ULB UNIVERSITÉ LIBRE DE BRUXELLES

Prospects for geo-neutrinos and supernova neutrinos with JUNO

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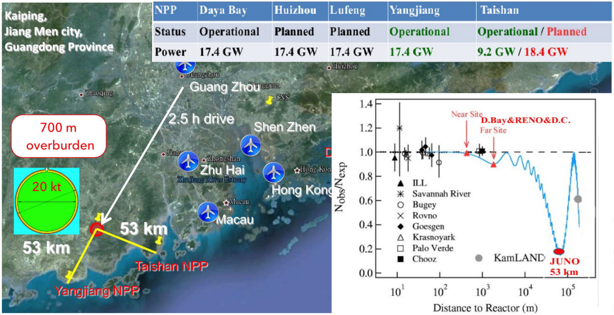
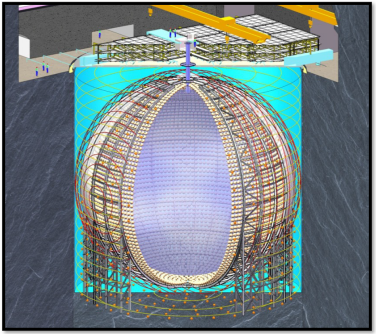
- JUNO (Jiangmen Underground Neutrino Observatory) is a medium baseline reactor neutrino experiment (53 km from the nuclear cores) .
- Its main objective is to determine the neutrino mass hierarchy using anti-neutrino flux coming from 8 nuclear reactors dispatched in two nuclear power plans (the combined 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

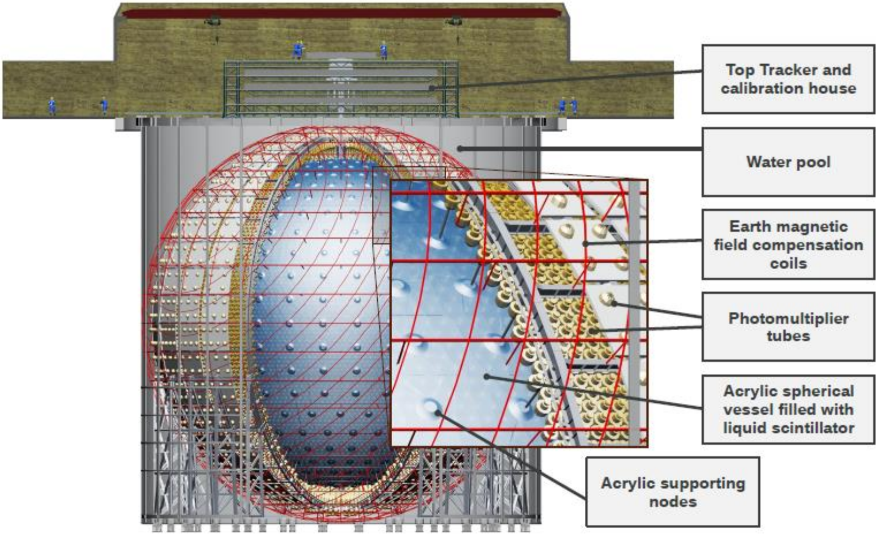
JUNO experiment detector concept

- 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.



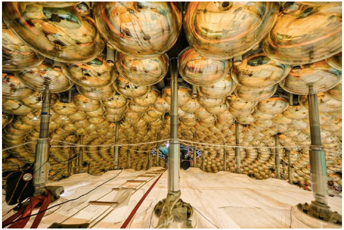
Experiment	Daya Bay	Borexino	KamLAND	JUNO
LS mass	20/detector t	~300 t	~1000 t	~20 000 t
Photon collection	~160/MeV	~500/MeV	~250/MeV	~1400/MeV
Energy resolution	~7.5%@ 1 MeV	~5%@ 1 MeV	~6%@ 1 MeV	2.9% @ 1 MeV
PMT number	192 8-in.	2212 8-in.	1325 20-in. & 554 17-in.	17612 20-in. & 25600 3-in

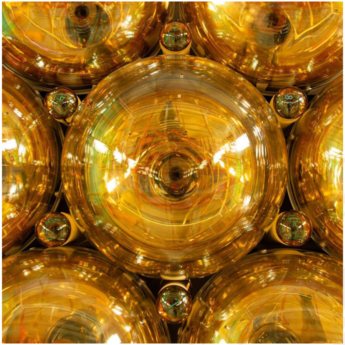
The JUNO detector



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)





Neutrino Physics with JUNO

JUNO have a rich physics potential :

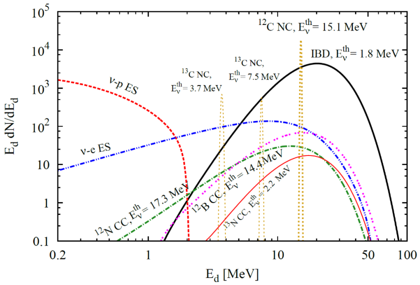
- Neutrino mass ordering with reactor $\overline{\nu_e}$ $\rightarrow$ see Mei's talk
- Earth's atmospheric neutrino
- Solar neutrino from ^8B
- Core collapse supernova (CCSN) neutrino studies $\rightarrow$ this talk
- Supernova diffuse neutrino background studies $\rightarrow$ this talk
- Geo-neutrinos coming from desegregation of Uranium (U) and Thorium (Th) in the mantle and the crust $\rightarrow$ 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	0-3 MeV

Core-Collapse Supernova (CCSN)

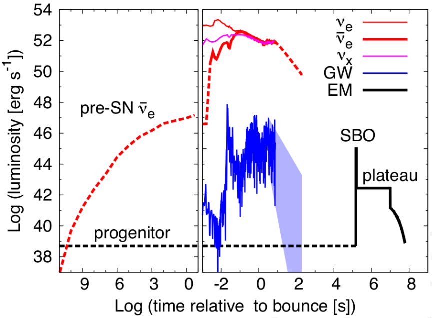
- JUNO has a great potential to observe several astronomical events in neutrinos:
  - Supernovae such as Core-Collapse Supernova (CCSN)
  - Neutron star mergers
  - Gamma ray bursts
- A CCSN releases 99% of its energy in neutrinos and antineutrinos of all flavors.
- Rate of CCSN in the Milky Way is 1.63 ± 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 $\rightarrow$ constrain CCSN physics by measuring :
  - CCSN neutrino spectrum
  - CCSN lightcurve



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

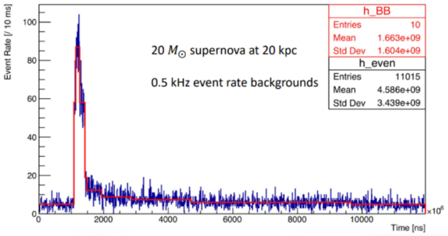
CCSN as multi-messenger (MM)

- 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

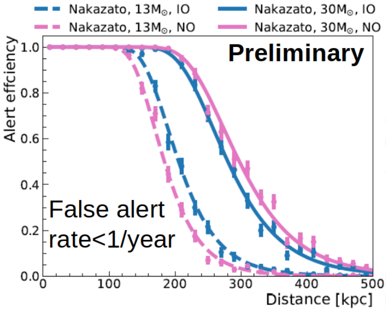


Identifying an astrophysical transient signal

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

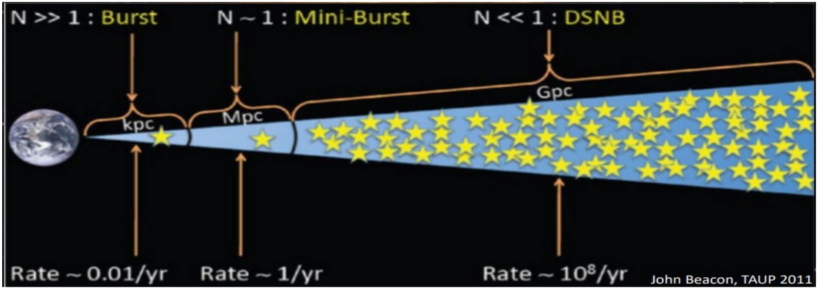


- Prompt Monitor:
  - Higher energy threshold (8MeV)
  - Faster alerts
- Online monitor /Global trigger:
  - IBD candidates (Eth 1MeV)
  - Lower background
- Multi-messenger (MM) trigger:
  - Lower energy threshold (<0.1 MeV)
  - Increase signal statistics
- Paper coming soon !



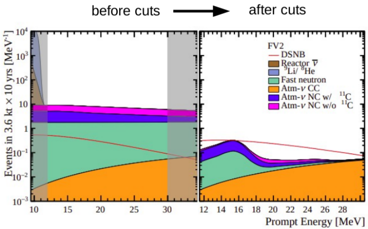
Diffuse supernova neutrino background

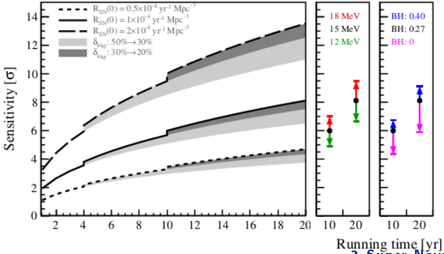
- Diffuse Supernova Neutrino Background (DSNB) = superposition of neutrino signals from all past supernova explosions, yet to be observed.
- Holds the precise information on the average CCSN neutrino spectrum, cosmic star-formation rate and fraction of failed black-hole forming SNe
- Garanteed steady 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

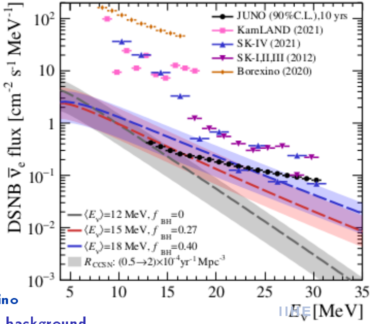


Diffuse supernova neutrino background

- 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

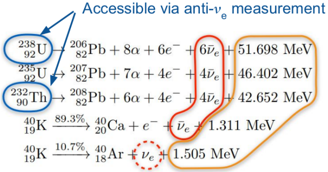


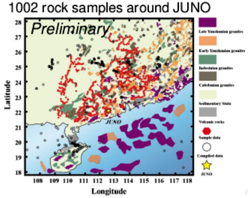




Geoneutrino

- 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 . **[Borexino , Kamland]**, Juno expect $\sim$ 400 event per year

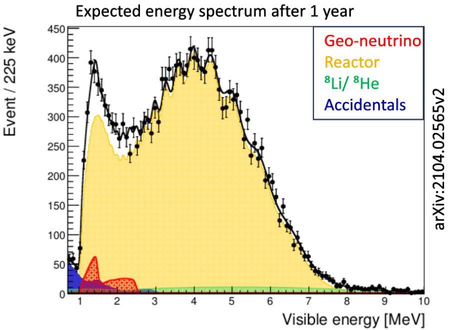




1 TNU (Terrestrial Neutrino Unit) = 1 event / 10^{32} target protons (~1kton LS) / year with 100% detection efficiency

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.