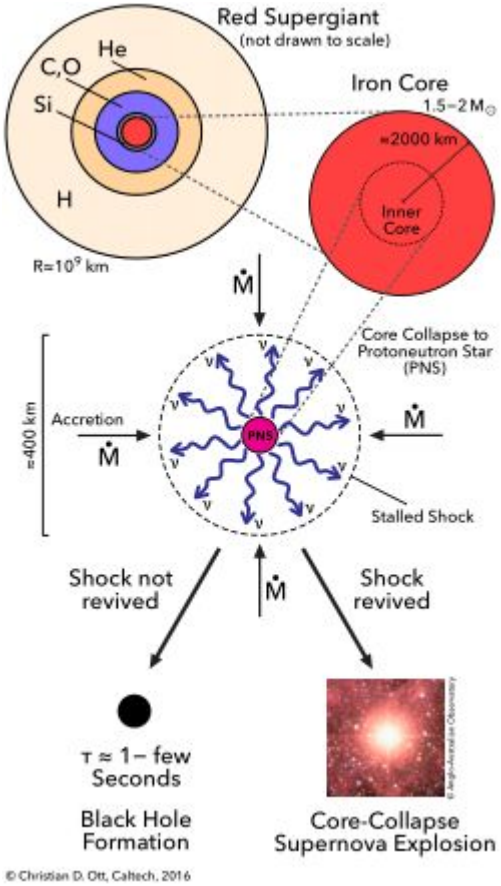
SNEWS 2.0

J Tseng
IOP Supernova Neutrinos in the Multimessenger Era
7 April 2022

UNIVERSITY OF OXFORD

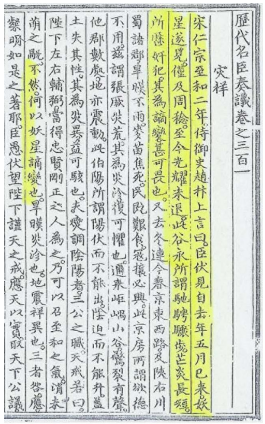
Outline

- Neutrinos and core-collapse supernovae
- Supernova Early Warning System (SNEWS)
- SNEWS2
- SNEWS2 calculations
- Follow-up engagement



Neutrinos and supernovae

- Supernovae are among the brightest objects in the sky
  - SN1054, probably an electron-capture SN, visible during day for 23 days, at night for 2 years

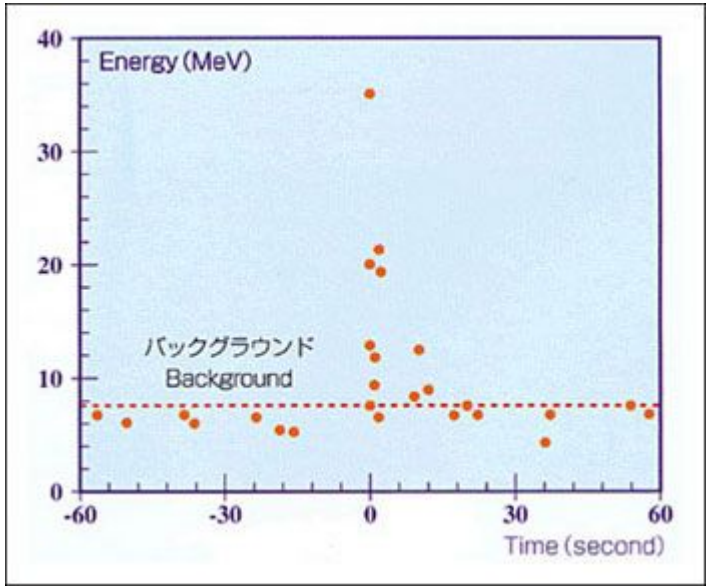


- And yet, core collapse supernova (CCSN) are expected lose ~99% of their energy via neutrinos

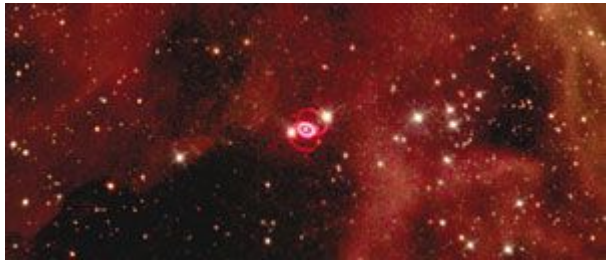
SN1987A

23 Feb 1987

Kamiokande



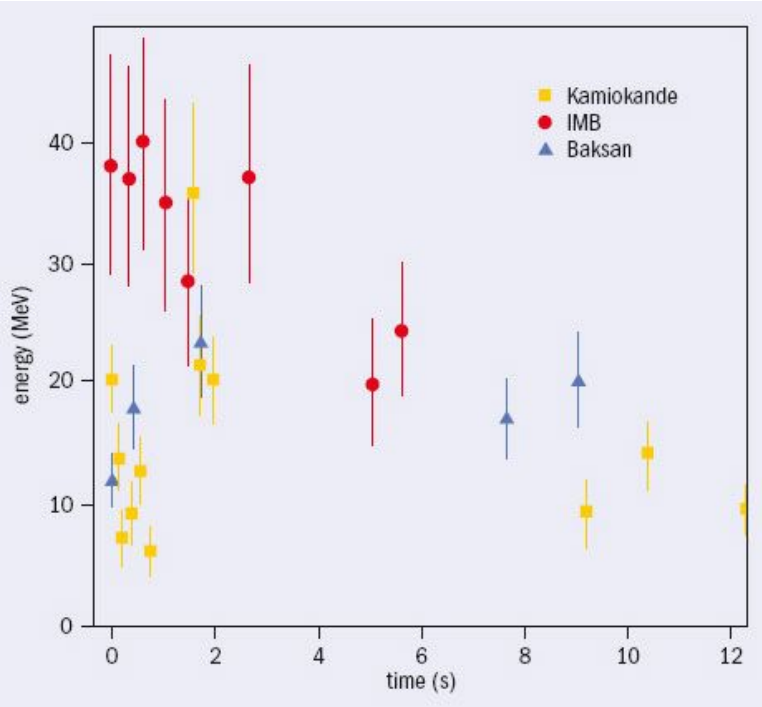
2-3 hours later:
Ian Shelton
(Toronto)
Oscar Duhalde
(Las Campanas)
Albert Jones
(AAVSO)

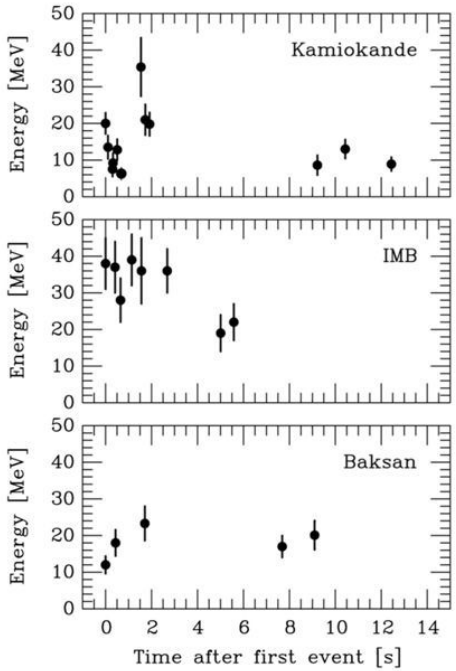


HST, 1990's

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

SN1987A neutrinos around the world





Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

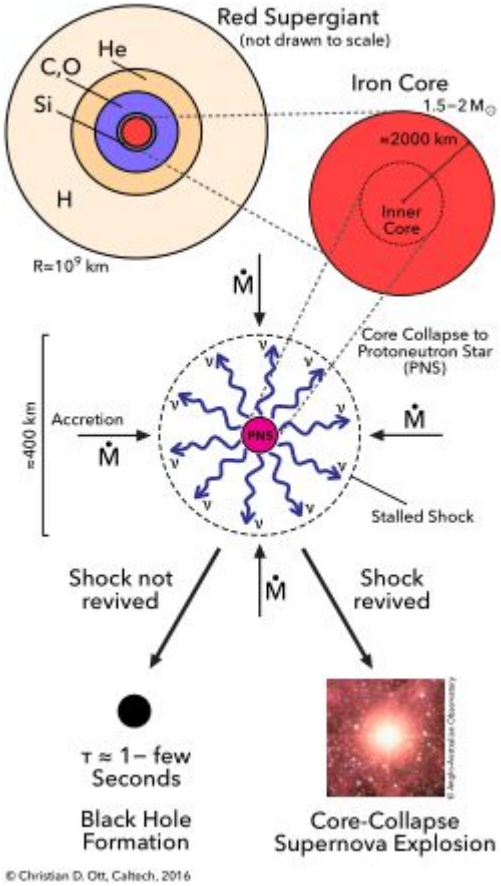
Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

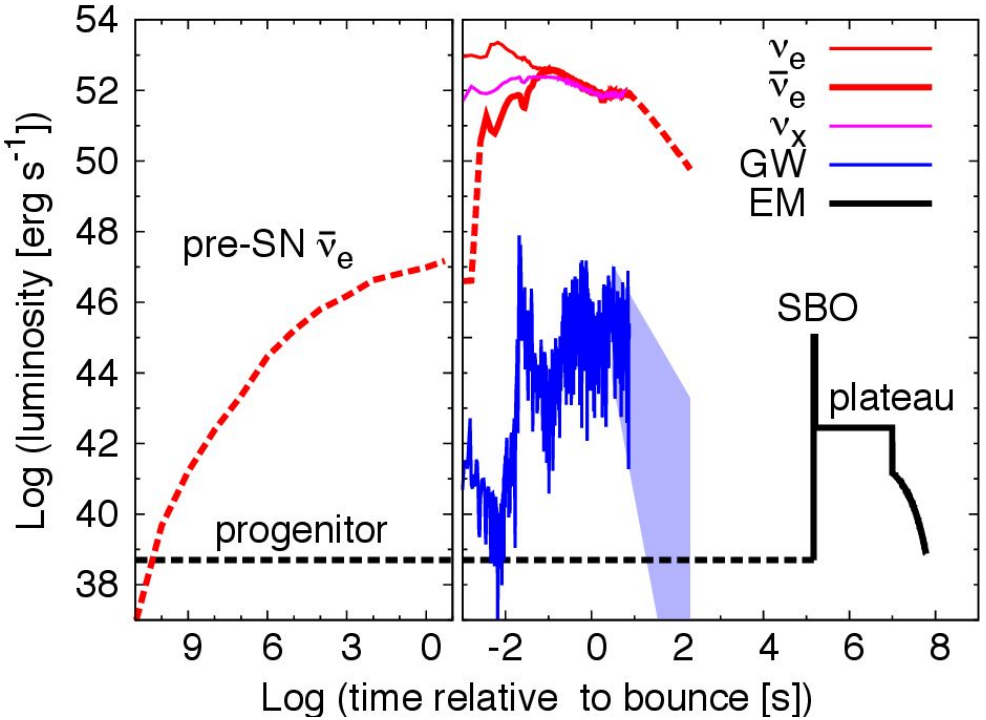
Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/−54 s

Within clock uncertainties, all signals are contemporaneous

Georg Raffelt, MPI Physics, Munich — Neutrinos in Astrophysics and Cosmology, NBI, 23–27 June 2014

Neutrinos and core-collapse supernovae





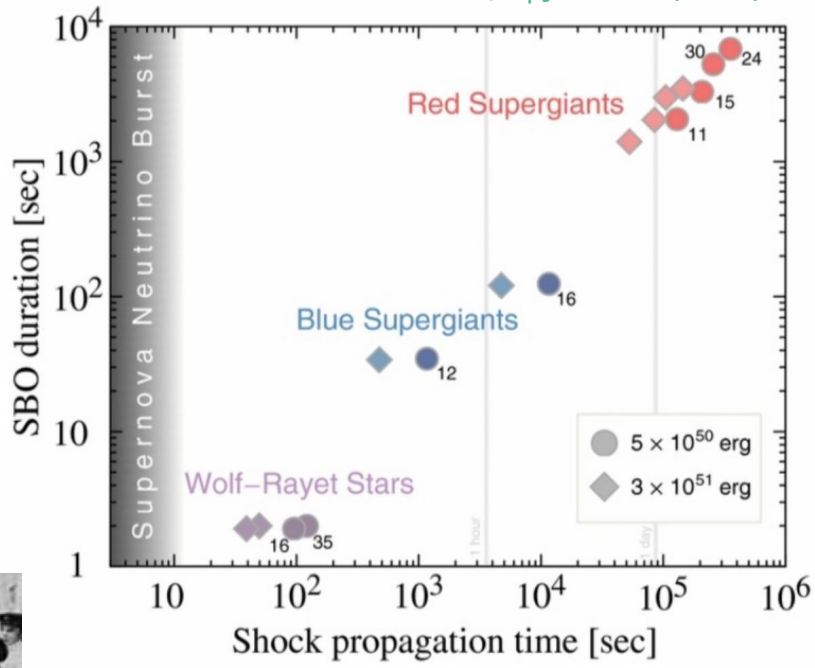
17 $M_\odot$ progenitor, 2D axisymmetric simulation

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

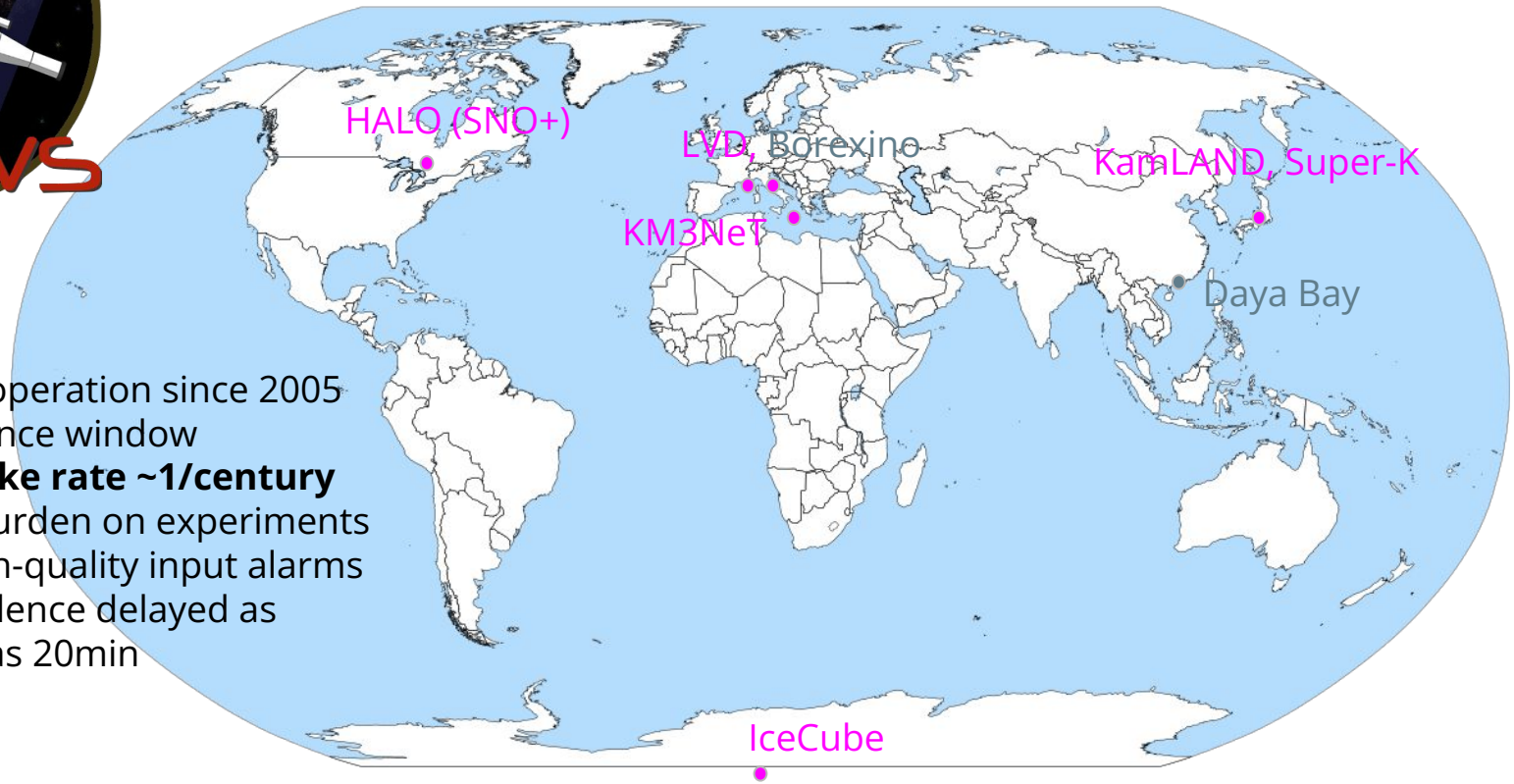
Race against time

- Neutrinos are the starting gun
- The race takes place once in a lifetime
  - 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

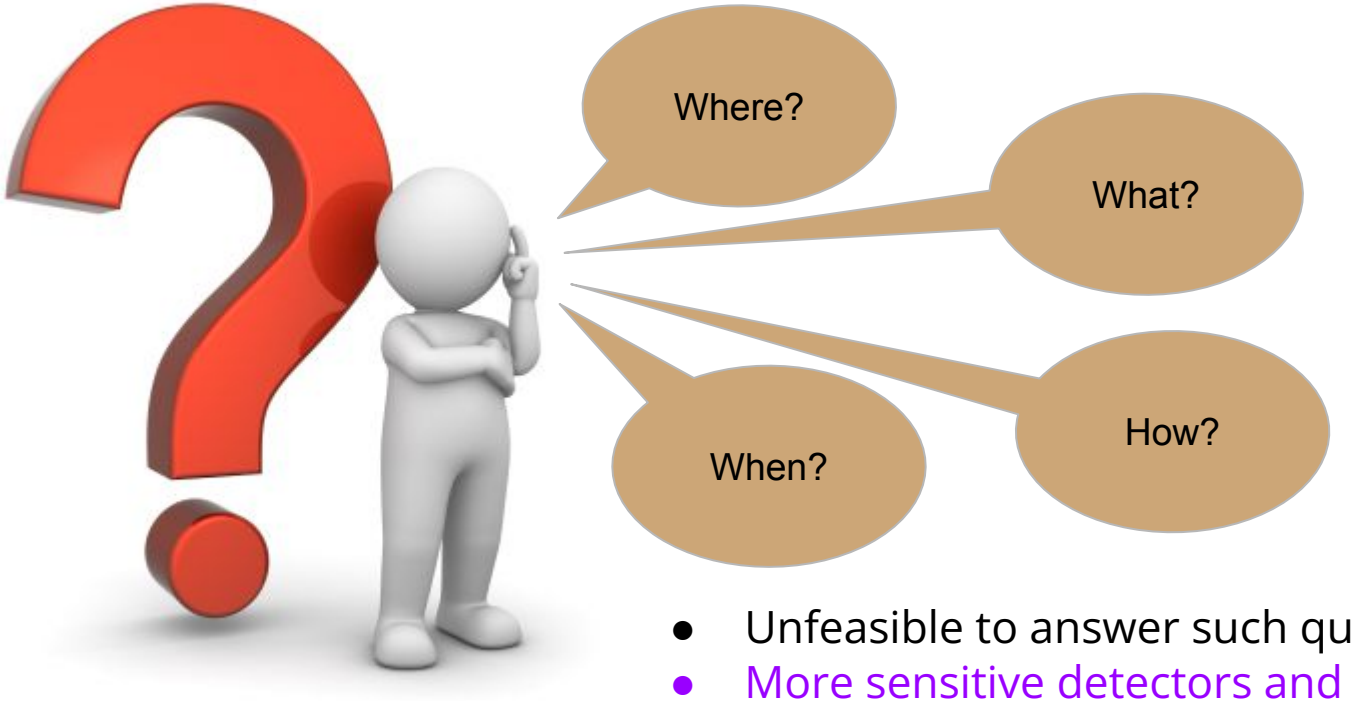


- Automated operation since 2005
- 10s coincidence window
- **Expected fake rate ~1/century**
  - High burden on experiments for high-quality input alarms
  - Coincidence delayed as much as 20min

SNEWS risks

- With fake rate ~ 1/century (and no galactic SN since 2005)…

Coincidence - what then?



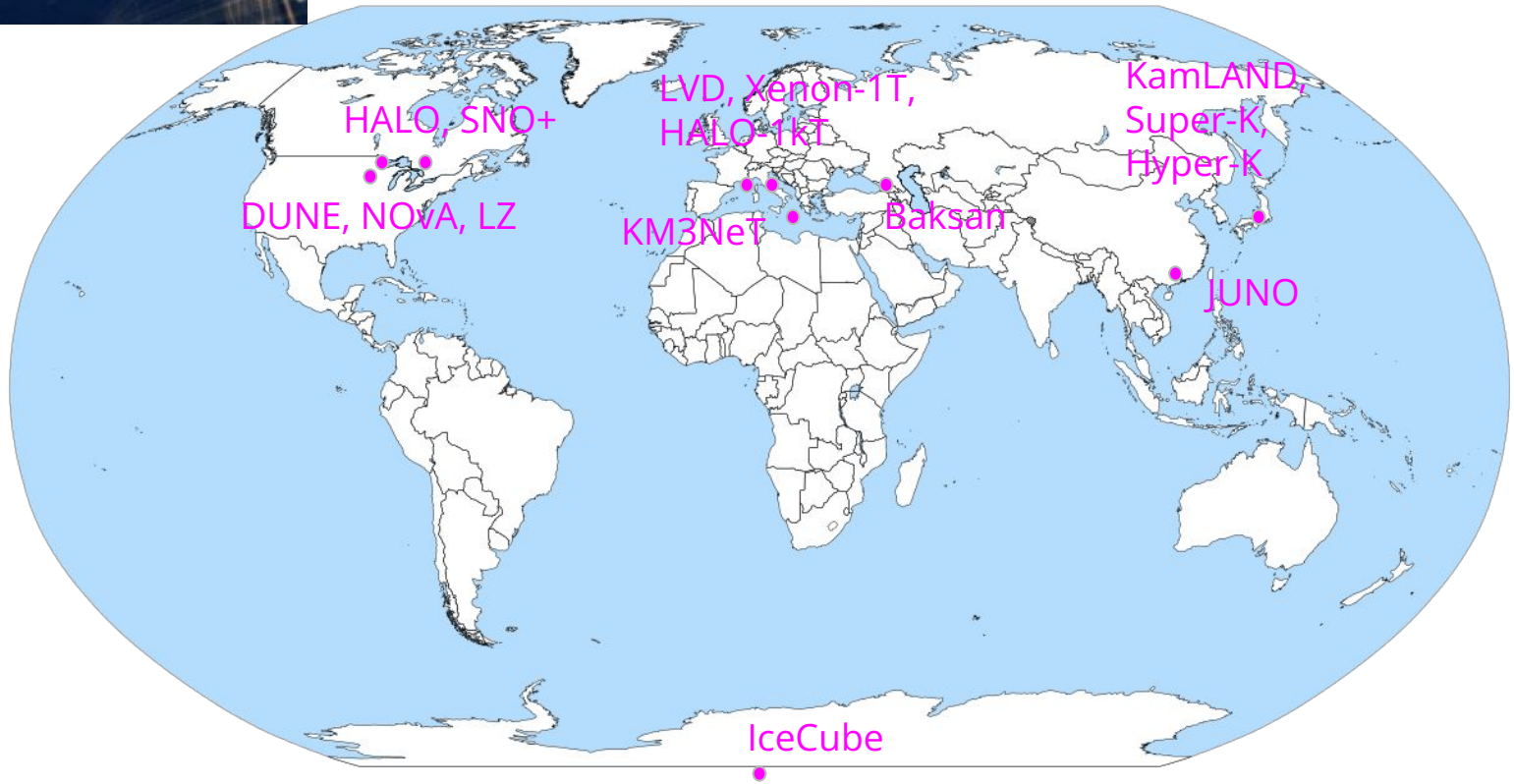
- Unfeasible to answer such questions in 2005
- More sensitive detectors and techniques…

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
  - Build on KamLAND monitoring
- Develop a follow-up strategy to prepare the astronomy community
- Engage amateur astronomers and citizen science communities

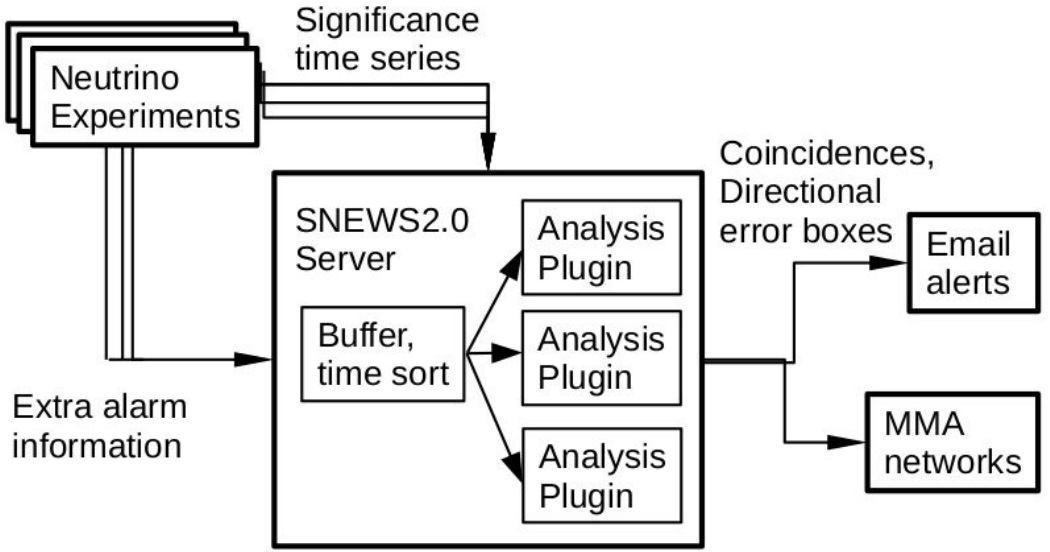
Whitepaper: S Al Kharusi et al., New J Phys 23 (2021) 3, 031201

SNEWS
SUPERNOVA EARLY WARNING SYSTEM



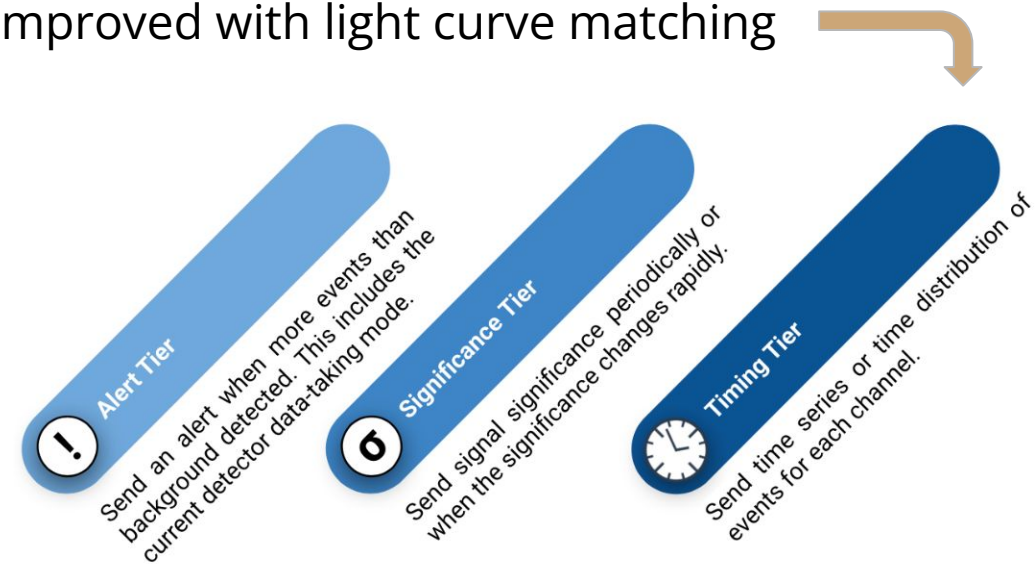
SNEWS2 calculations (pointing+)

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

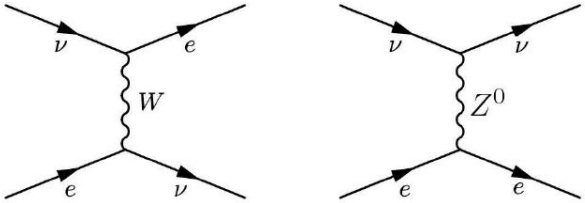


Where: direction strategies

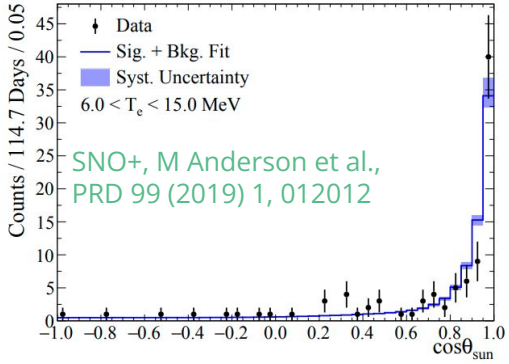
- Electron elastic scattering
- Triangulation with burst timing
- Triangulation improved with light curve matching



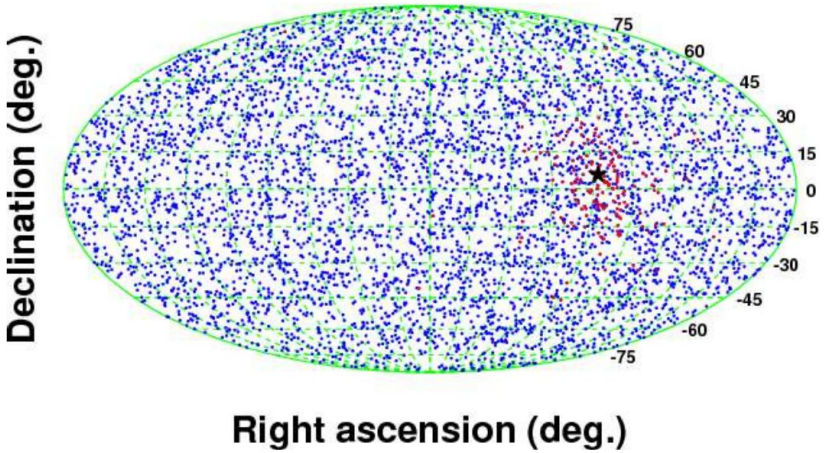
Electron elastic scattering



- Mostly used in water Cherenkov detectors
  - Often seen in solar neutrino analyses
  - Starting to be seen in liquid scintillator as well
- Small fraction of SN neutrino interactions
- Super-Kamiokande (32kT): 4.3 - 5.9° at 10kpc



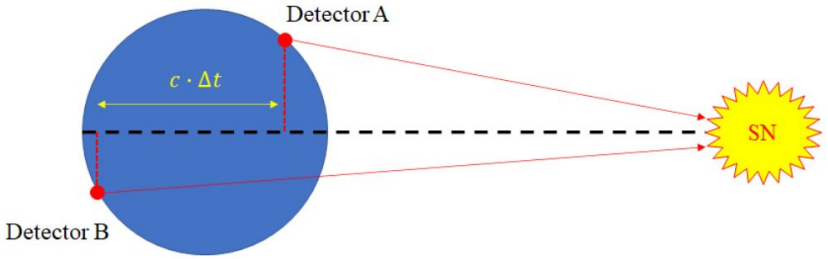
SNO+, M Anderson et al., PRD 99 (2019) 1, 012012



Super-K, K Abe et al 2016

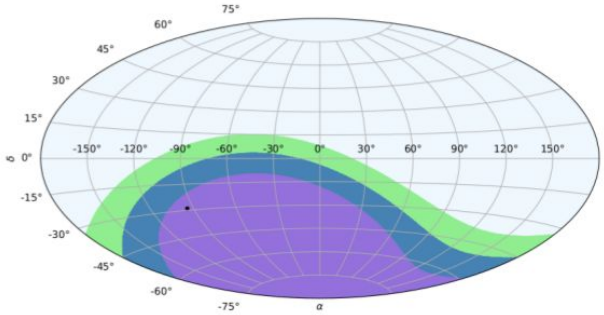
- Reconstruction takes minutes
- Super-K optimizing
- Hyper-K (220kT): 1 - 1.3°

Burst timing

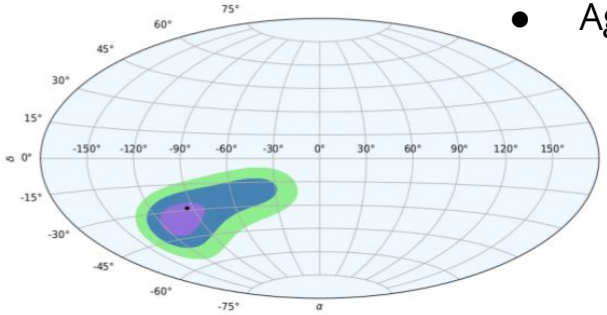


- Coincidence within 10s
- Maximum time difference between arrival times ~40ms
- Very fast, but less precise
  - Good to start slewing telescopes

Need to be careful:
- Detector clocks synchronized
- Agree on definition of burst time



SK+IceCube



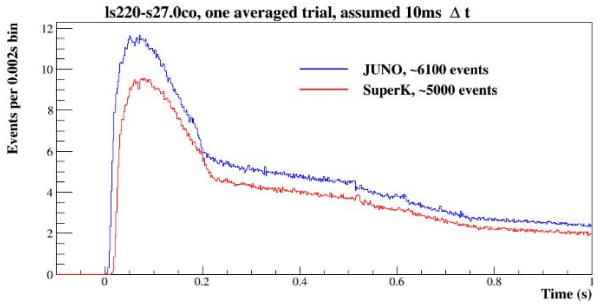
IceCube+JUNO+DUNE+HK

$8.8M_{\odot}$ progenitor, electron-capture SN (low yield)

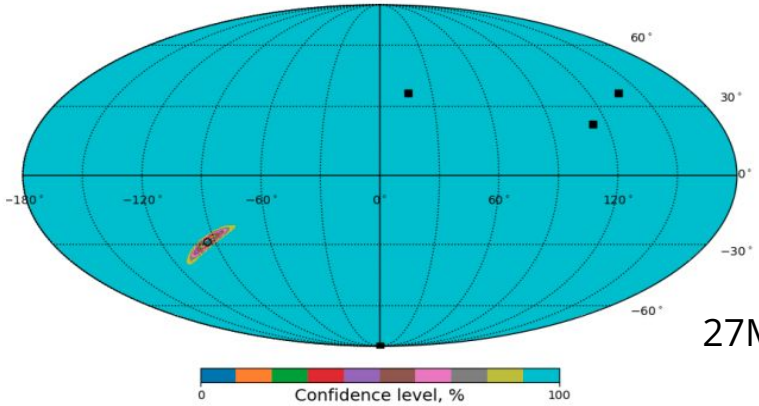
Linzer, Scholberg, PRD 100 (2019) 10, 103005

Time series matching

- Improve Δt for pairs of comparable time series, e.g., of IBD events
  - Cross correlation, χ^2, other metrics
  - Most statistical power from rapid changes in flux



IceCube+JUNO+HK+KM3NeT

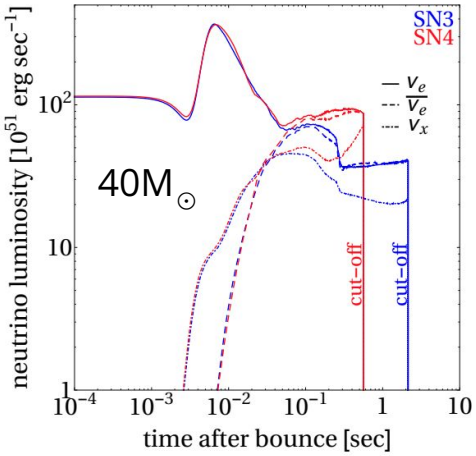


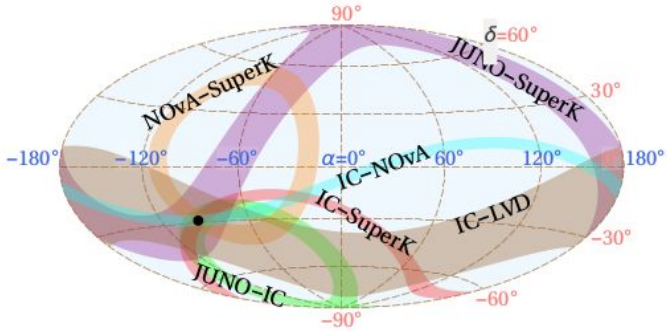
27M$_\odot$ progenitor

Coleiro et al., EPJ C 80 (2020) 9, 856

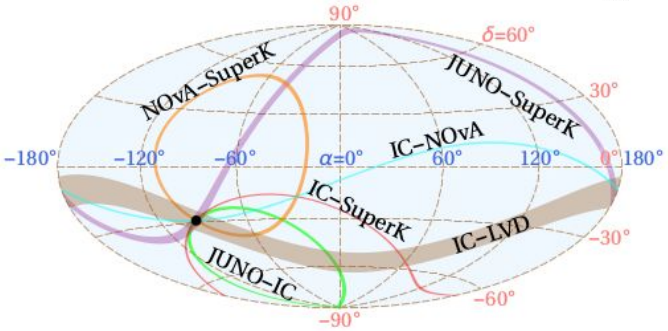
Time series matching

- Most rapid change: black hole formation
- Illustrative improvement in 1σ contours





Neutron star formation

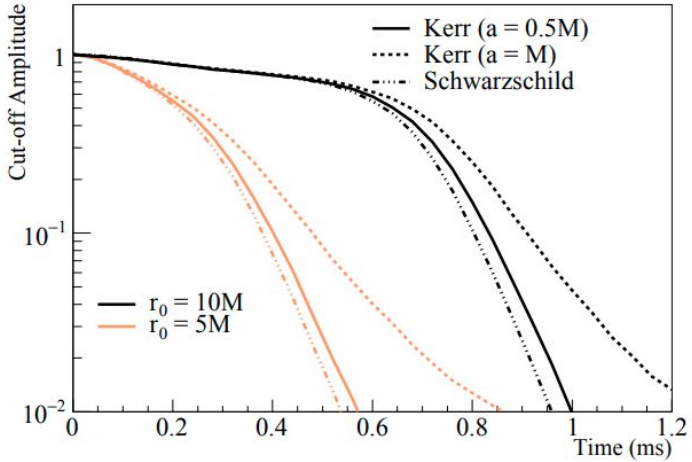


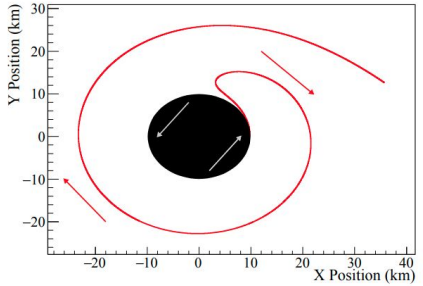
Black hole formation

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

Black hole cut-off

- How abrupt?
  - Simulations usually don't use full GR
  - Stop when approximations fail
  - Many simulations also consider only radial neutrino emissions
- Non-radial neutrino trajectories soften cut-off
  - Characteristic √27M time constant from leakage near photosphere of non-rotating BH
    [Podurets 1964; Ames and Thorne 1968]
    - O(0.1)ms for non-rotating BH
    - Systematic uncertainty with current experiments
  - Longer smearing for extreme rotation
  - Cut-off may encode information about PNS mass and rotation
- Neutrino echoes [Gullen et al, ApJ 926 (2022) 2, 212]
  - Scattering of neutrinos off surrounding material
  - Further softens cut-off, obscures √27M time constant



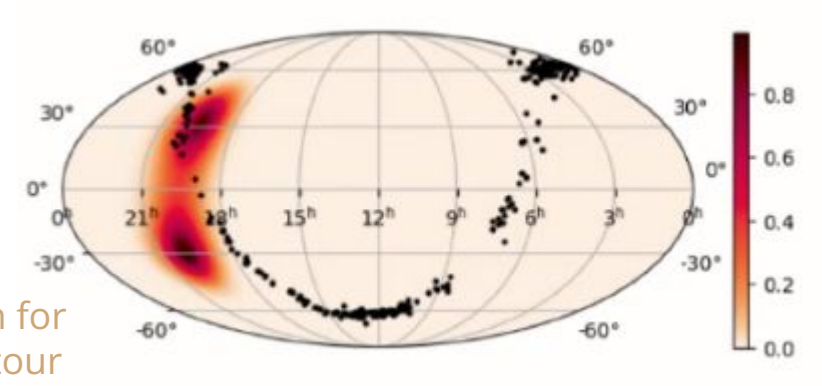


Sample neutrino trajectory around rotating BH

Wang, PRD 104 (2021) 10, 104030

Direction: result

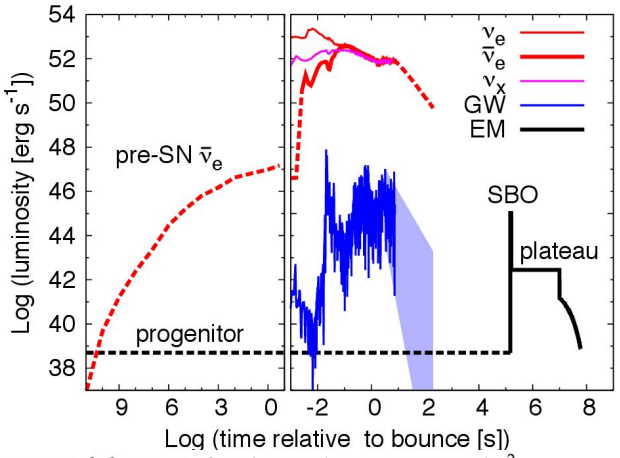
- Successive improvement as experiment data comes in
  a. Burst times → rough triangulation
  b. Time distributions → improved triangulation
  c. Experiment pointing using EES → likely to dominate in the end
- Report pointing as a skymap of confidence levels
  - superimpose on candidate stars

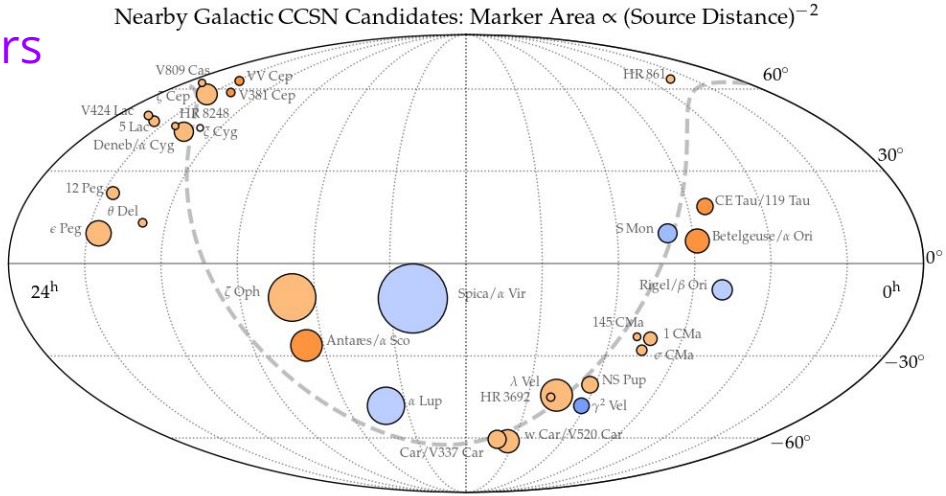


Sample result - deliberately chosen for big, non-trivial contour

Pre-supernova neutrinos

- Late-stage silicon burning emits at increasing rate
- Detectable for stars up to 1kpc
- Can increase warning time by hours
  - KamLAND pioneered publishing a pre-supernova significance
- Investigating whether IBD events can point back to SN



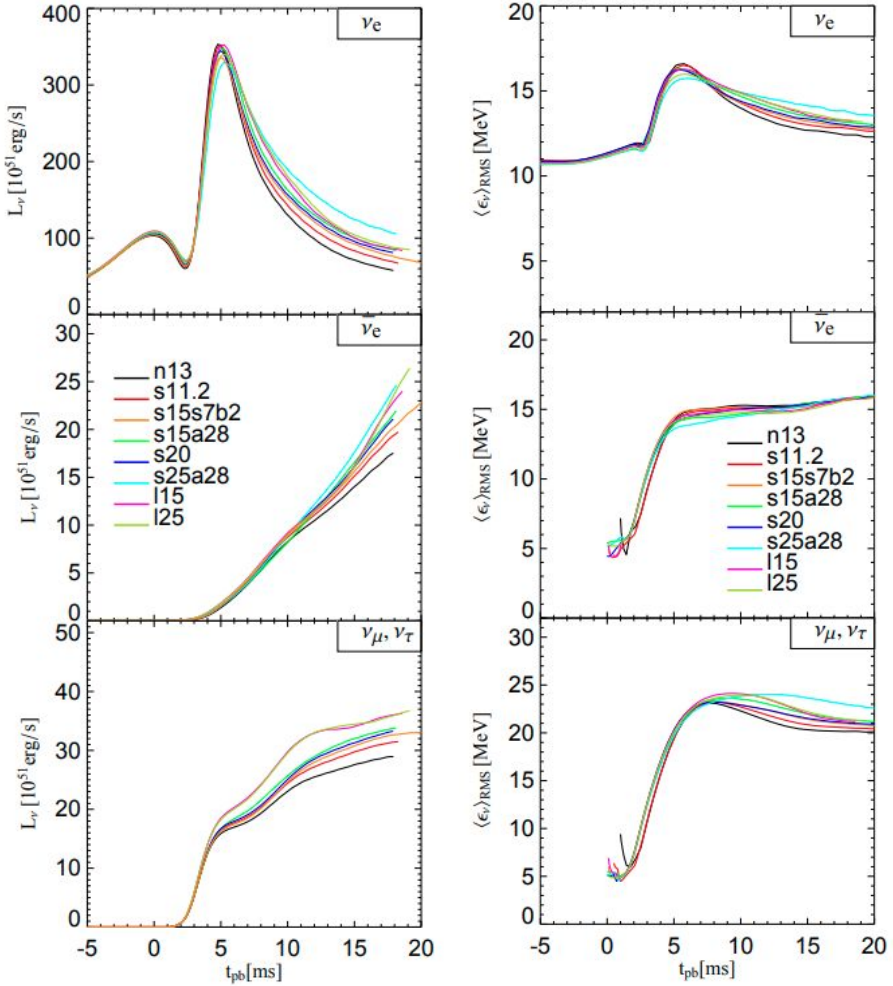


Mukhopadhyay et al., 2020

Distance

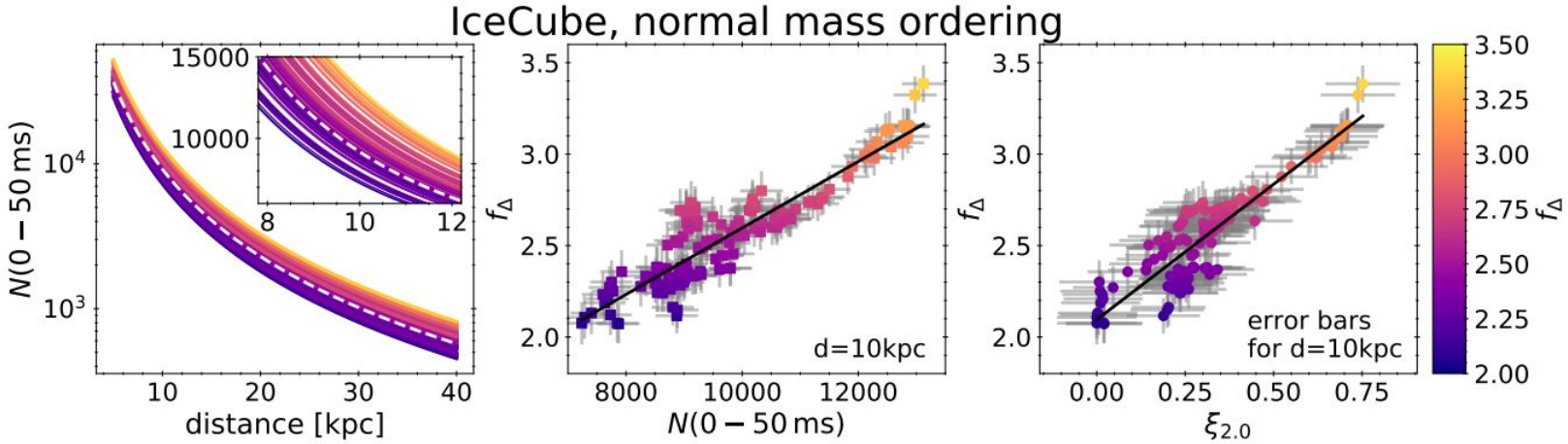
Kachelriess et al., PRD71 (2005) 063003

- 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

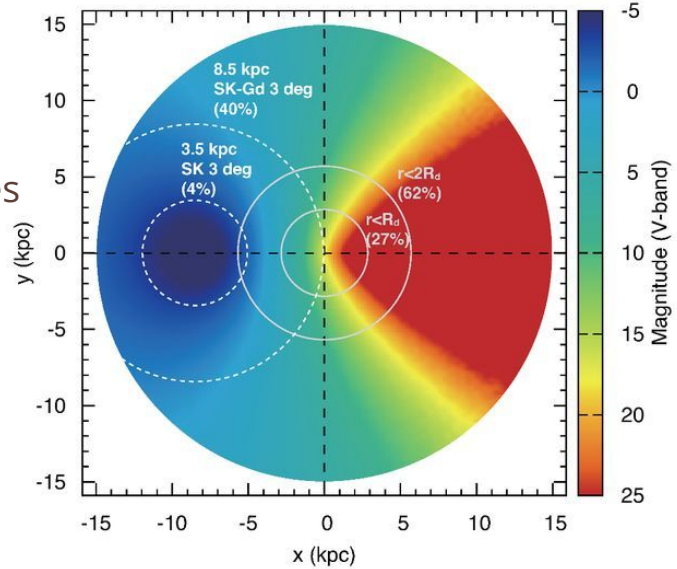


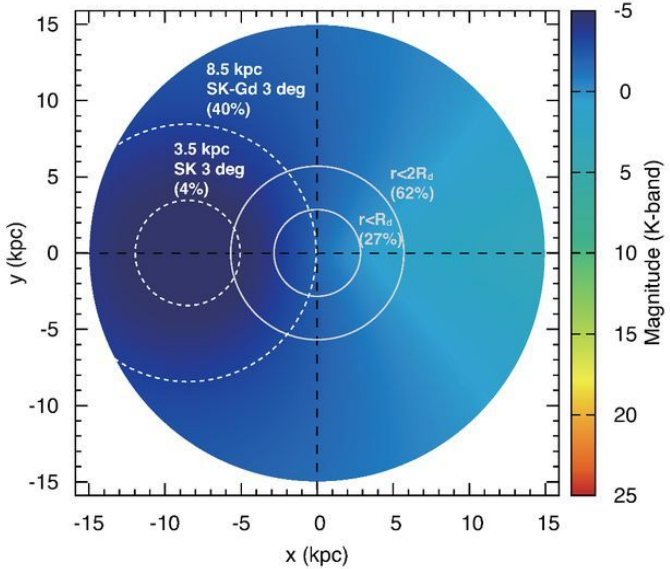
Segerlund et al., arxiv:2101.10624 (2021)

Why is distance relevant?

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

Optical magnitudes (plateau)





Near IR magnitudes (plateau)

SK pointing (% galactic CCSN rate)

- Sizable fraction of the galaxy obscured by dust
- May change optimal observation strategy

Not all supernovae are alike

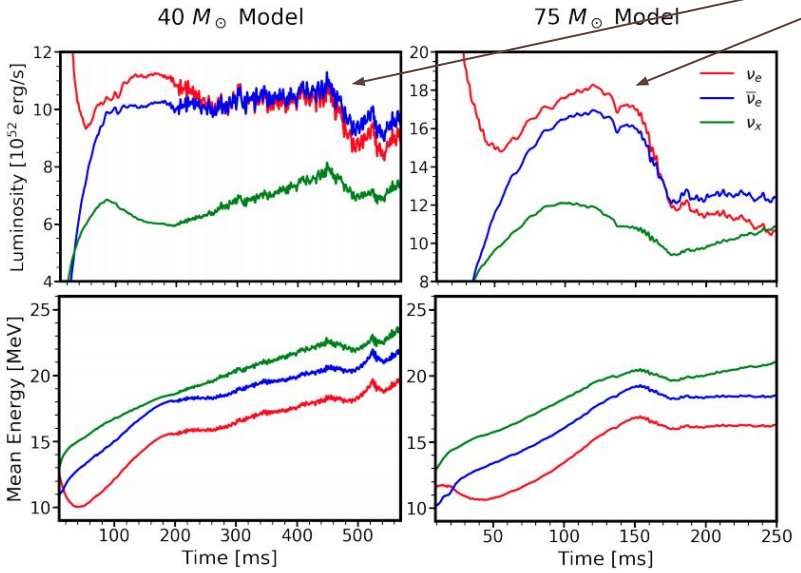
Software developed in SNEWS2 streamlines running diverse SN models and responses (e.g., SNEWPY)

Oscillations (standing accretion shock instability)

Long accretion (with angular momentum)

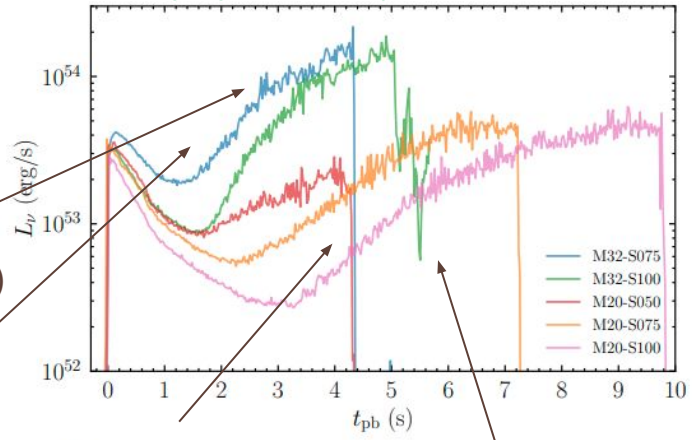
Abrupt cut-off

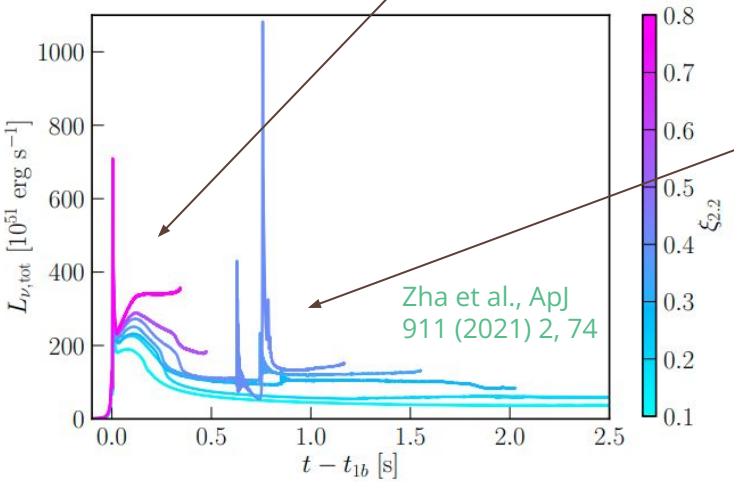
Secondary bursts (e.g., hadron-quark phase transition)



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

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

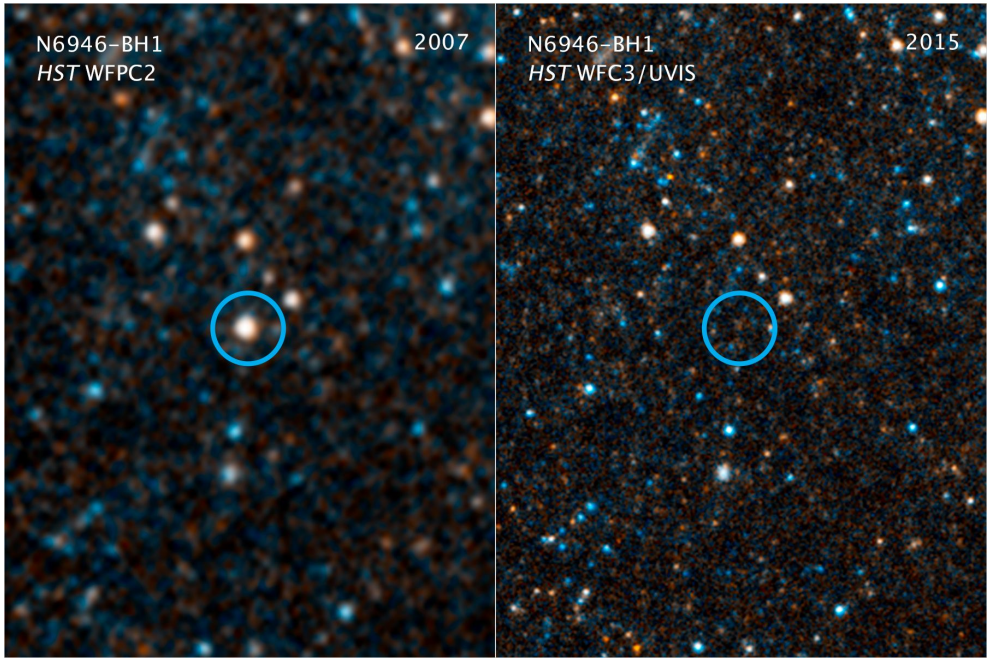




Failed supernovae

- Black hole formation is interesting and better for pointing
  - But will likely fail to revive shock / explosion → may not see in visible spectrum!

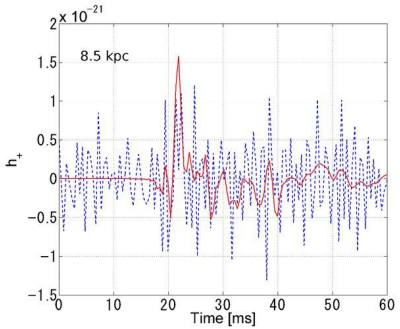
- Search for disappearing massive stars → failed SN $0.16^{+0.23}_{-0.12}$ at 90% CL [Neustadt et al 2021, MNRAS, 508, 516]
- Consistent with search in PTF/ZTF surveys over 10 yr, 231 galaxies, >17$M_{\odot}$ [Byrne & Fraser 2022, 2201.12187]

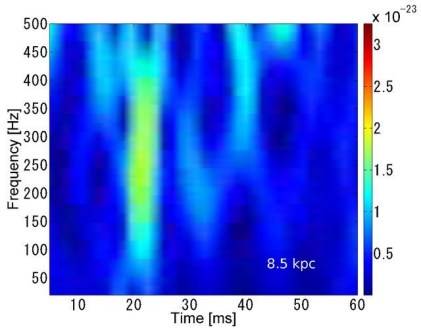


NASA, ESA, and C Kochanek (OSU)

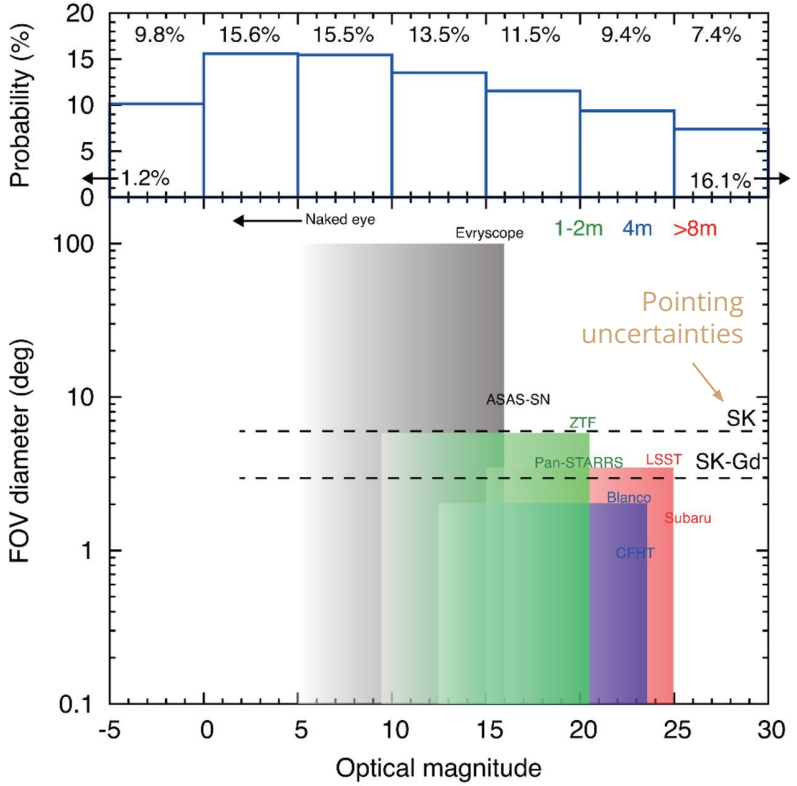
Follow-up

- Distribute SNEWS alerts and results automatically and widely
- Electromagnetic: engage with telescopes, surveys, communities
- Gravitational waves: SNEWS information could help untangle signal from noise





Distribution of galactic CCSN (IIP) by plateau magnitude, incl dust attenuation



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

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
- Global Rapid Advanced Network Devoted to the Multi-messenger Addicts
  - Network of robotic telescopes
  - Experienced with follow-up, amateur astronomer engagement
- Engage with fire drills and preparation

Conclusion

- Neutrinos start the race to get the most bang out of a galactic core-collapse supernova
- 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 community
- SNEWS2 is working with the observer community to develop follow-up strategies - more welcome!