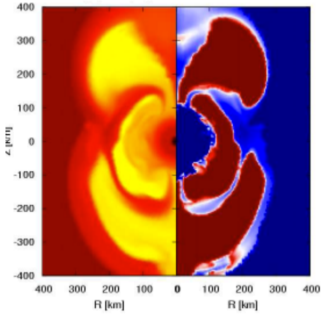
Numerical modeling of core-collapse supernovae and compact objects

Simulations

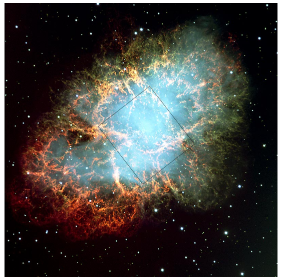


Y. Suwa (2010)

K. Sumiyoshi

Numazu College of Technology, Japan

Crab nebula



hubblesite.org

- Challenges to clarify supernova explosions
- Multi-physics at extreme conditions in 3D

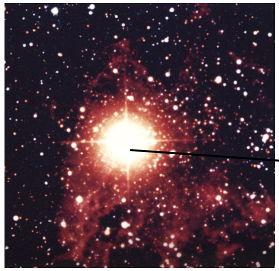
to understand birth places of neutron stars

Supernovae are fascinating

From Gravitation by Misner, Thorn, Wheeler

– Bright displays by explosions
  - Recorded in old Chinese literatures
– Supernova neutrinos from SN1987A
  - Neutrinos in supernova mechanism
– Birth places of neutron stars and black holes
  - Mass, rotations, distributions

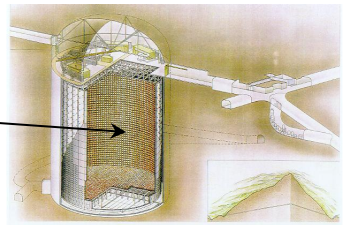
SN1987A


Mann "Shadow of a Star"

Neutrinos play important roles!

ν

Kamiokande


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

Prof. Koshiba


http://nobelprize.org/

Nobel prizes in 2002

Massive stars to neutron stars

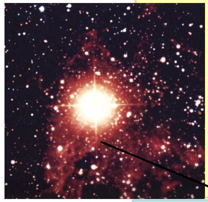
time

~10^7 years

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

stellar evolution

~1 second



- Collapse, bounce & explosion

difficult part!!

Supernova simulations

ν

~20 seconds

- Proto-neutron star cooling
  – neutrino bursts

neutron star models

- Neutron star cooling
  – X, γ-rays

~10^3 years

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

Challenges in supernova physics

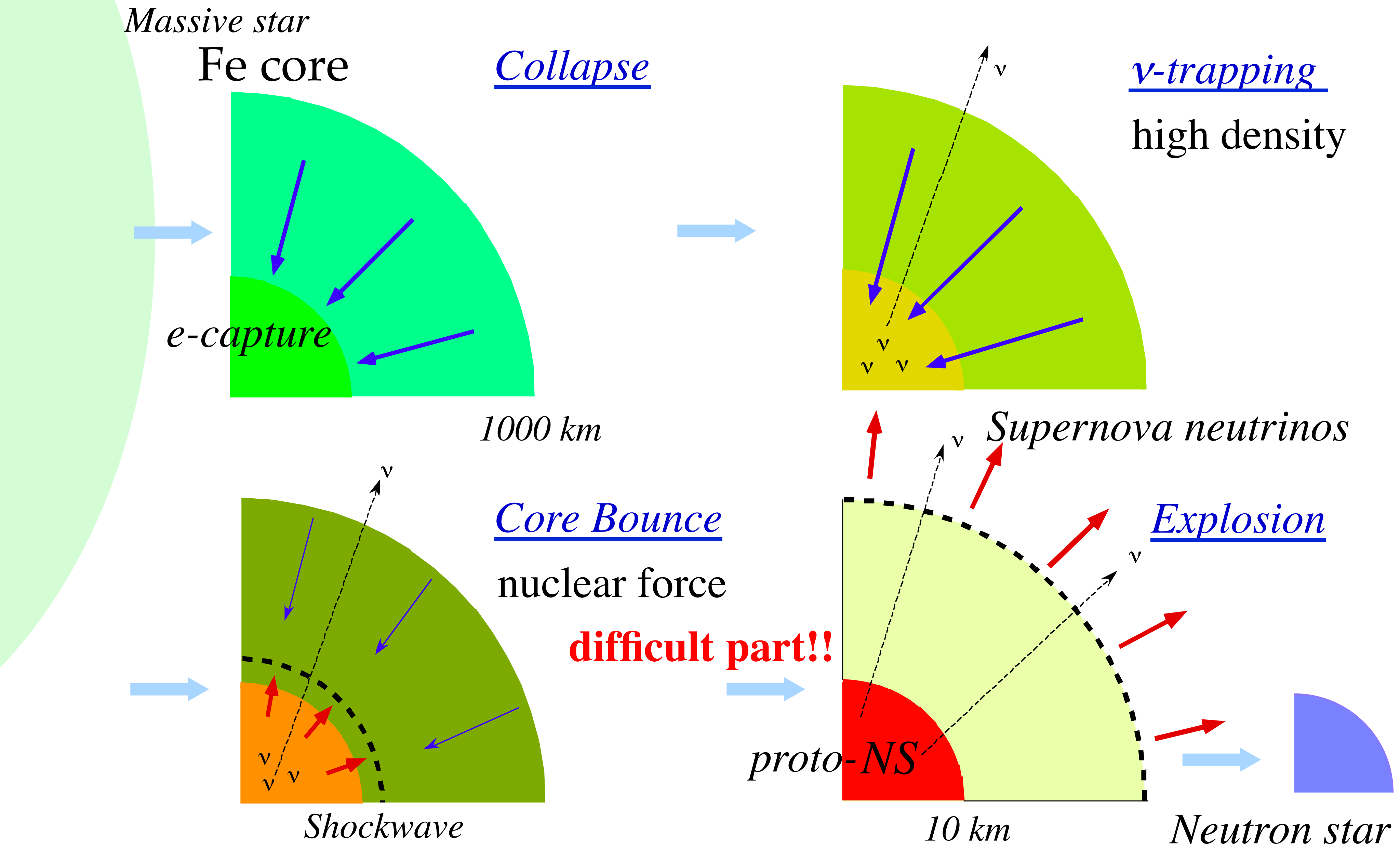
- Difficult to reproduce explosions in simulations

Major problems

- **Exotic conditions**
- **Counteracting ~1% effects**
- **Multi-dimensions**

- Need large scale simulations in supercomputers

Gravitational collapse, bounce and explosion



Exotic conditions: challenges in nuclear physics

- **Equation of state (EOS) in supernova core**
  - Dense more than nuclei: $\rho > \rho_0 = 3\text{x}10^{14}\,\text{g/cm}^3$
  - 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.
  $e^- + p \leftrightarrow \nu_e + n$
  $\nu_i + \text{Fe} \leftrightarrow \nu_i + \text{Fe}$
  $e^- + e^+ \leftrightarrow \nu_i + \nu_i$

- **Necessary inputs for numerical simulations**

Issues on equation of state (EOS)

- Data table of EOS
  - Nuclear theory

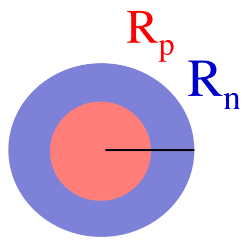
    for wide range of (ρ, T, Y_e)
- 2 major EOS sets
  - LS-EOS, Shen-EOS
    - New: Hempel, G. Shen

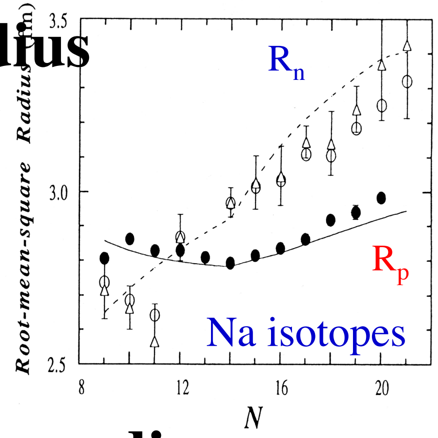
cccccccccccccccccccccccccccccccccccccccccccc
Temperature= 1.000000E-01

5.100000E+00	7.581421E-11	-2.000000E+00	1.000000E-02	-1.524779E+00
5.200000E+00	9.544443E-11	-2.000000E+00	1.000000E-02	-1.502472E+00
5.300000E+00	1.201574E-10	-2.000000E+00	1.000000E-02	-1.480166E+00
5.400000E+00	1.512692E-10	-2.000000E+00	1.000000E-02	-1.457861E+00
5.500000E+00	1.904367E-10	-2.000000E+00	1.000000E-02	-1.435557E+00
5.600000E+00	2.397456E-10	-2.000000E+00	1.000000E-02	-1.413255E+00
5.700000E+00	3.018218E-10	-2.000000E+00	1.000000E-02	-1.390953E+00
5.800000E+00	3.799711E-10	-2.000000E+00	1.000000E-02	-1.368653E+00
5.900000E+00	4.783553E-10	-2.000000E+00	1.000000E-02	-1.346354E+00
6.000000E+00	6.022137E-10	-2.000000E+00	1.000000E-02	-1.324056E+00
6.100000E+00	7.581421E-10	-2.000000E+00	1.000000E-02	-1.301759E+00
6.200000E+00	9.544443E-10	-2.000000E+00	1.000000E-02	-1.279464E+00
6.300000E+00	1.201574E-09	-2.000000E+00	1.000000E-02	-1.257169E+00
6.400000E+00	1.512692E-09	-2.000000E+00	1.000000E-02	-1.234876E+00
6.500000E+00	1.904367E-09	-2.000000E+00	1.000000E-02	-1.212584E+00
6.600000E+00	2.397456E-09	-2.000000E+00	1.000000E-02	-1.190294E+00

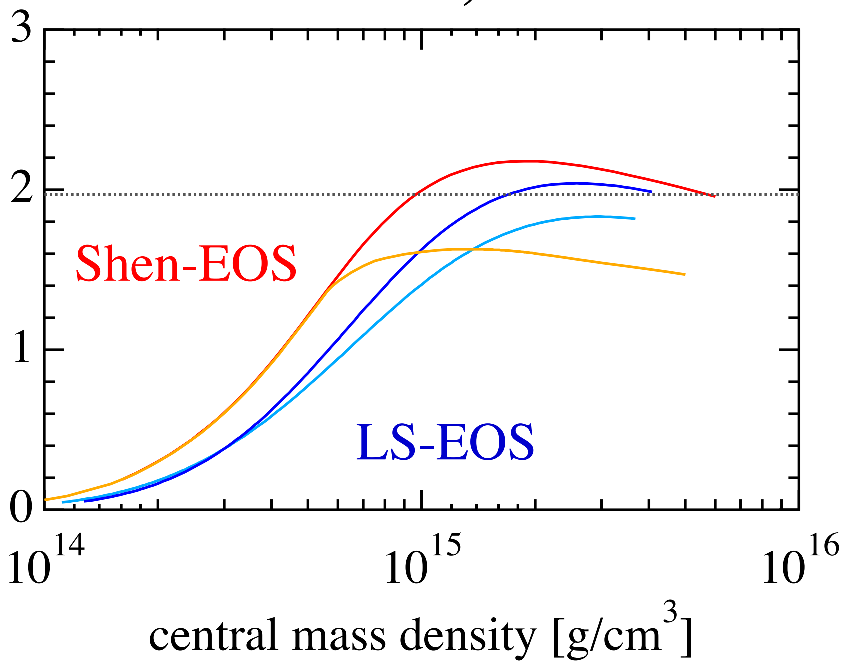
http://user.numazu-ct.ac.jp/~sumi/eos Shen-EOS table

Nuclear mass, radius





Neutron star mass, radius



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

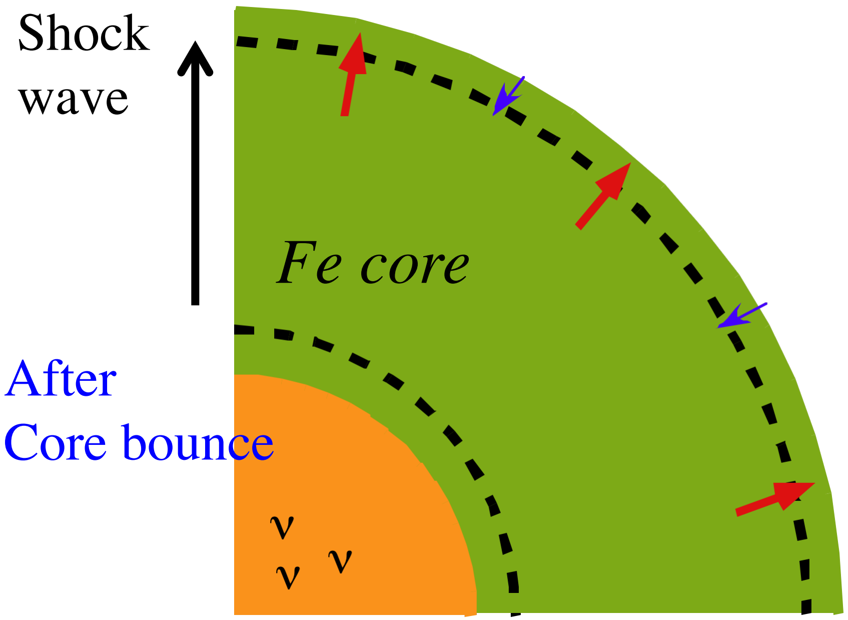
$$\Delta E_{Grav} = -\left(\frac{GM^2}{R_{Fe}} - \frac{GM^2}{R_{NS}}\right) \sim 10^{53}\, erg$$

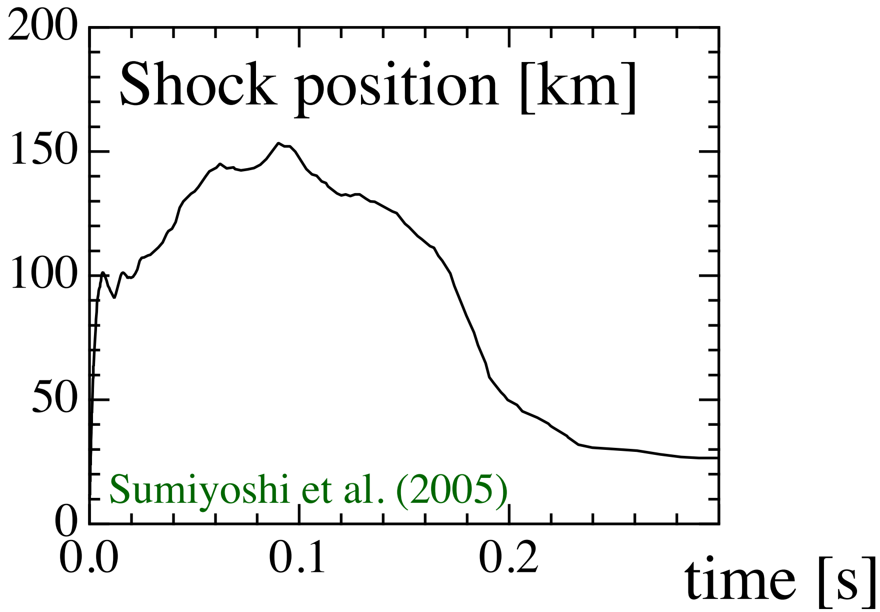
- Explosion energy: E_{exp} ~ 10^{51} erg
- Neutrino carries away: E_ν ~ 10^{53} erg

- 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

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

Energy loss due to Fe dissociation

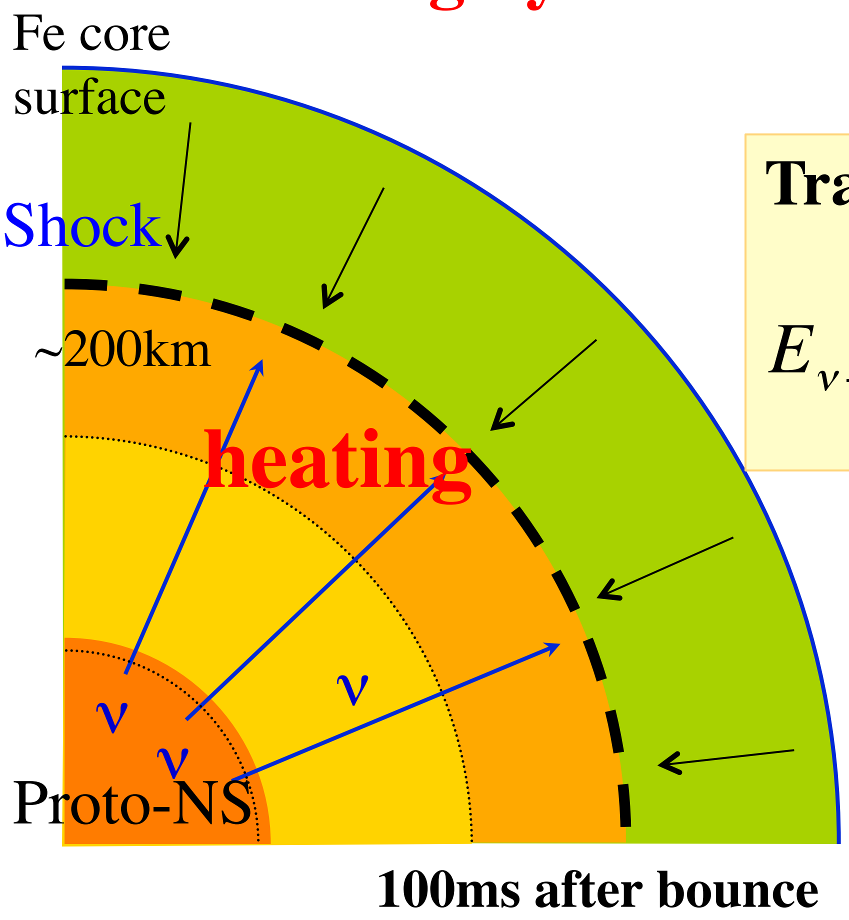
$$E_{loss} \sim -1.6 \times 10^{51} \left(\frac{M_{outer}}{0.1 M_{solar}} \right) erg$$

Neutrino heating mechanism for revival of shock

Heating by neutrino absorption

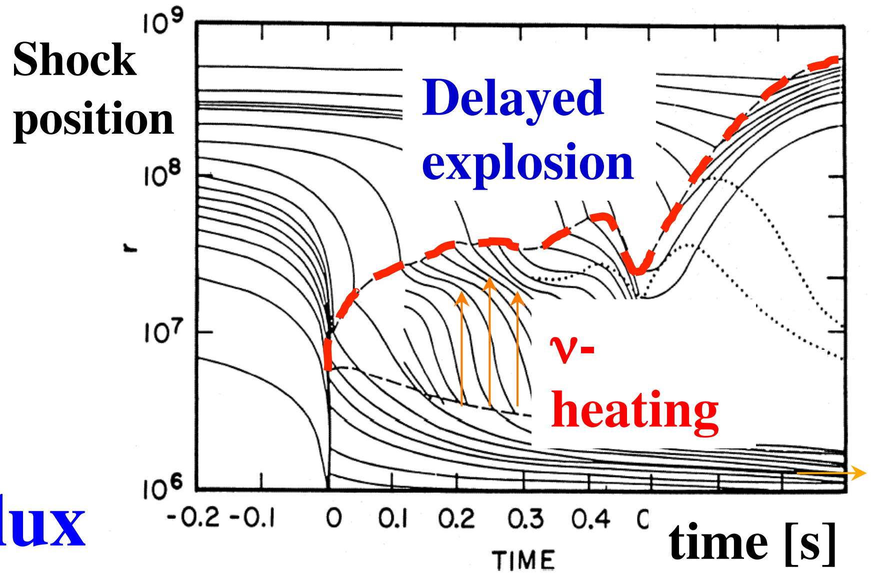
$\nu_e + n \rightarrow e^- + p,$

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



Transfer of energy from ν

$$E_{\nu-heat} \sim 2.2 \times 10^{51} \left(\frac{\Delta M}{0.1 M_{solar}} \right) \left(\frac{\Delta t}{0.1 s} \right) erg$$

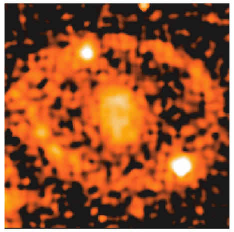


Depends on neutrino energy/flux

Bethe & Wilson ApJ (1985)

Multi-dimensions: new findings

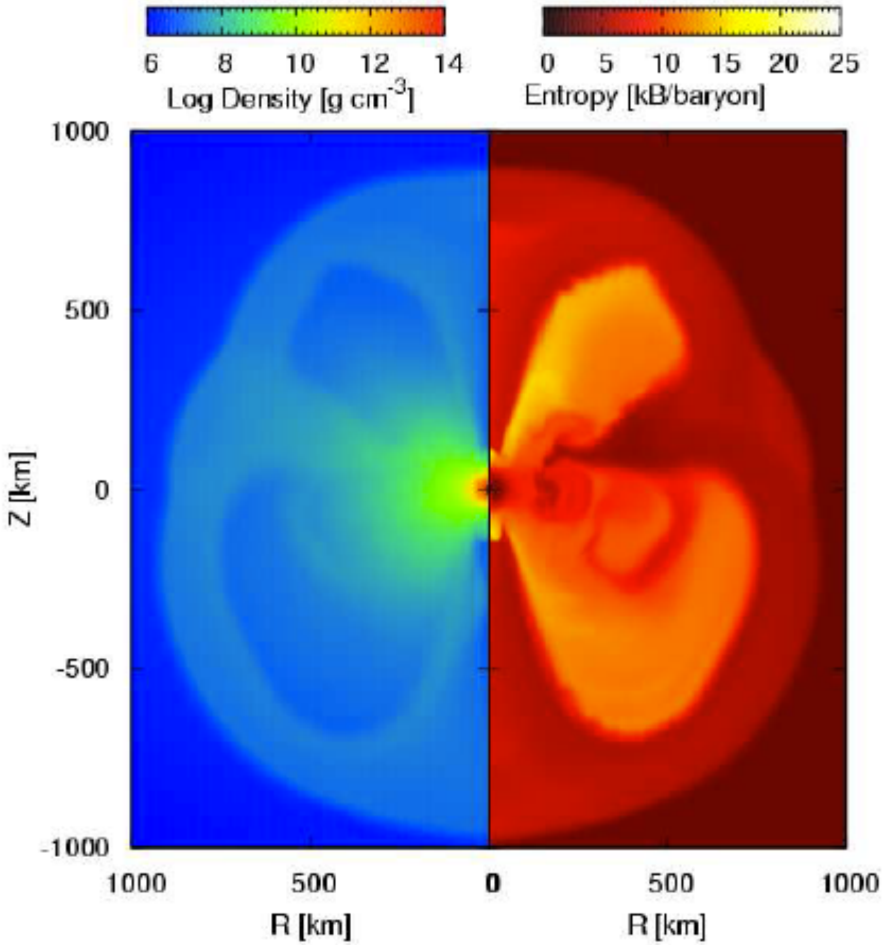
SN1987A

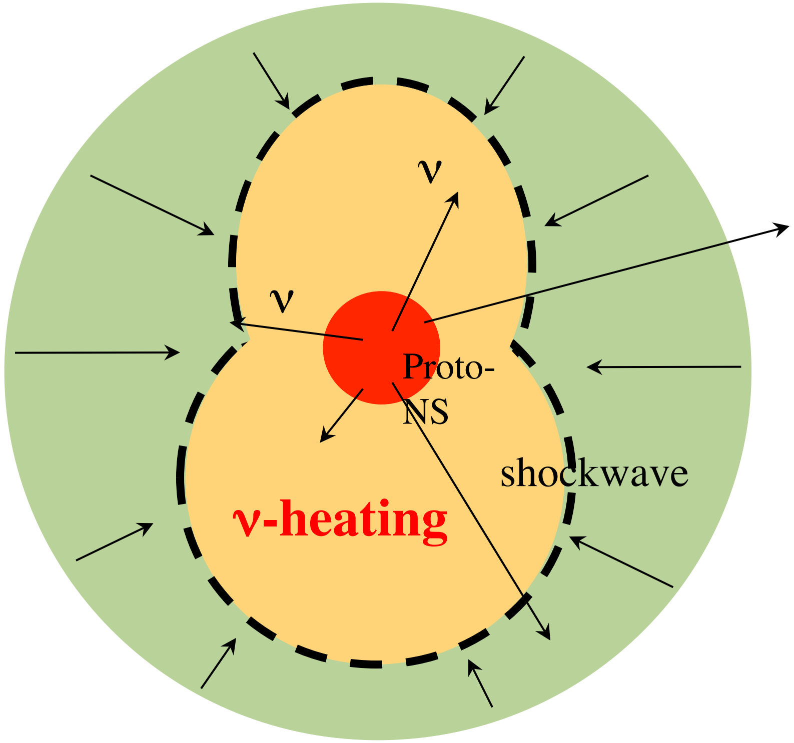


Wang (2002)

- Convection, SASI, rotation, magnetic etc - Observations

ν-heating and/or hydro instability





To obtain enough ν-heating

Suwa et al. (2010) PASJ

Challenges toward 3D simulations

Neutrino-radiation hydrodynamics

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

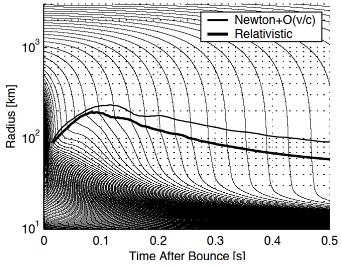
Several mechanisms, discussions not settled

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

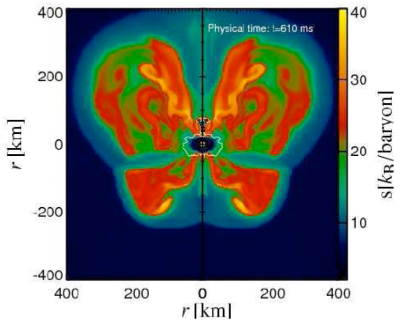
3D Neutrino transfer is 6D problems

(Sumiyoshi-Yamada, 2012 ApJS)

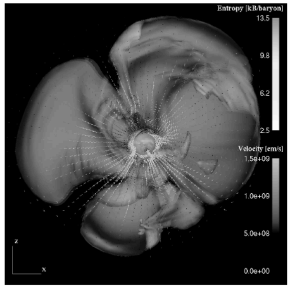
Liebendoerfer (2001)



Marek (2009)



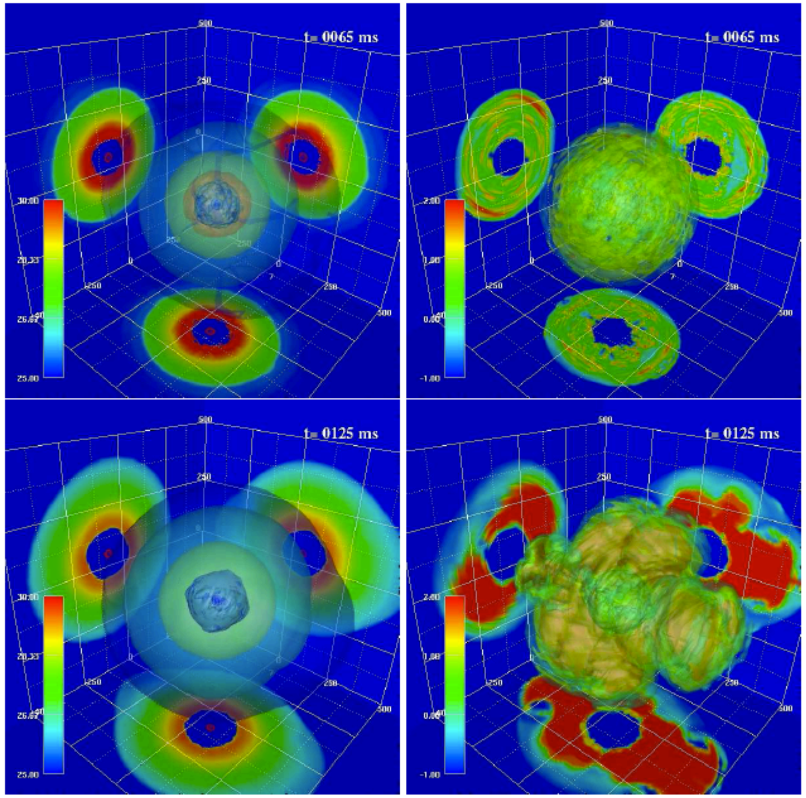
Iwakami (2008)



3D simulation of supernovae from a massive star

Explosions obtained, but still not conclusive

Need high resolutions, accurate ν-transfer



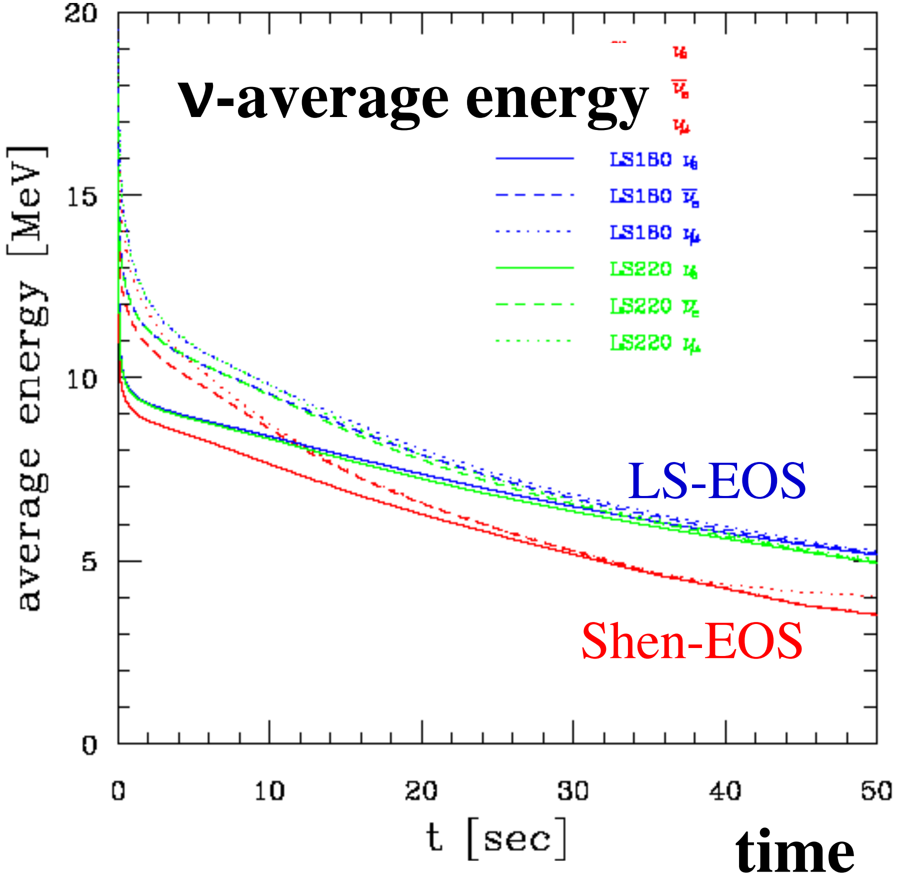
- Simulations running at K-computer, 10Peta-flops

@ Kobe, Japan

Takiwaki et al. (2012) ApJ

Assuming explosion, neutron star modeling

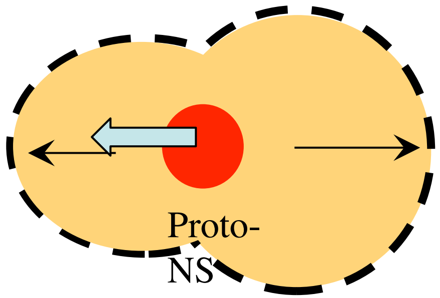
ν-bursts from proto-NS

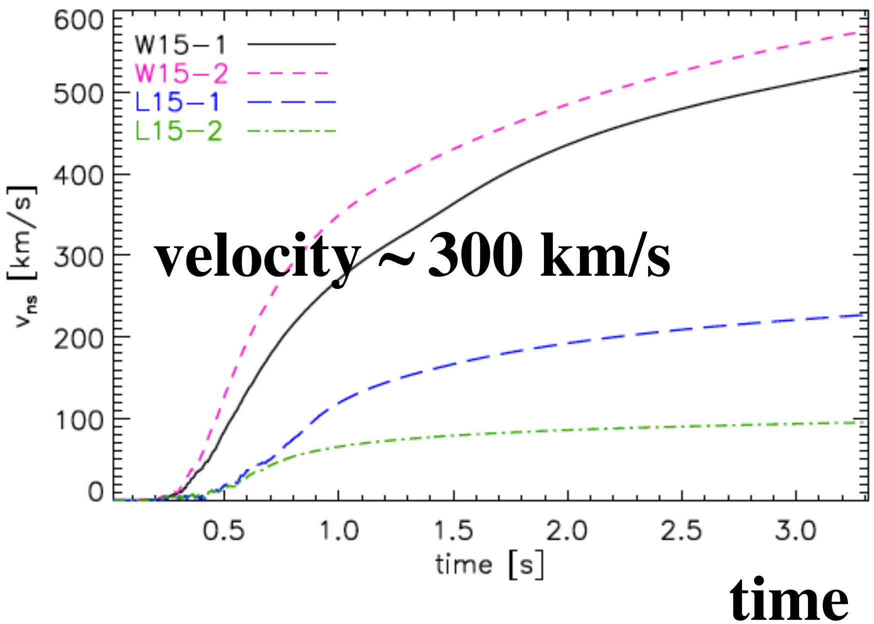


cooling of proto-NS

Suzuki et al. (2004)

pulsar kicks and rotations





postbounce 3D hydro

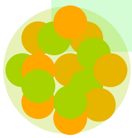
Janka (2012)

Supernovae: Multi-physics from fm to km

Extreme conditions, ~1% effects, multi-dimensions

Microphysics

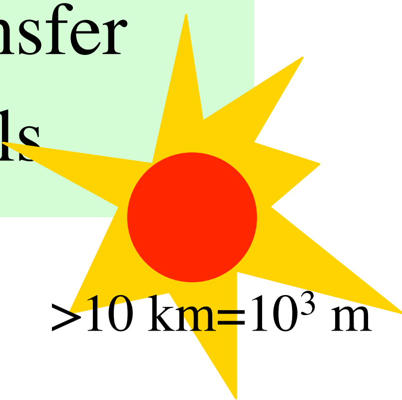
- Equation of state
- Neutrino reactions
- Nuclear data



~ fm=10^{-15} m

Macrophysics

- Hydrodynamics
- Neutrino transfer
- Stellar models



>10 km=10^{3} m

- **Numerical simulations of core-collapse supernovae**
  - Supercomputing technology

- Challenges continue to answer the birth of pulsars

2D: cases of explosions　　3D: current challenges

3D supernova project in collaboration with

- Supernova research
  - S. Yamada
  - H. Nagakura
  - H. Suzuki
- RMF-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
  - K. Kotake
  - T. Takiwaki
  - K. Nakazato
- Neutrino reactions
  - T. Sato
  - S. Nasu
  - S. Nakamura

Supercomputing resources at KEK, RCNP, YITP, UT

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- Grant-in-Aid for Scientific Research on Innovative Areas (20105004, 20105005)
- Grant-in-Aid for Scientific Research (22540296, 24244036)