JUNO: Status & Prospects

Iwan Morton-Blake

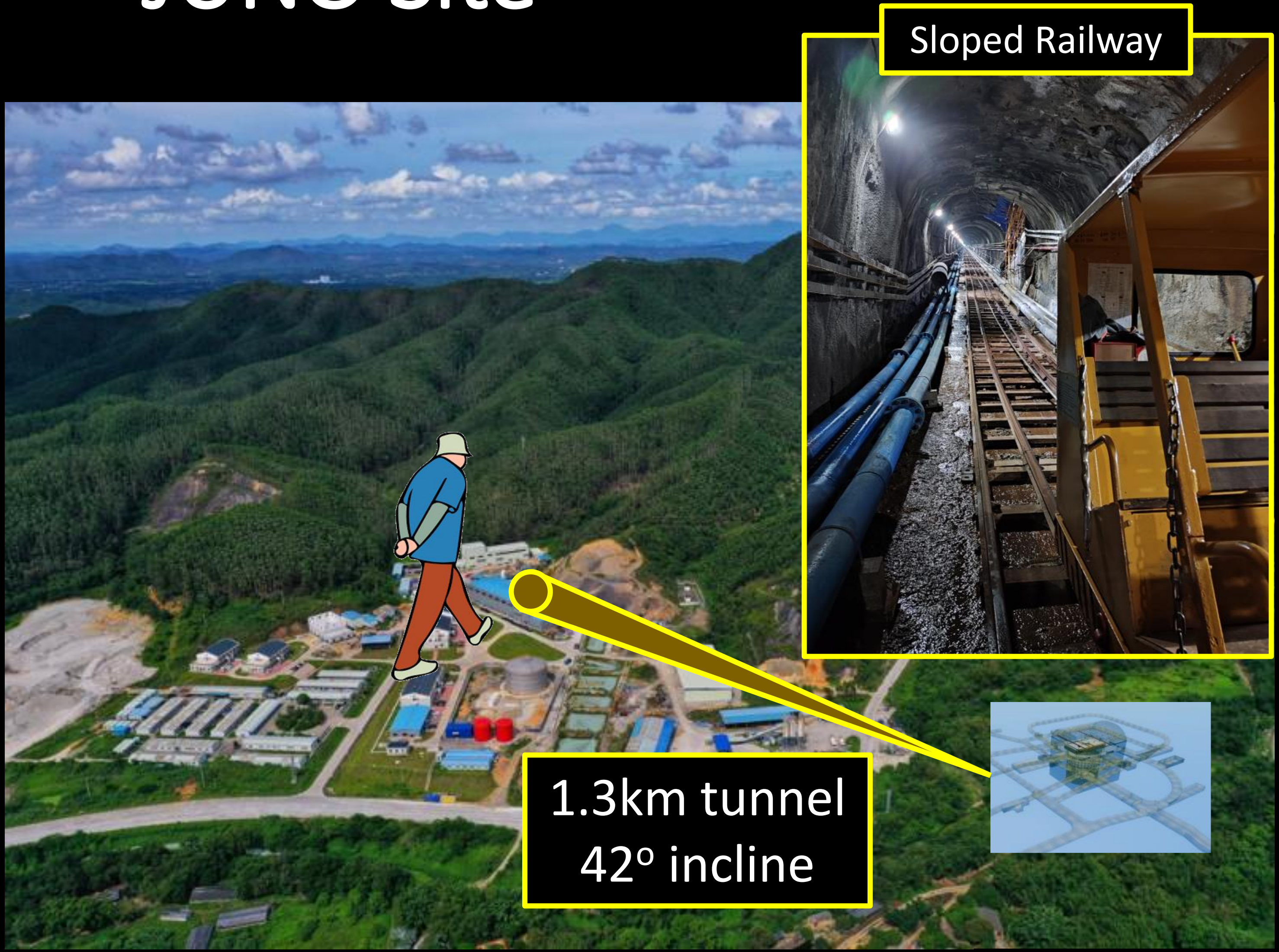
On behalf of the JUNO collaboration

李政道研究所
TSUNG-DAO LEE INSTITUTE

JUNO Site

The **J**iangmen **U**nderground **N**eutrino **O**bservatory in Southern China

JUNO Site



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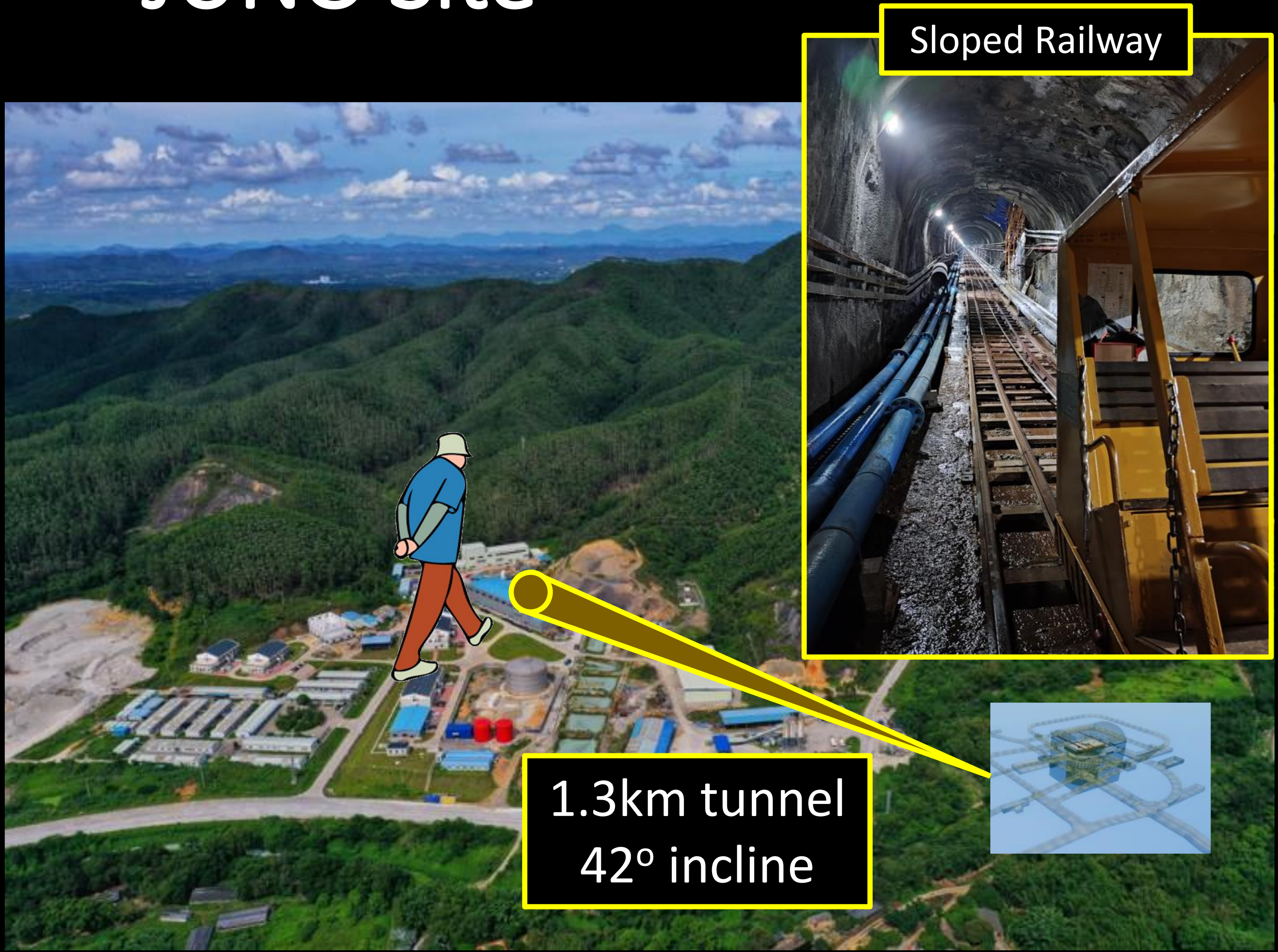

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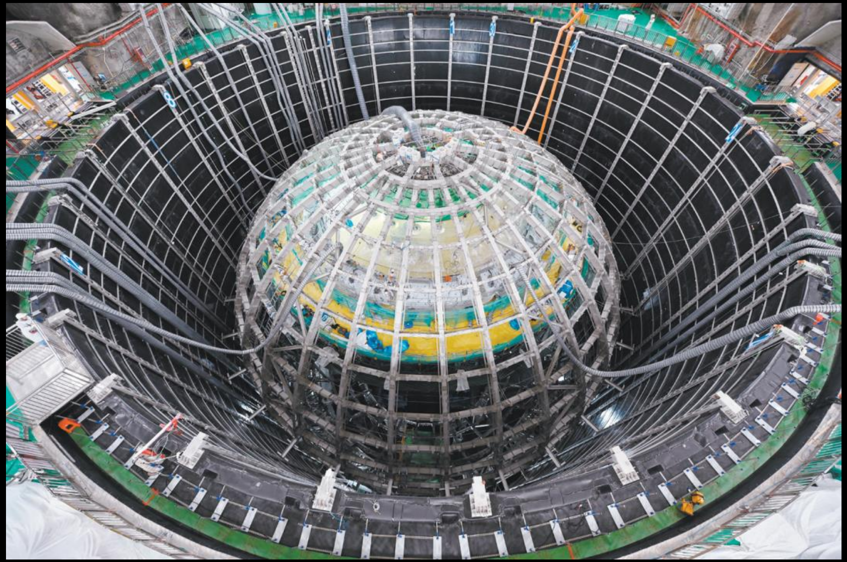
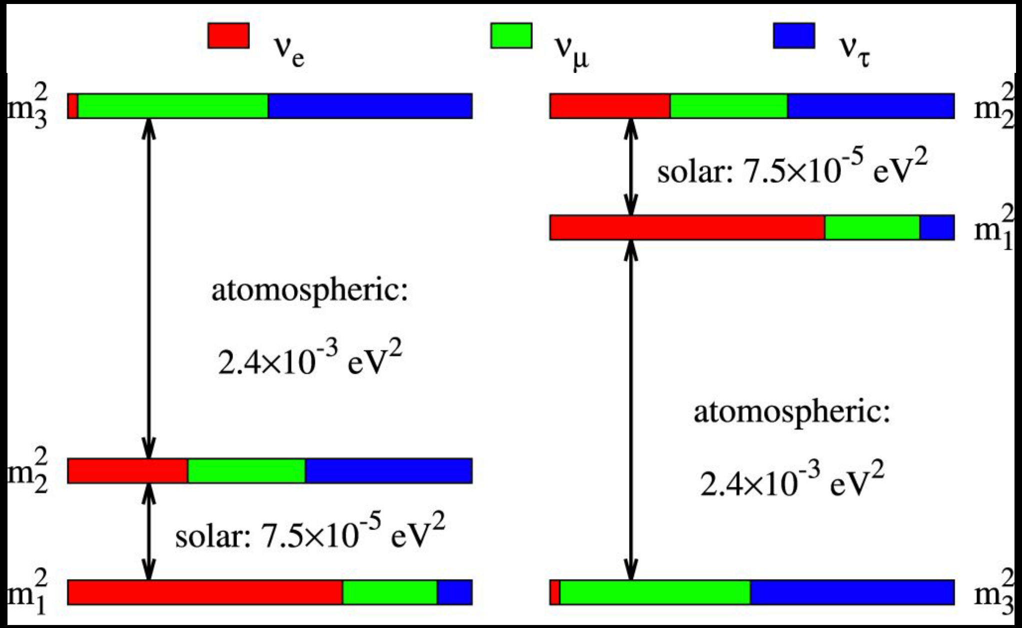


JUNO Physics Goals



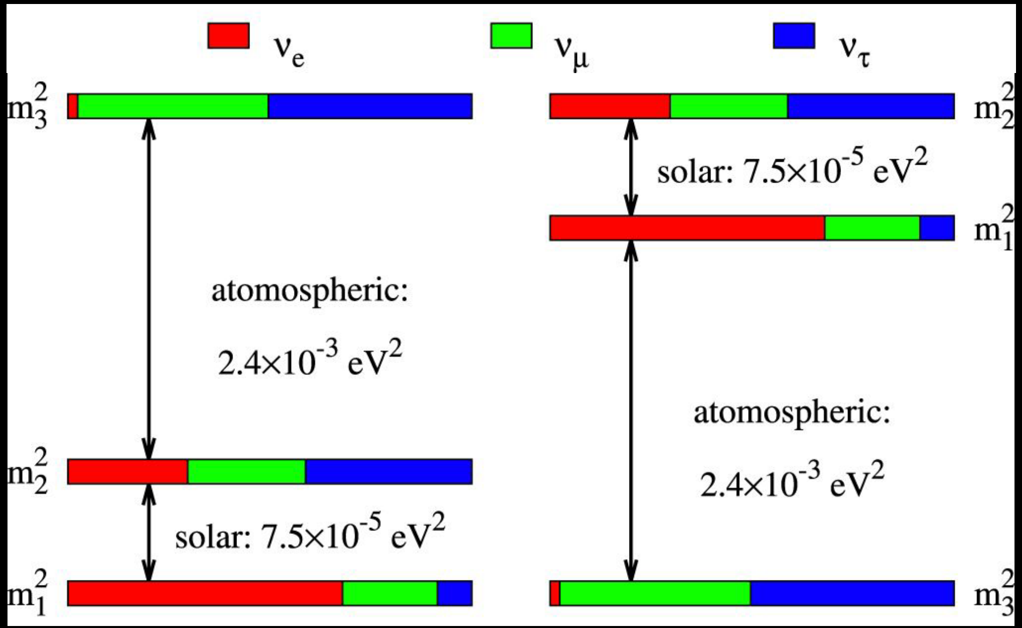
Normal Ordering
$m_1 < m_2 < m_3$

Inverted Ordering
$m_3 < m_1 < m_2$

Primary Physics Goal:
Determine Neutrino Mass Ordering (NMO)

JUNO : Reactor $\bar{\nu}_e$

Total thermal power of 26.6 GW



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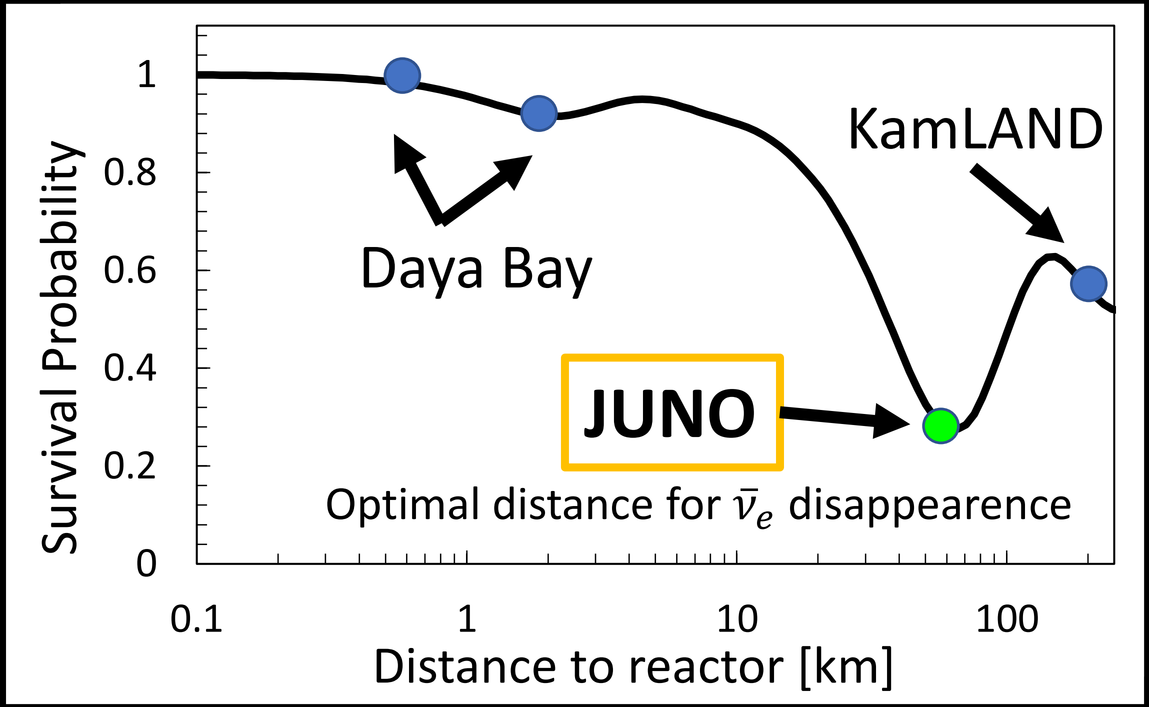
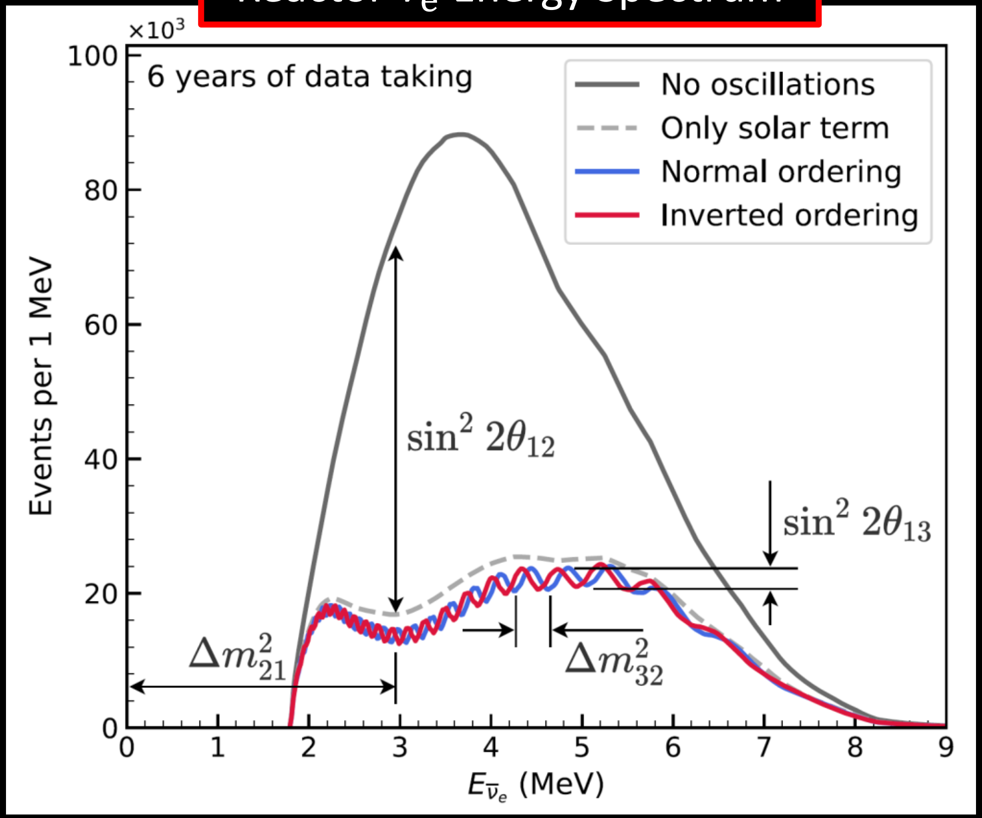


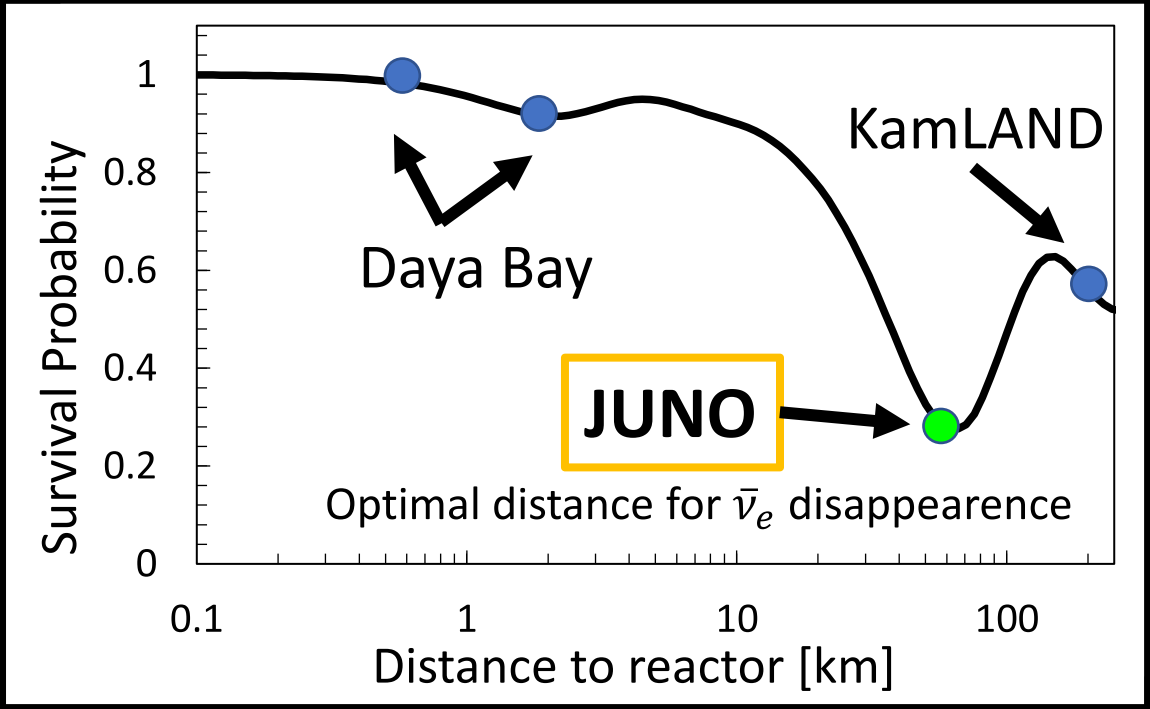
(Survival averaged over reactor energy spectrum)

JUNO : Reactor $\bar{\nu}_e$

Total thermal power of 26.6 GW

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



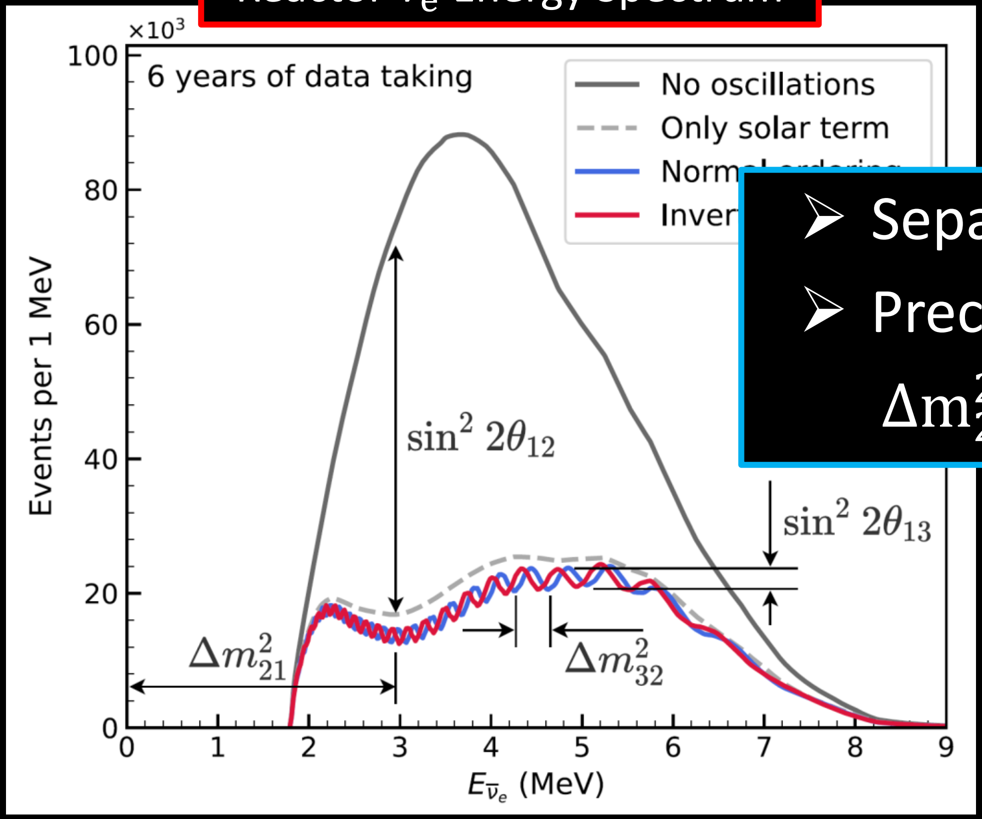


(Survival averaged over reactor energy spectrum)

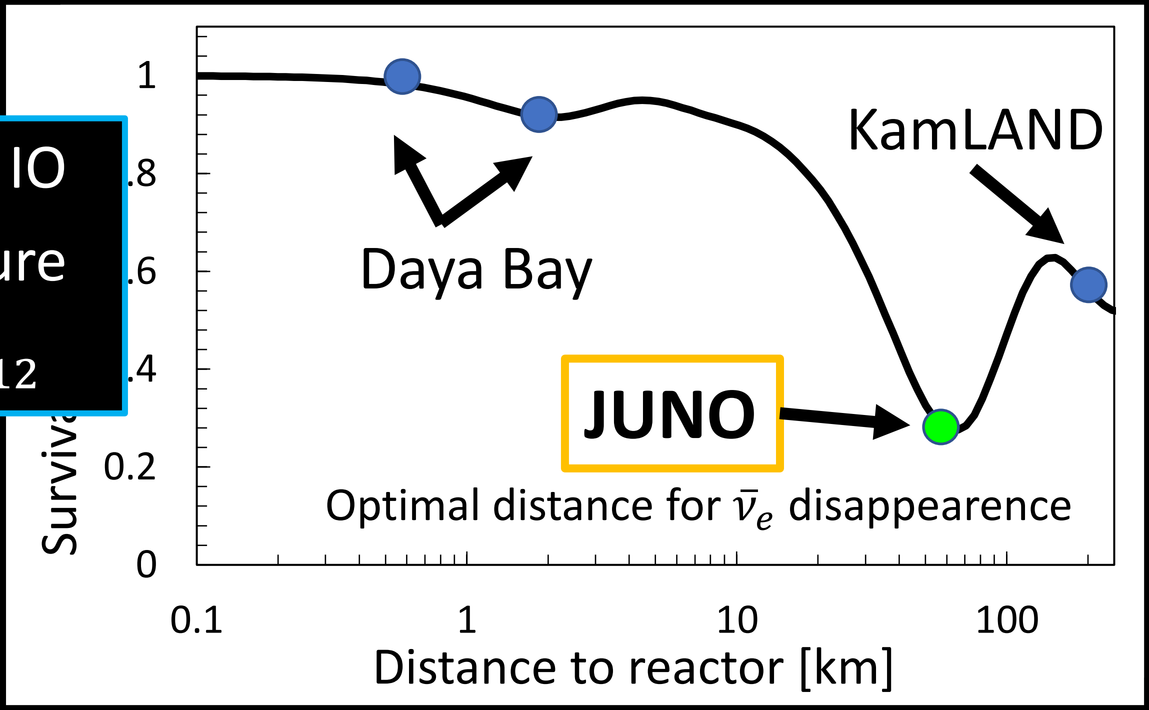
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

JUNO : Reactor $\bar{\nu}_e$

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



- Separate NO vs IO
- Precisely measure $\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}$



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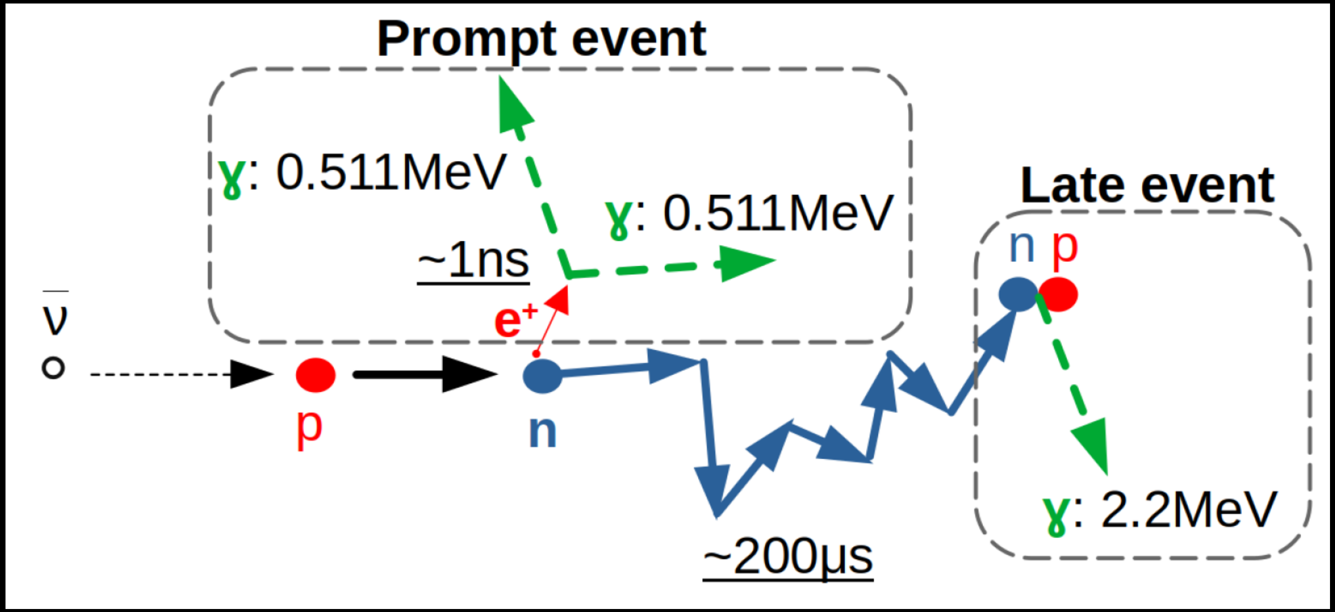
Reactor $\bar{\nu}_e$

Detection of $\bar{\nu}_e$



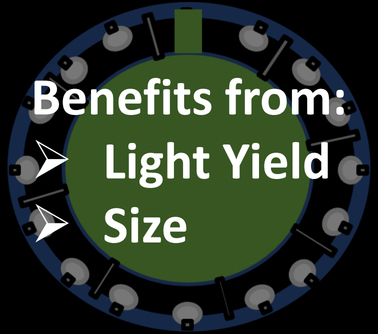
Inverse Beta Decay (IBD)

~10^5 suppression in random background single events

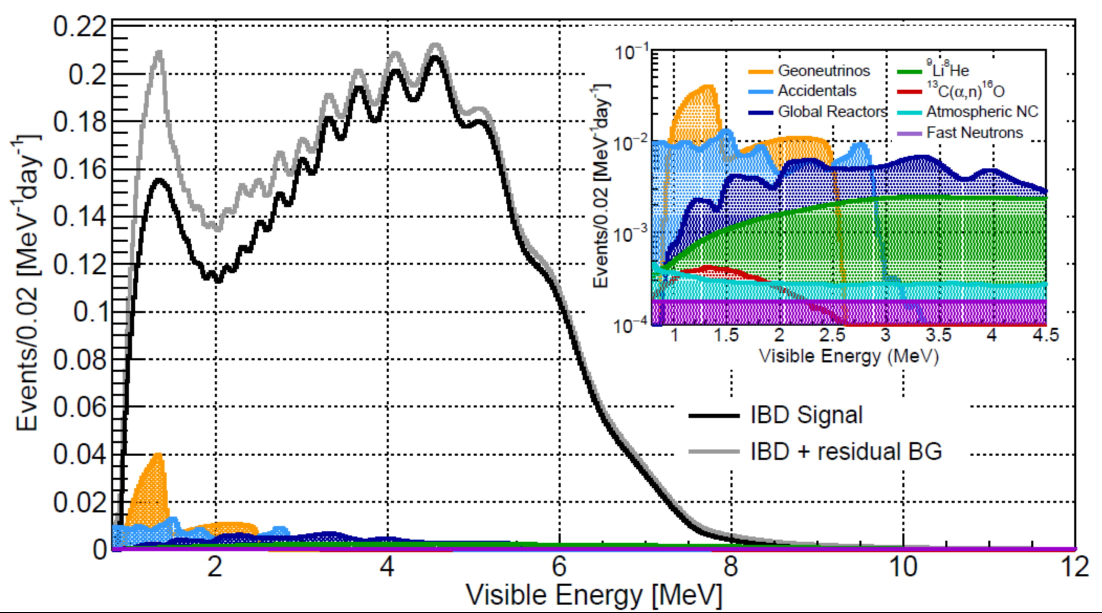
Reactor $\bar{\nu}_e$

[“Sub-percent precision measurement of neutrino oscillation parameters with JUNO,” Chin. Phys. C **46** (2022) no.12, 123001]

$\bar{\nu}_e$



Expected Energy Spectrum



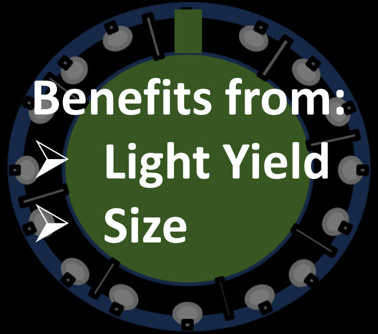
<u>Excellent Energy Resolution</u>
Needed to resolve fine oscillation structure

Reactors: ~47/day
Background: ~4.1/day

Reactor $\bar{\nu}_e$

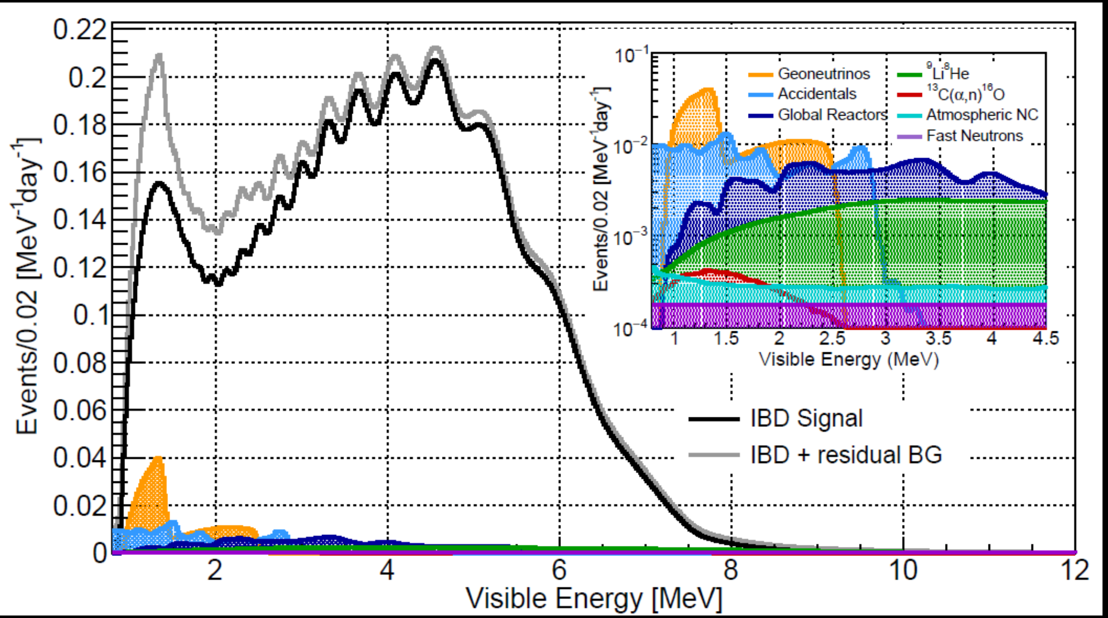
["Sub-percent precision measurement of neutrino oscillation parameters with JUNO," Chin. Phys. C **46** (2022) no.12, 123001]

$\bar{\nu}_e$



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

Expected Energy Spectrum



Expected Sensitivity

Reactor-only sensitivity to NMO

3σ in ~6 years

Sub-percent precision to oscillation params

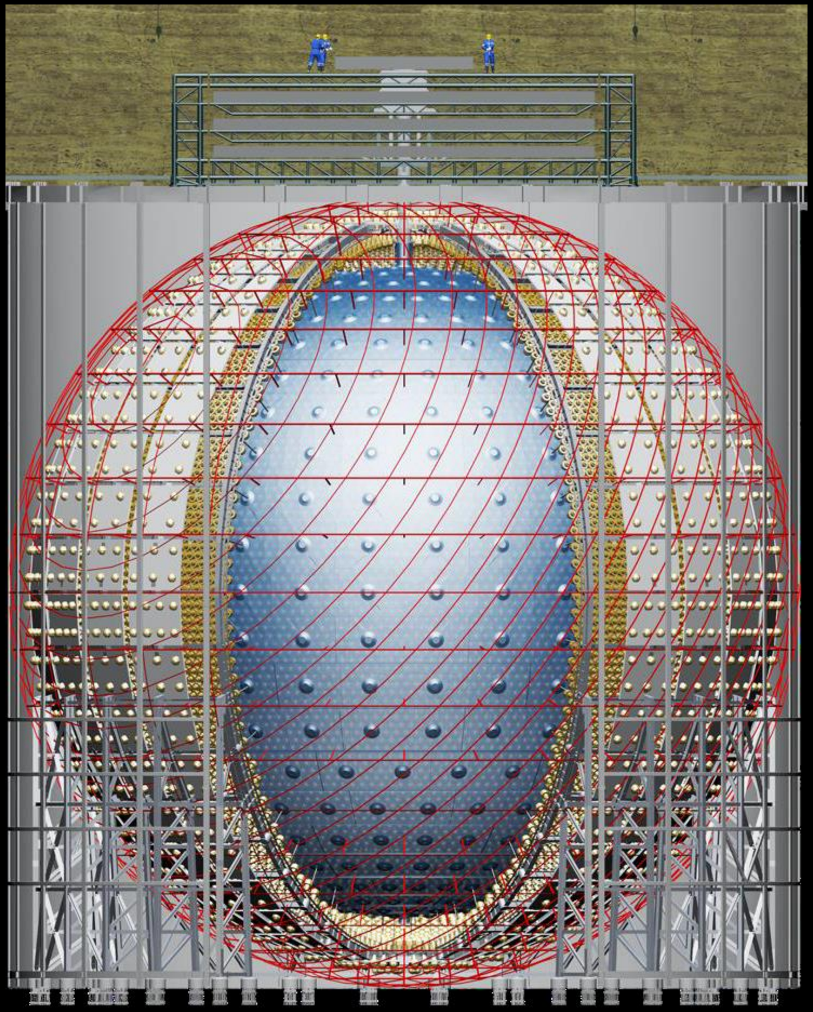
	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
PDG 2022	1.3%	2.4%	4.2%	3.2%
JUNO 6 yrs	~0.2%	~0.3%	~0.5%	~12%

Excellent Energy Resolution
Needed to resolve fine oscillation structure

Reactors: ~47/day
Background: ~4.1/day

JUNO Detector

~650m
overburden



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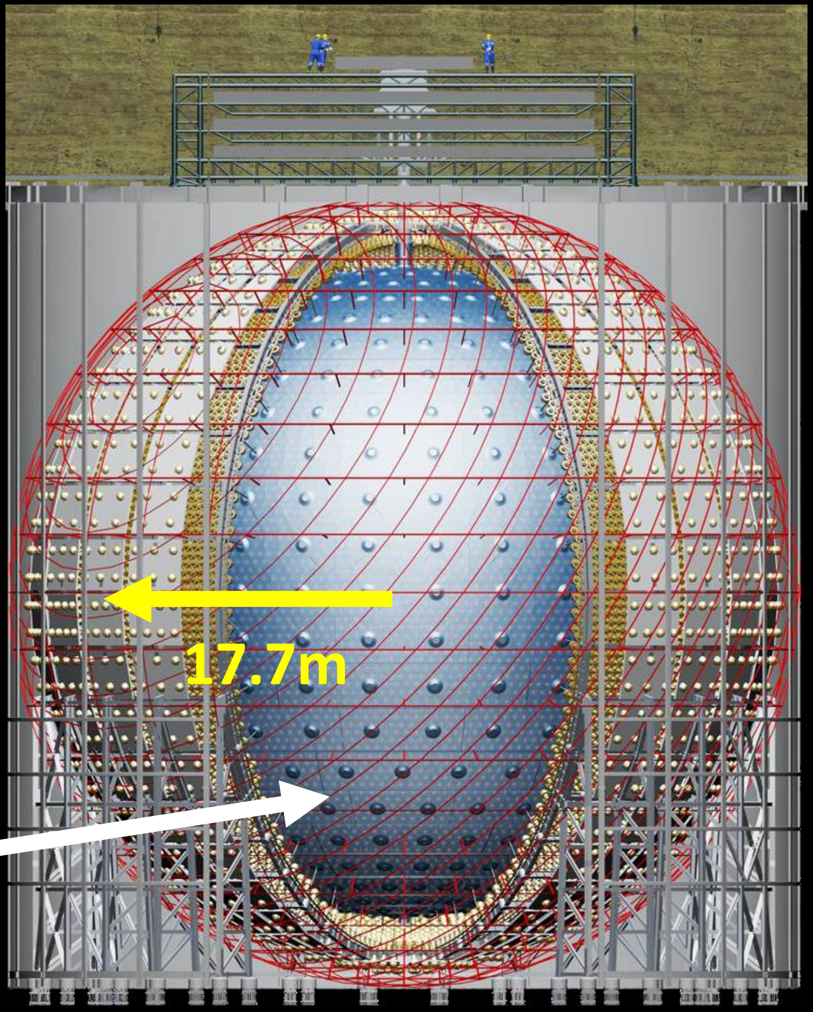


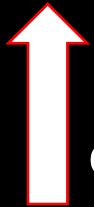
Acrylic Vessel

17.7m in radius

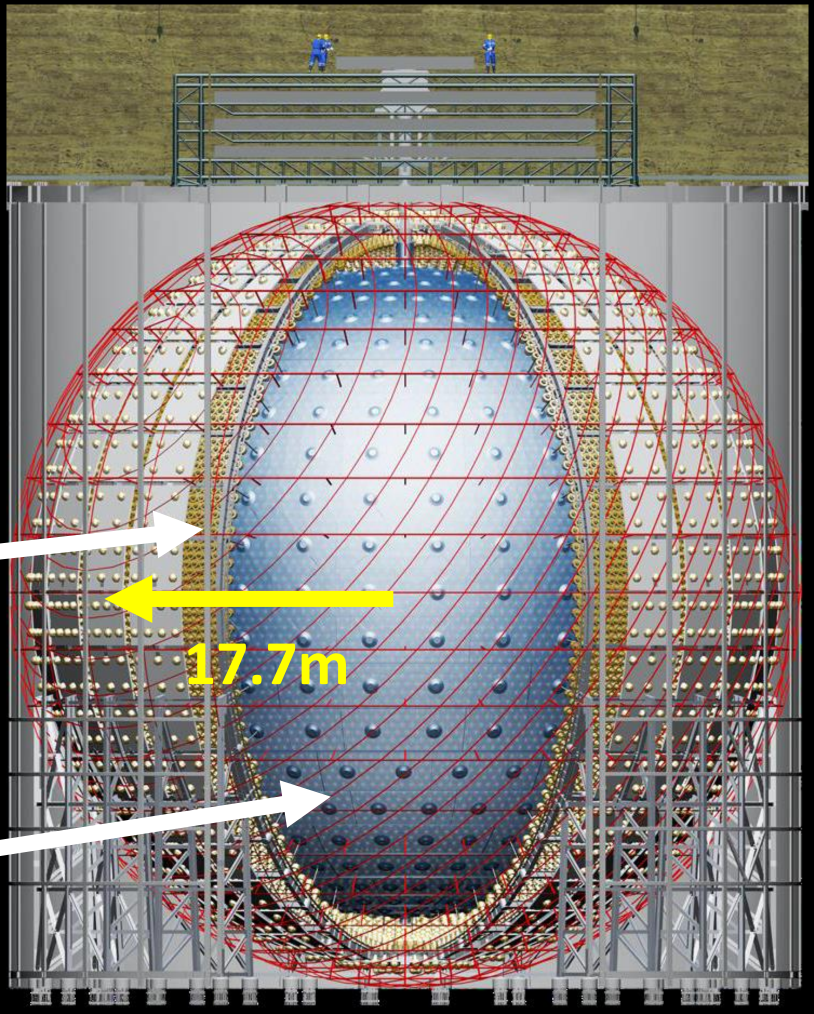
20 kilotons of liquid scintillator

LAB + 2.5 g/L PPO + 3 mg/L bis-MSB

JUNO Detector



PMTs
17,600 20” + 25,600 3”



Acrylic Vessel
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JUNO Detector

Outer Cherenkov Detector

35 kilotons ultrapure water

2400 20” PMTs

PMTs

17,600 20” + 25,600 3”

Acrylic Vessel

17.7m in radius

20 kilotons of liquid scintillator

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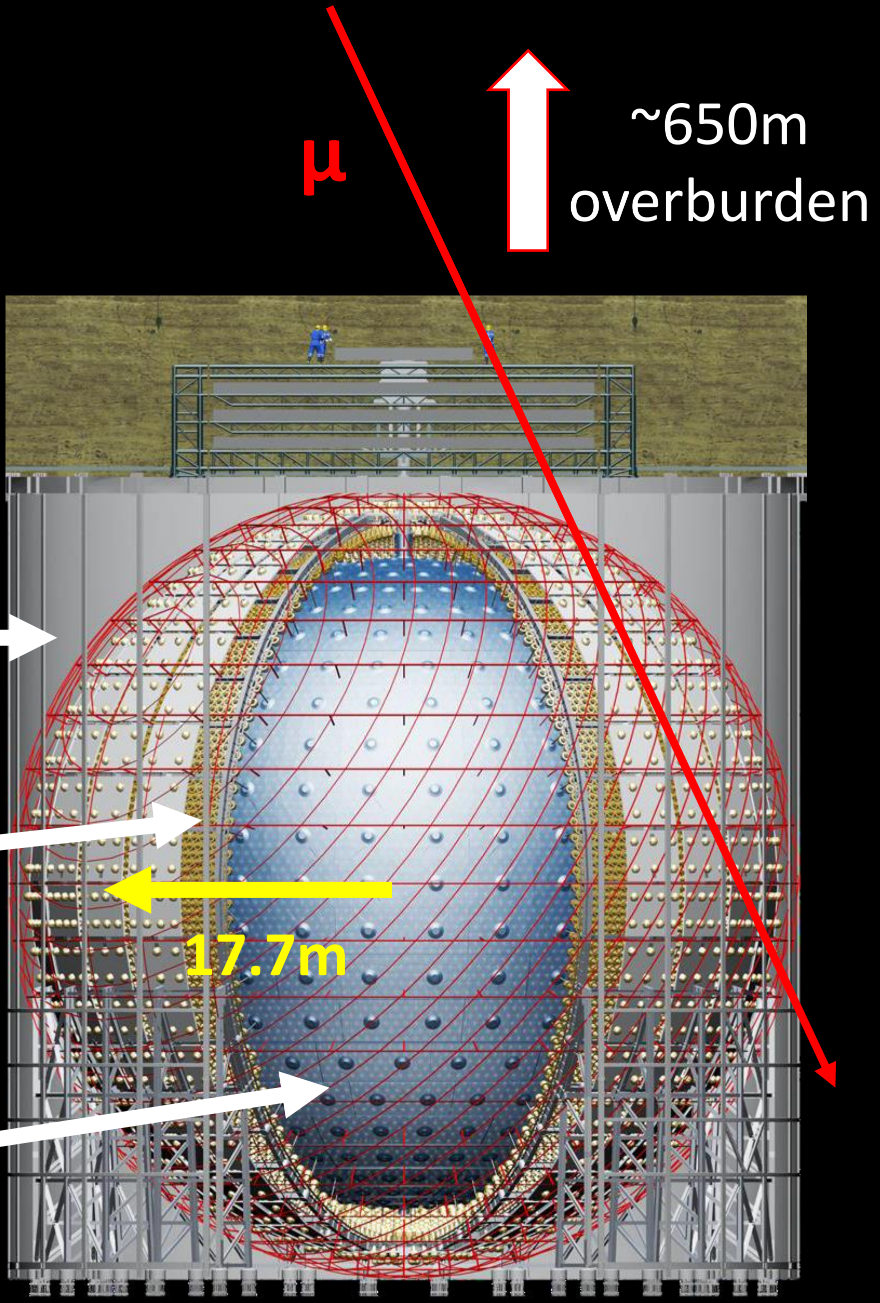


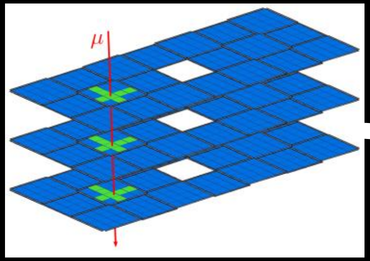
JUNO Detector

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

μ

~650m overburden

Top Tracker
Plastic scintillator layers [1]



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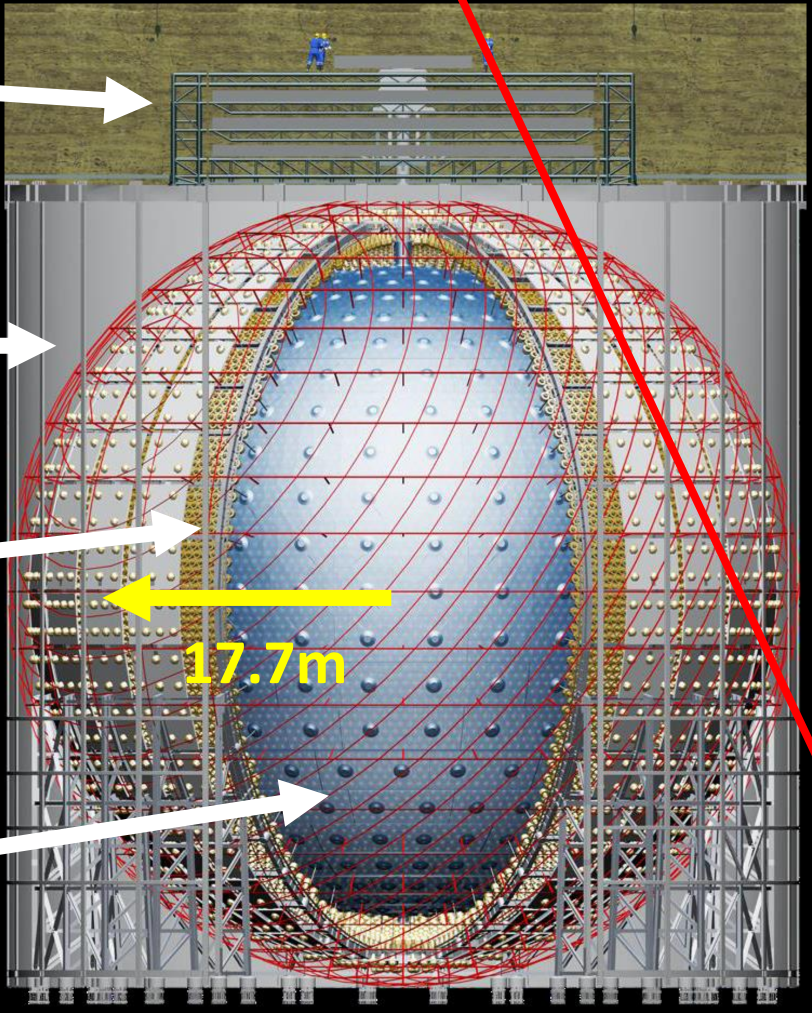
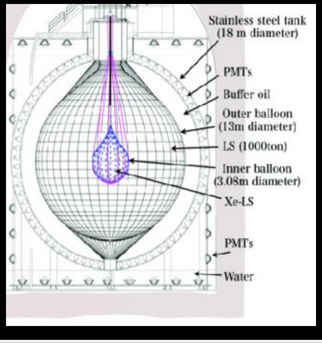
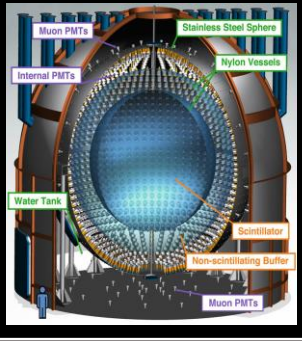
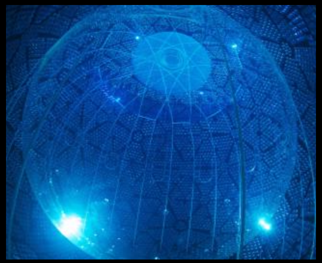


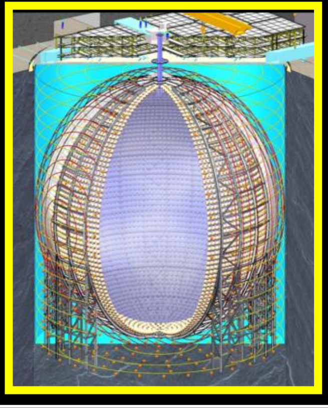
JUNO : Detector Comparisons

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







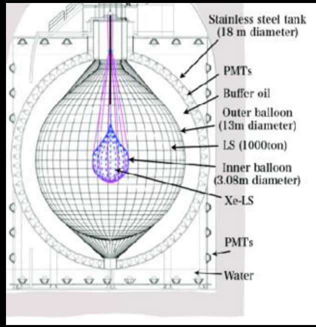


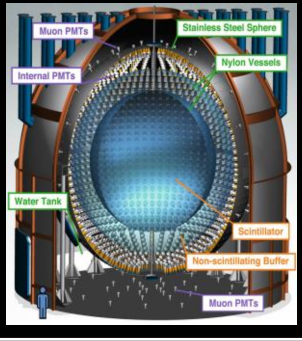
	KamLAND [2]	Borexino [3]	SNO+ [4]	**JUNO**
Target Mass [kilotons]	1	0.3	0.78	**20**
Number of PMTs	1900	2200	10,000	**18,000 + 26,000**
PMT Coverage	~34%	~30%	~50%	**~80%**
Light Collection [photoelectrons/MeV]	~250	~450	~520	**>1300**

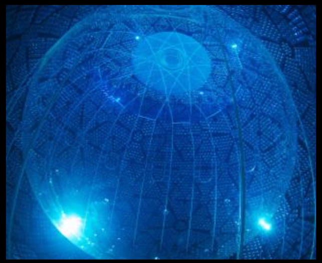
JUNO : Detector Comparisons

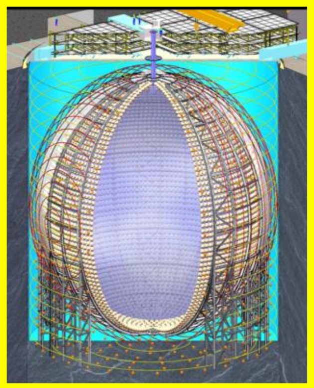
[“JUNO physics and detector”, Progress in Particle and Nuclear Physics 123 (2022) 103927](#)

JUNO:
Energy Resolution
3% @ 1MeV









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Installation

- Civil construction finished in Dec, 2021
- Completed Support Structure
- Ongoing PMT and Acrylic Vessel Installation
- Detector completion expected by end of 2023

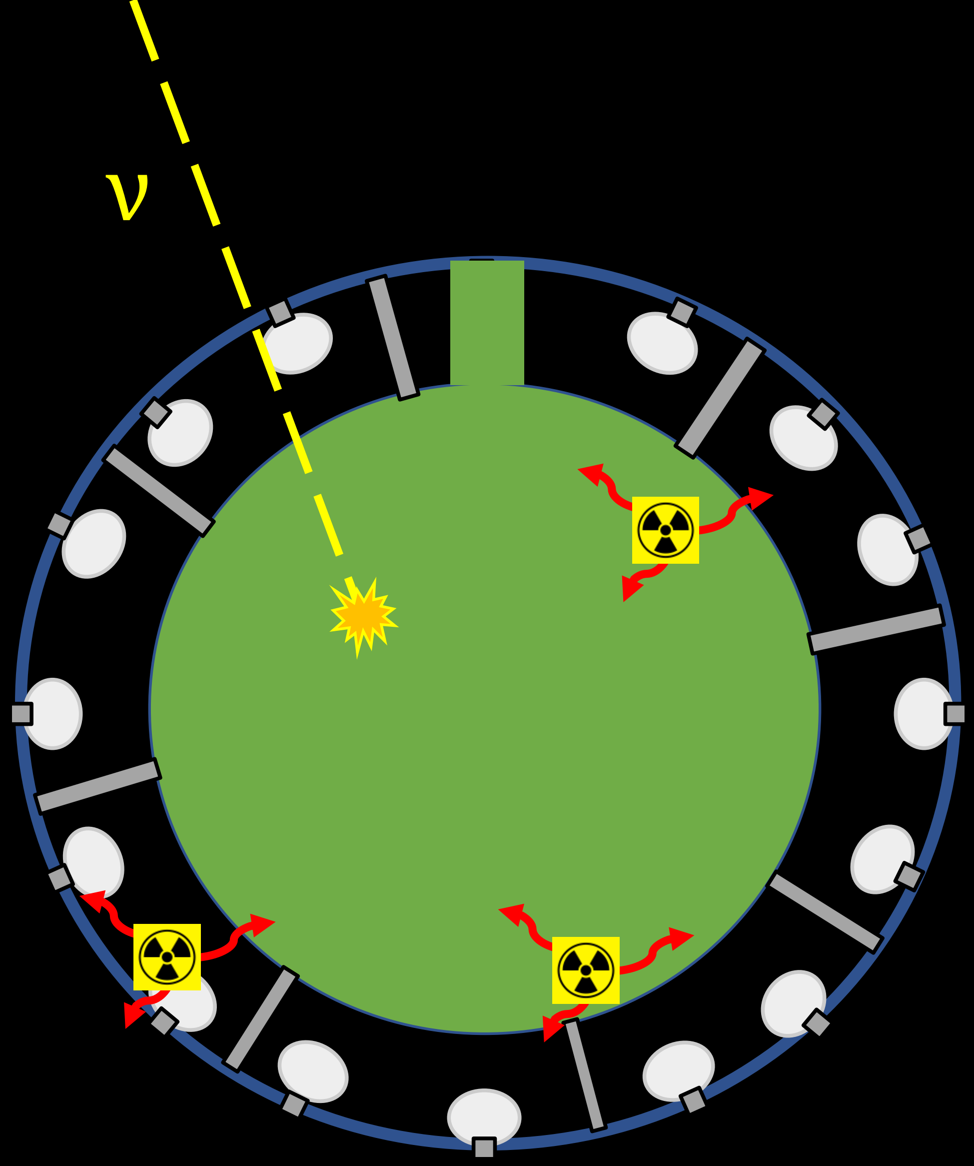
JUNO's Attributes

Ideal liquid scintillator detector has:

Size

<u>Light Collection</u>
Energy Resolution
+ Threshold

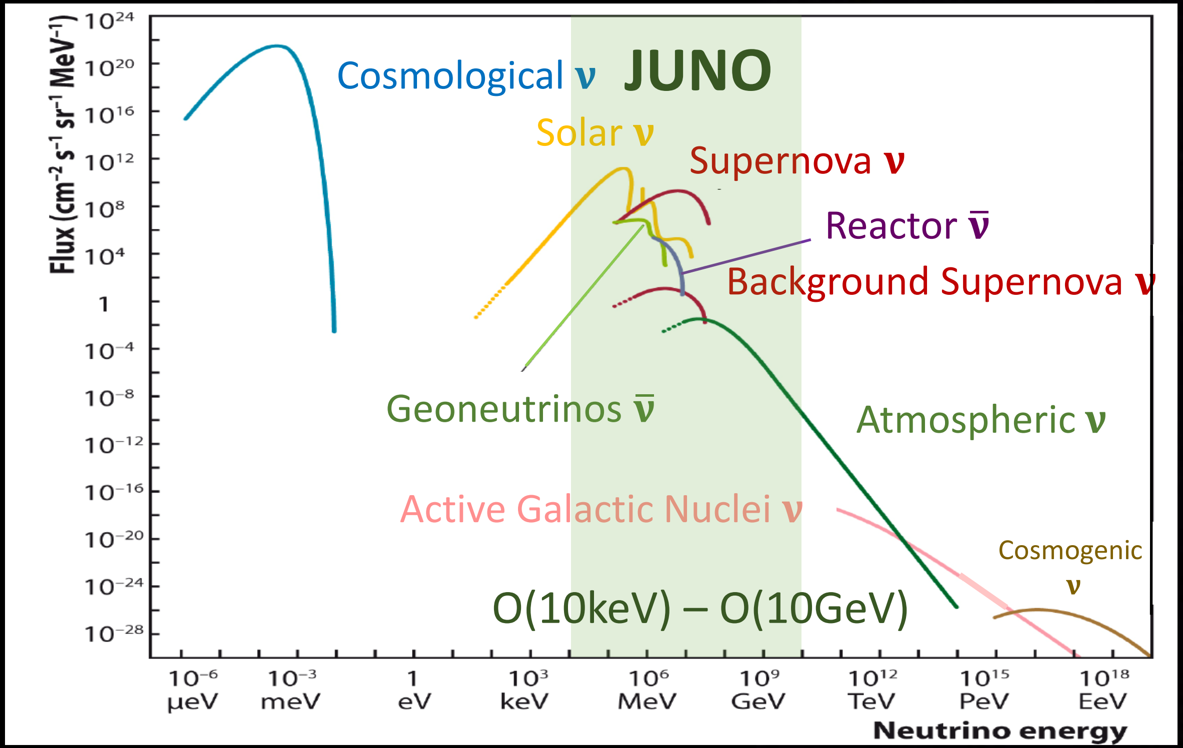
Low
Backgrounds



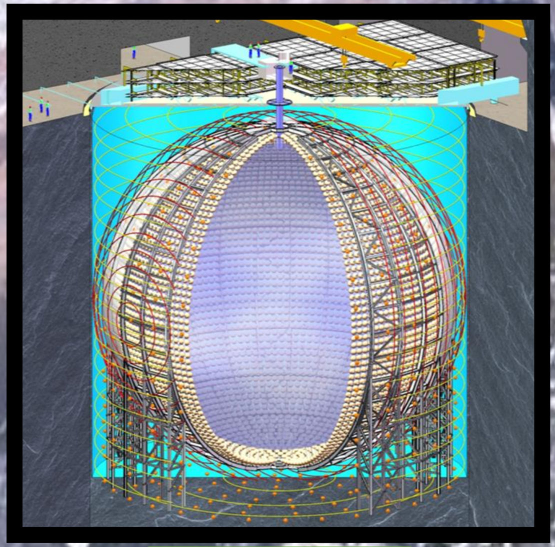
Important attributes are physics goal-dependent!

JUNO Physics Programme

Fig. from [5]



Wide range of measurable neutrino energies + sources!



JUNO

JUNO Physics Programme

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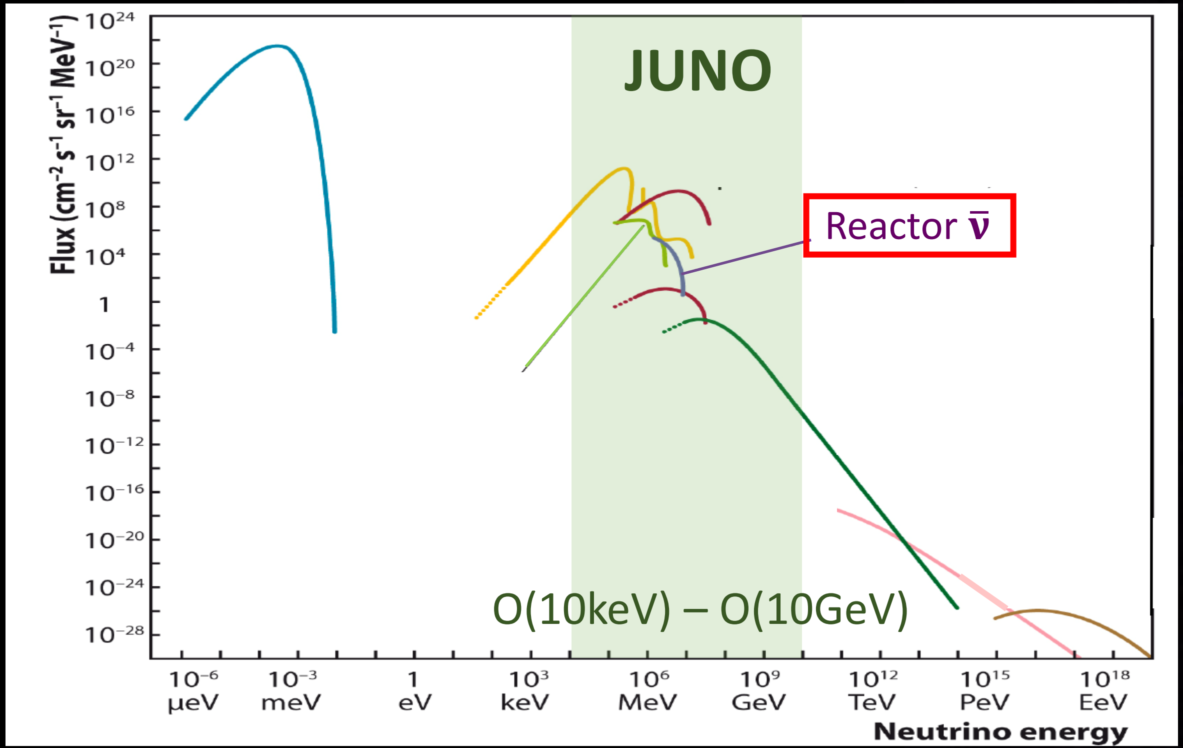
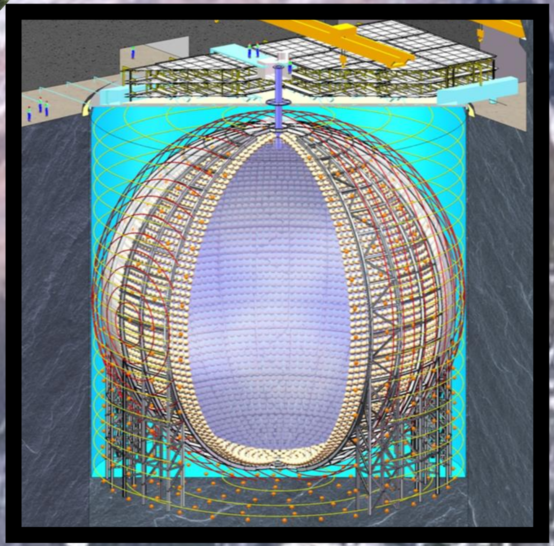


Reactors
0 – 12 MeV



JUNO

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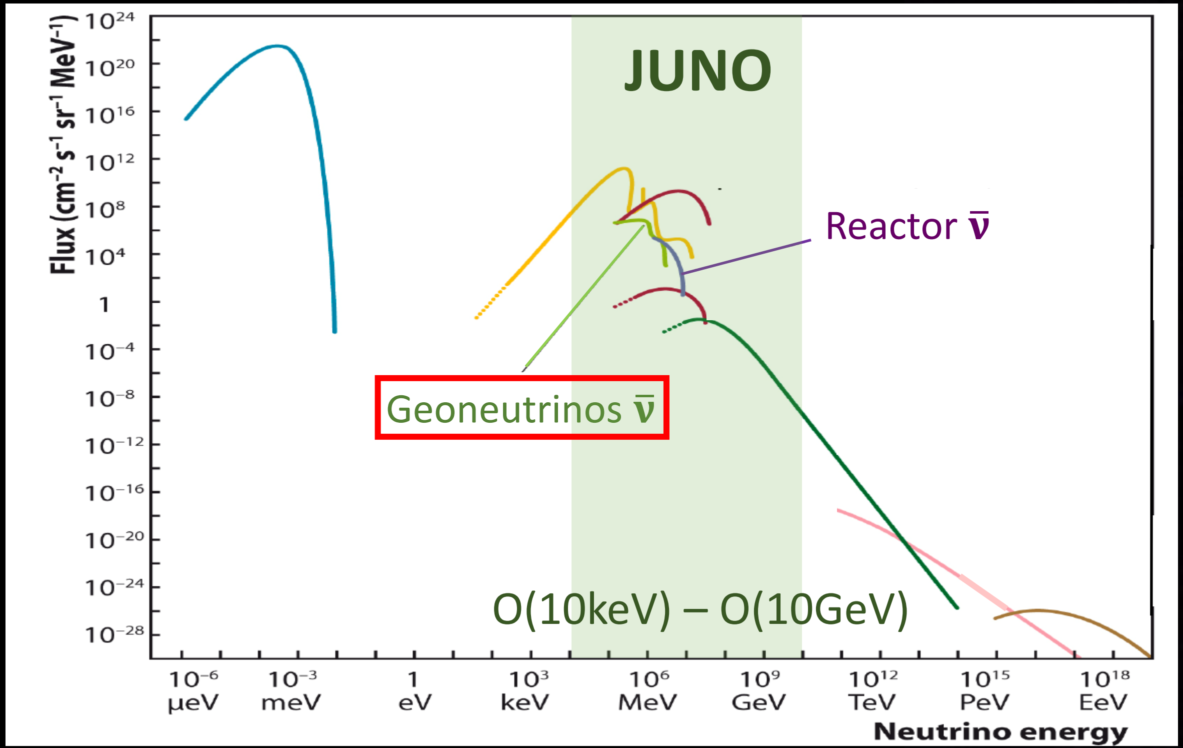
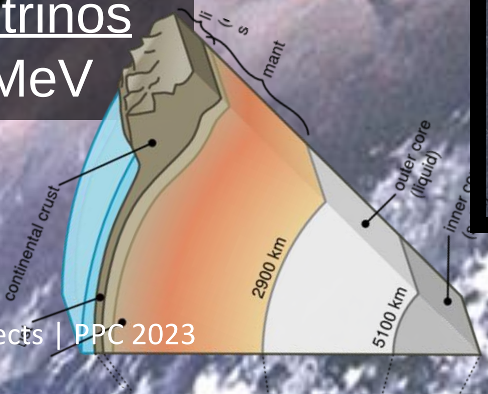
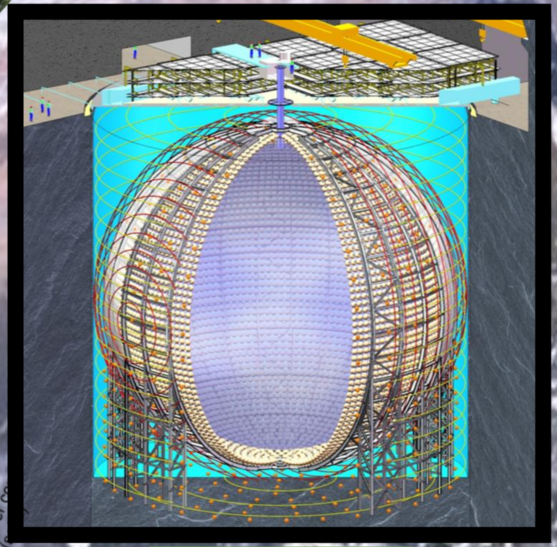


Reactors
0 – 12 MeV

Geoneutrinos
0 – 3 MeV



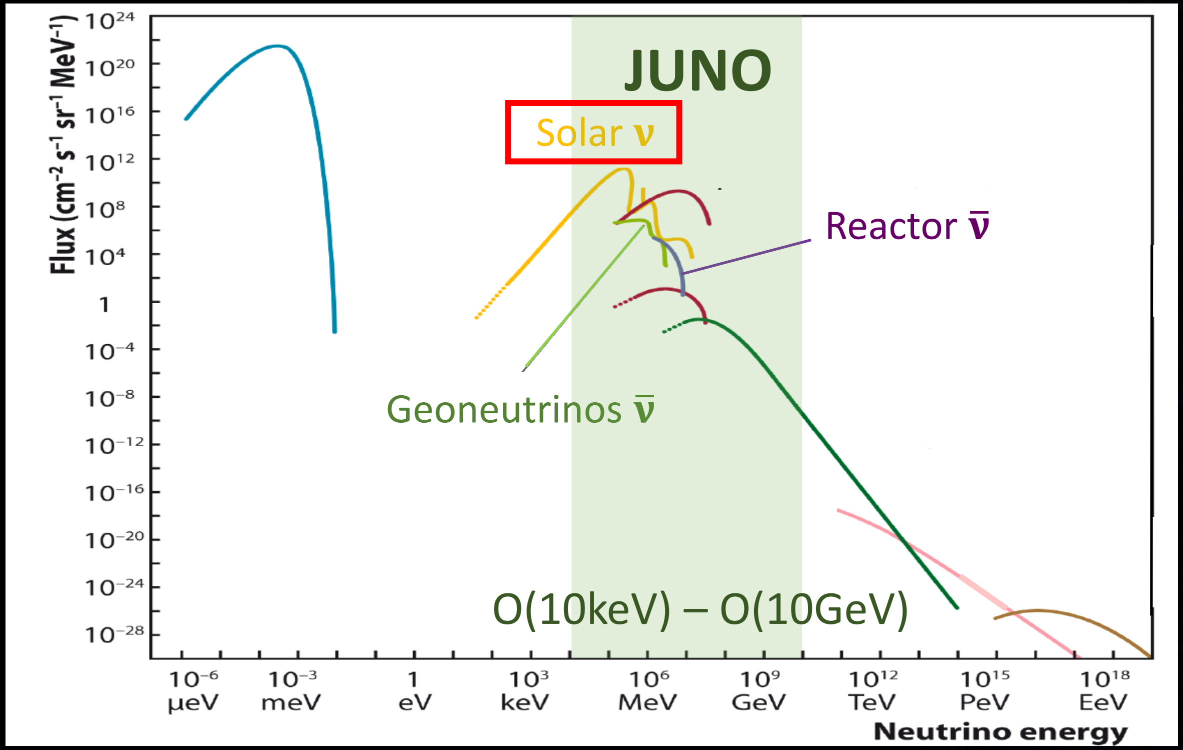


JUNO

JUNO Physics Programme

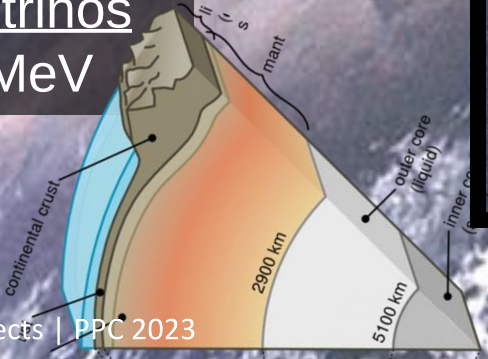
Solar
0 – 16 MeV

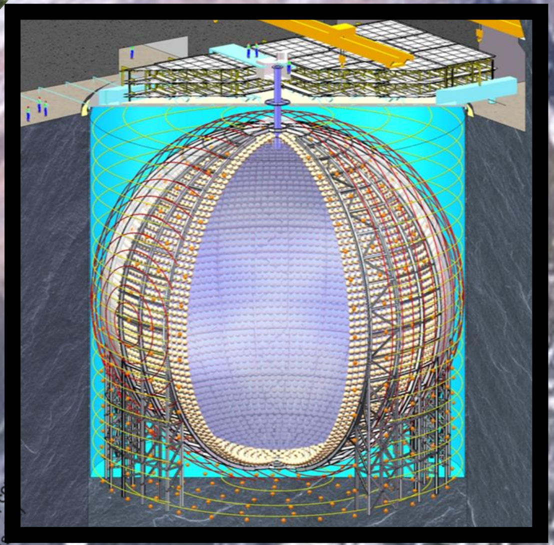
Fig. from [5]



Reactors
0 – 12 MeV

Geoneutrinos
0 – 3 MeV





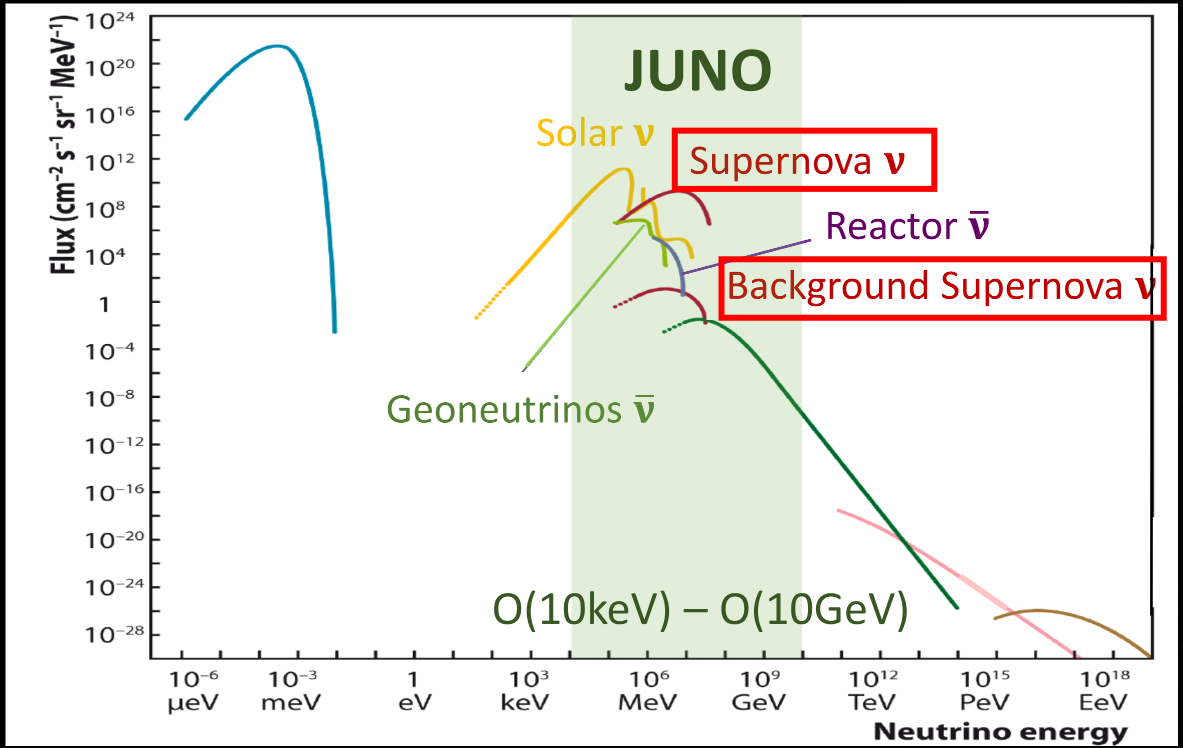
JUNO

JUNO Physics Programme

Supernovae
0 ~ 100 MeV

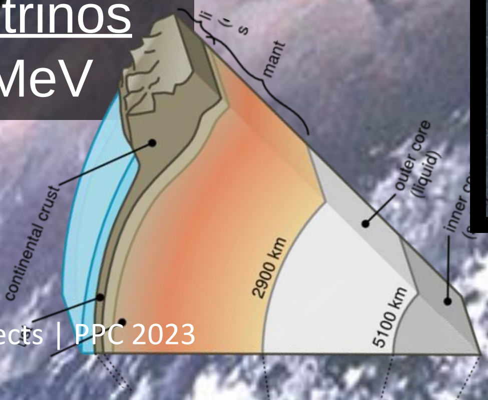
Solar
0 – 16 MeV

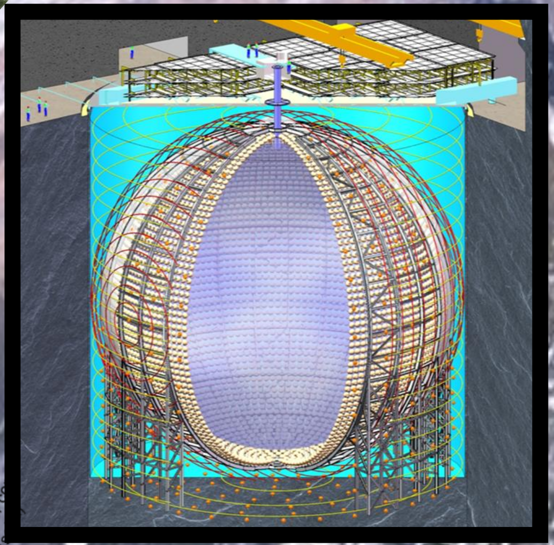
Fig. from [5]



Reactors
0 – 12 MeV

Geoneutrinos
0 – 3 MeV





JUNO

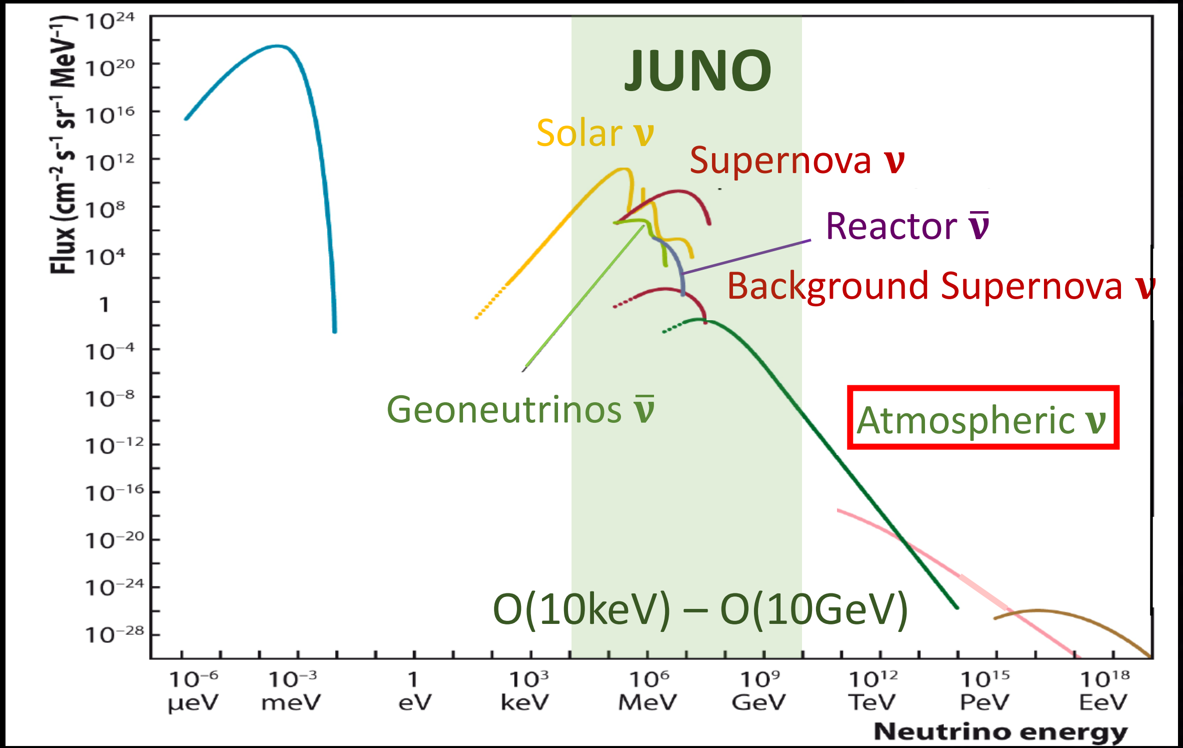
JUNO Physics Programme

Supernovae
0 ~ 100 MeV

Solar
0 – 16 MeV

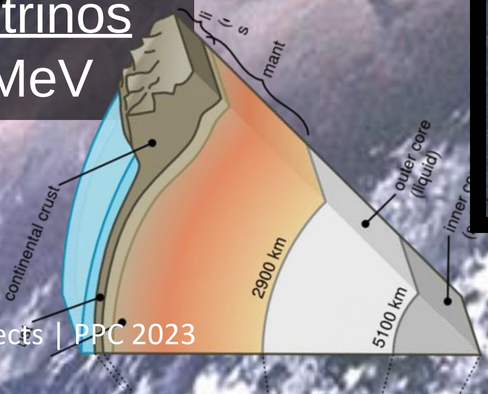
Atmospherics
0.1 – 100 GeV

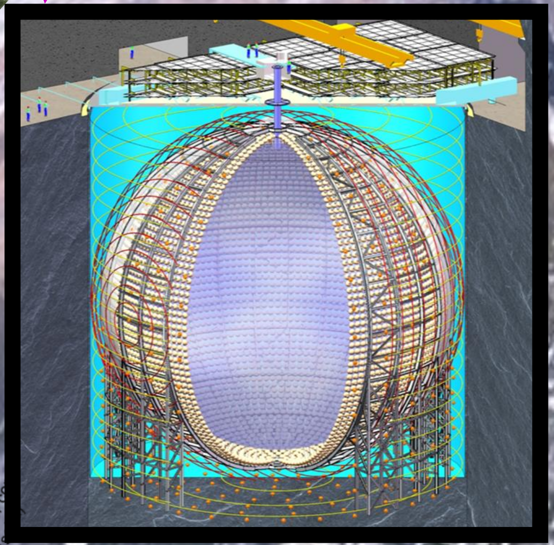
Fig. from [5]



Reactors
0 – 12 MeV

Geoneutrinos
0 – 3 MeV

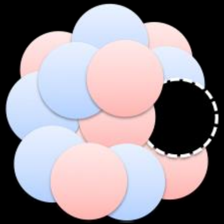




JUNO

JUNO Physics Programme

Atmospherics
0.1 – 100 GeV



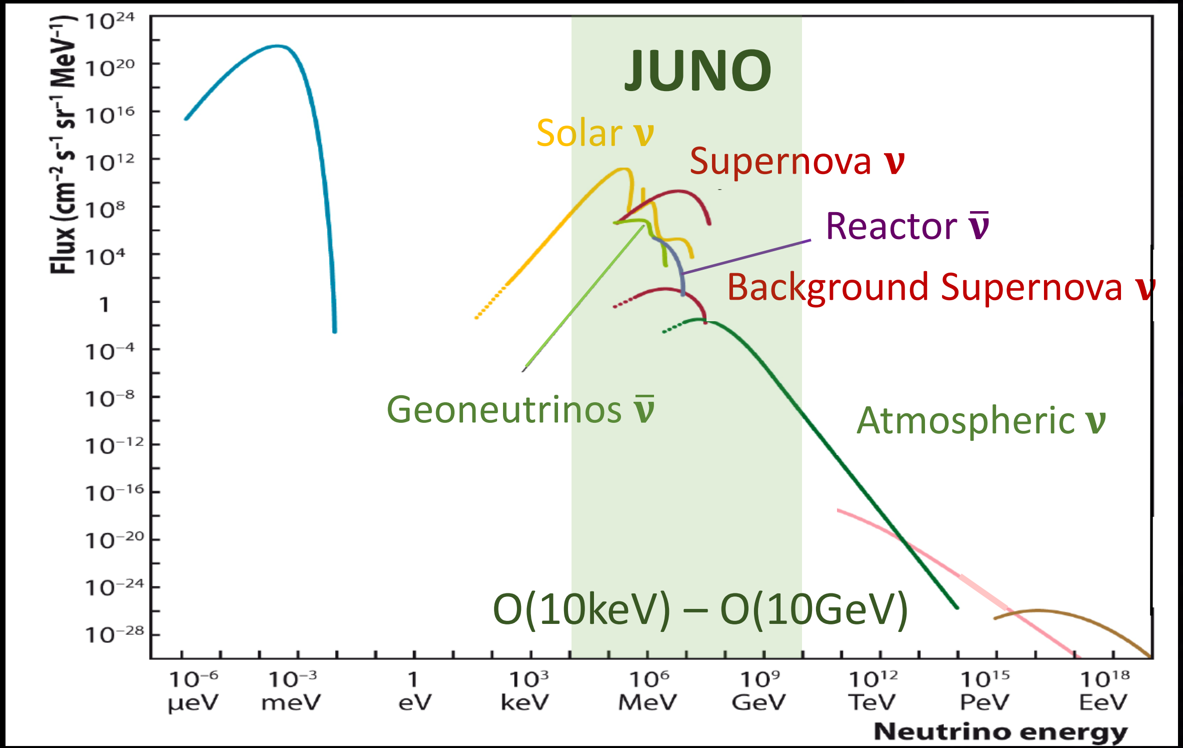
Exotic Searches

Supernovae
0 ~ 100 MeV

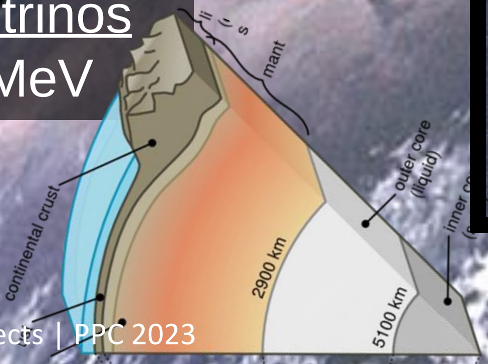
Solar
0 – 16 MeV

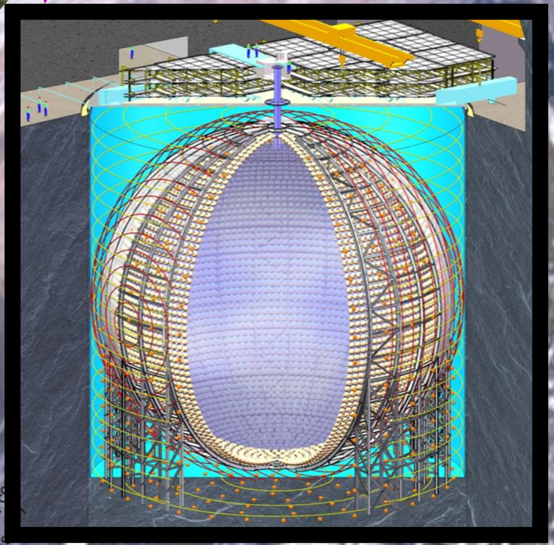
Reactors
0 – 12 MeV

Fig. from [5]



Geoneutrinos
0 – 3 MeV





JUNO

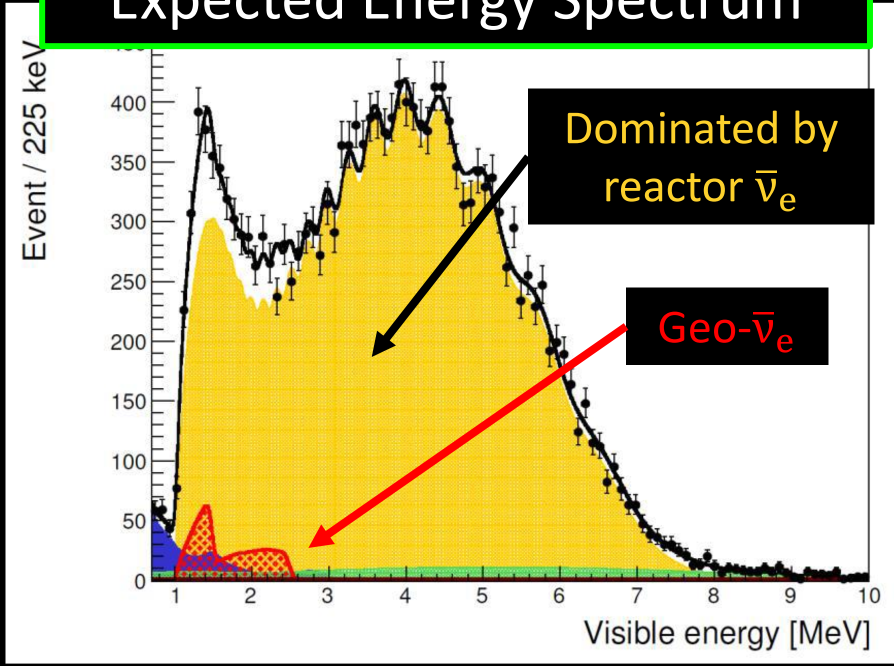
JUNO physics and detector, Progress in Particle and Nuclear Physics 123 (2022) 103927

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

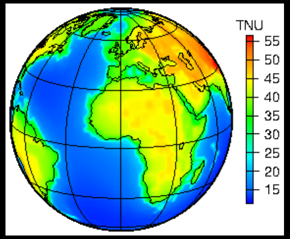
Geoneutrinos : $\bar{\nu}_e$

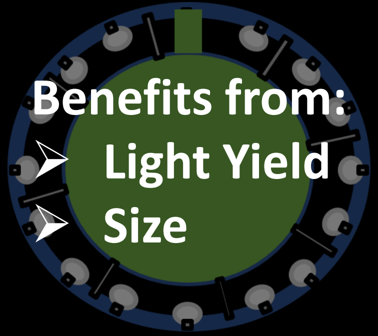
- Decay of radionuclides (U/Th/K) within the Earth

Expected Energy Spectrum



$\bar{\nu}_e$





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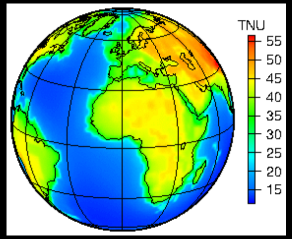
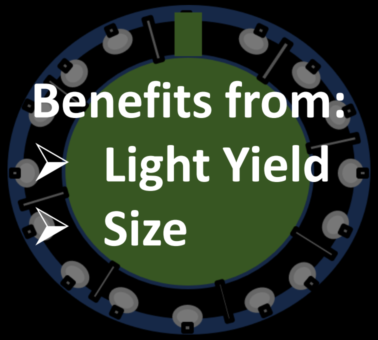
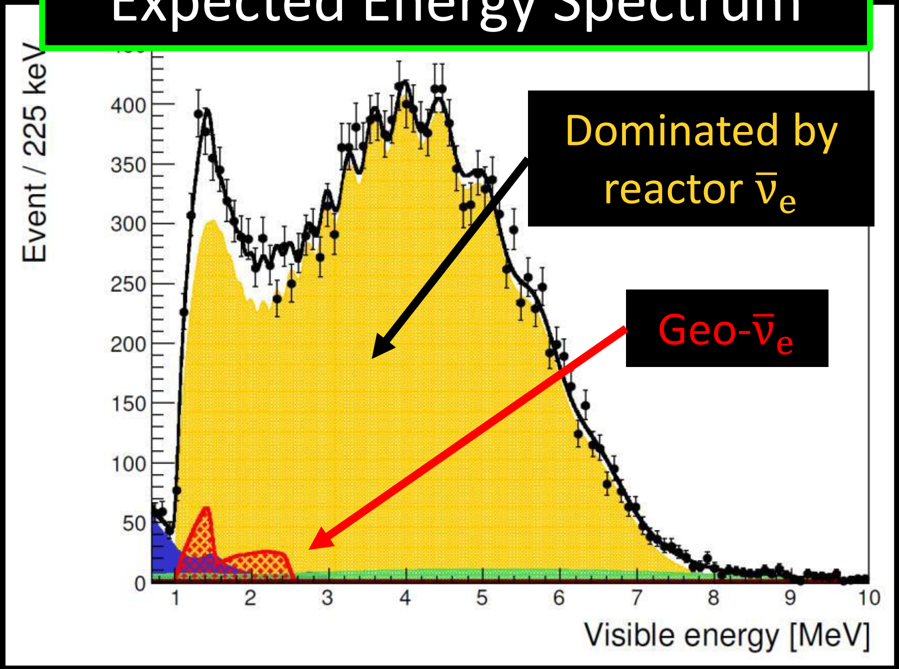
$\bar{\nu}_e$





Expected Energy Spectrum



- ➢ Measure U and Th abundances
- ➢ U/Th ratio in crust and mantle

Probes : Earth's formation, Mantle convection, Plate tectonics, Earth's magnetic field production

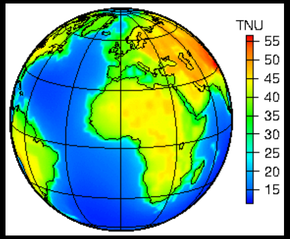
Geoneutrinos : $\bar{\nu}_e$

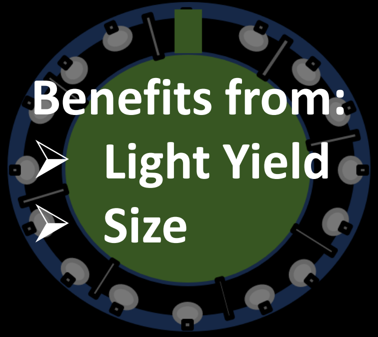
[JUNO physics and detector, Progress in Particle and Nuclear Physics 123 (2022) 103927]

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

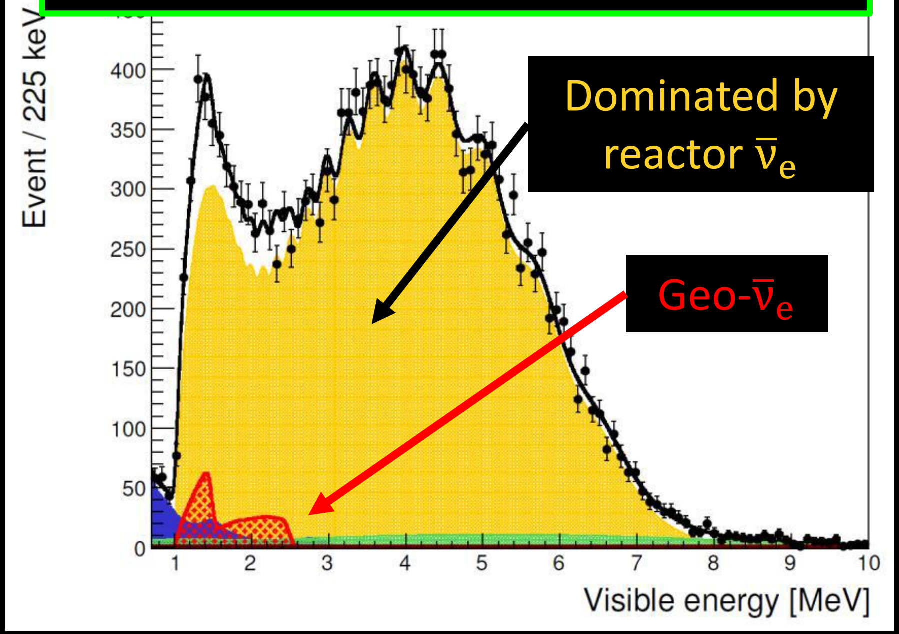
- Decay of radionuclides (U/Th/K) within the Earth

$\bar{\nu}_e$



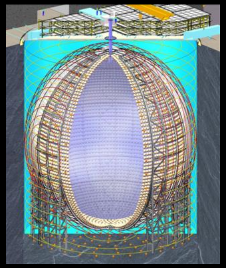


Expected Energy Spectrum



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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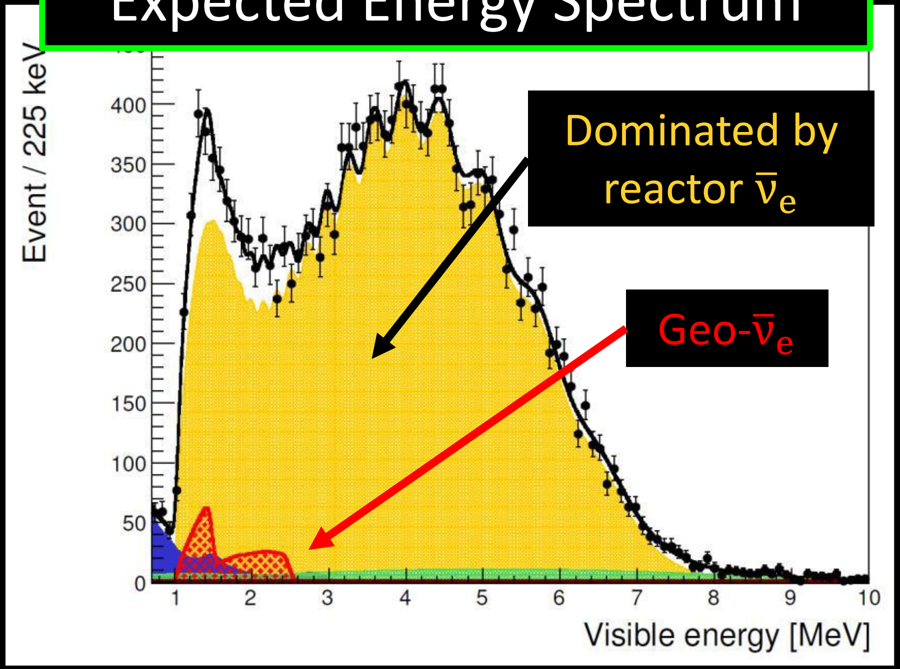

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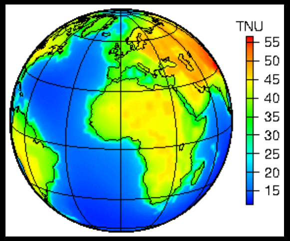
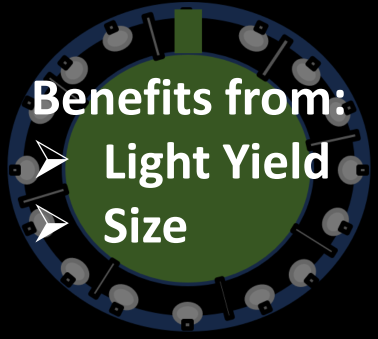
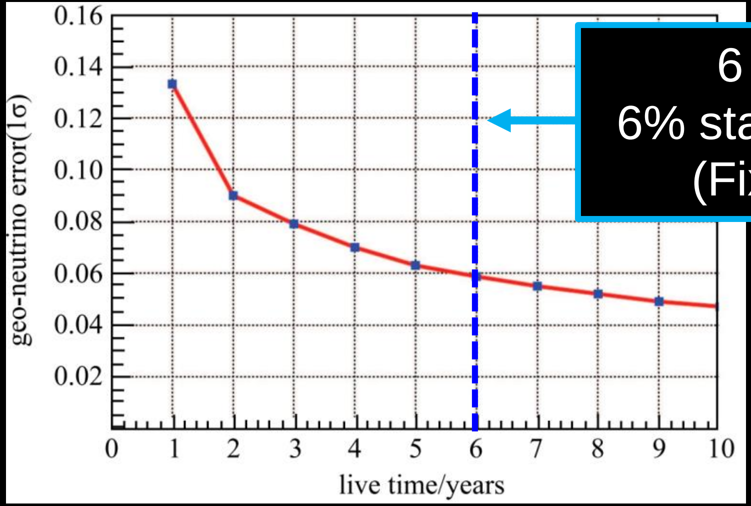




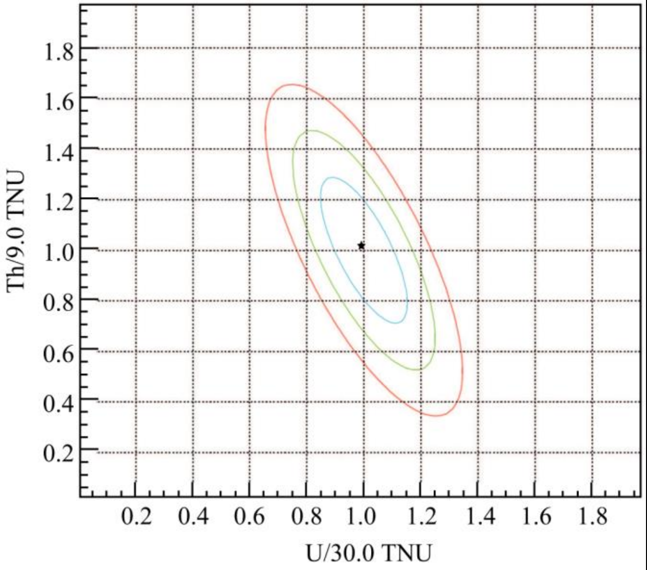
Benefits from:
- ➢ Light Yield
- ➢ Size

Expected Sensitivity



6 year livetime:
6% stat. uncertainty (1σ)
(Fixed U/Th ratio)

~30% uncertainty in U/Th ratio in 10 years

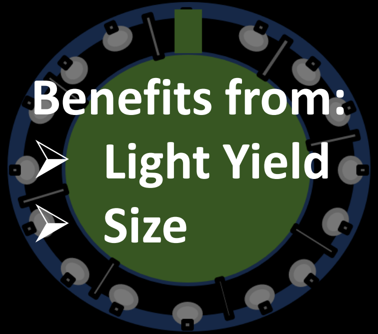


[JUNO physics and detector, Progress in Particle and Nuclear Physics 123 (2022) 103927](https://doi.org/)

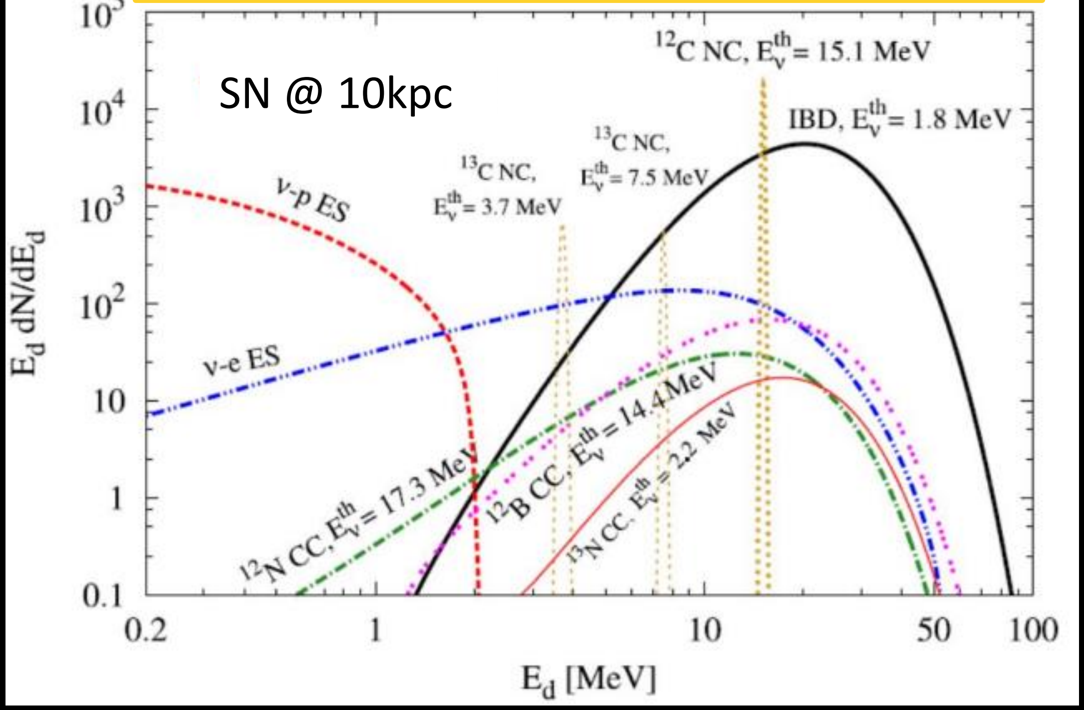
Core-Collapse Supernova Neutrinos

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

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



Expected Flux vs Visible Energy



Expected Event Rate (@10kpc)

Process	Num. Events (E_{thr} = 0.2MeV)
IBD | $\bar{\nu}_e + p \rightarrow e^+ + n$	~5000
pES | $\nu + p \rightarrow \nu + p$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$	~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

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

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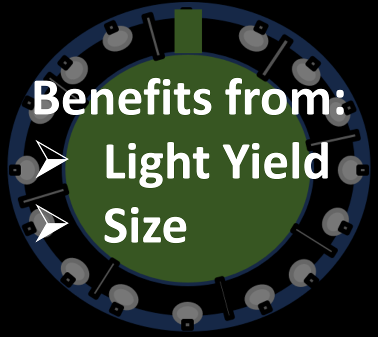

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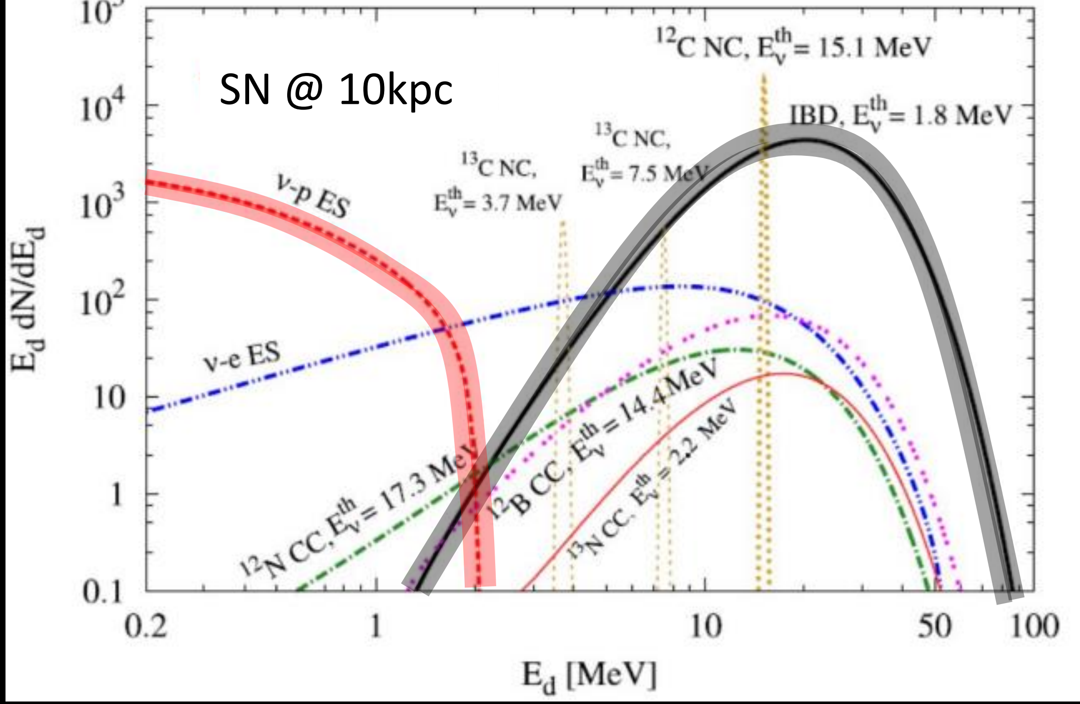

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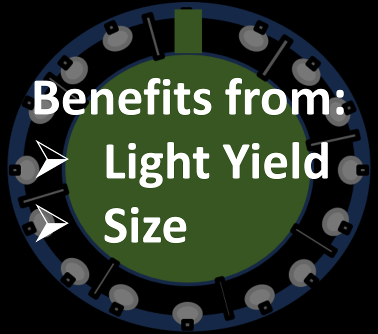
[JUNO physics and detector, Progress in Particle and Nuclear Physics 123 (2022) 103927]

Core-Collapse Supernova Neutrinos

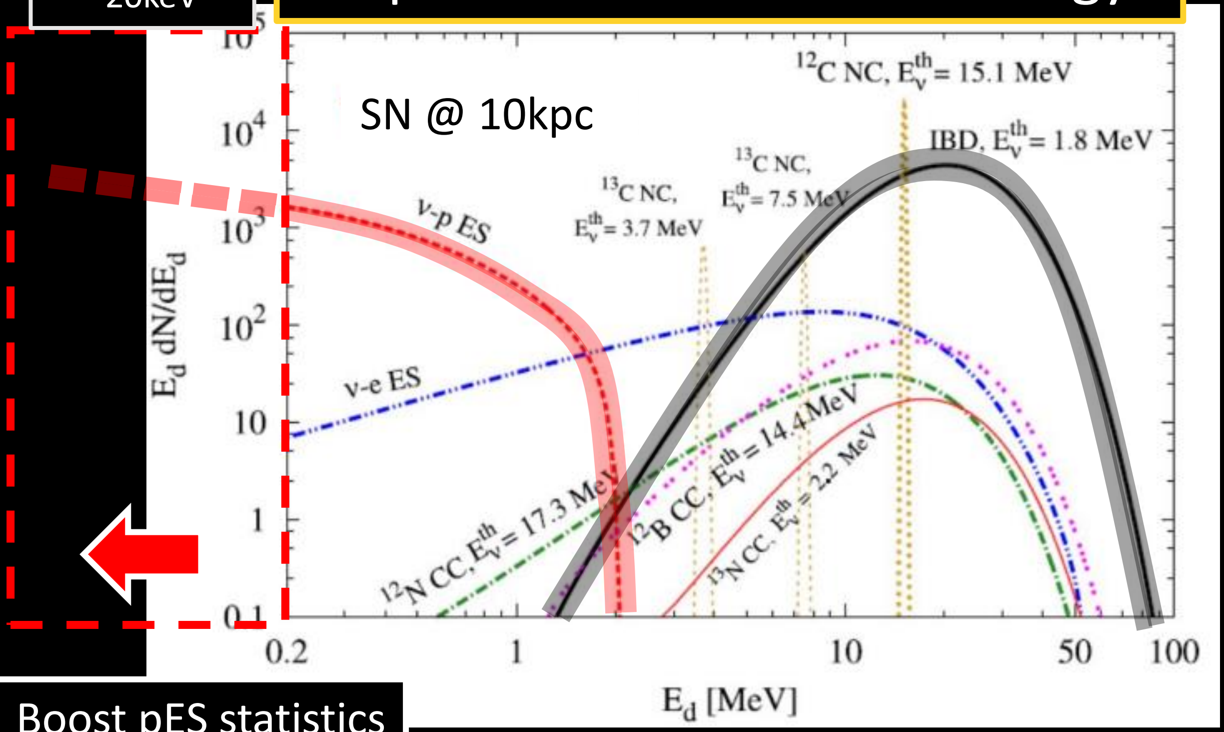
2 Independent Trigger Systems:
- Global Trigger E_{thr}~200 keV
- Multi-Messenger Trigger E_{thr}~20 keV

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



MM Trigger ~20keV

Expected Flux vs Visible Energy



Boost pES statistics

Expected Event Rate (@10kpc)

Process	Num. Events (E_{thr} = 0.2MeV)
IBD | $\bar{\nu}_e + p \rightarrow e^+ + n$	~5000
pES | $\nu + p \rightarrow \nu + p$ $(\overset{(-)}{\nu}_{e,\mu,\tau})$	~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
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Sensitivity to CEνNS \| $\nu + ^{12}C \rightarrow \nu + ^{12}C$

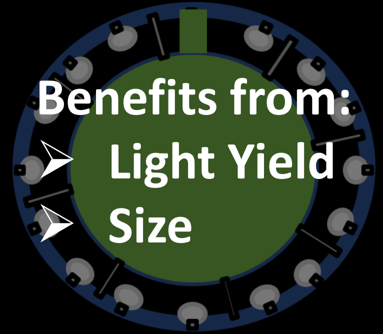
JUNO physics and detector, Progress in Particle and Nuclear Physics 123 (2022) 103927

Core-Collapse Supernova Neutrinos

- Rapid declarations of transient neutrino signals

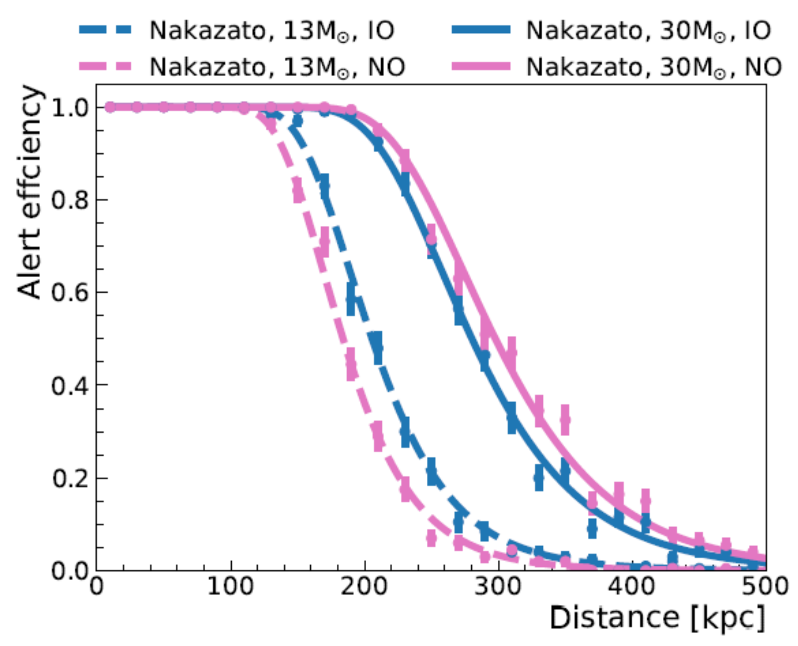
Aim to contribute to Supernova Early Warning System (SNEWS)

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



Alert eff. vs SN distance

(CCSN Monitoring paper in preparation)



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

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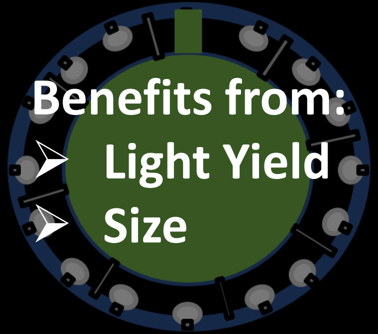

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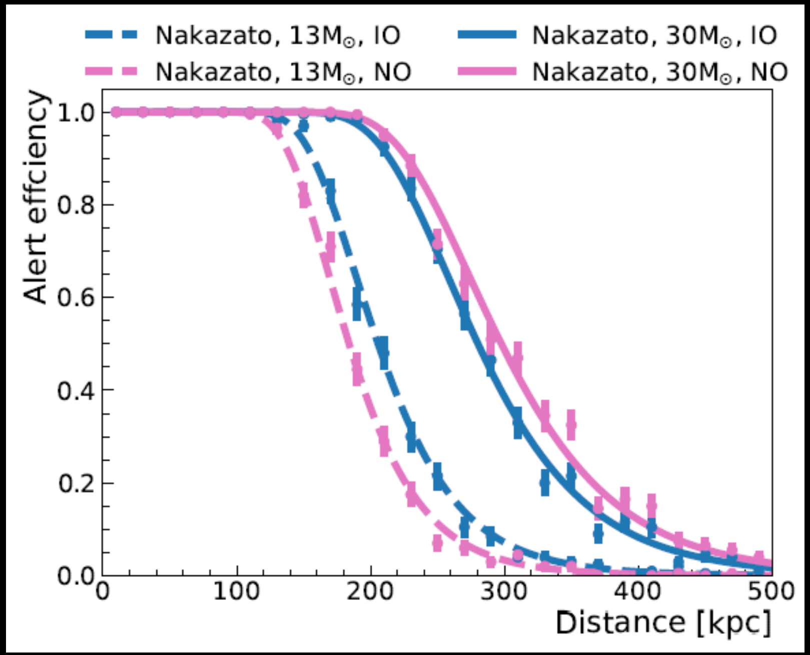


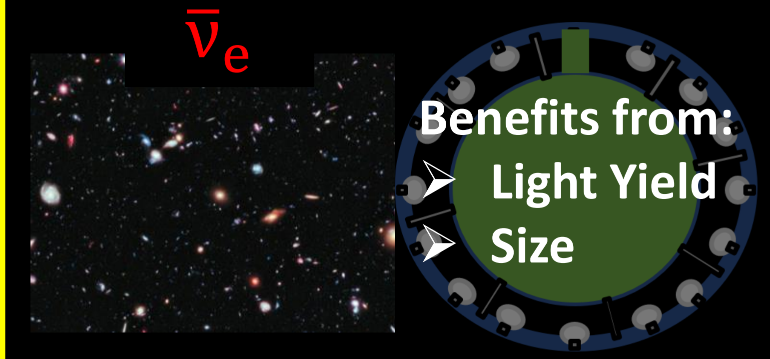
(CCSN Monitoring paper in preparation)

Measure CCSN Energy Spectrum + Time evolution

30 $M_\odot$ CCSN:

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

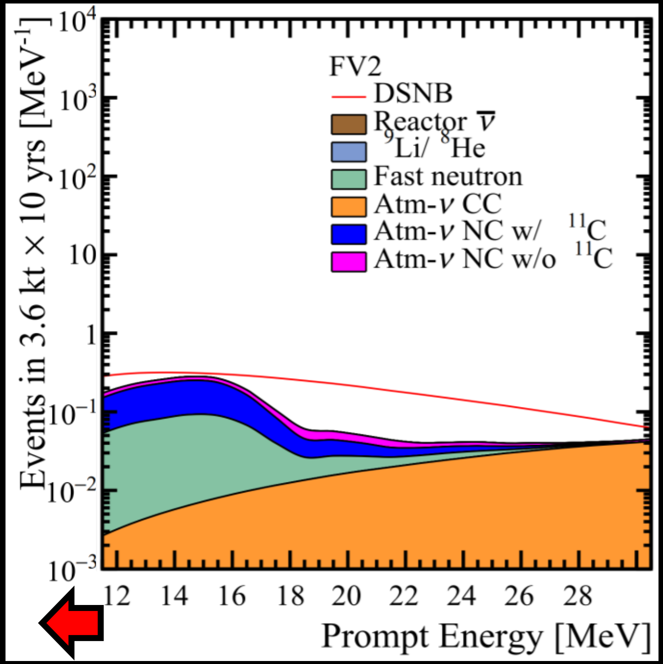
[“Prospects for Detecting the Diffuse Supernova Neutrino Background with JUNO,” JCAP **10** (2022), 033]



Diffuse Supernova Neutrino Background

- Integrated SN neutrino signal in the Universe
- Low Flux – Use low background IBD channel $\bar{\nu}_e$

Expected Signal + Background



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

Avoid Reactor IBDs <12MeV

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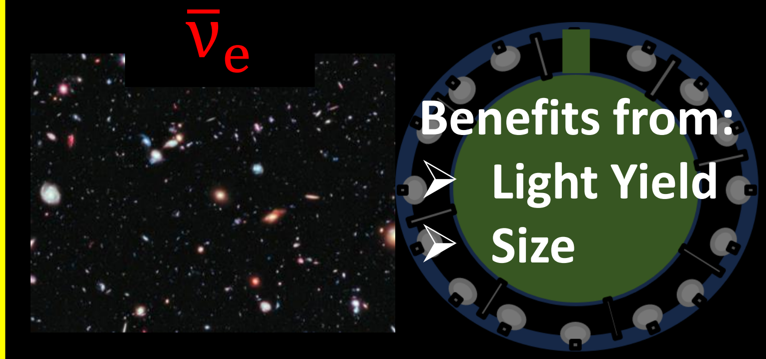
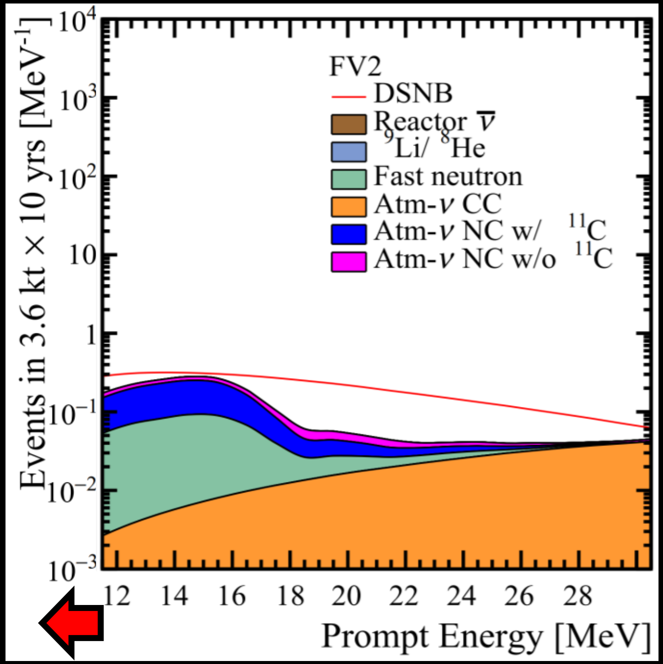
Diffuse Supernova Neutrino Background



- Integrated SN neutrino signal in the Universe
- Low Flux – Use low background IBD channel $\bar{\nu}_e$

Expected Signal + Background ➡ Expected Sensitivity vs Time



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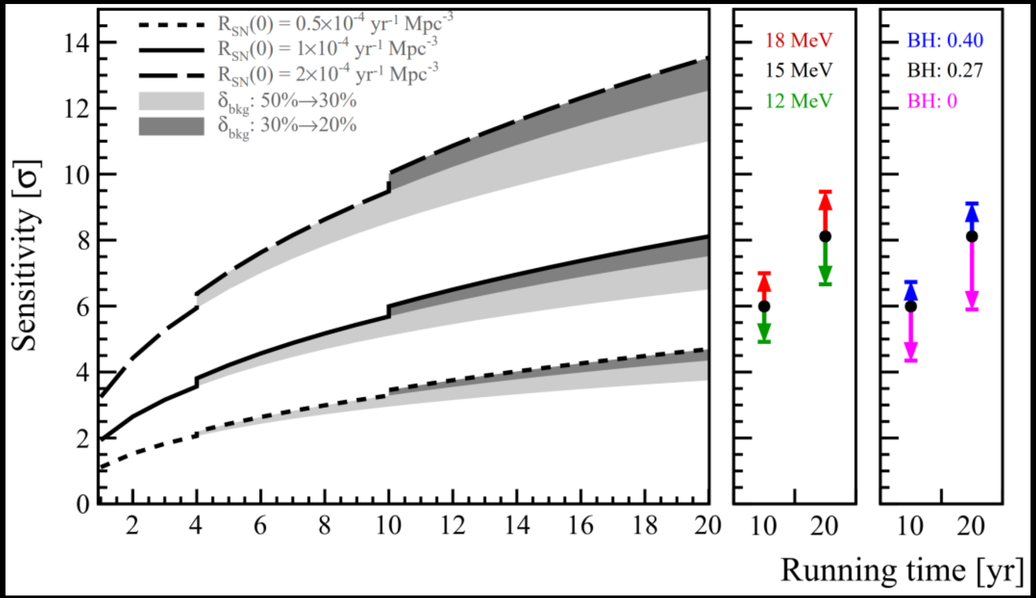


<u>DSNB</u>
<u>Disc. Potential</u>
3σ in 3 yrs with nominal models

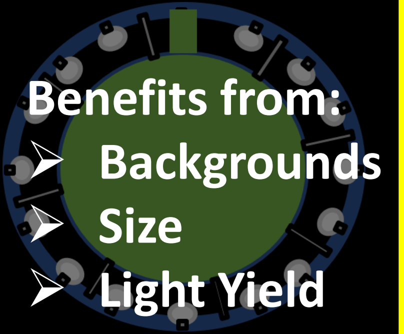
Avoid Reactor IBDs <12MeV

Solar Neutrinos

"Feasibility and physics potential of detecting ^{8}B solar neutrinos at JUNO," Chin. Phys. C **45** (2021) no.2, 023004

"Model Independent Approach of the JUNO ^{8}B Solar Neutrino Program," arXiv:2210.08437

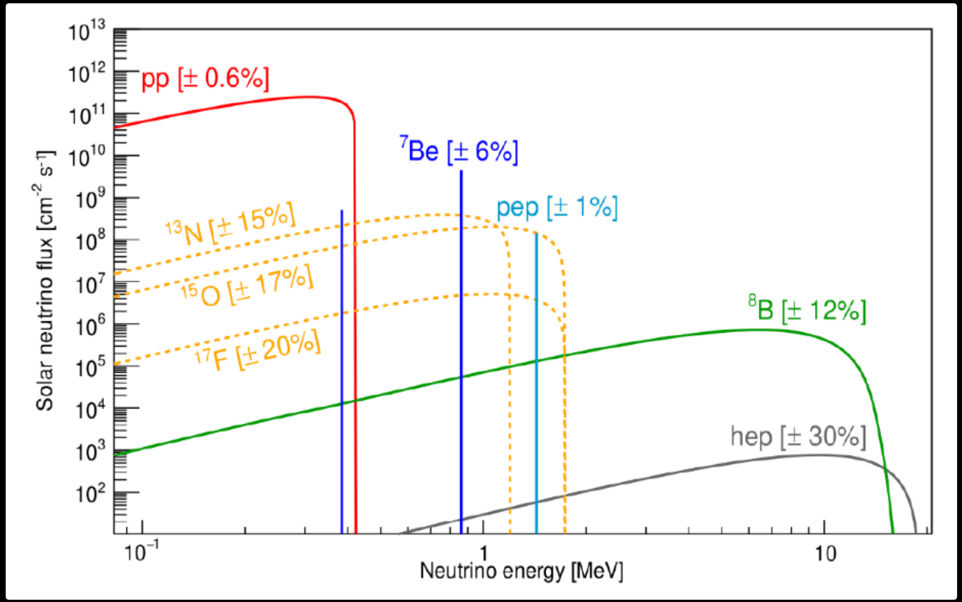
ν_x



Benefits from:
- Backgrounds
- Size
- Light Yield

- Nuclear fusion within the sun produces ν_e

Expected Flux



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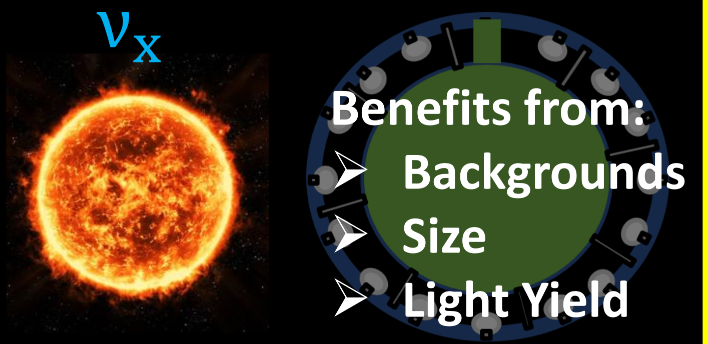

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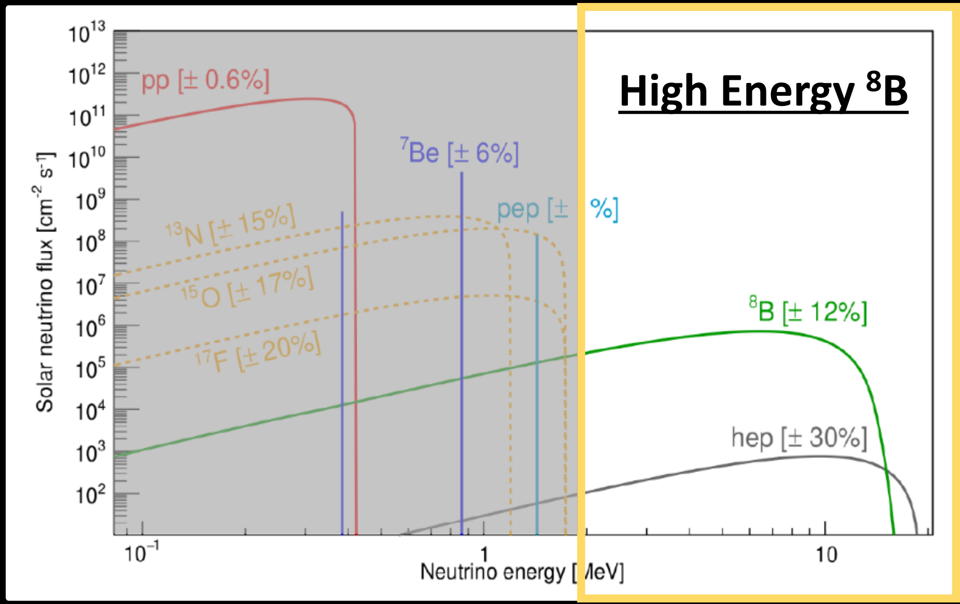

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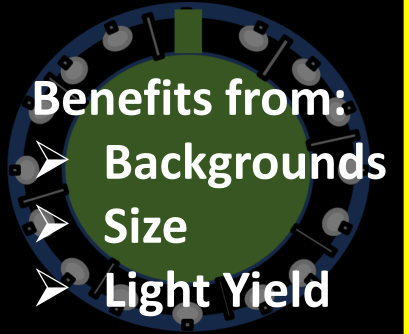

Benefits from:
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- Size
- Light Yield

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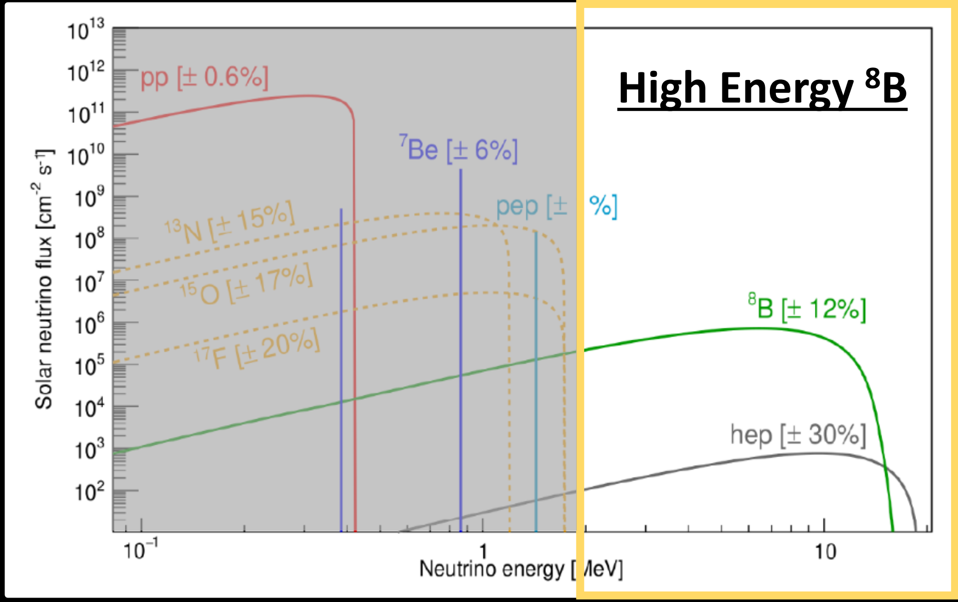
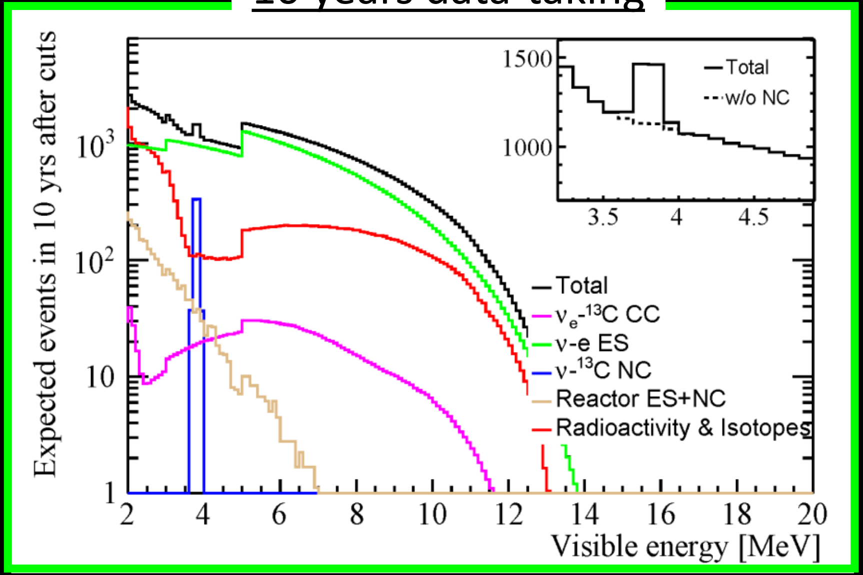
Expected Flux → Expected Signal + Background



10 years data-taking



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

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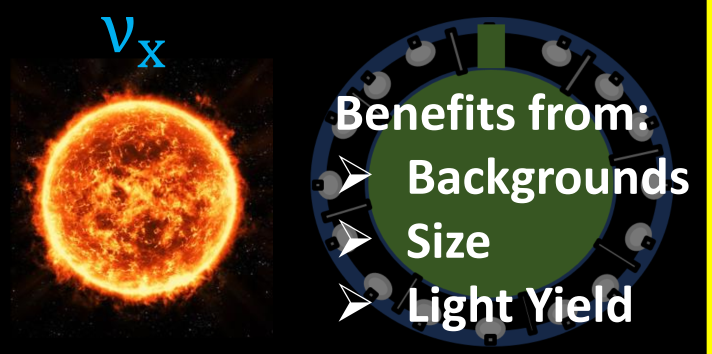
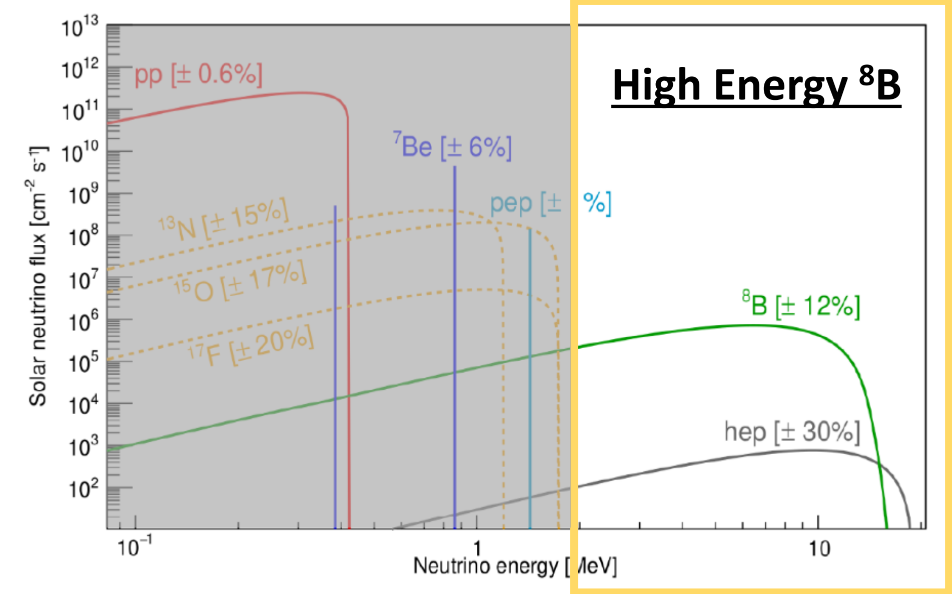


- Nuclear fusion within the sun produces ν_e

Expected Flux → Expected Signal + Background → Expected Sensitivity



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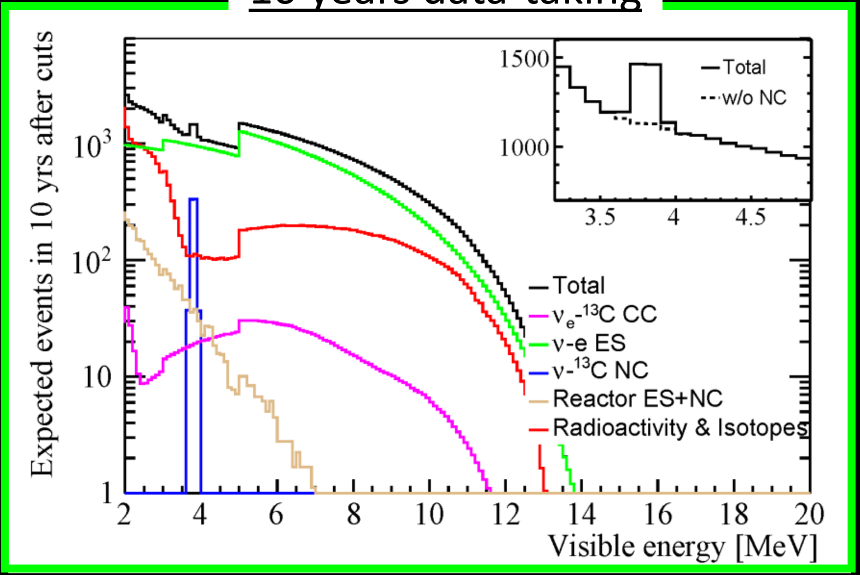


Oscillation Measurement
10 years exposure

ϕ_{8B} : 5%

θ_{12} : 8%

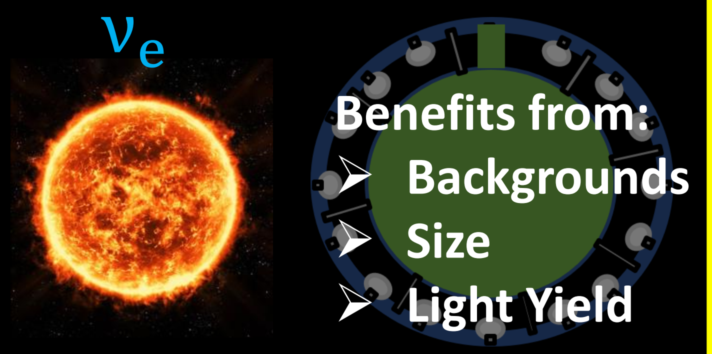
Δm^2_{21} : 20%

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

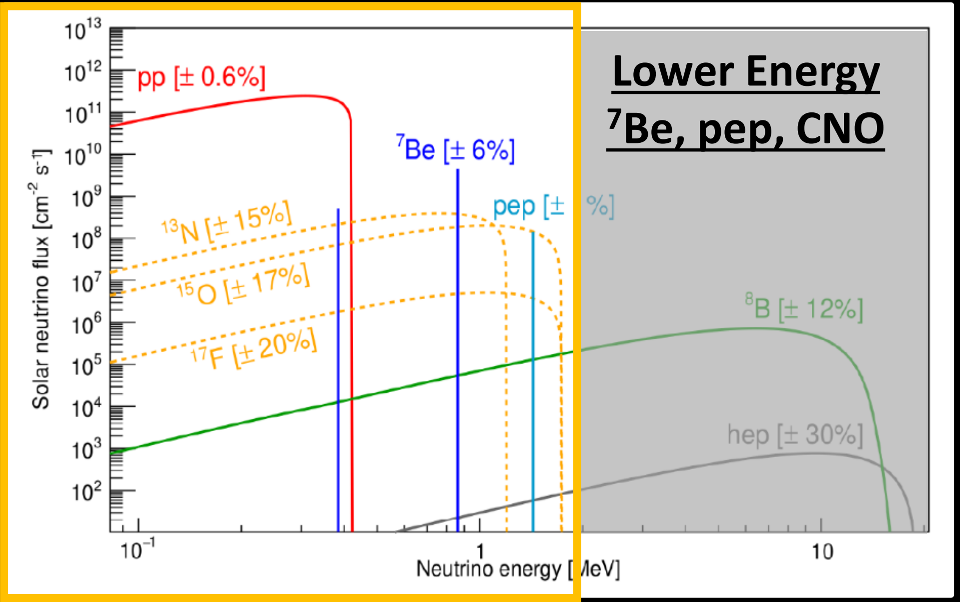
Solar Neutrinos

"JUNO sensitivity to ^{7}Be, pep, and CNO solar neutrinos" arXiv:2303.03910

- Lower energy chains : Dependent on background levels
- Probe the solar core – solar metallicity



Expected Flux



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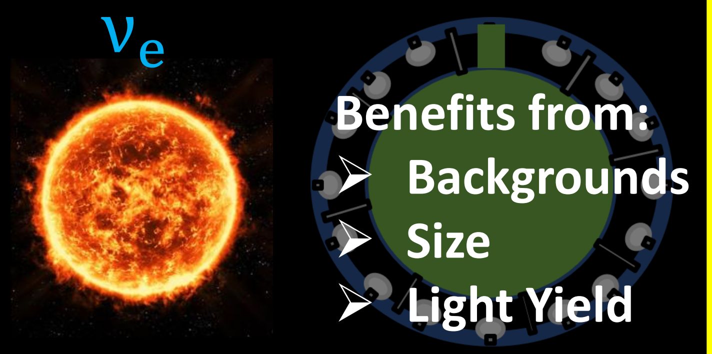

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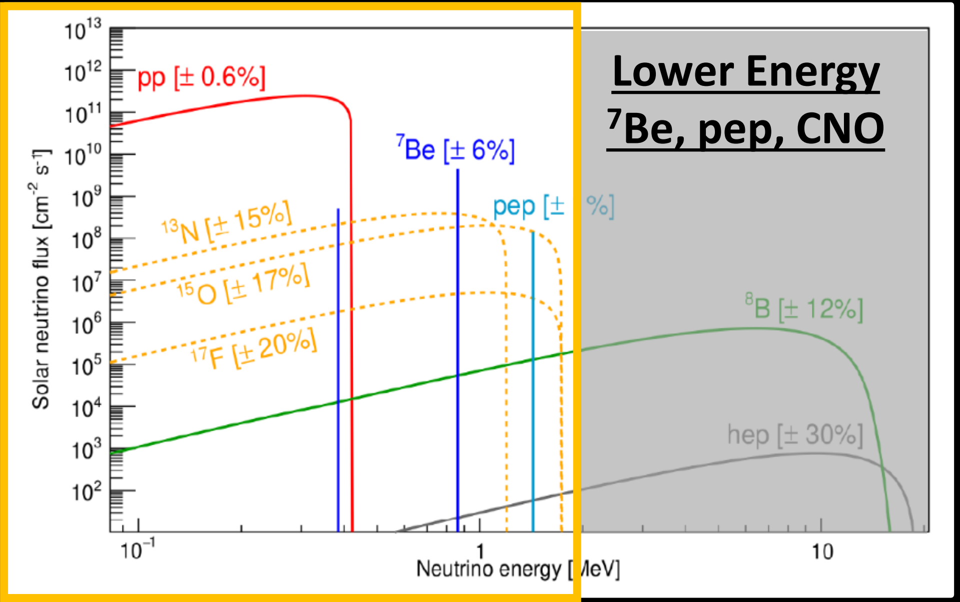
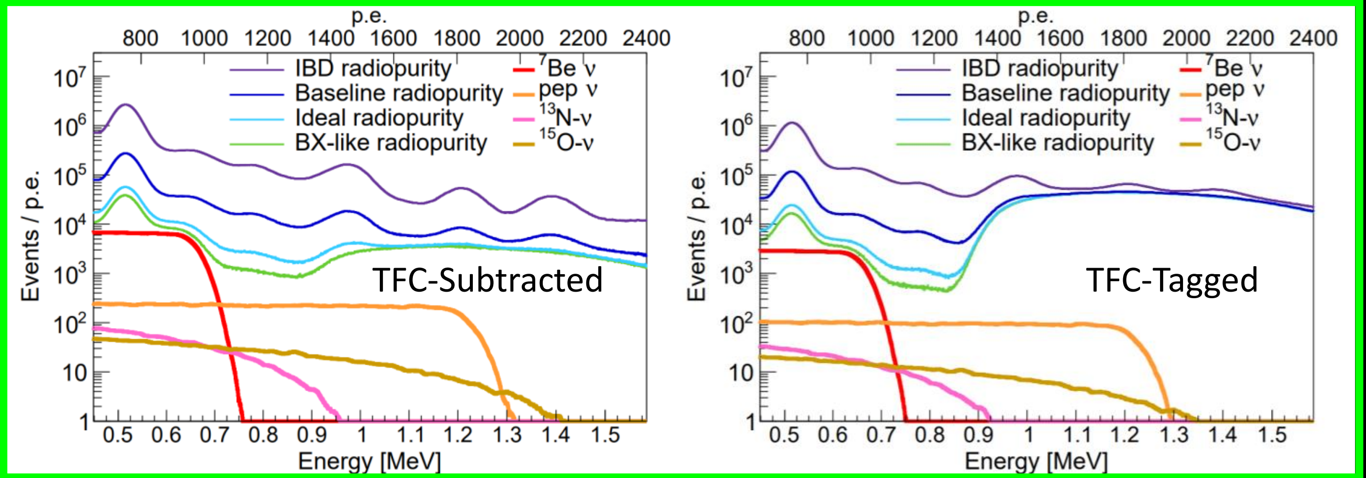
Expected Flux → Expected Signal + Background

6 years data-taking





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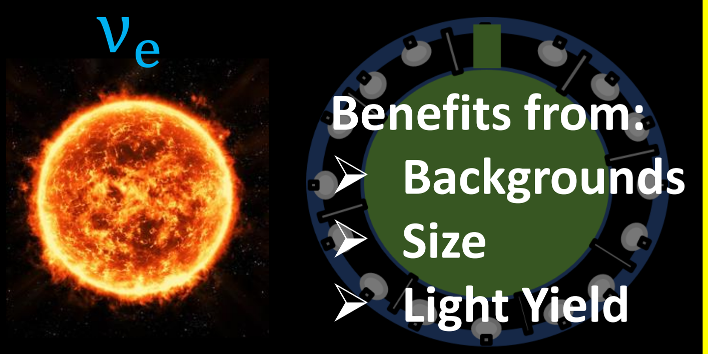

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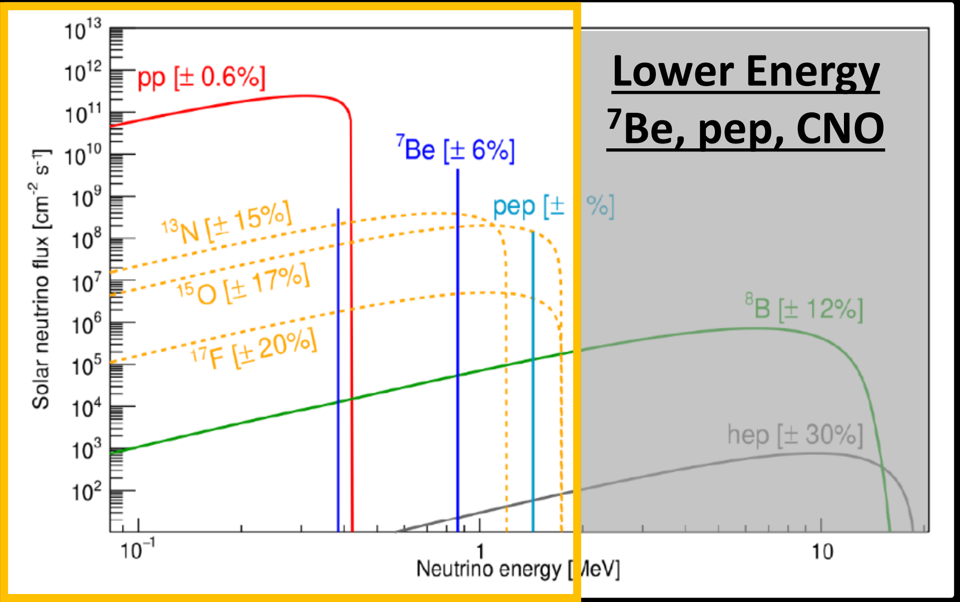
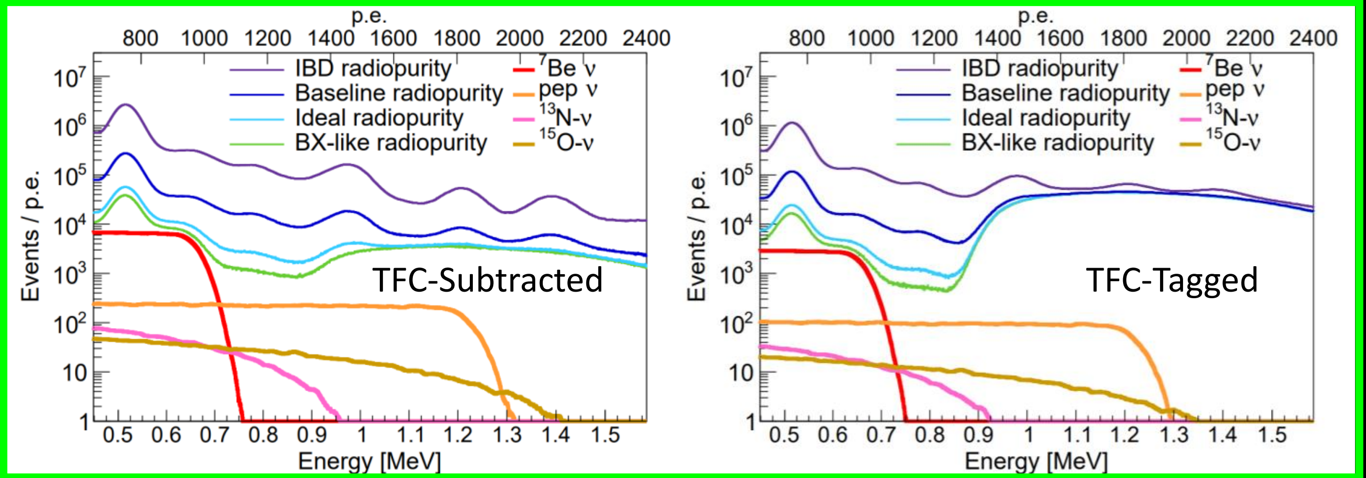
Expected Flux → Expected Signal + Background → Expected Sensitivity

6 years data-taking

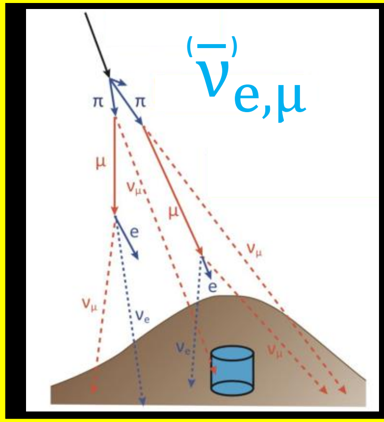


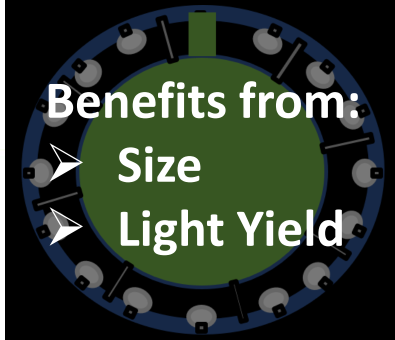


Signal \ Radiopurity Scenario	Low BGs (Borexino-like)	Higher BGs
^{7}Be	~0.2%	~0.5% (IBD)
pep	3%	17% (IBD)
CNO	12%	19% (Baseline)

Atmospherics

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

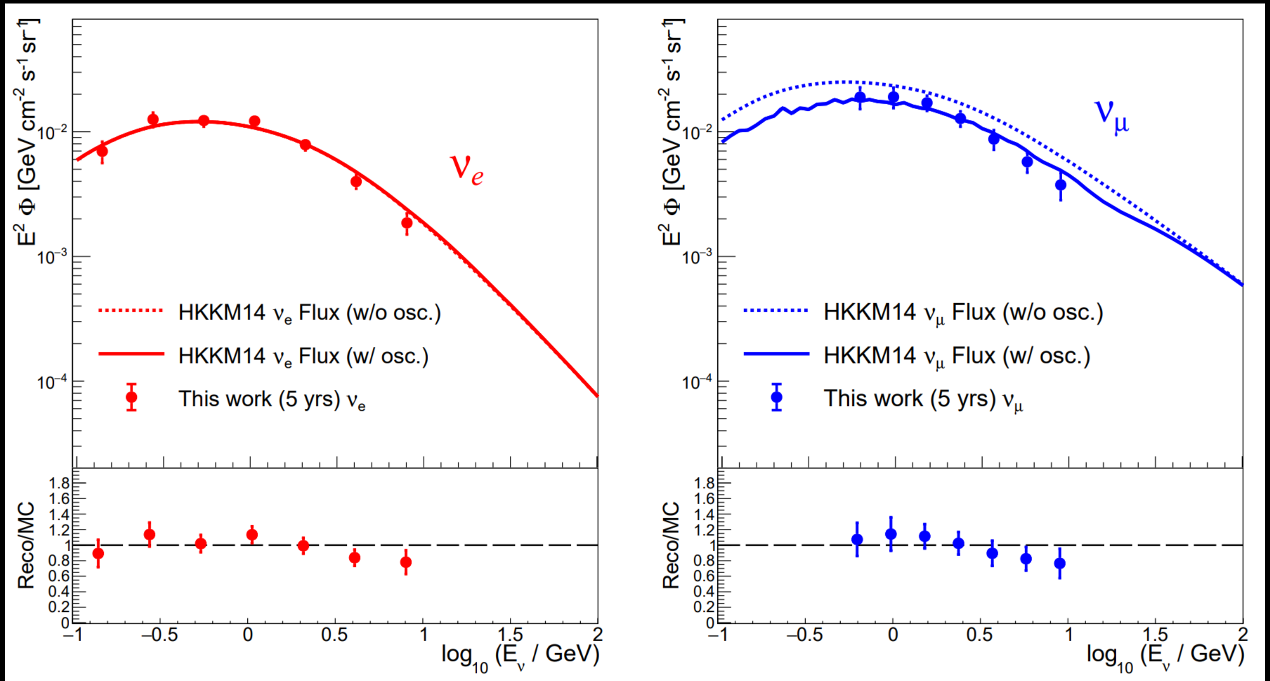




Benefits from:
- ➢ **Size**
- ➢ **Light Yield**

- Would be the first liquid scintillator measurement of atmospheric neutrinos through CC and NC interactions

Expected reconstructed energy spectra



Discriminate ν_e and ν_μ with hit patterns

~10-25% uncertainty in 5 years

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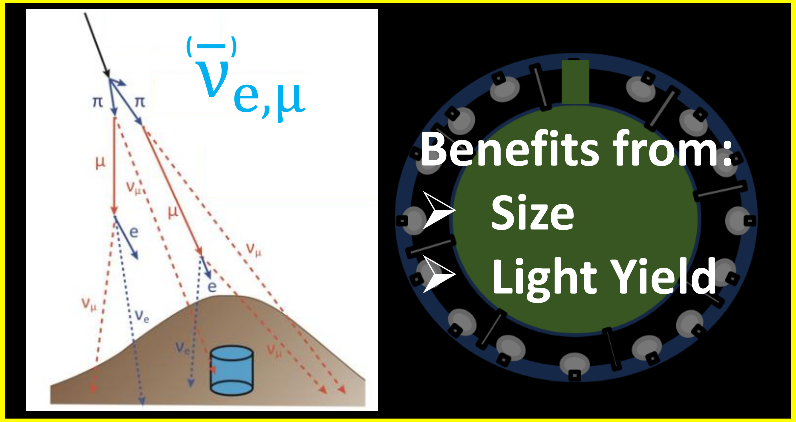

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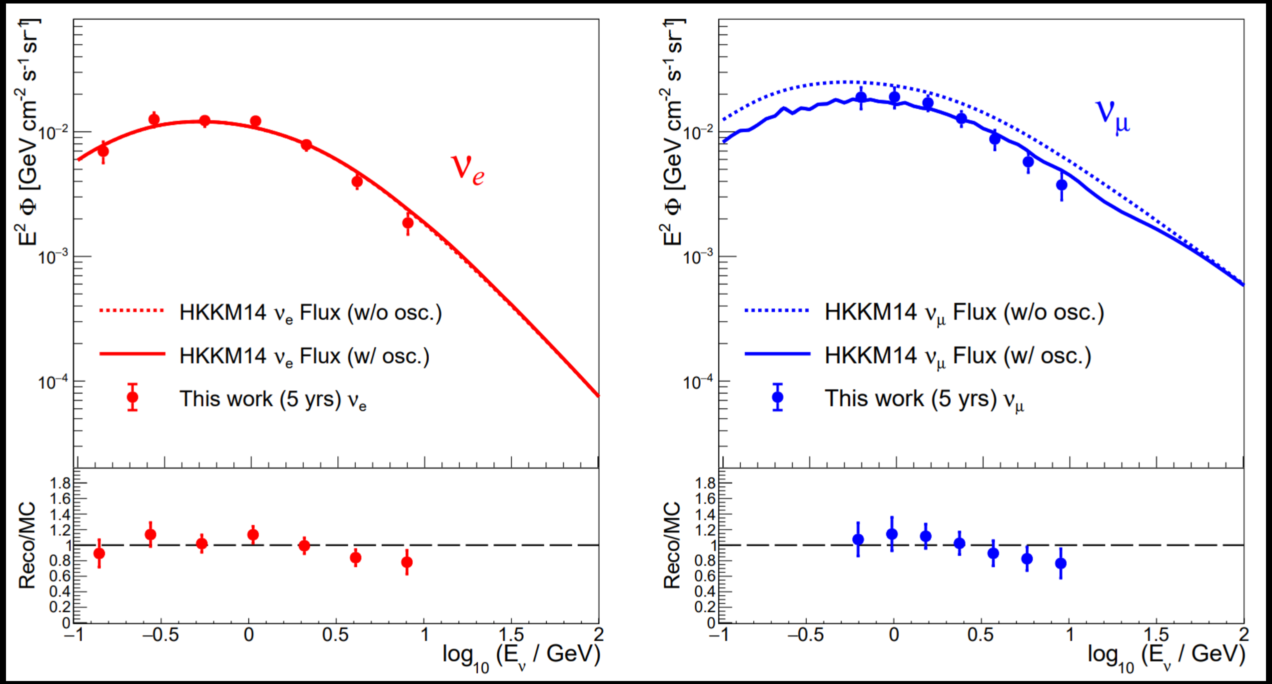


Discriminate ν_e and ν_μ with hit patterns

~10-25% uncertainty in 5 years

Expected Sensitivity

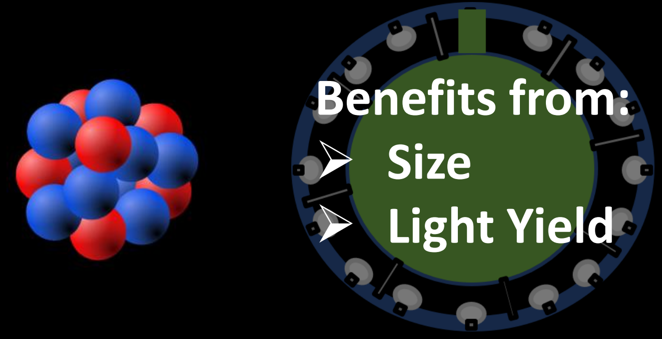
Matter effects provide sensitivity to Neutrino Mass Ordering

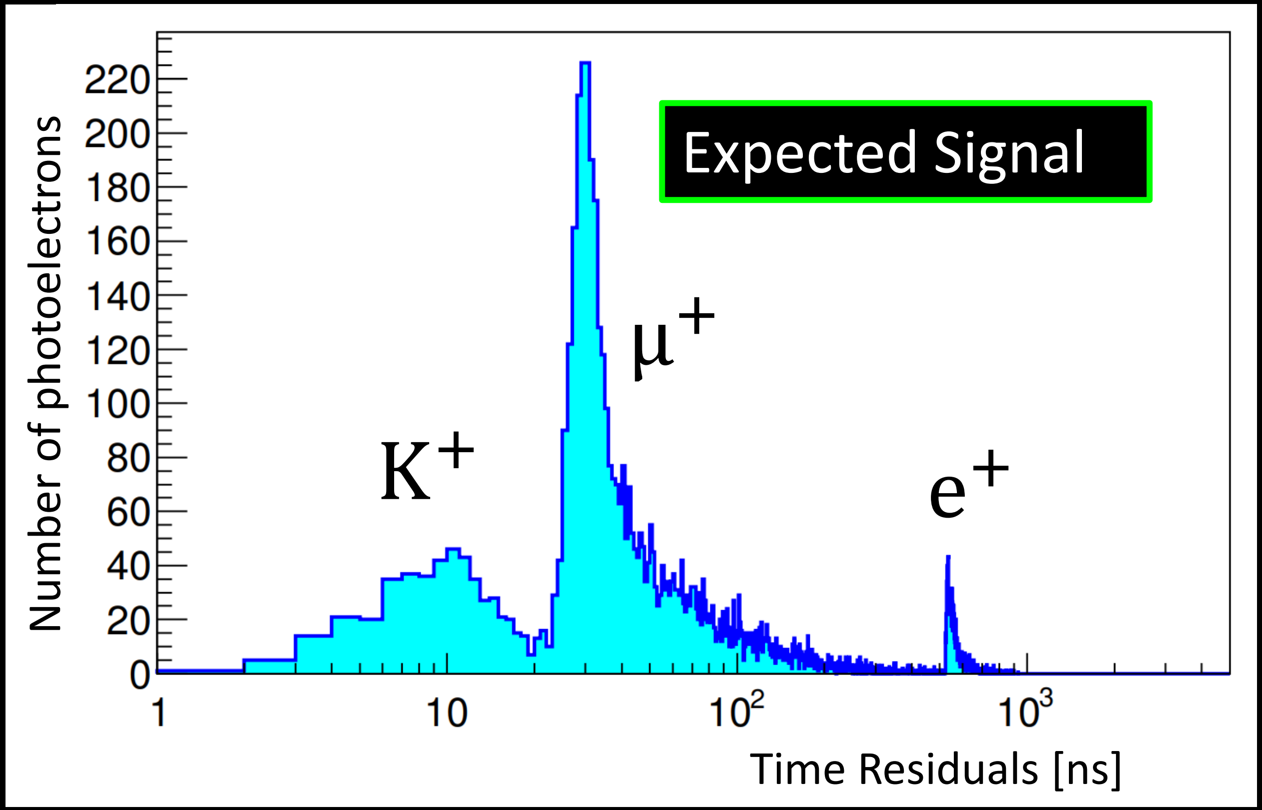
NMO expectation:
0.7-1.4σ in ~6 years exposure

Complementary to the reactor NMO analysis

Proton Decay

[JUNO physics and detector, Progress in Particle and Nuclear Physics 123 (2022) 103927](https://doi.org/10.1016/j.ppnp.2021.103927)





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

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

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

Expected Sensitivity

8.3×10^{33} years (90% C.L.)
in 10 years

Other decay modes also under investigation

The JUNO Experiment

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	SYSU	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	Tsinghua U.	Germany	U. Tuebingen
Brazil	PUC	China	UCAS	Italy	INFN Catania
Brazil	UEL	China	USTC	Italy	INFN di Frascati
Chile	PCUC	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	Latvia	IECS
China	CIAE	China	CUG-Beijing	Pakistan	PINSTECH (PAEC)
China	DGUT	China	ECUT-Nanchang City	Russia	INR Moscow
China	Guangxi U.	China	CDUT-Chengdu	Russia	JINR
China	Harbin Institute of Technology	Czech	Charles U.	Russia	MSU
China	IHEP	Finland	University of Jyvaskyla	Slovakia	FMPICU
China	Jilin U.	France	IJCLab Orsay	Taiwan-China	National Chiao-Tung U.
China	Jinan U.	France	LP2i Bordeaux	Taiwan-China	National Taiwan U.
China	Nanjing U.	France	CPPM Marseille	Taiwan-China	National United U.
China	Nankai U.	France	IPHC Strasbourg	Thailand	NARIT
China	NCEPU	France	Subatech Nantes	Thailand	PPRLCU
China	Pekin U.	Germany	RWTH Aachen U.	Thailand	SUT
China	Shandong U.	Germany	TUM	U.K.	U. Warwick
China	Shanghai JT U.	Germany	U. Hamburg	USA	UMD-G
China	IGG-Beijing	Germany	FZJ-IKP	USA	UC Irvine

21st JUNO collaboration meeting
February 2023, Kaiping

75 Institutes, 18 countries
> 700 collaborators

Conclusion

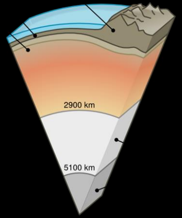
➢ JUNO, a 20kT liquid scintillator detector

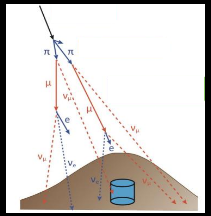
First-rate size and energy resolution

➢ 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





➢ Detector construction progressing : completion expected end of 2023!

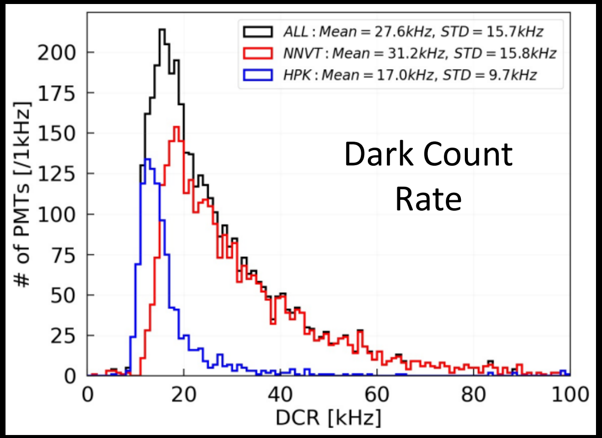
Backup

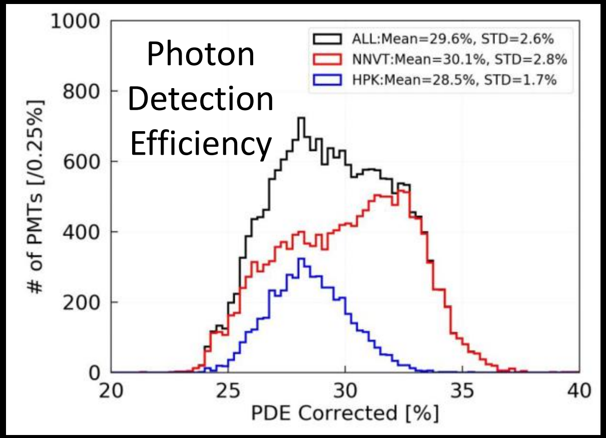
PMTs

- 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

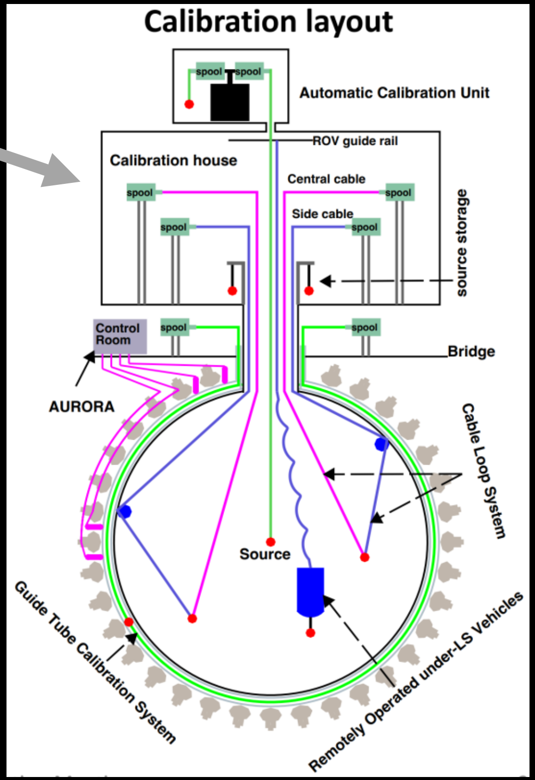
- ~13,000 NNVT PMTs with the best PDE used for Detector light collection
  - Rest used for outer water Cherenkov detector muon veto





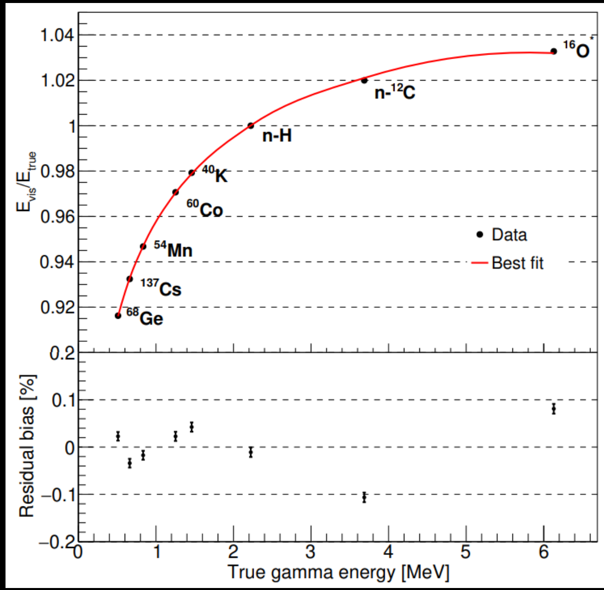
Calibration

“Calibration strategy of the JUNO experiment”, Journal of High Energy Physics volume 2021, Article number: 4 (2021)



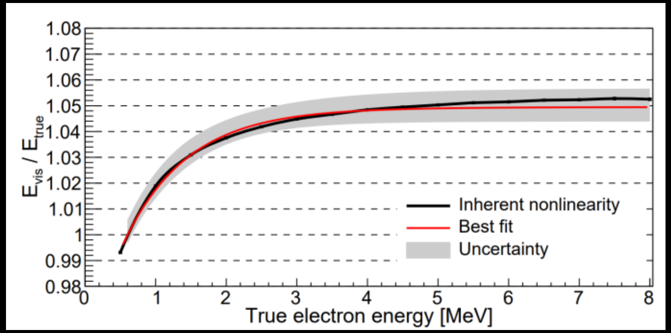
- Multiple calibration sources with varied energies.
- Sources can be manoeuvred in 3-dimensions within the central detector

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



Gamma non-linearity

Electron non-linearity

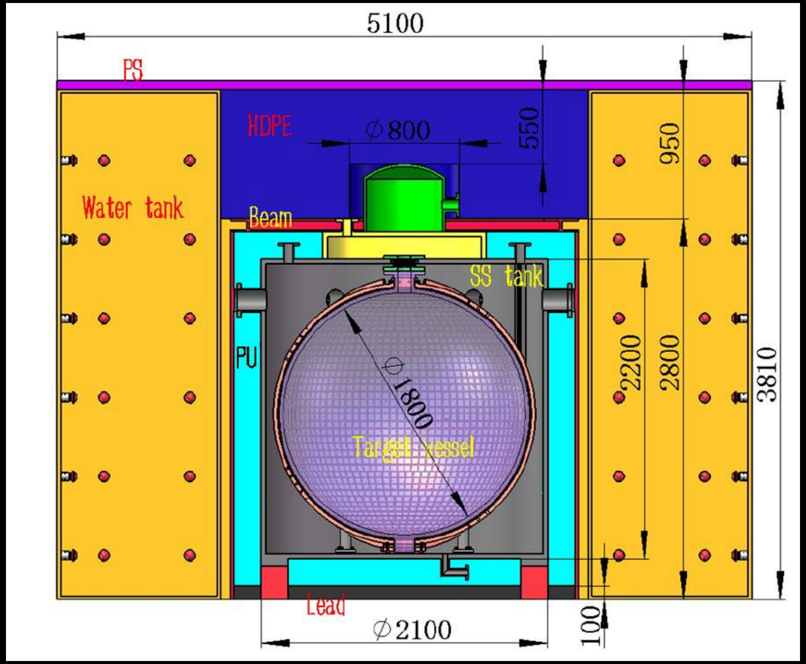


JUNO TAU Near Detector

- Near-detector to measure a reference reactor spectrum for JUNO

- 2.8 ton Gs-LS, located 30m from one of the nuclear reactor cores in Taishan
- Acrylic vessel
- 10m^2 SiPM with 94% coverage
- Operated at -50^{o}C
- 50% PDE -> 4500 PE/MeV
- -> Energy Resolution <2% @ 1MeV

- Precise reactor $\bar{\nu}_e$ measurements:
  Search for sterile neutrinos

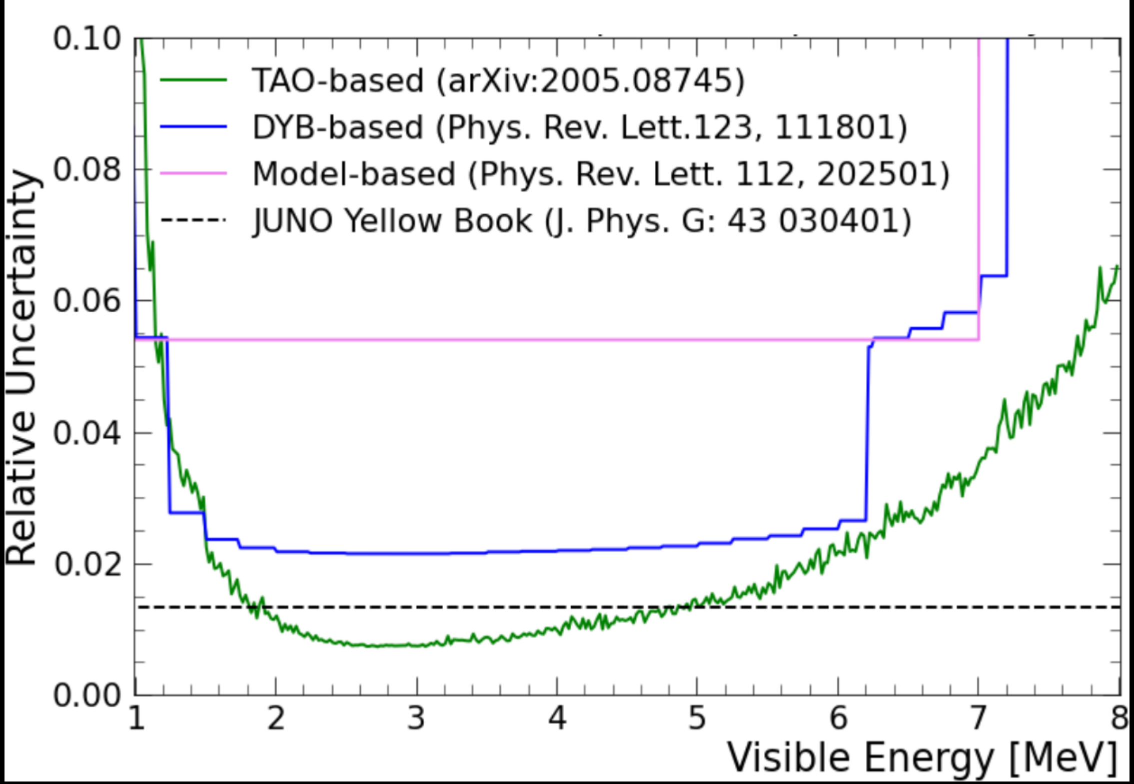


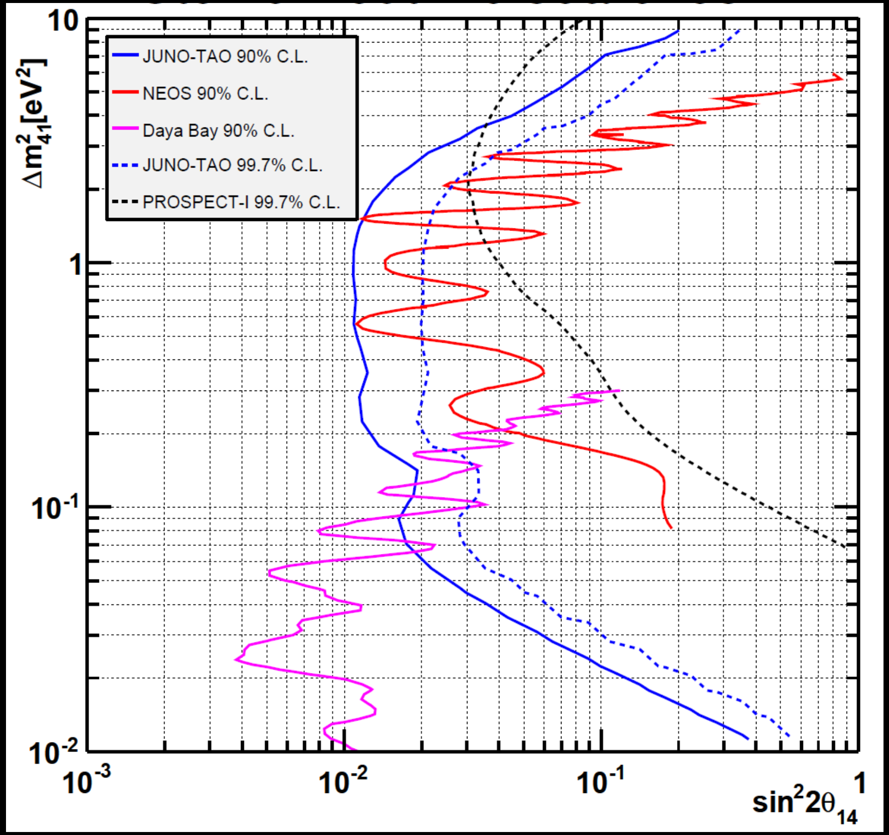
arXiv: 2005.08745

JUNO TAU Near Detector

"TAO Conceptual Design Report: A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution," arXiv:2005.08745

- High precision measurement of nuclear reactor $\bar{\nu}_e$ energy spectrum
- Search for sterile neutrinos





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

Detector components

- Acrylic Vessel : 12.4 ± 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

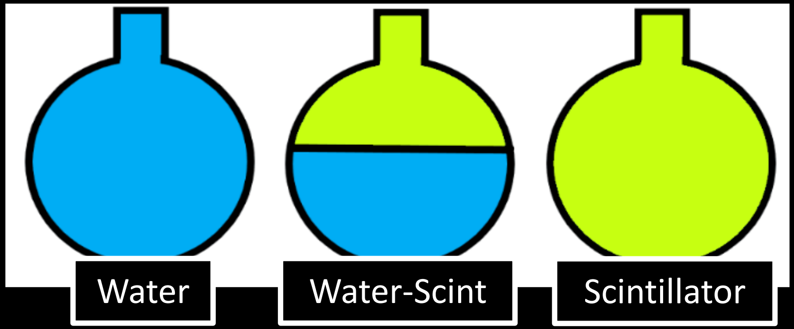
- Stainless steel support structure (completed June 24)
  - Supports acrylic vessel, PMTs and electronics affixed to
  - Assembly precision <3mm
- 590 connecting rods – connects to acrylic sphere

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

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

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[5] U. F. Katz and Ch. Spiering. High-Energy Neutrino Astrophysics: Status and Perspectives. Prog. Part. Nucl. Phys., 67:651–704, 2012.