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Neutrino Plasma Coupling in Dense Astrophysical Plasmas

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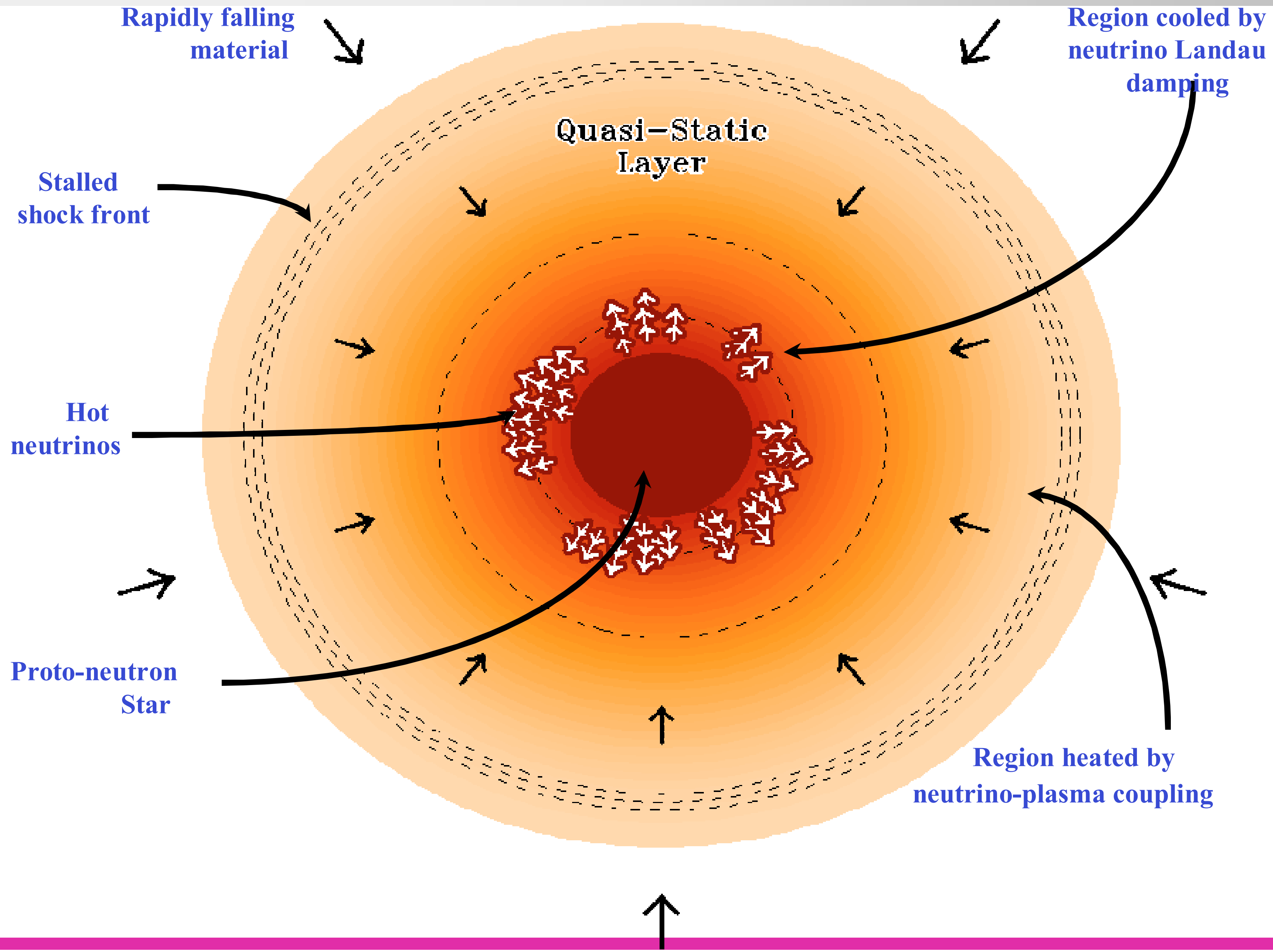
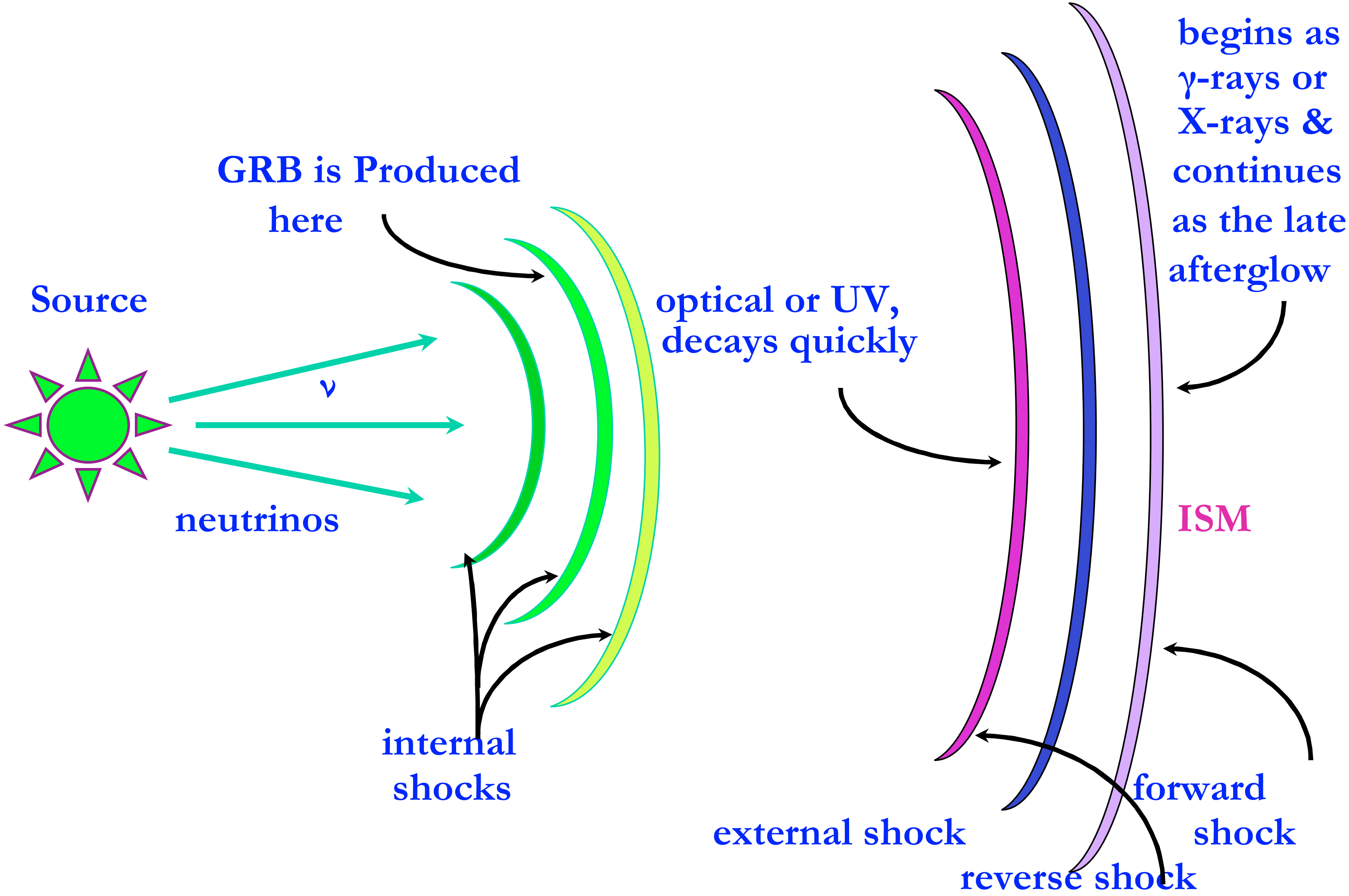
ABSTRACT

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 γ-ray range which suggests that this may be a possible mechanism for γ-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

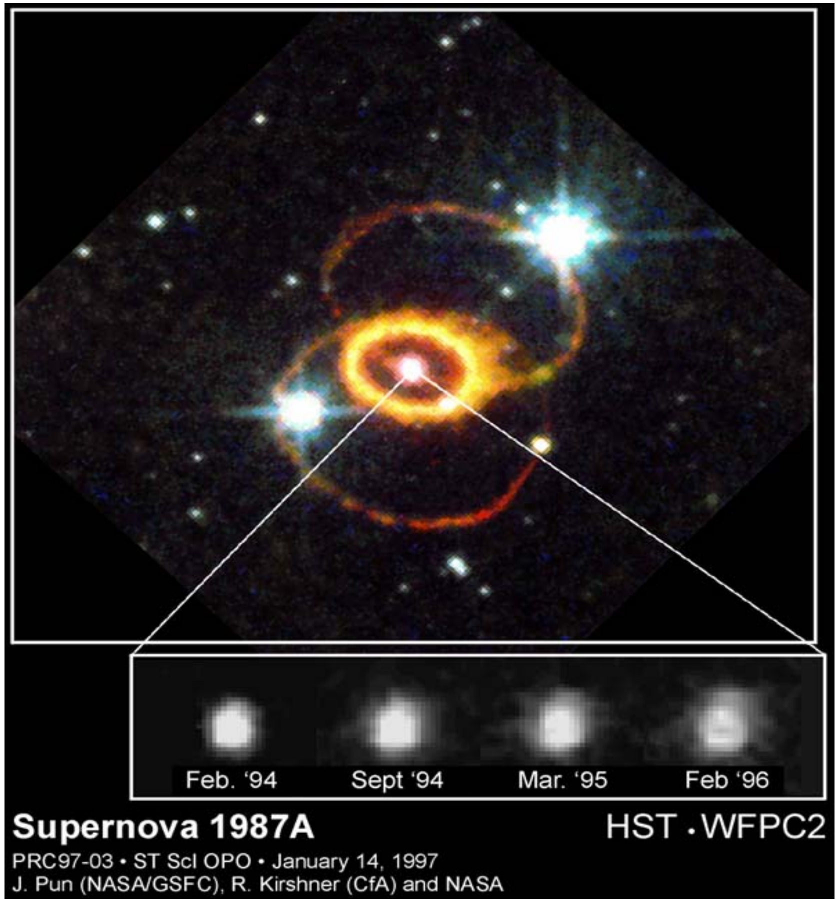


Non-Linear Scattering Instabilities



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 ~ 10^{51} erg •
• gravitational radiation < 1% •
• neutrinos 99 % •



¶ Electron density @ 100-300 km: $n_{e0} \sim 10^{29} - 10^{32}$ 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 $\Gamma \sim 0.01 - 0.1$

¶ ν_e luminosity @ neutrinosphere~ $10^{52} - 5\times10^{53}$ erg/s

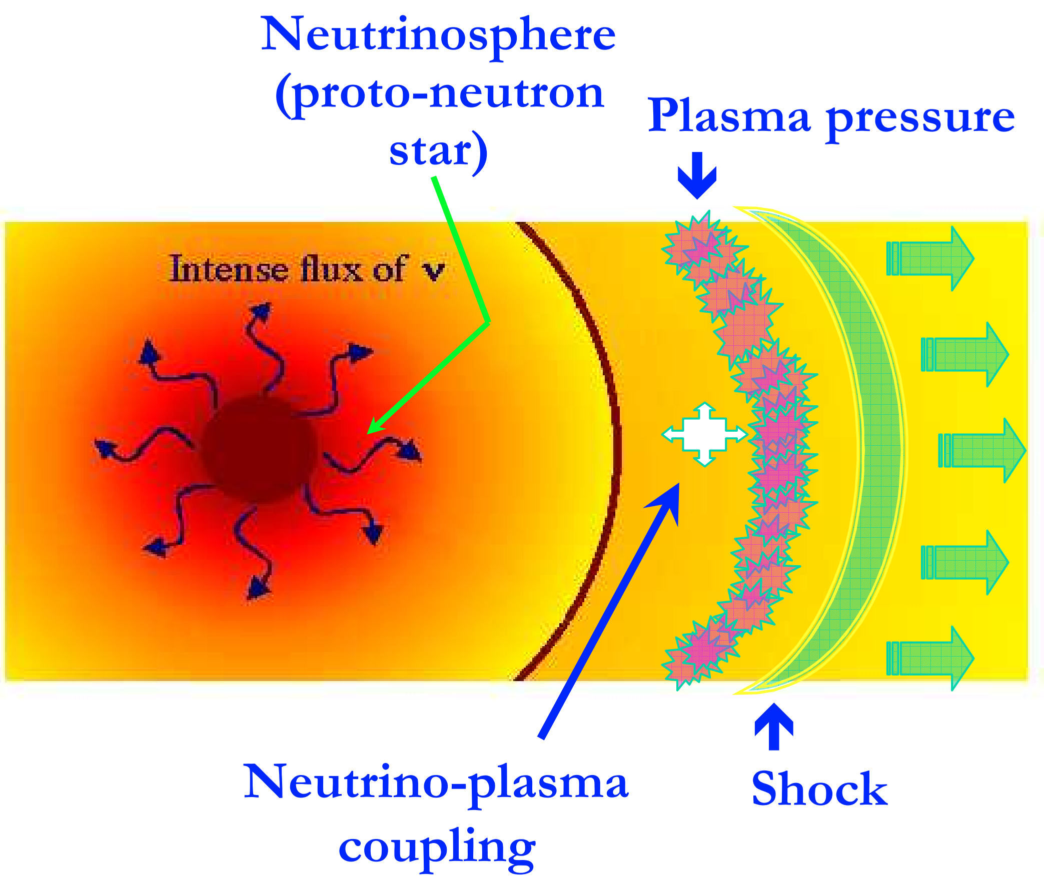
¶ ν_e intensity @ 100-300 Km ~ $10^{29} - 10^{30}$ W/cm^2

¶ Duration of intense ν_e burst ~ 5 ms
(resulting from $p+e\rightarrow n+\nu_e$)

¶ Duration of ν emission of all flavors ~ 1 - 10 s

Supernova Explosion

- **How to turn an implosion into an explosion**
  - New neutrino physics
  - λ_{mfp} for eν collisions ~ 10^{16} cm in collapsed star
  - λ_{mfp} for collective plasma-neutrino coupling ~ 100m
- **How?**
  - New non-linear force — neutrino ponderomotive force
  - For intense neutrino flux collective effects important
  - Absorbs 1% of neutrino energy
    ⇒ sufficient to explode star



Phys. Lett. A, 220, 107 (1996)

Phys. Rev. Lett., 88, 2703 (1999)

Neutrino dynamics in dense plasma

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

$$H_{eff} = \sqrt{\mathbf{p}_\nu^2 c^2 + m_\nu^2 c^4} + 2 G_F n_e(\mathrm{r}, t)$$

G_F - Fermi constant
n_e - electron density

¶ Effective potential due to **weak interaction** with background electrons
¶ Repulsive potential

$$\mathbf{F} = -\sqrt{2} G_F \nabla n_e(\mathrm{r}, t)$$

Force on a single neutrino due to electron density modulations

Neutrinos bunch in regions of lower electron density

$$\mathbf{F}_{pond} = -\sqrt{2} G_F \nabla n_\nu(\mathrm{r}, t)$$

Force on a single electron due to neutrino distribution

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

* ponderomotive force derived from semi-classical (L.O.Silva et al, ‘98) or quantum formalism (Semikoz, ‘87)

Neutrino Refractive Index

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_ν 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

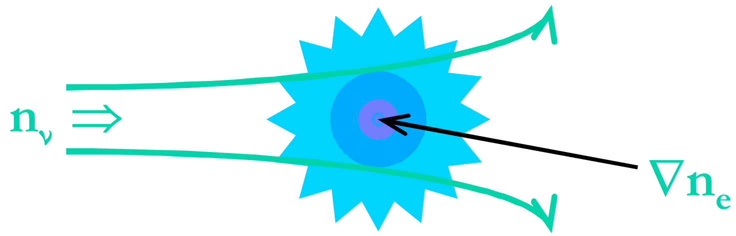
⇒ Refractive index $$N_\nu = \left(\frac{ck_\nu}{\omega_\nu}\right)^2 = \left(\frac{cp_\nu}{E_\nu}\right)^2$$

$$N_\nu \cong 1 - \frac{2\sqrt{2}G_F}{\hbar k_\nu c} n_e$$

Note: cut-off density $$n_{ec} > \frac{\varepsilon_\nu}{2\sqrt{2}G_F}$$

ε_ν neutrino energy

Electron neutrinos are refracted away from regions of dense plasma - similar to photons.



Neutrino Ponderomotive Force

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

$$F_{POND} = \frac{N-1}{2} \nabla \xi$$

[Landau & Lifshitz, 1960]

where ξ is the energy density of the neutrino beam.

$$N = 1 - \frac{2\sqrt{2}G_F}{\varepsilon_\nu} n_e \quad \Rightarrow \quad F_{Pond} = -\frac{\sqrt{2}G_F n_e}{\varepsilon_\nu} \nabla \xi$$

n_ν 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_{coll}

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

$\sigma_{\nu e}$ **is the neutrino-electron cross-section**

Total collisional force on all electrons is

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

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

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

For a 0.5 MeV plasma $\frac{F_{Pond}}{F_{coll}} \approx 10^{10}$

$\sigma_{\nu e} \Rightarrow$ 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)

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

Dispersion relation for electrostatic plasma waves

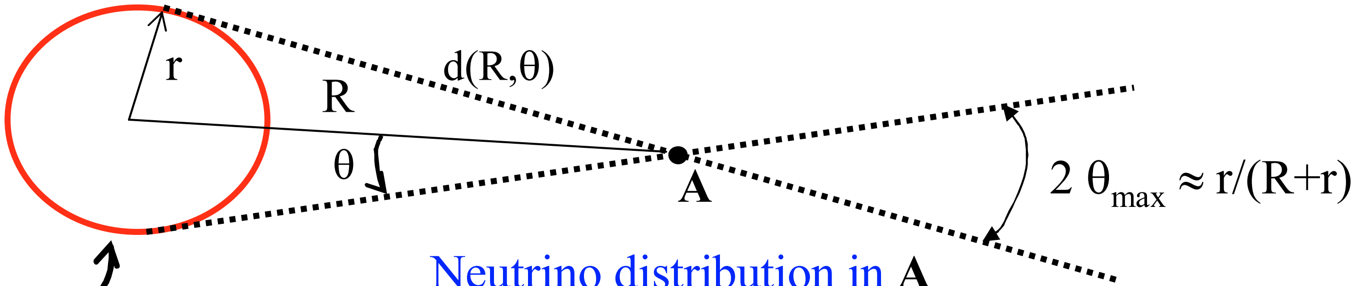
$$1 + \chi_e(\omega_L, \mathbf{k}_L) + \chi_\nu(\omega_L, \mathbf{k}_L) = 0$$

Electron susceptibility **Neutrino susceptibility**

$$\chi_\nu(\omega_L, \mathrm{k}_L) = -2G_F^2 \frac{k_L^3 n_{e0} n_{\nu 0}}{m_e \omega_{pe0}^2} \left(1 - \frac{\omega_L^2}{c^2 k_L^2} \right)^2 \chi_e \int d\mathbf{p}_\nu \frac{\mathbf{k}_L \cdot \frac{\partial \hat{f}_{\nu 0}}{\partial \mathbf{p}_\nu}}{\omega_L - \mathbf{k}_L \cdot \mathbf{v}_\nu}$$

Geometry of neutrino emission

Neutrino distribution in the neutrinosphere $\equiv$ $\mathbf{f_{\nu 0}\ (k_\nu)}$



Neutrinosphere

Neutrino distribution in **A**

$f_\nu\ (k_\nu,R,\theta)= f_{\nu 0}\ (k_\nu)/d^2(R,\theta)$

R>>r and $\theta_{max} \approx$ 30 mrad

for R>>r

$\mathbf{f(\theta)= const.\ |\theta|< \theta_{max}}$

$\mathbf{f(\theta)= 0\ |\theta|> \theta_{max}}$

Beamed distribution

Analysis in slab geometry gives good picture

$$\gamma_{max} \propto \left(\frac{\aleph}{1-\cos\theta_{max}} \right)^{1/2} \propto G_F$$

and $1/(1-\cos\theta_{max}) \approx 10^3$

Neutrino Beam-Plasma Instability

Monoenergetic neutrino beam

$$f_{\nu 0} = n_{\nu 0}\delta(\mathbf{p}_\nu - \mathbf{p}_{\nu 0})$$

Dispersion Relation

$$\omega_L^2 = \omega_{pe0}^2 + \left(\frac{m_\nu^2 c^4 \cos^2\theta}{E_{\nu 0}^2} + \sin^2\theta\right)\frac{\aleph k_L^4 c^4}{\left(\omega_L - k_L c\cos\theta \frac{p_{\nu 0} c}{E_{\nu 0}}\right)^2}$$

$\theta \equiv \mathbf{k}_L \wedge \mathbf{p}_{\nu 0}$

$$\aleph = \frac{2 G_F^2 n_{\nu 0} n_{e0}}{m_e c^2 E_{\nu 0}}$$

¶ If $m_\nu \rightarrow 0$ direct forward scattering is absent

¶ 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

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

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

Single ν-electron scattering $\propto$ $\mathbf{G_F^2}$

Collective plasma process much stronger than single particle processes

Neutrino Beam – de Broglie Wavelength

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

$$\chi_{\nu}(\omega_L, \mathrm{k}_L) \propto -\frac{n_{\nu 0}}{(\omega_L - k_L \cos\theta)^2} \underbrace{\int dp_{\nu x} \frac{\hat{f}_{\nu 0}}{|p_{\nu x}|}}_{=<\lambda_\nu>/2\pi\hbar}$$

From monoenergetic beam to arbitrary neutrino energy distribution

$$\frac{1}{E_{\nu 0}} = \frac{\lambda_{\nu 0}}{2\pi\hbar c} \rightarrow \frac{<\lambda_\nu>}{2\pi\hbar c}$$

$<\lambda_\nu>$ is the average de Broglie wavelength of neutrino distribution

For distributions with equal neutrino density $n_{\nu 0}$ and equal de Broglie wavelength $<\lambda_\nu>$, **growth rates are identical**

Role of electron-ion collisions in the instability (hydro)

BGK model of collisions ⇒ $$\chi_e(\omega_L,\mathbf{k}_L) = -\frac{\omega_{pe}^2}{\omega_L(\omega_L + i\nu_s)}$$

$\nu_s \approx \nu_{ei}$

Electron-ion collision frequency

New dispersion relation

$$\omega_L(\omega_L + i\nu_{ei}) = \omega_{pe0}^2 + \left(\frac{m_\nu^2 c^4 \cos^2\theta}{E_{\nu 0}^2} + \sin^2\theta\right)\frac{\aleph k_L^4 c^4}{\left(\omega_L - k_L c\cos\theta \frac{p_{\nu 0} c}{E_{\nu 0}}\right)^2}$$

Similar analysis as before leads to

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

(with collisions)

vs

$$\gamma_{\max} \propto G_F^{2/3}$$

(without collisions)

Instability threshold is $\propto G_F^2$

since it is proportional to **(Damping electrons) x (Damping neutrinos)**

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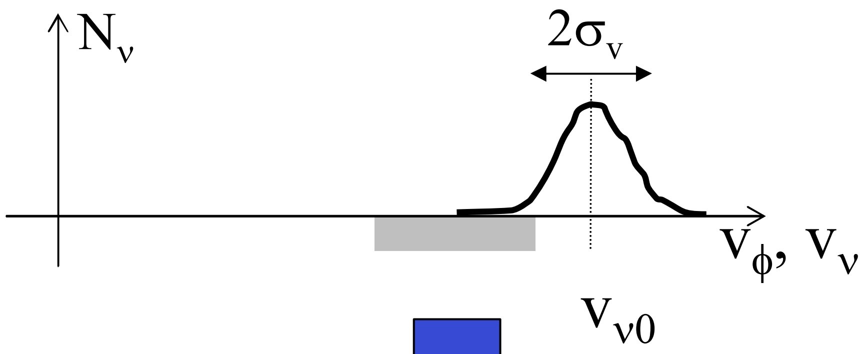
Instability regimes: hydrodynamic *vs* kinetic



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

Unstable PW modes (ω_L, k_L)

$N_{e0} = 10^{29}$ cm^{-3}	$\langle E_\nu \rangle$ =10 MeV
$L_\nu = 10^{52}$ erg/s	T_ν = 3 MeV
R_m = 300 Km	m_ν = 0.1 eV

$$\sigma_{v_\nu} / c \approx 10^{-16}$$

$$\left| \frac{\omega_L}{ck_L} - \frac{v_{\nu_0}}{c} \right| \approx \frac{\gamma_{max}}{\omega_{pe0}} \beta_\phi \approx 10^{-14} - 10^{-11}$$

Kinetic instability $\gamma \propto G_F^{\,2}$ **if** $\left| \frac{\omega_L}{k_L} - v_{\nu 0} \right| << \sigma_{v_\nu}$

Hydro instability $\gamma \propto G_F^{\,2/3}$ **if** $\left| \frac{\omega_L}{k_L} - v_{\nu 0} \right| >> \sigma_{v_\nu}$

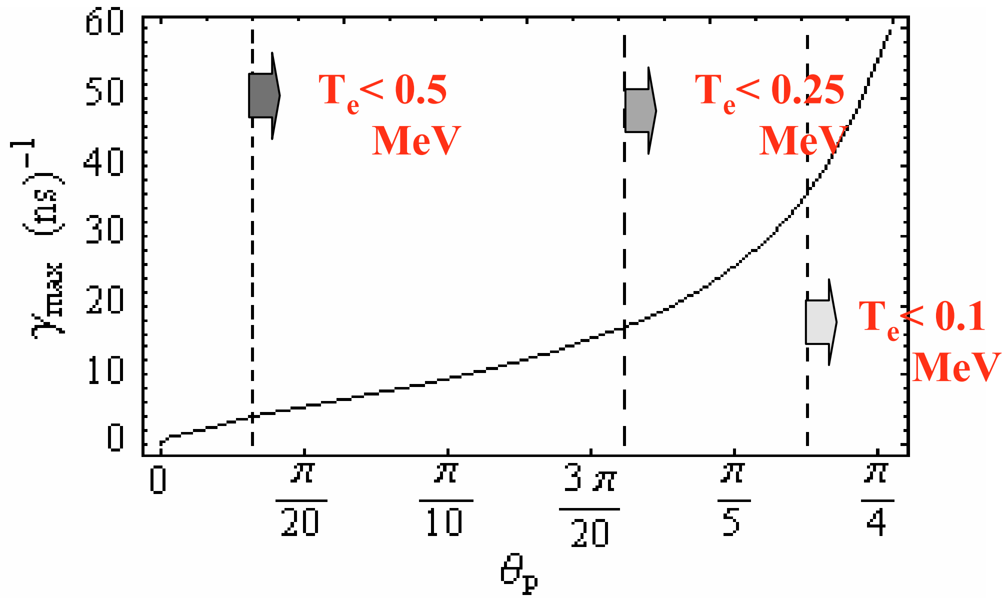
where $v_\nu = p_\nu c^2/E_\nu = p_\nu c^2/(p_\nu^2 c^2 + m_\nu^2 c^4)^{1/2}$

\- for $m_\nu \to 0$, $\sigma \to 0$ **hydro regime** -

Estimates of the Instability Growth Rates

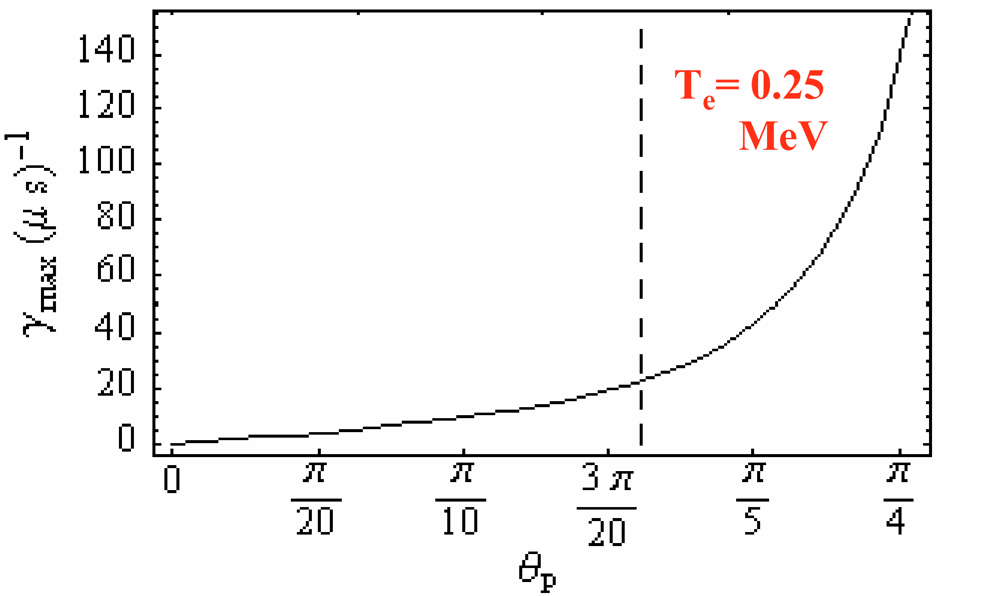
n_{e0}=10^{29} cm^{-3}
L_ν = 10^{52} erg/s
R_m = 300 Km
<E_ν>=10 MeV

Growth distance ~ 1 m
(without collisions)



Growth distance ~ 300 m
(with collisions)

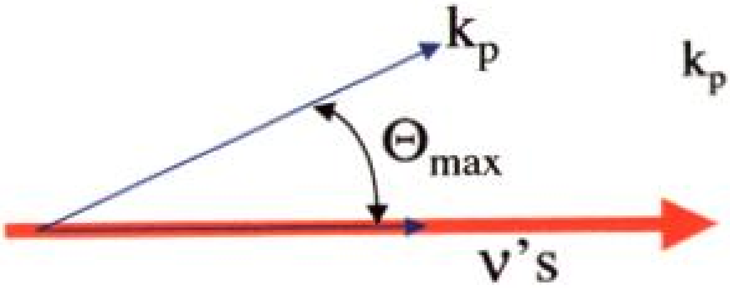
- 6 km for 20 e-foldings -



Mean free path for
neutrino electron single scattering ~
10^{11} km

Saturation Mechanism

Neutrino streaming instability saturates by electron Landau damping



$k_p \sim \omega_{pe0}/c \cos\Theta$ $\Theta_{max} \sim \mathrm{arcos}(v_{th}/c)$

$T_e \uparrow \Rightarrow \Theta_{max} \downarrow \Rightarrow$ Instability Shutdown

Simplified Model

Modes with
maximum growth rate

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

$$\frac{\partial |\mathbf{E}_k|^2}{\partial t} = 2\gamma_k |\mathbf{E}_k|^2$$

$\gamma_k = 0$ if $k > k_{max}$

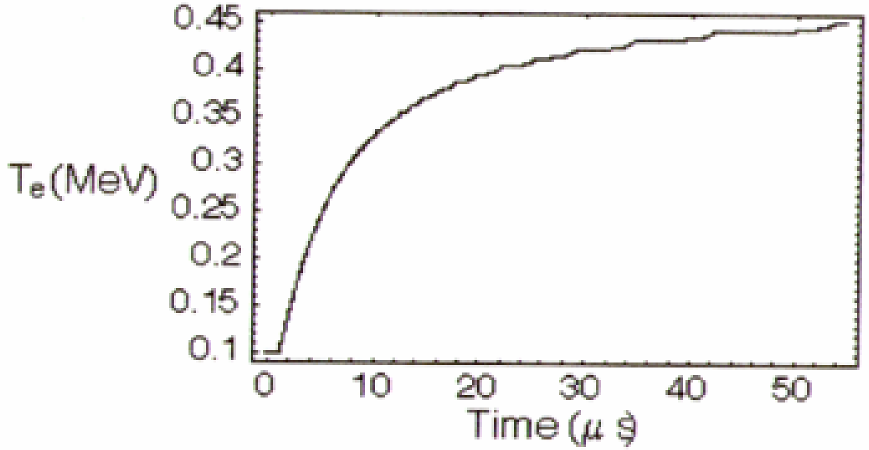
$$\frac{\partial W_{EPW}}{\partial t} = n_e \frac{\partial T_e}{\partial t} = \frac{1}{8\pi}\frac{\partial}{\partial t}\sum_{k \le k_{max}} |\mathbf{E}_k|^2$$

$k_{max} = \omega_{pe0}/v_{th}(T_e)$

Preliminary Results

$n_{e0}=10^{29}$ cm^{-3}
$L_\nu = 10^{52}$ erg/s
R_m = 300 Km
$\langle E_\nu \rangle$=10 MeV
T_{e0} = 0.1 MeV

including e-i collisions



$\Delta W_{EPW} \sim 10^{-4} W_\nu$

- 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 ν_e burst (~ ms) can heat the plasma efficiently;
- Detailed quasi-linear theory for ν's and e's will give signatures of ν-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:-

$$\frac{\partial f_\nu}{\partial t} + \underline{\mathrm{v}}_\nu \frac{\partial f_\nu}{\partial \underline{r}} + \underline{F}_\nu \frac{\partial f_\nu}{\partial \underline{p}_\nu} = 0 \qquad \frac{\partial f_e}{\partial t} + \mathrm{v}_e \frac{\partial f_e}{\partial \underline{r}} + \underline{\mathrm{F}}_e \frac{\partial f_e}{\partial \underline{p}_e} = 0$$

where

$$\underline{F}_\nu = -\sqrt{2} G_F \left(\underline{\nabla} n_e + \frac{1}{c^2}\frac{\partial J_e}{\partial t} - \frac{1}{c^2} \mathrm{v}_\nu \times \nabla \times J_e \right)$$

$$\underline{F}_e = -e\left(\underline{E} + \underline{\mathrm{v}}_e \times \underline{B}\right) - \sqrt{2} G_F \left(\nabla n_\nu + \frac{1}{c^2}\frac{\partial J_\nu}{\partial t} - \frac{\mathrm{v}_e}{\mathrm{c}^2} \times \nabla \times J_\nu \right)$$

note that we can introduce the boson fields E_ν and B_ν given by

$$E_\nu = -\underline{\nabla} n_e - \frac{1}{c^2}\frac{\partial J_e}{\partial t} \qquad B_\nu = \underline{\nabla} \times \underline{J}_e$$

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

$$\varepsilon_t + \chi_\nu = 0$$

where

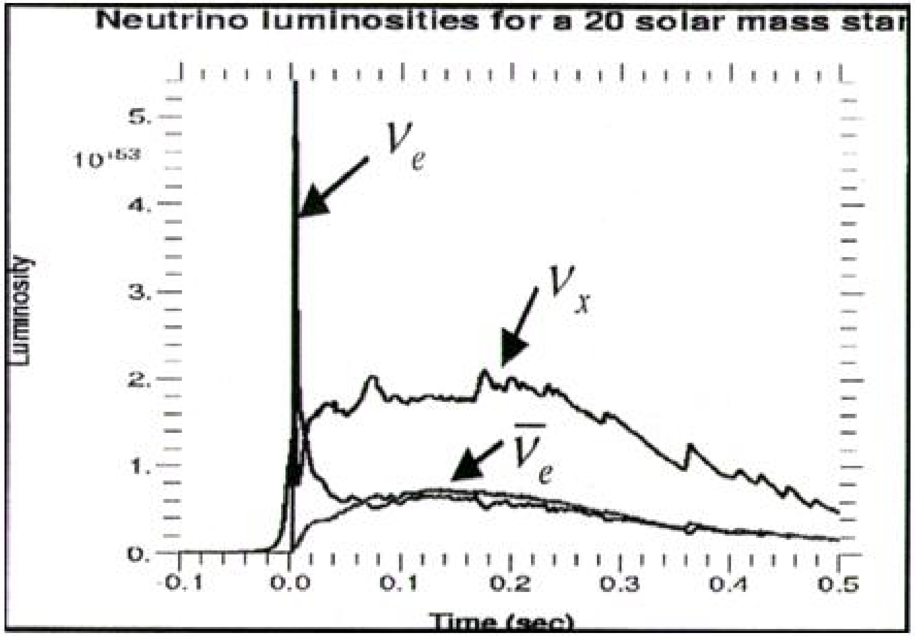
$$\chi_\nu = -2 G_F^2 A k_t \frac{n_{e0} n_{\nu 0}}{m_e \omega_{pe0}^2} \left(1 - \frac{\omega^2}{c^2 k^2} \right) \chi_e \int \frac{d\,\underline{p}_\nu k \frac{\partial f_{\nu 0}}{\partial p_\nu}}{\omega - \underline{k} \cdot \mathrm{v}_\nu}$$

$$A = 2\frac{\omega_p^2}{\omega}\left(\frac{\partial}{\partial \omega}\omega^2 \varepsilon^t\right)^{-1}$$

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 $5x10^{53}$ 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.

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Supernovæ explosions & neutrino driven instabilities

e-Neutrino burst

$L_\nu \sim 4\times10^{53}$ erg/s , $\tau \sim 5$ ms

Neutrino emission of all flavors

$L_\nu \sim 10^{52}$ erg/s , $\tau \sim 1$ s

drives plasma waves through neutrino streaming instability

plasma waves are damped (collisional damping)

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

Plasma heating

@ 100-300 km from center

Stimulated "Compton" scattering

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

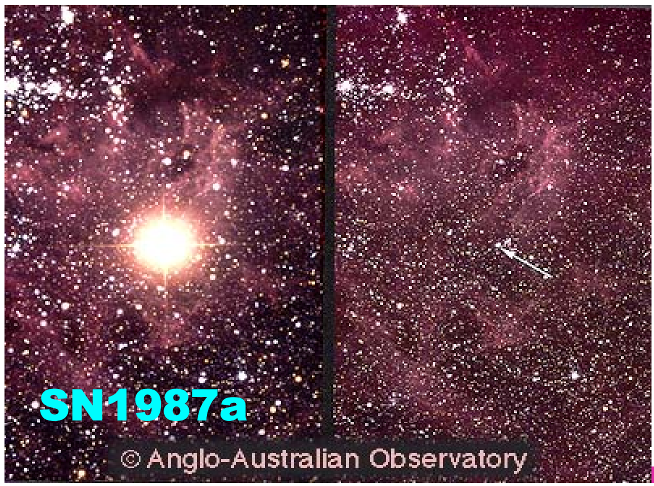
Less energy lost by shock to dissociate iron

Anomalous pressure increase behind shock

Revival of stalled shock in supernova explosion

(similar to Wilson mechanism)

Supernova Explosion!



Neutrino play a critical role in Type II (Ib, Ic) Supernovæ

- 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.

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Neutrino Landau Damping

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

- EPW wavevector $\mathbf{k}_L = \mathbf{k}_{L\|}$ defines parallel direction
- neutrino momentum $\mathbf{p}_\nu = \mathbf{p}_{\nu\|} + \mathbf{p}_{n\perp}$
- arbitrary neutrino distribution function $f_{\nu 0}$
- Landau's prescription in the evaluation of χ_ν

$$\chi_\nu(\omega_L, k_L) \propto \int d\mathbf{p}_\nu \frac{\mathbf{k}_L \cdot \frac{\partial \hat{f}_{\nu 0}}{\partial \mathbf{p}_\nu}}{\omega_L - \mathbf{k}_L \cdot \mathbf{v}_\nu}$$

$$k_L \int d\mathbf{p}_\perp \frac{|\mathbf{p}_\perp|}{c\left(1 - \frac{\omega_L^2}{c^2 k_L^2}\right)^{3/2}} \left\{ P \int \frac{\frac{\partial \hat{f}_{\nu 0}}{\partial \mathbf{p}_\|}}{\mathbf{p}_\| - \mathbf{p}_{\|0}} d\mathbf{p}_\| + i\pi \left(\frac{\partial \hat{f}_{\nu 0}}{\partial \mathbf{p}_\|}\right)_{\mathbf{p}_{\|0}} \right\}$$

Contribution from the pole

For a Fermi-Dirac neutrino distribution

$$\gamma_{\text{Landau}} \approx -\frac{k_L c}{2} \pi \frac{G_F^2 n_{e0} n_{\nu 0}}{m_e c^2 k_B T_\nu} \frac{\text{Li}_2(-\exp E_F / T_\nu)}{\text{Li}_3(-\exp E_F / T_\nu)}$$

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

for typical parameters

Neutrino Landau damping leads to damping of EPWs by energy transfer to the neutrinos

Important for the neutron star cooling process

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Plasma cooling by Neutrino Landau damping

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} - energy loss rate
$$Q_{EPW} = \int \frac{d\mathbf{k}}{(2\pi)^3} \gamma_{\nu Landau}(\mathbf{k}) W_{EPW}$$

W_{epw} - spectral energy density of EPWs - Bose distribution

$$Q_{EPW} = -\frac{3\pi}{4} \frac{W_{EPW}}{k_D^3} c \left(\frac{\omega_{pe0}}{c}\right)^4 \frac{G_F^2 n_{e0} n_{\nu 0}}{m_e c^2 E_{\nu 0}} \frac{Li_2(-\exp\mu/T)}{Li_3(-\exp\mu/T)} \left(\frac{3}{4} + \frac{1}{4\beta_{th}^4} - \frac{1}{\beta_{th}^2} - \ln\beta_{th}\right)$$

β_{th} - typical thermal velocity
$2\pi/k_d$ - Debye Length

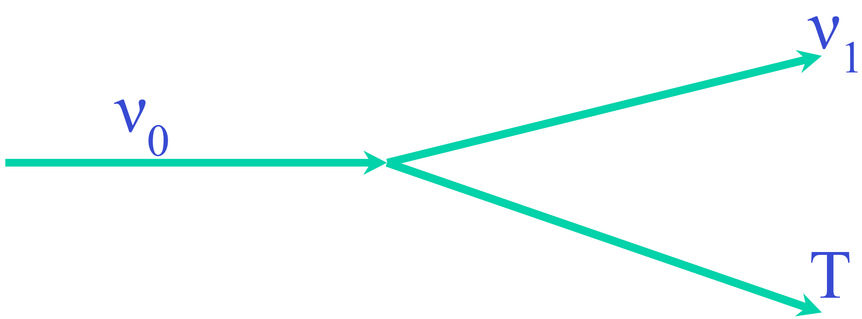
Dependence on neutrino distribution

Scaling with $\mathbf{G_F^2\, n_e^{5/2}\, n_\nu\, T_\nu^{-1}\, T_e^{5/2}}$

Stronger than mechanism proposed by Tsytovich (1961)
For a broad range of parameters more important than usual plasma cooling process

Coupling to Transverse Plasmas

1) Neutrino beam plasma instability can result in photon production.



In supernovæ the frequency of the photons is in the MeV energy range - *i.e.* γ-rays.

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

γ-Ray Bursts (GRBs)

A few percent of the neutrino energy must be converted to γ-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 γ-rays in supernova plasmas

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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 ν 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

Motivation

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} W/cm^2 and luminosities up to 10^{52} erg/s

Neutrinos in the Standard Model

Leptons	Electron e Electron neutrino ν_e	Muon μ Muon neutrino ν_μ	Tau τ Tau neutrino ν_τ

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

Length scales

← Compton Scale
HEP

Hydro Scale →
Shocks

Plasma scale

λ_D, λ_p, r_L

>> 14 orders of magnitude

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 ν flavor

Equivalent to mode conversion of waves in inhomogeneous plasmas

$$\frac{d^2\psi_i}{dx^2} + k_i^2\psi_i = 0 \qquad k_i^2 = \frac{E_i^2 - m_i^2 c^4 - V_{eff\ i}}{c^2\hbar^2}$$

i = 1, 2, 3 (each ν flavor)

Mode conversion when $k_1 = k_2$, $E_1 = E_2$

$$\frac{d^2\psi_1}{dx^2} + k_1^2\psi_1 = \lambda_1\psi_2$$

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

$$\lambda_i = \frac{1}{2}\frac{\Delta m^2 c}{\hbar^2}\frac{E_i}{p_i}\sin 2\theta$$

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 ν-e interaction Lagrangian

$$L_{\text{int}} = -\frac{G_F}{\sqrt{2}}(1 + C_V)(n_e - \mathbf{J}_e \cdot \mathbf{v}_\nu)$$

Semi-classical ν Hamiltonian

$$H_{eff} = \sqrt{\left(\mathbf{P}_\nu - \sqrt{2}G_F \frac{\mathbf{J}_e(\mathrm{r}, t)}{c^2}\right)^2 c^2 + m_\nu^2 c^4} + \sqrt{2}G_F n_e(\mathrm{r}, t)$$

$$\mathbf{P}_\nu = \mathbf{p}_\nu + \sqrt{2}G_F \frac{\mathbf{J}_e(\mathbf{r}, t)}{c^2}$$ ► **Neutrino Canonical Momentum**

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

- ν Charge $\sqrt{2}G_F$
- 4-Potential $\left(n_e, \frac{\mathbf{J}_e}{c}\right)$

► **Lorentz Gauge**

$$\nabla \cdot \frac{\mathbf{J}_e(\mathrm{r}, t)}{c} + \frac{1}{c}\frac{\partial n_e}{\partial t} = 0$$

Neutrino Dynamics in a Dense Plasma

Equations of motion

$$\mathbf{v}_\nu = \frac{d\mathbf{r}_\nu}{dt} = \frac{\mathbf{p}_\nu c^2}{\sqrt{\mathbf{p}_\nu^2 c^2 + m_\nu^2 c^4}}$$

Neutrinos bunch in regions of lower electron density

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

Equivalent equations of motion for electrons

$$\mathbf{v}_e = \frac{d\mathbf{r}_e}{dt} = \frac{\mathbf{p}_e c^2}{\sqrt{\mathbf{p}_e^2 c^2 + m_e^2 c^4}}$$

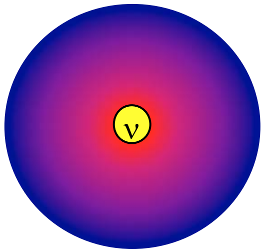
Ponderomotive force due to neutrinos

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

(Silva et al, PRE 1998, PRD 1998)

Neutrino Effective Charge in a Plasma

Neutrino repels nearby electrons - Dressed neutrino with equivalent charge



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

Fourier Transform + electrostatic waves

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

neutrino induced *charge*

$$e_\nu(\omega,\mathbf{k}) = -\frac{\sqrt{2}G_F\mathbf{k}^2}{4\pi e}\left(1-\frac{\omega^2}{k^2c^2}\right) \approx -\frac{\sqrt{2}\,G_F\mathbf{k}_D^2}{4\,\pi e} = -\frac{\sqrt{8}\,\pi e}{k_BT_e}G_F n_{e0}$$

(Nieves and Pal, '94)

(Mendonca et al, PLA 1997)

Kinetic equation for neutrinos

(describing neutrino number density conservation / collisionless neutrinos)

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

Kinetic equation for electrons driven by neutrino pond. force

(collisionless plasma)

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

+

Maxwell's Equations

(Silva et al, ApJ SS 1999)

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 ν's

Usual perturbation theory over kinetic equations + Poisson's equation

$$n_e = n_0 + n_{e1} \qquad f_e = f_{e0}(\mathbf{p}_e) + f_{e1}$$

$$\mathbf{v}_e = \mathbf{v}_1 \qquad f_\nu = f_{\nu 0}(\mathbf{p}_\nu) + f_{\nu 1}$$

$$\mathbf{v}_\nu = \mathbf{v}_{\nu 0} + \mathbf{v}_{\nu 1} \qquad \mathbf{E} = \mathbf{E}_1$$

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

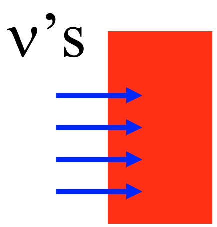
$$\chi_\nu(\omega_L, \mathrm{k}_L) = -2\, G_F^2 \frac{k_L^3 n_{e0} n_{\nu 0}}{m_e \omega_{pe0}^2} \left(1 - \frac{\omega_L^2}{c^2 k_L^2}\right)^2 \chi_e \int d\mathbf{p}_\nu \frac{\mathbf{k}_L \cdot \dfrac{\partial \hat{f}_{\nu 0}}{\partial \mathbf{p}_\nu}}{\omega_L - \mathbf{k}_L \cdot \mathbf{v}_\nu}$$

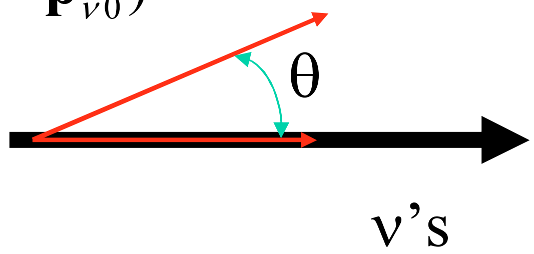
(Silva et al, PRL 1999)

Neutrino beam-plasma instability

Monoenergetic neutrino beam & slab geometry & cold plasma

$$f_{\nu 0} = n_{\nu 0}\delta(\mathbf{p}_\nu - \mathbf{p}_{\nu 0})$$





Dispersion Relation

$$\frac{\omega_L^2}{\omega_{pe0}^2} = 1 + \frac{\Delta_\nu k_L^4 c^4}{\omega_{pe0}^2} \frac{1}{\left(\omega_L - k_L c\cos\theta \dfrac{p_{\nu 0} c}{E_{\nu 0}}\right)^2} \left(\frac{m_\nu^2 c^4 \cos^2\theta}{E_{\nu 0}^2} + \sin^2\theta\right) \qquad \theta \equiv \mathbf{k}_L \wedge \mathbf{p}_{\nu 0}$$

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

Strong supression factor in Δ_ν for EPWs with $v_\phi \approx c$

$$\Delta_\nu = \frac{2G_F^2 n_{\nu 0} n_{e0}}{m_e c^2 E_{\nu 0}} \left(1 - \frac{\omega_L^2}{c^2 k_L^2}\right)^2$$

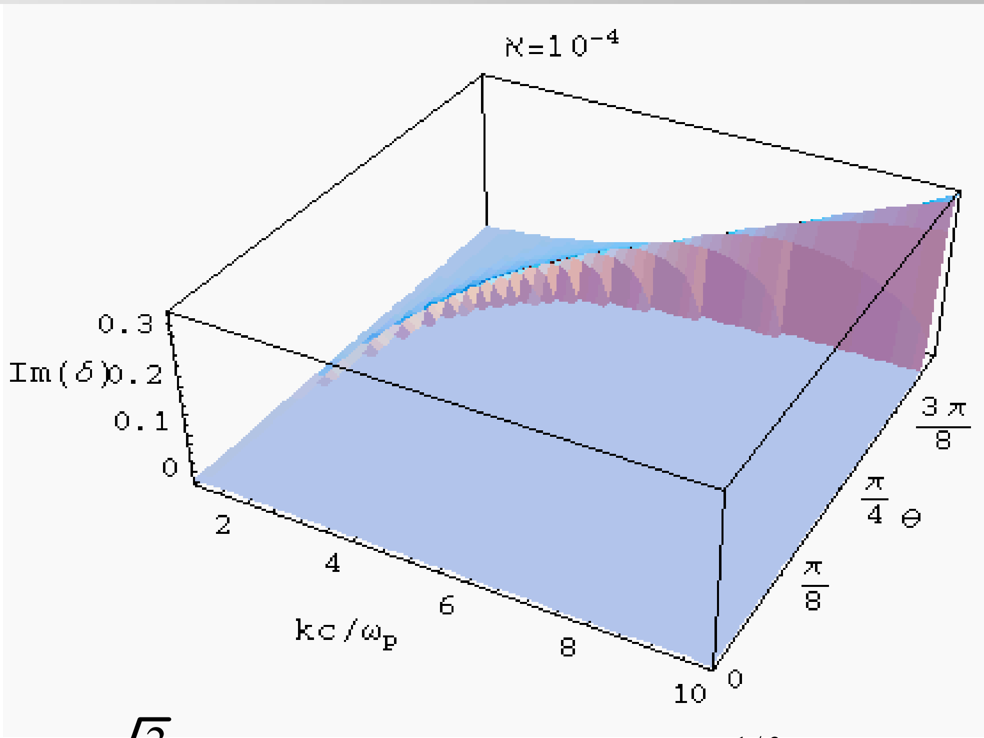
Instability analysis

Similar analysis as for two-stream instability:

maximum growth rate @

$$\mathbf{k_L\, v_{\nu 0\|} = k\, c\, \cos\theta \approx \omega_{pe0}}$$

- $\omega = \omega_{pe0} + \delta = k_L\, v_{\nu 0\|} + \delta$



Weak Beam $(\delta/\ \omega_{pe0} \ll 1)$ $\gamma_{\max} = \frac{\sqrt{3}}{2}\omega_{pe0}\left(\Delta_\nu (\sin\theta)^2(\tan\theta)^4\right)^{1/3} \propto G_F^{2/3}$

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

Single ν**-electron scattering** $\propto \mathbf{G_F^2}$

Collective mechanism much stronger than single particle processes

Supernovae II

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To form a neutron star > 3 × 10^{53} erg must be released

(gravitational binding energy of the original star)

• light+kinetic energy ~ 10^{51} erg •

• gravitational radiation < 1% •

• neutrinos 99 % •

¶ Electron density @ 100-300 km: n_{e0} ~ 10^{29} - 10^{32} cm^{-3}

¶ Electron temperature @ 100-300 km: T_e ~ 0.1 - 0.5 MeV

¶ Degeneracy parameter $\Theta = T_e/E_F$ ~ 0.5 - 0.7

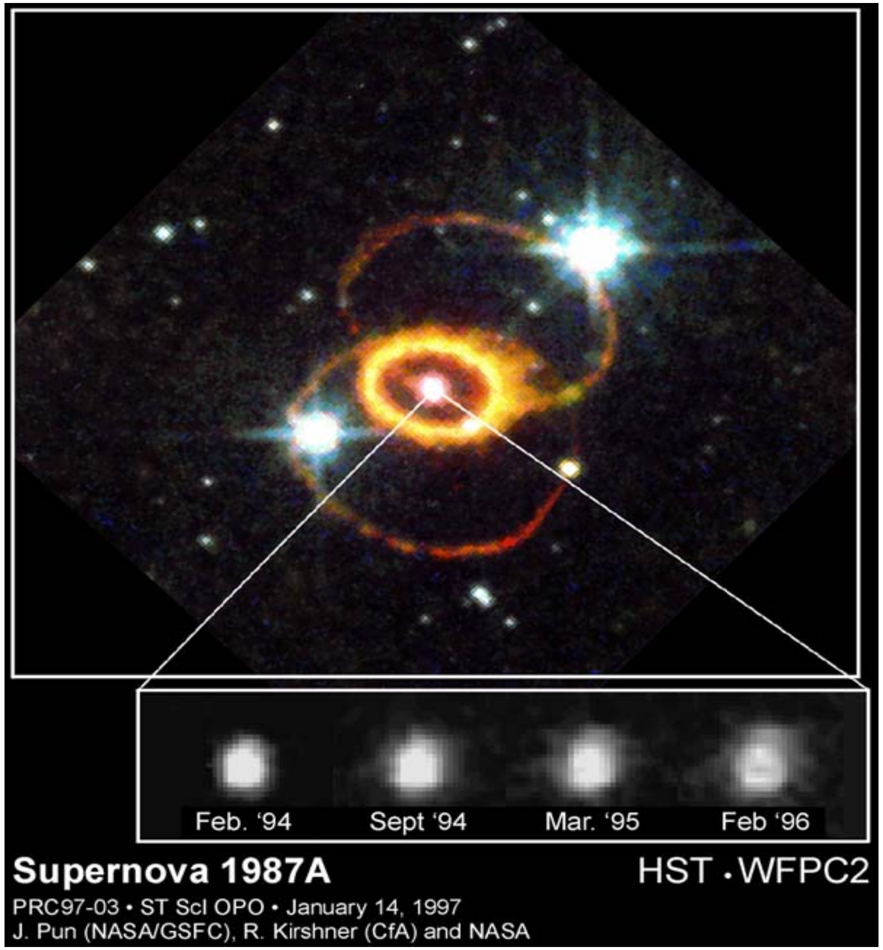
¶ Coulomb coupling constant Γ ~ 0.01 - 0.1

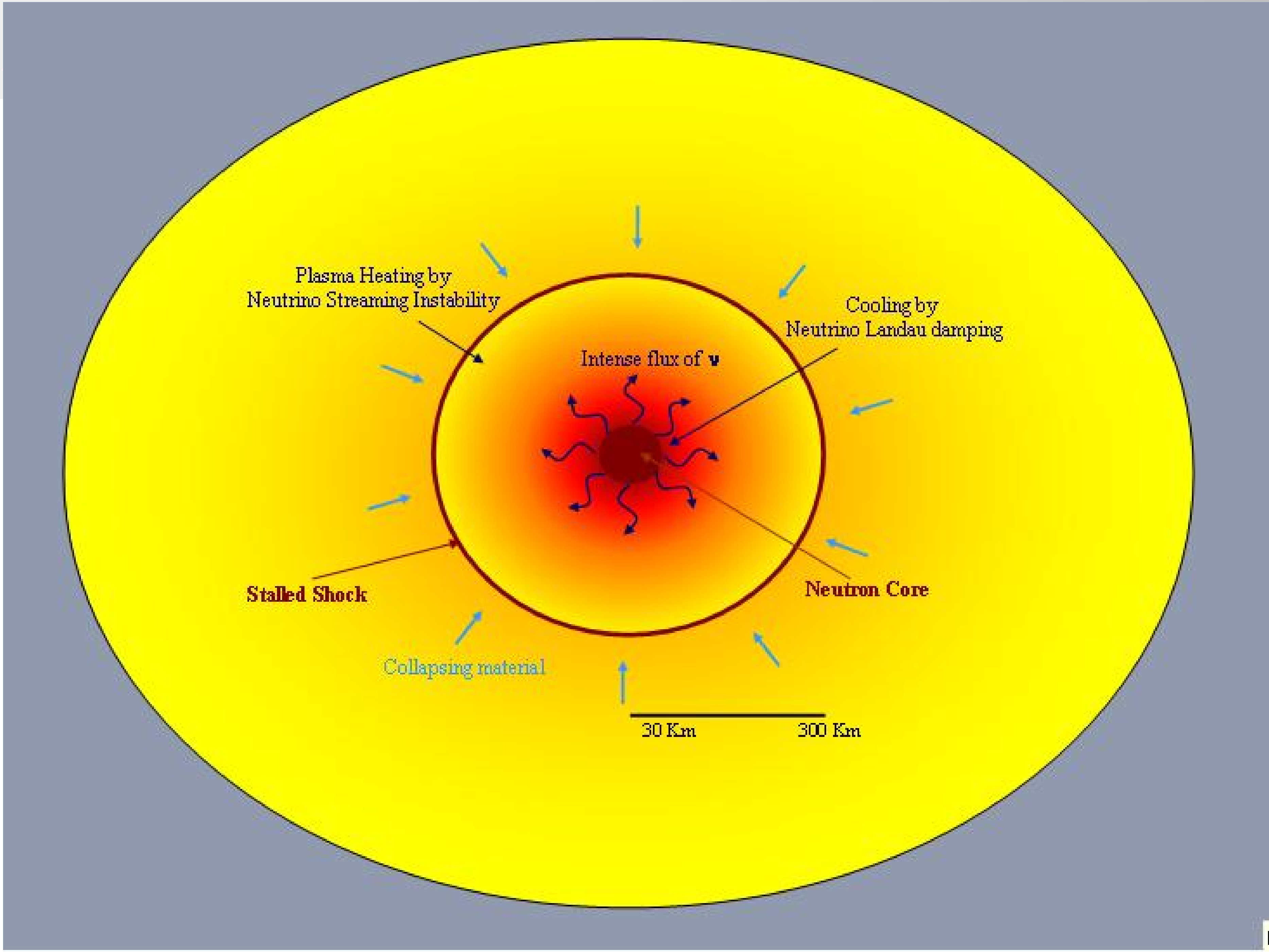
¶ ν_e luminosity @ neutrinosphere ~ 10^{52} - 5×10^{53} erg/s

¶ ν_e intensity @ 100-300 Km ~ 10^{29} - 10^{30} W/cm^2

¶ Duration of intense ν_e burst ~ 5 ms
(resulting from $p + e \rightarrow n + \nu_e$)

¶ Duration of ν emission of all flavors ~ 1 - 10 s





Plasma Heating by
Neutrino Streaming Instability
Cooling by
Neutrino Landau damping
Intense flux of ν
Stalled Shock
Neutron Core
Collapsing material
30 Km
300 Km

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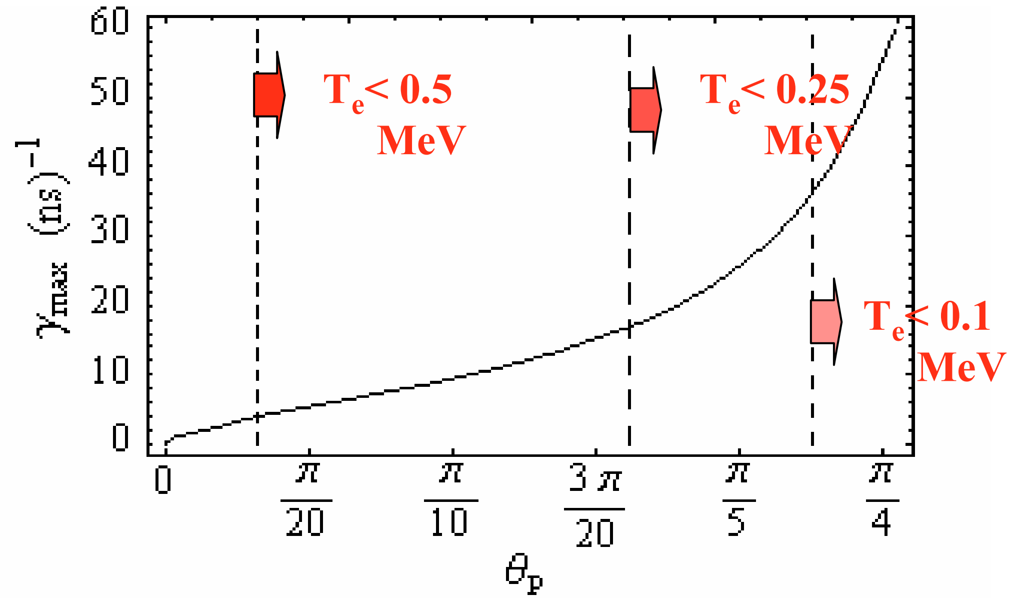
Estimates of the Instability Growth Rates

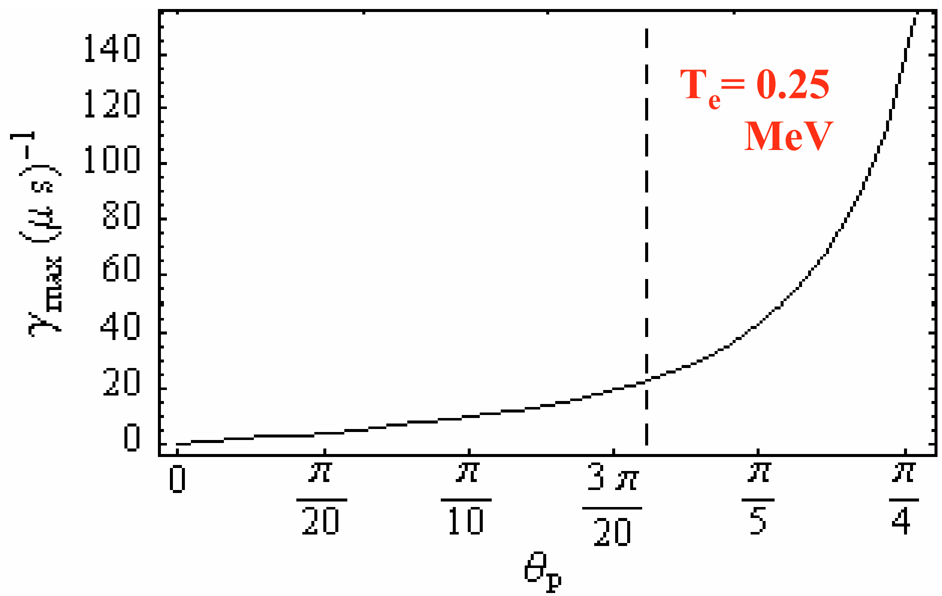
n_{e0} = 10^{29} cm^{-3}
L_ν = 10^{52} erg/s
R_m = 300 Km
$\langle E_\nu \rangle$ = 10 MeV

Growth distance ~ 1 m
(without collisions)



Growth distance ~ 300 m
(with collisions)

- 6 km for 20 e-foldings -



Mean free path for
neutrino electron single scattering ~
10^{11} km

Anomalous heating by neutrino streaming instability

$$\left(\frac{\Delta E_\nu}{10^{50}\,\mathrm{erg}}\right) \approx 1.2\times 10^{-1} \left(\frac{R}{500\,\mathrm{Km}}\right)^3 \left(\frac{T}{2\mathrm{MeV}}\right)\times$$

$$\left\{ 0.145\left(\frac{n}{10^{30}\,\mathrm{cm}^{-3}}\right) + \left(\frac{T}{2\mathrm{MeV}}\right)^3 \right\}$$

Neutrino heating to re-energize stalled shock

$$\left(\frac{\Delta E_\nu}{10^{50}\,\mathrm{erg}}\right) \approx 1 - 0.1$$

(Silva et al, PoP 2000)

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Supernovæ explosions & neutrino driven instabilities

e-Neutrino burst

$L_\nu \sim 4\times10^{53}$ erg/s , $\tau \sim 5$ ms

Neutrino emission of all flavors

$L_\nu \sim 10^{52}$ erg/s , $\tau \sim 1$ s

drives plasma waves through neutrino streaming instability

plasma waves are damped (collisional damping)

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

Plasma heating

@ 100-300 km from center

Stimulated "Compton" scattering

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

Less energy lost by shock to dissociate iron

Anomalous pressure increase behind shock

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

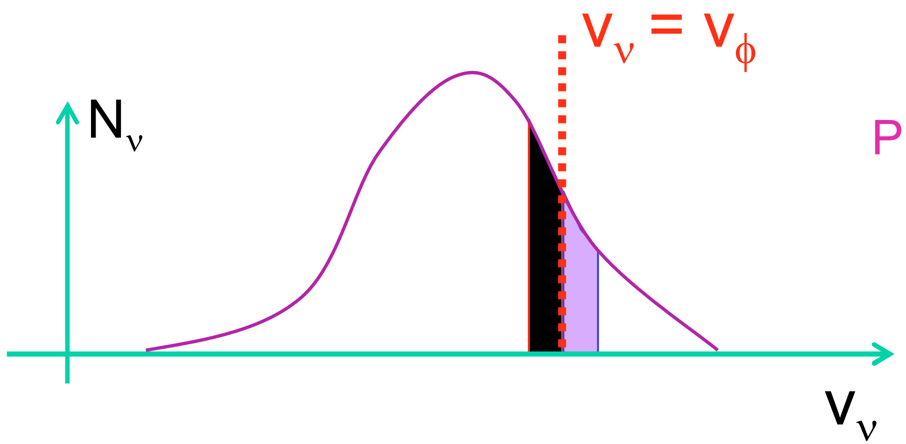
Supernova Explosion!

Neutrino Landau Damping I

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



Physical picture for electron Landau damping (Dawson, '61)

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

(Silva et al, PLA 2000)

Neutrino Landau damping II

Neutrino Landau damping reflects contribution from the pole in neutrino susceptibility

$$\chi_\nu(\omega_L, \mathrm{k}_L) \propto \int d\mathbf{p}_\nu \frac{\mathbf{k}_L \cdot \left(\partial \hat{f}_{\nu 0} / \partial \mathbf{p}_\nu\right)}{\omega_L - \mathbf{k}_L \cdot \mathbf{v}_\nu} \longrightarrow \int d\mathbf{p}_\perp \, |\mathbf{p}_\perp| \left\{ P \int \frac{\left(\partial \hat{f}_{\nu 0} / \partial \mathbf{p}_\parallel\right)}{\mathbf{p}_\parallel - \mathbf{p}_{\parallel 0}} d\mathbf{p}_\parallel + i\pi \left(\frac{\partial \hat{f}_{\nu 0}}{\partial \mathbf{p}_\parallel} \right)_{\mathbf{p}_{\parallel 0}} \right\}$$

EPW wavevector $\mathbf{k}_L = \mathbf{k}_{L||}$ defines parallel direction
neutrino momentum $\mathbf{p}_n = \mathbf{p}_{\nu||} + \mathbf{p}_{\nu\perp}$
arbitrary neutrino distribution function $f_{\nu 0}$
Landau's prescription in the evaluation of χ_ν

For a Fermi-Dirac neutrino distribution

$$\gamma_{\mathrm{Landau}} \approx -\frac{k_L c}{2} \pi \frac{G_F^2 n_{e0} n_{\nu 0}}{m_e c^2 k_B T_\nu} \left(1 - \frac{\omega_L^2}{c^2 k_L^2}\right)^2 \frac{\mathrm{Li}_2(-\exp E_F / T_\nu)}{\mathrm{Li}_3(-\exp E_F / T_\nu)}$$

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} energy loss rate - $$Q_{EPW} = \int \frac{d\mathbf{k}}{(2\pi)^3} \gamma_{\nu Landau}(\mathbf{k}) W_{EPW}$$

W_{epw} - spectral energy density of EPWs - Bose distribution

$$Q_{EPW} = -\frac{3\pi}{4} \frac{W_{EPW}}{k_D^3} c \left(\frac{\omega_{pe0}}{c} \right)^4 \frac{G_F^2 n_{e0} n_{\nu 0}}{m_e c^2 E_{\nu 0}} \frac{Li_2(-\exp \mu / T)}{Li_3(-\exp \mu / T)} \left(\frac{3}{4} + \frac{1}{4\beta_{th}^4} - \frac{1}{\beta_{th}^2} - \ln \beta_{th} \right)$$

β_{th} - typical thermal velocity
$2\pi/k_d$ - Debye Length

Typical turbulence cooling times ≈ 10^{-4} Gyr
Neutron star cooling time scale ≈ 1-10 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

Electroweak Weibel Instability

Usual perturbation theory over kinetic equations + Faraday's and Ampere's law

Cold plasma

$$\left(\omega^2 - k^2c^2\right)\left(1 - \omega\Delta_\nu \phi\left(\hat{f}_{\nu 0}\right)\right) = \omega_{pe0}^2 \qquad \mathbf{k} = k\mathbf{e}_z$$

$$\phi\left(\hat{f}_{\nu 0}\right) = \int d\mathbf{p}_\nu \frac{v_{\nu\perp}}{\omega - kv_{\nu z}} \cos^2\theta \left\{ \frac{\partial \hat{f}_{\nu 0}}{\partial p_{\nu\perp}} + \frac{k}{\omega} v_{\nu\perp} \frac{\partial \hat{f}_{\nu 0}}{\partial p_{\nu z}} - \frac{k}{\omega} v_{\nu z} \frac{\partial \hat{f}_{\nu 0}}{\partial p_{\nu\perp}} \right\}$$

Monoenergetic ν beam (m_ν = 0)

$$\hat{f}_{\nu 0} = \hat{f}_{\nu 0}\left(\mathbf{p}_{\nu\perp}, p_{\nu z}\right)$$

$$\left(\omega^2 - k^2c^2\right)\left(1 + \Delta_\nu \frac{k^2c^2}{\omega^2}\beta_{\nu x0}^2\right) = \omega_{pe0}^2 \qquad \omega \approx i\gamma_{\mathbf{Weibel}} \;\; \& \;\; \left|\gamma_{\mathbf{Weibel}}\right| << |k|$$

$$\gamma_{\mathbf{Weibel}} = \beta_{\nu x0} \frac{k^2c^2}{\sqrt{k^2c^2 + \omega_{pe0}^2}} \Delta_\nu^{1/2} \quad \propto \quad \mathbf{G}_{\mathbf{F}}$$

(Silva et al, PFCF 2000)

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Gamma Ray Bursters

- Short intense bursts of a few MeV γ-rays with x-ray to IR afterglow
- Total energy 10^{51}-10^{54} erg (with beaming of radiation ↓)
- Nonthermal GRB spectrum
- Duration a fraction of *s* to 100's of *s*

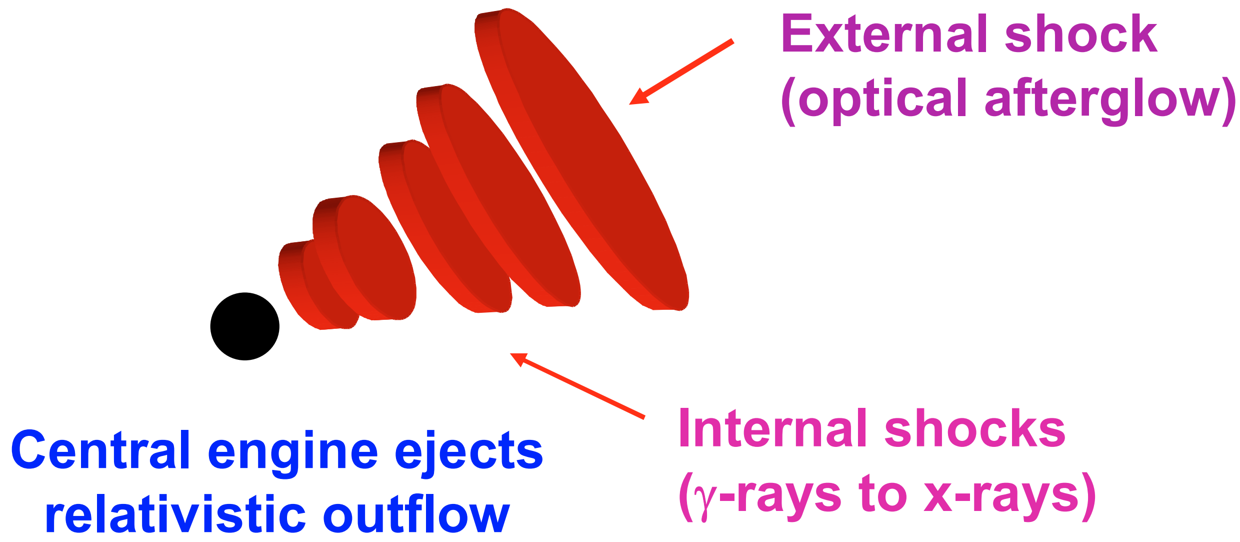
GRBs involve 3 stages:

- 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 (γ > 100, B-field close to equipartition)

Relativistic internal-external shocks fireball model

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

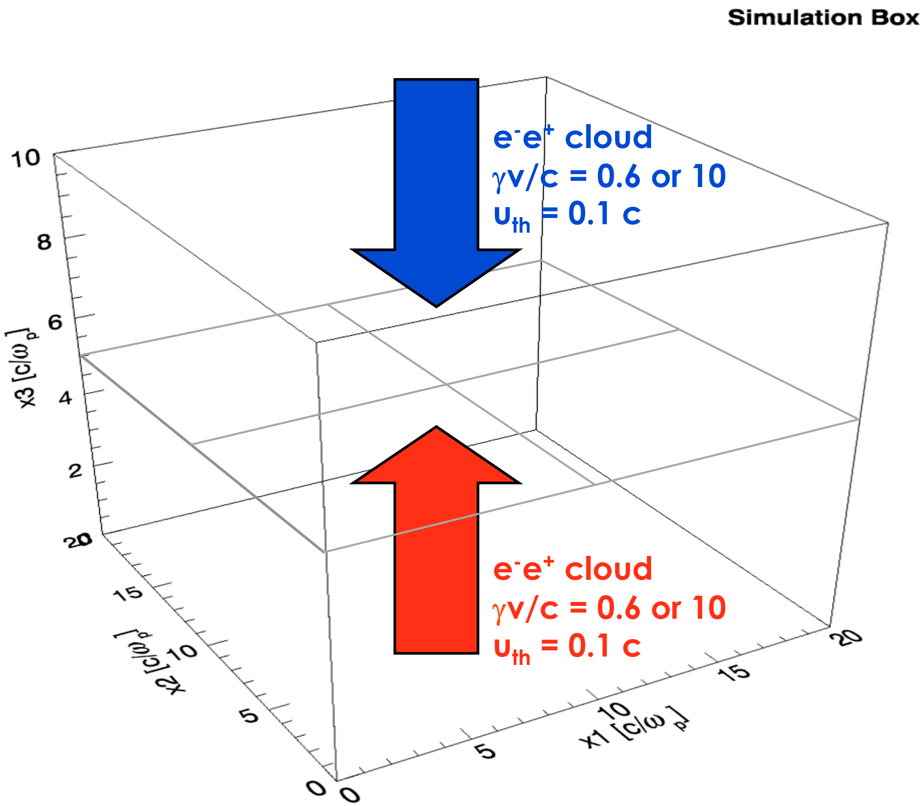
Necessary to generate B-field such that:

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

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

To definitely address this issue: 3D PIC simulations

3D PIC simulations of the e^+e^- Weibel instability



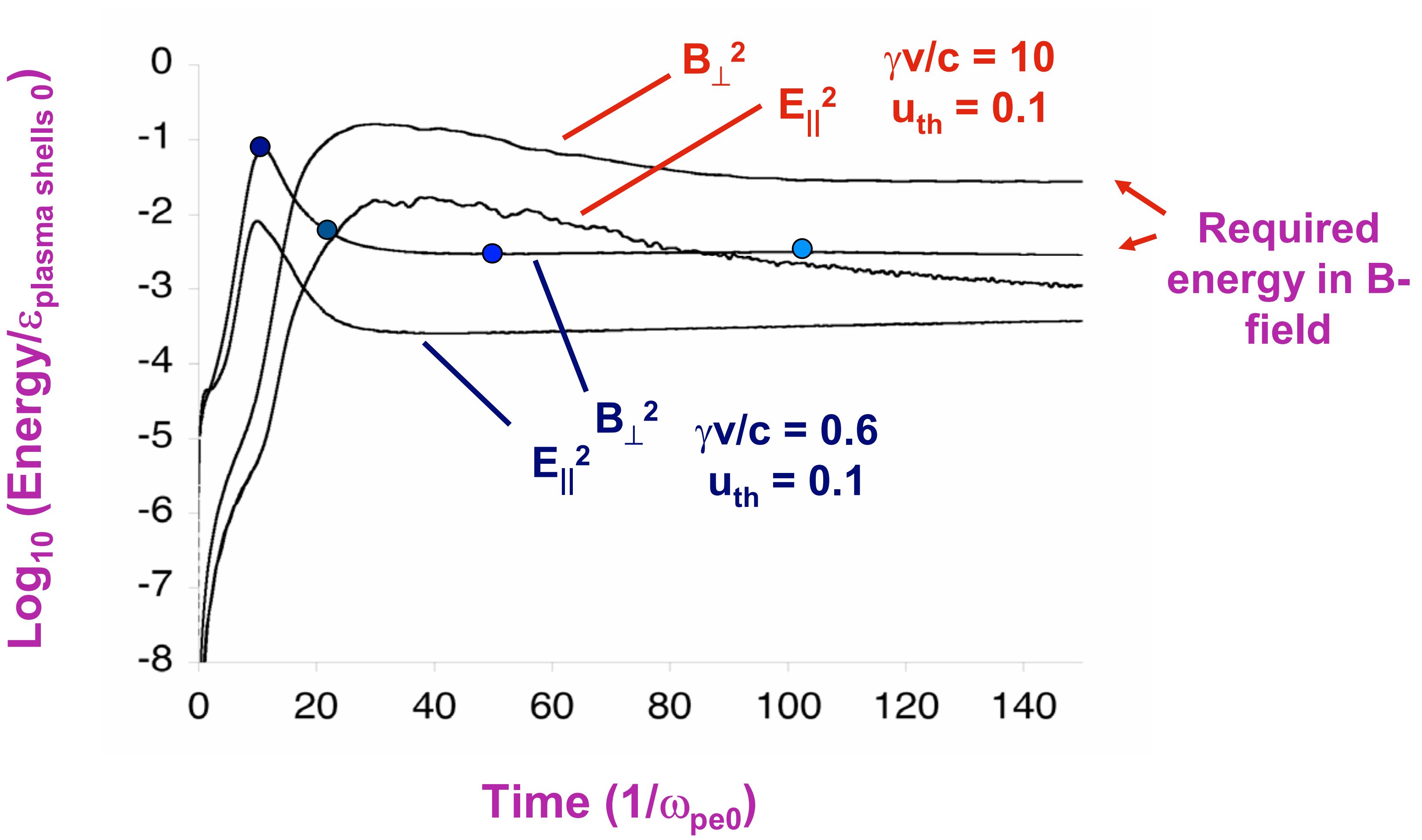
Simulation details

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)

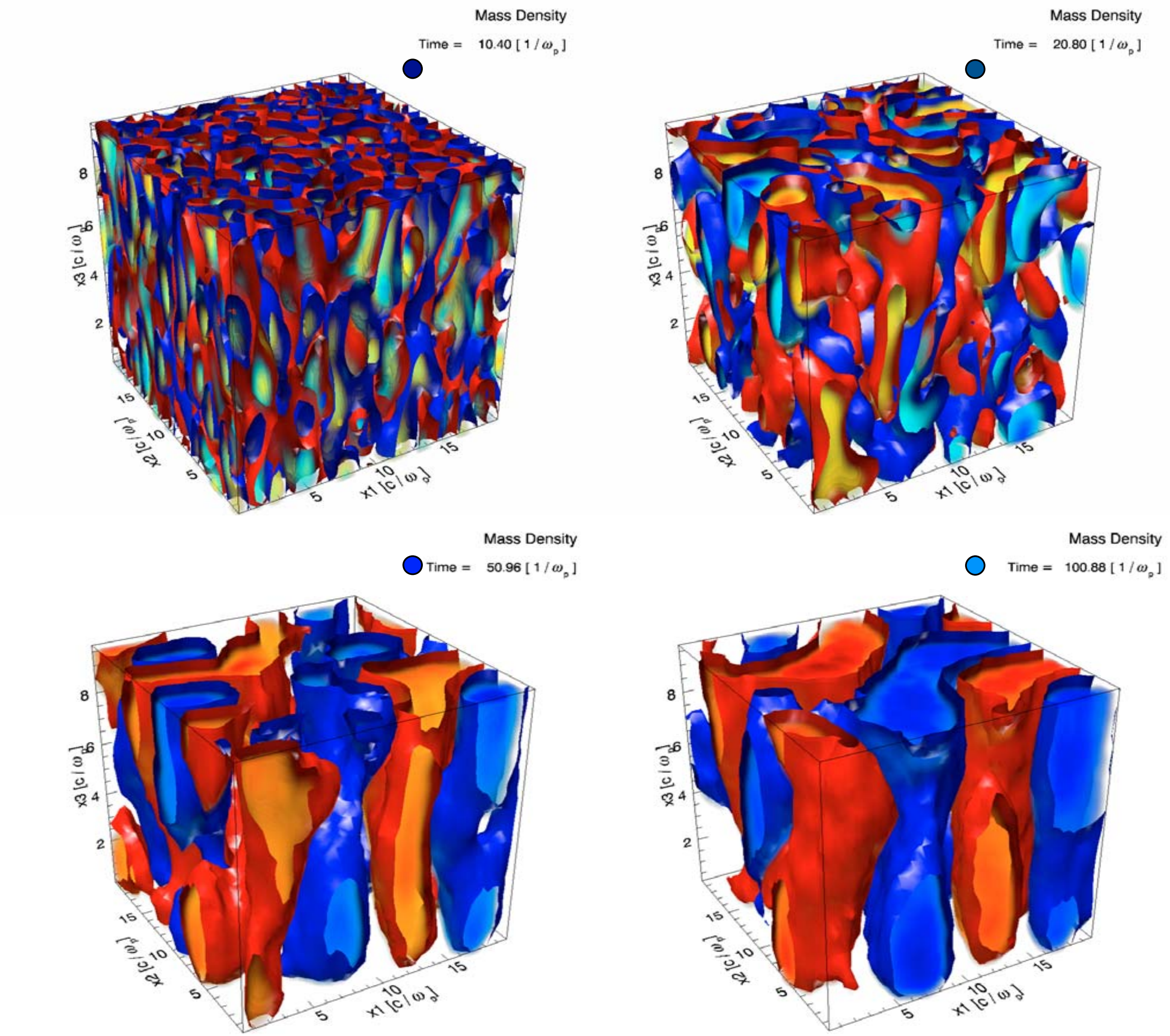
PIC codes
OSIRIS (R. G. Hemker, UCLA,2000)
PARSEC (J. Tonge, UCLA, 2002)

B-field evolution



(Silva et al, submitted ApJLett 2002)

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)

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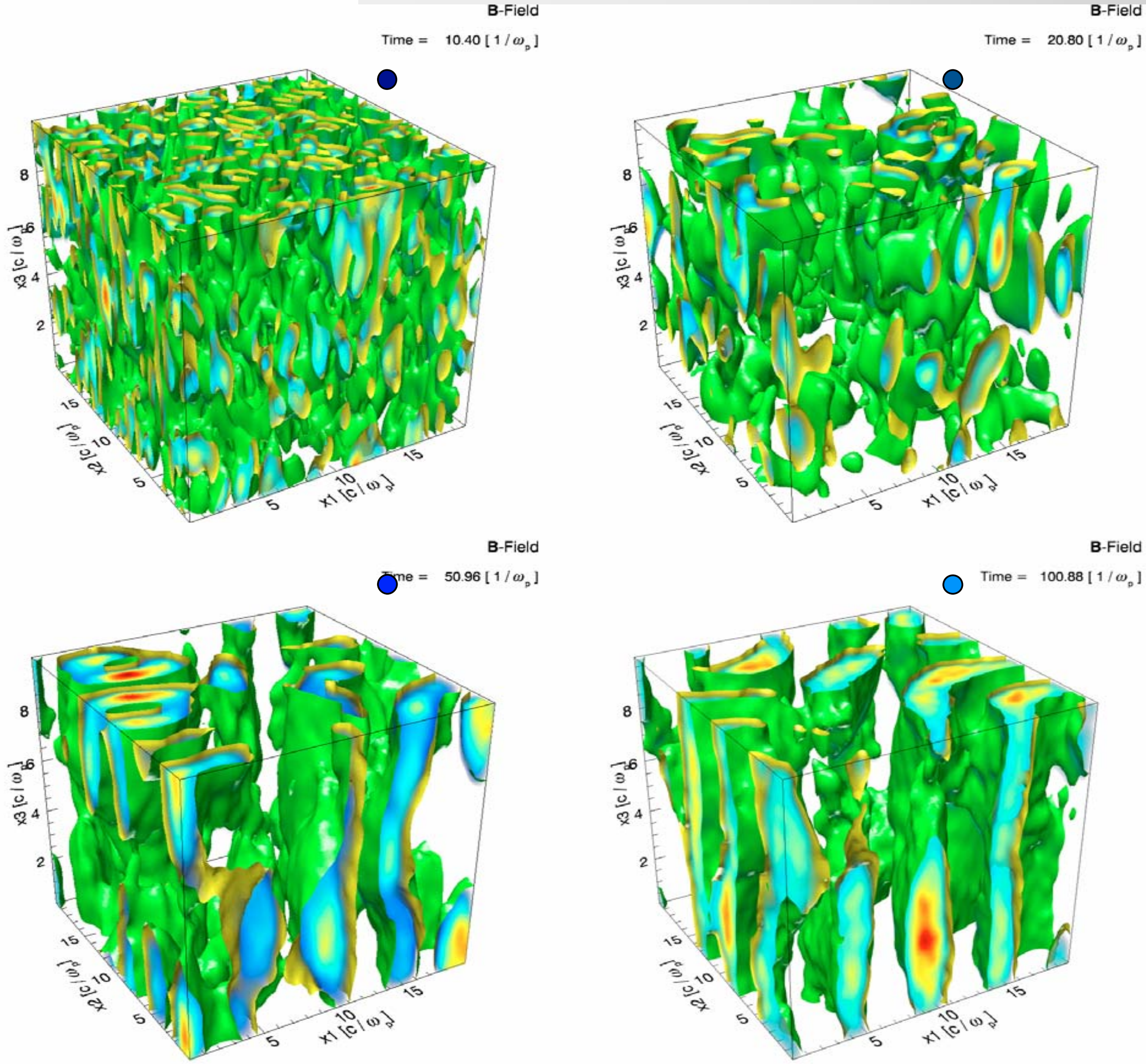
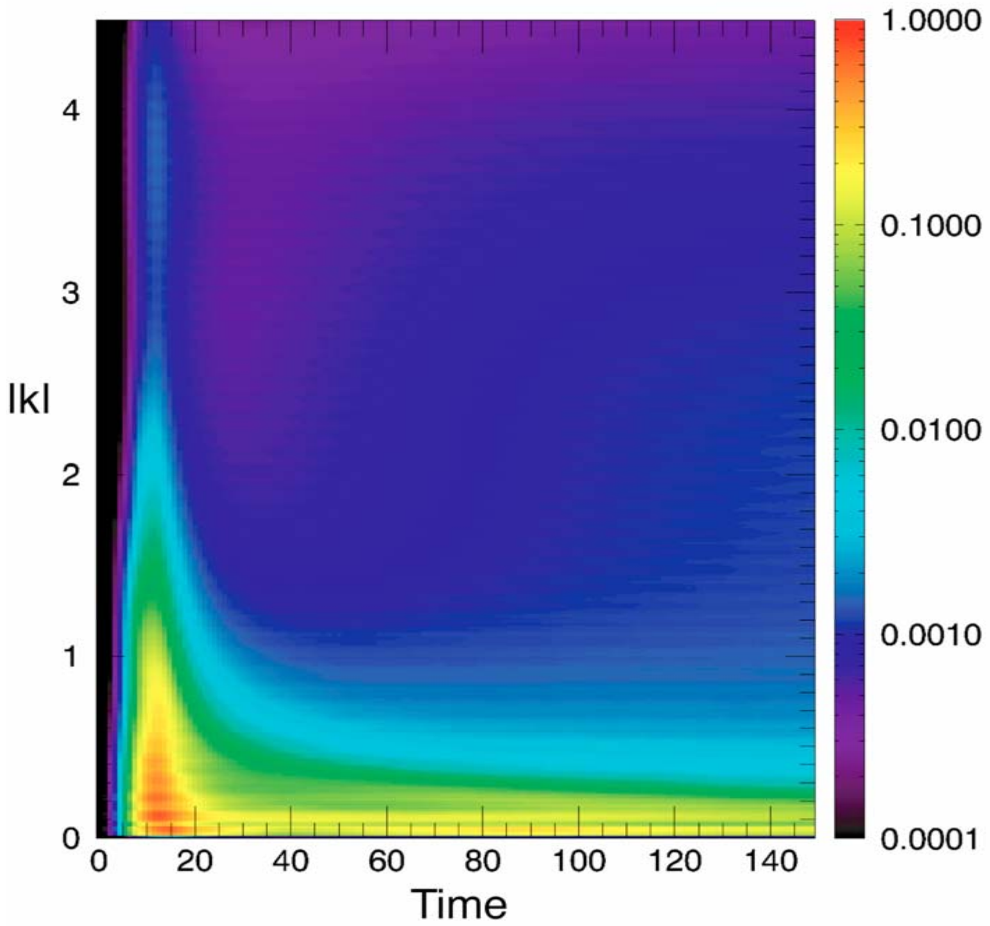
Magnetic field energy density ($\gamma v/c = 0.6$)



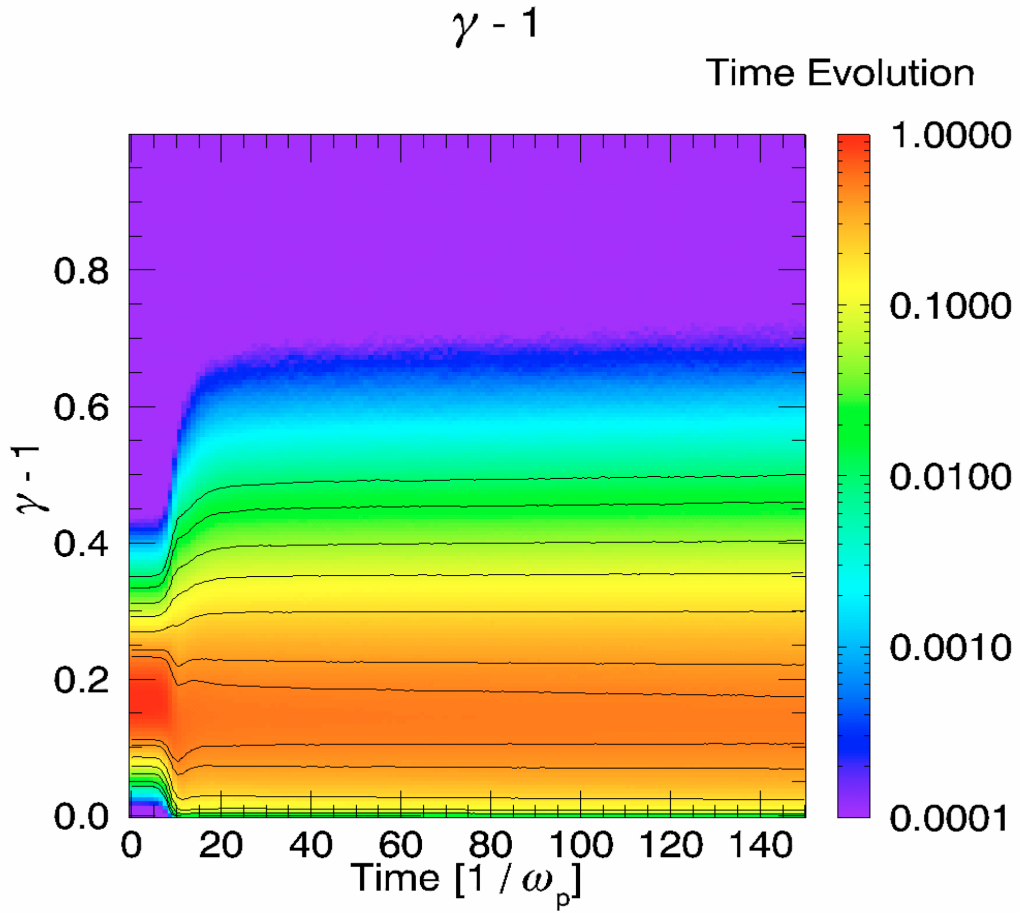
- Isosurfaces (Green - regions of lower values, Yellow regions of higher values) of the magnitude of the magnetic field
- Isosurfaces drawn at a) 0.1, b) 0.025, c) 0.01 and d) 0.006

Energy evolution ($\gamma v/c$ = 0.6)

B-field spectral energy density



Particle Kinetic Energy



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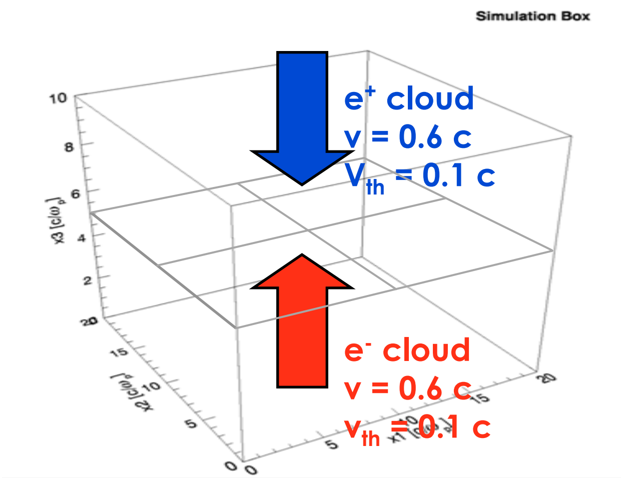
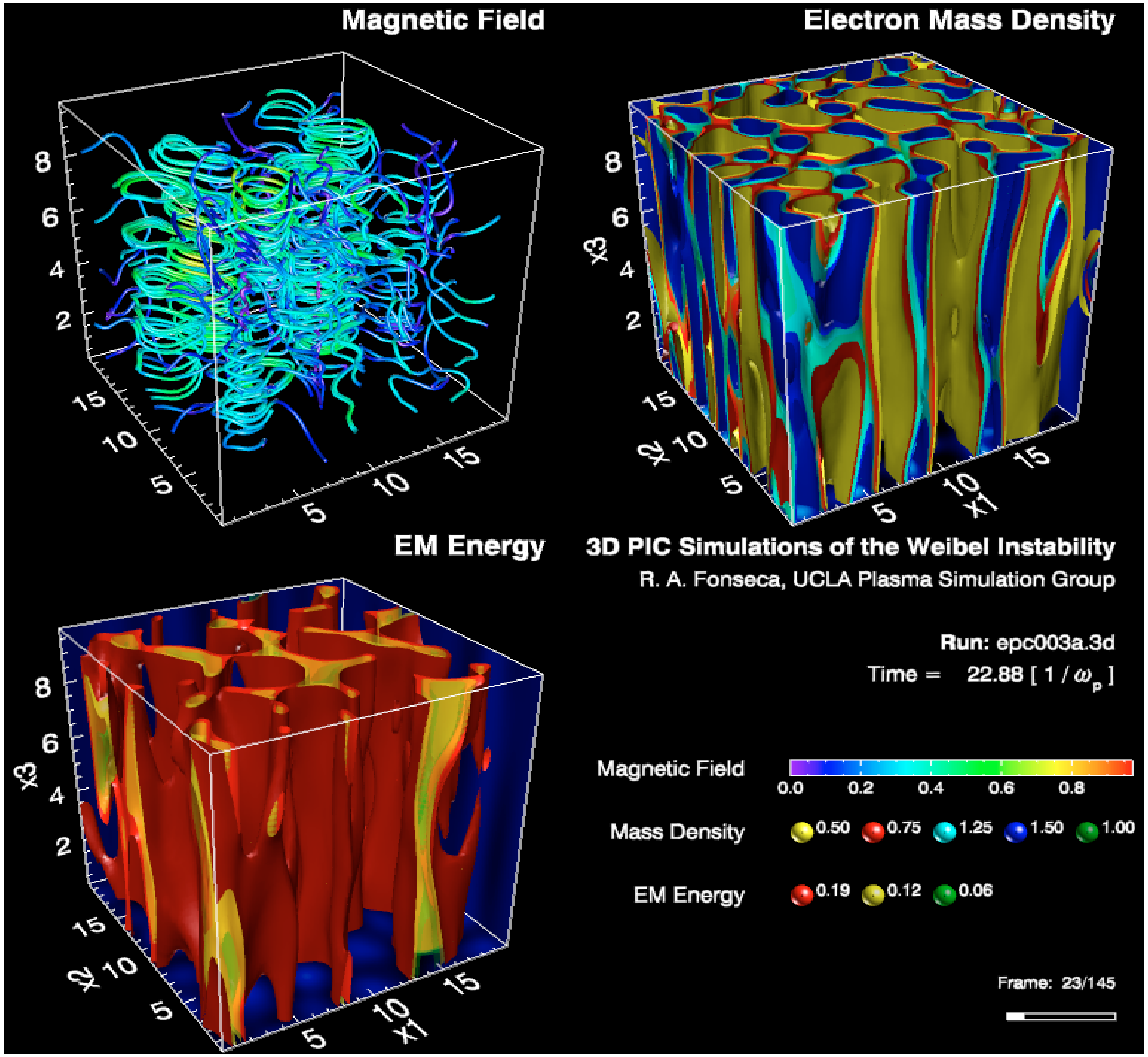
Electron-positron Weibel instability II



- **3D Simulation**
  200 x 200 x 100 cells (20 x 20 x 10 c^3/ω_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 NER□SC



(Fonseca et al, IEEE TPS 2002)

Conclusions and future directions I

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

(R.A. Fonseca, APS 2002, PoP 2003)

Conclusions and future directions II

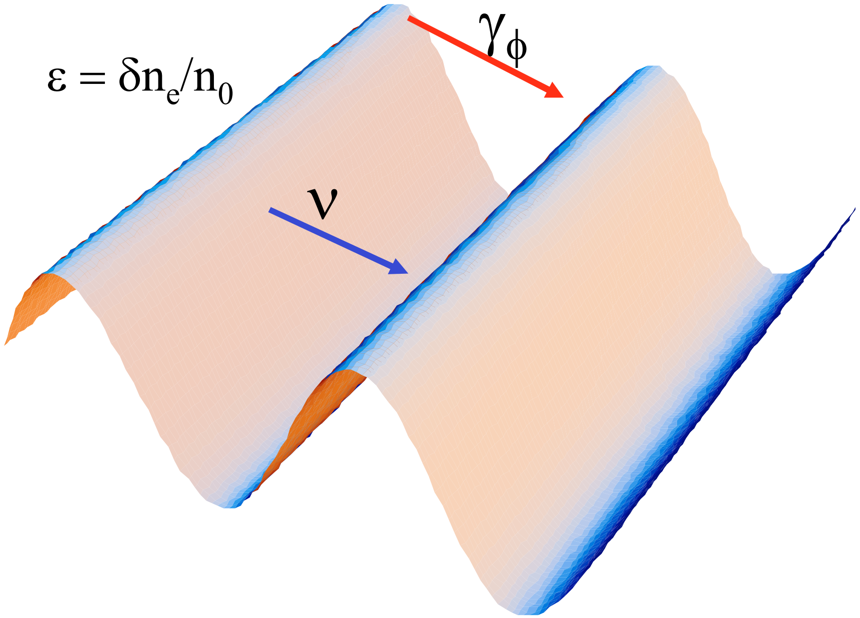
In different astrophysical conditions involving intense neutrino fluxes, neutrino driven plasma instabilities are likely to occur

- 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 ν driven anomalous processes to make connection with supernovae numerical models

(Oraevskii, Semikoz, Bingham, Silva, 2003)

Neutrino surfing electron plasma waves



$$\left|\Delta E_\nu\right|_{\max} \approx \left|\mathbf{F}\right| L_{dp} \approx 8\sqrt{2} G_F \varepsilon n_{e0}$$

$$\gamma_\phi = 10$$

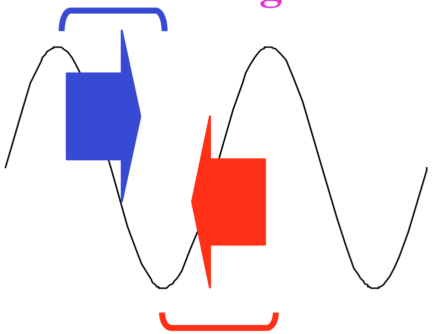
$$\varepsilon = 10^{-2}$$

$$n_{e0} = 10^{32}\, cm^{-3}$$

$$L_{dp} = \lambda_p \gamma_\phi^2 \approx 3\times 10^{-2}\, cm$$

$$dE_\nu / dL \approx 8\sqrt{2} G_F \varepsilon n_{e0} / (\lambda_p \gamma_\phi^2) \approx 200\, eV / cm$$

ν bunching



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

$$\left(\partial_t^2 + \omega_{pe0}^2\right)\delta n_e = \frac{\omega_{pe0}^2}{2m_e}\nabla^2 \int \frac{d\mathbf{k}}{(2\pi)^3}\hbar \frac{N_\gamma}{\omega_{\mathbf{k}}}$$

Neutrinos

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

δn_e Perturbed electron plasma density

Ponderomotive force

physics/9807049, physics/9807050

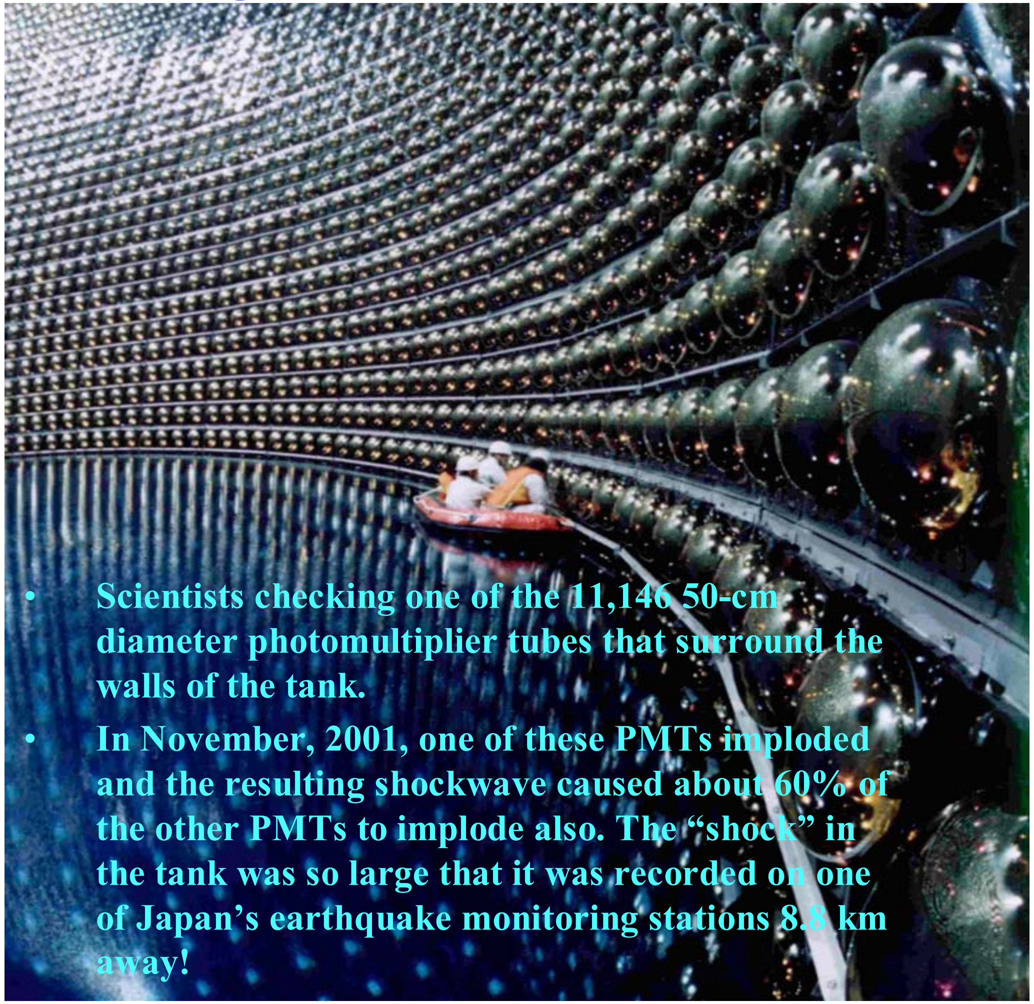
Kinetic/fluid equations for electron beam, photons, neutrinos coupled with electron density perturbations due to PW

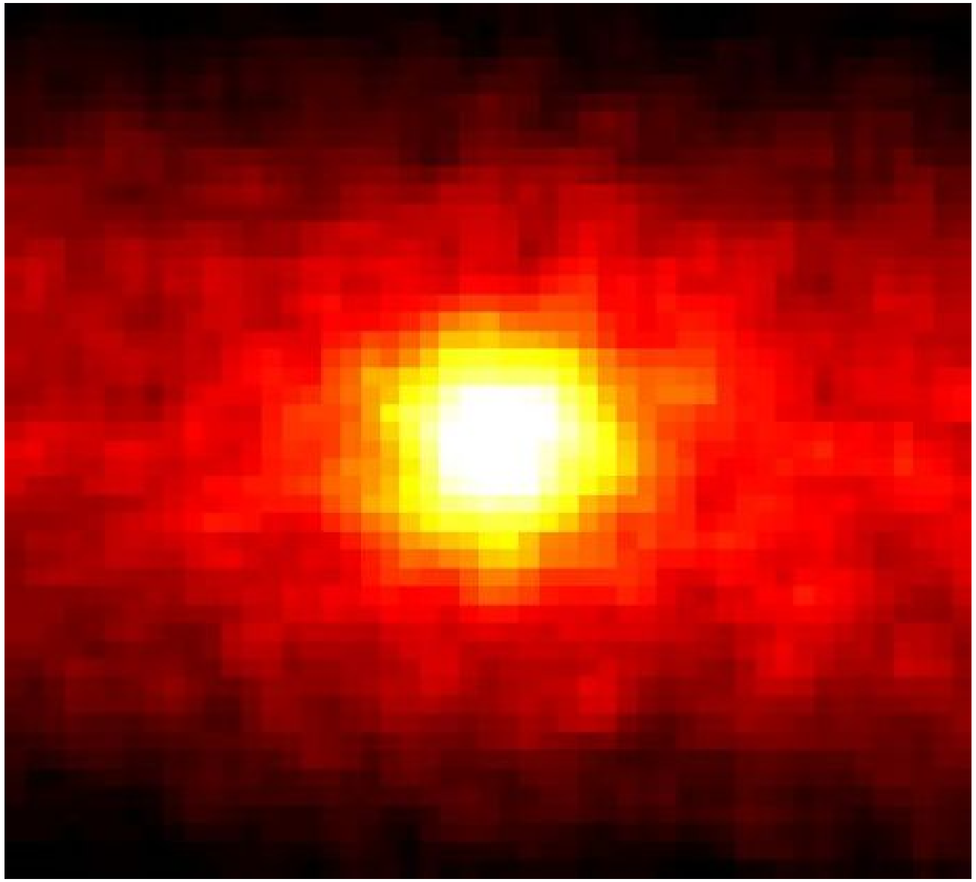
Self-consistent picture of collective e,γ,ν-plasma interactions

CCLRC Rutherford Appleton Laboratory

Super-Kamiokande

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





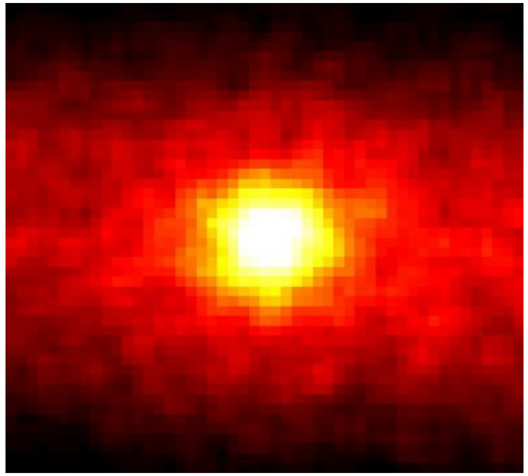
- Super-Kamiokande obtained this neutrino image of the Sun!

Neutrino from 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 ≈13 MeV of thermal energy

The "Solar Constant", S (Flux of solar radiation at Earth) is

$$S = 1.37 \times 10^6 \ \ \text{erg/cm}^2\text{s}$$

Neutrino flux at Earth, φ_ν,

$$\varphi_\nu = S / 13 \text{ MeV} \approx 6.7 \times 10^{10} \ \ \text{neutrinos/cm}^2\text{s}$$

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

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 ~10 km radius.
- **Problem**: How to reverse the implosion and create an explosion?