# The multi-messenger astrophysics potential of the JUNO experiment

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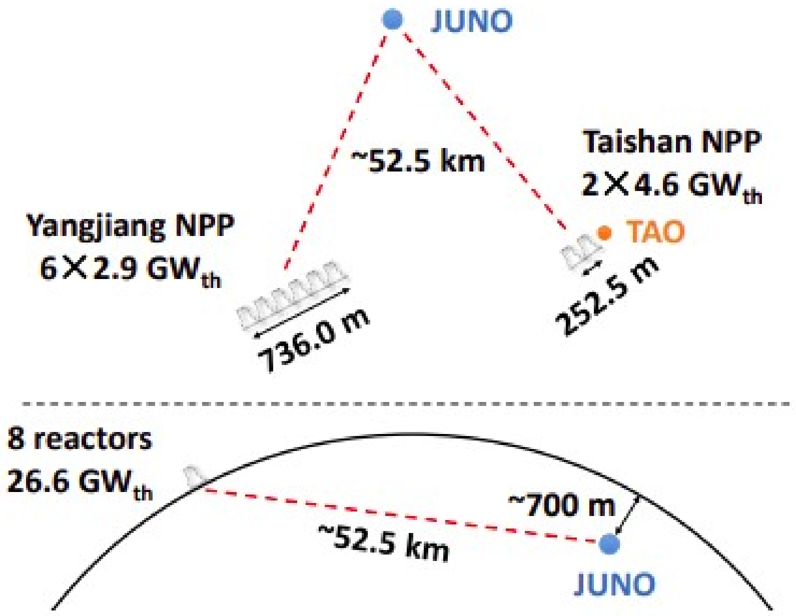
On behalf of the JUNO Collaboration

# The JUNO detector

- JUNO (Jiangmen Underground Neutrino Observatory) is a medium baseline (53 km) reactor neutrino experiment, located 700 m underground.
- 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 (LS) detector with impressive PMT coverage (>40k PMTs)



# The JUNO detector

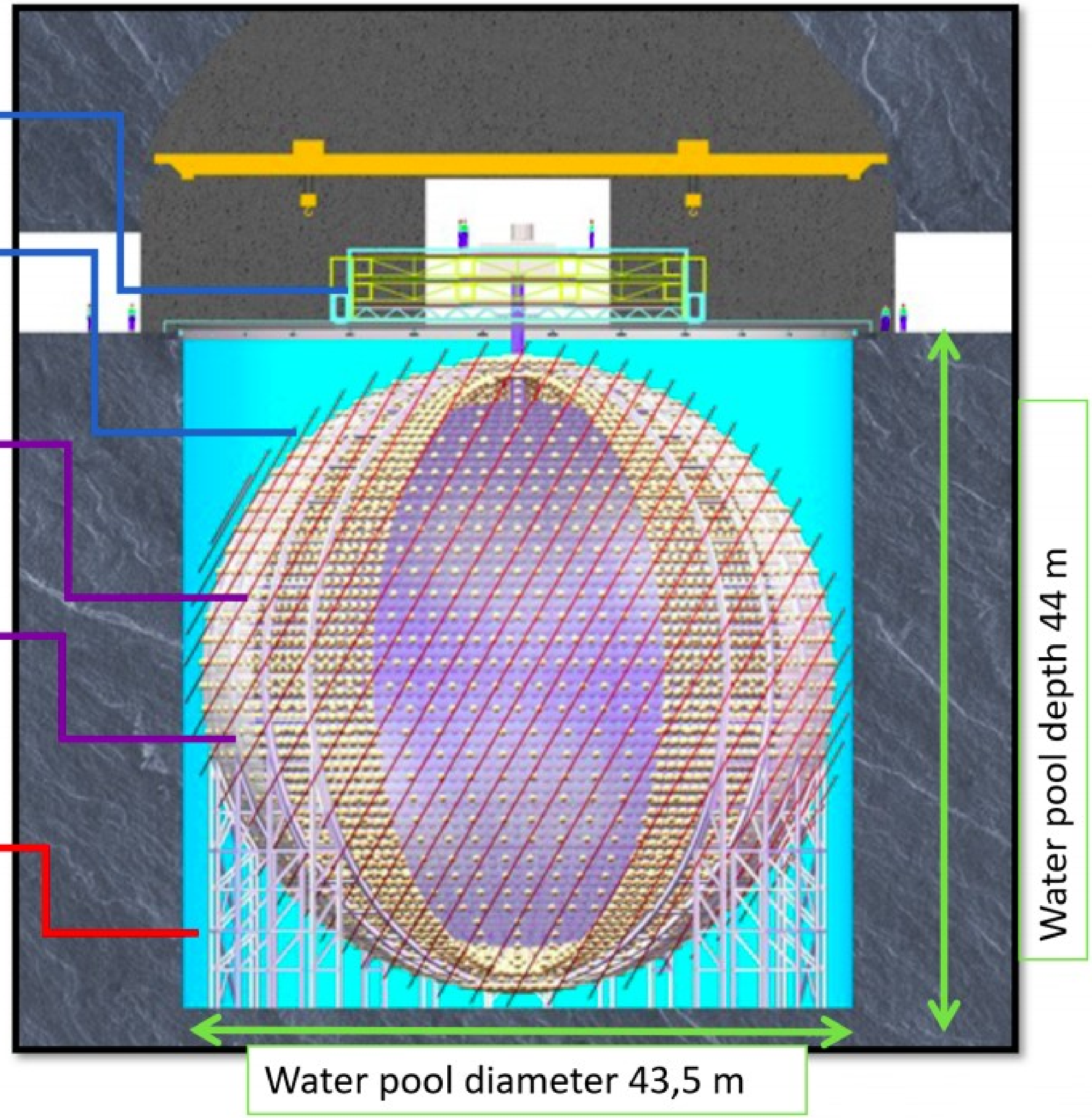
Top tracker

Earth Magnetic Fields shielding coils

Central detector:
- Steel structure
- Acrylic Sphere
- 20 kton LS

PMT:
- 17612 20'' PMTs
- 25600 3'' PMTs
- ~78% Coverage

Veto:
- 40 kton Pure water
- 2400 20'' PMTs

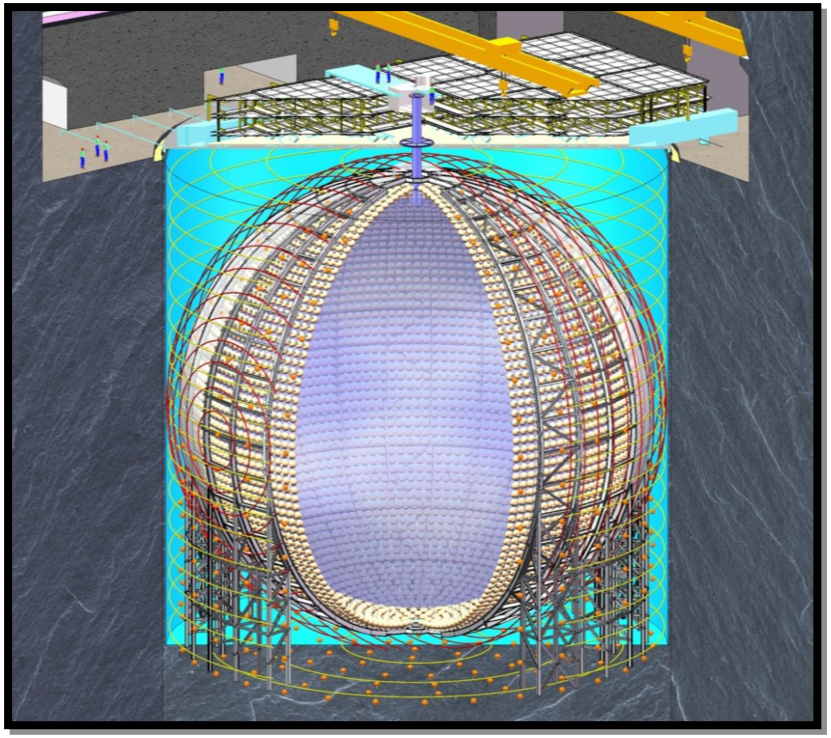


# The JUNO detector

**Primary goal:** precise measurement of reactor neutrino oscillations

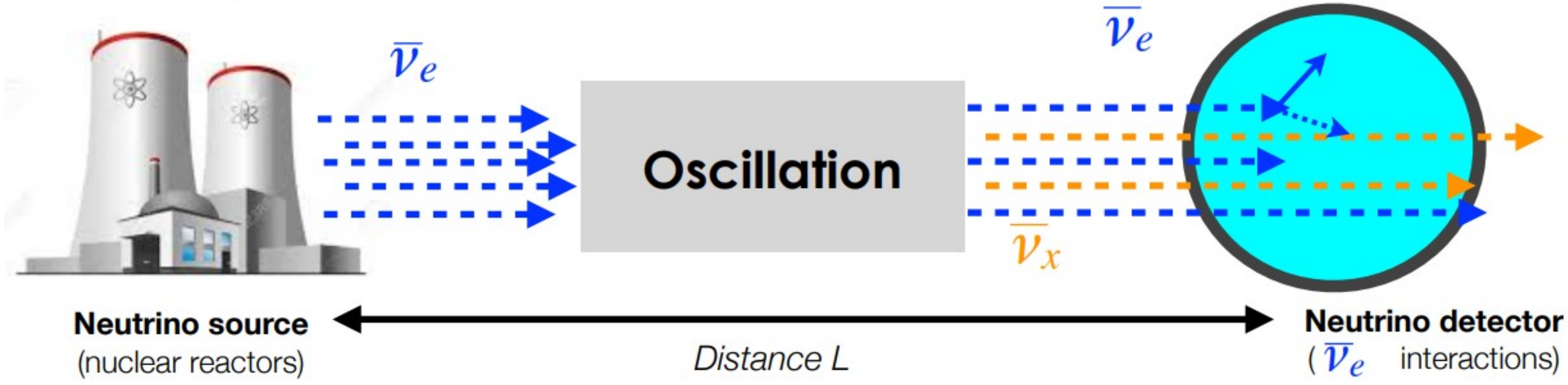
**Requirements:**
- High statistics (~$10^5$ events in 6 yr)
- Energy resolution: ~3% @1MeV
- Energy scale uncertainty < 1%

**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 | ~1640/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

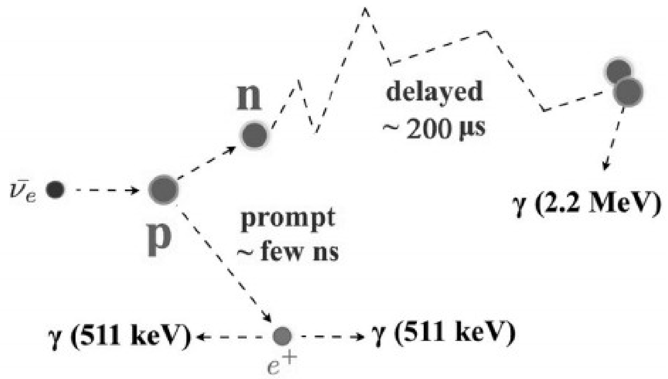



Reactor neutrinos are observed by Inverse Beta Decay (IBD): positron signal (1) and neutron capture (2)

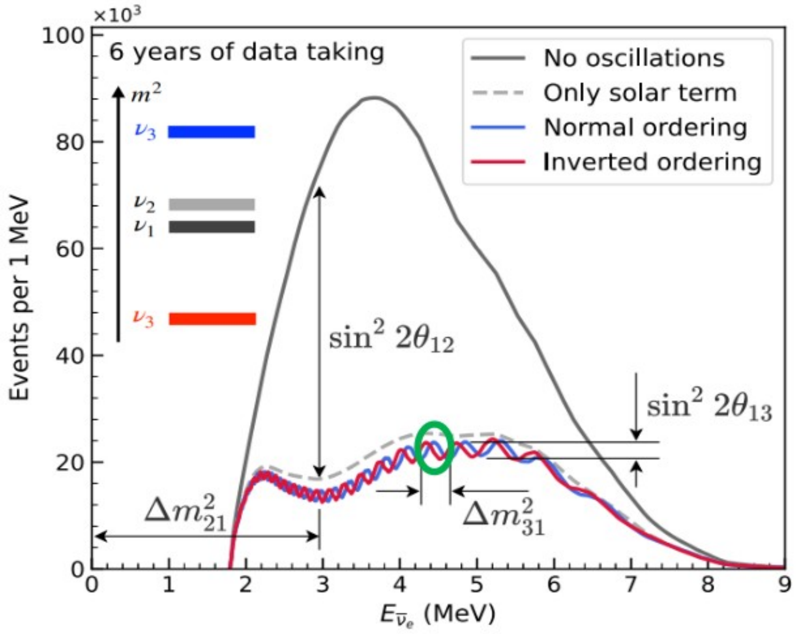
$$\overline{\nu}_e + p \rightarrow e^+ + n \qquad (1)$$

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

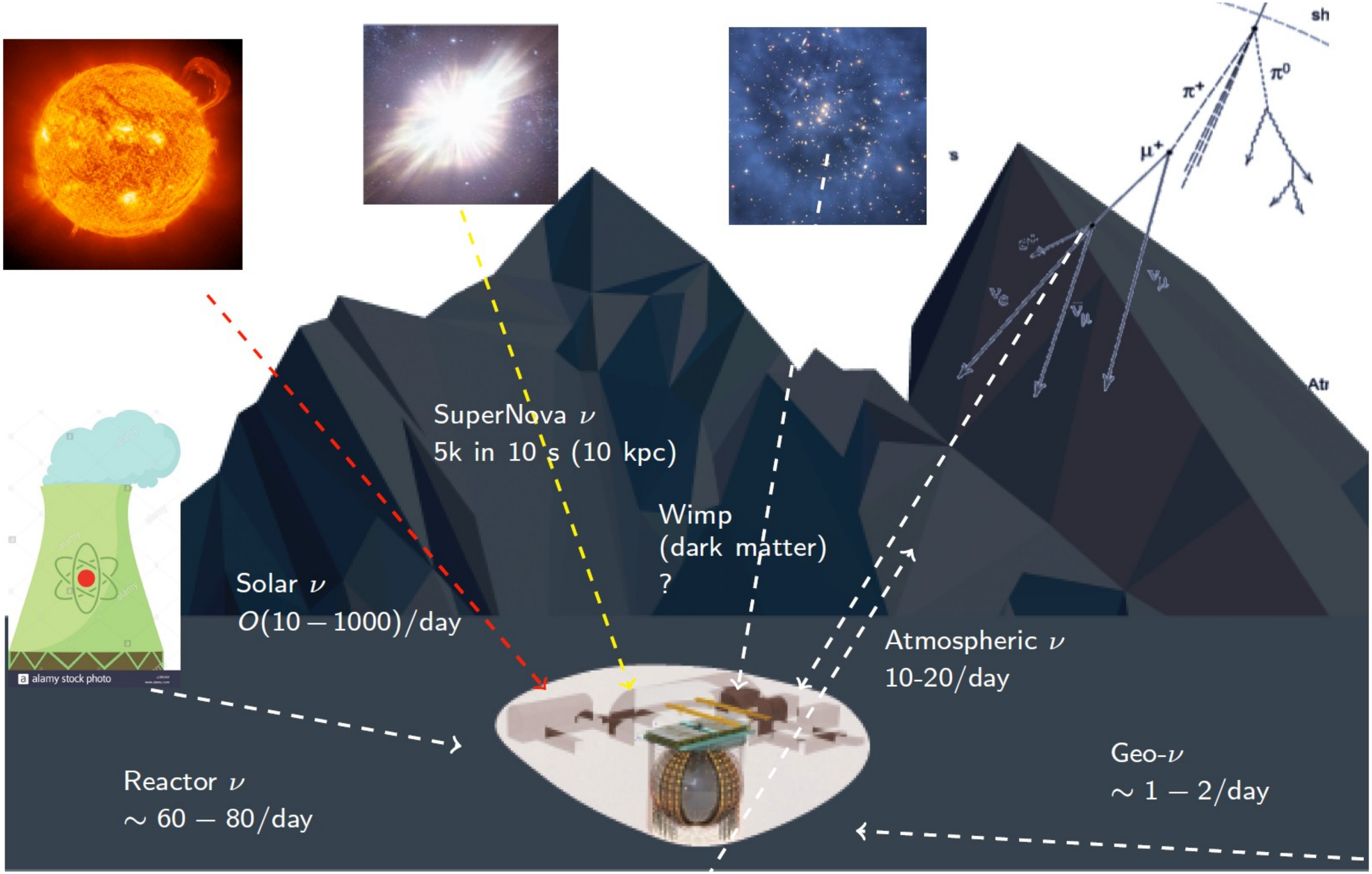
- Very clear signal: prompt + delay coincidence in the (visible) energy range ~[0.7,8] MeV:



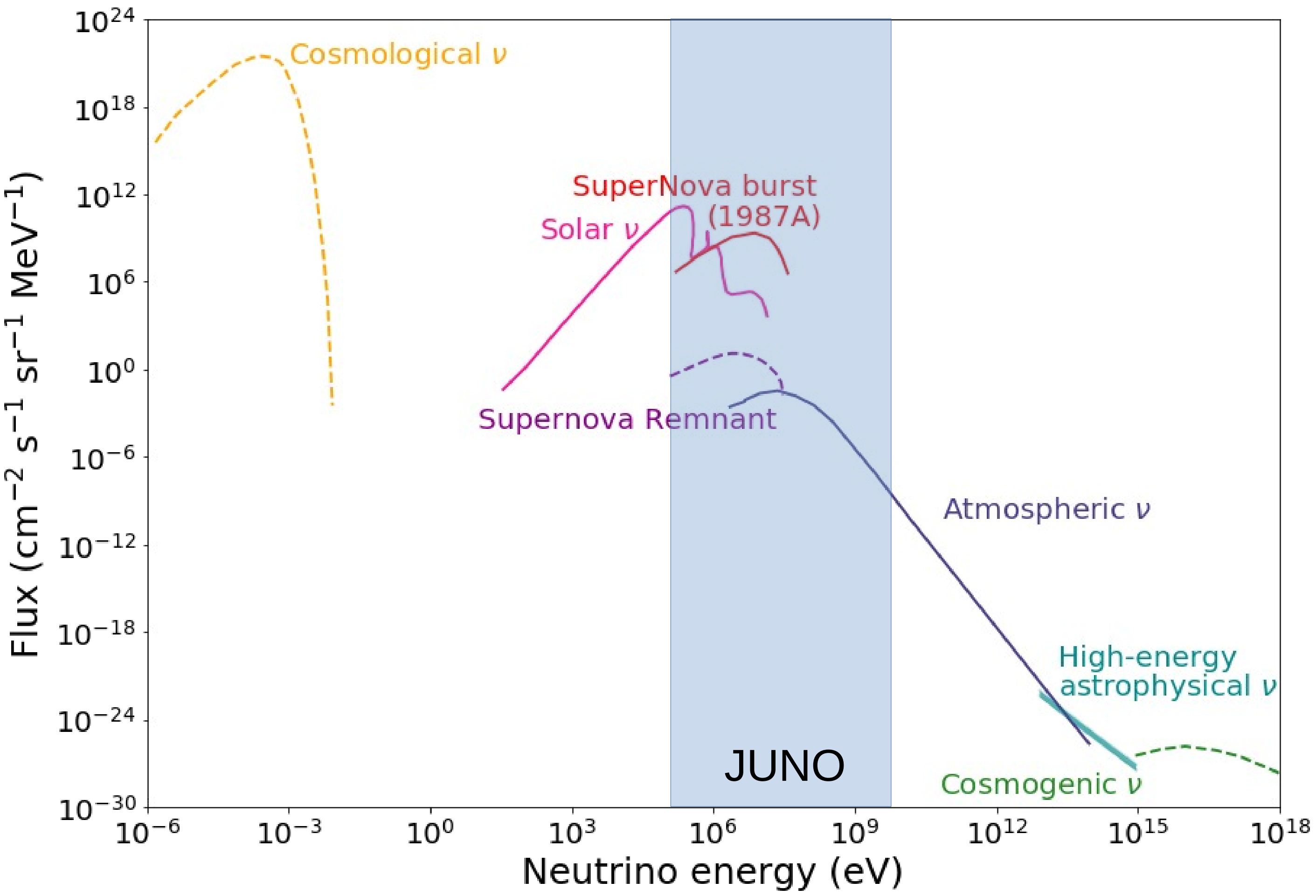

Oscillated reactor spectrum



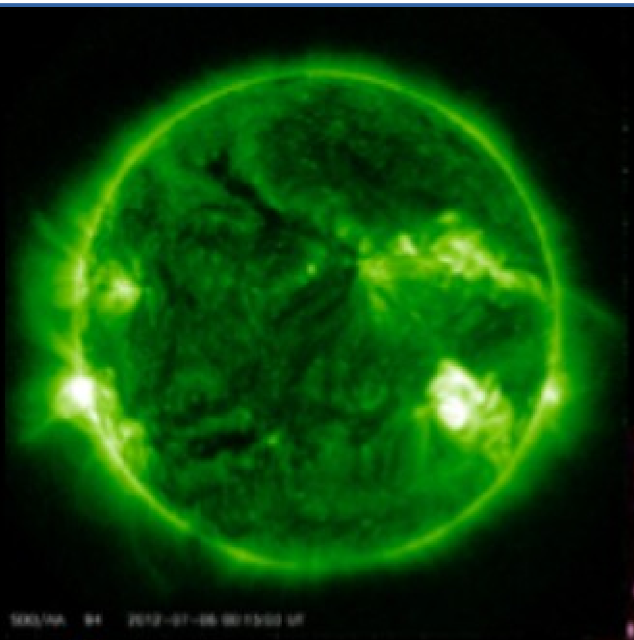
# JUNO physics program



# Neutrino landscape: spectrum of natural sources



# Multi-messenger sources



Sun

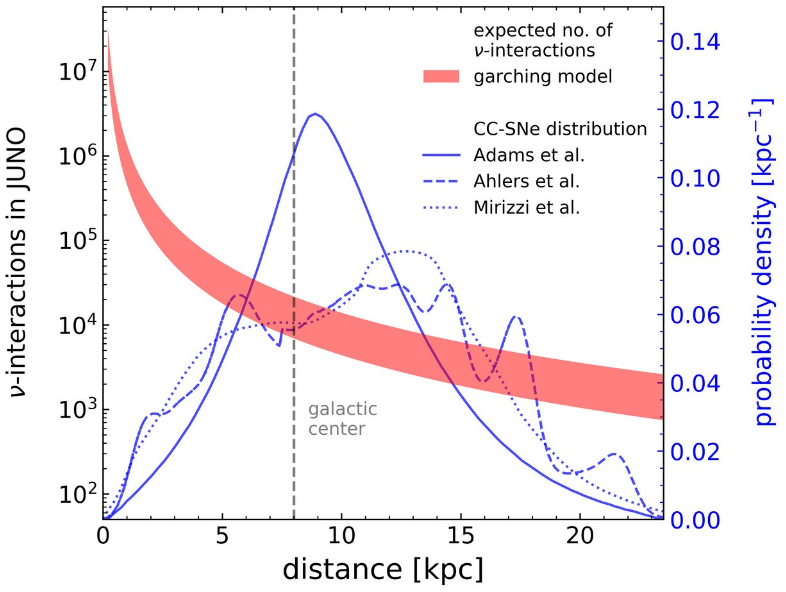
Supernova
SN1987A

Blazars (active galactic nuclei)
TXS 0506+056
(evidence)

# 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
- Sensitive to all neutrino flavors with high statistics through different interaction channels in the detector:
  - IBD → $\nu_e$ flux
  - ν-electron elastic scattering (ES) → $\nu_e$ flux (mainly)
  - ν-protron ES → all flavors (mainly $\nu_x$ flux)

Doing CCSN physics with neutrino data? Need:
- ✓ PID/event slection → all flavor flux evolution
- ✓ Good energy resolution → energy spectrum
- ✓ Good time resolution → time profile (lightcurve)
- ✓ Good angular resolution → pointing

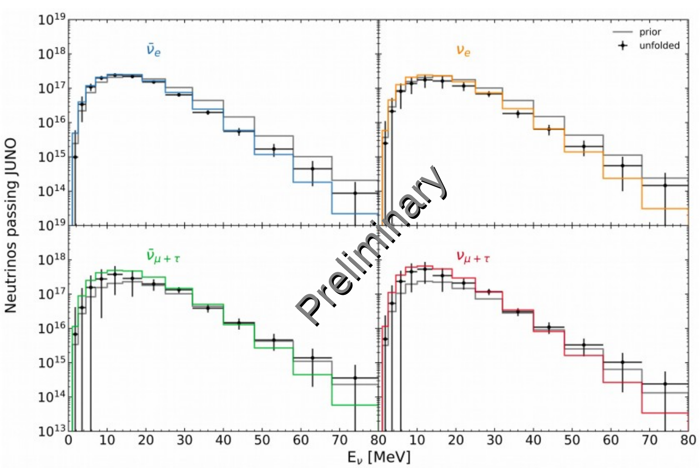


# Core-collapse supernova neutrinos in JUNO

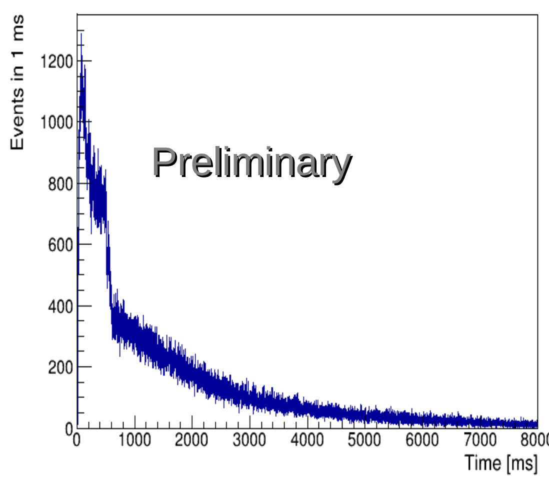
→Good energy and time resolution + flavor classification:
JUNO will measure:

Constrain CCSN physics!

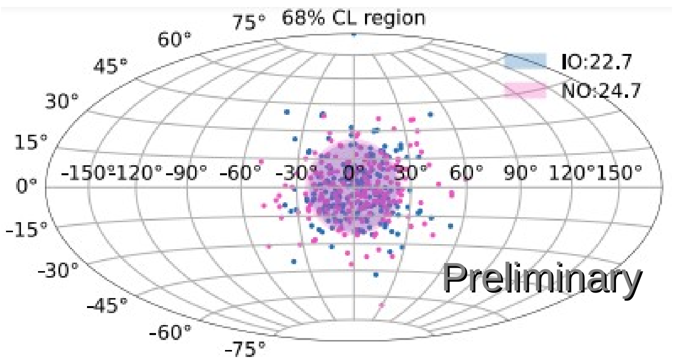
Flavor dependent energy spectrum

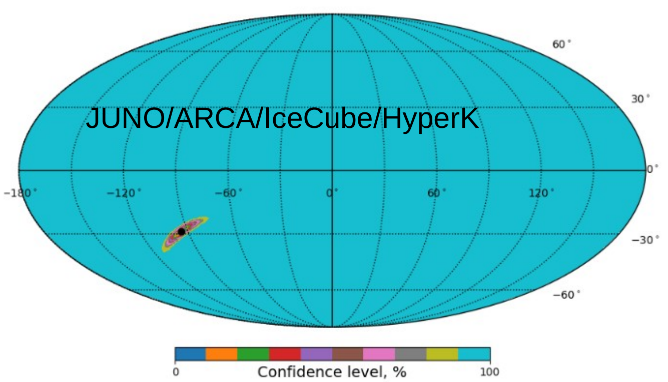



Lightcurve:




Direction:

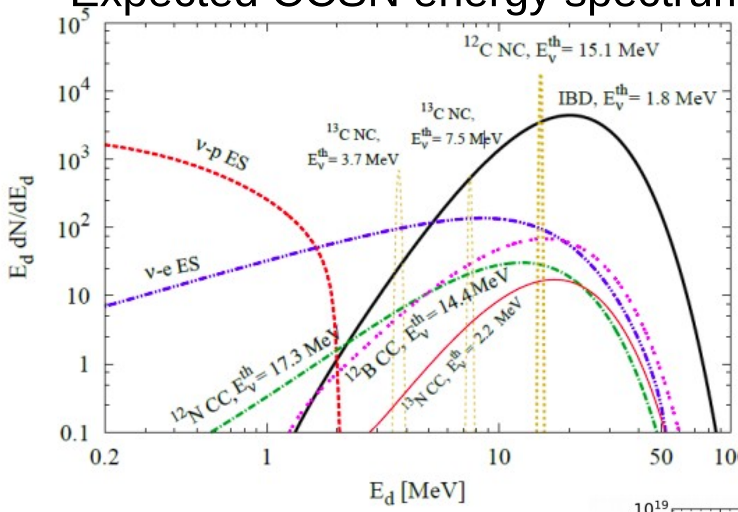


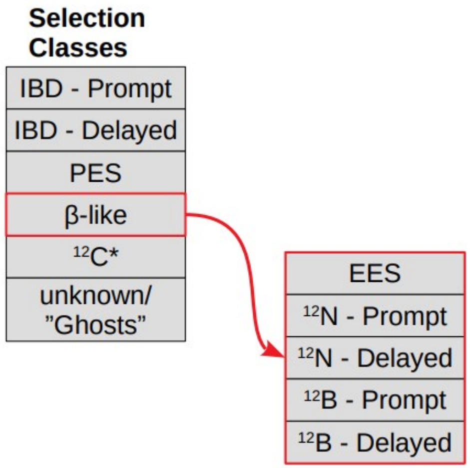



# CCSN neutrino spectrum

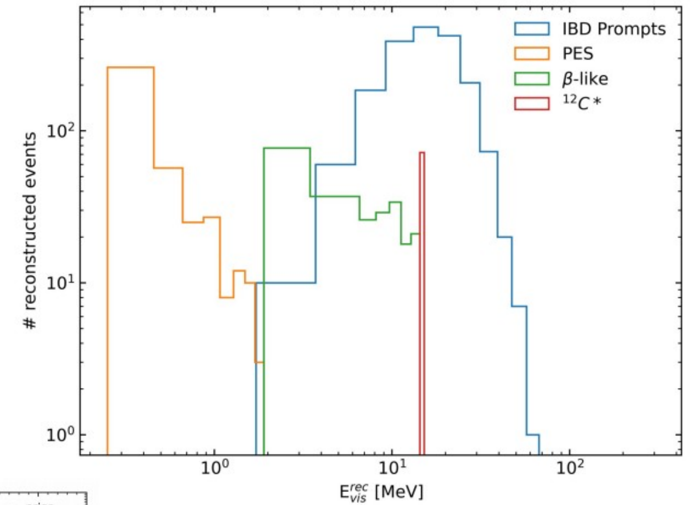
Use time-space coincidence (IBD) and energy cuts to select the different channels:

Expected CCSN energy spectrum:

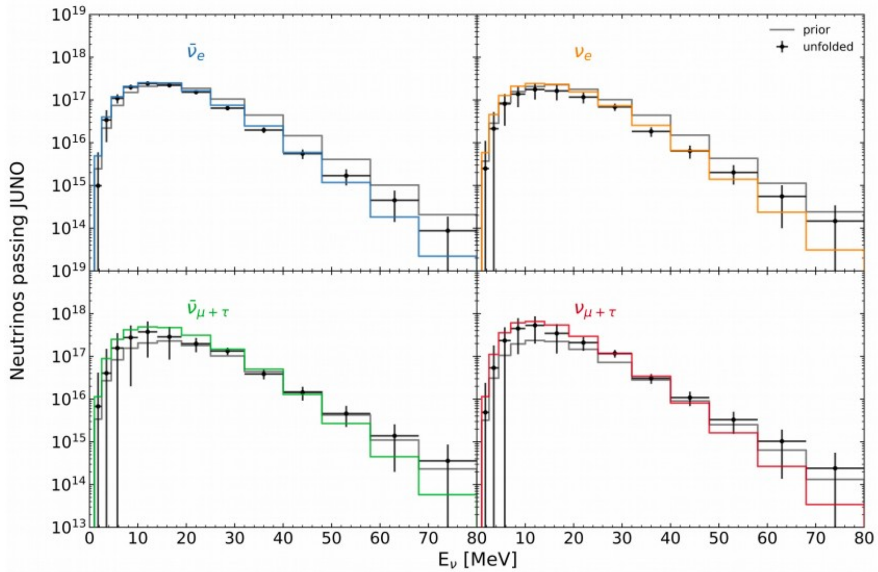



Reconstructed after selection:

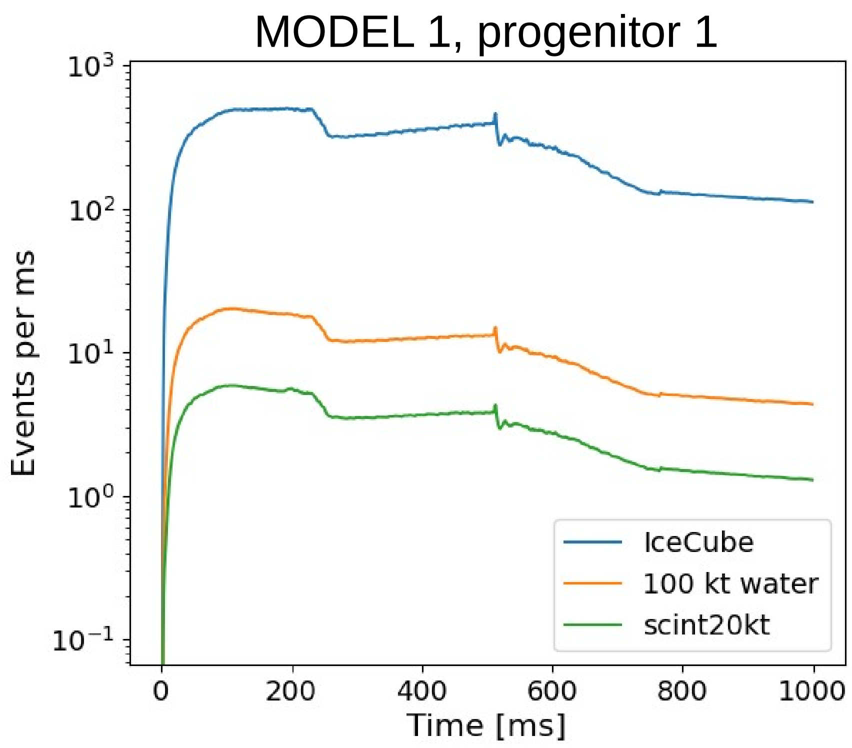


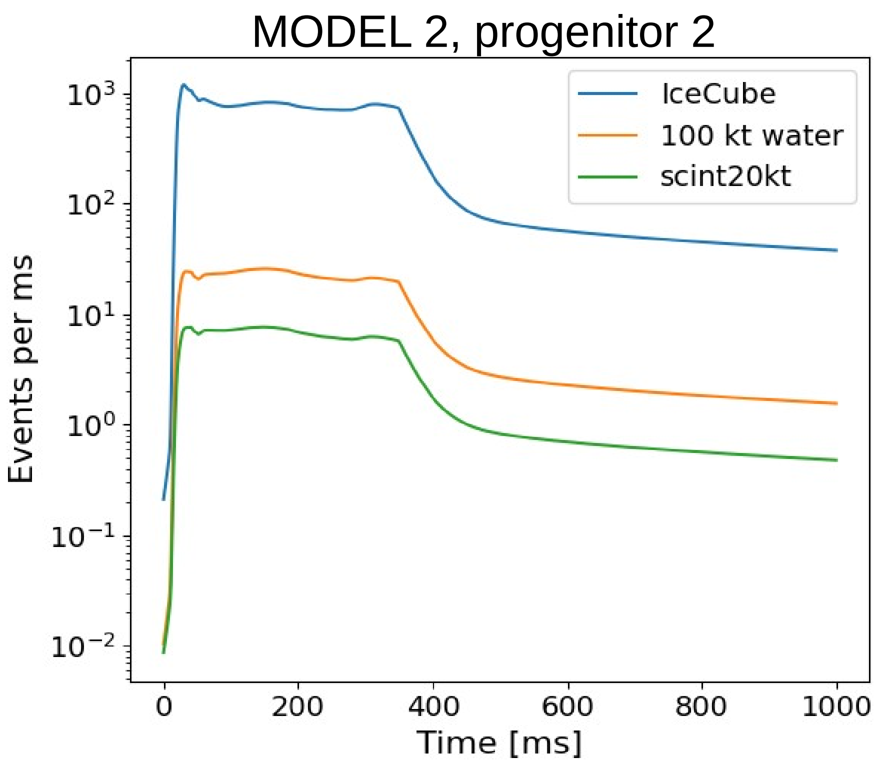

Flavor dependent neutrino energy spectrum UNFOLDED:



# CCSN neutrino lightcurve

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

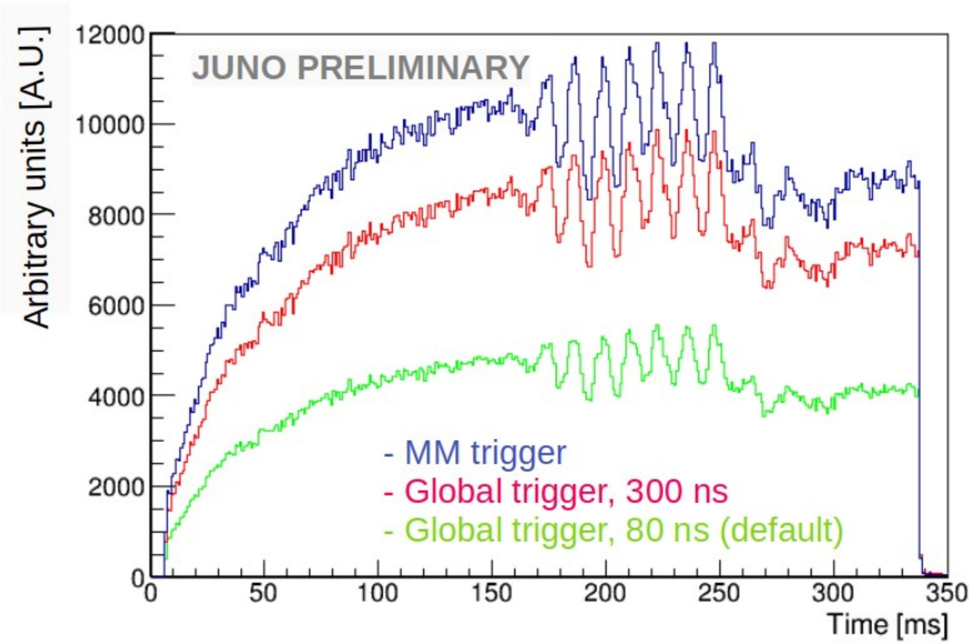



(Example using *snewpy*: https://github.com/SNEWS2/snewpy *and snowglobes https://github.com/SNOwGLoBES/snowglobes software*)

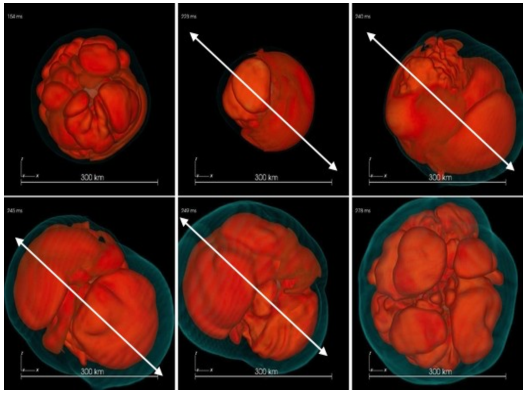
# CCSN neutrino lightcurve

- Neutrino lightcurve relies on event timing
- Event statistics matters for lightcurve studies (to resolve precise lightcurve features)
- Optimal event trigger is important:
  - **Global multiplicity trigger:**
    Default: 200 PMTs fired in 80 ns
  - **Multi-messenger (MM) trigger:**
    likelihood cut, low energy threshold



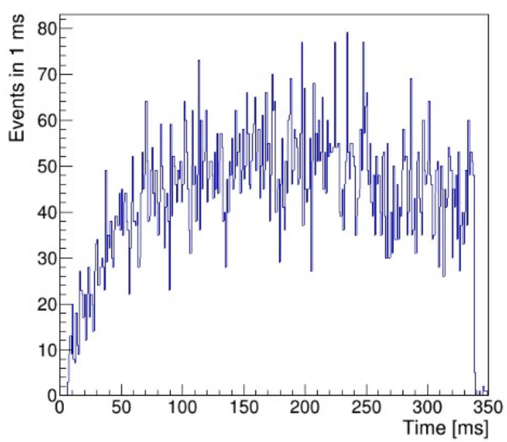

## Example of interesting lightcurve feature to study: SASI oscillations

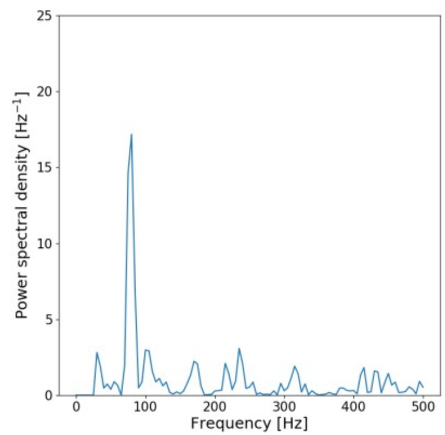
- SASI = standing accretion shock instability: predicted by 3D CCSN simulations
- Why is it interesting:
  - It favors explosion and final energetics
  - It could explain neutron star kicks observed
  - It might be accompanied by GW emission



# CCSN neutrino lightcurve

- **Observable:** fast-time variations of the detected rates, oscillating with a characteristic frequency (~80Hz) → Spectral analysis of the neutrino data (20 $M_{\odot}$, SASI direction):



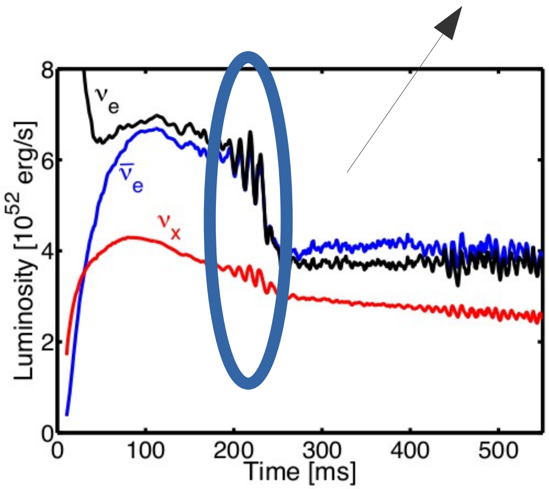

OBSERVED LIGHT-CURVE

(Fourier Transform)

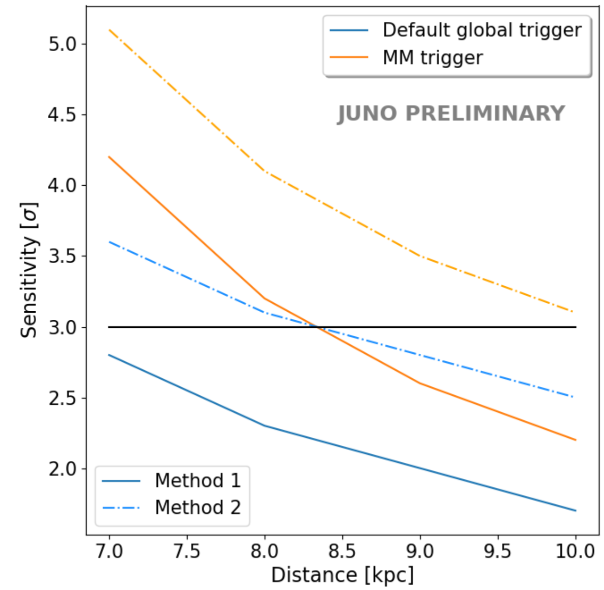
POWER SPECTRUM

DETECTION SENSITIVITY

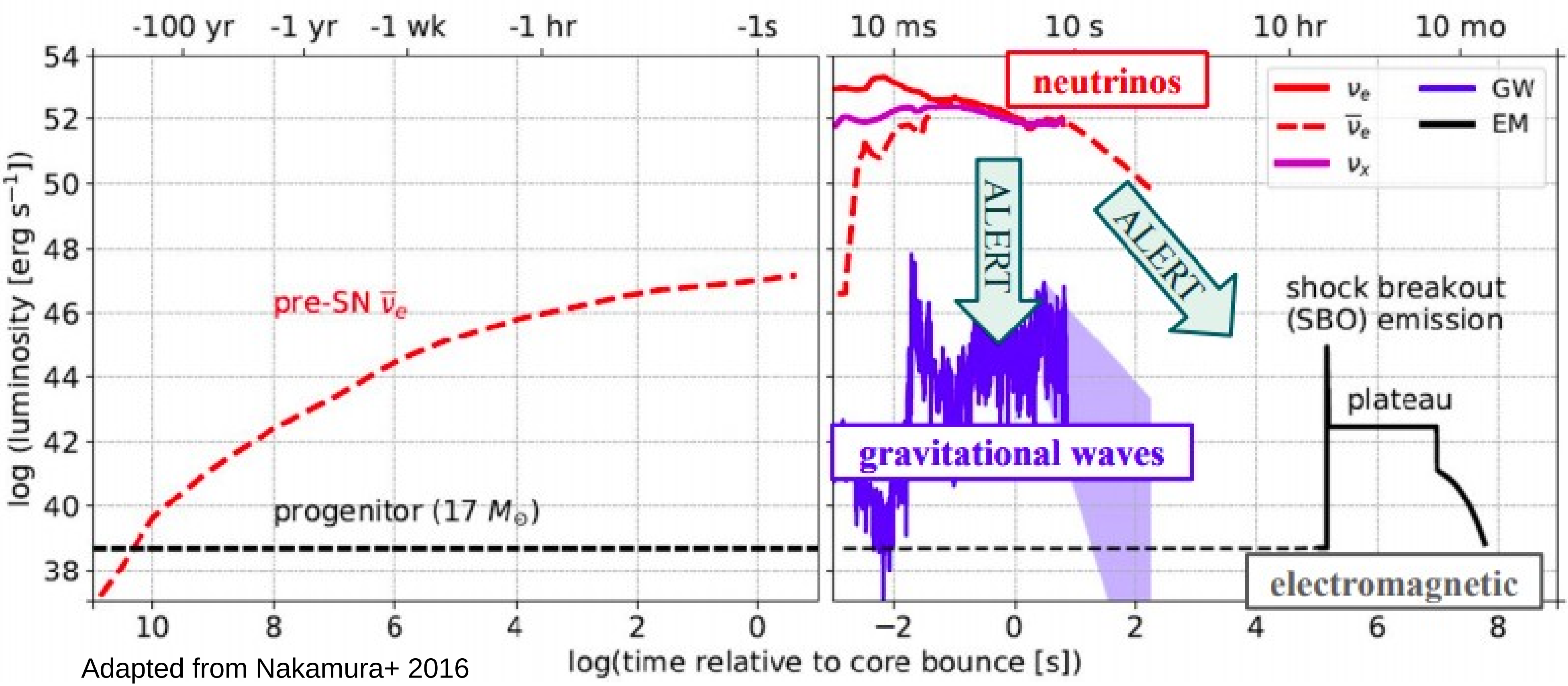
- Method 1: model independent (all f)
- Method 2: model dependent (f range)




THEORY (expected)



# Core-Collapse Supernova multi-messenger signal



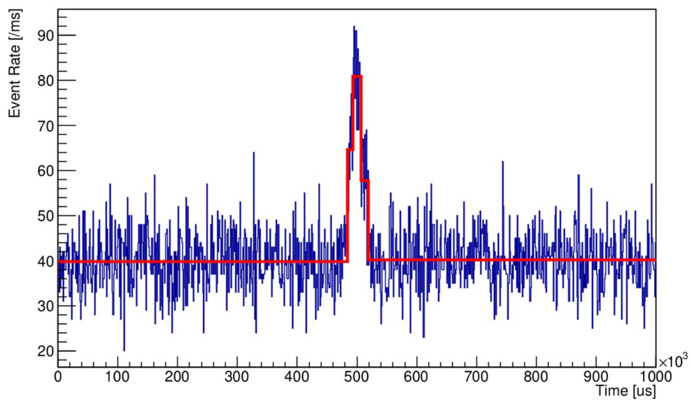

Adapted from Nakamura+ 2016

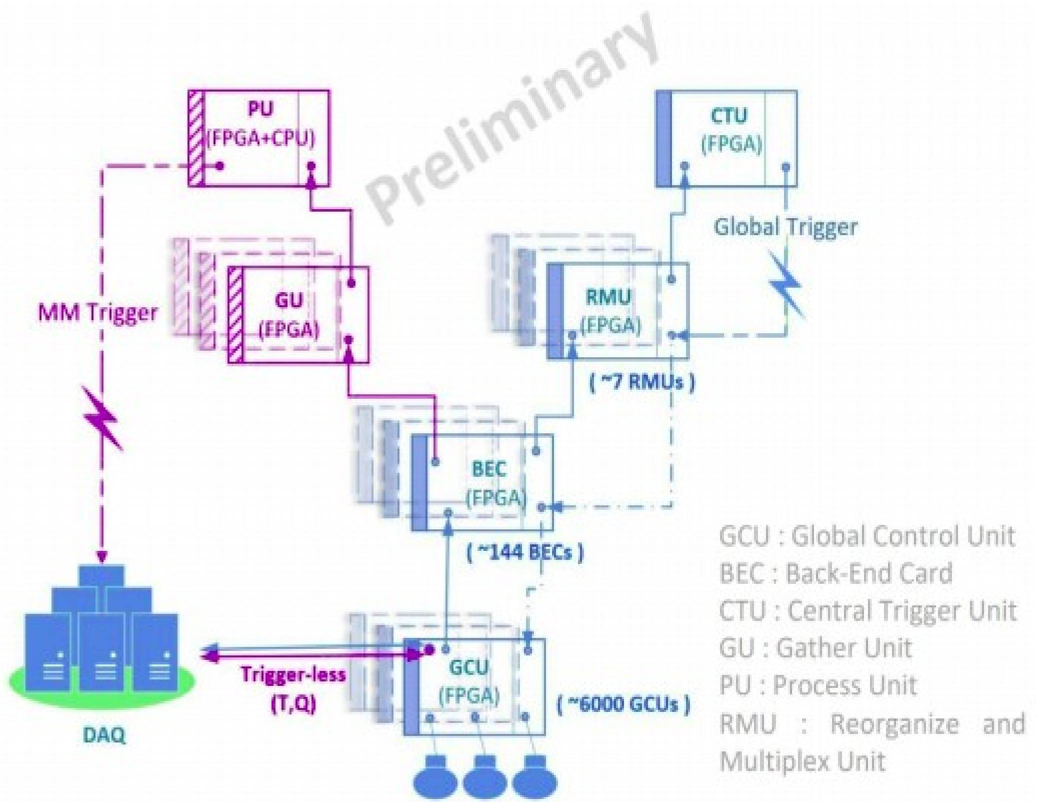
- Next nearby CCSN will produce neutrinos, GWs and **EM** radiation
- Neutrinos will act as an early alert for the multi-messenger follow-up

# 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 a localised increase (in time) of the detected rate:
  - 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

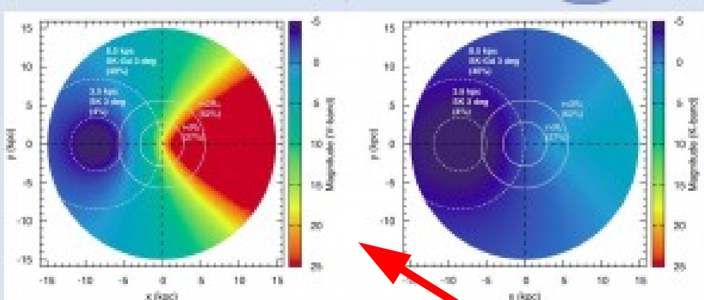
# Core-Collapse Supernova multi-messenger signal

## MOTIVATION: the multi-messenger signal

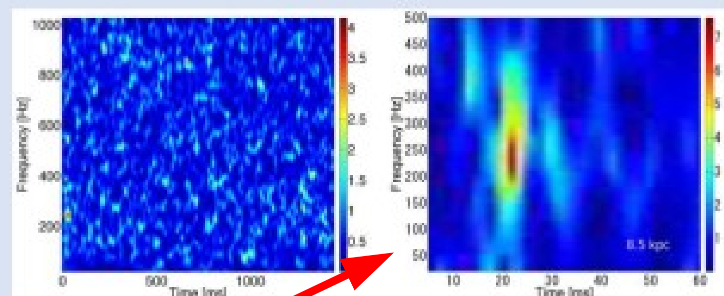
- Source position and distance using neutrinos are crucial for a successful MM follow-up
- Timing of the neutrino signal is key for those parameter estimates
- SNEWS will collect data from different experiments and send an alert to other observers

SNEWS
SUPERNOVA EARLY WARNING SYSTEM

EM observations




GW observations



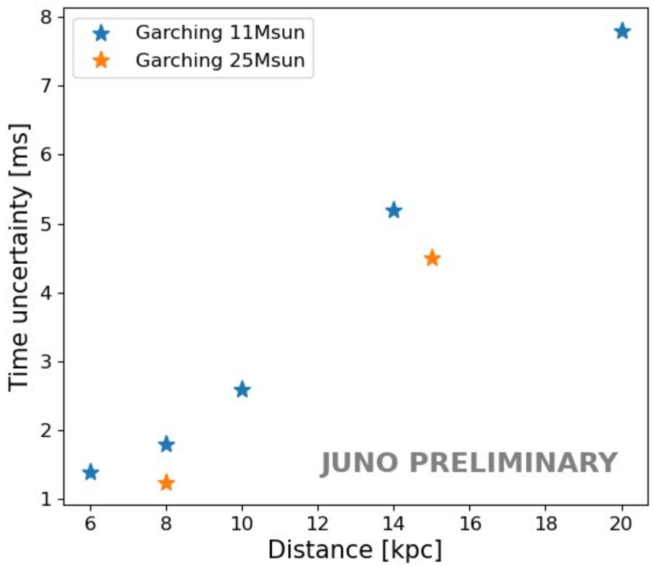

JUNO will also contribute on its own

# 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 (T0=0, core bounce)

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




## Distance estimate

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

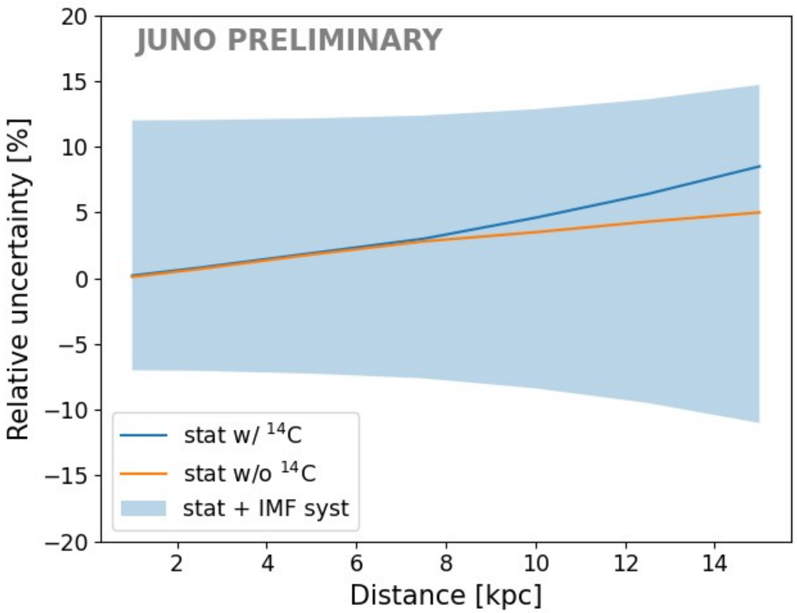



Figure: Statistical uncertainties (solid lines) with the MM trigger. The blue bands include the model systematics (IMF = initial mass function) uncertainty on top (more systematics ongoing).

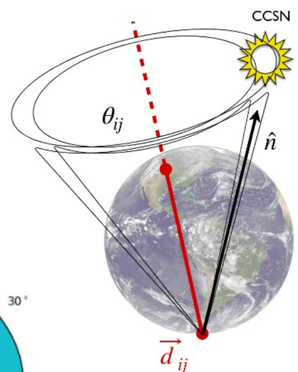
# CCSN neutrinos: pointing

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

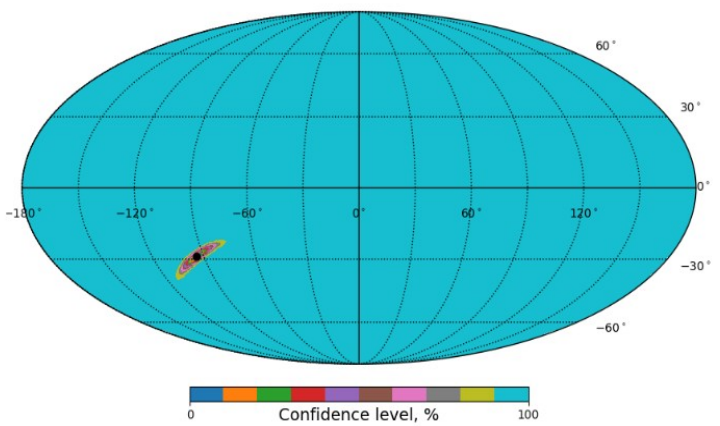
→ Two possible ways to go:

## Triangulation

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

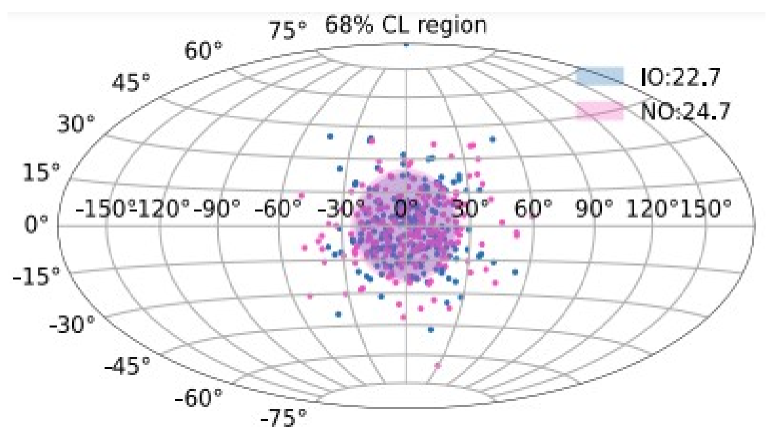



JUNO/ARCA/IceCube/HyperK




## JUNO: anysotropic interactions

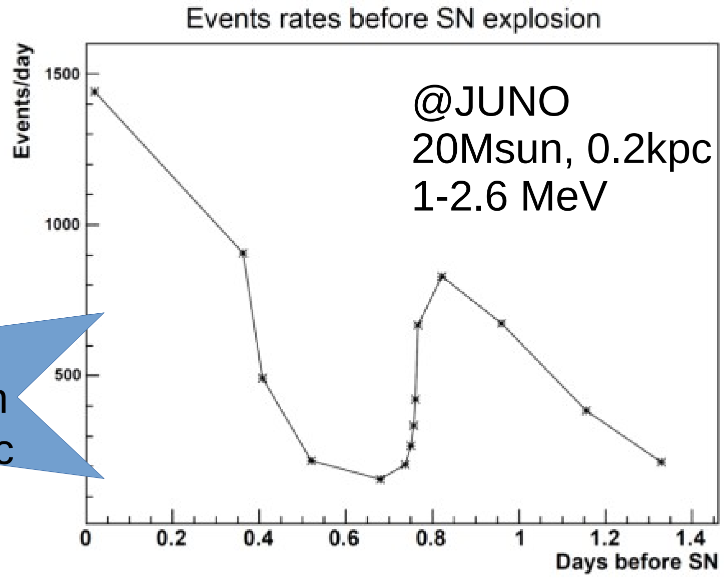
”The direction between the IBD prompt (positron) and delayed (neutron capture) reconstructed vertexes gives ν direction”

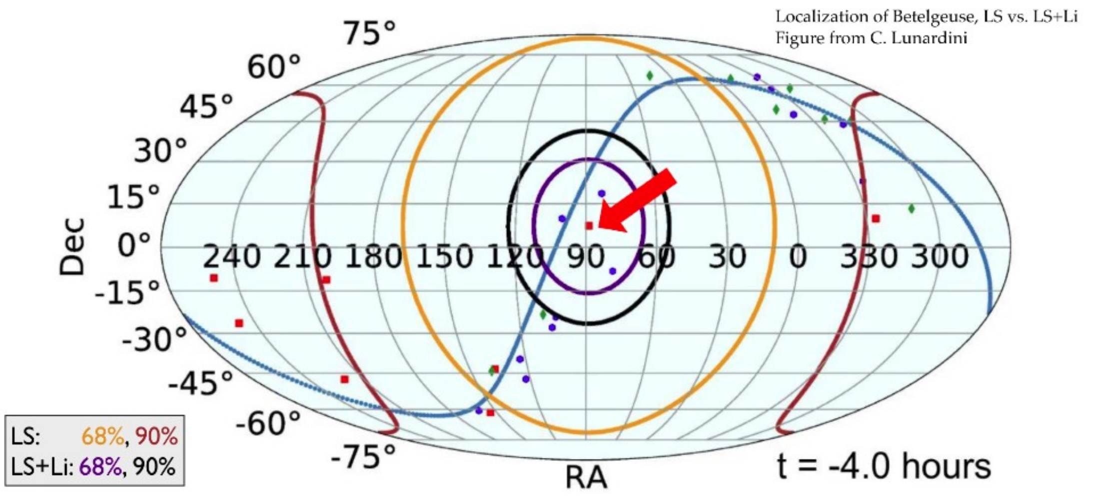


# Pre-supernova neutrinos

- Anti-$\nu_e$ emission previous to the explosion (Si burning phase) detectable hours to days before the stellar collapse
- Advance notice of the core collapse for neutrino and GW detectors and of the explosion for EM and high-energy neutrino telescopes
- Difficult detection due to low-luminosity, low mean Eν and longer time window
- Low-background detectors (JUNO, DUNE, Super-K) 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 *[Li+ 2020]*
  - - With Li doping: ~15 deg uncertainty (22 kton) [*Tanaka+Wakanabe 2020]*

pre-SN ν detection at d≤1kpc



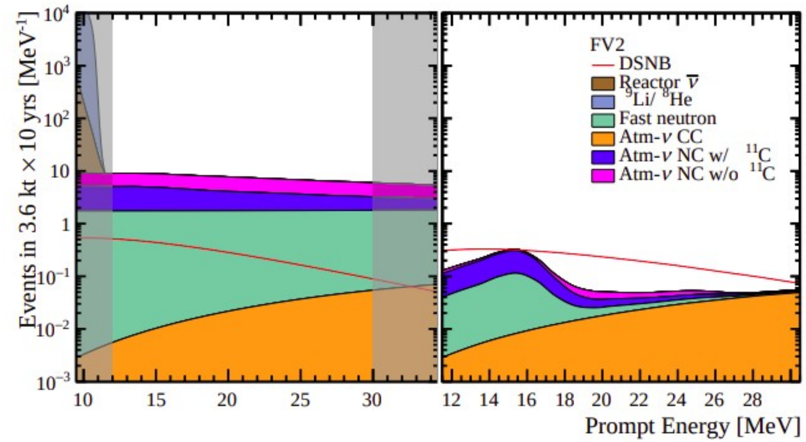



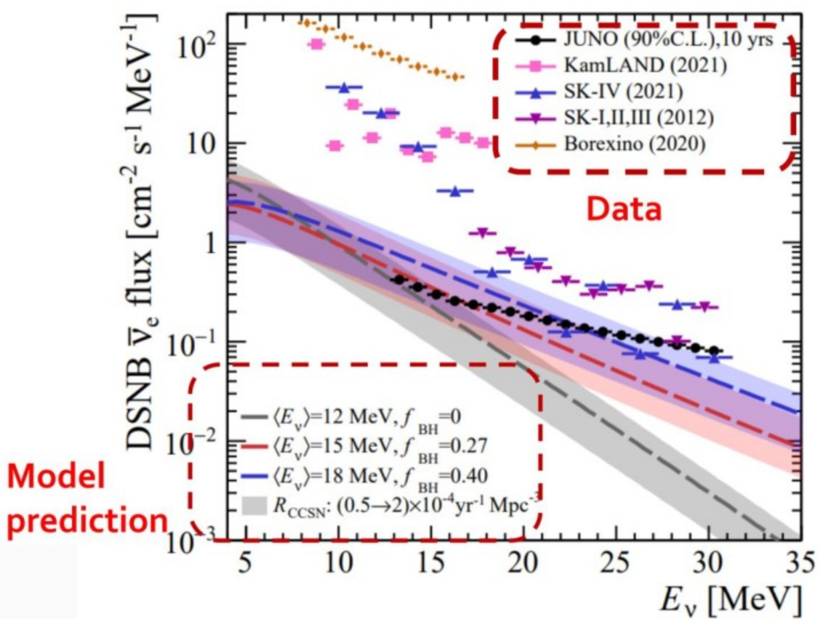
# Diffuse supernova neutrino background

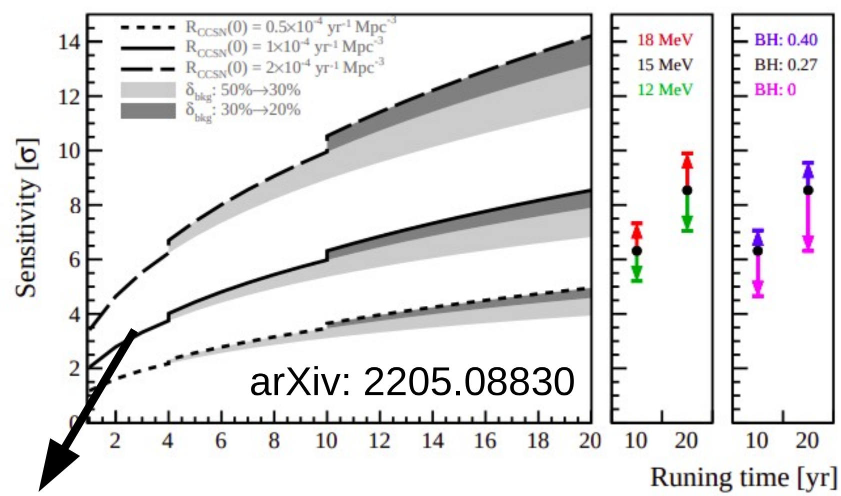
**Diffuse Supernova Neutrino Background (DSNB) =** superposition of neutrino signals from all past supernova explosions, **yet to be observed**

- Discovery of DSNB signal will bring 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

before cuts → after cuts



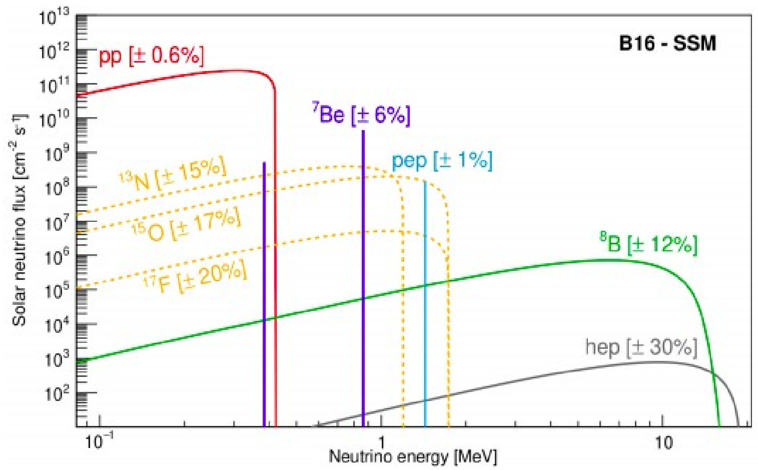



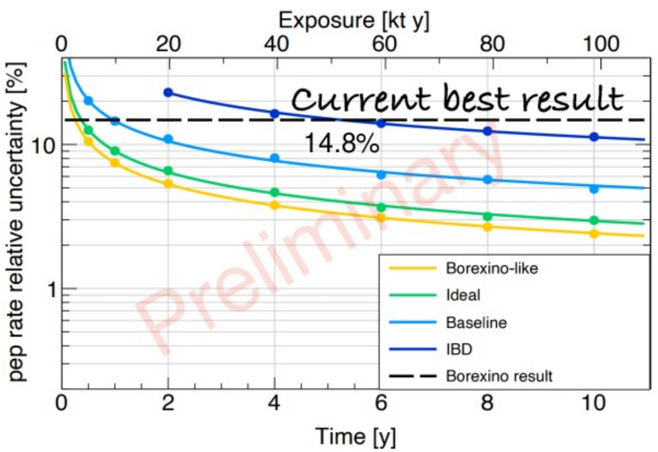

**3σ discovery after 3 years data taking for nominal model**

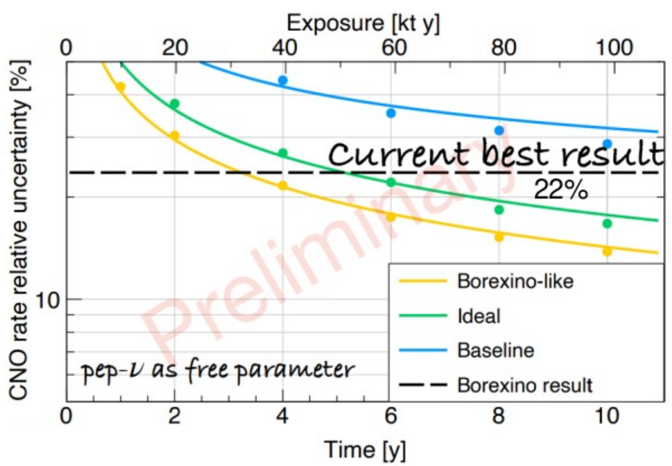
# Solar neutrinos

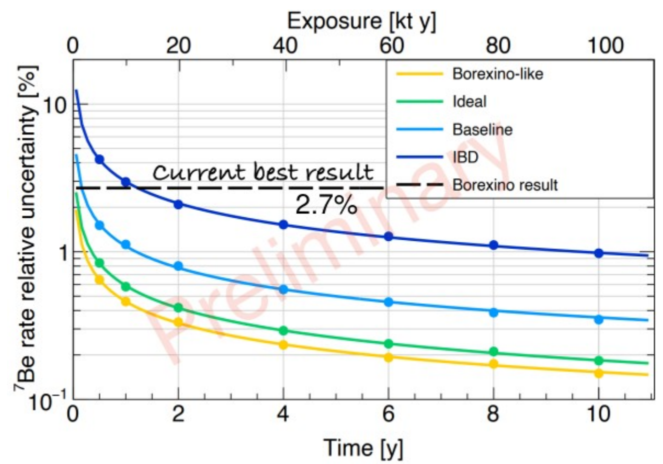
* Main detection channel → $\nu_e$ elastic scattering (ES)
* JUNO can benefit of its enormous statistics
* Different fluxes can be detected:
  - 7Be
  - 8B
  - Pep
  - CNO




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



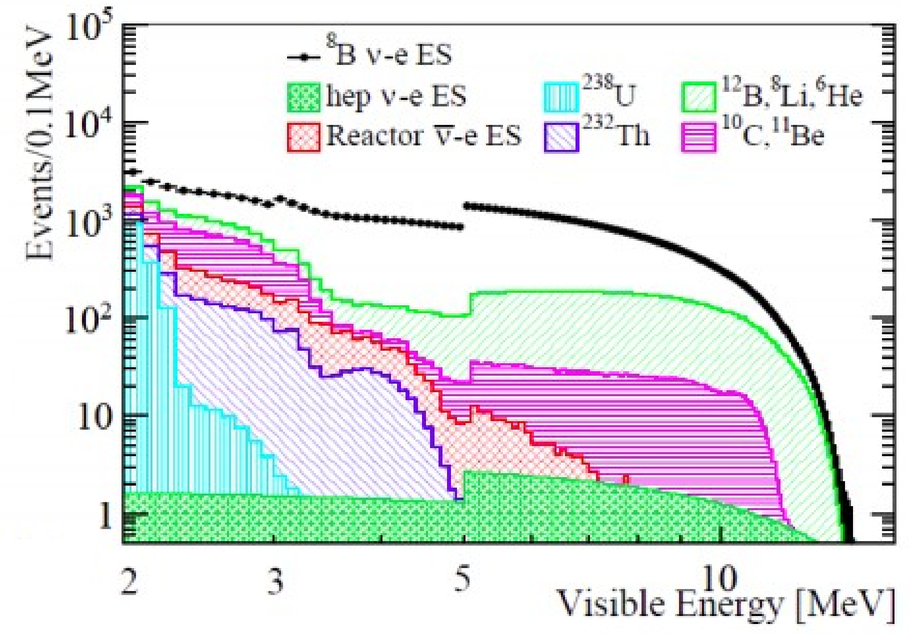

See: DOI:10.5281/zenodo.6785412

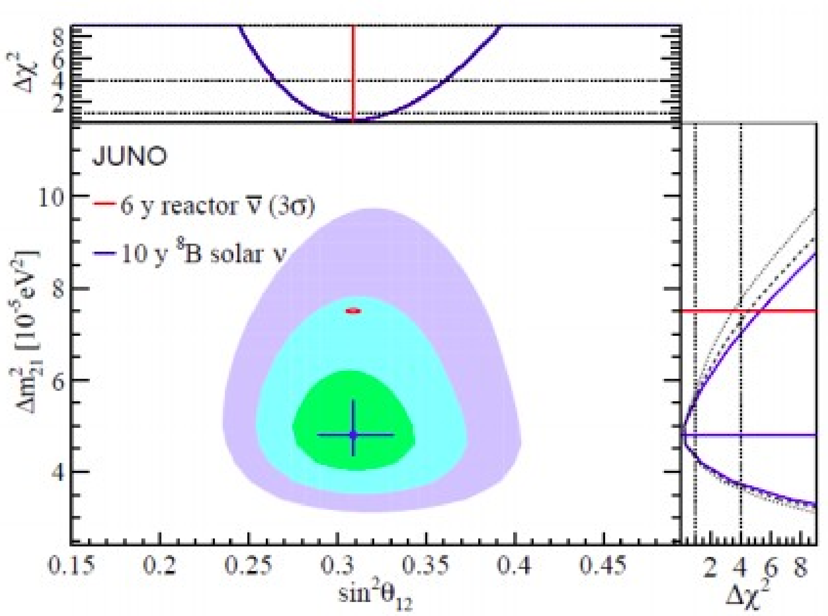
# Solar neutrinos

**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 $\Delta m^2_{12}$ with both solar and reactor neutrinos in one experiment



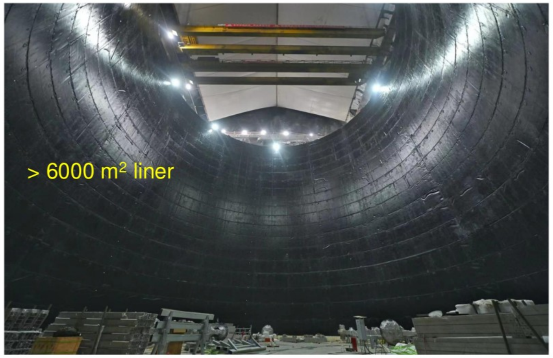
# Detector status:

- Central detector (CD):
  - Stainless stain structure installed
  - Accrylic sphere: installation started

- LS mixing and purification systems installed or almost ready → comissioning soon

- Electronics:
  - All PMTs produced, tested, and instrumented with waterproof potting
  - All components produced and connections tested → Installation will start next month

- Water Pool:
  - liner construction finished
  - Water pipes & extraction system: installations done → provide clean water underground soon

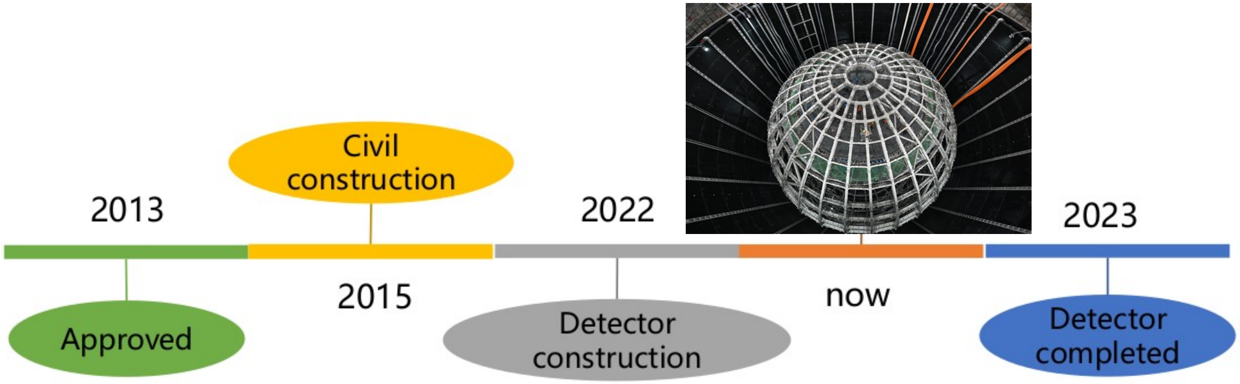


# Summary conclusions:

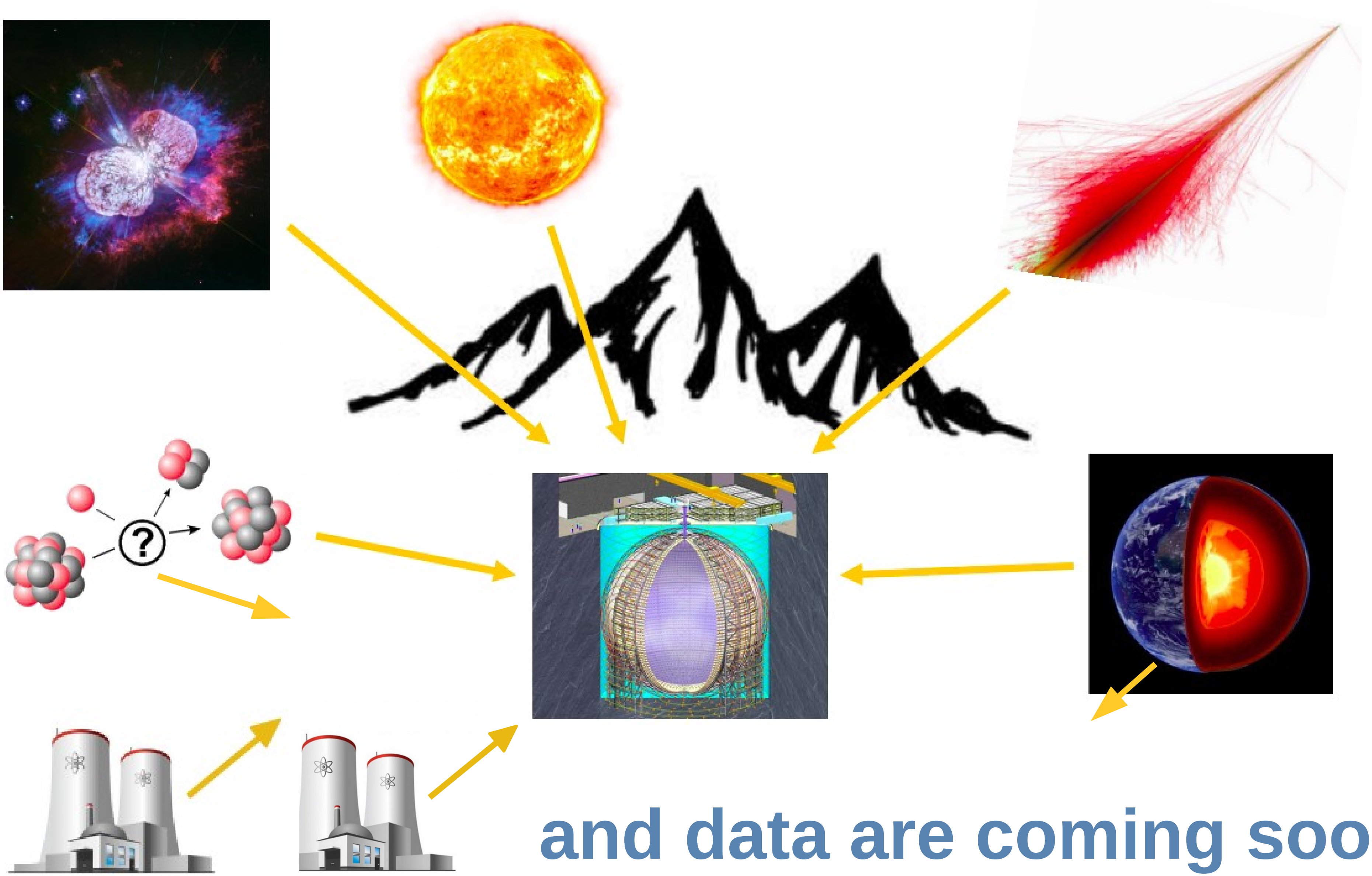
JUNO will be a multi-purpose neutrino experiment with a broad physics reach, including the observation of astrophysical sources/fluxes

- JUNO as neutrino telescope contributing to transient MM observations
- Major role in the next-generation Supernova Early Warning System (SNEWS 2.0)
- JUNO will be sensitive to all CCSN neutrino flavors with high statistics, with the potential to study and constrain CCSN physics
- JUNO will be key in the discovery of the DSNB signal and constraining the model
- JUNO will provide the most precise solar neutrino flux measurements, allowing to address some remaining questions (e.g. metallicity puzzle, NSI in extreme media)

JUNO construction its on its way and data are coming soon (beginning 2024)



# JUNO – AN INSTRUMENT WITH AN INCREDIBLE PHYSICS POTENTIAL



**and data are coming soon...**