Fast neutrino flavour conversion near the supernova core

based on arXiv:1706.03360, with B. Dasgupta, E. Lisi, A. Marrone, A. Mirizzi

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Flavour conversion: an overview
Shock wave

Outer layer

$\nu - \text{ sphere}$

$R \sim 10 \text{ km}$

$\nu_{\alpha}$

$\nu_{\beta}$

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MSW effects

Outer layer

Shock wave

$\nu - \text{sphere}$

$R \sim 10 \text{ km}$

$\nu_{\alpha}$

$\nu_{\beta}$
Collective effects

Outer layer

Shock wave

$\nu - \text{sphere}$

$R \sim 10 \text{ km}$

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Fast flavour conversions

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$\nu_\alpha$

$\nu_\beta$

$\nu$ - sphere

$R \sim 10 \text{ km}$

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Fast flavour conversions: current status
What is causing fast flavour conversions?

Different angular distributions for the different flavors can speed-up conversions

\[ R(\nu_{\mu,\tau}) > R(\bar{\nu}_e) > R(\nu_e) \]

B. Dasgupta, A. Mirizzi and M. Sen, JCAP 1702 (2017) no.02, 019

Different angular distributions can be found near the \( \nu_e \) - neutrinosphere
Outcome of fast flavour conversions

Survival probability for $\nu_e$

B. Dasgupta, A. Mirizzi and M. Sen, JCAP 1702 (2017) no.02, 019

Flavour equilibration is a possible outcome
How do we simulate flavour conversions?
Numerical approach

The equation of motion is written in terms of the density matrix $\rho$

$$\partial_t \rho_{p,x,t} + \mathbf{v}_p \cdot \nabla_x \rho_{p,x,t} = -i[H_{p,x,t}, \rho_{p,x,t}]$$

$$\rho = \frac{f_{\nu_e} - f_{\nu_x}}{2} \begin{pmatrix} s & S \\ S^* & -s \end{pmatrix}$$

INITIAL CONDITIONS

$S \ll 1, \, s \sim 1$
Numerical approach

The equation of motion is written in terms of the density matrix $\rho$ as:

$$\partial_t \rho_{p,x,t} + \mathbf{v}_p \cdot \nabla_x \rho_{p,x,t} = i[H_{p,x,t}, \rho_{p,x,t}]$$

$$\rho = \begin{pmatrix} s & S \\ S^* & -s \end{pmatrix}$$

UNSOLVABLE!!!!

INITIAL CONDITIONS

$\ll 1 \quad s \sim 1$
Linear stability analysis

We linearise in $S$ and look only for the onset of flavour conversion

$$S_{v}(t, x) = Q_{v}e^{i(k \cdot x - \omega t)}$$
Linear stability analysis

We linearise in $S$ and look for the onset of flavour conversion

$$S_v(t, x) = Q_v e^{i(k \cdot x - \omega t)}$$

**DISPERSION RELATION**

$$D(\omega, k) = 0$$

Two ways of solving the DR:

$$\omega = \Omega(k) \quad \omega \in \mathbb{C}, \ k \in \mathbb{R}$$

**TEMPORAL STABILITY**

$$k = K(\omega) \quad k \in \mathbb{C}, \ \omega \in \mathbb{R}$$

**SPATIAL STABILITY**
Instability theory applied to supernova neutrinos
Two beam model

crossing: $N_{v} > N_{\bar{v}}$ for $v_1$ and $N_{v} < N_{\bar{v}}$ for $v_2$

$\varepsilon > 0$: no crossing

$\varepsilon < 0$: crossing
Pure stability

\[ v_1 = 0.7 \]
\[ v_2 = 0.2 \]
\[ \varepsilon > 0 \]
Convective instability

\[ v_1 = 0.7 \]
\[ v_2 = 0.2 \]
\[ \varepsilon < 0 \]

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Absolute instability

\[ \begin{align*}
    v_1 &= 0.6 \\
    v_2 &= -0.3 \\
    \varepsilon &< 0
\end{align*} \]
Conclusions

Flavour conversions near the supernova core are possible. **Impact on SN explosion and r-processes**
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Requirements: **crossing** and **backward propagating modes**
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**Linear stability** analysis through DR is a **powerful tool** if used correctly
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Requirements: **crossing** and **backward propagating modes**

**Linear stability** analysis through DR is a **powerful tool** if used correctly

**Non-linear simulations** are mandatory to study possible flavor equilibrium
Thank you
Supernova collapse

Core-collapse supernovae are the final explosion of stars with $M > 8M_\odot$.

- Onion-shell structure
- Collapse
- Nuclear density

99% of binding energy $\sim 10^{53}$ erg emitted through neutrinos $\nu_e, \bar{\nu}_e, \nu_x$

- Emission time $\sim 10$ s
- Average $\nu$ energy $\sim 10$ MeV

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Flavour conversions: why study them?

Impact on neutrino heating of the shock

Impact on nucleosynthesis (r-process)


Flavour conversions: an overview

The rich phenomenology can be classified according to:

$$\lambda = \sqrt{2}G_F n_e$$

$$\mu = \sqrt{2}G_F n_\nu$$
Collective effects

Initial neutrino and antineutrino fluxes

G. L. Fogli, E. Lisi, A. Marrone and A. Mirizzi, JCAP 0712 (2007) 010

Final fluxes in inverted hierarchy (single-angle)

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Collective effects

Development time \( \sim (\omega \mu)^{1/2} \)

Global polarization vectors (single-angle)

G. L. Fogli, E. Lisi, A. Marrone and A. Mirizzi, JCAP 0712 (2007) 010
Linear stability analysis

We linearise in $S$ and look for the onset of flavour conversion

$$S_v(t, x) = Q_v e^{i(k \cdot x - \omega t)}$$
Damped instability

\[ v_1 = 0.6 \]
\[ v_2 = -0.3 \]
\[ \varepsilon > 0 \]
Can we have crossing in a SN?

Electron lepton number ($10^{31} \text{ cm}^{-3}$)

- $r = 30 \text{ km (x 3)}$
- $r = 37 \text{ km}$
- $r = 150 \text{ km}$
- $r = 54 \text{ km}$