2015/1/20@CfCA users’ meeting

超新星爆発シミュレーションの現状

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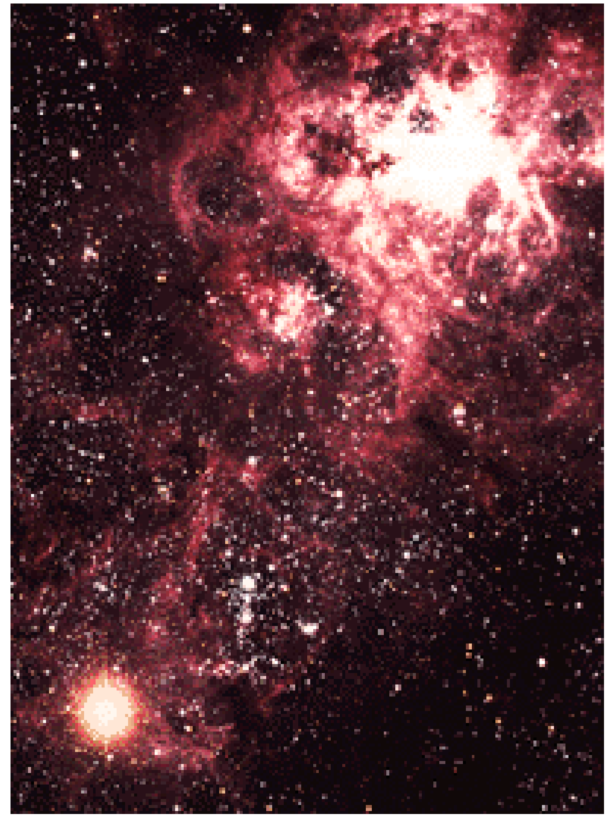
Most luminous object in Universe

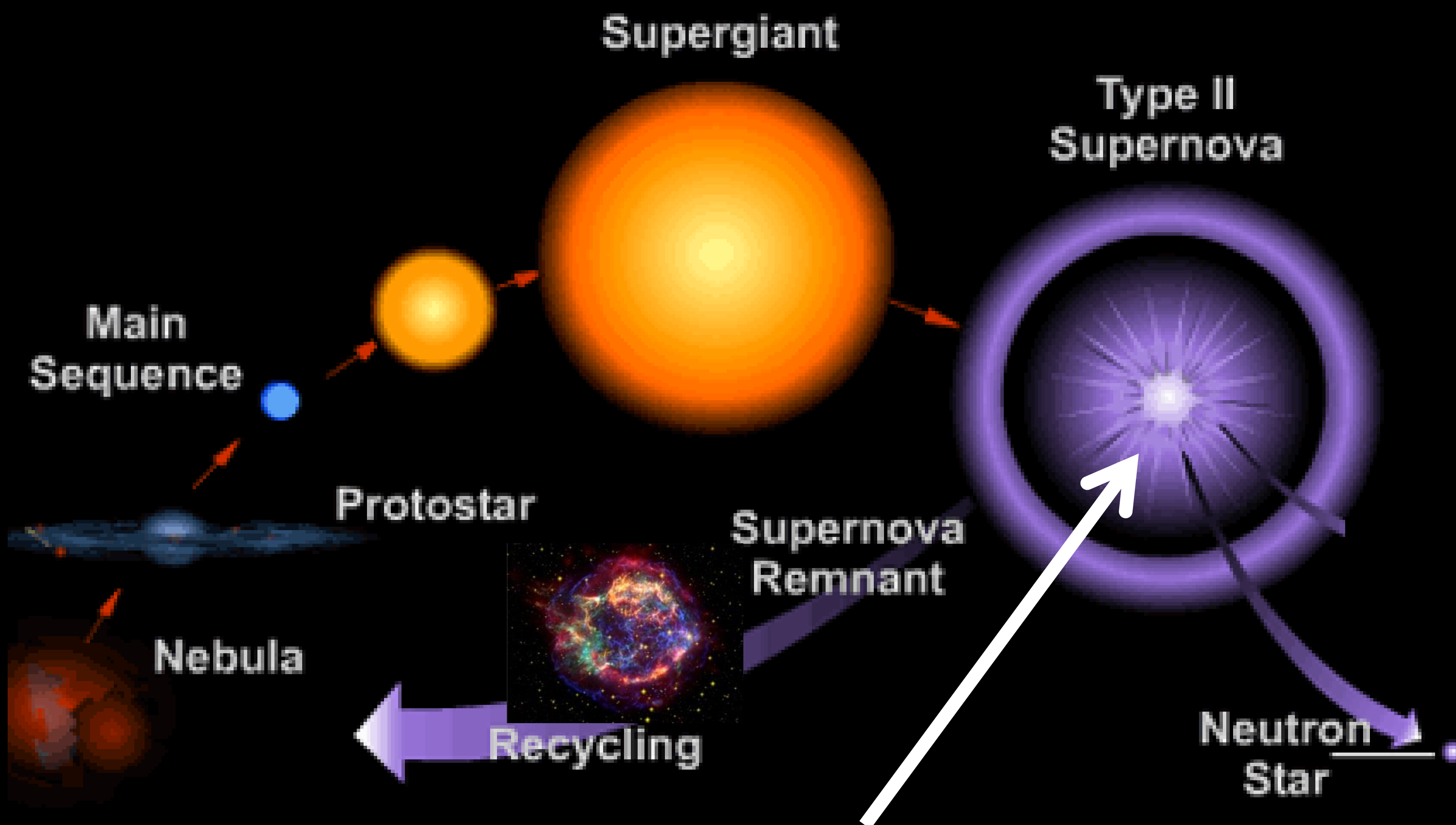


Visible light

Supernova 1987A in the Large Magellanic Cloud (1987 Oct)
D_LMC=48.8kpc=12 k ly

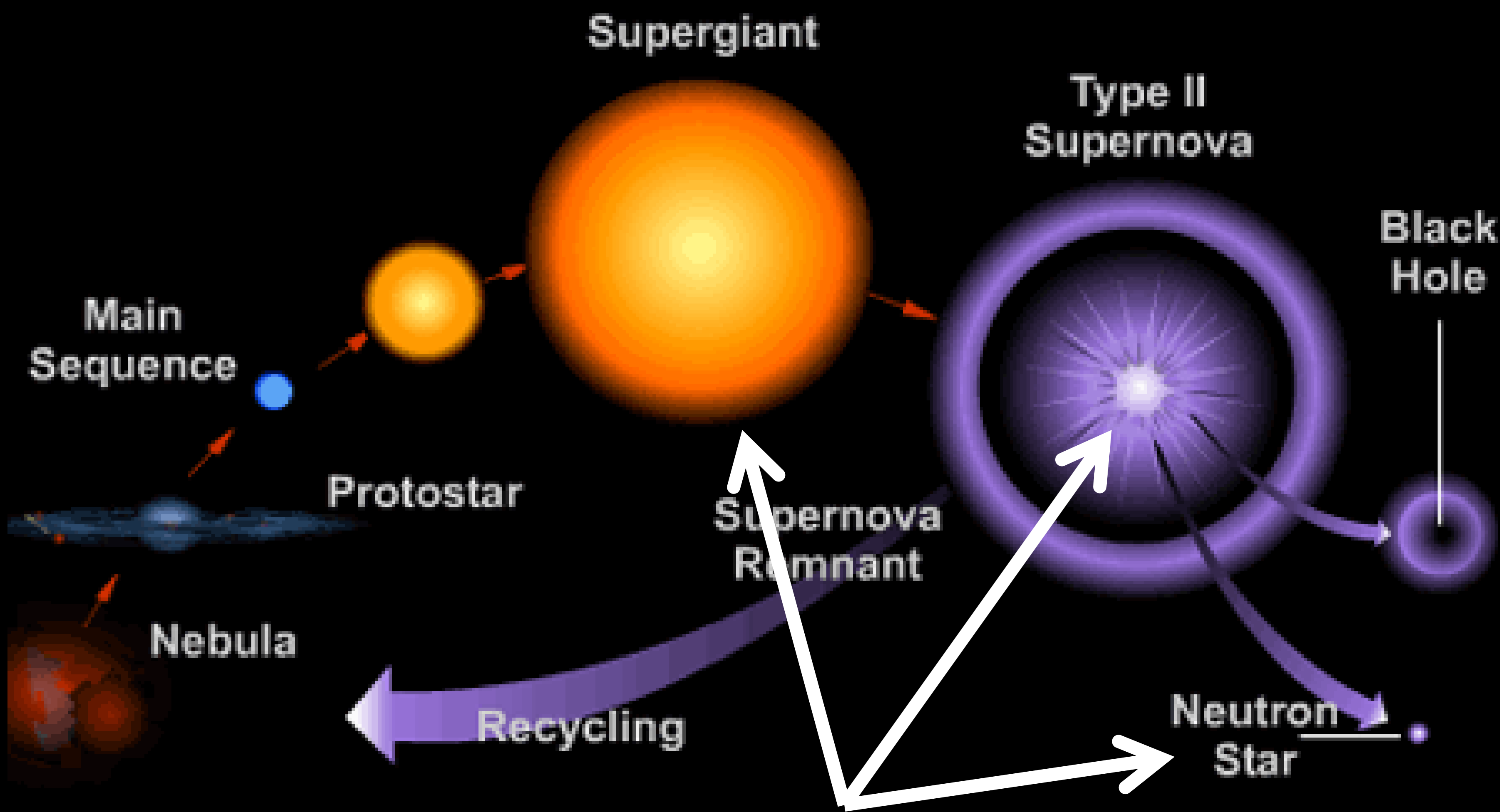
Supernovae(10pc)M=-18
1 billion of Sun（4.8）
Milkyway（M=-20.5）1/6
Decay 100day

星の一生と最期の大爆発



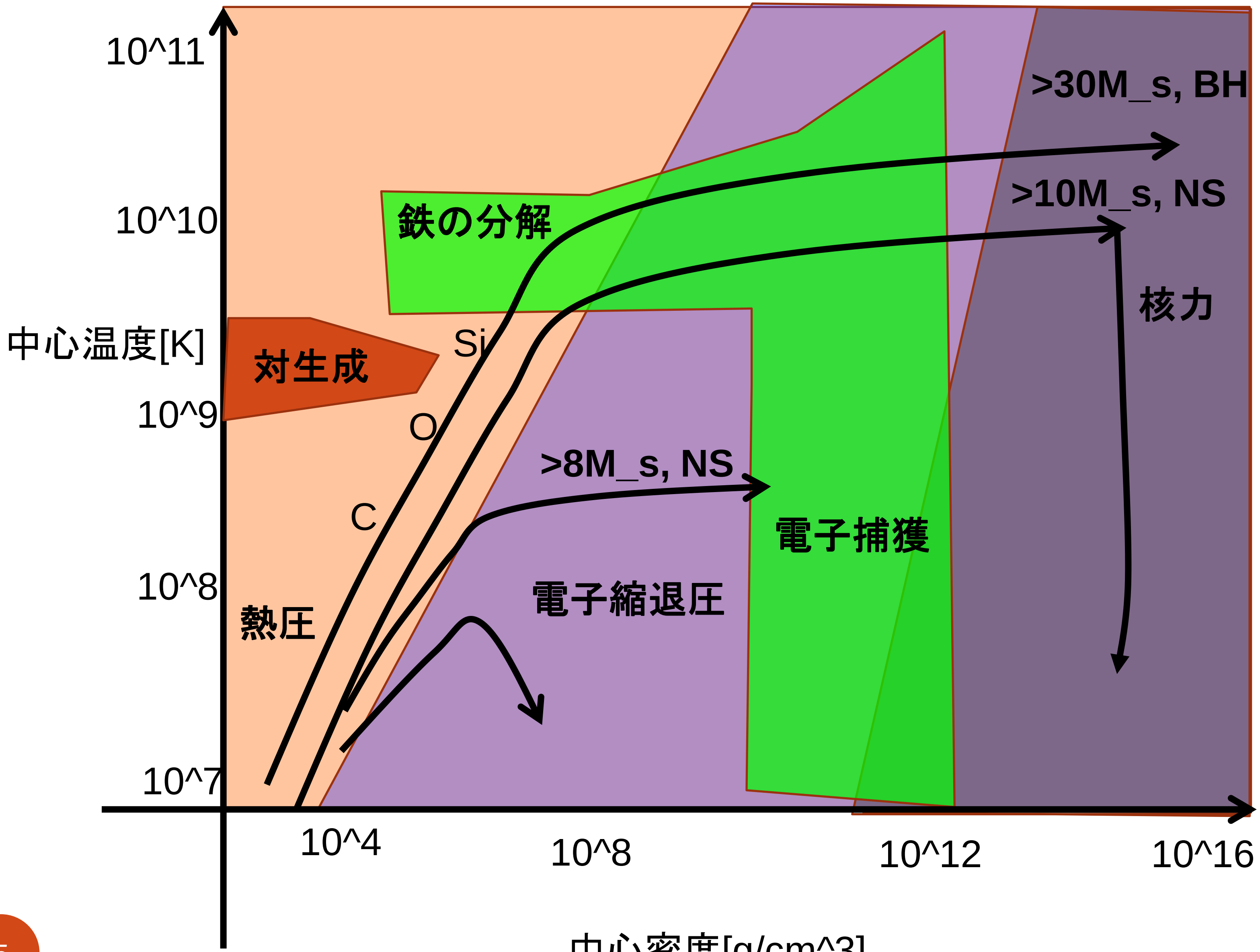
実は、ここでどうして爆発するのか
はっきりわかってない！

星の一生と最期の大爆発

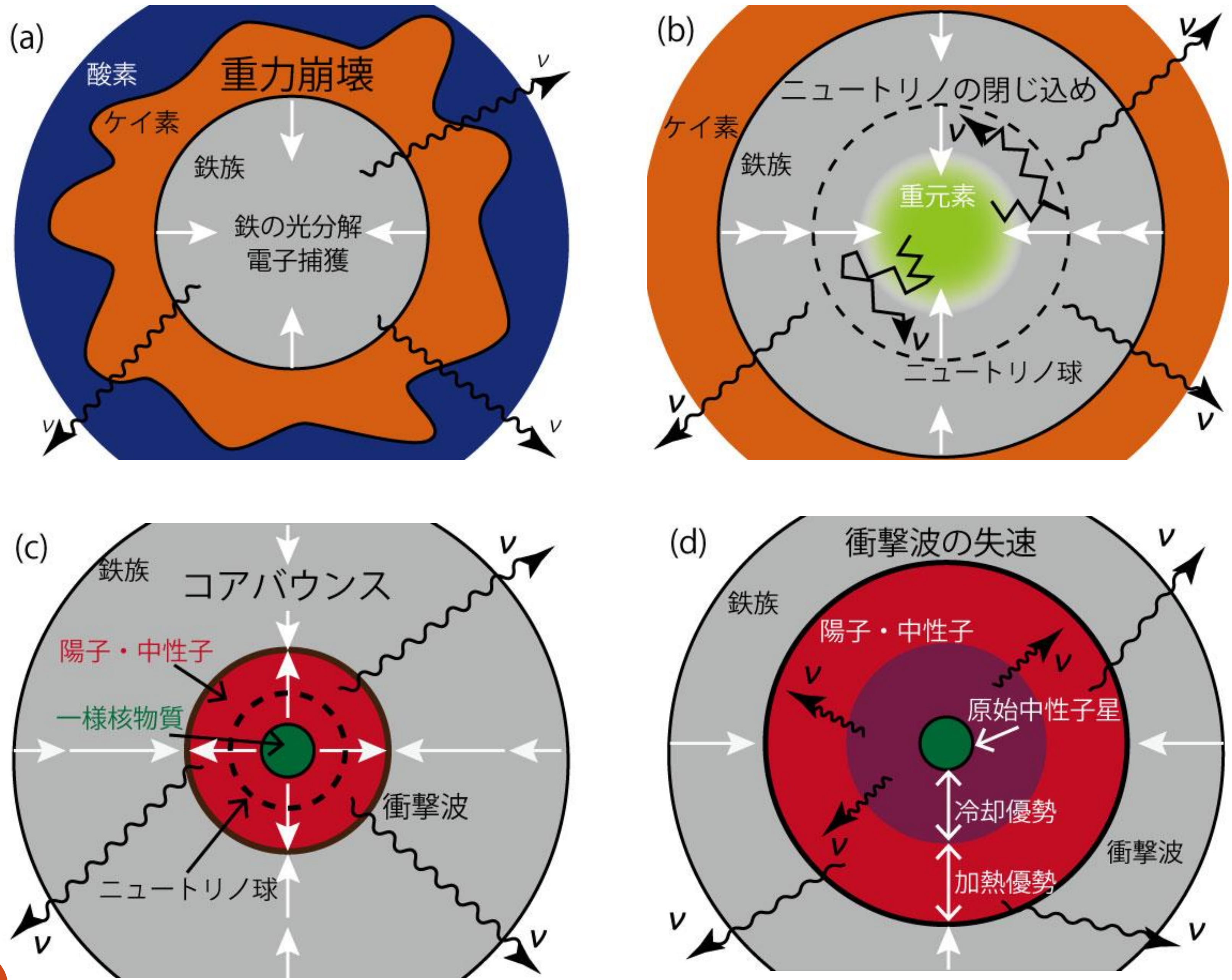


実はいろんな爆発をするが、
どんな親星がどんな風に爆発するのか分かってない

星の進化と重力不安定



10^11
10^10
10^9
10^8
10^7
中心温度[K]
10^4
10^8
10^12
10^16
中心密度[g/cm^3]
>30M_s, BH
>10M_s, NS
>8M_s, NS
鉄の分解
対生成
Si
O
C
熱圧
電子縮退圧
電子捕獲
核力



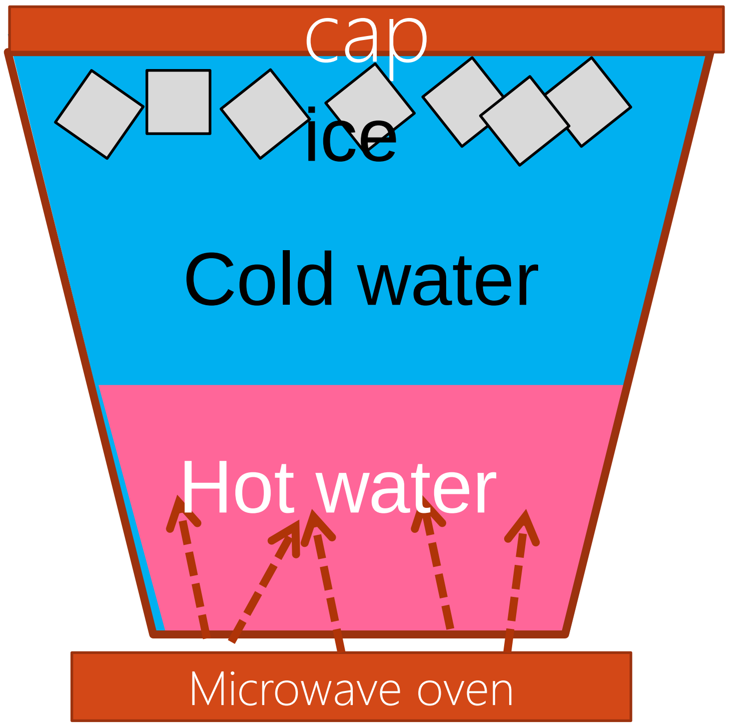
(a)
酸素
重力崩壊
ケイ素
鉄族
鉄の光分解
電子捕獲
ν
(b)
ニュートリノの閉じ込め
ケイ素
鉄族
重元素
ニュートリノ球
ν
(c)
鉄族
コアバウンス
陽子・中性子
一様核物質
衝撃波
ニュートリノ球
ν
(d)
衝撃波の失速
鉄族
陽子・中性子
原始中性子星
冷却優勢
加熱優勢
衝撃波
ν

Typical 1D simulation

Problem

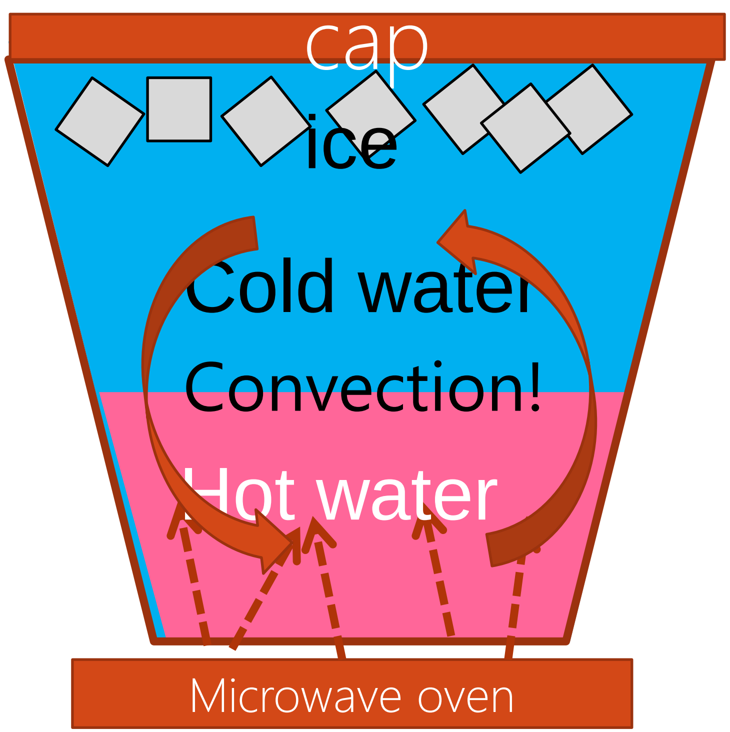
Supernova shock in simulation
tends to stall and
does NOT explode.

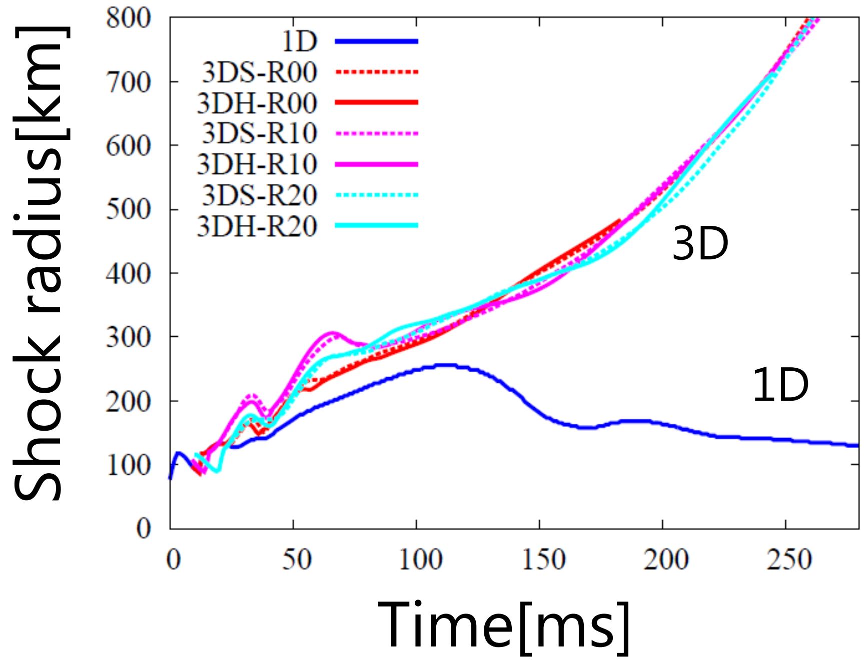
Long-lasting Problem ~1980.
In 2000-2005, state-of-the-art simulations with detailed neutrino transport confirm that!
(Liebendoerfer+2001, Rampp+2002, Thompson+2003 and Sumiyoshi+2005)



(in 1D)Neutrino heating < Cooling by Iron
=> fails to explode!

Era of 3D simulation is coming!





2 month times 16,000 cores are used in K computer

Most distinct development is shift from 1D to 3D(or 2D)!

We succeed to make a few explosion models!

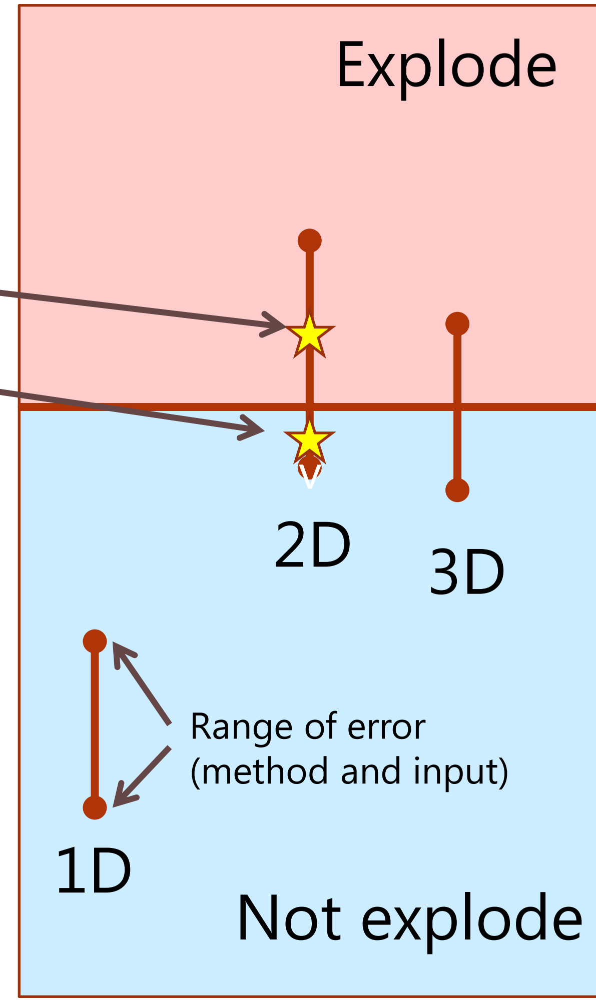
Takiwaki+2012,2014

Recent Problem of CC SNe

Results in multi-D models significantly depend on input physics and numerical methods!

2D models for multiple progenitors

- Bruenn+12：all explode
- Mueller+13：almost all explode
- Dolence+14：not explode
- Nakamura+14：all explode
- Suwa +14：half of them explode
- Hanke in prep: almost all explode



3D models for multiple progenitors

- Hanke in prep：not explode(3model)
- Melson+2015: explode(1 model)
- Mezzacappa+2015 explode（1model）
- Takiwaki in prep：half of them explode (2model explode, 1 model fails)

We have to update the input physics.

Important ingredients for core-collapse supernovae

We have to update all input physics and numerics.

- Dimentionality
- General Relativity
- Neutrino reactions
- Equation of state
- Progenitor Structure

Neutrino Reactions

$$p + e^- \leftrightarrow n + \nu_e$$

$$n + e^+ \leftrightarrow n + \bar{\nu}_e$$

$$\nu + \{n, p, A\} \rightarrow \nu + \{n, p, A\}$$

$$\nu + \bar{\nu} \leftrightarrow e^+ + e^-$$

reduced

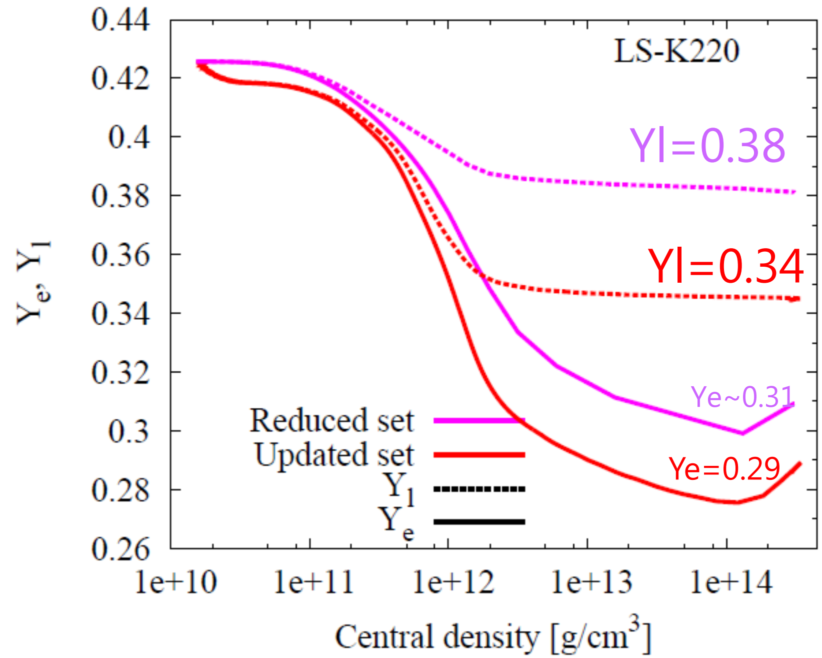
$$\nu_e + e^- \rightarrow \nu_e + e^-$$

$$A + e^- \rightarrow A' + \nu_e$$

$$\nu + \bar{\nu} + N + N \leftrightarrow N + N$$

updated

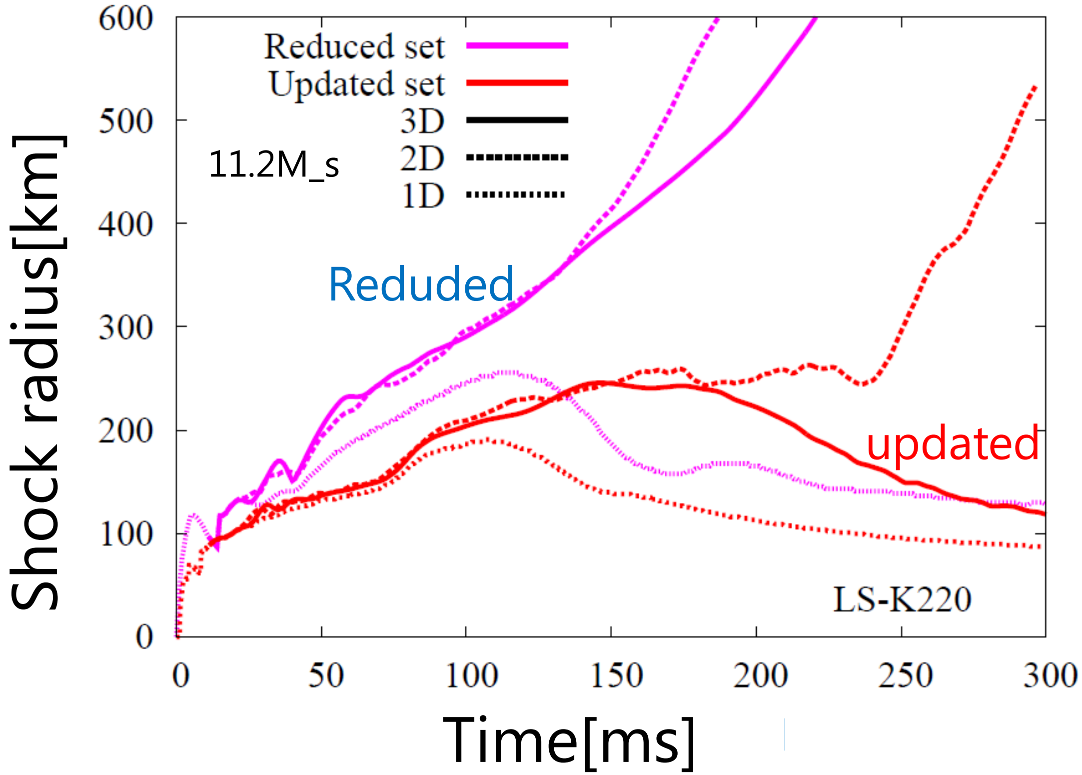
$$\nu_e + \bar{\nu}_e \leftrightarrow \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$$

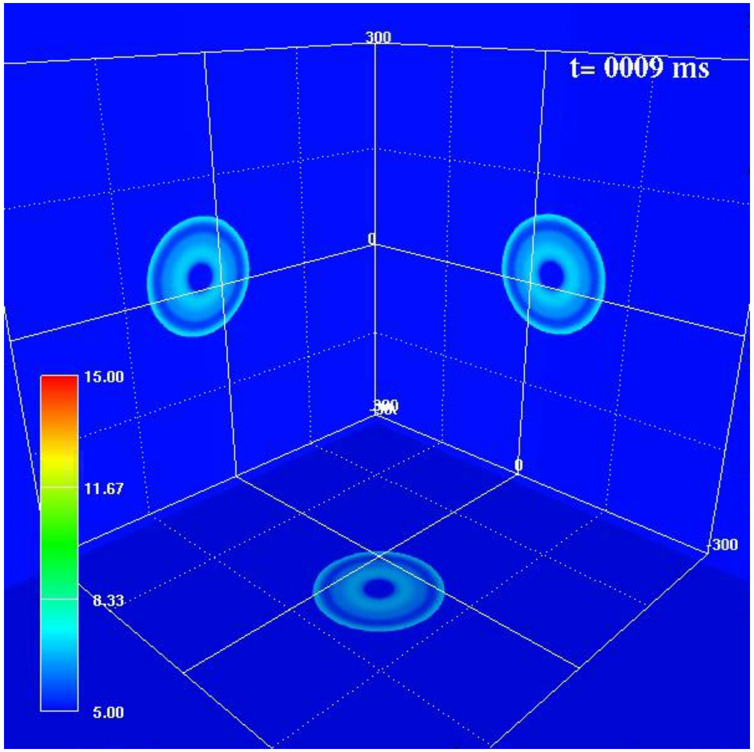


There are still several minor points that are remaining to be updated.

Updated set is roughly consistent with the more sophisticated works(e.g. Mueller+2010).

Multi-Dimensional Simulations



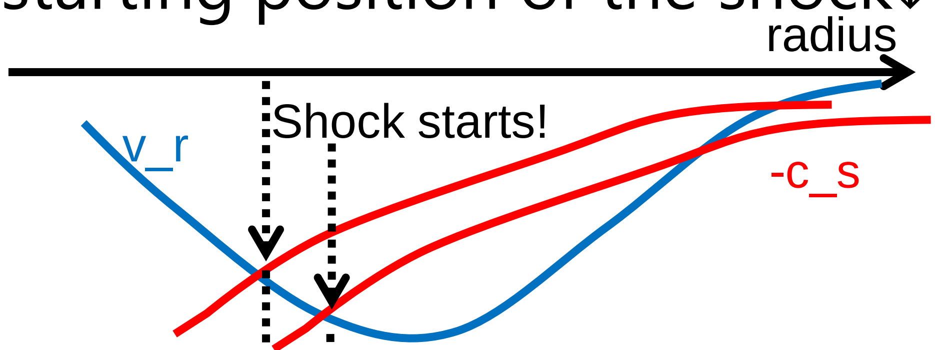


Unfortunately our 3D model with updated neutrino reaction does not explode.

But do not forget that we now ignore GR Effect that should help the explosion!

How does Y_l affect the evolution of the shock?

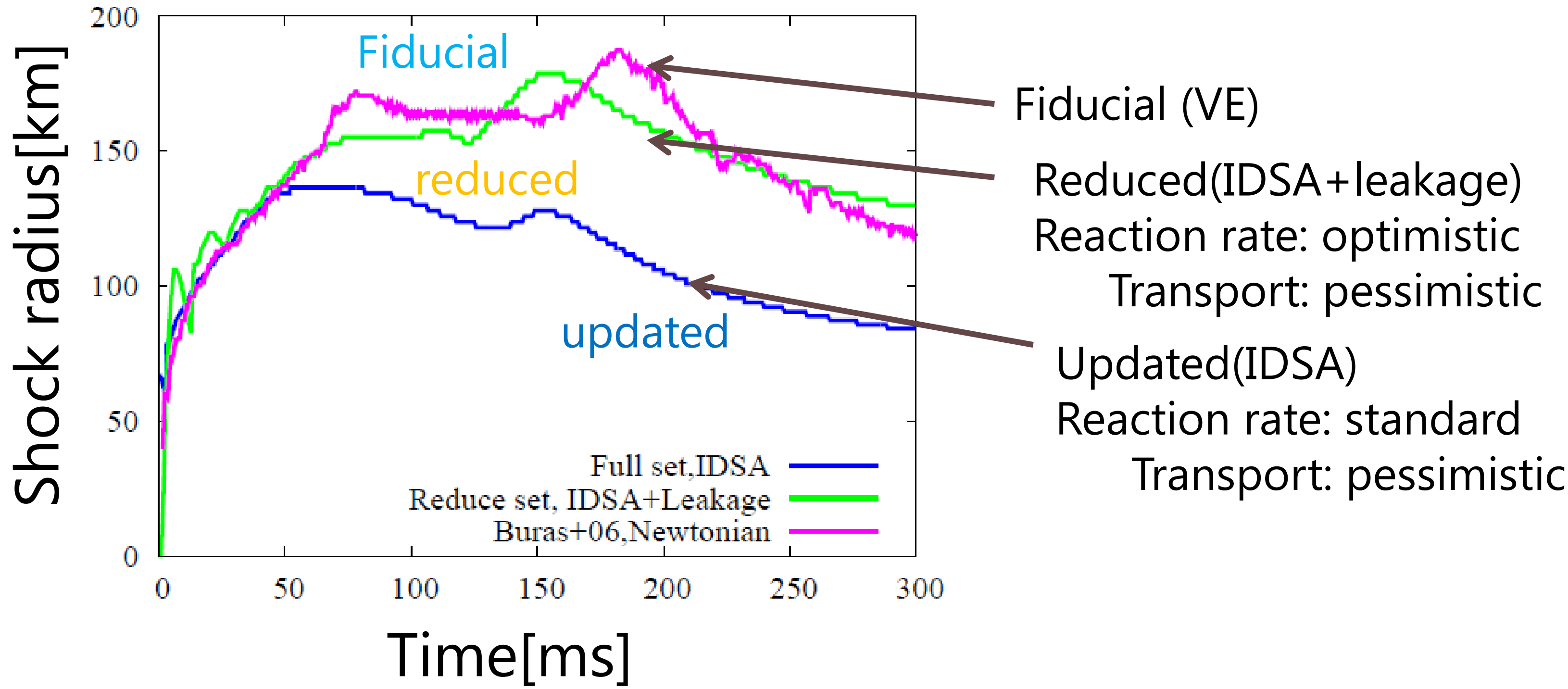
1. Electron capture rate ↑, Y_l ↓ $p + e^- \rightarrow n + \nu_e$
2. Pressure ↓, Sound speed↓, $P \propto (Y_l \rho)^{4/3}, c_s \sim \sqrt{P/\rho}$
   starting position of the shock↓



3. Mass of iron to dissociate ↑

4. The energy of the Shock ↓

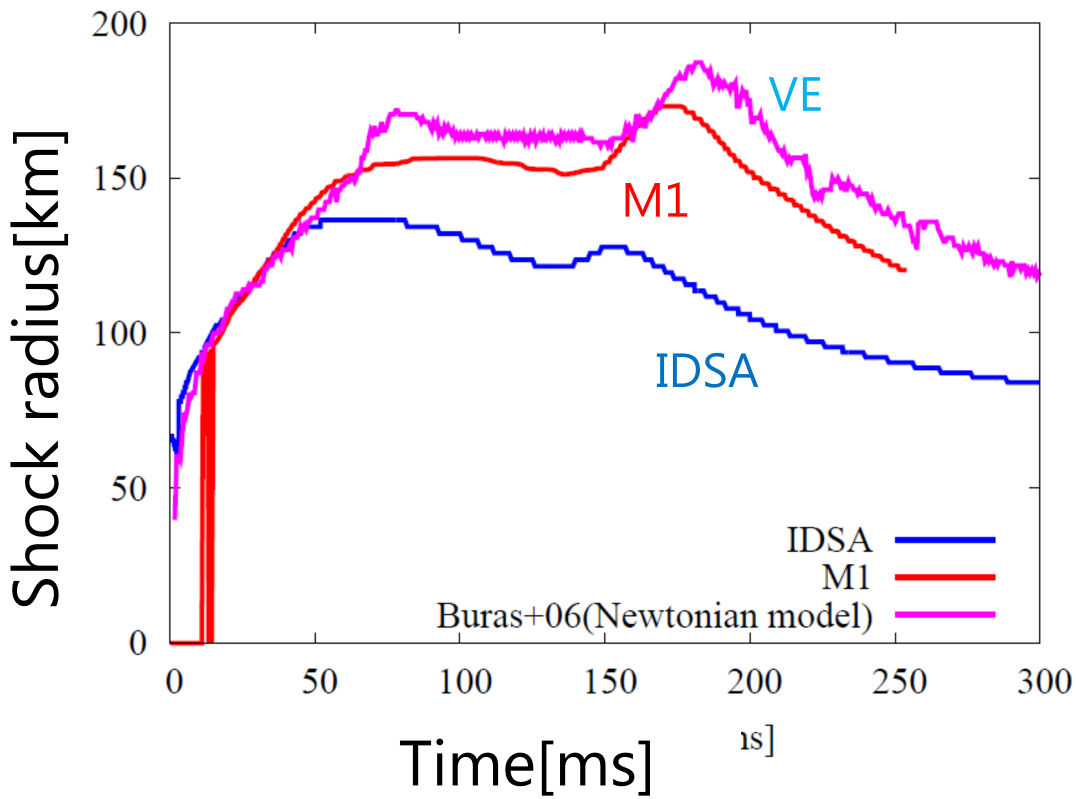
Comparison of the shock radius in 1D

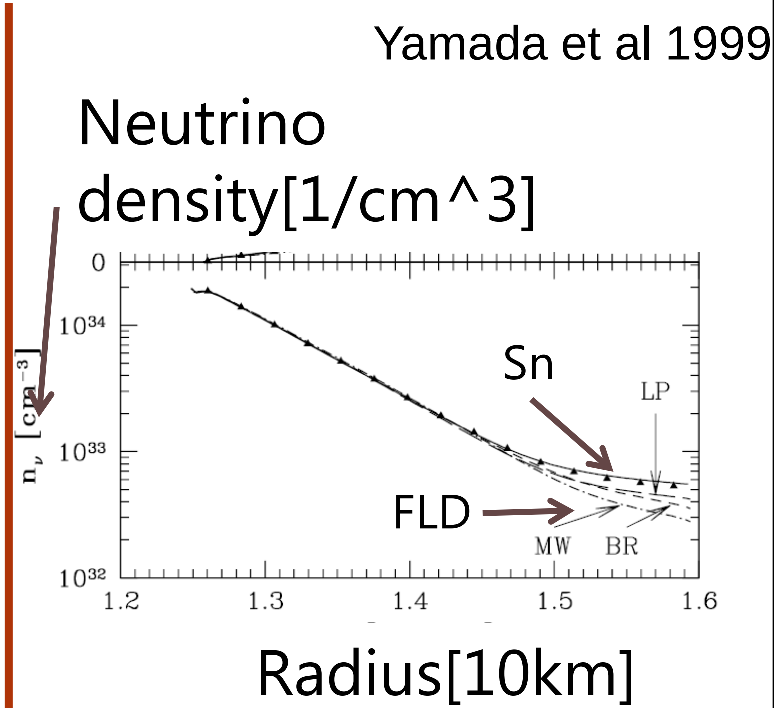


It's strange but reduced set is closer to the trajectory of more sophisticated calculation.

Optimistic estimation of the reaction cancels out pessimistic effects of the transport.

衝撃波半径の比較

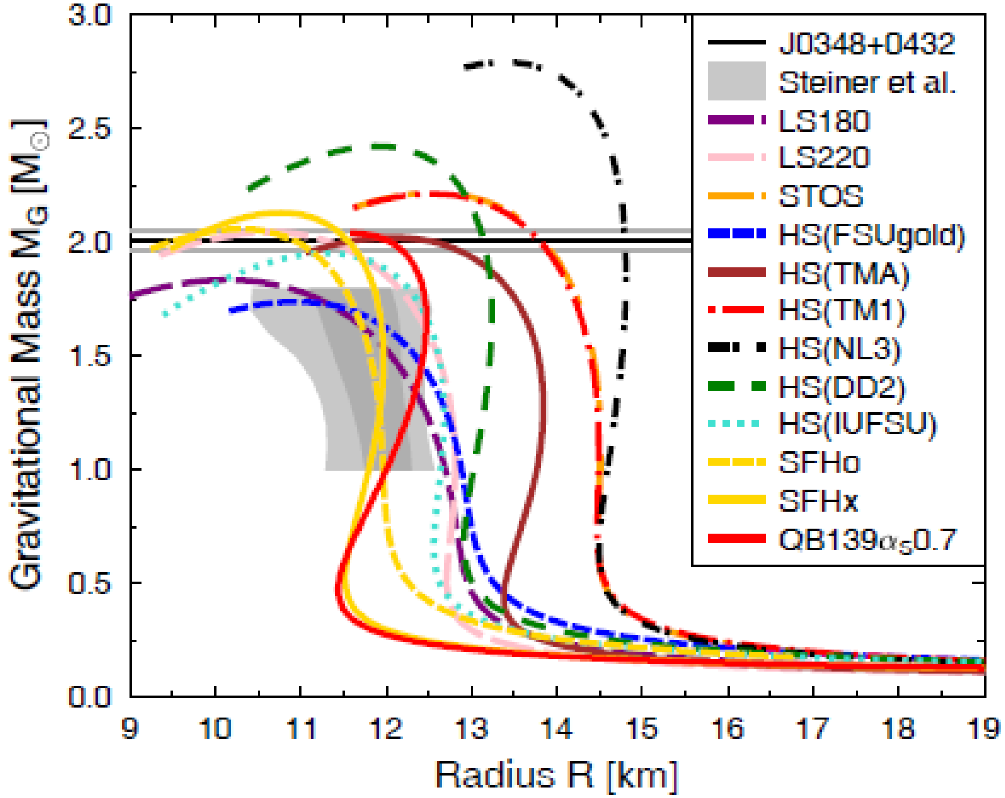




VE > M1 > IDSAの順。

第一原理的なものほど、ニュートリノがフリーストリーミングになるのが遅く、長く物質を加熱する(密度が高い)せいだと予想している。

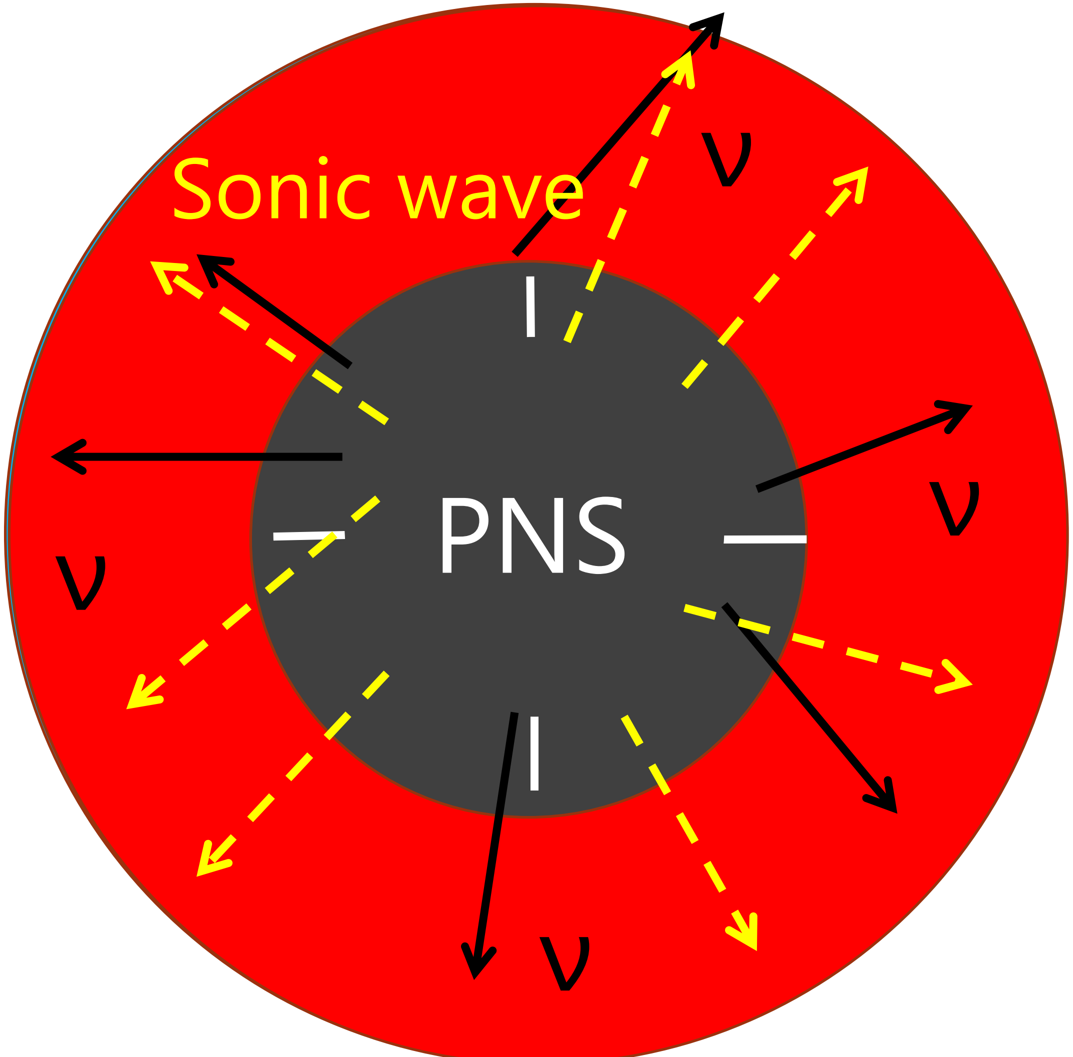
EOS



核力の不定性から様々なEOSが提案されている。
中性子星や原始中性子星の物性はEOSに強く依る。

よく、硬さに注目される。（この発表）では柔らかい＝コンパクト

Basic idea to connect EOS and Explosion

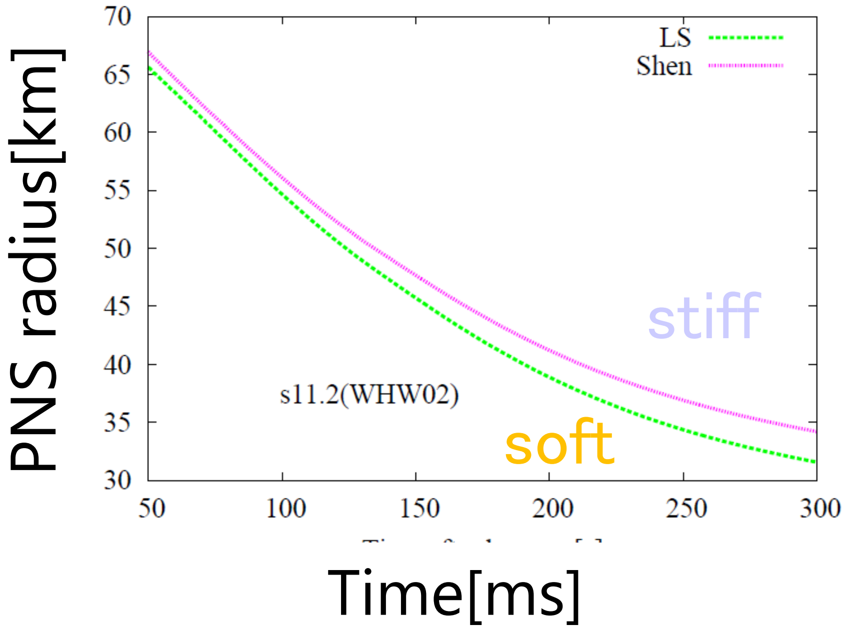


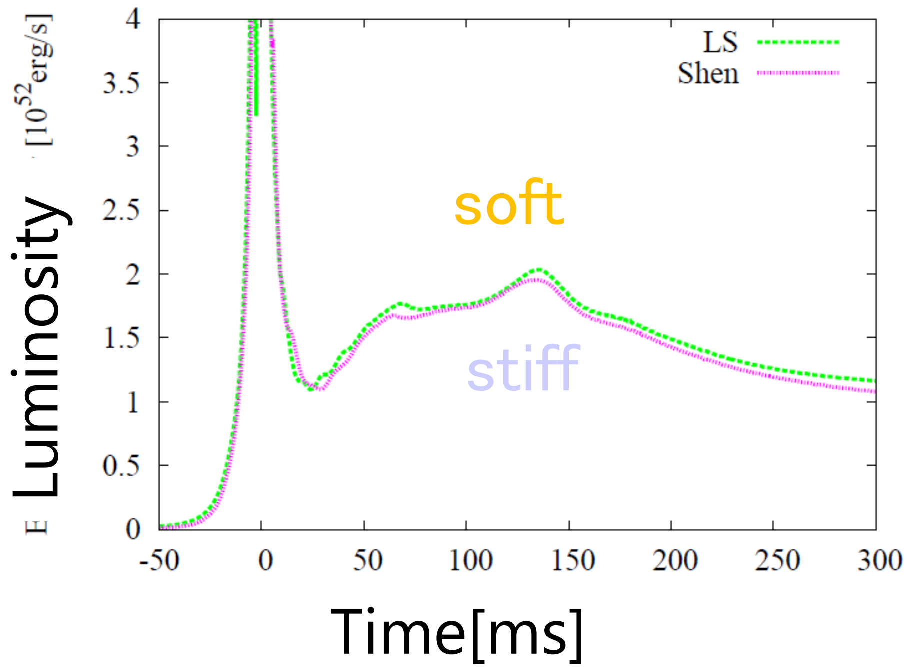
1. The PNS gradually shrinks by the gravity.
2. E_grav is released.
3. E_thermal is increased.
4. The L_ν and sonic waves are emitted from the surface of PNS.

Soft EOS releases large energy and makes the PNS dense, that produce strong acoustic wave.

Softer EOS is preferable to the explosion.

Neutrino Luminosity



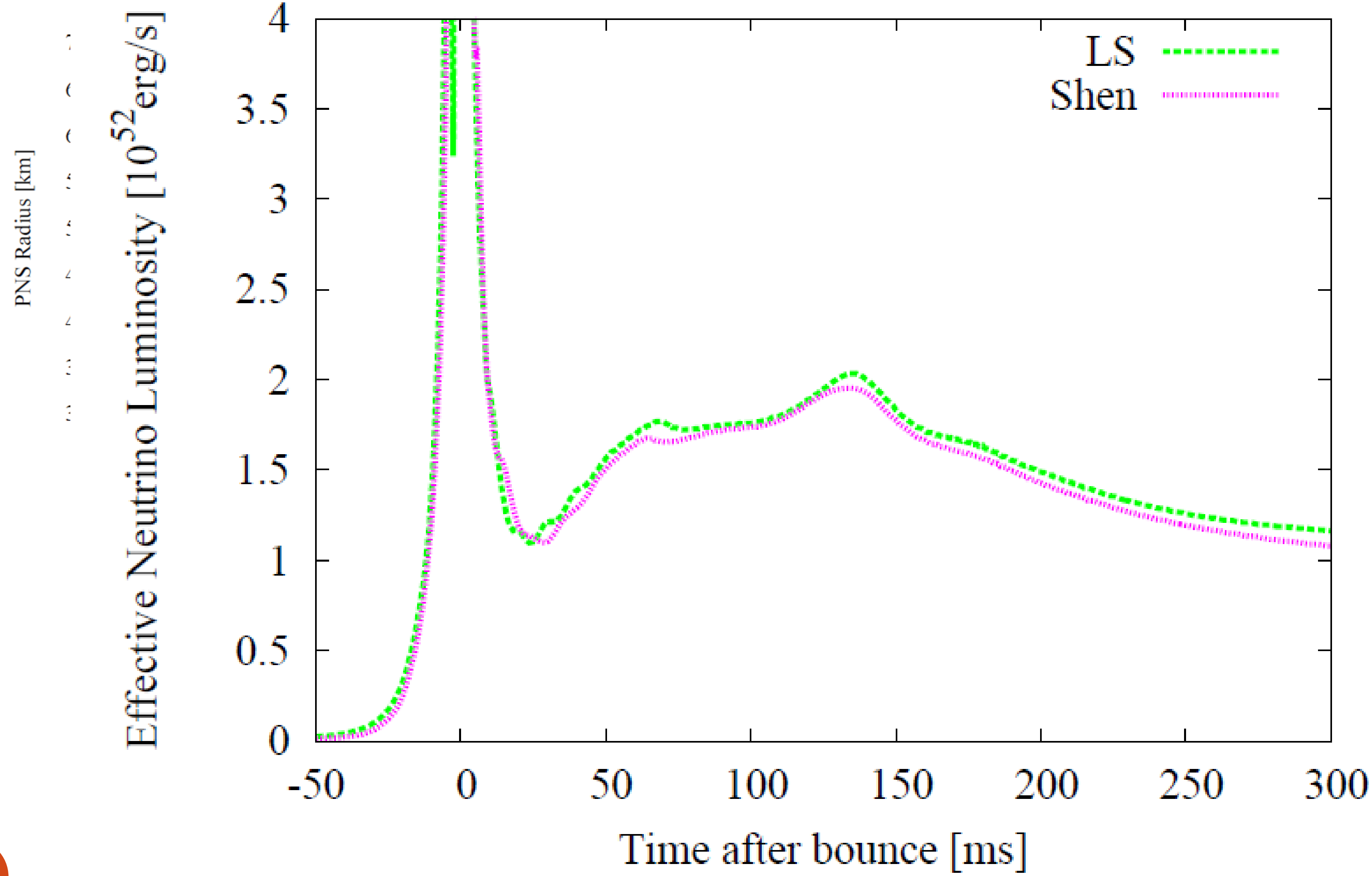


LS(K220):Soft EOS => rapidly shrink => Large L_ν

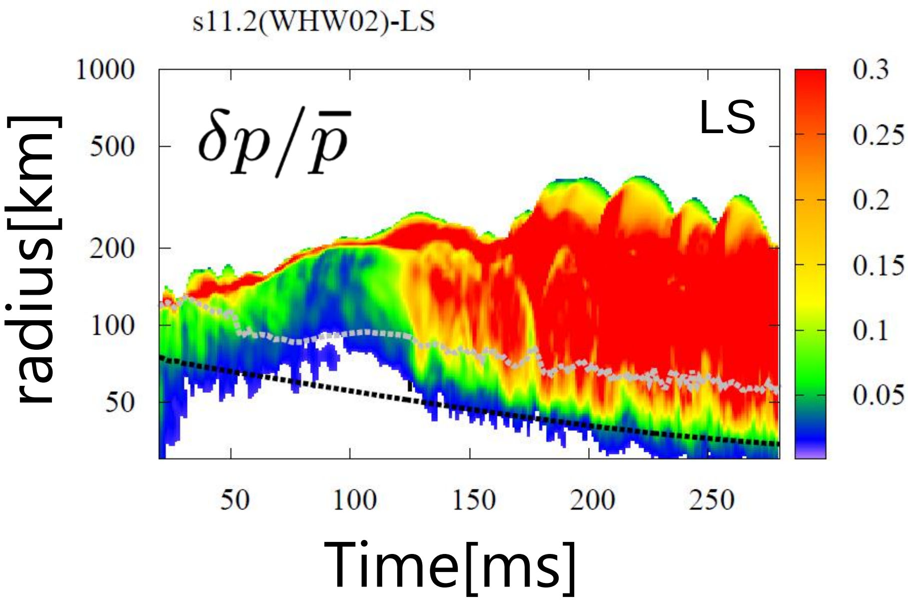
Shen: Stiff EOS => slowly shrink => small L_ν

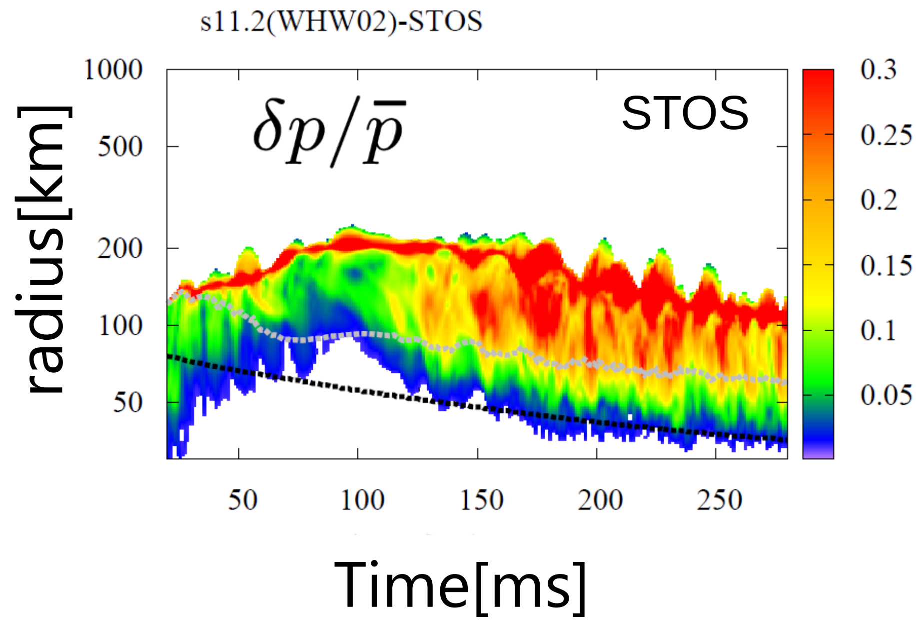
(Sumiyoshi+2005 and Fisher+ 2013 show similar results.)

Neutrino Luminosity



Sonic Wave





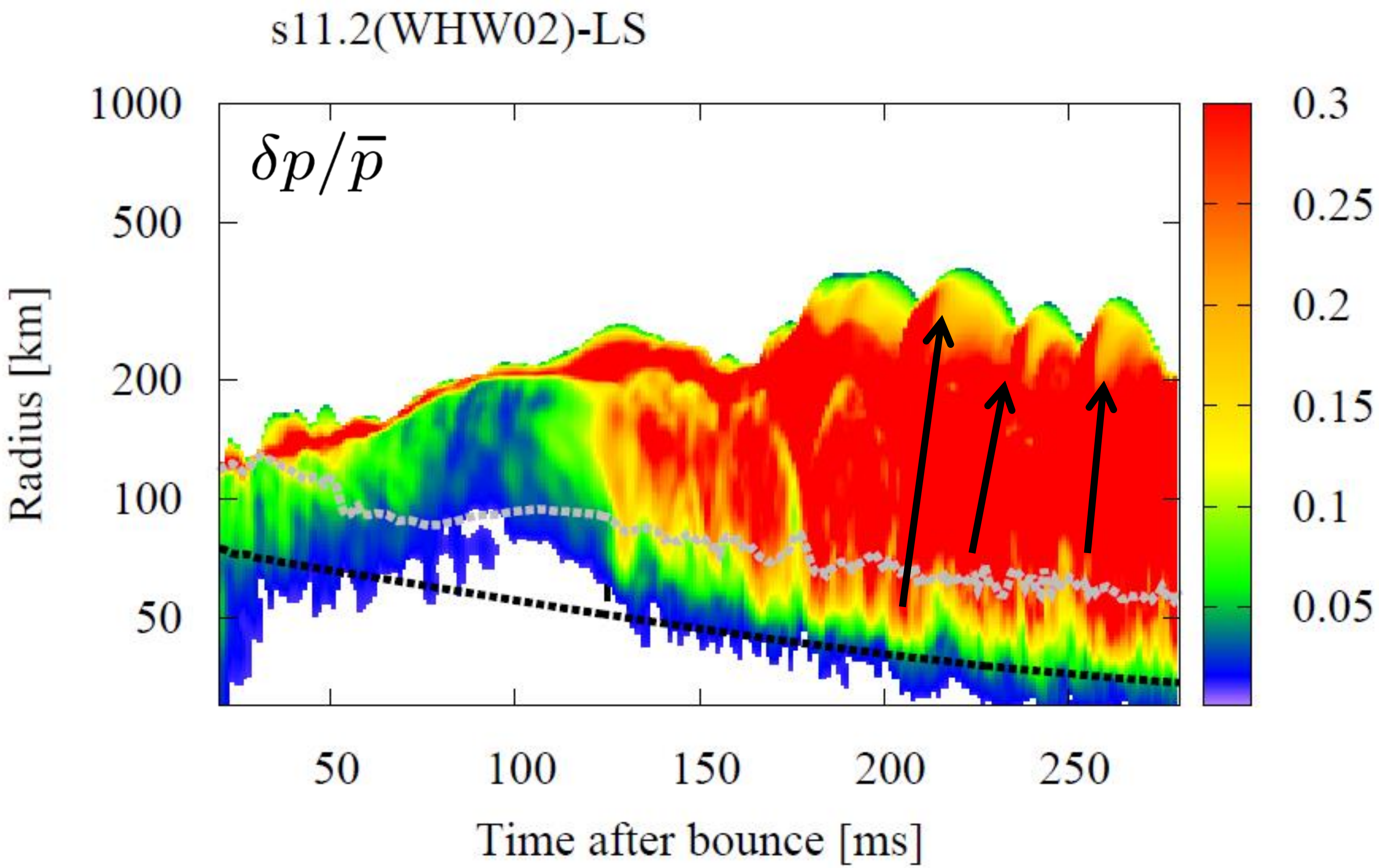
Gray: gain radius, black PNS radius

Strong sonic wave is reflected at the PNS!

(It is a little bit hard to see, but) softer EOS make stronger sonic wave.

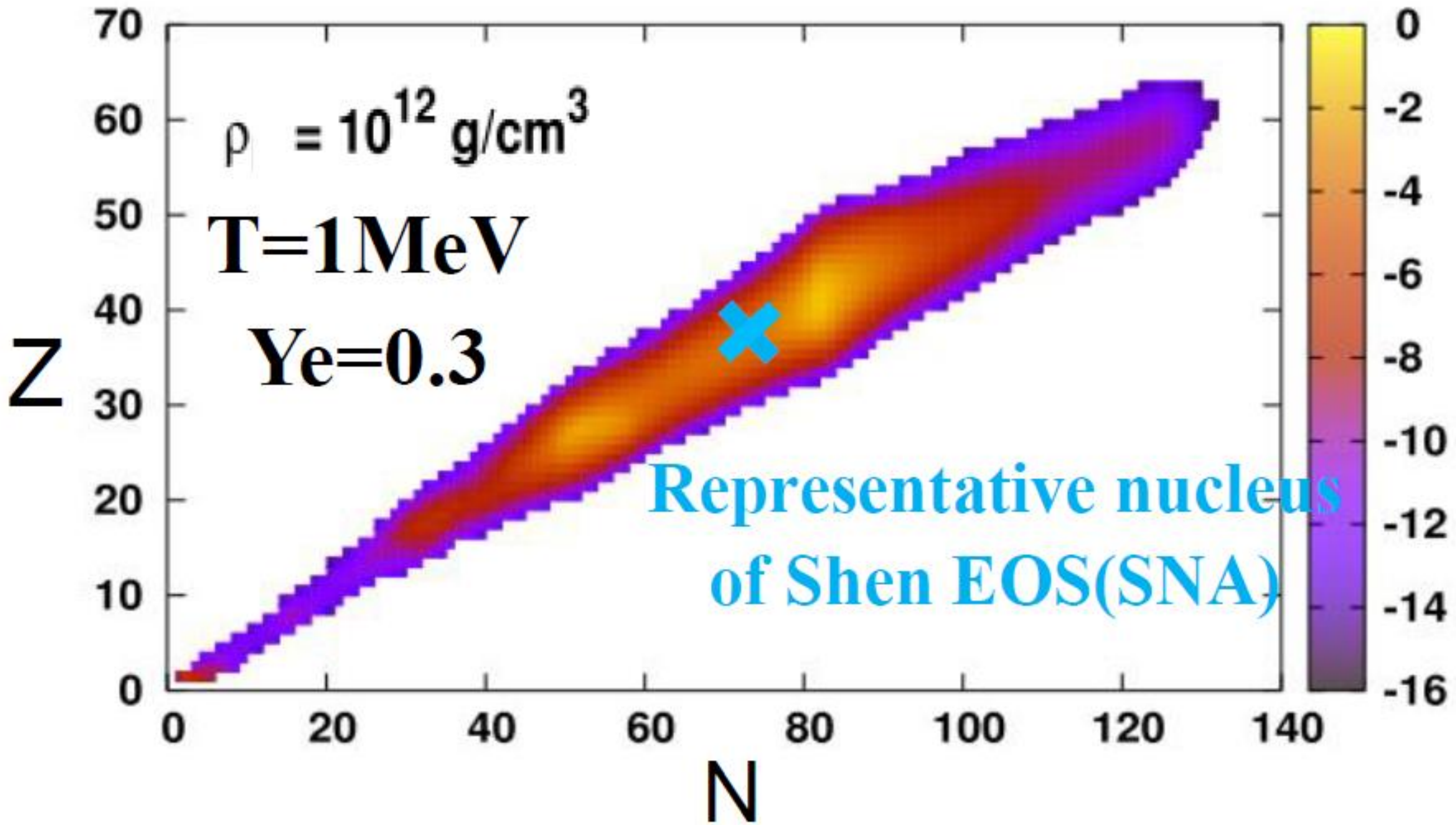
(Couch 2013 and Suwa+ 2013 show similar results.)

Sonic Wave



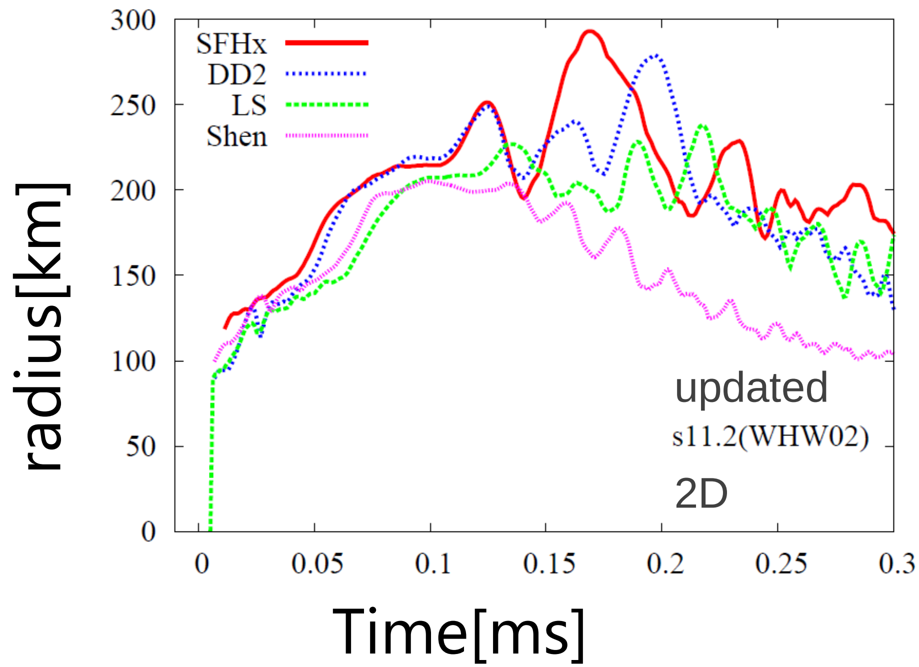
Gray: gain radius, black PNS radius

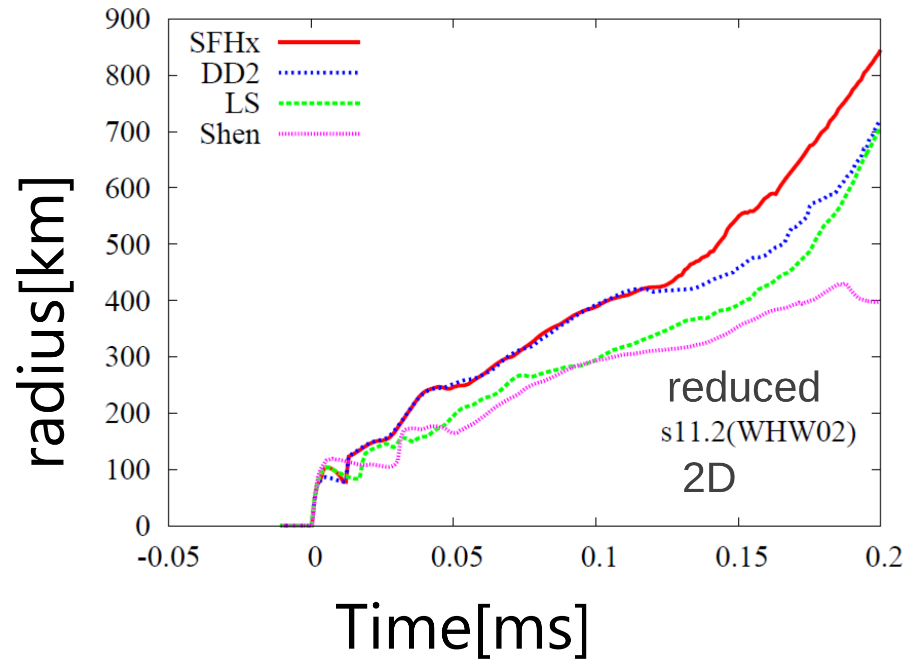
Emergence of Multi-species EOS



Our Model の abundance peak (N, Z) ~ (80, 40) がShenEOSの representative nucleus (76, 37)と異なる。

Emergence of Multi-species EOS





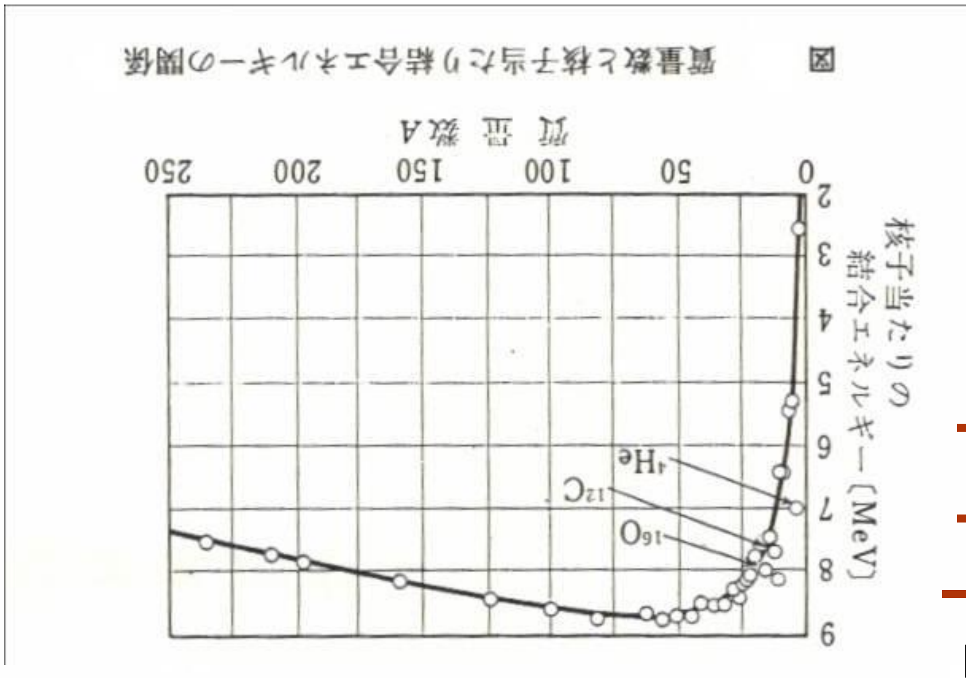
SFHx and DD2: Multi species of heavy nuclei is included.

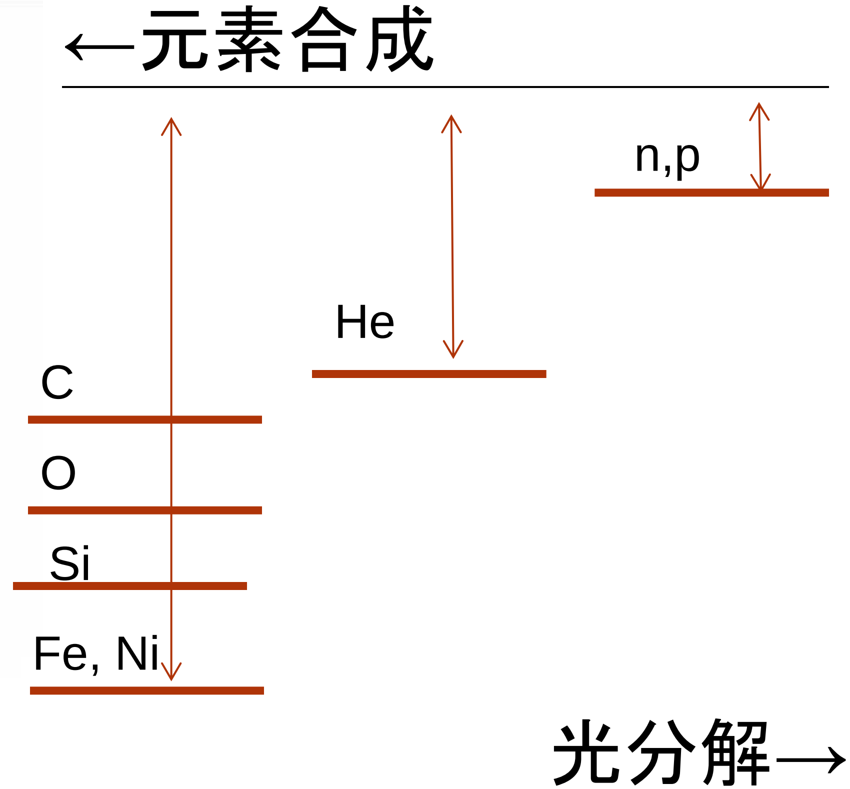
SFHx and DD2 > LS and STOS

Employing MS may help SNe explosion.

But in one-dimensional GR sim, that situation is contradictory. (Fisher+2014)

原子核と束縛エネルギー





元素合成：質量数が増加、束縛エネルギー増加

エネルギー解放

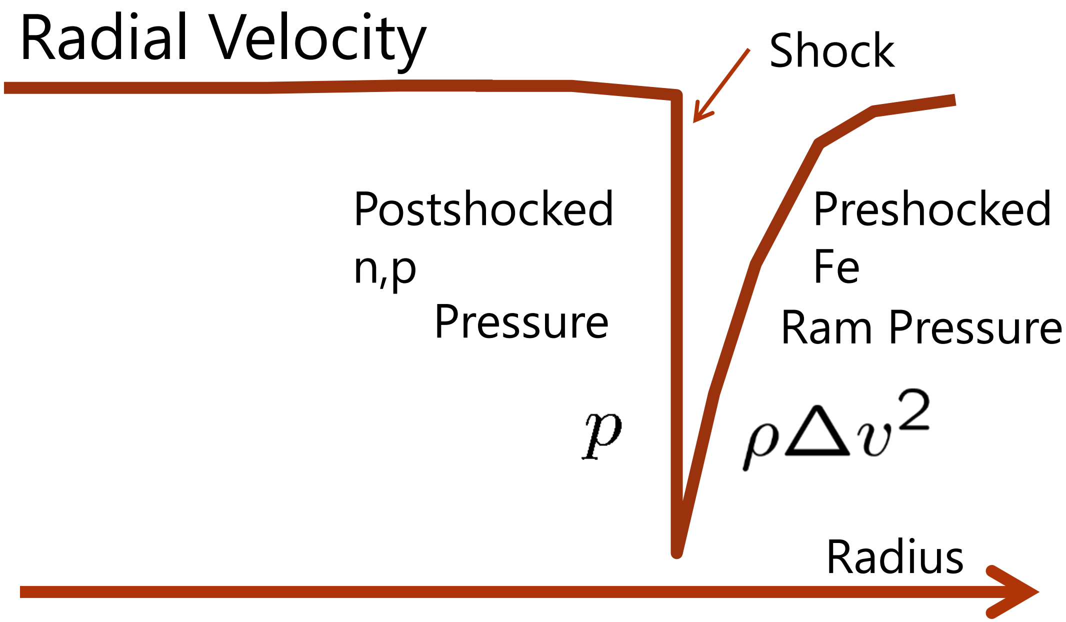
光分解：質量数が減少、エネルギー吸収

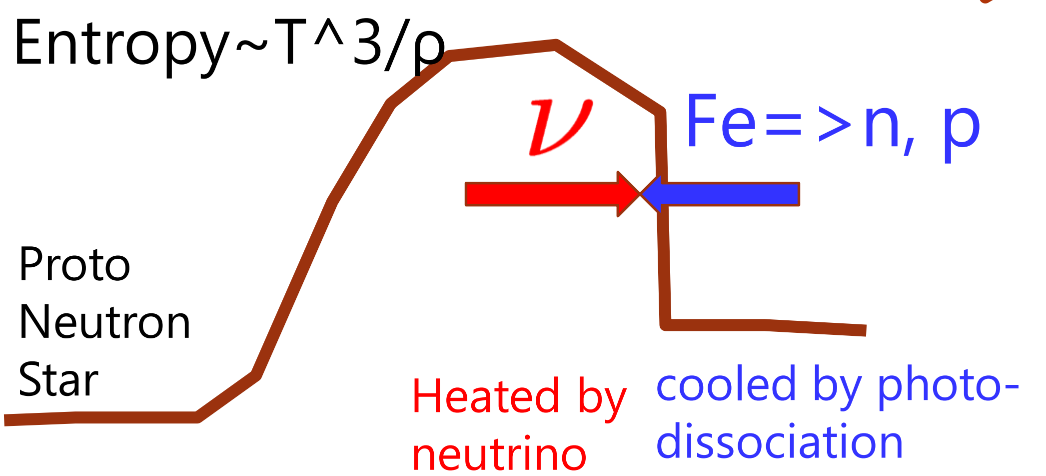
Summary

- 多次元シミュレーション:
  超新星は爆発しない問題から、爆発するかしないか分からない問題へ
- メソッドの改善と結果の比較が強く求められている
  ν-reaction rate: update!
  Transport: IDSA => M1-closure (=> Sn)
  EoS: Single nuclei => multi nuclei
  Gravity: Newtonian => GR ← 黒田仰生！
- 多少荒いモデルでの天文学も進んでいる ← 中村航！
  重力波、ニュートリノ、元素合成、可視光放射

輻射輸送法の精密化で計算コストが莫大に。
M1: 60倍, IDSA: 3倍, IDSA+leakage:1倍
できるモデルの数は少なくなる。

Key aspects of Neutrino Mechanism





When the shock is stalling, Pressure inside and ram pressure out side balances.

$$p \sim \rho \Delta v^2$$

RHS is determined by stellar structure(density profile).

LHS is determined by two ingredients.

(1) Photo-dissociation

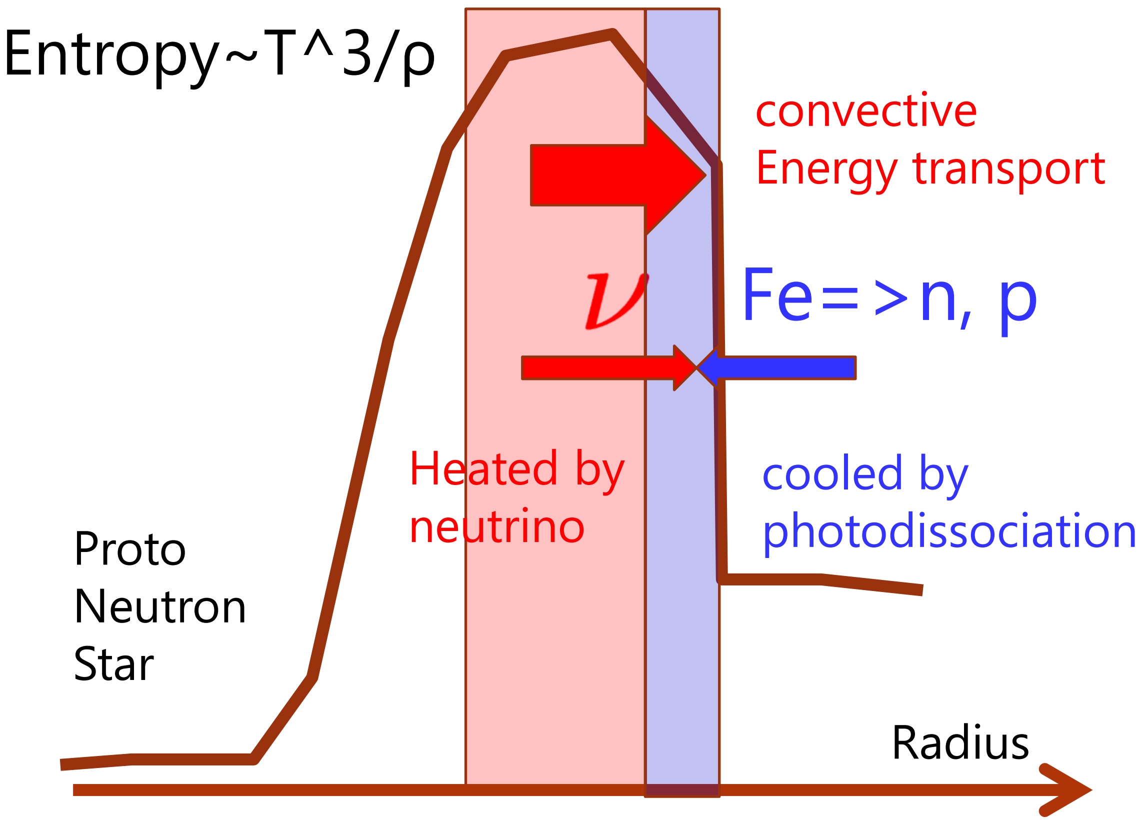
$$\mathrm{Fe} \rightarrow 30\mathrm{n} + 26\mathrm{p} - \Delta Q$$

(2) Neutrino Heating

$$\nu_e + \mathrm{n} \rightarrow \mathrm{e}^- + \mathrm{p} + \Delta Q$$

$$\bar{\nu}_e + \mathrm{p} \rightarrow \mathrm{e}^+ + \mathrm{n} + \Delta Q$$

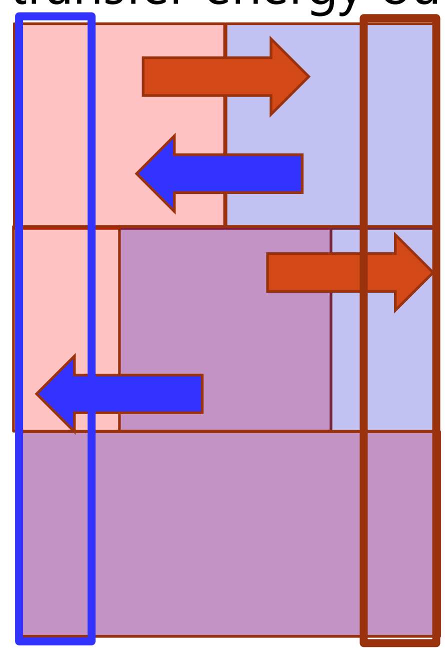
Key aspects of Neutrino Mechanism



Negative entropy gradient leads Rayleigh-Taylor instability

(Cold heavy matter is put over Hot light matter)

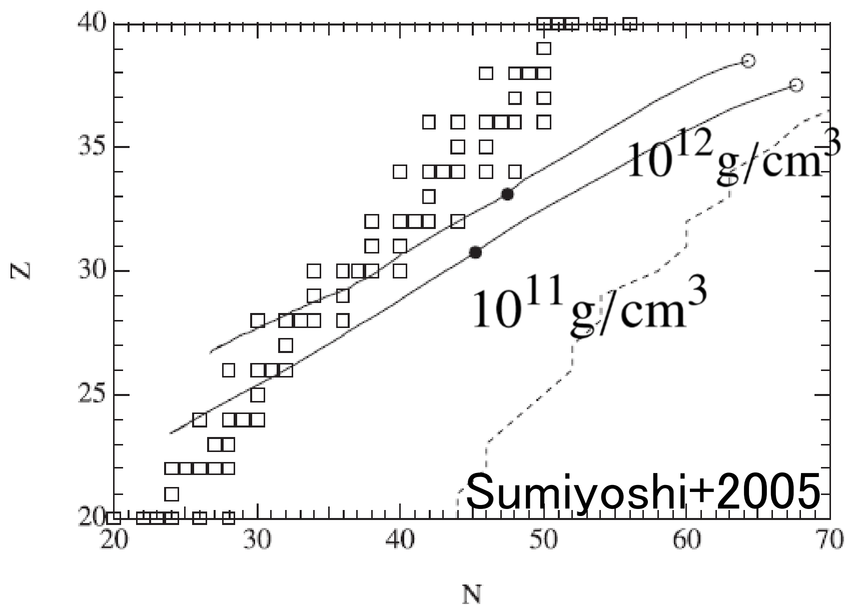
Rayleigh-Taylor convection transfer energy outward.



Cooler than the initial state but ν heat is active

Hotter than the initial state

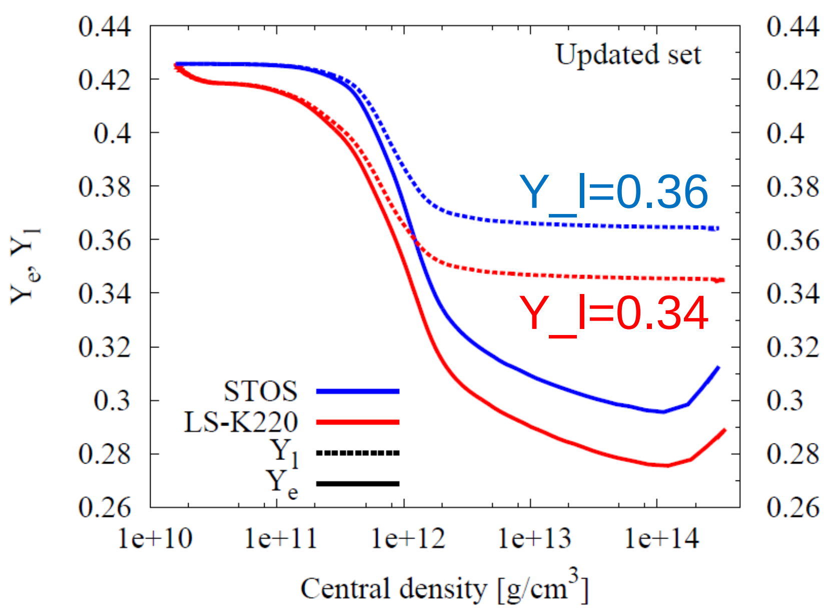
EOS dependence on Y_l

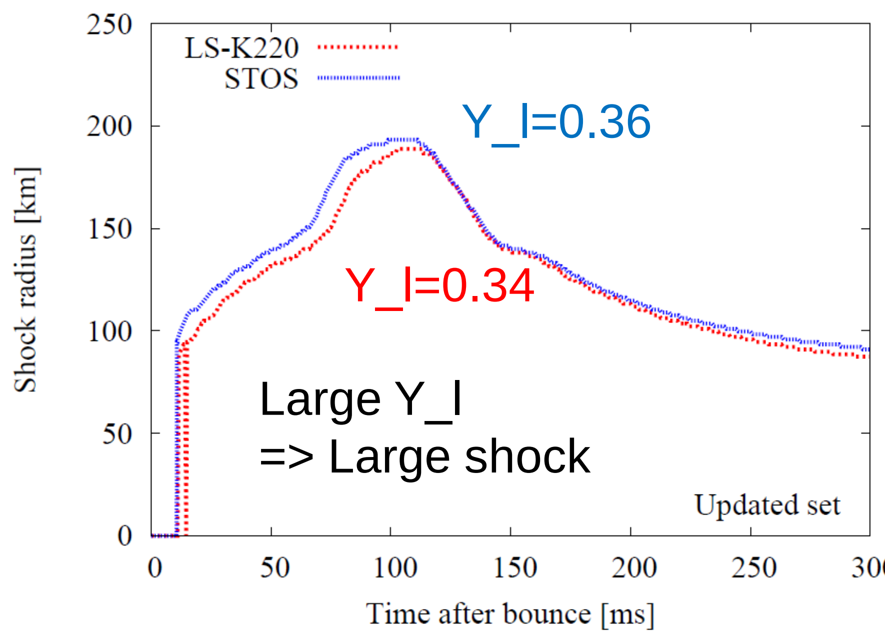


EOS changes the species of heavy nuclei.

$$A + e^- \rightarrow A' + \nu_e$$

Electron capture rate significantly depends on the species of the nuclei.





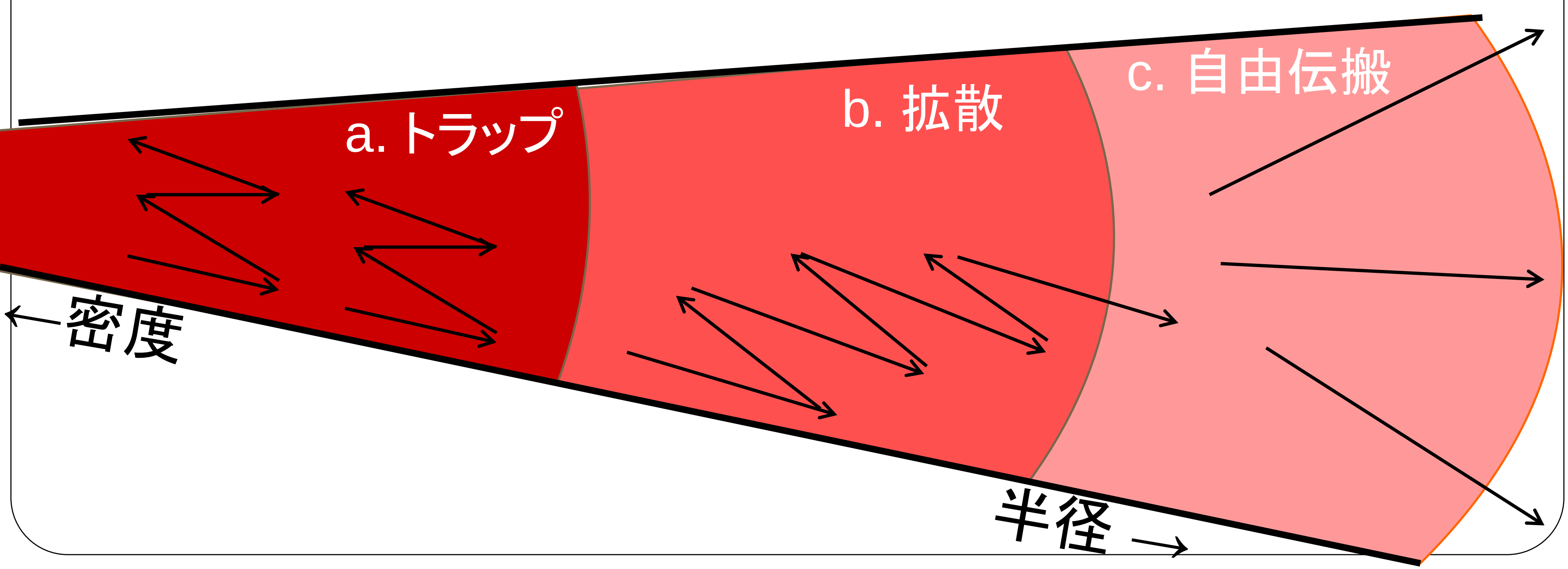
輻射輸送の一般論

輻射は高密度の物質から抜け出るとき、
物質との相互作用の強さにより、3通りに振る舞う。

a. 物質に完全にトラップ

b. 物質から拡散的に抜け出る

c.物質と全く相互作用せず、光速で伝搬



IDSA以外のやり方

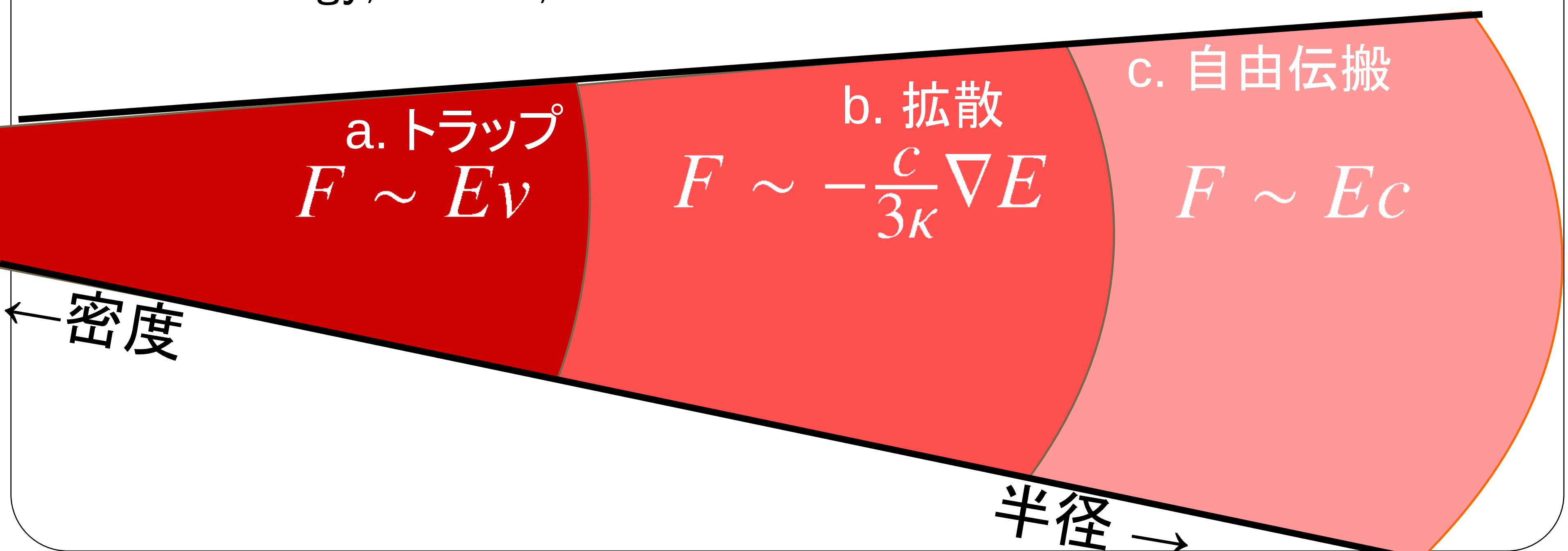
普通(FLD,M1など)は、

輸送方程式のフラックス(や圧力)を

各領域で適切になるように解く。

$$\frac{\partial E}{\partial t} + \frac{\partial F}{\partial x} = S_\nu$$

E: Energy, F: Flux, S: Source from neutrino interaction



IDSA(Isotropic Diffusion Source Approximation)

IDSAは、輻射をトラップ成分と伝搬成分に分けて、
別々に方程式を解く。
拡散タームをソースターム(IDS)にして両者を結ぶ

$$\frac{\partial E_{\rm t}}{\partial t} + \frac{\partial E_{\rm t} v}{\partial x} = S_\nu - S_{\rm IDS}, \quad S_{\rm IDS} = \frac{\partial F_{\rm dif}}{\partial x}$$

$$\frac{\partial E_{\rm f}}{\partial t} + \frac{\partial E_{\rm f} c}{\partial x} = S_{\rm IDS}$$