

# **Gravitational-Wave Signatures of Nonstandard Neutrino Properties** in Collapsing Stellar Cores

arXiv:2412.02750

NCTS Workshop The Future is Whispering,新竹

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# Overview

- How does a core-collapse supernova work?
- •GW generation in core-collapse supernovae
- Neutrino flavor conversions
- •Results from simulations in axial symmetry (2D)
- Outlook and summary

# How does a core-collapse supernova work?

















### (not to scale )













### Some numbers (back of the envelope):

gravitational binding energy of the PNS:  $E_{grav} \simeq$ 

mean energy of neutrinos:  $\langle \epsilon_{\nu} \rangle \sim 15 \text{ MeV}$  (measured from SN1987A) number of neutrinos  $N_{\nu} \simeq \frac{E_{grav}}{\langle \epsilon_{\nu} \rangle} \sim 10^{58}$ 

kinetic energy of a supernova:  $\sim 10^{51}$  erg (measure spectra) radiation energy of a supernova:  $\sim 10^{49}$  erg (integrate light curve) energy of gravitational waves:  $\sim 10^{47}$  erg (predictions)

$$\frac{GM_{NS}^{2}}{R_{NS}} \sim 10^{53} \,\mathrm{erg}$$

## Neutrino luminosity and mean energy at 400 km



## Neutrino luminosity and mean energy at 400 km



# **Production (cooling): Thermal (flavor blind):** $e^+ + e^- \rightarrow \nu_{\alpha} + \bar{\nu}_{\alpha}$ **Charged current (e only):** $p + e^- \rightarrow n + \nu_e$

$$n + e^+ \to p + \bar{\nu}_e$$





![](_page_16_Picture_3.jpeg)

![](_page_16_Figure_4.jpeg)

# Gravitational Wave generation in core-collapse supernovae

**Originate from "asymmetric" motion of large masses** 

 $\rightarrow$  Asymmetric explosion

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→ Standing Accretion Shock Instability (SASI)

![](_page_21_Figure_1.jpeg)

- $\rightarrow$  Asymmetric explosion
- → Standing Accretion Shock Instability (SASI)
- $\rightarrow$  Convection (inside the PNS or neutrino driven)

![](_page_22_Figure_1.jpeg)

- $\rightarrow$  Asymmetric explosion
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- $\rightarrow$  Convection (inside the PNS or neutrino driven)
- $\rightarrow$  Asymmetric neutrino emission

![](_page_23_Figure_1.jpeg)

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- $\rightarrow$  Convection (inside the PNS or neutrino driven)
- $\rightarrow$  Asymmetric neutrino emission
- $\rightarrow$  Rotation and rotational instabilities
- ⇒ Stochastic no generic pattern available for searches

![](_page_23_Picture_10.jpeg)

![](_page_24_Figure_1.jpeg)

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![](_page_24_Picture_10.jpeg)

# Neutrino flavor conversions

I want to know about the implication of neutrinos being electrically neutral, left-handed particles that only take part in the weak interaction.

What consequences does this have on the our ability to study neutrino-neutrino interactions? I am especially interested in interactions that can lead to flavor changes. Please generate an image for me that I can use for my talk at the workshop: "The future is whispering"

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![](_page_28_Picture_3.jpeg)

Here is the image you requested: A futuristic abstract representation of neutrinos as whispering particles, showcasing left-handedness and weak interaction, with visual elements suggesting flavor changes. Hyperdetailed and very realistic, suitable for a scientific workshop presentation. Bright, ethereal lighting with a palette of blues and purples, creating a sense of mystery and innovation.

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![](_page_30_Picture_3.jpeg)

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![](_page_30_Picture_6.jpeg)

Here is the image you requested: A hyper-detailed illustration of a vast, sparse field symbolizing low neutrino density, with tiny neutrinos barely interacting. Incorporate scientific symbols and graphs to emphasize detection challenges. Set against a dark, cosmic background with subtle highlights, conveying the elusive nature of neutrinos. Ideal for a scientific workshop presentation.

Neutrinos only take part in the weak interaction  $\rightarrow$  very hard to measure properties

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"Only neutrino" interactions  $\mathscr{L}_{eff} \supset G_F[G^{\alpha\beta}\bar{\nu}_{\alpha}\gamma^{\mu}\nu_{\beta}][G^{\xi\eta}\bar{\nu}_{\xi}\gamma_{\mu}\nu_{\nu}]$  $\rightarrow G^{\alpha\beta} = \delta^{\alpha\beta}$  gives SM  $\rightarrow$  non-SM interactions: neutrinos of different flavor

vector mediator of mass  $m_V$ , coupling strength  $g_V$ , with  $|G^{\alpha\beta}| \propto g_V^2/m_V^2$ 

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Non-SM couplings are poorly constrained!

vector mediator of mass  $m_V$ , coupling strength  $g_V$ , with  $|G^{\alpha\beta}| \propto g_V^2/m_V^2$ 

see Abbar, 2023

![](_page_34_Picture_0.jpeg)

![](_page_34_Picture_1.jpeg)

![](_page_35_Picture_0.jpeg)

### here km $\sigma_{\nu_x,\bar{\nu}_x} < \sigma_{\nu_e,\bar{\nu}_e} \rightarrow \text{cooling by } \nu_x, \bar{\nu}_x \text{ more efficient}$

![](_page_36_Picture_0.jpeg)

### $\sigma_{\nu_x,\bar{\nu}_x} < \sigma_{\nu_e,\bar{\nu}_e} \rightarrow \text{cooling by } \nu_x, \bar{\nu}_x \text{ more efficient}$

Assume  $\nu_x, \bar{\nu}_x \rightarrow \nu_e, \bar{\nu}_e$  conversions at fixed density

![](_page_36_Picture_4.jpeg)

![](_page_37_Picture_0.jpeg)

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Absorption of  $\nu_e, \bar{\nu}_e$  locally heats PNS matter enhances convection

![](_page_38_Picture_0.jpeg)

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Emission of GW from convection and g-modes near the PNS surface

![](_page_38_Figure_7.jpeg)

# Results from simulations in axial symmetry (2D)

![](_page_40_Figure_0.jpeg)

ر 10 Fluid velocity [1000 km/s]

41

![](_page_41_Figure_0.jpeg)

Convection in PNS enhanced by a factor of a few!

**Convection develops much earlier!** 

Impact on GW emission?

0

![](_page_42_Figure_0.jpeg)

 $\rightarrow$  quiescent phase (first 100-200 ms after bounce)

![](_page_42_Picture_3.jpeg)

![](_page_43_Figure_0.jpeg)

$$\rho_c = 10^{13} \text{ g cm}^{-3}$$

noFC

 $\rightarrow$  quiescent phase (first 100-200 ms after bounce)

![](_page_43_Picture_5.jpeg)

![](_page_44_Figure_0.jpeg)

$$\rho_{c} = 10^{13} \text{ g cm}^{-3}$$

noFC

- $\rightarrow$  quiescent phase (first 100-200 ms after bounce)
- → enhanced PNS convection leads to GW emission during the "quiescent phase"

![](_page_44_Figure_6.jpeg)

![](_page_45_Figure_0.jpeg)

 $\rightarrow$  quiescent phase (first 100-200 ms after bounce)

- $\rightarrow$  enhanced PNS convection leads to GW emission during the "quiescent phase"
- $\rightarrow$  "quiescent phase" absent in all models with FC in the inner parts of the PNS

 $\log_{10}(h_{char})$ 

-23

-24

![](_page_45_Figure_6.jpeg)

![](_page_45_Figure_7.jpeg)

![](_page_46_Figure_0.jpeg)

# Evidence for enhanced convection inside PNS

# Development of PNS convection takes time

# Outlook and summary

# The Future Is Whispering!

- ➡GW emissions from CCSN are more quiet and noisy
- Flavor conversions can influence GW emission
- Early activity in the GW signal as a new feature
- A new window to BSM physics by multi-messenger approach

![](_page_48_Picture_6.jpeg)