The neutrino gravitational memory from a core-collapse supernova

Mainak Mukhopadhyay, Carlos Cardona and Cecilia Lunardini

Department of Physics, Arizona State University

Arizona State University

Fermilab

NSF

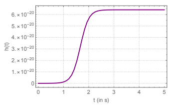
invisibles
neutrinos, dark matter & dark energy physics

Based on arXiv: 2105.05862

SCAN ME

1. The Memory

The GW strain h(t) converges to a non-zero value: memory is present

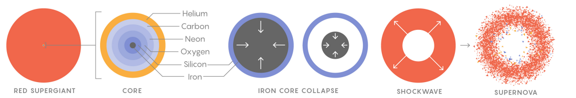


- **Permanent distortion** of the space-time metric.
- Needs **gravitationally unbound systems: Anisotropic emission of energy** (mass/radiation).
  - Memory has **never been observed**.
  - Observation requires: **a) very powerful emitter; b) development of anisotropy.**

Why? -> Numerical simulations are **computationally extremely costly** and hence **limited to ~ 1 s**.
-> Phenomenological models help to make **prediction of signatures** even **for long term emissions**.
-> Perfect for upcoming **next-generation Deci-Hz interferometers**.

Ideal candidates: **Core-collapse supernovae!**

2. SN Neutrinos

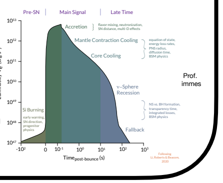


Credits: Lucy Reading - Ikkanda/Quanta Magazine

The star dies with a **core-collapse followed by an explosion as a supernova or an implosion into a BH (failed supernova).**

- Core collapse is accompanied by **massive thermal neutrino emission**: $E_\nu = 10 \sim 18$ MeV.
- **Total energy in neutrinos:** 3×10^{53} **ergs** in a burst of duration ~ 10 s.

Accretion phase: **t ~ 0.003 - 0.5 s**: Schokwave is stalled.
Cooling phase: **t ~ 0.5 - 40 s**: Shockwave re-energized by neutrino energy deposition.



Prof. immes

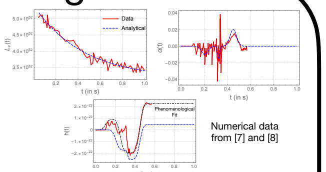
- **Anisotropy in progenitor develops during the accretion phase:** due to convection and Large scale sloshing motion of the shock front (SASI - Standing Accretion Shock Instability)
- Anisotropy in cooling phase has not been simulated and very little is known

3. Phenomenological Model

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

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

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



Numerical data from [7] and [8]

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

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

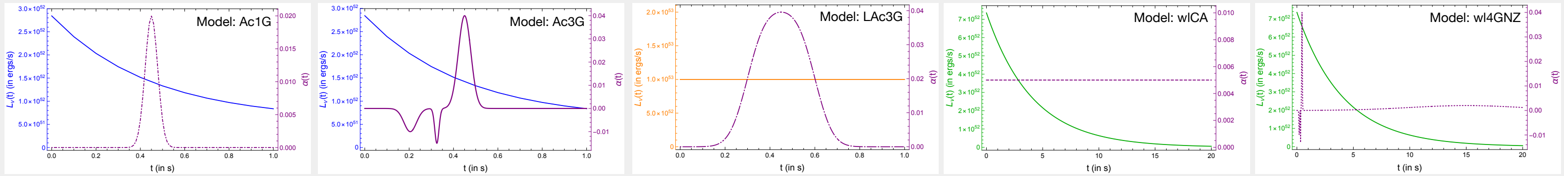
$$h_c(f) = 2f\,|\tilde{h}(f)|$$

4. Phenomenological Scenarios

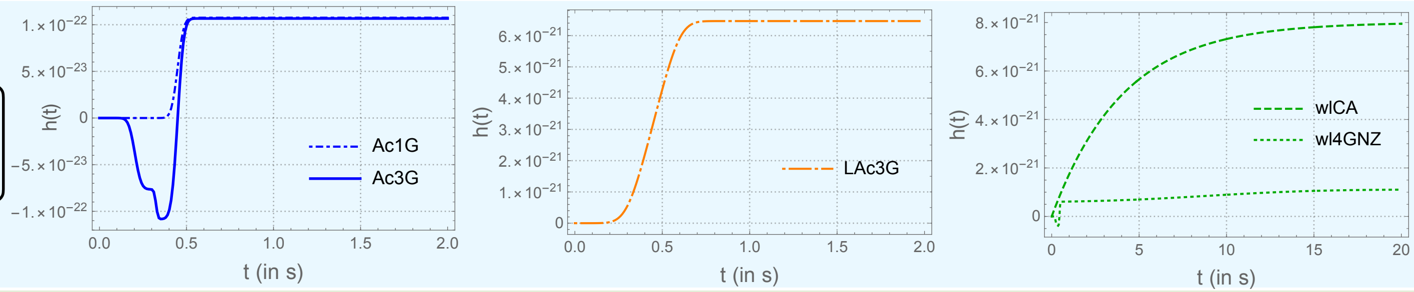
a) Models

Neutrino Luminosity: $L_\nu(t)$
Anisotropy parameter: $\alpha(t)$

- **Accretion-only models:** Zero anisotropy in cooling phase: $\delta t \sim 0.1 - 0.5\ s \rightarrow f \sim 2 - 10\ Hz$
- **Long-term evolution models:** non-zero anisotropy throughout: $\delta t \sim 1 - 10\ s \rightarrow f \sim 0.1 - 1\ Hz$



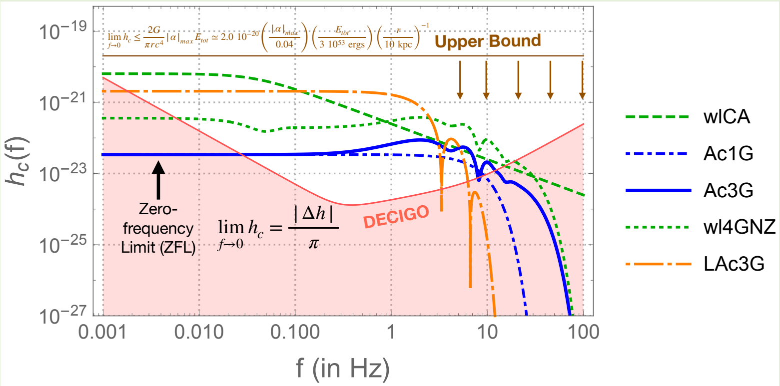
b) GW-strain h(t)

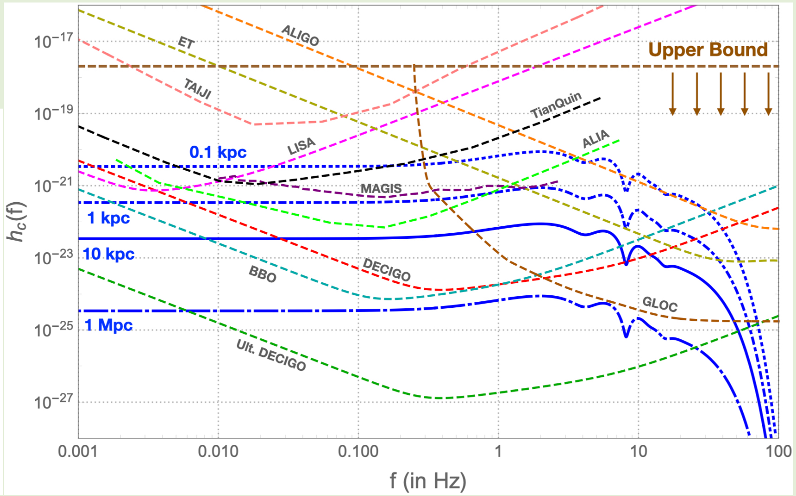


c) Detectability

(r = 10 kpc)

Detectable in the most pessimistic cases. **Sensitivity even upto Mpc distances and beyond!** (May be even more than HyperK)





5. Physics Potential

- GWM has been predicted by GR, if detected will **confirm another GR prediction.**
- **Multi-messenger channel** opens up: neutrinos + GW (~100 Hz) + **GW memory (~ 0.1 - 10 Hz)** + astro.
- Better **understanding of the esoteric anisotropy parameter** when combined with neutrino observations- SASI, fluid dynamics.
- **Theoretical avenues :** non-linear memory, quantum effects in gravity.

6. Takeaways

The SN neutrino memory is detectable at DeciHz interferometers

- This work provides a **new phenomenological model** which is:
  a) **consistent with numerical simulations,**
  b) **completely analytical** which is useful for phenomenological studies, detector response studies, data fits, etc.
- Helps in providing a plausible picture by **overcoming the computational limitations of numerical simulations.**
- **Uncertainties:** a) $\alpha(t)$ not very well-known (3D simulations suggest lower values),
  b) anisotropy in the cooling phase is unknown
- **Matter contributions** to the memory (which may be **sub-dominant at f $\lesssim$ 0.1 Hz**).

References

[1] Epstein, Astrophys. J. 223 (1978) 1037.
[2] Turner, Nature 274 (1978) 565.
[3] Favata, Class. Quant. Grav. 27 (2010) 084036
[4] Li, Fuller and Kishimoto, Phys. Rev. D 98 (2018) 023002.
[5] Sago, Ioka, Nakamura and Yamazaki, Phys. Rev. D 70 (2004) 104012
[6] Suwa and Murase, Physical Review D 80 (2009) .
[7] Vartanyan and Burrows, Astrophys. J. 901 (2020) 108
[8] Kotake, Iwakami, Ohnishi and Yamada, Astrophys. J. 704 (2009) 951

Mainak Mukhopadhyay
Graduate Student, ASU
Email: mmukhop2@asu.edu