2014/7/8 Joint Meeting among RESCEU-RIKEN-IPMU@RIKEN

# Explosion Mechanism of Core-collapse Supernovae

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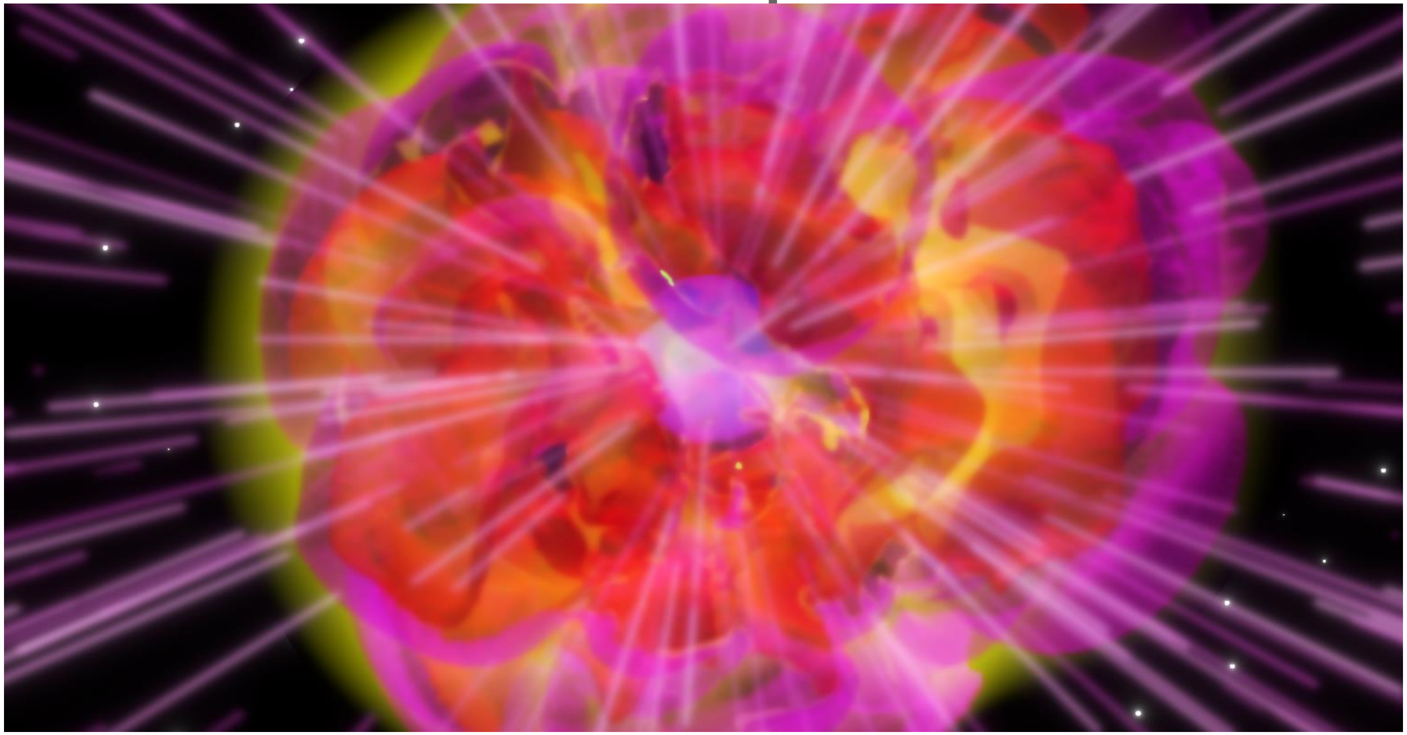
(NAOJ->RIKEN)

# Press Release in April



There are two press release on supernovae in last April

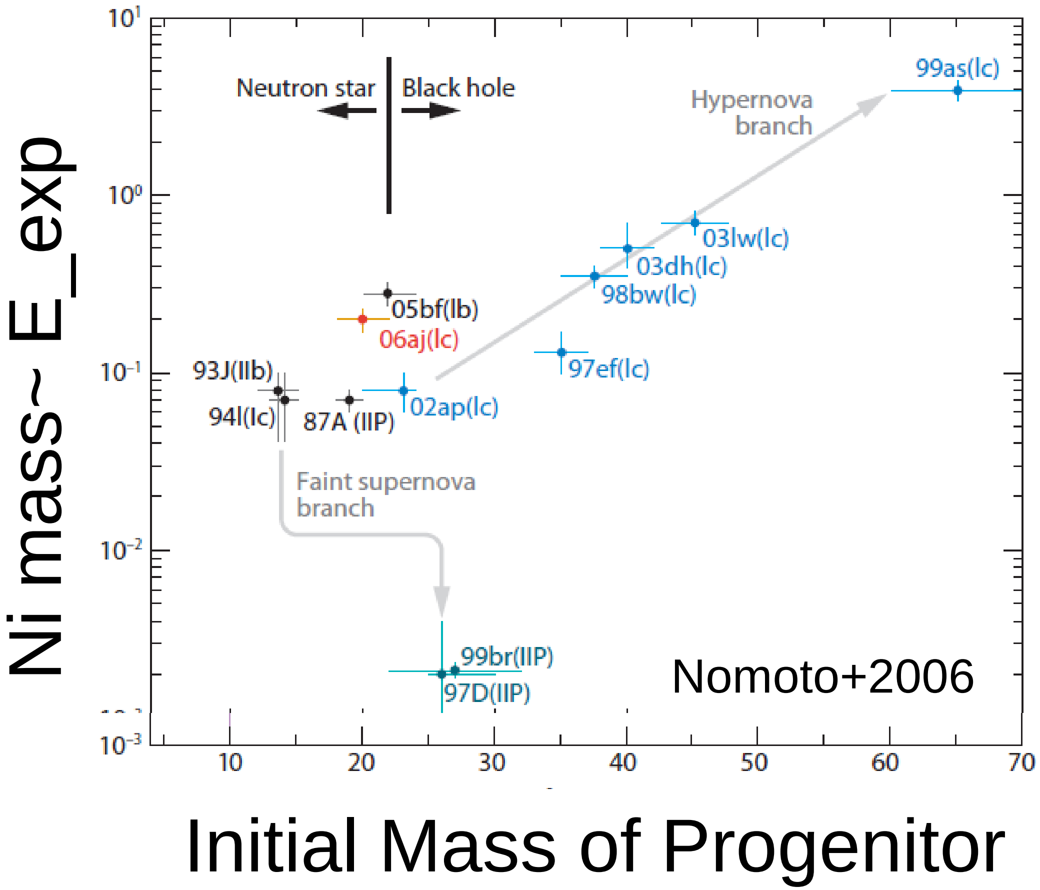
One: Lensed extremely luminous type Ia supernova.

The other: 3D explosion of type II supernova found in K-computer.

# Why is CC SN interesting?

- Last time of massive stars
- Birth of neutron star
- Mother of supernova remnant
- One of the most luminous object in the universe
- Target of  Multi-messenger astrophysics
- Source of heavy elements in galaxies
- 4 kinds of force affects the explosion mechanism

# Various Kinds of CC supernovae



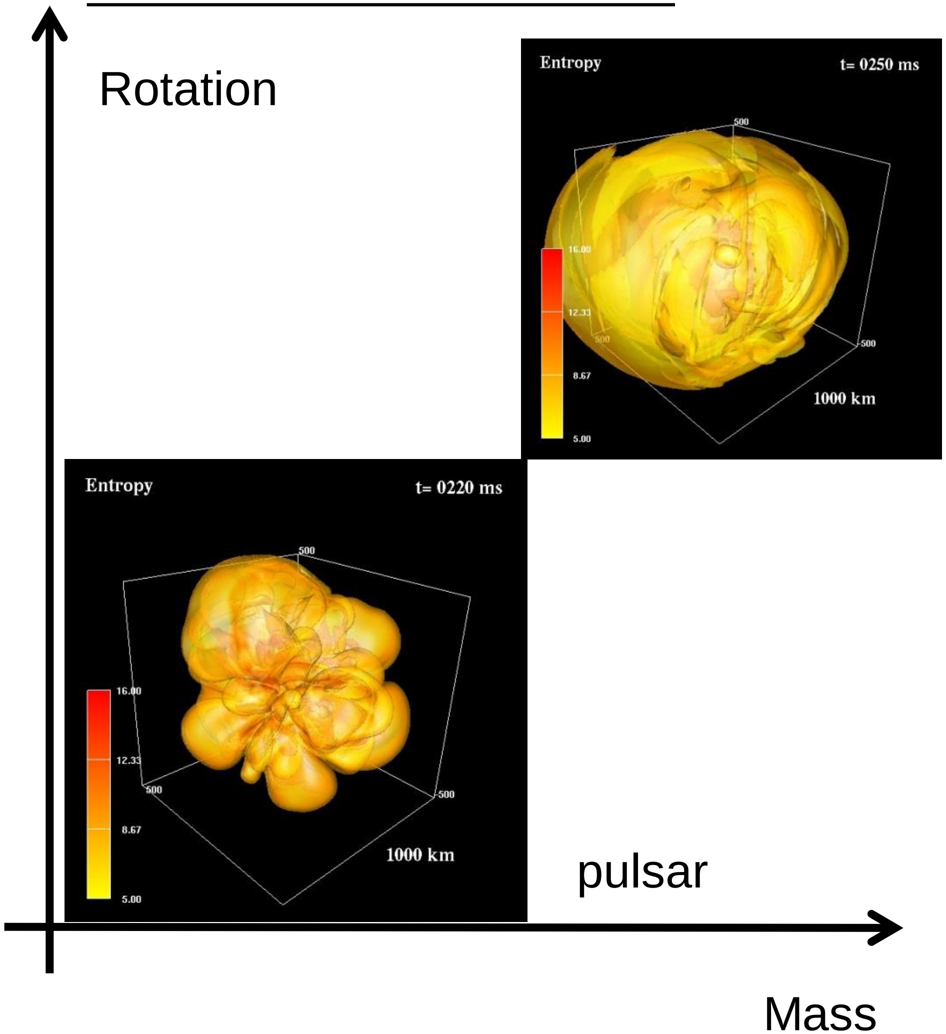

Fate of the star differs from the properties of the progenitor:

1. Mass
2. Metallicity
3. Rotation
4. Magnetic Field

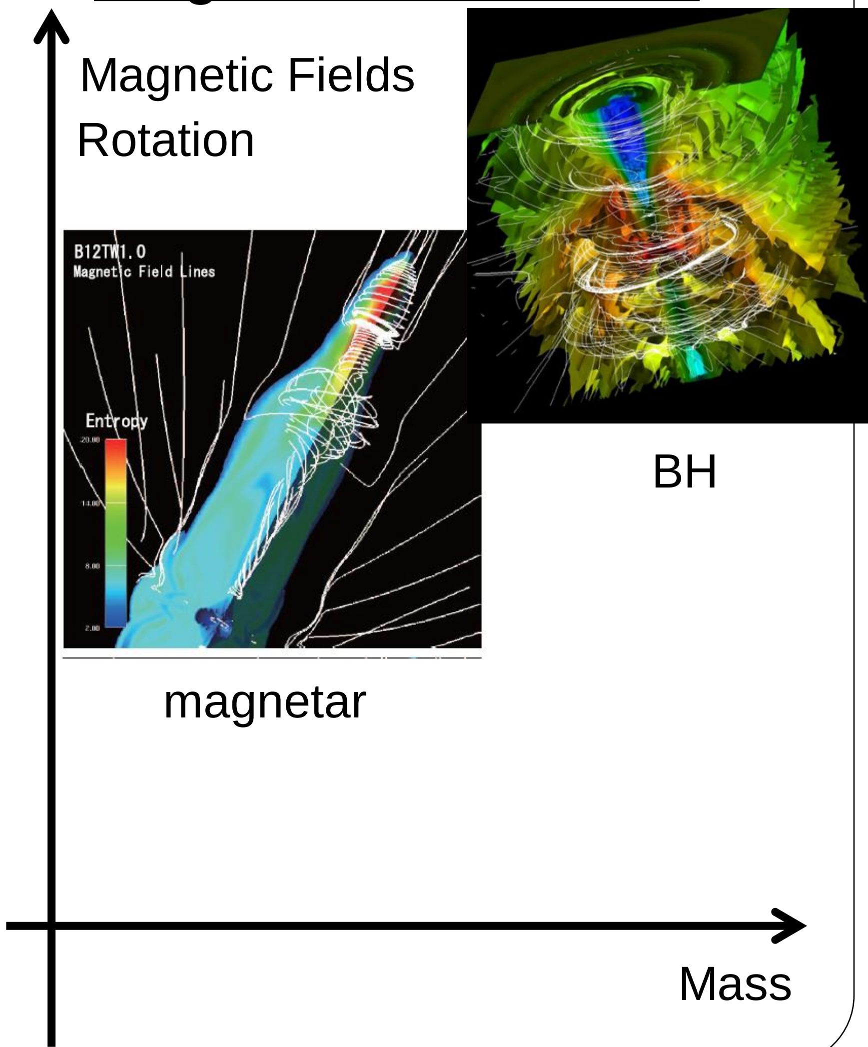
# Two class of CC SNe

We focus on this

## Neutrino Mechanism




## Magnetic Mechanism



# Neutrino Mechanism

I'll explain one by one

1. Initial setup
2. Key aspects of neutrino mechanism
3. Simulations
4. Effect of Rotation

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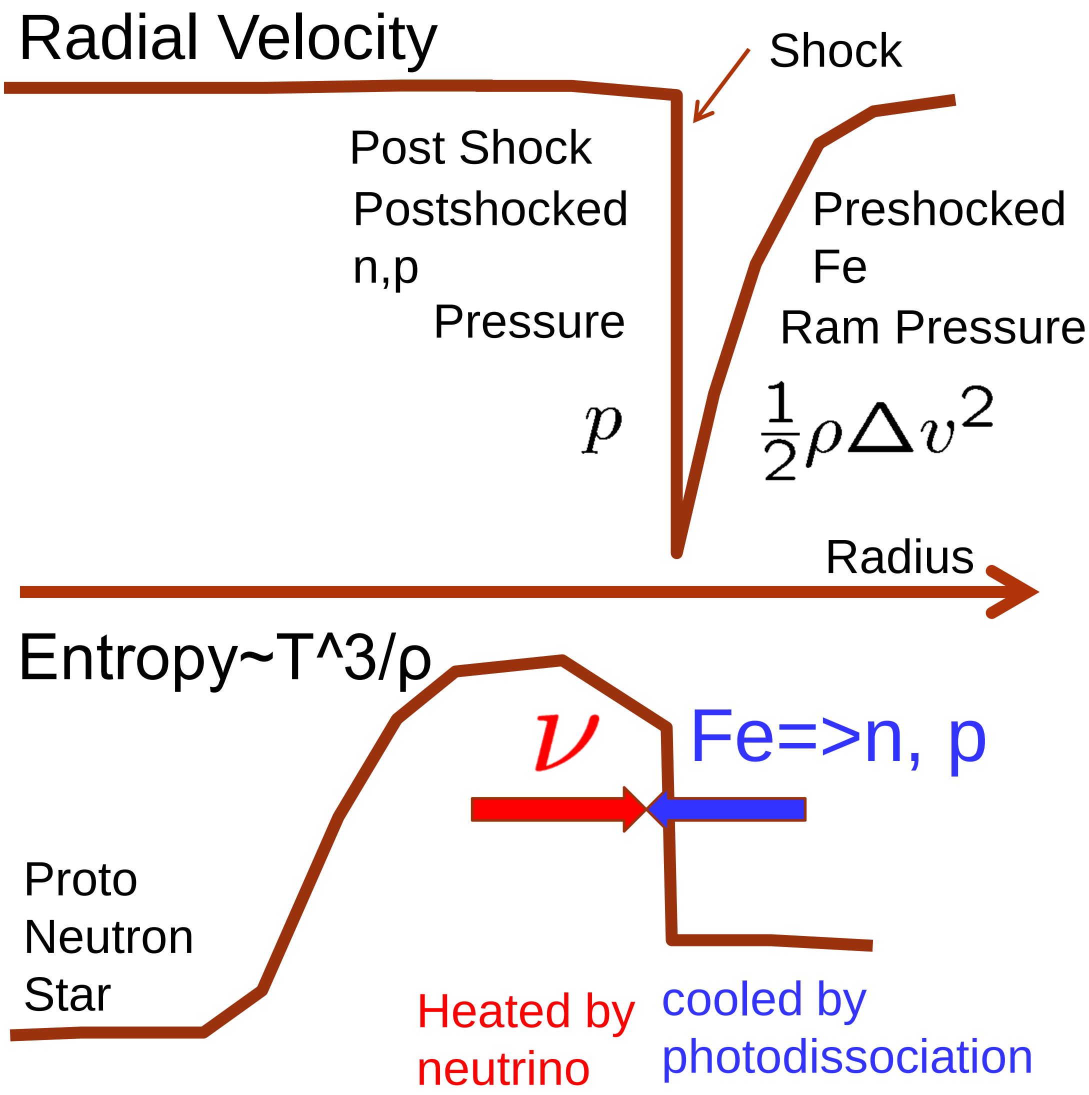
# Key aspects of Neutrino Mechanism




The shock is stalling. Pressure inside and ram pressure out side balances.

$$p = \frac{1}{2}\rho\Delta v^2$$

RHS is determined by stellar structure(density profile).

LHS is determined by two ingredients.

(1) Photodissociation

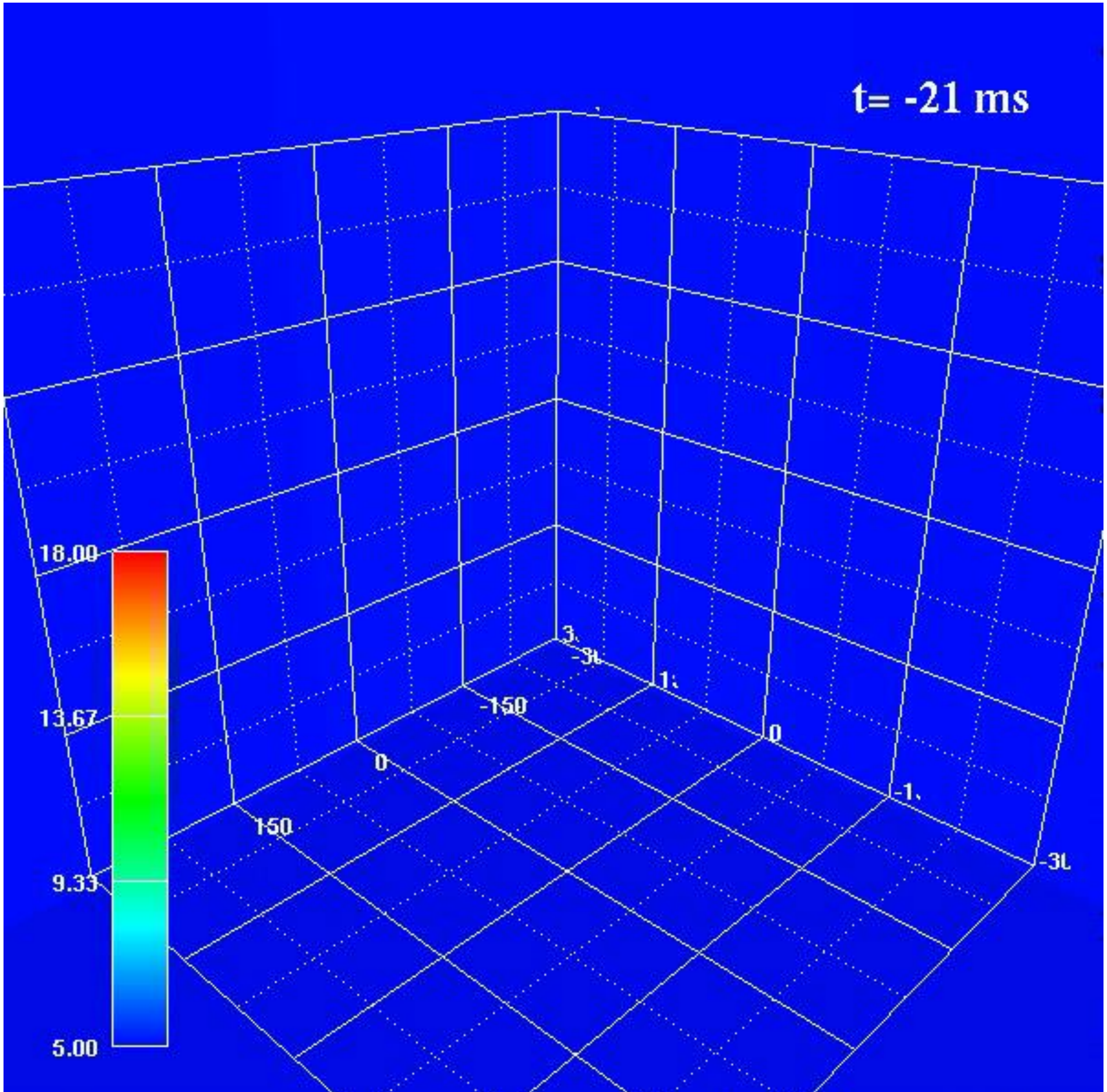
$$\mathrm{Fe} \rightarrow 30\mathrm{n} + 26\mathrm{p} - \Delta Q$$

(2) Neutrino Heating

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

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

# A example of the failed supernovae

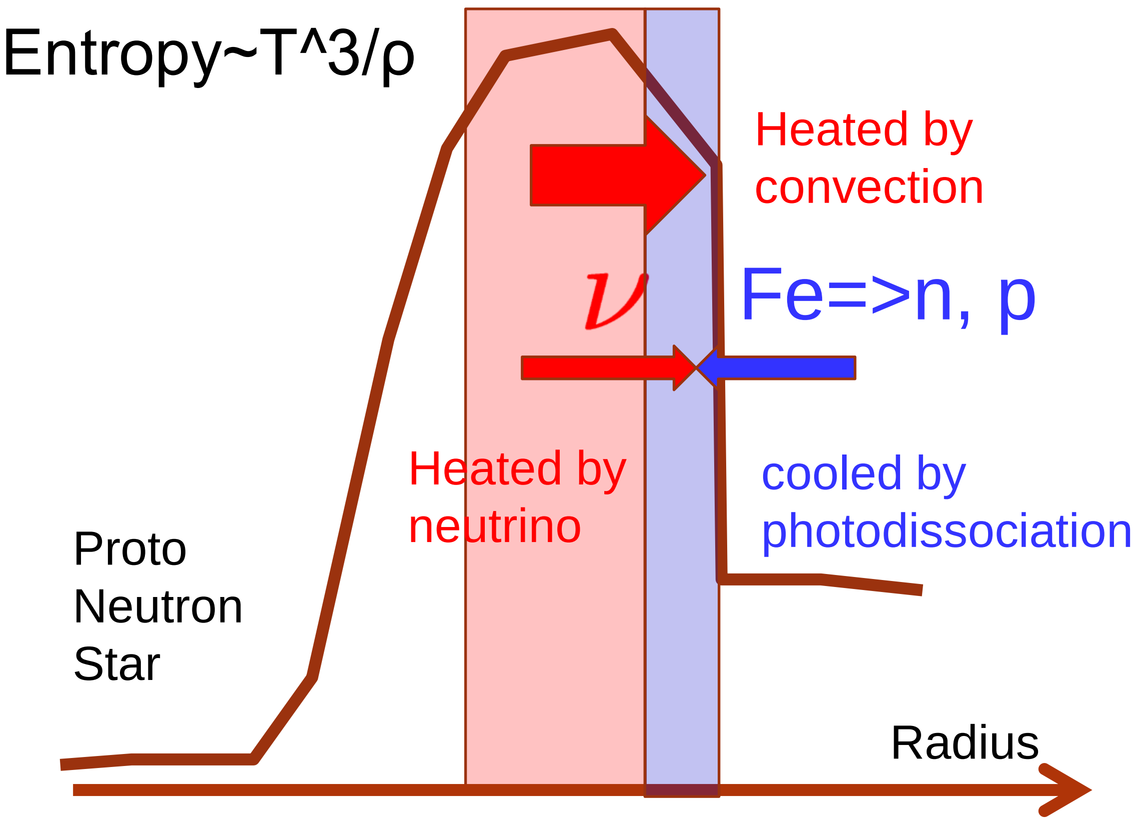



Non-Explosion
Is observed

Entropy is
visualized

Spherical
symmetric
simulations

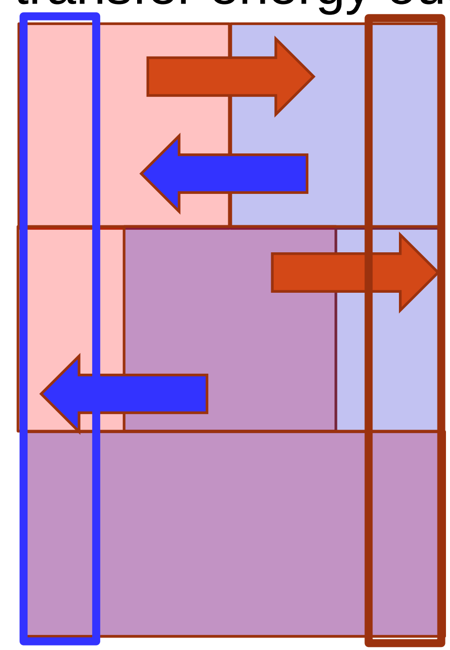
# Key aspects of Neutrino Mechanism




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

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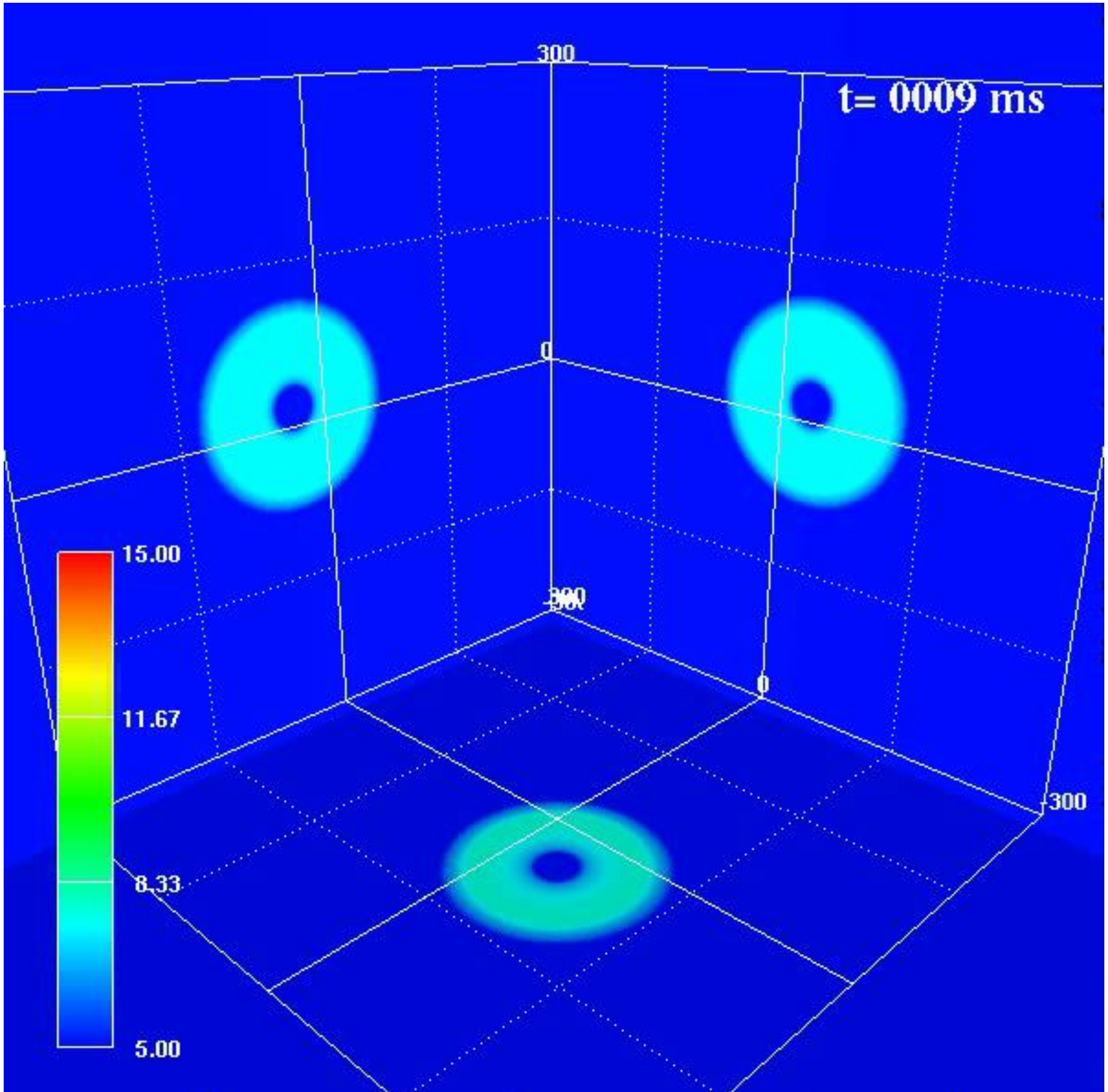
# s11.2(Light Progenitor) Ω=0rad/s



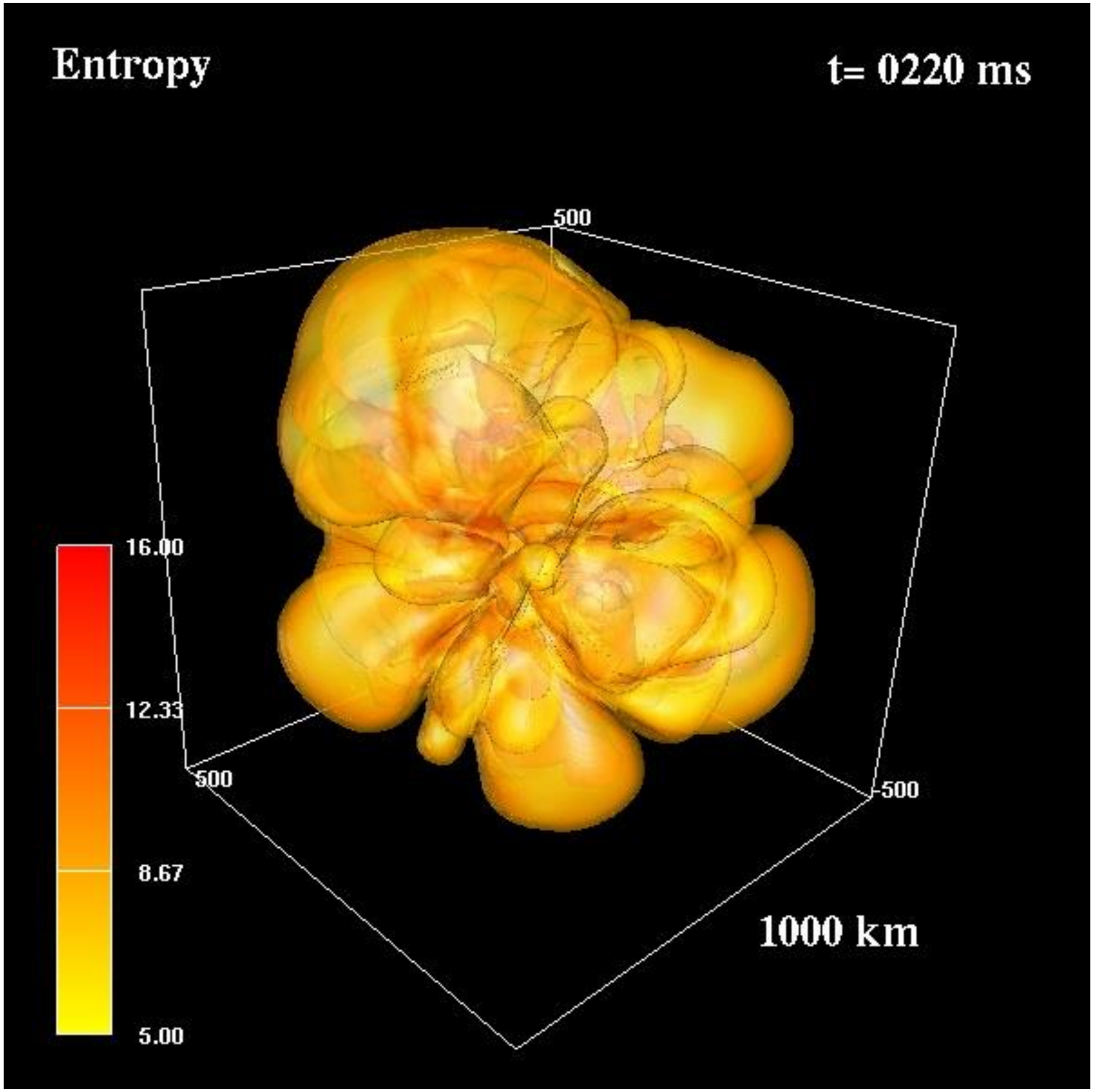

**Explode!**
**Convection Dominant**

EoS : LS-K220

resolution :
384(r)x128(θ)x256(φ)
The finest grid

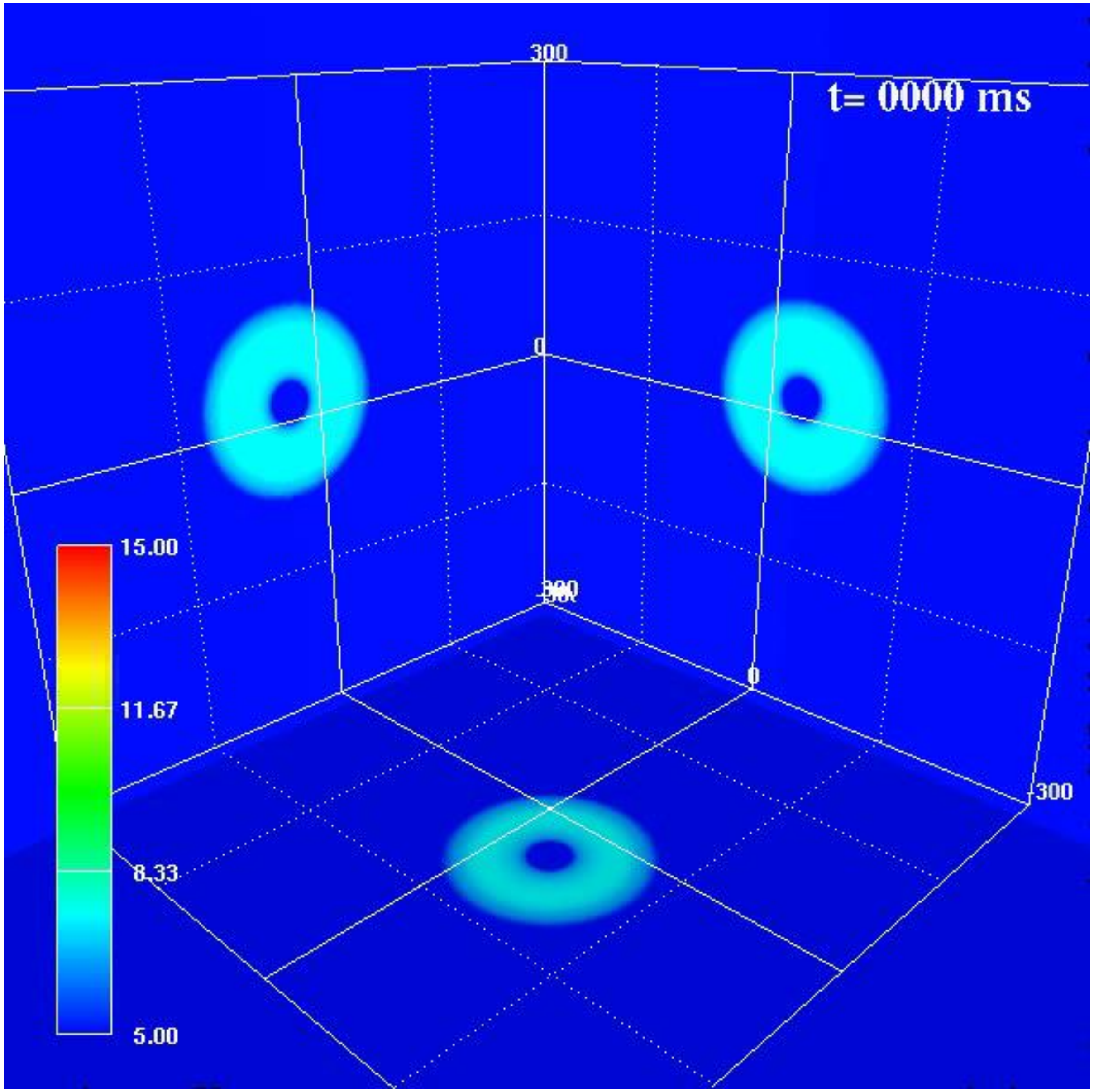
Neutrino Trasport :
Ray-by-Ray:IDSA
+Leakage
Hydro:
HLLE, 2nd order

# Shape of the explosion？




Many hot bubble is observed. That is evidence of strong convection.

# s27(heavey Progenitor) Ω=0rad/s




Failed

(or need long-term sim.)

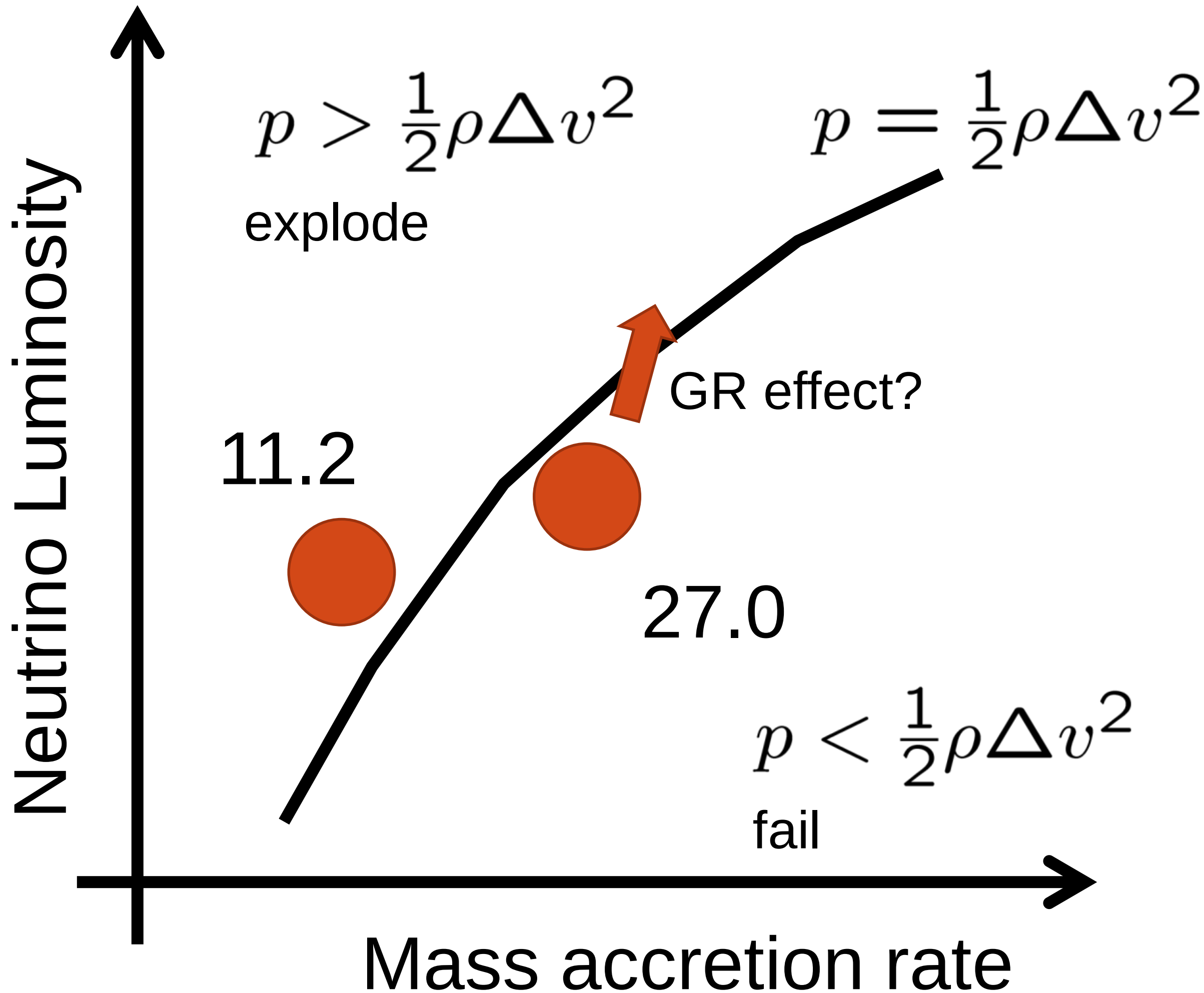
EoS：LS-K220

resolution：
384(r)x64(θ)x128(φ)

Neutrino Transport：
Ray-by-Ray:IDSA
+Leakage

Hydro:
HLLE, 2nd order

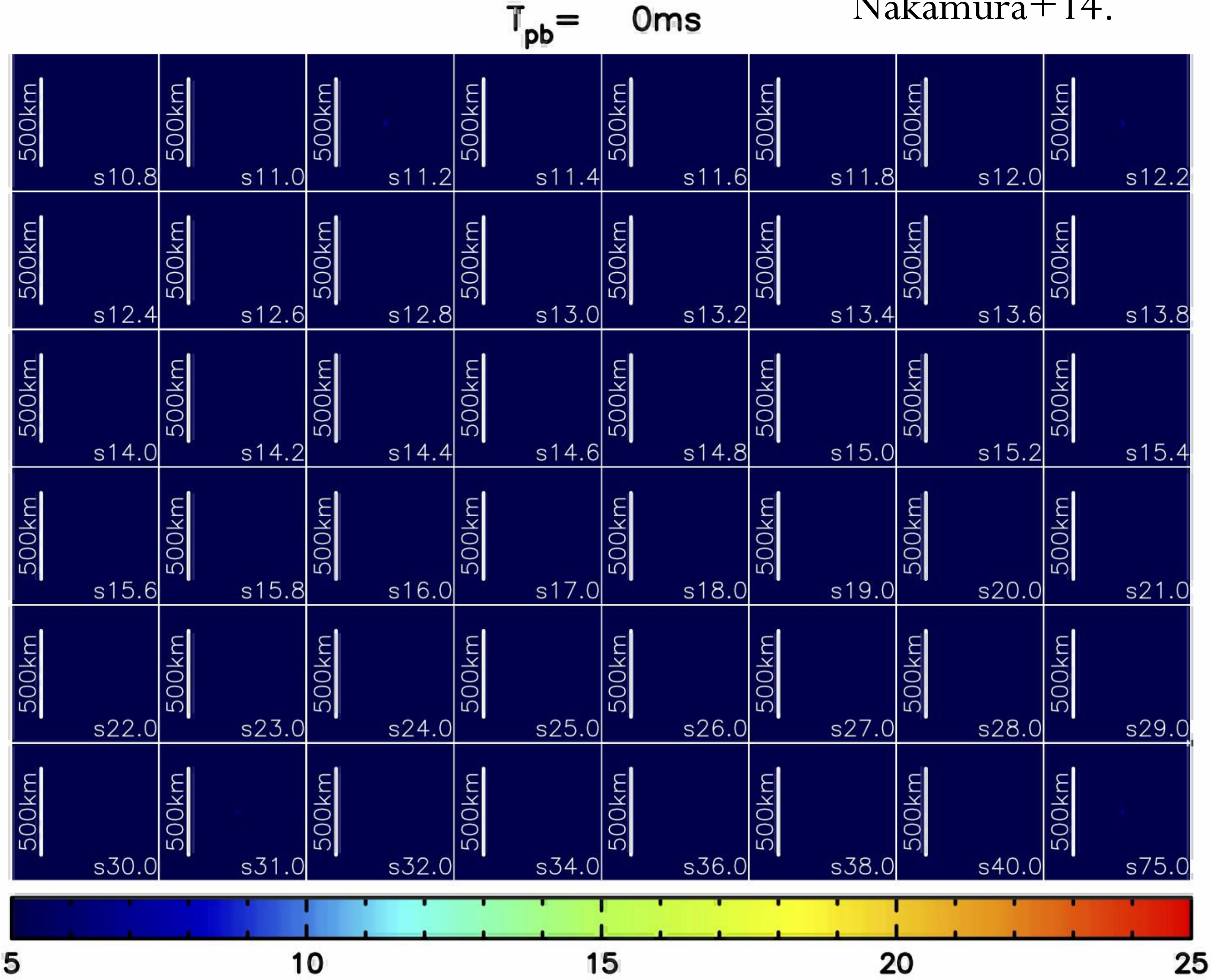
# Mass accretion vs neutrino heating




Heavier progenitor results high mass accretion rate and high ram pressure. That spoils the explosion.

GR effects(or update of microphysics) can change the situation.

Nakamura+14.



$T_{pb}$= 0ms
500km
s10.8
s11.0
s11.2
s11.4
s11.6
s11.8
s12.0
s12.2
s12.4
s12.6
s12.8
s13.0
s13.2
s13.4
s13.6
s13.8
s14.0
s14.2
s14.4
s14.6
s14.8
s15.0
s15.2
s15.4
s15.6
s15.8
s16.0
s17.0
s18.0
s19.0
s20.0
s21.0
s22.0
s23.0
s24.0
s25.0
s26.0
s27.0
s28.0
s29.0
s30.0
s31.0
s32.0
s34.0
s36.0
s38.0
s40.0
s75.0
5
10
15
20
25

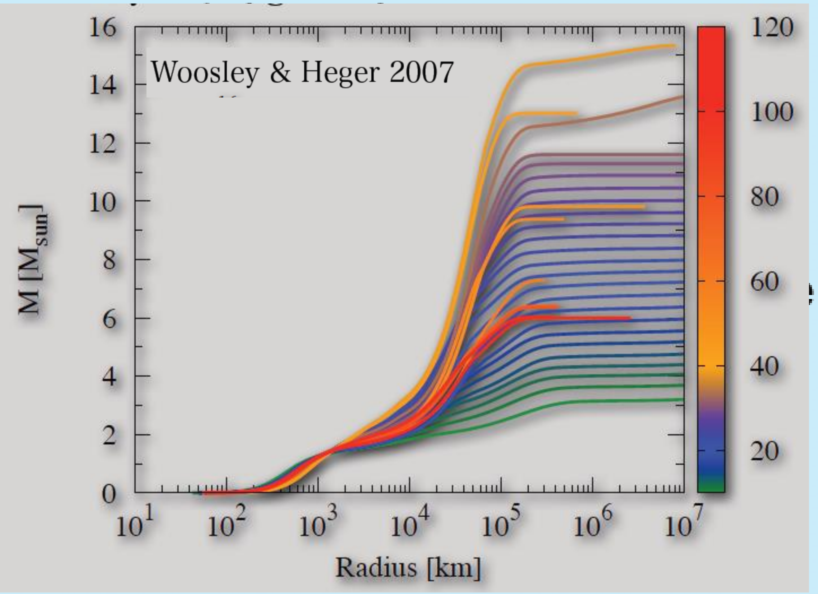
Nakamura+ 14.

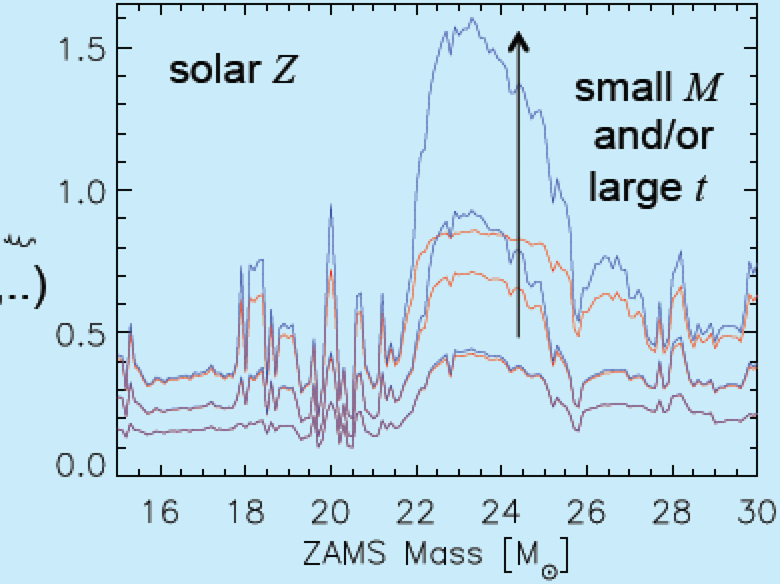
# Compactness of progenitors

- Compactness parameter $\xi$ (O'Connor & Ott '11 )
  - Ratio of mass $M$ to radius $R(M)$ which involves $M$

$$\xi = \frac{M/\ M_\odot}{R(M)/1000\mathrm{km}}$$

- Sukhbold & Woosley '13 (arXiv:1311.6546)



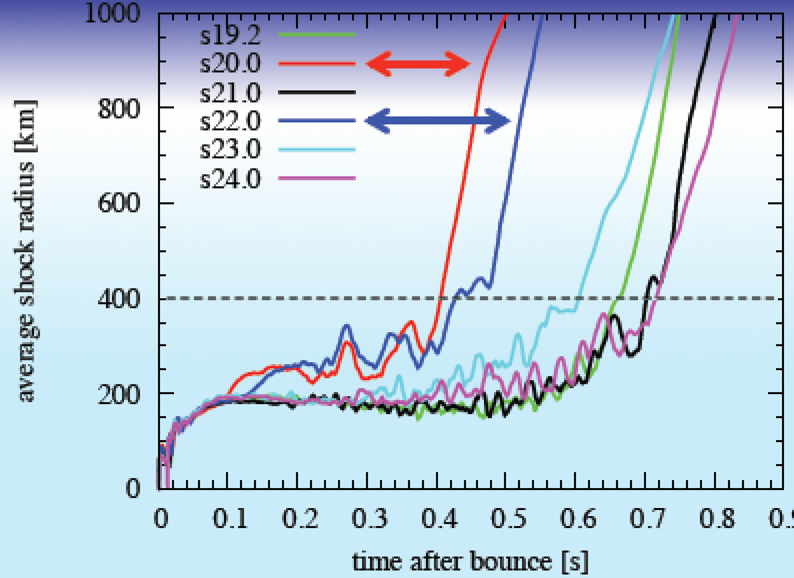



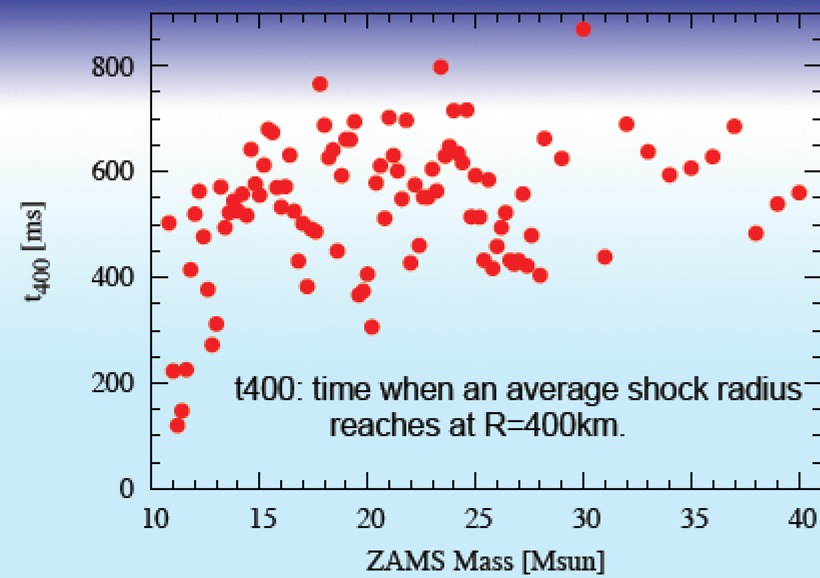

slide from suwa

- Average shock radii

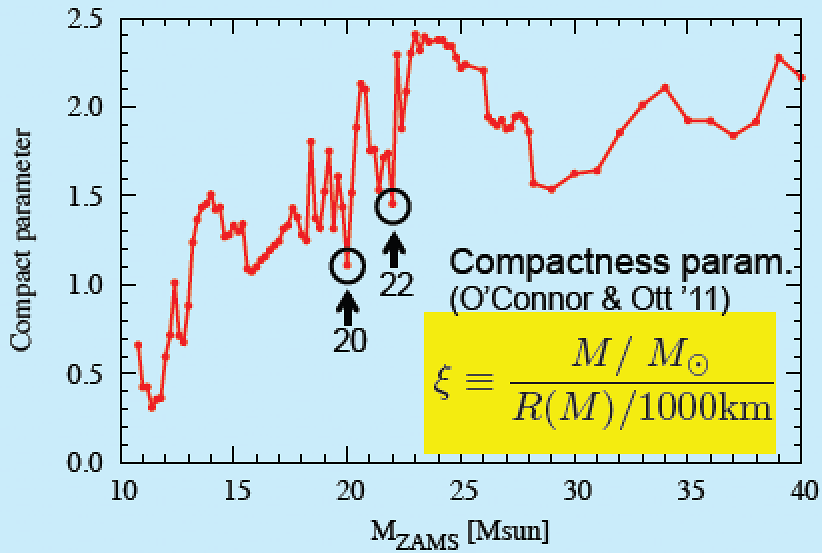
Nakamura+ 14.

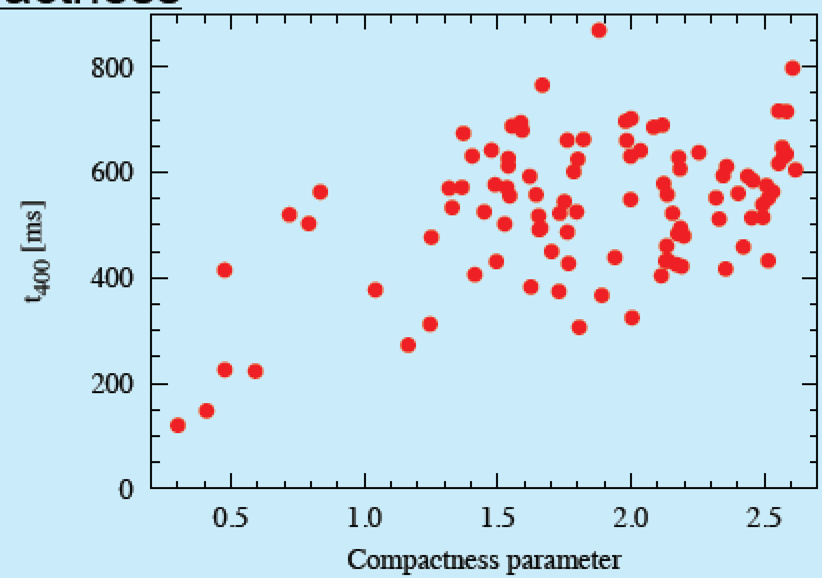
  - NOT a monotonic function of ZAMS masses



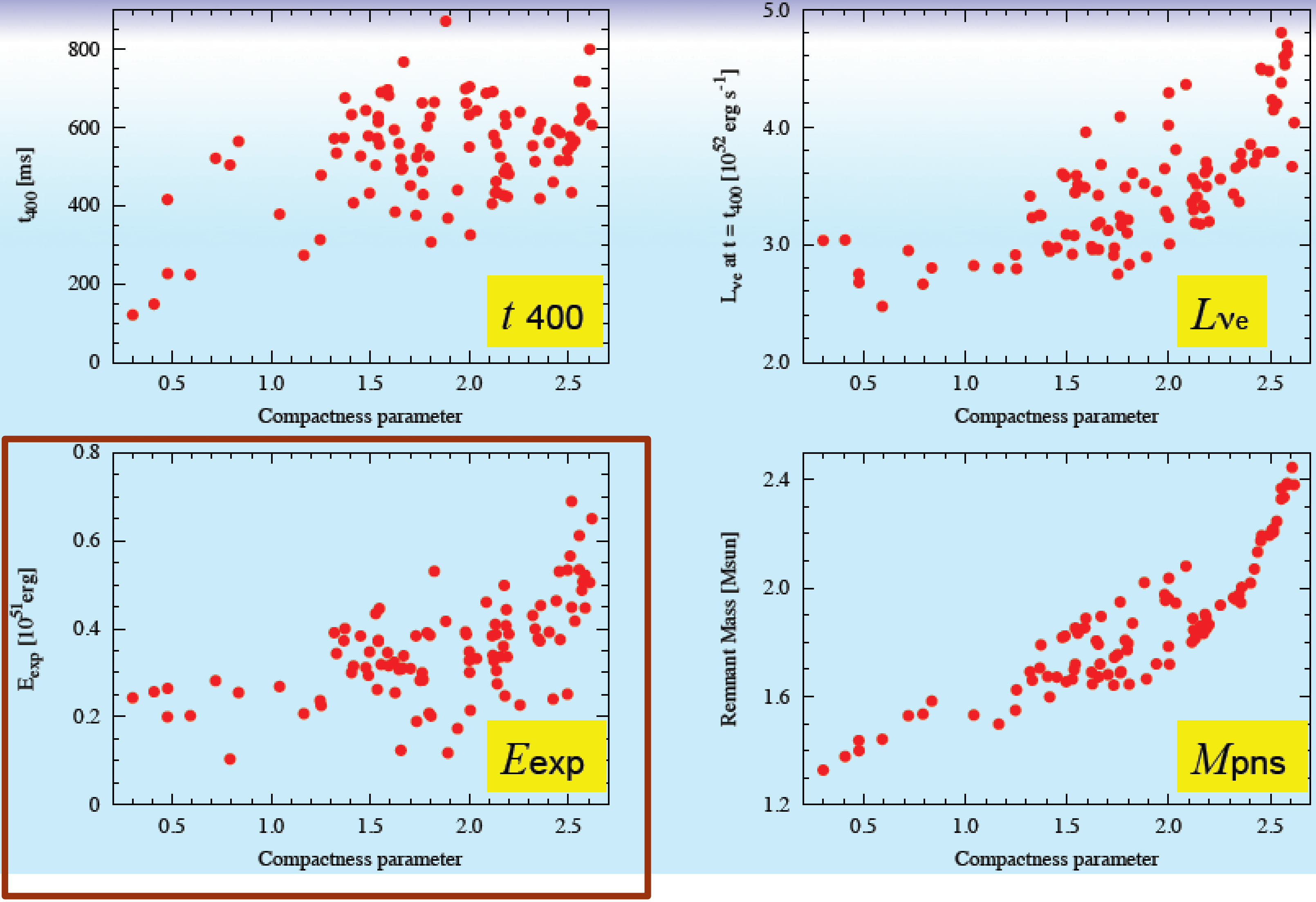

BUT correlating with compactness



Nakamura+ 14

# $t_{400}$, $L_{\nu e}$, $E_{exp}$, & $M_{pns}$ - $\xi$ parameter



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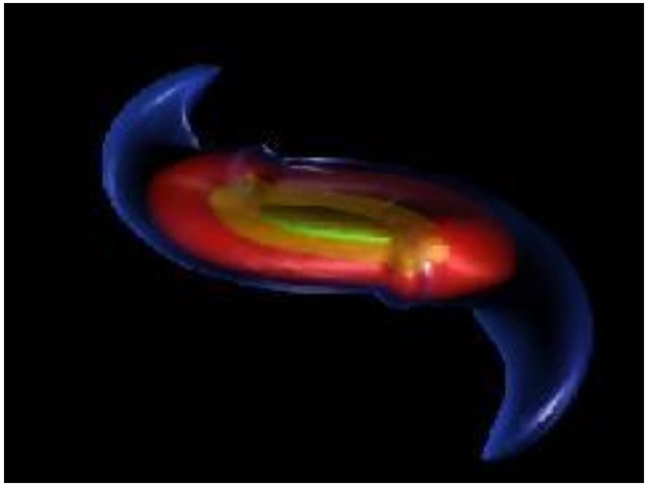
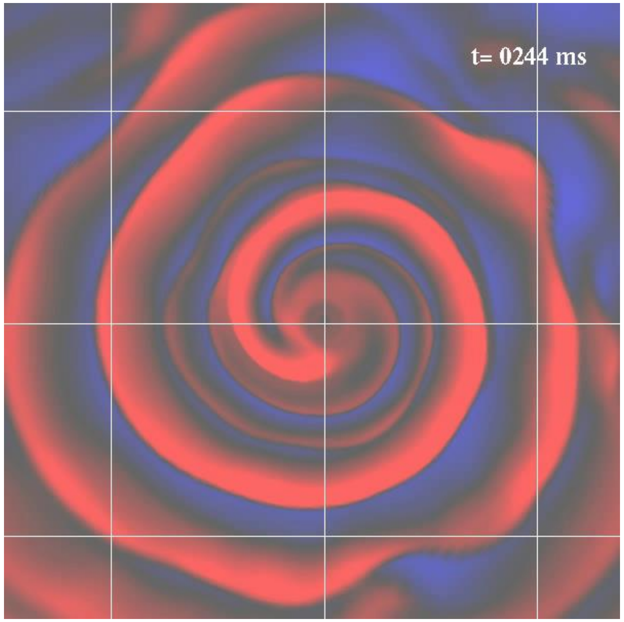
# Bar mode instability

Rapid Rotation => spiral instability





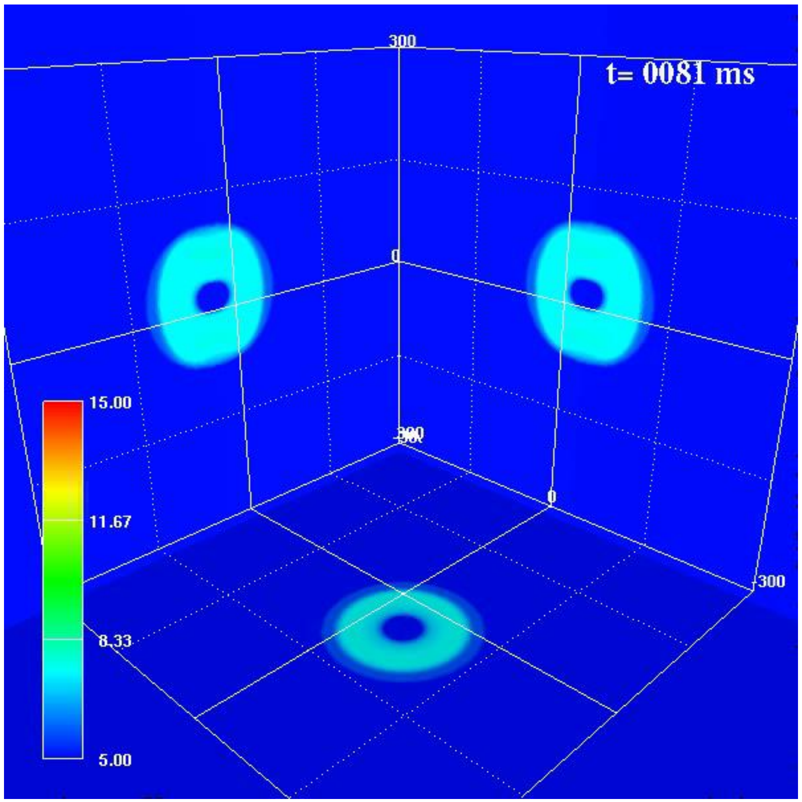

In the rigid ball,

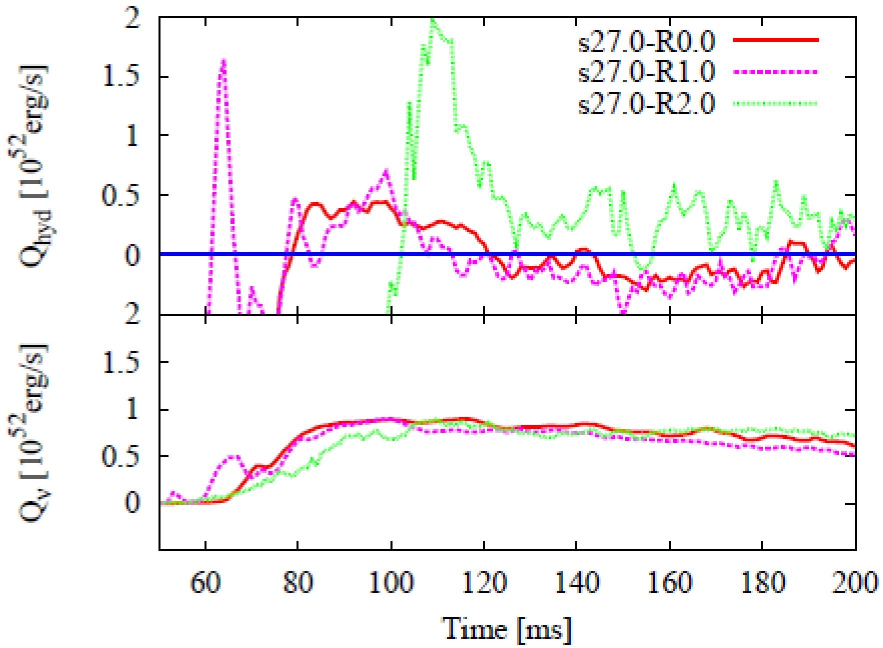
Rotational energy(T)/gravtational energy(W)=14%

In Sne case, criteria becomes smaller.

Called low-T/W instability

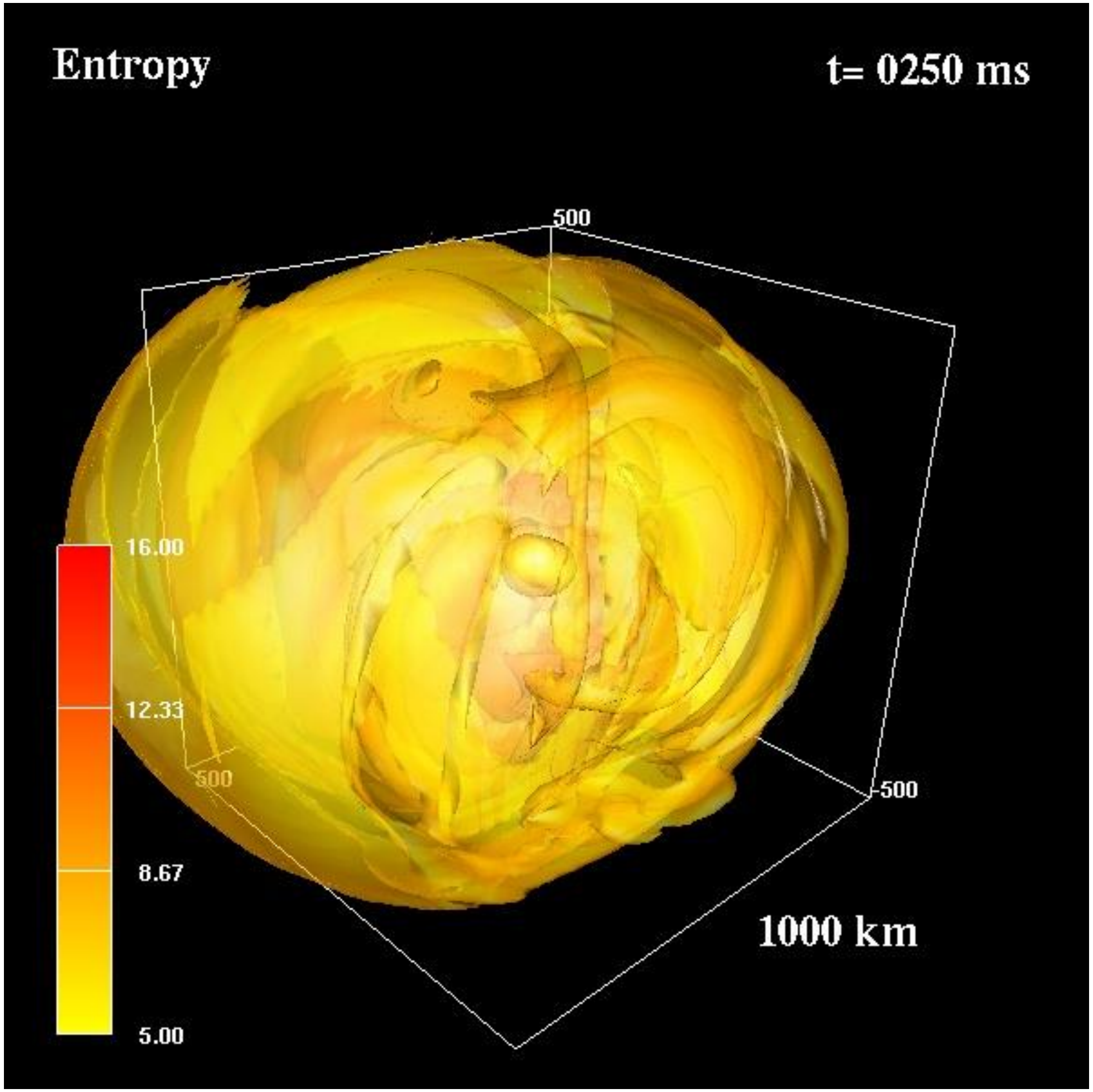
# Neutrino + rotation



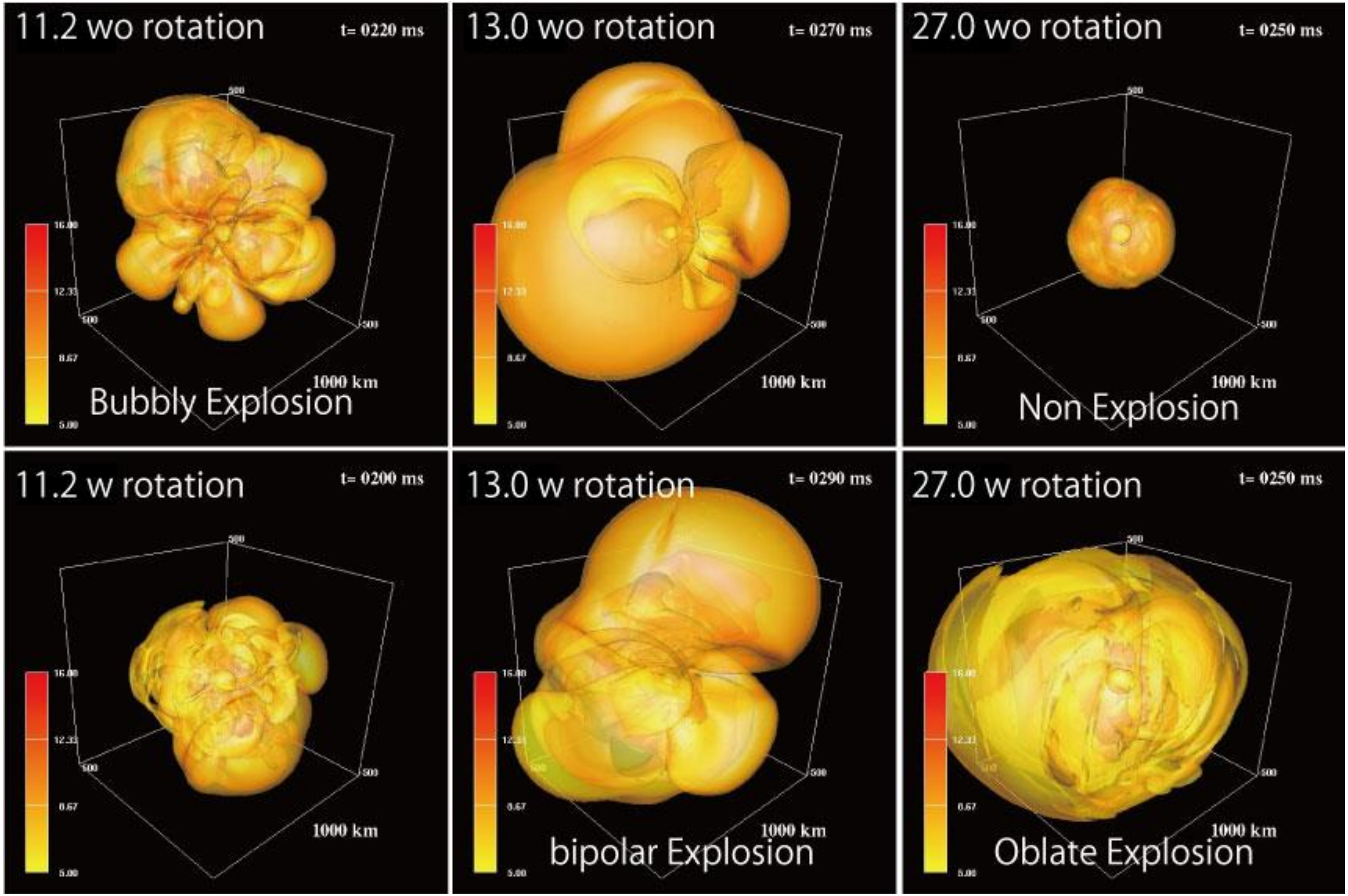




Spiral wave transfer the energy to the outer regon.
Finally explosion is found!

# Shape of the explosion？

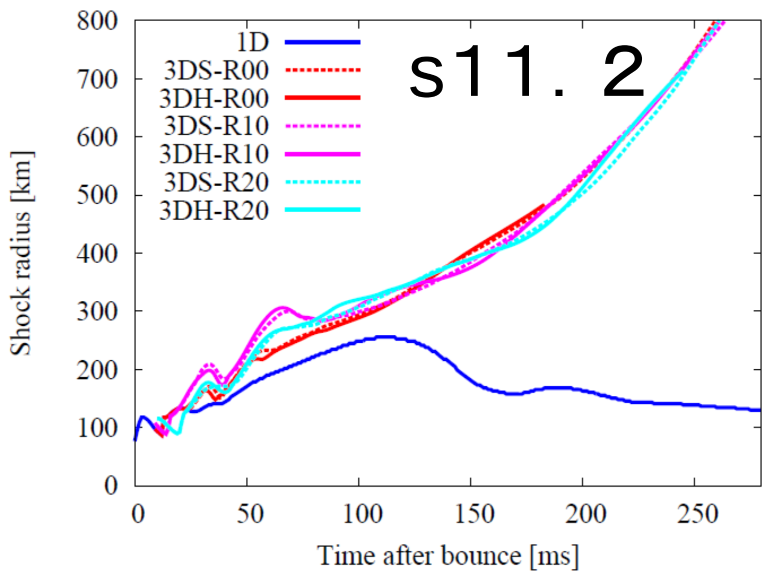



Strong expansion is found at equatorial plane

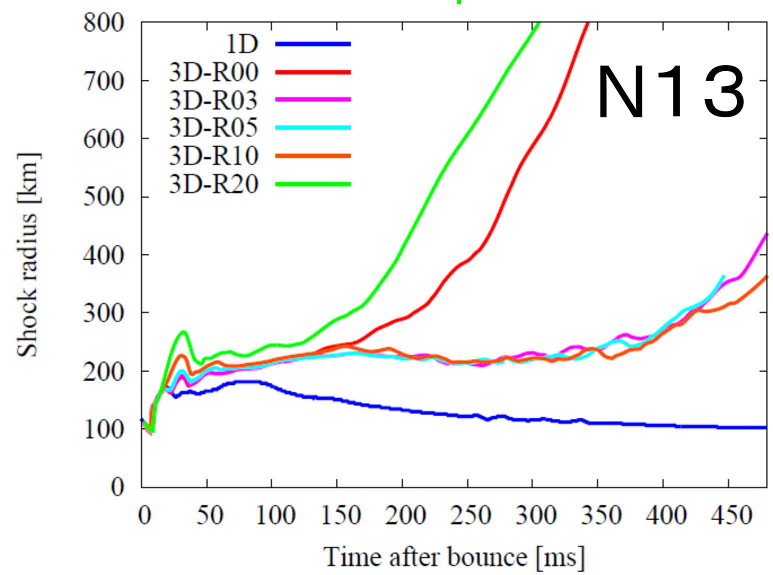


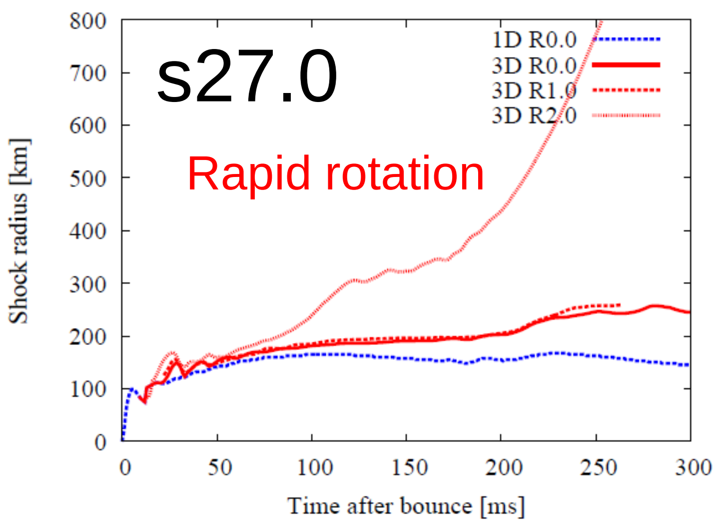

The mass of the progenitor and rotation make various type of Explosion(or Non Explosion).

# Does rotation affect the shock revival?




Rapid rotation



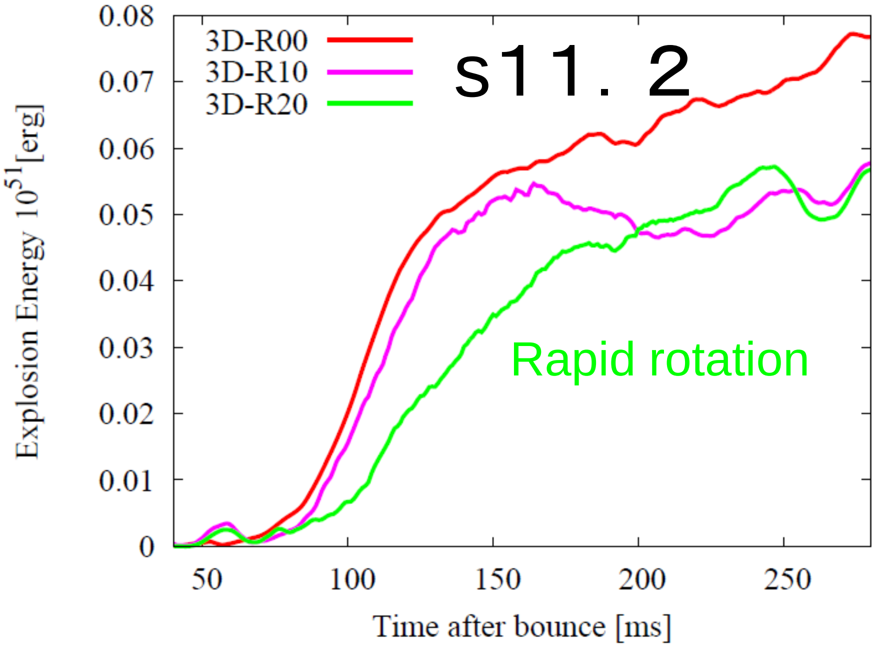

1D=> no shock revival

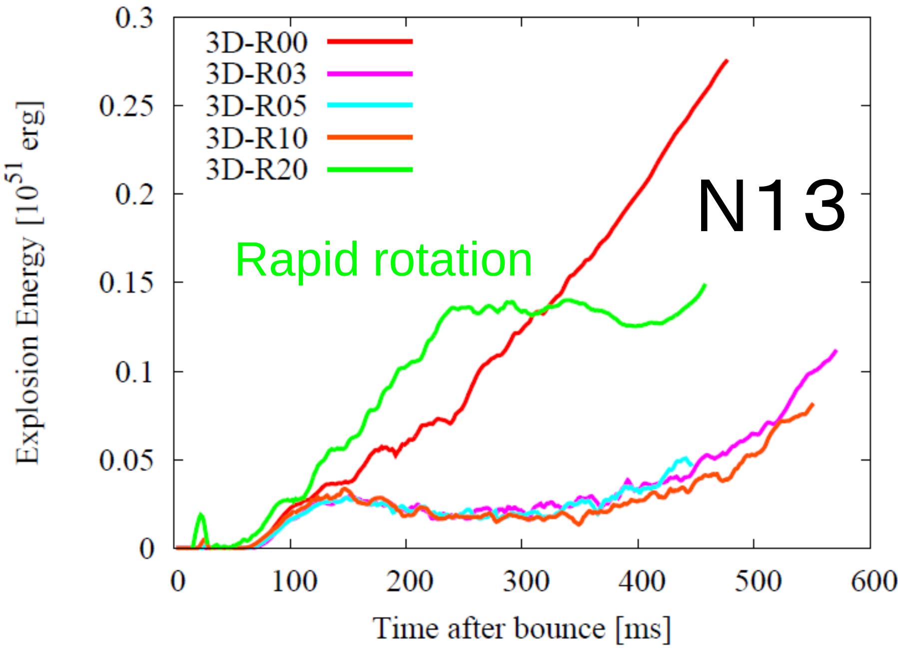
s11.2 : No

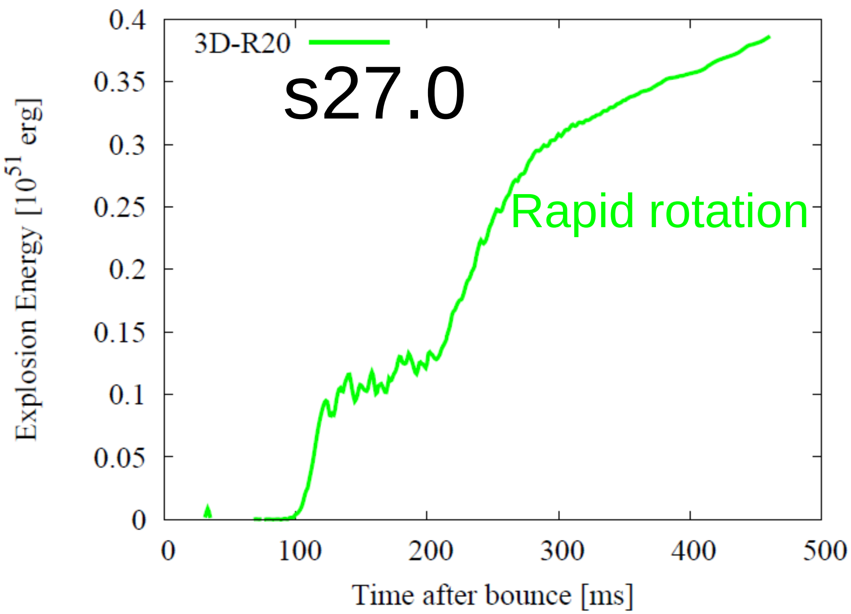
N13 : Yes

s27 : Yes

# How energetic is that?




Observe 0.1-0.4 10^51erg!
It’s close to 10^51 erg!

# Message

Although CC SNe are not completely understood, we are close to solve the problem.

(It's might be semi-final match or final match?)

Quite nice model (close to the real one) can be obtained.

When should we start the collaboration on astronomy with realistic supernovae model?

## Now's the time!

# 超新星シミュレーションの新問題

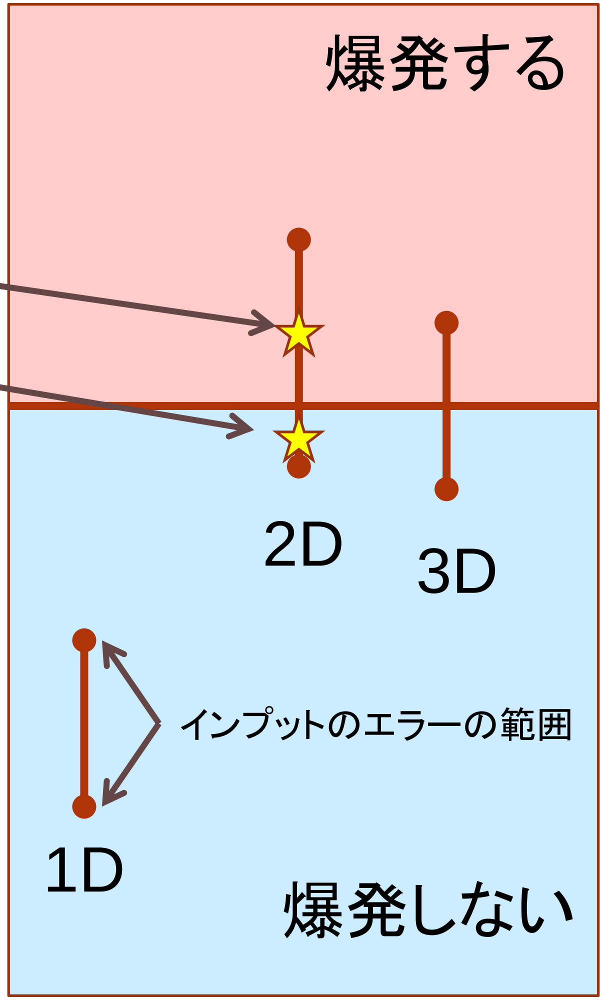
**多次元モデルは物理のインプットに敏感で手法によって爆発したりしなかったりする。**

**２次元モデル（複数親星に対して）**

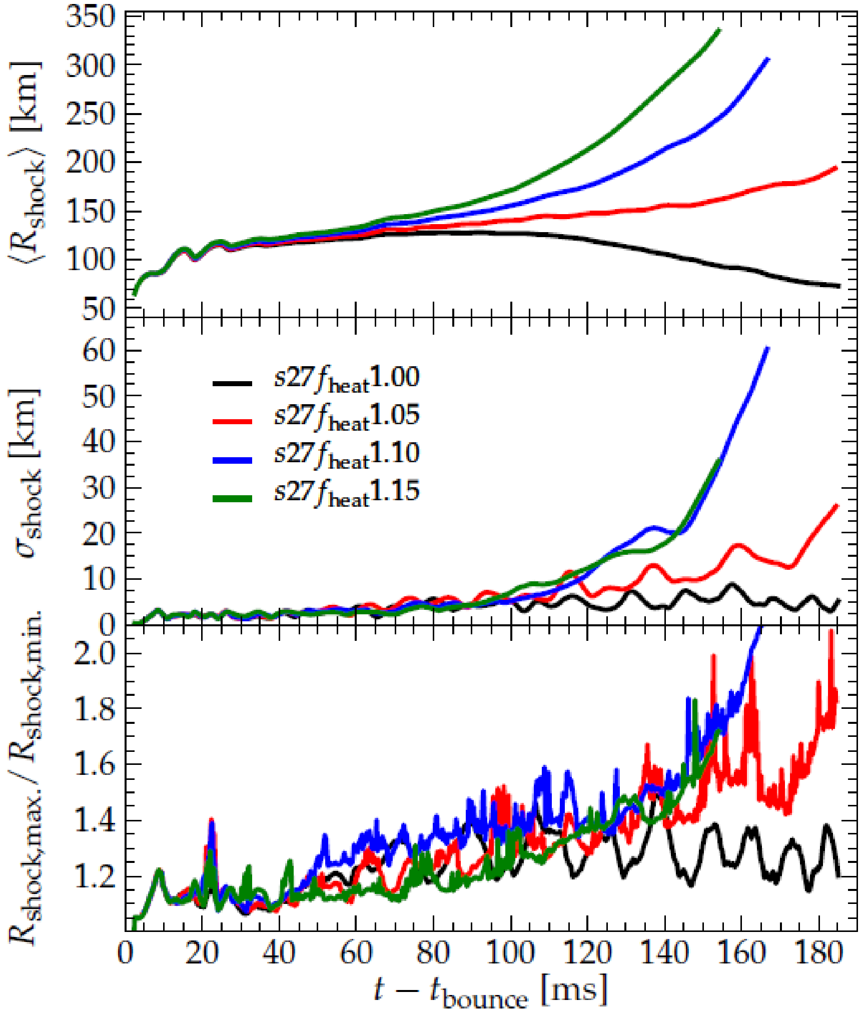
- Bruenn+12：**全部爆発**
- Mueller+13：**おおよそ爆発**
- Dolence+14：**一つも爆発しない**
- Nakamura+14：**全部爆発**
- Suwa in prep：**半分ほど爆発**
- Hanke in prep：**おおよそ爆発**

**３次元モデル（複数親星に対して）**

- Hanke in prep：**一つも爆発しない**
- Takiwaki in prep：**半分ほど爆発**



# 超新星シミュレーションの新問題




Ott+12

多次元モデルは爆発するにせよしないにせよ非常にぎりぎり。

定量的な評価を確定するためには相当手法に凝る必要がある！

今後は
数値計算の信頼性がとにかく大事！

# ロードマップ

とにかくすべてのインプットをアップデートせよ！
Most realisticmodelの変遷。

Takiwaki+14

ニュートリノ反応
現象論的GR

Hanke+13

フルGR
Non Ray-by-Ray

Kuroda in prep

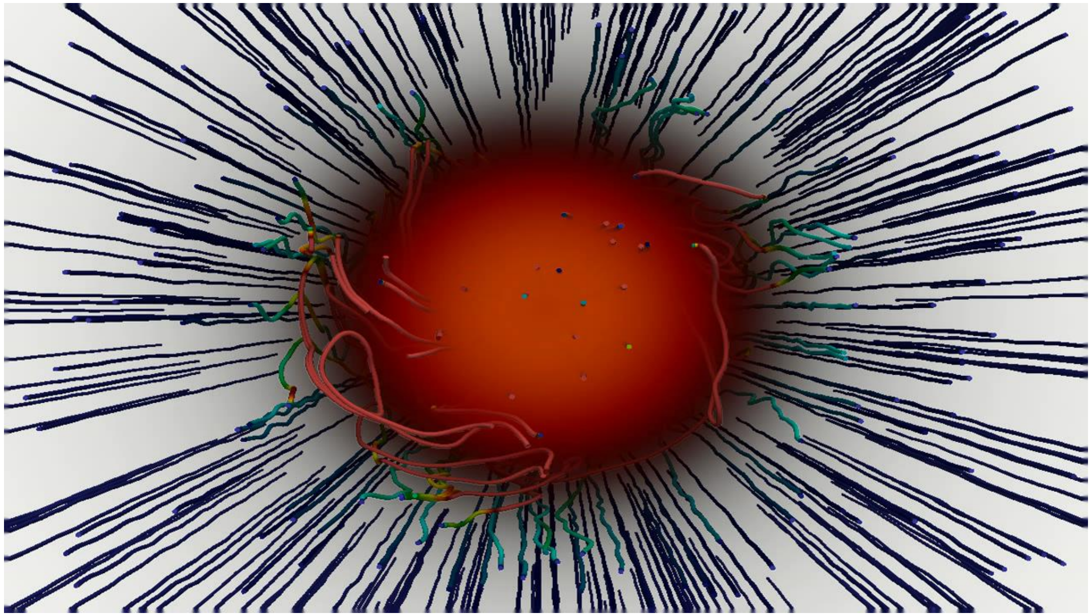
ペタスケール

６次元ボルツマン

エクサスケール
～2020

Kuroda論文での結論と6次元ボルツマンでの計算に今後は注目！
2020年ぐらいまでにはかなりの決着を見るのでは？

# ニュートリノ＋磁場



**磁気回転不安定性で対流安定な場所でも乱流的になる。**

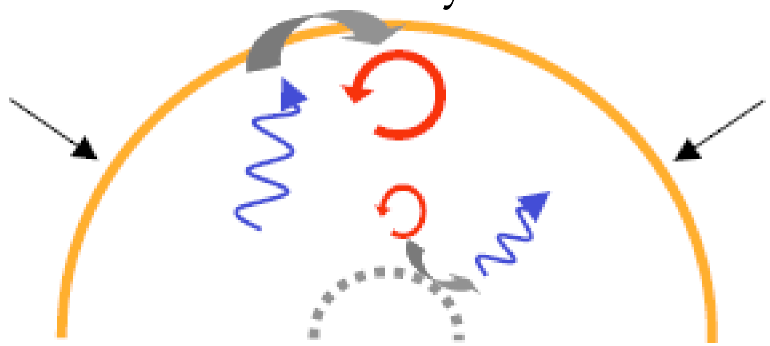
**それがニュートリノ加熱に効くかもしれない。**

高解像度計算が必要
すぐに完全な計算はできない
徐々に調べる

**現在、政田くんと研究中。澤井くんも同様のことを指摘。**

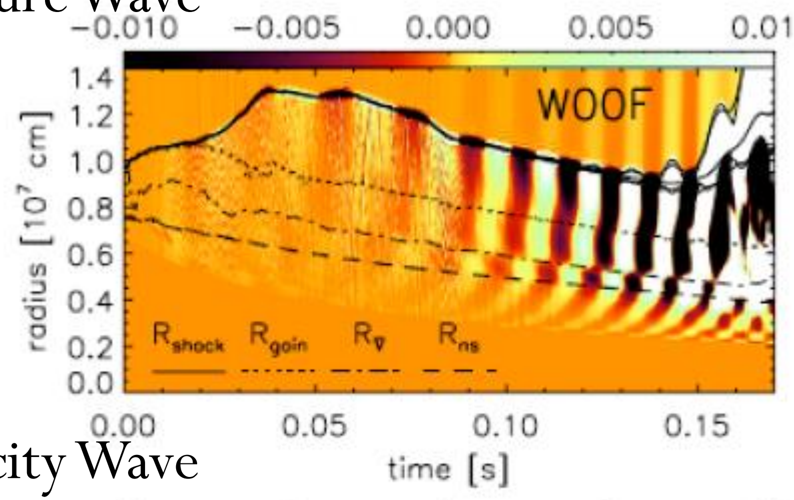
# ニュートリノ＋ＳＡＳＩ爆発

Advective-acoustic cycle

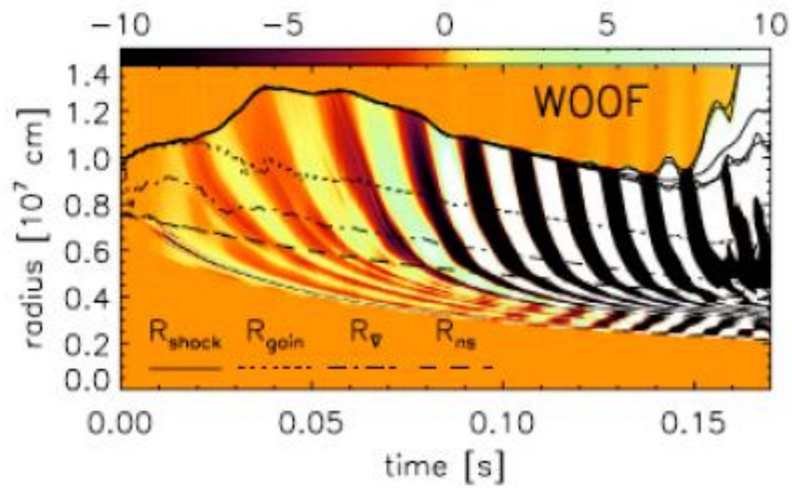


Foglizzo's slides

Pressure Wave



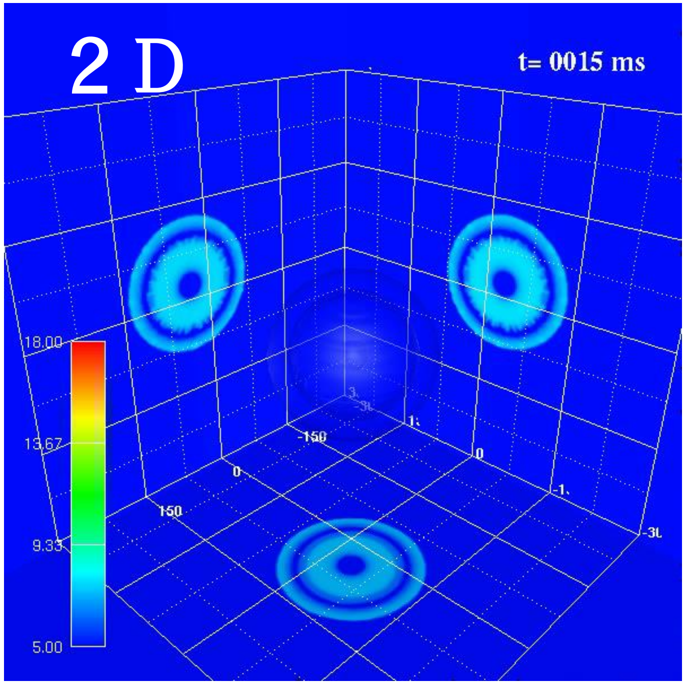

Vorticity Wave



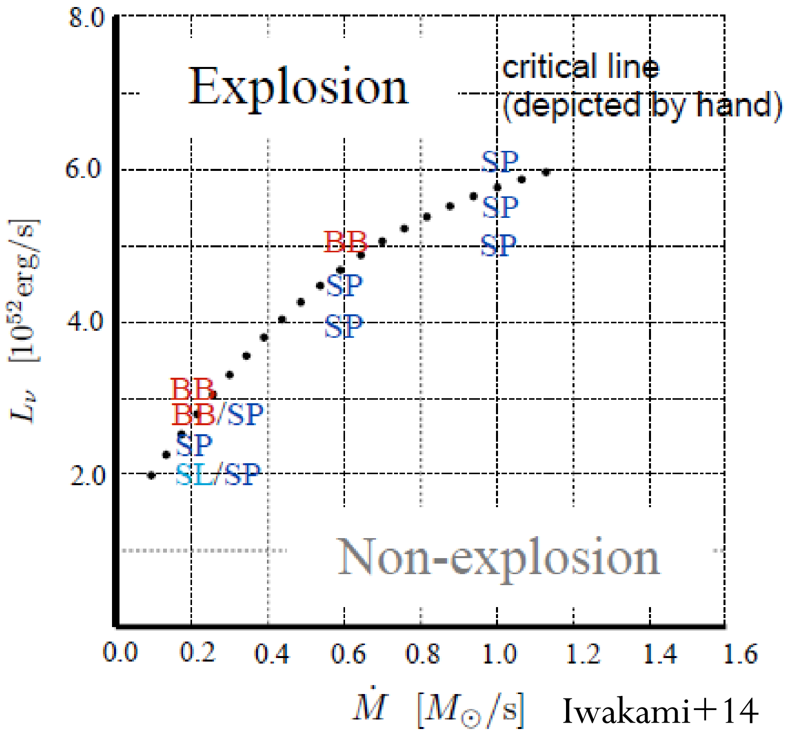

Standing Accretion Shock Instability(SASI)
渦が落ちる時間スケールで成長が律速。
上から物がどんどん降ってくるとき成長しやすい

Scheck+ 2008

# ＳＡＳＩ爆発は起こるか？




Takiwaki+2012




Iwakami+14

**ＣＣ的に爆発しにくいところでドミナントになる。この不安定性で爆発に転じるのは今のところ難しい見通し。**