SNEWS :
A network of detectors sensitive to core-collapse supernova neutrinos

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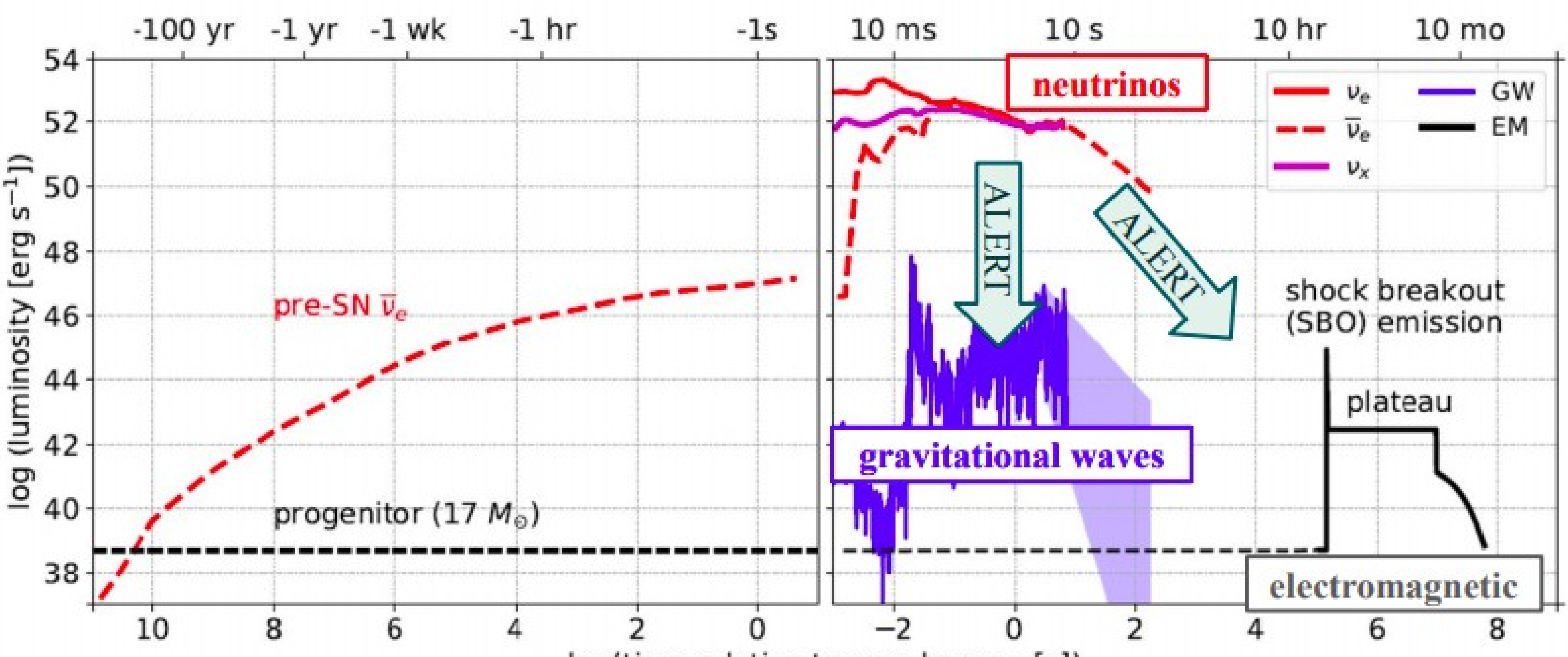
On behalf of the SNEWS Collaboration

Core-Collapse Supernova Multi-Messenger signal



Adapted from Nakamura et al. 2016

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

Why SNEWS?

Unique insights into astro-, particle and nuclear physics under extreme conditions → Extract as much multi-messenger information as possible

But… the expected rate of CCSN in the Milky Way is ~1.5 per century
→ **We need to be prepared!**

- Early and continuous monitoring is crucial
- Bring all neutrino detectors together → search coincident signal
- Coordination with the different electromagnetic telescopes, GW detectors and amateur astronomers

SNEWS
SUPERNOVA EARLY WARNING SYSTEM

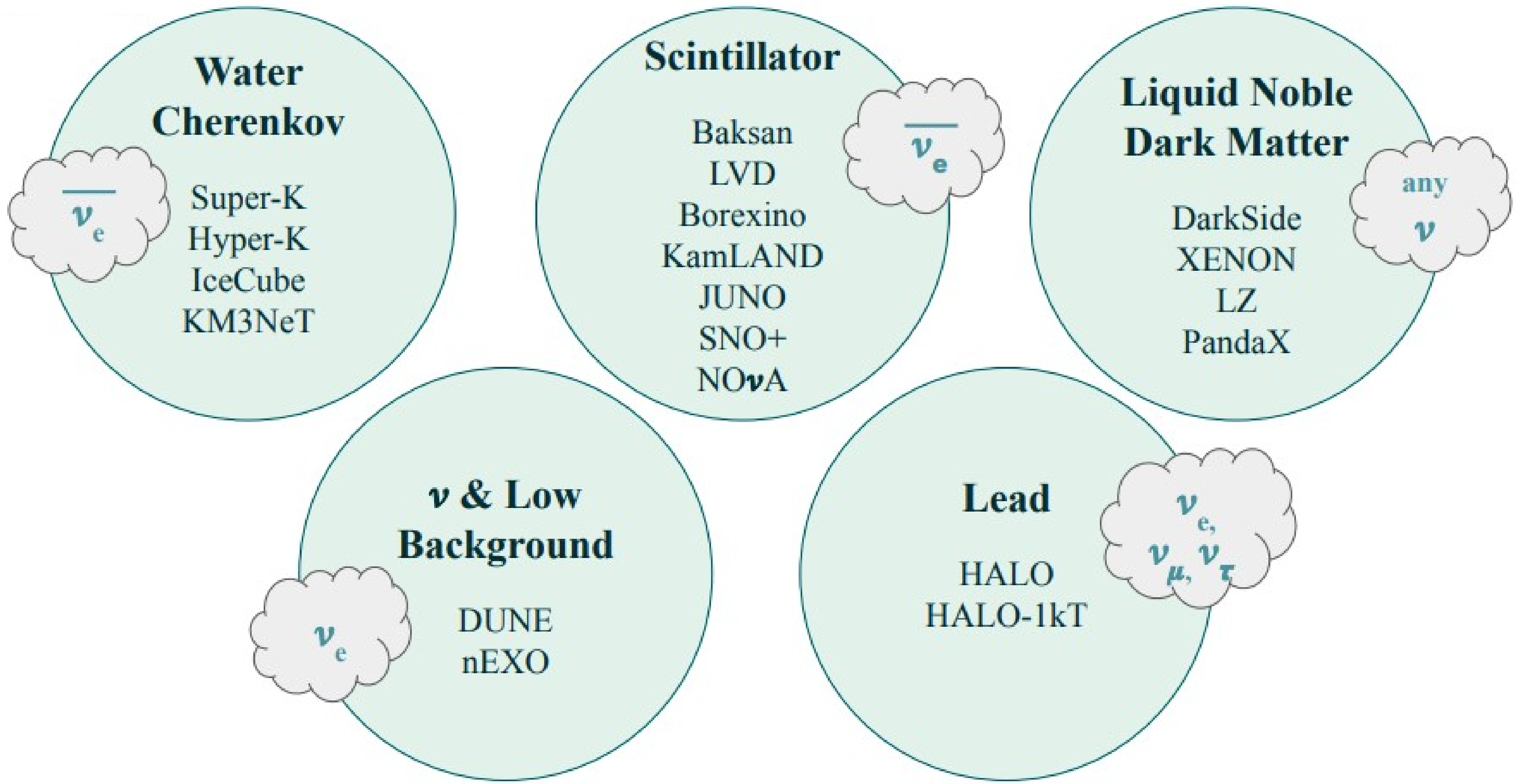
The goals of SNEWS

SNEWS1.0 has been guided by “the three P’s”:

- **Prompt:** provide an alert within < 1 h timescale
- **Positive**: false alert rate (FAR) < 1 per century
- **Pointing**: provide supernova localisation
  (pointing not included in SNEWS1.0 alerts)

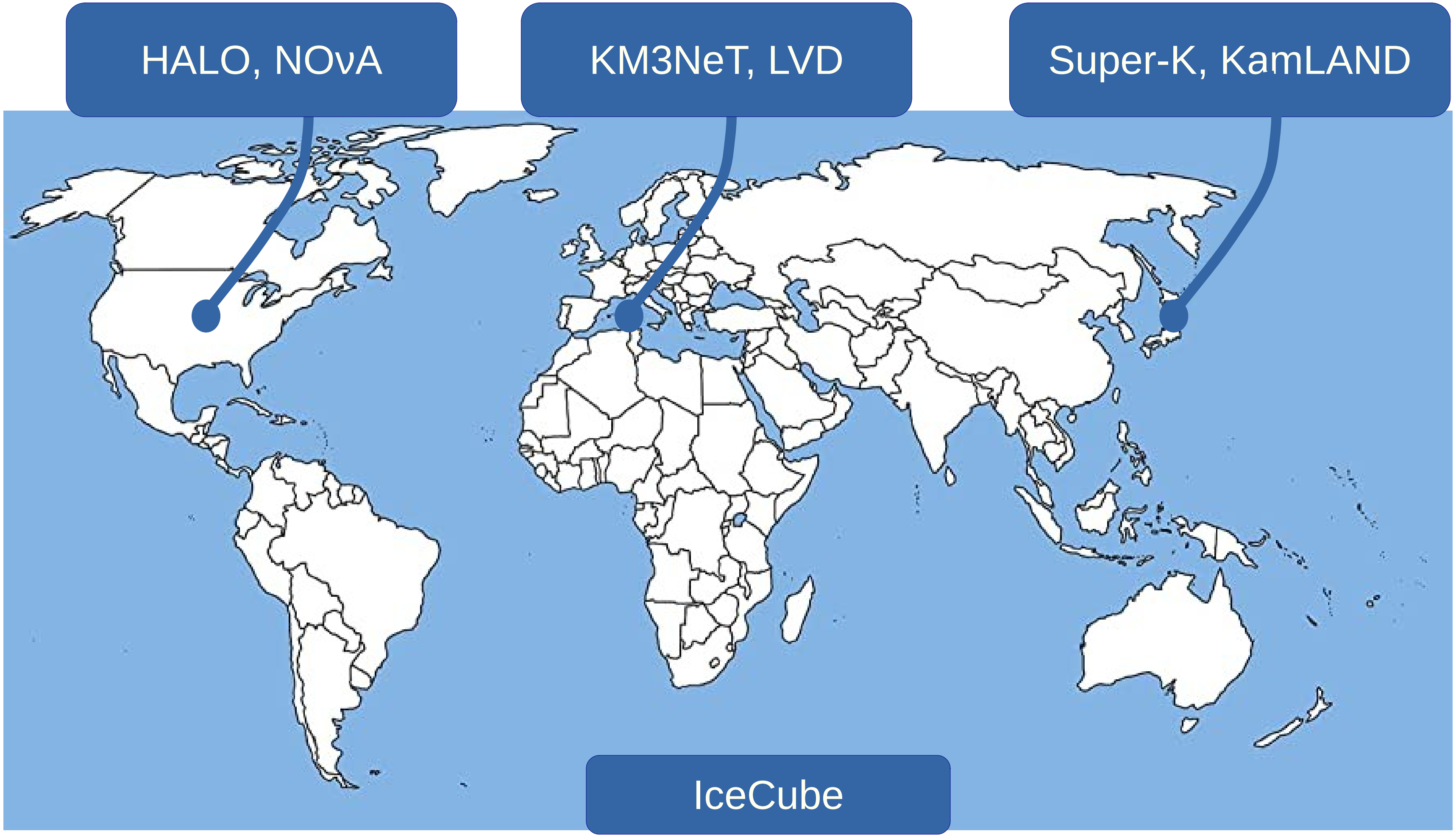
The goals of SNEWS

- Combining different detector triggers in real time allows for a positive and prompt alert + measuring the different flavor neutrino emission



SNEWS1.0

- Operating in automated mode for almost 20 years
- Currently: 7 detectors send alerts to the network



SNEWS1.0 → SNEWS2.0

→ Since 2019: Re-imagine SNEWS for today's new age of multi-messenger astronomy

- Basic implementation almost complete
- Negotiating MoUs with experiments
- Regular "fire drills" (test alerts) already taking place

→ Move from "3P's" to "3F's" of a good alert:

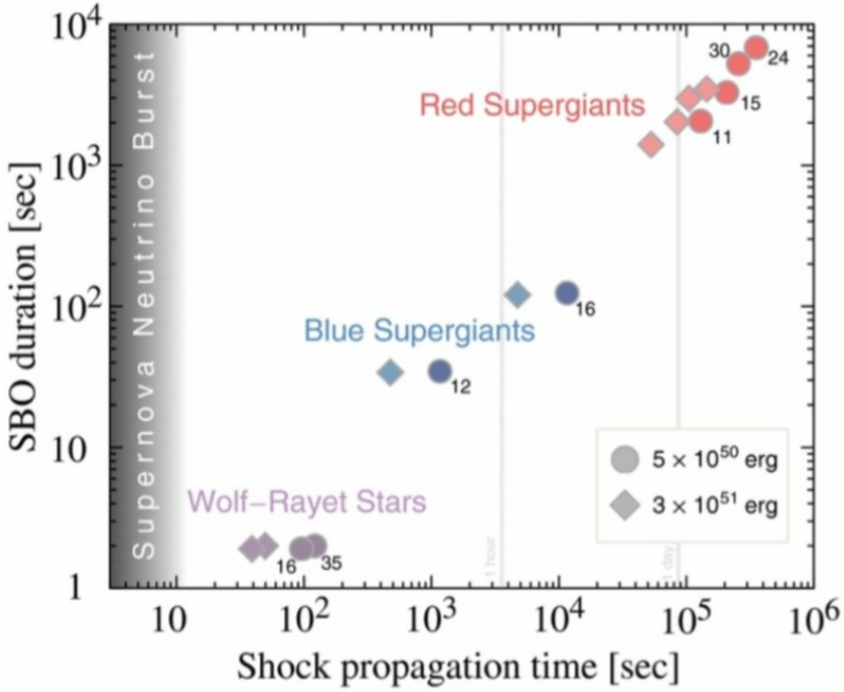
Prompt Positive Pointing	→	Fast False Alert Rate (FAR) Full featured

Why "Fast"?

- Neutrinos are emitted few-minutes to few-days before EM signal
  → **Telescopes might miss the EM signal otherwise**
  (bad conditions, not observing at the right moment, etc)
- Neutrinos are emitted together with gravitational waves
  → **Detection of GW counterpart difficult without neutrino alert**

Successful follow-up = rich physics outcome

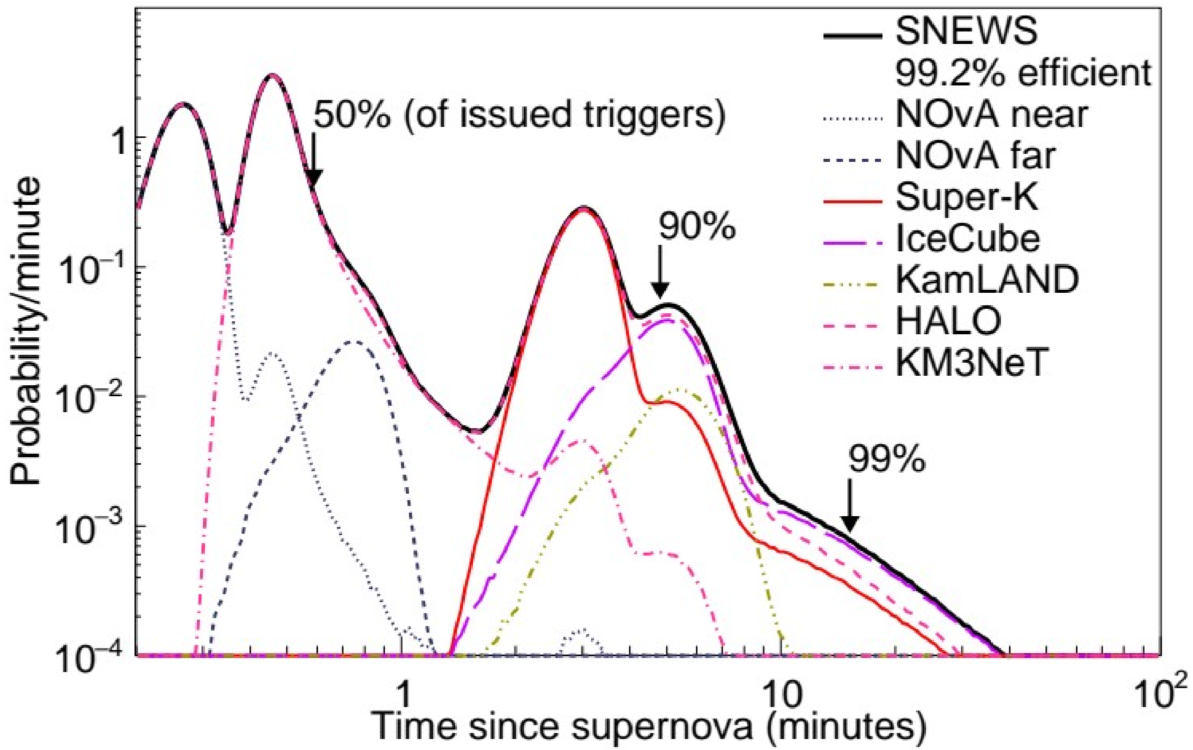
- Recording of the shock breakout (SBO): progenitor nature
- Identification of GW signal: additional physics



“Fast” alerts in SNEWS2.0

Lower latency:

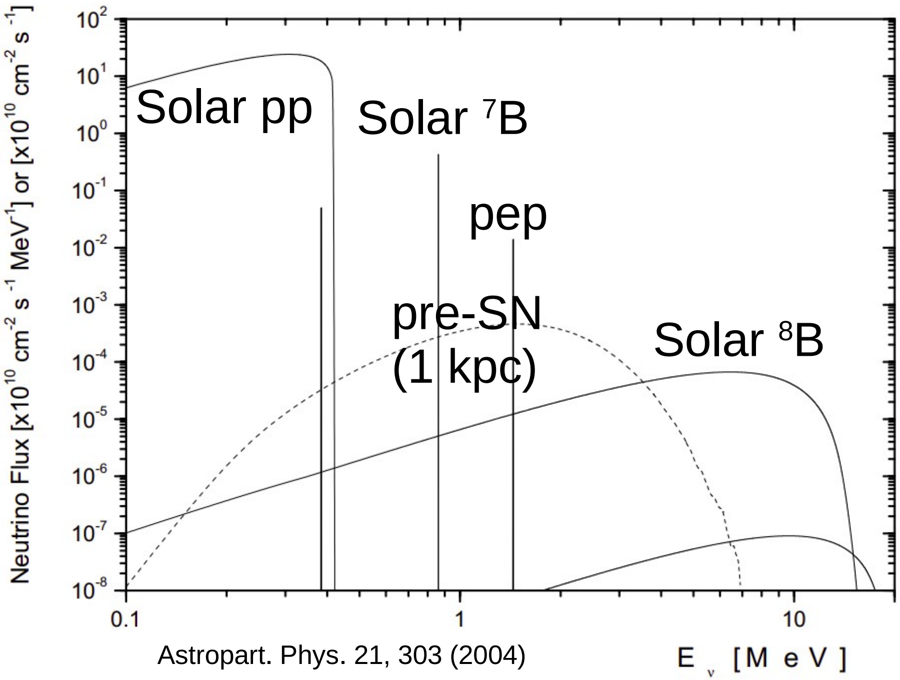
- More flexible SNEWS policy
- Expected server latency *O*(seconds)



- DAQ design of individual experiments is important
- Most current SNEWS experiments latency *O*(minutes)
- Improvement possible for various detectors in SNEWS2.0

“Fast”: Pre-supernova

- Neutrino emission previous to the explosion (during Si burning phase) detectable hours to days before the stellar collapse → **Fast notice**
- Difficult detection due to low-luminosity, low mean neutrino energy and longer time window of pre-supernova signal
- Low-background detectors can detect such signal for close by CCSN events (≤ 1 kpc) → KamLAND+SuperK already share combined alerts



Astropart. Phys. 21, 303 (2004)

False Alert Rate or "FAR"

When SNEWS started... only positive alerts (FAR < 1 in 100 years)

Now… it is fine to send out uncertain alerts if FAR is included:

→ No more need to avoid false positives at all costs, we want to extract as much information as possible

→ Allowing higher FAR enables to increase the distance horizon and the sensitivity to exotic and sub-threshold transients

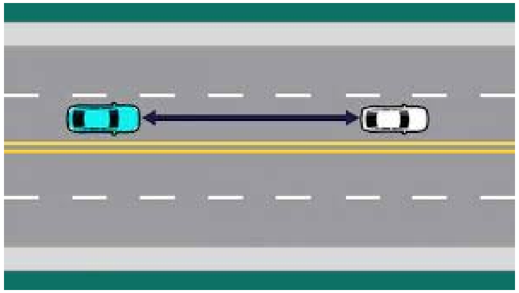
→ Astronomers can set their own FAR threshold

“Full featured”?

→ Provide as much additional information as possible for best follow-up strategy and physics outcome:

Timing of the neutrino signal

...When?

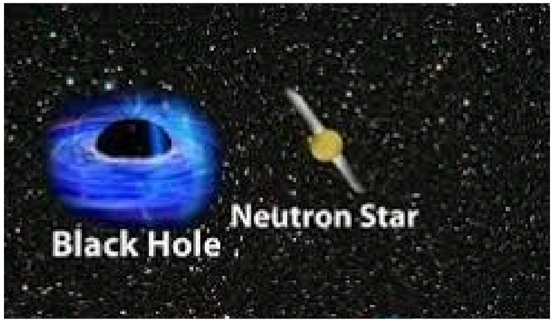


Distance

...How far?

Pointing (from 3p’s)

...Where?



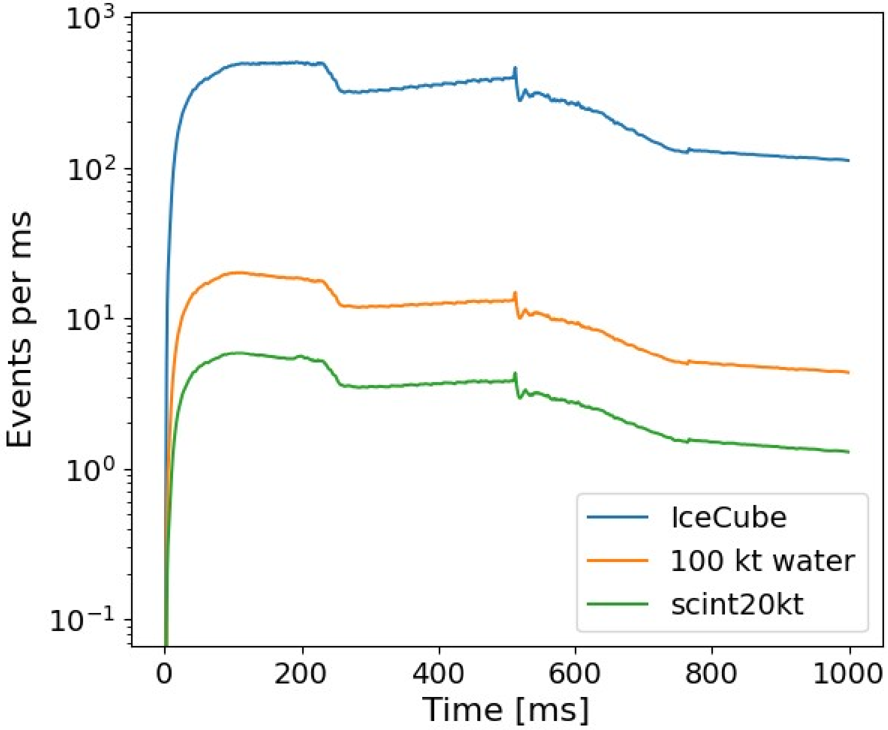
Type of remnant

...What kind?

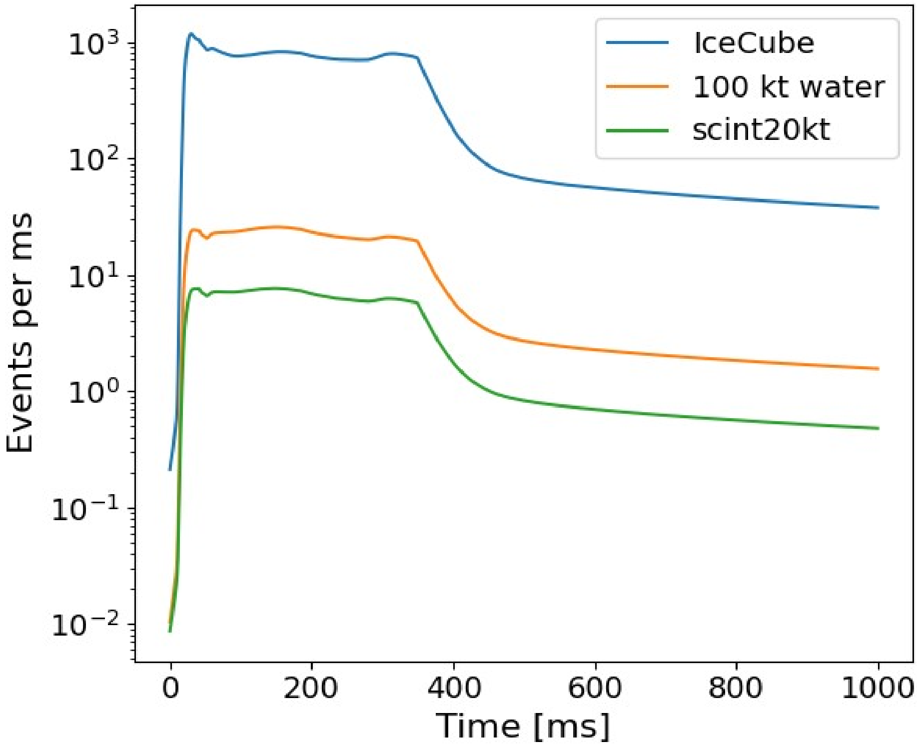
“Full featured”: Timing

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

MODEL 1, progenitor 1



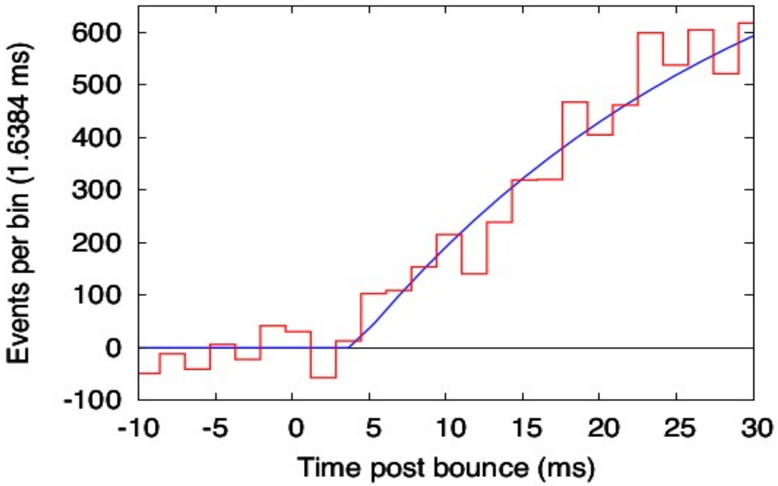
MODEL 2, progenitor 2



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

"Full featured": Timing

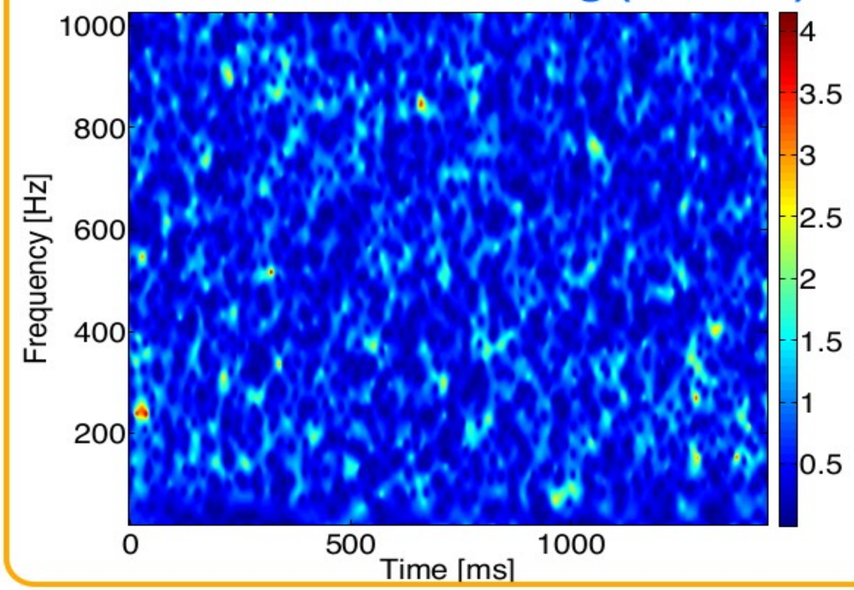
- Allows to define the time window for the GW signal search



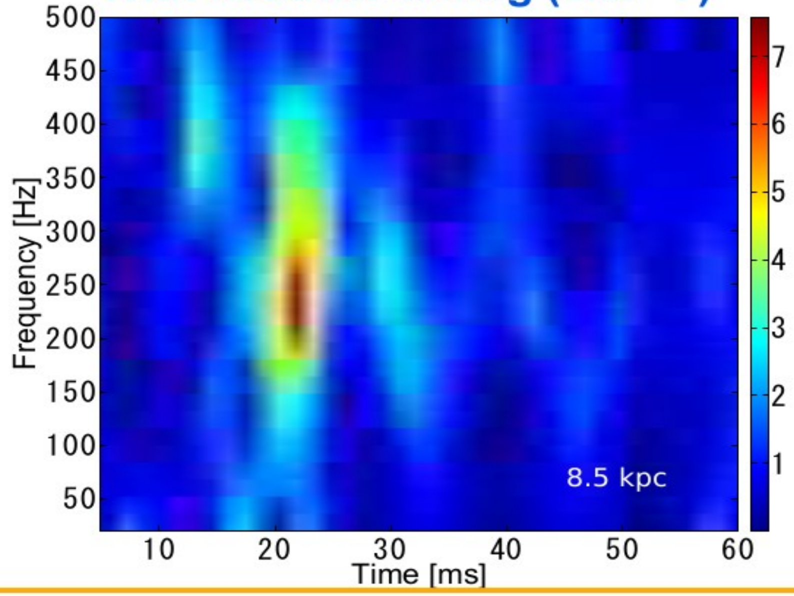
Probe core bounce time with neutrinos.

Timing for gravitational wave detection.

Without neutrino timing (S/N~3.5)



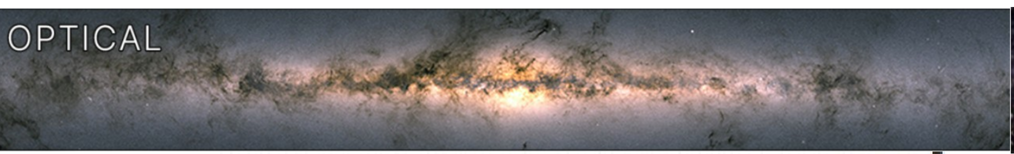
With neutrino timing (S/N ~7)



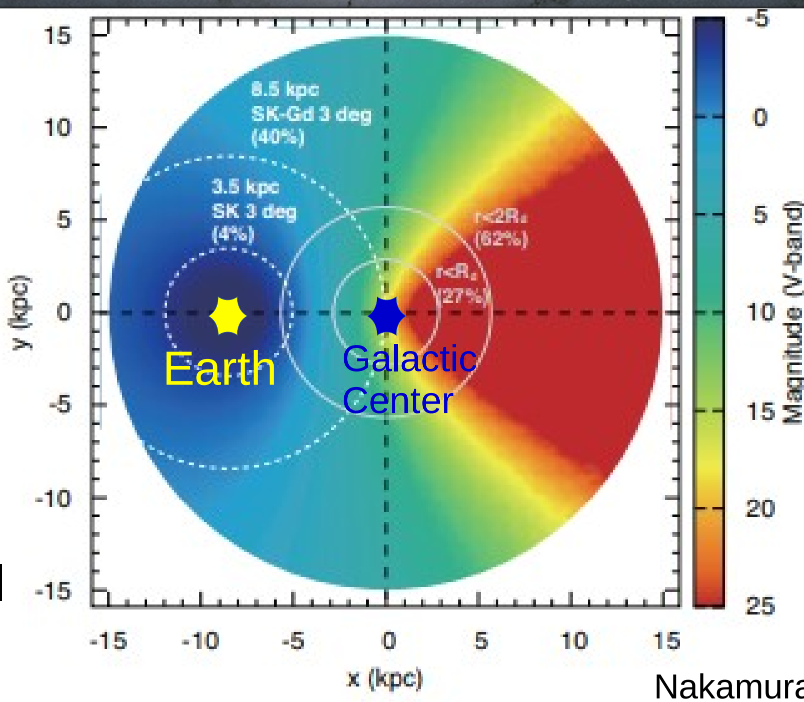
Pagliaroli+, PRL (2009), Halzen+ PRD (2009), Nakamura+, MNRAS (2016)

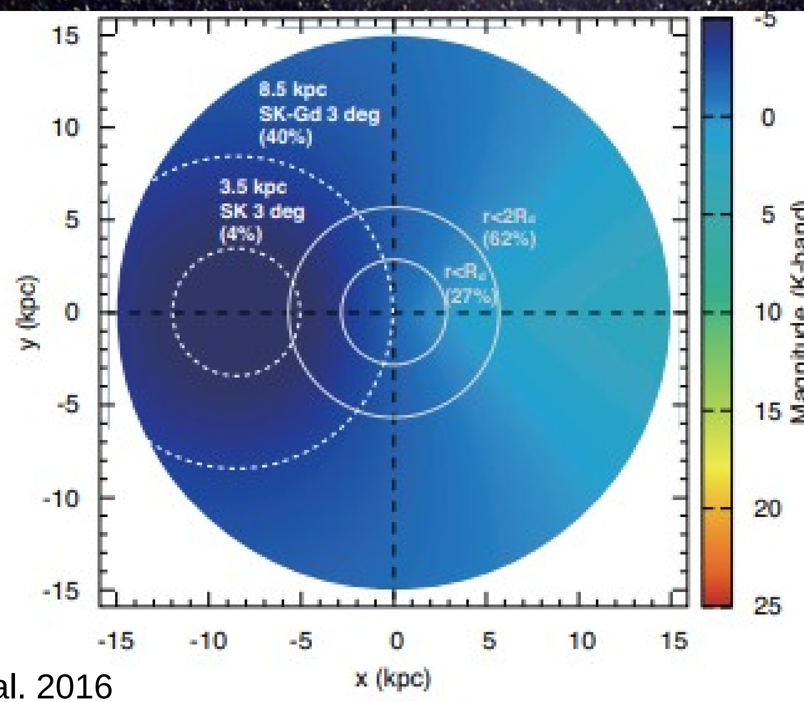
“Full featured”: Distance

- The source luminosity at different wavelengths depends on the distance → may affect the optimal observation strategy
- A lot of background light for Galactic sources + dust obscures part of the Galaxy (more near Galactic Center) → complicates the EM detection



optical





near IR

Nakamura et al. 2016

“Full featured”: Distance

→ Distance can be inferred using the detected neutrino event rate

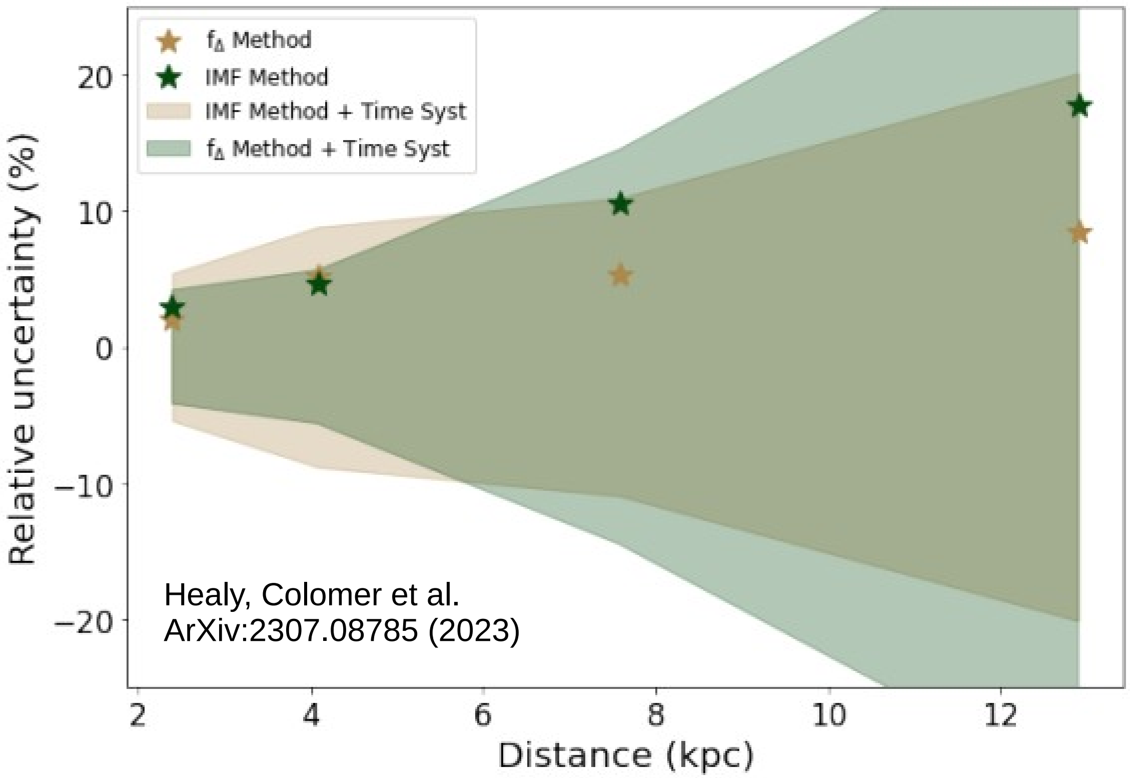
Segerlund et al., arxiv:2101.10624 (2021)

Observable: N50 = events observed in the first 50ms

Two methods:

- IMF: Expected N50 weighted over ~100 progenitor masses
→ lower stat unc, larger syst
- fΔ: Linear relation between N50 and fΔ=N50/N100-150
→ larger stat unc, lower syst

20 kt detector (stats of SK-JUNO)

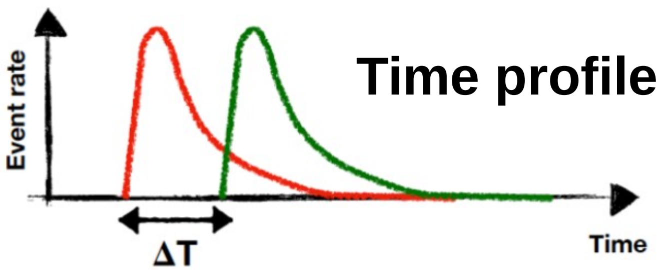


“Full featured”: Pointing

→ **Fast + Pointing = triangulation**

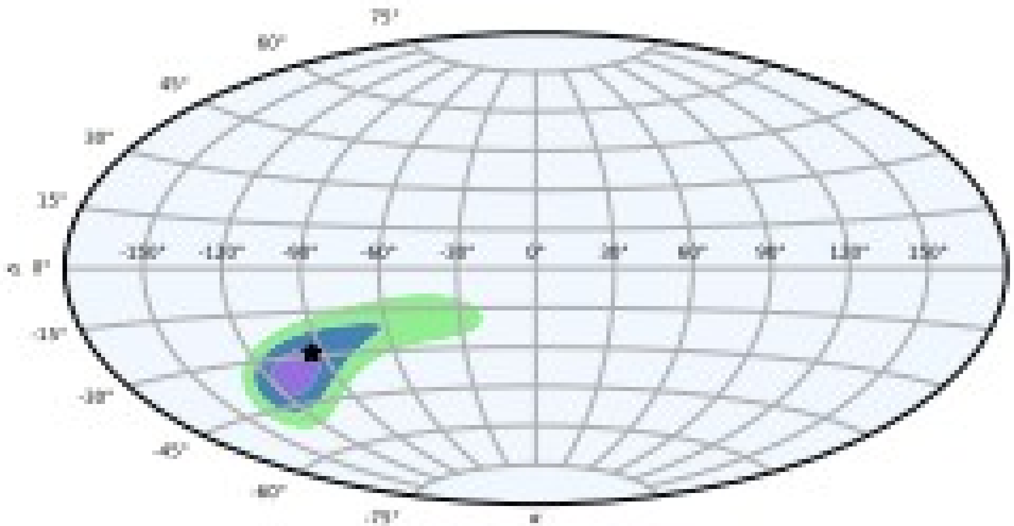
“The time delay between the signal at different detectors defines a sky region”

→ How to get these time delays?



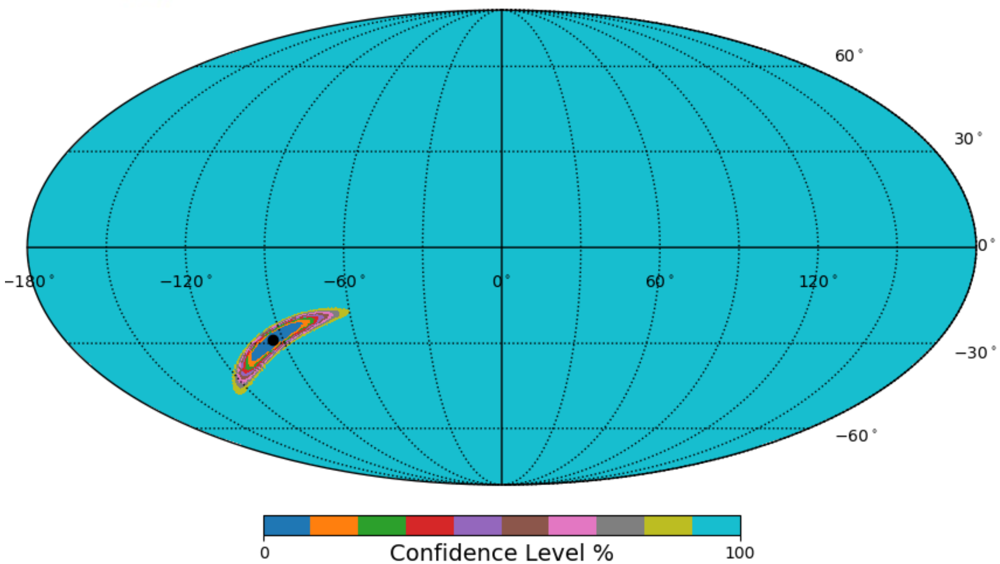
Time profile matching

First event times



IC-HK-DUNE-JUNO

Linzer and Scholberg
PRD 100 (2019) 10

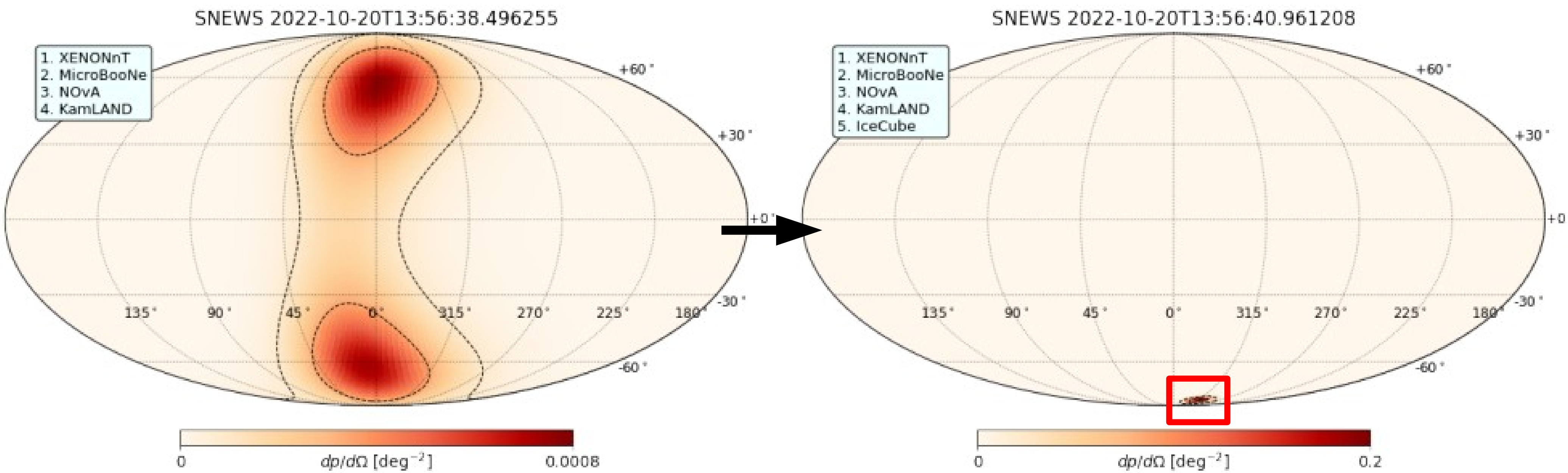


IC-HK-KM3NeT-JUNO

Coleiro, Colomer et al
EPJ C80 (2020) 856

“Full featured”: Pointing

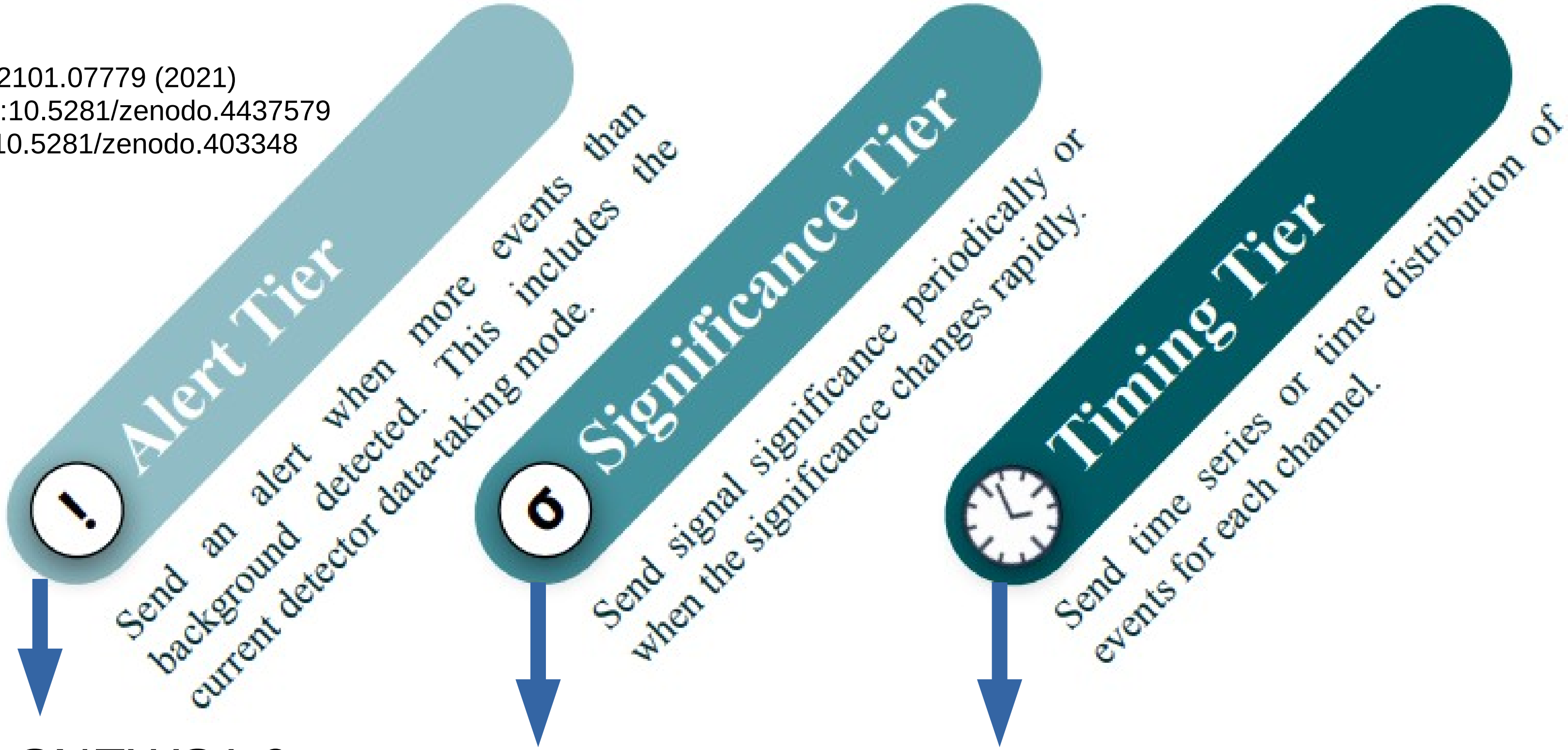
- First basic triangulation algorithm implemented in SNEWS
- Calculation and connection with the coincidence server has been tested in a distributed mock data challenge (fire drill):



SNEWS2.0: processing data

- Continuous data stream from detectors to SNEWS server → alert decision
- Infrastructure for message coordination and interfacing with clients
- Data exchange system relies on HOPSKOTCH, developed within SciMMA (Scalable Cyberinfrastructure for Multi-Messenger Astrophysics)
- Experiments can choose which degree of data they want to share and when

A.L Baxter+ arXiv:2101.07779 (2021)
SNEWS app → doi:10.5281/zenodo.4437579
Hopskotch → doi: 10.5281/zenodo.403348



Effectively SNEWS1.0

Experiments can share more data to enable new features

The SNEWS2.0 software

SNEWS 2.0 Server

Analysis tools for
- Coincidence
- Triangulation
- ...

Simulation tools

Develop analysis algorithms, set alert thresholds for experiments, etc.

Code publicly available in Github:
- SNEWS publishing tools
- SNEWS coincidence system
- snewpdag (for triangulation, etc)

snewpy offers:
- a simple and unified interface to hundreds of supernova simulations
- a large library of flavor transformations
- a fast (simplified) estimate of the expected event rate at different detectors

ApJ 925 (2022) 2, 107
JOSS 6 (2021) 03772

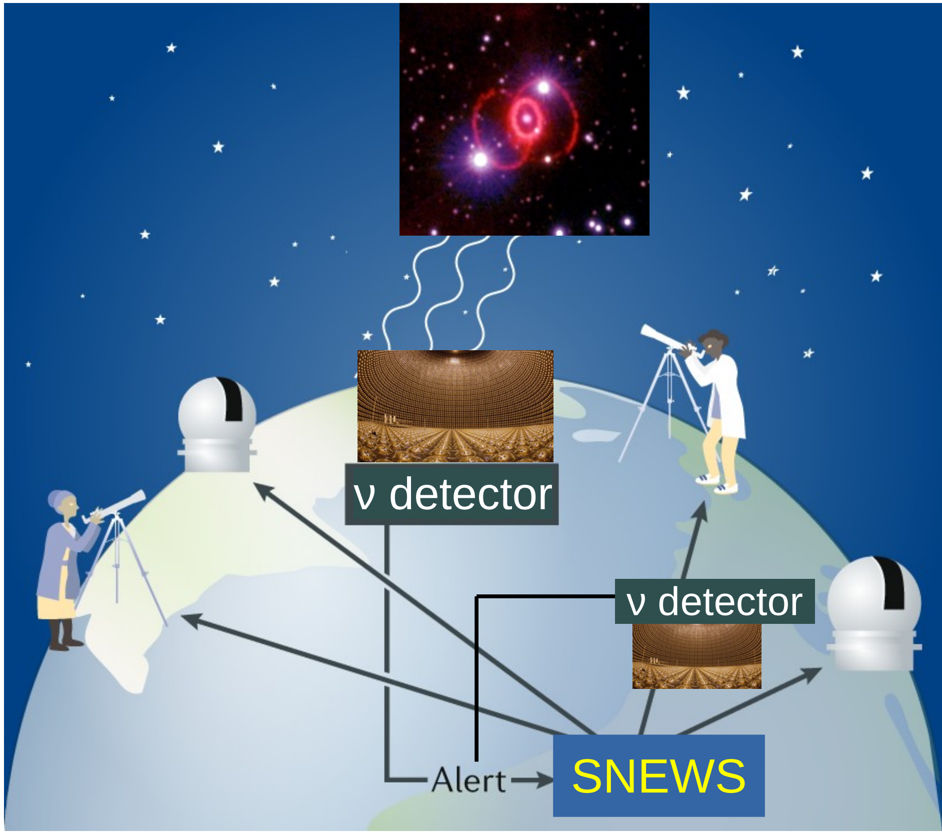
“Follow-up” in the multi-messenger era

- In 2000:

ATel & GCN started distributing alerts

  - Human-readable, unstructured, via email
  - Good strategy for SNEWS 1.0

- Today: ~10^7 alerts per day
  - Specialized brokers distribute/filter alerts
  - Large degree of automation
  - Robotic & fully automated telescopes



SNEWS can bring neutrino & astronomy communities together to prepare follow-up strategy → Ensure maximal science output

Who listens to SNEWS?

SNEWS meets the Astronomy Community

- GRANDMA (Global Rapid Advanced Network Devoted to the Multi-messenger Addicts) arXiv:2008.03962
  → Coordinates telescope observations of transient sources with large localization uncertainties

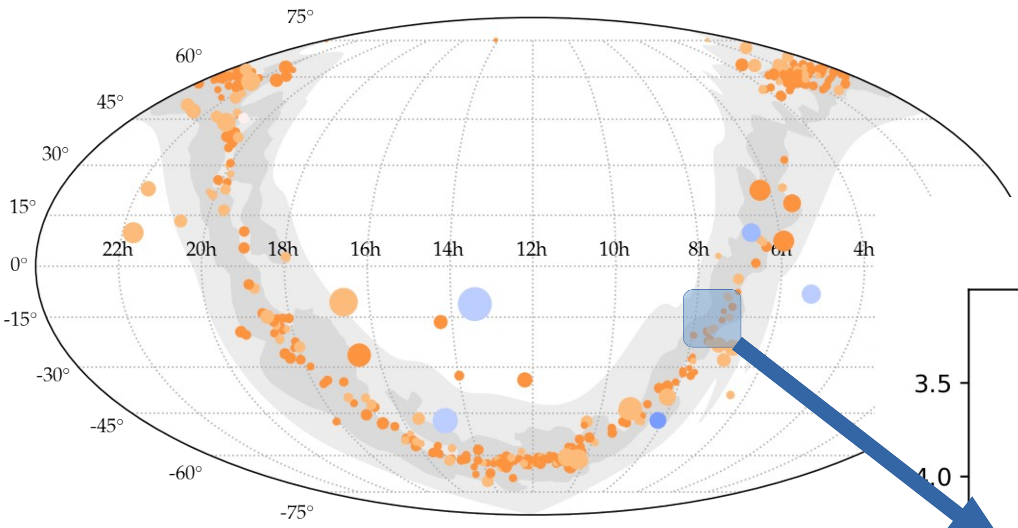
- AAVSO: Network of amateur astronomers (US)
  → often more flexible, large database, can send out alerts with observation requests to members

- REFITT (Recommender Engine for Intelligent Transient Tracking)
  → AI-based engine to plan & coordinate follow-up taking into account: available facilities, wavelengths, sensitivity, weather...

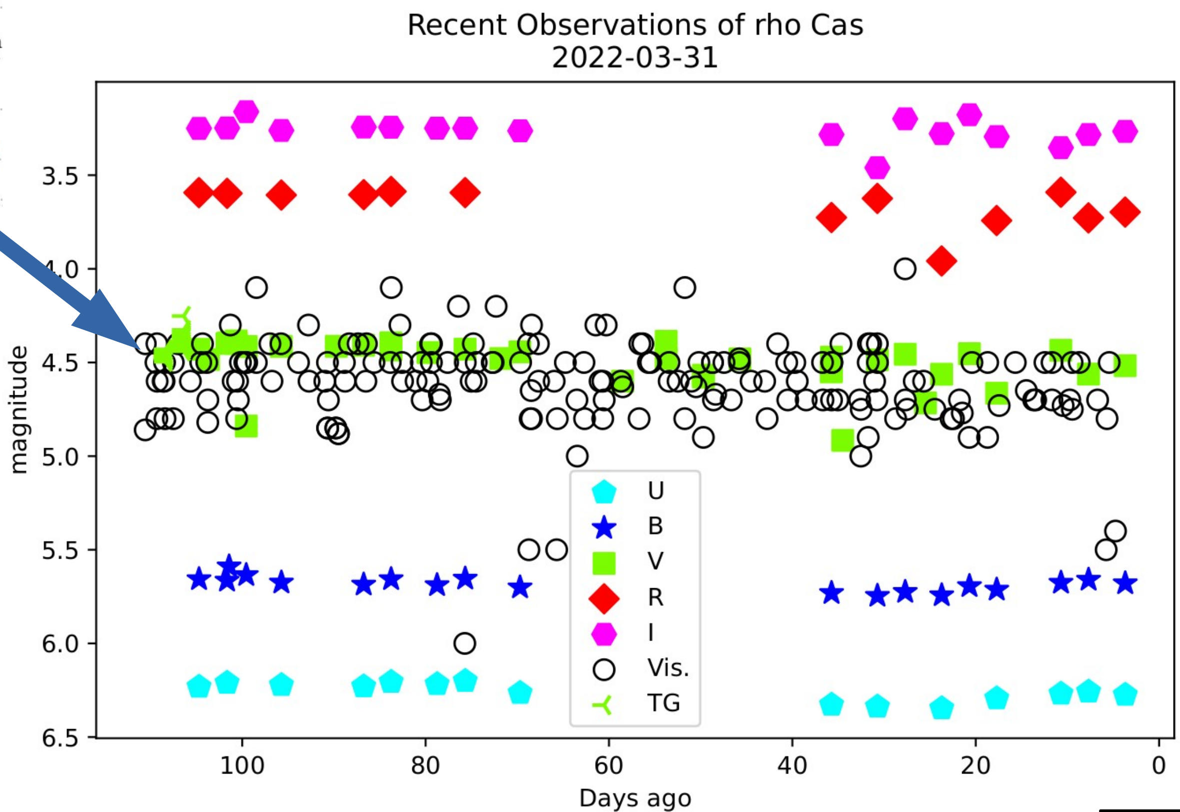
... and more

First “Follow-up” campaign

AAVSO started campaign to regularly observe Galactic CCSN candidate list



Example of one star monitored in different wavelengths:

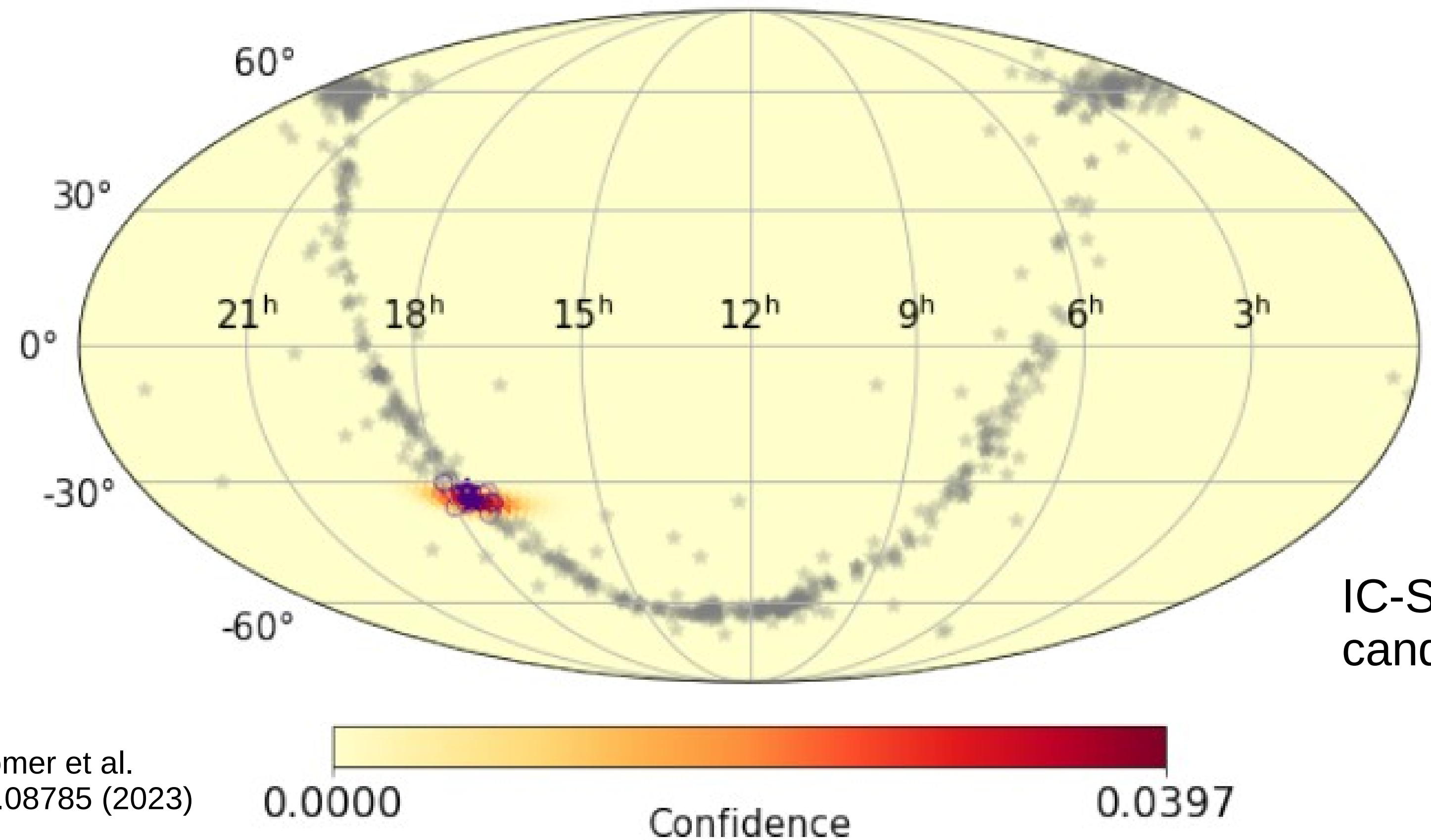


What does a network bring?

Galactic SN candidate list based on EM observables (~600 stars)

→ With neutrino network pointing: only 13 stars to follow-up

→ With neutrino network distance: just 2 stars left to observe



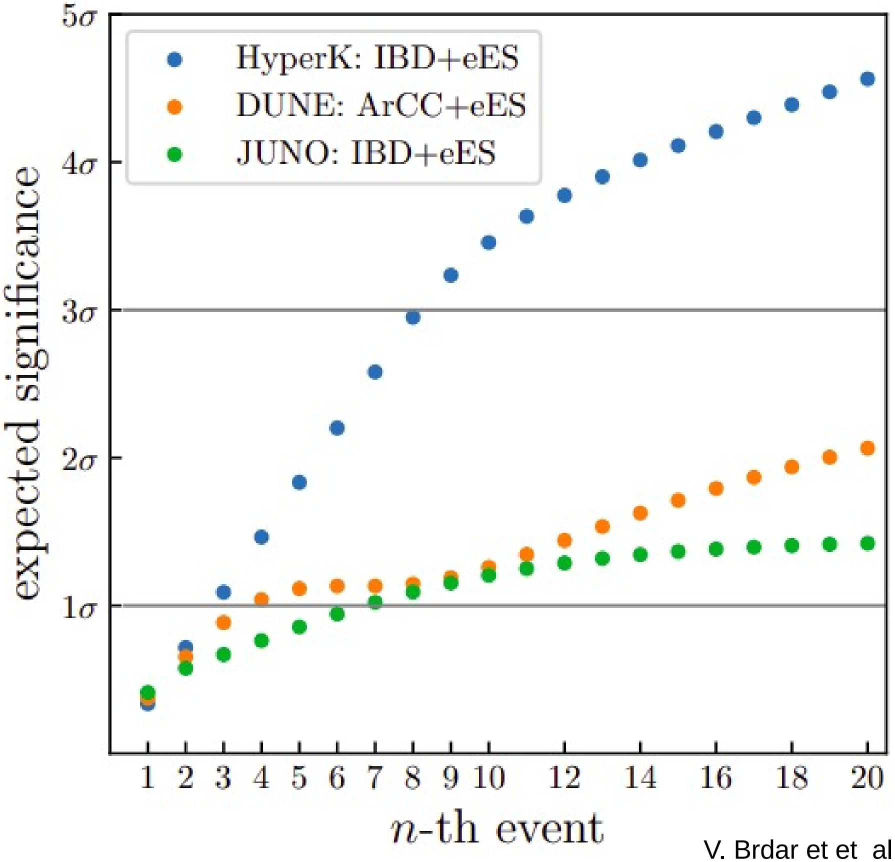
IC-SK-JUNO-SNO+
candidate ★ @4kpc

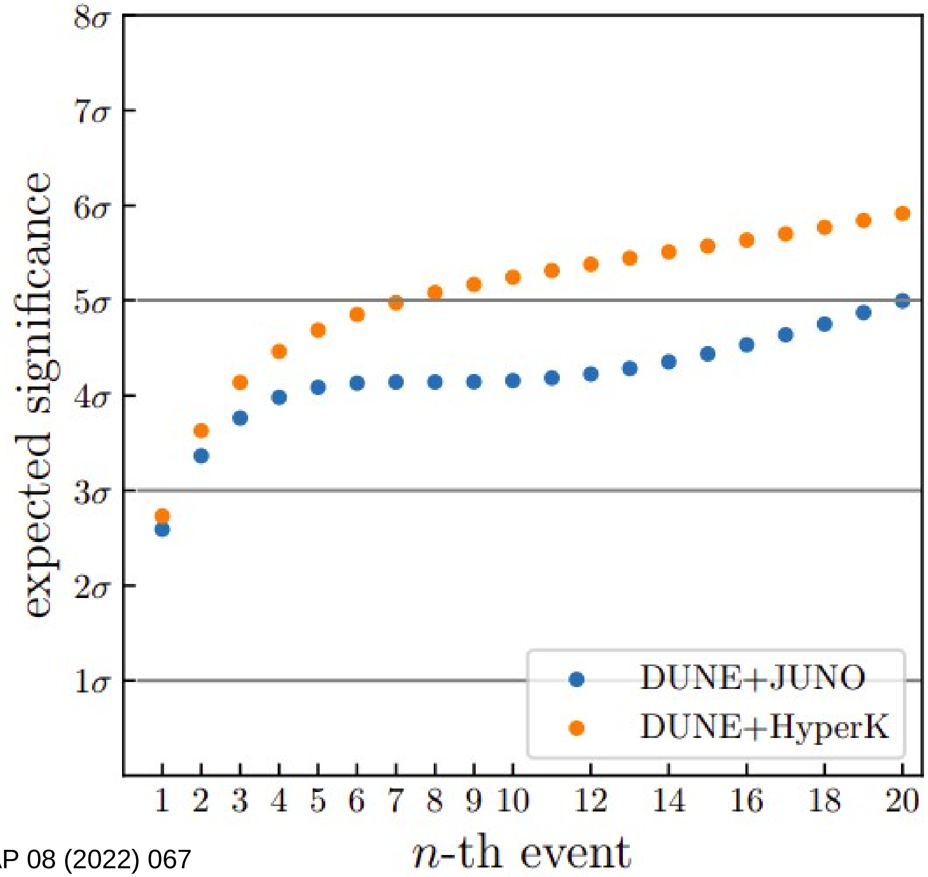
Healy, Colomer et al.
ArXiv:2307.08785 (2023)

What does a network bring?

More detectors = more interaction channels = all neutrino flavors
→ More neutrino physics with CCSN data

Example: determination of the neutrino mass ordering with CCSN neutrinos





V. Brdar et et al., JCAP 08 (2022) 067

Summary

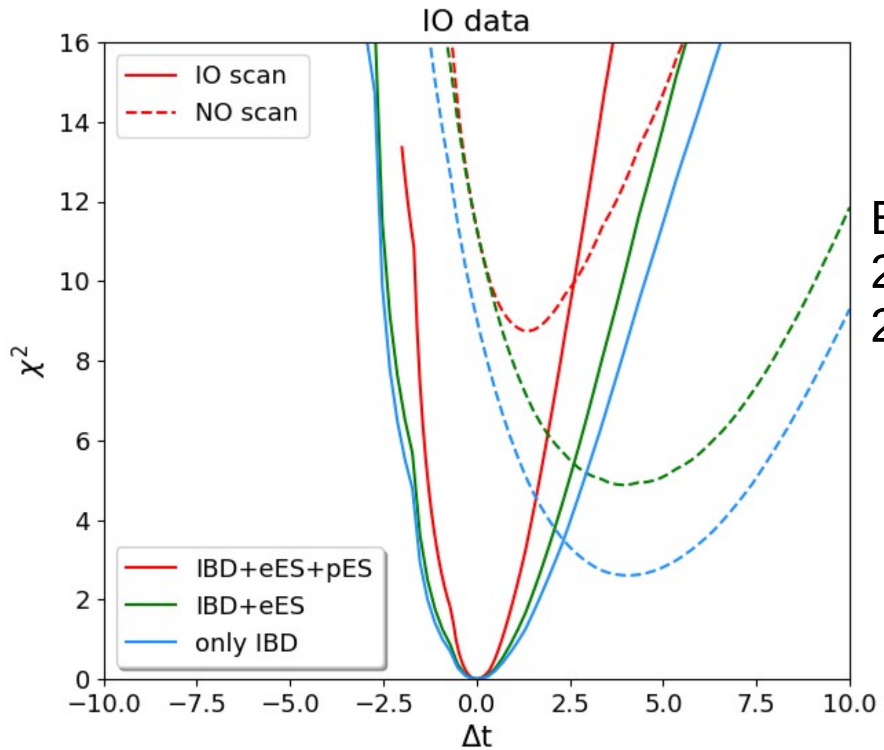
- A core-collapse will produce neutrinos with GWs, and before EM radiation →Early warning to identify the multi-messenger signals
- SNEWS2.0 will have a larger network of neutrino detectors, with more than 15 experiments simultaneously taking data
- With SNEWS2.0, the scientific reach of the observations will be maximized
- SNEWS2.0 will help coordinating the efforts for a global multi-messenger follow-up of the next CCSN explosion
- First fire drills have taken place and we learned a lot from them

What does a network bring?

More detectors = more interaction channels = all neutrino flavors
→ More neutrino physics with CCSN data

Best example: combine charged and neutral current (NC) interactions

(NC interactions insensitive to neutrino flavor transformations
→ enhanced sensitivity to neutrino oscillation scenarios)



Example:
20kton scintillator detector, 10 kpc
200 keV Eth for NC (pES)