超新星爆発の物理と数値シミュレーション

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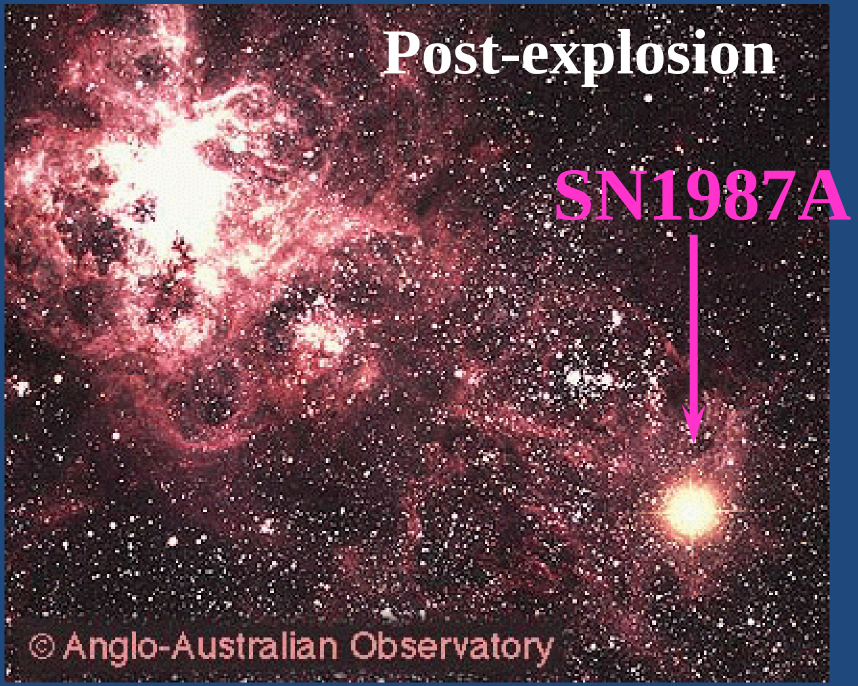
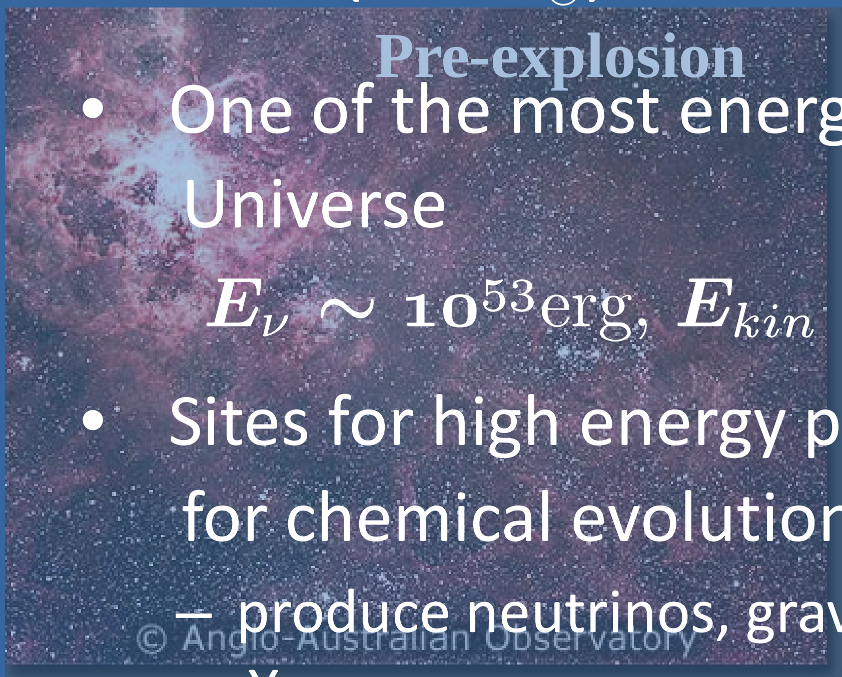
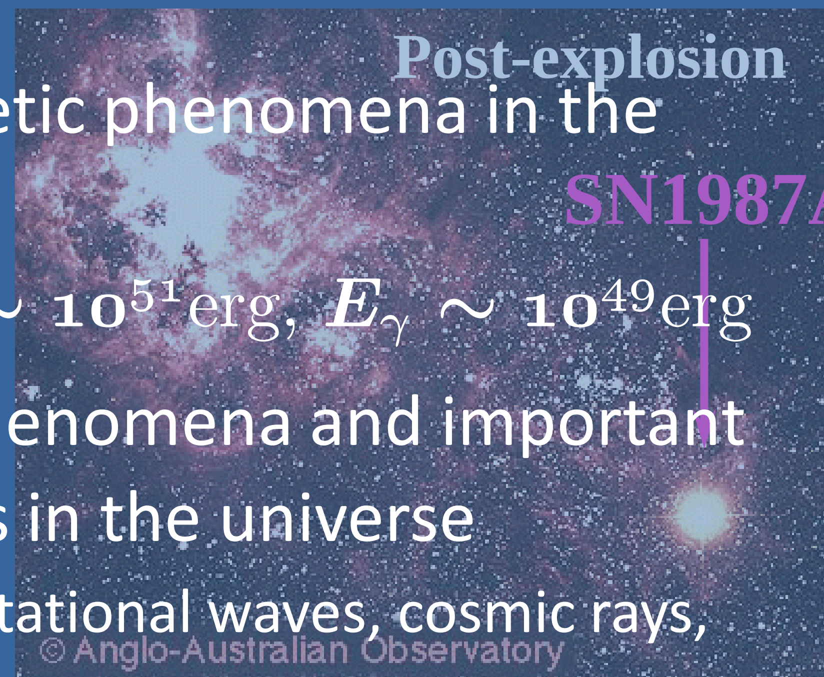
Fundamentals of Core-Collapse Supernovae



Fundamentals of Core-Collapse Supernovae

- Triggered by the gravitational collapse of massive stars ($\gtrsim 10 M_\odot$)





- One of the most energetic phenomena in the Universe

  $E_\nu \sim 10^{53}\mathrm{erg},\ E_{kin} \sim 10^{51}\mathrm{erg},\ E_\gamma \sim 10^{49}\mathrm{erg}$

- Sites for high energy phenomena and important for chemical evolutions in the universe
  - produce neutrinos, gravitational waves, cosmic rays, X-rays, gamma-rays
  - nucleosynthesis of heavy elements

Challenges in Supernova Research

Supernova is a complex interplay of

- **Micro Physics**
  - weak interactions
    - — neutrino interaction rates with matter
    - — neutrino oscillations
  - nuclear physics
    - — equation of state
    - — many body effects on neutrino reaction rates

- **Macro Physics**
  - hydrodynamics
    - — rotation
    - — convection
  - radiative transport
  - general relativity
    - — gravitational waves
  - magnetic field

We have to treat them all simultaneously and consistently.

Goals in Supernova Research

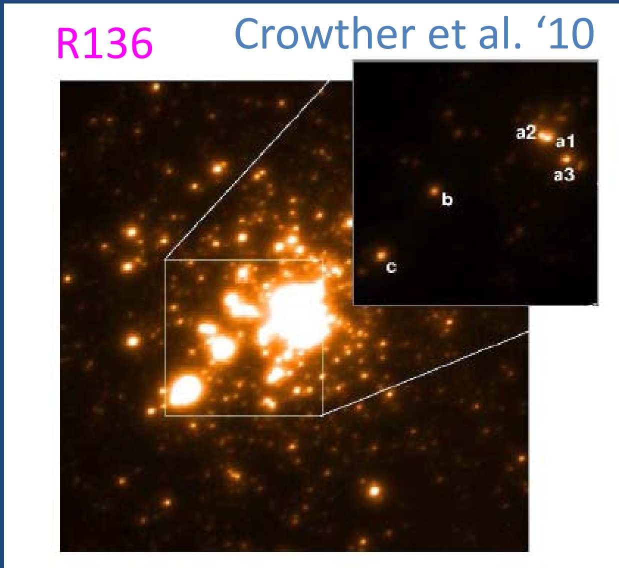
The supernova theory must address the following issues :

- ✓ How does the explosion occur and are the neutron star mass and explosion energy determined?
- ✓ How do the progenitors correspond to the supernova types?
- ✓ What is the origin of rotation, magnetic field, and proper motion of neutron stars?
- ✓ What is the relationship with other high energy objects such as GRBs
  — **hypernovae, magnetars**
- ✓ How do syntheses of heavy elements proceed?
  — **explosive nucleosynthesis, r-process**

CCSNe can be a new probe into the properties of dense hadronic matter as well as neutrinos!

Which Mass Stars Should We Blow Up?

- ✓ The present universe may be producing stars as massive as ~300M_{solar}.
- ✓ There is observational evidence that NS's are formed from very massive stars.
  - SGR 1806-20: $\gtrsim 50 M_\odot$
  - anomalous X-ray pulsar in young massive galactic cluster Westerlund 1: $\gtrsim 40 M_\odot$
  - anomalous X-ray pulsar 1E1048.1-5937 embedded in stellar wind bubble: $\sim 30-40 M_\odot$

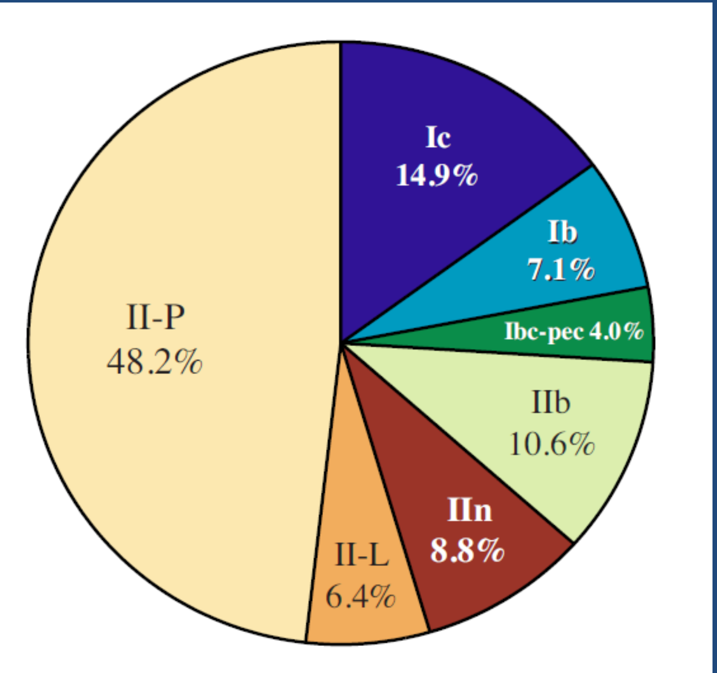


- ✓ The best bet for the minimum mass to produce CCSNe is 8±1M_{solar} at present.
- ✓ SNeII-P have been observed to be produced by 8.5-17M_{solar} stars.
- ✓ <u>Most of massive stars may explode to produce neutron stars!</u>

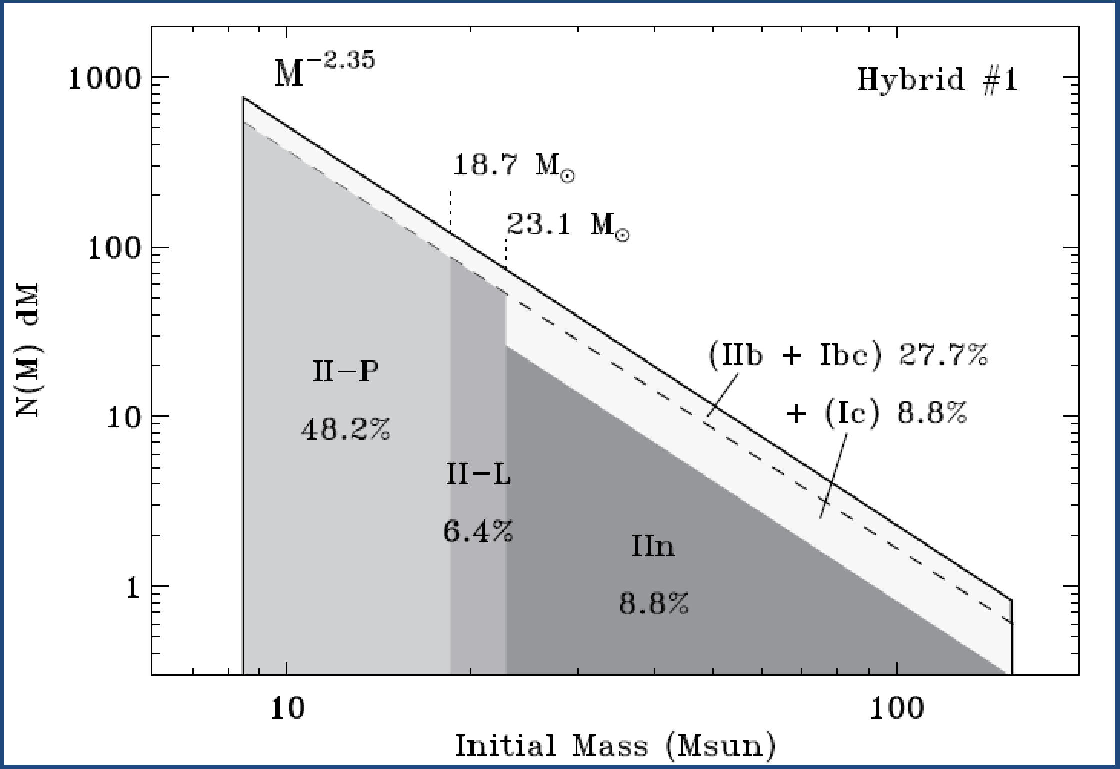
  — Core masses are not monotonic owing to mass losses.

SN Fractions

Smith et al. ’11



Core-Collapse SN Fractions



※ Quiet collapse to BH may not be required!

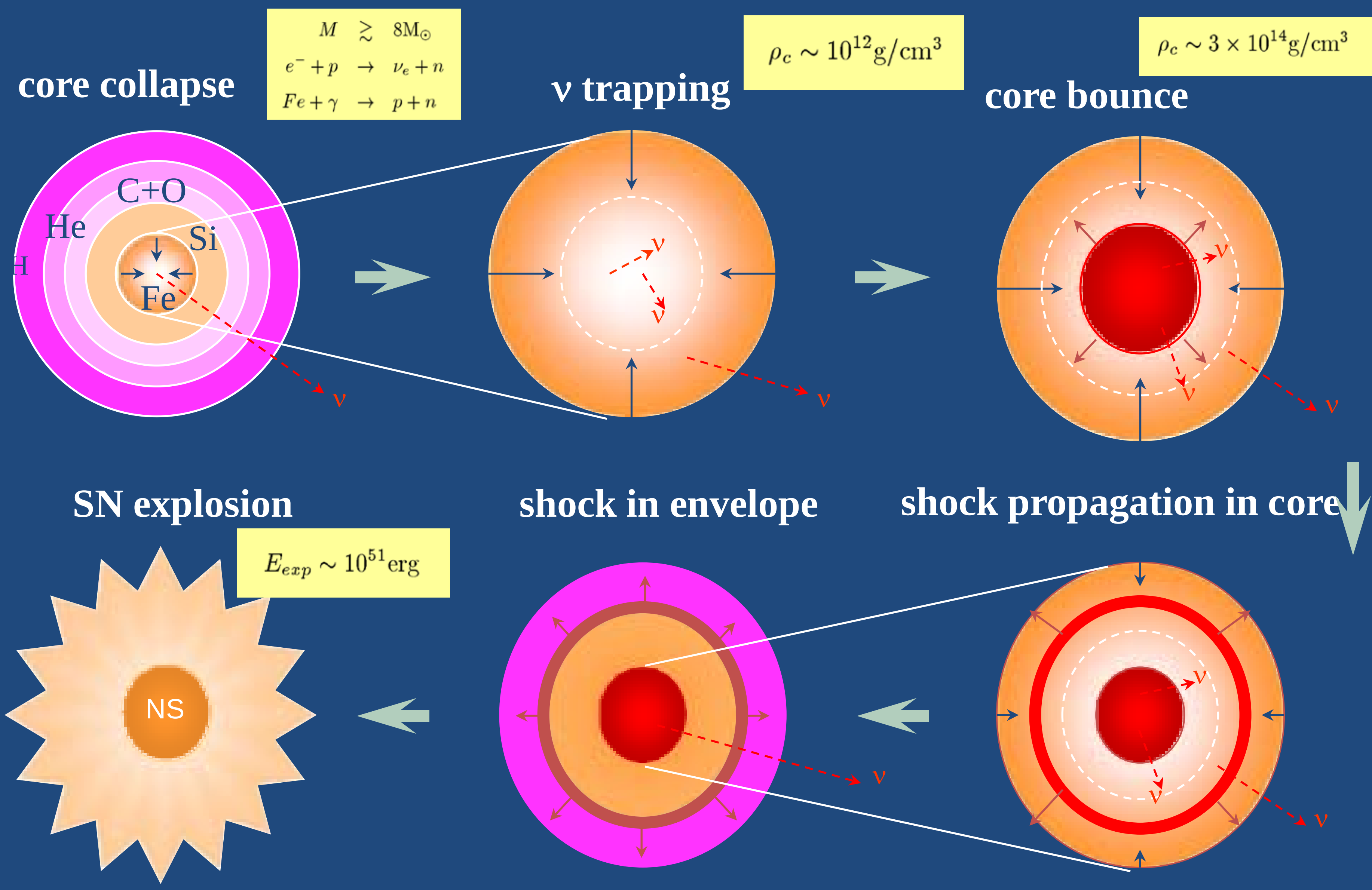
Very Luminous SNe

- ✓ Some SNe II-L (SN2008es, SN2005ap) and SNe IIn (SN2006gy, SN2006tf) are very bright.
  - $E_\gamma \sim 10^{51}$ erg
  - The late time light curves disfavor Ni-powered brightening.
  - Interactions with CSM produced by LBV-like activities are more likely
  - Explosion mechanisms are unknown.
    - pulsational instability
    - jet explosion as in GRB

    etc.
- ✓ Most luminous SNe are typically found in faint, small dwarf galaxies.
- ✓ There is another set of luminous SNe that show no H in their spectra, but have unusual light curves and spectra. → SNIpec
- ✓ Two luminous SNe (SN1999as and SN2007bi) show strong evidence of having been produced as a result of the pulsational pair instability. →SNIpp
  - $E_{exp} > 10^{52}$erg
  - $^{56}Ni > 4M_{solar}$
  - $M_{init} > 150M_{solar}$
  - There is evidence that SN2007bi was a single star.
  - SNIpec may be also of pulsational pair instability-origin, but not so extreme.

Canonical Evolutions of Core Collapse

Scenario of Collapse-Driven Supernovae



Latest 3D Simulation

Takiwaki et al '12

Onset of Core Collapse

✓ Cores of massive stars collapse when they lose stability against radial perturbations.

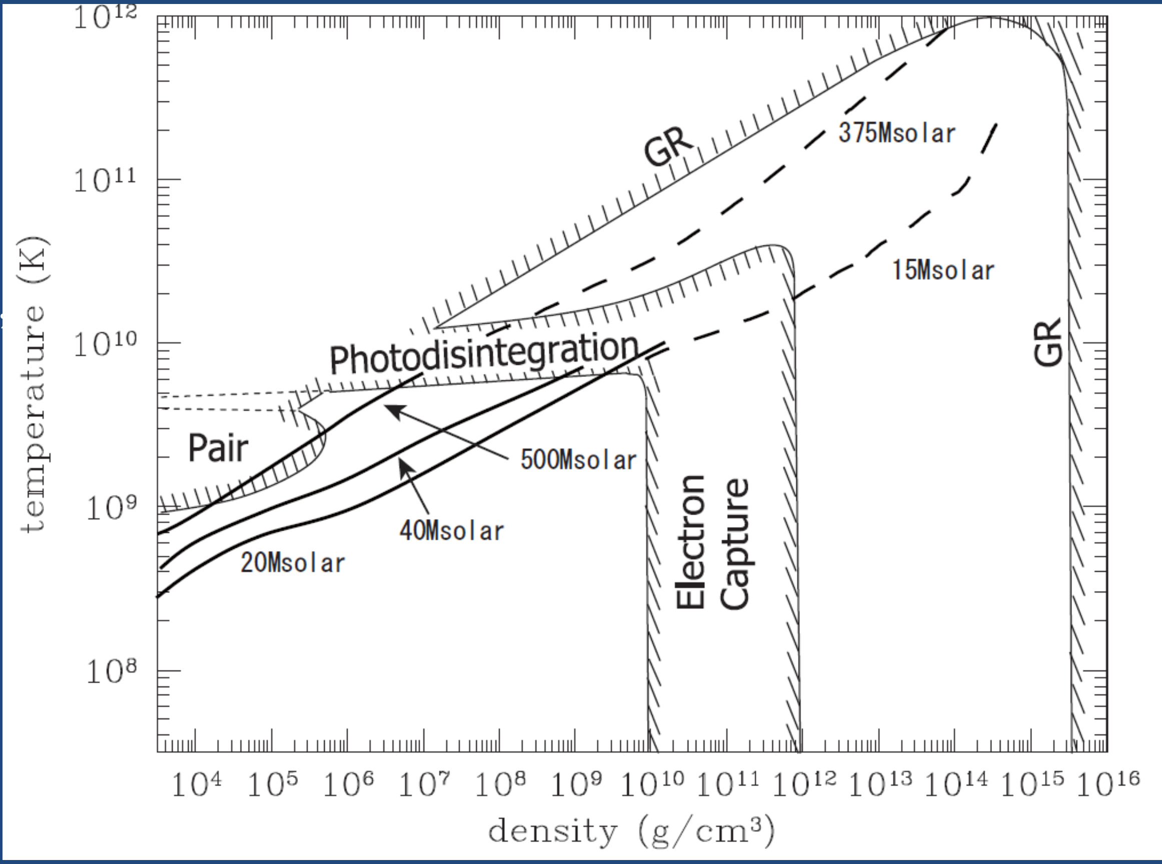
➢ (Newtonian) Criterion:

$$\text{adiabatic index } \Gamma = \left(\frac{\partial \ln p}{\partial \ln \rho}\right)_s < \frac{4}{3}$$

➢ Cores have low entropies, $s \sim 1k_B$, and are supported by degenerate electrons just like white dwarfs, having $\Gamma \sim 4/3$.

➢ Electron captures and photo-disintegrations tend to reduce Γ.

➢ As the density and temperature rise, these reactions proceed further, making the core even more unstable (positive feedback).



Neutrino Trapping

- ✓ Coherent scatterings on nuclei are the main source of neutrino opacity.

ν wave length: $\sim 20\text{fm}\left(\frac{\varepsilon_\nu}{10\text{MeV}}\right)^{-1}$

Nuclear radius: $\sim 5\text{fm}\,(A/56)^{1/3}$

ν mean free path: $\sim 10^6\,\text{cm}\left(\frac{\varepsilon_\nu}{10\text{MeV}}\right)^{-2}\left(\frac{\rho}{10^{12}\text{g/cm}^3}\right)^{-1}$

core radius: $\sim 10^7\,\text{cm}$

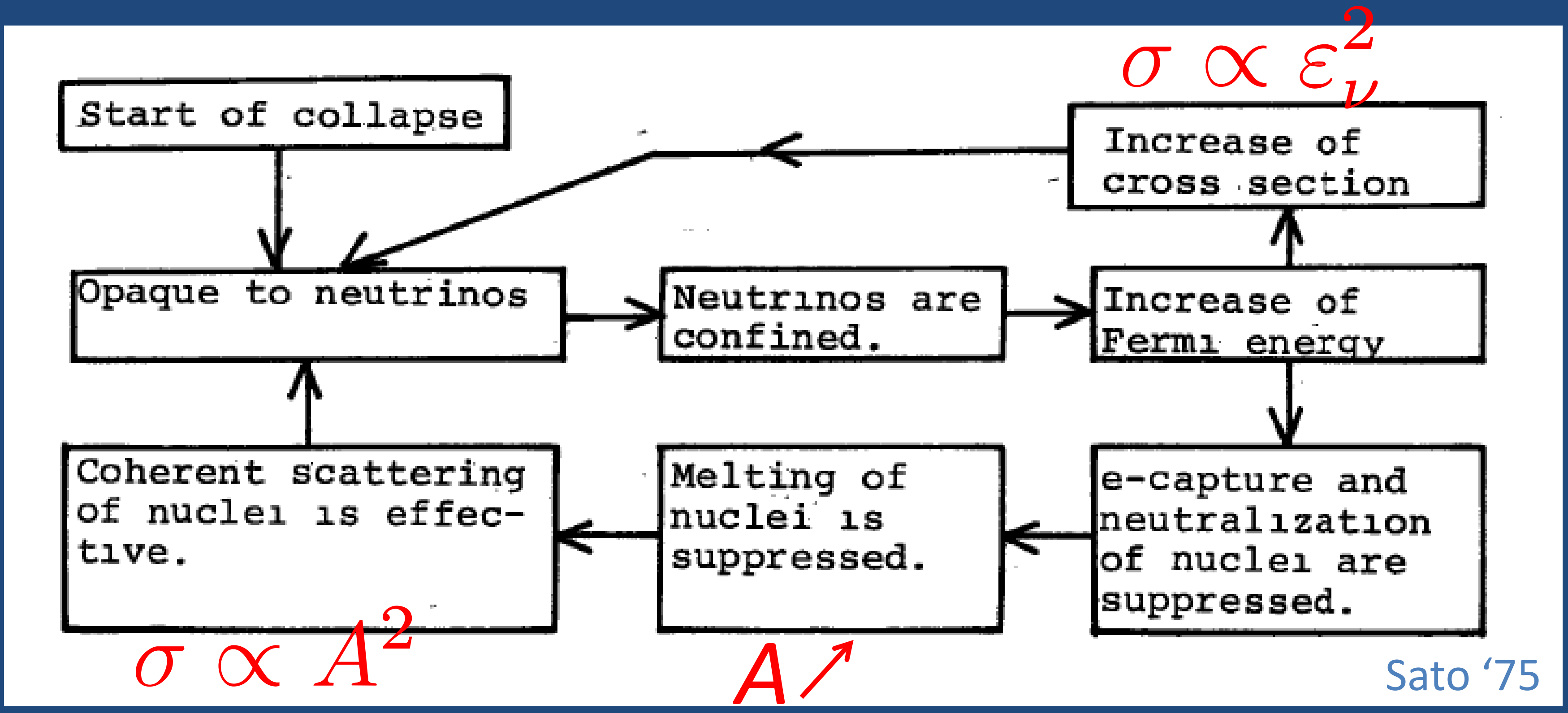
ν Diffusion time scale: $\sim 100\,\text{msec}\left(\frac{R_{PNS}}{3\times 10^6\text{cm}}\right)^2\left(\frac{\varepsilon_\nu}{10\text{MeV}}\right)^2\left(\frac{\rho}{10^{14}\text{g/cm}^3}\right)$

Dynamical time scale: $\sim 10\,\text{msec}\left(\frac{\rho}{10^{12}\text{g/cm}^3}\right)^{-1/2}$

- ✓ Neutrinos are essentially trapped in the core at $\rho \sim 10^{11}\text{g/cm}^3$ and diffuse out of the core thereafter.
- ✓ β-equilibrium is established at $\rho \sim 10^{12}\text{g/cm}^3$ and dynamics becomes adiabatic from this point to shock formation.

Positive Feedback in ν-trapping

✓ Weak neutral currents predicted by W-S theory have profound implications for supernova theory
- — Coherent scatterings make a core opaque for neutrinos.
- — Neutronization occurs much more slowly than the dynamical time scale.
- — Neutrinos diffuse out of the core.



Sato '75

Homologous Collapse

✓ Infalling cores are divided into two parts :

— inner core: subsonic and homologous

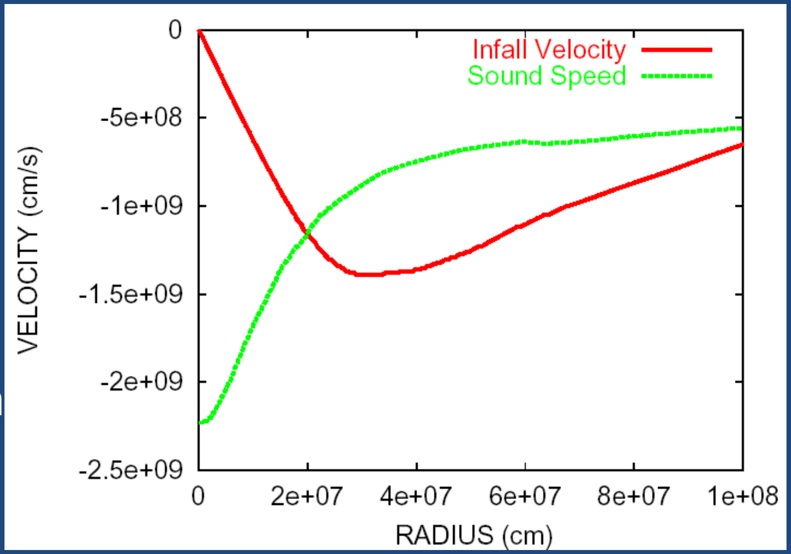
— outer core: supersonic and free fall-like

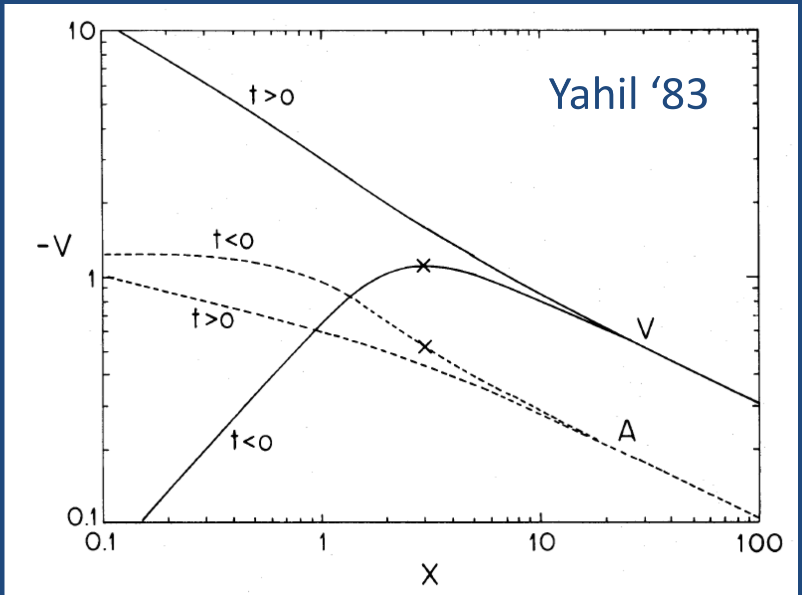
✓ The outer core is causally disconnected from the inner core.

— A shock wave produced at the boundary between the inner and outer cores.

✓ Yahil found a self-similar solution for Γ close to but slightly smaller than 4/3.

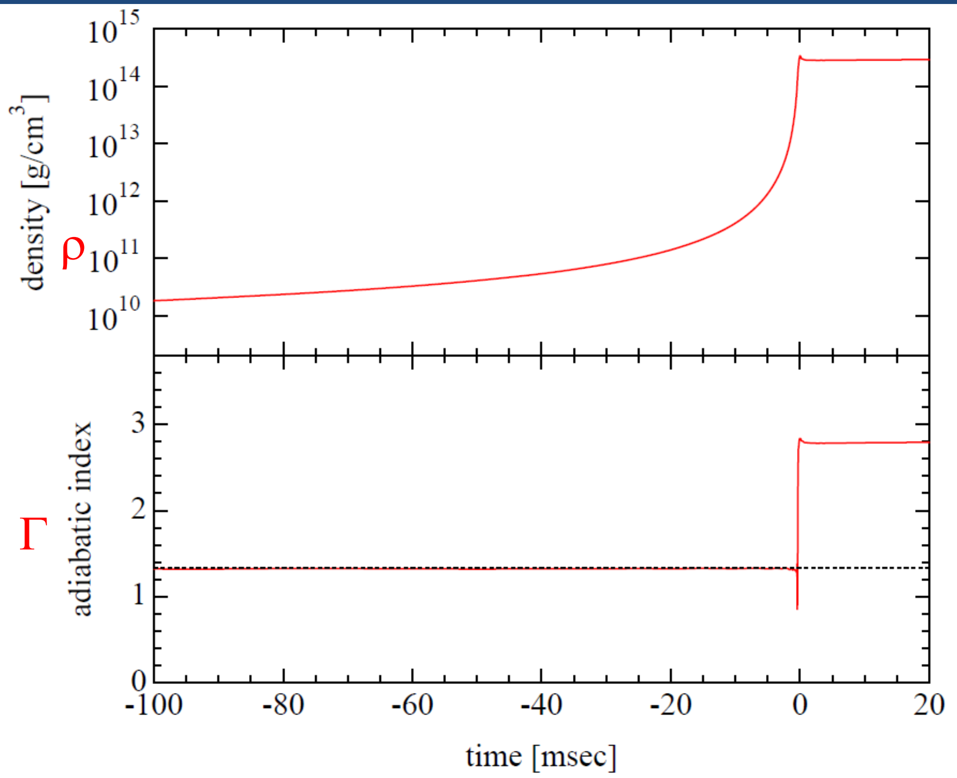
— The inner core mass is close to the Chandrasekhar mass corresponding to the reduced electron fraction and decreases in time.

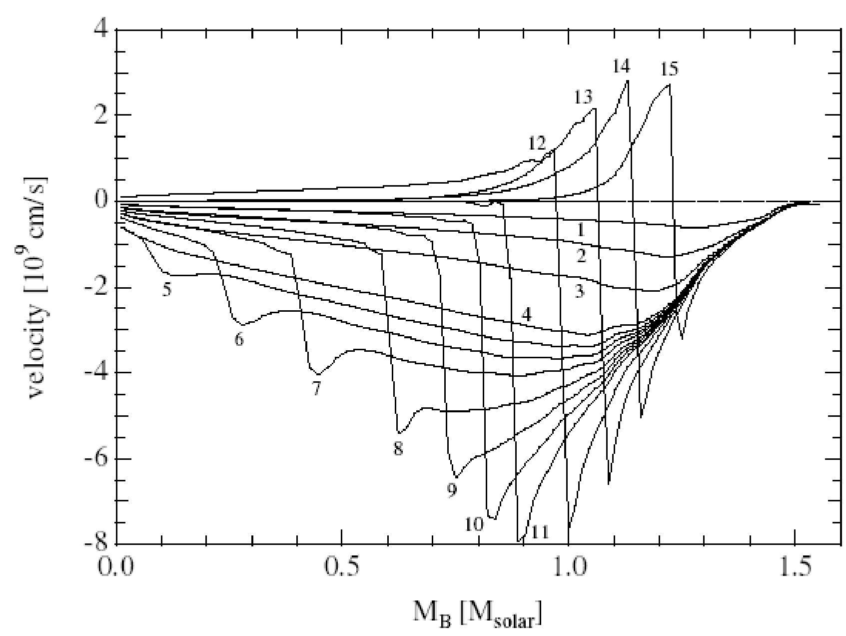




Core Bounce

- ✓ Matter becomes very stiff when the nuclear saturation density is exceeded.
- ✓ Matter then recovers stability against collapse and the inner core, the interior of which is causally connected, bounces as a whole.





✓ Most of gravitational energy is compensated for by internal energy and the energy imparted to the kinetic energy of outward motions is ~ a few x 10^{51} erg.

◆ Energy scales of relevance

- Rest mass energy: $\sim 10^{54}\mathrm{erg}\left(\frac{M}{M_\odot}\right)$

- Gravitational energy

  Progenitor core: $\sim -10^{51}\mathrm{erg}\left(\frac{M}{M_\odot}\right)^2\left(\frac{R_{core}}{10^8\mathrm{cm}}\right)^{-1}$

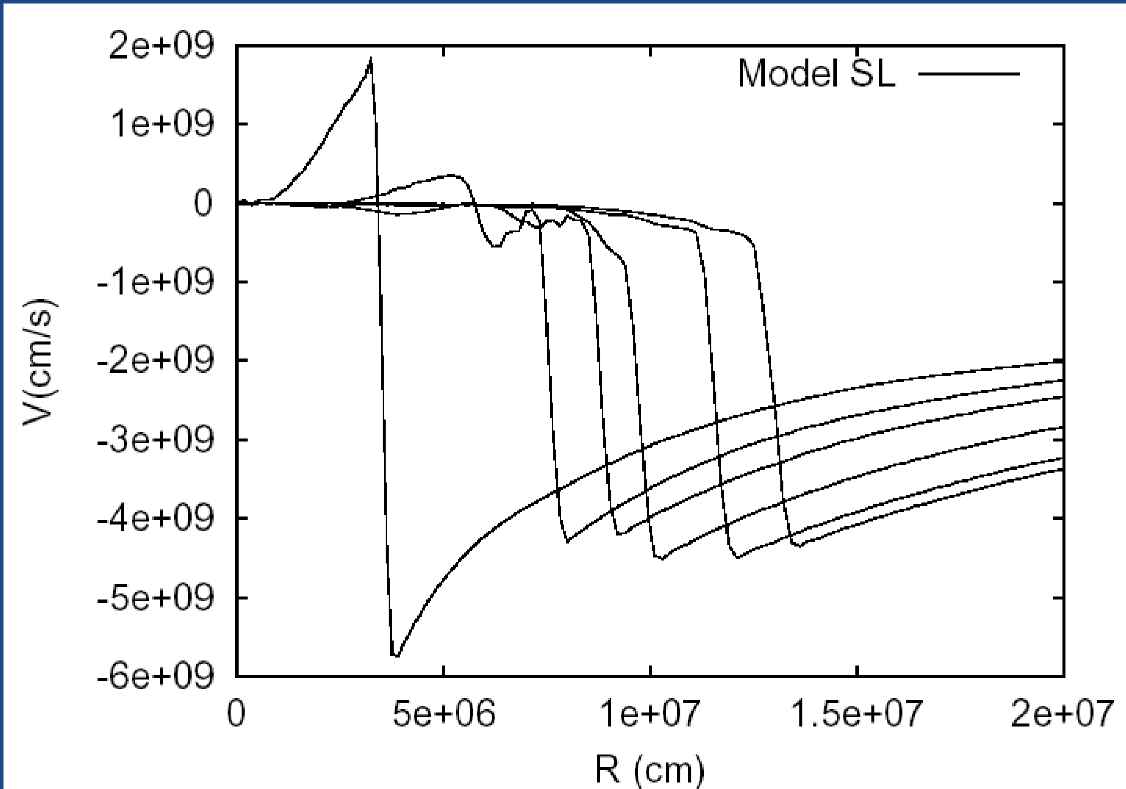
  Neutron star: $\sim -10^{53}\mathrm{erg}\left(\frac{M}{M_\odot}\right)^2\left(\frac{R_{NS}}{10^6\mathrm{cm}}\right)^{-1}$

- Shock wave: $\mathrm{a\ few} \times 10^{51}\mathrm{erg}$

Shock Propagation & Stagnation

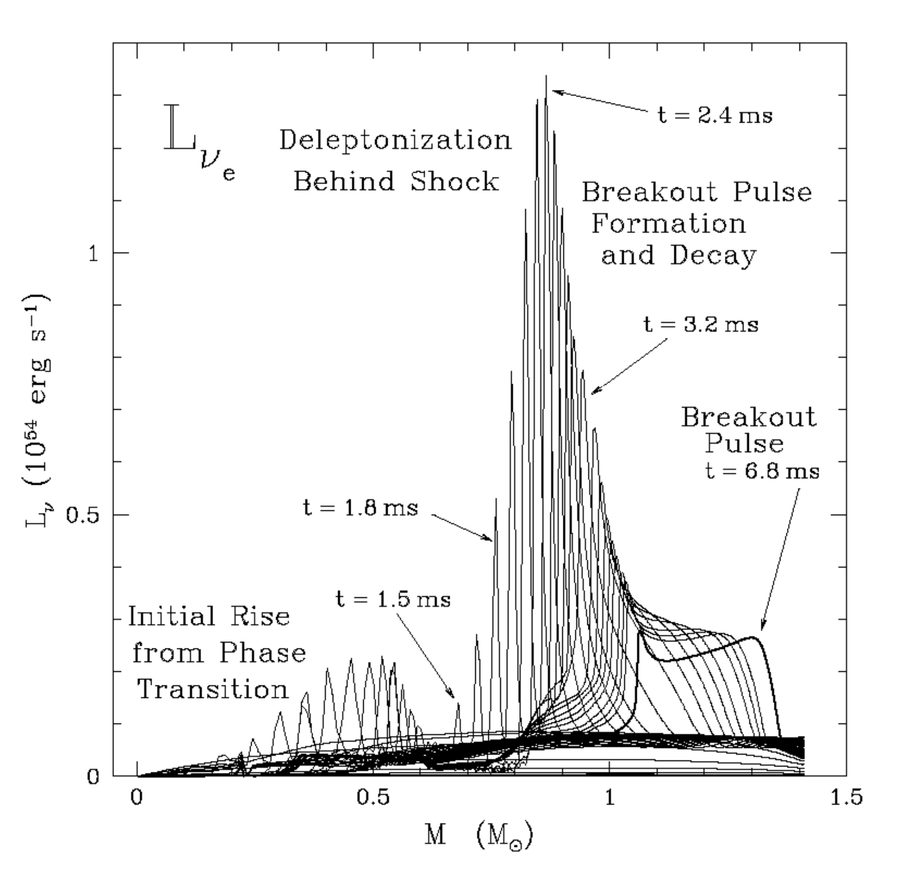
- ✓ The shock wave generated by core bounce propagates outwards initially.
- ✓ Photo-disintegrations of nuclei and neutrino cooling are energy sinks that make the shock wave stagnated at ~200km from the center in the core.
- ✓ The standing accretion shock wave then starts to recede back onto a nascent proto neutron star.

- ➢ Temperatures behind the shock wave is ~1MeV, high enough to dissociate heavy nuclei to Helium and nucleons.
- ➢ About 10^{51}erg is consumed to dissociate every $0.1M_{solar}$ of heavy nuclei.
- ➢ Massive cores and/or small inner cores are disadvantageous for successful shock break-out of the core.



Neutronization Bursts

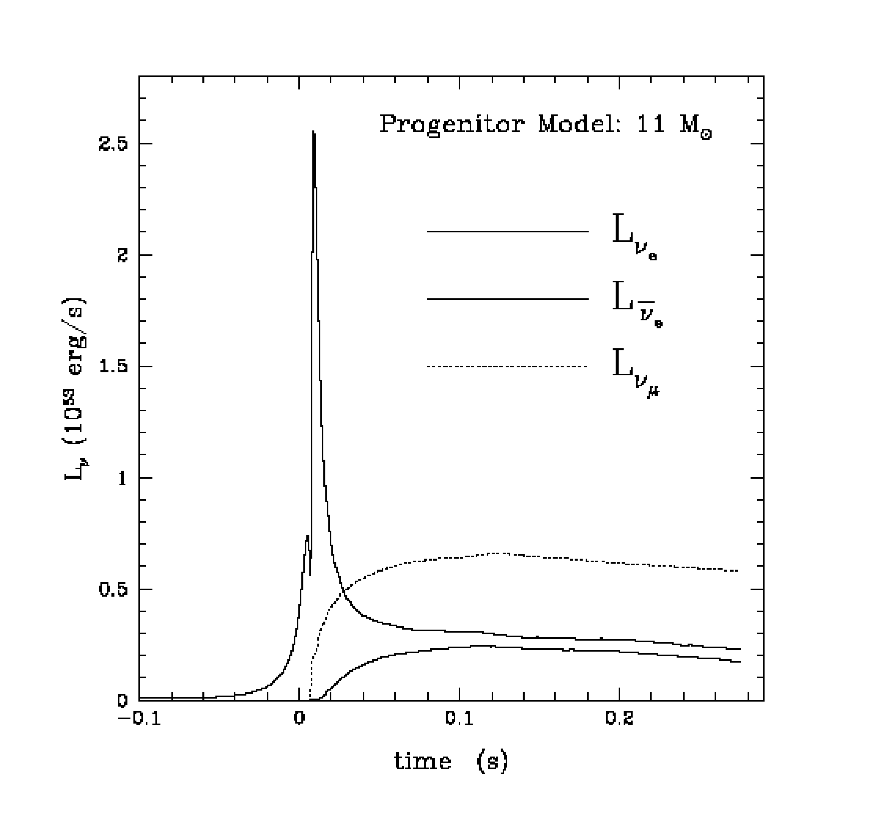
✓When the shock wave reaches the ν-sphere, heavy nuclei are photo-dissociated and the opacity is suddenly reduced and electron captures on protons are enhanced considerably, leading to the neutronization burst.



Thompson et al. '03

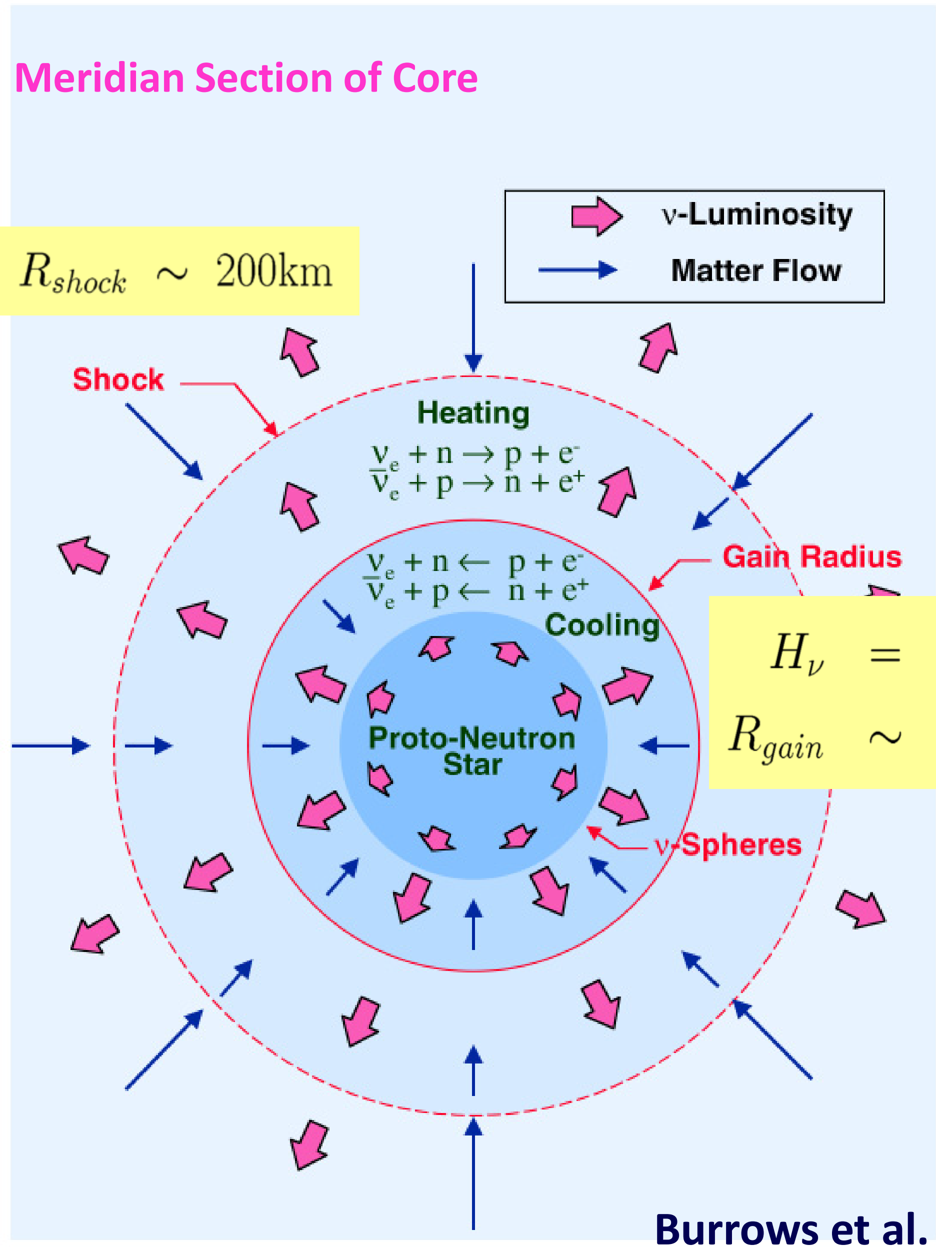
Neutronization Bursts

- ✓ Up to core bounce only ν_e's are produced and accumulated in the core.
- ✓ The luminosity is high, $O(10^{53}$erg/s) but the total energy is small, $O(10^{51}$erg). The burst will be detectable for SuperKamiokande for a Galactic event.



Thompson et al. '03

Neutrino Heating & Shock Revival



$$R_{shock} \sim 200\mathrm{km}$$

$$H_\nu = C_\nu$$

$$R_{gain} \sim 100\mathrm{km}$$

Burrows et al.

- ✓ Most of the liberated gravitational energy is stored in the proto neutron star as internal energy, which can be tapped by neutrinos.

$$E_G \sim E_{int} \sim 10^{53}\mathrm{erg}$$

- ✓ The initial shock energy is not large enough to push through the outer core.

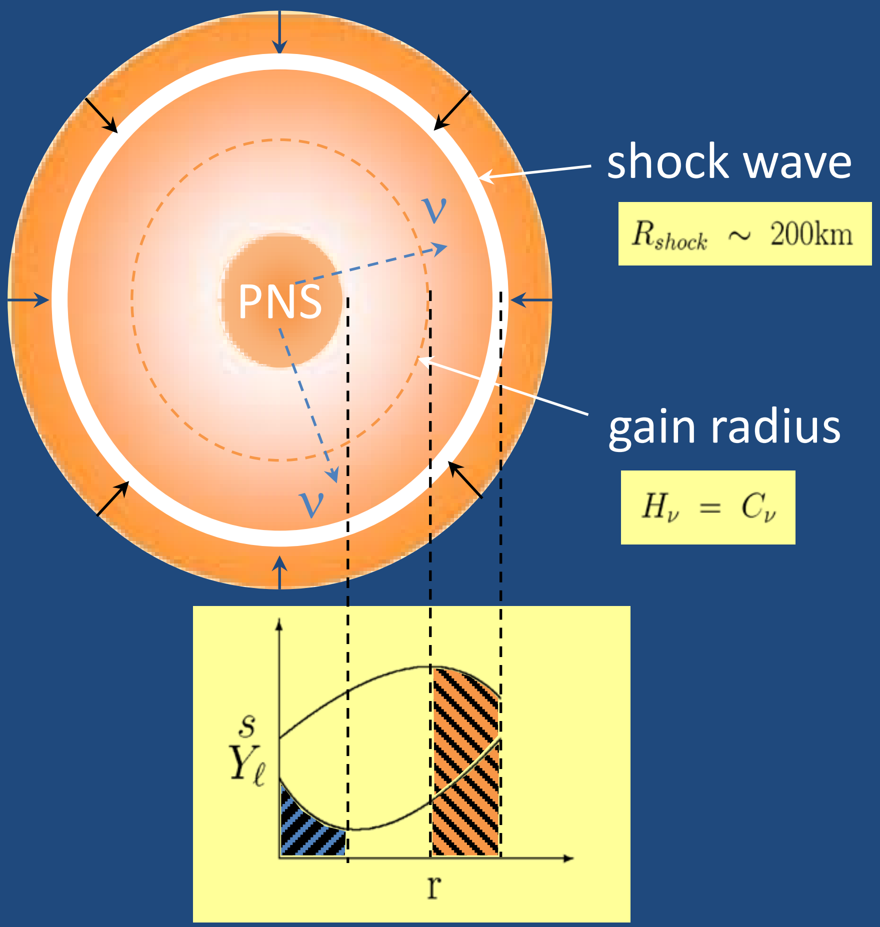
$$E_{sh} \lesssim 5 \cdot 10^{51}\mathrm{erg} < E^{loss}_{\nu,Fe}$$

- ✓ The shock is stalled inside the core and becomes an accretion shock. The shock should be somehow revived.

- ✓ The spherically symmetric con-figuration is unstable!

Hydrodynamical Instabilities

✓ Post bounce configuration



✓ **Convections**

- <u>prompt convection</u>
  - — weakening of prompt shock
  - — entropy-driven
  - — just behind shock
  - — not sustained long
- <u>Bethe convection</u>
  - — neutrino heating
  - — entropy-driven
  - — between shock and gain radius
- <u>lepton-driven convection</u>
  - — neutrino diffusion
  - — lepton-driven
  - — around ν-sphere

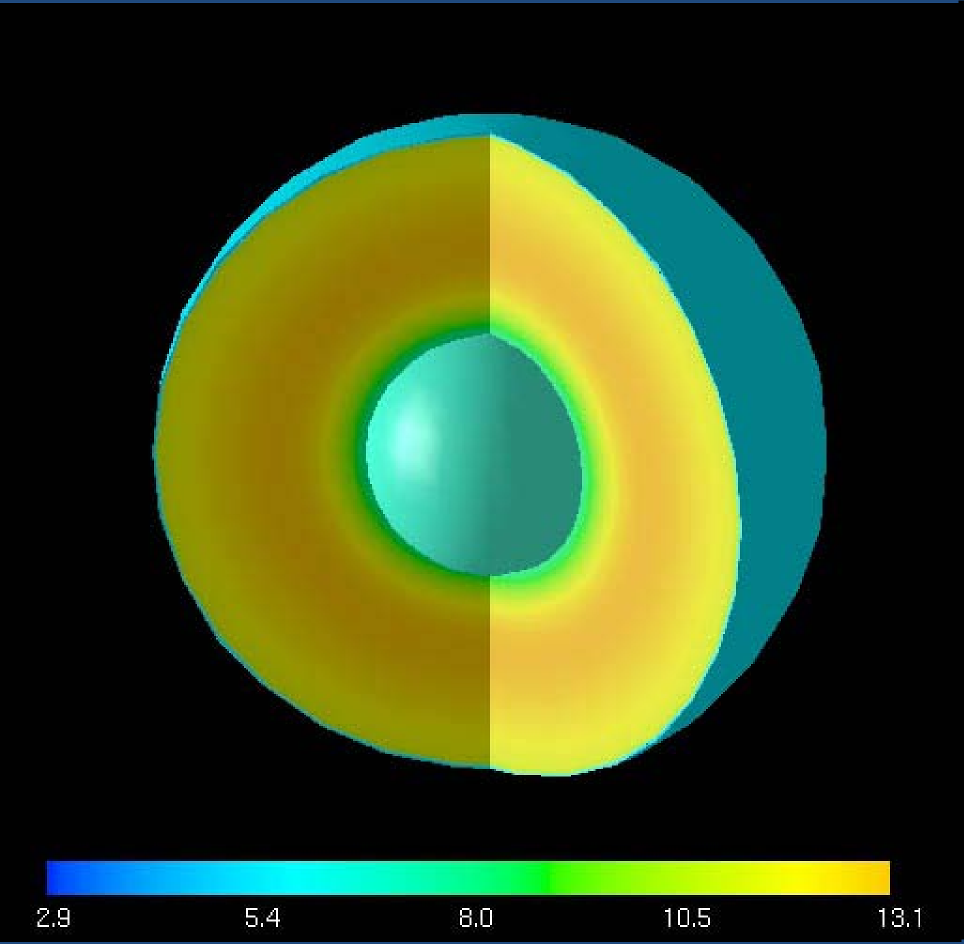
✓ **Standing Accretion Shock Instability (SASI)**

- — acousto-vortex cycle-driven
- — between shock and PNS surface

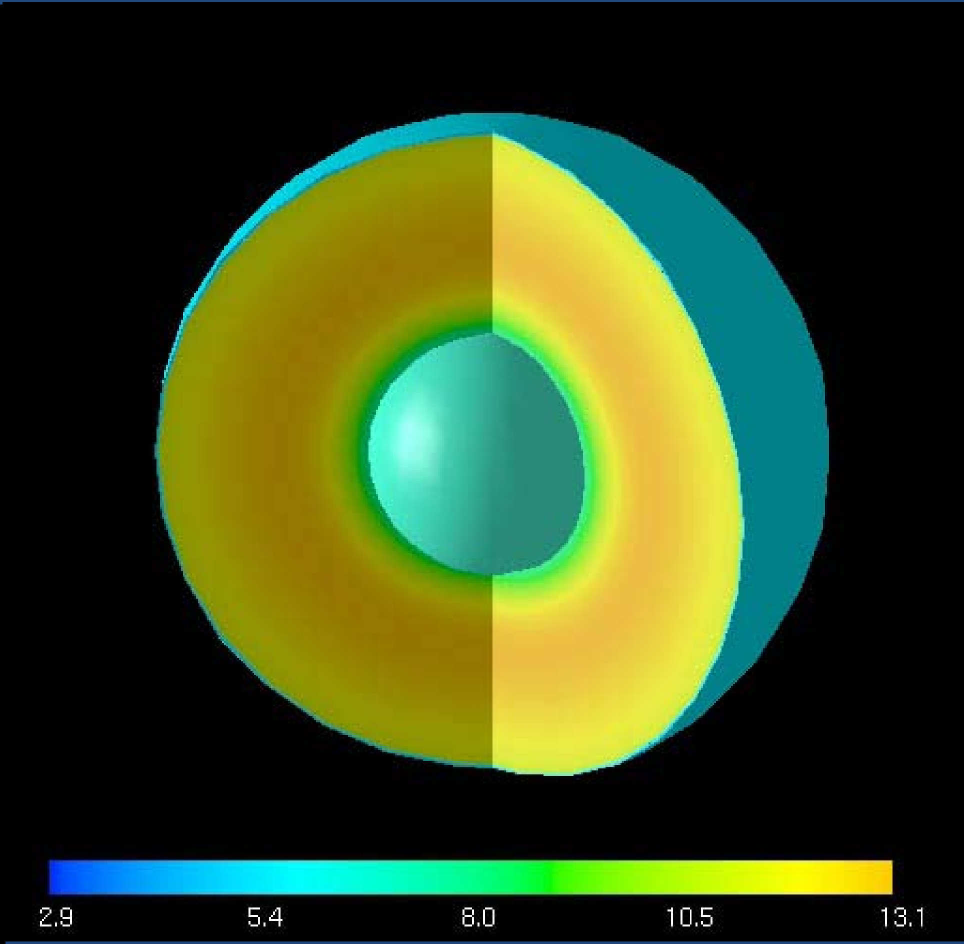
✓ (g-mode oscillations of PNS)

SASI in 2D and 3D

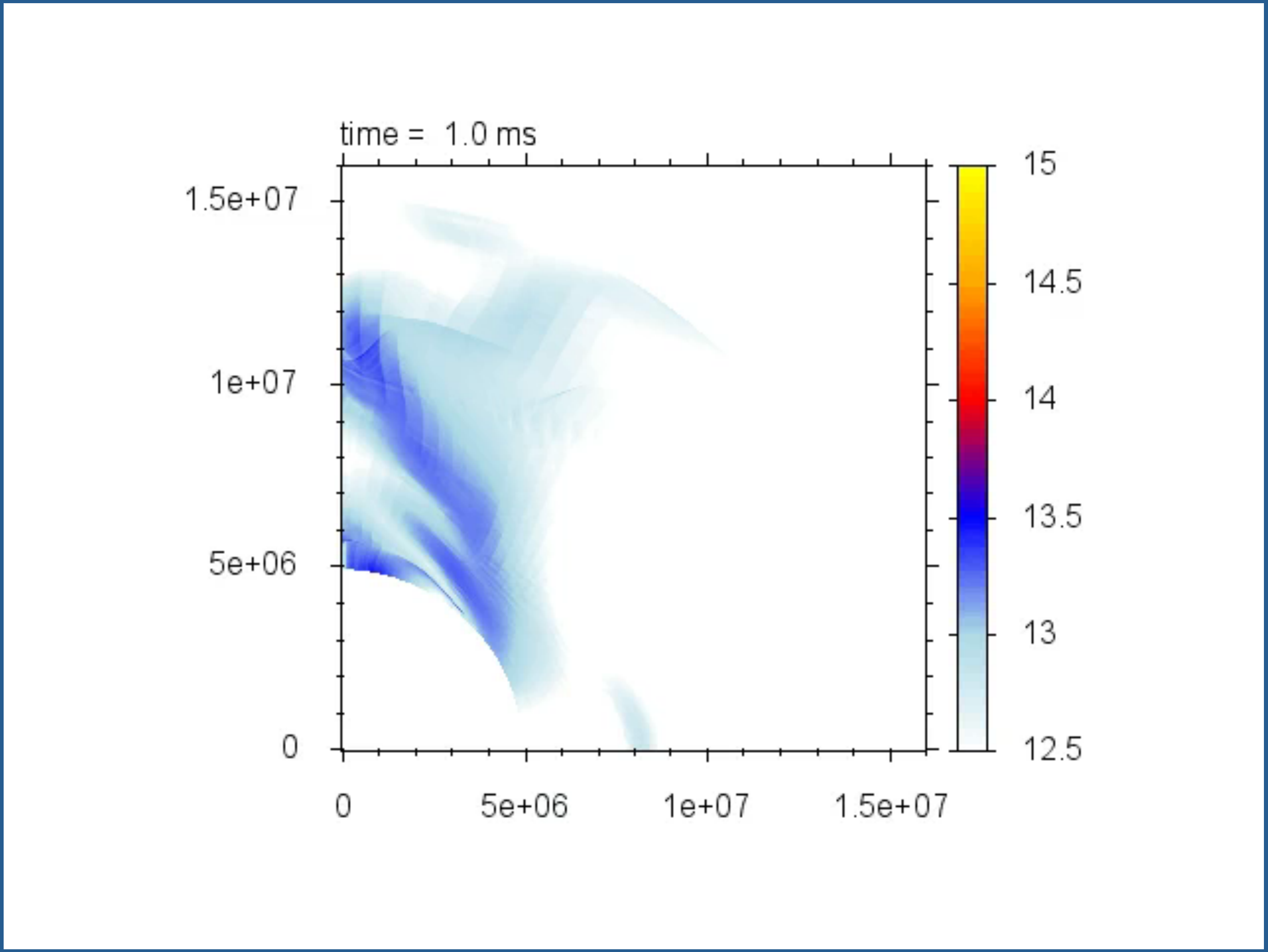
2D with axisymmetry



3D



Magnetohydrodynamical Instabilities: Magnetorotational Instability (MRI)



Sawai et al. '13

Summary of CCSNe

- ✓ CCSN is an explosion of massive stars triggered by core collapse.
- ✓ The liberated gravitational energy ~10^{53}erg is far greater than the typical explosion energy ~10^{51}erg. The problem is that it is stored as internal energy initially and unavailable for explosion directly.
- ✓ ν's are the only agents of non-local energy transport that can tap the internal energy stored in PNS.
- ✓ The density changes from ~10^{10} to 3-5 x 10^{14} g/cm^3 and temperature varies from ~10^{10} to a few x 10^{11}K.
- ✓ The matter changes its nature drastically at nuclear saturation density ~3×10^{14}g/cm^3.

Summary of CCSNe

- ✓ CCSN is an explosion of massive stars triggered by core collapse.
- ✓The liberated gravitational energy ~10^{53}erg is far greater

We are required to compute gas dynamics with the energy-transport by neutrinos and thermodynamical nature of matter being taken into account properly.

- ✓ ν's are the only agents of non-local energy transport that can tap the internal energy stored in PNS.
- ✓ The density changes from ~10^{10} to 3-5 x 10^{14} g/cm^3 and temperature varies from ~10^{10} to a few x 10^{11}K.
- ✓ The matter changes its nature drastically at nuclear saturation density ~3×10^{14}g/cm^3.

Basic Equations & Input Physics

ν-Radiation (Magneto) Hydrodynamics

✓ Gas dynamics is described with (magneto-) hydrodynamical equations.

- Dissipations can be neglected, since particle mean free paths are very short.

$$\lambda \sim 10^{-10}\mathrm{cm}\left(\frac{\sigma}{10^{-24}\mathrm{cm}^2}\right)\left(\frac{\rho}{10^{10}\mathrm{g/cm}^3}\right)$$

- Variables to be solved are baryonic number density, n_B, electron fraction, Y_e, (= proton fraction, Y_p), entropy per baryon, s, (alternatively, temperature, T, or internal energy density, e, total energy density, E, etc.) and velocities, $\boldsymbol{v}$, (plus magnetic fields, $\boldsymbol{B}$).

- Continuity eq., Euler eqs., eq. for electron fraction (plus induction eq.) are solved, employing an appropriate EOS.

- Spacetime geometry (gravitational potential in Newtonian gravity) is solved simultaneously.

✓ Continuity Eq.

$$\nabla_\mu (n_B u^\mu) = 0$$: Baryon number conservation

✓ Eq. for Y_e

$$\nabla_\mu (n_L u^\mu) = 0$$: Lepton number conservation

$$\Rightarrow \quad \nabla_\mu (n_e u^\mu) = -\nabla_\mu (n_{\nu_e} u^\mu)$$

$$\Rightarrow \quad u^\mu \nabla_\mu Y_e = -u^\mu \nabla_\mu Y_{\nu_e}$$

Expressed by collision terms of Boltzmann eq.

※ Heavy leptons are not abundant in supernova cores.

Energy-momentum tensors

$$T^{\mu\nu} = T_M^{\mu\nu} + T_R^{\mu\nu} (+ T_{EM}^{\mu\nu})$$

$$T_M^{\mu\nu} = \rho u^\mu u^\nu + (g^{\mu\nu} + u^\mu u^\nu) p$$

$$T_R^{\mu\nu} = E_R u^\mu u^\nu + u^\mu F_R^\nu + F^\mu u_R^\nu + P_R^{\mu\nu}$$

$$\left(T_{EM}^{\mu\nu} = \frac{1}{4\pi} \left[F^{\mu\rho} F_\rho^\nu - \frac{1}{4} g^{\mu\nu} F^{\rho\sigma} F_{\rho\sigma} \right] \right)$$

✓ Euler Equations

$$\nabla_\nu T^{\mu\nu} = 0$$

$$\text{or } \nabla_\nu T_M^{\mu\nu} = -\nabla_\nu T_R^{\mu\nu} (-\nabla_\nu T_{EM}^{\mu\nu})$$

Expressed by collision terms of Boltzmann eq.

✓ Einstein eq.

$$G^{\mu\nu} = T^{\mu\nu}$$

✓ Equation of State (EOS)

$$p = p(n_B, \varepsilon, Y_e)$$

※ ε can be replaced by other thermodynaical variable such as *s*, *T*, etc.

✓ Induction eq.

$$\begin{aligned} dF^{\mu\nu} &= 0 \\ \nabla_\nu F^{\nu\mu} &= \frac{4\pi}{c} j^\mu \\ F^{\mu\nu} u_\nu &= 0 \end{aligned}$$

- ✓ The agents of radiative transport of energy and momentum are neutrinos.
  - — Wave lengths of neutrinos are much shorter than the hydrodynamical length scale and neutrinos can be treated as particles and be described by kinetic equations such as Boltzmann equation.
    - Neutrino oscillations are the only processes, in which wave characters of neutrinos manifest themselves in macroscopic phenomena.
  - — Mean free paths of neutrinos are longer than the hydrodynamic length scale at low densities ($\rho_B \lesssim 10^{11} \mathrm{g/cm^3}$).
  - — Neutrino distributions are not the Fermi-Dirac distributions even locally at low densities and should be solved with the kinetic equations.

✓ Only electron-type neutrinos are produced before core bounce but all six types of neutrinos are abundant after bounce.

✓ Unless heavy leptons are produced, there is no difference between μ- and τ-neutrinos.

✓ The distribution of ν_μ (ν_τ) is different from that of $\bar{\nu}_\mu$ ($\bar{\nu}_\tau$) in principle. The difference is minor and neglected in practice.

✓ Tiny neutrino masses are neglected unless neutrino oscillations are considered.

$$m_\nu \lesssim 1\mathrm{ev} \ll E_\nu \sim O(\mathrm{MeV})$$

✓ Boltzmann Eq.

$$\frac{df}{d\lambda} = \left(\frac{\delta f}{\delta\lambda}\right)_c \Rightarrow p^\mu \frac{\partial f(x,p)}{\partial x^\mu} + \frac{dp^i}{d\lambda}\frac{\partial f(x,p)}{\partial p^i} = \left(\frac{\delta f(x,p)}{\delta\lambda}\right)_c$$

$$\lambda : \text{affine parameter} \quad p^\mu = \frac{dx^\mu}{d\lambda}, \quad \frac{dp^\mu}{d\lambda} = \Gamma^\mu_{\rho\sigma} p^\rho p^\sigma : \text{geodesic eq.}$$

Number current & Energy-momentum Tensor

$$n^\mu = \int \frac{d^3p}{E(p)} p^\mu f(x,p), \quad T^{\mu\nu} = \int \frac{d^3p}{E(p)} p^\mu p^\nu f(x,p)$$

※ In an orthonormal frame

Change of Number & Energy-momentum Densities

$$\nabla_\mu n^\mu = \int \frac{d^3p}{E(p)} \left(\frac{\delta f(x,p)}{\delta\lambda}\right)_c, \quad \nabla_\nu T^{\mu\nu} = \int \frac{d^3p}{E(p)} p^\mu \left(\frac{\delta f(x,p)}{\delta\lambda}\right)_c$$

※ In an orthonormal frame

Microphysical inputs in core collapse simulations:

- EOS : various thermodynamical quantities, such as p, T, μ, c_s and nuclear abundance X_A, as functions of 3 independent variables of your choice, e.g. (n_B, ε, Y_e)

- ν interactions :
  plugged in the collision term of Boltzmann eqs.

$$\left(\frac{\delta f(x,p)}{\delta \lambda}\right)_c$$

EOS

Lattimer & Swesty's EOS

✓ Based on a model free energy per baryon with the Skyrme-type parametrization:

$$f(n, Y_p, T) = E(n, Y_p, T)/n - Ts(n, Y_p, T)$$

$$E(n, Y_p, T) = \sum_t \frac{\hbar^2 \tau_t}{2 m_t^*} + [a + 4b Y_p(1 - Y_p)] n^2 + c n^{1+\delta} - Y_p n \Delta,$$

$$s(n, Y_p, T) = \sum_t \left(\frac{5 \hbar^2 \tau_t}{6 m_t^* T} - n_t \eta_t \right) / n.$$

t : isospin, τ_t : kinetic energy density, m_t^* : effective mass
Δ : n-p mass difference, $V_t = \delta E/\delta n_t$, $\eta_t = (\mu_t - V_t)/k_B T$

✓ The parameters *a*, *b*, *c* and δ are determined by the properties of zero temperature symmetric nuclear matter at its saturation density: saturation density, binding energy, bulk symmetry energy and bulk incompressibility.

Shen's EOS

- ✓ Relativistic mean field theory
- ✓ Nuclear interactions are described by meson exchanges.

$$
\begin{aligned}
\mathcal{L}_{RMF} \;=\;& \bar{\psi}\left[i\gamma_\mu\partial^\mu - M - g_\sigma\sigma - g_\omega\gamma_\mu\omega^\mu - g_\rho\gamma_\mu\tau_a\rho^{a\mu}\right]\psi \\
&+\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 \\
&-\frac{1}{4}W_{\mu\nu}W^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{4}c_3\left(\omega_\mu\omega^\mu\right)^2 \\
&-\frac{1}{4}R^a_{\mu\nu}R^{a\mu\nu} + \frac{1}{2}m_\rho^2\rho^a_\mu\rho^{a\mu}.
\end{aligned}
$$

ψ : nucleons, σ : scalar-isoscalar meson
ω : vector-isoscalar meson, ρ : vector-isovector meson

$$W_{\mu\nu} = \partial^\mu\omega^\nu - \partial^\nu\omega^\mu$$

$$R^a_{\mu\nu} = \partial^\mu\rho^{a\nu} - \partial^\nu\rho^{a\mu} + g_\rho\epsilon^{abc}\rho^{b\mu}\rho^{c\nu}$$

- ✓ The meson masses and coupling constants are determined to reproduce the properties of nuclear matter at its saturation as well as of finite nuclei.

Comparison of Standard EOS's

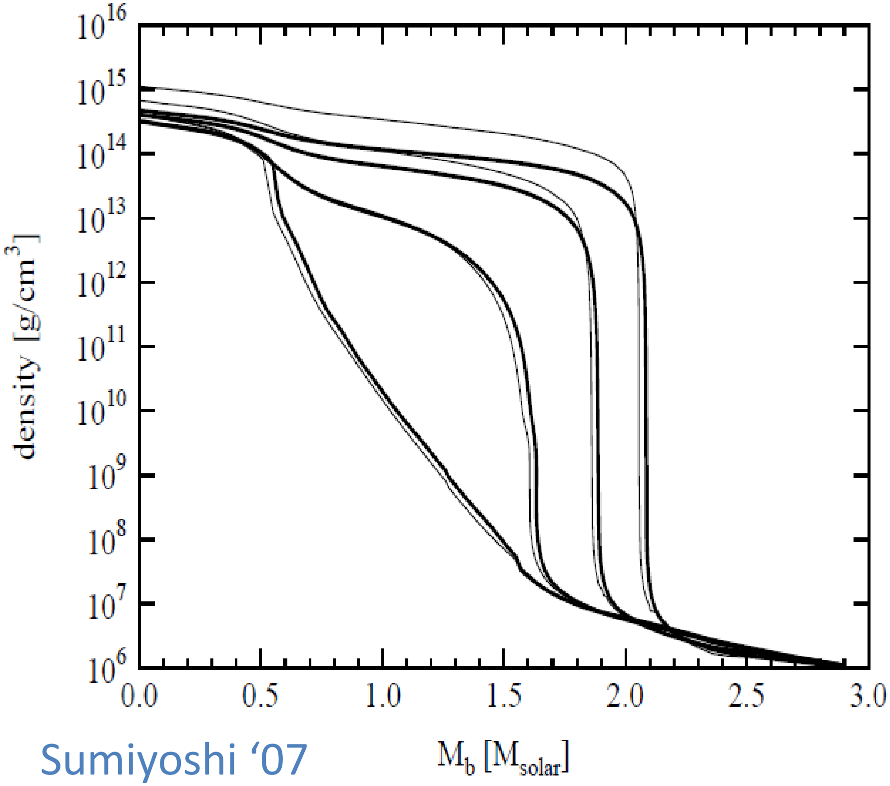
	incompressibility K [MeV]	bulk symmetry energy [MeV]	Maximum NS mass [$M_\odot$]
Lattimer & Swesty's EOS	180	29.3	1.8
	220	29.3	2.0
	375	29.3	2.7
Shen's EOS	281	36.9	2.2
Wolff's EOS	262	32.9	2.2

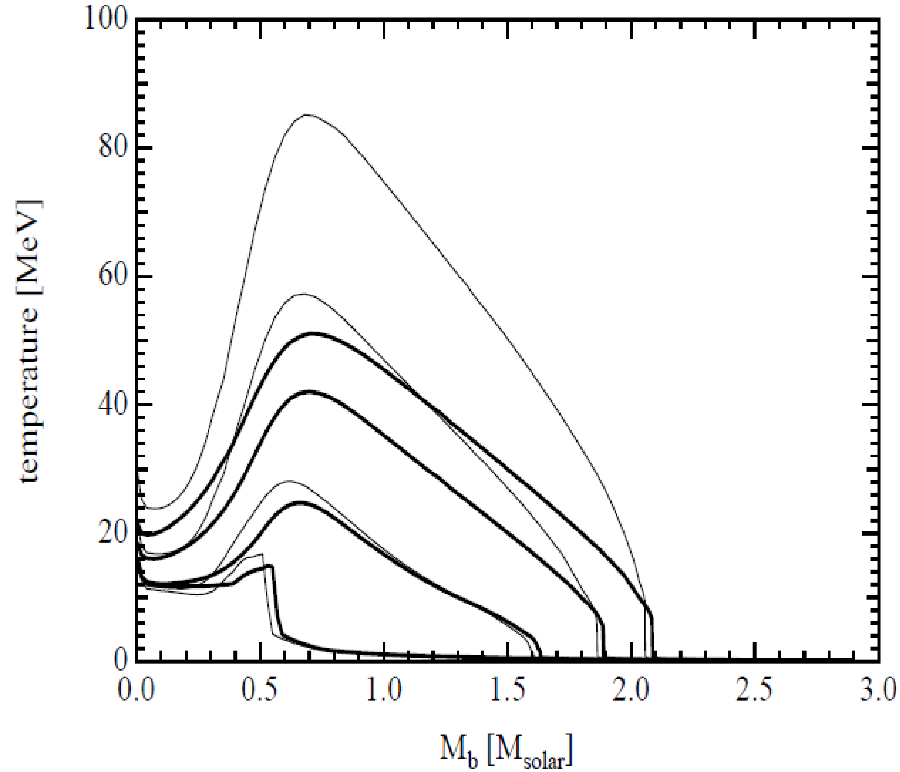
✓ Shen's EOS has a large symmetry energy.

✓ Lattimer & Swesty's EOS with K = 180MeV is too soft although it has been frequently used in the literature.

✓ Difference of EOS's manifests itself at later phases. It is more remarkable for black hole formations.

✓ Softer LS EOS gives a more compact and hotter PNS and the BH formation occurs earlier.





Sumiyoshi '07

✓ Other options are highly welcome.

— relativistic Brueckner-Hartree-Fock approx., variational method, etc.

— hyperons and Meson condensations

— quark matter

Neutrinos and Weak Interactions

- ✓ Neutrinos are not in equilibrium with matter in general and their distributions should be somehow solved.
  - — Neutrinos can be treated as classical particles.
  - — Kinetic descriptions are necessary in principle.

$$p^\mu \frac{\partial f(x,p)}{\partial x^\mu} + \frac{dp^i}{d\lambda}\frac{\partial f(x,p)}{\partial p^i} = \underline{\left(\frac{\delta f(x,p)}{\delta\lambda}\right)_c}$$

- ✓ Interactions of ν's give the source terms of the Boltzmann eqs. as well as the Euler and Y_e eqs.

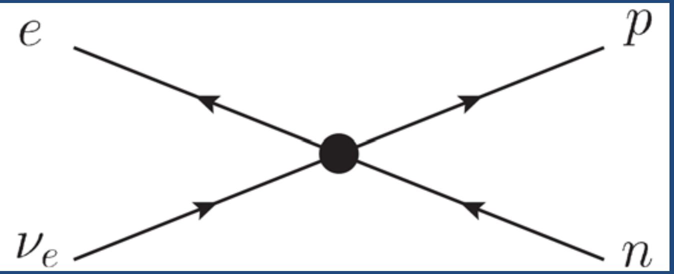
$$\nabla_\nu T_M^{\mu\nu} = -\nabla_\nu T_R^{\mu\nu} = \underline{-\int \frac{d^3p}{E(p)}\, p^\mu \left(\frac{\delta f(x,p)}{\delta\lambda}\right)_c}$$

$$\nabla_\mu n_e^\mu = -\nabla_\mu n_{\nu_e}^\mu = \underline{-\int \frac{d^3p}{E(p)}\, p^\mu \left(\frac{\delta f(x,p)}{\delta\lambda}\right)_c}$$

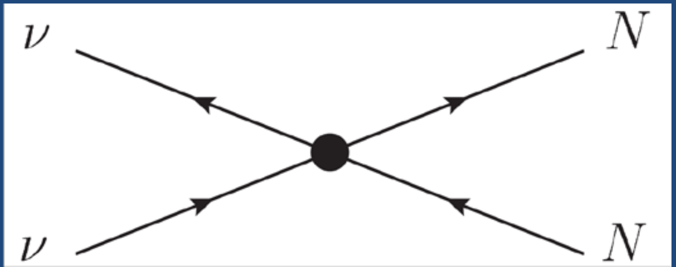
Major Reactions

✓ The following reactions have large cross sections and are commonly included in simulations.

- **absorptions and emissions on free nucleons**
  - — reaction rates roughly proportional to ε_ν^2
  - — mainly responsible for matter heating below stalled shocks



- **scatterings on free nucleons**
  - — reaction rates roughly proportional to ε_ν^2
  - — nearly iso-energetic

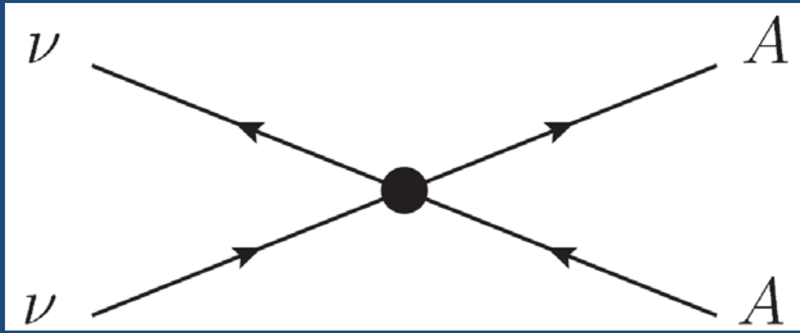


■ coherent scatterings on nuclei

— reaction rates roughly proportional to ε_ν^2 and A^2

— mainly responsible for neutrino trapping

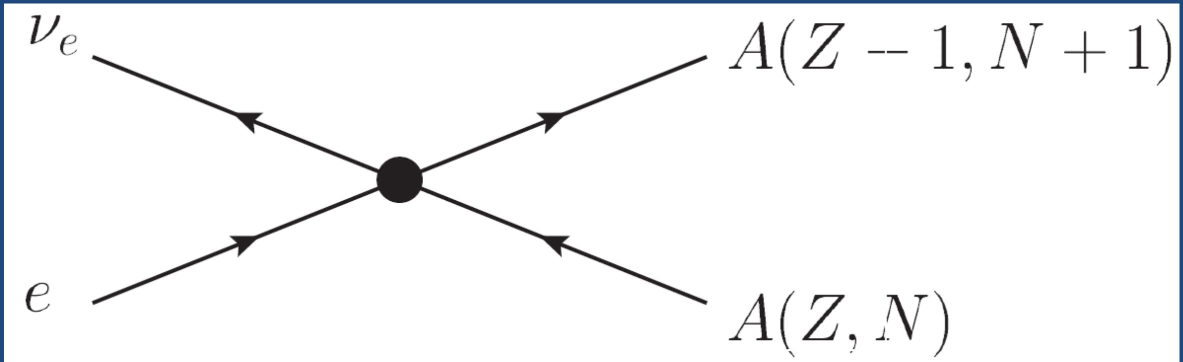
— nearly iso-energetic



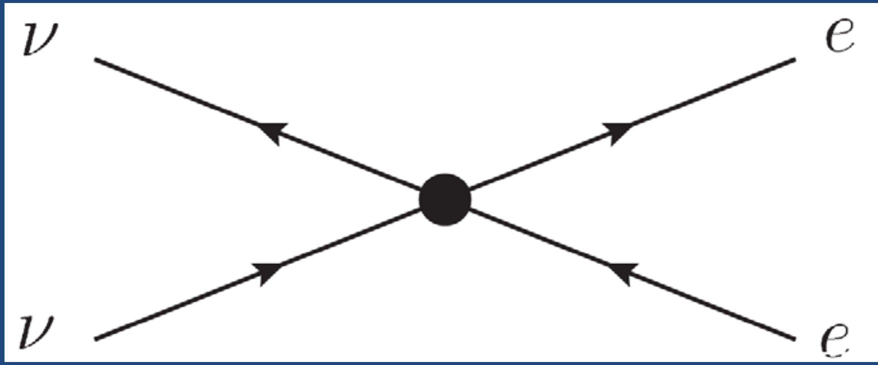
■ electron captures on Nuclei

— reaction rates roughly proportional to ε_ν^2

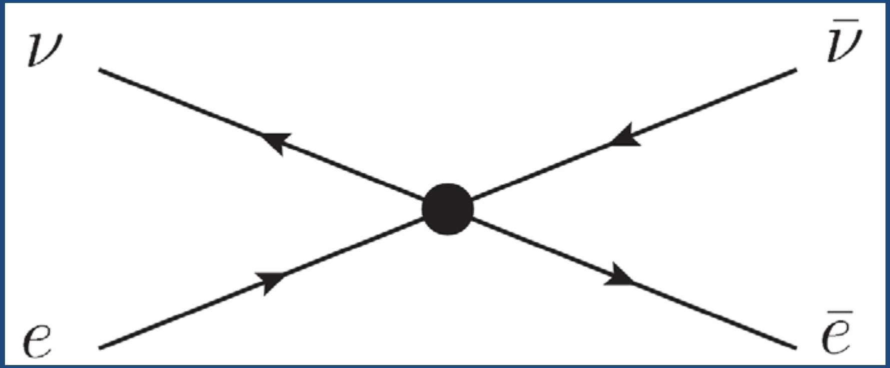
— mainly responsible for Y_e depletion in the collapsing phase



- scatterings on electrons and positrons
  - — reaction rates smaller and roughly proportional to ε_ν
  - — thermalizing neutrinos



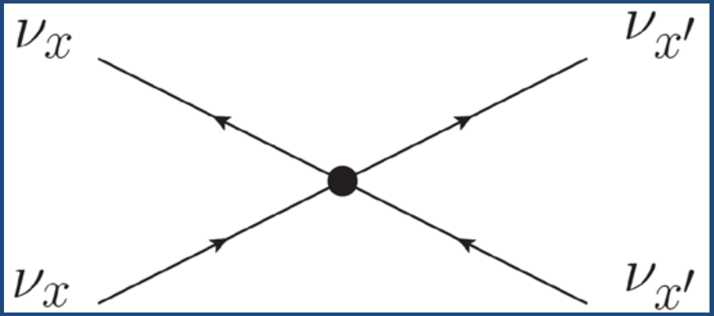
- annihilations and creations of electron and positron pairs
  - — reaction rates smaller and comparable to electron scatterings
  - — one of main sources of μ and τ neutrinos



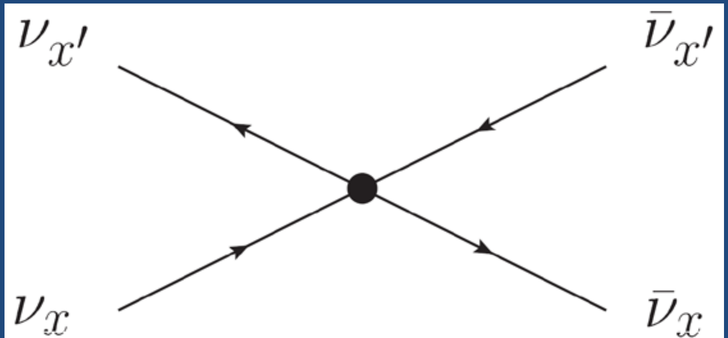
Additional Reactions

✓ The following reactions are as important as electron scatterings and pair processes.

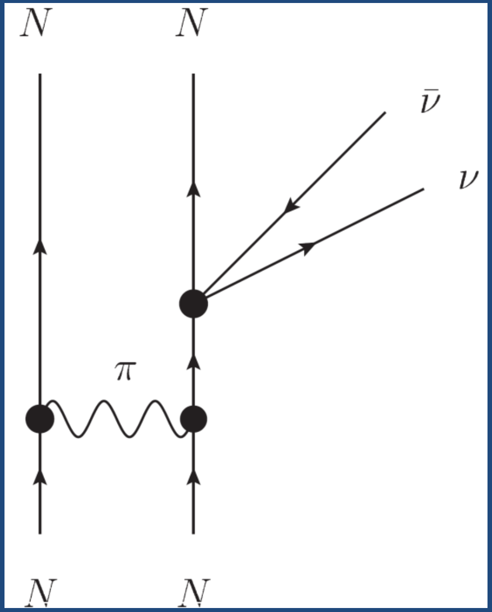
- scatterings on neutrinos
  - — reaction rates comparable to electron scatterings
  - — important for spectral softening for μ and τ neutrinos



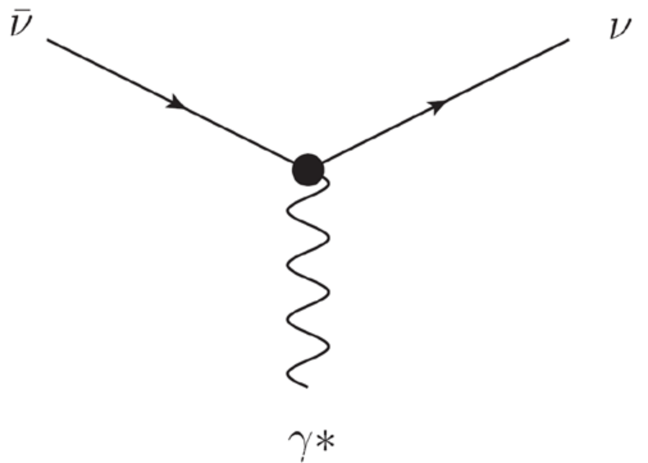
- pair annihilations and creations of neutrinos
  - — reaction rates comparable to electron scatterings
  - — important for spectral softening for μ and τ neutrinos



- nucleon bremsstrahlung of neutrino pairs
  - — one of main sources of μ and τ neutrinos
  - — sometimes greater than pair annihilations of e^+e^-



- plasmon decays
  - — a source of μ and τ neutrinos
  - — usually minor



Minor Corrections

- recoils of nucleons
  - — Nucleon masses are commonly assumed to be infinity and nucleon recoils are ignored.
- nucleon correlations
  - — Nucleons are usually assumed to be free but they are actually correlated spatially and temporarily by nuclear interactions.
- weak magnetism
  - — The hadronic currents have tensor component as well as vector and axial vector components.
- corrections to form factors
  - — finite momentum transfer
- modifications of phase space by magnetic fields
  - — Landau states and magnetic moments

etc.

Collision Terms

$$\left(\frac{\delta f}{\delta\lambda}\right)_c = (p\cdot u)\, S \qquad S\text{: reaction rates in the local comoving frame}$$

Emissions and Absorptions

$$S = (R^e(p)(1-f(p)) - R^a(p) f(p)), \qquad R^e(p) = e^{-\beta(E_\nu - \mu_\nu)} R^a(p)$$

Scatterings

$$S = \int \frac{d^3p'}{p'_0} (R^{in}(p',p) f(p')(1-f(p)) - R^{out}(p,p') f(p)(1-f(p'))),$$

$$R^{in}(p',p) = e^{\beta(E'_\nu - E_\nu)} R^{out}(p,p')$$

Pair processes

$$S = \int \frac{d^3p'}{p'_0} (R^p(p,p')(1-f(p))(1-f(p')) - R^a(p,p') f(p) f(p')),$$

$$R^a(p,p') = e^{\beta(E_\nu + E'_\nu)} R^p(p,p')$$

Summary

- ✓ To reveal the CCSNe mechanism we need to solve the radiation-(magneto-)hydrodynamics in multi-D with microphysical inputs being properly taken into account.
- ✓ Both numerics and input physics should be improved further.
- ✓ CCSNe and related high energy phenomena will provide us with invaluable information on hadron and neutrino physics.