The multi-messenger astrophysics potential of the JUNO experiment

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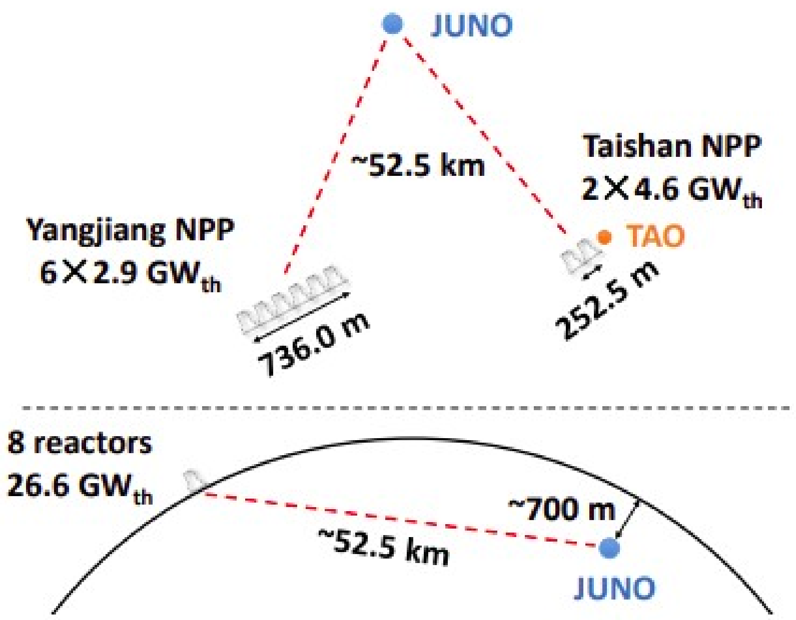
On behalf of the JUNO Collaboration

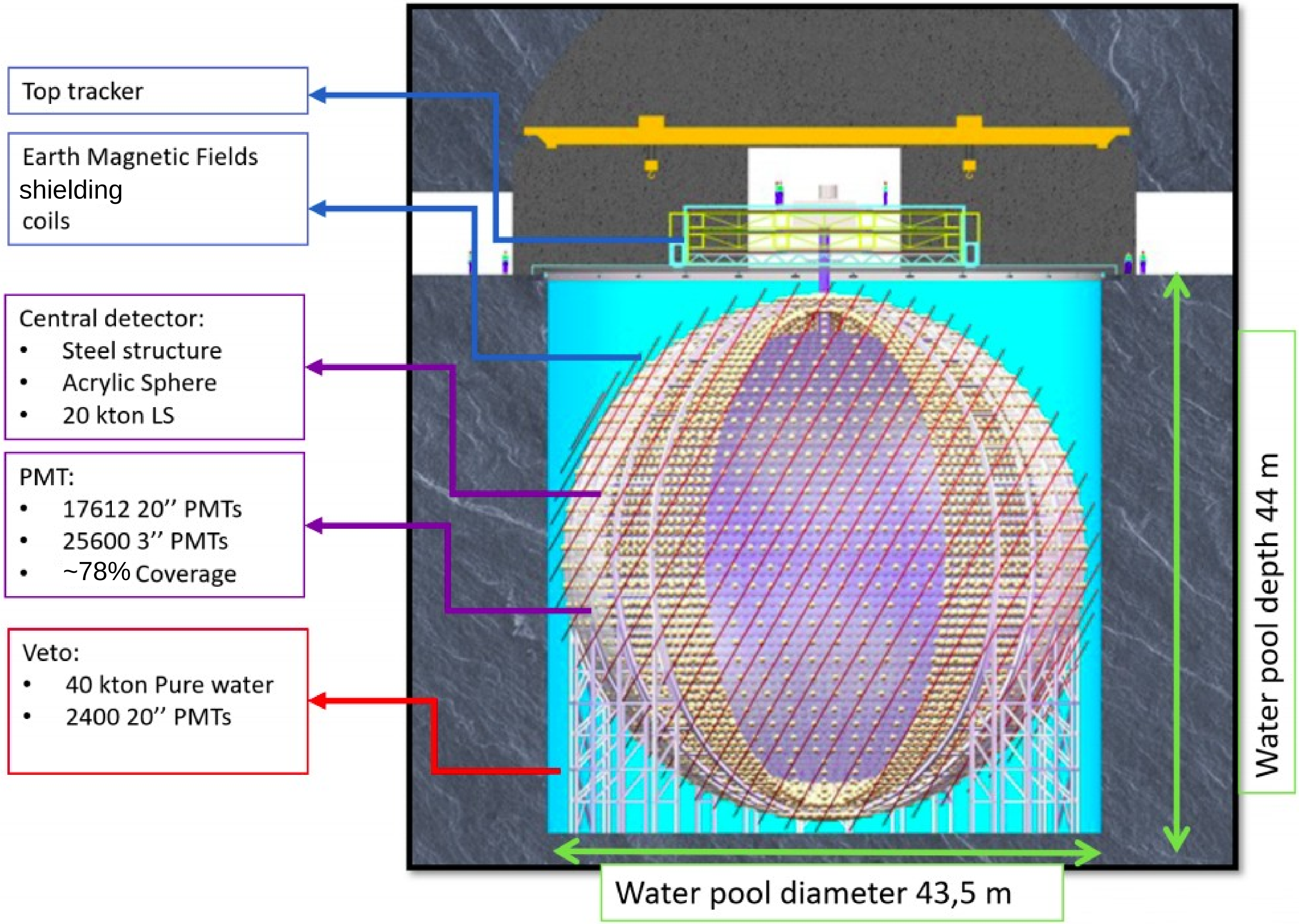
The JUNO detector

- 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 special experiment?
→ Largest and most precise ever built liquid scintillator (LS) detector with impressive PMT coverage (>40k PMTs)



The JUNO detector

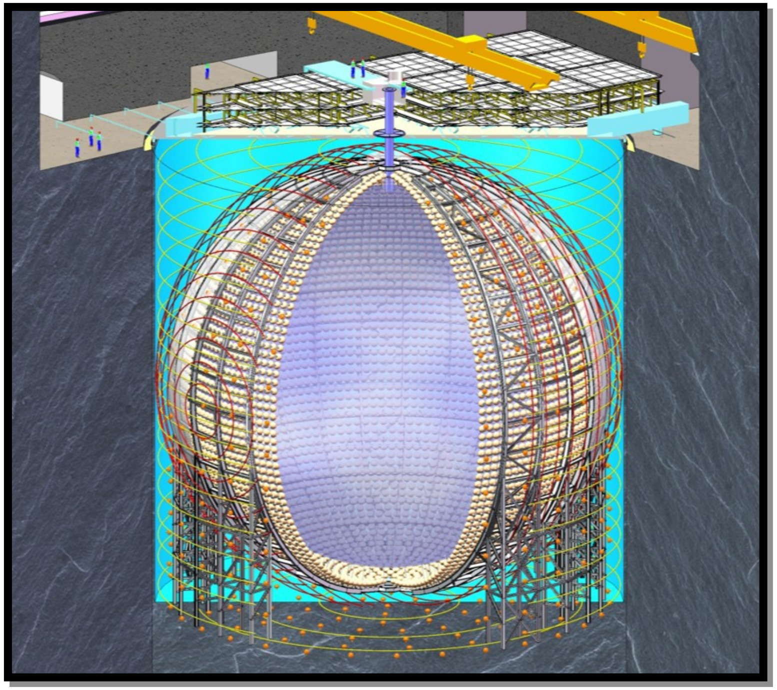


The JUNO detector

Primary goal: precise measurement of reactor neutrino oscillations and the neutrino mass ordering

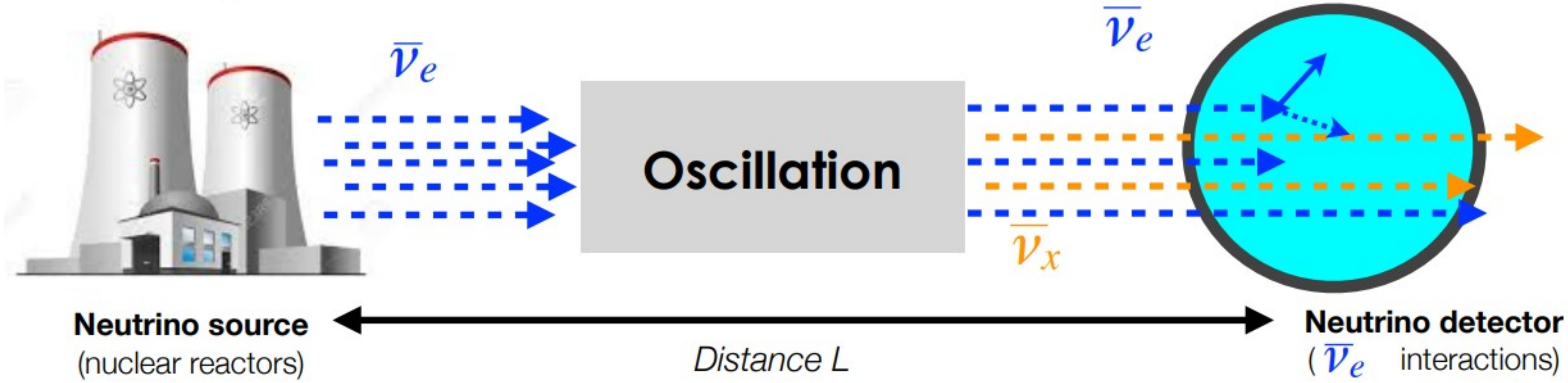
Requirements:
- High statistics (~10^5 events in 6 yr)
- Energy resolution: ~3% @1MeV
- Energy scale uncertainty < 1%

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 (close-by detector)



Experiment	Daya Bay	Borexino	KamLAND	JUNO
LS mass	~ 20 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

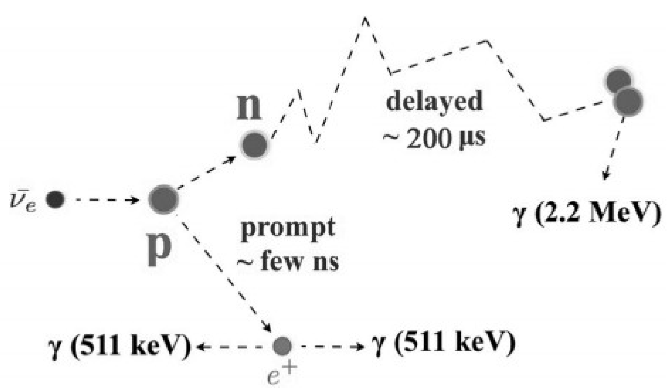


Reactor neutrinos are observed by Inverse Beta Decay (IBD): positron signal (1) and neutron capture (2)

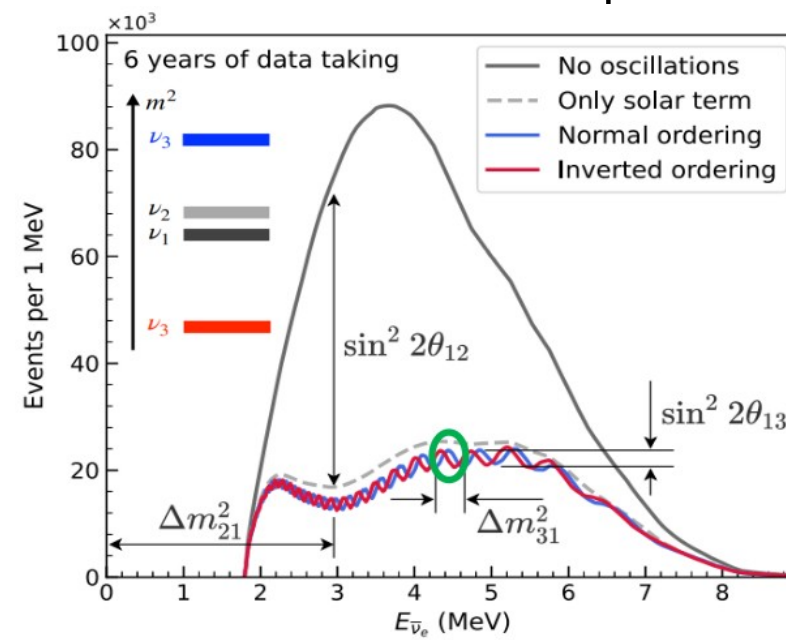
$$\overline{\nu}_e + p \rightarrow e^+ + n \qquad (1)$$

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

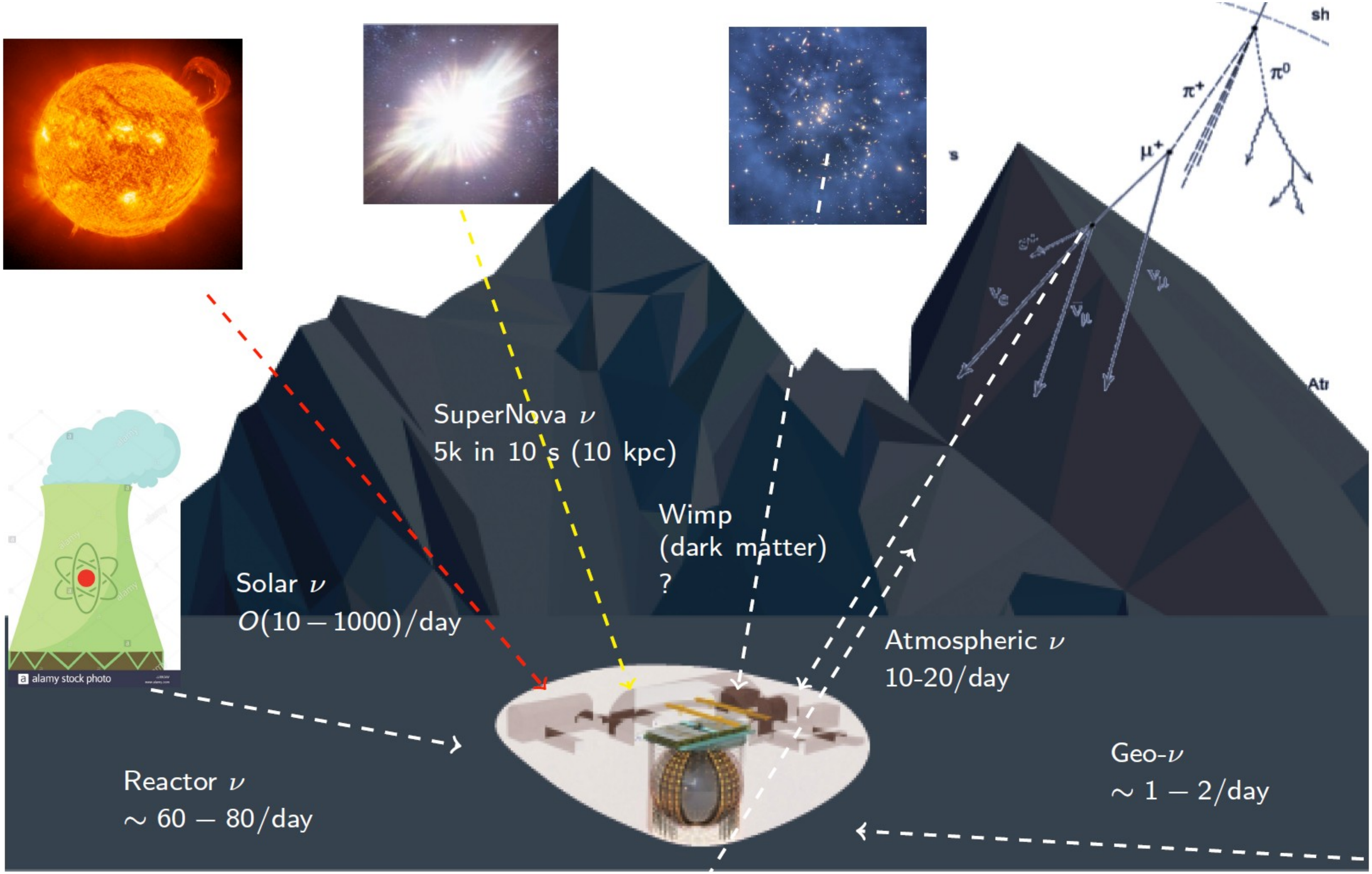
- Very clear signal: prompt + delay coincidence in the (visible) energy range ~[0.7,8] MeV:



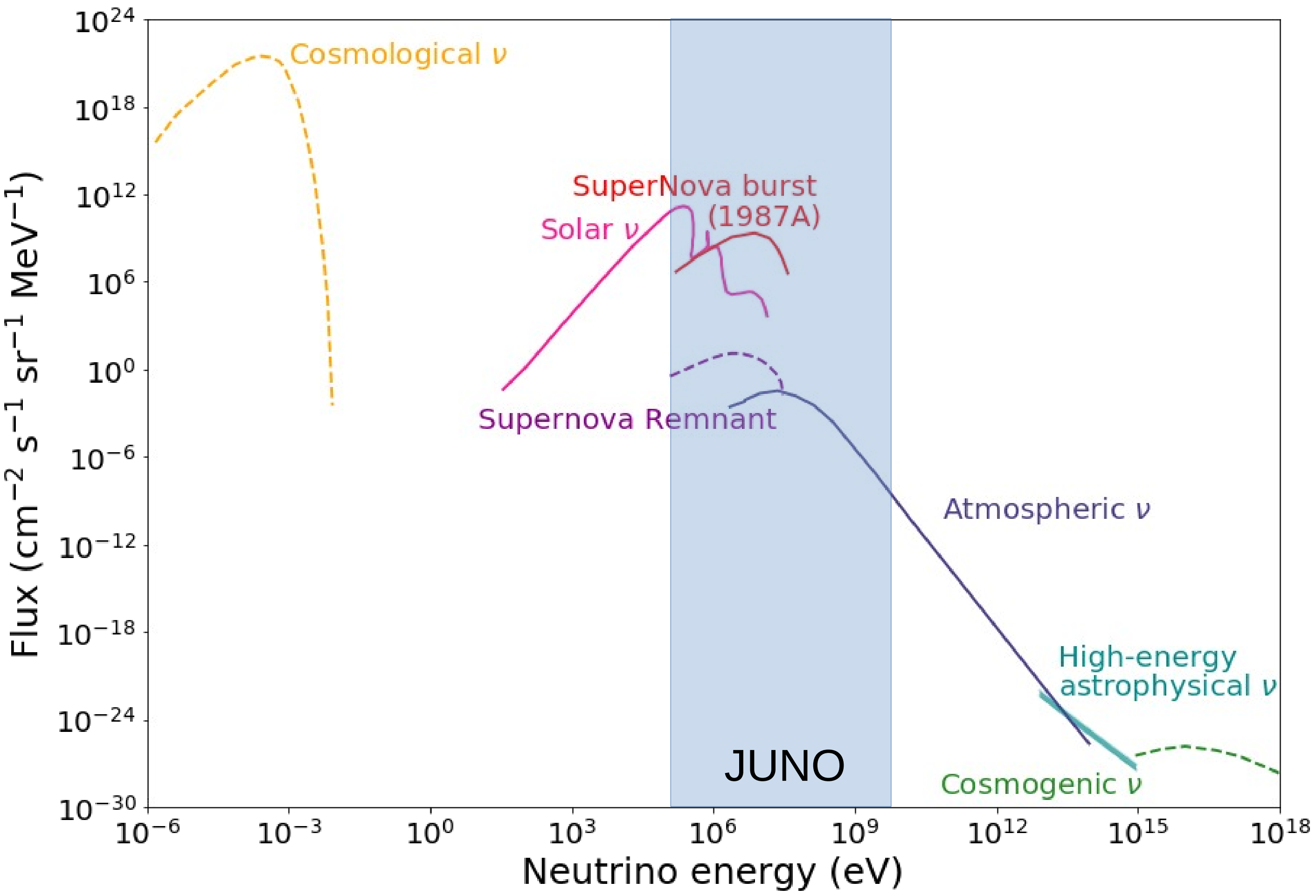
Oscillated reactor spectrum



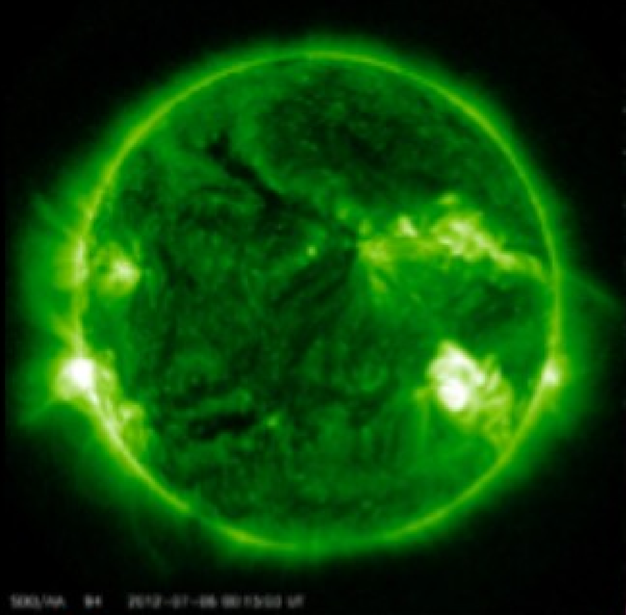
JUNO physics program



Neutrino landscape: spectrum of natural sources



Multi-messenger sources

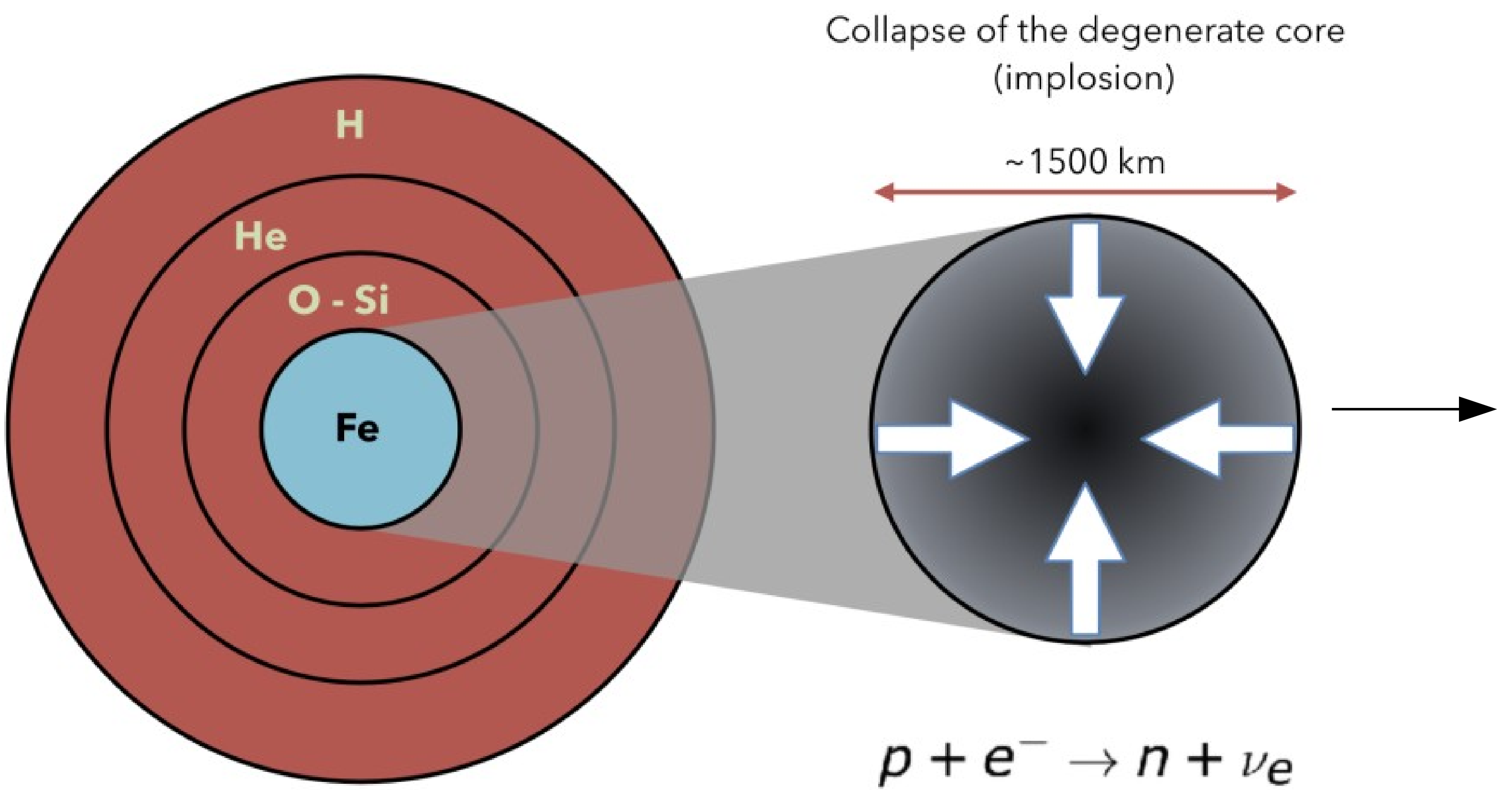


Sun

Supernova
SN1987A

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

Core-collapse supernova: explosion mechanism



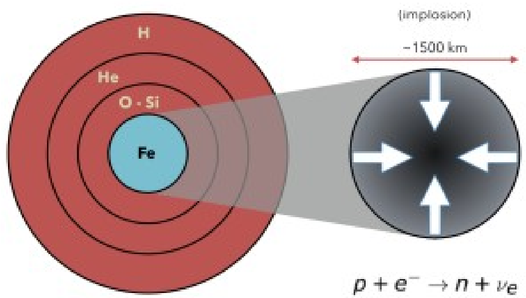
With collapse, shock wave forms and propagates…
until it gets stopped

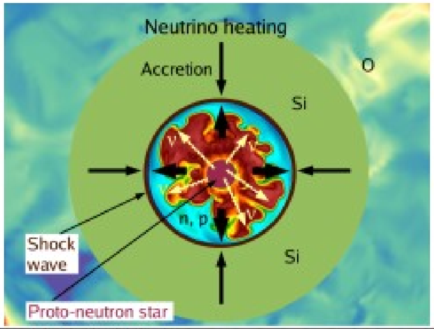
$$p + e^- \rightarrow n + \nu_e$$

Massive star $M \gtrsim 10 M_\odot$
Onion structure

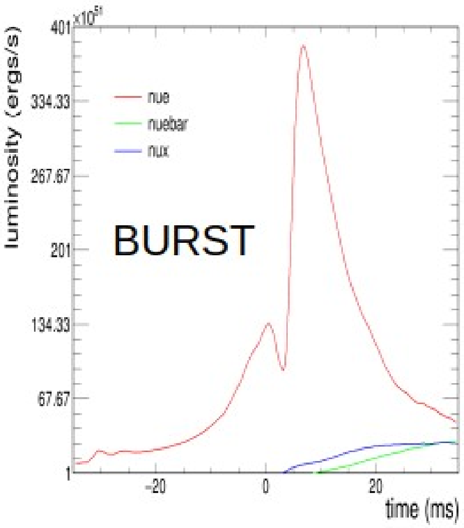
As $M_{core} \sim M_{chandrasekhar}$, pressure of degenerate electrons decreases due to electron captures and becomes insufficient to resist gravity → **collapse**

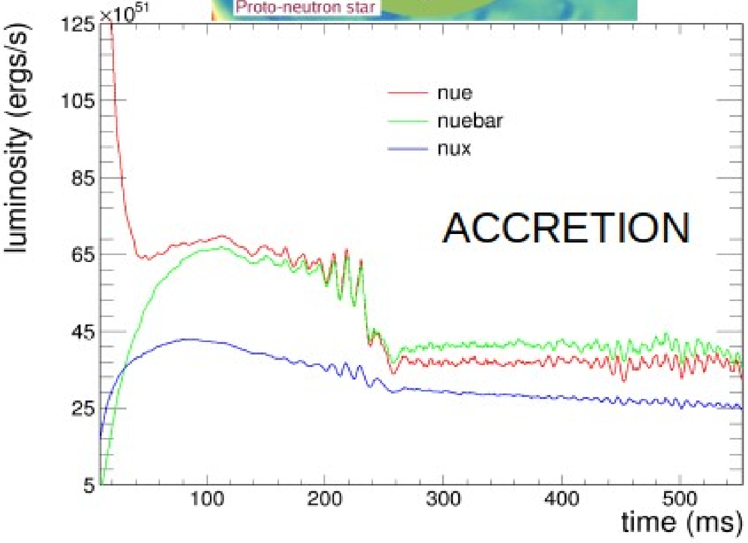
Core-collapse supernova: explosion mechanism

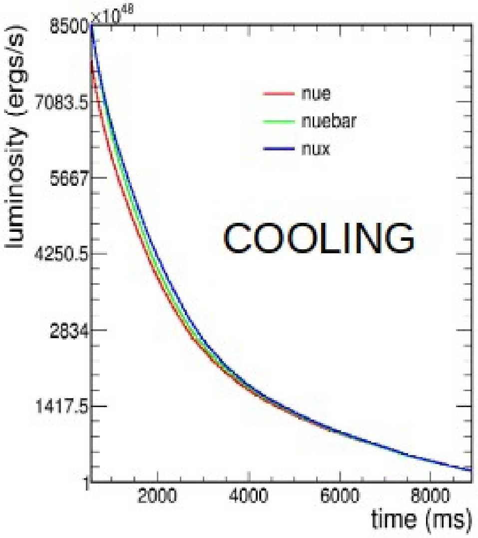




- Neutrino heating revives the shock by energy deposition → explosion
- 99% of the gravitational binding energy emitted through neutrinos







- Shock bounce
- Electron captures

- Hydrodynamical instabilities/convection
- Neutrino heating
- Shock revival

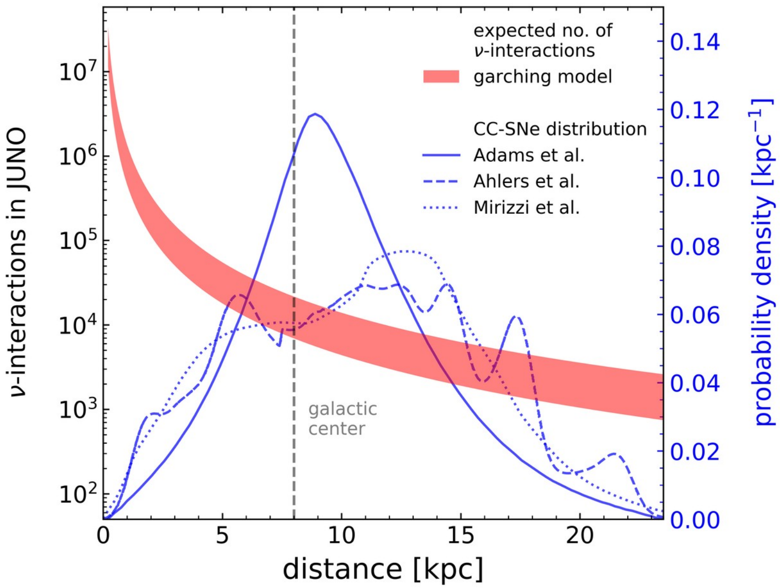
- Neutrino pair production of all flavors

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
- Sensitive to all neutrino flavors with high statistics through different interaction channels in the detector.
- Dominant channels:
  - IBD → $\bar{\nu}_e$ flux
  - ν-electron elastic scattering (ES) → all flavors (ν_e flux mainly)
  - ν-protron ES → all flavors

Doing CCSN physics with neutrino data? Need:

- ✓ PID/event slection → all flavor flux evolution
- ✓ Good energy resolution → energy spectrum
- ✓ Good time resolution → time profile (lightcurve)
- ✓ Good angular resolution → pointing

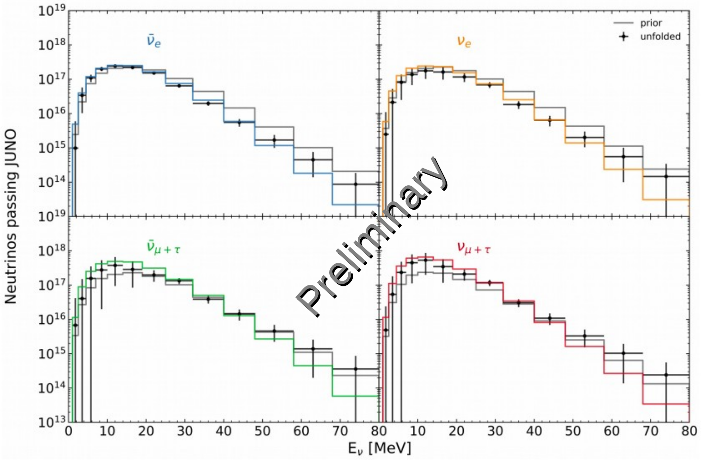


Core-collapse supernova neutrinos in JUNO

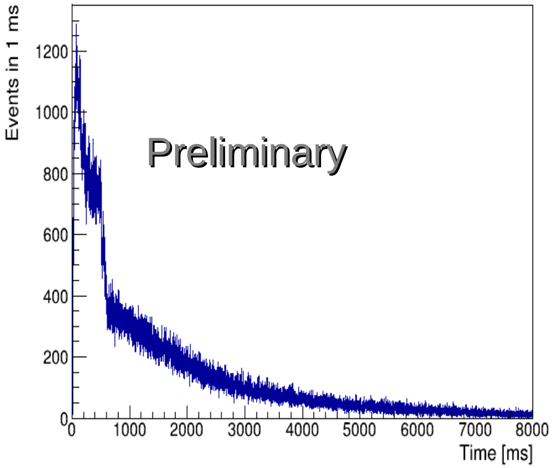
→Good energy and time resolution + flavor classification:
JUNO will measure:

Constrain CCSN physics!

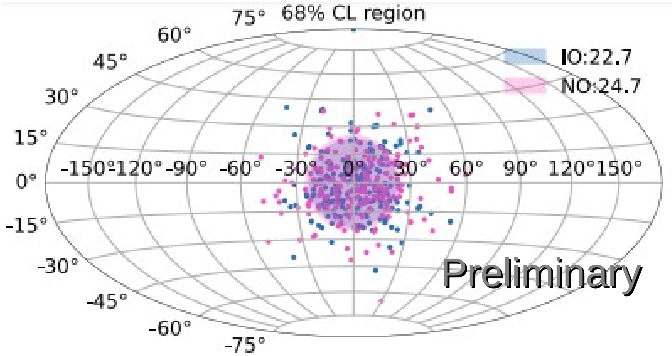
Flavor dependent energy spectrum

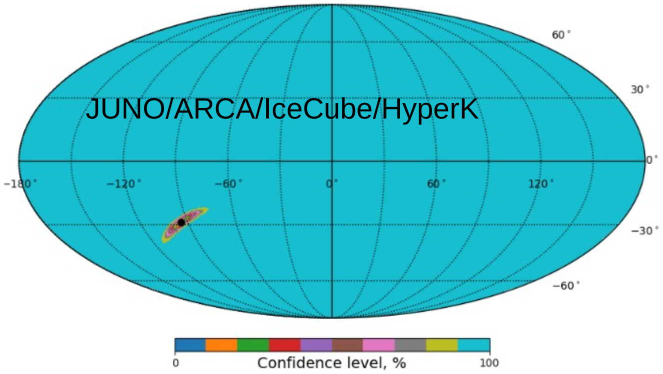


Lightcurve:



Direction:

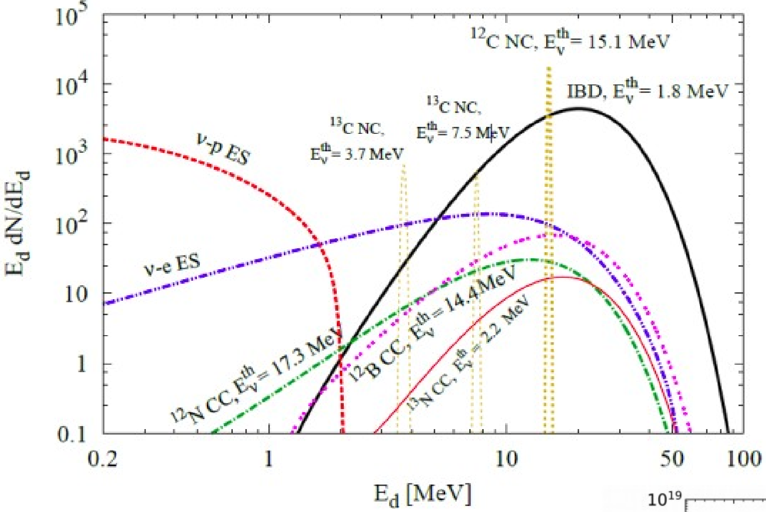


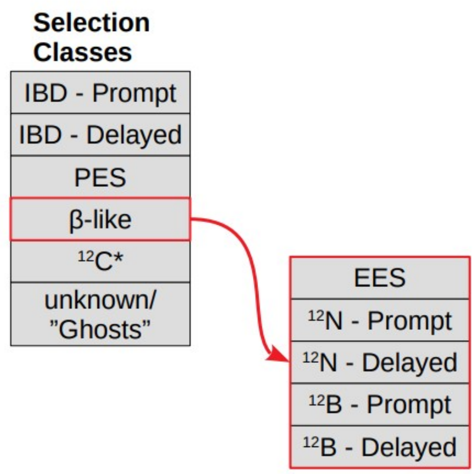


CCSN neutrino spectrum

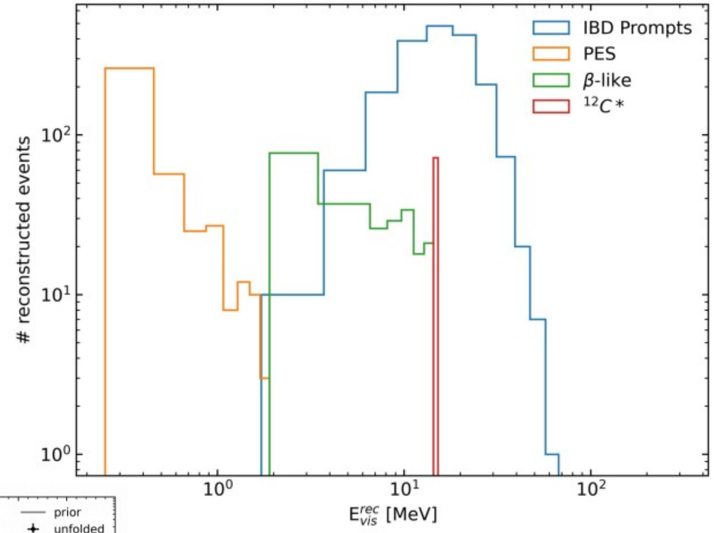
Use time-space coincidence (IBD) and energy cuts to select the different channels:

Expected CCSN energy spectrum:

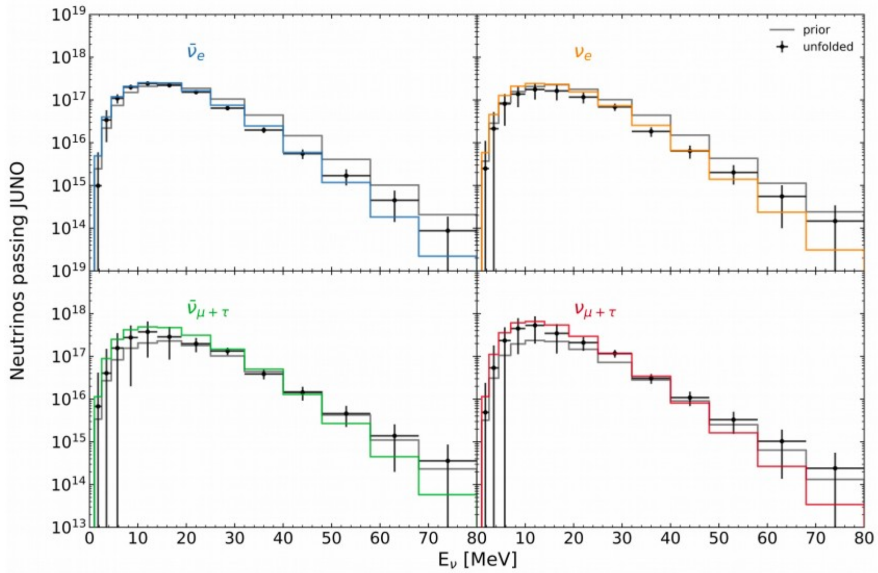




Reconstructed after selection:

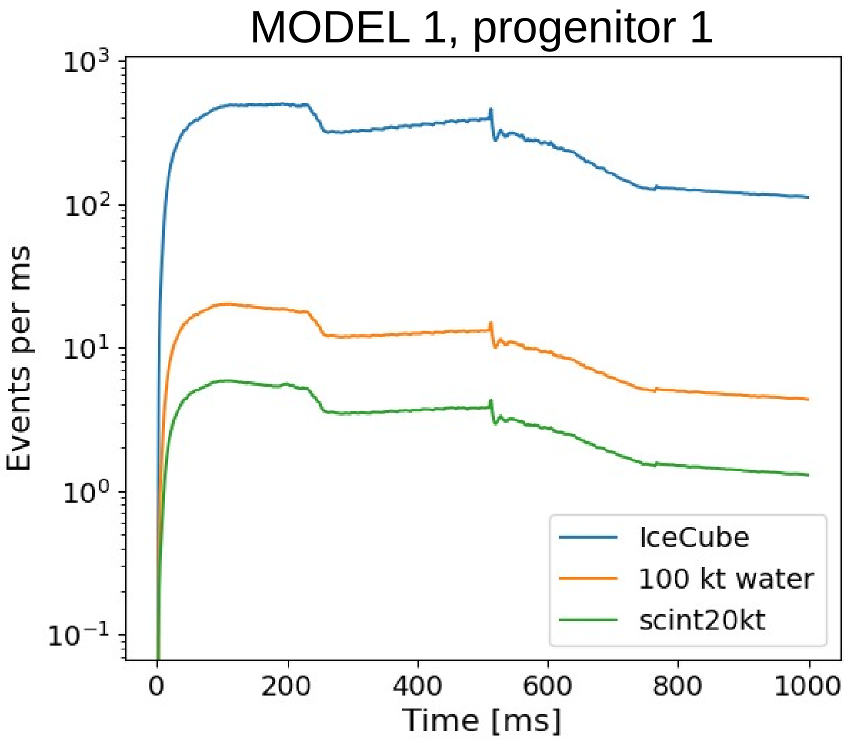


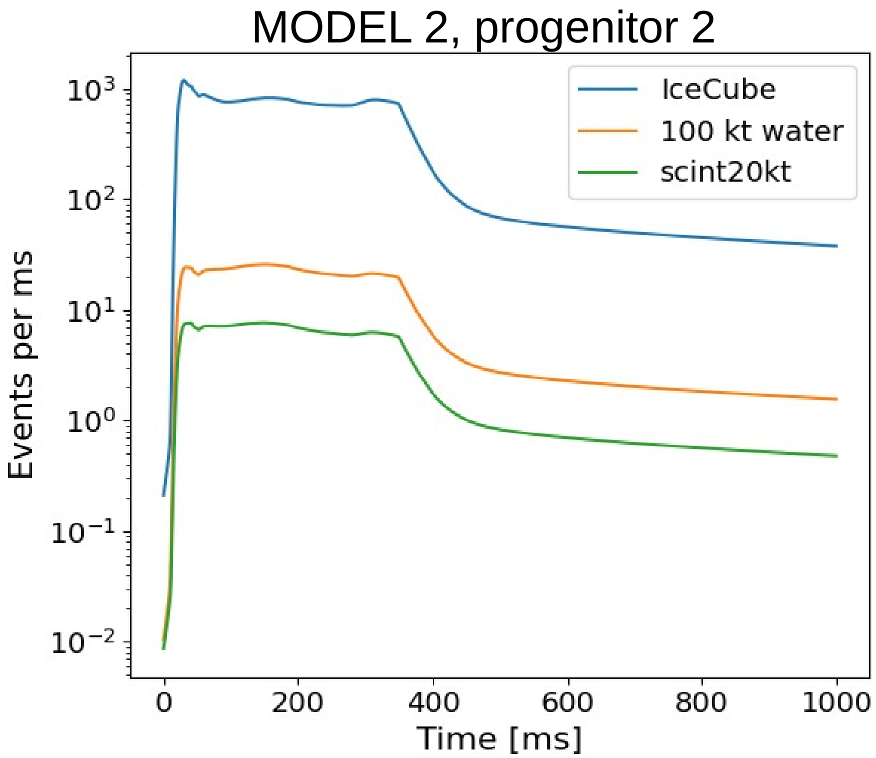
Flavor dependent neutrino energy spectrum UNFOLDED:



CCSN neutrino lightcurve

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

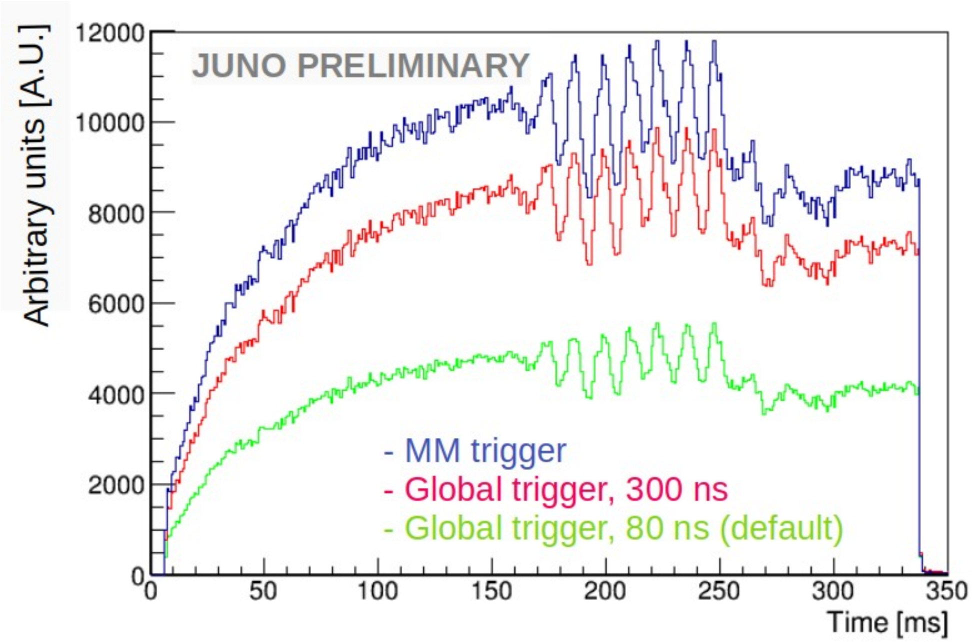




(Example using *snewpy*: https://github.com/SNEWS2/snewpy *and snowglobes https://github.com/SNOwGLoBES/snowglobes software*)

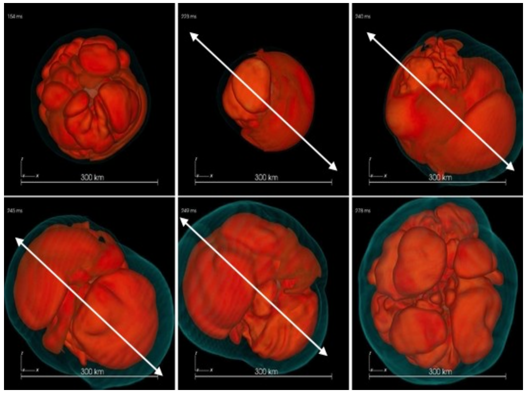
CCSN neutrino lightcurve

- 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



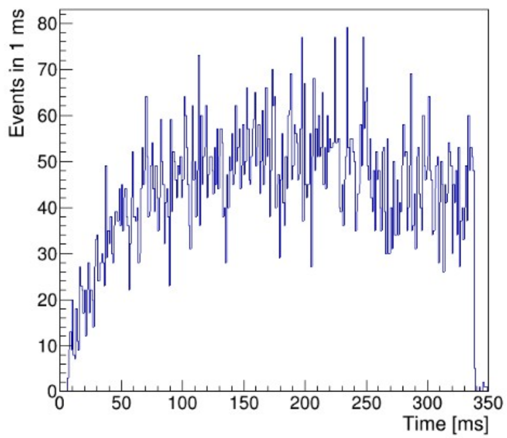
Example of interesting lightcurve feature to study: SASI oscillations

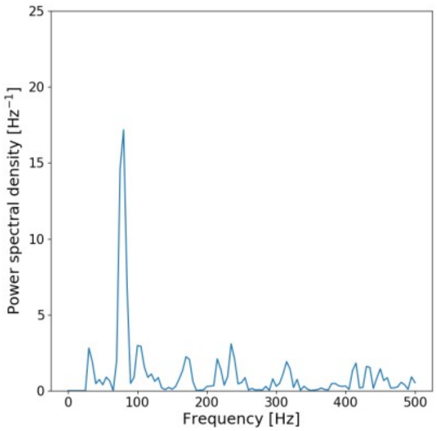
- SASI = standing accretion shock instability: predicted by 3D CCSN simulations
- Why is it interesting:
  - It favors explosion and final energetics
  - It could explain neutron star kicks observed
  - It might be accompanied by GW emission



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):



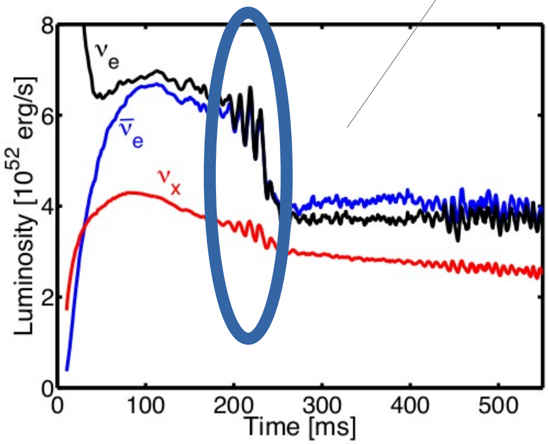


OBSERVED LIGHT-CURVE

(Fourier Transform)

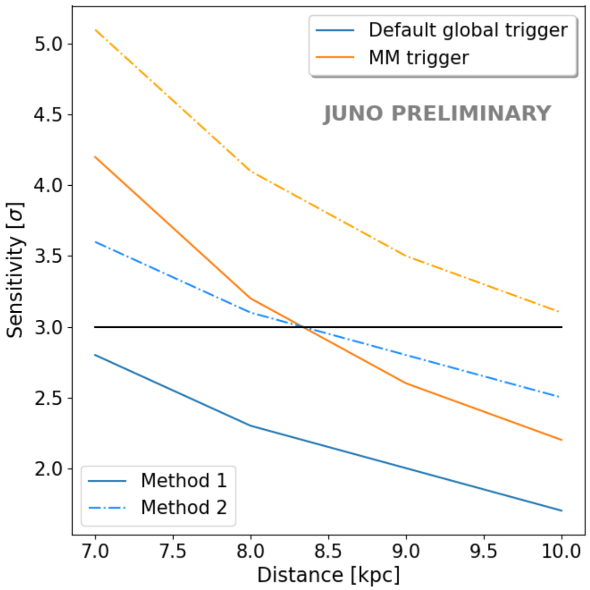
POWER SPECTRUM

DETECTION SENSITIVITY

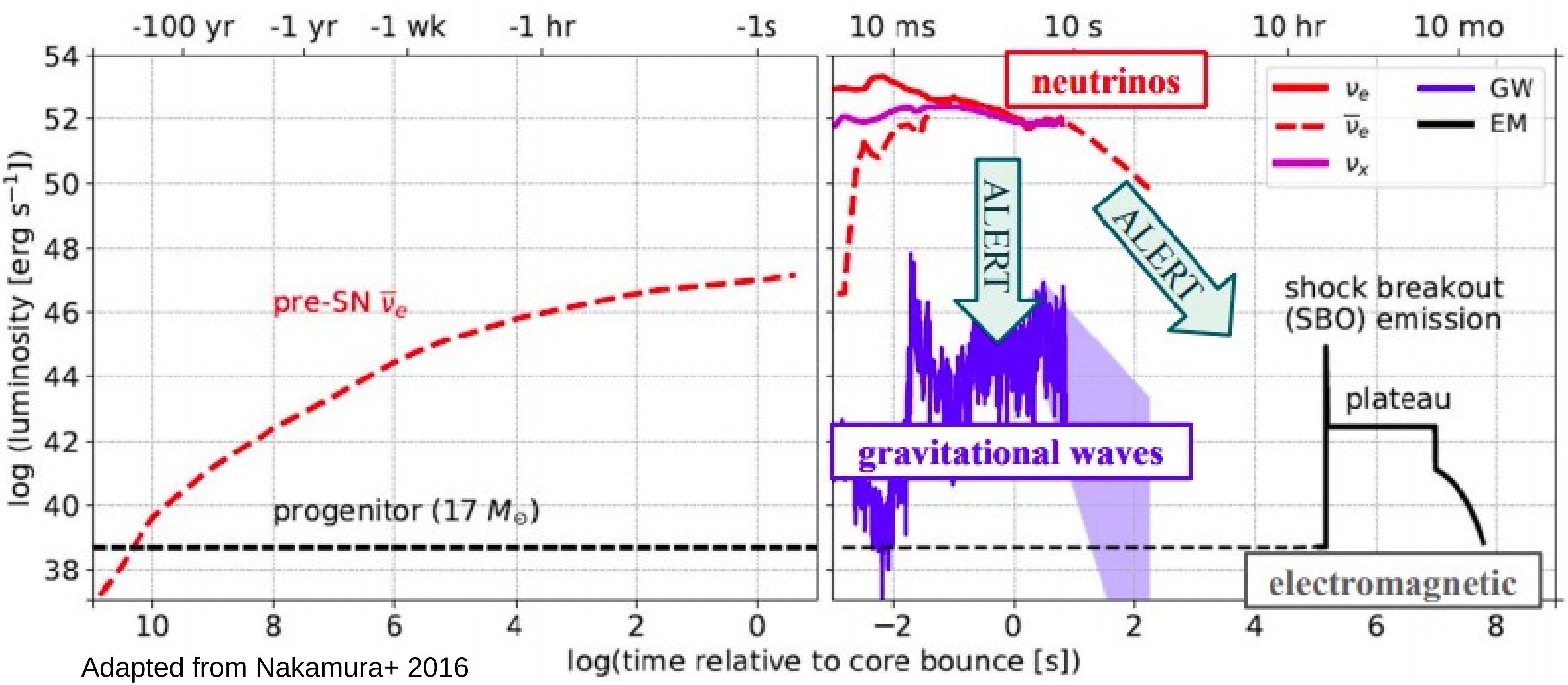


THEORY (expected)

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



Core-Collapse Supernova multi-messenger signal



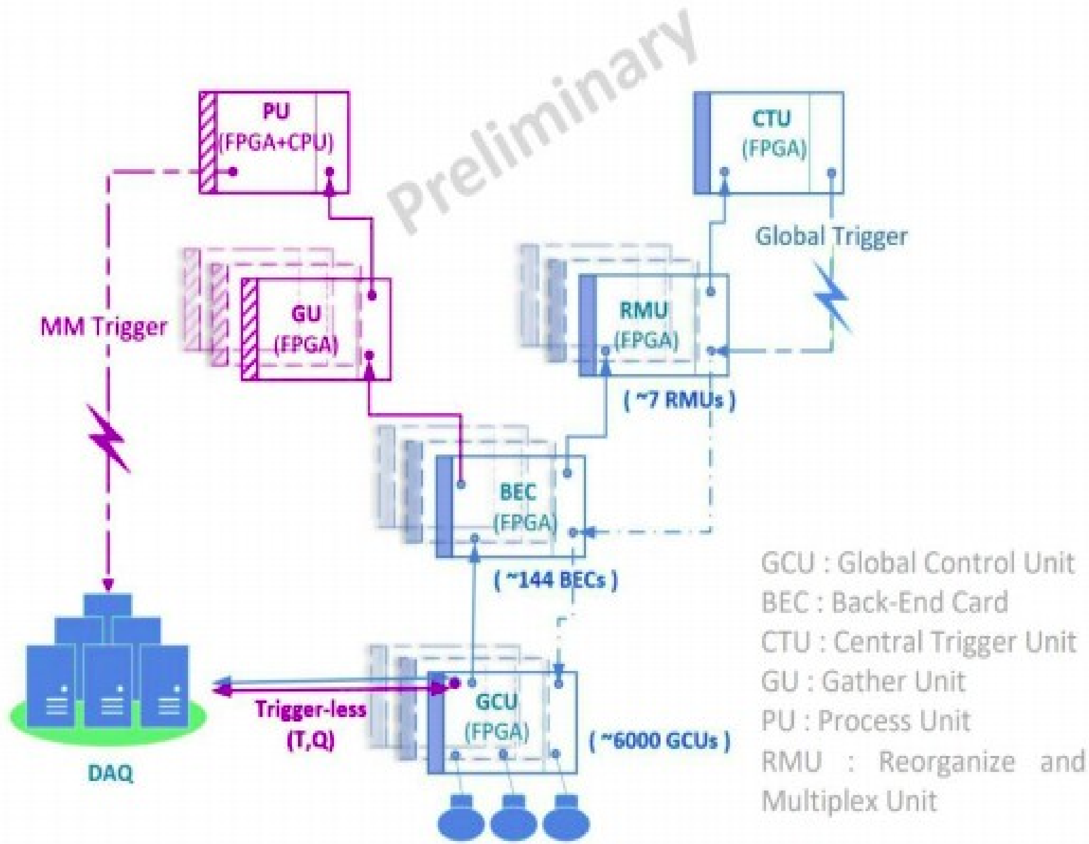
Adapted from Nakamura+ 2016

- 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

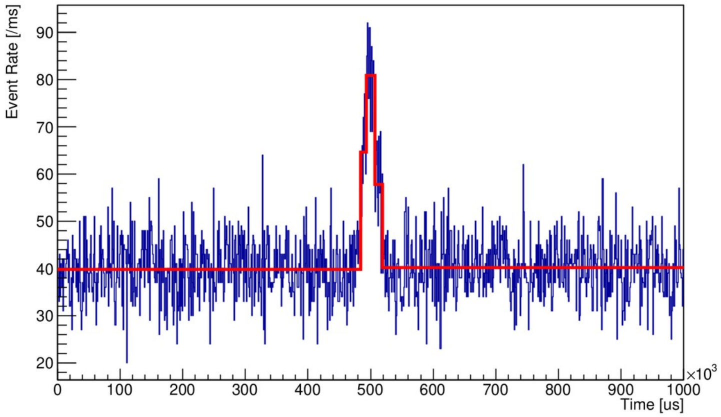
Two strategies to trigger a transient event:

- 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:

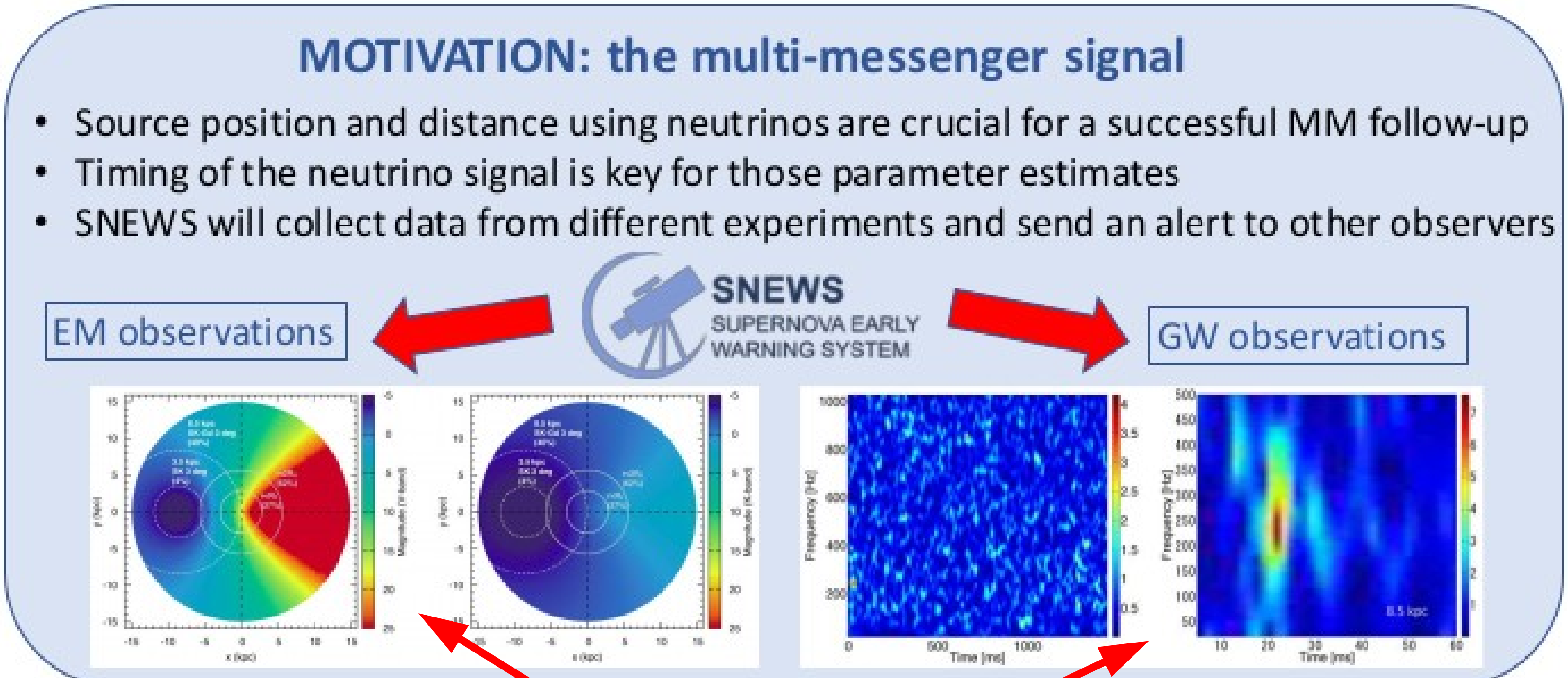
- Sliding window method
- Bayesian blocks algorithm



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

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)



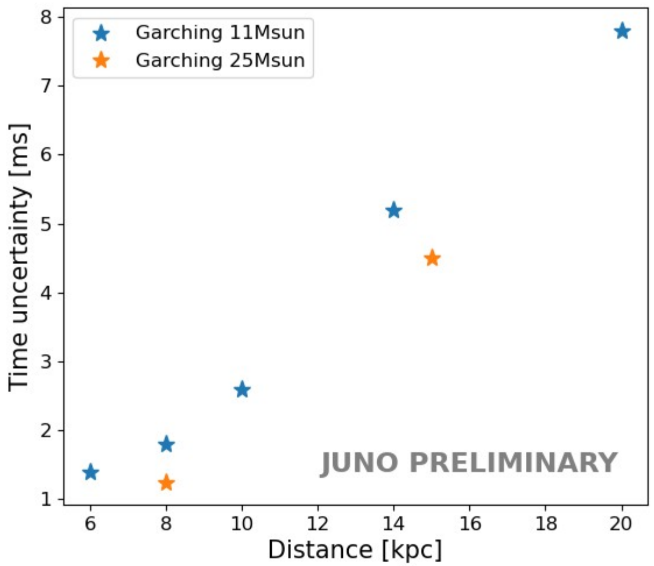
JUNO will also contribute on its own

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

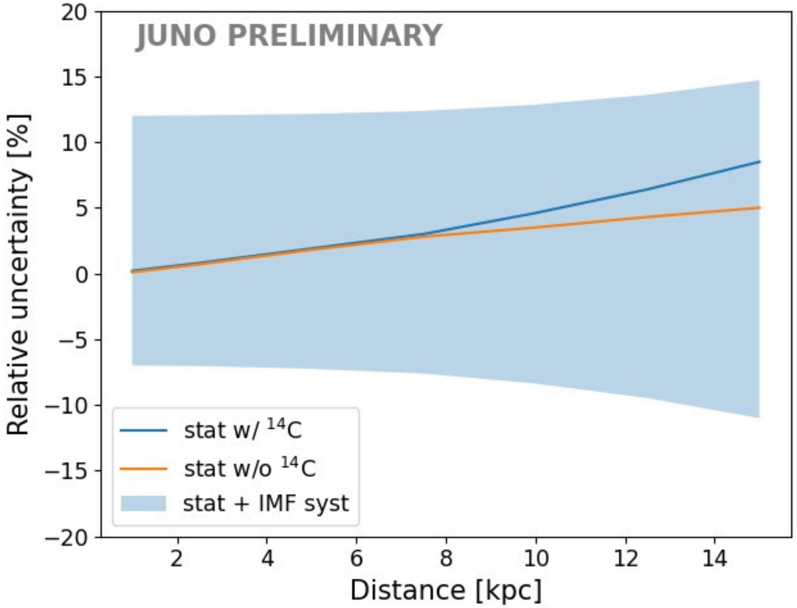


Figure: Statistical uncertainties (solid lines) with the MM trigger. The blue bands include the model systematics (IMF = initial mass function) uncertainty on top (more systematics ongoing).

CCSN neutrinos: pointing

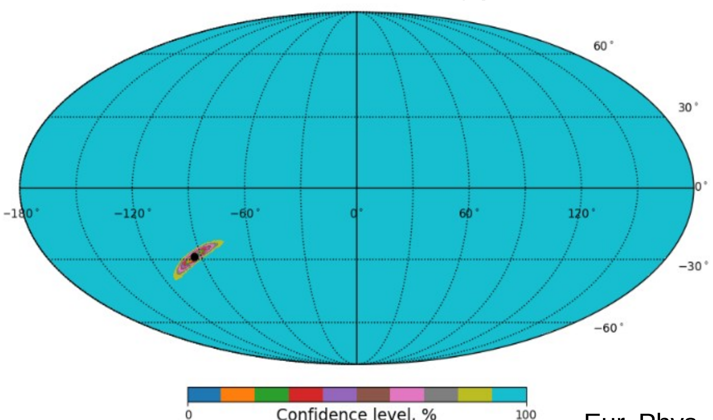
- Pointing to the source with neutrinos will help key for a successful MM follow-up
- But direction reconstruction is difficult at MeV energies: point-like emission…

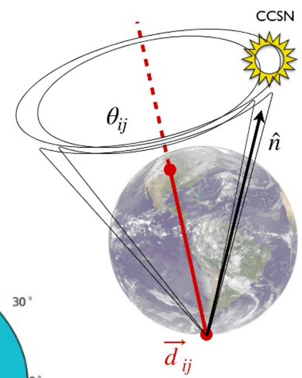
→ Two possible ways to go:

Triangulation

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

JUNO/ARCA/IceCube/HyperK

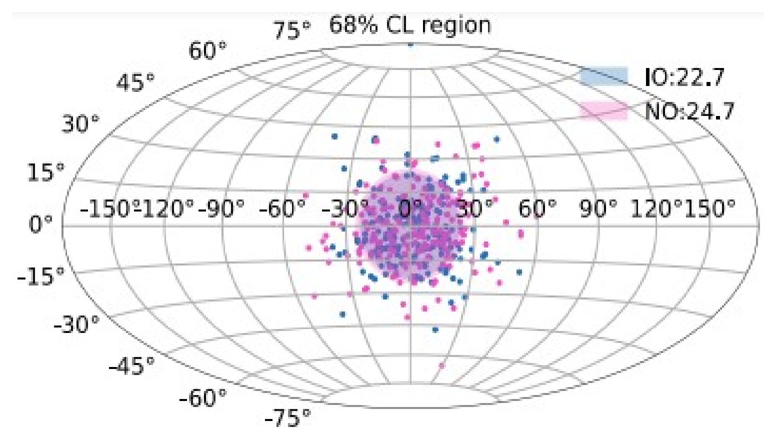




Eur. Phys. J. C 80, 856 (2020)

JUNO: anisotropic interactions

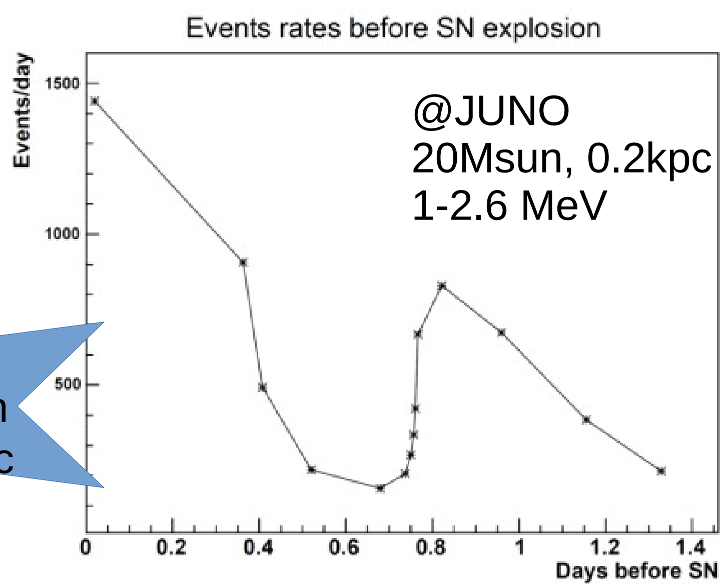
”The direction between the IBD prompt (positron) and delayed (neutron capture) reconstructed vertexes gives ν direction”

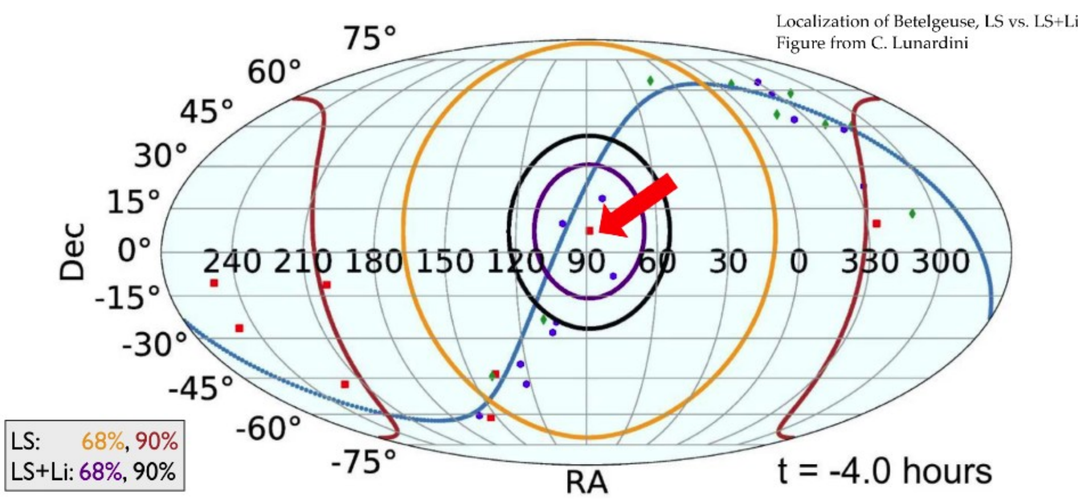


Pre-supernova neutrinos

- Anti-ν_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, SNO+, SuperK-Gd) can detect such signal for close by CCSN events ($\leq$ 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





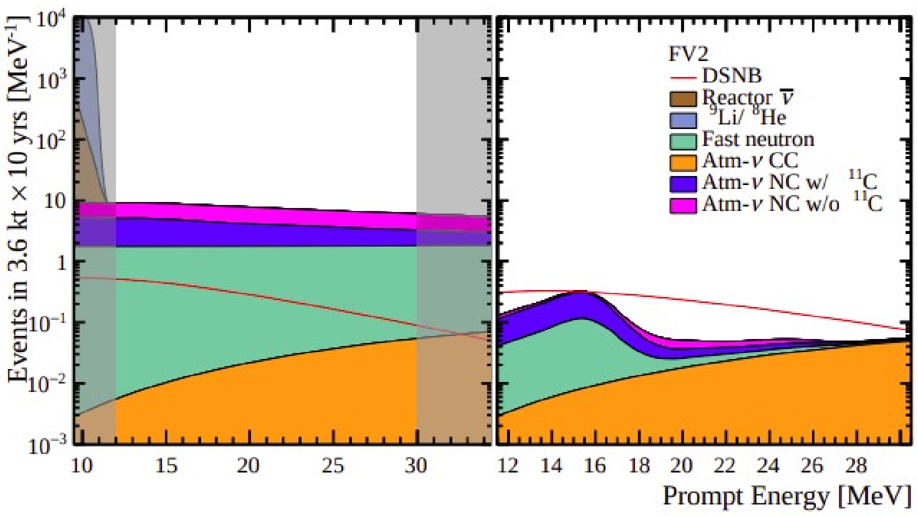
Diffuse supernova neutrino background

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

- 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
  - ...

- 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

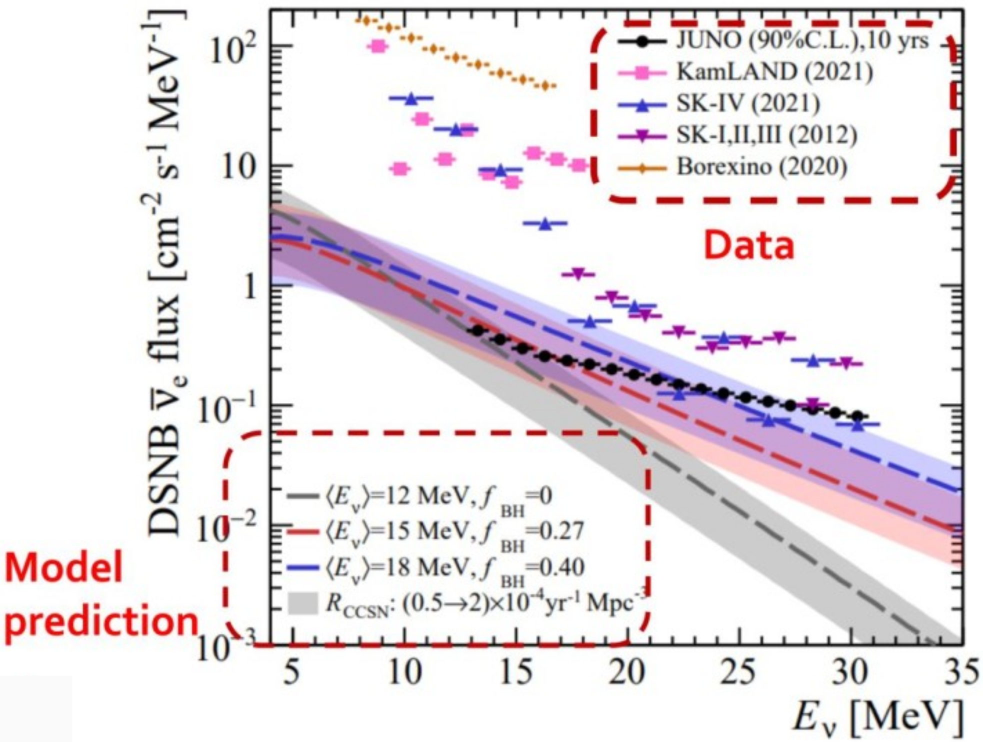
before cuts → after cuts

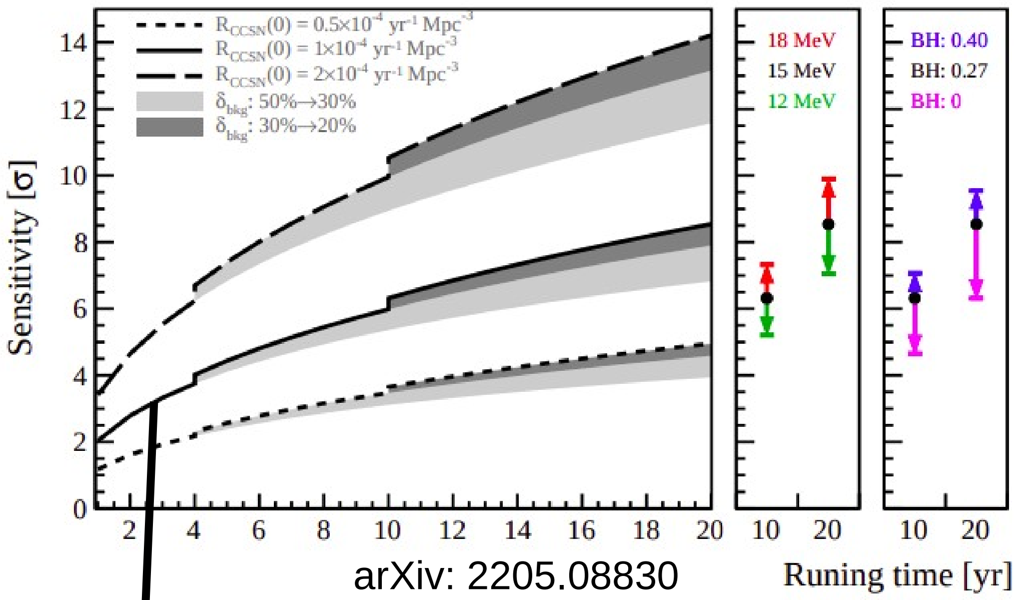


Diffuse supernova neutrino background

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





arXiv: 2205.08830

3σ discovery after 3 years data taking for nominal model

Detector status:

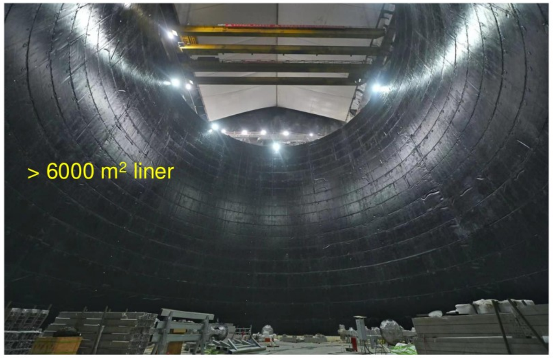
- Central detector (CD):
  - Stainless stain structure installed
  - Accrylic sphere: installation started

- LS mixing and purification systems installed
  → LS comissioning soon

- Electronics:
  - All PMTs produced, tested, and instrumented with waterproof potting
  - All components produced + connections tested

→ Installation will start next month

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

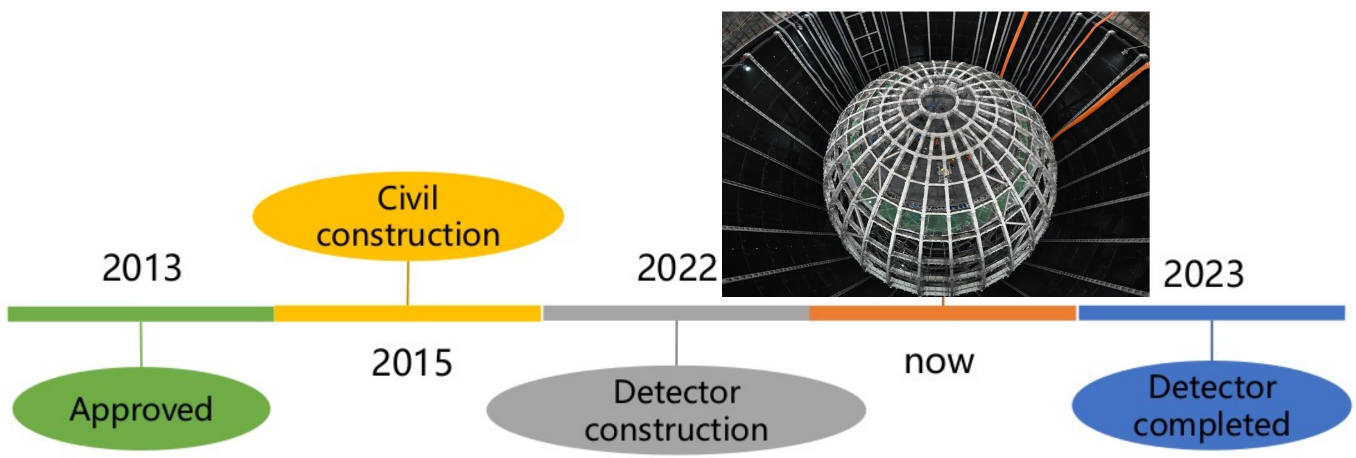


Summary/conclusions:

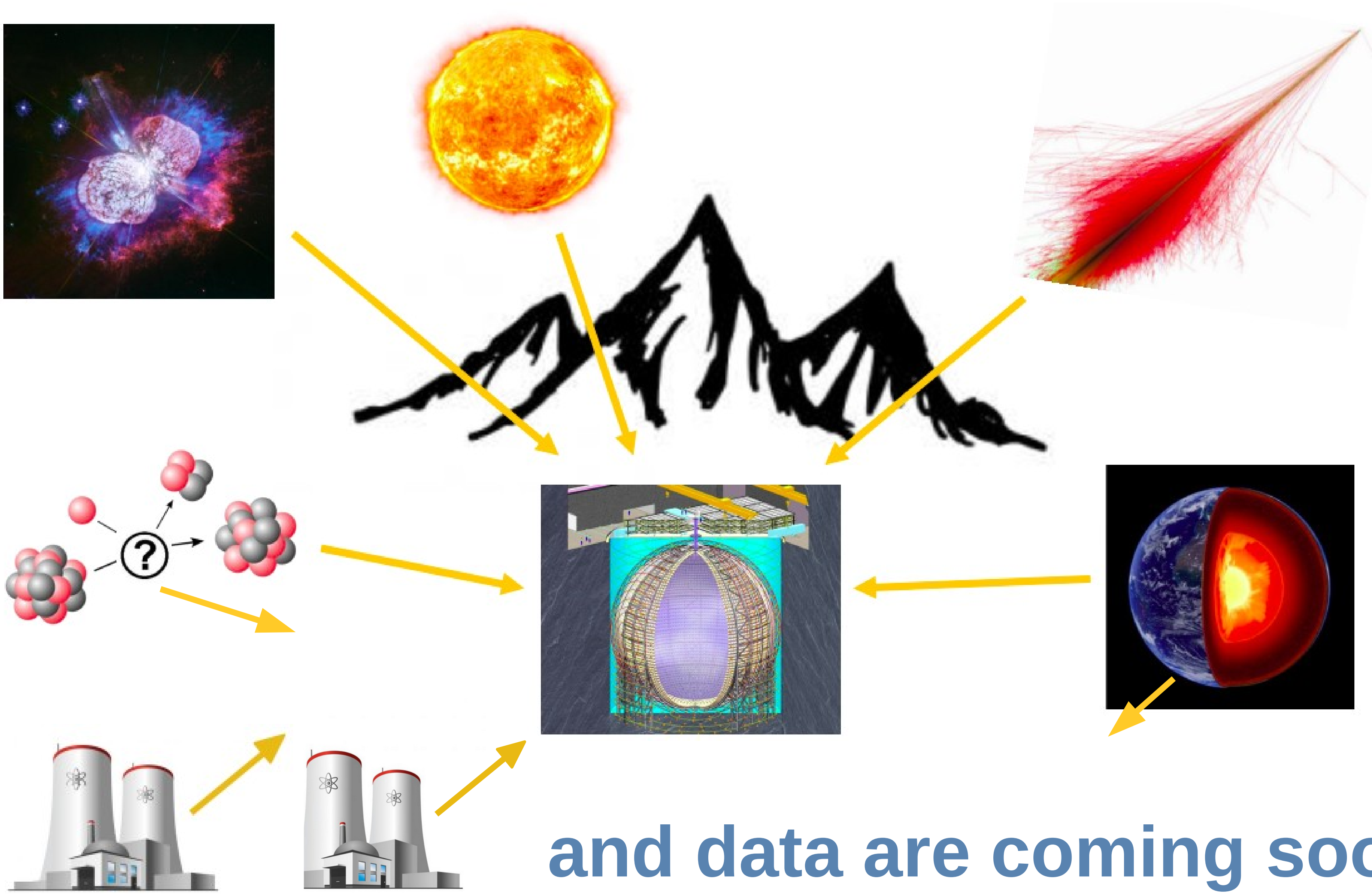
JUNO will be a multi-purpose neutrino experiment with a broad physics reach, including the observation of astrophysical sources/fluxes

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



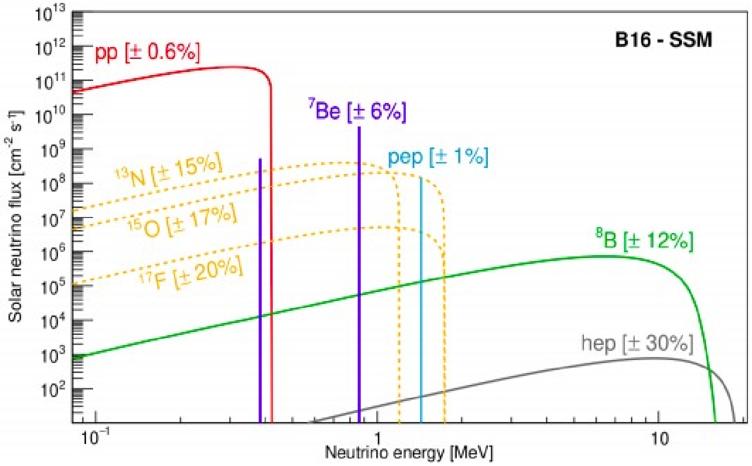
JUNO – A MULTI PURPOSE INSTRUMENT WITH WIDE PHYSICS POTENTIAL



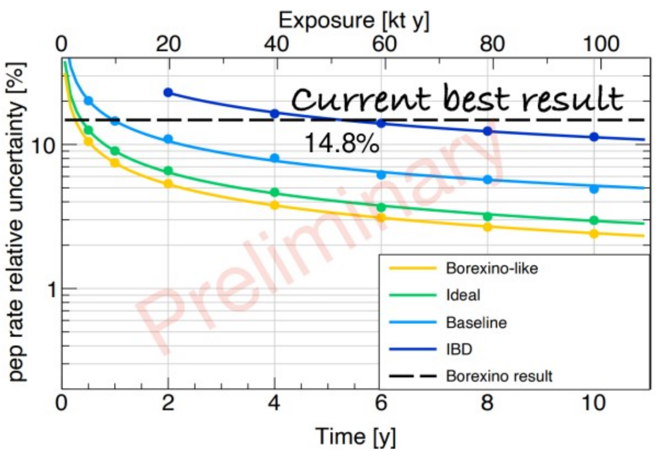
and data are coming soon...

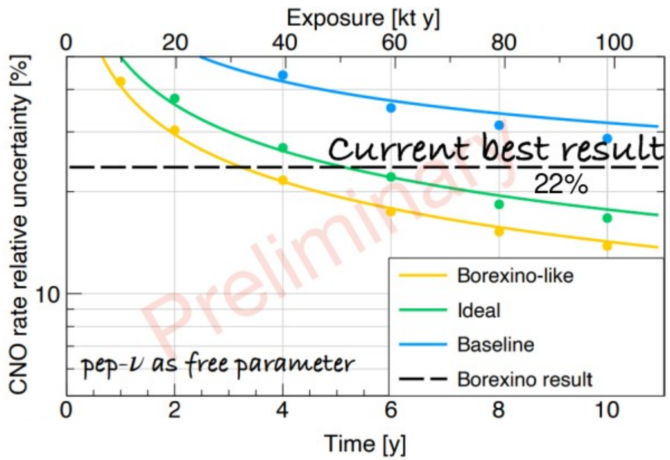
Solar neutrinos

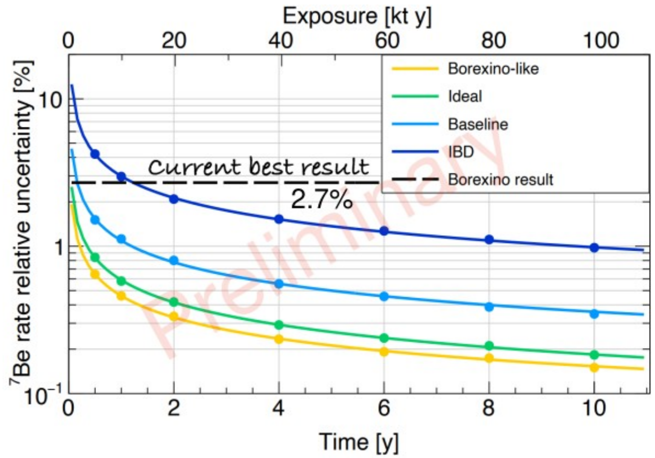
* Main detection channel → ν_e elastic scattering (ES)
* JUNO can benefit of its enormous statistics
* Different fluxes can be detected:
    - 7Be
    - 8B
    - Pep
    - CNO



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





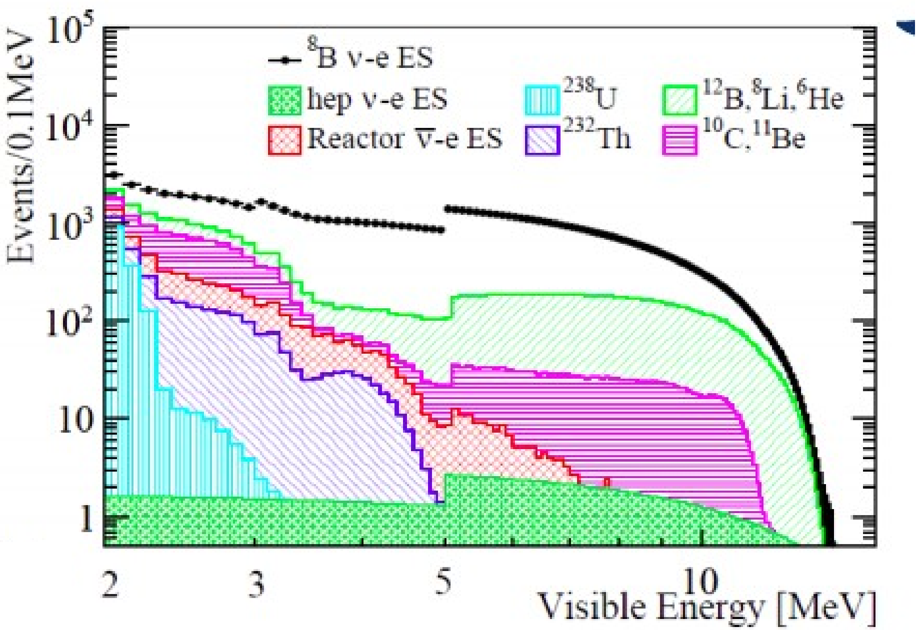


See: DOI:10.5281/zenodo.6785412

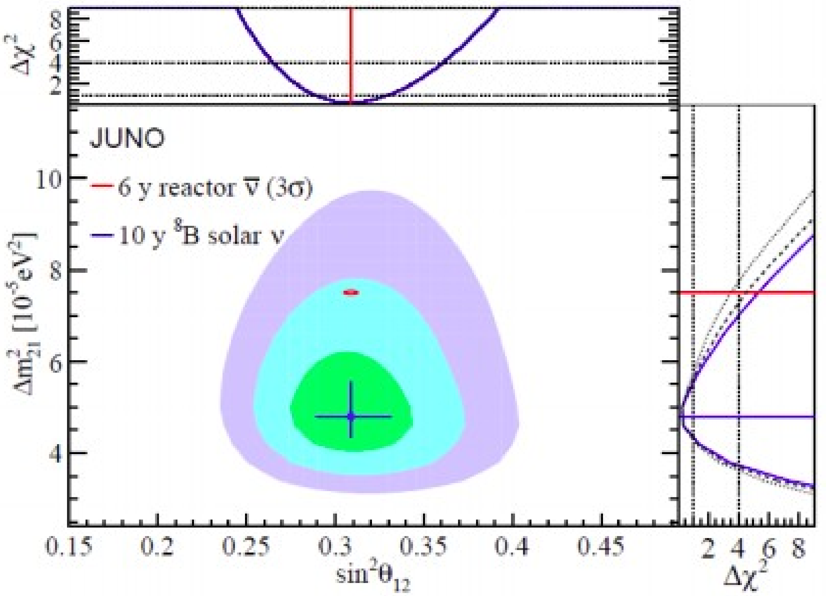
Solar neutrinos

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 Δm^2_{12} with both solar and reactor neutrinos in one experiment



→ JUNO will provide the most precise solar neutrino flux measurements, allowing to address some remaining questions (e.g. metallicity puzzle, NSI in extreme media)