



# SNEWS

## The SuperNova Early Warning System in the age of Multi-Messenger Astronomy

of  
Exploding Stars,  
Weakly-Interacting Particles,  
and Being Prepared



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# Multi-Messenger Supernovae



- Core-collapse SNe are dominated by non-photon messengers  
– All the messengers on one plot vs. time, by luminosity  
Alex Friedland calls them a “Gravity Powered Neutrino Bomb”

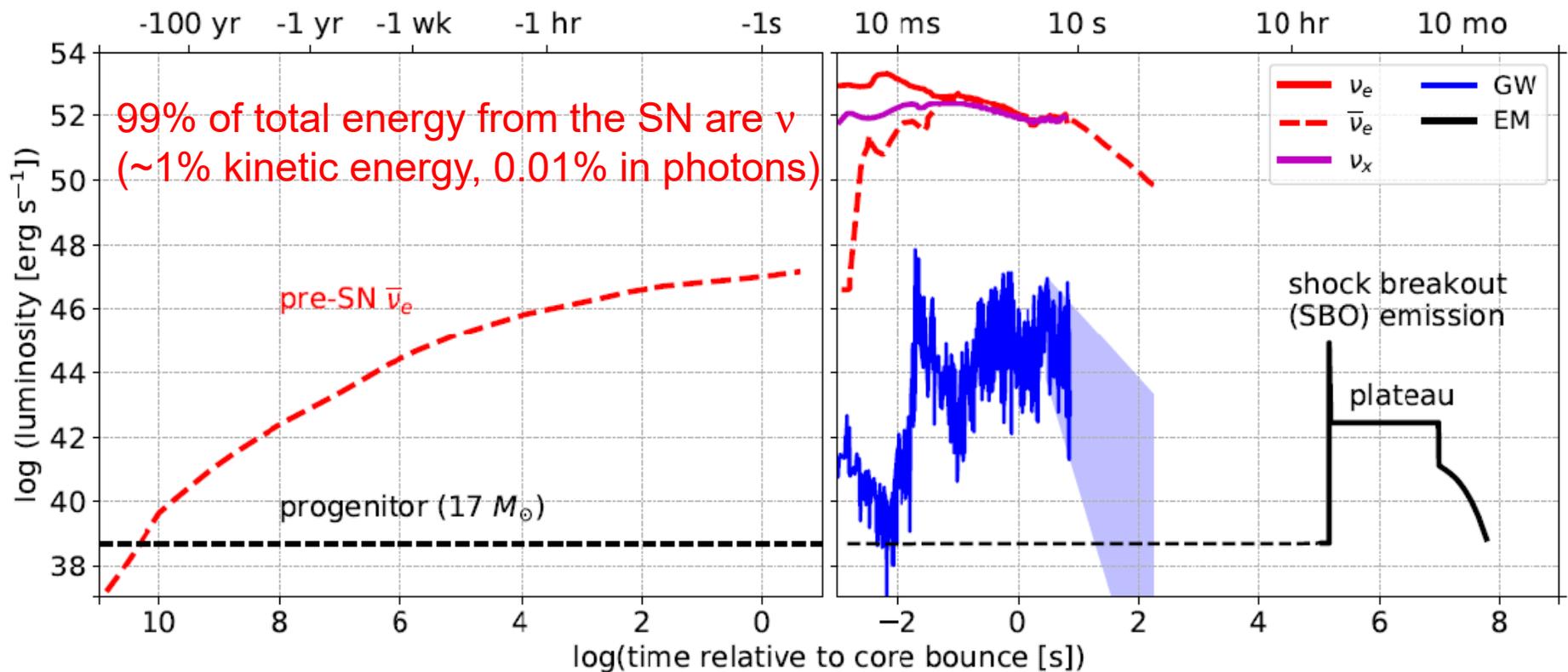


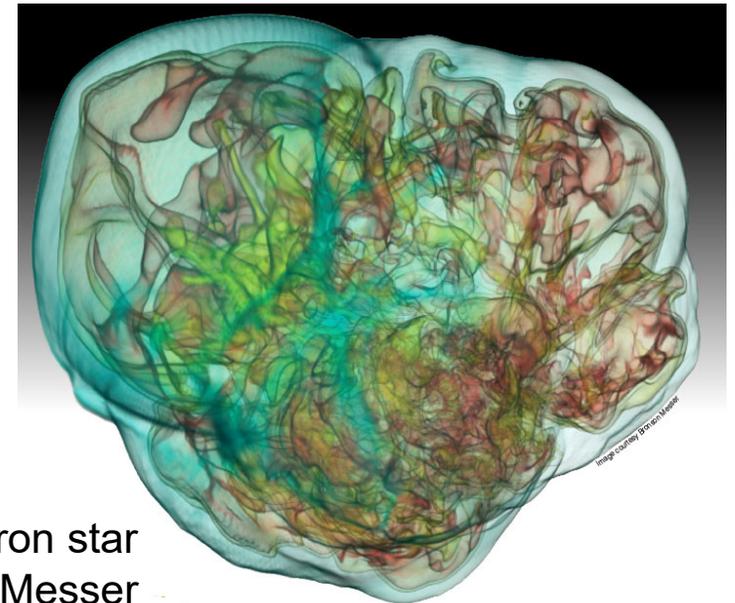
Figure from Nakamura *et al*, MNRAS 161, 3296 (2016)



# $\nu$ production



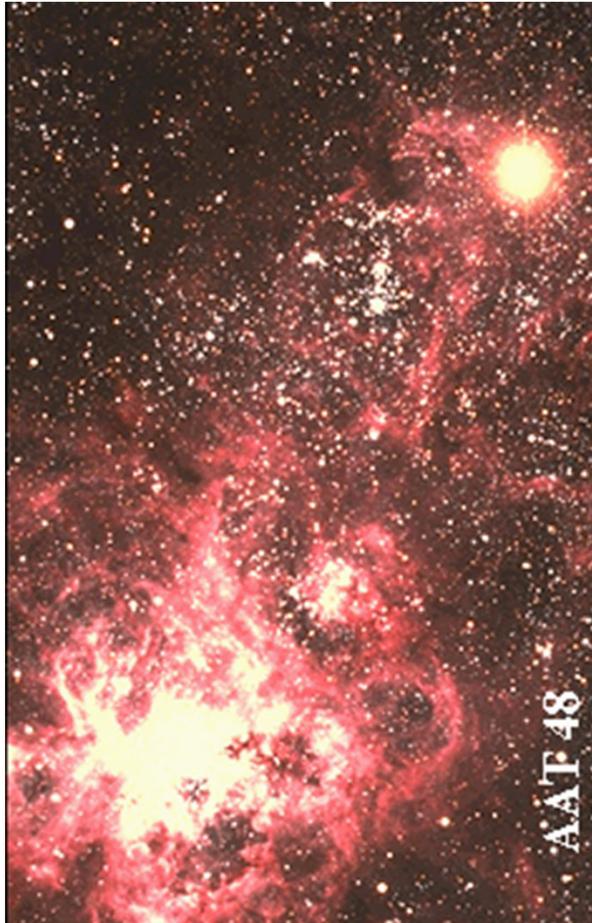
- $\sim 1\%$  of  $\nu$  produced by initial neutronization
  - $p^+ + e^- \rightarrow n + \nu_e$
- Thermal  $\bar{\nu}\nu$  pair production produces 99% of  $\nu$ 
  - $e^+e^- \rightarrow \bar{\nu}\nu$ ,  $e^- (Z,A) \rightarrow e^- (\bar{Z},A) \bar{\nu}\nu$ ,  $NN' \rightarrow NN'\bar{\nu}\nu$
  - Temperatures much larger than  $\nu$  rest mass
- Proto-neutron star transparent to  $\nu$ 
  - $\nu$  can escape
- But opaque to  $\gamma$ 
  - EM energy recycled back to thermal energy



Equal entropy surfaces in a proto-neutron star model by Bronson Messer



# Experimentally Confirmed



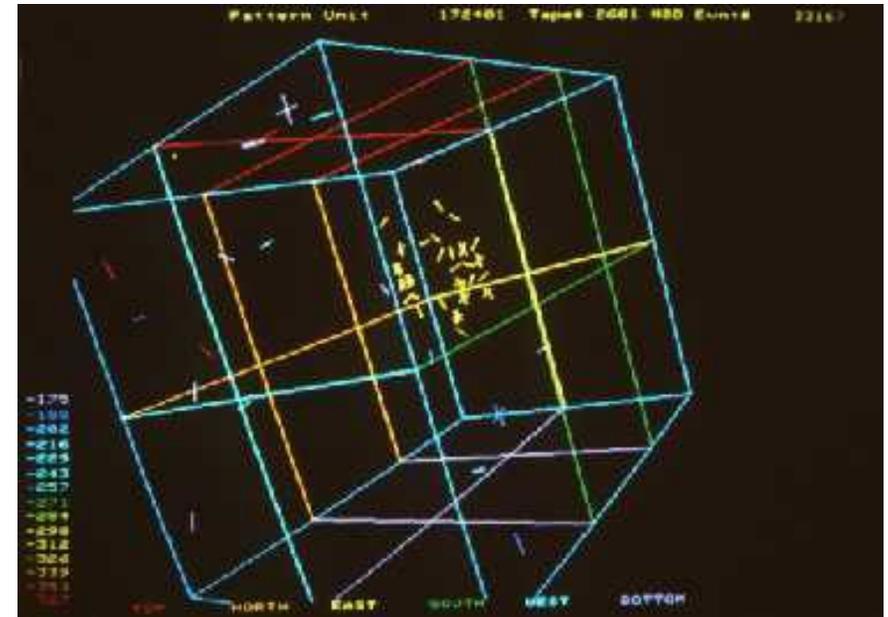
- SN1987A
  - Type II
  - In LMC, ~55kpc
- Well studied due to proximity
  - Although a peculiar SN, blue giant progenitor, odd dim light curve
- And close enough so that  $1/r^2$  didn't crush the  $\nu$  signal
  - Seen in  $\nu$  detectors!
- Indeed a Gravity Powered Neutrino Bomb



# Core Collapse Model Confirmed



- Take observed spectra, flux
- Project back to 55kpc
- Generalities of model confirmed!
  - ... given the low low statistics
- And time profile is about right too
- Signal also sets mass limit of  $m_{\nu_e} < 20\text{eV}$ 
  - No observed dispersion of  $\nu$  as a function of  $E_\nu$
- For a galactic SN happening tomorrow,
  - $R \sim 10$  kpc
  - Modern detectors,  $E_{\text{th}} \sim 5$  MeV,  $M \sim 10$ 's kt
    - 1000's of events would be seen



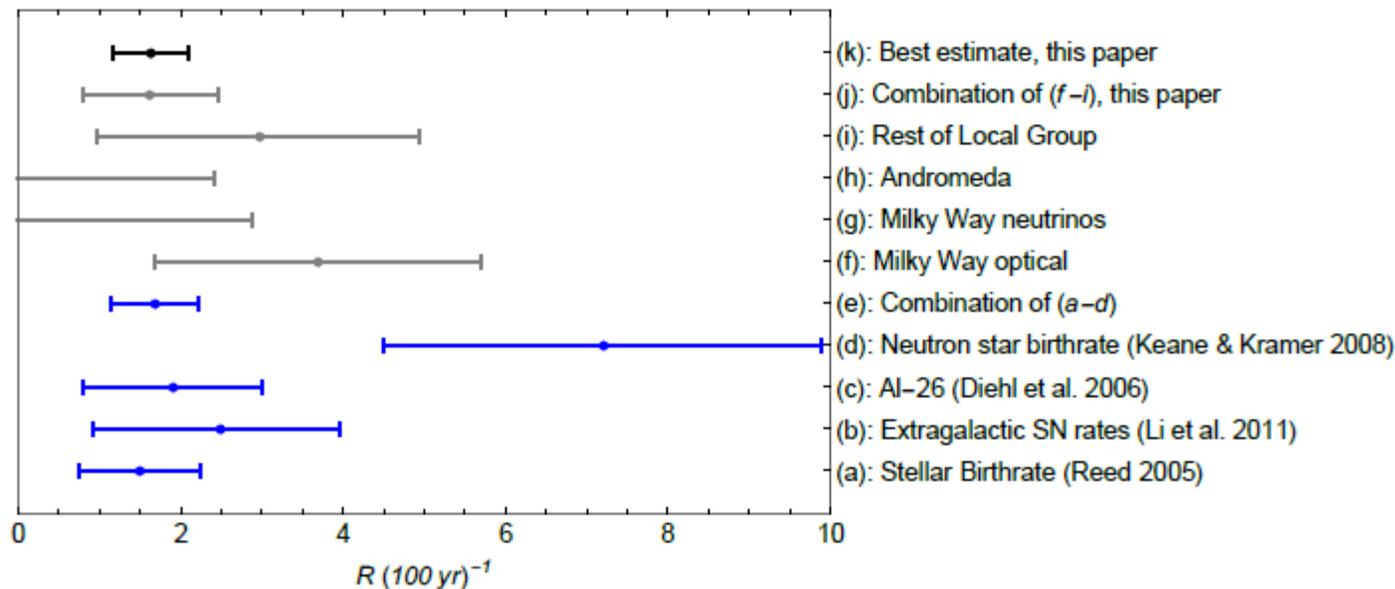
SN1987A  
 $\nu$  event  
seen in IMB



# Tomorrow?



- $1/r^2$  means only a CCSN in or around the Milky Way will be visible in  $\nu$  experiments
- Humans haven't seen a galactic SN since Kepler (*which was a Ia*), why bother looking?



Overall?

1.63 ± 0.46 per century!

Academically – one per career, if Monsieur Poisson cooperates

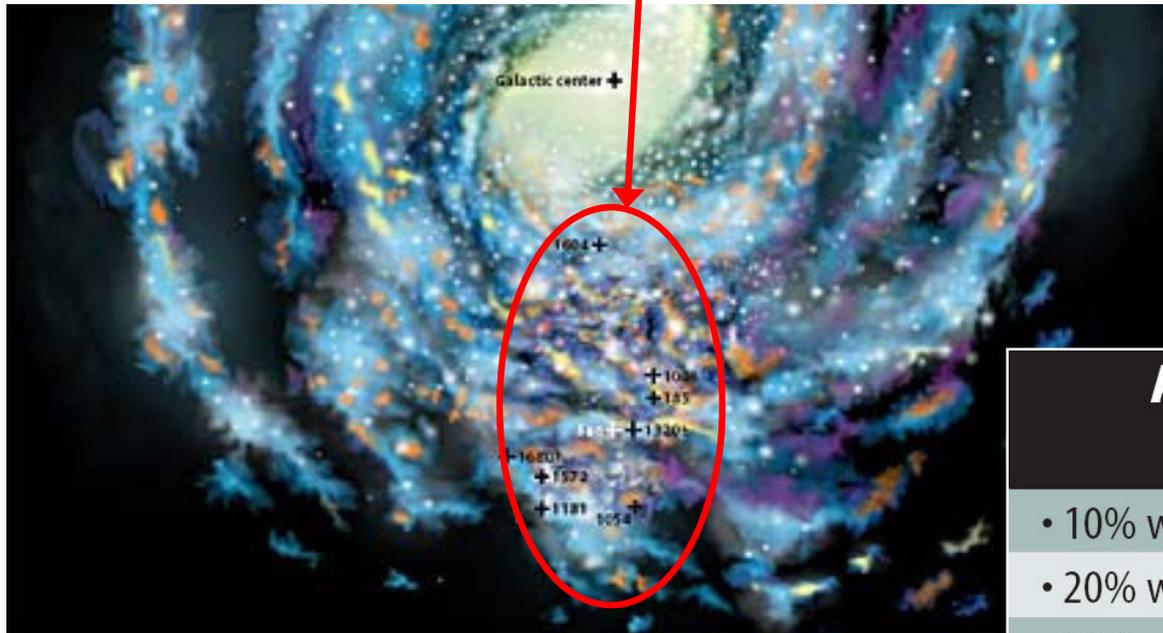
Latest estimates from Rozwadowska, Vissani, & Cappellaro, New. Astron. 83, 101498 (2020)



# Observational Efficiency



- Perhaps 1/6 would be easily seen optically



Historical SNe map from Sky & Telescope

## Apparent Brightnesses of Milky Way Supernovae

- 10% will peak brighter than magnitude  $-3$
- 20% will peak between magnitudes  $-3$  and  $+2$
- 20% will peak between magnitudes  $+2$  and  $+6$
- 20% will peak between magnitudes  $+6$  and  $+11$
- 30% will peak fainter than magnitude  $+11$

Only in the past decades have humans been able to “see” past galactic dust with  $\nu$ , IR, and radio

Progenitor:  
12–15 magnitudes fainter



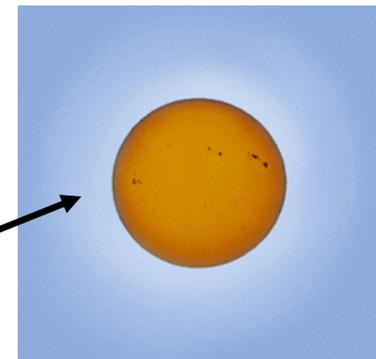
# Advance Warning



- Observations from  $t=0$ ?
  - Sure. Or very nearly so, certainly better than the serendipitous  $\sim$ hours of SN1987A, and far closer than the  $\sim$ days which is the best we can get on an extragalactic SN

- How?

- $\nu$ 's exit the SN promptly
- But stars are opaque to photons
- EM radiation is not released till the shock wave breaks out through the photosphere – a shock wave travel time over a stellar radius
- $\sim$ hour for compact blue progenitors,  $\sim$ 10 hours for distended red supergiants





# The Scheme



- Now that we know we can see SN  $\nu$ , how to do it differently the next time?
  - (*caveat – nearby only, from Milky Way and environs*)
- “Luck” = Opportunity x Preparation
  - Neutrinos are emitted promptly upon core collapse
  - Produce obvious signal in today’s detectors, most have automated analysis chain to trigger on SN  $\nu$
  - Instant information transfer now commonplace
  - A galactic SN would be close enough we’d really want to have very good observations starting at  $t=0$ 
    - *ie*, we’d have a prayer of *noticing* whatever cool things happen at or shortly after breakout
- So let’s trigger photon-based observations of the next galactic SN using the neutrino pulse



# Is This Practical?



- The neutrino experiments must be able to:
  - Identify a SN  $\nu$  signal
  - Confirm it's not noise
  - Get the word out
  - Figure out where people should be pointing
  - All in an hour
- Note that the GCN/Bacodine network does this in seconds for GRB's
  - Although they have a lot of practice: 1/day rather than 1/century
- LVK now doing a similar job with GWs



# Why a Network?



- SNEWS
  - Supernova Early Warning System
- Any single experiment has many sources of noise and few SNe
  - Flashing PMTs, light leaks, Electronic noise, Spallation, Coincident radioactivity
- Most can be eliminated by human examination
  - Takes about an hour: same as the headstart neutrinos have over photons
  - No experiment would want to make an automated SN announcement alone
- Noise will not simultaneously occur in some other experiment
  - But neutrinos from a real SN will

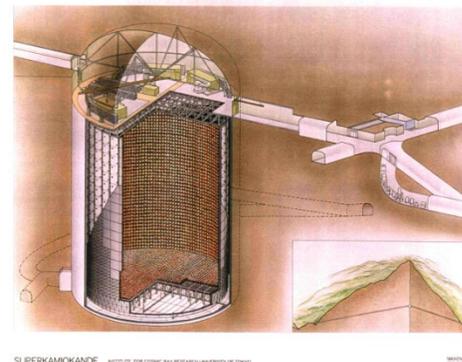
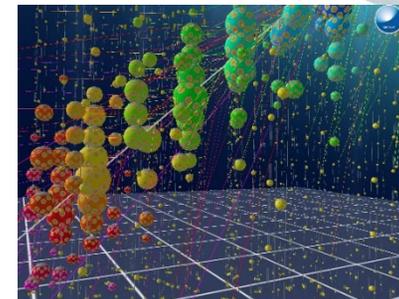
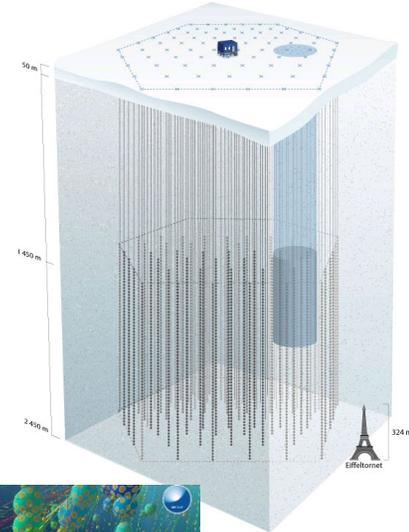
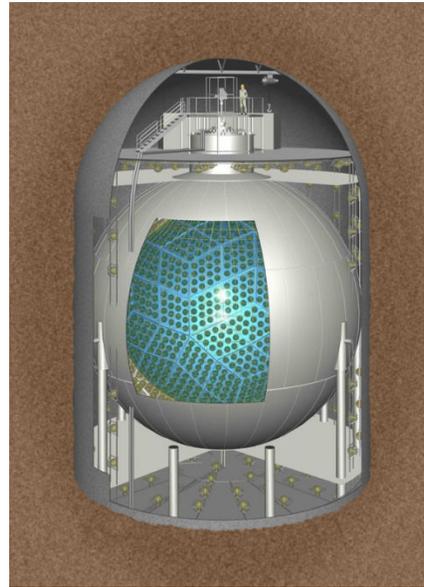




# The Experiments

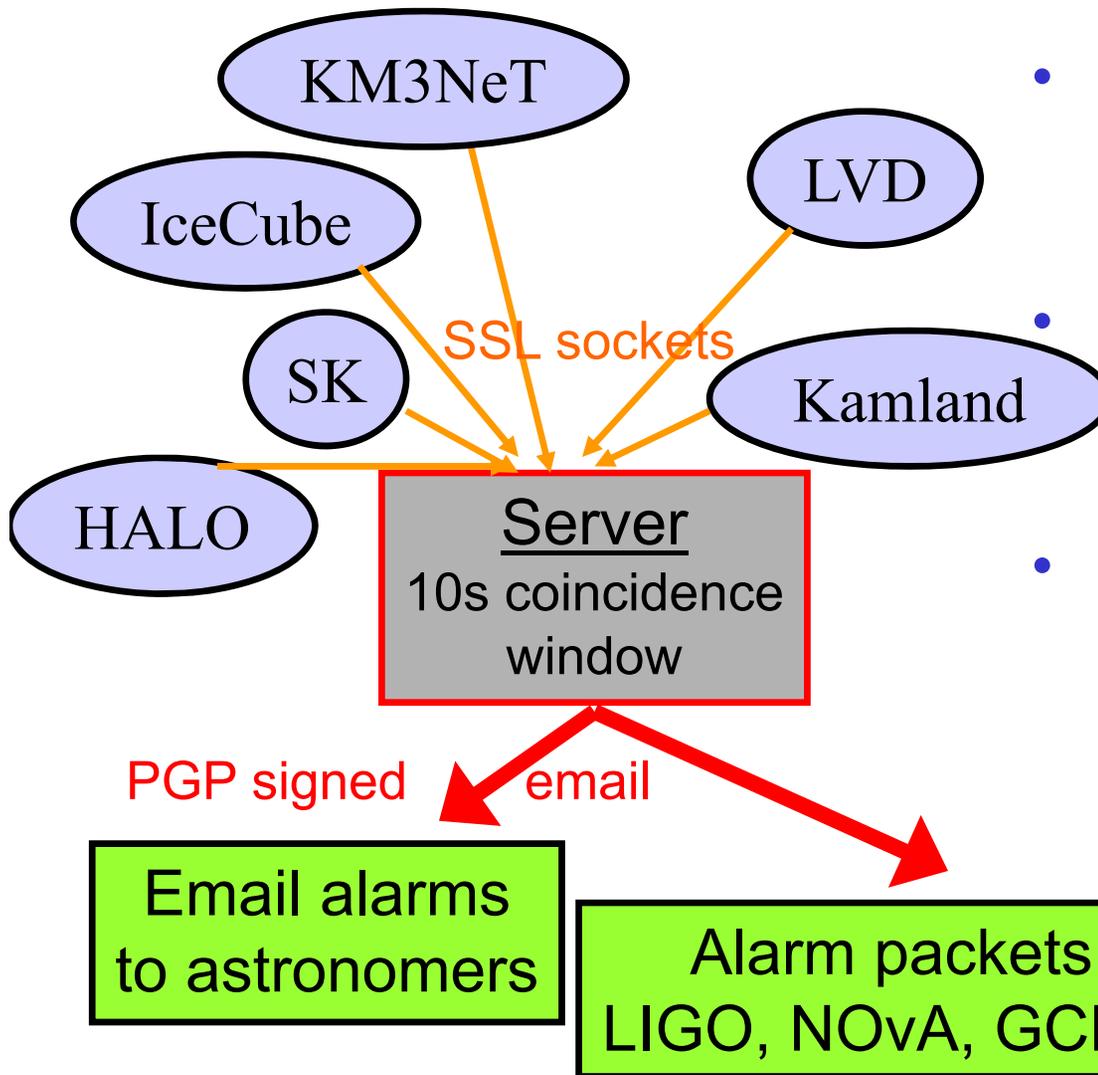


- Currently:
  - Super-K
  - LVD
  - IceCube
  - KM3NeT
  - Kamland
  - HALO
- Alumni:
  - MACRO, SNO, AMANDA, Daya Bay Borexino (*SNEWS operational for two decades now!*)
- In testing:
  - NOvA, SNO+, Baksan, Xenon, LUX, JUNO





# A Global Coincidence Trigger



- Experiments send blind TCP/IP packets to central coincidence server
- Secure, stable hosting at Brookhaven
  - Backup server at Bologna
- Other benefits such as down time coordination, working relationship between SN teams, etc



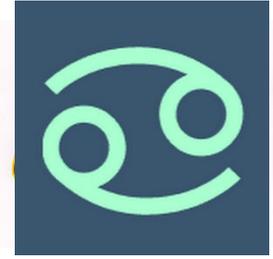
# Improvements for SNEWS 2.0



- What can we do to update SNEWS to provide:
  - Rewrite three decade old C codebase to maintainable Python using SCIMMA's tools
  - Multiple thresholds, to constantly exercise the machinery and to provide consumers with a “choose your own threshold” alert
  - Ability of experiments to compare v “light curves” real-time, to extract physics quickly: especially precision timing for triangulation
  - Get alerts out to the new networks, to best coordinate with modern multi-messenger networks
- (participating experiments can choose what level of data sharing they are comfortable with)



# SCIMMA



- The Scalable Cyberinfrastructure to support Multi-Messenger Astrophysics project is helping us replace our netrek-era sockets with something modern, maintainable, and scalable
- A joint SCIMMA/SNEWS team replicated the existing SNEWS architecture using the “Hopskotch” framework
  - We’re now adding more new SNEWS2.0 functionality

HOPSKOTCH





# New Physics for SNEWS 2.0



- Pre-supernova (*Si-burning*)  $\nu$  from nearby stars:
  - Kamland and Super-K with Gd loading do this now
  - SNO+ and JUNO will soon be able to as well
  - This is an area where combining low statistics could let these experiments expand their range further into the galaxy (*100's of pc  $\rightarrow$   $\sim$ kpc if you stack*)
- Pointing:
  - DUNE and Hyper-K will have per-event directionality
  - SK will improve theirs with Gd tagging
  - Maybe SNEWS can contribute triangulation
  - A new opportunity to provide directionality combination for those experiments?



# SNEWS' Goals



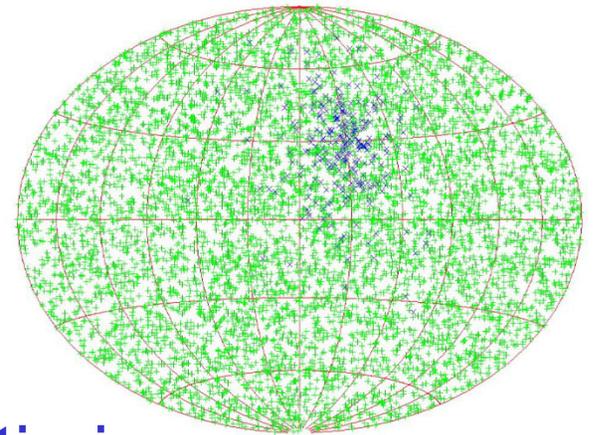
- At a workshop in Sept. 1998 at Boston U., neutrino physicists and astronomers came up with design goals: the “Three P’s”:
  - **Prompt** ( $\ll 1$  hour)
  - **Positive** (false alarms  $< 1/\text{century}$ )
  - **Pointing** (where should people look?)
- How well have we done in the nearly two decades we’ve been doing this?
  - Operational in test mode since 2001, fully operational July 1, 2005
- Should these goals change for the future?



# Pointing?

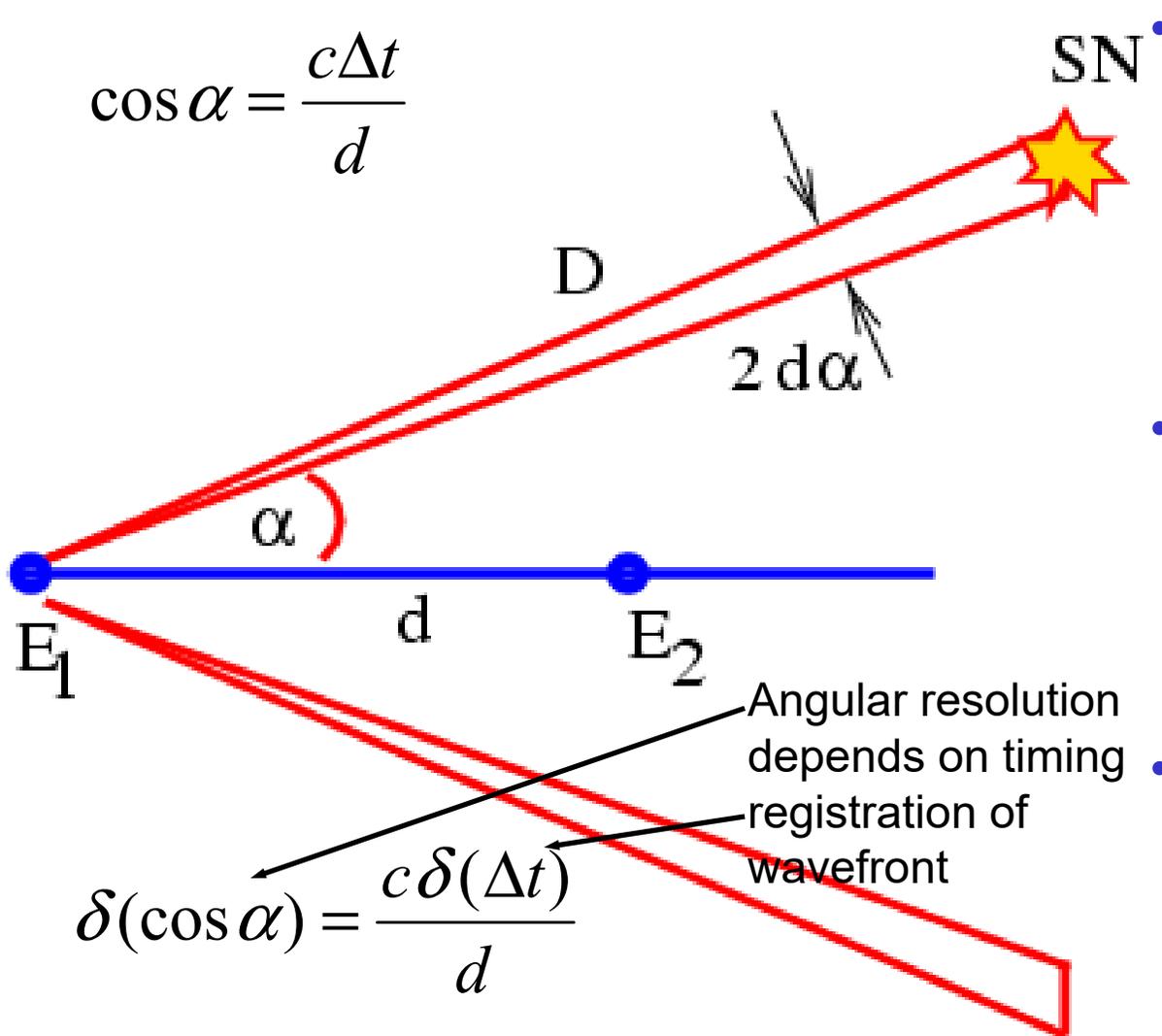


- Super-K can point back to within  $\sim 4^\circ$  using the sub-dominant electron elastic scatters
  - and will do this even better with Gd n capturing tag IBD interactions
- DUNE will also do this ( $\sim 5^\circ$ )
- For a long time, we thought that timing triangulation would be killed by counting statistics at the leading edge of the signal
  - Beacom&Vogel, astro-ph/9811350
  - ... or, is it?





# Triangulation



- Arrival time difference of SN v wavefront at different detectors
  - With 2 expts, circle on sky at angle  $\alpha$
  - 3 expts – 2 blobs
  - 4 expts – 1 point
- With modern detectors + fitting the whole v light curve rather than just the leading edge, this is now possible
- Same method as GW localization maps
  - SNEWS2.0 to publish HEALPIX maps

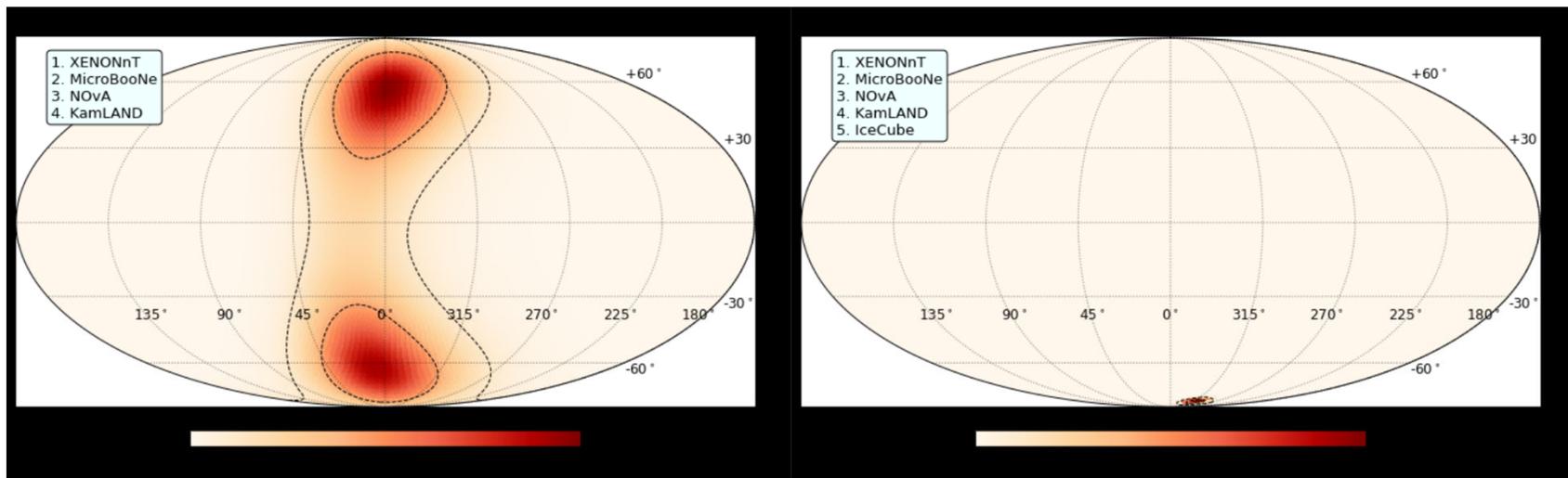
astro-ph.HE/2410.11984



# Potential Error Boxes



- The confidence interval on the sky from four smaller experiments (L), then add IceCube's high stats (R) to really zoom in



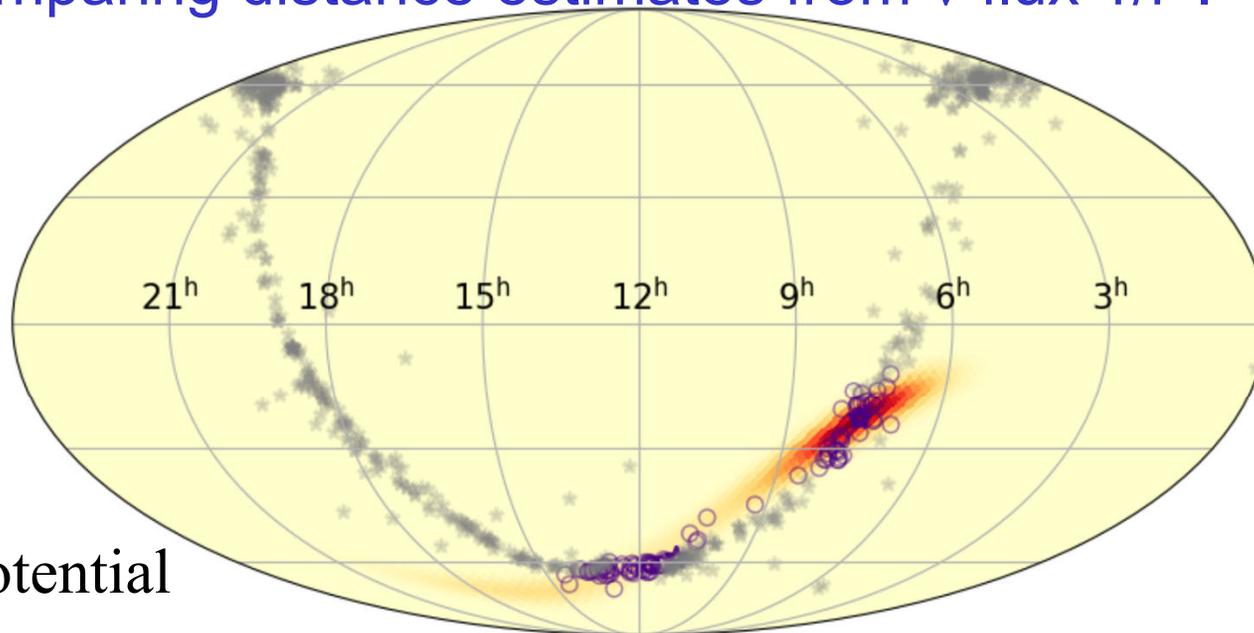
- The community could tile with ZTF, Rubin, and overlap with any high energy transient search boxes



# Combine with progenitor catalog



- What if Red Supergiant X-46 ( $113^\circ$ ,  $-22^\circ$ , 7.6kpc) explodes and SNEWS points back towards it? 105 stars are within the 90% region, 3 match when comparing distance estimates from  $v$  flux  $1/r^2$ .



640 RSG potential  
progenitors

*Healy et al,*

*Mon.Not.Roy.Astron.Soc. 529 (2024) 3630*

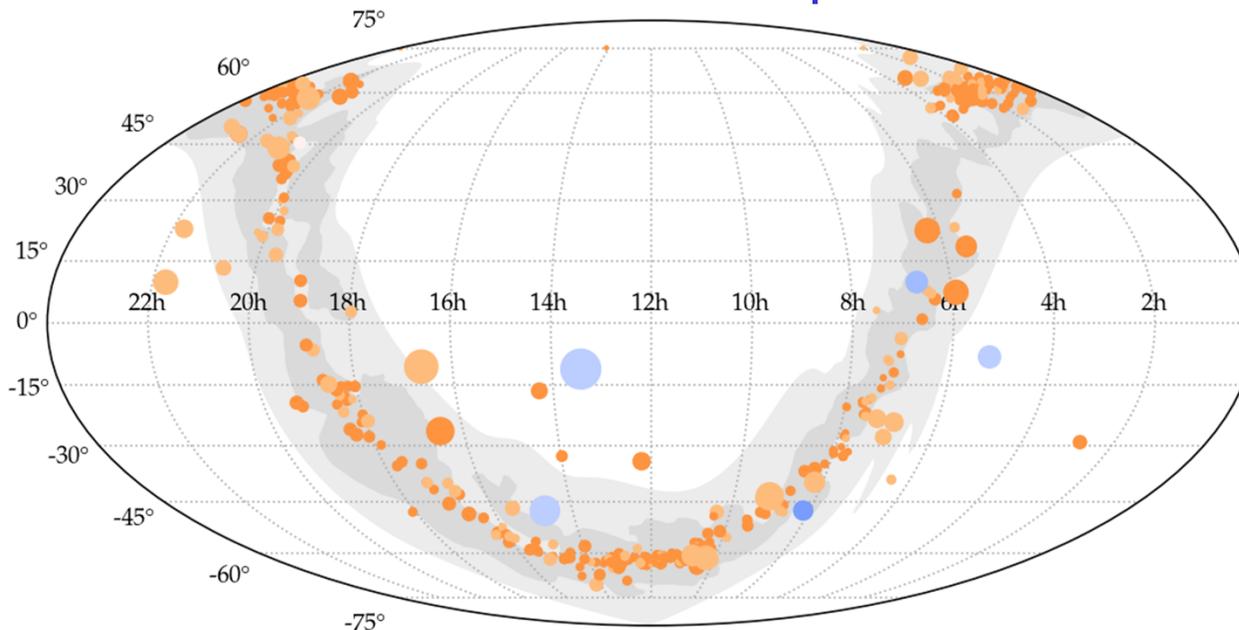




# Progenitor Monitoring



- AAVSO has started a progenitor monitoring campaign
  - For bright stars, to get a pre-SN baseline
  - Also get eyes on possible targets when combined with localization maps in event of SN alert



Catalog of bright potential CCSN progenitors. Diameter proportional to  $1/r^2$  (Healy et al, *Mon.Not.Roy.Astron.Soc.* 529 (2024) 3630)



# Using the Alert



- The resulting coincidence alert goes to:
  - Email list of interested people
    - Amateur network of many skilled eyeballs
    - Once someone optically ID's the new SN, we all know and can zoom in
    - Sign up for alert email, <http://snews.bnl.gov>
  - SCIMMA & GCN
    - Since photosphere breakout should really light up the high energy photon sky, use those photons to quickly localize
  - LIGO, NOvA, SBND, Xenon save buffered data on alert
    - Having a  $t_0$  helps GW wave searches
- What cool stuff with a once-in-a-lifetime nearby supernova would you like to learn?
  - Progenitor status?
  - Shockwave blowing through stellar system?
  - Stellar wind just before the end?
- Data you couldn't take after the fact
  - From a time window no-one's ever seen



# Summary



- While one of the  $\sim 200$  SNe  $\nu$  wavefronts currently traversing our galaxy hasn't arrived since 1987, experiments are ready for it
  - Experimental capabilities have evolved
  - Next generation experiments JUNO, DUNE, and Hyper-K will do much better in a few years than we can now
- There will be a bonanza of astro- and particle-physics knowledge when the next one passes
  - What can we do now to understand as much as possible as quickly as possible?
  - Timely info will yield better follow-up observations
- New SNEWS2.0 system in testing now, hope to have it live soon

See SNEWS2.0 whitepaper, Al Kharusi *et al*, NJP 23, 031201 (2021)



# Acknowledgements



- SNEWS2.0 development supported by NSF collaborative grant #2209534
  - <https://snews2.org>
  - Code at: <https://github.com/SNEWS2>
- OG SNEWS only functions with the cooperation of member experiments and their SN teams, plus Brookhaven and INFN Bologna
  - See <https://snews.bnl.gov> for more info and to sign up for the alert list

