Can self-interaction in supernova neutrinos cause changes in GW memory signals?

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Hearing beyond the standard model with cosmic sources of Gravitational Waves, International Centre for Theoretical Studies
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PLAN

Understand gravitational wave memory effects and memory signals.

$\Downarrow$

How memory signals arise in supernova neutrinos

$\Downarrow$

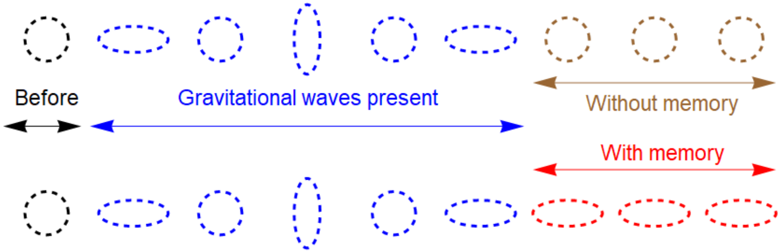
Self-interaction of supernova neutrinos

$\Downarrow$

Address the central question

GRAVITATIONAL WAVE MEMORY EFFECT

Net relative displacement and /or a net relative velocity caused by the passage of a gravitational wave pulse.



Permanent distortion!

Memory effects (introduction)

•Geodesic deviation in TT (transverse-traceless) gauge in linearised gravity

$$\underbrace{\Delta\xi^i}_{\text{Memory effect}} = \frac{1}{2} \underbrace{\Delta h^i{}_j}_{\text{Memory signal}} \xi^j$$

•ξ^i: Separation in geodesics, h_{ij}: Metric perturbation

$$\boxed{\Delta h_{ij}^{TT}(t,\vec{x}) = \lim_{t\to+\infty} h_{ij}^{TT}(t,\vec{x}) - \lim_{t\to-\infty} h_{ij}^{TT}(t,\vec{x})}$$

•Sourced wave eqn: $\Box \bar{h}_{ij} = \kappa T_{ij} \to h_{ij} \propto \ddot{Q}_{ij} \to \Delta\xi^i \propto \Delta\ddot{Q}_{ij}$

•Change in the double derivative of Q_{ij} at early and late times.

Memory: Relativistic sources

•The quadrupole formula to obtain the GW strain fails for velocities in the relativistic & ultrarelativistic regimes.

•The gravitational waveform is given by a formula analogous to the Lienard-Wiechart formula.

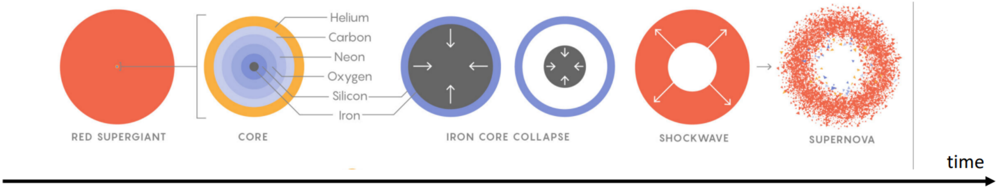
•For ultrarelativistic sources: $h^{ij}(t,\vec{x}) = \frac{4G}{r}\sum_a \gamma_a m_a \frac{v_a^i(t_r)v_a^j(t_r)}{1-\vec{N}\cdot\vec{v}_a(t_r)}$

•For relativisic fluids: $h^{ij}(t,\vec{x}) = \frac{4G}{r}\int dt'\, d^3x' \epsilon(\vec{x}',t') \frac{v^i(\vec{x}',t')v^j(\vec{x}',t')}{1-\vec{N}\cdot\vec{v}(\vec{x}',t')}\delta\left(t'-(t-r)\right).$

•For null fluids: $h^{ij}(t,\vec{x}) = \frac{4G}{r}\int dt'\, d^3x' \epsilon(\vec{x}',t') \frac{n'^i n'^j}{1-\vec{N}\cdot\vec{n}'}\delta\left(t'-(t-r)\right)$

Memory signal in supernova neutrinos

Core-collapse supernova



[Lunardini, COMHEP (2021)]

- $M > 8\, M_\odot \rightarrow$ Nuclear fusion $\rightarrow$ Fe core $\rightarrow$ Core collapse
- Incompressibility rise $\rightarrow$ Core bounce $\rightarrow$ Shock wave formation
- Shock wave travels outwards $\rightarrow$ the supernova explosion

Role of neutrinos?

•**Electrons convert to neutrons emitting a neutrino.**

•**Core compactness rises (10^{14} g/cm^3), production of neutrinos rise.**

•**Shock wave first stalls $\rightarrow$ reenergised by neutrino $\rightarrow$ explosion.**

•**Energy $\sim 10^{53}$ ergs.**

•**Such neutrino burst can lead to gravitational radiation.**

THE GENERATION OF GRAVITATIONAL RADIATION BY ESCAPING SUPERNOVA NEUTRINOS*

REUBEN EPSTEIN
Department of Earth and Planetary Sciences, Massachusetts Institute of Technology
Received 1977 August 22; accepted 1978 February 6

ABSTRACT

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Subject headings: gravitation — neutrinos — stars: collapsed — stars: supernovae

I. INTRODUCTION

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- **Anisotropic neutrino burst from supernova causes gravitational memory signal.**
- **Solve the Einstein field equations with neutrinos as the source.**

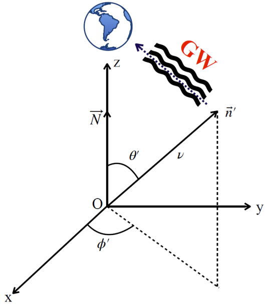
Memory signal from SN neutrinos

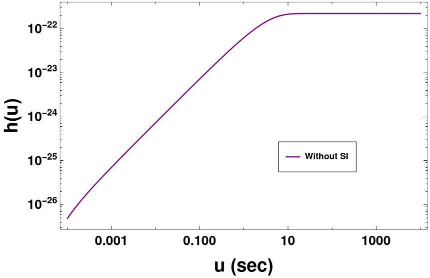
$$h^{ij}(t,\vec{x}) = \frac{4G}{r}\int dt'\, d\Omega' \int_{R_s}^{\infty} r'^2 dr' \epsilon(\vec{x}',t') \frac{n'^i n'^j}{1-\vec{N}\cdot\vec{n}'} \delta\left(t'-(t-r)\right).$$

R_s: **Proto-neutron star radius (PNS)** $= 10$ **km.**

$$\epsilon(\vec{x}',t') = \frac{L_{\nu_i}(t',r')}{4\pi r'^2}\alpha(\theta',\phi')$$

[Luminosity and anisotropy]





Including neutrino self-interaction (ν-SI)

Towards Powerful Probes of Neutrino Self-Interactions in Supernovae

Po-Wen Chang [1,2,*] Ivan Esteban [1,2,†] John F. Beacom [1,2,3,‡]
Todd A. Thompson [1,3,2,§] and Christopher M. Hirata [1,2,3,¶]

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[3] *Department of Astronomy, Ohio State University, Columbus, Ohio 43210*

(Dated: June 30, 2023)

Neutrinos remain mysterious. As an example, enhanced self-interactions (νSI), which would have broad implications, are allowed. At the high neutrino densities within core-collapse supernovae, νSI should be important, but robust observables have been lacking. We show that νSI make neutrinos form a tightly coupled fluid that expands under relativistic hydrodynamics. The outflow becomes either a burst or a steady-state wind; which occurs here is uncertain. Though the diffusive environment where neutrinos are produced may make a wind more likely, further work is needed to

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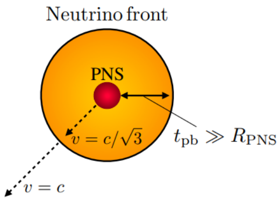

[2206.12426,2307.15115]

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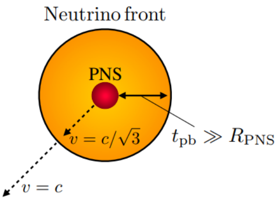


- **Just outside PNS the ν-density is high.**
- **ν-SI occurs. It cannot free-stream.**
- **$v = \frac{1}{\sqrt{3}}$ just after coming out of PNS.**
- **After traversing a length R_{fs} (free-streaming radius), $v = 1$.**

[2206.12426,2307.15115]

ν-SI details

- **Lagrangian of the ν-SI:** $\mathcal{L} = -\frac{1}{2} g \bar{\nu}\, \nu\, \phi$

- **Cross-section:** $\sigma_{\nu\nu} = g^4/(4\pi M_\phi^2) = \dfrac{1}{4\pi}(G')^2\, M_\phi^2.$

- **The scalar ϕ is the mediator with mass $M_\phi \sim 10$ MeV.**

- **At R_{fs}, optical depth is unity. $r > R_{fs}$, ν free streams.**

- **Optical depth:** $\tau(r) = -\int_\infty^r dr\, n_\nu(r) \sigma_{\nu\nu}$ **, Power-law model:** $n_\nu(r) = n_\nu^I \left(\frac{r}{R_S}\right)^{-\beta}$

$$[\beta = 2] \quad R_{fs} = 100\,\mathbf{km} \left(\frac{g}{7.53 \times 10^{-5}}\right)^4 \left(\frac{10\,\mathbf{MeV}}{M_\phi}\right)^2,$$

$$R_{fs} = 10^5\,\mathbf{km} \left(\frac{g}{4.23 \times 10^{-4}}\right)^4 \left(\frac{10\,\mathbf{MeV}}{M_\phi}\right)^2.$$

Memory signal including SI of supernova neutrinos

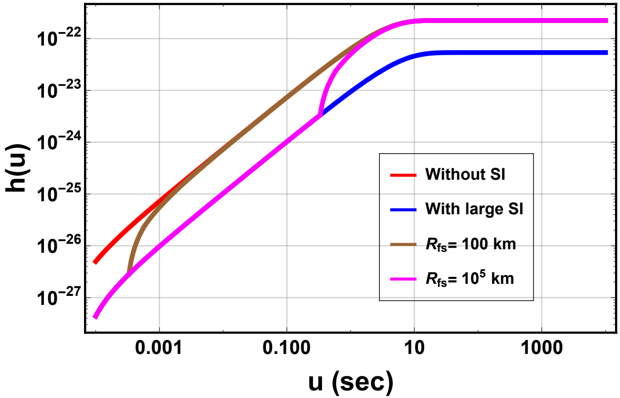
Total memory signal

$$h^{ij}(t,\vec{x}) = \frac{4G}{r}\int dt'\,\delta\left(t' - (t-r)\right)\, d\Omega' \left\{ \int_{R_s}^{R_{fs}} r'^2 dr'\,\epsilon(\vec{x}', t') \frac{v^i(\vec{x}', t')\, v^j(\vec{x}', t')}{1 - \vec{N}\cdot\vec{v}(\vec{x}', t')} + \int_{R_{fs}}^{\infty} r'^2 dr'\,\epsilon(\vec{x}', t') \frac{n'^i n'^j}{1 - \vec{N}\cdot\vec{n}'} \right\}$$

Diffusion region ($R_s < r < R_{fs}$), $v = 1/\sqrt{3}$

Free-streaming region ($r > R_{fs}$), $v = 1$

Time domain waveform

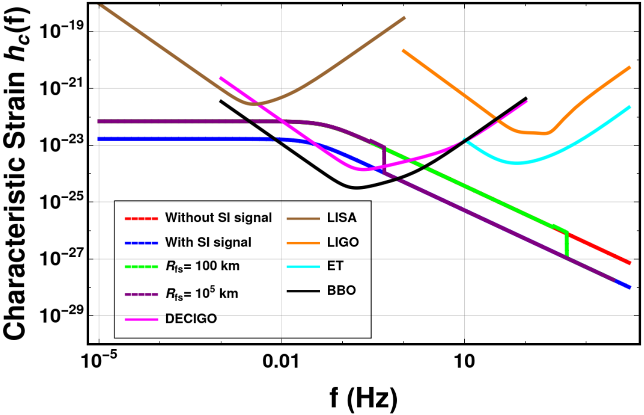


•Memory amplitude **with ν-SI is lower** compared to memory without SI.

•**Transition occurs when $R_{fs} > R_s$.**

•As R_{fs} increases, the transition happens at a **later time.**

Detection prospects



•Possibility of detection using **DECIGO and BBO**.

•For **lower values of R_{fs}**, detection is challenging for the current and planned detectors.

Summary and comments

•The current work is a proof-of-principle.

•It is possible to detect ν-SI from gravitational memory signal.

•GW burst signal from 3D SN explosion simulations will give a more realistic picture of the physical signal.

•Helpful in multimessenger astronomy.

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THANK YOU

BACKUP SLIDES

MODEL

$$\epsilon(\vec{x}', t') = \frac{L_{\nu_i}(t', r')}{4\pi r'^2}\alpha(\theta', \phi'),$$

- The luminosity expression is taken **arXiv: 2203.13365**

$$L_{\nu_i}(t', r') = \frac{1}{6}\frac{E_\nu}{\tau_\nu}\exp\left(-\frac{v_r t' - r'}{\tau_\nu}\right)\Theta(v_r t' - r')$$

- We assume **anisotropy** $\alpha(\theta, \phi) = \alpha \sin^2\phi$, where $\alpha = 0.005$
- The source is at a distance $r = 10$ **kpc** apart.