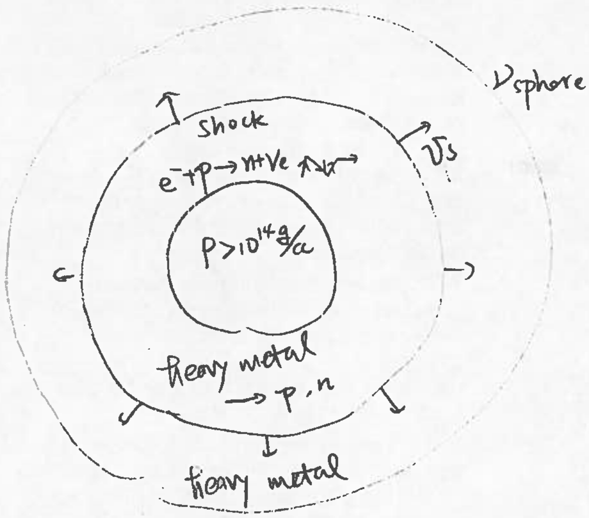
Neutrinos from CCSNe

$$E_B \simeq \frac{3}{5}\frac{GM_{NS}^2}{R_{NS}} \simeq 3\times10^{53}\left(\frac{M}{1.4M_\odot}\right)^2\left(\frac{10\,km}{R}\right)\ erg$$

99% are carried away by neutrinos!

① neutronizational burst:



$v_s \sim 10^4$ km/s

$R_{\nu\text{-sphere}} \sim 10^2$ km/s, $\rho_{\nu\text{-sphere}} \sim 10^{10} \sim 10^{11}\,g/cc$

- shock liberate $Fe \to n + p$
- $e^- + p \to n + \nu_e$
- before shock arrive neutrinosphere
  ν_e are still trapped trailing the shock, piling up
- after "
  ν_e freely go. $\longrightarrow$ neutronization burst
  @ $\sim$ 10 ms

$L_\nu \sim 10^{53} \sim 10^{54}$ erg/s, $\Delta t \sim 20-30$ ms.

③ how to estimate shock speed?

② accretion phase

* emission from matter accretion

$e^+ + e^- \rightarrow \nu + \bar{\nu}$

$\dot{M} \sim 0.5\, M_\odot/s$, $R_\nu = 50\,km$, $M = 1.4\, M_\odot$

$\rightarrow L_{\nu,acc} \sim \frac{GM\dot{M}}{R_\nu} \sim 40 \times 10^{51}\, erg/s$

* emission from core diffusion

$\nu_e + n \rightleftharpoons p + e^-$

$\bar{\nu}_e + p \rightleftharpoons n + e^+$

$e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$ } $\nu \#$, E, $\hat{q}$

$\nu + \bar{\nu} \rightleftharpoons \nu + \bar{\nu}$

$\nu + e^\pm \rightleftharpoons \nu + e^\pm \longrightarrow E, \hat{q}$

$\nu + N \rightleftharpoons \nu + N \longrightarrow \hat{q}$

$N + N \rightleftharpoons N + N + \nu + \bar{\nu}$

ν heating $\quad \nu + b \rightleftharpoons b' + l$

$\dot{q}_H \propto n_\nu \cdot E_\nu \cdot \sigma_{\nu b} \propto T_\nu^6 \cdot \left(\frac{R_\nu}{r}\right)^2$

$\dot{q}_c \propto n_l \cdot E_l \cdot \sigma_{lb} \propto T^6$

$\rightarrow$ gain radius @ $\dot{q}_H = \dot{q}_c$

③ cooling phase

$$E_g \sim \frac{3}{5}\frac{GM^2}{R} \sim 2\times10^{53}\ \mathrm{erg}\cdot\left(\frac{M}{1.4M_\odot}\right)^2\left(\frac{15\,\mathrm{km}}{R}\right)$$

$\Delta t \sim 10\,s$ ~ diffusion time scale...

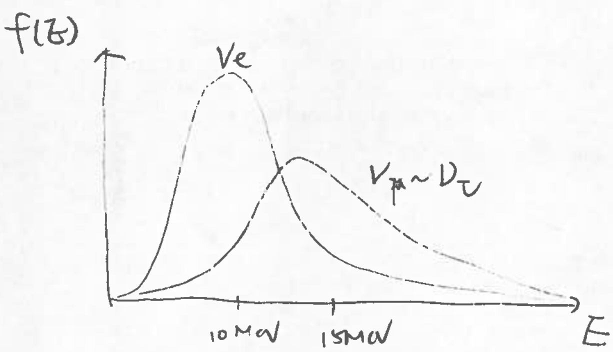
$$\rightarrow L_\nu \sim \frac{E_g}{6\Delta t} \sim 3.3\times10^{51}\ \mathrm{erg/s}.$$

* Energy hierarchy

$$\langle E_{\nu_e}\rangle < \langle E_{\bar\nu_e}\rangle < \langle E_{\nu_x}\rangle$$

* charge current

* neutron rich



any swap between $\nu_e \leftrightarrow \nu_{\mu,\tau}$ might have effect on:

* shock revival

* ν-associated nucleosynthesis : ex: neutrino-driven wind { r-process, νp-process

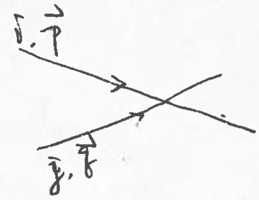
He shell

...

* detected ν signal.

$\nu-\nu$ forward scattering

$$P_L = \frac{1-\gamma_5}{2}$$

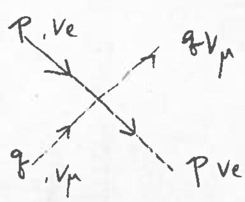


$$H^{NC}_{\nu\nu} = \frac{G_F}{\sqrt{2}}\left(\sum_a \bar{\nu}_{aL}\gamma^\mu \nu_{aL}\right)\left(\sum_b \bar{\nu}_{bL}\gamma_\mu \nu_{bL}\right)$$

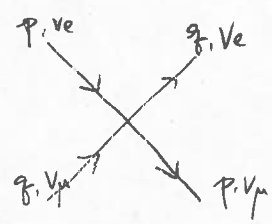
$\rightarrow$ in flavor space:

$$H^{(q)}_{\nu\nu} = \sqrt{2}G_F(1-\cos\theta_{pq})\left[\,|\nu_e^{(q)}|^2 + |\nu_\mu^{(q)}|^2 + \begin{pmatrix} |\nu_e^{(q)}|^2 & \nu_e^{(q)}\nu_\mu^{(q)*} \\ \nu_e^{(q)*}\nu_\mu^{(q)} & |\nu_\mu^{(q)}|^2 \end{pmatrix}\right]\cdot n_\nu^{(q)}$$

diagonal term



off-dia term



$$n_\nu^{tot}(R_\nu) \simeq \frac{L_\nu}{4\pi^2 R_\nu^2\langle E\rangle}\times 2\pi \simeq 5.3\times\overset{10^{31}}{\left(\frac{L_\nu}{10^{51}\,\mathrm{erg/s}}\right)}\cdot\left(\frac{10\,\mathrm{km}}{R_\nu}\right)\left(\frac{10\,\mathrm{MeV}}{\langle E\rangle}\right)\ \mathrm{cm}^{-3}\ \times 2\pi$$

$$F_{\nu,\,\mathrm{earth\ from}\ \odot} \simeq 10^{11}\ \frac{1}{\mathrm{cm}^2\cdot\mathrm{s}} \quad\rightarrow n_{\nu,E} \sim O(1)\ \mathrm{cm}^{-3}$$

$$n_\nu \text{ in Sun} \sim n_{\nu,E}\cdot\left(\frac{1\,\mathrm{AU}}{r_{prod}}\right)^2 \sim \left(\frac{1\,\mathrm{AU}}{0.1R_\odot}\right)^2 \sim \left(\frac{420}{0.1\cdot 2}\right)^2 \sim 4\times 10^6\ \mathrm{cm}^{-3}$$

$\sim 10^7$

strong ν-ν interaction

$$\vec{H}_{\nu\nu} = 2\sqrt{2}\, G_F \sum_j n_\nu^{(j)} (1-\cos\theta_{ij})\, \vec{s}_j \quad \rightarrow \text{ spin-spin coupling}$$

when $r \gg R_\nu$, $\quad n_\nu^{(j)} \propto n_\nu(R_\nu)\cdot\left(\frac{R}{r}\right)^2$, $\quad \langle 1-\cos\theta_{ij}\rangle \propto \left(\frac{R}{r}\right)^2$

$$\rightarrow \vec{H}^{(\alpha)}_{\nu\nu,\text{eff}} \sim 2\sqrt{2}\, G_F\, n_\nu^{(\alpha)} \cdot \frac{1}{4}\left(\frac{r}{R}\right)^4, \quad n_\nu^{(\alpha)} \propto \frac{L_\alpha}{\langle E\rangle \cdot R^2_{\nu_\alpha}}$$

In $\bar{\nu}$

$$S_{\bar{\nu}} = \langle \bar{\nu} | \sigma_y \vec{\sigma} \sigma_y | \bar{\nu} \rangle = -\frac{1}{2}\begin{pmatrix} 2\,\mathrm{Re}(a_x^* a_e) \\ 2\,\mathrm{Im}(a_x^* a_e) \\ |a_e|^2 - |a_x|^2 \end{pmatrix}$$

$\hat{z}_f$

$\uparrow \nu_e, \bar{\nu}_x$

$\downarrow \nu_x, \bar{\nu}_e$

$$\rightarrow \frac{d\vec{s}_i}{dt} = \vec{s}_i \times \left(\omega_i \vec{H}_V - \sum_j \mu_j \vec{s}_j\right), \quad \mu_j \equiv 2\sqrt{2}\, G_F\, n_\nu^{(\alpha)}(R_\nu)\cdot \frac{1}{4}\left(\frac{r}{R}\right)^4 \cdot f_j^{(\alpha)} \equiv \mu f_j^{(\alpha)}$$

$$\rightarrow \frac{d\vec{s}_i}{dt} = \vec{s}_i \times \left(\omega_i \vec{H}_V - \mu \sum_j f_j \vec{s}_j\right) \equiv \vec{s}_i \times \left(\omega_i \vec{H}_V - \mu \vec{S}\right)$$

$$\frac{d\vec{S}}{dt} = \left(\sum_i \omega_i f_i \vec{s}_i\right) \times \vec{H}_V - \mu \left(\sum_i f_i \vec{s}_i\right) \times \left(\sum_j f_j \vec{s}_j\right)$$

if $\mu \gg \omega_i$, $\quad \rightarrow \frac{d\vec{s}_i}{dt} \simeq \vec{s}_i \times \mu \vec{S} \quad \rightarrow \vec{s}_i$ rotate around $\vec{S}$ rapidly

$$\rightarrow \frac{d\vec{S}}{dt} \simeq \langle\omega\rangle \vec{S} \times \vec{H}_V \longrightarrow \vec{S} \text{ rotate around } \vec{H}_V \text{ slowly}$$

$$\langle\omega\rangle = \frac{\sum_i \omega_i f_i \vec{s}_i \cdot \vec{S}}{|\vec{S}|^2}$$

~ precession

In a frame which co-rotating with $\vec{S}$:

$$\frac{d\vec{S}}{dt} = \vec{s} \times \left[(\omega_i - \langle\omega\rangle) \vec{H}_V - \mu \vec{S} \right]$$

$\mu \gg \omega_i$, $\vec{H}_{tot} \propto -\hat{e}_z^f$

$\omega_i - \langle\omega\rangle = \mu S_z \longrightarrow$ resonance

$\mu \ll \omega \longrightarrow \vec{H}_{tot} \propto (\omega_i - \langle\omega\rangle_0) \vec{H}_V$

$\longrightarrow$ spectral split at $\langle\omega\rangle_{\mu=0}$