Revisiting supernova neutrino phenomenology with non-standard neutrino self-interactions

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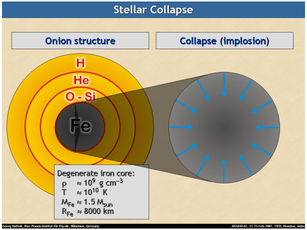
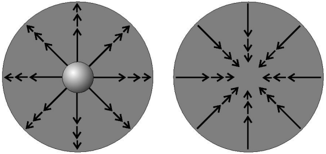
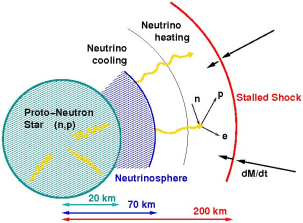
Supernova explosion



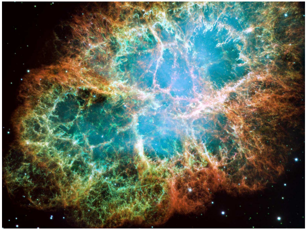
Explosion of a massive $6 - 8\ M_{\odot}$ star



Collapse of degenerate core.
Bounce and Shock.



Stalled shock and accretion



Explosion!

Flavor Oscillations in dense media: Collective effects

- Neutrino oscillation usually involves two kinds of terms

  1. Evolution due to vacuum oscillation.
  2. MSW potential term (matter effects)

- However, flavor evolution in a dense media $\rightarrow$ non-linear complicated problem $\rightarrow$ collective effects.

- High neutrino density can itself give rise to an MSW-like potential. Leads to self-interactions.

- Causes collective oscillations $\rightarrow$ neutrino flavor spectra in some energy ranges swap.

ν non-standard self-interactions (NSSI)

- Effective operator of the form $G_F\left(G^{\alpha\beta}\,\bar{\nu}_{\mathrm{L}\alpha}\gamma^{\mu}\nu_{\mathrm{L}\beta}\right)\left(G^{\zeta\eta}\,\bar{\nu}_{\mathrm{L}\zeta}\gamma_{\mu}\nu_{\mathrm{L}\eta}\right)$.
- $\alpha = \beta \rightarrow G^{\alpha\beta}$ is flavor-preserving $\rightarrow$ flavor-preserving NSSI (FP-NSSI).
- $\alpha \neq \beta \rightarrow G^{\alpha\beta}$ is flavor-violating $\rightarrow$ flavor-violating NSSI (FV-NSSI).

$$G = \begin{bmatrix} 1+\gamma_{ee} & \gamma_{ex} \\ \gamma_{ex}^{*} & 1+\gamma_{xx} \end{bmatrix} = g_{SM} + i\sigma\cdot\boldsymbol{g} = \begin{bmatrix} g_{SM}+g_3 & g_1 - ig_2 \\ g_1 + ig_2 & g_{SM}-g_3 \end{bmatrix}.$$

- Bounds give $\gamma_{\alpha\beta} \sim \mathcal{O}(1)$.

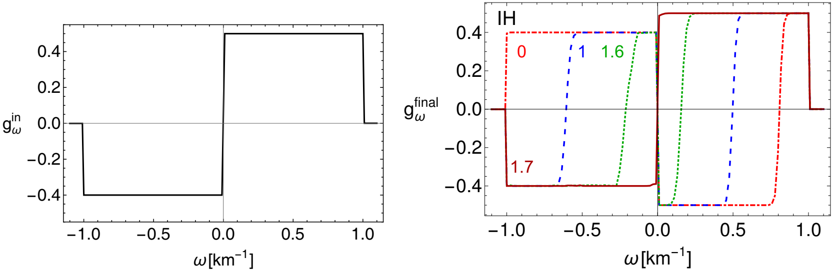
Bilenky and Santamaria(1999)

- $g_3 \equiv$ FP-NSSI and $g_1 \equiv$ FV-NSSI.

Single energy mode : Standard vs. Non-standard

Standard self-interaction	NSSI
Collective osc. only in IH.	In IH for $\|\boldsymbol{g}\| < g_{SM}$ and NH for $\|\boldsymbol{g}\| > g_{SM}$.
Need to break initial spherical symmetry in NH.	No need to break initial symmetry.
Need $\vartheta_0 \neq 0$.	Can happen for $\vartheta_0 = 0$.
Flavor lepton number(FLN) always conserved. Hence $\nu_e\bar{\nu}_e \to \nu_\mu\bar{\nu}_\mu$.	FLN need not be conserved.Hence $\nu_e\bar{\nu}_e \nrightarrow \nu_\mu\bar{\nu}_\mu$.

FP-NSSI : pinching of spectral swaps

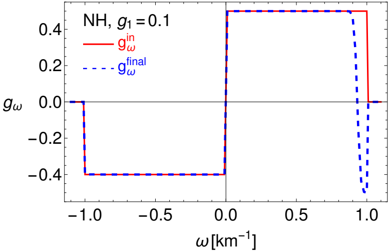


- Here $(\omega = \Delta m^2/2\,E_\nu)$

$$
\begin{aligned}
g_\omega &\propto F_{\nu_e}(\omega) - F_{\nu_\alpha}(\omega) \text{ for } \omega > 0\,, \\
&\propto F_{\bar{\nu}_\alpha}(\omega) - F_{\bar{\nu}_e}(\omega) \text{ for } \omega < 0\,.
\end{aligned}
$$

- FP-NSSI leads to pinching of spectral swaps.

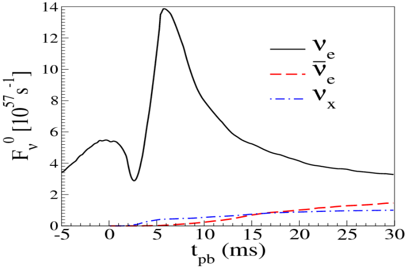
FV-NSSI : development of swaps away from crossing !



- Standard scenario → NH and " + " crossing is stable. Becomes unstable in presence of FV-NSSI.
- Since FLN is not conserved, no need to develop around a spectral crossing.
- Can have observable consequences in neutronization burst.

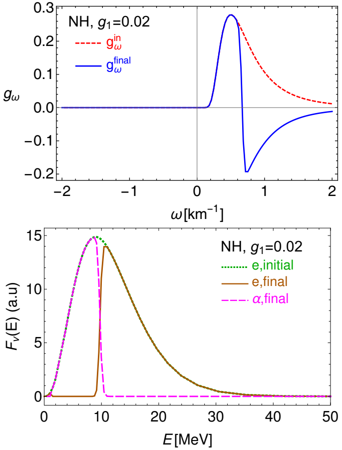
Neutronization burst

- Prompt emission of ν_e during the first 25 ms after bounce.
- ν_αs are absent during neutronisation. Hence no crossing in spectra, therefore no collective effects.
- Only MSW effects are considered.
- Hierarchy determination.



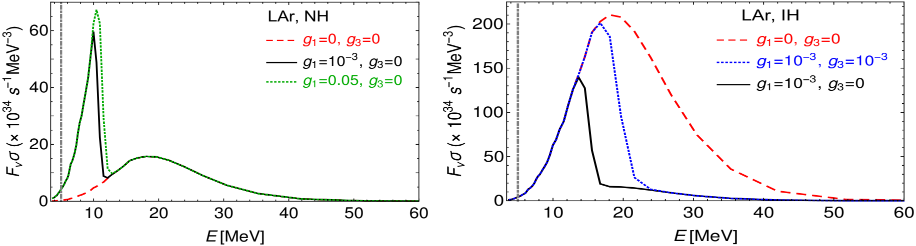
Garching simulations

Collective effects during neutronization burst!



Effects of $\nu_e \leftrightarrow \nu_\alpha$ collective oscillations on an initial ν_e spectrum during the neutronization burst.

Neutronization burst: signals



- Signals in a 40 Mt liquid Argon detector using $(\nu_e +^{40} Ar \rightarrow^{40} K^* + e^-)$ channel.
- Can make hierarchy determination ambiguous.
- Put flux dependent constraints on NSSI.

Caveats and Future prospects

- Extend to a three flavor framework.
- However, even simple approximations already bring out possible interesting features with the introduction of NSSI. Need a more rigorous study.

Thank You!