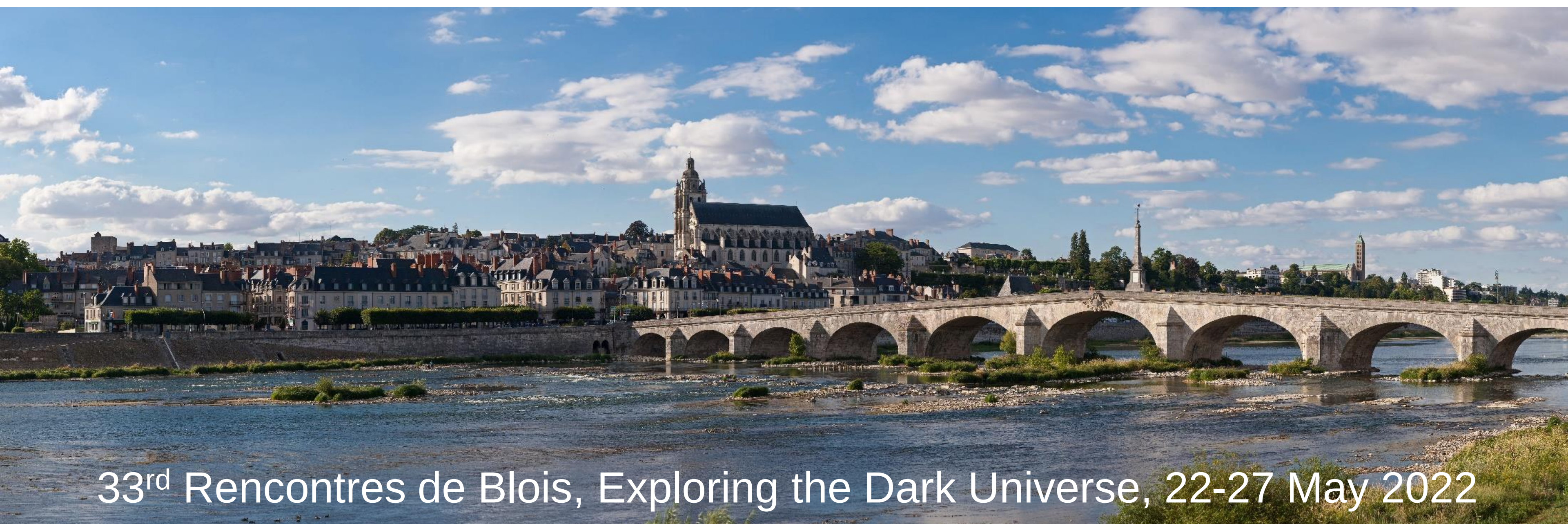
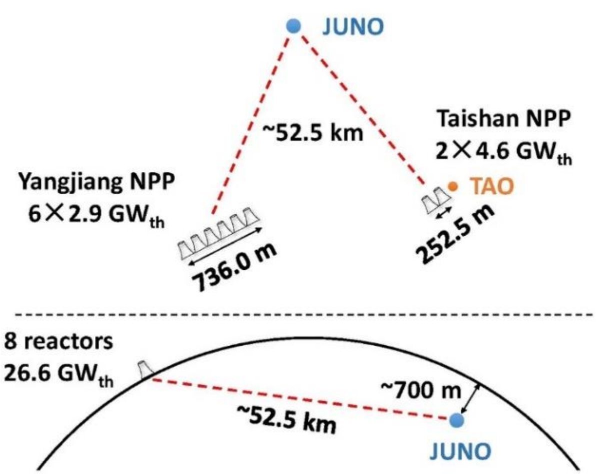
Status of the JUNO experiment and physics potential to detect low energy neutrinos from CCSN, DSNB, Sun and inner Earth

Frédéric Perrot *frederic.perrot@u-bordeaux.fr*

on behalf of the JUNO collaboration



Jiangmen Underground Neutrino Observatory



- JUNO experiment under construction in Jiangmen province in China at ~53 km from two nuclear power plants (total thermal power of 26.6 GW)
- Main goal is the determination of neutrino mass ordering at 3σ level in 6 years of data taking using reactor electron antineutrinos
- Detector located at 700 m depth to reduce muon flux and muon induced backgrounds
- Ancillary 1-ton TAO detector (Taishan Antineutrino Observatory) located at ~30 m from a reactor to precisely measure the neutrino energy spectrum

The JUNO Collaboration

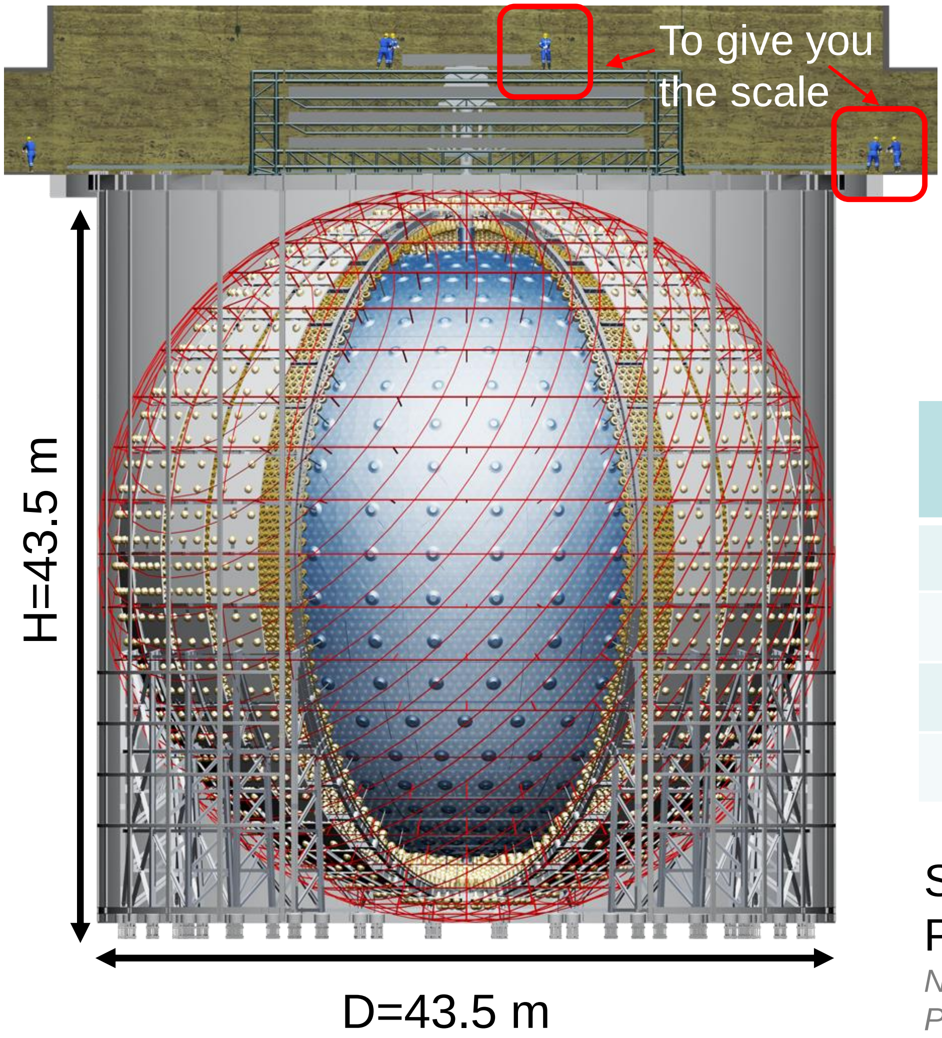
77 institutions, ~650 members

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		

The JUNO Collaboration

Last meeting in person in January, 2020 in Nanning, China

JUNO: a huge liquid scintillator detector



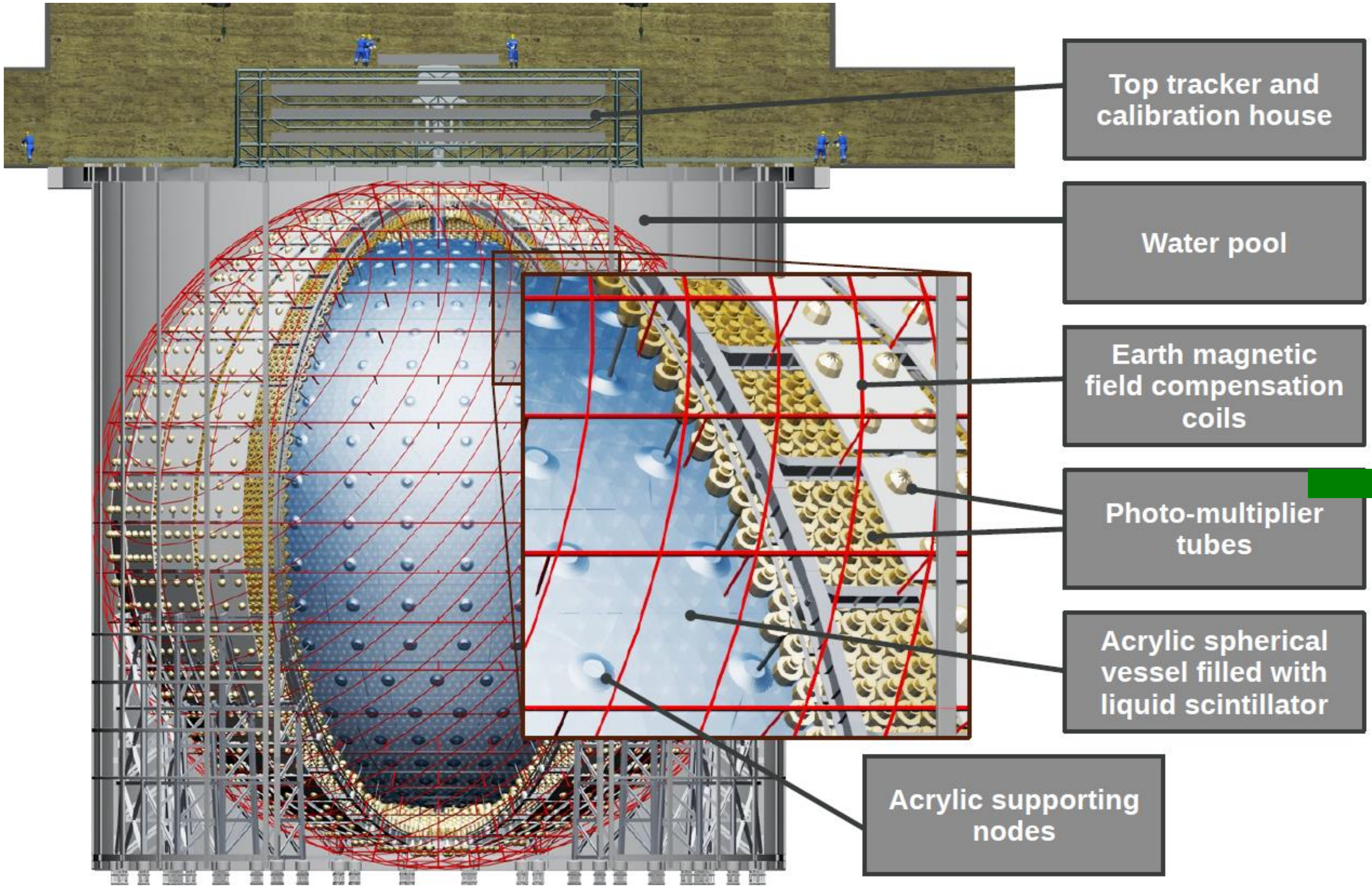
- A 20 kton liquid scintillator experiment
  → the biggest LS detector ever built !
- An acrylic sphere of 35.4 m diameter immersed in a cylindrical water pool
- A large and precise calorimeter

Experiment	Mass (tons)	Energy resolution at 1 MeV (σ)
Daya Bay	20	~7.5%
Borexino	~300	~5%
KamLAND	~1,000	~6%
JUNO	**~20,000**	**~3%**

Successful R&D program on LS transparency, PMT performances and calibration system

Nucl. Instrum. Meth. A 988 (2021) 164823
Prog. Part. Nucl. Phys. 123 (2022) 103927
JHEP 03 (2021) 004

JUNO: a huge liquid scintillator detector



17612 20-inch PMTs
25600 3-inch PMTs
→ 78% photocoverage

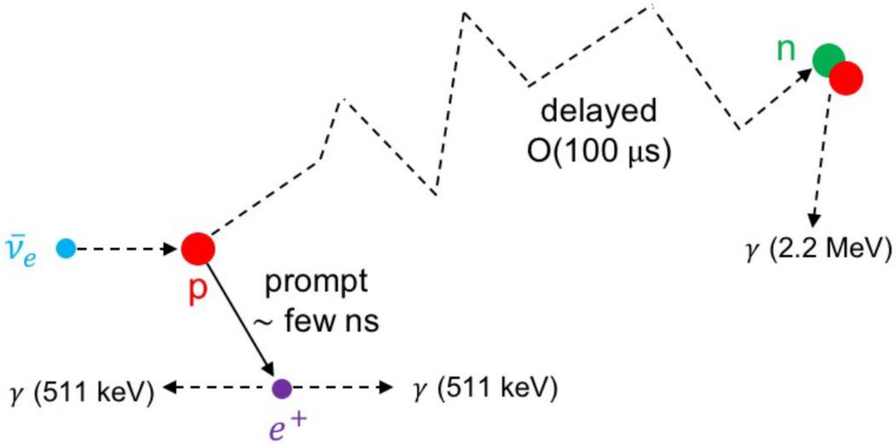
Electron antineutrino detection

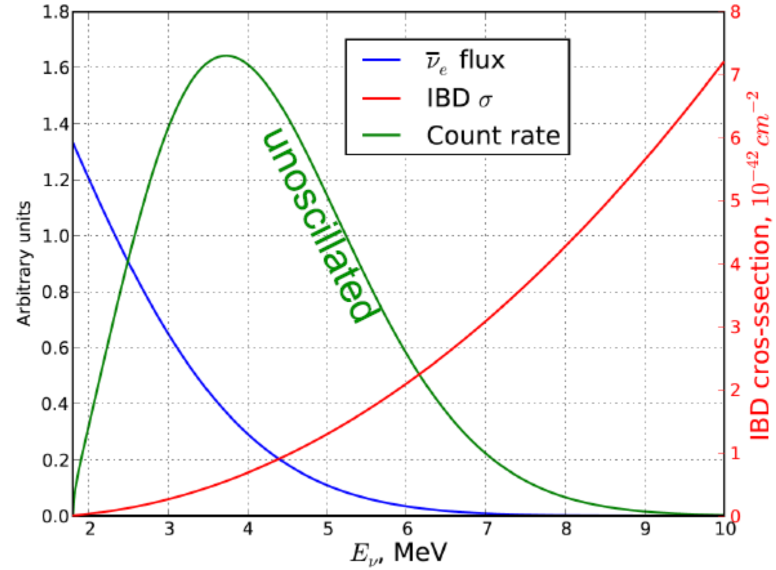
- Electron antineutrinos detected by Inverse Beta Decay (IBD) :

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Energy threshold: 1.8 MeV

Visible energy $E_{vis} = E(e^+) = E(\bar{\nu}_e) - 0.8$ MeV

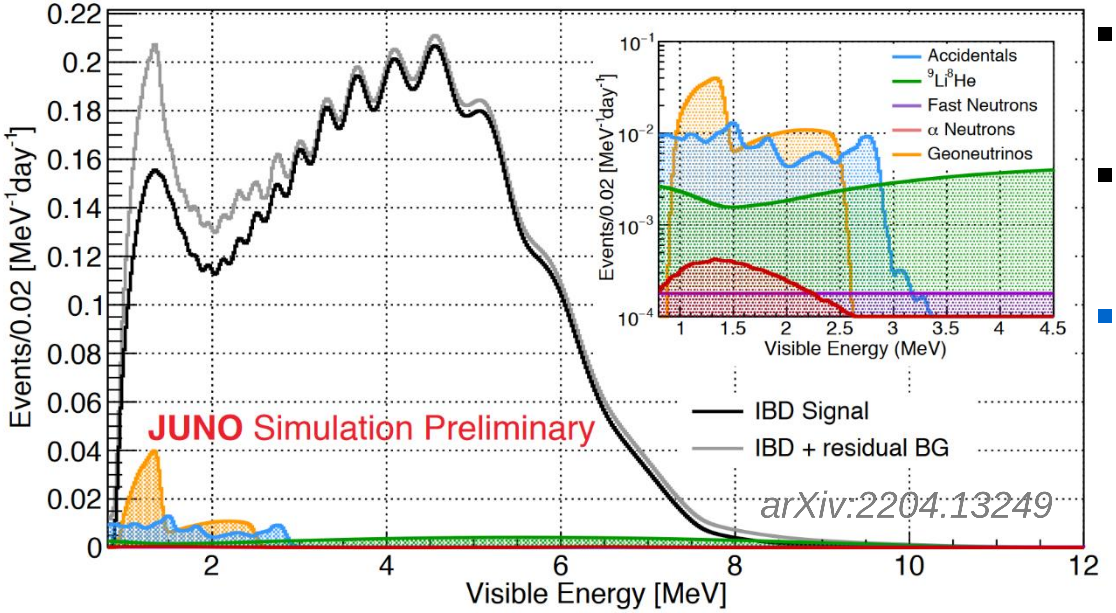




Neutrino signature :

- Prompt signal from e^+: ionization+annihilation in 2γ (1-10 MeV) → visible energy
- Delayed signal from neutron: capture on ^1H (2.2 MeV)
- Time correlation: ~ 200 µs

Signal and backgrounds



- **Visible energy spectrum from oscillated reactor $\overline{\nu_e}$ in JUNO**
- Background contribution from five main sources
- Accidentals are mainly coming from radiogenic elements such as $^{238}U/^{232}Th/^{40}K$ → material screening strategy achieved

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Main selection cuts:

- Energy threshold: $E_{vis} > 0.7\ MeV$
- Fiducial volume cut: $\mathrm{R_{LS}} < 17.2\ m$
- Timing cut: $\Delta T_{p-d} < 1\ ms$
- Spatial cut: $R_{p-d} < 1.5\ m$
- Cosmic muon veto cuts

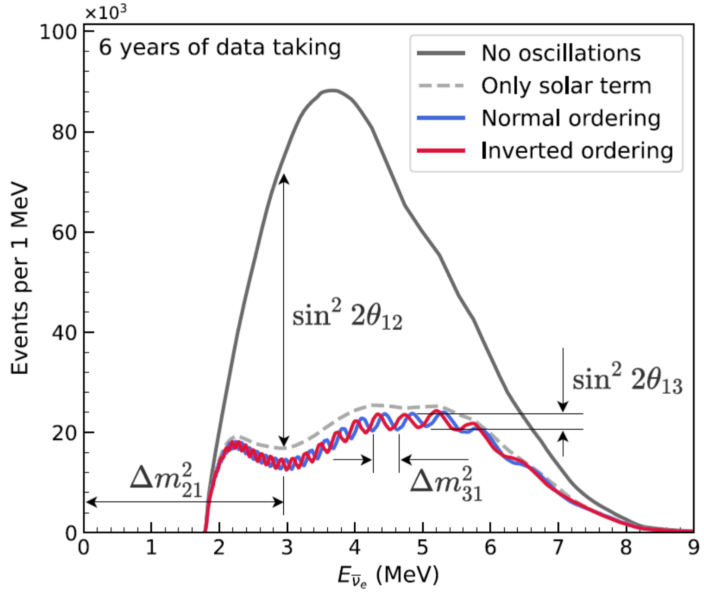
Background	Rate (day^{-1})
Geo-neutrinos	1.2
Accidentals	0.8
^{9}Li/^{8}He	1.4
Fast neutrons	0.1
^{13}C(α,n)^{16}O	0.05

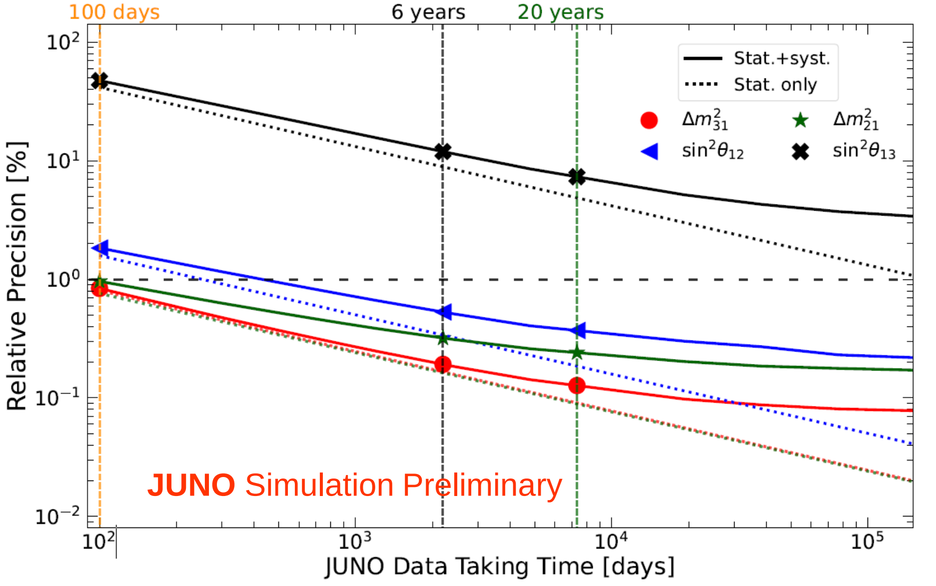
→ after selection cuts, ~47 $\bar{\nu}_e$ evt/day (~82% efficiency) and ~3.6 bckg evt/day

Neutrino oscillation studies using reactor $\overline{\nu_e}$

- JUNO's main goal is to determine the Neutrino Mass Ordering (normal or inverted) at 3σ level using spectral information in the oscillation pattern
- JUNO will detect for the 1st time Δm^2_{21} and Δm^2_{32} oscillation modes simultaneously

arXiv:2204.13249



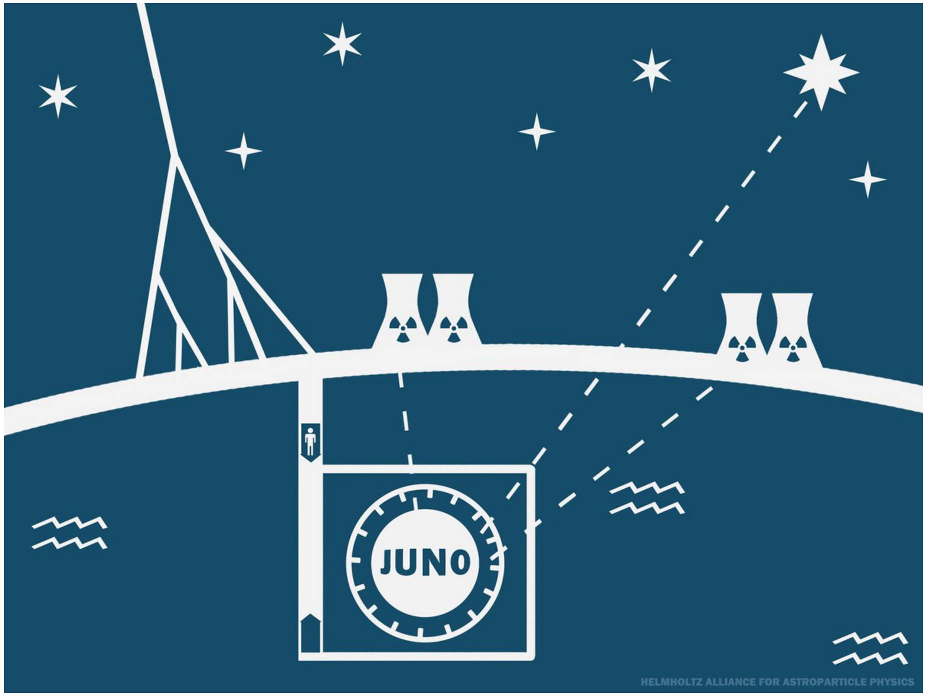


arXiv:2204.13249

	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
PDG2020	1.4%	2.4%	4.2%	3.2%

→ Subpercent precision will be reached for 3 of the parameters with JUNO only !

JUNO: an observatory for rare events



JUNO will have a vast neutrino program beyond reactor antineutrinos !

- "Neutrino Physics with JUNO", J. Phys. G **43** (2016) no.3, 030401
- "JUNO physics and detector", Prog. Part. Nucl. Phys. 123 (2022) 103927

Neutrino source	Signal rate	Energy range
Reactor	~47 evts/day	0-12 MeV
SN burst	~10^4 evts at 10 kpc	0-80 MeV
Diffuse SN background	2-4 evts/year	10-40 MeV
Sun ^{8}B	hundreds /year	0-16 MeV
Earth	~400 evts/year	0-3 MeV
Earth's atmosphere	hundreds /year	0.1-100 GeV

→ Described in this talk

Core Collapse Supernova neutrinos

- A Core-Collapse Supernova (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/century *New Astronomy Vol.83, 101498*
- JUNO with 20 kt LS has excellent capability of detecting all neutrino flavors

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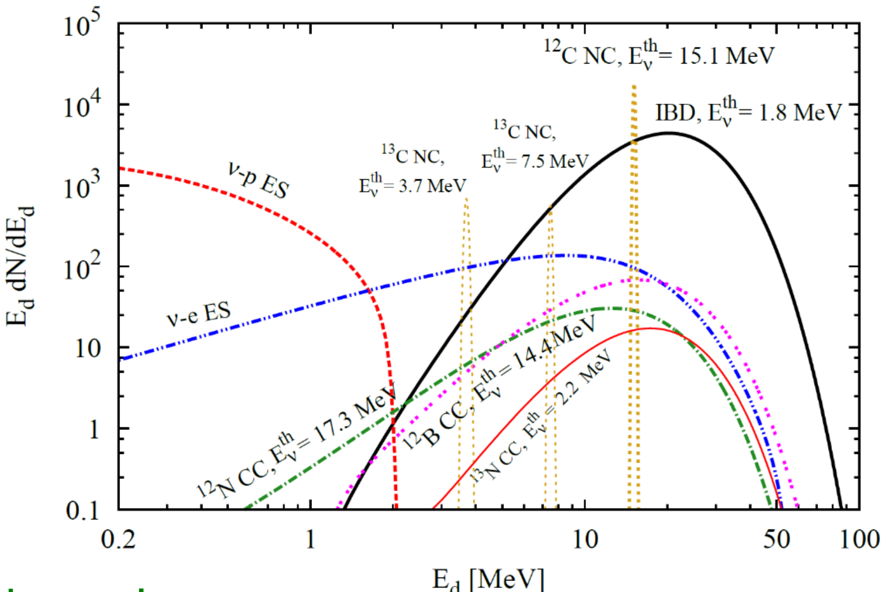


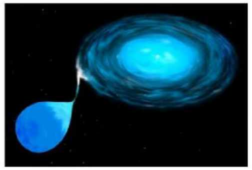
Type	Process	Nb of evts @10 kpc
CC (IBD)	$\bar{\nu}_e + p \rightarrow e^+ + n$	~5000
eES	$\nu + e \rightarrow \nu + e$	~300
pES	$\nu + p \rightarrow \nu + p$	~2000
NC	$\nu + {}^{12}C \rightarrow \nu + {}^{12}C^*$	~300
CC	$\nu_e + {}^{12}C \rightarrow e^- + {}^{12}N$ $\nu_e + {}^{12}C \rightarrow e^- + {}^{12}B$	~200

Main goals:

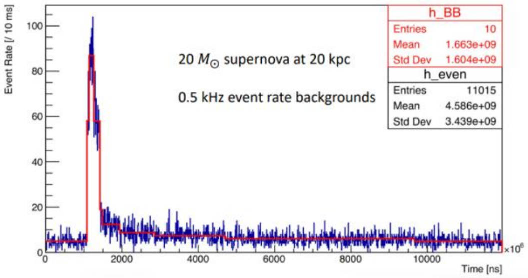
- Measurement of flavour content, time evolution, flux, energy spectrum
- Study of star parameters, SN physics, late-stage stellar evolution
- Constrain of absolute neutrino mass m_ν < (0.83 ± 0.24) eV (95% CL) @10 kpc

Multi-Messenger trigger in JUNO

- JUNO has a great potential to observe several astronomical events in neutrinos:
  - Supernovae (Pre-burst, type Ia, CCSN type II)
  - Neutron star mergers
  - Gamma ray bursts

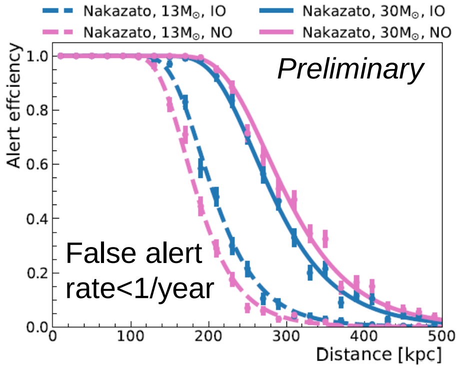



- Design of a Multi-Messenger (MM) trigger system in order to monitor transient signals in real time from the entire sky via all neutrino flavors



- Two trigger systems in JUNO: Global trigger with E_{thr} ~200 keV and MM trigger with E_{thr} ~20 keV

- Online SN monitoring with IBD events: 50% alert efficiency for 30 solar masses at ~300 kpc



→ JUNO will be a powerful neutrino telescope for transient MM observations

→ Major role in the next-generation Supernova Early Warning System (**SNEWS2.0**)

Diffuse Supernova Neutrino Background

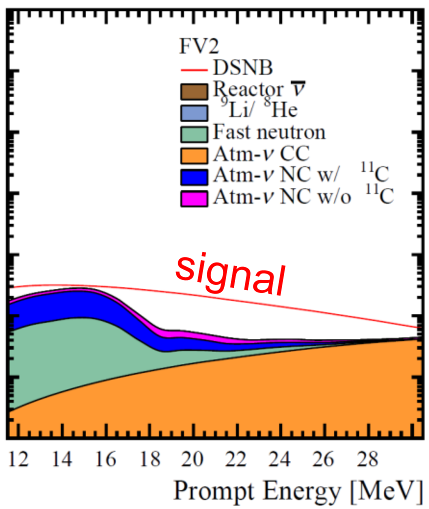
- Diffuse Supernova Neutrino Background (DSNB): integrated signal from all the SN explosions in the Universe.
- Holds the precise information on the average CCSN neutrino spectrum, cosmic star-formation rate and fraction of failed black-hole forming SNe

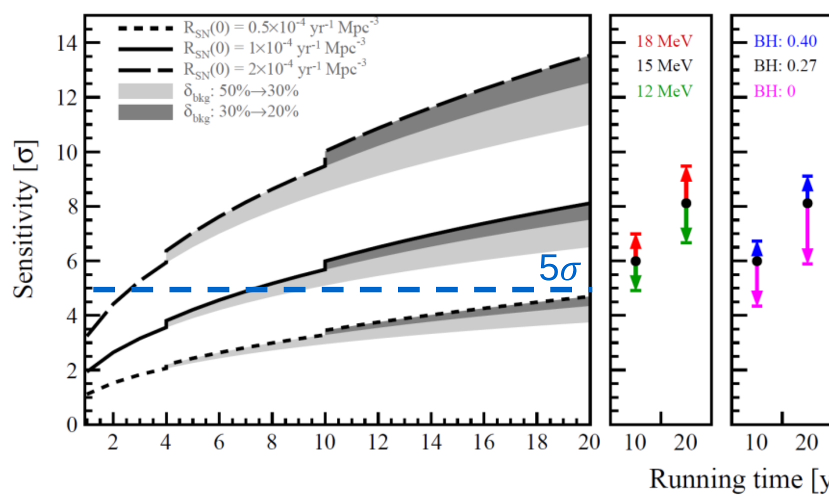
- $\bar{\nu_e}$ IBD DSNB signal in JUNO: constrained at low E (<10 MeV) by reactor $\bar{\nu_e}'s$, at high E by NC atmospheric $\nu's$

→ pulse shape discrimination in order to reduce NC atm $\nu's$ and fast neutrons

→ Optimal energy window [12-30 MeV] with 2-4 events/year expected

arXiv:2205.08830 [hep-ex]





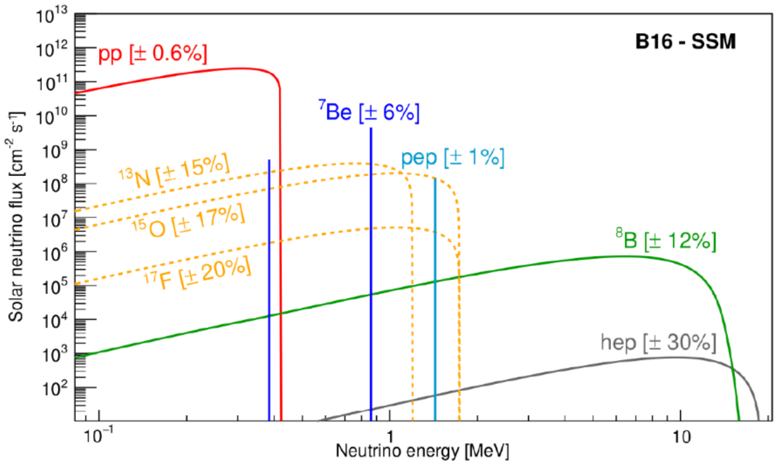
arXiv:2205.08830 [hep-ex]

→ 5σ sensitivity to detect DSNB signal with <10 years using nominal SN rate

→ JUNO will be one of the best candidates to observe DSNB signal for the 1st time

Solar neutrinos

- Neutrinos are produced in thermonuclear fusion reactions in the solar core up to 16 MeV
- Direct information about the solar metallicity
- Study of fundamental neutrino properties and neutrino interactions with matter



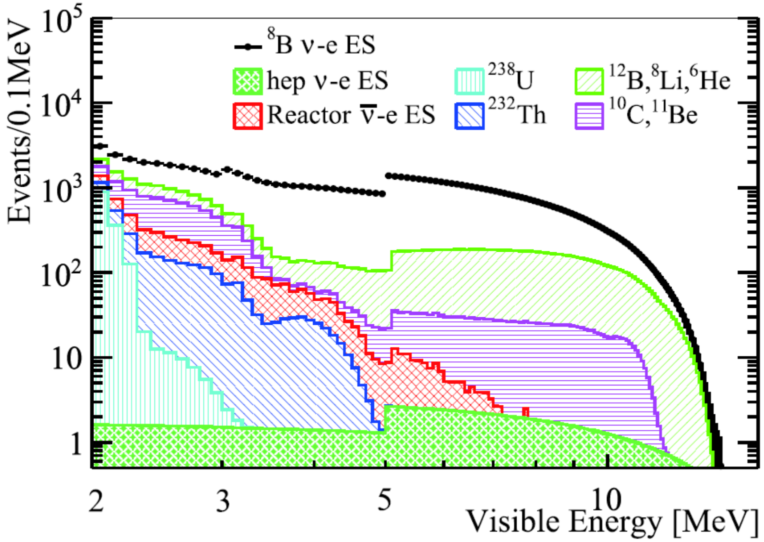
- JUNO can benefit from its huge LS mass to detect thousands of solar neutrinos
- Main channel: Elastic Scattering (ES) on electrons
- Statistics for 200 kton.year exposure

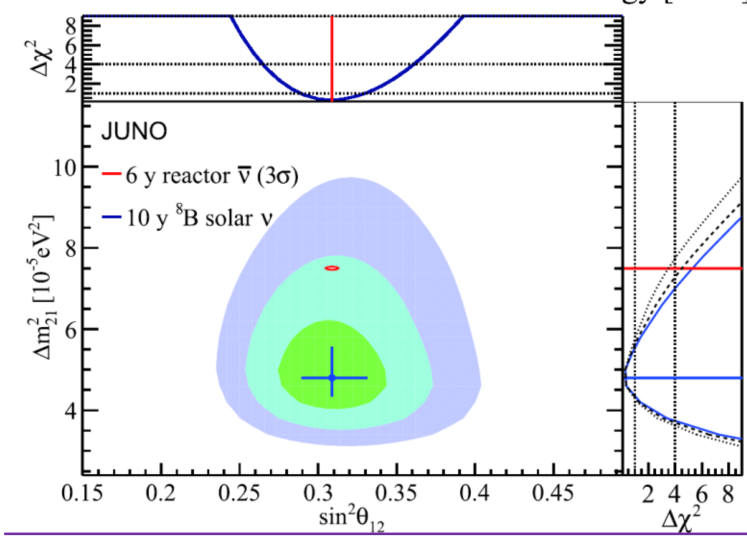
	Type	Reaction	Threshold	Final products	^{8}B	*hep*
1	ES	$\nu + e^- \rightarrow \nu + e^-$	0	e^-	3×10^5	640
2	CC	$\nu_e +^{12}\mathrm{C} \rightarrow e^- +^{12}\mathrm{N}$	16.8 MeV	e^-	0	0.41
3	CC	$\nu_e +^{13}\mathrm{C} \rightarrow e^- +^{13}\mathrm{N}$	2.2 MeV	e^- and ^{13}N decay	3768	14
4	NC	$\nu +^{12}\mathrm{C} \rightarrow \nu +^{12}\mathrm{C}^*\ (1^+)$	15.1 MeV	γ	0.2	5
5	NC	$\nu +^{13}\mathrm{C} \rightarrow \nu +^{13}\mathrm{C}^*\ (\frac{3}{2}^-)$	3.685 MeV	γ	3165	13.5

Solar neutrinos

High energy neutrinos: **from ^8B**

*Chinese Phys. C**45** 0230042 (2021)*





*Chinese Phys. C**45** 0230042 (2021)*

- Neutrino-electron ES
- 2 MeV energy threshold
- Assume LS U/Th radiopurity of 10^{-17} g/g
- Background reduction using fiducial volume cuts and active cosmogenic veto

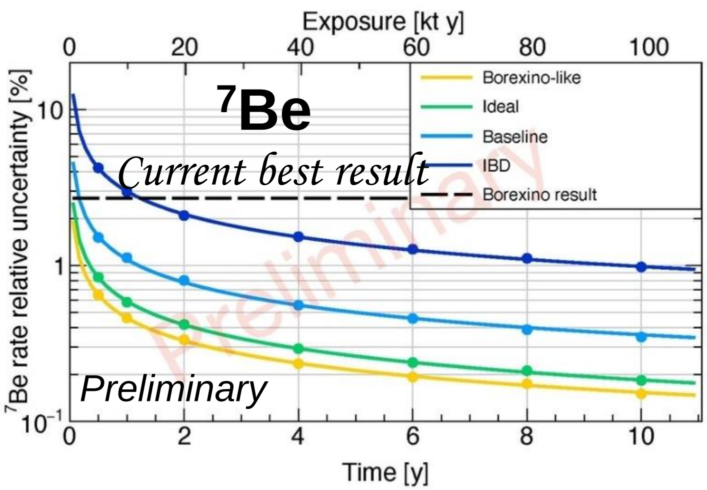
→ 60,000 expected signal events and 30,000 bckg events in 200 kton.year exposure

- Day-night asymmetry at a level of 0.9%
- Upturn of P_{ee} at 3σ if $\Delta m^2_{21} = 7.5 \times 10^{-5}\ eV^2$
- *Under study: independent ^8B solar neutrinos fluxes using CC and NC reactions on ^{13}C*
- Possibility to constrain $\sin^2\theta_{12}$ and Δm^2_{21} oscillation parameters using both solar and reactor neutrinos

Solar neutrinos

Low-intermediate energy neutrinos: **from ^{7}Be, pep and CNO**

- Huge statistics with JUNO compared to previous experiments
- Large mass allow to perform stringent fiducial volume cuts (R<13-15 m)
- Sensitivities very dependent on the intrinsic radioactivity of the liquid scintillator (For U/Th impurities, Reactor/Baseline: 10^{-15} g/g, Solar/Ideal:10^{-17} g/g)



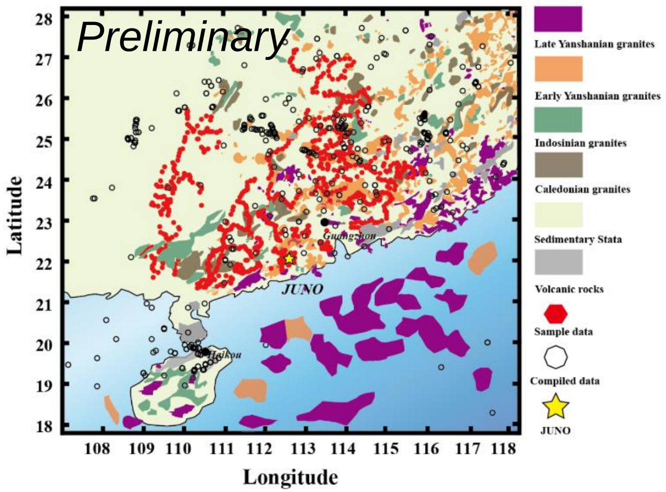
- ✓ Borexino result for **^{7}Be (2.7%)** would be matched in **1 year of data taking** in all the scenarios→ short-term measurements
- ✓ Borexino result for **pep and CNO** may be matched and overcomed in **few years** depending on the scenarios→ long-term meas.

→ JUNO has the potential to detect ^{7}Be, pep and CNO neutrinos with highly improved accuracy with respect to current state-of-the-art (depending on radiopurity scenario)

Geo-neutrinos

- Unique neutrino source to probe the inner structure of Earth, especially the Uranium (U) and Thorium (Th) abundances (no access to ^{40}K due to the 1.8 MeV threshold)
- Measure Th/U ratio in crust and mantle to understand Earth's formation
- Estimation of U and Th radiogenic power contribution to terrestrial heat production

1002 rock samples around JUNO



- Local geological studies ongoing to constrain crustal contribution (and thus derive mantle contribution) and to tackle largest uncertainty sources

- Up to now, only Borexino experiment and KamLAND experiments have detected geo-neutrinos with $52.6^{+9.4}_{-8.6}(stat)^{+2.7}_{-2.1}(sys)$ and $168.6^{+26.3}_{-26.5}$ events, respectively

Geo-neutrinos

- Expected signal in JUNO of 39 TNU (Terrestrial Neutrino Units), i.e. ~400 geo-neutrinos per year → more geo-neutrinos than ever measured in one year only

- The 500 km range of the crust around JUNO will contribute to more than 50% of the total signal → local refined geological models needed for precise measurement of the crustal signal and for disentanglement of the mantle signal

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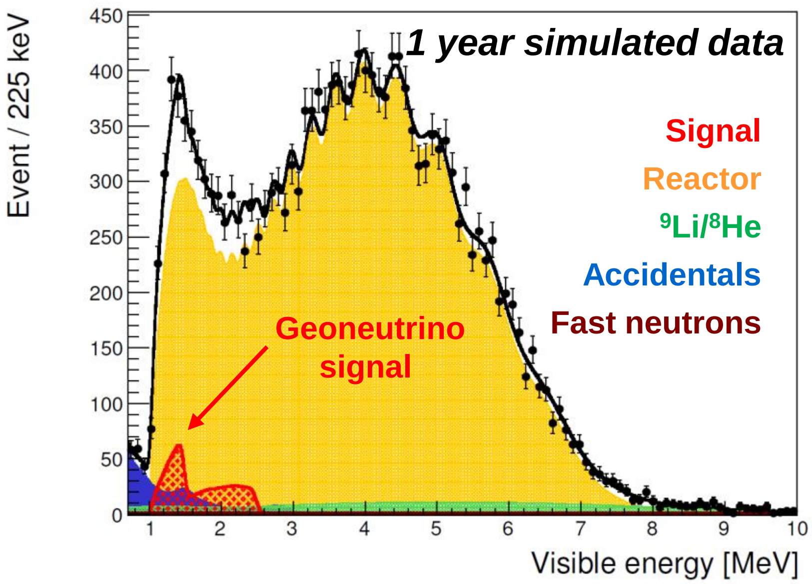
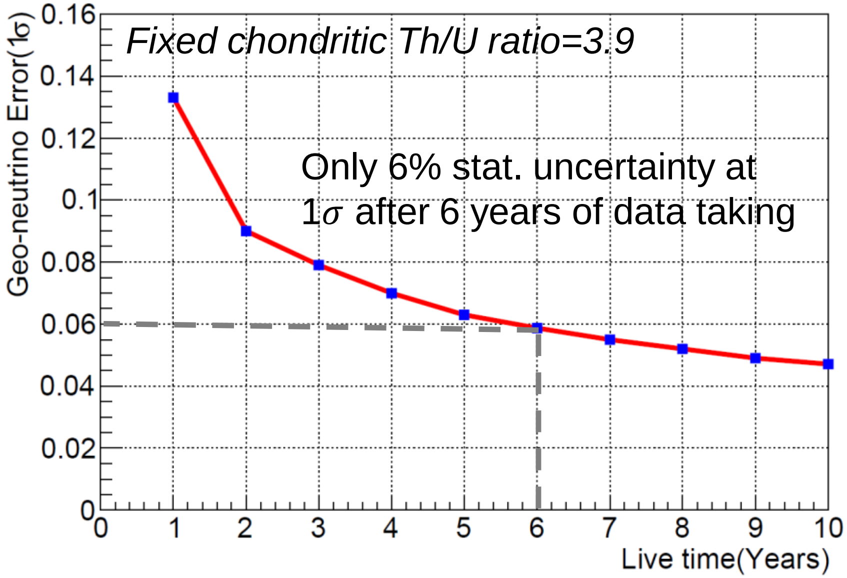
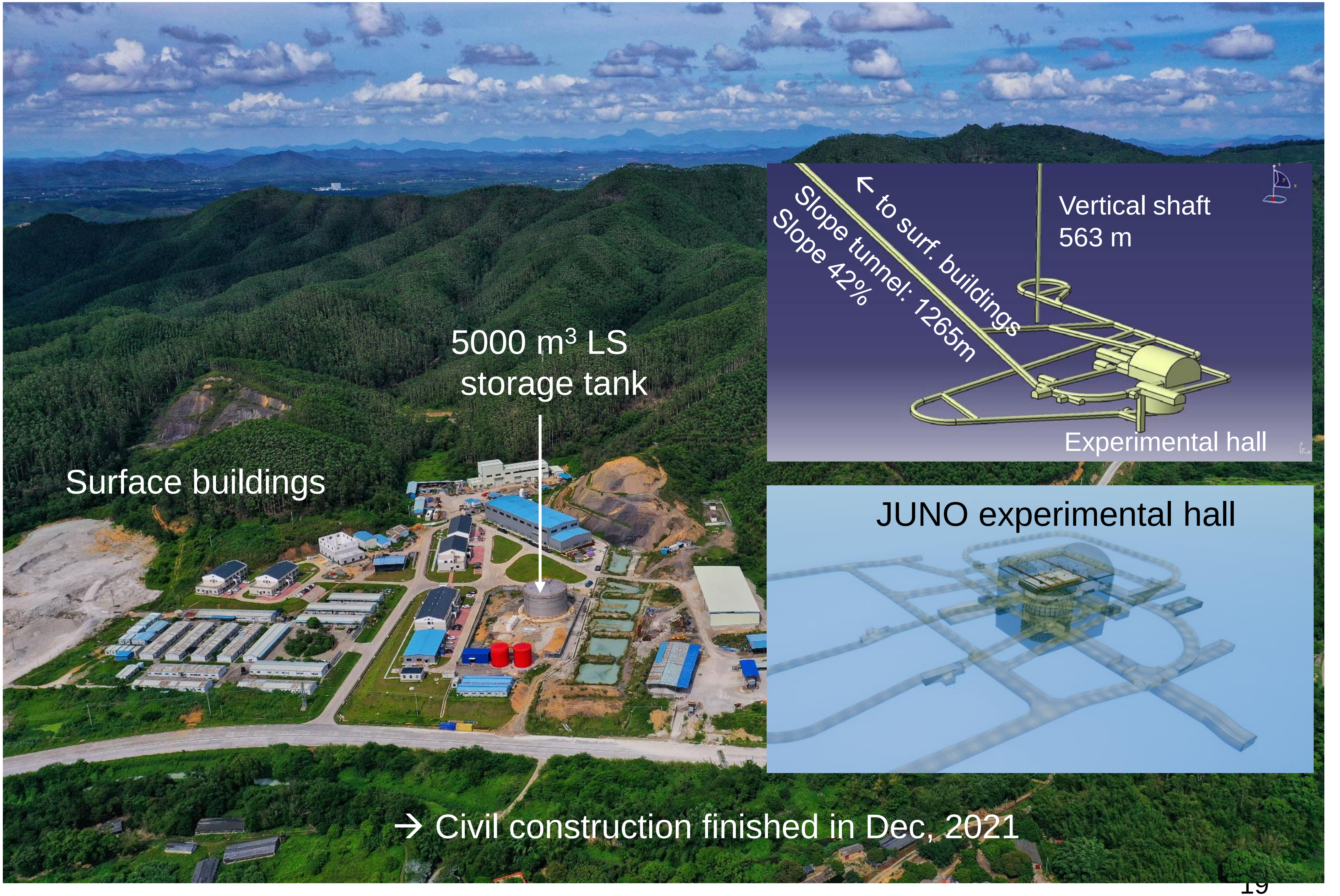


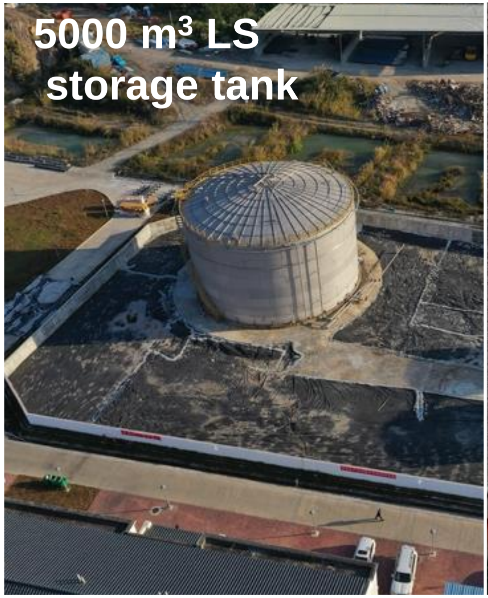


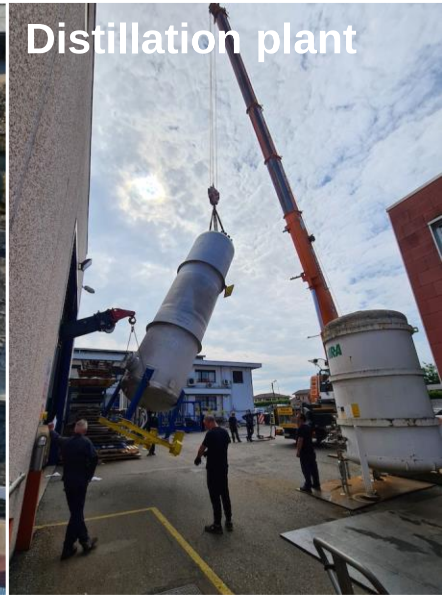
→ JUNO has the potential to constrain Th/U ratio in the observed geoneutrino signal

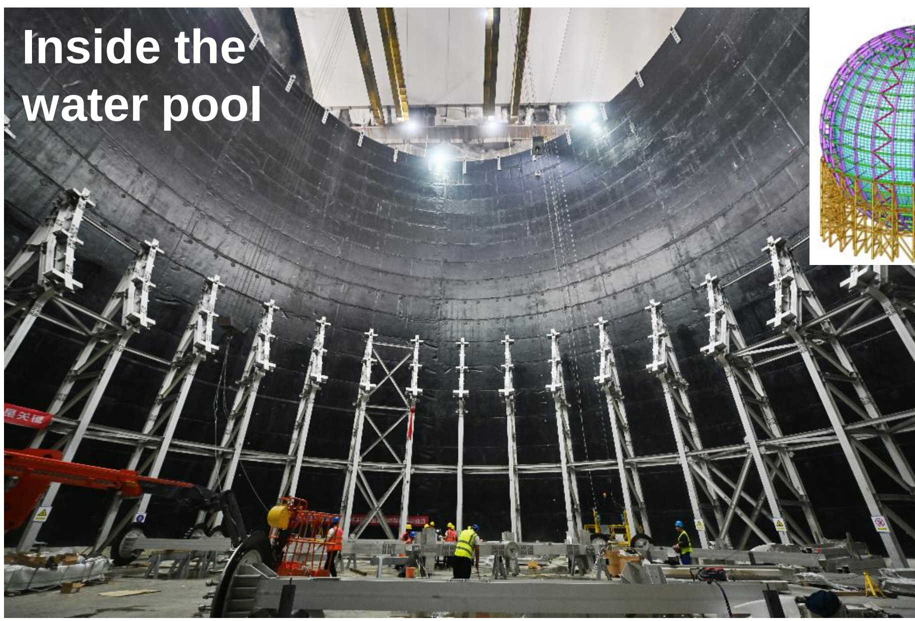
Surface buildings and experimental hall

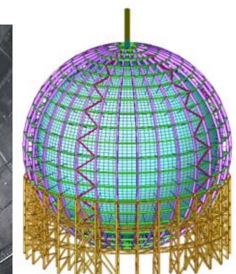


Civil construction and detector installation









Summary and conclusions

- JUNO is a next-generation neutrino experiment with huge performances:
  - the largest LS-based detector with 20 kton
  - an unprecedented energy resolution of 3% (σ) at 1 MeV
  - a precise energy calibration program to reach less than 1% uncertainty

- JUNO will address many neutrino questions:
  - Mass ordering determination at 3σ level and sub-percent precision measurement of 3 oscillation paramaters ($\sin^2\theta_{12}, \Delta m^2_{21}, \Delta m^2_{31}$)
  - Detection of CCSN with a JUNO trigger strategy for Multi-Messenger physics
  - Possible first detection of neutrinos from DSNB
  - Improvement on solar neutrino fluxes (^{8}B,…) depending on the LS radiopurity
  - Potential to constrain Th/U ratio in Earth by detecting $\mathcal{O}$(100) geo-$\nu's$ /year

- JUNO construction: along the realization path despite COVID-19 situation with detector completion and data taking expected by end of 2023