# 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

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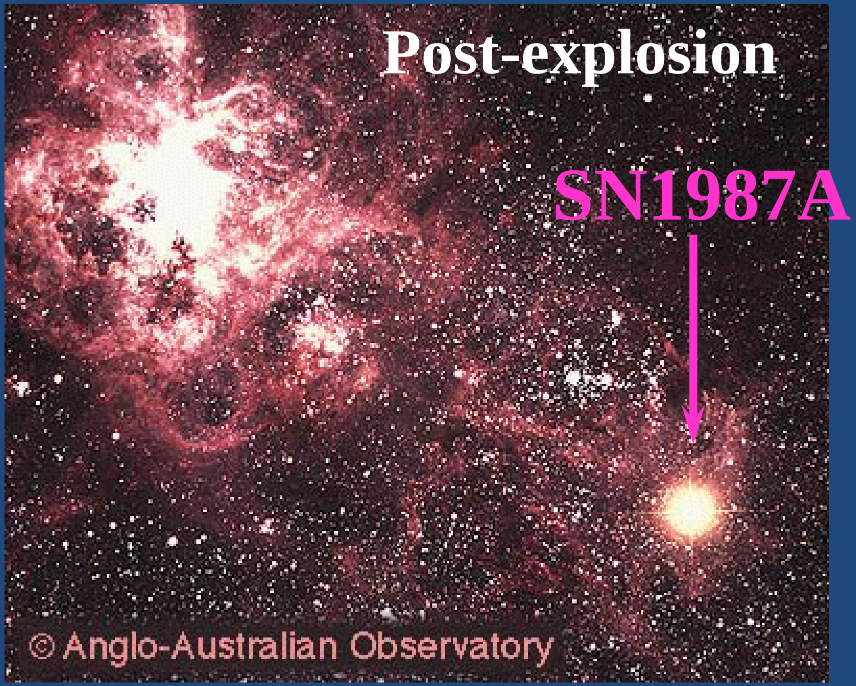

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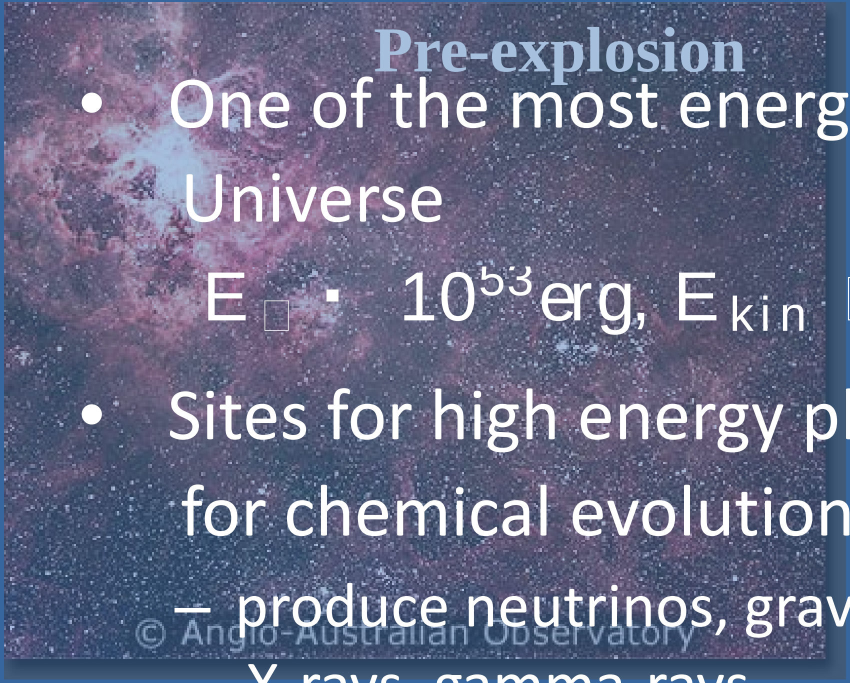
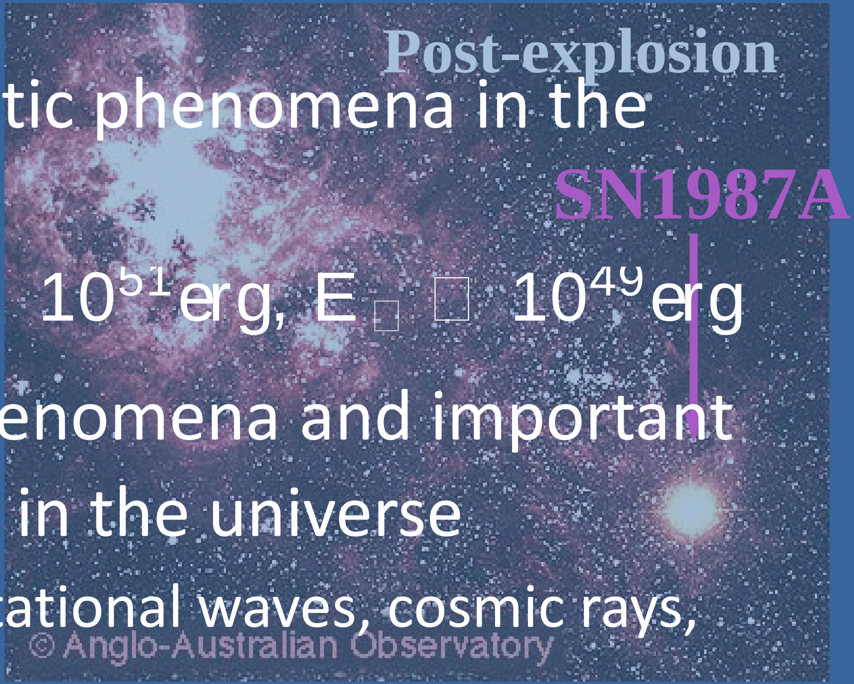
# Fundamentals of Core-Collapse Supernovae

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





- One of the most energetic phenomena in the Universe

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

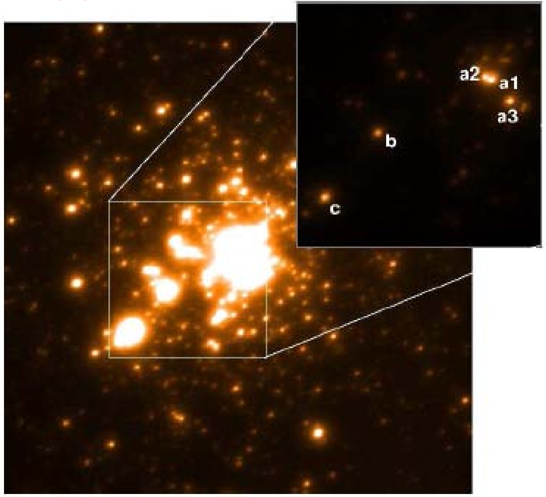
# Which Mass Stars Should We Blow Up?

✓ The present universe may be producing stars as massive as ~300$M_{solar}$.

✓ There is observational evidence that NS's are formed from very massive stars.

- SGR 1806-20: ≳ 50M.
- anomalous X-ray pulsar in young massive galactic cluster Westerlund 1: ≳ 40M□
- anomalous X-ray pulsar 1E1048.1-5937 embedded in stellar wind bubble:□ 30 □ 40M□

R136 Crowther et al. '10



✓ The best bet for the minimum mass to produce CCSNe is 8±1$M_{solar}$ at present.

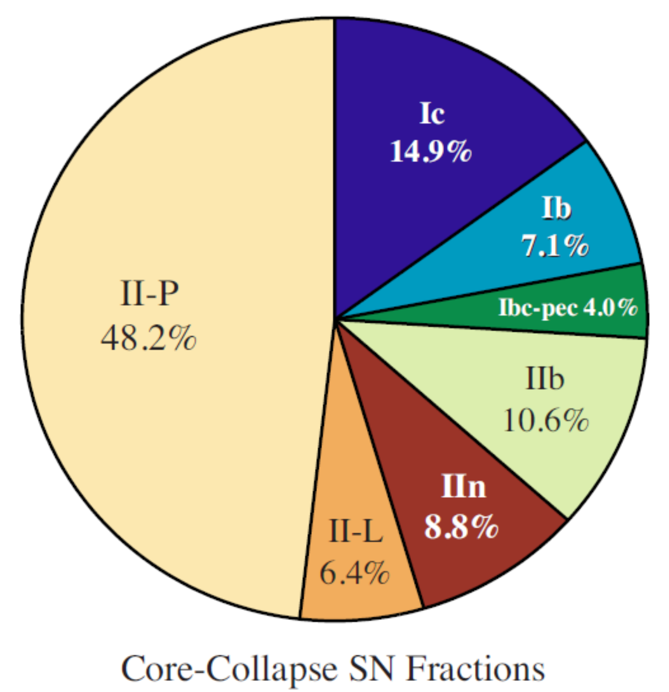
✓ SNeII-P have been observed to be produced by 8.5-17$M_{solar}$ stars.

✓ Most of massive stars may explode to produce neutron stars!

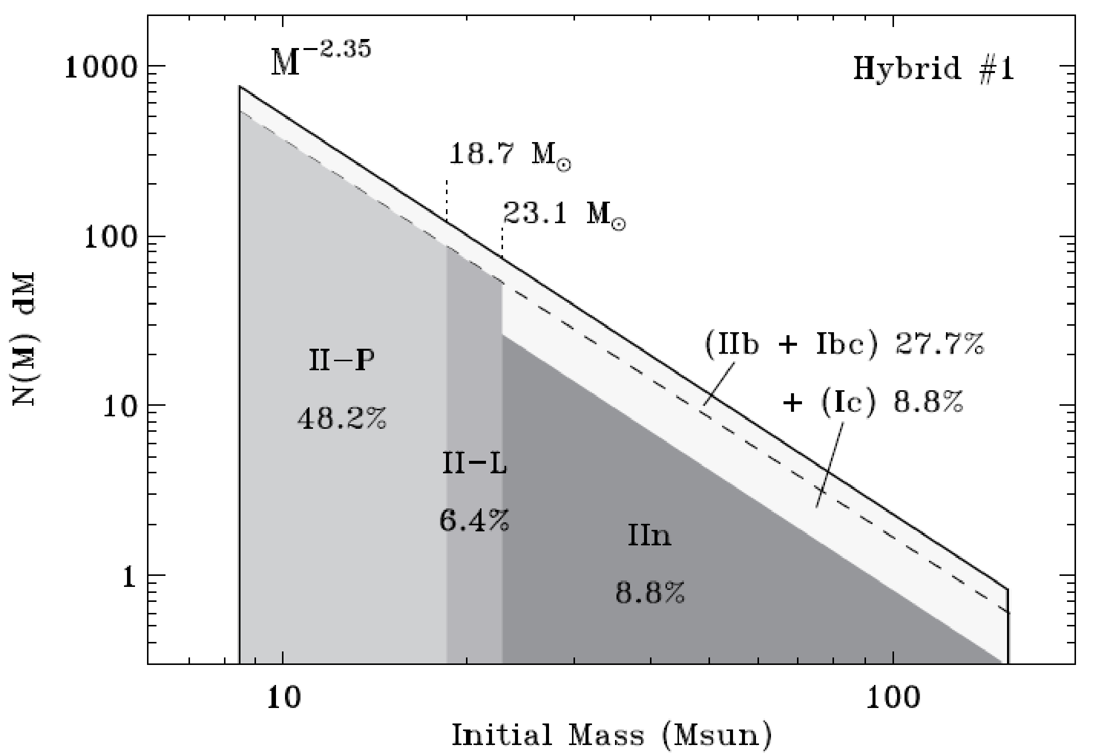
— Core masses are not monotonic owing to mass losses.

# SN Fractions

Smith et al. ’11



Core-Collapse SN Fractions



※ Quiet collapse to BH may not be required!

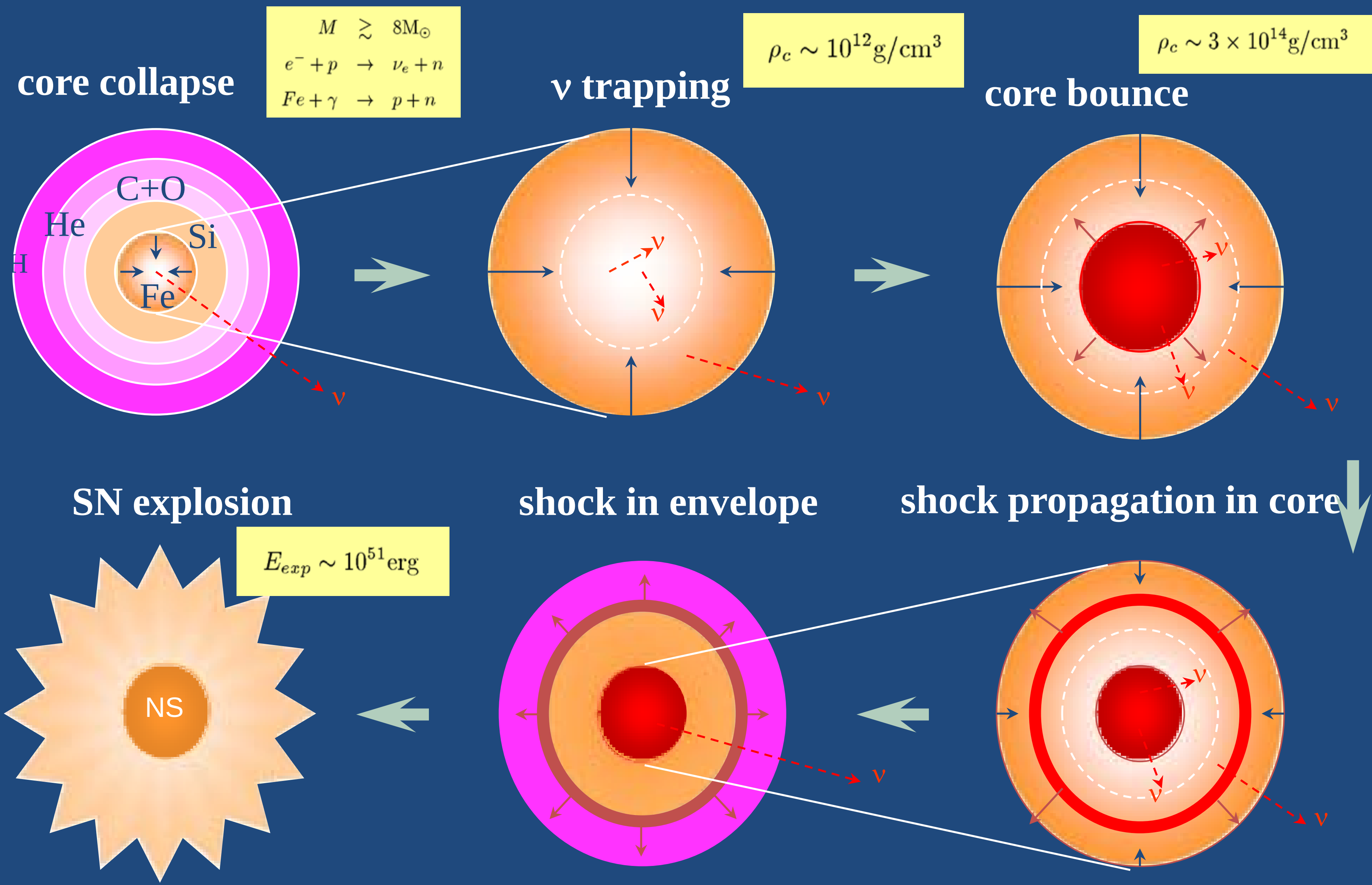
# Very Luminous SNe

- ✓ 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



**core collapse**

$$\begin{aligned} M &\gtrsim 8M_\odot \\ e^- + p &\rightarrow \nu_e + n \\ Fe + \gamma &\rightarrow p + n \end{aligned}$$

**ν trapping**

$\rho_c \sim 10^{12}\mathrm{g/cm^3}$

**core bounce**

$\rho_c \sim 3 \times 10^{14}\mathrm{g/cm^3}$

**shock propagation in core**

**shock in envelope**

**SN explosion**

$E_{exp} \sim 10^{51}\mathrm{erg}$

# Onset of Core Collapse

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

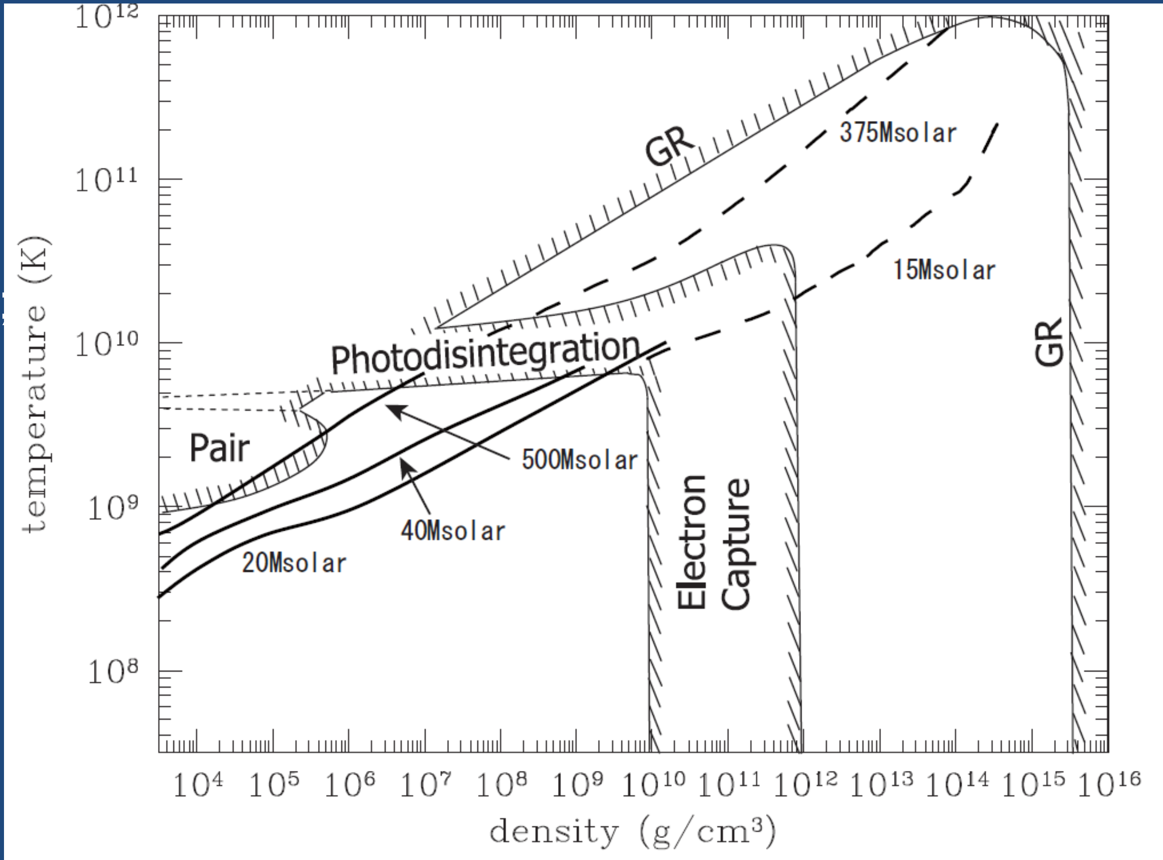
- (Newtonian) Criterion:

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

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

- Electron captures and photo-disintegrations tend to reduce $\Gamma$.

- 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: $\cdot\ 20\,\mathrm{fm}\ \frac{''\,.}{10\,\mathrm{MeV}}\ {}^{1}$

Nuclear radius: $\square\ 5\,\mathrm{fm}\ (A{=}56)^{1=3}$

ν mean free path: $\square\ 10^{6}\ \mathrm{cm}\ \square\ \frac{''\,\square}{10\,\mathrm{MeV}}\ \square_{\square\,2}\ \frac{\square}{10^{12}\,\mathrm{g{=}cm}^{3}}\ !\ \square\,1$

core radius: $\square\ 10^{7}\ \mathrm{cm}$

ν Diffusion time scale: $\square\ 100\,\mathrm{msec}\ \square\ \frac{R_{PNS}}{3\ \square\ 10^{6}\,\mathrm{cm}}\ \square^{2}\ \square\ \frac{''\,\square}{10\,\mathrm{MeV}}\ \square_{2}\ \frac{\square}{10^{14}\,\mathrm{g{=}cm}^{3}}\ !$

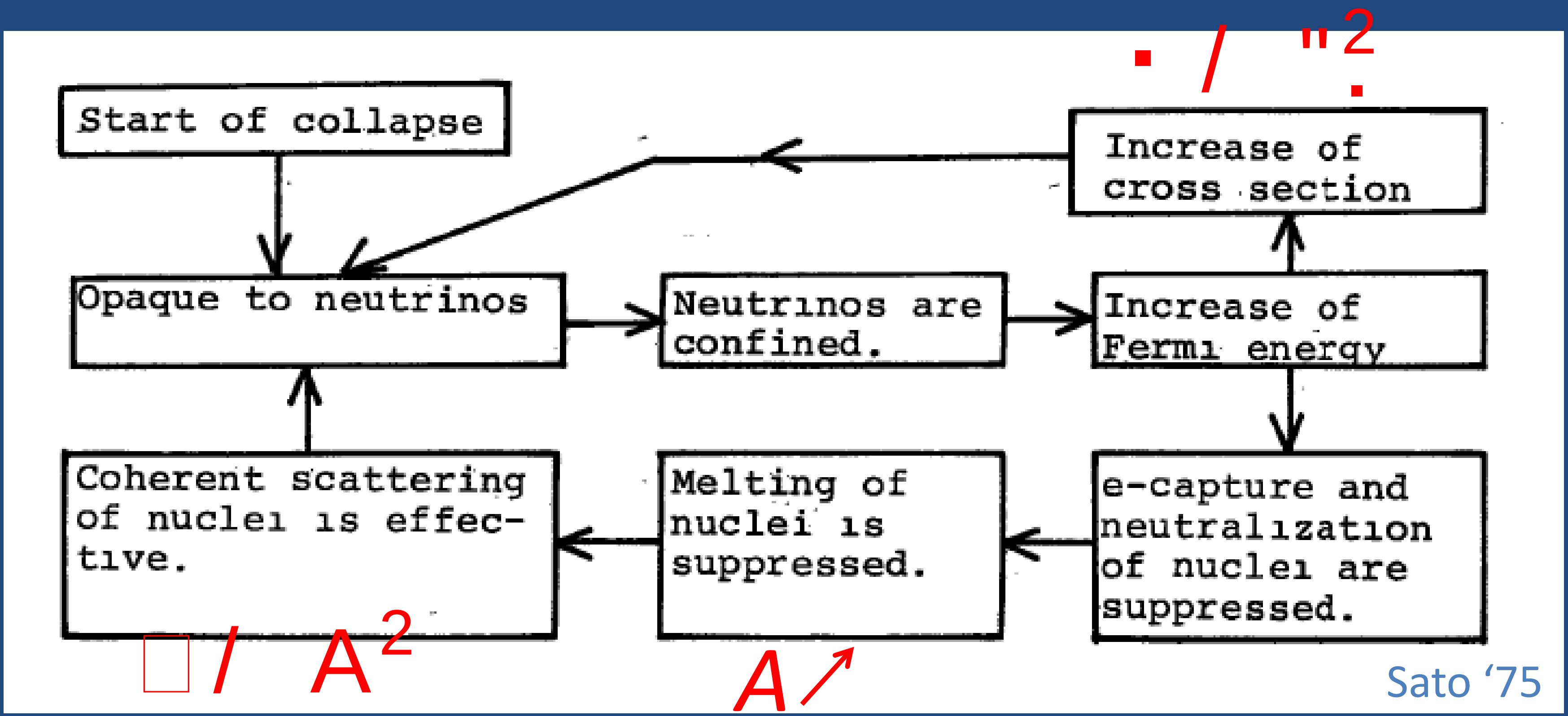
Dynamical time scale: $\square\ 10\,\mathrm{msec}\ \frac{\square}{10^{12}\,\mathrm{g{=}cm}^{3}}\ !\ \square\,1{=}2$

- ✓ Neutrinos are essentially trapped in the core at $\rho \sim 10^{11}\mathrm{g/cm}^3$ and diffuse out of the core thereafter.
- ✓ $\beta$-equilibrium is established at $\rho \sim 10^{12}\mathrm{g/cm}^3$ 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.



Start of collapse

Opaque to neutrinos

Neutrinos are confined.

Increase of Fermi energy

Increase of cross section

e-capture and neutralization of nuclei are suppressed.

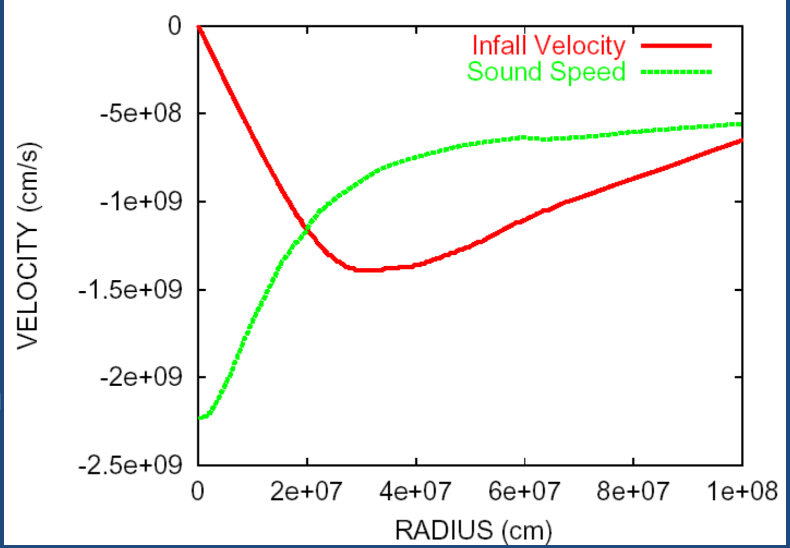
Melting of nuclei is suppressed.

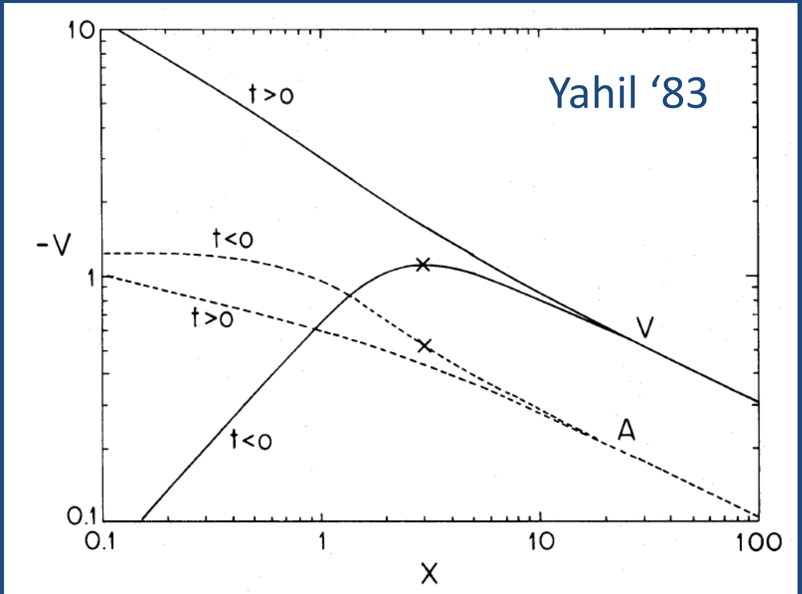
Coherent scattering of nuclei is effective.

Sato '75

# Homologous Collapse

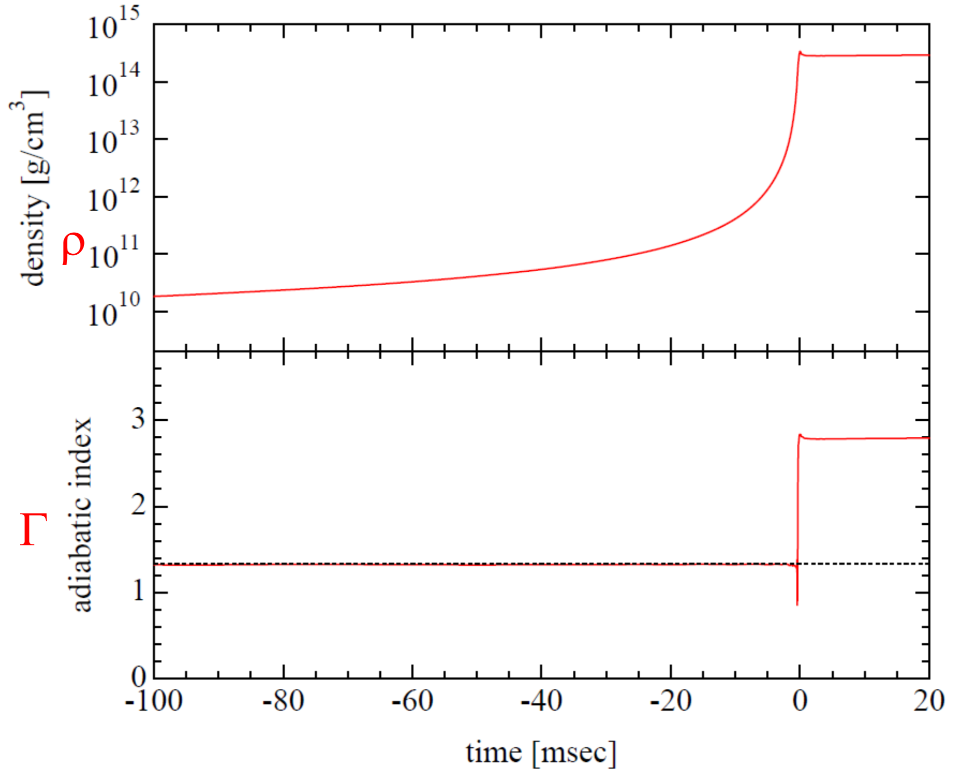
- ✓ Infalling cores are divided into two parts :
  - — inner core: subsonic and homologous
  - — outer core: supersonic and free fall-like
- ✓ The outer core is causally disconnected from the inner core.
  - — A shock wave produced at the boundary between the inner and outer cores.
- ✓ Yahil found a self-similar solution for $\Gamma$ 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.

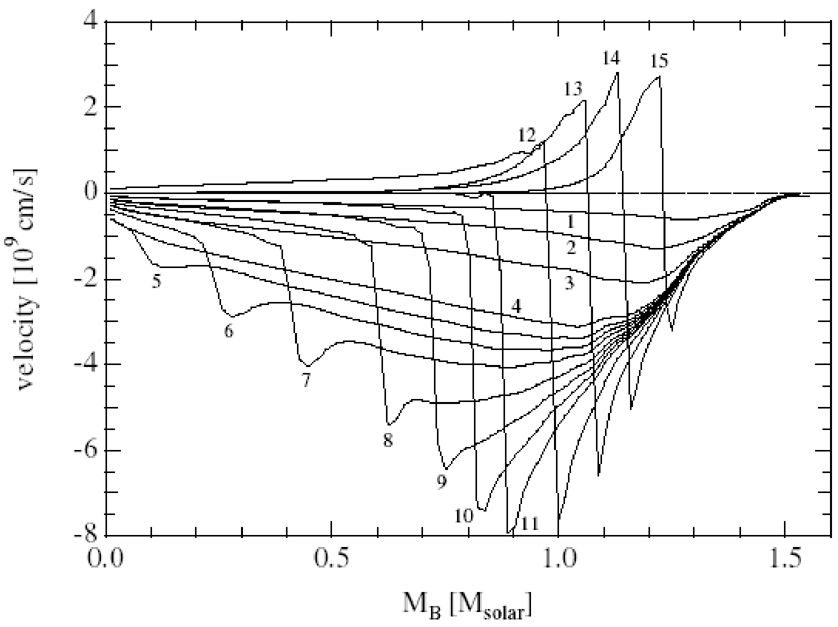




# Core Bounce

- ✓ 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

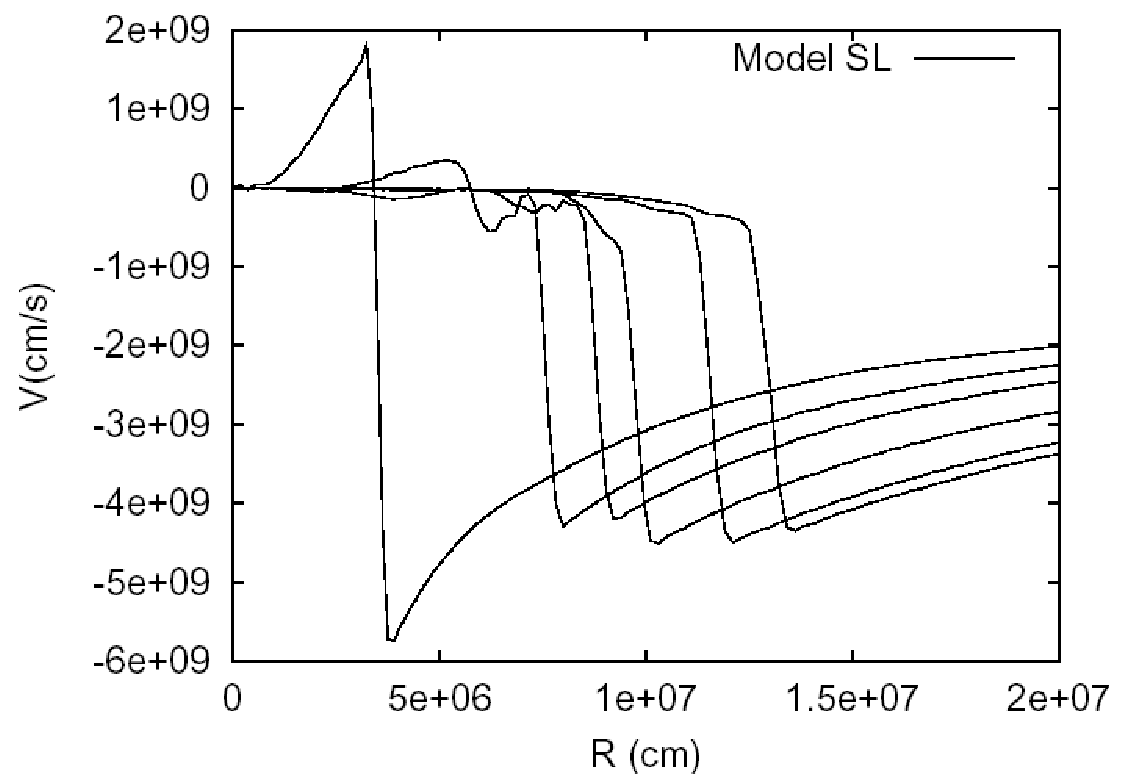
- Rest mass energy: $\sim 10^{54}\,\mathrm{erg}\left(\frac{M}{M_\odot}\right)$
- Gravitational energy
  Progenitor core: $\sim 10^{51}\,\mathrm{erg}\left(\frac{M}{M_\odot}\right)^2\left(\frac{R_{core}}{10^8\,\mathrm{cm}}\right)^{-1}$

  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: a few $\times\ 10^{51}\,\mathrm{erg}$

# Shock Propagation & Stagnation

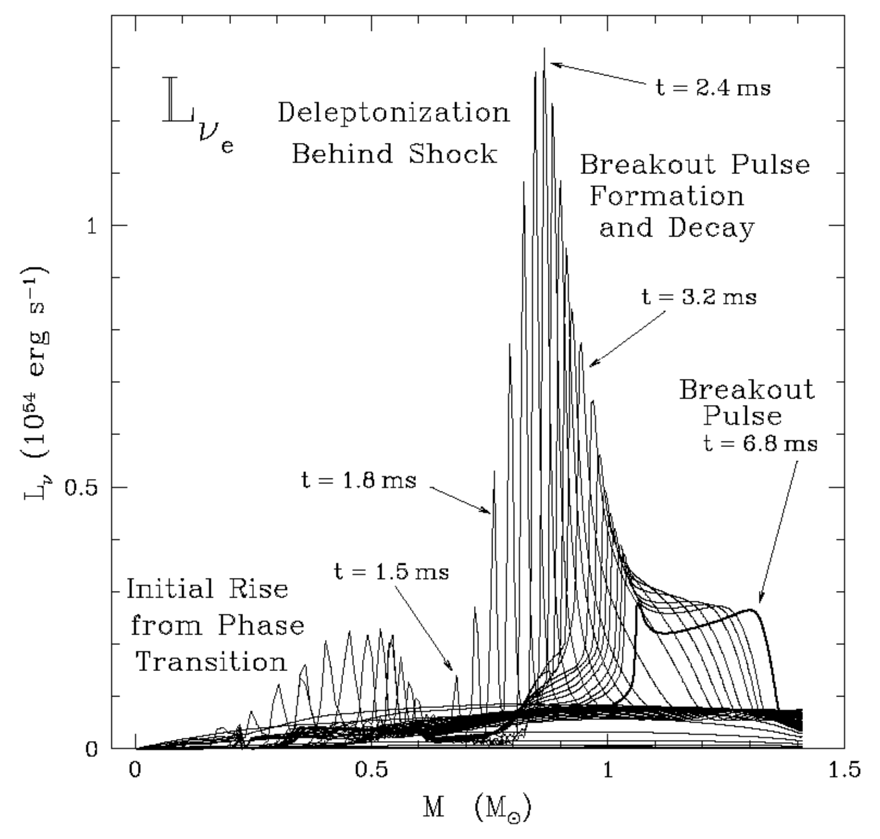
- ✓ The shock wave generated by core bounce propagates outwards initially.
- ✓ Photo-disintegrations of nuclei and neutrino cooling are energy sinks that make the shock wave stagnated at ~200km from the center in the core.
- ✓ The standing accretion shock wave then starts to recede back onto a nascent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

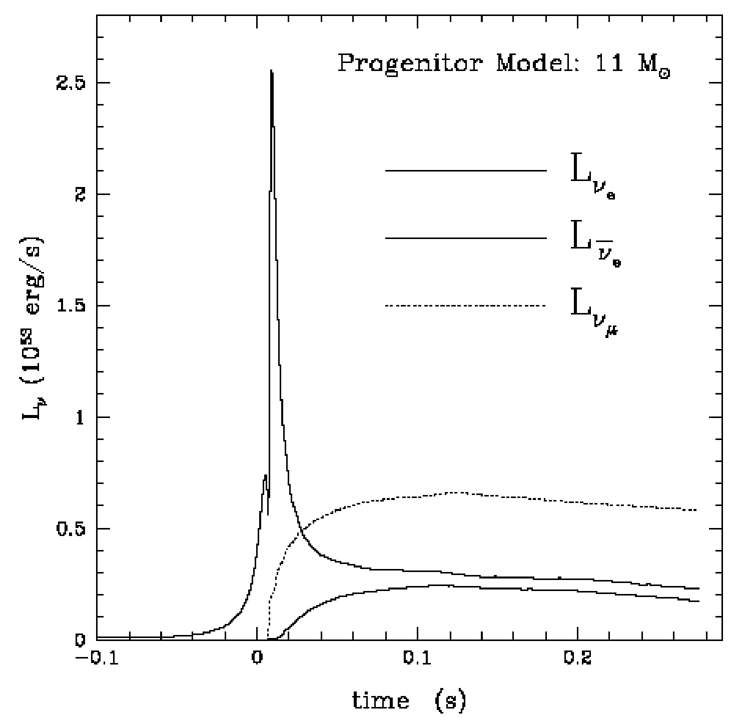
- ✓When the shock wave reaches the ν-sphere, heavy nuclei are photo-dissociated and the opacity is suddenly reduced and electron captures on protons are enhanced considerably, leading to the neutronization burst.



Thompson et al. '03

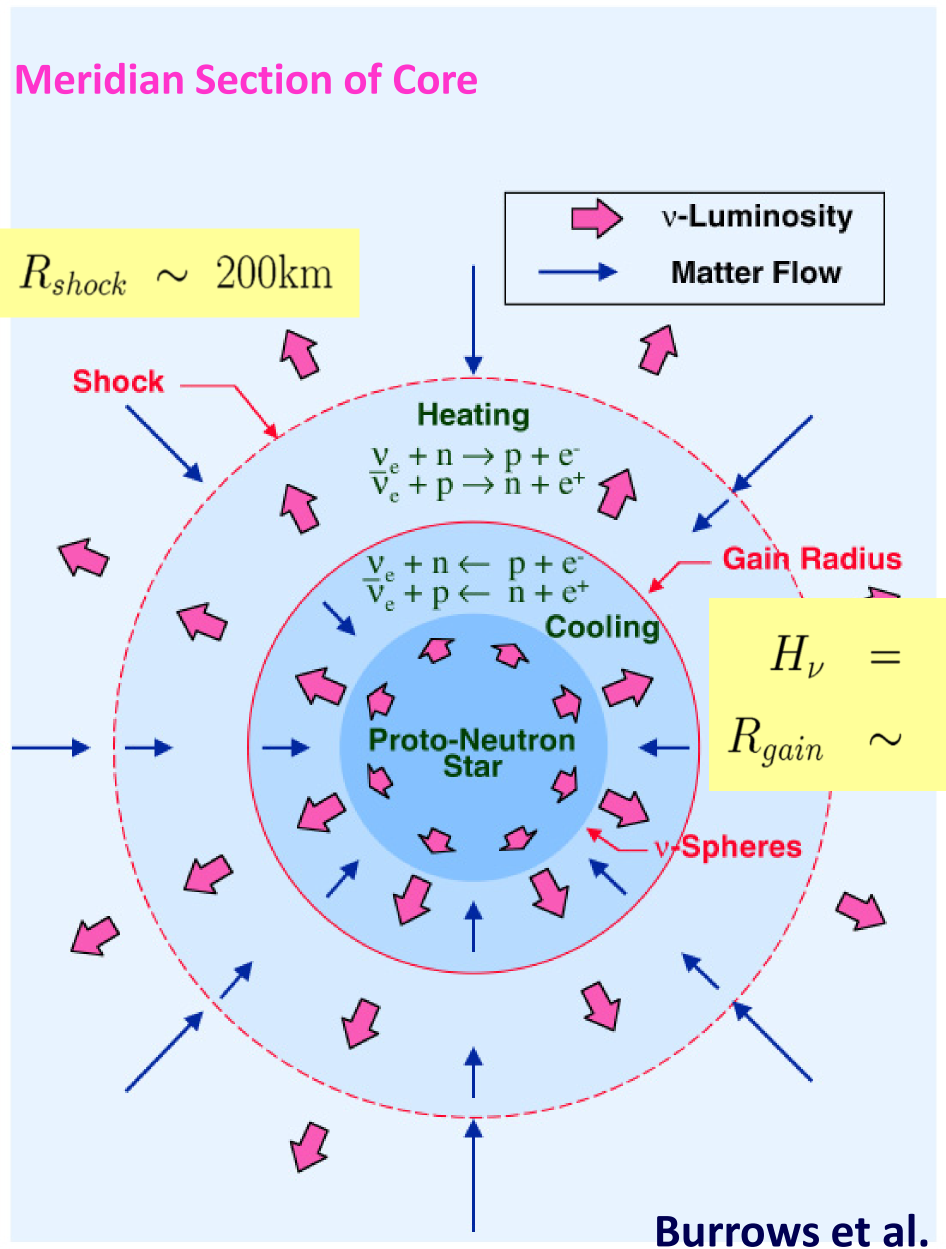
# Neutronization Bursts

- ✓ Up to core bounce only $\nu_e$'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



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

$$H_\nu = C_\nu$$

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

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

$$E_G \cdot E_{int} \sim 10^{53}\,\text{erg}$$

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

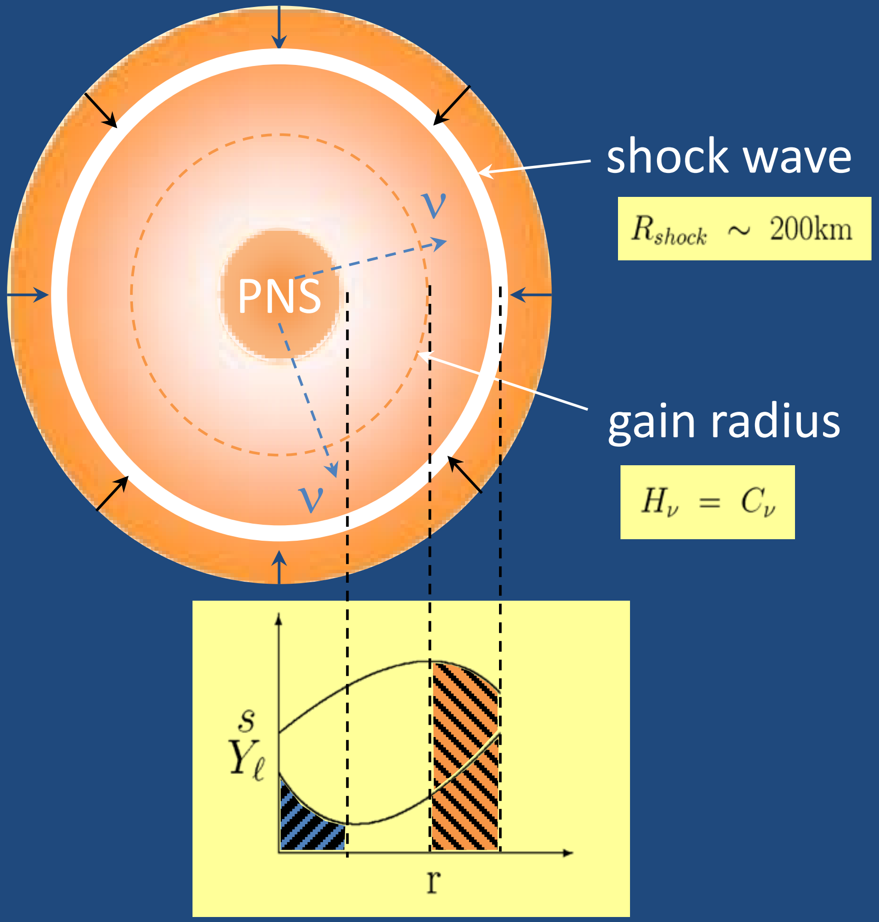
$$E_{sh} \lesssim 5 \times 10^{51}\,\text{erg} < E^{loss}_{\nu;Fe}$$

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

- ✓ **The spherically symmetric configuration is unstable!**

# Hydrodynamical Instabilities

✓ Post bounce configuration



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

$H_\nu = C_\nu$

✓ **Convections**

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

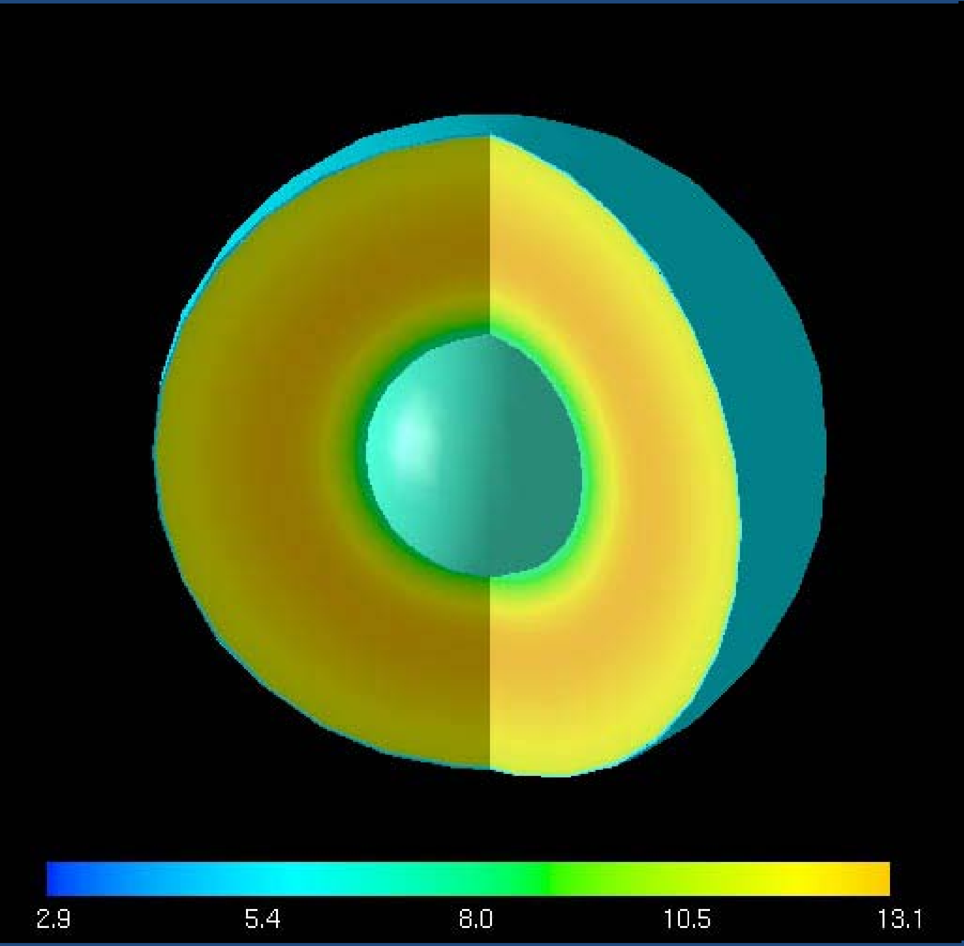
✓ **Standing Accretion Shock Instability (SASI)**

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

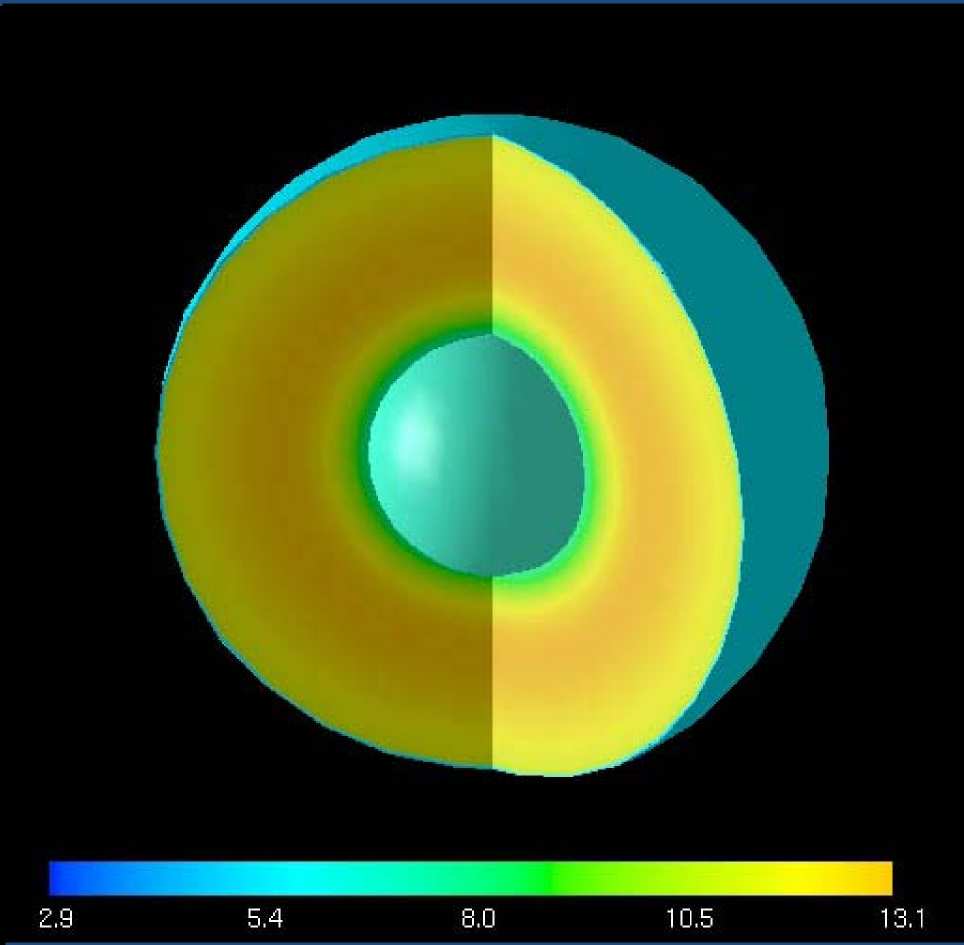
✓ (g-mode oscillations of PNS)

# SASI in 2D and 3D

2D with axisymmetry



3D



# 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.

✓ $\nu$'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 ~3x$10^{14}$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 ~3x$10^{14}$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.

$$\cdot\ \cdot\ \ 10^{\,10}\,\mathrm{cm}\ \cdot\ \frac{\square}{10^{\square 24}\,\mathrm{cm}^2}\ \square^{\sqcup}\ \frac{\square}{10^{10}\,\mathrm{g}{=}\mathrm{cm}^3}\ !$$

- 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.

$$r\ .\,(n_B\, u^{\square}) = 0$$ : Baryon number conservation

## ✓ Eq. for *$Y_e$*

$$r\ {}_{\square}(n_L\, u^{\square}) = 0$$ : Lepton number conservation

➡ $$r\ {}_{\square}(n_e u^{\square}) = \square r\ {}_{\square}(n_{\square_e}\, u^{\square})$$

➡ $$u^{\square} r\ {}_{\square} Y_e = \square u^{\square} r\ {}_{\square} Y_{\square_e}$$

↑

Expressed by collision terms of Boltzmann eq.

※ Heavy leptons are not abundant in supernova cores.

# Energy-momentum tensors

$$T^{\cdot\cdot} = T_M^{\square\square} + T_R^{\square\square} (+ T_{EM}^{\square\square})$$

$$T_M^{\square\square} = \square u^{\square} u^{\square} + (g^{\square\square} + u^{\square} u^{\square})p$$

.

$$T_R^{\square\square} = E_R u^{\square}_{\square} u^{\square} + u^{\square} F_R^{\square} + F^{\square} u_R^{\square} + P^{\square\square}_{R\,\square\square}$$

$$T_{EM}^{\square\square} = \frac{1}{4\square} F^{\square\square} F^{\square}_{\square} \text{ト} \frac{1}{4} g^{\square\square} F^{\square\square} F_{\square\square}$$

✓ Euler Equations

$$r_{\square} T^{\square\square} = 0$$

$$\text{or } r_{\square} T_M^{\square\square} = \square r_{\square} T_R^{\square\square} (\square r_{\square} T_{EM}^{\square\square})$$

Expressed by collision terms of Boltzmann eq.

✓ Einstein eq.

$$G^{\cdot\,\cdot} = T^{\square\square}$$

✓ Equation of State (EOS)

$$p = p(n_B \,; '' ; Y_e)$$

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

✓ Induction eq.

$$dF^{\square\square} = 0$$

$$r_{\square}F^{\square\square} = \frac{4\square}{c} j^{\square}$$

$$F^{\square\square}u_{\square} = 0$$

✓ 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 ( $\rho_B \lesssim 10^{11} g/cm^3$ ).
- 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 $\mu$- and $\tau$-neutrinos.

- ✓ The distribution of $\nu_\mu$ ($\nu_\tau$) 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. $\lesssim$ 1ev □ E□ □ O(MeV)

## ✓ Boltzmann Eq.

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

$\lambda$ : affine parameter $\quad p^{\mu} = \frac{dx^{\mu}}{d\lambda}, \quad \frac{dp^{\mu}}{d\lambda} = -\Gamma^{\mu}_{\nu\rho} p^{\nu} p^{\rho}$ : 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

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

※ In an orthonormal frame

## Microphysical inputs in core collapse simulations:

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

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

$$\left[\frac{\partial f(x;p)}{\partial t}\right]_c$$

EOS

# Lattimer & Swesty's EOS

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

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

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

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

t : isospin; $\tau_t$ : kinetic energy density; $m_t^*$ : effective mass

$\Delta$ : n-p mass difference; $V_t = \partial E / \partial n_t$ ; $\eta_t = (\mu_t - V_t)/k_B T$

- ✓ The parameters *a*, *b*, *c* and $\delta$ 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.

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

▪ : nucleons; □: scalar-isoscalar meson
! : vector-isoscalar meson; □: vector-isovector meson

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

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

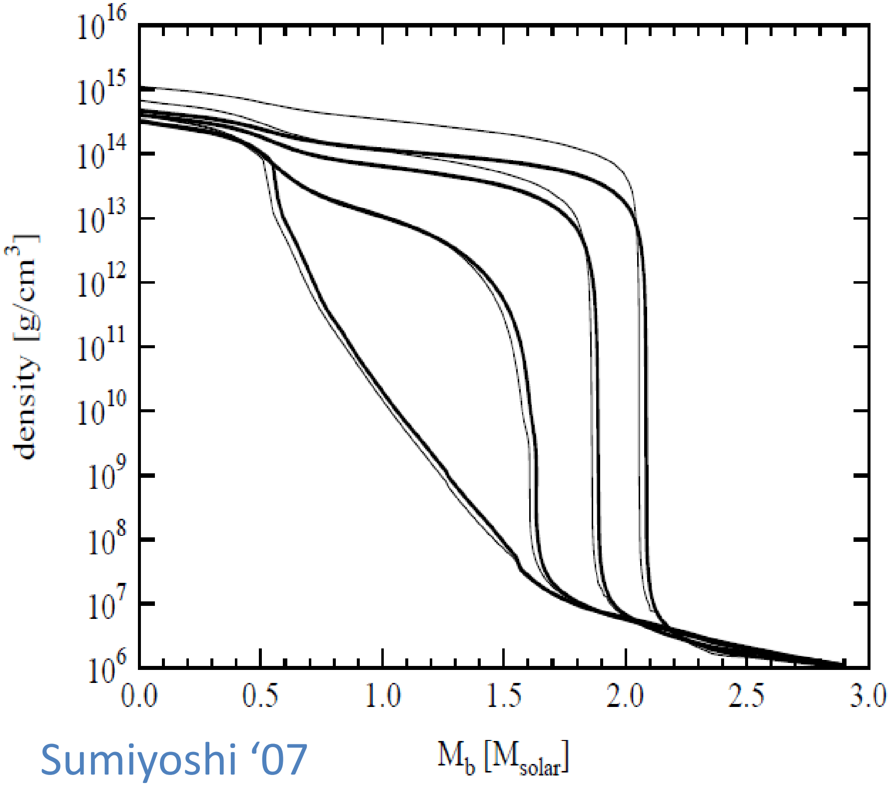
- ✓ The meson masses and coupling constants are determined to reproduce the properties of nuclear matter at its saturation as well as of finite nuclei.

# Comparison of Standard EOS's

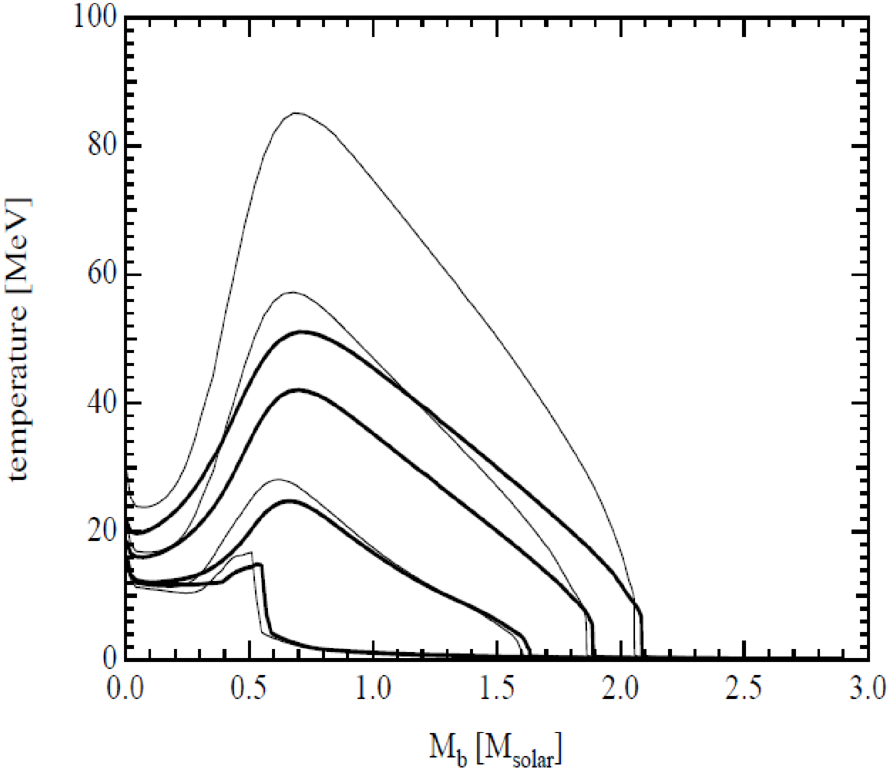
| | incompressibility K [MeV] | bulk symmetry energy [MeV] | Maximum NS mass [M. ] |
|---|---|---|---|
| Lattimer & Swesty's EOS | 180 | 29.3 | 1.8 |
| | 220 | 29.3 | 2.0 |
| | 375 | 29.3 | 2.7 |
| Shen's EOS | 281 | 36.9 | 2.2 |
| Wolff's EOS | 262 | 32.9 | 2.2 |

- ✓ 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.

$$p^\mu \frac{\partial f(x;p)}{\partial x^\mu} + \frac{dp^i}{d\tau}\frac{\partial f(x;p)}{\partial p^i} = \underline{\left[\frac{\delta f(x;p)}{\delta \tau}\right]_c}$$

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

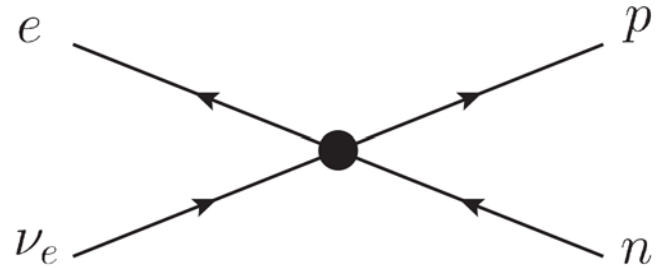
$$\nabla_\mu T_M^{\mu\nu} = -\nabla_\mu T_R^{\mu\nu} = \underline{-\int \frac{d^3p}{E(p)}\, p^\nu \left[\frac{\delta f(x;p)}{\delta \tau}\right]_c}$$

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

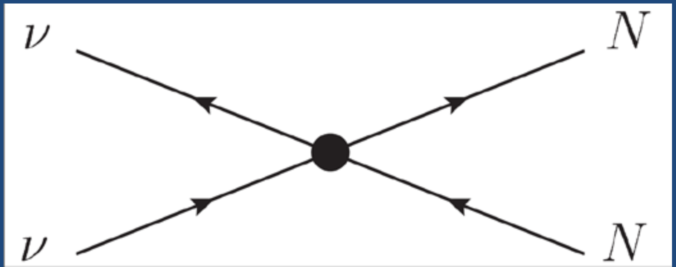
# Major Reactions

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

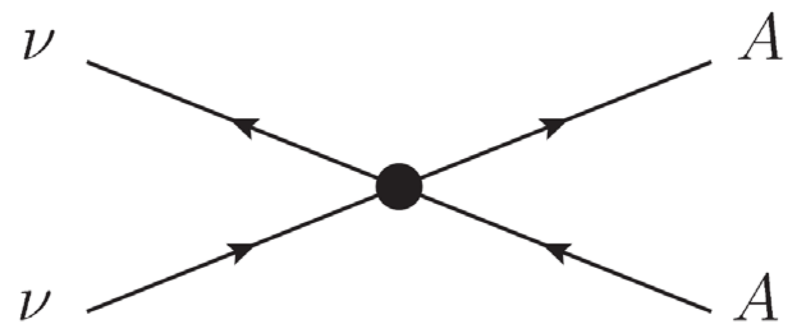
- absorptions and emissions on free nucleons
  - — reaction rates roughly proportional to $\varepsilon_\nu^2$
  - — mainly responsible for matter heating below stalled shocks



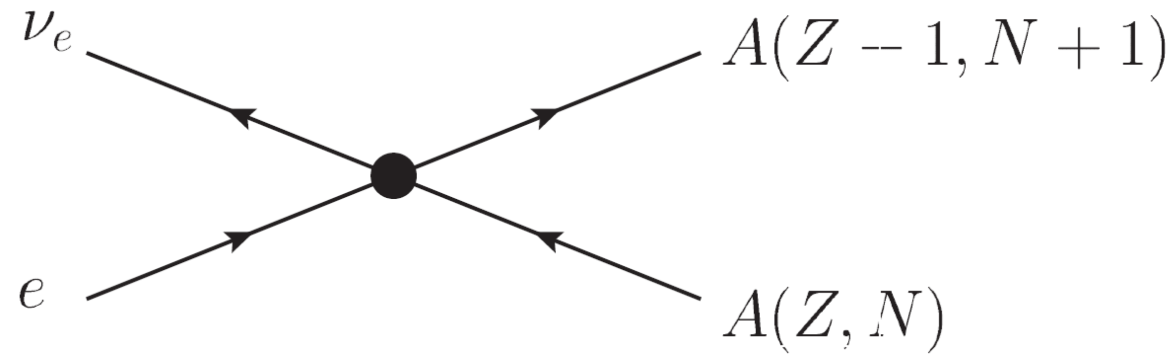
- scatterings on free nucleons
  - — reaction rates roughly proportional to $\varepsilon_\nu^2$
  - — nearly iso-energetic



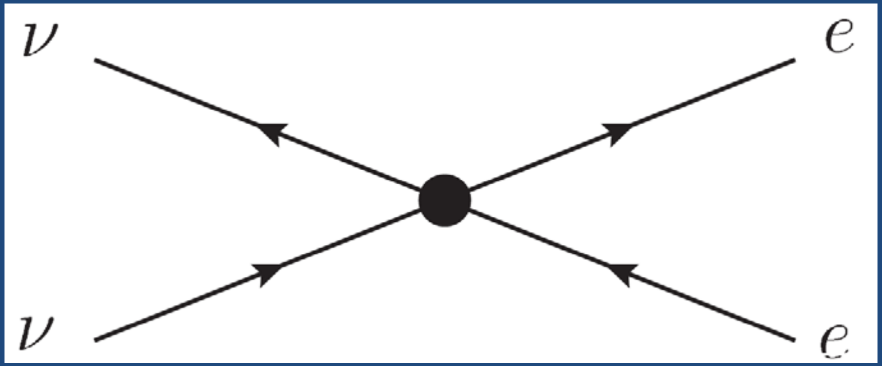
- coherent scatterings on nuclei
  - — reaction rates roughly proportional to $\varepsilon_\nu^2$ and $A^2$
  - — mainly responsible for neutrino trapping
  - — nearly iso-energetic



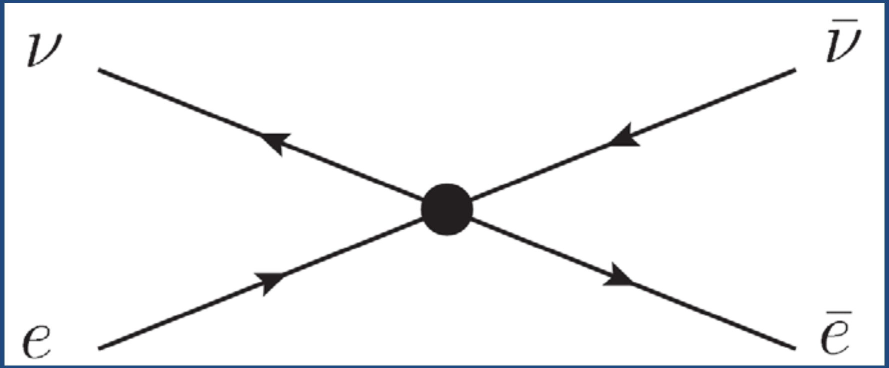
- electron captures on Nuclei
  - — reaction rates roughly proportional to $\varepsilon_\nu^2$
  - — mainly responsible for $Y_e$ depletion in the collapsing phase



- scatterings on electrons and positrons
  - — reaction rates smaller and roughly proportional to $\varepsilon_\nu$
  - — thermalizing neutrinos



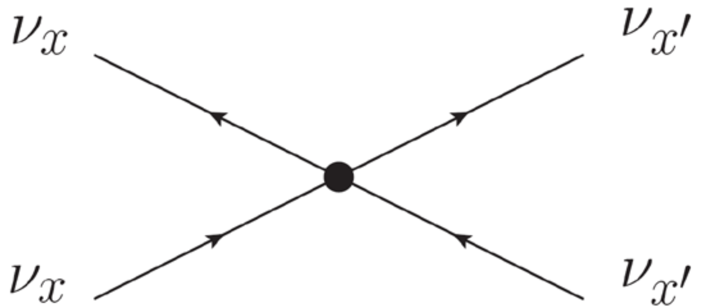
- annihilations and creations of electron and positron pairs
  - — reaction rates smaller and comparable to electron scatterings
  - — one of main sources of $\mu$ and $\tau$ neutrinos



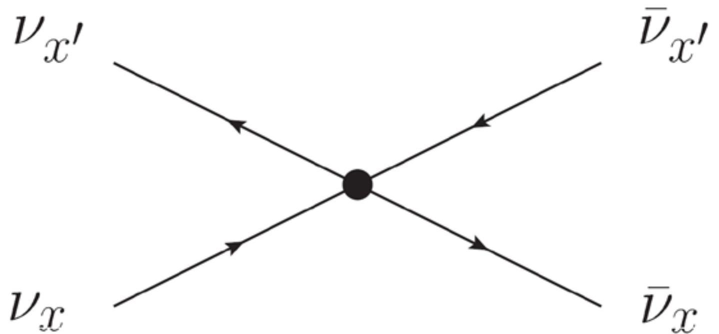
# Additional Reactions

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

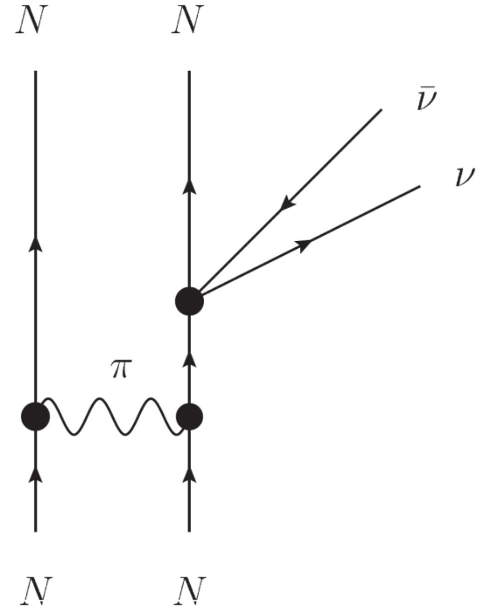
- scatterings on neutrinos
  - — reaction rates comparable to electron scatterings
  - — important for spectral softening for μ and τ neutrinos



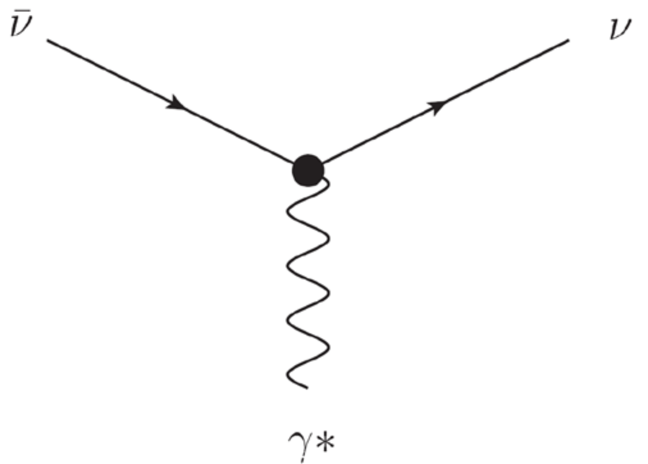
- pair annihilations and creations of neutrinos
  - — reaction rates comparable to electron scatterings
  - — important for spectral softening for μ and τ neutrinos



- 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

$$\left(\frac{\square f}{\square\square}\right)_c = (p \, \square u)\, S$$

S: reaction rates in the local comoving frame

- Emissions and Absorptions

$$S = (R^e(p)(1 \text{ト} f(p)) \square R^a(p) f(p)); \quad R^e(p) = e^{\text{ト} \square(E \,.\, \square \square_{\square})} R^a(p)$$

- Scatterings

$$S = \int \frac{d^3p^0}{p^0_0} (R^{in}(p^0; p) f(p^0)(1 \square f(p)) \square R^{out}(p; p^0) f(p)(1 \square f(p^0)));$$

$$R^{in}(p^0; p) = e^{\square(E^0_{\square} \square E_{\square})} R^{out}(p; p^0)$$

- Pair processes

$$S = \int \frac{d^3p^0}{p^0_0} (R^p(p; p^0)(1 \square f(p))(1 \square f(p^0)) \square R^a(p; p^0) f(p) f(p^0));$$

$$R^a(p; p^0) = e^{\square(E_{\square} + E^0_{\square})} R^p(p; p^0)$$

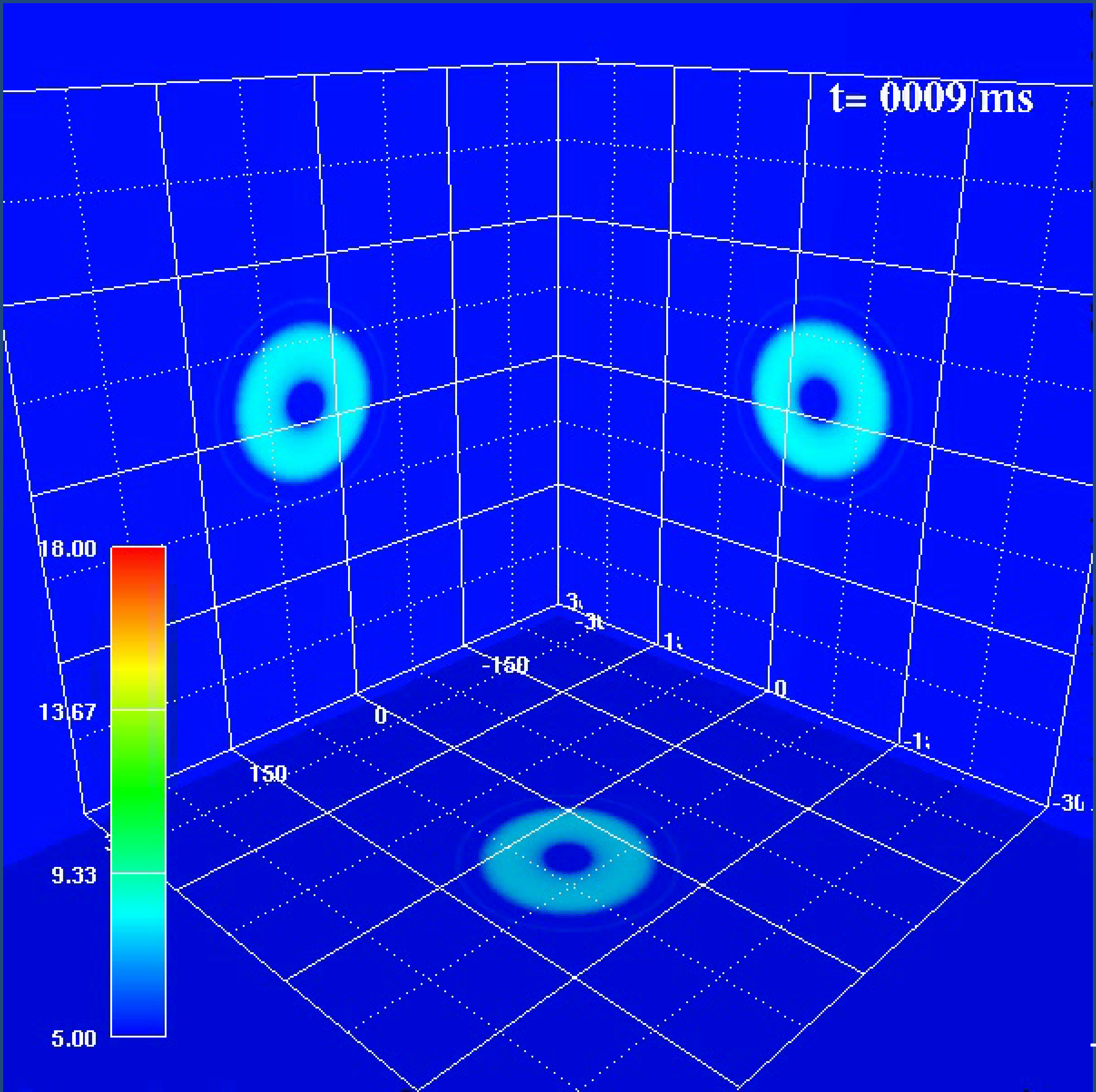
# Summary

- ✓ 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.

# Latest 3D Simulation



Takiwaki et al ‘12