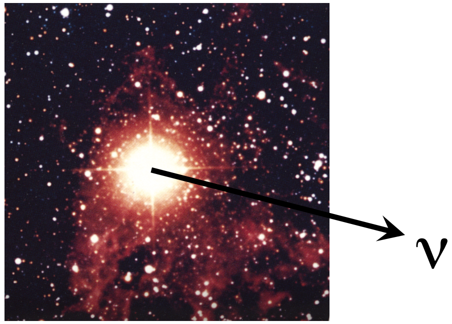
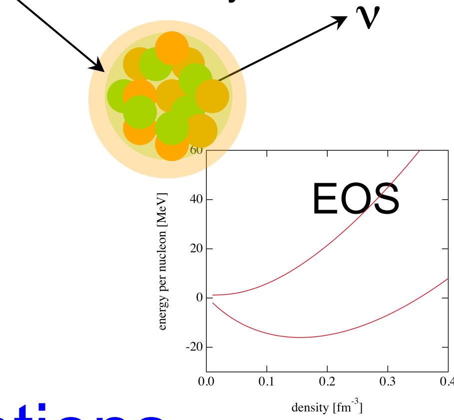
Core-collapse Supernovae: Nuclear matter and EOS

SN1987A



K. Sumiyoshi (Numazu)



- Status of supernova simulations
- Role of EOS: when and how?

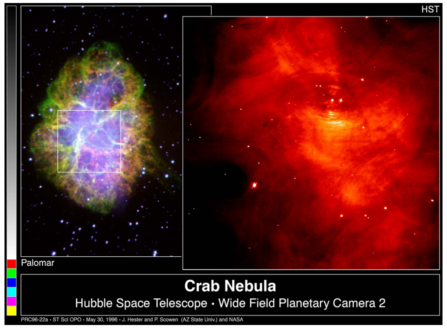
新学術「計算科学素核宇宙」そして「中性子星核物質」へ

Core-collapse supernovae are fascinating

– Birth of neutron stars and black holes

- Pulsars (1.4 solar mass in ~10km)
- Extremely dense: degenerate Fermions

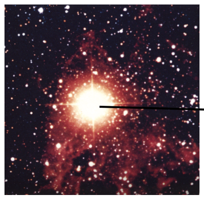
Crab Nebula (SN1054)



– Bright displays and supernova neutrinos

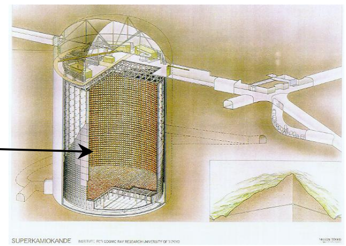
- Nobel prize in Physics in 2002
- Probe of hot & dense matter

SN1987A



supernova ν

Kamiokande



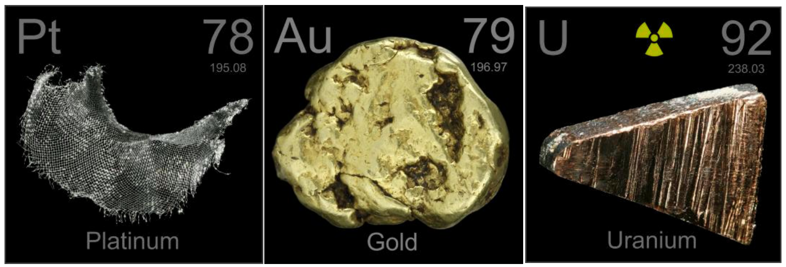
http://www-sk.icrr.u-tokyo.ac.jp/

Prof. Koshiba

http://nobelprize.org/

– Origin of heavy elements

- Explosive nucleosynthesis
- Half of elements beyond Fe



http://periodictable.com/

Massive stars to neutron stars

time

~10^7 years

- Fe core of ~$20M_{sun}$ star

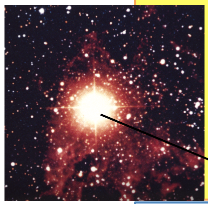
stellar evolution

~1 second

- Collapse, bounce & explosion

difficult part!!

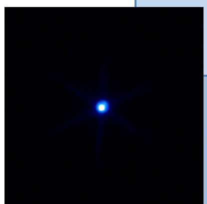
Supernova simulations



ν

~20 seconds

- Proto-neutron star cooling
  – neutrino bursts



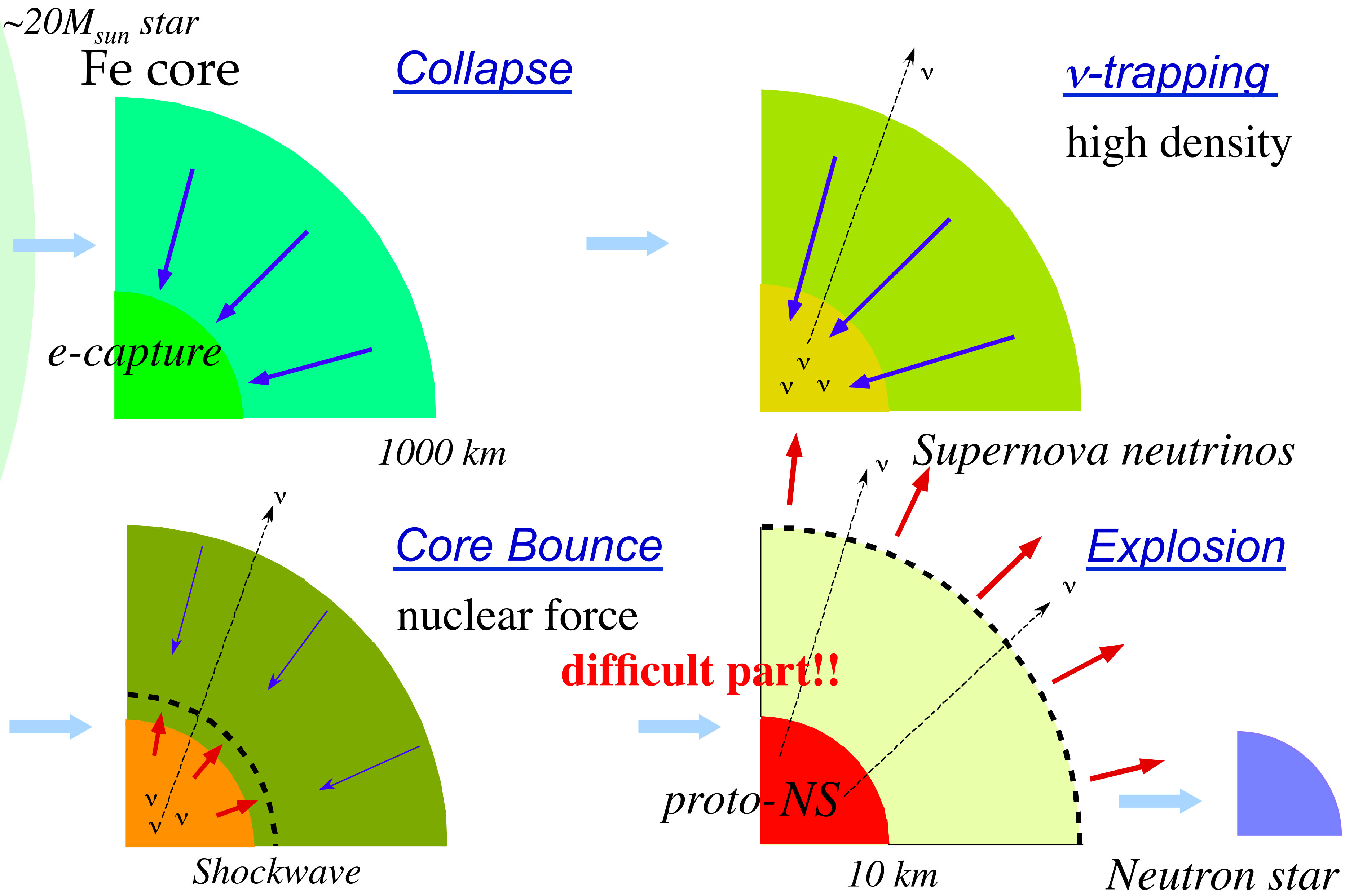
- Neutron star cooling
  – X, γ-rays

~10^3 years

neutron star models

http://chandra.harvard.edu/photo/ Mann "Shadow of a Star"

Gravitational collapse, bounce and explosion



<u>Exotic conditions</u>: challenges in nuclear physics

- **Equation of state (EOS) in supernova core**
  - Dense more than nuclei: $\rho > \rho_0 = 3\times10^{14}$ g/cm^3
  - Neutron-rich: $Y_p < Z/A = 0.46$ for ^{56}Fe
  - Very Hot: $T > 10^{11}$ K (~10 MeV)

- **Neutrino reactions in hot-dense matter**
  - Energy, angle dependent
  - All targets (n, p, nuclei, leptons)

  Emission, absorption, scattering & pairs

  ex. $e^- + p \leftrightarrow \nu_e + n$

  $\nu_i + Fe \leftrightarrow \nu_i + Fe$

  $e^- + e^+ \leftrightarrow \nu_i + \bar{\nu}_i$

- **Necessary inputs for numerical simulations**

  neutrino transfer (Boltzmann eqn.) + hydrodynamics

1% effects: energy budget for explosion

- Iron core to neutron star (M_{core}~$1.4M_{solar}$)
  - R_{Fe}~10^3 km → R_{NS}~10 km
- Gravitational energy released

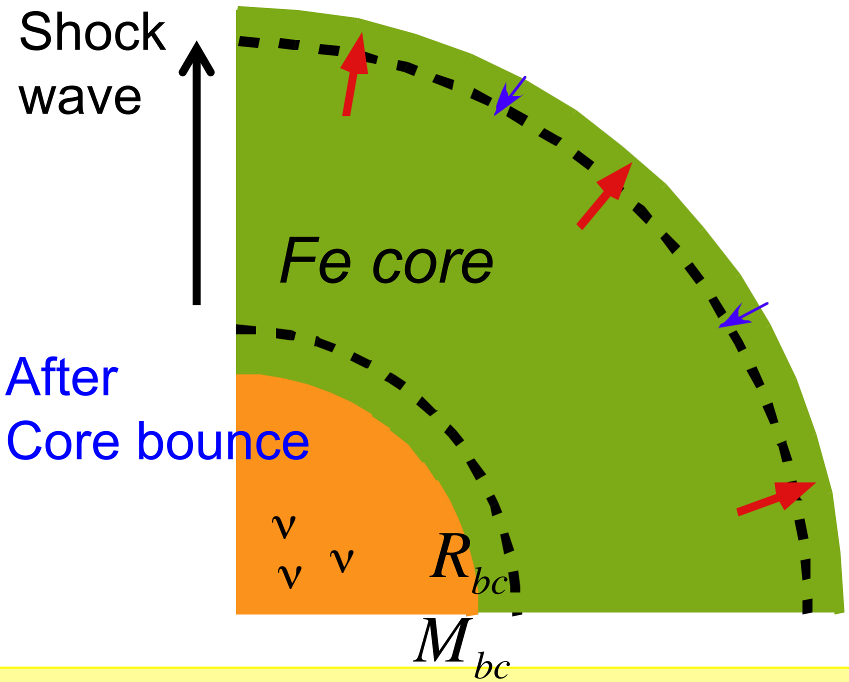
$$\Delta E_{Grav} = -\left(\frac{GM^2}{R_{Fe}} - \frac{GM^2}{R_{NS}} \right) \sim 10^{53} erg$$

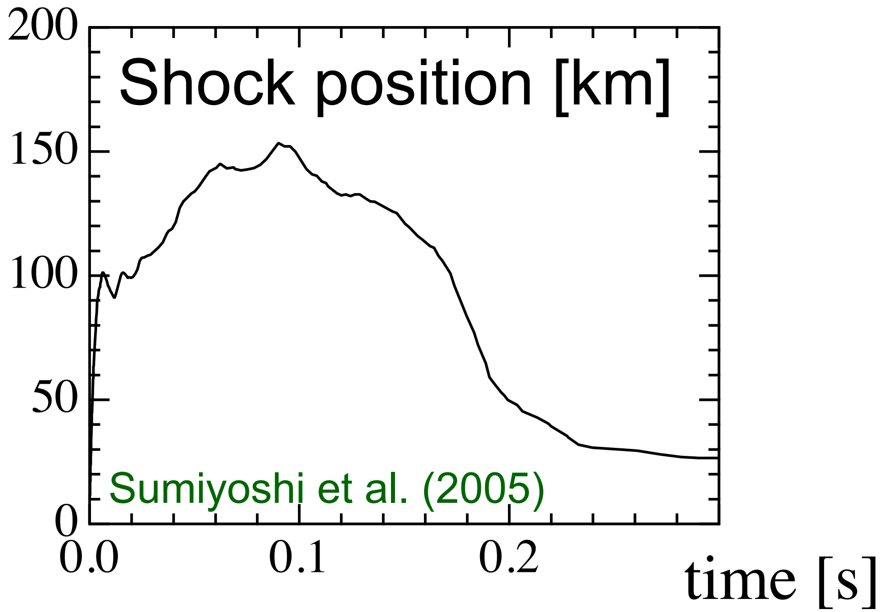
- Explosion energy: $E_{exp} \sim 10^{51}$ erg
- Neutrino carries away: $E_{\nu} \sim 10^{53}$ erg

- Only ~1% is used for the explosion
- Neutrino-matter interaction is essential

Initial shockwave stalls on the way

Energy is used during the propagation





Initial shock energy

$$E_{shock} \sim \frac{GM_{bc}^2}{R_{bc}} = several \times 10^{51} erg$$

Energy loss due to Fe dissociation

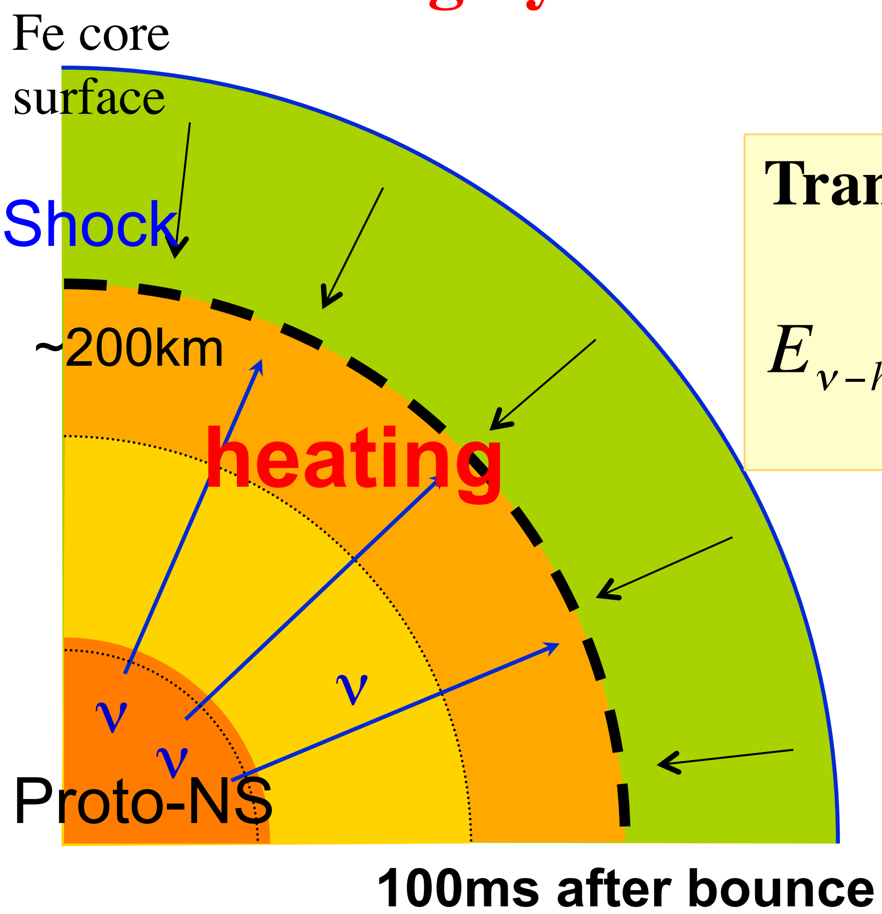
$$E_{loss} \sim -1.6 \times 10^{51} \left(\frac{M_{outer}}{0.1 M_{solar}} \right) erg$$

Neutrino heating mechanism for revival of shock

Heating by neutrino absorption

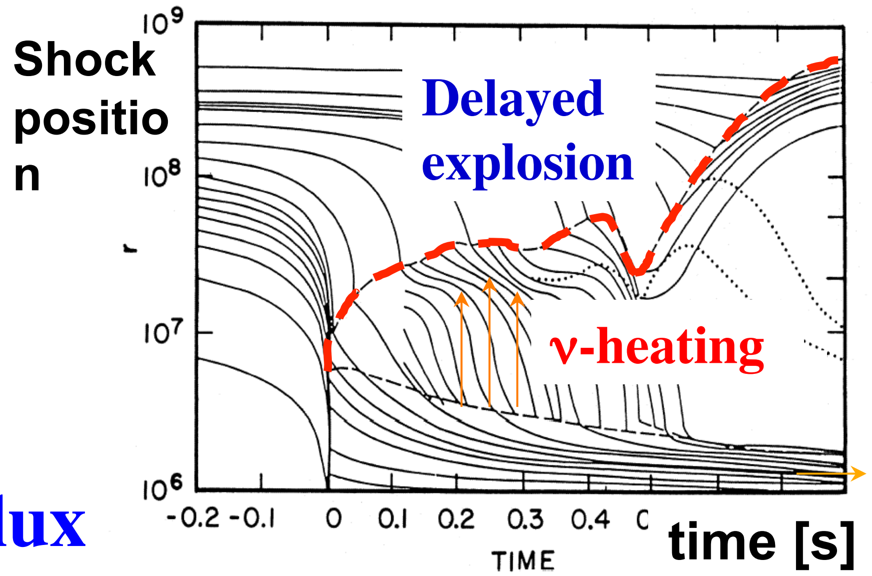
$\nu_e + n \rightarrow e^- + p,$

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



Transfer of energy from ν

$$E_{\nu-heat} \sim 2.2\times10^{51}\left(\frac{\Delta M}{0.1M_{solar}}\right)\left(\frac{\Delta t}{0.1s}\right)erg$$



Depends on neutrino energy/flux

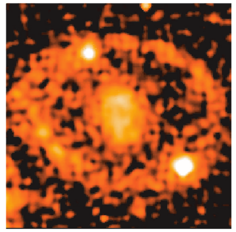
Bethe & Wilson ApJ (1985)

Multi-dimensions: new findings

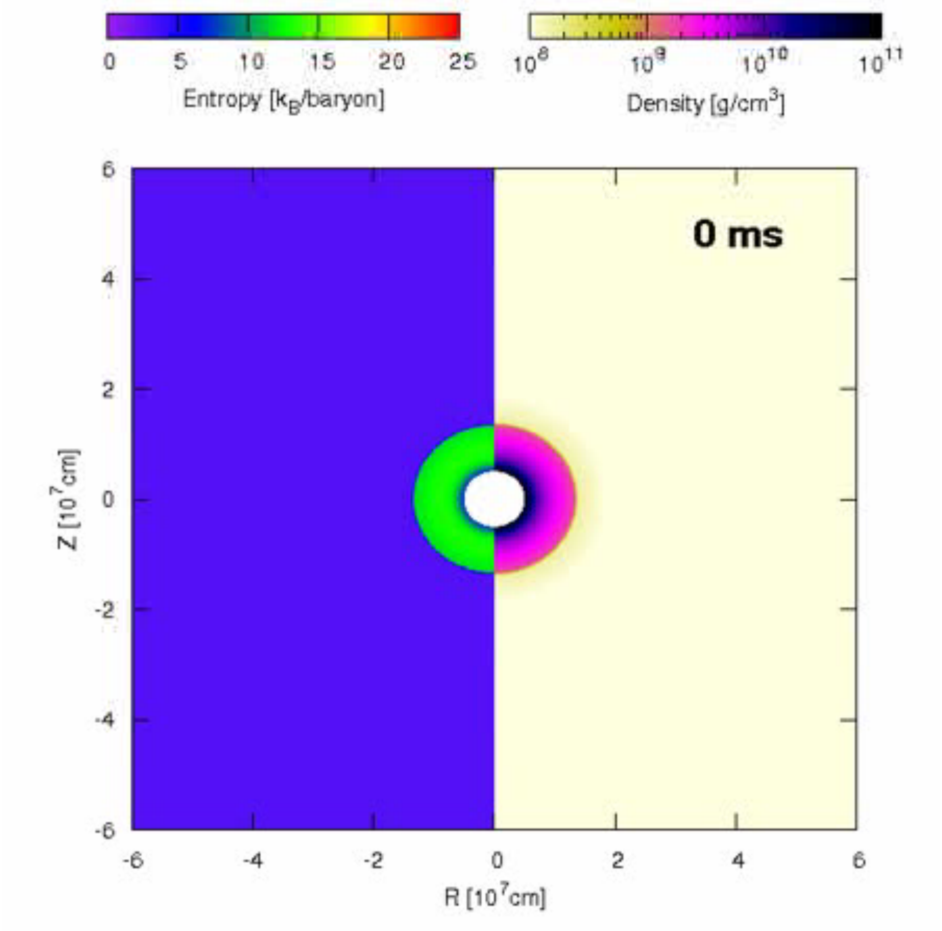
- Convection, SASI, rotation, magnetic etc - Observations

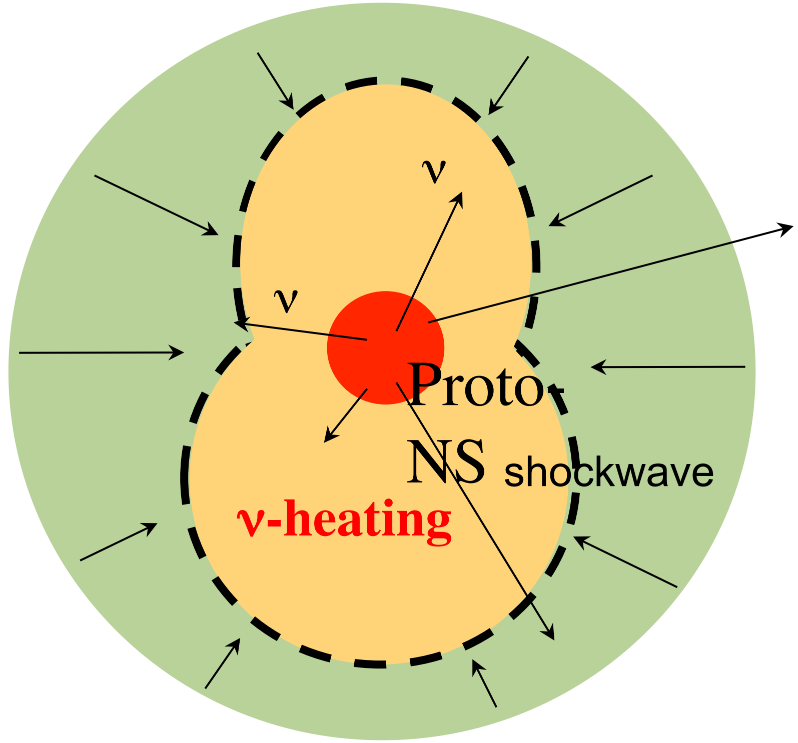
ν-heating and/or hydro instability

SN1987A



Wang (2002)





To obtain enough ν-heating

Ohnishi et al. (2006) ApJ

Challenges toward 3D simulations

Neutrino-transfer & hydrodynamics

- 1D: No explosion found
  - first principle calculations
- 2D: Cases of explosions
  - State-of-the-art, but approximate neutrinos

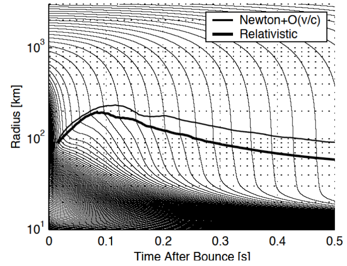
Several mechanisms, discussions not settled

- 3D: Explore new instabilities
  - Major challenges of supernova simulations

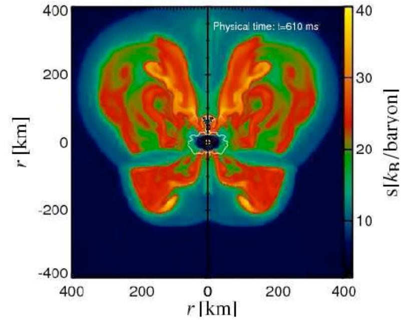
New code to solve 6D Boltzmann eqn.

(Sumiyoshi-Yamada, 2012 ApJS)

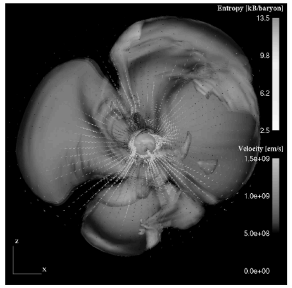
Liebendoerfer (2001)



Marek (2009)



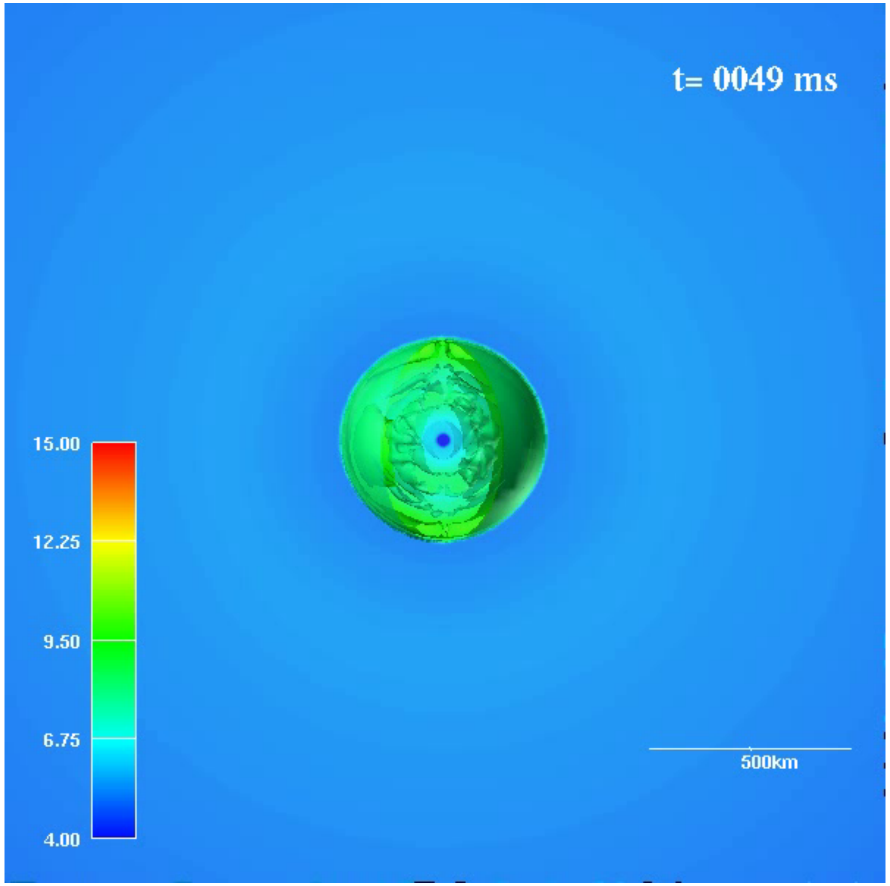
Iwakami (2008)



3D simulation of supernovae from a massive star

Explosions obtained, but still not conclusive

Need high resolutions, accurate ν-transfer



- Simulations running at K-computer, 10Peta-flops

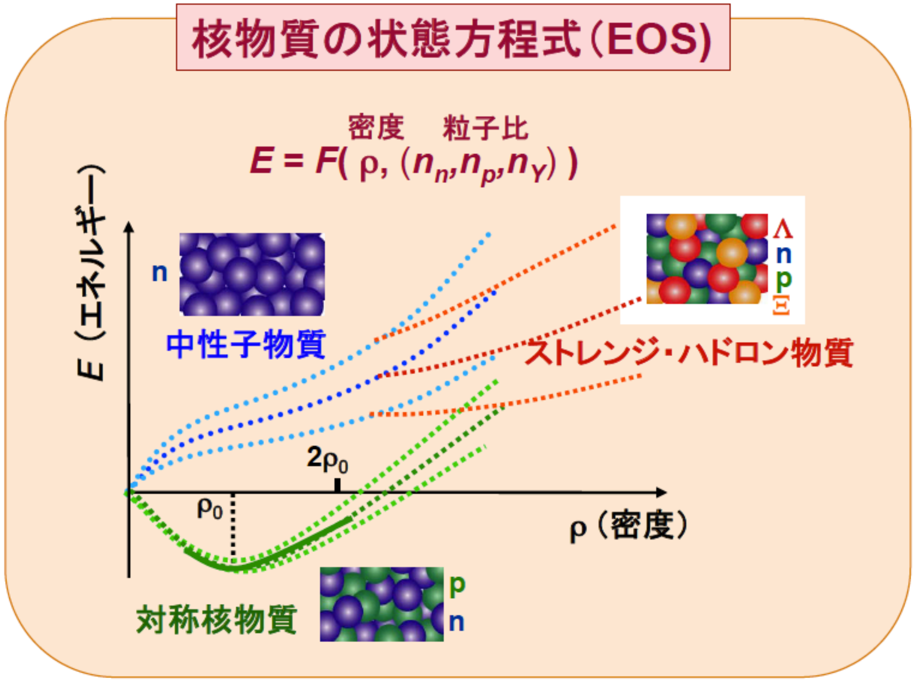
K computer

@ Kobe, Japan

Takiwaki et al. (2012) ApJ

Naive questions on EOS in supernovae

- Different from NS?
- Which part of ρ, Y_p?
- Soft EOS is better?
- Hyperons/quarks affect?



From Slides by H. Tamura @Kyoto

Shen equation of state for supernovae

H. Shen, Toki, Oyamatsu & Sumiyoshi NPA, PTP(1998), arXiv:1105.1666 (2011)

- Relativistic mean field theory+ local-density approx.
  - Based on relativistic Brueckner Hartree-Fock (RBHF) theory
  - Checked by exp. data of n-rich unstable nuclei
    - Nuclear structure: mass, charge radius, neutron skin,…

  Covers wide range of
  - Density: $10^{5.1} \sim 10^{16}$ g/cm^3
  - Proton fraction: $0 \sim 0.65$
  - Temperature: $0 \sim 400$ MeV

Uniform and non-uniform matter

- Data table ~140 MB (110 x 66 x 92 points)
  - Quantities: ε, p, S, μ_i, X_i, m*

Shen-EOS

cf. Lattimer-Swesty EOS
- Extension of compressible liquid model

LS-EOS

Extensions of Shen EOS tables

- Appearance of hyperons & quarks

Ishizuka et al. JPG (2006), Nakazato et al. PRD (2008) *Shen et al. ApJS (2012)*

EOS table	Framework	Nucleons	Hyperons	Quarks	Max. NS
Shen EOS 1998, NPA	RMF	n, p, α, nuclei	-	-	$2.2M_{sun}$
Hyperon EOS 2008, JPG	RMF in SU(3)	n, p, α, nuclei	Λ, Σ, Ξ	-	$1.6M_{sun}$
Quark EOS 2008, PRD	RMF + MIT bag model	n, p, α, nuclei	-	u, d, s	$1.8M_{sun}$

- Mixture of nuclei in NSE

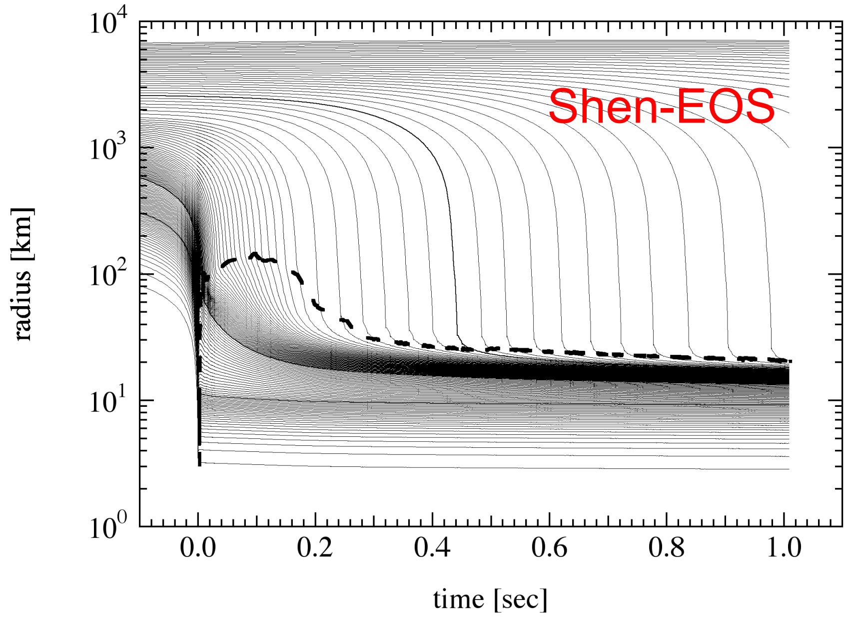
Furusawa et al. ApJ (2011)

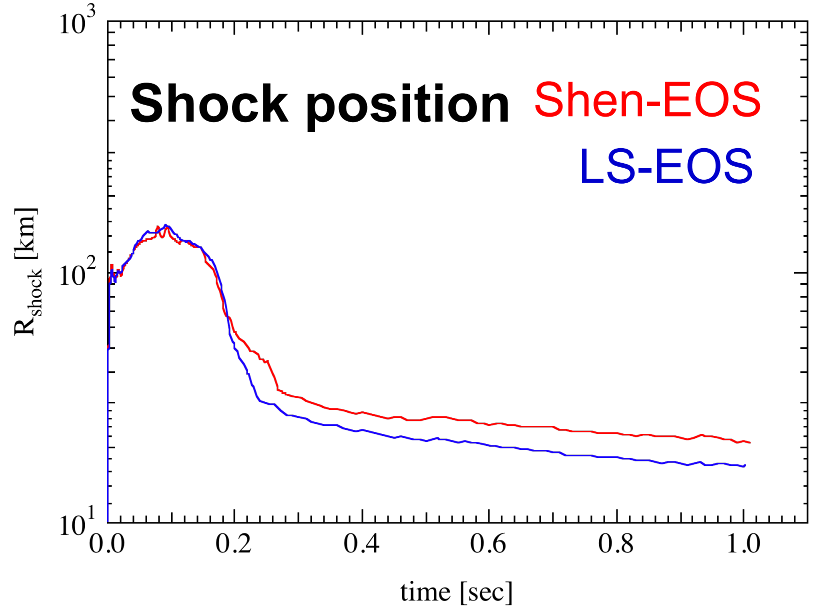
NSE EOS 2011, (ApJ)	RMF + NSE	n, p, α, NSE of nuclei	-	-	$2.2M_{sun}$

- Needs exp. data on nuclear mass, hyper-nuclei

EOS dependence: no explosion in 1D

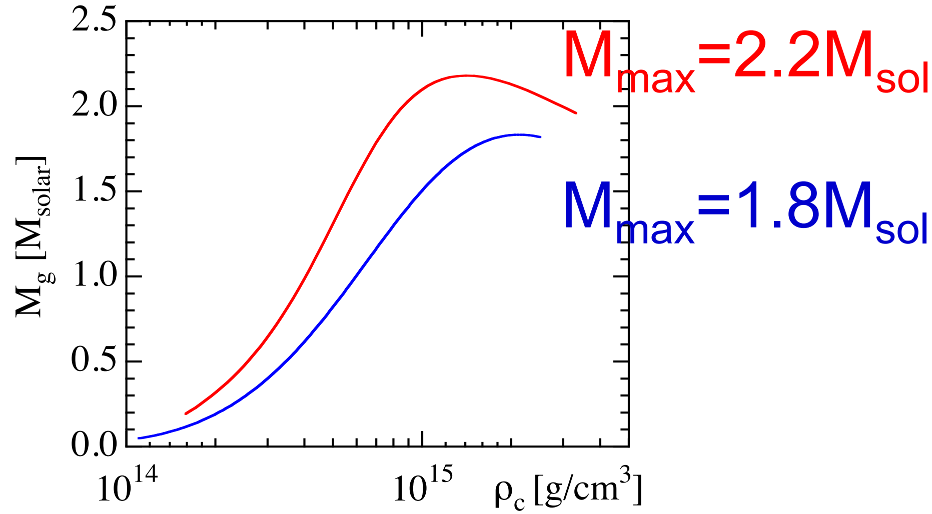
No revival of shockwave up to 1 sec. Sumiyoshi et al. ApJ (2005)





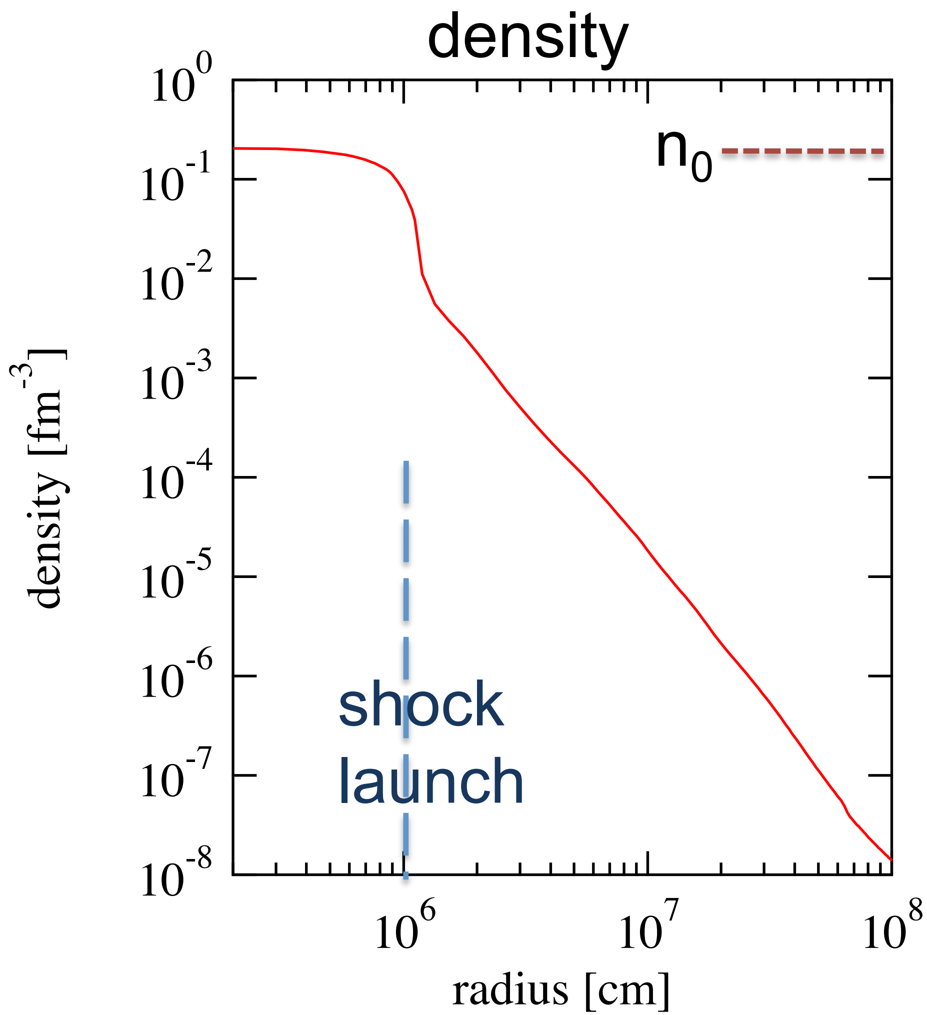
	A_{sym}	K
Shen	36.9	281
LS	29.3	180

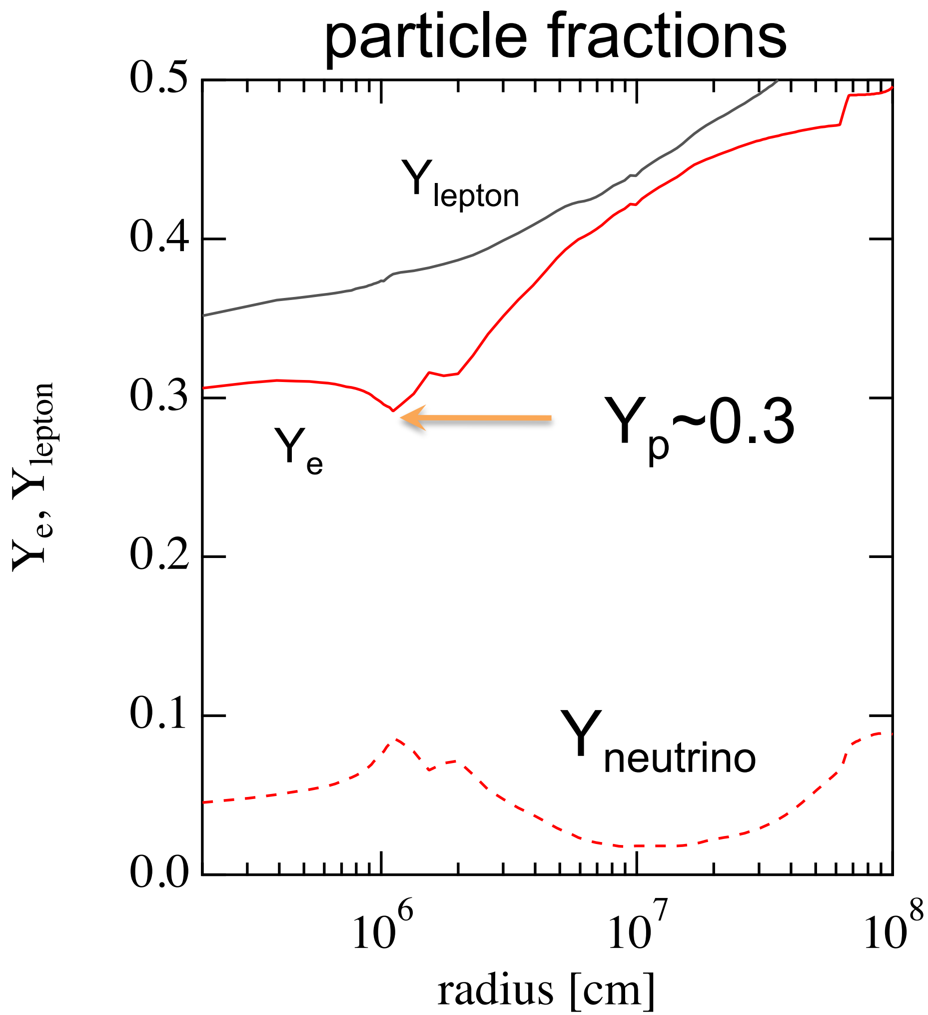
[MeV]



EOS condition at core bounce

- Just above n_0
- Still proton-rich with ν_e





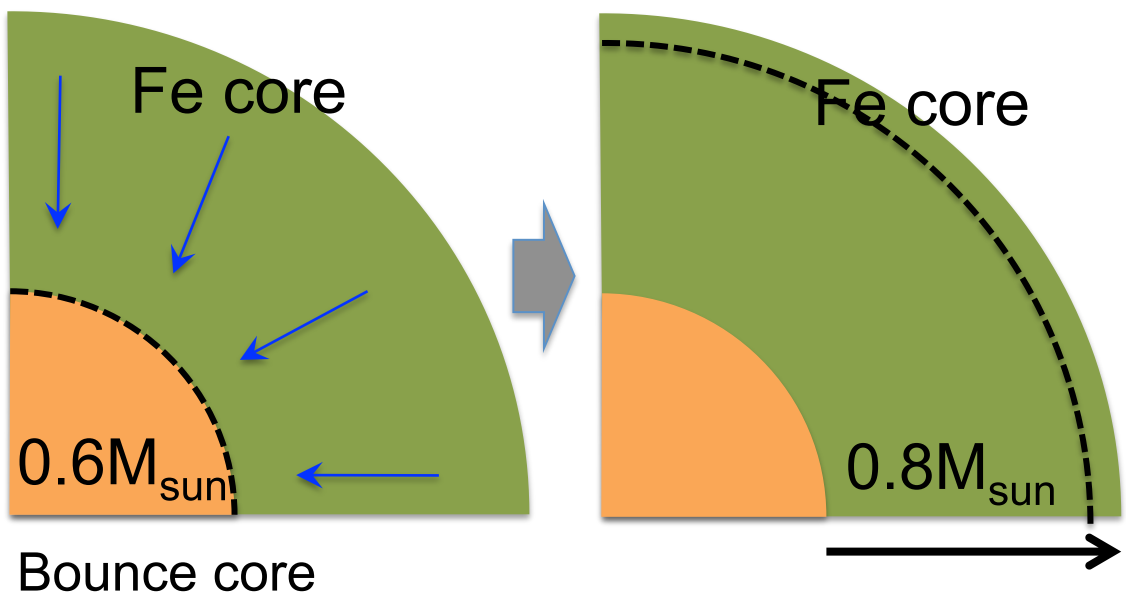
Sumiyoshi et al. (2005) ApJ

Soft EOS is better: YES but...

- Initial energy of shock wave: $E_{initial} \sim 10^{51}$ erg
  - Size of bounce core: R_{bc}, (M_{bc})
  - Soft EOS → Small R_{bc}

$$E_{initial} = \frac{GM_{bc}^2}{R_{bc}}$$

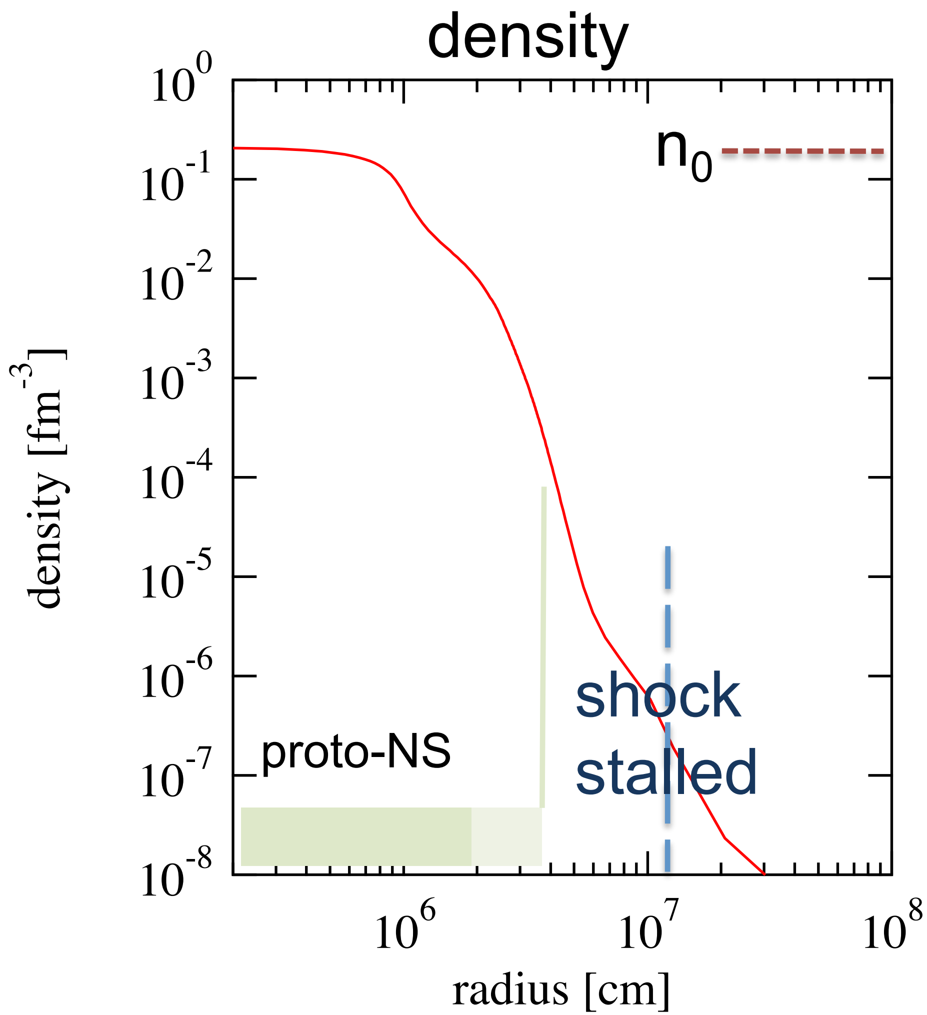
- EOS around n_0, $Y_p \sim 0.3$ is important ex. L, K_{sym}

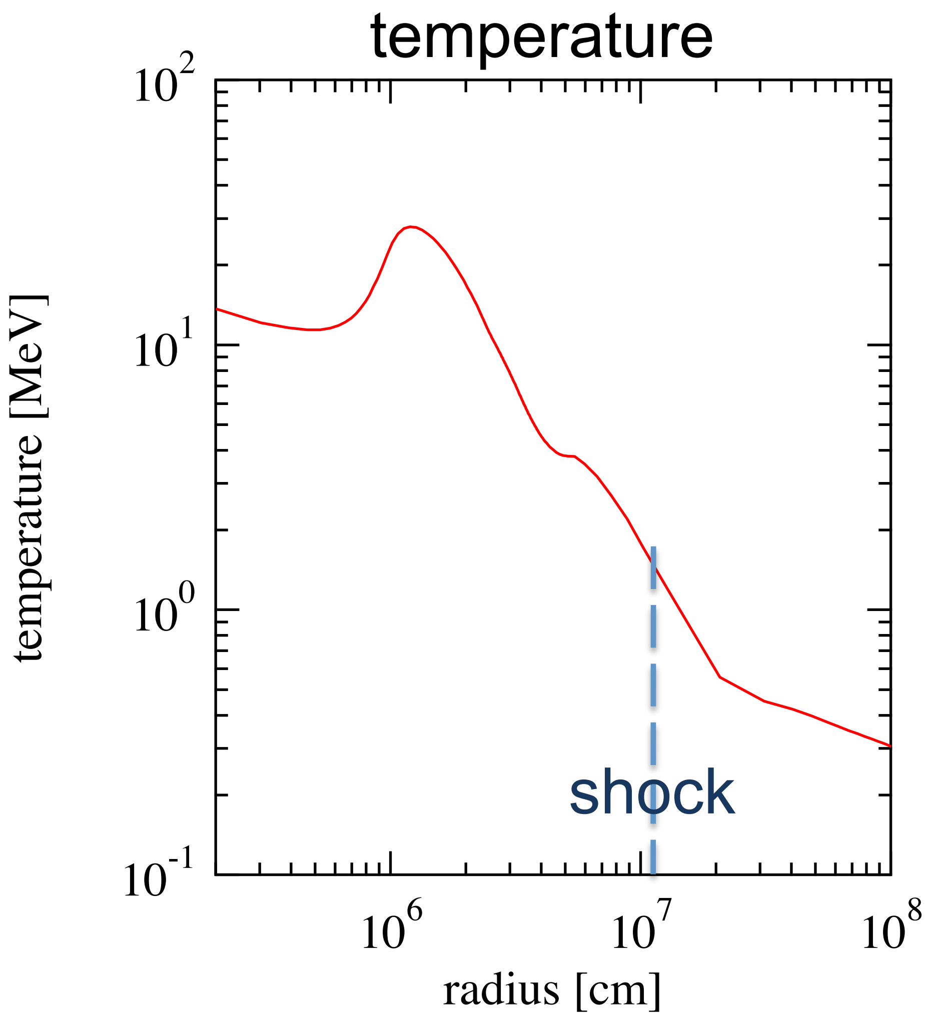


- Larger $E_{initial}$ is better for 2D/3D
- Position of stalled shock wave
- *e-capture rates*

EOS condition at 200ms after bounce

- Proto-NS at birth
- Temperature 1~10 MeV





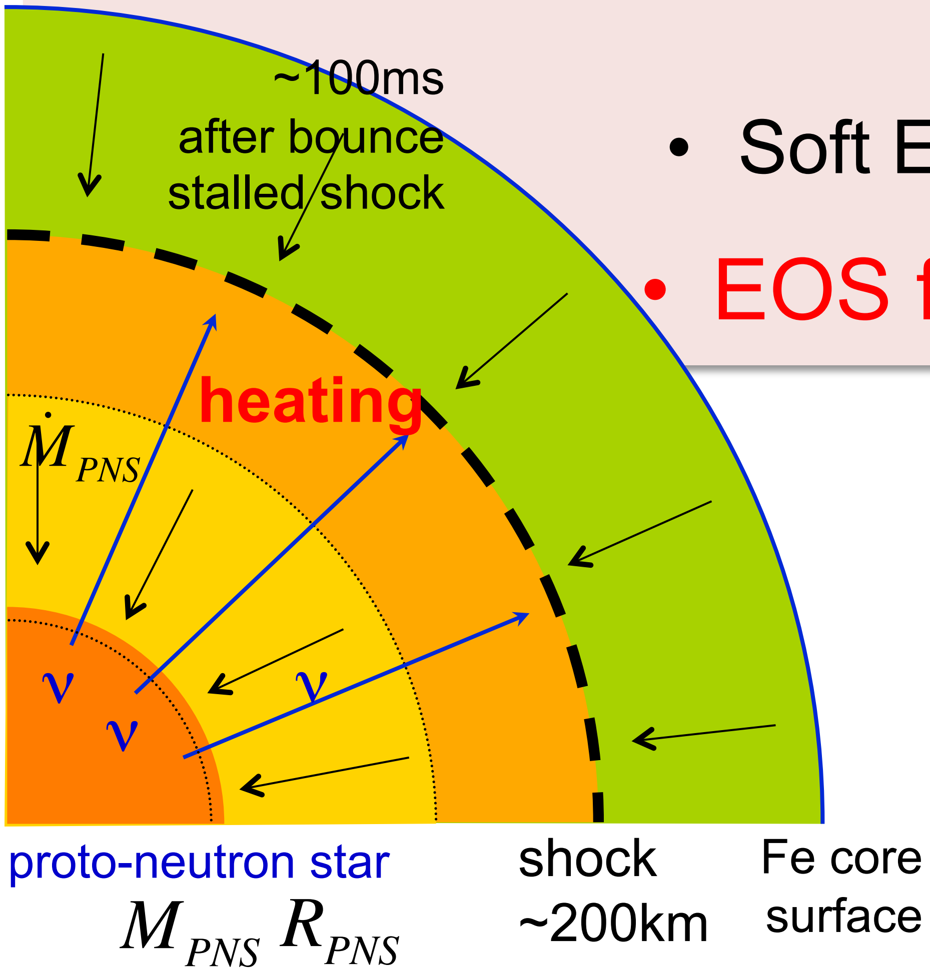
Sumiyoshi et al. (2005) ApJ

Soft EOS is better: also in 2D/3D?

- Neutrino heating: $E_{heating} \sim 10^{51}$ erg
  - – absorption of neutrinos

$$Q_{heating} \propto \frac{L_\nu E_\nu^2}{r^2} Y_N$$

- Soft EOS → Large L_ν, E_ν, $E_{heating}$
- EOS for proto-NS is important



ν-energy

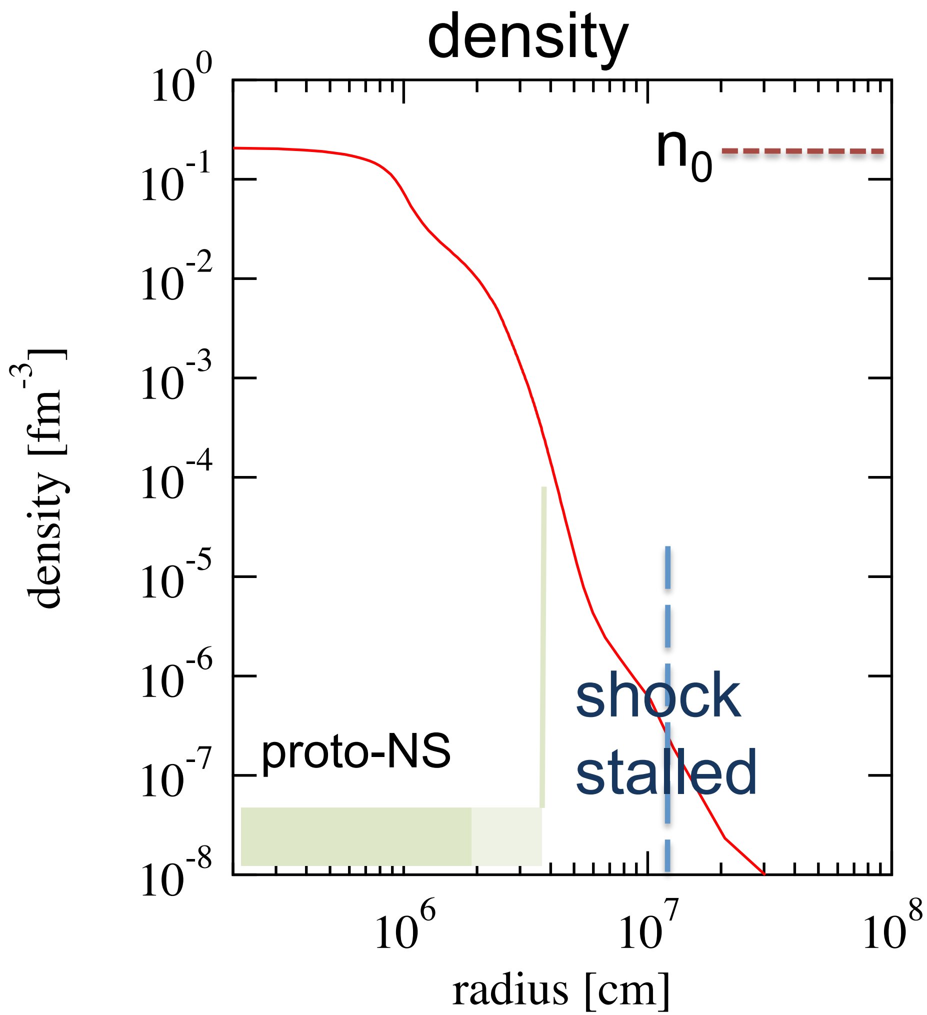
$$E_\nu = T_{PNS}$$

luminosity

$$L_\nu = \frac{G M_{PNS} \dot{M}_{PNS}}{R_{PNS}}$$

EOS condition at 200ms after bounce

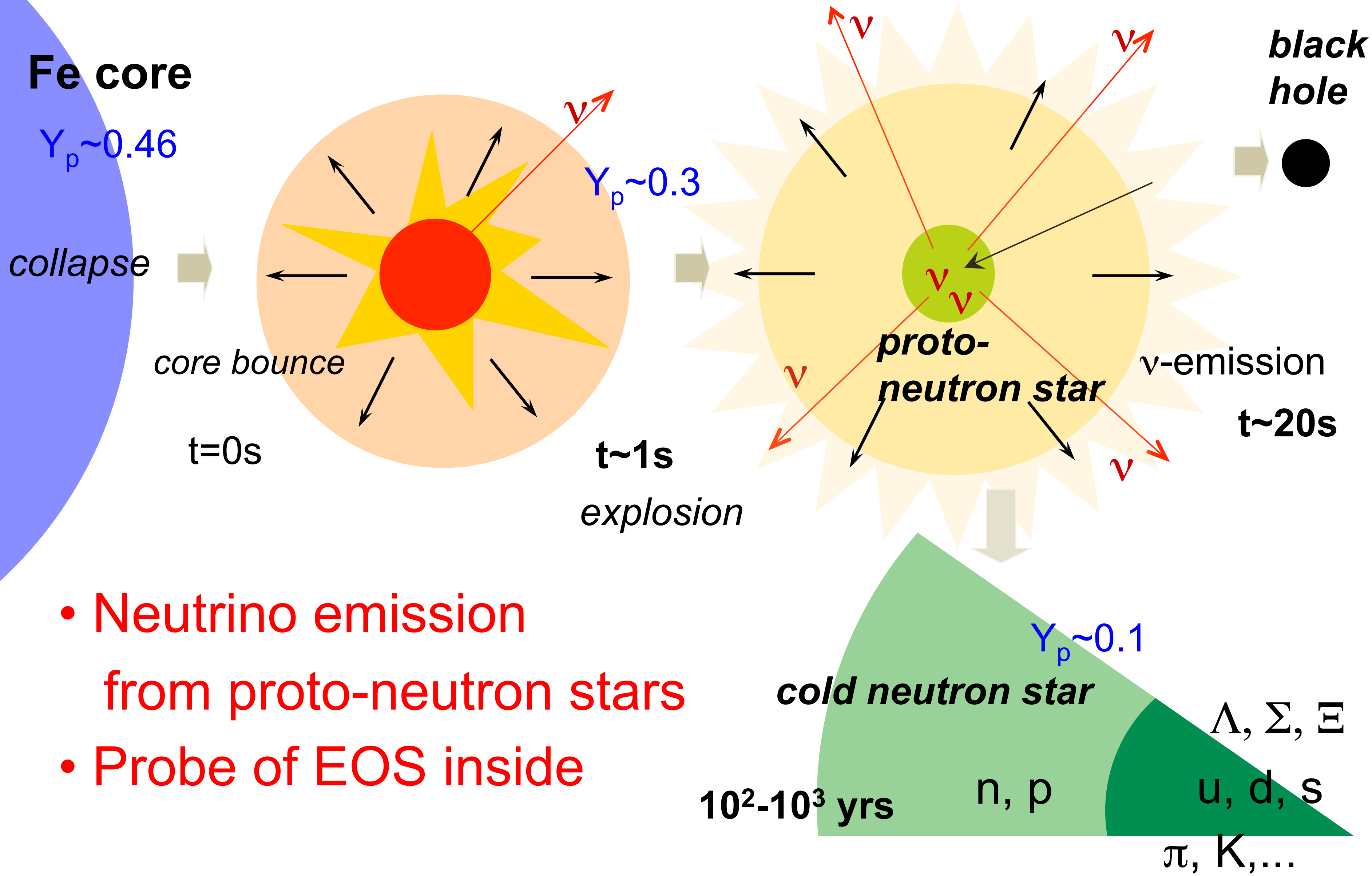
- Proto-NS at birth



- Important region
- $>n_0$: proto-NS mass, radius
- $\sim 10^{-3} n_0$: surface
  - neutrino emission, L_ν, E_ν
- $\sim 10^{-5} n_0$: heating region
  - targets, composition

Sumiyoshi et al. (2005) ApJ

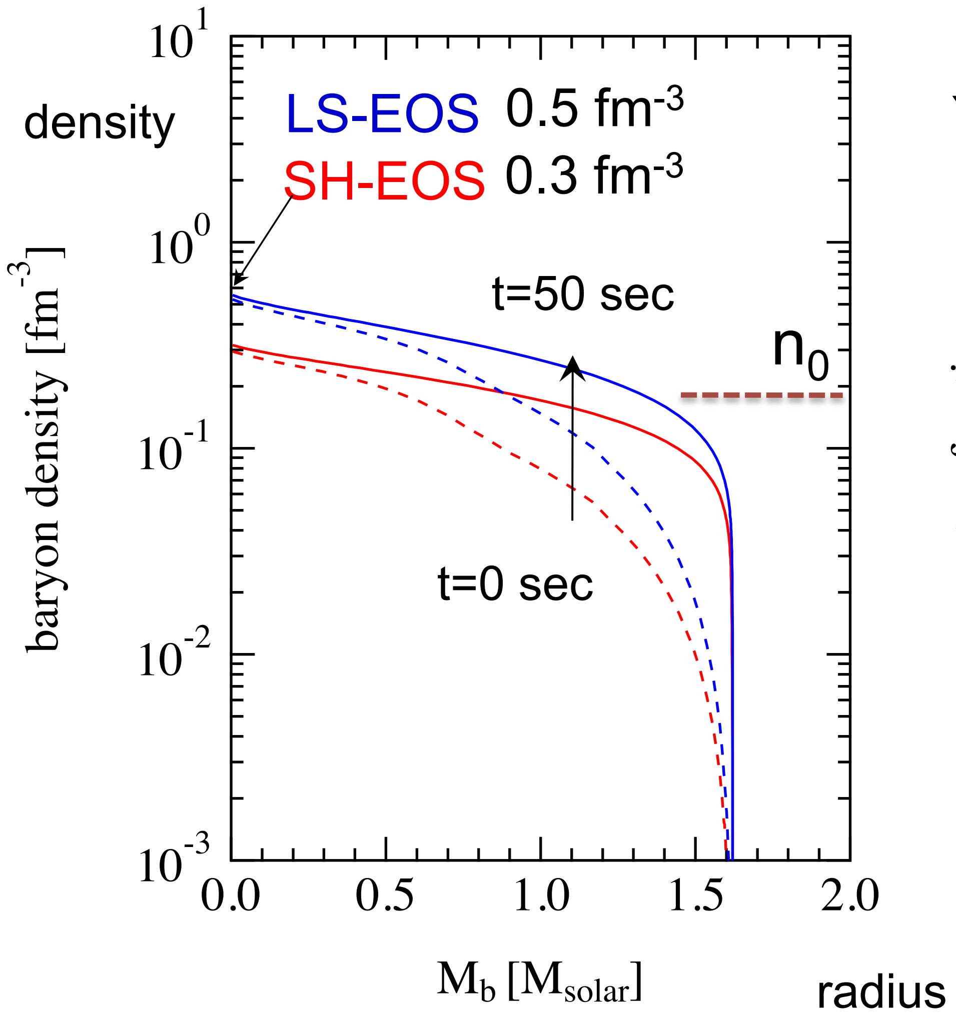
When hyperons/quarks appear?

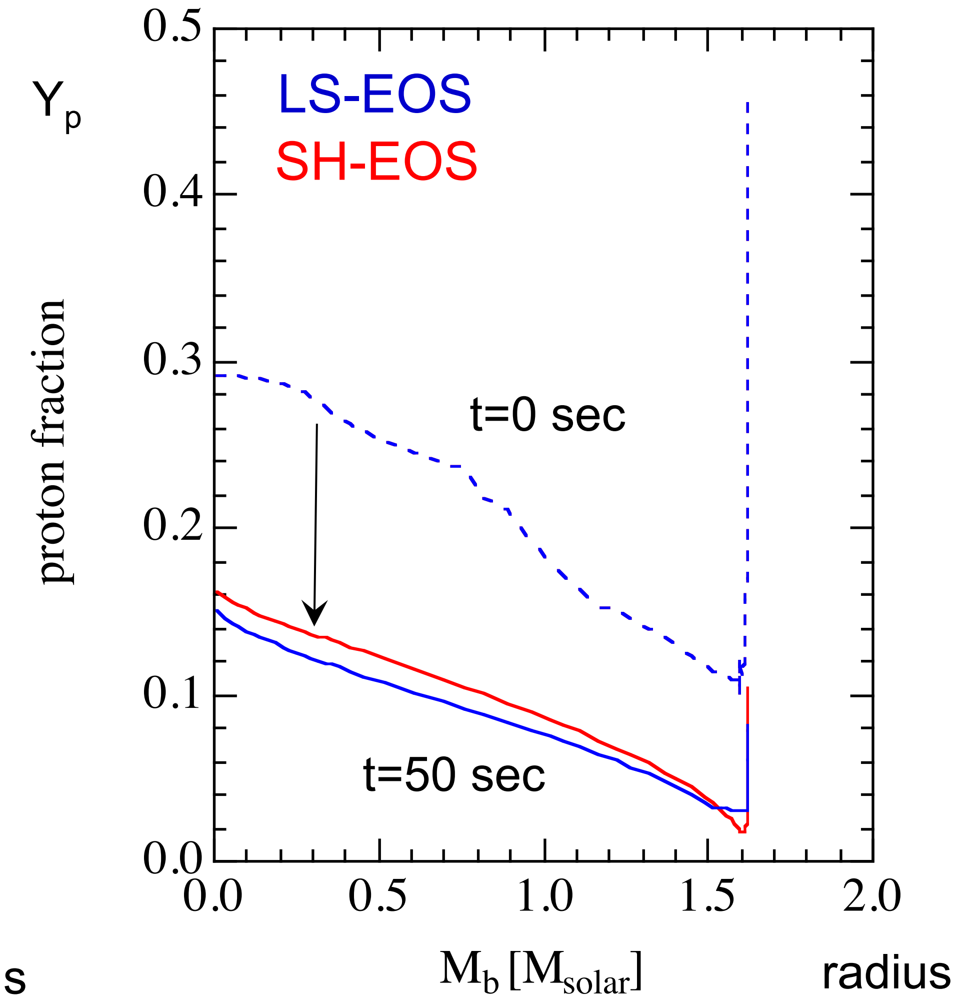


- Neutrino emission
  from proto-neutron stars
- Probe of EOS inside

Proto-neutron star evolution

Neutrino emission ⇒ T↓, density↑, Y_p↓,





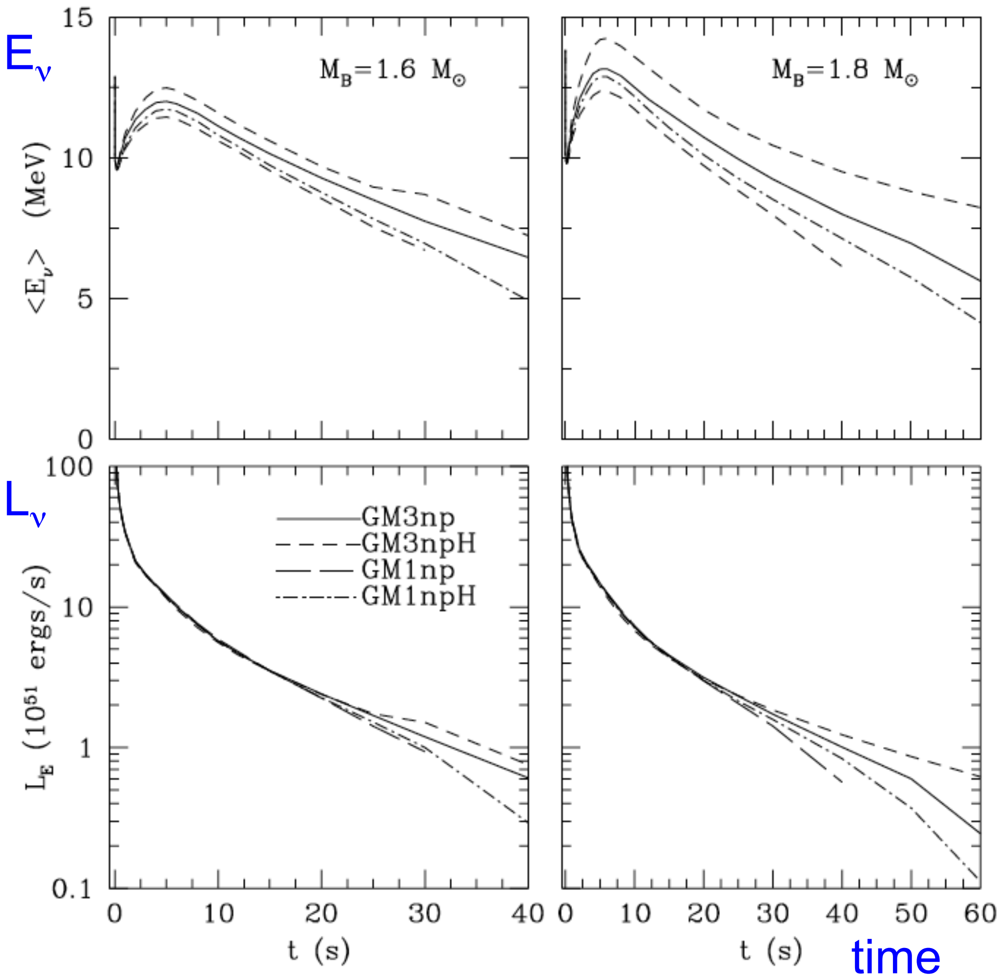
Sumiyoshi et al. (1995), H. Suzuki (2005), Nakazato (2012)

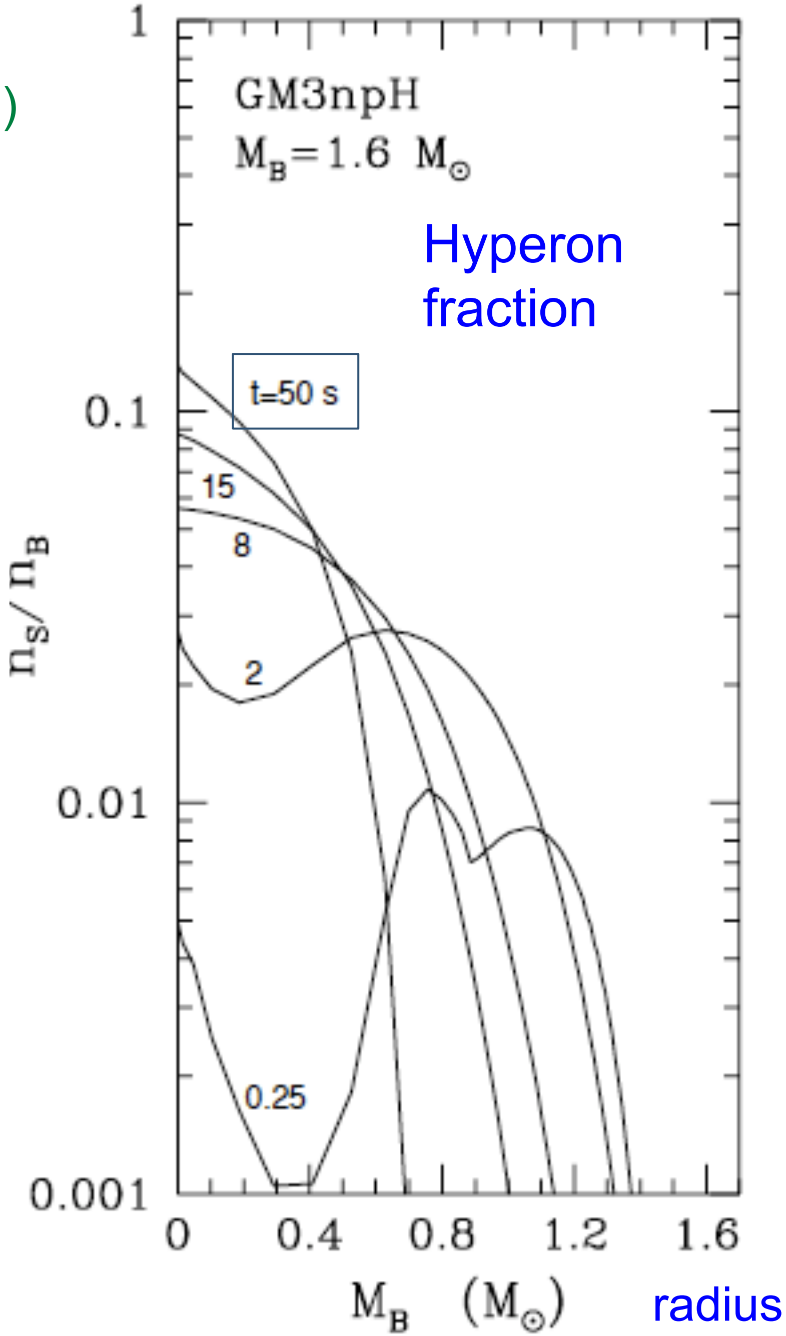
Simulation started from t_{pb}=0.4 sec

Hyperons in proto-NS

Pons et al. ApJ (1999)

- Appear at late phase of evolution
  - Difference in neutrino emission



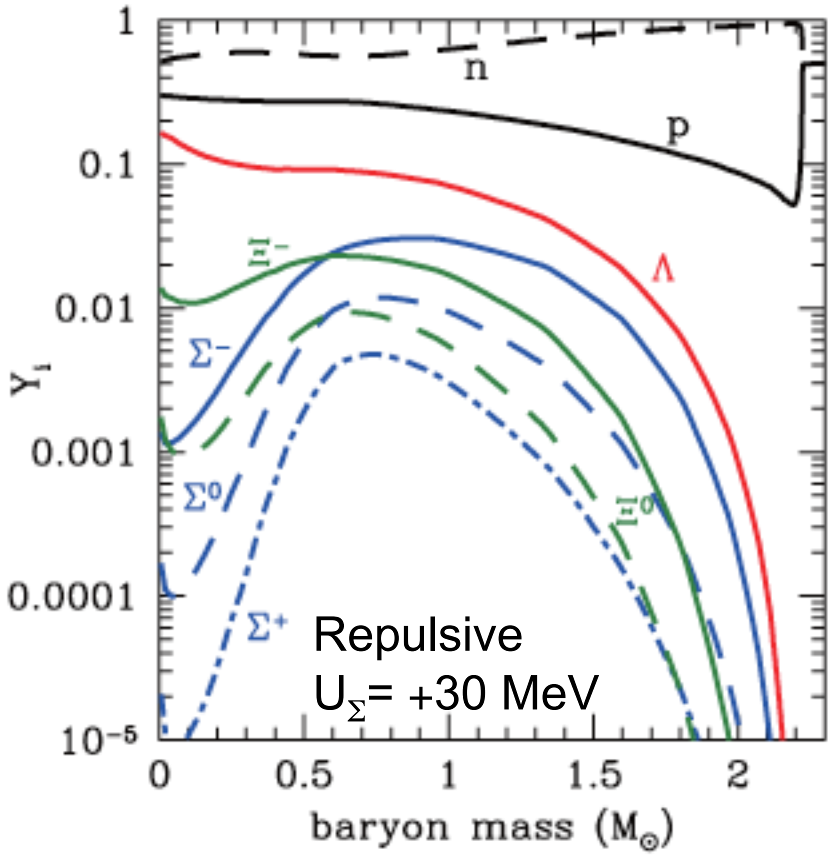


Neutrino burst from failed supernovae

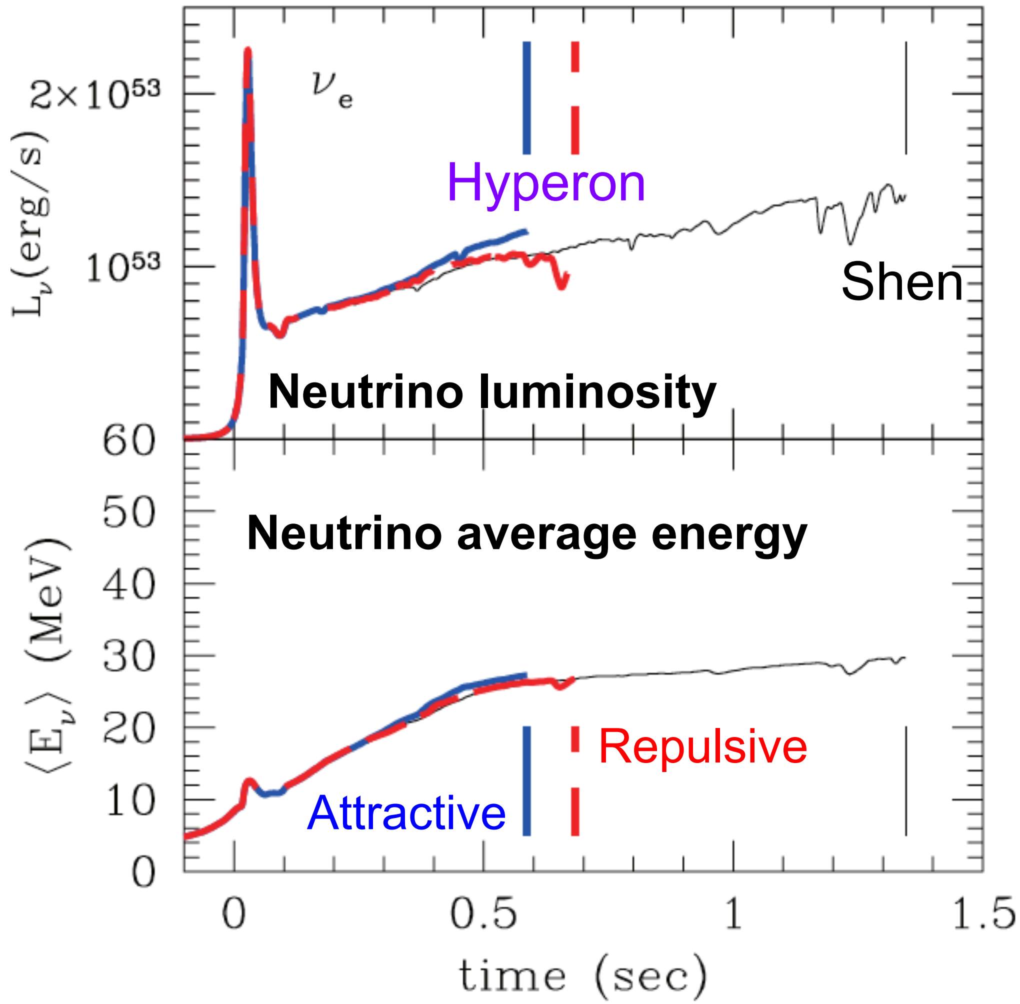
- Probe EOS soft/stiff, hyperon-mixture

40M_{sun}

Nakazato et al. ApJ (2012)



Hyperon mixture
in proto-neutron star



Summary and discussions

- Key role of EOS for successful explosion
  - Initial shock energy (just above n_0 with Y_p~0.3)
  - Neutrino heating (proto-neutron star EOS)
- Supernova neutrinos from proto-neutron stars
  - Appearance of hyperons/quarks
- Needs systematic EOS for 2D
  - Link to nuclear data (radii, masses, K, A_{sym})
- Unique best EOS table for 3D
  - Experiments & nuclear many body theories
  - Neutron star mass & radius constraint

3D supernova project in collaboration with

- Supernova research
  - S. Yamada
  - H. Suzuki
  - K. Nakazato
- EOS table
  - H. Shen
  - K. Oyamatsu
  - H. Toki
- Extension of EOS table
  - S. Furusawa
  - A. Ohnishi
  - C. Ishizuka
- Supercomputing
  - H. Matsufuru
  - A. Imakura
  - T. Sakurai
- Numerical simulations
  - H. Nagakura
  - K. Kotake
  - T. Takiwaki
- Neutrino reactions
  - T. Sato
  - S. Nasu
  - S. Nakamura

新学術領域「計算科学による素核宇融合」

Support from: HPCI Strategic Program Field 5
- Grant-in-Aid for Scientific Research on Innovative Areas (20105004, 20105005)
- Grant-in-Aid for Scientific Research (22540296, 24244036)
Supercomputing resources at KEK, RCNP, YITP, UT