Neutrino emission from proto neutron stars with MGFLD and M1 neutrino transfer

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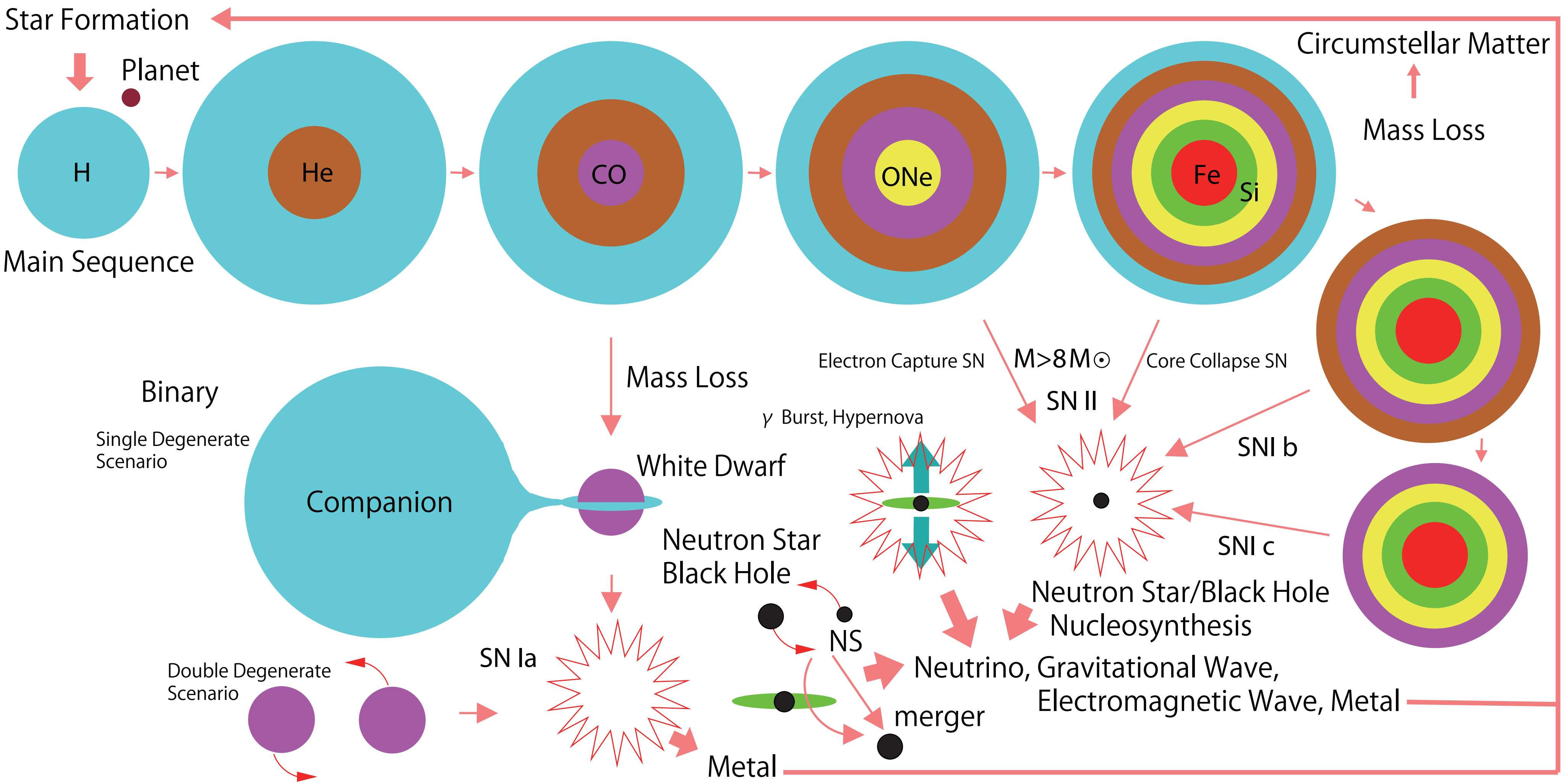
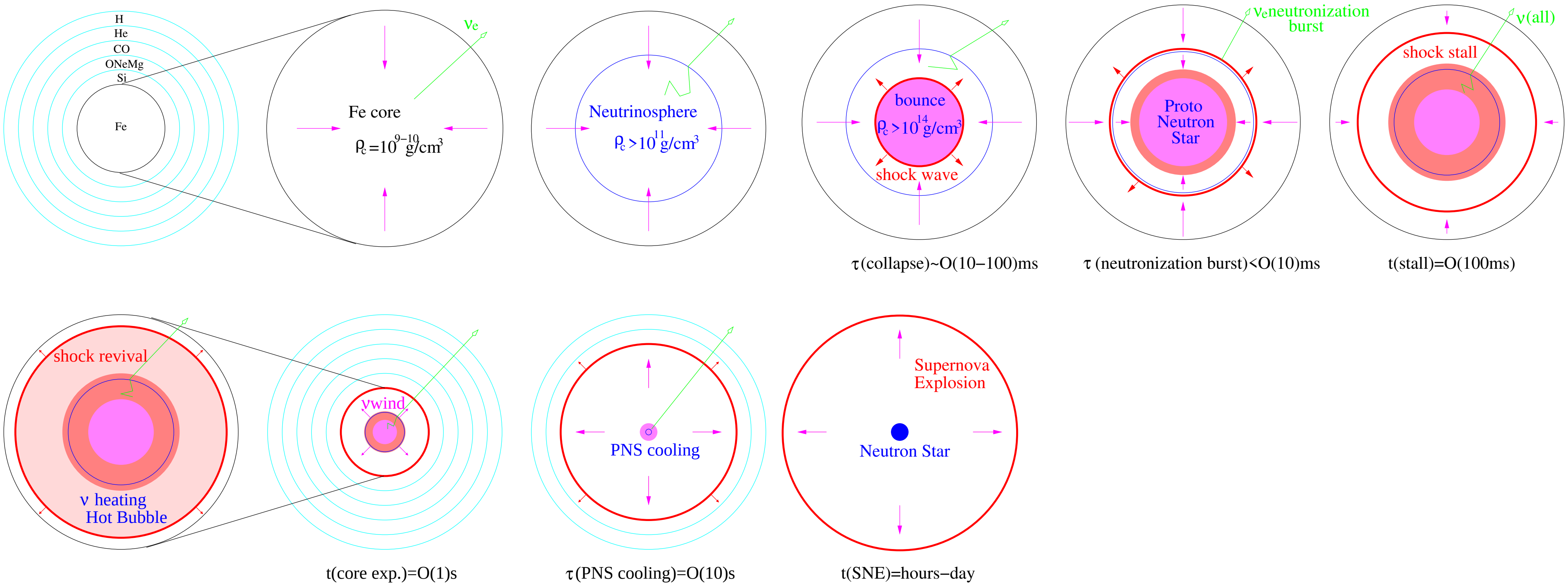




Collapse of Fe core → Bounce of inner core → Shock propagation, SN Explosion + **PNS** (Proto Neutron Star) Cooling with ν emission

PNS = bounced inner core (unshocked, cool)
+ accreted outer mantle (shocked, hot)

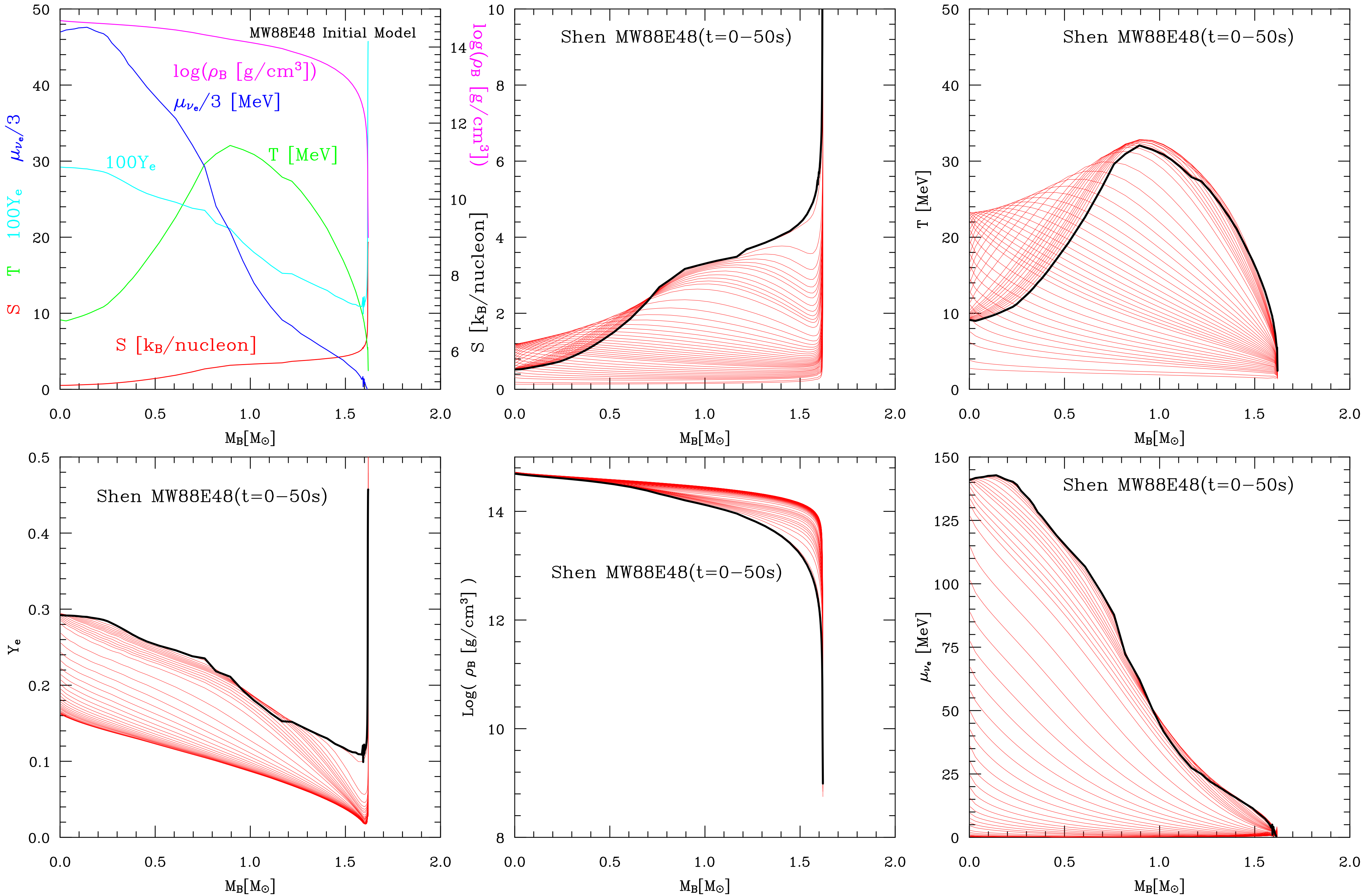
$T \sim 10\text{MeV}, \rho \gtrsim 10^{14}\text{g/cm}^3$, $\tau_{\text{weak}} \ll \tau_{\text{dyn}}$

ν: thermal equilibrium and chemical equilibrium with matter, $n_\nu \sim n_\gamma \sim n_{\text{e}}$

mean free path $\lambda_\nu \gg \lambda_\gamma, \lambda_{\text{e}}, \lambda_N$

⇒ Neutrinos carry out the energy and drive the PNS evolution

One of the main targets of neutrino astronomy



Electron Fraction : $Y_{\rm e} \equiv \frac{n_{\rm e^-} - n_{\rm e^+}}{n_B}$, Chemical Pot. of $\nu_{\rm e}$: $\mu_{\nu_{\rm e}} = \mu_{\rm p} + \mu_{\rm e} - \mu_{\rm n}$

Protoneutron Star Cooling

hot lepton-rich PNS	$\xrightarrow{\nu}$	cold Neutron Star
$T \sim O(10)\mathrm{MeV}$	$\xrightarrow{\text{cool down}}$	$T \sim 0$
$\mu_{\nu_e} \sim O(100)\mathrm{MeV}$	$\xrightarrow{\text{deleptonize}}$	$\mu_{\nu_e} \equiv \mu_p + \mu_e - \mu_n \sim 0$
	$\xrightarrow{\text{neutronize}}$	(ν-less β-equilibrium among n,p,e)
$R \sim 100\mathrm{km}$	$\xrightarrow{\text{shrink}}$	$R \sim 10\mathrm{km}$

$\tau_{\text{cool}} \sim \tau_{\text{diff}} = O(10)\text{sec}, \quad \tau_{\text{dyn}} \sim 1\text{msec} \ll \tau_{\text{diff}}$: quasistatic evolution

$\Rightarrow$ **the 2nd half of SN ν's** ($t = O(1) - O(100)$sec)

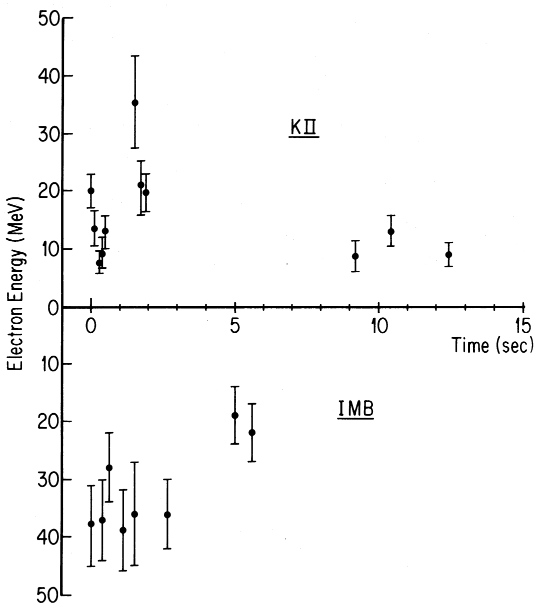
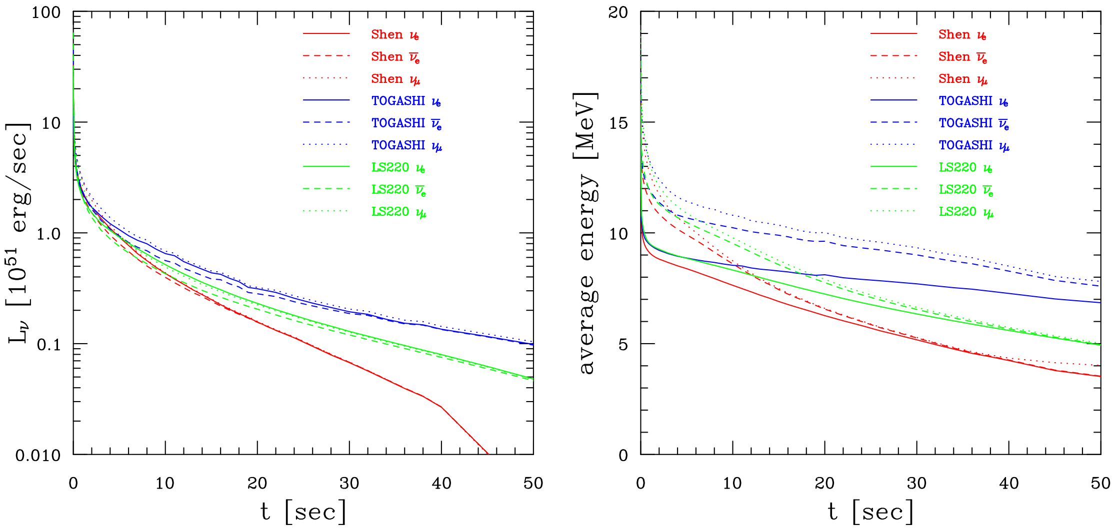


FIG. 1.—Electron energy in MeV vs. time in seconds for the Kamiokande II and the IMB data. The first events were placed at $t = 0$.

ν obs. of SN1987A, ApJ334, 891



ν's from PNS is one of promising probes for EOS (eq. of states)

Boltzmann equation for neutrino distribution function $f_\nu(t,\vec{r},\vec{p})$

$$\frac{\partial f_\nu}{\partial t}+\frac{d\vec{r}}{dt}\cdot\frac{\partial f_\nu}{\partial \vec{r}}+\frac{d\vec{p}}{dt}\cdot\frac{\partial f_\nu}{\partial \vec{p}}=\left.\frac{df_\nu}{dt}\right|_{\nu\ \text{interaction}} \qquad \text{in GR form}$$

Spherical symmetry $\Rightarrow f_\nu(t,r,p,\mu)$, $\mu\equiv\cos\theta=\vec{e}_r\cdot\vec{e}_p$: still need high comutational cost (suitable neither for long term simulations nor for systematic studies)
$\Rightarrow$ nth Angular Moment: $f_\nu^{(n)}(t,r,p)\equiv\int f_\nu\mu^n d\Omega$
solving moment equations ($\int$ (Boltzmann eq.)$\mu^n d\Omega$) for $n=0,1,\cdots,\infty\equiv$ solving Boltzmann equation

Reasonable simplification = truncation with finite $n_{\max}$

Flux Limited Diffusion Scheme (FLD)

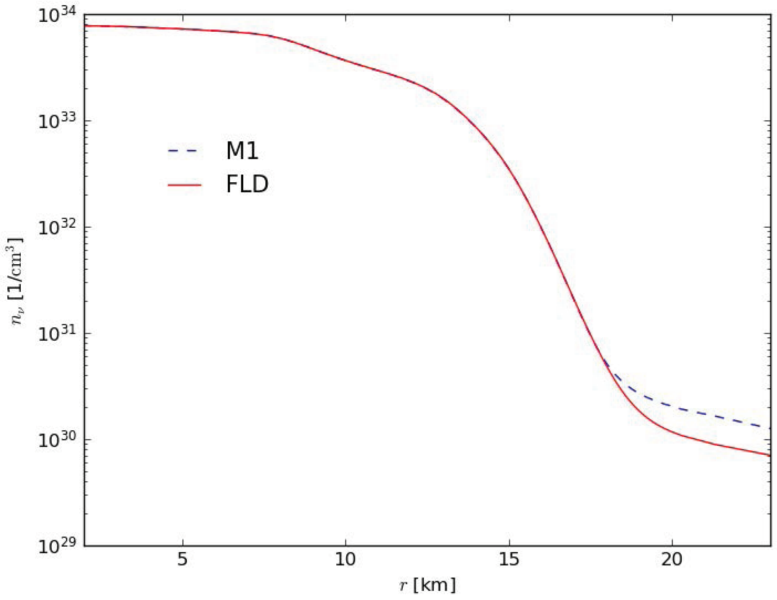
solve equations for 0th moment of Boltzmann equation ($n_{\max}=0$)
neutrino density $n_\nu(t,r,p)\propto f_\nu^{(0)}$: Multi Energy Group FLD (MGFLD)
neutrino flux $F_\nu\propto f_\nu^{(1)}$ is approximated as $-\frac{c\lambda}{3}\frac{\partial n_\nu}{\partial r}$ (diffusion approx.)
Instead of mean free path λ, the flux limter Λ is introduced in order to the flux should not exceed cn_ν (all νs move radially) in transparent region

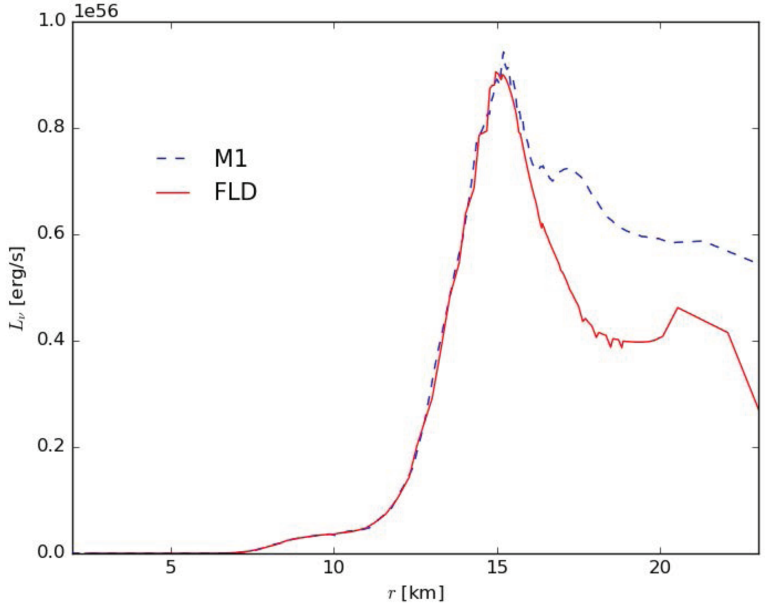
So far, we use the FLD scheme for long term ($O(100)$sec) PNSC simulations.
In order to perform more accurate calculations, we are developing a new numerical code using M1 scheme (see T. Shimura's Poster).

M1 Scheme solve equations for 0th and 1st moment of Boltzmann equation

assume some closure relations connecting 2nd moment to 0th and 1st moments ($n_{\max}=1$)

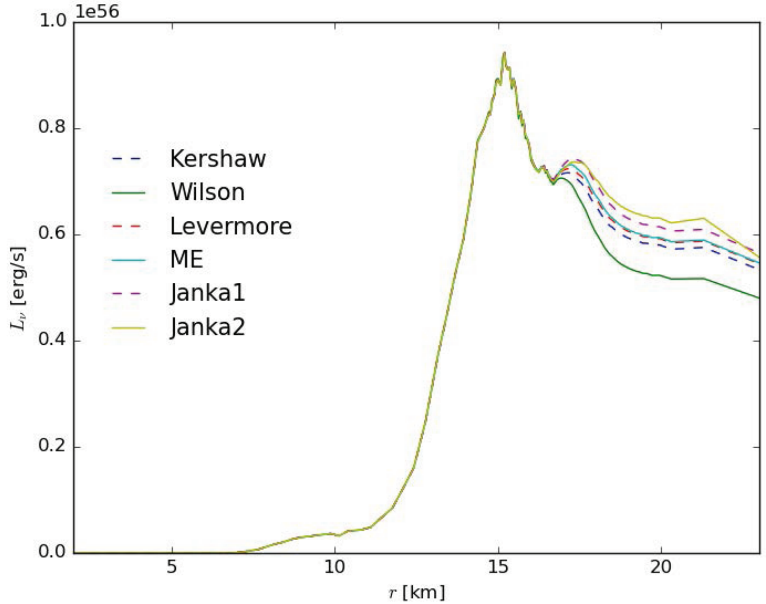
Comparison of steady flow with FLD and M1 scheme (T. Shimura's poster No.10_5)





Diffusive inner region: FLD = M1, semi-transparent surface: FLD < M1

Various closures



calibration can be done by comparison with results of Boltzmann solver.

TODO

- energy spectra
- quasistatic time evolution
- update of neutrino interaction rates
- convection
- systematic studies with various initial models and EOSs