Neutrinos from Natural Sources at JUNO

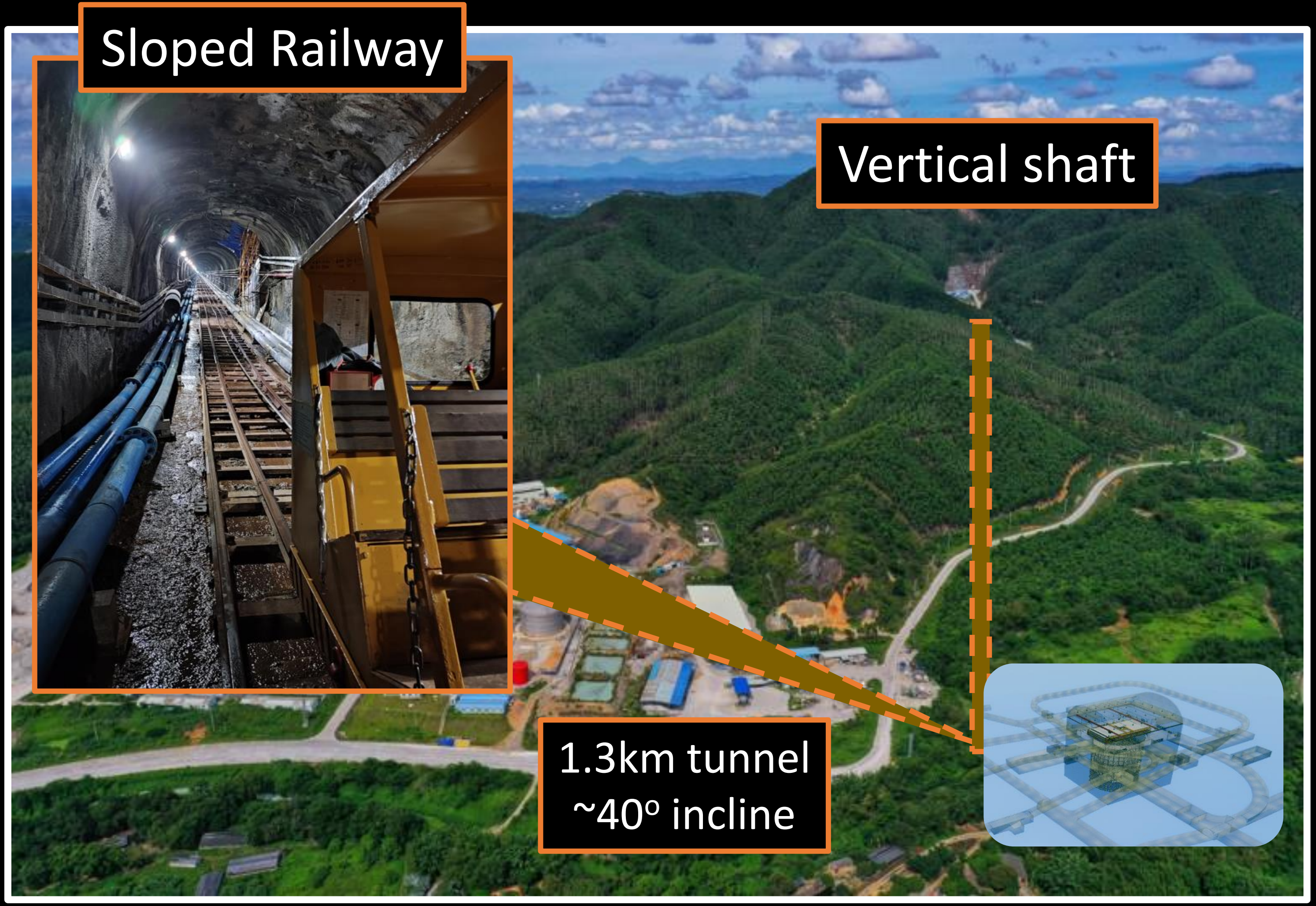
Iwan Morton-Blake

On behalf of the JUNO collaboration

李政道研究所
Tsung-Dao Lee Institute

NuFact 20/09/2024
Argonne National Laboratory, Chicago

Jiangmen Underground Neutrino Observatory



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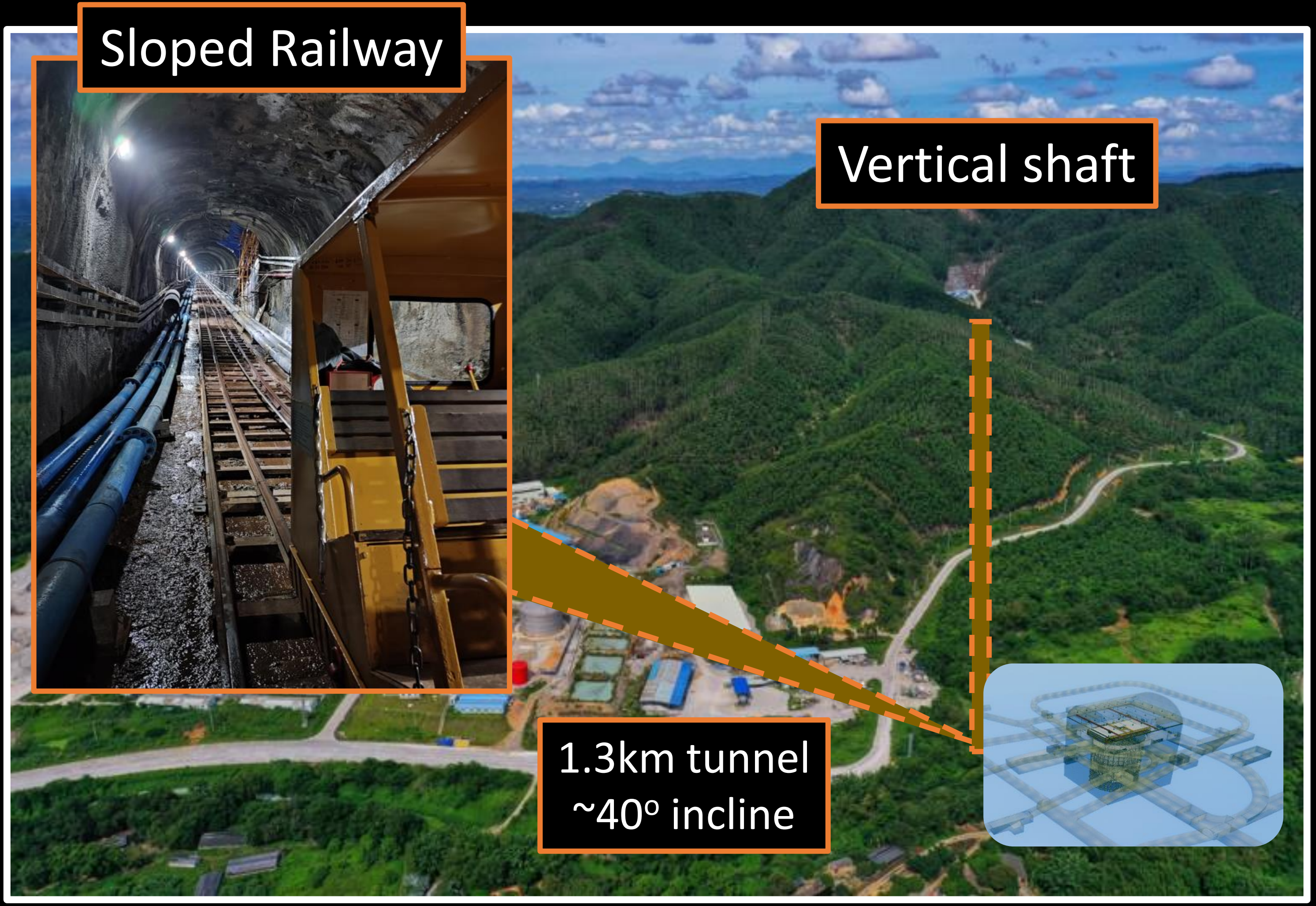
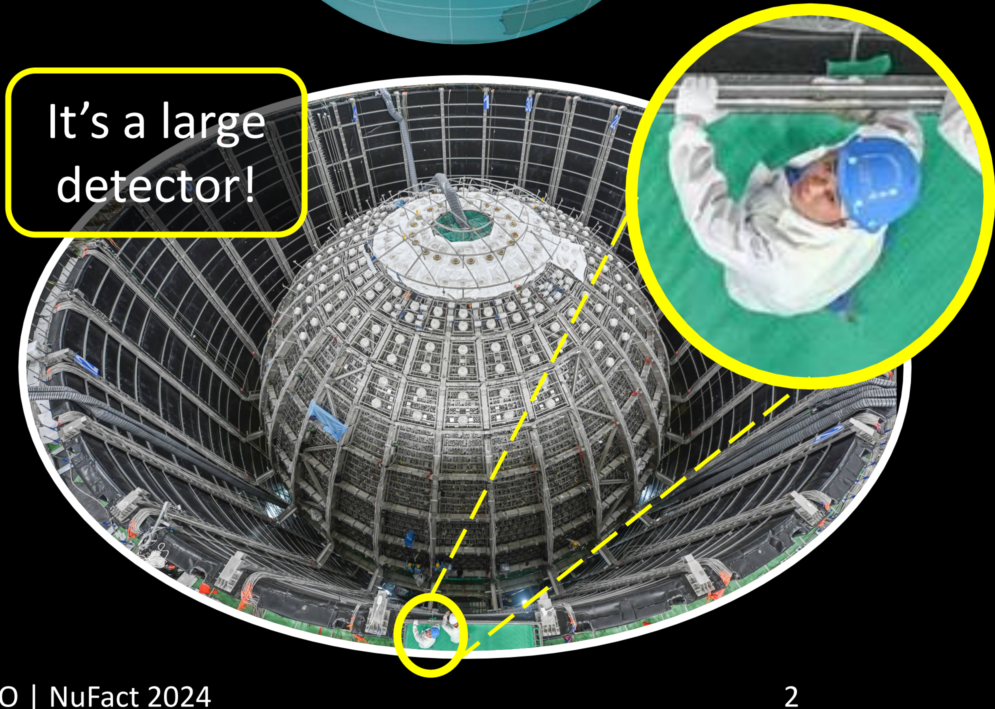
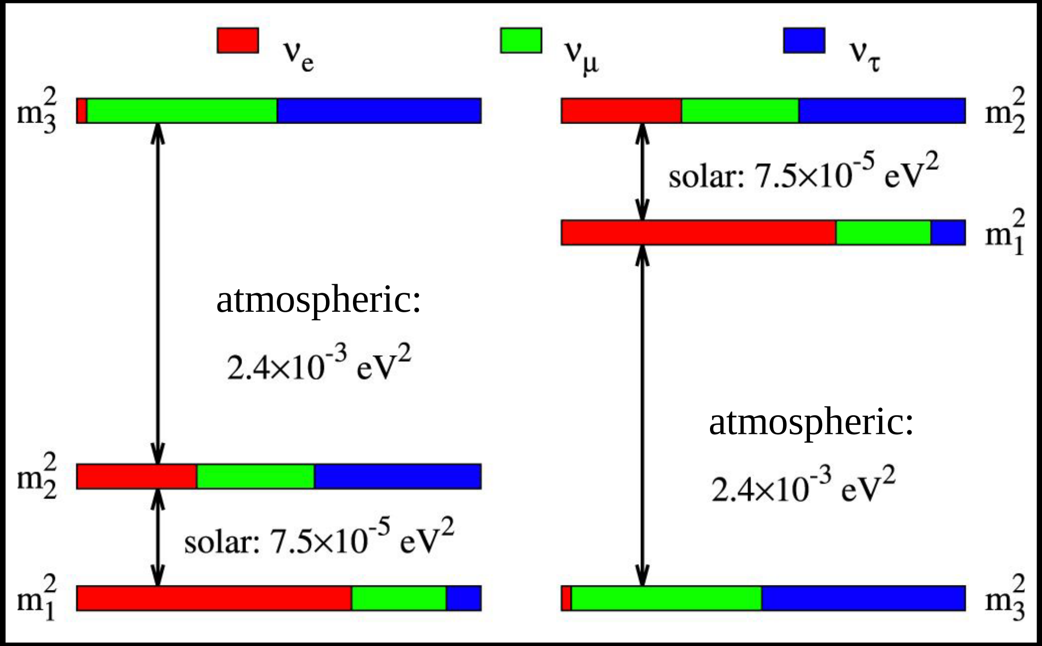




JUNO Physics Goals



Normal Ordering
$m_1 < m_2 < m_3$

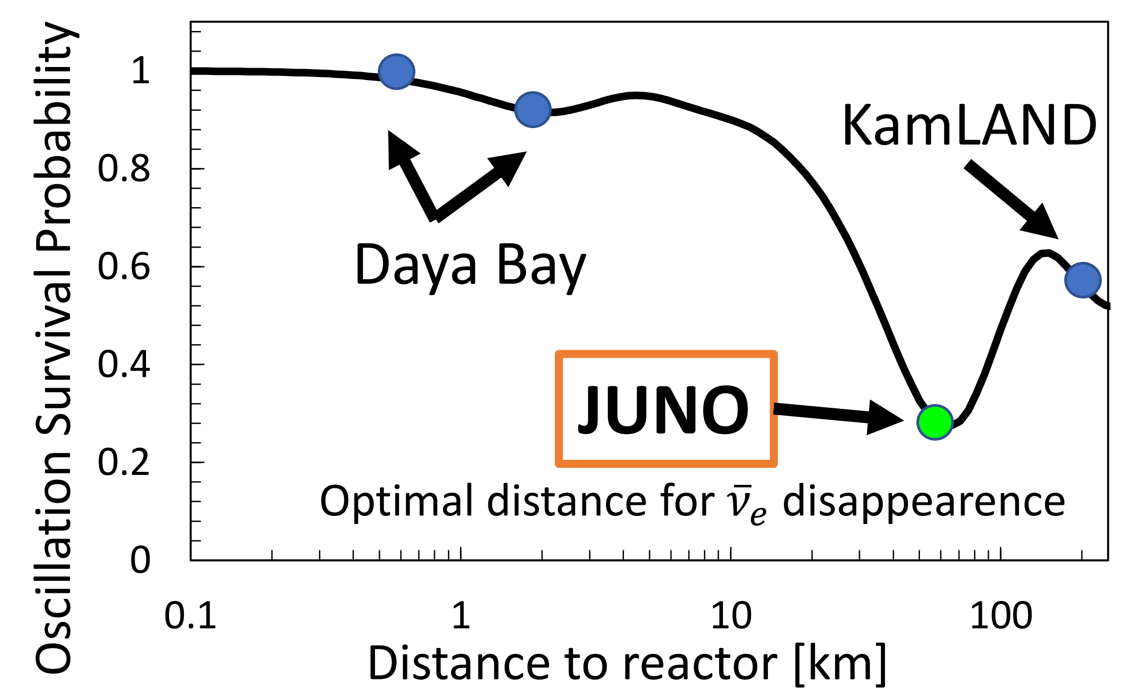
Inverted Ordering
$m_3 < m_1 < m_2$

Primary Physics Goal:
Determine Neutrino Mass Ordering (NMO)

#187. JUNO - Davide Basilico

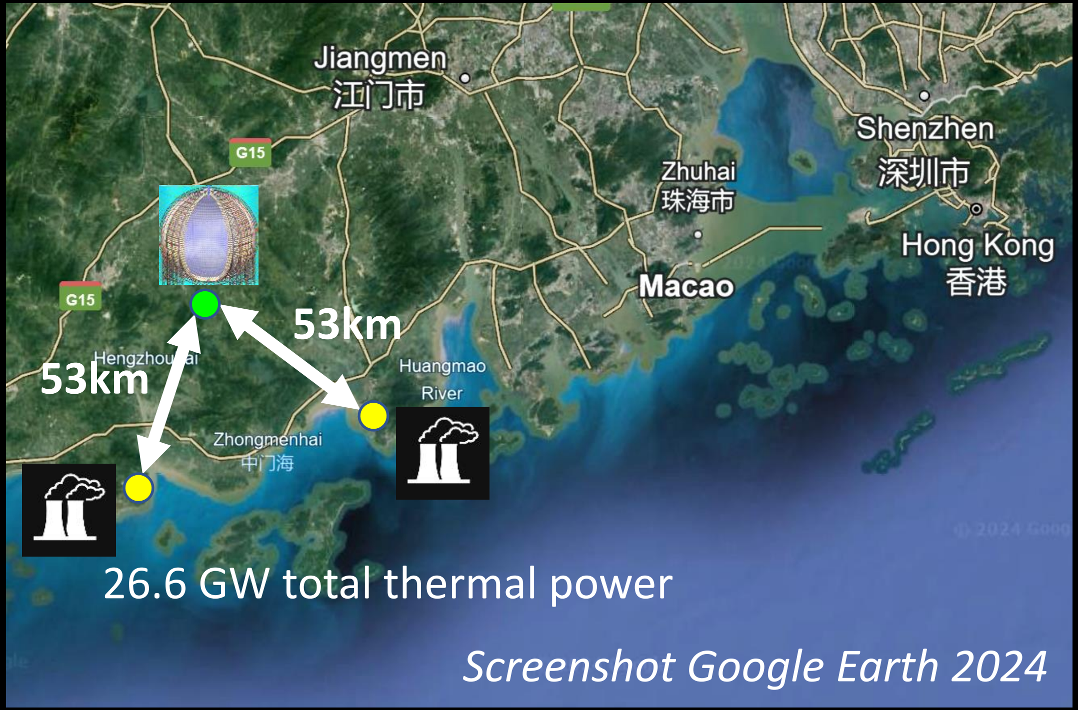
JUNO : Neutrinos from Nuclear Reactors

Medium/Long baseline reactor experiments



($\bar{\nu}_e$ survival averaged over reactor energy spectrum)

JUNO's nearest nuclear reactors

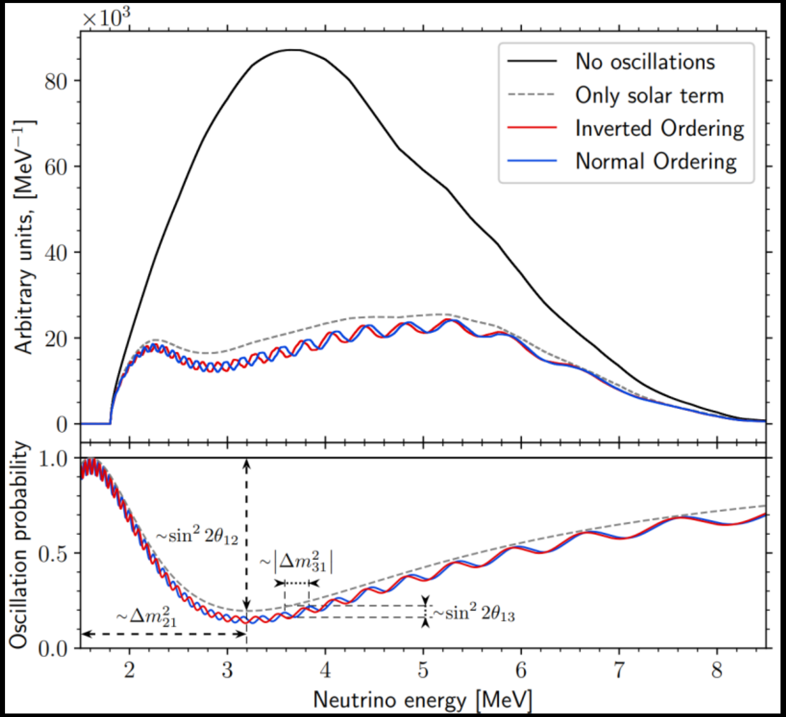


JUNO : Reactor Neutrinos

"Potential to Identify the Neutrino Mass Ordering with Reactor Antineutrinos in JUNO," arXiv:2405.18008 (2024)

"Sub-percent precision measurement of neutrino oscillation parameters with JUNO," Chin. Phys. C **46** (2022)

Reactor $\bar{\nu}_e$ Energy Spectrum



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

$$\Delta_{\mathrm{ij}} = \frac{\Delta m_{ij}^2 L}{4E}$$

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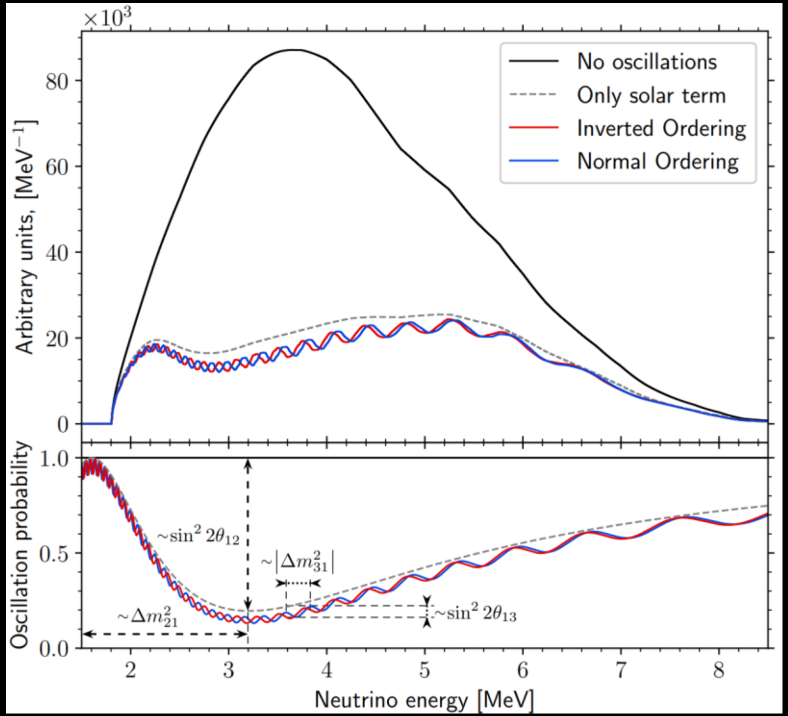
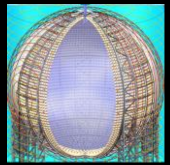
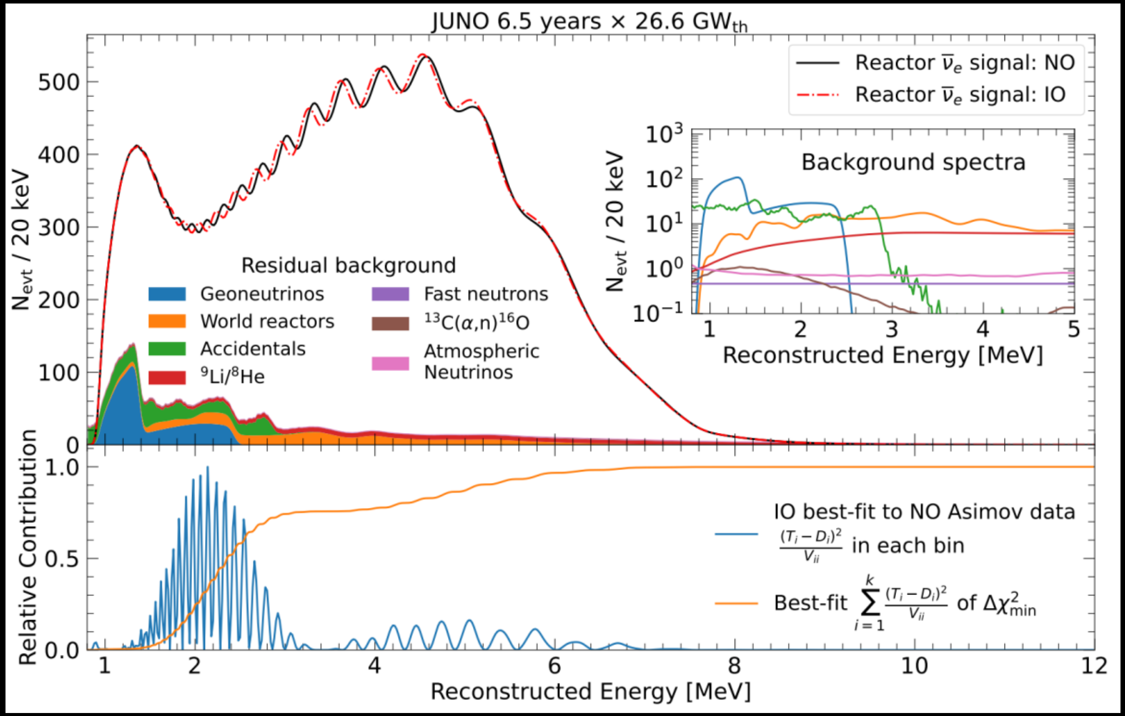


Detector Response



Expected Reconstructed Energy Spectrum



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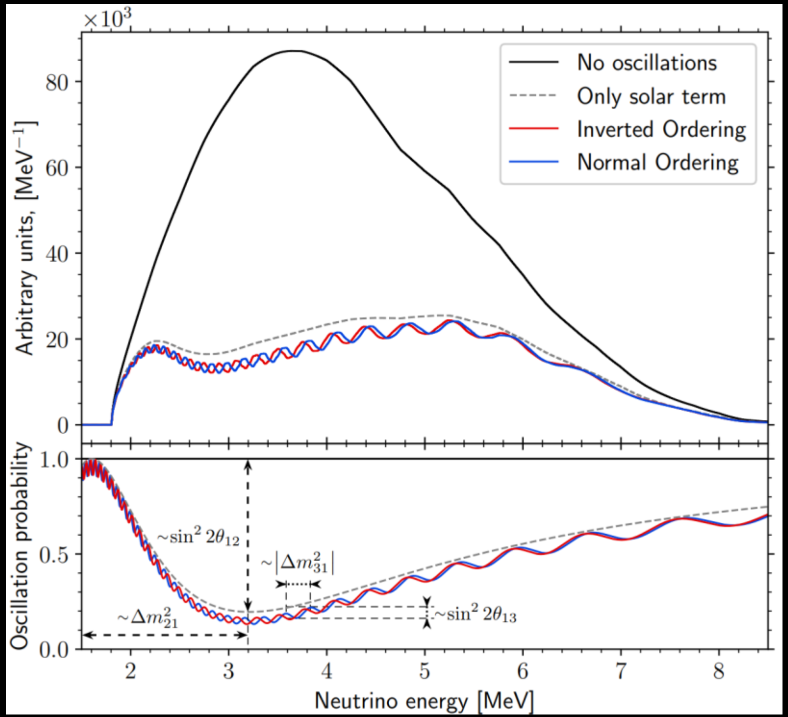

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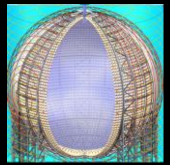

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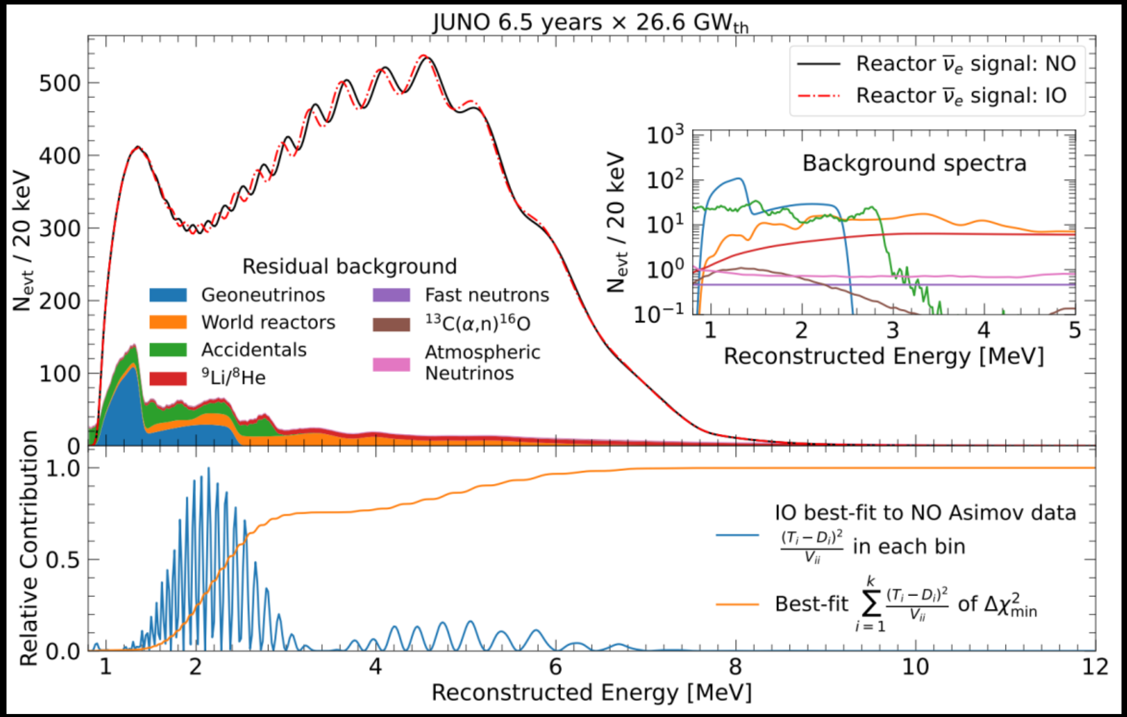

➢ Separate NO vs IO

➢ Precisely measure $\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}$

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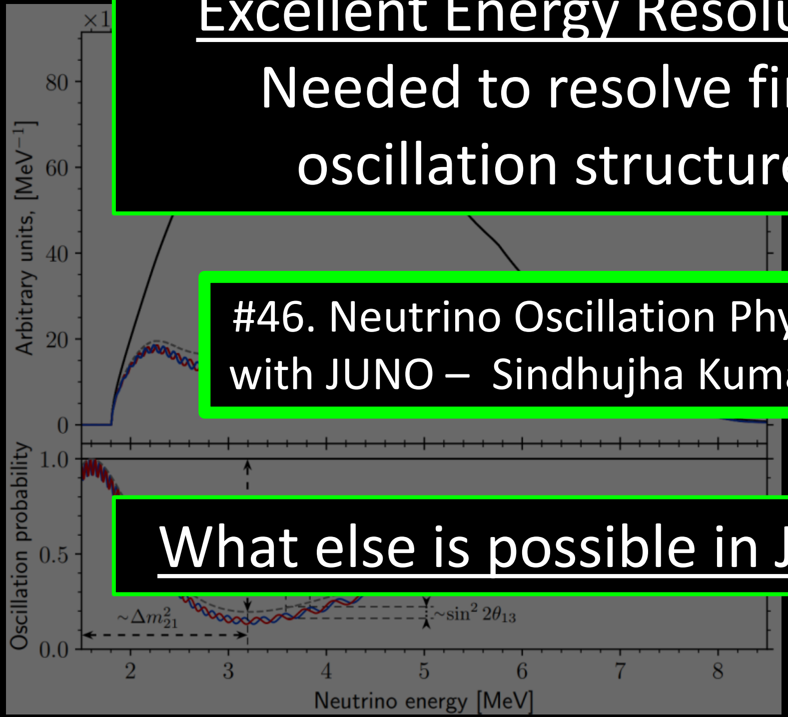
JUNO : Reactor Neutrinos

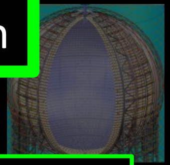
Reactor $\bar{\nu}_e$ Energy Spectrum



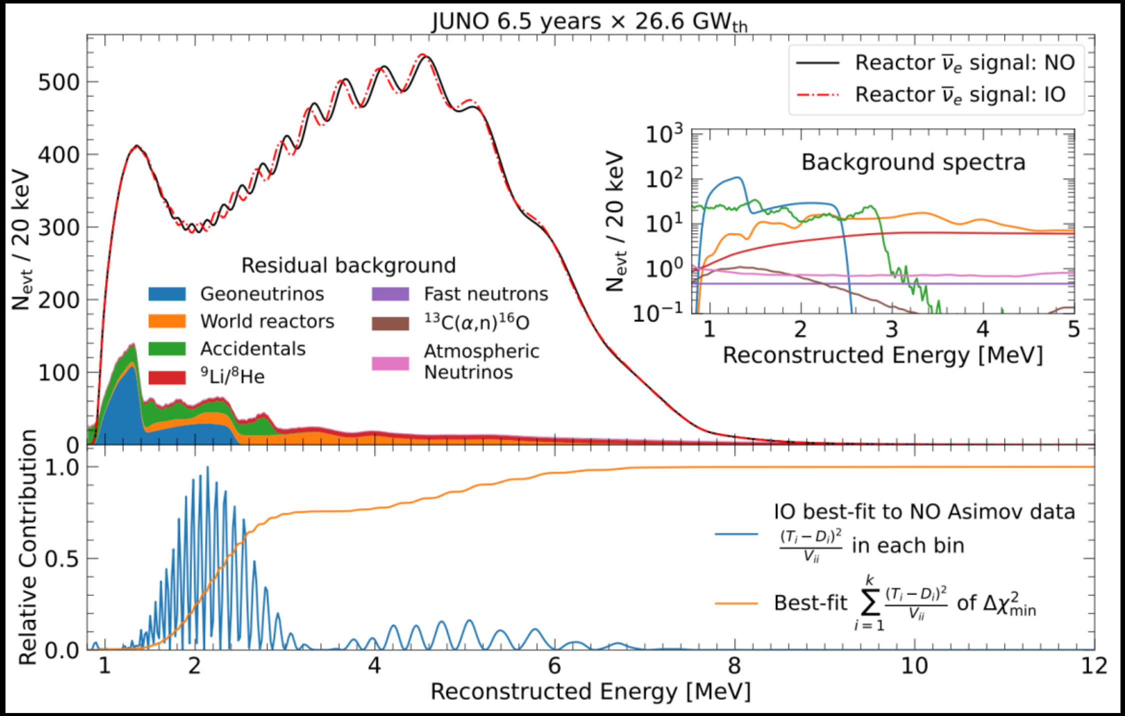
Excellent Energy Resolution
Needed to resolve fine oscillation structure

#46. Neutrino Oscillation Physics with JUNO – Sindhujha Kumaran

What else is possible in JUNO?



Expected Reconstructed Energy Spectrum



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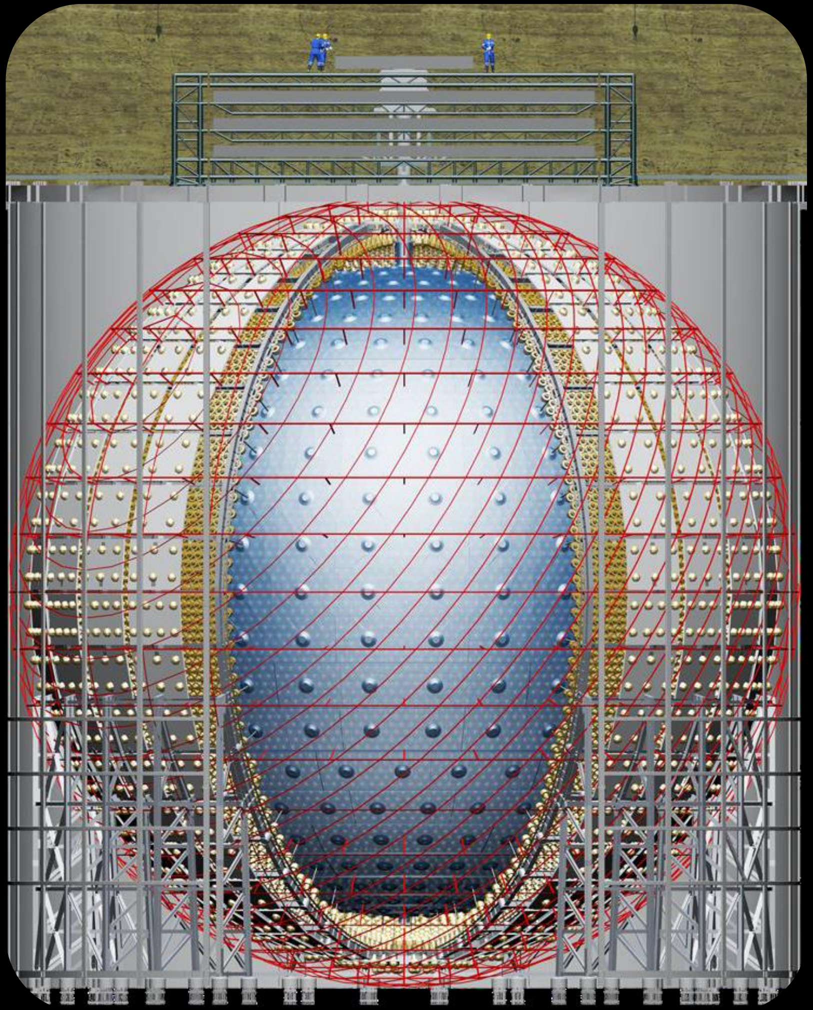
Contents

The JUNO Detector

~650m
overburden



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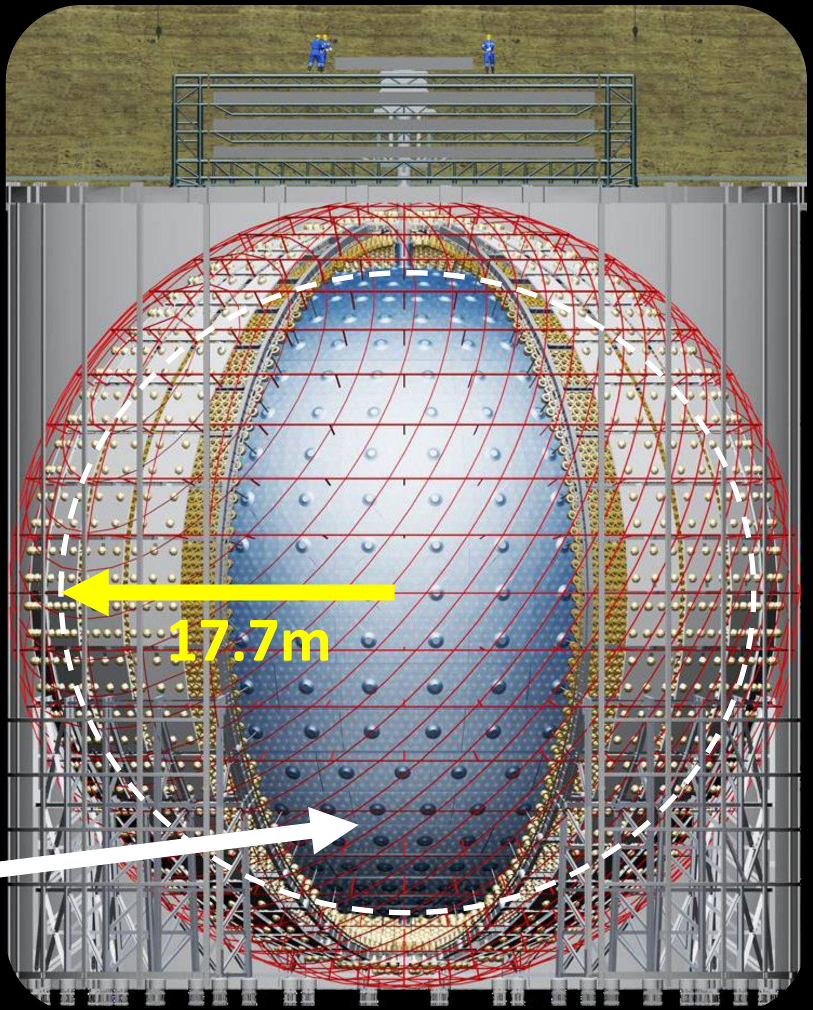
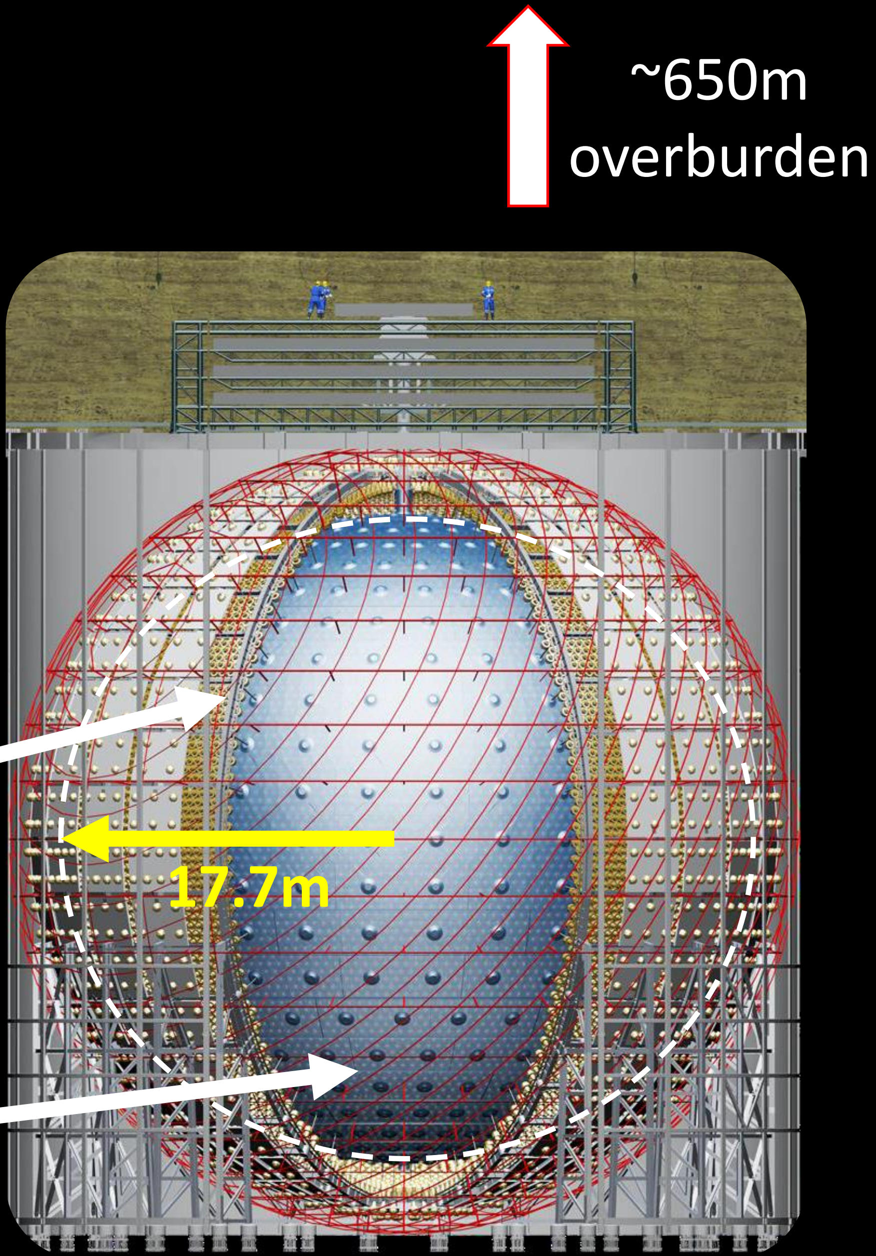
~650m overburden



Acrylic Vessel
17.7 m in radius
20 kilotons of liquid scintillator
LAB + 2.5 g/L PPO + 3 mg/L bis-MSB

The JUNO Detector



PMTs
17,612 20” + 25,600 3”

Acrylic Vessel
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20 kilotons of liquid scintillator
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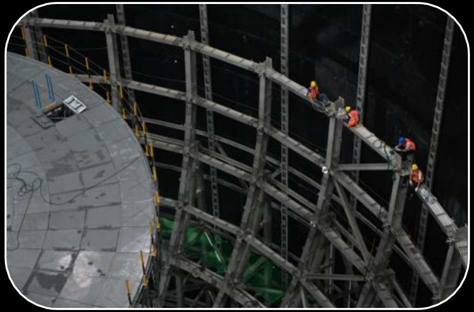
The JUNO Detector

↑ ~650m overburden



Outer Cherenkov Detector
35 kilotons ultrapure water
2400 20” PMTs

PMTs
17,612 20” + 25,600 3”

Acrylic Vessel
17.7 m in radius
20 kilotons of liquid scintillator
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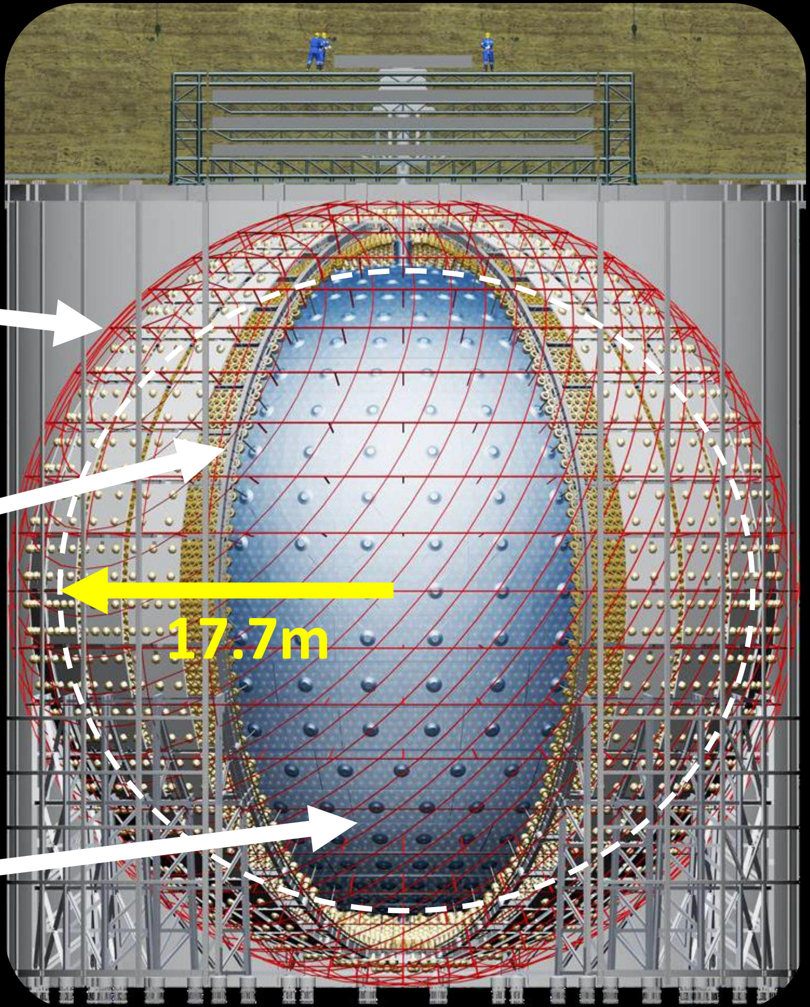
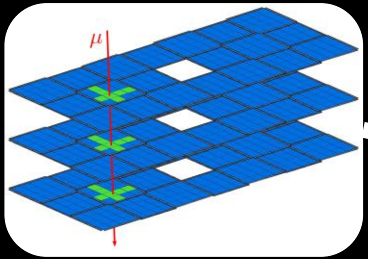
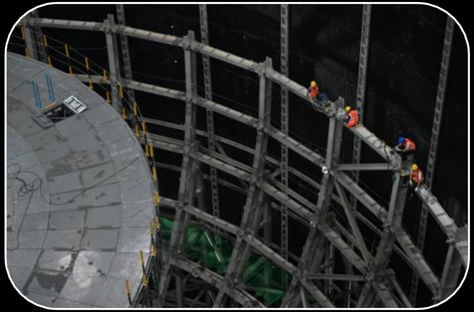


The JUNO Detector

Cosmic muons thru CD ~3Hz
Muon Veto > 99.5%

Top Tracker
Plastic scintillator layers





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35 kilotons ultrapure water
2400 20” PMTs

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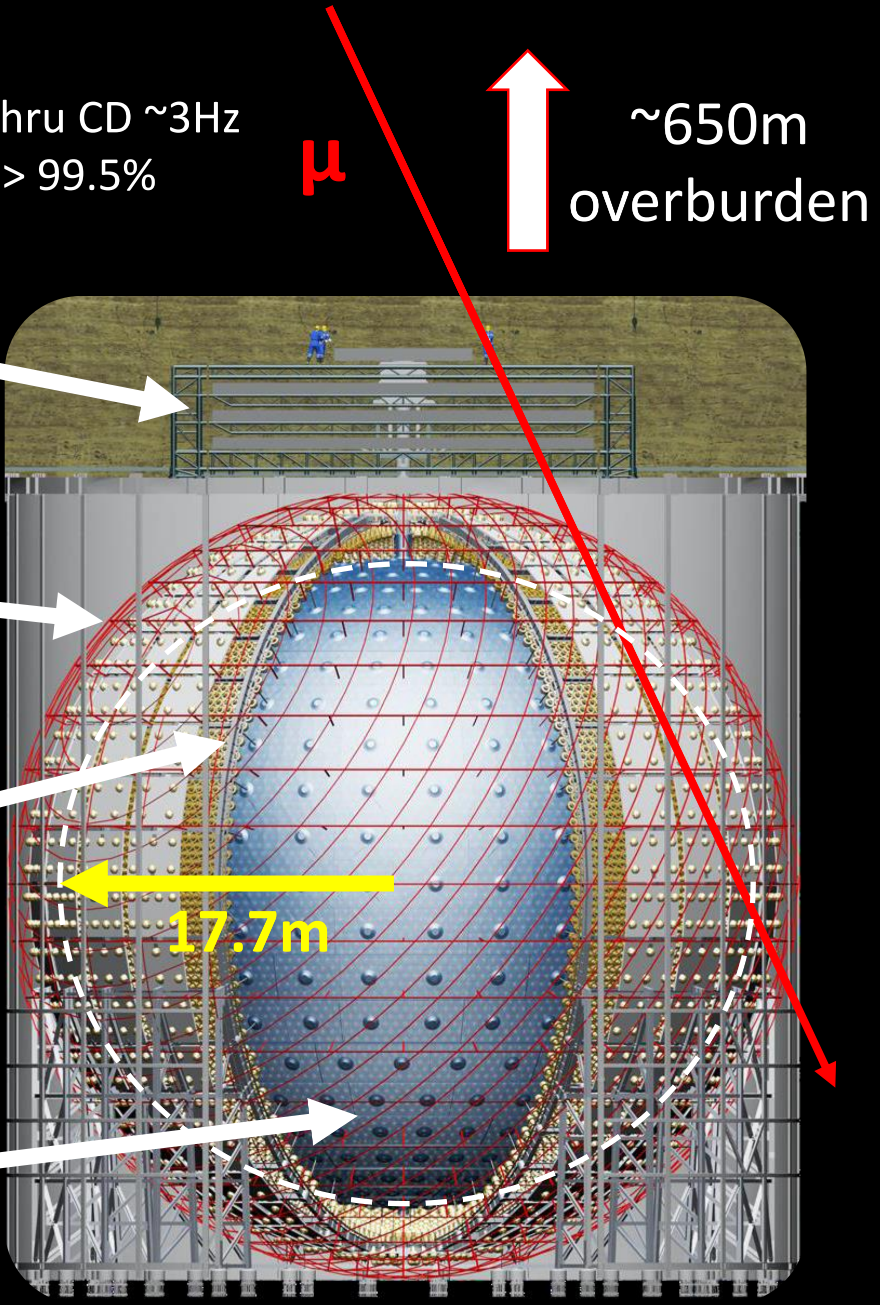


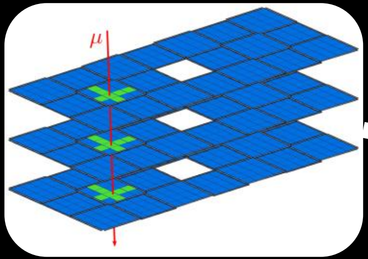
The JUNO Detector

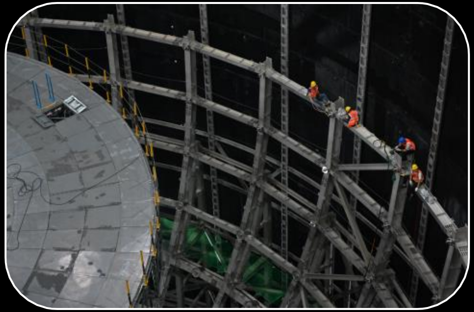
Cosmic muons thru CD ~3Hz
Muon Veto > 99.5%

μ

~650m overburden

Top Tracker
Plastic scintillator layers



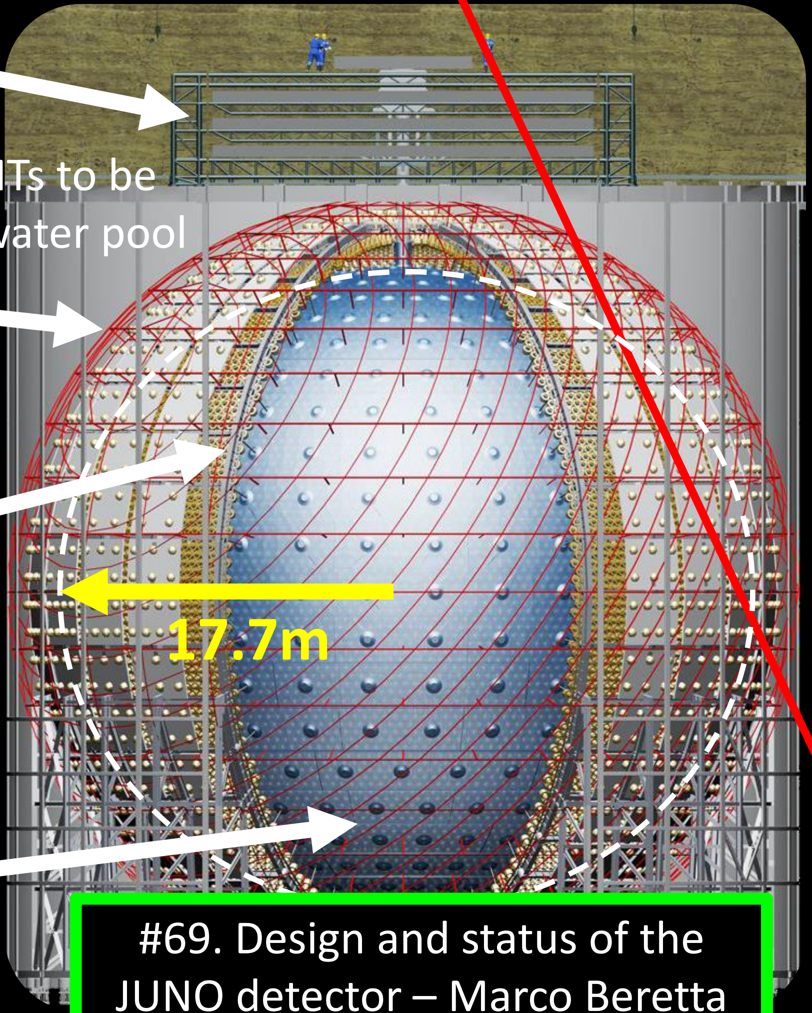


Outer Cherenkov Detector
35 kilotons ultrapure water
2400 20” PMTs

Spare PMTs to be placed in water pool

PMTs
17,612 20” + 25,600 3”

Acrylic Vessel
17.7 m in radius
20 kilotons of liquid scintillator
LAB + 2.5 g/L PPO + 3 mg/L bis-MSB



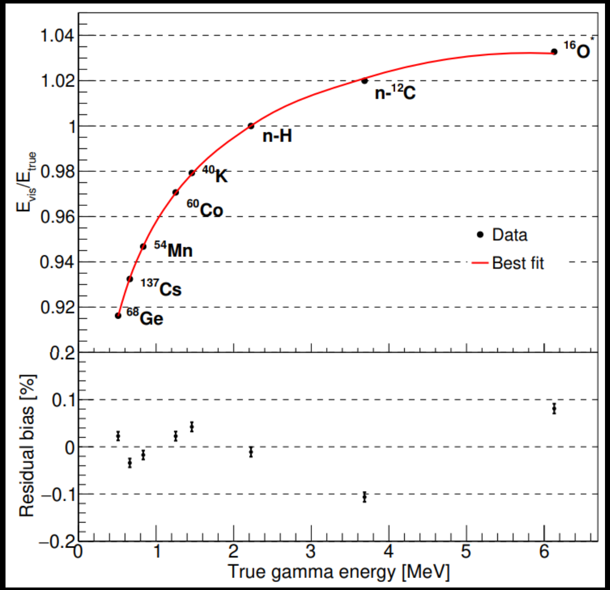
#69. Design and status of the JUNO detector – Marco Beretta

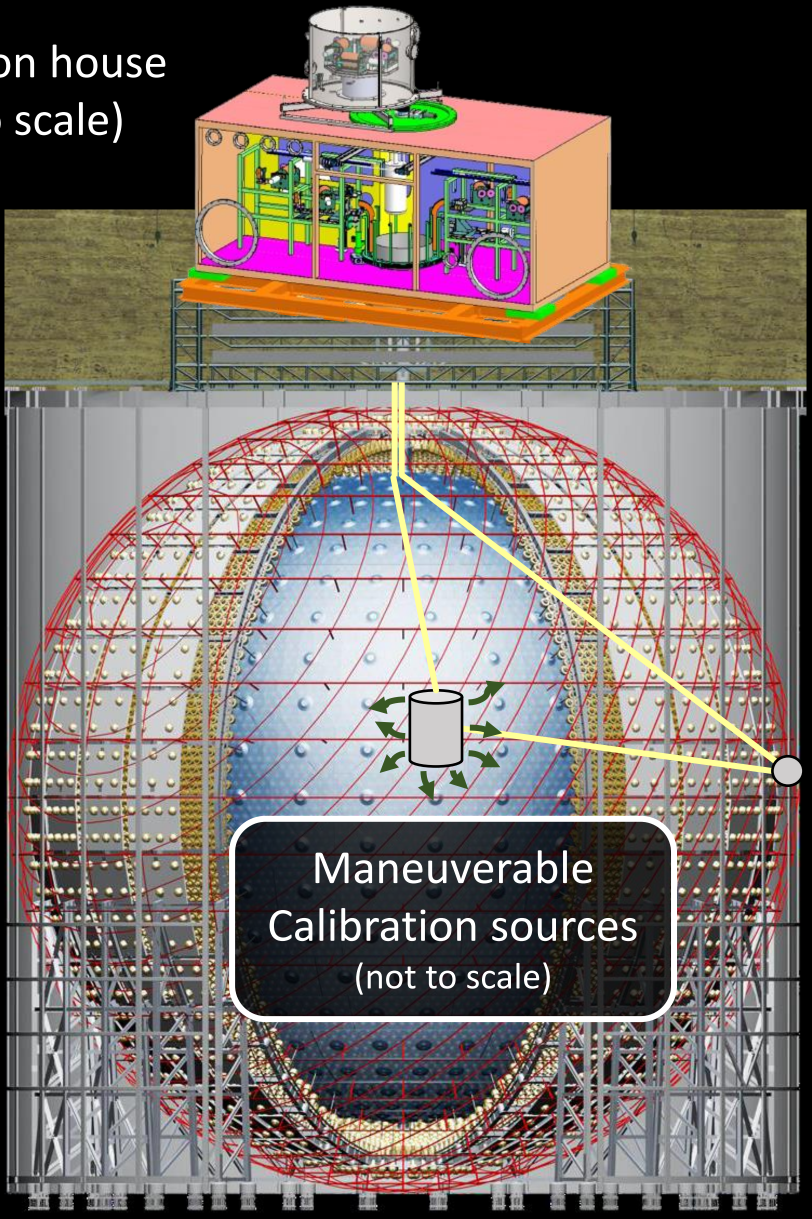
Calibration in JUNO

Calibration house
(not to scale)

Deployable calibration sources in JUNO

Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26 MeV





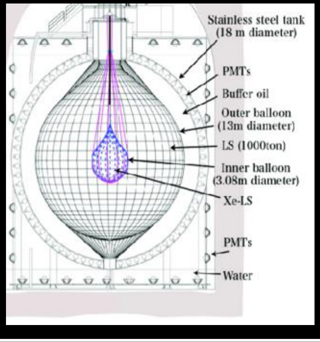
Tune reconstruction and simulation with deployable sources & naturally occurring interactions in the detector

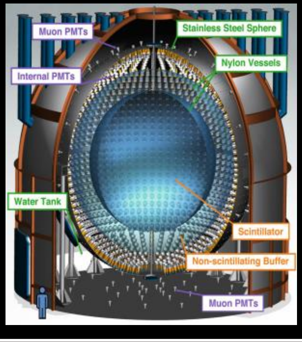
#47. Detector calibration in the JUNO experiment - Akira Takenaka

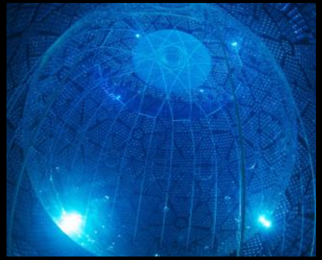
JUNO : Detector Comparison

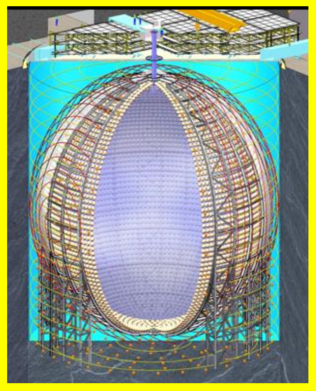
[“Prediction of Energy Resolution in the JUNO Experiment”, arXiv:2405.17860 (2024)]

JUNO:
Energy Resolution
< 3% @ 1MeV



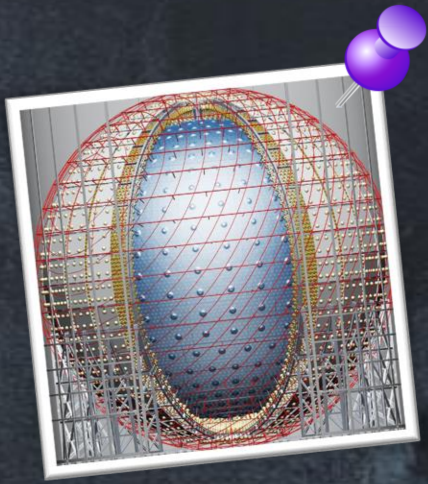


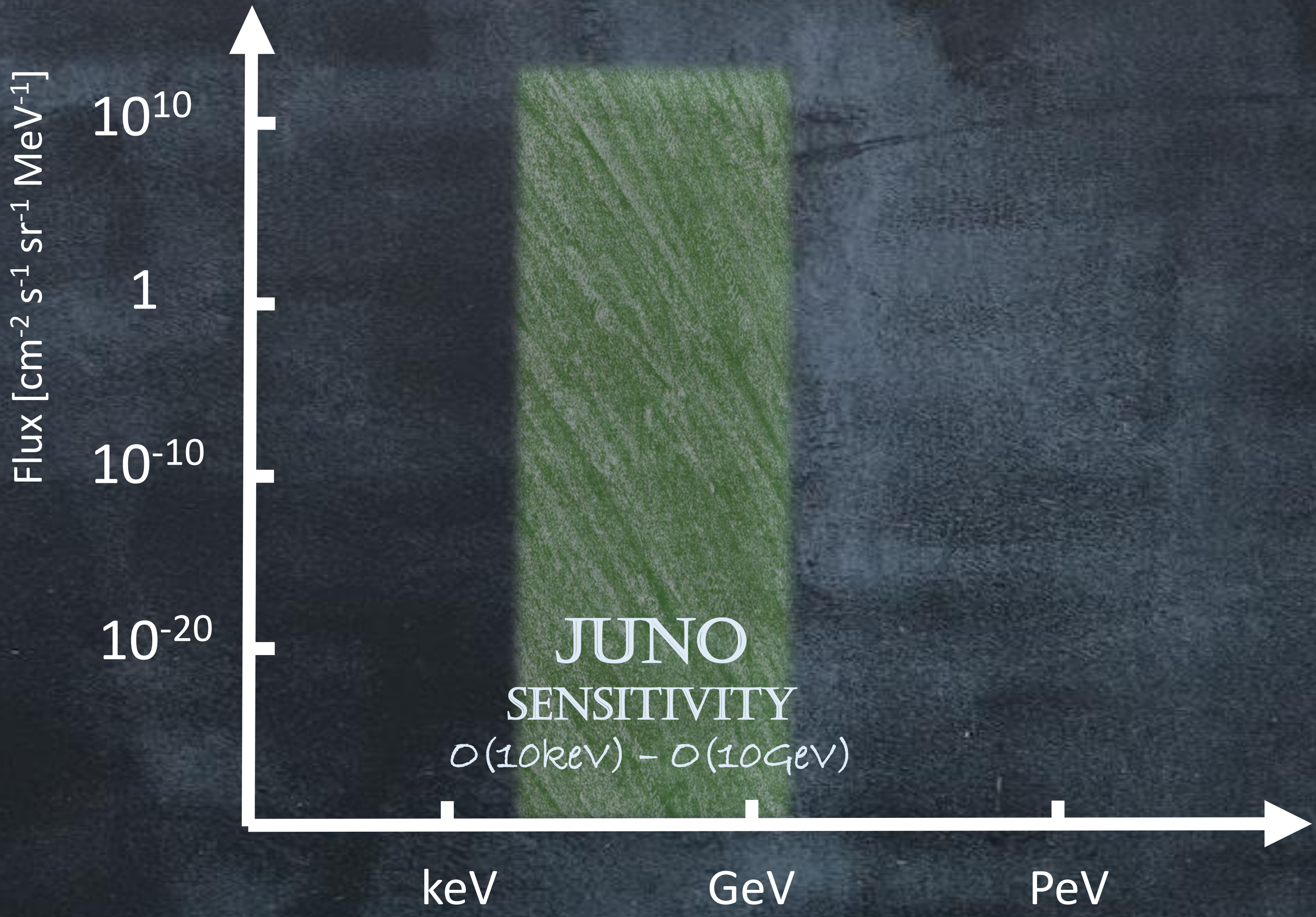




	KamLAND [1]	Borexino [2]	SNO+ [3]	JUNO
Target Mass [kilotons]	1.0	0.3	0.78	**20**
Number of PMTs	1900	2200	10,000	**17,612 + 25,600**
PMT Coverage	~34%	~30%	~50%	**78%**
Light Collection [photoelectrons/MeV]	~250	~450	~520	**~1600**

Neutrino Sources





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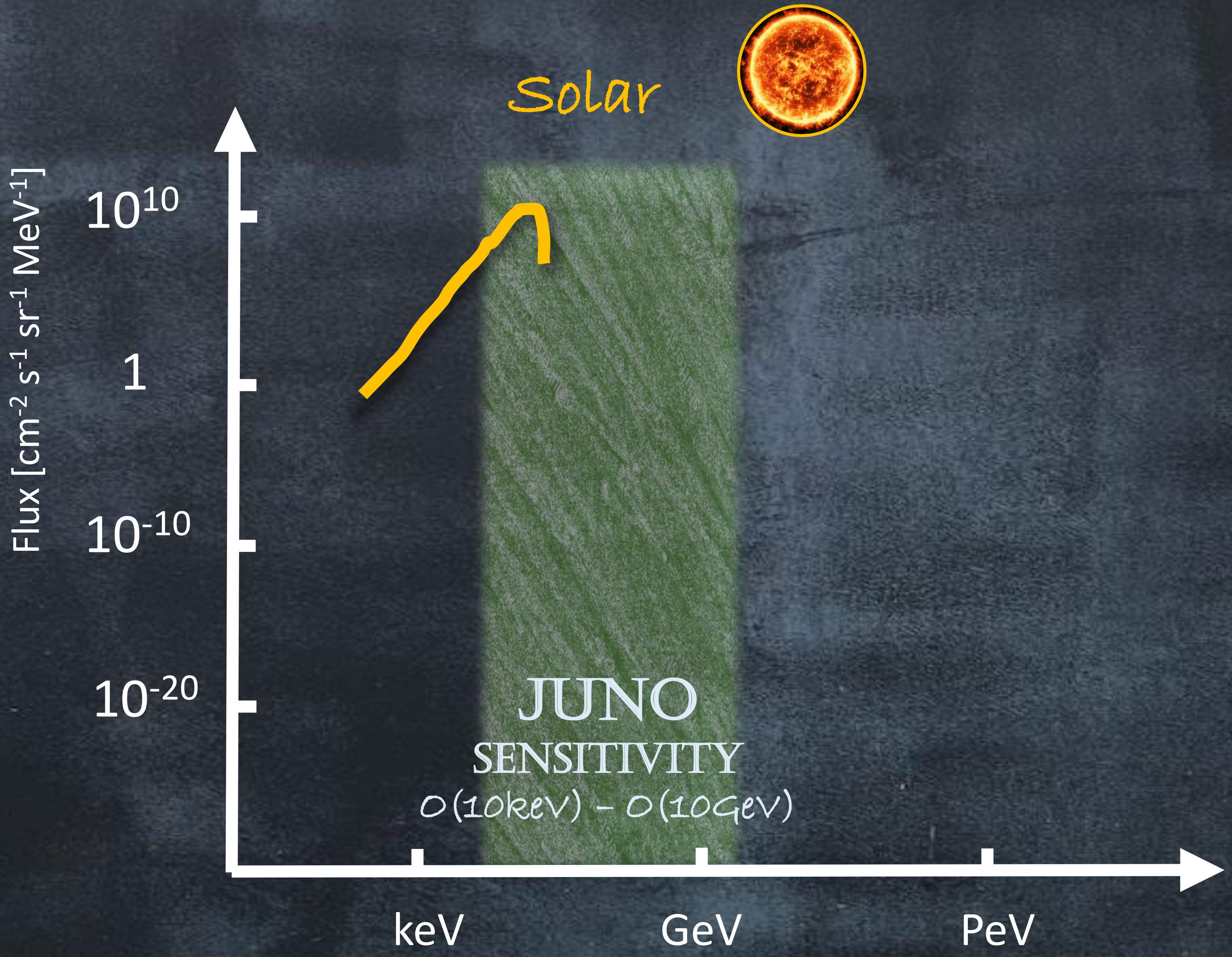

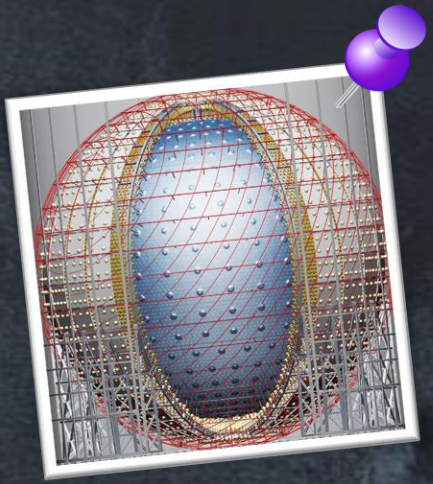

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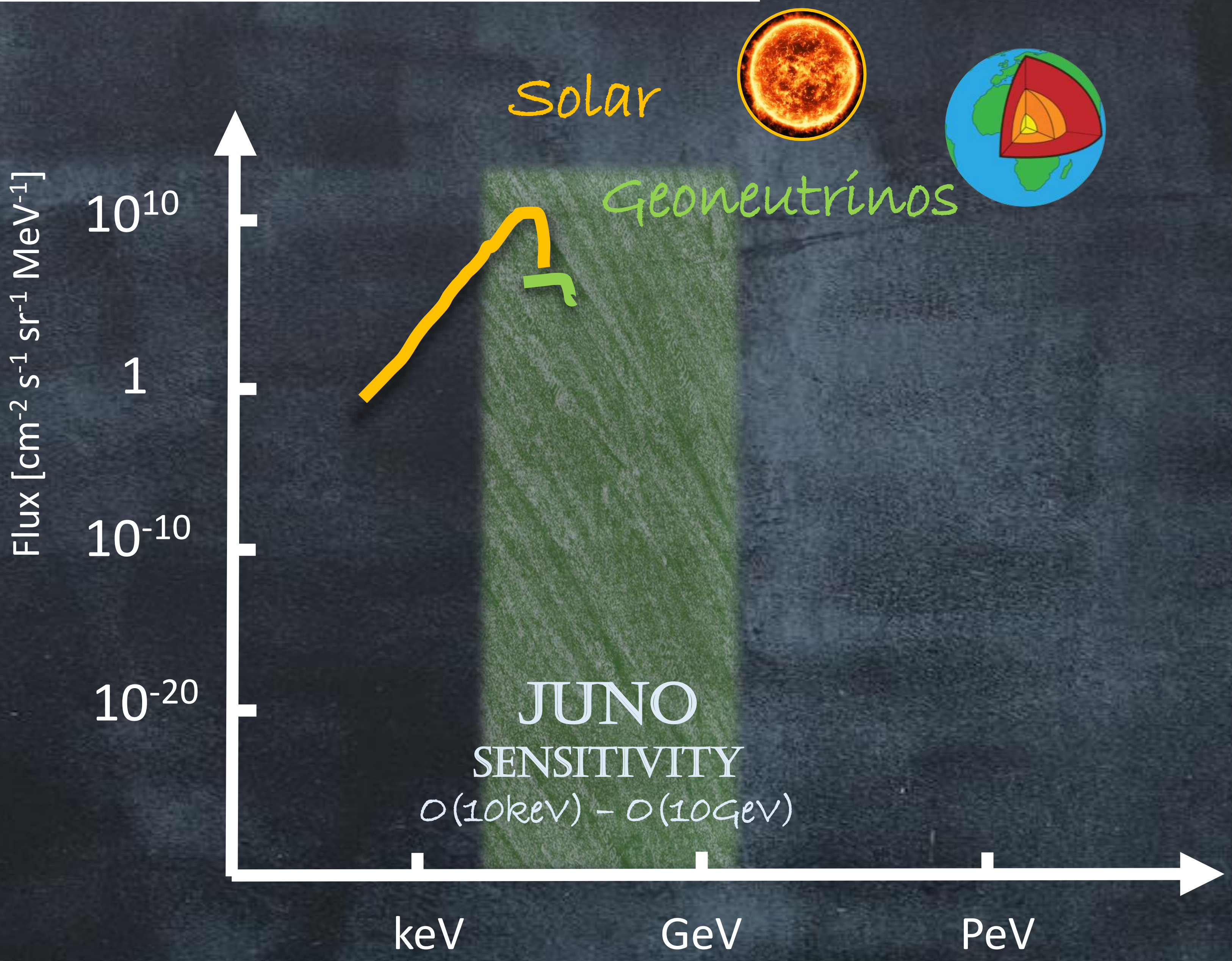

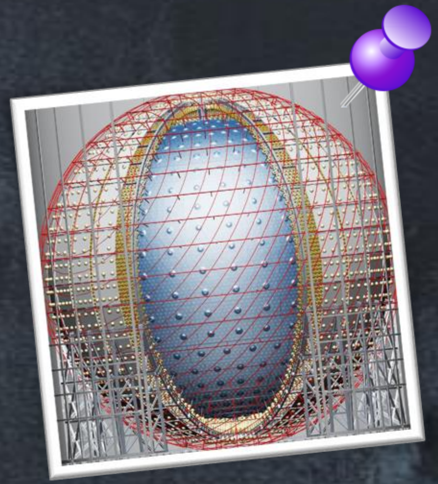

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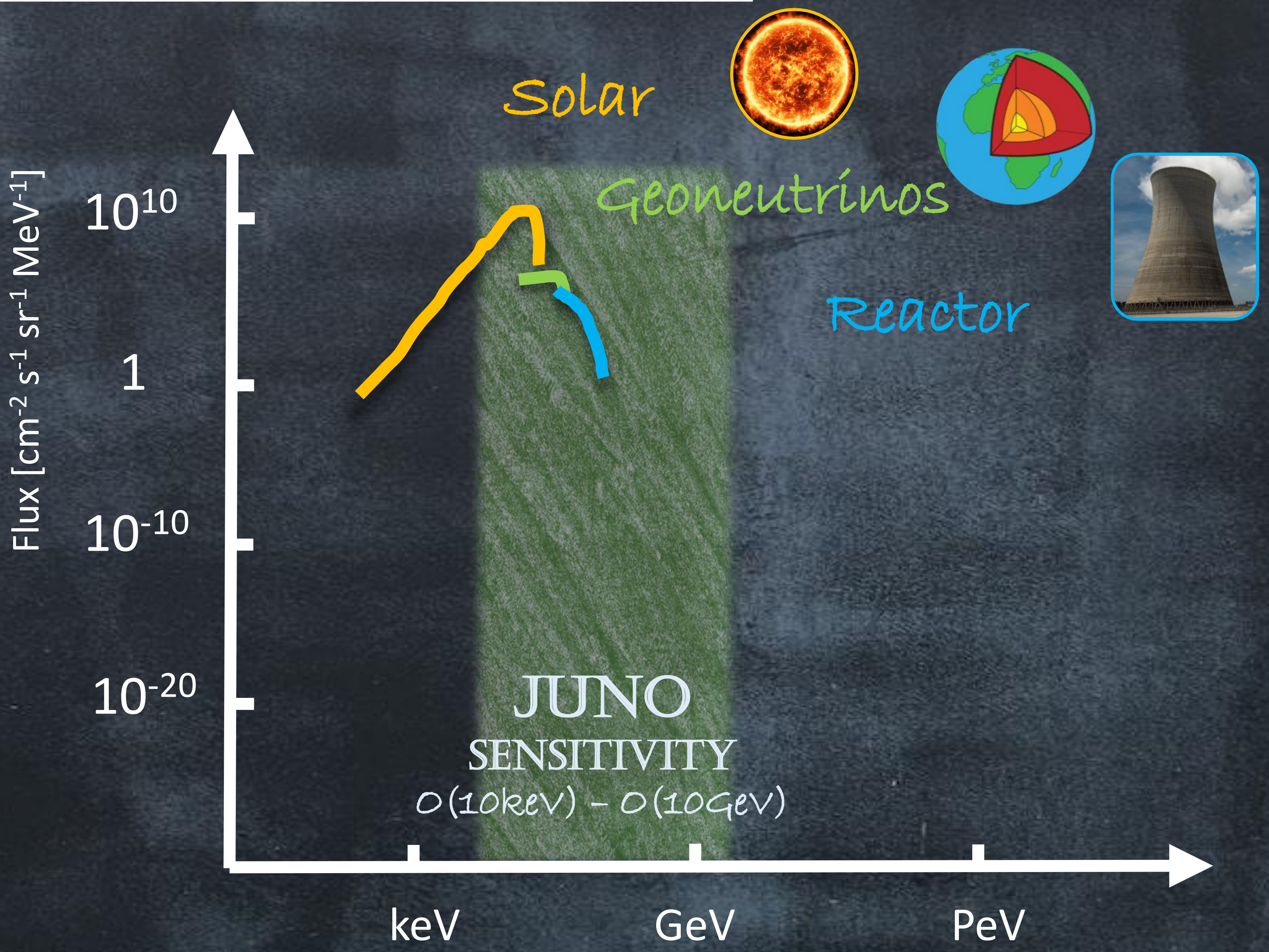

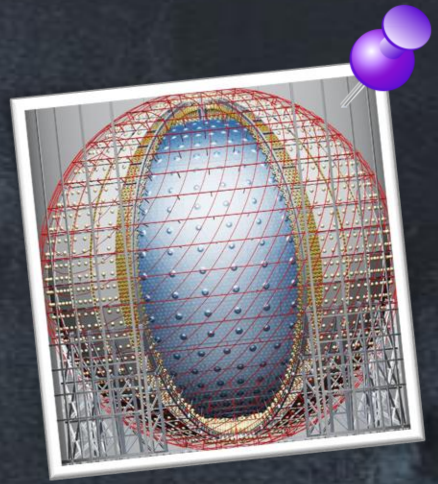

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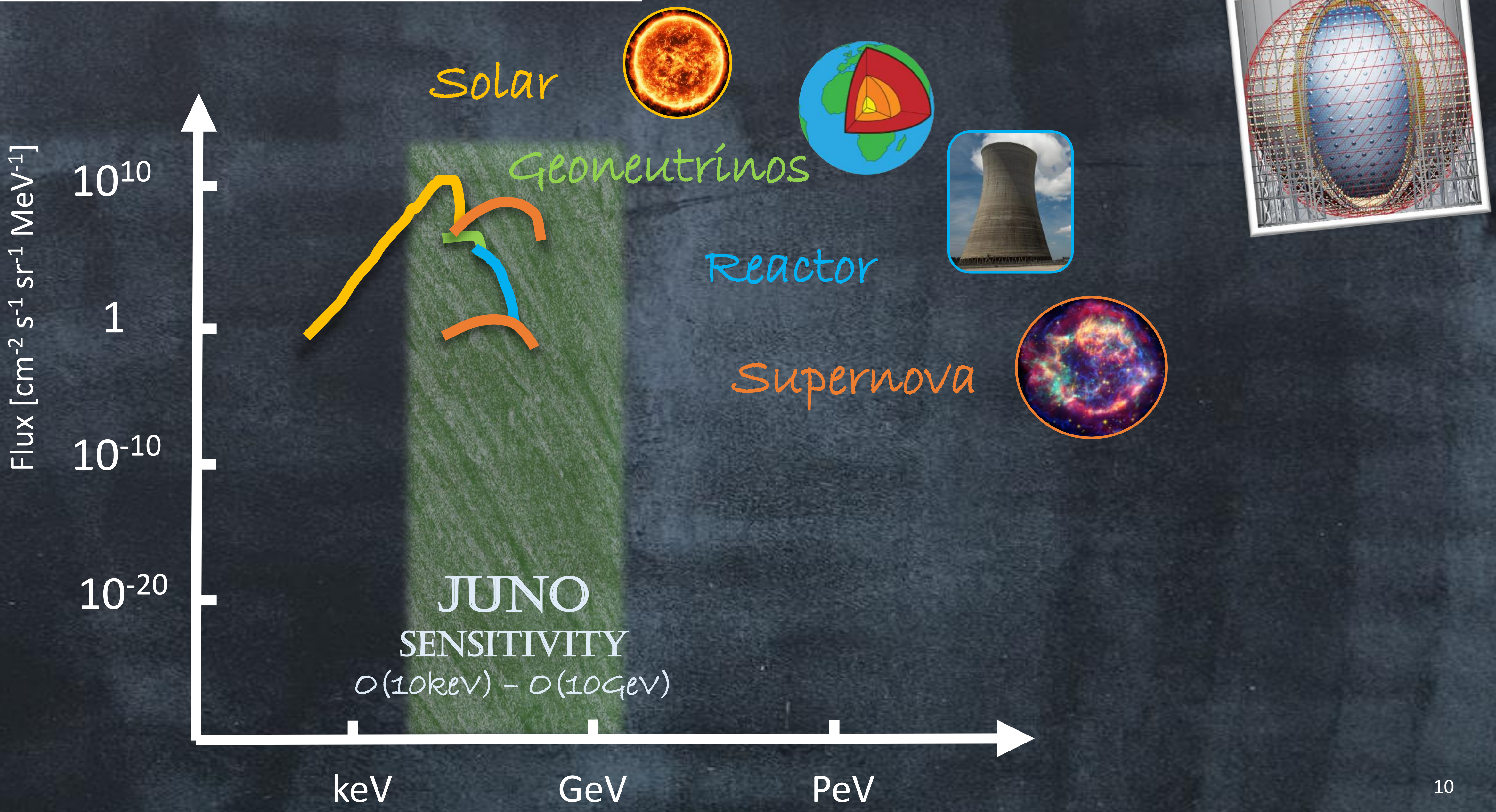

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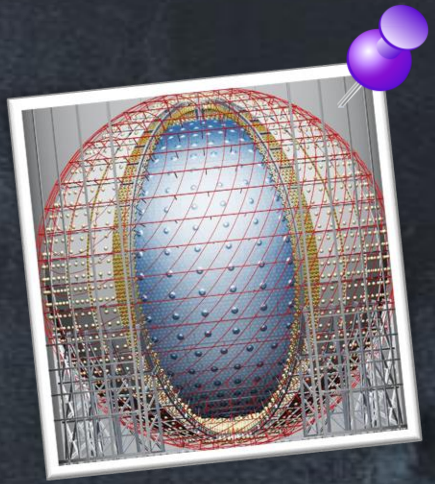


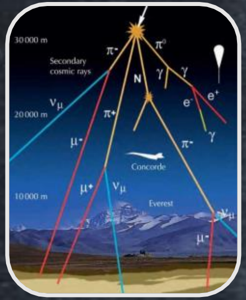
Solar

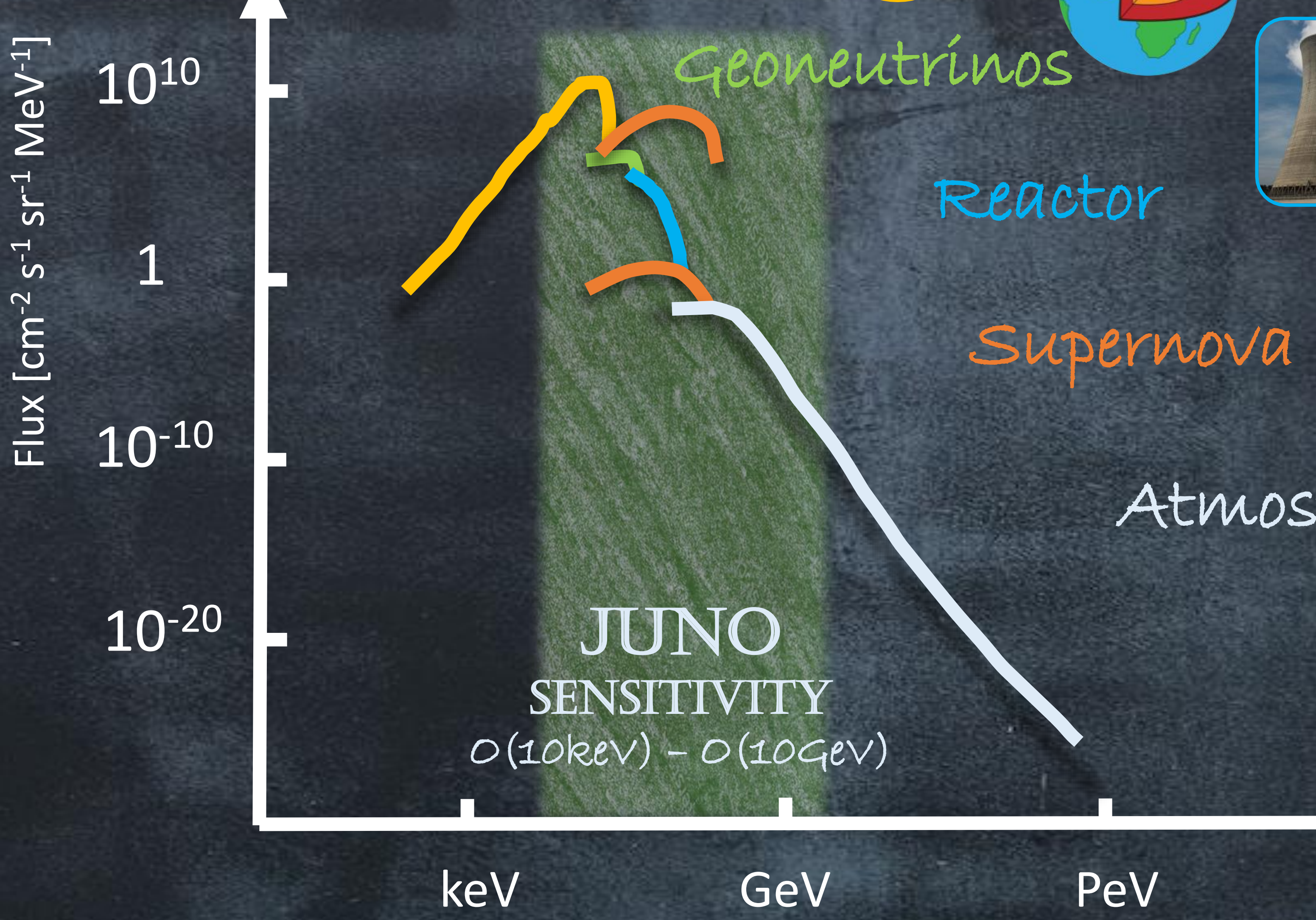
Geoneutrinos

Reactor

Supernova

Atmospheric





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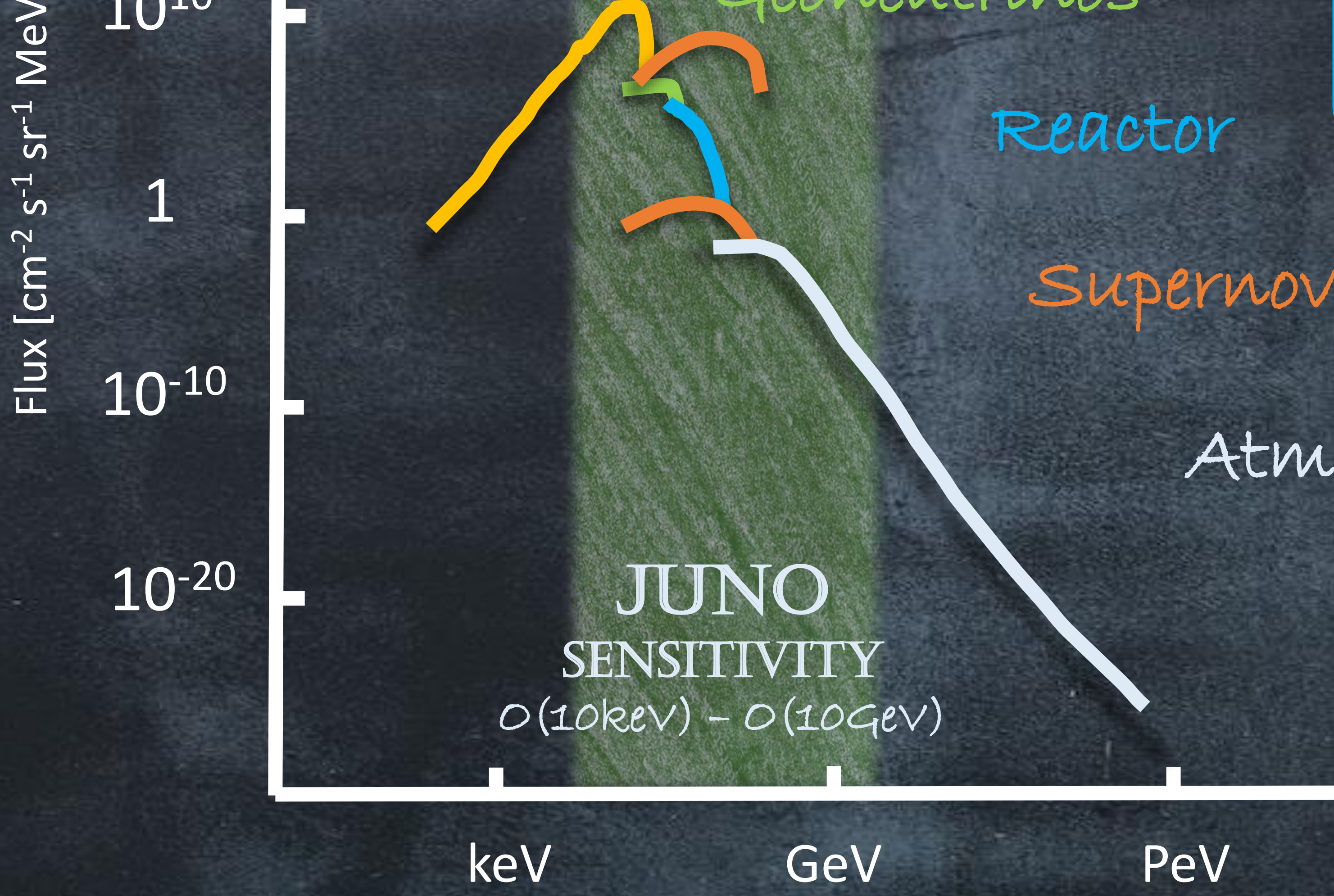


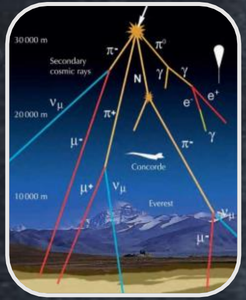
Solar

Geoneutrinos

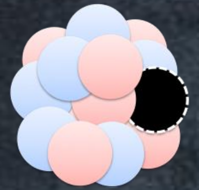
Reactor

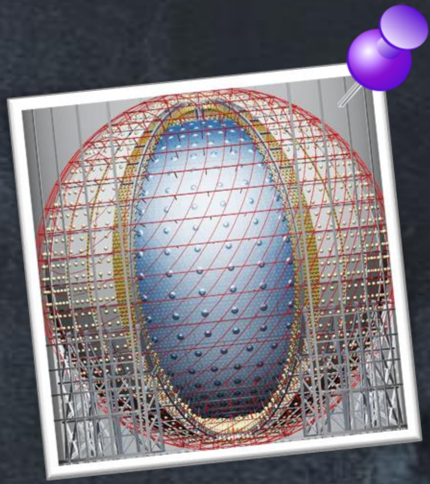
Supernova

Atmospheric



+ Exotic Searches

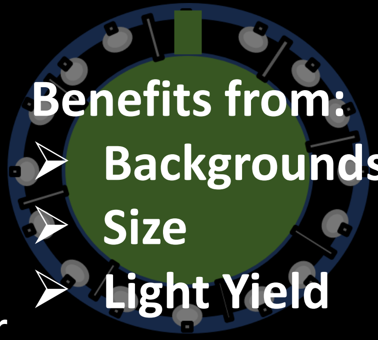




Natural Neutrino Sources

JUNO Physics Programme

ν_x



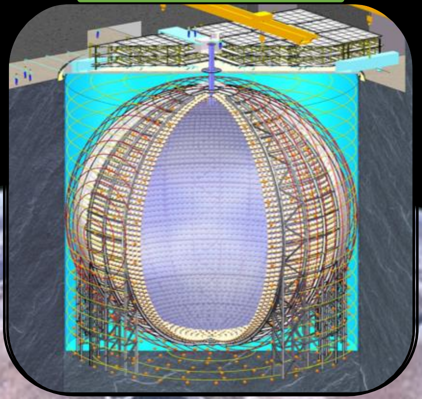
Benefits from:

- ➢ **Backgrounds**
- ➢ **Size**
- ➢ **Light Yield**

<u>Solar</u>

0 – 16 MeV

JUNO



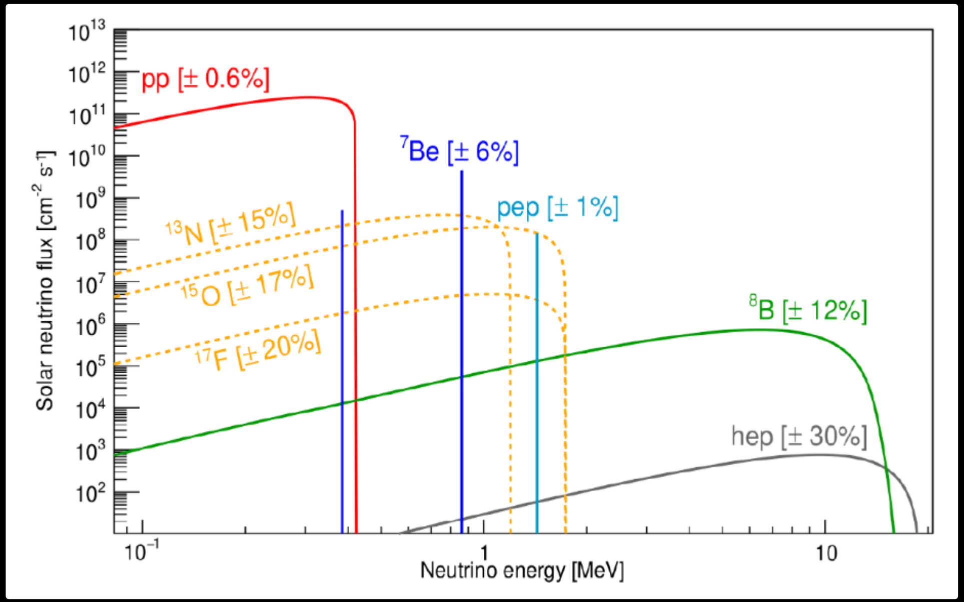
Solar Neutrinos

“Model Independent Approach of the JUNO ^{8}B Solar Neutrino Program,” Astrophys. J. 965 (2024) 2, 122.

“Feasibility and physics potential of detecting ^{8}B solar neutrinos at JUNO,” Chin. Phys. C **45** (2021)

Nuclear fusion within the sun produces ν_e

Expected Flux



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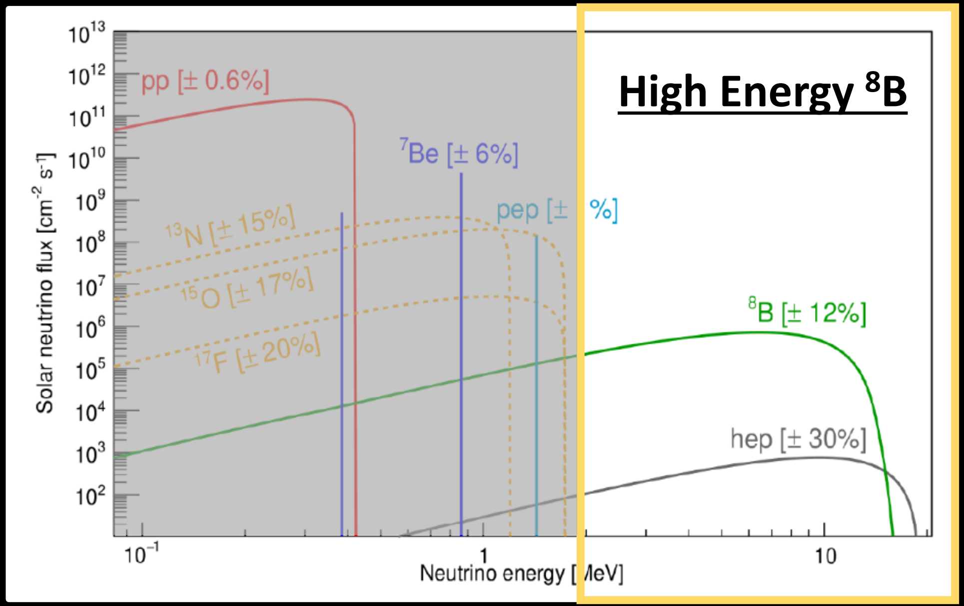

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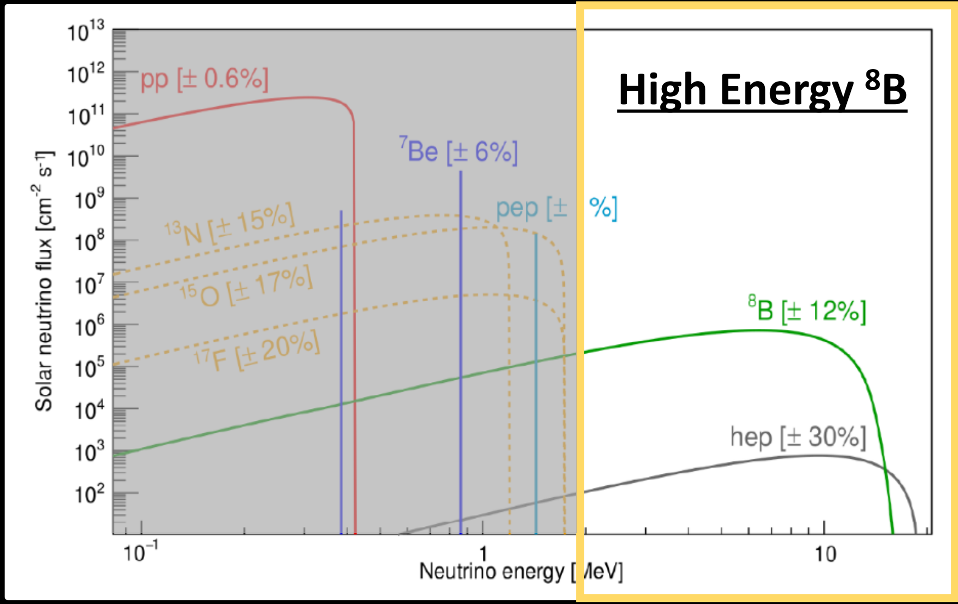
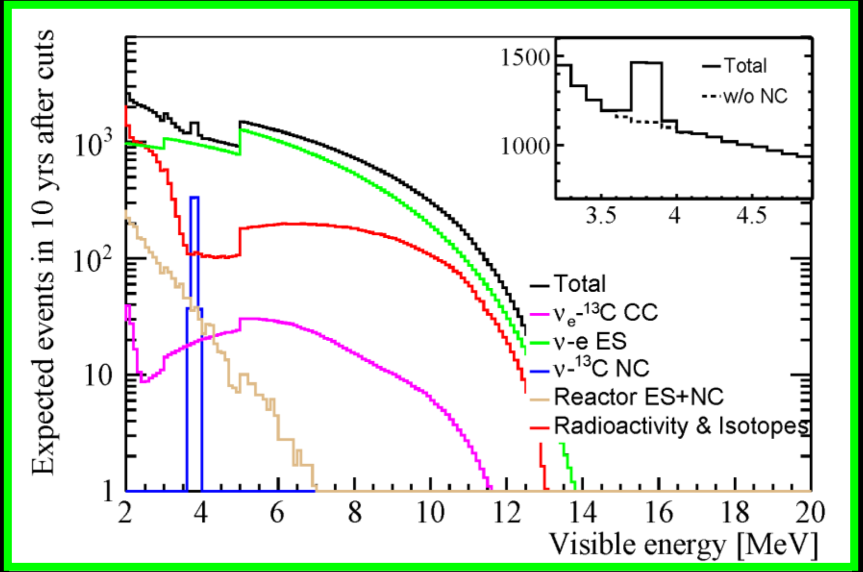
Solar Neutrinos

Nuclear fusion within the sun produces ν_e

Expected Flux → Expected Signal + Background



Reconstructed energy spectra



10 years data-taking

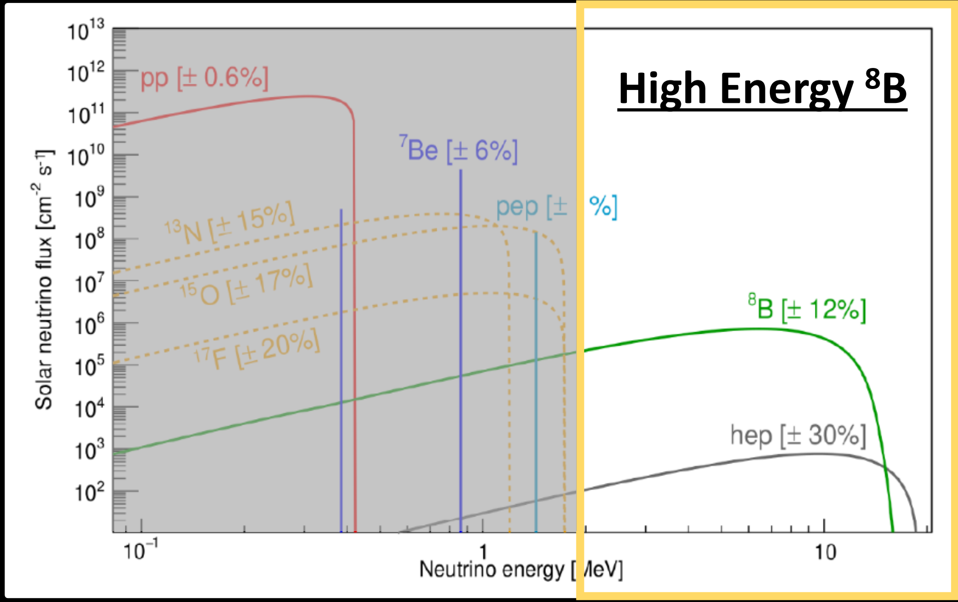
Solar Neutrinos

"Model Independent Approach of the JUNO ^{8}B Solar Neutrino Program," Astrophys. J. 965 (2024) 2, 122.

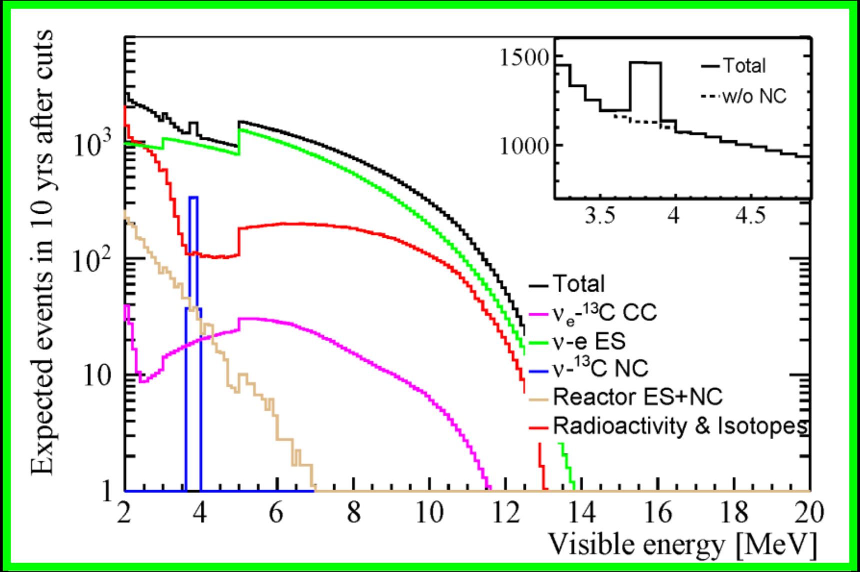
"Feasibility and physics potential of detecting ^{8}B solar neutrinos at JUNO," Chin. Phys. C **45** (2021)

ⓘ Nuclear fusion within the sun produces ν_e

Expected Flux ➡ Expected Signal + Background ➡ Expected Sensitivity



Reconstructed energy spectra



10 years data-taking

Oscillation and flux measurements

ϕ_{8B} : 5%

θ_{12} : 8%

Δm^2_{21} : 20%

10 years exposure

(Would be first observation of ^{8}B CC + NC interactions on ^{13}C)

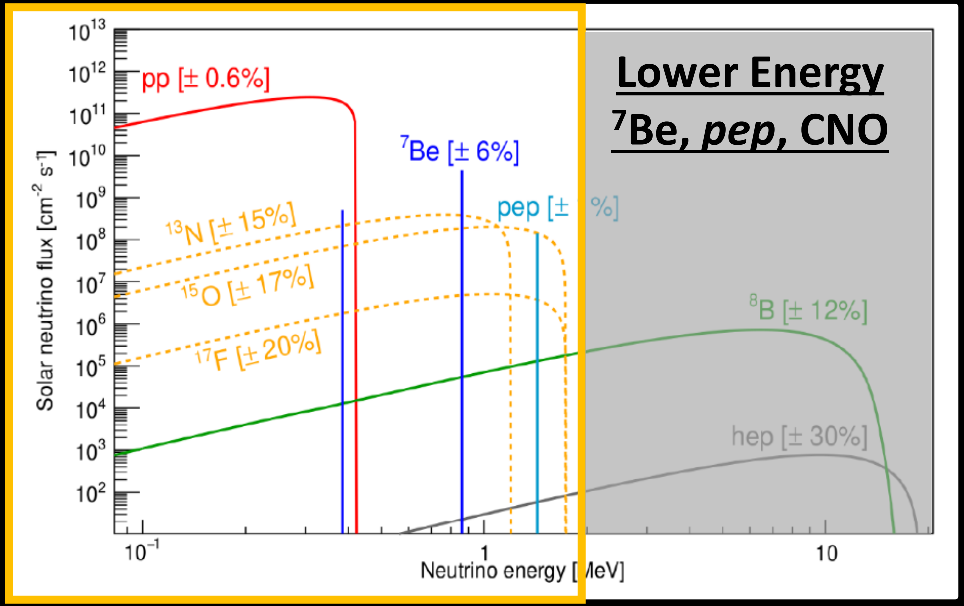
Solar Neutrinos

[“JUNO sensitivity to ^{7}Be, pep, and CNO solar neutrinos” JCAP 10 (2023)]

Lower energy chains : Sensitivity highly dependent on background levels

Can probe the solar core – measurement of the solar metallicity

Expected Flux → Expected Signal + Background → Expected Sensitivity



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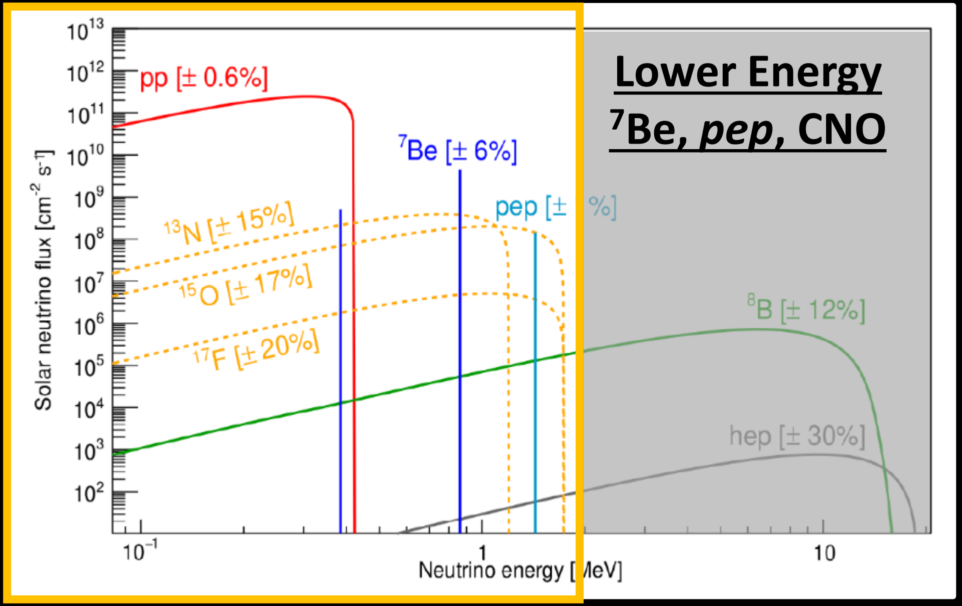

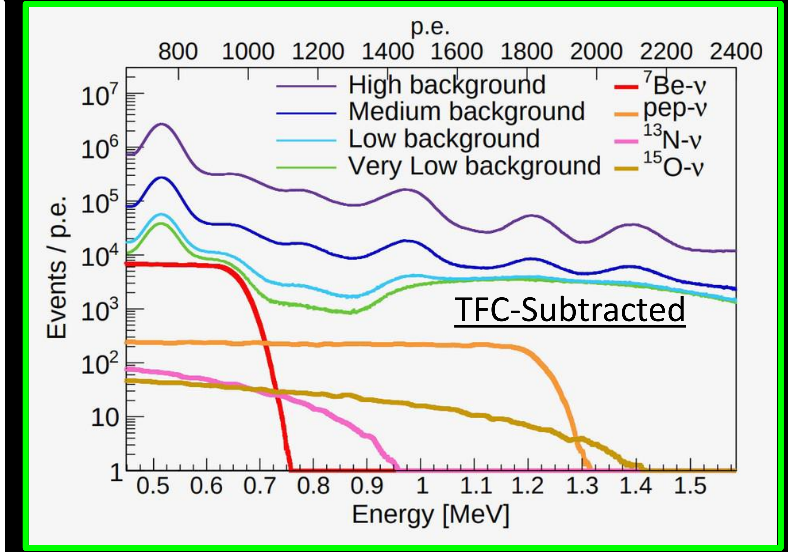

TFC → ^{11}C three-fold coincidence

V. low BG (Borexino): ~10^{-19} $g_{U,Th}/g_{LS}$

High BG: ~10^{-15} $g_{U,Th}/g_{LS}$

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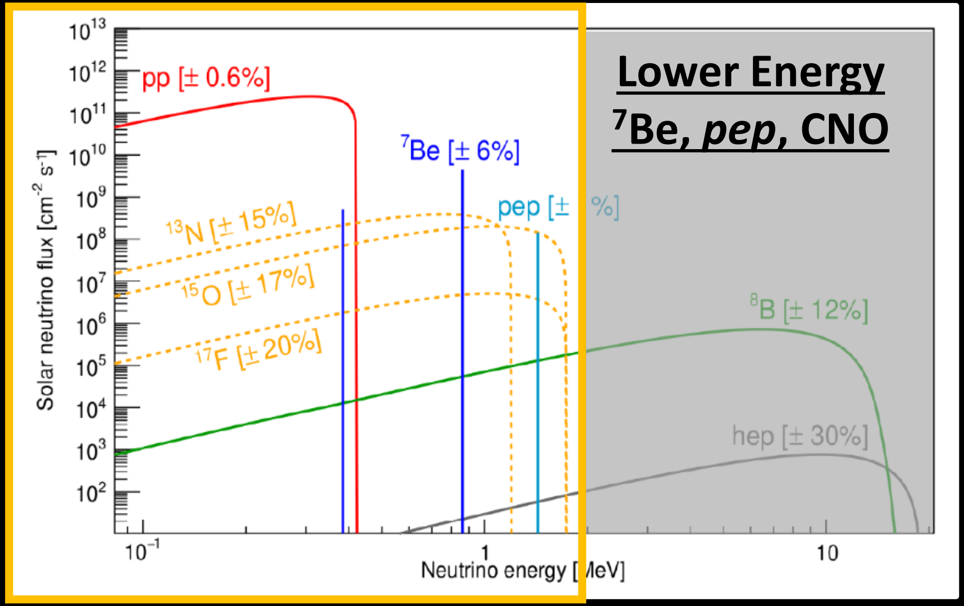

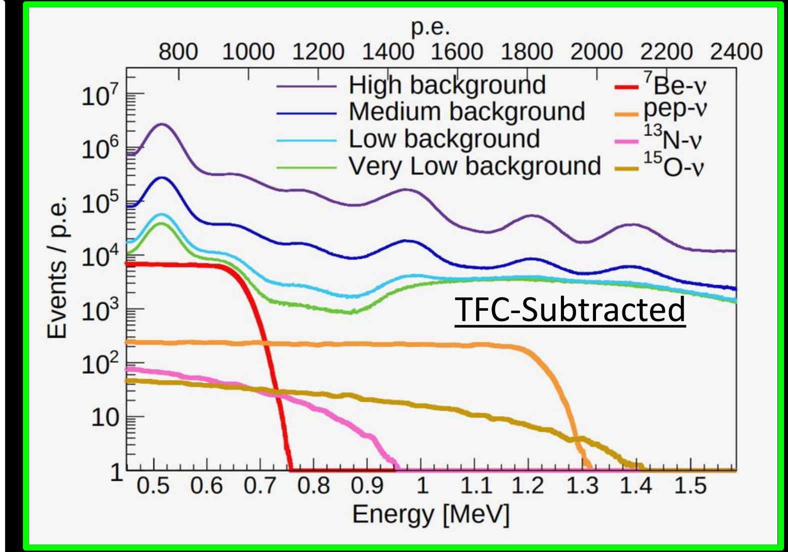

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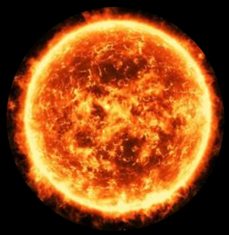
6 years data-taking

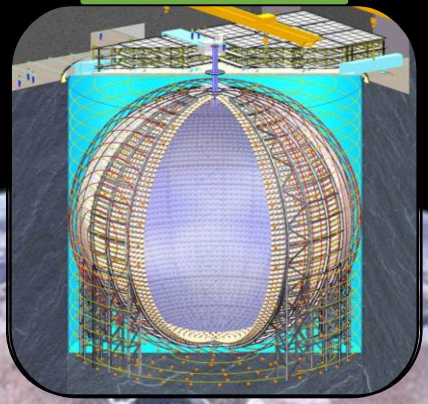
Signal	Very low BGs (Achieved in Borexino)	Higher BGs
^{7}Be	~0.2%	~0.5% (High BG)
pep	3%	17% (High)
CNO	12%	19% (Medium)

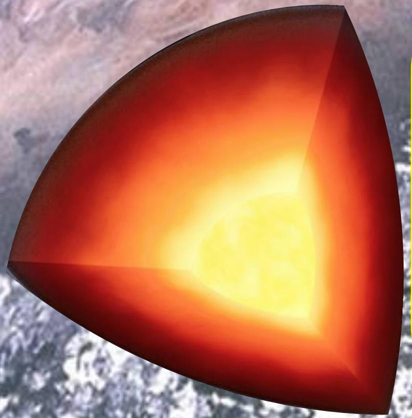
JUNO Physics Programme



Solar

JUNO

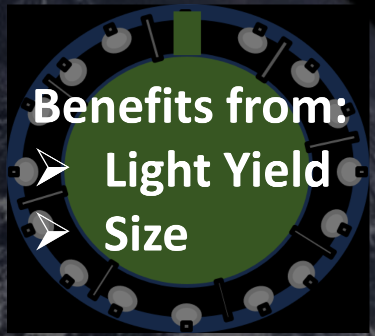




Geoneutrinos

0 – 3 MeV

$\bar{\nu}_e$



Geoneutrinos : $\bar{\nu}_e$

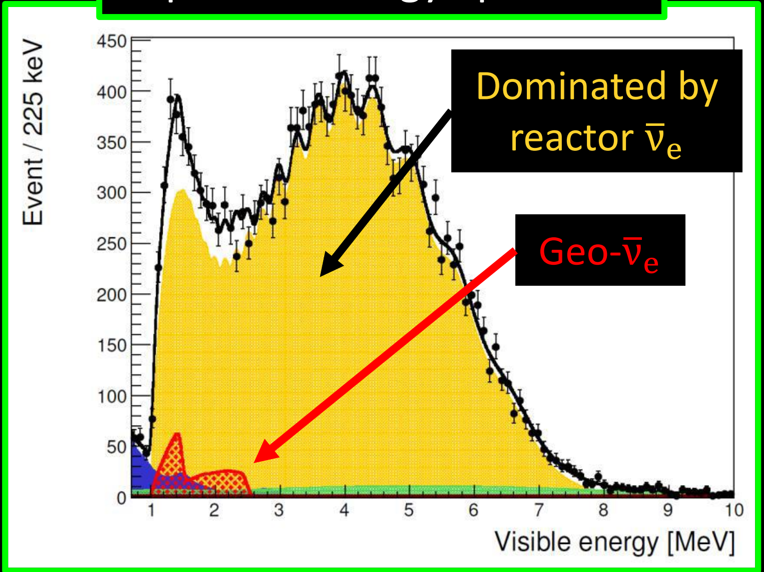
[JUNO physics and detector, Progress in Particle and Nuclear Physics 123 (2022) 103927]

[Strati et al. Progress in Earth and Planetary Science (2015) 2:5 DOI 10.1186/s40645-015-0037-6]

Decay of radionuclides (U/Th/K) within the Earth

- Can measure U and Th abundances.
- Measuring U/Th ratio in crust and mantle probes:
  - Earth's formation, mantle convection, plate tectonics, Earth's magnetic field production

Expected Energy Spectrum



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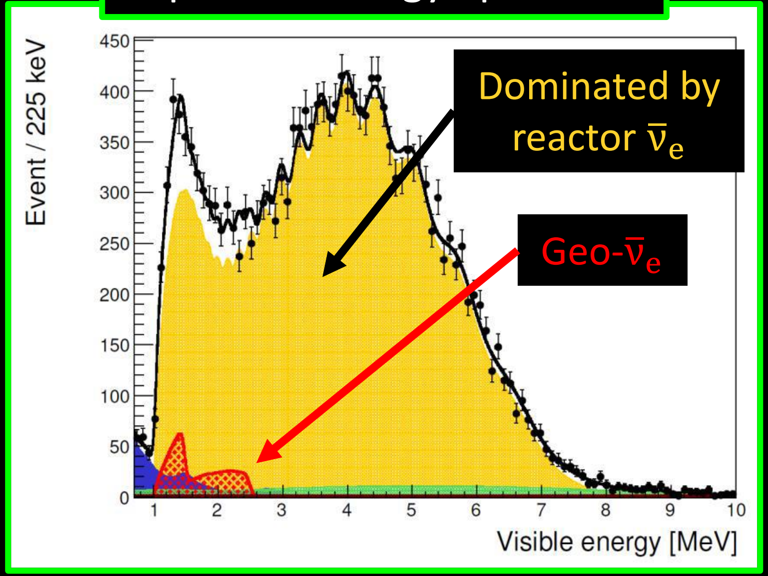

[JUNO physics and detector, Progress in Particle and Nuclear Physics 123 (2022) 103927](#)

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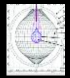
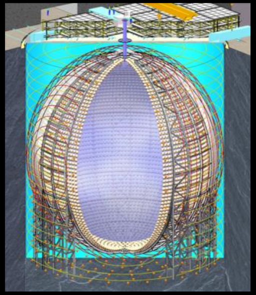
To date, total geo-$\bar{\nu}_e$ candidates:
Borexino + KamLAND : ~200 events





JUNO expects ~400 geo-$\bar{\nu}_e$ interactions per year

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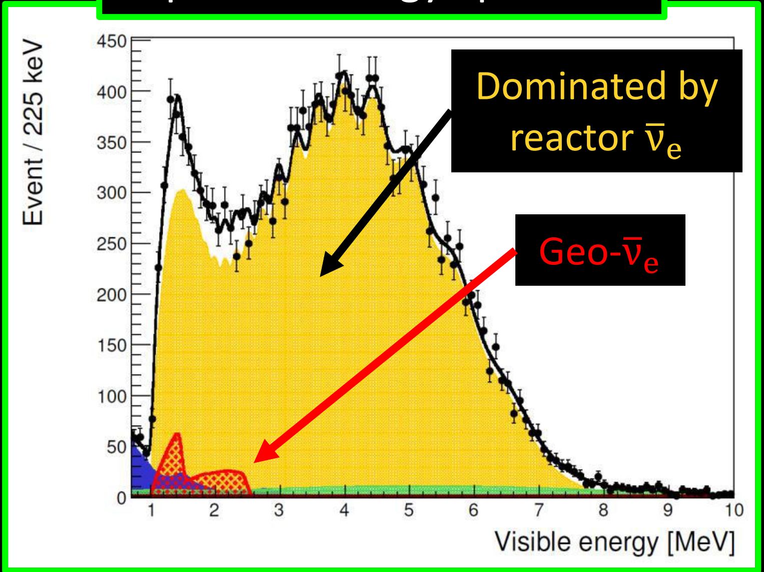

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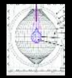

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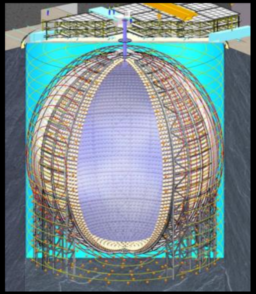


JUNO expects ~400 geo-$\bar{\nu}_e$ interactions per year

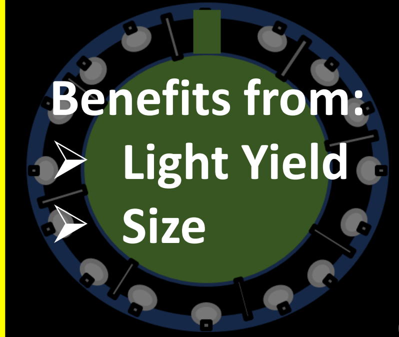
Expected Sensitivity

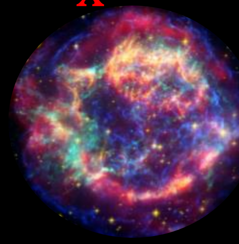
Fit scenario	Sensitivity (6 years data-taking)	
U/Th ratio fixed	U+Th flux ~10%	
U/Th free	U+Th ~18%	U/Th ratio ~70%

Publication under preparation

JUNO Physics Programme

$\nu_x + \bar{\nu}_x$



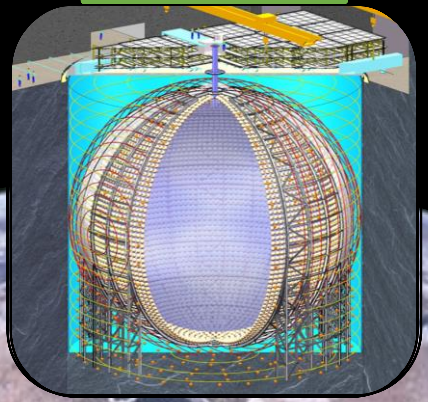


Supernovae

0 ~ 100 MeV

Solar

JUNO



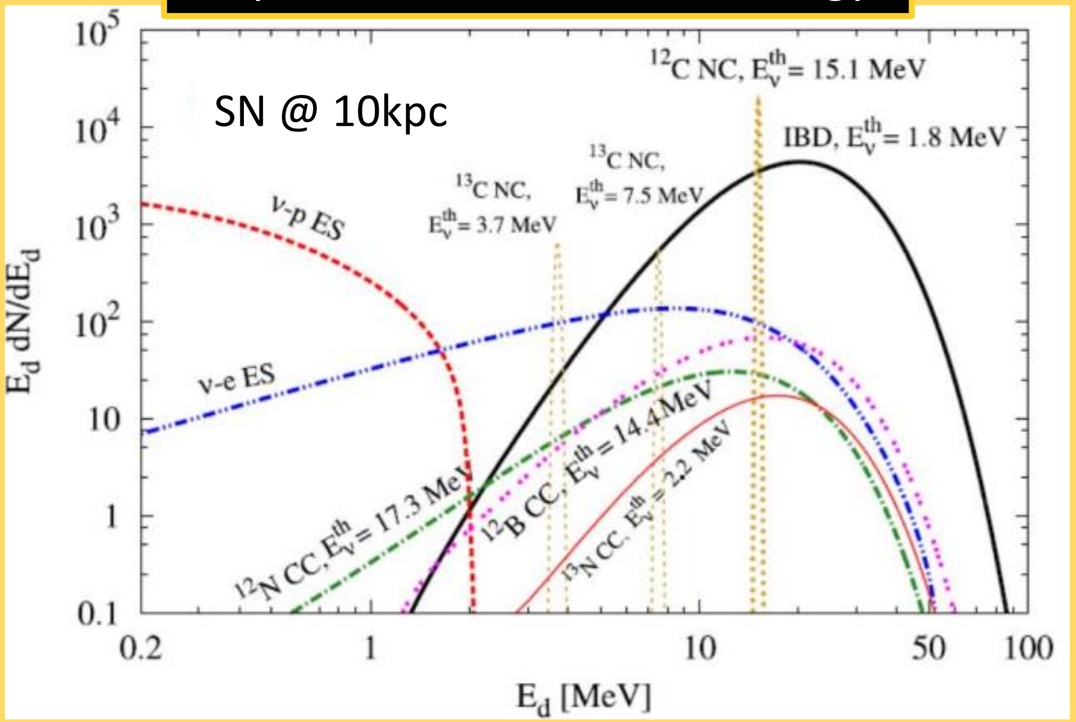
Geoneutrinos

Core-Collapse Supernova Neutrinos

"Real-time monitoring for the next core-collapse supernova in JUNO", Journal of Cosmology and Astroparticle Physics (2024)

ⓘ
- 99% of energy released in (anti-)neutrinos of <u>all flavours</u>
- ~3 CCSN per century in the Milky Way

Expected Flux vs Visible Energy



Expected Event Rate (@10kpc)

Process	Num. Events (E_{thr} = 0.2MeV)
<u>IBD</u> | $\bar{\nu}_e + p \rightarrow e^+ + n$	~5000
<u>pES</u> | $\nu + p \rightarrow \nu + p$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$	~2000
eES | $\nu + e \rightarrow \nu + e$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$	~400
CC | $\overset{(-)}{\nu}_e + ^{12}C \rightarrow e^{-(+)} + ^{12}N(^{12}B)$	~200
NC | $\nu + ^{12}C \rightarrow \nu + ^{12}C^*$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$ $\rightarrow \gamma(15.11\text{MeV})$	~300

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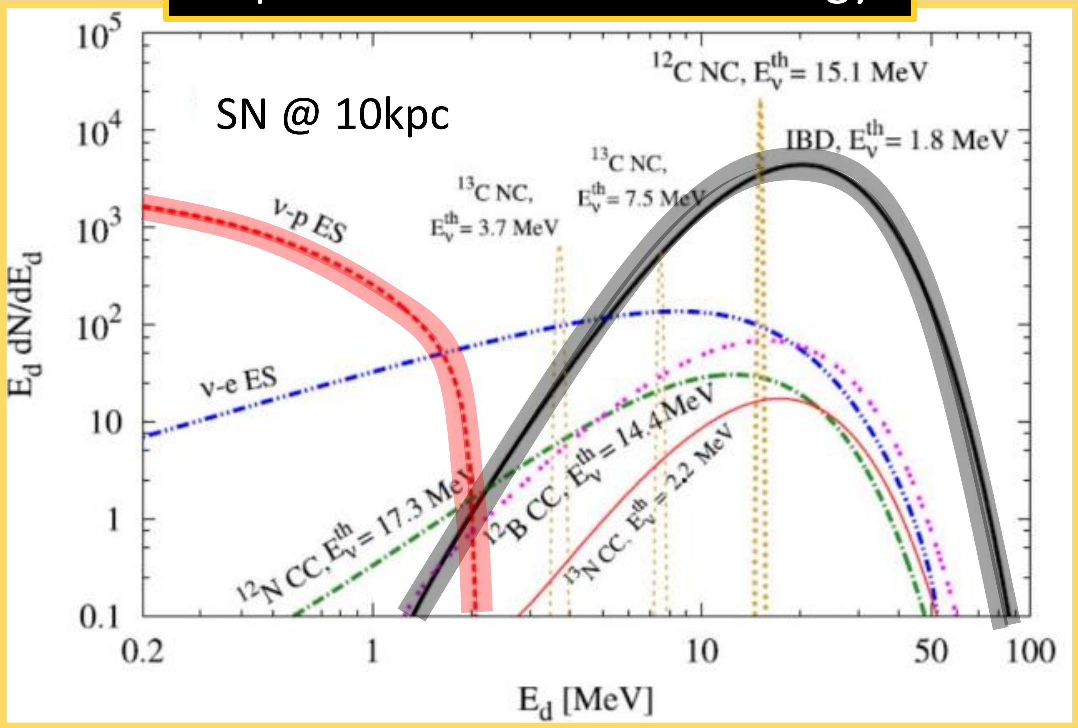

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Core-Collapse Supernova Neutrinos

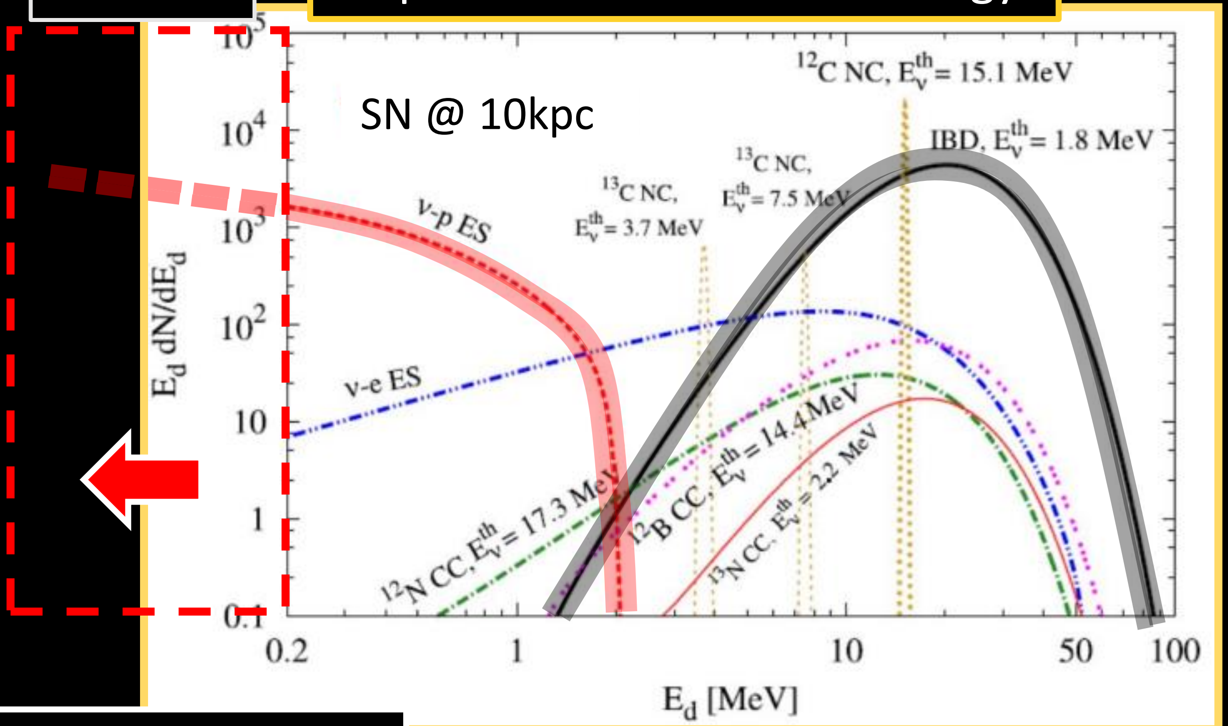
[“Real-time monitoring for the next core-collapse supernova in JUNO”, Journal of Cosmology and Astroparticle Physics (2024)]

2 Independent Trigger Systems:

- Global Trigger E_{thr}~200 keV
- Multi-Messenger Trigger E_{thr}~20 keV

MM Trigger ~20keV

Expected Flux vs Visible Energy



Boost pES statistics

Expected Event Rate (@10kpc)

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Aim for CEνNS | $\nu +^{12} C \rightarrow \nu +^{12} C$	

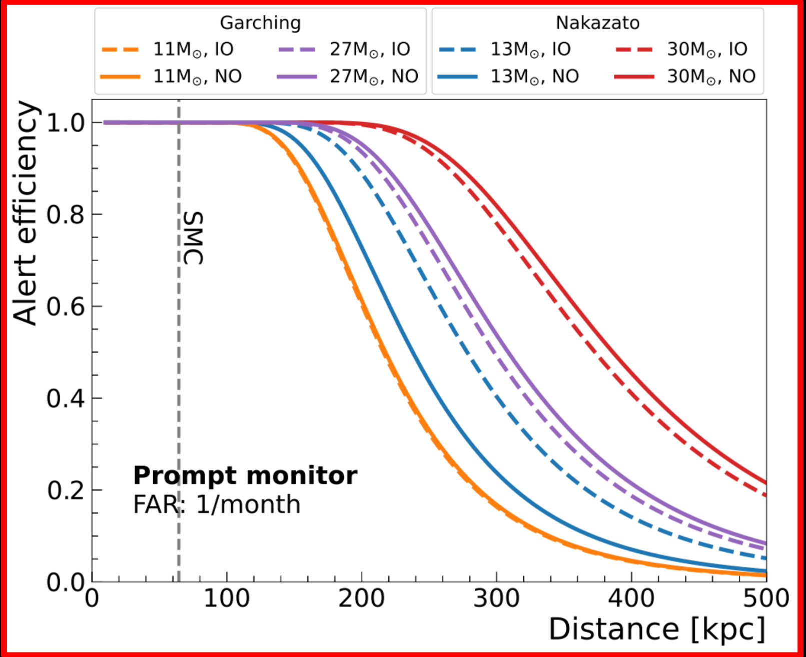
Core-Collapse Supernova Neutrinos

[“Real-time monitoring for the next core-collapse supernova in JUNO”, Journal of Cosmology and Astroparticle Physics (2024)]

Rapid declarations of transient neutrino signals

Aim to contribute to Supernova Early Warning System (SNEWS) [4]

Alert eff. vs SN distance



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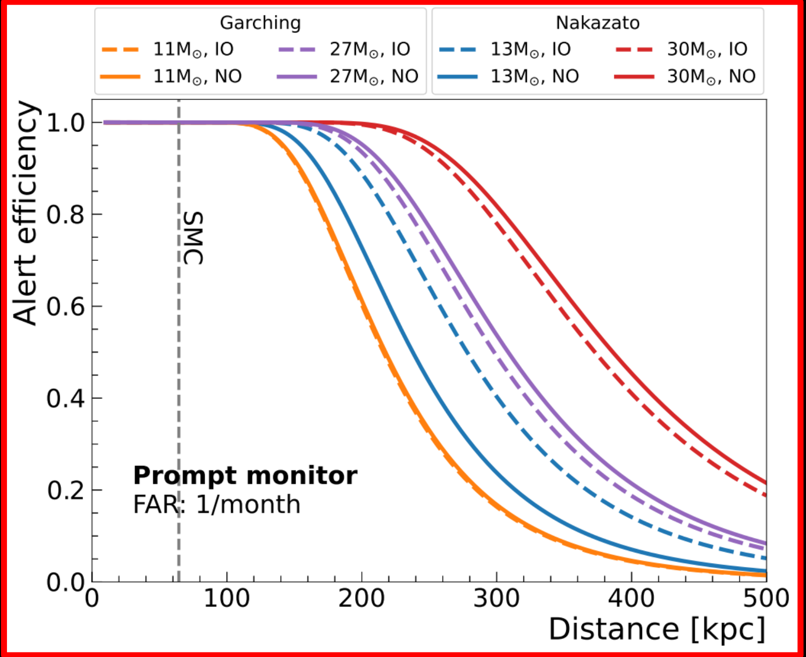
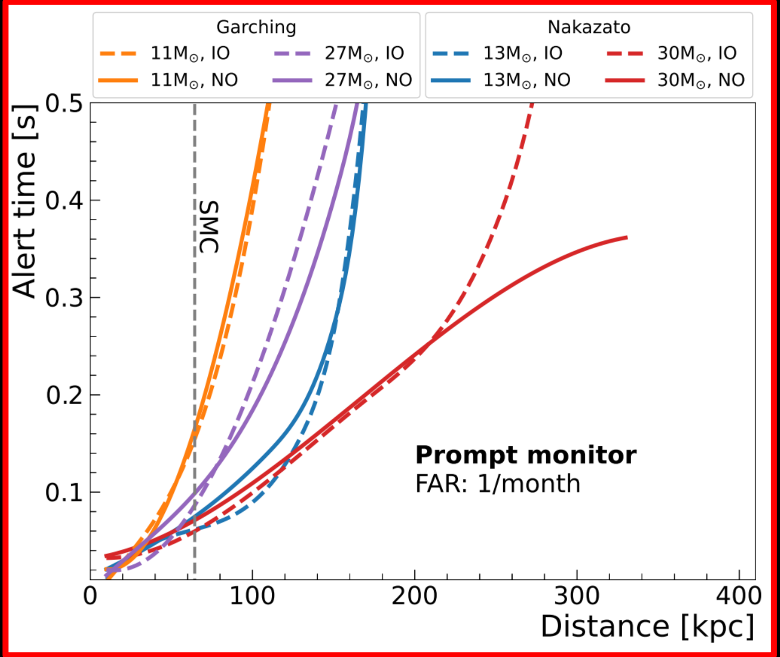


Alert time vs SN distance



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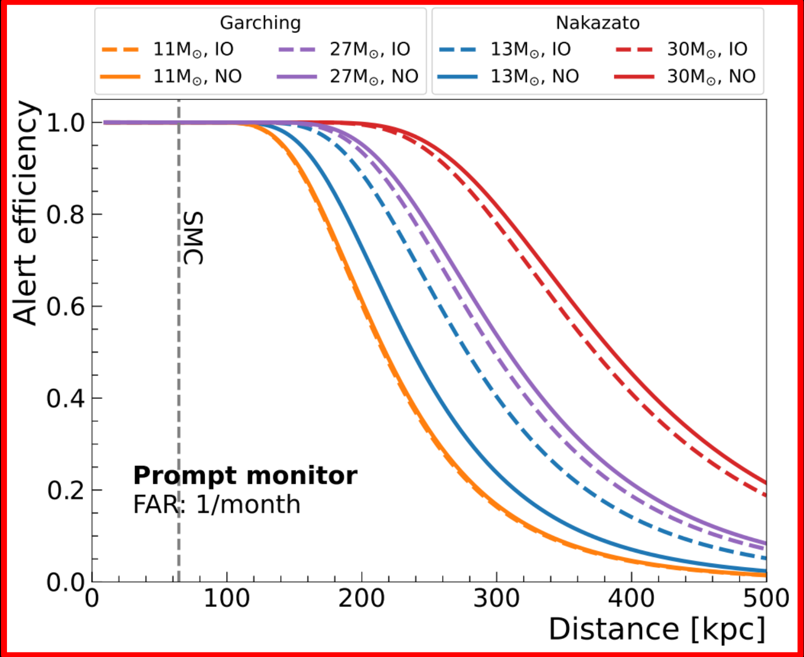

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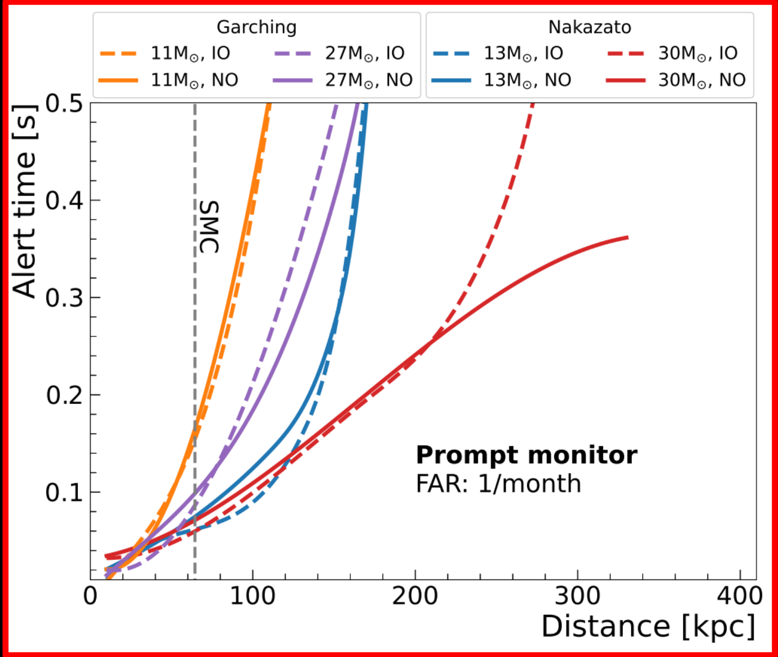


27 $M_\odot$ CCSN:

- ~50% alert efficiency at 300kpc
- Alert Time @ 10kpc ~10-30ms

CCSN Energy spectrum
+ Time evolution
→ Probe mass ordering

Diffuse Supernova Neutrino Background

Integrated SN neutrino signal in the Universe

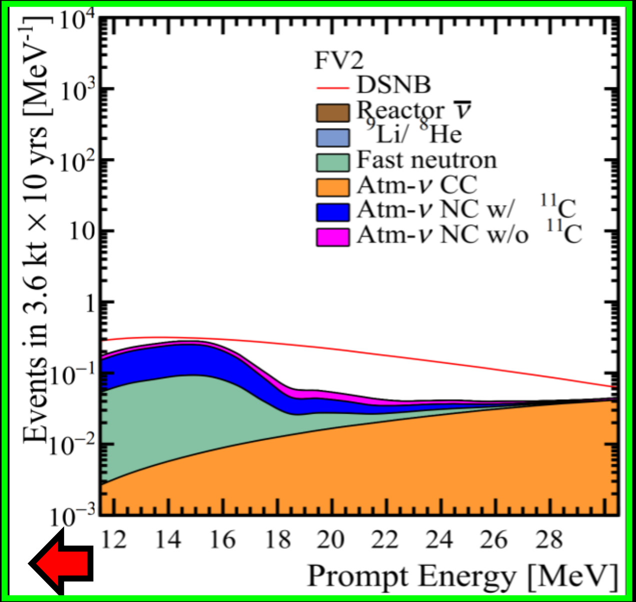
Low Flux – Use low background IBD channel $\bar{\nu}_e$

[“Prospects for Detecting the Diffuse Supernova Neutrino Background with JUNO,” JCAP **10** (2022)]

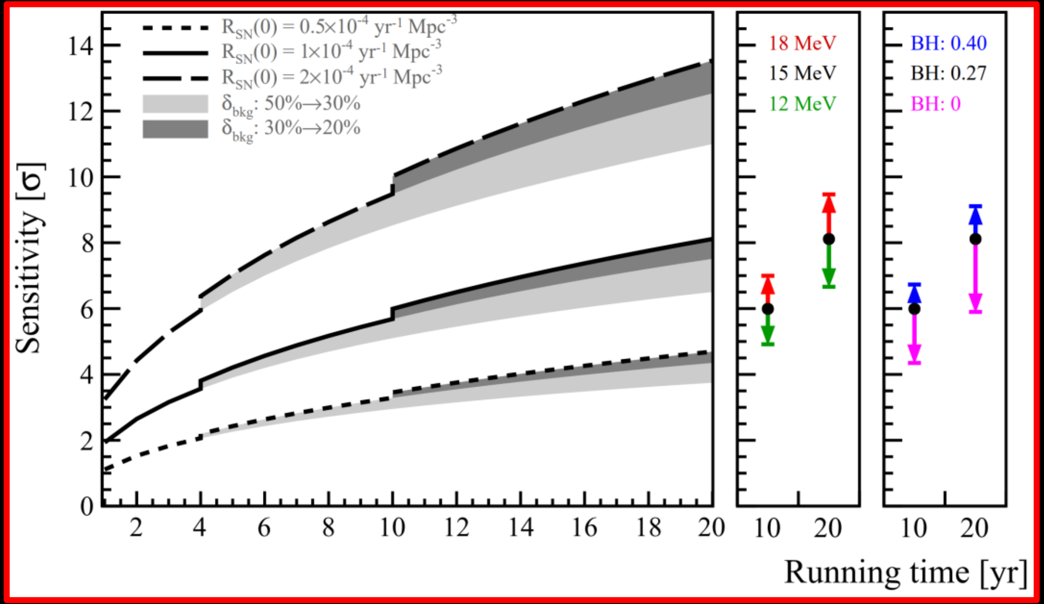
Expected Signal + Background

Expected Sensitivity vs Time

Expect 2-4 yr^{-1} (w/o PSD)



Avoid Reactor IBDs <12MeV

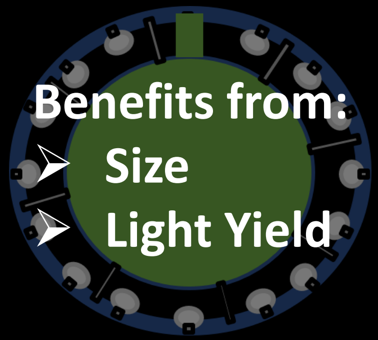


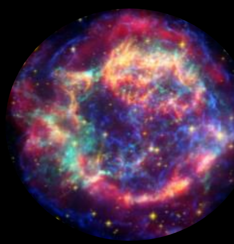
DSNB evidence

3σ in 3 yrs with nominal models

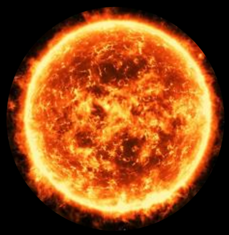
JUNO Physics Programme

Atmospherics
0.1 – 100 GeV
$\overset{(-)}{\nu}_{e,\mu}$



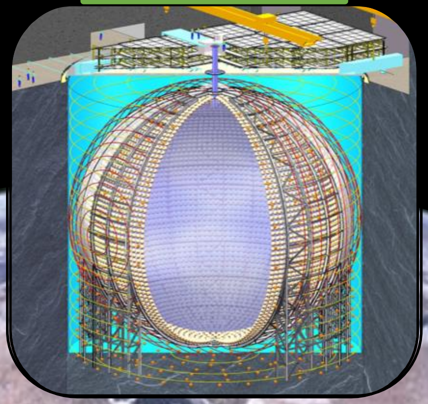


Supernovae



Solar

JUNO



Geoneutrinos

Atmospherics

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

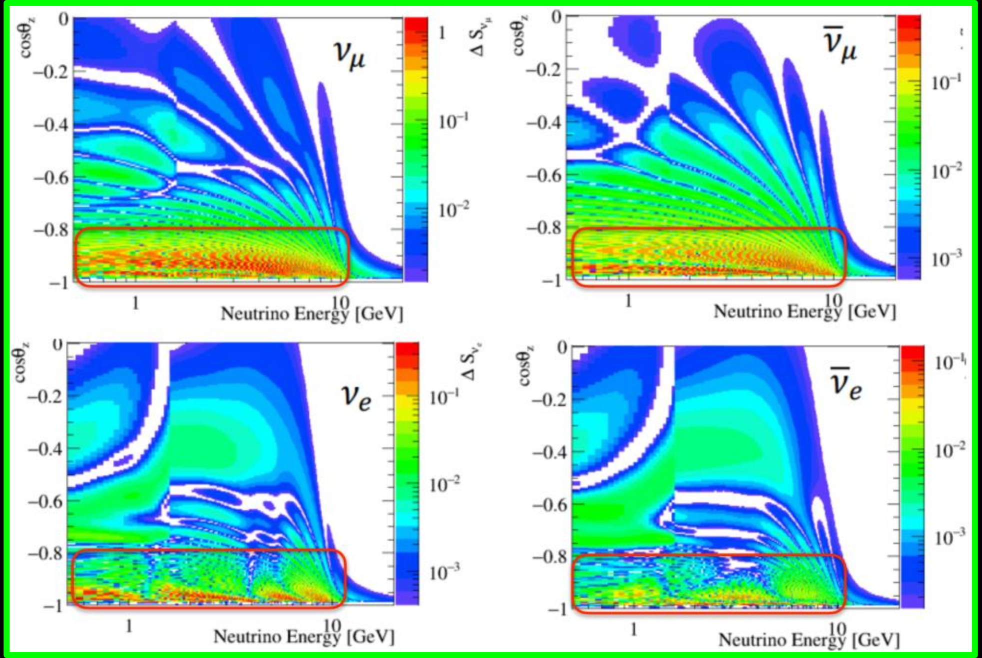
“JUNO sensitivity to low energy atmospheric neutrino spectra” The European Physical Journal C volume 81, Article number: 887 (2021)

Discriminate ν_e and ν_μ in LS with PMT hit patterns → ~10-25% uncertainty in 5 years

Measure differences in direction and energy spectra for $\overset{(-)}{\nu}_e$ and $\overset{(-)}{\nu}_\mu$

Expected direction and energy spectra

Atmos. Flux * Cross-section * Survival prob (NO - IO)



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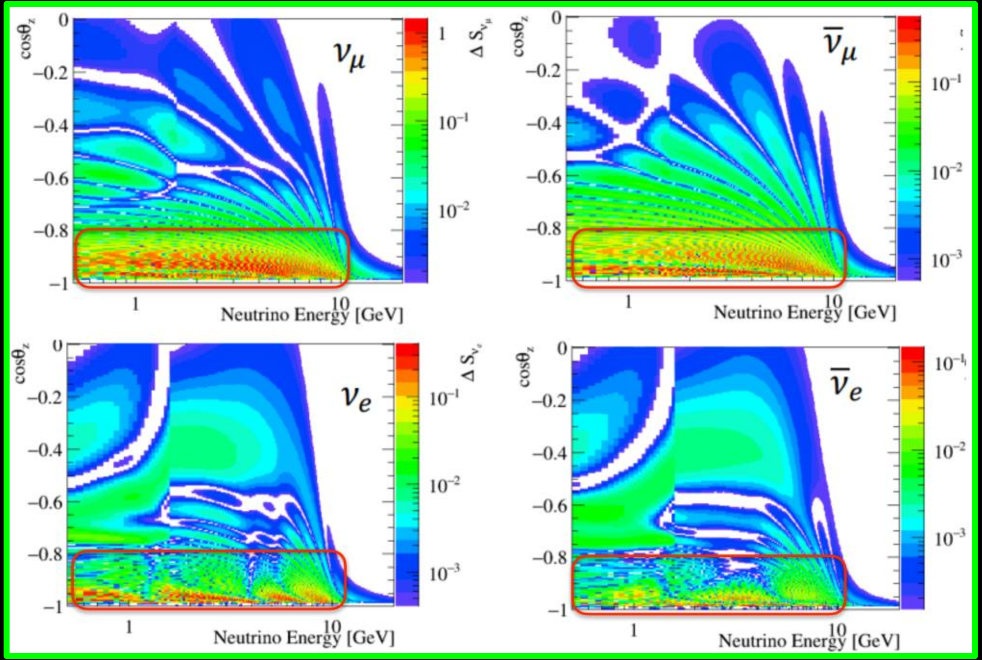


Expected Sensitivity

→ Would be first measurement of atmospheric neutrino oscillation in liquid scintillator

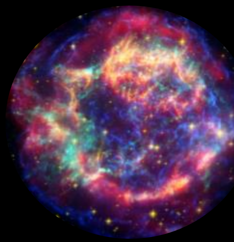
→ Matter effects over ~3-10GeV provide sensitivity to Neutrino Mass Ordering

→ Complementary to the reactor NMO analysis

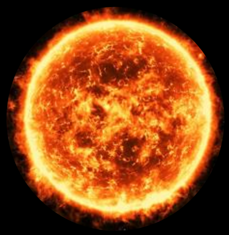
NMO expectation:
0.7-1.4σ in ~6 years exposure

JUNO Physics Programme

Atmospherics

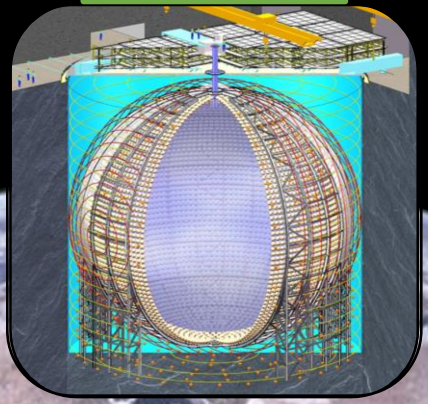


Supernovae

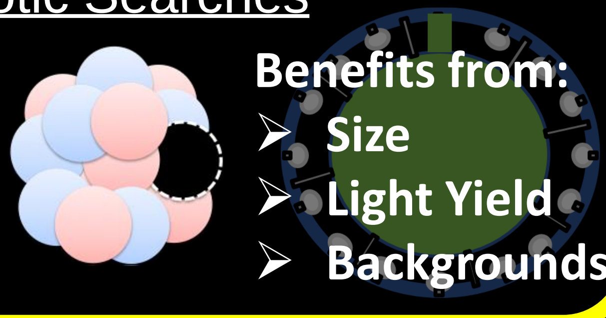


Solar

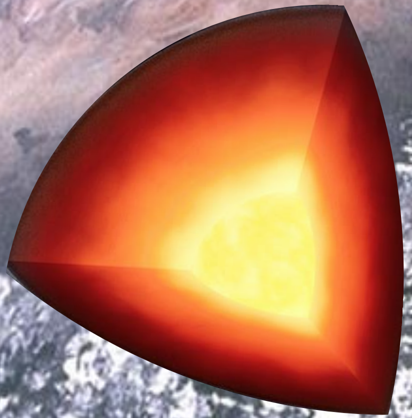
JUNO



Exotic Searches



Benefits from:
- **Size**
- **Light Yield**
- **Backgrounds**

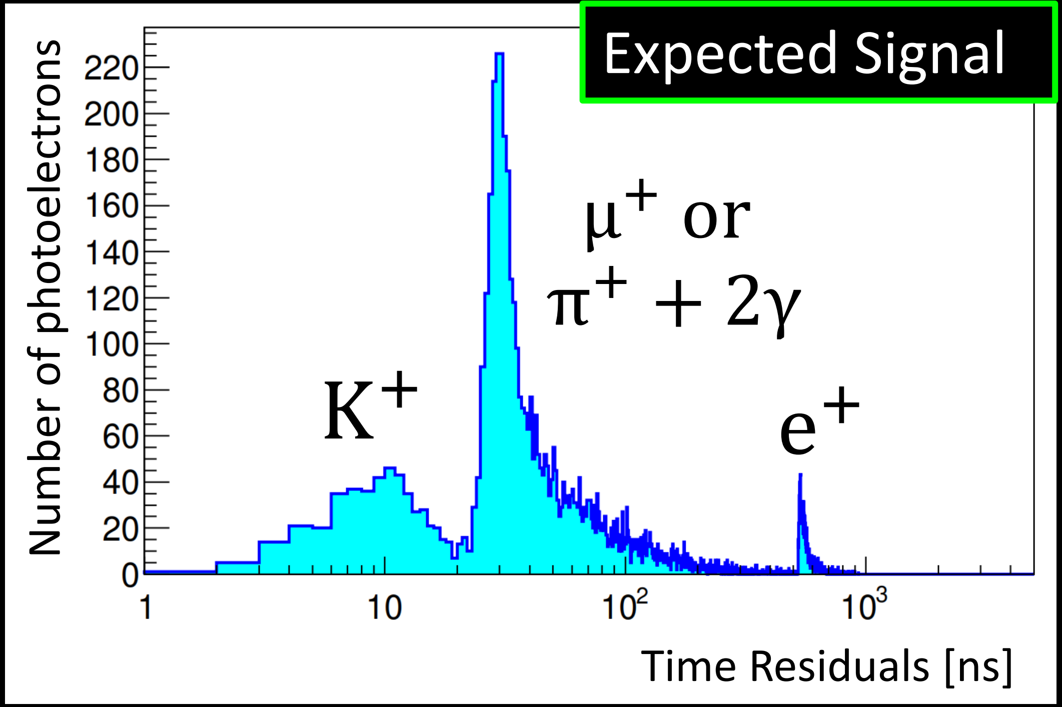


Geoneutrinos

Nucleon Decay

JUNO physics and detector, Progress in Particle and Nuclear Physics 123 (2022) 103927

Number of GUTs require baryon number violation and predict nucleon decay



Proton decay in LS: triple coincidence signal

$$p \rightarrow K^+ + \bar{\nu}$$

$$K^+ \rightarrow \mu^+ + \nu_\mu$$

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

LS light yield benefits K^+ identification

Expected Sensitivity

10 years data-taking:
9.6×10^{33} years (90% C.L.)

Nucleon Decay

"JUNO Sensitivity to Invisible Decay Modes of Neutrons", arXiv:2405.17792v1 (2024)

Neutron invisible decays in ^{12}C in LS

$n \rightarrow 3\nu$ or $nn \rightarrow 2\nu$

Neutrons in ^{12}C decay with triple coincidences

$^{11}C^* \rightarrow n + {}^{10}C$ $(BR_{n \rightarrow inv} = 3.0\%)$

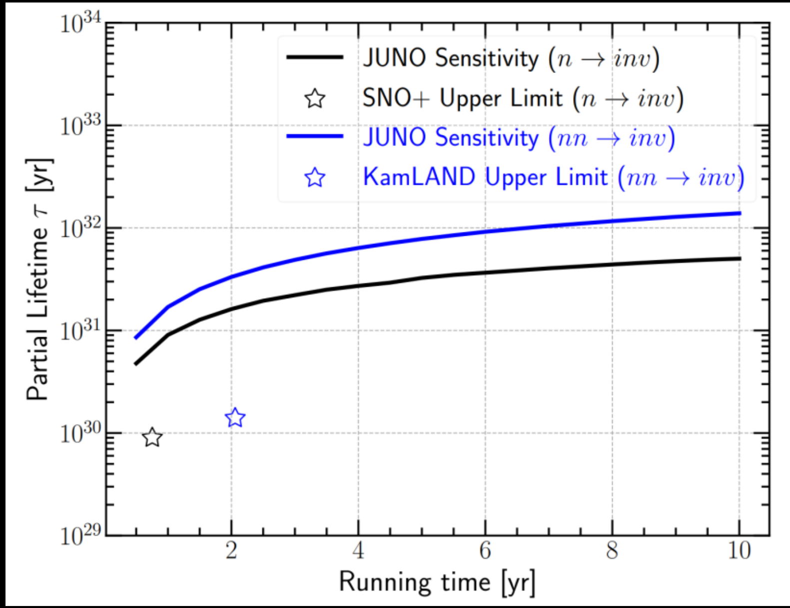
$^{11}C^* \rightarrow n + \gamma + {}^{10}C$ $(BR_{n \rightarrow inv} = 2.8\%)$

$^{10}C^* \rightarrow n + {}^{9}C$ $(BR_{nn \rightarrow inv} = 6.2\%)$

$^{10}C^* \rightarrow n + p + {}^{8}B$ $(BR_{nn \rightarrow inv} = 6.0\%)$

Primary backgrounds:
Reactor $\bar{\nu}_e$ + singles, atmospheric NC interactions

Expected Sensitivity



10 year data-taking:
τ/B ($n \rightarrow$ inv) 5.0×10^{31} years
τ/B ($nn \rightarrow$ inv) 1.4×10^{32} years
(90% C.L.)

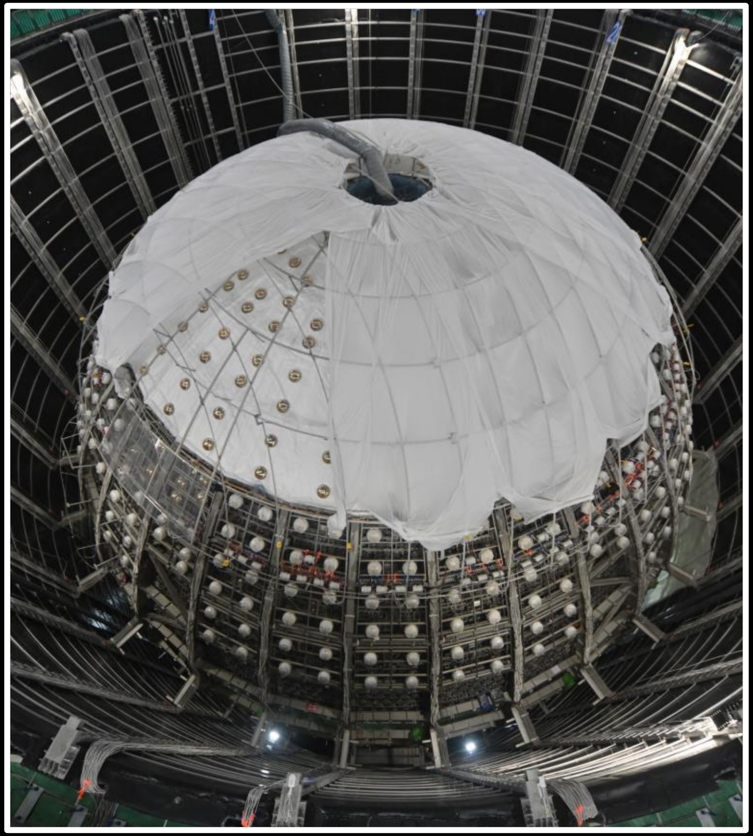
The JUNO Experiment

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	Tsinghua U.	Germany	U. Tuebingen
Belgium	Universite libre de Bruxelles	China	UCAS	Italy	INFN Catania
Brazil	PUC	China	USTC	Italy	INFN di Frascati
Brazil	UEL	China	U. of South China	Italy	INFN-Ferrara
Chile	SAPHIR	China	Wu Yi U.	Italy	INFN-Milano
Chile	UNAB	China	Wuhan U.	Italy	INFN-Milano Bicocca
China	BISEE	China	Xi'an JT U.	Italy	INFN-Padova
China	Beijing Normal U.	China	Xiamen University	Italy	INFN-Perugia
China	CAGS	China	Zhengzhou U.	Italy	INFN-Roma 3
China	ChongQing University	China	NUDT	Pakistan	PINSTECH (PAEC)
China	CIAE	China	CUG-Beijing	Russia	INR Moscow
China	DGUT	China	ECUT-Nanchang City	Russia	JINR
China	Guangxi U.	China	CDUT-Chengdu	Russia	MSU
China	Harbin Institute of Technology	Czech	Charles U.	Slovakia	FMPICU
China	IHEP	Finland	University of Jyvaskyla	Taiwan-China	National Chiao-Tung U.
China	Jilin U.	France	IJCLab Orsay	Taiwan-China	National Taiwan U.
China	Jinan U.	France	LP2i Bordeaux	Taiwan-China	National United U.
China	Nanjing U.	France	CPPM Marseille	Thailand	NARIT
China	Nankai U.	France	IPHC Strasbourg	Thailand	PPRLCU
China	NCEPU	France	Subatech Nantes	Thailand	SUT
China	Pekin U.	Germany	RWTH Aachen U.	U.K.	U. Liverpool
China	Shandong U.	Germany	TUM	U.K.	U. Warwick
China	Shanghai JT U.	Germany	U. Hamburg	USA	UMD-G
China	IGG-Beijing	Germany	GSI	USA	UC Irvine
China	SYSU	Germany	U. Mainz		

2024 Collaboration Meeting in Kaiping, China

74 Institutes, 17 countries
> 700 collaborators

Conclusion

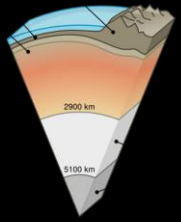


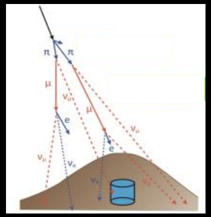
- JUNO: 20 kT liquid scintillator detector with first-rate size and energy resolution

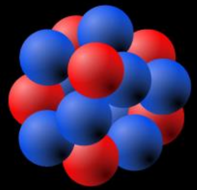
  Expected data-taking at the end of 2024

- Diverse physics program : O(10keV) – O(10GeV)
  - Reactor nu
  - Geo nu
  - Solar nu
  - Supernova

    Nearby CCSN + Diffuse Neutrino Background
  - Atmospheric nu
  - Searches for new physics







References

[1] G. Alimonti et al., The Borexino detector at the Laboratori Nazionali del Gran Sasso, Nucl. Instrum. Methods Phys. Res., Sect. A 600, 568 (2009).

[2] A. Gando et al., Measurement of the double-β decay halflife of 136Xe with the KamLAND-Zen experiment, Phys. Rev. C 85, 045504 (2012).

[3] S. Andringa et al., Current status and future prospects of the SNO+ experiment, Adv. High Energy Phys. 2016, 6194250 (2016).

[4] S Al Kharusi et al., SNEWS 2.0: a next-generation supernova early warning system for multi-messenger astronomy, New J. Phys. 23 031201 (2021).

Backup

Detector components

"Radioactivity control strategy for the JUNO detector," JHEP **11** (2021), 102

- Acrylic Vessel : 12.4 $\pm$ 0.4cm thick, >96% transparency for LS emission spectrum
- 265 Acrylic sphere segments, each assembled, polished, cleaned, then covered with PE protective film (to prevent exposure to air, preserve <1ppt radiopurity levels prior to installation)

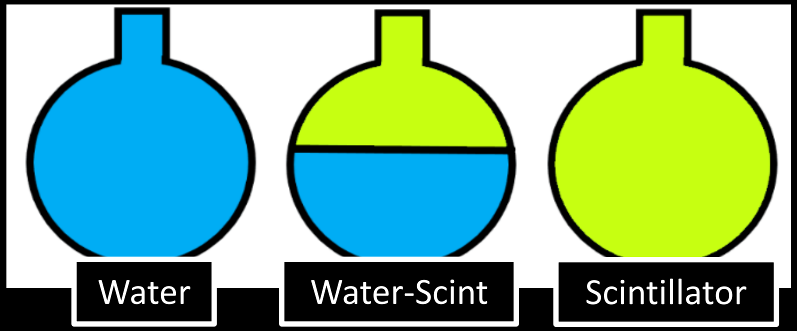
Acrylic segment covered with film

- Stainless steel support structure (completed June 24)
  - Supports acrylic vessel, PMTs and electronics affixed to
  - Assembly precision <3mm
- 590 connecting rods – connects to acrylic sphere

Radiopurity Control

“Radioactivity control strategy for the JUNO detector,” JHEP **11** (2021), 102

“The design and sensitivity of JUNO’s scintillator radiopurity pre-detector OSIRIS”, Eur. Phys. J. C **81** (2021) no.11, 973



- JUNO will undergo water filling following by liquid scintillator

LAB purification:

- LAB storage -> Filtration -> Distillation -> Mixing -> Water extraction -> Gas Stripping -> Radiopurity monitoring -> JUNO Central Detector

OSIRIS : 20 ton
Radioactivity monitoring system

- Target for IBD Analysis : ~10^{-15} g/gLAB U/Th
- “Ideal” Target : ~10^{-17} g/gLAB U/Th

PMTs

- 20” and 3” PMTs : Waterproof potting + testing
- Installation underway

- 15000x 20” MCP PMTs (NNVT) | 5000x 20” Dynode Hamamatsu
- TTS (σ) : 20” NNVT = 7.0 ns | 20” Hamamatsu = 1.3 ns
  3” HZC = 1.6 ns
- ~13,000 NNVT PMTs with the best PDE used for Detector light collection
  - Rest used for outer water Cherenkov detector muon veto