The JUNO experiment: status and prospects

Maxim Gonchar on behalf of the JUNO collaboration
Joint Institute for Nuclear Research

NUCLEUS 2022, July 13, 2022

v4

Glossary

- JUNO — **J**iangmen **U**nderground **N**eutrino **O**bservatory
  - The main experiment
  - The main detector
  - The project name: it has a few other detectors

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  - Satellite small short baseline antineutrino detector

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  - A utility detector to monitor scintillator internal radioactivity

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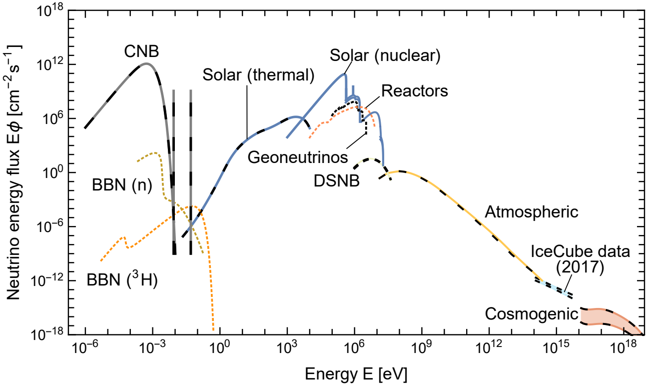
  - A utility detector to monitor scintillator internal radioactivity
- Serappis project — **SE**arch for **RA**re **PP**-neutrinos **In** **S**cintillator
  - A possible upgrade of OSIRIS to measure solar pp neutrinos

Physics with JUNO: neutrinos and more...



Vitagliano, Tamborra, Raffelt [1910.11878]

DSNB — Diffuse SuperNova Background

* Rates after selection

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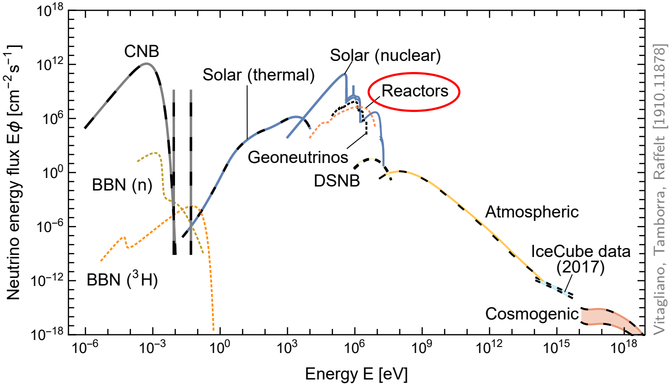

Osc. [2204.13249], TAO [2005.08745]

Neutrino physics

- Reactor
  - **Long baseline ~47 IBD/day**
  - Short baseline @TAO ~2000 IBD/day

DSNB — Diffuse SuperNova Background
IBD — Inverse Beta Decay
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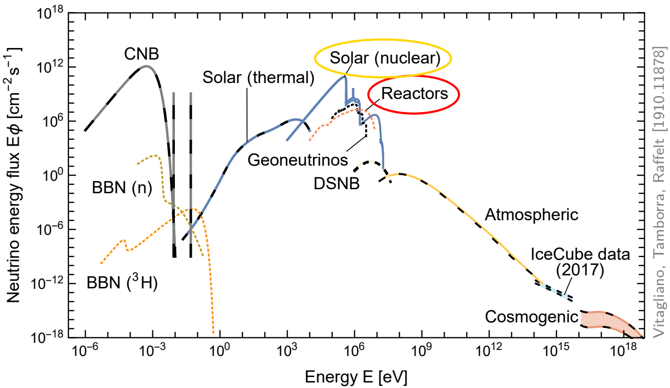
Physics with JUNO: neutrinos and more...



^{8}B [2006.11760], OSIRIS-Serappis [2109.10782], JUNO [2104.02565]

Neutrino physics

- Reactor ~47 IBD/day
- Solar
  - ^{7}Be ~130 ES/day
  - pep ~17 ES/day
  - CNO ~16 ES/day
  - ^{8}B (high E) ~16 ES/day
  - pp @OSIRIS ~ 16 ES/day
  - ^{7}Be @OSIRIS ~ 4.5 ES/day

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ES — Elastic Scattering
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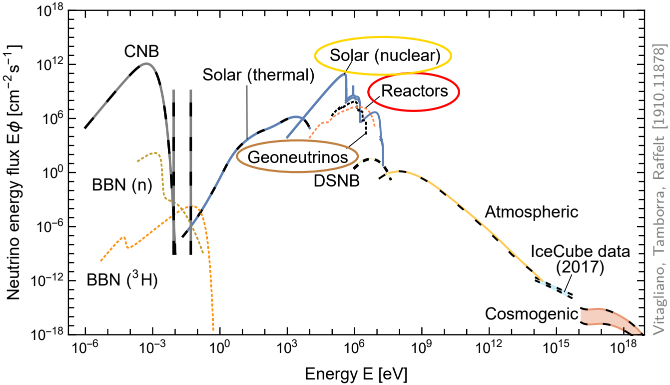
Physics with JUNO: neutrinos and more...

JUNO [2104.02565]



Neutrino physics

- Reactor ~47 IBD/day
- Solar
- Geo-neutrino ~400 IBD/year

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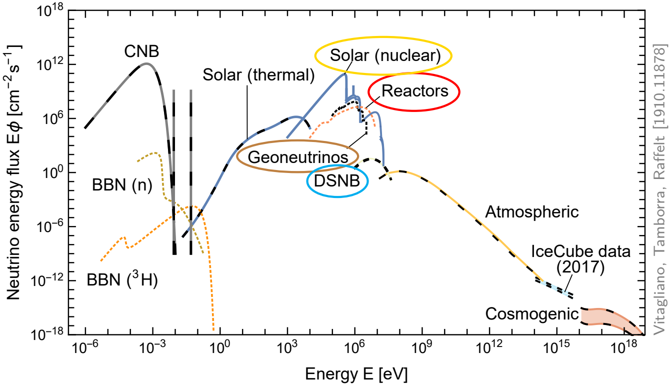
Physics with JUNO: neutrinos and more...



DSNB [2205.08830]

Neutrino physics

- Reactor ~47 IBD/day
- Solar
- Geo-neutrino ~400 IBD/year
- DSNB 2 – 4 IBD/year

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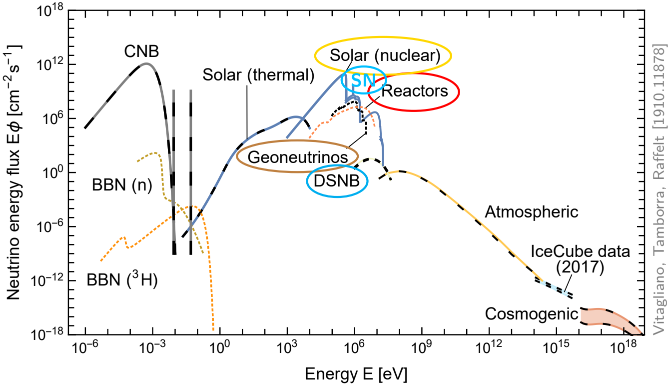
Physics with JUNO: neutrinos and more...

JUNO [2104.02565]



Neutrino physics

- Reactor ∼47 IBD/day
- Solar
- Geo-neutrino ∼400 IBD/year
- DSNB 2 – 4 IBD/year
- SuperNova 5000 IBD/2300 ES@10 kpc

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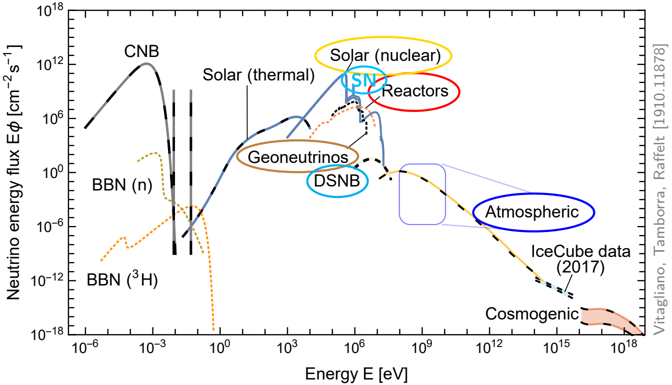
Physics with JUNO: neutrinos and more...

Atmospheric [2103.09908], JUNO [2104.02565]



Neutrino physics

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- Solar
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- Atmospheric $\mathcal{O}(100)$ CC/year

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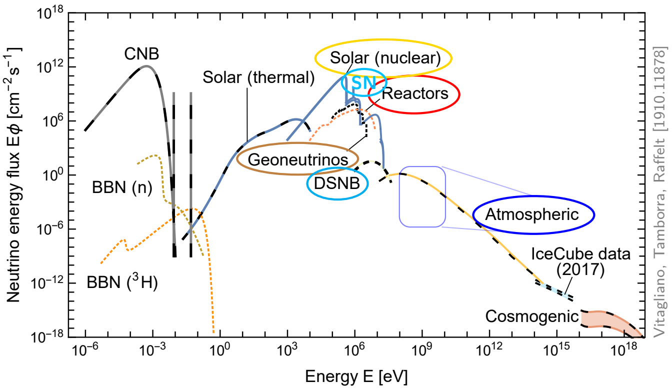
Physics with JUNO: neutrinos and more...

JUNO [2104.02565]



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Non-neutrino physics

- Proton decay
- Other searches...

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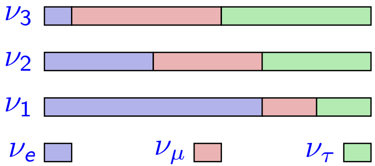
Mandatory slide I: Neutrino mixing



Weak and mass eigenstates differ:

$$|\nu_\alpha\rangle = \sum U^*_{\alpha i}|\nu_i\rangle$$

α – flavor states

i – mass states

Mixing parametrized by:

- three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$,
- CP-violating phase: δ_{CP}.

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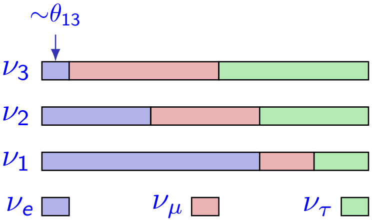

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Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix:

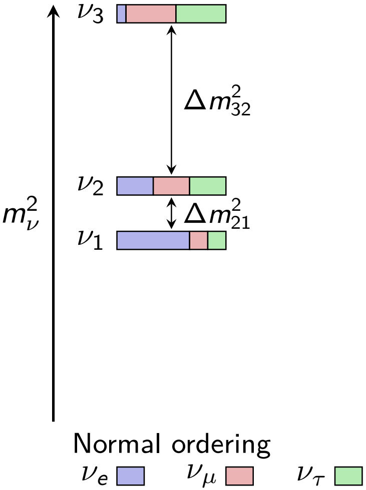
✓ $\theta_{23} \approx 45^\circ$ established through atmospheric and accelerator experiments: possibly maximal.

✓ $\theta_{12} \approx 34^\circ$ established through solar experiments and KamLAND: large, but not maximal.

✓ $\theta_{13} \approx 8^\circ$ established by reactor: **Daya Bay**, RENO, Double Chooz.

- δ_{CP} unknown: NOvA and T2K.

Mandatory slide II: Neutrino mass and ordering



Mass splitting: oscillations PDG2020

- $\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$
- $\left|\Delta m^2_{32}\right|_{\mathrm{NO}} = (2.453 \pm 0.033) \times 10^{-3}\ \mathrm{eV}^2$
- $\left|\Delta m^2_{32}\right| / \Delta m^2_{21} \sim 31$

Numbers updated: 2022.06.10

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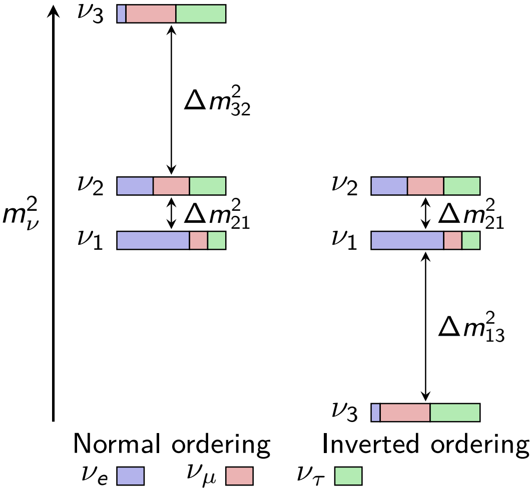

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- Mass ordering: is ν_1 lighter than ν_3?

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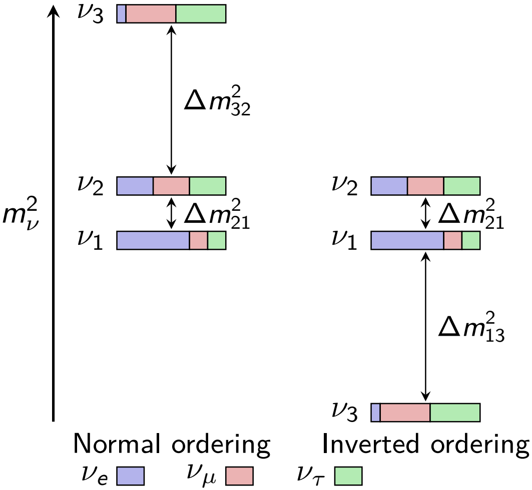

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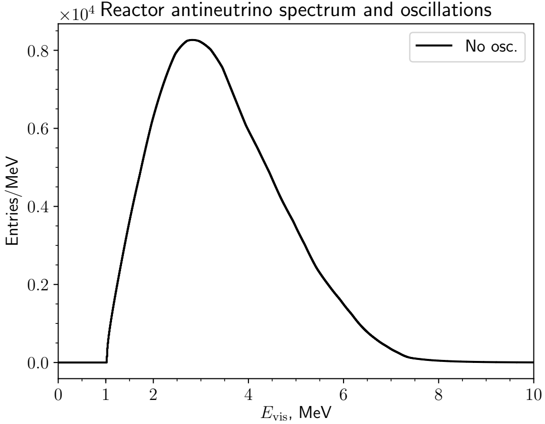
Neutrino mass

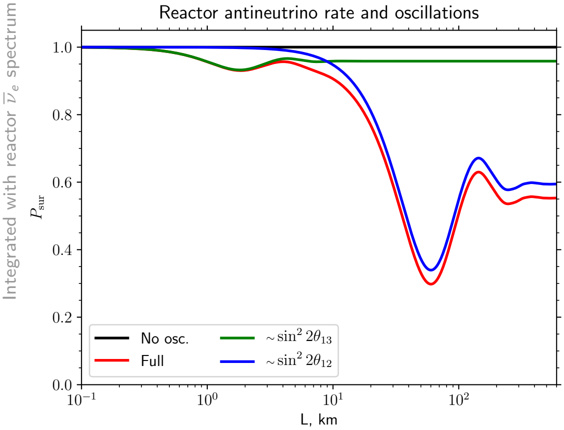
- Mass limits, meV:

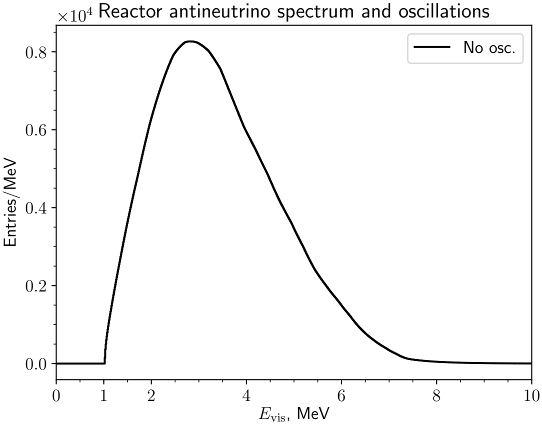
$m_2, m_3 > 0$	oscillations	
$\sum m_\nu \gtrsim 60$	oscillations	
$\sum m_\nu \lesssim 120$	cosmology	Planck
$m_{\nu_e} < 900$	direct	KATRIN [2105.08533]
$\langle m_{\beta\beta} \rangle < 156$	$0\nu\beta\beta$	Kamland-ZEN
$m_{\mathrm{light}} \lesssim 500$	$0\nu\beta\beta$	[2203.02139]

Numbers updated: 2022.06.10



$E_{\text{vis}} \approx E_\nu - 0.78\,\text{MeV}$





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~~δ_{CP}, θ_{23}~~

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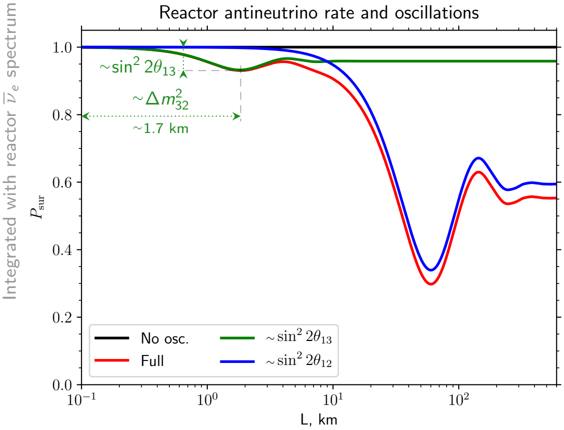

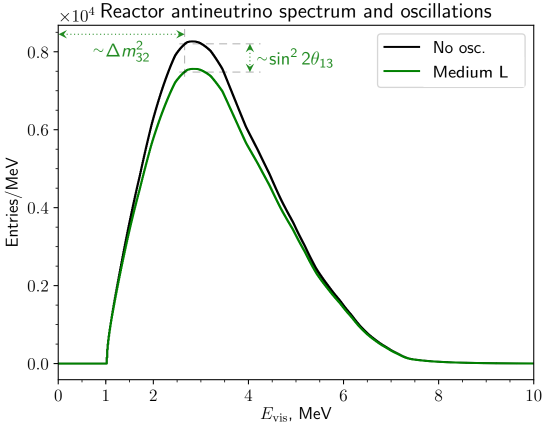

deficit value

minimum location

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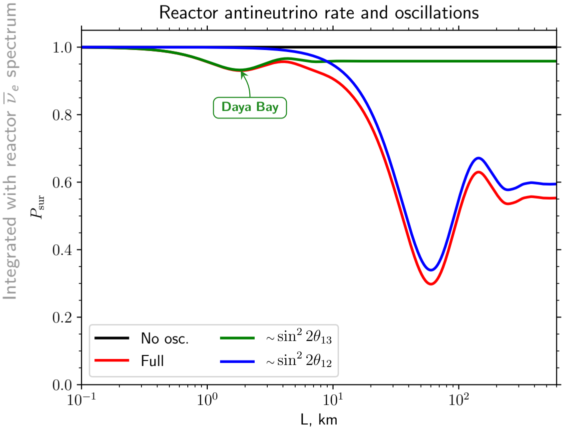

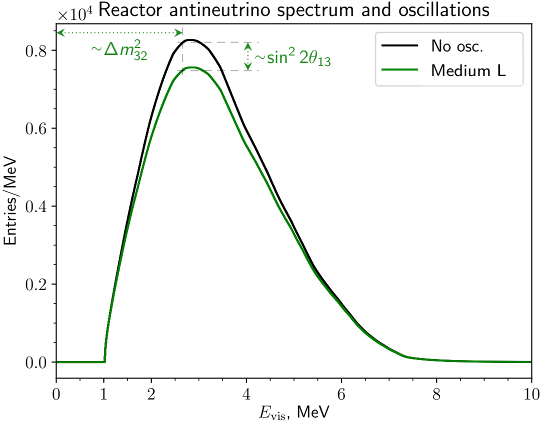

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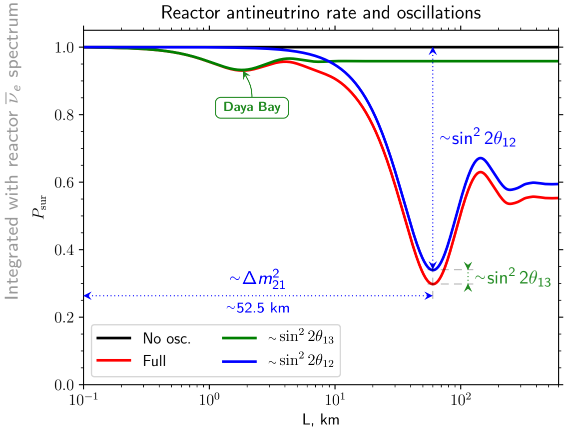

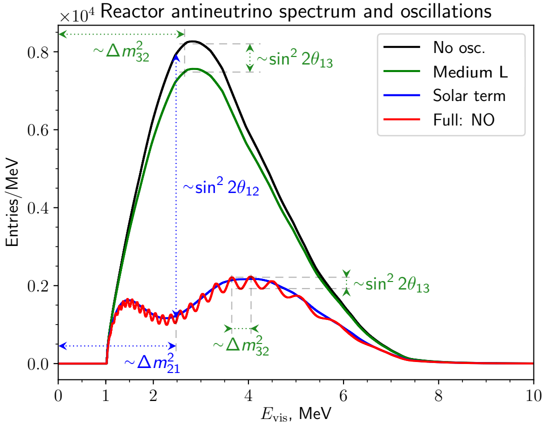

deficit value — minimum location — minimum location, solar

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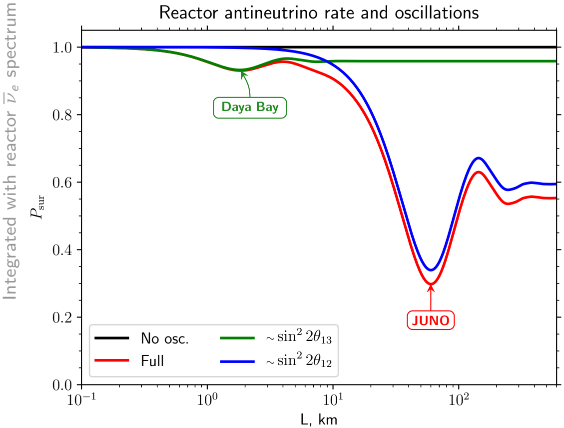

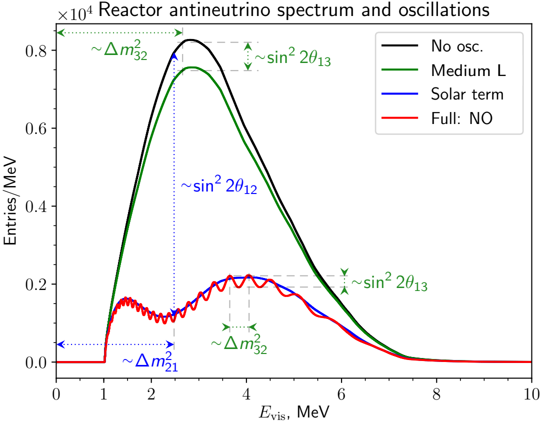

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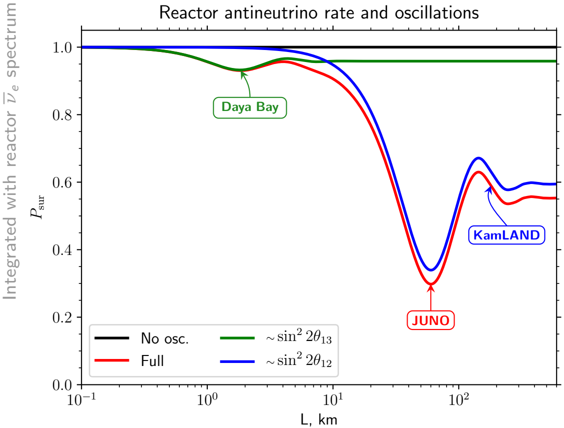

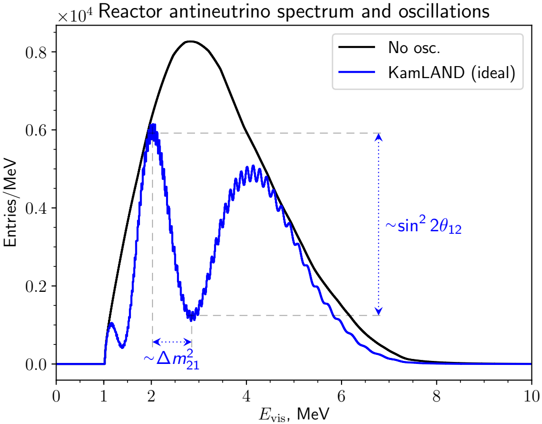

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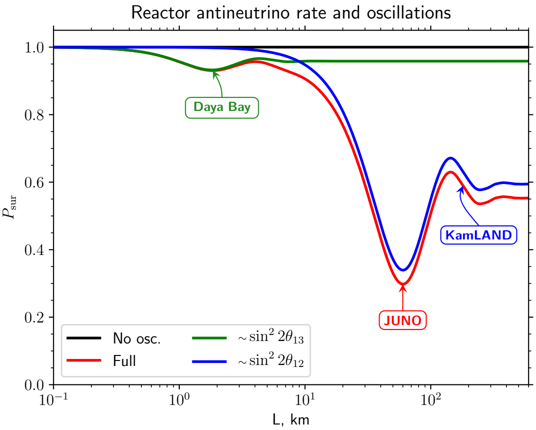
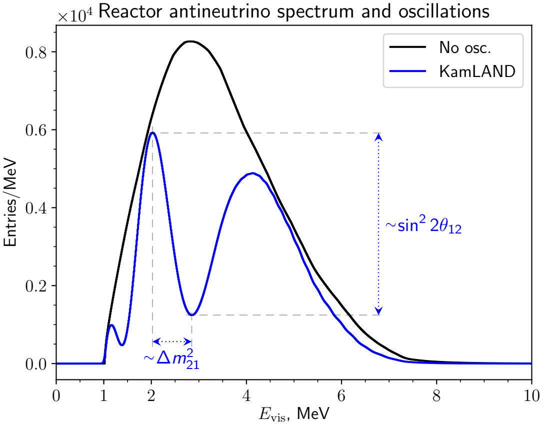
Integrated with reactor $\overline{\nu}_e$ spectrum





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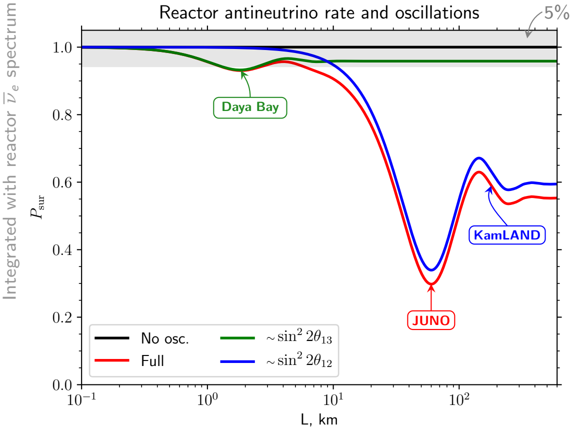

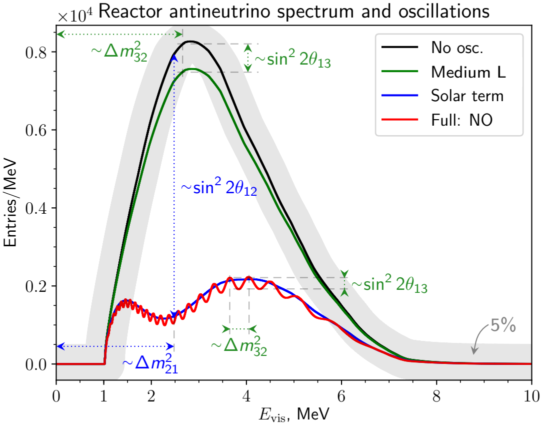

Challenges

- Unreliable antineutrino spectrum model: $\hookrightarrow$ know reference spectrum
- Energy resolution of the detector $\sigma < 3\%$ at 1 MeV: $\hookrightarrow$ resolve the peaks
- Energy scale of the detector (uncertainty $< 1\%$): $\hookrightarrow$ ensure the peak positions

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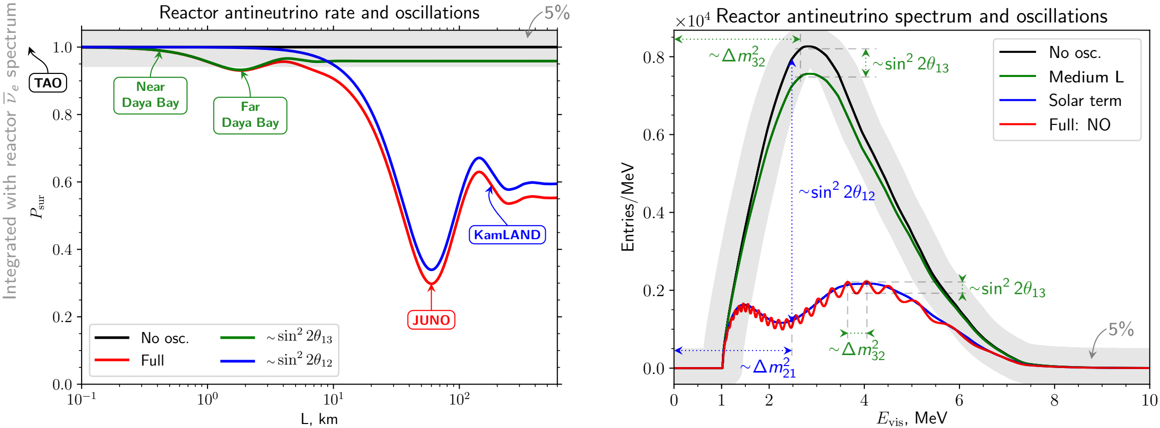

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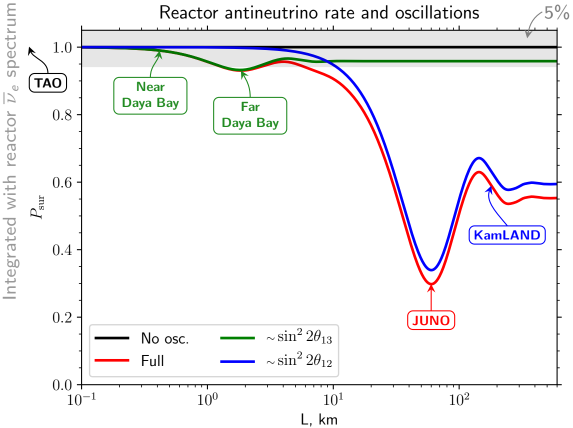

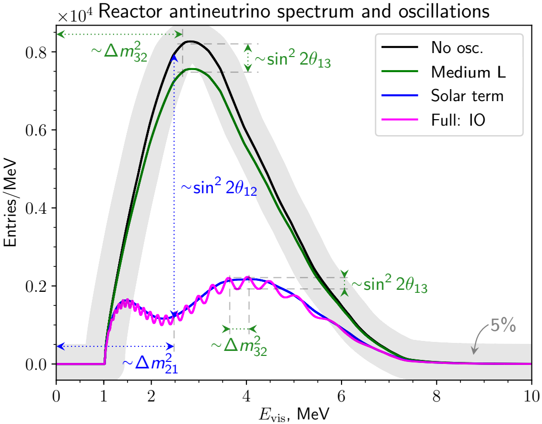

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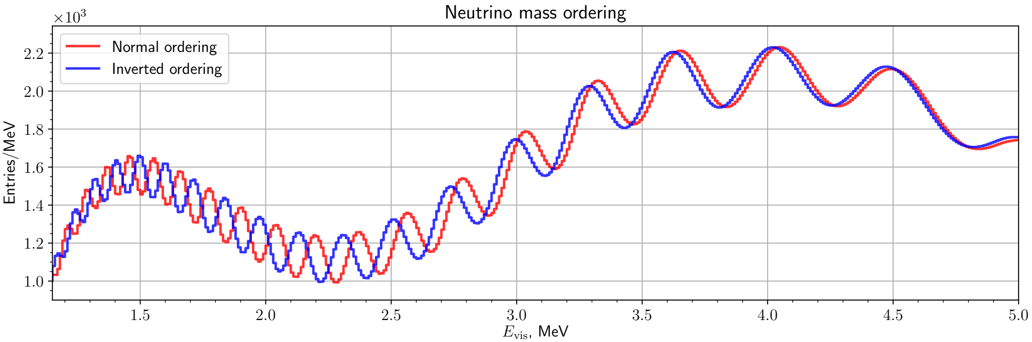

(plot: same Δm^2_{ee})

- Change of oscillation period with ordering $\ll$ energy resolution
- Cumulative effect across most of the energy range

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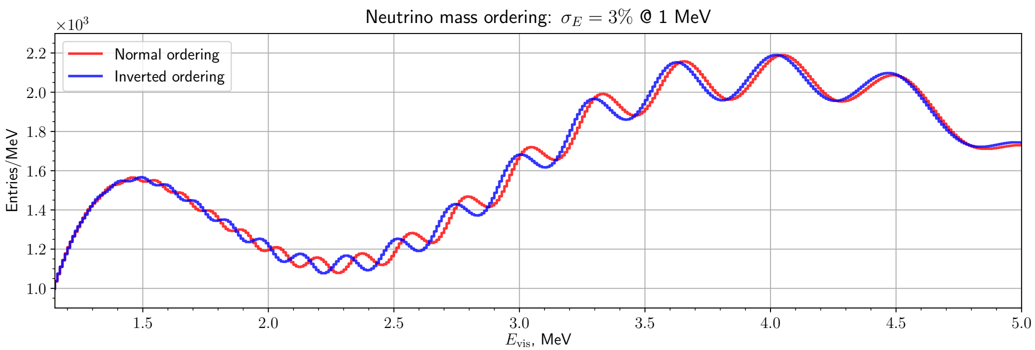
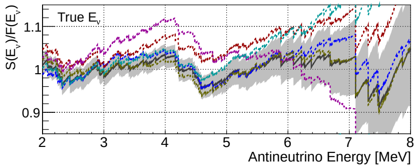


- Change of oscillation period with ordering $\ll$ energy resolution
- Cumulative effect across most of the energy range
- Possible threat: fine structure in reactor $\overline{\nu}_e$ spectrum

need a reference measurement!



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(plot: same Δm^2_{ee})

Dwyer&Langford [1407.1281], PRL114

The Experiment and its Status

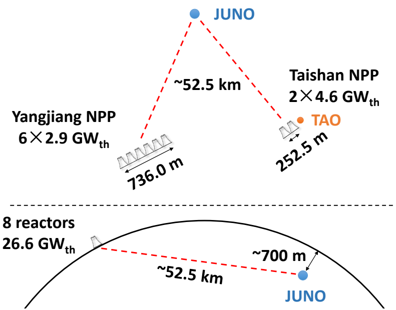
JUNO and TAO location

- JUNO — Jiangmen Underground Neutrino Observatory
- TAO — Taishan Antineutrino Observatory

	Yangjian (YJ)	Taishan (TS)
Thermal power, GW	2.9×6	4.6×2
Total, GW	26.6	
	signal	

JUNO and TAO location

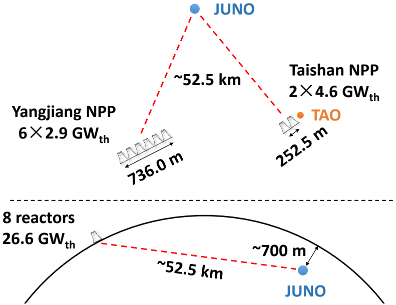
- JUNO — Jiangmen Underground Neutrino Observatory
- TAO — Taishan Antineutrino Observatory

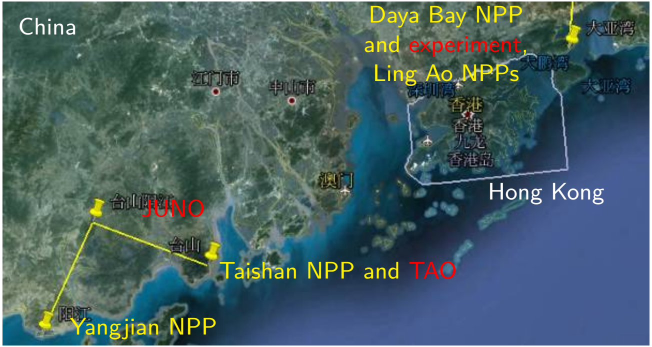


	Yangjian (YJ)	Taishan (TS)
Thermal power, GW	2.9×6	4.6×2
Total, GW	26.6	
	signal	

JUNO and TAO location

- JUNO — Jiangmen Underground Neutrino Observatory
- TAO — Taishan Antineutrino Observatory

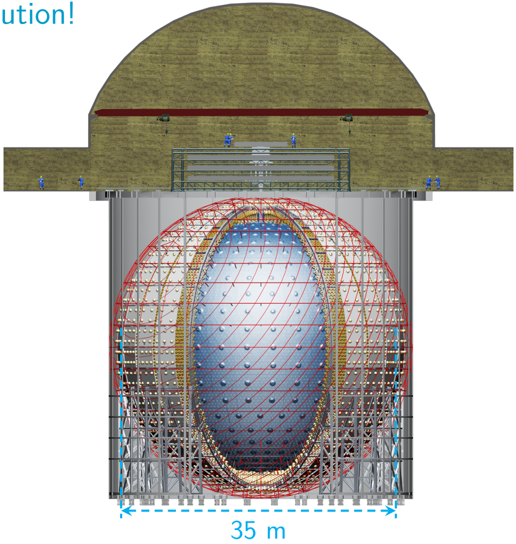




	Yangjian (YJ)	Taishan (TS)	Daya Bay/Ling Ao	World
Thermal power, GW	2.9×6	4.6×2	2.9×6	
Total, GW	26.6		17.4	…
	signal		background	

JUNO DETECTOR

More light $\rightarrow$ better resolution!
More statistics!



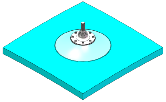
JUNO DETECTOR

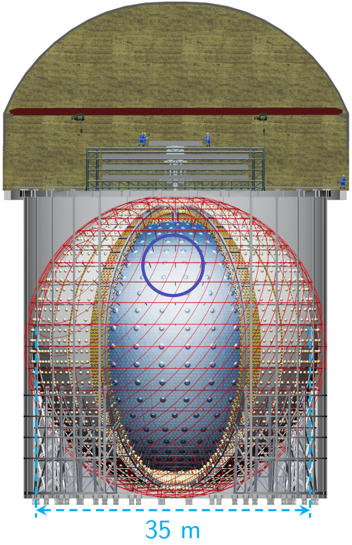
LS — Liquid Scintillator
LY — Light Yield

More light → better resolution!
More statistics!

Target

- 20 kt LS
- Optimized LY
- Acrylic sphere





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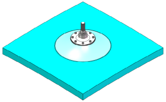

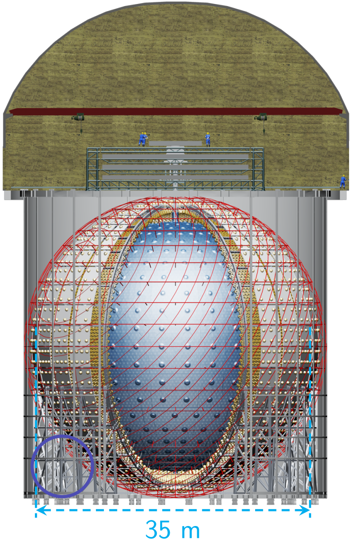

Support

- Stainless steel structure

JUNO DETECTOR

LS — Liquid Scintillator
LY — Light Yield
PMT — PhotoMultiplier Tube
QE — Quantum Efficiency
p.e. — photo-electron

More light → better resolution!
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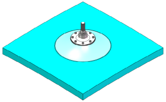

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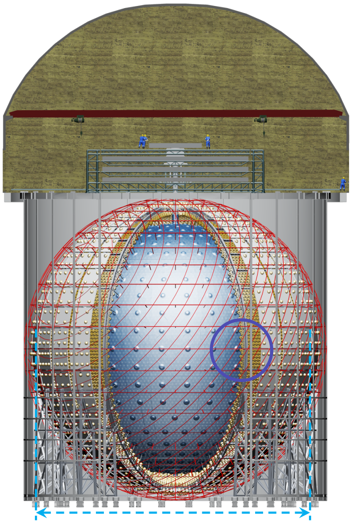

Light collection

- 18k 20" PMTs
- High QE: 29.6%
- 1665 p.e./MeV
- +26k 3" PMTs

Preliminary

JUNO DETECTOR

More light → better resolution!
More statistics!

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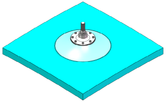

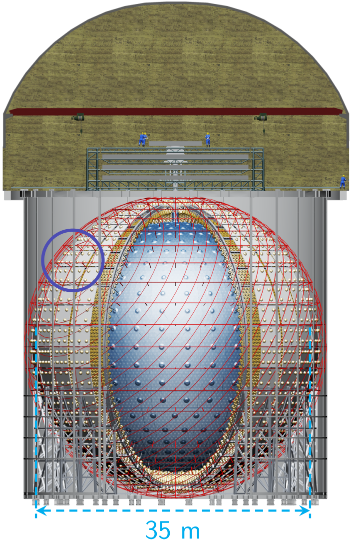

Coils

- Compensation of the Earth Magnetic Field

Support

- Stainless steel structure

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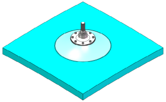


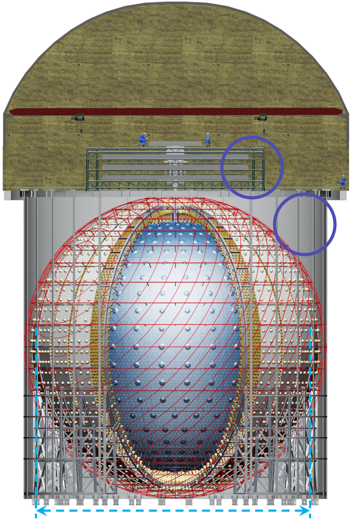
Coils

- Compensation of the Earth Magnetic Field

Support

- Stainless steel structure

▸ Inverse Beta Decay (IBD) selection ▸ Signal/Backgrounds



LS — Liquid Scintillator
LY — Light Yield
PMT — PhotoMultiplier Tube
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p.e. — photo-electron
PS — Plastic Scintillator

Muon veto

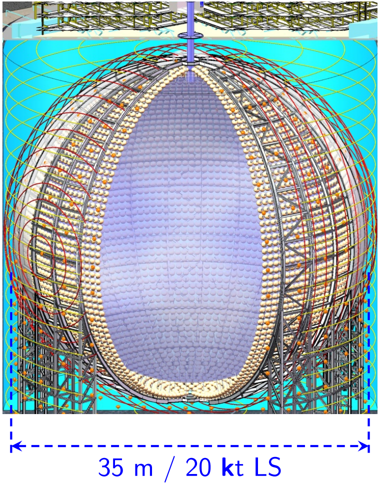
- Top Tracker: 3 layers PS
- Water pool

Light collection

- 18k 20" PMTs
- High QE: 29.6%
- 1665 p.e./MeV
- +26k 3" PMTs

Preliminary

JUNO and TAO detectors

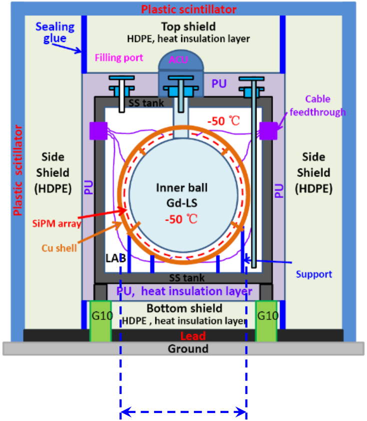


	JUNO
Attention	**Energy resolution** $\sigma \searrow$
Method	**Light collection** $\nearrow$
Scintillator	**LS**
PMTs	**18k 20"** **+26k 3"**
Coverage, %	**78**
Light col. p.e./MeV	**1665**
σ_E at 1 MeV, %	**2.9**
Thermal power, GW	**26.6**
Baseline	**52.5 km**
IBD/day	**47**

Preliminary

Validity: July 2022

JUNO and TAO detectors



1.8 m / 2.8 t GdLS, 1 t in FV

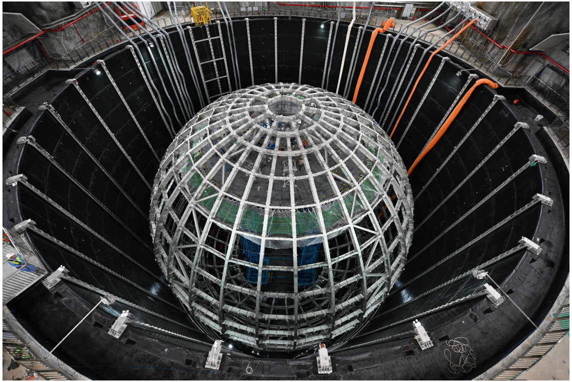
	TAO	JUNO
Attention	**Energy resolution** $\sigma \searrow$	
Method	**Light collection** $\nearrow$ **Dark noise** $\searrow$	
Scintillator	**GdLS @ -50°C**	LS
PMTs	**SiPM 1.5M 5 mm**	18k 20" +26k 3"
Coverage, %	**94**	78
Light col. p.e./MeV	**4500**	1665
σ_E at 1 MeV, %	**2**	2.9
Thermal power, GW	**4.6**	26.6
Baseline	**30 m**	52.5 km
IBD/day	**2000**	47

Preliminary

Validity: July 2022

JUNO construction status

- Stainless Steel Structure: done
- Acrylic sphere: installation in progress



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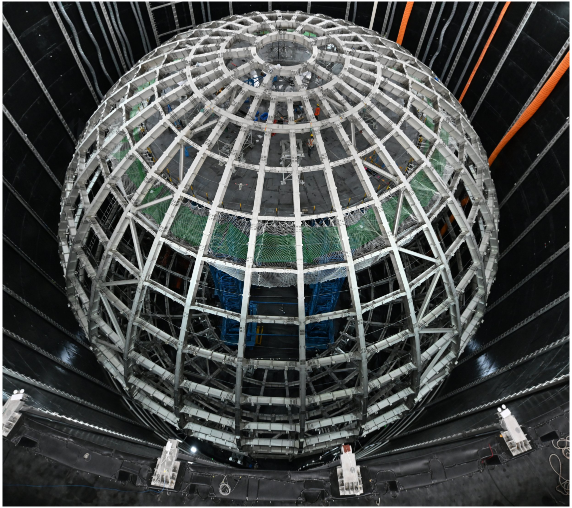
- Photomultiplier Tubes: ready for installation
- Electronics: assembly ongoing



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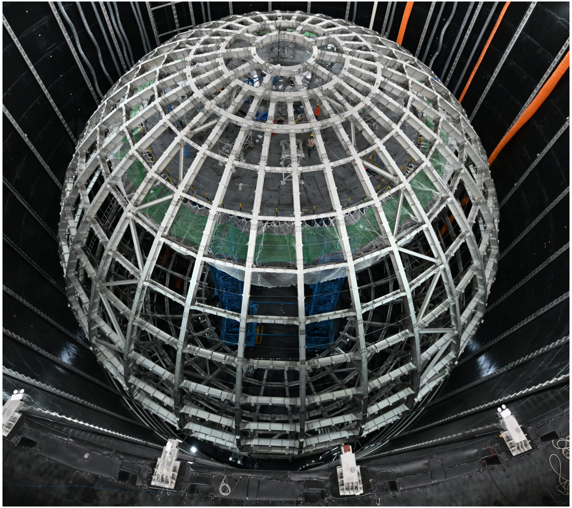

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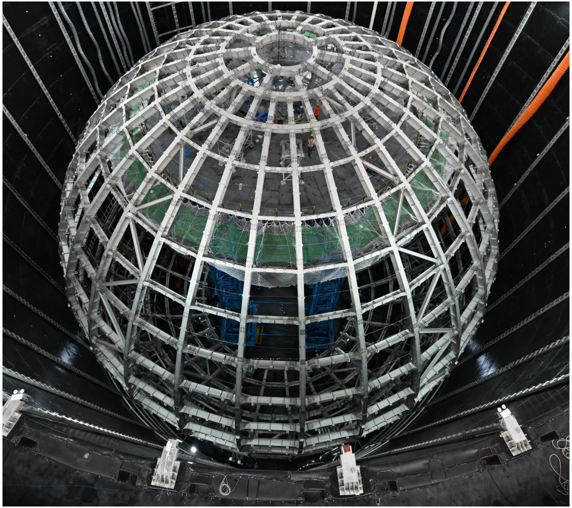

JUNO SCHEDULE

- 2014: Complete conceptual design. International collaboration established.
- 2015: Start civil construction, PMT production line.
- 2016: Bidding of detector components.
- 2017: Start PMT mass production. First electronics prototypes.
- 2018: PMT mass production and testing.
- 2019: Start PMT potting.
- 2020: End of civil construction. PMT testing. Electronics mass production.
- 2021: Underground lab preparation. Electronics mass production.
- 2022: PMT installation. Detector and veto construction. TAO assembly. OSIRIS assembly.
- 2023: **Detector completion!**

We are here

Photomultiplier tubes

		Large PMT,		Small PMT,
Diameter		20-inch		3-inch
Producer		Hamamatsu	NNVT	HZC
Quantity		5000	15'012	25'600
Charge Collection		Dynode	MCP	Dynode
Photon Detection Efficiency, %		28.50	30.10	25.00
Mean Dark Count Rate,	(Bare)	15.3	49.3	0.5
kHz	(Potted)	17.0	31.2	
Transit Time Spread (σ), ns		1.3	7	1.6
Dynamic range for 0–10 MeV		[0, 100], p.e.		[0, 2], p.e.
Coverage, %		75.00		3.00
Reference		[2205.08629]		[2102.11538]

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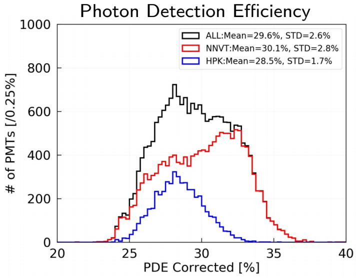
- ✓ All PMTs produced, tested. Waterproof potting applied.
- ✓ 12.6k most efficient NNVT PMTs are selected for the central detector.
  ↪ others will be installed in the Water Cherenkov detector.

Photomultiplier tubes



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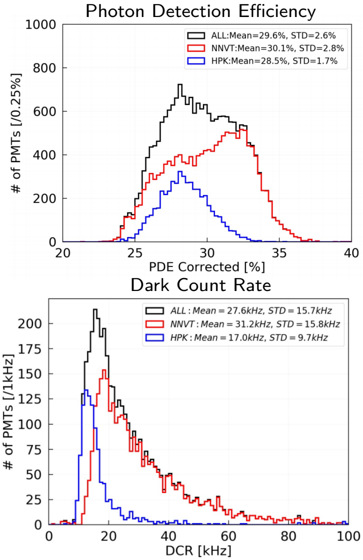

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Liquid scintillator

[2007.00314]

5000 m^3 LAB tank

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Al_2O_3: remove particles

Liquid scintillator

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Distillation:
remove radioactive impurities

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Add 2.5 g/L PPO
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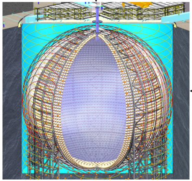
85%

single run

15%

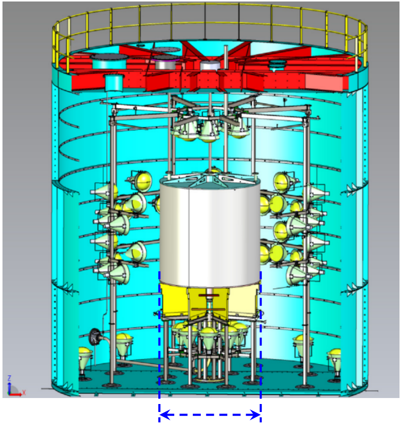
OSIRIS:
LS qualification



JUNO:
no recirculation

OSIRIS: Online Scintillator Internal Radioactivity Investigation System

[2103.16900]



3×3 m

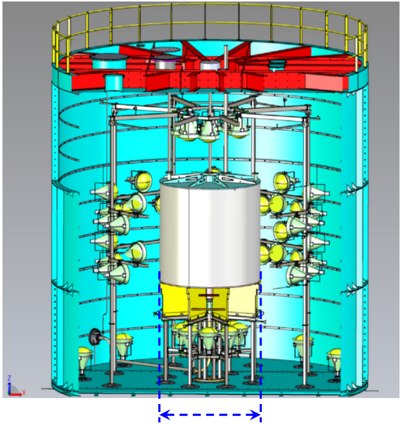
18 t LS, flow-through

OSIRIS: Online Scintillator Internal Radioactivity Investigation System

[2103.16900]

Goals

- Monitor LS during the filling of JUNO — 15% LS
- U/Th via tagging Bi-Po chains
  - Reactor baseline: 10^{-15} g/g — $\sim$ few days
  - Solar baseline: 10^{-17} g/g — $\sim$ 2-3 weeks
- Other isotopes measurement: ^{14}C, ^{210}Po, ^{85}Kr.



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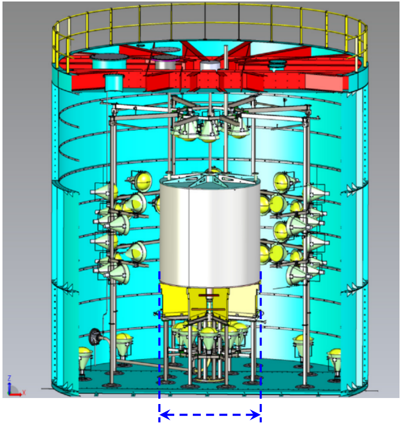
Detector

- 64 20-inch PMTs: — coverage 9%
- $\sigma_E = 6\%$ at 1 MeV: — 280 p.e./MeV



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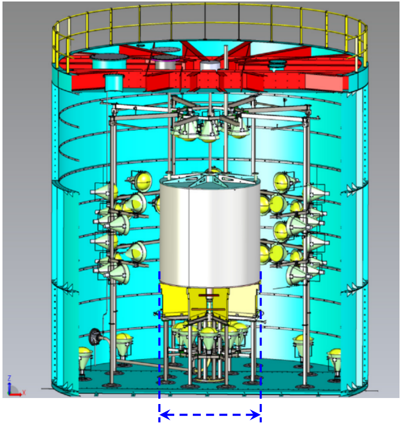
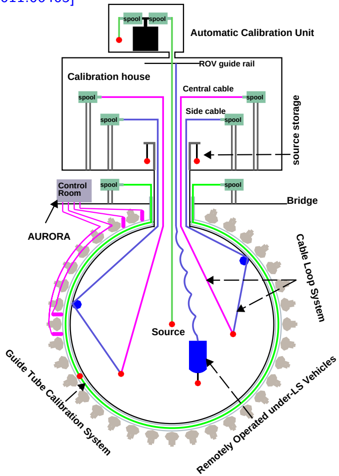
Status

- Expect to start commissioning in July.
- Possible upgrade to Serappis: measurement of solar pp neutrinos with 3.5% precision in 5 years



Calibration

[2011.06405]



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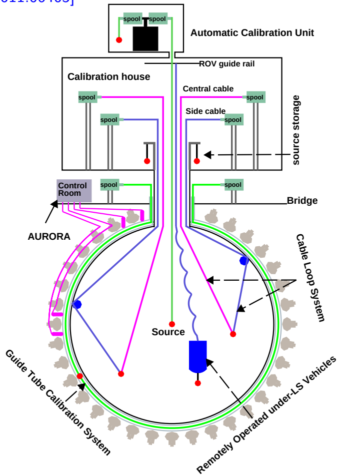

Goals

- Energy scale uncertainty $<1\%$
- Reaching desired $\sigma_E = 3\%$ at 1 MeV

Methods

- Cable Loop System, CLS 2d
- Guide Tube, GT 1d
- Remotely Operated under-LS Vehicle, ROV 3d

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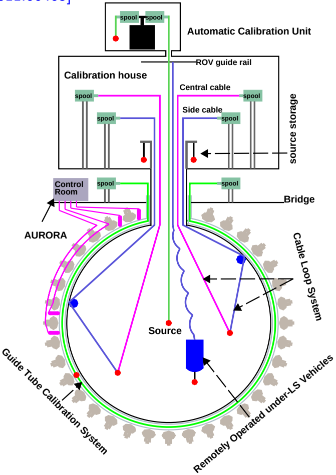

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Redundancy

- Multiple sources
- Multiple coatings:
  $\hookrightarrow$ shadowing effect $<0.15\%$
- Cross calibration with small PMTs

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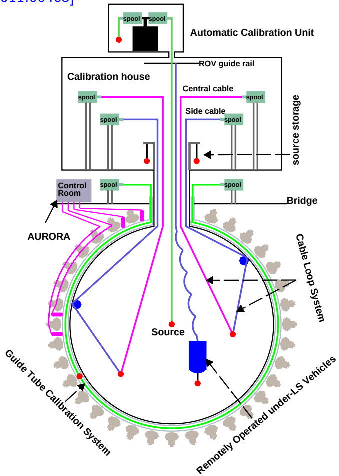

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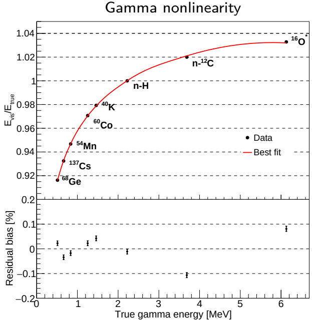
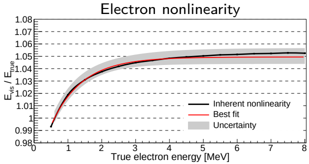


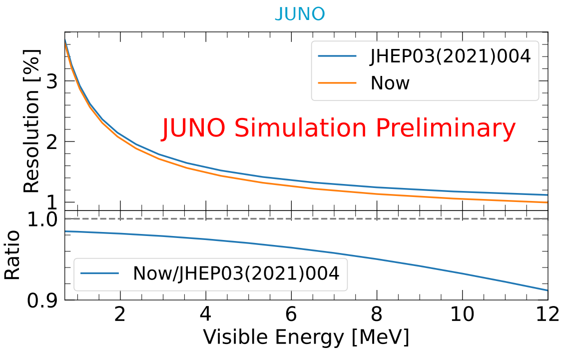


Energy resolution

Parametrization (illustrative)

$$\frac{\sigma}{E_{\text{vis}}} = \sqrt{\frac{a^2}{E_{\text{vis}}} + \frac{b^2}{1} + \frac{c^2}{E_{\text{vis}}^2}},$$

- Parameter a — photon statistics
- Parameter b:
  - Scintillation quenching
  - Contribution of Cherenkov light
  - Non-uniformity and reconstruction
- Parameter c:
  - γs related to annihilation
  - PMT Dark Noise



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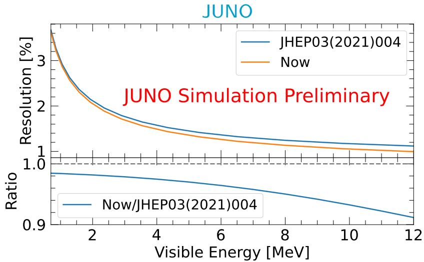
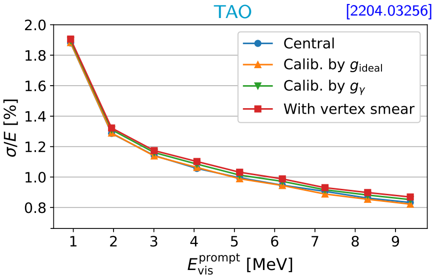
Parametrization (illustrative)

$$\frac{\sigma}{E_{vis}} = \sqrt{\frac{a^2}{E_{vis}} + \frac{b^2}{1} + \frac{c^2}{E_{vis}^2}},$$

Estimation

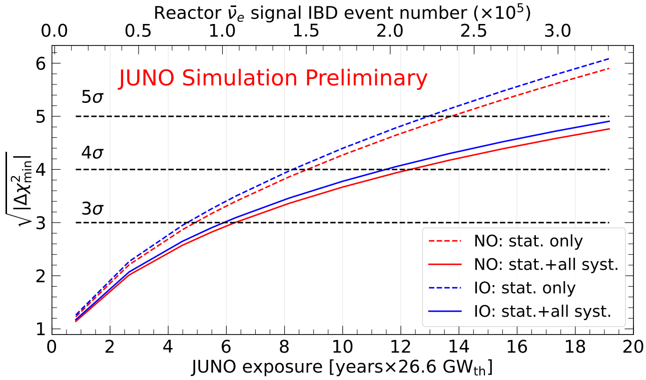
- JUNO resolution: 2.9% at 1 MeV
- TAO: 1.9% at 1 MeV
- Goal: combined analysis of JUNO+TAO data





Physics

Sensitivity to Neutrino Mass Ordering



- ✓ JUNO+TAO, 6 years×26.6 GW exposure: $\sim 3\sigma$
- ✓ +1% external constrain on Δm^2_{32}: $> 4\sigma$
- ✓ combined with accelerator/atmospheric experiment: $> 5\sigma$
  $\hookrightarrow$ sensitivity boost due to tension for wrong ordering

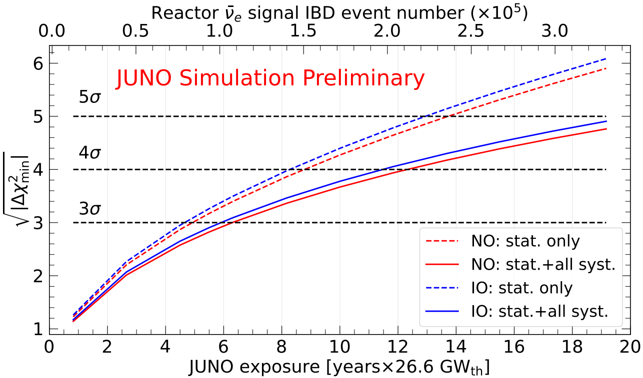
Signal and background

- Inverse beta decay: $\overline{\nu}_e + p \to e^+ + n$
  $\hookrightarrow$ double coincidence
- Signal: 47 $\overline{\nu}_e$/day, backgrounds: 9%

Extra

[2008.11280], JUNO+IceCube [1911.06745]

Sensitivity to Neutrino Mass Ordering



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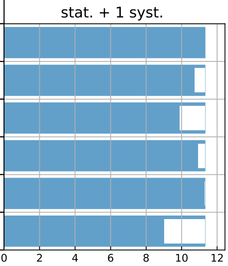
  ↪ sensitivity boost due to tension for wrong ordering

Impact of systematics:

	$\Delta\chi^2_{min}$
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0

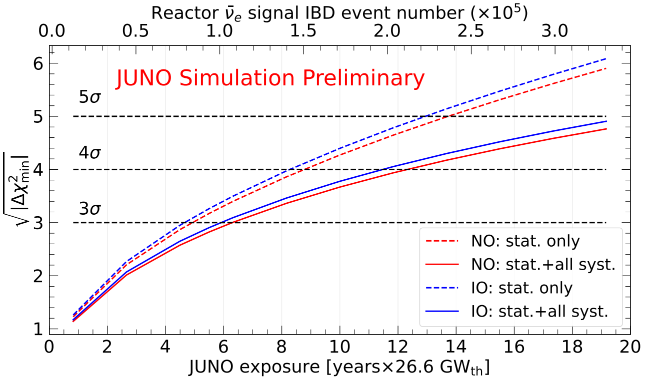


JUNO Simulation Preliminary

Extra

[2008.11280], JUNO+IceCube [1911.06745]

Sensitivity to Neutrino Mass Ordering



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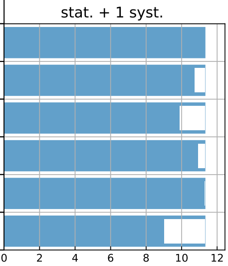

JUNO Simulation Preliminary

- Paper under preparation.
- Combination of reactor and atmospheric channels within JUNO is investigated.

Extra [2008.11280], JUNO+IceCube [1911.06745]

JUNO and neutrino oscillation parameters

[2204.13249]

- Percent precision for $\Delta m^2_{21}/\Delta m^2_{31}$: 100 days
- Few permille level for $\Delta m^2_{21}/\Delta m^2_{31}/\sin^2 2\theta_{12}$: 6 years

✓ Order of magnitude improvement over existing constraints.

JUNO AND NEUTRINO OSCILLATION PARAMETERS

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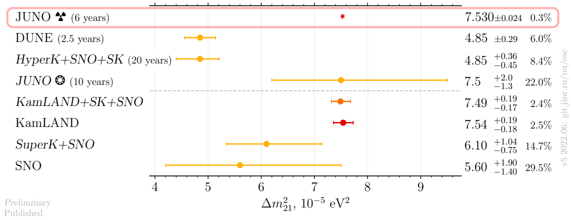

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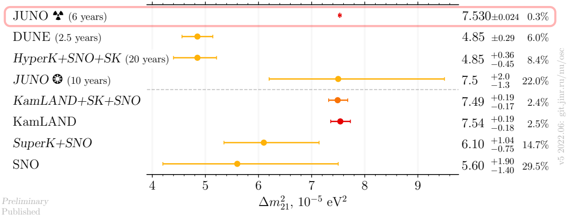

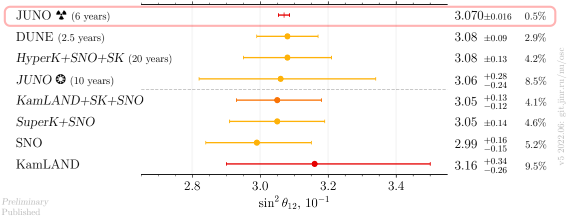

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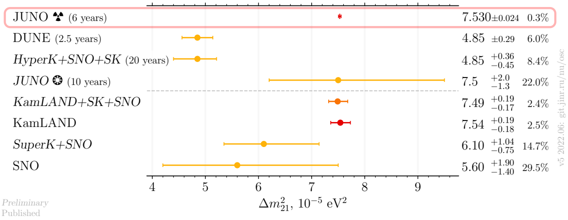
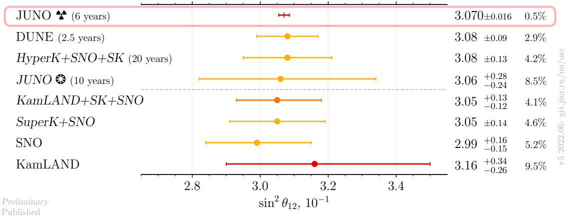
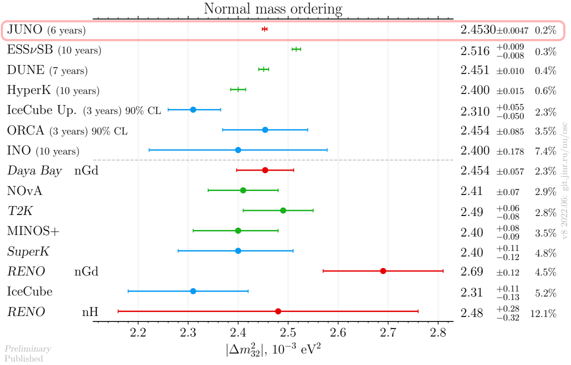
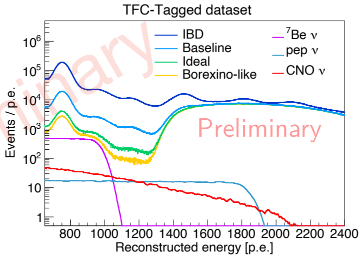






✓ Almost no correlation between measured parameters.

Intermediate energy solar neutrinos: ^{7}Be, pep, CNO



Detection

- Signal: ν_e elastic scattering off e^-
- Expected rate:
  - ^{7}Be ~ 130 ES/day
  - pep ~ 17 ES/day
  - CNO ~ 16 ES/day
- Limiting factors: LS purity, cosmic ray related background
- Baseline ^{238}U/^{232}Th contamination: 10^{-16} g/g

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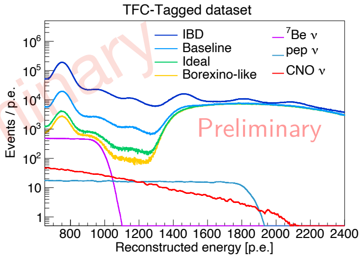

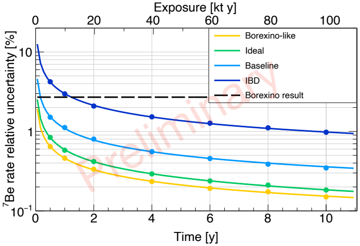

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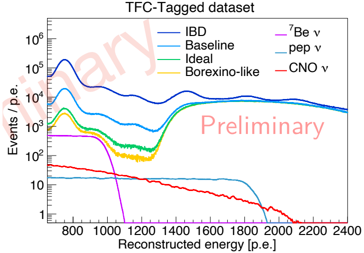

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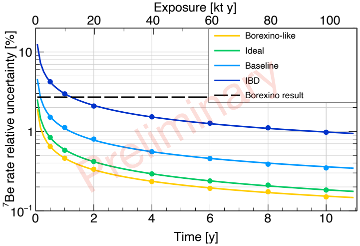

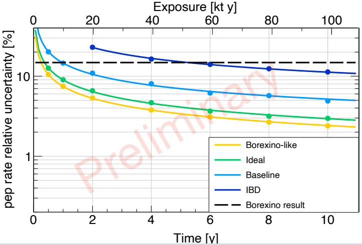

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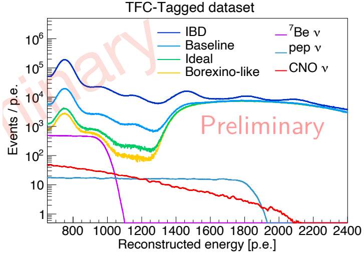

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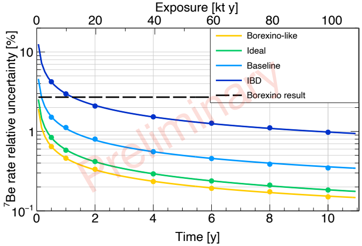
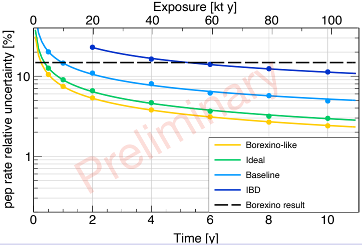
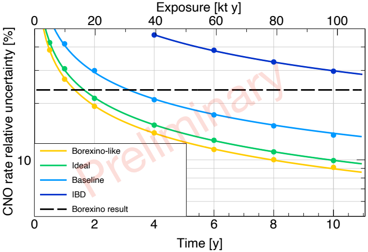
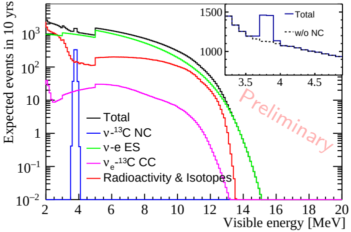
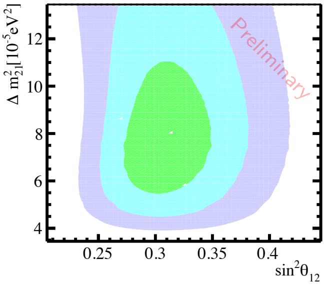






Oscillation physics with solar ^{8}B ν_e



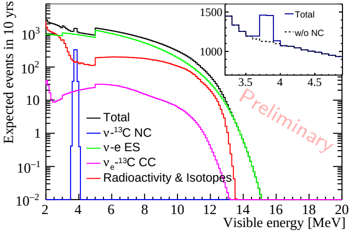


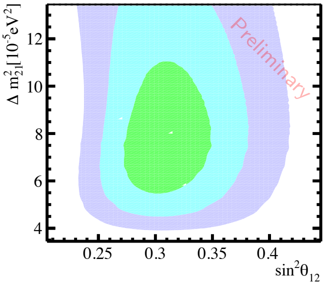
Oscillations

- ^{8}B ν_e are sensitive to the matter effect: Day/Night asymmetry

Extra

Oscillation physics with solar ^{8}B ν_e





Oscillations

- ^{8}B ν_e are sensitive to the matter effect: Day/Night asymmetry

Detection

- Elastic scattering off e^- — ~ 16 ν_e/day
- Neutral current on ^{13}C — ~ 73.8 ν_e/year
- Charged current on ^{13}C — ~ 64.7 ν_e/year
- Limiting factors: LS purity, cosmic ray related background
- Baseline $^{238}U/^{232}Th$ contamination: 10^{-16} g/g

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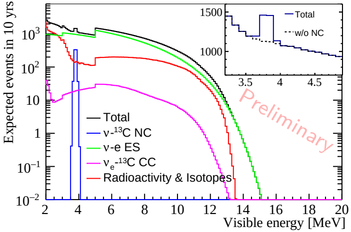

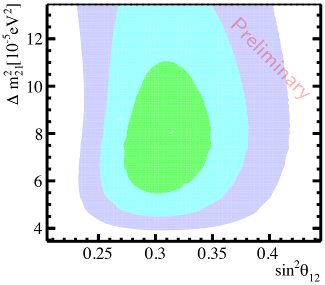

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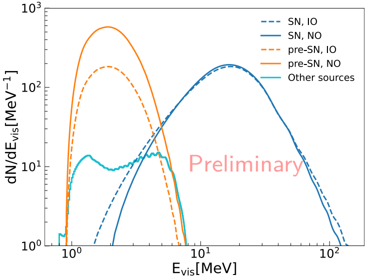
- Charged current on ^{13}C $\sim 64.7\ \nu_e/\text{year}$
- Limiting factors: LS purity, cosmic ray related background
- Baseline ^{238}U/^{232}Th contamination: 10^{-16} g/g

Data and analysis

- Events binned vs zenith angle $\cos\theta_z$ and ν_e energy
- 5%, $\sim$ 9% and $\sim$ 22% sensitivity to ^{8}B flux, $\sin^2 2\theta_{12}$ and Δm^2_{21}.

Extra

Core collapse SuperNova explosion

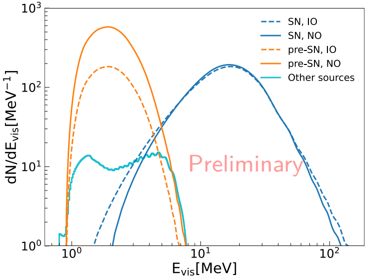


- Expect a few SuperNova explosions per century
- $\sim 10^4$ events in 10 s

On the plot

- SN @10 kpc
- pre-SN @0.2 kpc
- Reactor IBD background

Core collapse SuperNova explosion



On the plot

- SN @10 kpc
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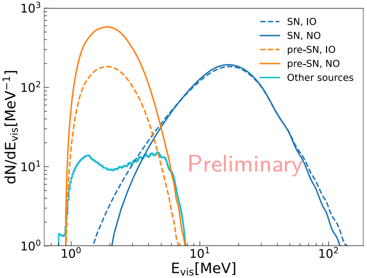
- Reactor IBD background

- Expect a few SuperNova explosions per century
- $\sim 10^4$ events in 10 s

Detection

- Dedicated trigger: 100 keV threshold
- Expected statistics:
  - 5000 IBD
  - 2000 ES off proton
  - 300 ES off electron
  - 300 $\nu\,^{12}\mathrm{C}$ NC
  - 200 $\nu\,^{12}\mathrm{C}$ CC
  - Negligible background

Core collapse SuperNova explosion



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- $\sim 10^4$ events in 10 s

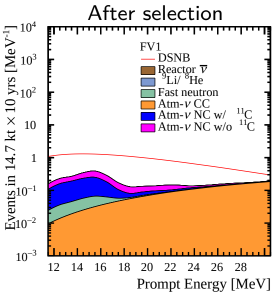
Detection

- Dedicated trigger: 100 keV threshold

Goals

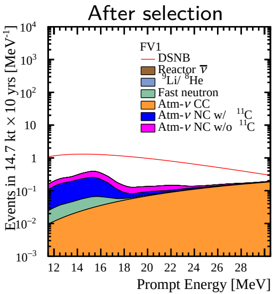
- Measure: flavor content, time evolution, flux, energy spectrum
- Study: stellar parameters, SN physics, late stage stellar evolution
- Constrain $m_\nu < (0.83 \pm 0.24)$ eV @90% CL @10 kpc [1412.7418]
- Multi-messenger trigger

Diffuse SuperNova neutrino background



[2205.08830]

Diffuse SuperNova neutrino background



DSNB

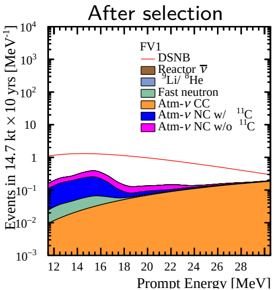
- Integrated signal of all the SuperNova explosions in the universe
- Not yet observed

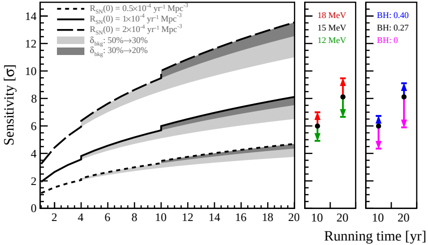
Detection

- Signal: inverse beta decay
- Expected rate: 2–4 $\overline{\nu}_e$/year
- Energies: E>12 MeV, above reactor IBD

[2205.08830]

Diffuse SuperNova neutrino background





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- Energies: E>12 MeV, above reactor IBD

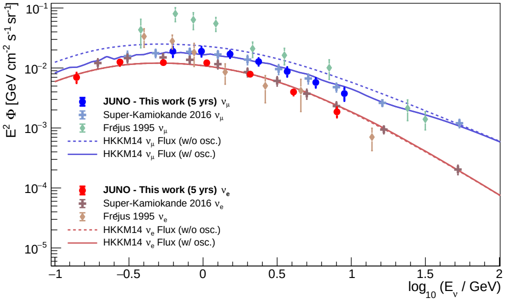
Discovery potential

- 5σ in 10 years
- 3σ in 3 years

[2205.08830]

Oscillation physics with atmospheric $\nu_\mu/\overline{\nu}_\mu$

[2103.09908][2104.02565]



Oscillations

- Matter effect: θ_z dependence

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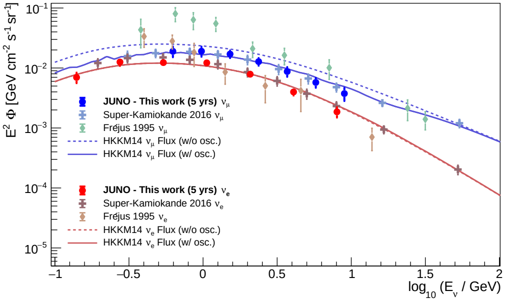


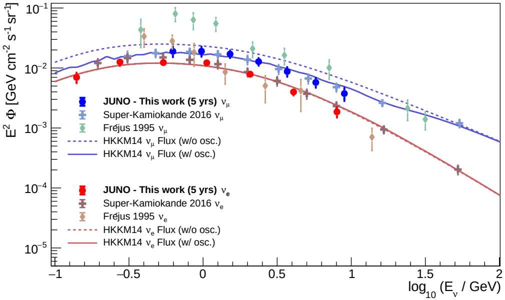
Oscillations

- Matter effect: θ_z dependence

Detection

- Primary channel: $\nu_\mu/\overline{\nu}_\mu$ CC
- Expected statistics, 200 kton-years: 1233/1035 events
- Limiting factors: angular resolution / PID purity

Oscillation physics with atmospheric $\nu_\mu/\overline{\nu}_\mu$



[2103.09908][2104.02565]

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- Matter effect: θ_z dependence

Detection

- Primary channel: $\nu_\mu/\overline{\nu}_\mu$ CC
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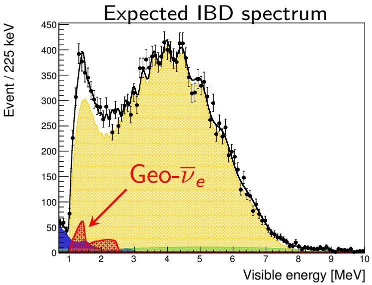
- Limiting factors: angular resolution / PID purity

Data and analysis

- Events binned vs zenith angle $\cos\theta_z$ (fine) and ν energy (coarse)
- $\sim 1\sigma$ sensitivity to ordering in 10 years
- Potential: combination with reactor analysis

Geo-neutrinos

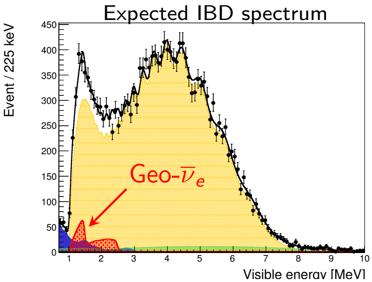


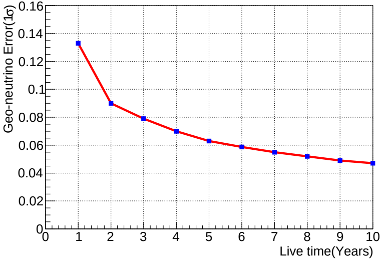
Source: $^{238}\mathrm{U}/^{232}\mathrm{Th}$ from Earth's crust and mantle

- $^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6e^- + 6\overline{\nu}_e$
- $^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4e^- + 4\overline{\nu}_e$
- there is also $^{40}\mathrm{K}$, which is below IBD threshold of 1.8 MeV
- 500 km of crust around JUNO contributes > 50% of signal
- Local geological studies: [1901.01945] [1903.11871]

[2104.02565]

Geo-neutrinos





Source: $^{238}\mathrm{U}/^{232}\mathrm{Th}$ from Earth's crust and mantle

- 500 km of crust around JUNO contributes $>50\%$ of signal
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Data

- KamLAND: 175 $\overline{\nu}_e$ in 8 years [2205.14934]
- Borexino: 53 $\overline{\nu}_e$ in 9 years [1909.02257]
- JUNO: 400 $\overline{\nu}_e$/year (40 TNU/year)

[2104.02565]

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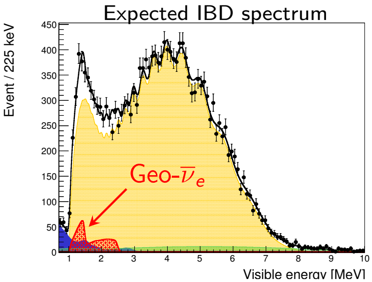

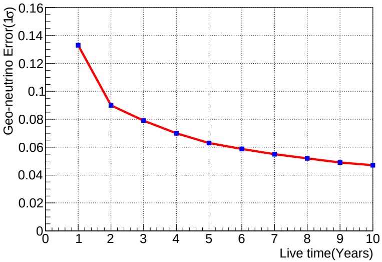

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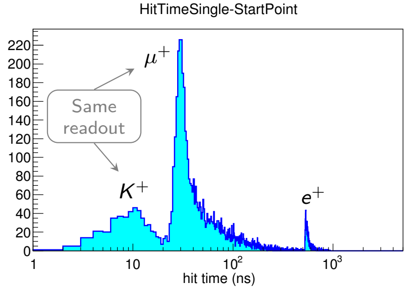
Goals

- 5% geo-$\overline{\nu}_e$ measurement in 10 years
- Measure: Th/U mass ratio
- Study: radiogenic heat production

[2104.02565]

Proton decay

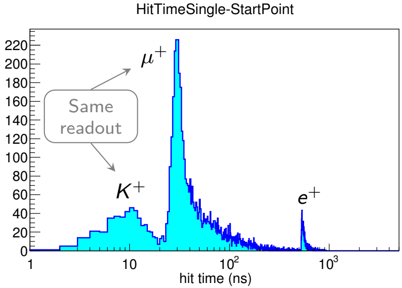


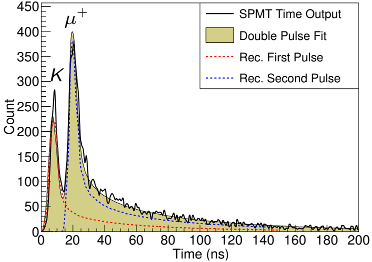
Signature

- $p \to \nu + K^+ \to \nu_\mu + \mu^+ \to \overline{\nu}_\mu + \nu_e + e^+$ GUT
- $p \to \nu + \pi^+ \to \nu_\mu + \mu^+ \to \overline{\nu}_\mu + \nu_e + e^+$ SUSY
- $p \to \mu^+\mu^+\mu^-$ under investigation

[2104.02565]

Proton decay





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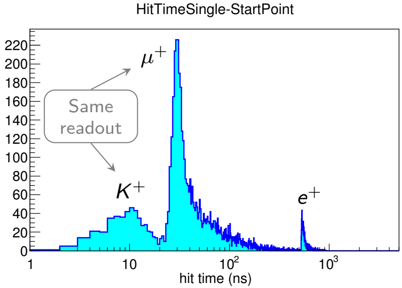
- $p \to \mu^+\mu^+\mu^-$ under investigation

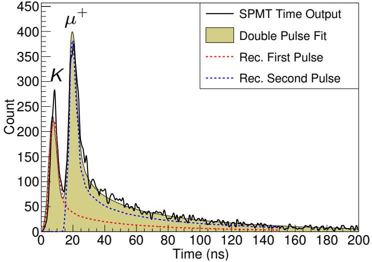
Data

- Signal: three-fold coincidence
- Backgrounds: atmospheric neutrinos, cosmic muons

[2104.02565]

Proton decay





Signature

- $p \to \nu + K^+ \to \nu_\mu + \mu^+ \to \overline{\nu}_\mu + \nu_e + e^+$ GUT
- $p \to \nu + \pi^+ \to \nu_\mu + \mu^+ \to \overline{\nu}_\mu + \nu_e + e^+$ SUSY
- $p \to \mu^+\mu^+\mu^-$ under investigation

Data

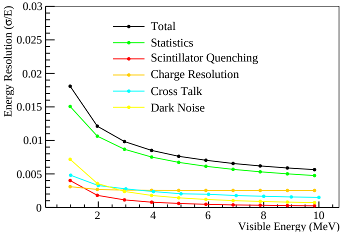
- Signal: three-fold coincidence
- Backgrounds: atmospheric neutrinos, cosmic muons

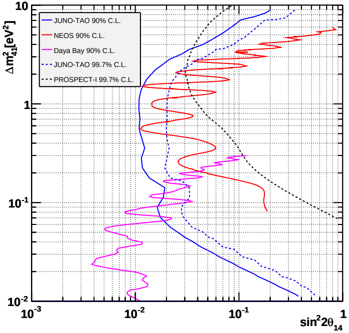
Sensitivity

- 8.34×10^{33} years 90% CL in 10 years

[2104.02565]

Sterile neutrino search with TAO





Primary goal

TAO CDR [2005.08745]

- Reference reactor $\overline{\nu}_e$ spectrum with $\sigma = 2\%$ at 1 MeV.

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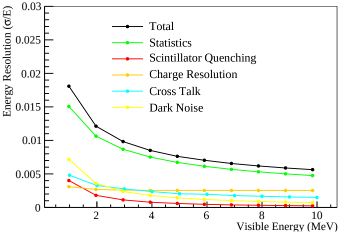

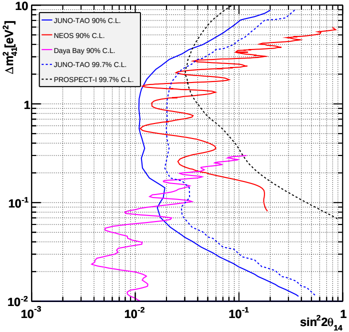

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- Relevant range: $0.5\,\text{eV}^2 \lesssim \Delta m^2_{41} \lesssim 5\,\text{eV}^2$
- ∼large L counterbalanced with high energy resolution

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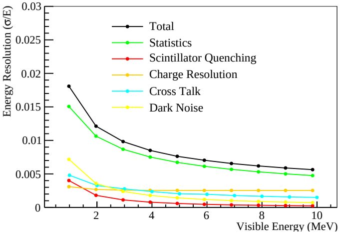

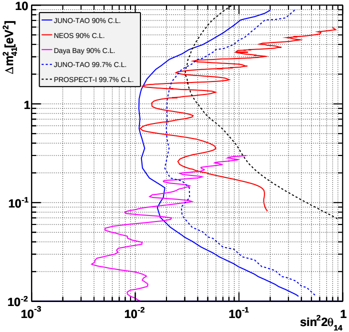

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- Inverse beta decay with nGd tag
- Expected rate: $\sim$2000 $\overline{\nu}_e$/day

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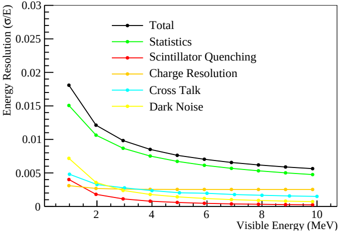

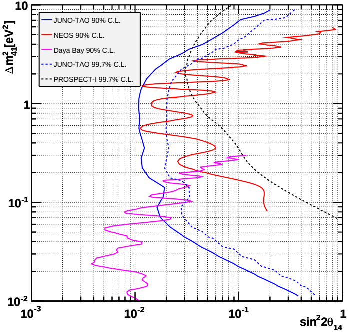

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Detection

- Inverse beta decay with nGd tag
- Expected rate: $\sim 2000\ \overline{\nu}_e/\text{day}$

Data and analysis

- Events, finely binned vs energy
- Simultaneous fit: TAO's 4 virtual subdetectors
- Probe Neutrino-4 best-fit: $\Delta m^2_{41}{=}7.25\,\text{eV}^2$, $\sin^2 2\theta_{14}{=}0.26$

JUNO SUMMARY

JUNO — a liquid scintillator detector with an unprecedented size and energy resolution.

Rich physics programme

- Reactor $\overline{\nu}_e$ at short and large baseline.
- Solar neutrinos from $^7\mathrm{Be}$, pep, CNO and $^8\mathrm{B}$. Possibly, *pp*.
- Atmospheric $\nu_\mu/\overline{\nu}_\mu$ and $\nu_e/\overline{\nu}_e$.
- SuperNova neutrinos and Diffuse SuperNova Neutrino Background.
- Geo-neutrinos.
- Proton decay.
- Other topics:
  - Search for dark matter.
  - Study PMNS matrix unitarity.
  - Probe Lorentz invariance.
  - Search for physics beyond standard model and exotic particles.
  - And more...

Detector completion in 2023!

Thank you for your attention!

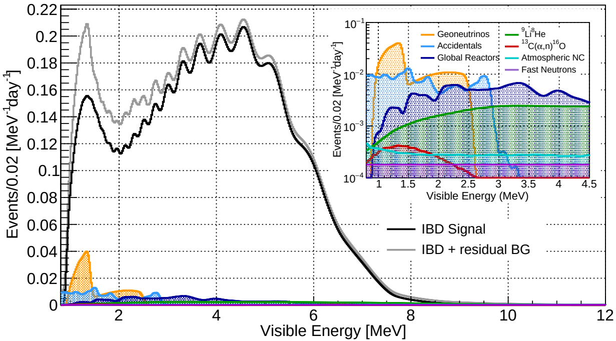
Spare slides:

JUNO COLLABORATION

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

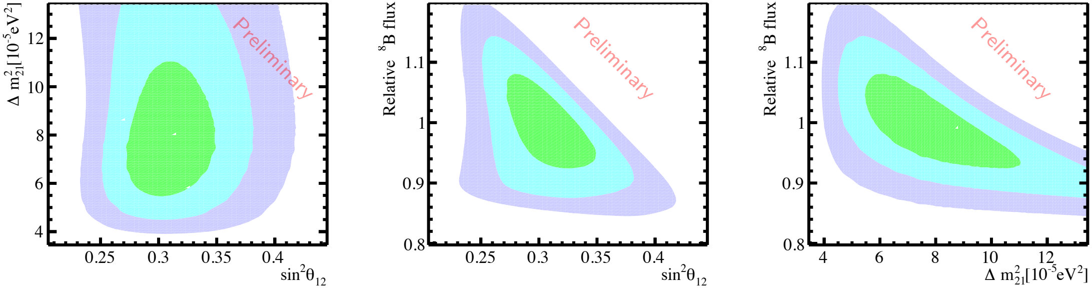
76 institutions from 18 countries

Sensitivity to Neutrino Mass Ordering



Preliminary!	Rate	Uncertainty, %	
Events	/day	rate	shape
Reactor IBD	47		
Geo-$\overline{\nu}_e$	1.2	30	5
Accidentals	0.8	1	negligible
Fast neutrons	0.1	100	20
^{8}He/^{9}Li	0.8	20	10
^{13}C$(\alpha, n)^{16}$O	0.05	50	50
Global reactors	1.0	2	5
Atmospheric $\overline{\nu}_e$	0.16	50	50

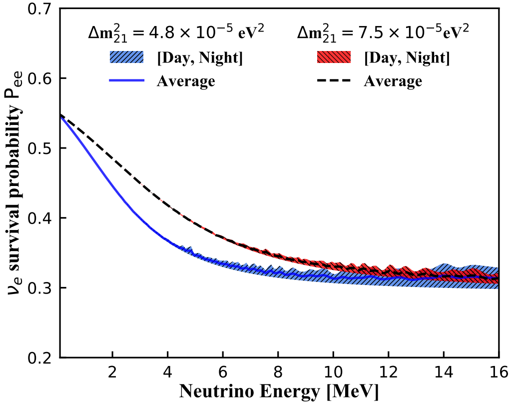
SOLAR ^{8}B ν_e



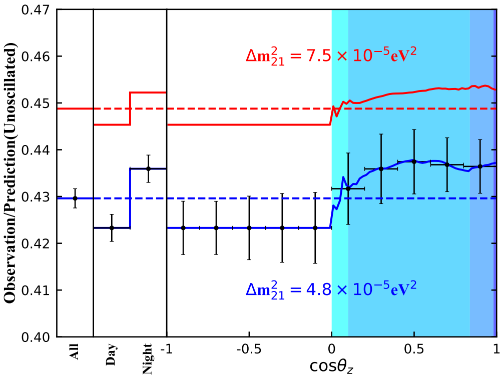
- No external constraints on the ^{8}B flux.

Day/Night effect with solar ^{8}B ν_e

Expected ν_e spectrum from ^{8}B



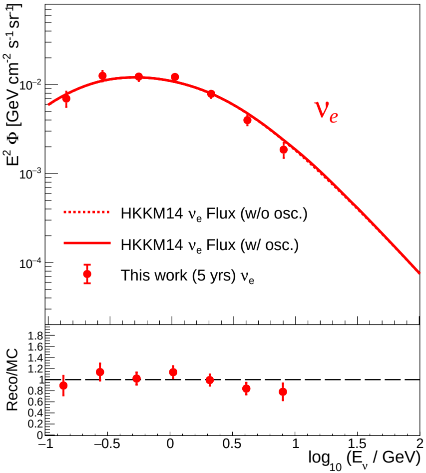
Day/Night asymmetry



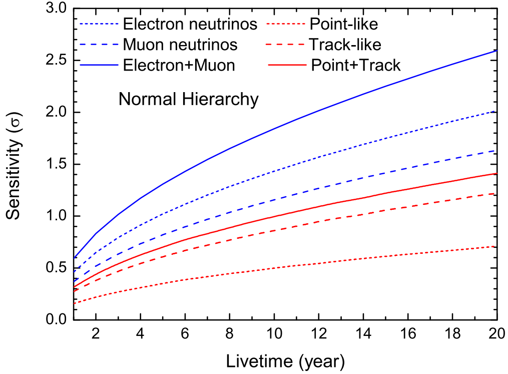
Solar ^{8}B [2006.11760], CPC45

Atmospheric neutrino oscillations

Atmospheric ν_e spectrum



NMO sensitivity vs time



Atmospheric ν_μ/ν_e spectra [2103.09908]

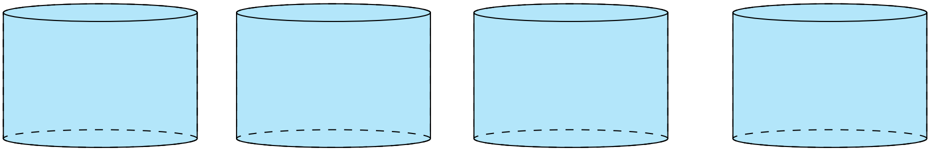
Background events

Neutrino background sources

- Nearby reactors with $L > 52.5$ km: Daya Bay, Ling Ao — treated as signal
- World reactors
- Geo-$\overline{\nu}_e$
- Atmospheric-$\overline{\nu}_e$

Non-neutrino backgrounds sources

Accidentals | β-n isotopes | Fast neutrons | $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$



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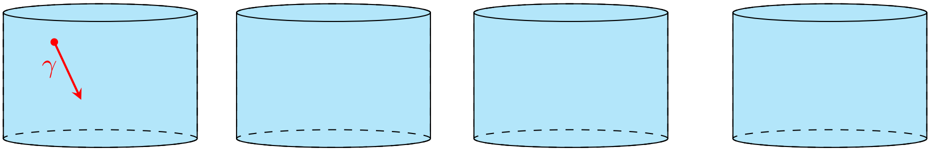

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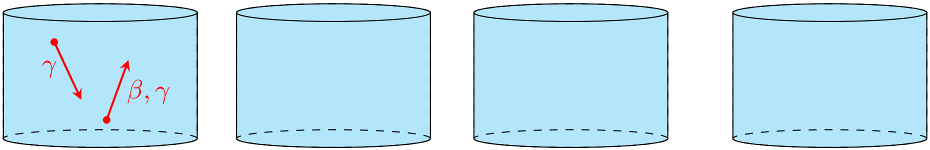

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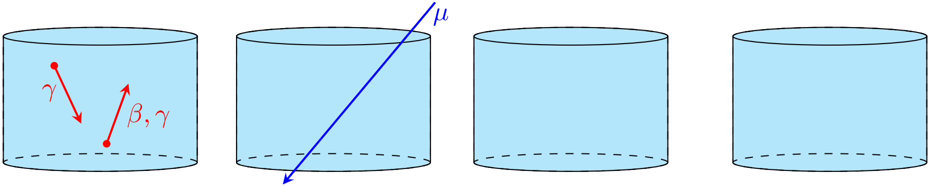

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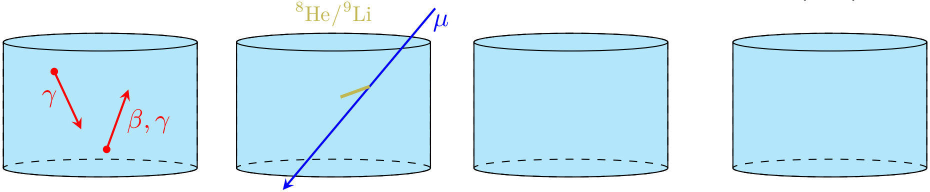

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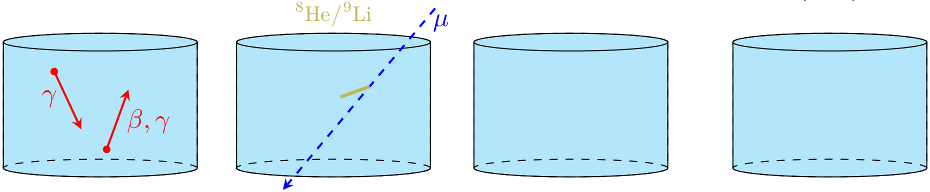

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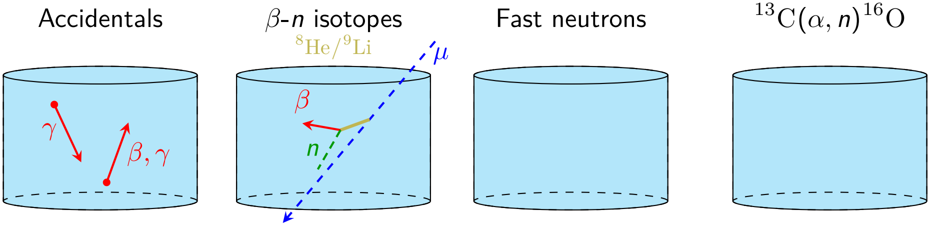

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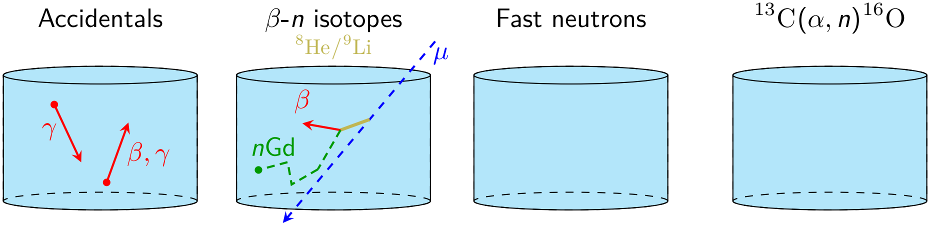

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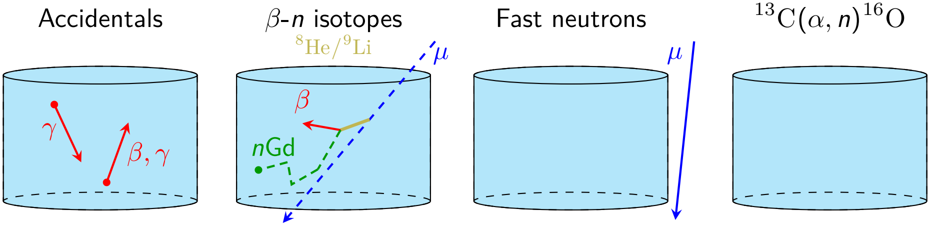

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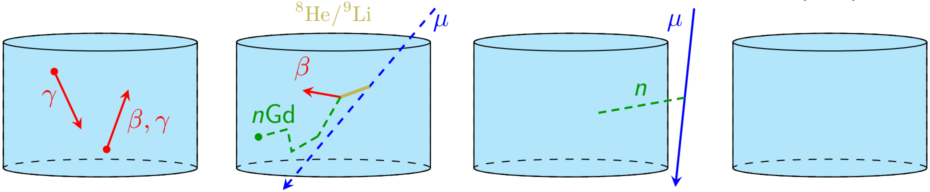

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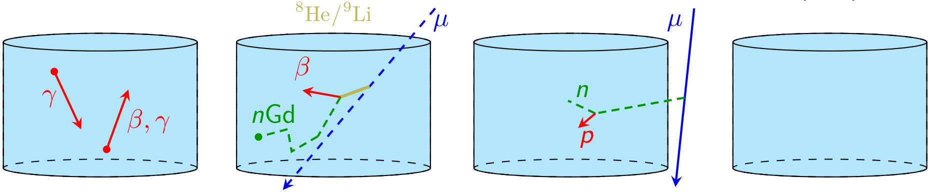

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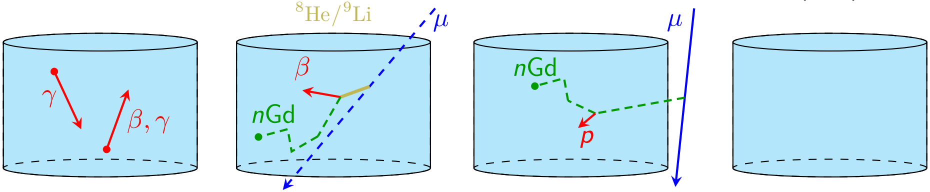

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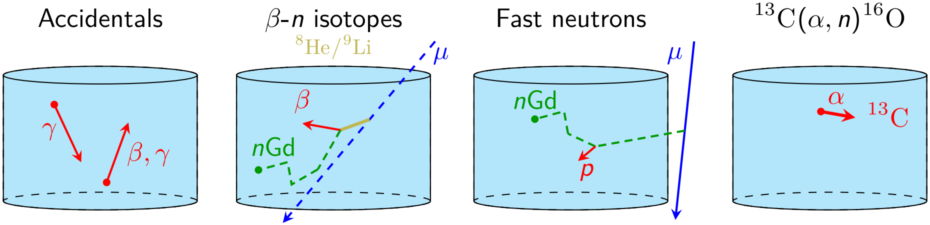

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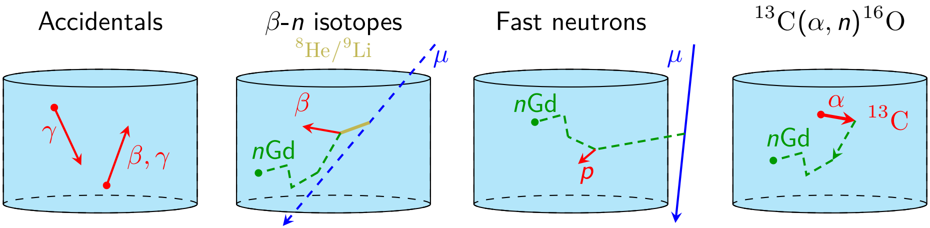
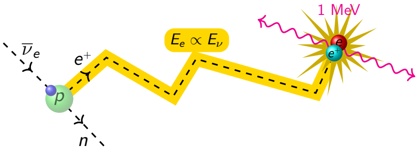


Inverse beta decay (IBD) and selection criteria



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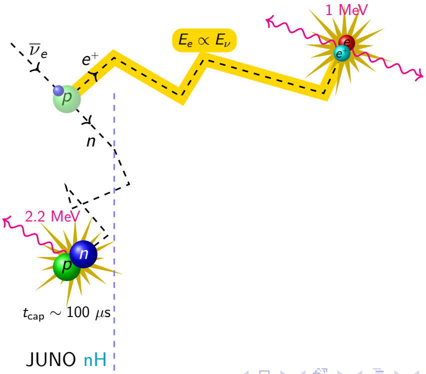

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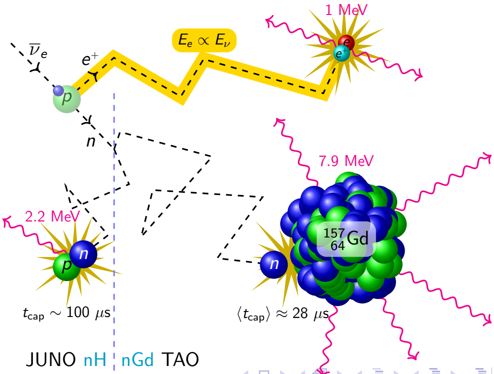

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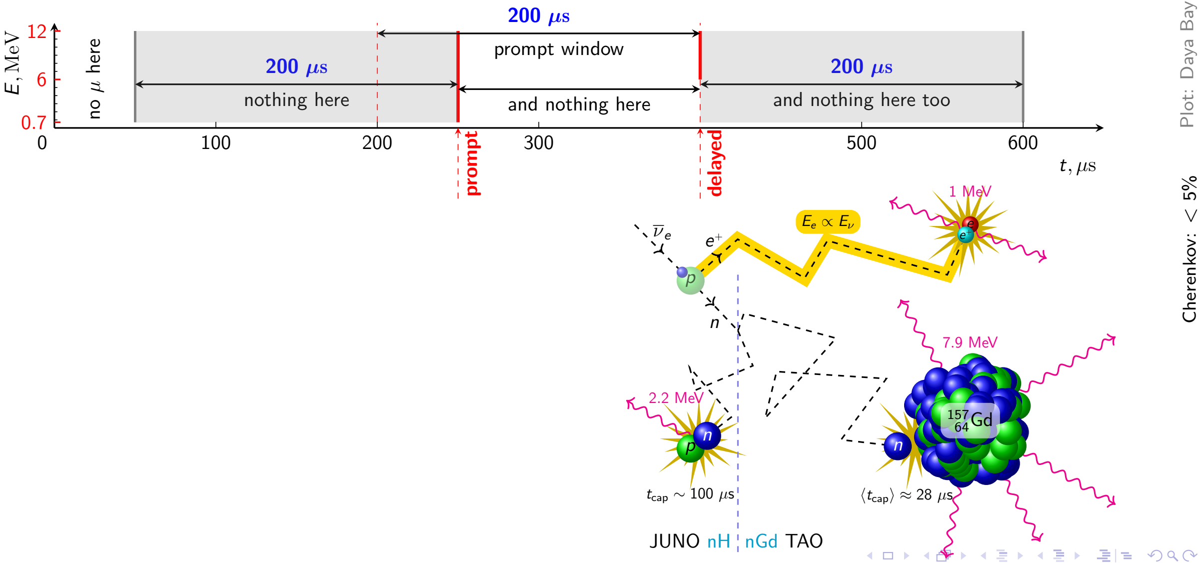

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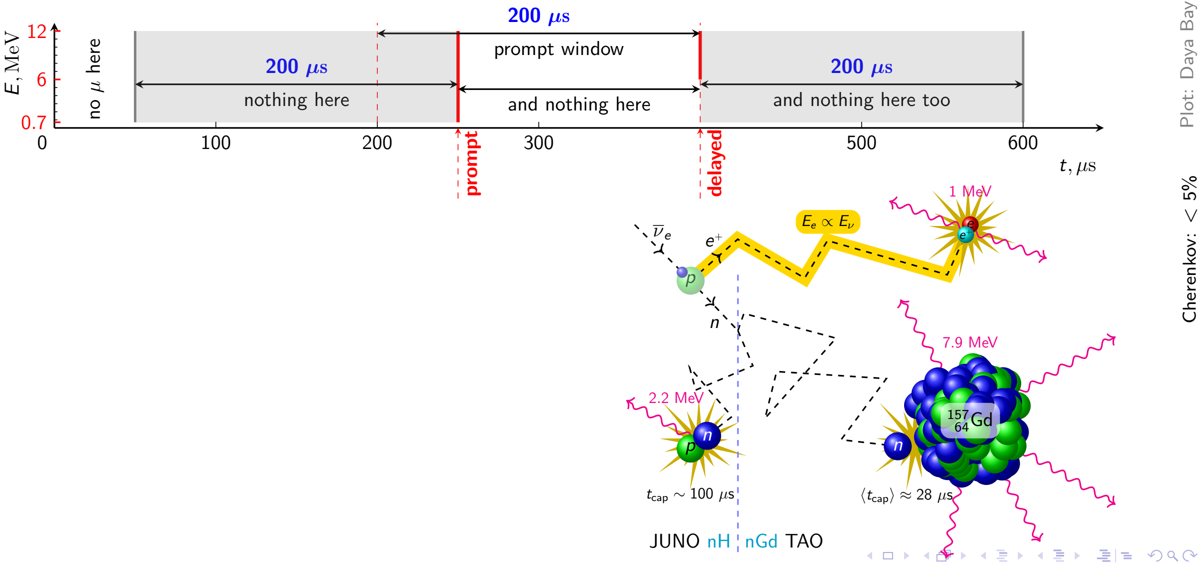

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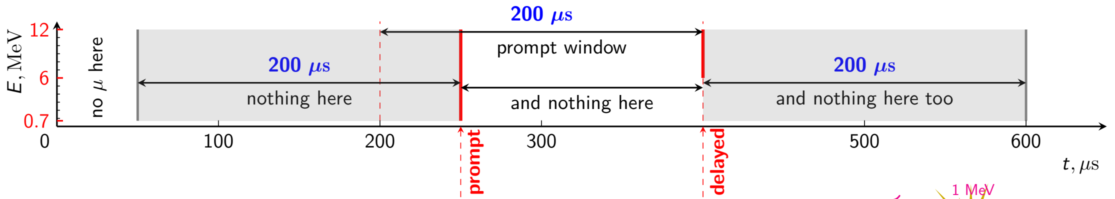
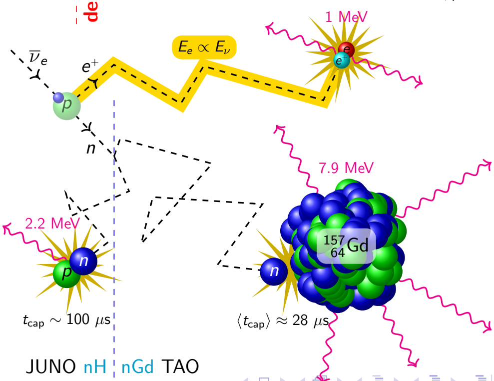


Plot: Daya Bay

Cut	JUNO nH
Fiducial volume	$R < 17$ m
Time	1 ms
Prompt E, MeV	
Delayed E, MeV	1.9 – 2.5
Distance, m	1.5
Muon veto	TBD
Multiplicity veto, us	TBD



Cherenkov: < 5%