Neutrinos and Supernovae

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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/Dark Energy

Intensities in excess of 10^{30} W/cm^2 and luminosities up to 10^{53} erg/s

Outline

Intense fluxes of neutrinos in Supernovae

Neutrino dynamics in dense plasmas (making the bridge with HEP)

Plasma Instabilities driven by neutrinos

Supernovae plasma heating: shock revival

Neutrino mode conversion (Neutrino oscillations)

Neutrino Landau damping

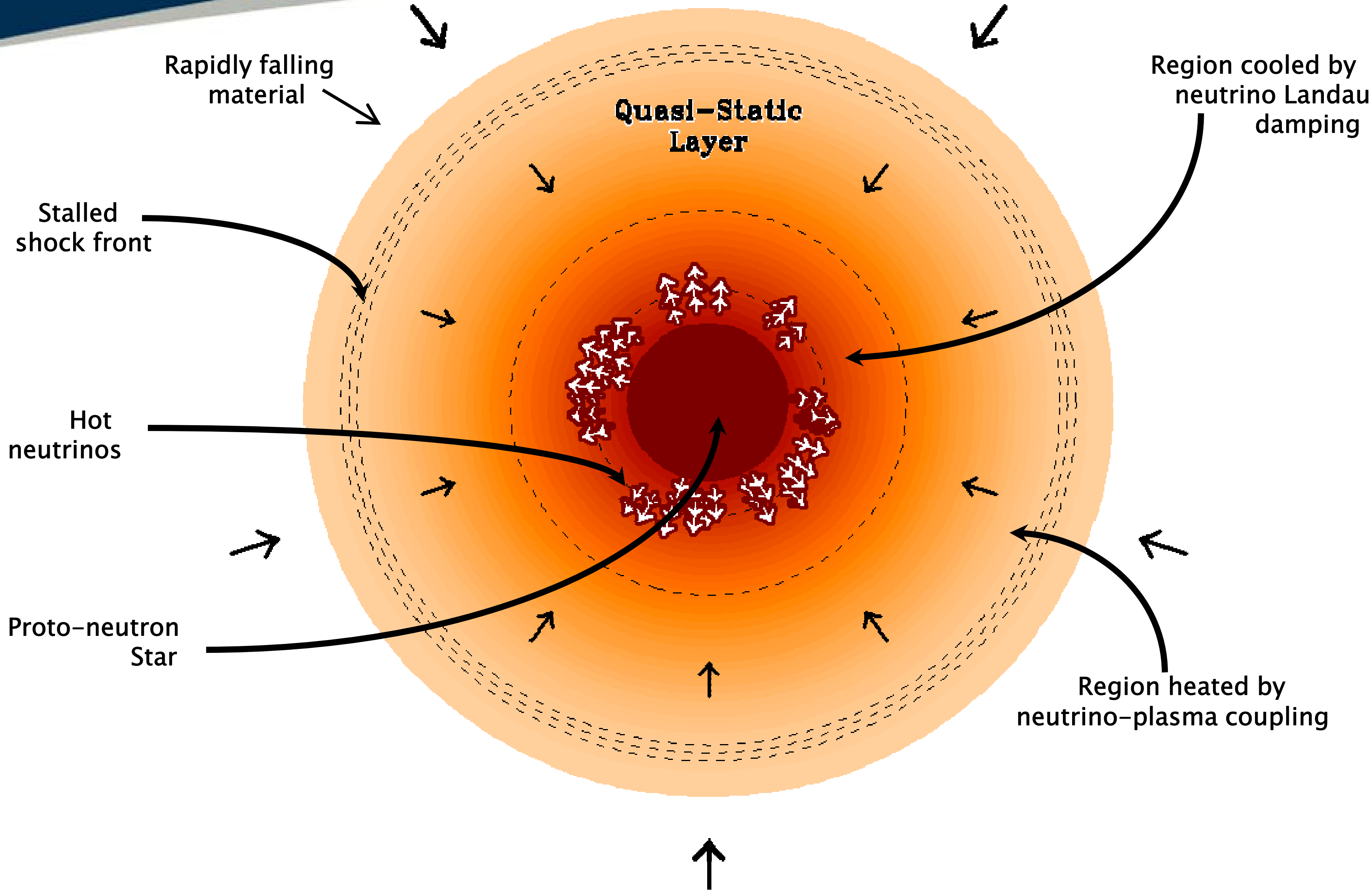
Neutron star cooling

Solar neutrino deficit

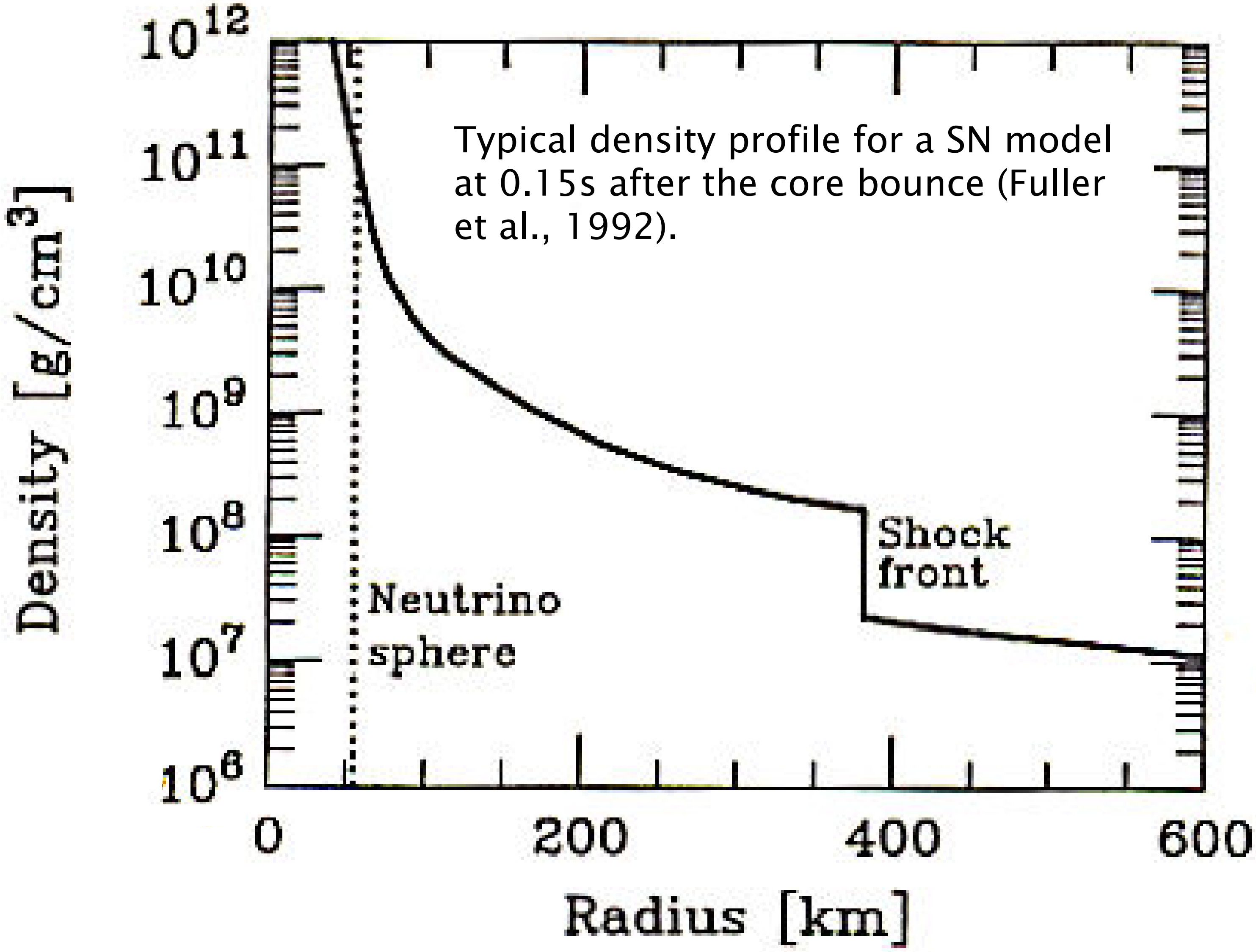
Gamma-ray bursters: open questions

Conclusions

Supernovæ Explosion



Typical Density Profile



Typical density profile for a SN model at 0.15s after the core bounce (Fuller et al., 1992).

Length scales

← Compton Scale
HEP

Hydro Scale →
Shocks

Plasma scale
$\lambda_D, \lambda_p, r_L$

Can intense neutrino winds drive collective and kinetic mechanisms at the *plasma scale* ?

Bingham, Bethe, Dawson, Su (1994)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Supernova Explosion

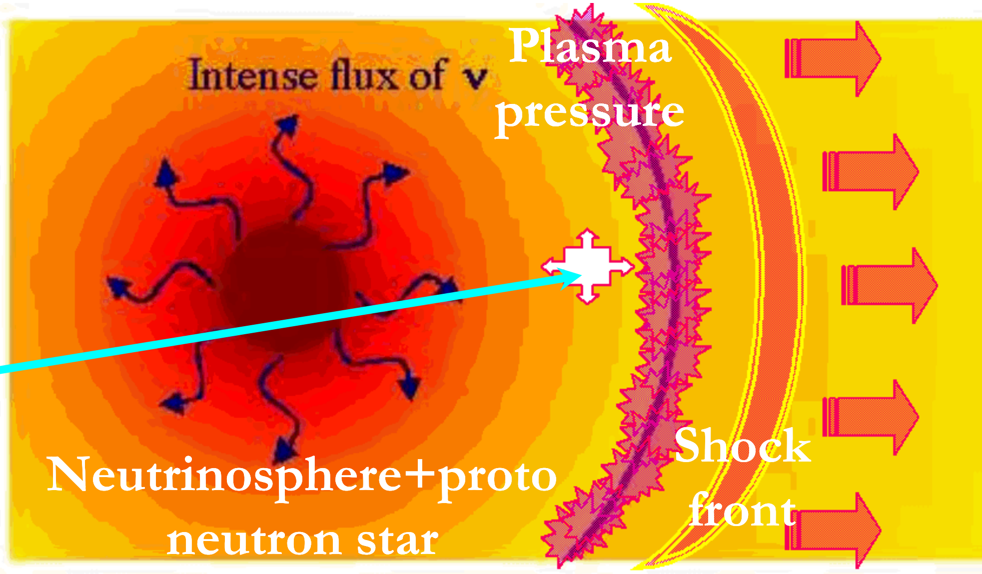
A supernova releases 5×10^{53} erg
(gravitational binding energy of the original star)

• neutrinos 99 % •

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

How to turn an implosion into an explosion?

⇒ Neutrino-plasma scattering instabilities in dense plasmas



Neutrino-plasma heating

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

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

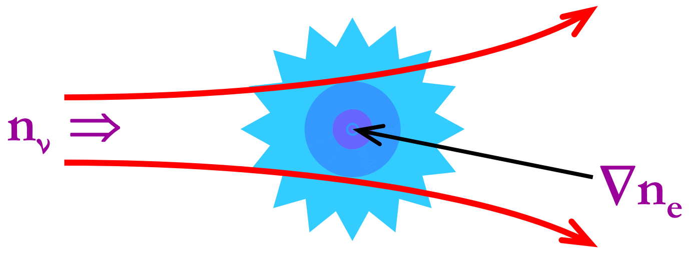
$$N_\nu \cong 1 - \frac{2\sqrt{2}G_F}{\hbar k_\nu c} n_e$$

Note: cut-off density

ε_ν neutrino energy

$$n_{ec} > \frac{\varepsilon_\nu}{2\sqrt{2}G_F}$$

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

$$\mathrm{F}_{POND} = \frac{N-1}{2}\nabla\xi$$

[Landau & Lifshitz, 1960]

where ξ is the energy density of the neutrino beam.

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

n_ν is the neutrino number density.

$$\boxed{\mathrm{F}_{\mathrm{Pond}} \equiv -\sqrt{2}G_F n_e \nabla n_\nu}$$

Bingham *et al.*, 1997.

Neutrino Dynamics in Dense Plasma

Dynamics governed by Hamiltonian (Bethe, ‘86):

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

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 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

$$\mathrm{F}_{\mathrm{coll}} = n_e f_{coll} = n_e \sigma_{\nu_e} \xi$$

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

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

For a 0.5 MeV plasma $\quad \dfrac{\mathrm{F}_{\mathrm{Pond}}}{\mathrm{F}_{\mathrm{coll}}} \approx 10^{10}$

$\sigma_{\nu e} \Rightarrow$ collisional mean free path of 10^{16} cm.

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Supernova II Physical Parameters

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: $n_{e0} \sim 10^{29} - 10^{32}$ cm^{-3}

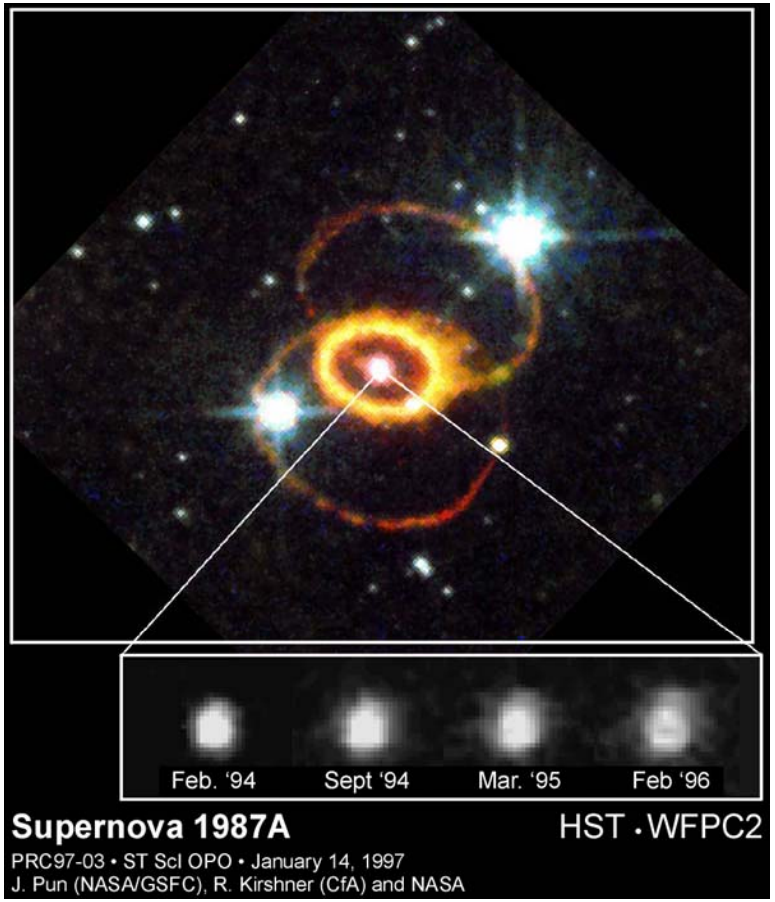
¶ Electron temperature @ 100-300 km: $T_e \sim 0.1 - 0.5$ MeV

¶ 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

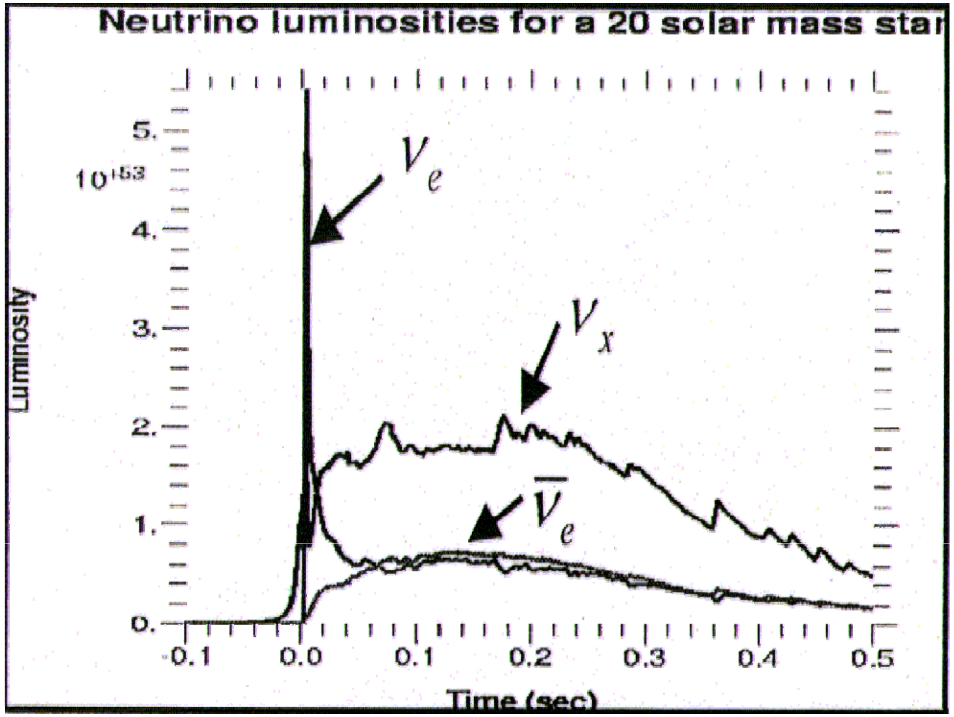


Supernova 1987A HST • WFPC2

PRC97-03 • ST ScI OPO • January 14, 1997
J. Pun (NASA/GSFC), R. Kirshner (CfA) and NASA

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.

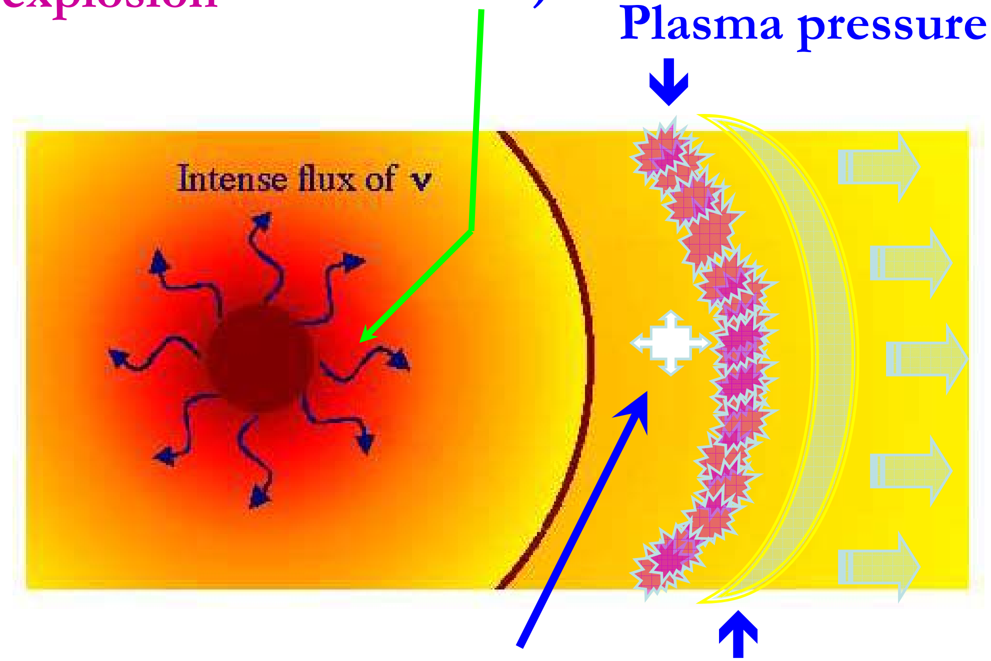


The initial electron neutrino pulse of 5×10^{53} ergs/second is followed by an “accretion” pulse of all flavours of neutrinos.

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.

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



Neutrinosphere (proto-neutron star)

Plasma pressure

Neutrino-plasma coupling

Shock

Bingham *et al.*, **Phys. Lett. A**, 220, 107 (1996)
Bingham *et al.*, **Phys. Rev. Lett.**, 88, 2703 (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**

Neutrino kinetics in a dense plasma

Kinetic equation for neutrinos

(describing neutrino number density conservation / collisionless neutrinos)

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

Kinetic equation for electrons driven by neutrino pond. force

(collisionless plasma)

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

$$+$$

Maxwell's Equations

(Silva et al, ApJ SS 1999)

Two stream instability driven by a neutrino beam

Usual perturbation theory over kinetic equations + Poisson's equation

$$n_e = n_0 + n_1 \qquad f_e = f_{e0}(\mathbf{p}_e) + f_{e1}$$

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

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

Dispersion relation for electrostatic plasma waves

[illegible]

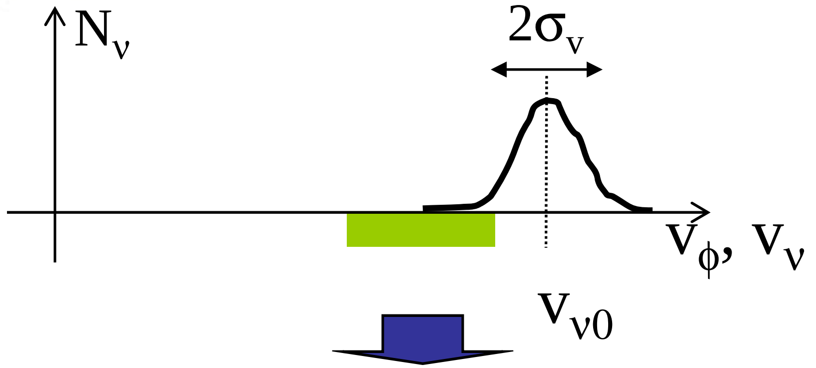
Electron susceptibility

Neutrino susceptibility

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

(Silva et al, PRL 1999)

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 $T_\nu = 3$ MeV
$R_m = 300$ Km $m_\nu = 0.1$ eV

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** $\left| \frac{\omega_L}{k_L} - v_{\nu 0} \right| >> \sigma_{v_\nu}$

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

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

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 Rate

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

Growth distance ~ 1 m
(without collisions)

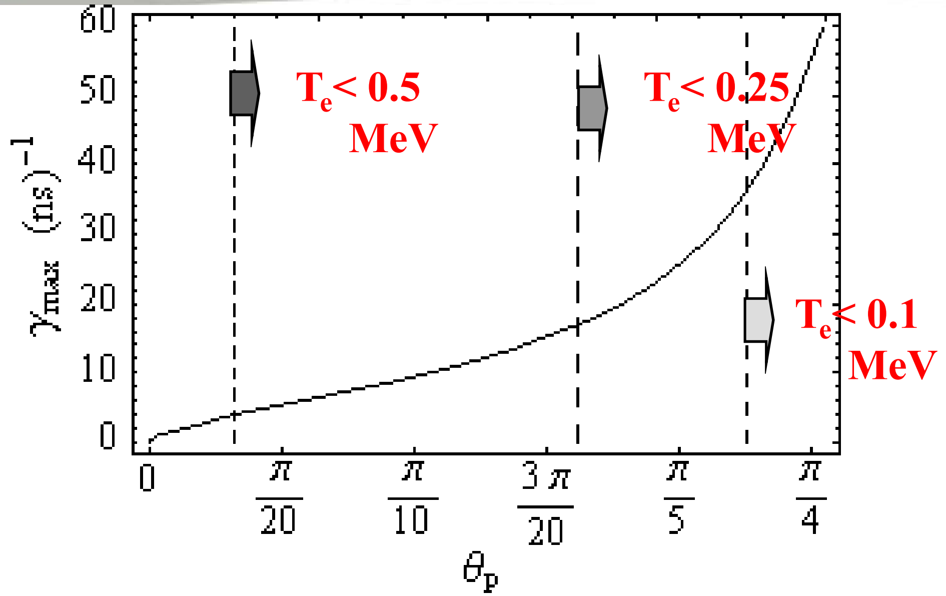
Growth distance ~ 300 m
(with collisions)

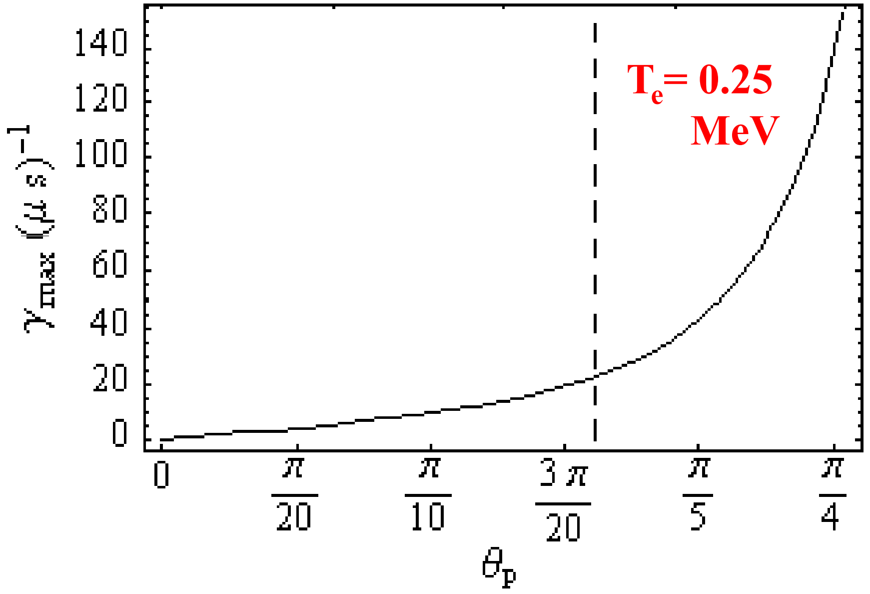
- 6 km for 20 e-foldings -

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

Single ν-electron scattering $\propto G_F^2$

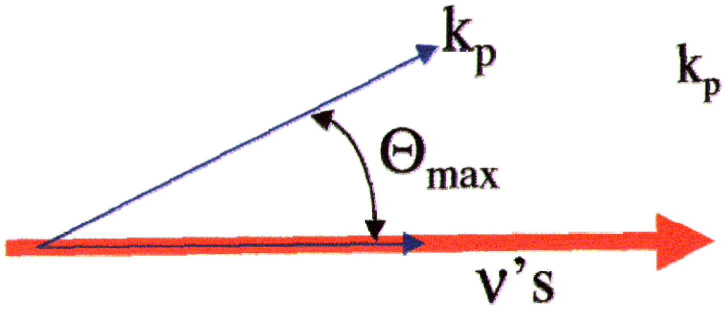
Collective mechanism much stronger than single particle processes





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

$$\mathbf{E_k} = E_k \delta(k_{\|} - \omega_{pe0}/c)\frac{\mathbf{k}}{|\mathbf{k}|} \Leftarrow \frac{\partial|\mathbf{E}_k|^2}{\partial t} = 2\gamma_k|\mathbf{E}_k|^2$$

γ_k=0 if $k > k_{max}$

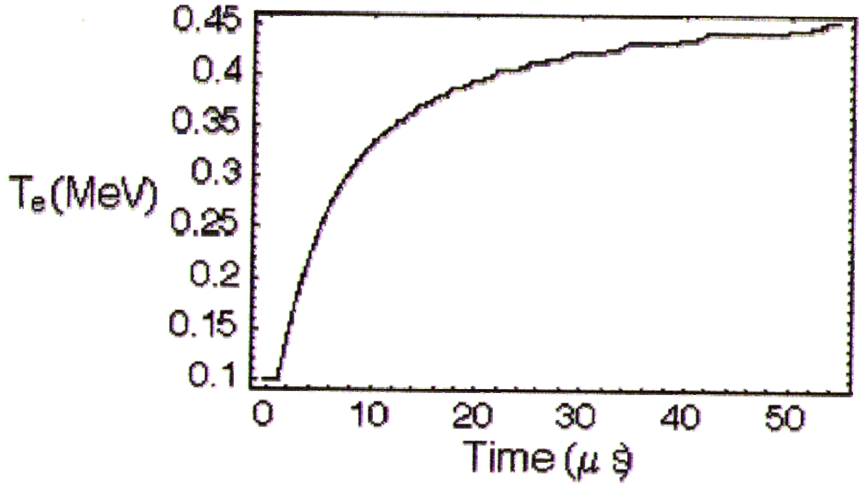
$$\frac{\partial W_{EPW}}{\partial t} = n_e\frac{\partial T_e}{\partial t} = \frac{1}{8\pi}\frac{\partial}{\partial t}\sum_{k \le k_{max}}|\mathbf{E}_k|^2$$

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

Electron Heating

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

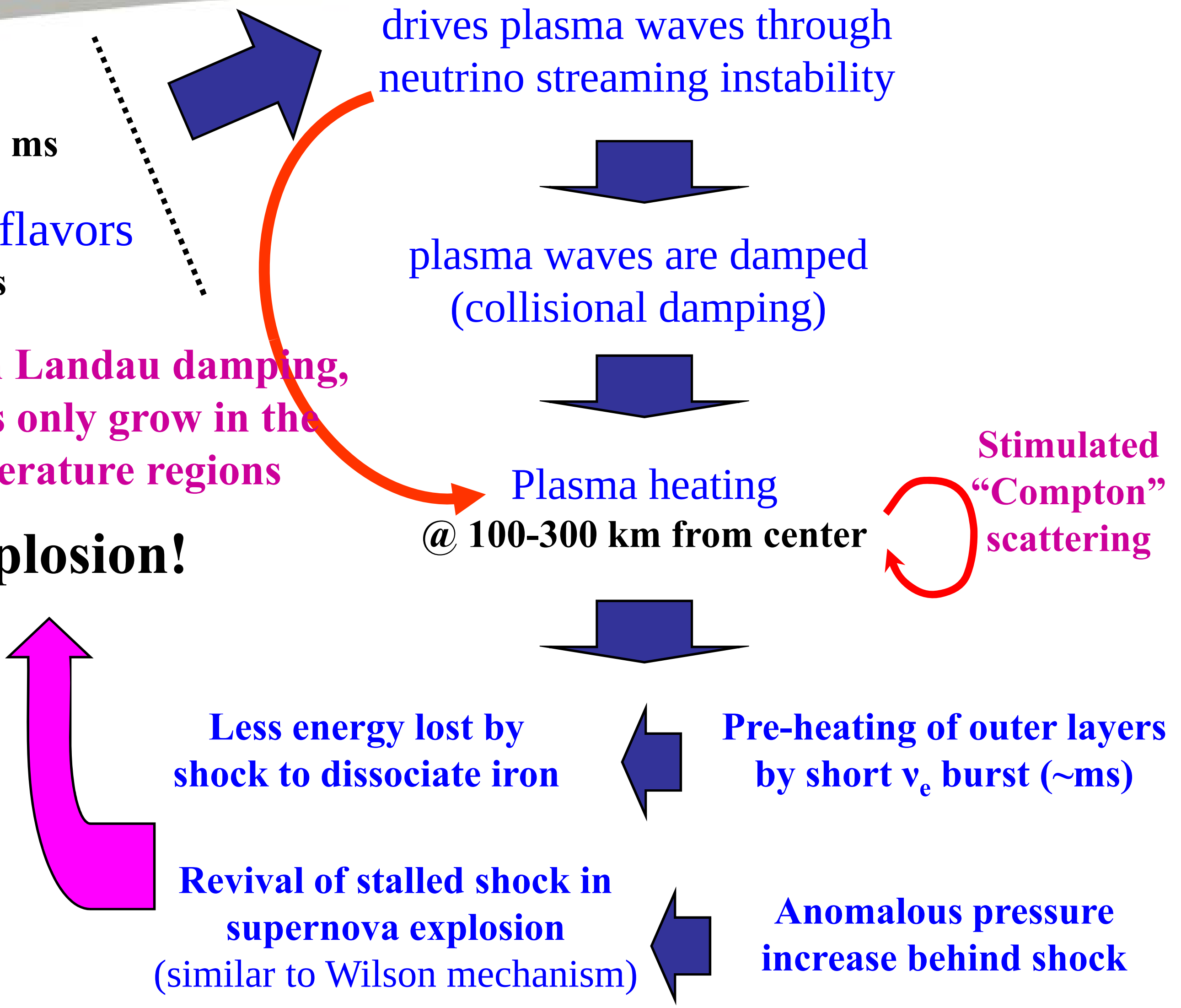
including e-i collisions



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

- 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

Supernovæ explosion and 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)

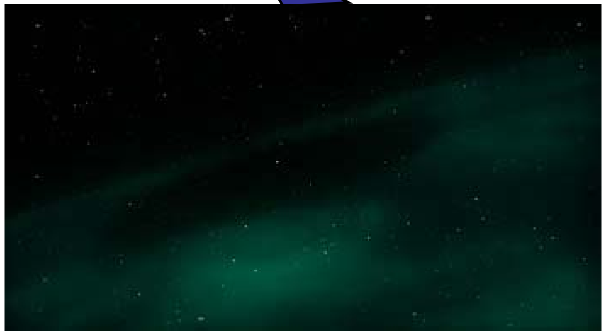
Less energy lost by shock to dissociate iron

Anomalous pressure increase behind shock

Revival of stalled shock in supernova explosion

(similar to Wilson mechanism)

Supernova Explosion!

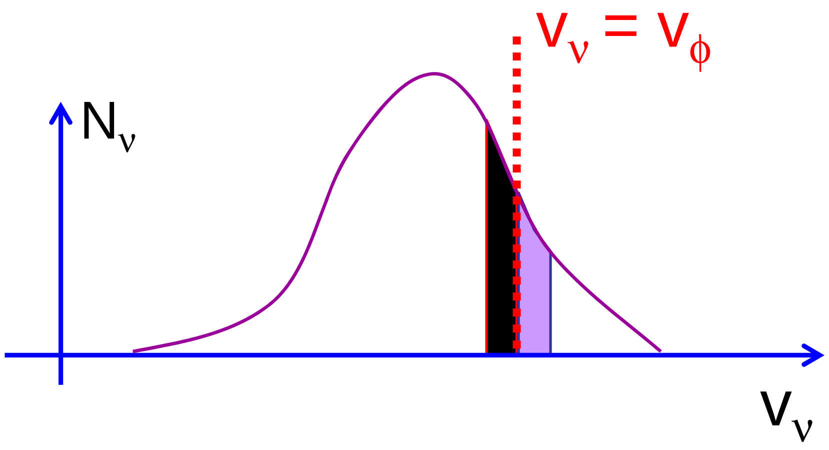


Neutrino Landau Damping I

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

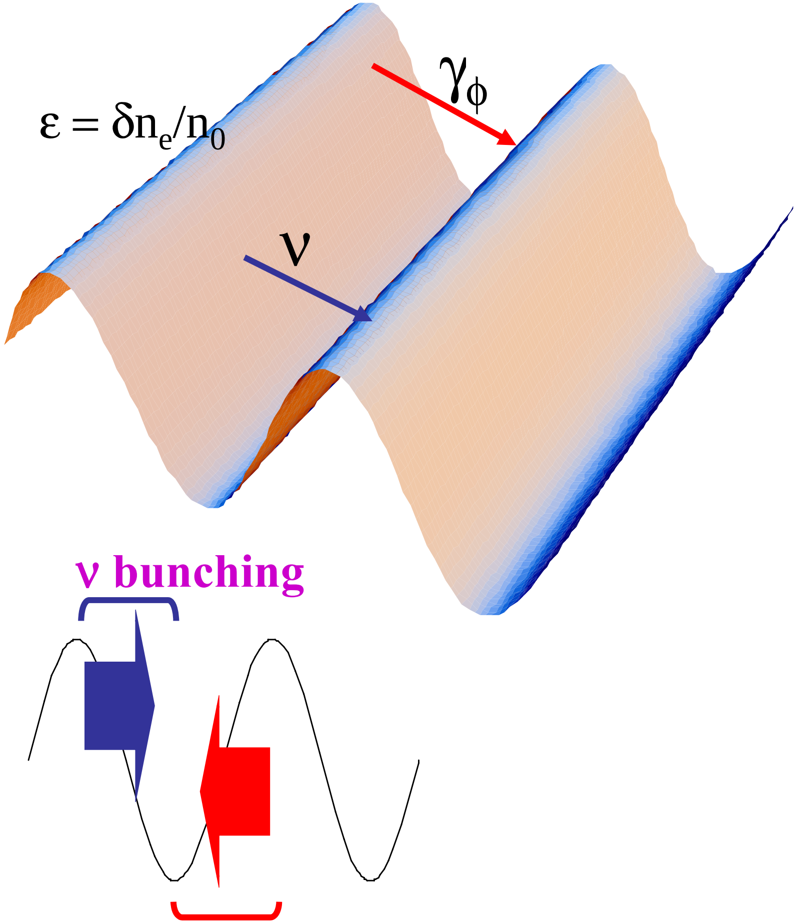


Physical picture for electron Landau damping
(Dawson, '61)

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

(Silva et al, PLA 2000)

Neutrino surfing electron plasma waves



[illegible]

$$\gamma_\phi = 10$$

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

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

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

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

Equivalent to physical picture for RFS of photons (Mori, '98)

Neutrino Landau damping II

Neutrino Landau damping reflects contribution from the pole in neutrino susceptibility

$$\chi_\nu(\omega_L,\mathbf{k}_L) \propto \int d\mathbf{p}_\nu \frac{\mathbf{k}_L\cdot(\partial \hat{f}_{\nu0}/\partial \mathbf{p}_\nu)}{\omega_L-\mathbf{k}_L\cdot\mathbf{v}_\nu} \longrightarrow \int d\mathbf{p}_\perp |\mathbf{p}_\perp| \left\{ P\int \frac{\left(\partial \hat{f}_{\nu0}/\partial p_\parallel\right)}{p_\parallel - p_{\parallel0}} dp_\parallel \boxed{+ i\pi \left(\frac{\partial \hat{f}_{\nu0}}{\partial p_\parallel}\right)_{p_{\parallel0}}} \right\}$$

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 $f_{\nu0}$
Landau's prescription in the evaluation of χ_ν

For a Fermi-Dirac neutrino distribution

$$\gamma_{Landau} \approx -\frac{k_L c}{2}\pi \frac{G_F^2 n_{e0} n_{\nu0}}{m_e c^2 k_B T_\nu}\left(1-\frac{\omega_L^2}{c^2 k_L^2}\right)^2 \frac{\mathrm{Li}_2(-\exp E_F/T_\nu)}{\mathrm{Li}_3(-\exp E_F/T_\nu)}$$

Neutrino play a critical role in Type II 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.