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

Indranil Chakraborty

IIT Bombay

Talk based on arXiv: 2311.03315, Phys. Rev. D 110, L061501

Collaborators: S. Mohanty (IITK), A. Hait (IITK), S. Bhattacharya (SNBNCBS), D. Bose (CUKmr)

PPC 2024: 17th International Conference on Interconnections between Particle Physics and Cosmology
October 16, 2024

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

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

PLAN

Understand gravitational wave memory effects and memory signals.

$\Downarrow$

How memory signals arise in supernova neutrinos

$\Downarrow$

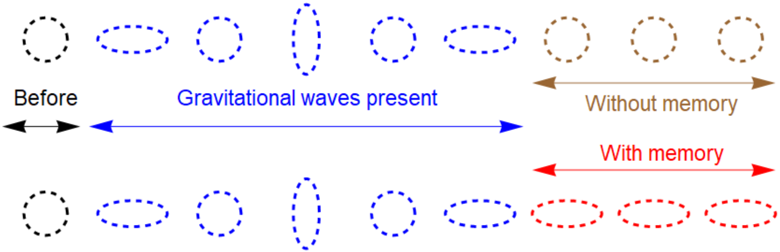
Self-interaction of supernova neutrinos

$\Downarrow$

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

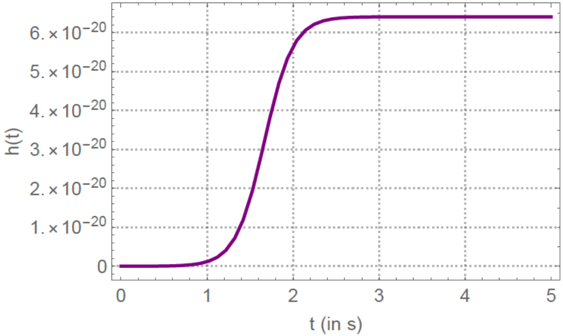
$$\underbrace{\Delta\xi^i}_{\text{Memory effect}} = \frac{1}{2}\underbrace{\Delta h^i{}_j}_{\text{Memory signal}}\,\xi^j$$

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

Memory signal

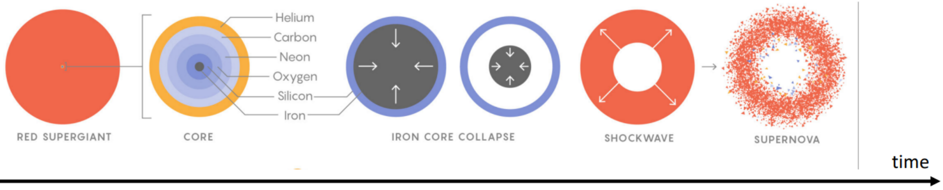


[Mukhopadhyay et al., JCAP (2021)]

- **DC shift in the GW amplitude.**
- **Such signals give rise to a permanent shift in the detector arms.**

Memory signal in supernova neutrinos

Core-collapse supernova



[Lunardini, COMHEP (2021)]

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

Role of neutrinos?

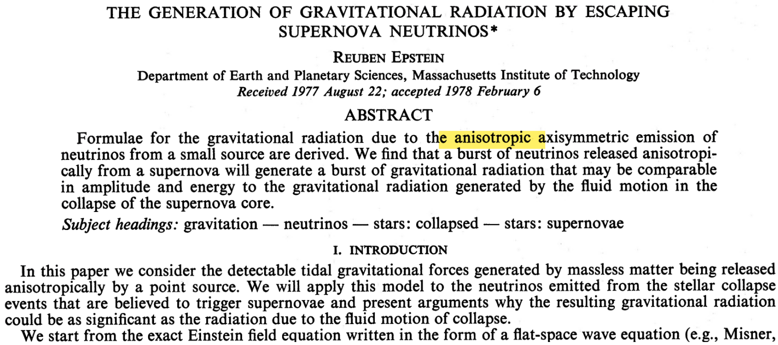
•**Electrons convert to neutrons emitting a neutrino.**

•**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

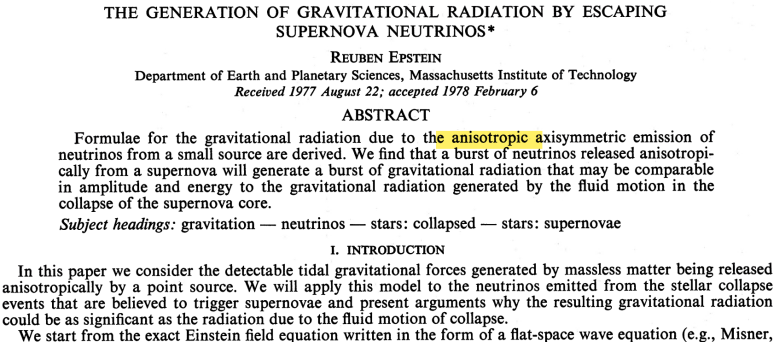
Formulae for the gravitational radiation due to the anisotropic axisymmetric emission of neutrinos from a small source are derived. We find that a burst of neutrinos released anisotropically from a supernova will generate a burst of gravitational radiation that may be comparable in amplitude and energy to the gravitational radiation generated by the fluid motion in the collapse of the supernova core.

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

I. INTRODUCTION

In this paper we consider the detectable tidal gravitational forces generated by massless matter being released anisotropically by a point source. We will apply this model to the neutrinos emitted from the stellar collapse events that are believed to trigger supernovae and present arguments why the resulting gravitational radiation could be as significant as the radiation due to the fluid motion of collapse.

We start from the exact Einstein field equation written in the form of a flat-space wave equation (e.g., Misner,



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

Formulae for the gravitational radiation due to the anisotropic axisymmetric emission of neutrinos from a small source are derived. We find that a burst of neutrinos released anisotropically from a supernova will generate a burst of gravitational radiation that may be comparable in amplitude and energy to the gravitational radiation generated by the fluid motion in the collapse of the supernova core.

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

I. INTRODUCTION

In this paper we consider the detectable tidal gravitational forces generated by massless matter being released anisotropically by a point source. We will apply this model to the neutrinos emitted from the stellar collapse events that are believed to trigger supernovae and present arguments why the resulting gravitational radiation could be as significant as the radiation due to the fluid motion of collapse.

We start from the exact Einstein field equation written in the form of a flat-space wave equation (e.g., Misner,

- Anisotropic neutrino burst from supernova causes gravitational memory signal.

- Solve the Einstein field equations with neutrinos as the source.

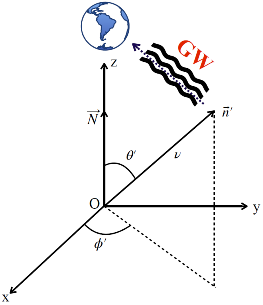
Memory signal from SN neutrinos

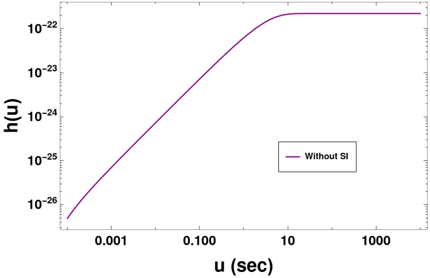
$$h^{ij}(t,\vec{x}) = \frac{4G}{r}\int dt'\, d\Omega' \int_{R_s}^{\infty} r'^2 dr' \epsilon(\vec{x}', t') \frac{n'^i n'^j}{1-\vec{N}\cdot\vec{n}'} \delta\left(t' - (t-r)\right).$$

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

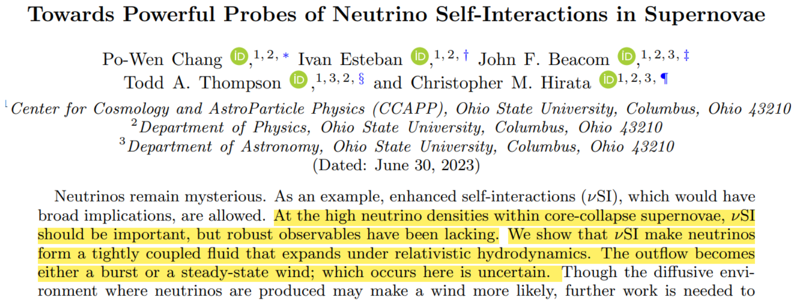
$$\epsilon(\vec{x}', t') = \frac{L_{\nu_i}(t', r')}{4\pi r'^2}\alpha(\theta', \phi')$$

[Luminosity and anisotropy]





Including neutrino self-interaction (ν-SI)

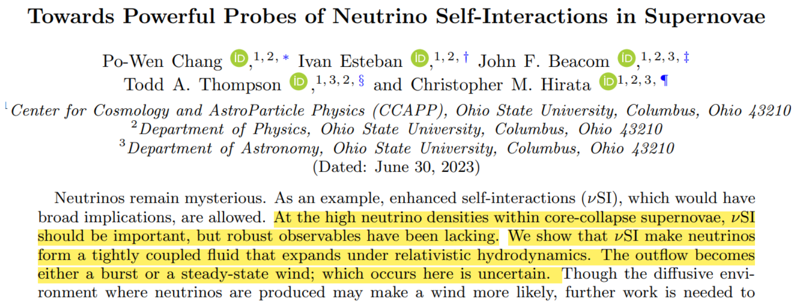


Towards Powerful Probes of Neutrino Self-Interactions in Supernovae

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,¶]
[1] *Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, Ohio 43210*
[2] *Department of Physics, Ohio State University, Columbus, Ohio 43210*
[3] *Department of Astronomy, Ohio State University, Columbus, Ohio 43210*

(Dated: June 30, 2023)

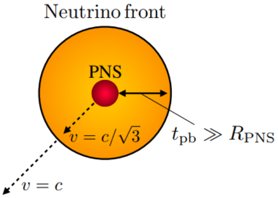
Neutrinos remain mysterious. As an example, enhanced self-interactions (νSI), which would have broad implications, are allowed. At the high neutrino densities within core-collapse supernovae, νSI should be important, but robust observables have been lacking. We show that νSI make neutrinos form a tightly 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



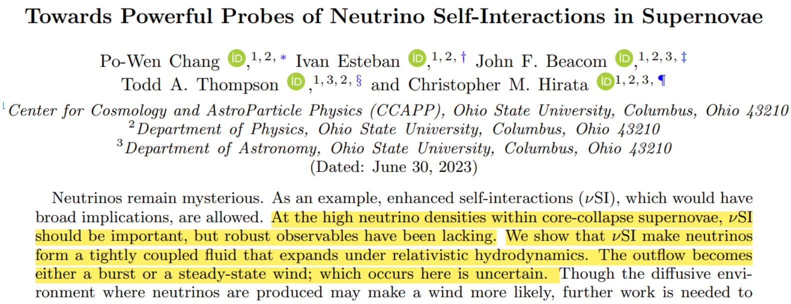
Towards Powerful Probes of Neutrino Self-Interactions in Supernovae

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,¶]
[1] *Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, Ohio 43210*
[2] *Department of Physics, Ohio State University, Columbus, Ohio 43210*
[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



[2206.12426,2307.15115]

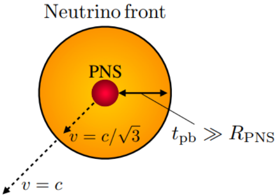


Towards Powerful Probes of Neutrino Self-Interactions in Supernovae

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,¶]

[1] *Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, Ohio 43210*
[2] *Department of Physics, Ohio State University, Columbus, Ohio 43210*
[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



- 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:** $n_\nu(r) = n_\nu^I \left(\frac{r}{R_S}\right)^{-\beta}$

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

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

Memory signal including SI of supernova neutrinos

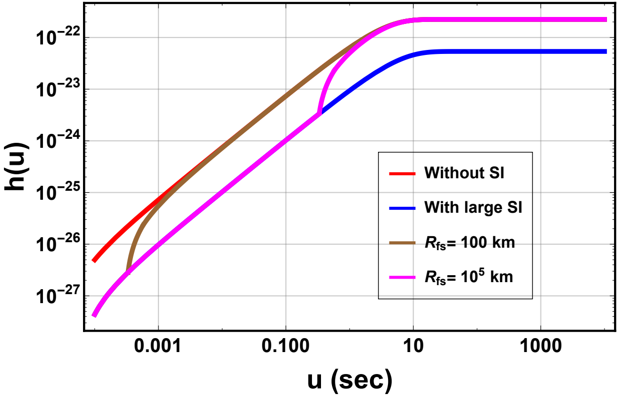
Total memory signal

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

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

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

Time domain waveform

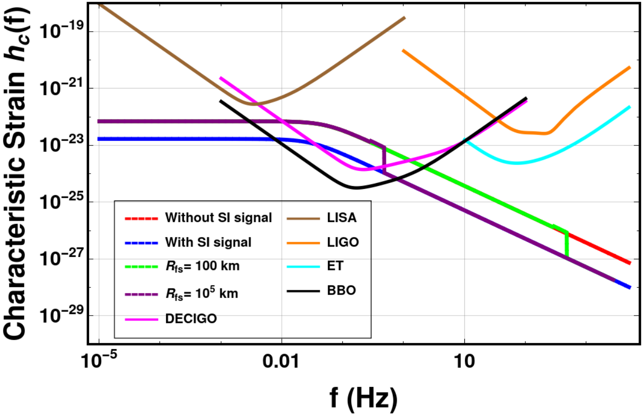


- Memory amplitude with ν-SI is lower compared to memory without SI.

- 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.

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.

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.**