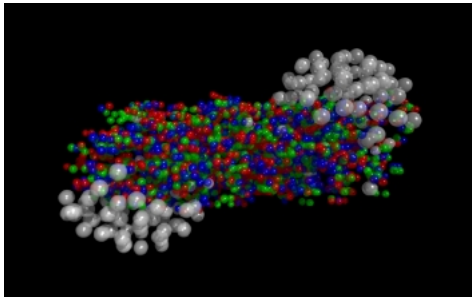
EOS and neutrinos in supernova explosions: From high to low densities

Heavy Ion Collision

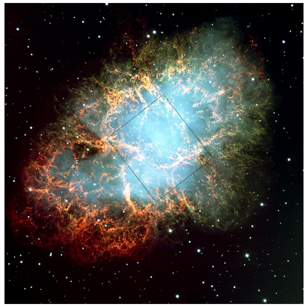


www.physik.uni-frankfurt.de

K. Sumiyoshi

Numazu College of Technology
Japan

Crab nebula



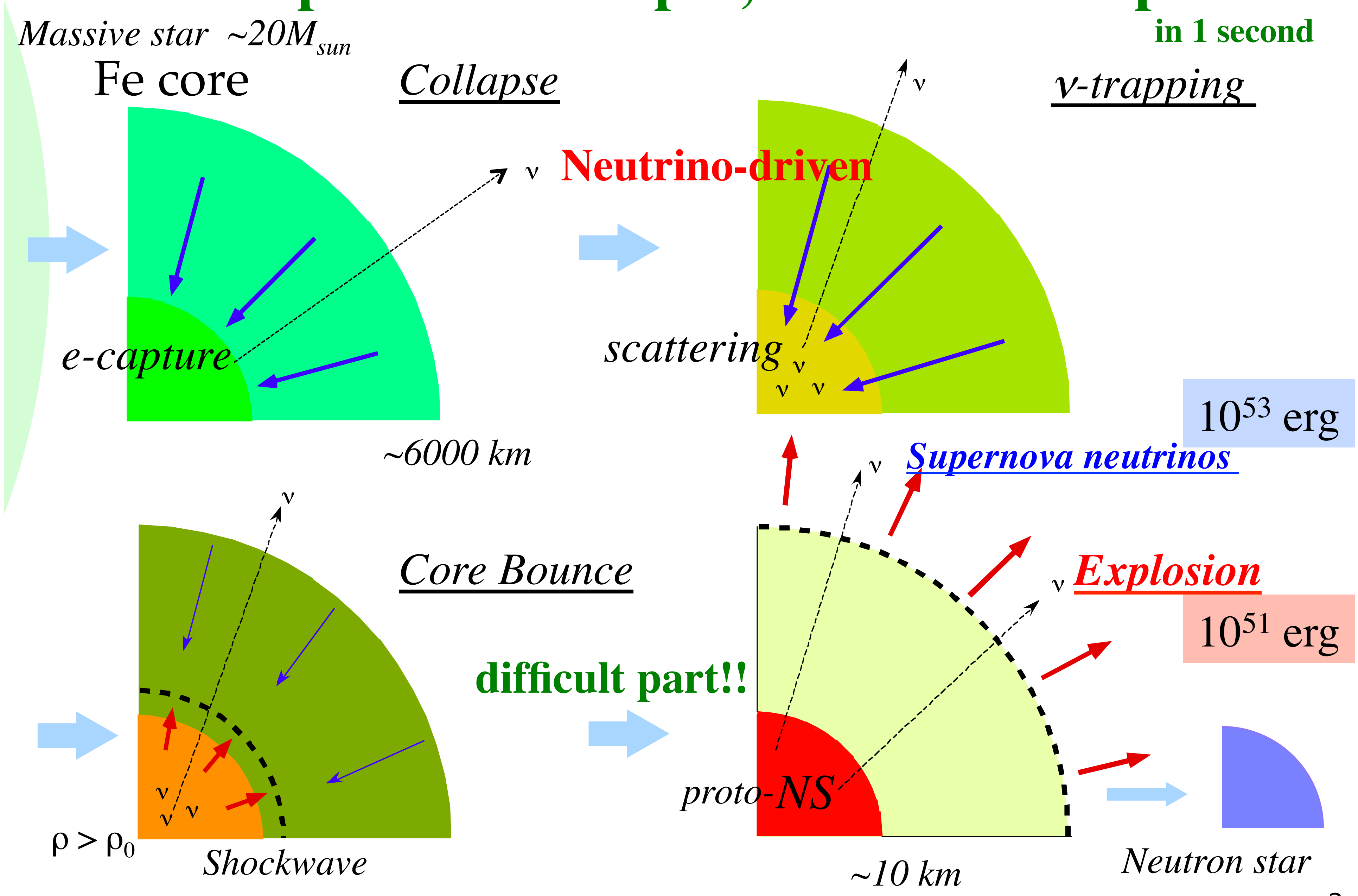
hubblesite.org

EOS in explosion mechanism: (ρ, T, Y_p) conditions
Stiffness & Composition of EOS: neutrino heating

Numazu near Mt. Fuji

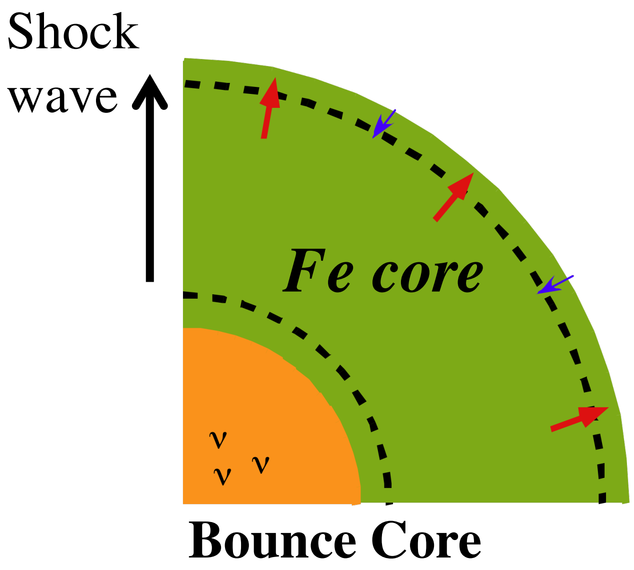
Wikipedia (trimmed)

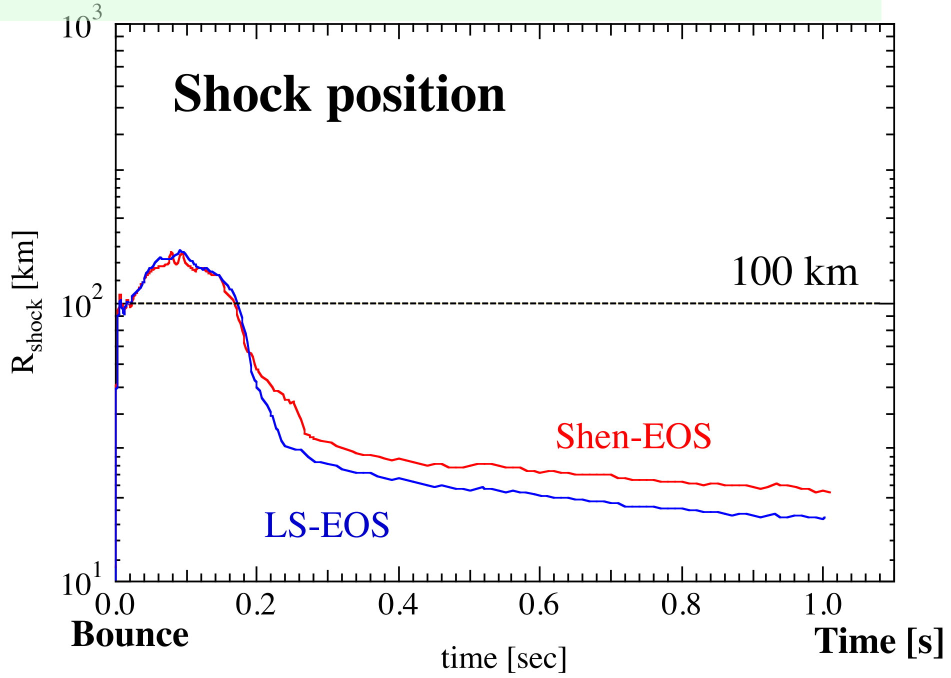
Core-collapse SNe: collapse, bounce and explosion



Difficulties: shock wave stalls on the way

1. Initial shock energy is used up by Fe dissociation
2. No explosion occurs in spherical (1D) simulations





Sumiyoshi et al. ApJ (2005)

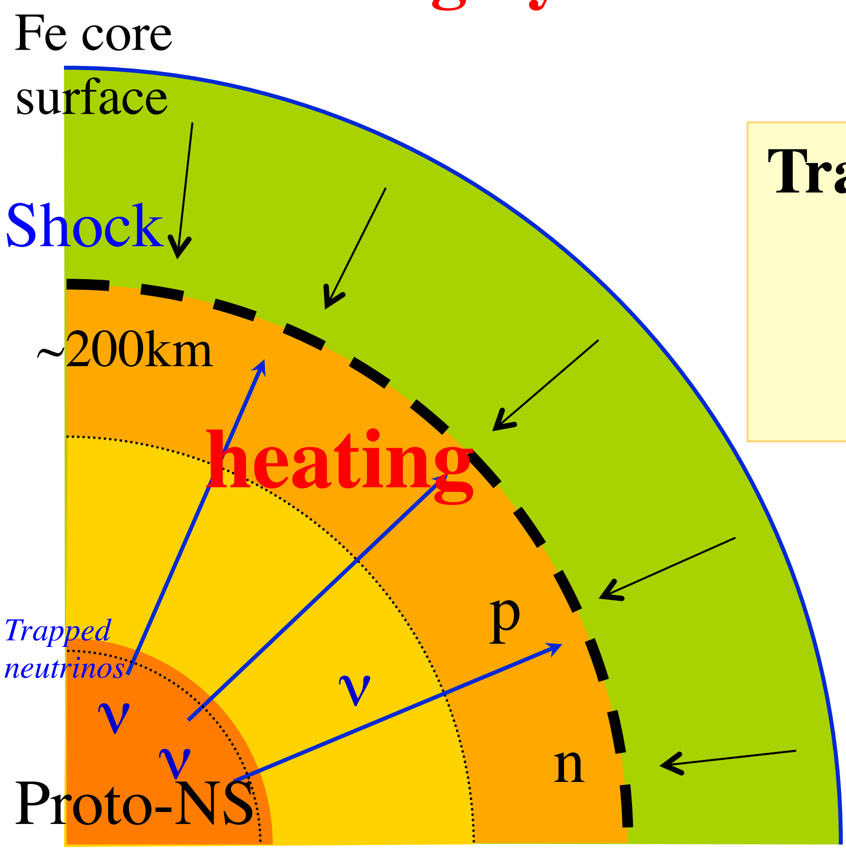
How to revive the stalled shock wave?

- Neutrino heating mechanism
- Multi-dimensional effects

Neutrino heating mechanism for revival of shock

Heating by neutrino absorption

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

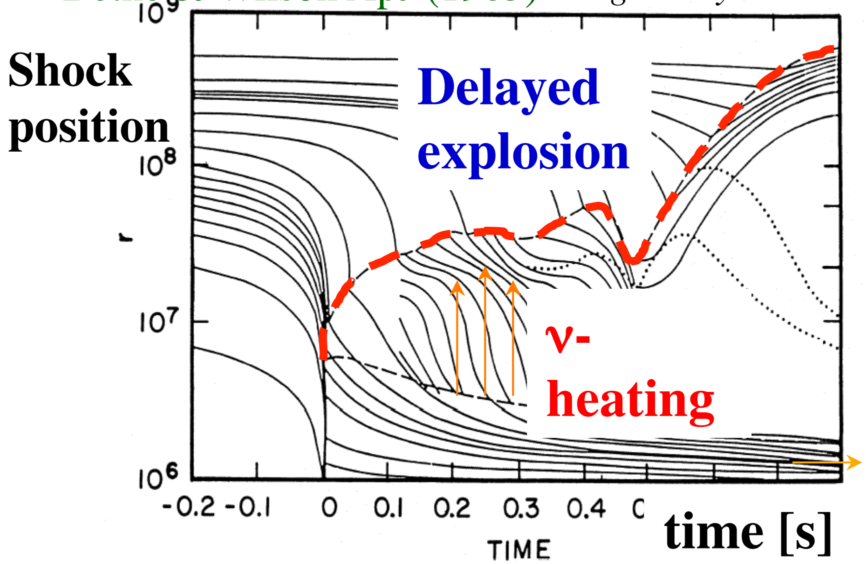


100ms after bounce

Transfer of energy from ν Janka A&A (1996)

$$E_{\nu-heat} \sim 2\times 10^{51}\left(\frac{\Delta M}{0.1M_{solar}}\right)\left(\frac{\Delta t}{0.1s}\right) erg$$

Bethe & Wilson ApJ (1985) *"Legendary simulation"*



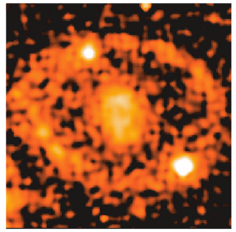
Neutrino energy/flux from trapped neutrinos → **neutrino matter interaction**

Neutrino heating and hydro instabilities

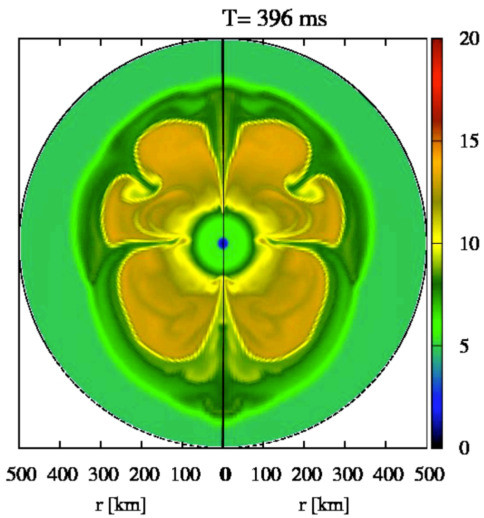
- Convection, SASI, rotation, magnetic etc - Observations

→ neutrino-matter in multi-dimensions

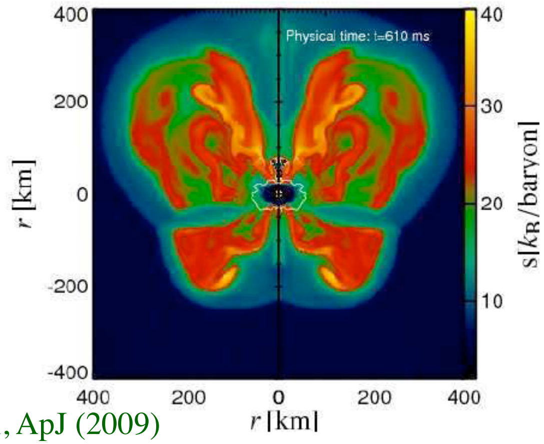
SN1987A



Wang (2002)



Suwa et al. (2010) PASJ

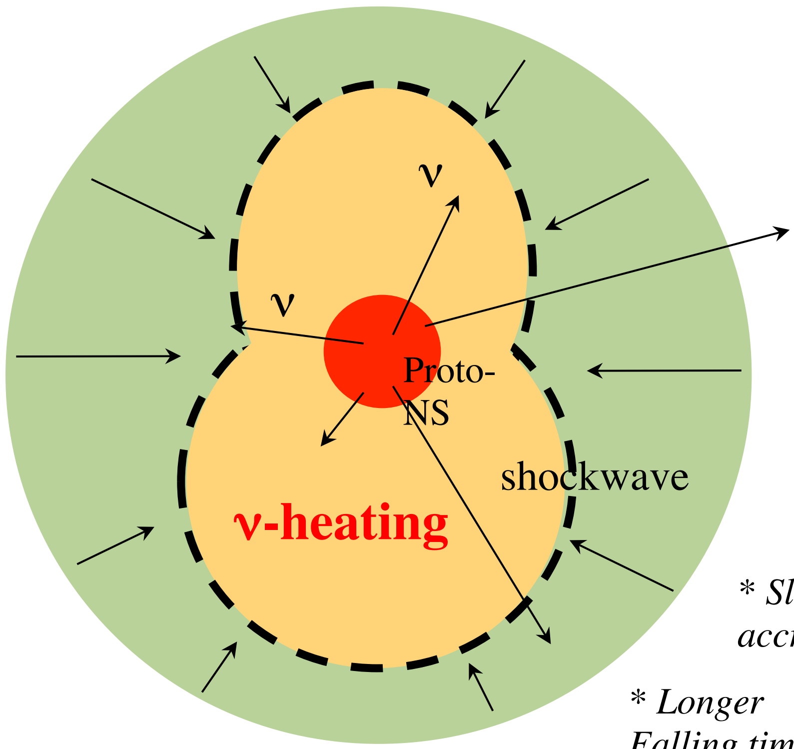


Marek et al, ApJ (2009)

Deformation of shock
Convection

➡

Enough time
for ν-heating



* *Slower accretion*

* *Longer Falling time*

State-of-the-art simulations of supernovae

Nuclear Physics

- Equation of state
- Neutrino reactions

  at 10^5-10^{15} g/cm^3, ~10^{11} K

Astrophysics

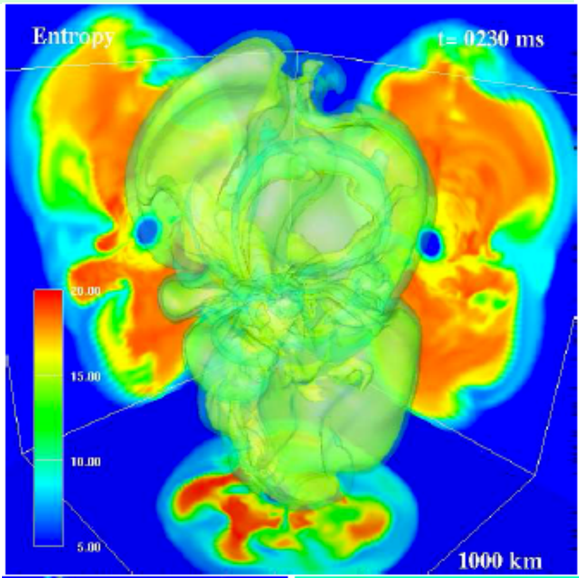
- Hydrodynamics
- Neutrino transfer
- Gravity (Gen. Rel.)

Supercomputing technology

- Numerical simulations of core-collapse supernovae

  Huge supercomputing power is necessary

Takiwaki (2015)



Current issues:

- What is the trigger of explosion?
  - 2D vs 3D?   Low explosion energy?

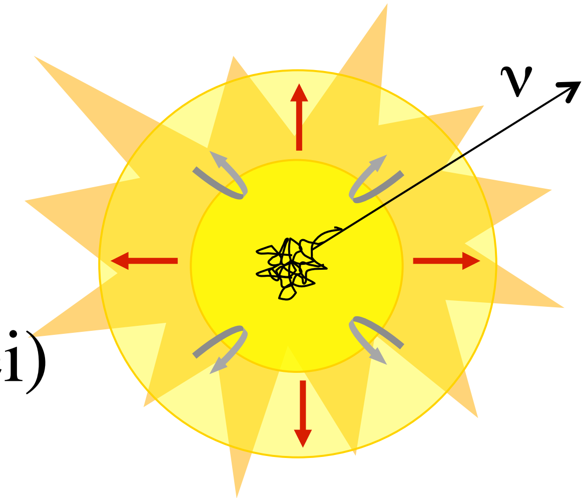
→ Dependence on nuclear physics

京 K computer

EOS is necessary inputs for numerical simulations

- Properties of dense matter determines:

1. Pressure-Density
   - Stellar structure, Dynamics
   - Neutron star mass, radius
2. Composition (proton, neutron, nuclei)
   - ν-reaction, ν-energy spectra



- Supernova EOS tables to cover wide range of (ρ, T, Y_e)

Benchmark 1990~

- *Extension of liquid-drop models (Skyrme-like):* **LS EOS**
- *Relativistic Mean Field approach:* **Shen EOS**

Recent 2000~

- *Mixture of nuclei: GShen, Hempel, Furusawa,…* **Furusawa**
- *RMF extensions: Sagert, Ishizuka, Nakazato, Steiner,…*
- *Nuclear many body: Togashi, Constantinou,…*

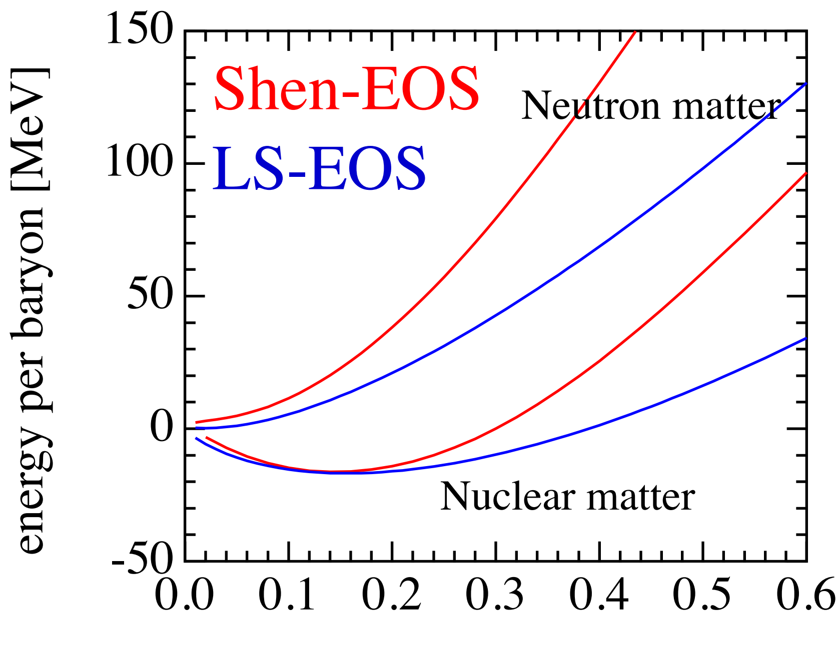
Comparison of EOS sets: benchmark

- Difference in stiffness & symmetry energy

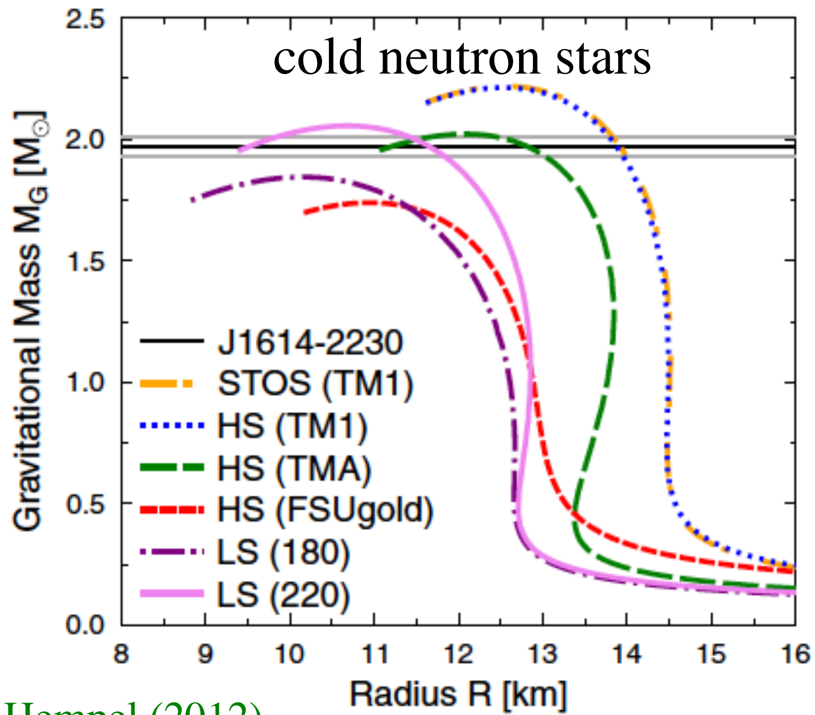
	LS-EOS	Shen-EOS
K [MeV]	180, 220, 375	281
A_{sym} [MeV]	29.3	36.9

180, 220: Frequently used for many simulations

- Two representatives
- Extremes in modern sense

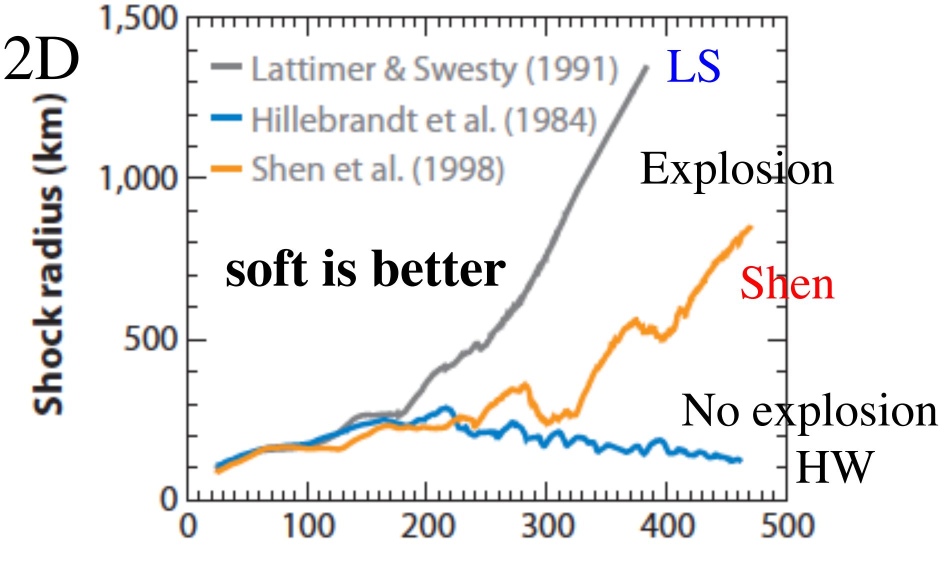


Sumiyoshi (2004) baryon density [fm^{-3}]

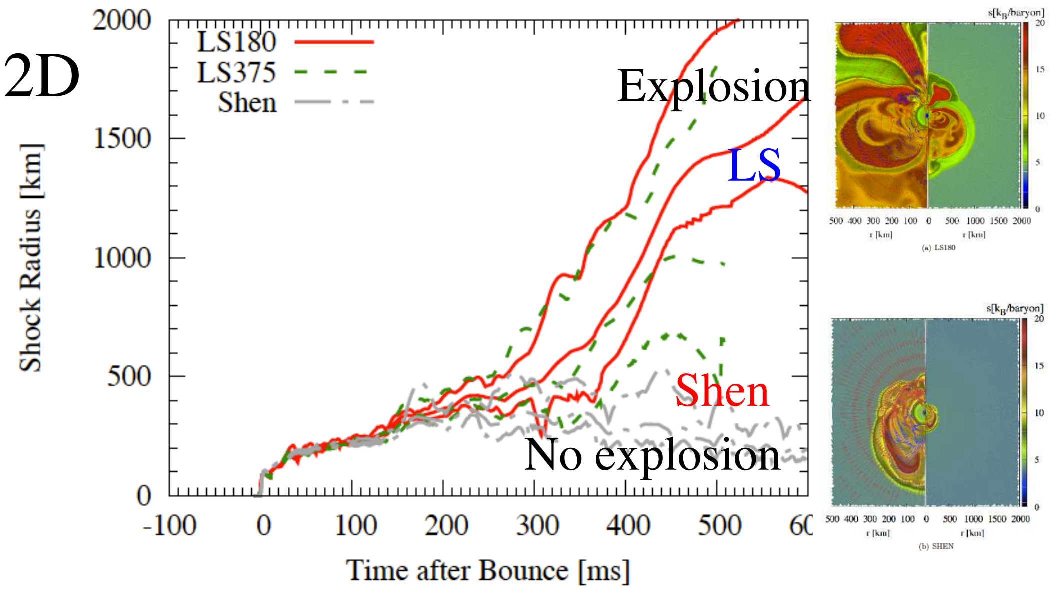


Hempel (2012)

EOS effects in multi-D: larger than 1D?

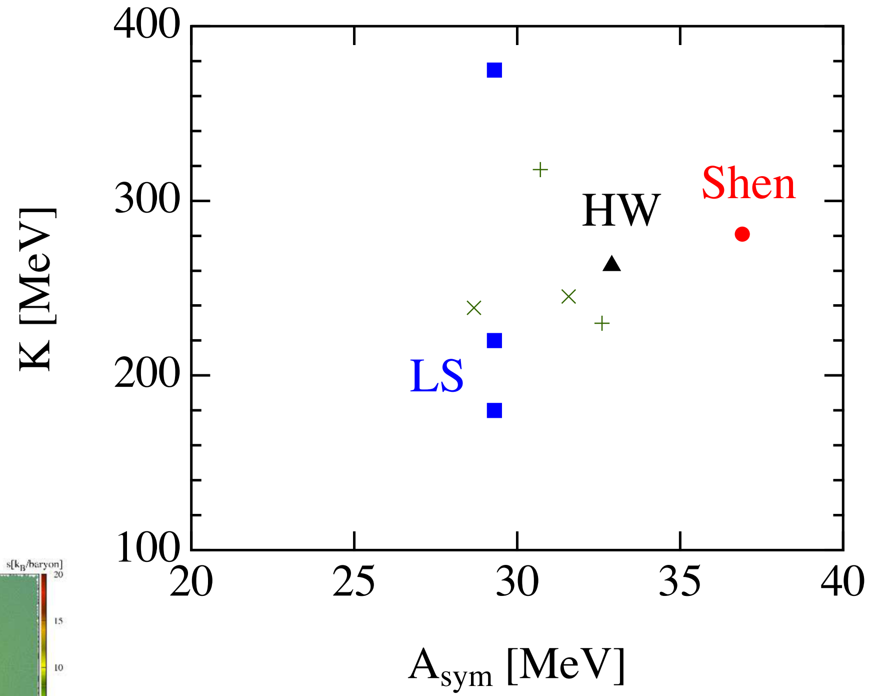


Janka ARNPS (2012)



Suwa et al. ApJ (2013)

Need more systematic studies



In 3D, LS 220MeV so far

Takiwaki (2012), Hanke (2013), Bruenn (2014), Lentz, Melson (2015)

Role of Equation of State

Hydrodynamics & Neutrino reactions

Stiff or Soft EOS: gravitational energy

- Parametric study of EOS effects in 80's

  Takahara ApJ (1985), Bruenn ApJ (1989)

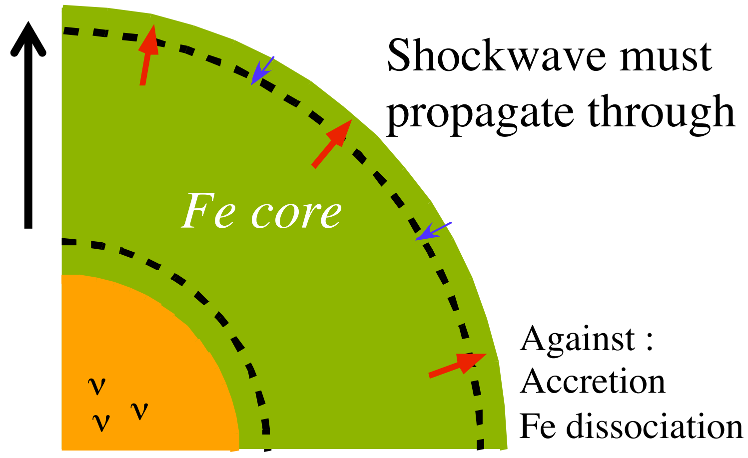
- EOS by analytic formula

  Baron et al. PRL (1985)

ex.

$$p = \frac{K_0 \rho_0}{9\gamma}[(\rho/\rho_0)^\gamma - 1]$$

K_0: In compressibility, ρ_0: nuclear matter density



Bounce Core

- Soft EOS is preferable

  K_0: 220 → 90 MeV (too extreme now to support $2M_{sun}$ NS)

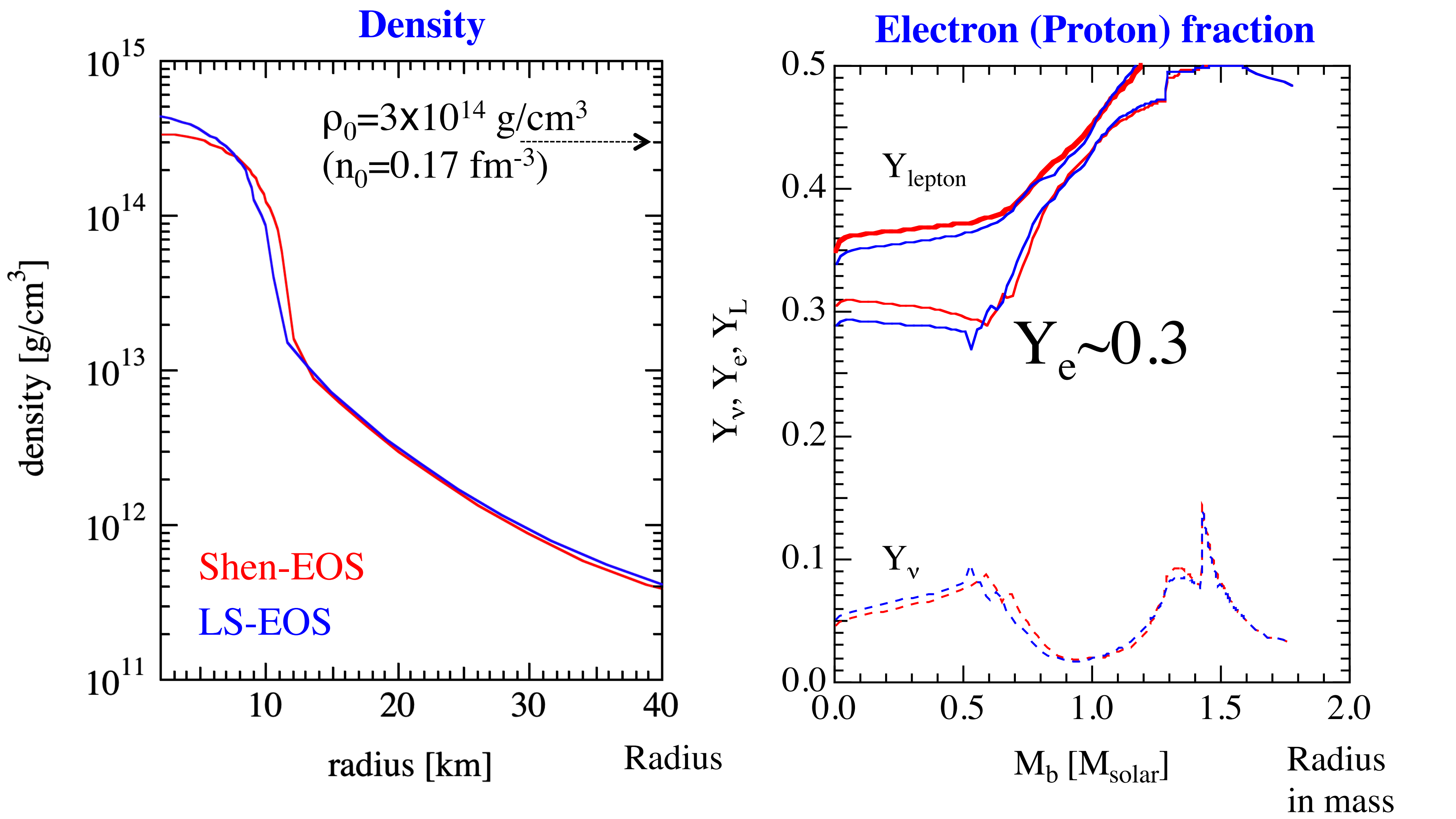
- For bounce core: compact and massive

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

General tendency:
Soft → More energy

Supernova profiles at core bounce: t_{pb}=0 ms

ρ: just above ρ_0, T~10 MeV, Y_p: not so neuron-rich yet

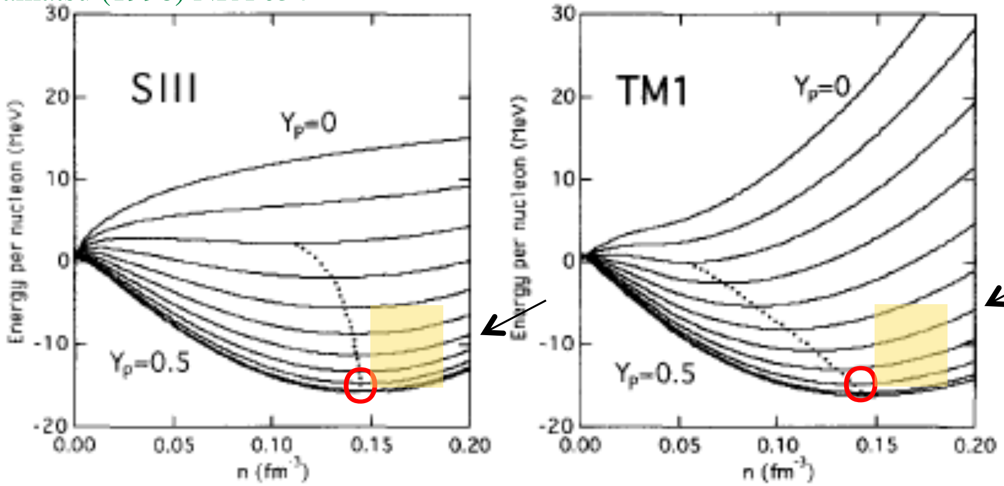


Sumiyoshi et al. ApJ 629 (2005) 922.

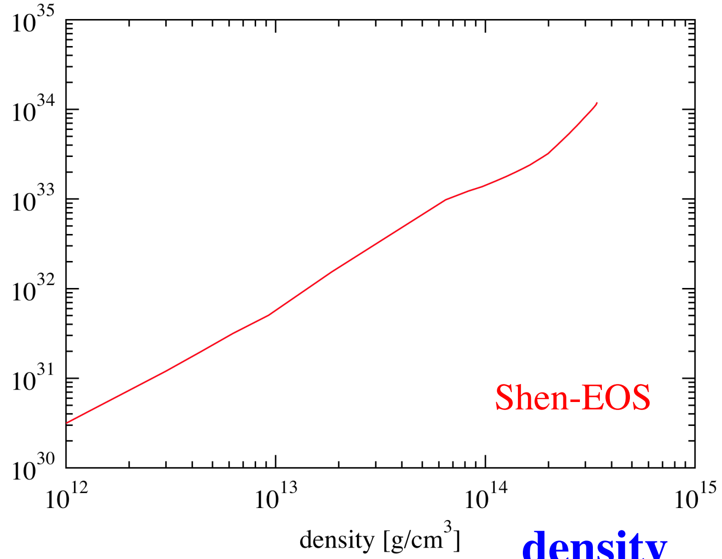
Asymmetric EOS near ρ_0 at core bounce

Not so far from the saturation point

Oyamatsu (1998) NPA 634



pressure



density

- Energy-density curve at Y_p=0.3

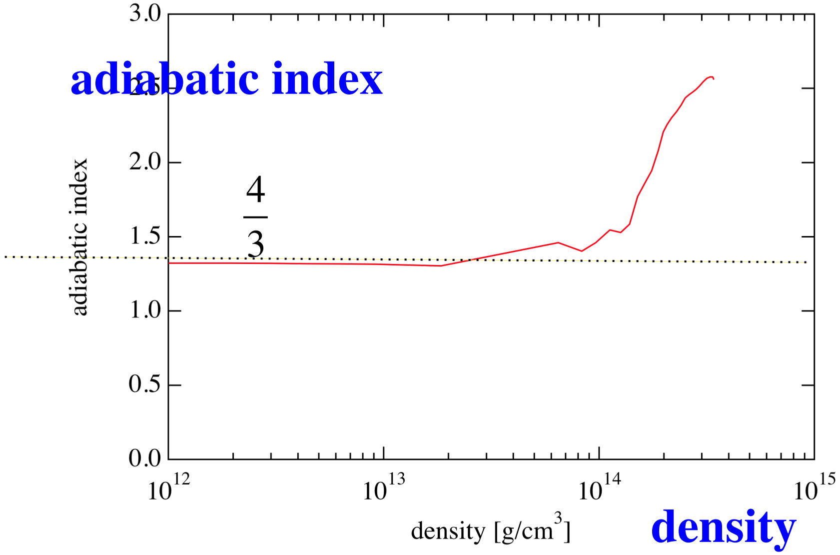
  Incompressibility: K(Y_p=0.3)
  Symmetry energy: $A_{sym}(\rho)$, L

- EOS stiffens: core bounce

  Adiabatic Index
  → Hydrodynamics

$$\Gamma = \left. \frac{d \log P}{d \log \rho} \right|_S$$

adiabatic index

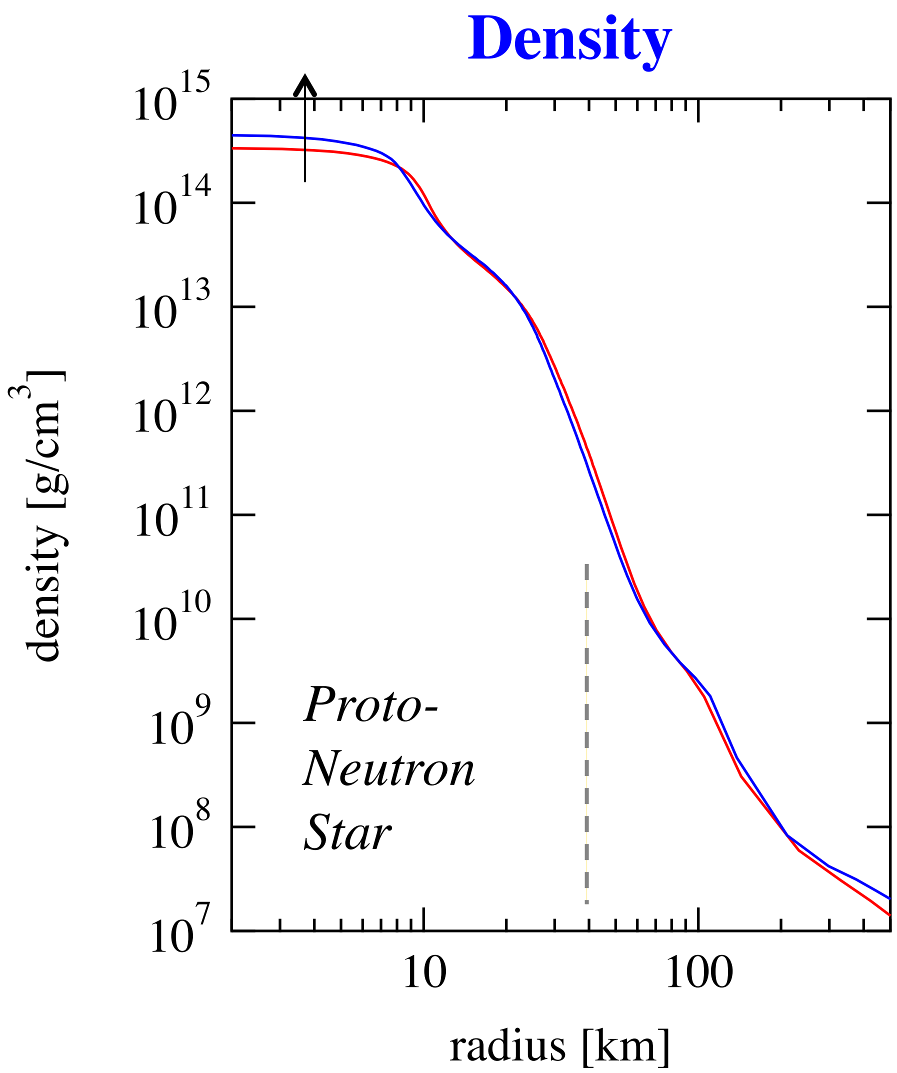


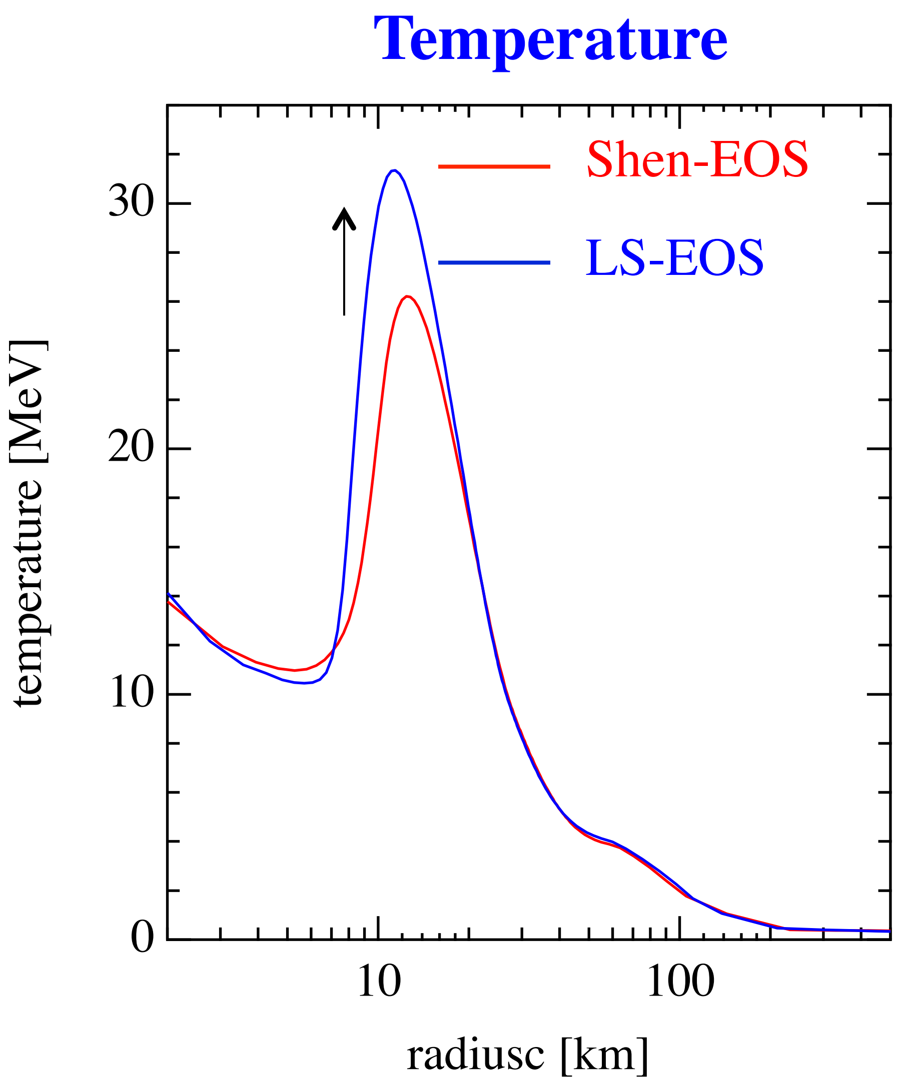
density

Sumiyoshi (2004) NPA

Supernova profiles at t_{pb}=150 ms: shock stalls

EOS difference becomes larger: soft EOS, high ρ, T





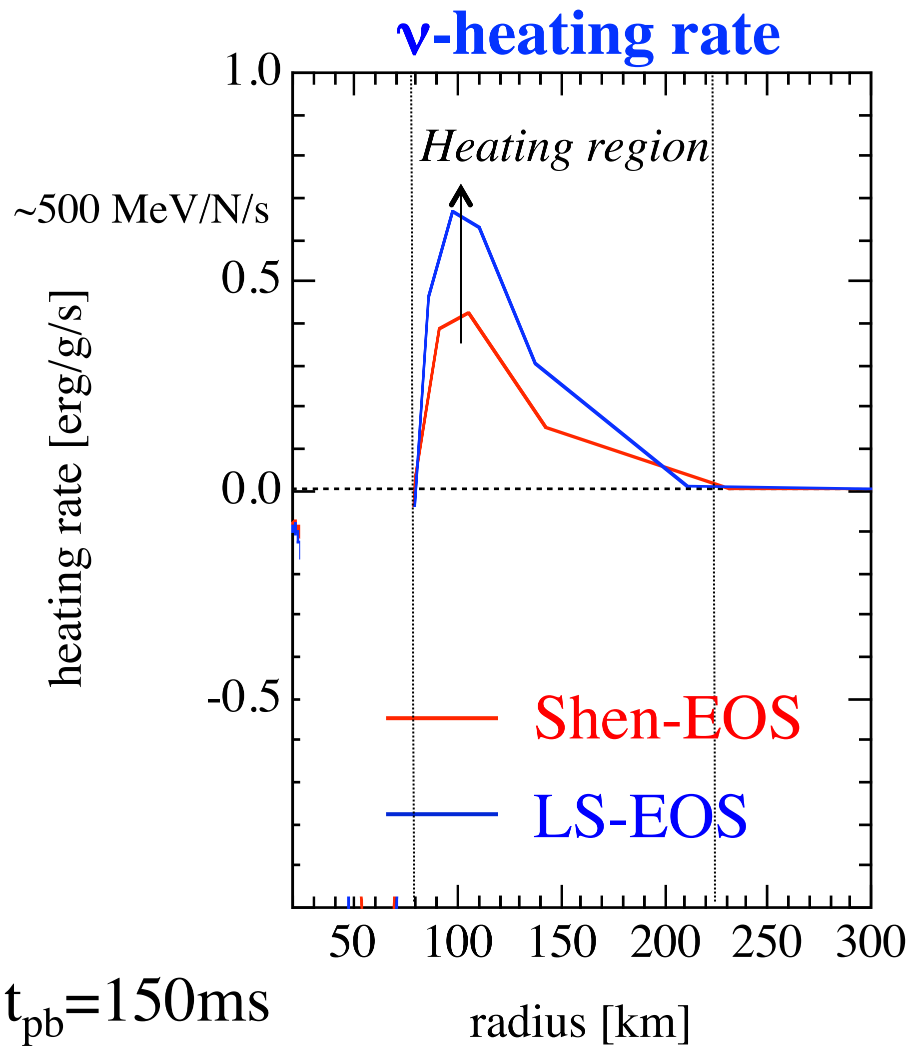
Sumiyoshi et al. ApJ 629 (2005)

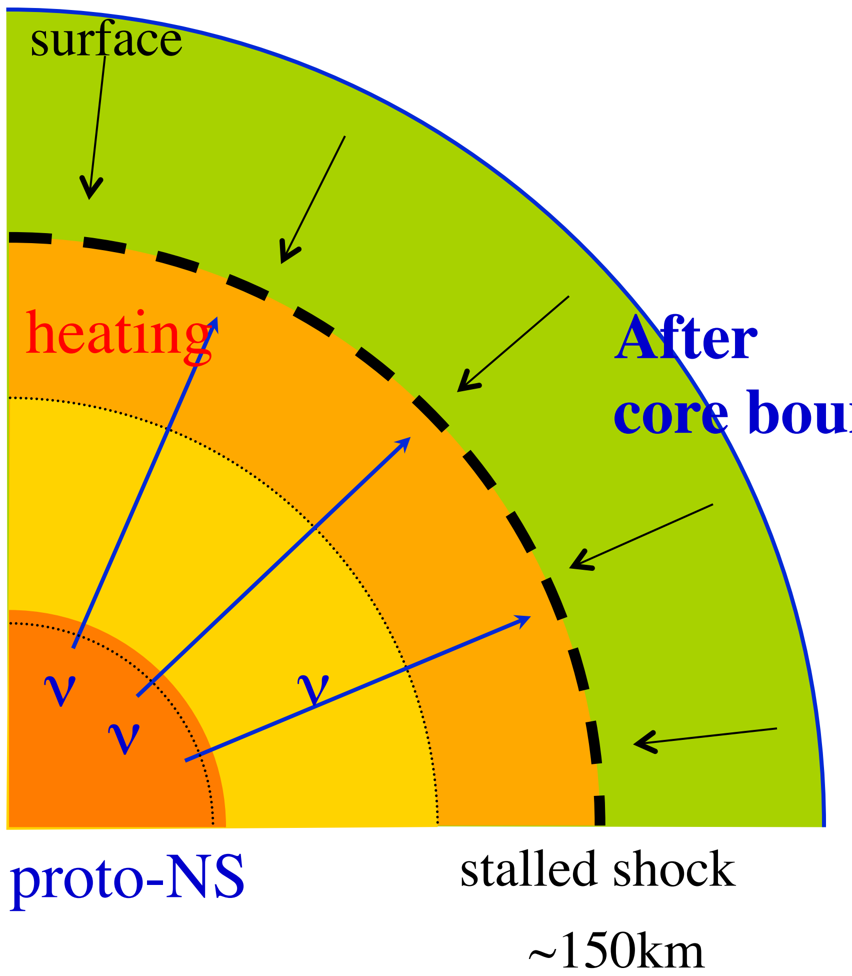
Different temperature: neutrino heating is different

LS-EOS: T ↑ , ν-luminosity ↑

Softer EOS : more heating
→ favorable for explosion

(Not enough 1D though)





t_{pb}=150ms

Sumiyoshi et al. ApJ 629 (2005)

Stiffness of EOS in multi-D

Favorable for explosion

- **EOS soft** $> \rho_0$

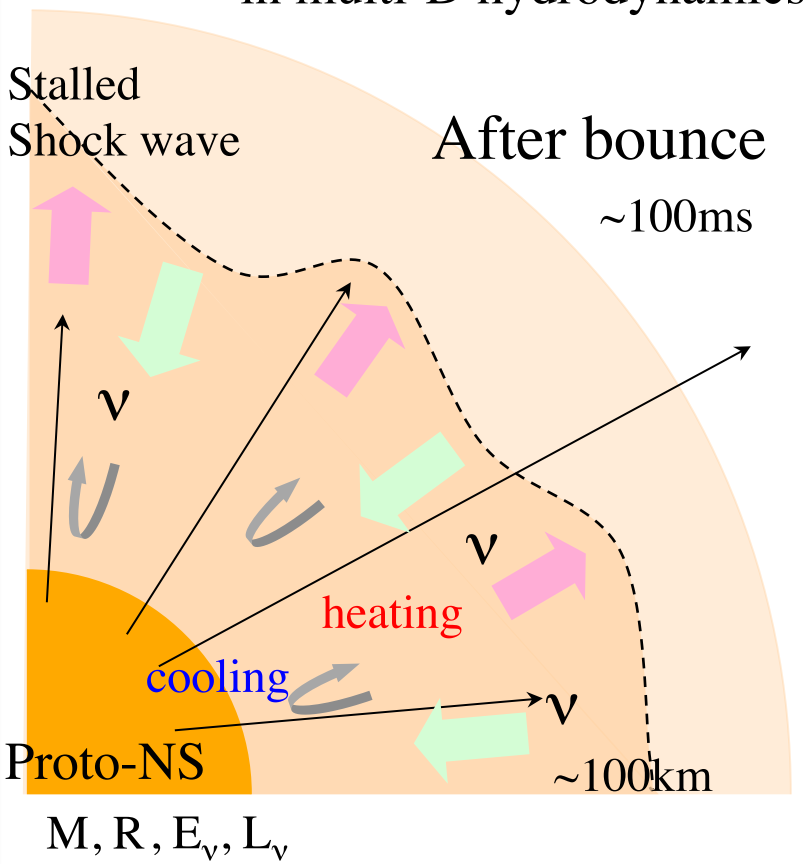
  Grav. energy ↑

  Compact, Inner ρ, T ↑

  ν-luminosity, energy ↑

IF opposite, maybe weaken explosions

ν-cooling & heating in multi-D hydrodynamics



Composition in supernova cores: NSE

Determined by Nuclear Statistical Equilibrium $T > 0.5$ MeV

- Mix of ^{56}Fe, …, ^{4}He, p, n, e^-, e^+, γ at (ρ, T, Ye)
  - Frequent reactions via electro-magnetic, strong interaction
  - (Z, A) + p ⇔ (Z+1, A+1) + γ (p, γ)
  - (Z, A) + n ⇔ (Z, A+1) + γ (n, γ) for example

  also (α, γ), (α, n), (α, p), (p, n) etc… are in equilibrium

→ Depends on nuclear mass & potentials in medium

Chemical potential of nuclei: μ(Z, A) $\mu(Z,A) = Z\mu_p + (A-Z)\mu_n$

Saha's eq. $n(Z,A) = \dfrac{g(Z,A)A^{3/2}}{2^A\theta^{A-1}} n_p^Z n_n^{A-Z} \exp(\dfrac{Q(Z,A)}{T})$

Q-value $Q(Z,A) = Zm_p + (A-Z)m_n - M(Z,A)$

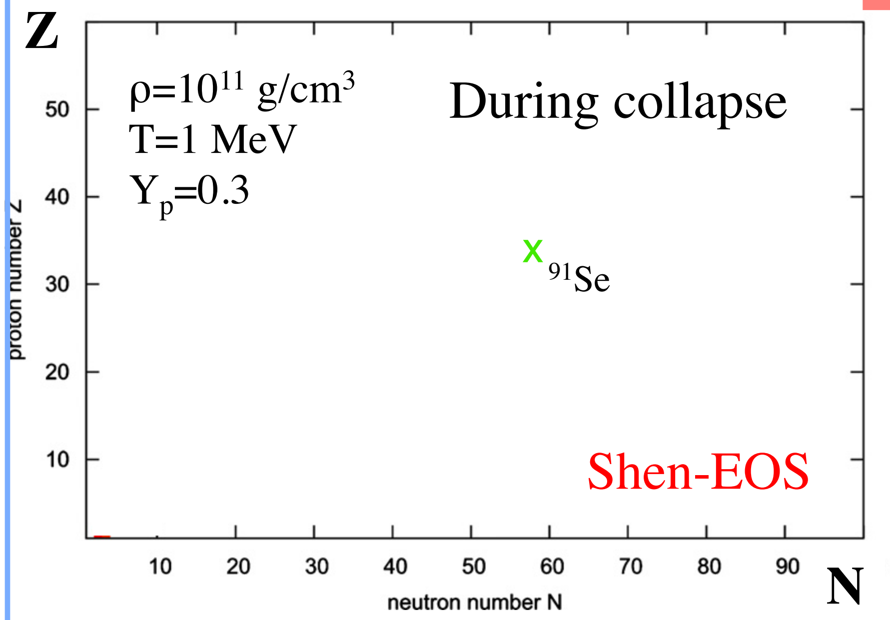
Non-relativistic Maxwell-Boltzmann gas

$$n = g\left(\frac{mkT}{2\pi\hbar^2}\right)^{3/2} \exp\left(\frac{\mu - mc^2}{kT}\right) \qquad \varepsilon = nmc^2 + \frac{3}{2}nkT \qquad P = nT$$

Mixture of nuclei in supernova EOS tables

Shen-EOS

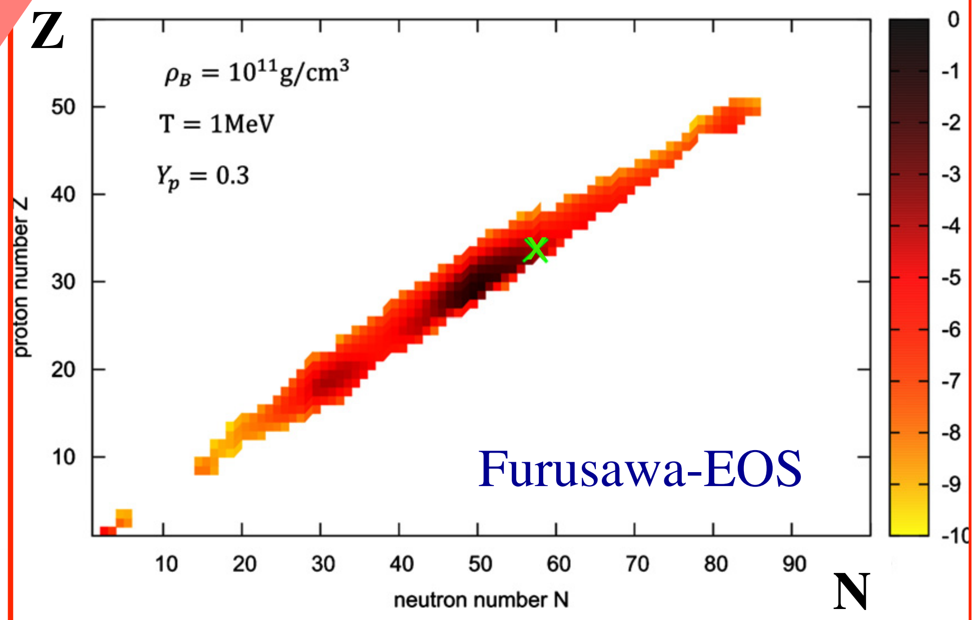
Neutron, proton, ^{4}He
One species of nuclei
approximation



A representative nuclei

Furusawa-EOS

Neutron, proton, d, t, ^{3}He, ^{4}He,…
All of nuclei up to A~1000
In nuclear statistical equilibrium



Wide variety of nuclei

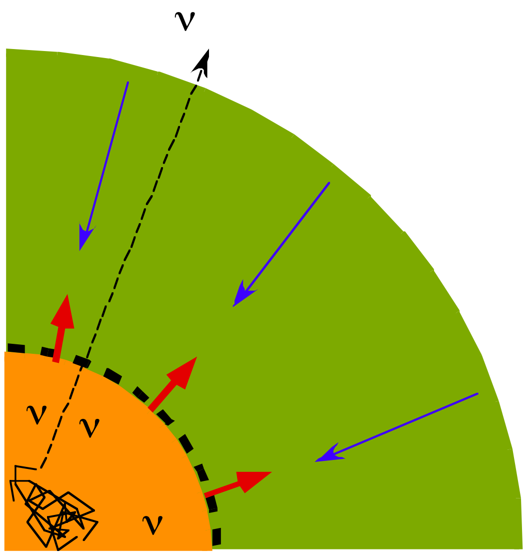
Furusawa, Yamada, Sumiyoshi & Suzuki ApJ (2011)

e-capture determines neutrino trapping

Less electron capture → more neutrino trapping → larger bounce core

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

$e^- + A \rightarrow \nu_e + A'$



Bounce core

Outer core

$$M_{outer} = M_{Fe} - M_{inner}$$

Shock must propagate through Fe core

Core size in mass:

$$M_{inner} = 1.457\left(\frac{Y_L}{0.5}\right)^2 M_{sun} \sim 0.6 - 0.9 M_{sun}$$

Energy loss by Fe dissociation:

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

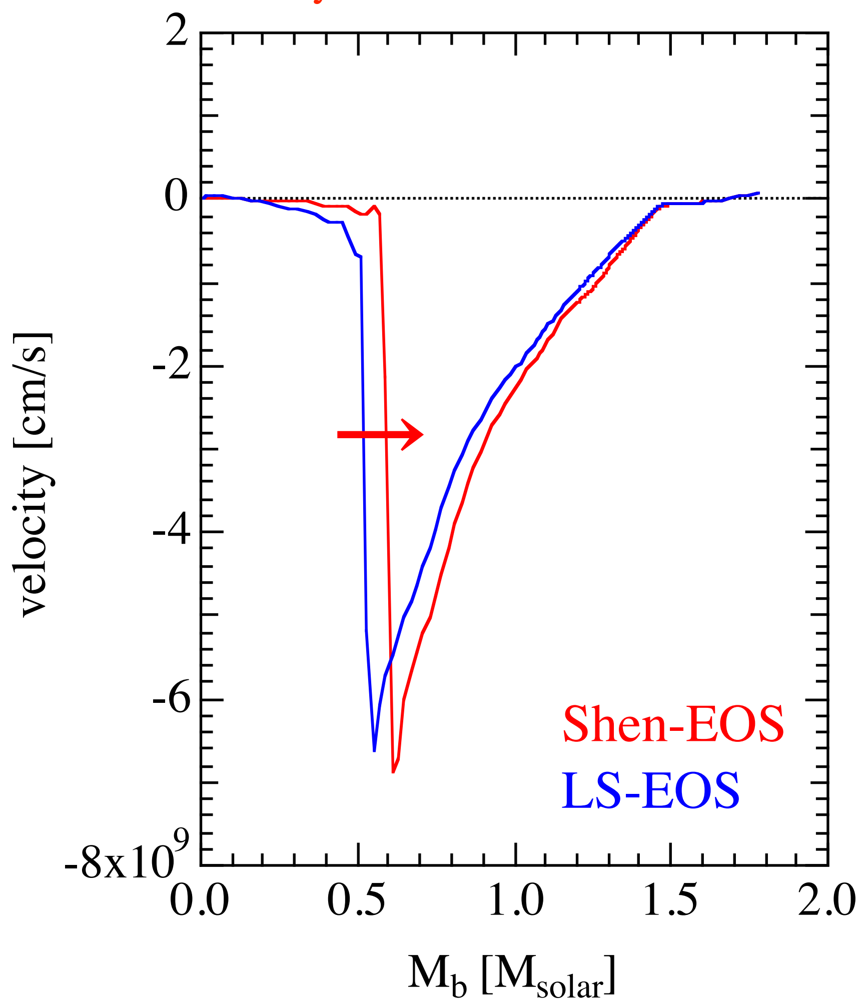
Initial shock energy

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

Composition of supernova matter: e-capture

- Mixture of free protons

Larger A_{sym} → Smaller Bruenn



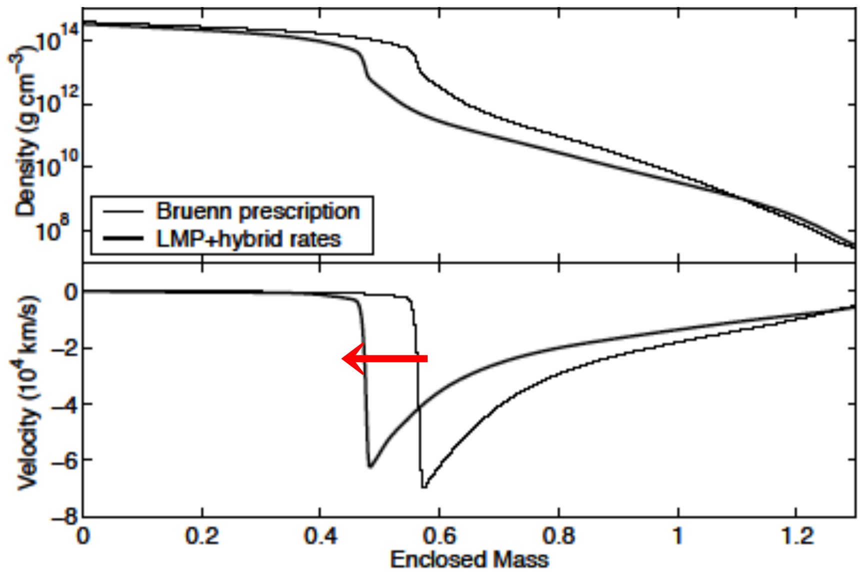
Sumiyoshi et al. ApJ 629 (2005) 922.

- Composition of nuclei

1-species & ^{4}He (Shen, LS)

→ Mixture (Hix)

- Electron capture on nuclei
  - FFN → GSI rates



Hix et al. PRL (2003)

Note: bottom figure in Fig.1

Neutrino emission at neutrino sphere

Determines neutrino flux and energy spectrum

- "Last reaction surface"

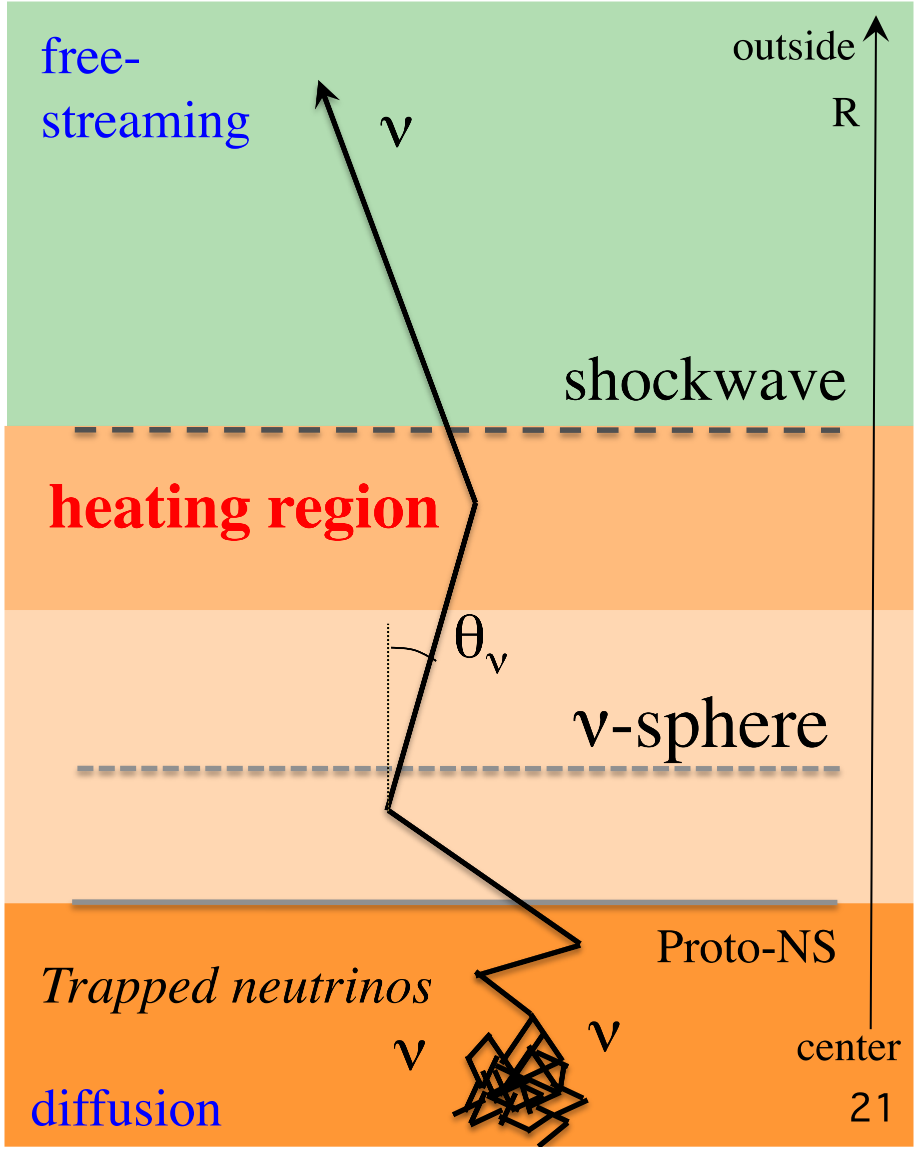
Optical depth

$$\tau = \int_{\infty}^{r} \frac{dr'}{\lambda(r')}$$

mean free path

$$\lambda(r) = \frac{1}{n(r)\sigma(E_\nu)}$$

- Density: 10^{10}-10^{12} g/cm^3
  $\sim 10^{-4}$-10^{-2} ρ_0
  - depends on neutrino energy & species
- Composition is important

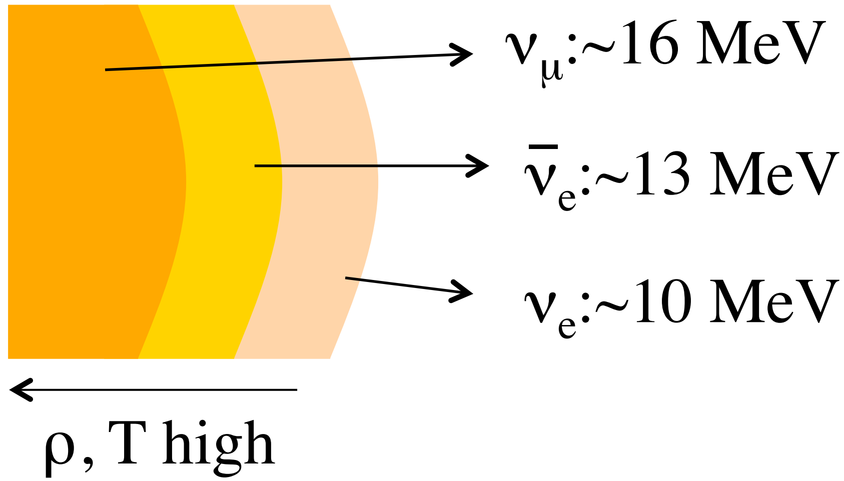


Neutrino flux: hierarchy of average enegy

– Different neutrino-sphere

– Depends on reactions

- $\sigma_{\nu\mu/\tau} < \sigma_{\bar{\nu}e} < \sigma_{\nu e}$
- $E_{\nu\mu/\tau} > E_{\bar{\nu}e} > E_{\nu e}$
- $L_{\nu\mu/\tau} \sim L_{\bar{\nu}e} \sim L_{\nu e}$



- ν_e : charged current $\quad e^- + p \Leftrightarrow \nu_e + n$
- $\bar{\nu}_e$: charged current $\quad e^+ + n \Leftrightarrow \bar{\nu}_e + p$
- $\nu_{\mu/\tau}, \bar{\nu}_{\mu/\tau}$: neutral current $\quad \nu_i + N \Leftrightarrow \nu_i + N$

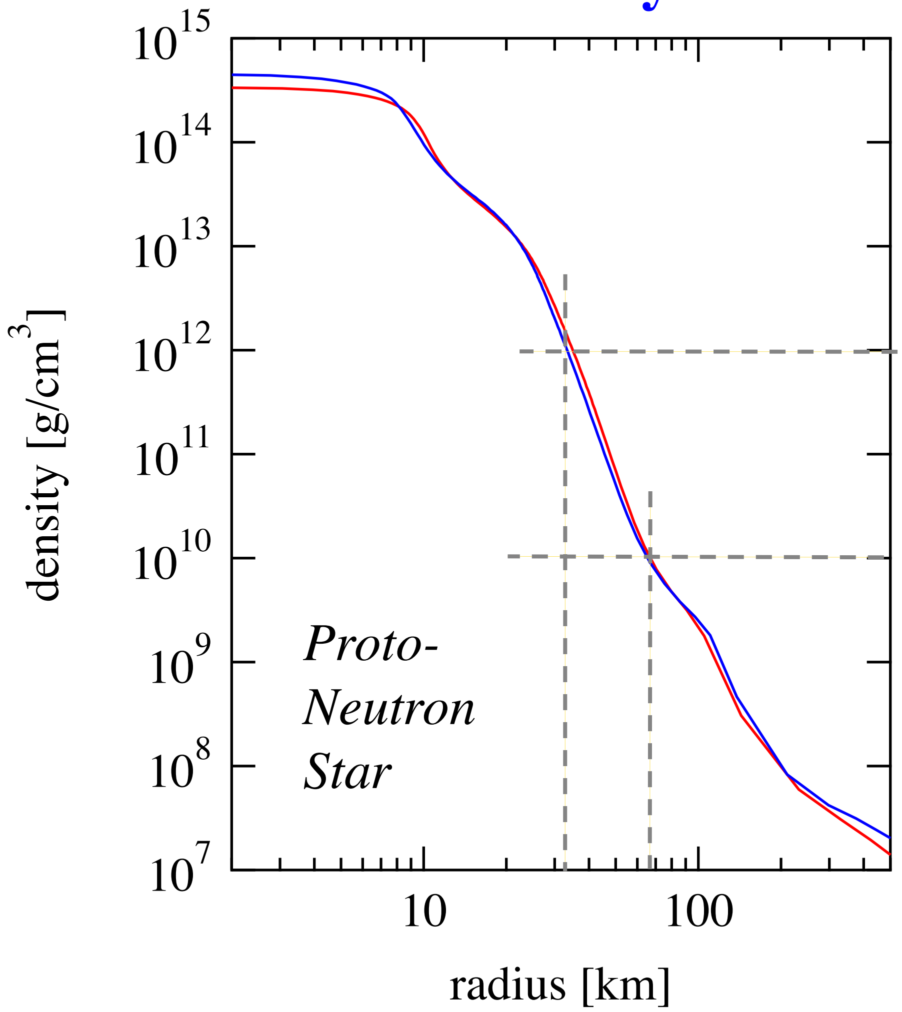
– Affect neutrino heating, supernova neutrino signal

nucleosynthesis: neutron richness (ex. R-process)

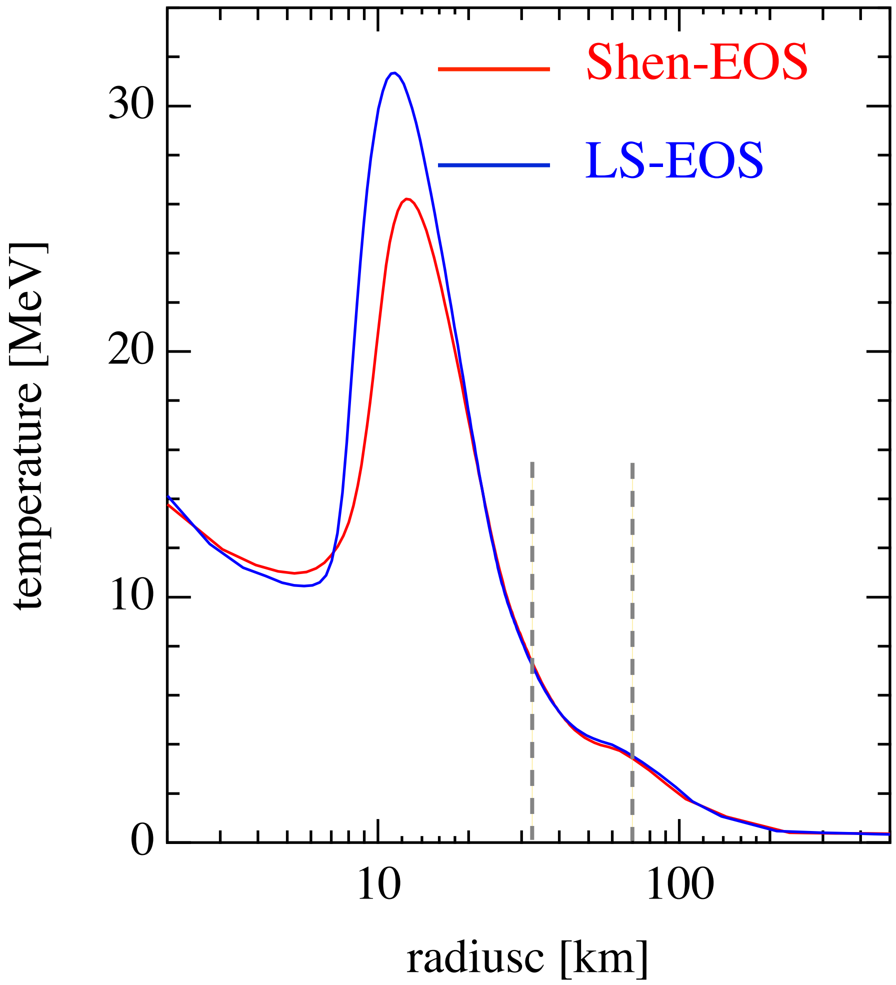
Supernova profiles at t_{pb}=150 ms: shock stalls

Location of neutrino sphere: surface of proto-neutron star

Density



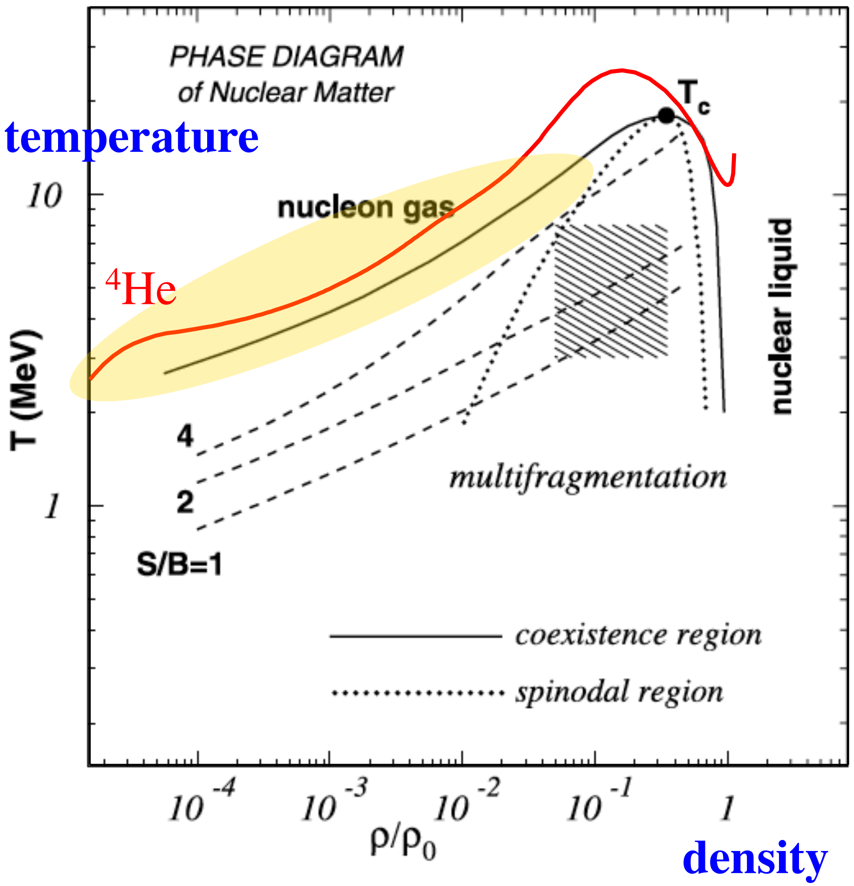
Temperature



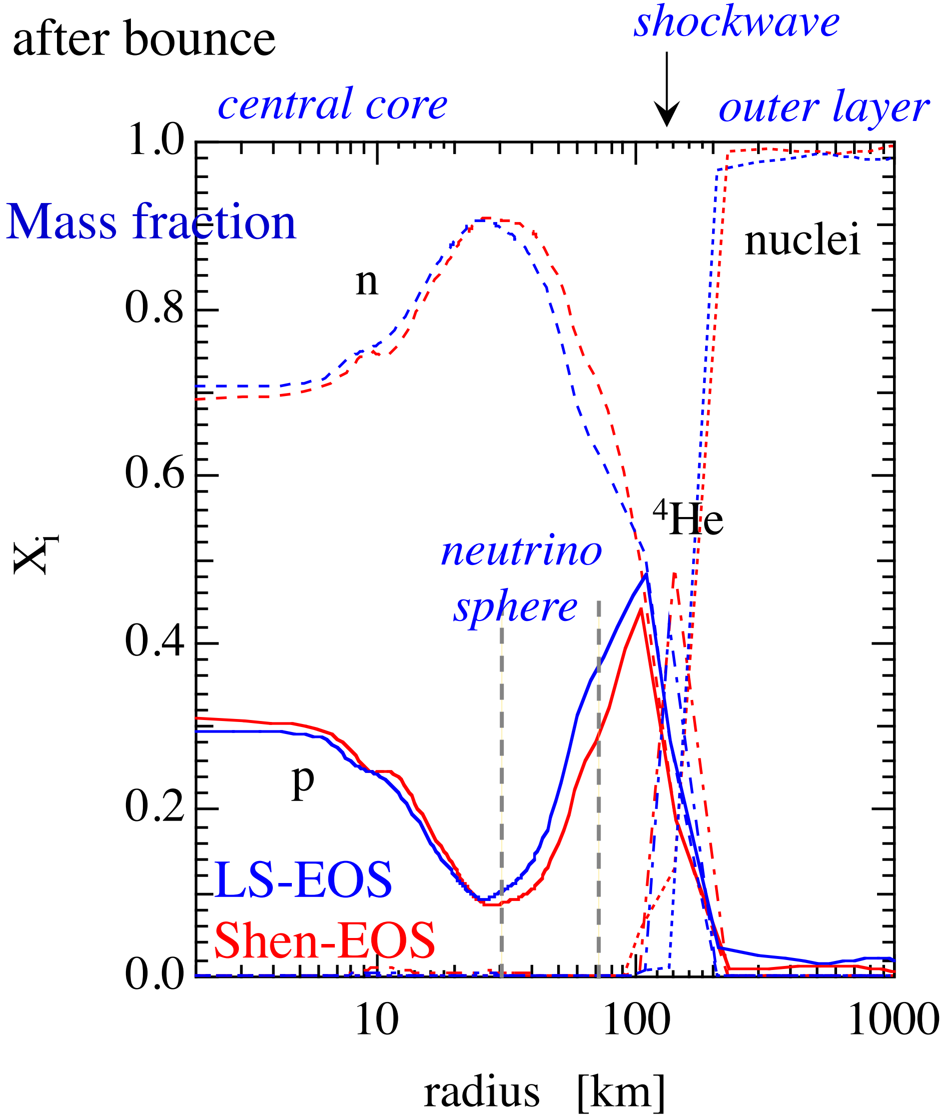
Sumiyoshi et al. ApJ 629 (2005)

Interesting region in phase diagram

Botvina-Mishustin NPA (2010)



at t_{pb}=150ms after bounce



Near the phase boundary:
light clusters (^{4}He etc.) appear

Sumiyoshi et al. ApJ (2005)

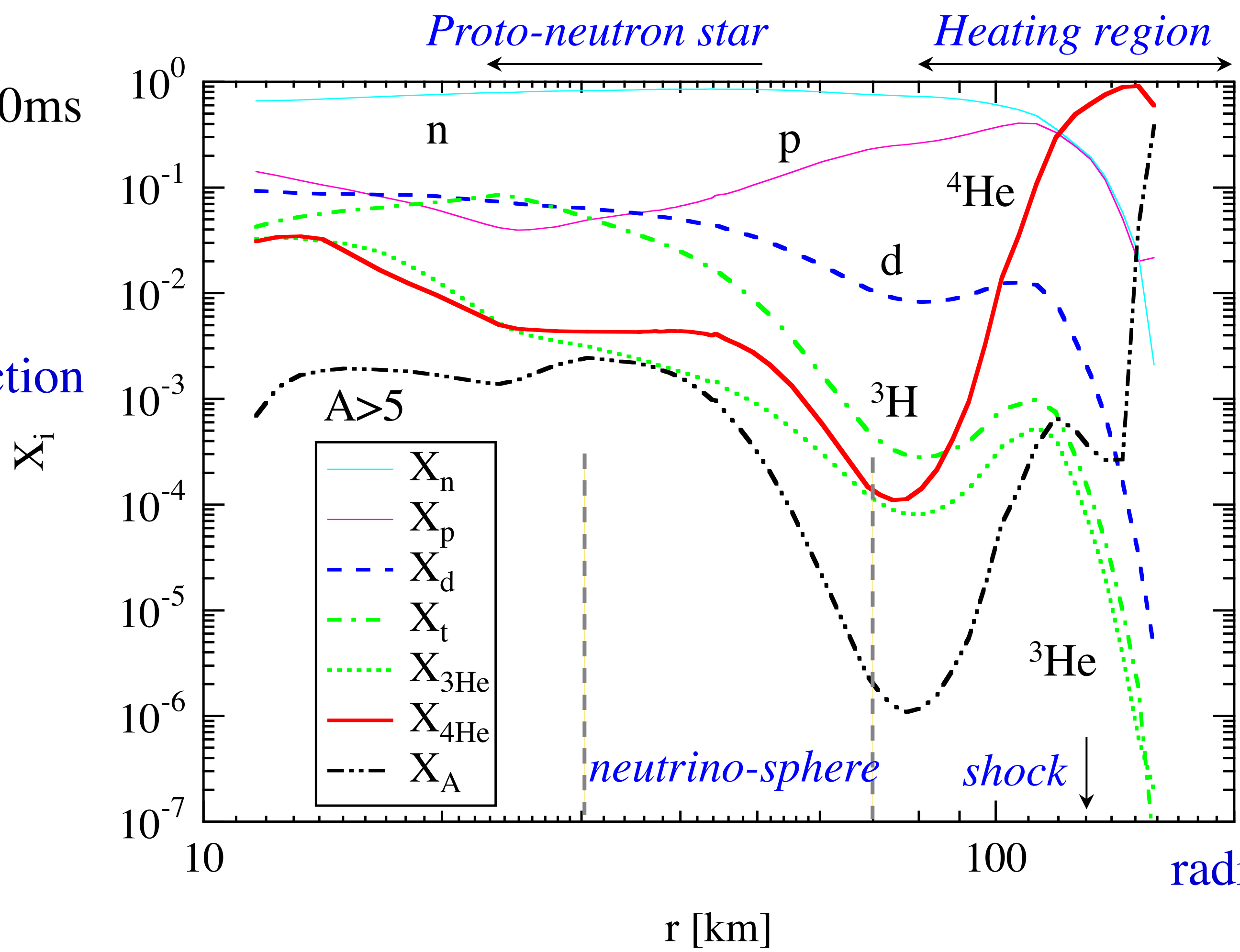
Light clusters other than ^{4}He can appear

Multi-compositions with p, n, d, ^{3}H, ^{3}He, ^{4}He, nuclei

Sumiyoshi & Röpke PRC (2008)

At t_{pb}=150ms

Mass fraction



radius [km]

- ^{4}He abundant at r > 100km → heating/cooling rates
- d, t, ^{3}He abundant at r < 50km → ν-emission, absorption

See also Arcones et al. PRC (2008) for proto-NS

Neutrino reactions with light clusters

- Deuterons

ex. $d + e^- \rightarrow n + n + \nu_e,$

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

cf. $p + e^- \rightarrow n + \nu_e$

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

Nasu et al. PRC (2015)

- Tritons, ^{3}He

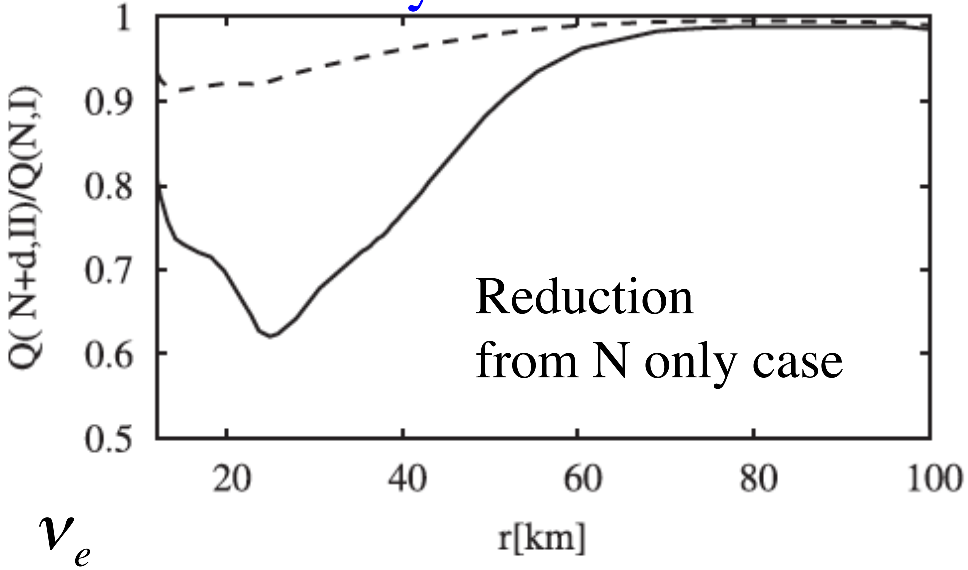
$\nu_e + {}^3H, {}^3He \rightarrow breakup$

O'Connor, Arcones PRC (2007, 2008)

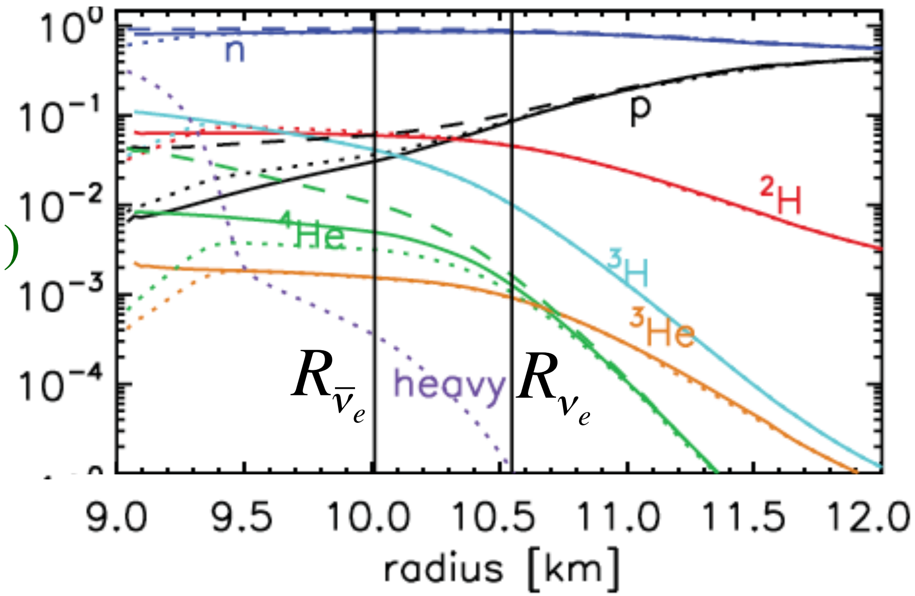
- Modifications:

- ν-sphere, emissivity

Emissivity of neutrinos: ratio



ν_e

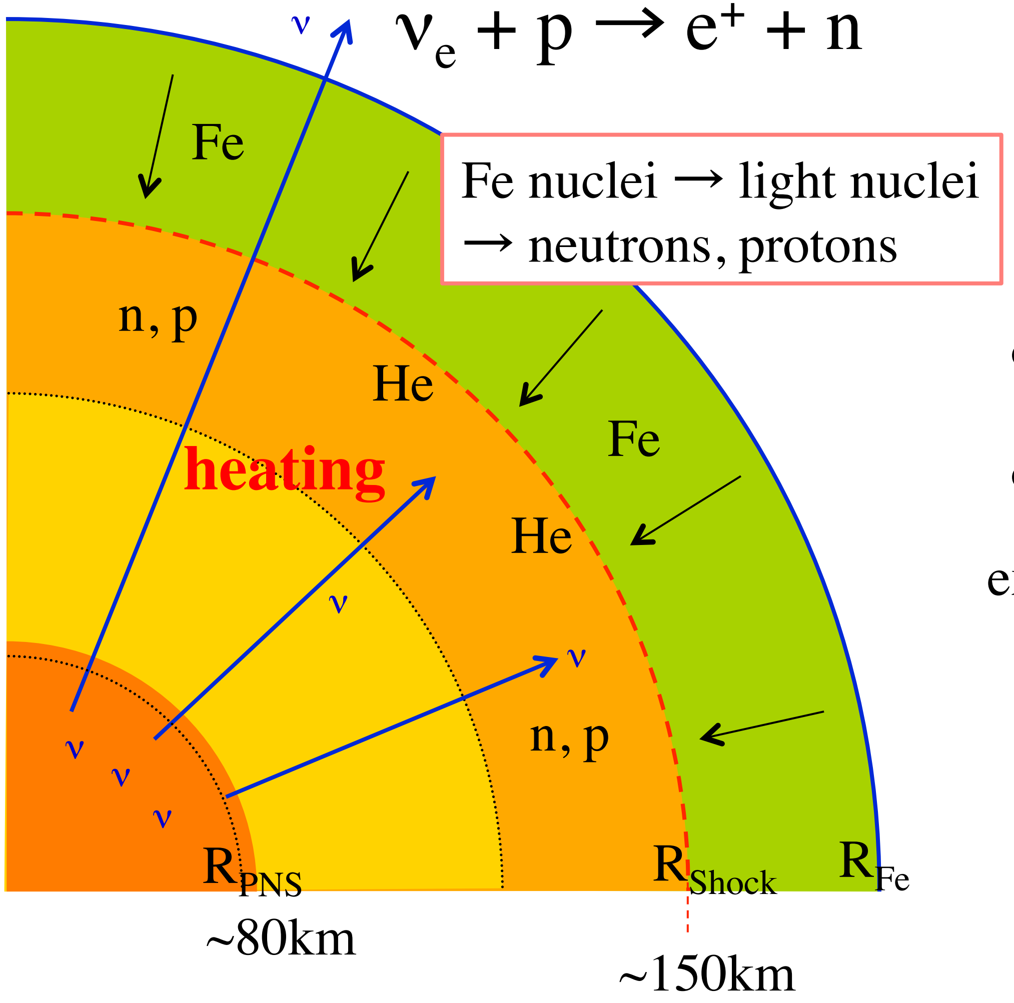


Note: top figure in Fig.2

Absorption of neutrinos: neutrino heating

- Nucleons: ~200MeV/s

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



- Nuclei: 0~30MeV/s

$$\nu_i + A \longrightarrow e^- + A'$$
$$\bar{\nu}_i + A \longrightarrow e^+ + A'$$
$$\nu_i + A \longrightarrow \nu_i' + A'$$

depends on species!!

- Fe, ^{4}He Haxton PRL (1988)
- Light nuclei (d, t, ^{3}He)

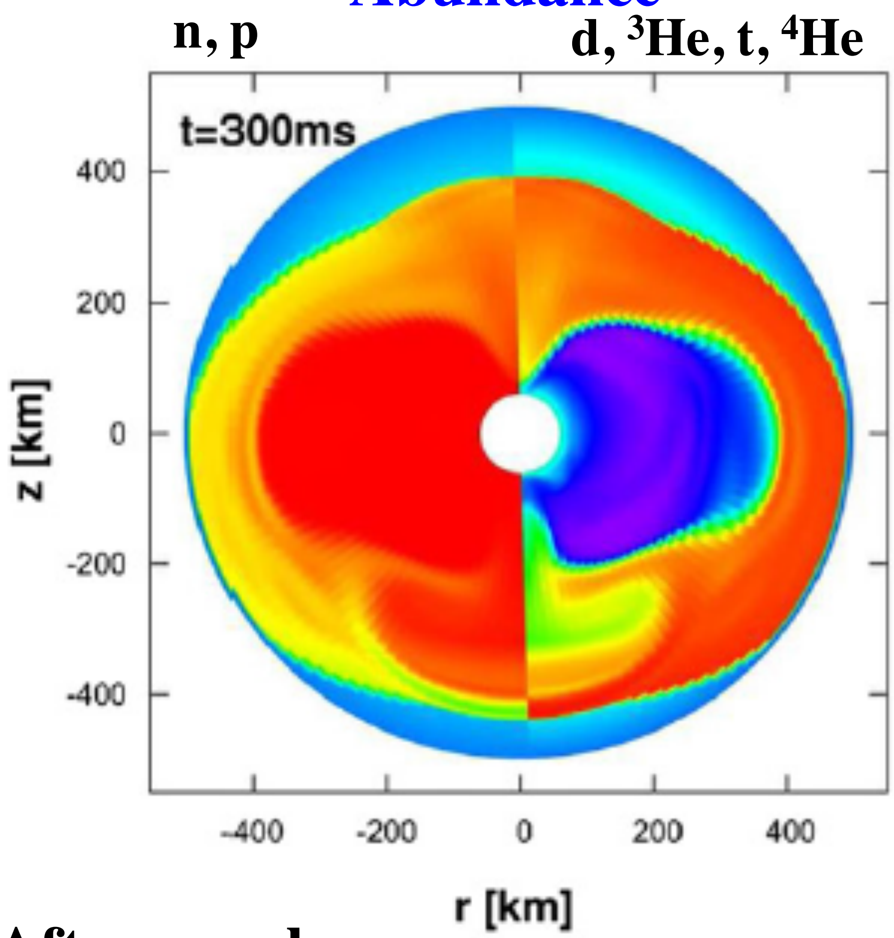
ex.
$$\nu_e + d \rightarrow e^- + p + p$$
$$\bar{\nu}_e + d \rightarrow e^+ + n + n$$
$$\nu + d \rightarrow \nu + p + n$$
$$\bar{\nu} + d \rightarrow \bar{\nu} + p + n$$

Nakamura et al. PRC (2009)
O'Connor et al. PRC (2007)

2D supernova simulations with light clusters

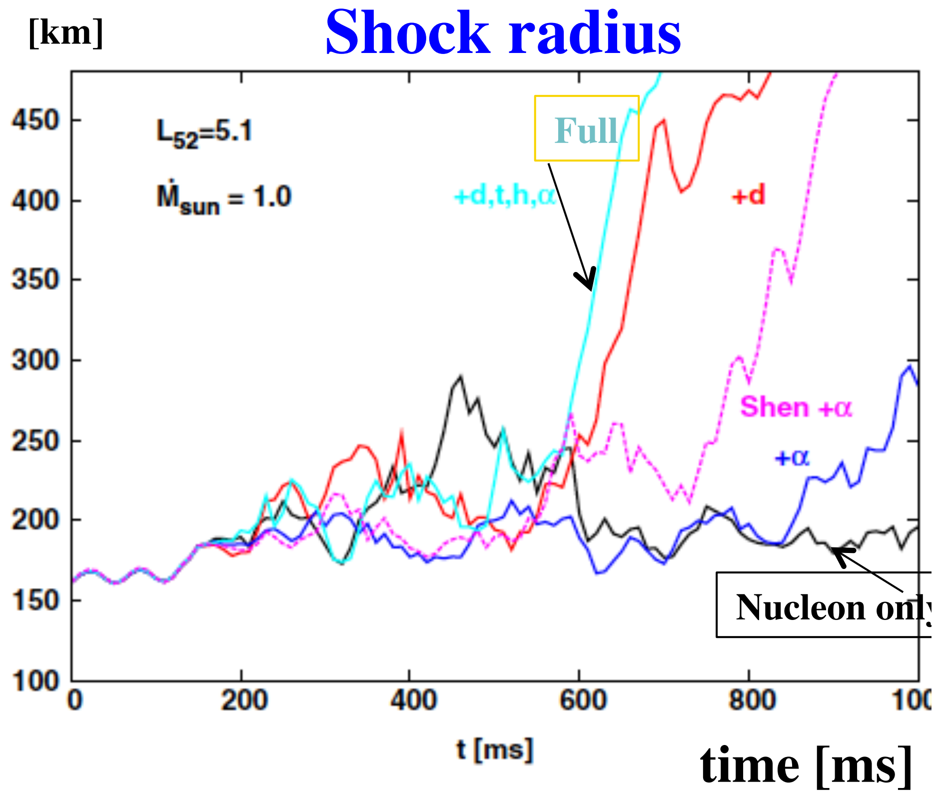
Furusawa et al. ApJ (2013)

- (d, ^{3}He, t, ^{4}He) appear



After core bounce

- ν-absorption (d, ^{3}He, t)

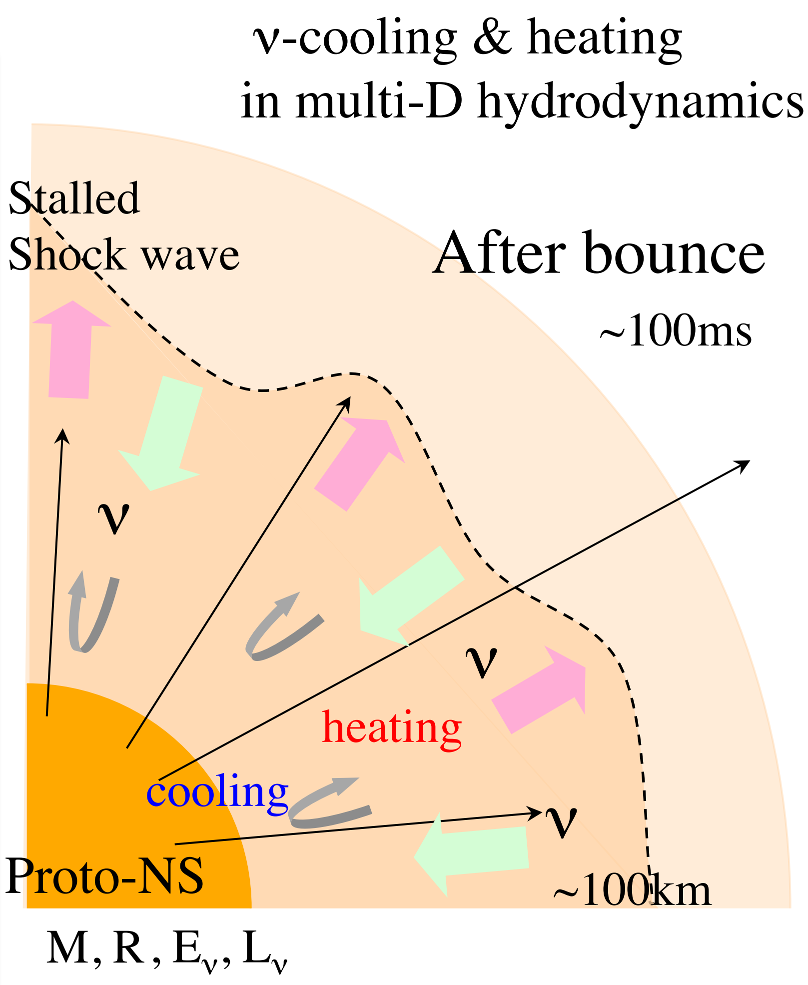


- Possible effects on shock revival when it is marginal

Stiffness & Composition of EOS in multi-D

Favorable for explosion

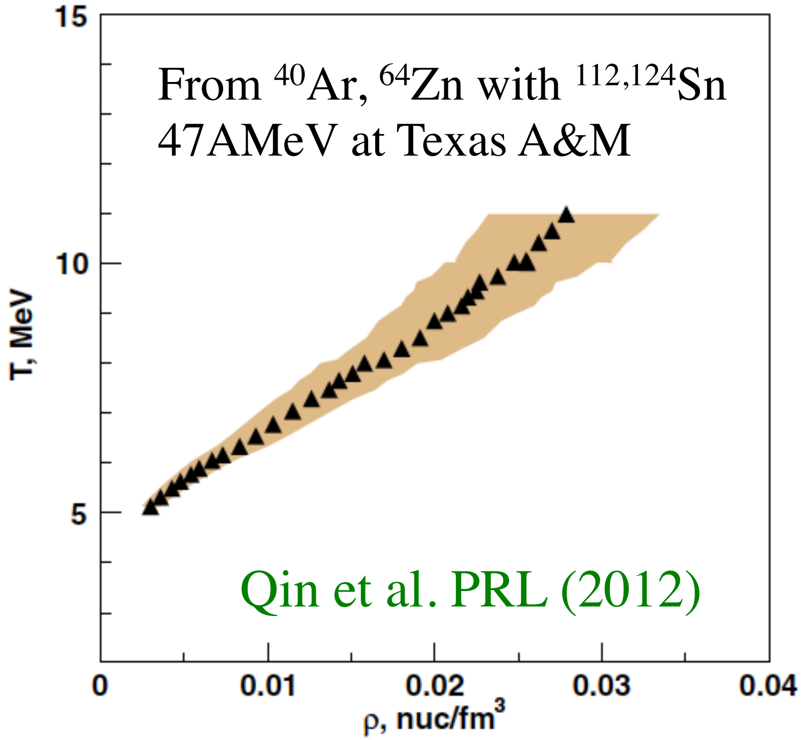
- **EOS soft** $> \rho_0$
  - Grav. energy ↑
  - Compact, Inner ρ, T ↑
  - ν-luminosity, energy ↑
- **More ν-absorption, emis.**
  - at heating region $\sim 10^{-5}\ \rho_0$
  - at proto-NS surface $\sim 10^{-2}\ \rho_0$
  - Composition & ν-reactions



IF opposite, maybe weaken explosions

Examine nuclear physics in multi-D simulations

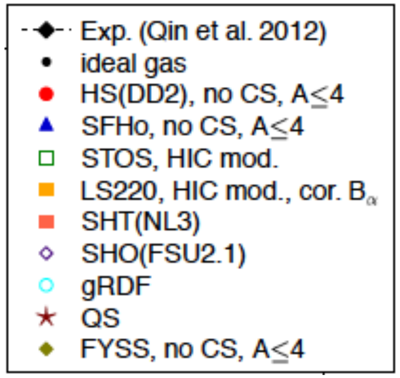
Composition: Experiments & Supernova EOS

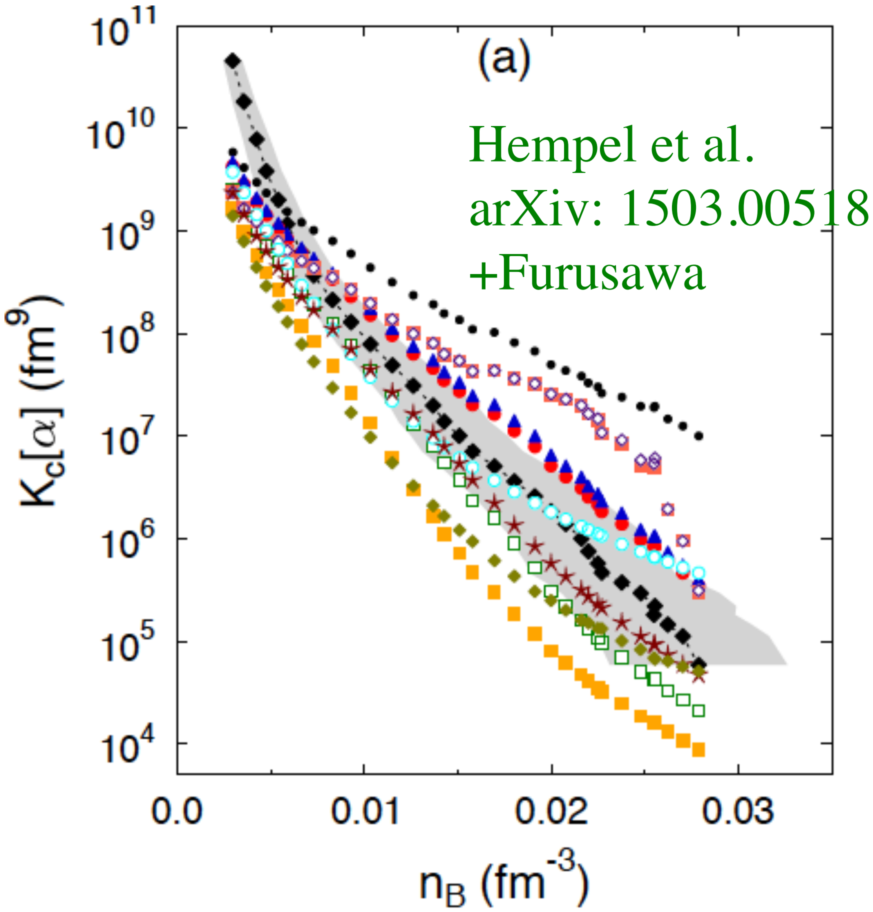


- Equilibrium constant

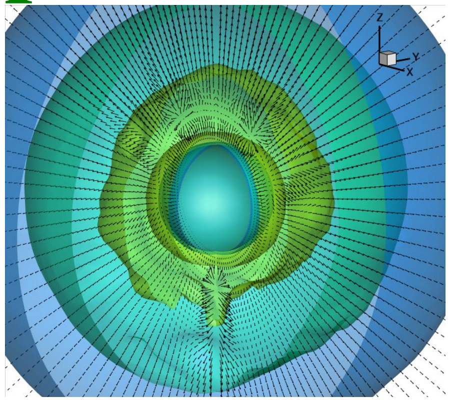
$$K_c(A, Z) = \frac{\rho(A, Z)}{\rho_p^Z \rho_n^{(A-Z)}}$$

Set of supernova EOS





Toward full simulations of 3D supernovae



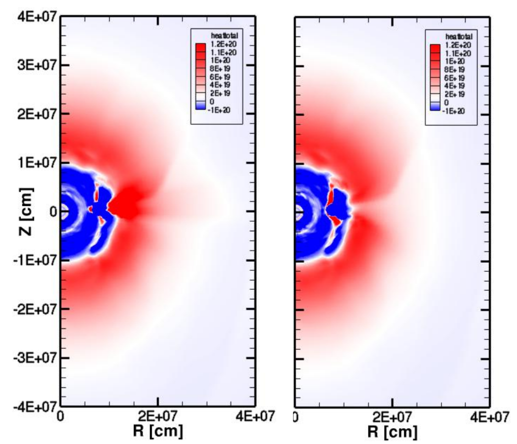
- Solver of Boltzmann equation in 6D

  Sumiyoshi & Yamada, ApJS (2012)

  – Describes 6D neutrino distributions

  – Examine new features of 3D transport

  – Check approximate methods



- 6D Boltzmann-Hydrodynamics

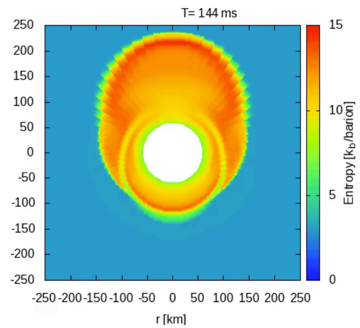
  Nagakura et al. ApJS (2015) Iwakami

  – With Doppler shift, angle aberration

  – 2D supernova simulations running

    - SASI Shock dynamics, Core collapse

→ need Exa-scale supercomputers for 3D



KEK SR16000

AICS K-Computer

Equation of state in supernova explosions

- **Stiffness: pressure, energy vs density**
  - Gravitational energy, Temperature: Explosion energy
- **Composition: mixture of nucleons, nuclei**
  - Neutrino emission and absorption: Neutrino heating
- **Similar conditions: heavy ion collisions**
  - Density-temperature regime: mixture of nuclei

- **Numerical studies of core-collapse supernovae**
  - State-of-the-art simulations on K-computer

We need the best nuclear physics

Fujitsu

Core-collapse supernovae is one of target simulations on K-computer

10Pflops supercomputer at AICS, Kobe

Project in collaboration with

- Numerical simulations
  - H. Nagakura
  - W. Iwakami
  - S. Yamada
- Supernova research
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Supernovae is one of the target simulations of K-computer and Exa-scale machine

- *HPC resources at KEK, YITP, UT, RCNP*

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