超新星にまつわる物理:
状態方程式依存性と重力波放出

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計算科学研究機構
Advanced Institute for Computational Science

Core-collapse supernovae

- One of the most energetic explosion in the universe
  - $E_{exp} \sim 10^{51}$ erg
  - $E_{grav} \sim 10^{53}$ erg ($\sim 0.1\ M_\odot\ c^2$)
  - $E_\nu \sim 10^{53}$ erg
- Transition from a massive stellar core to a neutron star (Birth of neutron stars!)

✤ All known interactions are important

Macrophysics

- Gravity
  - core collapse
- Elecromagnetic
  - pulsar, magnetar,
  - magnetorotational explosion

Microphysics

- Weak
  - neutrino physics
- Strong
  - equation of state of dense matter

Systematics in supernova simulations

Our Goal: Produce Successful Explosion! of ~10^{51} erg

- **Dimensionality of hydrodynamics** — Iwakami+ 08, Nordhaus+ 10, Hanke+ 11, Takiwaki+ 12
- **General relativity** — Liebendörfer+01, Müller+ 12, Kuroda+ 12,
- **Neutrino physics**
  - Scheme to solve Boltzmann equation — Ott+ 08, Shibata+ 11, Sumiyoshi & Yamada 12
  - Interaction rate — Langanke+ 03, Arcones+ 08, Lentz+ 12
  - Collective oscillation — Raffelt & Smirnov 07, Duan+ 10, Dasgupta+ 10
- **Nuclear equation of state** — Lattimer & Swesty 91, H. Shen+ 98, G. Shen+ 10, Furusawa+ 11, Hempel+ 12
- **Initial condition** — Nomoto & Hashimoto 88, Woosley & Weaver 95, Woosley+ 02, Limongi & Chieffi 06, Woosley & Heger 07, Yoshida+ 12
  - progenitor structure (mixing, wind...)
  - rotation / magnetic field

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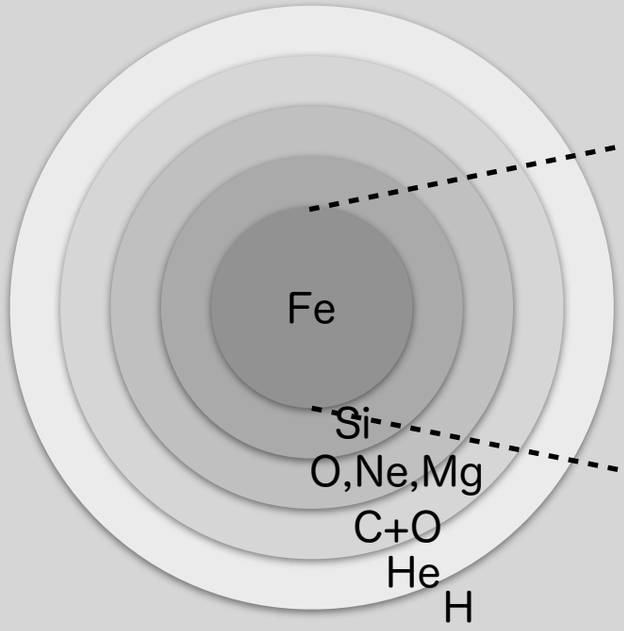
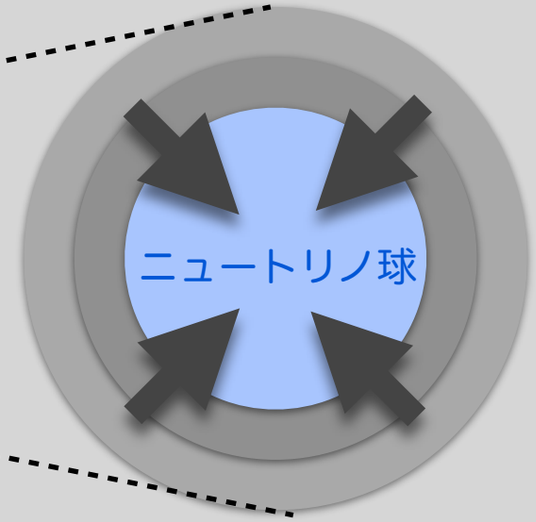
Standard scenario of core-collapse supernovae

星の進化の最終段階

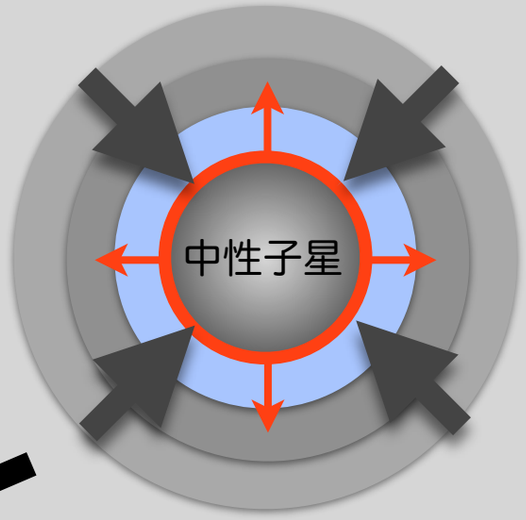


ニュートリノ球形成
（ニュートリノトラップ）



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

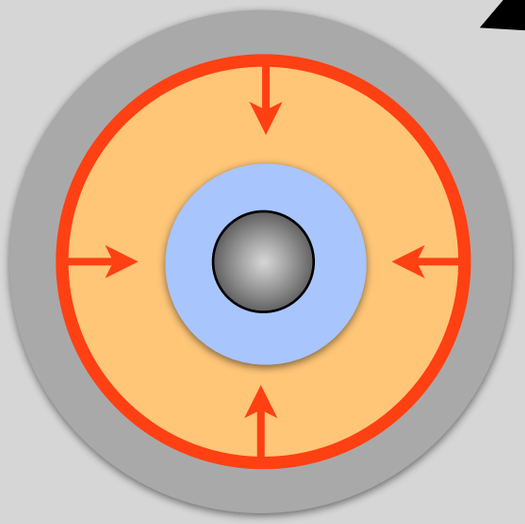
中性子星形成
（コアバウンス）



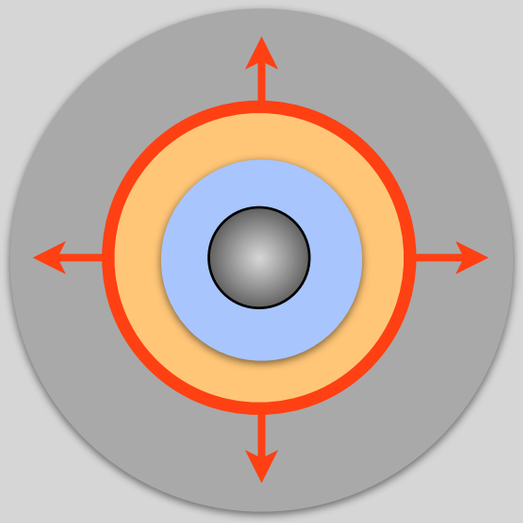
$\rho_c \sim 10^{14}$ g cm^{-3}

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

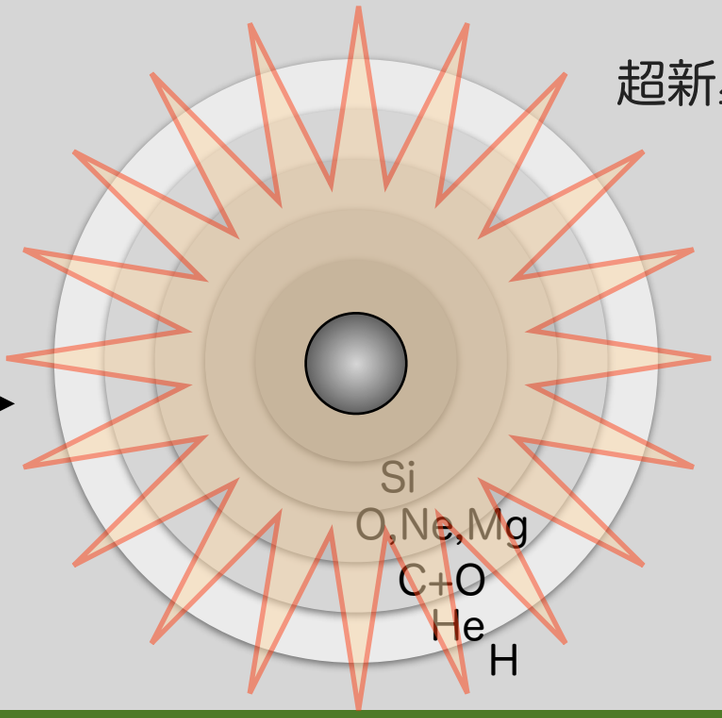
衝撃波の停滞



衝撃波の復活

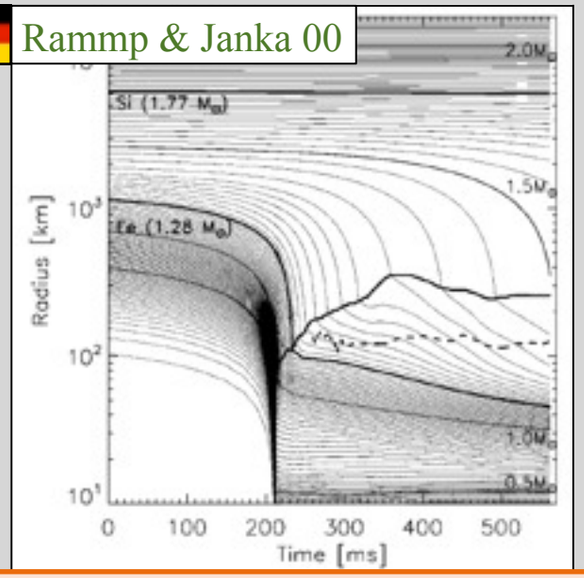


超新星爆発！

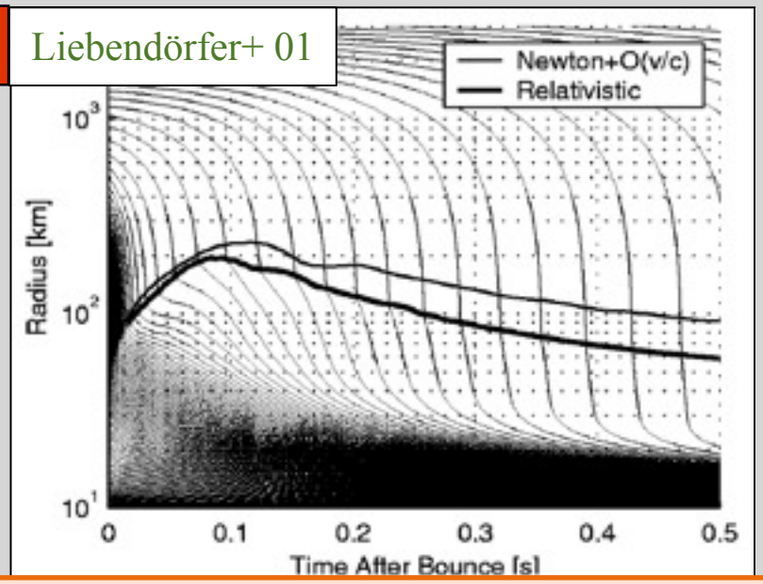


1D simulations: fail to explode

Rammp & Janka 00

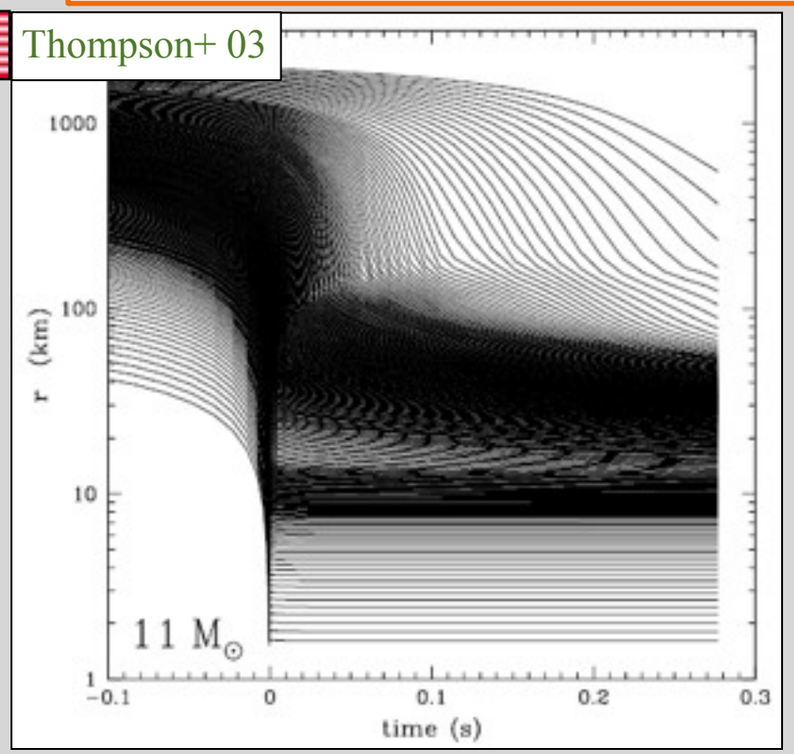


Liebendörfer+ 01

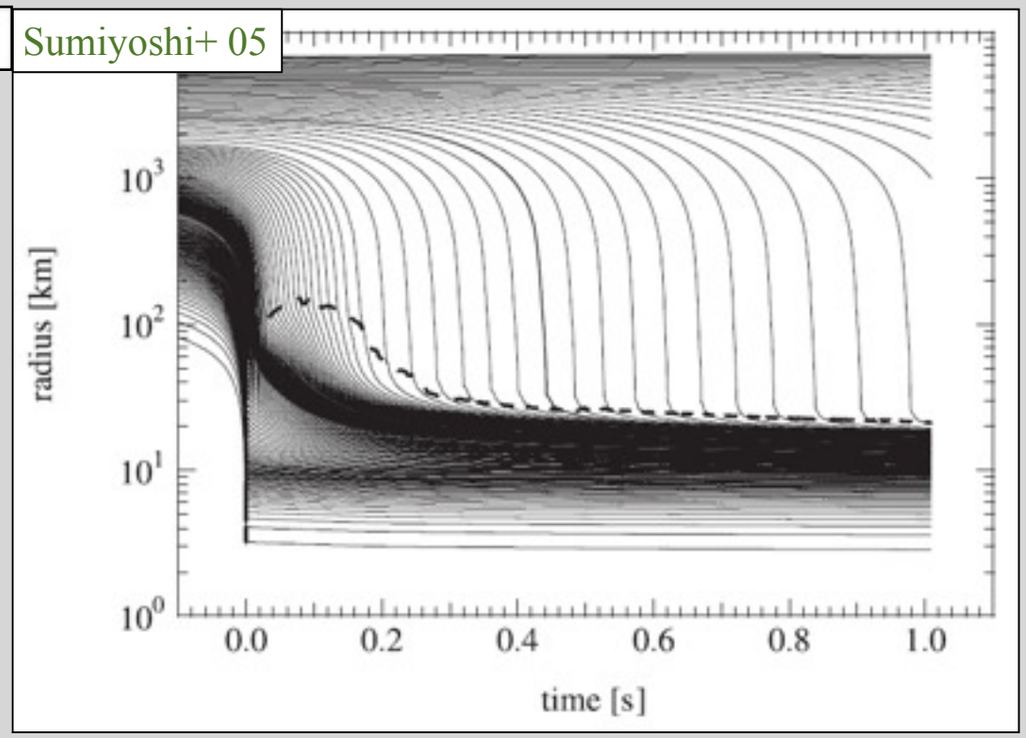


By including all available physics to simulations, we concluded that the explosion cannot be obtained in 1D!
(The exception is an 8.8 $M_\odot$ star; Kitaura+ 06)

Thompson+ 03

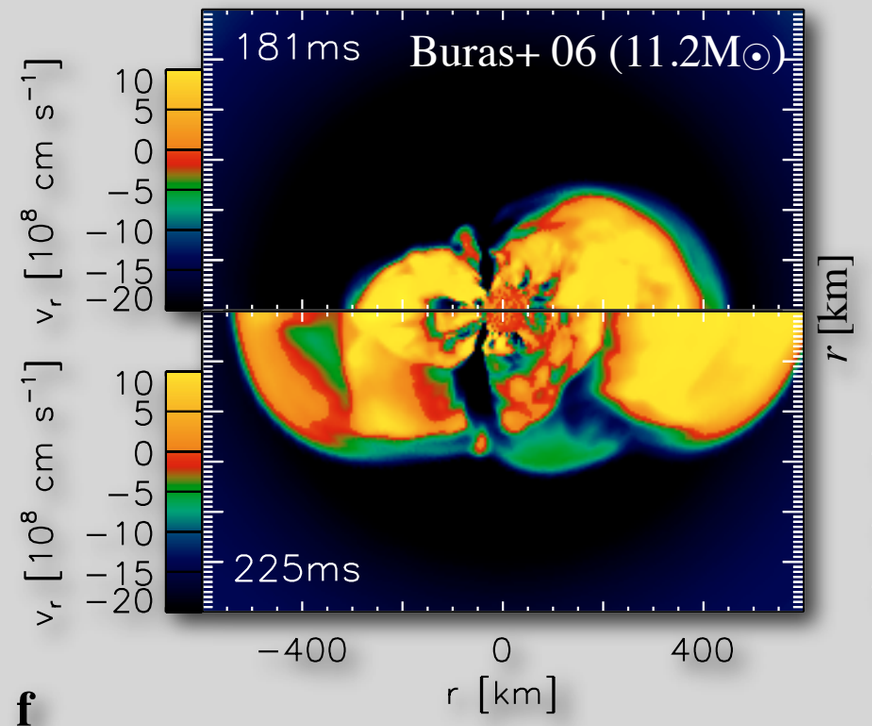


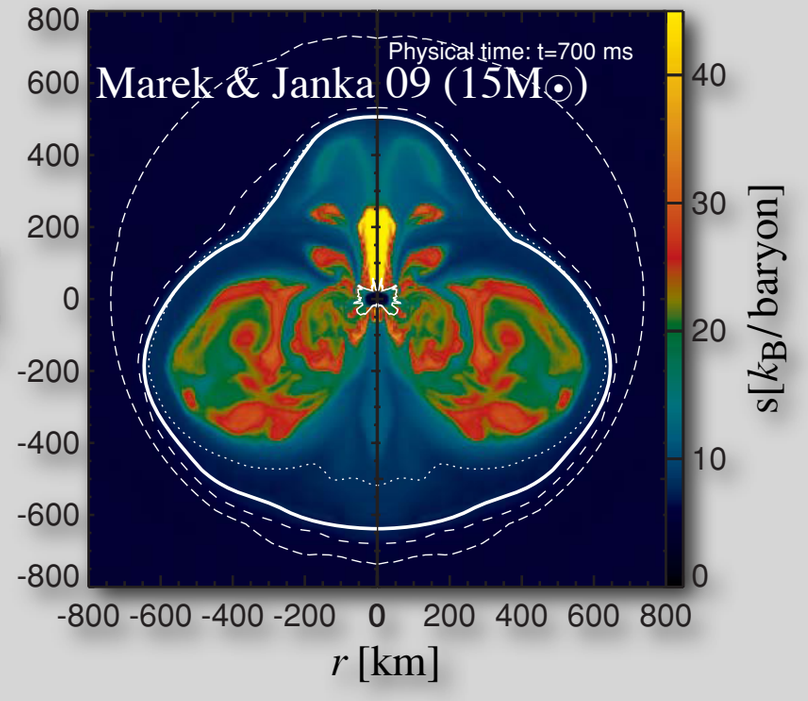
Sumiyoshi+ 05

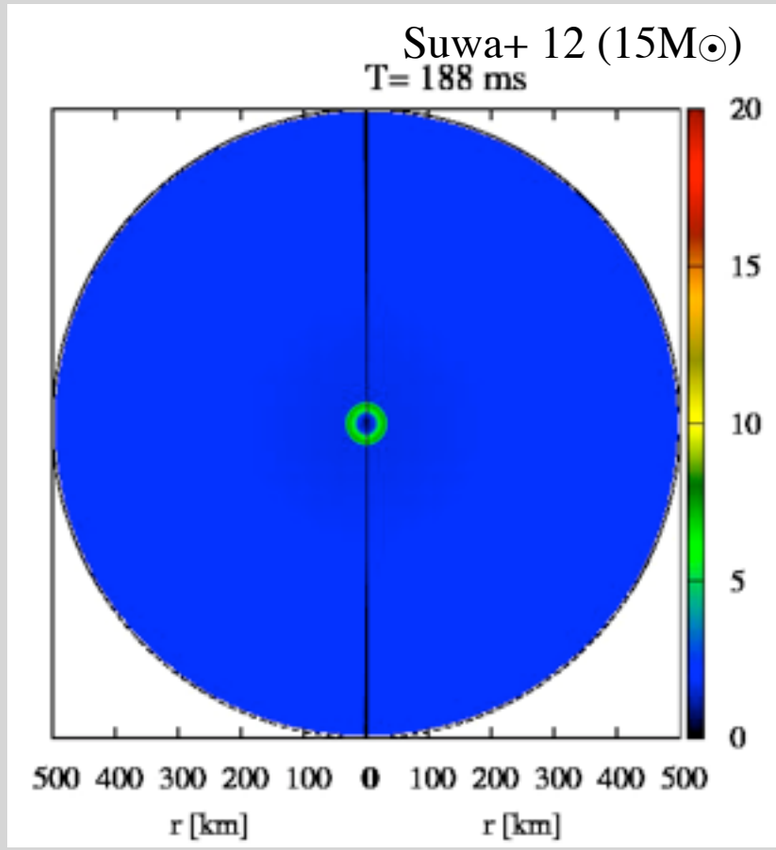


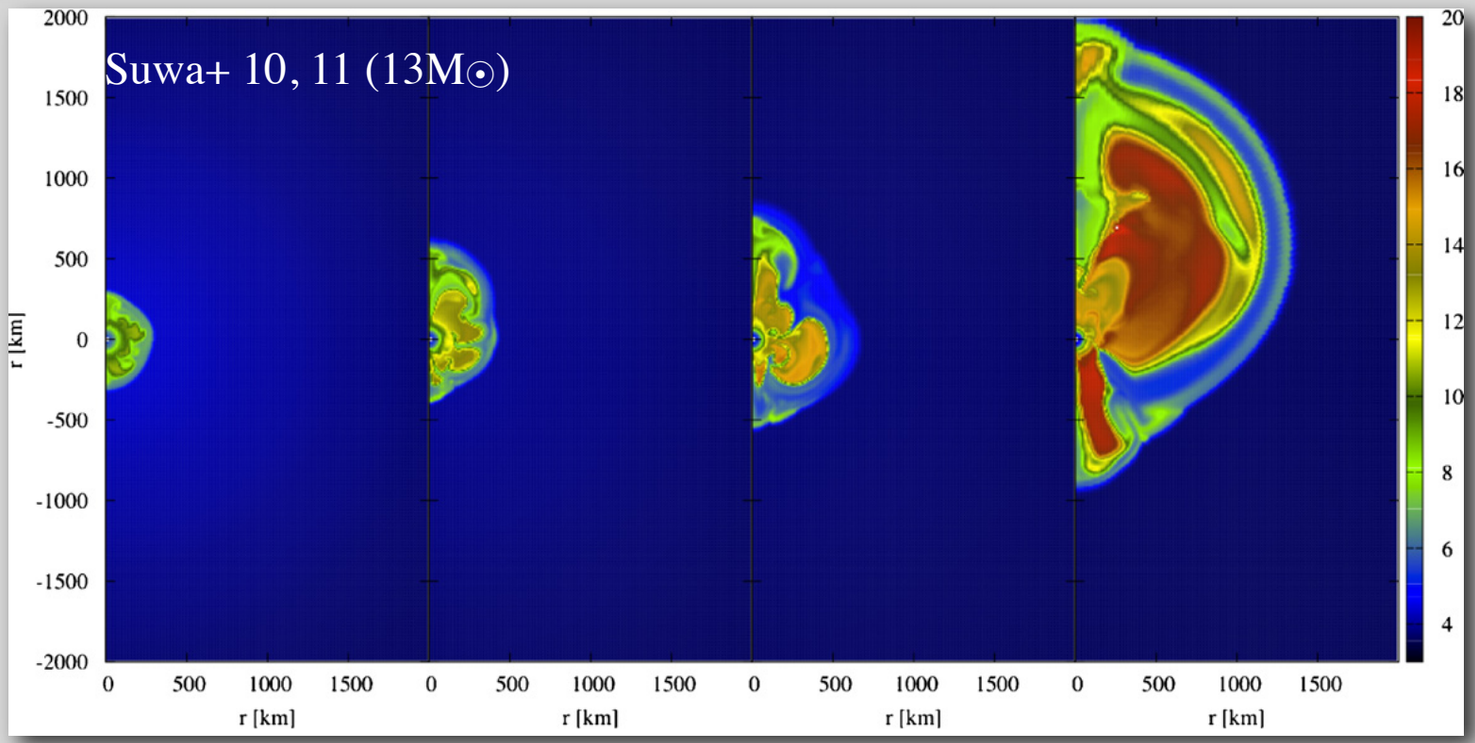
Neutrino-driven explosion

Recently, we have successful exploding models driven by neutrino heating





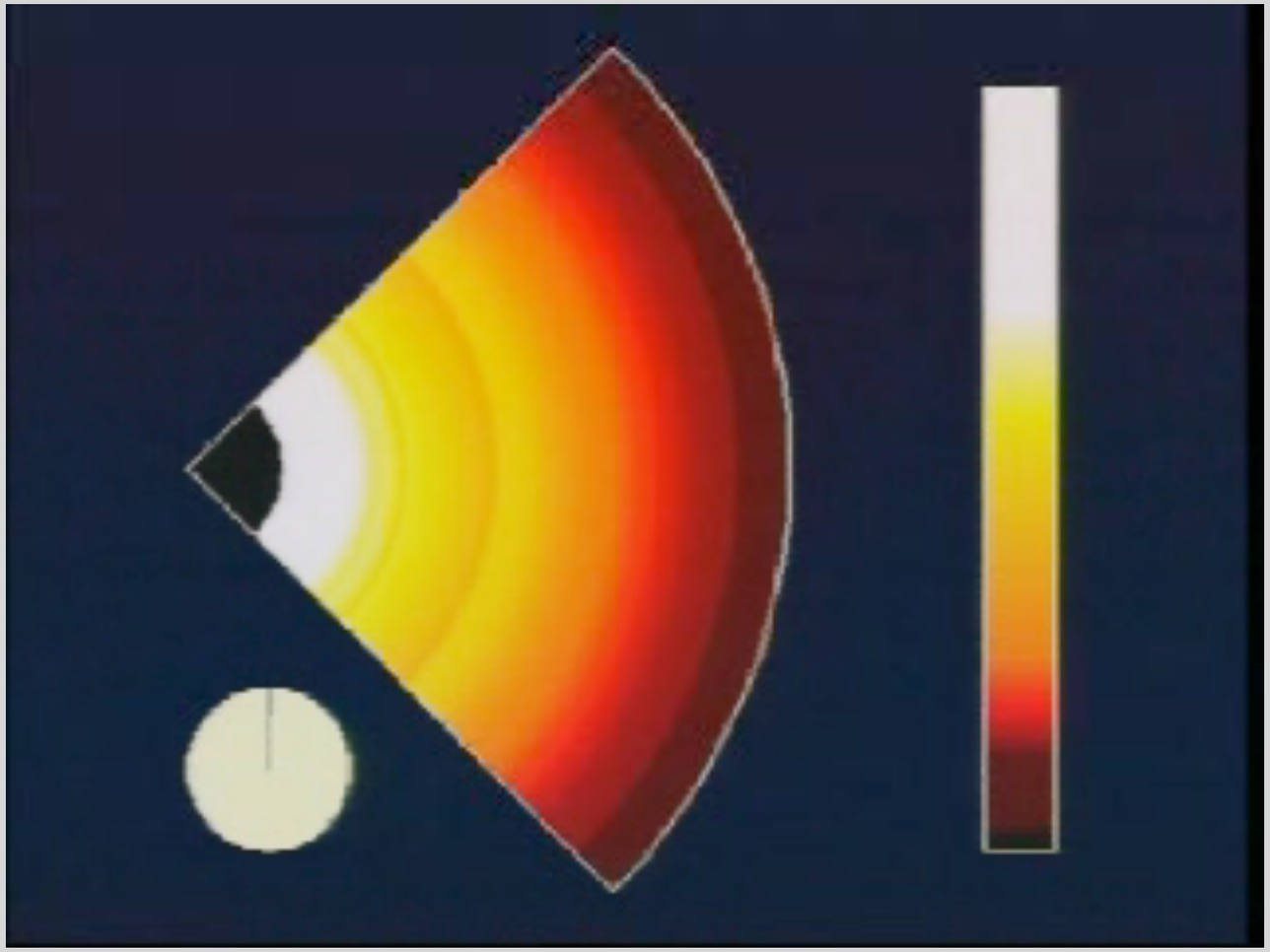




* Neutrino heating is amplified due to multi-D effects such as
  - Convective motion behind the shock wave
  - Standing Accretion Shock Instability (SASI)

Convection and SASI

Convection



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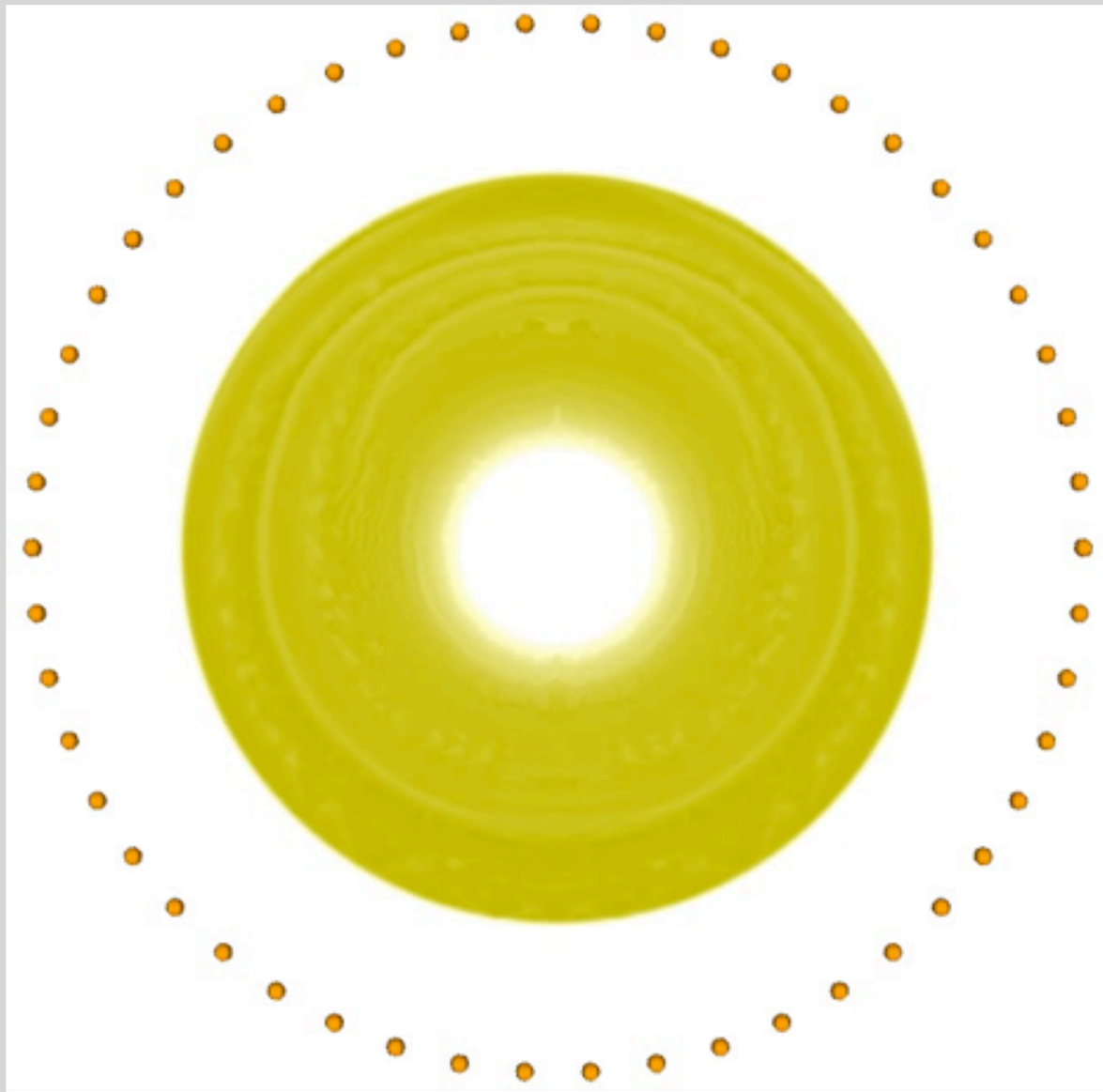
* driven by entropy and/or chemical composition distribution
* from small scale to large scale

SASI

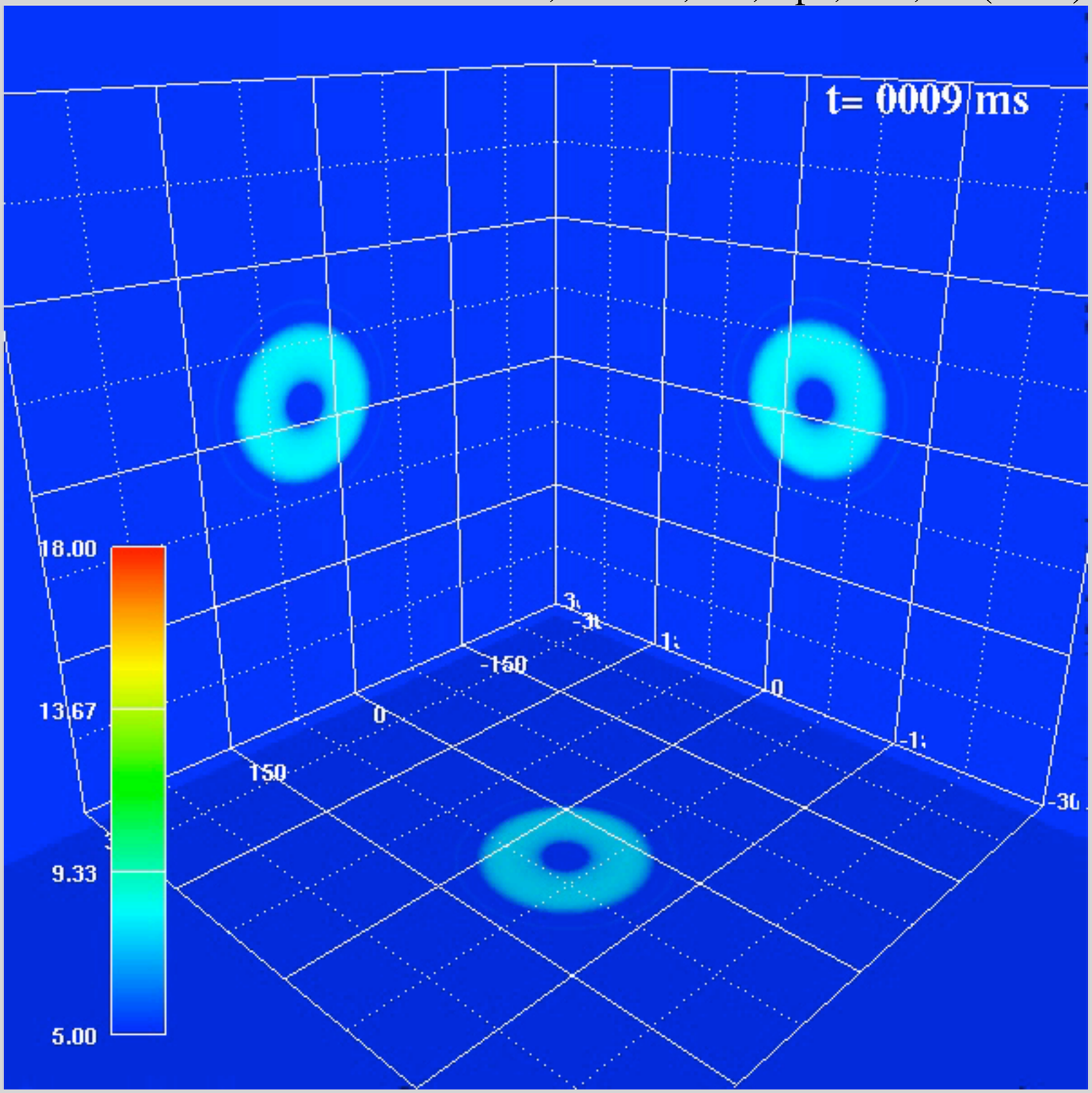


Blondin & Mezzakappa 06

* disturbance of spherical shock
* intrinsically large scale

3D simulation with neutrino transfer

Takiwaki, Kotake, YS, ApJ, **749**, 98 (2012)



320(r)x64(θ)x128(φ)x20(E_ν)

XT4@NAOJ

T2K-Tsukuba

K computer

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)

	incompressibility K [MeV]	symmetry energy J (S) [MeV]	slope of symmetry energy L [MeV]
LS	180, 220, 375	29.3	73.8 (from Steiner+ 2012)
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)

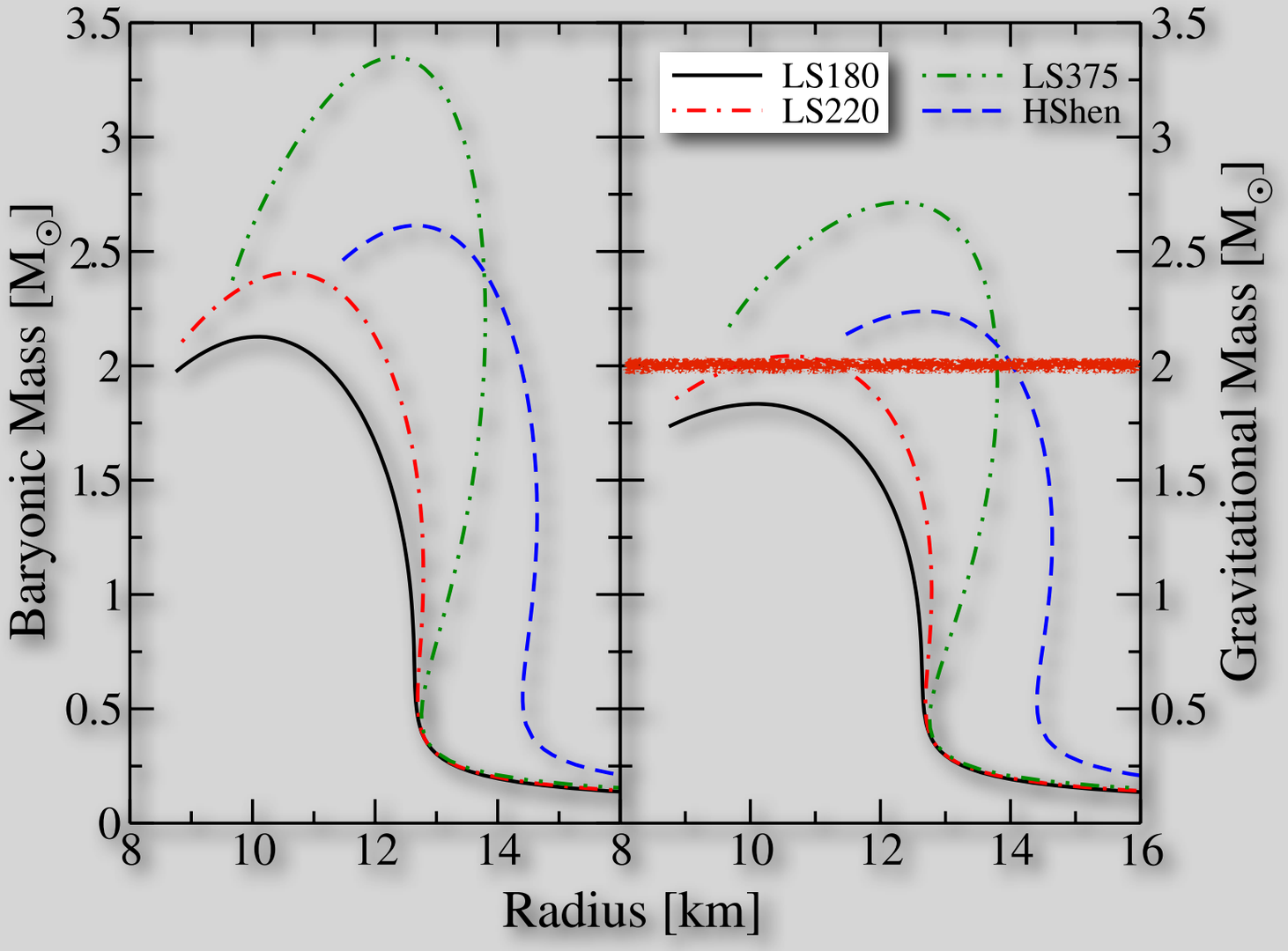
$$E(x,\beta) = -E_0 + \frac{1}{18}Kx^2 + \frac{1}{162}K'x^3 + \ldots + \beta^2\left(J + \frac{1}{3}Lx + \ldots\right) + \ldots ,$$

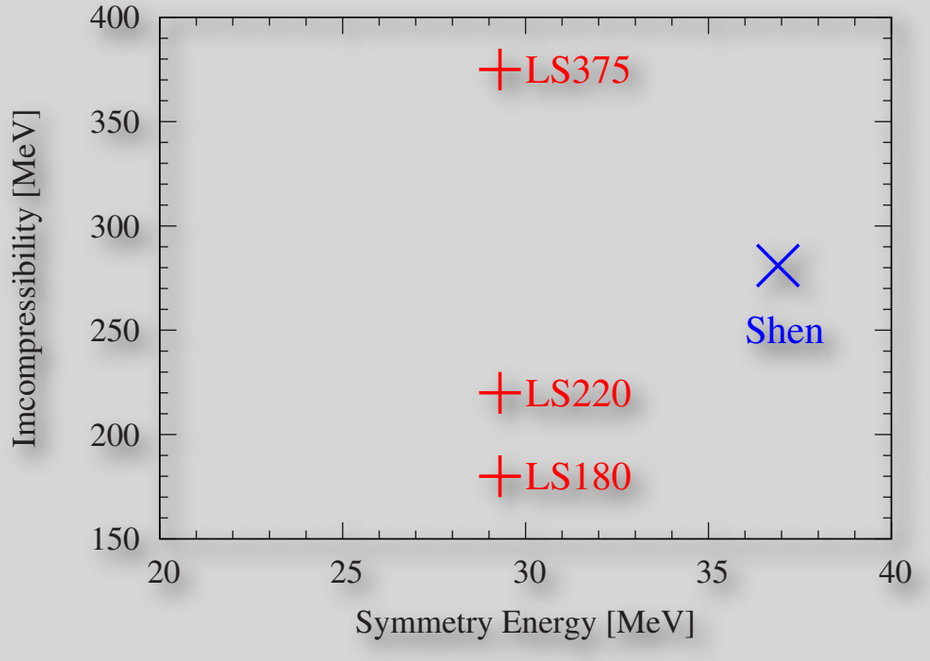
Equation of state

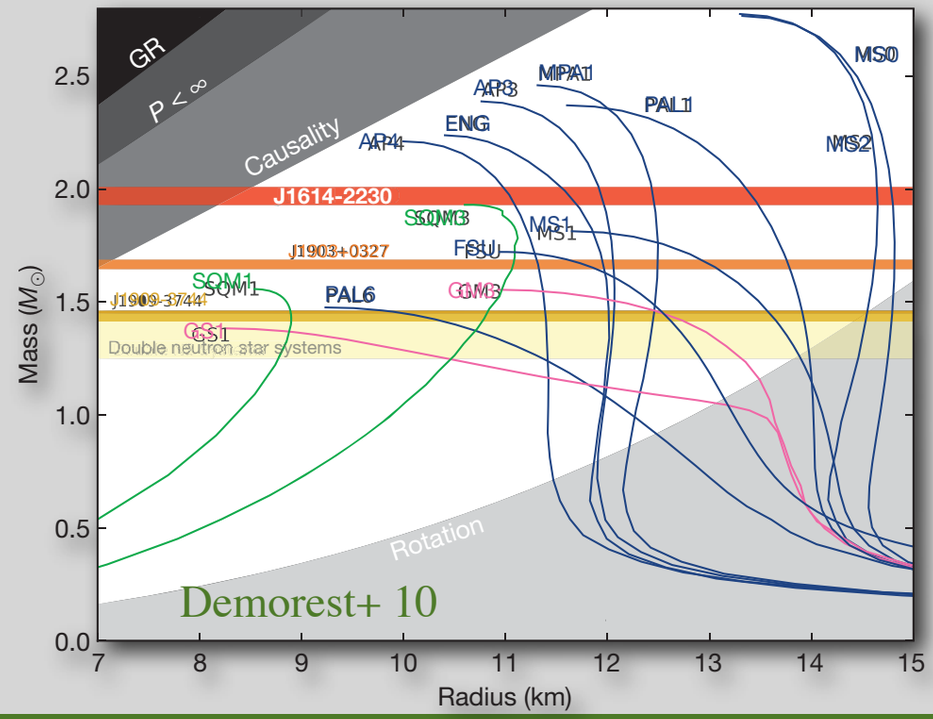
The “standard” equations of state (EOS) in supernova community

- Lattimer & Swesty EOS (liquid drop)
- Shen EOS (relativistic mean field)

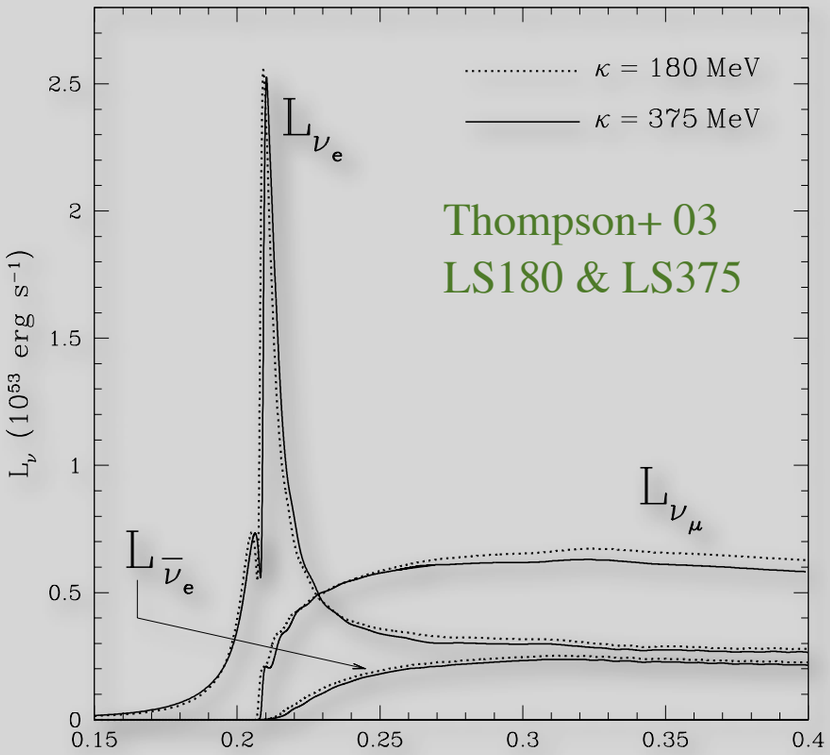
O’Connor & Ott 10

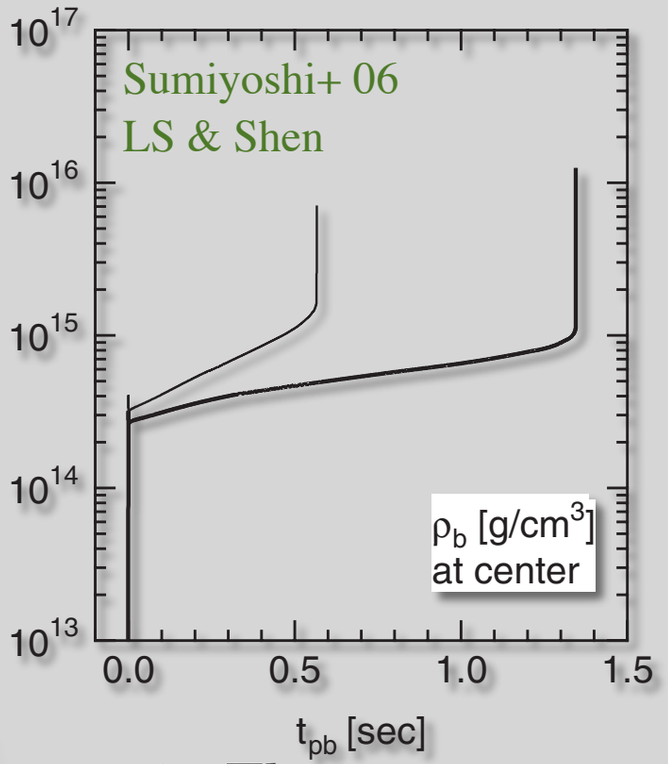


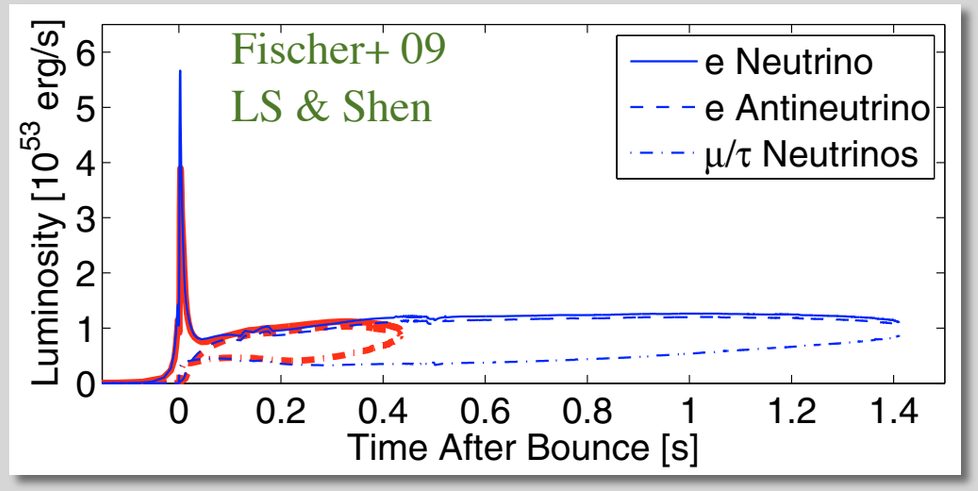


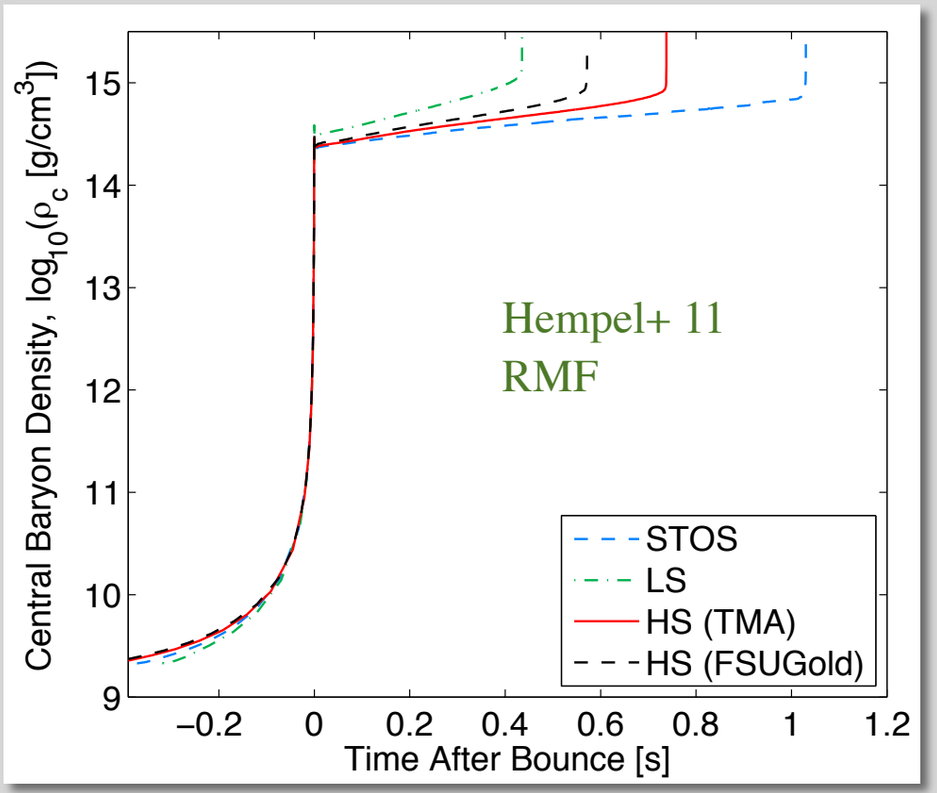


Studies on EOS dependence









* There are several works, which investigated the EOS dependence with 1D simulation
* Since 1D simulations fail to produce explosion, the representable physical quantities in these studies are
  - BH formation time
  - neutrino luminosity/spectrum evolution
* How about the explosion? Does it produce 10^{51} erg explosion?

Numerical simulation

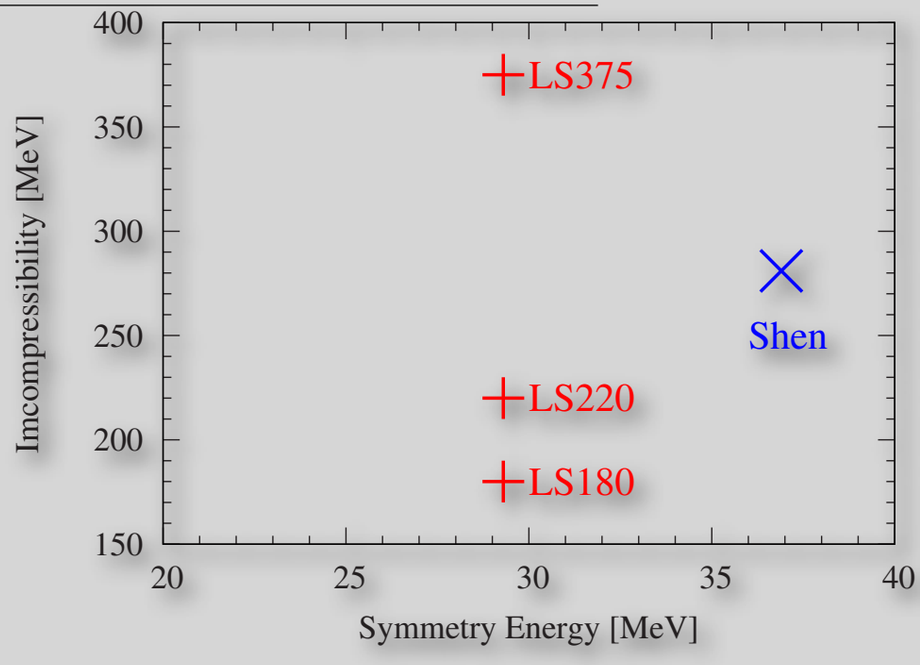
* EOS: LS180, (LS220,) LS375, and Shen

* Axisymmetric simulation (ZEUS-2D; Stone & Norman 92)

* Hydrodynamics + Neutrino transfer

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

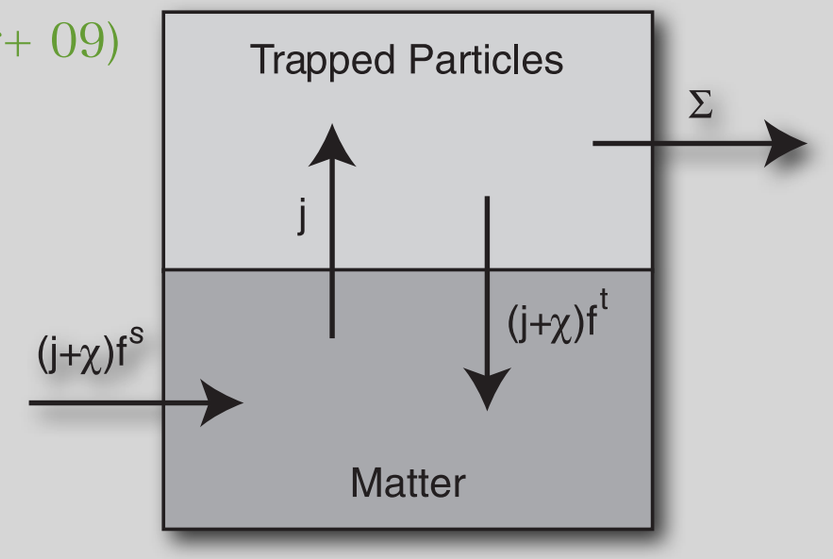
(Lindquist 1966; Castor 1972; Mezzacappa & Bruenn 1993)



Note: Of course the other parameters differ as well.

- Isotropic Diffusion Source Approximation (Liebendörfer+ 09)
- electron-type neutrino/antineutrino

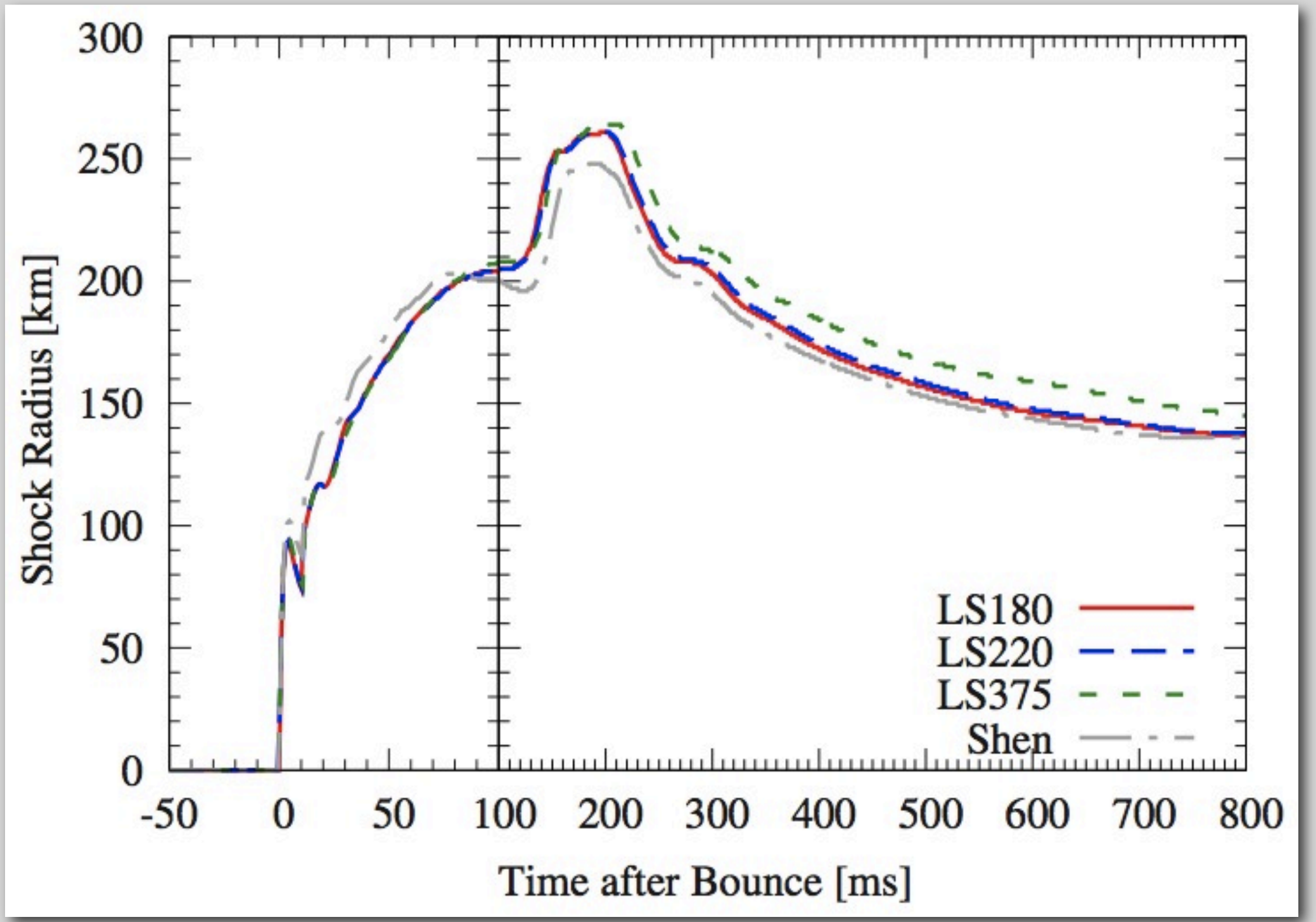
* progenitor: 15 $M_\odot$ (Woosley & Weaver 95)



Results in 1D simulation

Evolution of shock radius

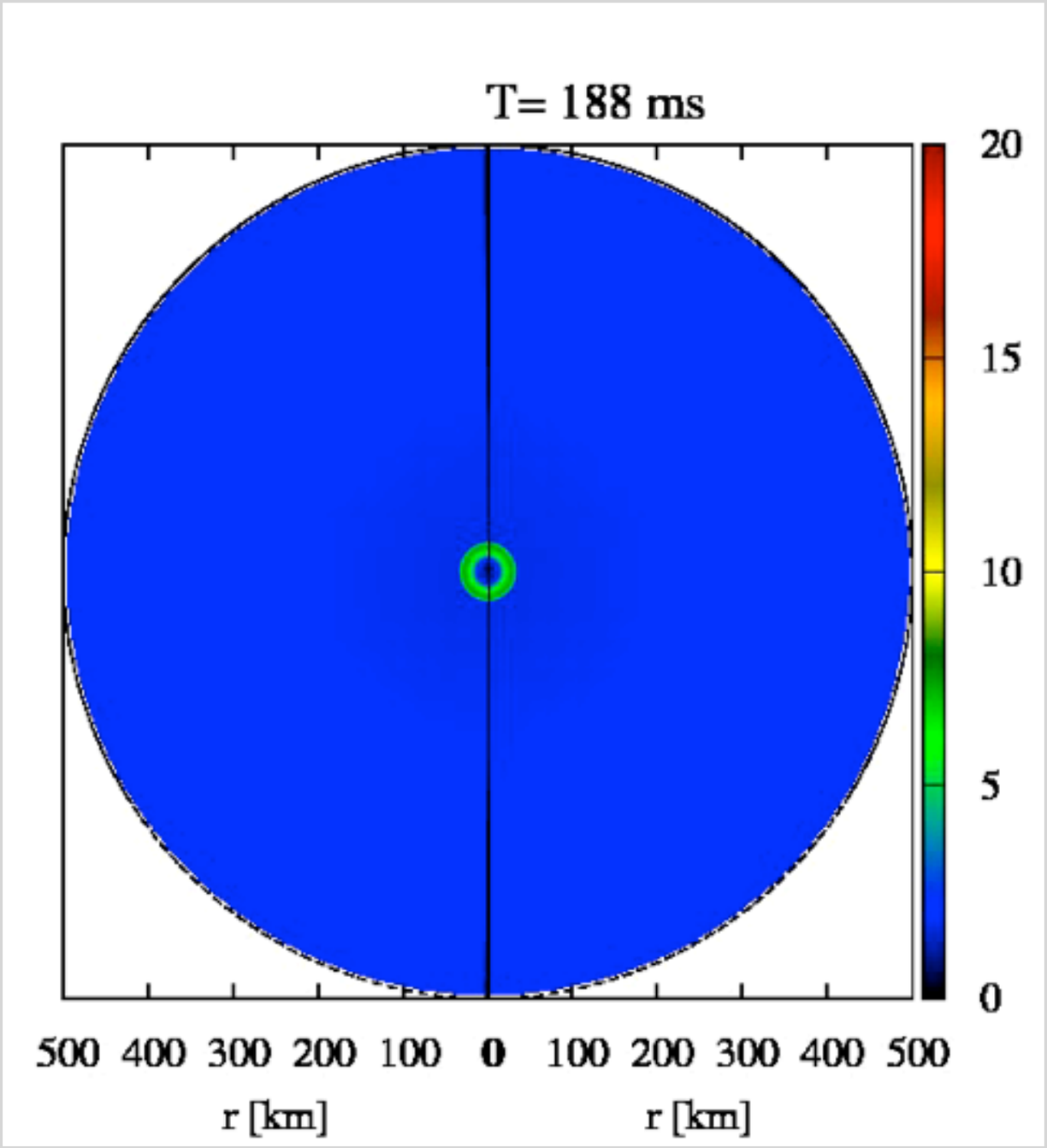
YS, Takiwaki, Kotake, Fischer, Liebendörfer, Sato arXiv:1206.6101



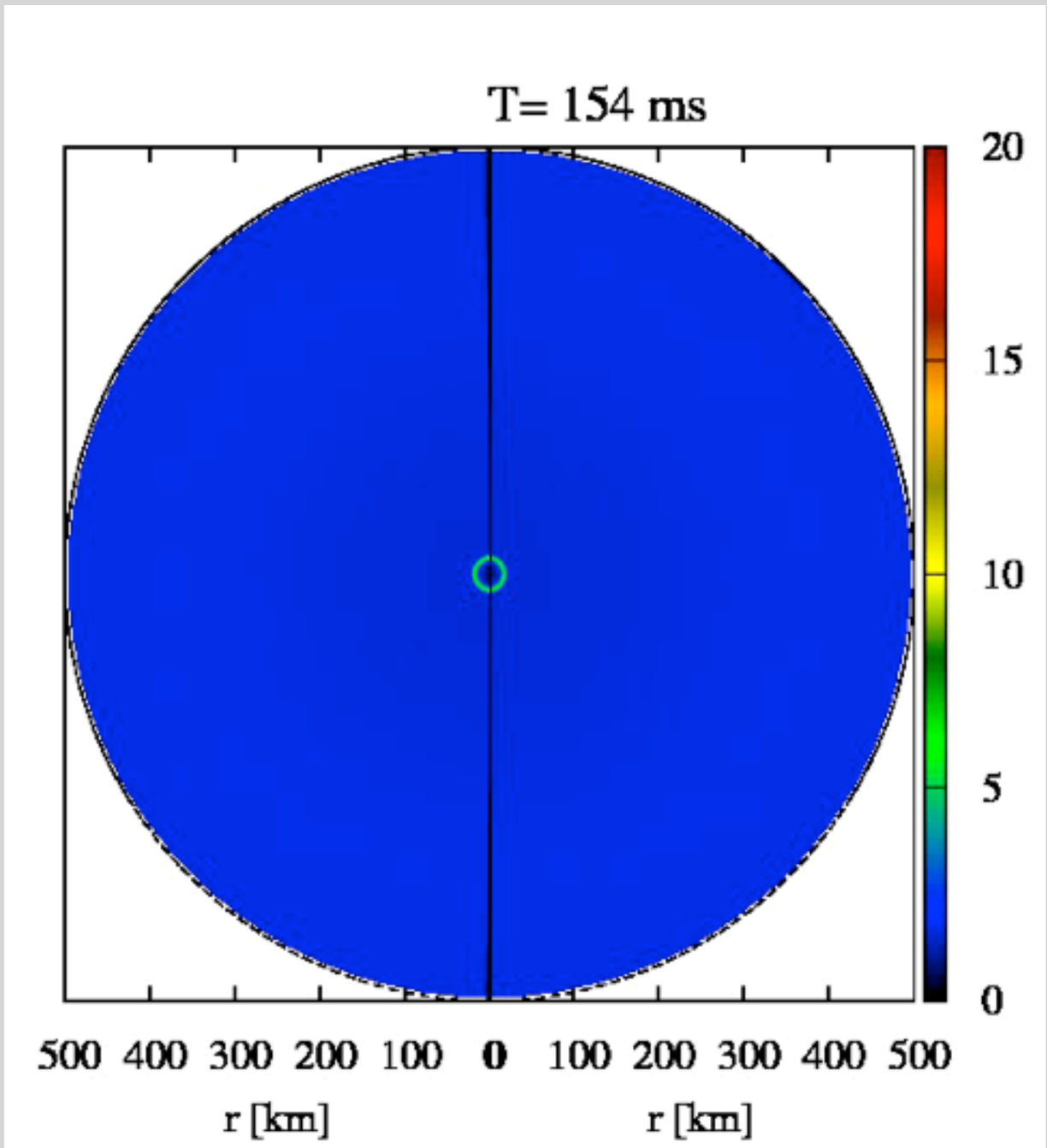
Entropy evolution

YS, Takiwaki, Kotake, Fischer, Liebendörfer, Sato arXiv:1206.6101

LS180

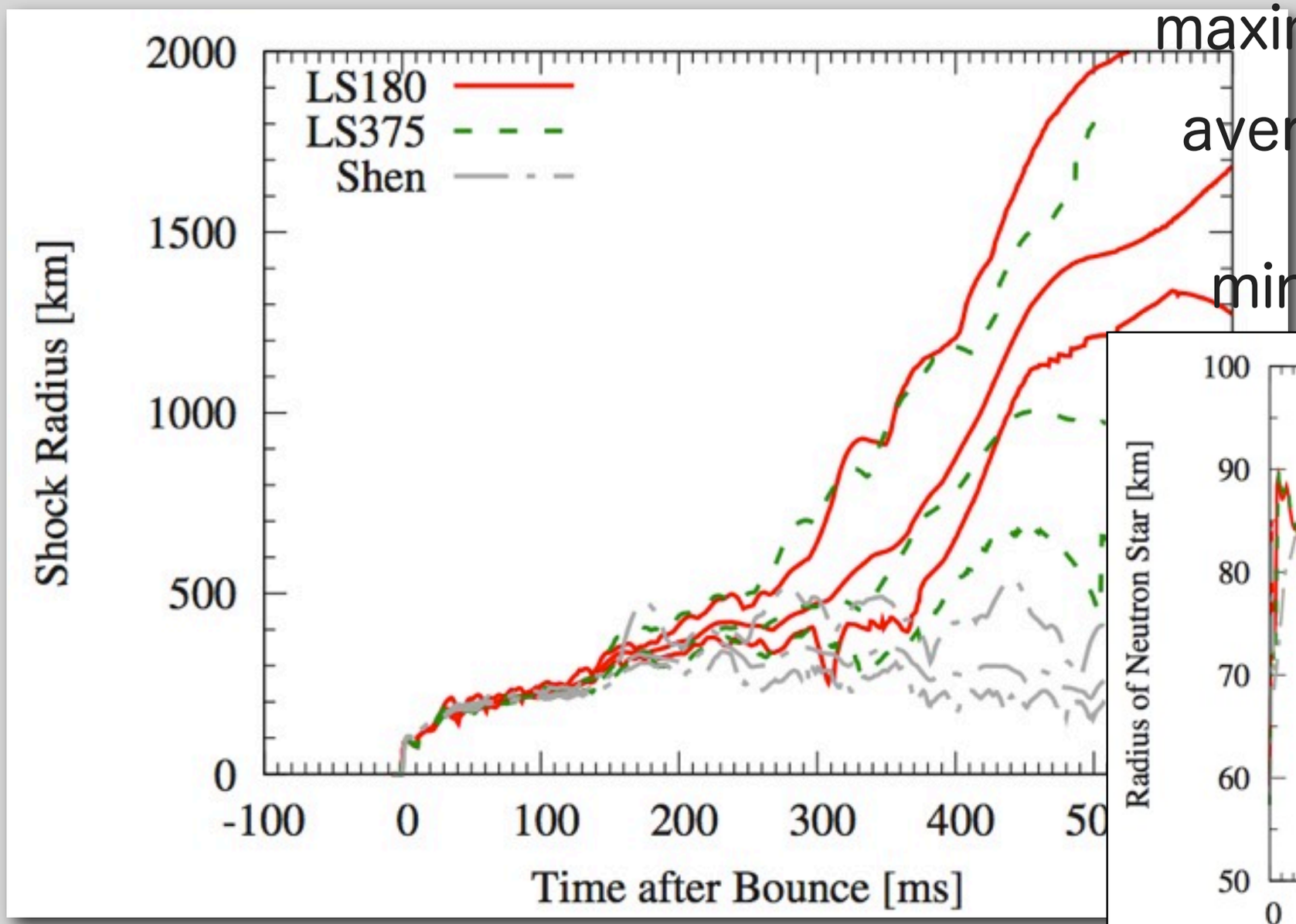


Shen



Shock radius

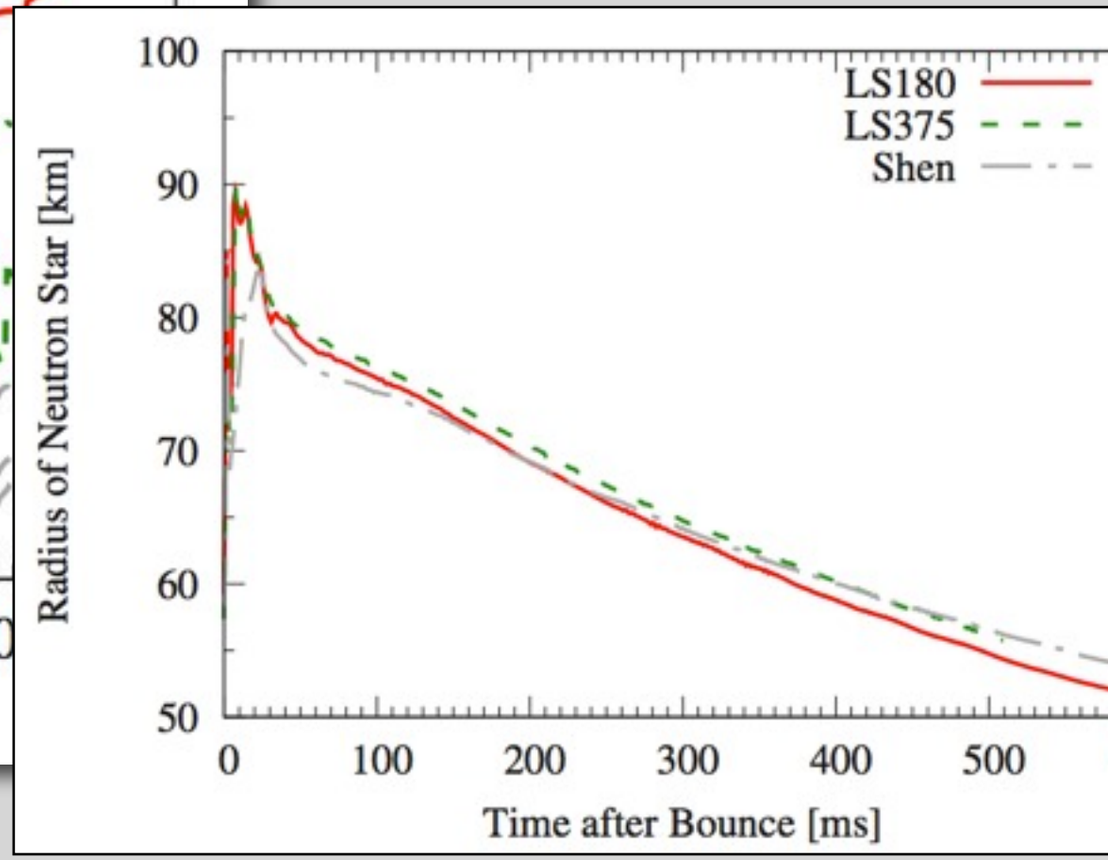
YS, Takiwaki, Kotake, Fischer, Liebendörfer, Sato arXiv:1206.6101



maximum

average

minimum



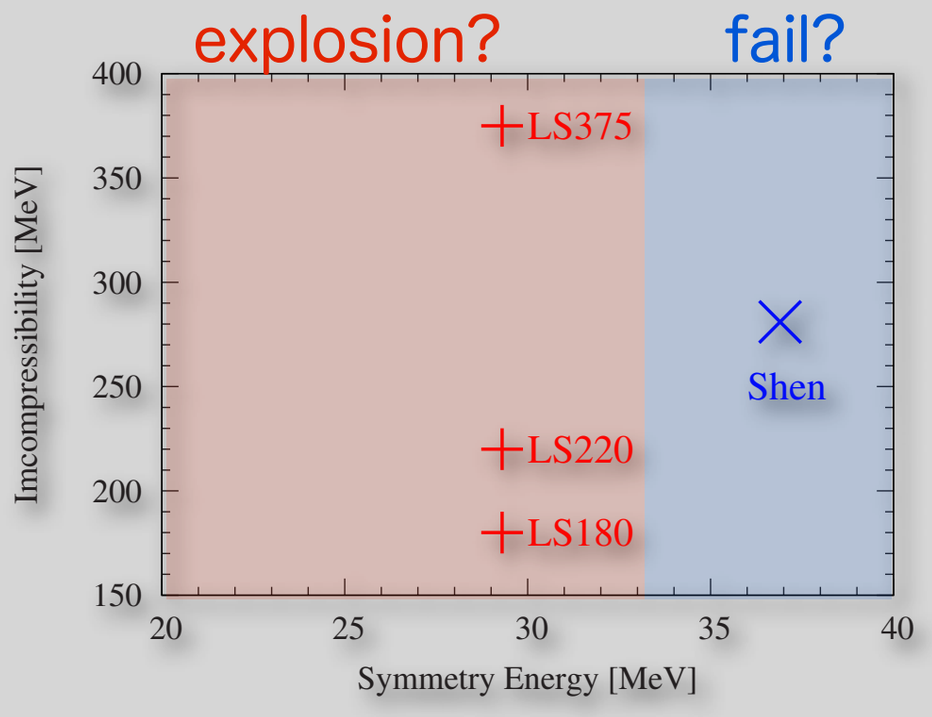
LS180 and LS375 succeed the explosion

Shen EOS fails

More rapid contraction of NS is better for the explosion!

Summary and discussion

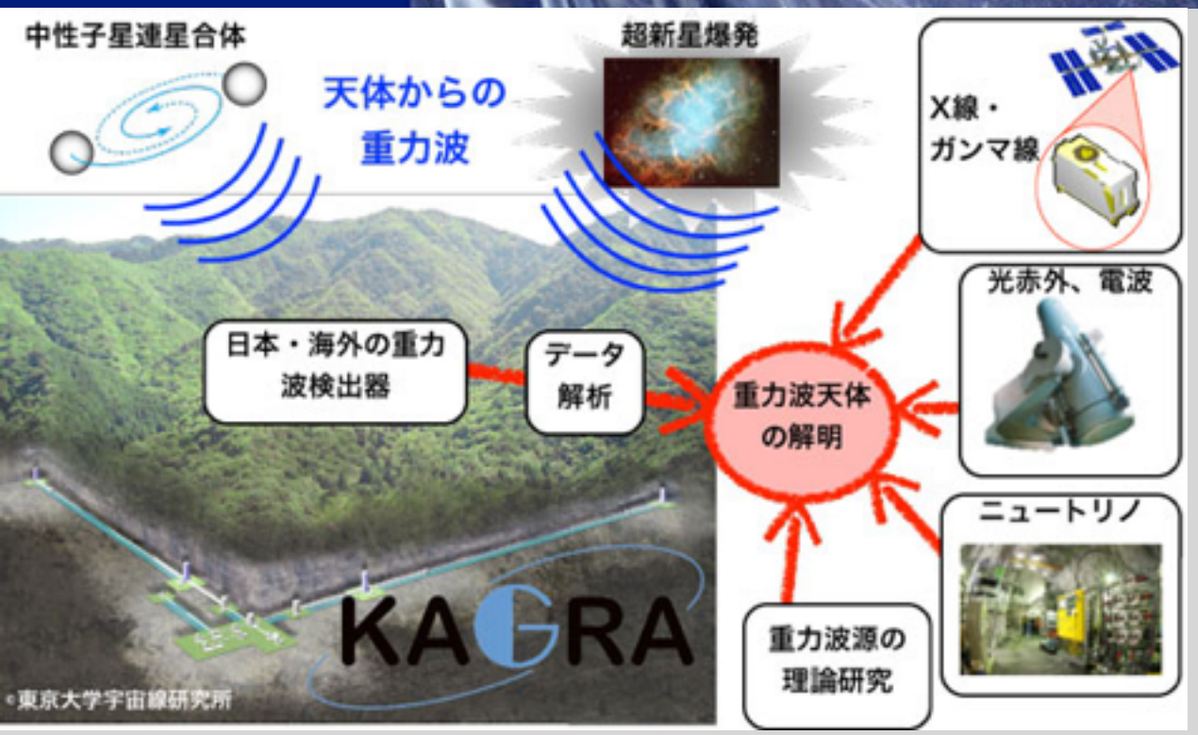
* We perform axisymmetric simulations of a core-collapse supernova driven by the neutrino heating and investigate the dependence on the equation of state
  - Lattimer & Swesty EOS: explosion
  - Shen EOS: failure

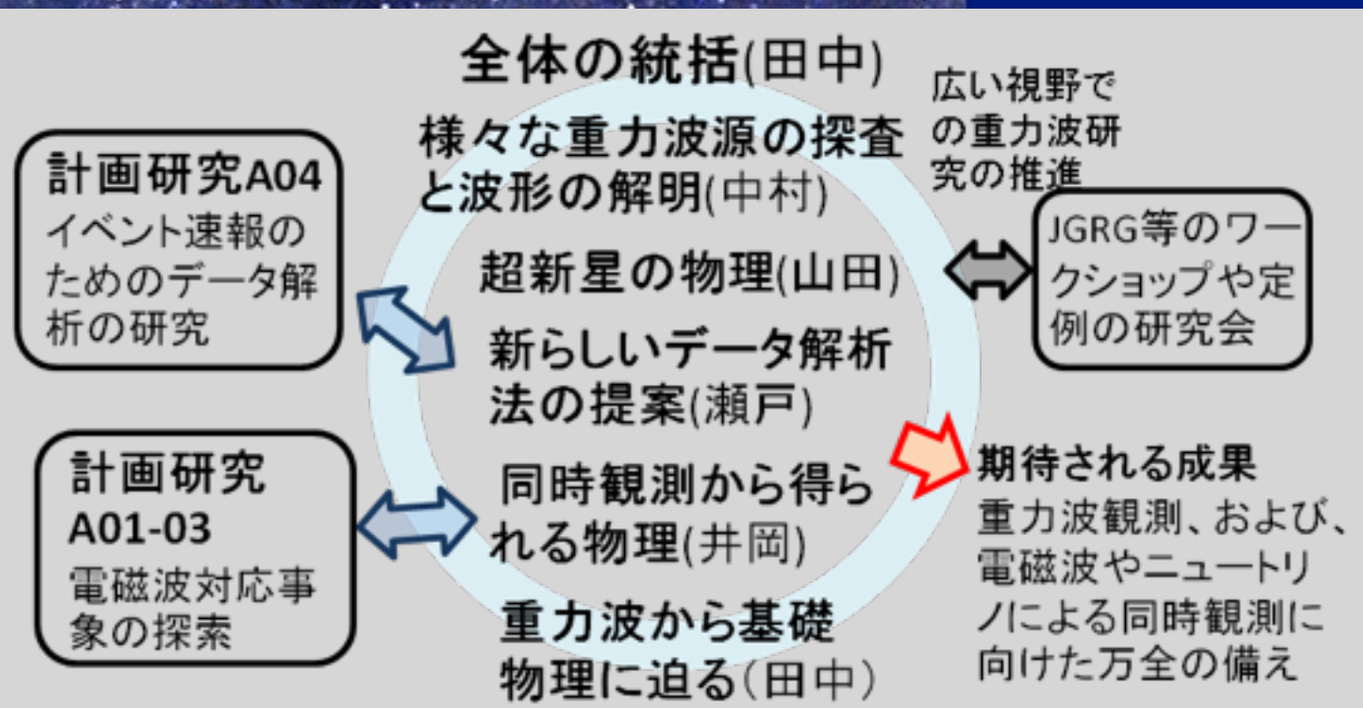


Note: Of course the other parameters differ as well.

* The EOS with faster contraction of the neutron star is better for the explosion
* In order to make the complete understanding of EOS impacts, a more systematic study is strongly required!

新学術領域「重力波天体」

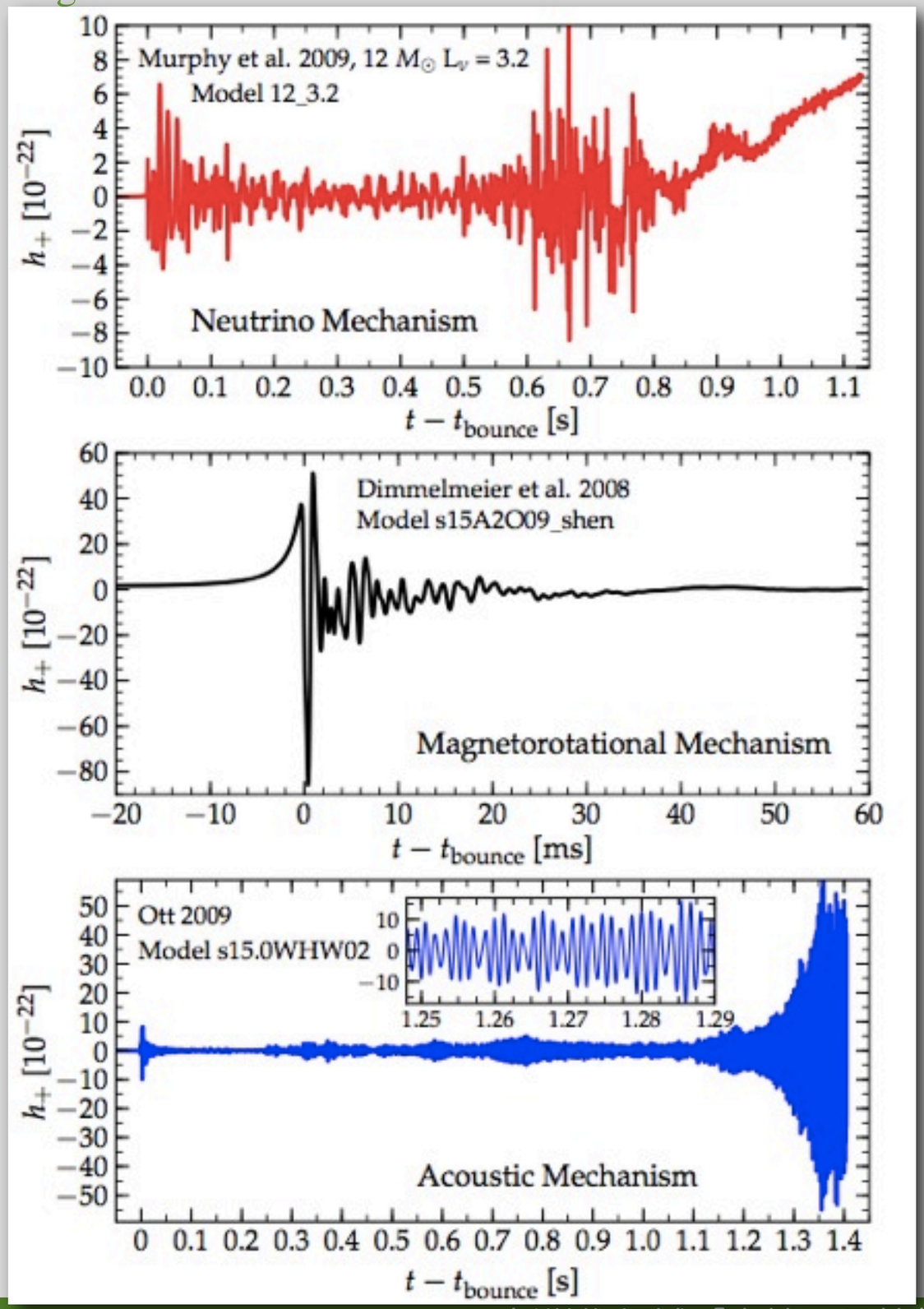




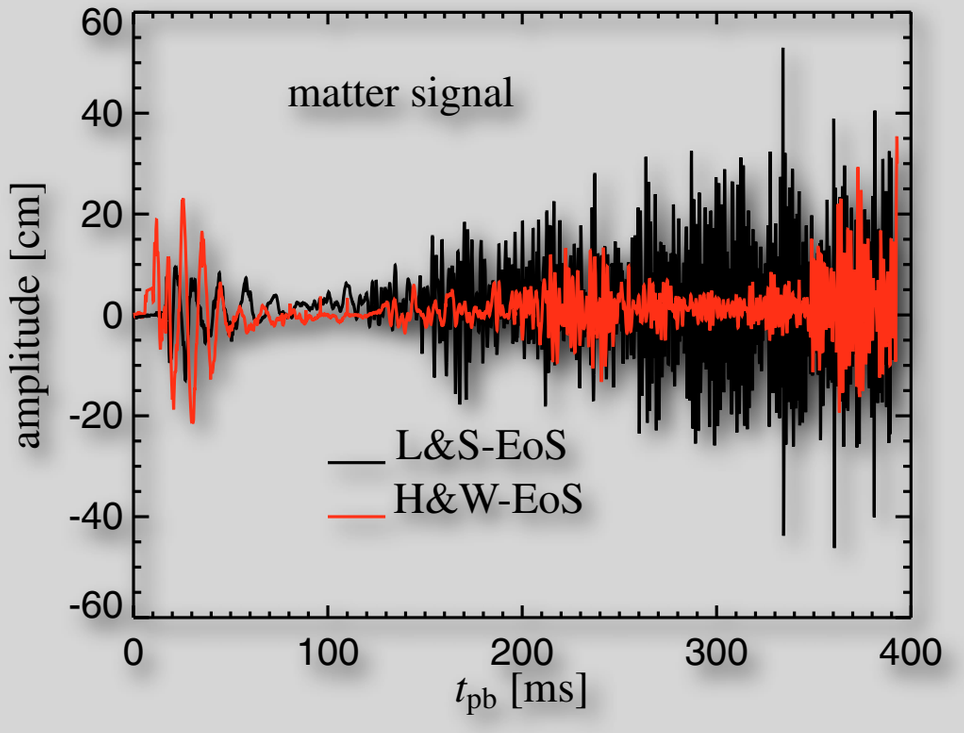
* マルチメッセンジャーが旗印
* 重力波との同時観測のためのシステム作り
* 様々な「目」を使って複合的に現象を「視る」

超新星からの重力波

Logue+ 12



Marek+ 09

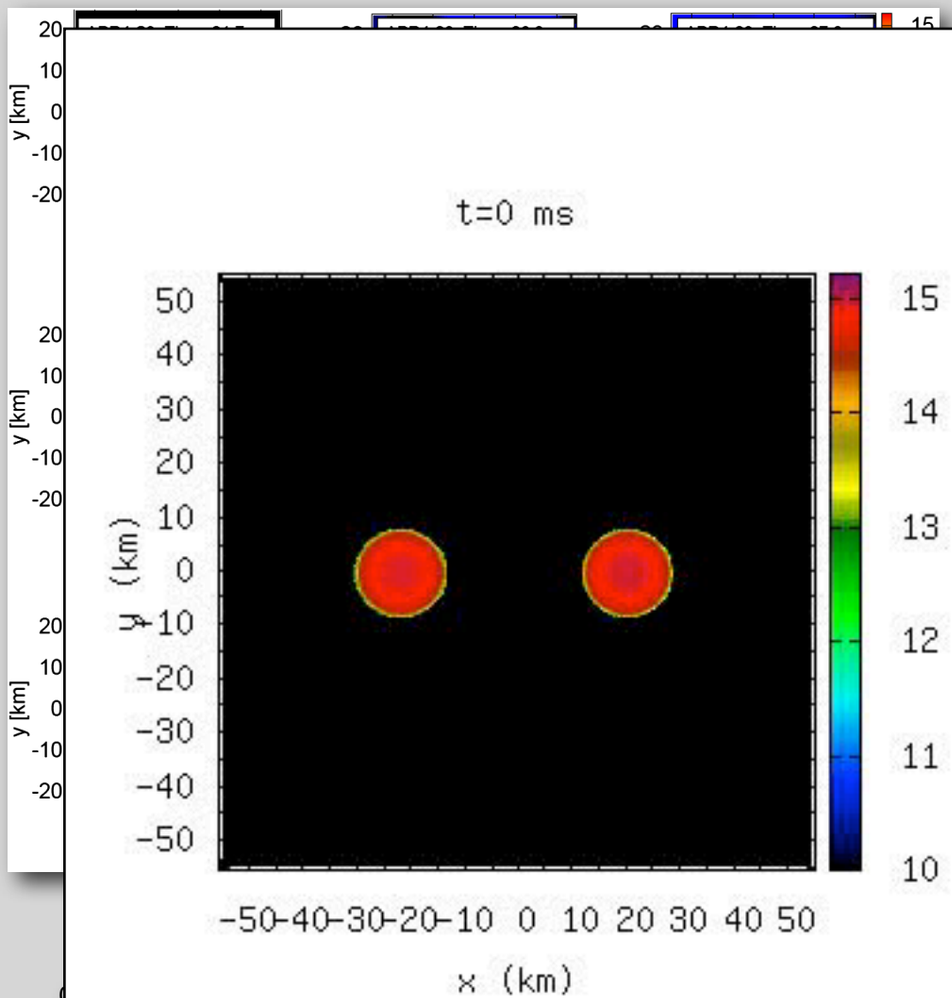


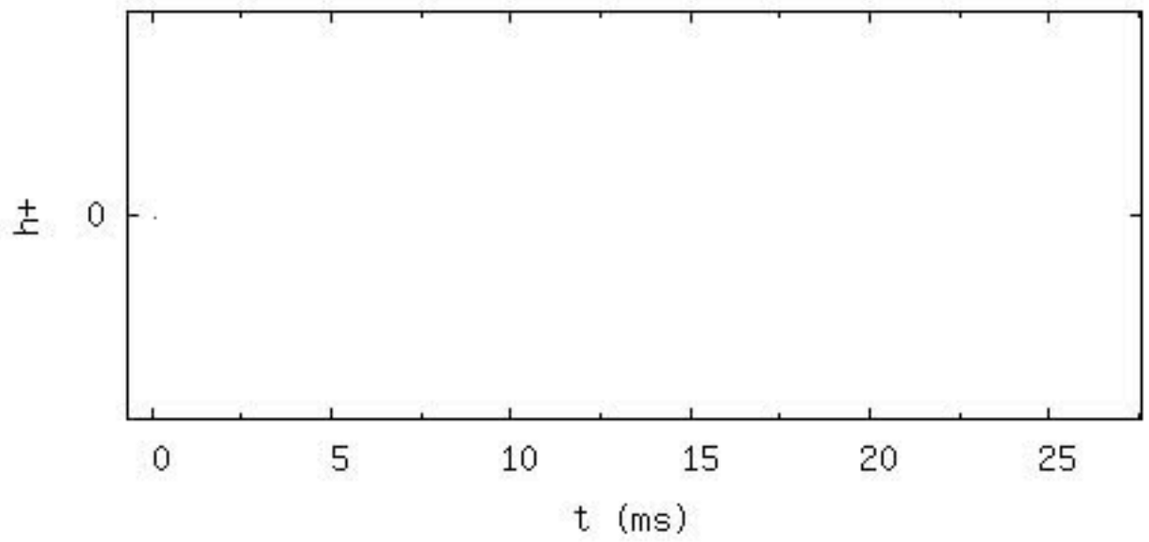
* **ニュートリノ駆動型爆発**
  - 対流
  - 非球対称ニュートリノ放射
* **磁場駆動型爆発**
  - 強回転による歪んだ中性子星形成
* **音波駆動型爆発**
  - 中性子星振動
* **重力波を使って**
  - **爆発メカニズムを探る**
  - **核物質状態方程式を探る**

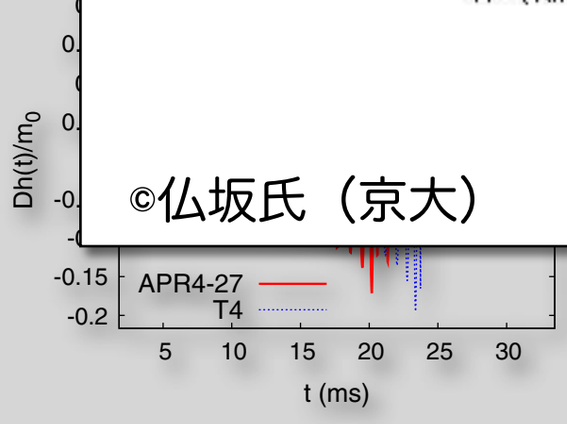
連星中性子星合体からの重力波と状態方程式

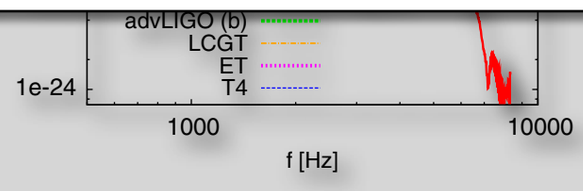
Hotokezaka+ 11

Bauswein & Janka 11









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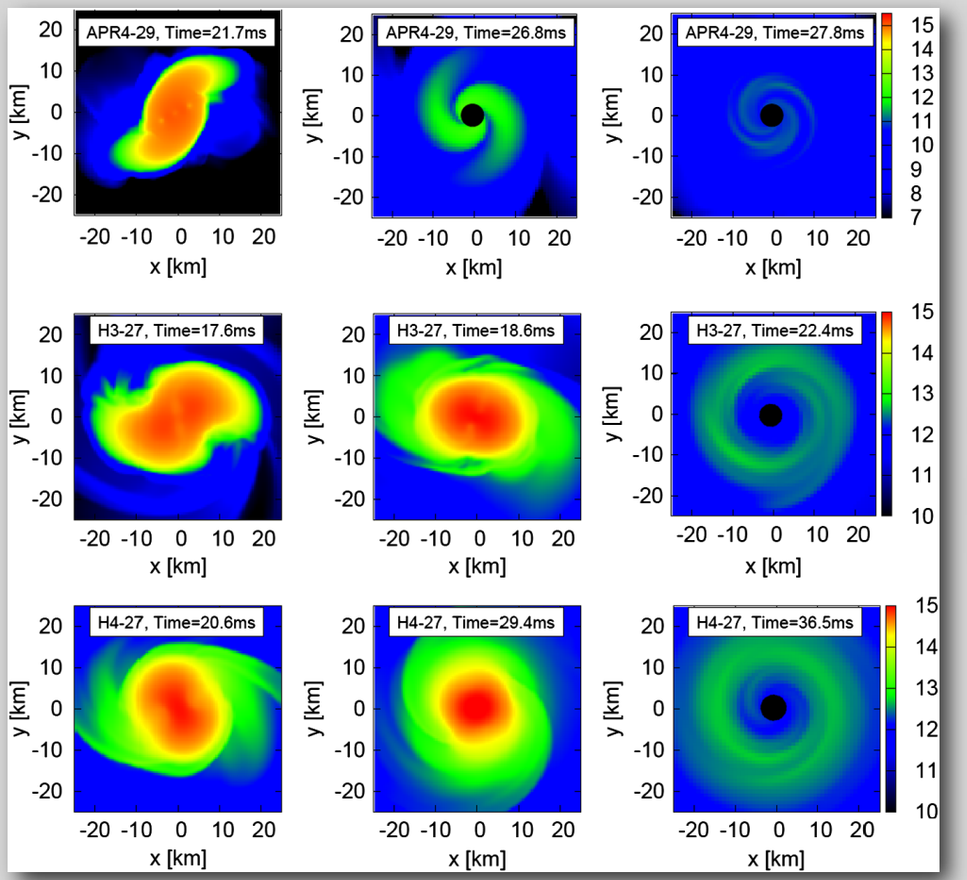
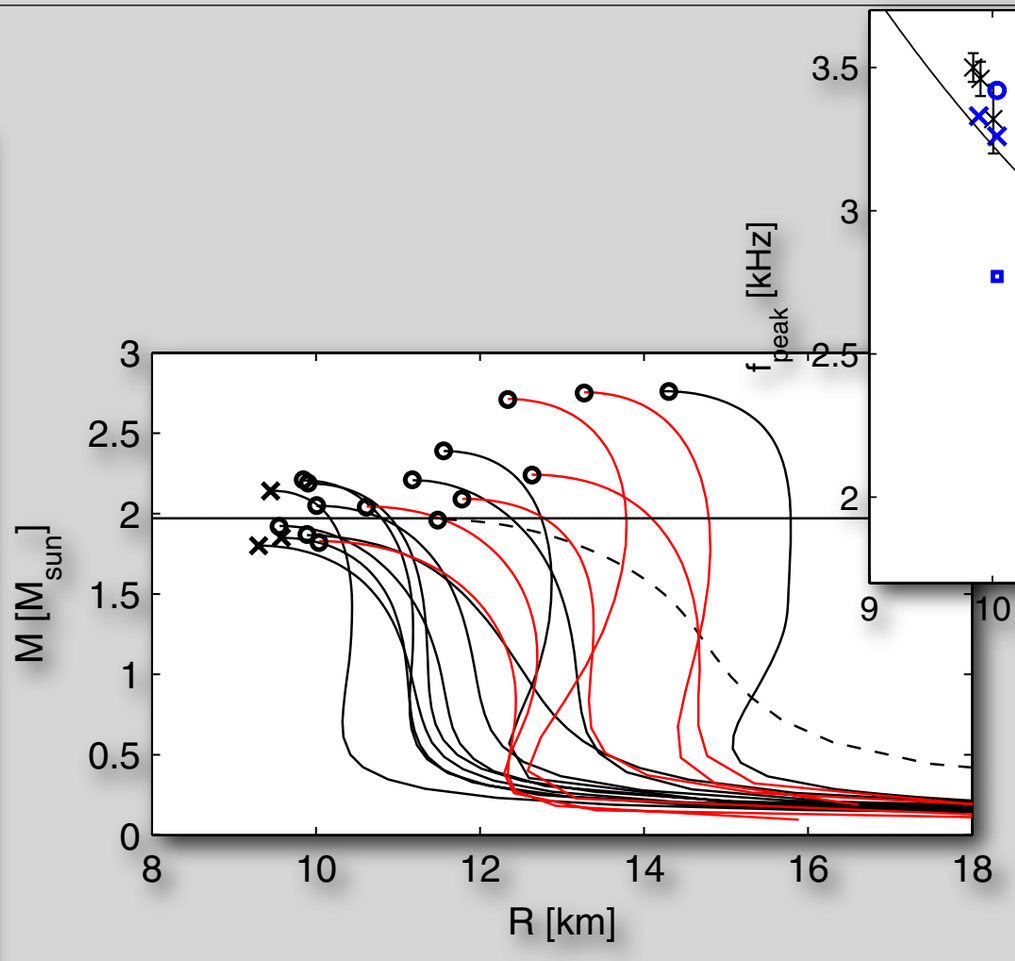
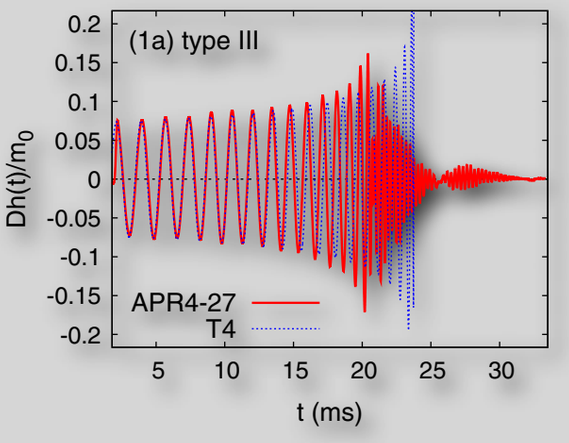
* M-R 関係に対する新しい制限に成りうる

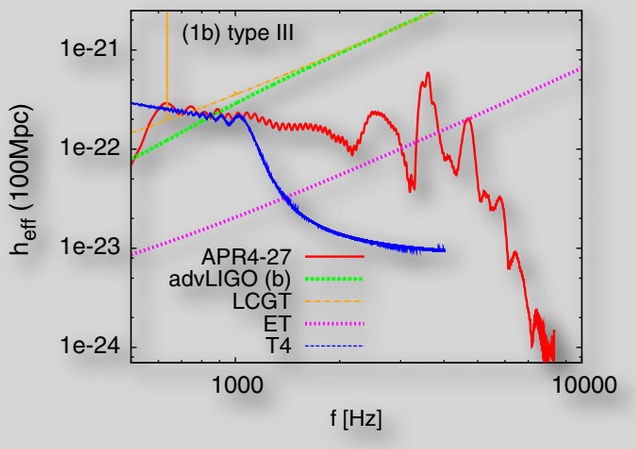
連星中性子星合体からの重力波と状態方程式

Hotokezaka+ 11









* 数多くの EOS を用いて系統的にシミュレーションすることが可能に
* 重力波波形から中性子星半径の情報
* M-R 関係に対する新しい制限に成りうる

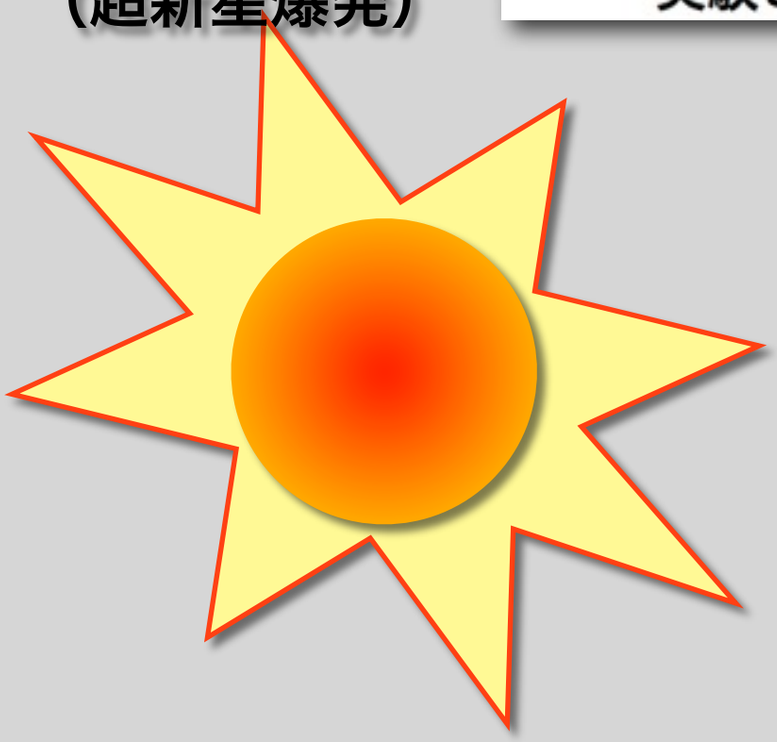
まとめ

科研費 KAKENHI 文部科学省　科学研究費補助金　新学術領域研究（領域番号 2404）

実験と観測で解き明かす中性子星の核物質（暫定版）

中性子星の形成
（超新星爆発）

中性子星の合体



中性子星の引き起こす
ダイナミカルな天体現象