From supernovae through protoneutron stars to neutron stars

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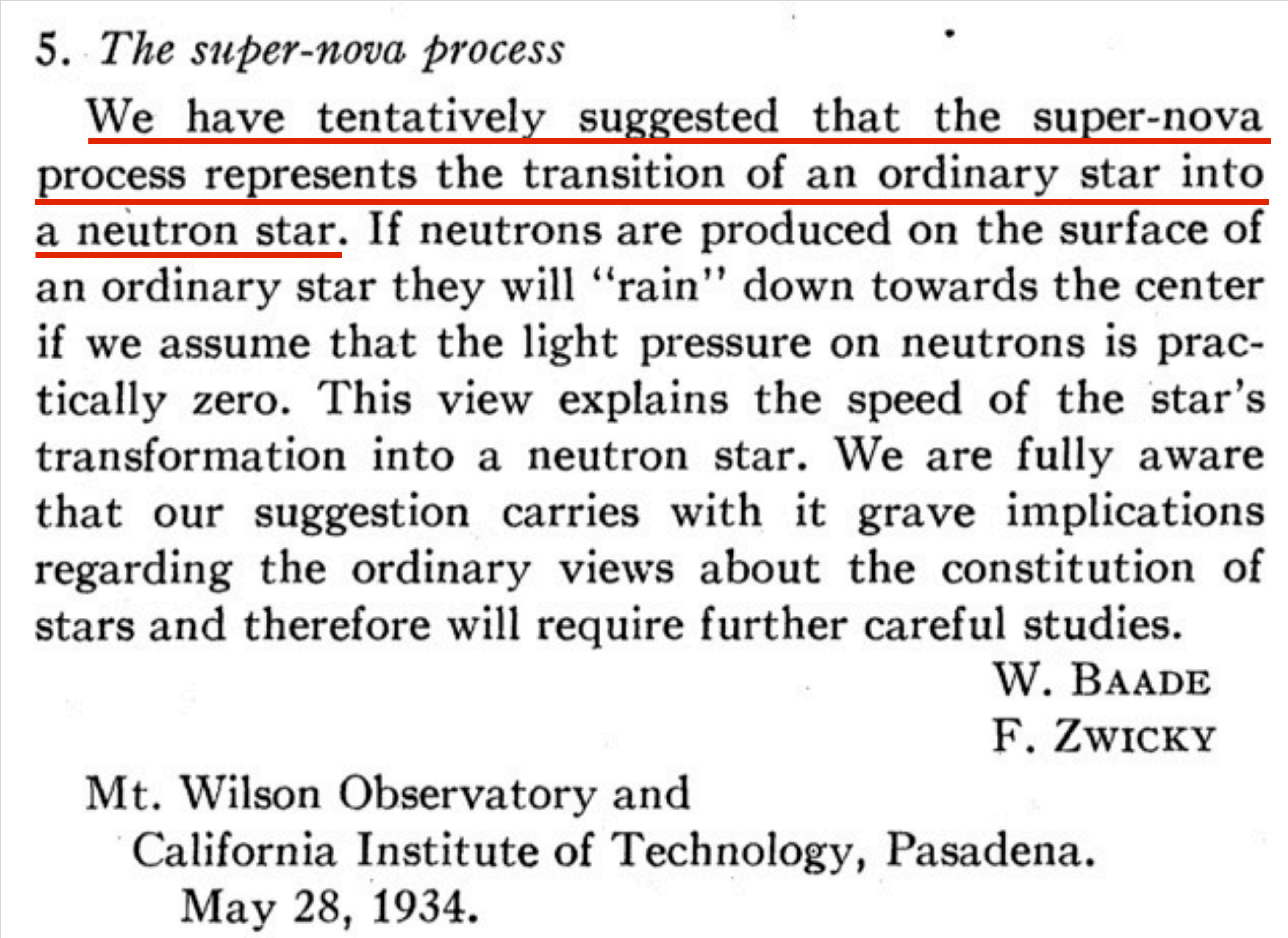
Supernovae make neutron stars



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
- Ejecta mass: $\sim M_\odot$
- Ni mass: $\sim 0.1 M_\odot$

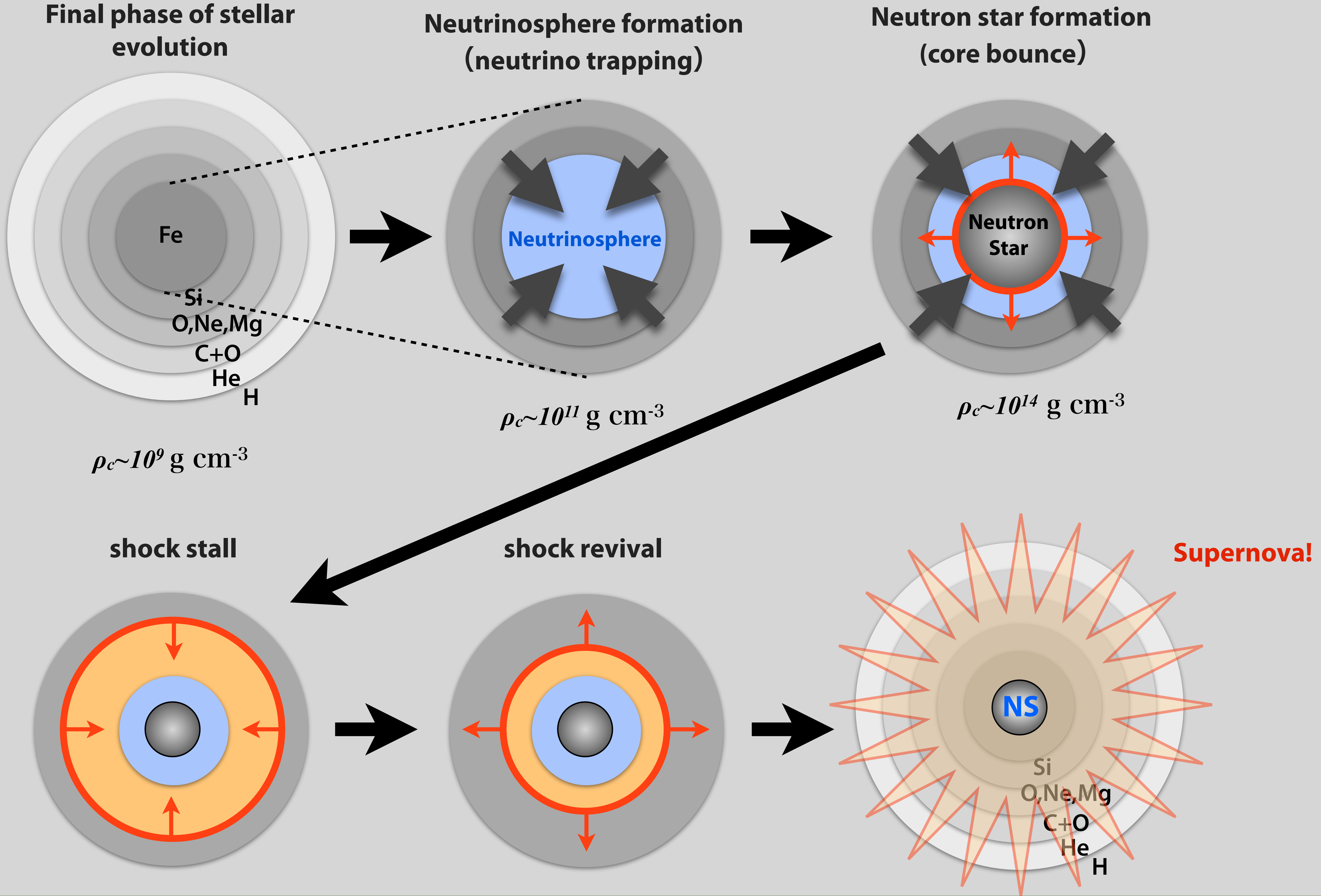
measured by fitting SN light curves

- 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}

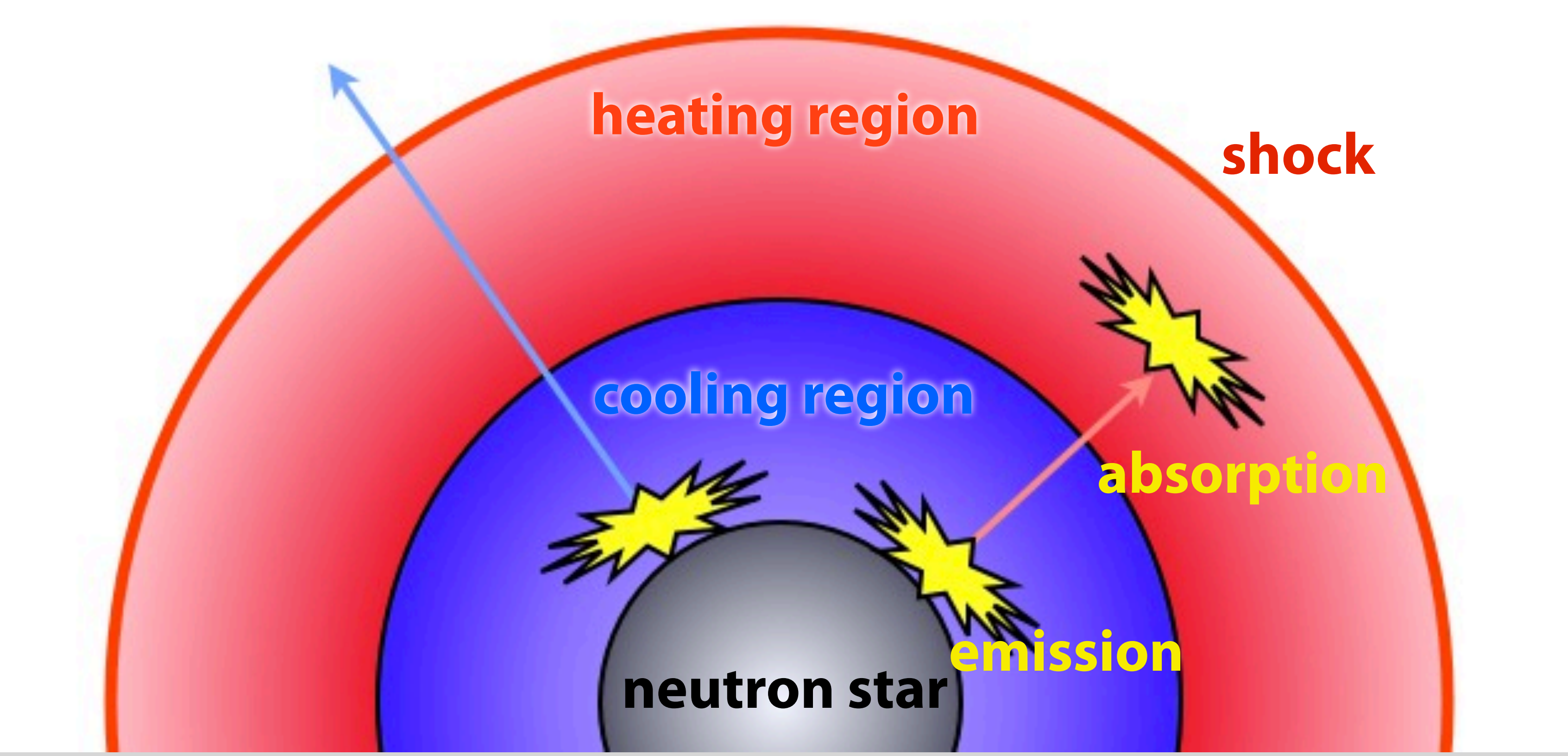
$\rho_c \sim 10^{14}$ g cm^{-3}

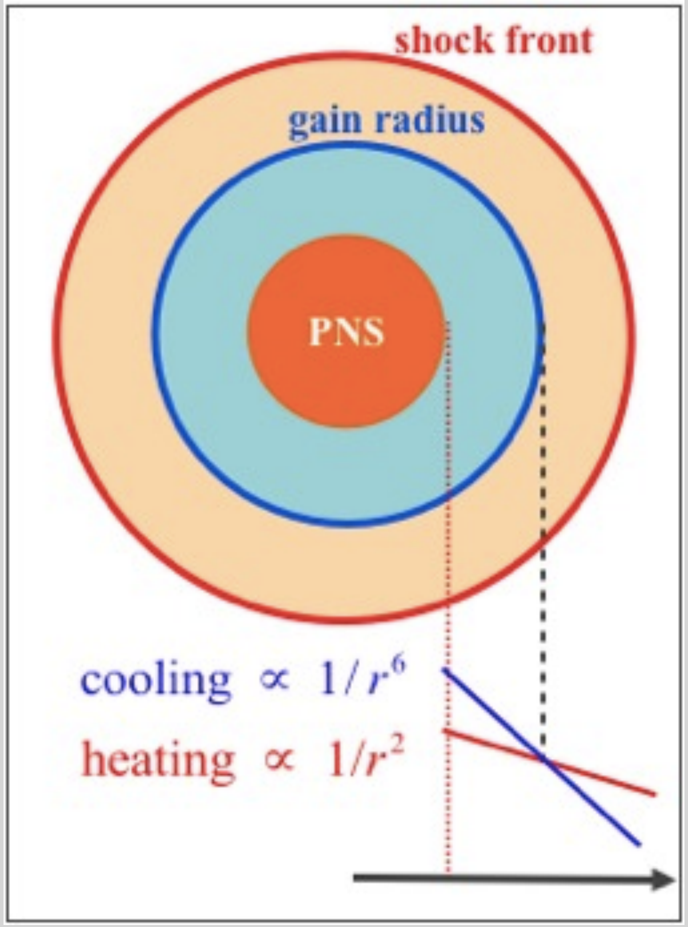
shock stall

shock revival

Supernova!

Current paradigm: neutrino-heating mechanism

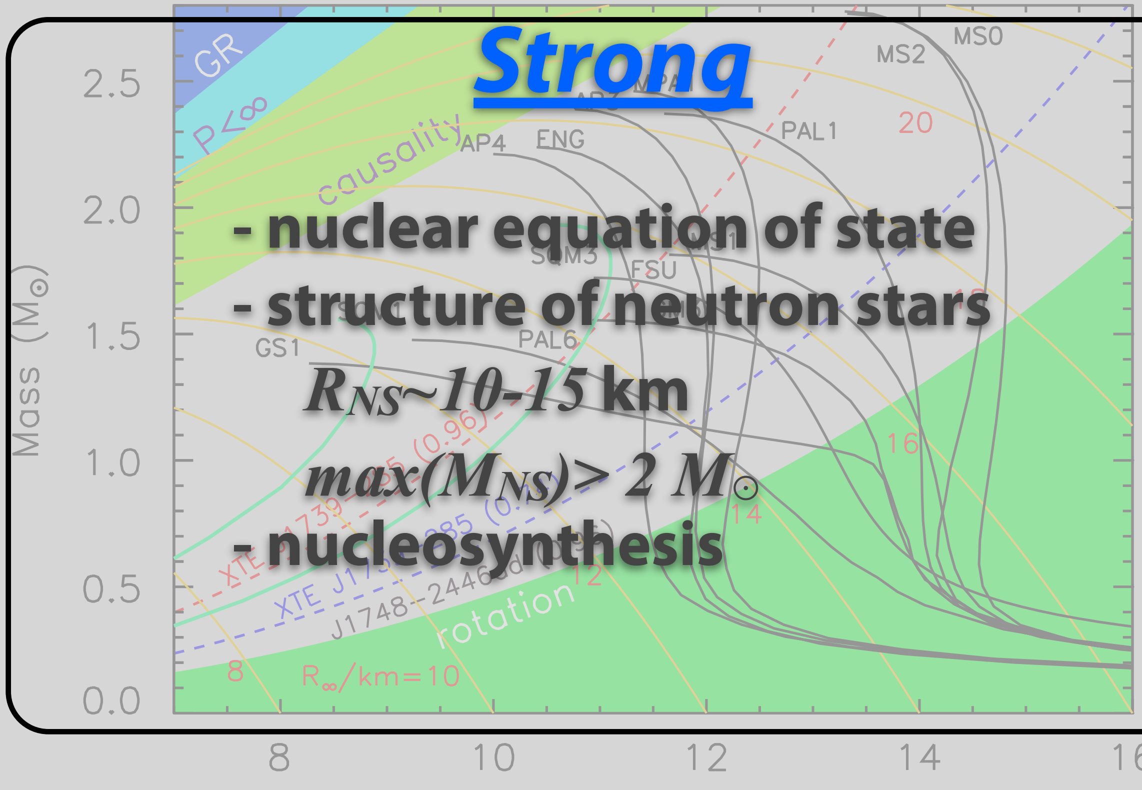




- Energy is transferred by neutrinos
- Most of them are just escaping from the system, but are partially absorbed
- In gain region, neutrino heating overwhelms neutrino cooling

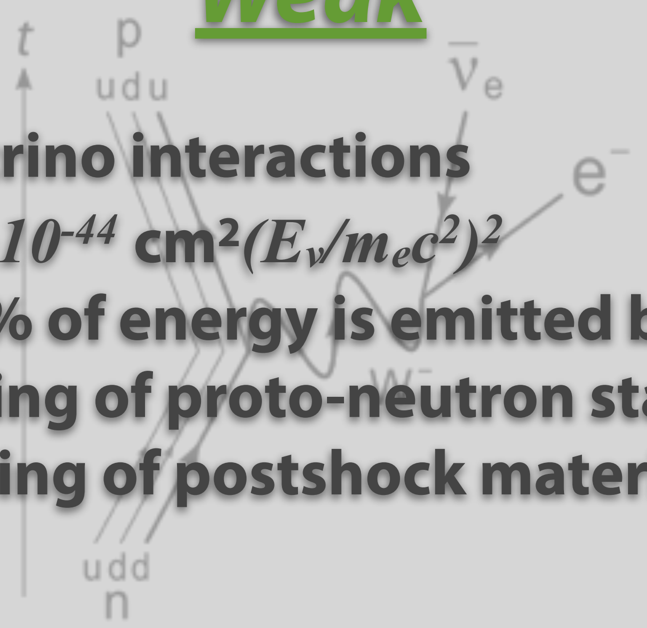
Physical ingredients

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



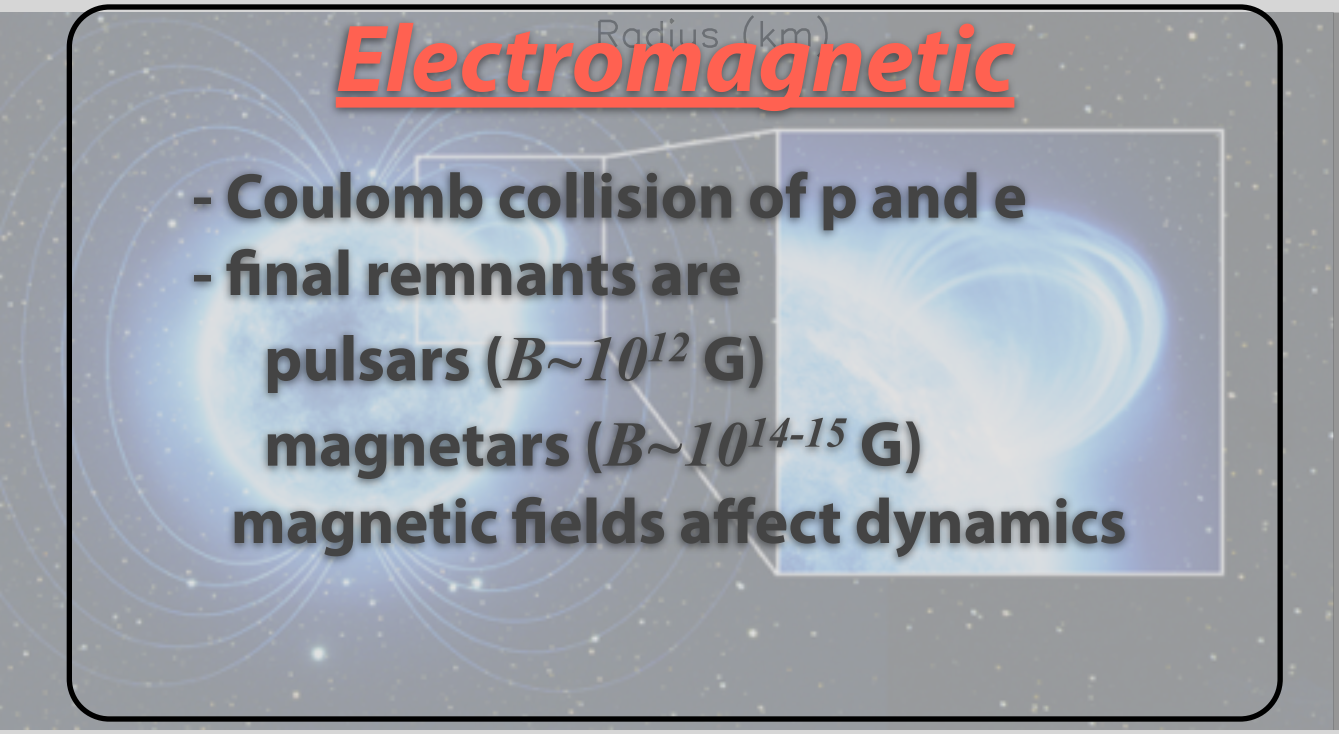
Strong

- nuclear equation of state
- structure of neutron stars
  $R_{NS}\sim10\text{-}15$ km
  $max(M_{NS})> 2\ M_\odot$
- nucleosynthesis



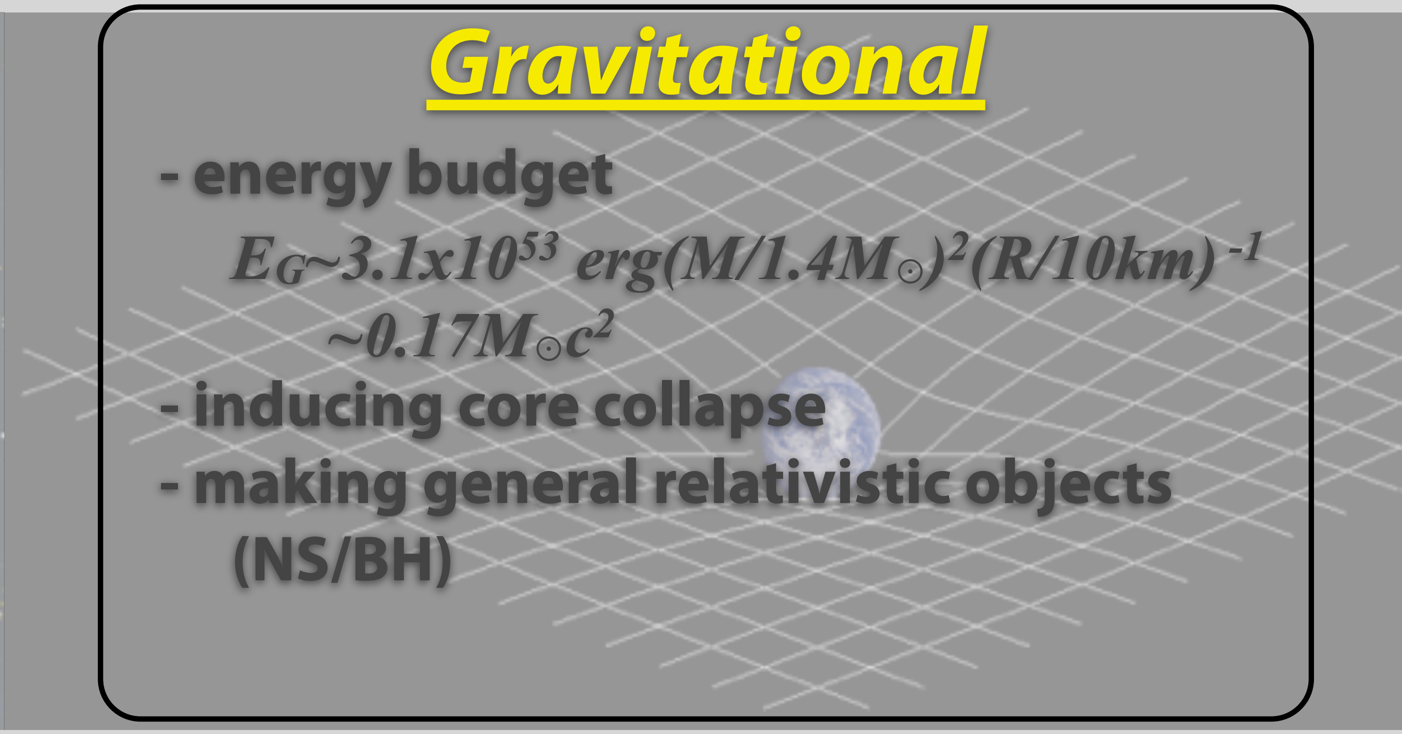
Weak

- neutrino interactions
  $\sigma_\nu\sim10^{-44}$ cm$^2(E_\nu/m_ec^2)^2$
- ~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 ($B\sim10^{12}$ G)
  magnetars ($B\sim10^{14\text{-}15}$ G)
  magnetic fields affect dynamics



Gravitational

- energy budget
  $E_G\sim3.1\times10^{53}$ erg$(M/1.4M_\odot)^2(R/10\text{km})^{-1}$
  $\sim0.17M_\odot c^2$
- 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

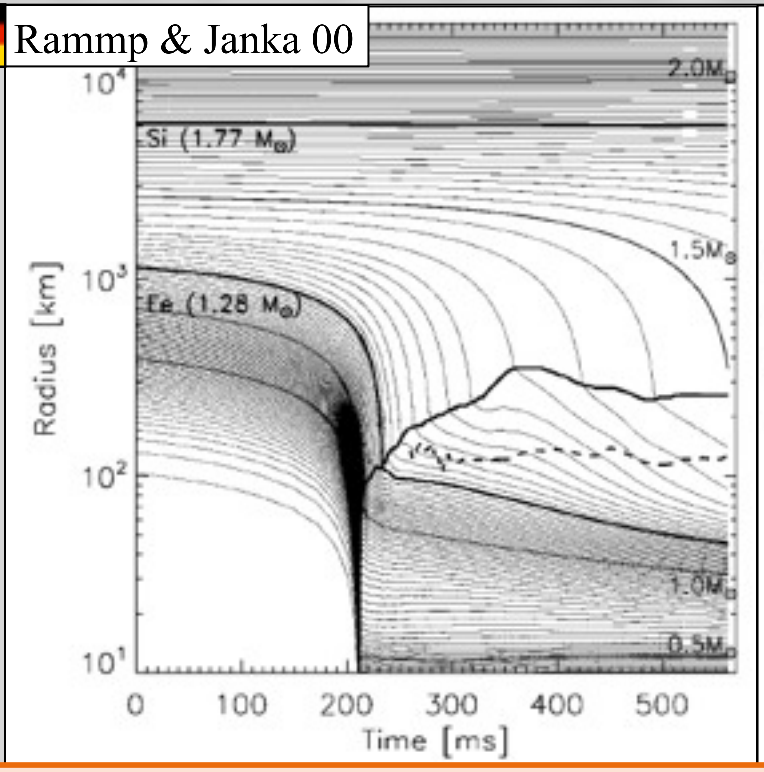
$$\frac{df}{cdt} + \mu\frac{\partial f}{\partial r} + \left[\mu\left(\frac{d\ln\rho}{cdt} + \frac{3v}{cr}\right) + \frac{1}{r}\right]\left(1-\mu^2\right)\frac{\partial f}{\partial\mu}$$
$$+ \left[\mu^2\left(\frac{d\ln\rho}{cdt} + \frac{3v}{cr}\right) - \frac{v}{cr}\right]E\frac{\partial f}{\partial E}$$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

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

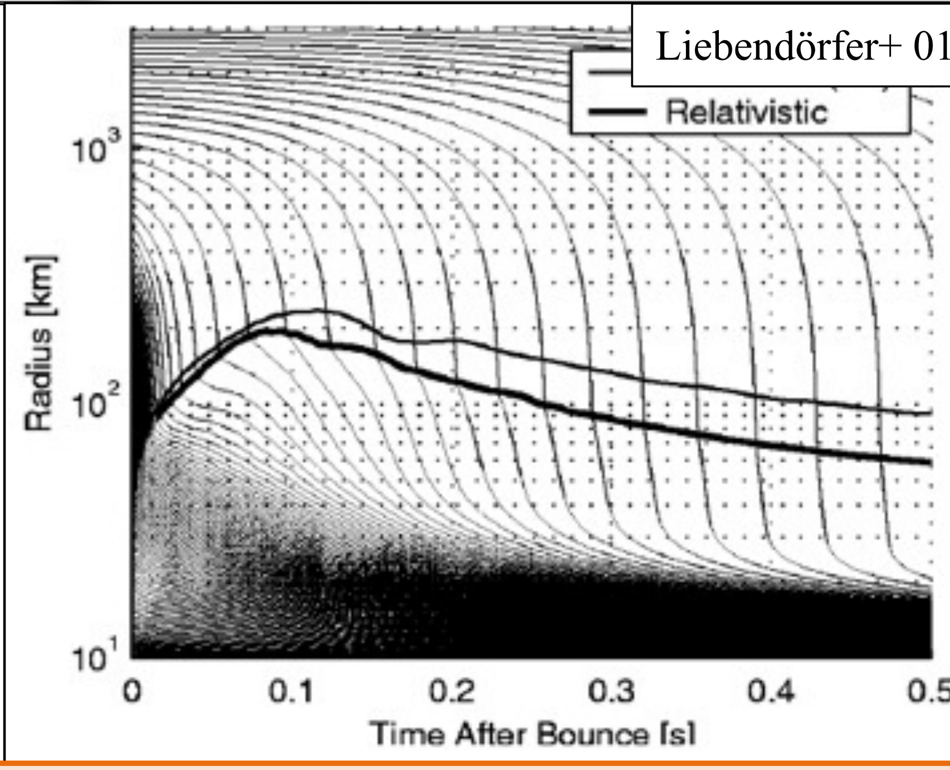
f: neut. dist. func, μ: $\cos\theta$, E: neut. energy, j: emissivity, χ: absorptivity, R: scatt. kernel

1D simulations fail to explode

Rammp & Janka 00



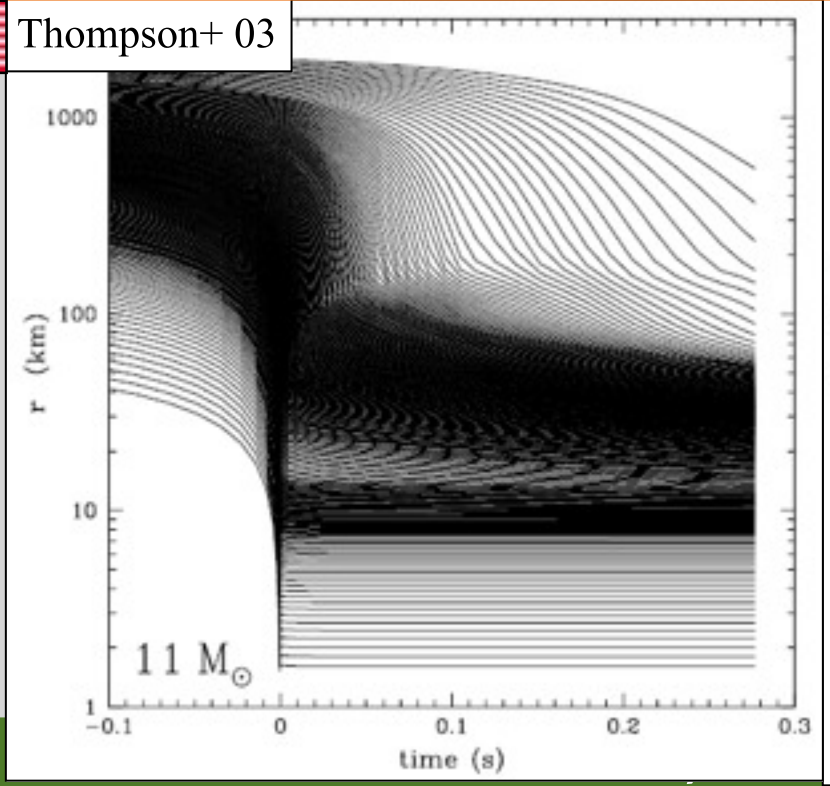
Liebendörfer+ 01



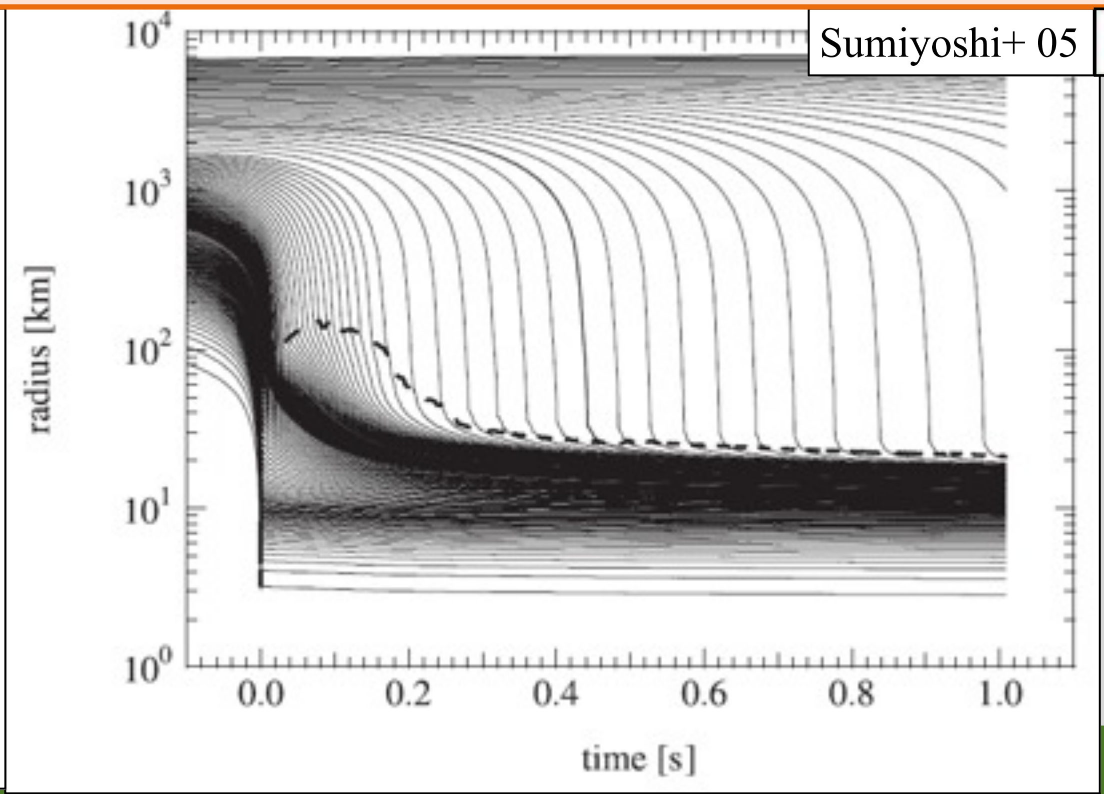
By including all available physics to simulations, we concluded that the explosion cannot be obtained in 1D!

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

Thompson+ 03



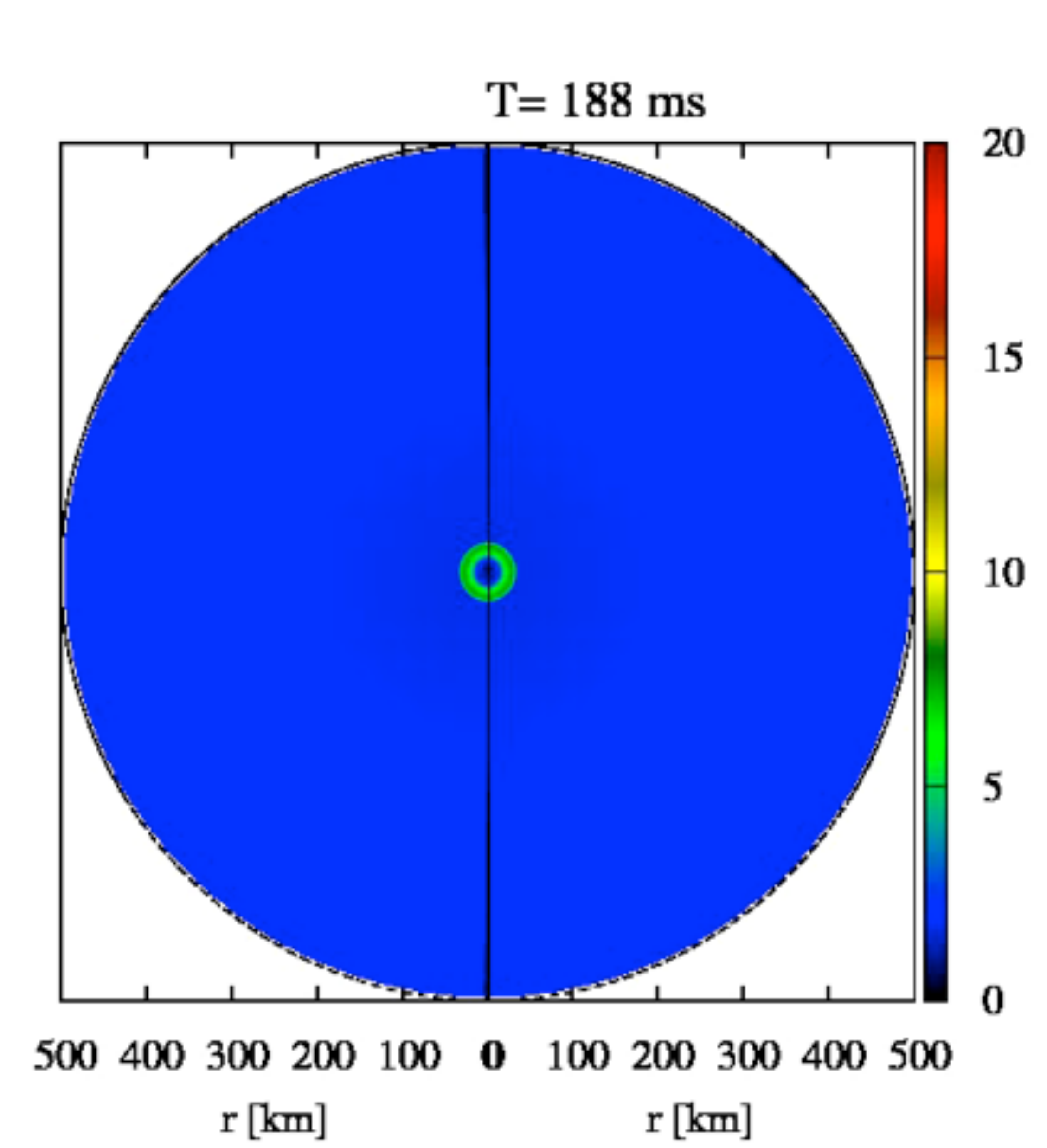
Sumiyoshi+ 05



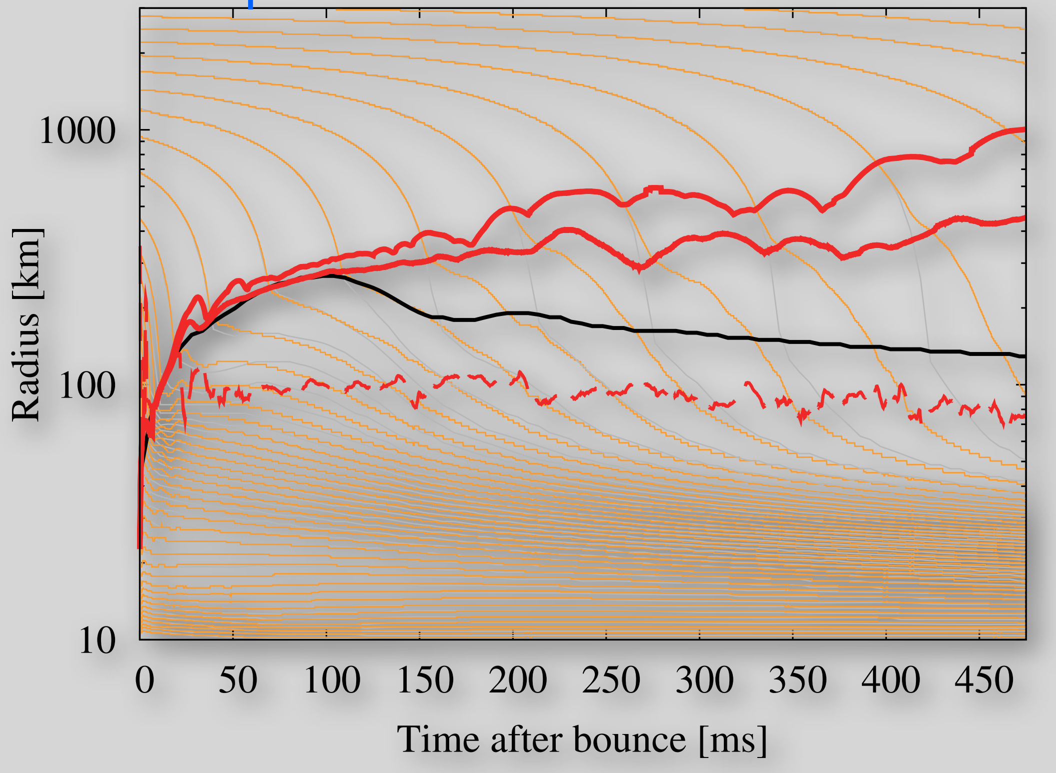
Neutrino-driven explosion in multi-D simulation

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

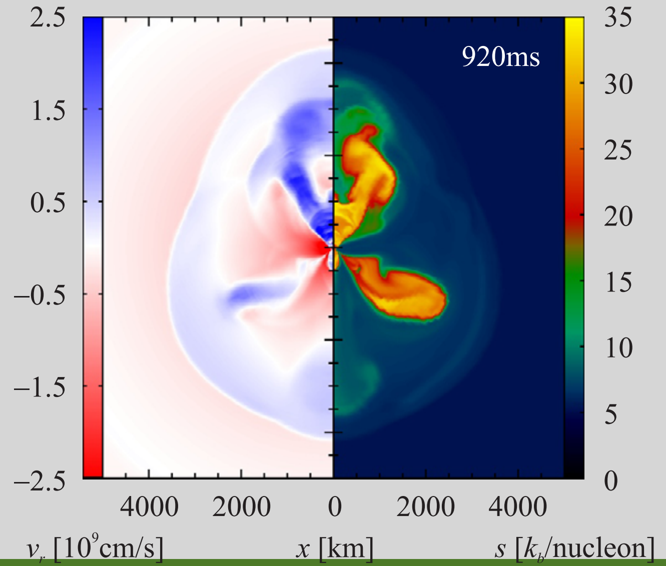
[Suwa+ PASJ, **62**, L49 (2010); ApJ, **738**, 165 (2011); ApJ **764**, 99 (2013); PASJ, **66**, L1 (2014); arXiv:1406.6414]



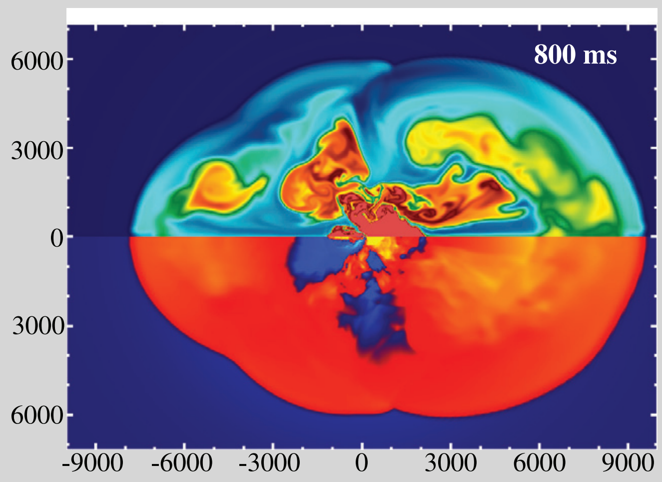
comparison between 1D and 2D



Müller, Janka, Marek (2012)



Brruenn et al. (2013)



Dimensionality and numerical simulations

※grid-based codes only, not completed

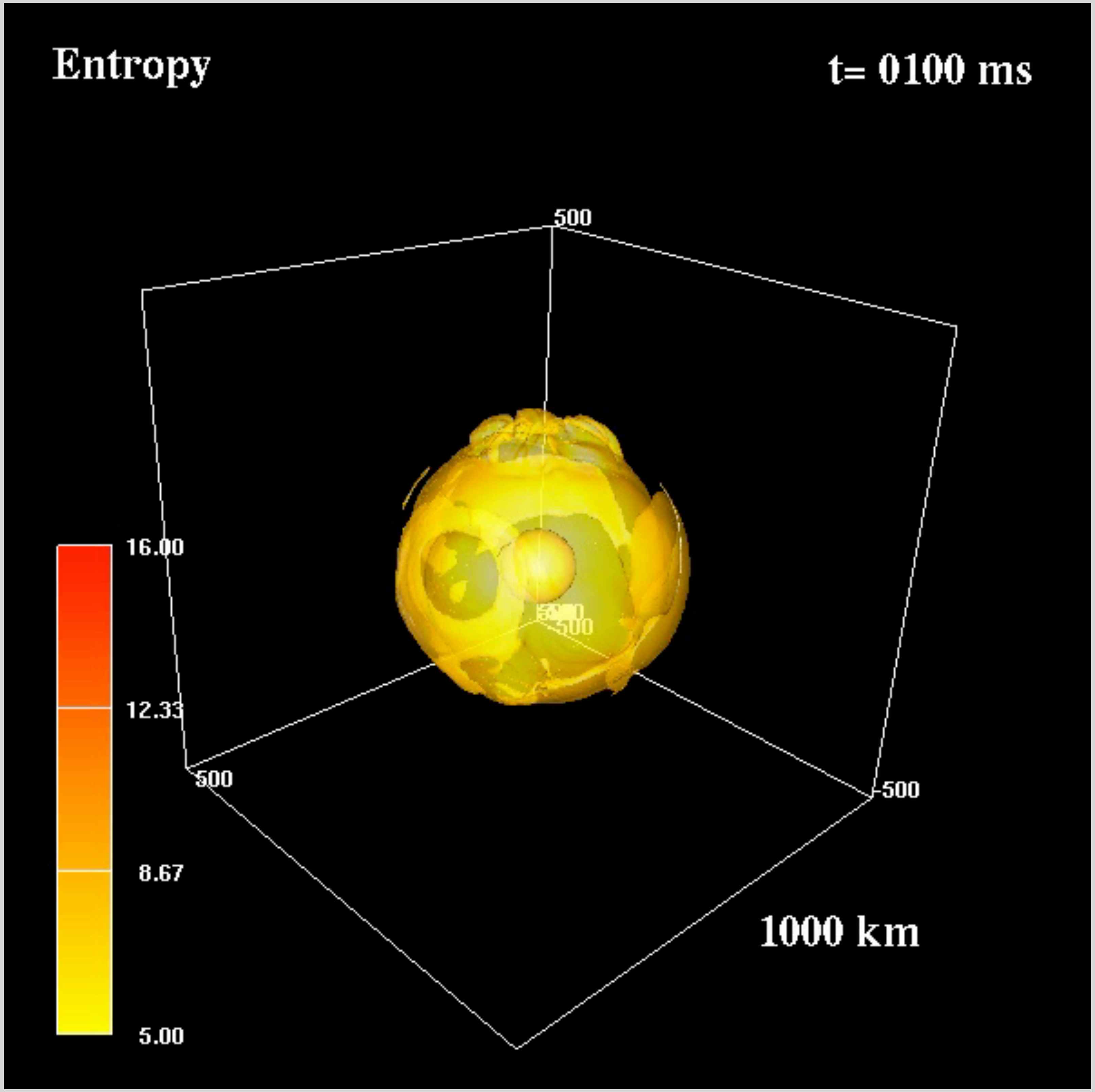
Only the simulations in this region can judge the neutrino-driven explosion

Dimension \ Neutrino Treatment	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

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$_\nu$)

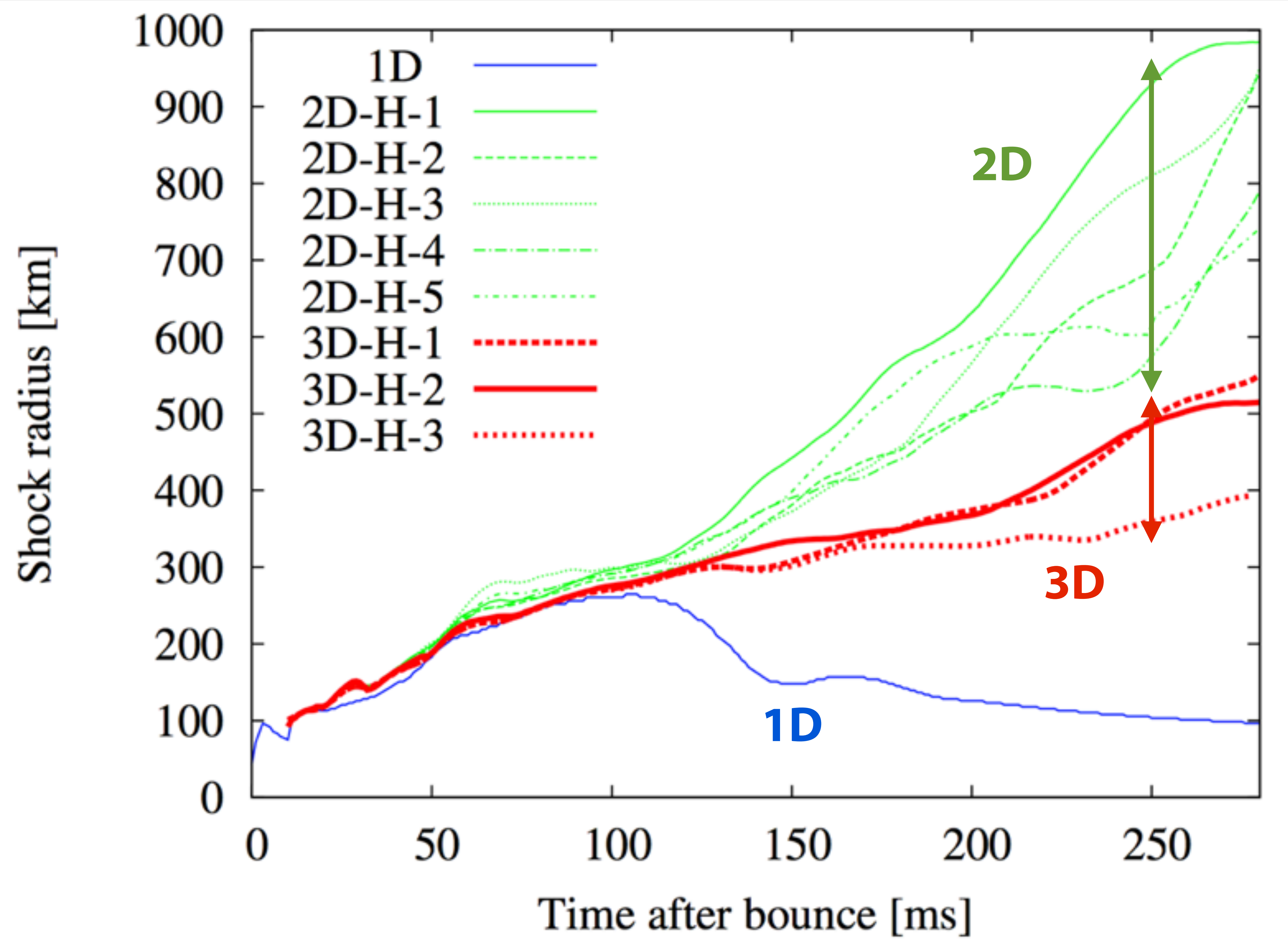
XT4

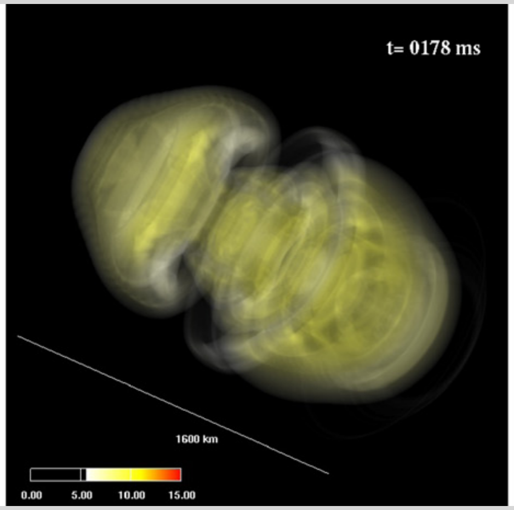
T2K-Tsukuba

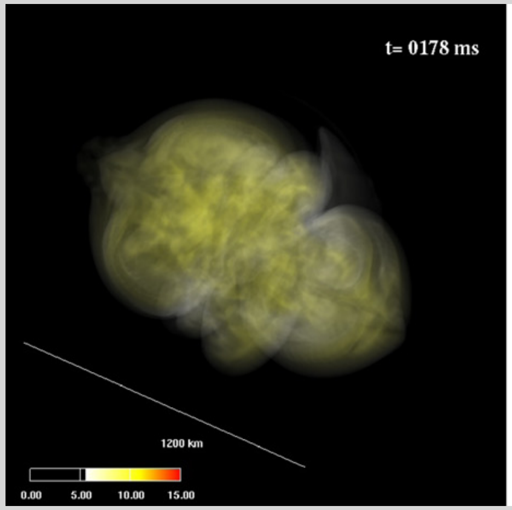
K computer

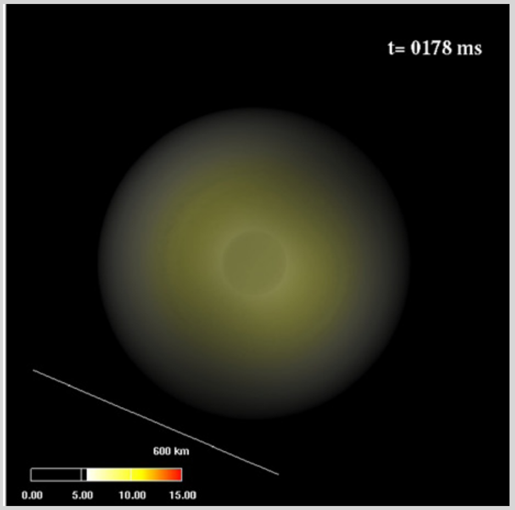
Dimensionality and initial perturbation

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









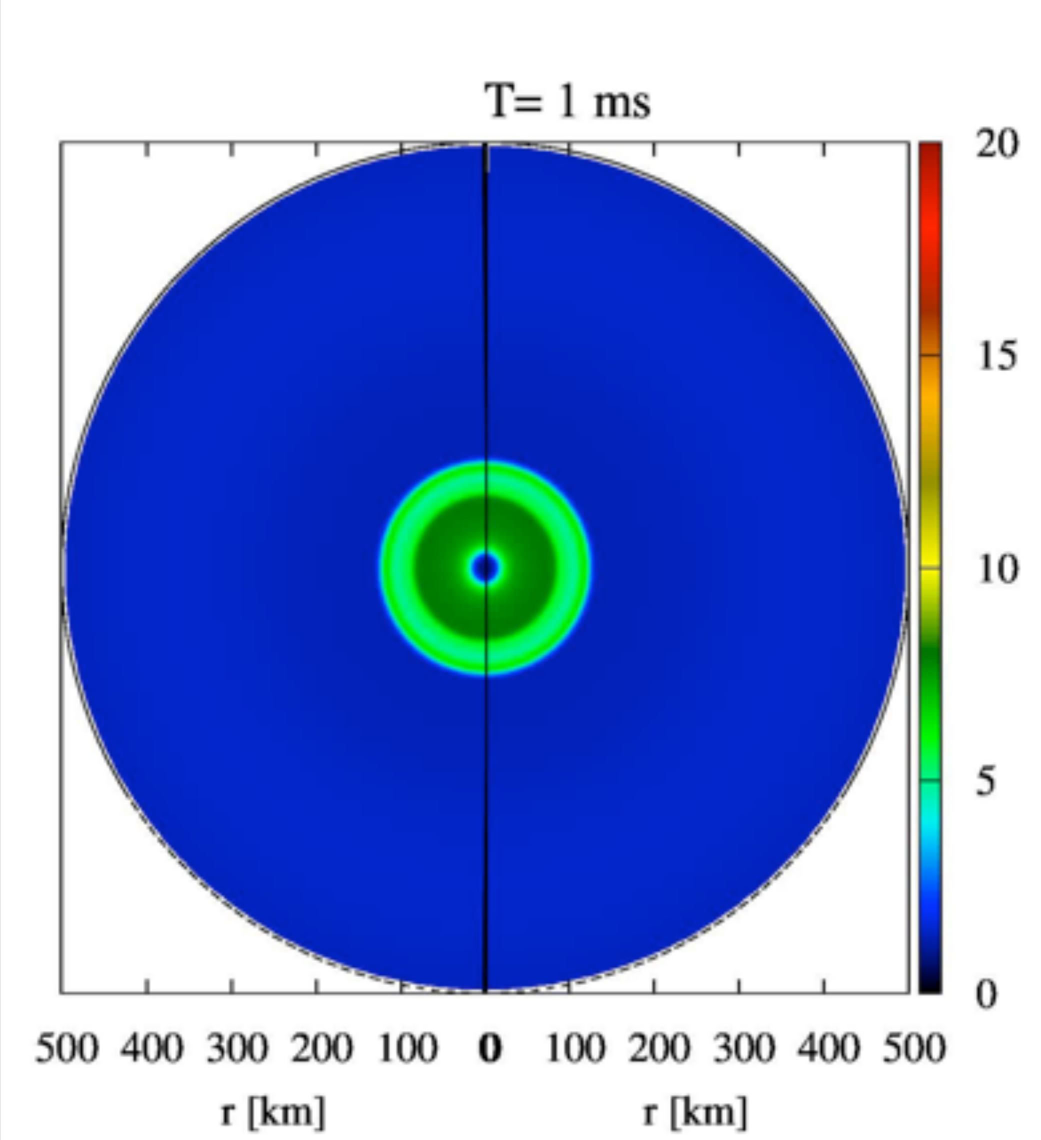
Note: there are problems

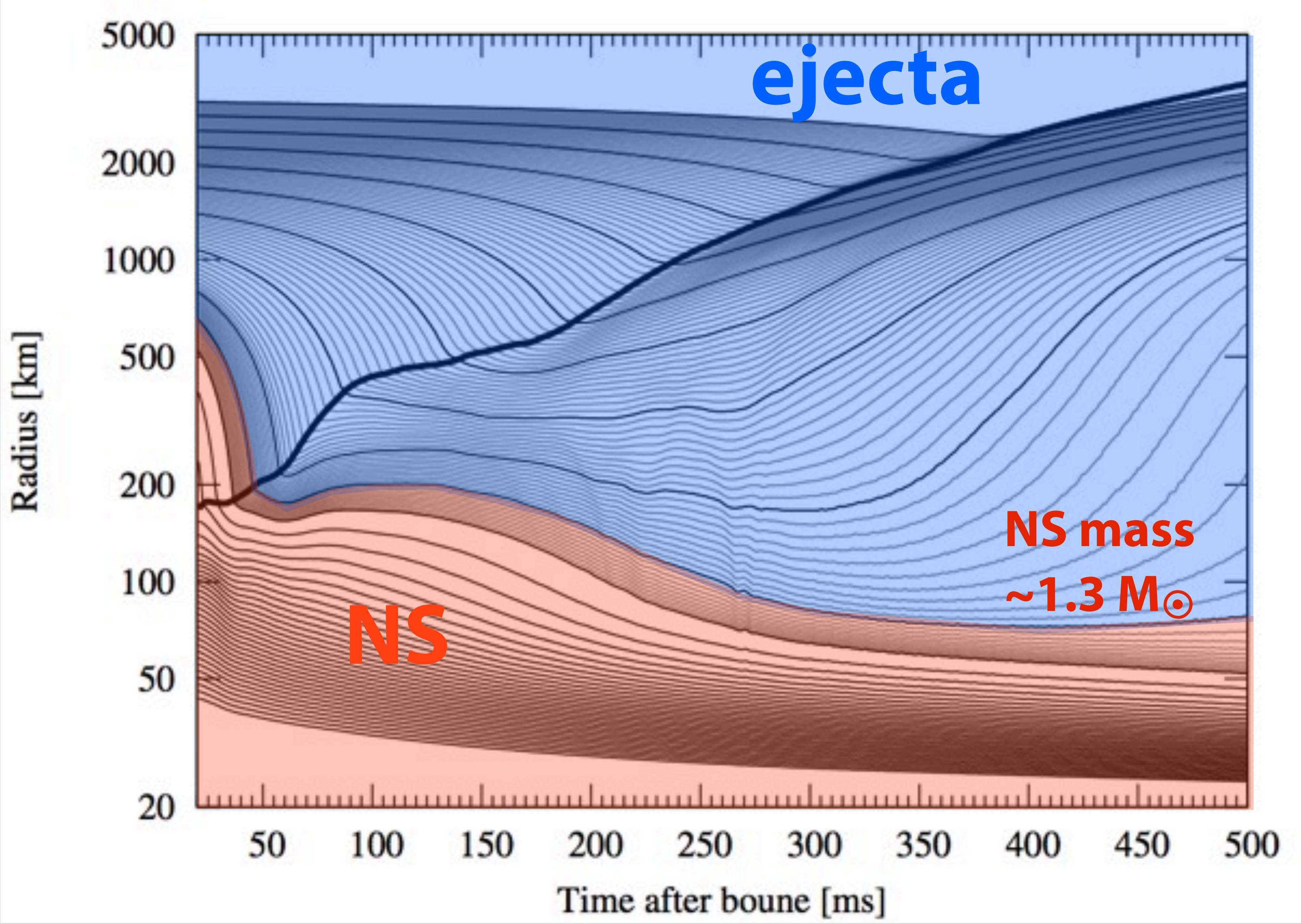
- **Explosion energy of simulations ($O(10^{49\text{-}50})$ erg) are much smaller than observational values ($O(10^{51})$ erg)**
- **Results from different groups are incompatible**
- We need more effort to understand supernova mechanism

- In the following, I focus on neutron star (NS) formation with supernova (SN) simulations

From SN to NS-1

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

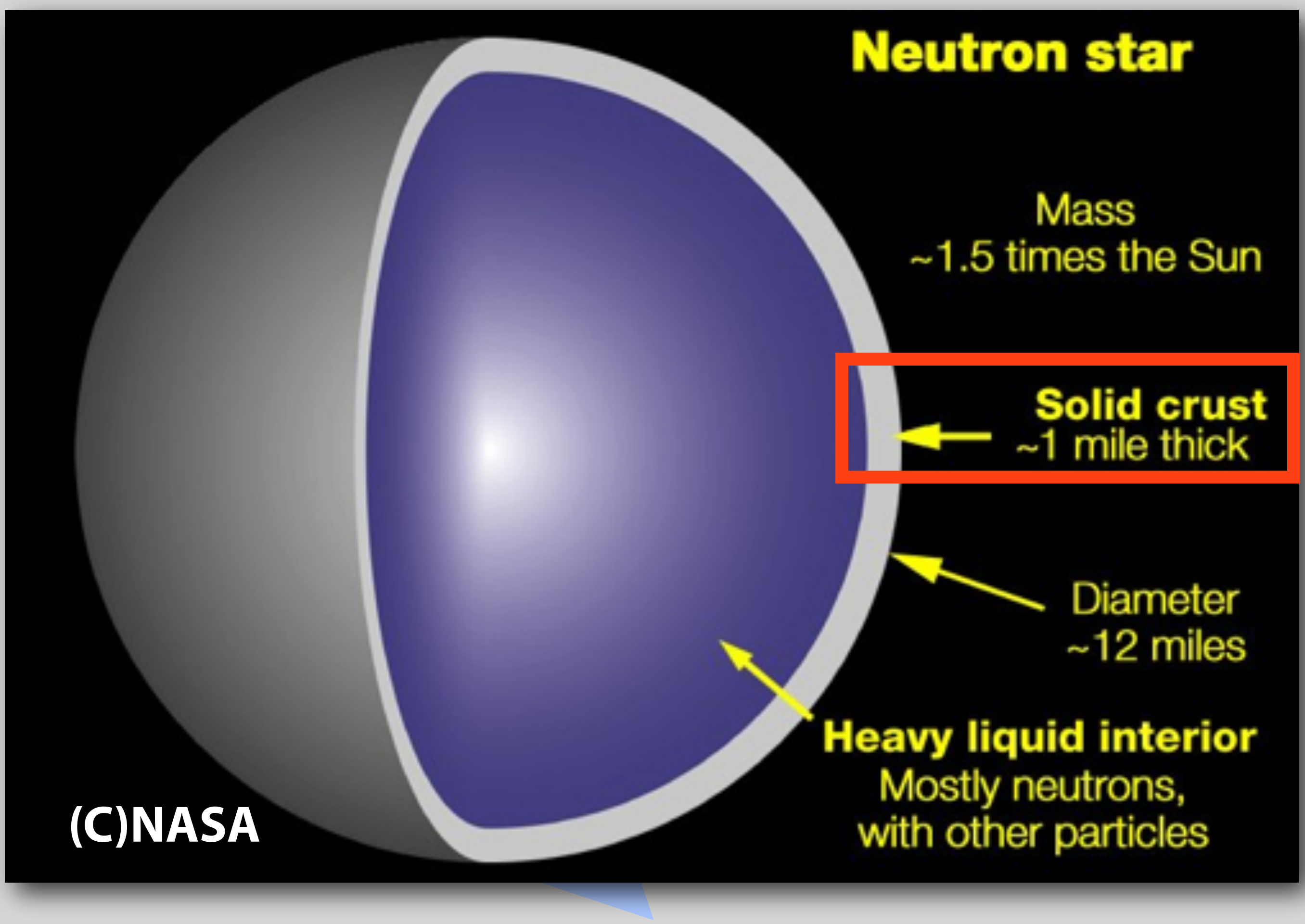


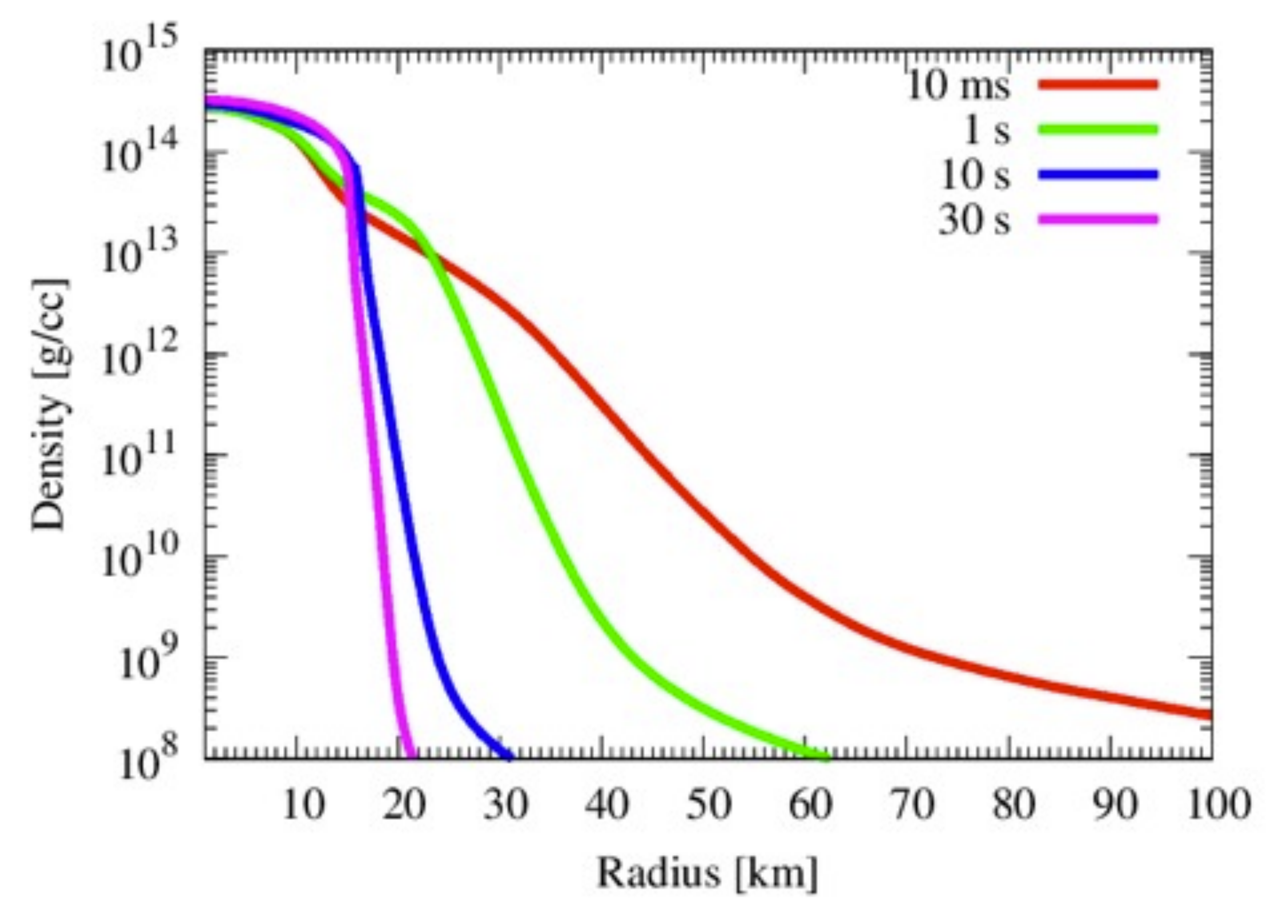


- **Progenitor:** $11.2\ M_\odot$ (Woosley+ 2002)
- **Successful explosion! (but still weak with E_{exp}~10^{50} erg)**
- **The mass of NS is $\sim 1.3\ M_\odot$**
- **The simulation was continued in 1D to follow the PNS cooling phase up to ~70 s p.b.**

From SN to NS-2

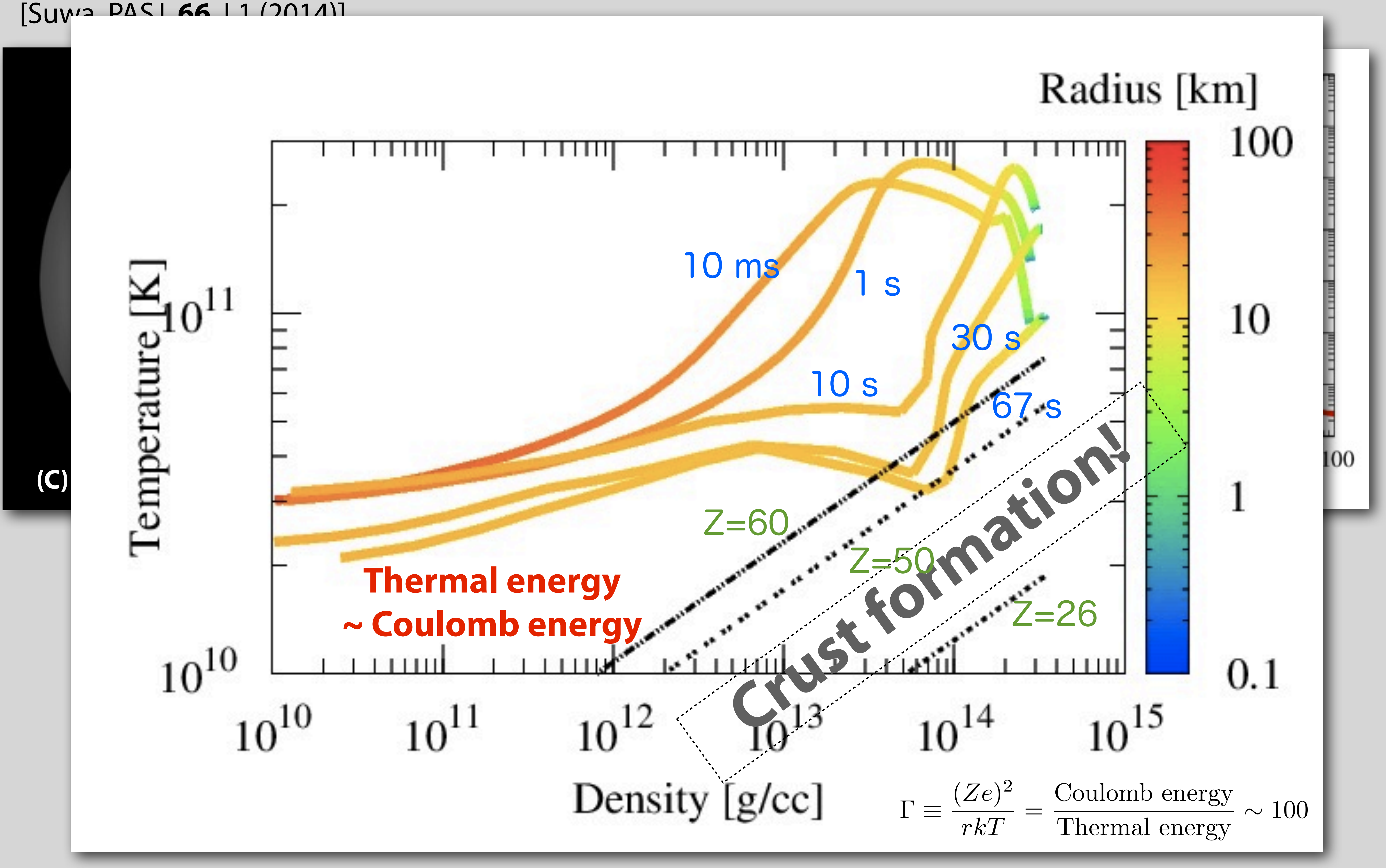
[Suwa, PASJ, **66**, L1 (2014)]





From SN to NS-2

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

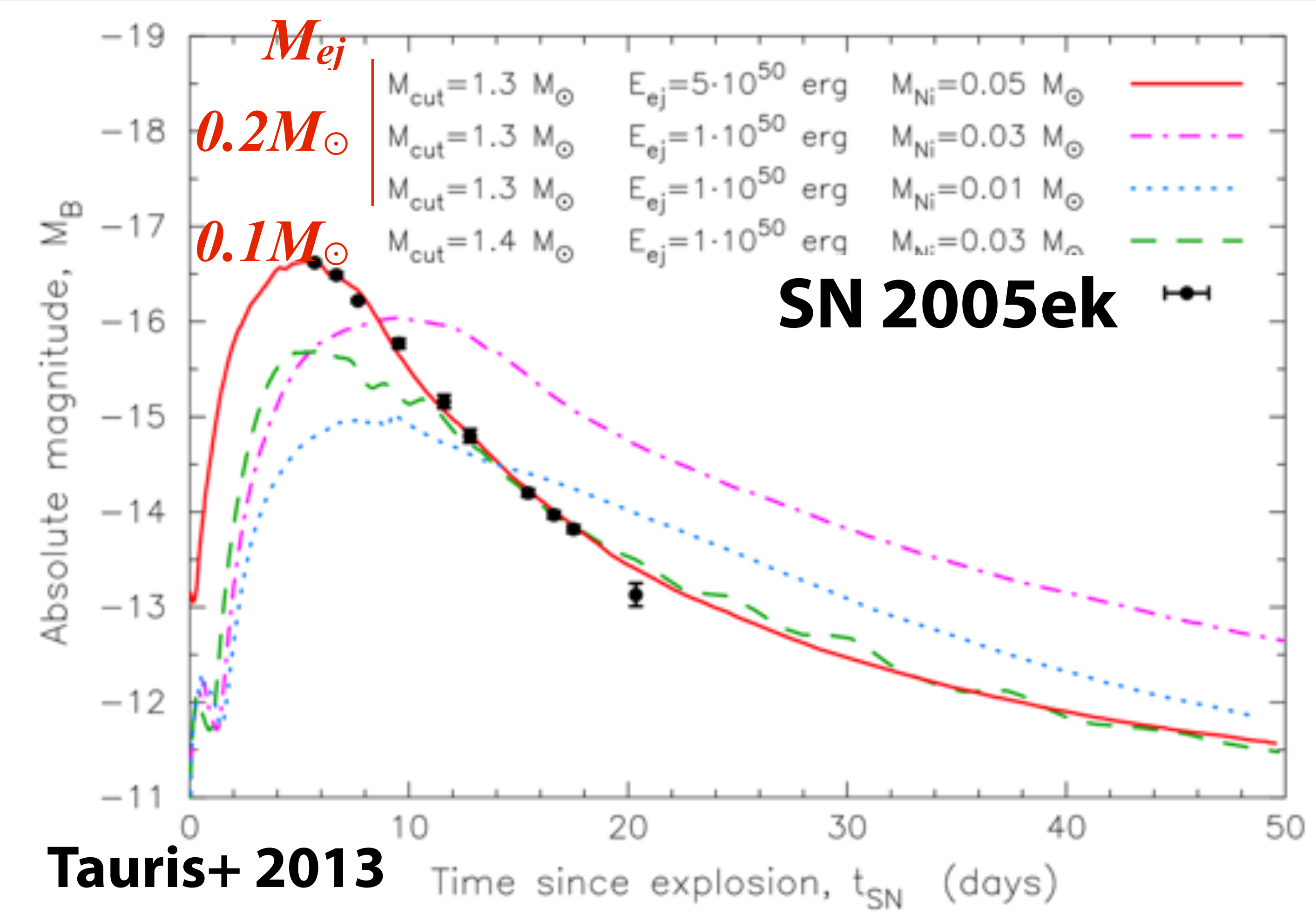


Thermal energy
~ Coulomb energy

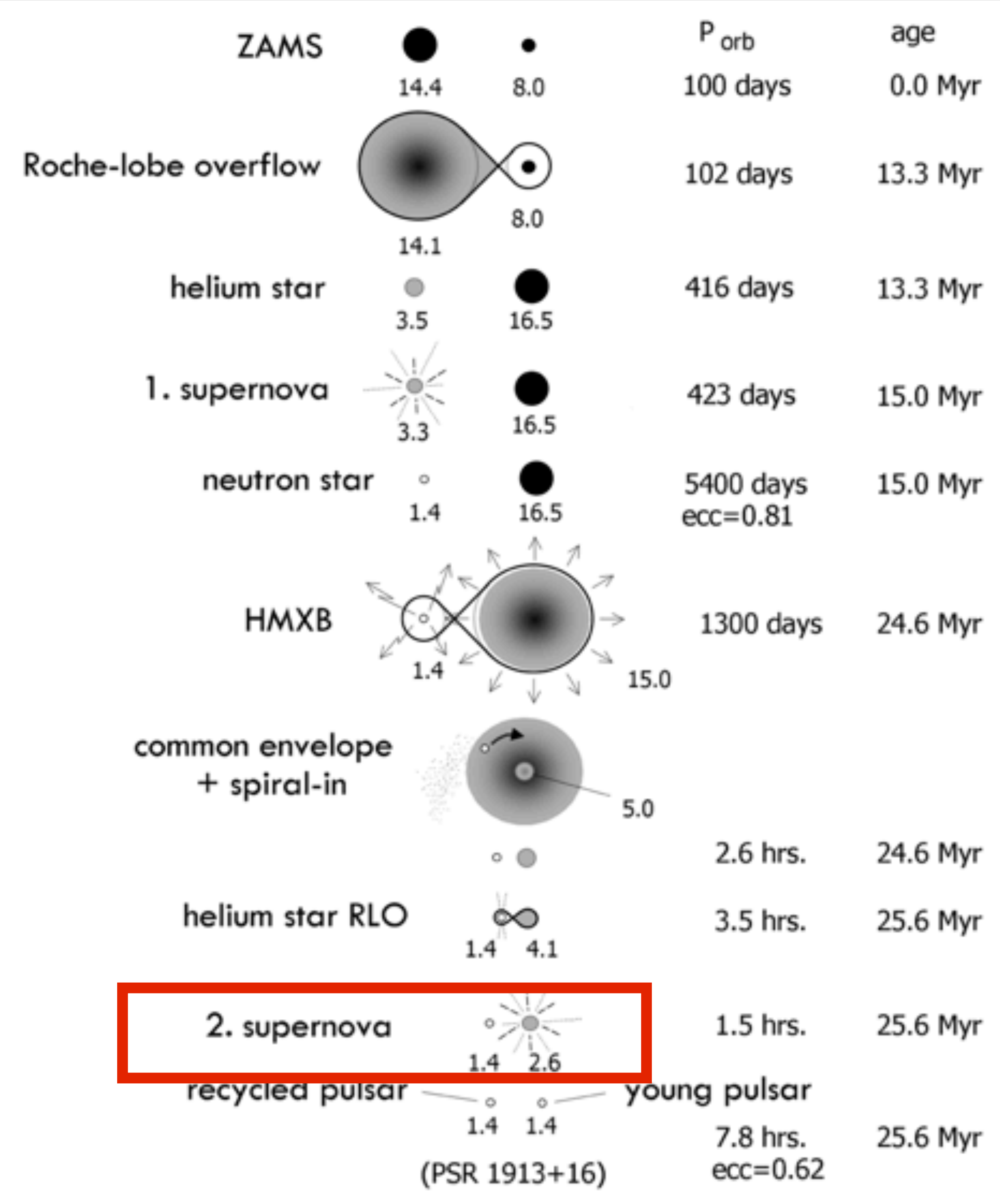
Crust formation!

$$\Gamma \equiv \frac{(Ze)^2}{rkT} = \frac{\text{Coulomb energy}}{\text{Thermal energy}} \sim 100$$

Ultra-stripped type-Ic supernovae-1



Tauris+ 2013

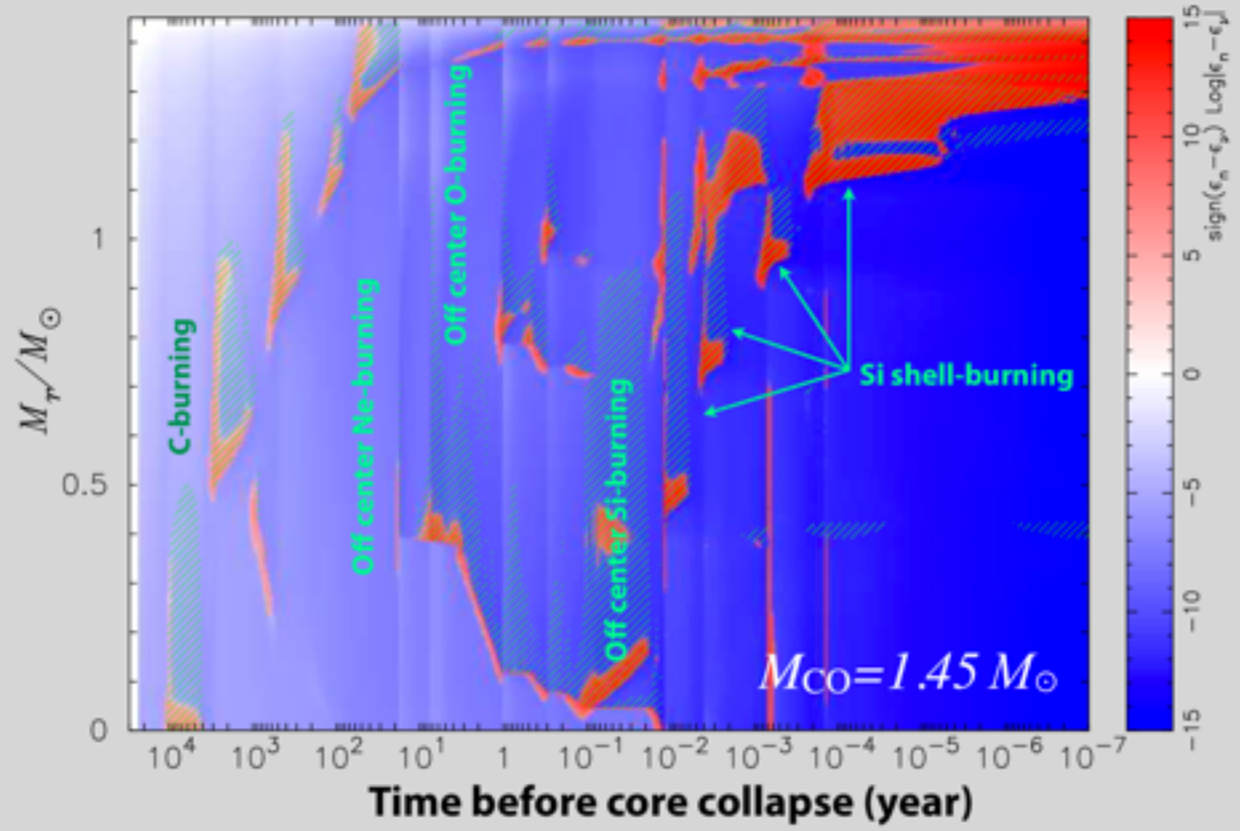


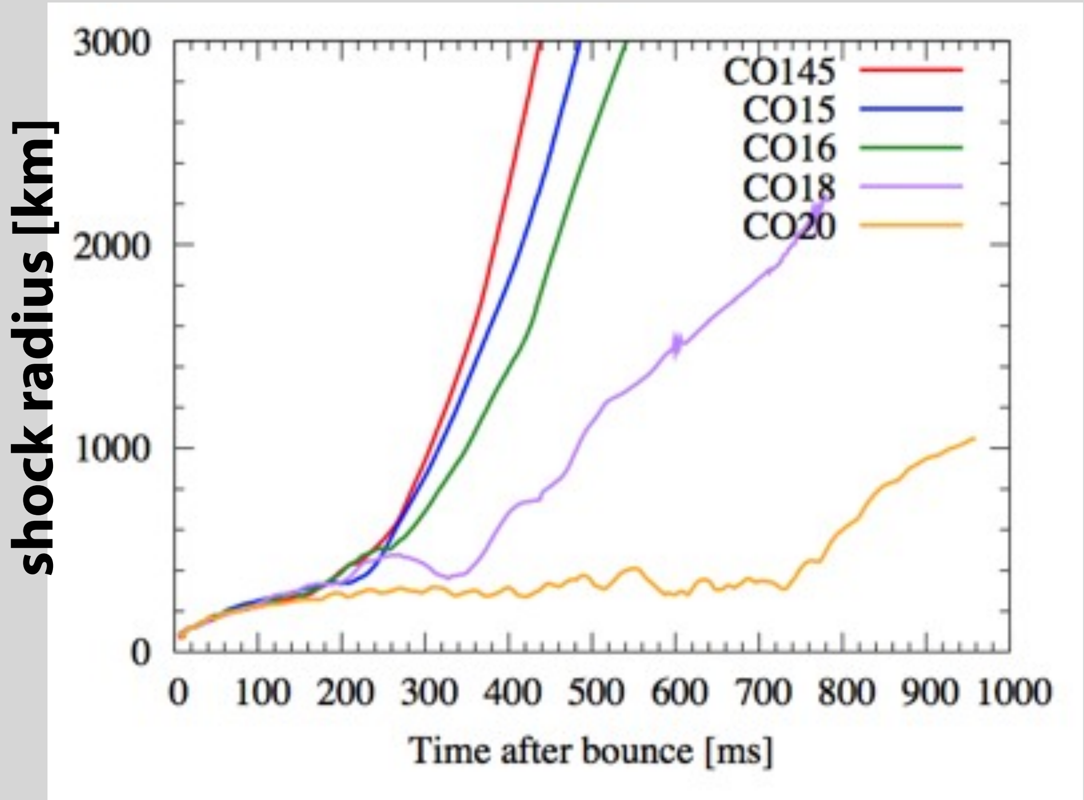
Tauris & van den Heuvel 2006

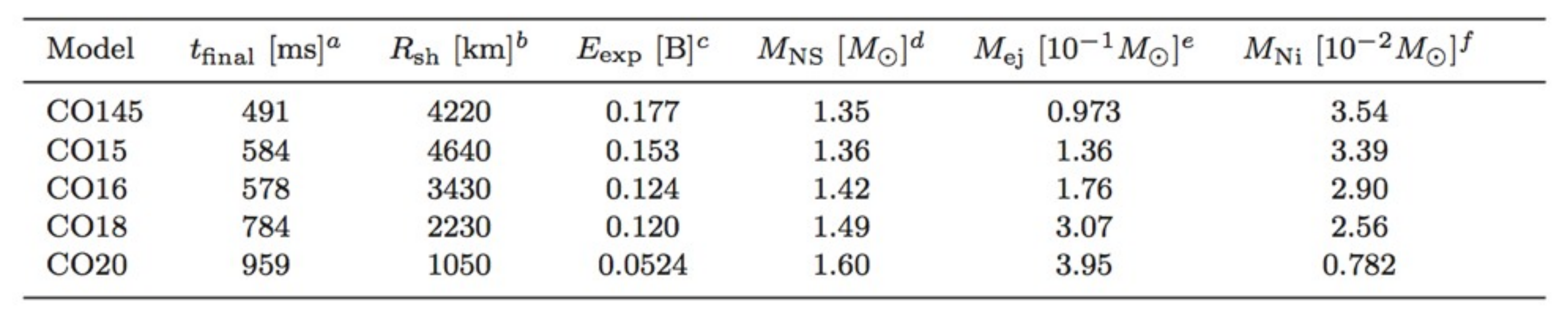
- **new class of SNe**
- **rapidly evolving light curve -> very small ejecta mass**
- **possible generation sites of binary neutron stars**

Ultra-stripped type-Ic supernovae-2

[Suwa, Yoshida, Shibata, Umeda, Takahashi, arXiv:1506.08827]







Model	$t_{\rm final}$ [ms]^a	$R_{\rm sh}$ [km]^b	$E_{\rm exp}$ [B]^c	$M_{\rm NS}$ $[M_\odot]^d$	$M_{\rm ej}$ $[10^{-1}M_\odot]^e$	$M_{\rm Ni}$ $[10^{-2}M_\odot]^f$
CO145	491	4220	0.177	1.35	0.973	3.54
CO15	584	4640	0.153	1.36	1.36	3.39
CO16	578	3430	0.124	1.42	1.76	2.90
CO18	784	2230	0.120	1.49	3.07	2.56
CO20	959	1050	0.0524	1.60	3.95	0.782

Ejecta mass~$O(0.1)M_\odot$, NS mass~$1.4\ M_\odot$, explosion energy~$O(10^{50})$ erg, Ni mass~$O(10^{-2})\ M_\odot$; everything consistent w/ Tauris+ 2013

Summary

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

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!**