A FUTURE NEAR-EARTH SUPERNOVA: MULTIMESSENGER SCENARIOS

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Contents

- Core collapse supernovae (CCSN): overview

- A near Earth CCSN: *unique* opportunities
  1. pre-supernova neutrinos
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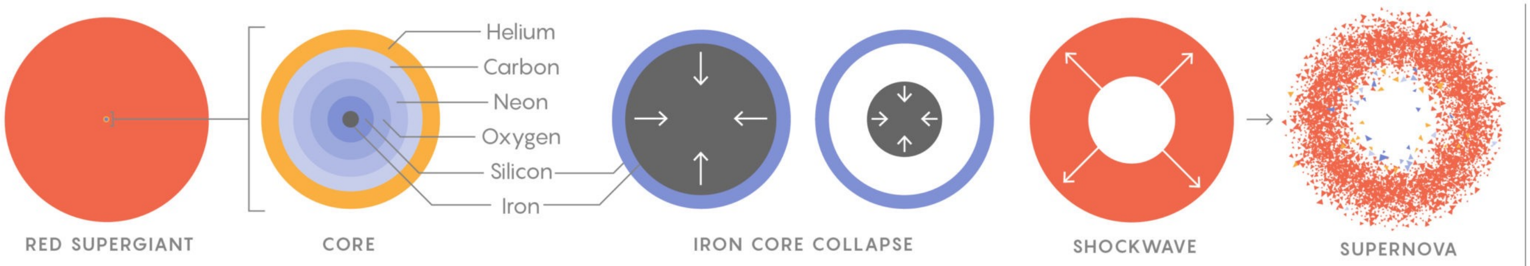
  3. (The gravitational wave memory)

- Discussion and conclusions

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

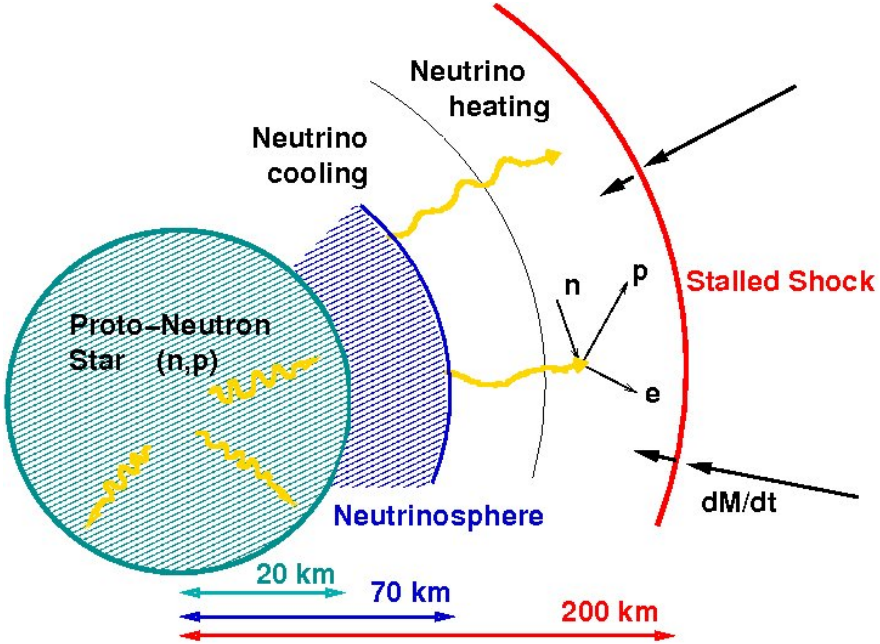
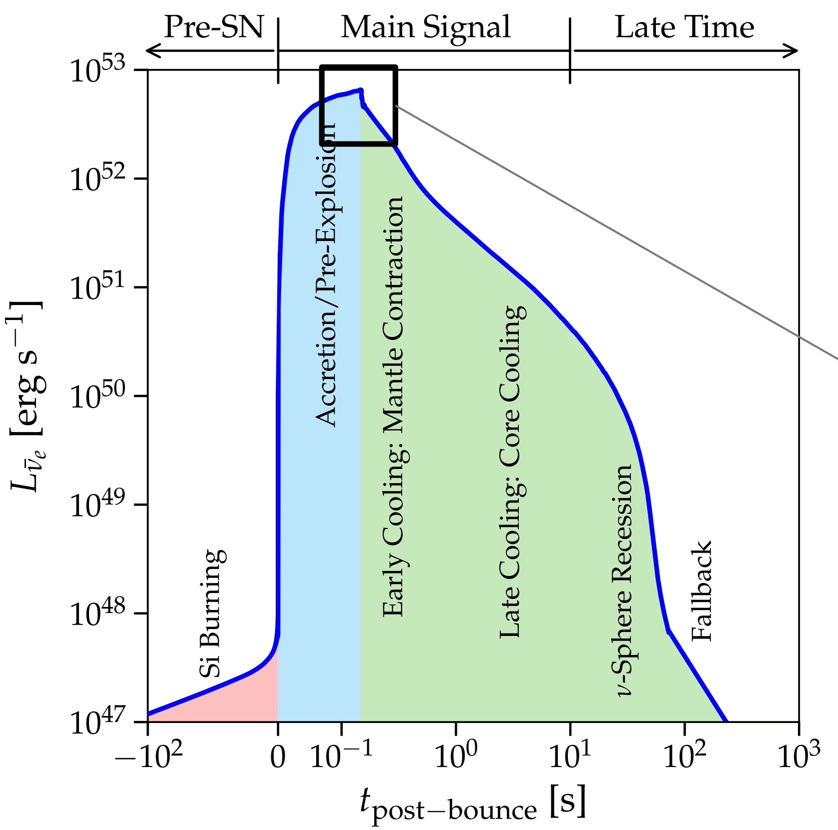
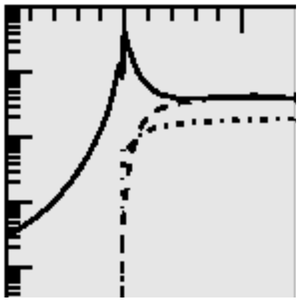


Figure: Amol Dighe, talk at WHEPP XV, 2017

Direct narrative of near-core events



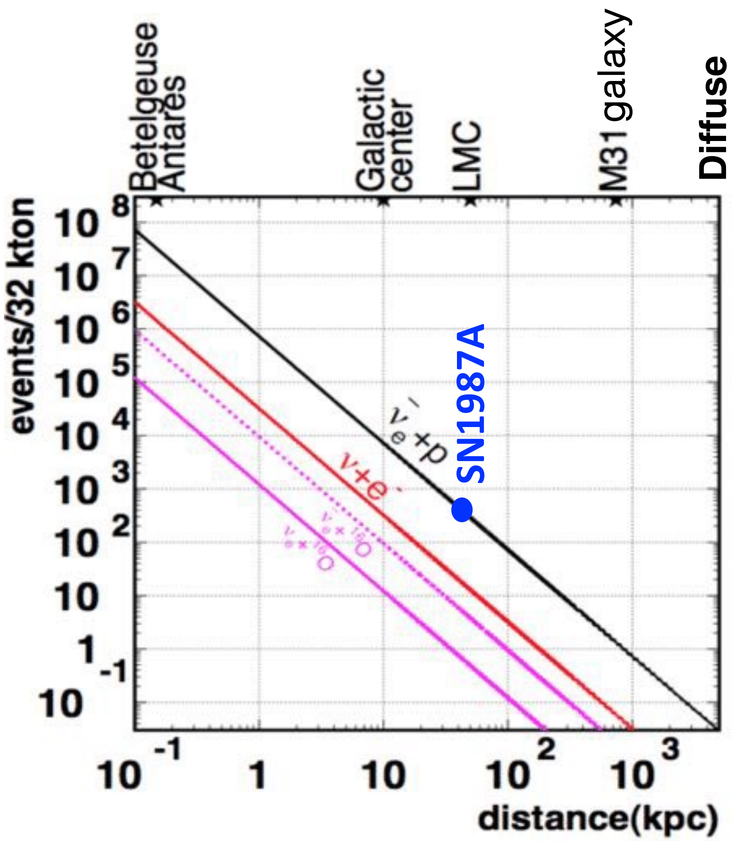
Neutronization: $e^- + p \rightarrow n + \nu_e$



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

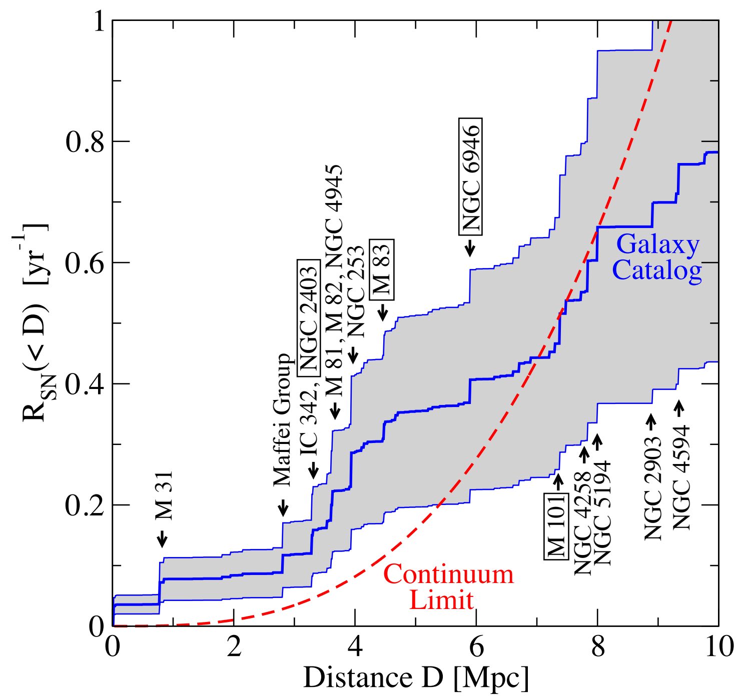
High (low) statistics, low (high) probability

- 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



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

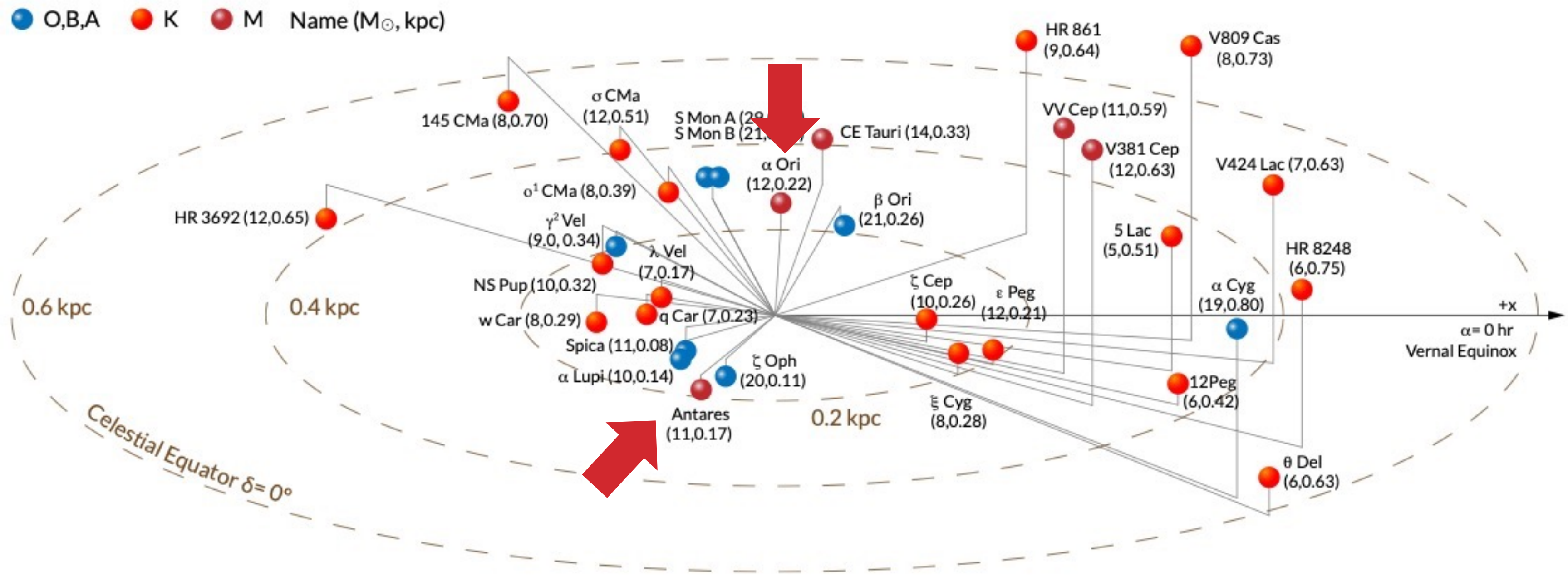
This talk

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)

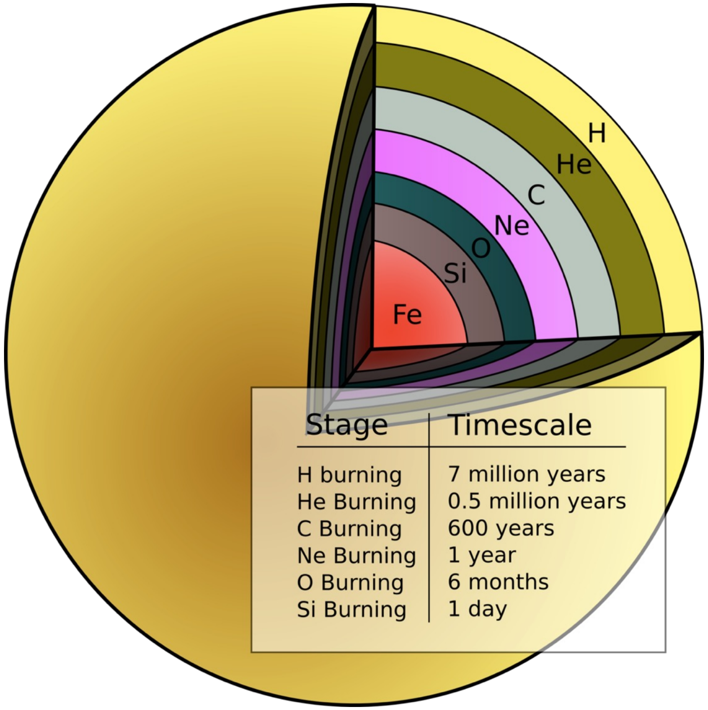


Mukhopadhyay, CL, Timmes and Zuber, Astrophys.J. 899 (2020) 2, 153

1. Pre-supernova neutrinos

Betelgeuse dimming? Check the neutrinos!

- Before core collapse: dimming, mass ejection, could be observed
  - False alarms common
- Last stages of fusion chain
  - rapid evolution of isotopic composition, density, temperature
  - *increase of neutrino emission*
    - *detectable!*



Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

A. C. Phillips, *The Physics of Stars, 2nd Edition* (Wiley, 1999)

Odrzywolek, Misiaszek, and Kutschera, Astropart. Phys. 21, 303 (2004)

Itoh, Hayashi, Nishikawa and Kohyama, 1996, ApJS, 102, 411
Kato, Azari, Yamada, et al. 2015, ApJ, 808, 168
Kato, Yamada, Nagakura, et al. 2017, arXiv:1704.05480
Simpson et al., Astrophys.J. 885 (2019) 133
Guo et al., *PLB* 796 (2019)
Kato, Hirai and Nagakura, arxiv:2005.03124
Li et al. JCAP 05 (2020) 049
Mukhopadhyay, CL, Timmes and Zuber, 2004.02045

Direct probe of advanced stellar evolution

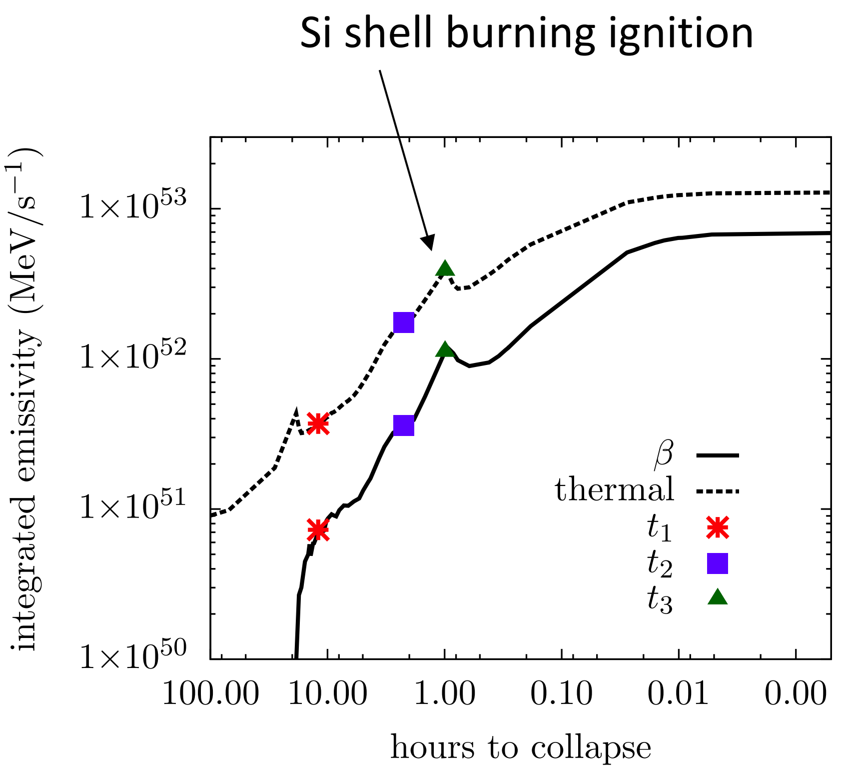
- Evolution of temperature, density
  - ν from thermal processes

$$\gamma^* \rightarrow \nu_\alpha + \bar{\nu}_\alpha$$
$$e^\pm + \gamma \rightarrow e^\pm + \nu_\alpha + \bar{\nu}_\alpha$$
$$e^+ + e^- \rightarrow \nu_\alpha + \bar{\nu}_\alpha$$

- isotopic evolution
  - ν from beta processes

$$A(N,Z) \rightarrow A(N-1,Z+1) + e^- + \bar{\nu}_e$$
$$A(N,Z) \rightarrow A(N+1,Z-1) + e^+ + \nu_e$$

$$A(N,Z) + e^- \rightarrow A(N+1,Z-1) + \nu_e$$
$$A(N,Z) + e^+ \rightarrow A(N-1,Z+1) + \bar{\nu}_e$$

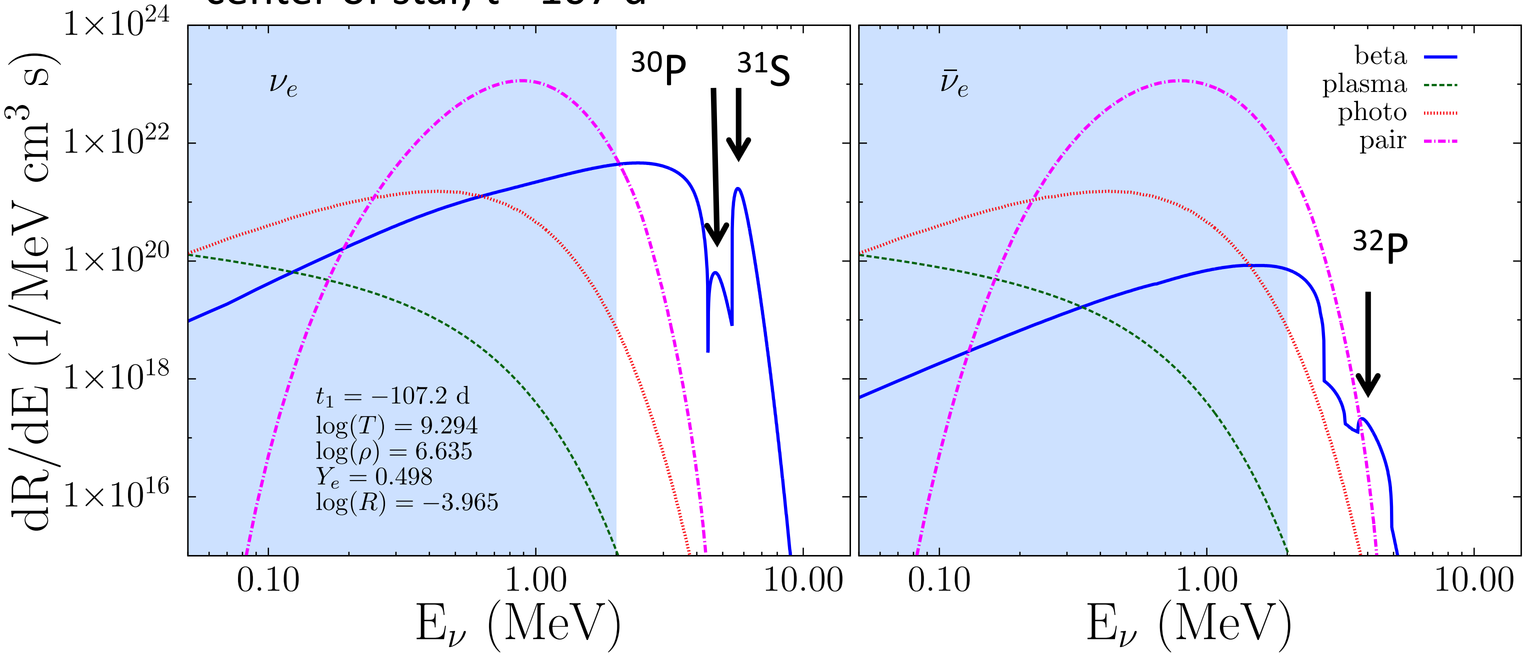


K .M. Patton. CL, R. Farmer and F. X. Timmes, ApJ 851 (2017) no.1, 6 ; ApJ. 840 (2017) no.1, 2

- β-processes important in detectable window!
- few isotopes contribute to most of signal
  - Importance of medium-mass species: Al, P, Na, Ne,…

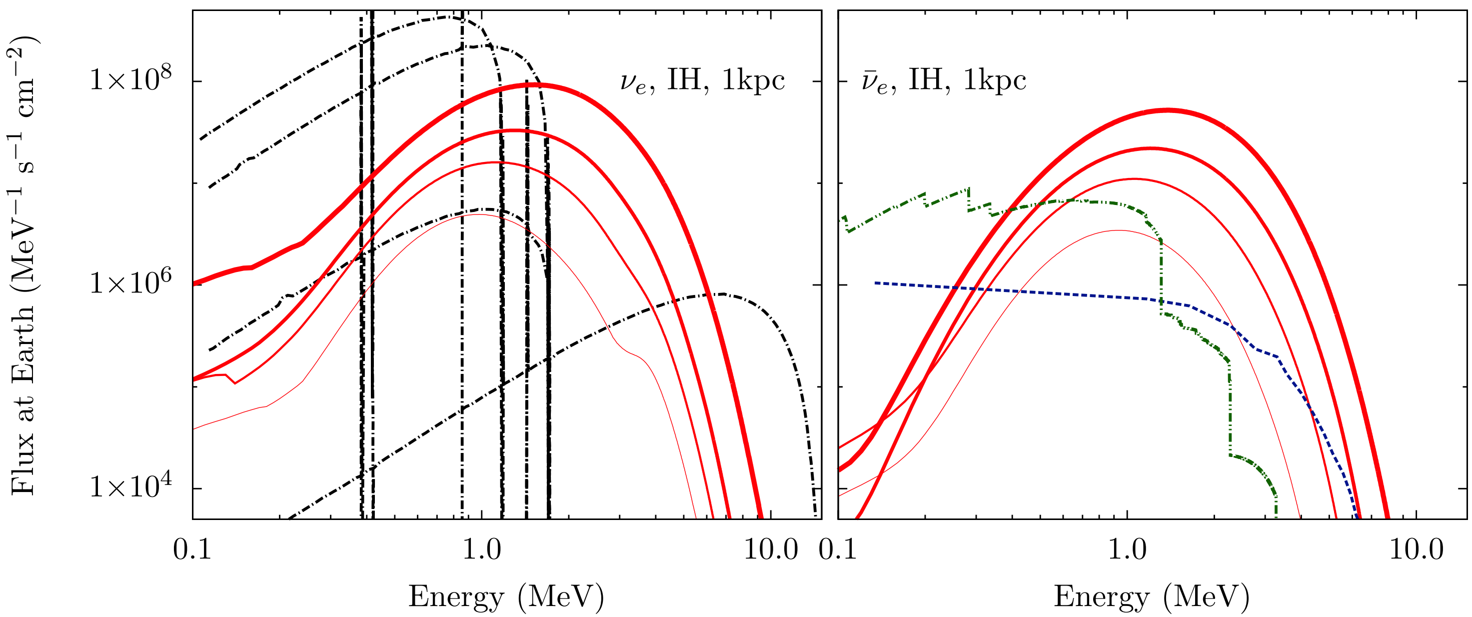
K .M. Patton. CL, R. Farmer and F. X. Timmes, ApJ 851 (2017) no.1, 6 ; ApJ. 840 (2017) no.1, 2

~ center of star, t=-107 d



Detectability of pre-supernova neutrinos

D=1 kpc ; dashed/dotted: solar, reactor, atmospheric



t4	0 hrs
t3	-1 hr
t2	-2 hrs
t1	-12 hrs

K .M. Patton. CL, R. Farmer and F. X. Timmes, ApJ 851 (2017) no.1, 6

spectacular signal for Betelgeuse (D=200 pc), in ~6 hrs:

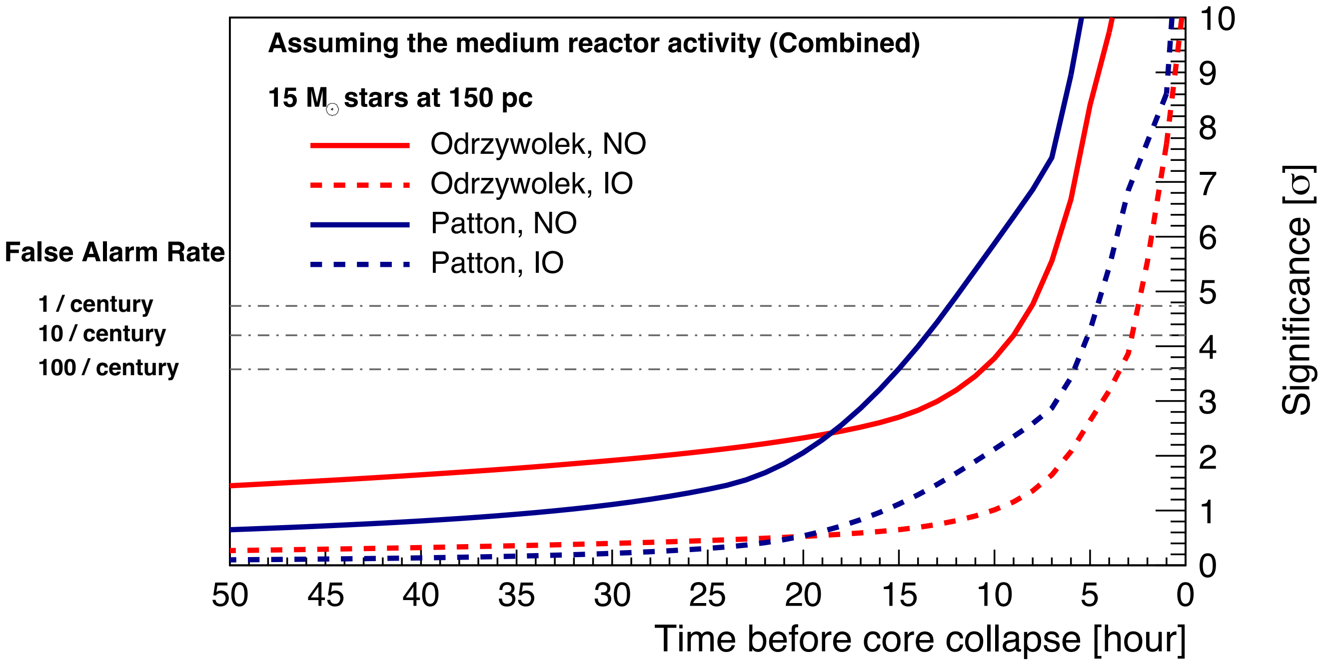
~ 50 events at DUNE

~ 800 events at HyperK (E>4.5 MeV)

> 2000 events at JUNO

Early alert

- Alert ~12 hours pre-collapse, for 15 Msun star at D=150 pc (e.g., Betelgeuse)
- SuperK-Gd at 0.033% Gd concentration



SuperK + KAMLAND, Abe et al., arxiv:2404.09920 ; see also Machado et al., Astrophys. J., 935, 40

Impact of pre-supernova alert

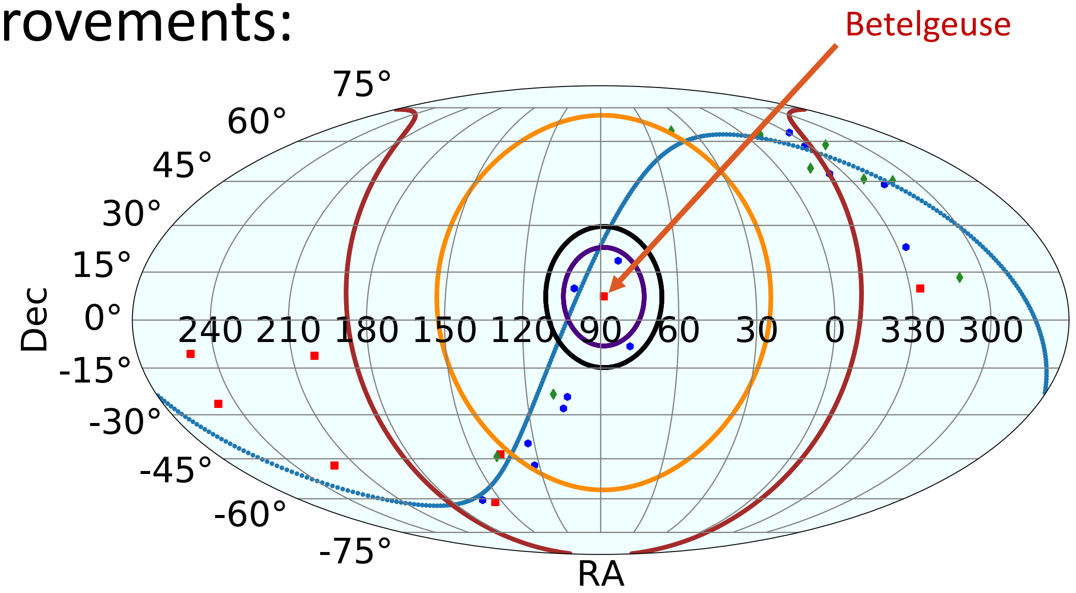
- Prepare scientific community
  - Make technical preparations for upcoming neutrino burst and GW
  - Localization of progenitor
  - Point direction-dependent detectors (telescopes, axion detectors, etc.)
  - Shield sensitive equipment

- Inform governments and public
  - Set up community viewings, educational opportunities
  - Prevent disinformation (conspiracy theories, etc.)

Pointing with liquid scintillator

- Sensitivity up to 1 kpc; angular error ~70° from $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Need ~10 kt liquid scintillator detector (JUNO)
  - Can provide shortlist of 4-10 candidates, about 1 hour prior to collapse

- Possible long term improvements:
  - ~30° with THEIA (100 kt)
  - ~10° with LS+Lithium



t = -1.0 hour

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

2. The gamma ray echo

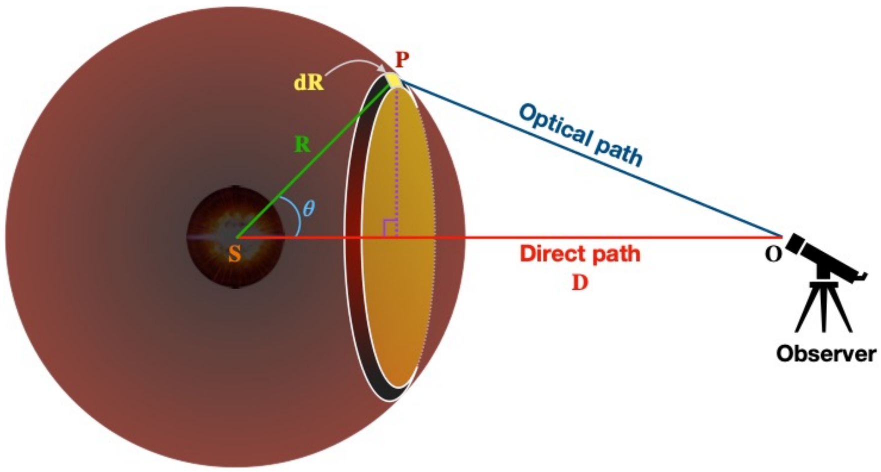
Star as a neutrino mega-detector?

- IBD in the star's 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!

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)

A gamma ray *echo* of SN neutrinos

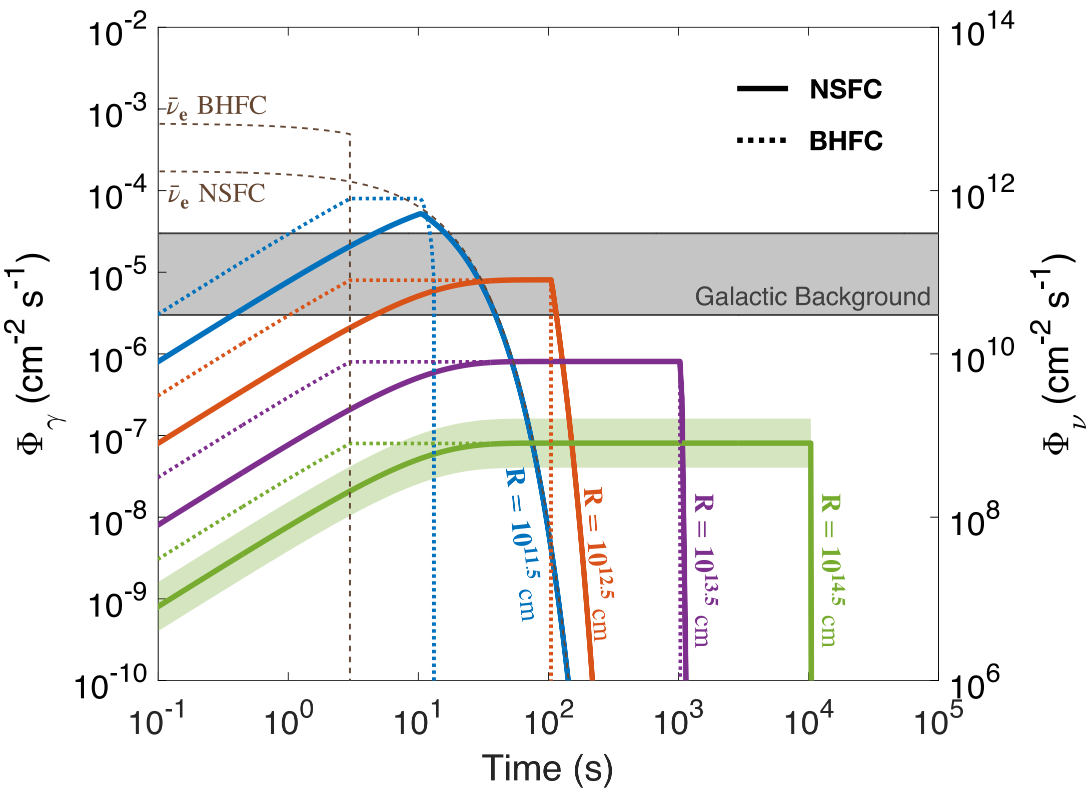


- photon flux from surface shell (dR ~ photon m.f.p. ≪ R)
- Photon-neutrino *time delay* : $\Delta t = \frac{R}{c}\,(1 - cos\theta)$

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

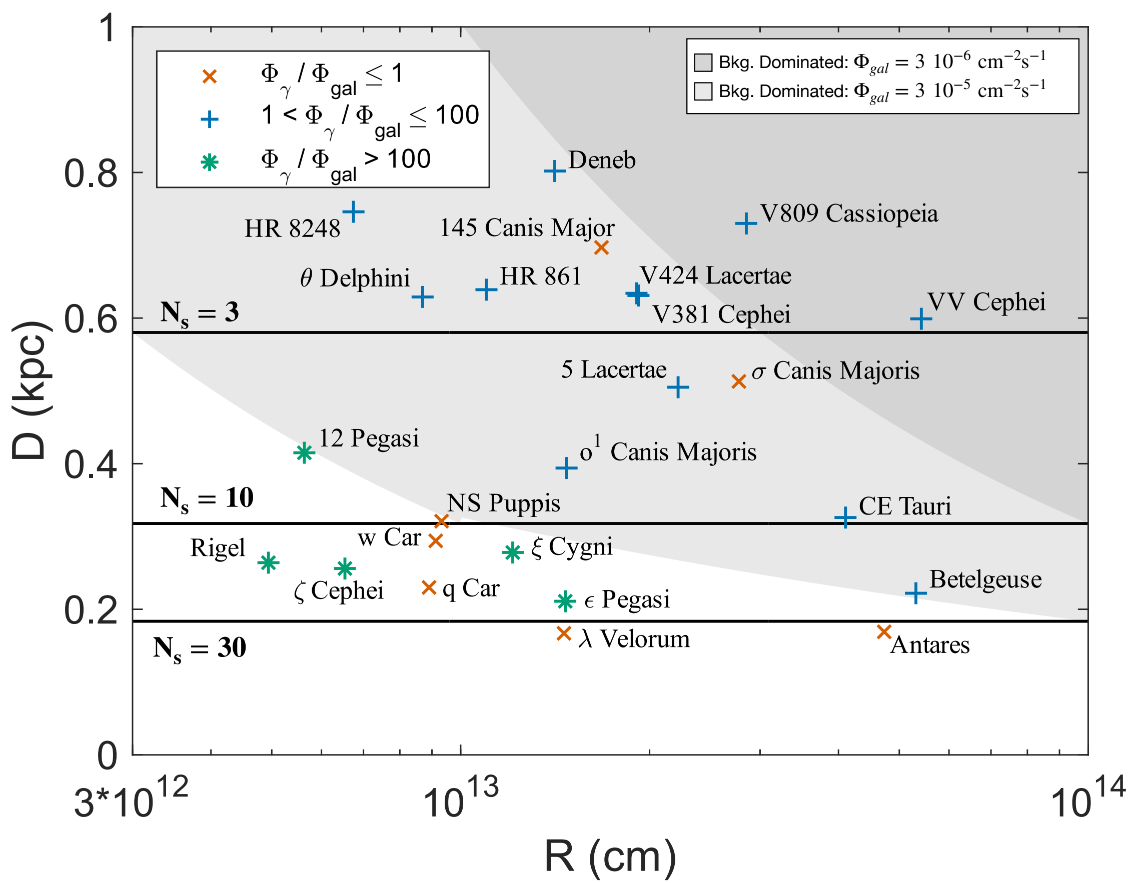
($\eta_\gamma \simeq$ 1.74, avg. number of 0.511 MeV photons per positron)

- Minutes/hours-long echo, starts in coincidence with neutrino burst
- Main background: diffuse galactic 0.511 MeV flux



NSFC = Neutron-star forming collapses;
BHFC=Black hole forming collapses.
Shadings: astrophysical uncertainties.
Background is for aperture $\delta\theta \sim 3^\circ$

CL, J. Loeffler, M. Hurley, E. Farag and F. X. Timmes, arxiv:2312.13197, accepted in ApJ



$N_S = \phi_\gamma AR/c$ = number of detected photons. Shown for eff. area A = 10^3 cm^2

- Requires next-(next-) generation telescope, A~ 10^3 cm^2
  - AMEGO, GECCO (angular resolution ~3°)

Kierans et al, Proc. SPIE Int.Soc.Opt.Eng. 11444, 1144431 (2020); Orlando *et al,* JCAP07 (2022) 036

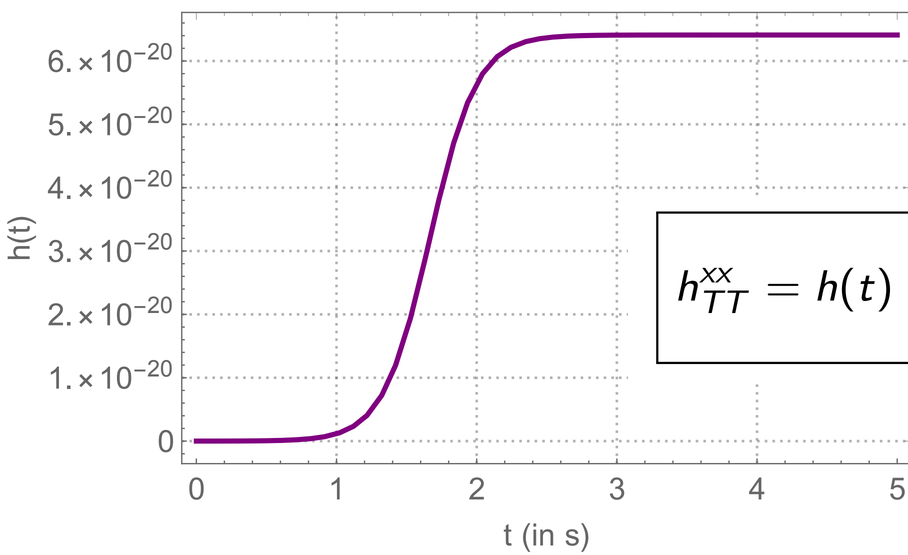
What can we learn?

- 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)

3. The gravitational wave memory

The GW memory of SN neutrinos

- *Memory* = a permanent distortion of the local space time metric
  - due to *anisotropic* matter/energy emission



$$h_{TT}^{xx} = h(t) = \frac{2G}{rc^4} \int_{-\infty}^{t-r/c} dt' L_\nu(t') \alpha(t')$$

- Neutrino emission timescale t ~ O(10) s → sub-Hz scale
  - promising for future Deci-Hz detectors!

Zel’dovich and Polnarev, Sov. Astron. 18 (1974) 17.
Braginskii and Thorne, Nature 327 (1987) 123.
Epstein, Astrophys. J. 223 (1978) 1037.
Turner, Nature 274 (1978) 565.
M. Favata, Class. Quant. Grav. 27 (2010) 084036

Probing near-core dynamics: anisotropy

- Develops during accretion phase
  - Due to convection and Standing Accretion Shock Instabilities (SASI)

$$\alpha(t) = \frac{1}{L_\nu(t)} \int_{4\pi} d\Omega' \; \Psi(\vartheta', \varphi') \; \frac{dL_\nu(\Omega', t)}{d\Omega'}$$

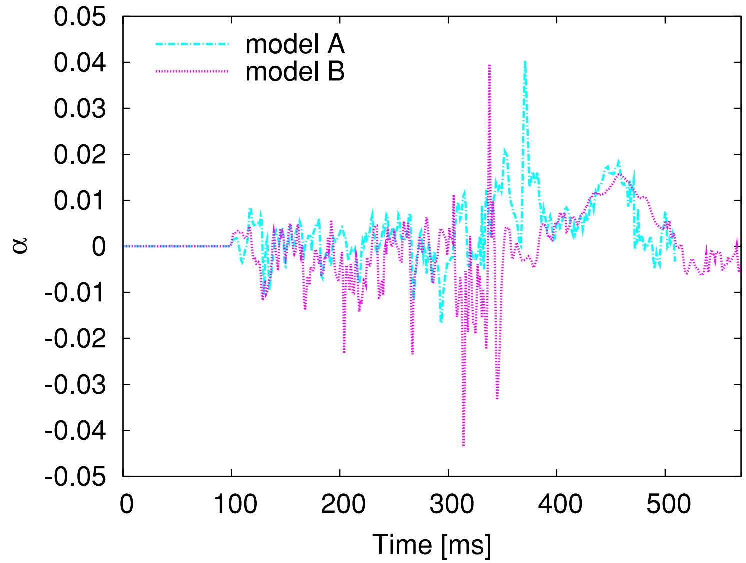


fig. from Kotake, Iwakami, Ohnishi and Yamada, Astrophys. J. 704 (2009) 951

See also Muller, Janka and Wongwathanarat, Astron. Astrophys. 537 (2012)

Building a phenomenological model

M. Mukhopadhyay, C. Cardona and CL, JCAP 07 (2021), 055

- toy $L_\nu(t)$: global shape (only valid locally) :

$$L_\nu(t) = \lambda + \beta \ \exp\left(-\chi\, t\right) \ ,$$

- toy $\alpha(t)$: multi-Gaussian+constant:

$$\alpha(t) = \kappa + \sum_{j=1}^{N} \xi_j \ \exp\left(-\frac{(t-\gamma_j)^2}{2\sigma_j^2}\right) \ ,$$

- result: analytical $h(t)$

$$h(t) = \sum_{j=1}^{N} \left\{ \left[h_{1j} \left(\text{erf}\left(\rho_j \ \tau_{1j}\right) + \text{erf}\left(\rho_j (t - \tau_{1j})\right) \right) \right] + \left[h_{2j} \left(\text{erf}\left(\rho_j \ \tau_{2j}\right) + \text{erf}\left(\rho_j (t - \tau_{2j})\right) \right) \right] \right\}$$
$$+ \left[h_3 \left(\frac{\beta}{\chi} \left(1 - \exp\left(-t\chi\right)\right) + \lambda t \right) \right] \ ,$$

$$\tilde{h}(f) = \sum_{j=1}^{N} \left[\left(h_{1j} \frac{i}{\pi f} \exp\left(\frac{-\pi^2 f^2}{\rho_j^2}\right) \exp\left(i2\pi f \tau_{1j}\right)\right) + \left(h_{2j} \frac{i}{\pi f} \exp\left(\frac{-\pi^2 f^2}{\rho_j^2}\right) \exp\left(i2\pi f \tau_{2j}\right)\right)\right] + \left(\sqrt{2\pi}\; h_3 \frac{\beta}{\chi} \left(\frac{1}{i2\pi f} - \frac{1}{-\chi + i2\pi f}\right)\right),$$

$$h_{1j} = \frac{2G}{rc^4}\sqrt{\frac{\pi}{2}}\beta\xi_j\sigma_j \exp\left(\frac{\chi}{2}(-2\gamma_j + \sigma_j^2\chi)\right),$$

$$\rho_j = \frac{1}{\sqrt{2}\sigma_j},$$

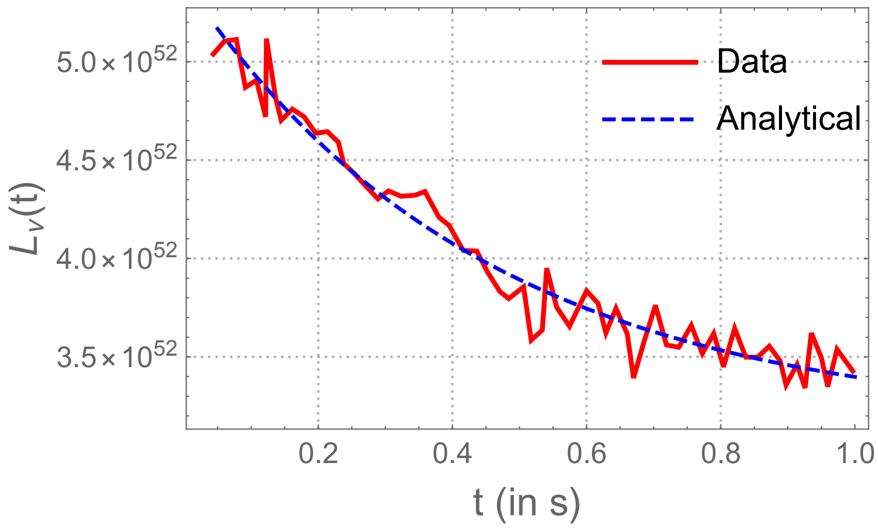
$$\tau_{1j} = \gamma_j - \sigma_j^2\chi,$$

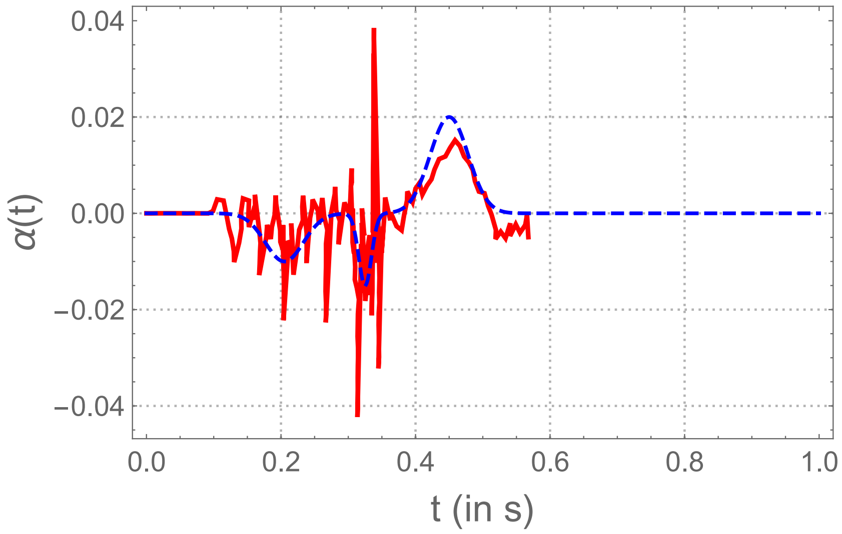
$$h_{2j} = \frac{2G}{rc^4}\sqrt{\frac{\pi}{2}}\lambda\xi_j\sigma_j,$$

$$\tau_{2j} = \gamma_j,$$

$$h_3 = \frac{2G}{rc^4}\kappa.$$

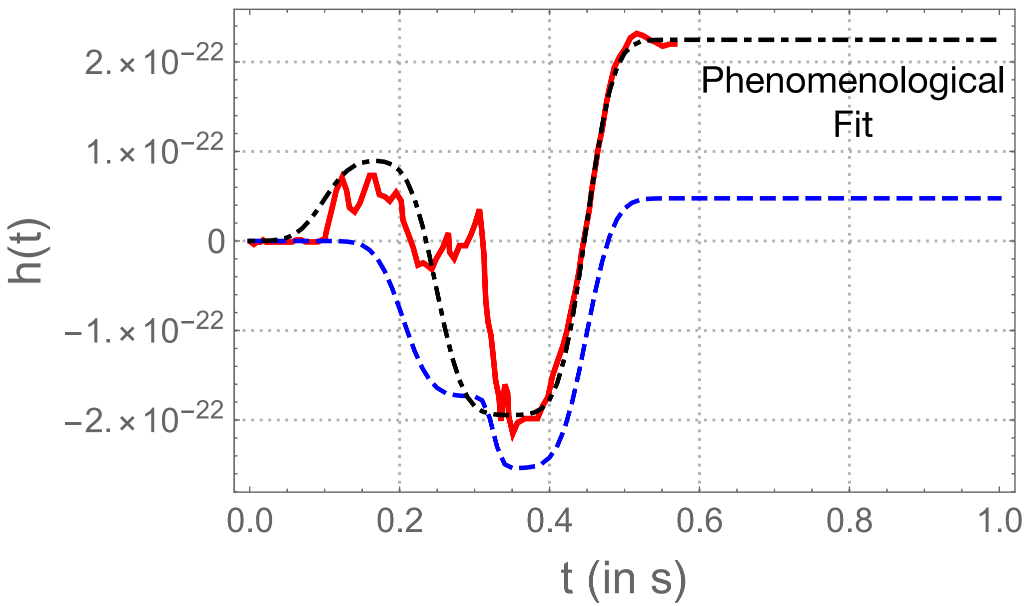
Reproducing numerical results





left data: Vartanyan and Burrows, Astrophys. J. 901 (2020) 108 ;
right data: Kotake, Iwakami, Ohnishi and Yamada, Astrophys. J. 704 (2009) 951.

- toy model reproduces low frequency trends (relevant for Deci-Hz detectors)

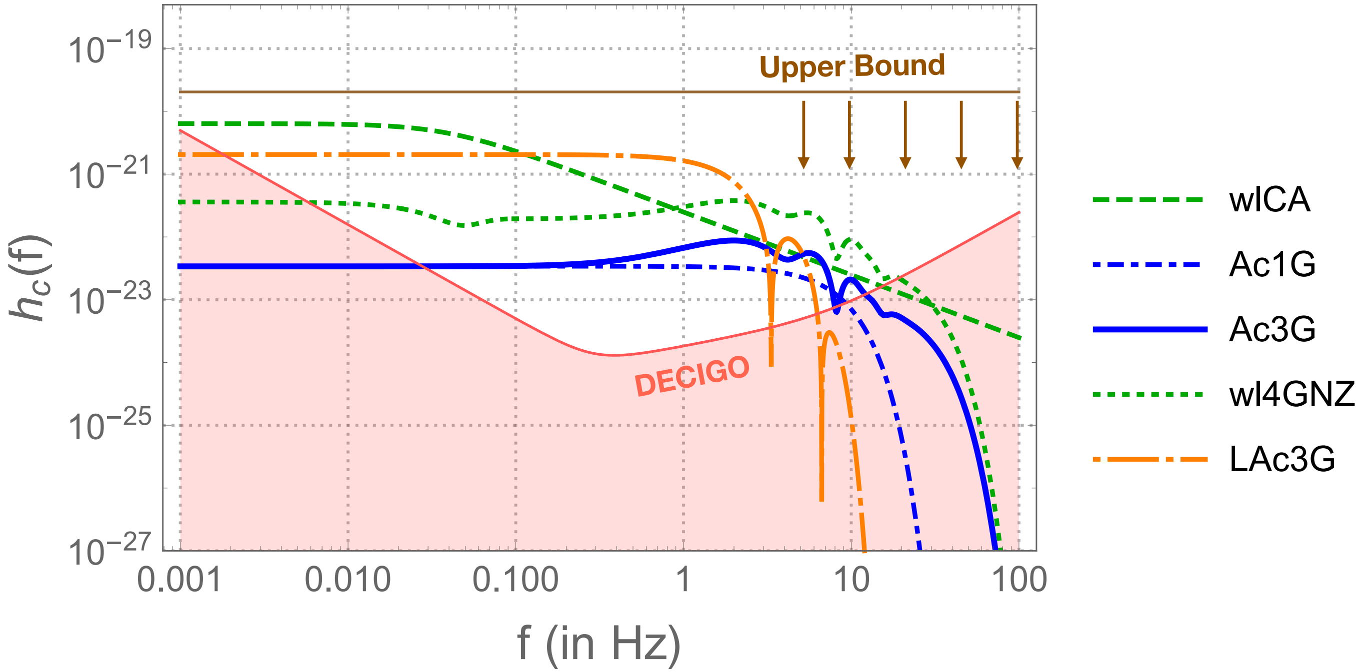


Data: Kotake, Iwakami, Ohnishi and Yamada, Astrophys. J. 704 (2009) 951.

- toy h(t) reproduces numerical result
  - dashed: computed from L(t) and α(t)
  - dot-dashed: toy formula for h(t) with effective parameters

Detectable at future Deci-Hz interferometers

$h_c(f) \equiv 2f|\tilde{h}(f)|$ ($\tilde{h}$: Fourier transform)
A- and LA- : anisotropy in accretion phase only ;
w- : anisotropy is non-zero throughout
(D=10 kpc)

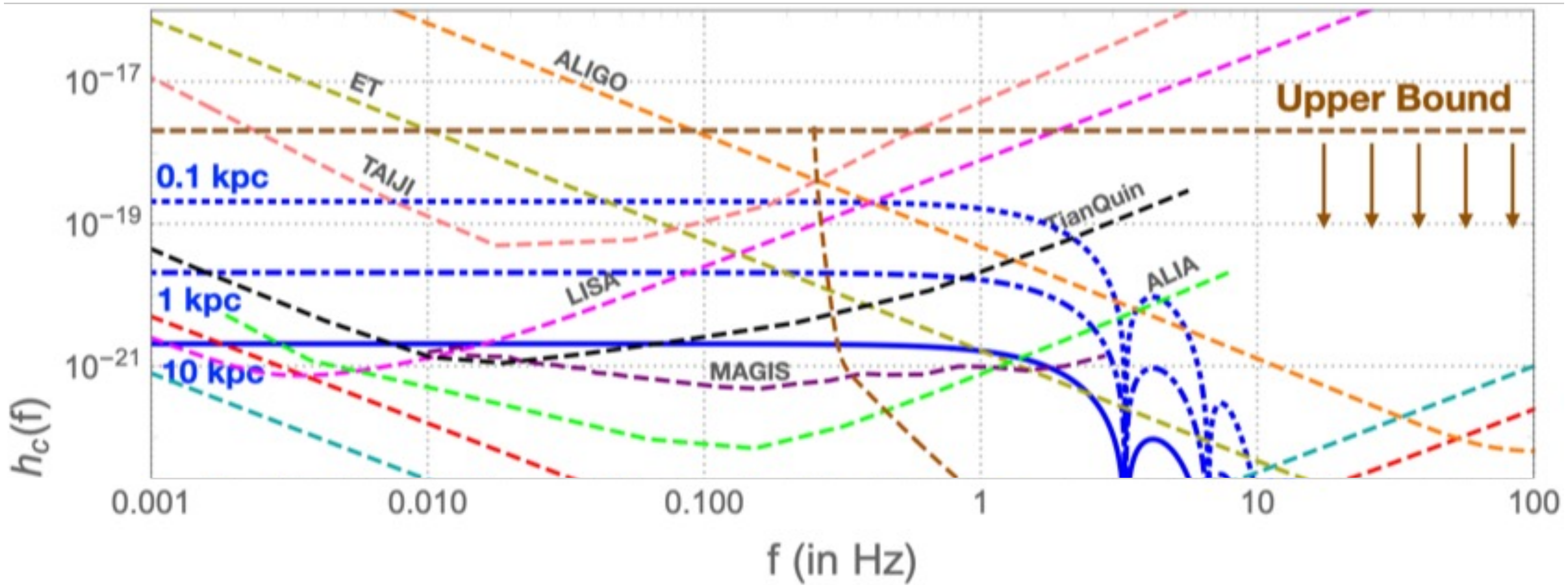


M. Mukhopadhyay, C. Cardona and CL, JCAP 07 (2021), 055

Summary of detection prospects

Accretion only model, Ac3G. Detectable with Advanced LIGO for near-Earth SN !

C. Richardson et al., *PRD* 105 (2022) 10, 103008
K. Gill, arxiv:2405.13211

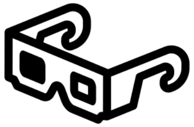


Physics potential

- Another General Relativity prediction will be confirmed
  - Precision tests of gravity: quantum effects? Non-linear memory?
- A new multimessenger component
  - potential for supernova alerts
- test anisotropy → probe fluid dynamics in accretion phase
  - jointly with detected neutrino burst: precision measurement?

Discussion and conclusions

Near Earth supernova: preparedness is key!

- Global event that will reach the masses 
  - Unique opportunity (and responsibility!) to educate

- Predictable up to a day in advance
  - thanks to pre-supernova neutrinos

Are you prepared?
What would you do?

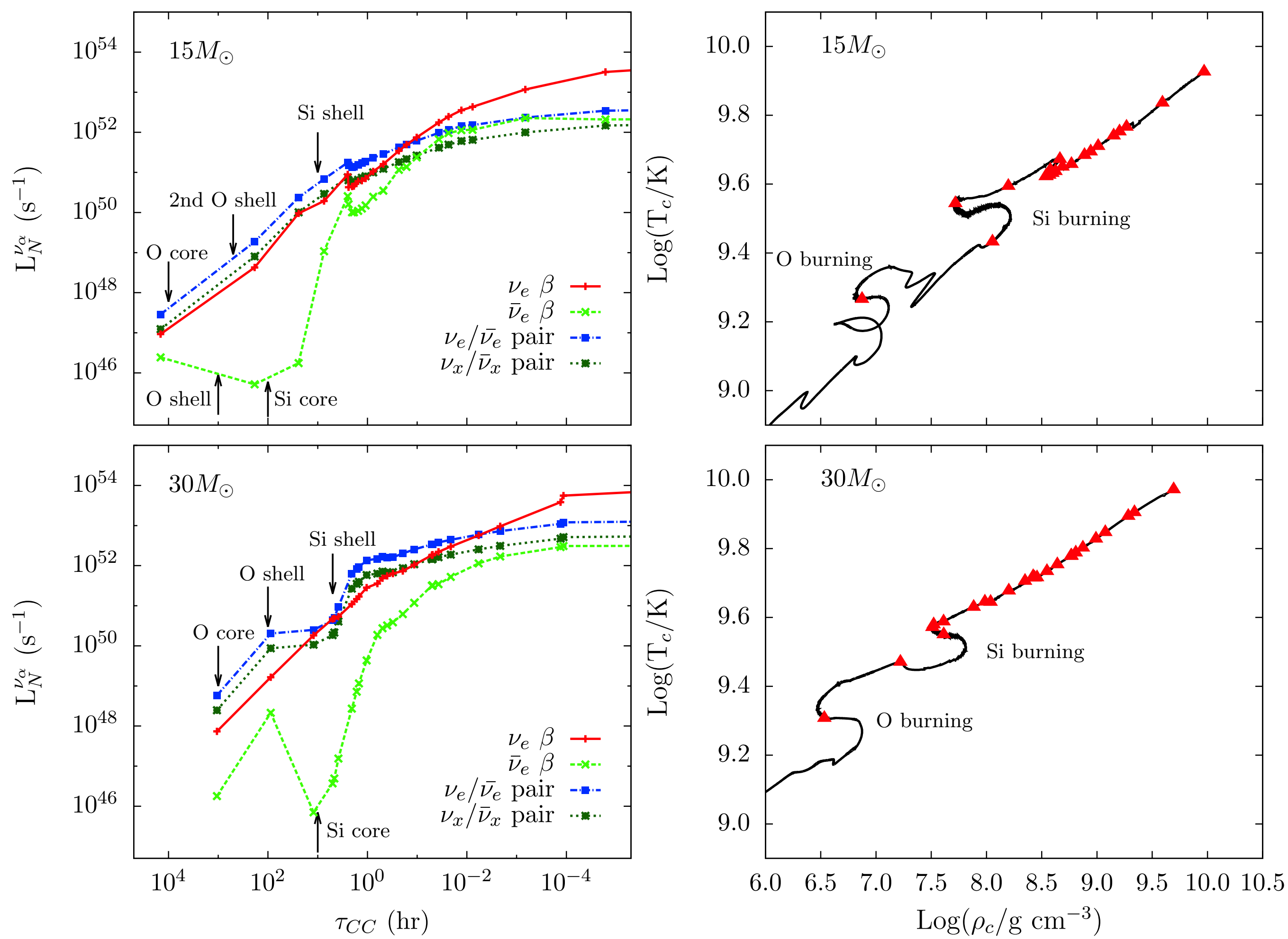
Unique scientific opportunities

- Pre-supernova neutrinos: learn about pre-collapse phase
  - E.g., watch the silicon shell burning ignition in real time
- Observe phenomena where neutrinos are the *source*
  - Gamma ray echo: probe physics at the star's envelope
  - GW memory: test GR, and more


Thank you!

BACKUP

Presupernova evolution



- Main contributing isotopes :

t (hrs)	total ν_e	E=2 MeV ν_e
-12.01	^{55}Co, ^{53}Fe, ^{56}Ni, ^{54}Fe, ^{57}Ni	^{55}Co, ^{56}Ni, ^{57}Ni, ^{54}Fe, ^{52}Fe
-2.2	^{54}Fe, ^{55}Fe, ^{55}Co, ^{53}Fe, ^{57}Co	^{55}Fe, ^{55}Co, ^{54}Fe, ^{57}Co, ^{57}Ni
-0.99	^{55}Fe, ^{54}Fe, ^{56}Ni, ^{57}Co, ^{55}Co	^{55}Fe, ^{55}Co, ^{57}Co, ^{54}Fe, ^{56}Ni
0	^{55}Fe, ^{56}Fe, ^{1}H, ^{57}Fe, ^{54}Mn	^{55}Fe, ^{1}H, ^{56}Fe, ^{57}Fe, ^{54}Fe

t (hrs)	total $\bar{\nu}_e$	E=2 MeV $\bar{\nu}_e$
-12.01	^{28}Al, ^{24}Na, ^{27}Mg, ^{60}Co, ^{31}Si	^{28}Al, ^{24}Na, ^{60}Co, ^{32}P, ^{23}Ne
-2.2	^{28}Al, ^{56}Mn, ^{27}Mg, ^{60}Co, ^{54}Mn	^{28}Al, ^{56}Mn, ^{60}Co, ^{55}Mn, ^{54}Mn
-0.99	^{56}Mn, ^{60}Co, ^{28}Al, ^{52}V, ^{55}Mn	^{56}Mn, ^{60}Co, ^{28}Al, ^{52}V, ^{55}Mn
0	^{56}Mn, ^{62}Co, ^{55}Cr, ^{52}V, ^{53}V	^{56}Mn, ^{62}Co, ^{55}Cr, ^{52}V, ^{53}V

Numbers of events

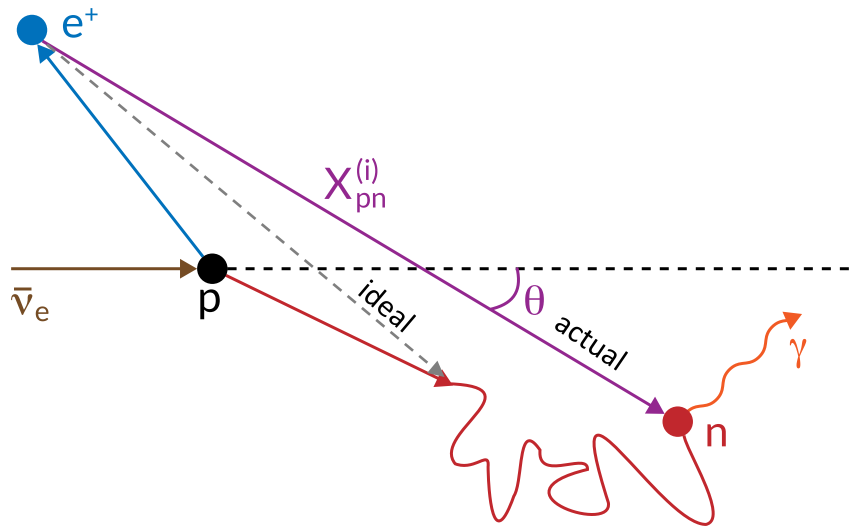
2 hours pre-collapse, D = 1 kpc (for Betelgeuse : multiply by 25)

detector	composition	mass	interval	N_β^{el}	N^{el}	N_β^{CC}	N^{CC}	$N^{tot} = N^{el} + N^{CC}$
JUNO	C_nH_{2n}	17 kt	$E_e \geq 0.5$ MeV	9.3 [4.1]	39.0 [28.8]	0 [0]	12.3 [36.9]	51.3 [65.8]
SuperKamiokande	H_2O	22.5 kt	$E_e \geq 4.5$ MeV	0.11 [0.04]	0.17 [0.08]	0 [0]	0.65 [1.9]	0.82 [2.0]
DUNE	LAr	40 kt	$E \geq 5$ MeV	0.07 0.03	0.1 0.05	0.64 [0.04]	0.91 [0.17]	1.0 [0.22]

el = elastic scattering on electrons
CC = Charged Current on nuclei
β = contribution of neutrinos from beta processes

.. = results for inverted mass hierarchy
[..] = results for normal mass hierarchy

Experimental sensitivity

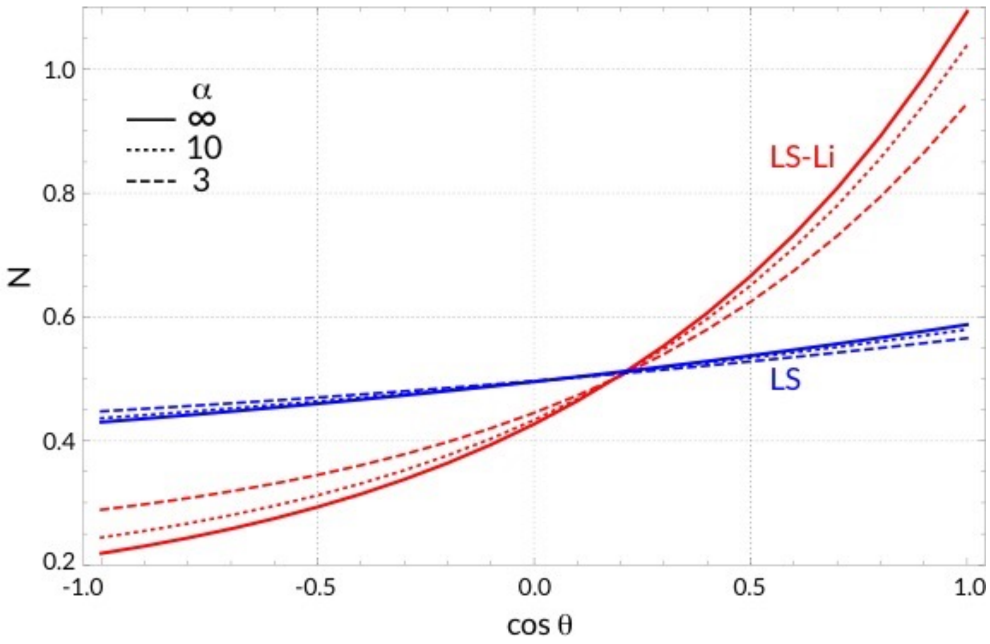


- LS : Linear AlkylBenzene (SNO+, JUNO)
  - Directionality limited by neutron thermalizing before capture
  - Resolution of e^+ annihilation also important

- LS-Li : LS with Lithium salts for faster n capture: ${}^6\mathrm{Li} + n \rightarrow t\,(2.73\ \mathrm{MeV}) + \alpha$
  - Enhanced directionality by shortening neutron capture range

Tanaka & Watanabe, 2014, Scientific Reports, 4, 4708

Directionality: low-to-moderate



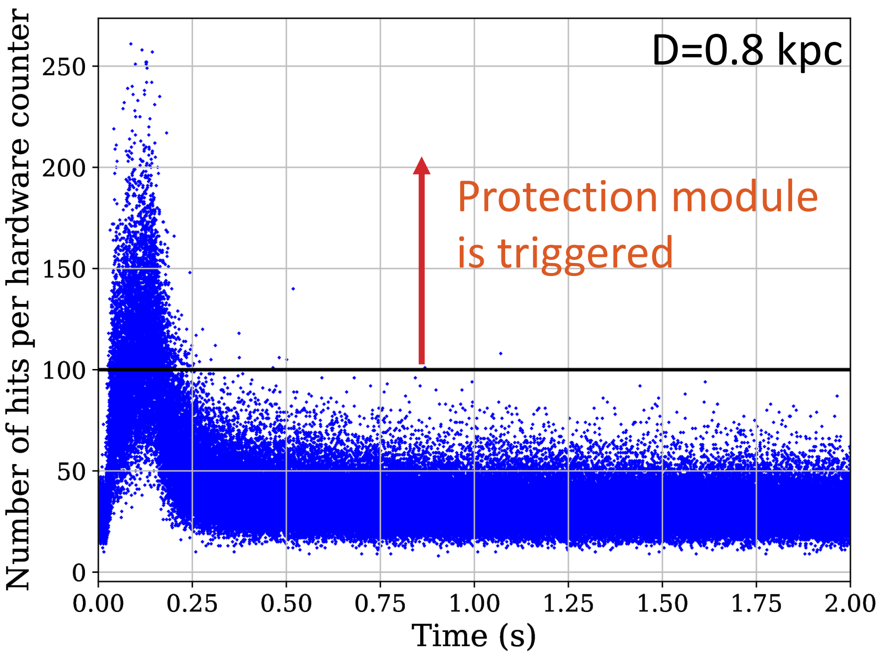
$$\alpha = N_S / N_{\mathrm{Bkg}}$$

	Forward-Backward asymmetry	
α	LS	LS-Li
∞	0.1580	0.7820
10.0	0.1418	0.7165
3.0	0.1170	0.5911

Tanaka & Watanabe, 2014, Scientific Reports, 4, 4708
For geoneutrinos (similar spectrum as pre-SN)

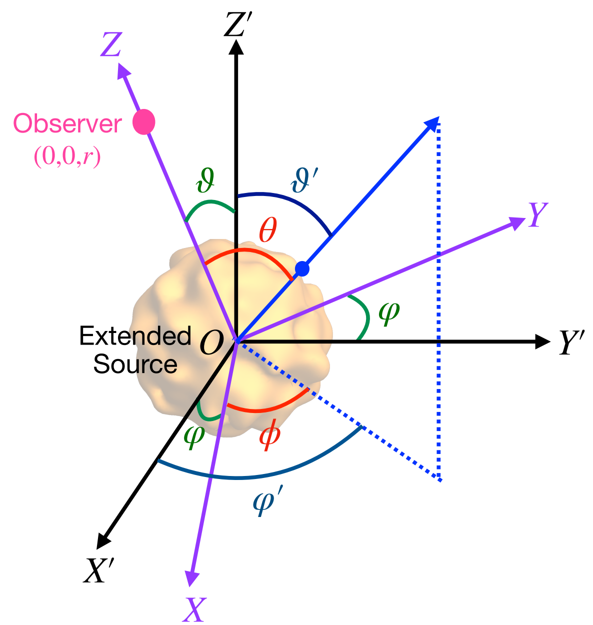
Preparedness: near-Earth supernova

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



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

How to calculate the memory

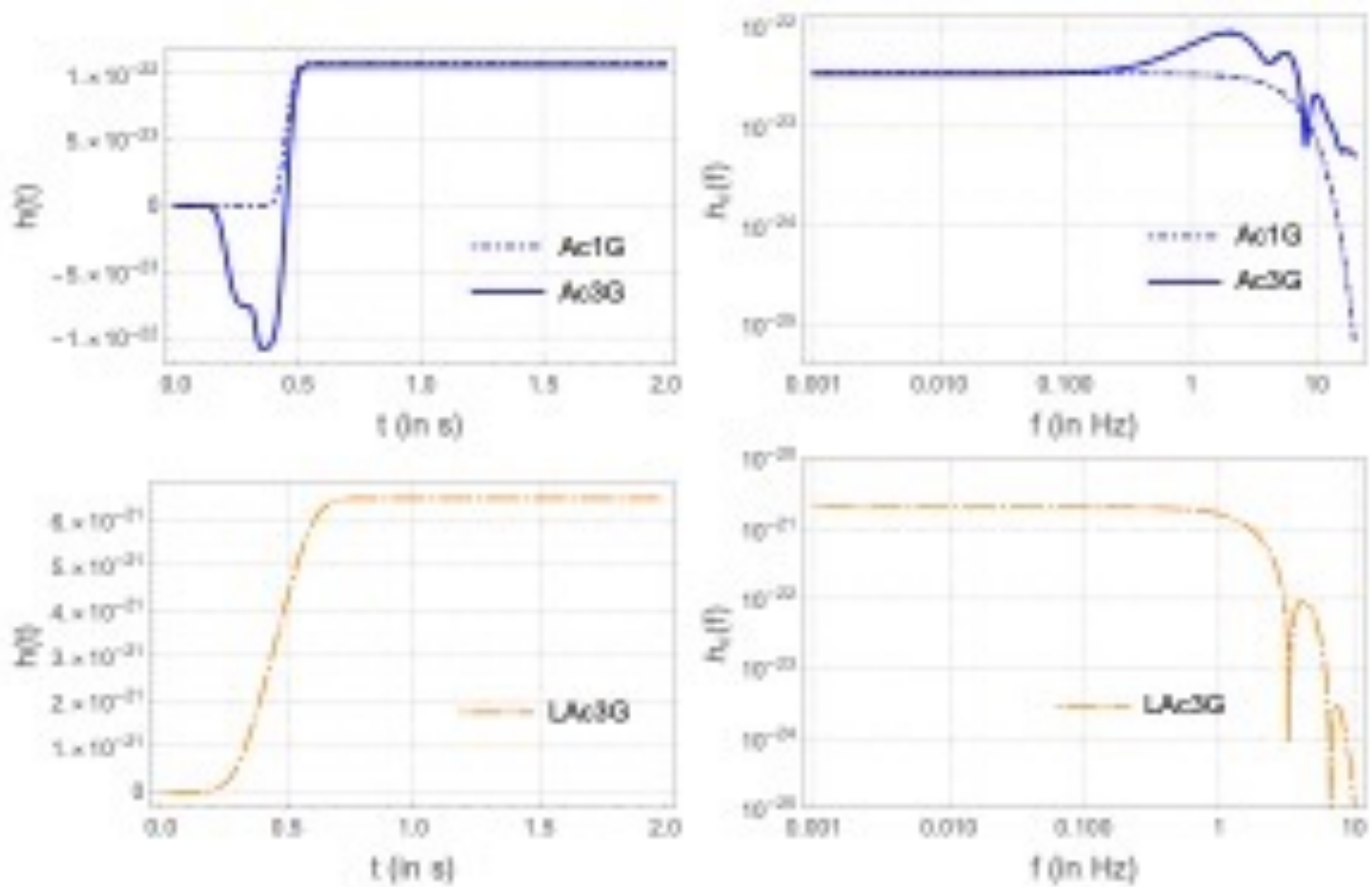


- solving Einstein's equation, in weak-field approximation: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$
- longitudinal polarization ($h^{xx}_{TT} = -h^{yy}_{TT} = -h^{+}_{TT}$):

$$h^{xx}_{TT} = \frac{2G}{rc^4} \int_{-\infty}^{t-r/c} dt' \int_{4\pi} (1 + \cos\theta) \cos 2\phi \frac{dL_\nu(\Omega', t')}{d\Omega'} d\Omega'.$$

- Change of separation of free-falling masses: $\delta l_j = \frac{1}{2} h^{TT}_{jk} l^k$

Accretion only models (D=10 kpc)



Long term evolution models