Neutrinos in JUNO @IIHE

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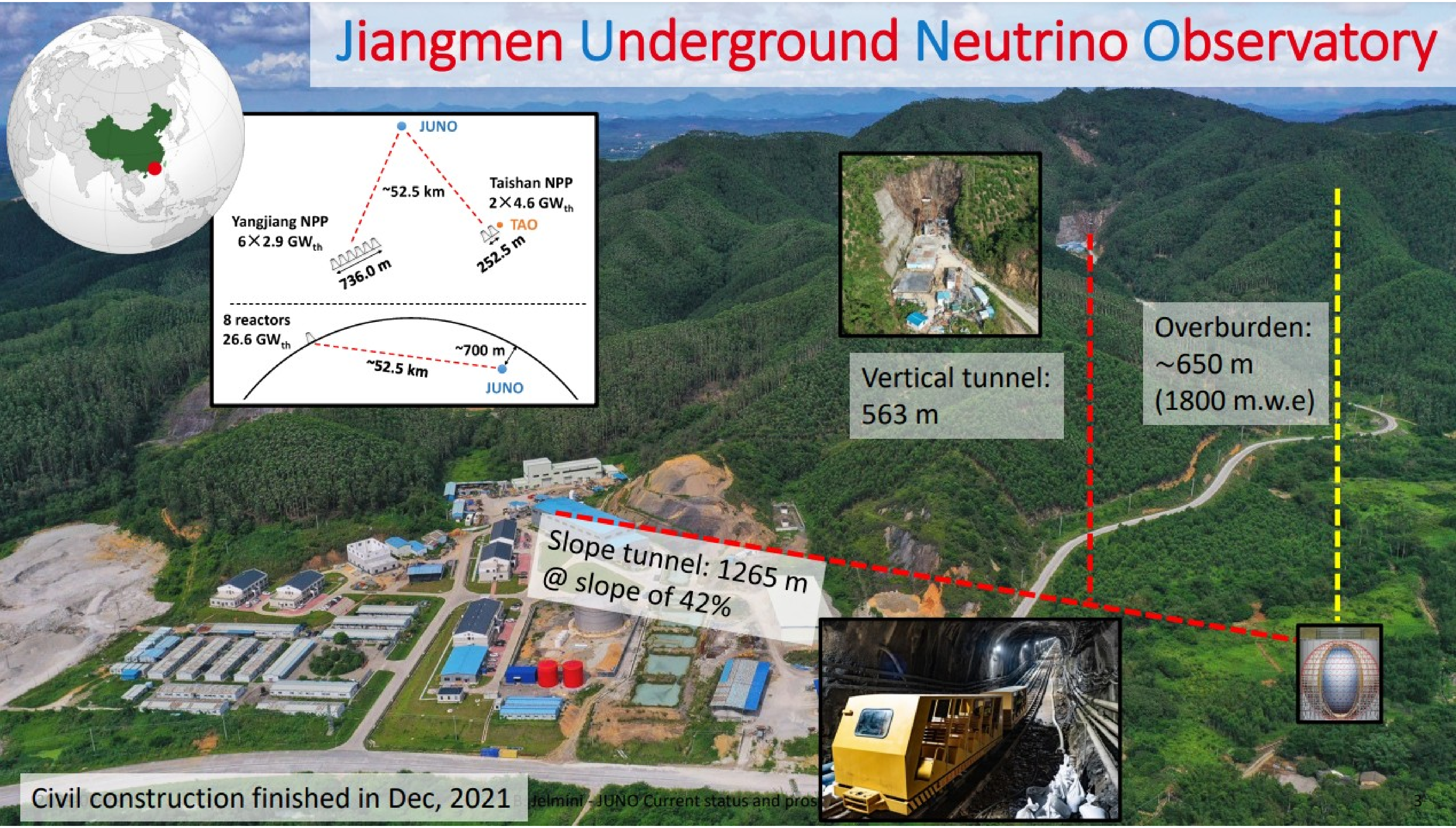
Belgium neutrino meeting – March 2024 - UCL

The JUNO detector



Jiangmen Underground Neutrino Observatory

Vertical tunnel: 563 m

Overburden: ~650 m (1800 m.w.e)

Slope tunnel: 1265 m @ slope of 42%

Civil construction finished in Dec, 2021

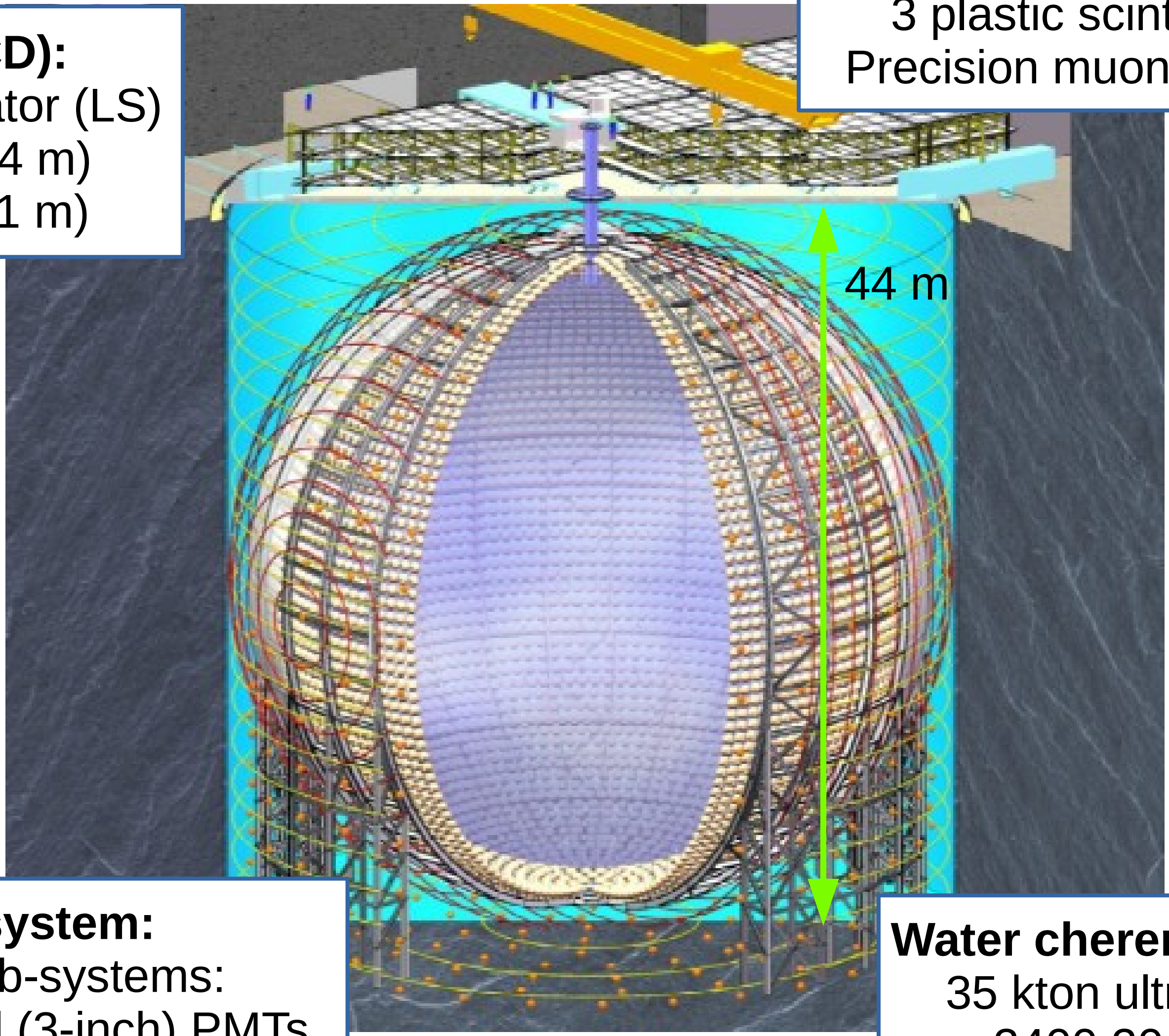
B. Jelmini - JUNO Current status and pros

3

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)



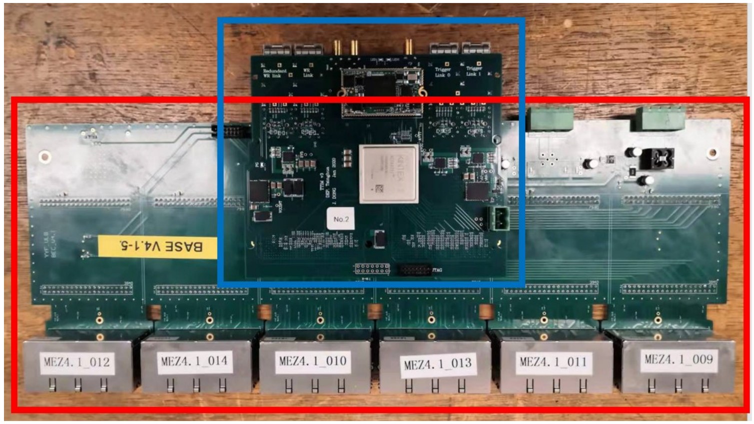
Light detection system:
>40000 PMTs in 2 sub-systems:
large (20-inch) and small (3-inch) PMTs

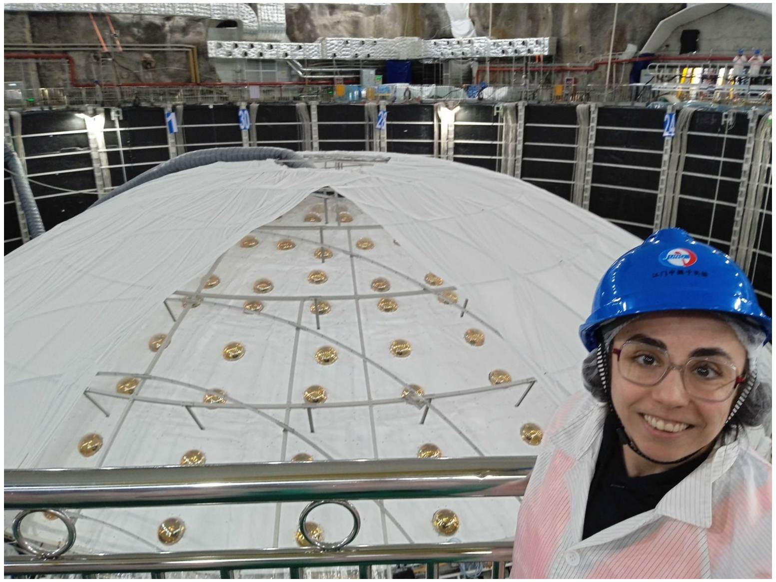
Water cherenkov detector:
35 kton ultra-pure water
2400 20-inch PMTs

Status of JUNO – focus on back-end electronics

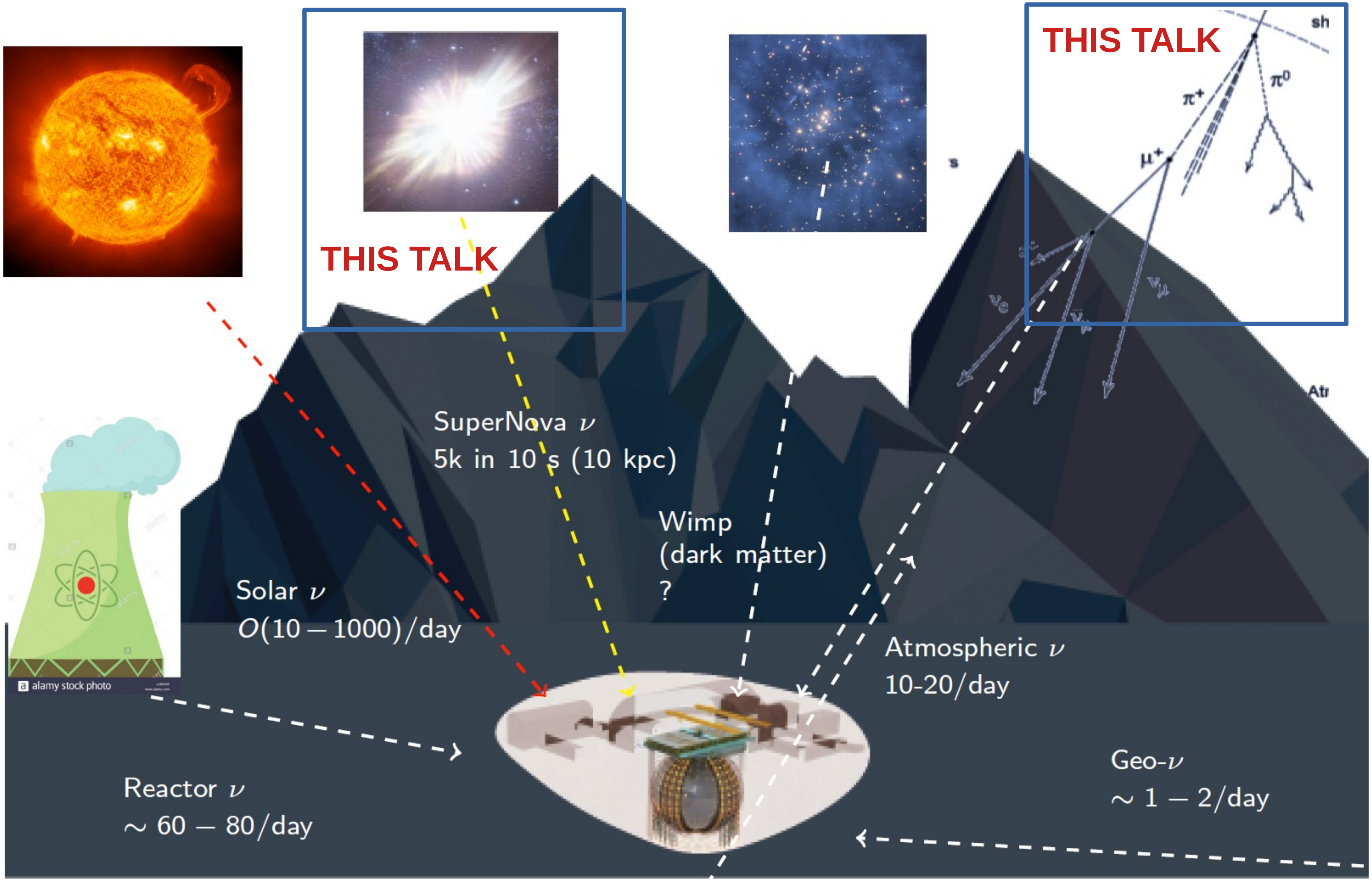
- JUNO electronics in two sub-systems:
  → underwater and outside water
- IIHE JUNO group responsible of the production, design and test of the BEC
  → BEC= back-end electronics cards
- BEC status: all outside water electronics in place → under commissioning

- Upper hemisphere completed: acrylic sphere + underwater electronics installed
- First LS batch has been filled into OSIRIS (small JUNO) this week for requirements qualifications → LS characterisation soon
- Lower hemisphere completed + water filling before the end of the year
- First commissioning and physics data in 2025





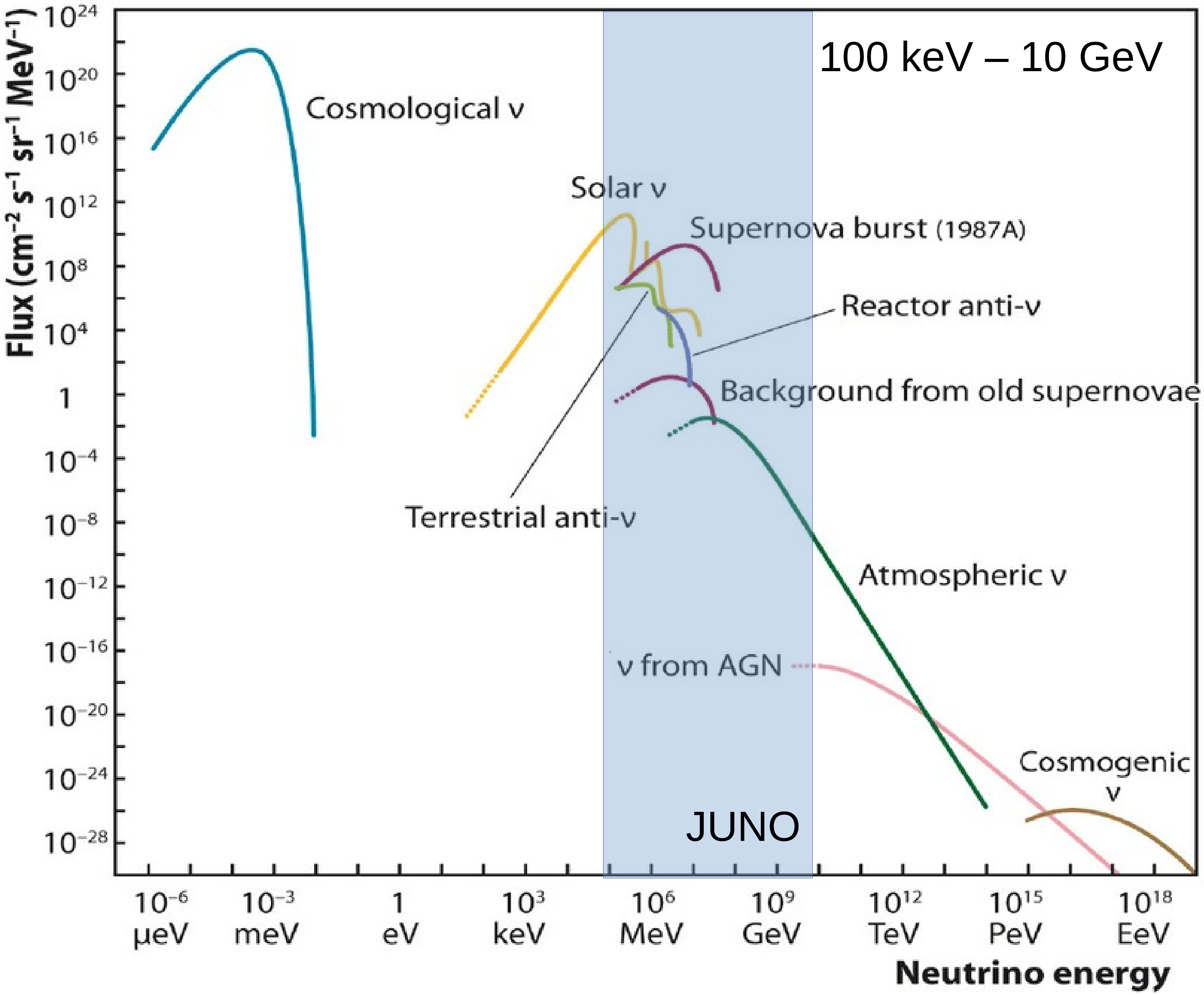
JUNO physics program



THIS TALK

THIS TALK

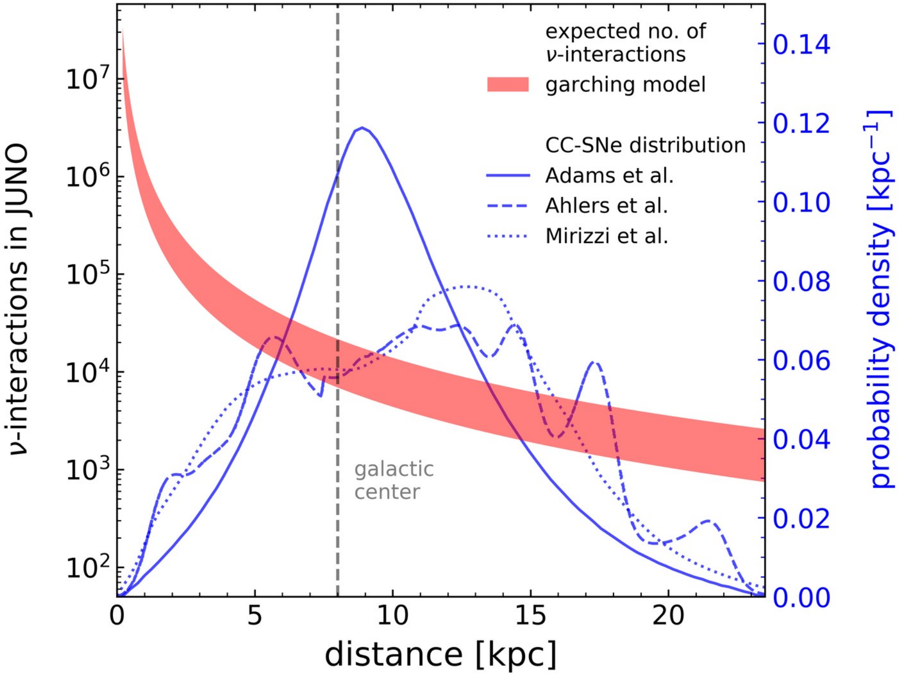
Where does JUNO stand?



Core-collapse supernova neutrinos in JUNO (<100 MeV)

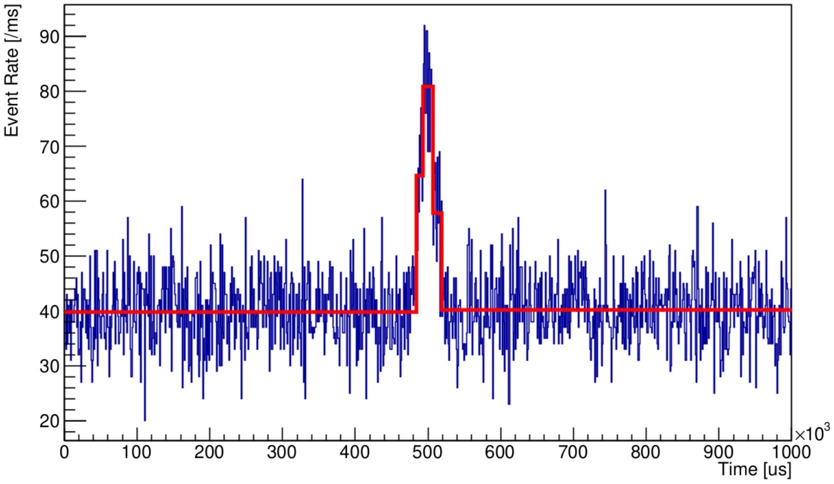
If there is a Galactic CCSN, JUNO has:

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



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

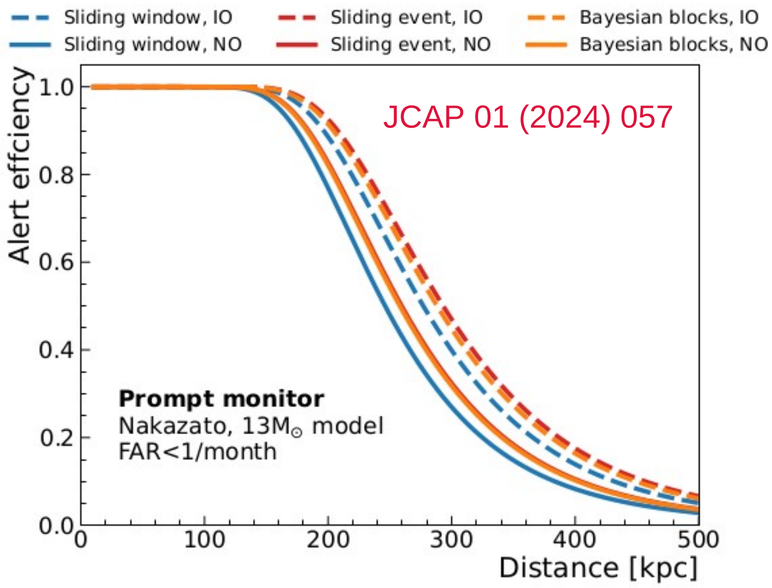


If transient astrophysical signal triggered:
→ All (triggerless) data are stored to obtain the most physics reach in offline analysis

- Prompt 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



JCAP 01 (2024) 057

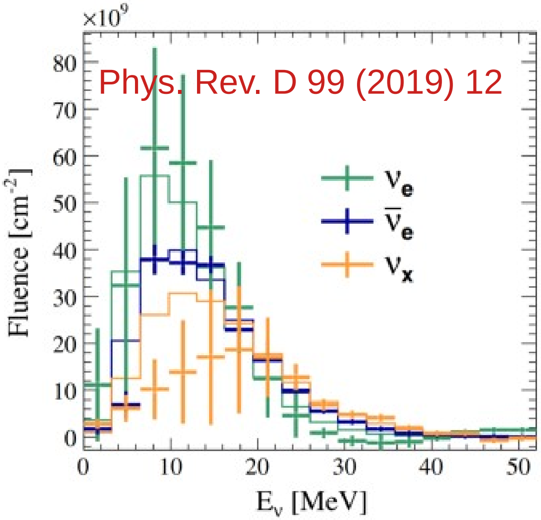
Core-collapse supernova neutrinos physics in JUNO

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

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

Constrain CCSN physics
- and the models

Flavor dependent energy spectrum



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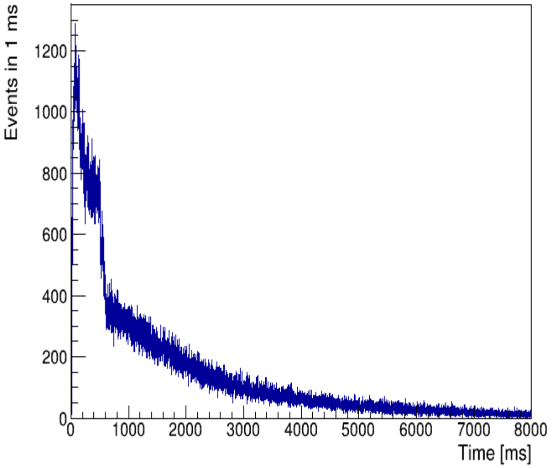
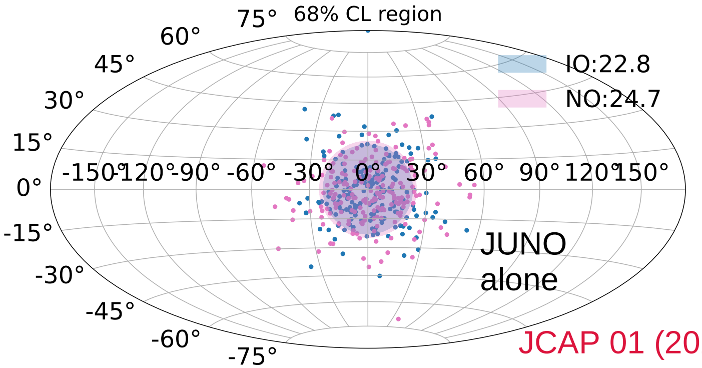
Lightcurve:



Direction:



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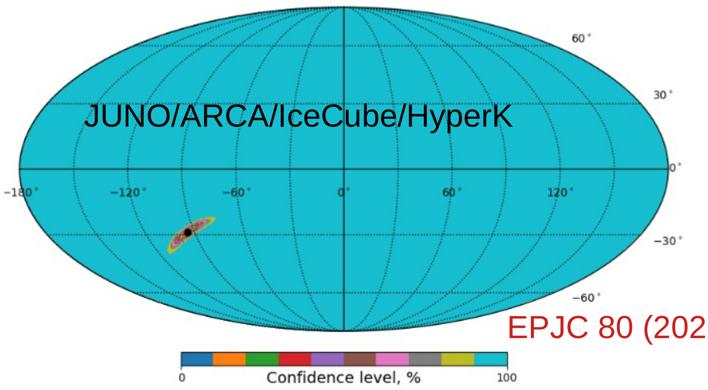

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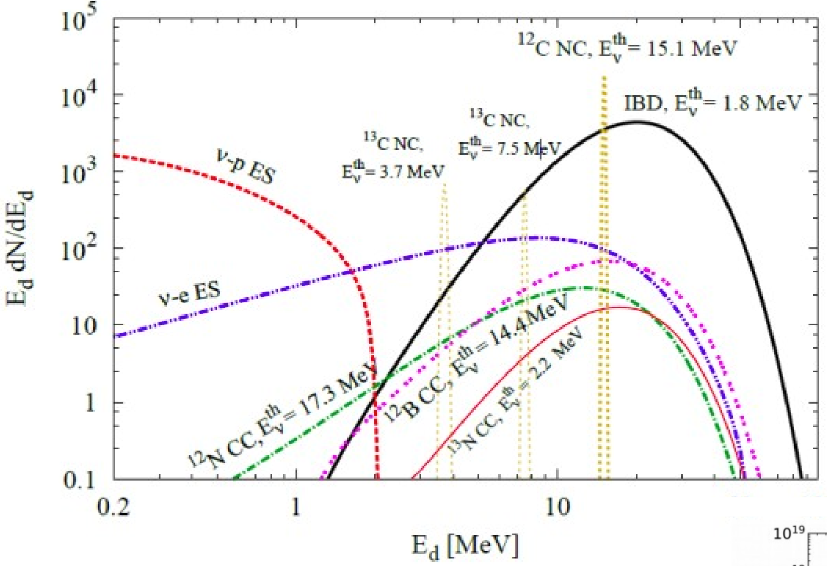
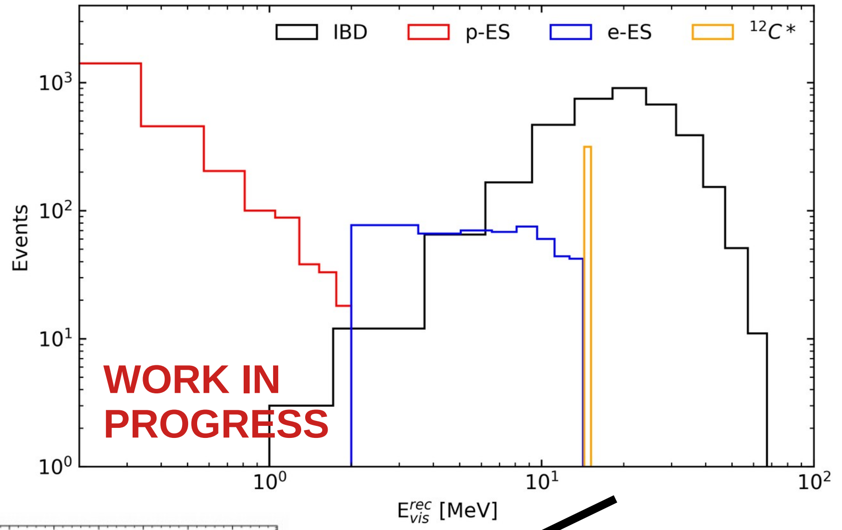
CCSN neutrino spectrum

Identification of the different interaction channels – flavor dependent physics:

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

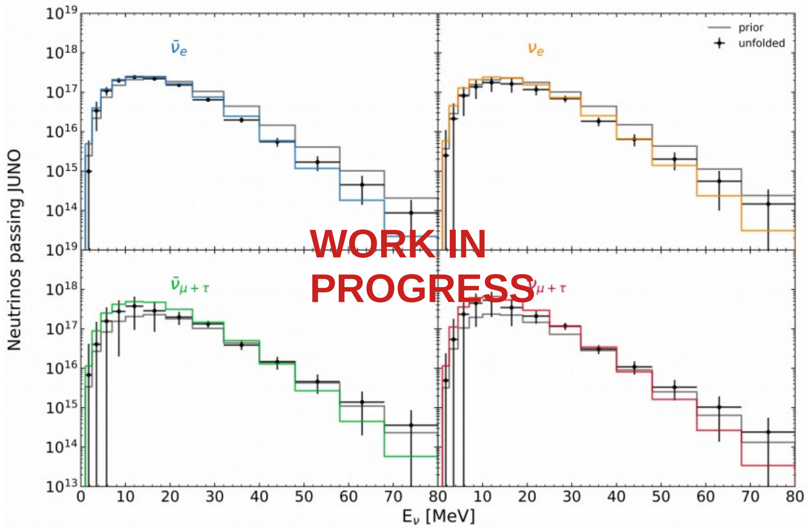


UNFOLDING RESULTS:

detected rates per channel

↓

emitted flux per ν favor



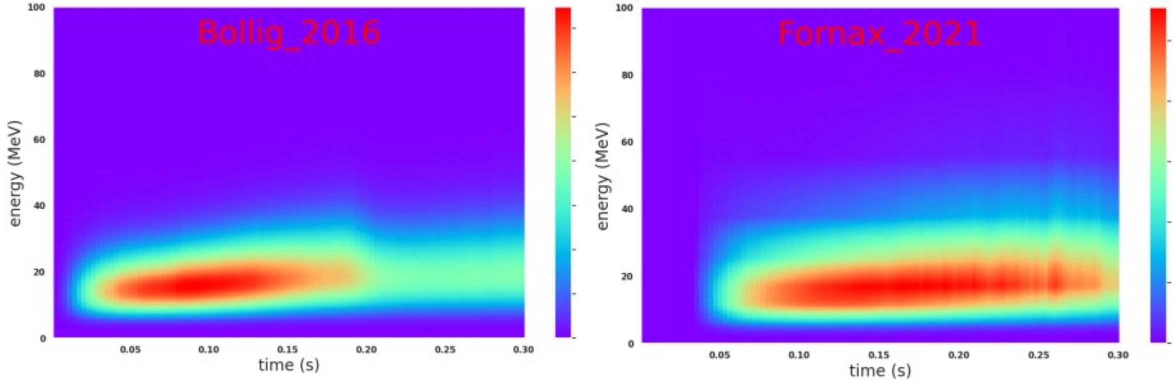
Flavor dependent energy spectrum UNFOLDED

Discriminating CCSN models

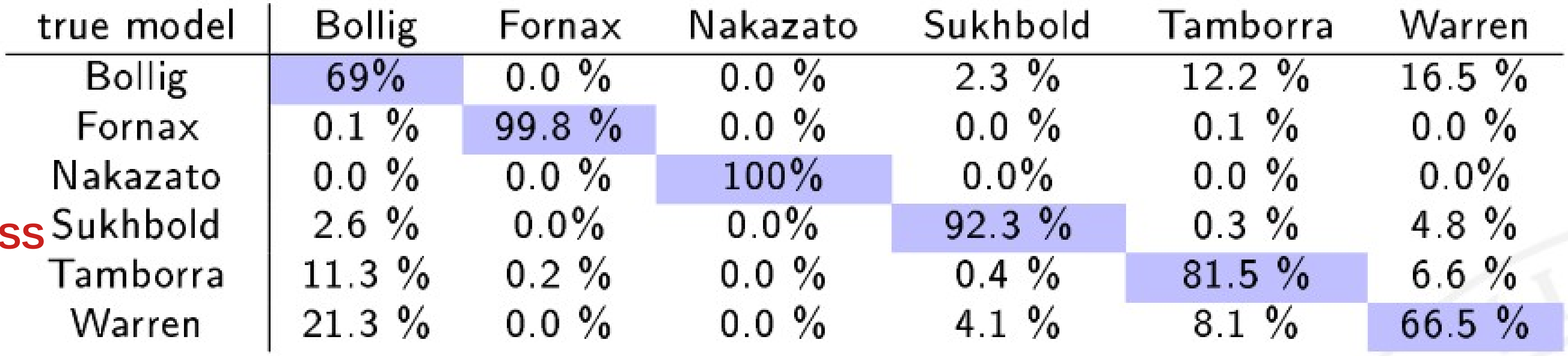
- Why?
  - Only 24 neutrino events from 1987A
    + only 1-2 CCSN per century in our Galaxy
  - Hundreds of models in the market
  - Understanding of physics in the core and unveil progenitor properties

- How to do it?
  - Large signal statistics in the detector
  - Time and energy model dependency: good time and energy resolution
  - Poisson likelihood approach

- **Results:**
  - JUNO will identify the true CCSN model in over ~67% of the cases for CCSN @40 kpc (only IBD) (no detector effects included yet)



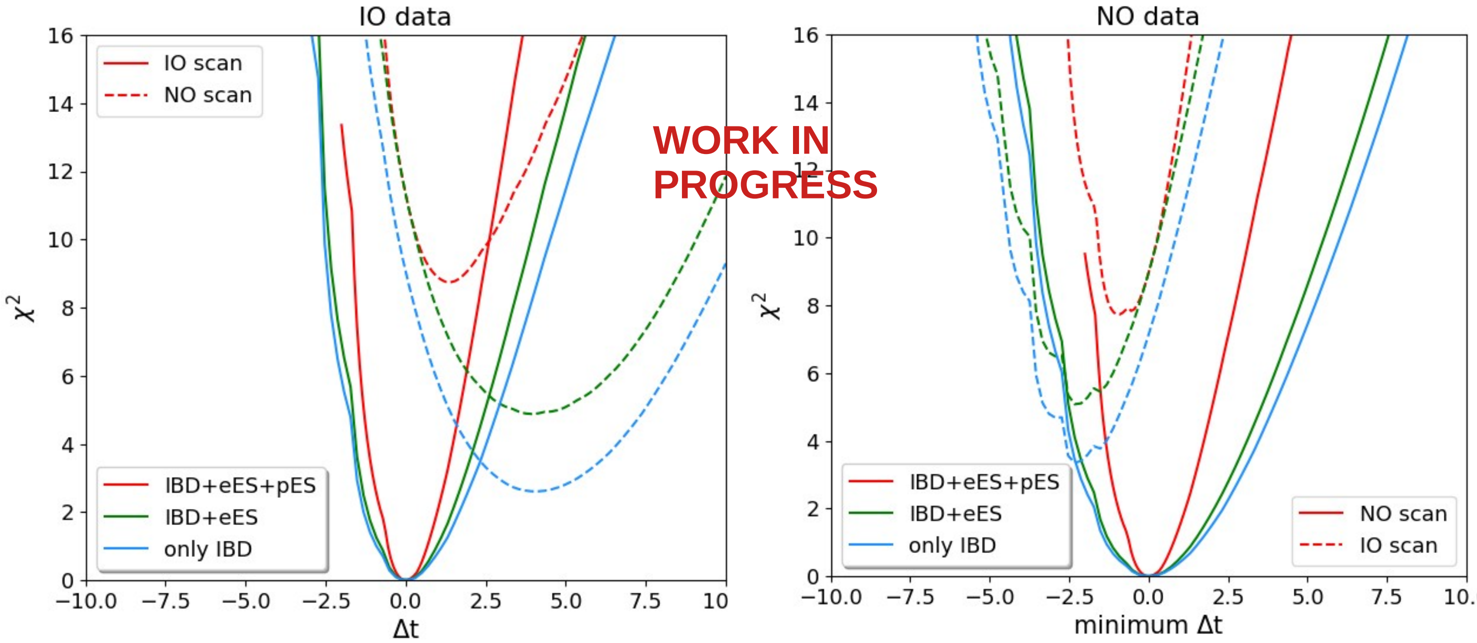
WORK IN PROGRESS



true model	Bollig	Fornax	Nakazato	Sukhbold	Tamborra	Warren
Bollig	69%	0.0 %	0.0 %	2.3 %	12.2 %	16.5 %
Fornax	0.1 %	99.8 %	0.0 %	0.0 %	0.1 %	0.0 %
Nakazato	0.0 %	0.0 %	100%	0.0%	0.0 %	0.0%
Sukhbold	2.6 %	0.0%	0.0%	92.3 %	0.3 %	4.8 %
Tamborra	11.3 %	0.2 %	0.0 %	0.4 %	81.5 %	6.6 %
Warren	21.3 %	0.0 %	0.0 %	4.1 %	8.1 %	66.5 %

Neutrino physics with CCSN: neutrino mass ordering

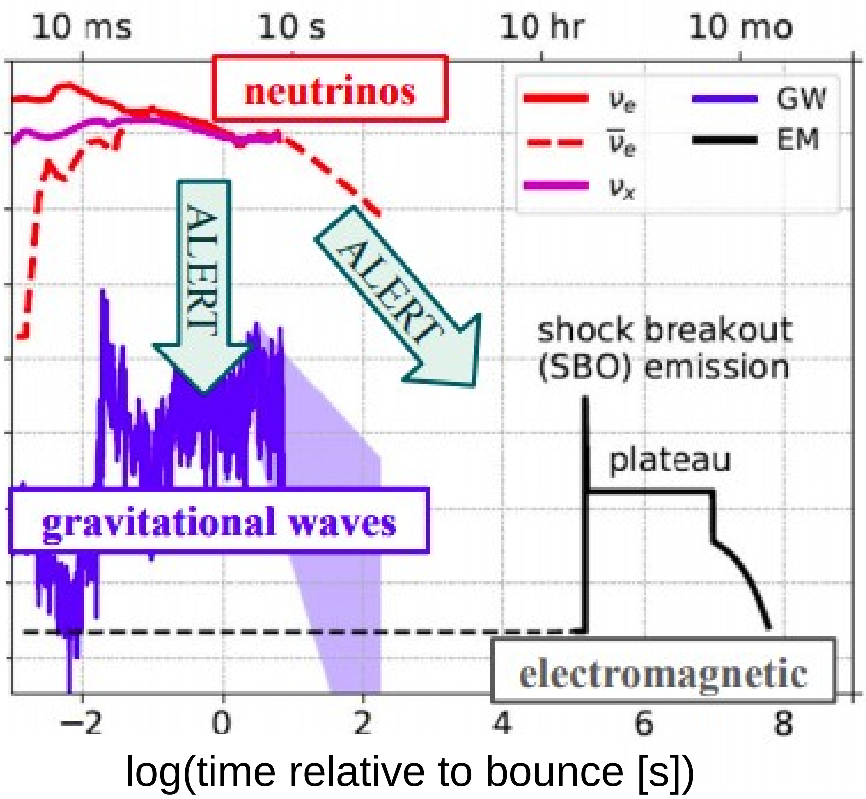
- Different observed neutrino time profile depending on the NMO
- Make it **model independent**: focus in time window [-20ms,+20ms] around core collapse
- Poisson χ2 with free parameter: starting time of the neutrino signal (T0)
- **Key: neutral current (NC) interactions** (insensitive to flavor transformations)
  - → Neutronisation peak unchanged with NMO for NC events → much accurate T0
  - → JUNO will have a large sample of NC events (p-ES interactions, 100keV-2 MeV)
  - → Boost the sensitivity by combining all neutrino interactions

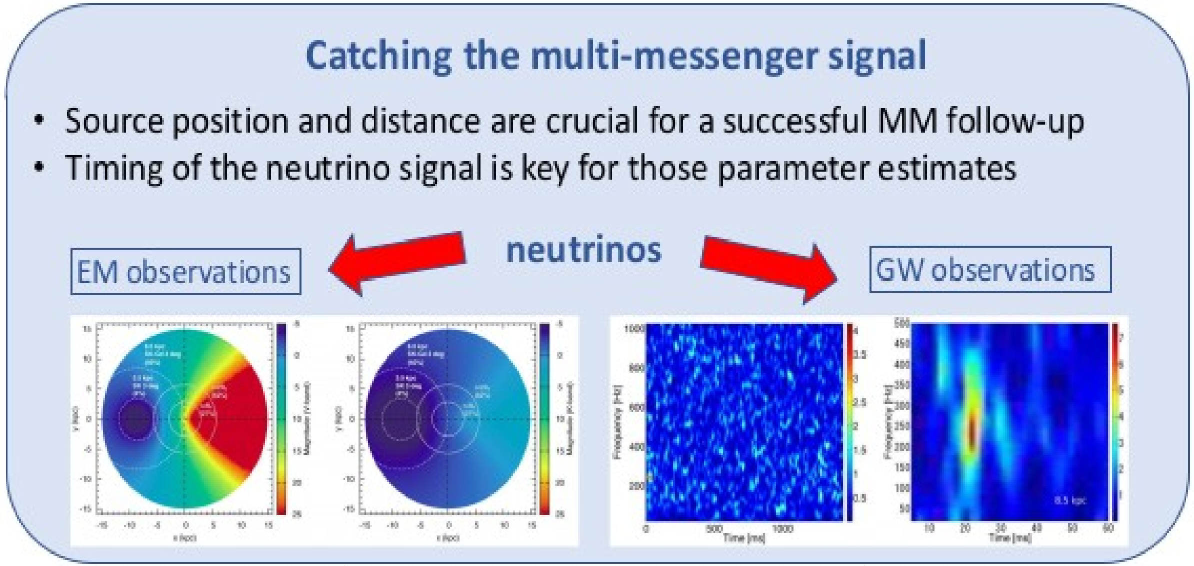


WORK IN PROGRESS

Result:
Expected sensitivity ~2.5-3σ @10 kpc (no detector effects included yet, asimov)

Core-Collapse Supernova multi-messenger signal





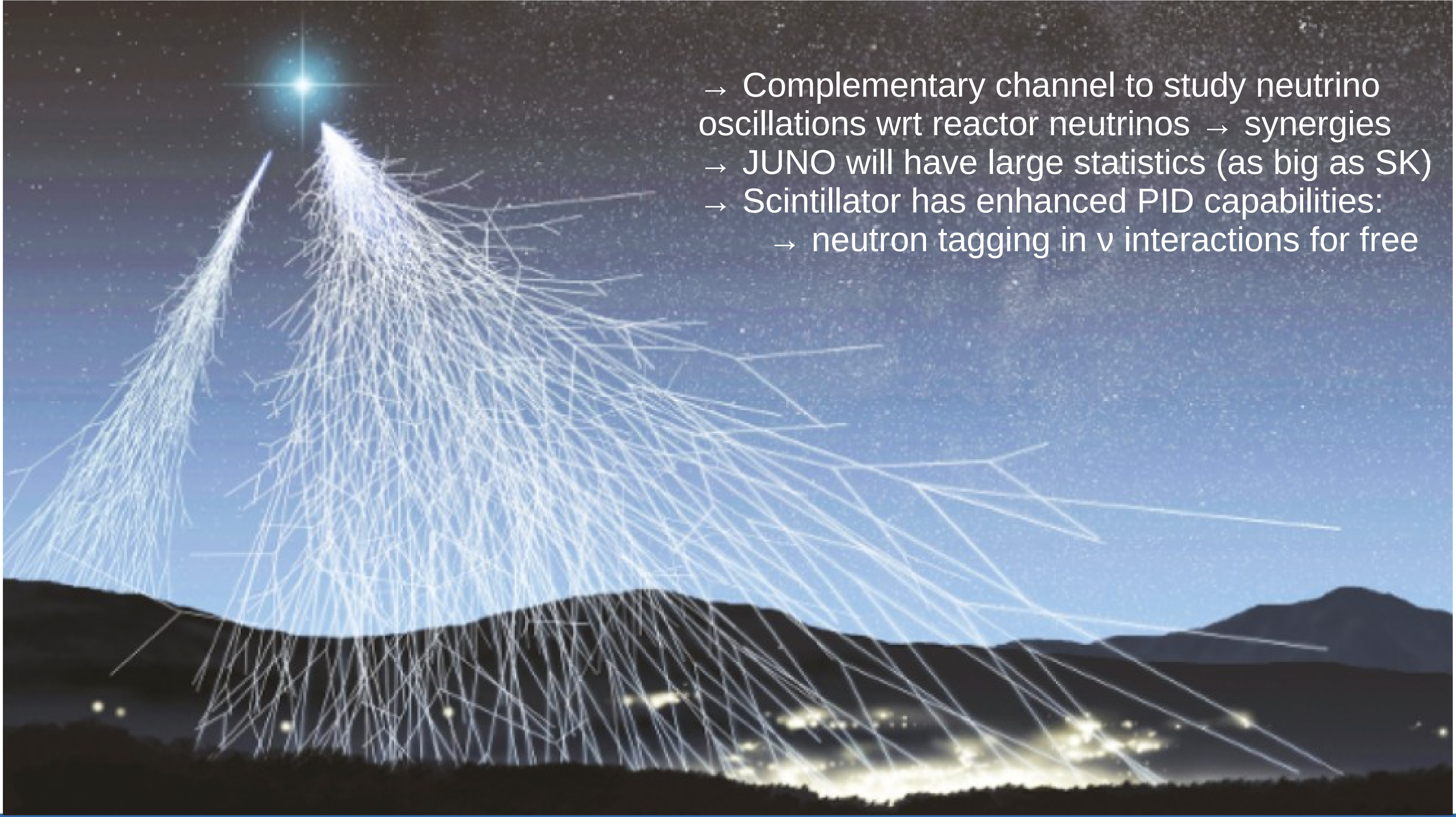
Catching the multi-messenger signal

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

- 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
- Distance uncertainty: <10% for CCSN up to 6kpc
- Source direction uncertainty: ~25deg @10kpc

Atmospheric neutrinos in JUNO (>100 MeV)



→ Complementary channel to study neutrino oscillations wrt reactor neutrinos → synergies

→ JUNO will have large statistics (as big as SK)

→ Scintillator has enhanced PID capabilities:

  → neutron tagging in ν interactions for free

Signal & background: selection

Challenge: ~4 cosmic muons per second (background) VS ~4 atmospheric neutrinos per day

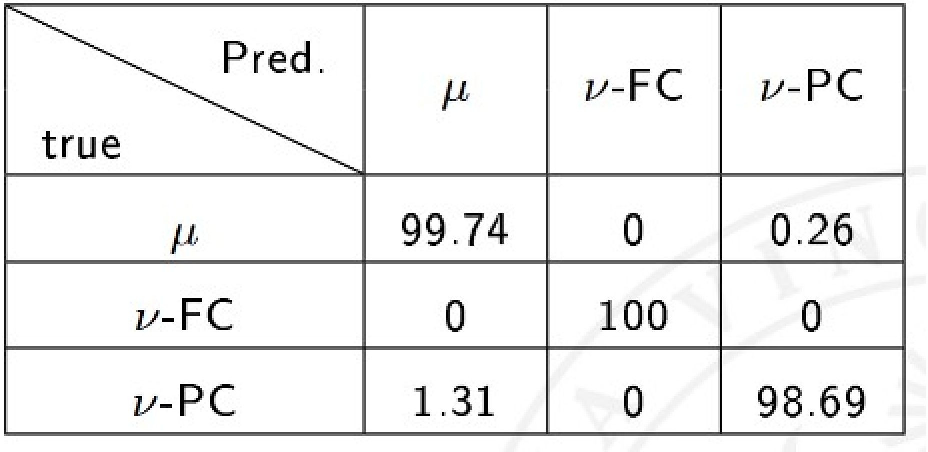
Online event classification:

Energy cut + time difference between CD and WP trigger + TT veto used to remove muons

- Remaining muon contamination O(10-5):
  → S/N ~ 1
- Signal efficiency ~78%

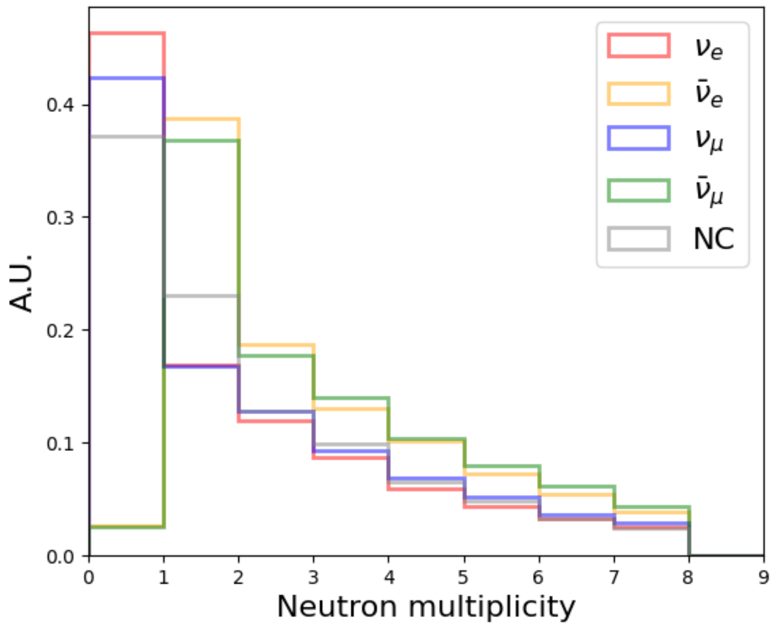
Offline: going further with ML approach

- Events not fully contained in JUNO at large energy → separate fully VS partially contained
- Improve the signal efficiency once the contamination has been reduced online
- Uses PMT waveform features as input



Pred. true	μ	ν-FC	ν-PC
μ	99.74	0	0.26
ν-FC	0	100	0
ν-PC	1.31	0	98.69

Neutron identification: PID

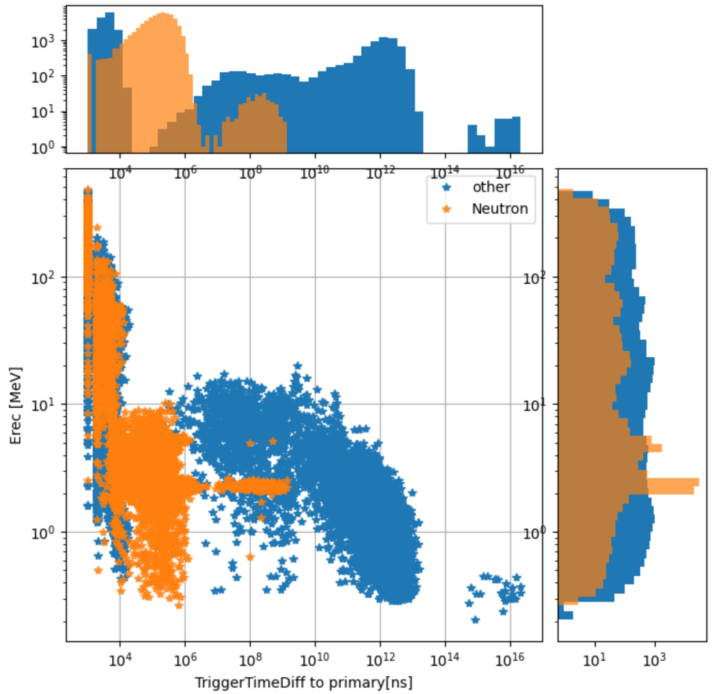


- Matter effects on neutrino oscillations depend on the neutrino flavor, and are swapped between neutrino and anti-neutrino for IO/NO

➔ It is critical to separate neutrino flavors and ν/$\bar{\nu}$

The number of neutrons produced on atmospheric neutrino interactions help for this PID classification

→ Neutrons are localised in time and energy with respect to the other secondary triggers

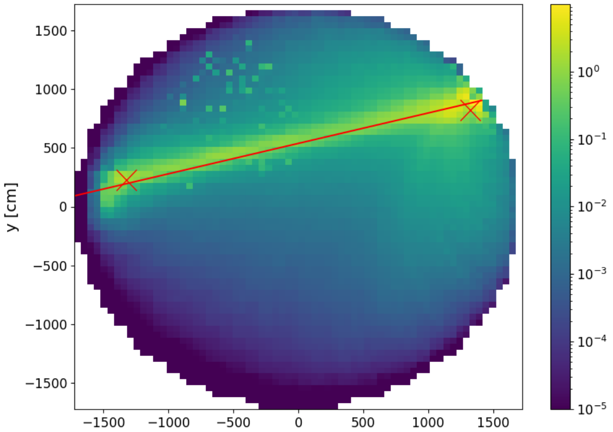


Results:
- Efficiency cuts: 93.1%
- Efficiency machine learning: 99.7%

Event reconstruction

Challenge: many not fully contained events, part of the energy deposited outside the detector

Method: Use PMT detected light pattern to reconstruct the light emission probability



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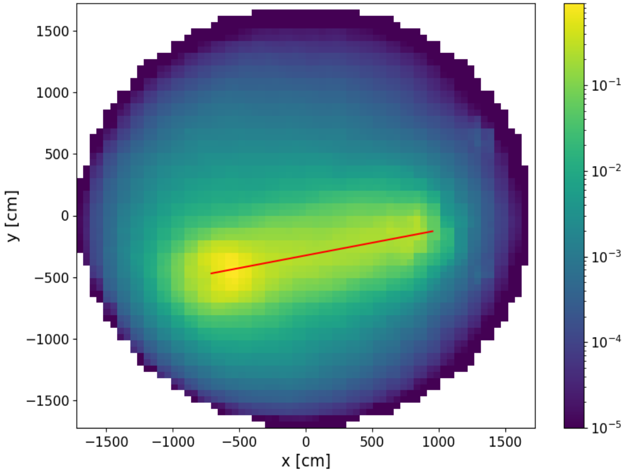
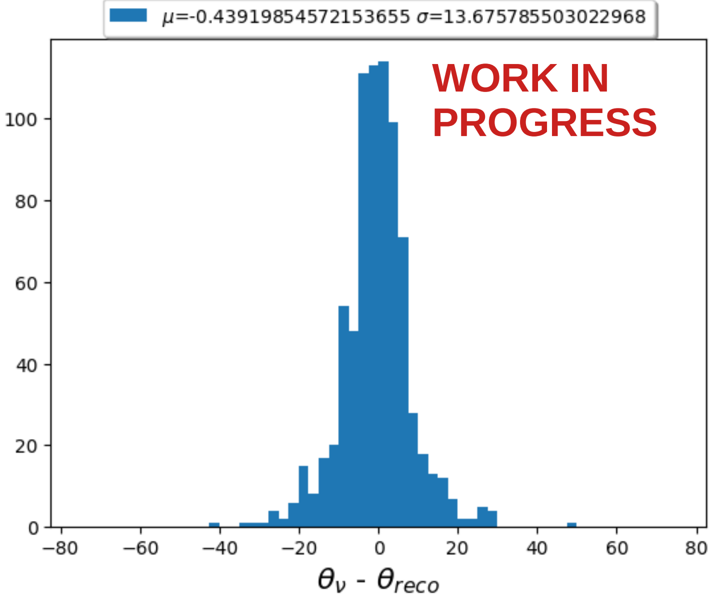


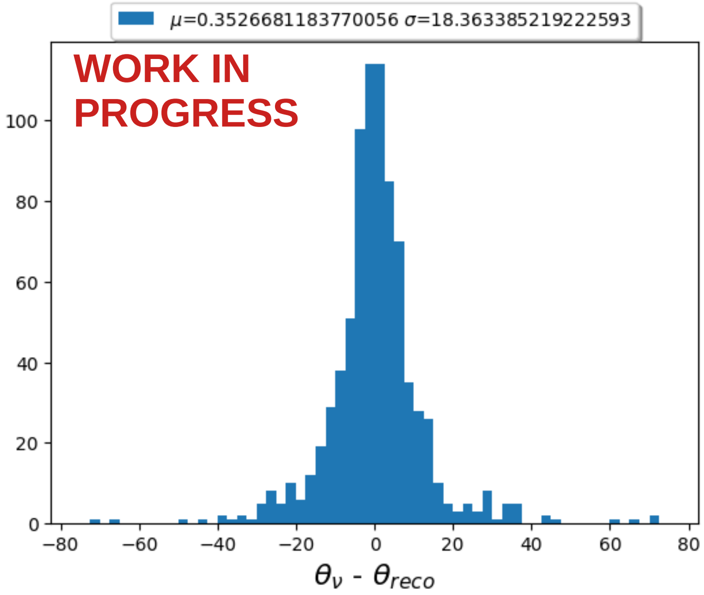
From light emission topology to the particle direction → fit track

→ electronics effects, waveform reco and vertex error included
→ uncertainty within the requirements for oscillation analysis

Error on the $\theta_{\nu\mu}$ ~14 deg



Error on the $\theta_{\nu e}$ ~18 deg



Sensitivity to the NMO with atmospheric neutrinos

Detector response: event reconstruction + PID

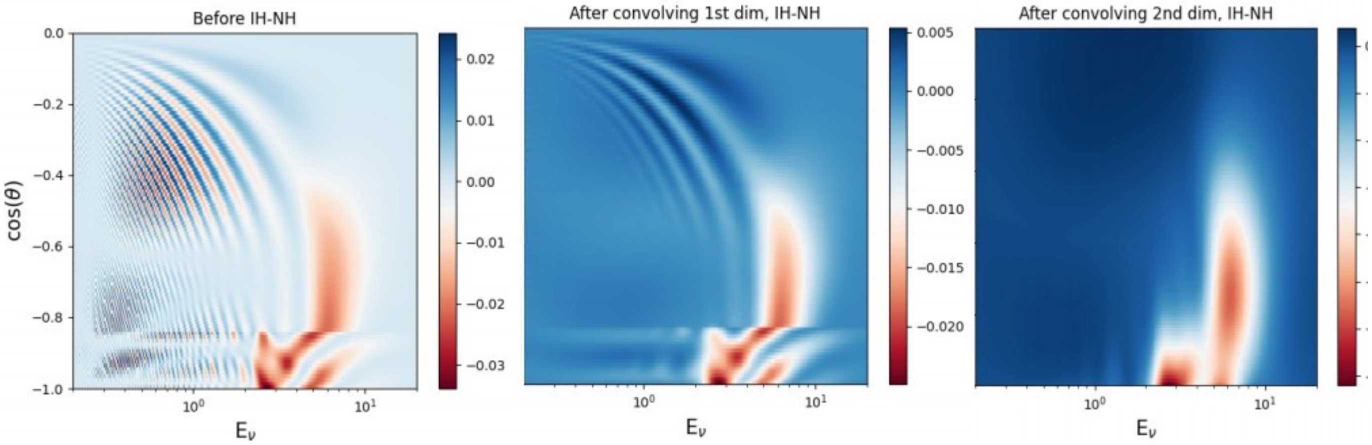
Expected at reconstruction

True expected

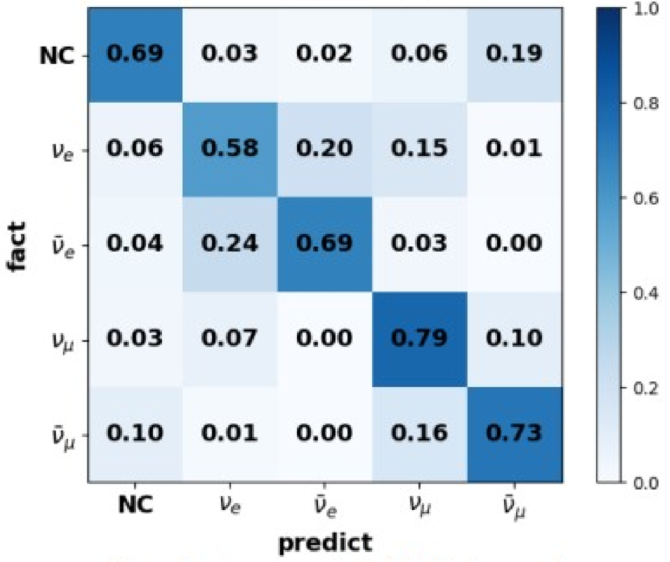
Energy resolution

Angular resolution

$$\mathsf{T}'(E',\theta')_{ij} = \mathsf{T}_{ij} \otimes gauss[(i-i'),\sigma_{E(i)}] \otimes gauss[(j-j'),\sigma_{\theta}(j)]$$



WORK IN PROGRESS

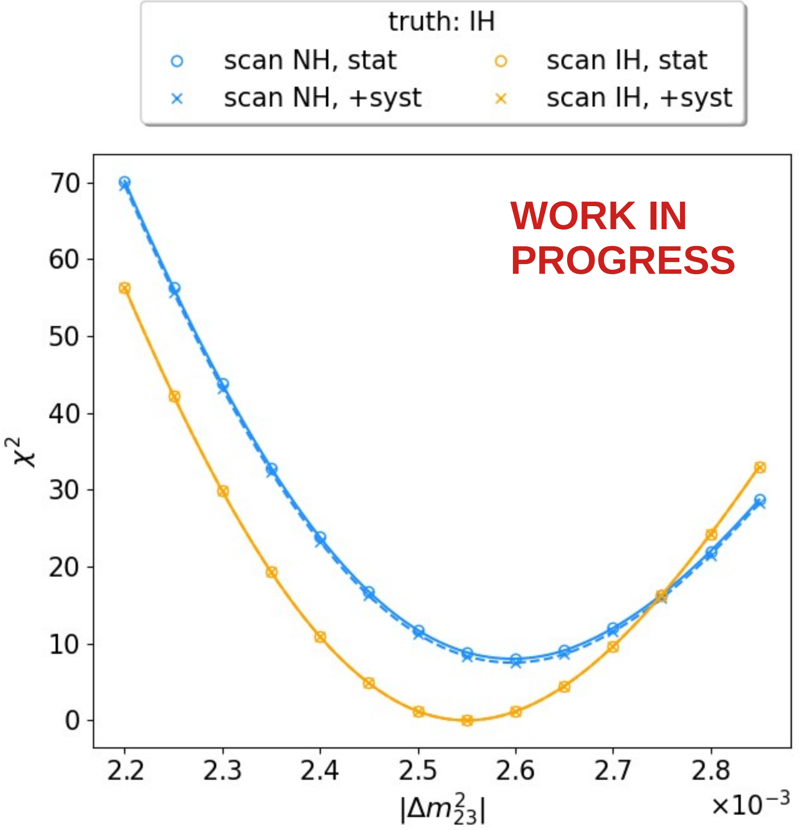


	NC	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$
NC	0.69	0.03	0.02	0.06	0.19
ν_e	0.06	0.58	0.20	0.15	0.01
$\bar{\nu}_e$	0.04	0.24	0.69	0.03	0.00
ν_μ	0.03	0.07	0.00	0.79	0.10
$\bar{\nu}_\mu$	0.10	0.01	0.00	0.16	0.73

Confusion matrix(Efficiency)

Sensitivity to the NMO with atmospheric neutrinos

- Systematics currently implemented: dominated by 20% normalisation error
- Expected sensitivity (Asimov) evaluated for 10 years of data taking:
  - ➔ Δχ2 ~ 7-8 (NO/IO) → biggest impact comes from the PID
- Full MC sensitivity with all final systematics will be coming soon



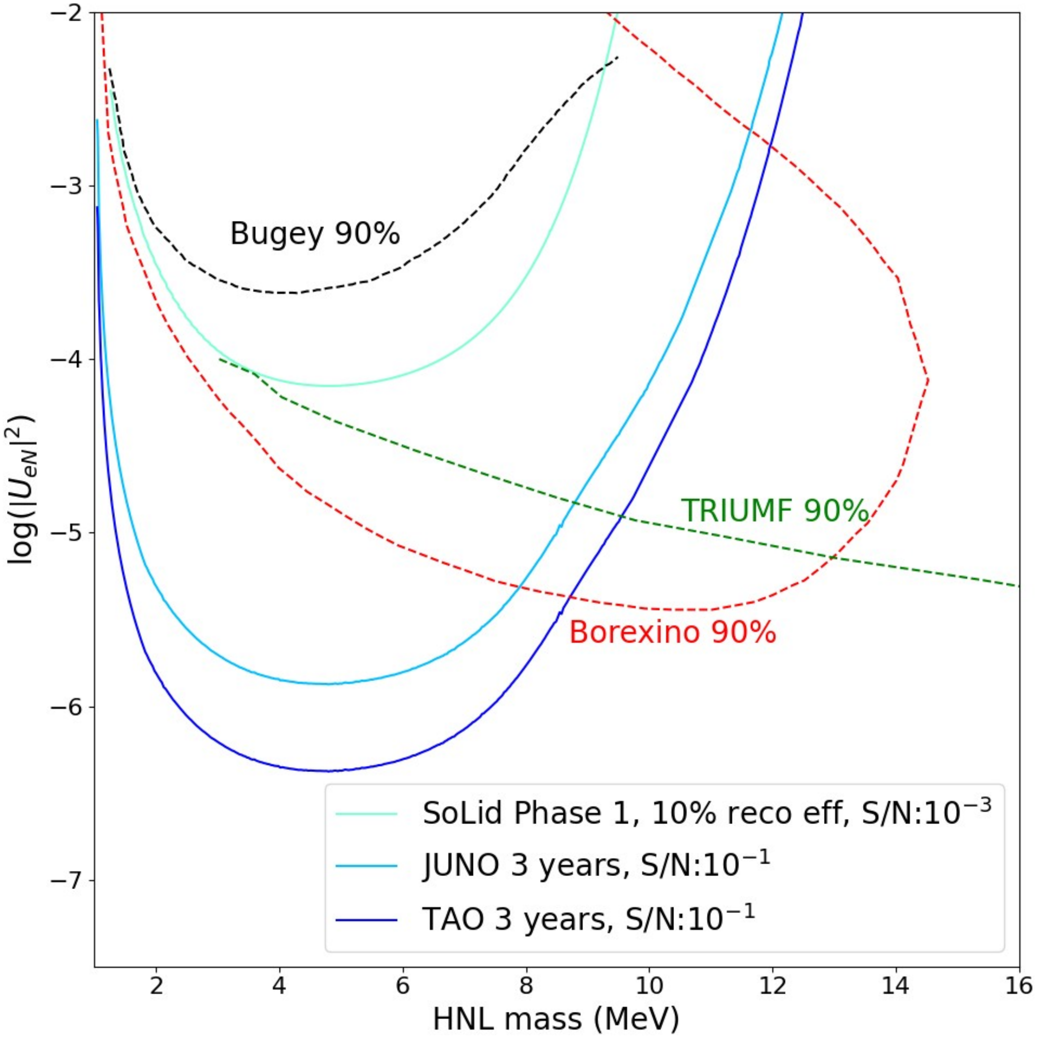
Heavy neutal lepton searches

- HNLs at MeV mass range can shed light into the matter-anti-matter asymmetry in the Universe + origin of neutrino masses

- Reactor neutrino experiments are ideal to search for MeV HNLs in the laboratory:
  → HNLs produced in the reactor beta decays via HNL-νe mixing

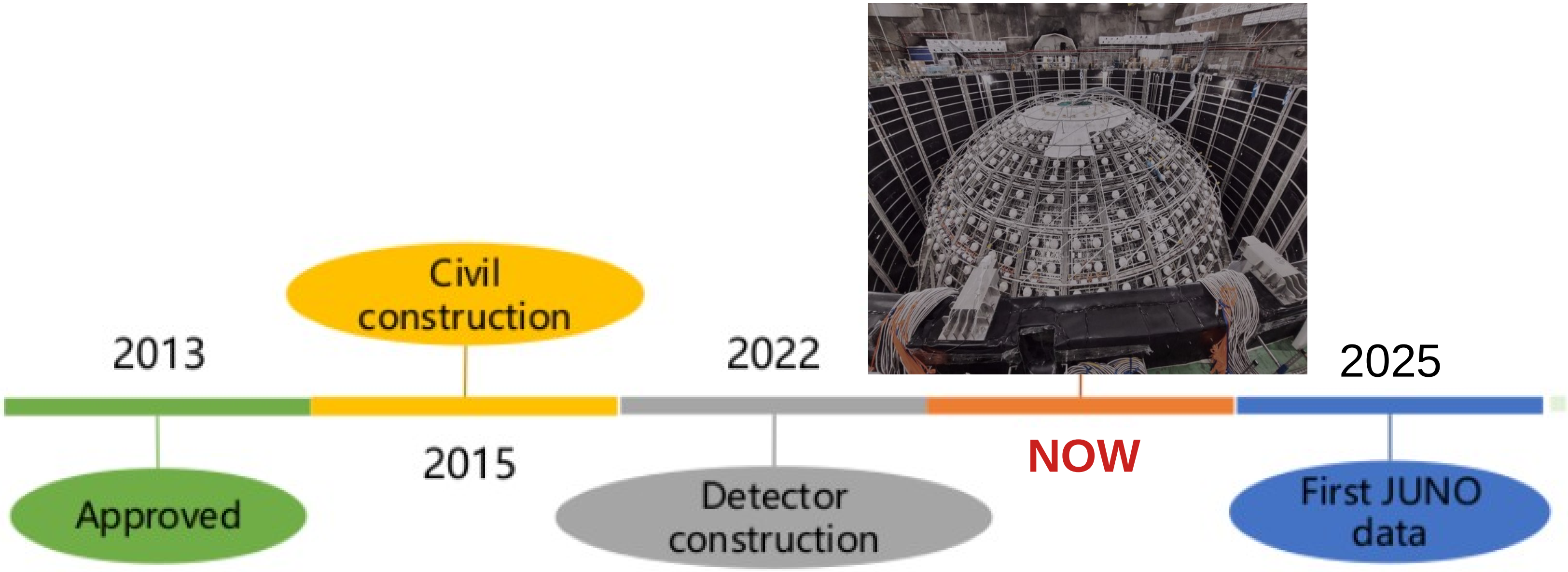
- Collaboration between ULB, VUB, UAntwerp and UCL:
  → Pheno paper with sensitivity estimates for SoLid + JUNO + TAO arXiv:2403.04662

- Reactor experiments can explore a complementary parameter space to peak beam searches and solar neutrinos, providing best current limits

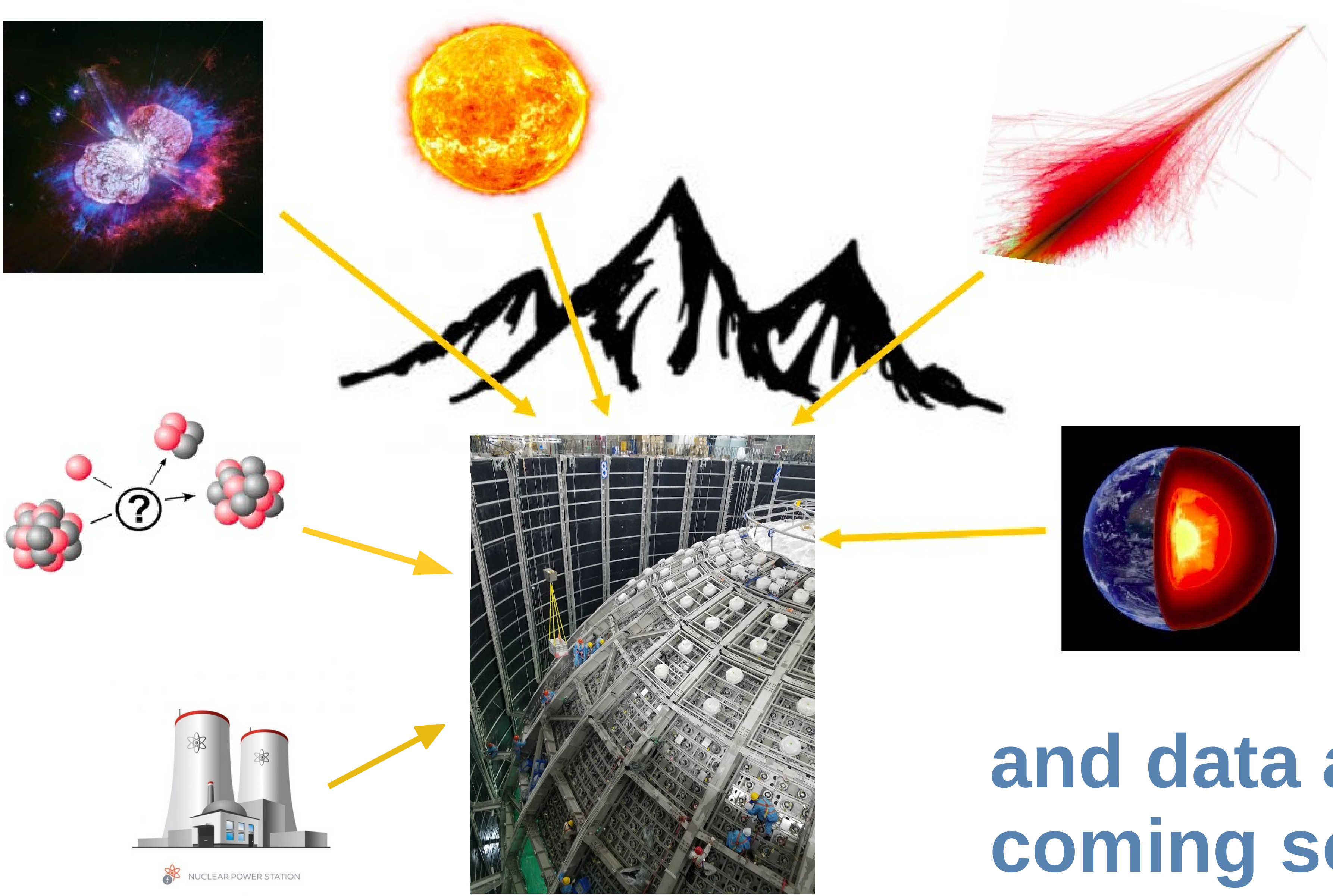


Conclusions

- JUNO (the biggest liquid scintillator detector built) is at half its construction
  - Electronics installed and under commissioning
- JUNO will bring the most precise measurement of most oscillation parameters using reactor neutrinos (main goal)
- JUNO will have good potential as a neutrino telescope for CCSN and MM searches
- JUNO will also be a great atmospheric neutrino experiment → synergies with reactor
- JUNO will start to be filled at the end of 2024, and first data will come next year



JUNO – A NEUTRINO EXPERIMENT WITH AN INCREDIBLE PHYSICS POTENTIAL



and data are coming soon...

BACK-UP

The JUNO detector

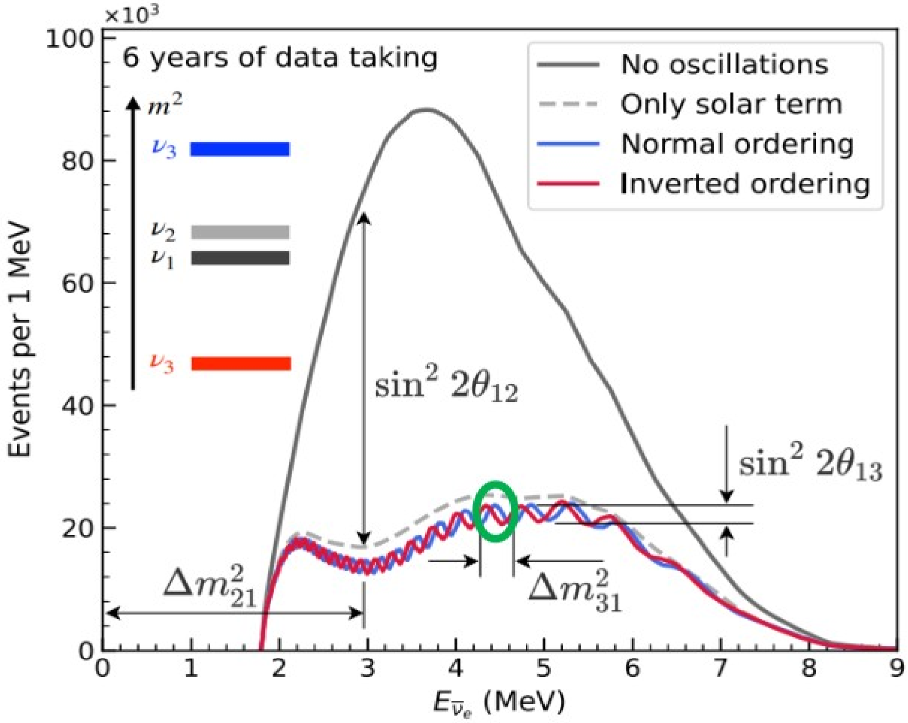
Primary goals:
- precise measurement of oscillation parameters
- determination of the neutrino mass ordering

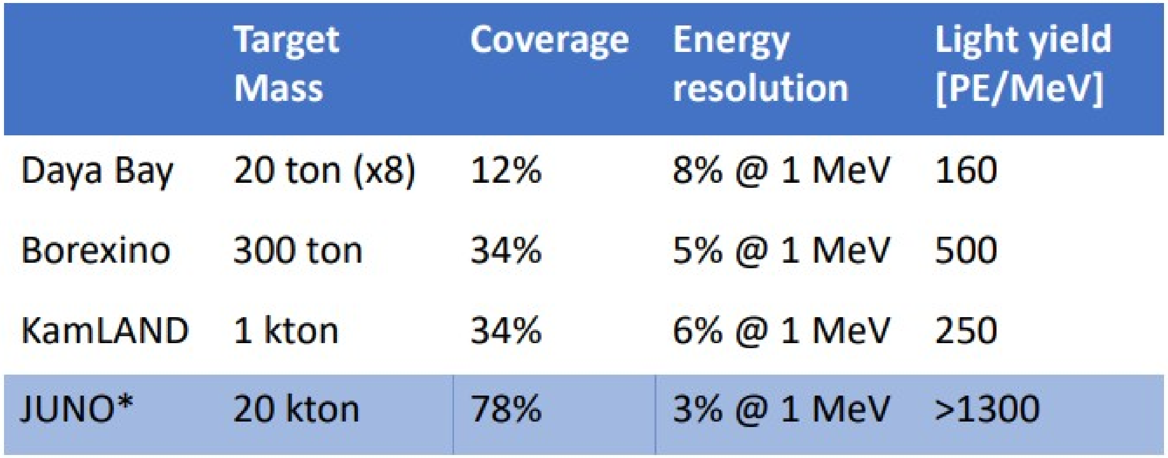
Requirements:
- High statistics (~10^5 events in 6 yr)
- Energy resolution: ~3% @1MeV
- Energy scale uncertainty < 1%

How?

→ Largest and most precise ever built LS detector

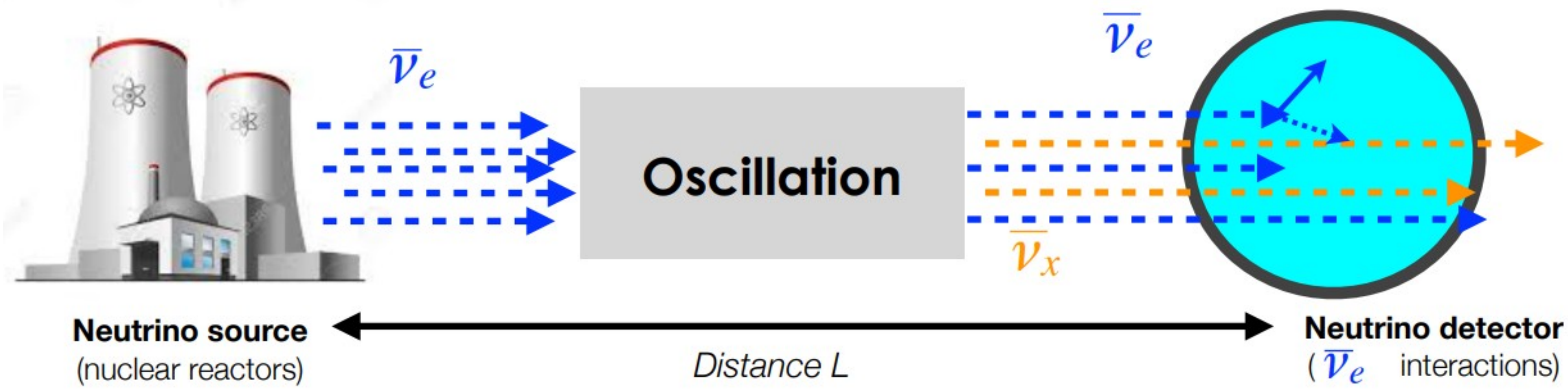
- Large LS volume (20 kton)
- High LS light yield & transparency
- High PMT coverage and efficiency
- Two complementary PMT systems
- Complementary calibration systems
- Using JUNO + close-by detector





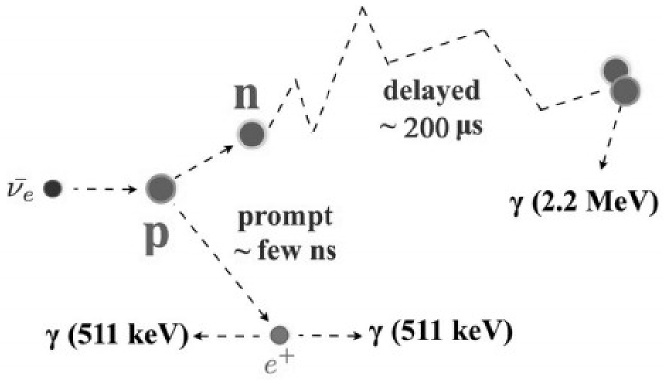
	Target Mass	Coverage	Energy resolution	Light yield [PE/MeV]
Daya Bay	20 ton (x8)	12%	8% @ 1 MeV	160
Borexino	300 ton	34%	5% @ 1 MeV	500
KamLAND	1 kton	34%	6% @ 1 MeV	250
JUNO*	20 kton	78%	3% @ 1 MeV	>1300

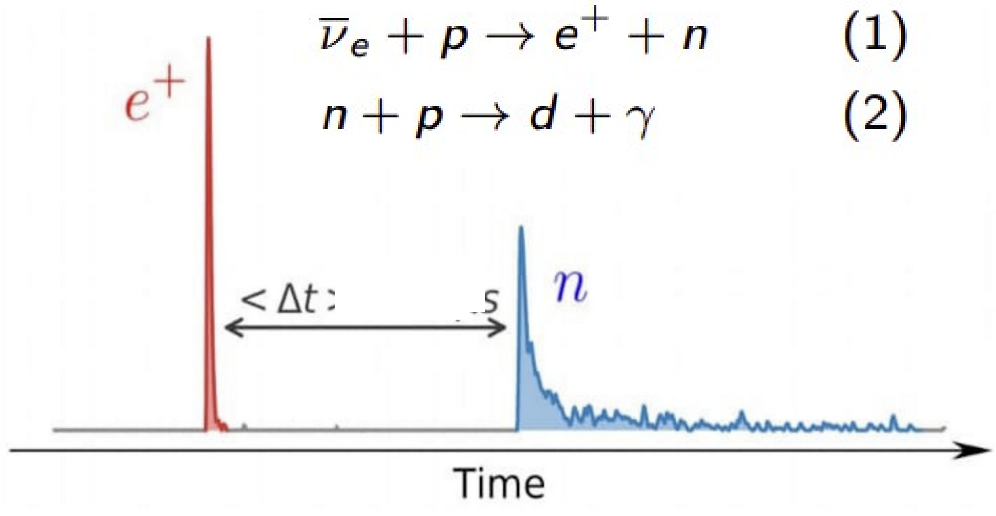
Reactor neutrino detection



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

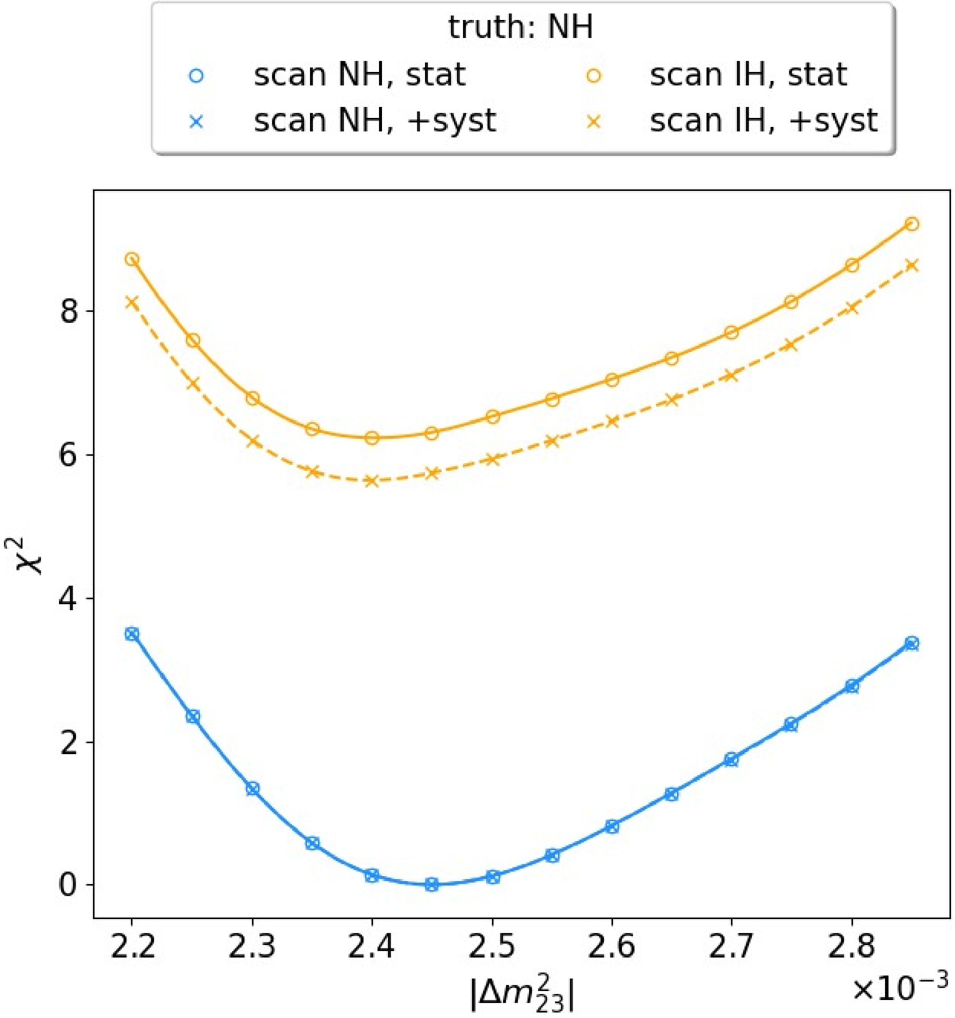




$$\overline{\nu}_e + p \rightarrow e^+ + n \qquad (1)$$

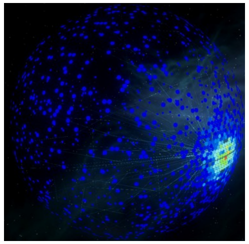
$$n + p \rightarrow d + \gamma \qquad (2)$$

Atmospheric neutrino osicllations: sencisitivity



With coarse binning

CCSN neutrinos: pointing

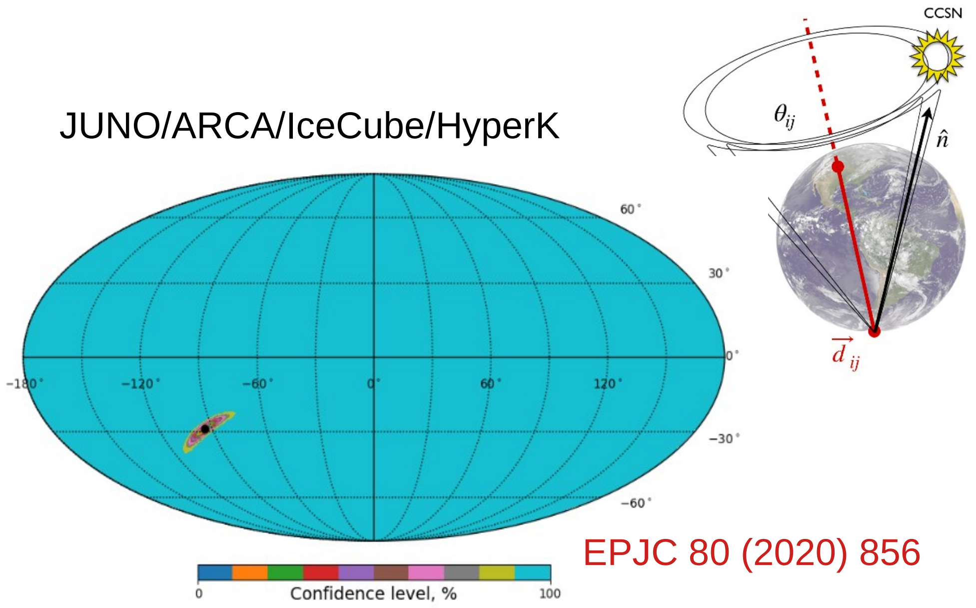


- Pointing to the source with neutrinos is key for a successful MM follow-up
- But direction reconstruction is difficult at MeV energies: point-like emission…
- ➔ Two possible ways to go:

Triangulation

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

JUNO/ARCA/IceCube/HyperK



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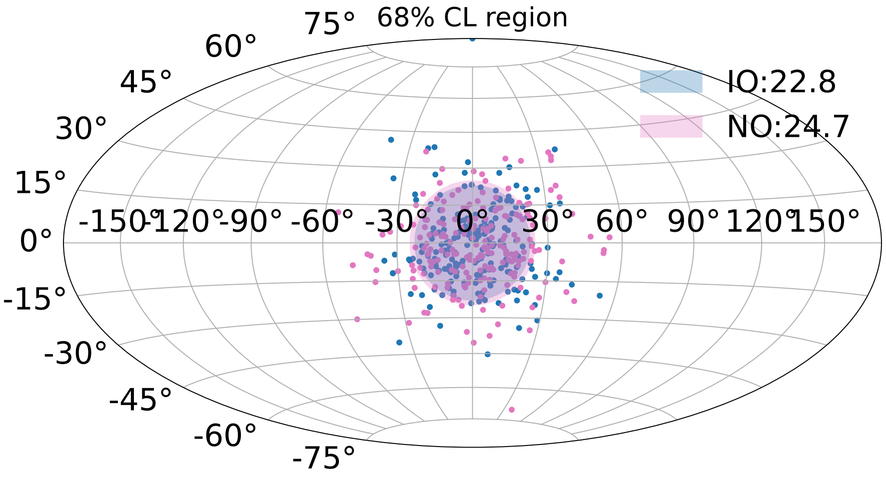
JUNO IBD: anisotropic interactions

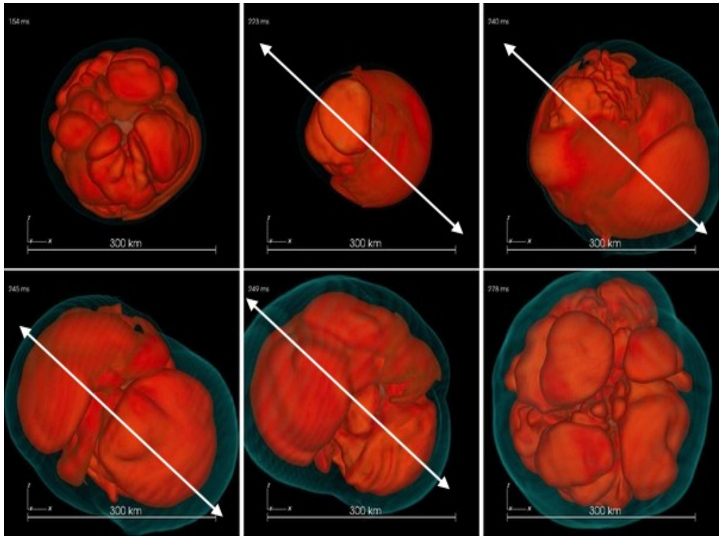
”The direction between the IBD prompt (positron) and delayed (neutron capture) reconstructed vertexes gives ν direction”



CCSN neutrino lightcurve

Example of interesting lightcurve feature to study: SASI oscillations

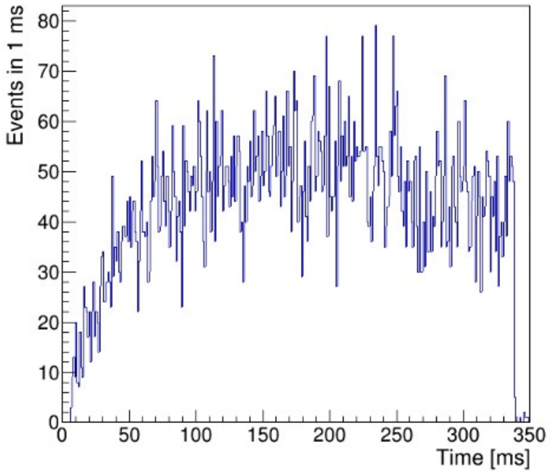
- SASI = standing accretion shock instability: predicted by 3D CCSN simulations
- Why is it interesting:
  - It appears in failed explosions
  - It can explain neutron star kicks observed
  - It would be accompanied by GW emission

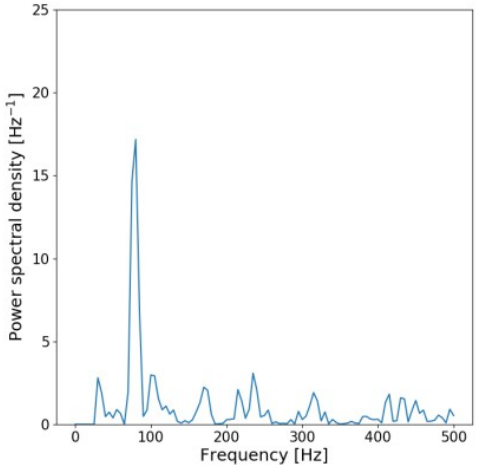


- **Observable:** fast-time variations of the detected rates, with a characteristic oscillation frequency (~80Hz) → Spectral analysis of the neutrino data

CCSN neutrino lightcurve

Example of interesting lightcurve feature to study: SASI oscillations





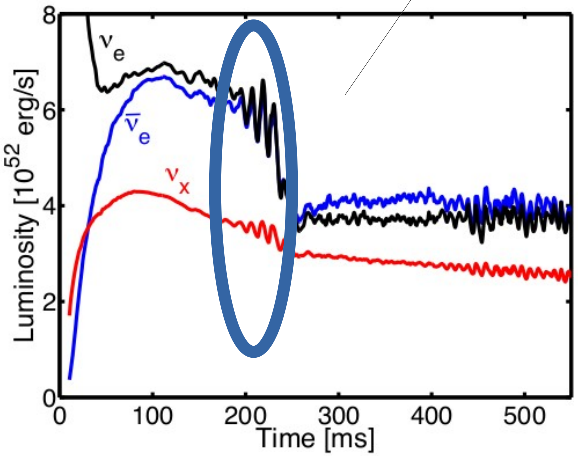
20 Msun, Tambora 2014

(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)

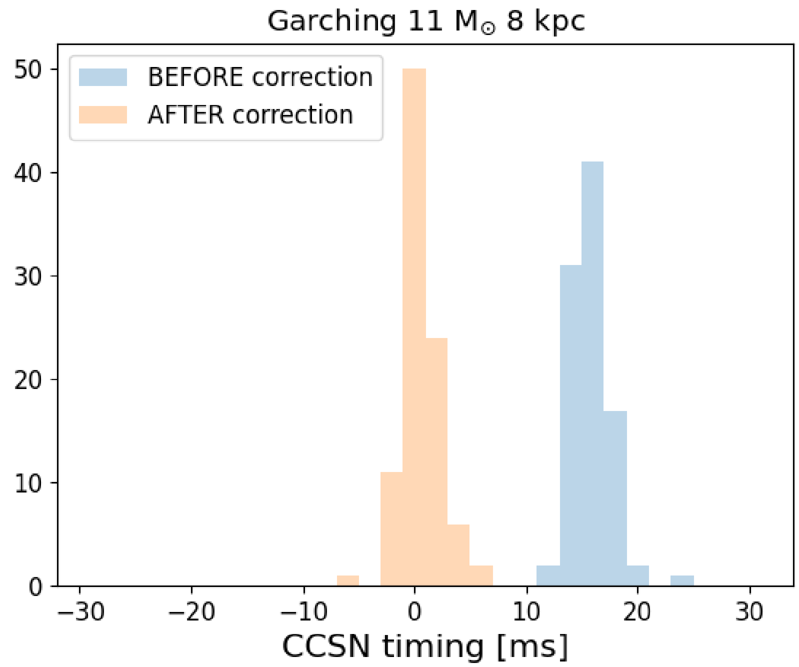
Multi-messenger astronomy

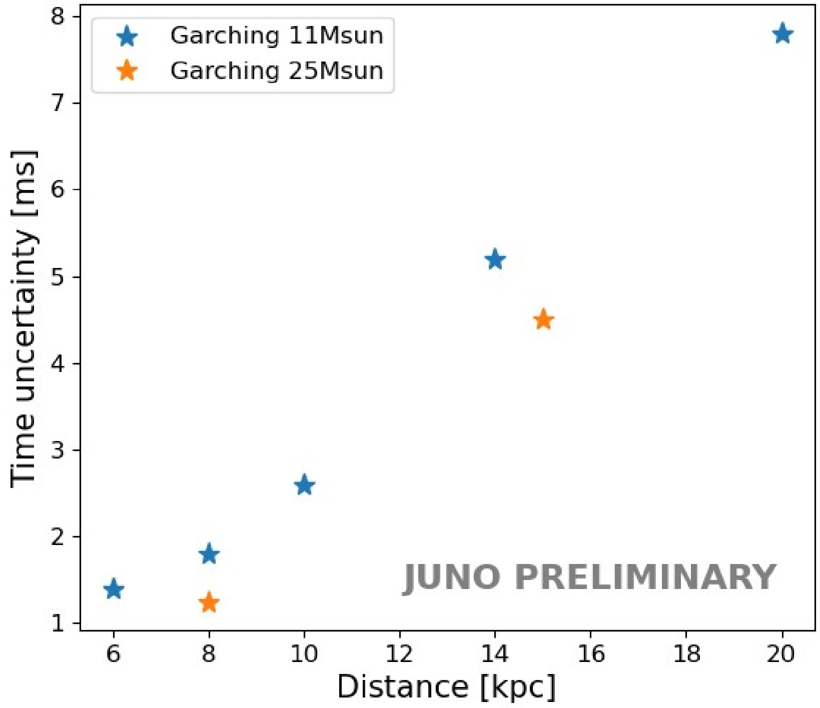
Timing the neutrino signal arrival

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

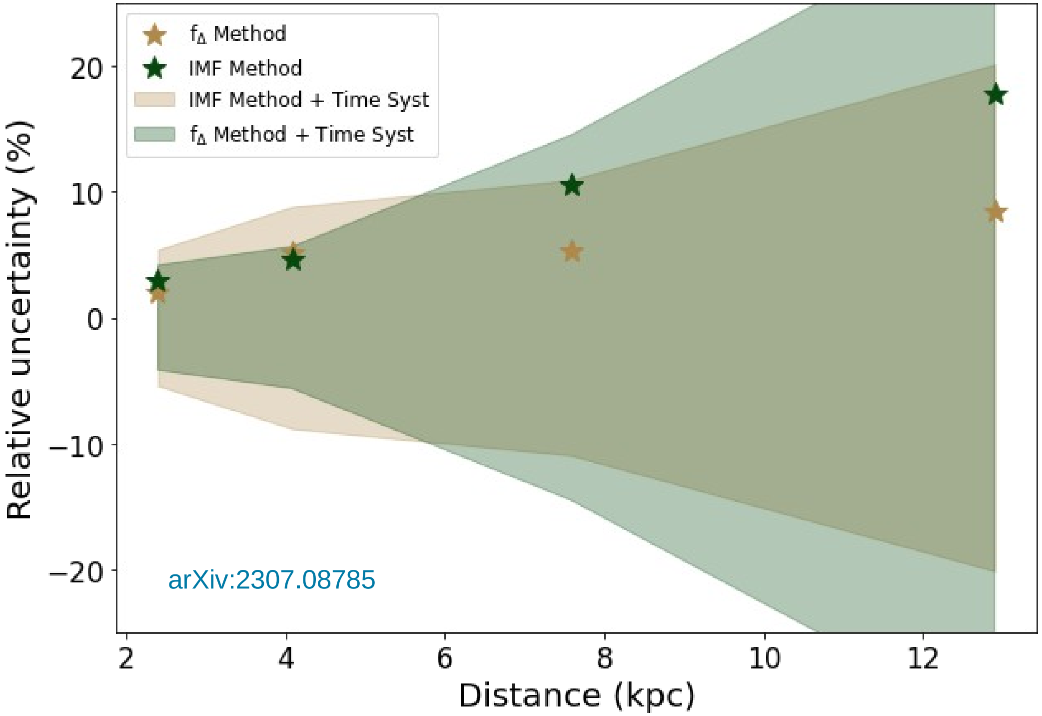
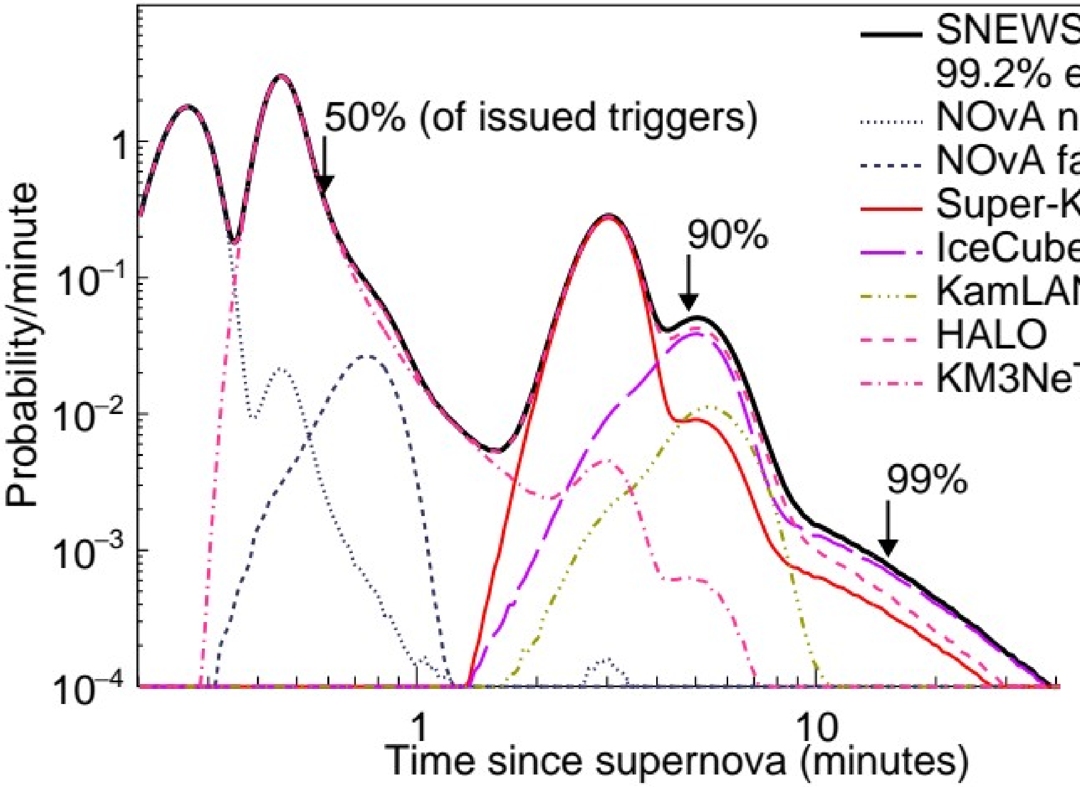
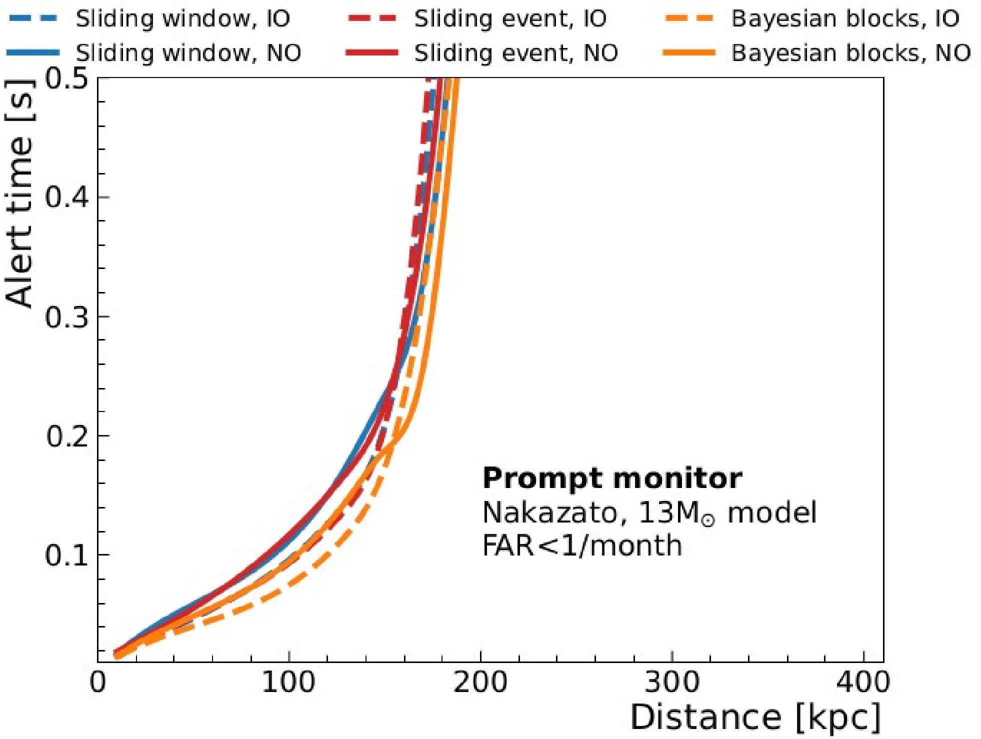


Figure: Statistical uncertainties (solid lines). The bands include the model (IMF) and T0 systematic uncertainties on top.

Multi-messenger astronomy



Most of experiments in SNEWS have ~minutes latency



JUNO latency is below a second even for far away events