Neutrinos from explosive astrophysical objects

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公募研究「爆発的天体現象とニュートリノ輸送」

Supernovae are stellar deaths

Remarks on Super-Novae and Cosmic Rays

5. *The super-nova process*

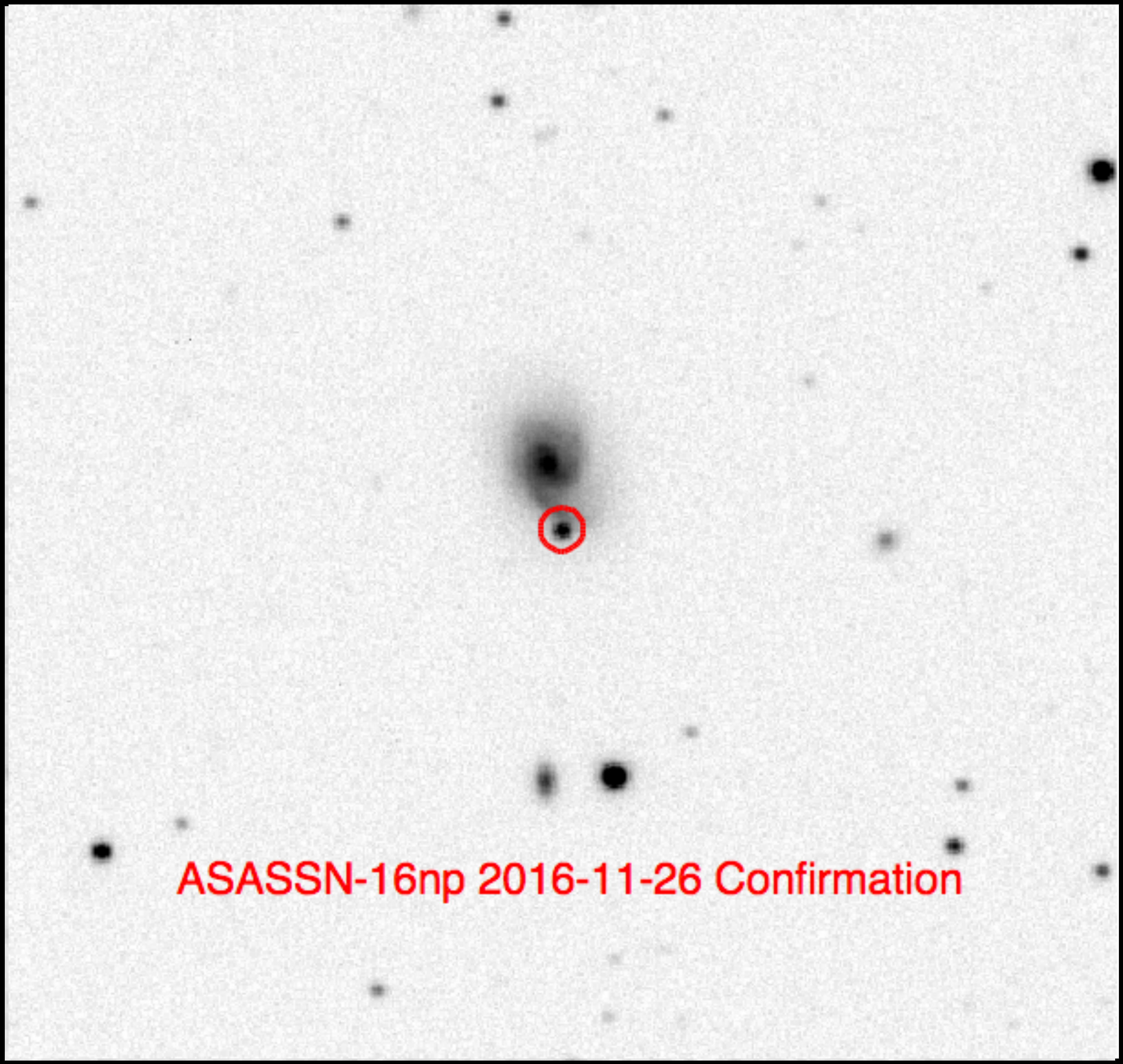
We have tentatively suggested that the super-nova process represents the transition of an ordinary star into a neutron star. If neutrons are produced on the surface of an ordinary star they will "rain" down towards the center if we assume that the light pressure on neutrons is practically zero. This 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

A supernova



(c)ASAS-SN project

Key observables characterizing supernovae

10^{51}erg = 10^{44}J = 6.2x10^{53}GeV
$M_\odot$ (solar mass) = 2.0x10^{30}kg = 1.1x10^{57}GeV/c^2

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

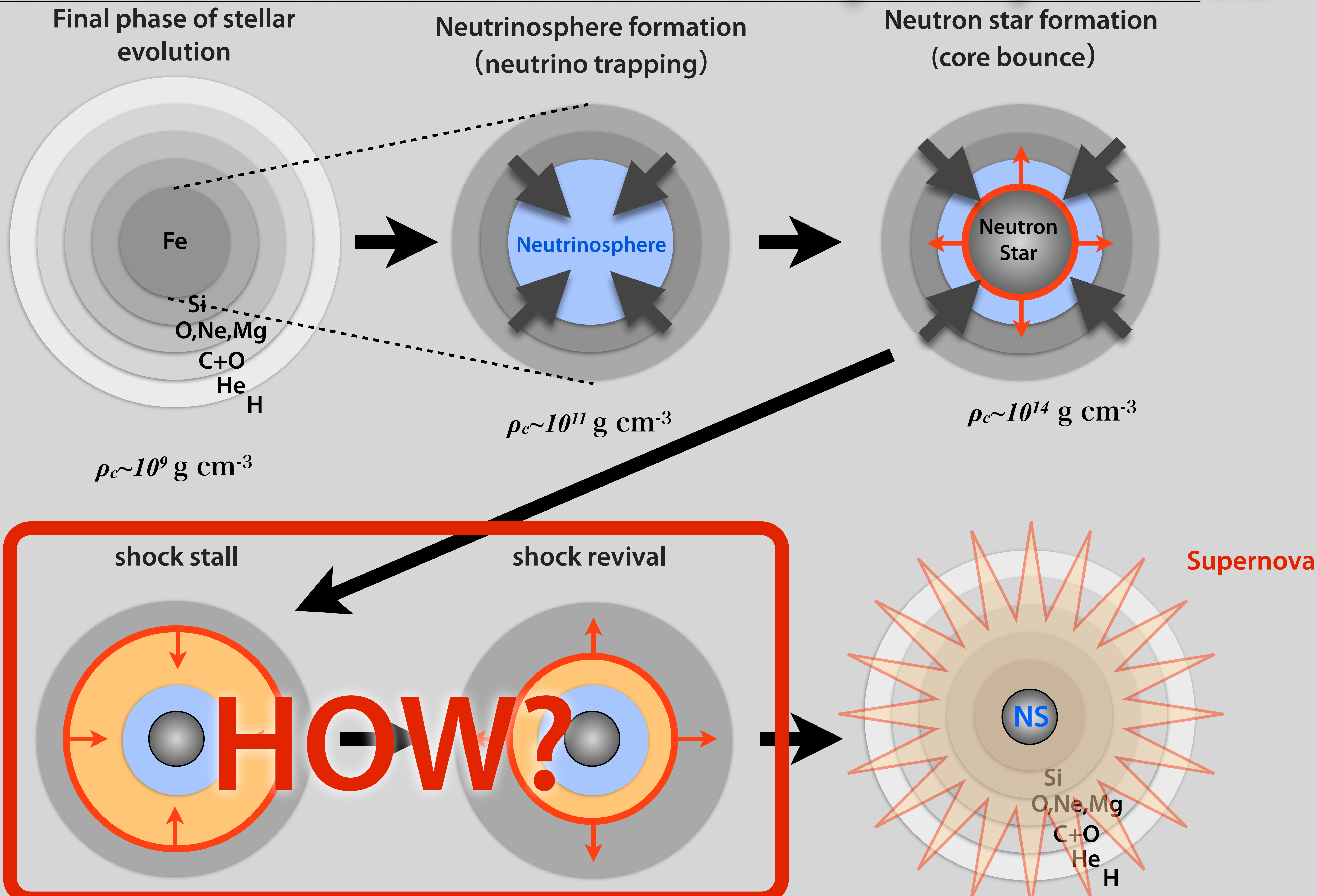
measured by fitting SN light curves (i.e. time evolution of brightness)

- Neutron star mass: ~1 - 2 $M_\odot$

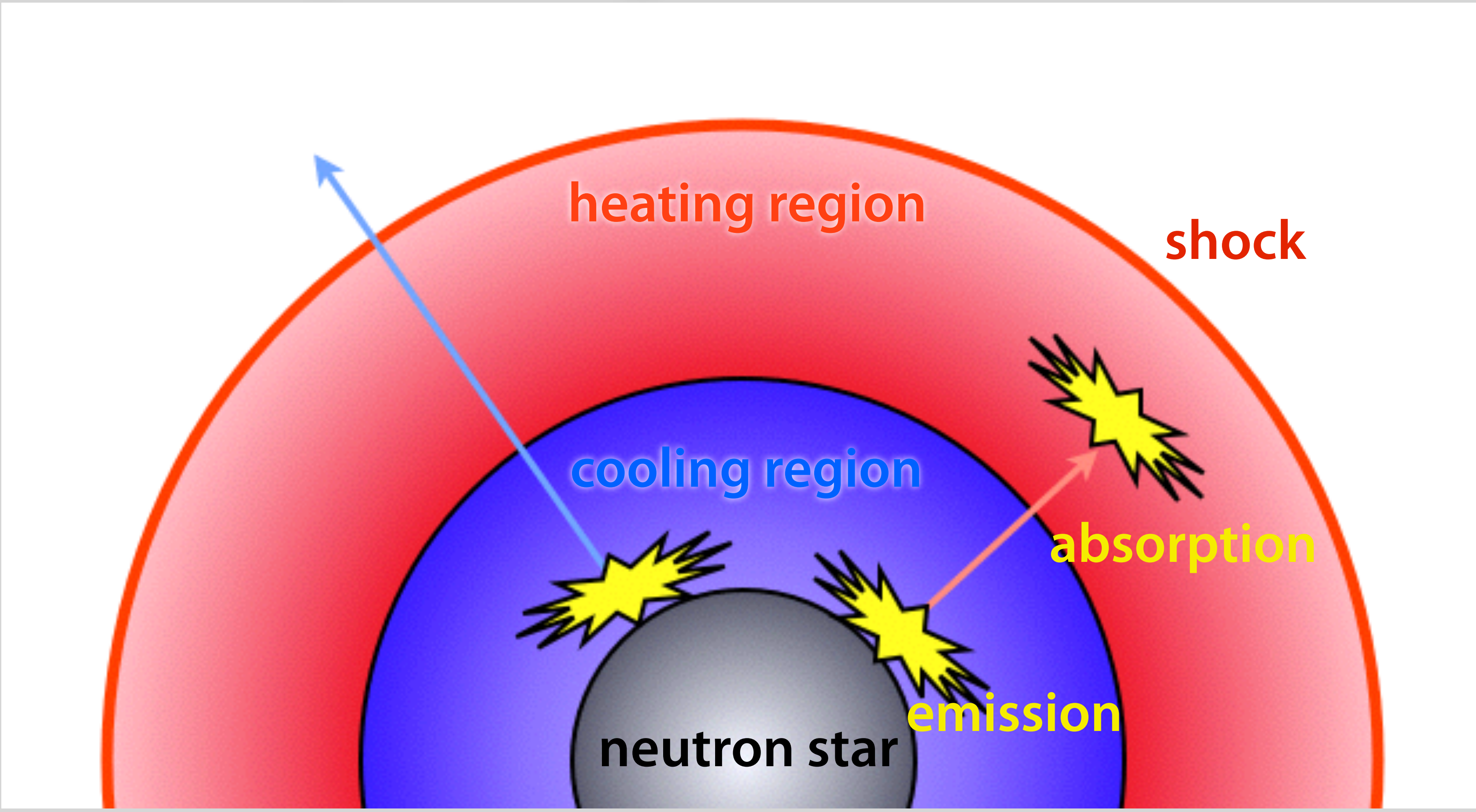
measured by binary systems

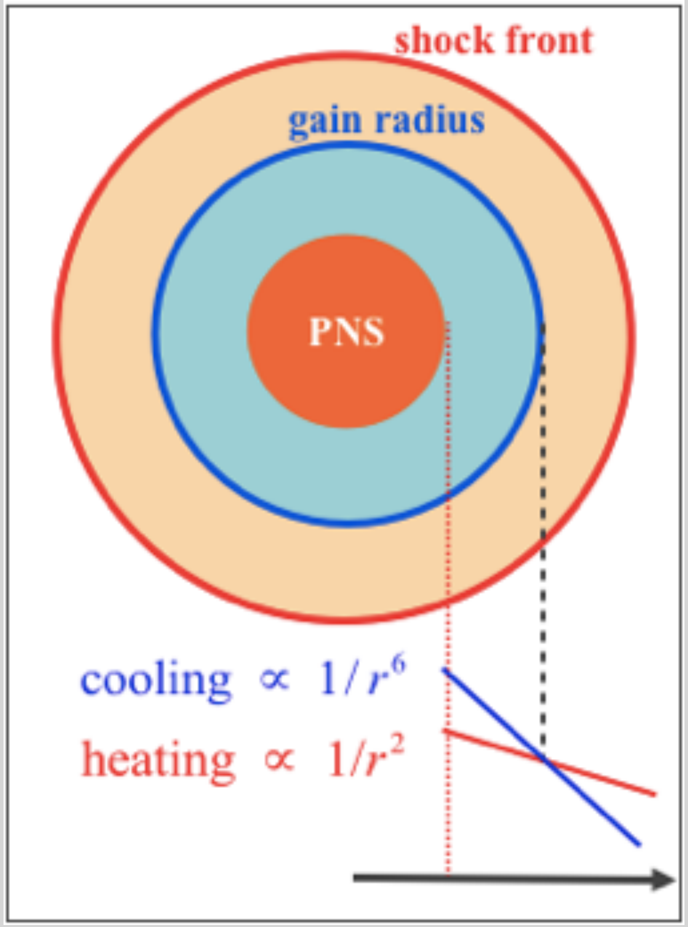
final goal of first-principle (*ab initio*) simulations

Standard scenario of core-collapse supernovae



Current paradigm: neutrino-heating mechanism



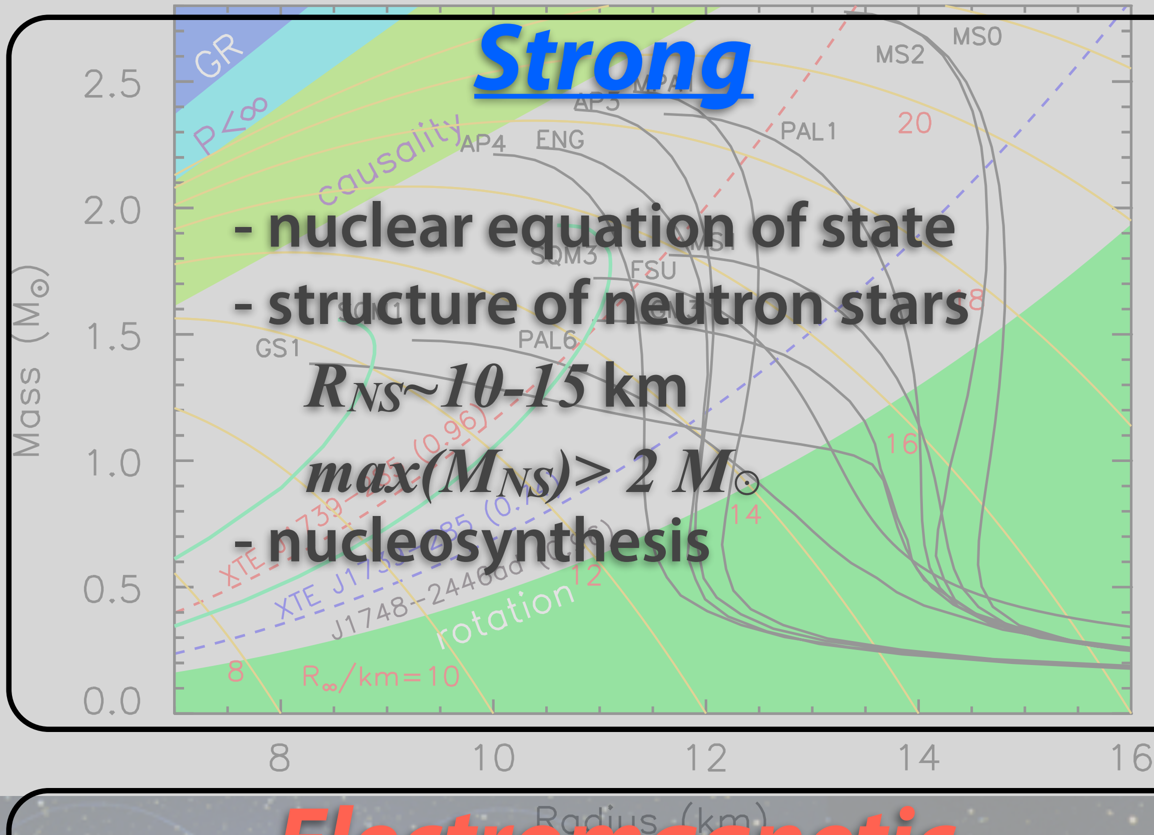


- A CCSN emits $O(10^{58})$ of neutrinos with $O(10)$ MeV.
- Neutrinos transfer energy
  - Most of them are just escaping from the system (cooling)
  - Part of them are absorbed in outer layer (heating)
- Heating overwhelms cooling in heating (*gain*) region

Physical ingredients

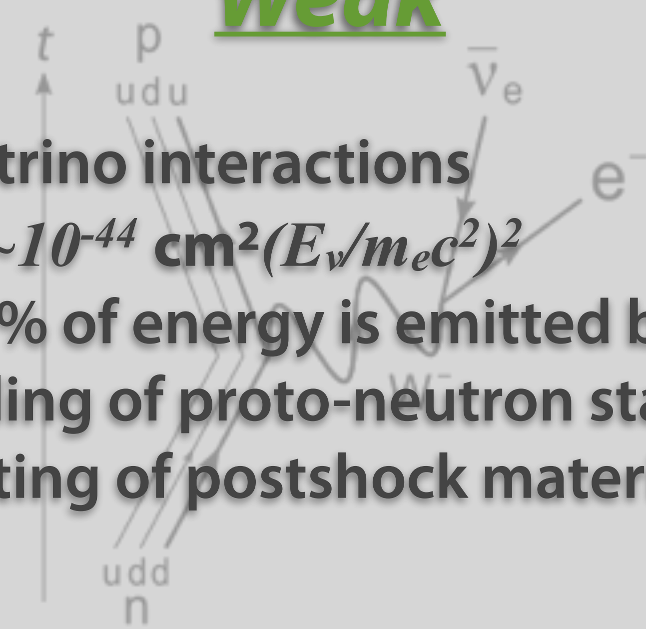
ALL known interactions are involving and playing important roles

Strong



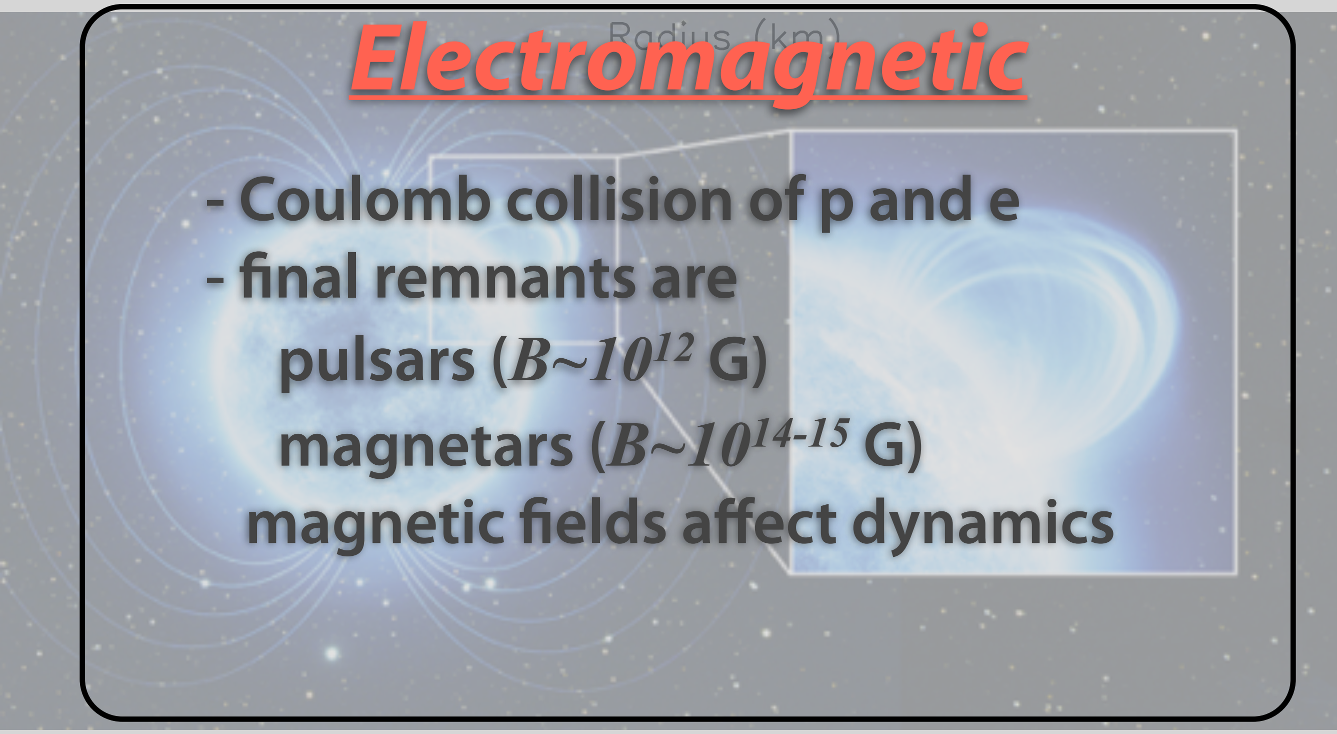
- nuclear equation of state
- structure of neutron stars
  - R_{NS}~10-15 km
  - $max(M_{NS})> 2 M_\odot$
- nucleosynthesis

Weak



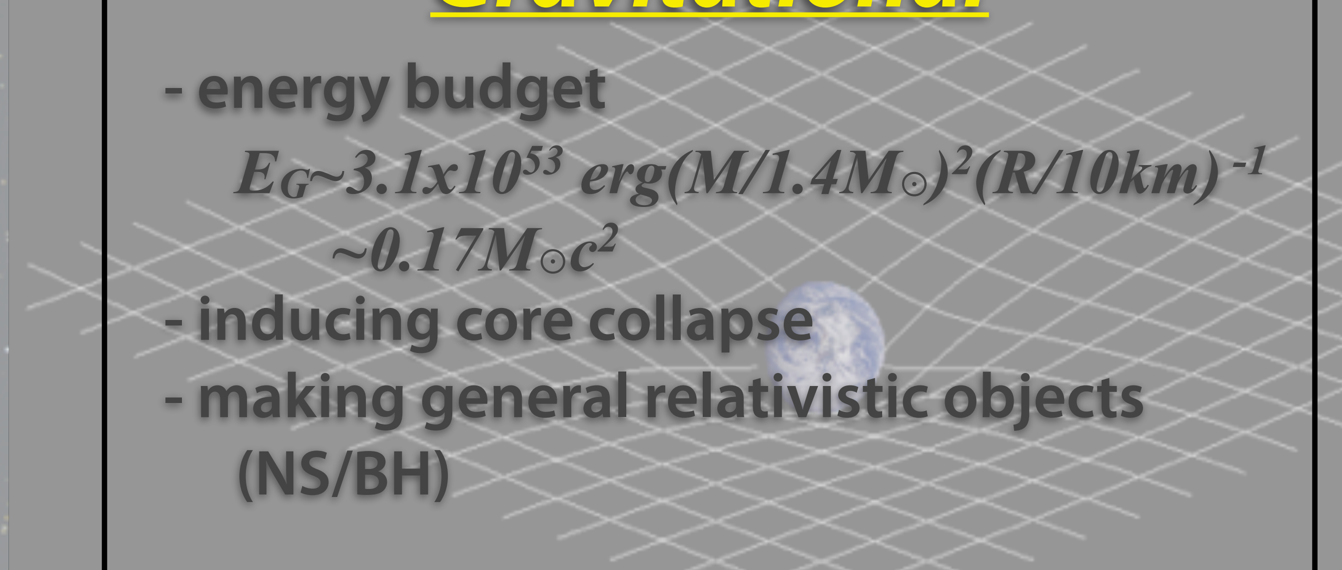
- neutrino interactions
  - $\sigma_\nu \sim 10^{-44}$ cm$^2(E_\nu/m_ec^2)^2$
- ~99% of energy is emitted by ν's
- cooling of proto-neutron star
- heating of postshock material

Electromagnetic



- Coulomb collision of p and e
- final remnants are
  - pulsars (B~10^{12} G)
  - magnetars (B~$10^{14\text{-}15}$ G)
  - magnetic fields affect dynamics

Gravitational



- energy budget
  - $E_G \sim 3.1\times10^{53}$ erg$(M/1.4M_\odot)^2(R/10\text{km})^{-1}$
  - $\sim 0.17 M_\odot c^2$
- 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

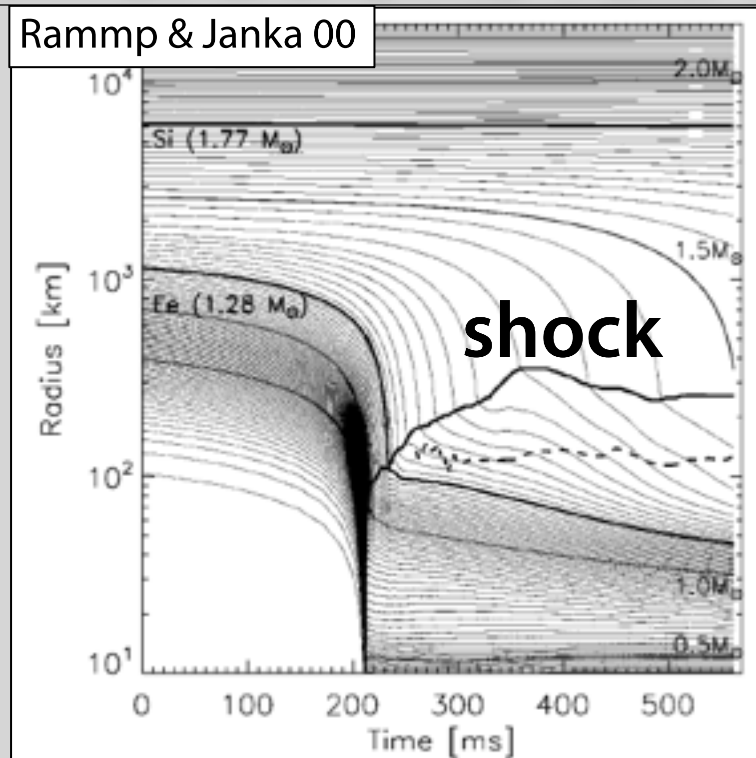
Neutrino Boltzmann equation

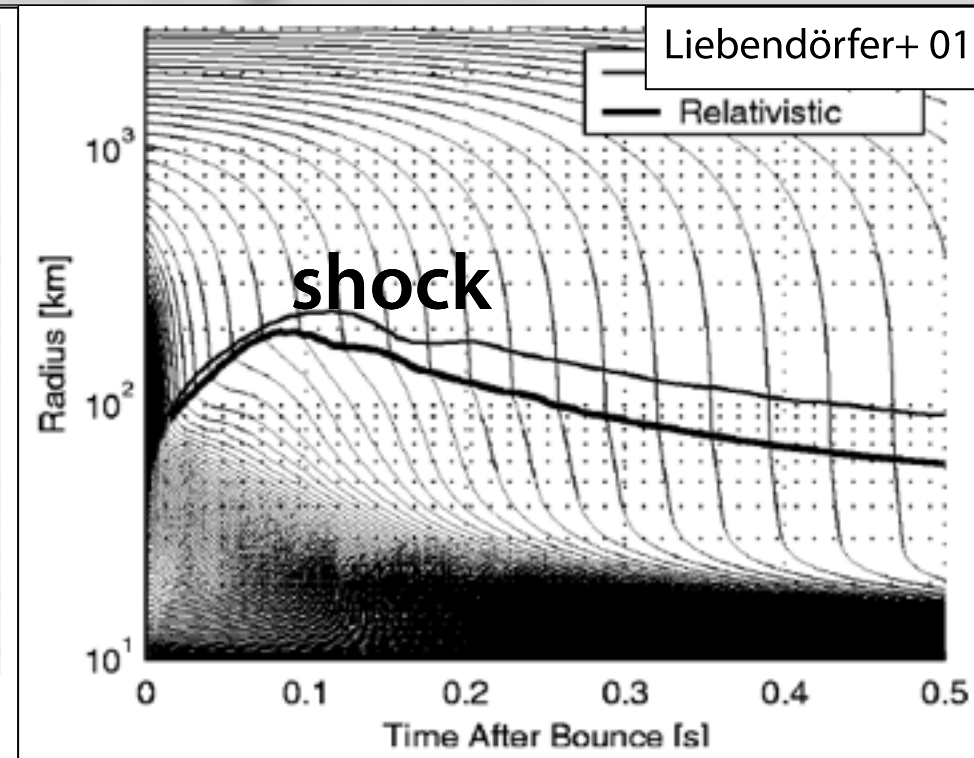
$$\frac{df}{cdt} + \mu \frac{\partial f}{\partial r} + \left[\mu \left(\frac{d \ln \rho}{cdt} + \frac{3v}{cr} \right) + \frac{1}{r} \right] \left(1 - \mu^2\right) \frac{\partial f}{\partial \mu}$$
$$+ \left[\mu^2 \left(\frac{d \ln \rho}{cdt} + \frac{3v}{cr} \right) - \frac{v}{cr} \right] E \frac{\partial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

ρ: density, $\mathbf{v}$: 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

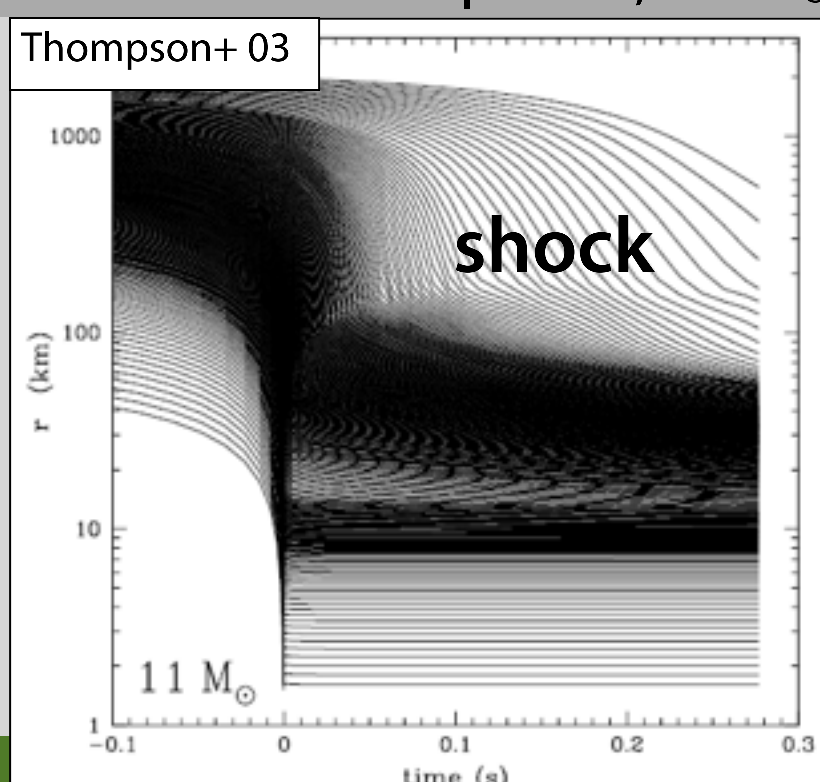
1D SN simulations fail to explode

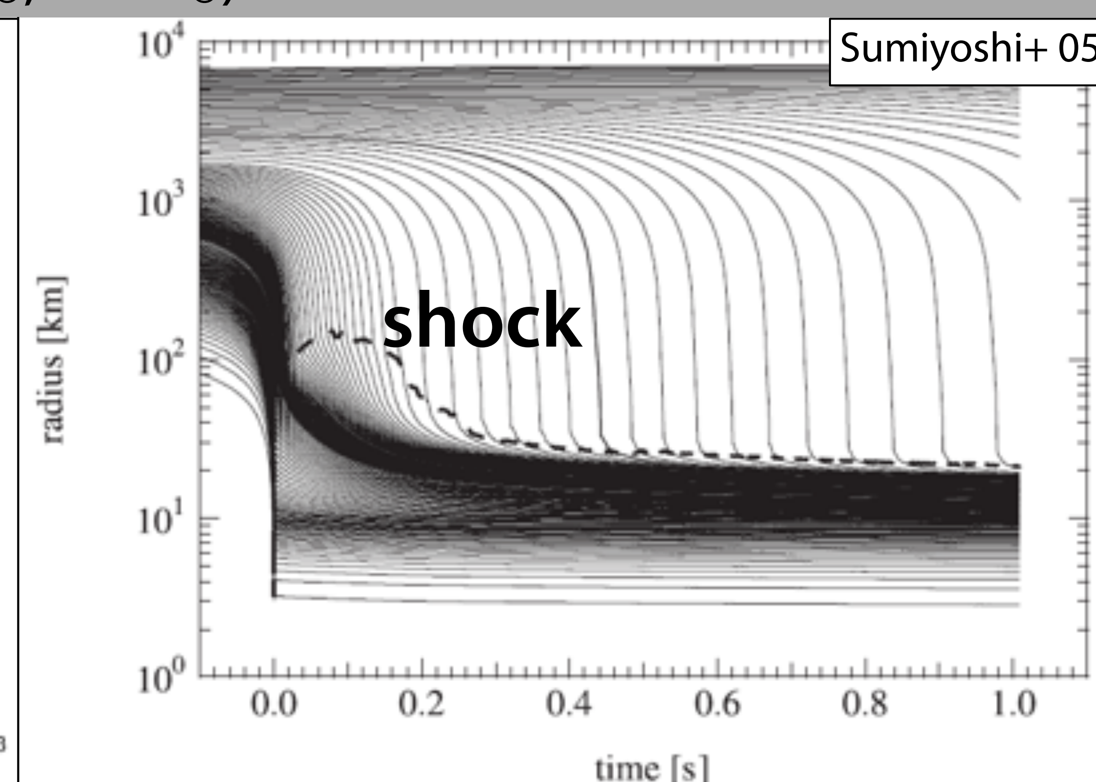




By including all available physics to simulations, we concluded that the explosion cannot be obtained in 1D!

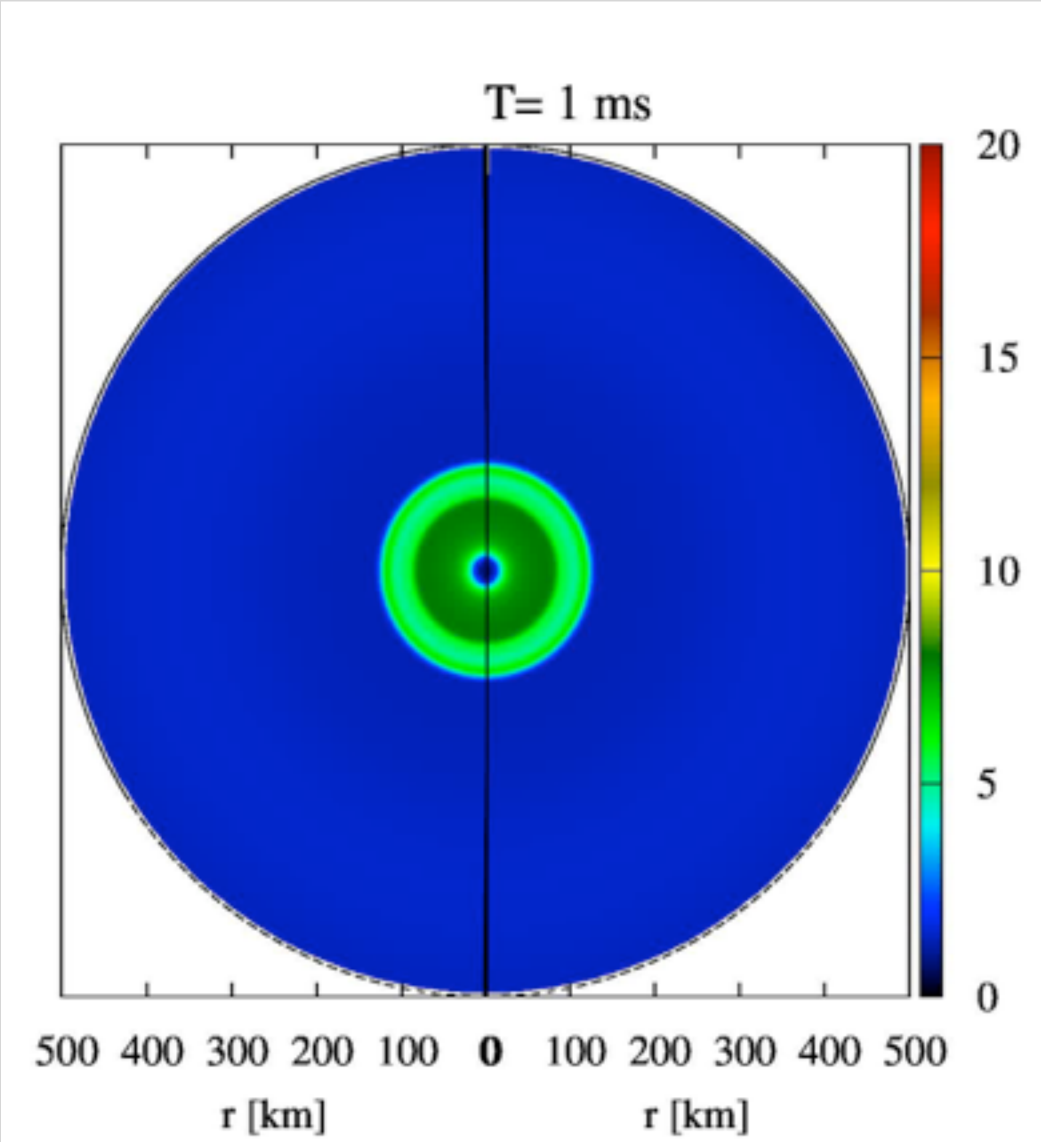
(There are a few exceptions; 8.8M$_\odot$, 9.6M$_\odot$)

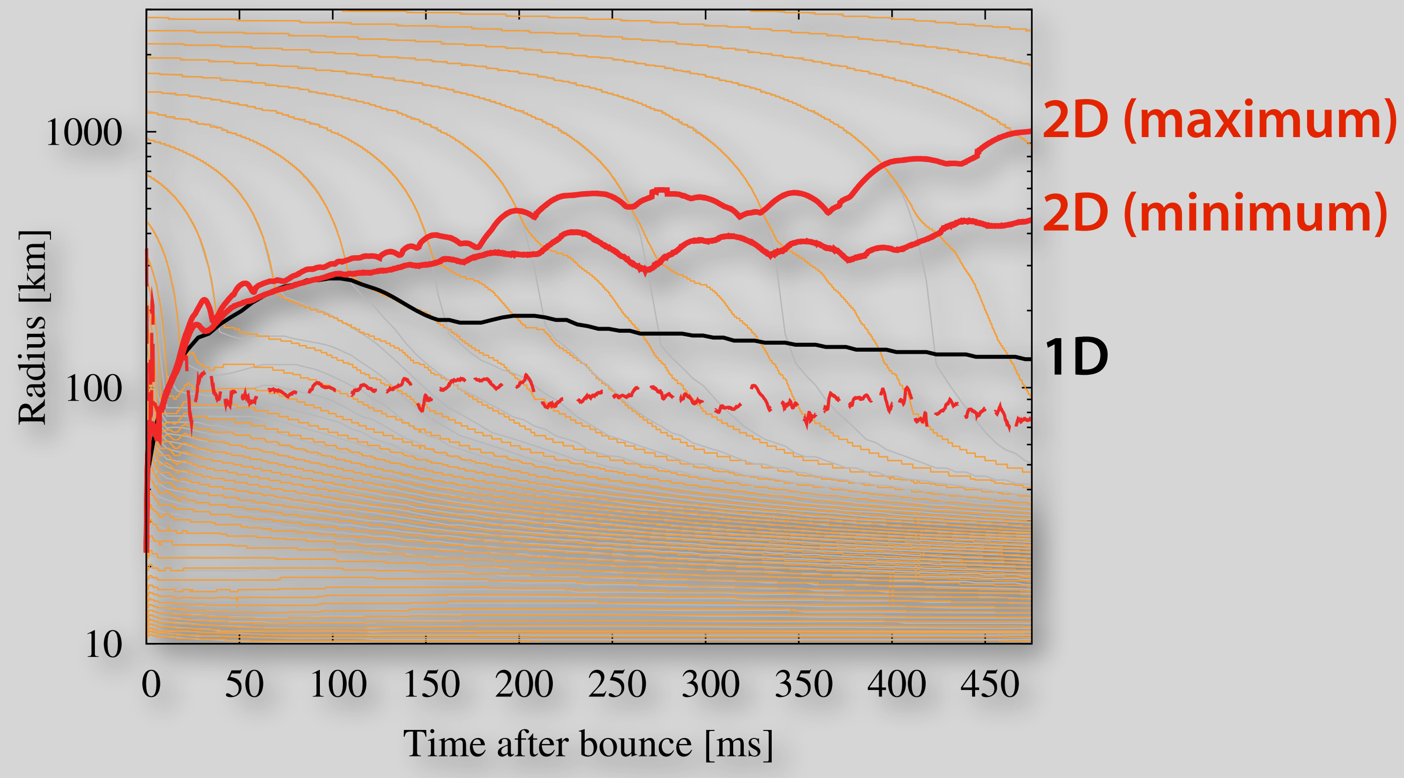




Neutrino-driven explosion in multi-D simulation

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



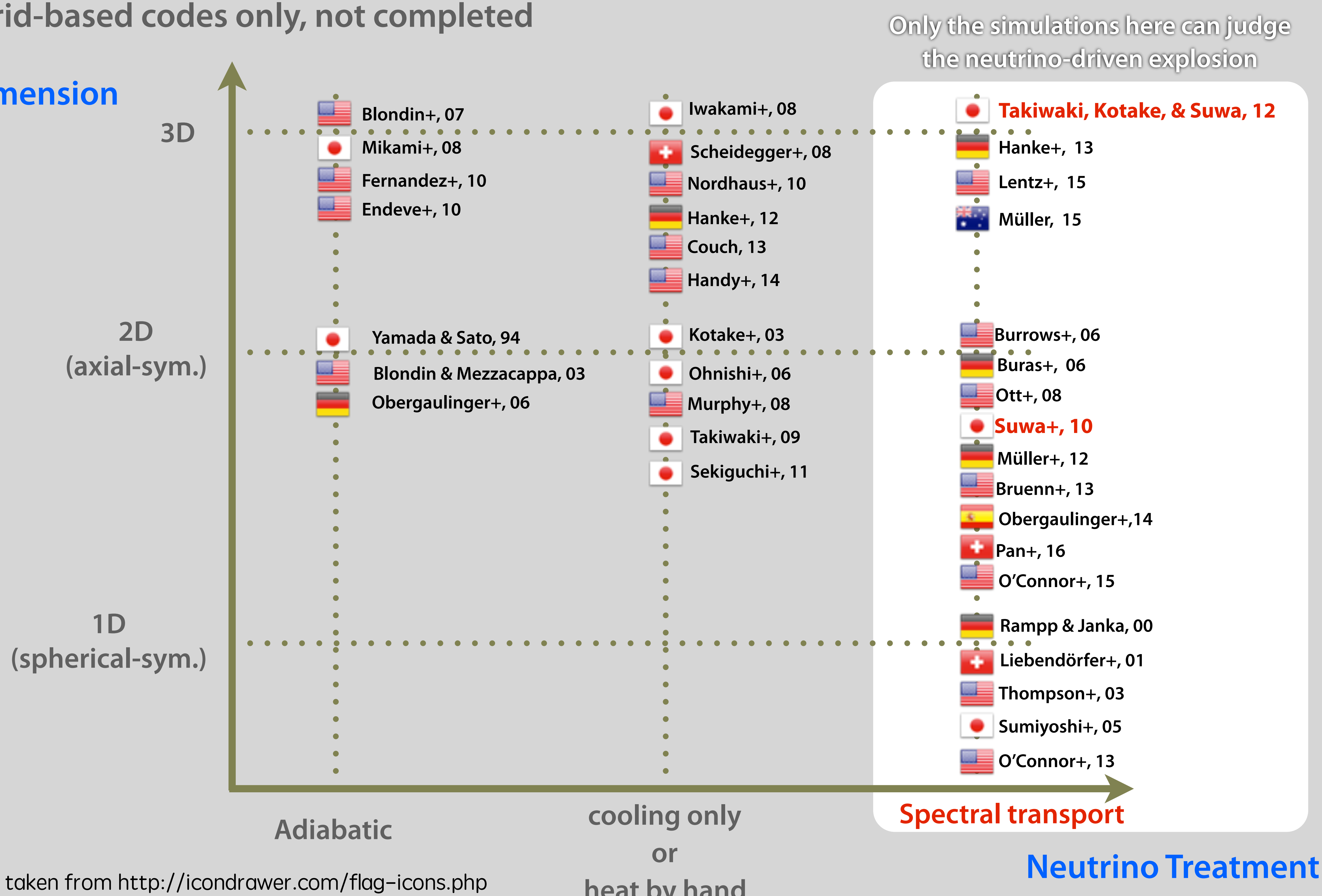


Suwa+ (2D)
PASJ, **62**, L49 (2010)
ApJ, **738**, 165 (2011)
ApJ, **764**, 99 (2013)
PASJ, **66**, L1 (2014)
MNRAS, **454**, 3073 (2015)
ApJ, **816**, 43 (2016)

- **The neutrino heating rate is greatly amplified by multi-D hydrodynamic effects**
  - **convection**
  - **standing-accretion shock instability**

Dimensionality and neutrino transfer

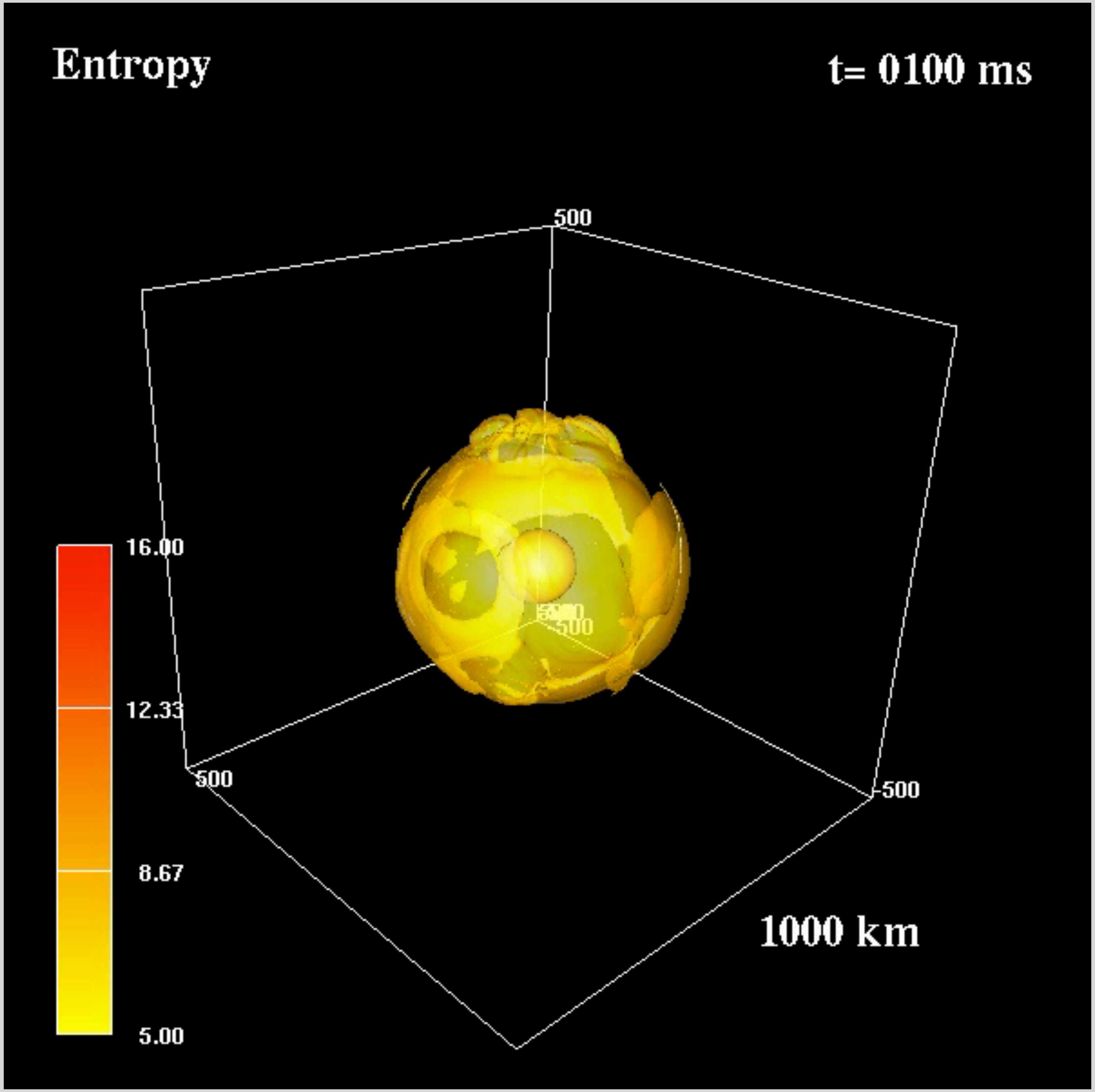
※grid-based codes only, not completed



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); MNRAS, **461**, L112 (2016)]



$M_{ZAMS}=11.2\ M_{\odot}$

384(r)x128(θ)x256(φ)x20(E_{ν})

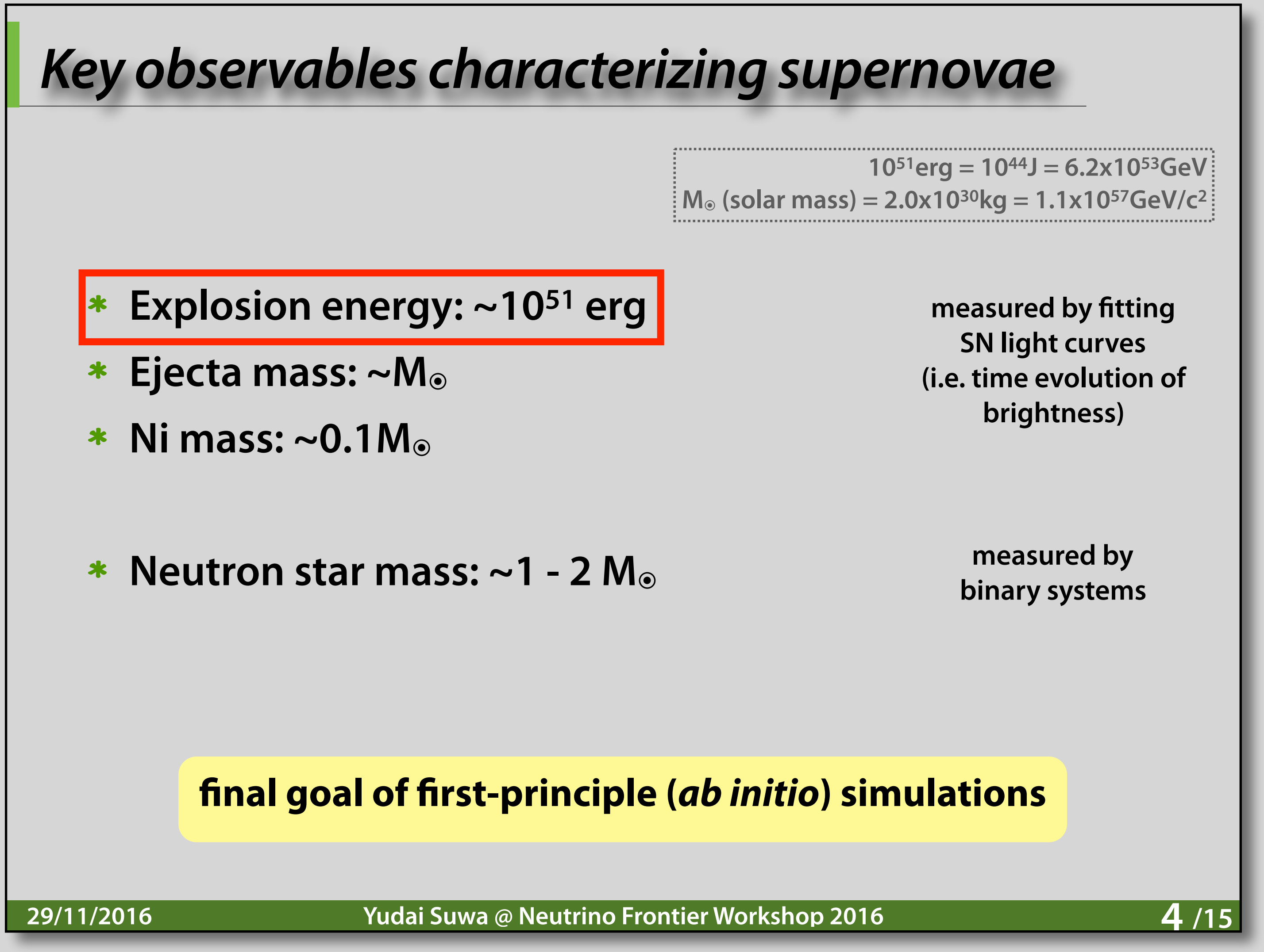
XT4

T2K-Tsukuba

K computer

Note: there are problems

- 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
- We need still more efforts to understand supernova mechanism



Possible solution: extension of neutrino transfer eq.

$$\mathbf{L}[f]=\mathbf{C}[f]$$

Liouville operator (number conservation in phase space)

Collision operator (particle interactions)

- **Relativistic correction**
  Collision operator used in simulations is truncated up to O(v/c) and higher order terms are not taken into account, which may change neutrino spectrum and heating rate.

- **Quantum correction**
  Liouville operator is based on classical particle picture. Quantum effects would introduce additional terms. Related to neutrino oscillation and chiral anomaly.

Summary

* **Neutrinos play essential roles in supernova explosions**
* **None of modern simulations have obtained realistic explosions so far**
* **We might be missing something important**
* **Two possibilities in neutrino transfer equation**
  * relativistic correction
  * quantum correction