J Tseng

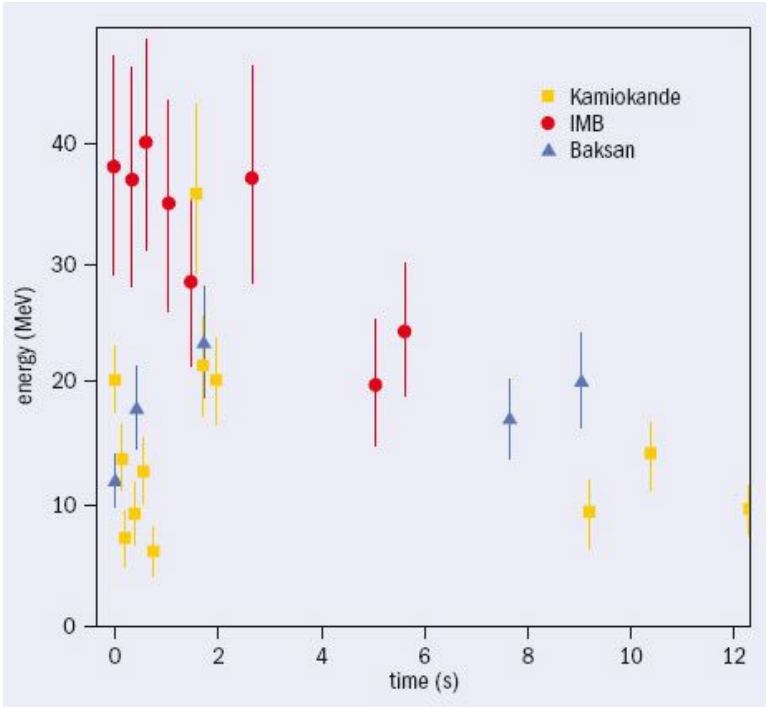
3rd Astro-COLIBRI workshop

17 September 2024

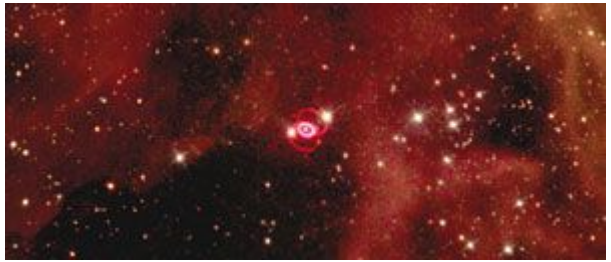
UNIVERSITY OF OXFORD

SN1987A

23 Feb 1987



2-3 hours later:
Ian Shelton
(Toronto)
Oscar Duhalde
(Las Campanas)
Albert Jones
(AAVSO)



HST, 1990's

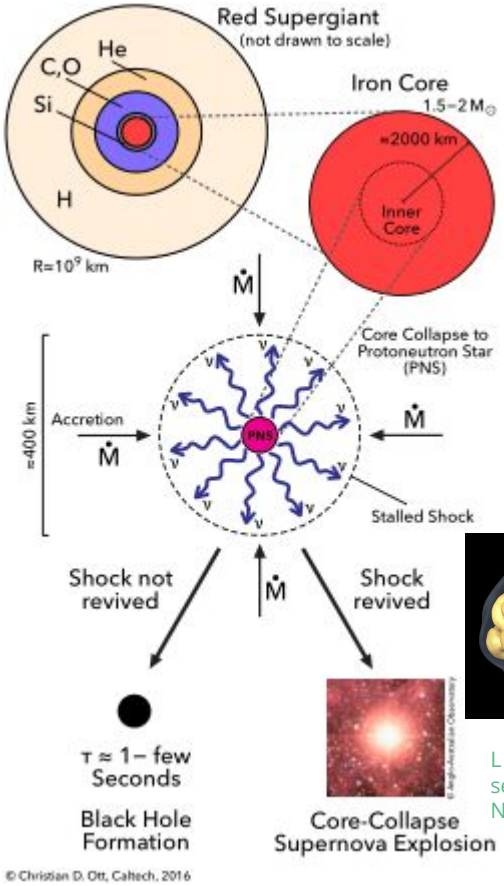
Before/after images © Anglo-Australian Observatory / David Malin

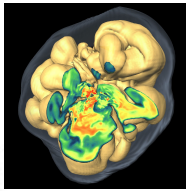
Galactic core-collapse supernova rate

- The bad news: from a survey of historical records, nearby observations, massive stars, neutron star birthrate, ^{26}Al abundance,
  rate is 1.63 ± 0.46 per century
  (Rozwadowska, Vissani, Cappellaro,
  New Astron 83 (2021) 101498)

Galactic CCSN are extremely rare but also extremely rich in physics!

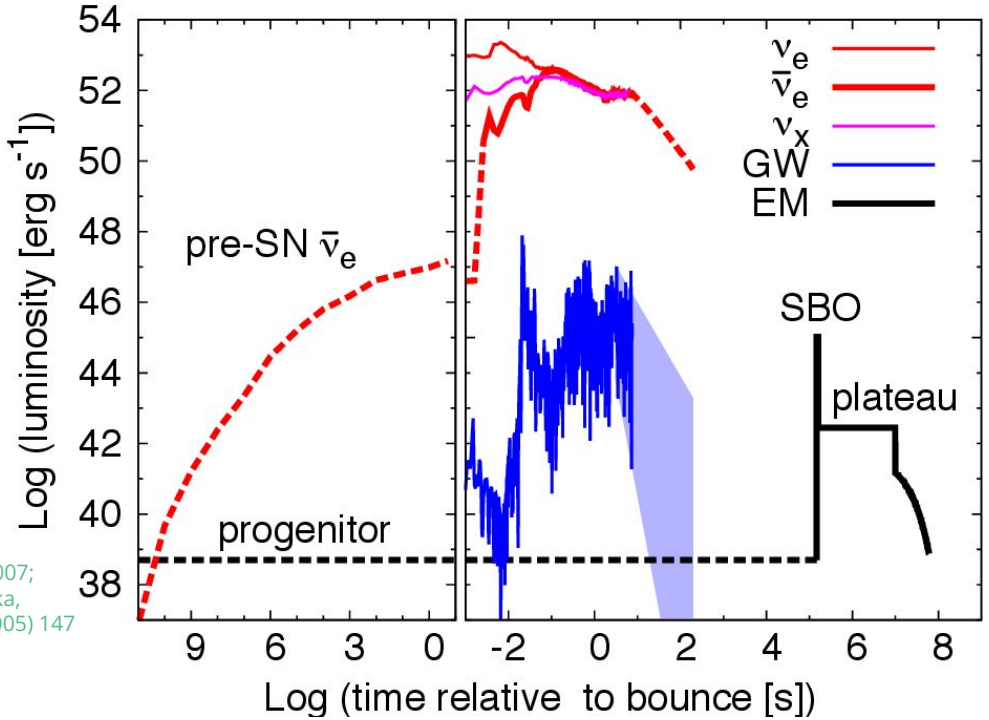
Neutrinos and core-collapse supernovae





15Msun, 0.5s

L Scheck, MPA, 2007; see Woolsey, Janka, Nature Phys 1 (2005) 147



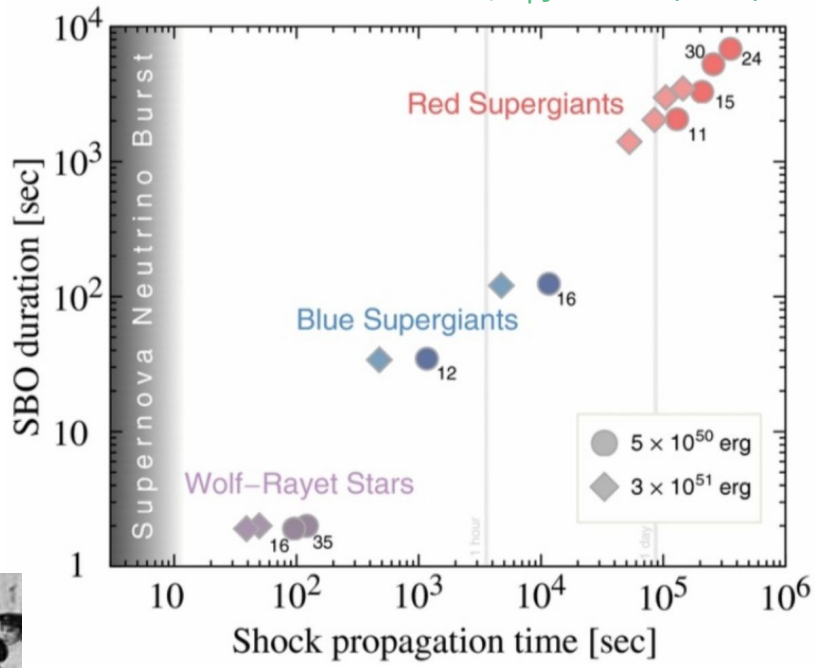
17 $M_\odot$ progenitor, 2D axisymmetric simulation

K Nakamura et al., MNRAS 461 (2016) 3296; pre-SN Odrzywolek et al. (2004)

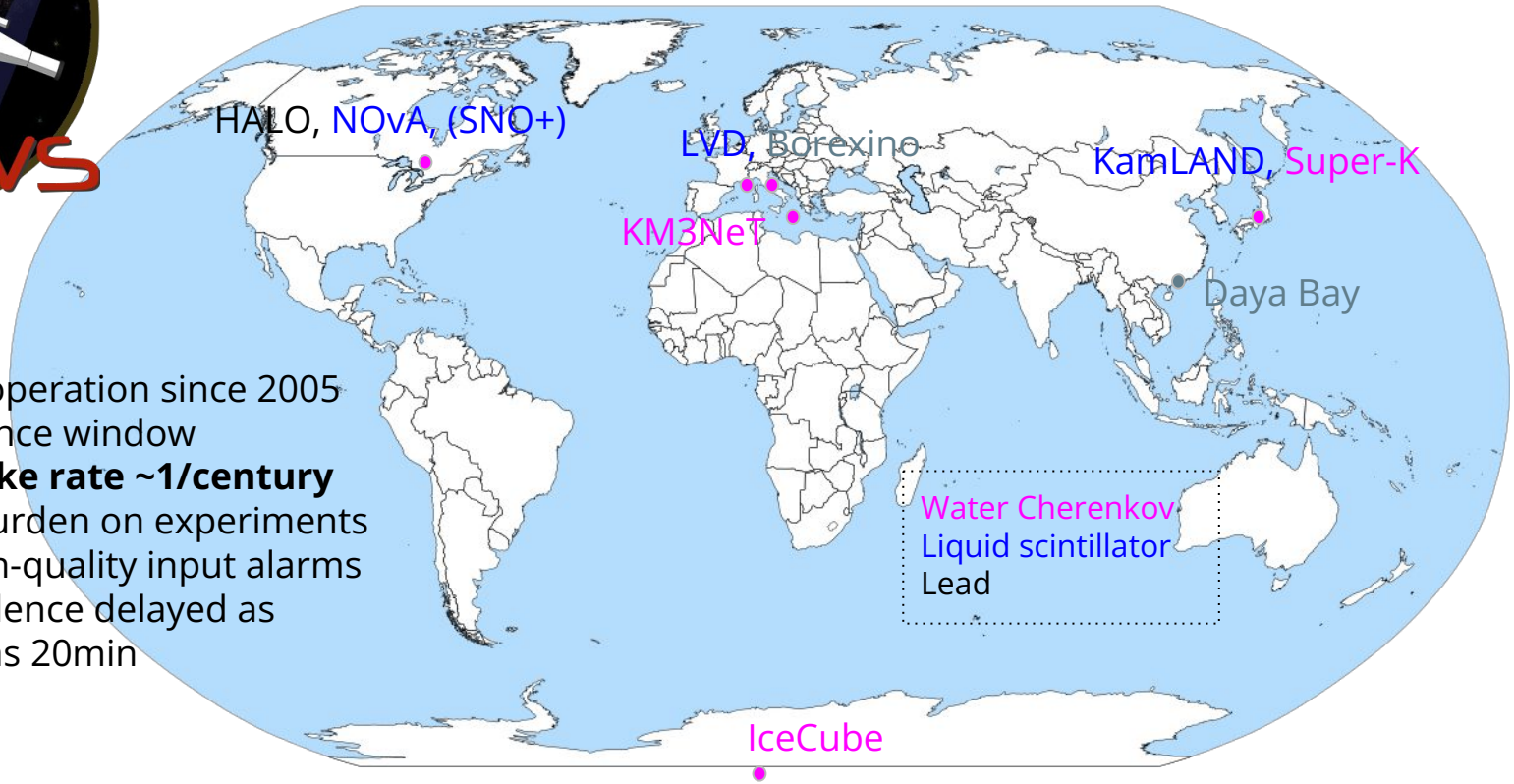
Race against time

- Neutrinos are the starting gun
- The race takes place once in a career
  - You don't know when
  - You don't know how long it lasts
  - You want all hands on deck:
    every possible radiation and wavelength

Kistler et al, ApJ 778:81 (2013)



Current members

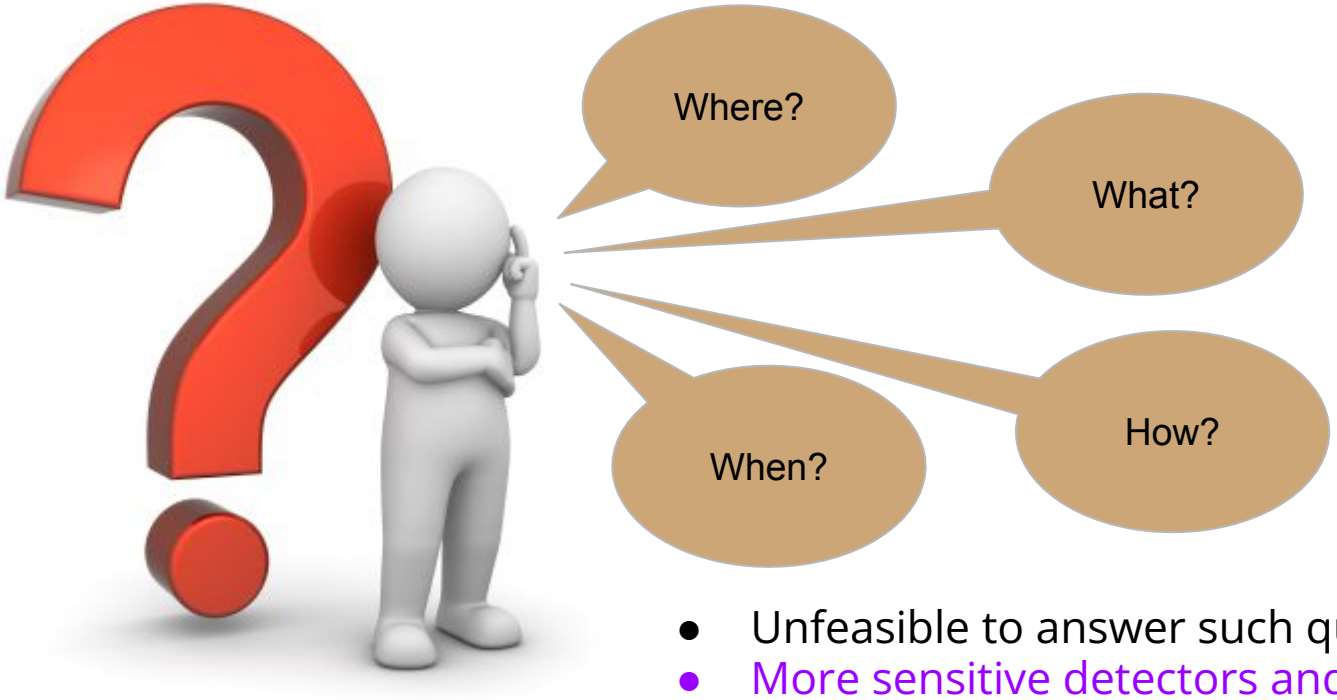


- Automated operation since 2005
- 10s coincidence window
- **Expected fake rate ~1/century**
  - High burden on experiments for high-quality input alarms
  - Coincidence delayed as much as 20min

SNEWS risks

- With fake rate ~ 1.63/century (and no galactic SN since 2005)…

Coincidence - what then?



- Unfeasible to answer such questions in 2005
- More sensitive detectors and techniques…

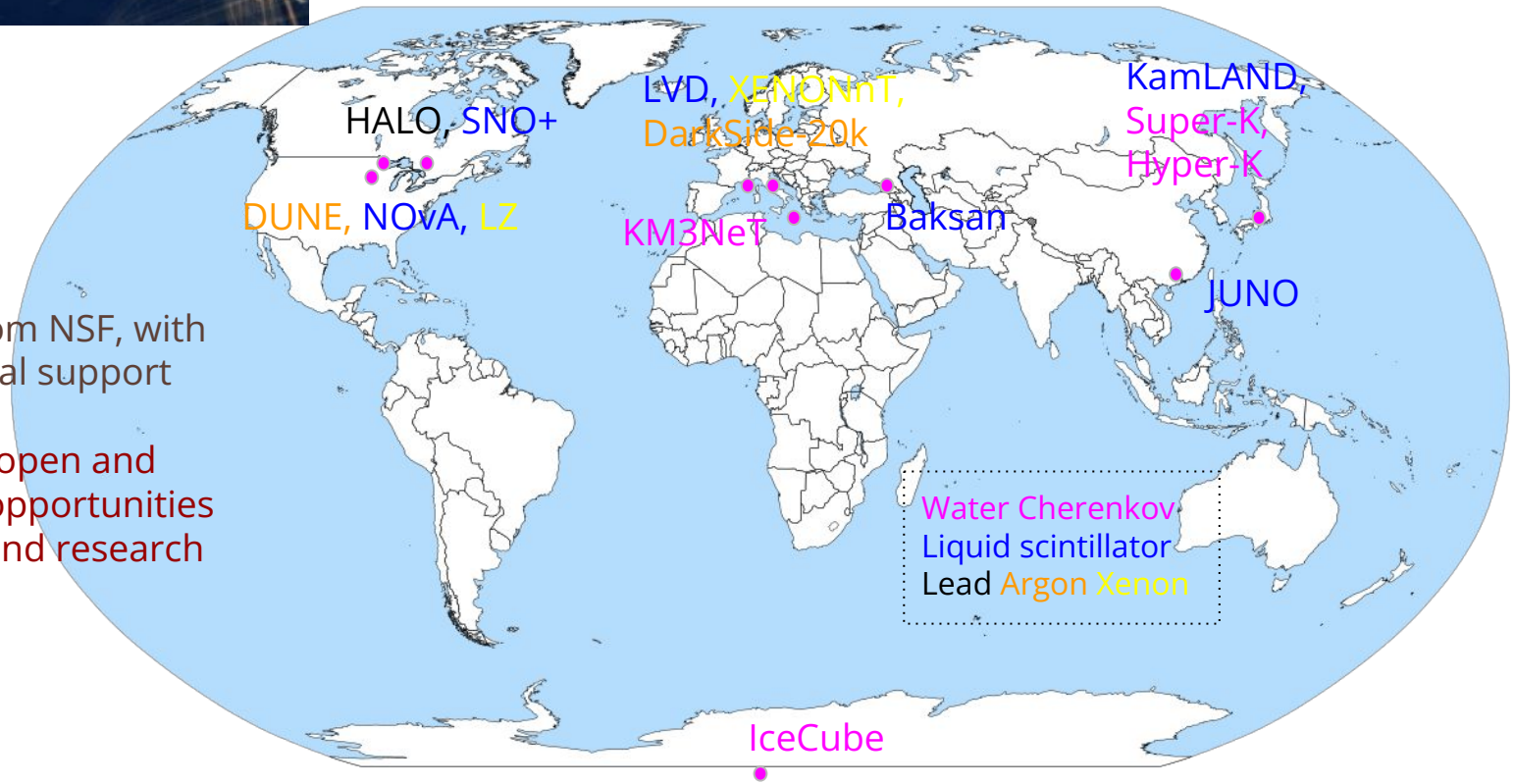
SNEWS2: goals

- Reduce threshold for generating alerts
  - Aim for false alarm rate ~1/month: firedrills, “proof of life”, backgrounds
- Reduce alert latency
- Provide pointing information
- Implement a pre-supernova alert
- Develop follow-up strategies to prepare the astronomy community
- Engage amateur astronomers and citizen science communities

Whitepaper: S Al Kharusi et al., *New J Phys* 23 (2021) 3, 031201
Alert system: M Kara et al., arxiv:2406.17743 [astro-ph.IM]
snews2.org

SNEWS
SUPERNOVA EARLY WARNING SYSTEM

Contacts: Alec Habig, Segev BenZvi

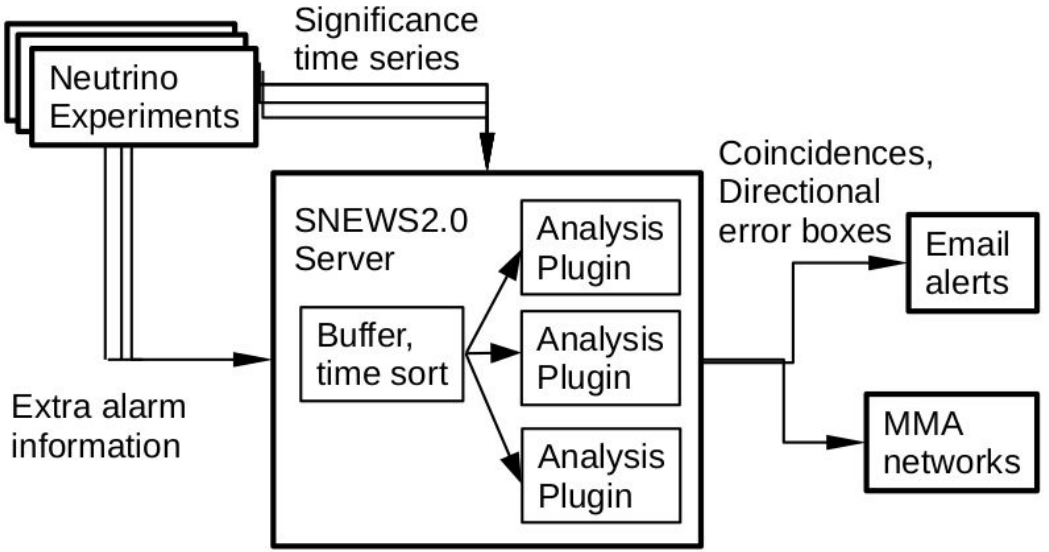


Major funding from NSF, with other international support

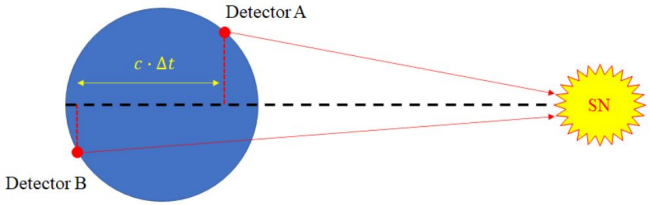
SNEWS activities open and informal: many opportunities for connections and research collaboration

SNEWS2 calculations (pointing+)

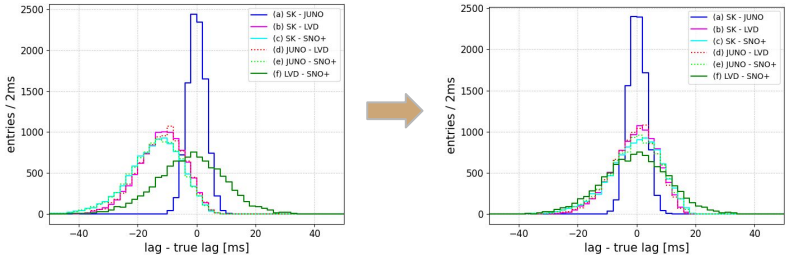
- Provide rapid calculation of observationally relevant quantities
- Direction
- Distance
- Features

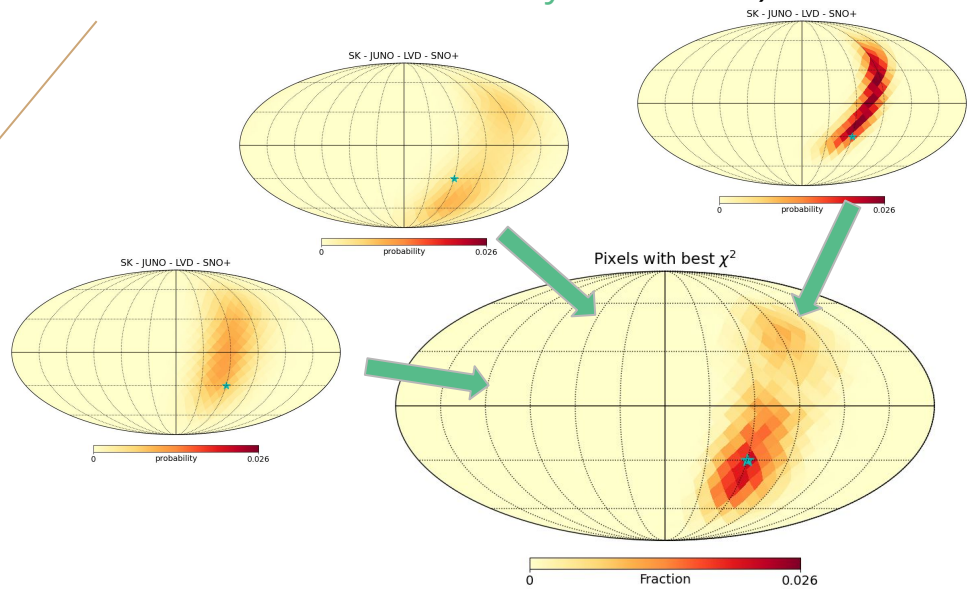


Pointing



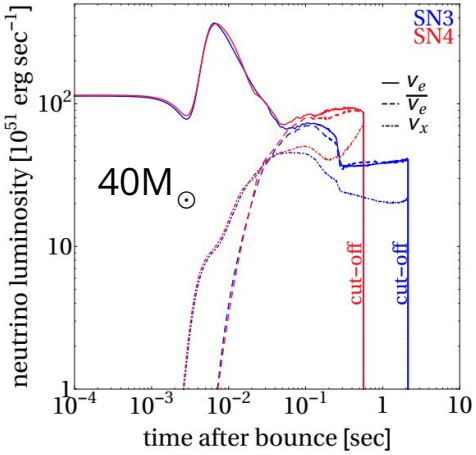
- Electron elastic scattering expected to give most precise pointing
- Triangulation with burst timing: very fast, robust livetime, less precise
  - First event times (with data-driven bias corrections and uncertainty estimation)
  - Residual biases ≲ 1ms
  - Reasonable confidence intervals
    → follow-up search priorities

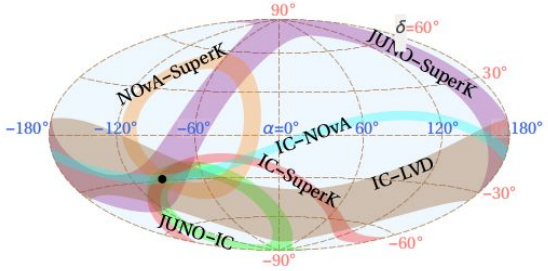




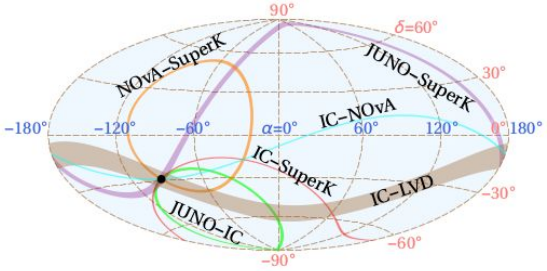
Time series matching

- Time series matching with cross-correlation, χ^2, other metrics
  - Take advantage of other lightcurve features
- Most rapid change: black hole formation
- Illustrative improvement in 1σ contours



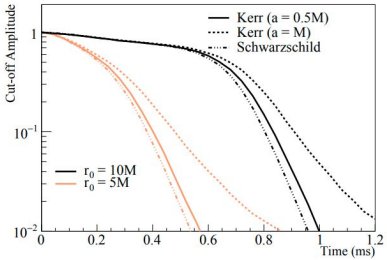


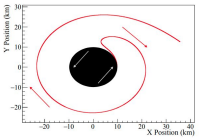
Neutron star formation



Black hole formation

Cutoff with non-radial ν paths





Sample neutrino trajectory around rotating BH

Brdar, Lindner, Xu, JCAP 04 (2018) 025, based on Garching CCSN models

Wang, PRD 104 (2021) 10, 104030

Not all supernovae are alike

Also note that most massive stars exist in binary systems, but models are of single stars

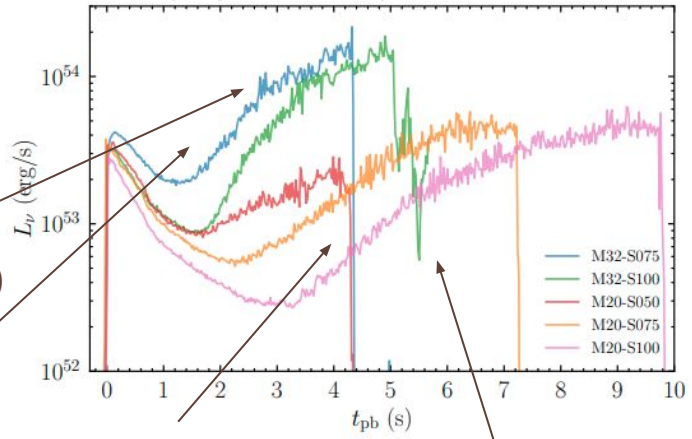
Oscillations (standing accretion shock instability)

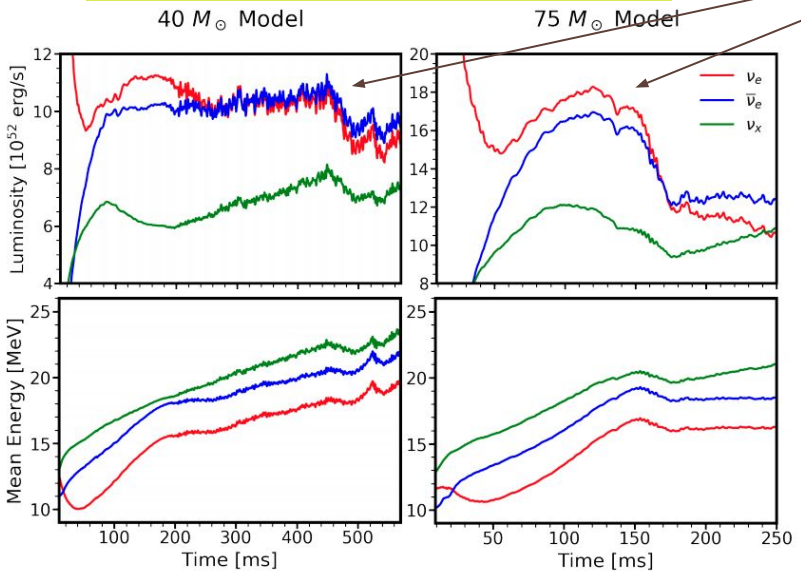
Long accretion (with angular momentum)

Abrupt cut-off

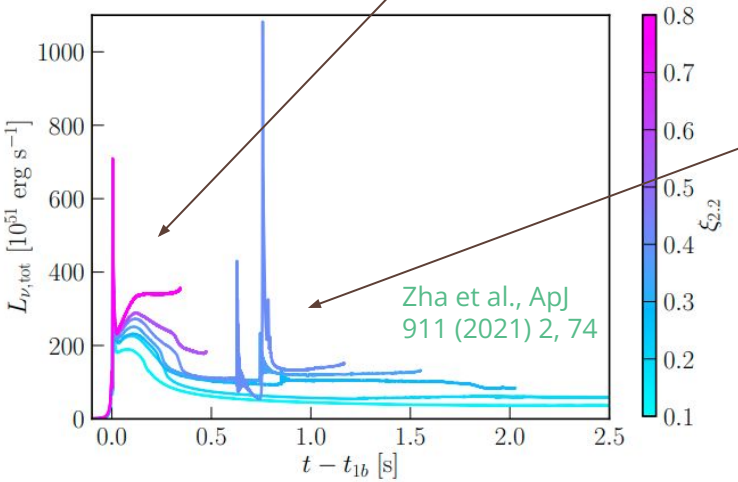
Secondary bursts (e.g., hadron-quark phase transition)

Fujibayashi et al., ApJ 919 (2021) 2, 80





Walk et al., PRD 101, 123013 (2020)

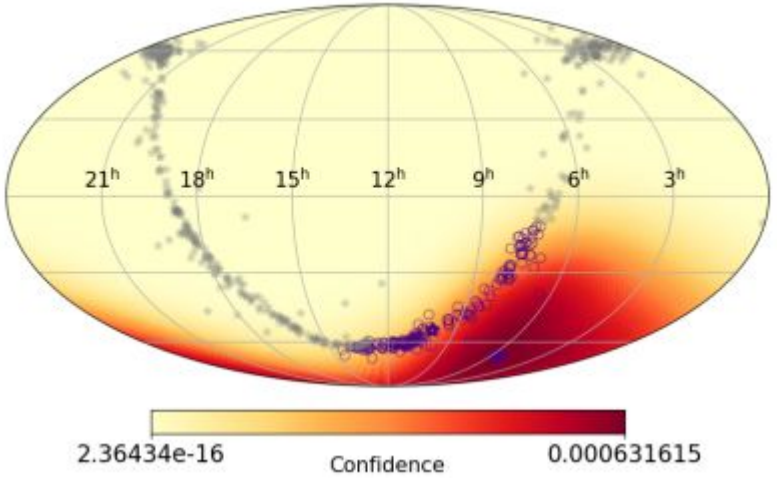


Zha et al., ApJ 911 (2021) 2, 74

Direction: result

- Successive improvement as experiment data comes in
  a. Burst times → rough triangulation
  b. Time distributions → improved triangulation
  c. Experiment pointing using EES → likely to dominate in the end
- Report pointing as a skymap of confidence levels
  - superimpose on candidate stars

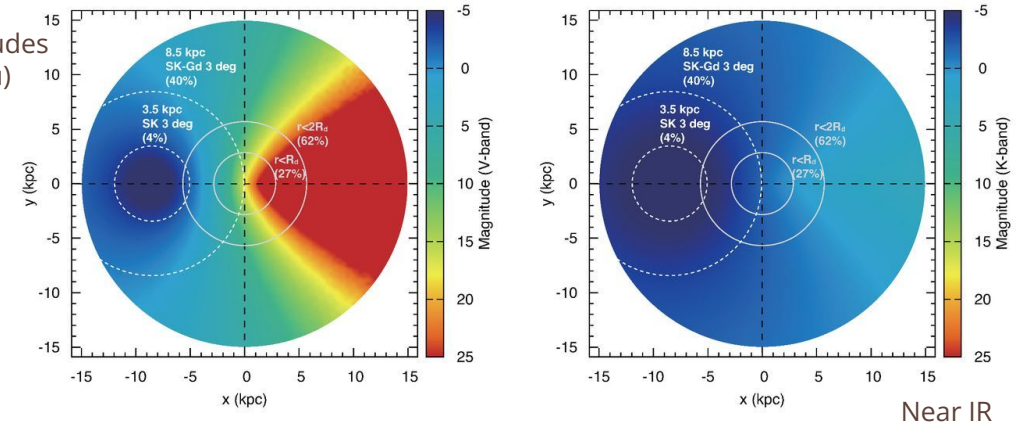
Sample result - deliberately chosen for big, non-trivial contour



Distance

K Nakamura et al., MNRAS 461 (2016) 3296

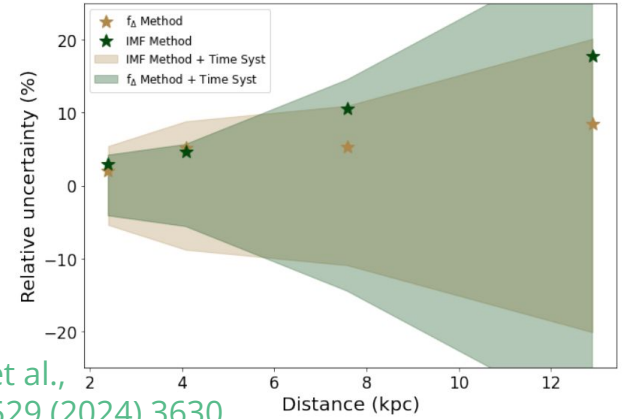
Optical magnitudes (plateau)



SK pointing (% galactic CCSN rate)

Near IR magnitudes (plateau)

- Sizable fraction of the galaxy obscured by dust
  - Distance estimate may change optimal observation strategy
- Neutronization burst (ν_e) self-limited by electron captures
  - Potential standard candle, stable vs progenitor mass
  - Difficult because of low yield
- 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



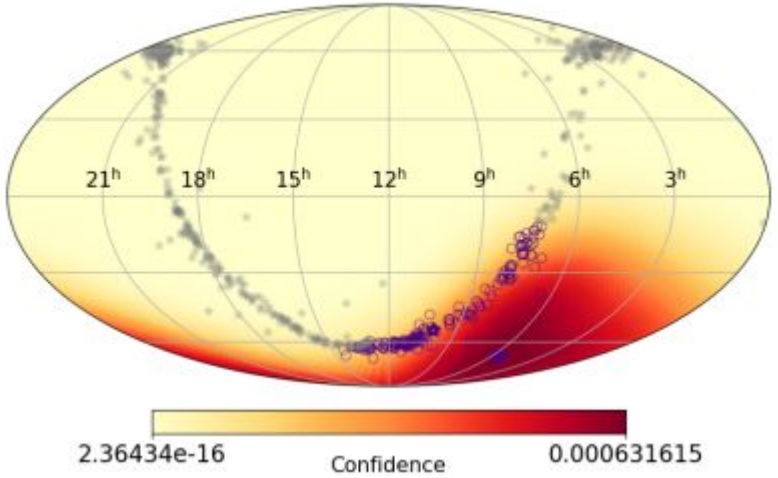
S Healy et al., MNRAS 529 (2024) 3630

Other SNEWS2 activities

snewpy

- SNEWPY simulation tools
  - Unified interface to hundreds of supernova simulations
  - Library of flavor transformations
  - Simplified estimate of expected event rates at detectors
  - A Baxter, *J Open Source Softw* 6 (2021) 67, 3772
- sntools
  - Event generator for supernova neutrino interactions
  - Originally for Hyper-Kamiokande, but spreading to other detectors
- Regular seminars: contact Marta Colomer

- Catalog of 578 highly probable and 62 likely red supergiants
- AAVSO started campaign to regularly observe candidates
- Example localization:
  187 in 90% credible region (direction),
  3 with distance estimation



S Healy et al., *MNRAS* 529 (2024) 3630

Follow-up communities

- American Association of Variable Star Observers
  - Recording amateur observations since 1911
  - Played critical role in early observations of SN1987A
  - Developing narrowfield search strategies
  - Campaign for regular observation of candidate stars
- Global Rapid Advanced Network Devoted to the Multi-messenger Addicts
  - Network of robotic telescopes
  - Experienced with follow-up, amateur astronomer engagement
- Recommender Engine for Intelligent Transient Tracking (REFITT, arxiv:2003.08943)
  - AI engine to plan & coordinate follow-up
- Engage with fire drills and preparation

Conclusion

- Neutrinos from a Galactic core-collapse supernova could yield a rich harvest of physics on fundamental questions
- A galactic CCSN is very rare, so must make the most of the opportunity

- Neutrinos start the race to get the most bang out of a galactic CCSN
- SNEWS has been providing automatic coincidence detection since 2005
- SNEWS2 aims not only to detect coincidences, but provide critical information to guide follow-up in the observer (and Astro-COLIBRI) community

SNEWS
SUPERNOVA EARLY WARNING SYSTEM