2015/05/15
「宇宙の歴史をひもとく地下素粒子原子核研究」
2015年領域研究会

３次元超新星モデルからのニュートリノ予測

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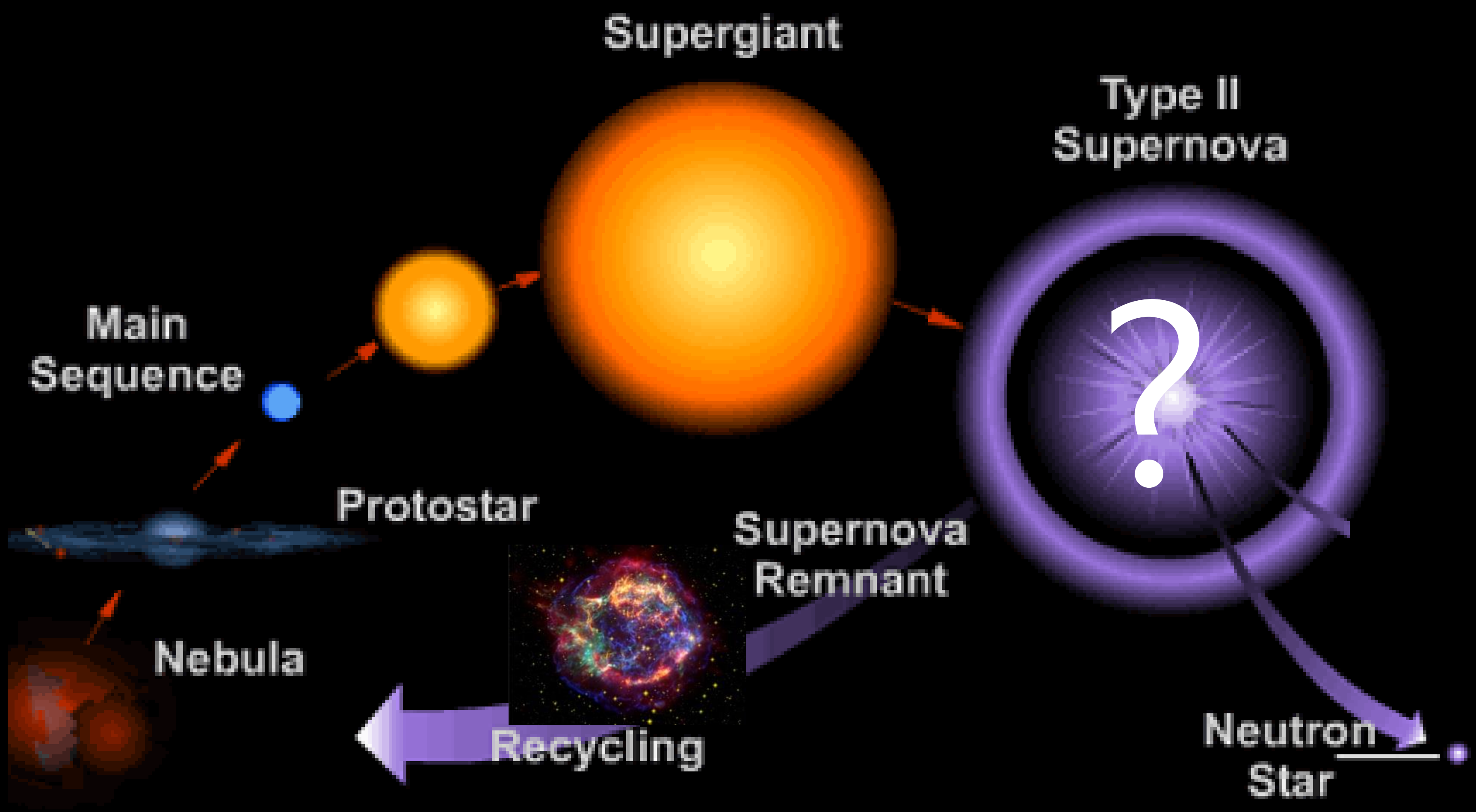
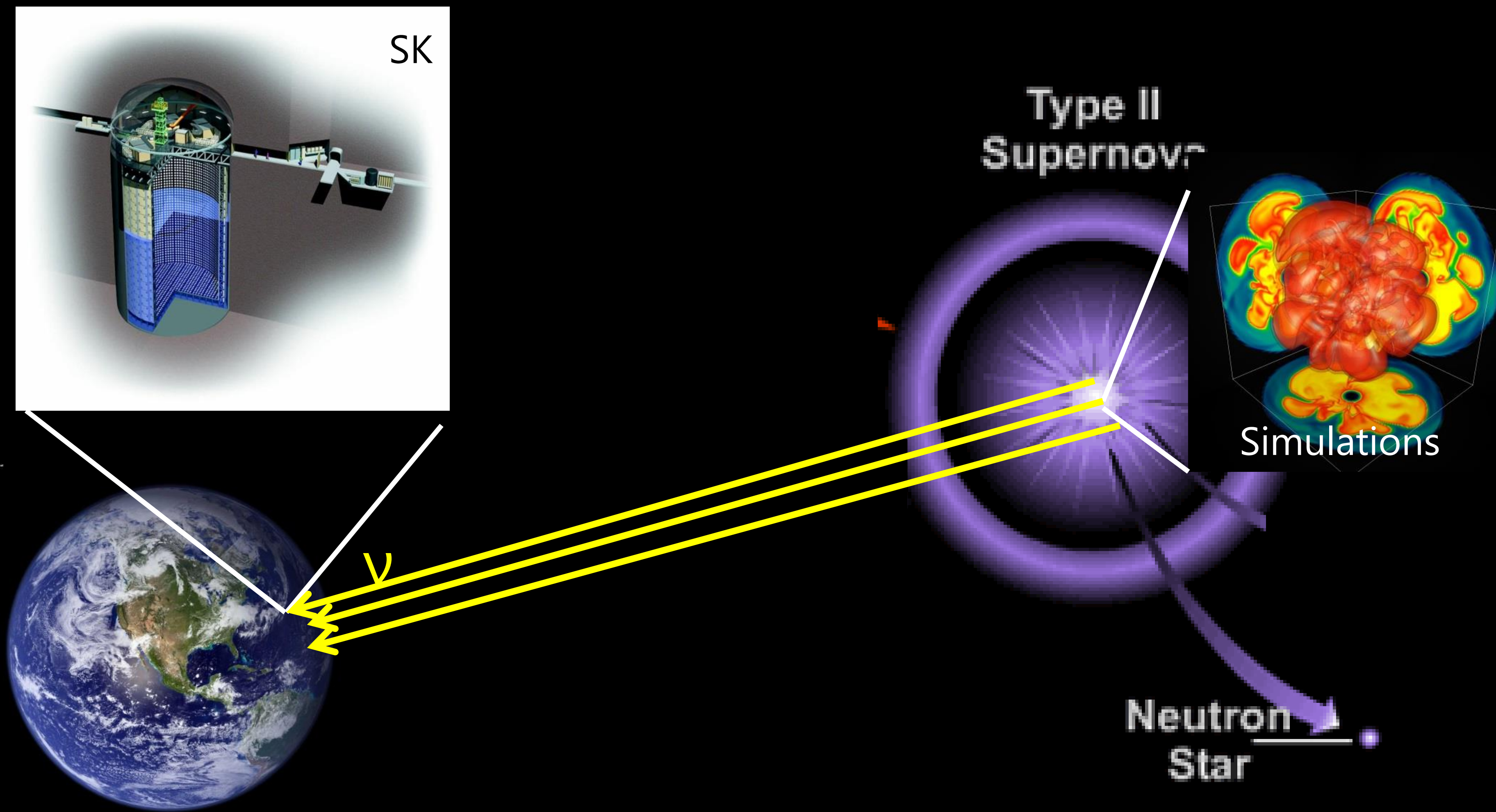
Supernovae: the death of the star



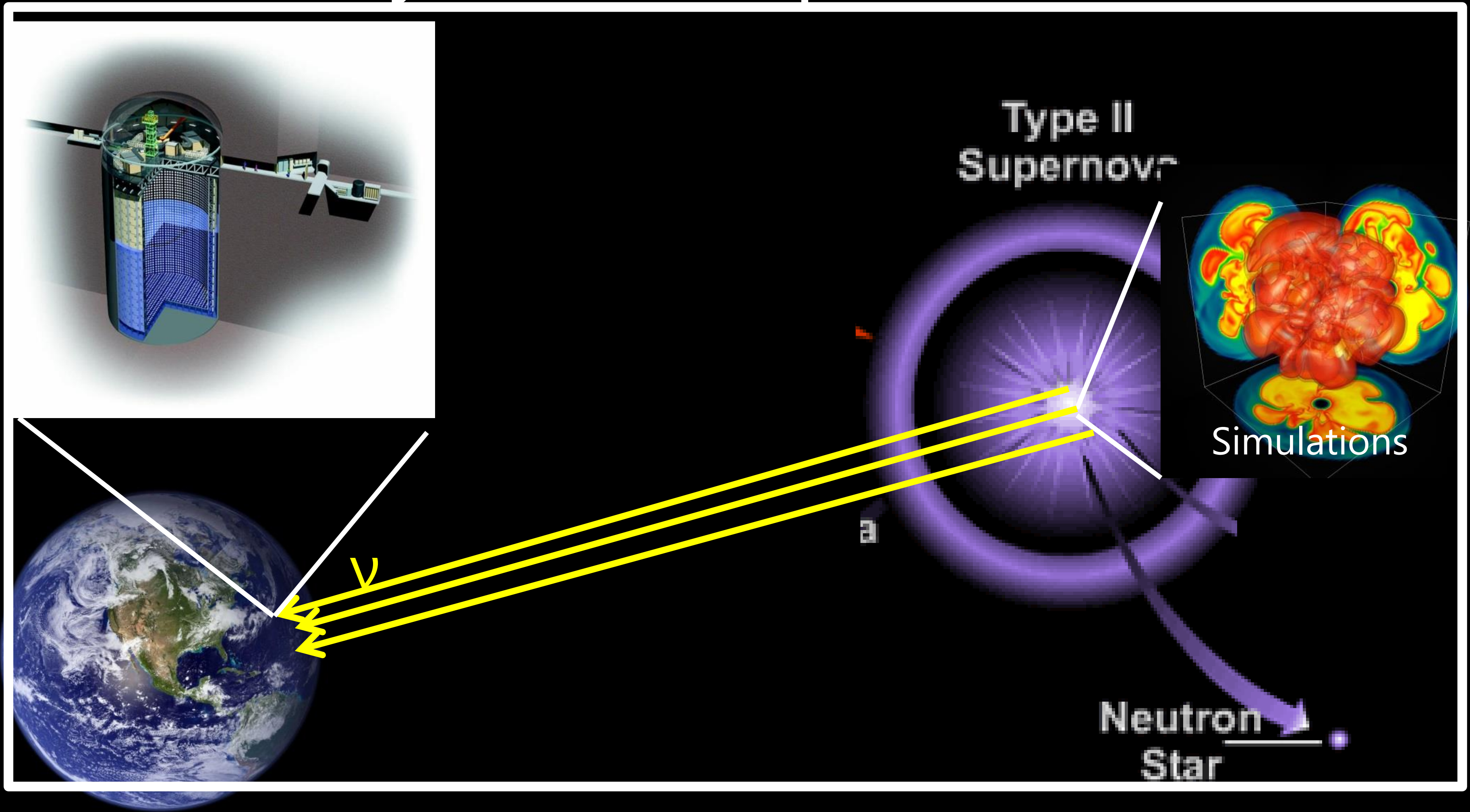
Q:How does the explosion occur?

Supernovae and Neutrino Signal



ν signals have the answer.
GW are also important.

Goal of my research plan



Prediction of ν signals and giving clue to decode the ν signals.

Story of my talk

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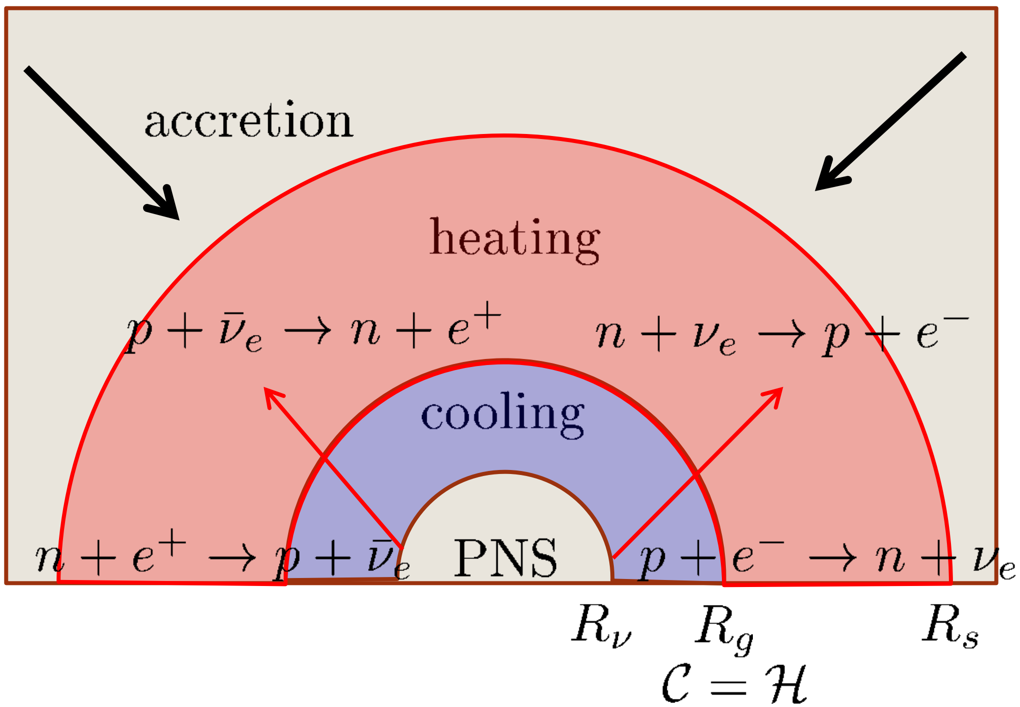
Neutrino Heating Mechanism

Janka 01



-Cooling term

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

$$Q_\nu^- = (3\alpha^2+1)\frac{\pi\,\sigma_0\,c\,(kT)^6}{(hc)^3(m_e c^2)^2}\frac{\rho}{m_u} \times [Y_p\mathcal{F}_5(\eta_e) + Y_n\mathcal{F}_5(-\eta_e)]$$

$$\approx 145\,\frac{\rho}{m_u}\left(\frac{kT}{2\,\mathrm{MeV}}\right)^6 \left[\frac{\mathrm{MeV}}{\mathrm{s}}\right]$$

$$\rho_{\mathrm{proton}} \times \rho_{\mathrm{electron}}(\propto T^3) \times \sigma(\propto T^2) \times \bar{E}(\propto T)$$

-Heating term

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

$$Q_\nu^+ = \frac{3\alpha^2+1}{4}\frac{\sigma_0\langle\epsilon_{\nu_e}^2\rangle}{(m_e c^2)^2}\frac{\rho}{m_u}\frac{L_{\nu_e}}{4\pi r^2\langle\mu_\nu\rangle}(Y_n + 2Y_p)$$

$$\approx 160\,\frac{\rho}{m_u}\frac{L_{\nu_e,52}}{r_7^2\langle\mu_\nu\rangle}\left(\frac{kT_{\nu_e}}{4\,\mathrm{MeV}}\right)^2 \left[\frac{\mathrm{MeV}}{\mathrm{s}}\right].$$

$$\rho_{\mathrm{neutron}} \times \rho_{\mathrm{neutrino}}(\propto T_\nu^3/r^2) \times \sigma(\propto T_\nu^2) \times \bar{E}(\propto T_\nu)$$

$$\rho \propto r^{-3} \quad T \propto r^{-1}$$

$$\mathcal{C} \propto 1/r^9 \quad \mathcal{H} \propto 1/r^5$$

If we assume hydrostatic profile with pressure of radiation dominant.

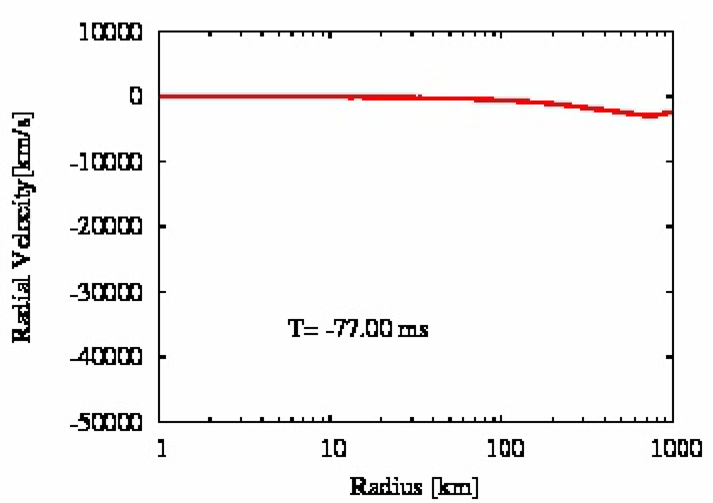
Above gain radius, the heating is dominant.

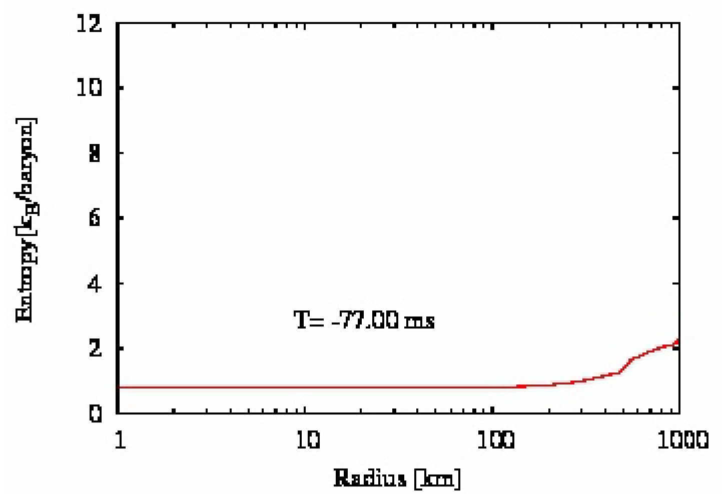
Shock and Entropy

Entropy:T^3/ρ

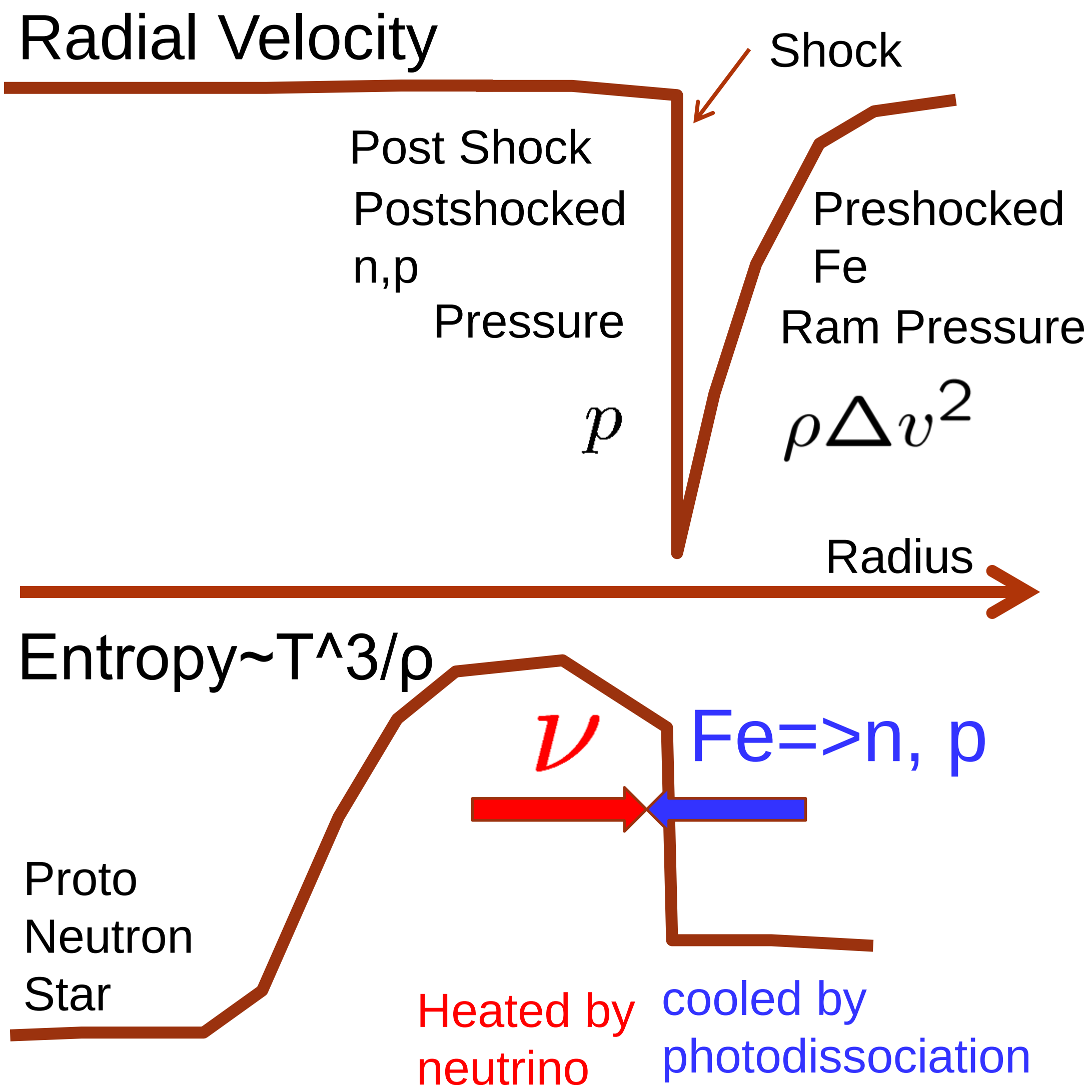
It’s a good measure for the shock.

At the shock, kinetic energy is converted to heat and temperature increases(i.e. entropy also increases.)





Key aspects of Neutrino Mechanism



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

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

RHS is determined by stellar structure(density profile).

LHS is determined by two ingredients.

(1) Photodissociation

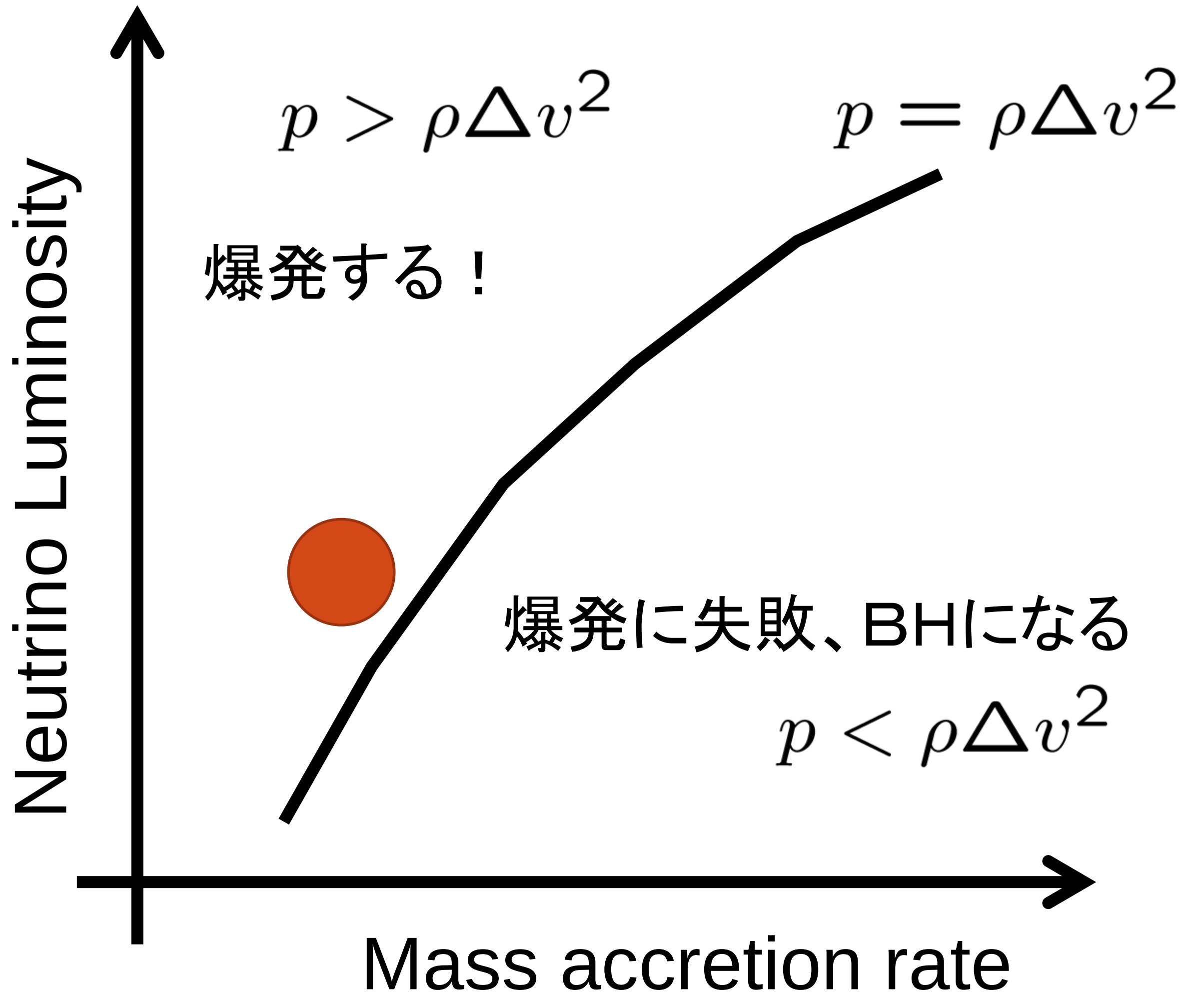
$$\mathrm{Fe} \rightarrow 30\mathrm{n} + 26\mathrm{p} - \Delta Q$$

(2) Neutrino Heating

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

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

Mass accretion vs neutrino heating



質量降着率
vs ニュートリノ光度
で爆発するかどうか決まる。
＝＞クリティカルカーブ

ただし、定量的にはまだわからない。
理論と観測を比較する必要あり！

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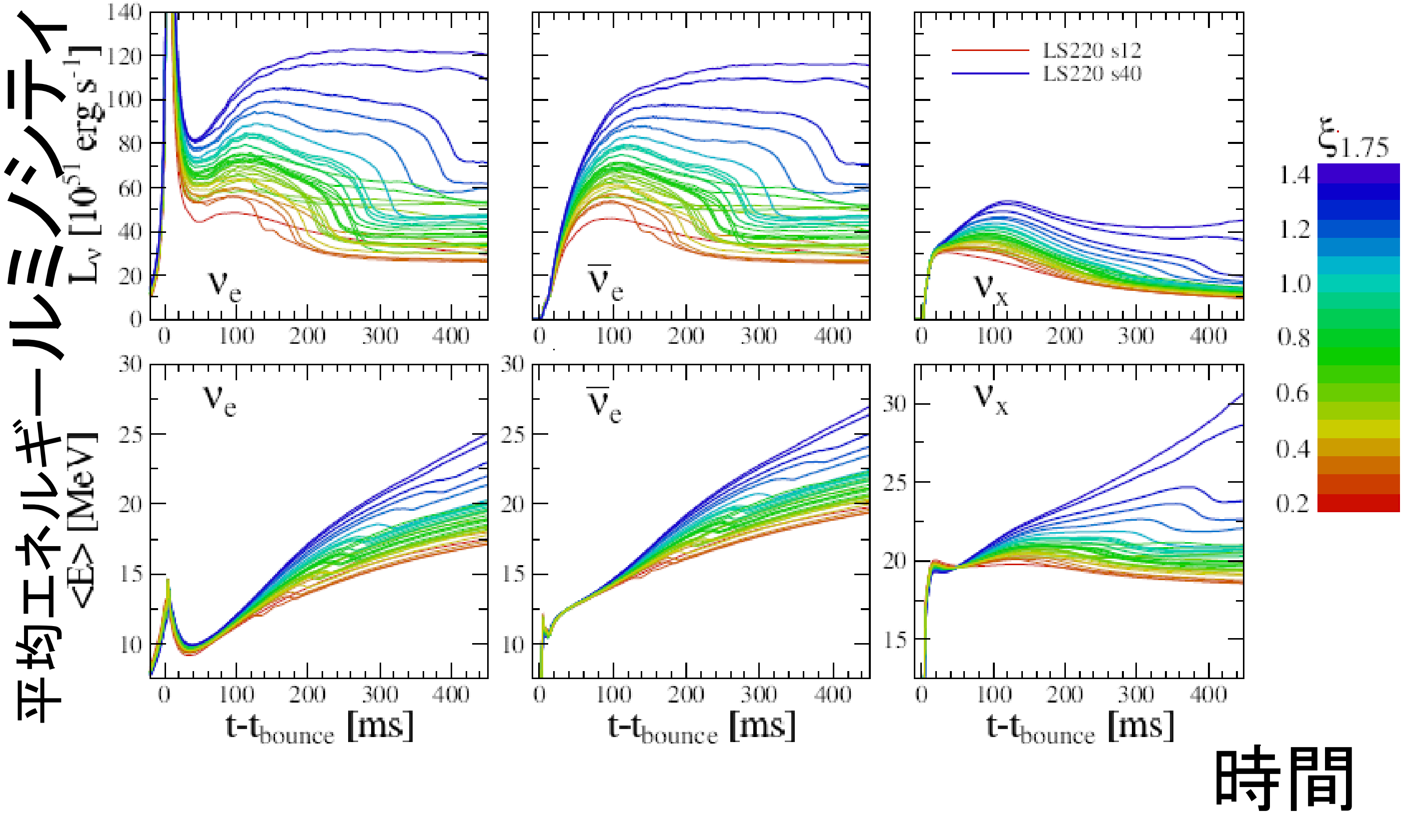
Extract mass accretion history

O'Connor and Ott 2012

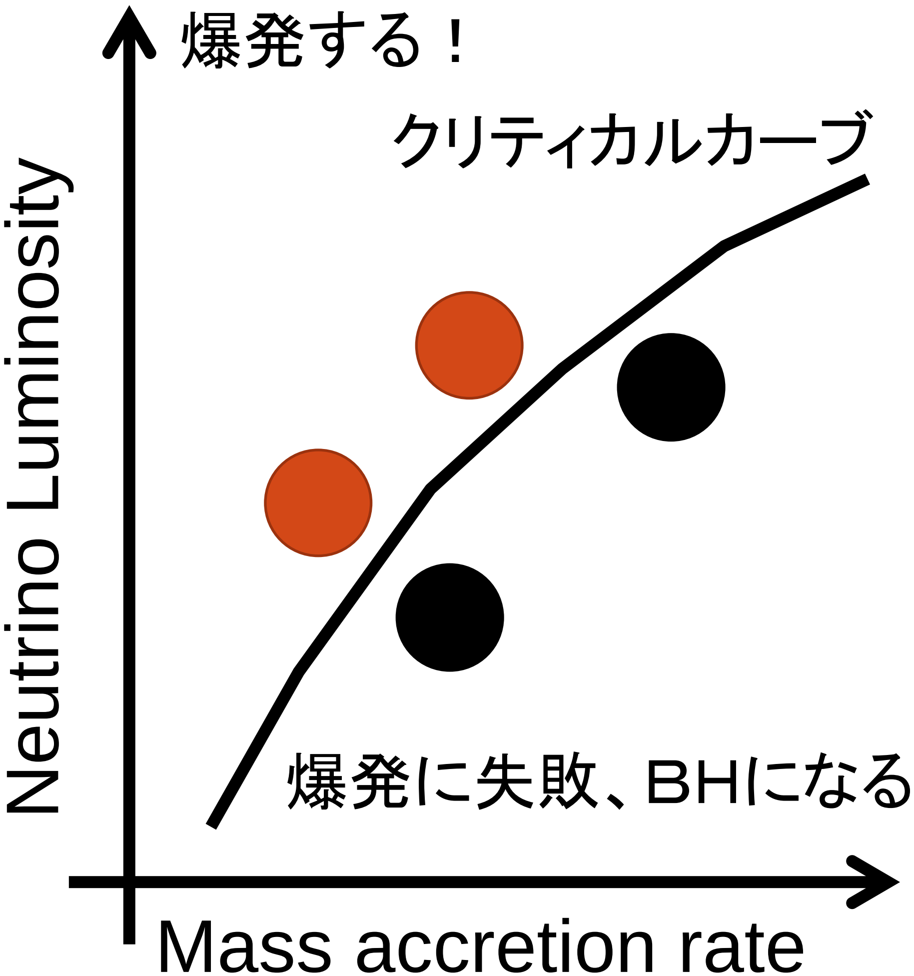


青：重い星（質量降着率が高い）

赤：軽い星（質量降着率が低い）

ルミノシティから質量降着率の情報を得る。

Mass accretion vs neutrino heating



（1）観測のイベント数をニュートリノ光度に焼きなおす
（2）得られたニュートリノ光度とシミュレーション結果のカタログを比較して、似た親星のデータを選び出す。
（3）爆発した（しなかった）星の質量降着率とルミノシティの情報が分かり、観測からクリティカルカーブの情報を得ることができる。

概念は上記の通り、だが変数選び等では、まだ改善の余地がある。

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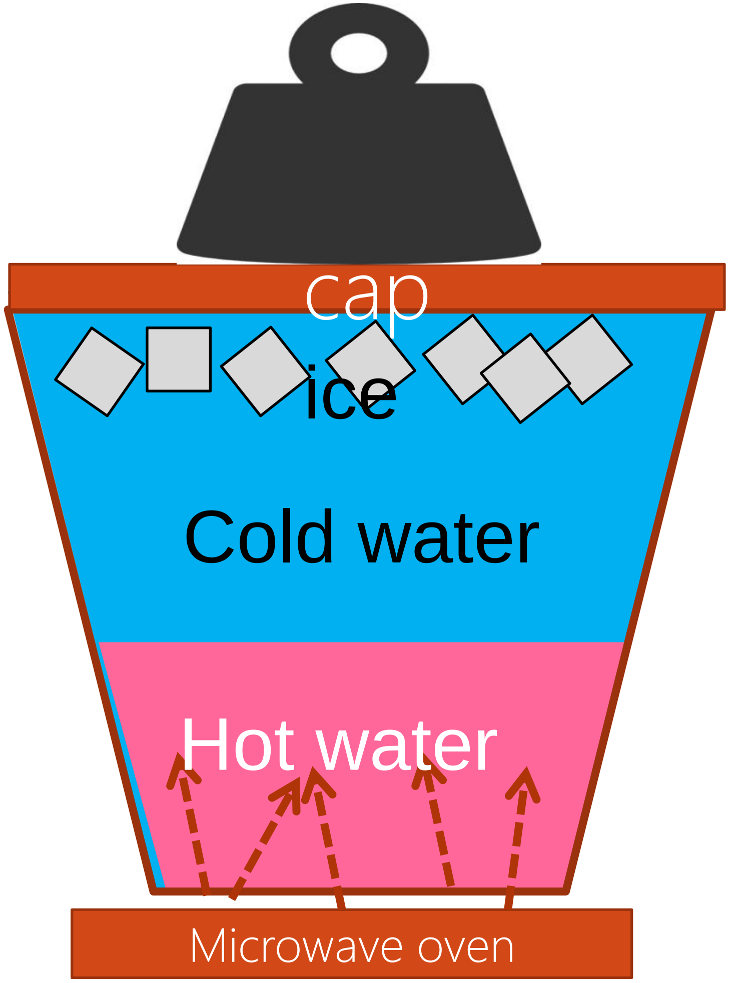
Typical 1D simulation

Problem

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



Long-lasting Problem ~1980.

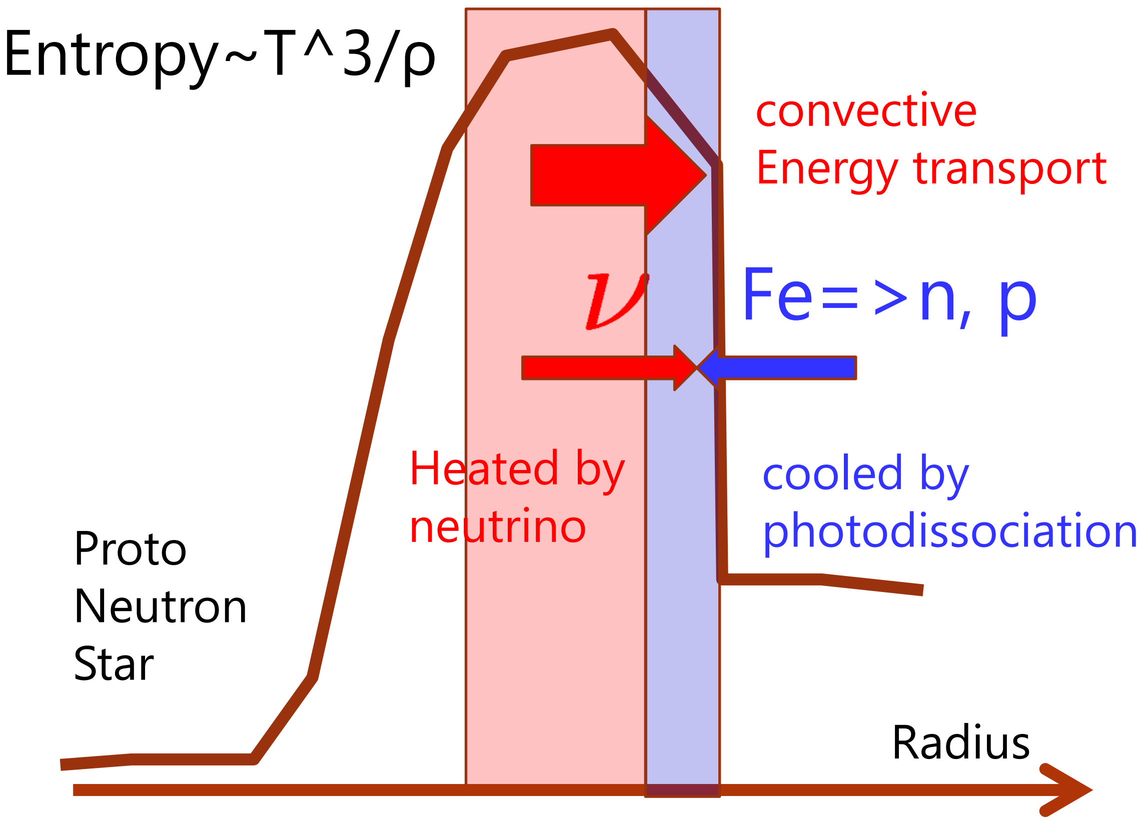
In 2000-2005, state-of-the-art simulations with detailed neutrino transport confirm that!

(Liebendoerfer+2001, Rampp+2002, Thompson+2003 and Sumiyoshi+2005)

(in 1D)Neutrino heating < ram pressure
=> fails to explode!

From 1D to 3D

Key aspects of Neutrino Mechanism

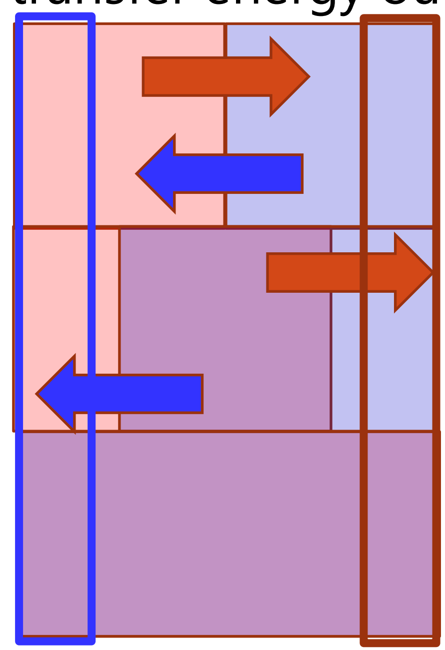


Negative entropy gradient leads Rayleigh-Taylor instability

(Cold heavy matter is put over Hot light matter)

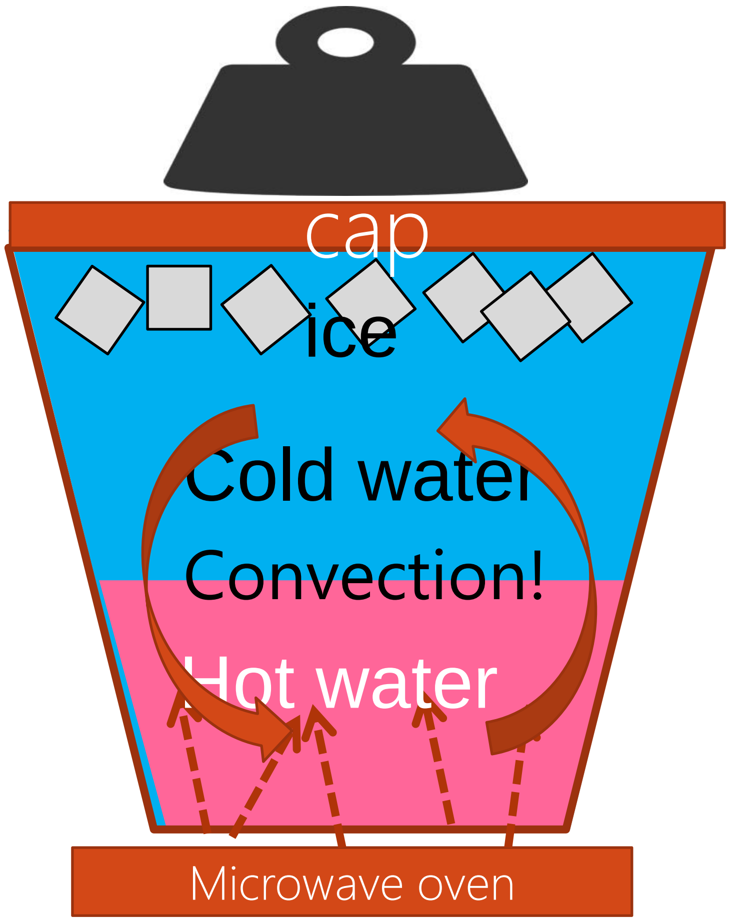
Rayleigh-Taylor convection transfer energy outward.

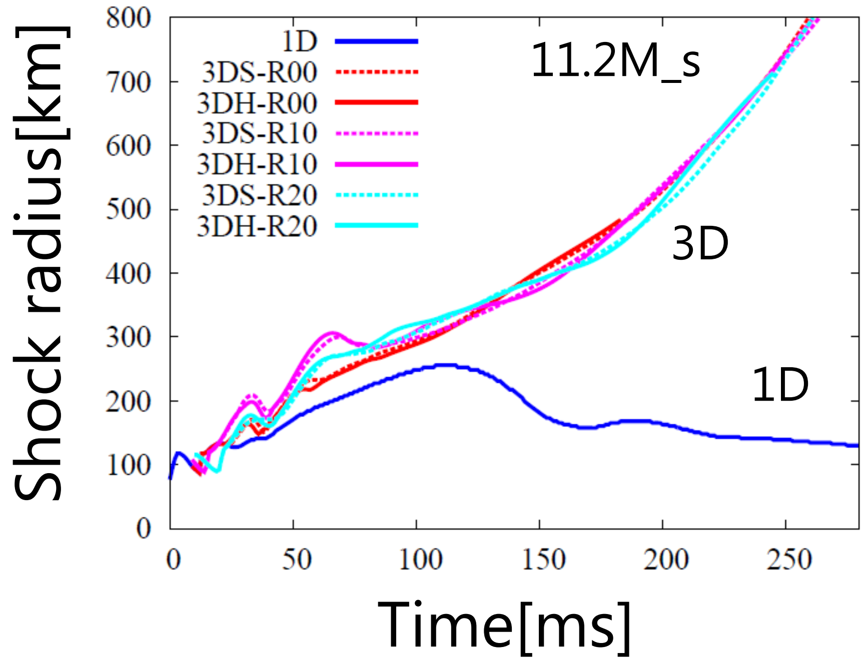
Cooler than the initial state but ν heat is active



Hotter than the initial state

Successful 3D simulation



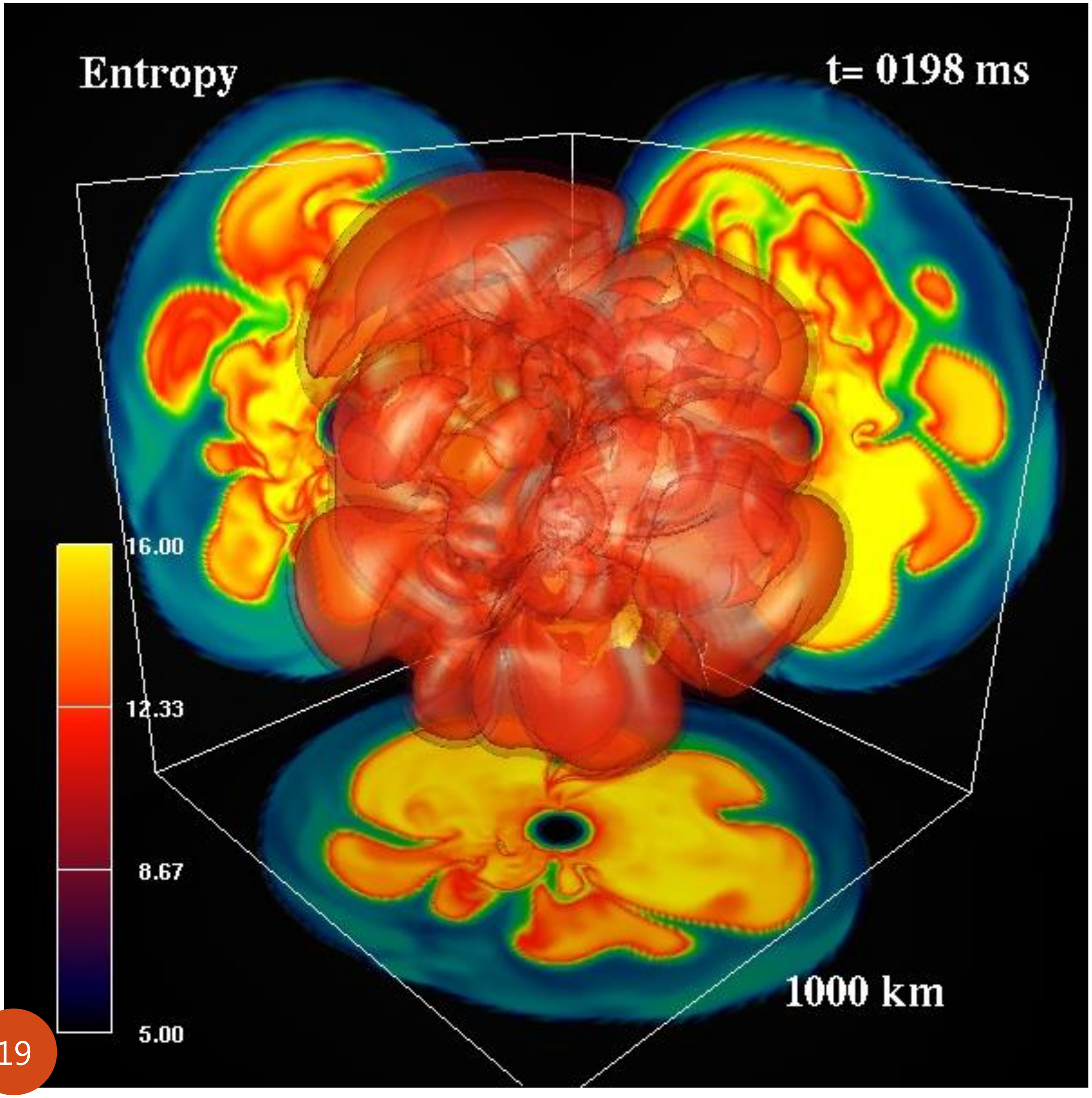


2 month times 16,000 cores are used in K computer

With convection hot water at the bottom is transported near the cap. The pressure at the cap become higher. Explosion occurs with the process.

Takiwaki+2012,2014, in prep

Shape of the explosion？

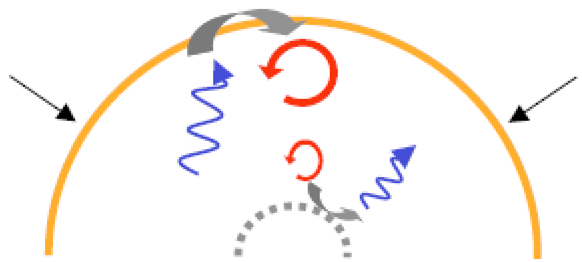


Many hot bubble is observed.

That is evidence of strong convection.

S A S I
(Standing Accretion Shock Instability)

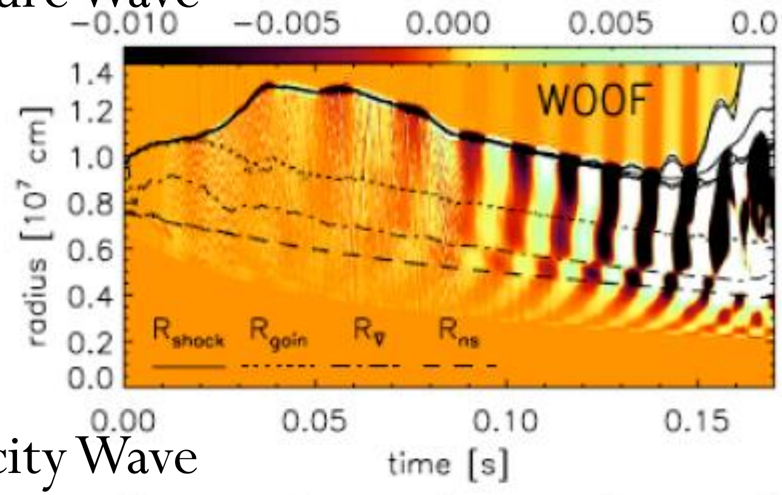
Scheck+ 2008



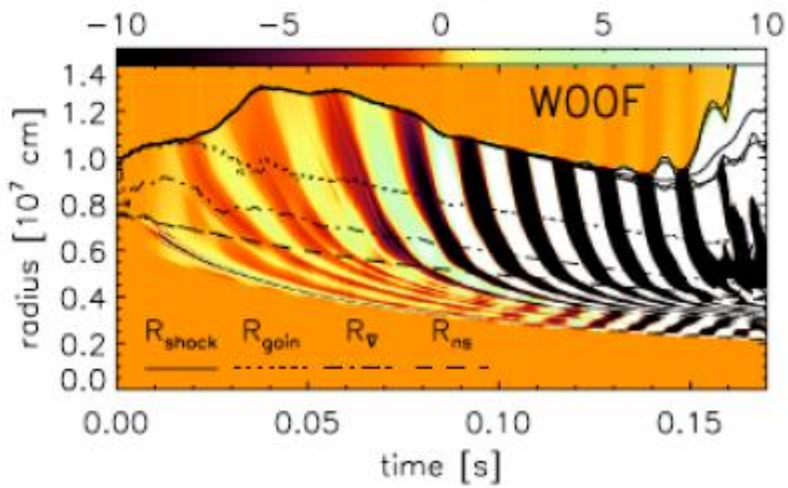
Advective-acoustic cycle

From Foglizzo's slides

Pressure Wave

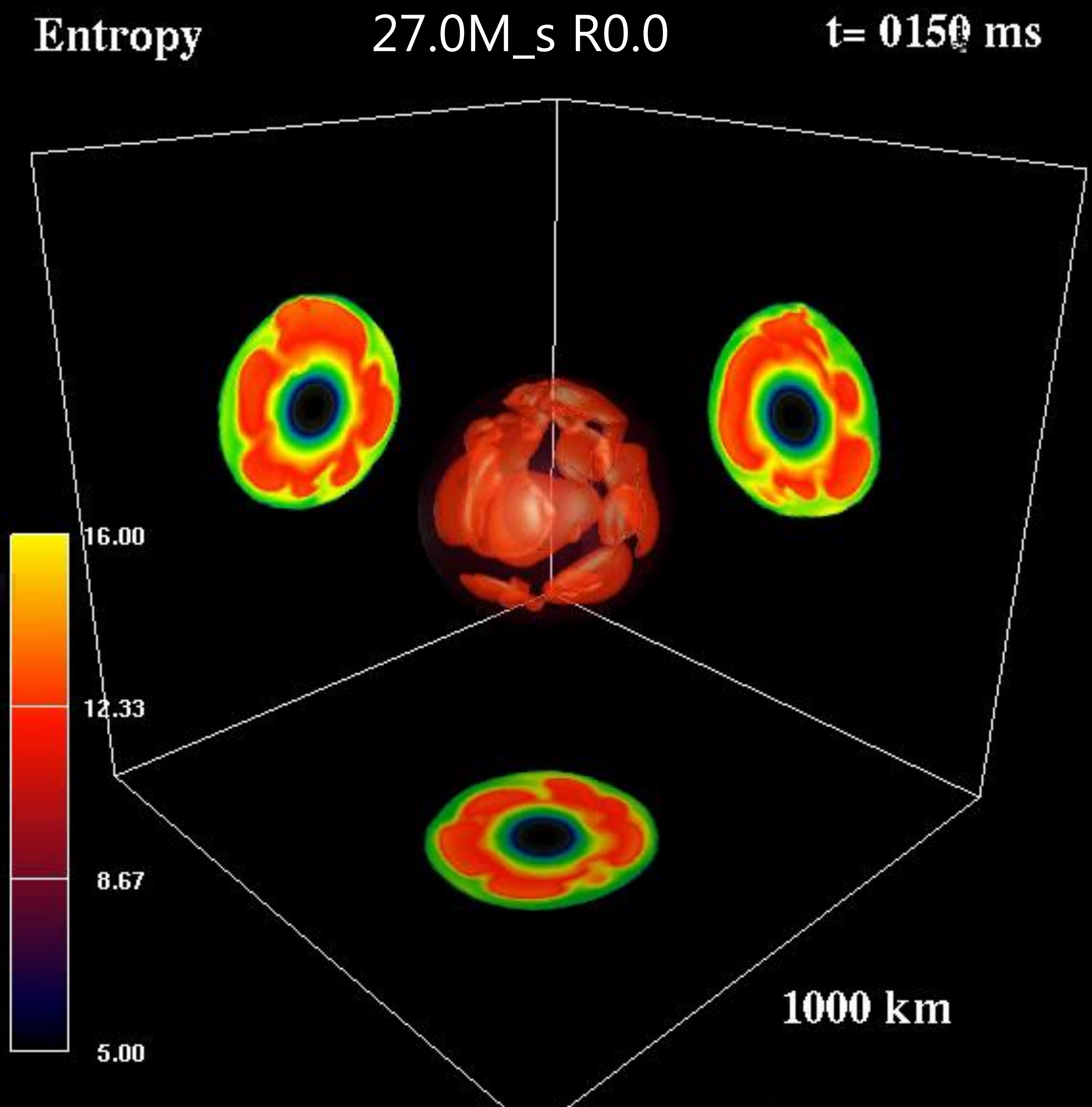


Vorticity Wave



Standing Accretion Shock Instability(SASI)

27.0M_s R0.0



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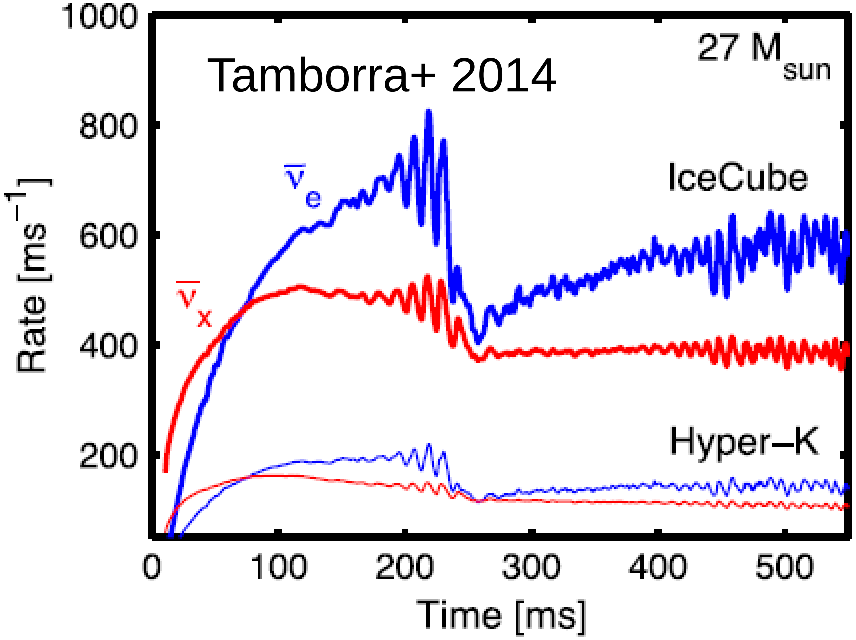
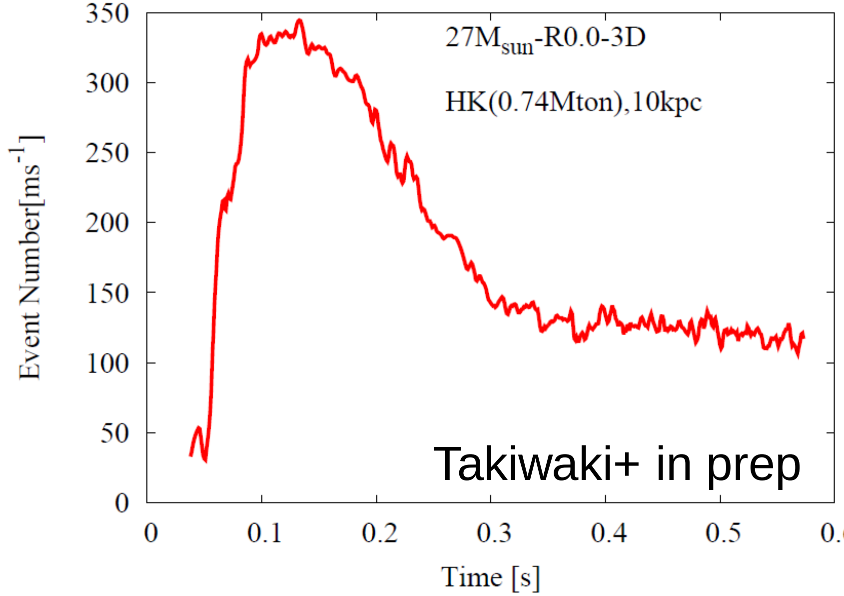
Neutrino signals from no-rotating model

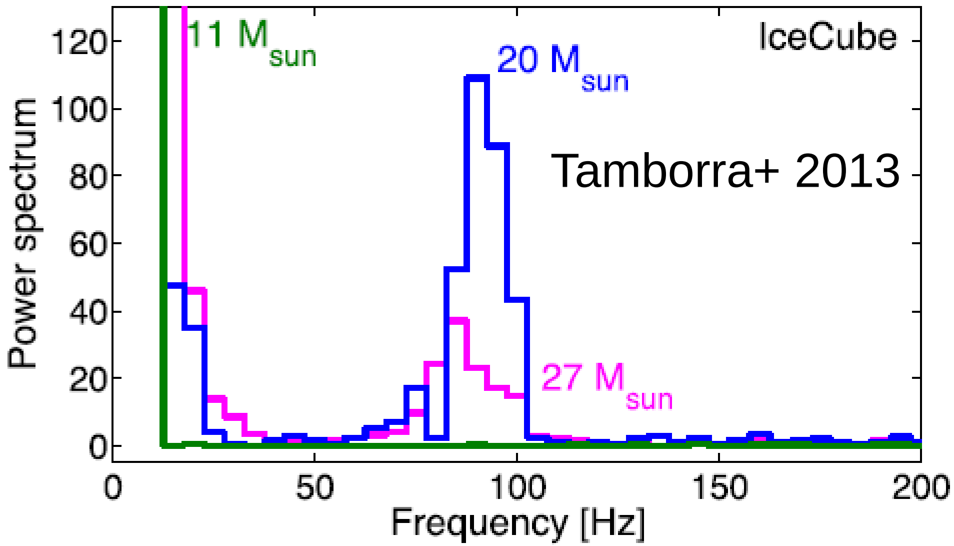




SASIによる揺れがニュートリノ観測に現れる。

SASIの強さと見る方向によってはうまく見れない可能性も。

Efficient technique for extracting feature of the signal



周波数空間でみると特徴がはっきりわかる。

⇒SASIの証拠

⇒爆発メカニズムがかなり特定できる。

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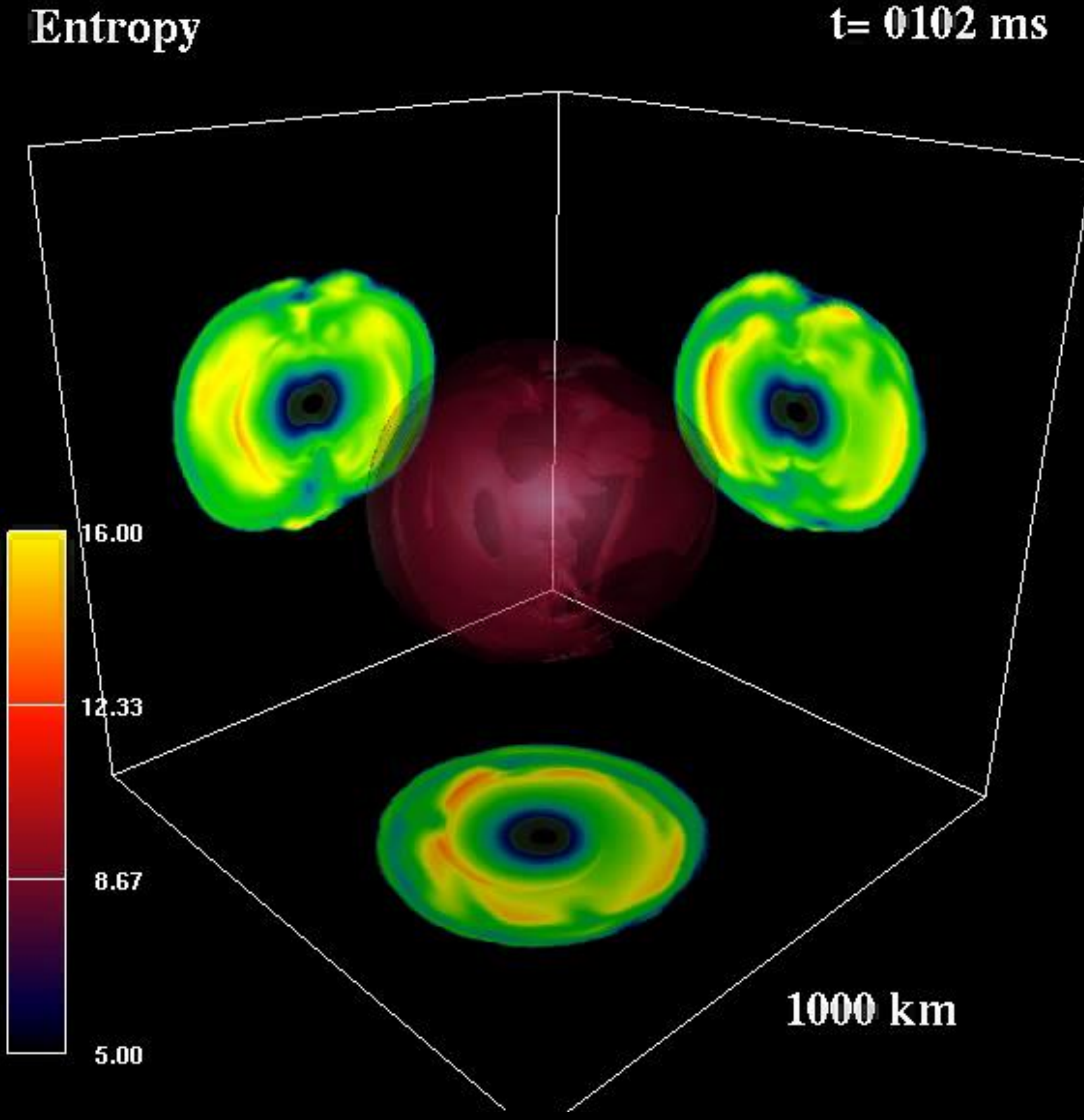
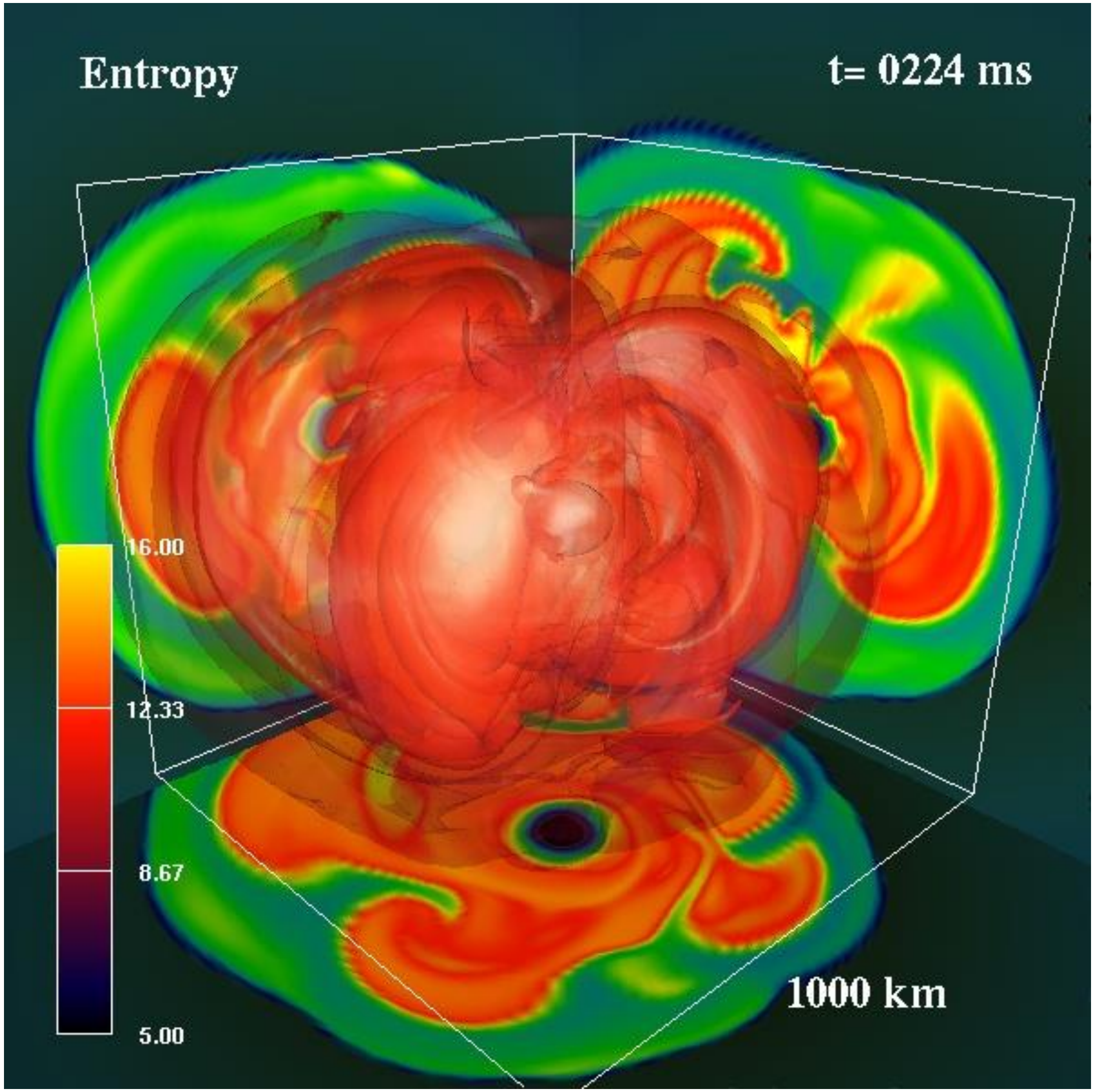
3D model with rotation

27.0M_s R2.0



Rotational Explosion

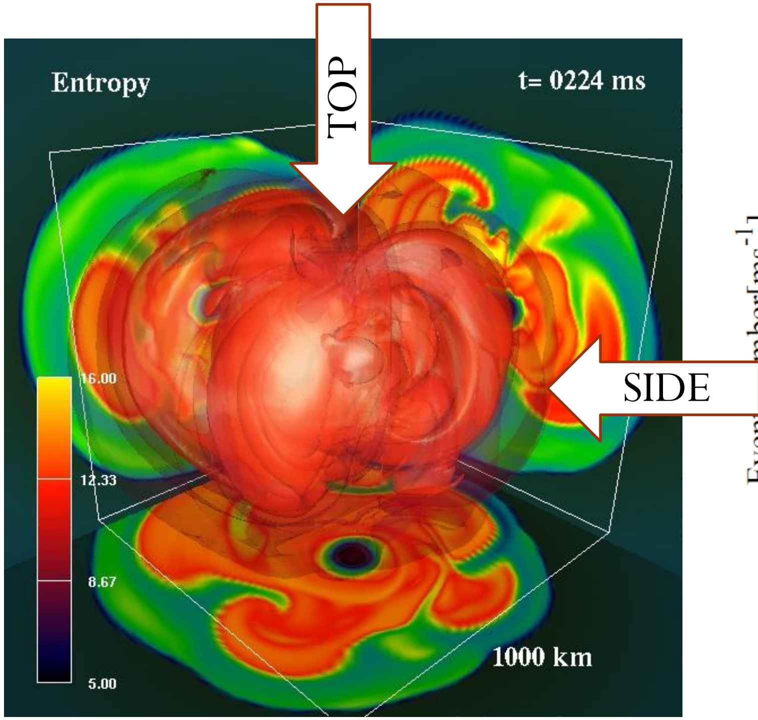


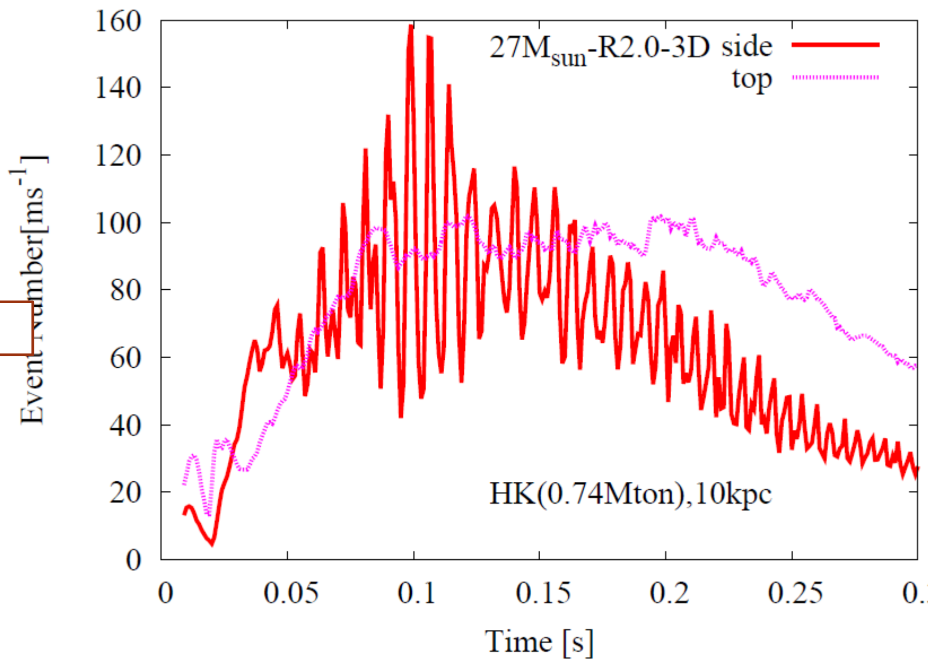
Strong expansion is found at equatorial plane

Eexp~5x10^50erg

(see also Nakamura+14 and Iwakami+14)

Neutrino signals from rotating model





Takiwaki+ in prep

Period of spiral mode is extracted by ν −signal

Summary & Future prospect

超新星の爆発メカニズムを解明するためには以下の2つが重要。

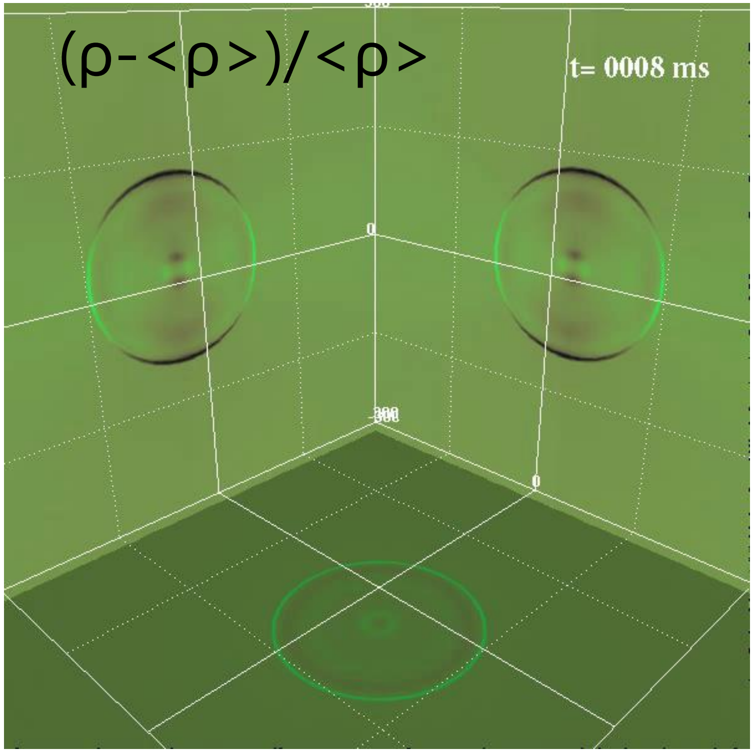
(1)爆発がルミノシティ―質量降着率の平面のどこにくるのか特定する。

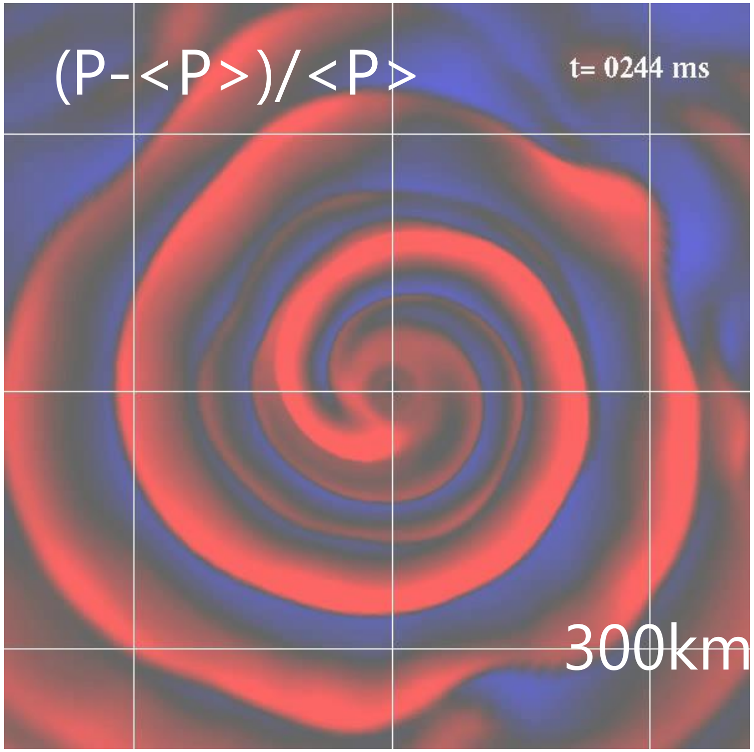
(2)ルミノシティの時間変動を解析し、SASIの周波数(or 回転周波数)のところにピークがあるか調べる。

(1)の精度をよくするためには、電子タイプνシグナルの情報やエネルギーの情報を使うと良い。ν振動の効果も踏まえる。

(2)は今のところIce cubeが有利そうではあるが、他の検出器も使うことで何か分からないか、検討をする。

Spiral Mode



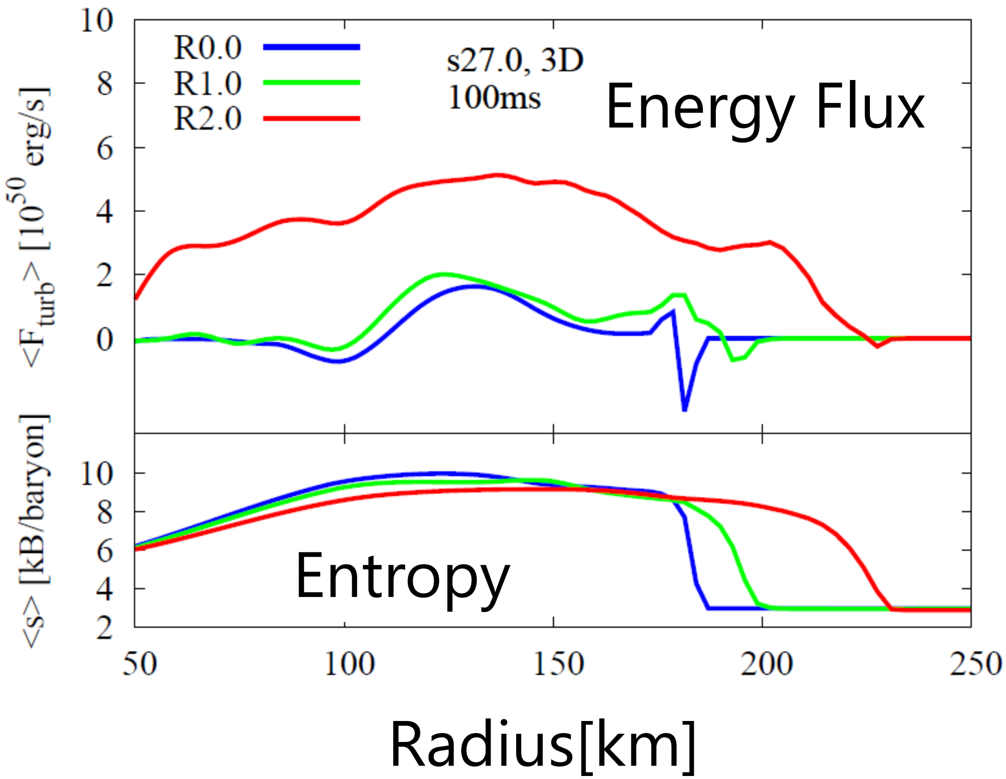


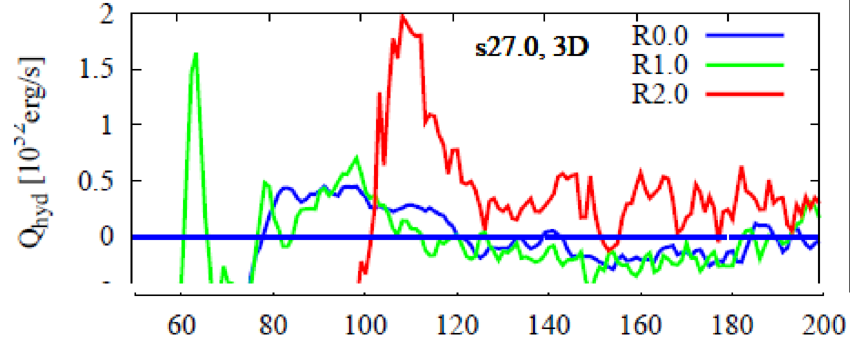
Rotational energy(T)/gravitational energy(W) reach some criteria => Spiral mode arises

In the rigid ball: 14%

In SNe case: ~ 6% (Called low-T/W instability)

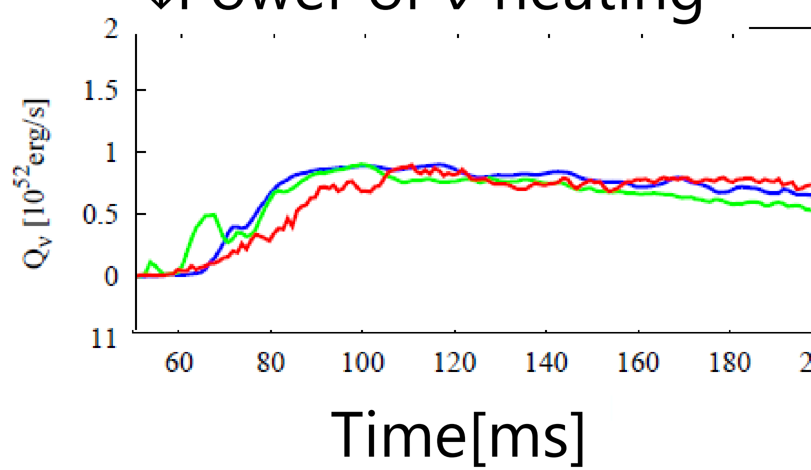
Energy Transport by spiral mode





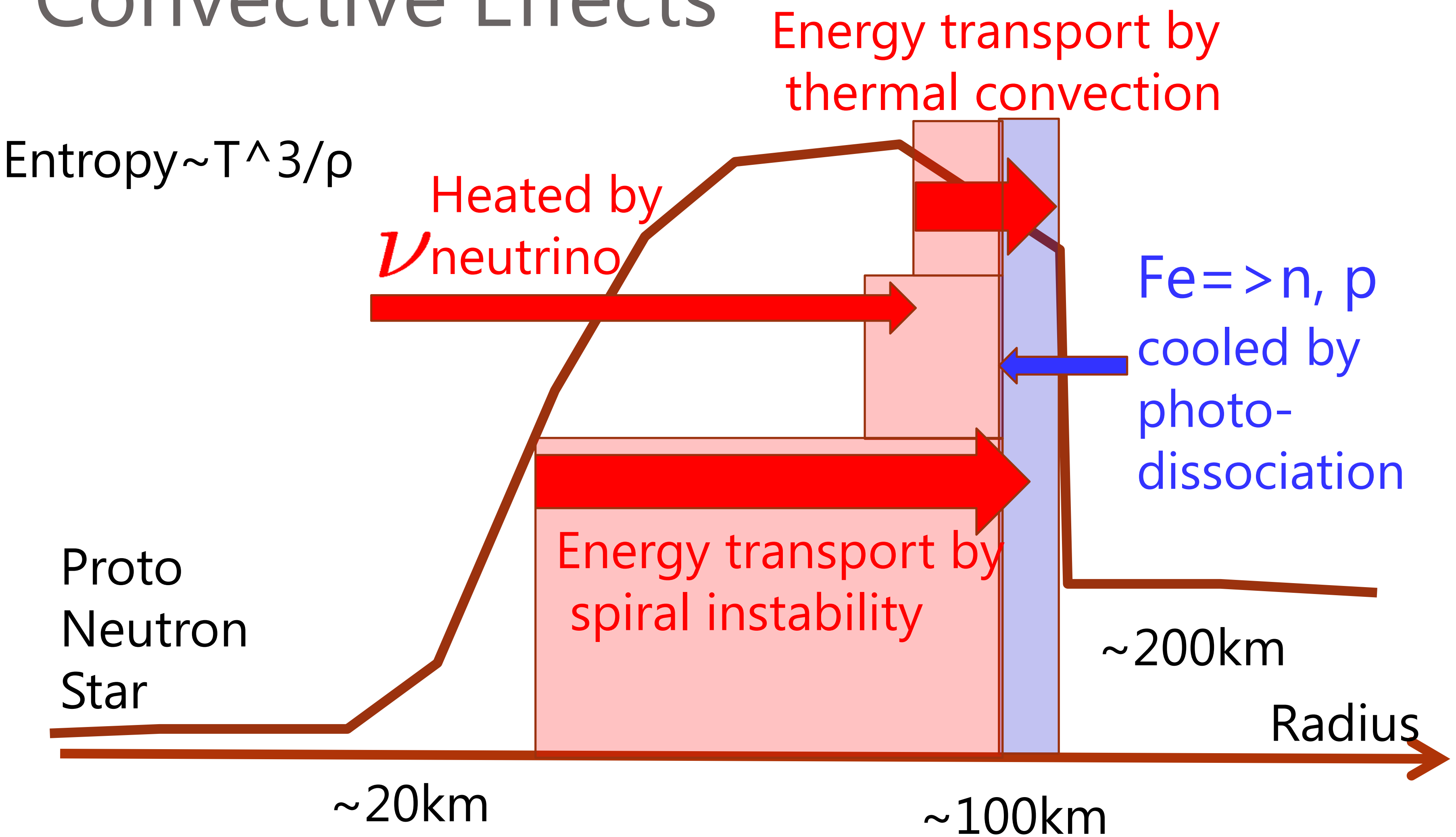
↑Power of spiral mode

↓Power of ν heating



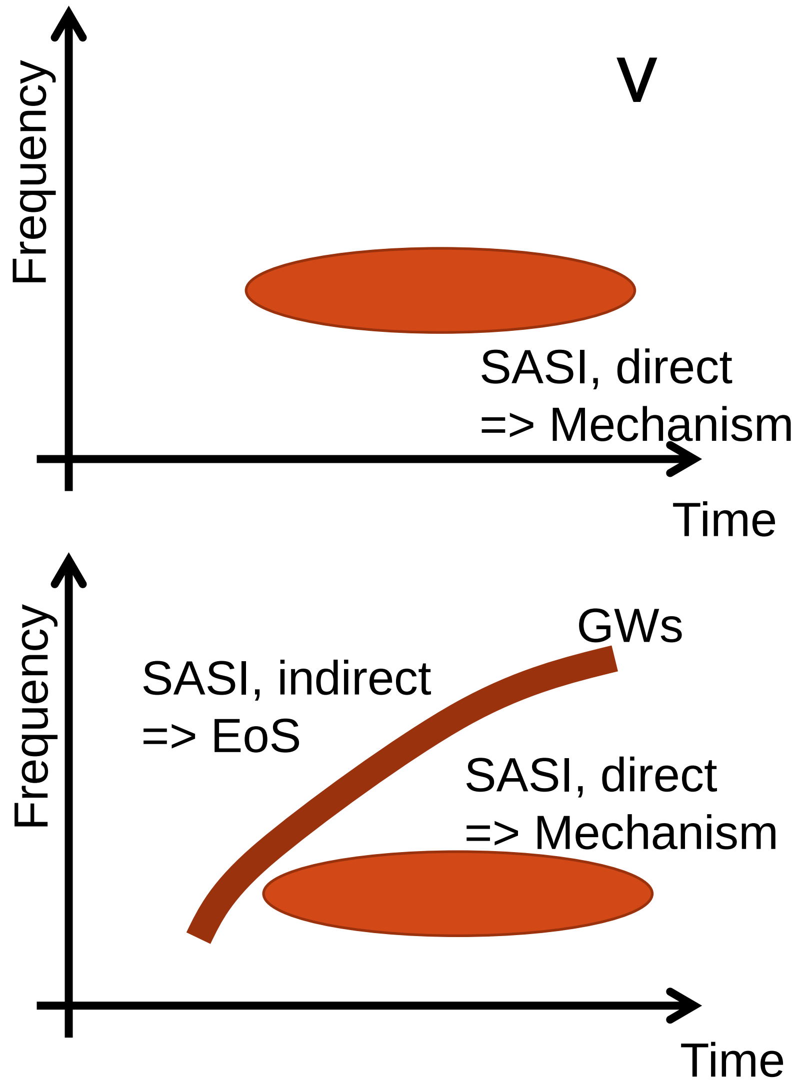
Strong positive energy flux emerges in rotating model.
The power of that is comparable to ν −heating.

Convective Effects

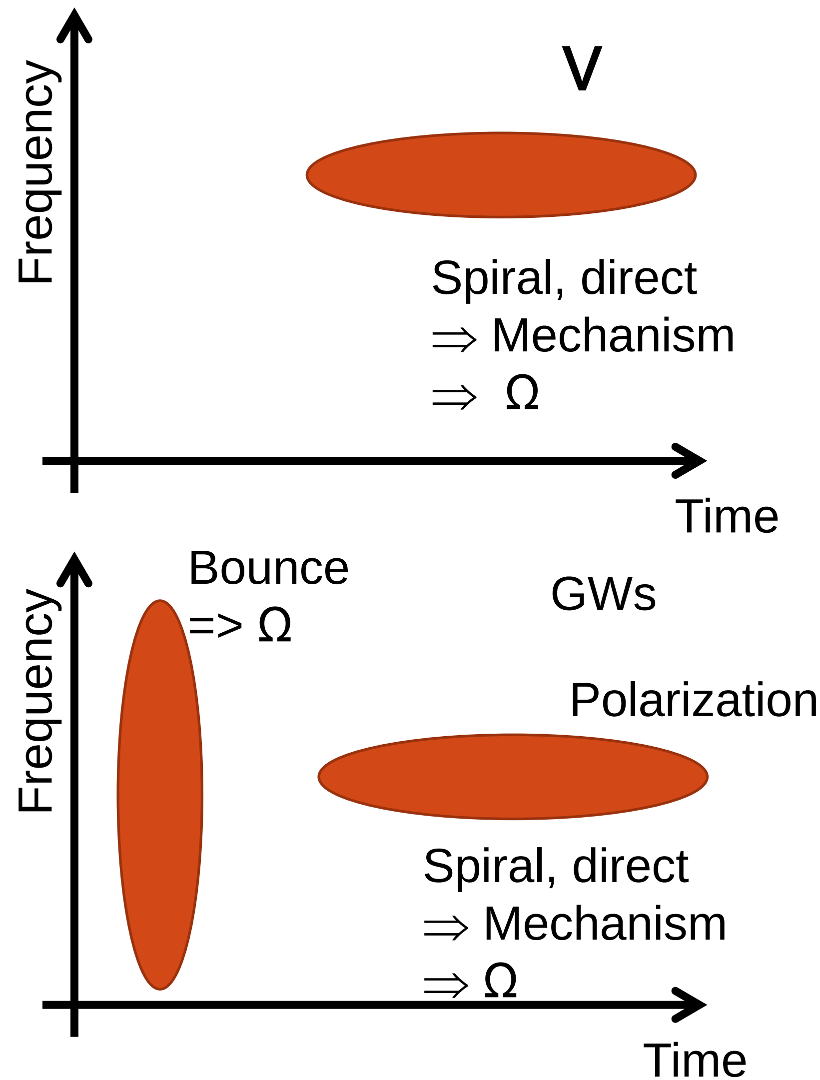


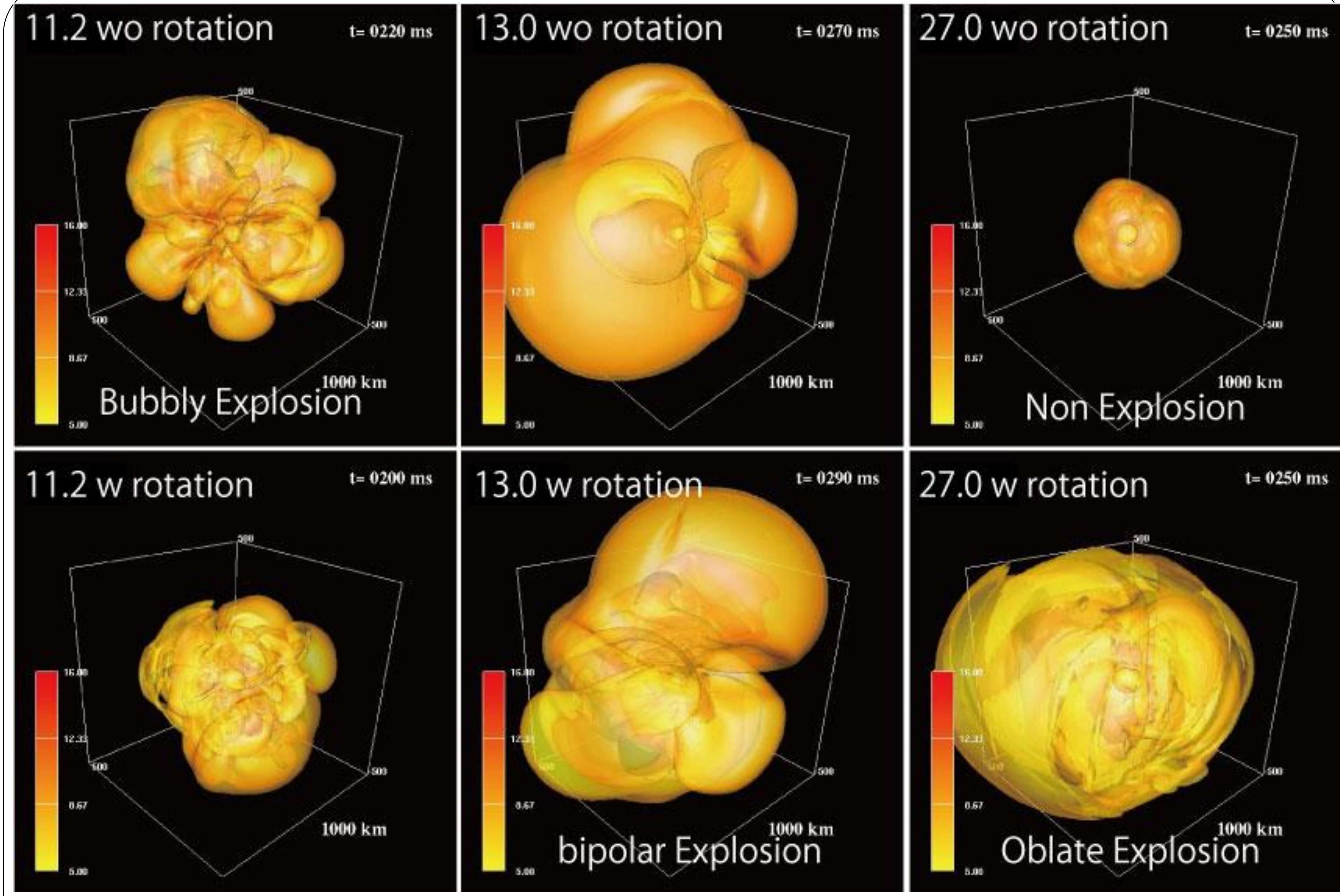
What will be found by ν and GW.

Non rotating

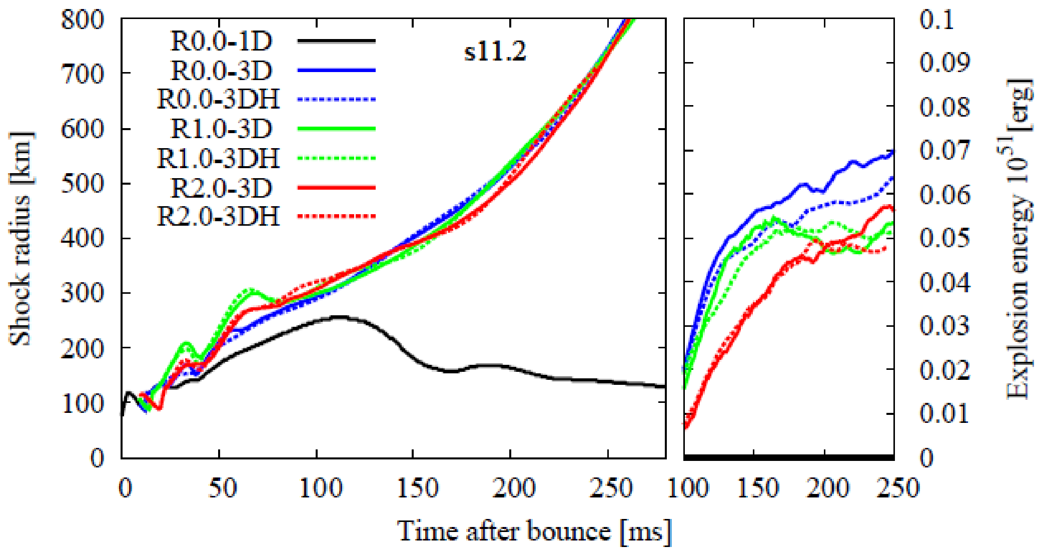


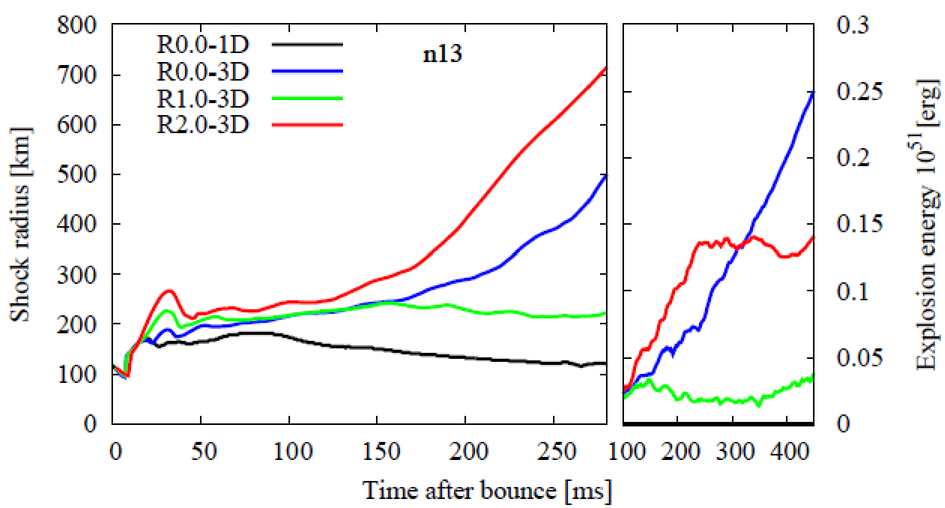
rotating

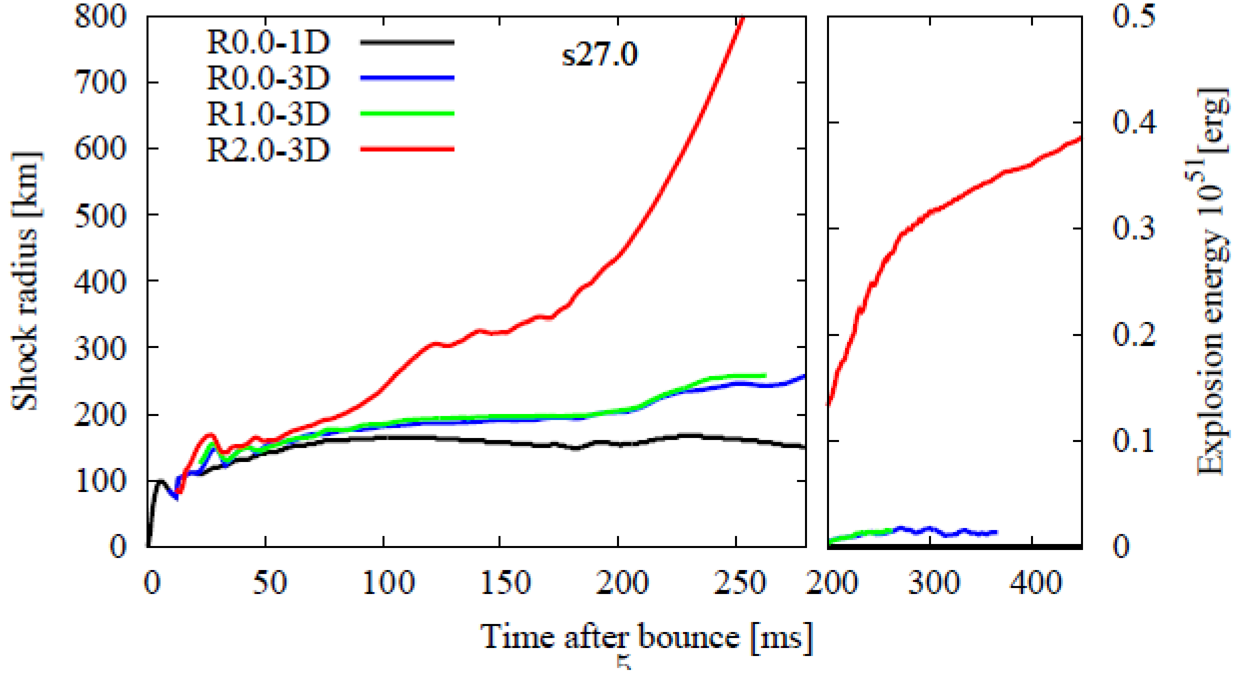



11.2 wo rotation
t= 0220 ms
1000 km
Bubbly Explosion
13.0 wo rotation
t= 0270 ms
1000 km
27.0 wo rotation
t= 0250 ms
1000 km
Non Explosion
11.2 w rotation
t= 0200 ms
1000 km
13.0 w rotation
t= 0290 ms
1000 km
bipolar Explosion
27.0 w rotation
t= 0250 ms
1000 km
Oblate Explosion

Averaged shock radius and Exp. Energy

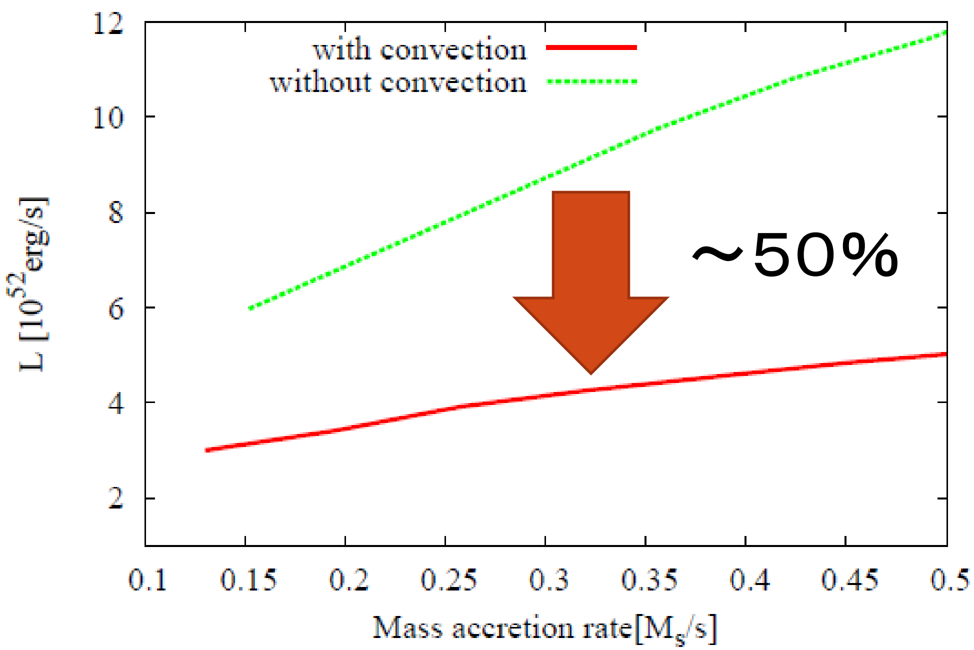




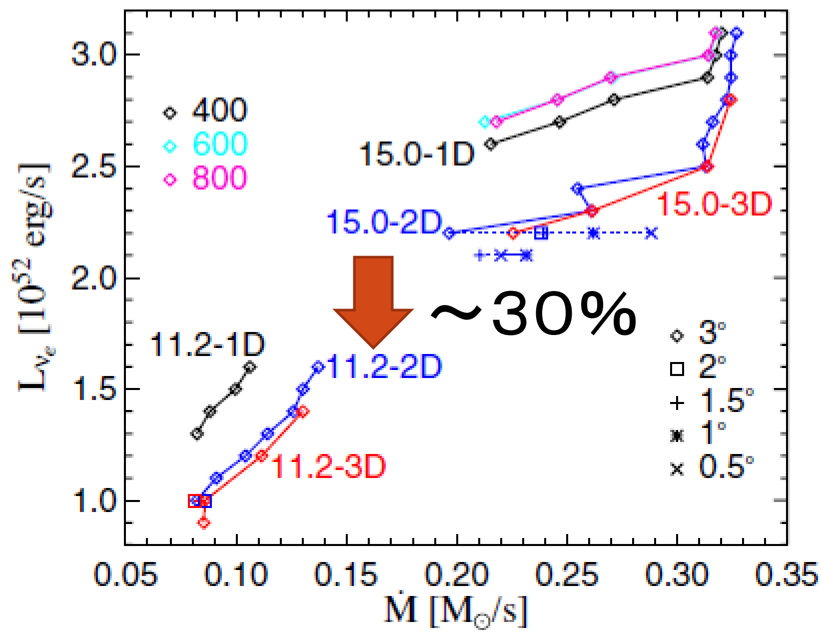


s27.0
R0.0-1D
R0.0-3D
R1.0-3D
R2.0-3D
Shock radius [km]
Explosion energy 10^{51}[erg]
Time after bounce [ms]

Quantitative estimation of convective effect



Yamasaki+ 2006



Hanke+2012

Convection reduces critical luminosity by 50%.

Toward making convincing model

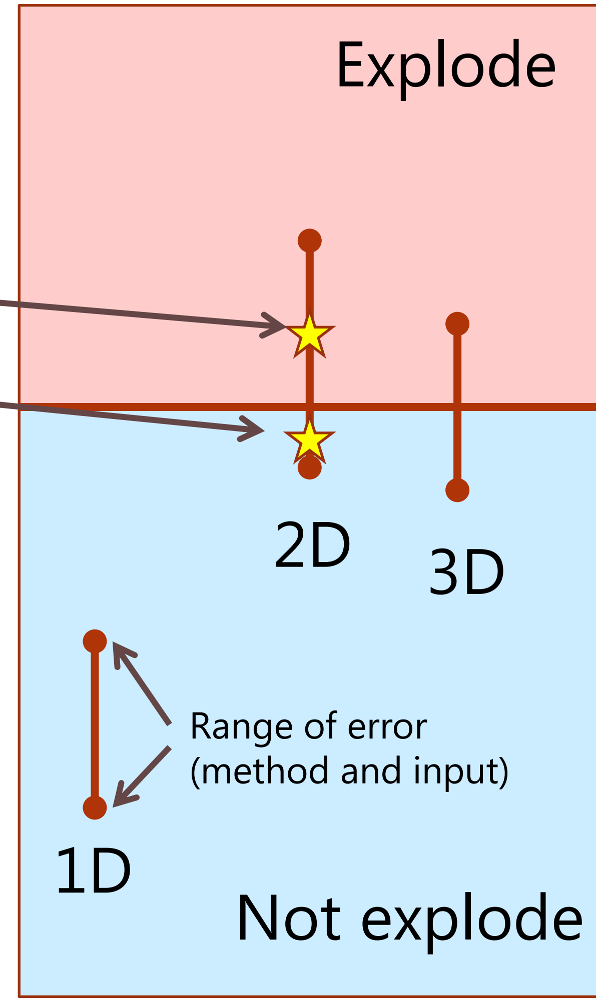
Multi-D model is very delicate that depends on input physics and methods strongly!

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

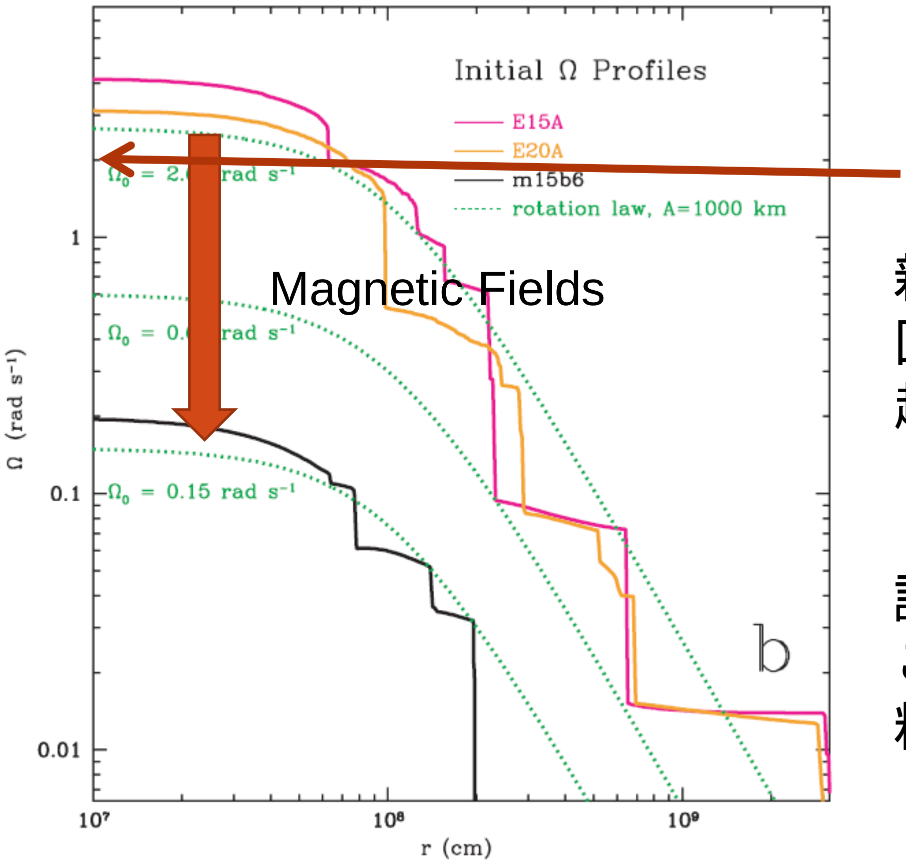
3D models for multiple progenitors

- Hanke in prep : not explode(3model)
- Takiwaki in prep : half of them explode (failed in heavier progenitor)



It's urgent to brush up the numerical and physical methods.

Rotation rate before the collapse



Our model of rapid rotation

Ott+ 2006

親星の進化計算で磁場をいれると、
回転速度は非常に下がる。
超新星コアは速く自転してはいけない?

議論：
この磁場の入れ方には不定性がある。
精密理論ではない。

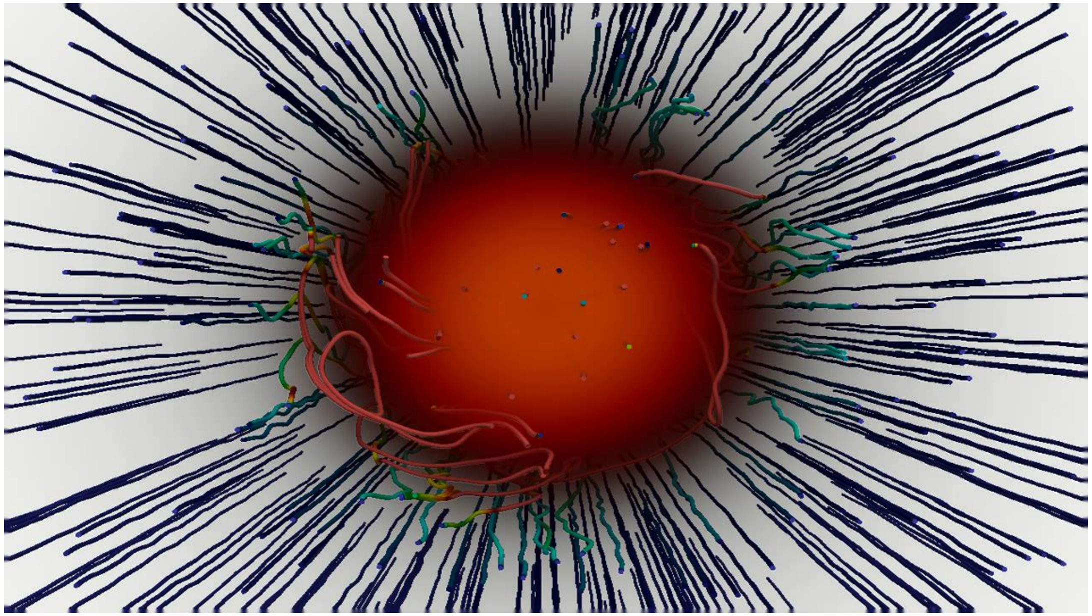
Rotation rate after the collapse

S27-R2.0 => 2000 rad/s@400ms after bounce

Initial period of pulsar~10ms => 100 rad/s
Fastest pulsar ~ 16ms
Club 19 ms

Ott+ 2006

Effect of Magnetic field



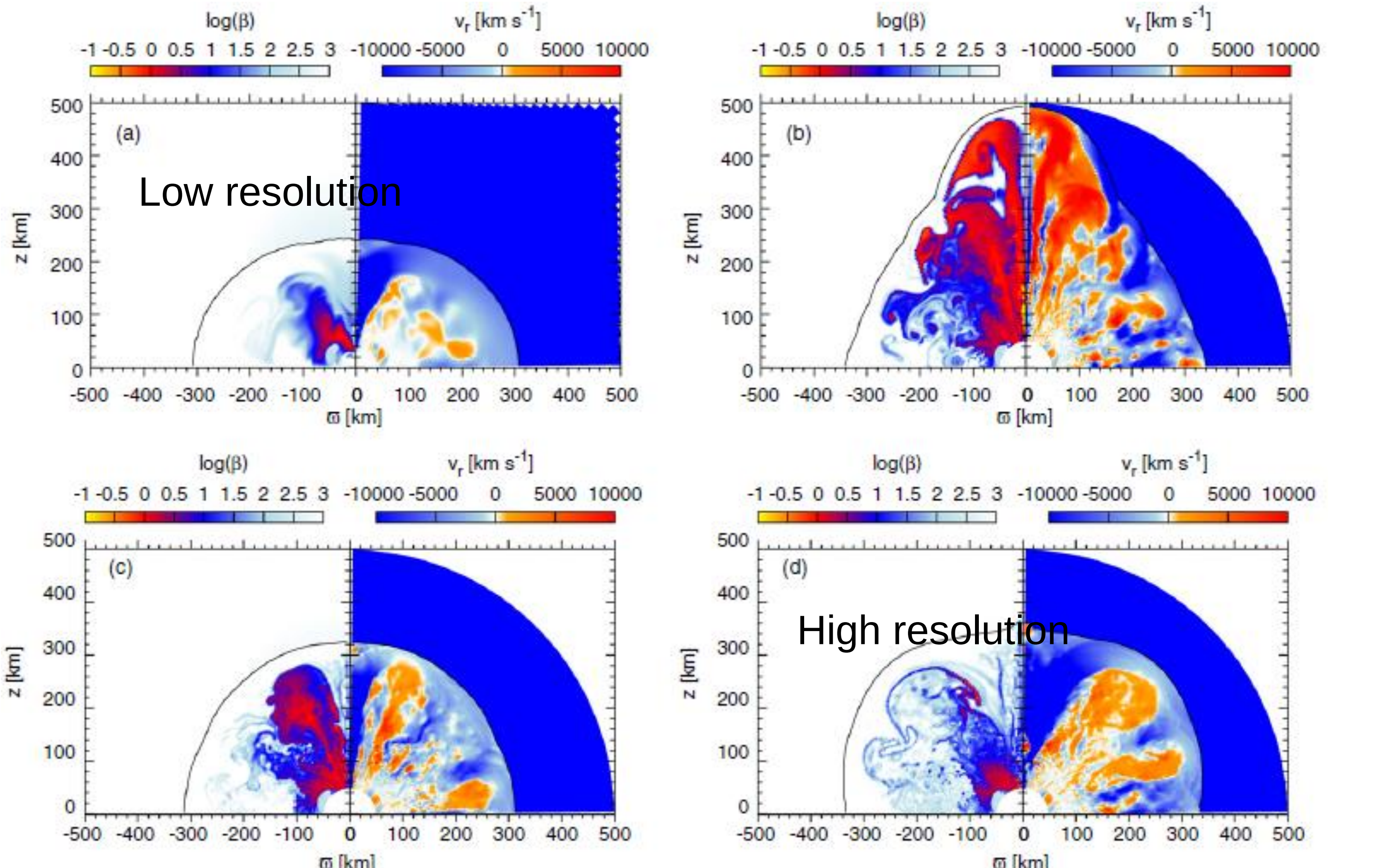
Masada+ 2014

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光度が上がったり、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

MRI+ν-heating

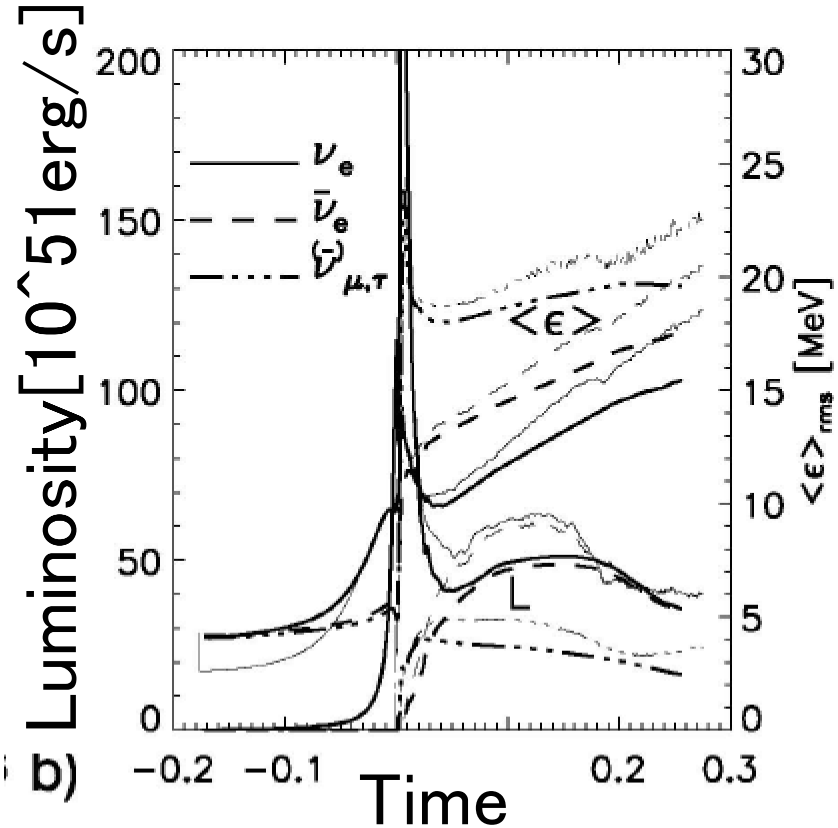


Sawai+ 2014

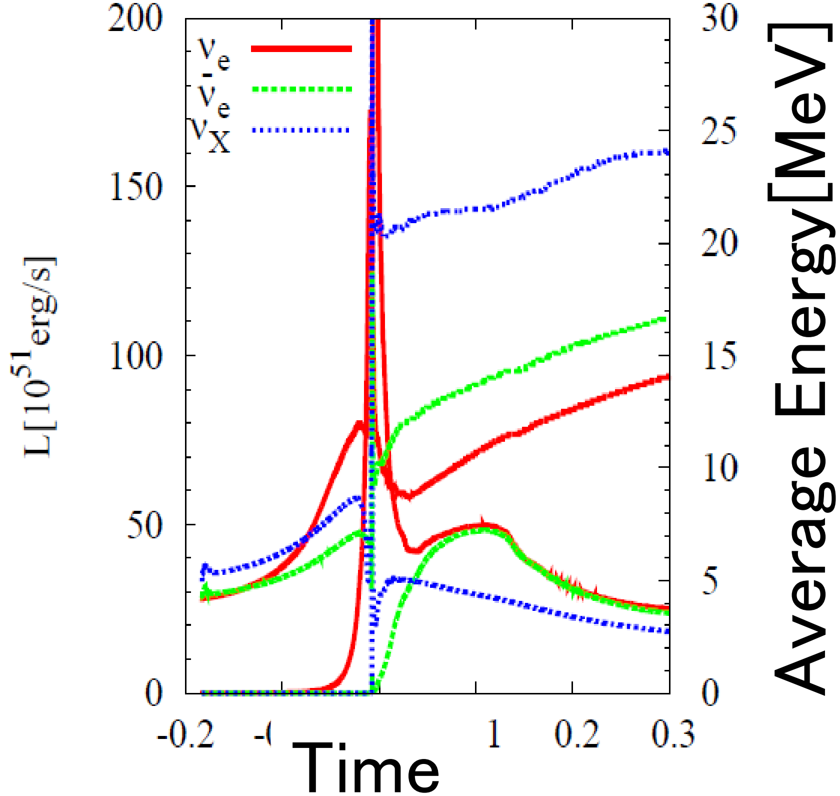
Strong convection arise by MRI

Angular momentum is transported

ルミノシティとエネルギー



Liebendoerfer et al 2005



Our newest version of IDSA

Sn and VE

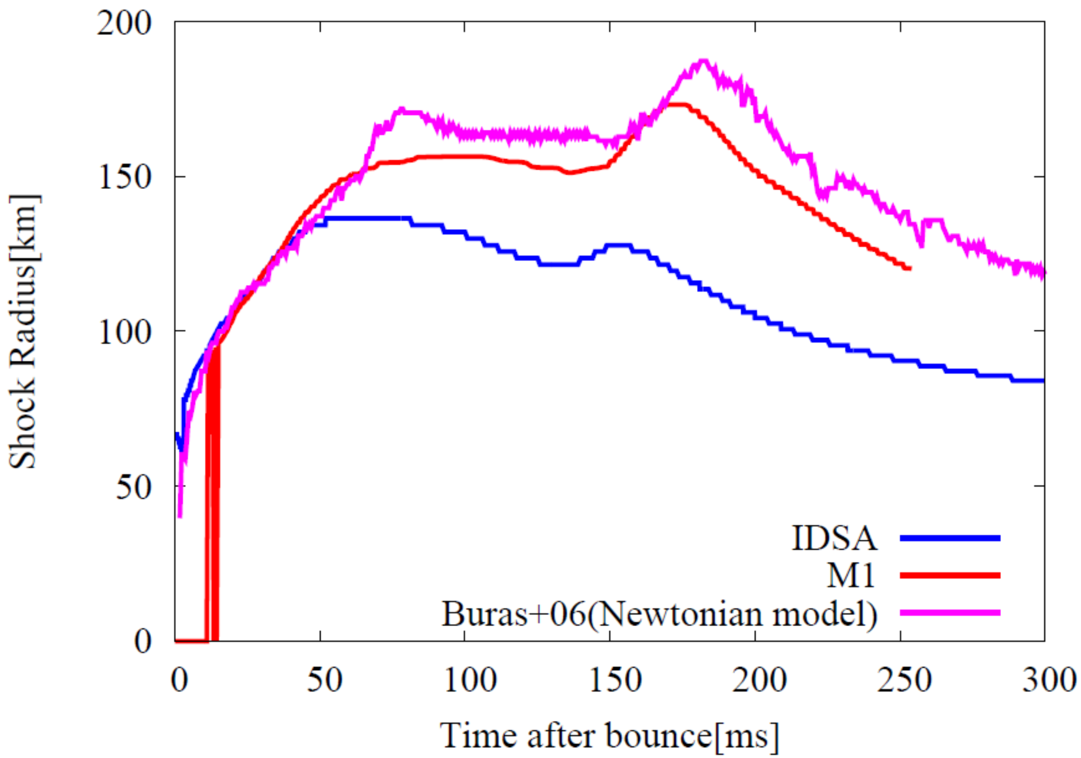
General relativistic simulation

ecp,aecp,eca,csc,nsc,pap,nes,nbr

Newtonian Gravity

Roughly consistent!

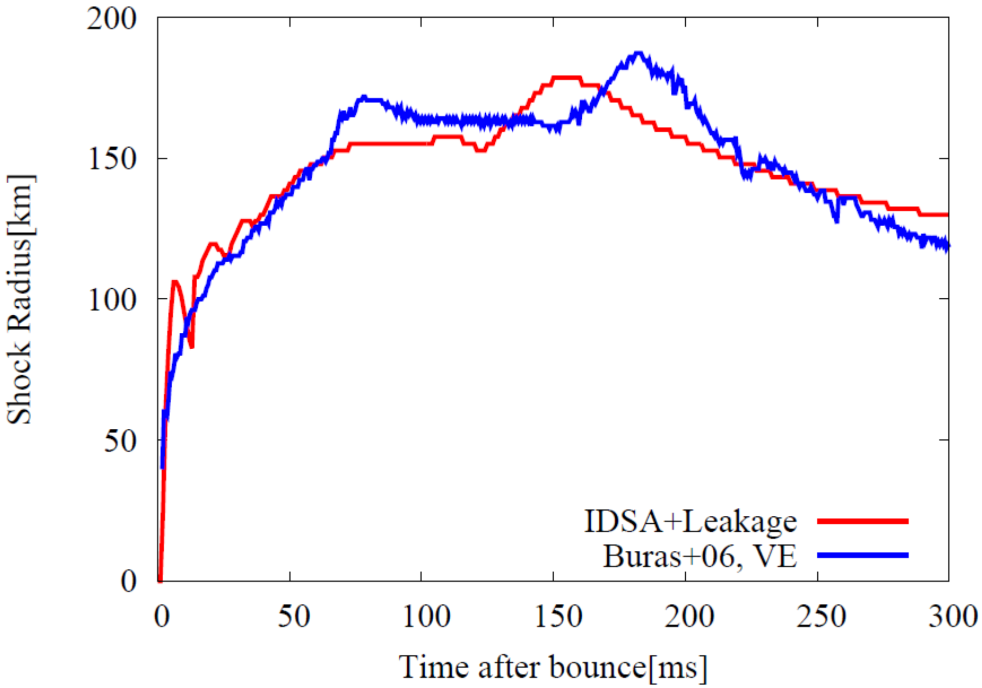
衝撃波半径の比較



VE ＞ M1 ＞ IDSA

The exact flux factor is smaller than approximate flux facor?

Detailed comparison



Comparison between Buras+06(Newtonian) and IDSA

Plot is obtained by digital curve tracer

Similar results is obtained by cancelation of positive and negative effect.

＋: NES is not included in IDSA

－： Flux factor is larger for IDSA, heating rate is small.

Oscillation Method

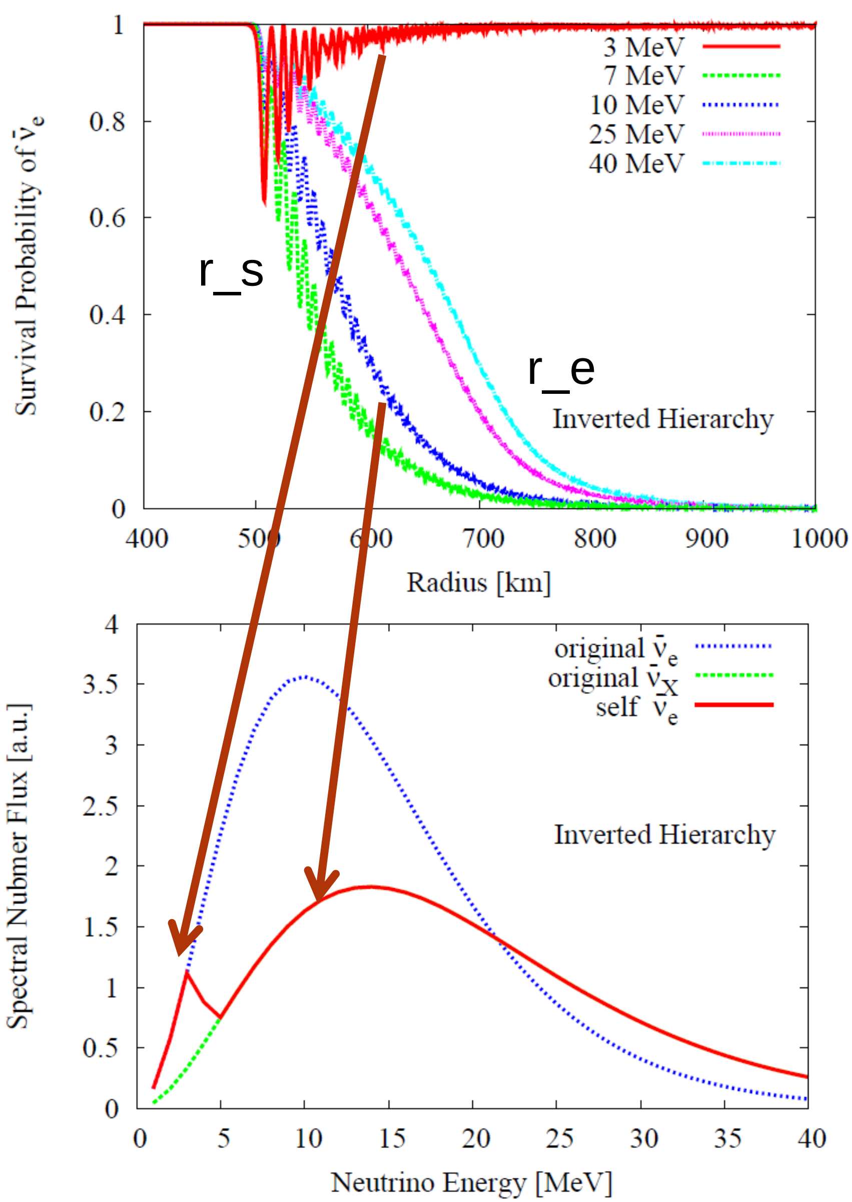
Based on Dasgupta 2010

Features

1. Both collective and MSW effects
   for collective effect single angle approximation is used
2. Three flavor
3. Parameters are tuned to recent experiments

$\sin^2 2\theta_{13} = 0.84$
$\sin^2 2\theta_{12} = 1.0$
$\sin^2 2\theta_{13} = 0.29$
$\Delta m_{21}^2 = 7.6\text{d-}05$
$|\Delta m_{31}^2| = 2.5\text{d-}03$

Example of self-interaction



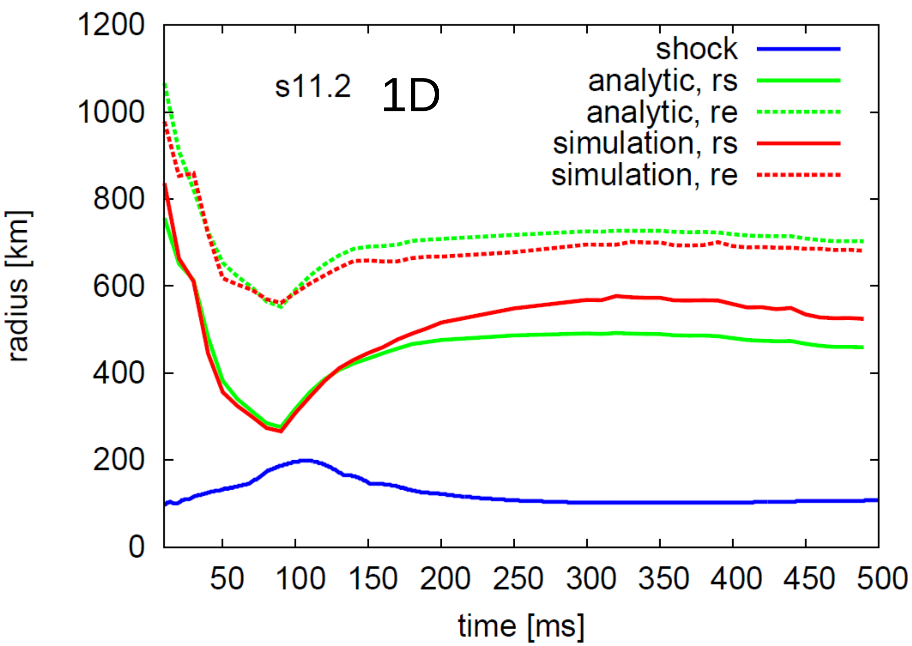
Inverted Hierarchy m_3 < m_1

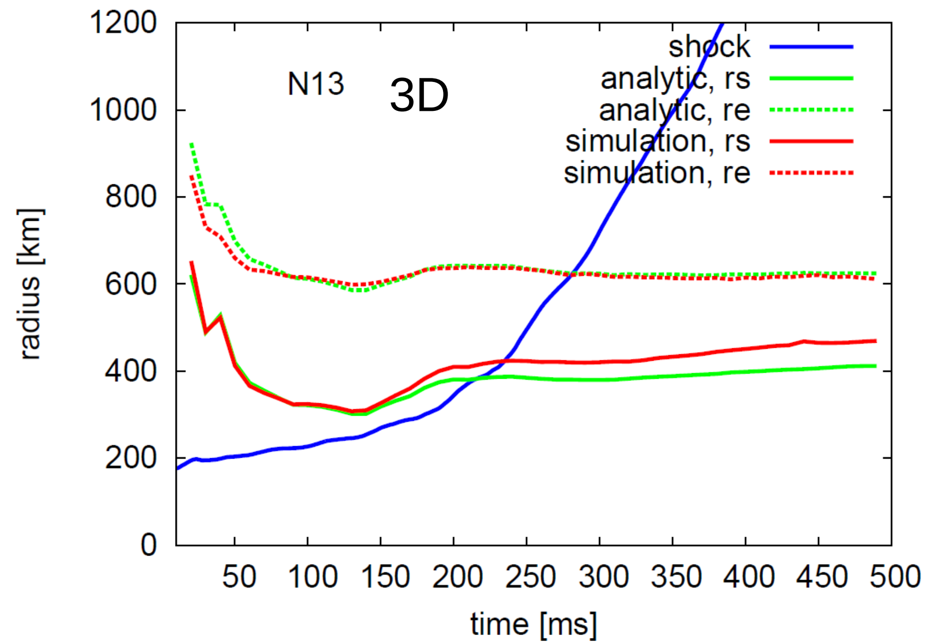
Low energy anti-electron neutrino survives.

High energy anti-electron neutrino is completely swapped by anti-v_X.

Radius for the swap (r_s, r_e) is rather consistent with the previous work.

Time Evolution

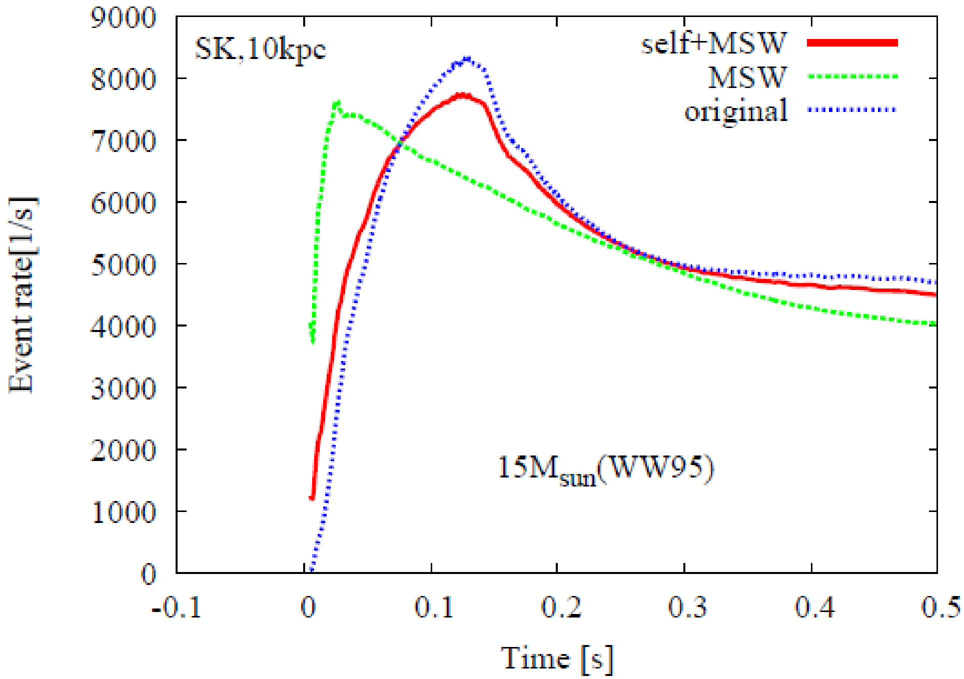




(r_s, r_e) are a little different for the progenitor.

In multi-D model, we found explosion and oscillation should affect to the shock at later phase.

Prediction for the ν observation in SK



Self: anti ν _e => anti− ν _X

MSW: anti− ν _X=> anti ν _e

Self+MSW = original anti− ν _e

(actually 7:3 mixture)