Jiangmen Underground Neutrino Observatory: Status and physics prospects

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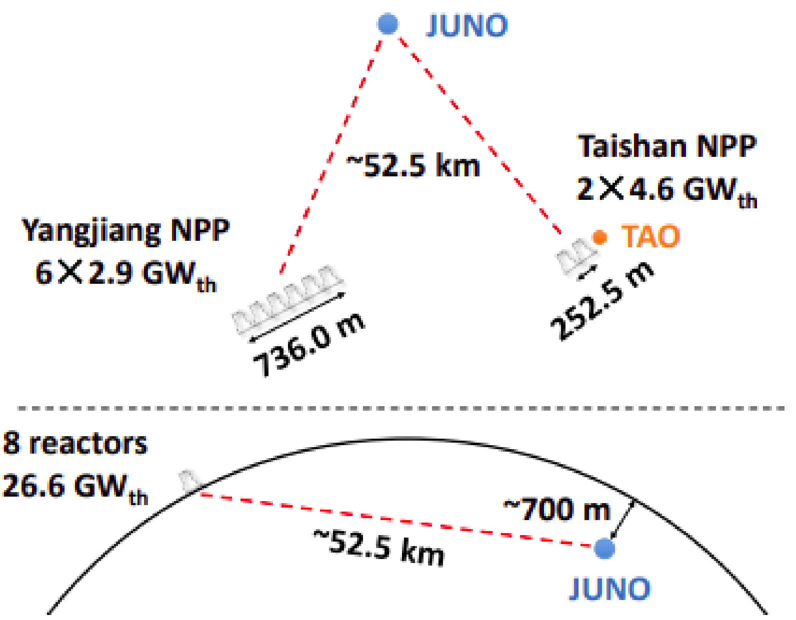
On behalf of the **JUNO Collaboration**

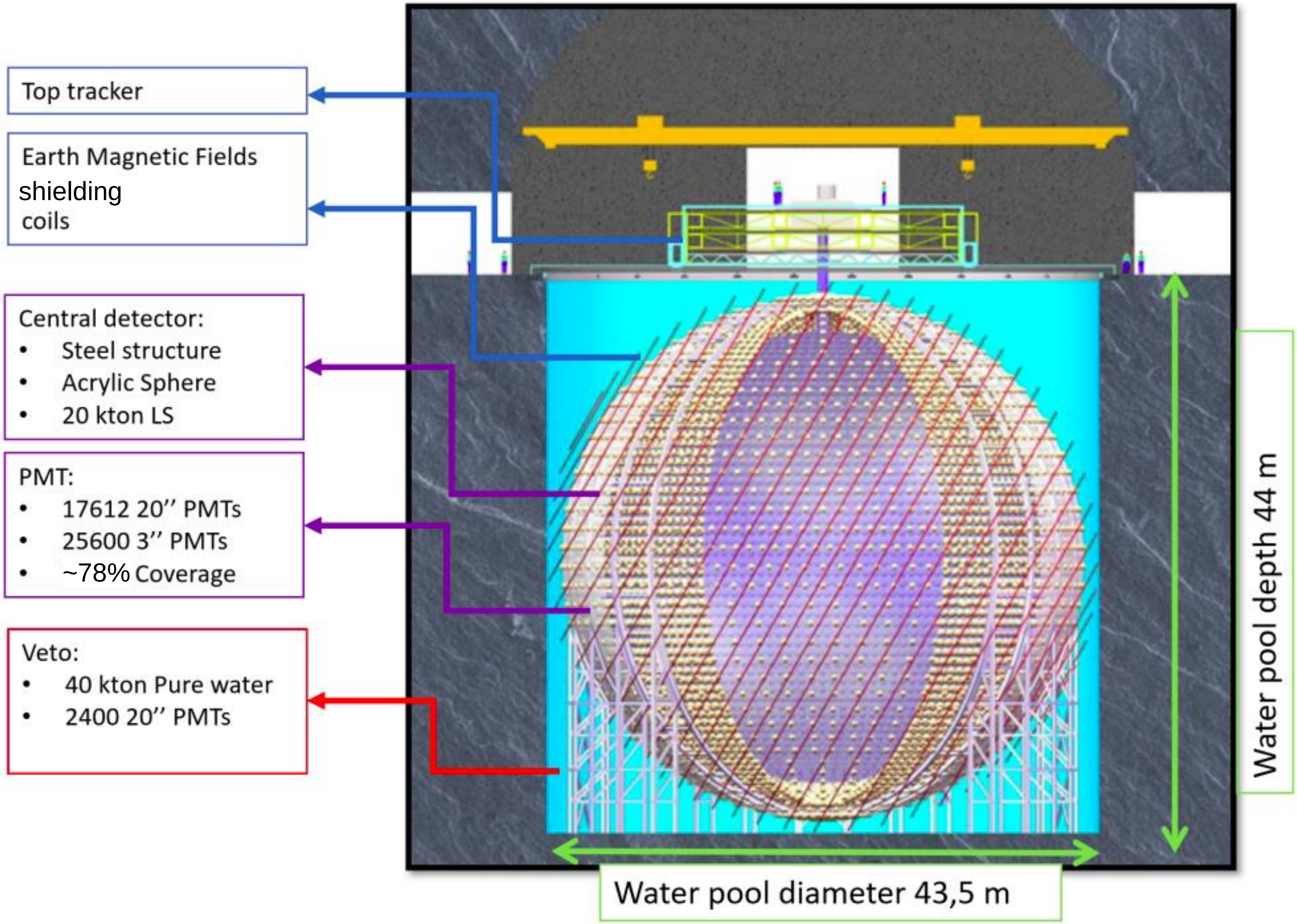
The JUNO main detector

- JUNO (Jiangmen Underground Neutrino Observatory) is a medium baseline (53 km) reactor neutrino experiment, located 650 m overburden.
- JUNO measures the neutrino flux from 8 reactor cores dispatched in two nuclear power plants (combined thermal power of 26.6 GW).

Why is JUNO a particular experiment?
→ Largest and most precise ever built liquid scintillator (20 kton LS) detector with impressive PMT coverage (78%) and 3% at 1 MeV energy resolution



The JUNO detector



JUNO - TAO

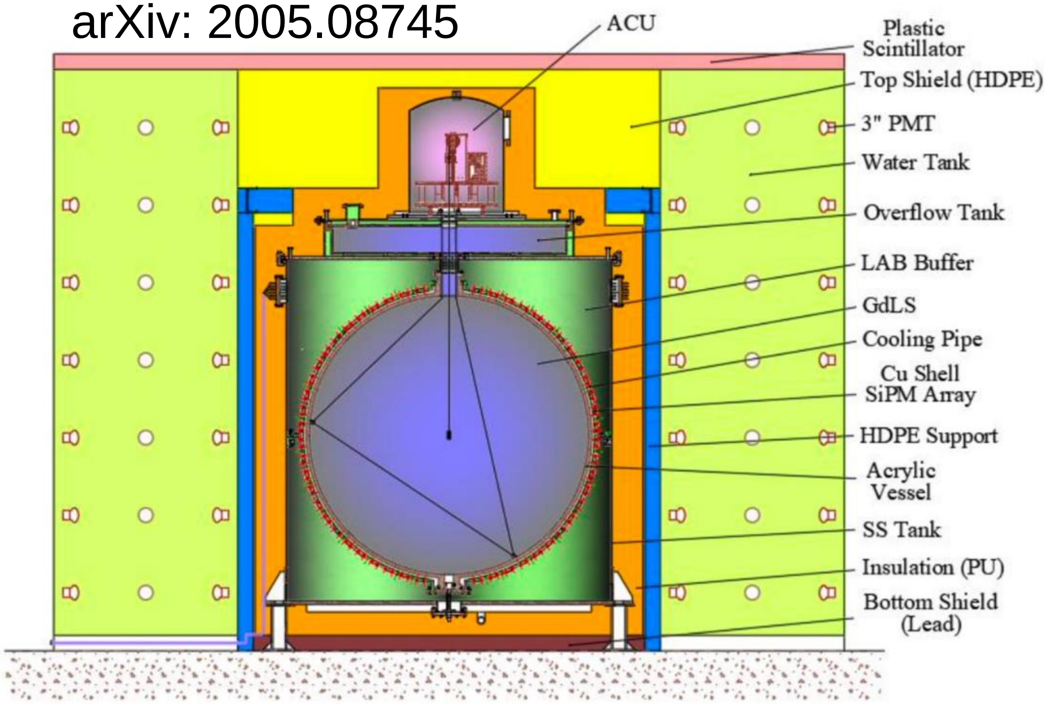
TAO (Taishan Anti-neutrino Observatory), satellite detector of JUNO:

- 2.8 kton of Gd-dopped LS
- Located ~30 m from one nuclear core
- Energy resolution: < 2%/√E[MeV]
- 94% coverage with SiPMs

Goals:

- Precise and independent measurement of the reactor neutrino spectrum with high event statistics
- Monitoring reactor for nuclear safeguards
- Search for light sterile neutrinos
- Make improved measurements of isotopic yields & spectra

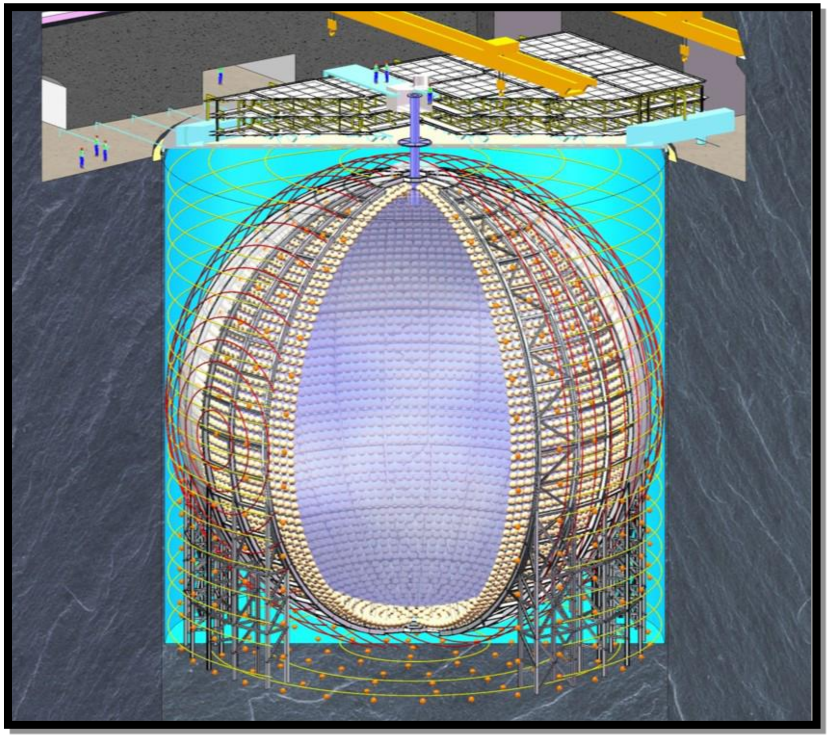
arXiv: 2005.08745



1:1 prototype under construction in ICHEP

The JUNO detector

Primary goal: precise measurement of reactor neutrino oscillations and Neutrino Mass Ordering (NMO) determination



Requirements:

- High statistics (~10^5 events in 6 yr)
- Energy resolution: ~3% @1MeV
- Energy scale uncertainty < 1%

How?

- Large LS volume (20 kton)
- High LS light yield & transparency
- High PMT coverage and efficiency
- Two complementary PMT systems
- Complementary calibration systems
- Using JUNO+TAO

Experiment	Daya Bay	Borexino	KamLAND	JUNO
LS mass	20/detector t	~300 t	~1000 t	~20 000 t
Photon collection	~160/MeV	~500/MeV	~250/MeV	~1665/MeV
Energy resolution	~7.5%@ 1 MeV	~5%@ 1 MeV	~6%@ 1 MeV	~3% @ 1 MeV
PMT number	192 8-in.	2212 8-in.	1325 20-in. & 554 17-in.	17612 20-in. & 25600 3-in

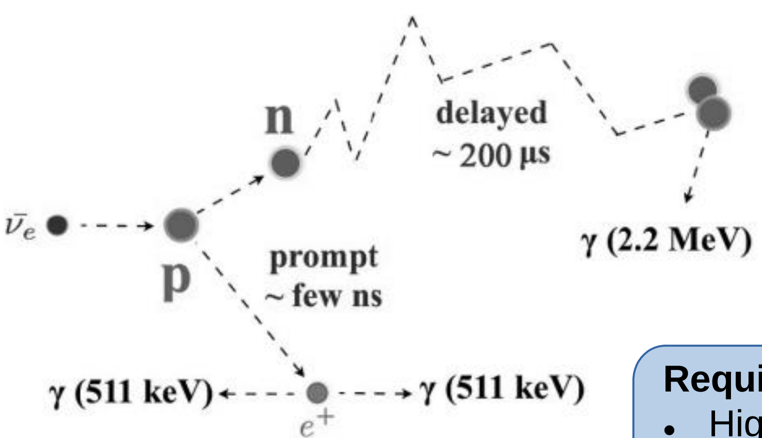
Neutrino detection in JUNO

- Reactor electron anti-neutrinos are observed by Inverse Beta Decay (IBD) via the positron signal (1), and the following neutron capture (2):

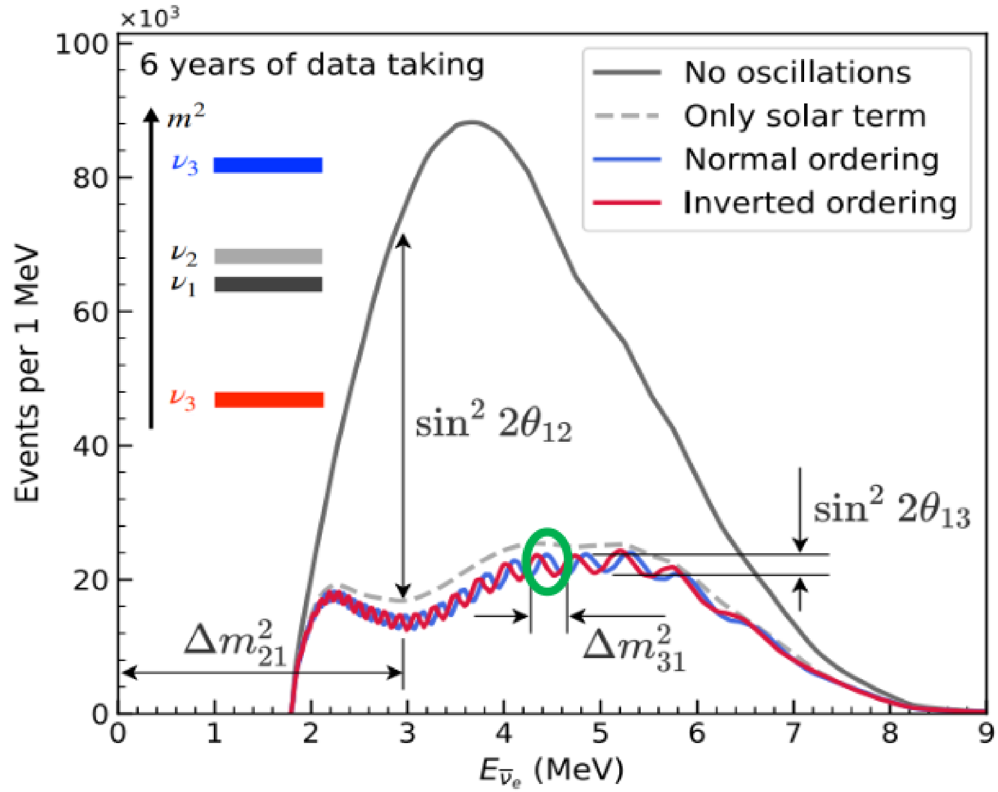
$$\overline{\nu}_e + p \rightarrow e^+ + n \qquad (1)$$

$$n + p \rightarrow d + \gamma \qquad (2)$$

- Very clear signal: prompt + delay coincidence in the (visible) energy range ~[0.7,8] MeV:

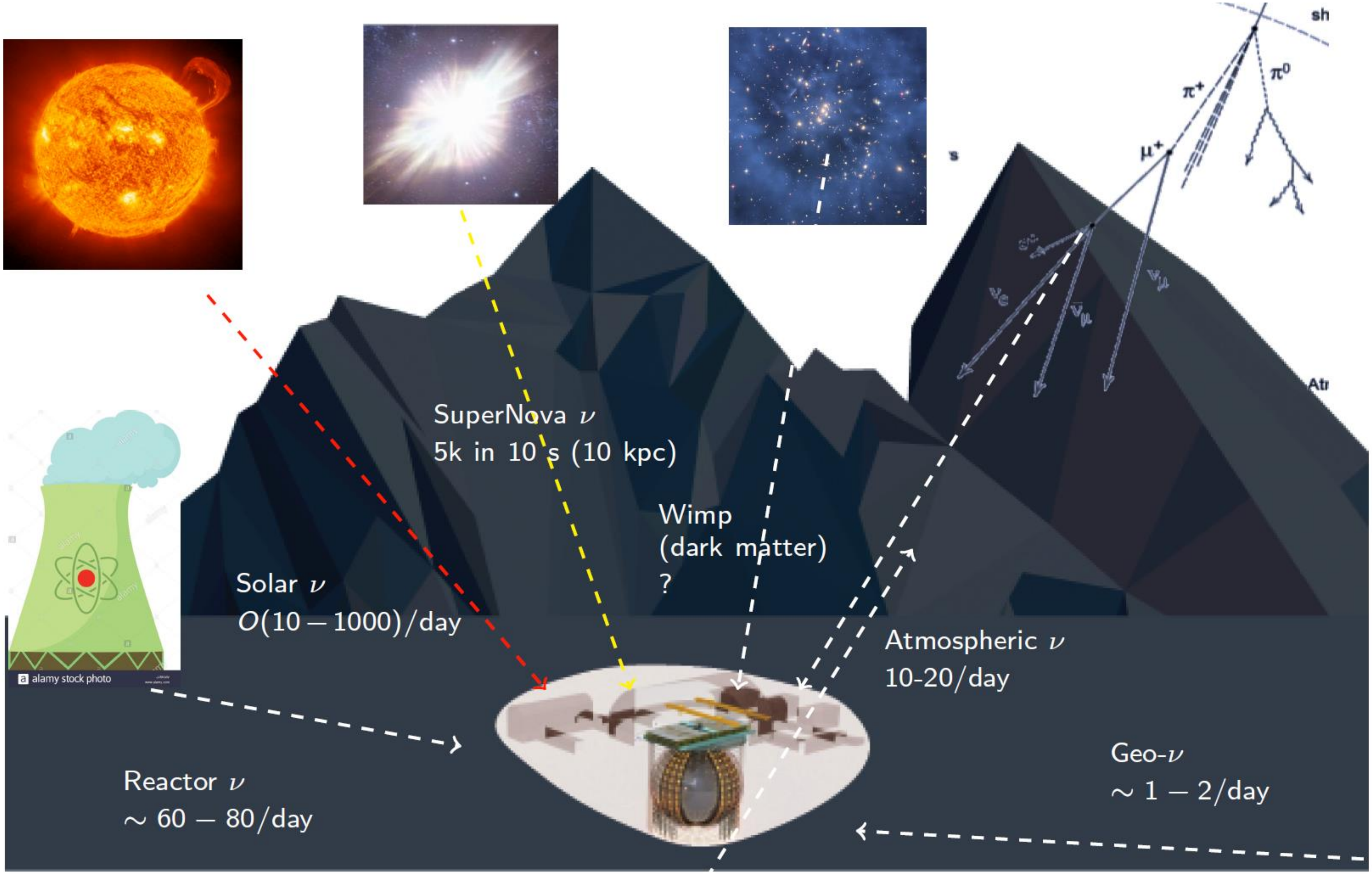


Sensitive to $\overline{\nu}_e$ survival probability:



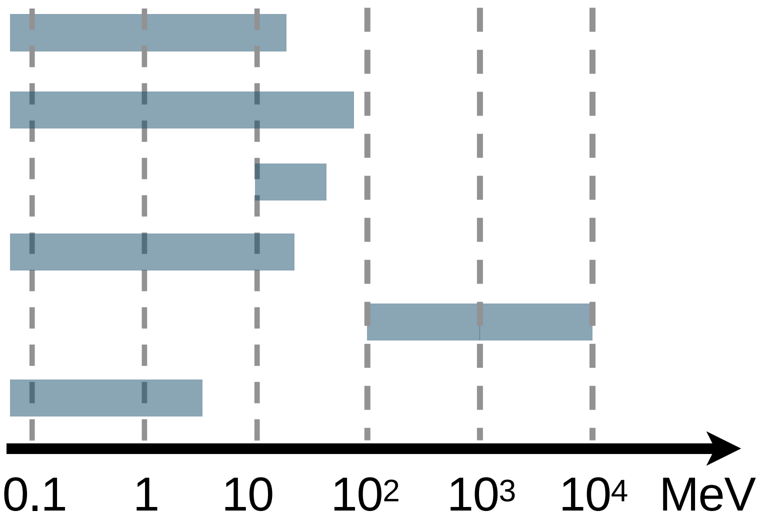
Requirements (KEY):
- High statistics
- Energy resolution: ~3% @1MeV
- Energy scale uncertainty < 1%

JUNO physics program

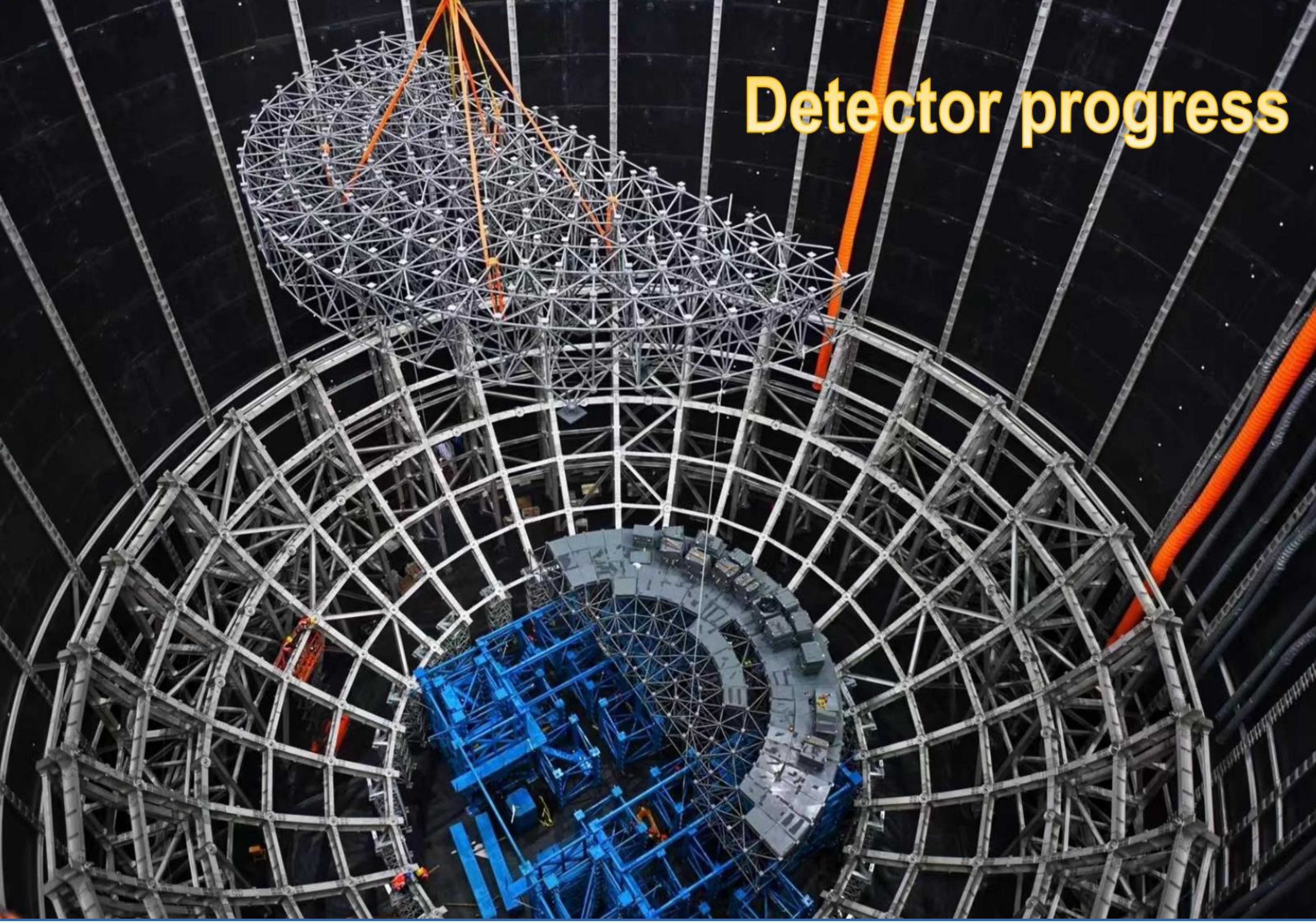


JUNO energy region

Neutrino source	Expected signal	Energy Region
Reactor	45 evts / day	
Supernova burst	10^4 evts at 10 kpc	
Diffuse supernova background	2-4 evts/ year	
Sun ^{8}B (^{7}Be)	16 (490) / day	
Cosmic rays	100+ / year	
Earth crust & mantle	400 / year	



Detector progress



Status of the central detector

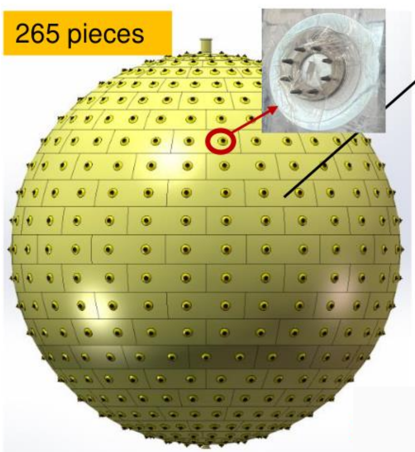
Acrylic sphere (LS container) → Supported by **Stainless Steel (SS) Structure**:

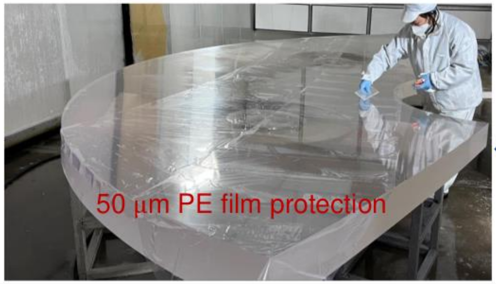
Inner diameter: 35.40±0.04 m

Thickness: 124±4 mm

Light transparency > 96% @ LS

Radiopurity: U/Th/K < 1 ppt



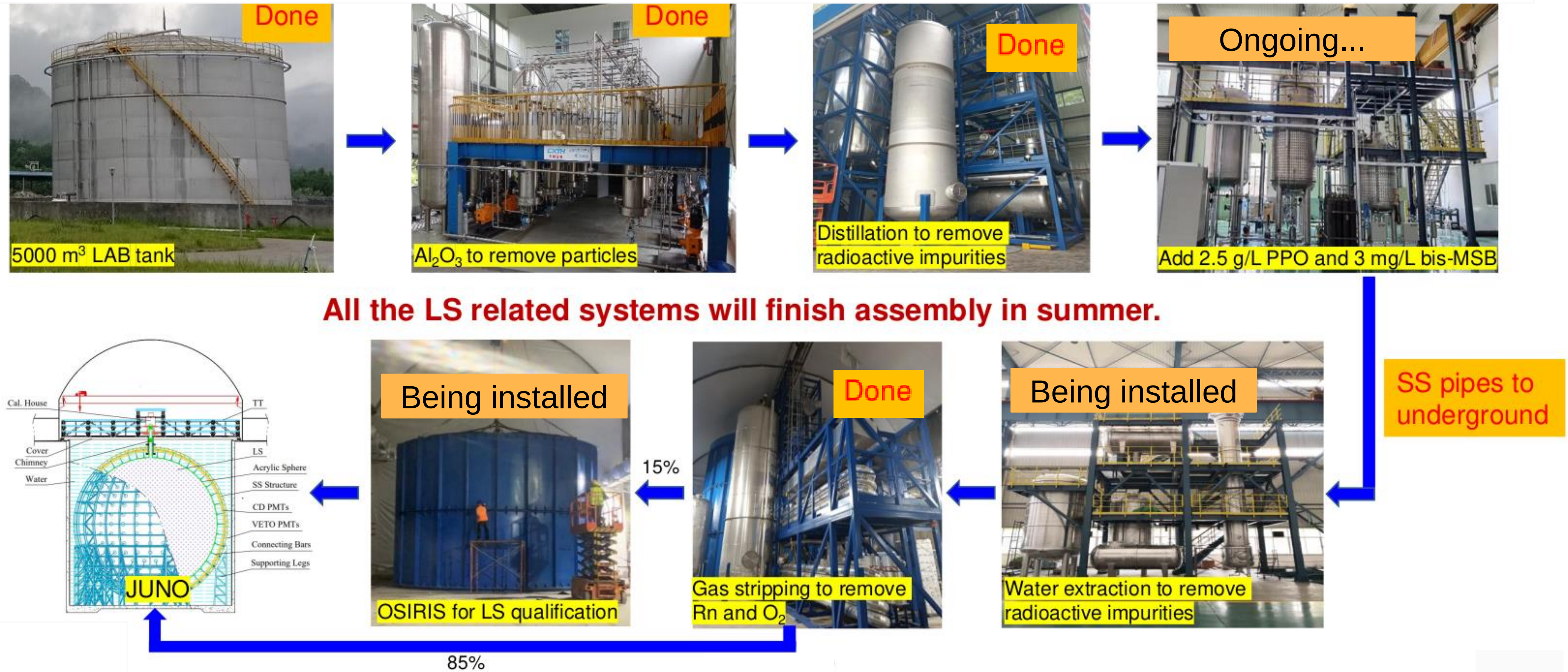


- Installation completed

- All pieces ready on site
- Installation just started

Status: liquid scintillator

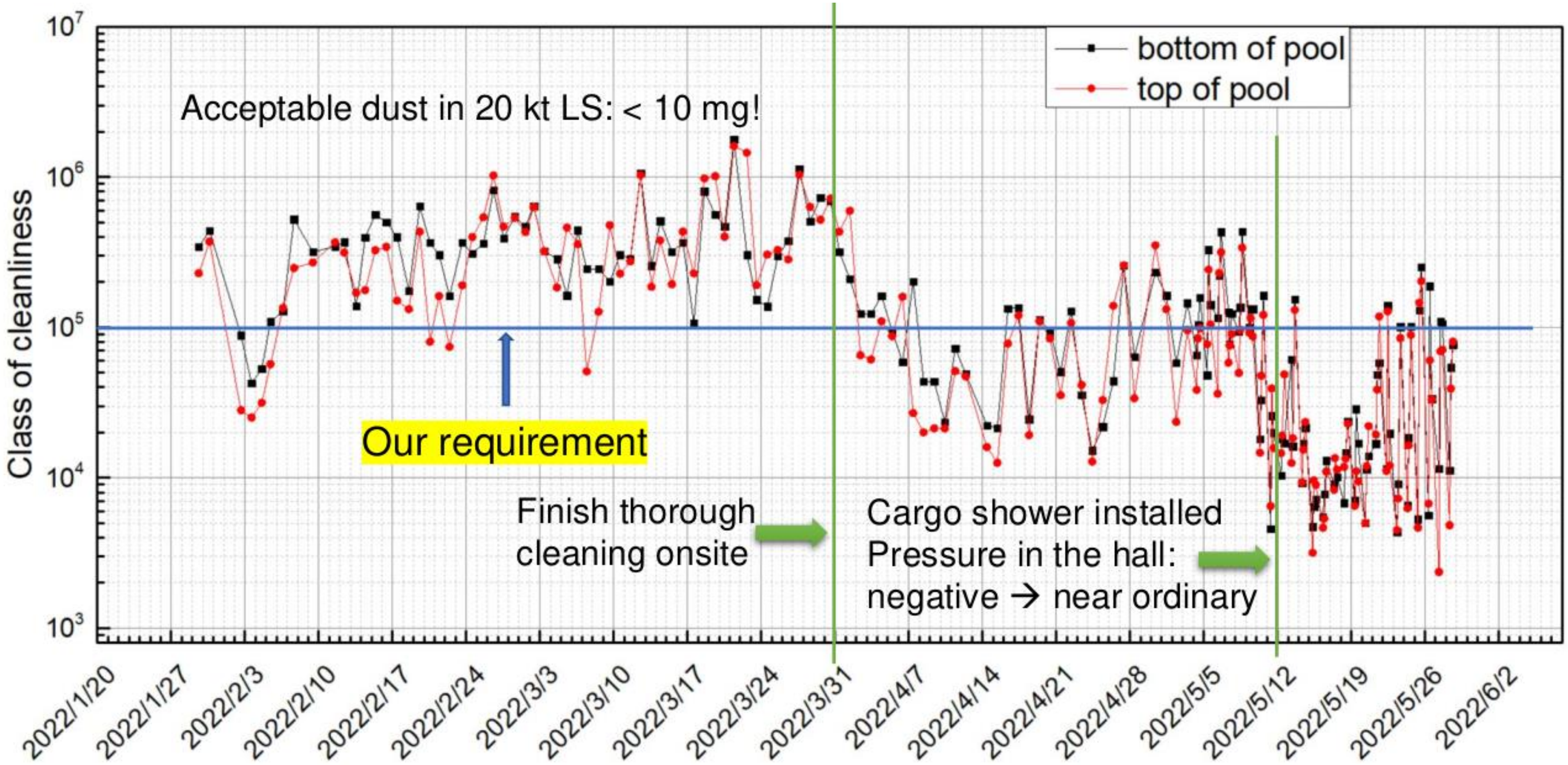
Highly transparent and low radiopurity LS for better E resolution and lower background



OSIRIS: 20t JUNO pre-detctor, to observe JUNO filling and verify liquid purification system

Liquid scintillator:
LS mixing + purification systems are almost ready →will start commissioning after summer

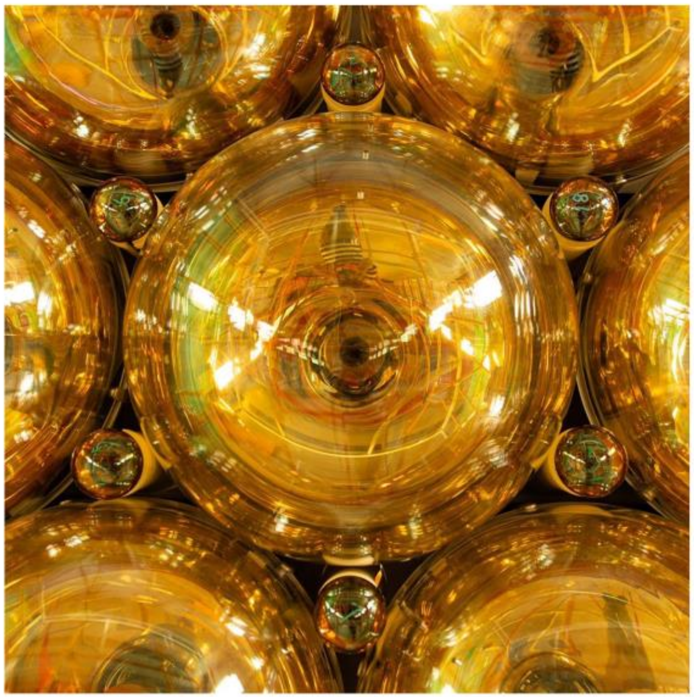
Environmental cleanliness control

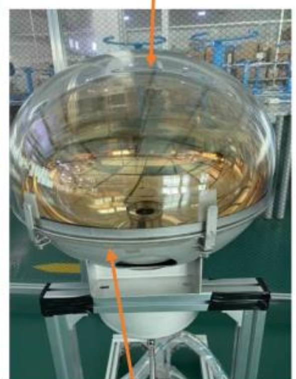


With great efforts onsite: the cleanliness in the hall reaches better than Class 100,000

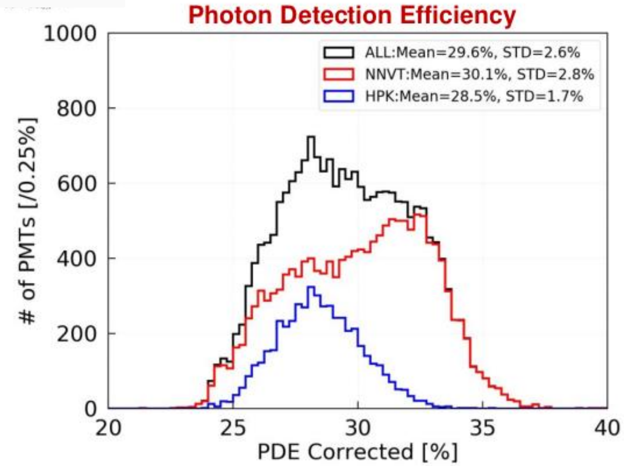
Status: electronics (PMTs)

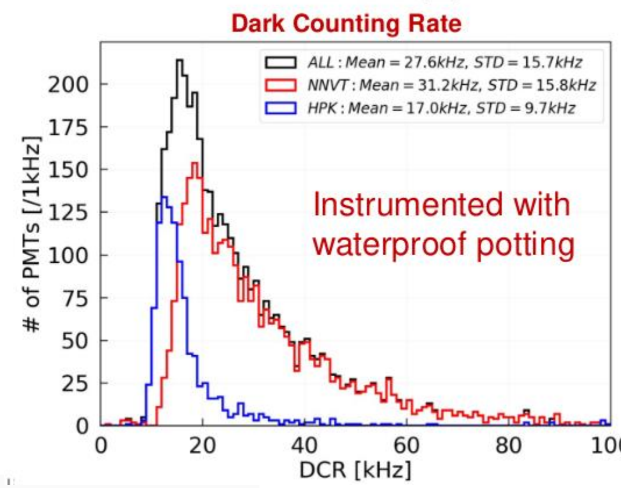
Synergetic 20-inch and 3-inch PMT systems to ensure energy resolution and charge linearity





Clearance between PMTs: 3 mm → **Assembly precision: < 1 mm**





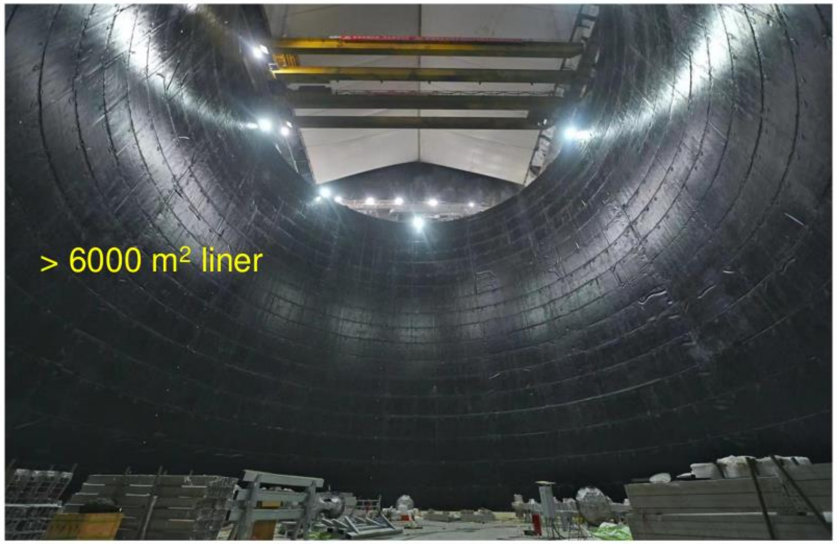
Underwater electronics
\+
High PMT coverage
\+
High PMT efficiency
↓
Improve E resolution

Electronics:
- All PMTs produced, tested, and instrumented with waterproof potting
- Assembly finished and connections being tested → Installation in October

Status: veto detectors

Water pool:

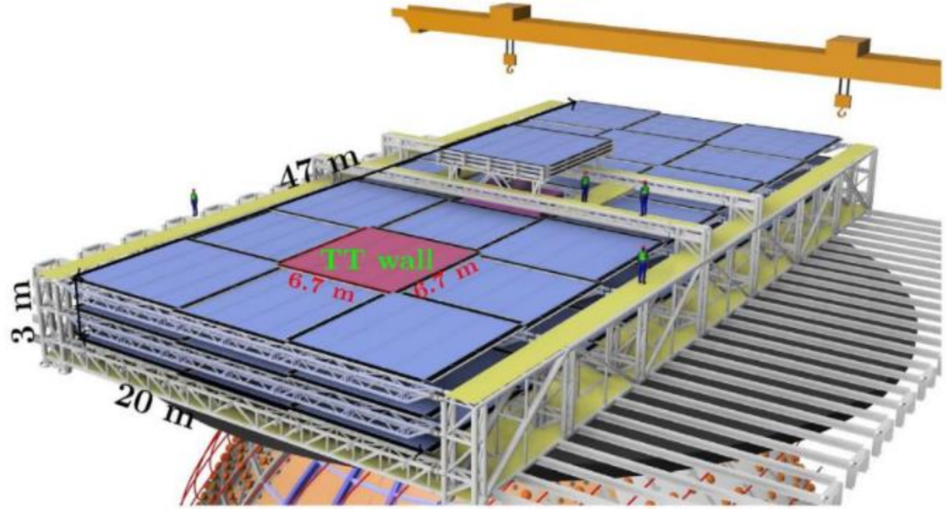
- 35 kton of ultrapure water cherenkov detector
- Will act as passive shield and veto for cosmic muons (> 99.5% efficiency, 2400 20' PMTs)



- Water pool liner construction finished
- Water pipes and extraction system: installations done → will provide clean water underground soon

Top tracker:

- Built from OPERA's tracker layers
- Goal: study and veto cosmogenic backgrounds and atmospheric muons



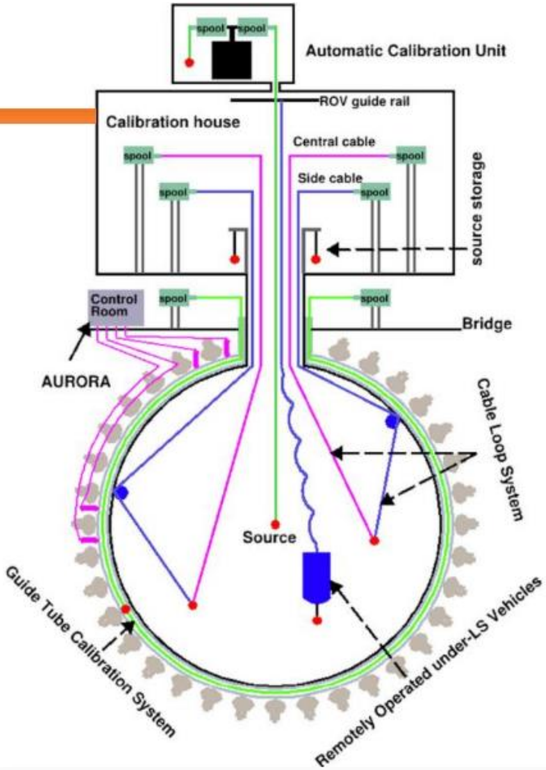
- Prototype working
- Modules already at JUNO site
- Mechanical structure design done
- Electronic design done

→ To be produced and tested this year

Detector calibration

- Crucial to understand detector response non-uniformity and achieve: <1% energy scale uncertainty + 3% at 1MeV energy resolution
- Four complementary sub-systems: 1D,2D and 3D scan with multiple calibration sources

Cable system finished prototype test



JHEP 03 (2021) 004

Distributed Computing Infrastructure

5 Data Centers

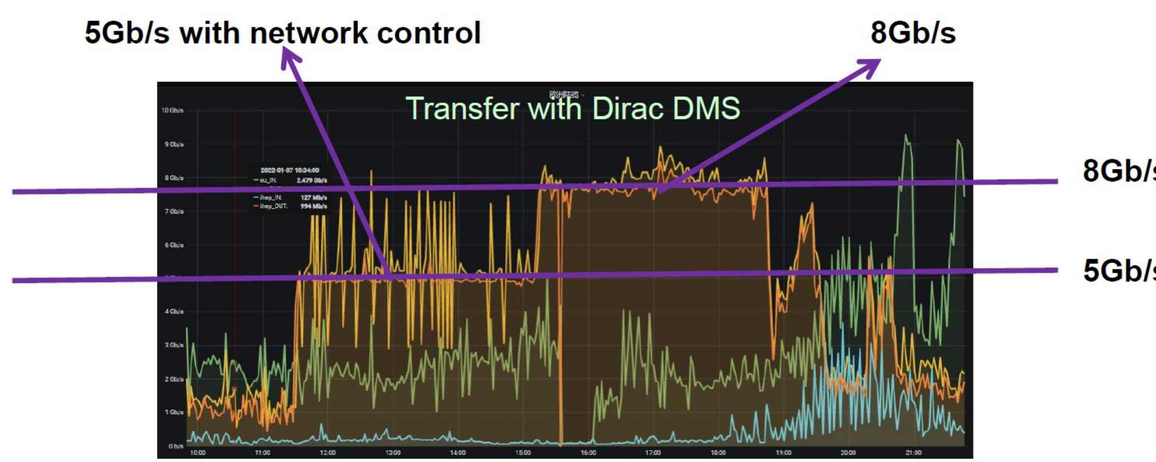
IHEP, INFN CNAF, MSU, CCIN2P3, JINR DUBNA

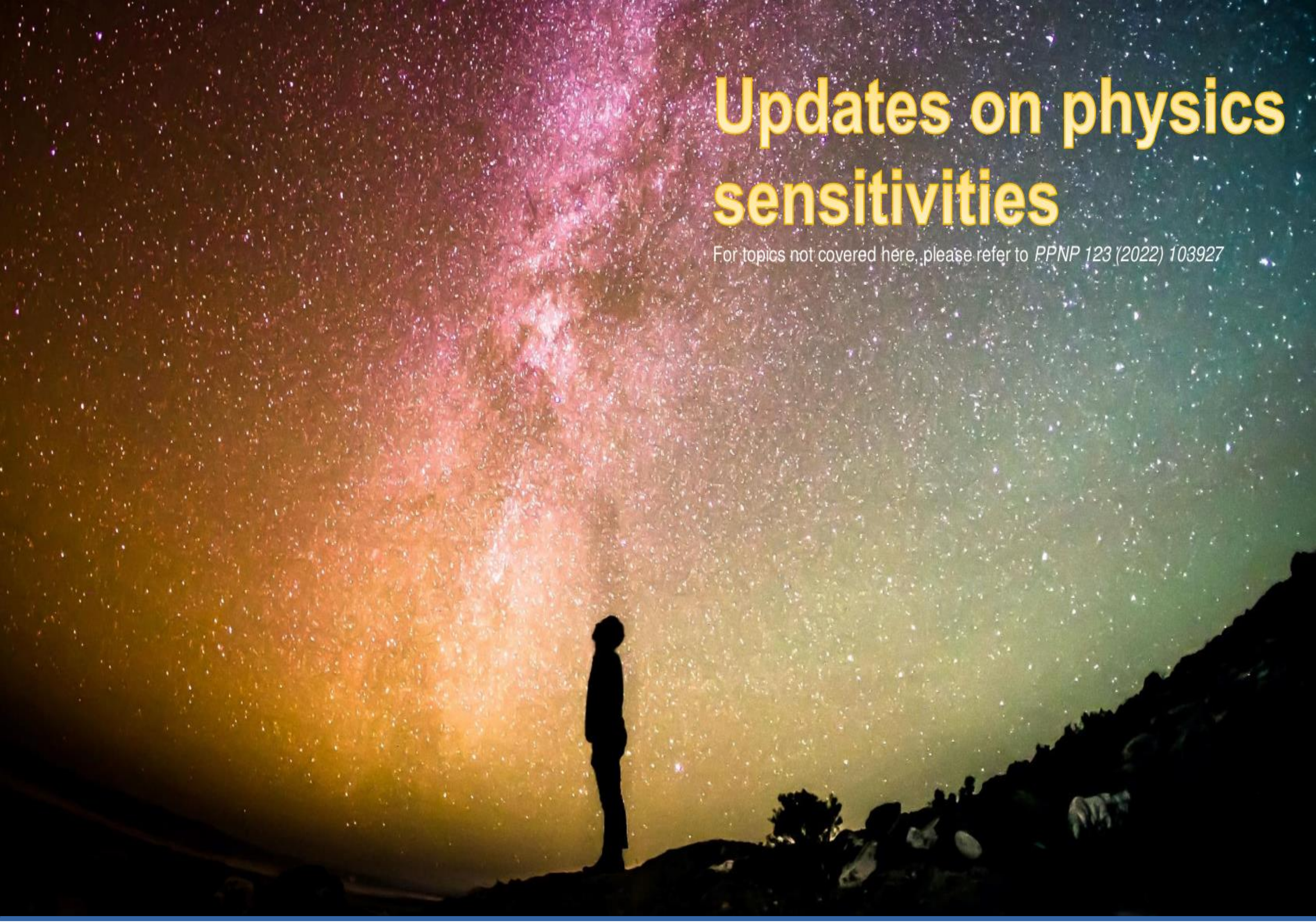
- Based on international connections between NREN used for LHC experiments
- Accepted in LHCONE community
- Based on Worldwide LHC Computing Grid and DIRAC
- Widely tested, more and more used
- Based on a MoU upon signature

Actual resources

CPU	Disk	Tape
102 kHS06	6.2 PB	3.5 PB

First Data Challenge





Updates on physics sensitivities

For topics not covered here, please refer to *PPNP 123 (2022) 103927*

Reactor neutrino oscillations

Analysis updates:

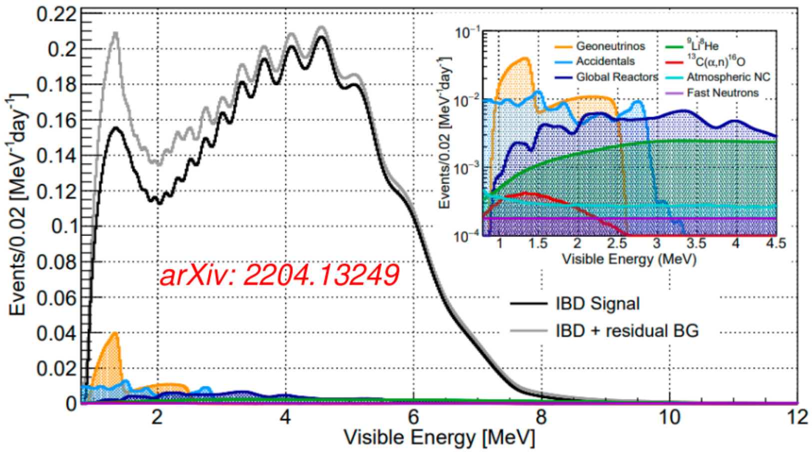
- Two reactor cores less (8 VS 10)
- Updated accidental baseline rate (see arXiv:2107.03669 for more details)
- Contribution from all other reactor power plants included in the analyses
- Constraints from TAO considered
- Better understanding of the detector:
  - New detector response (e.g. energy non-linearity)
  - Updated light yield and energy resolution:

Change	Light yield in detector center [PEs/MeV]	Energy resolution	Reference
Previous estimation	1345	3.0% @1MeV	*JHEP03(2021)004*
Photon Detection Efficiency (27%→30%)	+11%↑	**2.9% @ 1MeV**	arXiv: 2205.08629
New Central Detector Geometries	+3%↑		
New PMT Optical Model	+8%↑		*EPJC 82 329 (2022)*

→ Impact on the neutrino oscillation analyses?

**See detailed poster contributions at Neutrino2022:
https://zenodo.org/communities/neutrino2022-posters?page=1&size=20

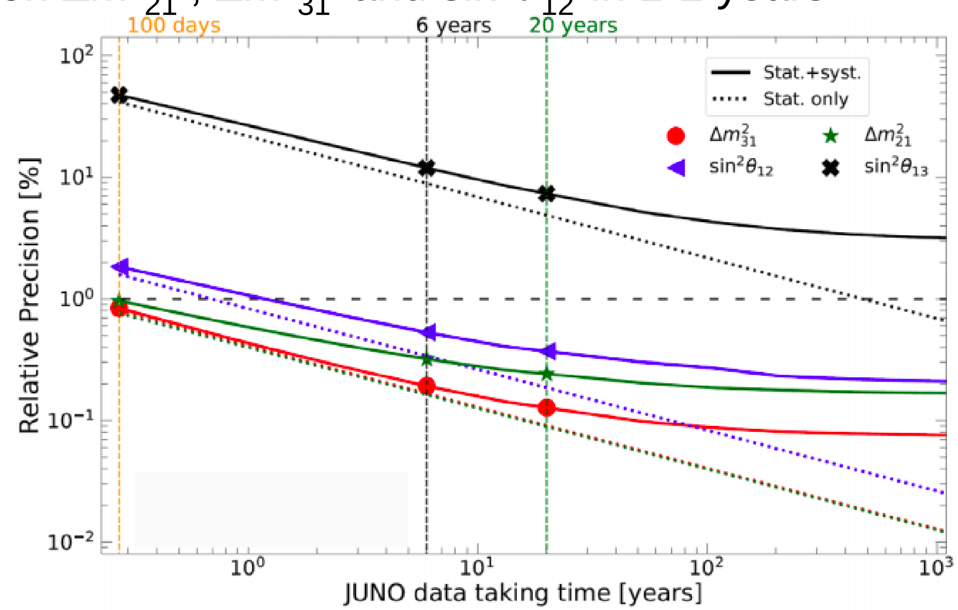
Reactor neutrino oscillations



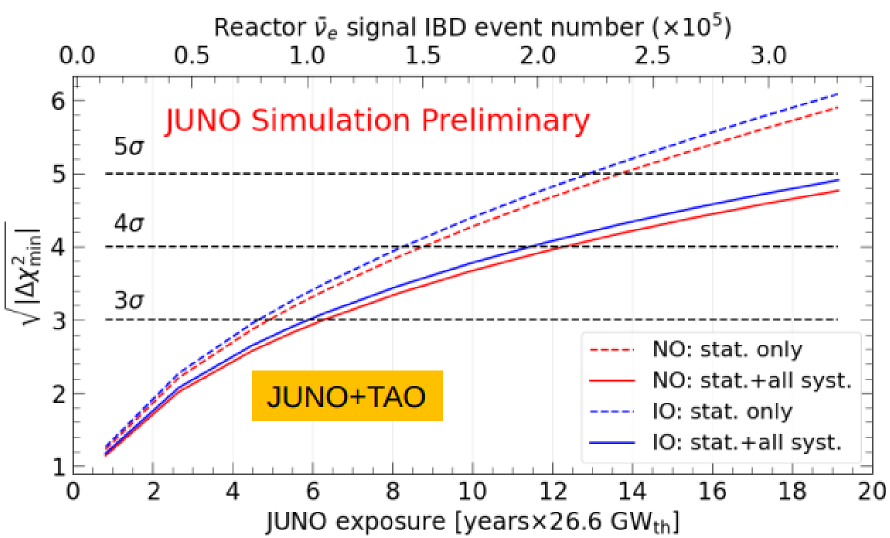
Sub-percent precision measurement of the oscillation parameters (arXiv: 2204.13249)

- Profit from spectrum precise measurement to extract oscillation parameters with <1% precision
- Probe simultaneously Δm^2_{21} and $\Delta m^2_{32}/\Delta m^2_{31}$ driven oscillations

→ JUNO will reach sub-percent precision level on Δm^2_{21} , Δm^2_{31} and $\sin^2\theta_{12}$ in 1-2 years



Determination of the neutrino mass ordering



→ Sensitivity: 3σ in ~6 yrs of data taking

Atmospheric neutrinos

→ **Neutrino oscillations and NMO can also be assessed using atmospheric neutrinos**

Why atmospheric neutrinos?

- Complementary detection channels: independent measurements and systematics
- **Boost of NMO sensitivity using both channels:**

→ NMO determination at 3σ faster!

- Exploit matter effects on oscillations
- Additional parameters: $\sin^2\theta_{23}$ and δ_{CP}

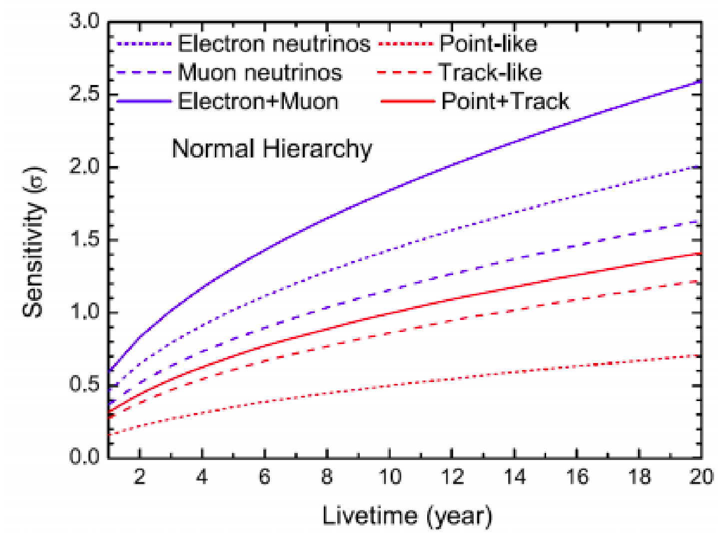
Ongoing analysis

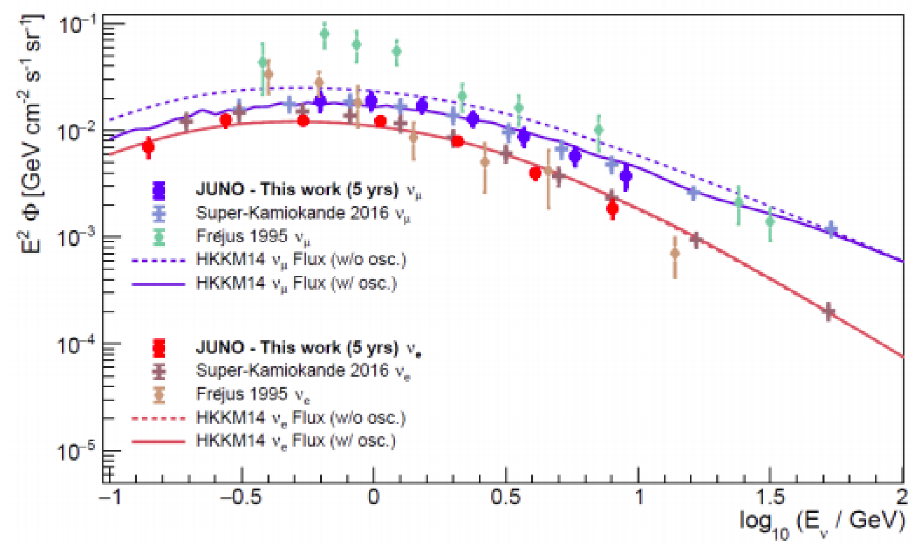
→ Flavor - dependent energy spectrum can be measured in the (0.1 - 10) GeV energy range

→ ν_e/ν_μ discrimination based on time pattern of scintillation light possible

Results published in Eur. Phys. J. C (2021) 81:887

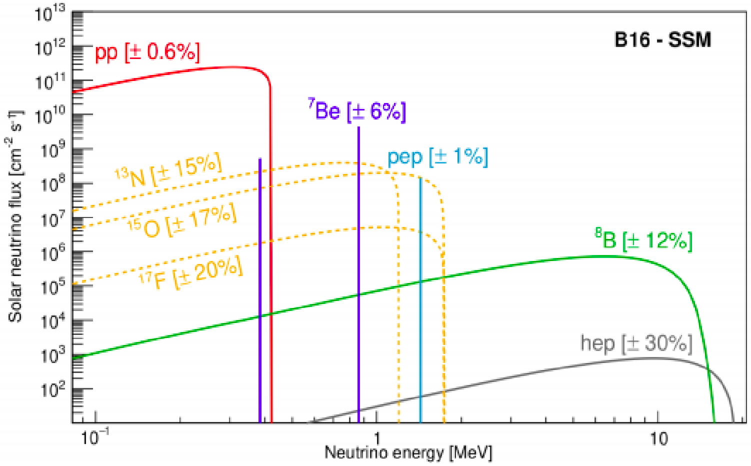
→ Promising potential for GeV neutrino physics



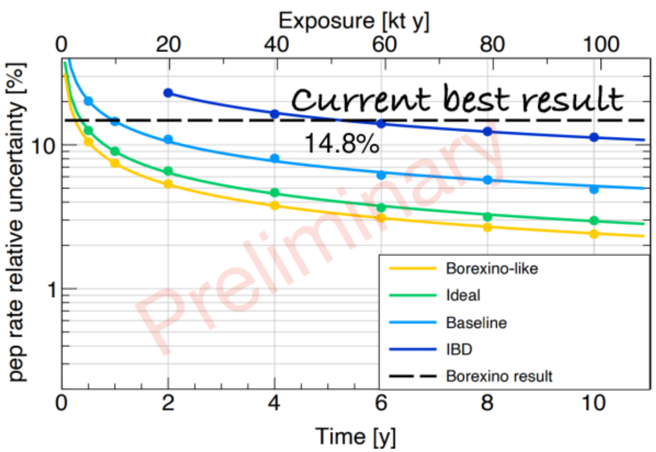


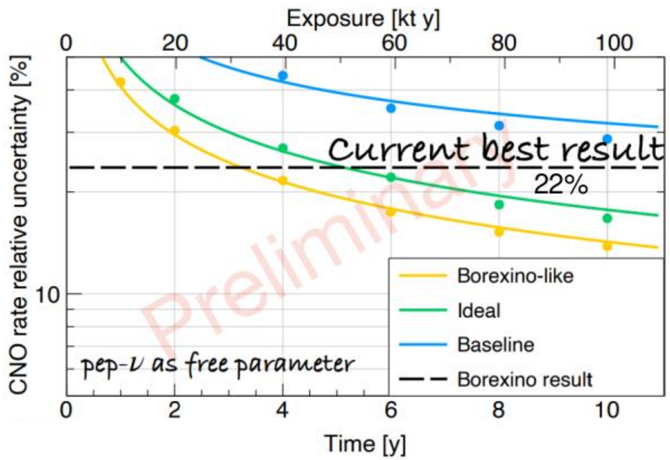
Solar neutrinos

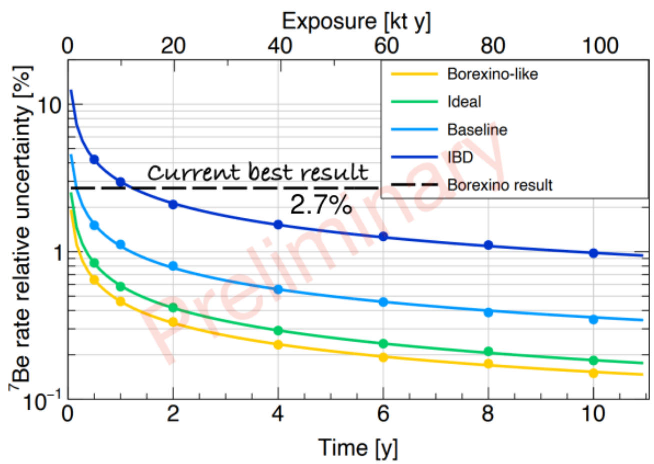
* Main detection channel → ν_e elastic scattering (ES)
* JUNO can benefit of its enormous statistics
* Different fluxes could be detected:
  - 7Be
  - 8B
  - Pep
  - CNO



- **Intermediate and low energy neutrinos** (< 2MeV): **Measure simultaneously pep, ^{7}Be and CNO fluxes** → Crucial: internal level of radioactivity







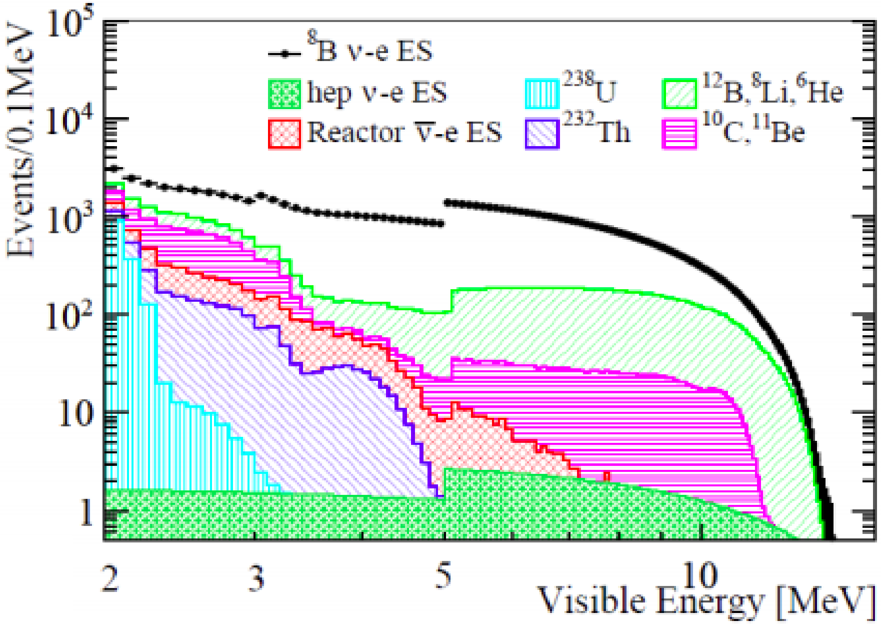
See: DOI:10.5281/zenodo.6785412

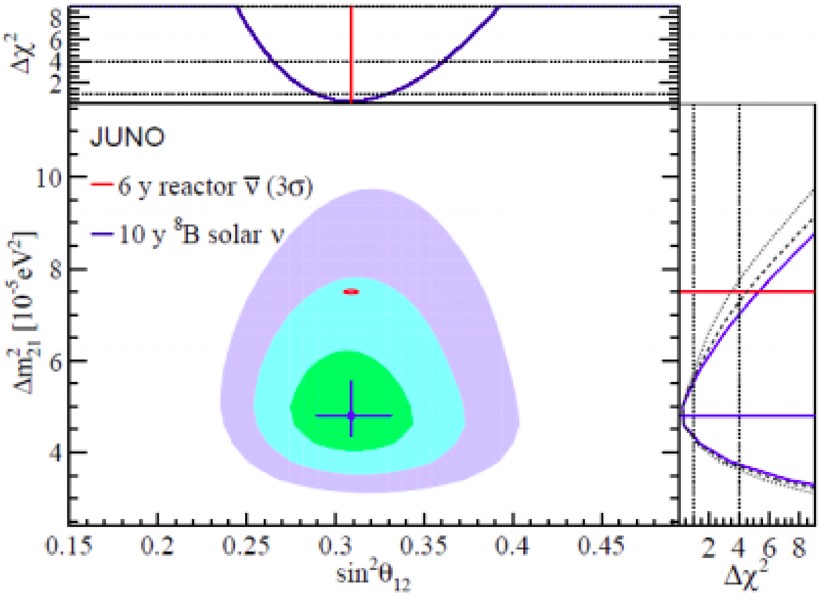
Solar neutrinos

High energy (^{8}B neutrinos) – Chin. Phys. C 45 (2021)

- Possibility to use CC and NC interactions on ^{13}C
- Unprecedented detection threshold at 2 MeV
- More precision: contribute to solve metallicity puzzle
- Spectral shape: study day/night asymmetry + other NSI

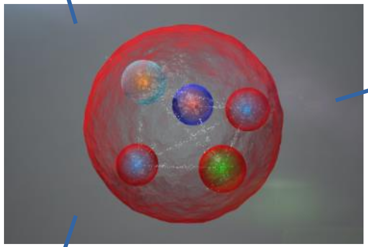
→ Simultaneous determination of $\sin^2\theta_{12}$ and Δm^2_{12} with both solar and reactor neutrinos in one experiment





Exotic physics

Nucleon decay:
Kaon mode
Signal: 3-fold coincidences
Background: atmospherics
Competitive sensitivity



Beyond Standard Model:
- Light sterile neutrino searches:
→ test the neutrino reactor anomaly
→ good limits on sterile mass δm_{41}
- Magnetic monopoles
- Leptonic unitarity test
- Lorentz Invariance Violation
- Majorana neutrinos

Dark matter:
→ Indirect search of dark matter decay from the Sun
→ Good sensitivity to spin-independent
and spin-dependent cross-sections

And more …

Geoneutrinos

- Unique neutrino source to probe the inner structure of Earth
- Earth's Th/U ratio and mantle still not fully known yet:
- Study radiogenic contribution to terrestrial heat production

Supernova burst neutrinos

- In case of Galactic CCSN, JUNO will be able to detect the CCSN flux from all neutrino flavors with high statistics

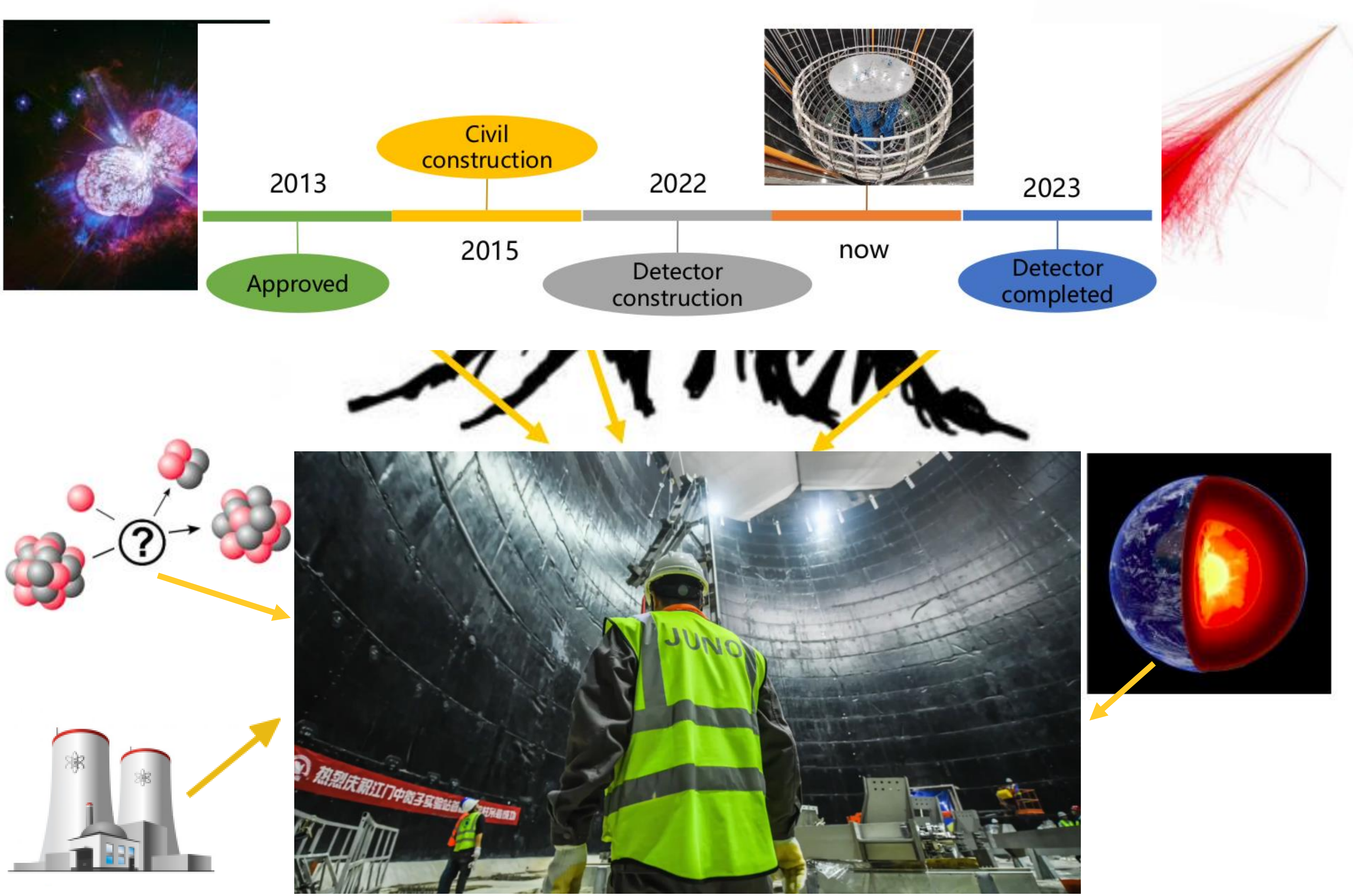
Multi messanger astronomy

- Two strategies to trigger a transient event:
  - Prompt Real-time Monitor:
    - Higher energy threshold (~1MeV)
    - Increase sensitivity horizon
  - Multi-messenger (MM) trigger:
    - Lower energy threshold (~20 keV)
    - Increase signal statistics

Diffuse supernova neutrino background

- superposition of neutrino signals from all past supernova explosions, **yet to be observed**

JUNO – AN INSTRUMENT WITH AN INCREDIBLE PHYSICS POTENTIAL



JUNO – AN INSTRUMENT WITH AN INCREDIBLE PHYSICS POTEN...

Backup

Geoneutrinos

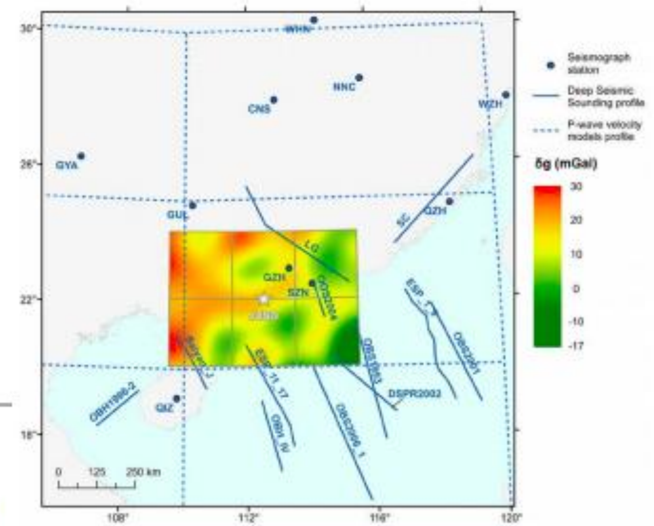
- Unique neutrino source to probe the inner structure of Earth (from ^{238}U and ^{232}Th decays in Earth's mantle and crust)
- Earth's Th/U ratio and mantle still not fully known yet: important parameter to understand Earth's formation
- Study radiogenic contribution to terrestrial heat production

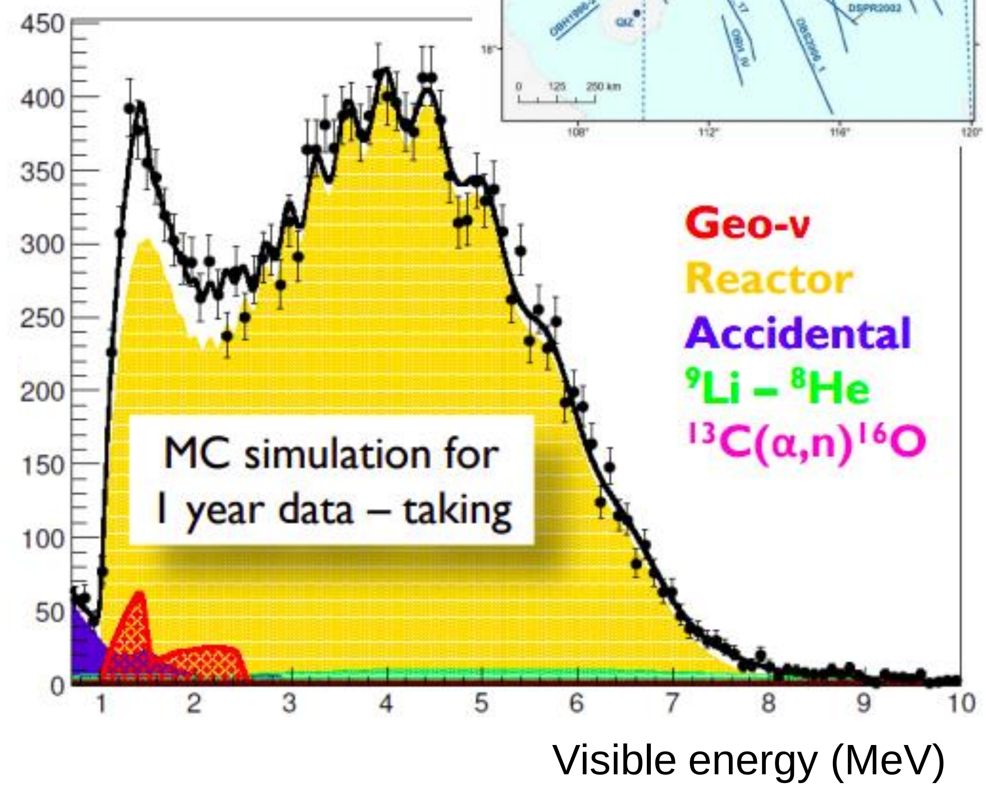
→Signal from local crust is crucial for the interpretation of results
→Local geological studies ongoing to tackle largest uncertainty source

→Major improvement with respect to Borexino and KamLAND due to higher statistics in JUNO (400 ev/yr expected)

Main backgrounds:

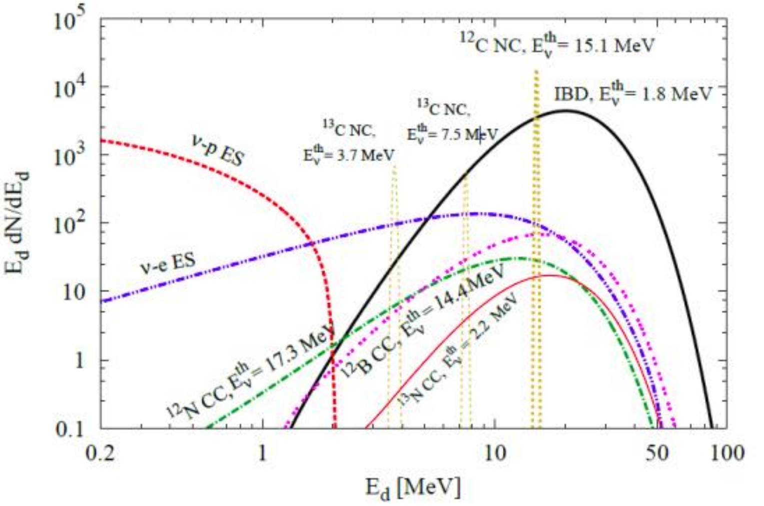
- Cosmogenic isotopes
- Fast neutrons
- Accidentals





Supernova burst neutrinos

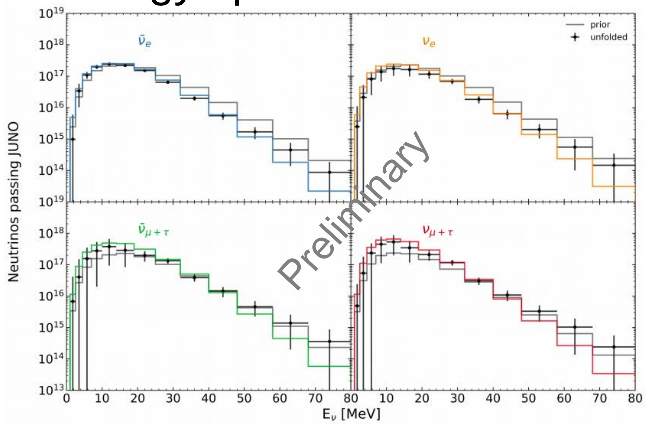
- If there is a Galactic CCSN, JUNO will be able to detect the CCSN flux from all neutrino flavors with high statistics
- Dominant detection channels: IBD, ν-p ES, and ν-e ES
- High signal rate → almost background free observation



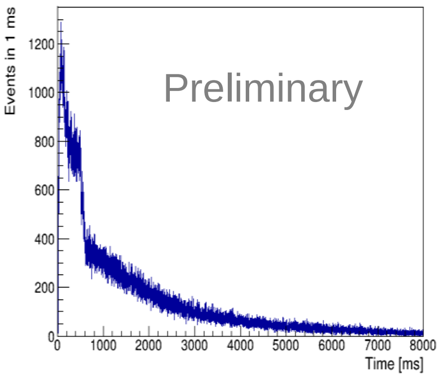
→ Good energy and time resolution + flavor classification: JUNO will measure:

Constrain CCSN physics!

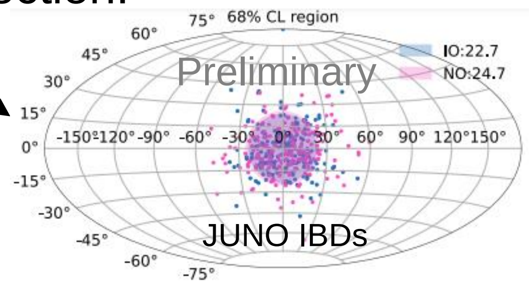
Flavor dependent energy spectrum

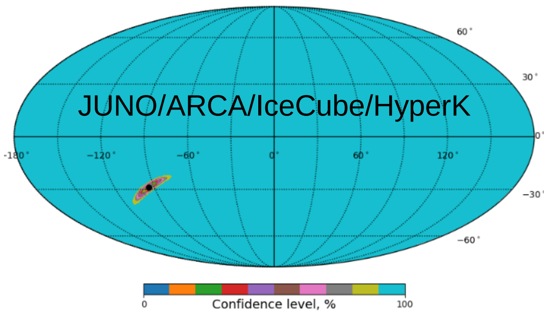


Lightcurve: (time profile)



Direction:





+ pre-SN ν detection at d≤1kpc

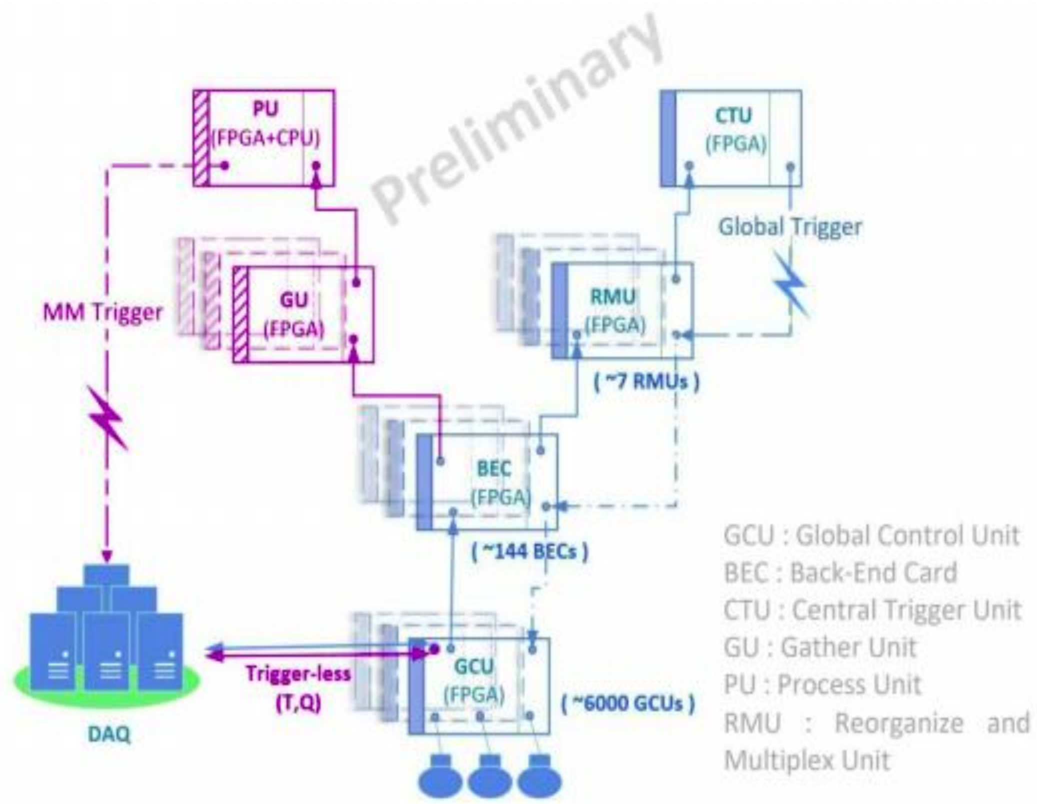
Multi-messenger astronomy

Two strategies to trigger a transient event:

- Prompt Real-time Monitor:
  - Higher energy threshold (~1MeV)
  - Increase sensitivity horizon
- Multi-messenger (MM) trigger:
  - Lower energy threshold (~20 keV)
  - Increase signal statistics

Real-time monitoring based on:
  - Sliding window method
  - Bayesian blocks algorithm

If transient astrophysical signal triggered:
→ All (triggerless) data are stored to obtain the most physics reach in offline analysis

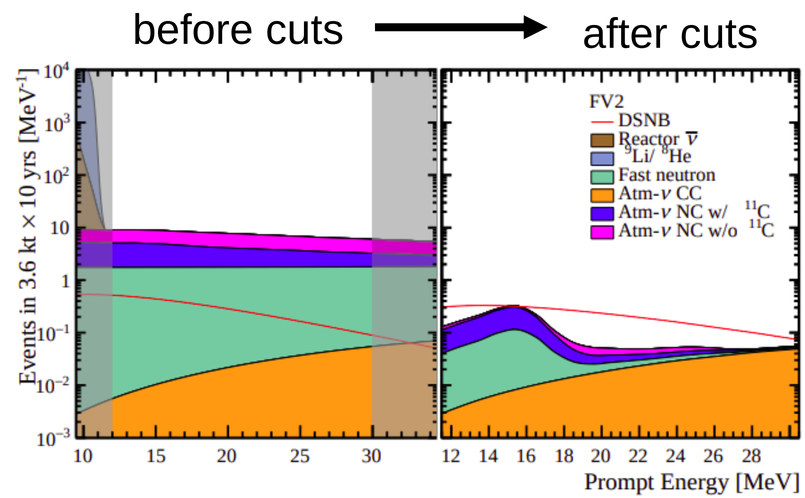


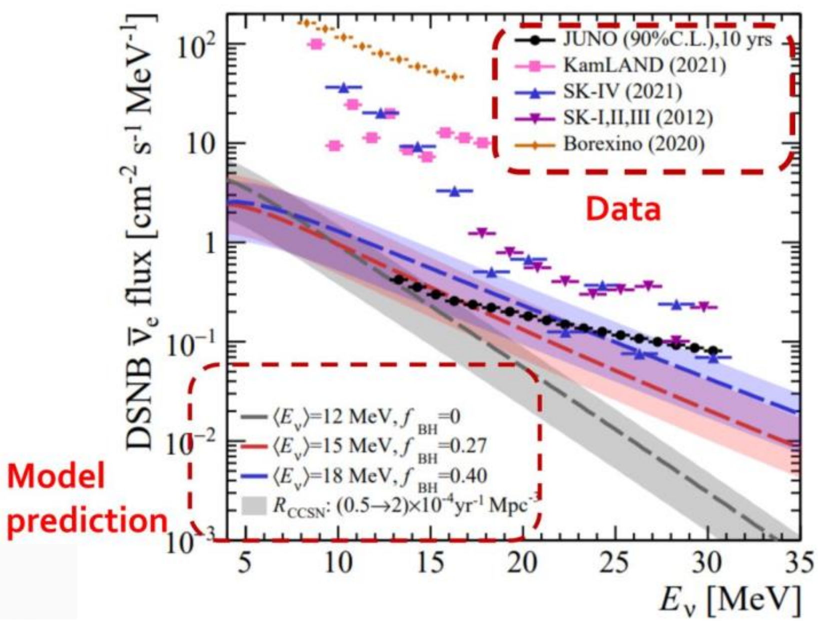
- ➔ JUNO as a powerful neutrino telescope for transient MM observations
- ➔ Major role in the next-generation Supernova Early Warning System (SNEWS 2.0)

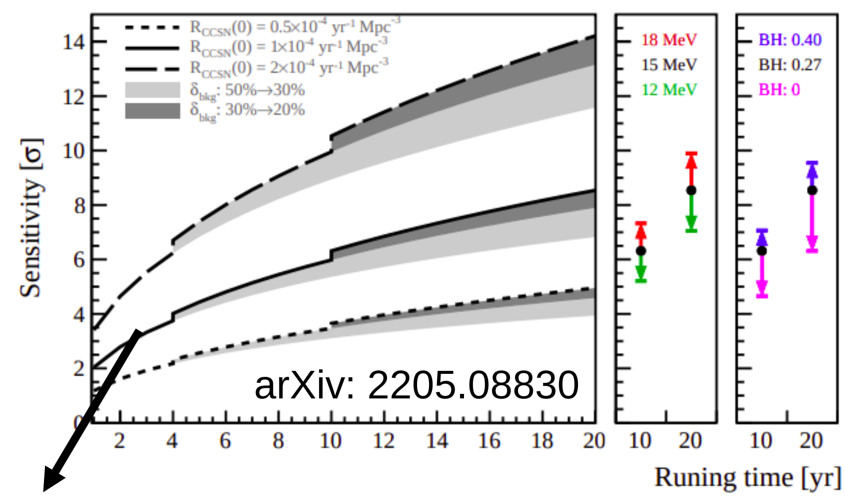
Diffuse supernova neutrino background

Diffuse Supernova Neutrino Background (DSNB) = superposition of neutrino signals from all past supernova explosions, **yet to be observed**

- Discovery of DSNB signal will provide important information on astrophysics and cosmology
- Detection in JUNO via IBD, with main background from NC atmospheric neutrinos
- Selection: [12-30] MeV + fiducial volume + PSD (pulse shape discrimination, signal vs background)
  → efficient background rejection







3σ discovery after 3 years data taking for nominal model