SuperNova Early Warning System (SNEWS 2.0)

Jost Migenda
they/them

Introduction: Supernova

- Massive star explodes, leaving a neutron star or black hole

- ~99% of energy emitted as neutrinos

- Unique insights into astro-, particle and nuclear physics under extreme conditions

- Problem: just 1–3 SN/century in our Milky Way!

NASA/ESA, Hubble Key Project Team, High-Z SN Search Team
http://www.spacetelescope.org/images/opo9919i/

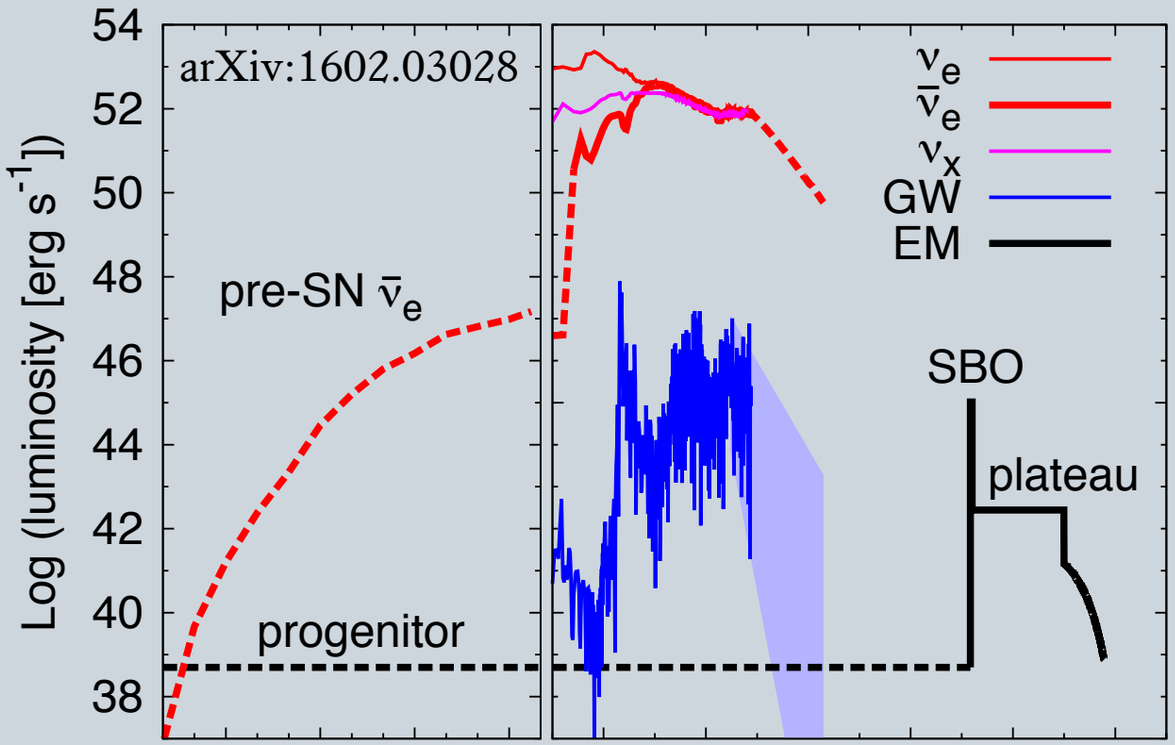
Note: In this talk, “supernova” is short for “core-collapse supernova”. Type Ia SNe have a different physical mechanism and produce fewer neutrinos, so I’ll ignore them. (Apart from SN1994D, because this photo is so pretty.)

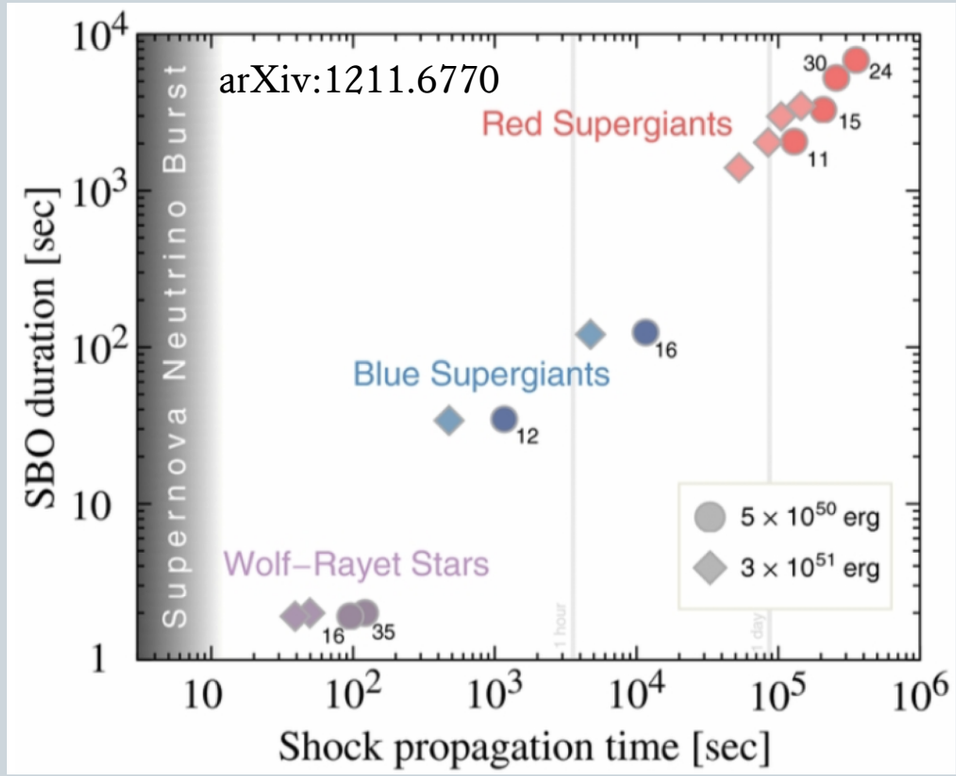
Introduction: Supernova

- Once-in-a-lifetime event
  ➔ Extract as much multi-messenger information as possible!

- Neutrinos emitted minutes to hours before light

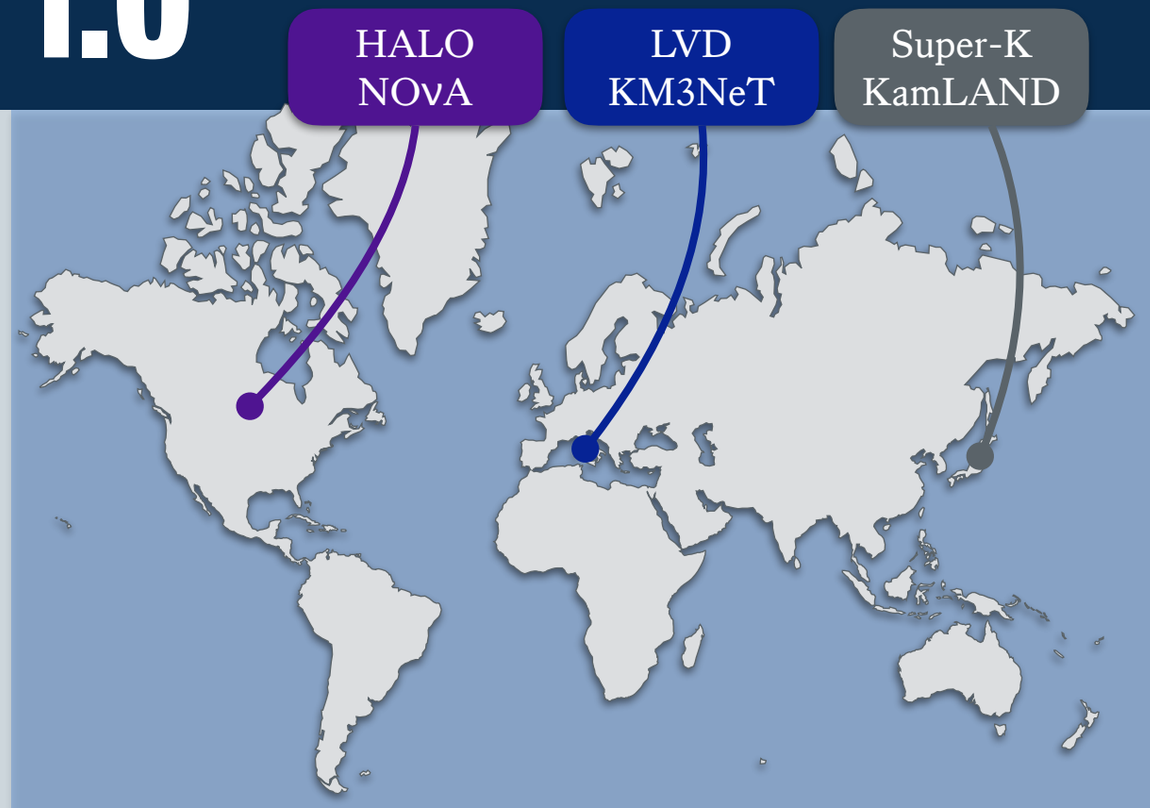
- Can build a SuperNova Early Warning System with neutrino detectors

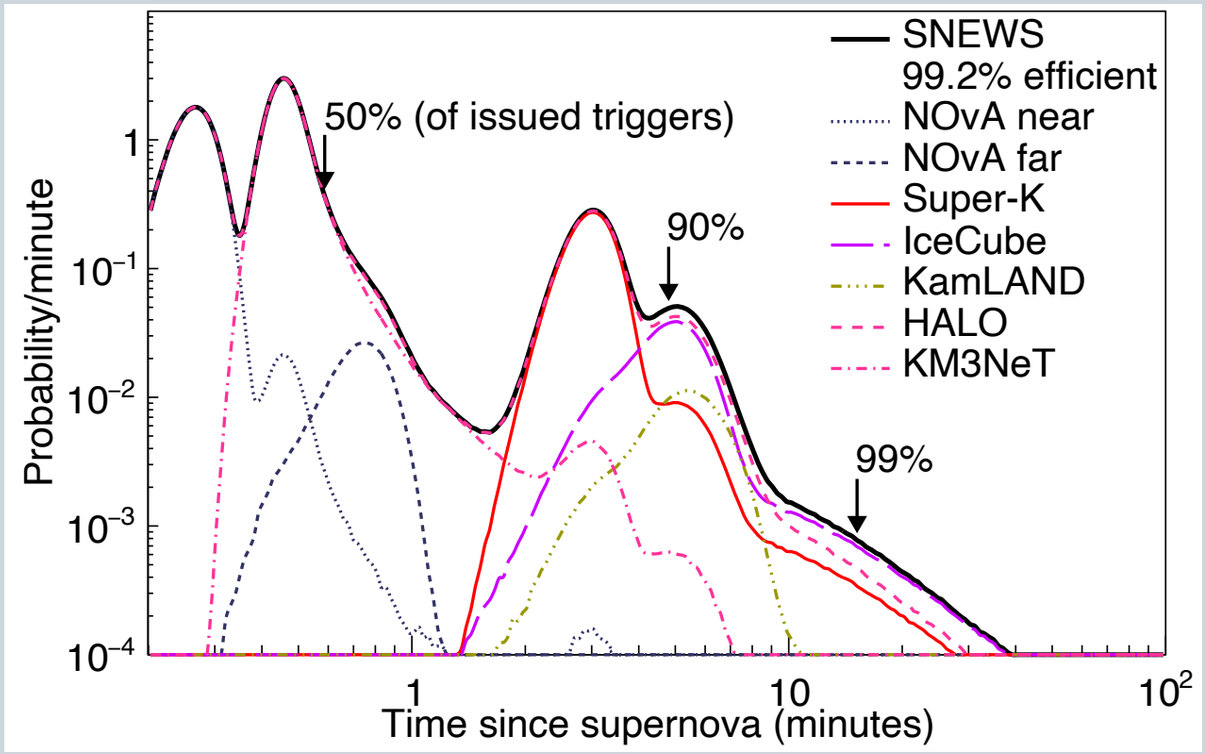




SNEWS 1.0

- Started >20 years ago, running in automated mode since 2005
- Now: 7 participating detectors →





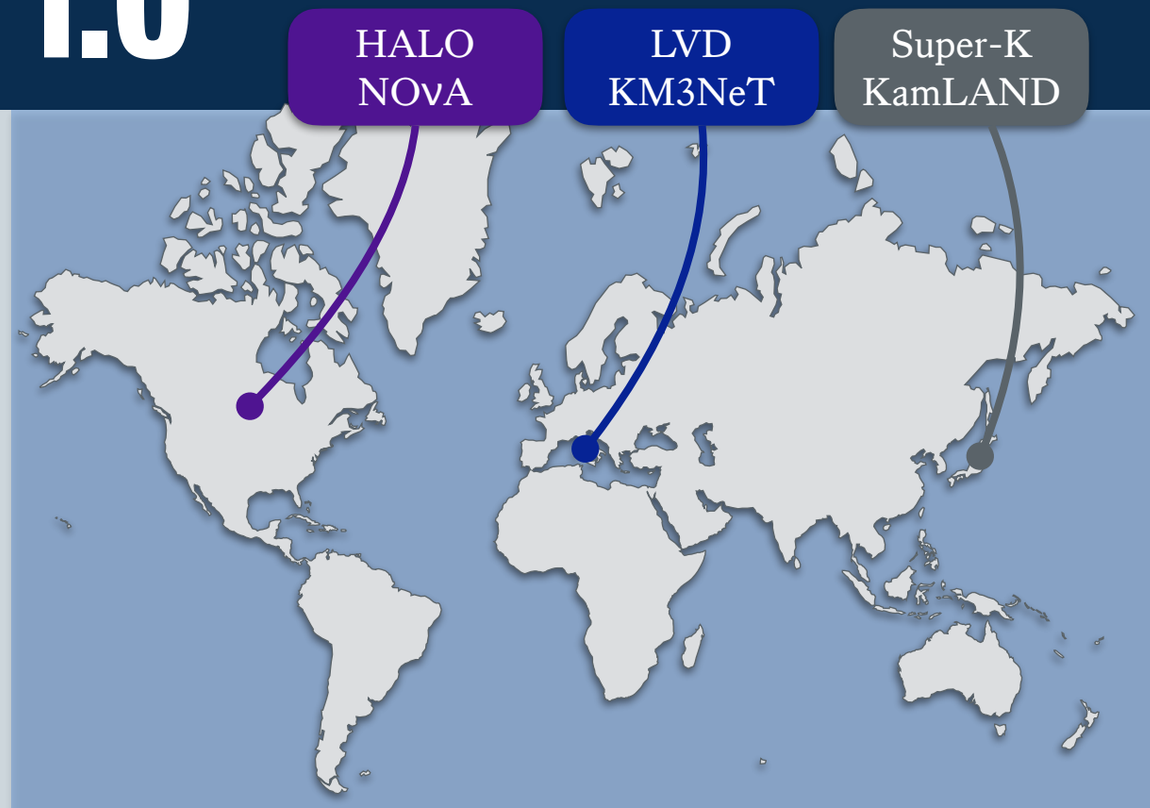
"3 P's" of a good alert *(K.Scholberg, 2000)*

✅ Prompt: send alert within ~min

❌ Pointing: *(left up to individual experiments)*

✅ Positive: false-alarm rate < 1 per 100 years

SNEWS 1.0



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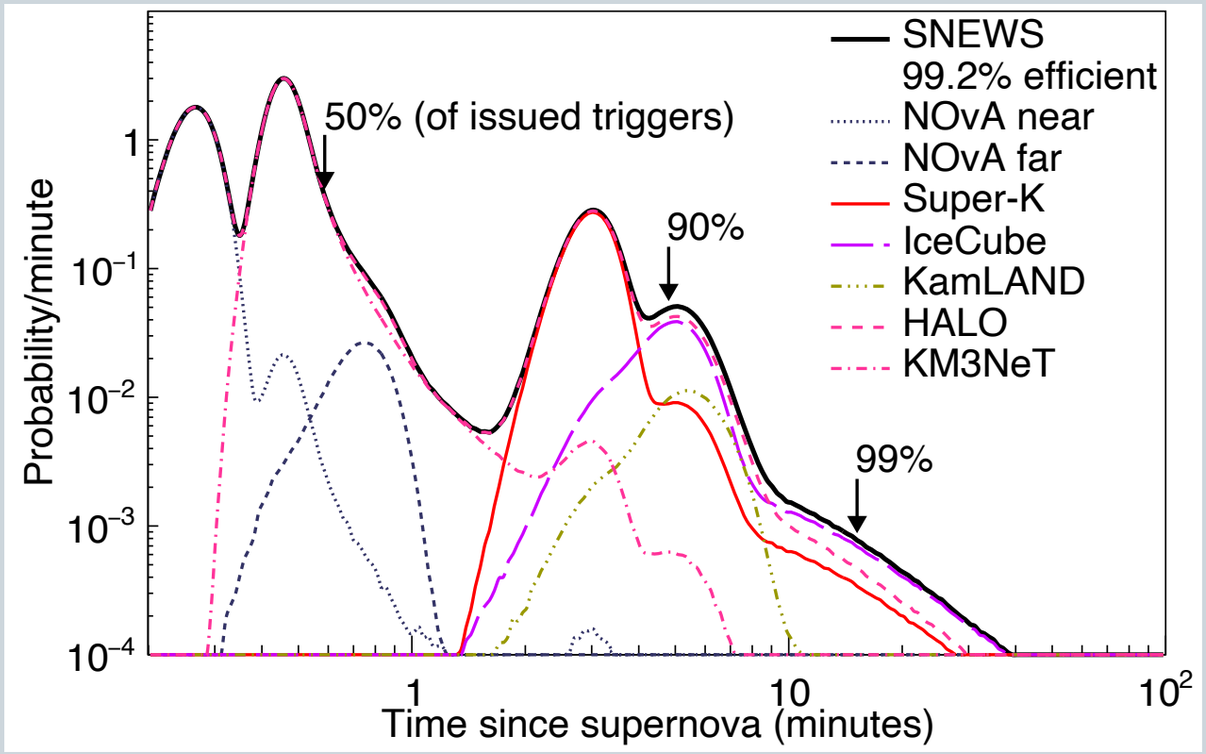

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limiting factor

SNEWS 2.0

- Since 2019: re-imagined SNEWS for today's new age of multi-messenger astronomy
  (arXiv:2011.00035 / DOI:10.1088/1367-2630/abde33)

- Basic implementation almost complete

- Negotiating MoUs & regular "fire drills" in coming months

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

✅ Prompt

❌ Pointing

✅ Positive

- Fast
- Full-featured
- FAR

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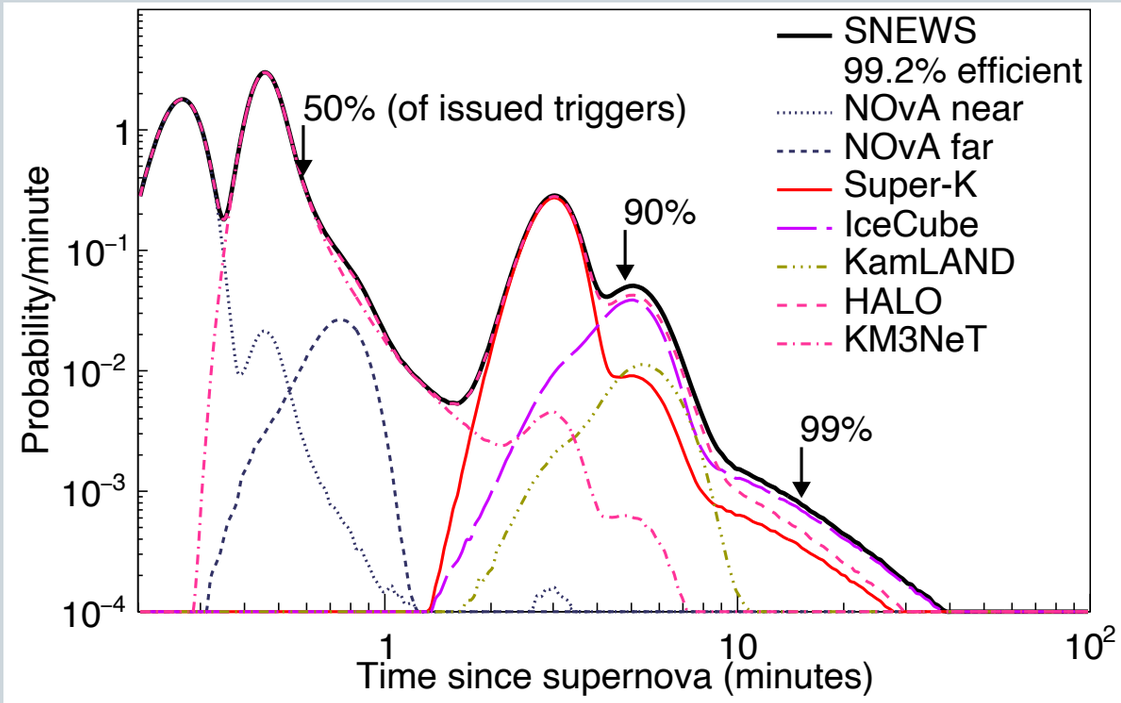
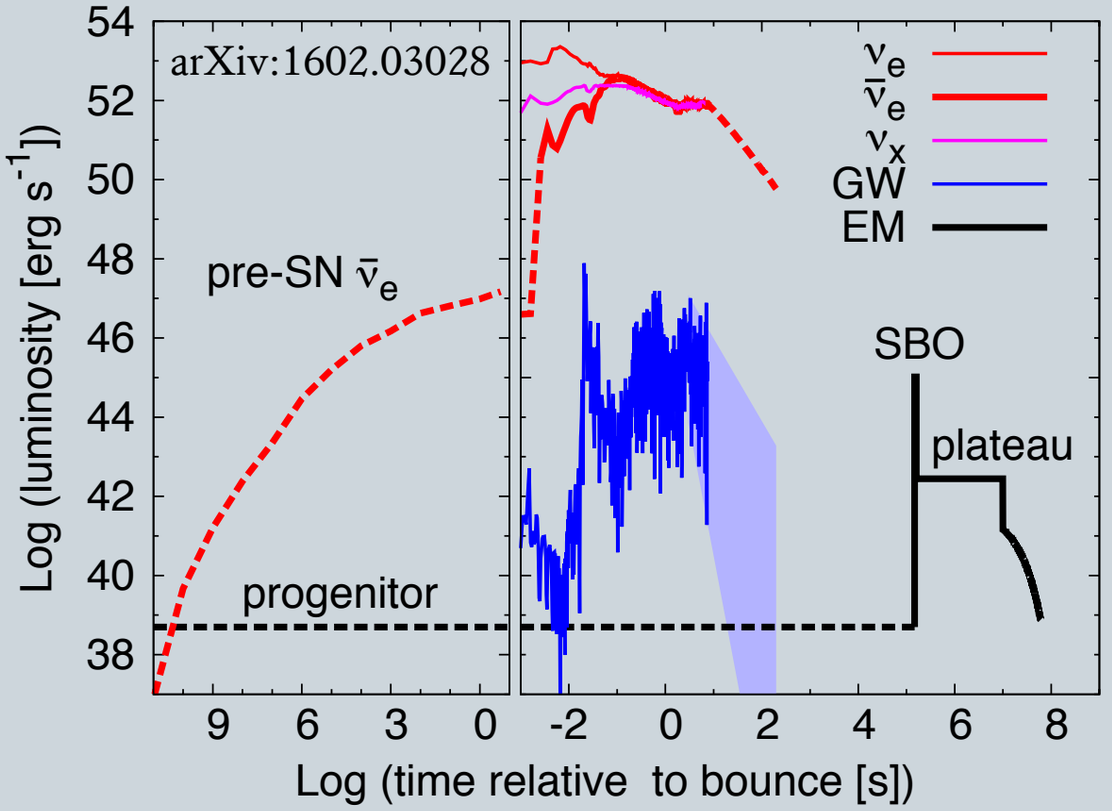
✅ Fast

- Lower latency
  - More flexible SNEWS policy
  - DAQ design of individual experiments is important



- Pre-supernova neutrino alert
  - ~hours warning from Si burning
  - KamLAND already shares significance, some other experiments are sensitive
  - Low statistics ➔ severely distance limited (<1 kpc)

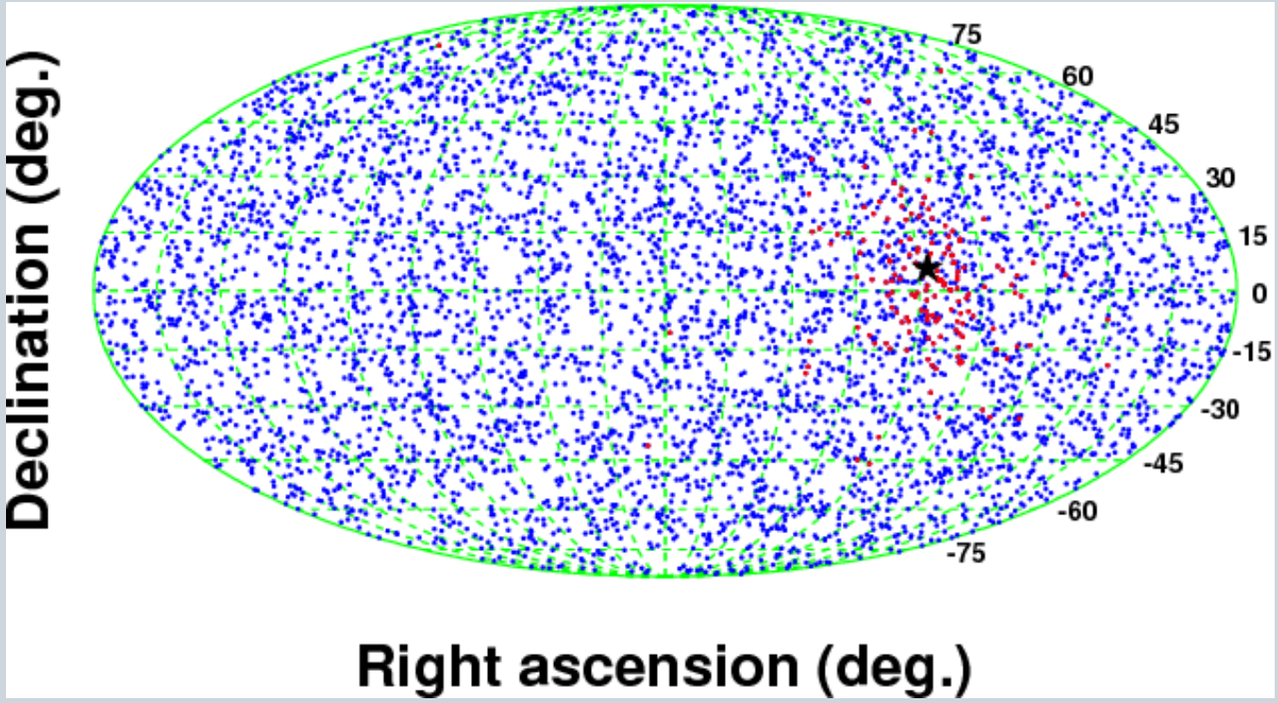


✅ Full-Featured

- Want to know as much additional information as possible to inform follow-up strategy
  - Pointing (“3 P’s”)
  - Distance
  - Event type
  - …

✅ Full-Featured

- Two ways to determine direction
  - Directional information from reconstructed events
  - Triangulation between different experiments



SK: IBD + ^{16}O-CC (blue) and e scattering (red) events, arXiv:1601.04778

- Mainly from ν-e scattering in WCh detectors
- Good accuracy (e.g. Super-K: ~5° at 10 kpc)
- Slow, requires full event reconstruction
- Up to each experiment, SNEWS can combine info from detectors & progenitor lists

✅ Full-Featured

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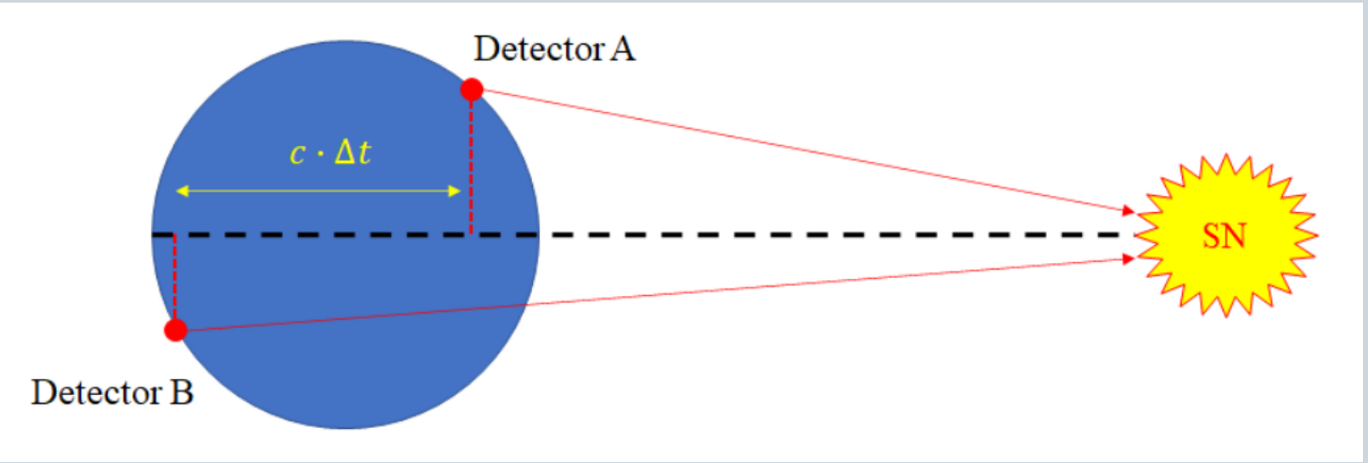

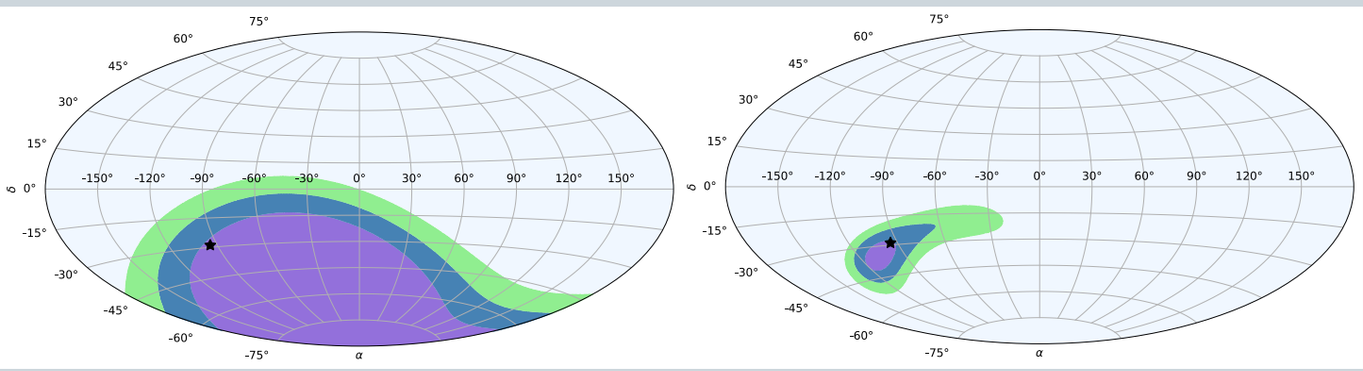

⬆️ SK+IC

arXiv:1909.03151

⬆️ HK+IC+JUNO+DUNE

- Arrival time difference up to ~40 ms between detectors
- If clocks synchronised & common definition of t_0, can identify direction
- Less precise, but very fast
- Identify suitable telescopes, start slewing

✅ Full-Featured

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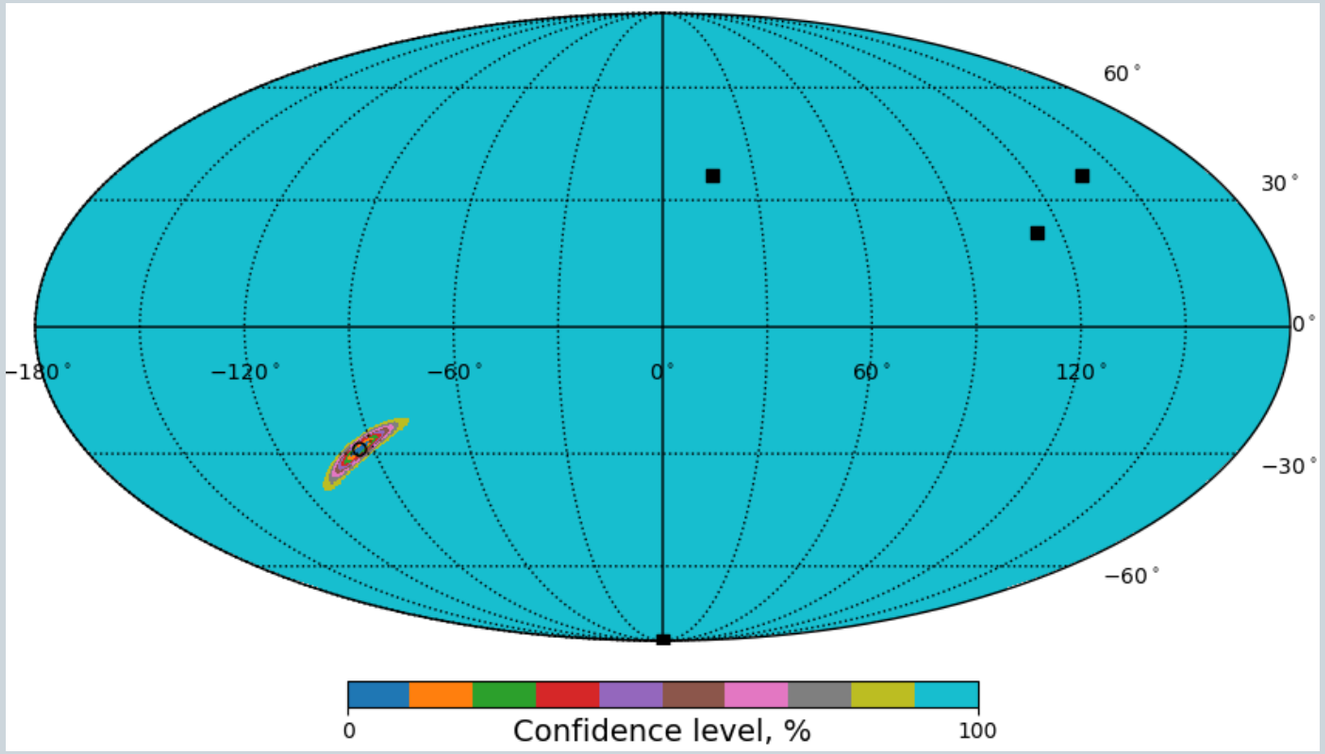


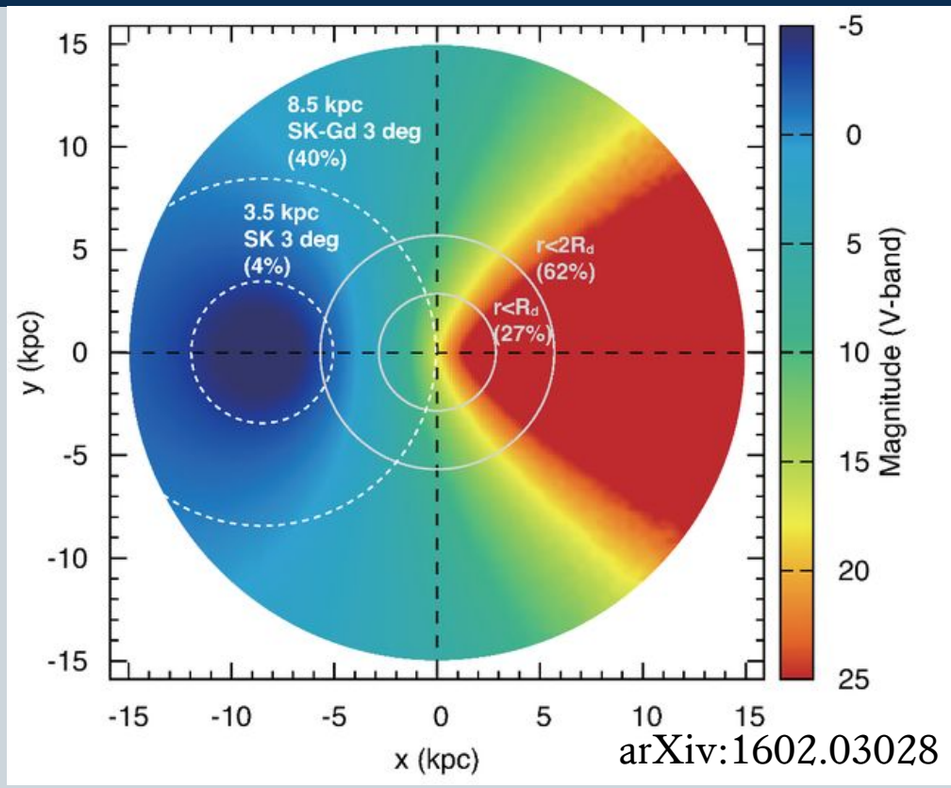
IC+ARCA+HK+JUNO (arXiv:2003.04864)

- Instead of just t_0, use time series matching to improve accuracy
- Similar experiments only (e.g. IBD-dominated)
- Rapid changes in flux (e.g. BH cut-off) very powerful

✅ Full-Featured

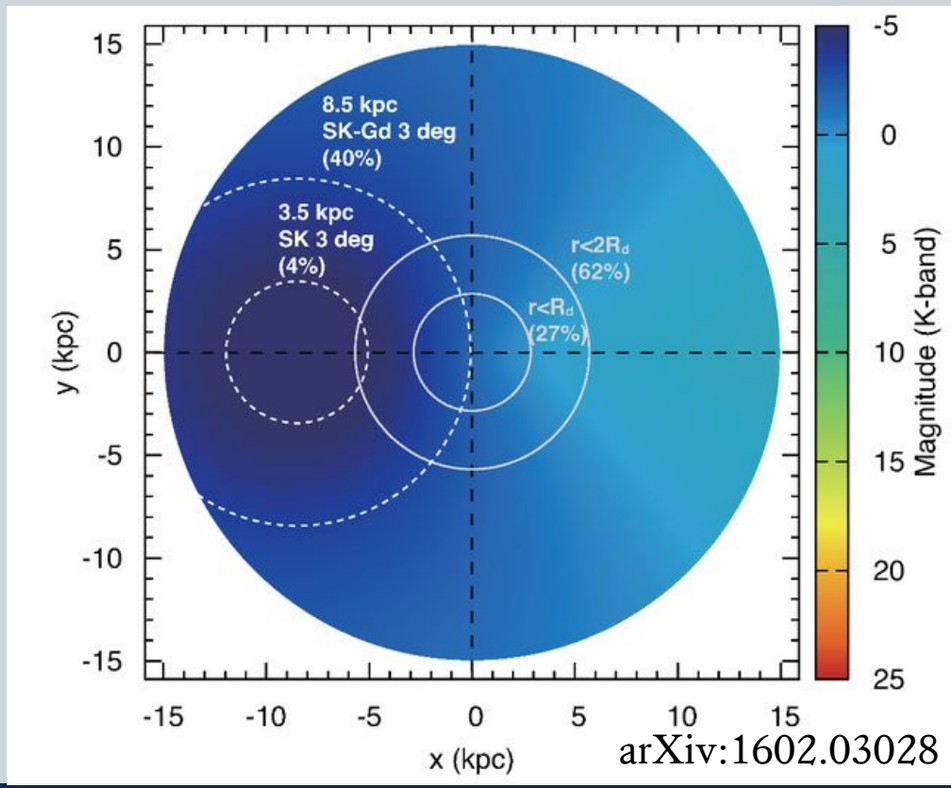
- Distance may affect the optimal observation strategy
  - Dust obscuration near GC
  - If close: direction may let us create "shortlist" of candidate stars
  - Estimate from event rate

  (or in more advanced ways, see supplementary slides)



- Event type
  - Sudden cut-off in ν signal can indicate black hole formation
  - Identify non-core-collapse events? (SN Ia, PISN, binary merger, …)

⬆ Optical Near-IR ⬇



✅ FAR

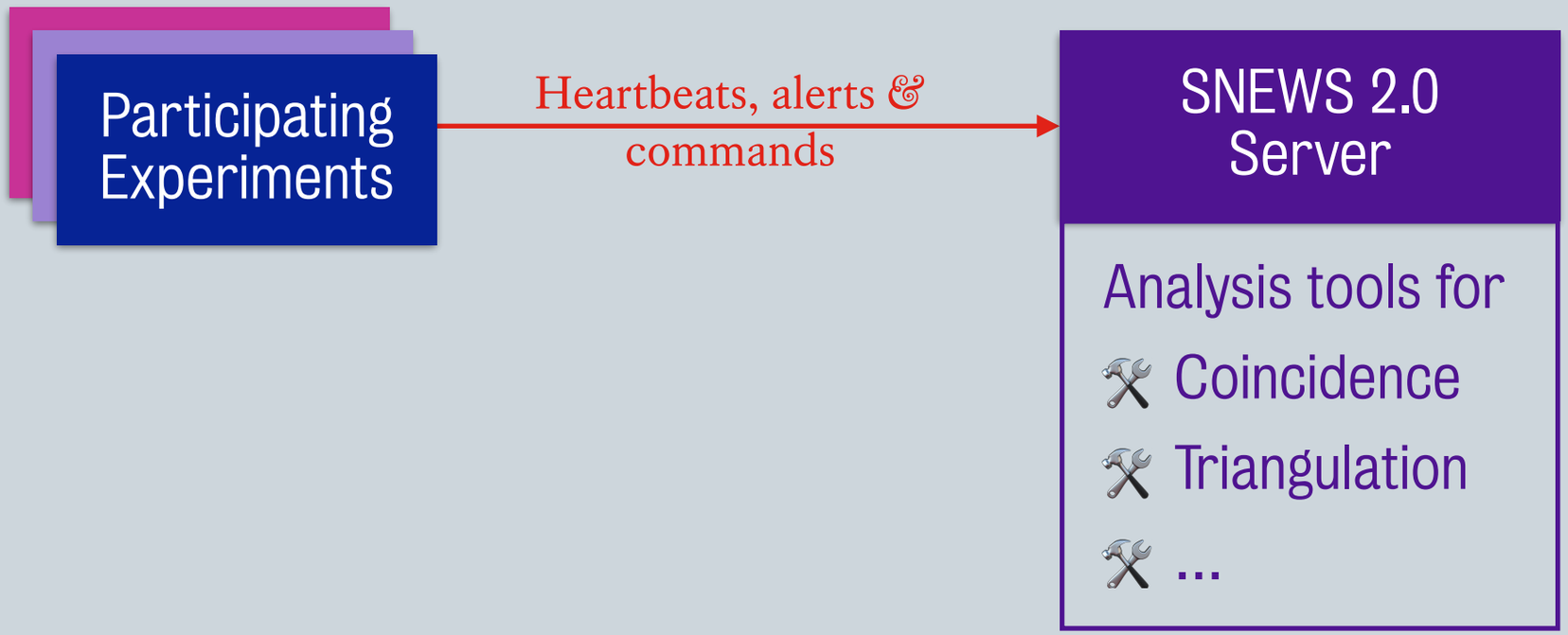
- GW alerts have demonstrated that it's fine to send out uncertain alerts if false alarm rate is included
  - No "Boy who cried wolf" effect
    - Astronomers can set their own FAR threshold
- Allowing higher FAR enables sensitivity at farther distance, e.g. for LMC & exotic transients

SNEWS 2.0 Software Overview

Participating Experiments

Astronomers, GW detectors, general public

SNEWS 2.0 Software Overview



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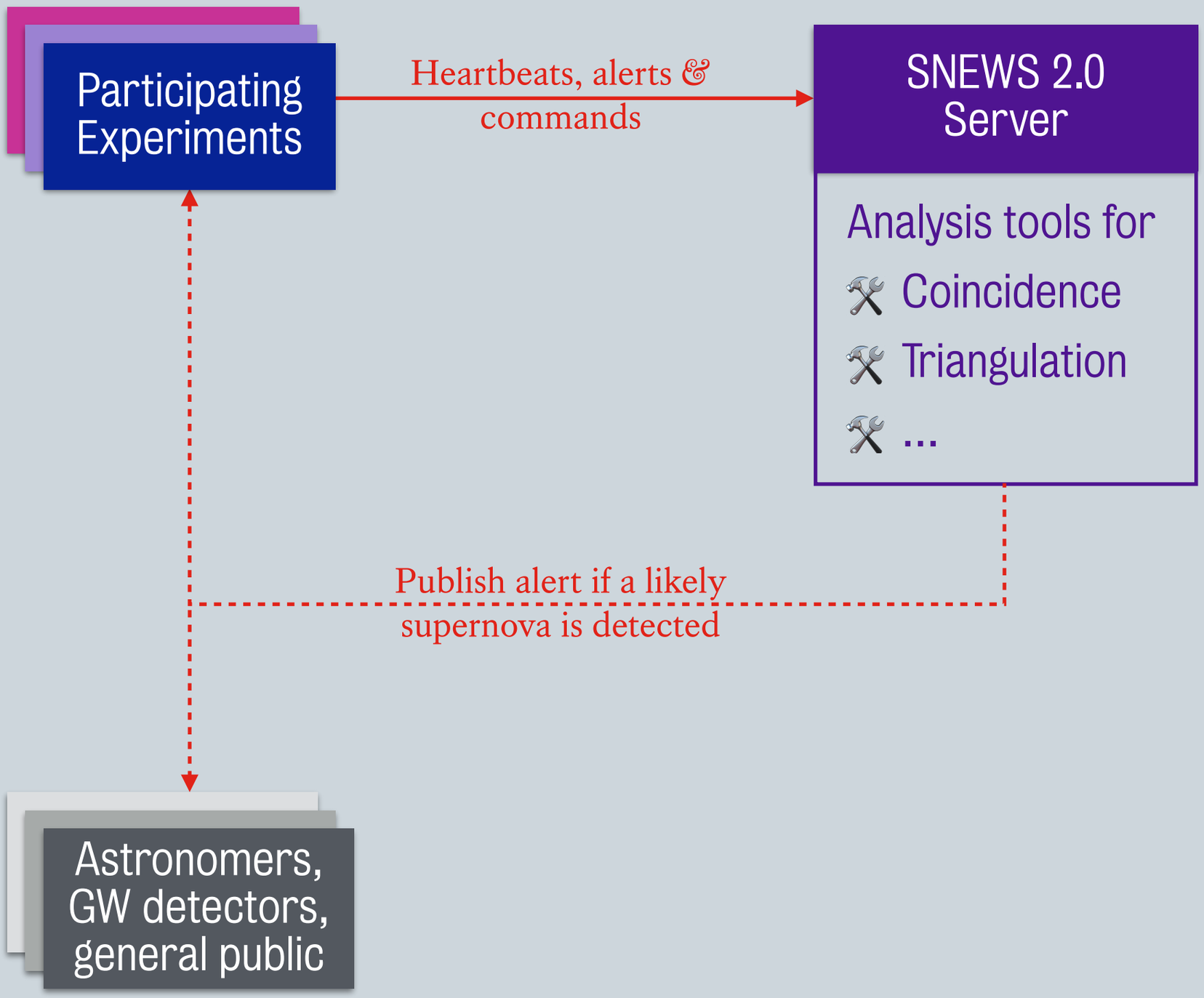


SNEWS 2.0 Software Overview

Participating Experiments

Heartbeats, alerts & commands

SNEWS 2.0 Server

Analysis tools for

- Coincidence
- Triangulation
- ...

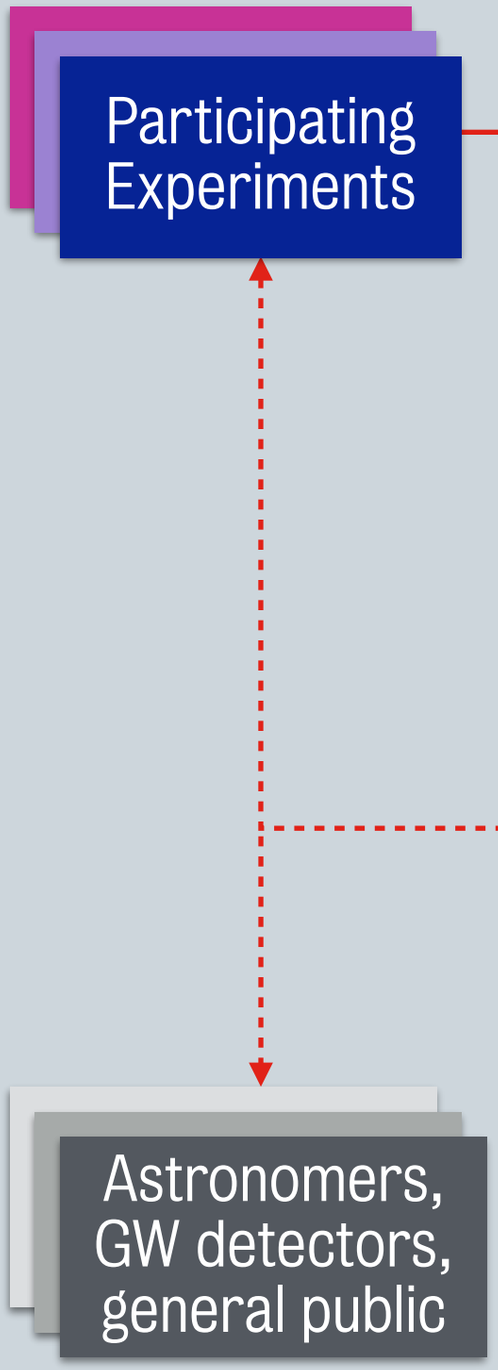
Simulation tools

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

Publish alert if a likely supernova is detected

Astronomers, GW detectors, general public

SNEWS 2.0 Software Overview



Publicly available on GitHub:

- SNEWS Publishing Tools
- Online analysis tools
- snewpy

Offline Simulation Tools: SNEWPY

SNEWPY offers ...

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➔ Try in a Binder!

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Can use these in your code!

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Usage of SNEWPY

- SNEWS-internally
- By other software:
  - sntools (DOI:10.21105/joss.02877)
  - ASTERIA (DOI:10.5281/zenodo.3926834)

smooth transition from quick initial estimates to advanced analyses

- In non-SNEWS papers:

Neutrino Echos following Black Hole Formation in Core-Collapse Supernovae

Samuel Gullin,[1] Evan P. O'Connor,[1] Jia-Shian Wang,[2] and Jeff Tseng[2]

[1] *The Oskar Klein Centre, Departm*
Stockholm University, AlbaNova, SE-10
[2] *Department of Physics, Oxford University, Ox*

arXiv:2109.13242

arXiv:2203.05141

Detectability of hadron-quark phase transition in neutrino signals of failing core-collapse supernova

Zidu Lin,[1] Shuai Zha,[2] Evan P. O'Connor,[3] and Andrew W. Steiner[1,4]

[1] *Department of Physics and Astronomy, University of Tennessee Knoxville*
[2] *Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai 200240, China*
[3] *The Oskar Klein Centre, Department of Astronomy, Stockholm University, AlbaNova, SE-106 91 Stockholm, Sweden*
[4] *Physics Division, Oak Ridge National Laboratory*
(Dated: March 11, 2022)

Follow-Up: A New Era

- 1997: ATel & GCN started distributing alerts
  - Human-readable, unstructured, via mailing list
  - Good strategy for SNEWS 1.0
- Today: up to 10^7 alerts per night (LSST)
  - Specialized brokers distribute & filter alerts for end users, large degree of automation
  - Many robotic & fully automated telescopes
- SNEWS is important forum to bring neutrino & astronomy communities together and prepare follow-up strategy

  ➔ Ensure maximal science output!

SNEWS 🤝 Astronomy Community

- GRANDMA (Global Rapid Advanced Network Devoted to the Multi-messenger Addicts, arXiv:2008.03962)
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    - Network of “amateur” astronomers in 100+ countries, archive database with ~10^6 observations/year, can send out alerts with observation requests to members
    - Amateur astronomers often more flexible (e.g. photometry in different observation bands, spectra, higher cadence, larger FOV, …)
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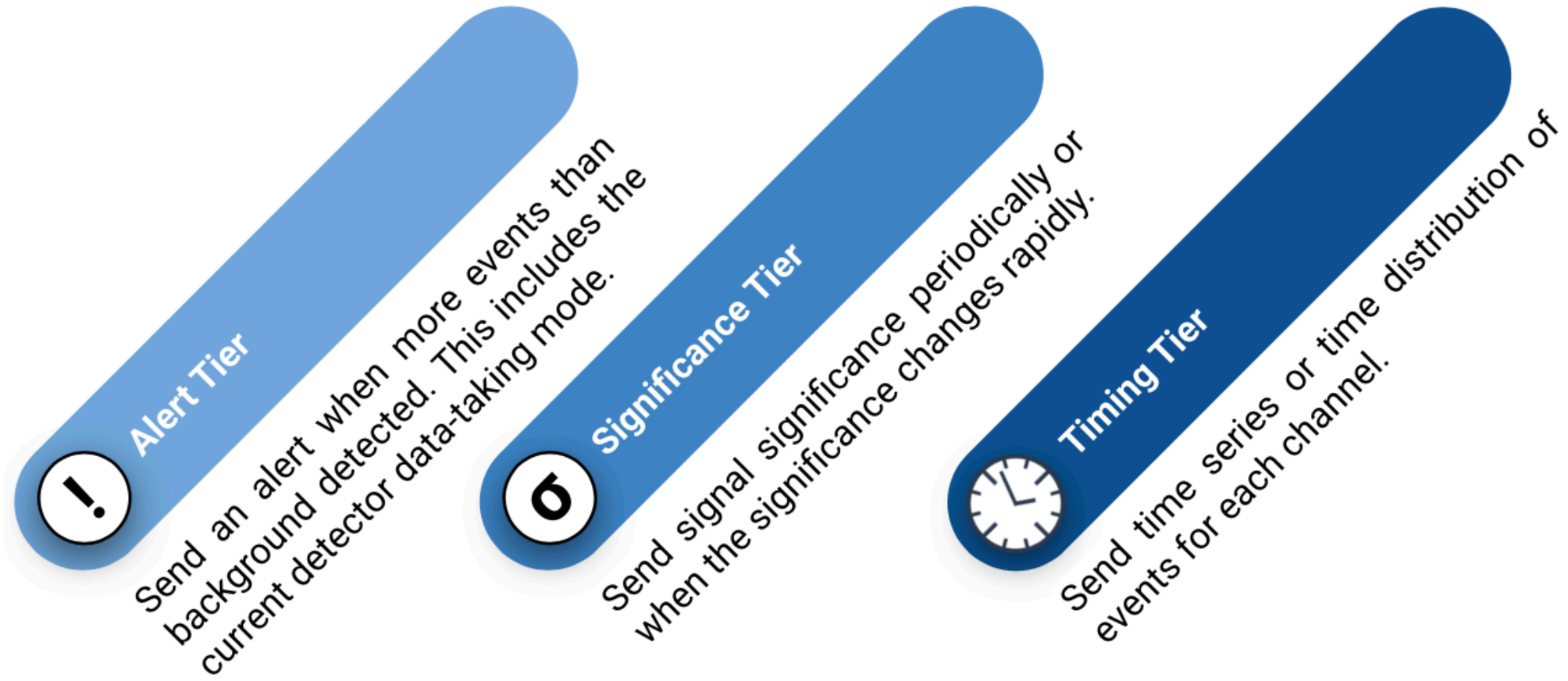
    - Starting campaign to regularly observe SN candidate list
- REFITT (Recommender Engine for Intelligent Transient Tracking, arXiv:2003.08943)
  - AI-based engine to plan & coordinate follow-up strategy, taking into account available facilities (wavelengths, sensitivity, current weather, …)
- *… and more!*

Participating in SNEWS 2.0



Effectively SNEWS 1.0

Experiments can share more data to enable more new features

Experiments can start simple and join more tiers over time!

Summary

- SuperNova Early Warning System was re-invented for the age of multi-messenger astronomy
- SNEWS 2.0 is almost ready
  - Regular fire drills in coming months
  - MoUs with first experiments (including KM3NeT) under discussion
- Very active field, ongoing improvements

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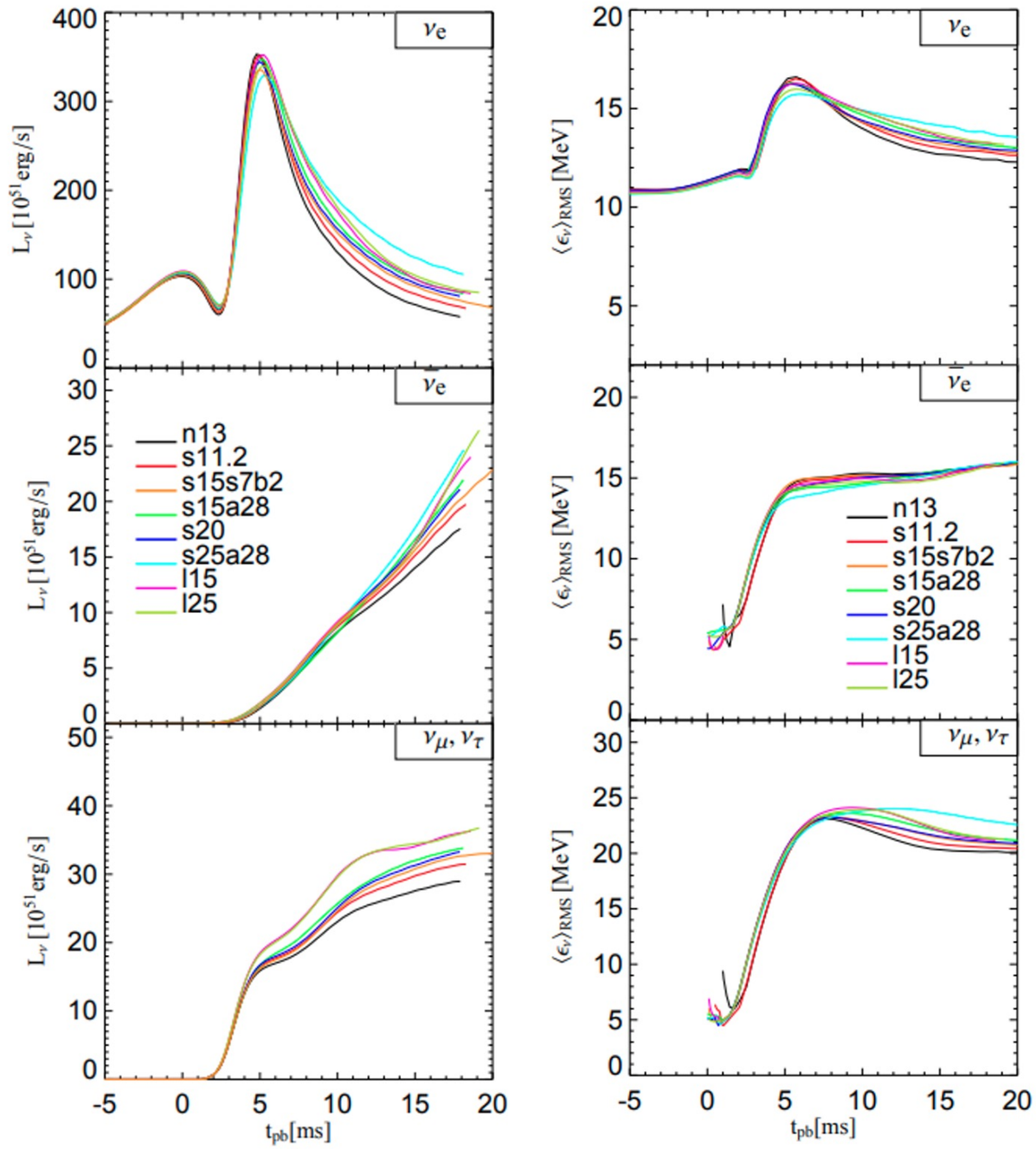
Let's make the most of this once-in-a-lifetime opportunity!

Backup Slides

Distance

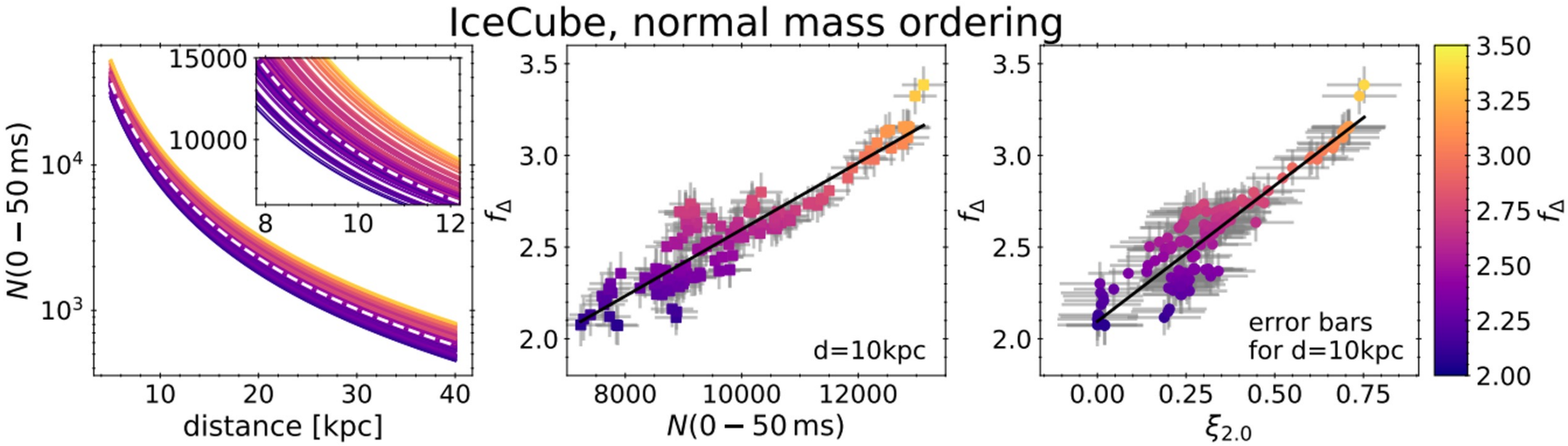
Kachelriess et al., PRD71 (2005) 063003

- Neutronization burst (ν_e) self-limited by electron captures
  - Potential standard candle, stable vs progenitor mass
  - Yield can be used to estimate distance to SN
- 1MT water Cherenkov detector
  - Average 112 EES events at 10kpc
  - 5% uncertainty on distance
- SNO+ and JUNO should also get a sizable number of proton elastic scattering events



Distance

- Anti-ν_e yield ratio of (100,150)ms / (0,50)ms related to “compactness”
  - Can also be related to mass → similar sensitivity, smaller detectors using IBD



Segerlund et al., arxiv:2101.10624 (2021)

Collaboration with SCiMMA

- Scalable Cyberinfrastructure for Multi-Messenger Astrophysics
  - NSF-funded project used by IceCube, LIGO, …
  - Develops HOPSKOTCH: “a scalable, high-throughput low-latency platform for handling real-time data streams for MMA applications”
- SNEWS & SCiMMA started close collaboration in 2020
  - SNEWS: Don’t need to implement & maintain basics like identity/access management, pub-sub infrastructure, …
  - SCiMMA: Real-world test of early protoype, rapid user feedback
- Paper: “Collaborative Experience between Scientific Software Projects using Agile Scrum Development” (arXiv:2101.07779, DOI:10.1002/spe.3120)

SNEWS Publishing Tools

- Developing SNEWS Publishing Tools on top of HOPSKOTCH
- Publish or subscribe from notebook or CLI
- `schema_version` and `meta` included in every message schema

```
from snews_pt.snews_pub import SNEWSTiersPublisher
from datetime import  datetime
test_time = datetime.utcnow().strftime("%y/%m/%d %H:%M:%S:%f")

message = SNEWSTiersPublisher(detector_name='XENONnT',
                              machine_time=test_time,
                              neutrino_time=test_time,
                              p_val=0.0007,
                              p_values=[0.001, 0.02, 0.005],
                              t_bin_width=0.5,
                              firedrill_mode=False)

message.send_to_snews()
```

```
-------------------------------------------------------------------
Sending message to CoincidenceTier on kafka://kafka.scimma.org/snews.experiments-test
_id                 :19_CoincidenceTier_22/08/03 02:05:43:869112
detector_name       :XENONnT
machine_time        :22/08/03 02:05:43:869112
neutrino_time       :22/08/03 02:05:43:869112
p_val               :0.0007
meta                :{}
schema_version      :1.1.0
sent_time           :22/08/03 02:05:43:878058
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```

```
jost@Macintosh ~/D/A/S/S/S/snews_pt (main)> snews_pt publish my_alert.json
```

```
schema_version       :1.1.0
sent_time            :22/08/03 02:05:43:878058
```

SNEWS Publishing Tools

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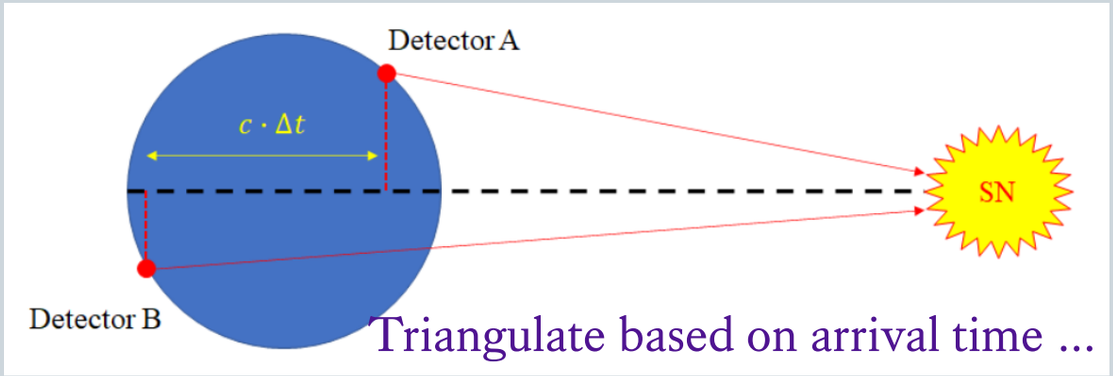
```
In [*]: from snews_pt.snews_sub import Subscriber
        Subscriber().subscribe()

        You are subscribing to ALERT
        Broker:kafka://kafka.scimma.org/snews.alert-firedrill
```

```
(snews) kara-unix@iap-nb-034:auxiliary$ ls custom*
custom_script.py
(snews) kara-unix@iap-nb-034:auxiliary$ snews_pt subscribe -p custom_script.py
Redirecting output to custom_script.py
You are subscribing to ALERT
Broker:kafka://kafka.scimma.org/snews.alert-firedrill
```

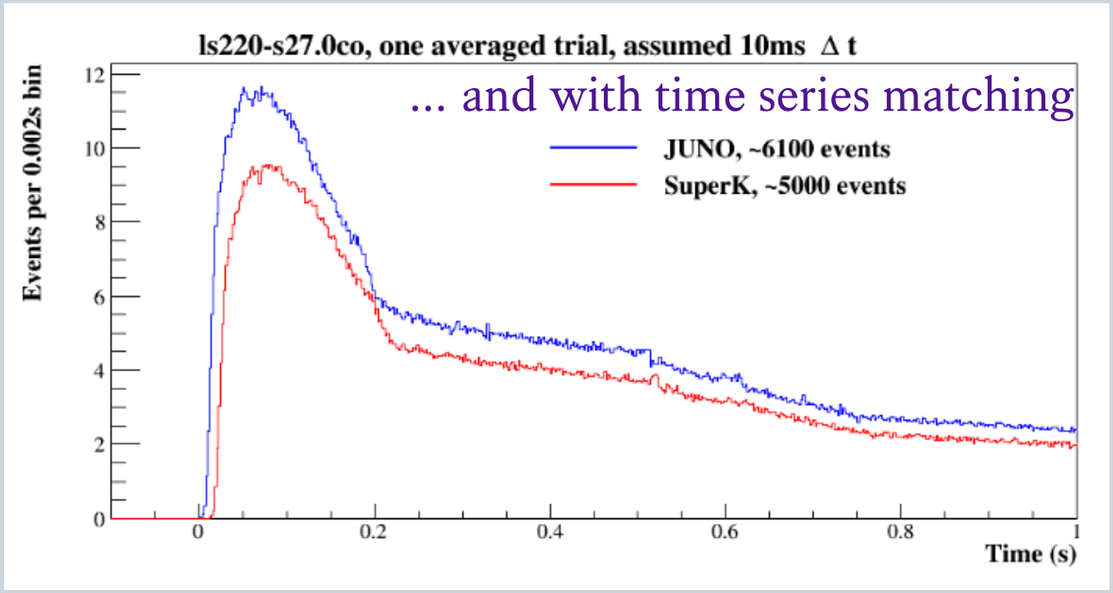
Real-time Analysis Tools

- Publicly available on GitHub



Triangulate based on arrival time ...

- Coincidence System



- Heartbeat Handler
- SNEWPDAG
  - Directed Acyclic Graph built from different plugins
  - Estimate distance, triangulate direction, compare with progenitor distribution, ...