# 状態方程式がニュートリノ駆動型爆発に及ぼす影響

# On the Importance of the Equation of State for the Neutrino-Driven Supernova Explosion Mechanism

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Collaboration with

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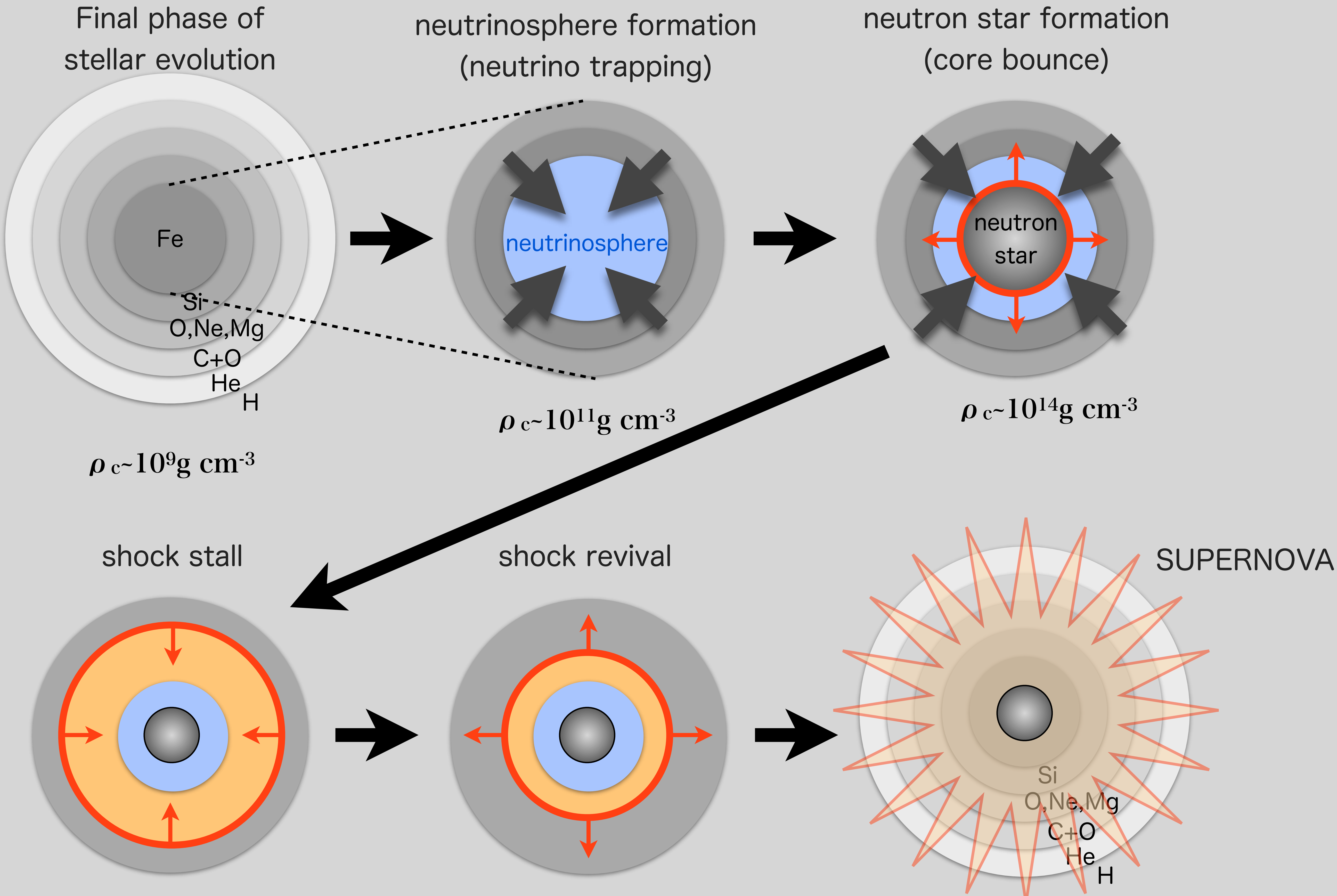
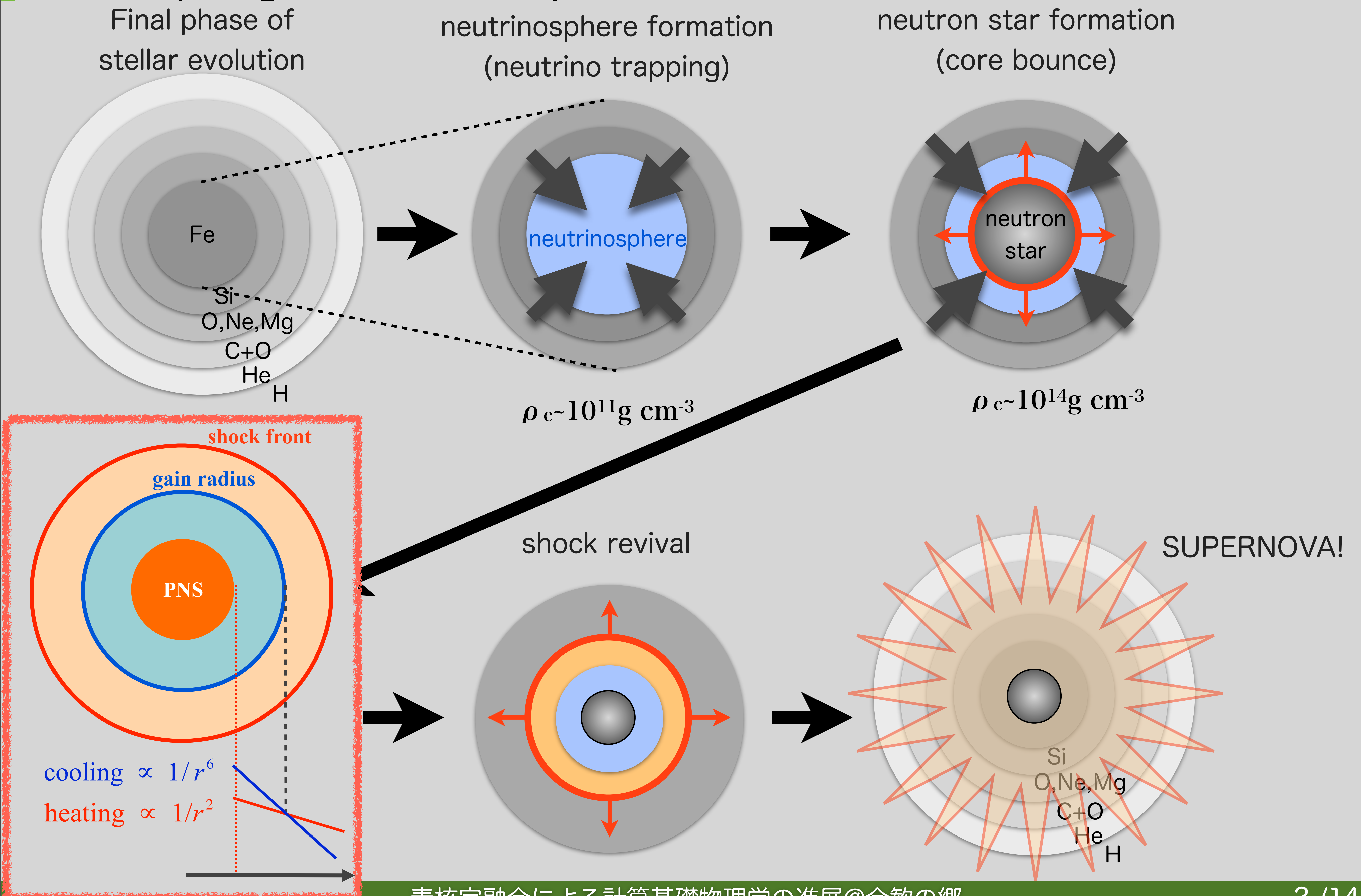
# From progenitor to supernova



# From progenitor to supernova



# 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. (2011)
  - 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 | --- |
| HShen | 281 | 36.9 | 111 |
| HW | 263 | 32.9 | --- |
| GShen | 271.5 (NL3)<br>230.0 (FSU) | 37.29 (NL3)<br>32.59 (FSU) | 118.2 (NL3)<br>60.5 (FSU) |
| Hempel | 318 (TMA)<br>230 (FSU) | 30.7 (TMA)<br>32.6 (FSU) | 90 (TMA)<br>60 (FSU) |

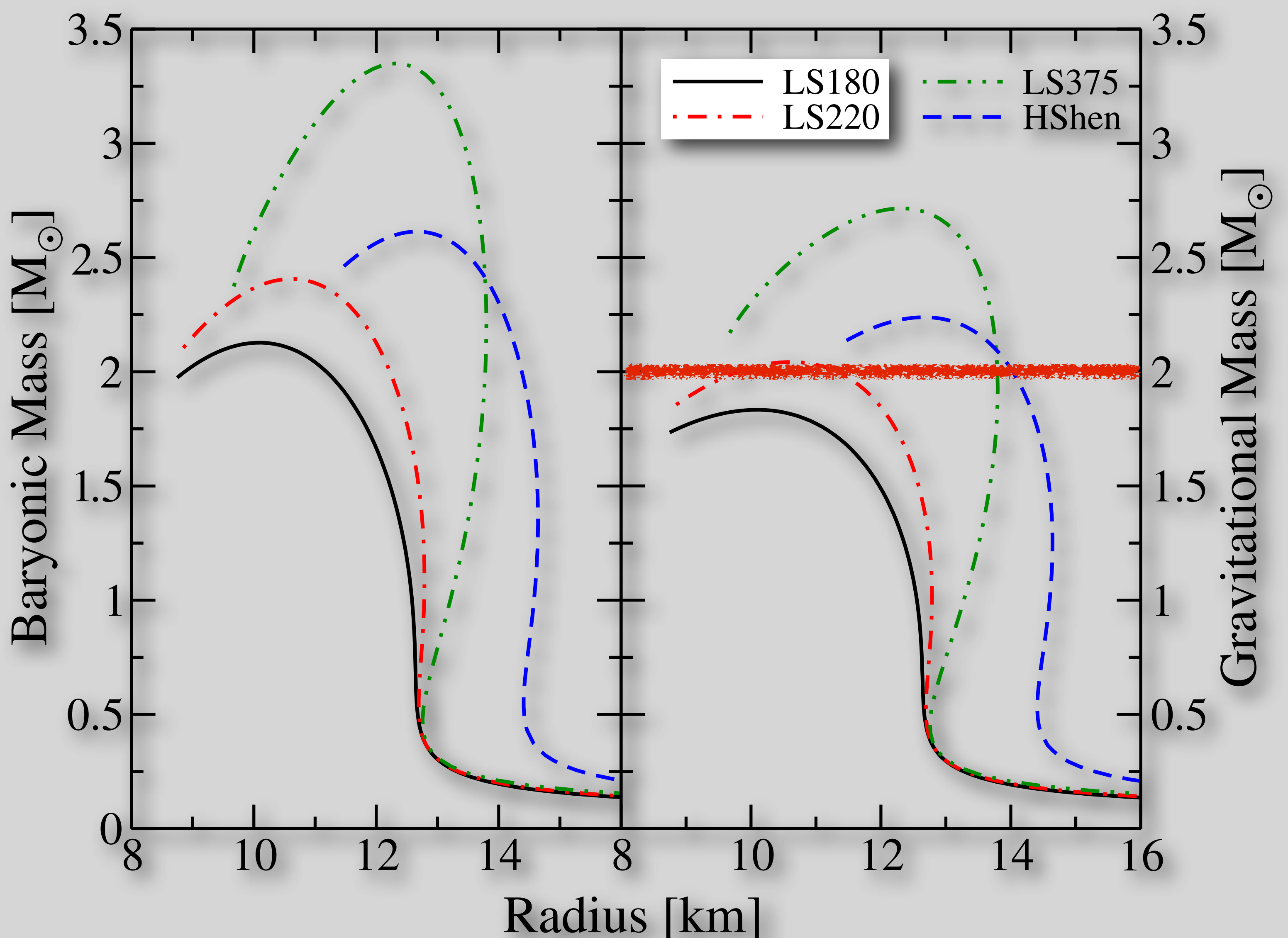
$$E(x,\beta) = -E_0 + \frac{1}{18}Kx^2 + \frac{1}{162}K'x^3 + \ldots + \beta^2\left(J + \frac{1}{3}Lx + \ldots\right) + \ldots ,$$

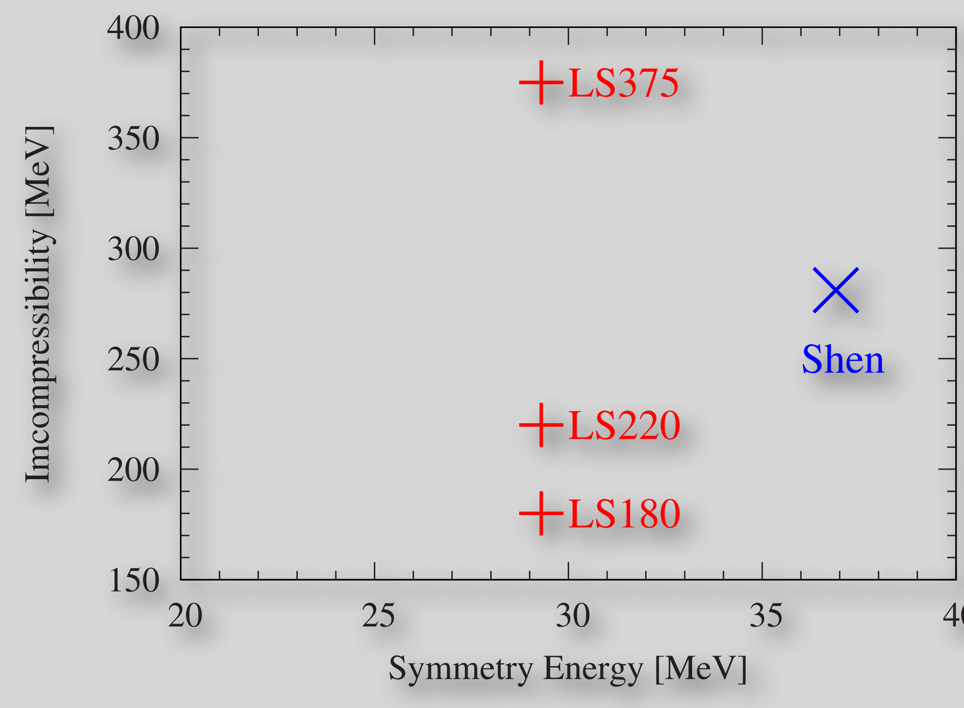
# Equation of state

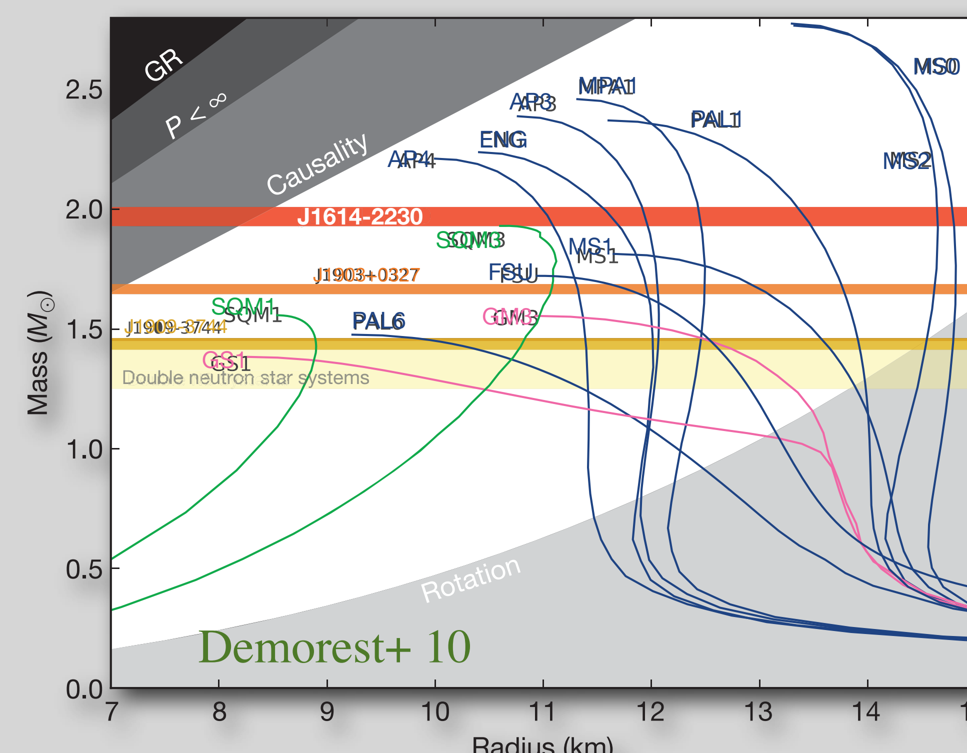
The “standard” equation of states (EOSs) in supernova community

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

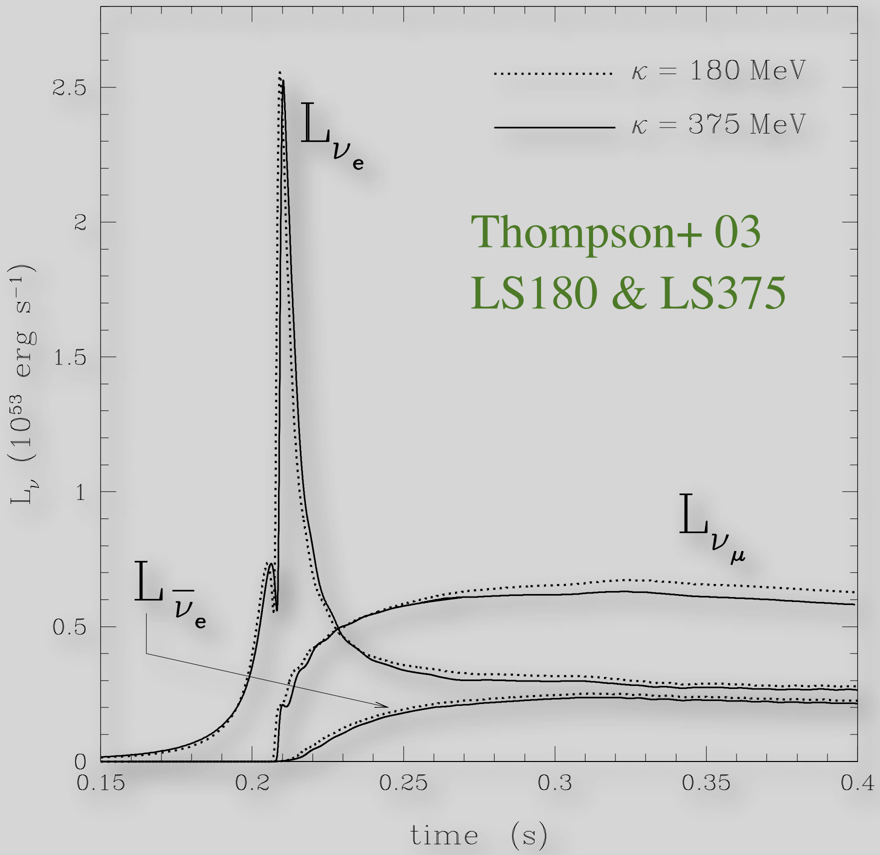
O’Connor & Ott 10

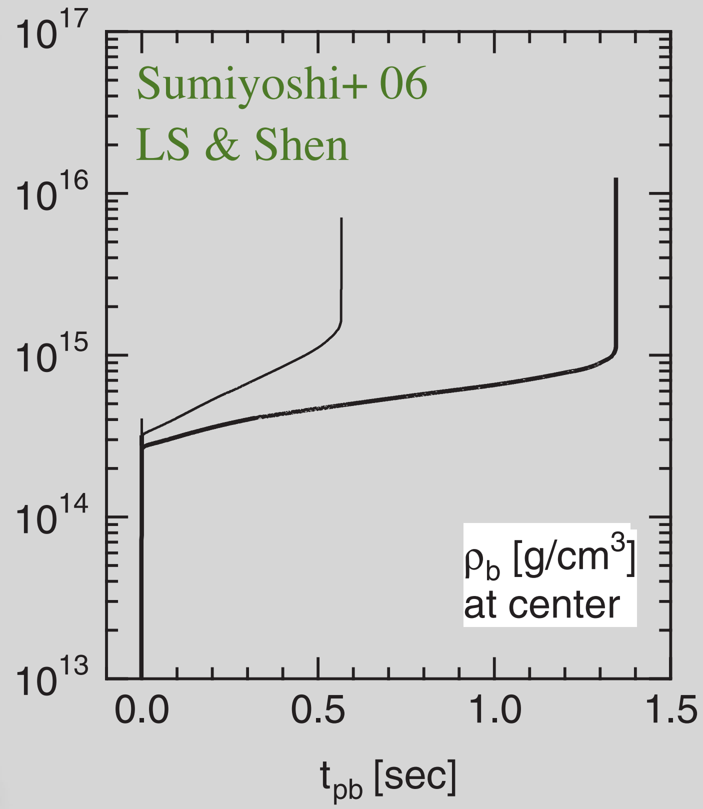


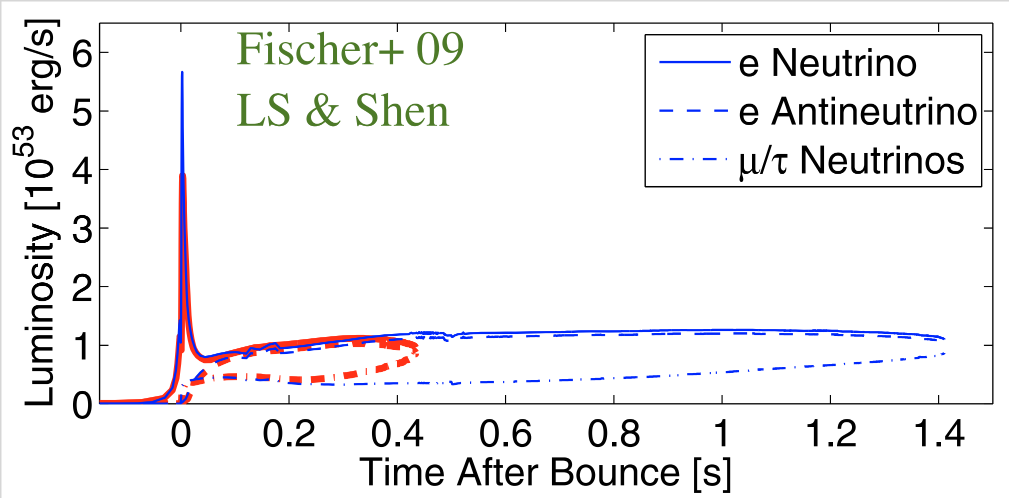



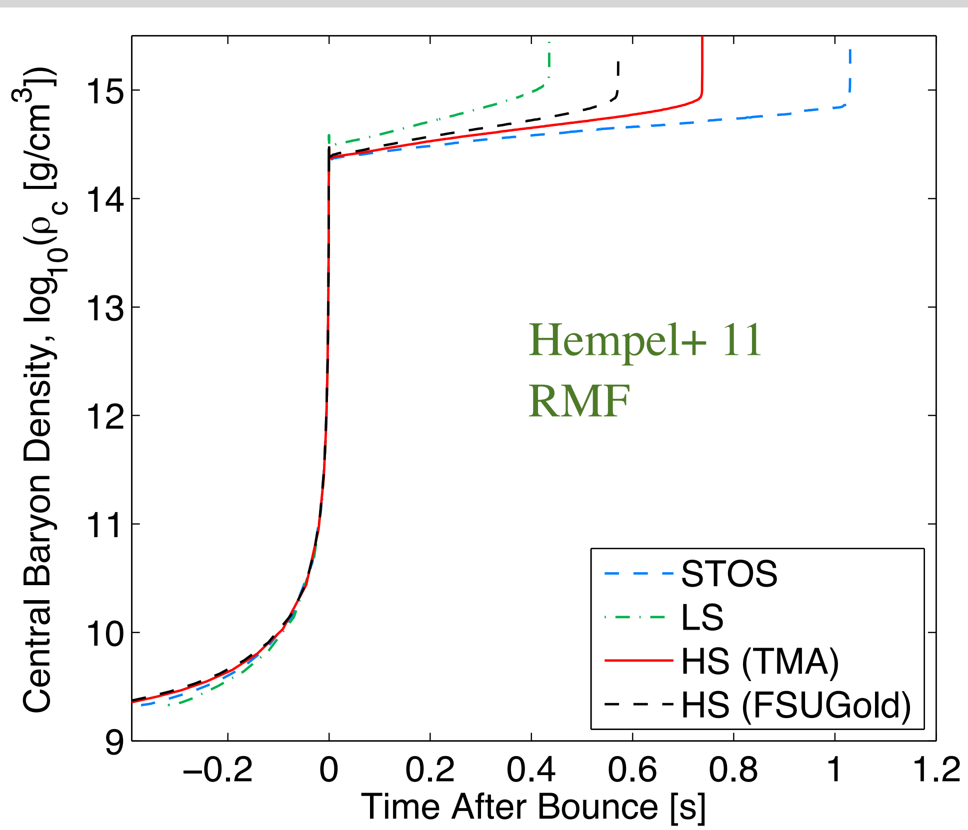



# Studies on EOS dependence



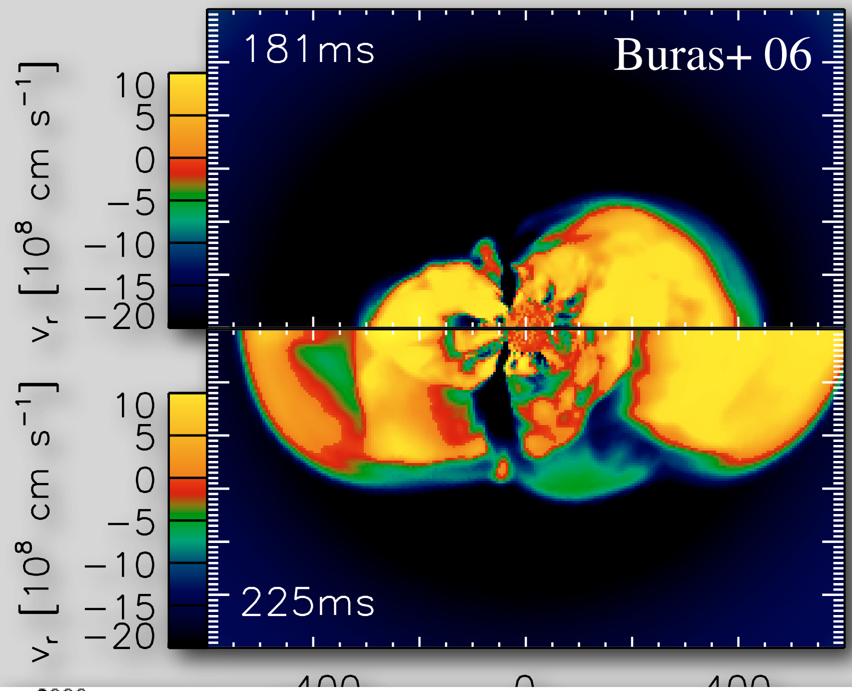

- There are several works, which investigated the EOS dependence with 1D simulation
- Since 1D simulations fail to produce explosion, the representable physical quantities in these studies are
  - BH formation time
  - neutrino luminosity/spectrum evolution
- **How about the explosion?**

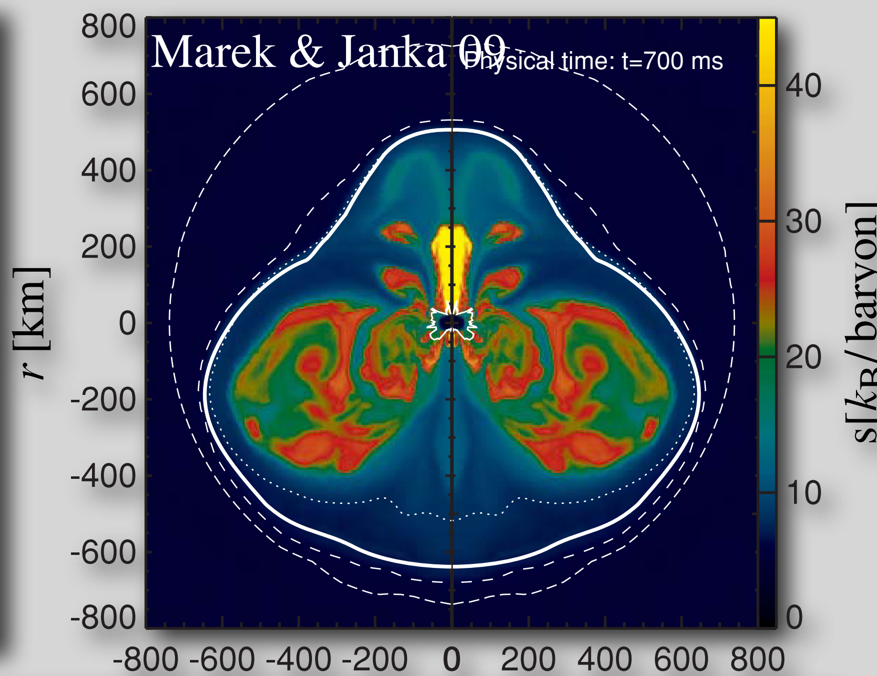


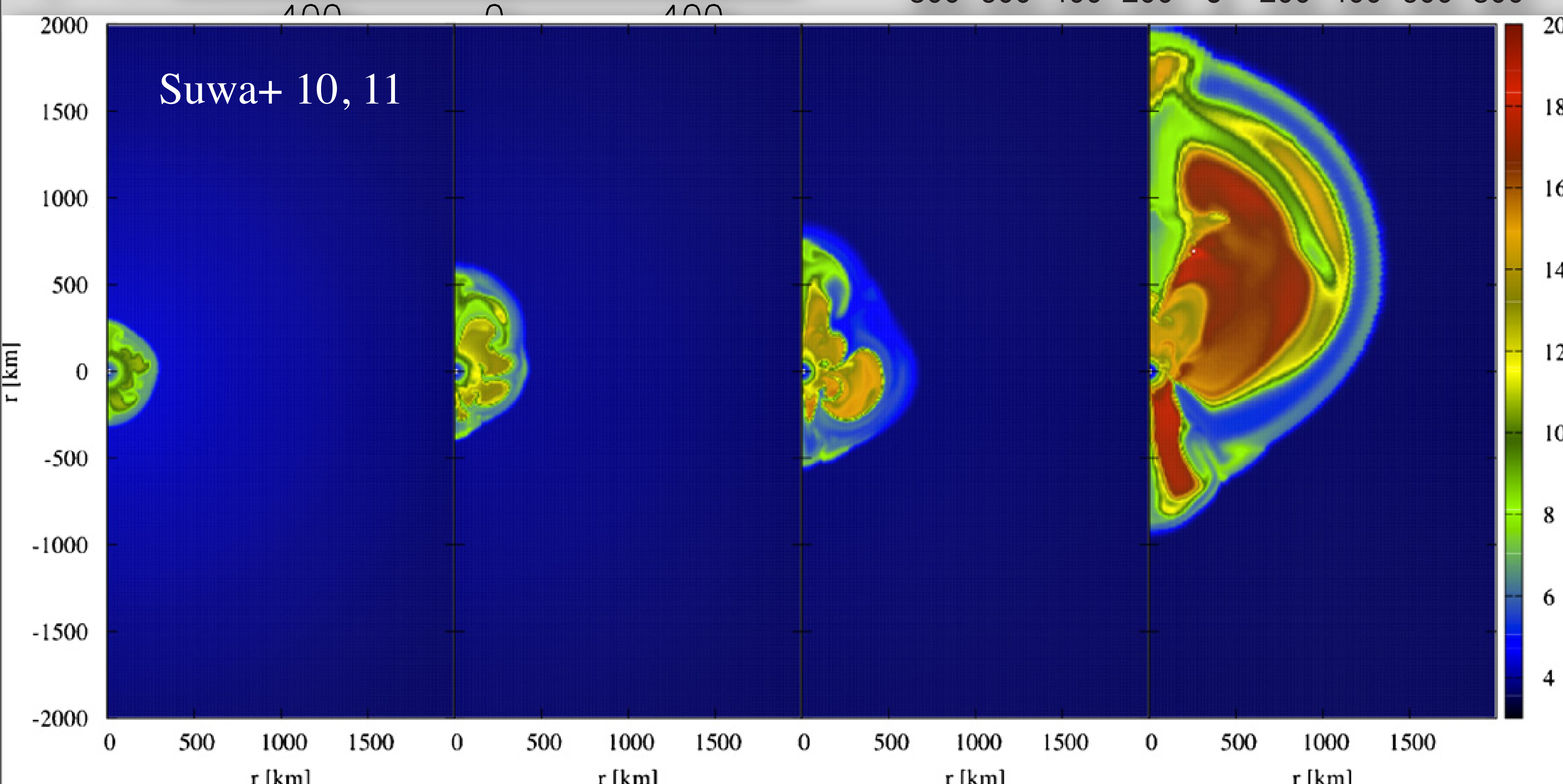
2011年12月4日日曜日

# Neutrino-driven explosion

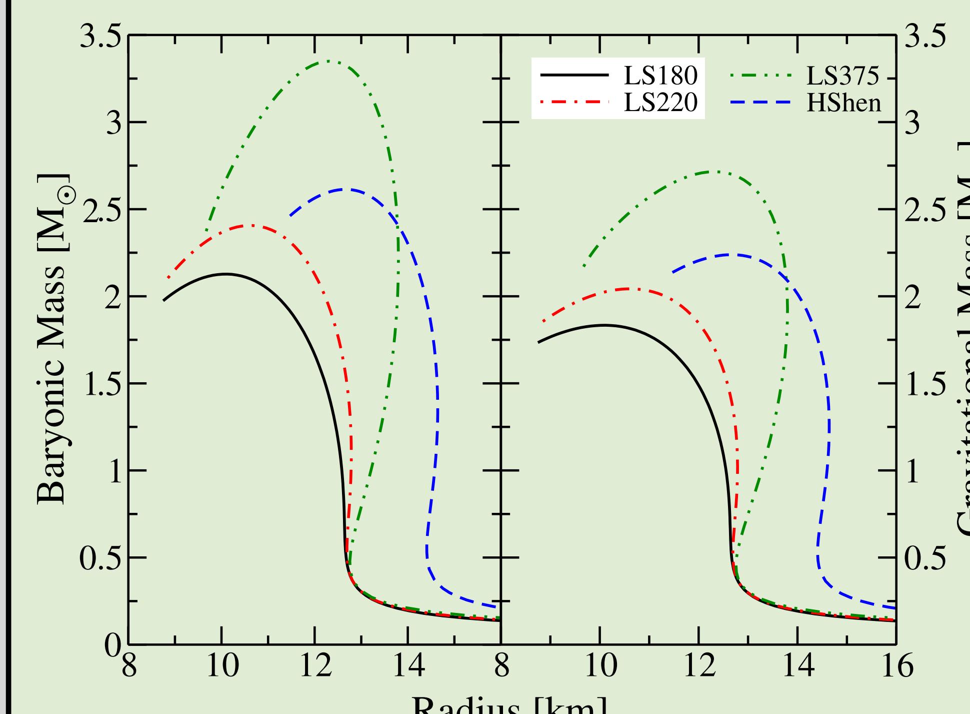
Recently, we have successful exploding models driven by neutrino heating




All of these simulations employ LS180, which, however, cannot support a 2M⊙ NS. How about stiffer EOS?



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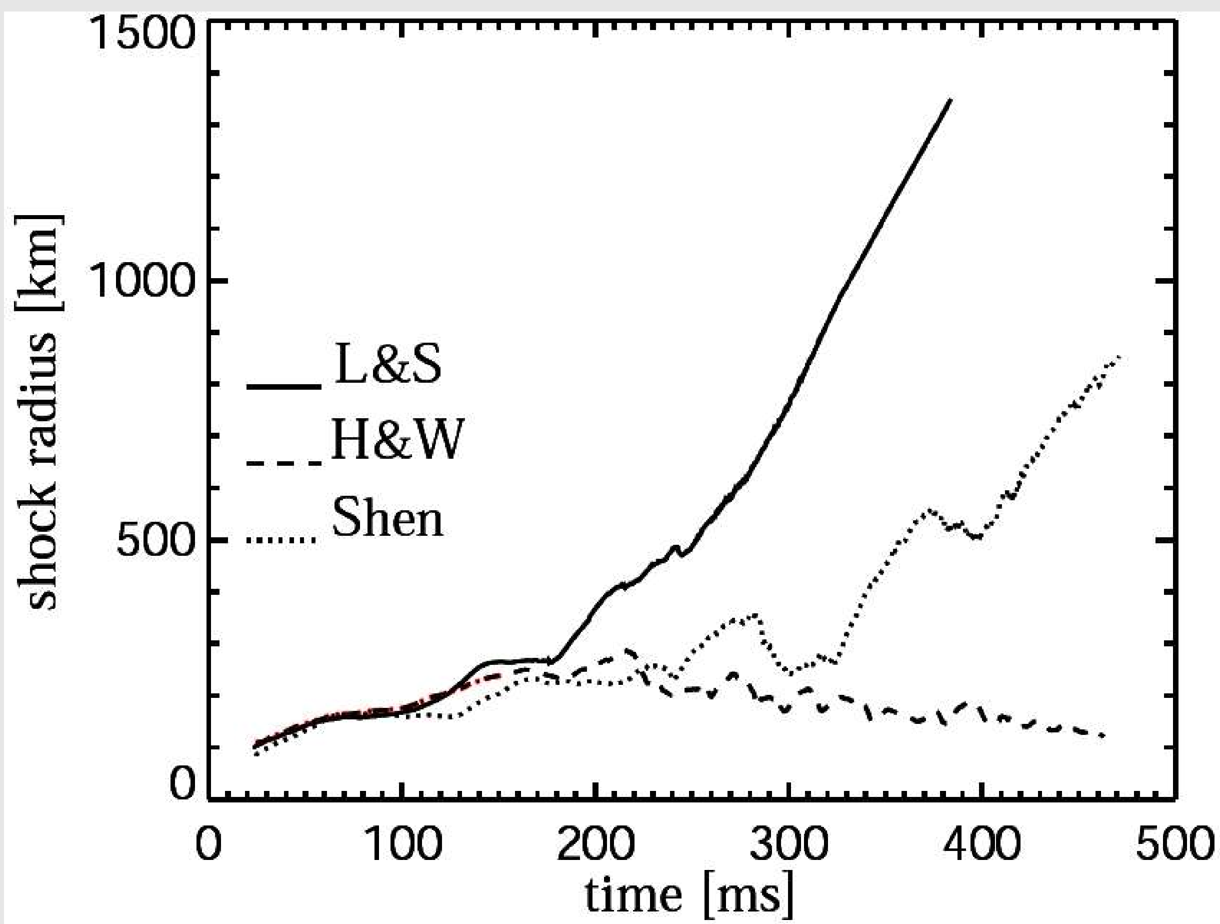
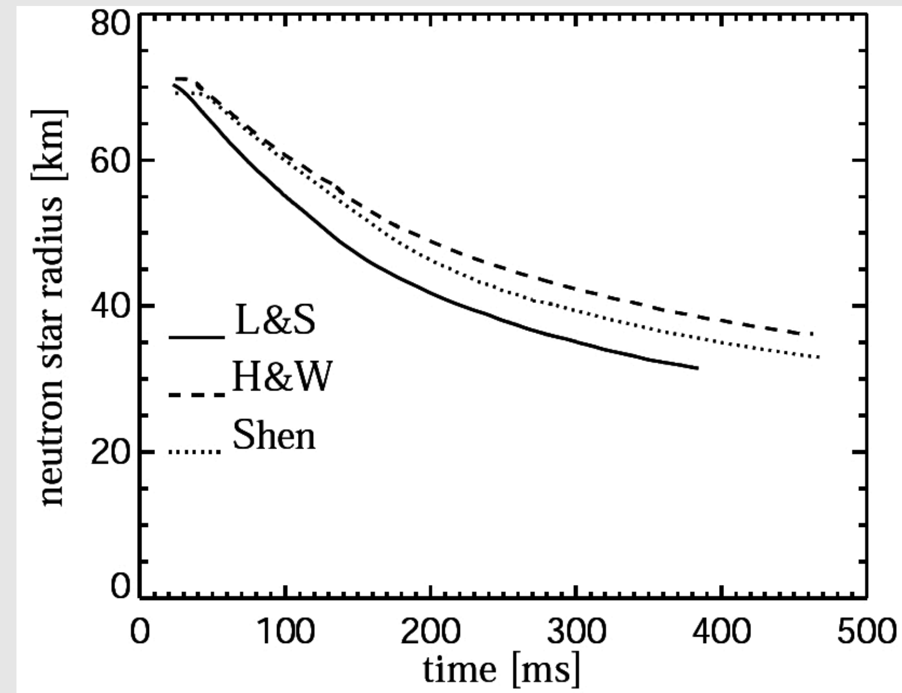
# EOS and shock evolution

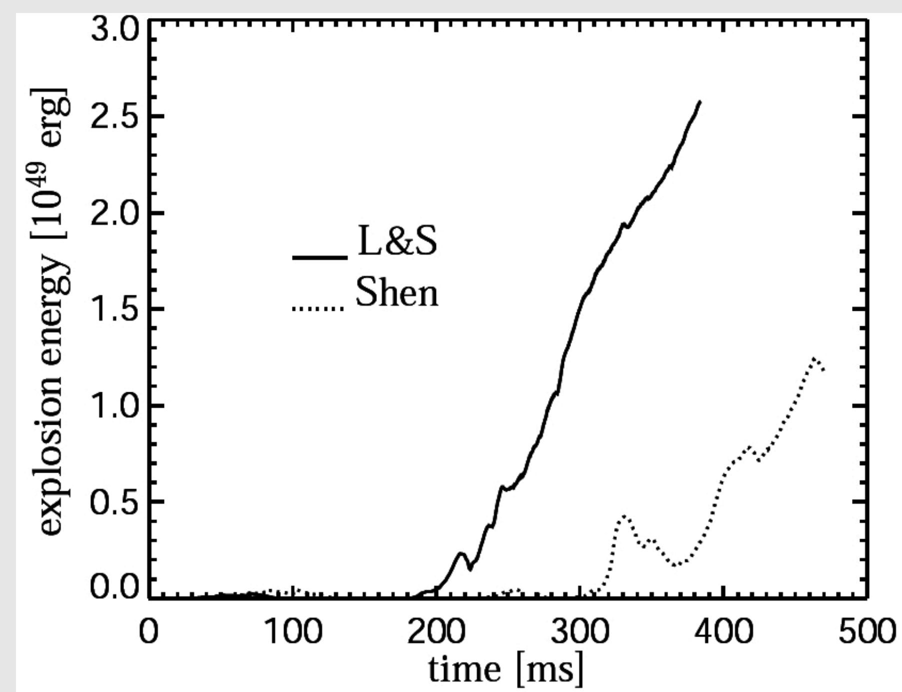
from H.-Th. Janka's presentation

## 2D Explosions of 11.2 $M_{sun}$ star : Test of EoS Influence

- Simulations for 3 different nuclear EoSs: Lattimer & Swesty (L&S), Hillebrandt & Wolff (H&W), Shen et al.
- "Softer" (L&S) EoS and thus more compact PNS leads to earlier explosion




(Marek & THJ, 2009, in preparation)

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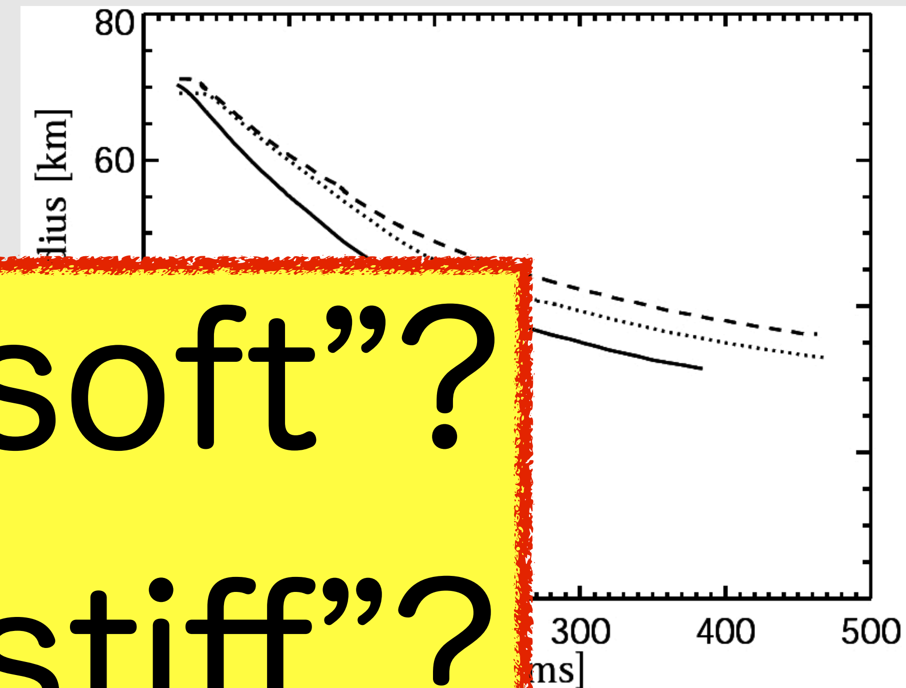
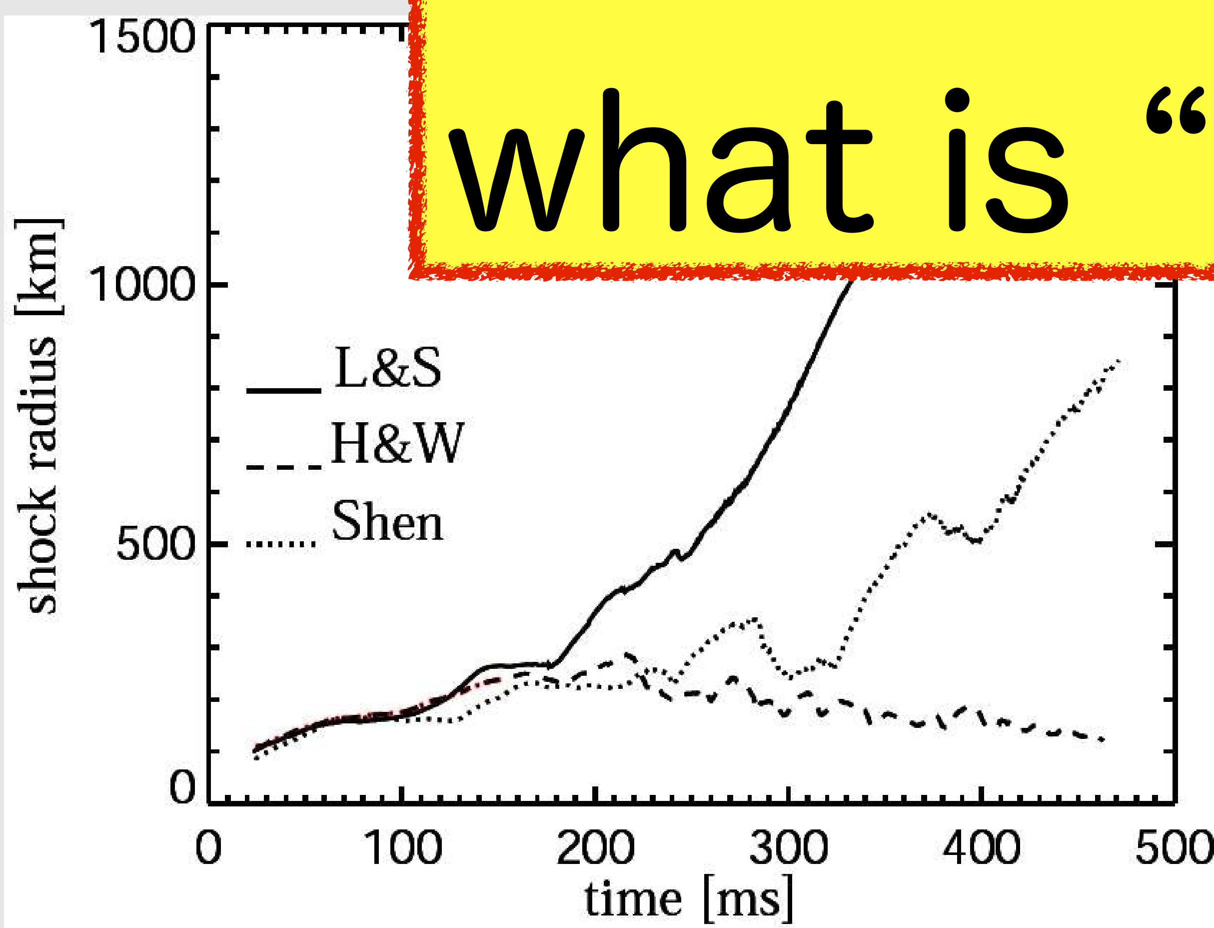
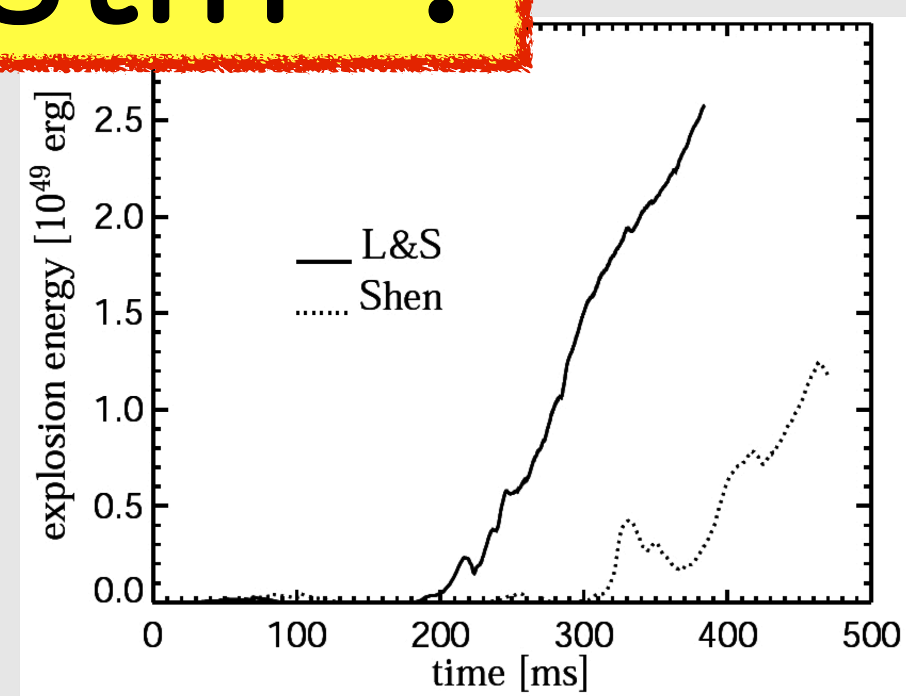
- "Softer" (L&S) PNS leads to




# what is "soft"?

# what is "stiff"?

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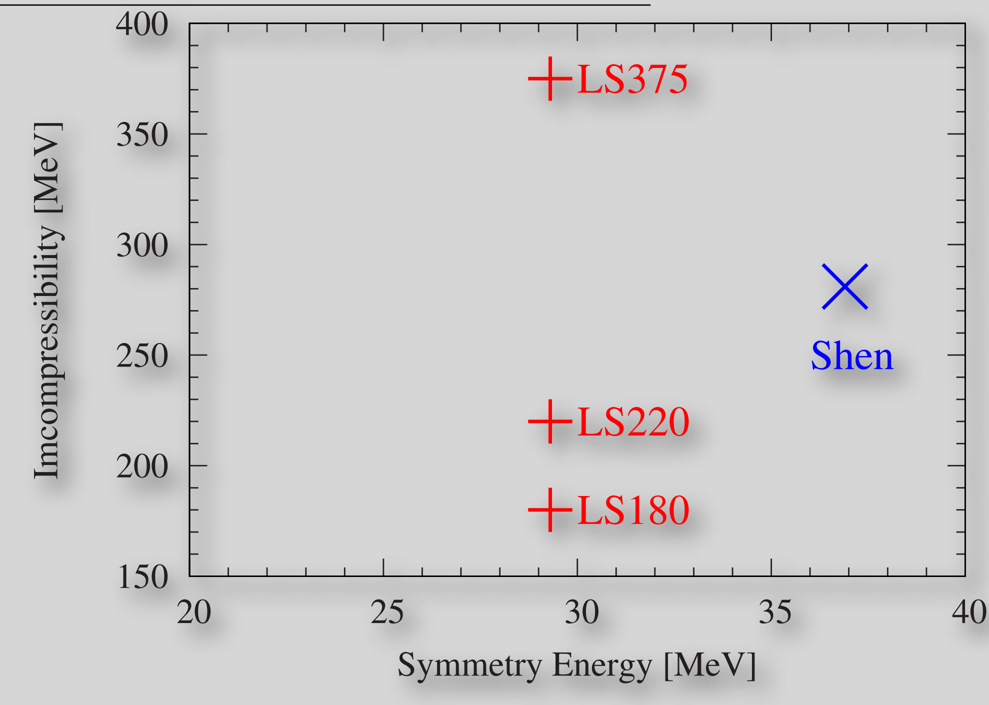
# Numerical simulation

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




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

* Hydrodynamics + Neutrino transfer

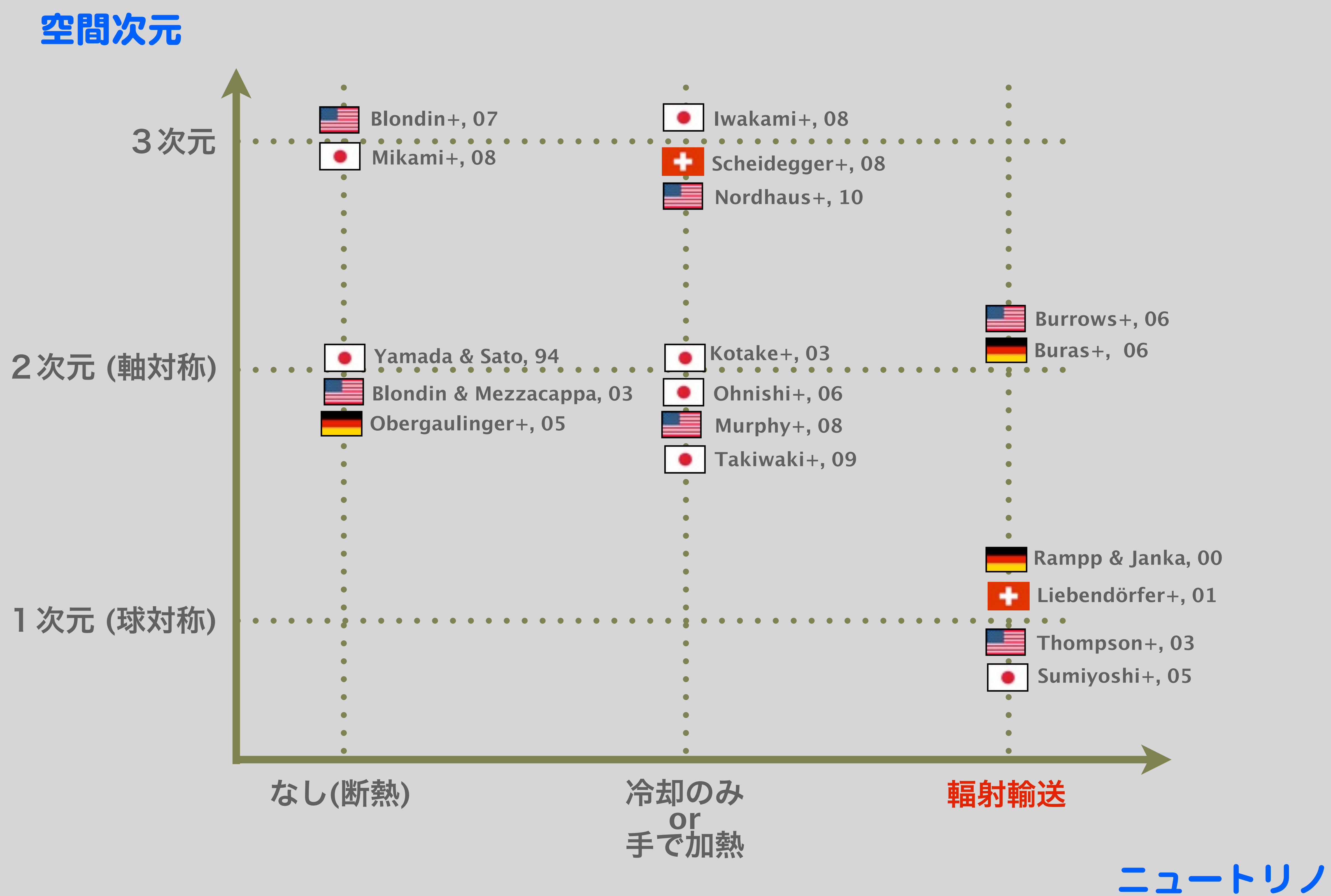
$$\frac{df}{cdt} + \mu\frac{\partial f}{\partial r} + \left[\mu\left(\frac{d\ln\rho}{cdt} + \frac{3v}{cr}\right)\right](1-\mu^2)\frac{\partial f}{\partial \mu} + \left[\mu^2\left(\frac{d\ln\rho}{cdt} + \frac{3v}{cr}\right) - \frac{v}{cr}\right]D\frac{\partial f}{\partial E}$$
$$= j(1-f) - \chi f + \frac{E^2}{c(hc)^3}\left[(1-f)\int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

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

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

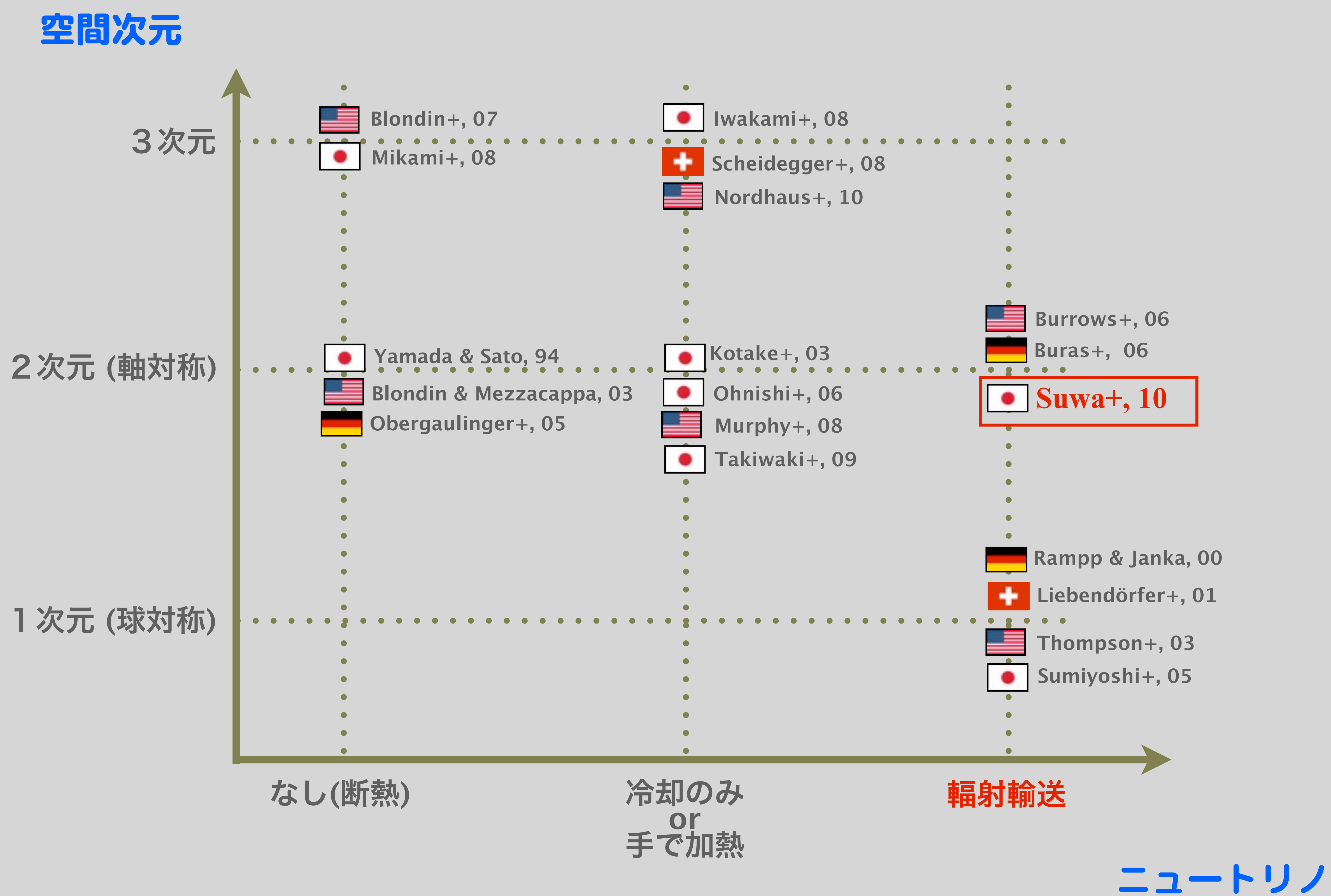
* progenitor: 15 $M_\odot$ (Woosley & Weaver 95)

# 研究の立ち位置



空間次元
3次元
2次元 (軸対称)
1次元 (球対称)
Blondin+, 07
Mikami+, 08
Iwakami+, 08
Scheidegger+, 08
Nordhaus+, 10
Burrows+, 06
Buras+, 06
Yamada & Sato, 94
Blondin & Mezzacappa, 03
Obergaulinger+, 05
Kotake+, 03
Ohnishi+, 06
Murphy+, 08
Takiwaki+, 09
Rampp & Janka, 00
Liebendörfer+, 01
Thompson+, 03
Sumiyoshi+, 05
なし(断熱)
冷却のみ
or
手で加熱
輻射輸送
ニュートリノ

# 研究の立ち位置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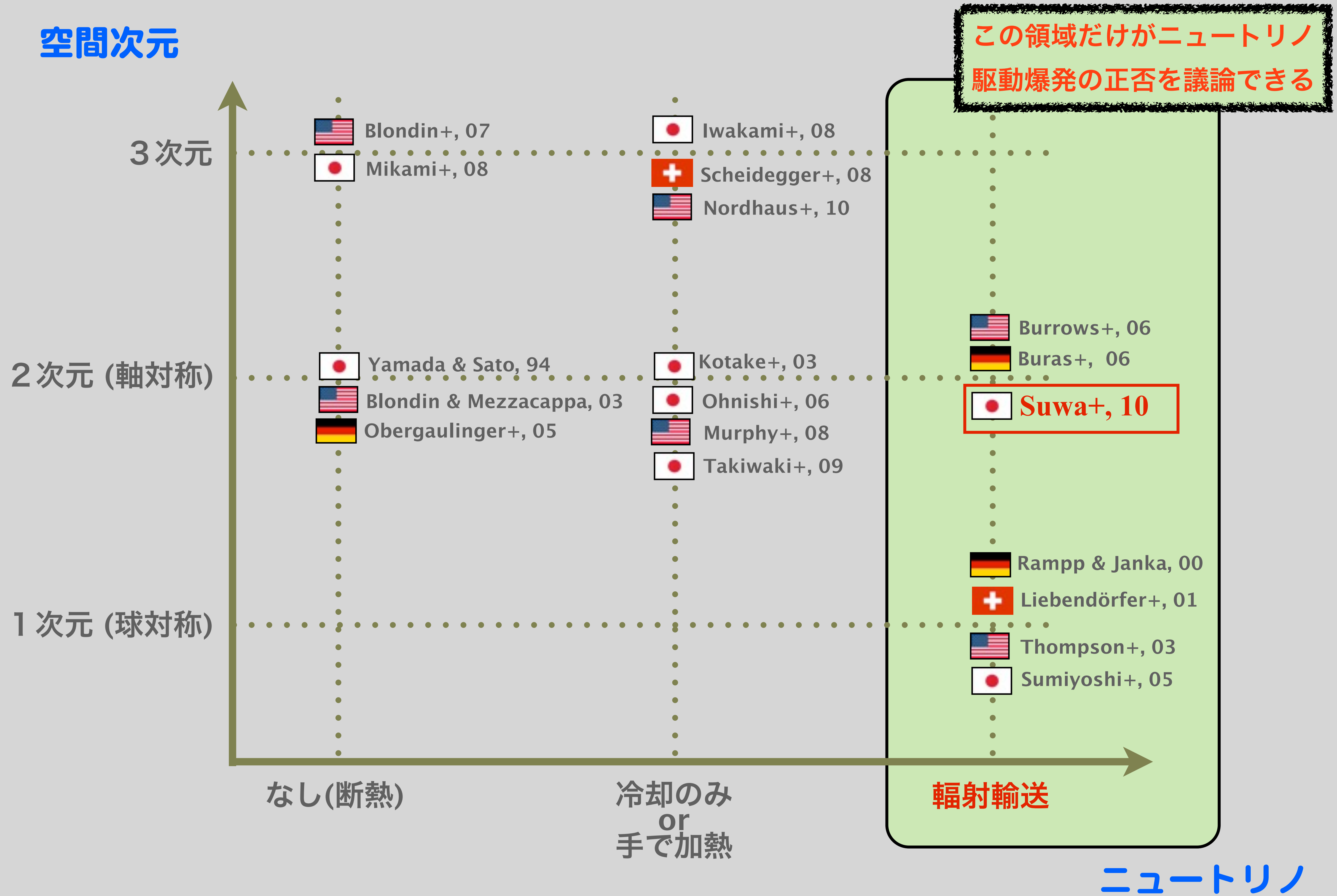

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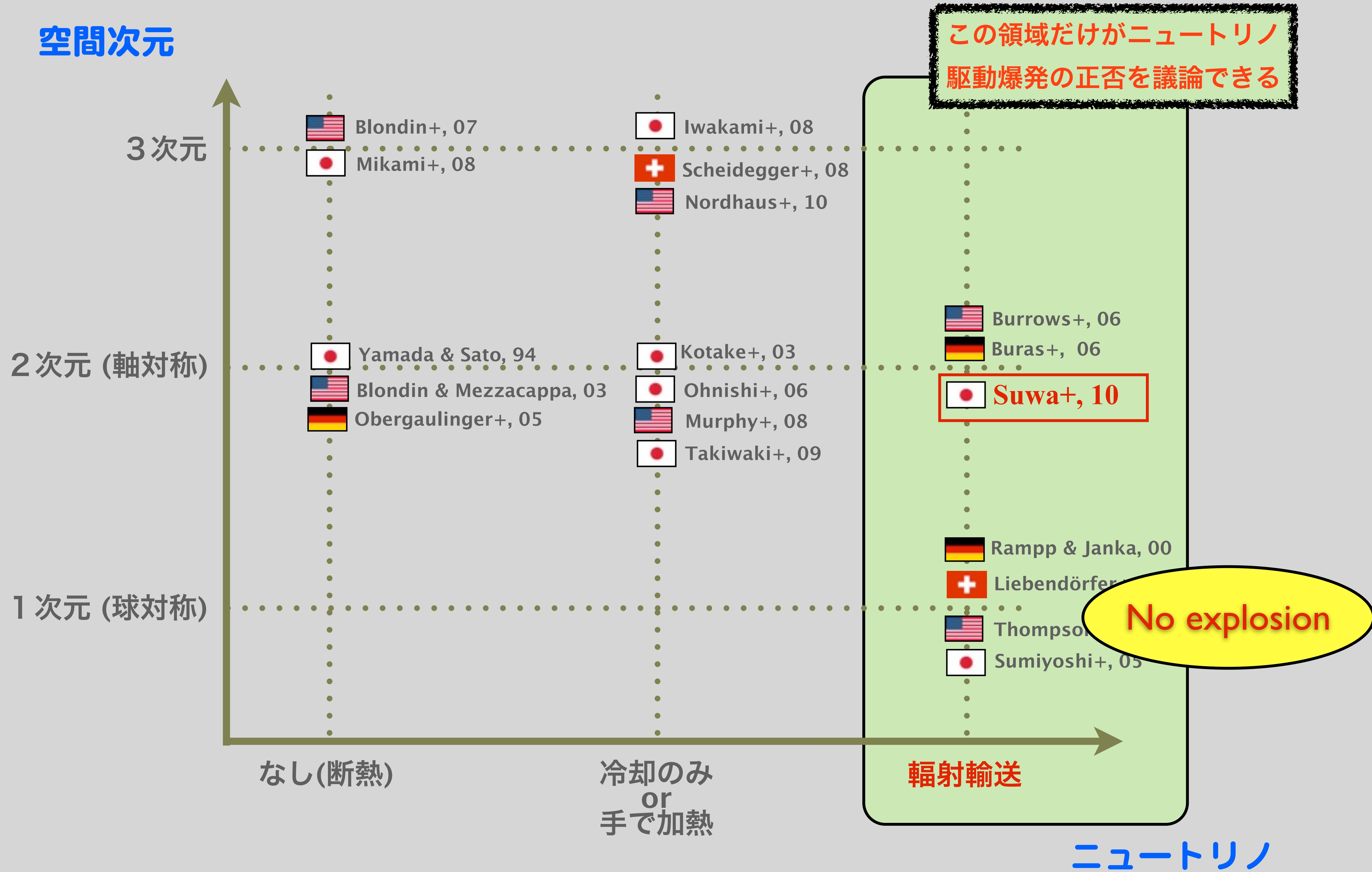

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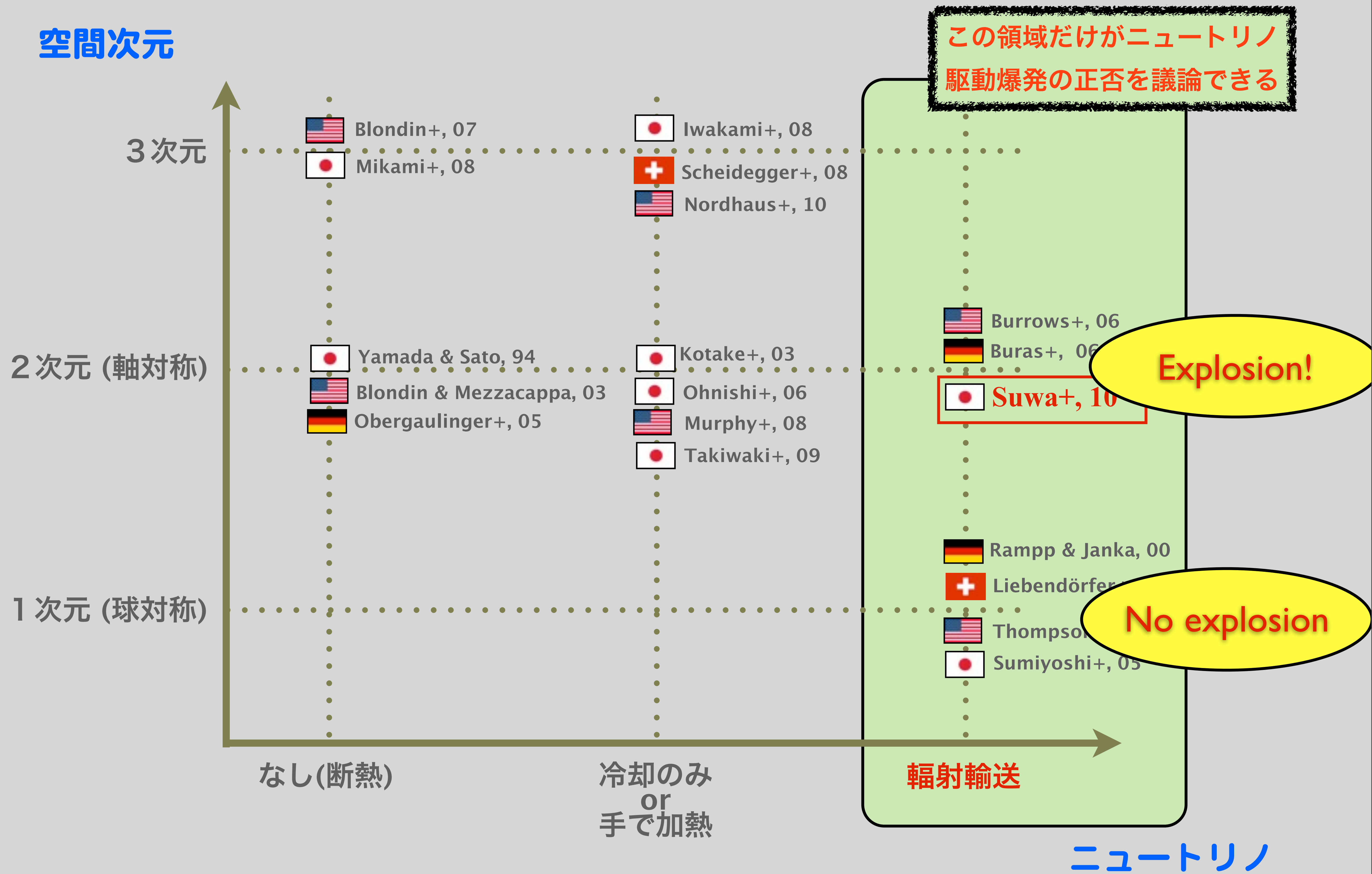

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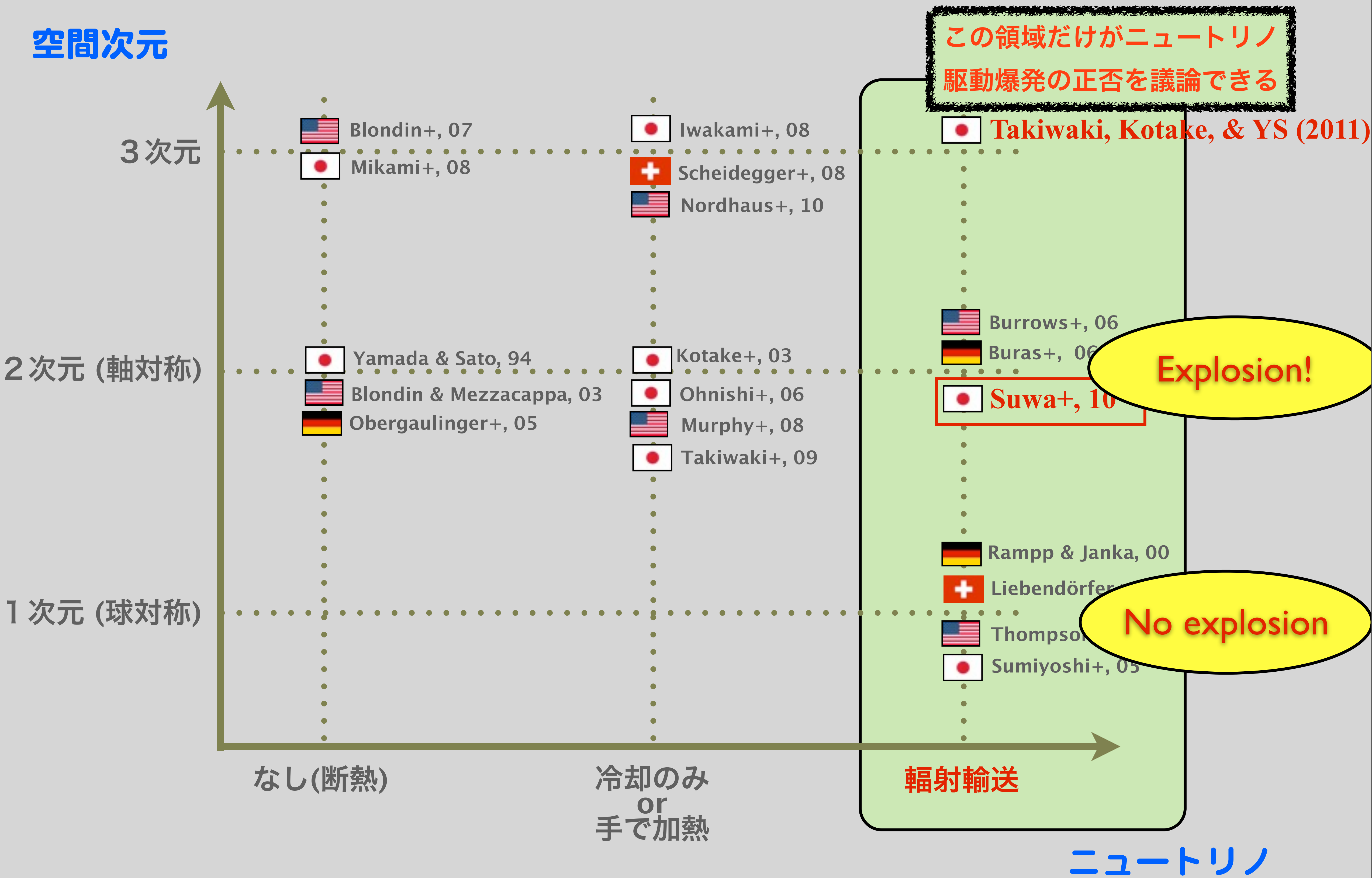
Explosion!
Rampp & Janka, 00
Liebendörfer
Thompso
Sumiyoshi+, 05
No explosion

# 研究の立ち位置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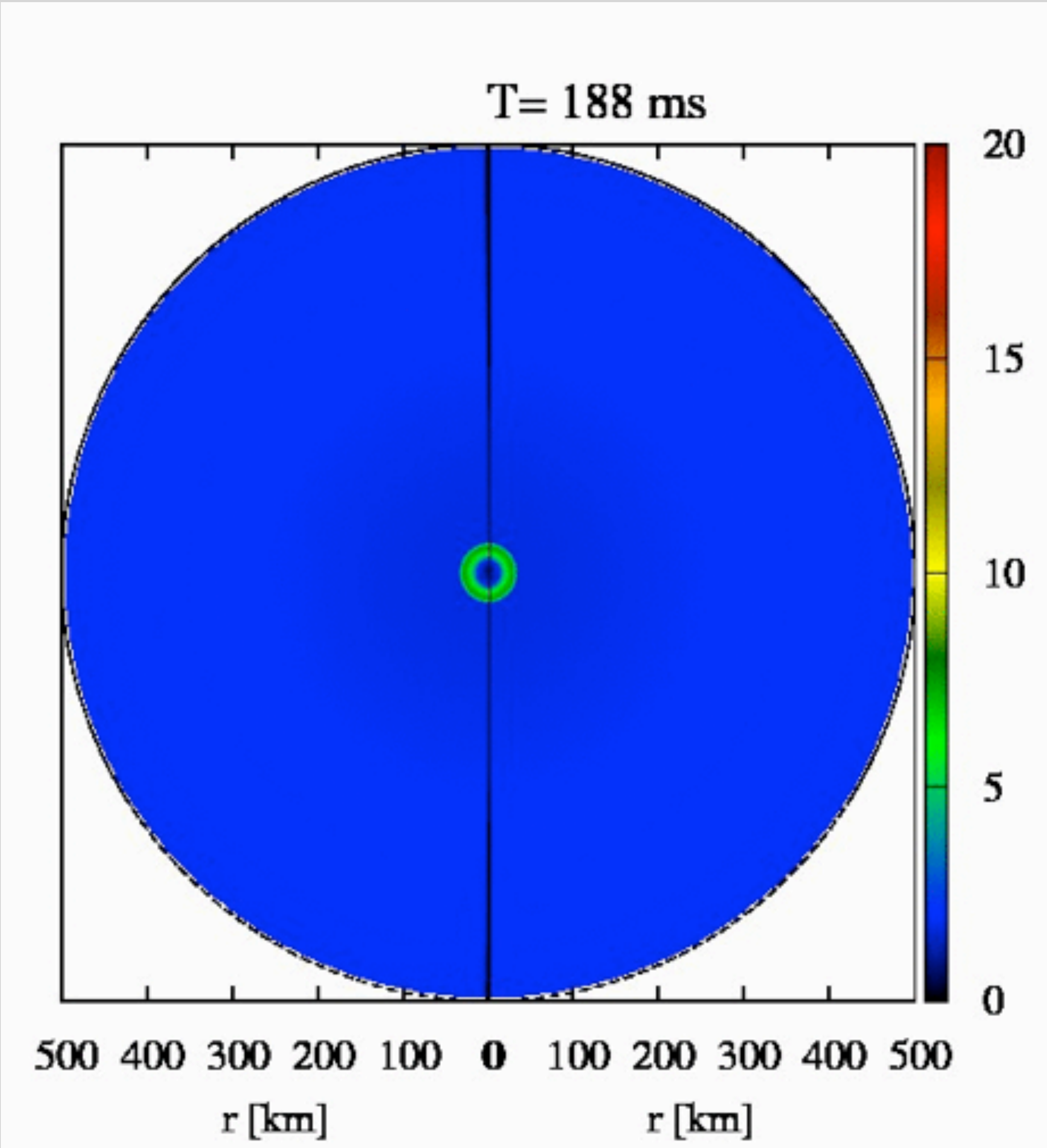
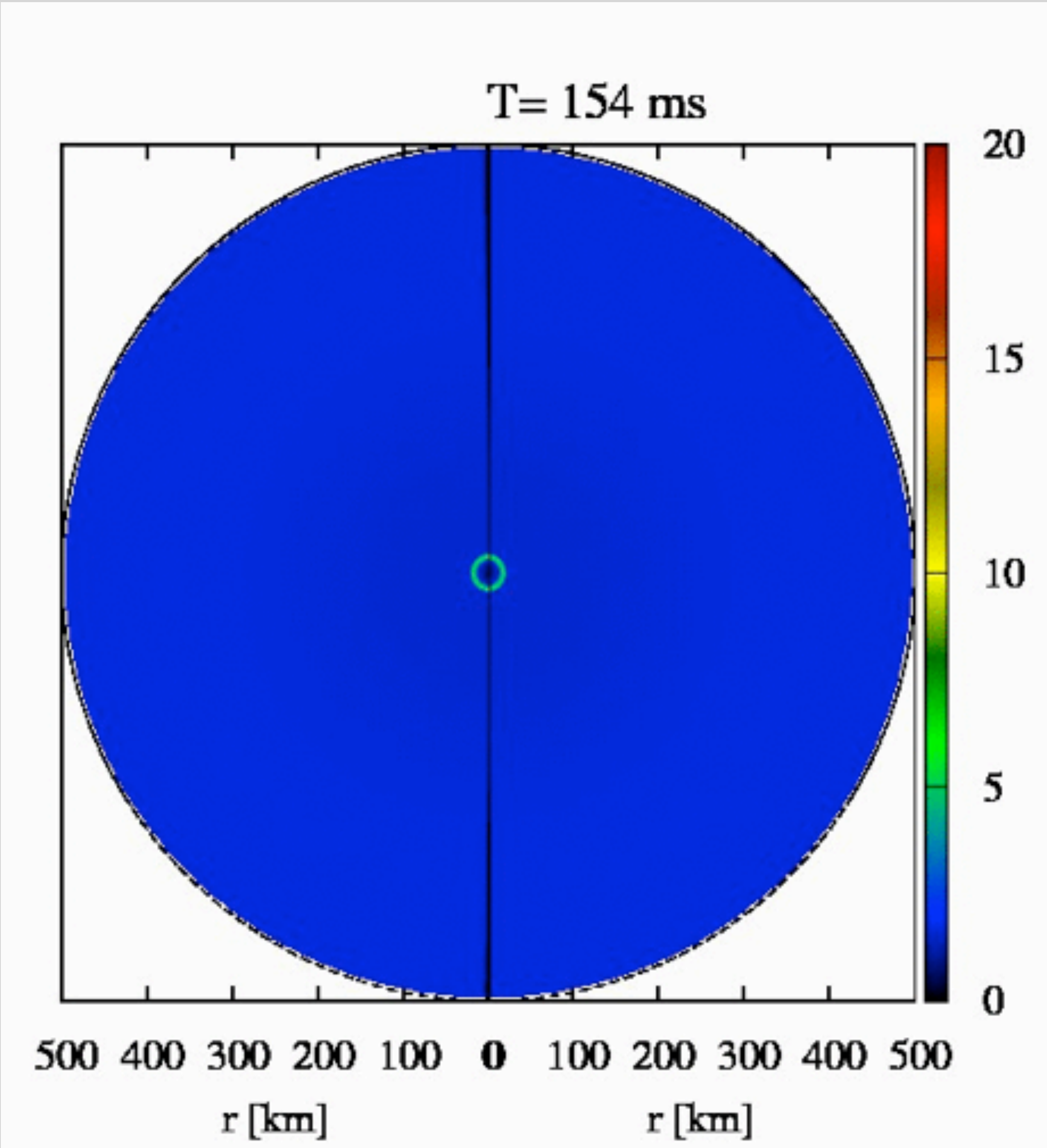
# Entropy evolution

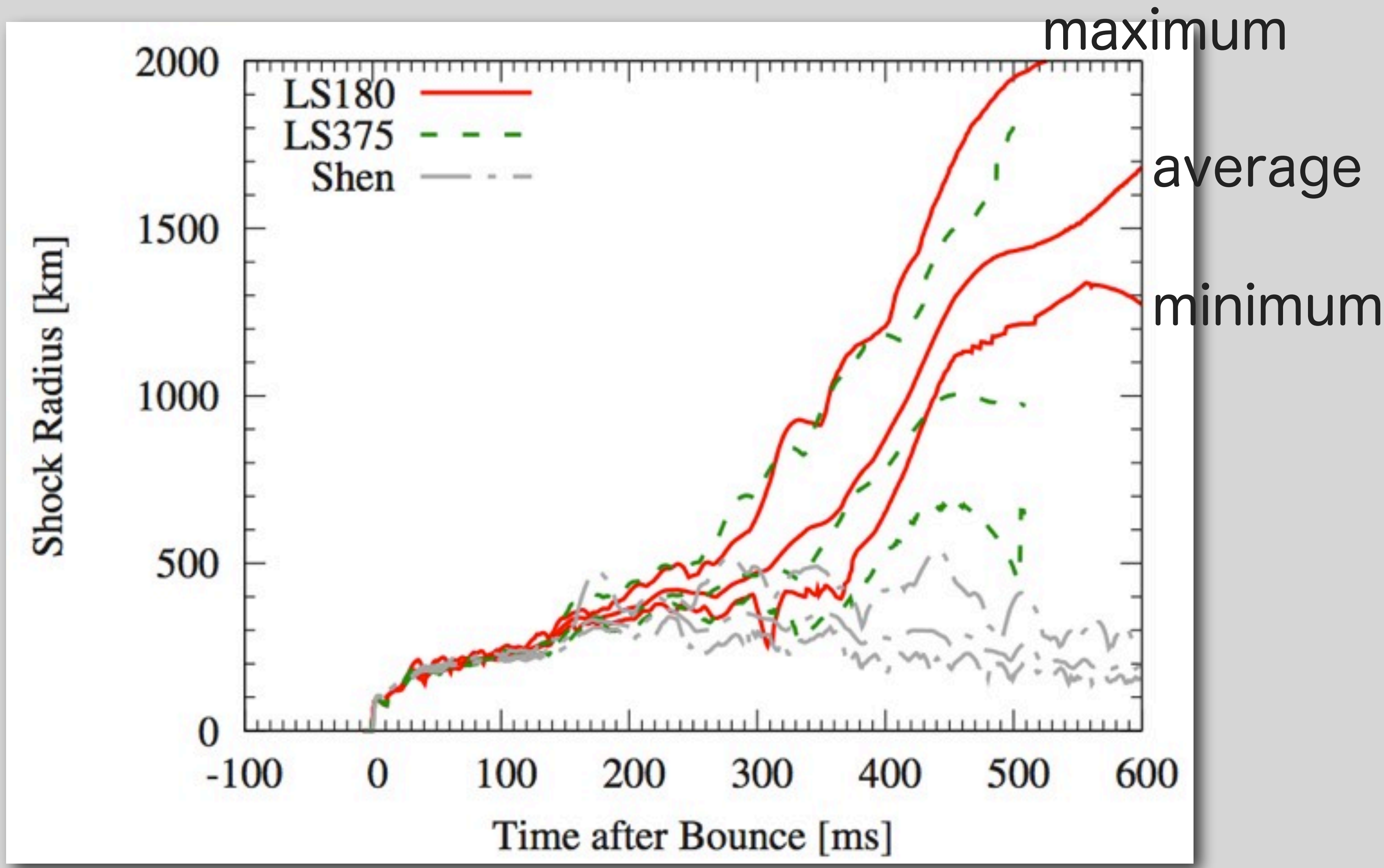
LS180




Shen



# Shock radius




LS180 and LS375 succeed the explosion

Shen EOS fails

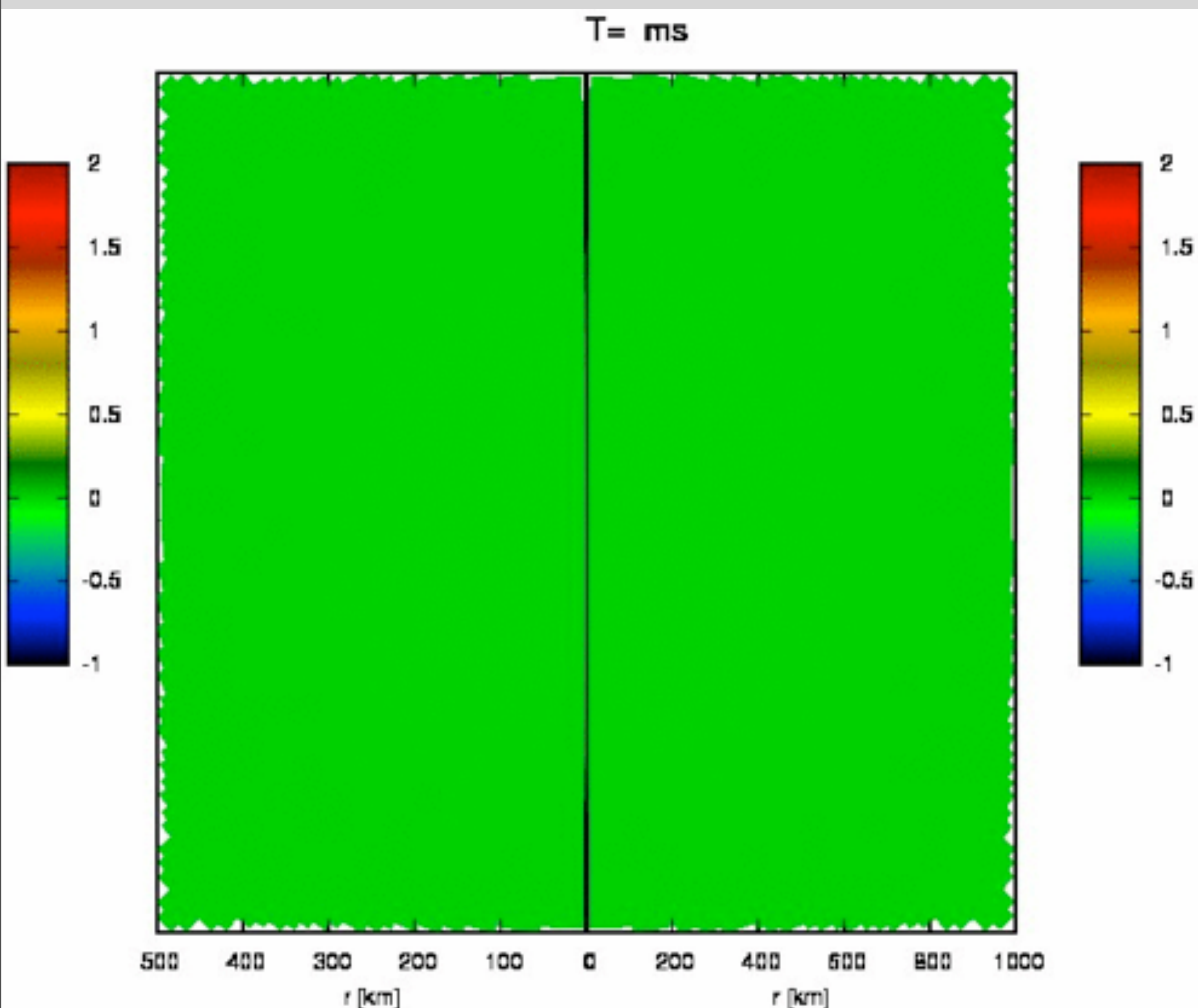
# Dispersion of the moment

$$\frac{\mathcal{M}(r,\theta) - \overline{\mathcal{M}}(r)}{\overline{\mathcal{M}}(r)}$$

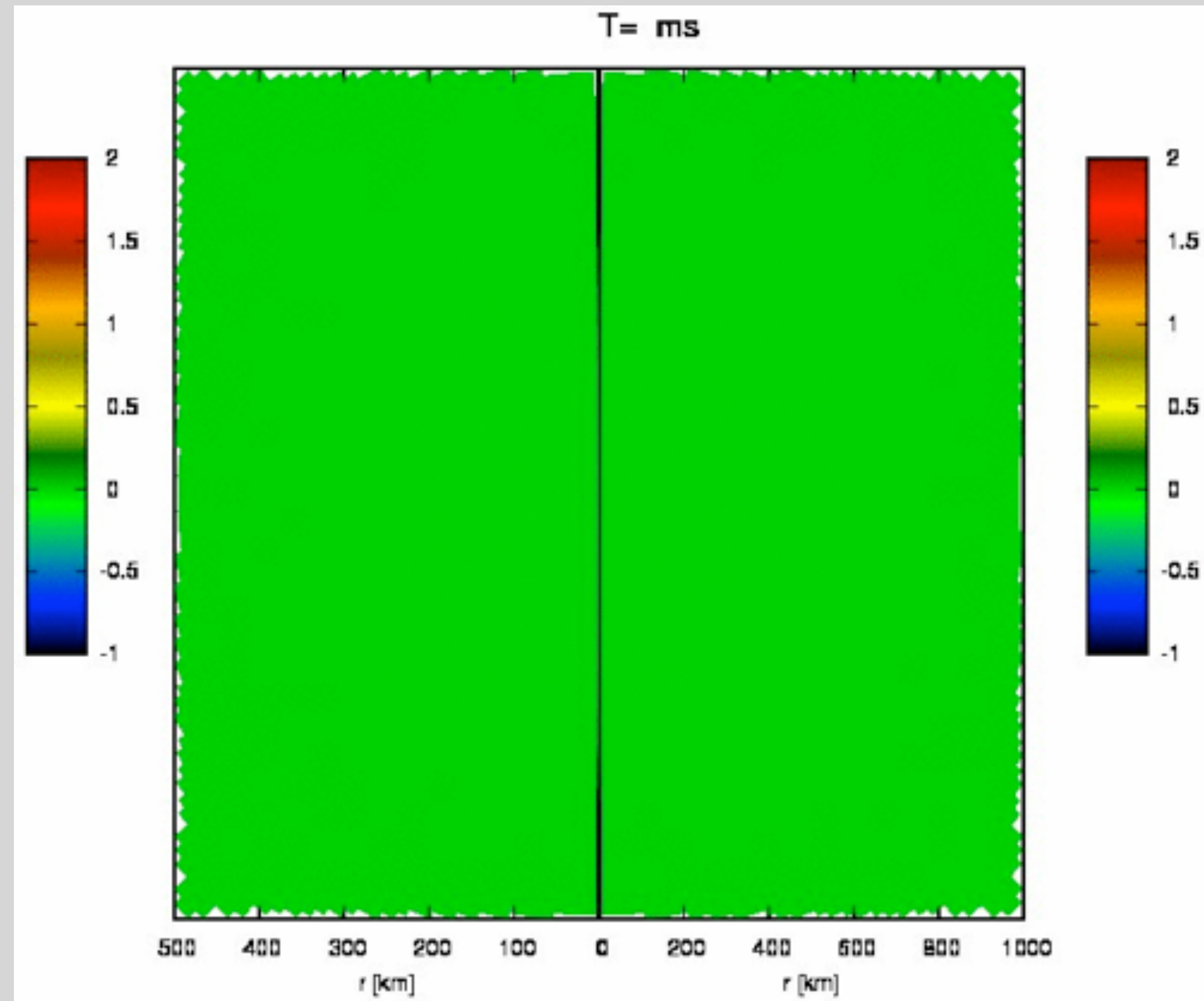
$$\mathcal{M}(r,\theta) \equiv \rho(r,\theta) v_r^2(r,\theta) + P(r,\theta),$$

$$\overline{\mathcal{M}}(r) \equiv \frac{1}{2}\int_0^\pi \mathcal{M}(r,\theta)\sin\theta d\theta.$$

LS180

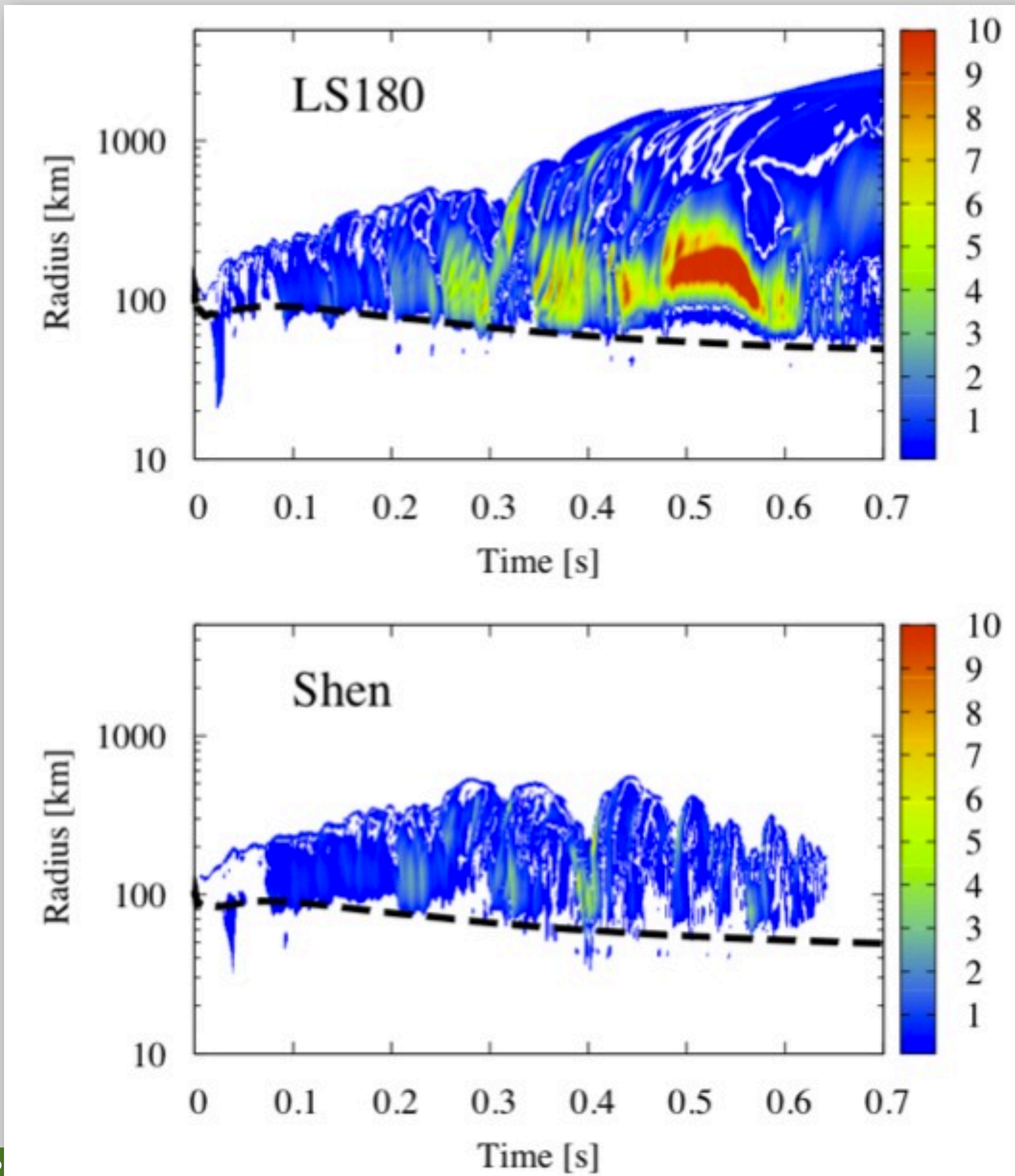



Shen




$$cf. \ \frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla(\cdot \rho \boldsymbol{u}\boldsymbol{u} + P) = 0$$

# Dispersion of the moment



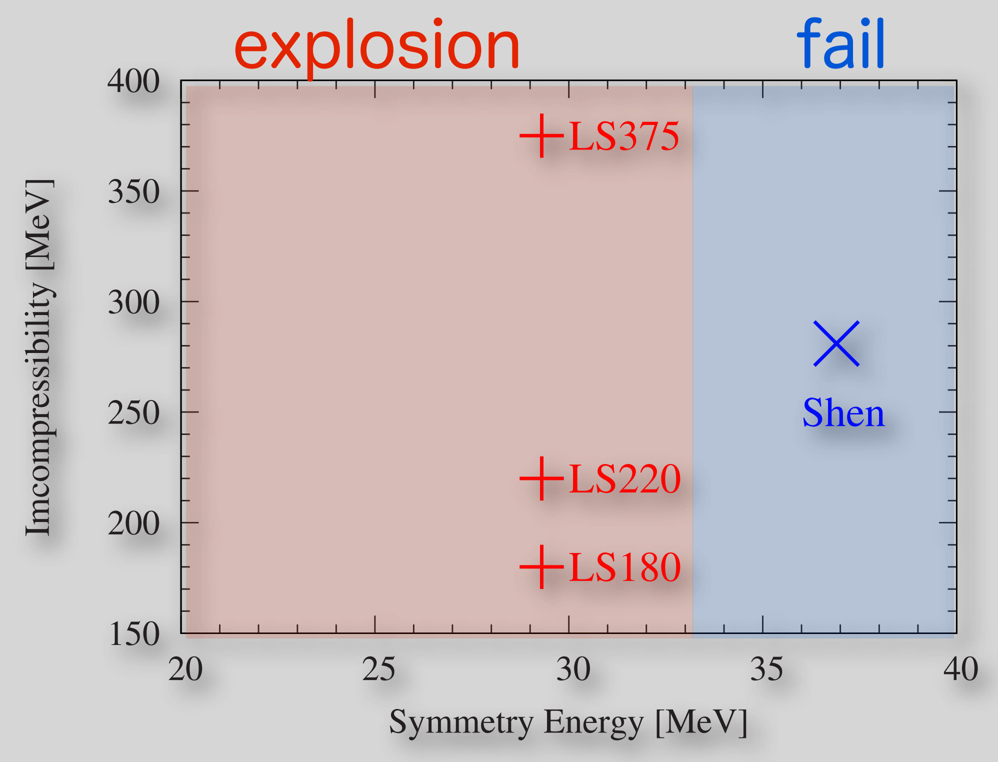

$$\frac{\left\{\frac{1}{2}\int_0^\pi \left[\mathcal{M}(r,\theta)-\overline{\mathcal{M}}(r)\right]^2 \sin\theta d\theta\right\}^{1/2}}{\overline{\mathcal{M}}(r)}$$

$$\mathcal{M}(r,\theta) \equiv \rho(r,\theta) v_r^2(r,\theta) + P(r,\theta),$$

$$\overline{\mathcal{M}}(r) \equiv \frac{1}{2}\int_0^\pi \mathcal{M}(r,\theta)\sin\theta d\theta.$$

# 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




* The symmetry energy would have greater impact than the incompressibility
* The difference of the incompressibility does not affect the dynamics very much at least with the current setup
* In order to make the complete understanding of EOS impacts, a more systematic study is strongly required!