THE GAMMA RAY ECHO OF SUPERNOVA NEUTRINOS

Cecilia Lunardini

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Thoughts on Baha and George

- as *community leaders*

"I want to hire you!"

George (circa 2003)

Baha-powered sabbatical at the NAOJ, Tokyo (2023)

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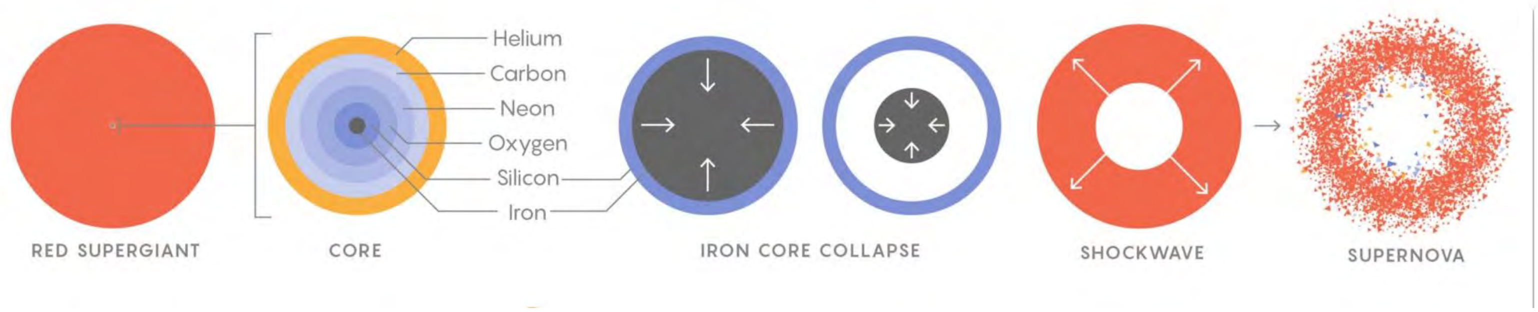
Core collapse supernovae: overview

Stellar death: a core collapse supernova

Credit: Lucy Reading-Ikkanda/Quanta Magazine



time

Advanced nuclear fusion

Loss of pressure; free fall; core formation

Falling matter bounces; shockwave; ***Cooling via neutrinos***

Star explodes

Neutrino burst, ~ 10 s

Neutrinos from core collapse

- Neutrinos *thermalized* in ultra-dense matter
  - Surface emission
  - Fermi-Dirac spectrum, E ~ 10-15 MeV

- Neutrino cooling of proto-neutron star is most efficient
  - *gravitational* binding energy:

    $L_\nu \sim G\,M^2{}_f/R_f - G\,M^2{}_i/R_i \sim 3\ 10^{53}$ ergs

    ($R_f \sim 10$ Km)

- Cooling timescale ~ neutrino diffusion time
  - Time ~ (size^2)/(mean free path) ~ 10 s

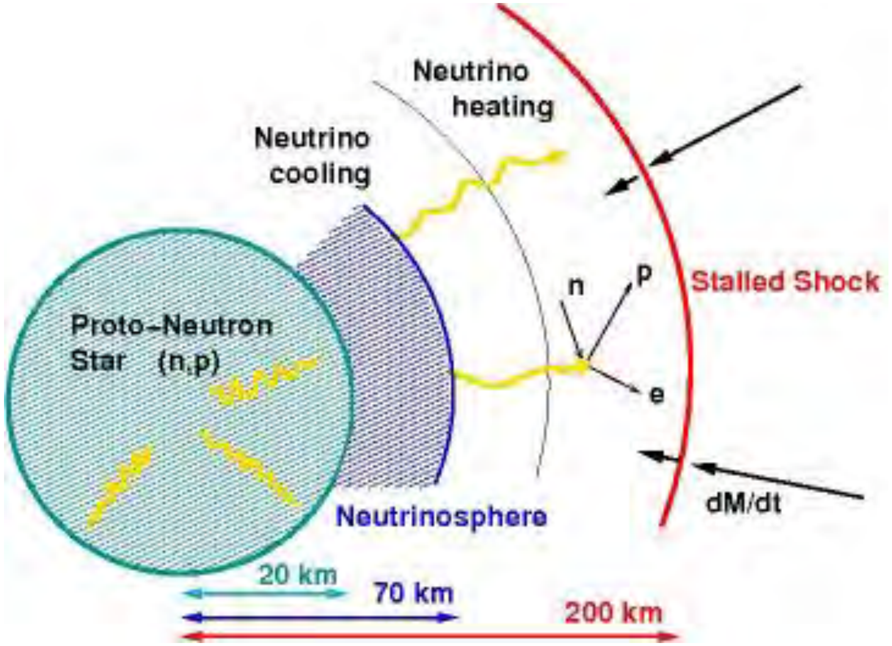
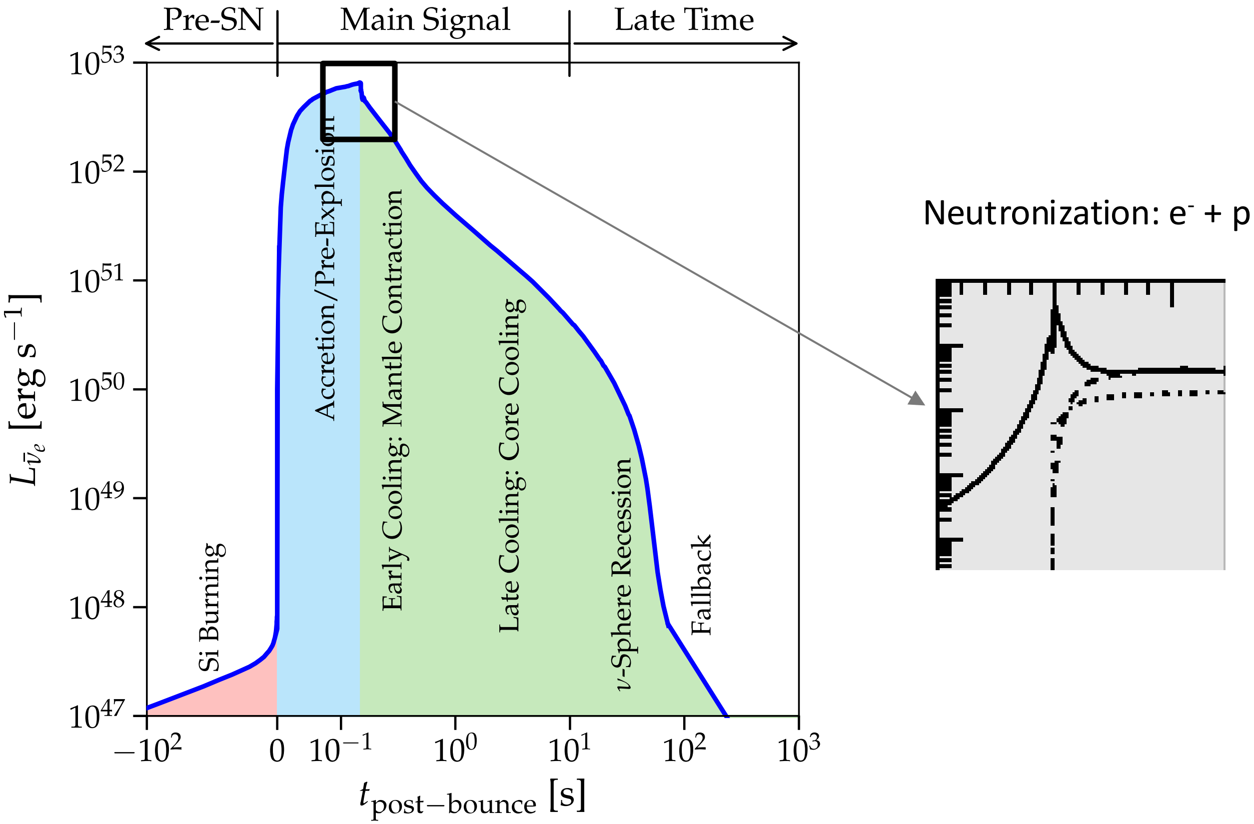


Figure: Amol Dighe, talk at WHEPP XV, 2017

Direct narrative of near-core events

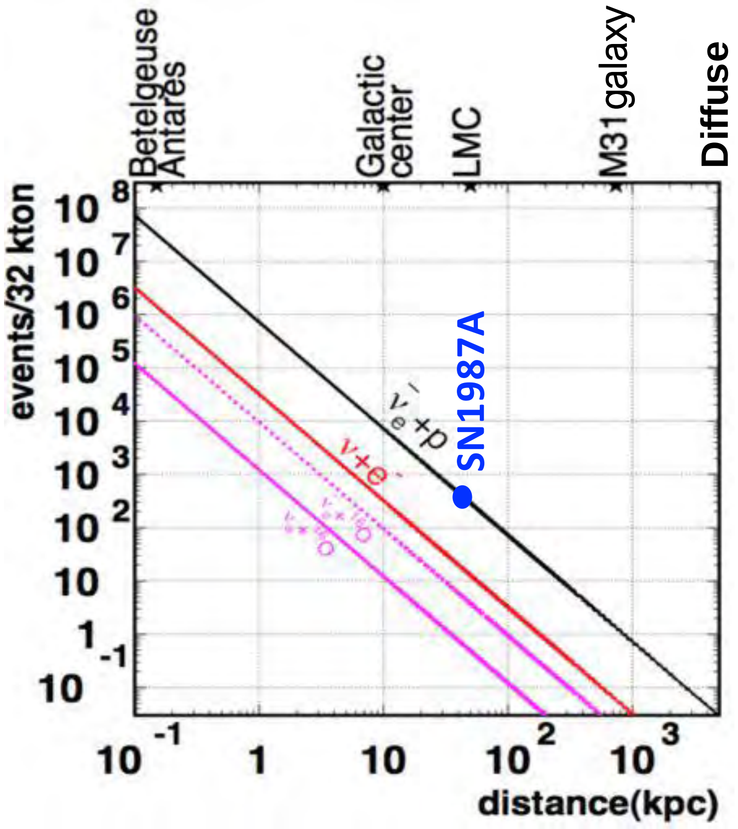


Neutronization: $e^- + p \rightarrow n + \nu_e$

Li, Roberts and Beacom, *Phys.Rev.D* 103 (2021) 2, 023016

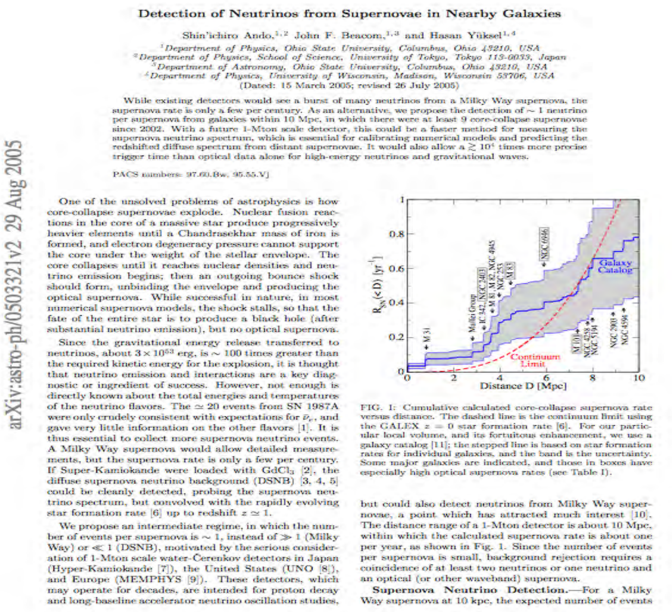
High (low) statistics, low (high) probability

- Water Cherenkov detectors: $\bar{\nu}_e + p \rightarrow e^+ + n$
    - $N \sim 10^4$ (D/10 kpc)



Pablo Fernandez, Super-Kamiokande coll., PhD thesis, 2017.

Rate of collapses *within* distance D



arXiv:astro-ph/0503321v2 29 Aug 2005

Detection of Neutrinos from Supernovae in Nearby Galaxies

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(Dated: 15 March 2005; revised 26 July 2005)

While existing detectors would see a burst of many neutrinos from a Milky Way supernova, the supernova rate is only a few per century. As an alternative, we propose the detection of ~ 1 neutrino per supernova from galaxies within 10 Mpc, in which there were at least 9 core-collapse supernovae since 2002. With a future 1-Mton scale detector, this could be a faster method for measuring the supernova neutrino spectrum, which is essential for calibrating numerical models and predicting the redshifted diffuse spectrum from distant supernovae. It would also allow a $\gtrsim 10^4$ times more precise trigger time than optical data alone for high-energy neutrinos and gravitational waves.

PACS numbers: 97.60.Bw, 95.55.Vj

One of the unsolved problems of astrophysics is how core-collapse supernovae explode. Nuclear fusion reactions in the core of a massive star produce progressively heavier elements until a Chandrasekhar mass of iron is formed, and electron degeneracy pressure cannot support the core under the weight of the stellar envelope. The core collapses until it reaches nuclear densities and neutrino emission begins; then an outgoing bounce shock should form, unbinding the envelope and producing the optical supernova. While successful in nature, in most numerical supernova models, the shock stalls, so that the fate of the entire star is to produce a black hole (after substantial neutrino emission), but no optical supernova.

Since the gravitational energy release transferred to neutrinos, about 3×10^{53} erg, is ~ 100 times greater than the required kinetic energy for the explosion, it is thought that neutrino emission and interactions are a key diagnostic or ingredient of success. However, not enough is directly known about the total energies and temperatures of the neutrino flavors. The $\simeq 20$ events from SN 1987A were only crudely consistent with expectations for $\bar{\nu}_e$, and gave very little information on the other flavors [1]. It is thus essential to collect more supernova neutrino events. A Milky Way supernova would allow detailed measurements, but the supernova rate is only a few per century. If Super-Kamiokande were loaded with $GdCl_3$ [2], the diffuse supernova neutrino background (DSNB) [3, 4, 5] could be cleanly detected, probing the supernova neutrino spectrum, but convolved with the rapidly evolving star formation rate [6] up to redshift $z \simeq 1$.

We propose an intermediate regime, in which the number of events per supernova is ~ 1, instead of $\gg 1$ (Milky Way) or $\ll 1$ (DSNB), motivated by the serious consideration of 1-Mton scale water-Čerenkov detectors in Japan (Hyper-Kamiokande [7]), the United States (UNO [8]), and Europe (MEMPHYS [9]). These detectors, which may operate for decades, are intended for proton decay and long-baseline accelerator neutrino oscillation studies,

FIG. 1: Cumulative calculated core-collapse supernova rate versus distance. The dashed line is the continuum limit using the GALEX $z = 0$ star formation rate [6]. For our particular local volume, and its fortuitous enhancement, we use a galaxy catalog [11]; the stepped line is based on star formation rates for individual galaxies, and the band is the uncertainty. Some major galaxies are indicated, and those in boxes have especially high optical supernova rates (see Table I).

but could also detect neutrinos from Milky Way supernovae, a point which has attracted much interest [10]. The distance range of a 1-Mton detector is about 10 Mpc, within which the calculated supernova rate is about one per year, as shown in Fig. 1. Since the number of events per supernova is small, background rejection requires a coincidence of at least two neutrinos or one neutrino and an optical (or other waveband) supernova.

Supernova Neutrino Detection.—For a Milky Way supernova at 10 kpc, the expected number of events

Ando, Beacom & Yuksel, PRL 95 (2005)

Within our lifetime....

Credit: ESA/Hubble, NASA

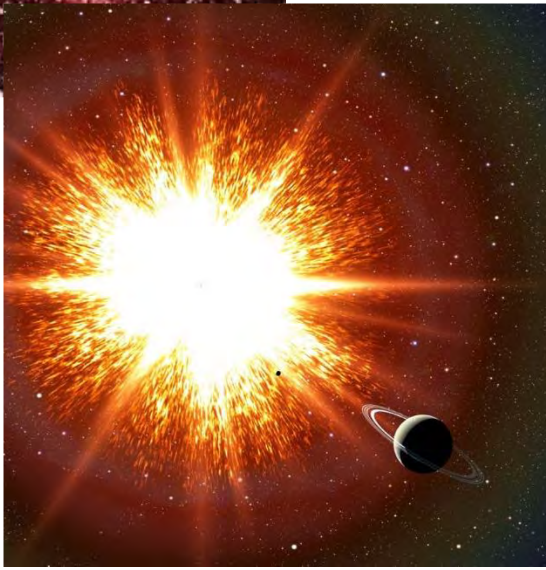
Guaranteed:
multiple SNe, (quasi-)diffuse flux

Credit: Anglo-Australian observatory

Possible:
single, galactic SN burst

This talk →

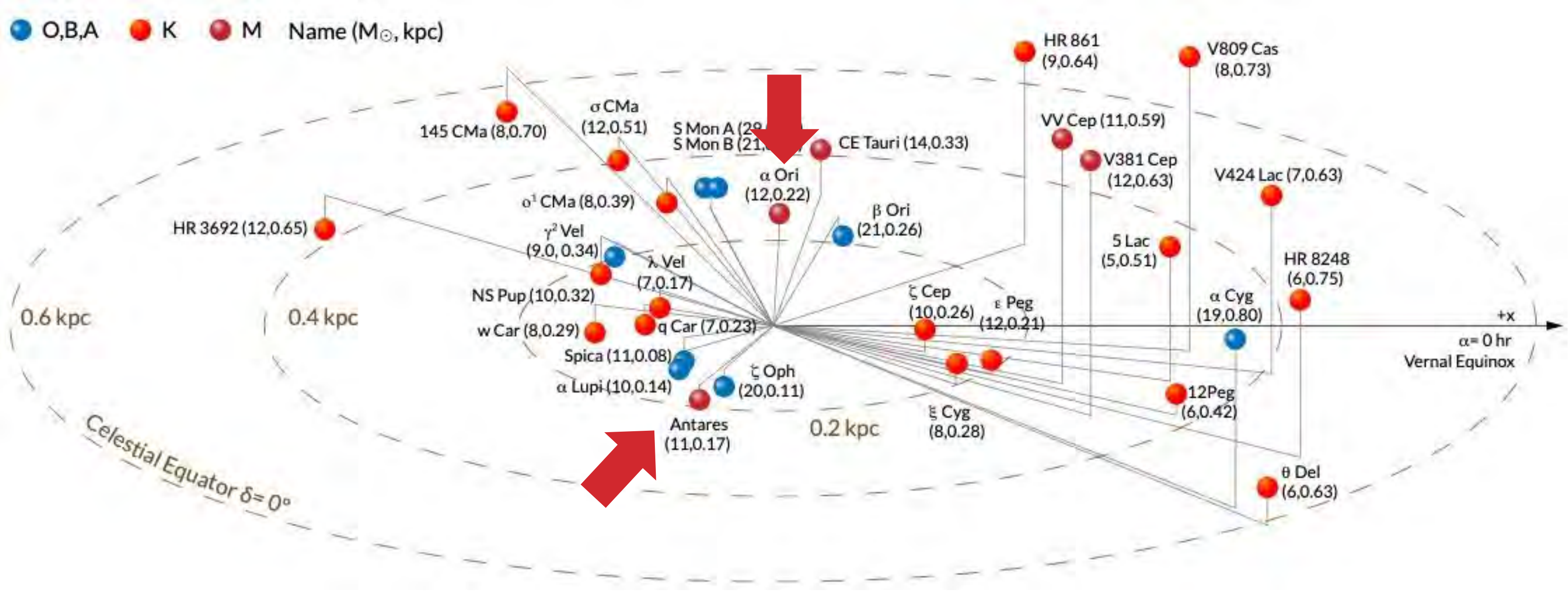
Exceptional:
single, near-Earth SN burst



SmithsonianScience.org

Near Earth CCSNe: candidates

- $D \lesssim$ 1 kpc : 31 stars in supergiant phase
  - E.g., Betelgeuse (D = 0.22 kpc), Antares (D=0.17 kpc)



Mukhopadhyay, CL, Timmes and Zuber, Astrophys.J. 899 (2020) 2, 153

The gamma ray echo of a neutrino burst

Star as a neutrino mega-detector?

- IBD in the star's hydrogen envelope: $\bar{\nu}_e + p \rightarrow e^+ + n$

- Positrons lose energy and annihilate at rest : $e^+ + e^- \rightarrow \gamma + \gamma$
  - *0.511 MeV gamma rays* signature!

- neutron is captured: $n + p \longrightarrow {}^2\mathrm{H} + \gamma$
  - 2.22 MeV gamma rays
  - Subdominant (not considered here)

Bisnovatyi-Kogan, Imshennik, Nadyozhin and Chechetkin, Astrophys. Space Sci. 35, 23 (1975).
Ryazhskaya, N. Cim. 22C, 115 (1999).
Lu and Qian, PRD 76, 103002 (2007)
CL, J. Loeffler, M. Mukhopadhyay, M. Hurley, E. Farag and F. X. Timmes, *Astrophys.J.* 969 (2024) 2, 149

Positron annihilation

Lu and Qian, PRD 76, 103002 (2007)

- Example: envelope with

$$T \sim 10^4 \text{ K} \qquad \rho \sim 10^{-8} \text{ g cm}^{-3} \qquad Y_p = 0.7 \qquad Y_e = 0.85$$

- Positron thermalization:
  - Mostly due to excitation of free electrons
  - is *fast*: ~ 10^{-2} s
  - Occurs before annihilation in ~ 87 % of the cases
- Annihilation:
  - Mostly on free electrons
  - $\langle E_\gamma \rangle = 511\ KeV$, $\Delta E_\gamma \cong 2\ KeV$

Surface emission

- Gamma rays undergo Compton scattering
  - Mean free path << of stellar radius:

$$l_C \sim O(10^9)\ \mathrm{cm} \qquad R = 10^{13.5}\ \mathrm{cm}$$

- Emission rate follows neutrino luminosity
  - Time-integrated flux:

$$N_+ \simeq \frac{Y_p \langle\sigma_{\mathrm{IBD}}\rangle}{Y_e \sigma_C} N_{\bar\nu} \simeq 1.25\ 10^{41}$$

$$N_\gamma = \frac{1}{2}\eta_\gamma N_+ \sim N_+ \ ,$$

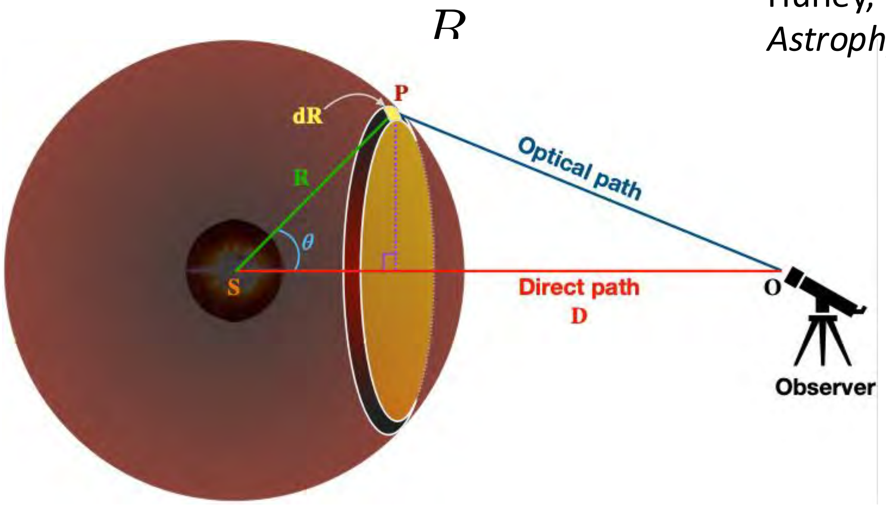
$$\Phi_{\gamma,tot} = \frac{N_\gamma}{4\pi D^2} \sim 10^{-3}\ \mathrm{cm}^{-2} \left(\frac{D}{\mathrm{kpc}}\right)^{-2}$$

Requires telescope with A> 10^2 cm^2

($\eta_\gamma \simeq 1.74$, avg. number of photons per positron)

A gamma ray *echo* of SN neutrinos

CL, J. Loeffler, M. Mukhopadhyay, M. Hurley, E. Farag and F. X. Timmes, *Astrophys.J.* 969 (2024) 2, 149

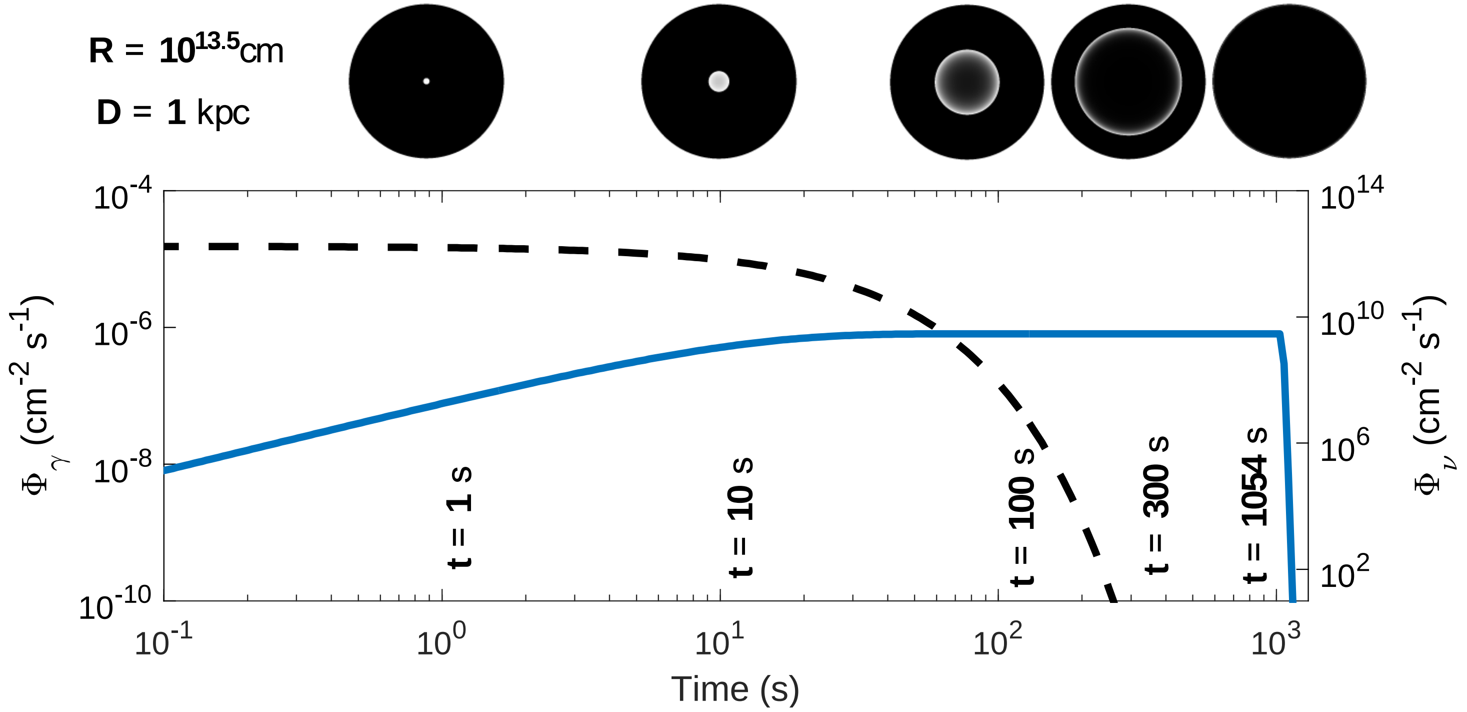


- photon flux from surface shell (dR ~ photon m.f.p. ≪ R)
- Photon-neutrino *time delay* : $\Delta t = \frac{R}{c}\,(1 - cos\theta)$

$$\Phi_\gamma(t,R,D) = \frac{\eta_\gamma}{8\pi D^2}\,\frac{Y_p\langle\sigma_{\rm IBD}\rangle}{Y_e\sigma_{\rm C}}\int_0^1 L_\nu\Big(t - \frac{R}{c}(1-\cos\theta)\Big)d(cos\theta)$$

($\eta_\gamma \simeq 1.74$, avg. number of 0.511 MeV photons per positron)

- Minutes/hours-long echo:
  - starts in coincidence with neutrino burst



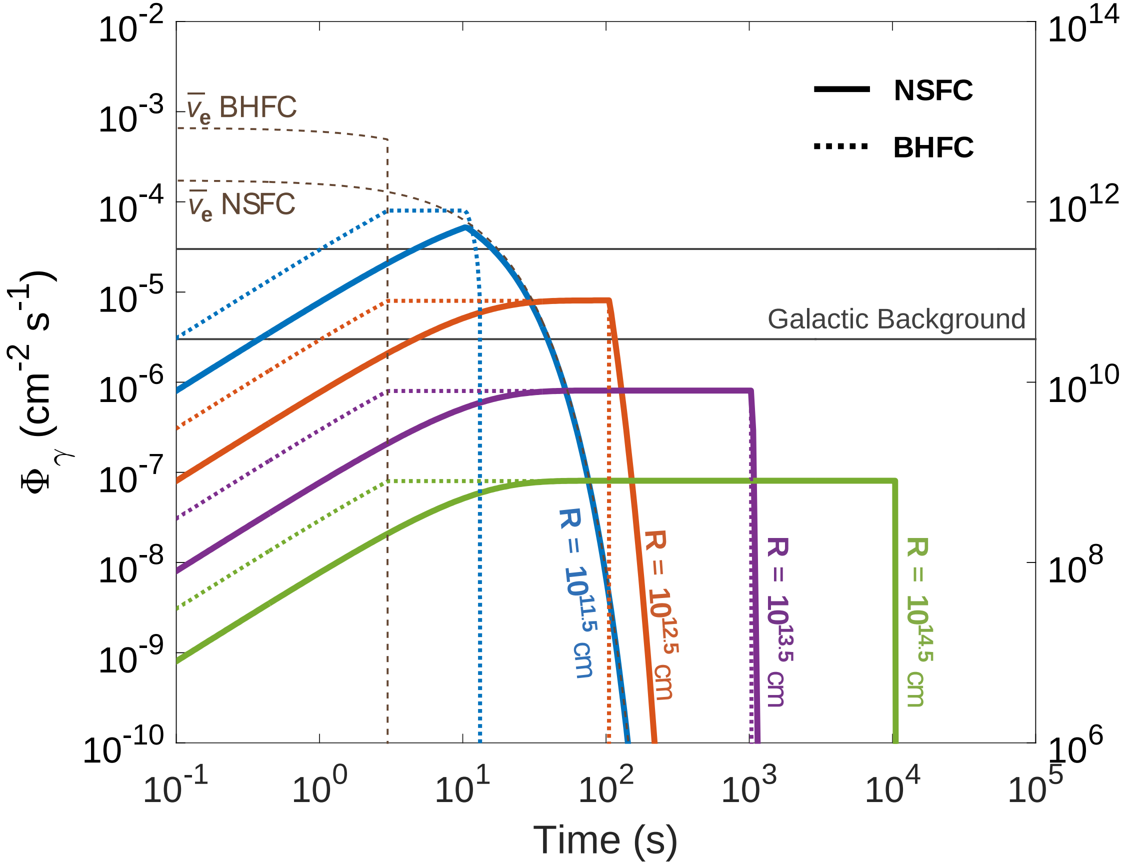
- Calculation parameters:

$$E_{\nu,tot} = 5\ 10^{52}\ \text{ergs} \qquad \langle E_\nu \rangle = 15\ \text{MeV} \qquad \langle E^2_\nu \rangle = 293.2\ \text{MeV}^2$$

$$(1+\alpha)^{-1} = \langle E^2_\nu \rangle / \langle E_\nu \rangle^2 - \qquad \alpha = 2.3$$

$$L_\nu(t) = \begin{cases} L_0 e^{-t/\tau} & 0 \le t \le t_0 \\ 0 & \text{elsewhere} \end{cases} \qquad \tau = 3\ \text{s}$$

$$\sigma_C = 3\ 10^{-25}\ \text{cm}^2 \qquad \langle \sigma_{IBD} \rangle = 2.05\ 10^{-41}\ \text{cm}^2$$



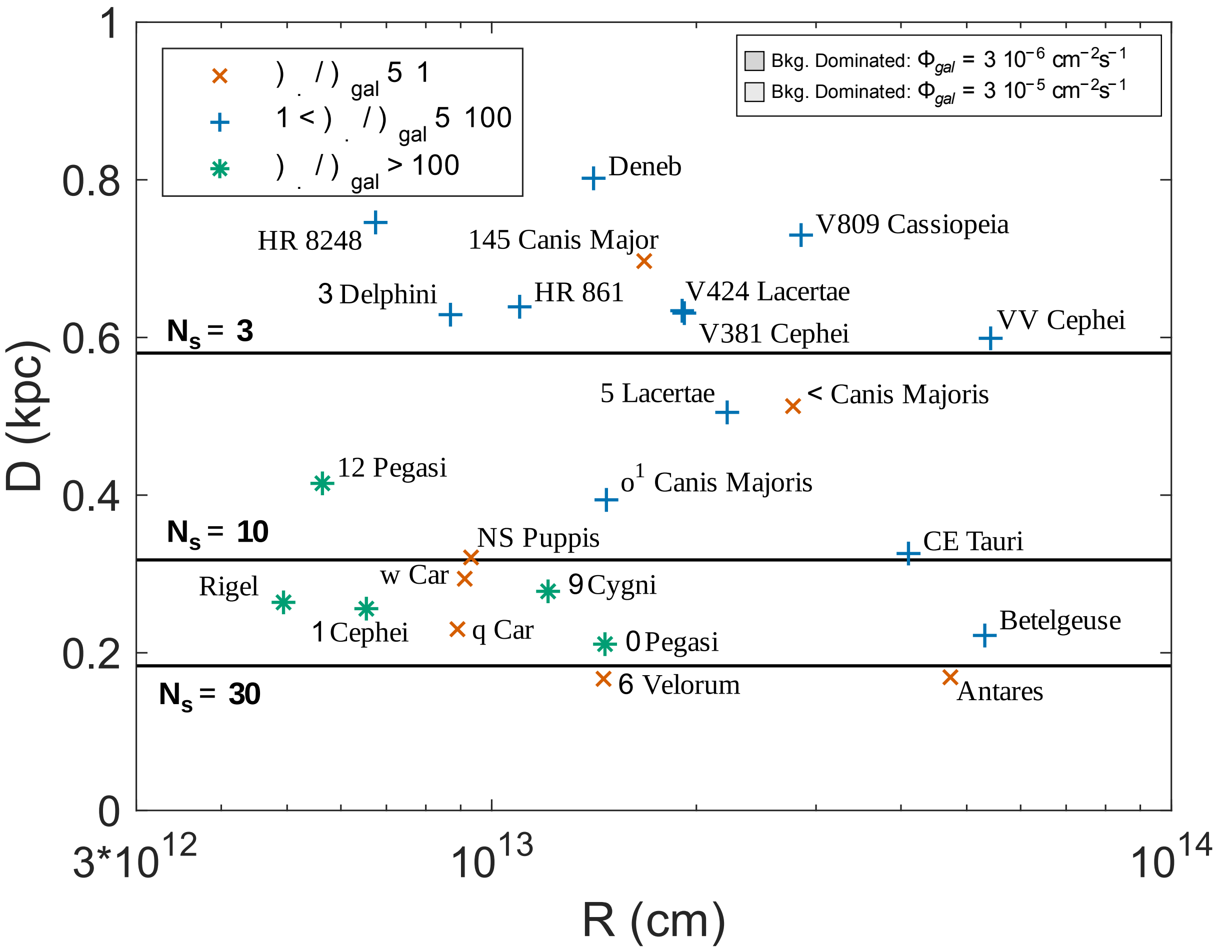
NSFC = Neutron-star forms

BHFC=Black hole forms

Background is for resolution $\delta\theta \sim 3^\circ$

- Main background: diffuse galactic 0.511 MeV flux
  - Better S/B ratio for smaller R (shorter echo)

Detectability: signal, S/B ratio



- $N_S = \phi_\gamma AR/c$ number of detected photons (shown: A = 10^3 cm^2)

Detection prospects

- Upcoming: COSI, $\mathrm{A} > 20\ \mathrm{cm}^2$, resolution $\delta\theta = 4.1°$
  - could be sensitive to Betelgeuse (D=0.2 kpc) with a factor of 2 improvement
  - 25% sky coverage

- Distant future: AMEGO (A= $3\ 10^3\ \mathrm{cm}^2$), GECCO (A= $800\ \mathrm{cm}^2$), resolution $\delta\theta \sim 3°$
  - Sensitivity to 1 kpc

Tomsick, J. A. 2021, PoS, ICRC2021, 652
Caputo, R., et al., 2022, J. Astron. Telesc. Instrum. Syst., 8, 044003,
Kierans et al, Proc. SPIE Int.Soc.Opt.Eng. 11444, 1144431 (2020);
Orlando *et al*, JCAP07 (2022) 036

Discussion and conclusions

What can we learn?

- Test neutrino emission *away* from line of sight
- Complementary measurement of stellar radius
- Test for stellar envelope composition
- Star as *near* detector (neutrino flux at star’s surface)

Possible generalizations

- More realistic envelope
  - Subdominant interactions
  - Realistic nuclear composition
  - Non-spherical star

- Non-hydrogen envelopes?

- non-envelope hydrogen: clouds, companion star, …

Conclusions

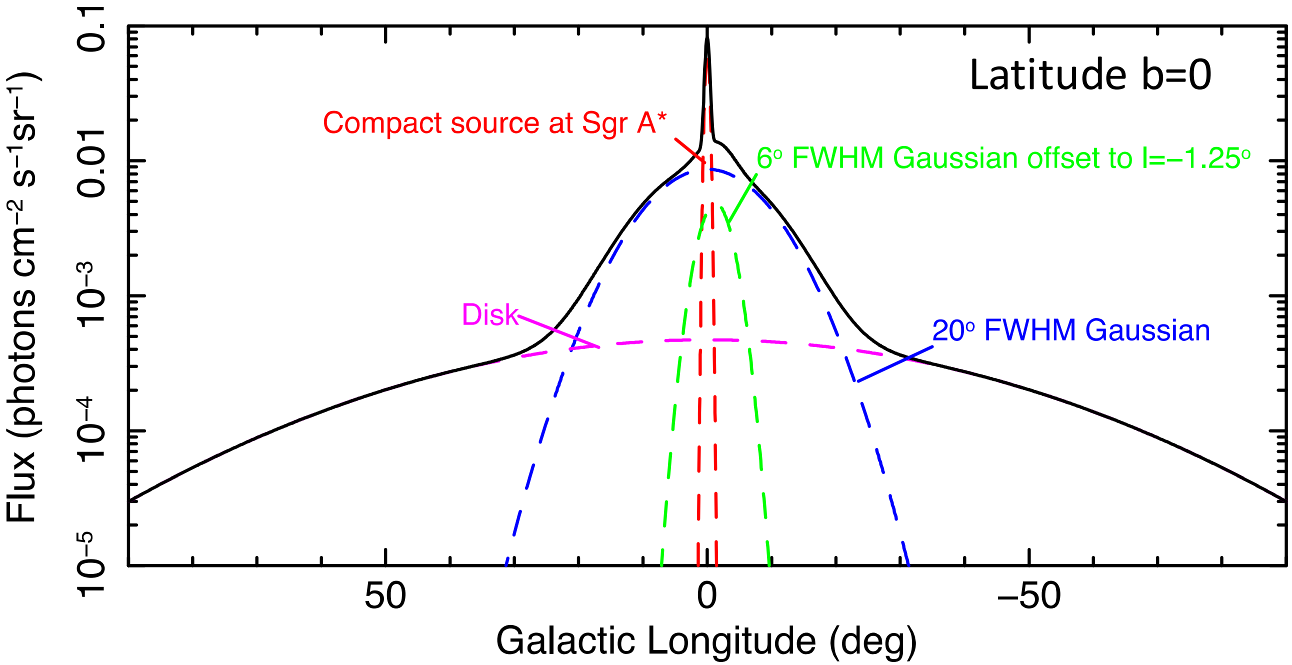
- A near-Earth supernova is *possible*
  - 30+ candidates at D < 1 kpc (Betelgeuse, Antares, Rigel, …)
  - It can happen *any day!*
  - Unique multimessenger opportunities

- Detectable multimessenger signals that have neutrinos as *source*
  - Gamma ray echo
  - Gravitational wave memory

Thank you!

BACKUP

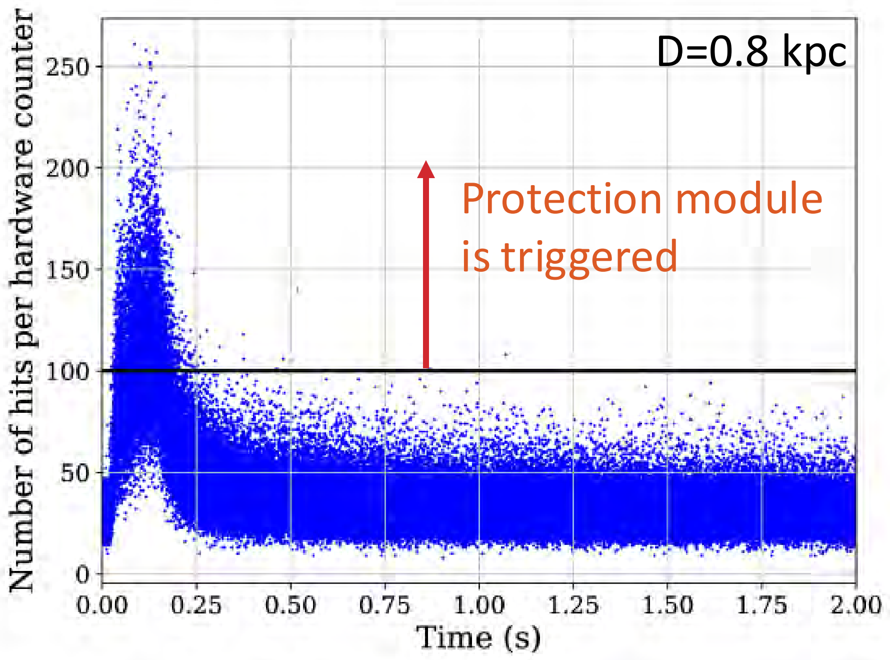
- Galactic 511 KeV background



Skinner, G., Diehl, R., Zhang, X.-L., Bouchet, L., & Jean, P. 2015, PoS, Integral2014, 054

Preparedness: near-Earth supernova

- Danger of Data Acquisition System overload!
  - New SuperK protection module with veto



M. Mori et al. (SuperK. coll.), arxiv:2404.08725