Prospects for geo-neutrinos and supernova neutrinos with JUNO

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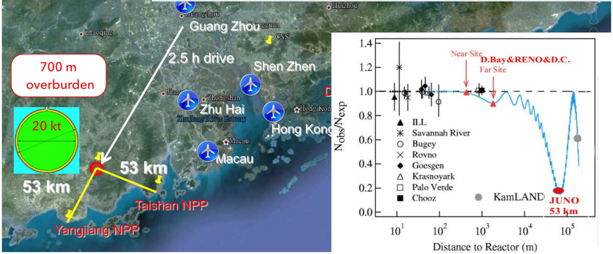
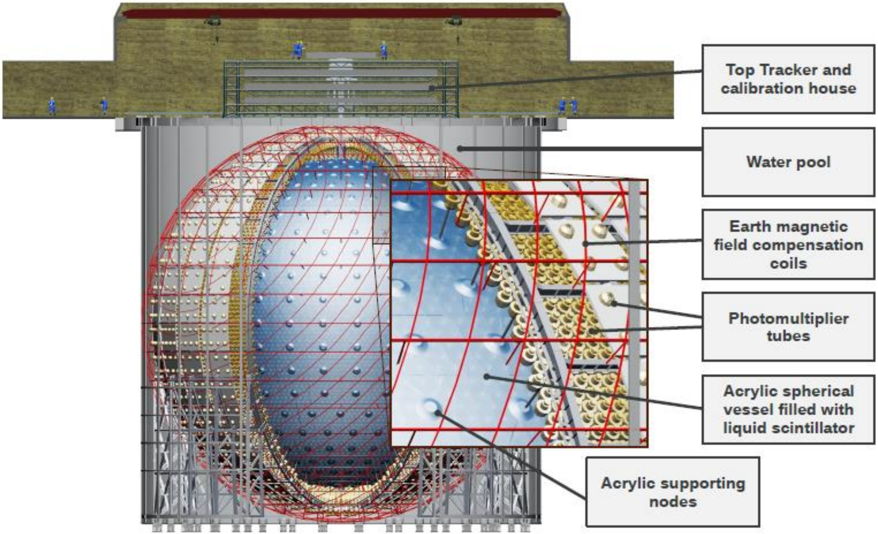
5. Summary

- JUNO (Jiangmen Underground Neutrino Observatory) is a medium baseline reactor neutrino experiment (53 km from the nuclear cores) .
- Its main objective is to determine the neutrino mass hierarchy using anti-neutrino flux coming from 8 nuclear reactors dispatched in two nuclear power plans (the combined thermal power of those is 26.6 GW)
- What makes JUNO experiment particular :
  - it will be the largest ever built liquid scintillator detector for neutrino physics
  - the number of photo-multiplier tubes (PMTs) installed is very impressive (more than 40k PMTs)

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Operational	Operational / Planned
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	9.2 GW / 18.4 GW

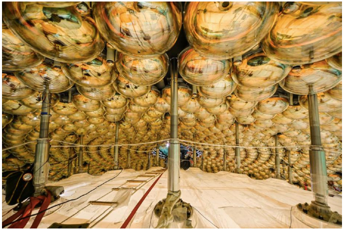


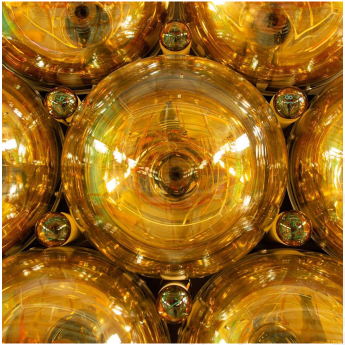
The JUNO detector



Detector main components

- CD: Acrylic sphere with steel truss containing the LS (20 kton): large volume for gaining statistics.
- Double calorimetry :
  17612 20 inch PMTs cover 75% of the surface and 25600 3 inch cover 3% of the surface. Large coverage and double calorimetry to improve energy resolution.
- Muon veto : uses the OPERA tracker layers. Provides a tagged muon sample to study muon reconstruction and background contamination in the CD
- Calibration : 4-complementary systems: Automatic calibration unit (1D- centralaxis scan), Cable loop and guide tube calibration systems (2D), remotely operated vehicules (3D) – radiative sources (photon, positrons, neutrons). See paper: arXiv:2011.06405





Neutrino Physics with JUNO

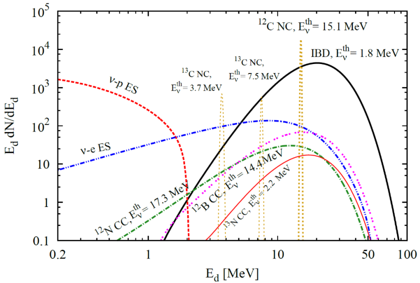
JUNO have a rich physics potential :

- Neutrino mass ordering with reactor $\overline{\nu_e}$
- Earth's atmospheric neutrino
- Solar neutrino from ^8B
- Core collapse supernova (CCSN) neutrino studies → this talk
- Supernova diffuse neutrino background studies → this talk
- Geo-neutrinos coming from desegregation of Uranium (U) and Thorium (Th) in the mantle and the crust → this talk

Summary of the expected number of event with JUNO for the different neutrino sources :

Source	signal rate	Energy range
Reactor	~ 47 events$/day$	0-12 MeV
Sun ^8B	$O(100)$ events$/year$	0-16 MeV
Earth's atm.	~ 400 events$/year$	0.1-100 GeV
SN burst	$\sim 10^4$ events @$10kpc$	0-80 MeV
SN Background	$2-4$ events$/year$	10-40 MeV
Earth (geo-ν)	~ 400 events$/year$	0-3 MeV

- JUNO has a great potential to observe several astronomical events in neutrinos:
  - Supernovae such as Core-Collapse Supernova (CCSN)
  - Neutron star mergers
  - Gamma ray bursts
- A CCSN releases 99% of its energy in neutrinos and antineutrinos of all flavors.
- Rate of CCSN in the Milky Way is 1.63 ± 0.46 per century **[New Astronomy Vol.83, 101498]**
- JUNO with 20 kt LS has excellent capability of detecting all neutrino flavors through Charge current (CC), Neutral current (NC) and Elastic scatering (ES)
- Good energy and time resolution and flavor classification → constrain CCSN physics by measuring :
  - CCSN neutrino spectrum
  - CCSN lightcurve

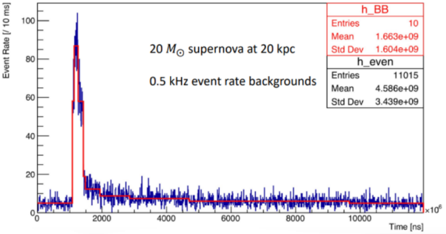


Type	detailed process	Event number at 10 kpc
CC (IBD)	$\overline{\nu_e} + p \to e^+ + n$	$\sim$ 5000
eES	$\nu + e \to \nu + e$	$\sim$ 300
pES	$\nu + p \to \nu + p$	$\sim$ 2000
NC	$\nu + {}^{12}C \to \nu + {}^{12}C^*$	$\sim$ 300
CC	$\nu + {}^{12}C \to \nu + {}^{12}N$ $\nu + {}^{12}C \to \nu + {}^{12}B$	$\sim$ 200

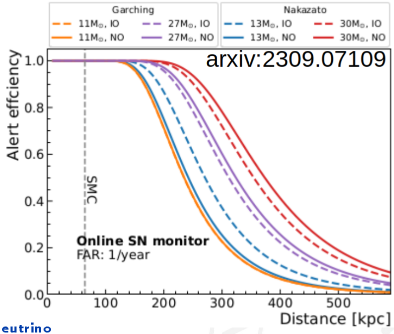
JUNO physics and detector, 10.1016/j.ppnp.2021.103927

Identifying an astrophysical transient signal

- Real-time monitoring based on a localized increase (in time) of the detected rate.
- Send altert to the EM telescopes.
- Two strategies to trigger a transient event:
  - Sliding window method
  - Bayesian blocks algorithm

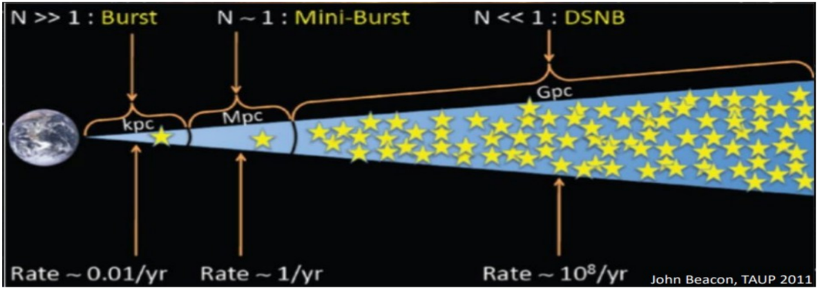


- Prompt Monitor:
  - Higher energy threshold (8MeV)
  - Faster alerts
- Online monitor /Global trigger:
  - IBD candidates (Eth $\sim$ 1MeV)
  - Lower background
- Multi-messenger (MM) trigger:
  - Lower energy threshold (<0.1 MeV)
  - Increase signal statistics
- Preprint available on **arxiv:2309.07109**.



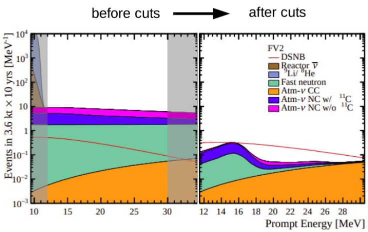
Diffuse supernova neutrino background

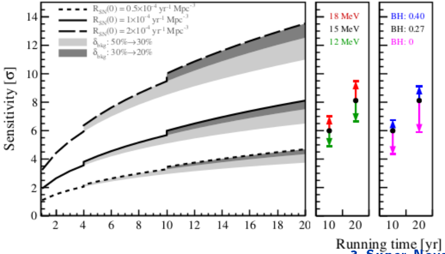
- Diffuse Supernova Neutrino Background (DSNB) = superposition of neutrino signals from all past supernova explosions, yet to be observed.
- Holds the precise information on the average CCSN neutrino spectrum, cosmic star-formation rate and fraction of failed black-hole forming SNe
- Garanteed steady source of O(MeV) neutrinos
- Discovery of DSNB signal will bring information on astrophysics and cosmology:
  - star formation and CCSN rates in the Universe + star evolution
  - black hole formation rates in the Universe

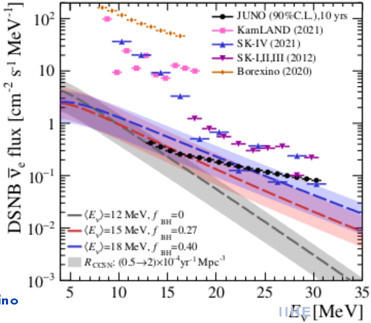


Diffuse supernova neutrino background

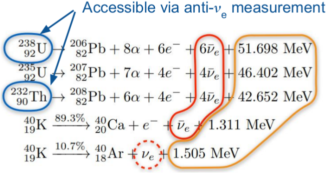
- Detection in JUNO via IBD
- Main background: neutral current atmospheric neutrinos
- Event selection:
  - Energy range [12-30] MeV
  - Fiducial volume
  - pulse shape discrimination
- efficient background rejection:
  - Signal: 4-7 events per year
  - Background: 5 events per year
- paper **arxiv:2205.08830**

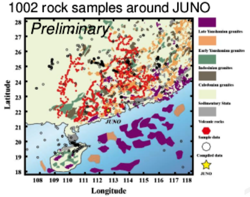






- Unique neutrino source to probe the inner structure of Earth, especially the Uranium (U) and Thorium (Th) abundances
- Measure Th/U ratio in lithosphere and mantle to understand Earth's formation
- Estimation of U and Th radiogenic power contribution to terrestrial heat production
- Lithosphere (crust + CLM) predictions :
  - Global model : 30.9 TNU **[Prog. in Earth and Planet. Sci. 2, 5, 2015]**
  - JULOC model : 40.4 **[Phys.Earth.Planet.Inter. 299, 2020]**
- Mantle prediction 3 possibility of BSE models:
  - Cosmochemical (CC): $\sim$ 2TNU
  - Geochemical (GC):$\sim$ 10 TNU
  - Geodynamical (GD):$\sim$ 20 TNU



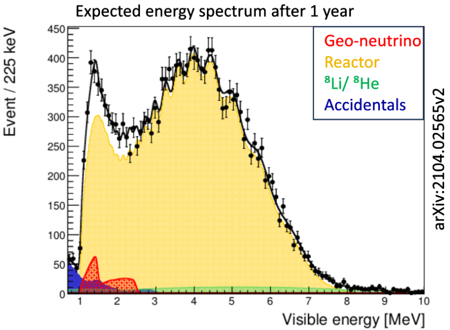


- Up to now, only Borexino experiment and KamLAND experiments have detected , respectively $\sim$ 50 and $\sim$ 170 geoneutrino events **[arxiv:1909.02257 , arxiv:2205.14934]**. Juno expect $\sim$ 400 events per year

1 TNU (Terrestrial Neutrino Unit) = 1 event / 10^{32} target protons (~1kton LS) / year with 100% detection efficiency

Geoneutrino measurement

- Signal of geoneutrino: ~ 1 event per day
- Signal is mixed with reactor antineutrino signal. JUNO is designed to study those.
- In the energy range no possibility to distinguish between the two signals.
- Th/U abundance fixed to the chondritic ratio, only 10% stat. uncertainty at 1σ after 6 years of data taking with JUNO



Expected geoneutrino precision*
(assuming Th/U mass ratio fixed to 3.9)

PRELIMINARY

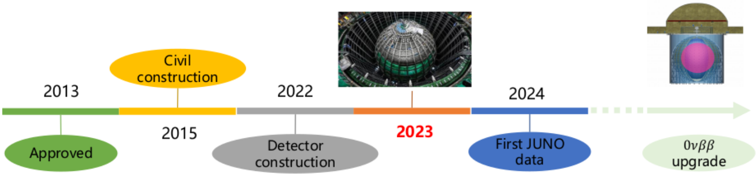
1 year	**~22%**
6 years	**~10%**
10 years	**~8%**

* These and further sensitivity numbers are shown for the first time. Paper under preparation.

- Existing Th/U abundance measurements :
  - 2020 Borexino 17% with 8.9 years [**M.Agostini et al., Phys. Rev. D 101, 2020**]
  - 2022 KamLAND 15% with 14.3 years [**S.Abe et al., Geophys. Res. Lett. 49 (16), 2022**]

Summary

- JUNO is a next-generation neutrino experiment with huge performances:
  - the largest LS-based detector with 20 kton
  - an unprecedented energy resolution of 3% at 1 MeV
  - a precise energy calibration program to reach less than 1% uncertainty
- Detection of CCSN with a JUNO trigger strategy for Multi-Messenger physics
- Possible first detection of neutrinos from DSNB
- Precise measurement of total geoneutrino flux:
  - JUNO will reach the level of Borexino and KamLAND (15%) within few years, assuming fixed chondritic Th/U, and improve it to 10% in 6 years
- Potential to observe signal from mantle: JUNO is expected to provide the most statistically significant measurement, complementary to KamLAND and Borexino. Ongoing effort on the local geological model will improve the result.

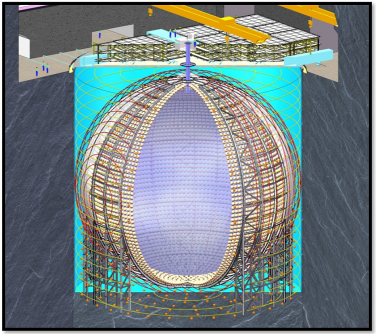



Thank you for your attention

Back-up

JUNO experiment detector concept

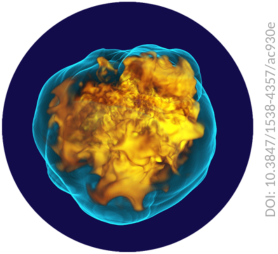
- 10^5 events in 6 year of data taking to achieve the determination of neutrino mass hierarchy at $3-\sigma$.
- Energy resolution 3%@1 MeV:
  1) high liquid scintillator light yield and transparency
  2) high photo-cathode coverage and photo detection efficiency .
- Energy scale uncertainty $< 1\%$:
  1) calibration system
  2) stereo-calorimetry.



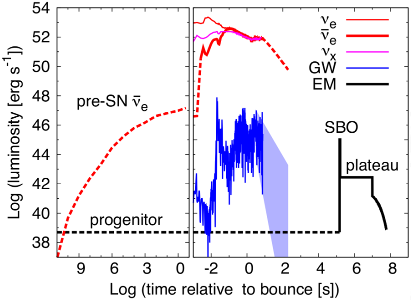
Experiment	Daya Bay	Borexino	KamLAND	JUNO
LS mass	20/detector t	~300 t	~1000 t	~20 000 t
Photon collection	~160/MeV	~500/MeV	~250/MeV	~1400/MeV
Energy resolution	~7.5%@ 1 MeV	~5%@ 1 MeV	~6%@ 1 MeV	2.9% @ 1 MeV
PMT number	192 8-in.	2212 8-in.	1325 20-in. & 554 17-in.	17612 20-in. & 25600 3-in

CCSN as multi-messenger (MM)

- CCSN are source of :
  - neutrinos of different flavors ($\nu_e, \overline{\nu}_e, \nu_x$).
  - gravitational wave (GW).
  - photons (EM).
- Neutrino burst at the same time as GW peak and $\sim$ 1 day before Shock break out (SBO) EM emission. $\rightarrow$ early alert for the follow-up



- Source position and distance estimation crucial for MM follow-up $\rightarrow$ timing of neutrino signal is key for the parameter estimates
- JUNO alert time (latency): 15-20 ms @10 kpc
- JUNO signal arrival time uncertainty: 2-3 ms @10 kpc

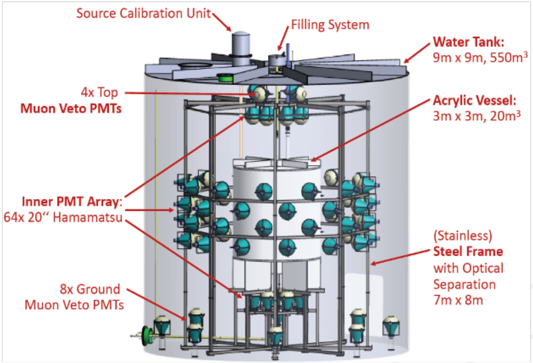


Liquid scintillator

- solvent: Linear Alkyl Benzene doped with 2.5 g/l PPO and 3 mg/l bis-MSB
- highest possible light yield:
  - long attenuation length measured: > 20 m at 430 nm
- high radio-purity required:
  - For reactor anti-neutrinos :
    1. $^{238}U/^{232}Th < 10^{-15}$ g/g
    2. $^{40}K < 10^{-16}$ g/g
    3. ^{210}Pb 10^{-22} g/g
  - For solar neutrinos:
  - For reactor anti-neutrinos :
    1. $^{238}U/^{232}Th < 10^{-17}$ g/g
    2. $^{40}K < 10^{-18}$ g/g
    3. ^{210}Pb 10^{-24} g/g
- a a LS purification pilot plant built and commissioned at Daya Bay. A. Abusleme et al., *JUNO+Daya Bay collarborations*, Nucl. Instr. Meth. **A 988** (2021) 164823, `arXiv:2007.00314`
- We already managed to get ^{222}Rn suppression up to 94%

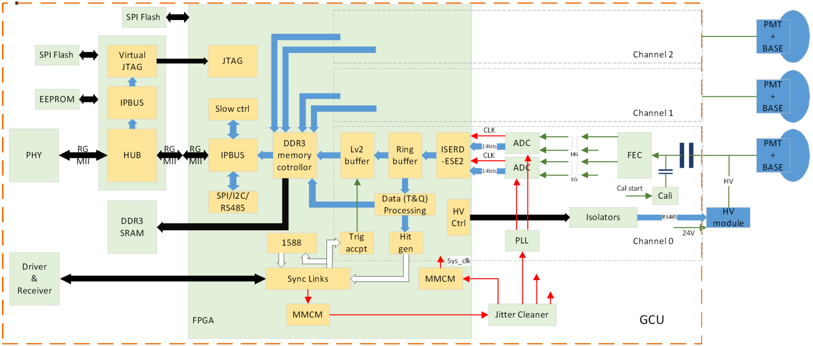
OSIRIS (Online Scintillator Internal Radioactivity Investigation System) as 20 ton liquid scintillator (LS) detector is used to monitor the radio-purity during LS filling and monitor the quality of LS entering the JUNO CD.

- solvent: Linear Alkyl Benzene
- Sensitivity: 10 g/g for U/Th within 24 h measurement. Measure ∼19 t LS per day
- Detector: 81 20" PMTs for photon detection
- 2.5 m water shielding + 12 20" PMTs
- filling of the OSIRIS detector begin of October 2023



The OSIRIS Detector

Global control unit (GCU)



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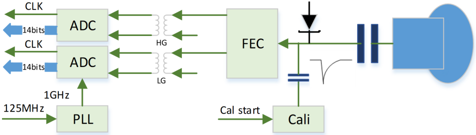

- Dynamic ranges:
  - Low Gain(8:1): 0~7.5V(4000pe)
  - High Gain(1:1): 0~960mV(128pe)
- Dual channels ADCs.
- Energy resolution: 0.1pe@1pe, 1%@>100pe
- Analog bandwidth: 200MHz
- Adjustable bias count
- Adjustable test pulse inject
- Over-voltage protection from circuit and FEC chips itself.

- FEC: A current amplifier ASIC designed by Yan Xiongbo(IHEP).
- Balun: single-end to differential converter
- ADC: 2 channels analog to digital converter designed by Li Fule(Tsinghua)
- PLL: LMX2581SQE the RMS jitter is 100fs
- Calibration circuit: generate a test pulse to calibrate the full chain of front-end circuit.
- Protection circuit: with 2 diodes BAS16J.

Global trigger scheme