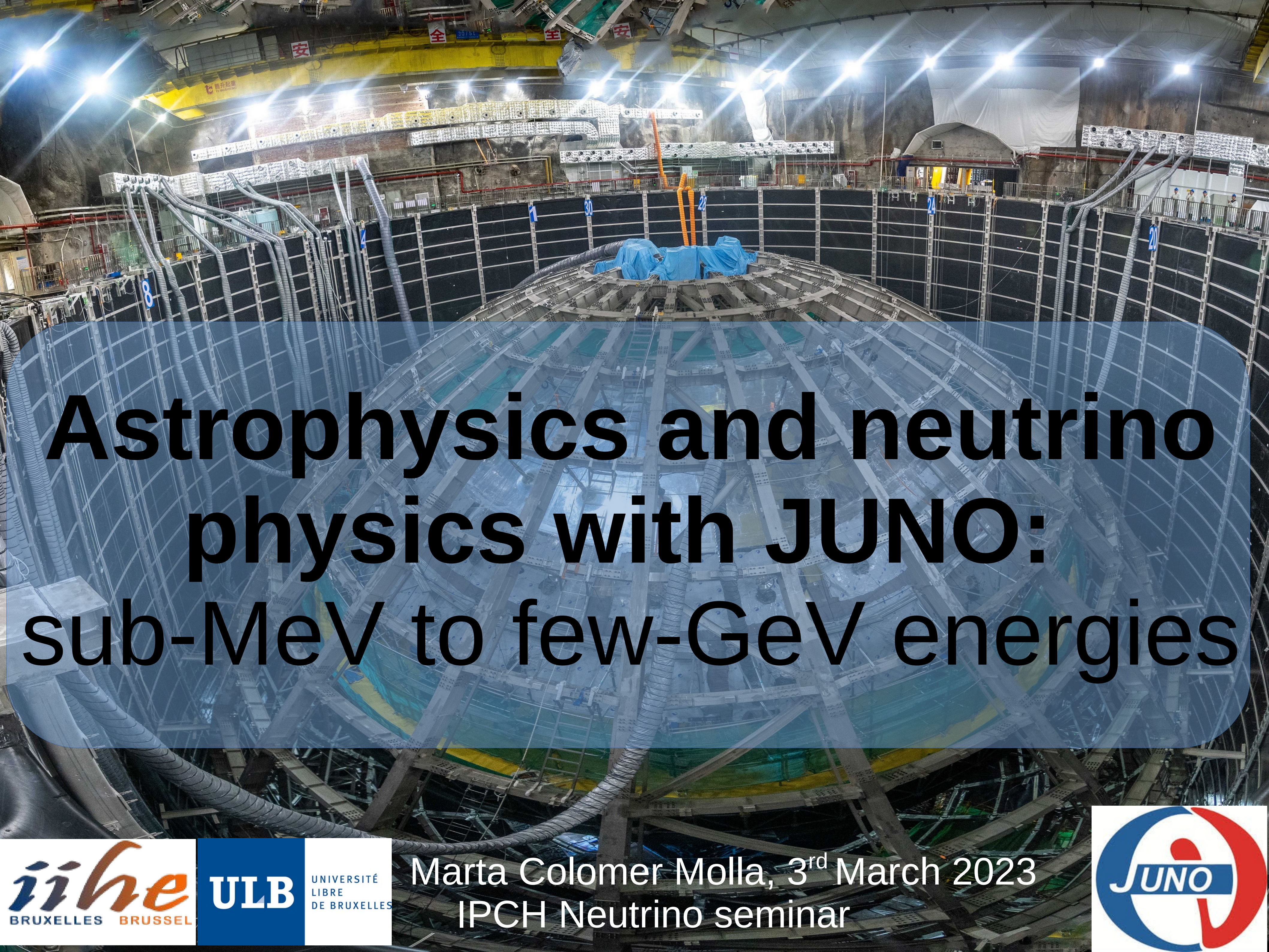


Astrophysics and neutrino physics with JUNO:

sub-MeV to few-GeV energies

Marta Colomer Molla, 3rd March 2023
IPCH Neutrino seminar

The neutrino puzzle

67 years after the discovery of neutrinos…

What we know:

- Three neutrino flavors exist (at least)
- Neutrinos oscillate → they are massive
- Most oscillation parameters are measured
- Astrophysical sources (i.e. the Sun and supernova explosions) produce neutrinos
- Neutrinos can also be produced in reactors or accelerators

The missing pieces:

- What is the neutrino mass ordering?
- What is the he absolute neutrino mass?
- What is the neutrino nature: dirac or Majorana?
- What is the value of CP phase (δ)?
- How many neutrino flavors exist? (sterile neutrinos?)

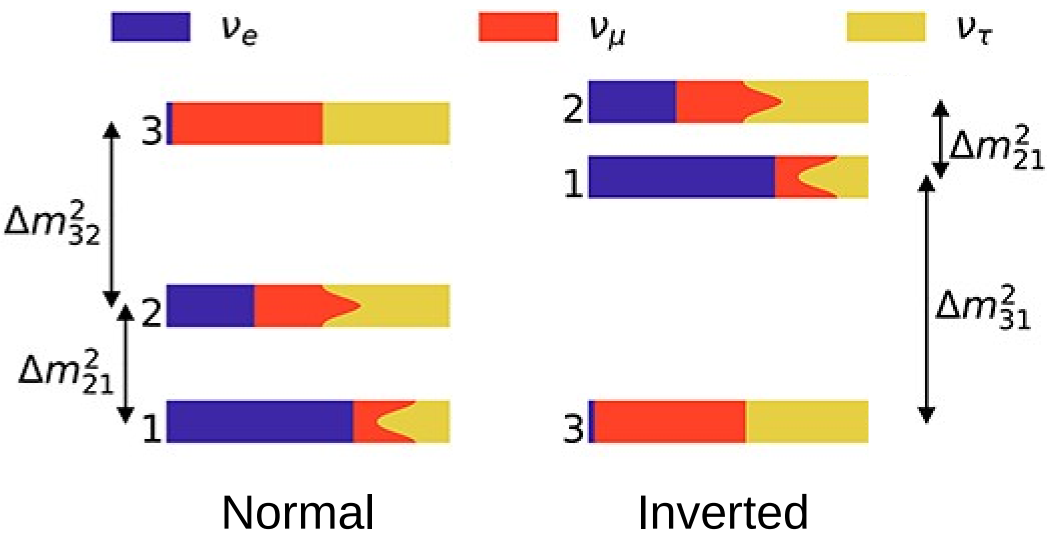
θ_{23} & ΔM^2_{32} | CP phase δ & θ_{13} | θ_{12} & ΔM^2_{21} | Majorana phase

$$\mathbf{V} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric accelerator | reactor accelerator | solar reactor | Double beta decays

Where can reactor neutrinos help particularly?

- **What is the neutrino mass ordering (NMO)?**



Two complementary approaches:

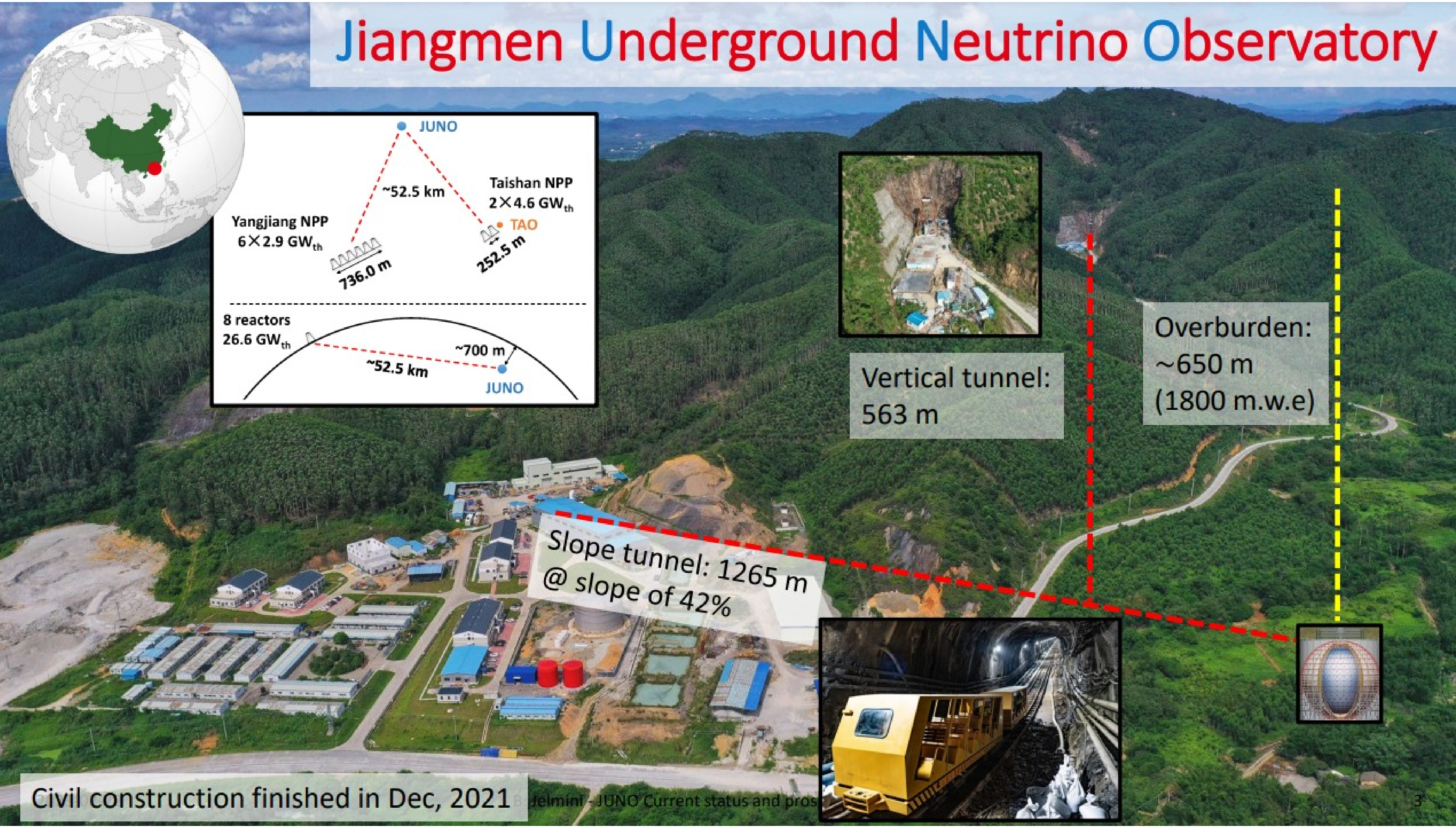
- Matter-enhanced oscillations with accelerator or atmospheric neutrinos
- Vacuum oscillations with reactor neutrinos, independent of matter effects ($\sin^2\theta_{23}$, δ)

Exploit complementarity between the three channels to solve existing degeneracies

Latest NuFIT5.1 (2021) results

	best fit MO	$\Delta\chi^2$(MO)	best fit δ_{CP}	$\Delta\chi^2$(CPC)	oct. θ_{23}	$\Delta\chi^2$(oct.)
accelerator	IO	1.5	275°	2.0	2nd	2.2
+ reactors	NO	2.7	195°	0.4	2nd	0.5
+ atmospheric	**NO**	**7.1**	**230°**	**4.0**	**1st**	**3.2**

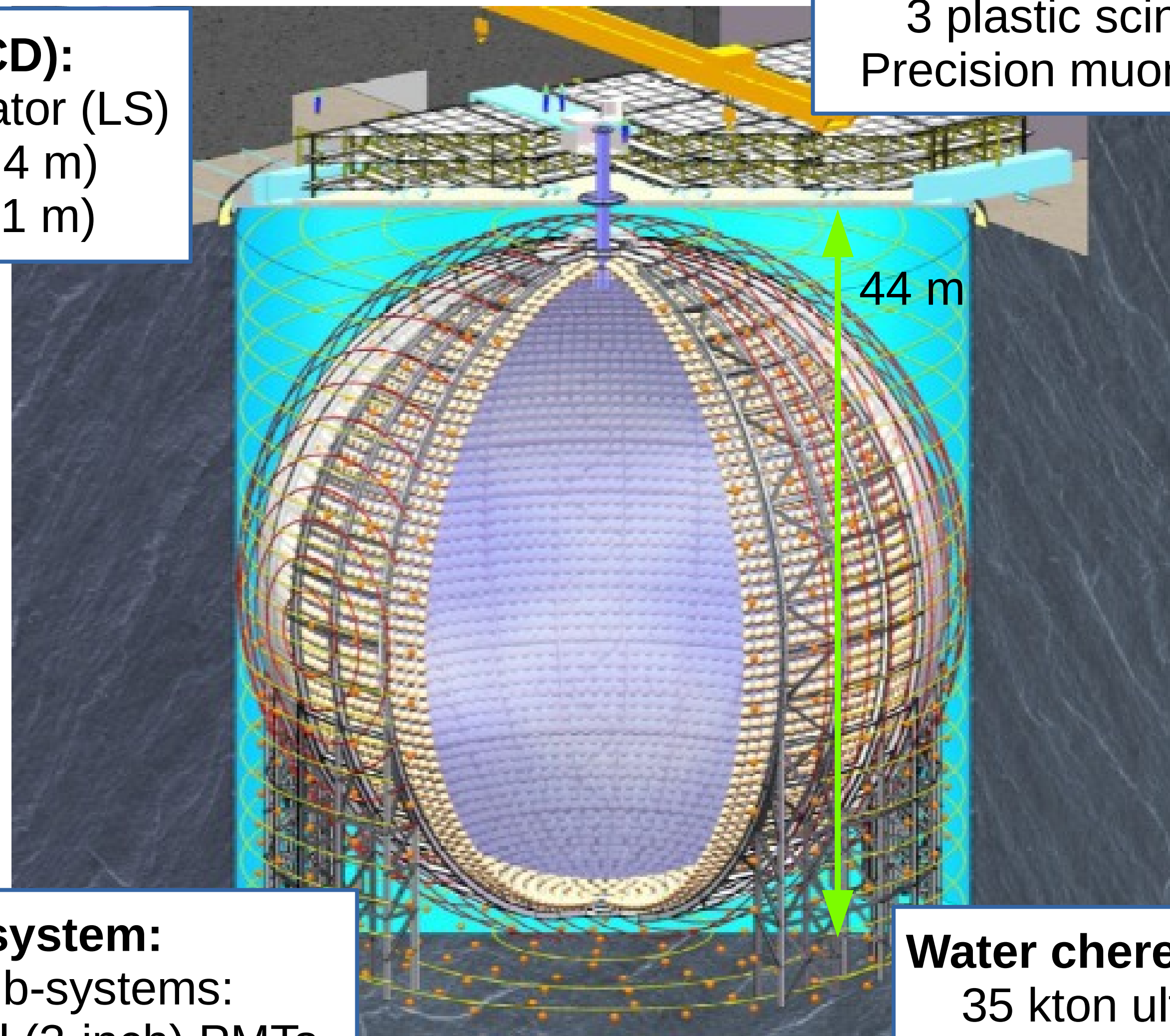
The JUNO detector



The JUNO detector

Central detector (CD):
20 kton of Liquid Scintillator (LS)
Accrylic vessel (ϕ 35.4 m)
Steel structure (ϕ 40.1 m)

Top Tracker:
3 plastic scintillator layers
Precision muon tagging (veto)



Light detection system:
>40000 PMTs in 2 sub-systems:
large (20-inch) and small (3-inch) PMTs

Water cherenkov detector:
35 kton ultra-pure water
2400 20-inch PMTs

The JUNO detector

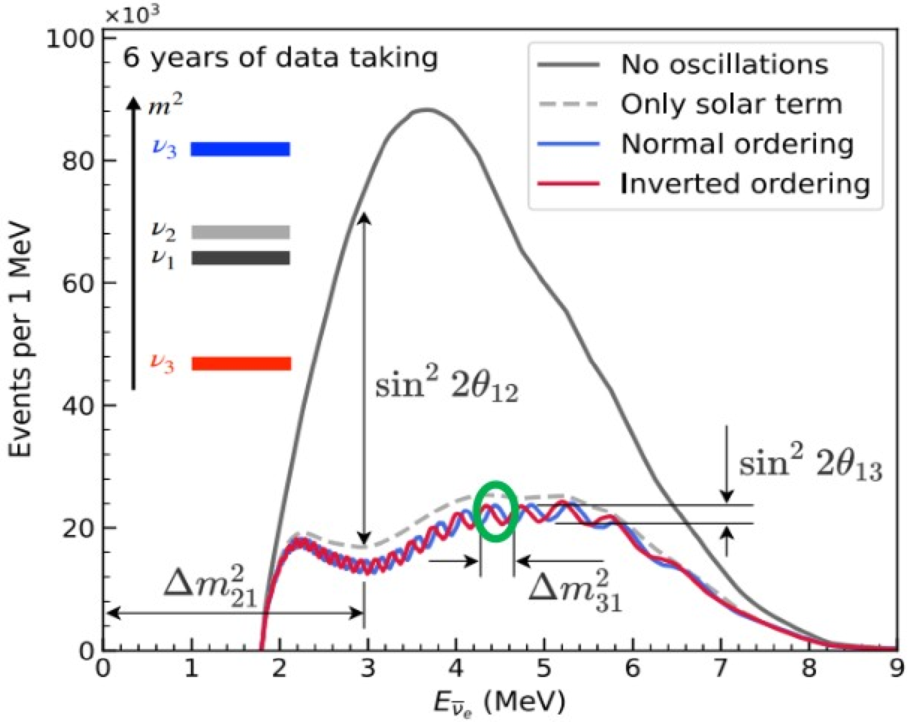
Primary goals:
- precise measurement of oscillation parameters
- determination of the neutrino mass ordering

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

How?

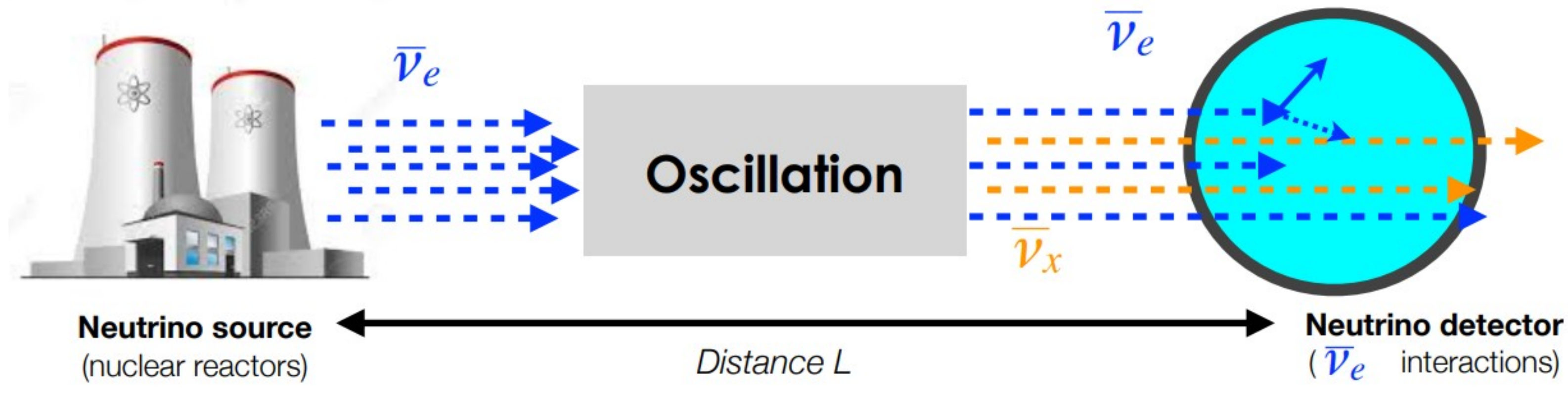
→ **Largest and most precise ever built LS detector**

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



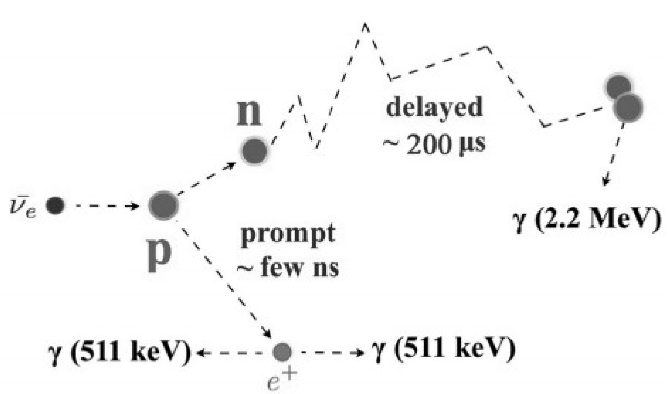
	Target Mass	Coverage	Energy resolution	Light yield [PE/MeV]
Daya Bay	20 ton (x8)	12%	8% @ 1 MeV	160
Borexino	300 ton	34%	5% @ 1 MeV	500
KamLAND	1 kton	34%	6% @ 1 MeV	250
JUNO*	20 kton	78%	3% @ 1 MeV	>1300

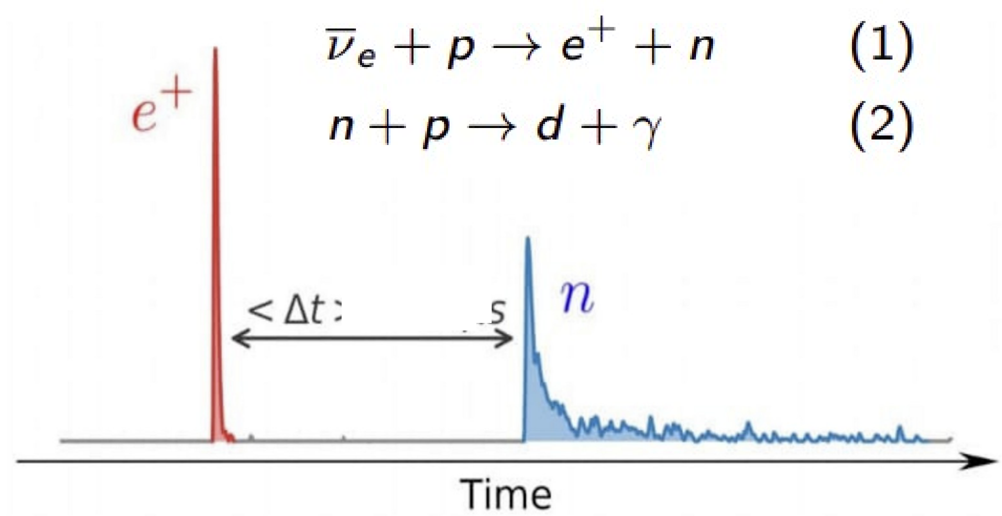
Reactor neutrino detection



Reactor anti-neutrinos are observed by Inverse Beta Decay (IBD):
(1) – Energy deposited by positron (carries neutrino energy)
– Positron annihilation into two gammas (511 keV)
(2) Neutron capture scintillation emission

- Very clear signal: prompt + delay coincidence



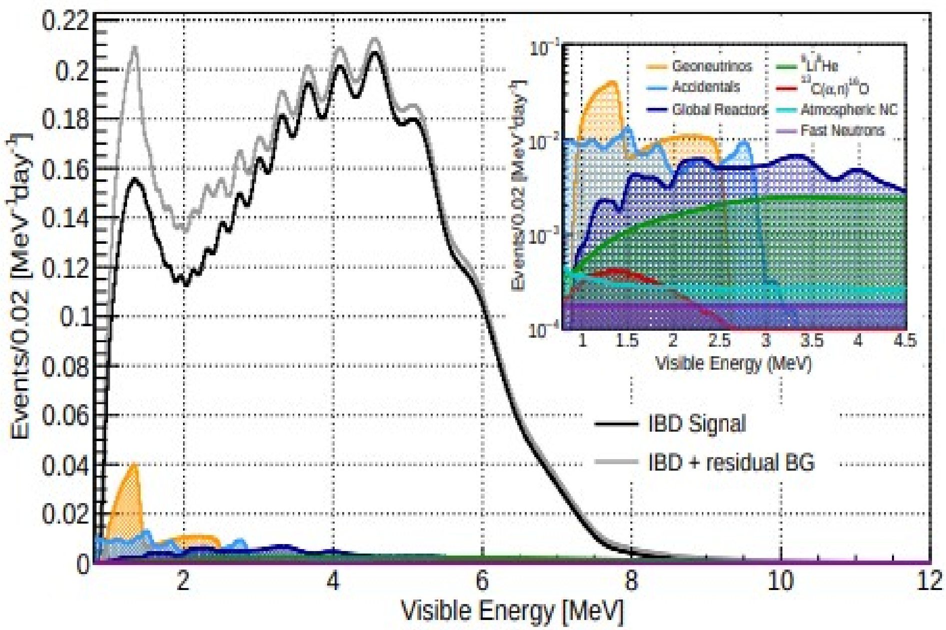


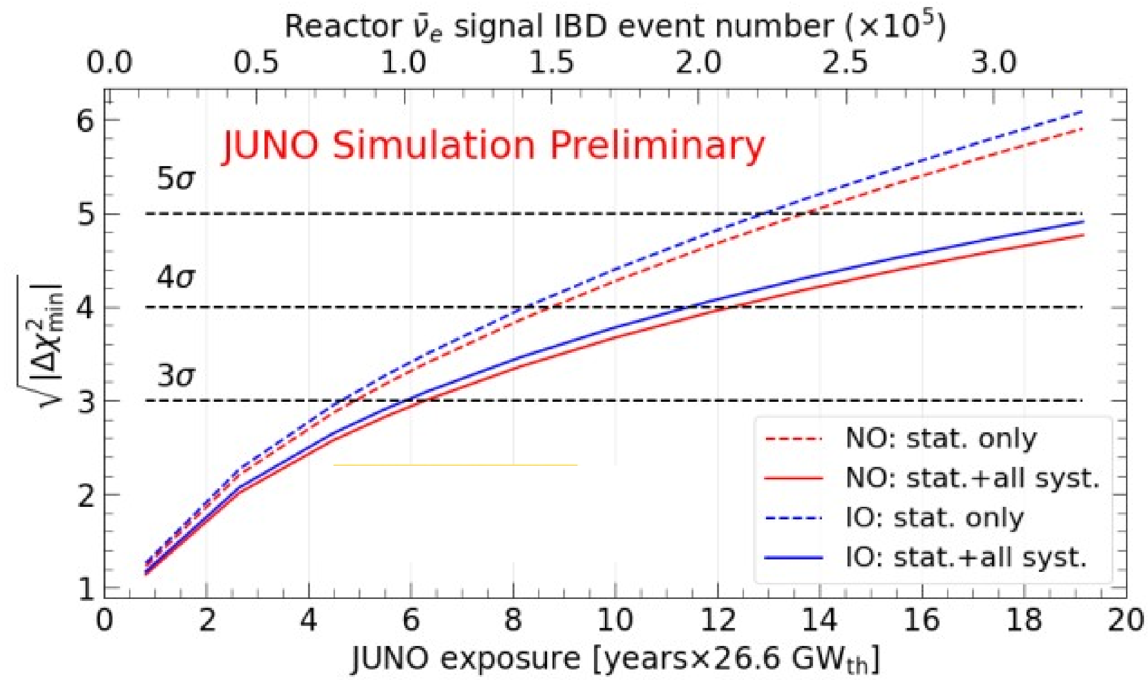
Reactor neutrino oscillations

Determination of the neutrino mass ordering (paper in preparation)

After selection cuts:
- Expected signal rate: 47.1 IBD/day
- Expected background rate: 4.11 /day

Expected visible energy spectrum in JUNO





$$\Delta\chi^2 = |\chi^2_{min}(NO) - \chi^2_{min}(IO)| \approx \textbf{9-10}$$
For 6 years of data taking.

→ Determination of the NMO at 3σ within ~6 yrs

Reactor neutrino oscillations

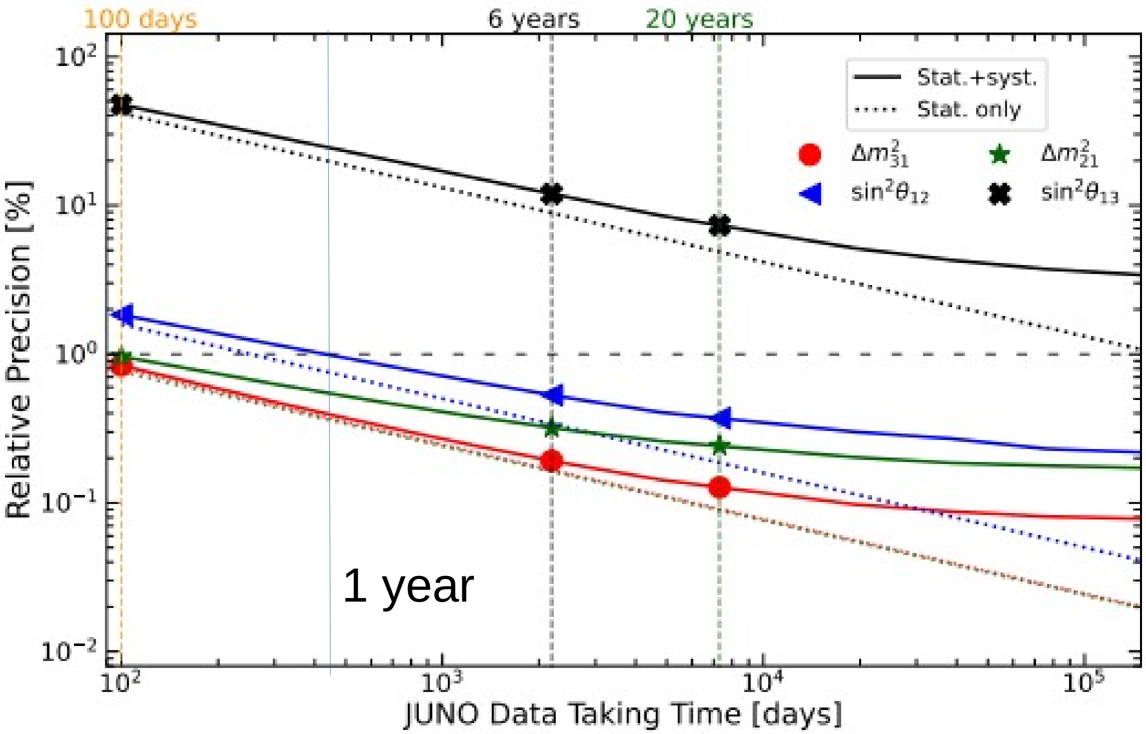
Sub-percent precision measurement of the oscillation parameters, Chin. Phys. C 46 (2022)

- Profit exquisite spectrum resolution:

→ extract oscillation parameters with unprecedented precision

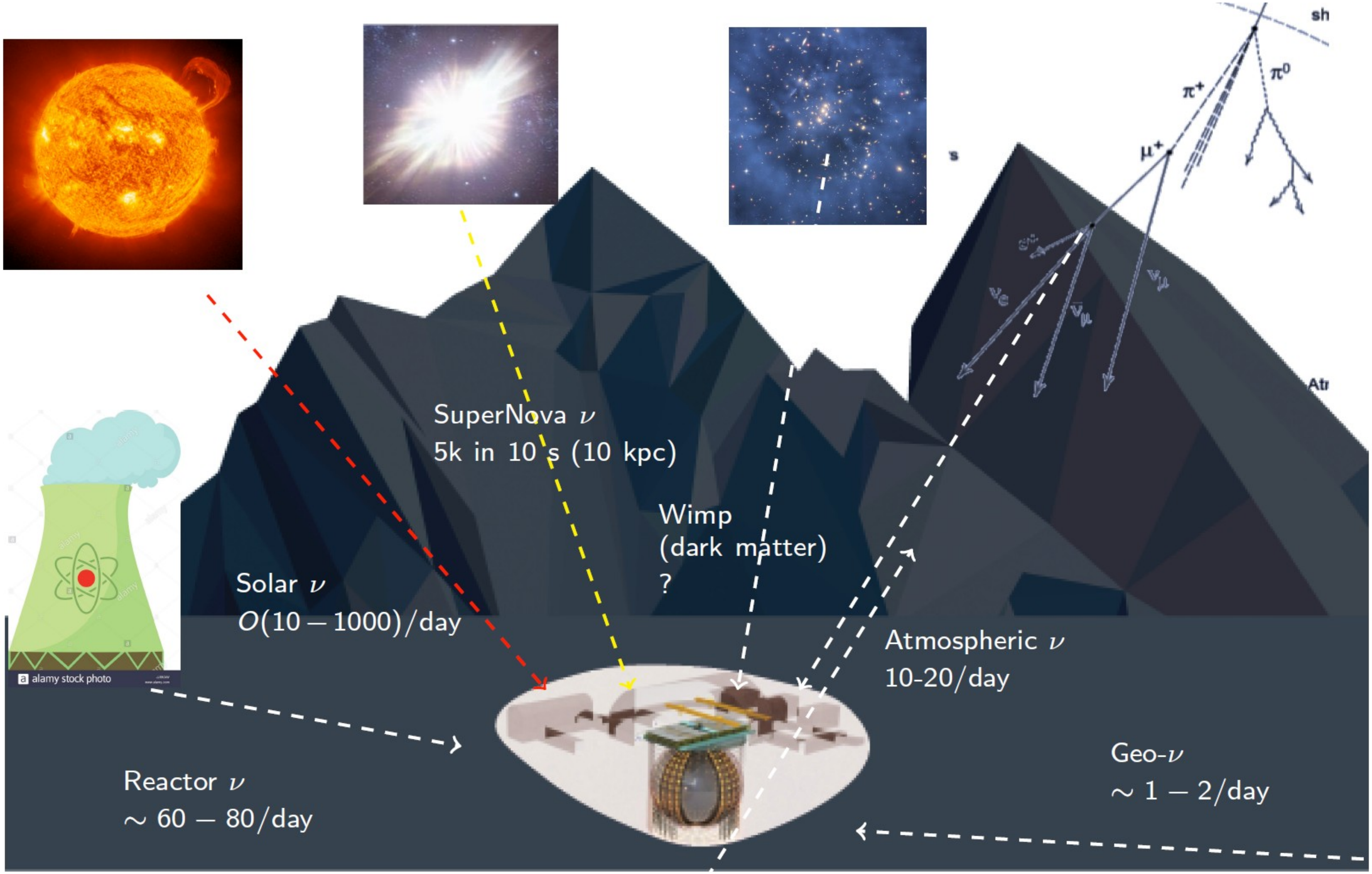
- Probe simultaneously Δm^2_{21} and Δm^2_{31} driven oscillations

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

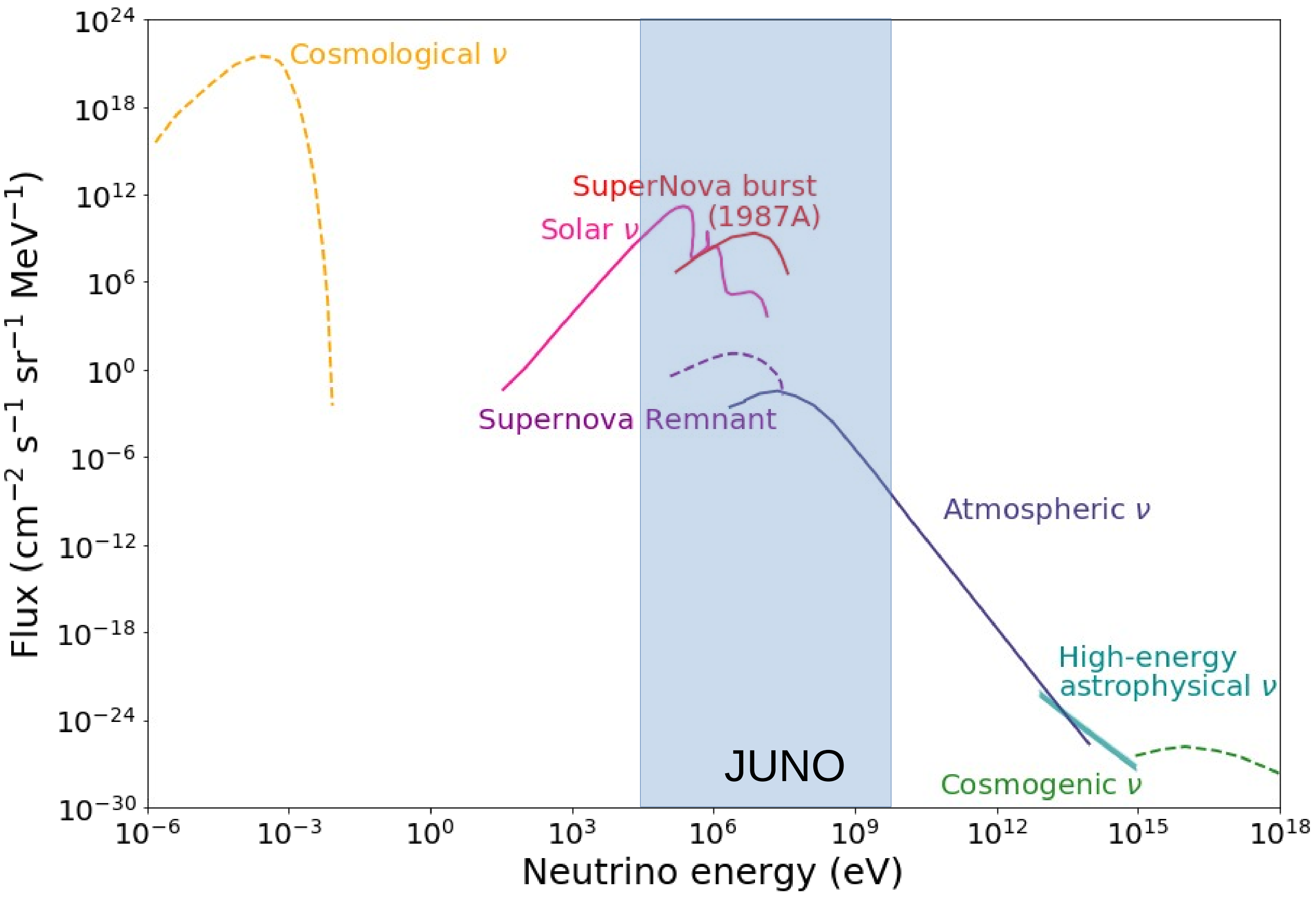


	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
PDG 2020	1.4%	2.4%	4.2%	3.2%
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%

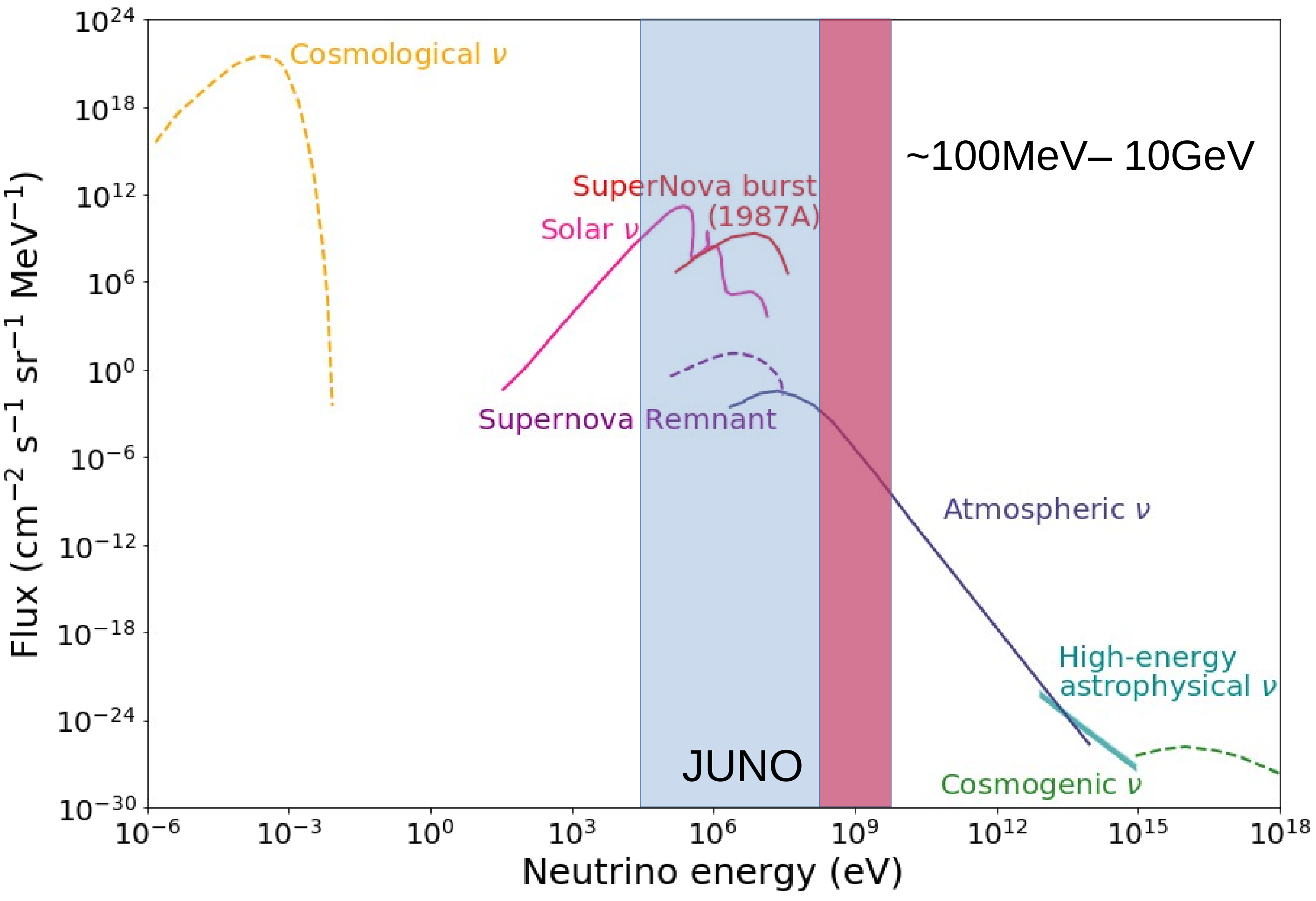
JUNO physics program



Neutrino landscape: spectrum of natural sources



spectrum of natural sources:
i) atmospheric neutrinos (GeV)



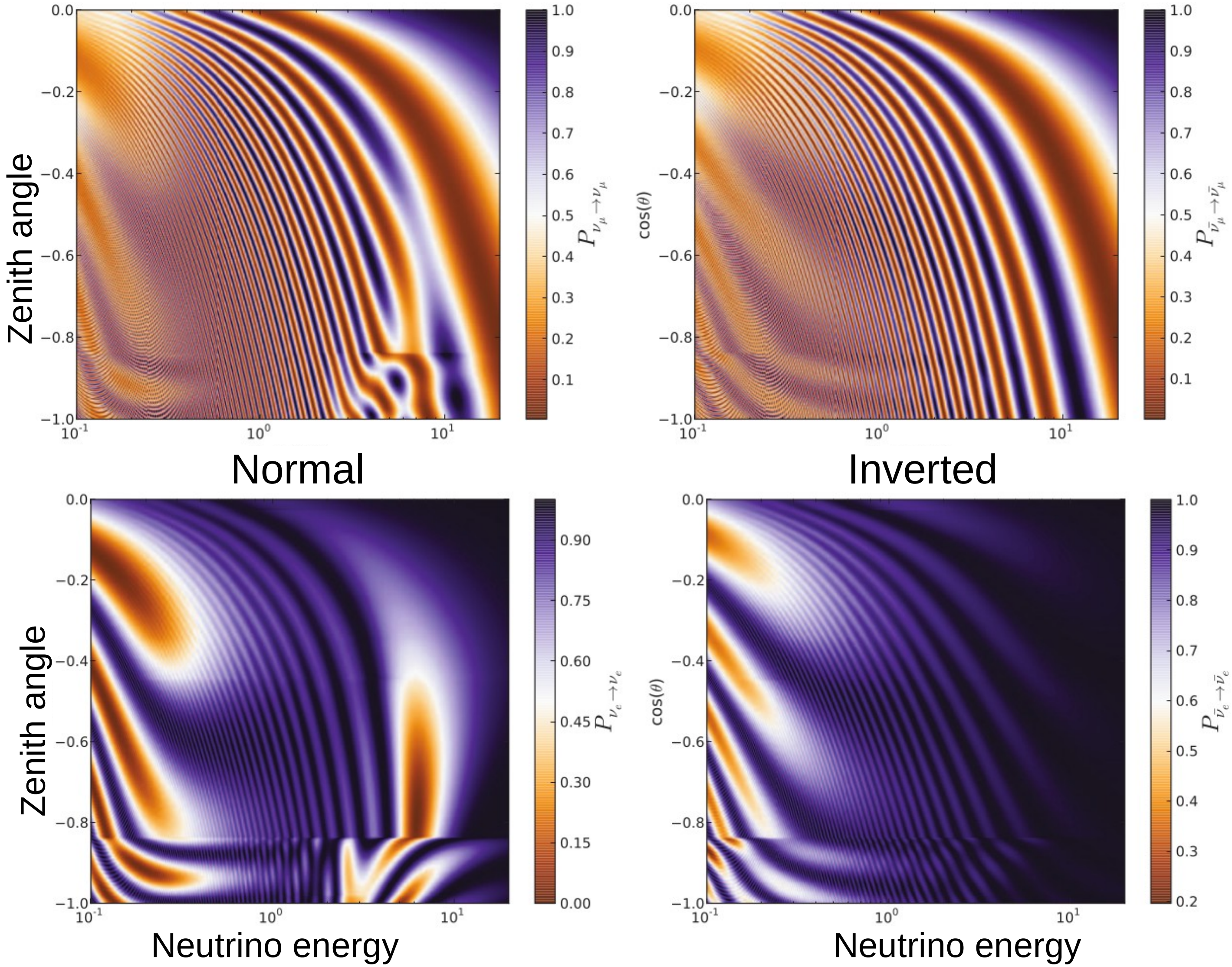
Atmospheric neutrinos

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

→ Exploit matter effects on neutrino oscillations:

ν_μ survival probability

ν_e survival probability

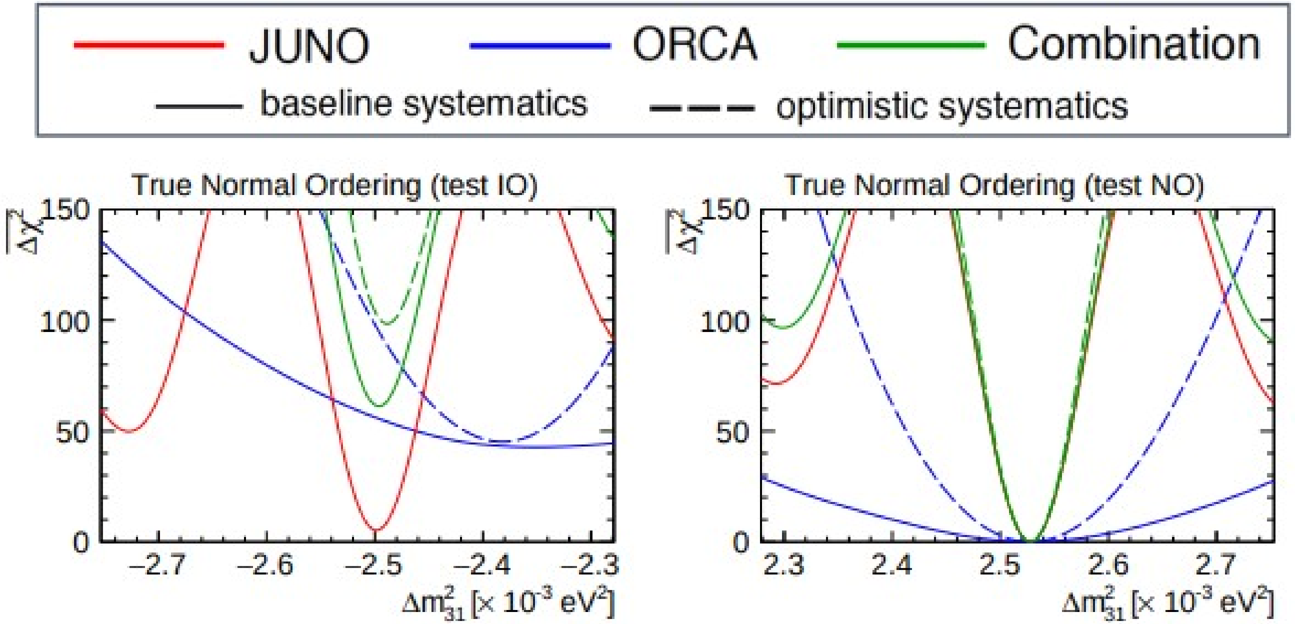


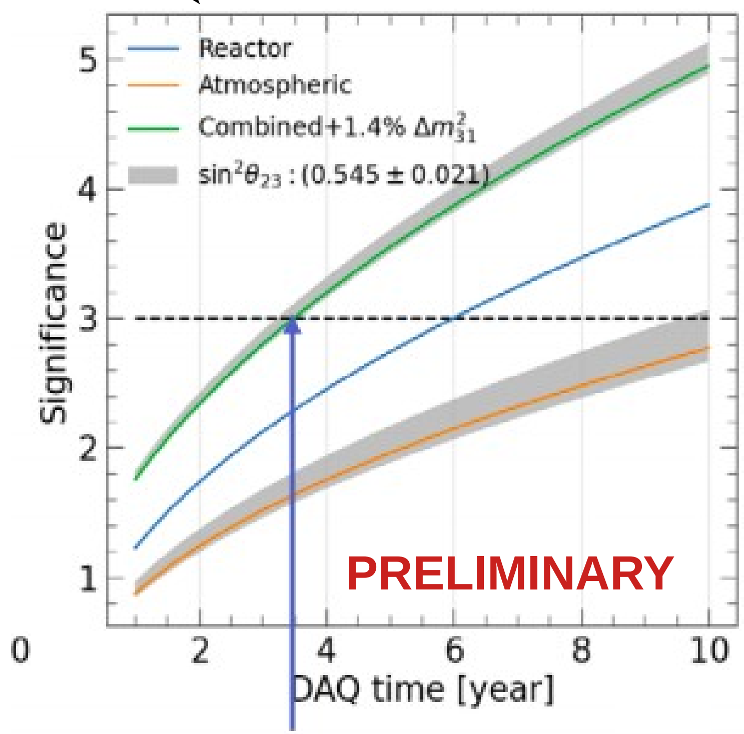
Atmospheric neutrinos

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

- Complementary detection channels: independent measurements and systematics
- **Exploit synergy with reactor neutrinos**
- **Boost of NMO sensitivity using both channels → JUNO can do it alone**

→ **NMO determination at 3σ ~2 years faster!**



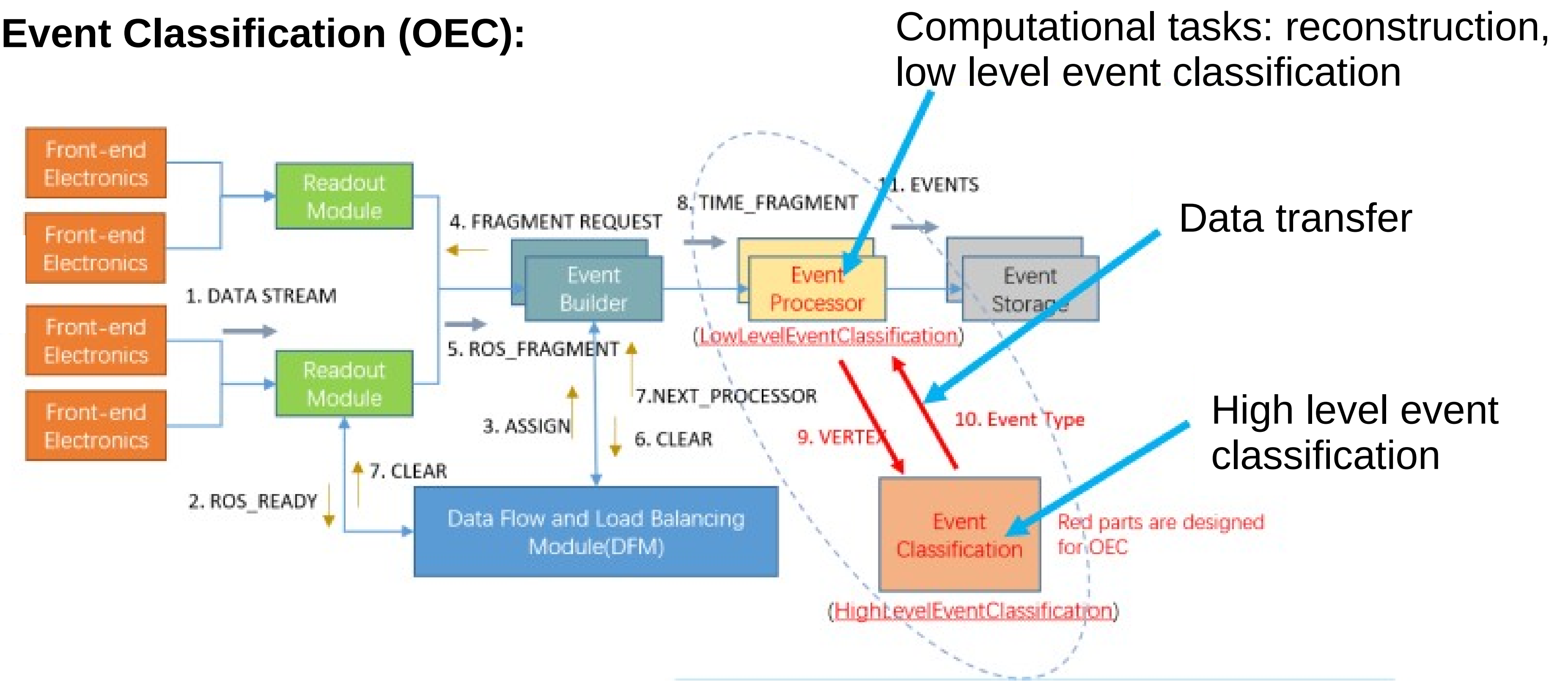


JHEP 03 (2022) 055

Atmospheric neutrinos

- **Detectors like JUNO are not initially designed for doing GeV physics**
- Measuring atmospheric neutrino oscillations effects (NMO) requires:
  - Efficient background reduction: 4 Hz of muons VS few atmospheric ν per day in the CD
  - → Need dedicated online processing and filtering of the data (very large data flow):

Online Event Classification (OEC):



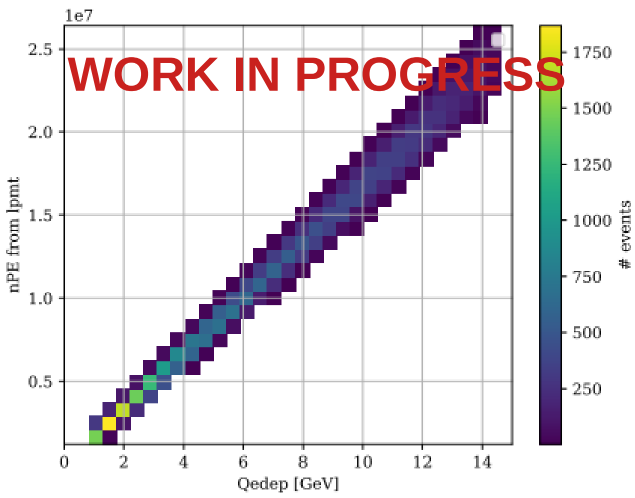
Atmospheric neutrinos

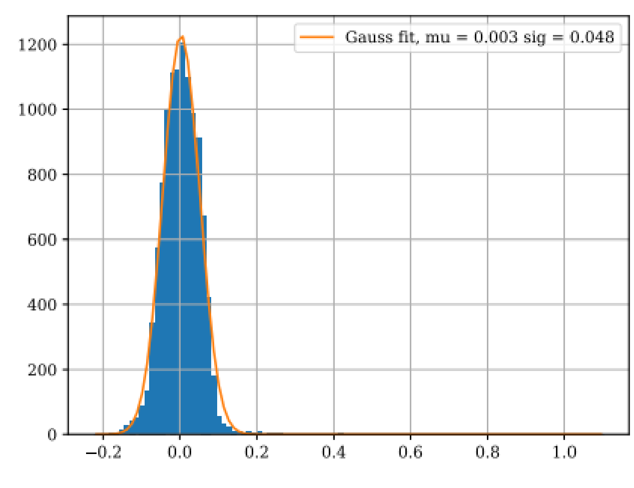
- Measuring atmospheric neutrino oscillations effects (NMO) requires:
  - Good energy (<5%) and direction (<20 deg on ν angle) reconstruction
  - Discriminating between electron and muon neutrinos AND ν against anti-ν (PID)

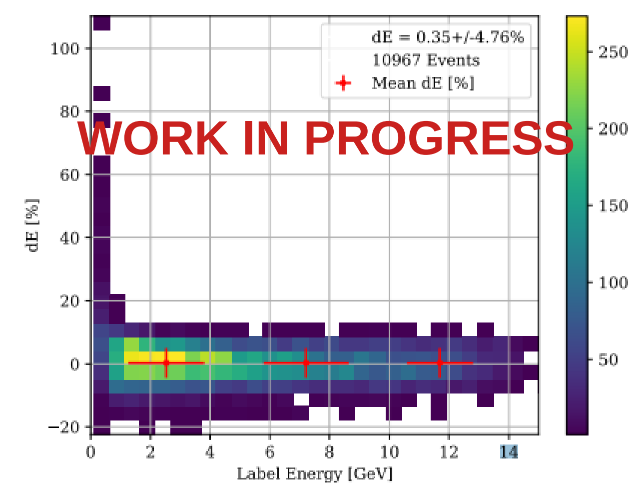
Note: Implementation and validation of reconstruction and PID algorithms into the official JUNO software ongoing, results shown here don't include yet the full electronics and noise effects

Energy reconstruction:
using the linearity between the detected charge and the visible energy (benchmark)

Energy resolution ~5%

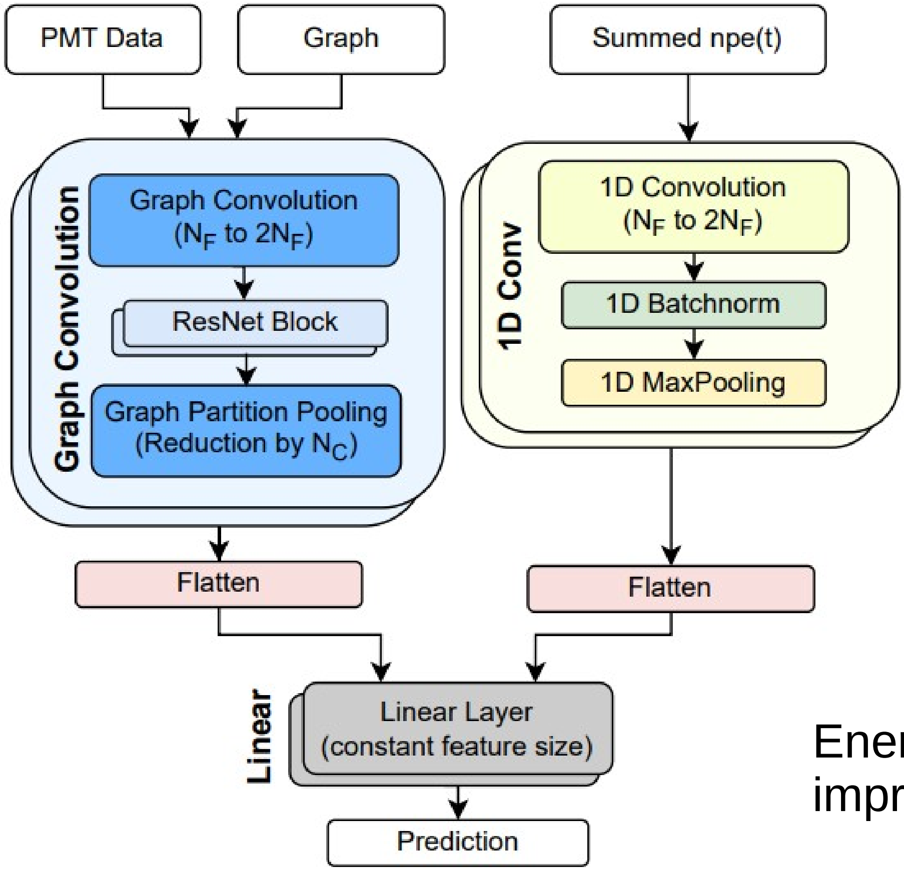




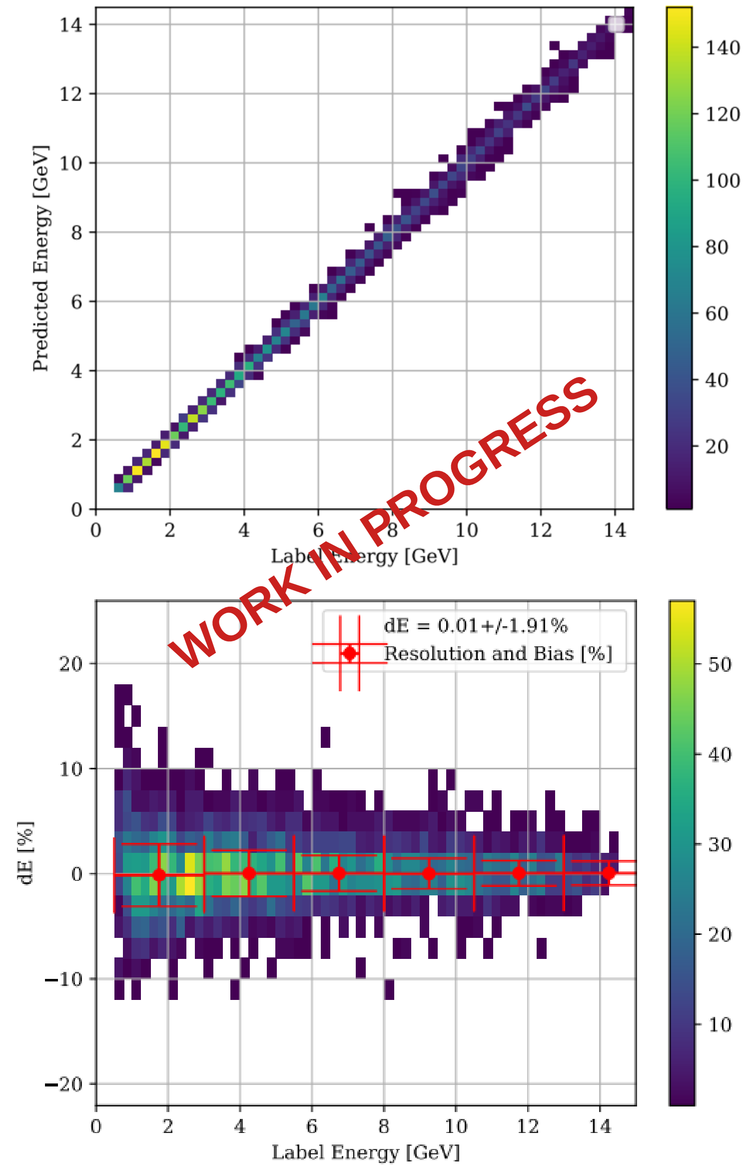


Atmospheric neutrinos

Energy reconstruction using machine learning (ML): Graph Convolutional networks



Energy resolution improved to ~2%

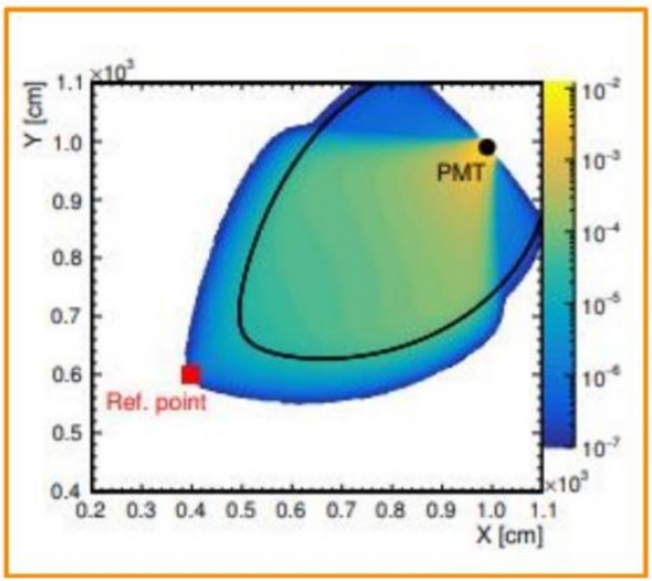


Atmospheric neutrinos

- Measuring atmospheric neutrino oscillations effects (NMO) requires:
  - Good energy (<5%) and direction (<20 deg on ν angle) reconstruction
  - Discriminating between electron and muon neutrinos AND ν against anti-ν

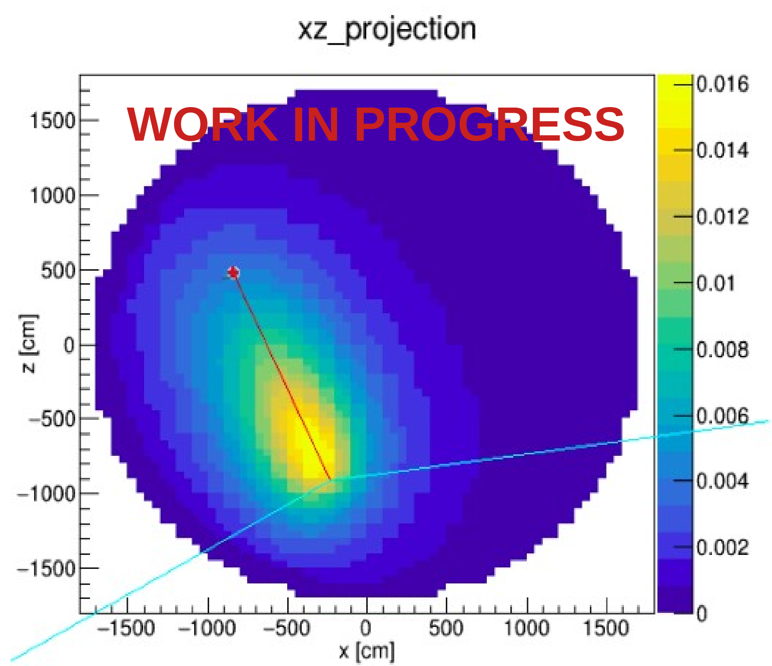
Direction reconstruction with topological reconstruction method:

Reconstruction of the emission probability map of the detected photons → gives track direction



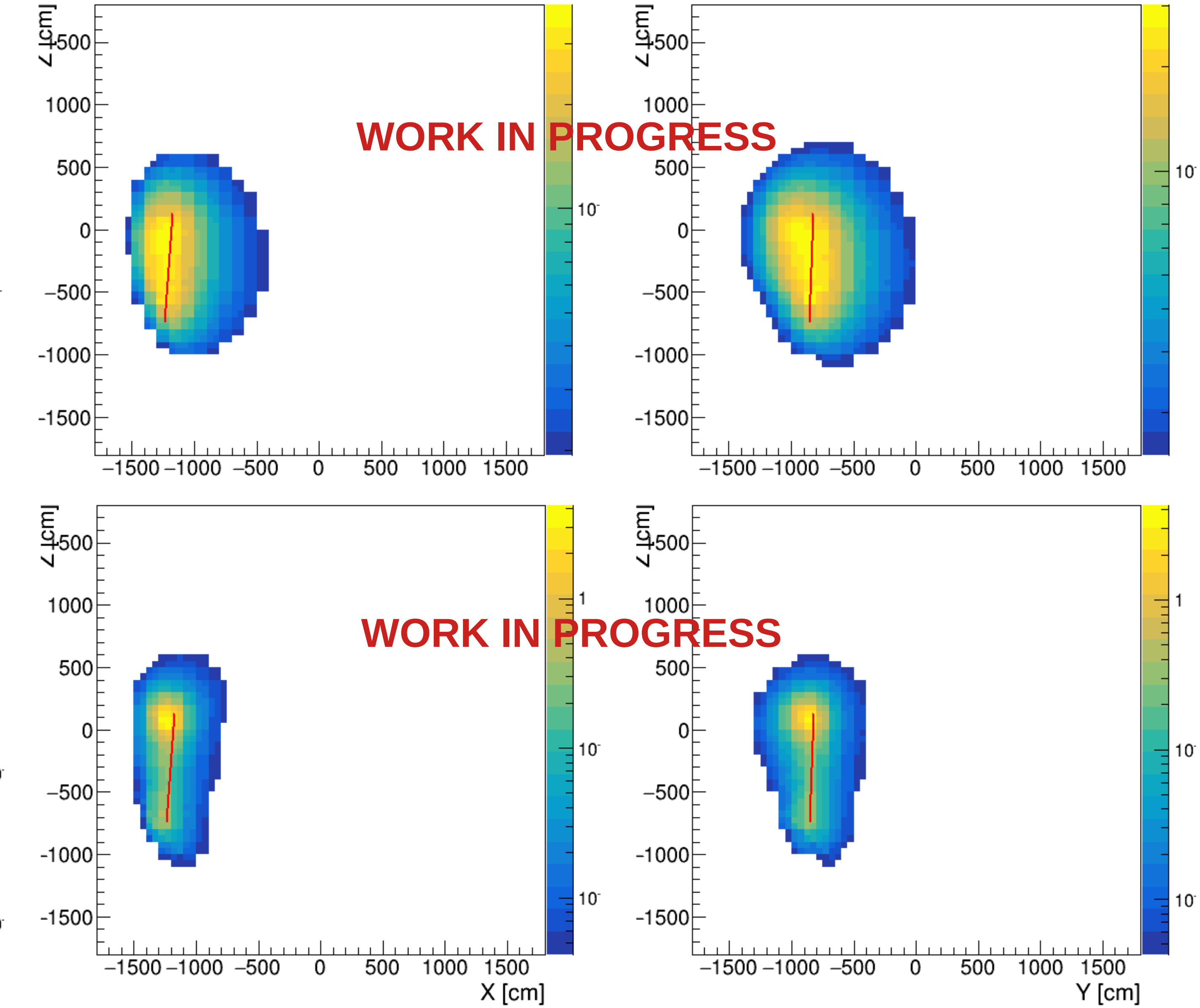
Probability map for each pmt

Iterative process



Reconstruction of 3 GeV ν_μ

Atmospheric neutrinos



Using all detected hits

complementary information

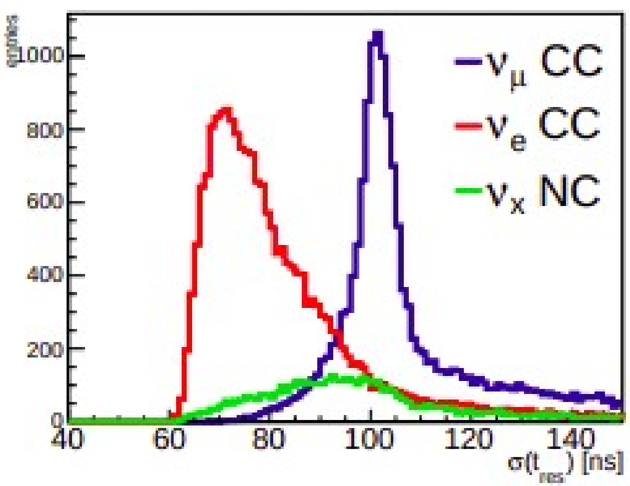
Using the first hit detected by each PMT

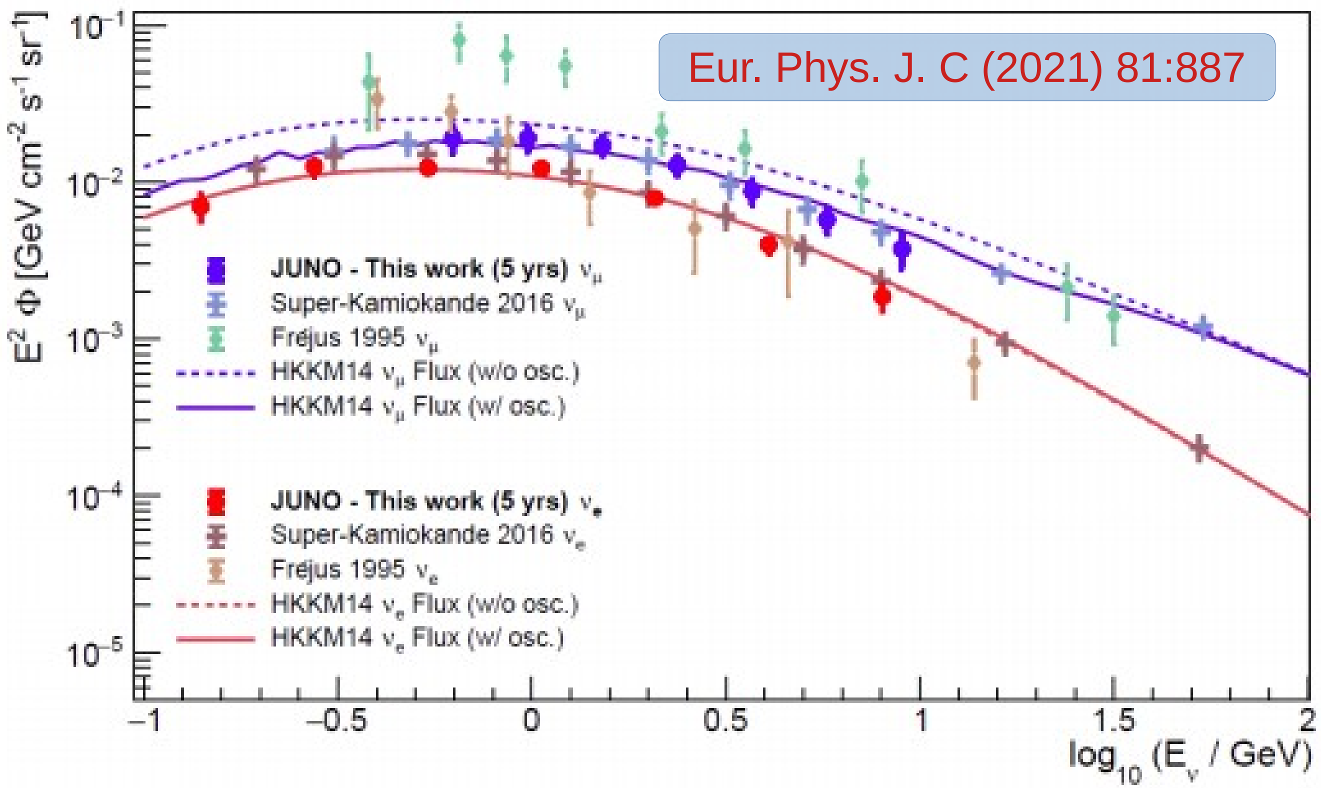
Atmospheric neutrinos

→ **Atmospheric neutrino flux measurement**

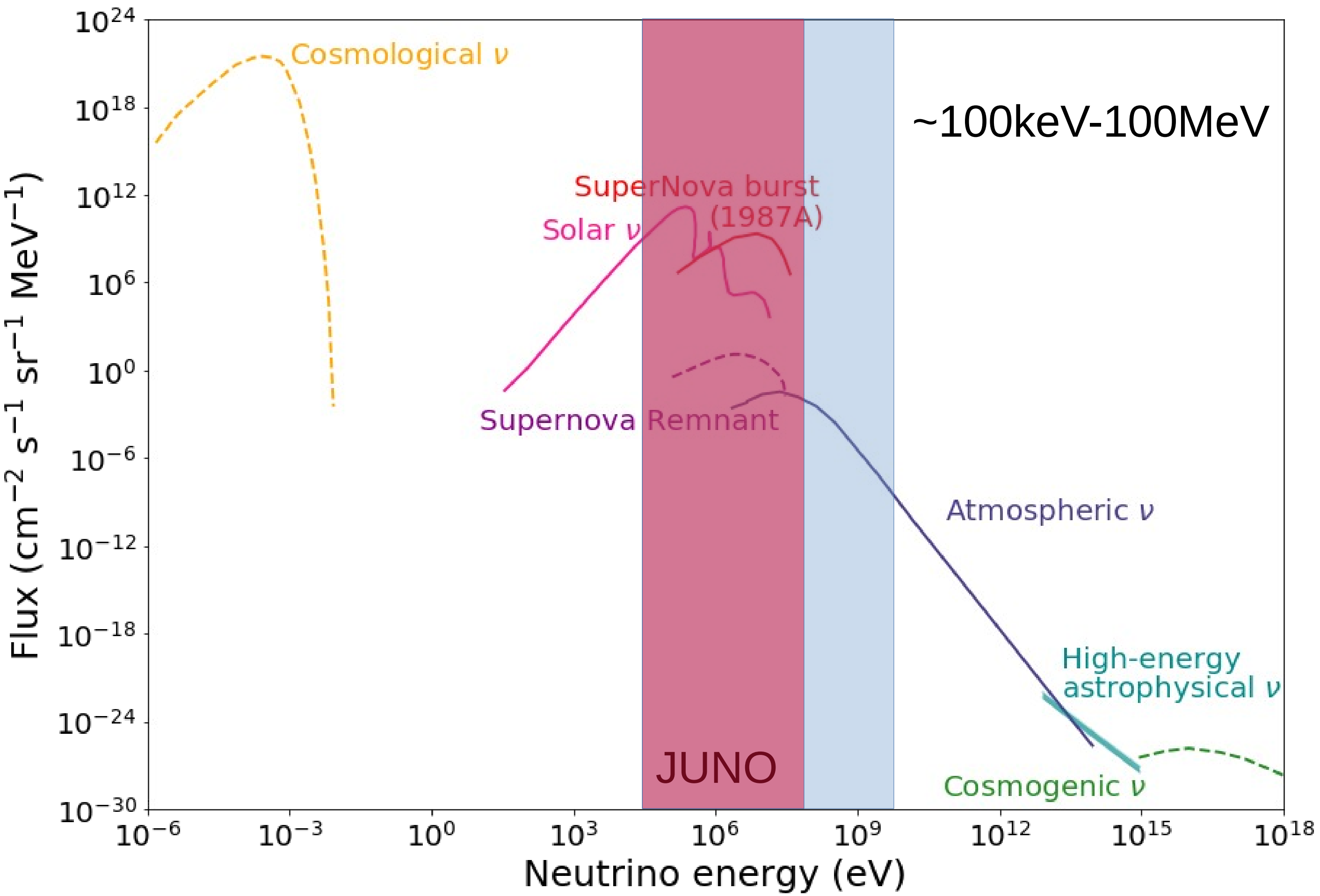
→ Flavor - dependent energy spectrum can be measured in the (0.1 - 10) GeV energy range
→ ν_e/ν_μ discrimination based on time pattern of scintillation light possible

Evis ~2-10 GeV

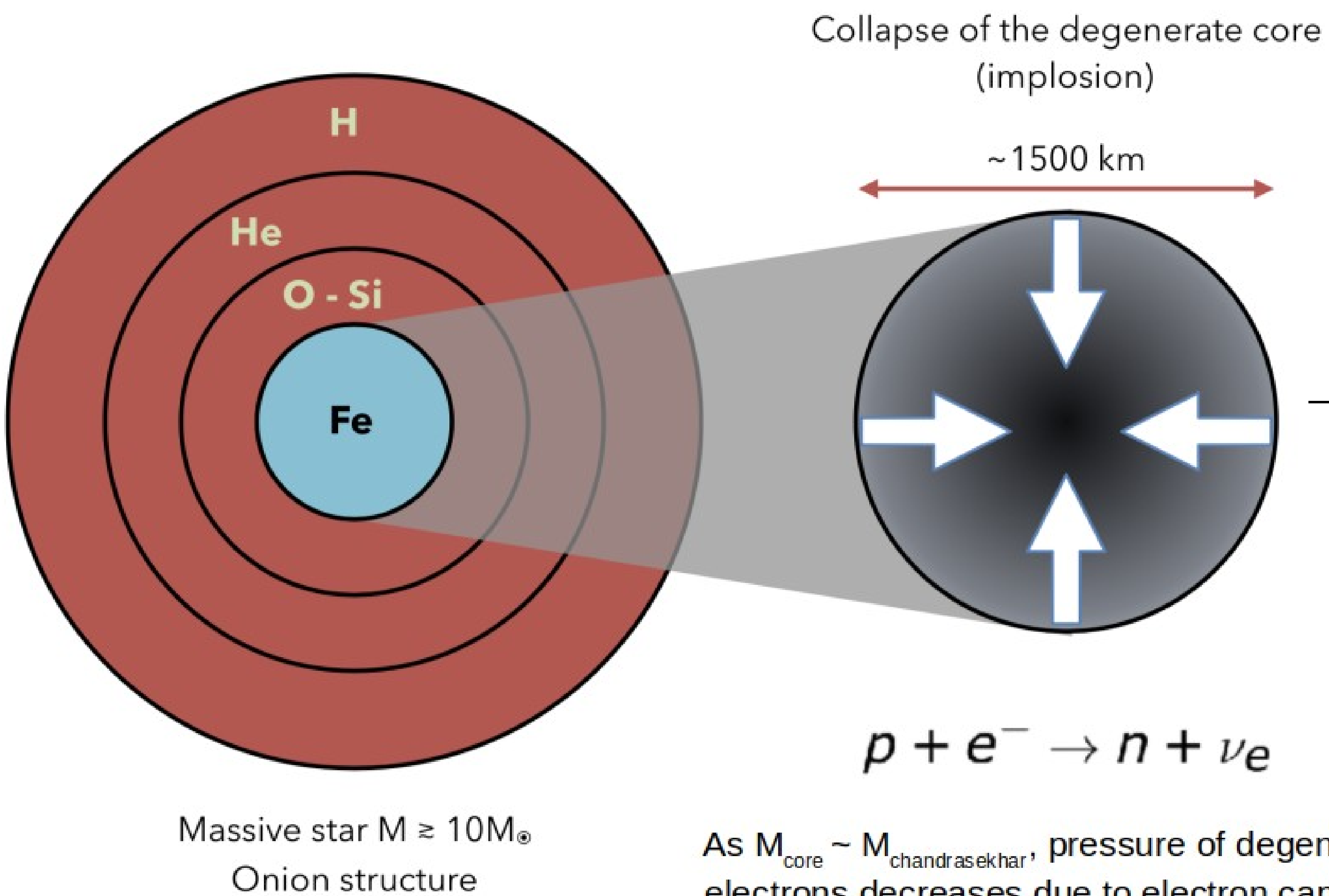




spectrum of natural sources: ii) supernova neutrinos (MeV)



Core-collapse supernova: explosion mechanism

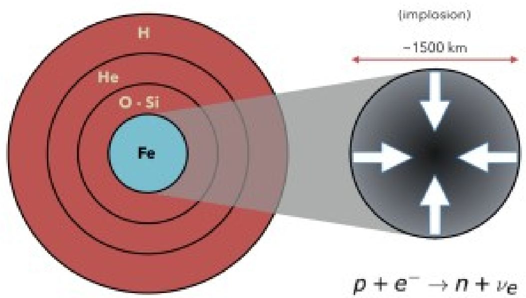


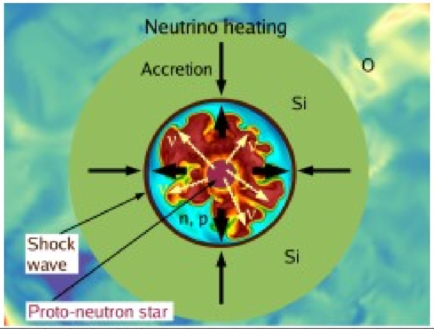
$$p + e^- \rightarrow n + \nu_e$$

As $M_{core} \sim M_{chandrasekhar}$, pressure of degenerate electrons decreases due to electron captures and becomes insufficient to resist gravity → **collapse**

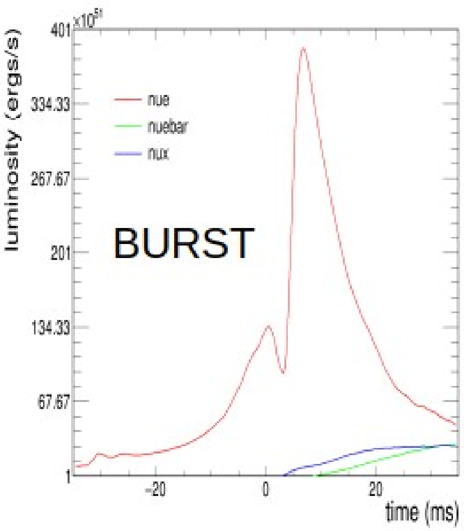
→ With collapse, shock wave forms and propagates… until it gets stopped

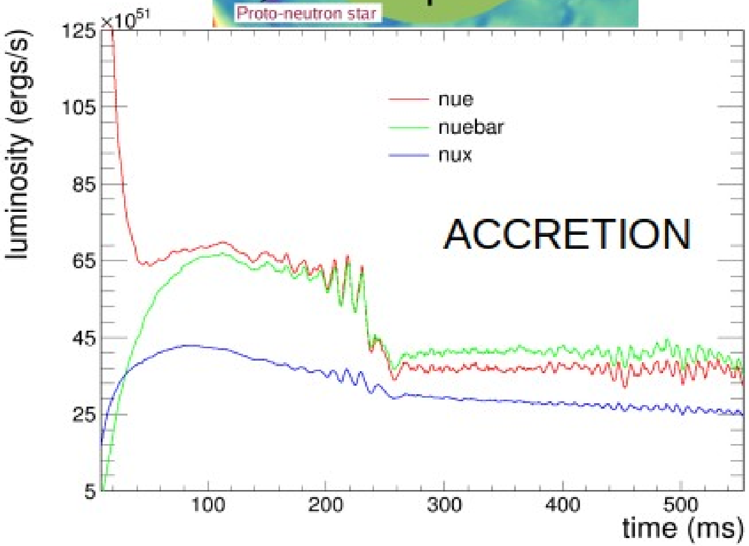
Core-collapse supernova: explosion mechanism

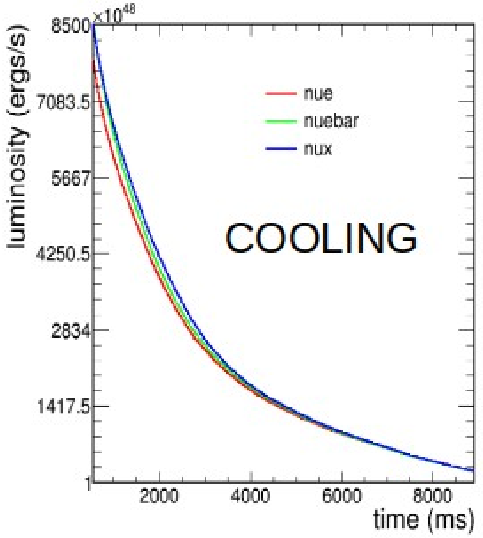




- Neutrino heating revives the shock by energy deposition → explosion
- 99% of the gravitational binding energy emitted through neutrinos







- Shock bounce
- Electron captures

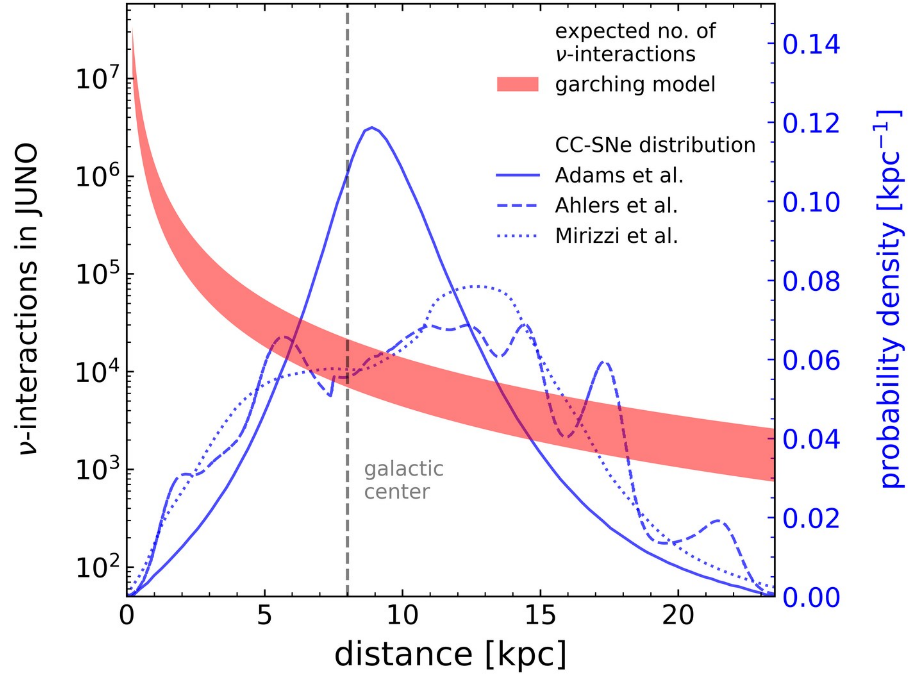
- Hydrodynamical instabilities/convection
- Neutrino heating
- Shock revival

- Neutrino pair production of all flavors

Core-collapse supernova neutrinos in JUNO

- If there is a Galactic CCSN, JUNO will be able to detect the CCSN flux from all neutrino flavors with high statistics
- High signal rate → almost background free observation

- Dominant interaction channels in JUNO:
  - IBD → $\underline{\nu}_e$ flux
  - ν-electron elastic scattering (ES) → all flavors (ν_e flux mainly)
  - ν-protron ES → all flavors



Doing CCSN physics with neutrino data? Need:

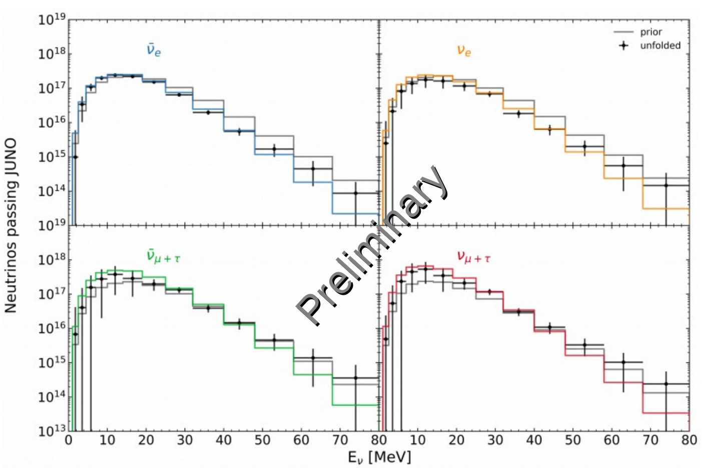
- ✓ Event selection (PID) → all flavor flux evolution
- ✓ Good energy resolution → energy spectrum
- ✓ Good time resolution → time profile (lightcurve)
- ✓ Good angular resolution → pointing

Core-collapse supernova neutrinos in JUNO

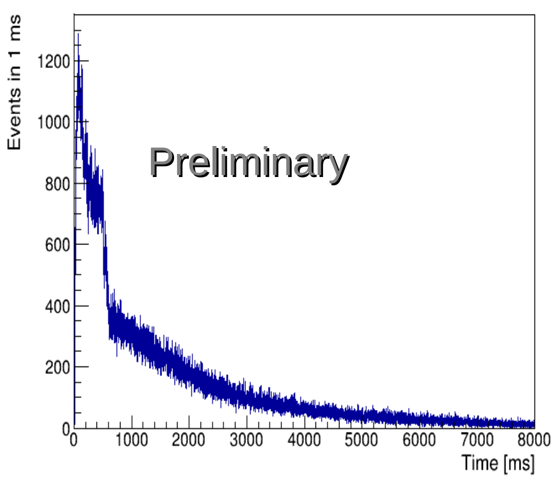
→Good energy and time resolution + flavor classification:
JUNO will measure:

Constrain CCSN physics!

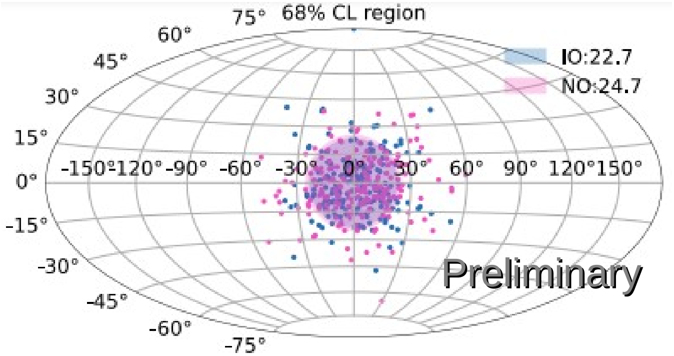
Flavor dependent energy spectrum

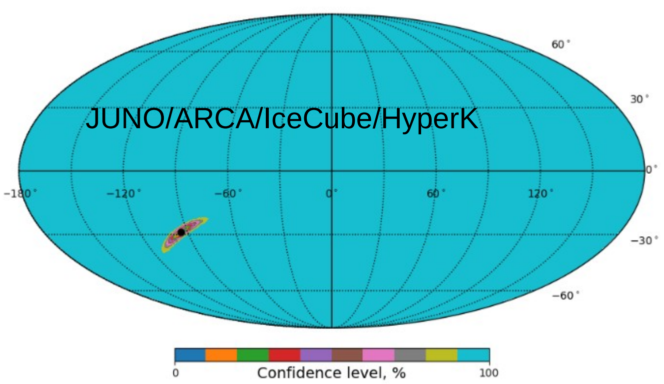


Lightcurve:



Direction:

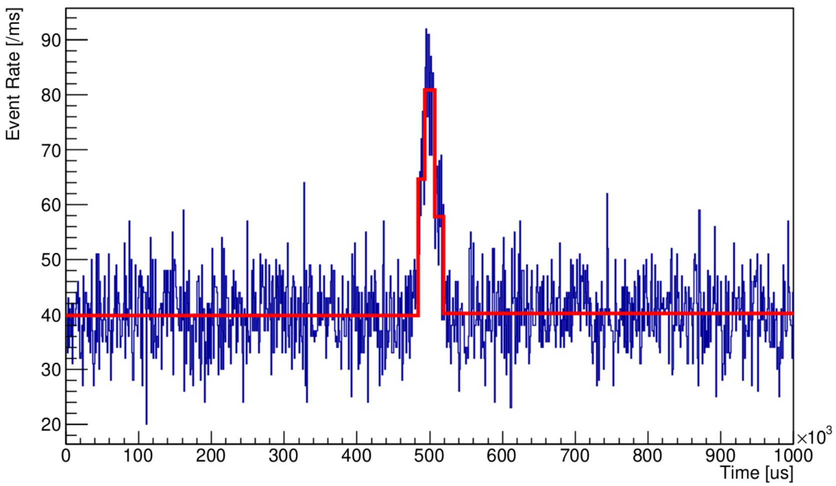




Identifying an astrophysical transient signal

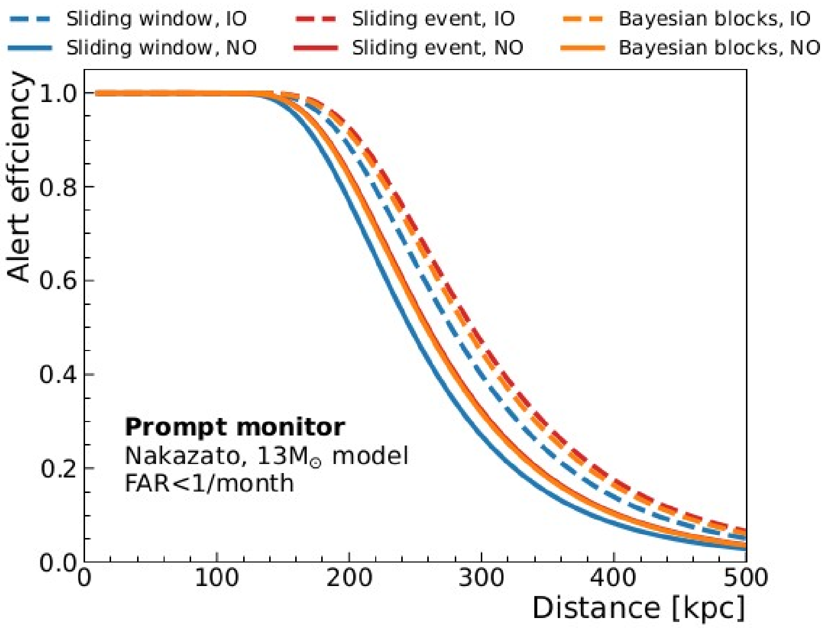
Real-time monitoring based on a localised increase (in time) of the detected rate.
Two strategies to trigger a transient event:

- 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

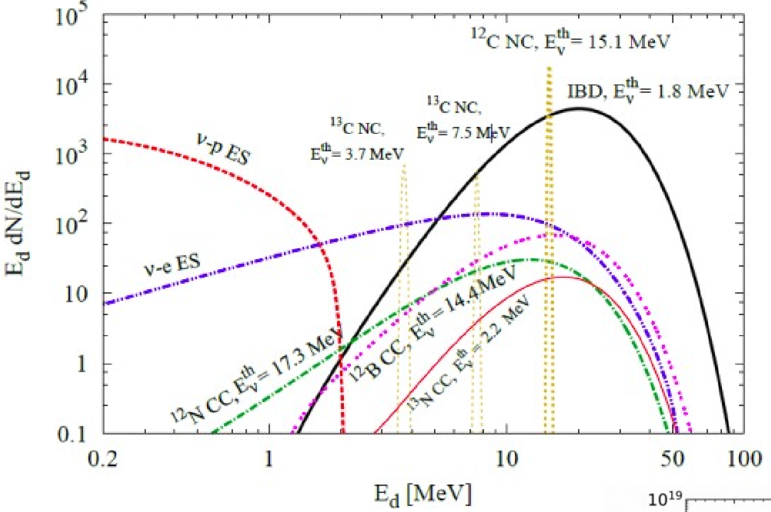
- Prompt Real-time Monitor:
  - Higher energy threshold (~1MeV)
  - Increase sensitivity horizon
- Multi-messenger (MM) trigger:
  - Lower energy threshold (<100 keV)
  - Increase signal statistics

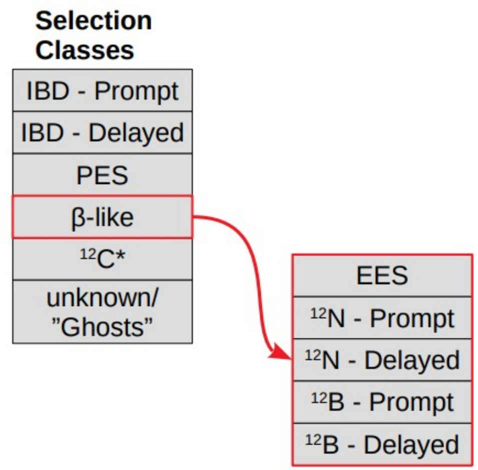


CCSN neutrino spectrum

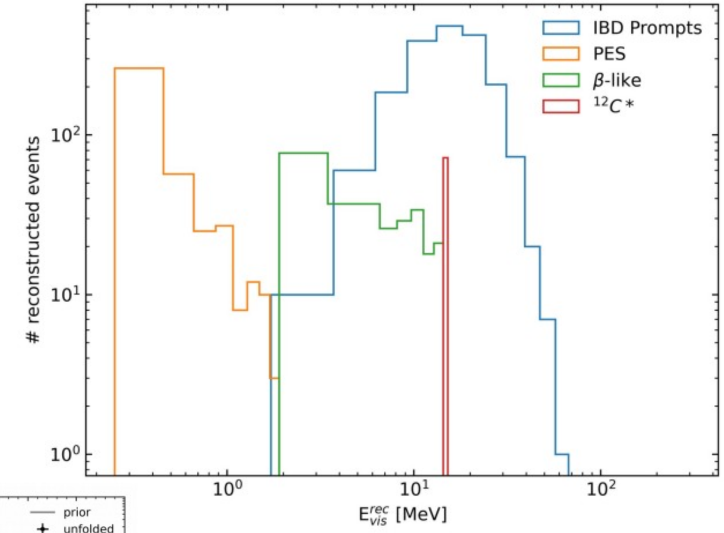
Use time-space coincidence (IBD) and energy cuts to select the different channels:

Expected CCSN energy spectrum:

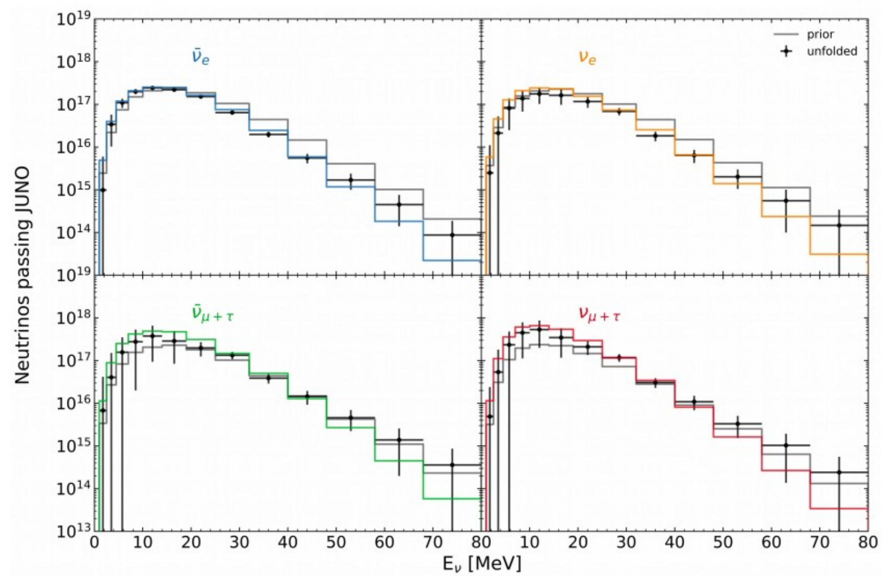




Reconstructed after selection:

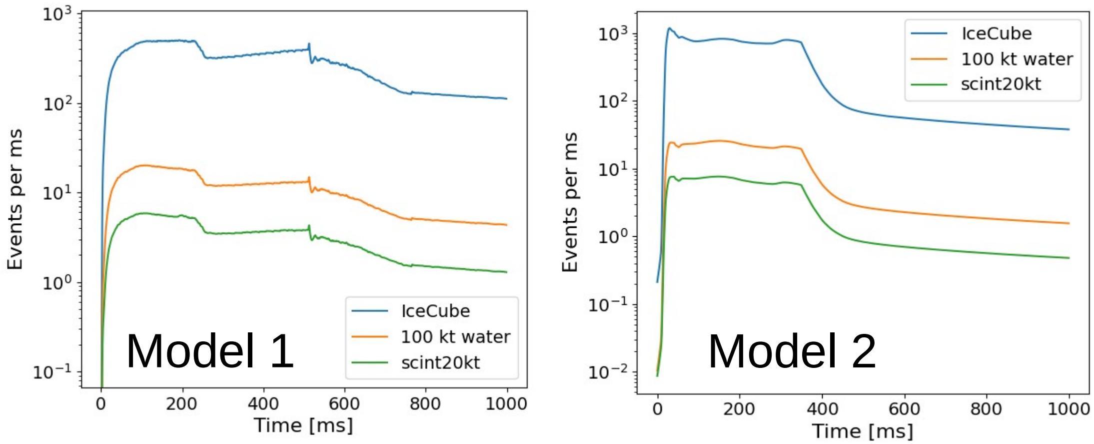


Flavor dependent neutrino energy spectrum UNFOLDED:



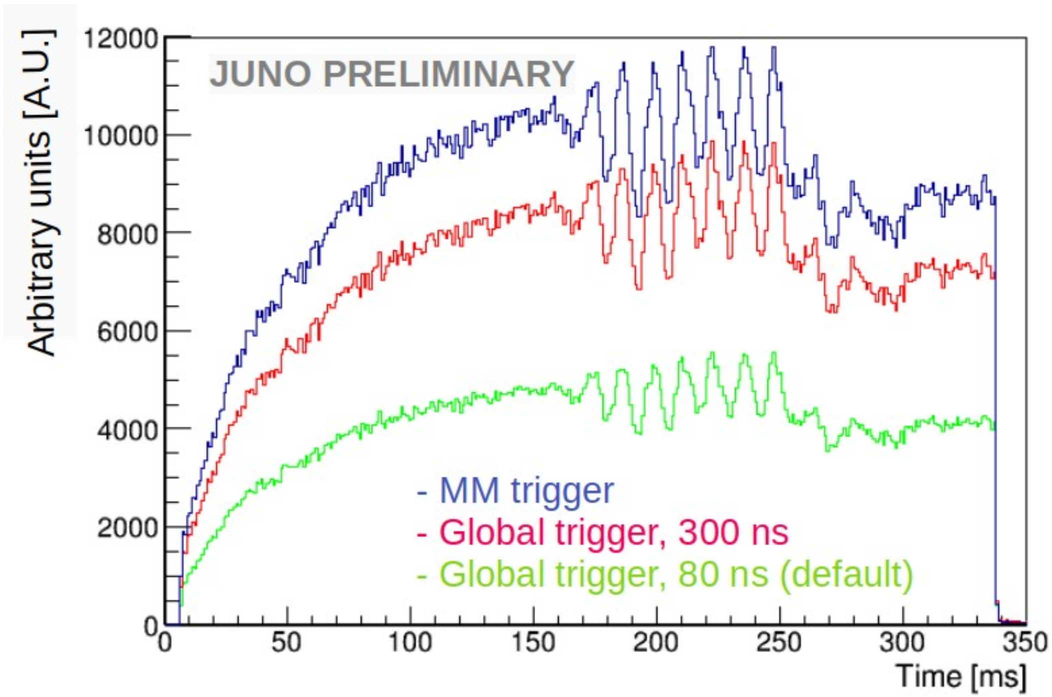
CCSN neutrino lightcurve

➔ Neutrino time profile brings information on the CCSN physics (and the models)



- Neutrino lightcurve relies on event timing
- Statistics matters in lightcurve studies (to resolve precise lightcurve features)
- Optimal physics event trigger is important

- **Global multiplicity trigger:** Default: 200 PMTs fired in 80 ns
- **Multi-messenger (MM) trigger:** likelihood cut, low energy threshold



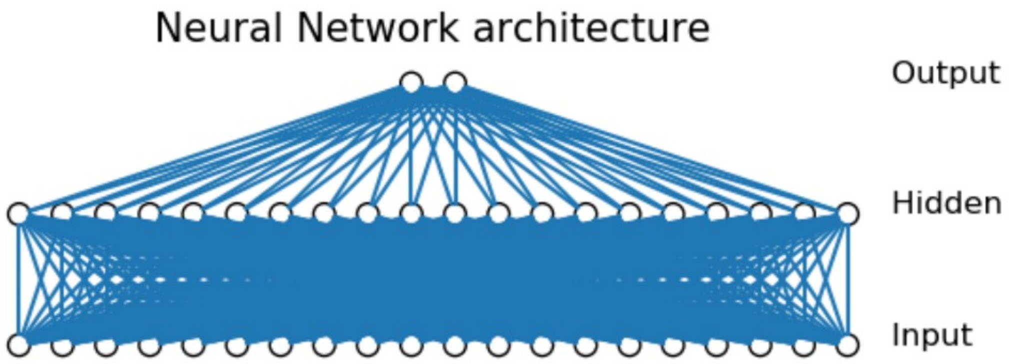
Machine learning based level-1 trigger in JUNO

Motivations:

- Level-1 (L1) trigger based on machine learning (ML) (firmware implemented) will need less logic resources than the current JUNO L1 trigger
- L1 trigger based on a Neural Network which could perform better at low-energies (below ~200 keV) than the current trigger:
  - → Many interesting physical signals expected in this energy regime (motivation for the MM trigger low-energy threshold)

Requirements:

- Final trigger rate has to be low enough to be handled by the DAQ
- It has to be hardware implementable and fast for real-time processing



Simple architecture:
- 20 input nodes (20 clock cycles of triggered event)
- 1 layer, 20 hidden nodes
- activation function: ReLU

ML-based L1 trigger in JUNO

Multi-layer perceptron

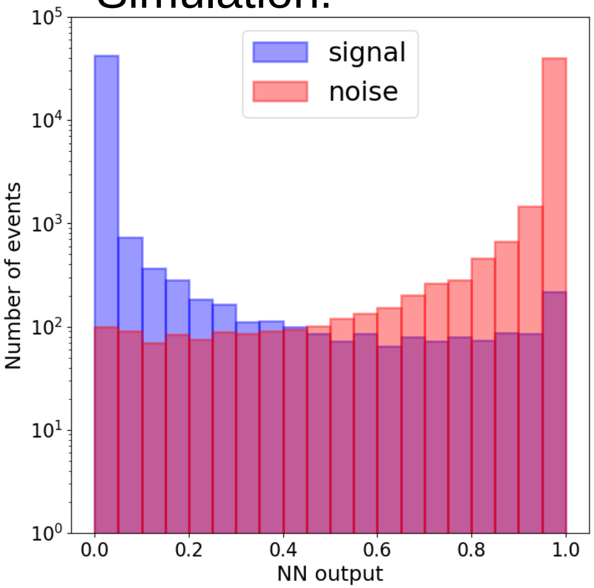
- Feedforward neural network
- Trained using backpropagation (epochs)
- Training time ∼9 min
- Training accuracy for 50 keV = % of correctly classified events ∼ 98%

Extreme machine learning

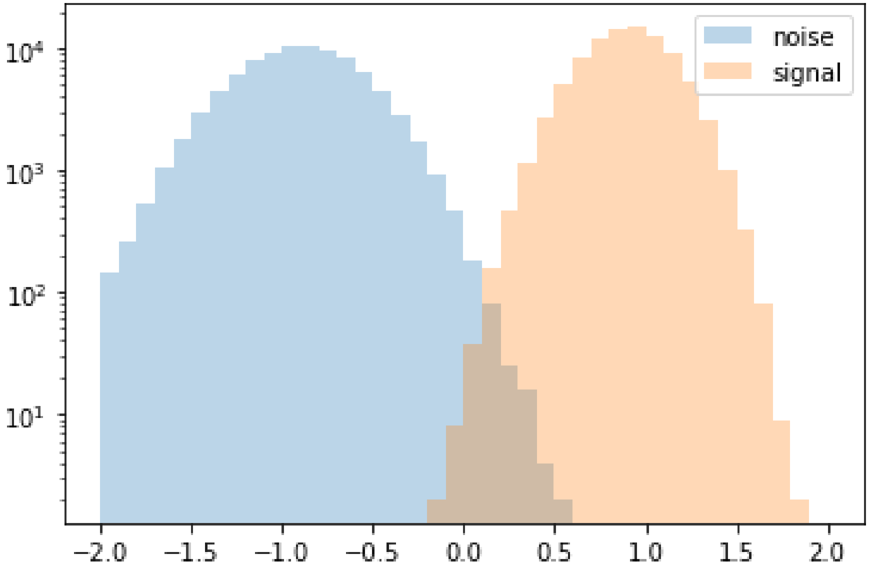
- Feedforward neural network
- Trained using a least-squares fit
- Training time below 1 s (∼80 ms)
- Training accuracy for 50 keV = % of correctly classified events = 99.8%

IEEE TNS 68 (2021) 8

Simulation:



FPGA implementation:

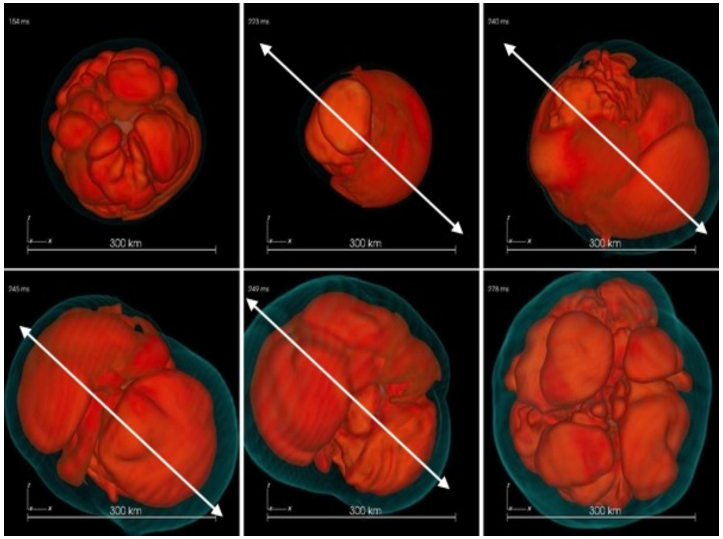


→ This method provides significant improvement, to be tested on FPGA

CCSN neutrino lightcurve

Example of interesting lightcurve feature to study: SASI oscillations

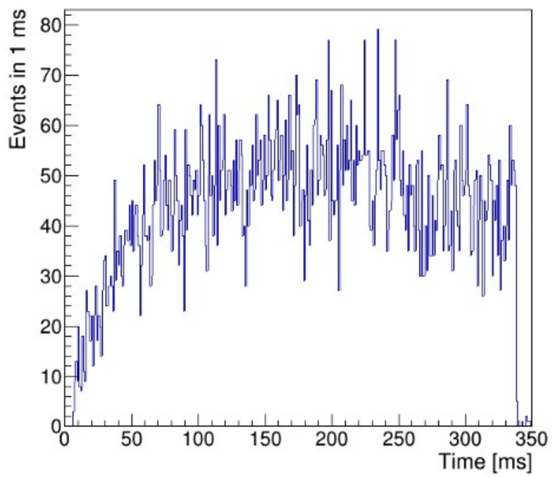
- SASI = standing accretion shock instability: predicted by 3D CCSN simulations
- Why is it interesting:
  - It favors explosion and final energetics
  - It can explain neutron star kicks observed
  - It would be accompanied by GW emission

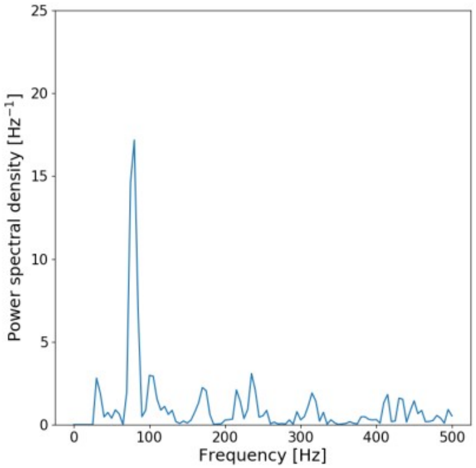


- **Observable:** fast-time variations of the detected rates, with a characteristic oscillation frequency (~80Hz) → Spectral analysis of the neutrino data

CCSN neutrino lightcurve

Example of interesting lightcurve feature to study: SASI oscillations

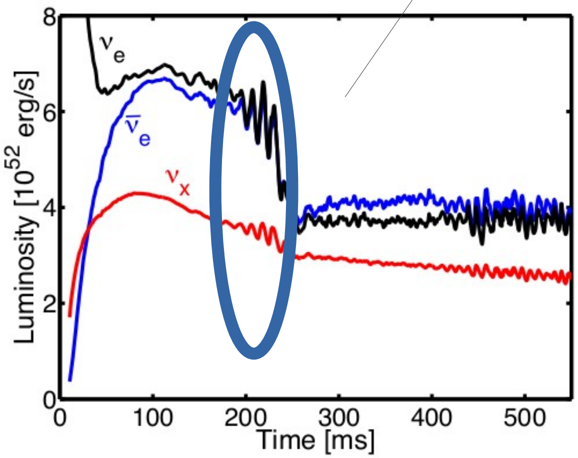




20 Msun, Tambora 2014

(Fourier Transform)

OBSERVED LIGHT-CURVE → POWER SPECTRUM → DETECTION SENSITIVITY

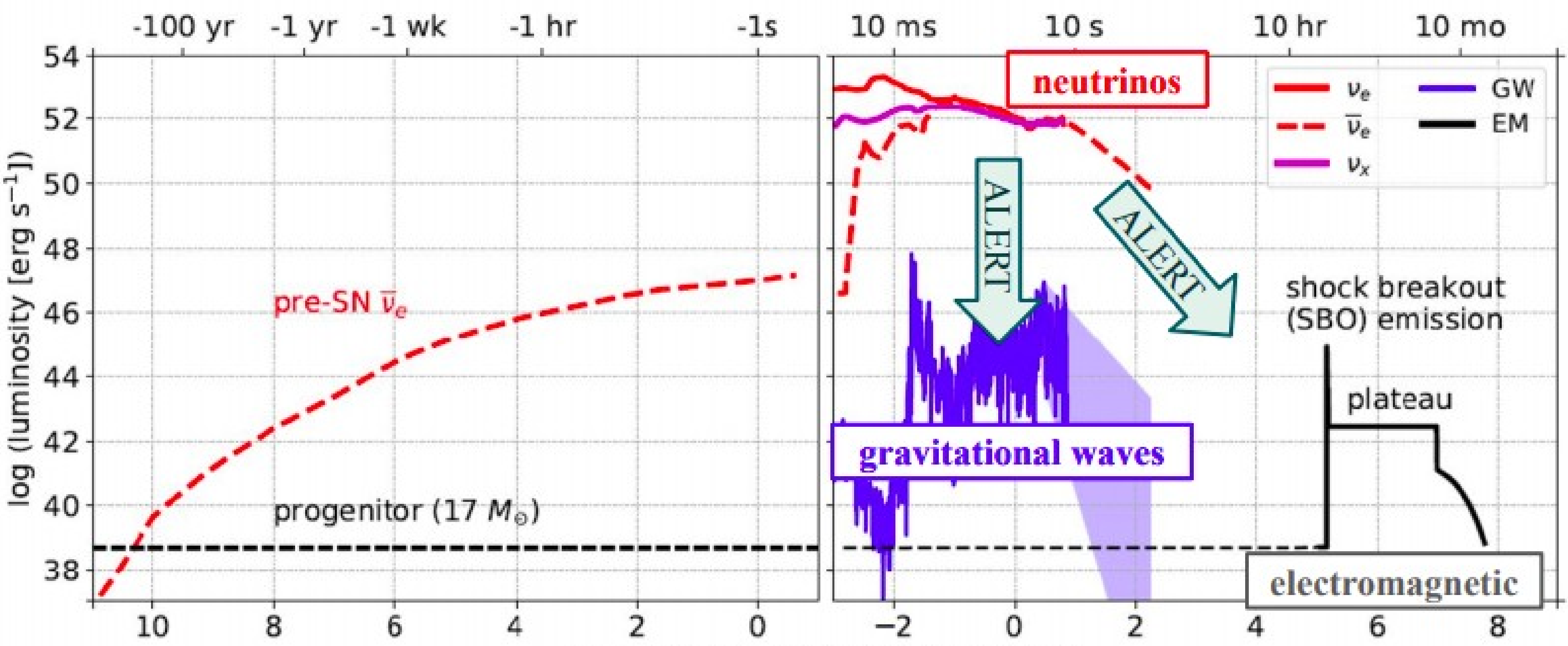


THEORY (expected)

- Method 1: model independent (search at any frequency)
- Method 2: model dependent (search in the “known” SASI frequency range)

→ JUNO will be sensitive to observe the SASI peak at ~3σ up to the Galactic Center (~8kpc)

Core-Collapse Supernova multi-messenger signal



Adapted from Nakamura+ 2016

- Next nearby CCSN will produce neutrinos, GWs and **EM** radiation
- Neutrinos will act as an early alert for the multi-messenger follow-up

Core-Collapse Supernova multi-messenger signal

SNEWS: The supernova early warning system → Network of detectors combined to observe CCSN neutrinos, coordinated with other multi-messenger observatories (New J. Phys. 23 2021)

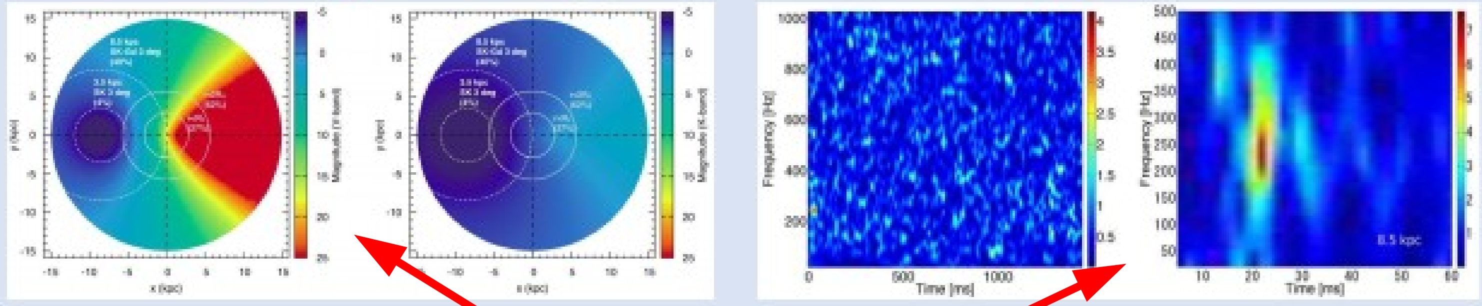
MOTIVATION: the multi-messenger signal

- Source position and distance using neutrinos are crucial for a successful MM follow-up
- Timing of the neutrino signal is key for those parameter estimates
- SNEWS will collect data from different experiments and send an alert to other observers

SNEWS SUPERNOVA EARLY WARNING SYSTEM

EM observations

GW observations



JUNO will also contribute on its own

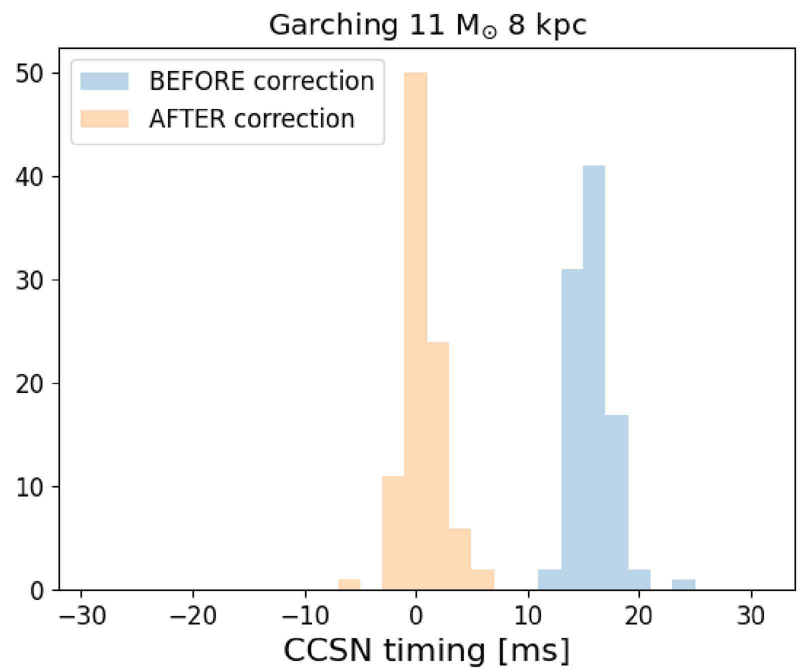
Multi-messenger astronomy

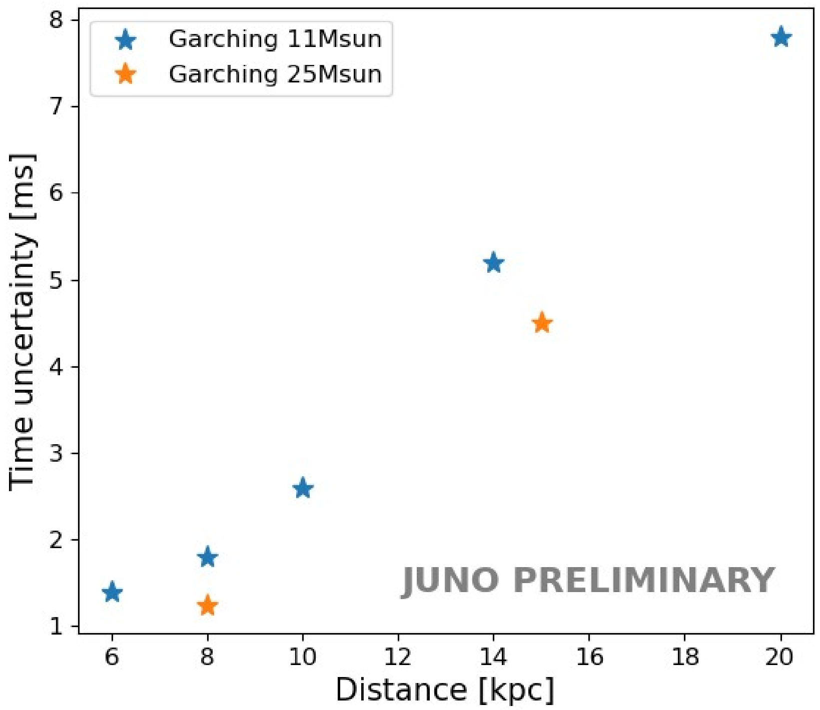
Timing the neutrino signal arrival

How? Using the high-significance Prompt CCSN Monitor trigger time

But... Trigger time will be biased with respect to the truth arrival time

Bias correction: Fit the relation between the expected trigger time and the expected number of events in the first 50 ms, N50





Multi-messenger astronomy

Distance estimate

Based on: arXiv:2101.10624
Observable: Nevents in the first 50ms, N50

Methods:

1. Using the expected signal weighted over initial mass function (IMF)
• Lower stat. uncertainty, larger systematic

2. Using the linear relation between N50 and fΔ = N50/N(100-150)
• Larger stat. uncertainty, lower systematic

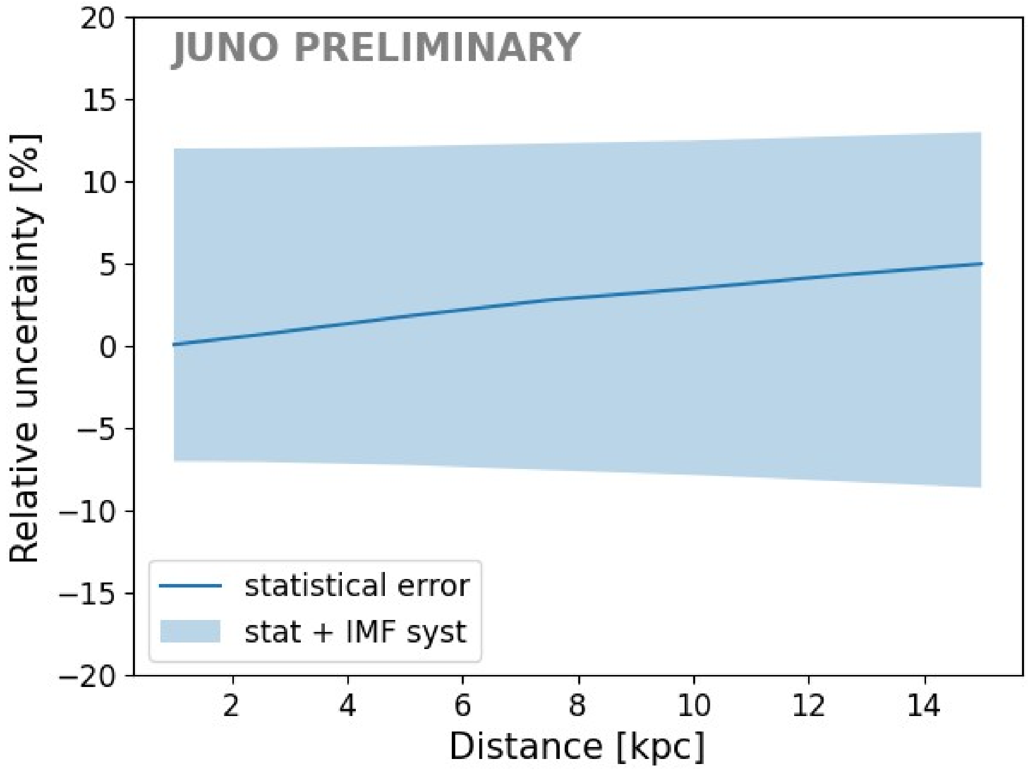
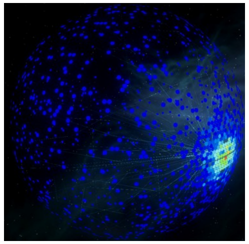


Figure: Statistical uncertainties (solid line). The blue bands include the model systematics (IMF) uncertainty on top (more syst. ongoing).

CCSN neutrinos: pointing

- Pointing to the source with neutrinos is key for a successful MM follow-up
- But direction reconstruction is difficult at MeV energies: point-like emission…

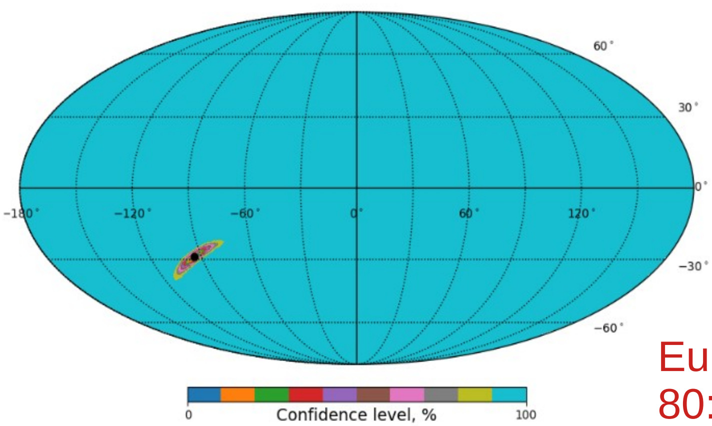
➔ Two possible ways to go:

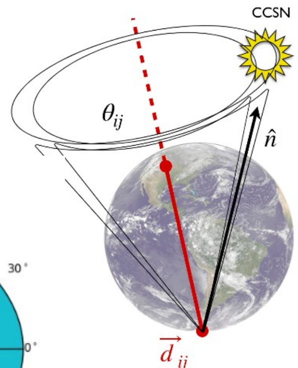


Triangulation

”The time delay between the signal at different detectors defines a sky region”

JUNO/ARCA/IceCube/HyperK

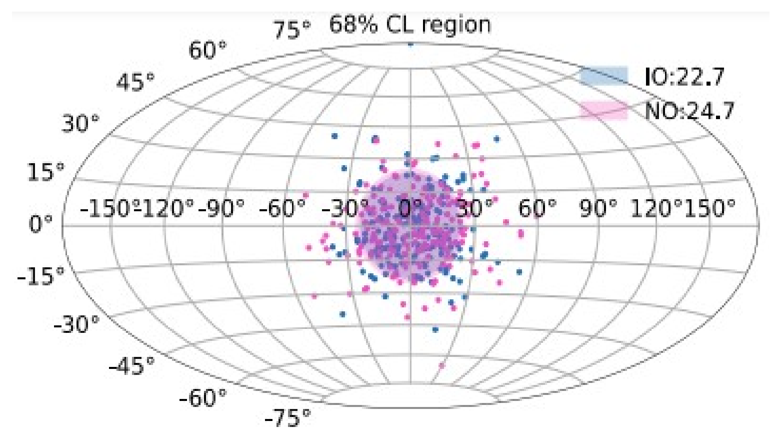




Eur. Phys. J. C 80: 856 (2020)

JUNO: anisotropic interactions

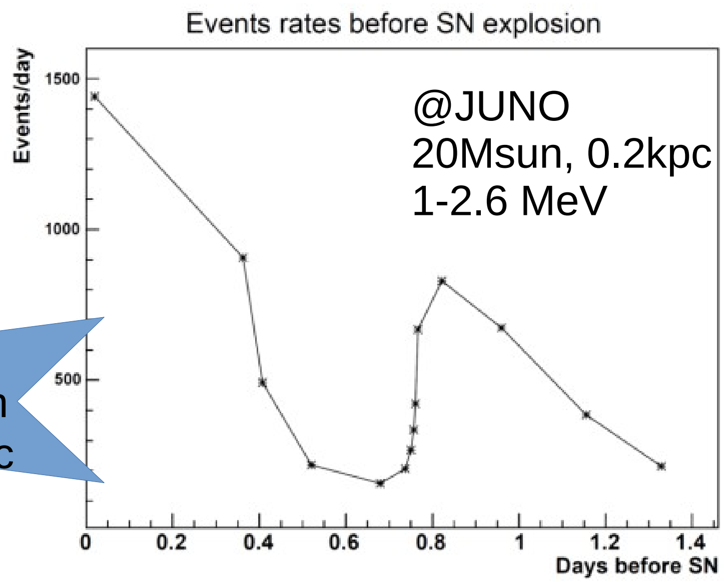
”The direction between the IBD prompt (positron) and delayed (neutron capture) reconstructed vertexes gives ν direction”

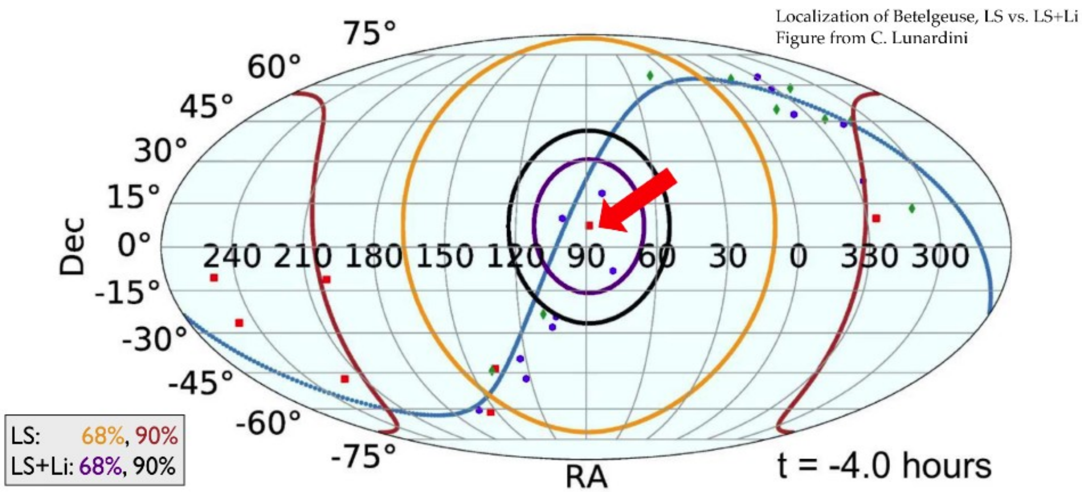


Pre-supernova neutrinos

- Neutrino emission previous to the explosion (Si burning phase) detectable hours to days before the stellar collapse
- Advance notice of the core collapse for other telecopes
- Difficult detection due to low-luminosity, low mean Eν and longer time window
- Low-background detectors (JUNO, SNO+, SuperK-Gd) can detect such signal for close by CCSN events (≤ 1 kpc)
- LS detectors (JUNO) can access directionality from IBD events
  - LS without doping: ~60 deg uncertainty for 22 kton detector *JCAP 05 (2020) 049*
  - With Li doping: ~15 deg uncertainty (22 kton) Sci Rep 4, 4708 (2014)

pre-SN ν detection at d≤1kpc



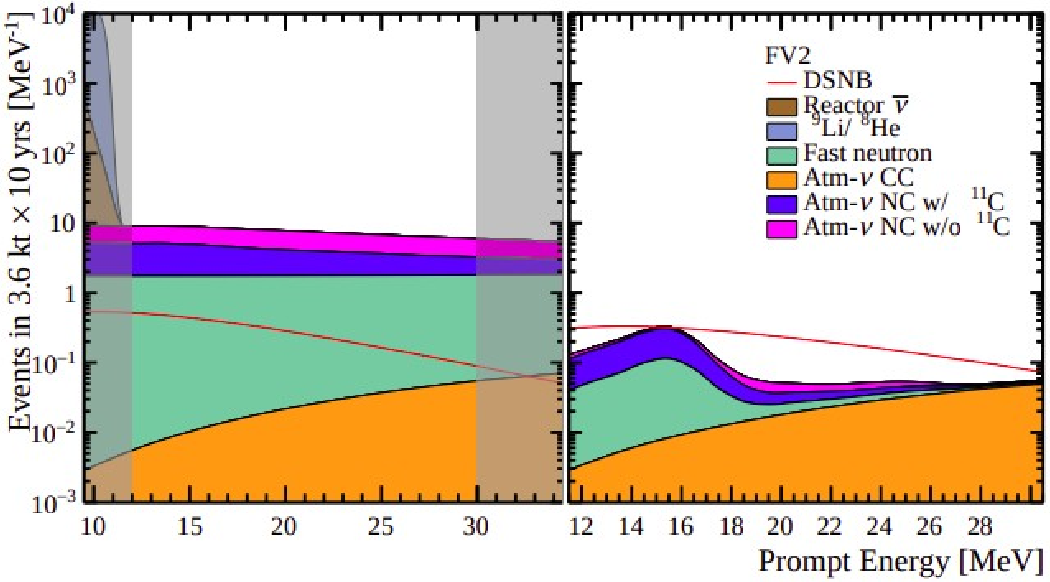


Diffuse supernova neutrino background

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

- 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 (BH) formation rates in the Universe
  - ...

before cuts → after cuts

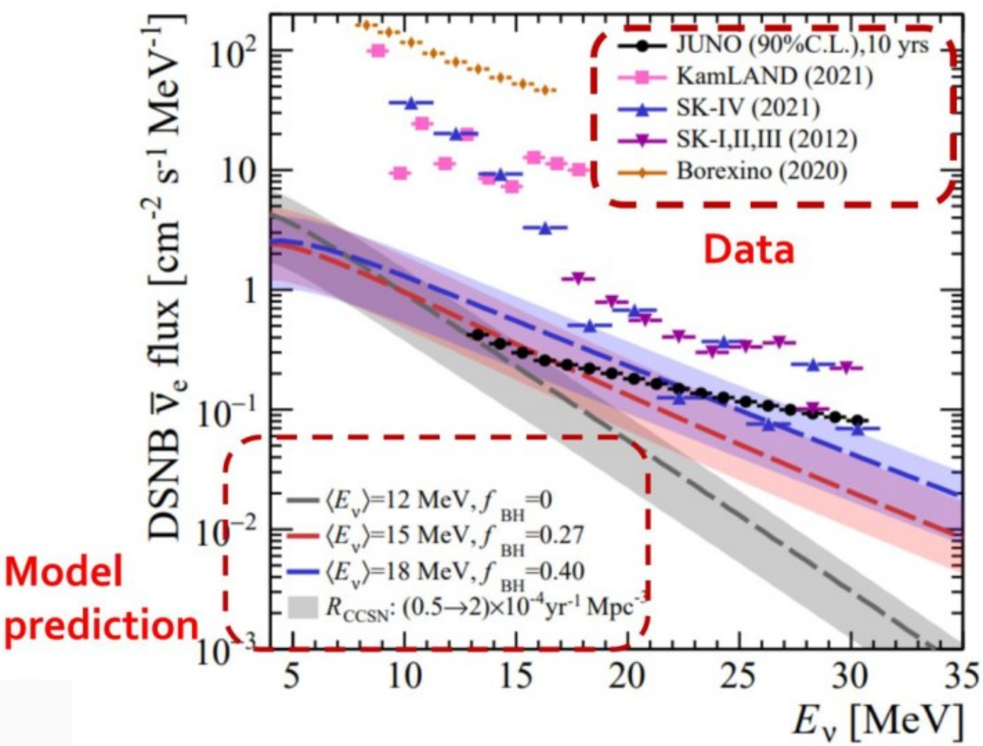


- Detection in JUNO via IBD, with main background from NC atmospheric neutrinos
- Selection: [12-30] MeV + fiducial volume + PSD (pulse shape discrimination, signal vs background) → efficient background rejection

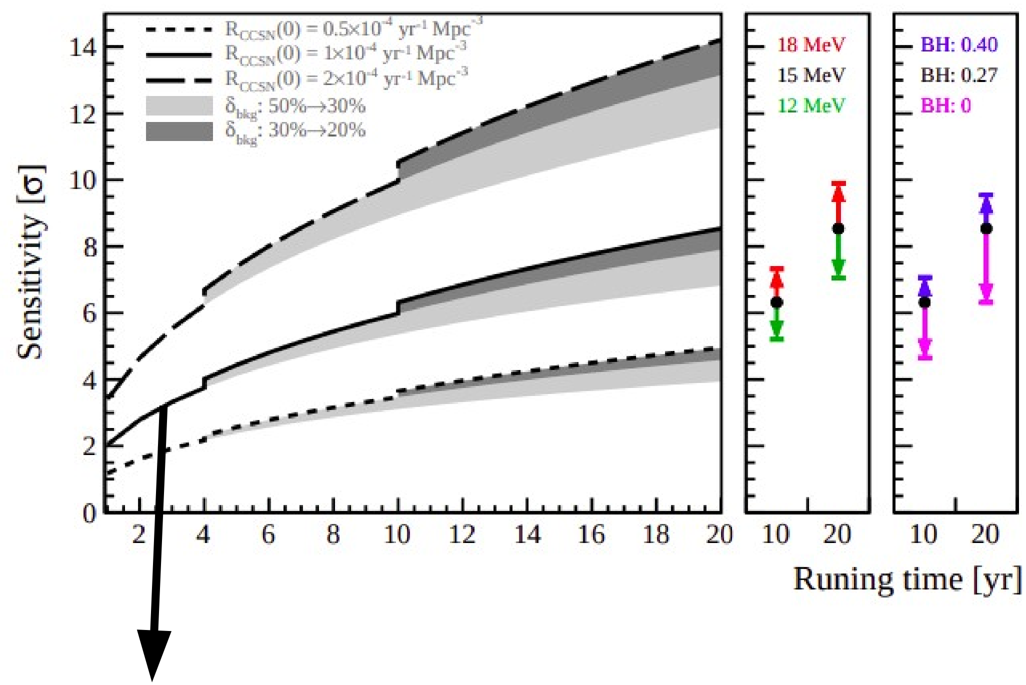
Diffuse supernova neutrino background

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

→ JUNO will be key in the discovery of the DSNB signal and constraining its flux

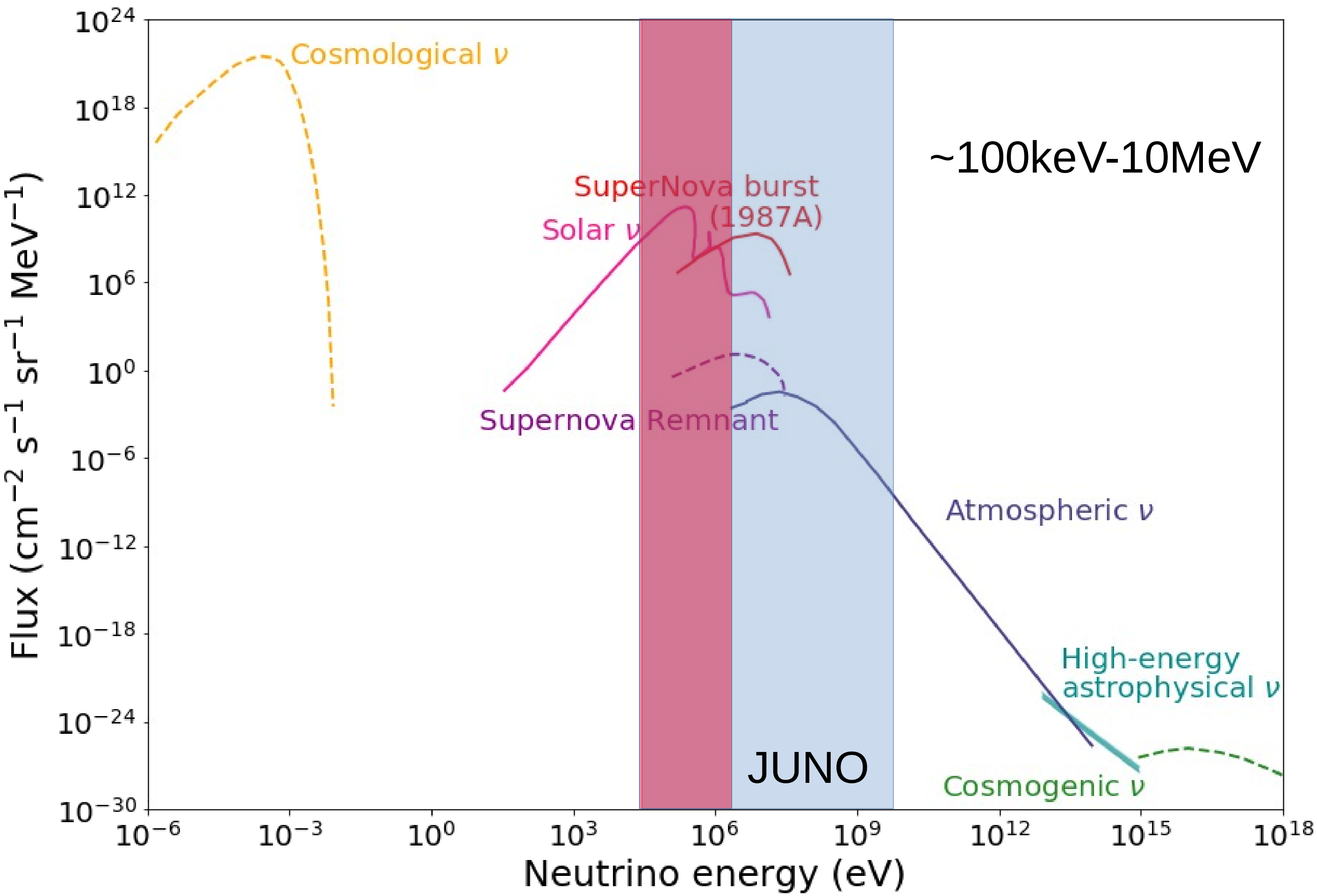


JCAP 10 (2022) 033



3σ discovery after 3 years data taking for nominal model

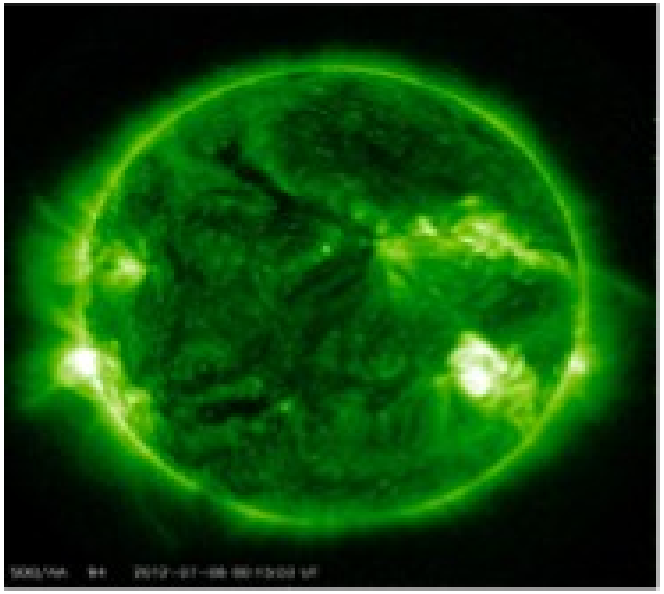
spectrum of natural sources: iii) solar neutrinos (MeV)

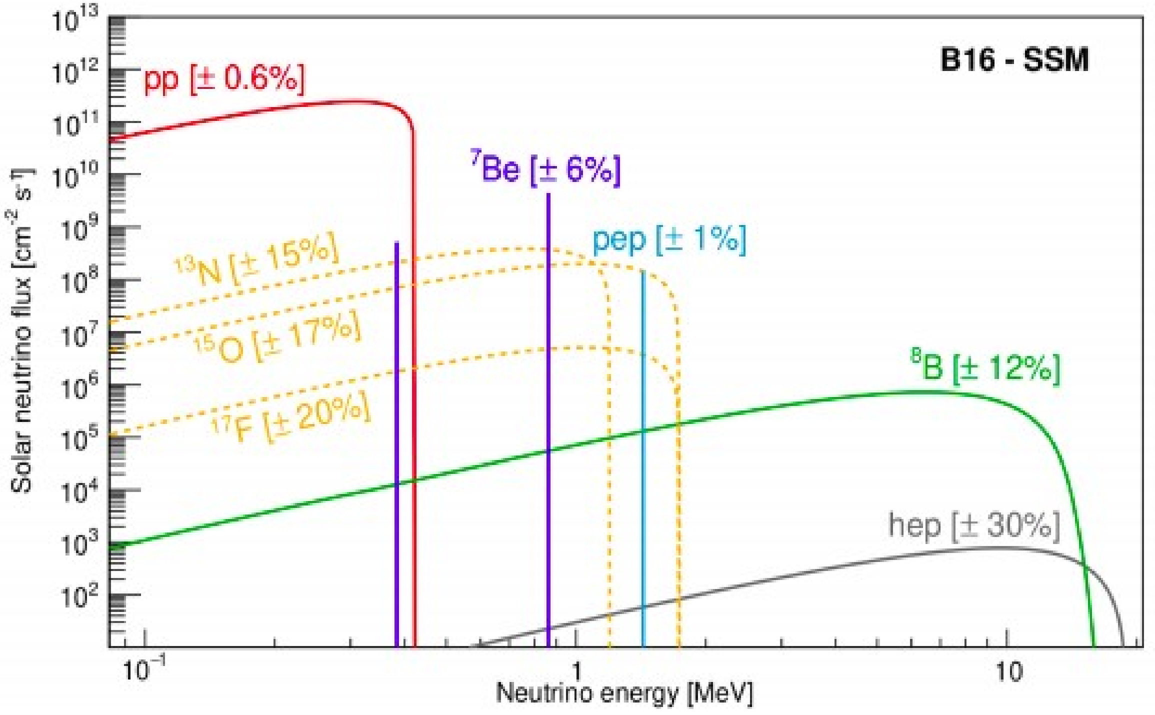


Solar neutrinos

* The Sun the first astrophysical source observed in neutrinos → discovery of ν oscillations
* Main detection channel → ν_e elastic scattering (ES)
* JUNO can benefit of its enormous statistics
* Different fluxes can be detected:

- ^{8}B
- ^{7}B
- pep
- CNO



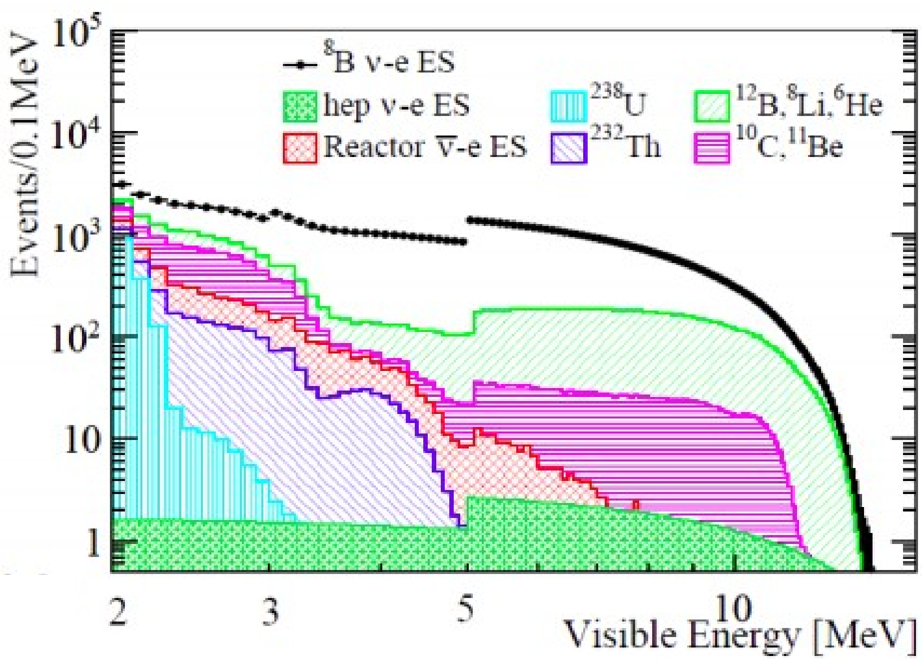


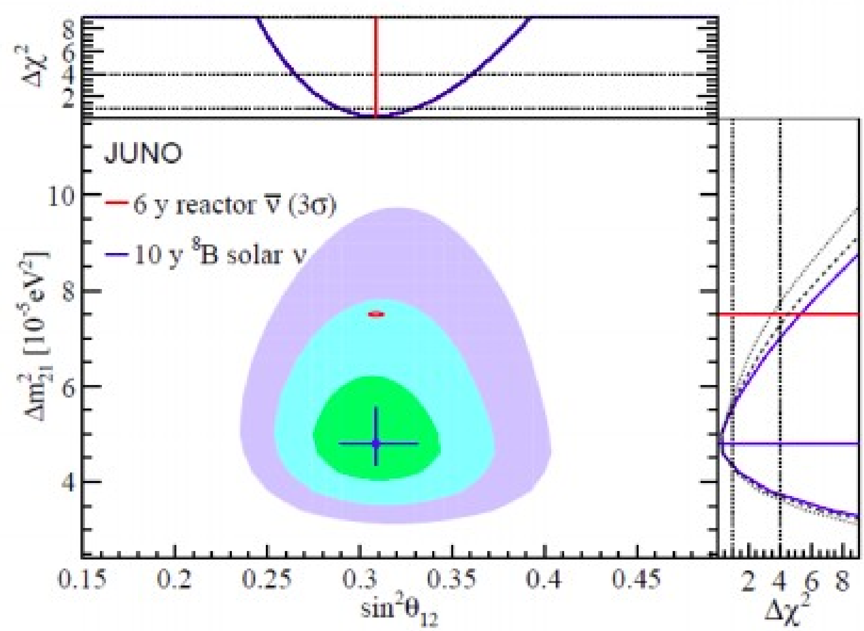
Solar neutrinos

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
- Better precision: contribute to solve metallicity puzzle
- Spectral shape: study day/night asymmetry + other NSI

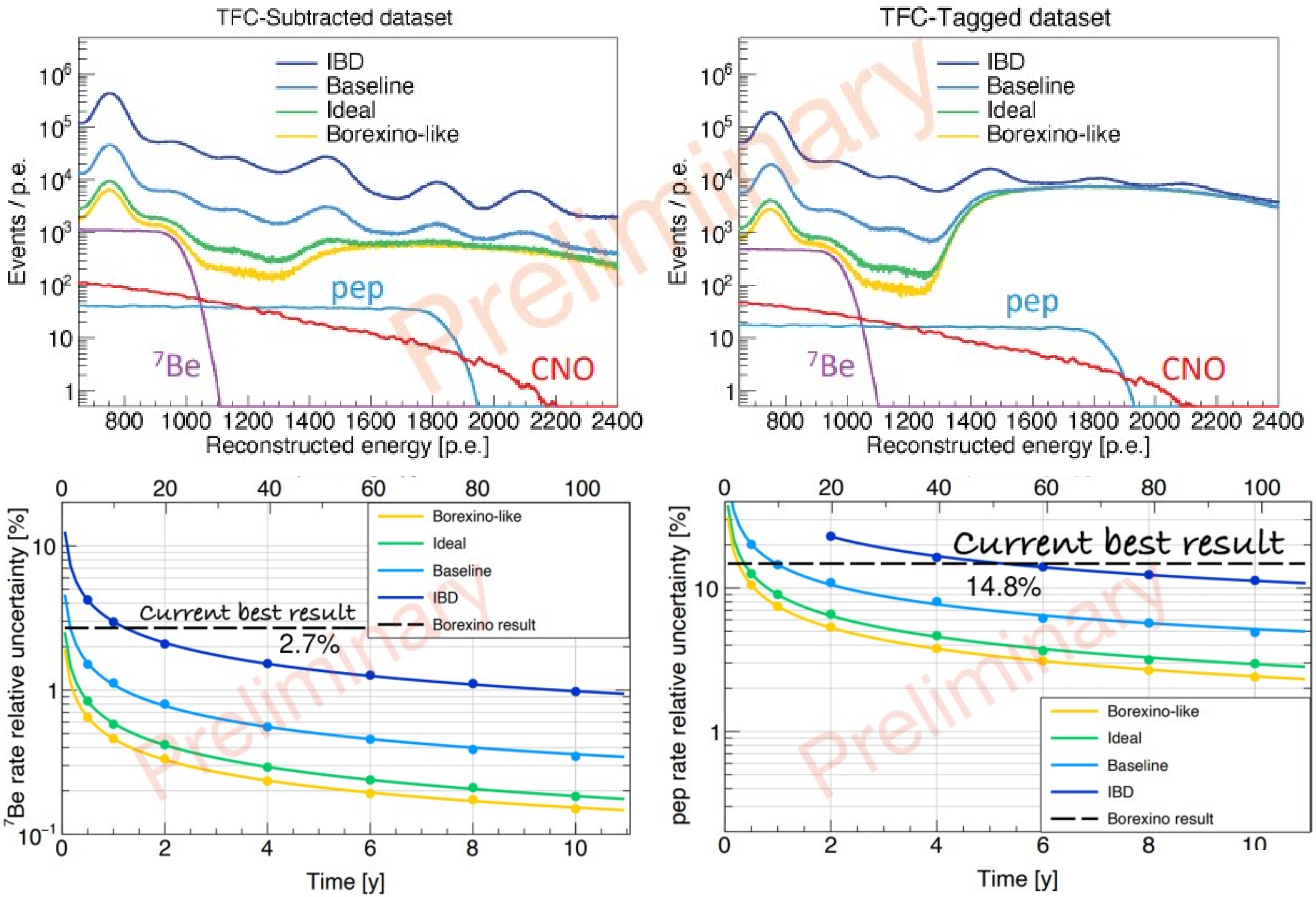
→ Simultaneous determination of $\sin^2\theta_{12}$ and Δm^2_{12} with both solar and reactor neutrinos in one experiment





Solar neutrinos

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

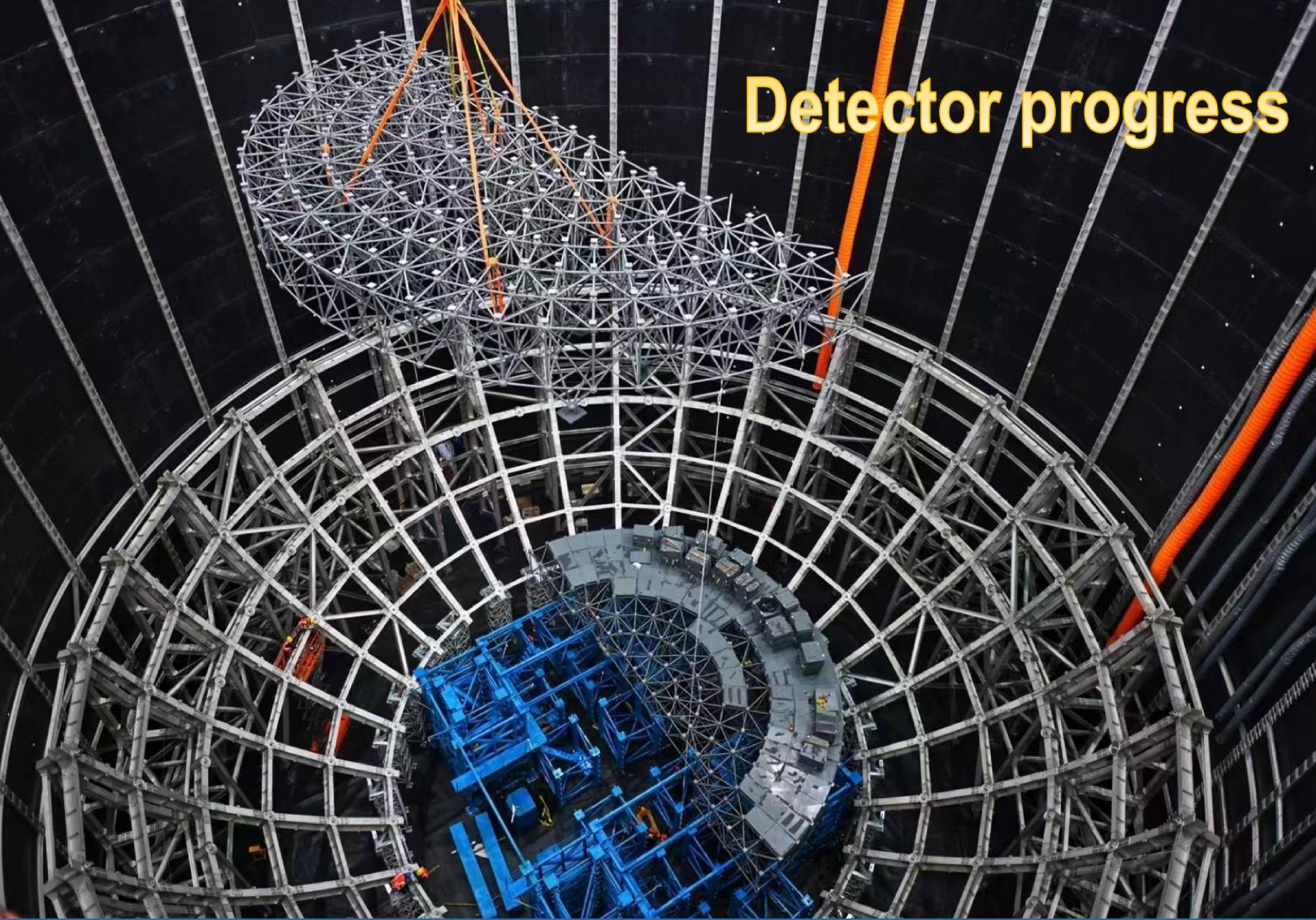


- Different radiopurity scenarios considered

- Two datasets:
^{11}C enriched / depleted

- Improve Borexino results:
7Be and pep in 1-2 years

Detector progress



Status of the central detector

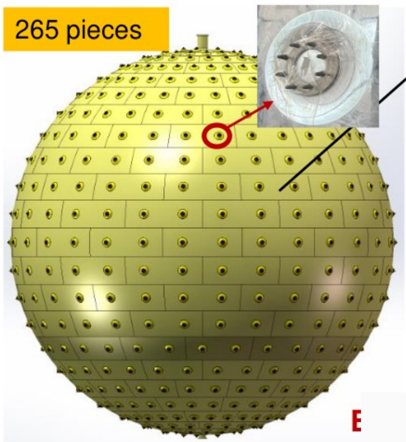
Acrylic sphere (LS container) → Supported by **Stainless Steel (SS) Structure**:

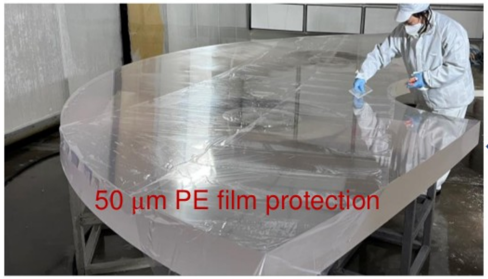
Inner diameter: 35.40±0.04 m

Thickness: 124±4 mm

Light transparency > 96% @ LS

Radiopurity: U/Th/K < 1 ppt





- Installation ongoing: 6/23 layers completed

- Installation completed last June 2022

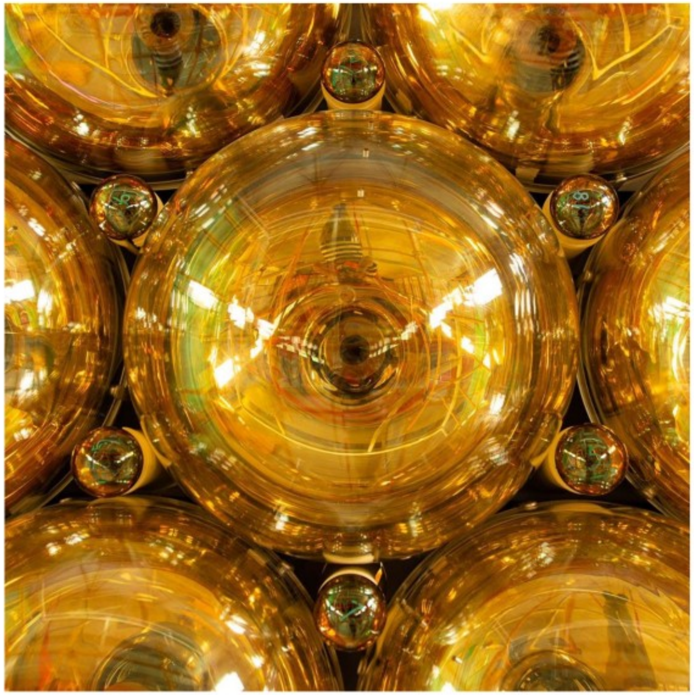
Status: liquid scintillator

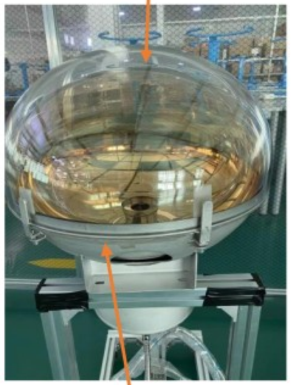
Four purification plants to achieve target radio-purity 10^{-17} g/g U/Th and 20 m attenuation length at 430 nm.

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

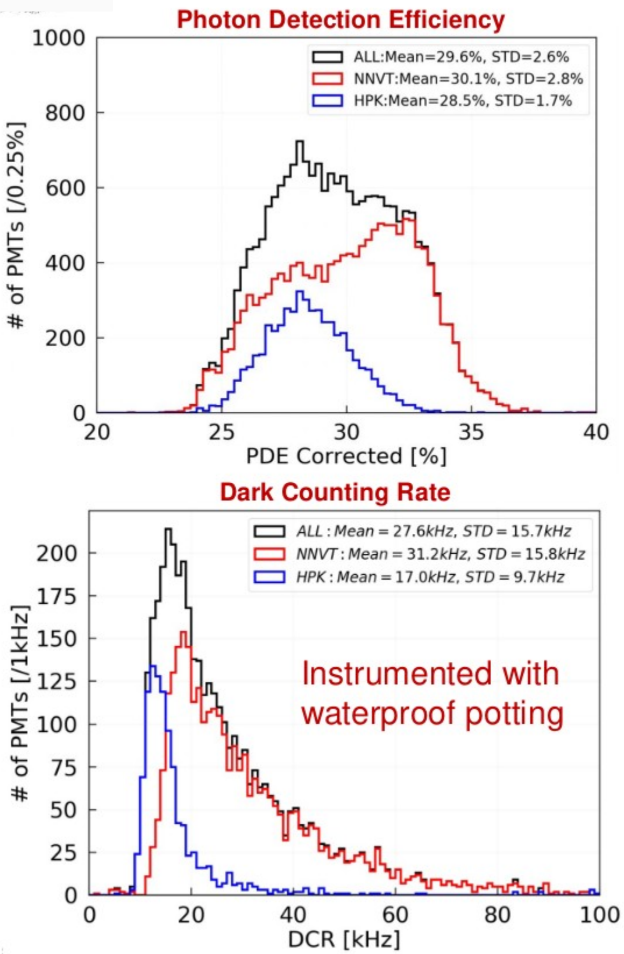
Status: electronics (PMTs)

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

↓

Improve signal to noise ratio

↓

Improve E resolution

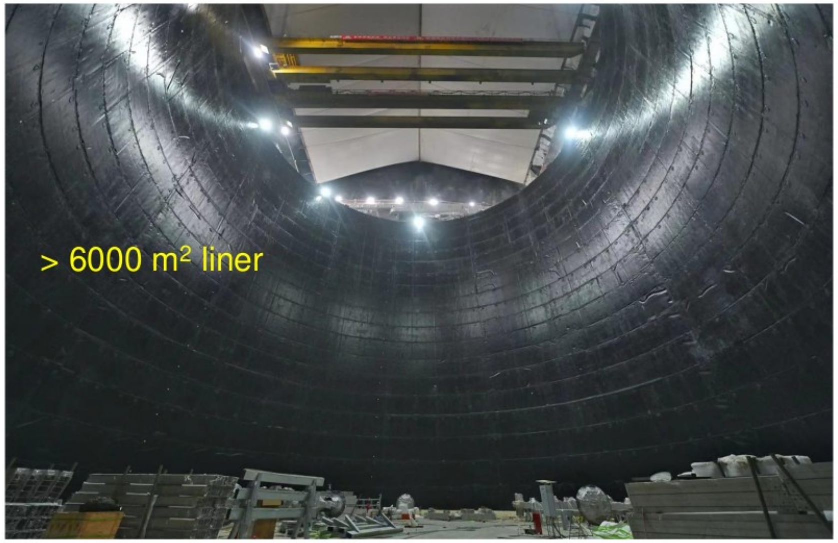
Electronics:

- All PMTs produced, tested, and instrumented with waterproof potting
- Assembly and connection tests finished → Installation started in October

Status: veto detectors

Water pool:

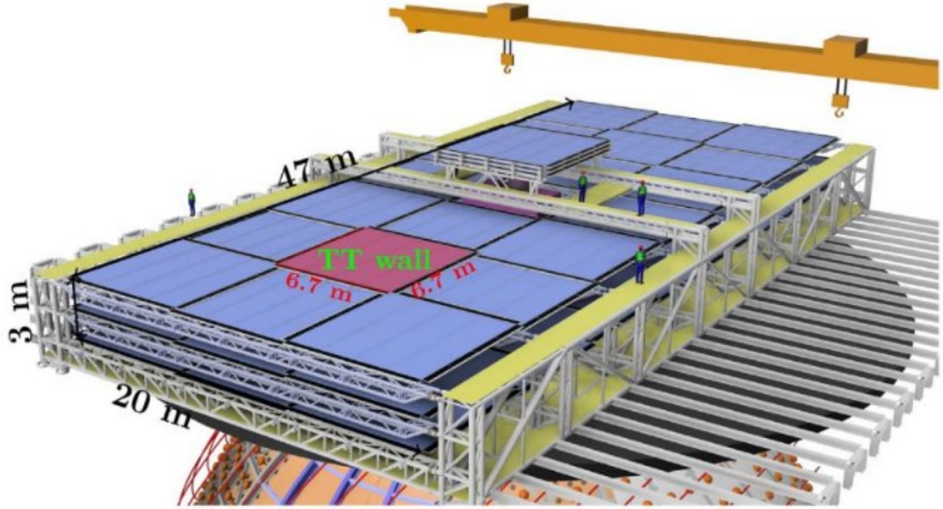
- 35 kton of ultrapure water cherenkov detector
- will act as passive shield and veto for cosmic muons (> 99.5% efficiency, 2400 large PMTs)



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

Top tracker: (paper in preparation)

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



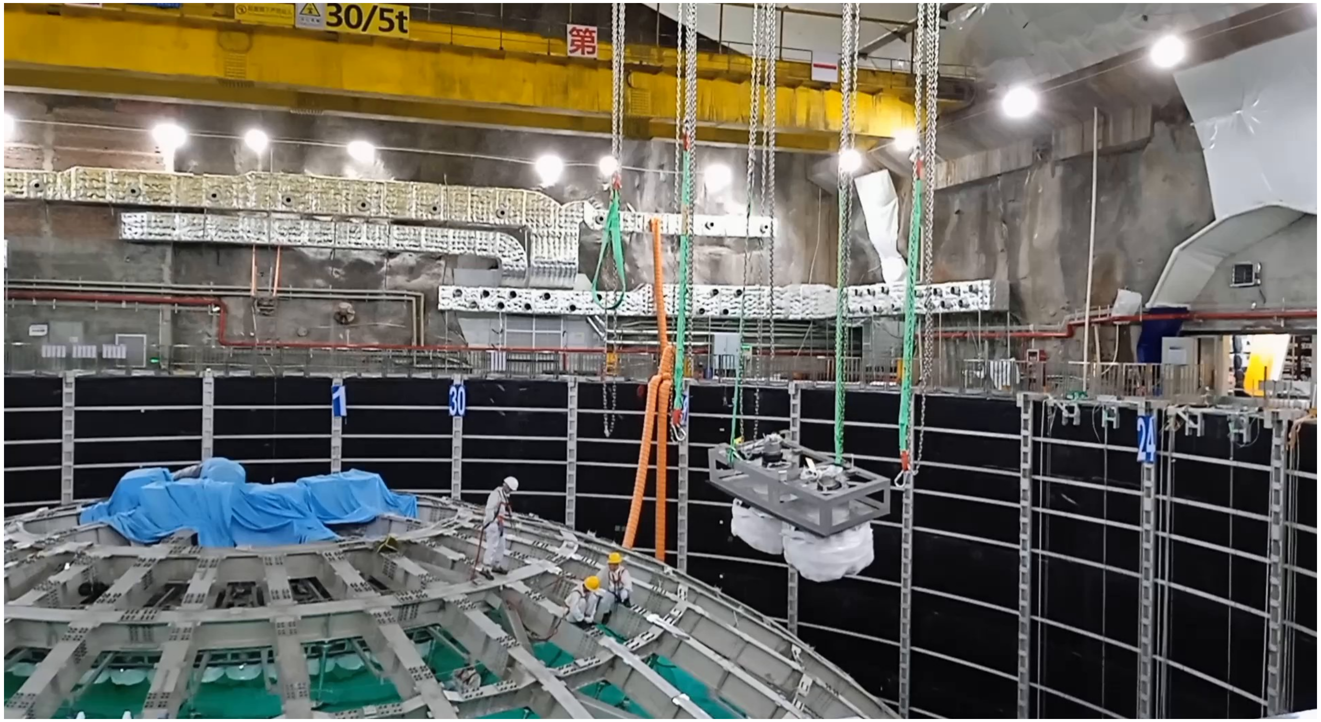
- Prototype working at IPHC
- Modules already at JUNO site
- Mechanical structure design done
- Electronic design done

➔ To be produced and tested this year

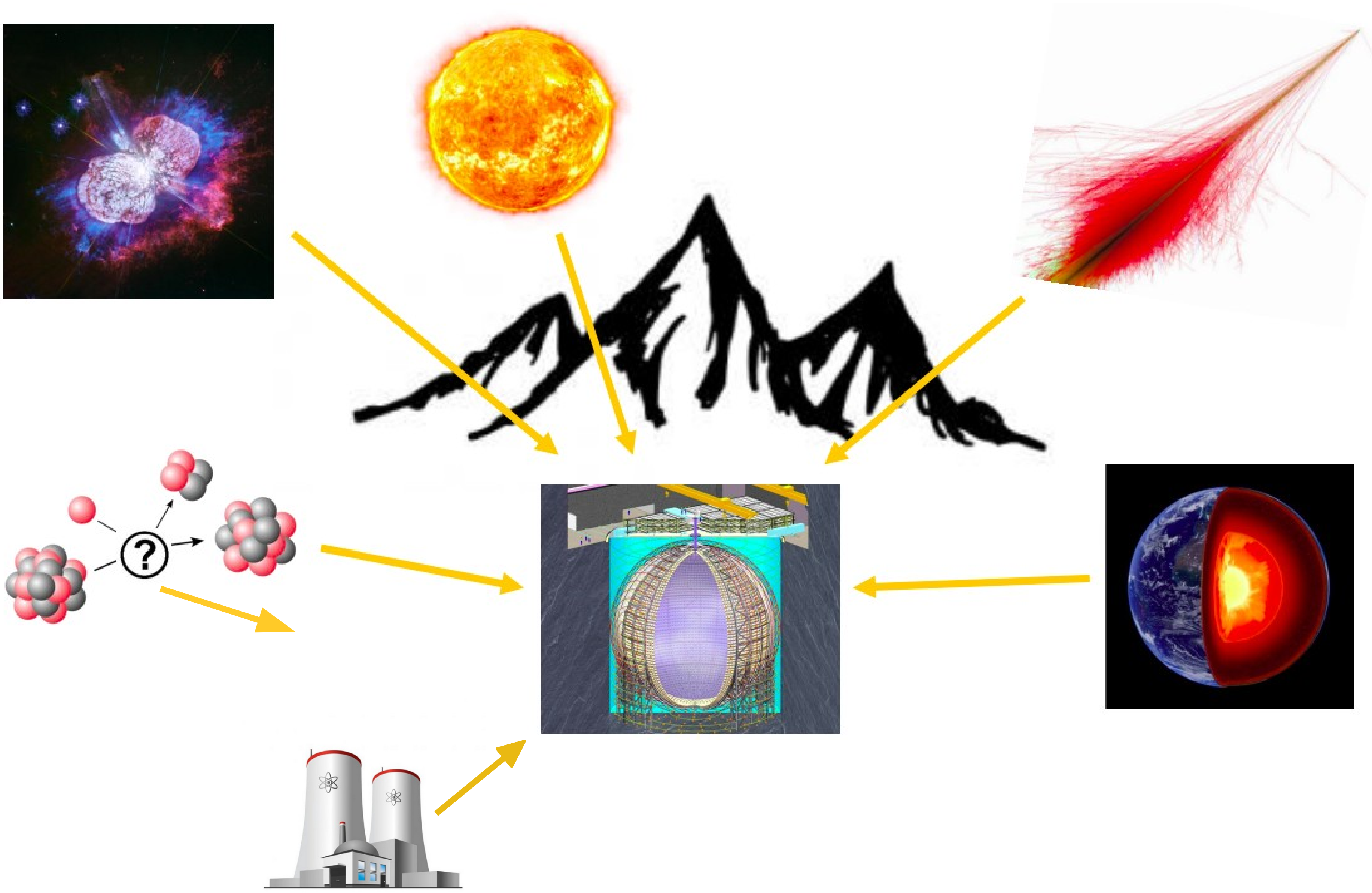
JUNO: detector status

- Installation of the accrylic sphere and the large PMTs ongoing from the top
- All electronics are being installed and tested after installation
- Successful first light-off test done in December

→ Full construction/installation will be finished at the end of the year
→ Filling, commissioning and first physics test run expected in 2024



JUNO – AN INSTRUMENT WITH AN INCREDIBLE PHYSICS POTENTIAL



JUNO - TAO

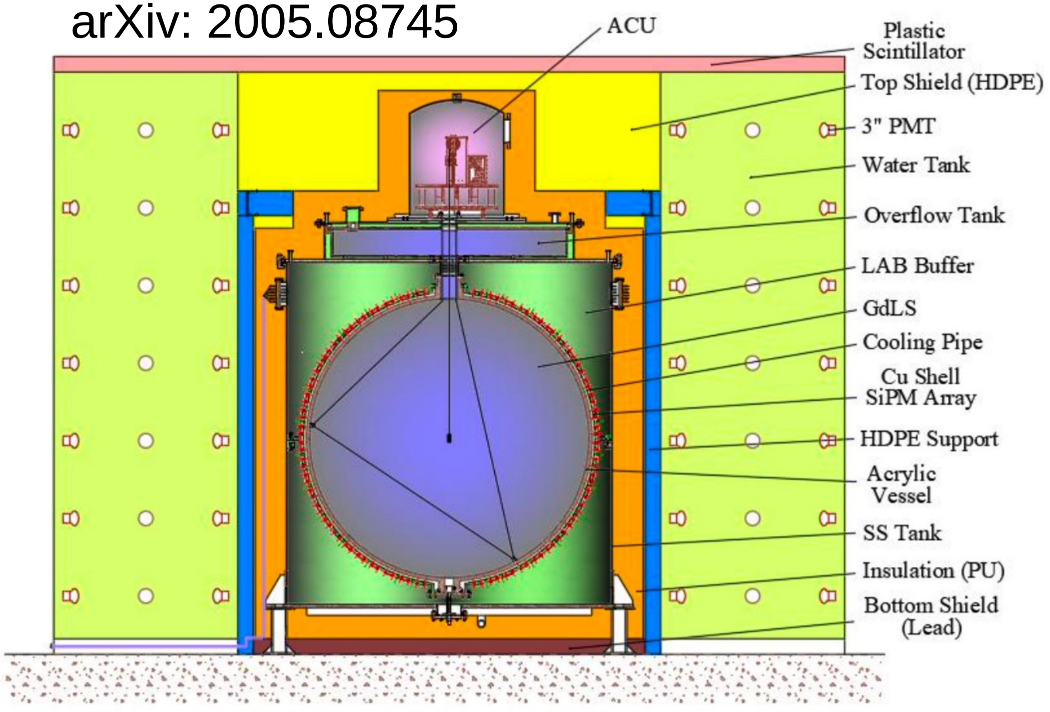
TAO (Taishan anti-neutrino Observatory), satellite detector of JUNO:

- 2.8 kton of Gd-dopped LS
- Located ~30 m from one nuclear core
- Energy resolution: 1.5%/√E[MeV]
- 94% coverage with SiPMs

Goals:

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

arXiv: 2005.08745



1:1 prototype under construction in China