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Neutrino Plasma Coupling
in Dense Astrophysical Plasmas

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Neutrino Plasma Coupling in Dense Astrophysical Plasmas

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There is considerable interest in the propagation dynamics of neutrinos in a background dispersive medium, particularly in the search for a mechanism to explain the dynamics of type II supernovæ and solve the solar neutrino problem. Neutrino interactions with matter are usually considered as non self-consistent single particle processes. We describe neutrino streaming instabilities within supernovæ plasmas, resulting in longitudinal and transverse waves using coupled kinetic equations for both neutrinos and plasma particles including magnetic field effects. The transverse waves have energies in the $\gamma$-ray range which suggests that this may be a possible mechanism for $\gamma$-ray bursts which are associated with supernovæ. Another interesting result is an asymmetry in the momentum balance imparted by the neutrinos to the core of the exploding star due to a magnetic field effect. This can result in a directed velocity of the resulting neutron star or pulsar and can explain the so called natal kick.
Non-Linear Scattering Instabilities

GRB is Produced here

Source

ν

neutrinos

internal shocks

optical or UV, decays quickly

ISM

begins as γ-rays or X-rays & continues as the late afterglow

forward shock

reverse shock

external shock
Supernovae IIa physical parameters

To form a neutron star $3 \times 10^{53}$ erg must be released (gravitational binding energy of the original star)
- light+kinetic energy $\sim 10^{51}$ erg
- gravitational radiation $< 1\%$
- neutrinos $99 \%$

- Electron density @ 100-300 km: $n_e \sim 10^{29} - 10^{32}$ cm$^{-3}$
- Electron temperature @ 100-300 km: $T_e \sim 0.1 - 0.5$ MeV
- Degeneracy parameter $\Theta = T_e/E_F \sim 0.5 - 0.7$
- Coulomb coupling constant $\Gamma \sim 0.01 - 0.1$
- $\nu_e$ luminosity @ neutrinosphere $\sim 10^{52} - 5 \times 10^{53}$ erg/s
- $\nu_e$ intensity @ 100-300 Km $\sim 10^{29} - 10^{30}$ W/cm$^2$
- Duration of intense $\nu_e$ burst $\sim 5$ ms
  (resulting from $p+e \rightarrow n+\nu_e$)
- Duration of $\nu$ emission of all flavors $\sim 1 - 10$ s
• How to turn an implosion into an explosion
  – New neutrino physics
  – $\lambda_{\text{mfp}}$ for $e\nu$ collisions $\sim 10^{16} \text{ cm}$ in collapsed star
  – $\lambda_{\text{mfp}}$ for collective plasma-neutrino coupling $\sim 100\text{ m}$

• How?
  – New non-linear force — neutrino ponderomotive force
  – For intense neutrino flux collective effects important
  – Absorbs 1\% of neutrino energy
    $\Rightarrow$ sufficient to explode star

Neutrino dynamics in dense plasma

Single particle dynamics governed by Hamiltonian (Bethe, ‘87):

\[ H_{\text{eff}} = \sqrt{p_v^2 c^2 + m_v^2 c^4} + 2G_F n_e (r, t) \]

\( p_v \) - Effective potential due to weak interaction with background electrons
\( m_v \) - Repulsive potential

\( G_F \) - Fermi constant
\( n_e \) - Electron density

\[ F_{\text{pond}} = -\sqrt{2}G_F \nabla n_v (r, t) \]

Force on a single electron due to neutrino distribution

Ponderomotive force* due to neutrinos pushes electrons to regions of lower neutrino density

\[ F = -\sqrt{2}G_F \nabla n_e (r, t) \]

Force on a single neutrino due to electron density modulations

Neutrinos bunch in regions of lower electron density

* ponderomotive force derived from semi-classical (L.O.Silva et al, ‘98) or quantum formalism (Semikoz, ‘87)
The interaction can be easily represented by neutrino refractive index.

The dispersion relation:
\[
(E_\nu - V)^2 - p_\nu^2 c^2 - m_\nu^2 c^4 = 0
\]

(Bethe, 1986)

\(E\) is the neutrino energy, \(p\) the momentum, \(m_\nu\) the neutrino mass.

The potential energy
\[V = \sqrt{2} G_F n_e\]
\(G_F\) is the Fermi coupling constant, \(n_e\) the electron density

⇒ Refractive index
\[N_\nu = \left(\frac{ck_\nu}{\omega_\nu}\right)^2 = \left(\frac{cp_\nu}{E_\nu}\right)^2\]

\[N_\nu \approx 1 - \frac{2\sqrt{2} G_F}{\hbar k_\nu c} n_e\]

Note: cut-off density
\[n_{ec} > \frac{\varepsilon_\nu}{2\sqrt{2} G_F}\]
\(\varepsilon_\nu\) neutrino energy

Electron neutrinos are refracted away from regions of dense plasma - similar to photons.
For intense neutrino beams, we can introduce the concept of the Ponderomotive force to describe the coupling to the plasma. This can then be obtained from the 2nd order term in the refractive index.

**Definition**

\[ F_{POND} = \frac{N - 1}{2} \nabla \xi \quad \text{[Landau & Lifshitz, 1960]} \]

where \( \xi \) is the energy density of the neutrino beam.

\[ N = 1 - \frac{2\sqrt{2}G_F n_e}{\varepsilon_v} \quad \Rightarrow \quad F_{Pond} = -\frac{\sqrt{2}G_F n_e}{\varepsilon_v} \nabla \xi \]

\( n_\nu \) is the neutrino number density.

\[ F_{Pond} \equiv -\sqrt{2}G_F n_e \nabla n_\nu \]
Neutrino Ponderomotive Force (2)

Force on one electron due to electron neutrino collisions $f_{\text{coll}}$

$$f_{\text{coll}} = \sigma_{\nu_e} \xi$$

$$\sigma_{\nu_e} = \left( \frac{G_F k_B T_e}{2\pi \hbar^2 c^2} \right)^2$$

$\sigma_{\nu_e}$ is the neutrino-electron cross-section

Total collisional force on all electrons is

$$F_{\text{coll}} = n_e f_{\text{coll}} = n_e \sigma_{\nu_e} \xi$$

$$\frac{F_{\text{Pond}}}{F_{\text{coll}}} = \frac{\sqrt{2\pi \hbar^3 c^3}|k_{\text{Mod}}|}{G_F k_B^2 T^2 k_v}$$

$|k_{\text{mod}}|$ is the modulation wavenumber.

For a 0.5 MeV plasma

$$\frac{F_{\text{Pond}}}{F_{\text{coll}}} \approx 10^{10}$$

$\sigma_{\nu_e} \Rightarrow$ collisional mean free path of $10^{16}$ cm.
Kinetic Equation for neutrinos

Kinetic equation for neutrinos
(describing neutrino number density conservation / collisionless neutrinos)

$$\frac{\partial f_\nu}{\partial t} + \mathbf{v}_\nu \cdot \frac{\partial f_\nu}{\partial \mathbf{r}} - \sqrt{2} G_F \left( \nabla n_e + \frac{1}{c^2} \frac{\partial \mathbf{J}_e}{\partial t} - \frac{\mathbf{v}_\nu}{c^2} \times \nabla \times \mathbf{J}_e \right) \cdot \frac{\partial f_\nu}{\partial \mathbf{p}_\nu} = 0$$

Electron density oscillations driven by neutrino pond. force
(collisionless plasma)

$$\frac{\partial f_e}{\partial t} + \mathbf{v}_e \cdot \frac{\partial f_e}{\partial \mathbf{r}} - \sqrt{2} G_F \left( \nabla n_e + \frac{1}{c^2} \frac{\partial \mathbf{J}_e}{\partial t} - \frac{\mathbf{v}_e}{c^2} \times \nabla \times \mathbf{J}_e \right) \cdot \frac{\partial f_e}{\partial \mathbf{p}_\nu} - e \left( \mathbf{E} + \mathbf{v}_e \times \mathbf{B} \right) \cdot \frac{\partial f_e}{\partial \mathbf{p}_e} = 0$$

Dispersion relation for electrostatic plasma waves

$$1 + \chi_e (\omega_L, \mathbf{k}_L) + \chi_\nu (\omega_L, \mathbf{k}_L) = 0$$

Electron susceptibility    Neutrino susceptibility

$$\chi_\nu (\omega_L, \mathbf{k}_L) = -2 G_F^2 \frac{k_L^3 n_{e0} n_{\nu0}}{m_e \omega_{pe0}} \left( 1 - \frac{\omega_L^2}{c^2 k_L^2} \right)^2 \chi_e \int d\mathbf{p}_\nu \frac{k_L \cdot \hat{\mathbf{f}}_{\nu0}}{\omega_L - \mathbf{k}_L \cdot \mathbf{v}_\nu}$$
Neutrino distribution in the neutrinosphere \( \equiv f_{\nu_0}(k_{\nu}) \)

Neutrino distribution in \( \mathbf{A} \)
\[
f_{\nu}(k_{\nu}, R, \theta) = f_{\nu_0}(k_{\nu})/d^2(R, \theta)
\]

for \( R \gg r \)
\[
f(\theta) = \text{const.} \quad |\theta| < \theta_{\text{max}}
\]
\[
f(\theta) = 0 \quad |\theta| > \theta_{\text{max}}
\]

\( R \gg r \) and \( \theta_{\text{max}} \approx 30 \text{ mrad} \)

Beamed distribution

Analysis in slab geometry gives good picture

\[
\gamma_{\text{max}} \propto \left( \frac{N}{1 - \cos \theta_{\text{max}}} \right)^{1/2} \propto G_F
\]

and \( 1/(1 - \cos \theta_{\text{max}}) \approx 10^3 \)
Neutrino Beam-Plasma Instability

Monoenergetic neutrino beam

\[ f_{\nu_0} = n_{\nu_0} \delta(p_{\nu} - p_{\nu_0}) \]

Dispersion Relation

\[ \omega_L^2 = \omega_{pe0}^2 + \left( \frac{m_{\nu}^2 c^4 \cos^2 \theta}{E_{\nu_0}^2} + \sin^2 \theta \right) \frac{\mathcal{N} k_L c^4}{\left( \omega_L - k_L c \cos \theta \frac{p_{\nu_0} c}{E_{\nu_0}} \right)^2} \]

\[ \theta \equiv k_L \wedge p_{\nu_0} \]

\[ \mathcal{N} = \frac{2 G_F^2 n_{\nu_0} n_{e0}}{m_e c^2 E_{\nu_0}} \]

\[ \text{If } m_\nu \to 0 \text{ direct forward scattering is absent} \]

\[ \text{Similar analysis of two-stream instability:} \]

- Maximum growth rate for \( k_L v_{\nu_0||} = k_c \cos \theta \approx \omega_{pe0} \)
- \( \omega = \omega_{pe0} + \delta = k_L v_{\nu_0||} + \delta \)

Weak Beam (\( \delta/\omega_{pe0} \ll 1 \)) Growth rate

\[ \gamma_{\text{max}} = \frac{\sqrt{3}}{2} \omega_{pe0} \left( \frac{\tan^2 \theta}{\sin^2 \theta} \right)^{1/3} \propto G_F^{2/3} \]

Strong Beam (\( \delta/\omega_{pe0} \gg 1 \)) \( \gamma_{\text{max}} \propto G_F^{1/2} \)

Single \( \nu \)-electron scattering \( \propto G_F^2 \)

Collective plasma process much stronger than single particle processes
Neutrino beam with arbitrary momentum distribution

\[ f_{\nu 0} = n_{\nu 0} \hat{f}(p_{\nu x}) \delta(p_{\nu y}) \delta(p_{\nu z}) \]

Neutrino susceptibility

\[ \chi_{\nu}(\omega_L, k_L) \propto -\frac{n_{\nu 0}}{(\omega_L - k_L \cos \theta)^2} \int dp_{\nu x} \frac{\hat{f}_{\nu 0}}{|p_{\nu x}|} \]

From monoenergetic beam to arbitrary neutrino energy distribution

\[ \frac{1}{E_{\nu 0}} = \frac{\lambda_{\nu 0}}{2 \pi \hbar c} \rightarrow \frac{\langle \lambda_{\nu} \rangle}{2 \pi \hbar c} \]

For distributions with equal neutrino density \( n_{\nu 0} \) and equal de Broglie wavelength \( \langle \lambda_{\nu} \rangle \), growth rates are identical

\( \langle \lambda_{\nu} \rangle \) is the average de Broglie wavelength of neutrino distribution
Role of electron-ion collisions in the instability (hydro)

BGK model of collisions

\[ \chi_e(\omega_L, k_L) = -\frac{\omega_{pe}^2}{\omega_L(\omega_L + i\nu_s)} \]

New dispersion relation

\[ \omega_L(\omega_L + i\nu_{ei}) = \omega_{pe0}^2 + \left( \frac{m^2_e c^4 \cos^2 \theta}{E_{\nu 0}} + \sin^2 \theta \right) \frac{\frac{\omega_{pe0}}{\nu_{ei}}}{\omega_L - k_L c \cos \theta \frac{P_{\nu 0} c}{E_{\nu 0}}} \]

Similar analysis as before leads to

\[ \gamma_{\text{max}} = \frac{\sqrt{2}}{2} \omega_{pe0} \left( \frac{\tan^2 \theta}{\sin^2 \theta} \frac{\omega_{pe0}}{\nu_{ei}} \right)^{1/2} \propto G_F \]

(with collisions)

\[ \nu_s \approx \nu_{ei} \]

Electron-ion collision frequency

Instability threshold is \( \propto G_F^2 \)

since it is proportional to (Damping electrons) \( \times \) (Damping neutrinos)
Instability regimes: hydrodynamic vs kinetic

If region of unstable PW modes overlaps neutrino distribution function kinetic regime becomes important

Unstable PW modes \((\omega_L, k_L)\)

- Neutrino distribution function

Kinetic instability \(\gamma \propto G_F^2\) if

- \(\frac{\omega_L}{k_L} - \nu_{v0} \ll \sigma_{v_v}\)

Hydro instability \(\gamma \propto G_F^{2/3}\) if

- \(\frac{\omega_L}{k_L} - \nu_{v0} \gg \sigma_{v_v}\)

\(\frac{\omega_L}{ck_L} - \frac{\nu_{v0}}{c} \approx \frac{\gamma_{\max}}{\omega_{p e 0}} \beta_\phi \approx 10^{-14} - 10^{-11}\)

where \(\nu_v = p_v c^2/E_v = p_v c^2/(p_v^2 c^2 + m_v^2 c^4)^{1/2}\)

- for \(m_v \to 0, \sigma \to 0\) hydro regime

- Hydro instability regimes

- Kinetic instability regimes

\(N_{e0} = 10^{29} \text{ cm}^{-3}\)
\(L_v = 10^{52} \text{ erg/s}\)
\(R_m = 300 \text{ Km}\)
\(<E_v> = 10 \text{ MeV}\)
\(T_v = 3 \text{ MeV}\)
\(m_v = 0.1 \text{ eV}\)
\( n_{e0} = 10^{29} \text{ cm}^{-3} \)
\( L_{\nu} = 10^{52} \text{ erg/s} \)
\( R_m = 300 \text{ Km} \)
\( <E_{\nu}> = 10 \text{ MeV} \)

Growth distance \( \sim 1 \text{ m} \) (without collisions)

Growth distance \( \sim 300 \text{ m} \) (with collisions)

- 6 km for 20 e-foldings -

Mean free path for neutrino electron single scattering \( \sim 10^{11} \text{ km} \)
Saturation Mechanism

Neutrino streaming instability saturates by electron Landau damping

\[ k_p \sim \frac{\omega_{pe0}}{c} \cos \Theta \]
\[ \Theta_{\text{max}} \sim \arccos\left(\frac{v_{th}}{c}\right) \]

\[ T_e \uparrow \Rightarrow \Theta_{\text{max}} \downarrow \Rightarrow \text{Instability Shutdown} \]

Modes with maximum growth rate

\[ E_k = E_k \delta(k_\parallel - \omega_{pe0}/c) \frac{k}{|k|} \]

Simplified Model

\[ \frac{\partial |E_k|^2}{\partial t} = 2\gamma_k |E_k|^2 \]
\[ \gamma_k = 0 \text{ if } k > k_{\text{max}} \]

\[ \frac{\partial W_{EPW}}{\partial t} = n_e \frac{\partial T_e}{\partial t} = \frac{1}{8\pi} \frac{\partial}{\partial t} \sum_{k \leq k_{\text{max}}} |E_k|^2 \]
\[ k_{\text{max}} = \frac{\omega_{pe0}}{v_{th}(T_e)} \]
Preliminary results indicate strong heating up to 0.5 MeV;
- Further analysis is necessary to include relativistic corrections on electron
  Landau damping - present model overestimates eLD;
- Initial $v_e$ burst ($\sim$ ms) can heat the plasma efficiently;
- Detailed quasi-linear theory for $v$'s and $e$'s will give signatures of $v$-driven
  instabilities and more accurate results → information to be included in
  supernovae code
- Stimulated “Compton” scattering must also be considered
Transverse plasmon neutrino interactions

• For transverse plasmon neutrino interactions the kinetic equations are:

\[
\frac{\partial f_v}{\partial t} + \mathbf{v}_v \cdot \nabla f_v + F_v \frac{\partial f_v}{\partial p_v} = 0 \quad \frac{\partial f_e}{\partial t} + \mathbf{v}_e \cdot \nabla f_e + F_e \frac{\partial f_e}{\partial p_e} = 0
\]

where

\[
F_v = -\sqrt{2}G_F \left( \nabla n_e + \frac{1}{c^2} \frac{\partial J_e}{\partial t} - \frac{1}{c^2} \mathbf{v}_v \times \nabla \times J_e \right)
\]

\[
F_e = -e(\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \sqrt{2}G_F \left( \nabla n_v + \frac{1}{c^2} \frac{\partial J_v}{\partial t} - \frac{\mathbf{v}_v}{c^2} \times \nabla \times J_v \right)
\]

note that we can introduce the boson fields \( E_v \) and \( B_v \) given by

\[
E_v = -\nabla n_e - \frac{1}{c^2} \frac{\partial J_e}{\partial t} \quad B_v = \nabla \times J_e
\]

• The dispersion relation for transverse plasmons in the collisionless limit is

\[
\epsilon_t + \chi_v = 0
\]

where

\[
\chi_v = -2G_F^2 A k_t \frac{n_{e0} n_{v0}}{m_e \omega^2} \left( 1 - \frac{\omega^2}{c^2 k^2} \right) \int \frac{d p_v k}{\omega - k \cdot \mathbf{v}_v} \frac{\partial f_{v0}}{\partial p_v}
\]

\[
A = 2 \frac{\omega_p^2}{\omega} \left( \frac{\partial}{\partial \omega} \omega^2 \epsilon' \right)^{-1}
\]
Neutrino heating is necessary for a strong explosion

The shock exits the surface of the proto-neutron star and begins to stall approximately 100 milliseconds after the bounce.

The initial electron neutrino pulse of $5 \times 10^{53}$ ergs/second is followed by an “accretion” pulse of all flavours of neutrinos.

This accretion pulse of neutrinos deposits energy behind the stalled shock, increasing the matter pressure sufficiently to drive the shock completely through the mantle of the star.
Neutrino emission of all flavors
\[ L_\nu \sim 10^{52} \text{ erg/s}, \tau \sim 1 \text{ s} \]

e-Neutrino burst
\[ L_\nu \sim 4 \times 10^{53} \text{ erg/s}, \tau \sim 5 \text{ ms} \]

Due to electron Landau damping, plasma waves only grow in the lower temperature regions.

Plasma heating
@ 100-300 km from center

Supernova Explosion!

Stimulated “Compton” scattering

Less energy lost by shock to dissociate iron

Pre-heating of outer layers by short $\nu_e$ burst (~ms)

Revival of stalled shock in supernova explosion (similar to Wilson mechanism)

Anomalous pressure increase behind shock
• Neutrino spectra and time history of the fluxes probe details of the core collapse dynamics and evolution.

• Neutrinos provide heating for “delayed” explosion mechanism.

• Sufficiently detailed and accurate simulations provide information on convection models and neutrino mass and oscillations.
General dispersion relation describes not only the neutrino fluid instability
but also the neutrino kinetic instability

\[ \chi_\nu(\omega_L, k_L) \propto \int d\mathbf{p}_\nu \frac{k_L \cdot \partial \hat{f}_{\nu0}}{\omega_L - k_L \cdot v_\nu} \]

\[ \gamma_{\text{Landau}} \approx -\frac{k_L c}{2} \frac{G_F^2 n_{e0} n_{\nu0}}{m_e c^2 k_B T_\nu} \frac{\text{Li}_2(-\exp E_F / T_\nu)}{\text{Li}_3(-\exp E_F / T_\nu)} \]

\[ \gamma_{\text{Landau}} \approx 10^{-6} \text{ s}^{-1} \]

Neutrino Landau damping leads to damping of EPWs by energy transfer to the neutrinos
Important for the neutron star cooling process
Neutrinos drain energy from the plasma by damping plasma waves - unlike the usual neutron star cooling plasma process the number of neutrinos is conserved - 

\[ Q_{\text{epw}} - \text{energy loss rate} \quad Q_{\text{EPW}} = \int \frac{d\mathbf{k}}{(2\pi)^3} \gamma_{\text{Landau}}(\mathbf{k}) W_{\text{EPW}} \]

\[ W_{\text{epw}} - \text{spectral energy density of EPWs - Bose distribution} \]

\[ Q_{\text{EPW}} = -\frac{3\pi}{4} \frac{W_{\text{EPW}}}{k_D^3} \left( \frac{\omega_{pe0}}{c} \right)^4 \frac{G_F^2 n_e n_v}{m_e c^2 E_{v0}} \frac{\text{Li}_2(-\exp\mu/T)}{\text{Li}_3(-\exp\mu/T)} \left( \frac{3}{4} \frac{1}{4\beta_{th}^4} - \frac{1}{\beta_{th}^2} - \ln\beta_{th} \right) \]

\[ \beta_{th} - \text{typical thermal velocity} \]
\[ \frac{2\pi}{k_D} - \text{Debye Length} \]

Dependence on neutrino distribution

Scaling with \( G_F^2 n_e^{5/2} n_v T_v^{-1} T_e^{5/2} \)

Stronger than mechanism proposed by Tsytovich (1961)

For a broad range of parameters more important than usual plasma cooling process
1) Neutrino beam plasma instability can result in photon production.

\[ \nu \rightarrow \nu_1 + T \]

In supernovæ the frequency of the photons is in the MeV energy range - i.e. $\gamma$-rays.

2) The neutrino heated plasma can also produce electron-positron pairs. If the rate of production is greater than the rate of annihilation then the resulting structure is a relativistic electron/positron fireball.

**\gamma-Ray Bursts (GRBs)**

A few percent of the neutrino energy must be converted to $\gamma$-rays to explain the GRBs which are thought to be associated with supernovæ (1).
Conclusions

• General description of neutrino formed scattering instabilities into longitudinal and transverse plasmons.
• Neutrino Landau damping.
• Quasi-linear theory developed
• Possibility of neutrino generation of $\gamma$-rays in supernova plasmas
Outline

Intense fluxes of neutrinos in Astrophysics
Neutrino dynamics in dense plasmas (making the bridge with HEP)
Plasma Instabilities driven by neutrinos
Supernovae, neutron stars and $\nu$ driven plasma instabilities

Gamma-ray bursters: open questions
e$^+e^-$ 3D electromagnetic beam plasma instability
Consequences on GRBs and relativistic shocks
Conclusions and future directions
Neutrinos are the most enigmatic particles in the Universe

Associated with some of the long standing problems in astrophysics

- Solar neutrino deficit
- Gamma ray bursters (GRBs)
- Formation of structure in the Universe
- Supernovae II (SNe II)
- Stellar/Neutron Star core cooling
- Dark Matter

Intensities in excess of $10^{30} \text{ W/cm}^2$ and luminosities up to $10^{52} \text{ erg/s}$
An electron beam propagating through a plasma generates plasma waves, which perturb and eventually break up the electron beam.

Electroweak theory unifies electromagnetic force and weak force.

A similar scenario should also be observed for intense neutrino bursts.
Can intense neutrino winds drive collective and kinetic mechanisms at the plasma scale?

Bingham, Bethe, Dawson, Su (1994)
The MSW effect - neutrino flavor conversion

Flavor conversion - electron neutrinos convert into another \( \nu \) flavor

Equivalent to mode conversion of waves in inhomogeneous plasmas

\[
\frac{d^2 \psi_i}{dx^2} + k_i^2 \psi_i = 0 \quad \quad \quad \quad \quad k_i^2 = \frac{E_i^2 - m_i^2 c^4 - V_{\text{eff} i}}{c^2 \hbar^2}
\]

\( i = 1, 2, 3 \) (each \( \nu \) flavor)

Mode conversion when \( k_1 = k_2, E_1 = E_2 \)

\[
\frac{d^2 \psi_1}{dx^2} + k_1^2 \psi_1 = \lambda_1 \psi_2 \quad \quad \quad \quad \quad \lambda_i = \frac{1}{2} \frac{\Delta m^2 c}{\hbar^2} \frac{E_i}{p_i} \sin 2 \theta
\]

\[
\frac{d^2 \psi_2}{dx^2} + k_2^2 \psi_2 = \lambda_2 \psi_1
\]

Fully analytical MSW conversion probabilities derived in unmagnetized plasma and magnetized plasma

(Bingham et al., PLA 97, 2002)
The effective potential of neutrinos

Semi-classical effective $\nu$-e interaction Lagrangian

$$L_{\text{int}} = -\frac{G_F}{\sqrt{2}}(1 + C_V)(n_e - J_e \cdot v_\nu)$$

Semi-classical $\nu$ Hamiltonian

$$H_{\text{eff}} = \sqrt{\left( P_\nu - \sqrt{2} G_F \frac{J_e(r, t)}{c^2} \right)^2 c^2 + m_\nu^2 c^4 + \sqrt{2} G_F n_e(r, t)}$$

$$P_\nu = p_\nu + \sqrt{2} G_F \frac{J_e(r, t)}{c^2}$$

Neutrino Canonical Momentum

Equivalent to interaction of charged particle with an e.m. field

- $\nu$ Charge: $\sqrt{2} G_F$
- 4-Potential: $\left( n_e, \frac{J_e}{c} \right)$

Lorentz Gauge

$$\nabla \cdot \left( \frac{J_e(r, t)}{c} \right) + \frac{1}{c} \frac{\partial n_e}{\partial t} = 0$$
**Neutrino Dynamics in a Dense Plasma**

**Equations of motion**

\[
\mathbf{v}_\nu = \frac{d\mathbf{r}_\nu}{dt} = \frac{p_\nu c^2}{\sqrt{p_\nu^2 c^2 + m_\nu^2 c^4}}
\]

Neutrinos bunch in regions of lower electron density

\[
\mathbf{F}_\nu = \frac{d\mathbf{p}_\nu}{dt} = -\sqrt{2} G_F \left( \nabla n_e (r, t) + \frac{1}{c^2} \frac{\partial J_e (r, t)}{\partial t} - \frac{\mathbf{v}_\nu}{c} \times \nabla \times \frac{J_e (r, t)}{c} \right)
\]

**Equivalent equations of motion for electrons**

\[
\mathbf{v}_e = \frac{d\mathbf{r}_e}{dt} = \frac{p_e c^2}{\sqrt{p_e^2 c^2 + m_e^2 c^4}}
\]

Ponderomotive force due to neutrinos

\[
\mathbf{F}_e = \frac{d\mathbf{p}_e}{dt} = -e \left( \mathbf{E} + \frac{\mathbf{v}_e}{c} \times \mathbf{B} \right) - \sqrt{2} G_F \left( \nabla n_\nu (r, t) + \frac{1}{c^2} \frac{\partial J_\nu (r, t)}{\partial t} - \frac{\mathbf{v}_e}{c} \times \nabla \times \frac{J_\nu (r, t)}{c} \right)
\]

(Silva et al, PRE 1998, PRD 1998)
Neutrino repels nearby electrons - Dressed neutrino with equivalent charge

\[ F_\nu = -\sqrt{2} G_F \left( \nabla n_e(r, t) + \frac{1}{c^2} \frac{\partial J_e(r, t)}{\partial t} - \frac{\mathbf{v}_\nu}{c} \times \nabla \times \mathbf{J}_e(r, t) \right) \]

\[ F = -i\sqrt{2} G_F k \left( 1 - \frac{\omega^2}{k^2 c^2} \right) n_e(\omega, k) = -\frac{\sqrt{2} G_F k^2}{4\pi e} \left( 1 - \frac{\omega^2}{k^2 c^2} \right) E(\omega, k) = e_\nu(\omega, k) E(\omega, k) \]

\[ e_\nu(\omega, k) = -\frac{\sqrt{2} G_F k^2}{4\pi e} \left( 1 - \frac{\omega^2}{k^2 c^2} \right) \approx -\frac{\sqrt{2} G_F k_D^2}{4\pi e} = -\frac{\sqrt{8} \pi e}{k_B T_e} G_F n_{e0} \]

(Nieves and Pal, ’94)
(Mendonca et al, PLA 1997)
Neutrino kinetics in a dense plasma

Kinetic equation for neutrinos
(describing neutrino number density conservation / collisionless neutrinos)

\[
\frac{\partial f_\nu}{\partial t} + \mathbf{v}_\nu \cdot \frac{\partial f_\nu}{\partial \mathbf{r}} - \sqrt{2} G_F \left( \nabla n_e (r, t) + \frac{1}{c^2} \frac{\partial \mathbf{J}_e (r, t)}{\partial t} - \frac{\mathbf{v}_\nu}{c} \times \nabla \times \frac{\mathbf{J}_e (r, t)}{c} \right) \cdot \frac{\partial f_\nu}{\partial \mathbf{p}_\nu} = 0
\]

Kinetic equation for electrons driven by neutrino pond. force
(collisionless plasma)

\[
\frac{\partial f_e}{\partial t} + \mathbf{v}_e \cdot \frac{\partial f_e}{\partial \mathbf{r}} - \sqrt{2} G_F \left( \nabla n_\nu (r, t) + \frac{1}{c^2} \frac{\partial \mathbf{J}_\nu (r, t)}{\partial t} - \frac{\mathbf{v}_e}{c} \times \nabla \times \frac{\mathbf{J}_\nu (r, t)}{c} \right) \cdot \frac{\partial f_e}{\partial \mathbf{p}_e} - e \left( \mathbf{E} + \frac{\mathbf{v}_e}{c} \times \mathbf{B} \right) \cdot \frac{\partial f_e}{\partial \mathbf{p}_e} = 0
\]

\[+\]

Maxwell’s Equations

Electroweak plasma instabilities

Two stream instability
  Neutrinos driving electron plasma waves $v_\phi \sim c$
  Anomalous heating in SNe II

Collisionless damping of electron plasma waves
  Neutrino Landau damping
  Anomalous cooling of neutron stars

Electroweak Weibel instability
  Generation of quasi-static B field
  Primordial B and structure in early Universe
Two stream instability driven by $\nu$'s

Usual perturbation theory over kinetic equations + Poisson’s equation

\[
\begin{align*}
    n_e &= n_0 + n_{e1} & f_e &= f_{e0}(p_e) + f_{e1} \\
    v_e &= v_1 & f_v &= f_{v0}(p_v) + f_{v1} \\
    v_\nu &= v_{\nu0} + v_{\nu1} & E &= E_1
\end{align*}
\]

Dispersion relation for electrostatic plasma waves

\[
1 + \chi_e(\omega_L, k_L) + \chi_\nu(\omega_L, k_L) = 0
\]

Electron susceptibility \hspace{2cm} Neutrino susceptibility

\[
\chi_\nu(\omega_L, k_L) = -2 \ G_F^2 \ \frac{k_L^3 n_{e0} n_{v0}}{m_e \omega_{pe0}^2} \left( 1 - \frac{\omega_L^2}{c^2 k_L^2} \right)^2 \ \chi_e \int d\mathbf{p}_\nu \ \frac{k_L \cdot \partial \tilde{f}_{\nu0}}{\omega_L - k_L \cdot v_\nu} \frac{\partial \hat{f}_\nu}{\partial p_\nu}
\]

(Silva et al, PRL 1999)
Neutrino beam-plasma instability

Monoenergetic neutrino beam & slab geometry & cold plasma

\[ f_{\nu_0} = n_{\nu_0} \delta(p_\nu - p_{\nu_0}) \]

\[ \nu' \text{'s} \]

Dispersion Relation

\[ \frac{\omega_L^2}{\omega_{pe_0}^2} = 1 + \frac{\Delta \nu k_L^4 c^4}{\omega_{pe_0}^2} \left( \frac{1}{\omega_L - k_L c \cos \theta \frac{p_{\nu_0} c}{E_{\nu_0}}} \right)^2 \left( \frac{m_{\nu}^2 c^4 \cos^2 \theta}{E_{\nu_0}^2} + \sin^2 \theta \right) \]

\[ \theta \equiv k_L \cdot p_{\nu_0} \]

If \( m_\nu \to 0 \) direct forward scattering (\( \theta = 0 \)) is absent

Strong suppression factor in \( \Delta \nu \) for EPWs with \( v_\phi \approx c \)
Instability analysis

Similar analysis as for two-stream instability:

maximum growth rate \( @ \)

\[ k_L v_{\nu 0||} = k c \cos \theta \approx \omega_{pe0} \]

\( \omega = \omega_{pe0} + \delta = k_L v_{\nu 0||} + \delta \)

Weak Beam (\( \delta / \omega_{pe0} << 1 \))

\[ \gamma_{\text{max}} = \frac{\sqrt{3}}{2} \omega_{pe0} \left( \Delta \nu (\sin \theta)^2 (\tan \theta)^4 \right)^{1/3} \propto G_F^{2/3} \]

Strong Beam (\( \delta / \omega_{pe0} >> 1 \))

\[ \gamma_{\text{max}} \propto G_F^{1/2} \]

Single \( \nu \)-electron scattering \( \propto G_F^2 \)

Collective mechanism much stronger than single particle processes
To form a neutron star > $3 \times 10^{53}$ erg must be released

(gravitational binding energy of the original star)

- light+kinetic energy $\sim 10^{51}$ erg
- gravitational radiation < 1%
- neutrinos 99%

- Electron density @ 100-300 km: $n_e \sim 10^{29} - 10^{32}$ cm$^{-3}$
- Electron temperature @ 100-300 km: $T_e \sim 0.1 - 0.5$ MeV
- Degeneracy parameter $\Theta = T_e / E_F \sim 0.5 - 0.7$
- Coulomb coupling constant $\Gamma \sim 0.01 - 0.1$
- $\nu_e$ luminosity @ neutrinosphere $\sim 10^{52} - 5 \times 10^{53}$ erg/s
- $\nu_e$ intensity @ 100-300 Km $\sim 10^{29} - 10^{30}$ W/cm$^2$
- Duration of intense $\nu_e$ burst $\sim 5$ ms
  (resulting from $p + e \rightarrow n + \nu_e$)
- Duration of $\nu$ emission of all flavors $\sim 1 - 10$ s
Estimates of the Instability Growth Rates

\[ n_e^0 = 10^{29} \text{ cm}^{-3} \]
\[ L_\nu = 10^{52} \text{ erg/s} \]
\[ R_m = 300 \text{ Km} \]
\[ <E_\nu> = 10 \text{ MeV} \]

Growth distance \( \sim 1 \text{ m} \)  
(without collisions)

Growth distance \( \sim 300 \text{ m} \)  
(with collisions)

- 6 km for 20 e-foldings -

Mean free path for 
neutrino electron single scattering \( \sim 10^{11} \text{ km} \)
Anomalous heating by neutrino streaming instability

\[
\left( \frac{\Delta E_\nu}{10^{50} \text{erg}} \right) \approx 1.2 \times 10^{-1} \left( \frac{R}{500 \text{Km}} \right)^3 \left( \frac{T}{2 \text{MeV}} \right) \times \\
\left\{ 0.145 \left( \frac{n}{10^{30} \text{cm}^{-3}} \right) + \left( \frac{T}{2 \text{MeV}} \right)^3 \right\}
\]

Neutrino heating to re-energize stalled shock

\[
\left( \frac{\Delta E_\nu}{10^{50} \text{erg}} \right) \approx 1 - 0.1
\]

(Silva et al, PoP 2000)
Neutrino emission of all flavors
\[ L_\nu \sim 10^{52} \text{ erg/s}, \tau \sim 1 \text{ s} \]

e-Neutrino burst
\[ L_\nu \sim 4 \times 10^{53} \text{ erg/s}, \tau \sim 5 \text{ ms} \]

Due to electron Landau damping, plasma waves only grow in the lower temperature regions.

Supernova Explosion!

Supernovae explosions & neutrino driven instabilities

Plasma heating @ 100-300 km from center

Stimulated “Compton” scattering

Less energy lost by shock to dissociate iron

Pre-heating of outer layers by short $v_e$ burst (~ms)

Revival of stalled shock in supernova explosion (similar to Wilson mechanism)

Anomalous pressure increase behind shock
What if the source of free energy is in the plasma?
*Thermal spectrum of neutrinos interacting with turbulent plasma*

Collisionless damping of EPWs by neutrinos moving resonantly with EPWs

General dispersion relation describes not only the neutrino fluid instability but also the neutrino kinetic instability

*(Silva et al, PLA 2000)*
Neutrino Landau damping reflects contribution from the pole in neutrino susceptibility

\[ \chi_\nu(\omega_L, k_L) \propto \int dp_\nu \frac{k_L \cdot (\hat{f}_{\nu 0} / \partial p_\nu)}{\omega_L - k_L \cdot v_\nu} \rightarrow \int dp_\perp \begin{pmatrix} P \int \left( \frac{\partial \hat{f}_{\nu 0}}{\partial p_\parallel} \right) dp_\parallel \right) + i\pi \left( \frac{\partial \hat{f}_{\nu 0}}{\partial p_\parallel} \right) \left( p_\parallel - p_\parallel^0 \right) \end{pmatrix} \]

EPW wavevector \( k_L = k_\parallel \) defines parallel direction
neutrino momentum \( p_n = p_\parallel + p_\perp \)
arbitrary neutrino distribution function \( f_{\nu 0} \)
Landau’s prescription in the evaluation of \( \chi_\nu \)

For a Fermi-Dirac neutrino distribution

\[ \gamma_{\text{Landau}} \approx -\frac{k_L c}{2} \pi \frac{G_F^2 n_{e0} n_{\nu 0}}{m_e c^2 k_B T_\nu} \left( 1 - \frac{\omega_L^2}{c^2 k_L^2} \right)^2 \frac{\text{Li}_2(-\exp E_F / T_\nu)}{\text{Li}_3(-\exp E_F / T_\nu)} \]
Anomalous cooling of neutron stars

Neutrinos drain energy from the plasma by damping plasma waves unlike the usual neutron star cooling *plasma process* the number of neutrinos is conserved -

\[ Q_{epw} \text{ energy loss rate} = Q_{EPW} = \int \frac{d\mathbf{k}}{(2\pi)^3} \gamma_{\text{Landau}}(\mathbf{k}) W_{EPW} \]

\[ W_{epw} - \text{spectral energy density of EPWs - Bose distribution} \]

\[ Q_{EPW} = -\frac{3\pi}{4} \frac{W_{EPW}}{k_D^3} c \left( \frac{\omega_{pe0}}{c} \right)^4 \frac{G_F^2 n_{e0} n_{\nu0}}{m_e c^2 E_{\nu0}} \frac{Li_2(-\exp\mu/T)}{Li_3(-\exp\mu/T)} \left( \frac{3}{4} + \frac{1}{4\beta_{th}^4} - \frac{1}{\beta_{th}^2} - \ln \beta_{th} \right) \]

\[ \beta_{th} - \text{typical thermal velocity} \]
\[ 2 \pi/k_d - \text{Debye Length} \]

Typical turbulence cooling times \( \approx 10^{-4} \text{ Gyr} \)
Neutron star cooling time scale \( \approx 1-10 \text{ Gyr} \)
Weibel instability

Free energy in particles (e, i, e⁺) transferred to the fields (quasi-static B field)

Fundamental plasma instability
- laser-plasma interactions
- shock formation
- magnetic field generation in GRBs

Signatures: B field + filamentation + collisionless drag

Free energy of neutrinos/anisotropy in neutrino distribution transferred to electromagnetic field
Usual perturbation theory over kinetic equations + Faraday’s and Ampere’s law

Cold plasma

\[
(\omega^2 - k^2 c^2) \left(1 - \omega \Delta_v \phi(\hat{f}_{v0})\right) = \omega_{pe0}^2 \quad \text{for} \quad k = k e_z
\]

\[
\phi(\hat{f}_{v0}) = \int d\mathbf{p}_v \frac{v_{\perp}}{\omega - kv_z} \cos^2 \theta \left\{ \frac{\partial \hat{f}_{v0}}{\partial p_{\perp}} + k \frac{\partial \hat{f}_{v0}}{\partial p_{v_z}} - \frac{k}{\omega} v_{\perp} \frac{\partial \hat{f}_{v0}}{\partial p_{v_z}} - \frac{k}{\omega} v_z \frac{\partial \hat{f}_{v0}}{\partial p_{\perp}} \right\}
\]

Monoenergetic $\nu$ beam ($m_\nu = 0$)

\[
(\omega^2 - k^2 c^2) \left(1 + \Delta_v \frac{k^2 c^2}{\omega^2} \beta_{v0}^2 \right) = \omega_{pe0}^2 \quad \text{for} \quad \omega \approx i \gamma_{\text{Weibel}} \quad \& \quad |\gamma_{\text{Weibel}}| \ll |k|
\]

\[
\gamma_{\text{Weibel}} = \beta_{v0} \frac{k^2 c^2}{\sqrt{k^2 c^2 + \omega_{pe0}^2}} \Delta_v^{1/2} \propto G_F
\]

(Silva et al, PFCF 2000)
Gamma Ray Bursters

- Short intense bursts of a few MeV $\gamma$-rays with x-ray to IR afterglow
- Total energy $10^{51}$-$10^{54}$ erg (with beaming of radiation $\downarrow$)
- Nonthermal GRB spectrum
- Duration a fraction of s to 100’s of s

GRBs involve 3 stages:
- Central engine (?) produces relativistic outflow
- This energy is relativistically transferred from the source to optically thin regions
- The relativistic ejecta is slowed down and the shocks that form convert the kinetic energy to internal energy of accelerated particles, which in turn emit the observed gamma-rays ($\gamma > 100$, B-field close to equipartition)
External shocks arise due to the interaction of the relativistic matter with the interstellar medium.

Internal shocks arise from the collisions of plasma shells: faster shells catch up with slower ones and collide.
To explain present observations near equipartition B-fields have to be present.

Necessary to generate B-field such that:

\[ |B|^2/\varepsilon_{\text{plasma shells}} \sim 10^{-5} - 10^{-3} \]

Weibel instability can be the mechanism to generate such fields (Medvedev and Loeb, 2000)

To definitely address this issue: 3D PIC simulations
Simulation details

- 200 x 200 x 100 cells (20 x 20 x 10 $c^3/\omega_p^3$ volume) or
- 256 x 256 x 100 cells (25.6 x 25.6 x 10 $c^3/\omega_p^3$ volume)
- 16 particles per species per cell
- >100 million particles total
- Periodic system

CRAY T3E 900 - NERSC (64 nodes)
epp cluster (40 nodes)

PIC codes
- OSIRIS (R. G. Hemker, UCLA, 2000)
- PARSEC (J. Tonge, UCLA, 2002)
B-field evolution

\[
\log_{10}(\text{Energy} / \varepsilon_{\text{plasma shells}}) = 0
\]

\[
0 \quad 20 \quad 40 \quad 60 \quad 80 \quad 100 \quad 120 \quad 140
\]

\[
\frac{1}{\omega_{\text{pe}0}}
\]

\[
\begin{align*}
B_{\perp}^2 & \quad E_{\parallel}^2 & \quad \gamma/v/c = 10 & \quad u_{\text{th}} = 0.1 \\
E_{\parallel}^2 & \quad B_{\perp}^2 & \quad \gamma/v/c = 0.6 & \quad u_{\text{th}} = 0.1
\end{align*}
\]

Required energy in B-field

Mass density evolution ($\gamma v/c = 0.6$)

- **Red** Iso-surfaces: species with initial positive $j_{x3}$
- **Blue** Iso-surfaces: species with initial negative $j_{x3}$
- All isosurfaces drawn at a density value of 1.1 (initial density = 1.0)
Magnetic field energy density ($\gamma \nu/c = 0.6$)

- Isosurfaces (Green - regions of lower values, Yellow regions of higher values) of the magnitude of the magnetic field
- Isosurfaces drawn at a) 0.1, b) 0.025, c) 0.01 and d) 0.006
Energy evolution \((\gamma \nu/c = 0.6)\)

B-field spectral energy density

Particle Kinetic Energy

\(\gamma - 1\)

\(\text{Time Evolution}\)
Electron-electron--positron positron Weibel instability II

• 3D Simulation
  200 x 200 x 100 cells (20 x 20 x 10 \(c^3/\omega_p^3\) volume)
  8 particles per species per cell, 64 million particles total

• Computer
  Simulations were run on 64 nodes of the Cray-T3E 900 at NERSC

(Fonseca et al, IEEE TPS 2002)
In gamma ray bursters, Weibel instability can explain near equipartition B-fields

Weibel instability also crucial to understand pulsar winds, and relativistic shock formation

Challenge: relativistic collisionless shocks e⁻e⁺/i (theory) and three-dimensional PIC simulations of relativistic shocks

In different astrophysical conditions involving intense neutrino fluxes, neutrino driven plasma instabilities are likely to occur

- Anomalous heating in SNe II
- Plasma cooling by neutrino Landau damping in neutron stars
- Electroweak Weibel instability in the early universe

Challenge: reduced description of $\nu$ driven anomalous processes to make connection with supernovae numerical models

(Oraevskii, Semikoz, Bingham, Silva, 2003)
Neutrino surfing electron plasma waves

\[ |\Delta E_\nu|_{\text{max}} \approx |F| L_{dp} \approx 8\sqrt{2} G_F \varepsilon n_{e0} \]

\( \gamma_\phi = 10 \)
\( \varepsilon = 10^{-2} \)
\( n_{e0} = 10^{32} \text{ cm}^{-3} \)
\( L_{dp} = \lambda_p \gamma_\phi^2 \approx 3 \times 10^{-2} \text{ cm} \)
\( dE_\nu / dL \approx 8\sqrt{2} G_F \varepsilon n_{e0} / (\lambda_p \gamma_\phi^2) \approx 200 \text{ eV / cm} \)

Equivalent to physical picture for RFS of photons (Mori, '98)
Plasma waves driven by electrons, photons, and neutrinos

**Electron beam**

\[
\left( \partial_t^2 + \omega_{pe0}^2 \right) \delta n_e = -\omega_{pe0}^2 n_{e-beam}
\]

**Photons**

\[
\left( \partial_t^2 + \omega_{pe0}^2 \right) \delta n_e = \frac{\omega_{pe0}^2}{2m_e} \nabla^2 \int \frac{dk}{(2\pi)^3} \hbar \frac{N_\gamma}{\omega_k}
\]

**Neutrinos**

\[
\left( \partial_t^2 + \omega_{pe0}^2 \right) \delta n_e = \sqrt{2n_{e0}G_F} \frac{m_e}{m_e} \nabla^2 n_\nu
\]

$\delta n_e$ Perturbed electron plasma density

**Ponderomotive force**

physics/9807049, physics/9807050

Kinetic/fluid equations for electron beam, photons, neutrinos coupled with electron density perturbations due to PW

Self-consistent picture of collective e,γ,ν-plasma interactions
Super-Kamiokande

- Japanese Super-Kamiokande experiment – a large spherical “swimming pool” filled with ultra-pure water which is buried 1000 metres below ground!

- Scientists checking one of the 11,146 50-cm diameter photomultiplier tubes that surround the walls of the tank.

- In November, 2001, one of these PMTs imploded and the resulting shockwave caused about 60% of the other PMTs to implode also. The “shock” in the tank was so large that it was recorded on one of Japan’s earthquake monitoring stations 8.8 km away!

- Super-Kamiokande obtained this neutrino image of the Sun!
Solar Neutrinos

The p-p chain

\[ 4p + 2e^- \rightarrow He^4 + 2\nu_e + 2\gamma + 26.7\text{MeV} \]

3% of the energy is carried away by neutrinos
One neutrino is created for each \( \approx 13 \text{ MeV} \) of thermal energy
The “Solar Constant”, \( S \) (Flux of solar radiation at Earth) is

Neutrino flux at Earth, \( \phi_\nu \),

\[ \phi_\nu = \frac{S}{13 \text{ MeV}} \approx 6.7 \times 10^{10} \text{ neutrinos/cm}^2\text{s} \]

These are all electron neutrinos (because the p-p chain involves electrons).

**PROBLEM:** Only about one-thirds of this flux of neutrinos is actually observed.

**SOLUTION:** The MSW Effect

Neutrinos interact with the matter in the Sun and “oscillate” into one of the other neutrino “flavours” – Neutrino matter oscillations – electron neutrinos get converted to muon or tau neutrinos and these could not be detected by the early neutrino detectors!
Big Bang Neutrinos

• The “Big Bang” Model of cosmology predicts that neutrinos should exist in great numbers – these are called **relic neutrinos**.

• During the Lepton era of the universe neutrinos and electrons (plus anti particles) dominate:
  - $\sim 10^{86}$ neutrinos in the universe
  - Current density $n_{\nu} \sim 220 \text{ cm}^{-3}$ for each flavour!

• Neutrinos have a profound effect on the Hubble expansion:
  - Dark matter
  - Dark energy
  - Galaxy formation
  - Magnetic field generation

\[ \text{in the early universe} \]
Supernovæ II Neutrinos

• A massive star exhausts its fusion fuel supply relatively quickly.
• The core implodes under the force of gravity.
• This implosion is so strong it forces electrons and protons to combine and form neutrons – in a matter of seconds a city sized superdense mass of neutrons is created.
• The process involves the weak interaction called “electron capture”
  \[ p^+ + e^- \rightarrow n + \nu_e \]
• A black hole will form unless the neutron degeneracy pressure can resist further implosion of the core. Core collapse stops at the “proto-neutron star” stage – when the core has a \( \sim 10 \) km radius.
• **Problem**: How to reverse the implosion and create an explosion?