mass Hierarchy
2. Precision Measurements of mixing parameters

“Neutrino physics with JUNO “ - J. Phys. G 43 (2016) 030401

Astrophysical sources

1. Supernova burst neutrinos
2. Diffuse supernova neutrinos
3. Solar neutrinos
4. Geo-neutrinos
5. Atmospheric neutrinos

Others

1. Sterile neutrinos
2. Exotic searches

   Indirect dark matter search

   Proton decay

   Other probes of new physics

List of JUNO Members

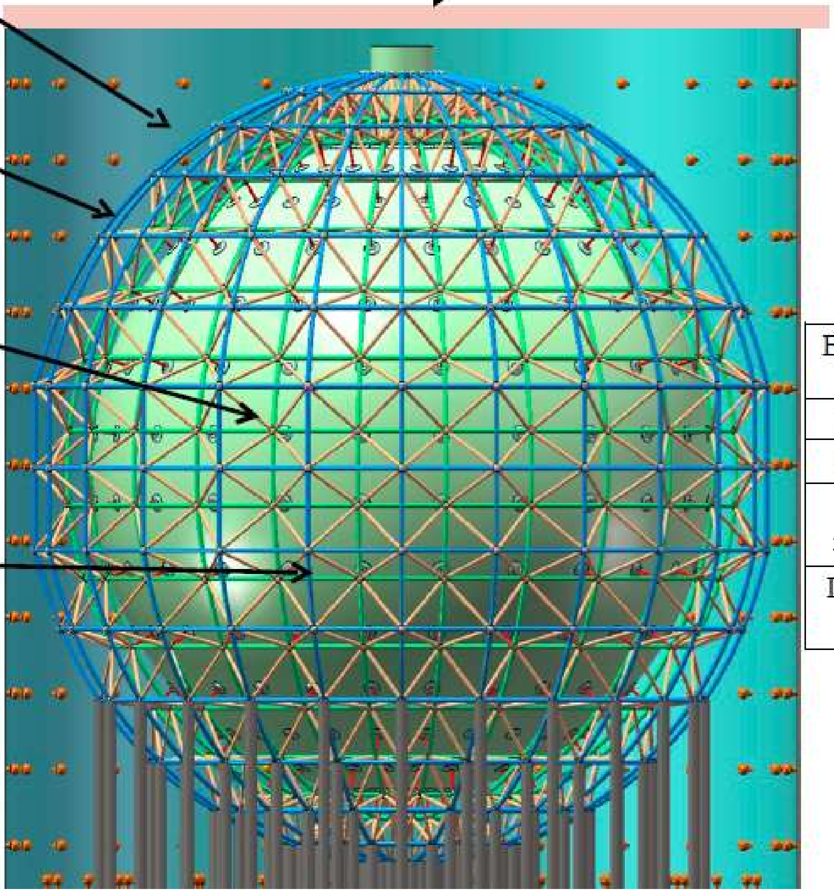
Country	Institute
Armenia	Yerevan Physics Institute
Belgium	Universite libre de Bruxelles
Brazil	PUC
Brazil	UEL
Chile	PCUC
Chile	UTFSM
China	BISEE
China	Beijing Normal U.
China	CAGS
China	ChongQing University
China	CIAE
China	DGUT
China	ECUST
China	Guangxi U.
China	Harbin Institute of Technology
China	IHEP
China	Jilin U.
China	Jinan U.
China	Nanjing U.
China	Nankai U.
China	NCEPU
China	Pekin U.
China	Shandong U.
China	Shanghai JT U.
China	IMP-CAS
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	NUDT
Czech	Charles U.
Finland	University of Oulu
France	APC Paris
France	CENBG
France	CPPM Marseille
France	IPHC Strasbourg
France	LLR Palaiseau
France	Subatech Nantes
Germany	Forschungszentrum Julich ZEA2
Germany	RWTH Aachen U.
Germany	TUM
Germany	U. Hamburg
Germany	IKP FZJ
Germany	U. Mainz
Germany	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
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

= 71 members

Observers

1. Department of Physics, Jyvaskyla University, (Finland)
2. Institute of Electronics and Computer Science, (Riga, Latvia)

The Juno Detector



Underground detector: more than 700 m of rock overburden

Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~ 300 ton	~ 1kton	**20 kton**
Coverage	~ 12%	~ 34%	~ 34%	~ 80%
Energy resolution	$7.5\%/\sqrt{E}$	~ $5\%/\sqrt{E}$	~ $6\%/\sqrt{E}$	~ $3\%/\sqrt{E}$
Light yield	~ 160 p.e./MeV	~ 500 p.e./MeV	~ 250 p.e./MeV	**~ 1200** p.e./MeV

Oscillation Current Status

$$\mathbf{U_{3\times3}} = \mathbf{U}_{\mathrm{PMNS}}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor eigenstates	atmospheric mixing	reactor mixing & CP violation	solar mixing	mass eigenstates
	$\theta_{23} \approx (45\pm9)°$	$\theta_{13} \approx (8.9\pm1.4)°$, δ_{CP}=?	$\theta_{12} \approx (34\pm3)°$	

Resolved issues:

- Three non-zero mixing angles have been measured
- Two independent mass-squared differences $|\Delta m^2_{31}|$ (or $|\Delta m^2_{32}|$) and Δm^2_{21} have been measured

Unresolved issues:

- **Mass hierarchy**
- **CP-violating phase**
- **Theta(23) octant**

Constitutes the main focus of the future neutrino oscillation experiments.

Mass Hierarchy

From global fits

(see JHEP 1701 (2017) 087; arXiv: 1703.04471[hep-ph])

$\Delta m^2_{21} = (7.37 \pm 0.17) \text{ x } 10^{-5} eV^2$

(Solar + KL)

$|\Delta m^2_{31(32)} = (2.52 \pm 0.04) \text{x} 10^{-3}|\ eV^2$

(Atmospheric + LBL)

Two possible scenarios

NH

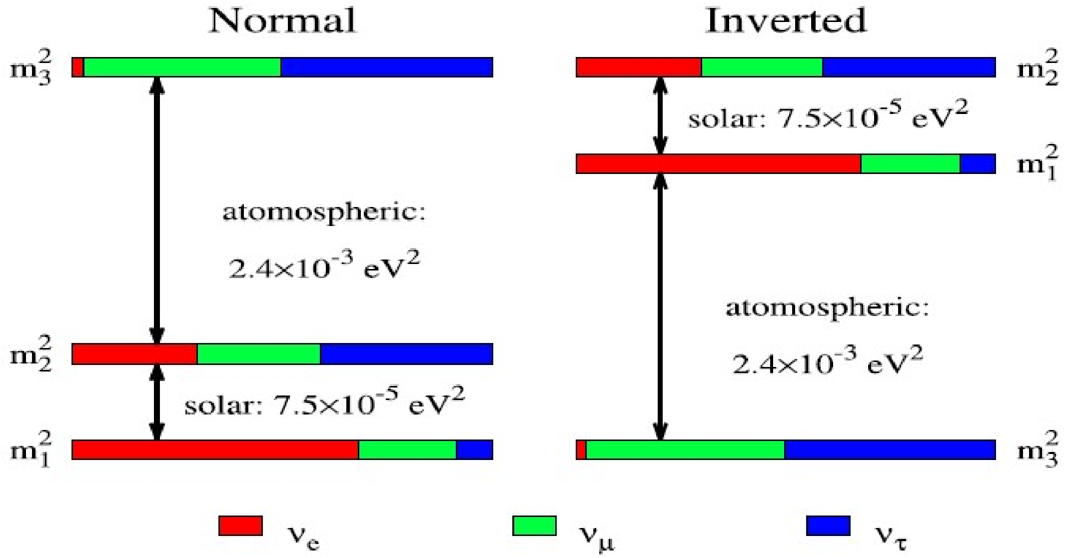
$|\Delta m^2_{31}| = |\Delta m^2_{32}| + \Delta m^2_{21}$

$|\Delta m^2_{31}| > |\Delta m^2_{32}|$

IH

$|\Delta m^2_{31}| = |\Delta m^2_{32}| - \Delta m^2_{21}$

$|\Delta m^2_{31}| < |\Delta m^2_{32}|$



Why measure MH?

- helps to resolve δCP
- define the goal of0νββ
- important discriminator for model building of the neutrino masses

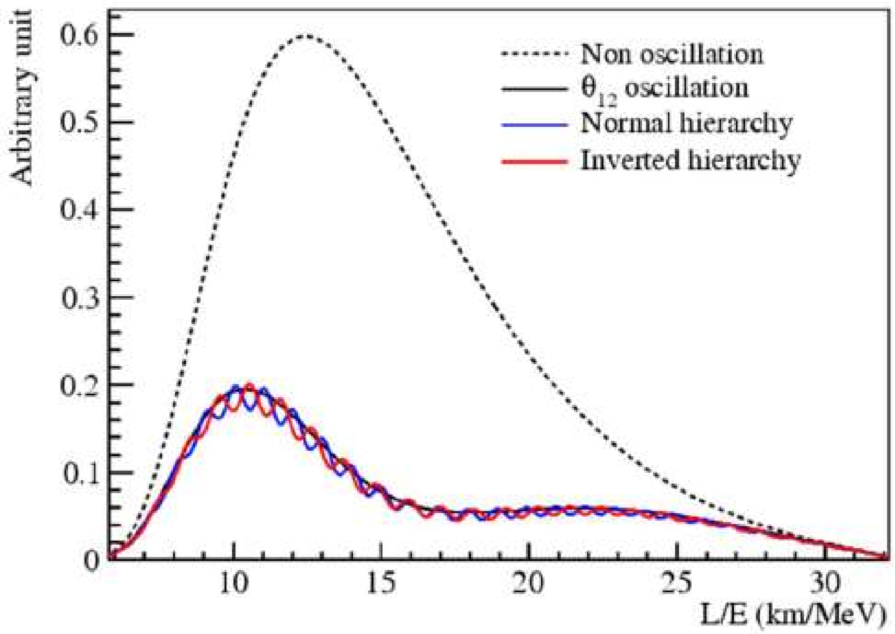
Vacuum oscillation: reactor neutrinos S. T. Petcov et al., PLB 533 (2002) 94

How to measure

$$P_{\overline{\nu}_e\to\overline{\nu}_e} = 1 - \sin^2 2\Theta_{13}\left(\cos^2\Theta_{12}\,\mathbf{\sin^2\Delta_{31}} + \sin^2\Theta_{12}\,\mathbf{\sin^2\Delta_{32}}\right) - \cos^4\Theta_{13}\sin^2 2\Theta_{12}\sin^2\Delta_{21}$$

$$\Delta_{ij} = \Delta m_{ij} L/4E$$

E: neutrino energy
L: distance to source



JUNO Collaboration, J. Phys. G 43, 030401 (2016)

- **How the interference happens?**

L/E spectrum contains the MH infroamtion:

L/E spectrum ⇔ Δm^2 spectrum(oscillation frequency)

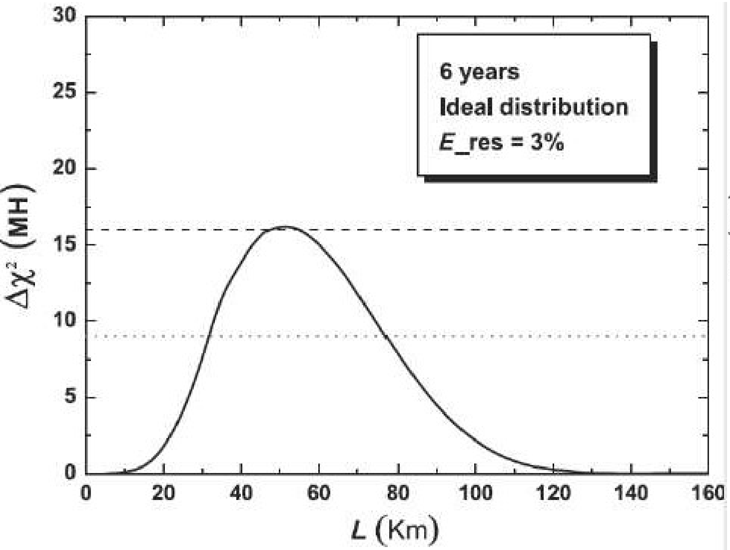
J. Learned et. al. hep-ex/0612022 L. Zhan et. al. 0807.3203

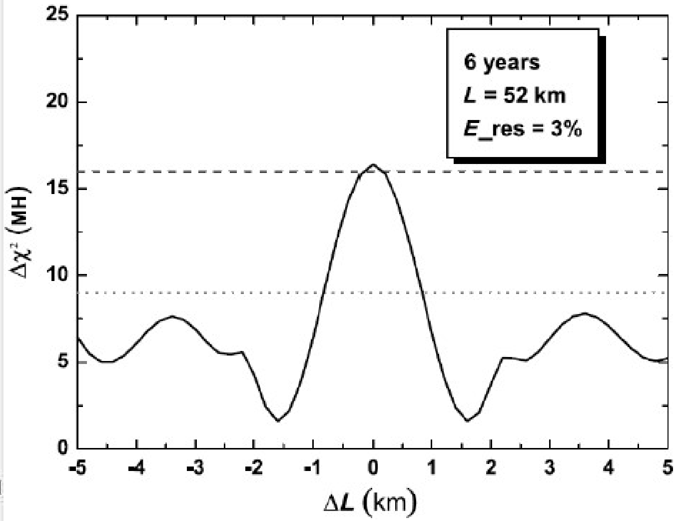
- **Requirements for measuring MH:**

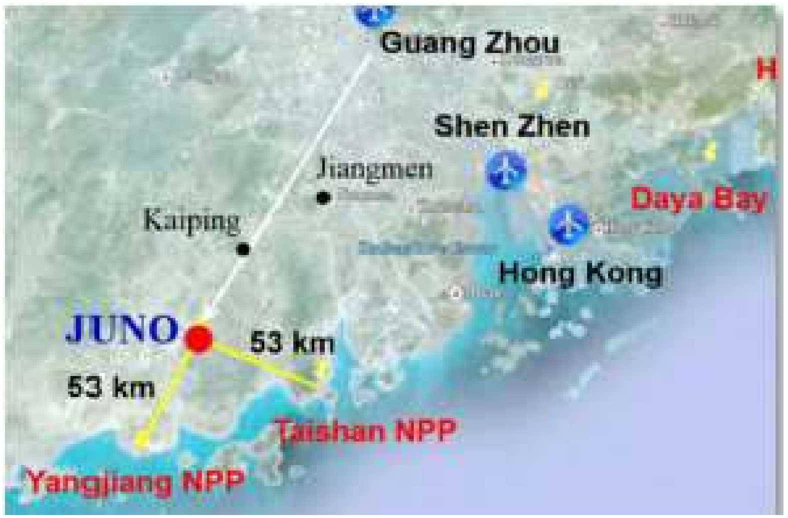
• position with advantageous *L*/*E* ratio
• low energy threshold
• excellent energy resolution
• low energy scale uncertainty

Baseline Optimization

• ~53 km distance to two nuclear power plants (35.8 GW Pth)





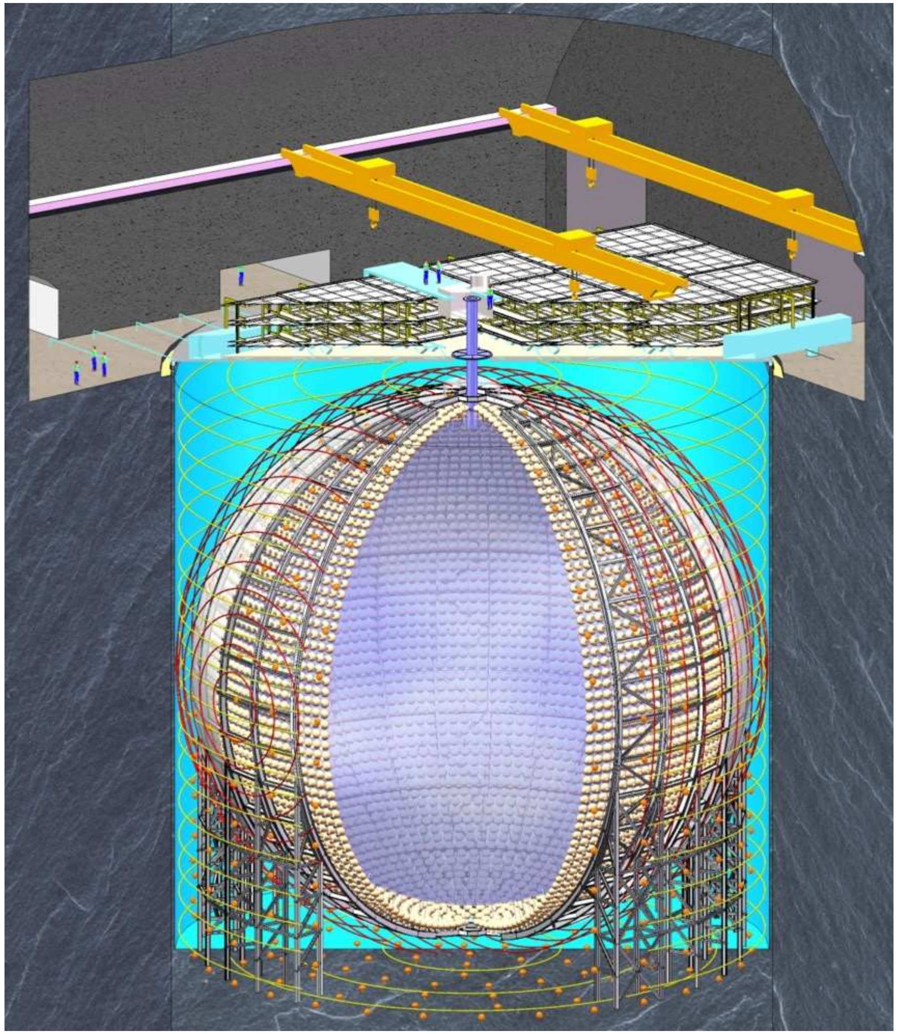


Y. F. Li et al., PRD.88.013008

➢ JUNO selected the experiment site with Considering the baseline optimization and impact of the baseline difference

➢ A candidate site was identified by taking account of the physical performance and detailed geological survey.

Excellent Energy Resolution



The energy resolution as or better than the size of $\Delta m^2_{21}/|\Delta m^2_{31}|$

- **Low energy threshold:**
  20 kt liquid scintillator

- **Excellent energy resolution:**
  Arcylic tank：φ35.4m
  （PMT sphere：φ40.1m）
  ~18,000 20” PMTs
  ~36,000 3” PMTs
  77% coverage
  QE ≈30%

$\Delta E/E=3\%/\sqrt{E(MeV)}$

Energy scale uncertainty < 1%

Signal and Background

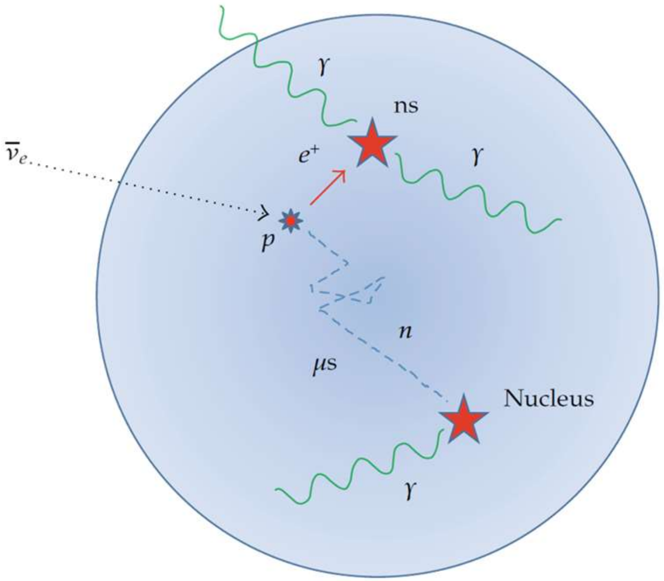
- Signal channel:

Inverse Beta Decay (IBD),

Prompt and

delayed coincidence signature

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

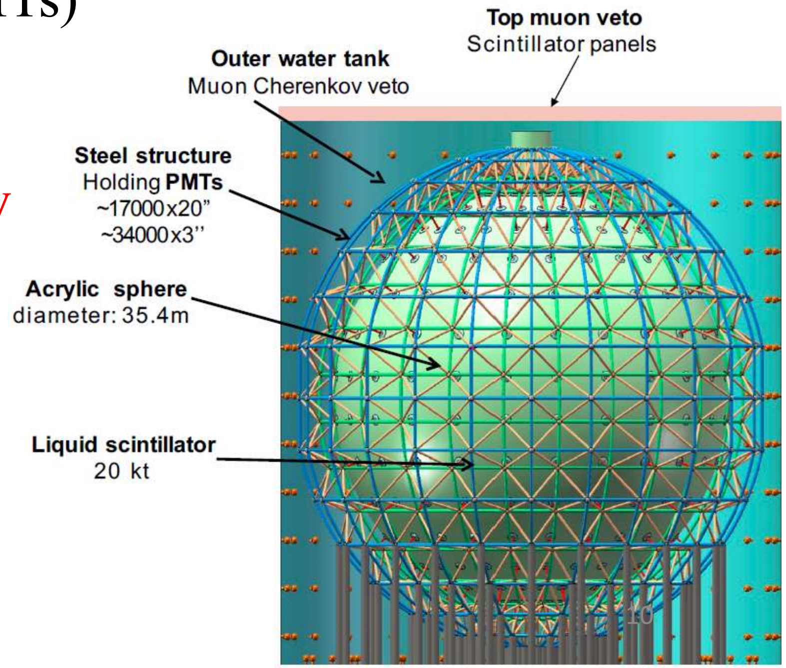


- Background reduction:

1. ~700 m rock overburden (~ 1900 m.w.e.)
2. Top tracker (IPHC Strasbourg)
3. Ultra pure water buffer as Cherenkov veto (2400 20” PMTs)

After cuts:

60 IBD/day vs 3.8 background events/day



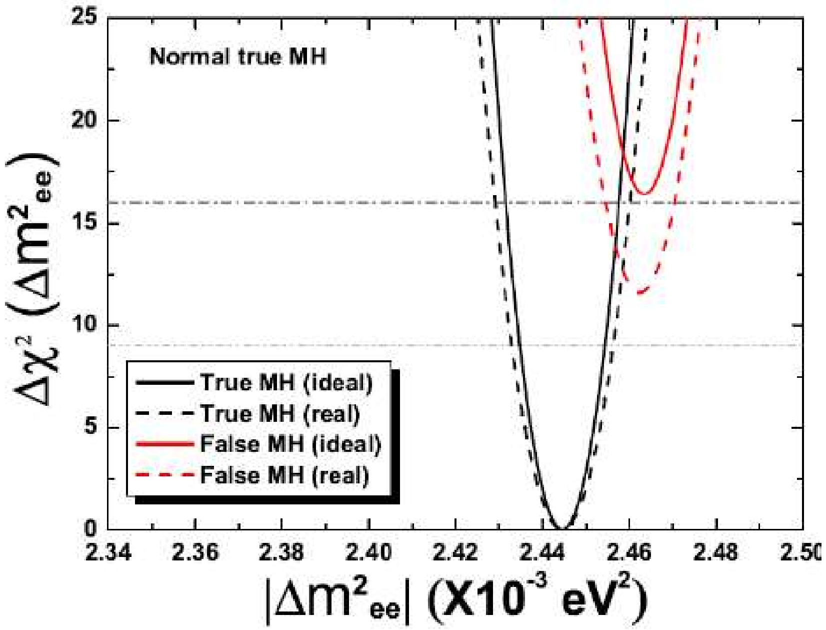
MH sensitivity for JUNO

$$:= \Delta m^2_{ee}$$

$$P_{\overline{\nu}_e \to \overline{\nu}_e} = 1 - \sin^2 2\Theta_{13} \left(\cos^2 \Theta_{12} \sin^2 \Delta_{31} + \sin^2 \Theta_{12} \sin^2 \Delta_{32} \right) - \cos^4 \Theta_{13} \sin^2 2\Theta_{12} \sin^2 \Delta_{21}$$

$$\Delta_{ij} = \Delta m_{ij} L / 4E$$

E: neutrino energy
L: distance to source



Y. F. Li et al., PRD.88.013008

Median sensitivity on MH after100k IBD (6 yr of running):

- **3σ (ΔX^2>10) with the spectral measurement**
- **4σ if including an external $\Delta m^2(\mu\mu)$ measurement** spread of reactor cores, uncertainties from reactor neutrino flux, the energy scale and non-linearity.

Advantages

JUNO looks at almost **vacuum oscillations** and, therefore, it **doesn’t sufffer** from the **uncertainty** on **Earth density** profile **and** the **ambiguity** of **CP-violating phase**.

Other Oscillation Probes

- JUNO can measure antineutrino spectrum with excellent energy resolution
- **Precision measurement of** the neutrino oscillation parameters to an accuracy of better than 1%,

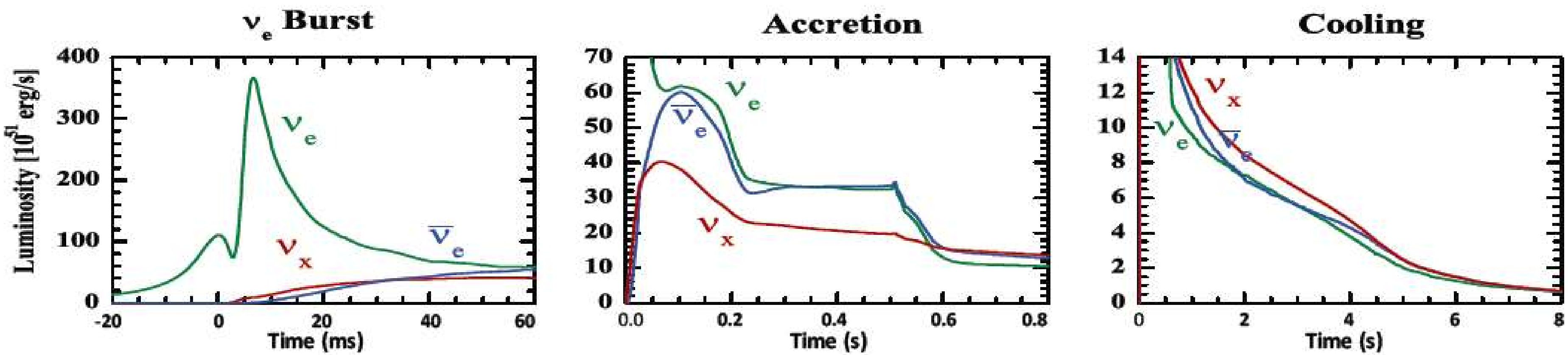
JUNO Collaboration, J. Phys. G 43, 030401 (2016)

Oscillation Parameter	Current accuracy (global 1σ) **	Dominant experiment(s)	JUNO Potentiality
Δm_{21}^2	2.3%	KamLAND	0.59%
$\Delta m^2 = \lvert m_3^2 - \frac{1}{2}(m_1^2 + m_2^2)\rvert$	1.6%	MINOS, T2K	0.44%
$\sin^2(\theta_{12})$	~4-6%	SNO	0.67%

Esteban et. al, JHEP 1701 (2017) 087 and F. Capozzi et al., arXiv: 1703.04471[hep-ph]

Observatory of Astrophysical Sources

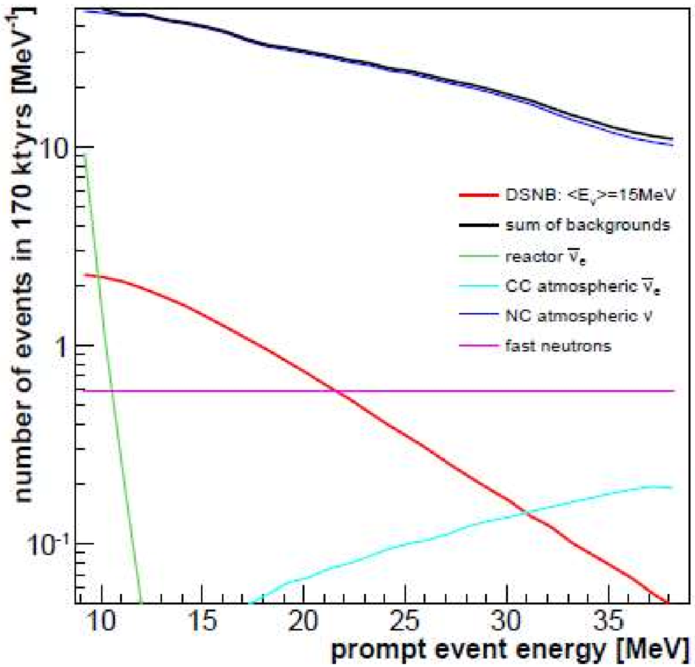
Supernova Neutrino Physics @ JUNO

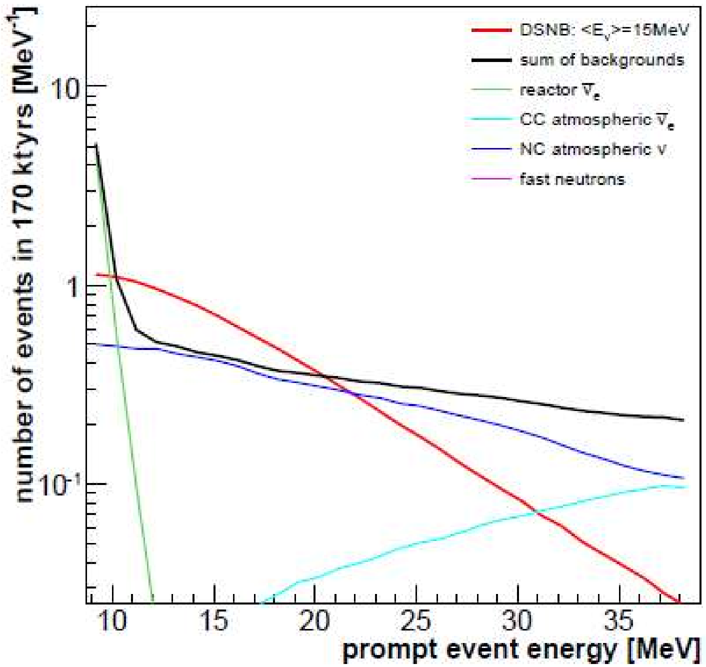


- For a SN at a distance of10kpc, JUNO will register about 5000 events from IBD, 2000 events from all-flavor elastic neutrino-proton scattering (>0.2 MeV).
- SN neutrino events with high statistics, flavor information, good energy resolution, give us a great opportunity to understand the mechanism of supernova explosion and physical pictures of the neutrino oscillation.

Process	Type	Events ($\langle E_\nu \rangle$ = 14 MeV)
$\bar{\upsilon}_e + p \rightarrow e^+ + n$	CC	5.0×10^3
$\upsilon + p \rightarrow \upsilon + p$	NC	1.2×10^3
$\upsilon + e \rightarrow \upsilon + e$	ES	3.6×10^2
$\upsilon + {}^{12}C \rightarrow \upsilon + {}^{12}C^*$	NC	3.2×10^2
$\upsilon_e + {}^{12}C \rightarrow e^- + {}^{12}N$	CC	0.9×10^2
$\bar{\upsilon}_e + {}^{12}C \rightarrow e^+ + {}^{12}B$	CC	1.1×10^2
N.B.: Other $\langle E_\upsilon \rangle$ values	needed to be	considered for a complete picture

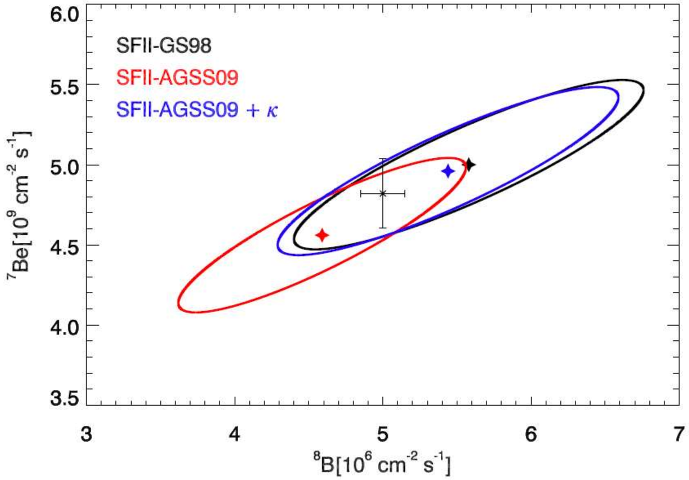
DSNB@JUNO

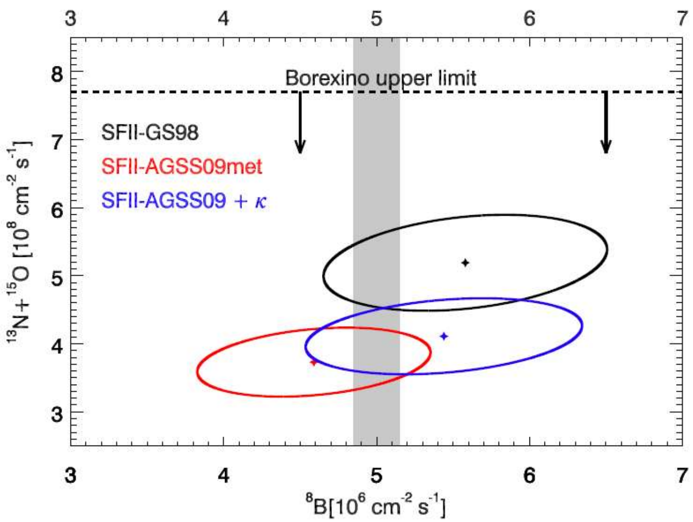




- DSNB: the integrated neutrino flux from past Core collapse SN rate
- Gives: cosmic star-formation rate， the average spectrum and rate of failed SN
- Strong atmospheric neutrino background, pulse-shape discrimination techniques
- 3***σ*** expected for observation after 10 yr
- non-detection improve current limits and exclude a significant range of DSNB parameter space.

Solar neutrinos @ JUNO



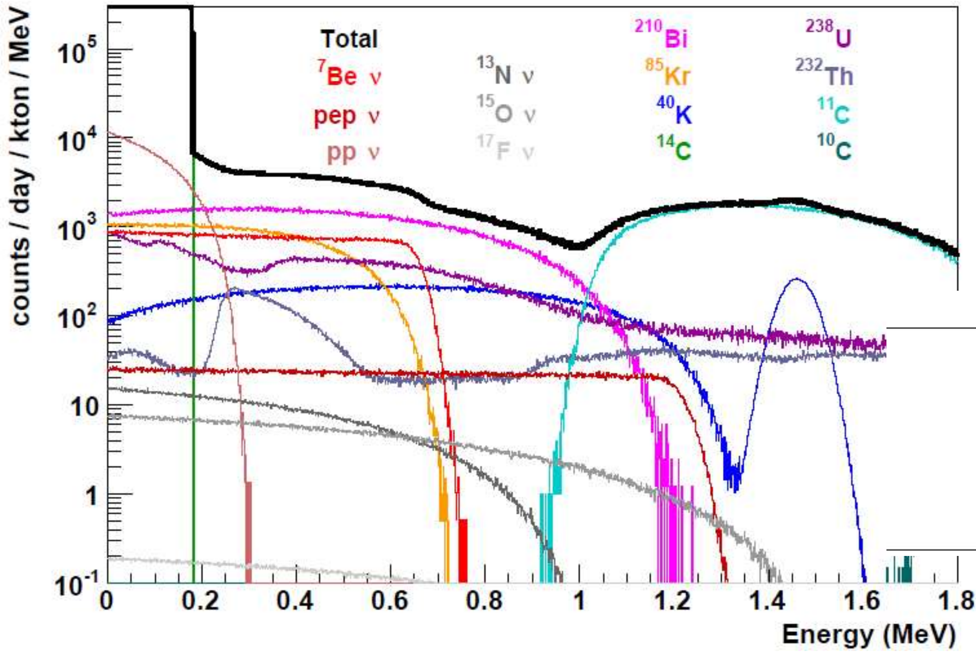


□ ν_e elastic neutrino electron scattering

Study of part of the pp solar fusion chain

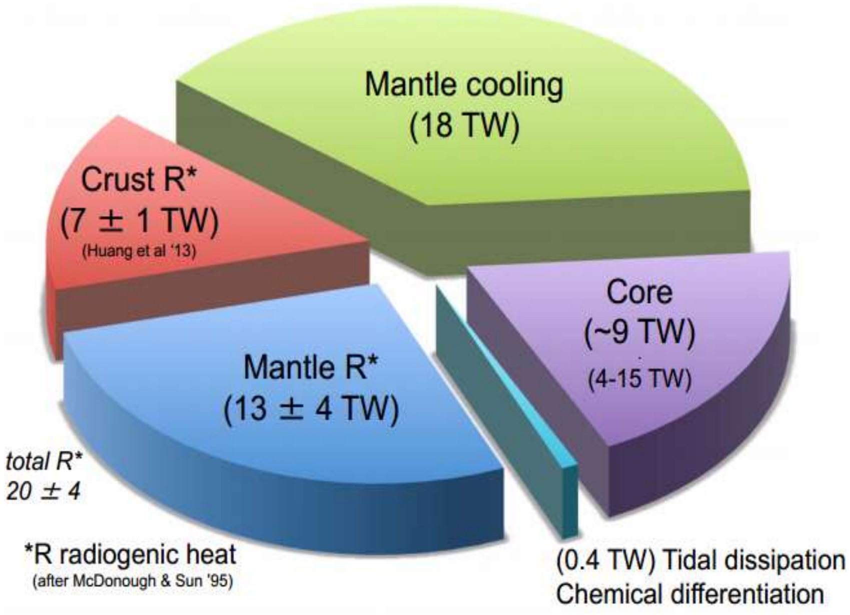
- **^{7}Be neutrinos:**
  sub-MeV part of spectrum
- **^{8}B neutrinos**

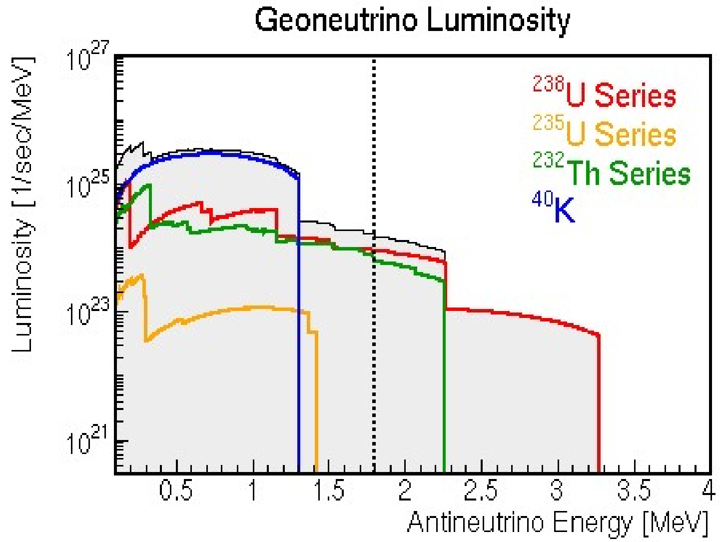
Test of **MSW** oscillation **pattern.** Impact on **Solar Models**. Metallicity problem

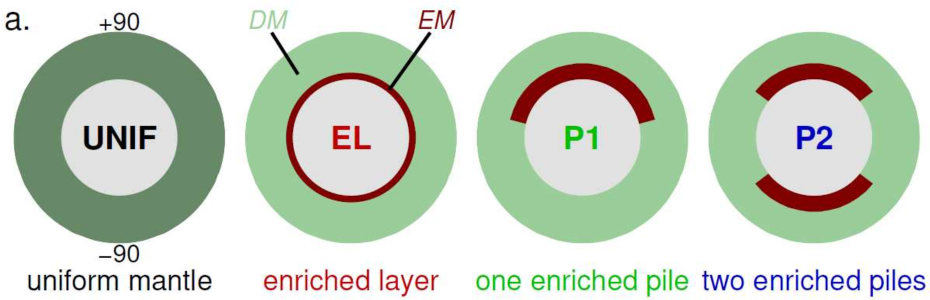


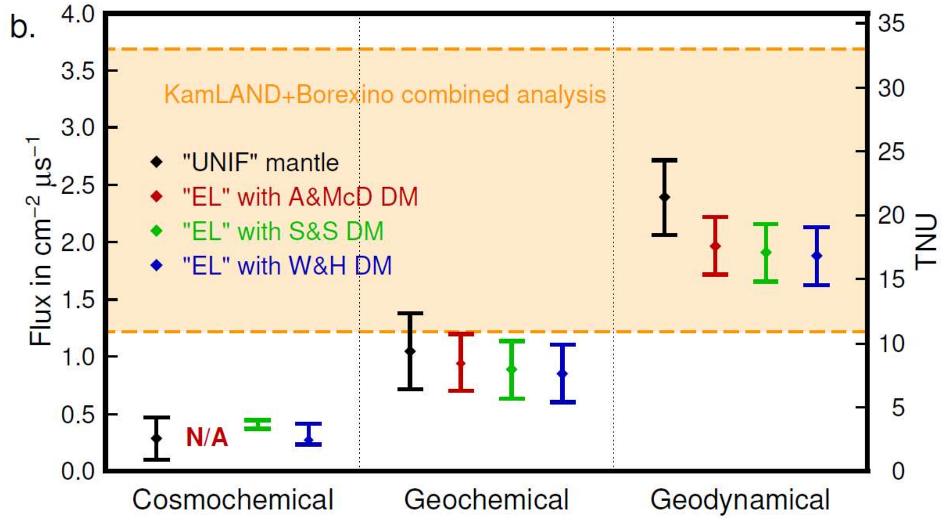
	baseline
^{210}Pb	5×10^{-24} [g/g]
^{85}Kr	500 [counts/day/kton]
^{238}U	1×10^{-16} [g/g]
^{232}Th	1×10^{-16} [g/g]
^{40}K	1×10^{-17} [g/g]
^{14}C	1×10^{-17} [g/g]

Geo-neutrino physics





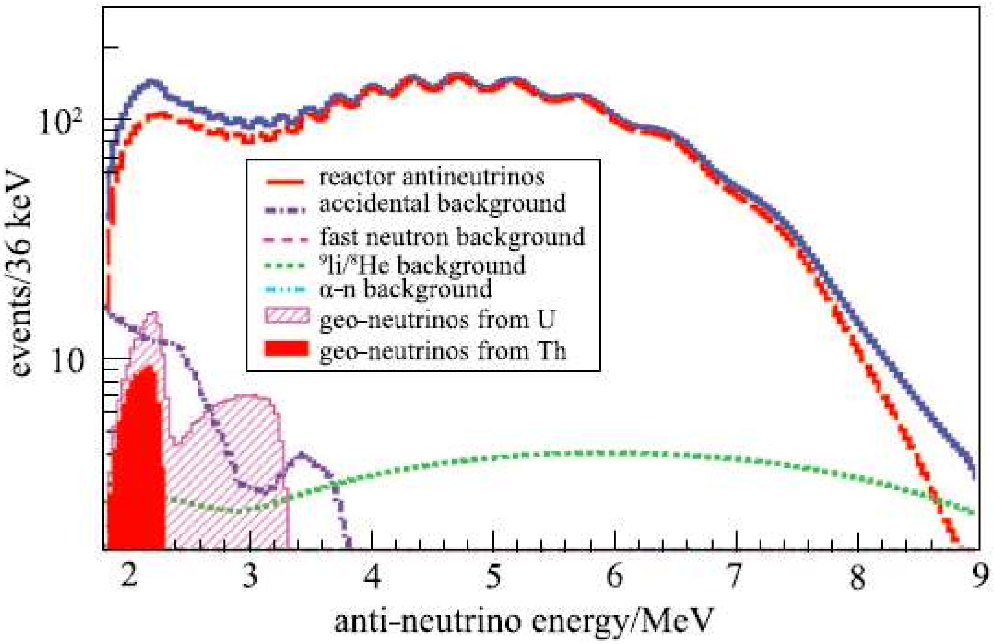


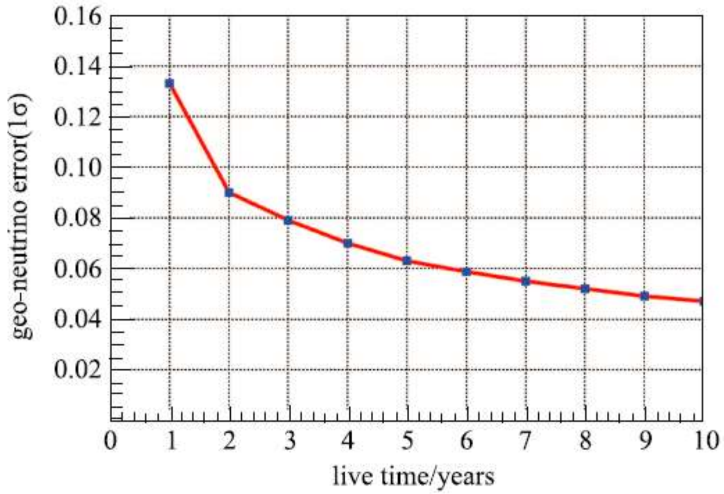


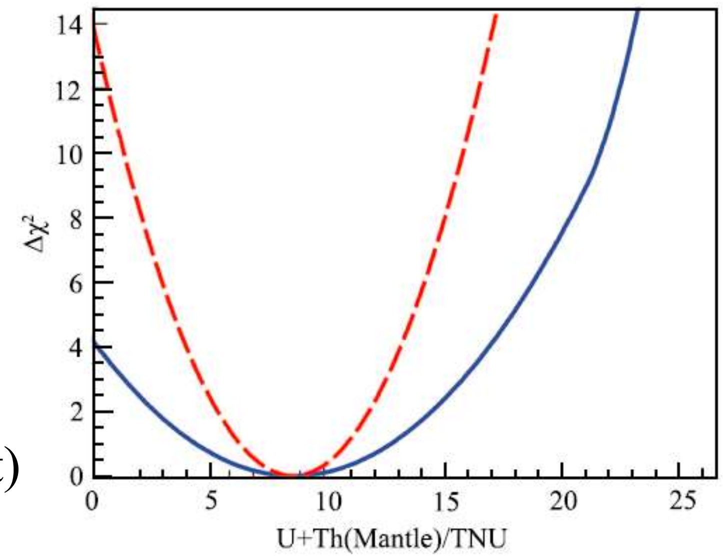
the future… *Geoneutrino studies*

Geo-neutrino physics @ JUNO

R. Han et al. Chin.Phys.C(2016)



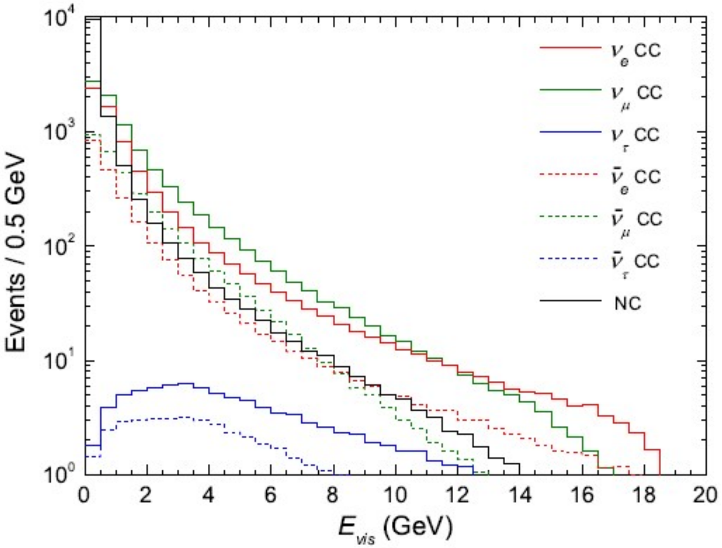


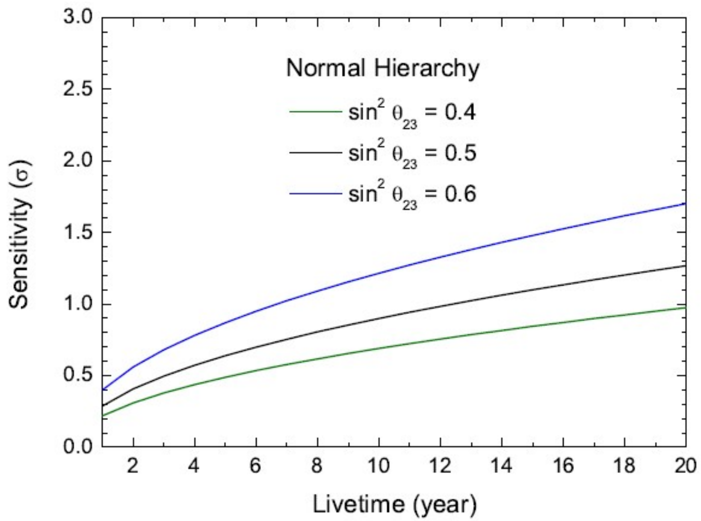


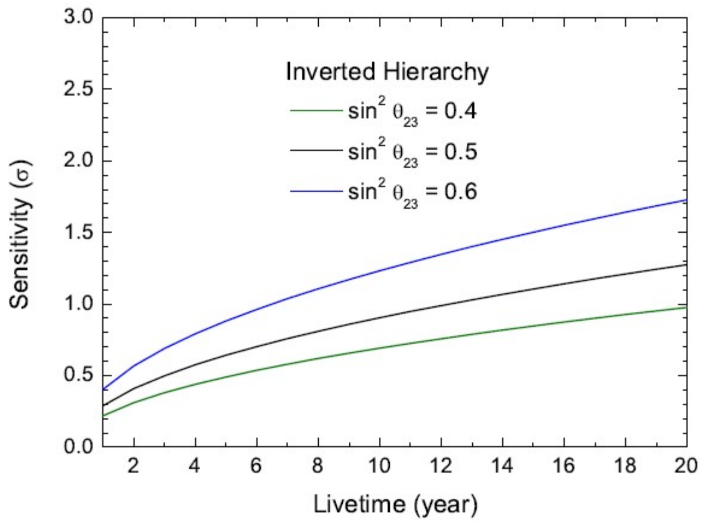
- 400events/year, much larger than before
- With 10 years: total uncertainty reach 5%（2TNU
- Comparison of the global reference model (18% crust) and a benchmark accuracy of the local model(8% crust)
- 3D local crust model is building now….

Atmospheric Neutrinos

- Atmospheric neutrinos are a very important neutrino source to study the neutrino oscillation physics.
- The JUNO central detector has a very low energy threshold and can measure atmospheric neutrinos with excellent energy resolution.

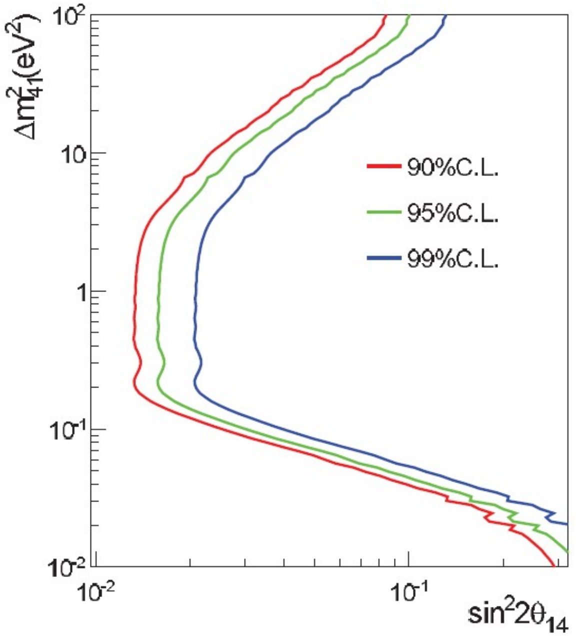


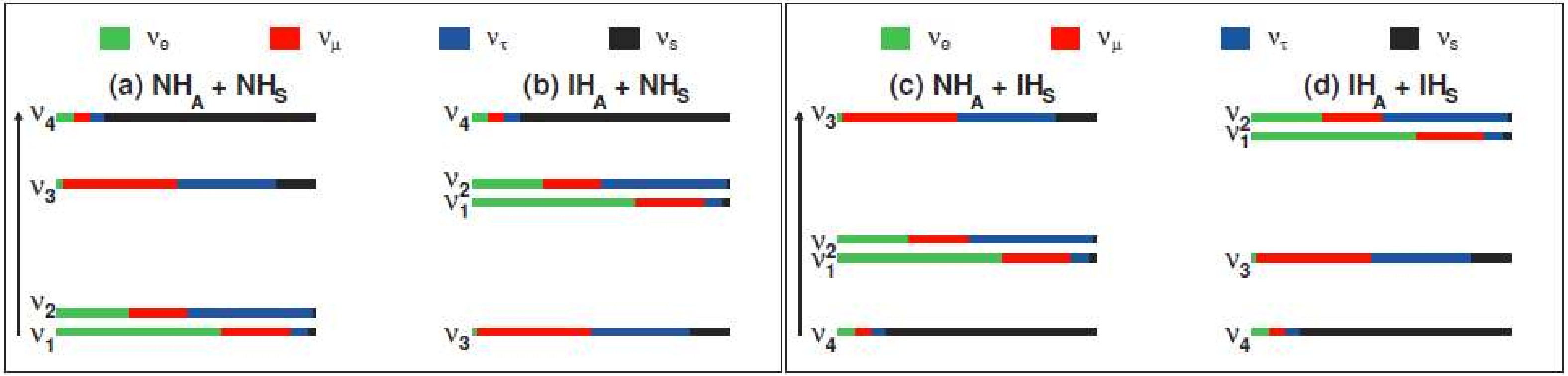




Sterile Neutrinos

- Sterile neutrinos are gauge singlets of the Standard Model. They do not participate in standard weak interactions but couple to the active neutrinos through non-zero mixing between active and sterile flavors.
- The diameter of the JUNO central detector will be around 35 meters, which is perfectly suitable for a short-baseline oscillation experiment with a radioactive neutrino source sensitive to eV-scale sterile neutrinos.
- Sensitivity search at JUNO, assuming a 50 kCi ^{144}Ce source at the detector center, with 450 days of data-taking. show the 90, 95 and 99% confidence levels including the reactor antineutrino background.

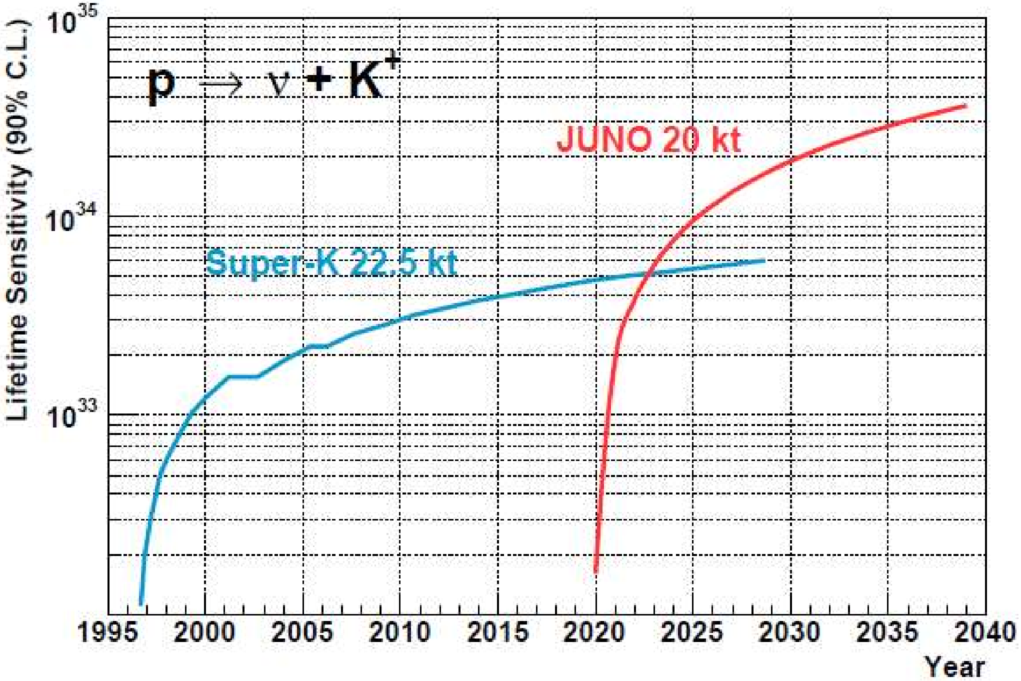




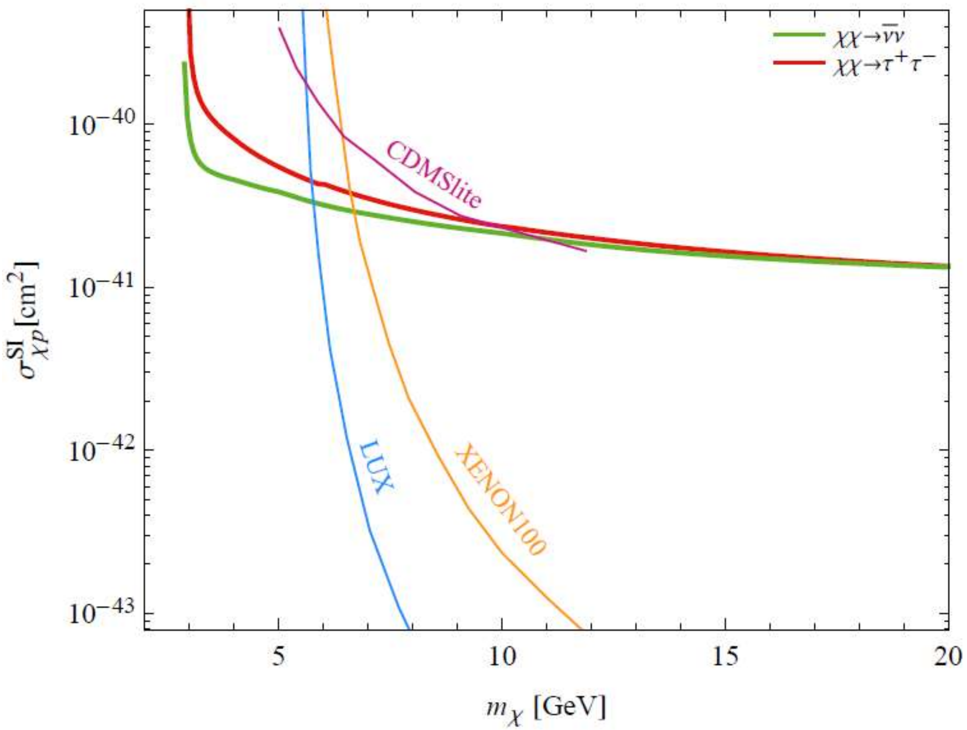
Exotic searches

- Indirect dark matter search
- Nucleon decay
- Non-standard interaction
- Test unitarity using absolute measurements
- Other probes of new physics

Nucleon decay

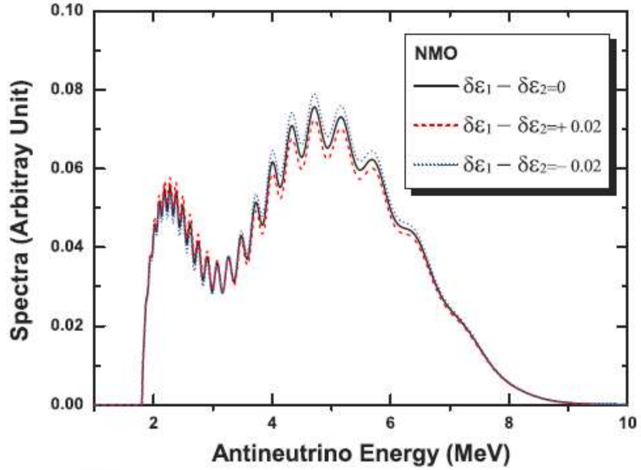


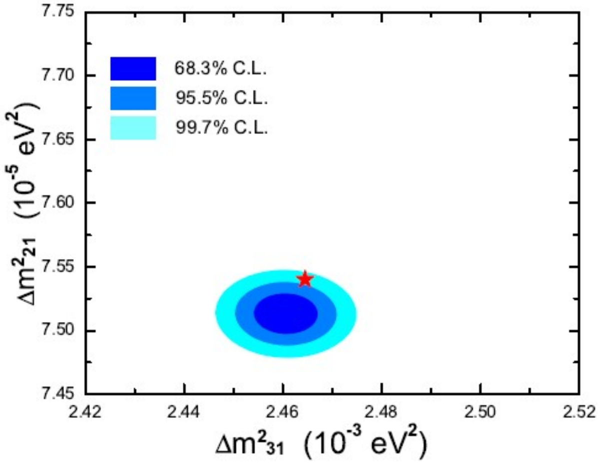
Neutrinos from Dark Matter



Others

Non-standard Interactions





Summary

- **JUNO**: A funded project under construction; a 20kt LS detector in China with the purpose to Determine the neutrino mass hierarchy with reactor anti-neutrinos; unprecedented energy resolution and energy scale precision
- **Furthermore,** great potential regarding Astrophysical neutrinos, Atmospheric neutrinos, Exotic Search...
- **Significance:** after 100k IBD events (6 yr of data taking), 3-4 sigma