Super-Kamiokande's Supernova monitoring: A trigger for multi-messenger research

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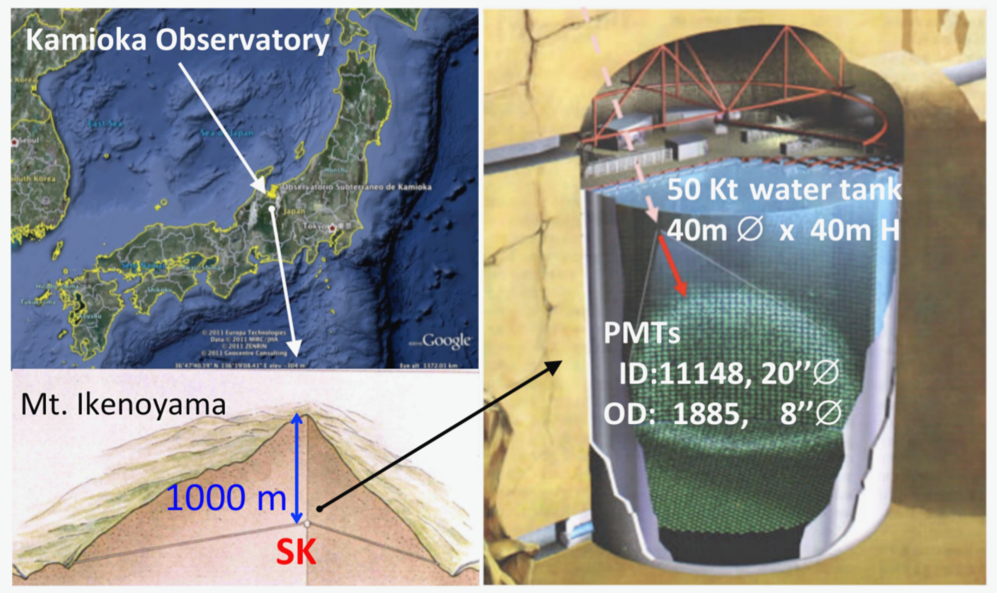
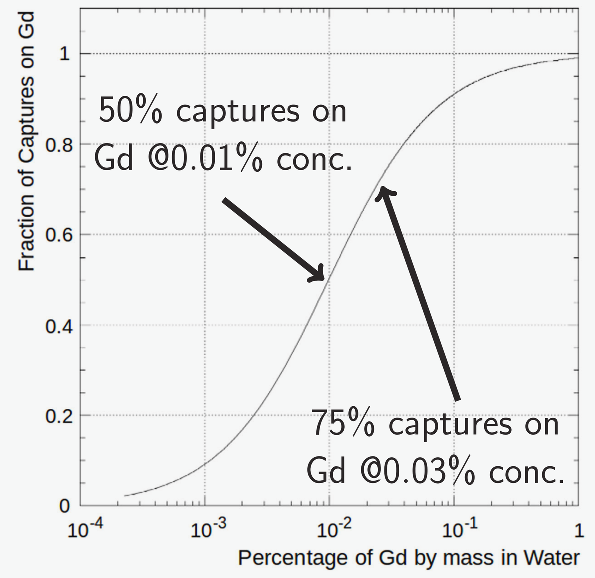
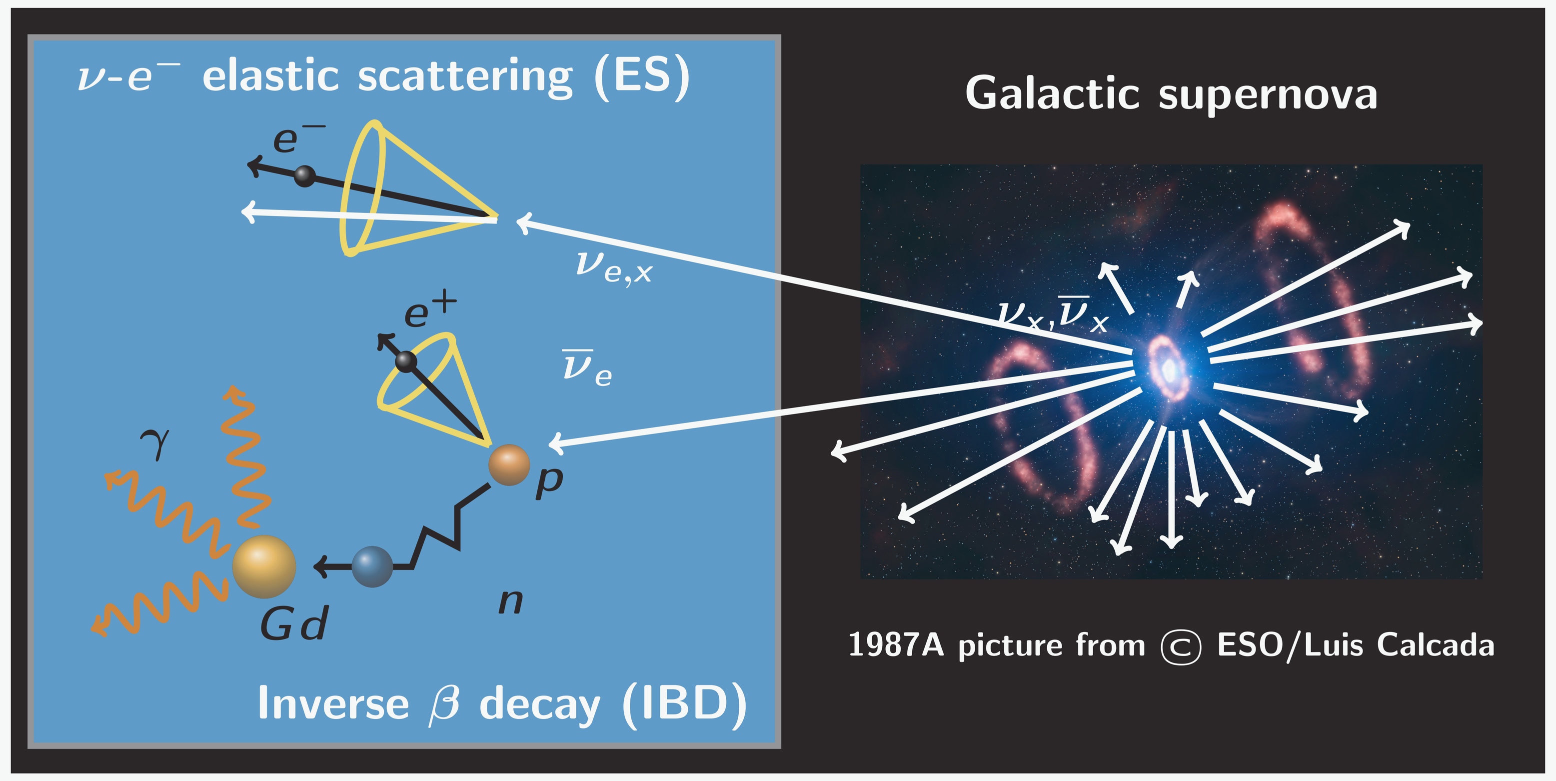
1 Context: Super-Kamiokande experiment



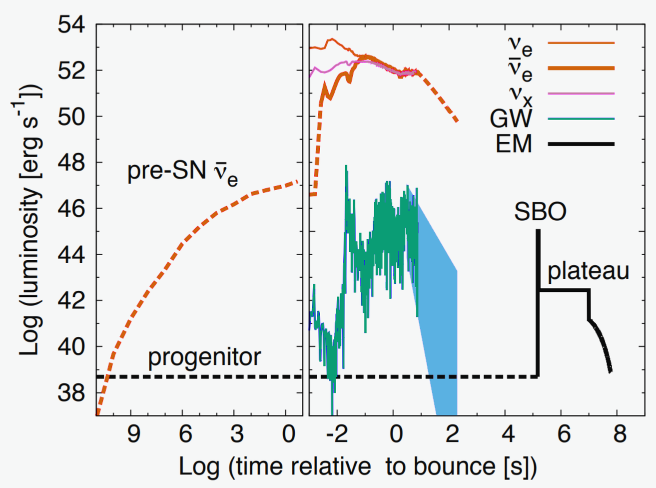


- Super-Kamiokande (SK) is a neutrino experiment located in the Kamioka mine, about 1 km under Mt. Ike (Ikenoyama), in Kamioka-cho (Japan).
- 50 ktons water Čerenkov detector, operated since 1996.
- Gadolinium (Gd) was loaded in the water at a concentration of 0.03%
  → Improve neutron capture detectability
  → Inverse β Decay (IBD) tagging ($\sim$ 51.3% efficiency)
- In a supernova ν burst, electron scattering (ES) interactions provided pointing information. **Tagging IBD improve ES purity**, leading to **better pointing accuracy**



2 Context: Supernova neutrino bursts

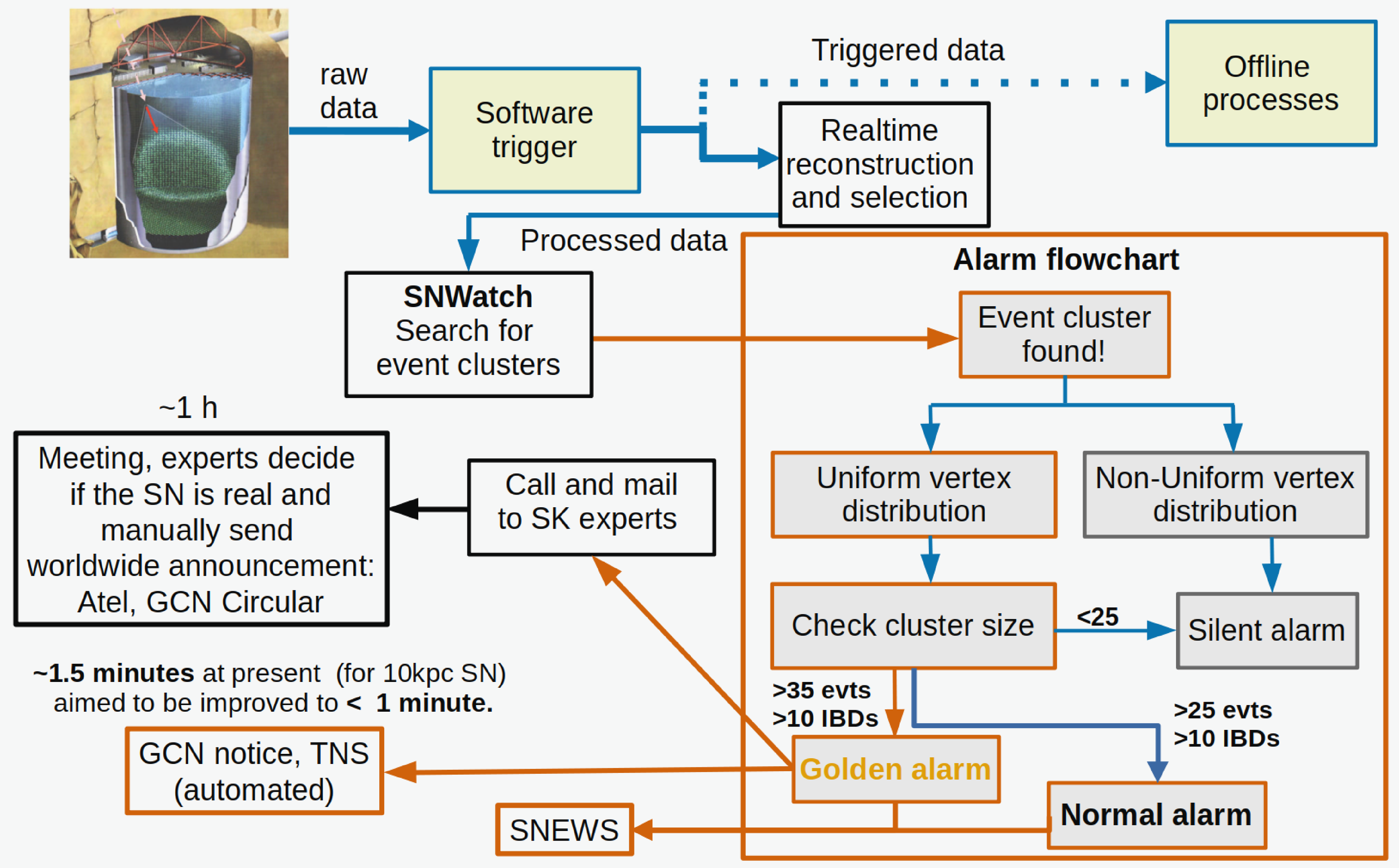
- Since SN1987A we know core-collapse SN produce a large number of neutrinos. $\sim$ 99% of the SN energy is carried away by neutrinos. If close enough, this burst of neutrinos can be detected on Earth.
- The ν burst is produced few minutes to several hours before the electromagnetic signal, **its detection could give an early warning to astronomers**.



K. Nakamura et al., Mon. Not. Roy. Astron. Soc. 461 (2016)

- In order to give such early warning, the neutrino experiment needs to:
  → Reconstruct the **direction** and the **distance** of the supernova
  → Release the alarm in a **short amount of time** ($\sim$minutes)

3 Supernova burst monitoring in SK



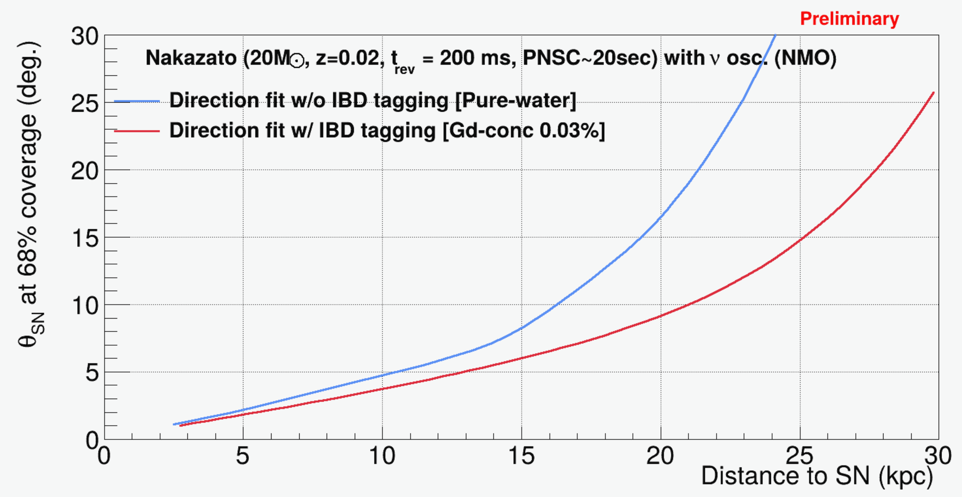
- Super-Kamiokande's alarm channels:

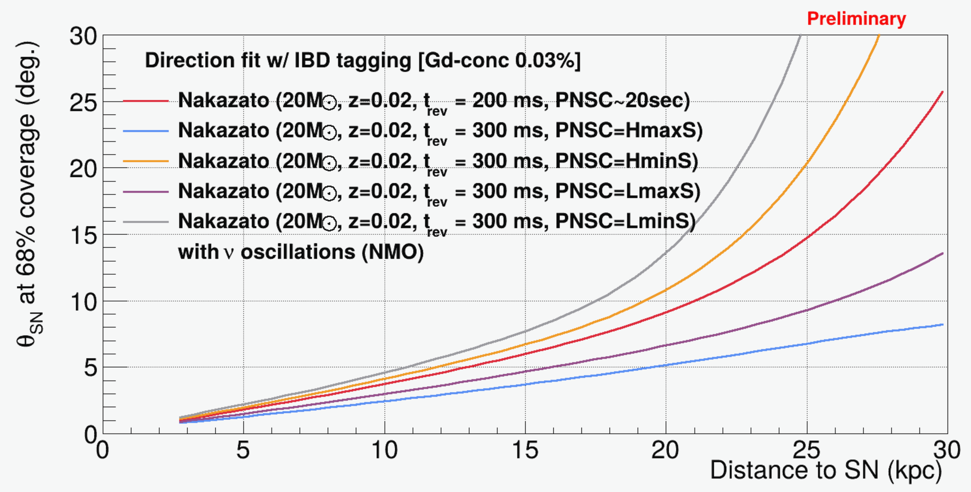
Channel	Timestamp	Direction	Distance	Latency	Note
GCN (Kafka)	✓	✓	✓	$\sim$ 1 sec	Automated
GCN (Classic)	✓	✓	✓	$\sim$ 40 sec	Automated
TNS	✓	✓	✓	$<5sec$	Automated
SNEWS (1.0, 2.0)	✓	×	×	$<5sec$	Automated
Atel	✓	✓	✓	$\sim 1h$	Manual
GCN Circular	✓	✓	✓	$\sim 1h$	Manual

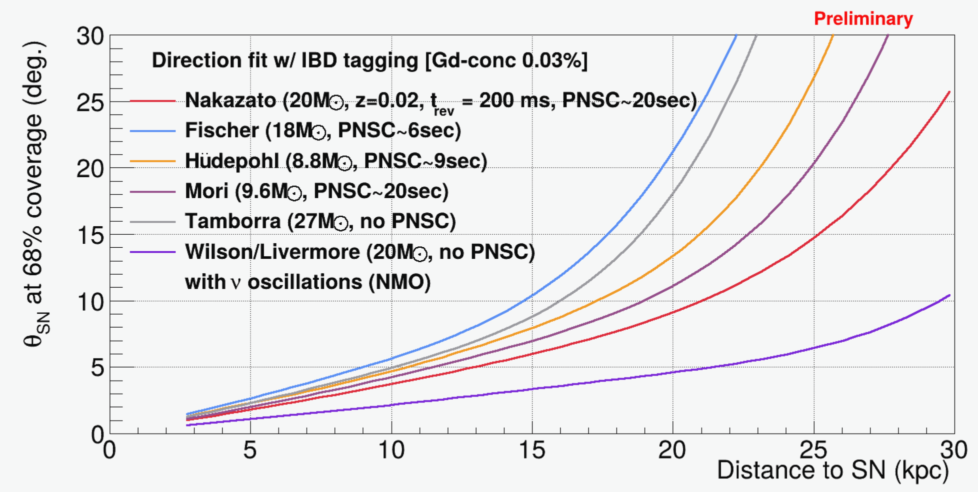
- **GCN (Kafka) notices is our default alarm channel**, its system allowing to update easily alarm information if needed
  → Check here: `https://gcn.nasa.gov/missions/sksn`
- $>$ 99.81% automated alarm probability up to 65kpc (SMC)

4 Proto Neutron Star Cooling impact on supernova pointing accuracy and distance estimation (NEW)

- Pointing accuracy @10kpc (default NK 20M⊙, PNSC 20sec) with lastest analysis framework: $\mathbf{3.78 \pm 0.04^\circ}$ (1σ) $5.51 \pm 0.06^\circ$ (90C.L.)
- Proto Neutron Star Cooling (PNSC) ν production is not negligible, extend up to 30 $\sim$ 100 sec. Using these neutrino can allow to improve pointing accuracy, at the cost of a slower/delay analysis. → We studied models with extreme cases of PNSC (HmaxS, HminS, LmaxS, and LminS).
- Unfortunatly most SN ν models do not consider or cut off the PNSC ν production after few seconds.



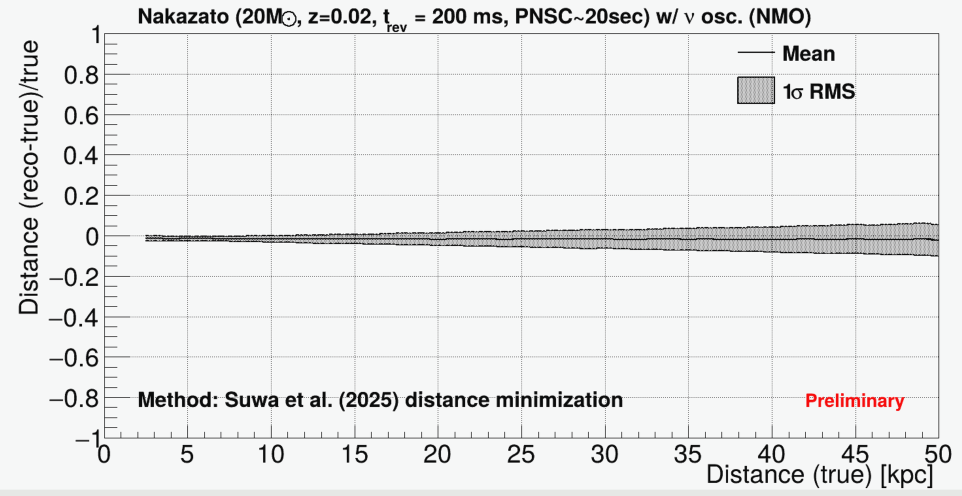


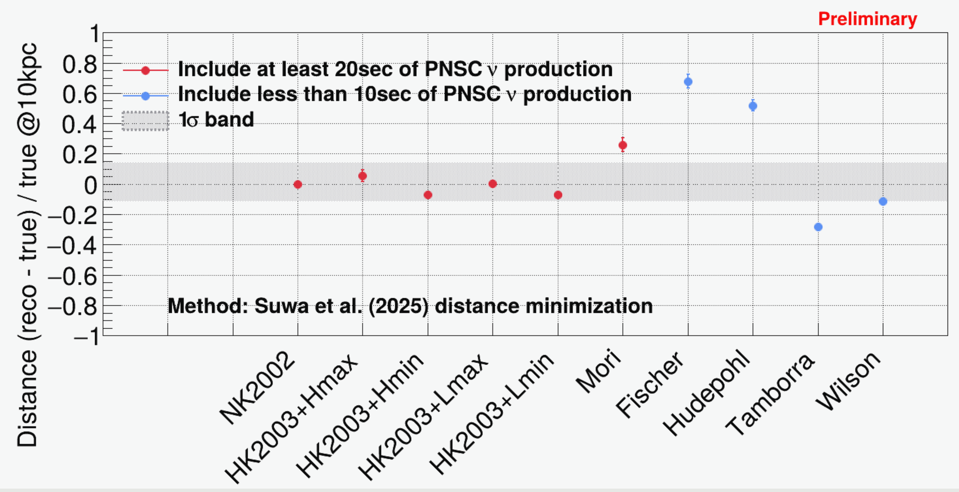


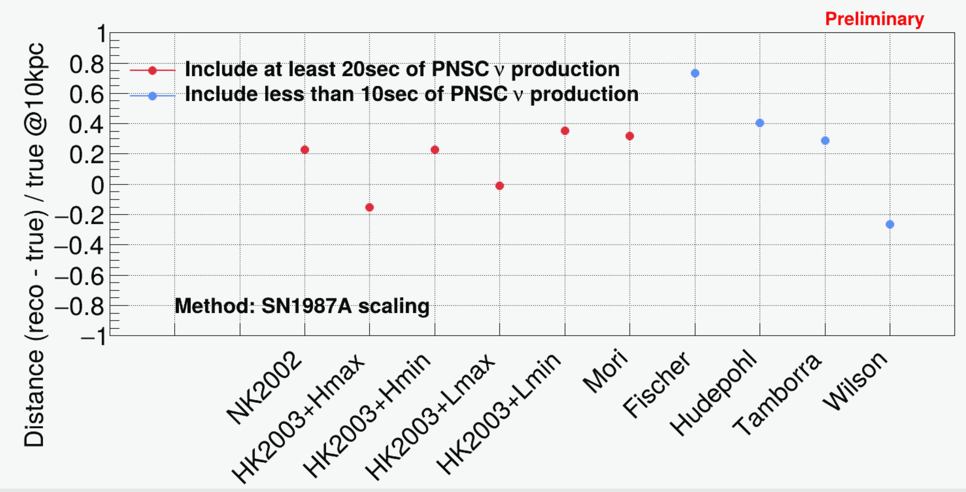
- Distance from the SN is currently determined by scaling Kamiokande-II SN1987A observed number of events to the observed number of events in SK. (outdated, statistically limited) → It results in a strong model dependency of the distance estimation
- Suwa et al. (2025 ApJ 980 117) provided a modern method, based on PNSC ν production ($\sim$model indep.). Minimization over rates and avg. energy:

$$E_{e^+} = 25.3\,\mathrm{MeV}\left(\frac{M_{PNS}}{1.4\,M_\odot}\right)^{3/2}\left(\frac{R_{PNS}}{10\,\mathrm{km}}\right)^{-2}\left(\frac{g\beta}{3}\right)\left(\frac{t+t_0}{100\,\mathrm{s}}\right)^{-3/2} \qquad \mathcal{R} = 720\,\mathrm{s}^{-1}\left(\frac{M_{\mathrm{det}}}{32.5\,\mathrm{kton}}\right)\left(\frac{D}{10\,\mathrm{kpc}}\right)^{-2}\left(\frac{E_{e^+}}{25.3\,\mathrm{MeV}}\right)^{5}\left(\frac{R_{PNS}}{10.0\,\mathrm{km}}\right)^{2}$$

- Suwa et al. method provide a distance estimation $<$ 30% uncertainty for models including at least 20 sec of PNSC ν production







5 Summary / Key points

- **Promising results with new distance estimation method**. We are looking to implement it as our new default estimation method soon.
- PNSC ν production up to 30 $\sim$ 100 sec post burst. **Extended (slower) analysis** can improve precision → under investigation

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