From supernovae to neutron stars

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Key observables characterizing supernovae

* **Explosion energy:** $\sim 10^{51}$ **erg**
* **Ejecta mass:** $\sim M_\odot$
* **Ni mass:** $\sim 0.1 M_\odot$

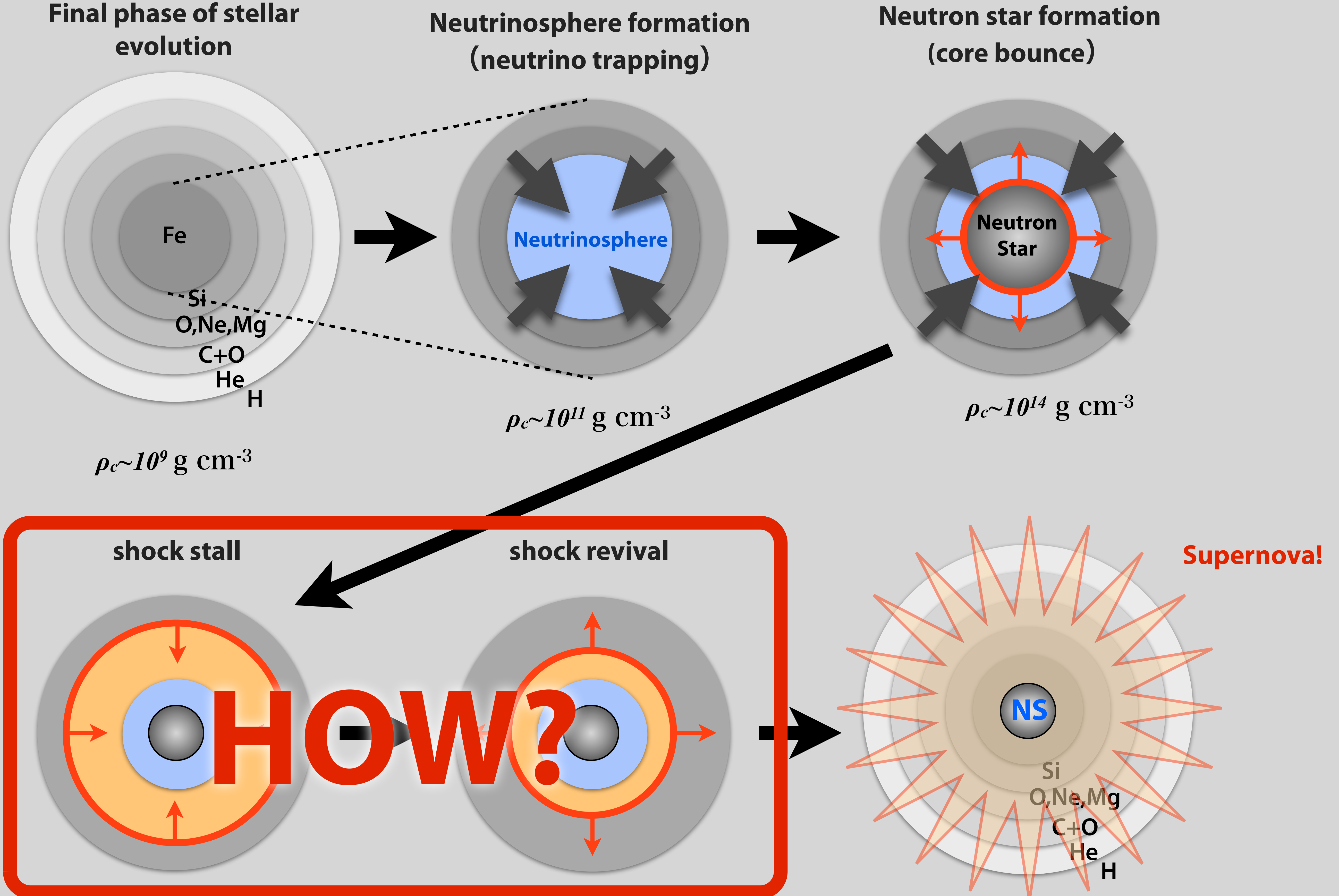
measured by fitting SN light curves

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

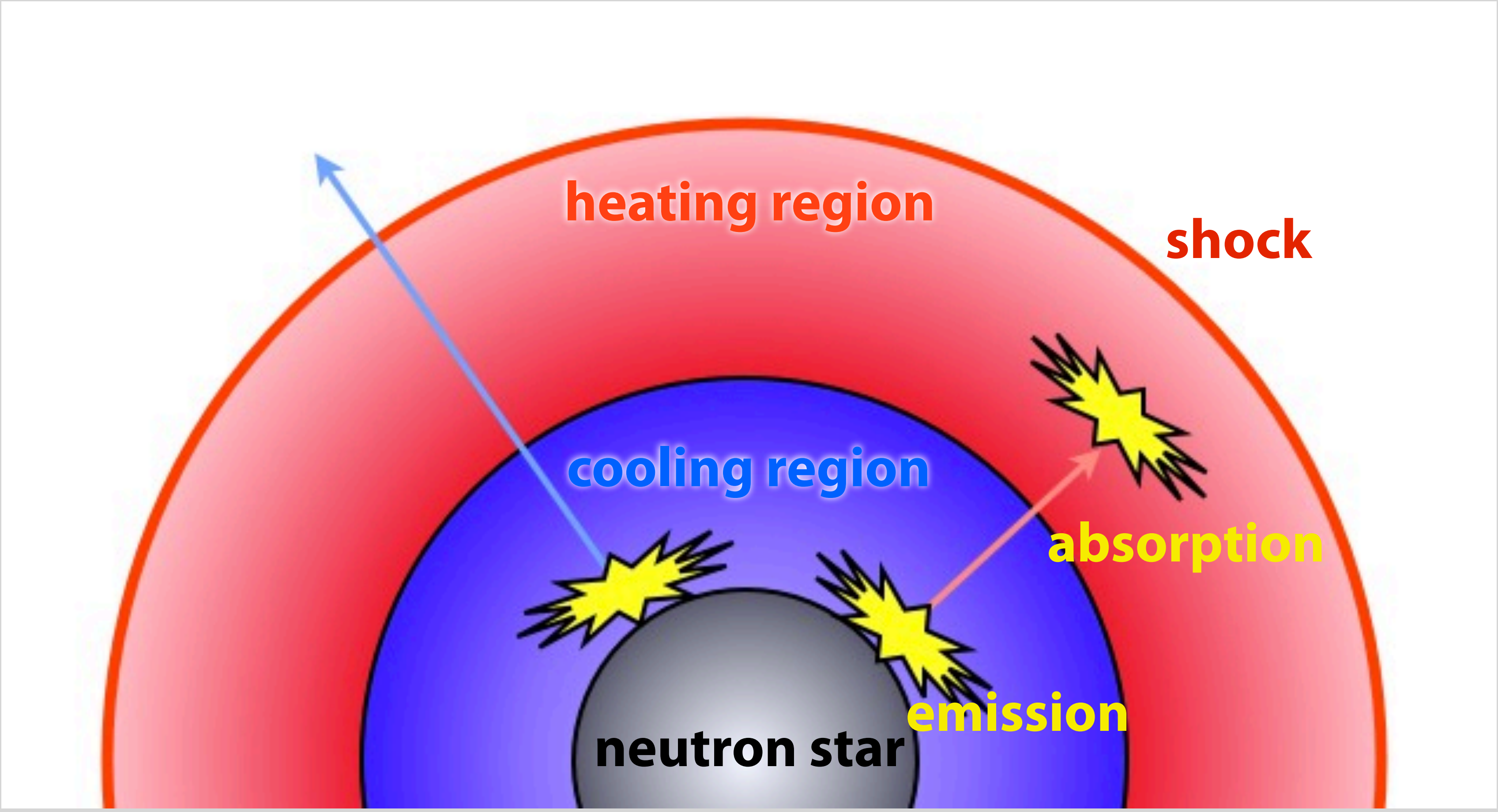
measured by binary systems

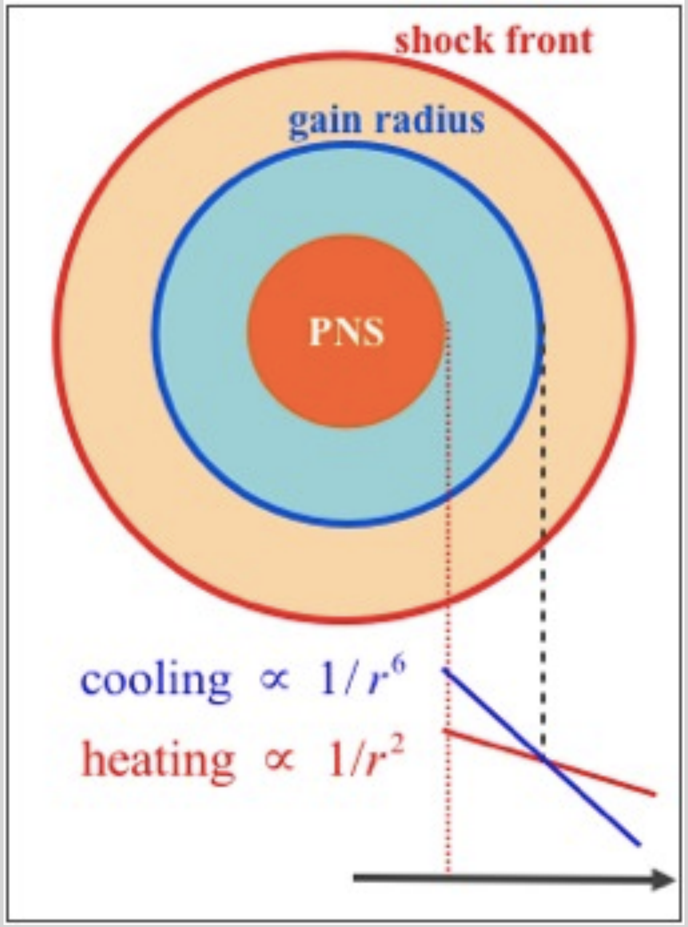
final goal of first-principle (*ab initio*) simulations

Standard scenario of core-collapse supernovae



Current paradigm: neutrino-heating mechanism

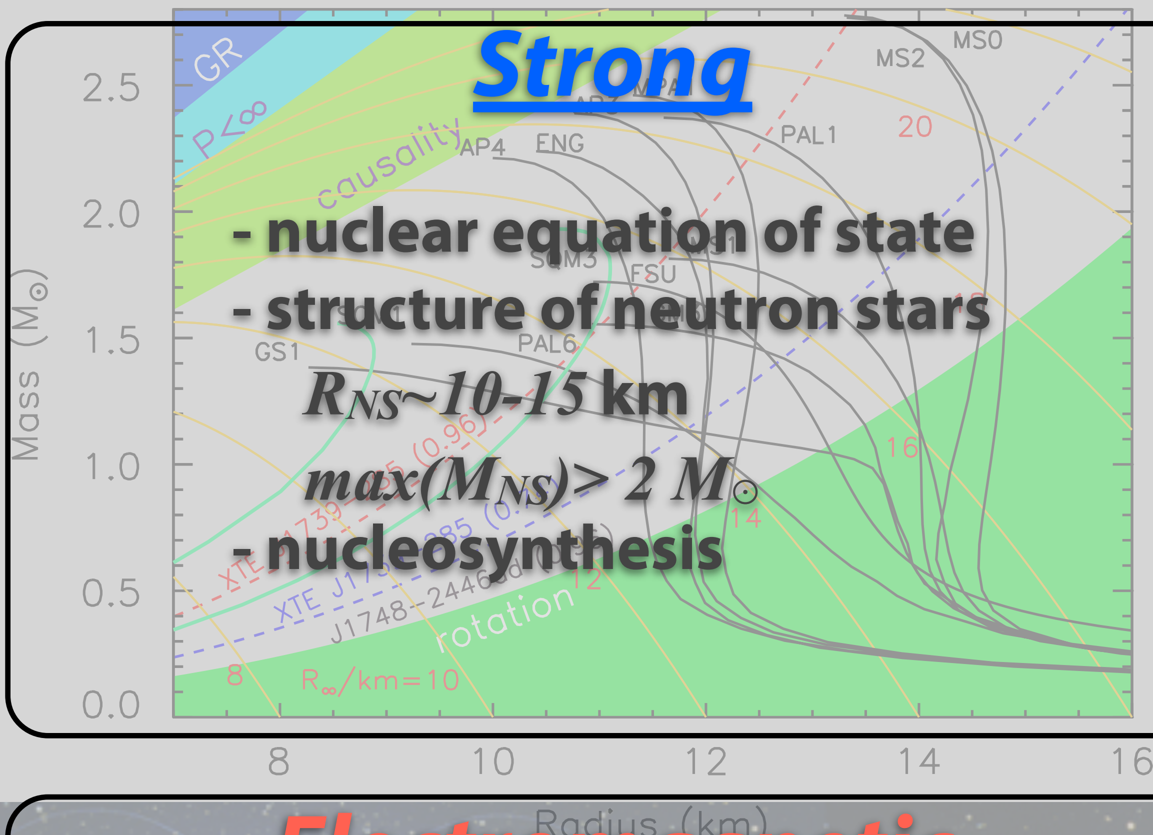




- Energy transferred by neutrinos
- Most of them just escaping from the system, but partially absorbed
- In gain region, neutrino heating overwhelms neutrino cooling

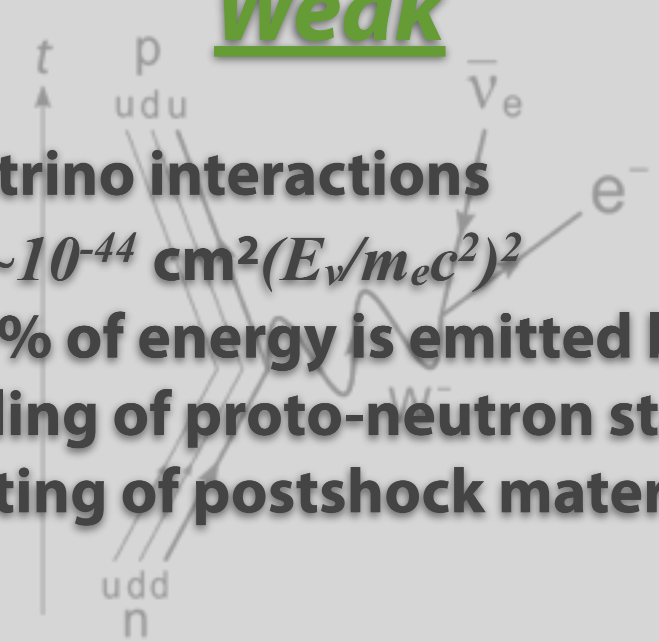
Physical ingredients

All **known interactions are involving and playing important roles**



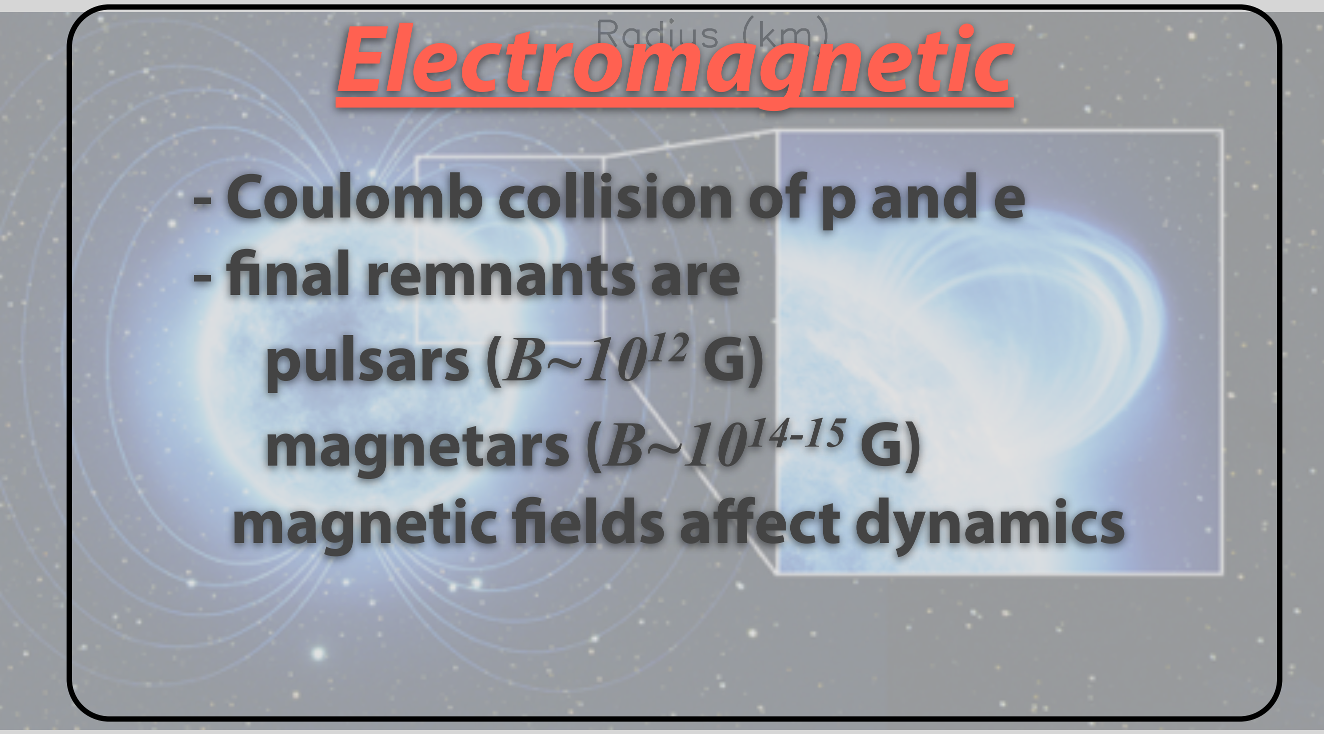
Strong

- nuclear equation of state
- structure of neutron stars
  - R_{NS}~10-15 km
  - $max(M_{NS}) > 2\ M_\odot$
- nucleosynthesis



Weak

- neutrino interactions
  - $\sigma_\nu \sim 10^{-44}$ cm²$(E_\nu/m_e c^2)^2$
- ~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
  - $E_G \sim 3.1\times10^{53}\ erg(M/1.4M_\odot)^2(R/10km)^{-1}$
  - $\sim 0.17 M_\odot c^2$
- inducing core collapse
- making general relativistic objects (NS/BH)

What do simulations solve?

Numerical Simulations

Hydrodynamics 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

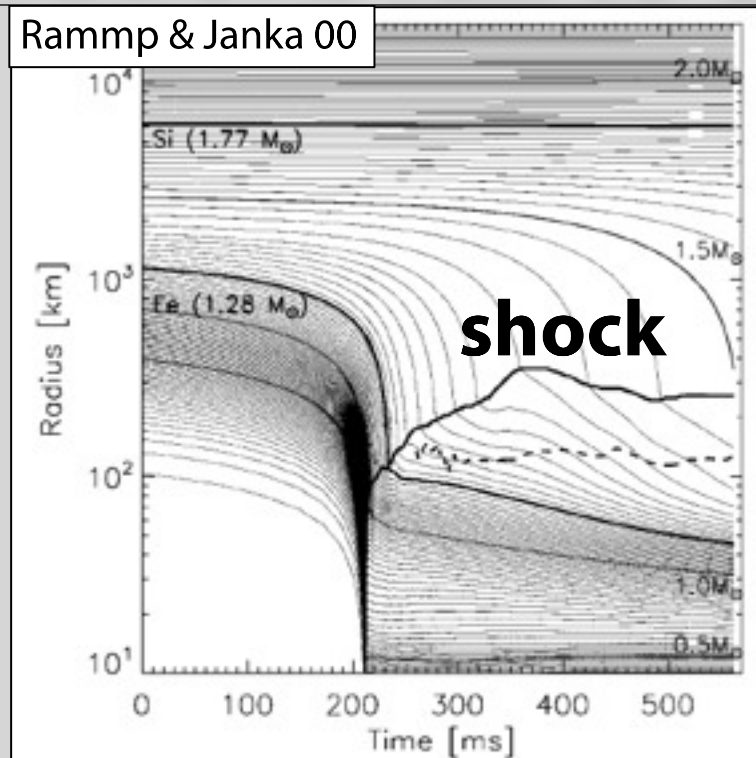
Neutrino Boltzmann equation

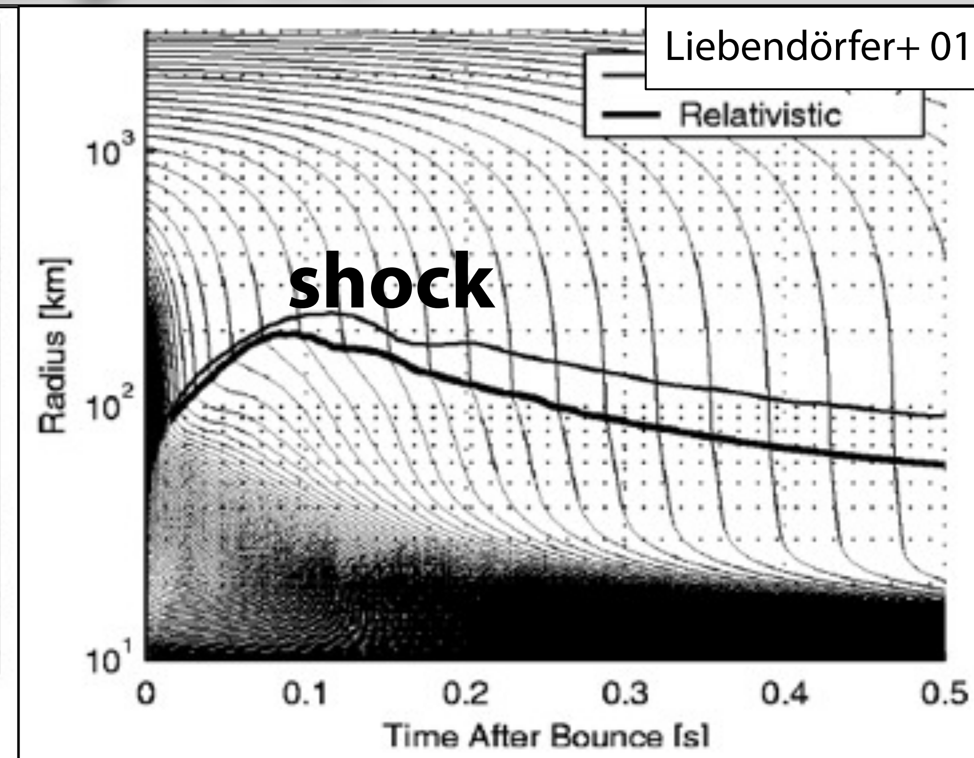
$$\frac{df}{cdt} + \mu\frac{\partial f}{\partial r} + \left[\mu\left(\frac{d\ln\rho}{cdt} + \frac{3v}{cr}\right) + \frac{1}{r}\right]\left(1-\mu^2\right)\frac{\partial f}{\partial\mu} + \left[\mu^2\left(\frac{d\ln\rho}{cdt} + \frac{3v}{cr}\right) - \frac{v}{cr}\right]E\frac{\partial f}{\partial E}$$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

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

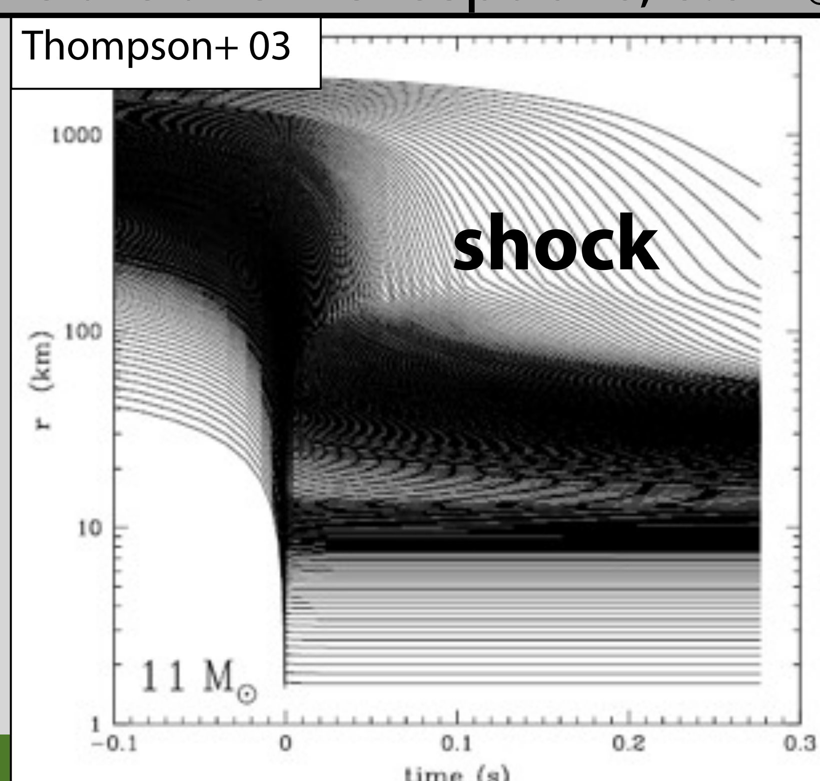
1D simulations fail to explode

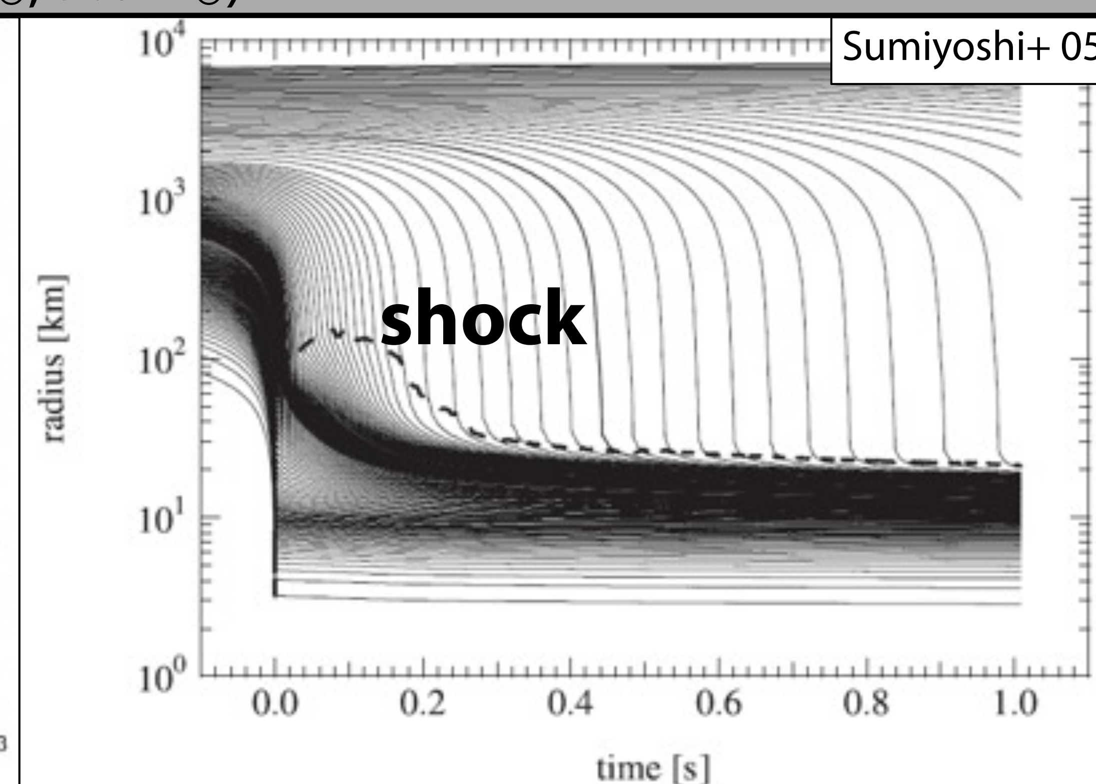




By including all available physics to simulations, we concluded that the explosion cannot be obtained in 1D!

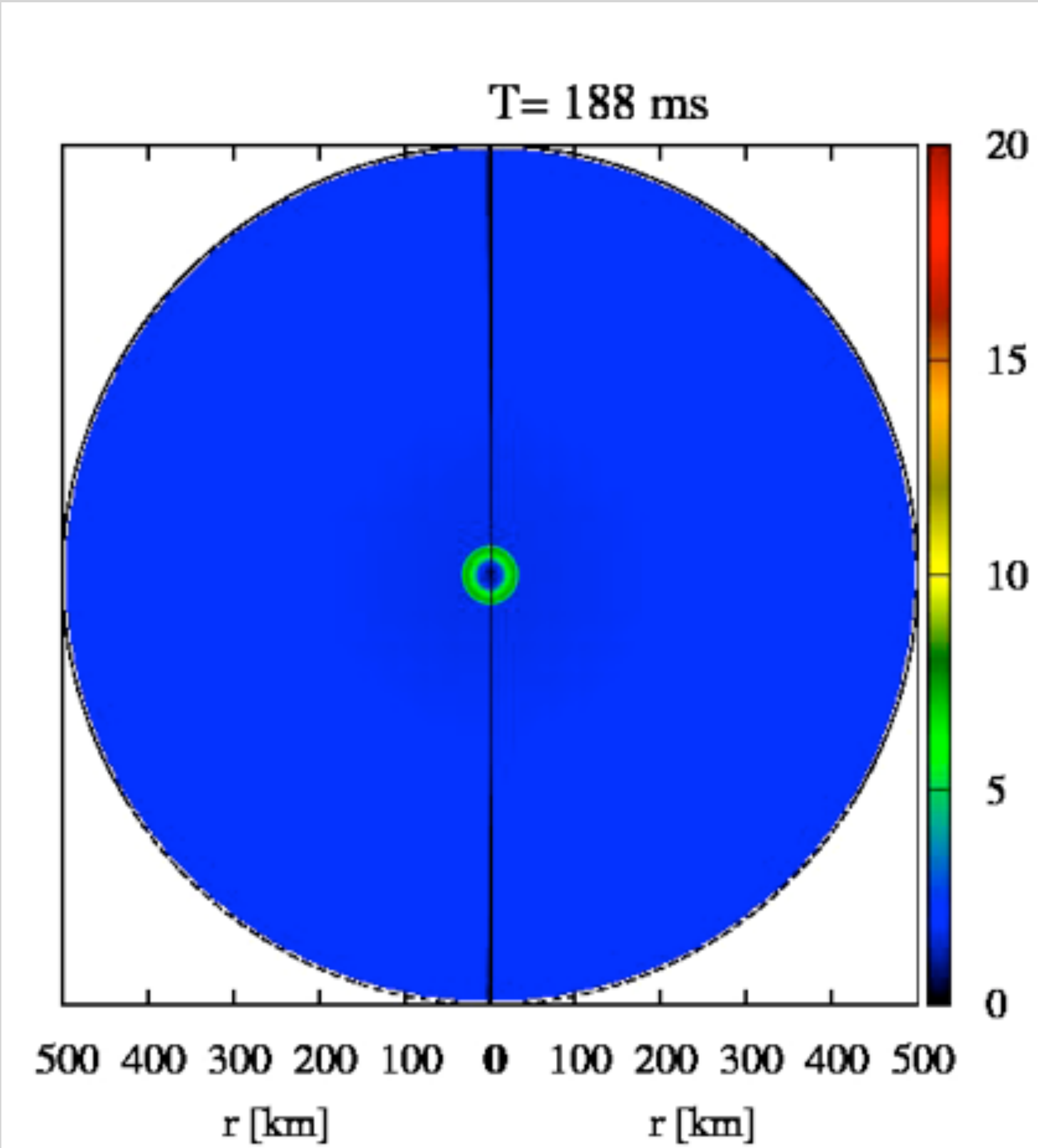
(There are a few exceptions; 8.8M$_\odot$, 9.6M$_\odot$)



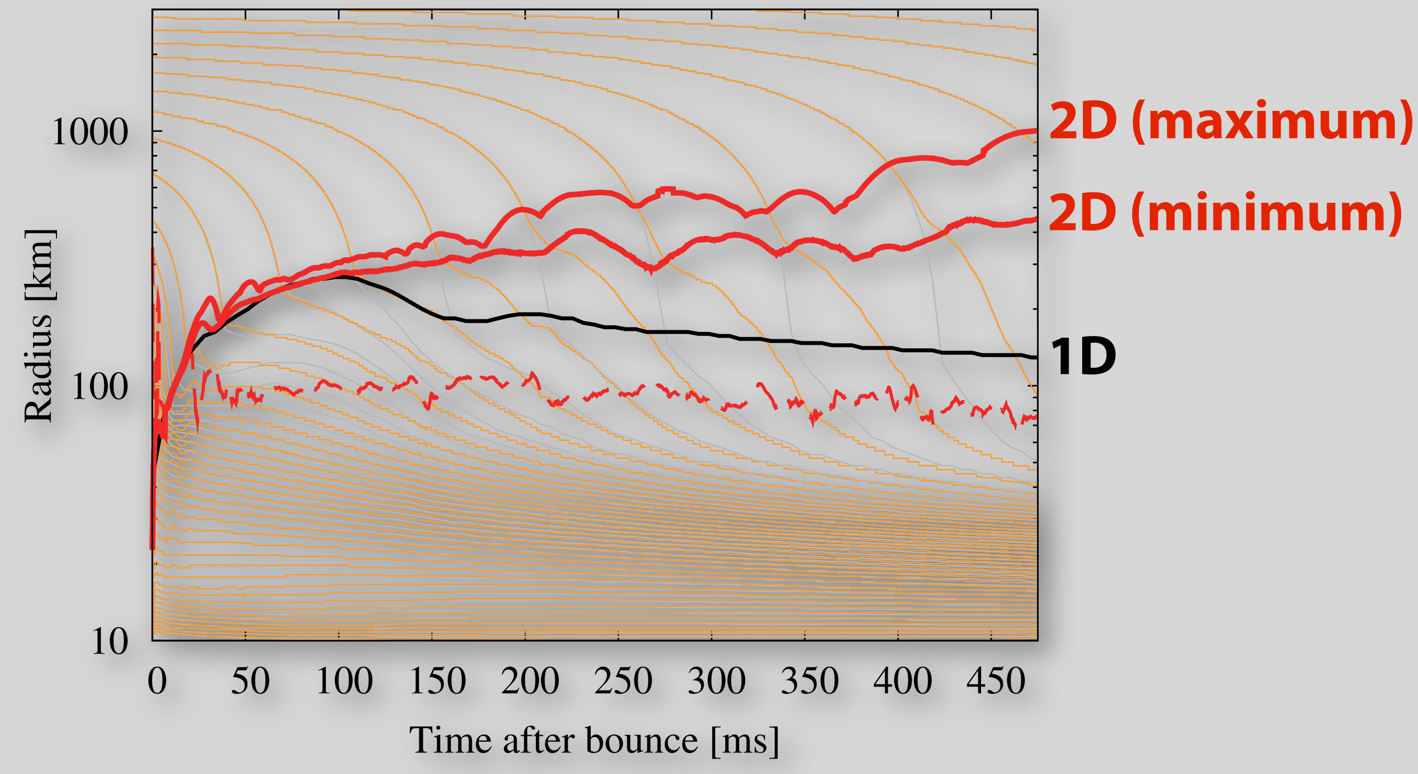


Neutrino-driven explosion in multi-D simulation

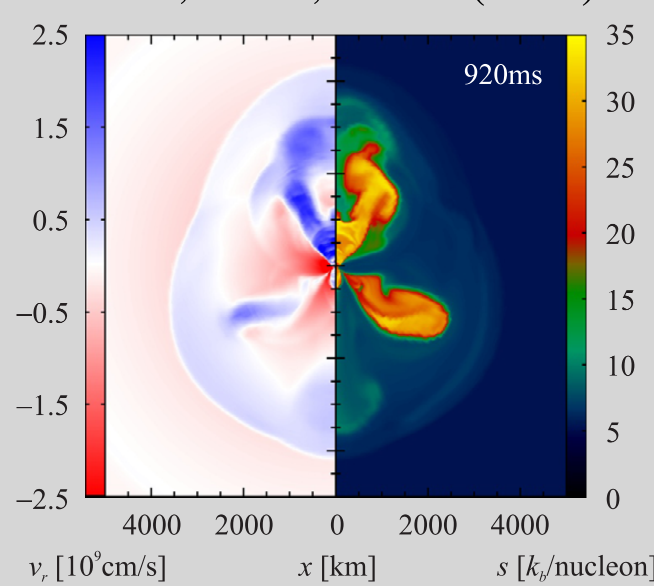
We have exploding models driven by neutrino heating with 2D/3D simulations



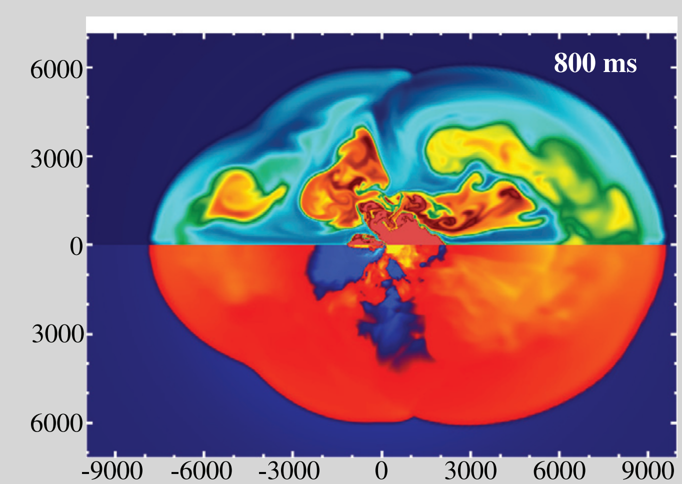
Suwa+ (2D)	PASJ, **62**, L49 (2010)
	ApJ, **738**, 165 (2011)
	ApJ, **764**, 99 (2013)
	PASJ, **66**, L1 (2014)
	MNRAS, **454**, 3073 (2015)
	ApJ, **816**, 43 (2016)



Müller, Janka, Marek (2012)

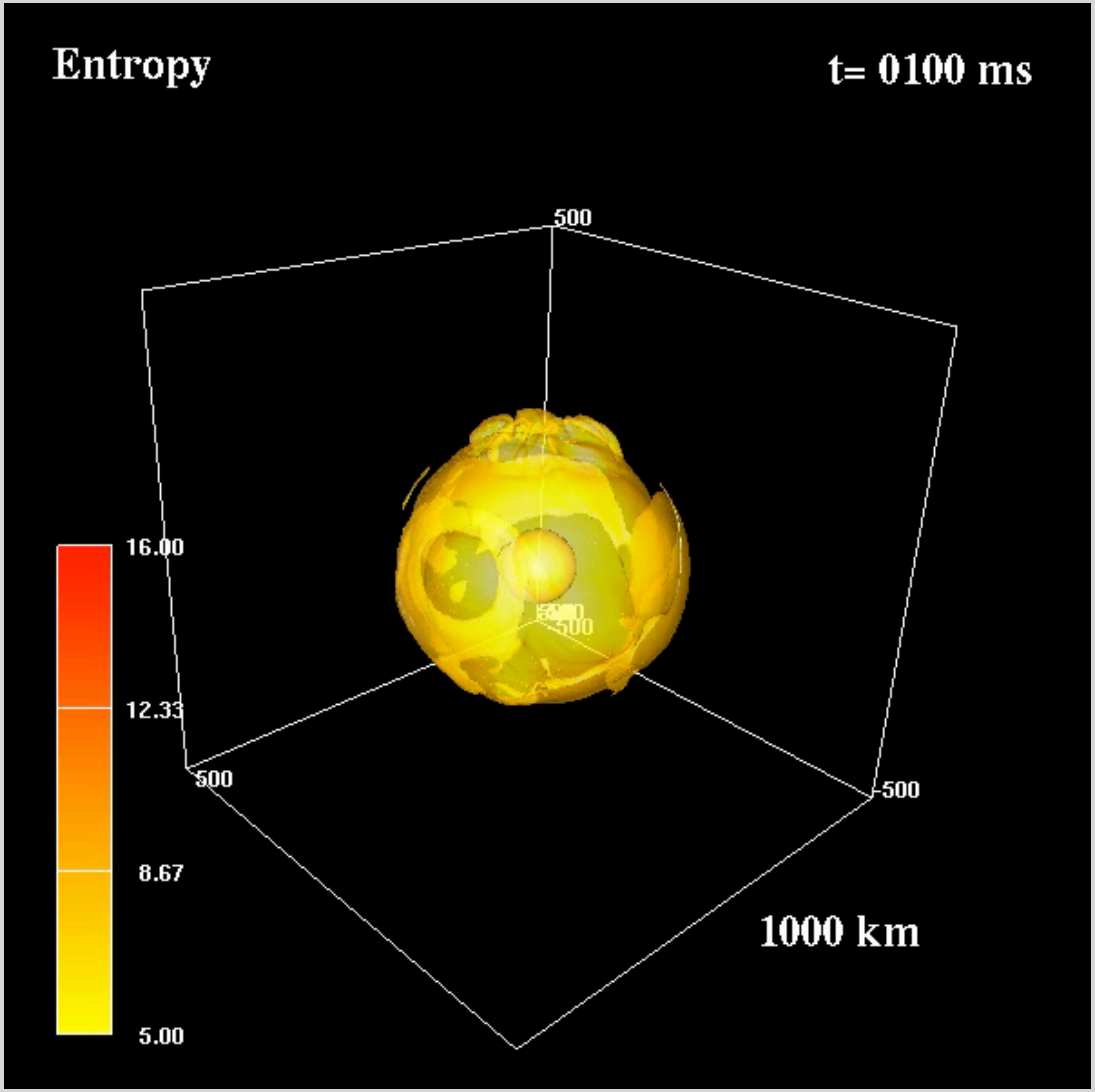


Brruenn et al. (2013)



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)

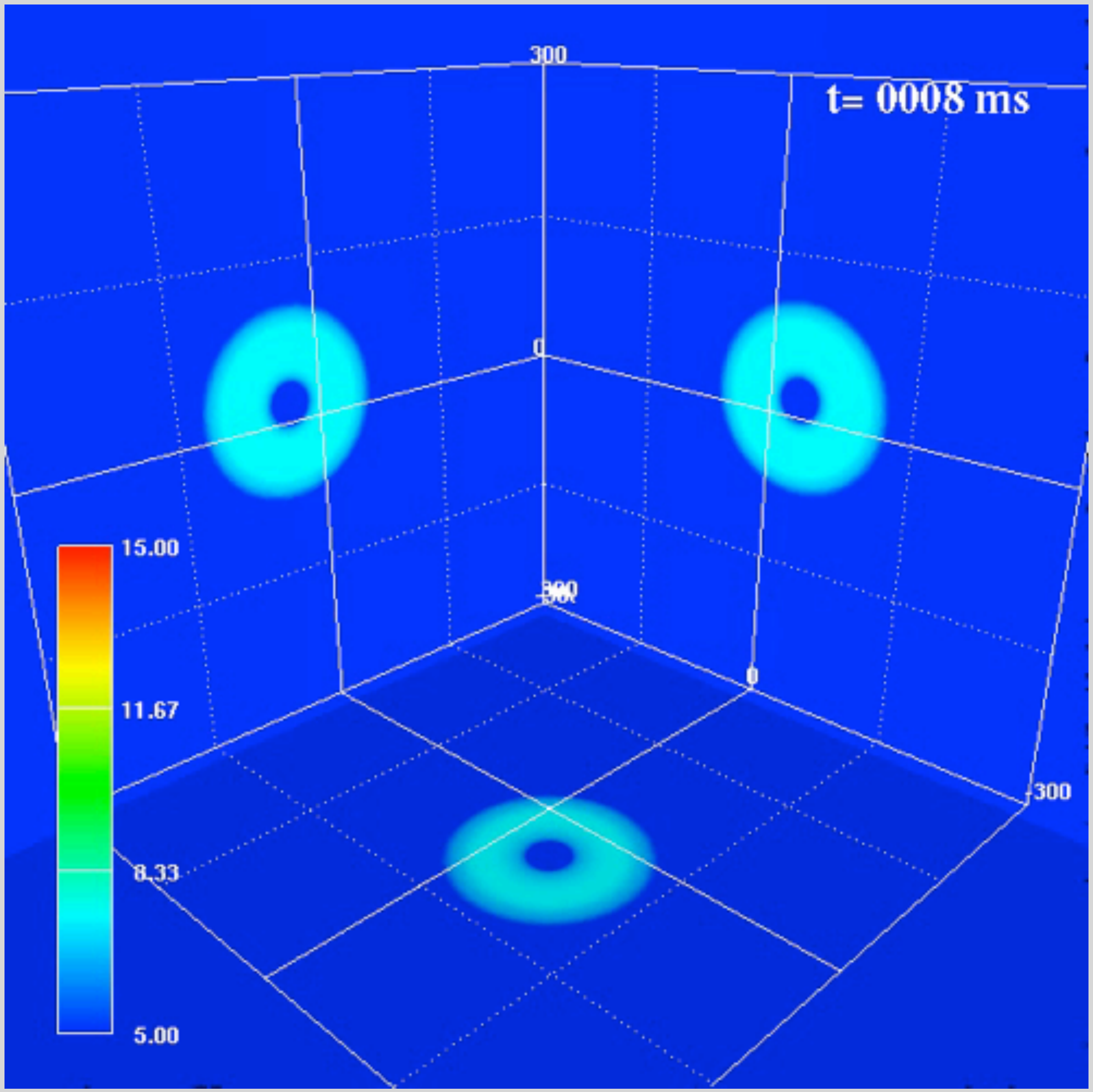
XT4

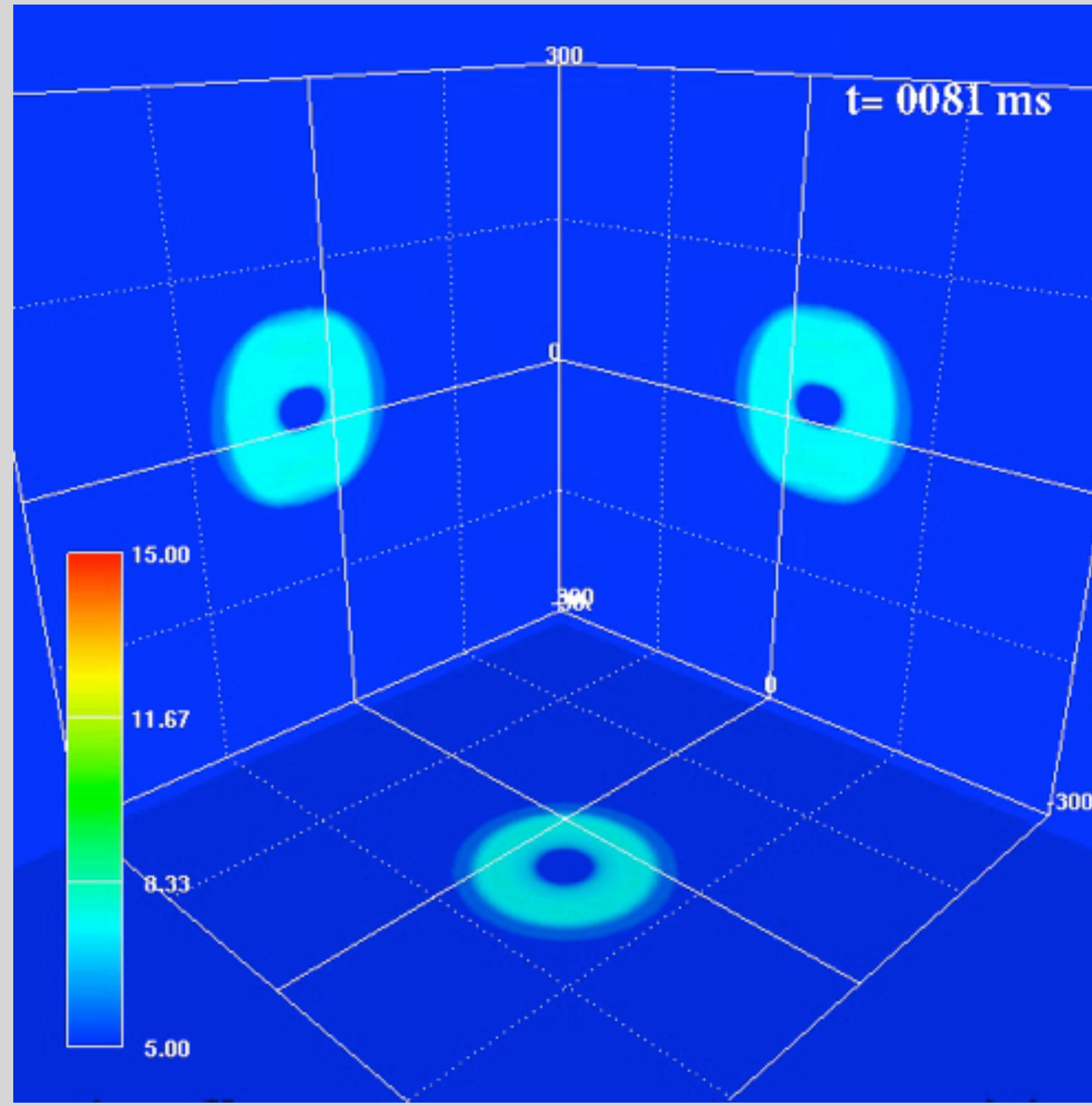
T2K-Tsukuba

K computer

Impacts of rotation

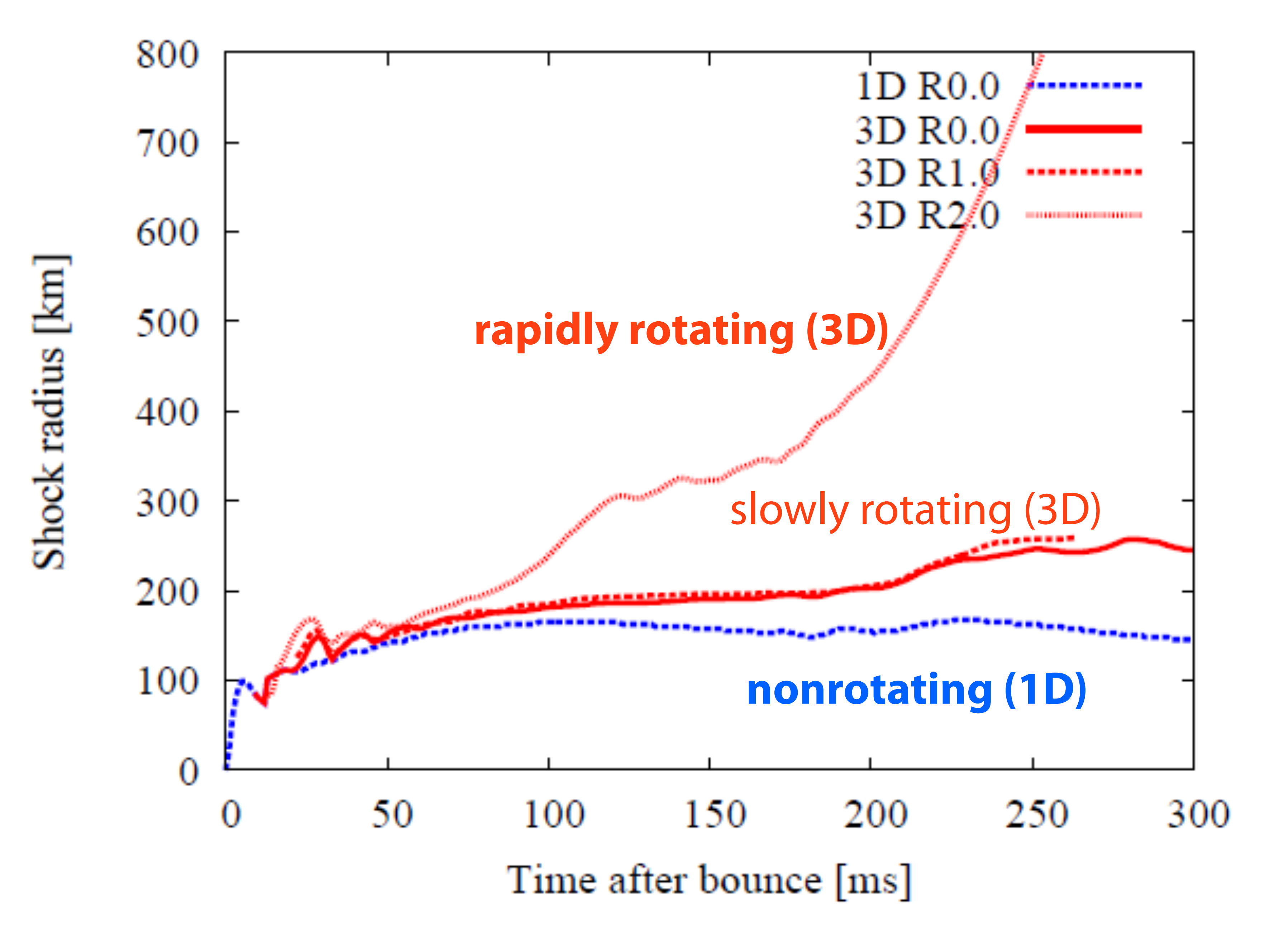
w/o rotation $M_{ZAMS}=27M_\odot$ **w/ rotation**

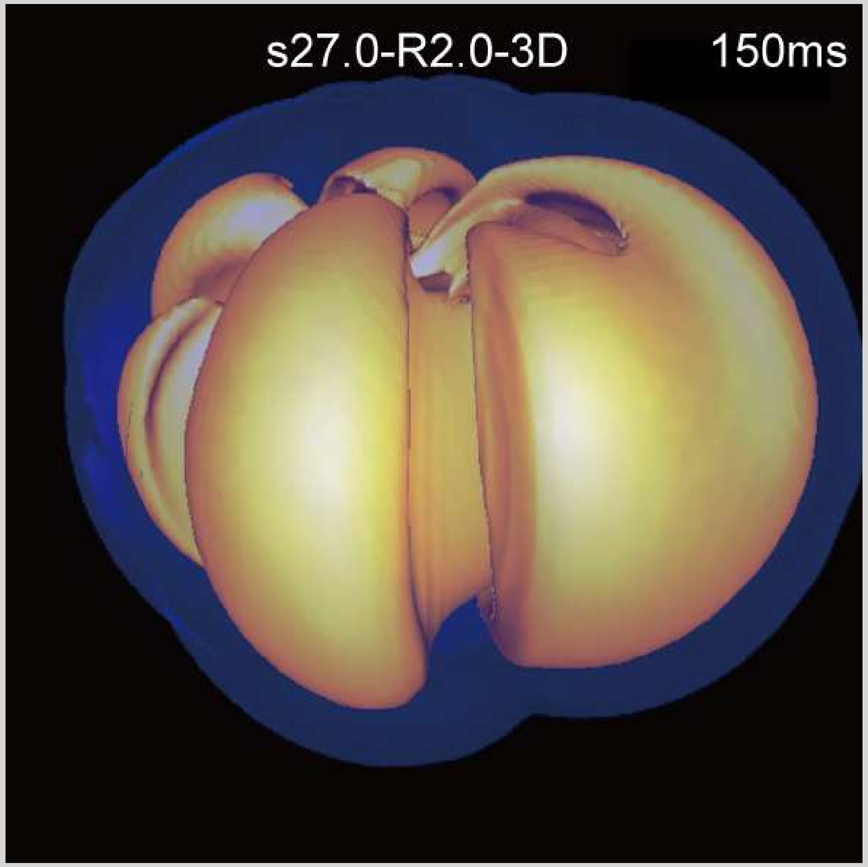




To explode or not to explode

$M_{ZAMS}=27M_{\odot}$





Takiwaki, Kotake, Suwa, arXiv:1602.06759

Neutron star formation

- **In the following, I focus on neutron star (NS) formation with supernova (SN) simulations**
  - Once we obtain shock launch and mass accretion onto a protoneutron star (PNS) ceases, PNS evolution is (probably) not affected by explosion details

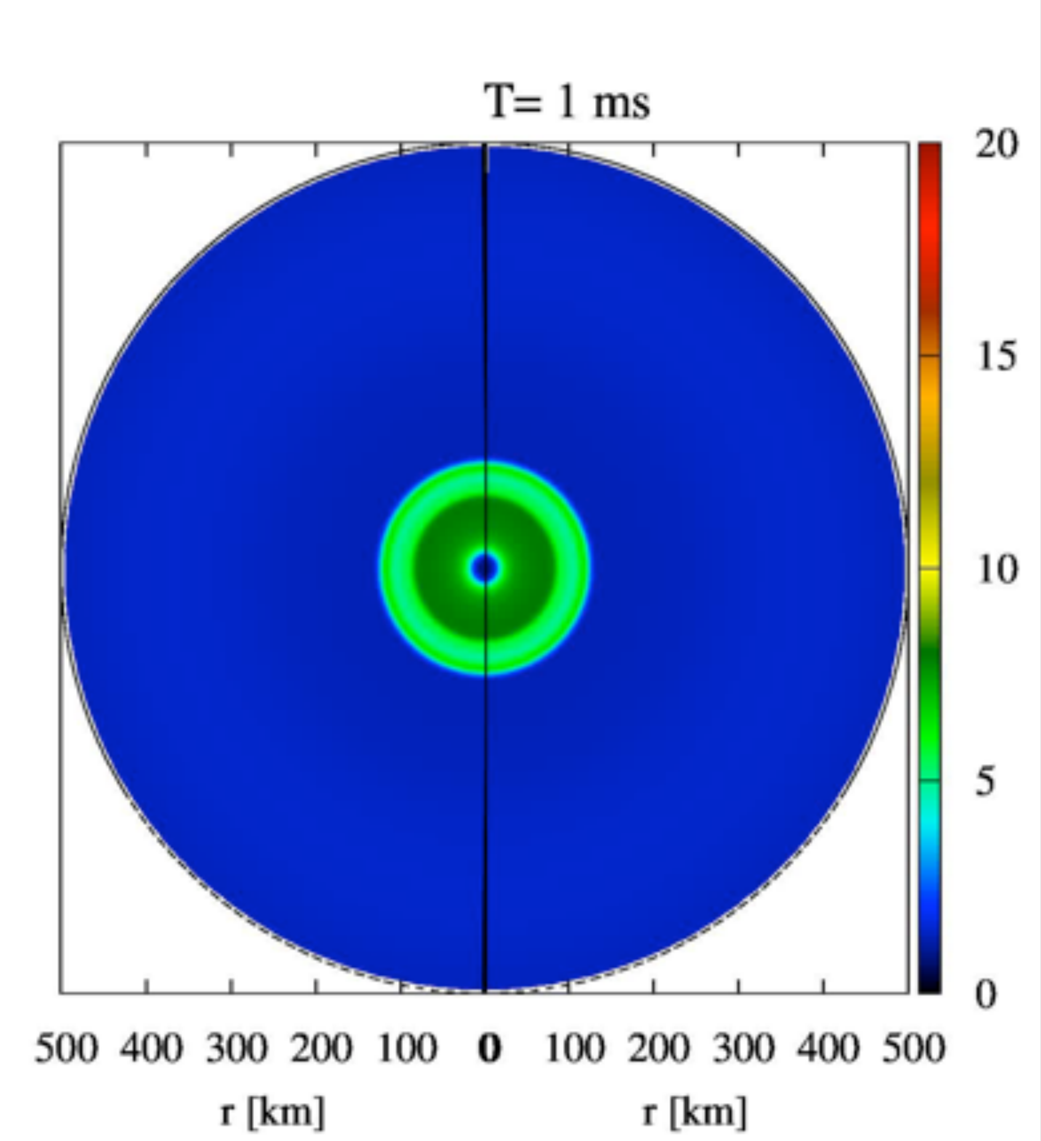
NB)

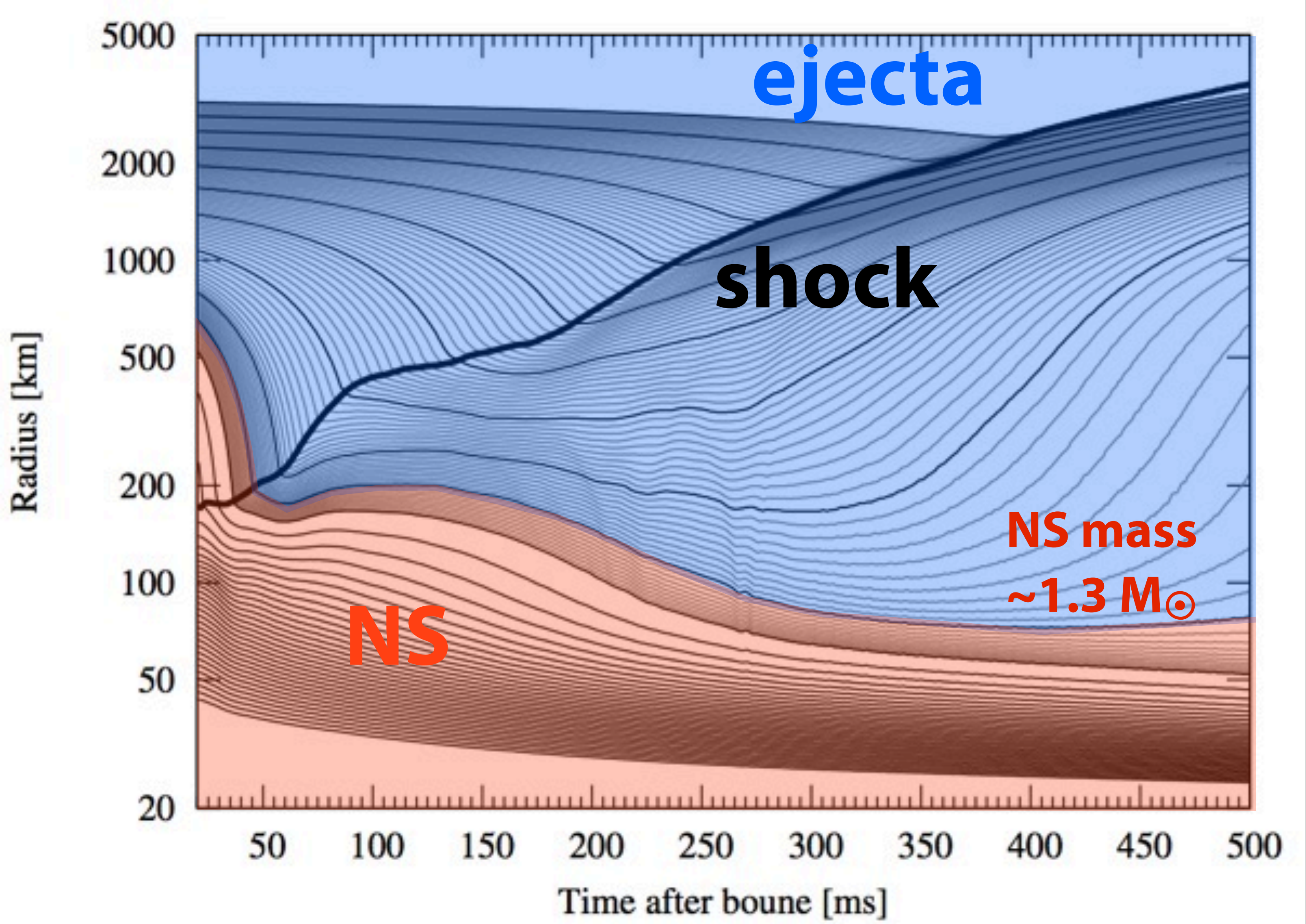
- **Explosion energy of simulations ($O(10^{49\text{-}50})$ erg) is much smaller than observational values ($O(10^{51})$ erg)**
- **Results from different groups are contradictory**

1. NS crust formation

From SN to NS

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

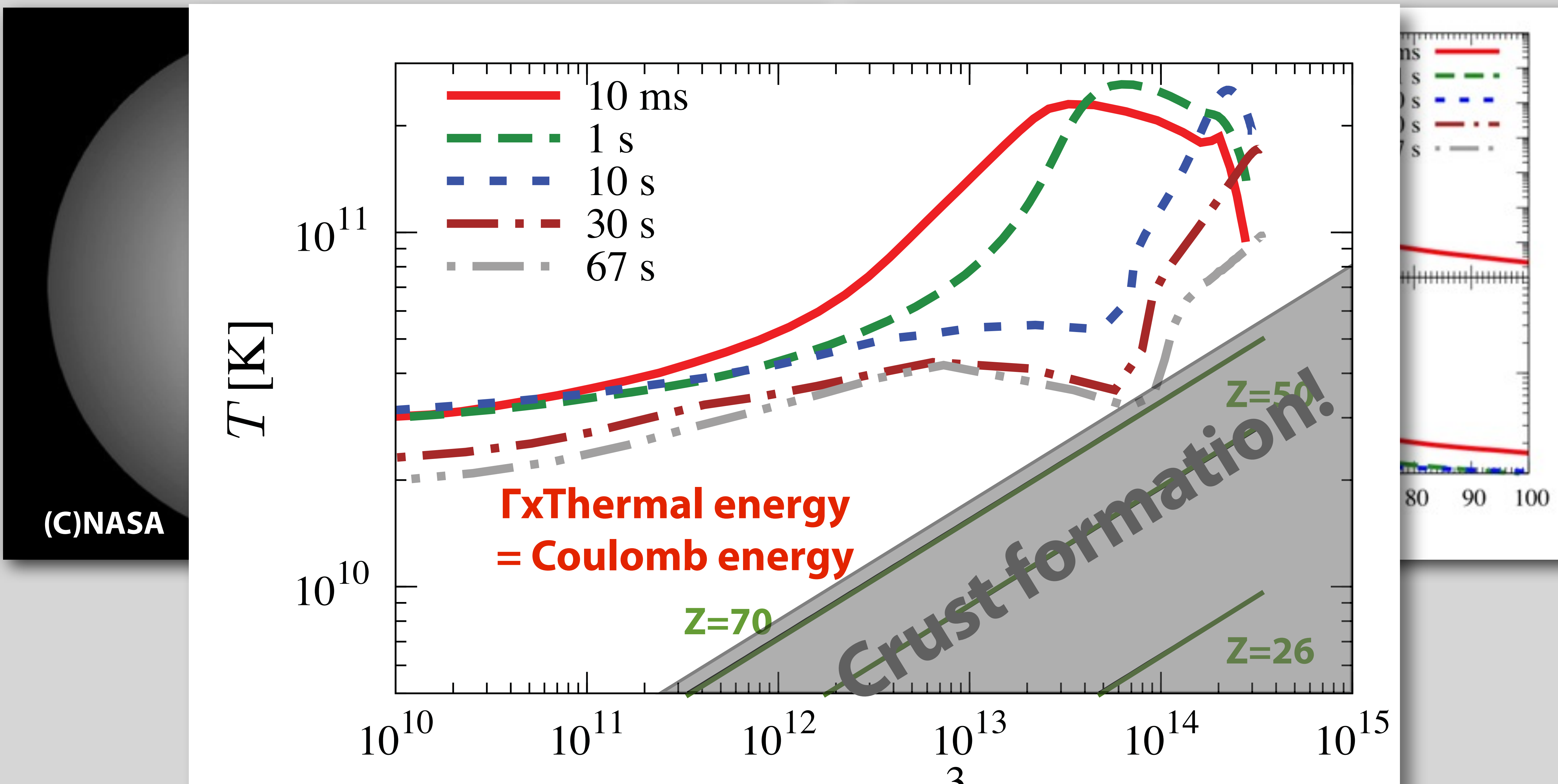




- **Progenitor:** $11.2\ M_\odot$ (Woosley+ 2002)
- **Successful explosion! (but still weak with** E_{exp}~10^{50} **erg)**
- **The mass of NS is** $\sim 1.3\ M_\odot$
- **The simulation was continued in 1D to follow the PNS cooling phase up to ~70 s p.b.**

From SN to NS

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



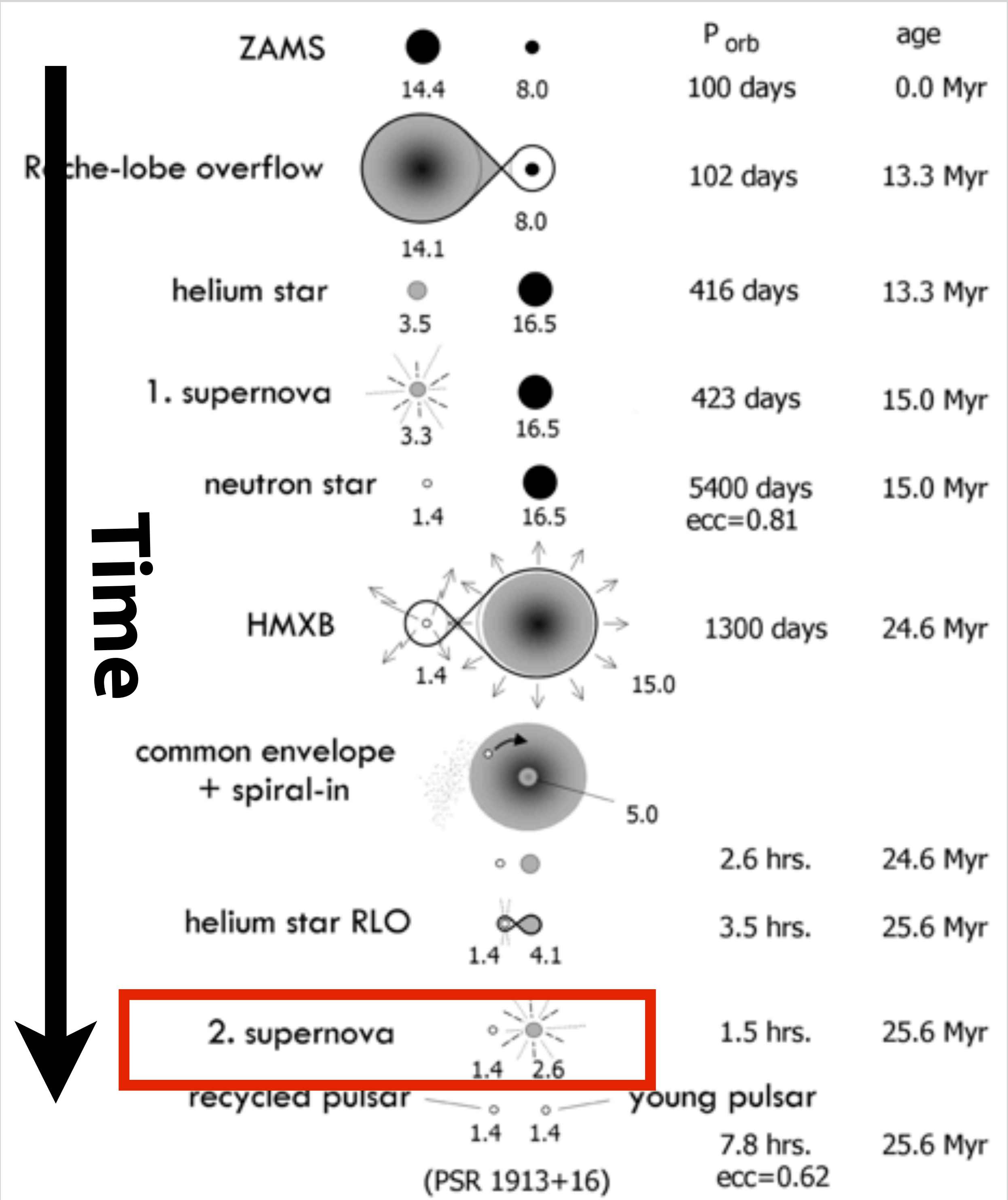
$$\Gamma \equiv \frac{(Ze)^2}{r k_B T} = \frac{\text{Coulomb energy}}{\text{Thermal energy}} \sim 200$$

From SN to NS: Implications

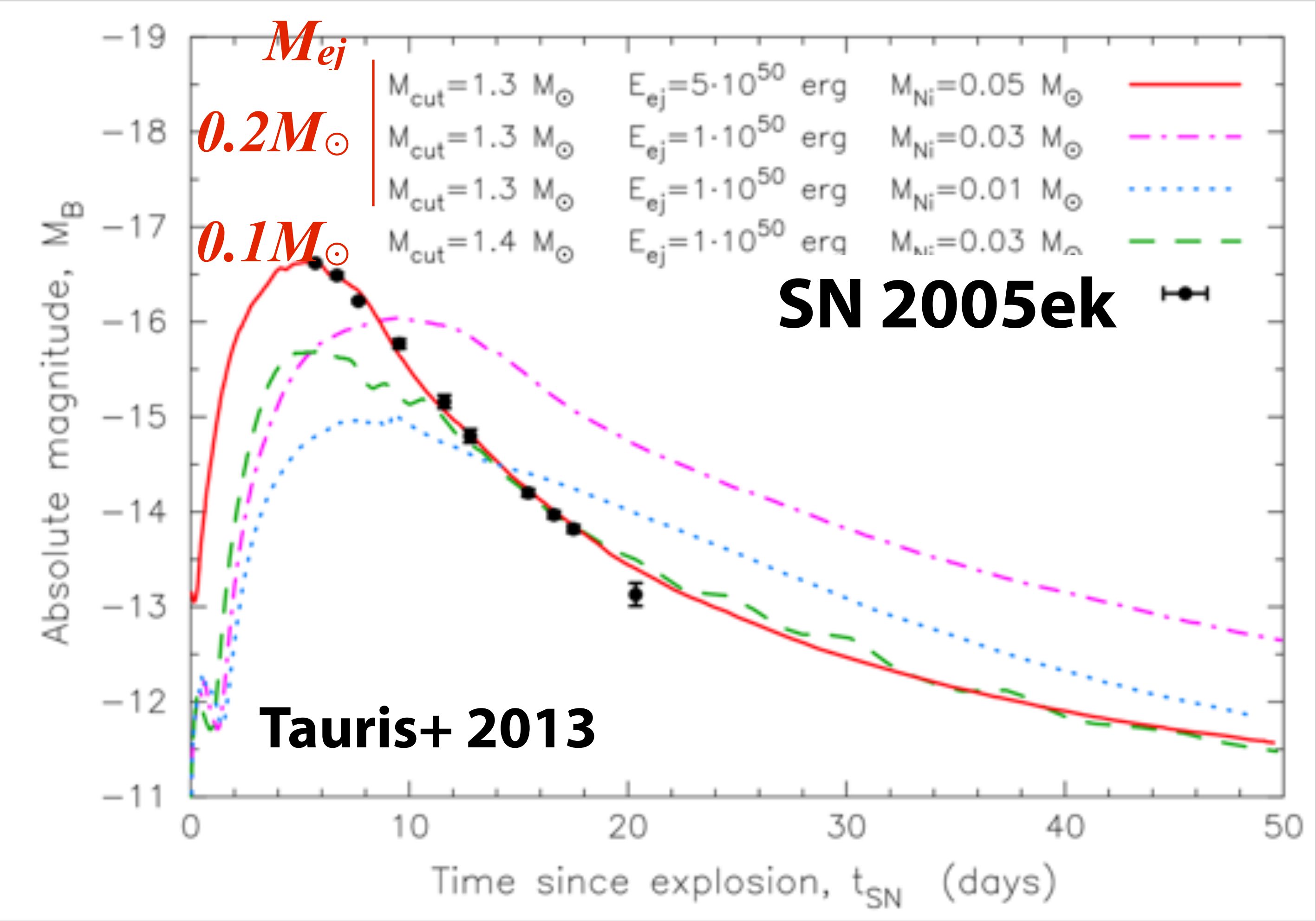
- **Crust formation time should depend on EOS** (especially symmetry energy?)
- **We may observe crust formation via neutrino luminosity evolution of a SN in our galaxy**
  - Cross section of neutrino scattering by heavier nuclei or *nuclear pasta* is much larger than that of neutrons and protons
  - 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

2. Binary NS formation

How to make binary NSs?



Tauris & van den Heuvel 2006



- new class of SNe
- rapidly evolving light curve -> very small ejecta mass
- possible generation sites of **binary neutron stars** (synergy w/ gravitational wave!)

Ultra-stripped type-Ic supernovae

[Suwa, Yoshida, Shibata, Umeda, Takahashi, MNRAS, **454**, 3073 (2015)]

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MNRAS **454**, 3073–3081 (2015) doi:10.1093/mnras/stv2195

Neutrino-driven explosions of ultra-stripped Type Ic supernovae generating binary neutron stars

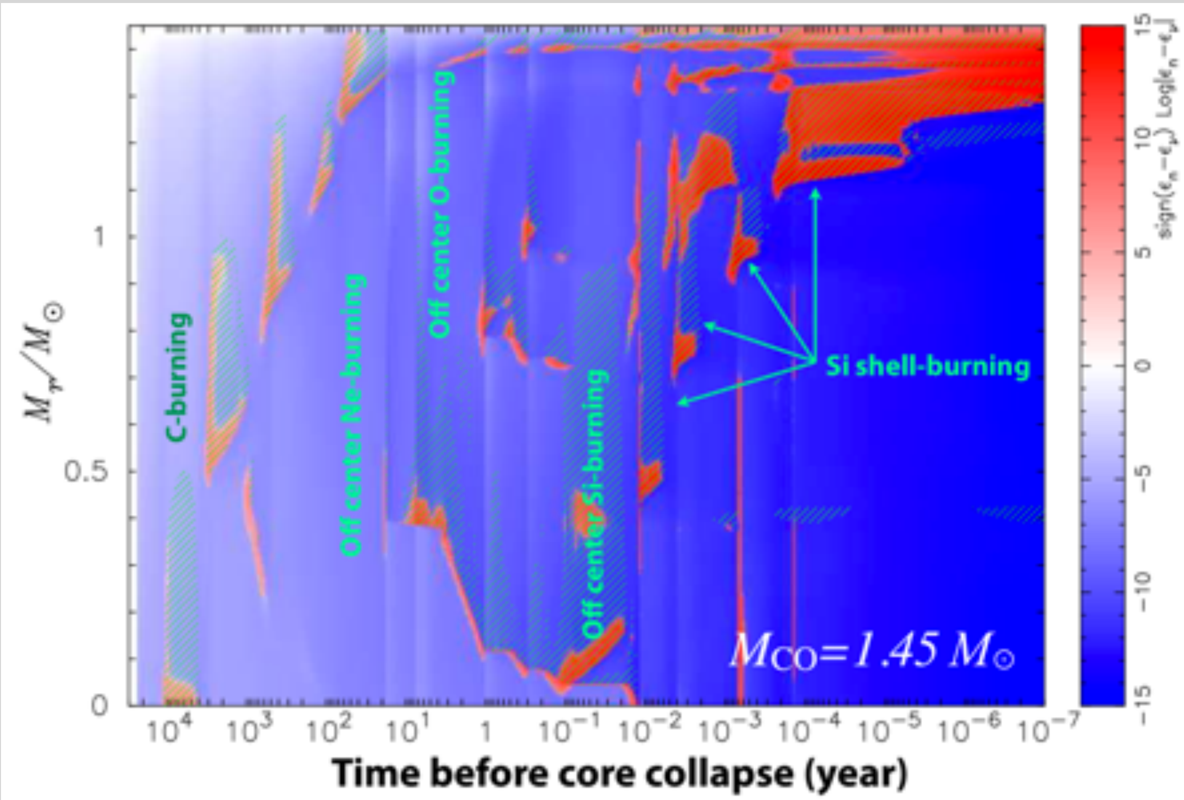
Yudai Suwa,[1,2★] Takashi Yoshida,[1,3] Masaru Shibata,[1] Hideyuki Umeda[3] and Koh Takahashi[3]

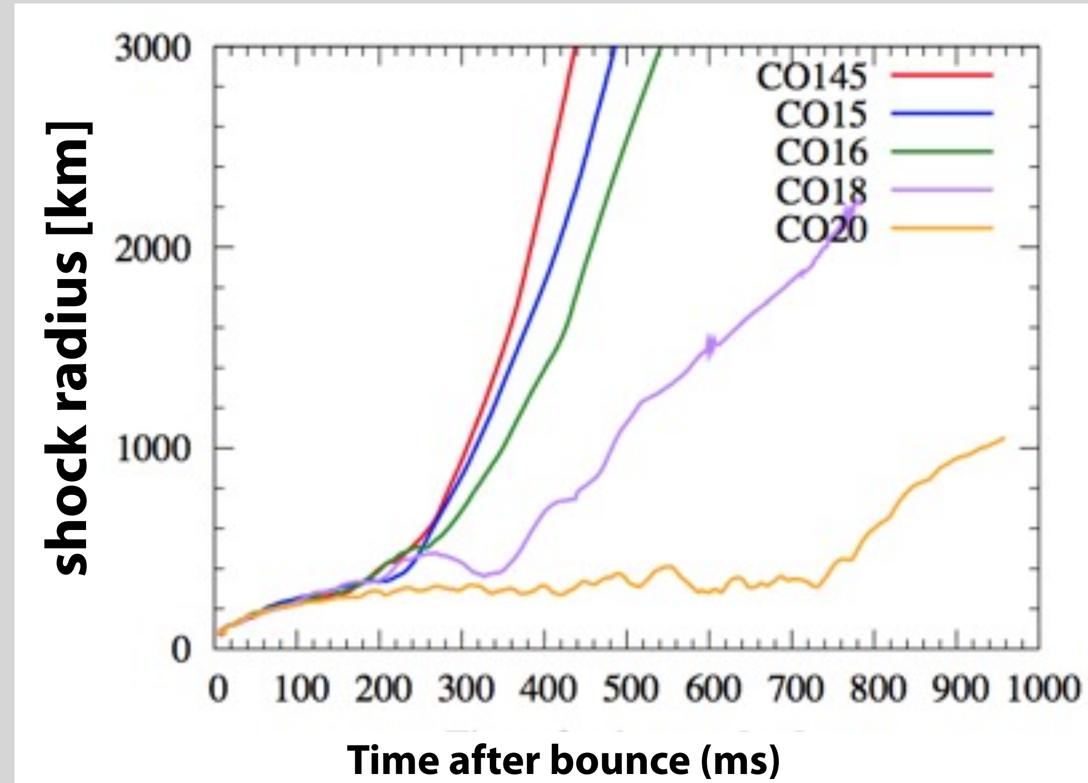
ABSTRACT

We study explosion characteristics of ultra-stripped supernovae (SNe), which are candidates of SNe generating binary neutron stars (NSs). As a first step, we perform stellar evolutionary simulations of bare carbon–oxygen cores of mass from 1.45 to 2.0 $M_\odot$ until the iron cores become unstable and start collapsing. We then perform axisymmetric hydrodynamics simulations with spectral neutrino transport using these stellar evolution outcomes as initial conditions. All models exhibit successful explosions driven by neutrino heating. The diagnostic explosion energy, ejecta mass, Ni mass, and NS mass are typically $\sim 10^{50}$ erg, $\sim 0.1\ M_\odot$, $\sim 0.01\ M_\odot$, and $\approx 1.3\ M_\odot$, which are compatible with observations of rapidly evolving and luminous transient such as SN 2005ek. We also find that the ultra-stripped SN is a candidate for producing the secondary low-mass NS in the observed compact binary NSs like PSR J0737−3039.

Ultra-stripped type-Ic supernovae

[Suwa, Yoshida, Shibata, Umeda, Takahashi, MNRAS, **454**, 3073 (2015)]





Model	$t_{\rm final}$[a] [ms]	$R_{\rm sh}$[b] [km]	$E_{\rm exp}$[c] [B]	$M_{\rm NS,baryon}$[d] [$M_\odot$]	$M_{\rm NS,grav}$[e] [$M_\odot$]	$M_{\rm ej}$[f] [$10^{-1}M_\odot$]	$M_{\rm Ni}$[g] [$10^{-2}M_\odot$]	$v_{\rm kick}$[h] [km s^{-1}]
CO145	491	4220	0.177	1.35	1.24	0.973	3.54	3.20
CO15	584	4640	0.153	1.36	1.24	1.36	3.39	75.1
CO16	578	3430	0.124	1.42	1.29	1.76	2.90	47.6
CO18	784	2230	0.120	1.49	1.35	3.07	2.56	36.7
CO20[i]	959	1050	0.0524	1.60	1.44	3.95	0.782	10.5

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

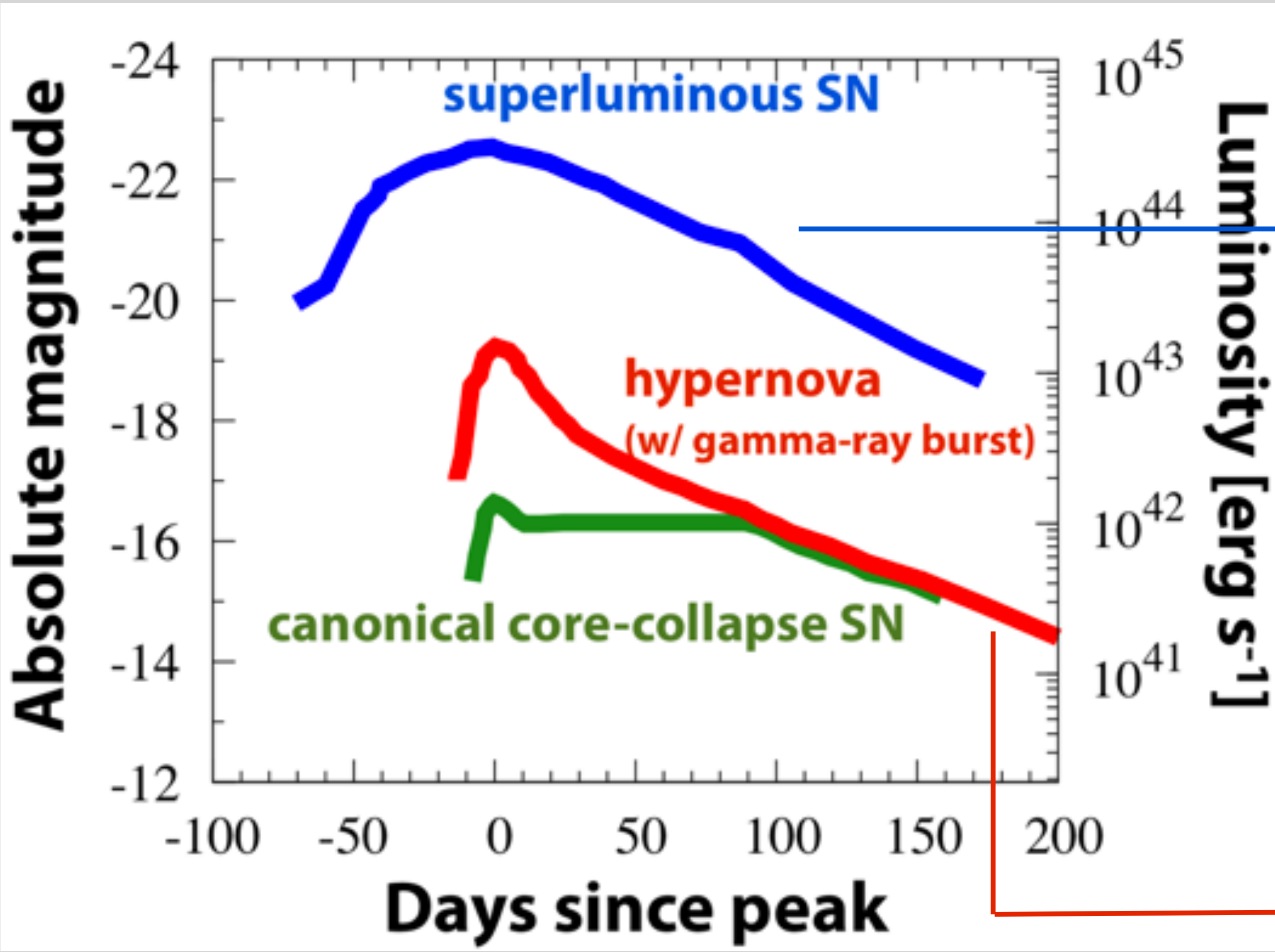
Ultra-stripped type-Ic supernovae: Implications

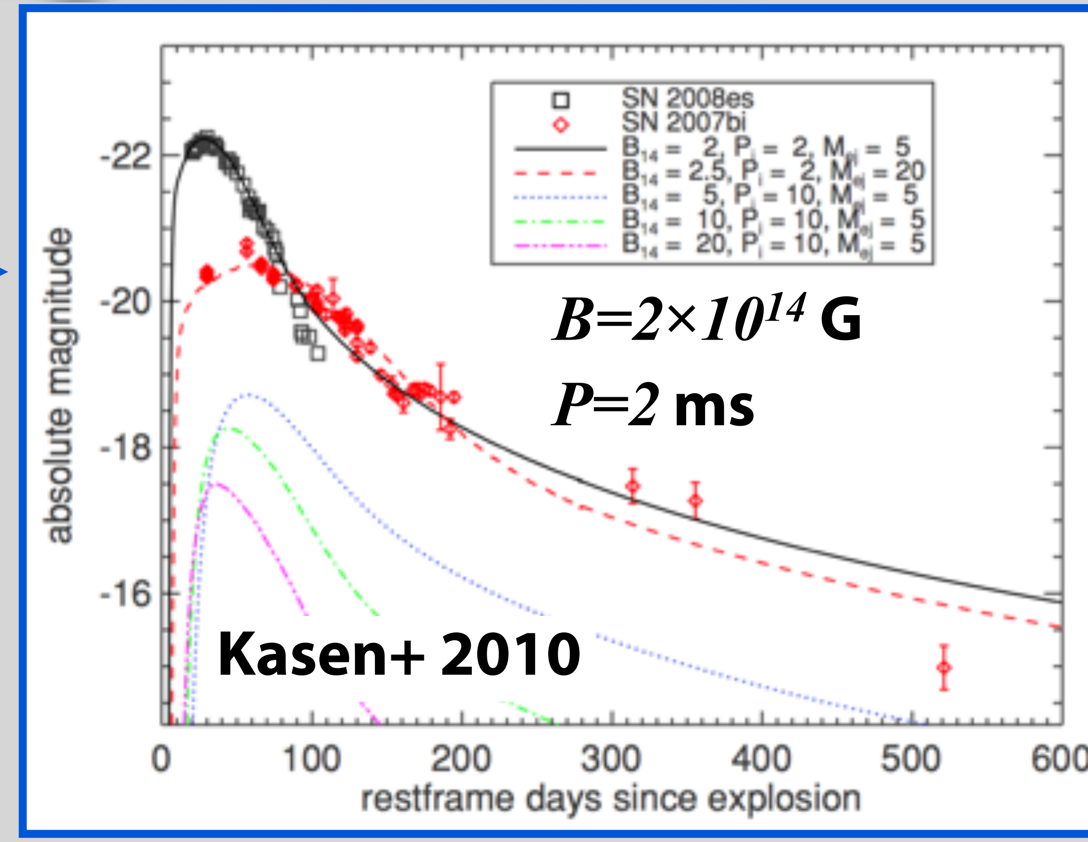
* **small kick velocity due to small ejecta mass**
* **small eccentricity (e~0.1), compatible with binary pulsars J0737-3039 (e=0.088 now and ~0.11 at birth of second NS)** Piran & Shaviv 05
* **event rate (~1% of core-collapse SN)** Tauris+13, 15, Drout+ 13, 14
  * SN surveys (e.g., HSC, PTF, Pan-STARRS, and LSST) will give constraint on NS merger rate

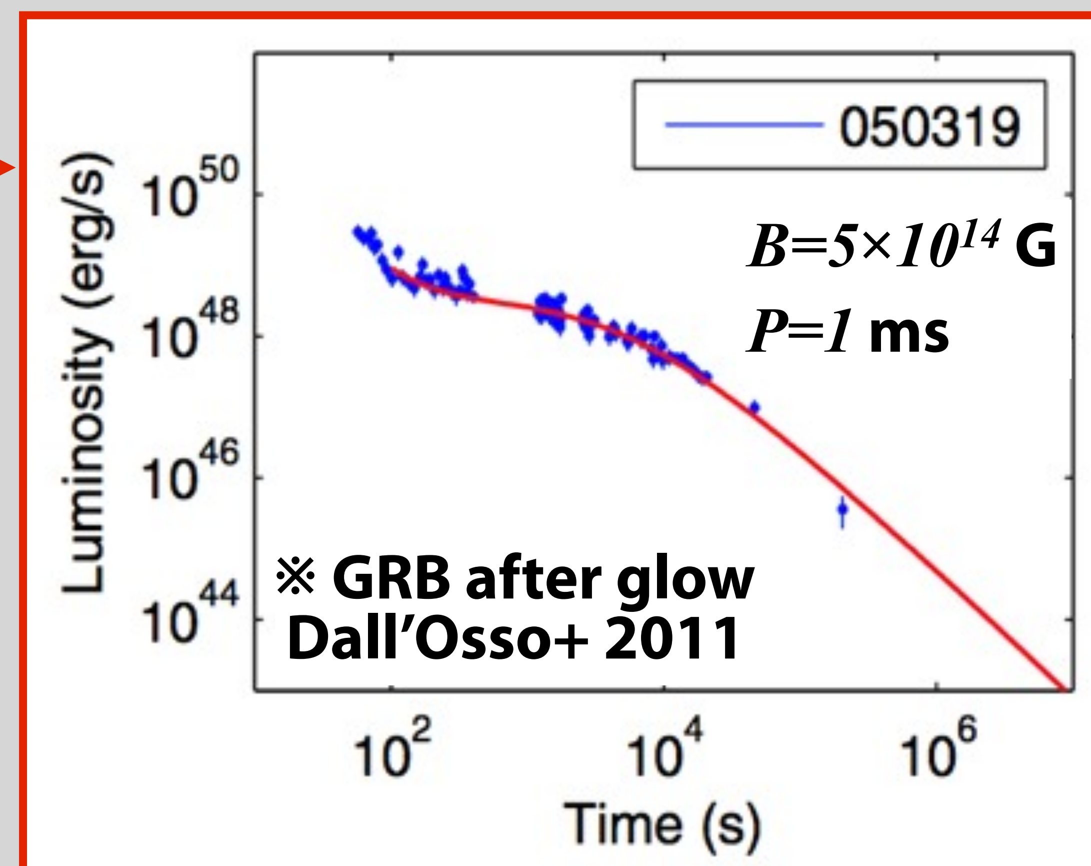
* **nucleosynthesis calculations and radiation transfer simulations will be done based on our model**

3. Magnetar formation

Magnetar formation and bright transients



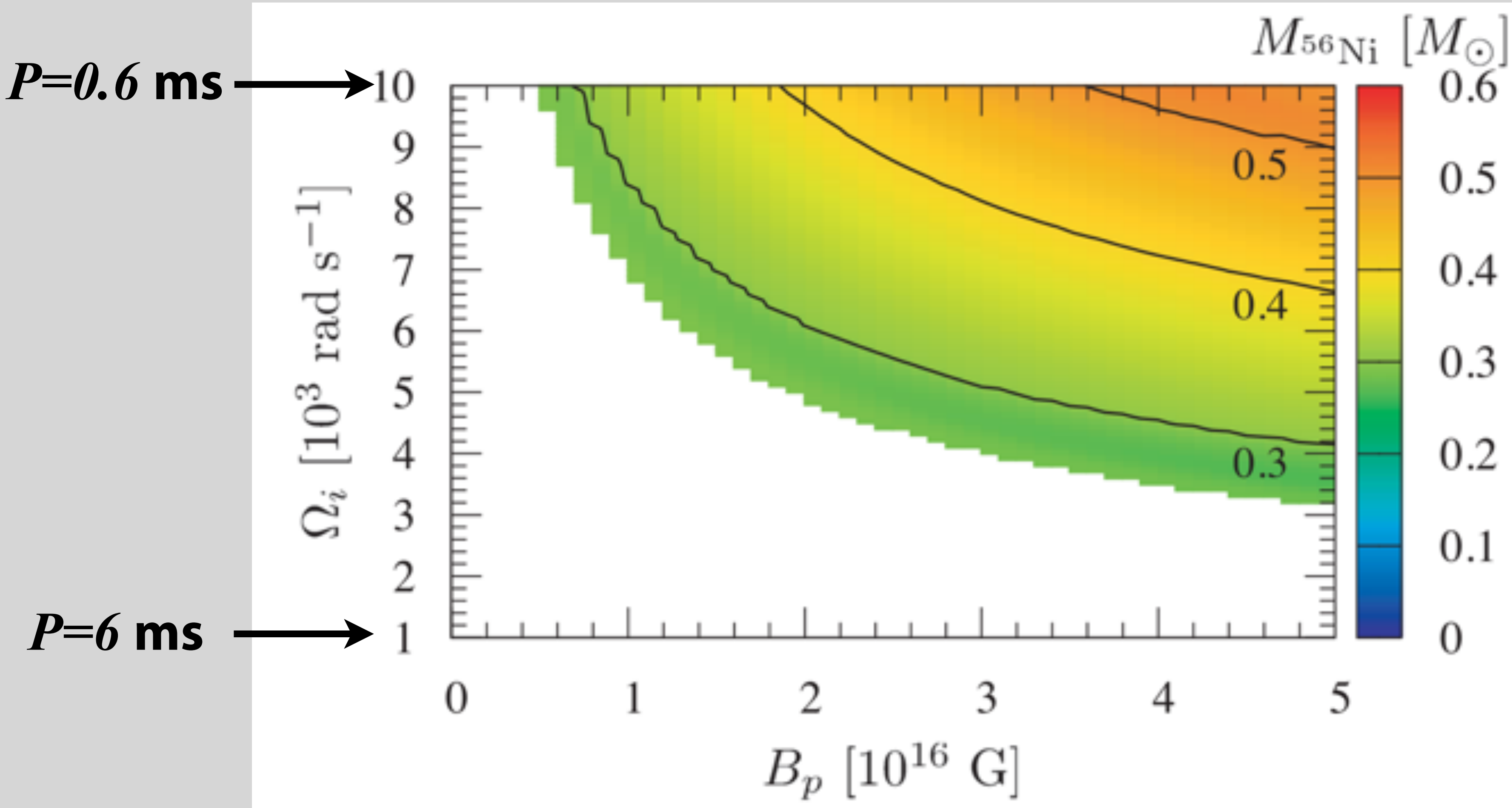




- **SLSNe and GRB afterglows can be fitted by strongly magnetize NS (magnetar) model**
- **ALL models based on dipole radiation formula ($L\sim B^2P^{-4}$, $\Delta t\sim B^{-2}P^2$)**
- $B\sim O(10^{14})$**G,** $P\sim O(1)$**ms**

Magnetar formation and bright transients

[Suwa, Tominaga, MNRAS, **451**, 4801 (2015)]



$$L_\mathrm{w} = 6.18 \times 10^{51} \mathrm{erg\ s^{-1}} \times \left(\frac{B_\mathrm{p}}{10^{16}\ \mathrm{G}}\right)^2 \left(\frac{R}{10\ \mathrm{km}}\right)^6 \left(\frac{\Omega}{10^4\ \mathrm{rad\ s^{-1}}}\right)^4 .$$

$$T_\mathrm{d} = \frac{3Ic^3}{B_\mathrm{p}^2 R^6 \Omega_\mathrm{i}^2} = 8.08\ \mathrm{s} \left(\frac{B_\mathrm{p}}{10^{16}\ \mathrm{G}}\right)^{-2} \left(\frac{R}{10\ \mathrm{km}}\right)^{-6} \times \left(\frac{\Omega_\mathrm{i}}{10^4\ \mathrm{rad\ s^{-1}}}\right)^{-2} \left(\frac{I}{10^{45}\ \mathrm{g\ cm^2}}\right) .$$

* **To make consistent model for GRB & hypernovae, we need $O(0.1)M_\odot$ of ^{56}Ni to explain hypernova (optical) components**
* **Postshock temperature of shock driven by magnetar dipole radiation should be $>5\times10^9$ K**
* **For $M_\mathrm{Ni}>0.2\ M_\odot$, $(B/10^{16}\mathrm{G})^{1/2}(P/1\ \mathrm{ms})^{-1}>1$ is necessary**

Summary

- **Supernova explosions by neutrino-heating mechanism have become possible in the last decade**
- **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...
  - **magnetar formation**
    - related to super-luminous supernovae, hypernovae, gamma-ray bursts...