From supernovae to neutron stars

Yudai Suwa[1,2]

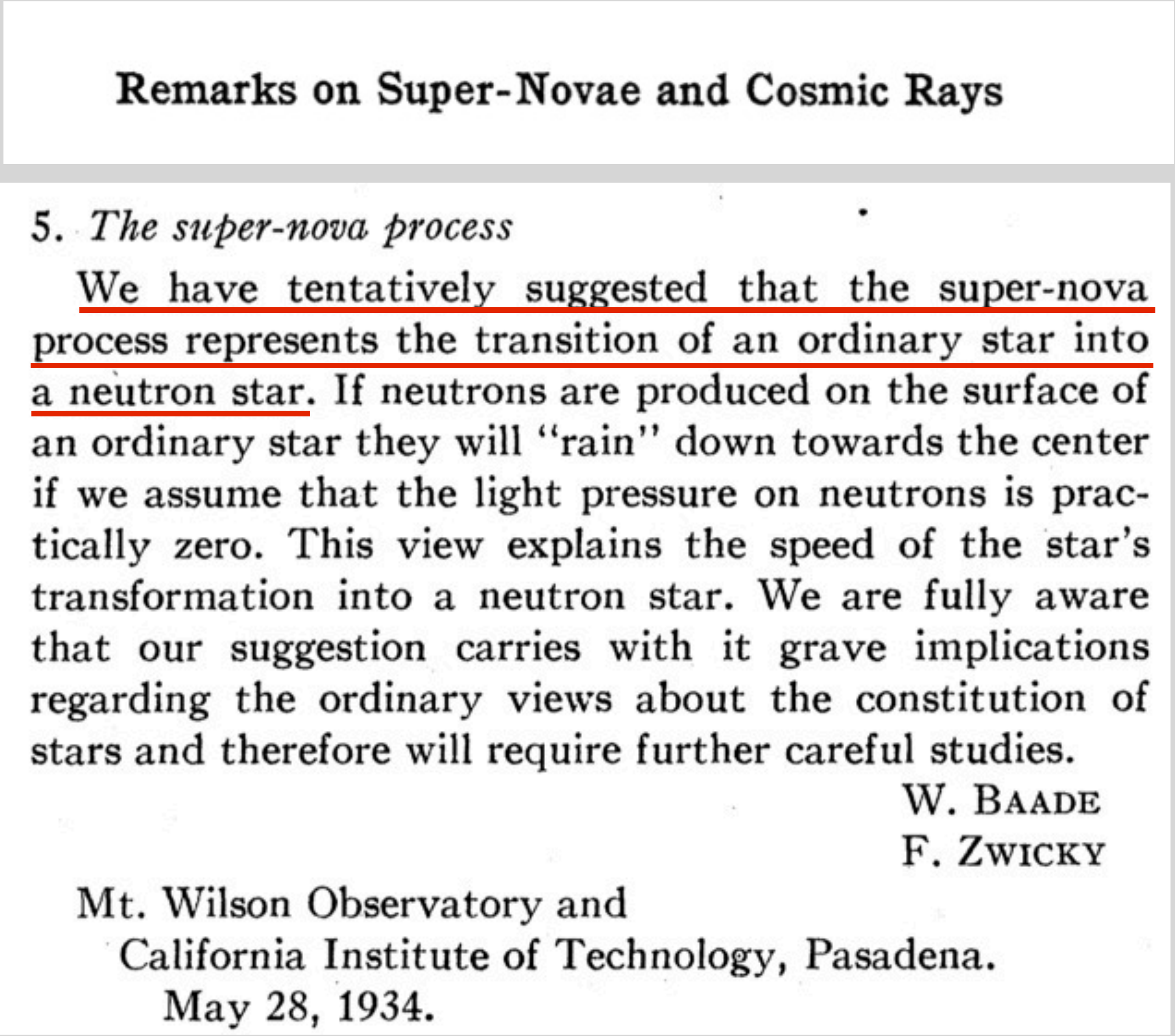
[1]Yukawa Institute for Theoretical Physics, Kyoto University
[2]Max Planck Institute for Astrophysics, Garching

Introduction: what is supernova?

Supernova

SN 2011fe

Supernovae make neutron stars



Remarks on Super-Novae and Cosmic Rays

5. *The super-nova process*

We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This view explains the speed of the star's transformation into a neutron star. We are fully aware that our suggestion carries with it grave implications regarding the ordinary views about the constitution of stars and therefore will require further careful studies.

W. Baade
F. Zwicky

Mt. Wilson Observatory and
California Institute of Technology, Pasadena.
May 28, 1934.

Baade & Zwicky 1934

Key observables characterizing supernovae

- Explosion energy: $\sim 10^{51}$ erg$=10^{44}$ J
- Ejecta mass: $\sim M_\odot = 1.989\times 10^{30}$ kg
- Ni mass: $\sim 0.1 M_\odot$

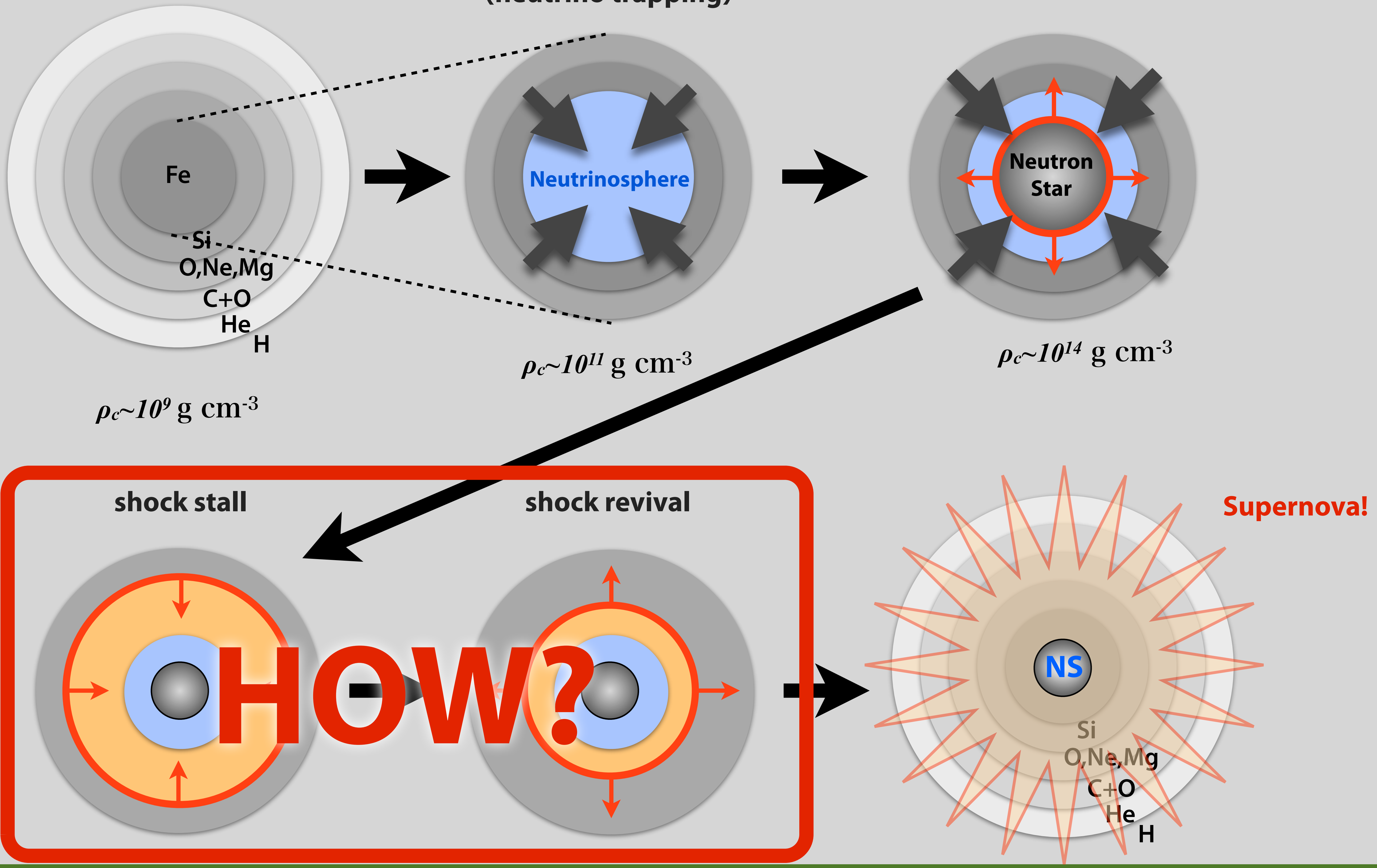
measured by fitting SN light curves

- NS mass: $\sim 1 - 2 M_\odot$

measured by binary systems

final goal of first-principle (*ab initio*) simulations

Standard scenario of core-collapse supernovae



Final phase of stellar evolution

Neutrinosphere formation (neutrino trapping)

Neutron star formation (core bounce)

$\rho_c \sim 10^{9}$ g cm^{-3}

$\rho_c \sim 10^{11}$ g cm^{-3}

$\rho_c \sim 10^{14}$ g cm^{-3}

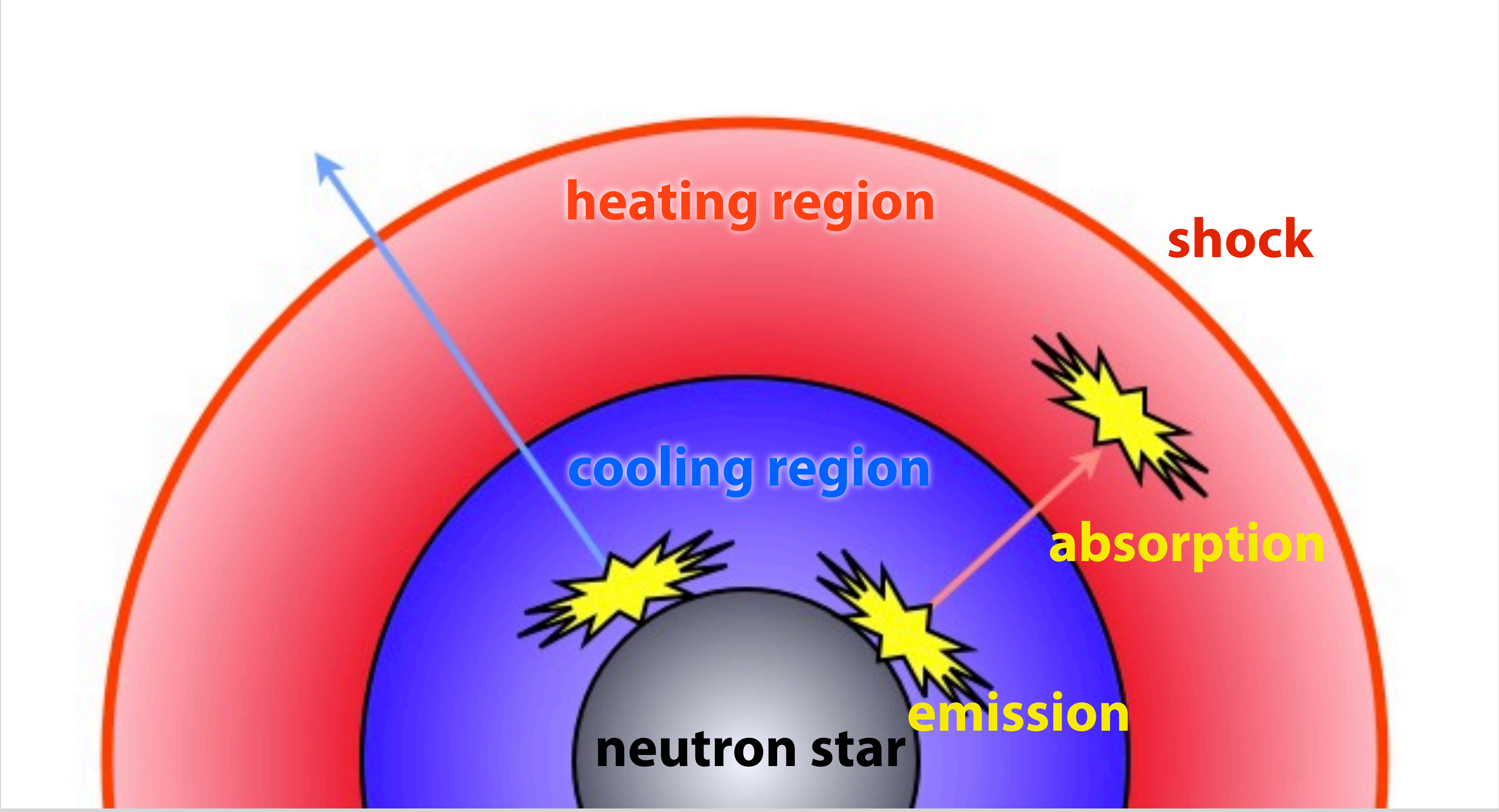
shock stall

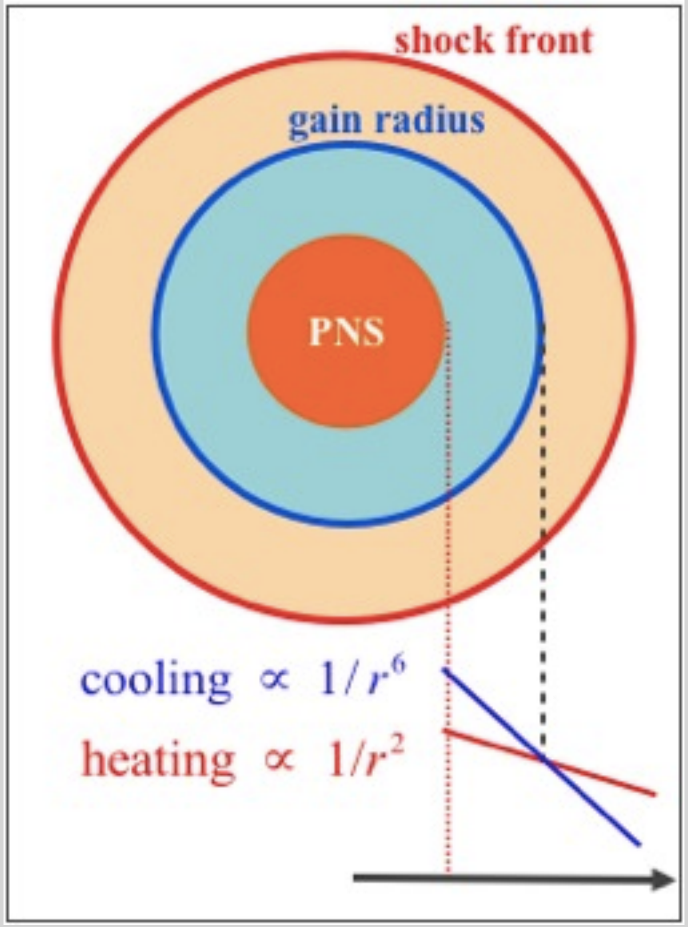
shock revival

HOW?

Supernova!

Current paradigm: neutrino-heating mechanism



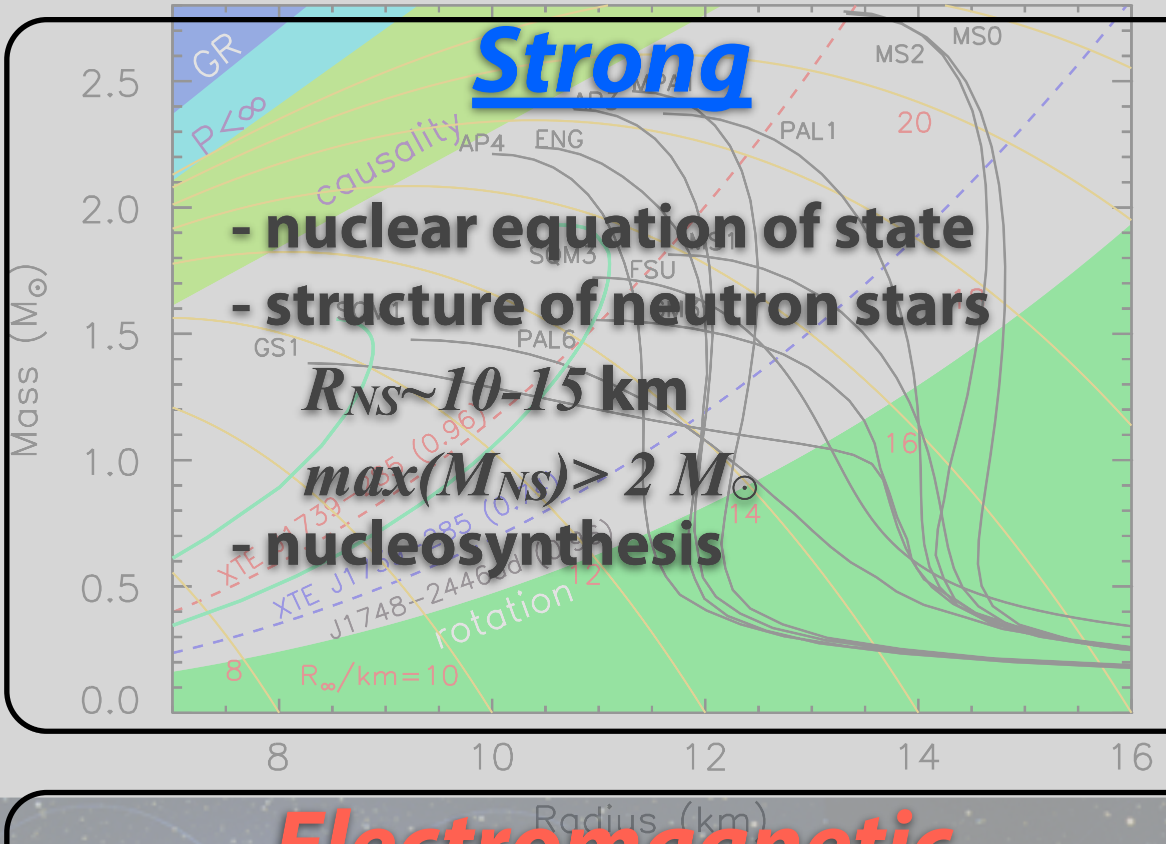


- Energy is transferred by neutrinos
- Most of them are just escaping from the system, but are partially absorbed
- In gain region, neutrino heating overwhelms neutrino cooling

Numerical simulations

Physical ingredients

In these violent explosions, all known interactions are involving and playing important roles;

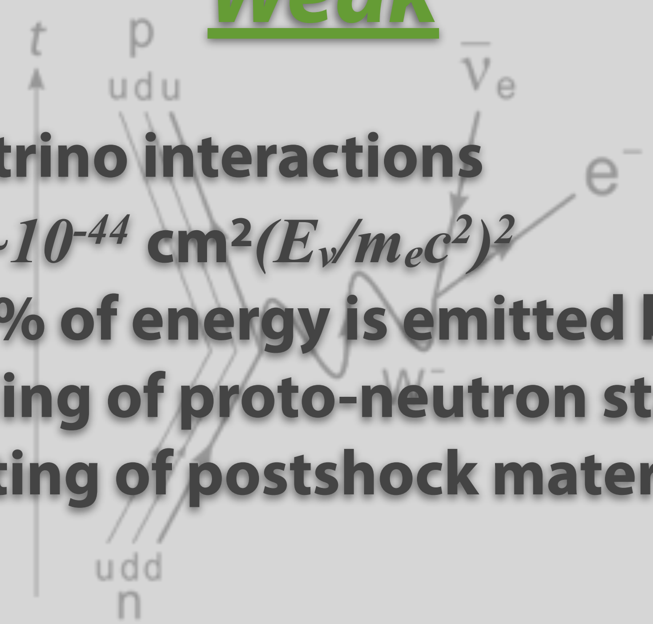


Strong

- nuclear equation of state
- structure of neutron stars

  R_{NS}~10-15 km

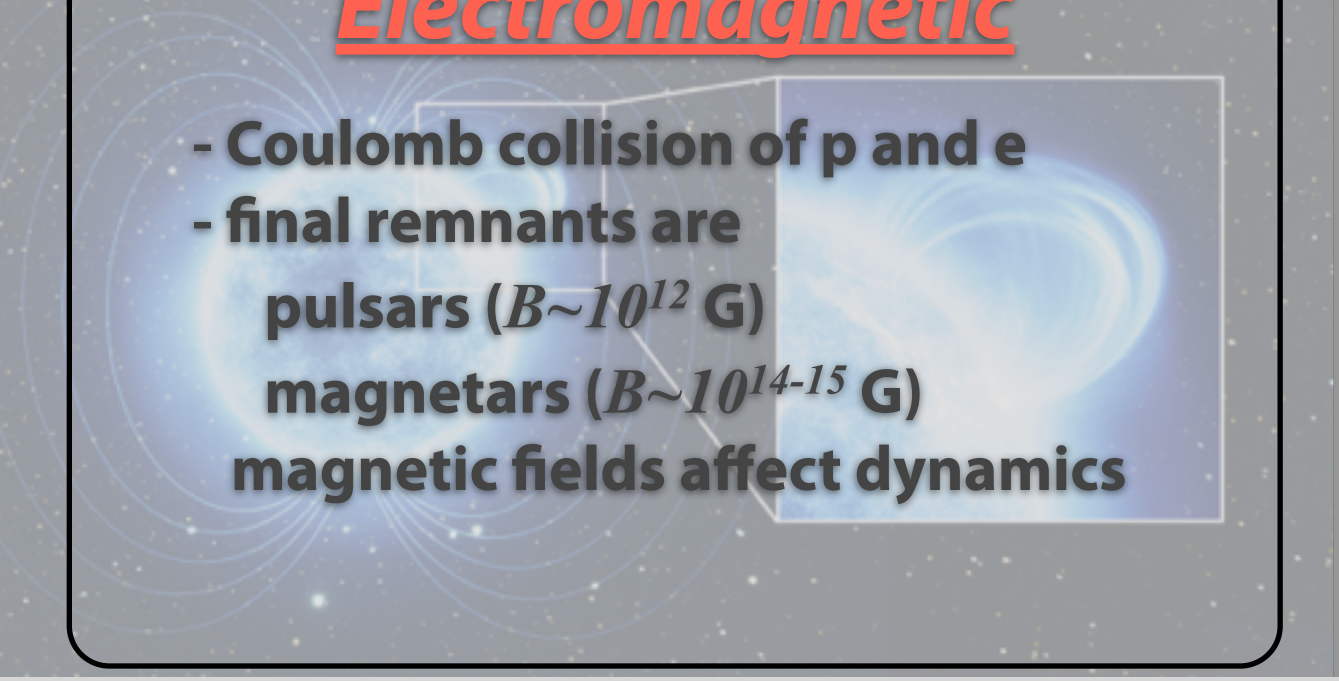
  $max(M_{NS}) > 2\ M_\odot$
- nucleosynthesis



Weak

- neutrino interactions

  $\sigma_\nu \sim 10^{-44}$ cm$^2(E_\nu/m_e c^2)^2$
- ~99% of energy is emitted by ν's
- cooling of proto-neutron star
- heating of postshock material



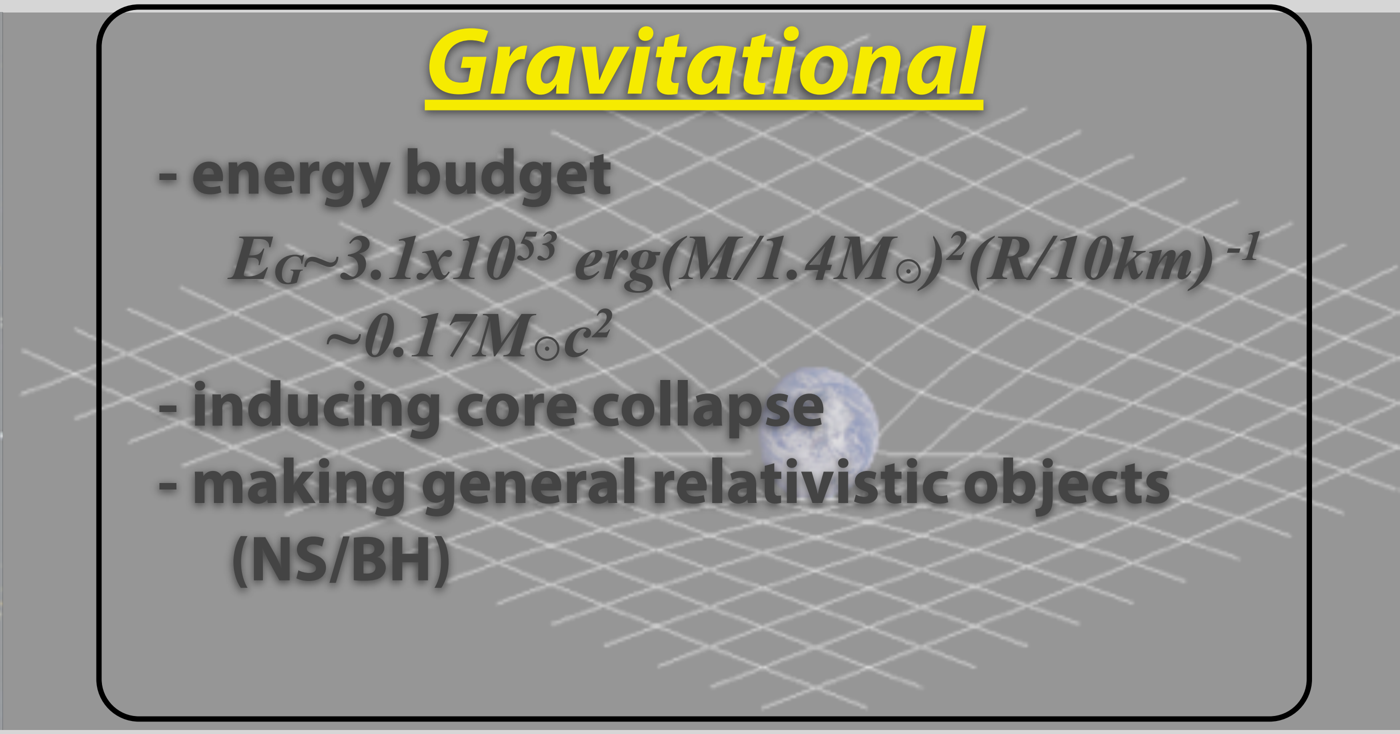
Electromagnetic

- Coulomb collision of p and e
- final remnants are

  pulsars ($B \sim 10^{12}$ G)

  magnetars ($B \sim 10^{14\text{-}15}$ G)

  magnetic fields affect dynamics



Gravitational

- energy budget

  $E_G \sim 3.1\text{x}10^{53}\ \text{erg}(M/1.4M_\odot)^2(R/10\text{km})^{-1}$

  $\sim 0.17 M_\odot c^2$
- inducing core collapse
- making general relativistic objects (NS/BH)

What do simulations solve?

Numerical Simulations

Hydrodynamic equations

$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0,$$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla P - \rho \nabla \Phi,$$

$$\frac{de^*}{dt} + \nabla \cdot \left[\left(e^* + P \right) \mathbf{v} \right] = -\rho \mathbf{v} \cdot \nabla \Phi + Q_E,$$

$$\frac{dY_e}{dt} = Q_N,$$

$$\triangle \Phi = 4\pi G \rho,$$

Solve simultaneously

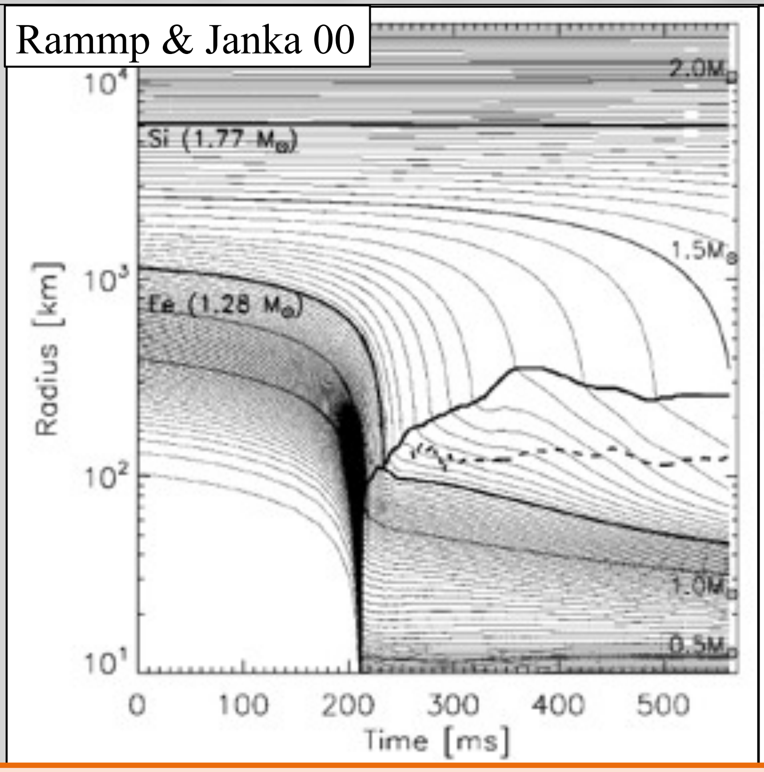
Neutrino Boltzmann equation

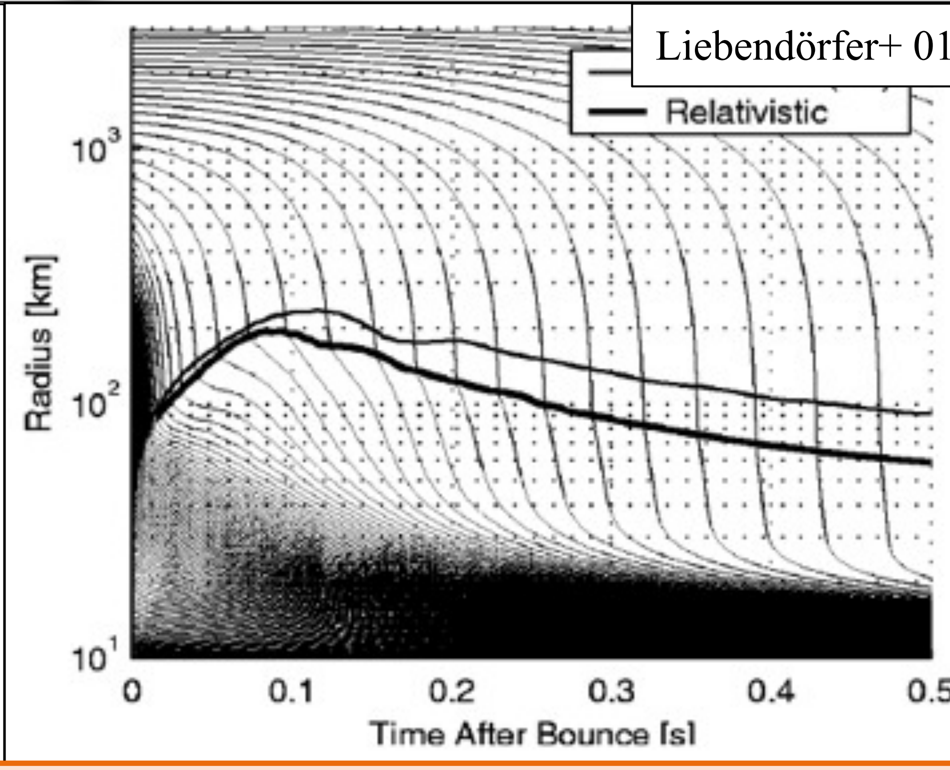
$$\begin{aligned}
&\frac{df}{cdt} + \mu \frac{\partial f}{\partial r} + \left[\mu \left(\frac{d \ln \rho}{cdt} + \frac{3v}{cr} \right) + \frac{1}{r} \right] \left(1 - \mu^2\right) \frac{\partial f}{\partial \mu} \\
&+ \left[\mu^2 \left(\frac{d \ln \rho}{cdt} + \frac{3v}{cr} \right) - \frac{v}{cr} \right] E \frac{\partial f}{\partial E} \\
&= j \left(1 - f\right) - \chi f + \frac{E^2}{c \left(hc\right)^3} \\
&\times \left[\left(1 - f\right) \int R f' d\mu' - f \int R \left(1 - f'\right) d\mu' \right].
\end{aligned}$$

ρ: density, v: velocity, P: pressure, Φ: grav. potential, e^*: total energy, Y_e: elect. frac., Q: neutrino terms

f: neut. dist. func, μ: $\cos\theta$, E: neut. energy, j: emissivity, χ: absorptivity, R: scatt. kernel

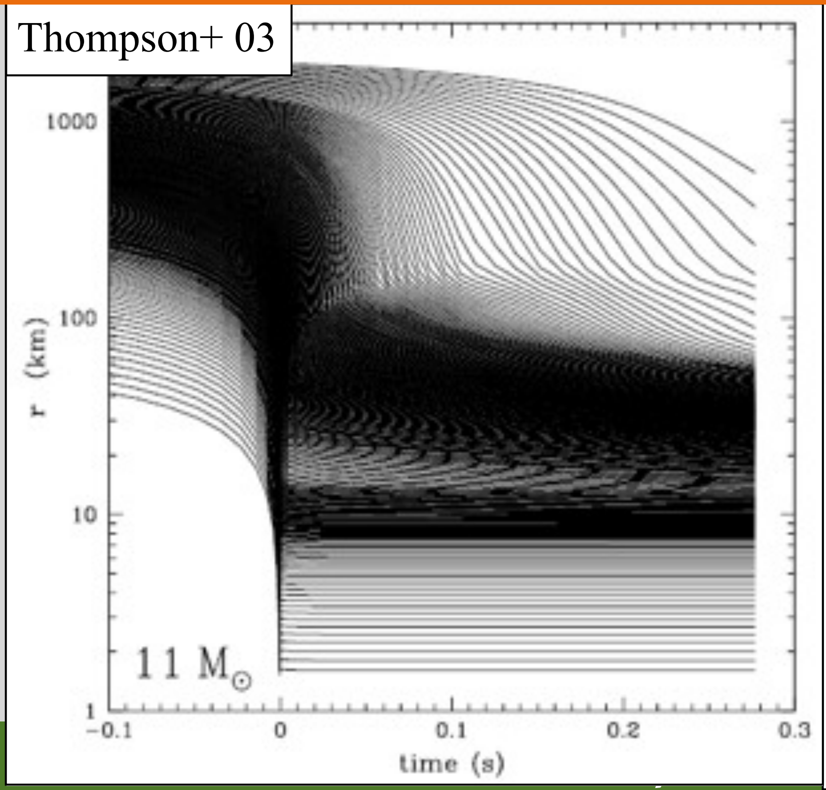
1D simulations fail to explode

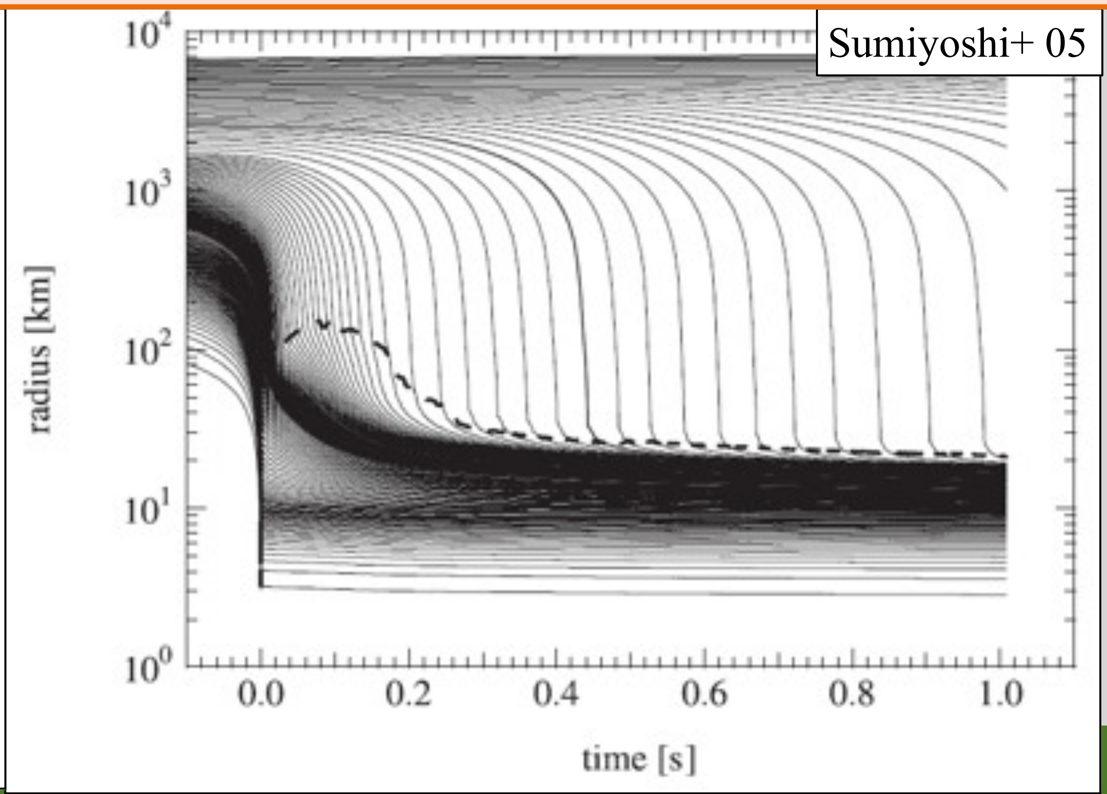

Rammp & Janka 00


Liebendörfer+ 01

By including all available physics to simulations, we concluded that the explosion cannot be obtained in 1D!

(The exception is an 8.8 $M_\odot$ star; Kitaura+ 06)


Thompson+ 03

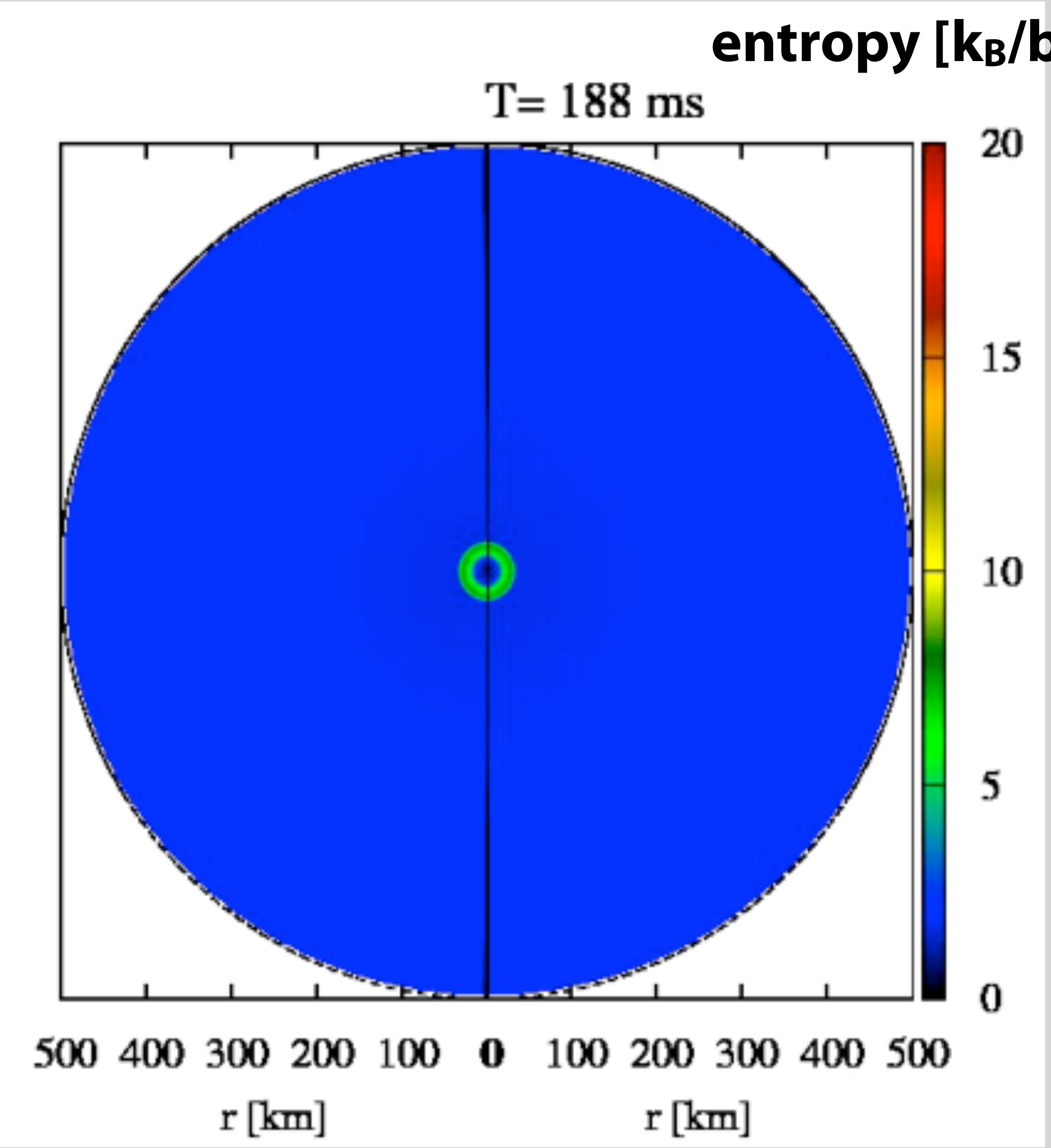

Sumiyoshi+ 05

Neutrino-driven explosion in multi-D simulation

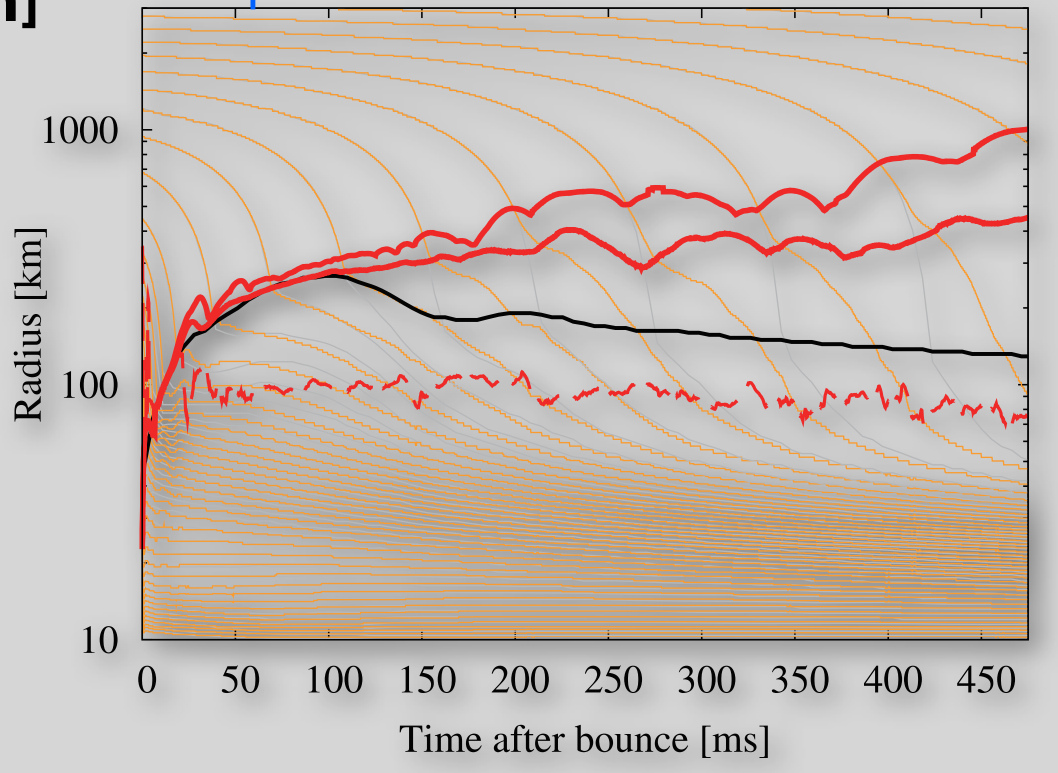
We have exploding models driven by neutrino heating with 2D/3D simulations

[Suwa+ PASJ, **62**, L49 (2010); ApJ, **738**, 165 (2011); ApJ **764**, 99 (2013); PASJ, **66**, L1 (2014); arXiv:1406.6414]

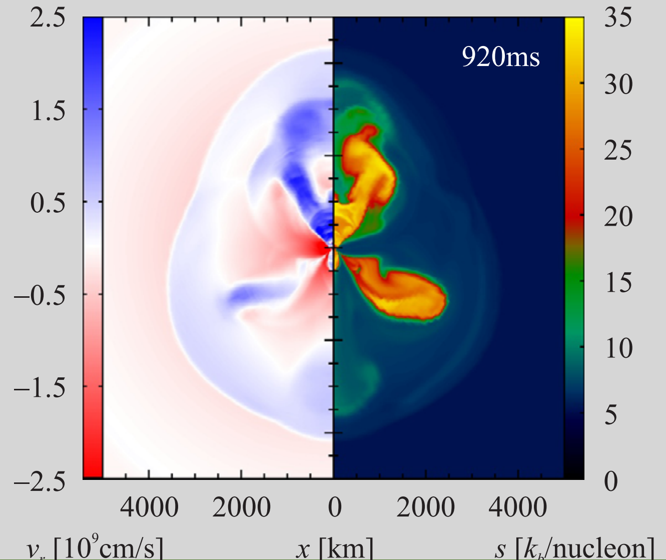
entropy [k_B/baryon]



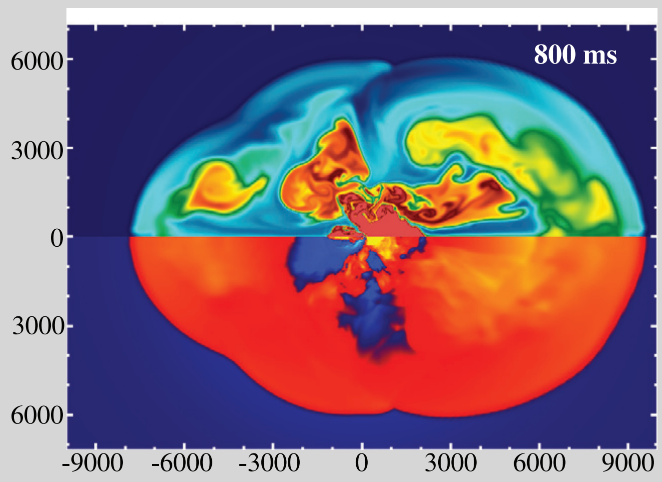
comparison between 1D and 2D



Müller, Janka, Marek (2012)

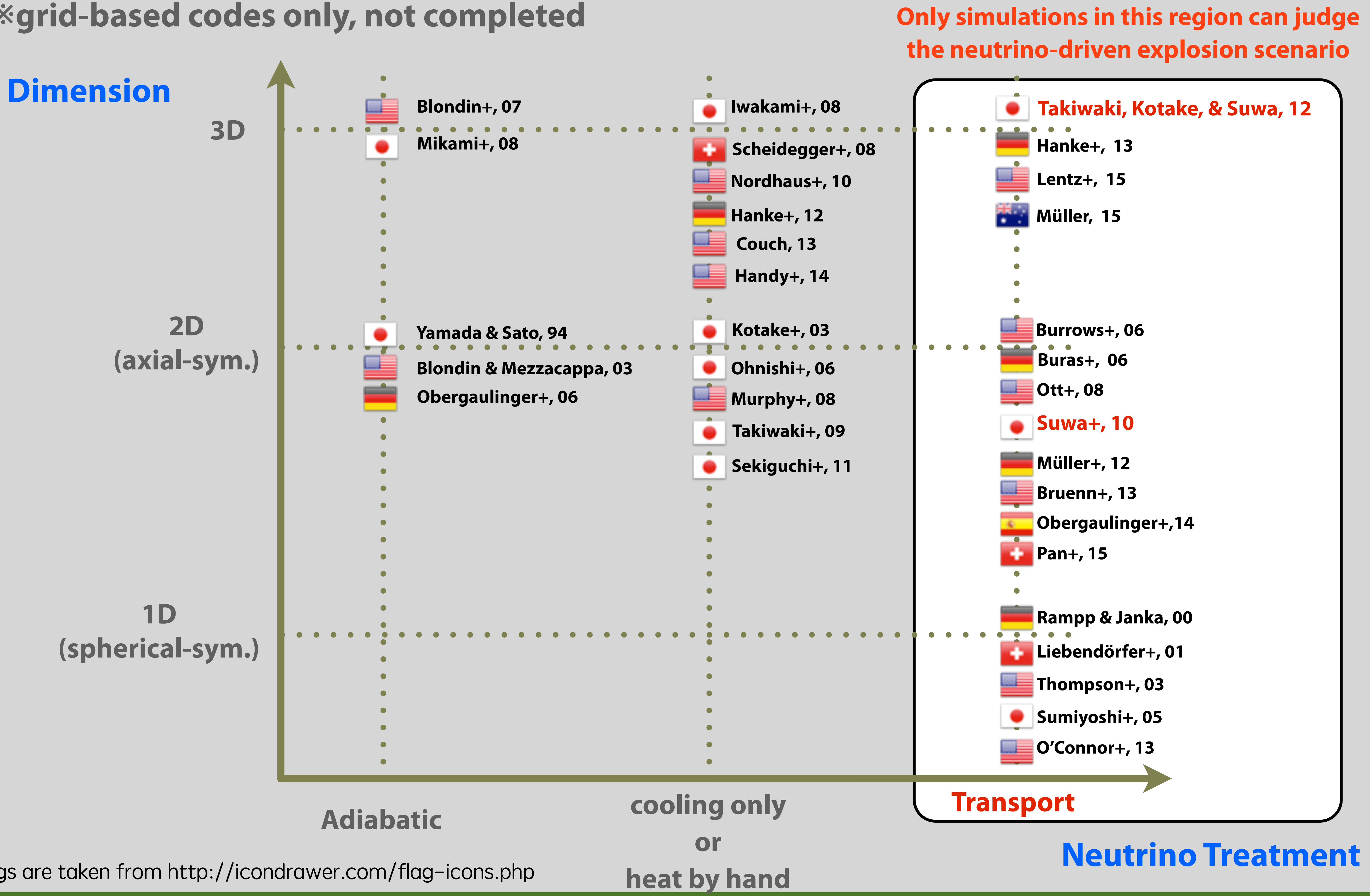


Brruenn et al. (2013)



Dimensionality and numerical simulations

※grid-based codes only, not completed



Only simulations in this region can judge the neutrino-driven explosion scenario

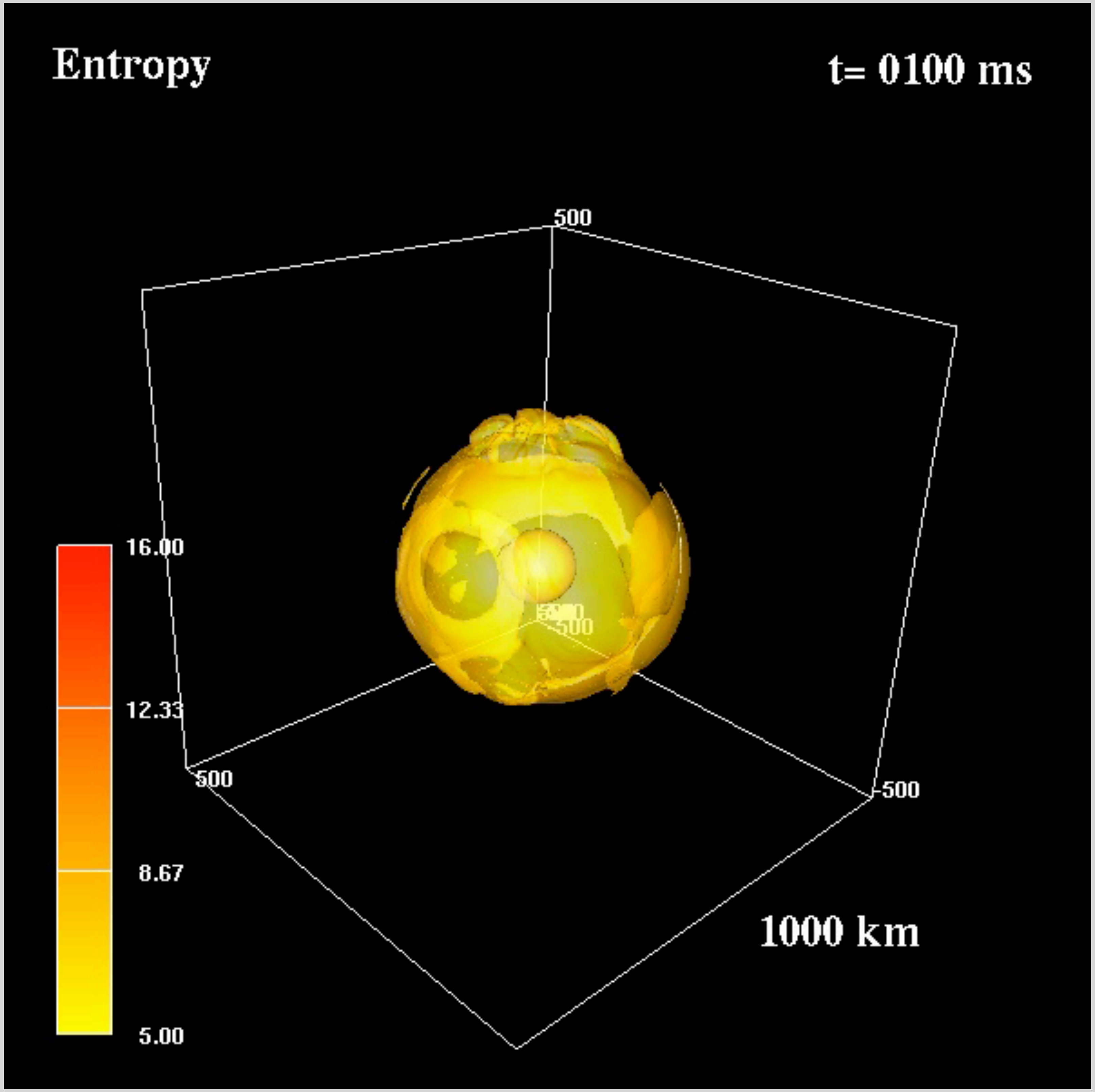
Dimension	Adiabatic	cooling only or heat by hand	Transport
3D	Blondin+, 07 Mikami+, 08	Iwakami+, 08 Scheidegger+, 08 Nordhaus+, 10 Hanke+, 12 Couch, 13 Handy+, 14	Takiwaki, Kotake, & Suwa, 12 Hanke+, 13 Lentz+, 15 Müller, 15
2D (axial-sym.)	Yamada & Sato, 94 Blondin & Mezzacappa, 03 Obergaulinger+, 06	Kotake+, 03 Ohnishi+, 06 Murphy+, 08 Takiwaki+, 09 Sekiguchi+, 11	Burrows+, 06 Buras+, 06 Ott+, 08 Suwa+, 10 Müller+, 12 Bruenn+, 13 Obergaulinger+,14 Pan+, 15
1D (spherical-sym.)			Rampp & Janka, 00 Liebendörfer+, 01 Thompson+, 03 Sumiyoshi+, 05 O'Connor+, 13

Neutrino Treatment

flags are taken from http://icondrawer.com/flag-icons.php

3D simulation with spectral neutrino transfer

[Takiwaki, Kotake, Suwa, ApJ, **749**, 98 (2012); ApJ, **786**, 83 (2014)]



M_{ZAMS}=11.2 $M_\odot$

384(r)x128(θ)x256(φ)x20(E_ν)

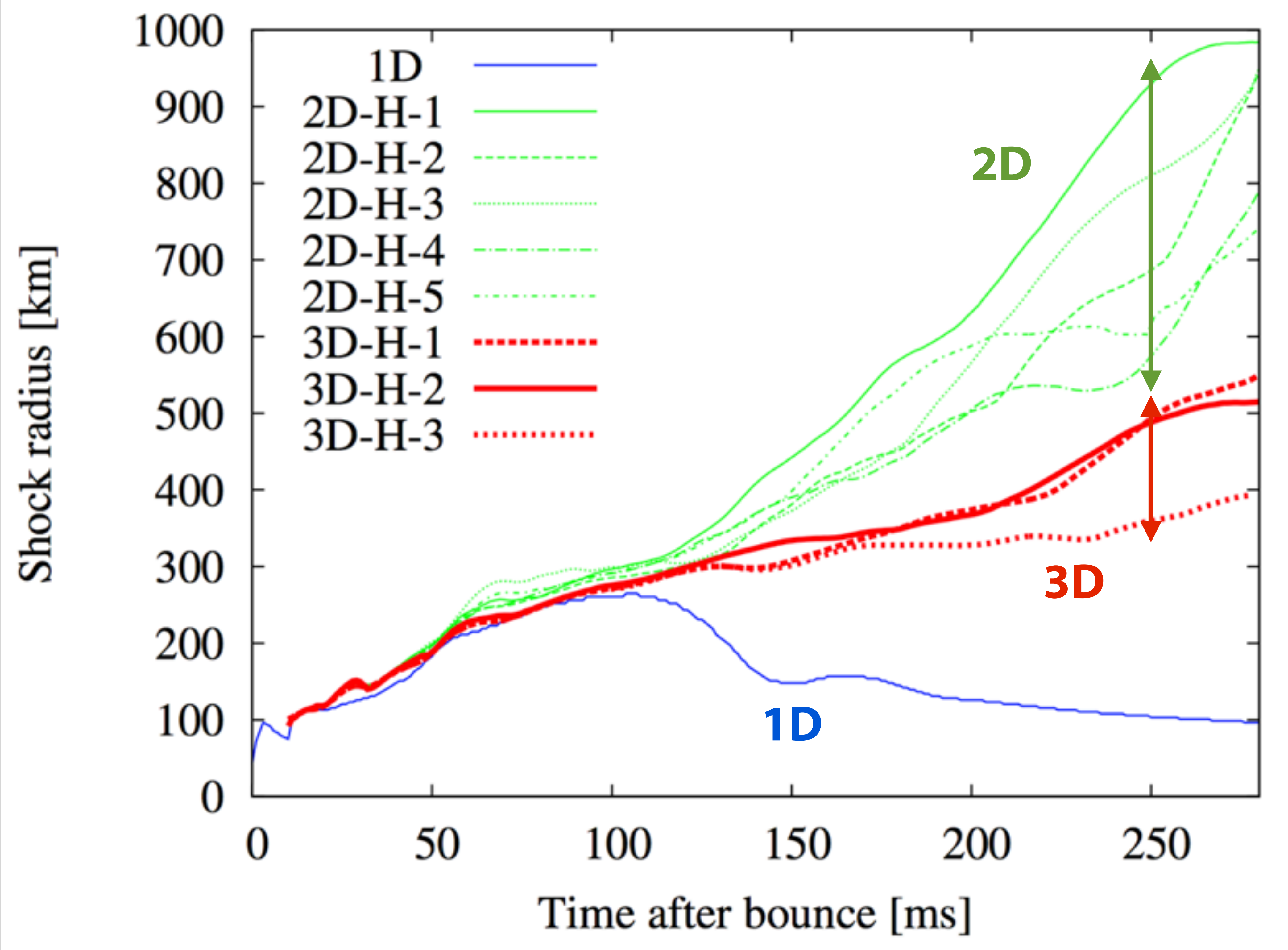
XT4

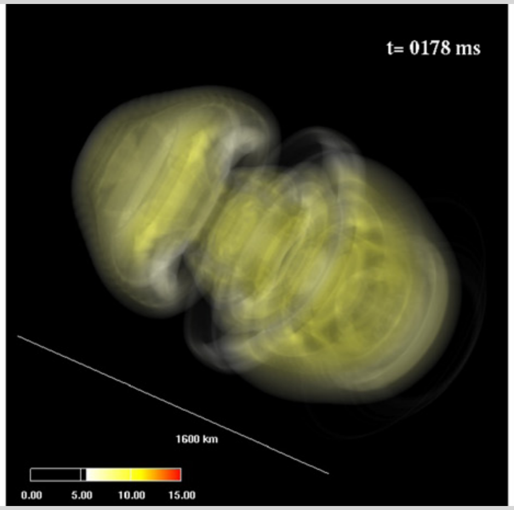
T2K-Tsukuba

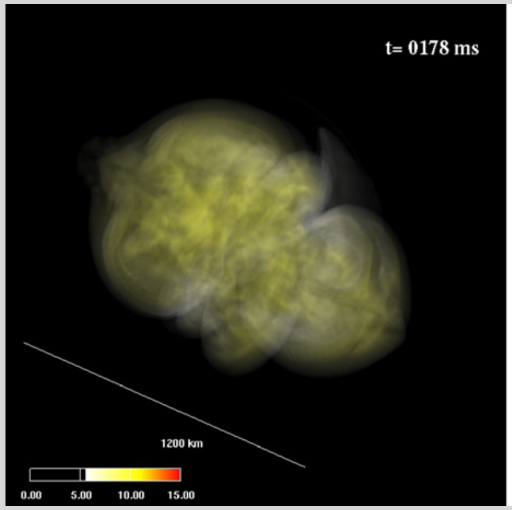
K computer

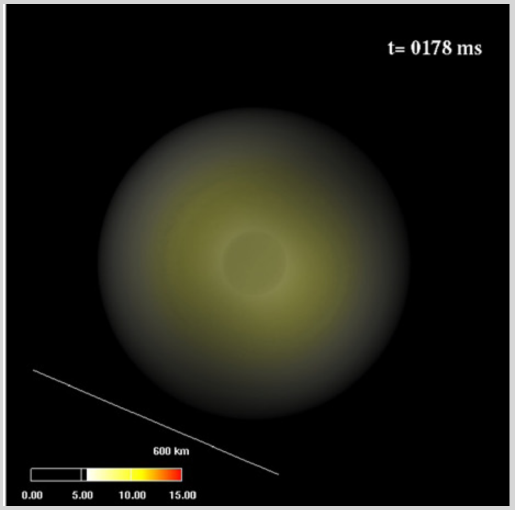
Dimensionality and initial perturbation

[Takiwaki, Kotake, Suwa, ApJ, **786**, 83 (2014)]







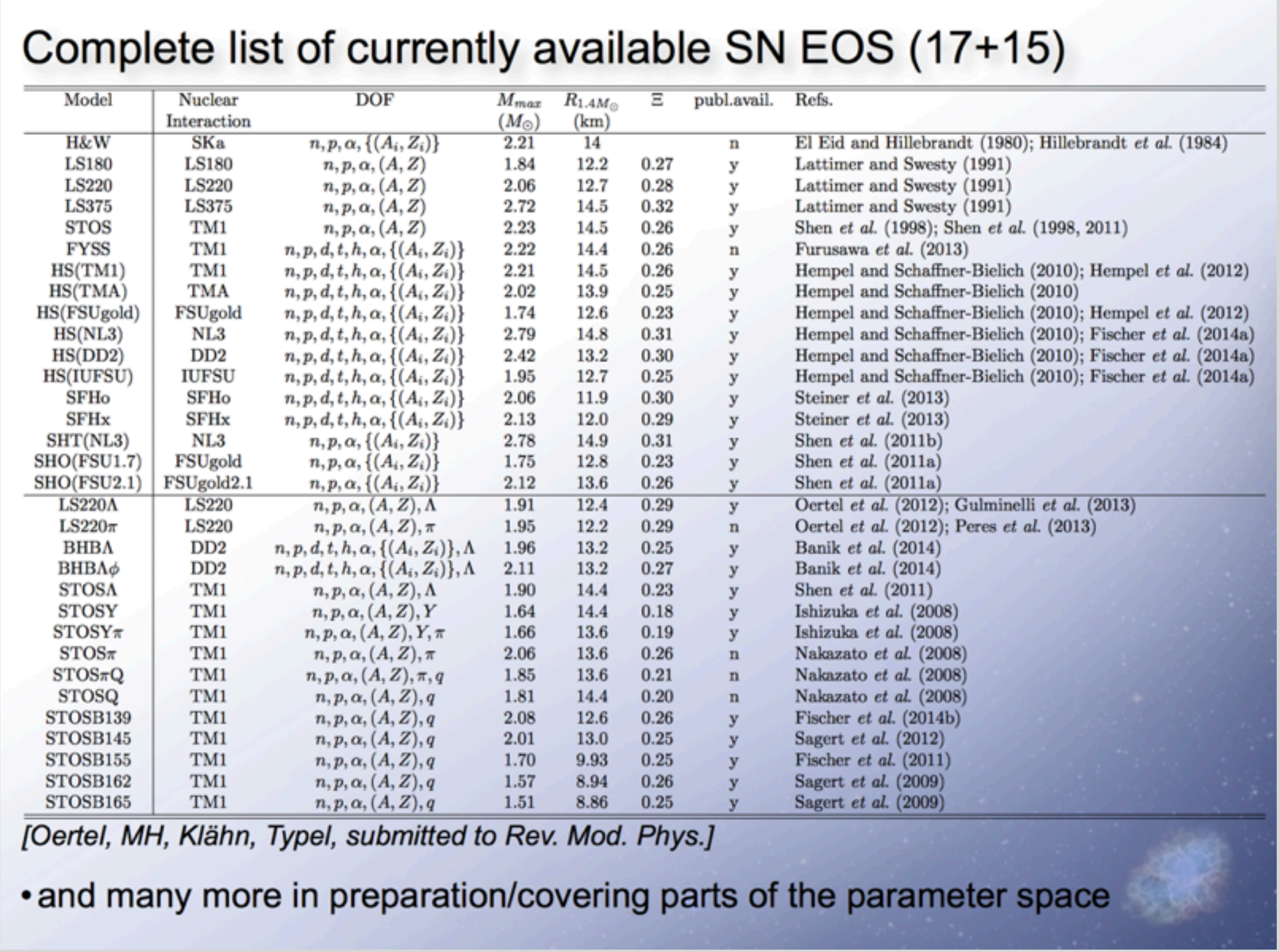


Note) explosion energy is still too small ($\sim 10^{50}$ erg) compared to observations ($\sim 10^{51}$ erg)

Equation of state dependence

List of SN EOS

Courtesy of M. Hempel



Complete list of currently available SN EOS (17+15)

Model	Nuclear Interaction	DOF	M_{max} ($M_\odot$)	$R_{1.4M_\odot}$ (km)	Ξ	publ.avail.	Refs.
H&W	SKa	$n, p, \alpha, \{(A_i, Z_i)\}$	2.21	14		n	El Eid and Hillebrandt (1980); Hillebrandt *et al.* (1984)
LS180	LS180	$n, p, \alpha, (A, Z)$	1.84	12.2	0.27	y	Lattimer and Swesty (1991)
LS220	LS220	$n, p, \alpha, (A, Z)$	2.06	12.7	0.28	y	Lattimer and Swesty (1991)
LS375	LS375	$n, p, \alpha, (A, Z)$	2.72	14.5	0.32	y	Lattimer and Swesty (1991)
STOS	TM1	$n, p, \alpha, (A, Z)$	2.23	14.5	0.26	y	Shen *et al.* (1998); Shen *et al.* (1998, 2011)
FYSS	TM1	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.22	14.4	0.26	n	Furusawa *et al.* (2013)
HS(TM1)	TM1	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.21	14.5	0.26	y	Hempel and Schaffner-Bielich (2010); Hempel *et al.* (2012)
HS(TMA)	TMA	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.02	13.9	0.25	y	Hempel and Schaffner-Bielich (2010)
HS(FSUgold)	FSUgold	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	1.74	12.6	0.23	y	Hempel and Schaffner-Bielich (2010); Hempel *et al.* (2012)
HS(NL3)	NL3	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.79	14.8	0.31	y	Hempel and Schaffner-Bielich (2010); Fischer *et al.* (2014a)
HS(DD2)	DD2	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.42	13.2	0.30	y	Hempel and Schaffner-Bielich (2010); Fischer *et al.* (2014a)
HS(IUFSU)	IUFSU	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	1.95	12.7	0.25	y	Hempel and Schaffner-Bielich (2010); Fischer *et al.* (2014a)
SFHo	SFHo	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.06	11.9	0.30	y	Steiner *et al.* (2013)
SFHx	SFHx	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}$	2.13	12.0	0.29	y	Steiner *et al.* (2013)
SHT(NL3)	NL3	$n, p, \alpha, \{(A_i, Z_i)\}$	2.78	14.9	0.31	y	Shen *et al.* (2011b)
SHO(FSU1.7)	FSUgold	$n, p, \alpha, \{(A_i, Z_i)\}$	1.75	12.8	0.23	y	Shen *et al.* (2011a)
SHO(FSU2.1)	FSUgold2.1	$n, p, \alpha, \{(A_i, Z_i)\}$	2.12	13.6	0.26	y	Shen *et al.* (2011a)
LS220Λ	LS220	$n, p, \alpha, (A, Z), \Lambda$	1.91	12.4	0.29	y	Oertel *et al.* (2012); Gulminelli *et al.* (2013)
LS220π	LS220	$n, p, \alpha, (A, Z), \pi$	1.95	12.2	0.29	n	Oertel *et al.* (2012); Peres *et al.* (2013)
BHBΛ	DD2	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}, \Lambda$	1.96	13.2	0.25	y	Banik *et al.* (2014)
BHBΛφ	DD2	$n, p, d, t, h, \alpha, \{(A_i, Z_i)\}, \Lambda$	2.11	13.2	0.27	y	Banik *et al.* (2014)
STOSΛ	TM1	$n, p, \alpha, (A, Z), \Lambda$	1.90	14.4	0.23	y	Shen *et al.* (2011)
STOSY	TM1	$n, p, \alpha, (A, Z), Y$	1.64	14.4	0.18	y	Ishizuka *et al.* (2008)
STOSYπ	TM1	$n, p, \alpha, (A, Z), Y, \pi$	1.66	13.6	0.19	y	Ishizuka *et al.* (2008)
STOSπ	TM1	$n, p, \alpha, (A, Z), \pi$	2.06	13.6	0.26	n	Nakazato *et al.* (2008)
STOSπQ	TM1	$n, p, \alpha, (A, Z), \pi, q$	1.85	13.6	0.21	n	Nakazato *et al.* (2008)
STOSQ	TM1	$n, p, \alpha, (A, Z), q$	1.81	14.4	0.20	n	Nakazato *et al.* (2008)
STOSB139	TM1	$n, p, \alpha, (A, Z), q$	2.08	12.6	0.26	y	Fischer *et al.* (2014b)
STOSB145	TM1	$n, p, \alpha, (A, Z), q$	2.01	13.0	0.25	y	Sagert *et al.* (2012)
STOSB155	TM1	$n, p, \alpha, (A, Z), q$	1.70	9.93	0.25	y	Fischer *et al.* (2011)
STOSB162	TM1	$n, p, \alpha, (A, Z), q$	1.57	8.94	0.26	y	Sagert *et al.* (2009)
STOSB165	TM1	$n, p, \alpha, (A, Z), q$	1.51	8.86	0.25	y	Sagert *et al.* (2009)

[Oertel, MH, Klähn, Typel, submitted to Rev. Mod. Phys.]

- and many more in preparation/covering parts of the parameter space

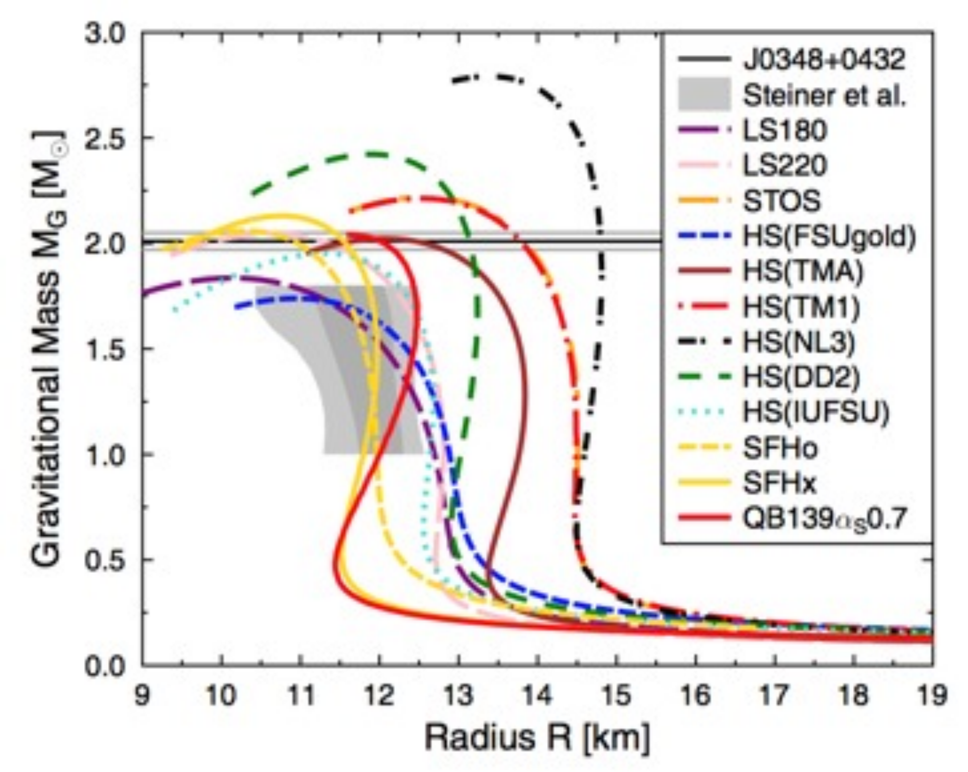
Finite temperature EOSs

- Lattimer & Swesty (LS) (1991)
  - based on compressible liquid drop model
  - variants with K=180, 220, and 375 MeV
- H.Shen et al. (1998, 2011)
  - relativistic mean field theory (TM1)
  - including hyperon component (~2011)

- Hillebrandt & Wolff (1985)
  - Hartree-Fock calculation
- G.Shen et al. (2010, 2011)
  - relativistic mean field theory (NL3, FSUGold)
- Hempel et al. (2012)
  - relativistic mean field theory (TM1, TMA, FSUGold)

More recently, Steiner+ (2013), Furusawa+ (2013), etc.

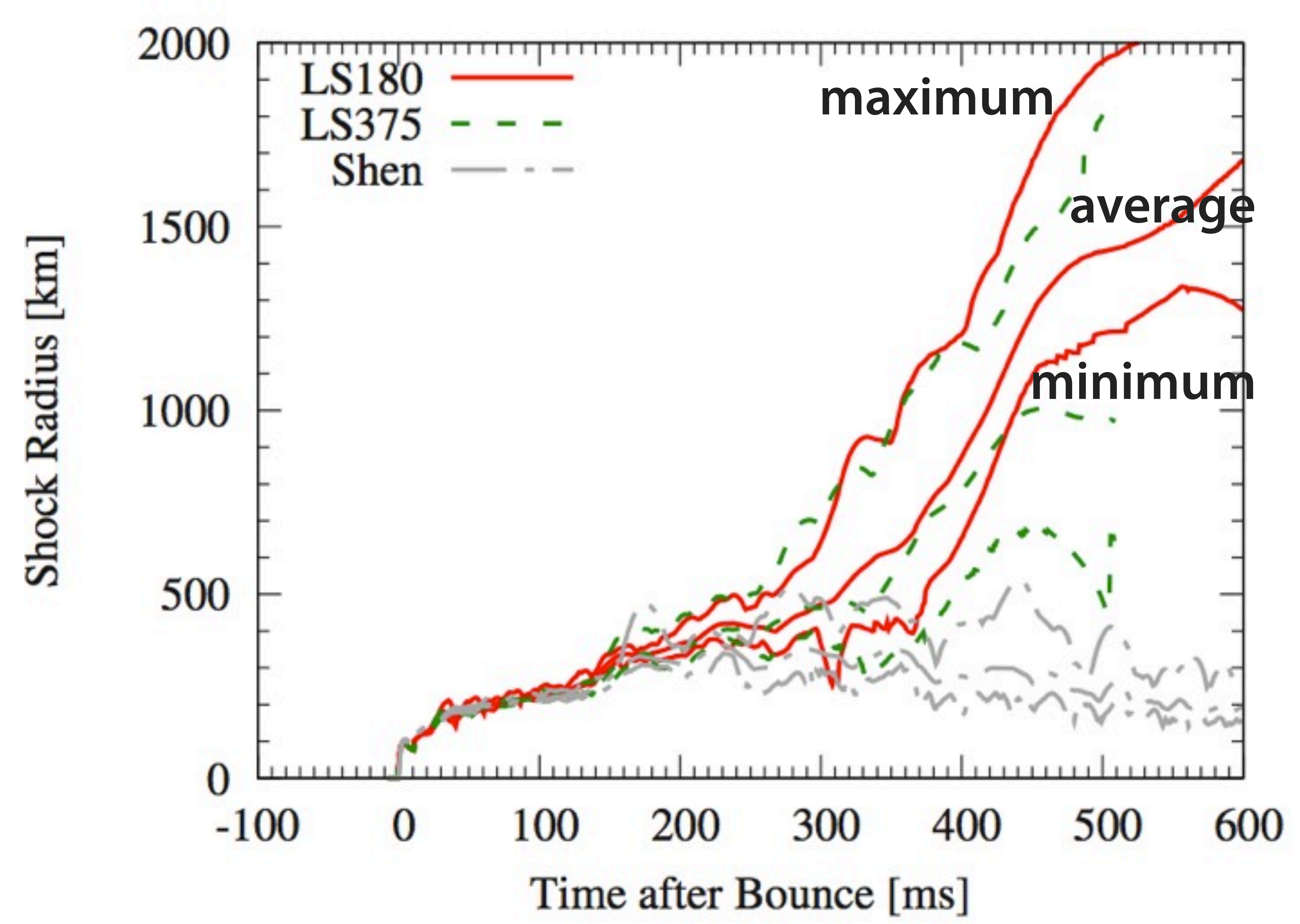
	incompressibility K [MeV]	symmetry energy J (S) [MeV]	slope of symmetry energy L [MeV]
LS	180, 220, 375	29.3	---
HShen	281	36.9	111
HW	263	32.9	---
GShen	271.5 (NL3) 230.0 (FSU)	37.29 (NL3) 32.59 (FSU)	118.2 (NL3) 60.5 (FSU)
Hempel	318 (TMA) 230 (FSU)	30.7 (TMA) 32.6 (FSU)	90 (TMA) 60 (FSU)



[Fischer, Hempel, Sagert, Suwa, Schaffner-Bielich, EPJA, **50**, 46 (2014)]

Shock radius evolution depending on EOS

[Suwa, Takiwaki, Kotake, Fischer, Liebendörfer, Sato, ApJ, **764**, 99 (2013)]

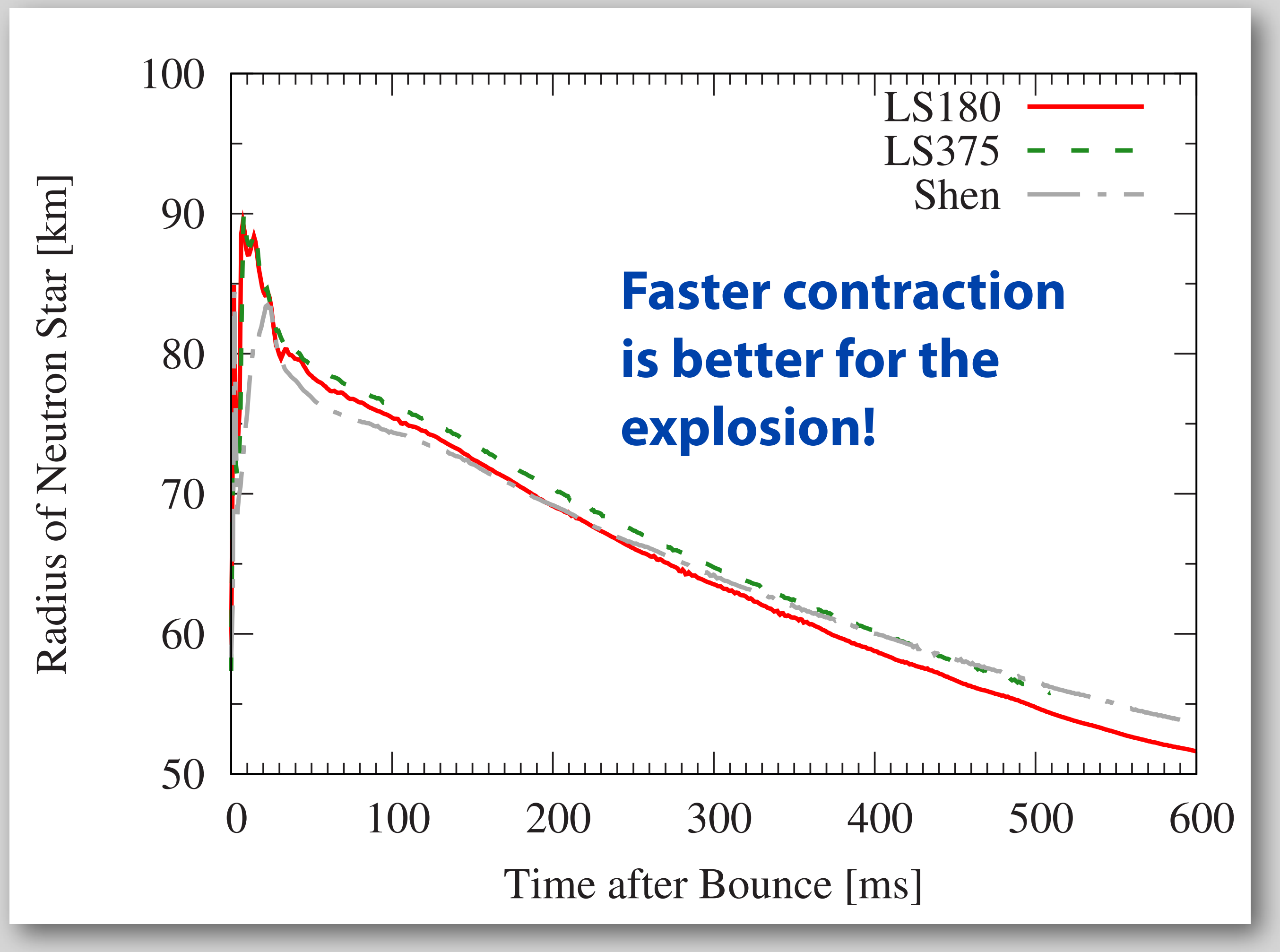


LS180 and LS375 succeed the explosion

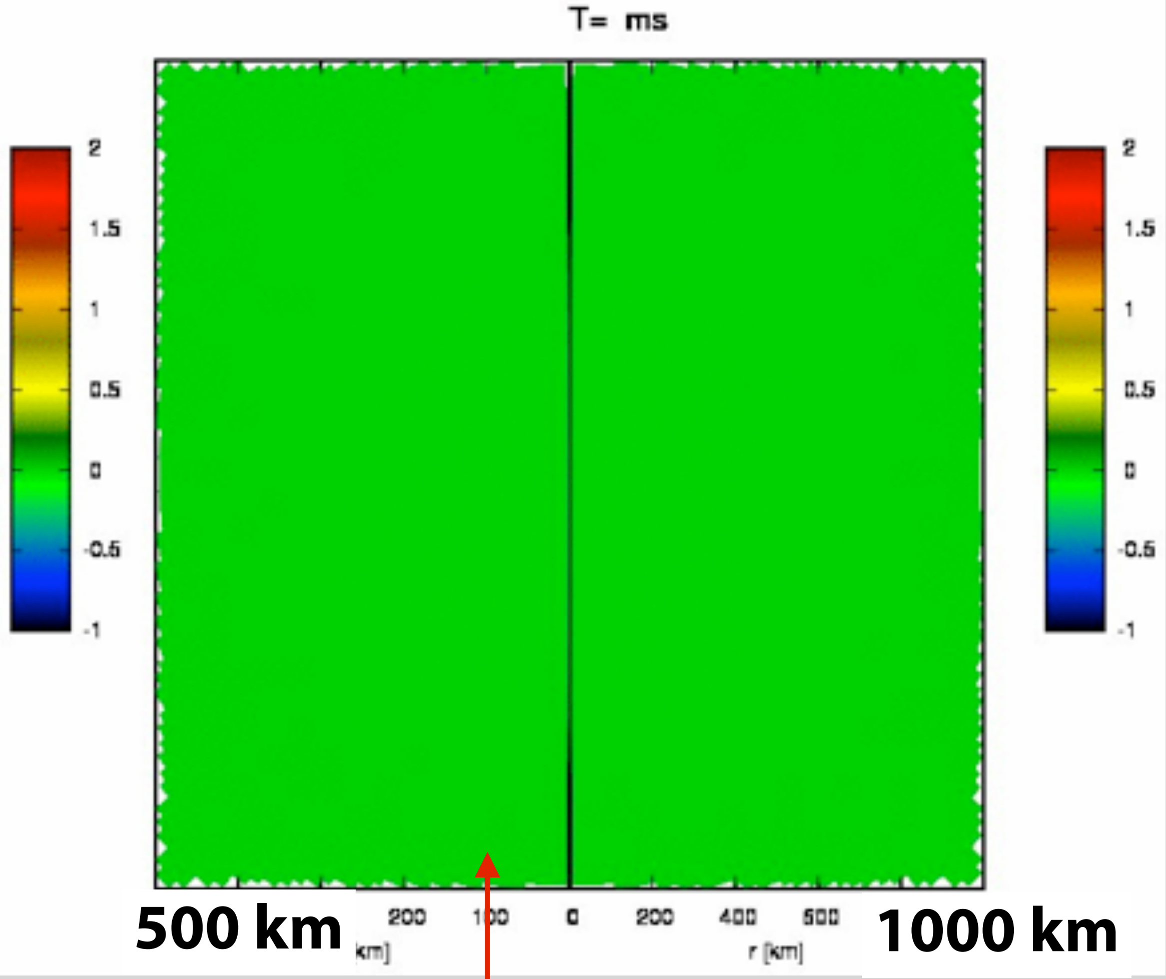
HShen EOS fails

Radius of neutron star

[Suwa, Takiwaki, Kotake, Fischer, Liebendörfer, Sato, ApJ, **764**, 99 (2013)]



Faster contraction is better for the explosion!

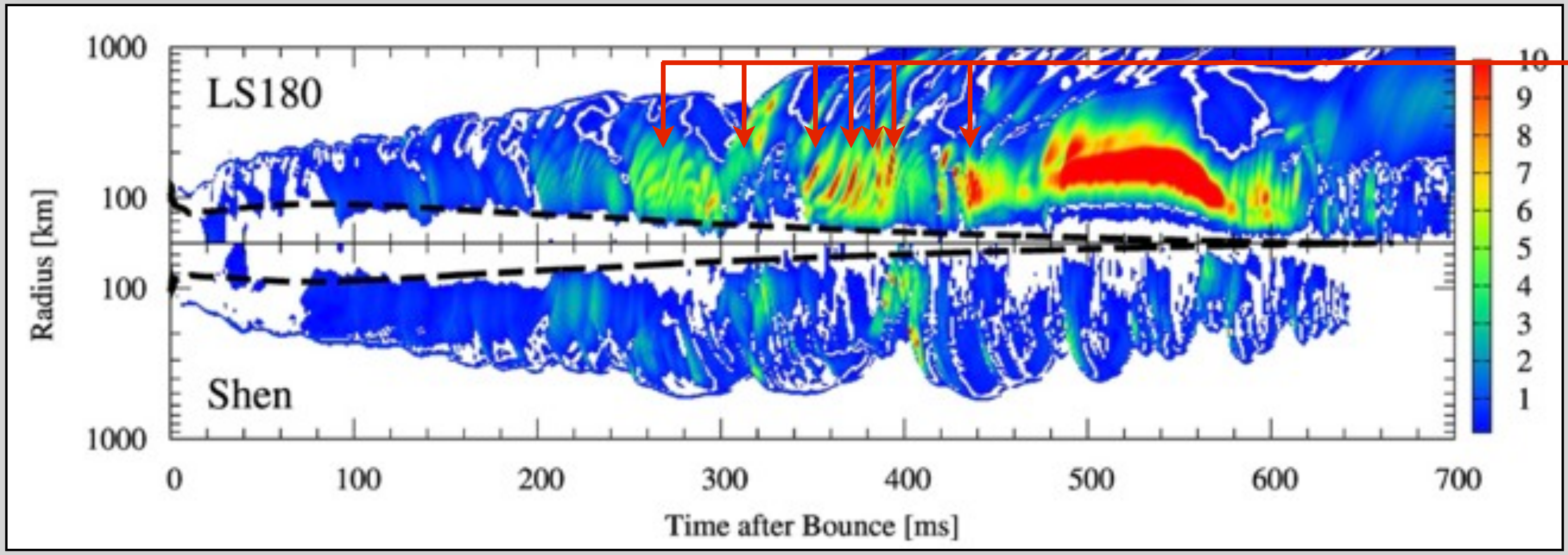


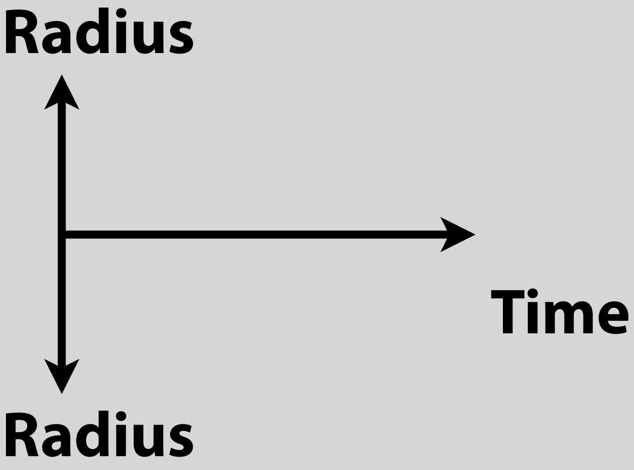
500 km

1000 km

→5000 km

Pressure perturbation





Radius

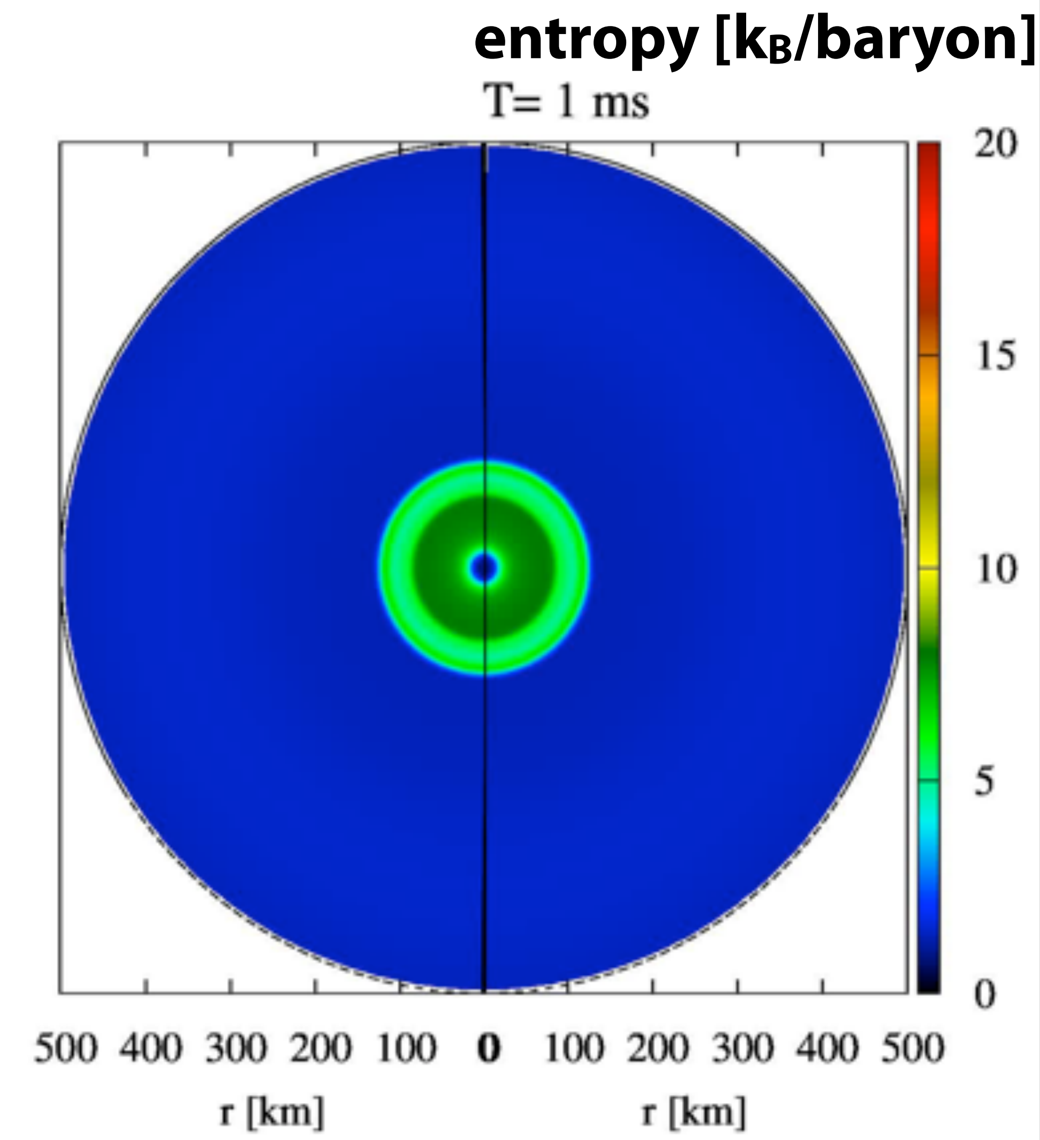
Time

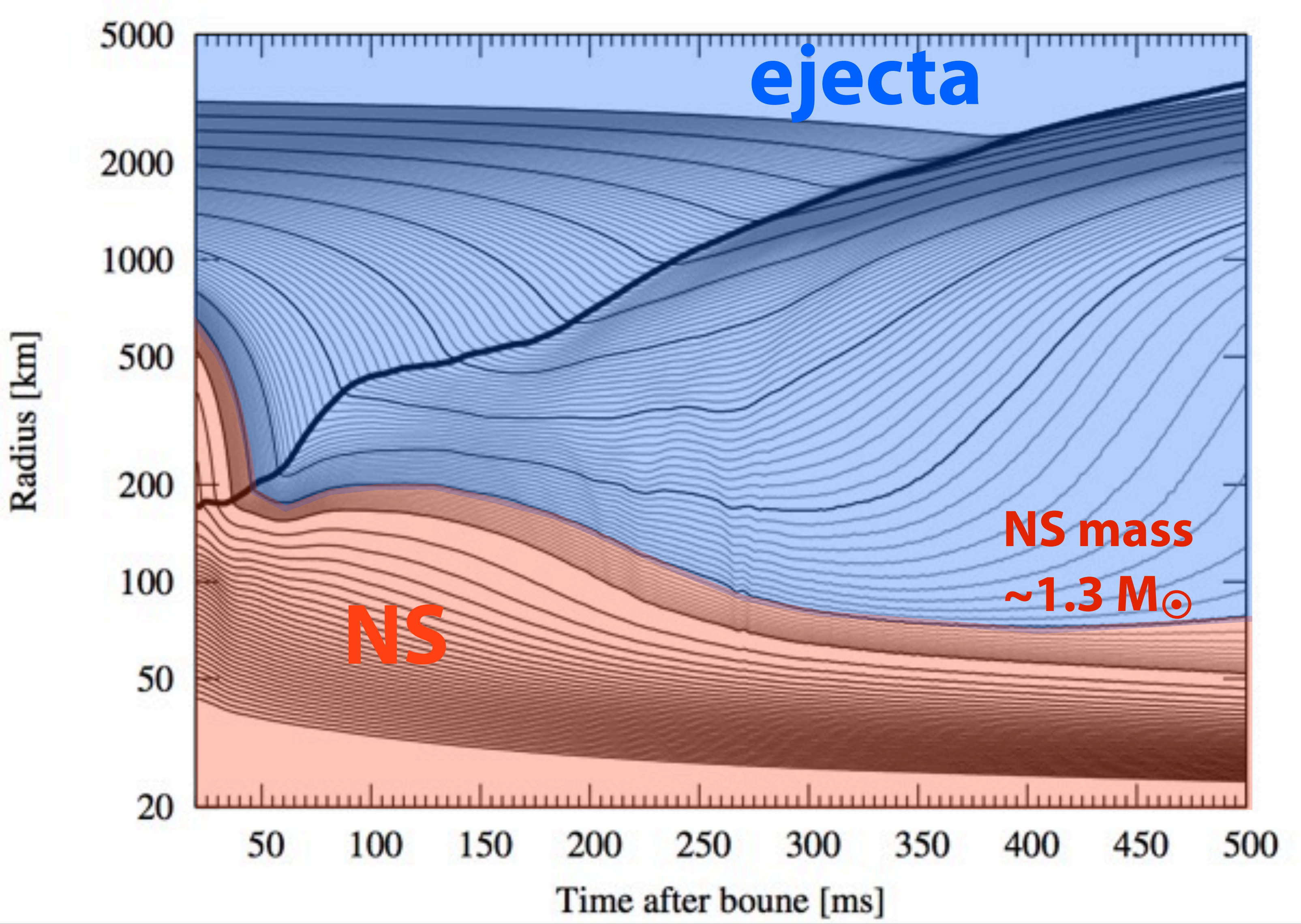
Radius

From supernovae to neutron stars

From SN to NS-1

[Suwa, Takiwaki, Kotake, Fischer, Liebendörfer, Sato, ApJ, **764**, 99 (2013); Suwa, PASJ, **66**, L1 (2014)]

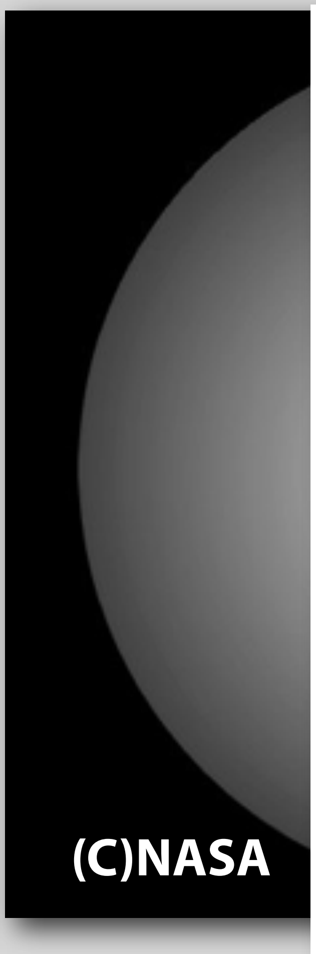


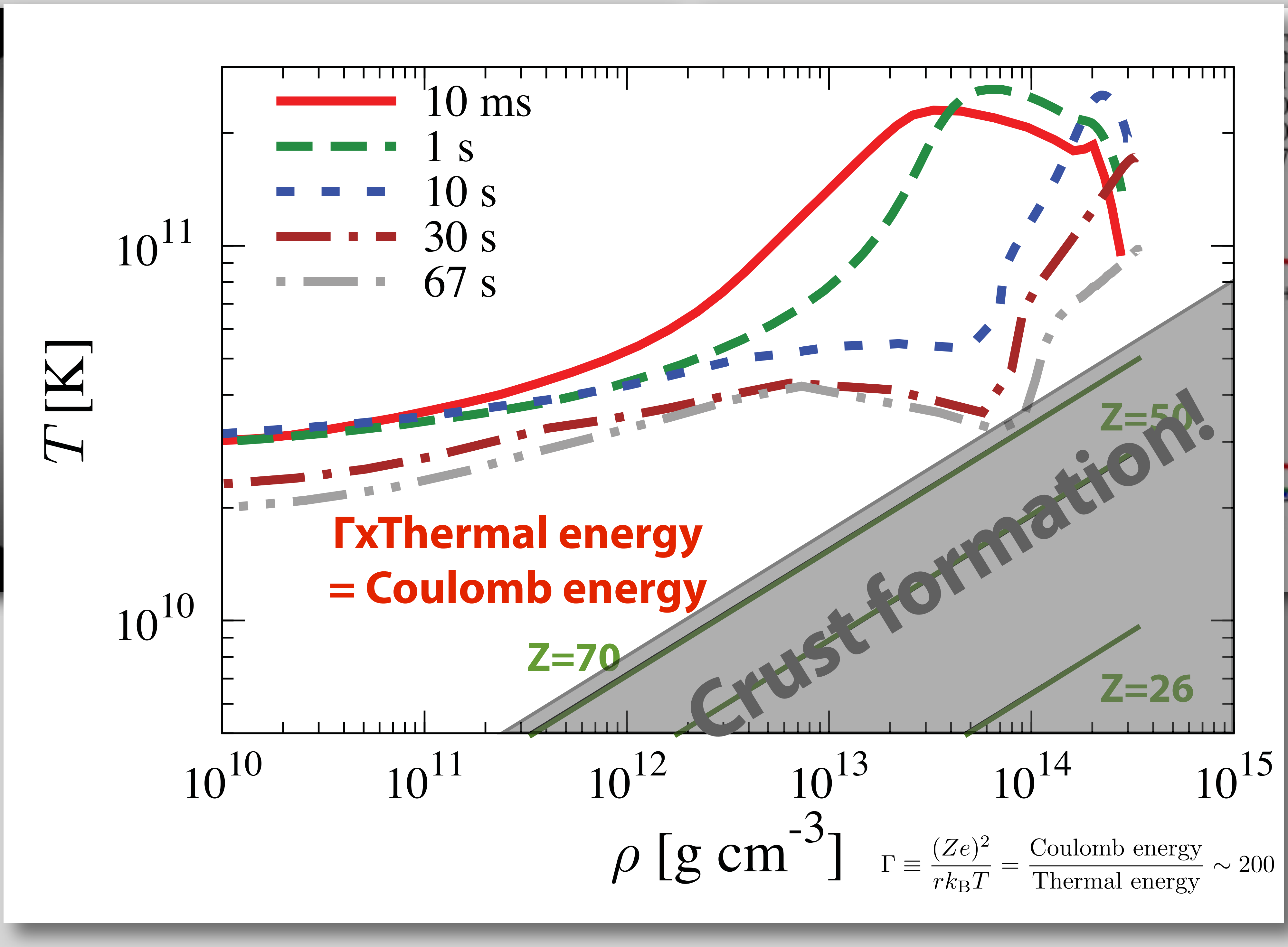


- **Progenitor:** $11.2\ M_\odot$ (Woosley+ 2002)
- **Successful explosion! (but still weak with** $E_{exp}{\sim}10^{50}$ **erg)**
- **The mass of NS is** $\sim 1.3\ M_\odot$
- **The simulation was continued in 1D to follow the PNS cooling phase up to ~70 s p.b.**

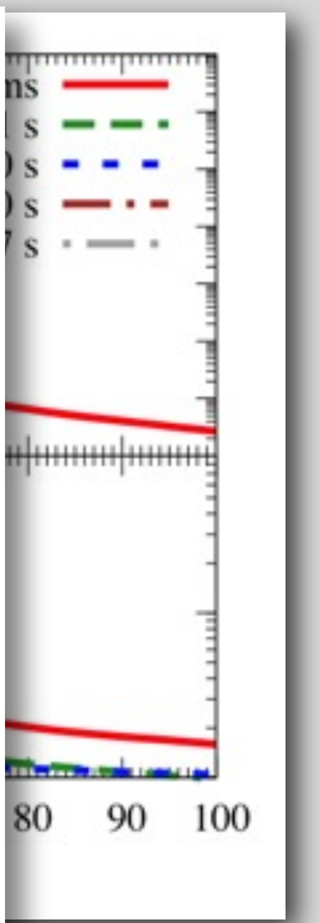
From SN to NS-2

[Suwa, PASJ, **66**, L1 (2014)]





$$\Gamma \equiv \frac{(Ze)^2}{r k_B T} = \frac{\text{Coulomb energy}}{\text{Thermal energy}} \sim 200$$



Implications

- **Crust formation time should depend on EOS** (especially symmetry energy?)
- **We may observe crust formation via neutrino luminosity evolution**
  - Cross section of neutrino scattering by heavier nuclei or pasta is much larger than that of neutrons and protons
  - Neutrino luminosity may suddenly drop when we have heavier nuclei!
- **Magnetar (large B-field NS) formation**
  - competitive process between crust formation and magnetic field escape from NS

Summary

- **Supernova explosions by neutrino-heating mechanism have become possible**
- **Consistent modeling from iron cores to (cold) neutron stars (i.e. until NS crust formation) is doable now**
  - related to neutrino observations, magnetar formation, NS pasta, nuclear EOS...

Announcement

- **A long-term workshop at Yukawa Institute for Theoretical Physics in Kyoto University**

- **"Nuclear Physics, Compact Stars, and Compact-star Mergers" (NPCSM2016)**
- **Oct. 17 (Mon.) -- Nov. 18 (Fri.), 2016**

- **Please join us!**