JUNO physics potential with astrophysical neutrinos

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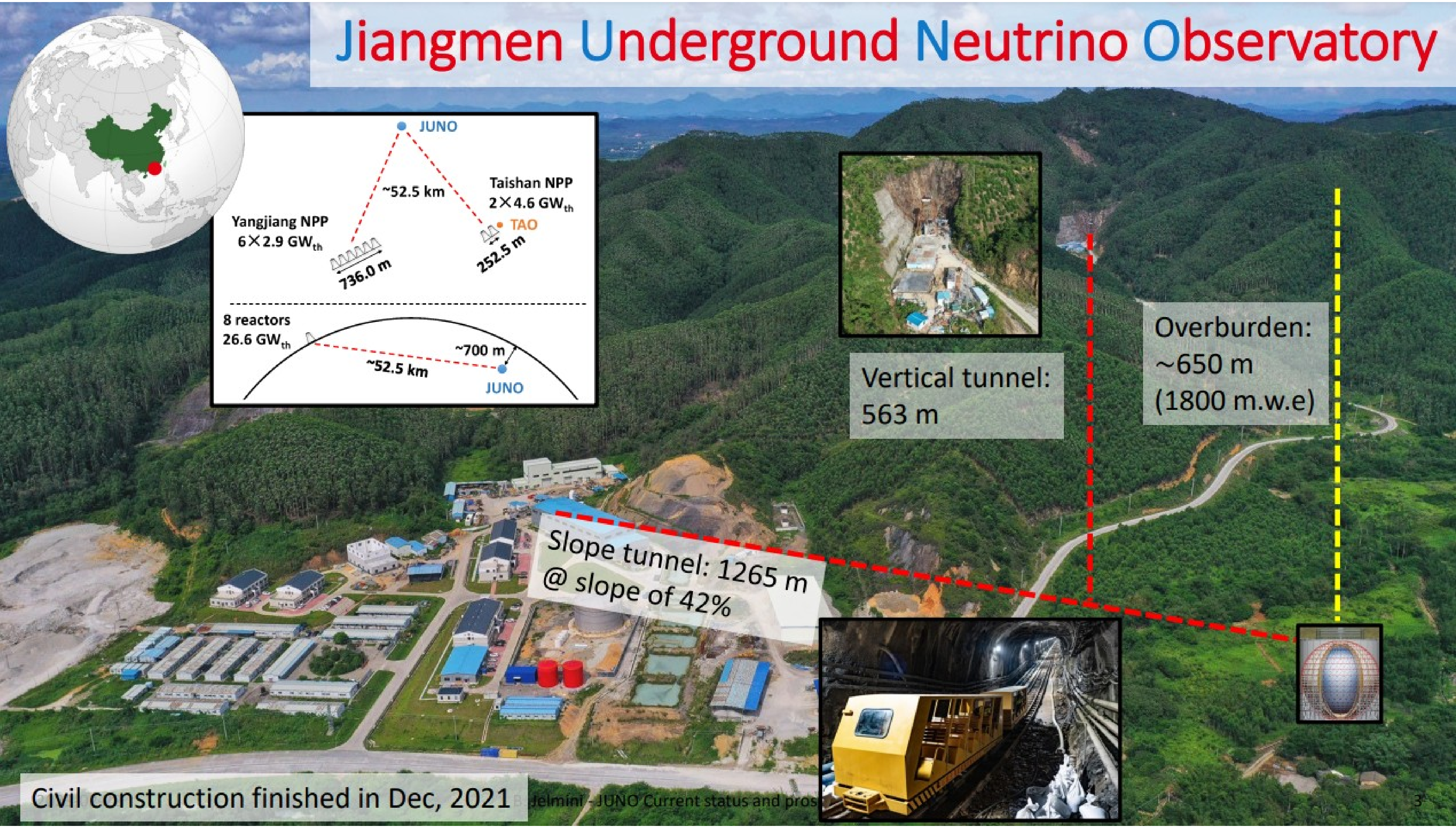
On behaf of the JUNO collaboration

ICRC2023 - 28th July 2023 - Nagoya

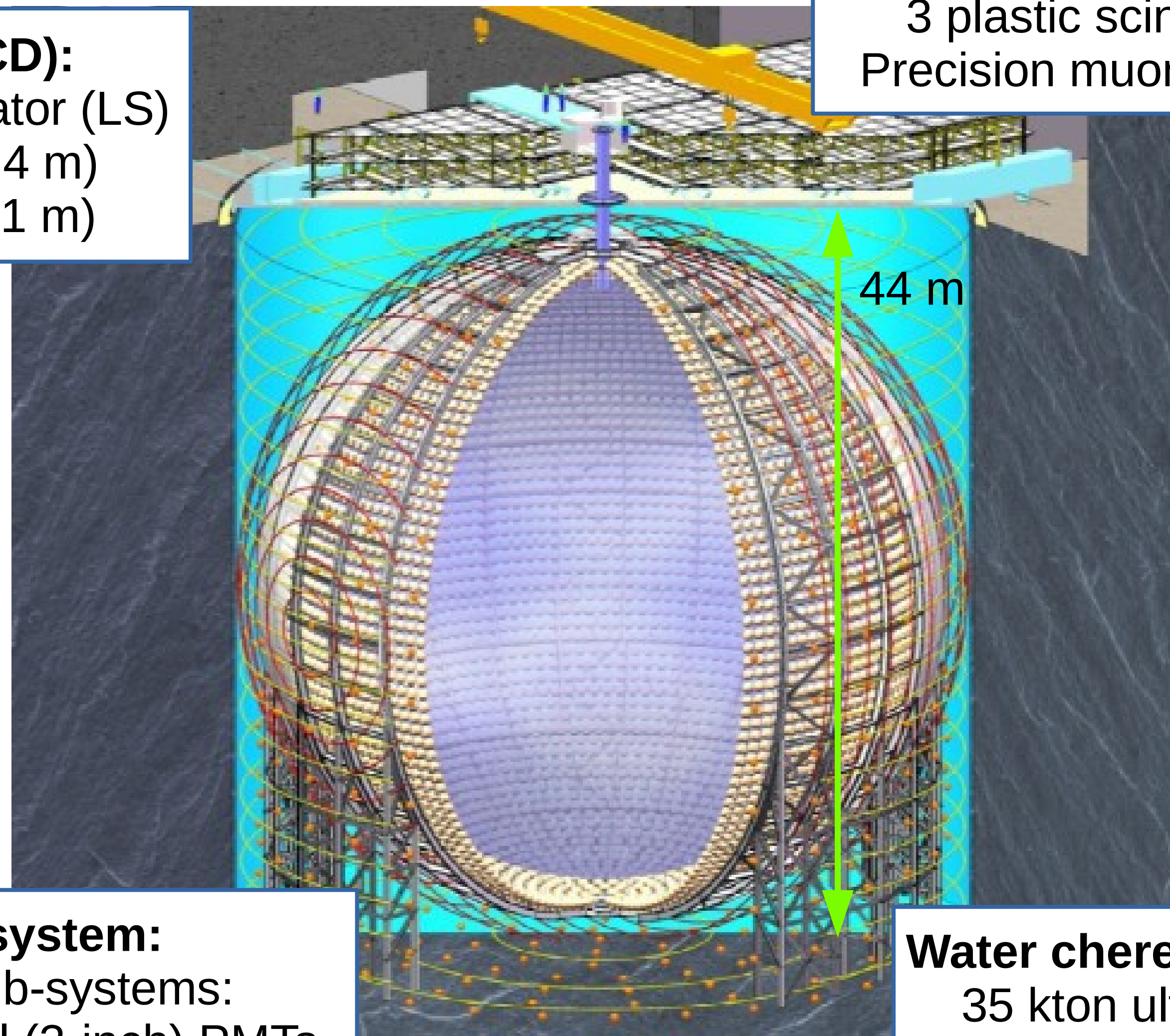
The JUNO detector



The JUNO detector

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

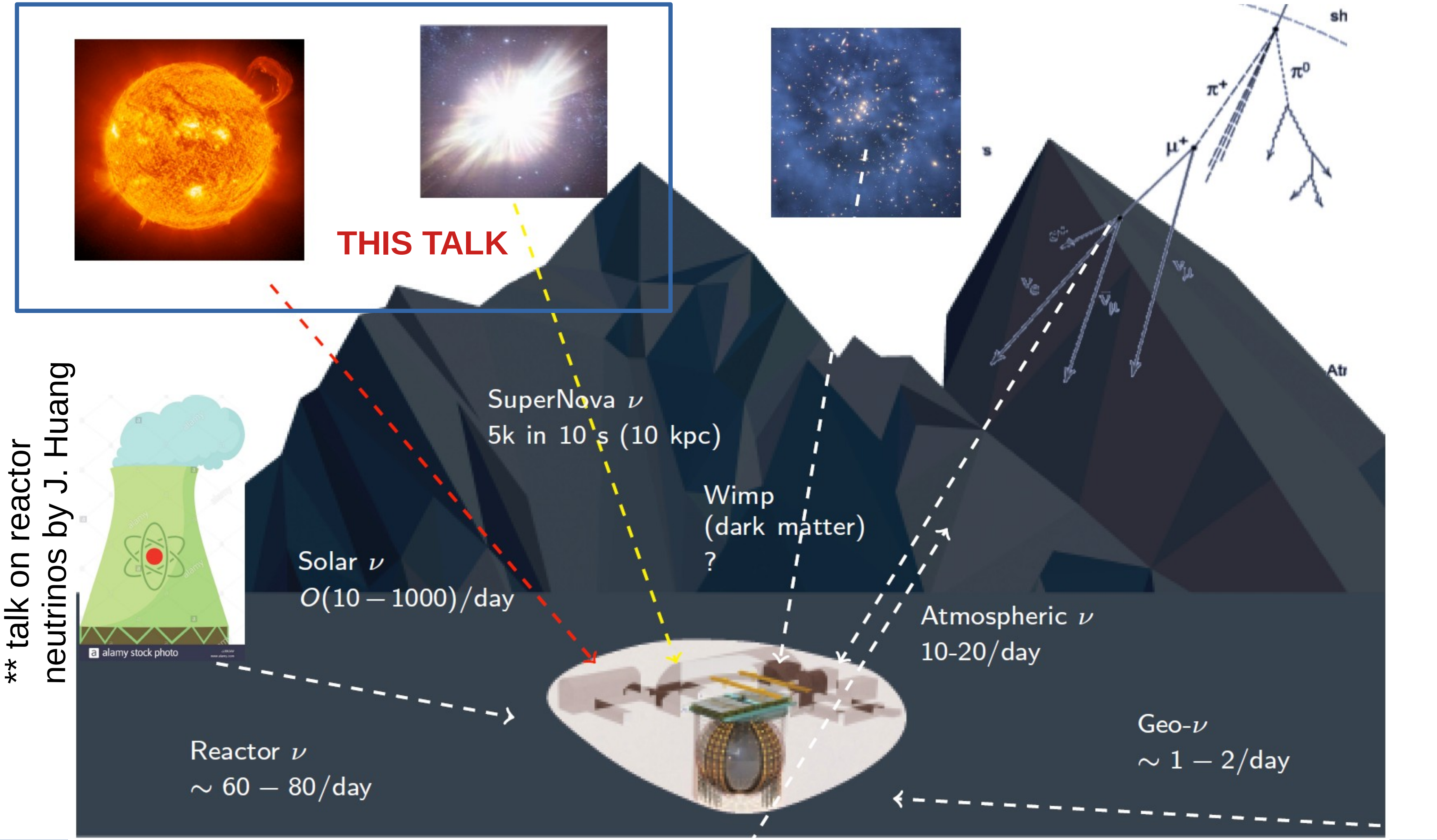
Central detector (CD):
20 kton of Liquid Scintillator (LS)
Accrylic vessel (ϕ 35.4 m)
Steel structure (ϕ 40.1 m)



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

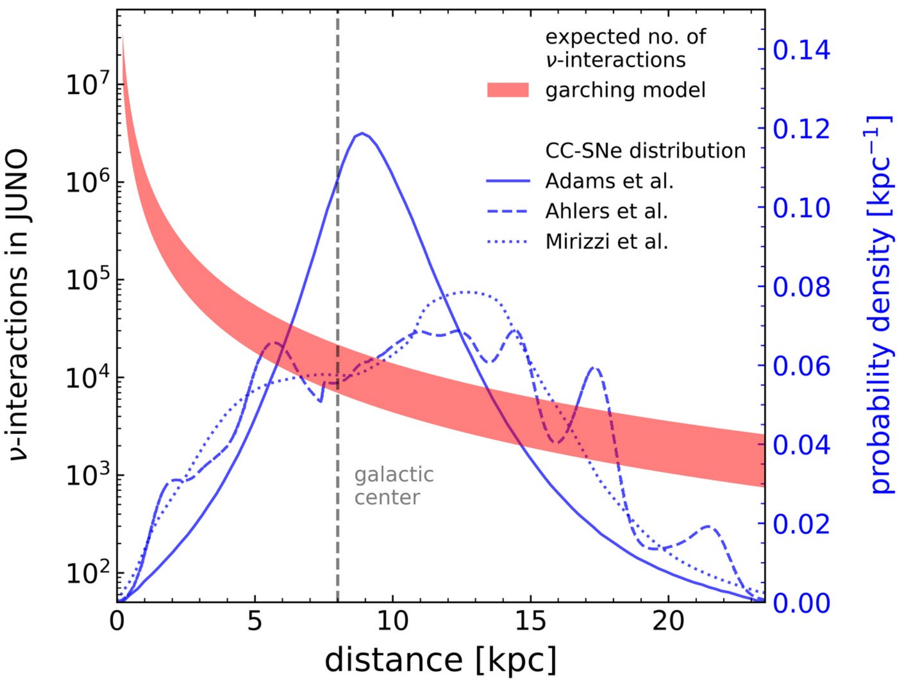
JUNO physics program



Core-collapse supernova neutrinos in JUNO

If there is a Galactic CCSN, JUNO has:

- High signal event statistics
- Almost no background
- Sensitivity to all neutrino flavors



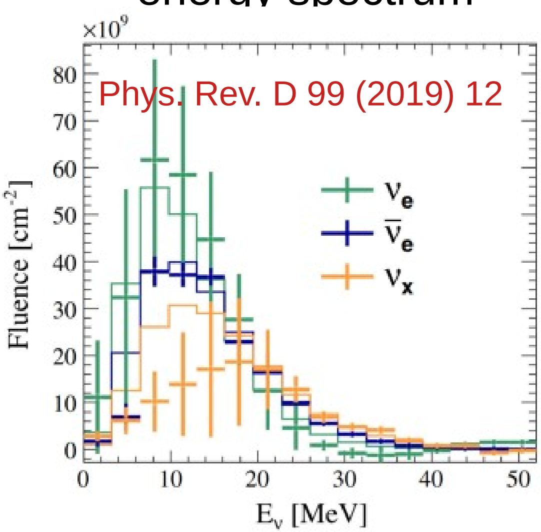
Core-collapse supernova neutrinos in JUNO

Doing CCSN physics with neutrino data? What do we need?

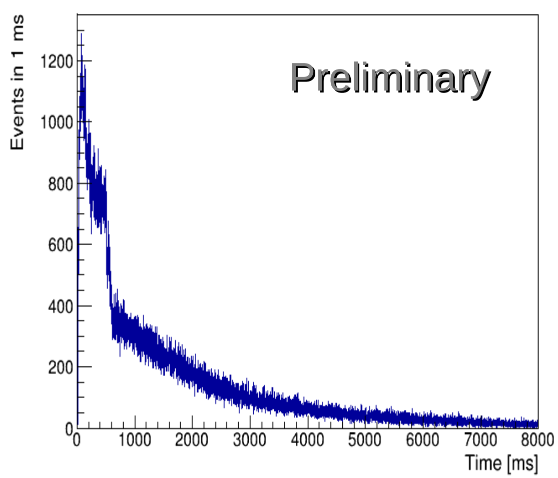
→Good energy and time resolution + flavor classification: JUNO will measure:

Constrain CCSN physics

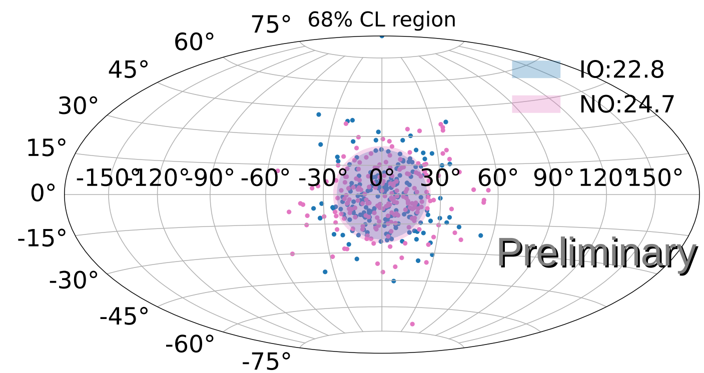
Flavor dependent energy spectrum

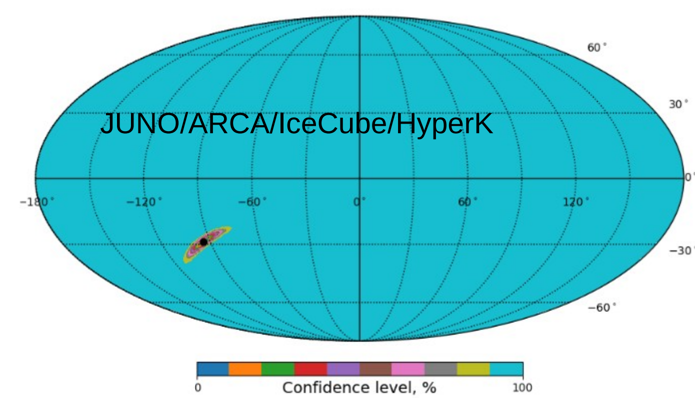


Lightcurve:



Direction:

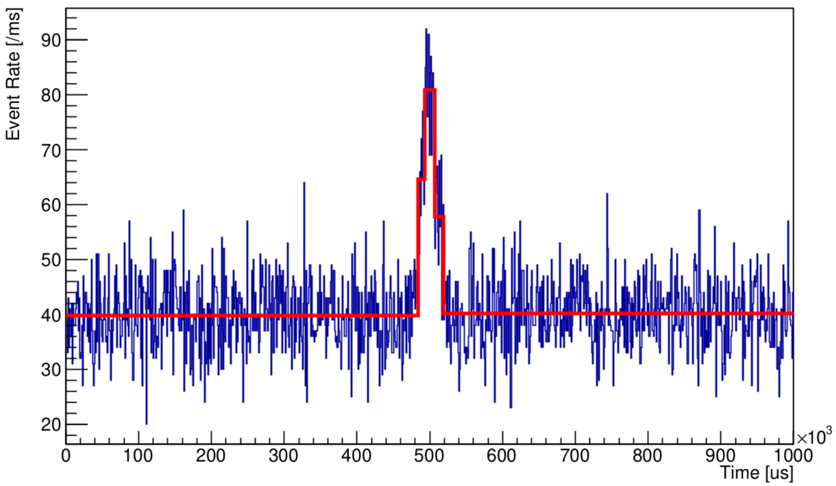




Identifying an astrophysical transient signal

PAPER in preparation

- 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

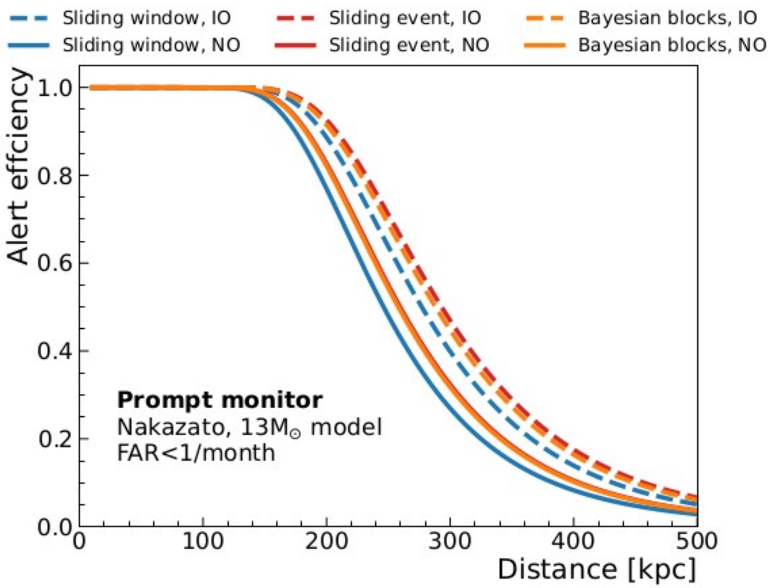


If transient astrophysical signal triggered:
→ All (triggerless) data are stored to obtain the most physics reach in offline analysis

- Prompt Monitor:
- Higher energy threshold (~8MeV)
- Faster alerts

- Online monitor:
- IBD candidates (Eth ~ 1MeV)
- Lower background

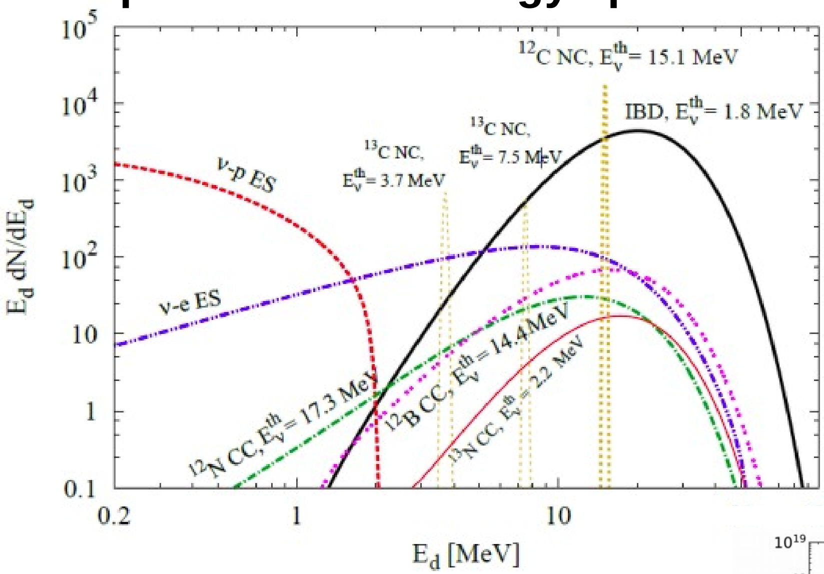
- Multi-messenger (MM) trigger:
- Lower energy threshold (<0.1 MeV)
- Increase signal statistics



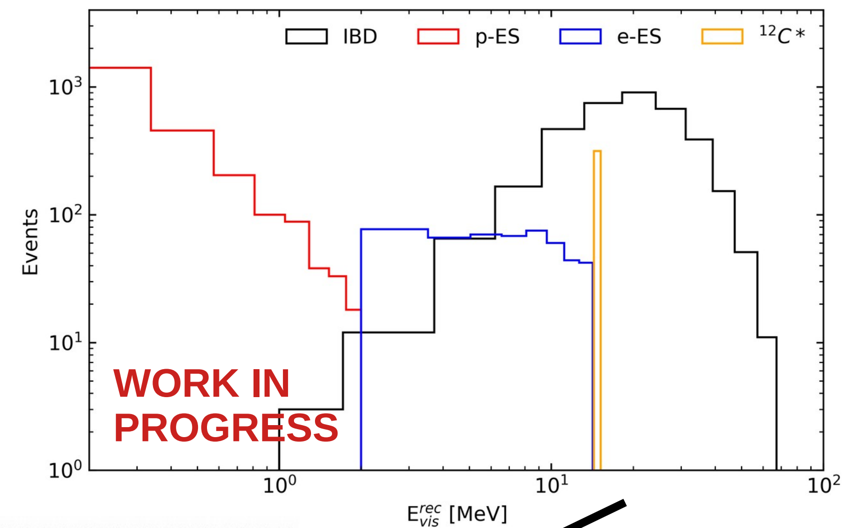
CCSN neutrino spectrum

Identification of the different interaction channels:

Expected CCSN energy spectrum:



Reconstructed after selection:



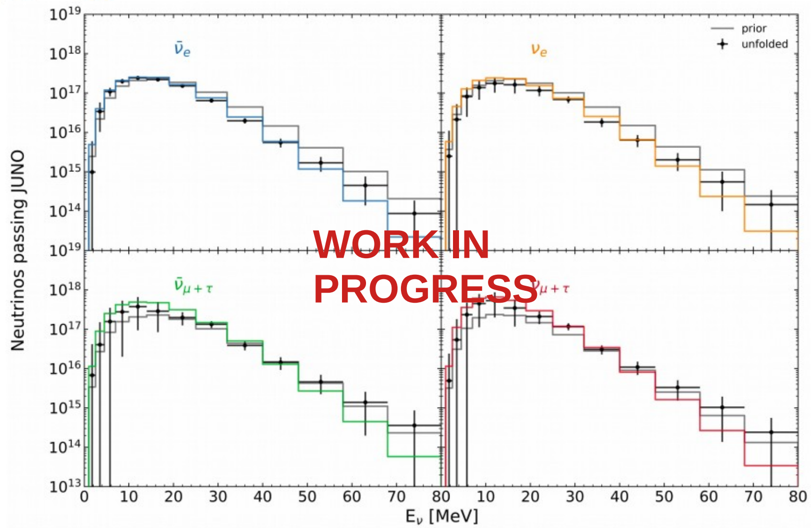
Main channels:

- IBD → ν_e flux
- ν-e scattering → ν_e flux mainly
- ν-protron ES → all flavors

UNFOLDING RESULTS:

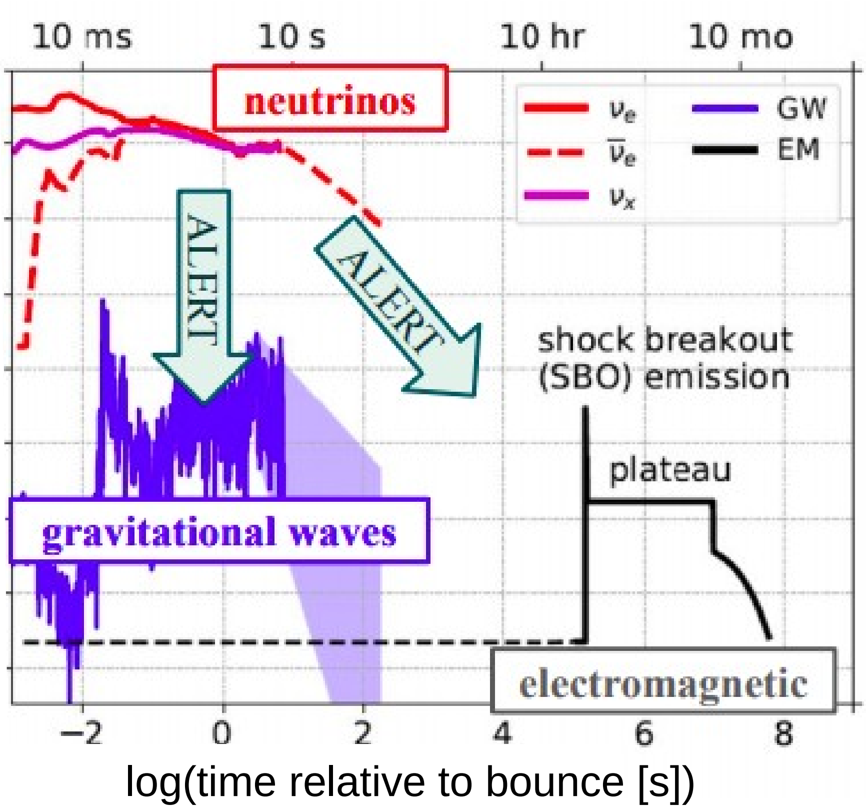
detected rates per channel

emitted flux per ν favor



Flavor dependent energy spectrum UNFOLDED

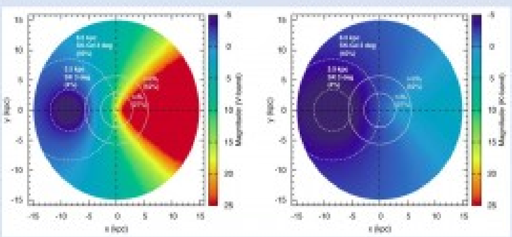
Core-Collapse Supernova multi-messenger signal

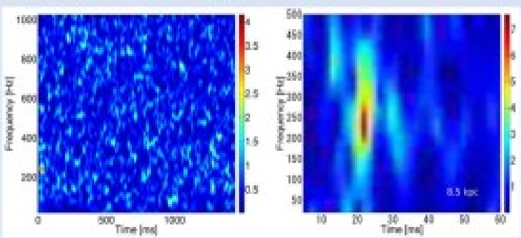


Catching the multi-messenger signal

- Source position and distance are crucial for a successful MM follow-up
- Timing of the neutrino signal is key for those parameter estimates

EM observations ← neutrinos → GW observations

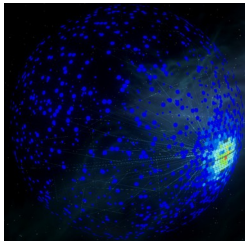




- Multi-messenger (MM) signal: neutrinos, GWs and **EM** radiation
- Neutrinos = early alert for the follow-up

- Alert time (latency): 15-20 ms @10 kpc
- Signal arrival time uncertainty: 2-3 ms @10 kpc

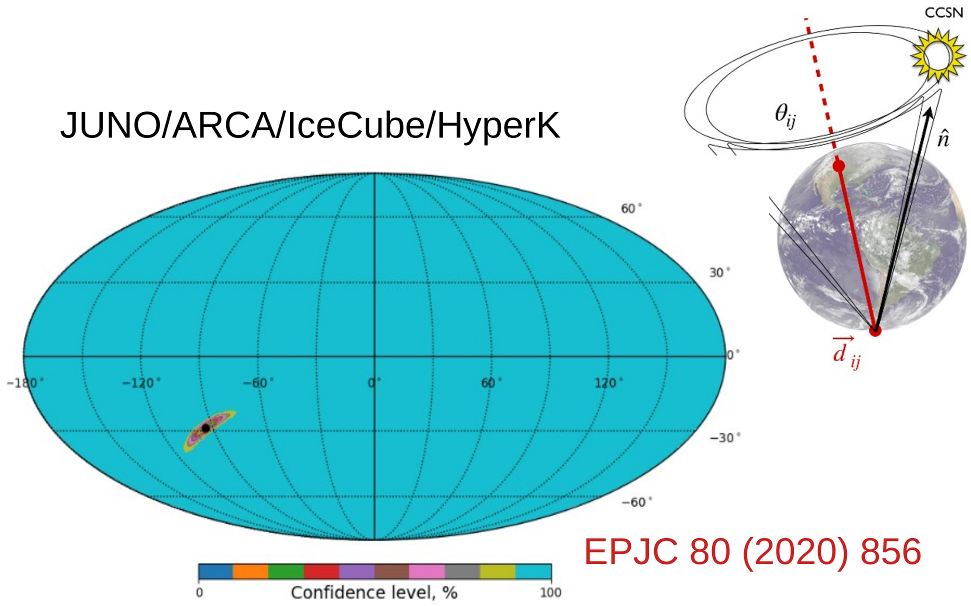
CCSN neutrinos: pointing



- 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

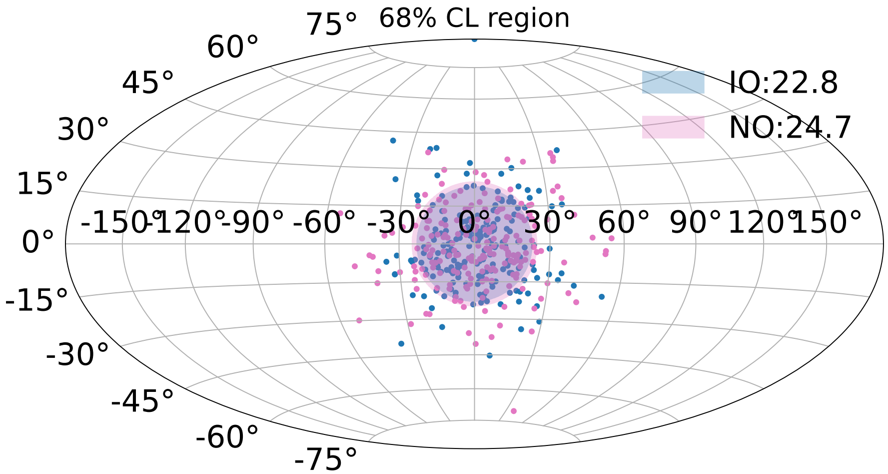
”The time delay between the signal at different detectors defines a sky region”



EPJC 80 (2020) 856

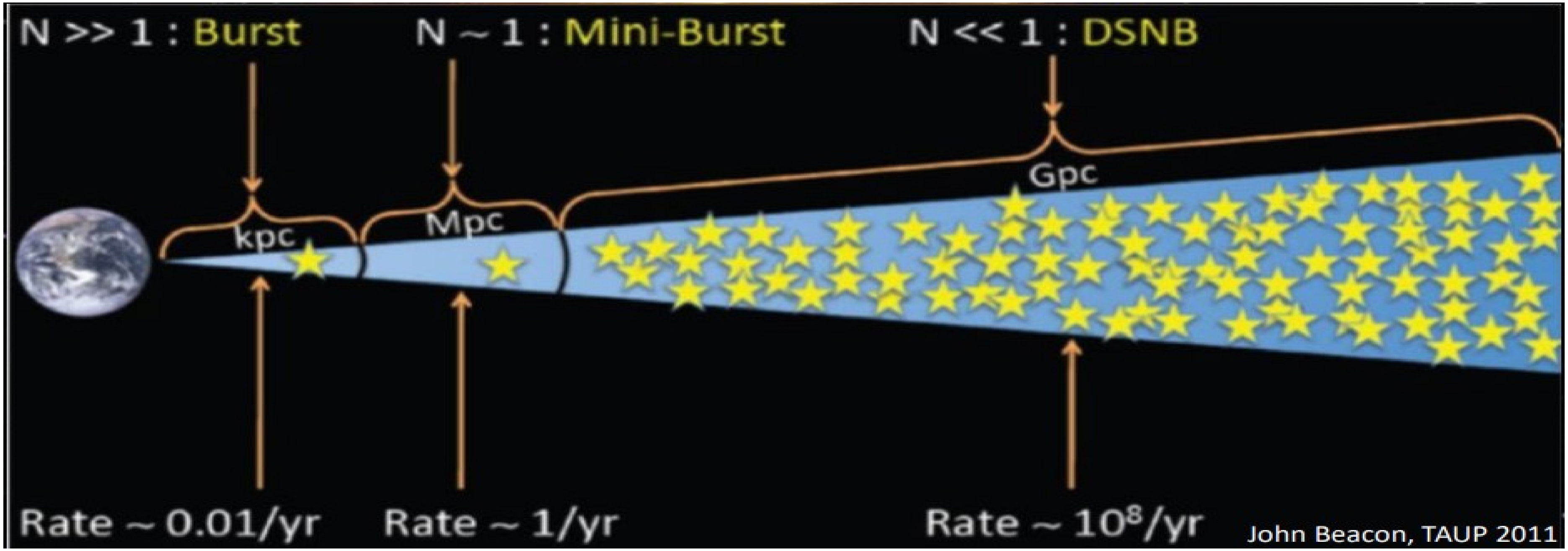
JUNO IBD: anisotropic interactions

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



Diffuse supernova neutrino background

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

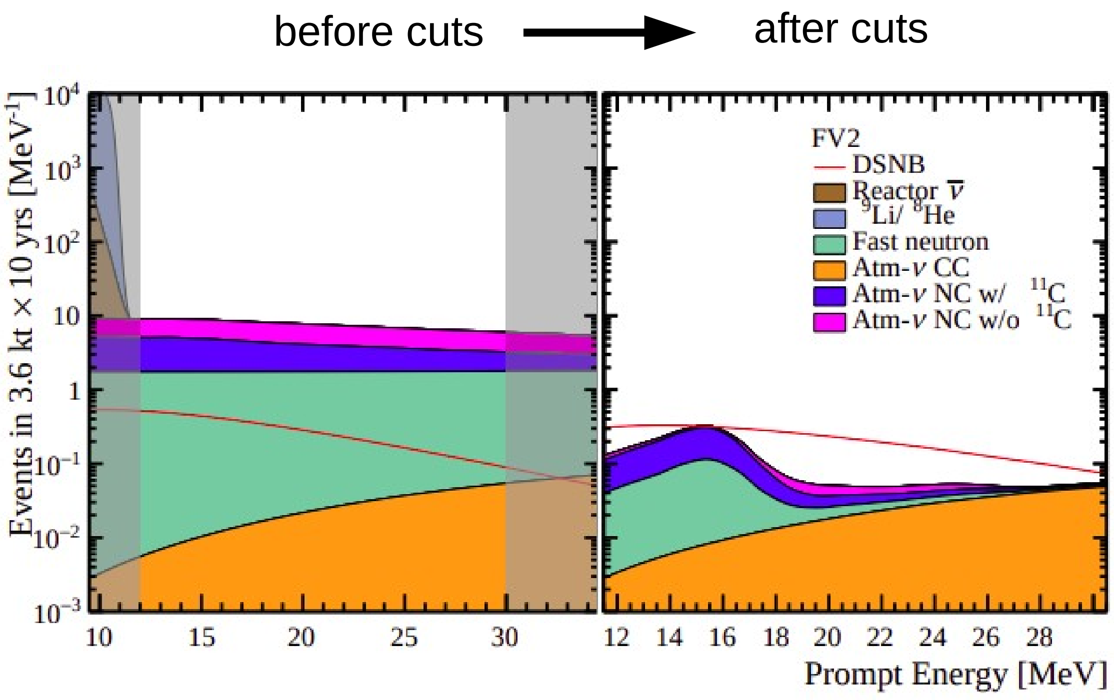


- Garanteed steady source of O(MeV) neutrinos
- Discovery of DSNB signal will bring information on astrophysics and cosmology:
  - star formation and CCSN rates in the Universe + star evolution
  - black hole (BH) formation rates in the Universe
  - ...

Diffuse supernova neutrino background

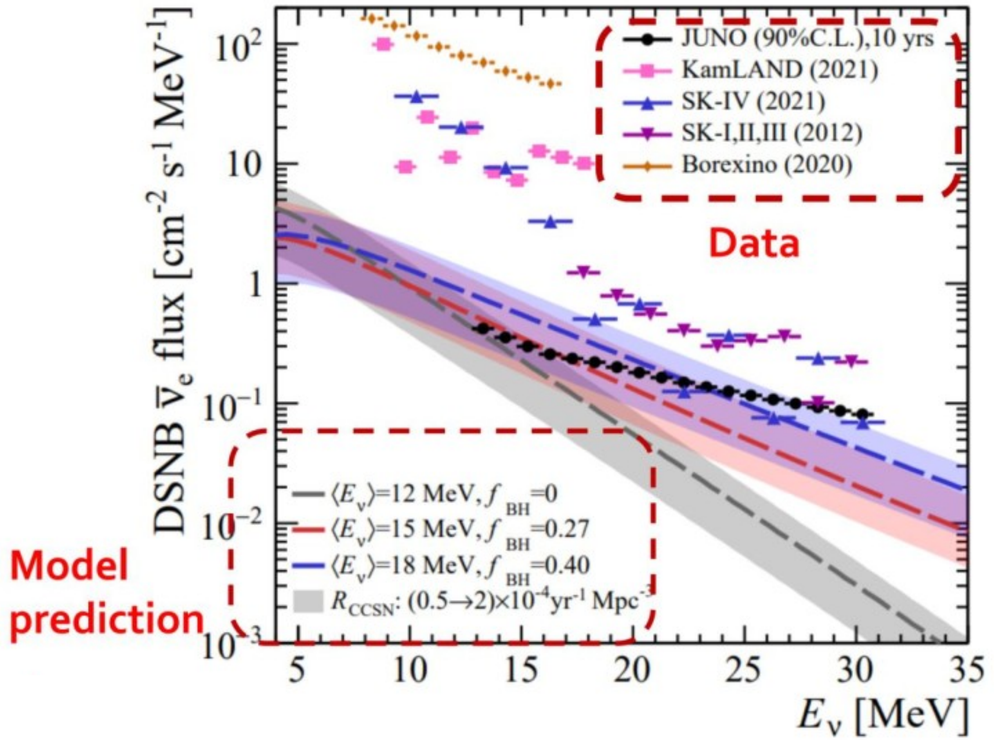
- Detection in JUNO via IBD
- Main background:
  neutral current atmospheric neutrinos
- **Event selection:**
  - Energy range [12-30] MeV
  - Fiducial volume
  - PSD (pulse shape discrimination)

→ efficient background rejection:
  Signal: ~4-7 events per year (75%)
  Background: ~5 events per year

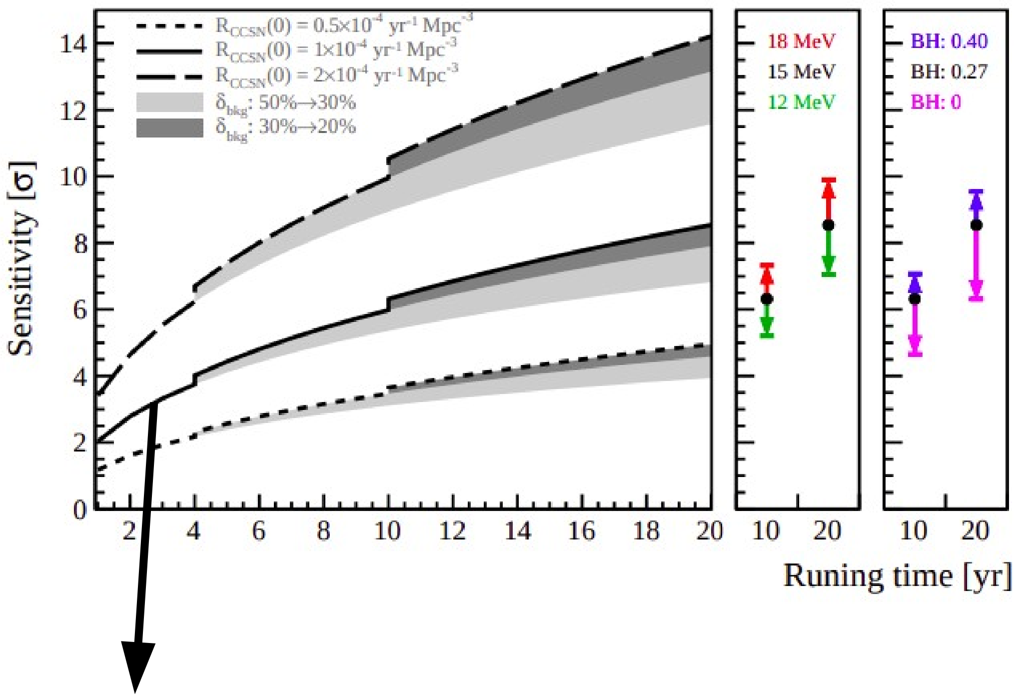


Diffuse supernova neutrino background

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

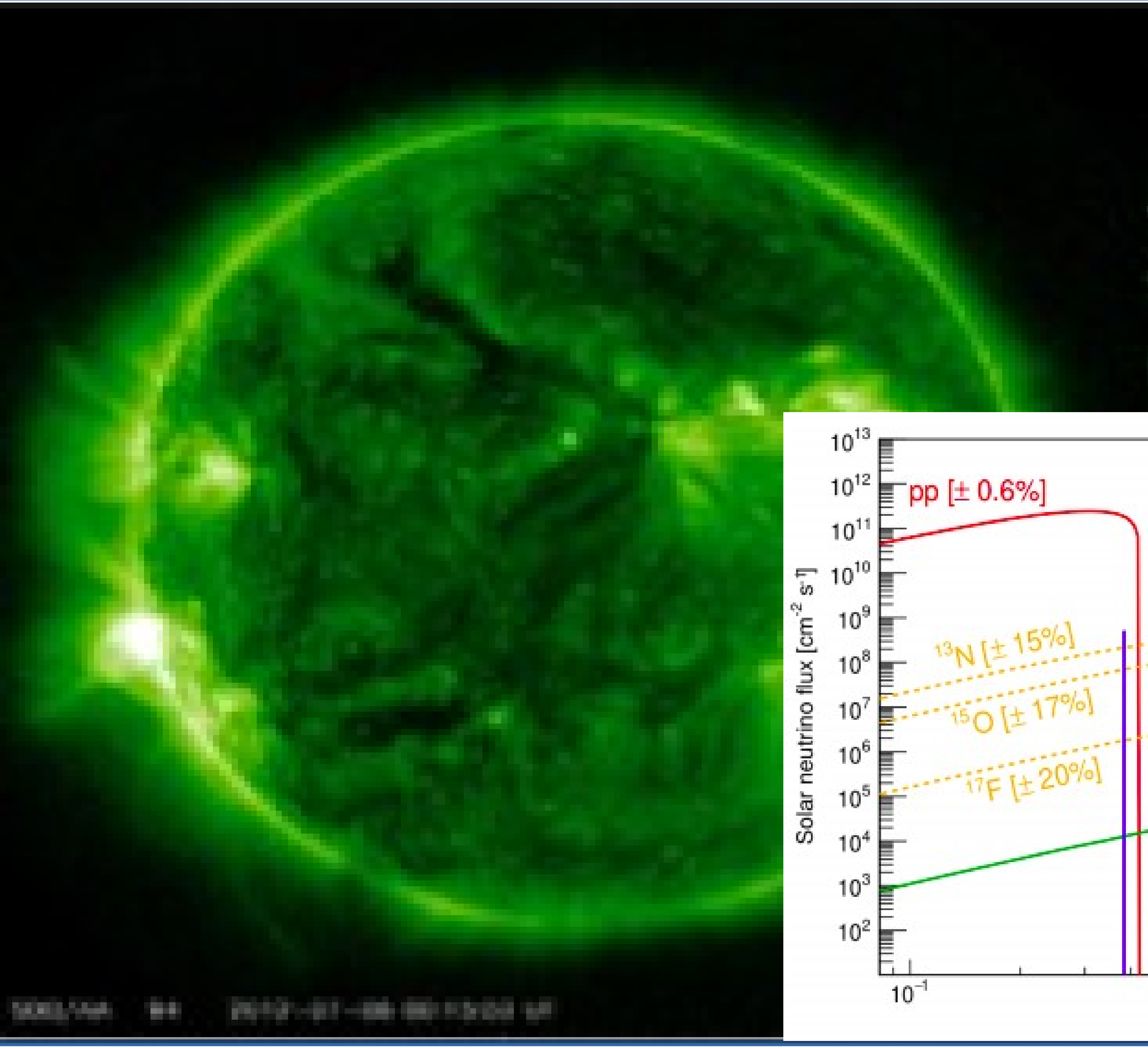


JCAP 10 (2022) 033

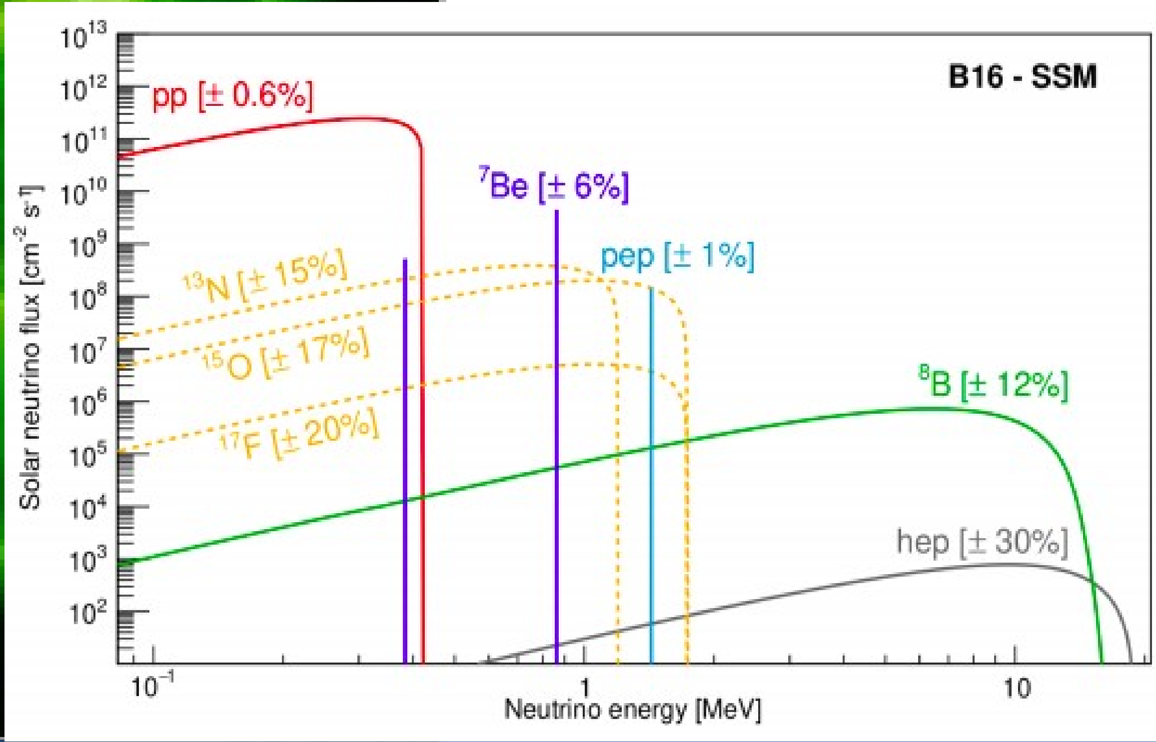


3σ discovery after 3 years data taking for reference model

Solar neutrinos



* Main detection channel
→ ν_e elastic scattering (ES)
* JUNO benefits of huge statistics
* Different fluxes can be detected:
    - ^{8}B
    - ^{7}B
    - pep
    - CNO

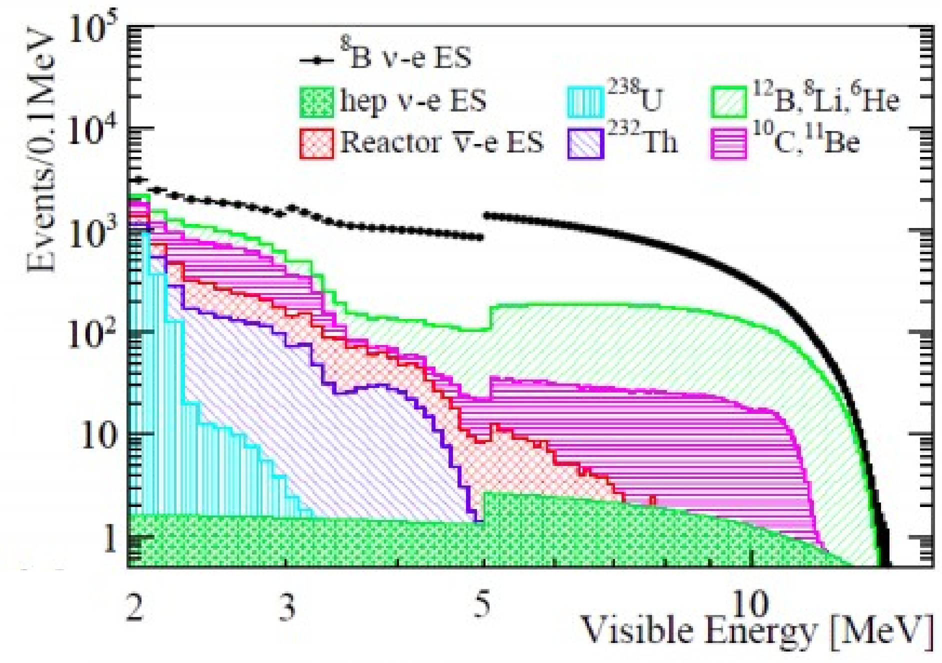


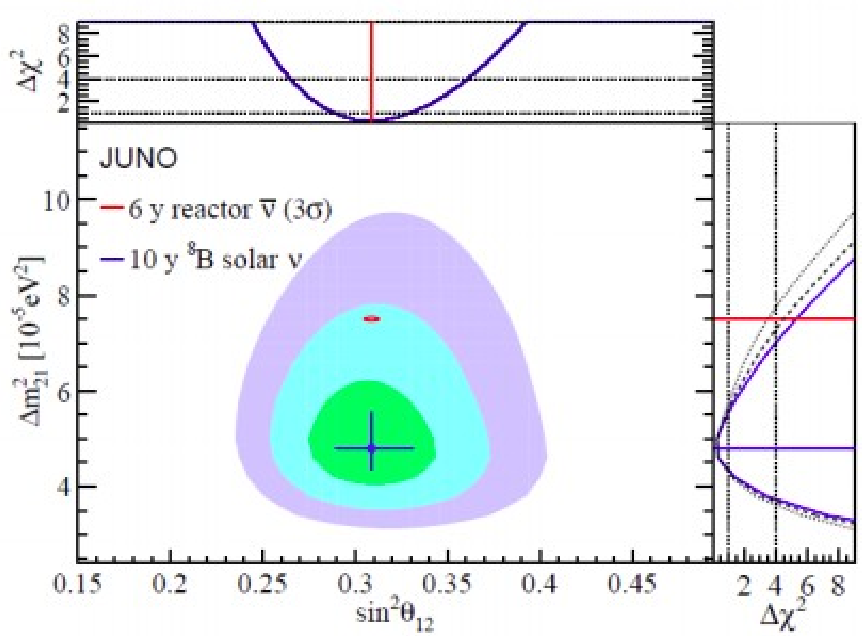
Solar neutrinos

High energy (^{8}B neutrinos) – Chin. Phys. C 45 (2021)
arXiv:2210.08437 (2022)

- 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





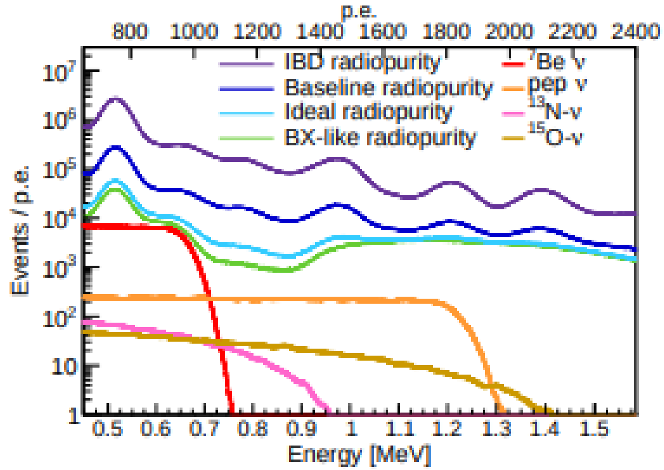
Solar neutrinos

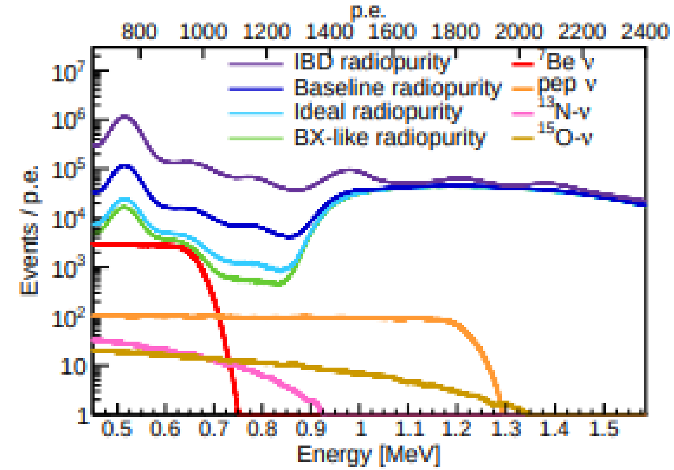
- **Intermediate and low energy neutrinos** (< 2MeV)**:** arXiv:2303.03910

  - Measure simultaneously pep, ^{7}Be and CNO fluxes

→ Crucial: internal radioactivity

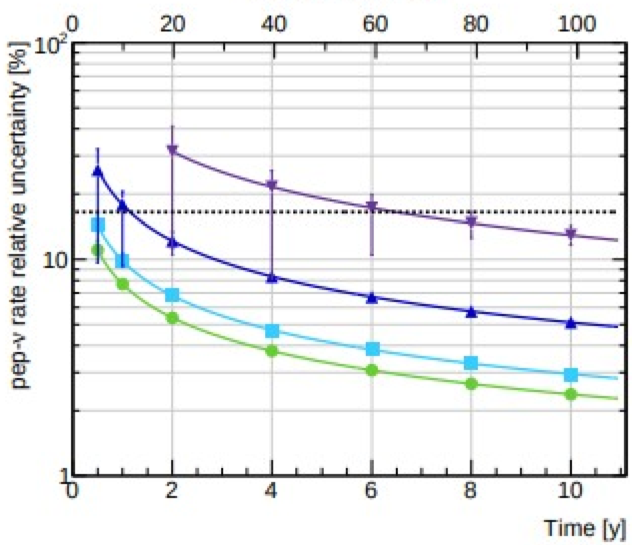
Requirement: <1e-17g/g

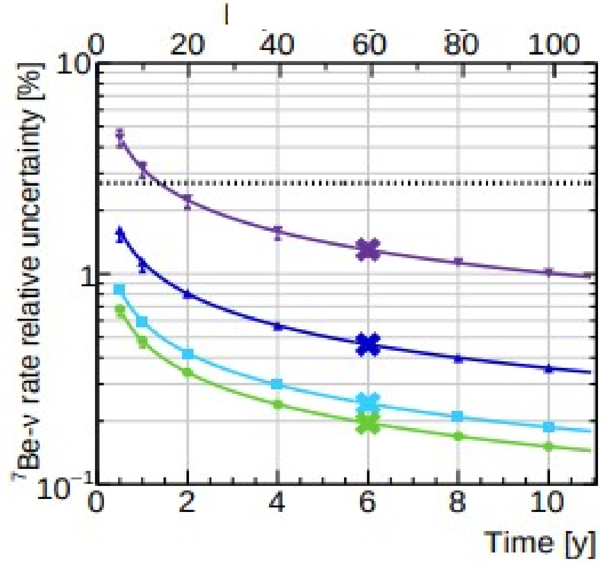




- Two datasets:

^{11}C enriched / depleted





- Different radiopurity scenarios considered

IBD radiopurity

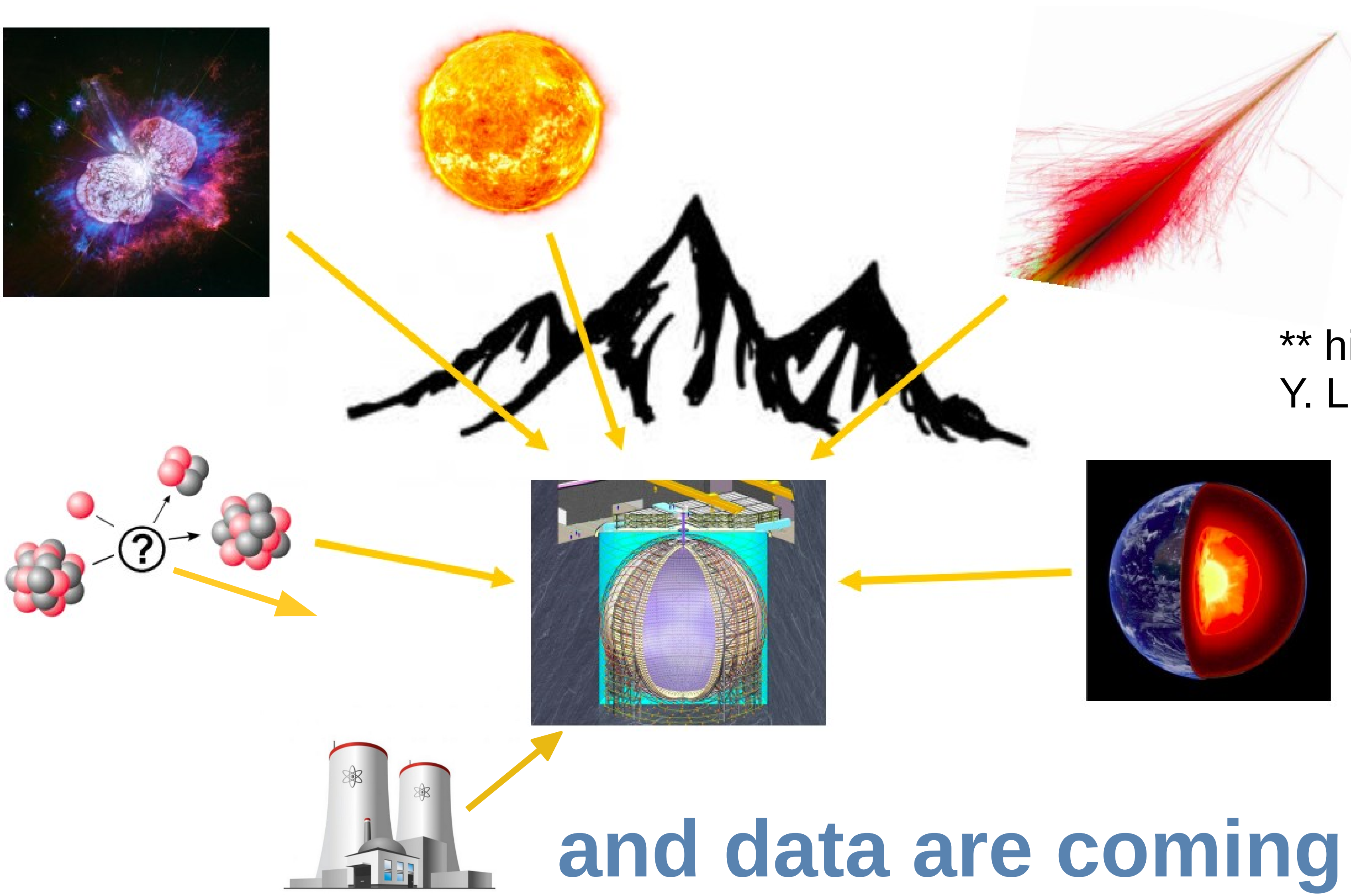
Baseline radiopurity

Ideal radiopurity

BX-like radiopurity

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

JUNO – AN INSTRUMENT WITH AN INCREDIBLE PHYSICS POTENTIAL



** highlight talk by Y. Li next week!

and data are coming soon...

BACK-UP

The JUNO detector

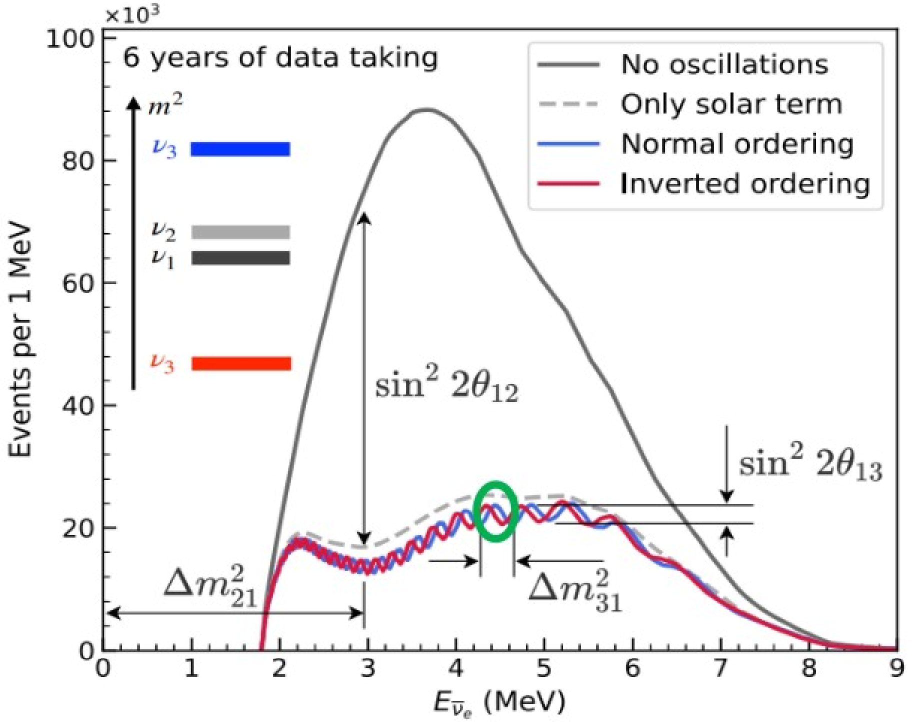
Primary goals:
- precise measurement of oscillation parameters
- determination of the neutrino mass ordering

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

How?

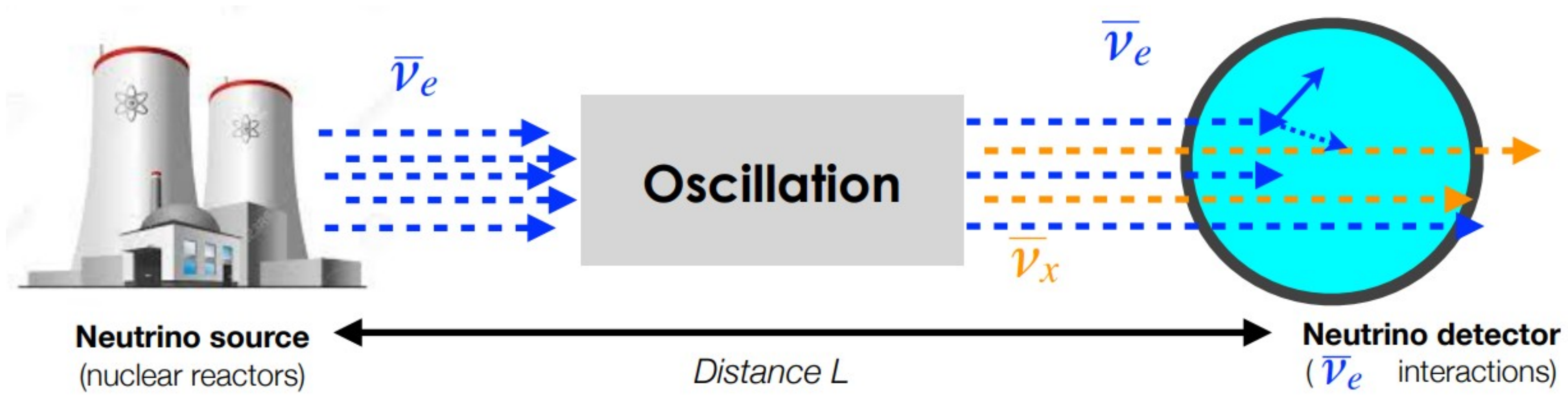
→ **Largest and most precise ever built LS detector**

- 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



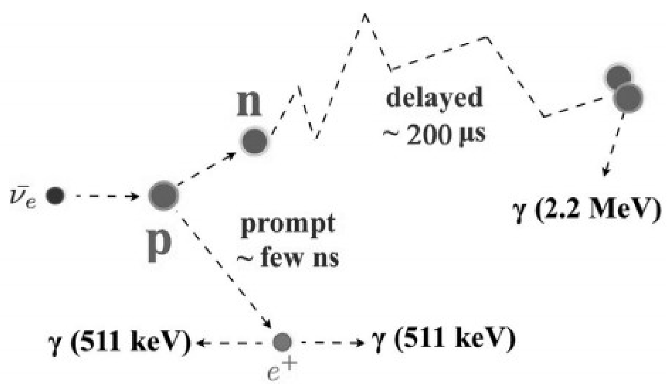
	Target Mass	Coverage	Energy resolution	Light yield [PE/MeV]
Daya Bay	20 ton (x8)	12%	8% @ 1 MeV	160
Borexino	300 ton	34%	5% @ 1 MeV	500
KamLAND	1 kton	34%	6% @ 1 MeV	250
JUNO*	20 kton	78%	3% @ 1 MeV	>1300

Reactor neutrino detection



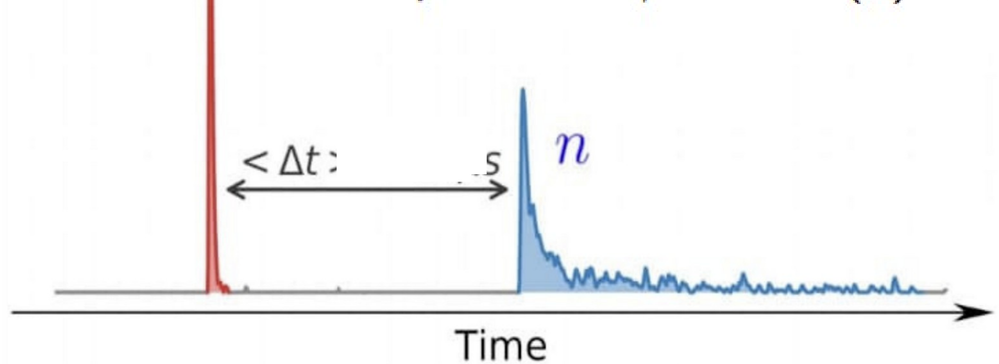
Reactor anti-neutrinos are observed by Inverse Beta Decay (IBD):
(1) – Energy deposited by positron (carries neutrino energy)
– Positron annihilation into two gammas (511 keV)
(2) Neutron capture scintillation emission

- Very clear signal: prompt + delay coincidence



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

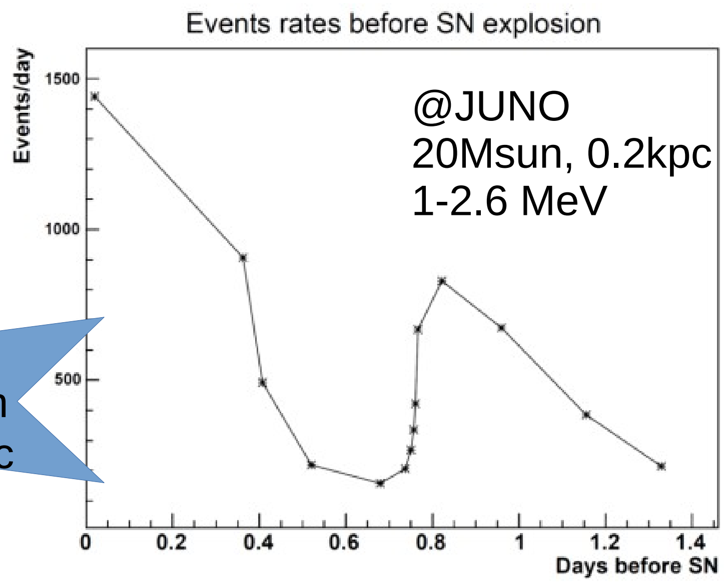
$$n + p \to d + \gamma \qquad (2)$$

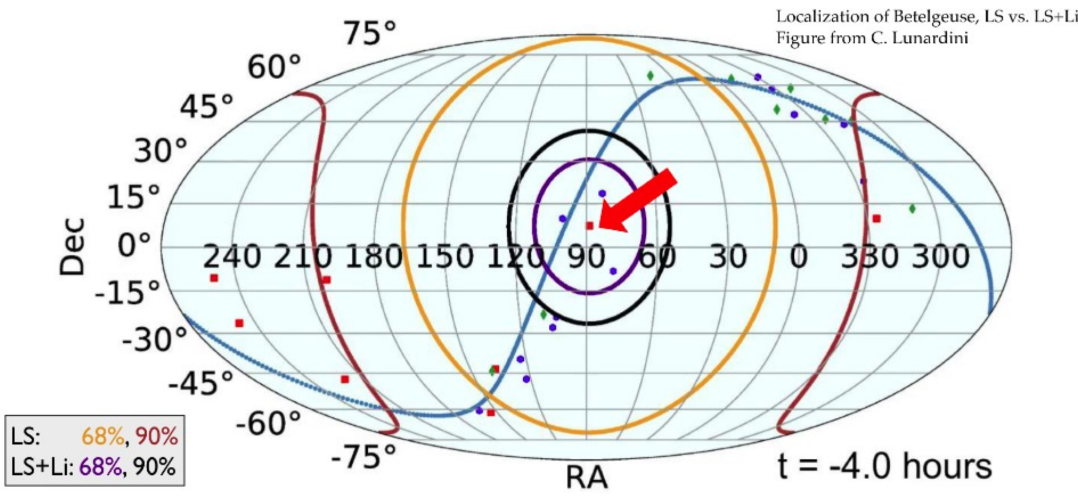


Pre-supernova neutrinos

- 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

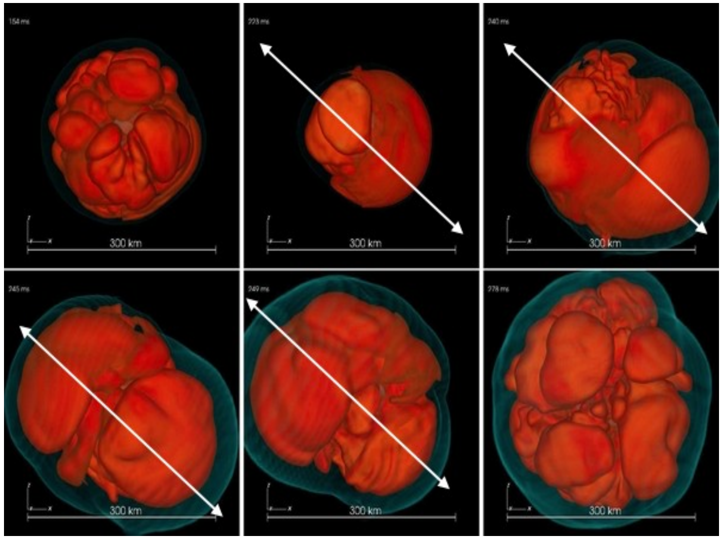




CCSN neutrino lightcurve

Example of interesting lightcurve feature to study: SASI oscillations

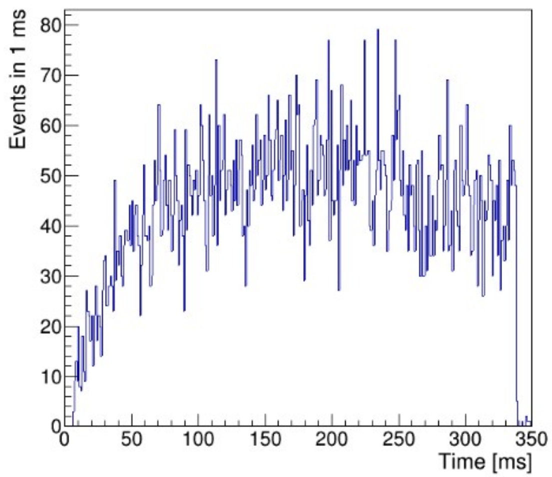
- SASI = standing accretion shock instability: predicted by 3D CCSN simulations
- Why is it interesting:
  - It appears in failed explosions
  - It can explain neutron star kicks observed
  - It would be accompanied by GW emission

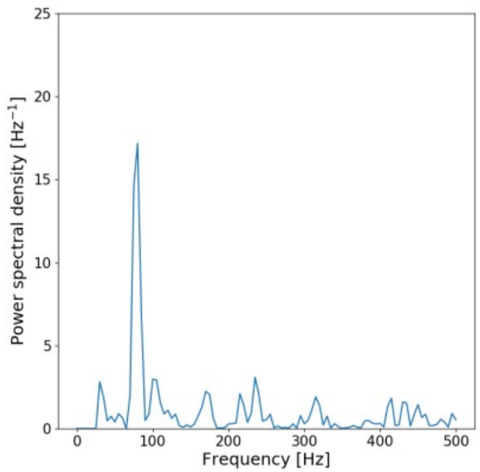


- **Observable:** fast-time variations of the detected rates, with a characteristic oscillation frequency (~80Hz) → Spectral analysis of the neutrino data

CCSN neutrino lightcurve

Example of interesting lightcurve feature to study: SASI oscillations

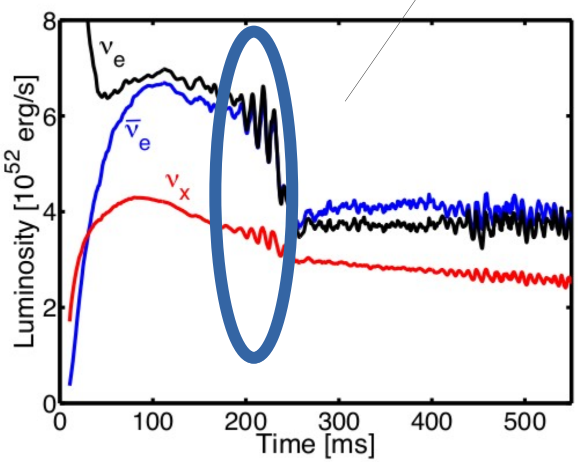




20 Msun, Tambora 2014

(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)

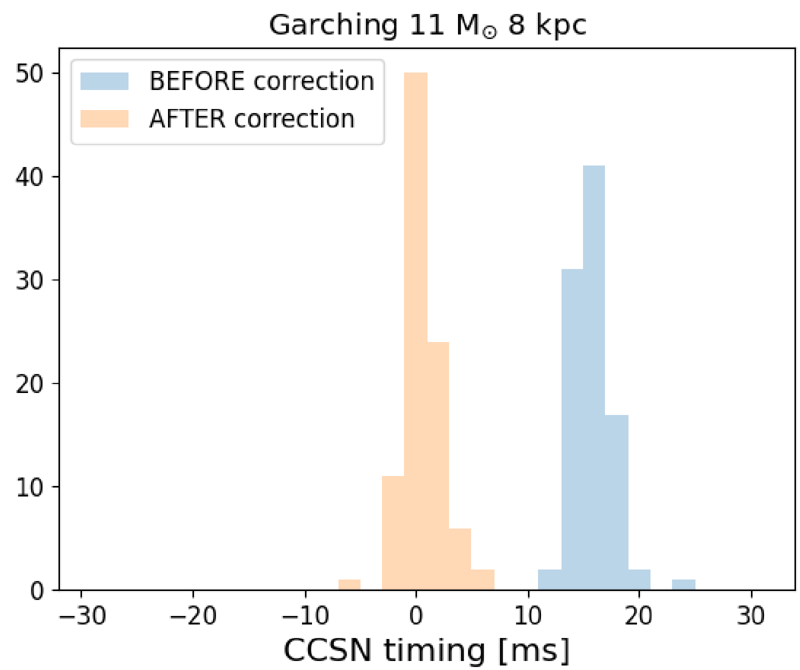
Multi-messenger astronomy

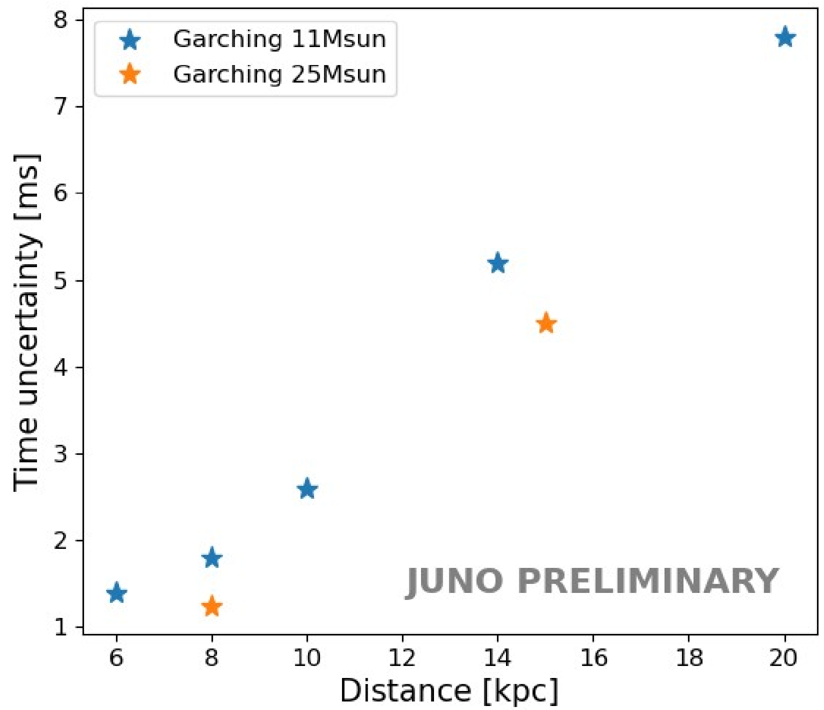
Timing the neutrino signal arrival

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

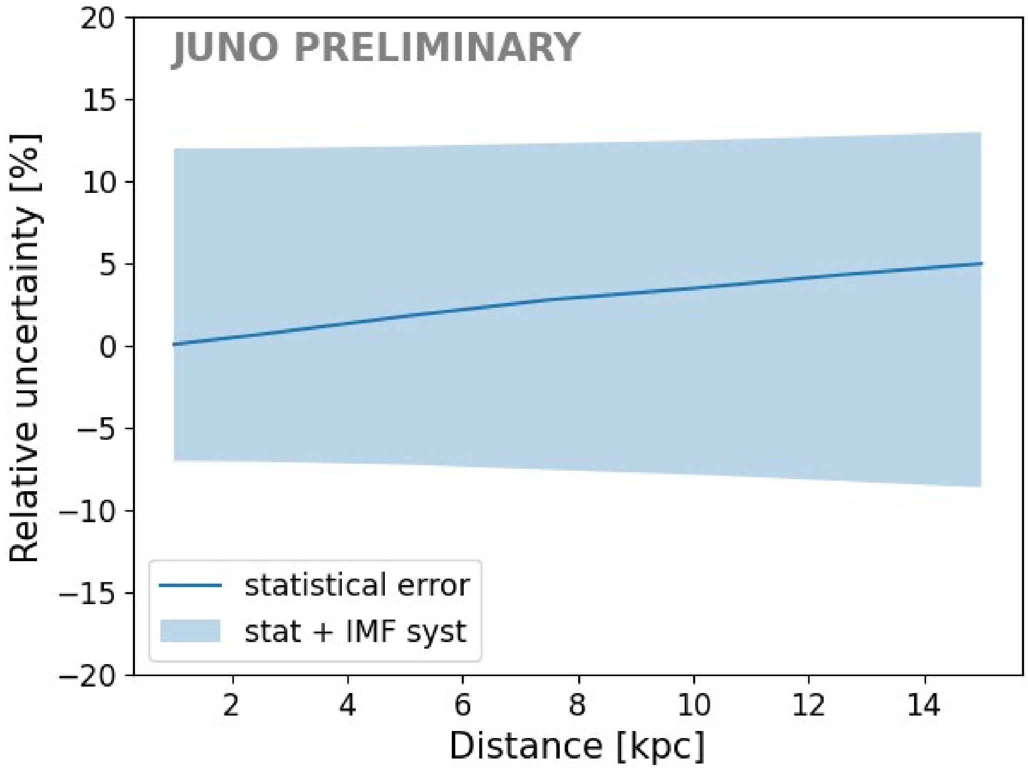


Figure: Statistical uncertainties (solid line). The blue bands include the model systematics (IMF) uncertainty on top (more syst. ongoing).