自転、磁場超新星の爆発シナリオ

(Current status of aspherical Type II supernovae models)

固武　慶

（早大理工）

in collaboration with

山田章一(早大理工）佐藤勝彦（東大理）

第17回「宇宙ニュートリノ」研究会 2005年6/29

Plan of my talk and timetable

Section 1　Introduction　(～3 min)

Section 2　Standard Supernova Physics（～ 7 min)

Section 3　Explosion Mechanism of Core-Collapse Supernovae　(～25min)

「Asymmetry & Explosion Mechanism」

Section 4 Gravitational Waves from anisotropic neutrino emissions in the supernova core

(~10 min)

Prospects

1.Introduction
(～5 min)

What are core-collapse supernovae？

Ancient Time

Meigetuki (明月記) by Sadaie Fujiwara (藤原定家)
(at the end of Heian epoch)

Several historical supernovae are known.

Modern time

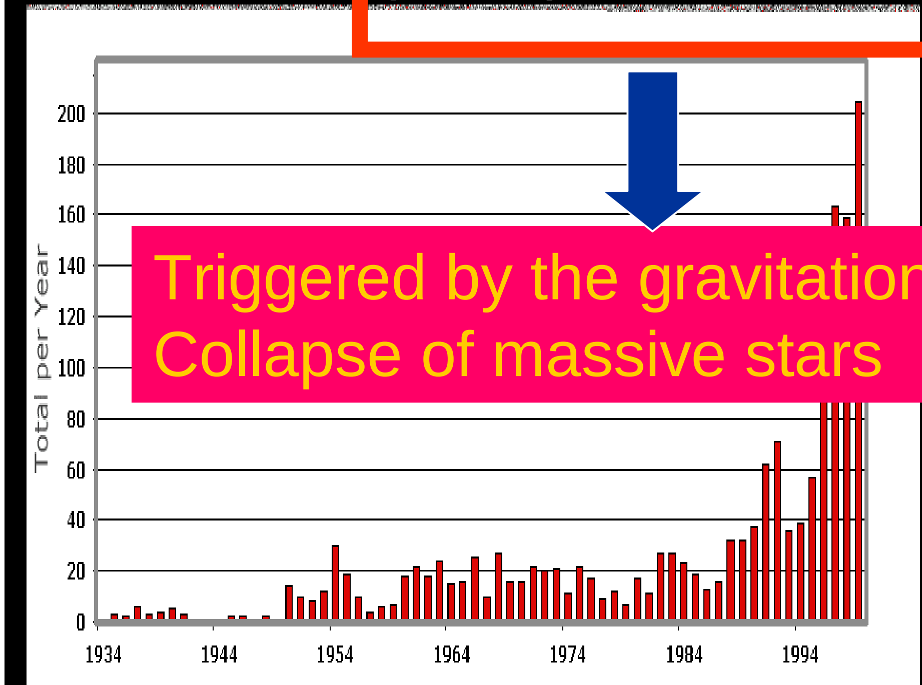
1932 Zwicky & Baarde categorized supernovae into two types

Without H Line / with

Type I

Type II

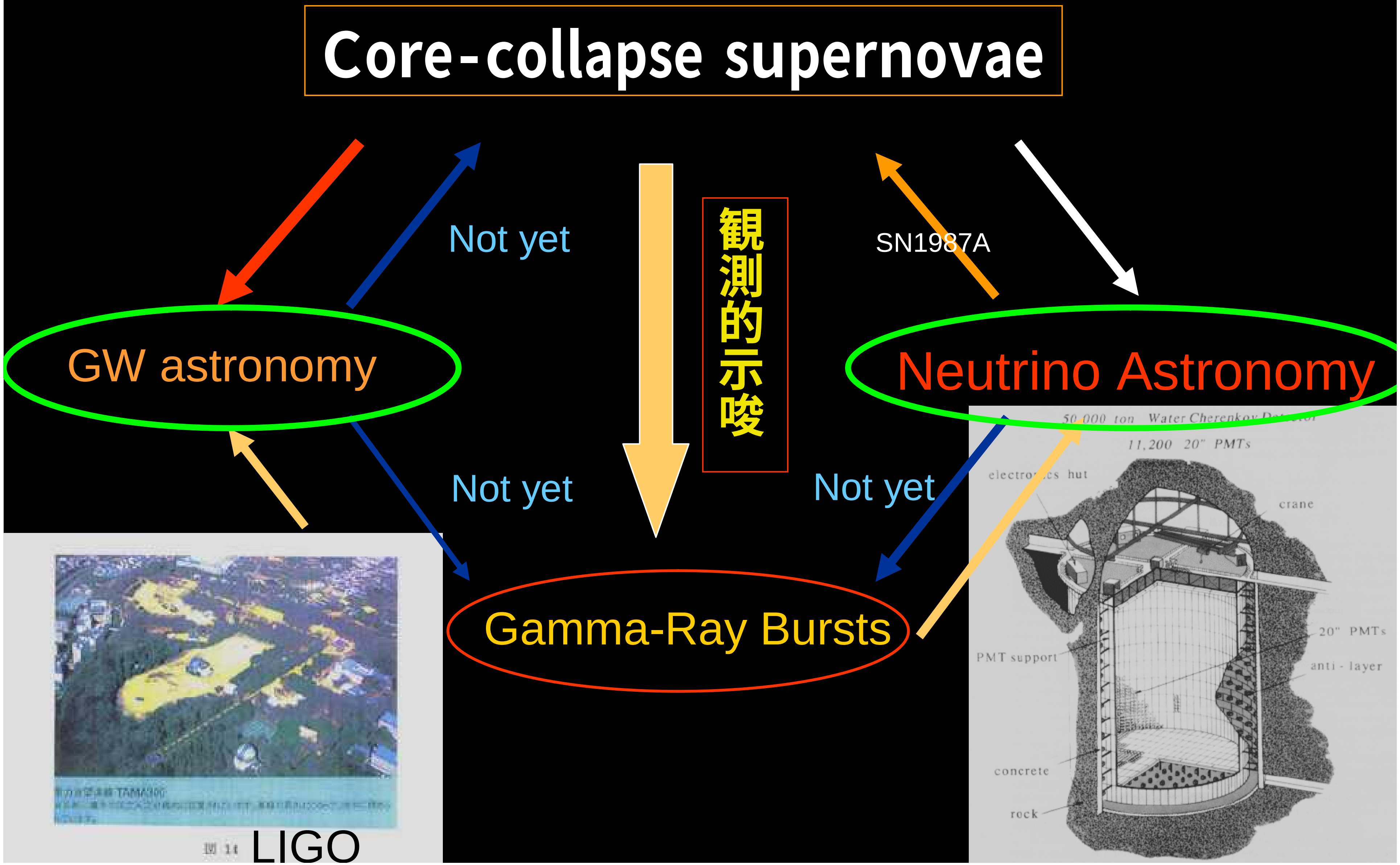
Core-collapse supernovae
(Collapse-driven supernovae)



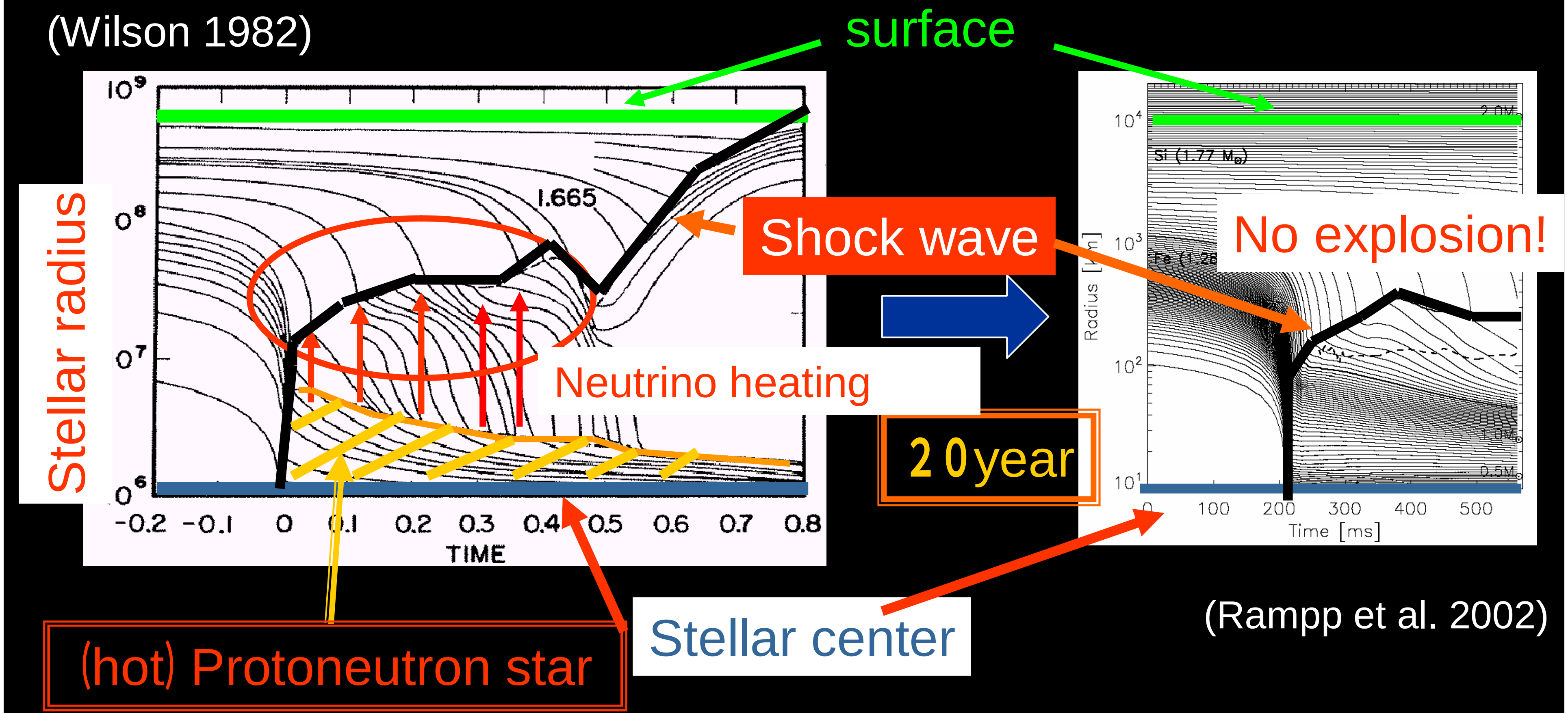
Triggered by the gravitational
Collapse of massive stars

Nowadays

Importance of Core-collapse SNe



However one cannot tell the explosion mechanism clearly.



Assuming spherical symmetry of the star,
only neutrino heating cannot produce the successful explosions !

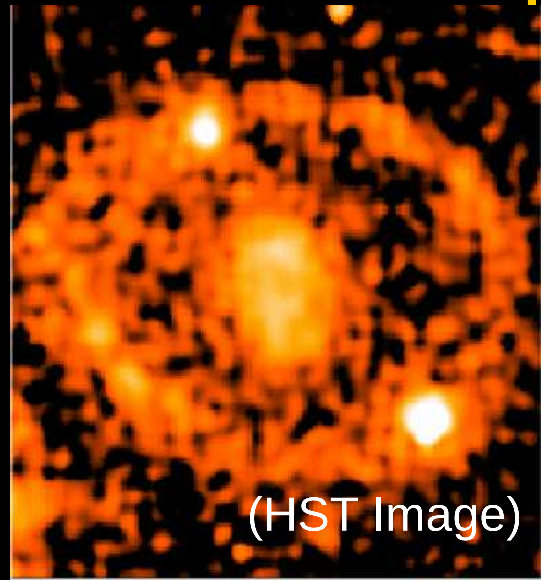
Rotation and Magnetic field

It's because rotation and magnetic field are supported by

Observations,

: Massive stars in main sequence rotate very fast (~ 200km/s) .

: Ring like circumstellar matter in SN 1987A (Plait et al. '95)



(HST Image)

: Polarization observations show that core collapse supernovae are generally asymmetric. (Wang et al. '02)

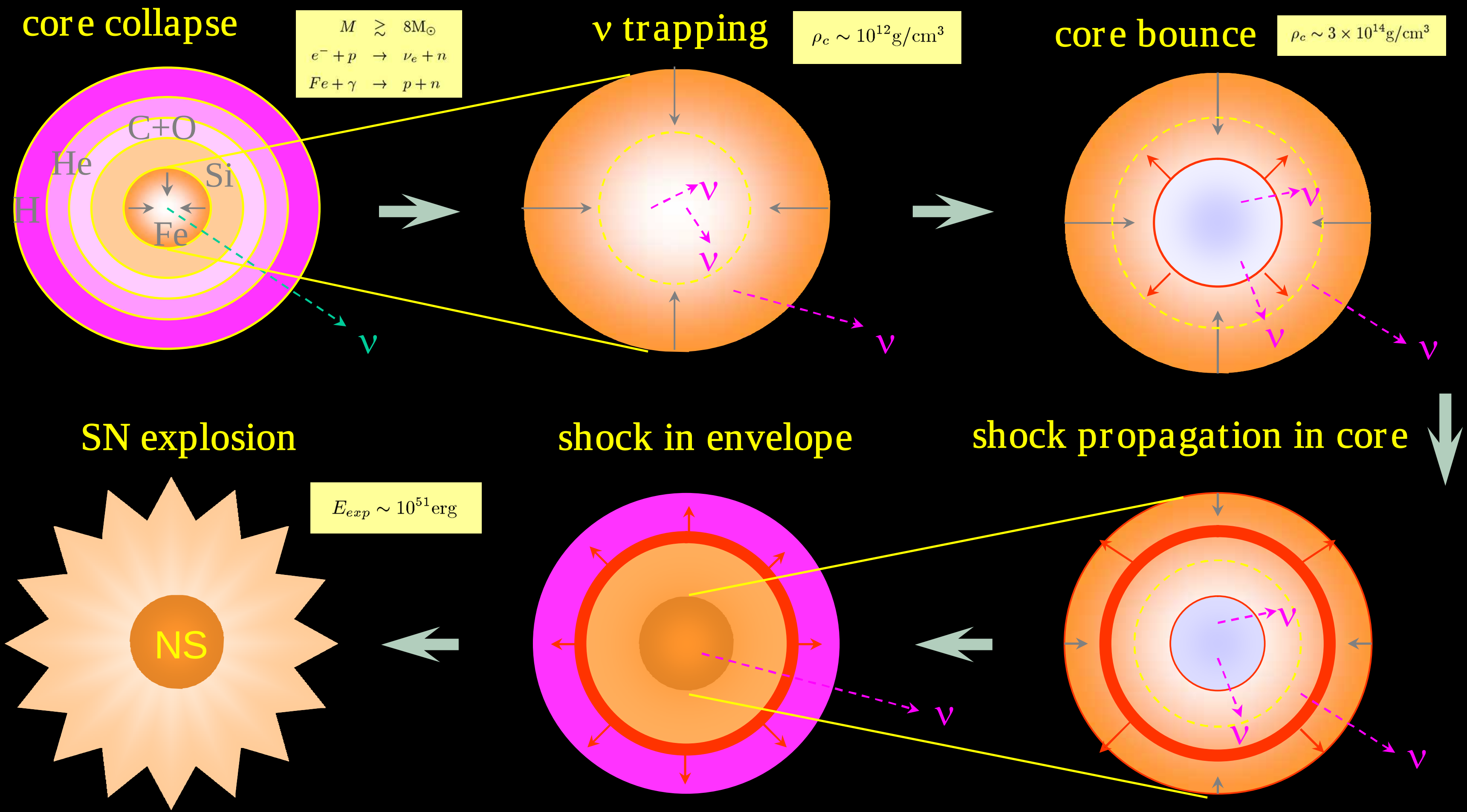
: Neutron star, produced after explosion, are strongly magnetized.

We should investigate the effects of rotation and magnetic fields on the neutrino heating mechanism.

2.Standard Supernova Physics

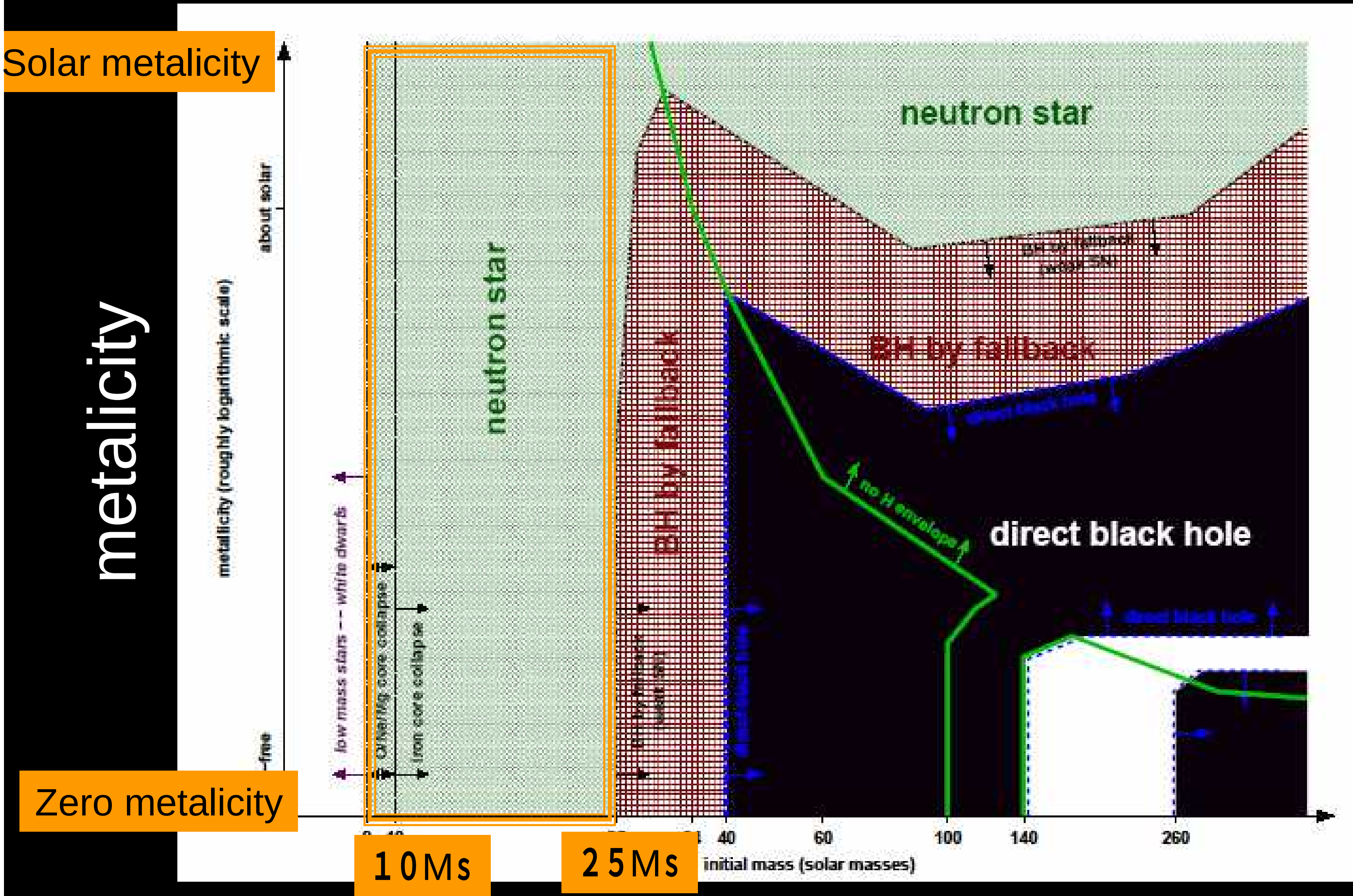
超新星爆発に至るまでの典型的な
系の時間発展そこでの物理

Standard scenario of core-collapse supernovae



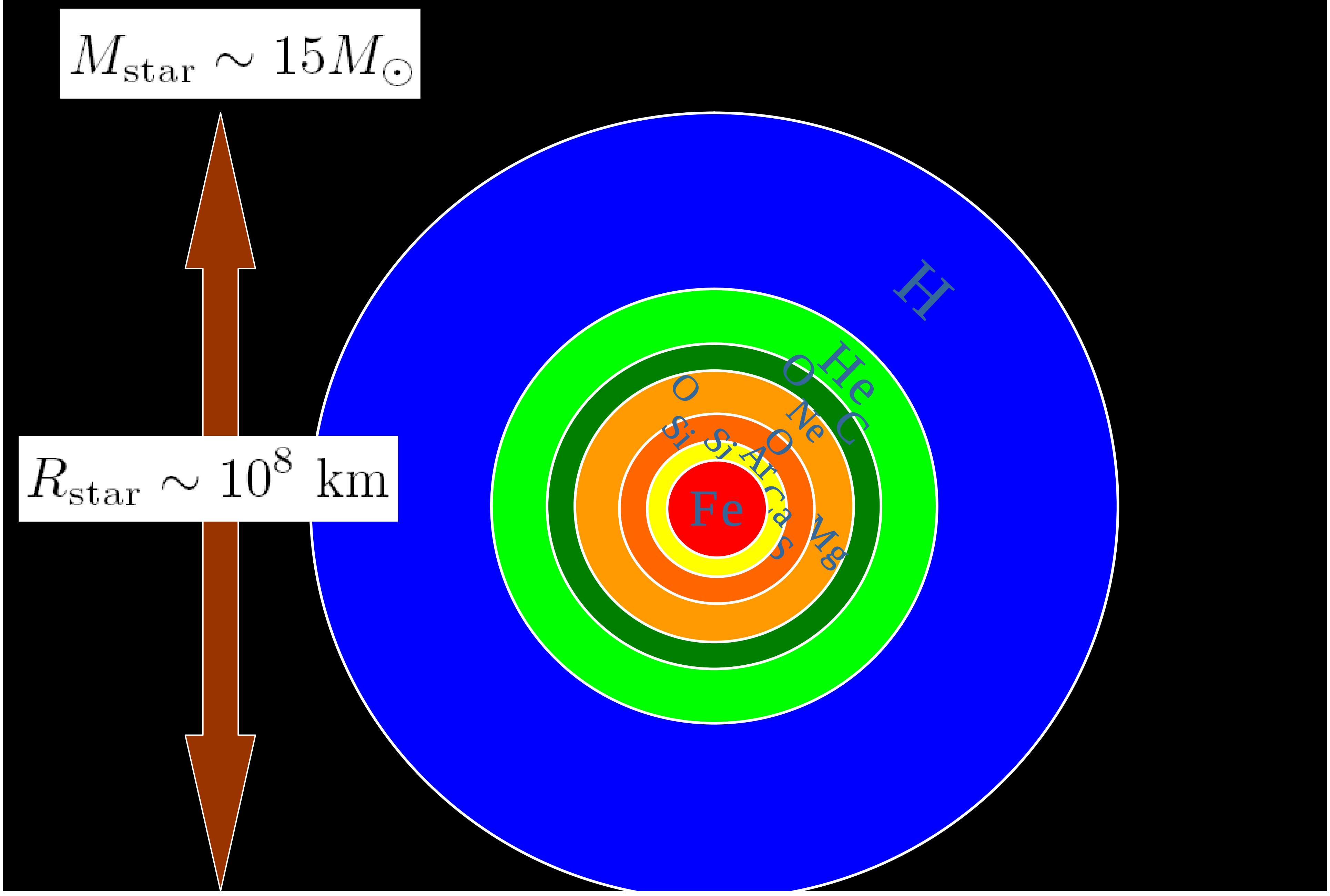
How massive stars end their life ?

Heger et al. 03

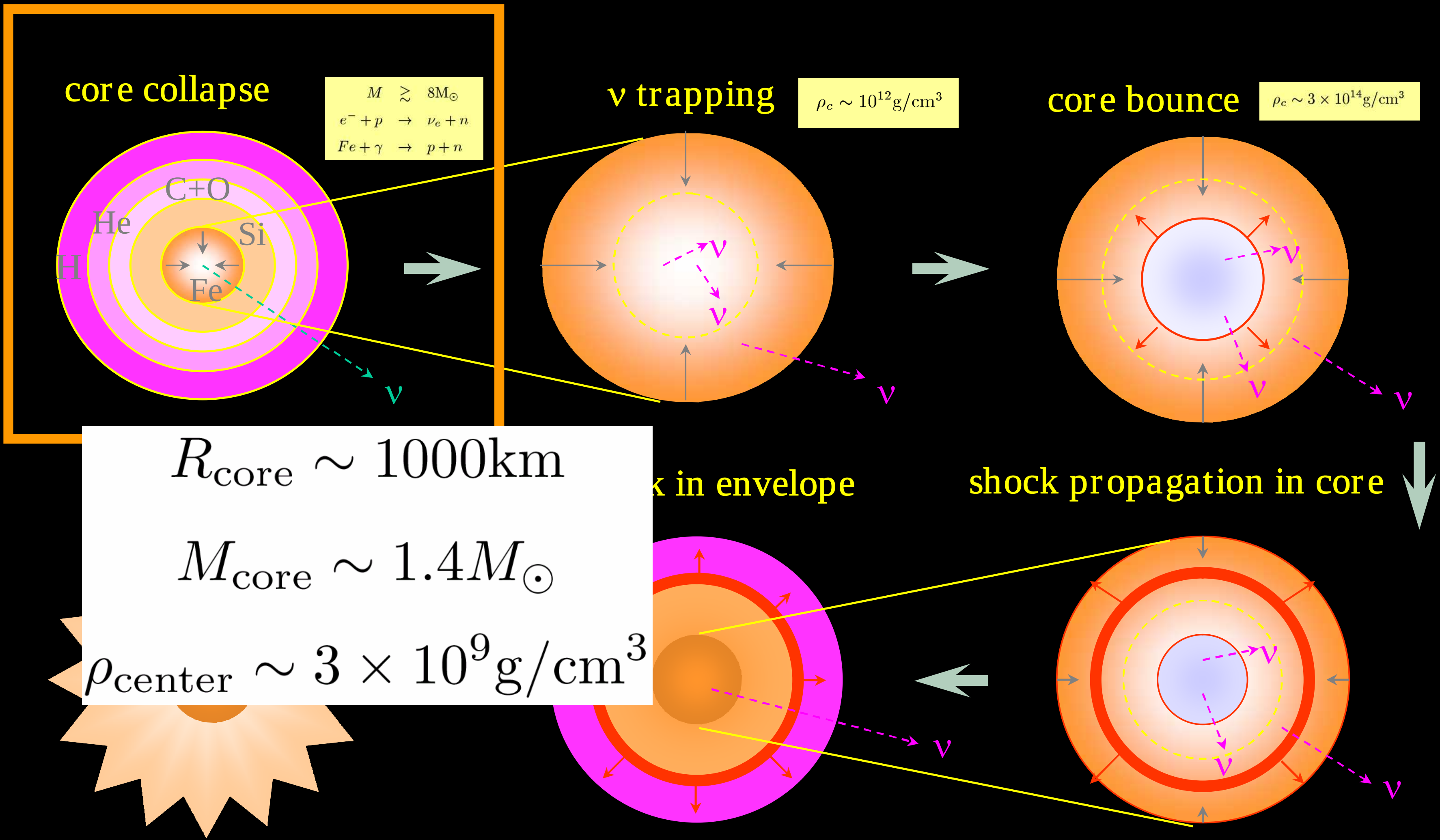


Initial stellar mass

Stellar structure just before gravitational collapse



Standard scenario of core-collapse supernovae

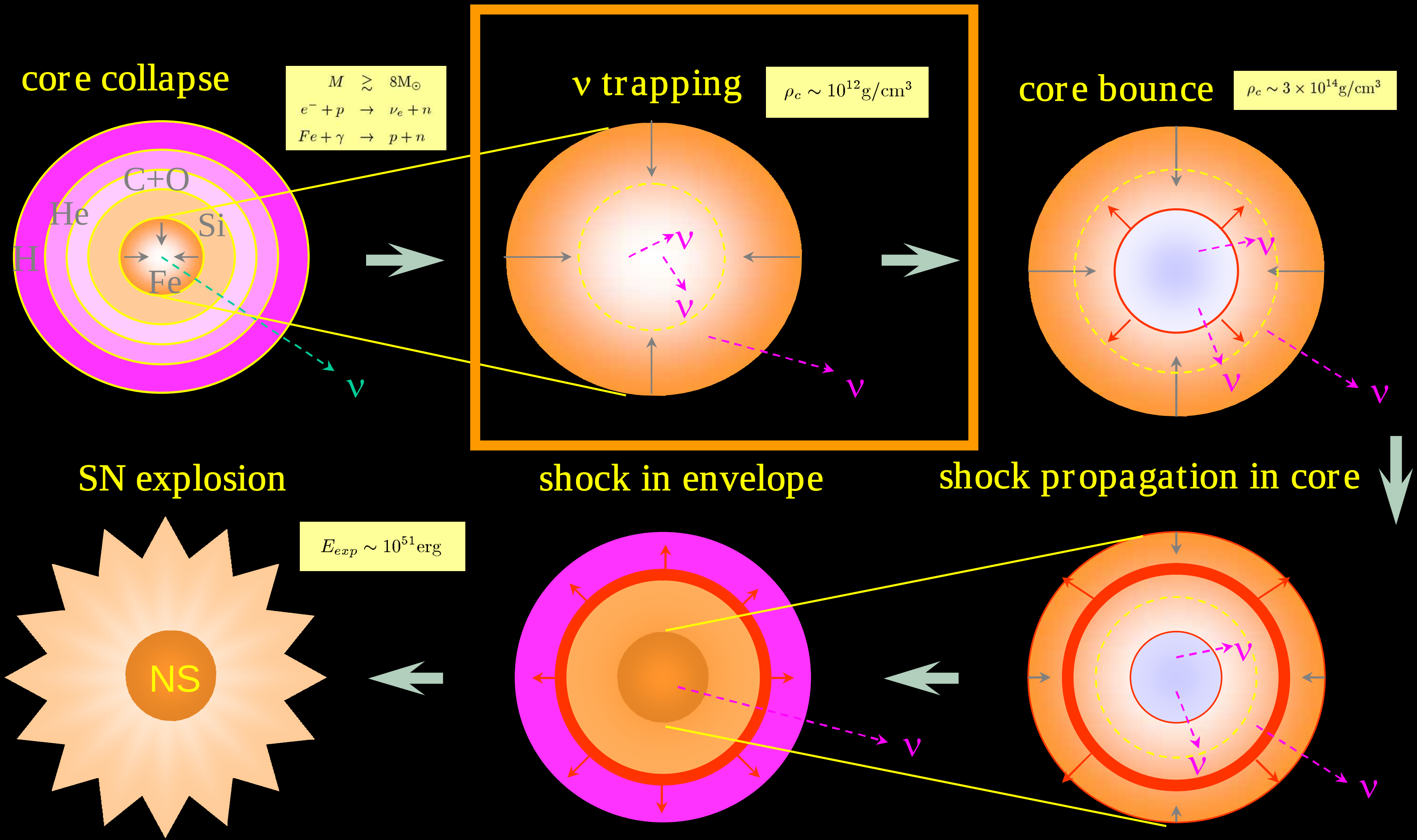


$$R_{\mathrm{core}} \sim 1000\mathrm{km}$$

$$M_{\mathrm{core}} \sim 1.4 M_\odot$$

$$\rho_{\mathrm{center}} \sim 3 \times 10^9 \mathrm{g/cm^3}$$

重力崩壊型超新星爆発のstandard scenario



Step 2 Neutrino Trapping
(K.Sato,1975)

ニュートリノ ➡ Weak interacting particle

参考： $\sigma \sim 10^{-38}\mathrm{cm}^2 \quad (\mathrm{at\ 1GeV})$ << $\sigma_{\mathrm{T}} \sim 10^{-25}\mathrm{cm}^2$

超新星コアに於ける最も断面積が大きな反応
＝原子核によるcoherent scattering

$$\nu_e + (Z, A) \rightarrow \nu_e + (Z, A)$$

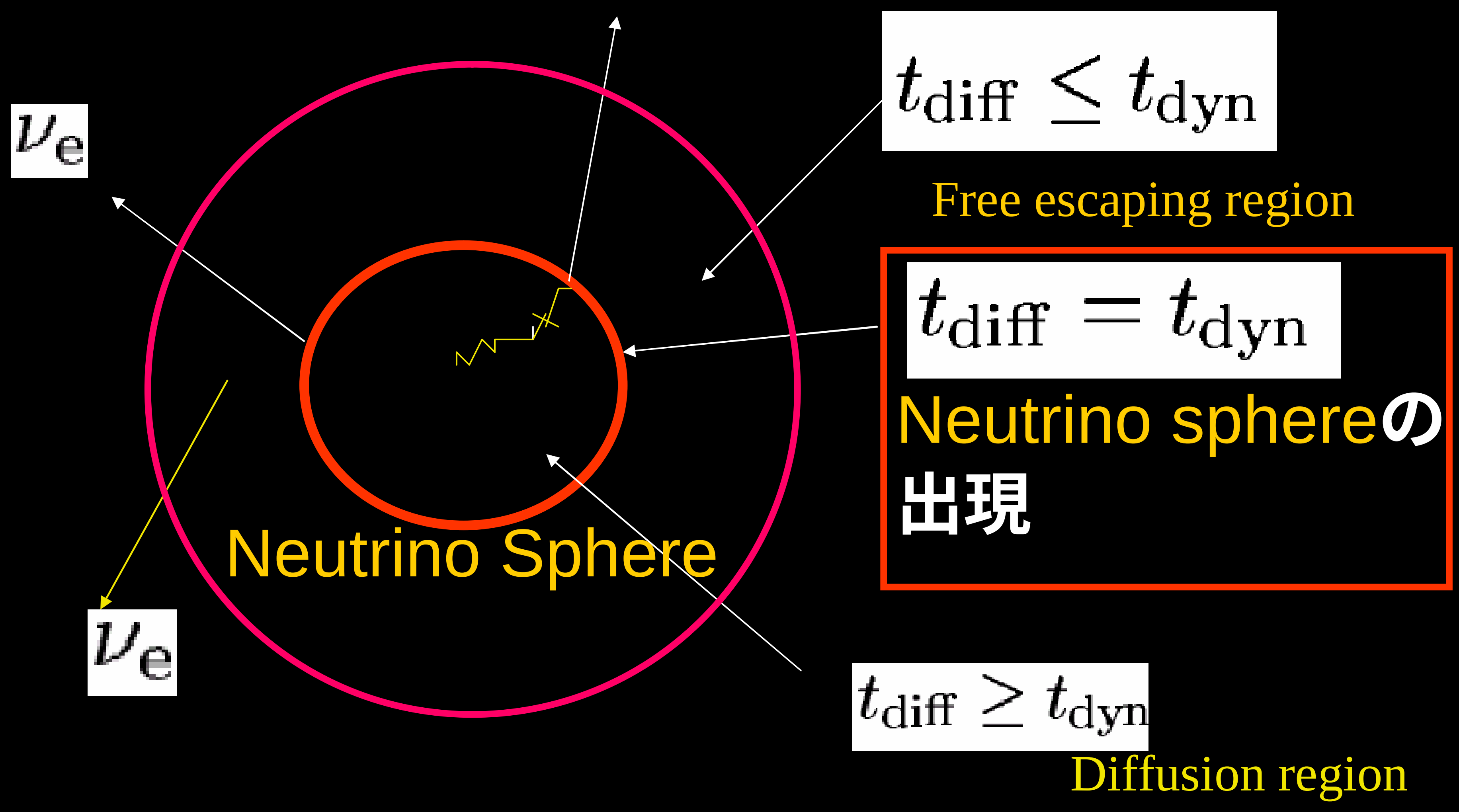
Neutrino がコアにトラップされるかどうか調べるためには、二つのtimescale を比べればよい。

コアの落下時間 τ_{ff}

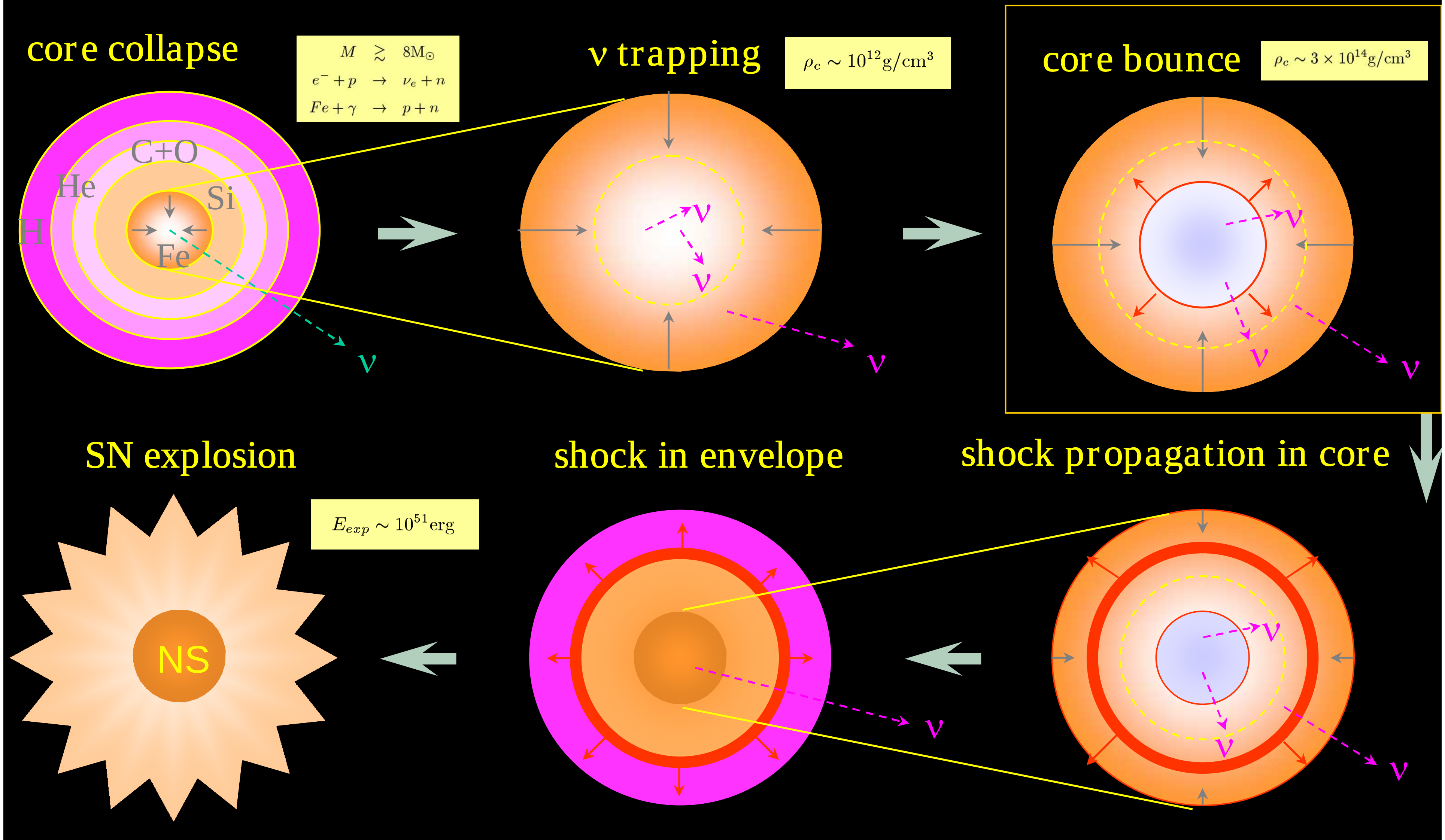
Coherent 散乱によるdiffusion timescale τ_{diff}

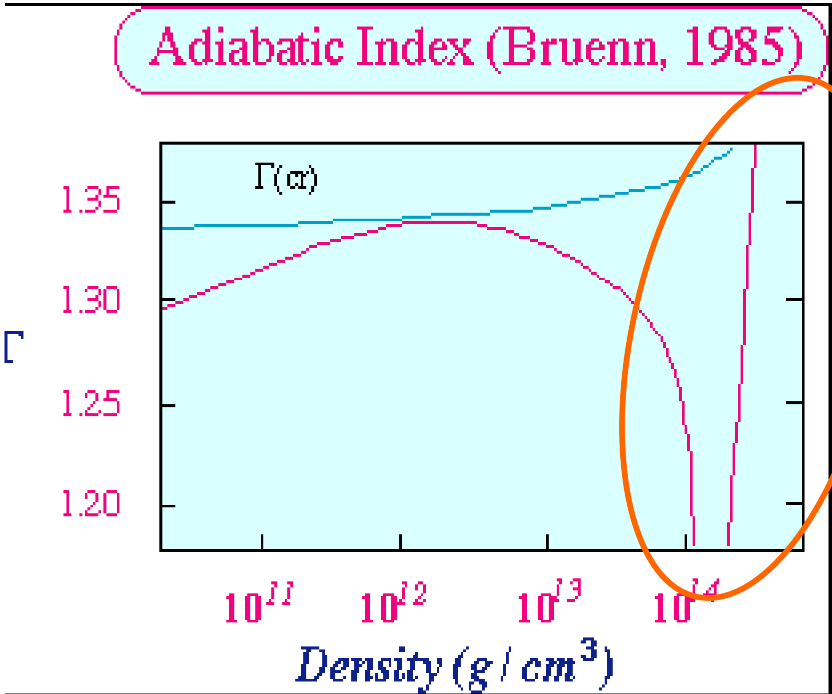
$$\tau_{ff} \sim \frac{1}{\sqrt{G\rho}} = 4 \times 10^{-3}\ \mathrm{s}\left(\frac{\rho}{1 \times 10^{12}\ \mathrm{g\ cm^{-3}}}\right)^{-1/2} = \tau_{\mathrm{diff}} \sim 8 \times 10^{-2}\mathrm{s}\left(\frac{\rho}{1 \times 10^{12}\ \mathrm{g\ cm^{-3}}}\right)$$

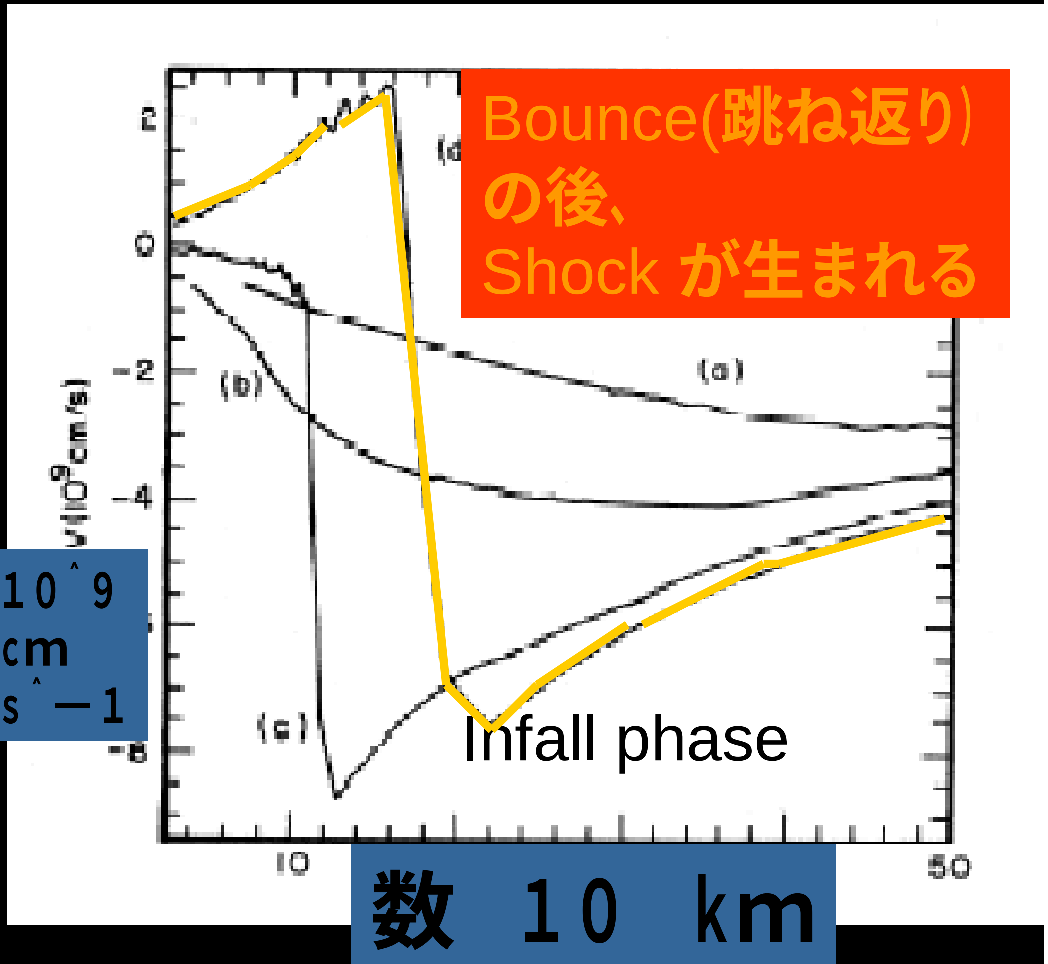
$$\rho \sim \rho_{\mathrm{trap}} \sim 1.4 \times 10^{11}\ \mathrm{g\ cm^{-3}}$$



Standard scenario of core-collapse SNe





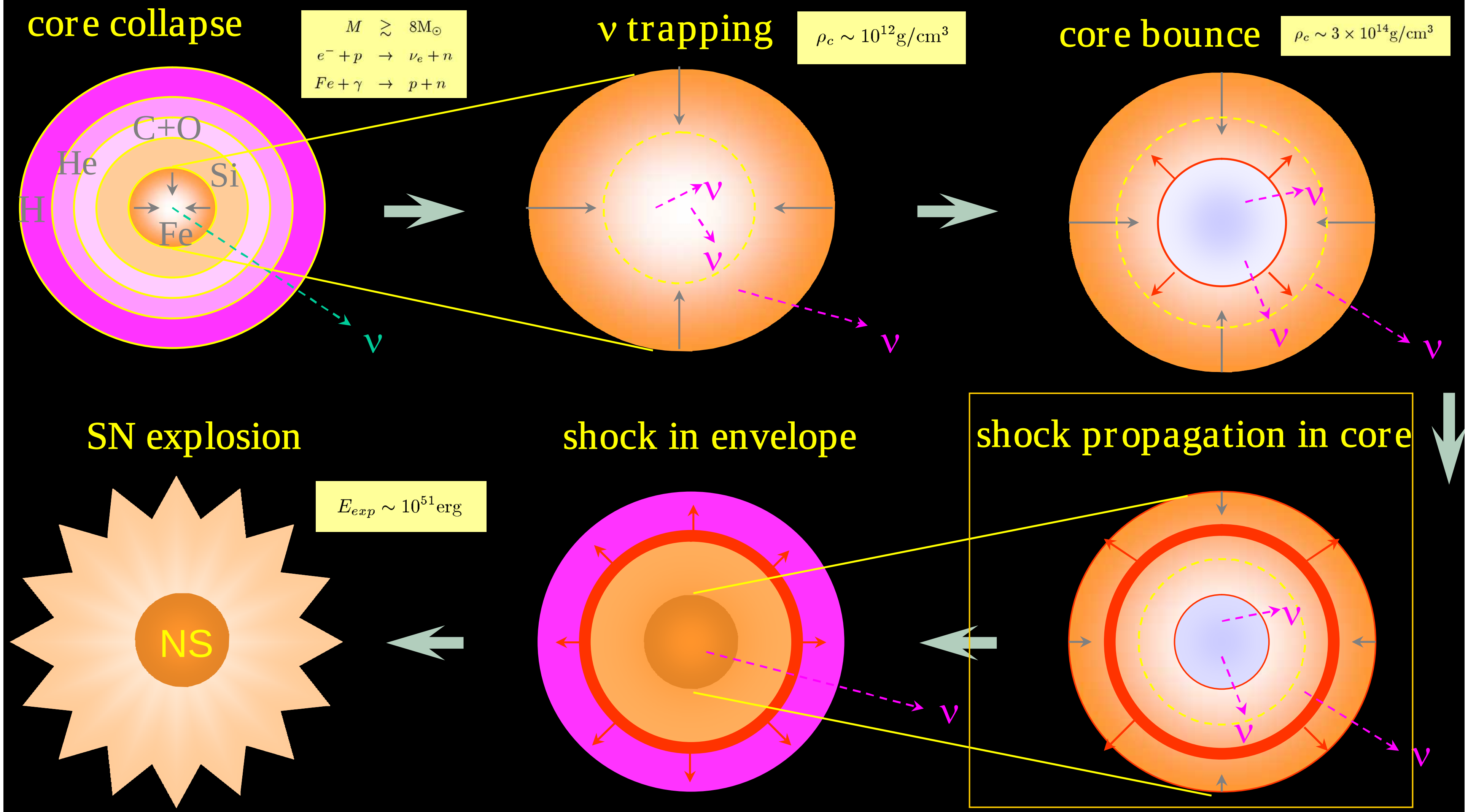


核密度を越えると、
状態方程式が硬くなる。

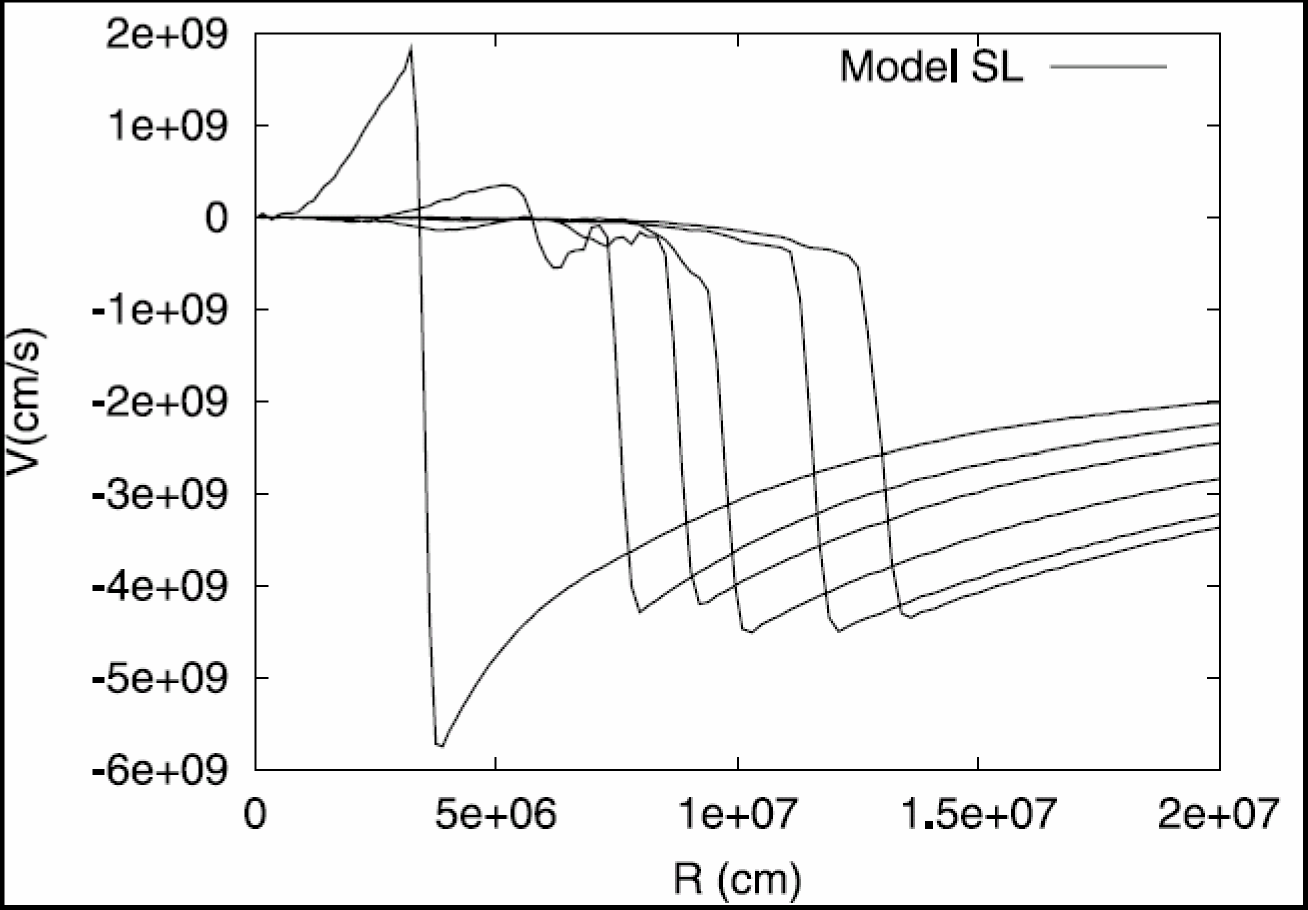
$$P = K\rho^{\Gamma}$$

Adiabatic index: Γ ↑

Standard scenario of core-collapse SNe

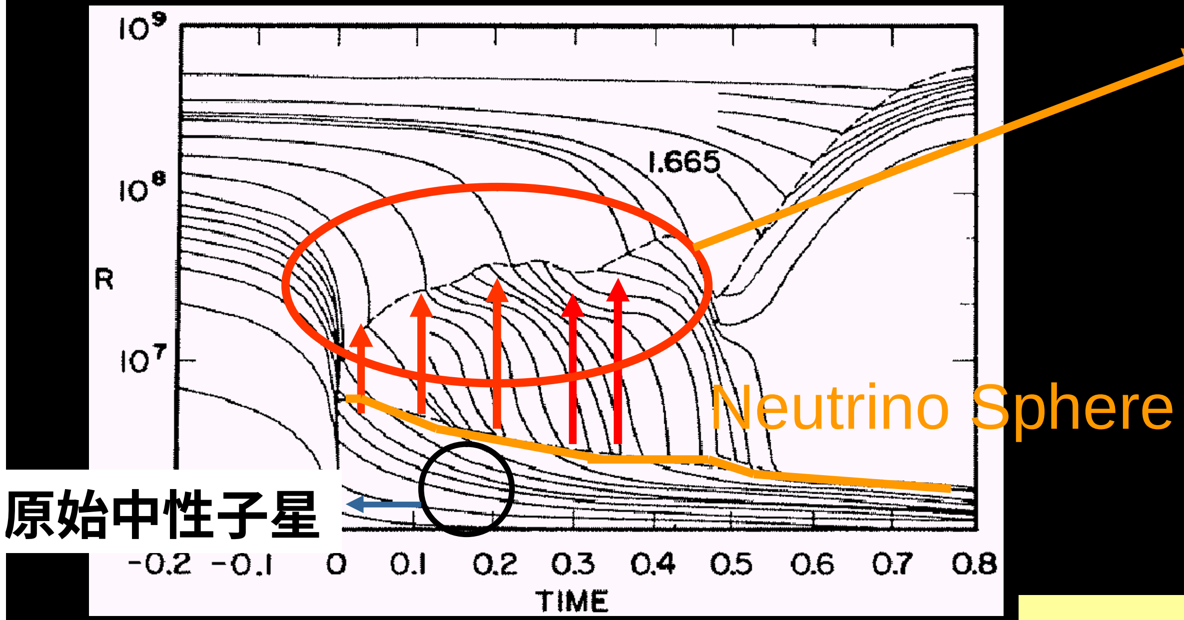


Supernova Explosion： Prompt explosion



Prompt explosion fails!
mainly due to photodissociation of Fe nuclei.

Neutrino Heating Mechanism (Wilson '85)で爆発させる！



Heating Processes

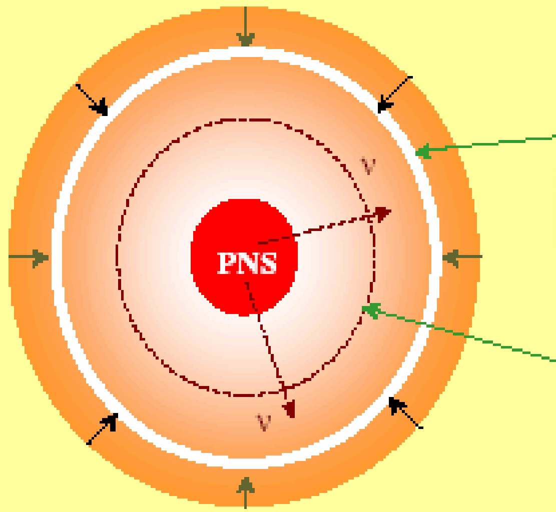
$$\nu_e + n \rightarrow e^- + p$$

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

$$\nu + e \rightarrow \nu + e$$

1秒

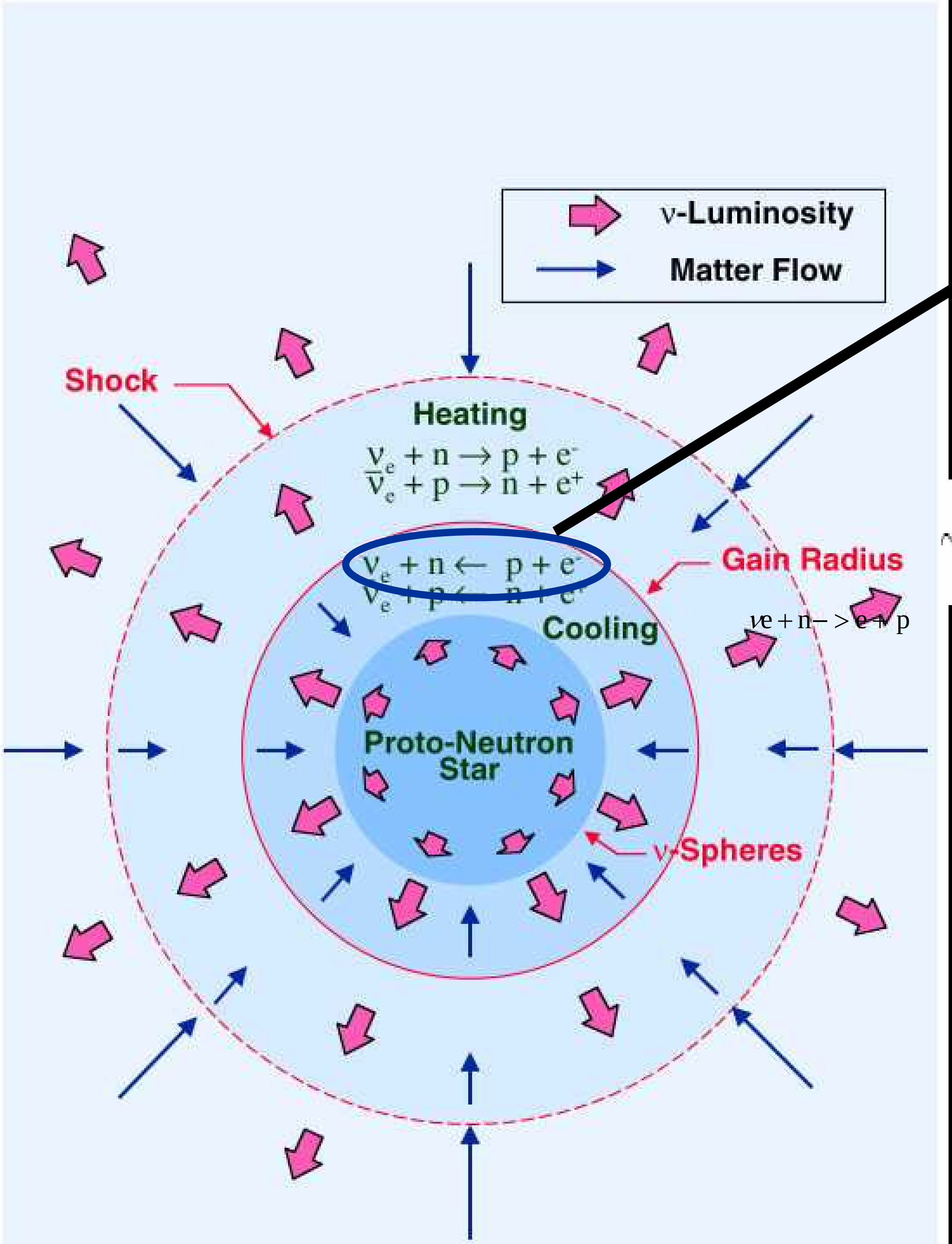
Delayed Explosion



$R_{shock} \sim 200\text{km}$

$H_\nu = C_\nu$

$R_{gain} \sim 100\text{km}$



Order Estimation

Heating rate

$$\nu e + n -> e + p$$

$$\left(\frac{dE}{dt}\right)_{\rm abs} = \frac{L\sigma}{4\pi R^2}$$

$$\sim 50\mathrm{MeV/s}\left(\frac{L}{10^{52}\ \mathrm{erg/s}}\right)\left(\frac{E_\nu}{10\ \mathrm{MeV}}\right)^2\left(\frac{R}{1.5\times 10^7\mathrm{cm}}\right)^{-2}$$

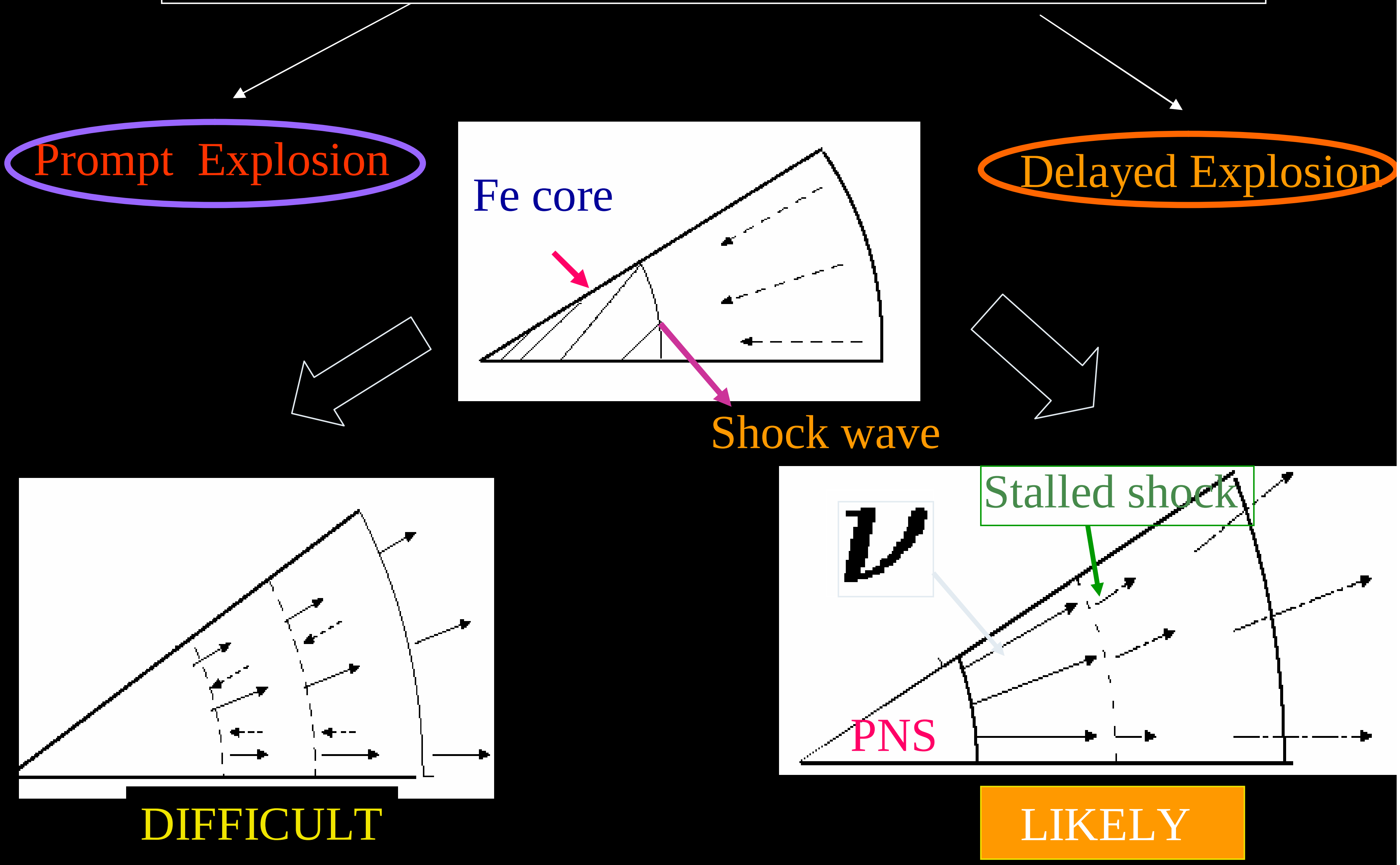
Binding energy

$$-\frac{GM_{1.5M_\odot}}{R/(1.5\times 10^7\mathrm{cm})}\frac{1}{N_A} \sim -13\mathrm{MeV}$$

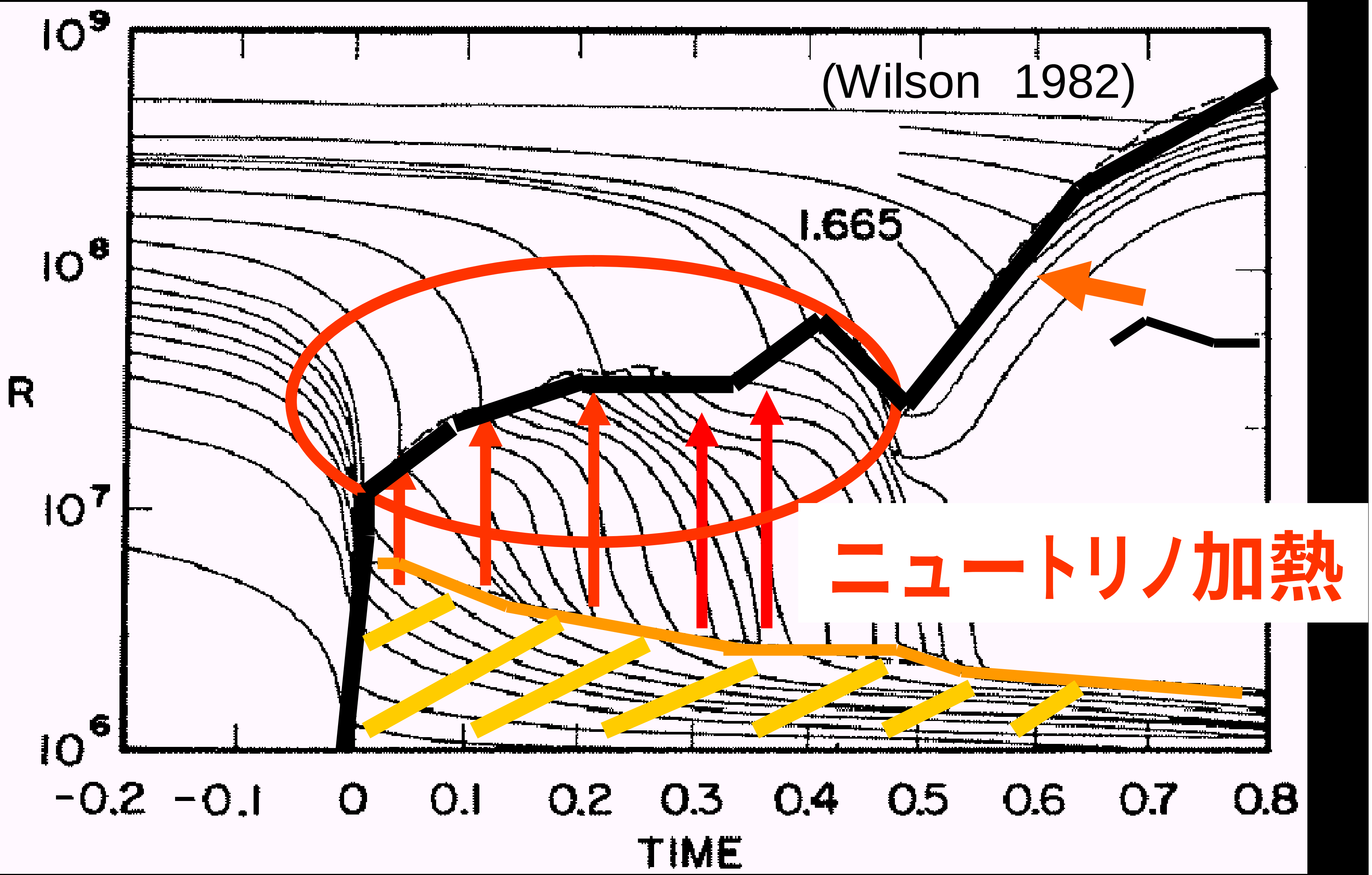
Shedding of neutrinos about 0.25 s is sufficiently to expel a neutron.

Summary of Standard Supernova Scenarios.

Explosion Mechanism of Collapse-Driven Supernovae



Wilson から　20年！



Status of Spherical Models

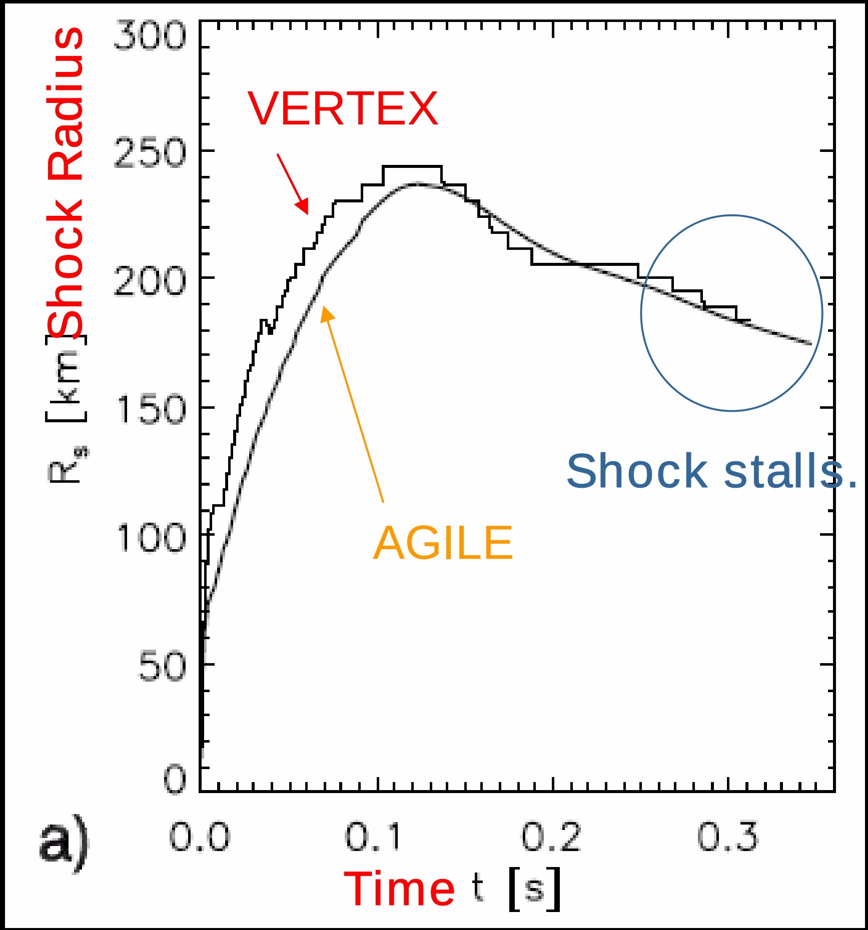
1D models,

Comparison of different groups,

AGILE-BOLTZMANN (Oak –Ridge)
Hydro: implicit GR
Neutrino transport; 1D, Sn method
(Mezzacappa & Bruenn 1993)

VERTEX (MPA)

Hydro; explicit Newtonian
Neutrino transport: VEF method
(Rampp & Janka 2002)



(Liebendoefer et al. 2003)

cannot produce explosions.

Step beyond Spherical Models

For realistic supernovae simulations, many physical ingredients had better be taken into account.

More realistic

Macro Physics:

- Convection
- Rotation
- Magnetic fields
- General Relativity

MultiD simulations are urgent.

Micro Physics:

- Equation of state
- Neutrino transport

Section 3：

Asymmetry

<->

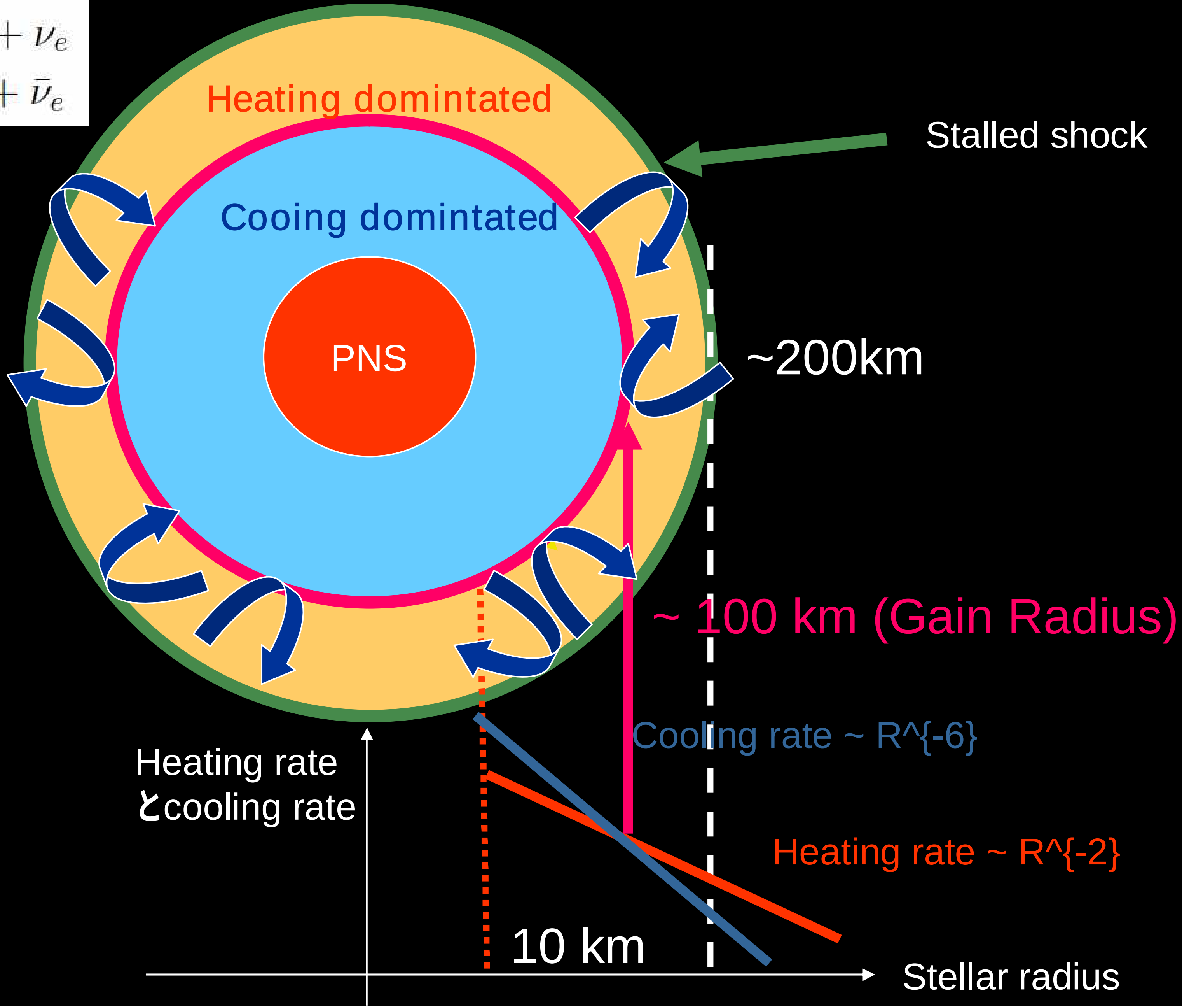
Explosion mechanism

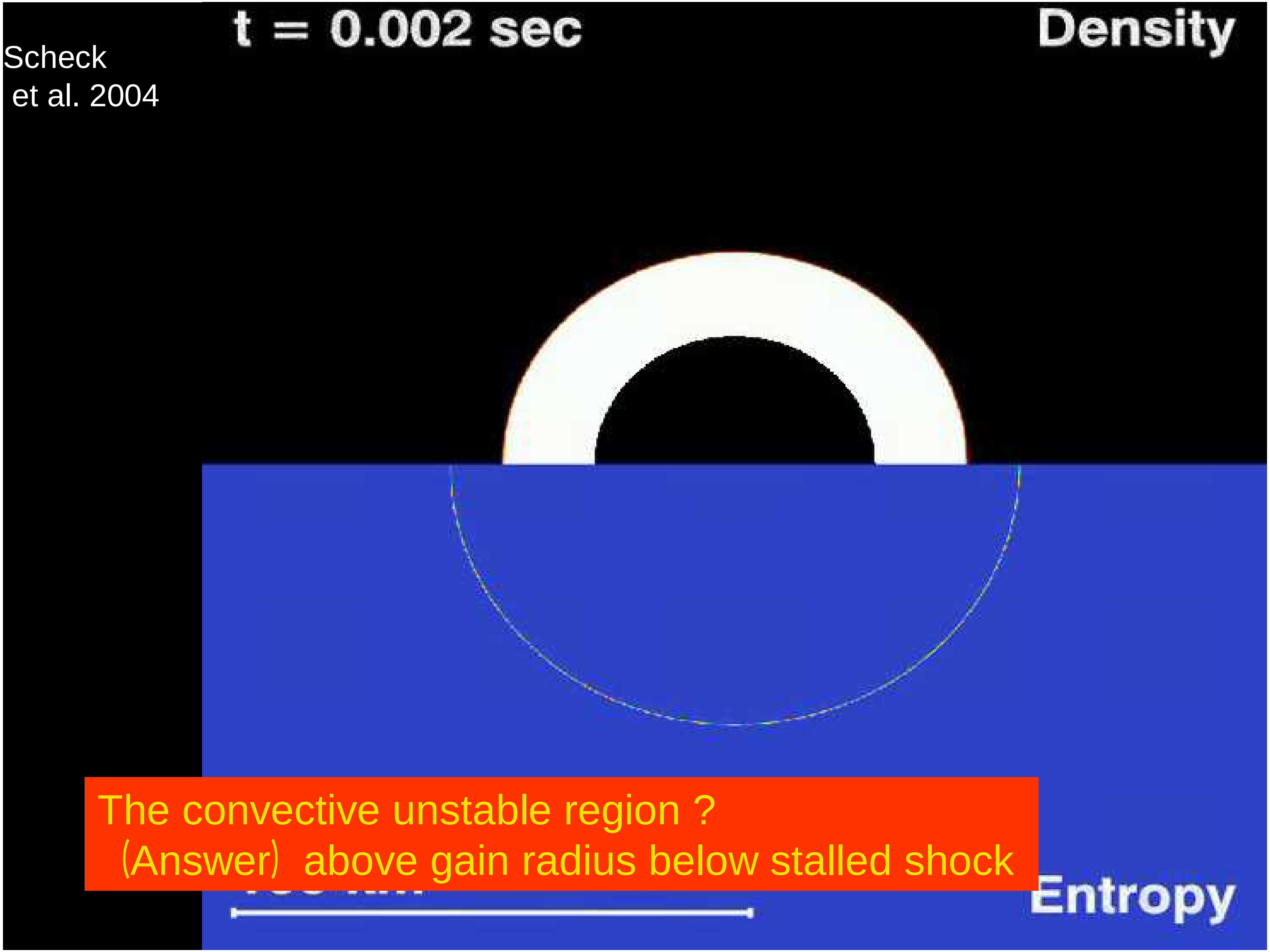
What causes “Asymmetry” ?

How “Asymmetry” affects the neutrino heating ?

超新星の何処で対流が起こるか？

$$p + e^- \rightleftarrows n + \nu_e$$
$$n + e^+ \rightleftarrows p + \bar{\nu}_e$$

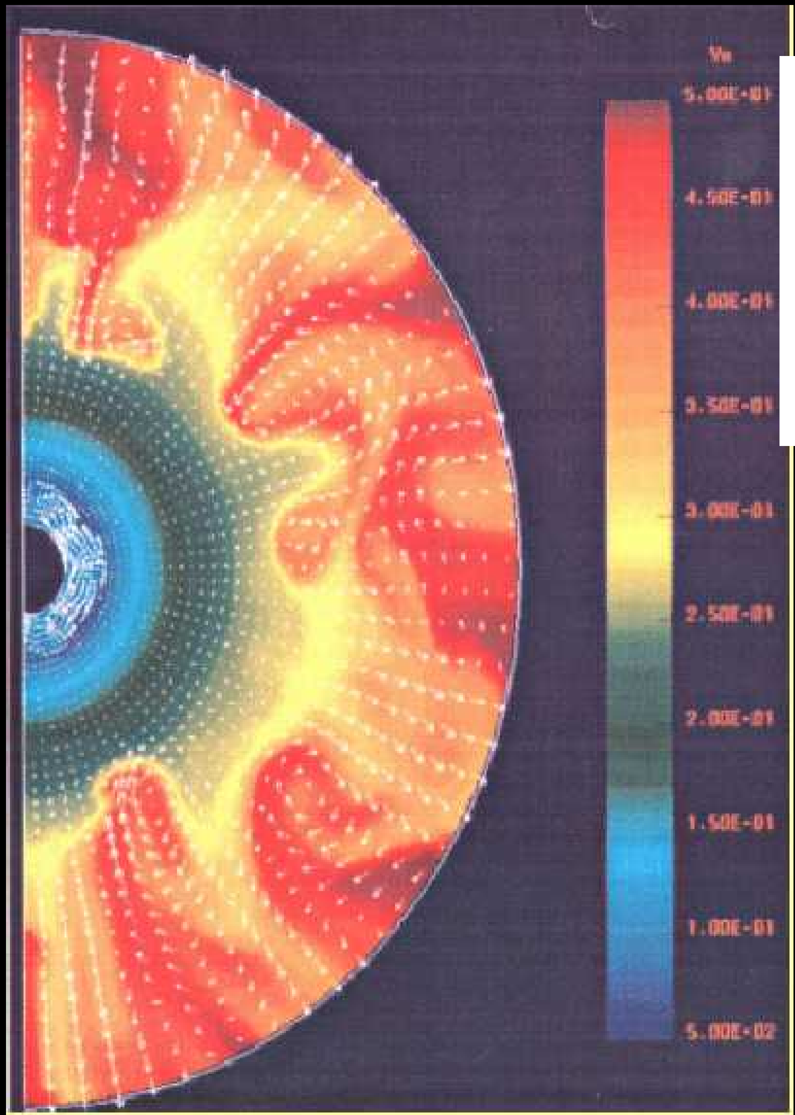




Scheck et al. 2004

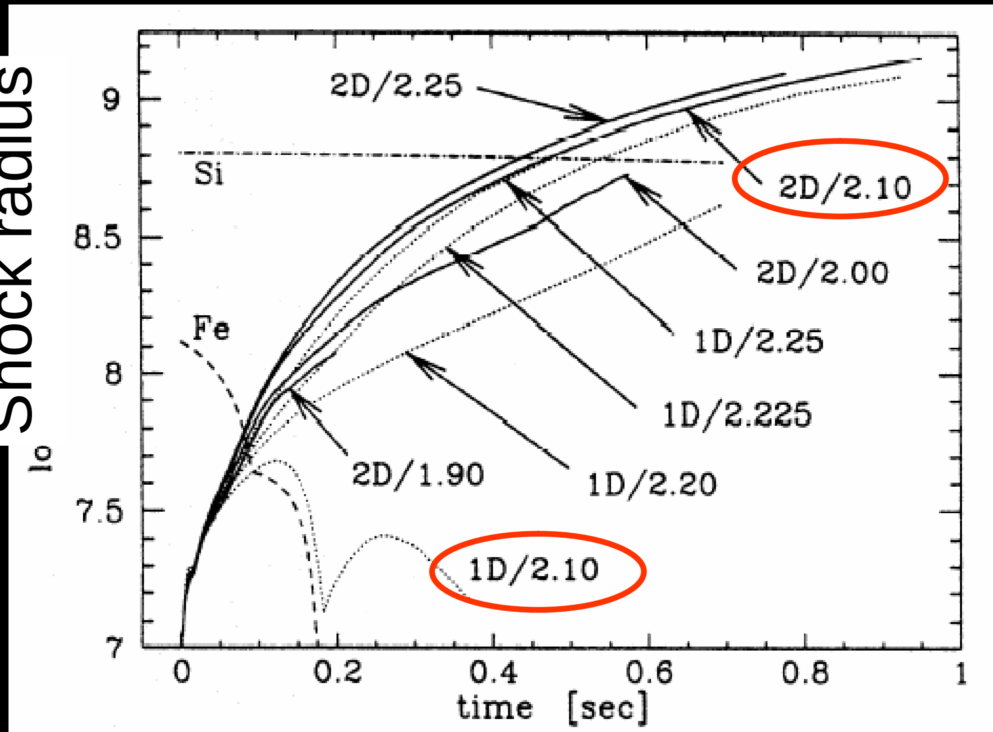
The convective unstable region ?
(Answer) above gain radius below stalled shock

Convections rise the efficient of neutrino heating



(Janka et al. 96)

Shock radius



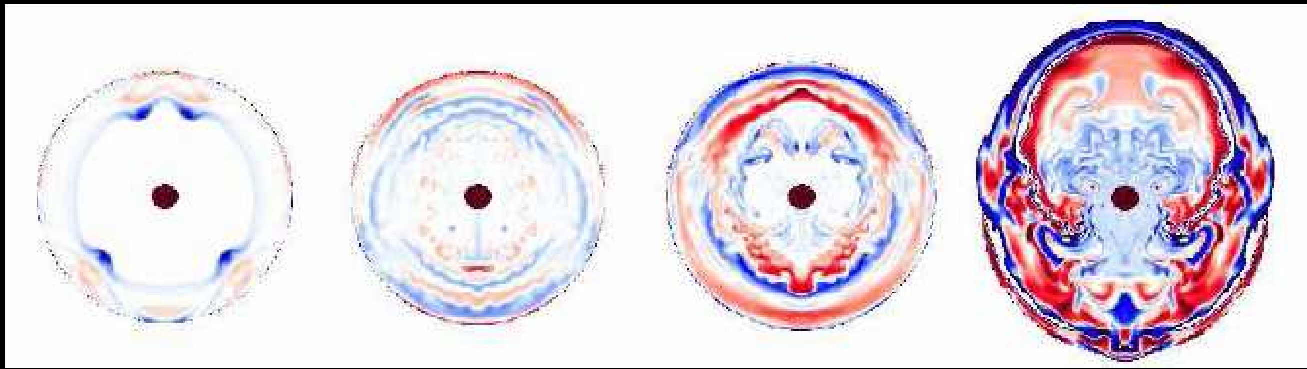
Shedding time of neutrinos (s)

As a result of convections, neutrino Heating is enhanced.

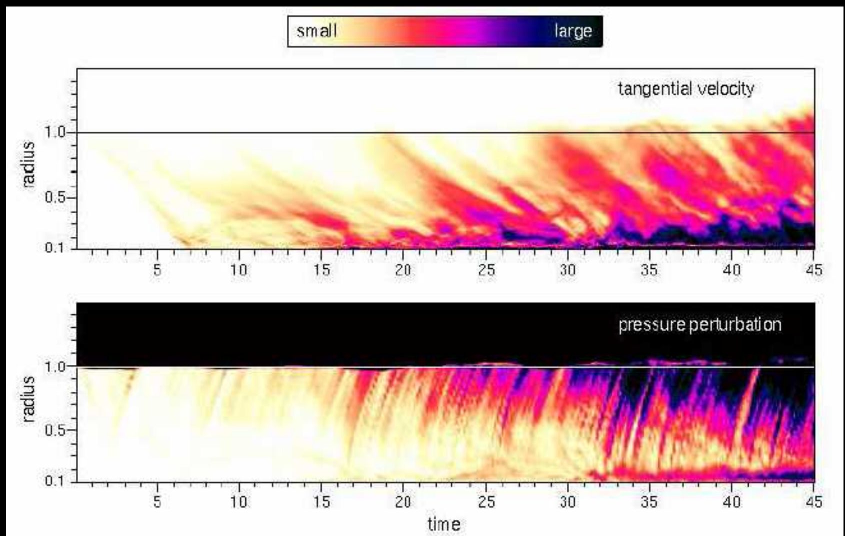
Effect of SASI = Standing Accretion-Shock Instability

Standing shock and non-radial perturbation

Blondin et al. 2002

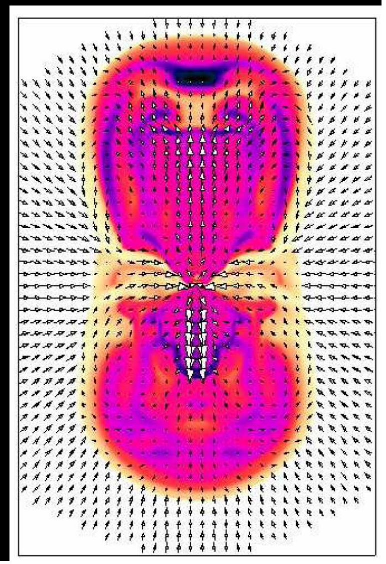


Pressure-wave and fluid element



Growth of the non-radial perturbation

L = 1 mode prevails!



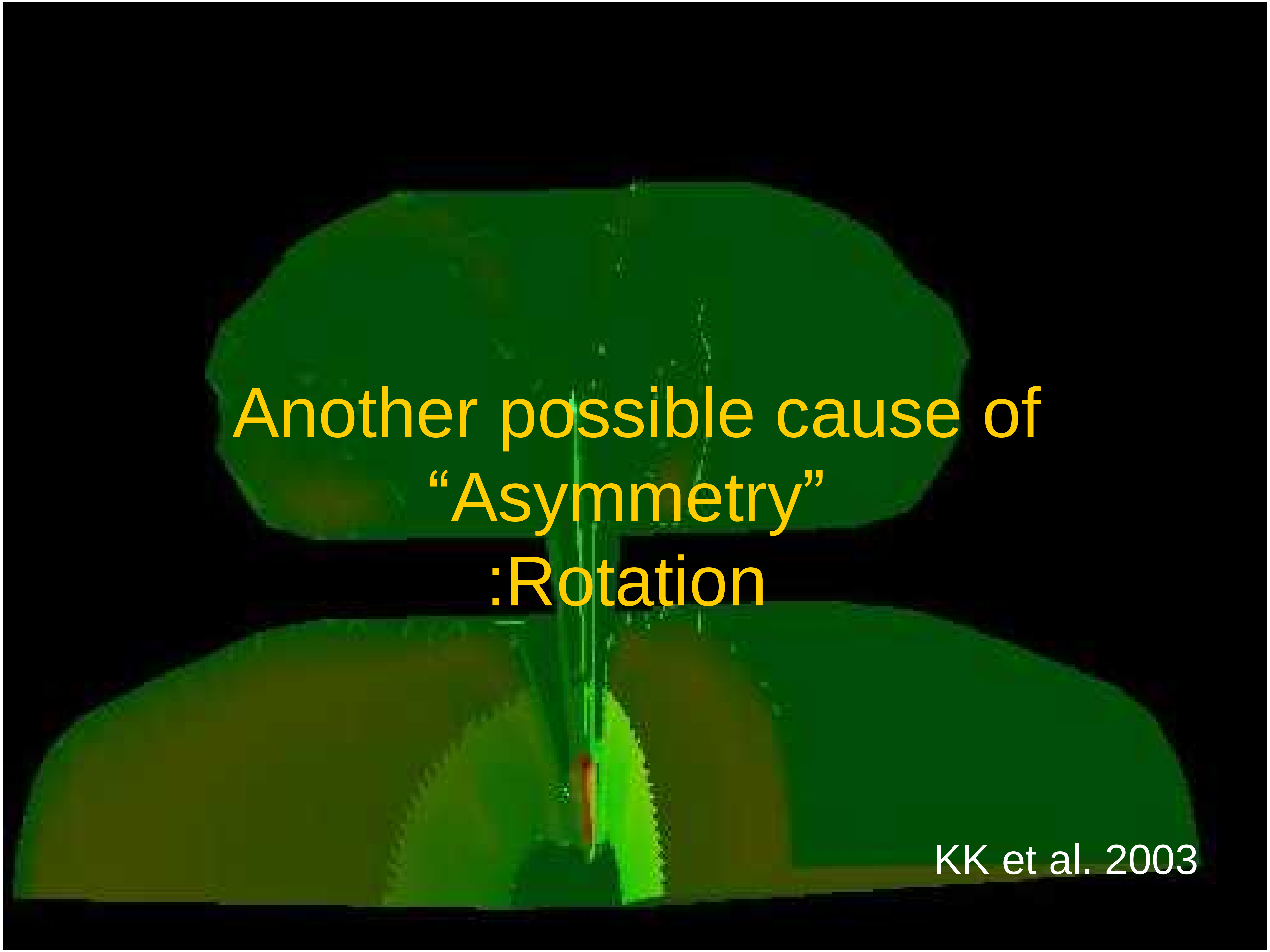
Short summary：
Effect of convection

- Convection enhances the neutrino heating

- SASI may be able to produce the large asymmetry

  (Incoherent scattering and SASI,

  Ohnishi, Kotake, Yamada in prep)

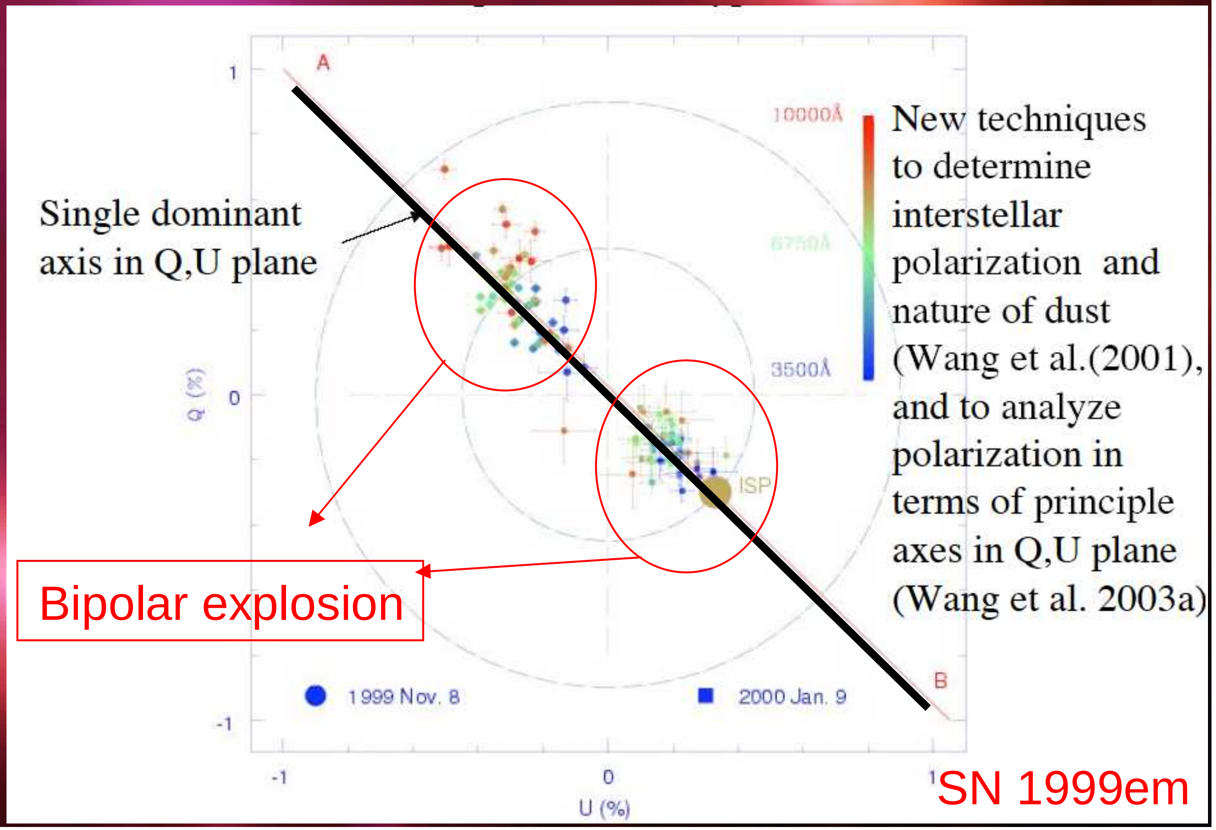

Another possible cause of
"Asymmetry"
:Rotation
KK et al. 2003

Observed Asymmetry in Supernovae

Polarization Observations:

- All core collapse supernovae show significant polarization, ~ 1 %, requires distortion axis rations of ~ 2 to 1. (Wang et al. '96)

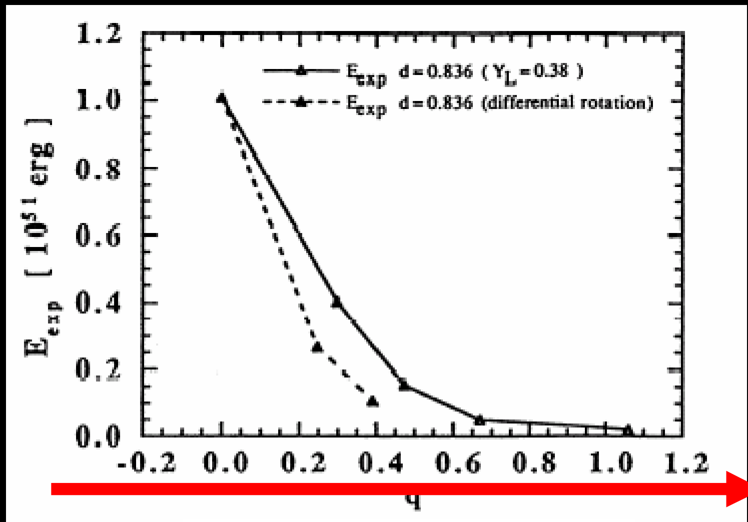
- Bipolar nature, (Wang et al. 01, Wang et al. 03)



Is rotation good for the prompt explosions ?

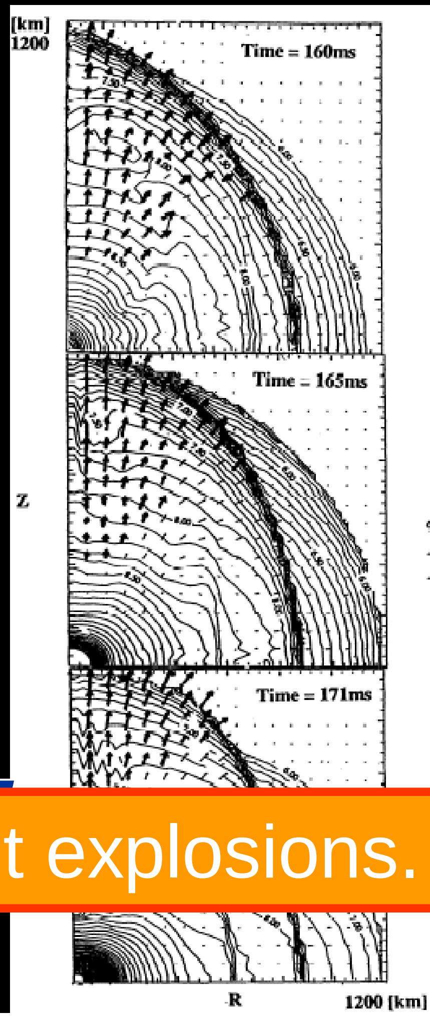
Yamada and Sato. ‘94、 simplified EOS＋2D hydro
+ adiabatic calculations

Explosion energy



Faster rotation

Faster rotation



Explosion monotonically decreases with the

released gravitational energy at bounce

Rotation is found to do no good to prompt explosions.

Unknown and Known things about rotation

Rotation

Is rotation good for prompt Explosion ? No!
(Yamada & Sato, '94)

Next to be investigated is whether rotation does good or not to the neutrino heating mechanism.

Ref.

LeBlanc & Wilson '70, Mueller & Hillebrandt '81, Bodenheimer & Woosley '83 , Symbalisty '84, Moenchemeyer & Mueller '89, Janka & Moenchmeyer '89 Yamada & Sato '94, Fryer & Heger 2000, Bueas et al. 03, Fryer & Warren 2003, etc…

2D rotati

K et al. 03

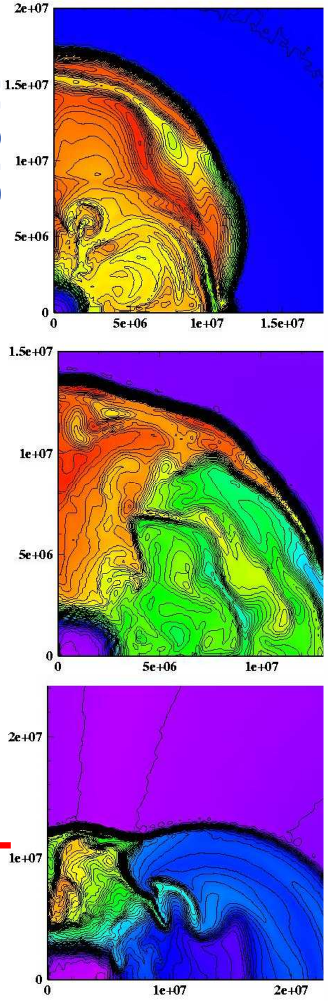
Shell + weak diff

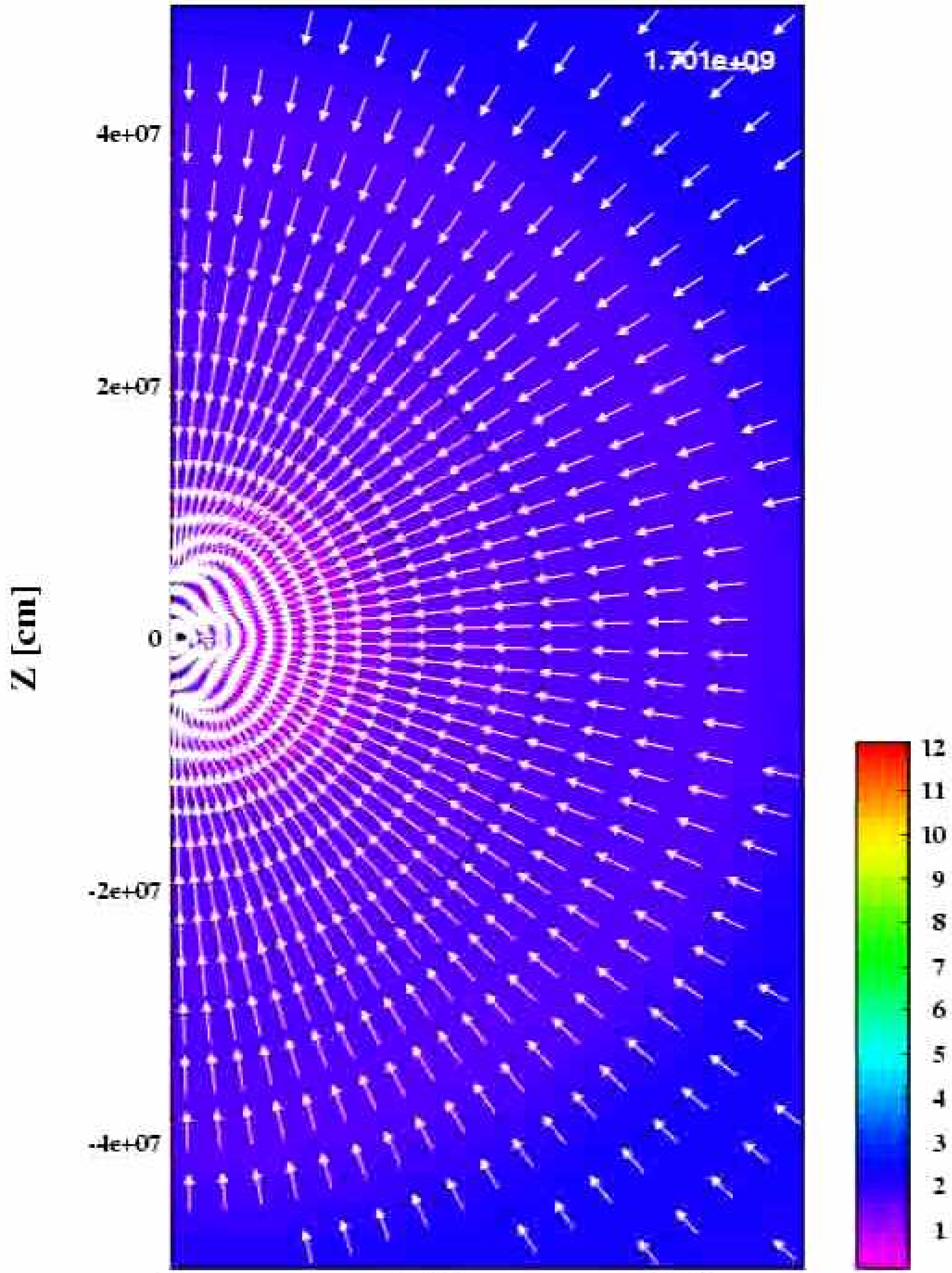
trong diff rot

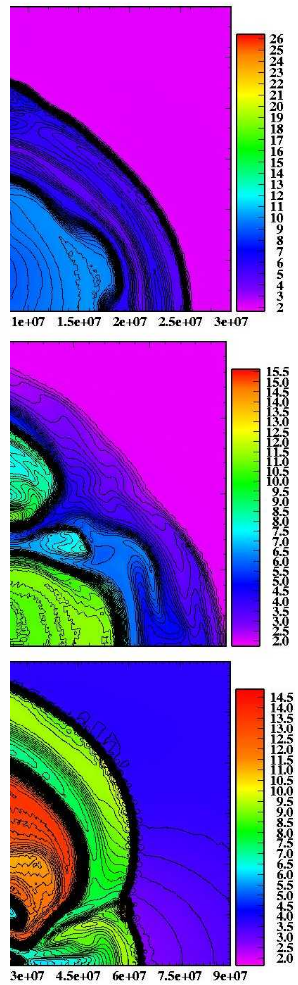
slow

moderate

rapid

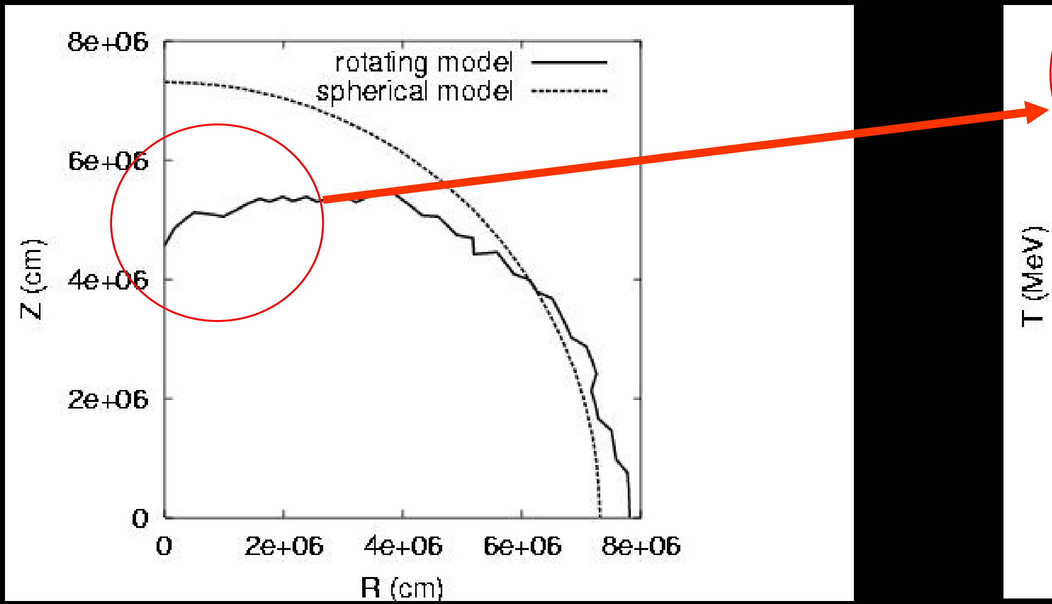




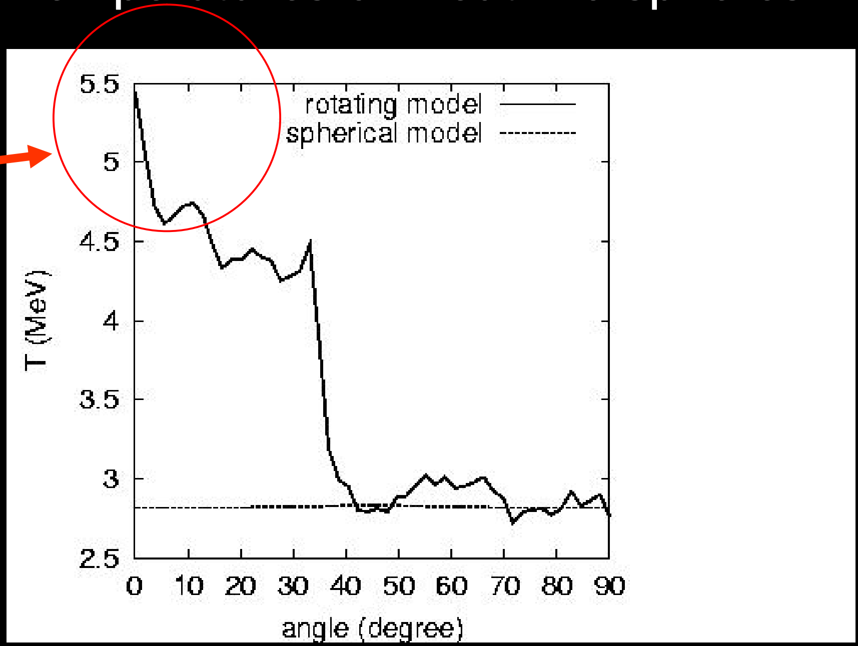


Comparison of the neutrino sphere between spherical and rotating models.

The shapes



Temperatures on neutrino spheres



- The shape of the neutrino sphere is deformed to be oblate by rotation.
- As a result, the temperature near the rotational axis becomes higher than that near the equatorial plane. (These features are common to the other models)

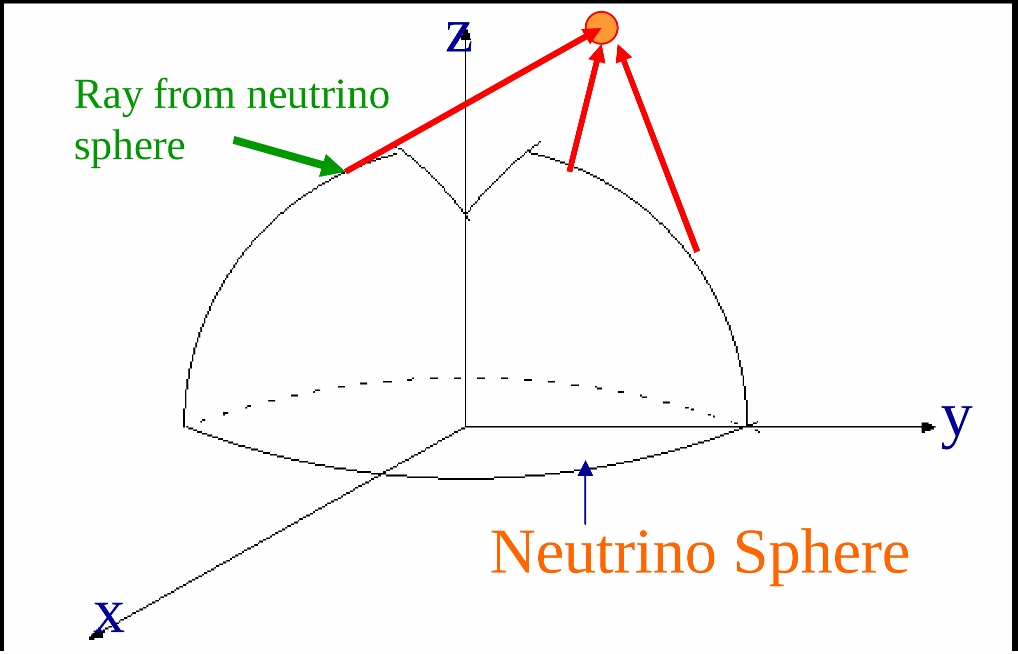
Heating Rates outside the neutrino sphere.

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

Heating Rate $Q_\nu^+ = \frac{3\alpha^2+1}{4} \frac{\sigma_0 c n_j}{(m_e c^2)^2} \int d\epsilon_\nu d\Omega \ \epsilon_\nu^5 \ f_\nu(\epsilon_\nu, \mu)$ (Janka. '01)

Assuming neutrino radiation is isotropic locally, $f_\nu(\epsilon_\nu)$

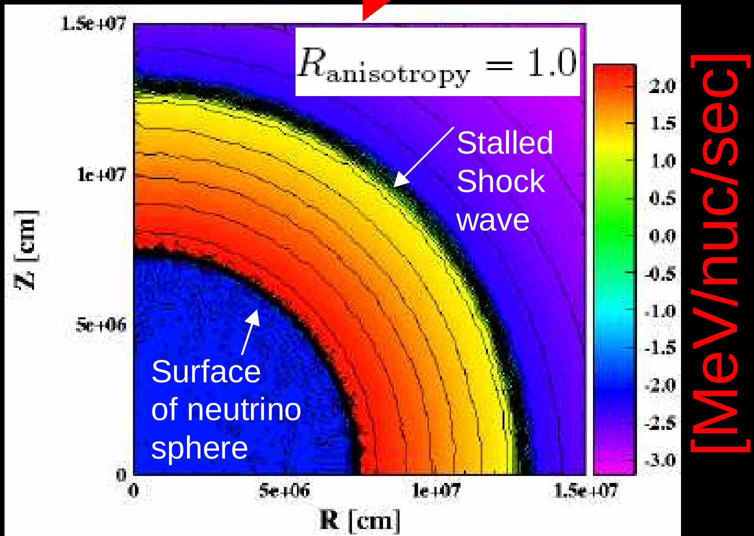
Therefore, $Q_\nu^+ \propto \sum_{\text{all the points on } \nu \text{ sphere}} d\epsilon_\nu \ \epsilon_\nu^5 \ f(\epsilon_\nu) \ \times d\Omega$



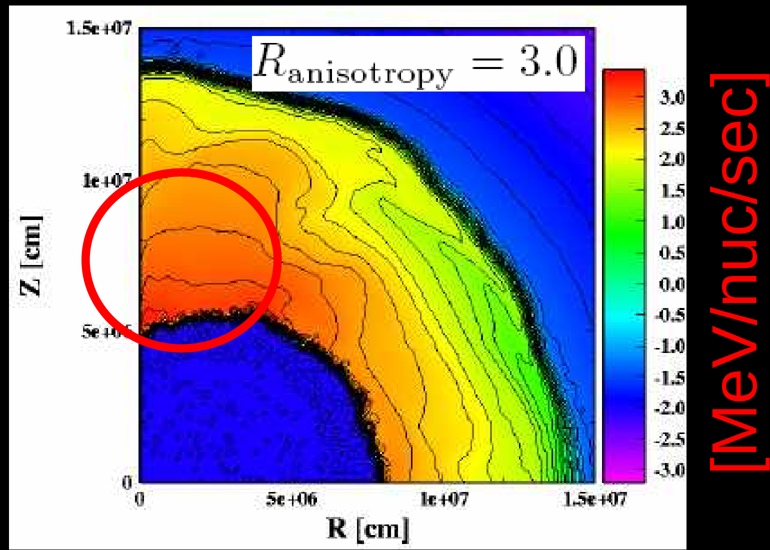
Heating rates outside the neutrinosphere

$R_{\text{anisotropy}} \equiv Q^+_{\nu\ \text{pole}} / Q^+_{\nu\ \text{equator}}$

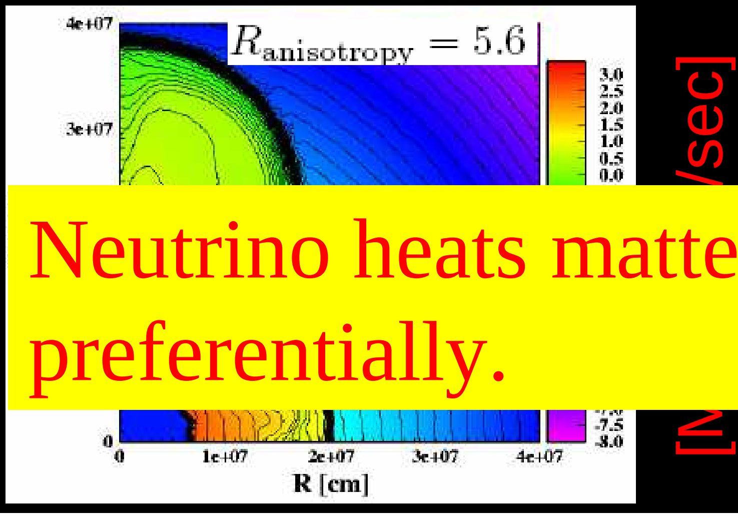
Spherical model



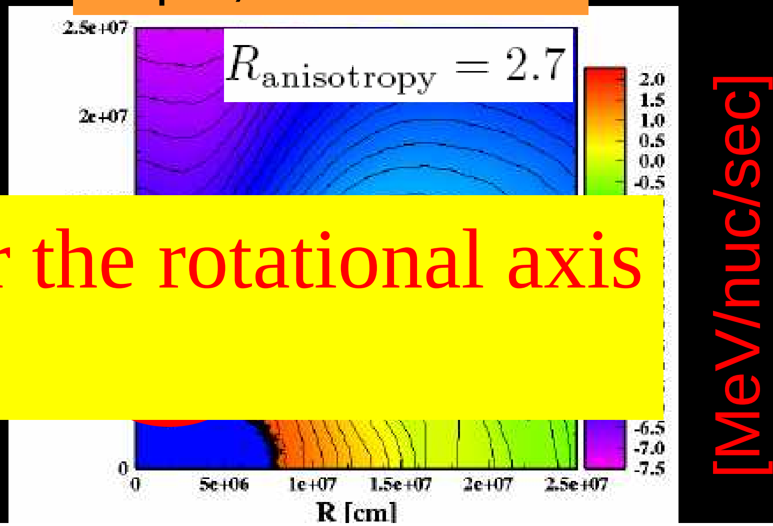
Moderate, weak diff rot (Heger's)



Moderate, strong diff rot.



Rapid, weak diff rot



Neutrino heats matter near the rotational axis preferentially.

Convective stability analysis

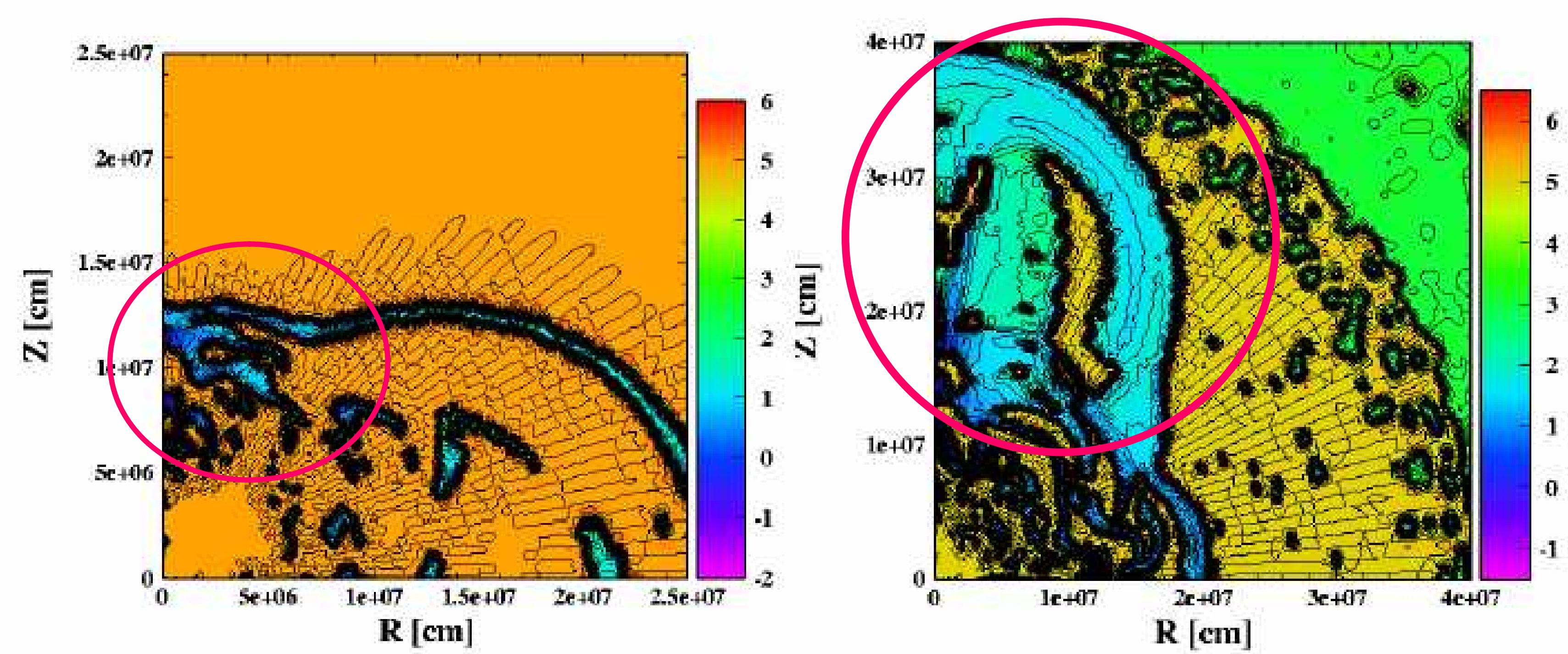
Solberg & Høiland instability condition,

$$\frac{1}{X^3}\frac{dj^2}{dX} + \frac{\vec{a}}{\rho}\left[\left(\frac{\partial\rho}{\partial S}\right)_{P,Y_l} \mathrm{grad}\ S + \left(\frac{\partial\rho}{\partial Y_l}\right)_{P,S} \mathrm{grad}\ Y_l\right] \leq 0$$

Høiland condition

Ledoux condition

(j ; specific ang. momentum, X:distance from the rotational axis, $\vec{a}$ is effective gravity)



Convection are likely to occur near the rotational axis (~10 ms).

Detailed estimation of neutrino emissivity

Multigroup Flux Limited Diffusion Scheme (MGFLD) KK et al in prep

Input neutrino physics

Neutrino interactions	Bruenn (1985)
$\nu_e + n \rightleftarrows e + p$	Absorption and emission on nucleons
$\bar{\nu}_e + p \rightleftarrows e^+ + n$	Absorption and emission on nucleons
$\nu_e + A \rightleftarrows e + A'$	Absorption and emission on nuclei
$\nu + e \rightleftarrows \nu + e$	Neutrino electron scattering
$\nu + N \rightleftarrows \nu + N$	Isoenergetic scattering (recoils are neglected)
$\nu + A \rightleftarrows \nu + A$	Coherent scattering on nuclei(recoils are neglected)
$e + e^+ \rightleftarrows \nu + \bar{\nu}$	Pair reactions
$\nu + \bar{\nu} + N + N \rightleftarrows N + N$	Nucleon bremsstrahlung

Radiation equations with LP flux limitter

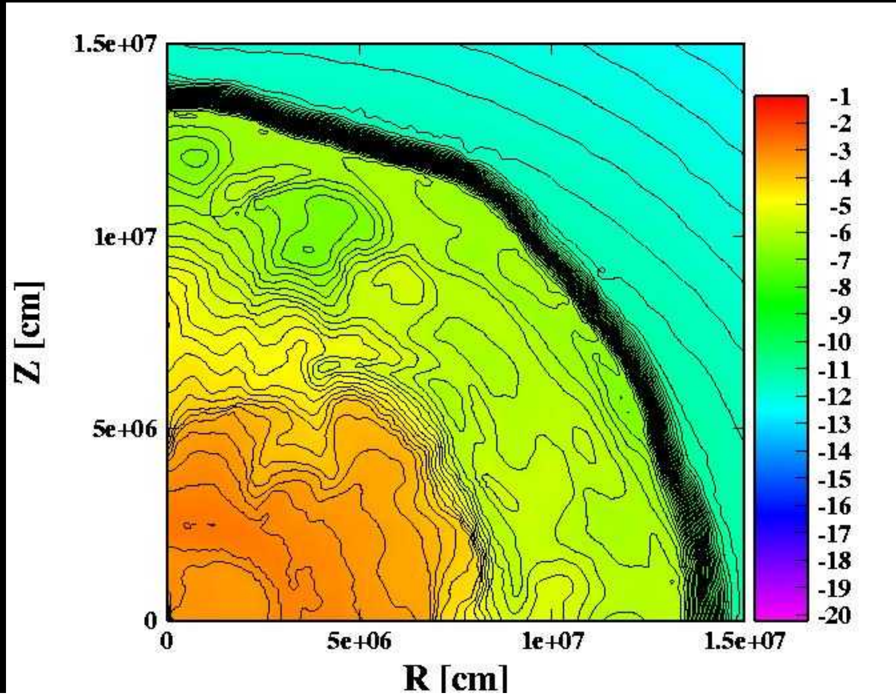
$$\frac{1}{c}\frac{\partial \psi_0}{\partial t} - \nabla \cdot [\boldsymbol{\Lambda}(\nabla\psi_0 - \boldsymbol{A}_1\psi_0 - \boldsymbol{C}_1)] + \nabla \cdot \boldsymbol{v}\ \omega \frac{\partial}{\partial \omega}\psi_0 = j(1-\psi_0) - \frac{\psi_0}{\lambda^a} + A_0\psi_0 + \boldsymbol{B}_0 \cdot \boldsymbol{\psi}_1 + C_0.$$

$$\frac{\partial Y_e}{\partial t} = -\frac{m_u}{\rho}\frac{4\pi c}{(2\pi\hbar c)^3}\int_0^\infty \omega^2 d\omega \left\{ j(\omega)[1-\psi_0(\omega)] - \frac{\psi_0(\omega)}{\lambda^a(\omega)} \right\}$$

$$\left(\frac{\partial E}{\partial t}\right) = -\frac{4\pi c}{(2\pi\hbar c)^3}\int_0^\infty \omega^3 d\omega \{ j(\omega) - [j(\omega) + 1/\lambda^{(a)}(\omega) - A_0(\omega)]\psi_0(\omega) + B_0(\omega)\psi_1(\omega) + C_0(\omega)\}.$$

Neutrino Emissivity in rotating core

(~30msec after bounce of Heger's rotating evolution model : Omega_0 ~ 4 rad/s)

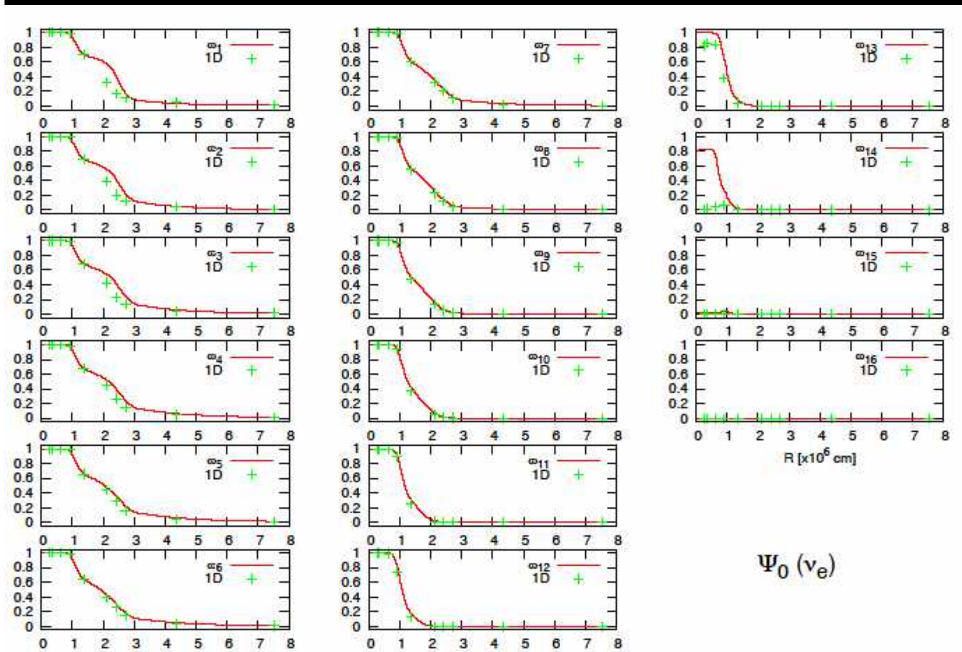


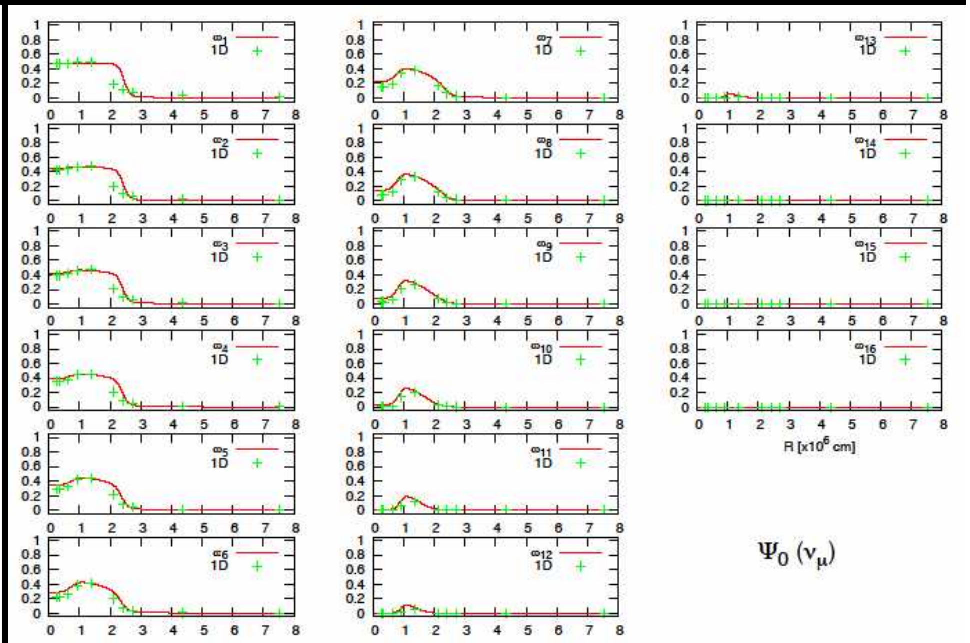
Anisiotropic Neutrino radiations do exist

Test Calculations of our MGFLD code

Kotake, Ohnishi, Yamada, Sato, 2005 in prep.

Distribution function of electron-neutrino/muon-neutrino per neutrino energy-bin (16 energy mesh-points from 0.9MeV ~ 110 MeV logarithmically)





Compared with the Monte Carlo simulations by Janka et al, our code is able to successfully reproduce their result.

Short Summary of Effect of rotation on neutrino heating

(1) Neutrino spheres are deformed to be oblate due to rotation, and the temperatures on the spheres are higher near the rotational axis.

(2) Neutrino radiation from the deformed neutrino sphere heats matter near the rotational axis more preferentially.

(3) Regions near the rotational axis are convective unstable.

These results suggest that the jet like explosion might be induced. (Shimizu et al. '01)

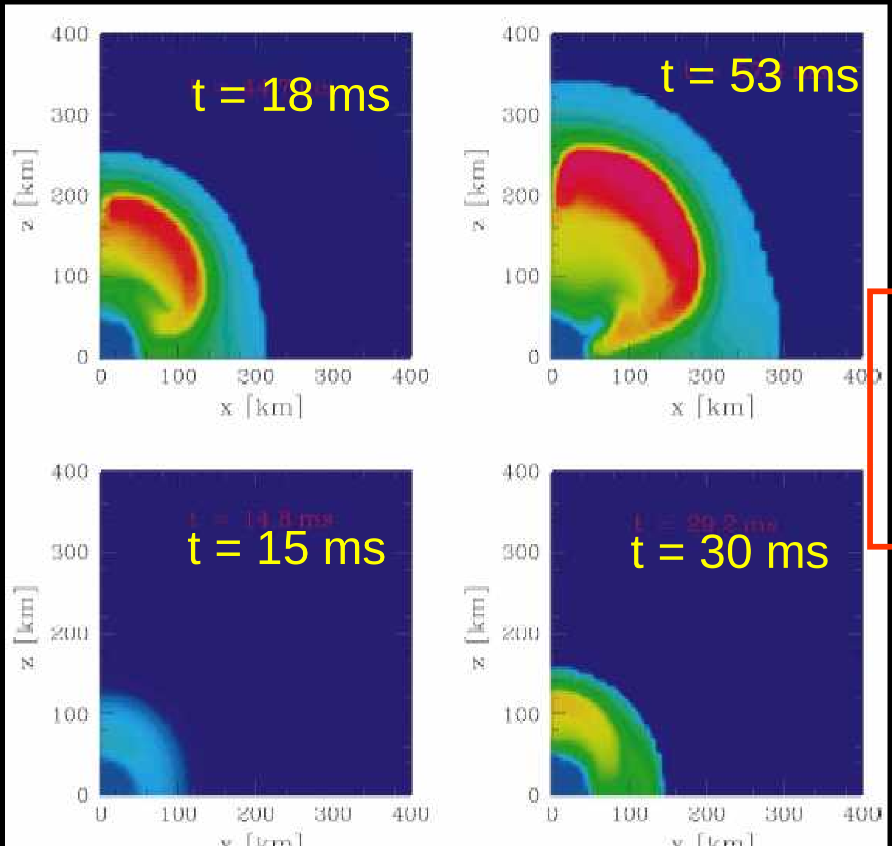
Is anisotropic neutrino radiation good for explosion ?

Shimizu et al. 01, Madokoro et al. 03,04

--- 2D hydro

--- light bulb approx from the fixed neutrino sphere

--- outside neutrino sphere only

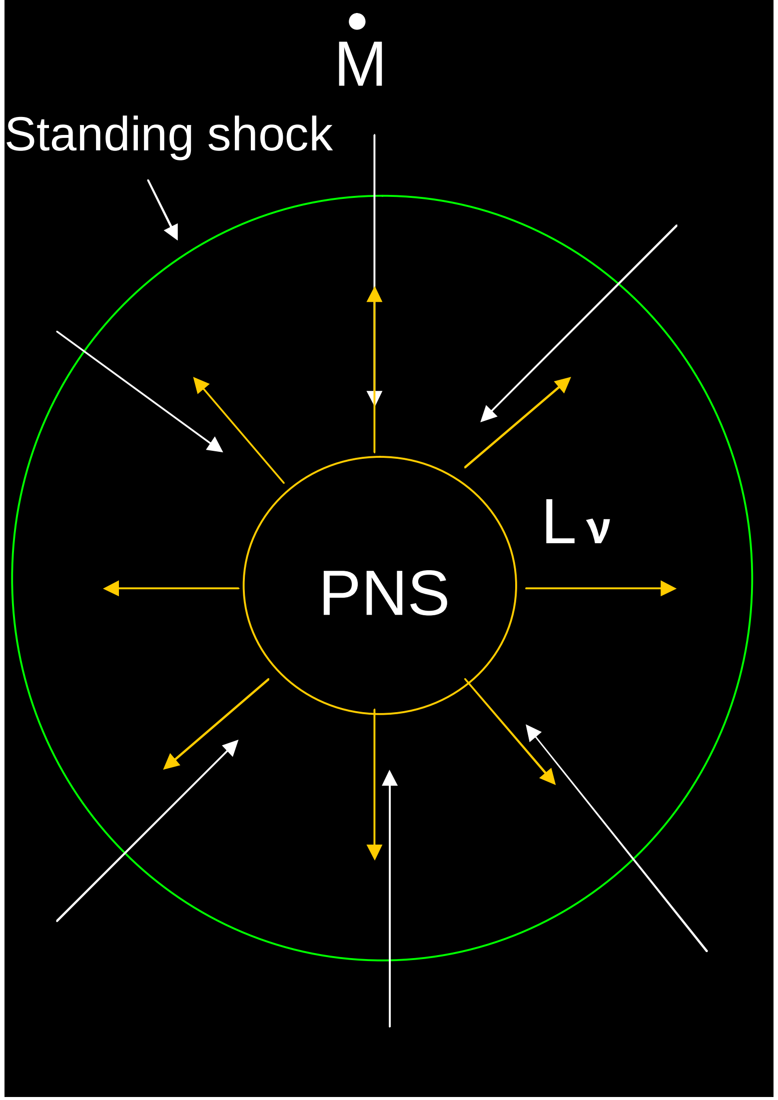


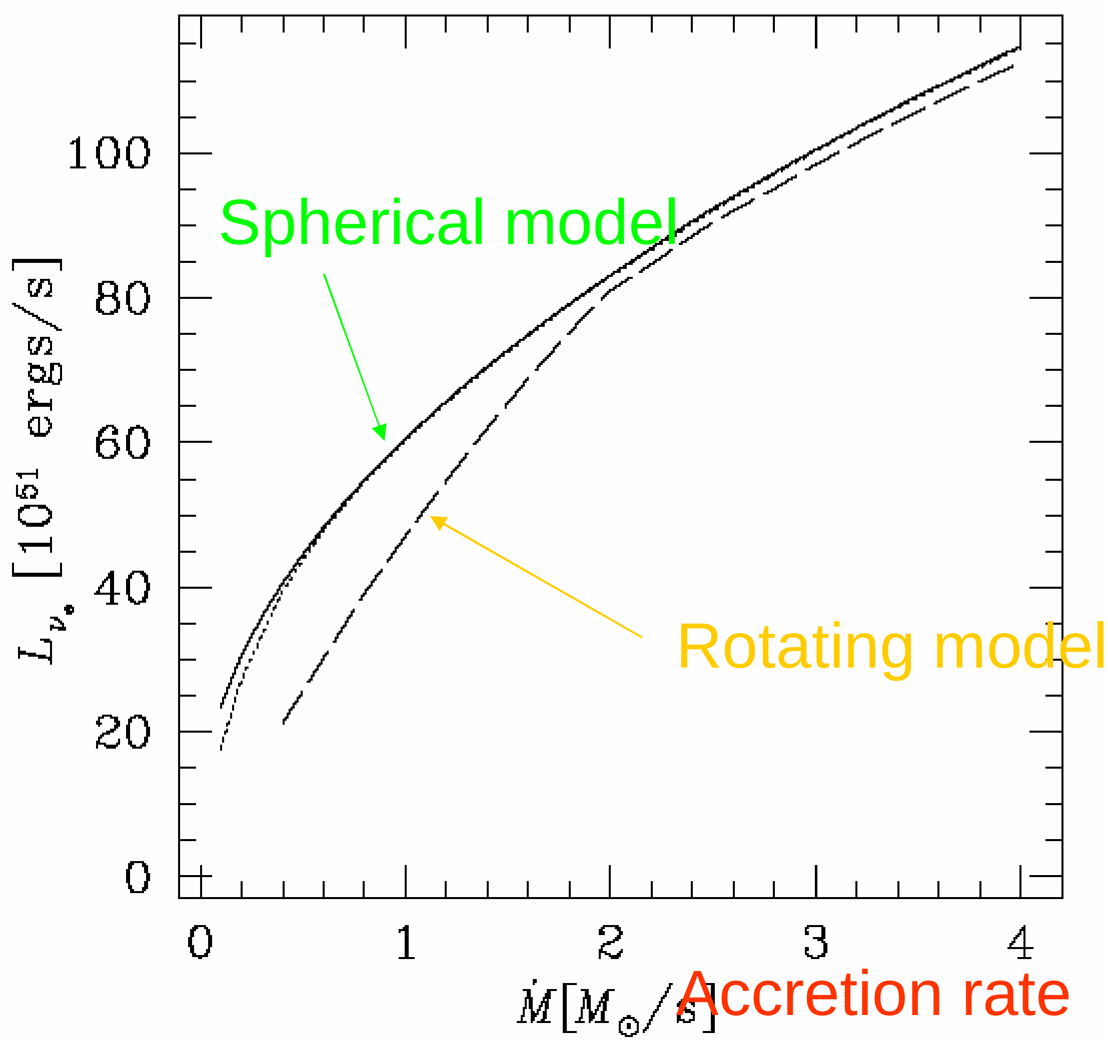
If the anisotropic neutrino heating survives in the later phases, it will be good!

Is anisotropic neutrino rad. good for explosion？

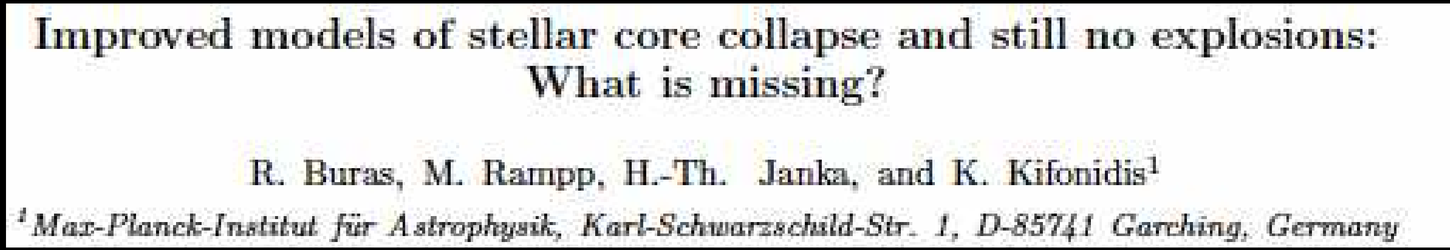
Evidence ２、critical luminosity for shick revival is lowered

(Yamada,KK,Yamasaki,2004、Yamasaki& Yamada05)





Rotational Core-collapse with Detailed neutrino transport

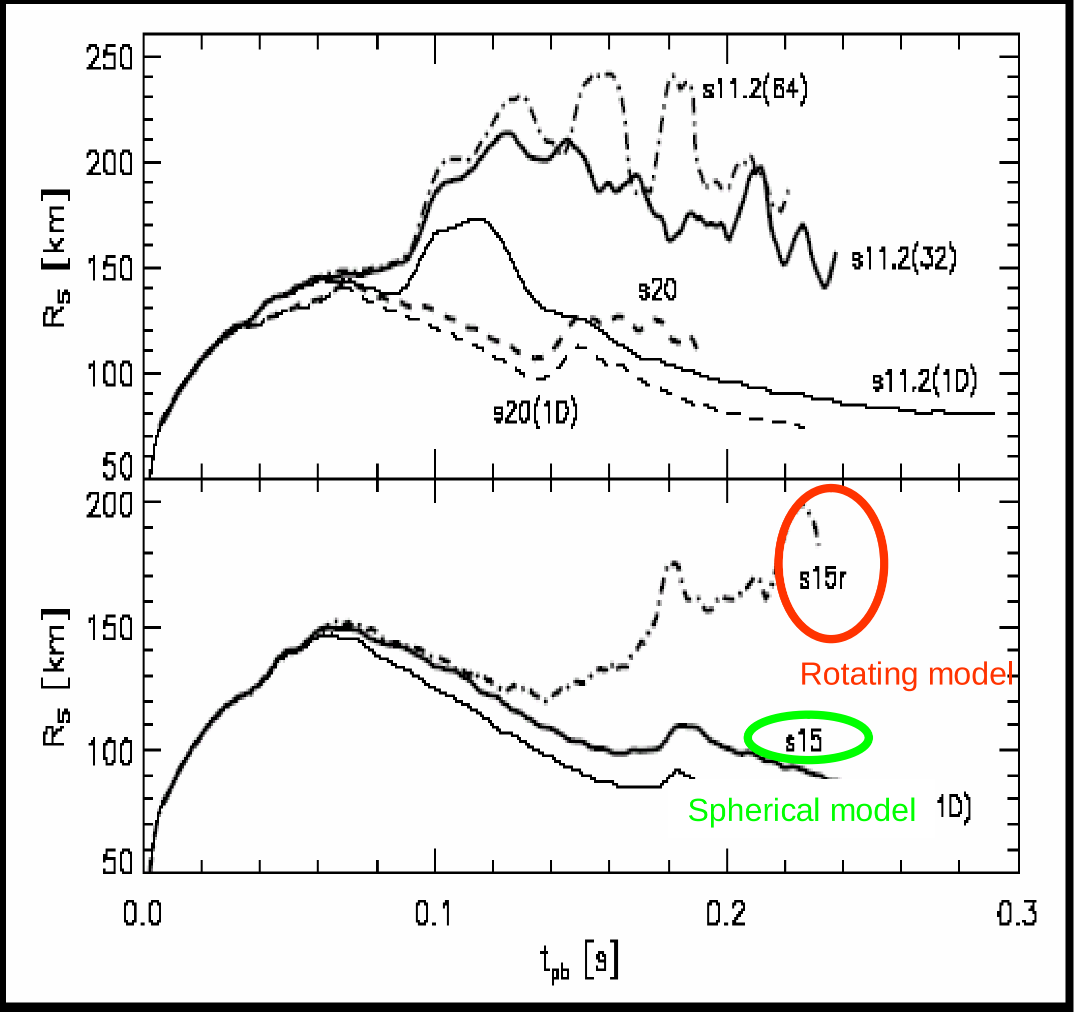

Improved models of stellar core collapse and still no explosions: What is missing?

R. Buras, M. Rampp, H.-Th. Janka, and K. Kifonidis[1]

[1] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85741 Garching, Germany

Hydro:2dim Newtonian
Neutrino transfer: VEF
(must be one dimension)
Input physics: state-of-art
Weak interactions

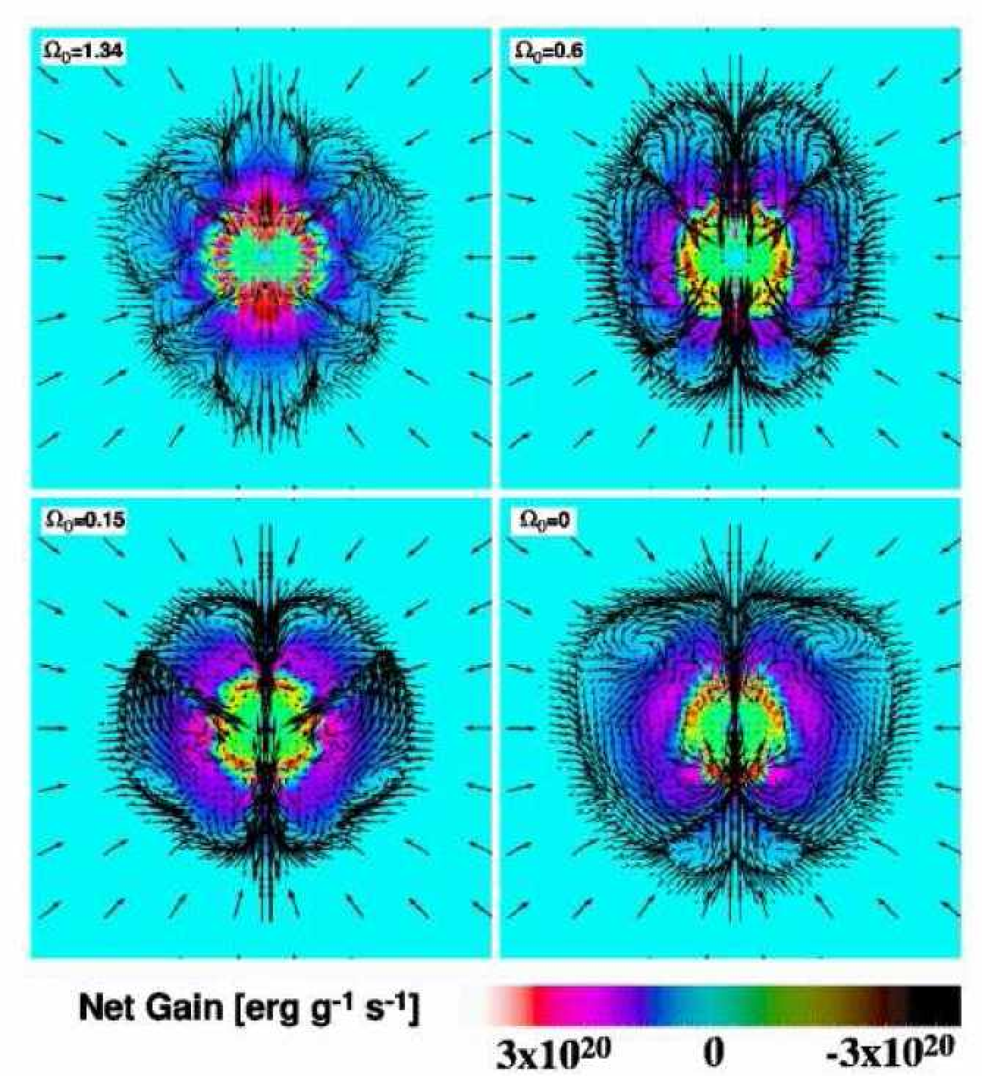
Lateral heating of Neutrino should be Important!



December 2004

Anisotropies in the Neutrino Fluxes and Heating Profiles in Two-dimensional, Time-dependent, Multi-group Radiation Hydrodynamics Simulations of Rotating Core-Collapse Supernovae

R. Walder[1], A. Burrows[1], C.D. Ott[2], E. Livne[3], M. Jarrah[4]



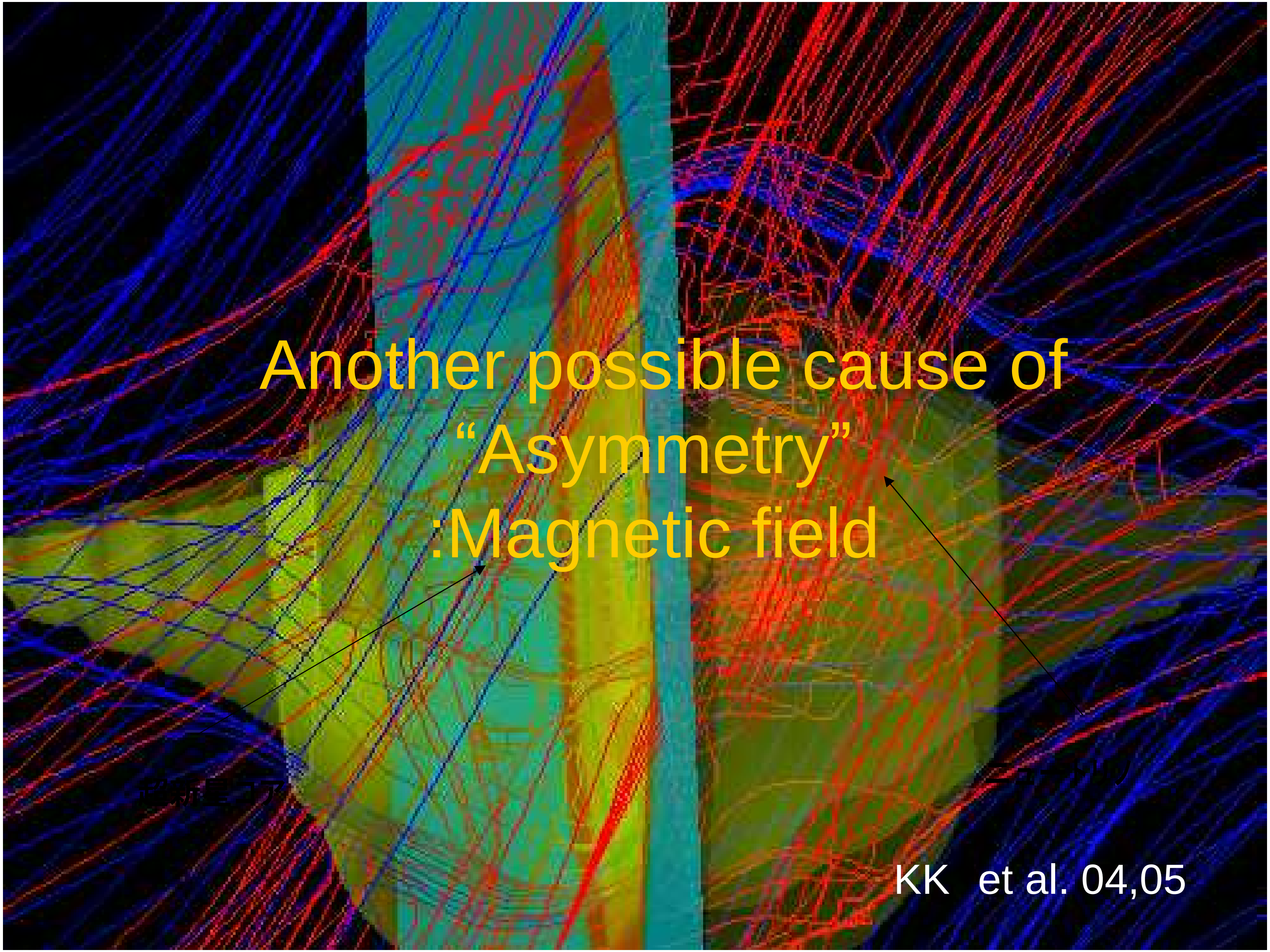
Anisotropy ratio is about 1 ~ 2.5

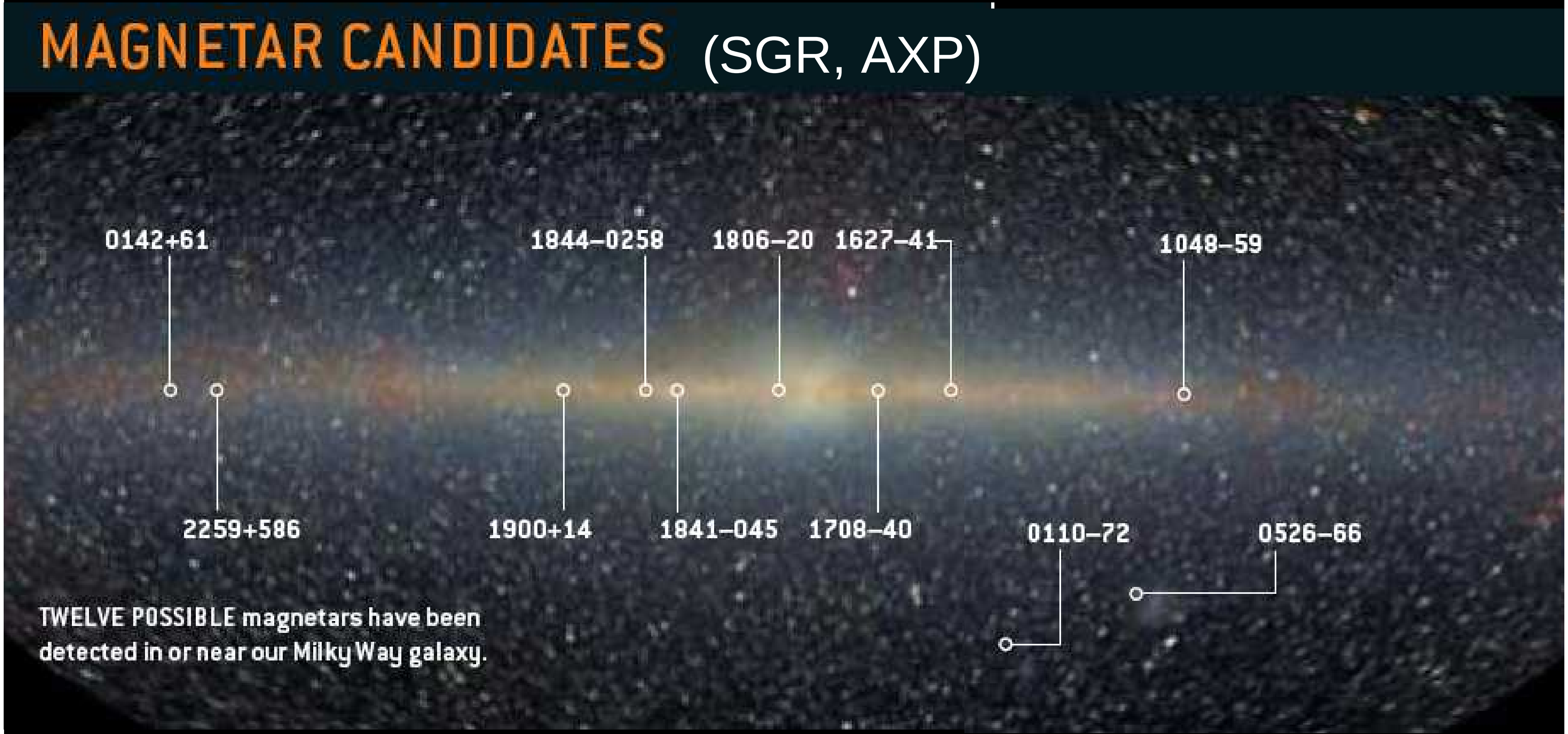
↑

Consistent with ours

↕

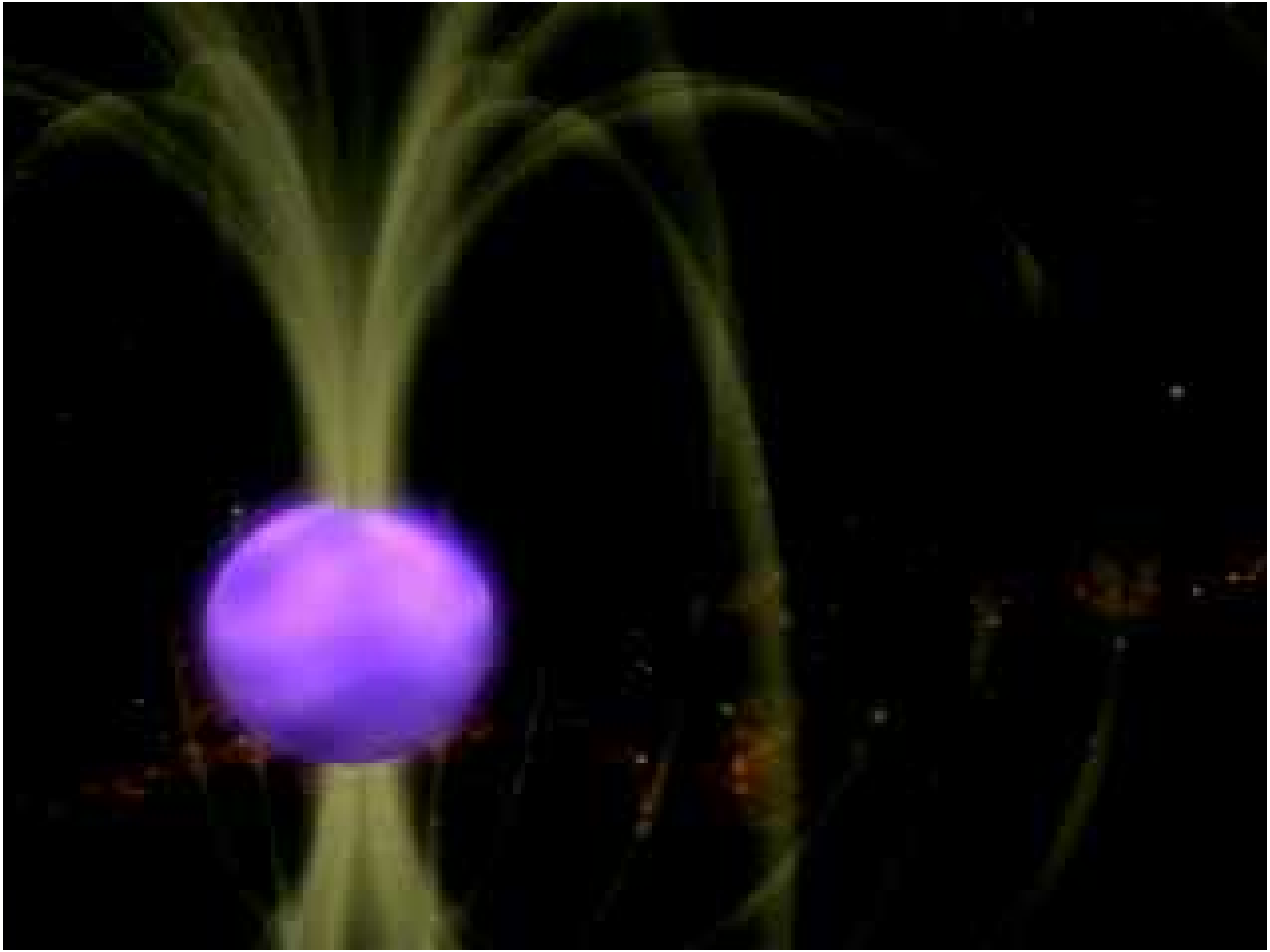
Not mentioned yet that explosion is really obtained.


Another possible cause of
"Asymmetry"
:Magnetic field
超新星コア
ニュートリノ
KK et al. 04,05



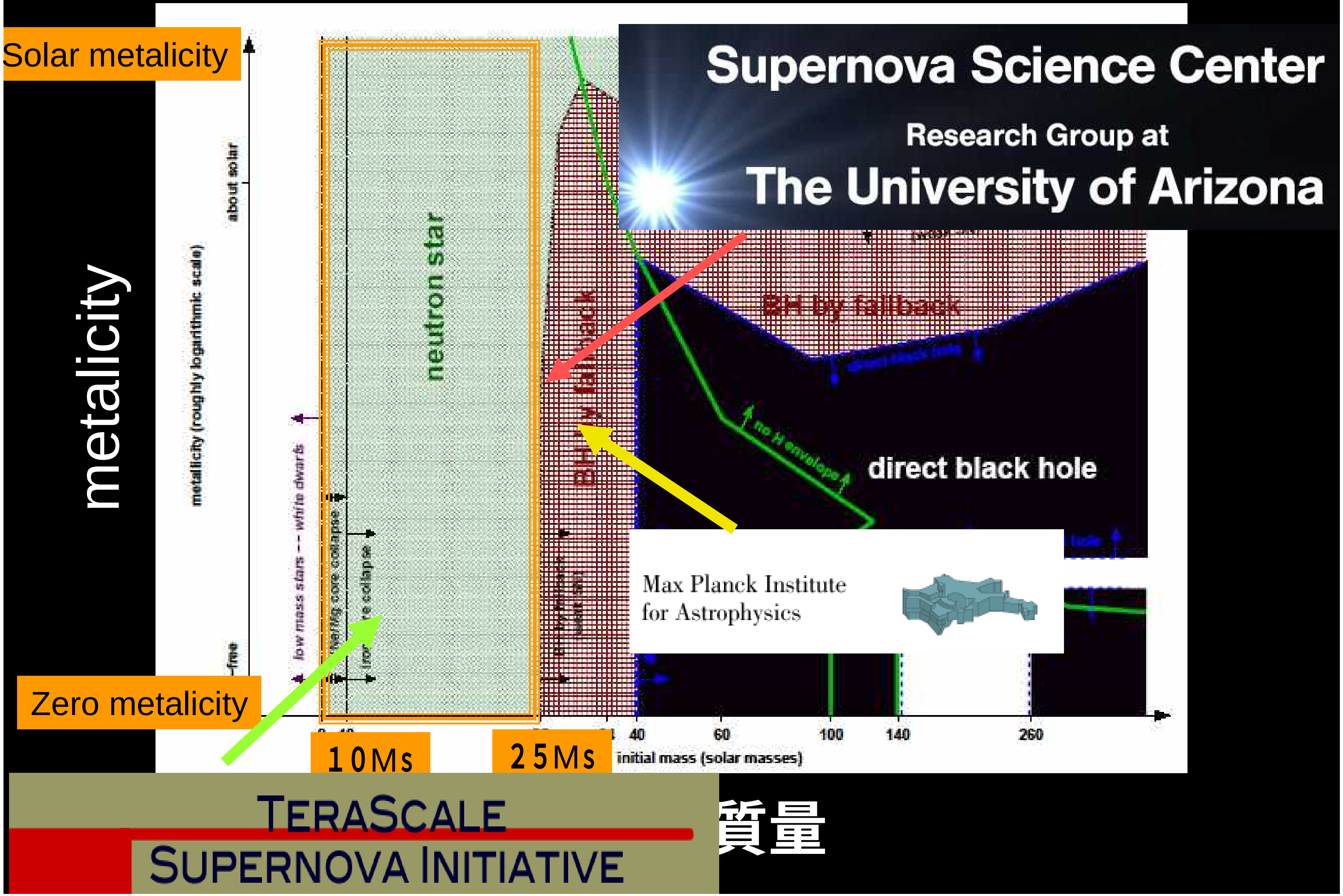
Kouveliotou et al. 2003

- 12 magnetars are known
- concentrated on the galactic plane



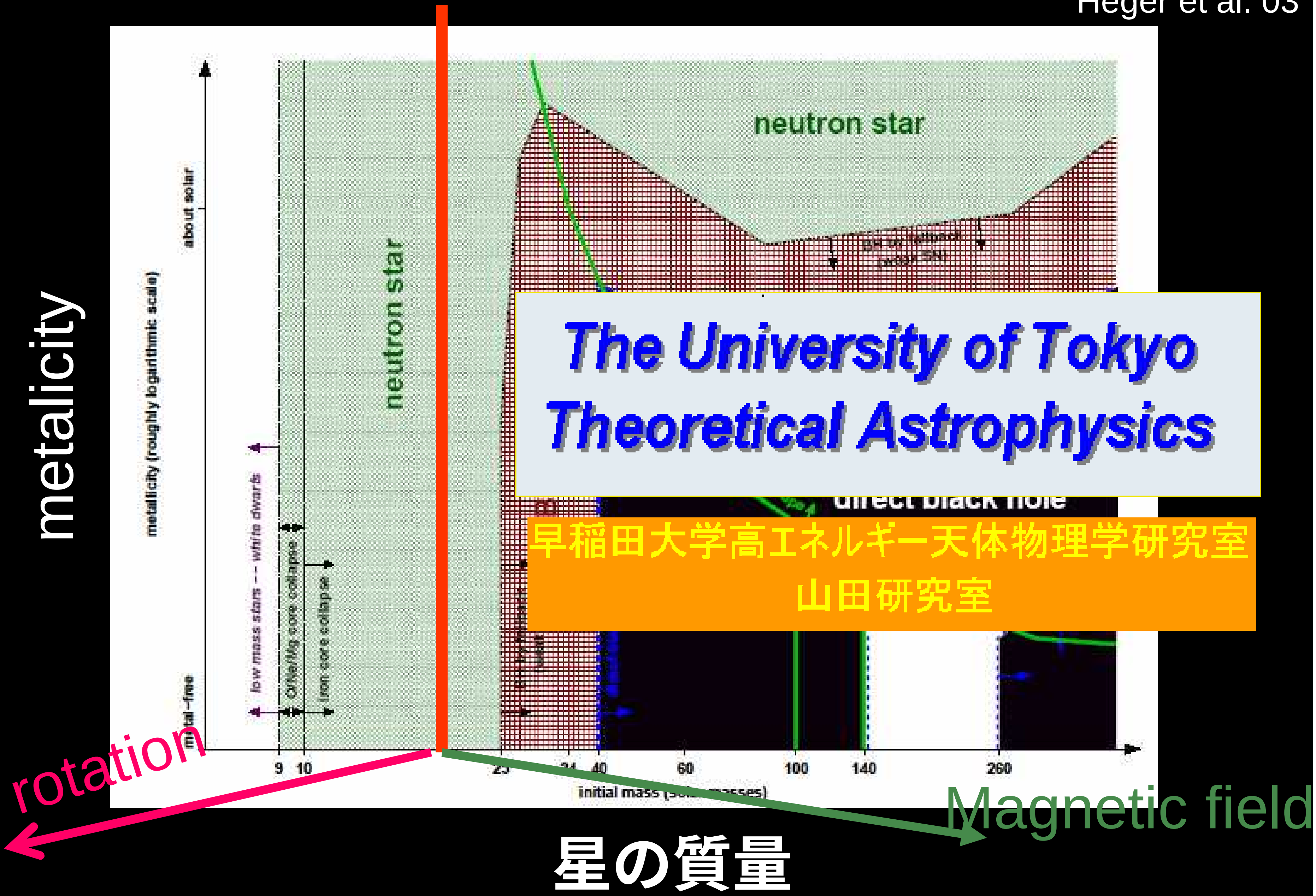
How massive stars end their life ?

Heger et al. 03



How massive stars end their life ?

Heger et al. 03



Magnetohydrodynamic Effects on Core-Collapse Supernovae

Yamada & Sawai, ApJ, (2004)
Takiwaki,KK,Nagataki,Sato ApJ (2004)
Sawai, KK, Yamda (2005) ApJ in press

一番問題なのは、初期磁場の強さ

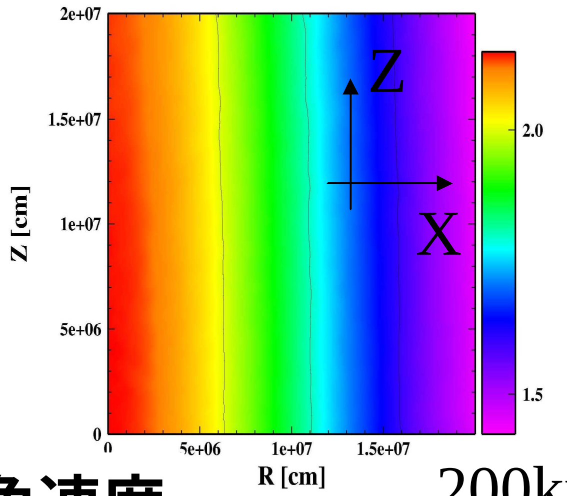
- 初めから強いと仮定。
- 初めは弱くてもダイナモ等で増幅させる。

角速度や初期磁場をいろいろ変えてこれらの影響を調べた

初期条件

$$\Omega = \Omega_0 \times \frac{X_0^2}{X^2 + X_0^2} \cdot \frac{Z_0^4}{Z^4 + Z_0^4}$$

$X_0 = 100\mathrm{km}, Z_0 = 1000\mathrm{km}$

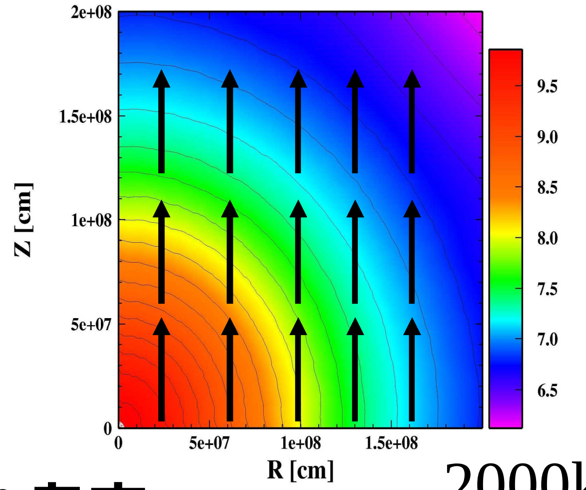


角速度

200km

一様 Poloidal な

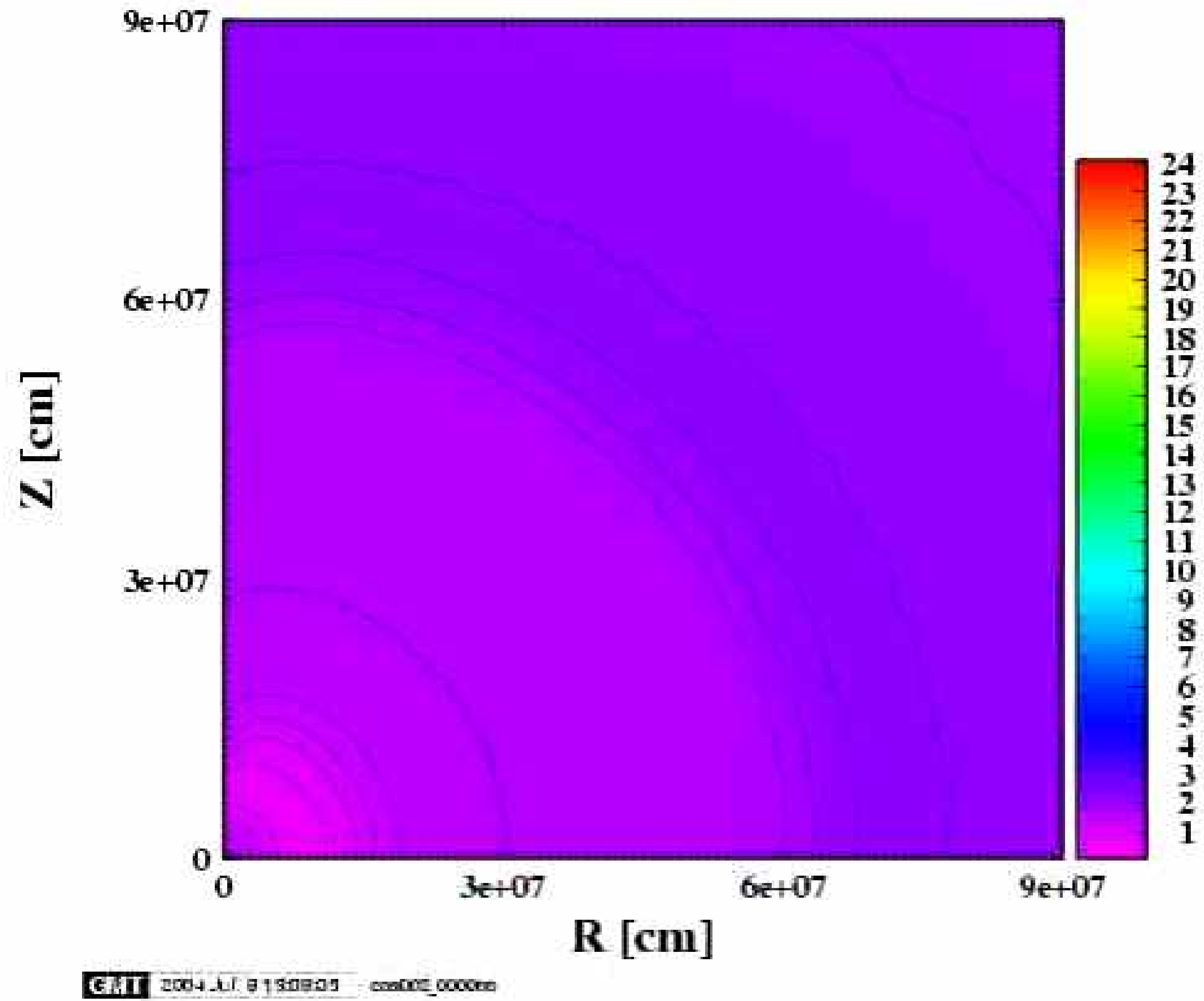
$B_z = B_p(\mathrm{const.})$



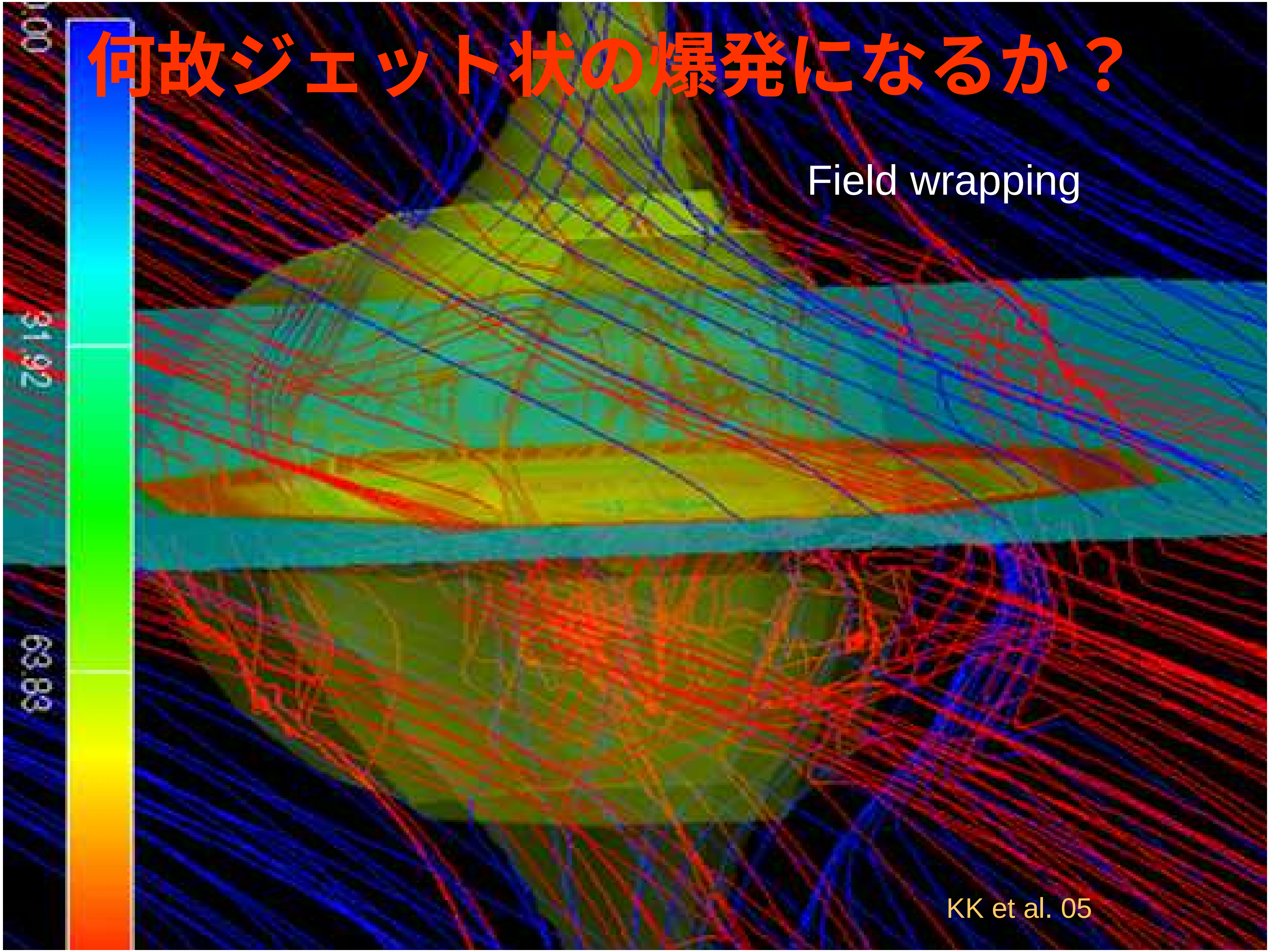
密度

2000km

親星は、
２０太陽質量モデル


9e+07
6e+07
3e+07
0
Z [cm]
0
3e+07
6e+07
9e+07
R [cm]
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1

何故ジェット状の爆発になるか？

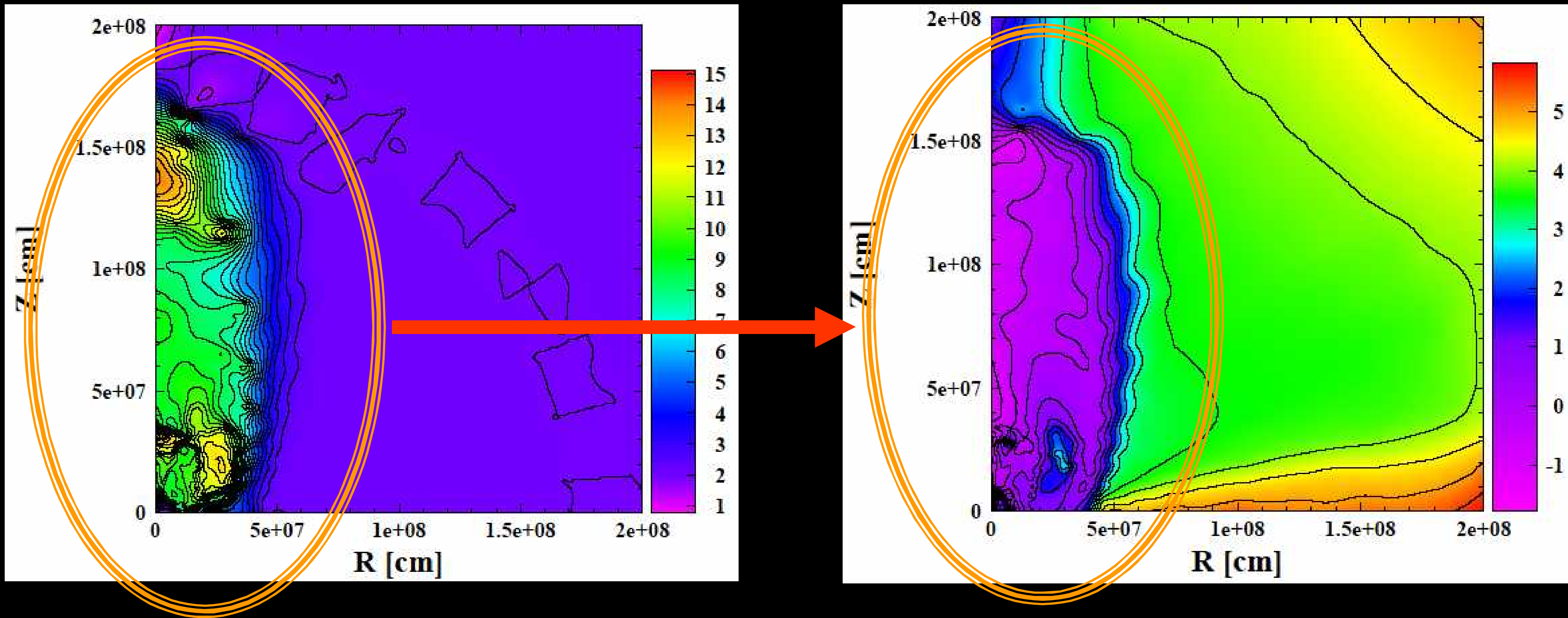


何故ジェット状の爆発になるか？

Contour of plasma β

$: P_{mag} / P_{matter}$

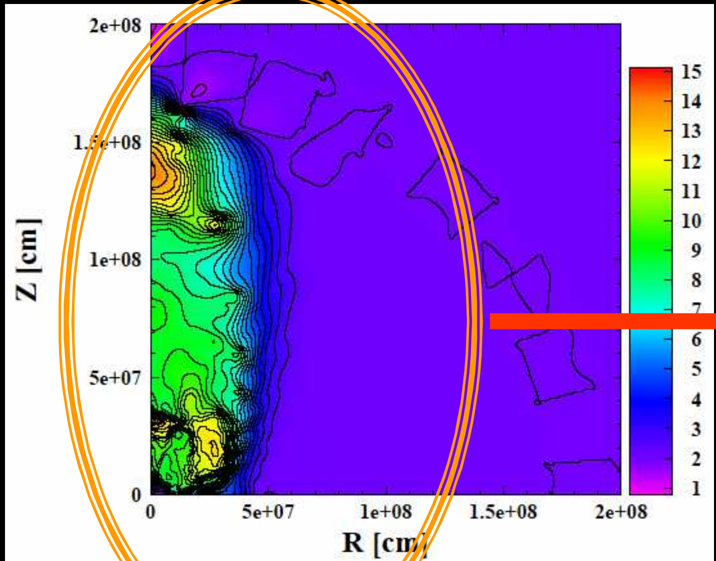
Contour of entropy per baryon



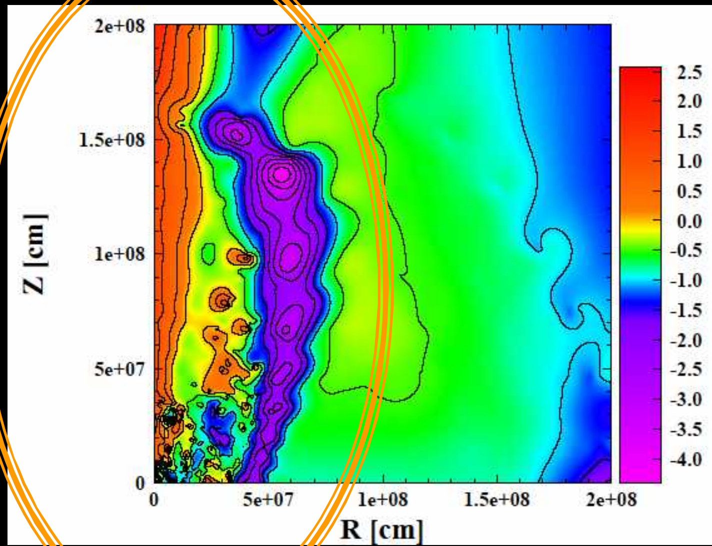
Shock wave is shown to be magneto-driven.

何故ジェット状の爆発になるか？

Contour of entropy per baryon



Contour of F_{hoop}/F_{mag}



The hoop stress, 磁場で絞る効果

$F_{hoop} = \frac{B_\phi^2}{X}$

magnetic pressure, 磁場で膨らむ効果

$F_{mag} = \frac{1}{2}\frac{\partial B_\phi^2}{\partial X}$

磁場の効果で絞られている。
これがjet-like explosionの原因

爆発の強さの比較のまとめ

Takiwaki,KK,Nagataki,Sato(2005)

T/|W|　　弱磁場でも爆発に寄与

磁場(ガウス)

	1%	2%	4%
0	0	0	0
10^9	0.05	0.00077	0
3×10^{10}	4.7	0.73	0.03
10^{12}	44.0	5.6	1.8

最大　　爆発のエネルギー(10^50 erg)

回転↑
↓
細い衝撃波
爆発のエネルギー↓

磁場↑
↓
細い衝撃波
爆発のエネルギー↑

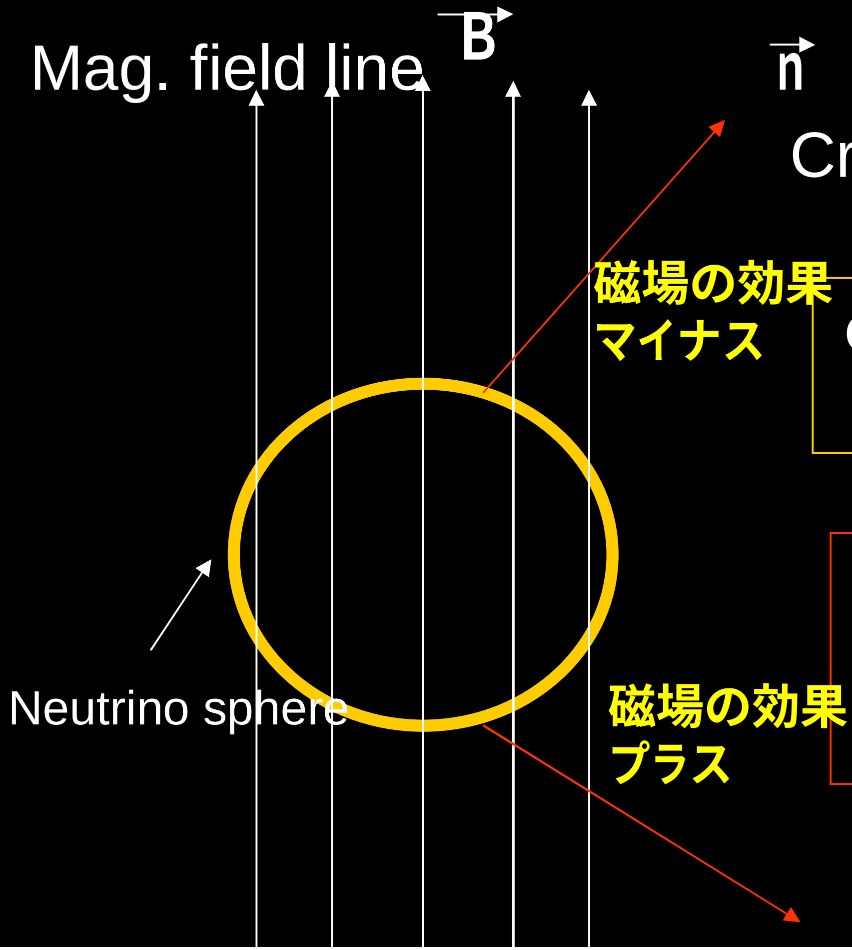
爆発のエネルギーはShock Frontが1500kmに達したときにエネルギーが正の部分の和

爆発は回転が弱く磁場が強いほうが強い。

North-South heating asymmetry in strongly magnetized core and pulsar kicks

(KK et al. 2005)

Weinberg & Salam theory -> parity violation
: left-handed neutrinos



Cross section：

Horowitz 1999, Duan and Qian 03, Ando 03

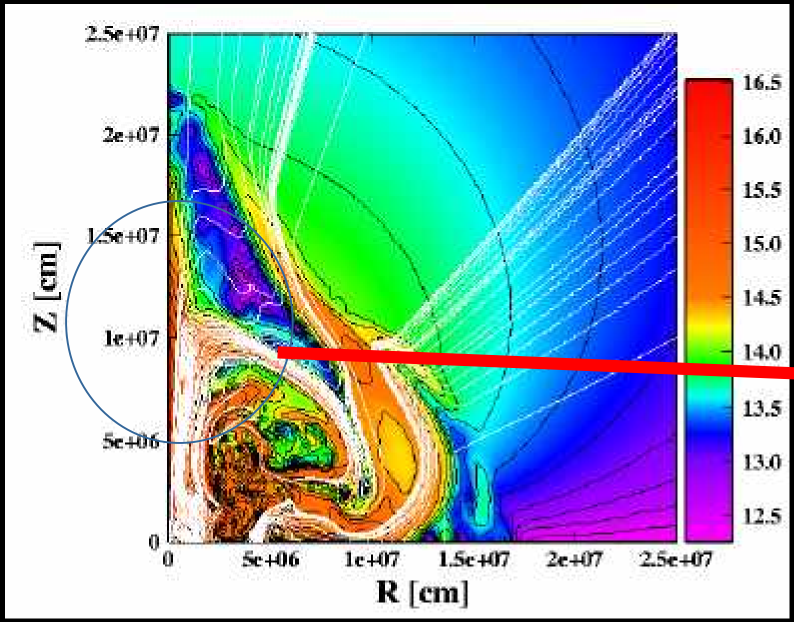
$$\sigma(B) = \sigma(B=0)\,(1 + \vec{n}\cdot\vec{B}\,\alpha)$$

Neutrino heating becomes north-South asymmetric
> Cause for the pulsar kick

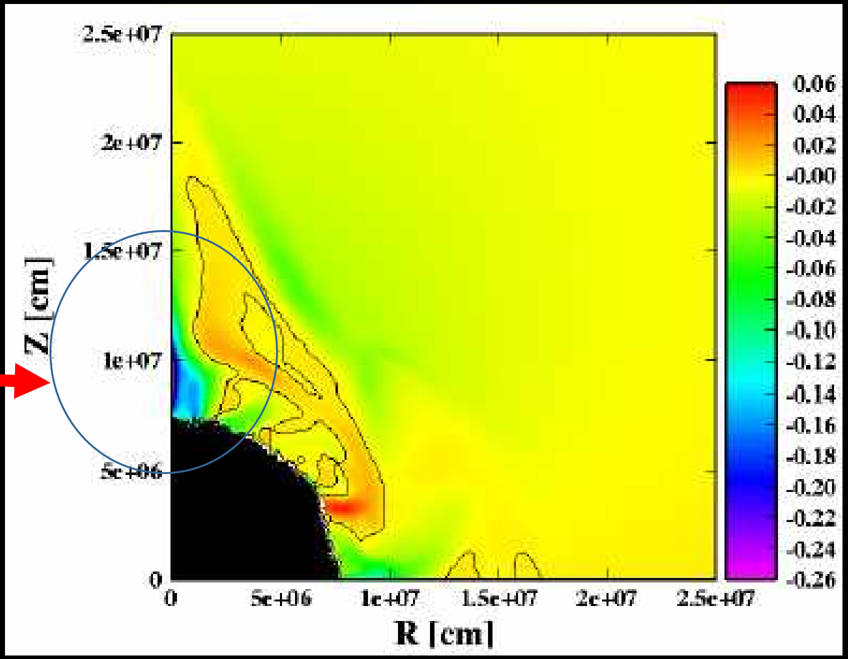
Neutrino heating rate in the strongly magnetized core

Standard model

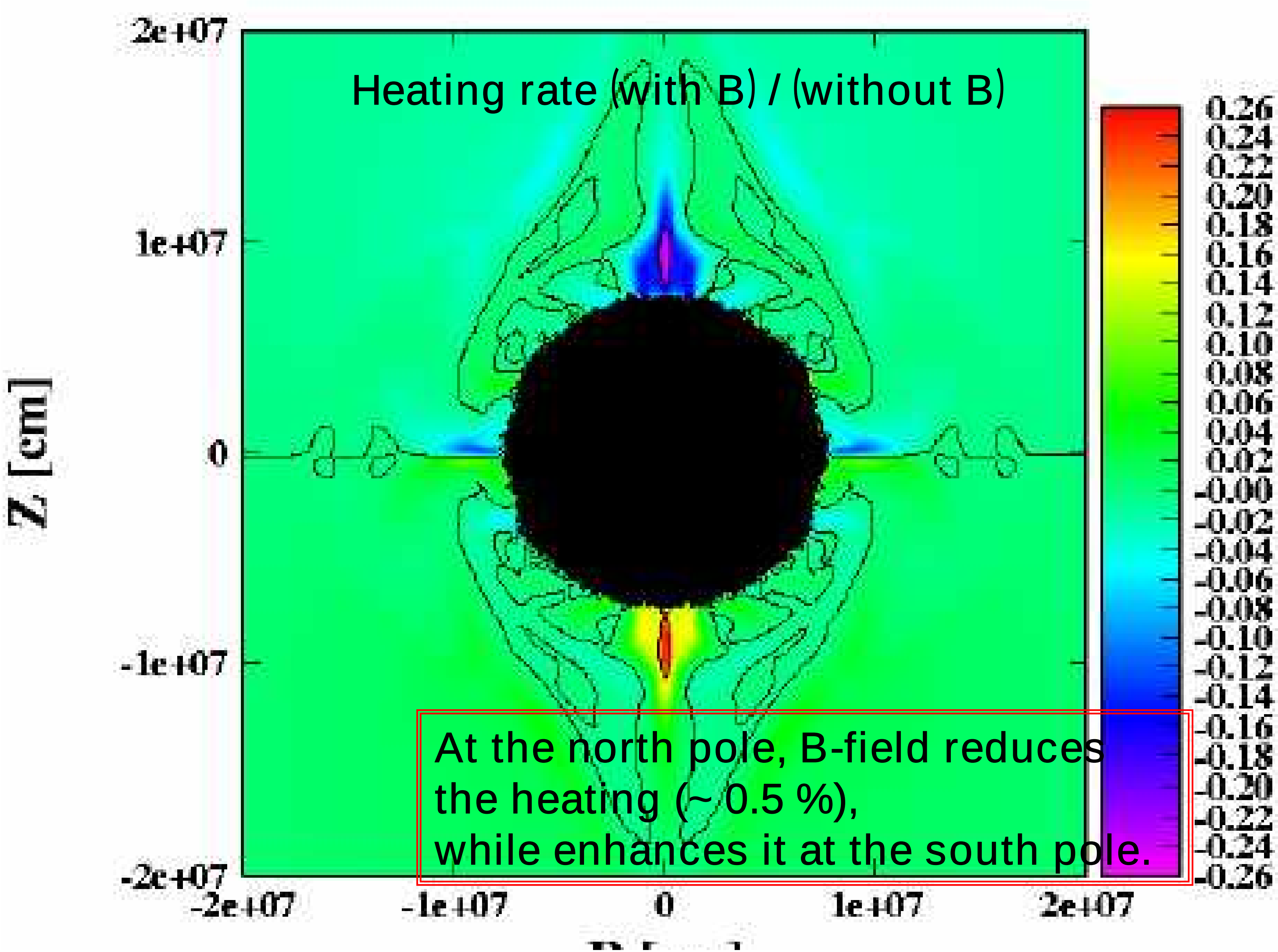
Configuration Of B-field



Heating rate (with B) / (without B)



Along the rotational axis, B-field is in the same direction.
Strength of B-field is strongest there.
−> B-field plays an important role for producing the asymmetry


Heating rate (with B) / (without B)
At the north pole, B-field reduces
the heating (~ 0.5 %),
while enhances it at the south pole.
Z [cm]
2e+07
1e+07
0
-1e+07
-2e+07
-2e+07
-1e+07
0
1e+07
2e+07
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
-0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
-0.16
-0.18
-0.20
-0.22
-0.24
-0.26

<u>Meaning of ～0．5　% of the neutrino heating asymmetry</u>

Scheck et al. (2004) added 0.1 % random density perturbation

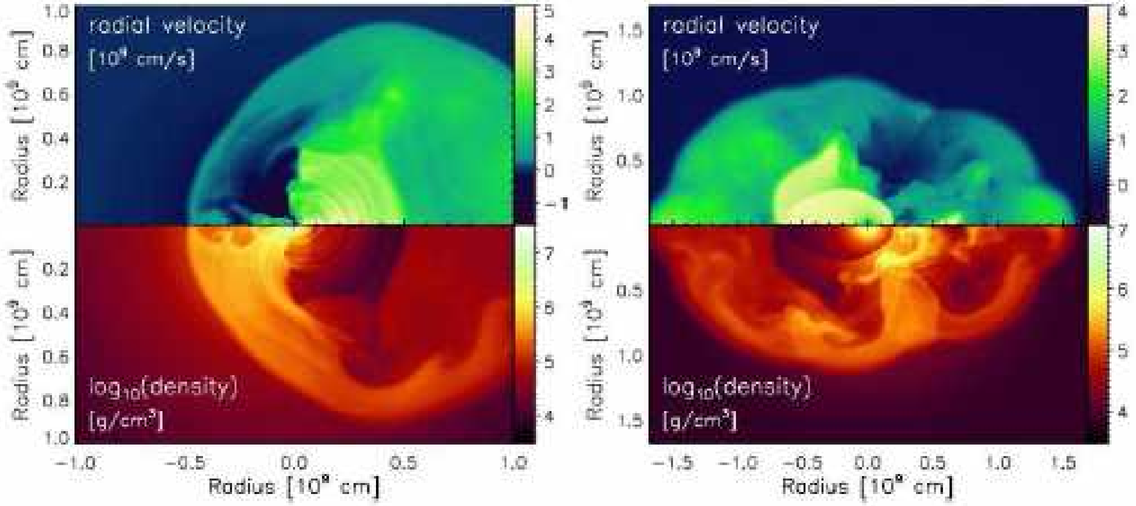
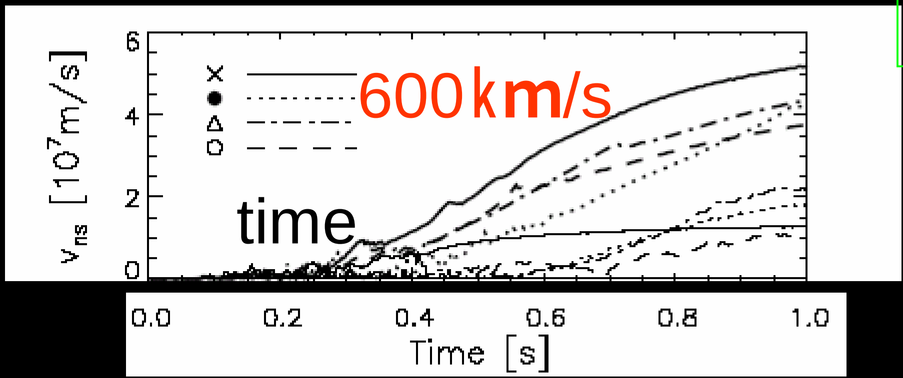


FIG. 2: Two models (based on progenitor WPE15) at 1 s after SN shock formation. The PNS is at the coordinate center. The left plot (scale reduced to show more details) displays a case with $L_{\mathrm{ib}} = 2.97 \times 10^{52}$ erg s^{-1}, $E_{\mathrm{exp}} = 0.4 \times 10^{51}$ erg, and a recoil velocity of $v_{\mathrm{ns}} = -350$ km s^{-1}. The model on the right has $L_{\mathrm{ib}} = 4.45 \times 10^{52}$ erg s^{-1}, $E_{\mathrm{exp}} = 1.2 \times 10^{51}$ erg, and $v_{\mathrm{ns}} = +520$ km s^{-1}.

In their models, the directions of pulsar kicks are totally random

Our results suggest that the magnetar is kicked toward the north pole of the star.



Short summary of Section 3 :
Asymmetric Supernovae & Explosion mechanism

Why
"Asymmetric" supernovae ??

↑

Although all the known microphysical process are included, spherical models cannot produce explosion.

"Asymmetric" supernovae

Convection

- Good for enhancing neutrino heating, however, only with it, successful explosions are not obtained. (Buras et al. 2003)
- Importance of SASI (Blondin 2002, Fogglizo 2002) (Without rotation or B-field, large anisotropy is likely to be produced.)

Rotation

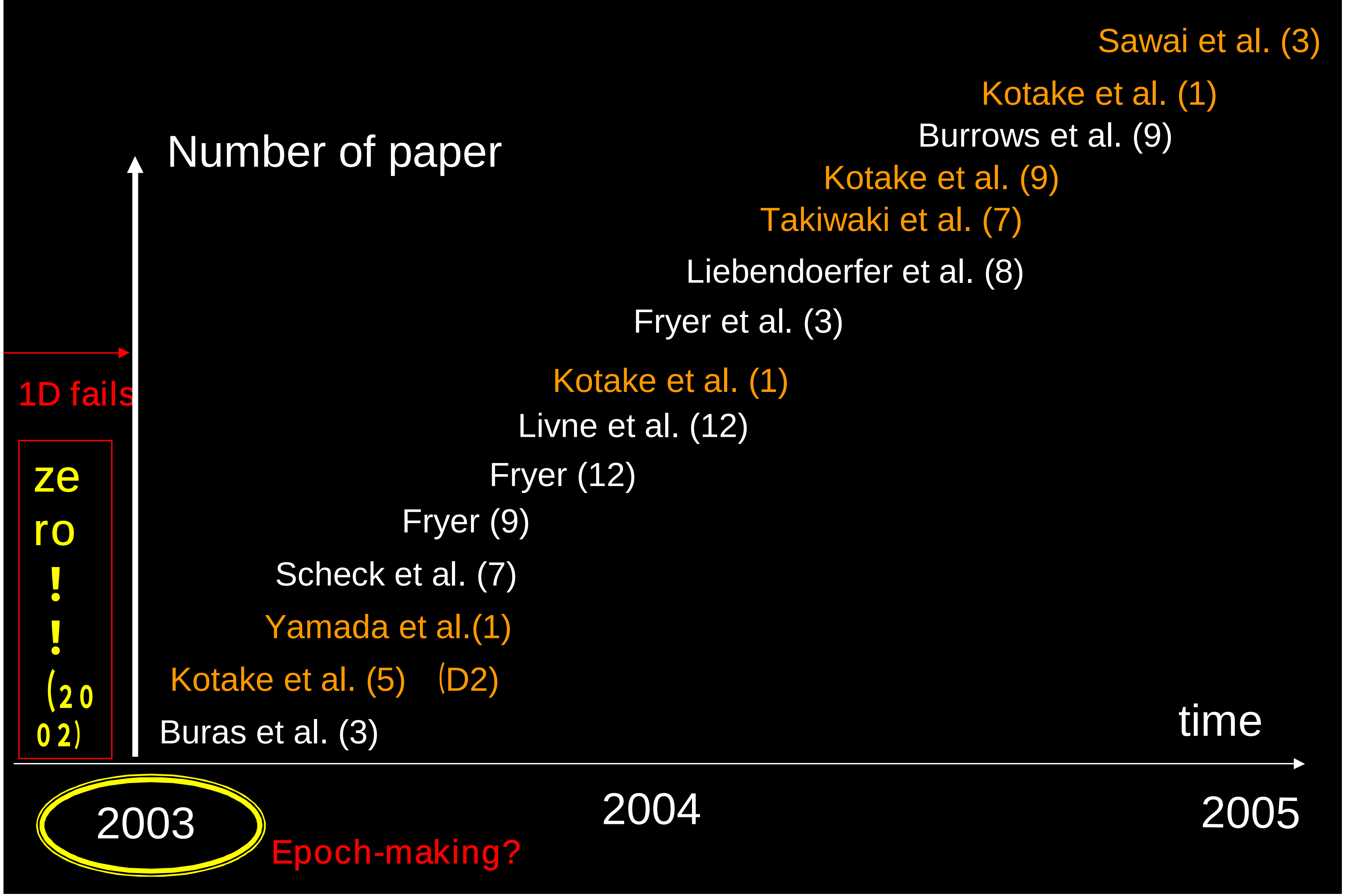
- Rotation induced anisotopic neutrino radiation does really exist. (KK et al. 2003, Walder et al. 05)
- Meanwhile, it is not yet know whether it really produces the explosion (KK et al. in preparation)

Magnetic Field

- Likely to be a seed for the natal kick (KK et al. 2005)
- There remain many issues to be addressed, such as MRI

(Sawai et al. 2005, Takiwaki et al,05)

Since 2003, multi-D studies has begun to blossom



Supernova group (explosionist) in the world

	dimension	neutrino	idea
Germany			
Max Planck Institute for Astrophysics	2D	Boltzmann	SASI
U.S.			
Supernova Science Center Research Group at The University of Arizona	2D	MGFLD	Anisotropic neu. Rad.
TeraScale Supernova Initiative	3D	SEFLD	?
The University of Tokyo Theoretical Astrophysics	2D (B-field)	MGFLD	Anisotropic neu. Rad.

図 14

TAMA300

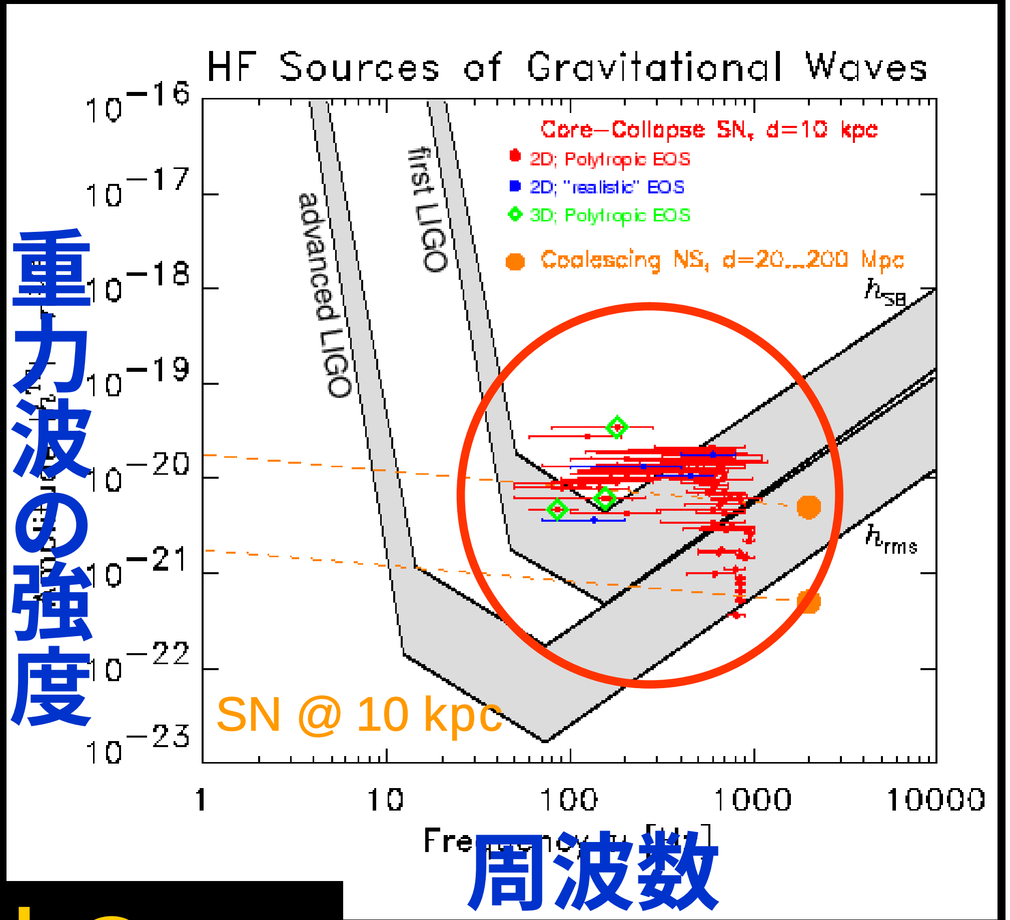
Section 4
Gravitational Waves from core-collapse supernovae

LIGO

Introduction

重力崩壊型超新星爆発

重力波の放出源

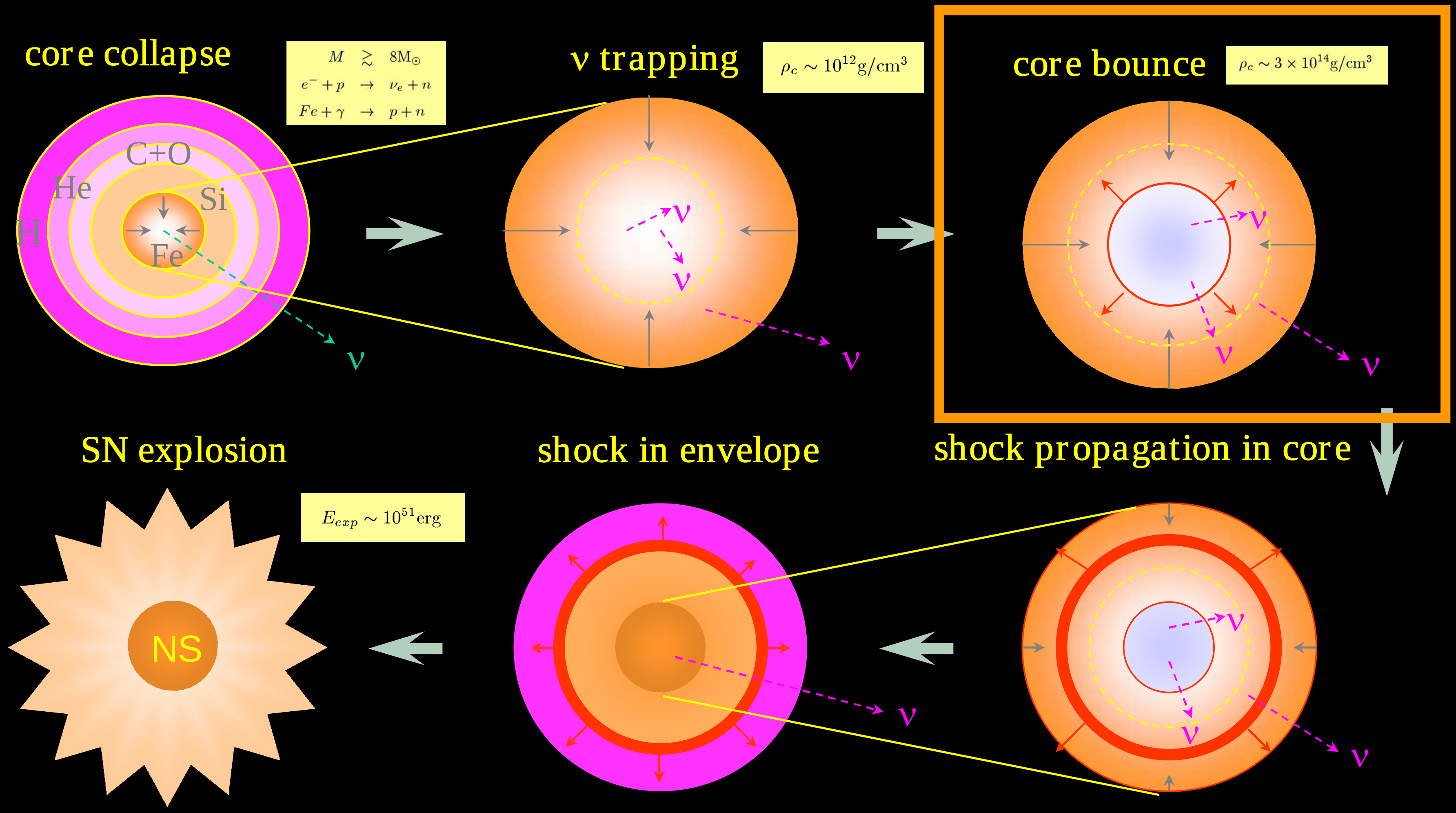


現在稼動中の
重力波検出範囲内

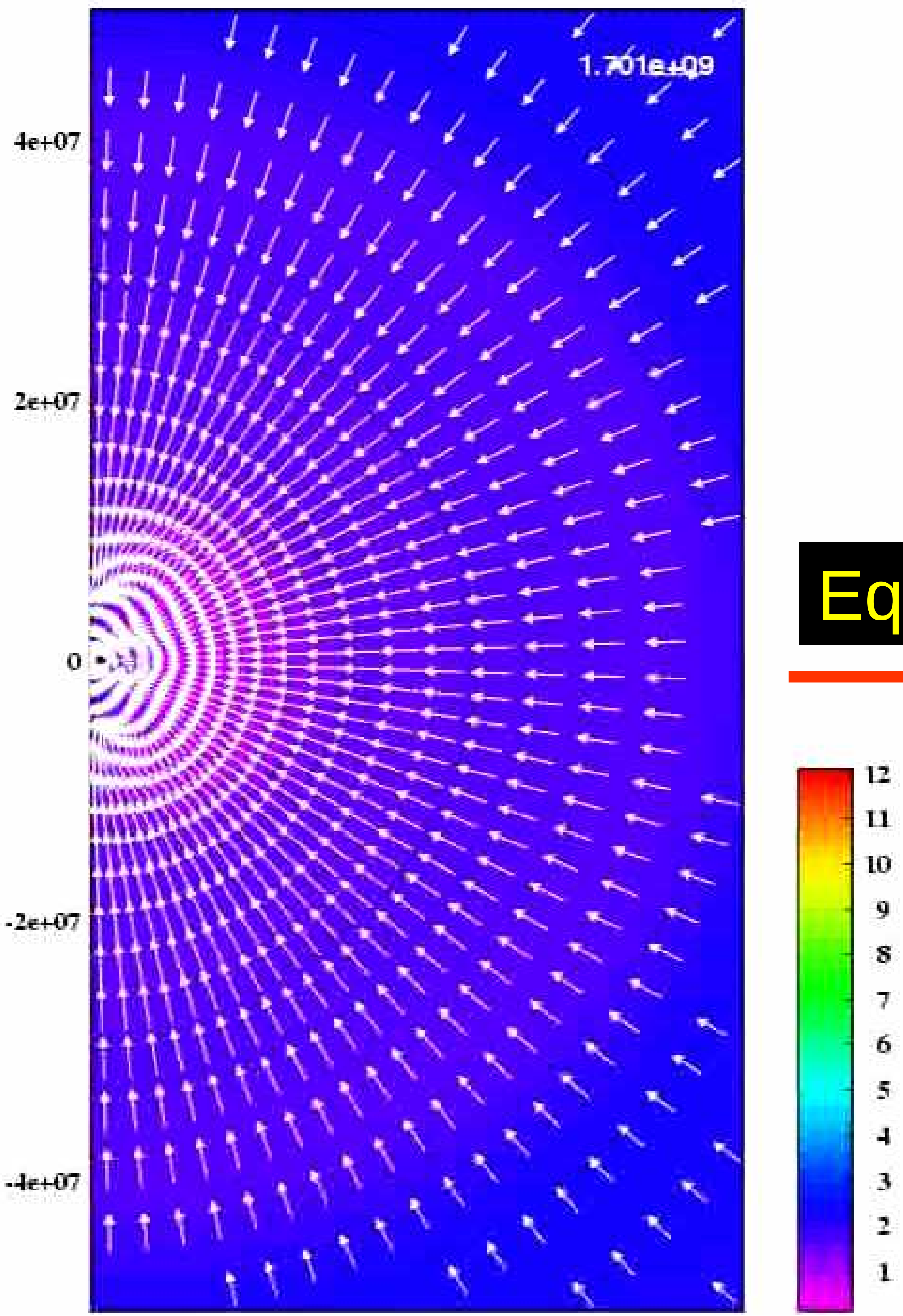
更に、次世代検出器、LCGT(日本)、LIGO II（アメリカ）などが計画予定。

Introduction

コアバウンス時



Rotational Axis



Equatorial plane

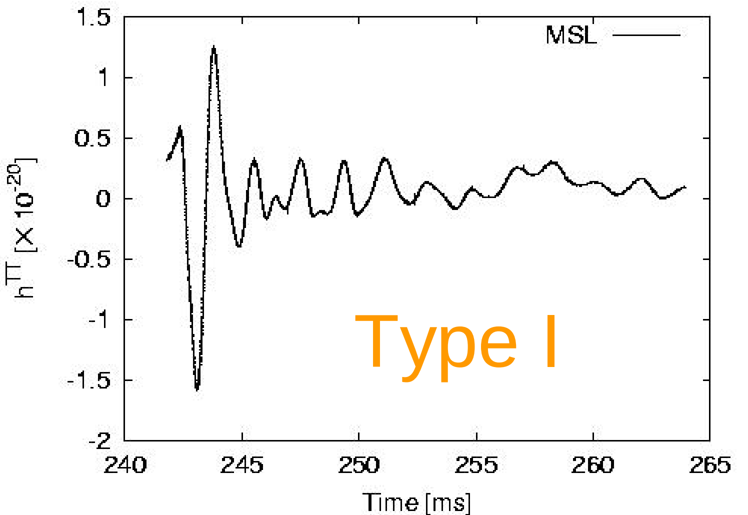
Contour of entropy

K.K et al. (2003)

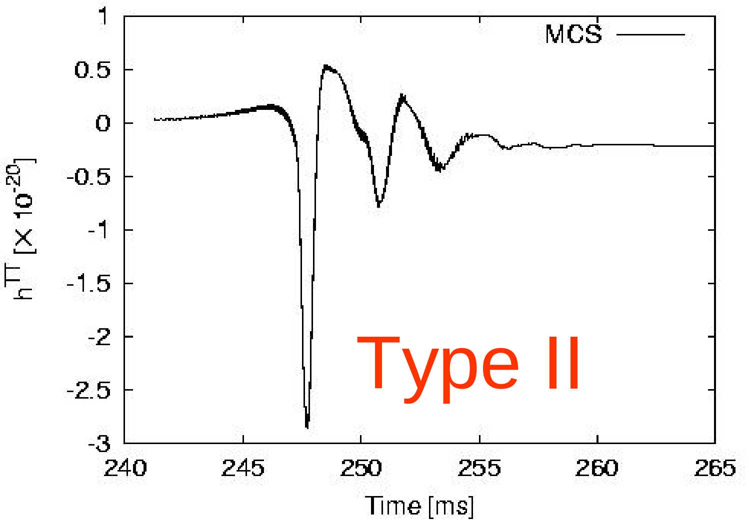
コアバウンス時の重力波

2D or 3D, realistic or polytropic EOS, detailed neutrino reaction

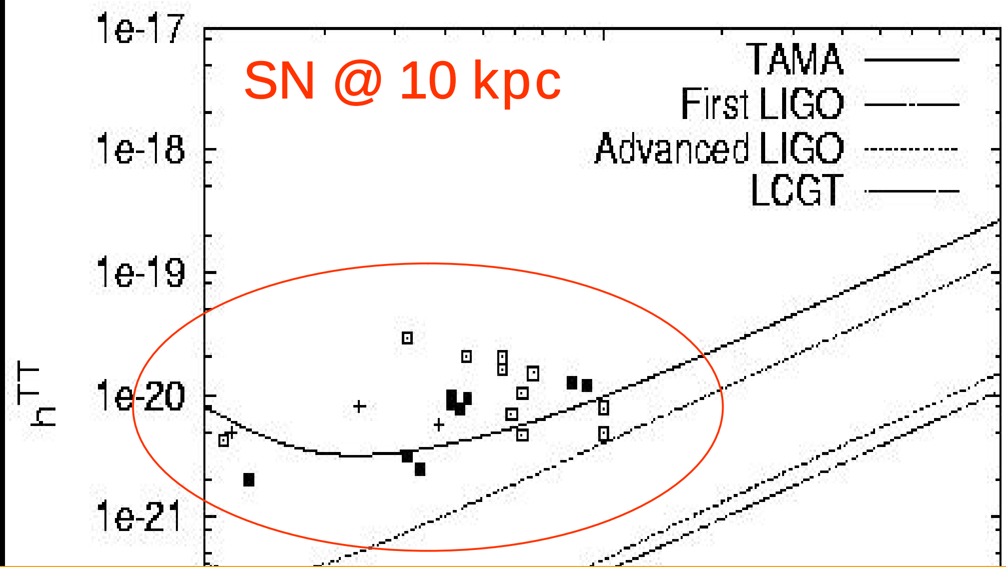
一様回転、標準自転速度



微分回転、高速自転

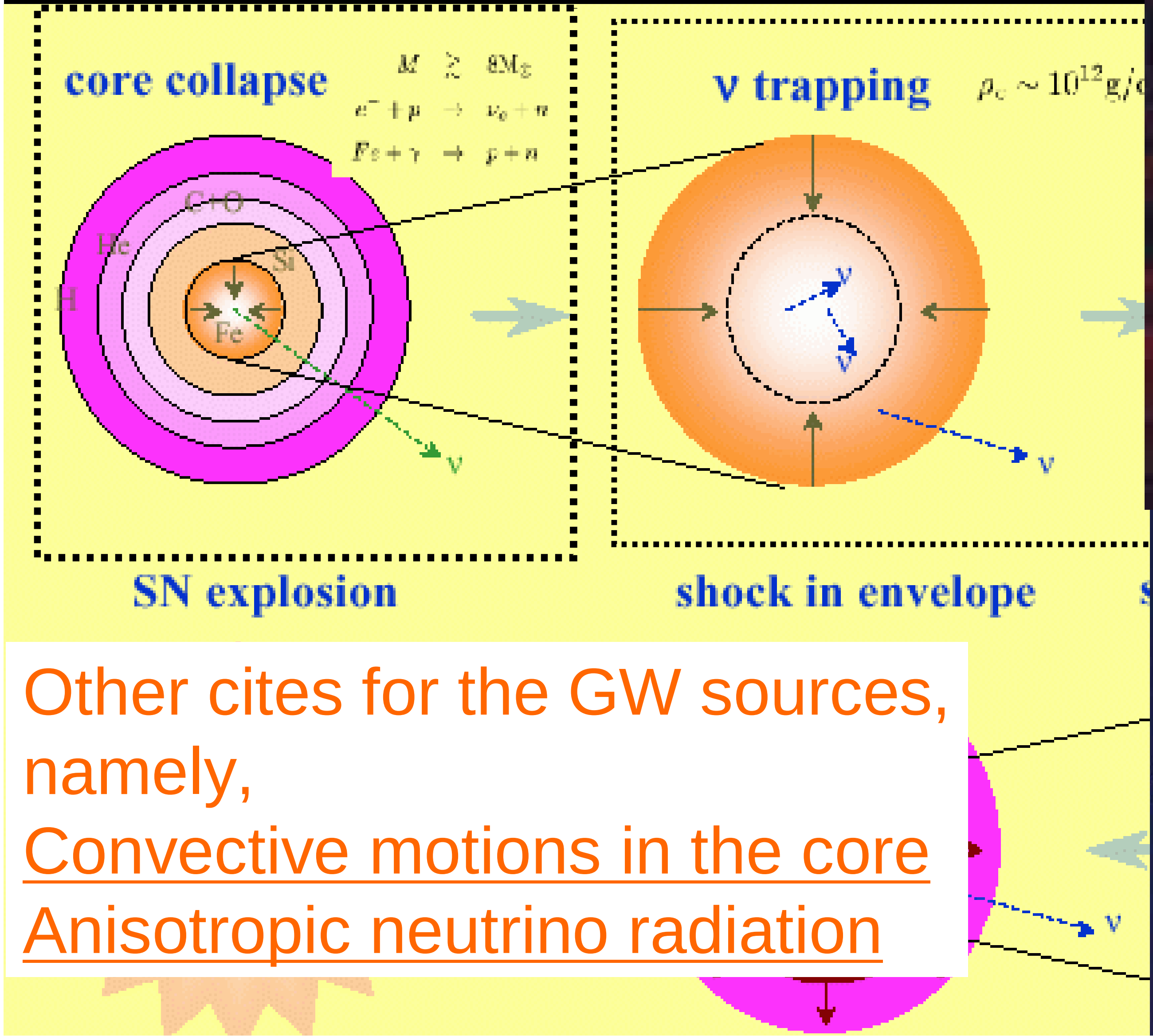


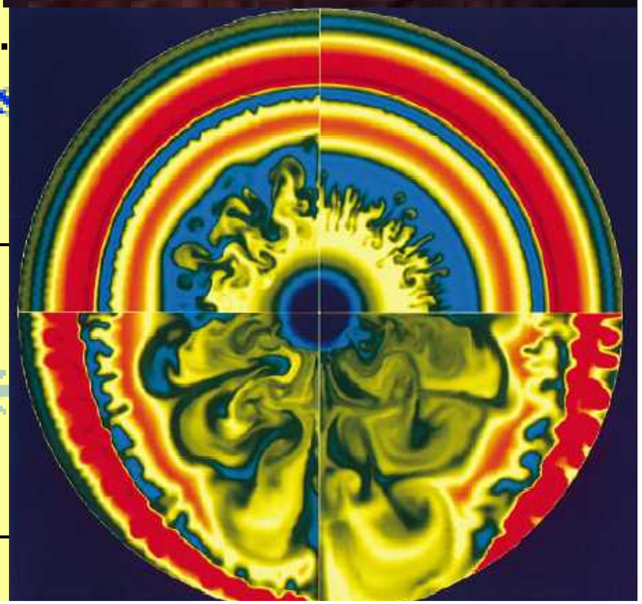
NR:Moenchmeyer et al. ’91,Yamada et al. ’95Zwerger et al. ’97,Rampp et al. ’98,Dimmelmeier et al. ’02
Fryer et al. 02,Ott et al. ’03,(2D, LS EOS),Mueller et al. ’03,Fryer et al. ’04 (3D), KK et al. (03,04)
GR:Shibata(03),Shibata&Sekiguchi (04).



銀河中心の超新星バウンス時の重力波は、現在稼動中の検出器の限界内にある。

GWs discussed until now are emitte





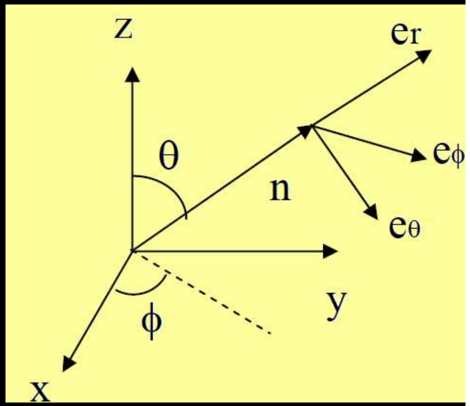
Other cites for the GW sources, namely,

<u>Convective motions in the core</u>

<u>Anisotropic neutrino radiation</u>

What is GW from anisotropic neutrino radiation ?

$$h^{\mu\nu}(t, \boldsymbol{x}) = 4 \int \frac{T^{\mu\nu}(t - |\boldsymbol{x} - \boldsymbol{x}'|, \boldsymbol{x}')}{|\boldsymbol{x} - \boldsymbol{x}'|} d^3x'$$



Neutrino radiation field,
(exact form)

$$T^{\alpha\beta} = \int \frac{d^3p}{2E_\nu} p^\alpha p^\beta f_\nu(x, p)$$

Epstein '78, Turner '78

$$T^{ij}(t, \boldsymbol{x}) = n^i n^j \frac{L_\nu(t, \boldsymbol{x})}{r^2}, \quad (\boldsymbol{n} = \boldsymbol{x}/r)$$

TT gauge taken.

Standard formula,

$$h_{ij}^{TT}(t, \boldsymbol{x}) = \frac{4G}{c^4} \frac{1}{r} \int_{-\infty}^{t} dt' \int_{4\pi} d\Omega' \; \frac{(n_i n_j)^{TT}}{1 - \cos\theta'} L_\nu(t', \Omega')$$

Typical amplitude and frequency of GWs from neutrinos

Neutrino origin：

$$h_\nu(t) = \frac{2G}{c^4 R}\int_0^t dt L_\nu(t')\alpha(t')$$

Typical amplitude：

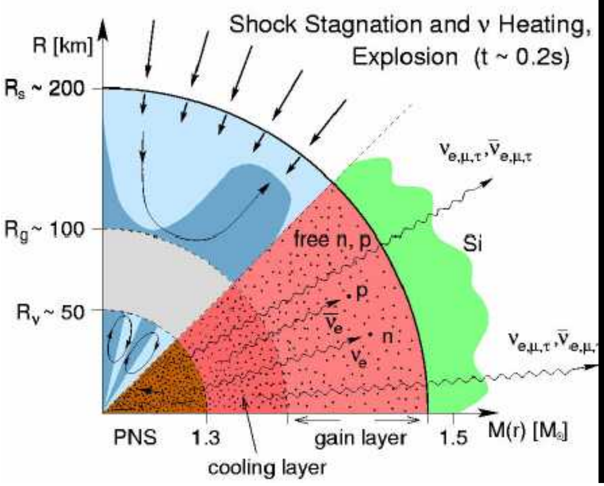
$$|h_\nu| \sim 10^{-20}\left(\frac{\alpha}{0.1}\right)\left(\frac{L_\nu}{10^{52}\ \mathrm{erg}}\right)\left(\frac{\Delta t}{1\ \mathrm{sec}}\right)\left(\frac{R}{10\ \mathrm{kpc}}\right)^{-1}$$

$$h_\nu \sim h_{\mathrm{bounce}} \sim 10^{-20}$$

~ as large as the one at bounce

Typical frequency：

$$t_\nu \sim \frac{1}{\sqrt{G\rho}} \geq 10\ \mathrm{msec}\left(\frac{\rho_{\mathrm{trap}}}{10^{11}\ \mathrm{gcm}^{-3}}\right)^{-1/2}$$



$$\nu_\nu \sim \frac{1}{t_\nu} \leq 100\ \mathrm{Hz}$$

とわかる。

Frequencies of GWs from neutrinos are rather low!

我々の研究

自転の様子（微分回転の程度）によって、
ニュートリノ起源の重力波がどのように変化するか調べたい。
(K.K et al. PRD 2005)

初期モデル

Strength:
自転： T/|W| = 0.5 % <- Heger et al. (2001)

Configurations
Cylindrical：

$$\Omega = \Omega_0 \times \frac{{X_0}^2}{X^2 + {X_0}^2} \cdot \frac{Z_0^4}{Z^4 + Z_0^4}$$

Shell-type rotation

$$\Omega = \Omega_0 \times \frac{{R_0}^2}{r^2 + R_0^2}$$

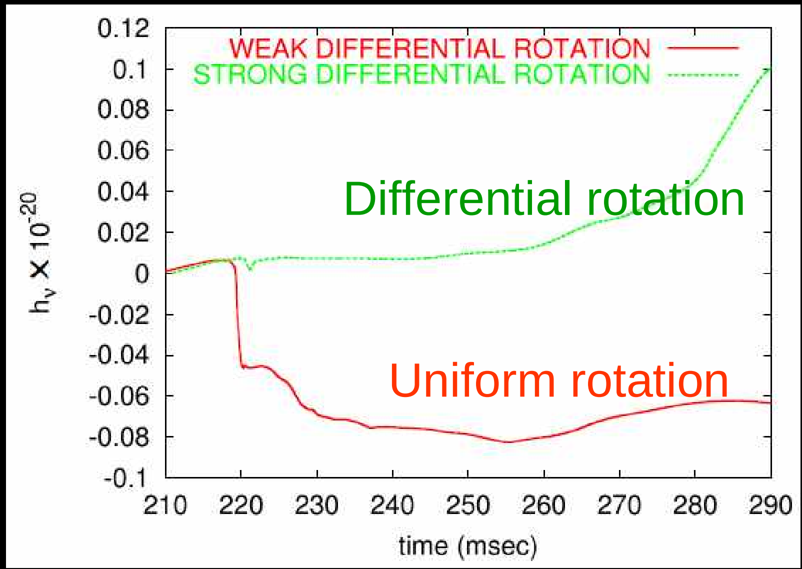
Ro, Xo を1000km から100 kmづつ減らして行く。

20 model 計算した。

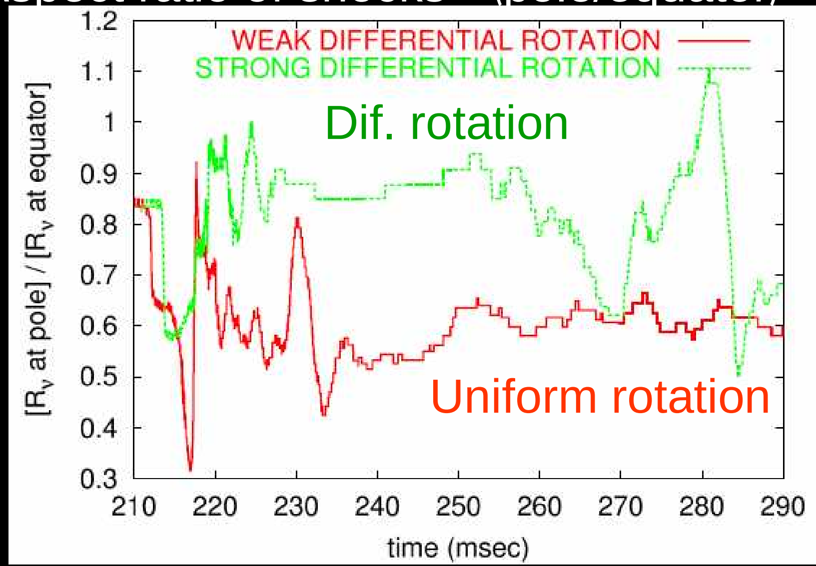
Results：Waveforms from anisotropic neutrino radiation

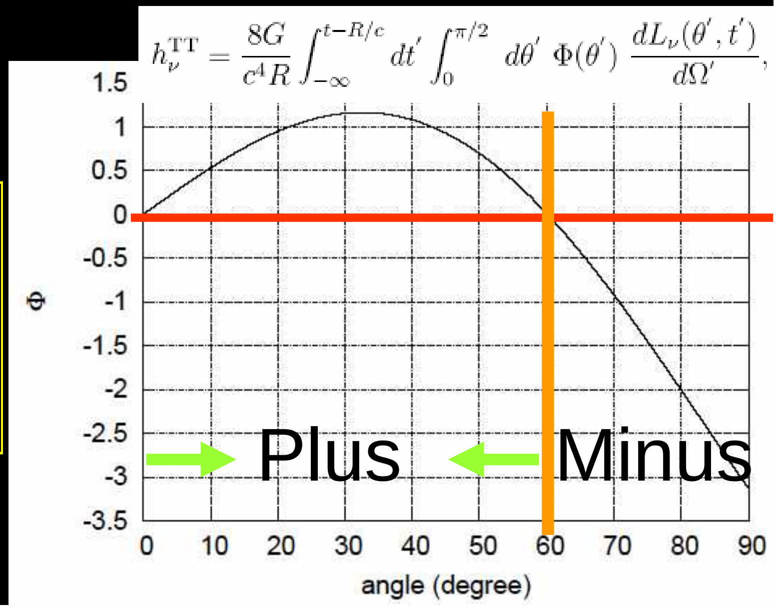
Comparison between differential or uniformally rotating model

waveform



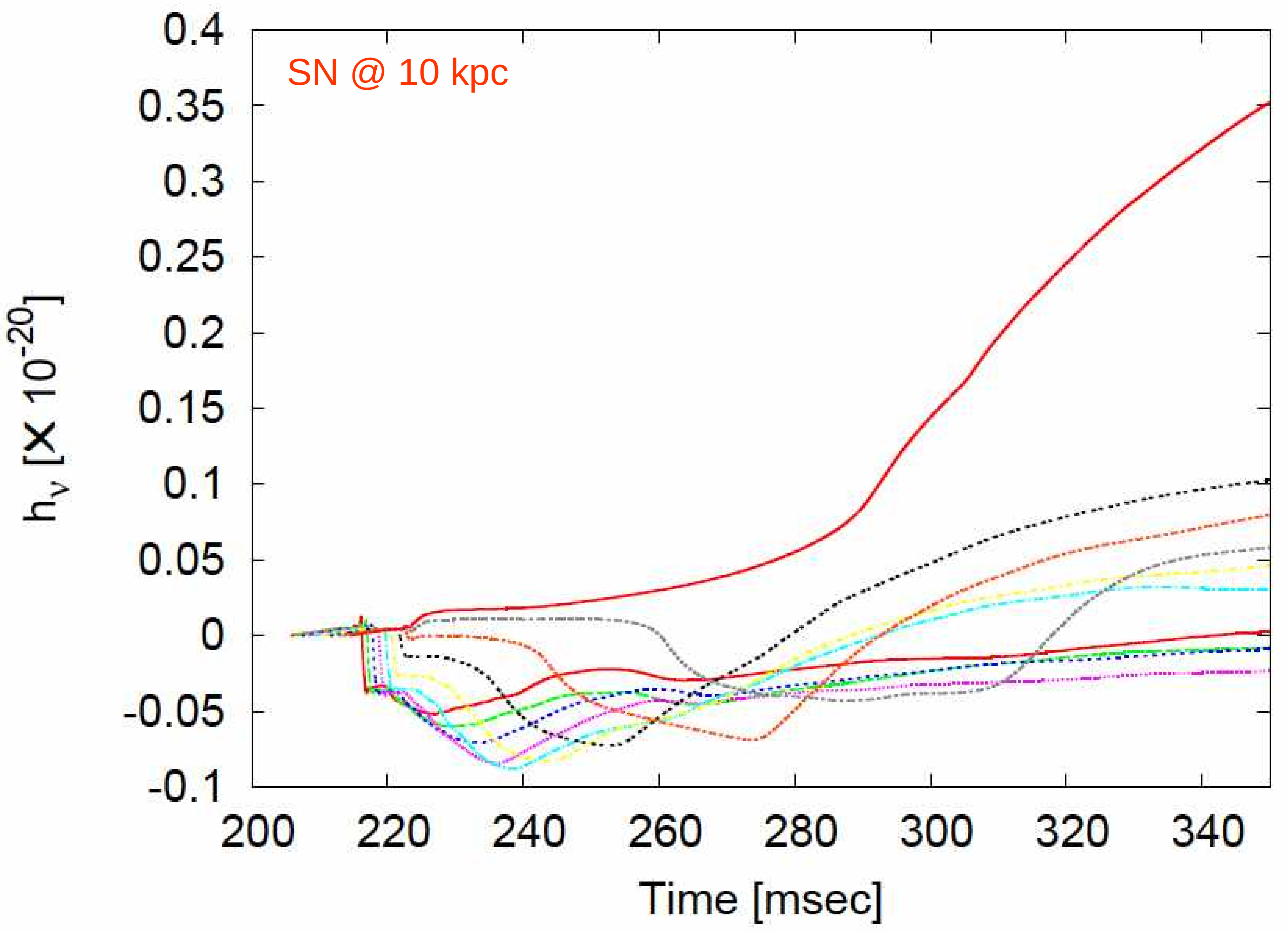
Aspect ratio of shocks (pole/equator)





Differential rotation is found to dominantly determine the waveforms from the anisotropic neutrino radiation.

Relation between the degree of differential rotation and the waveforms.

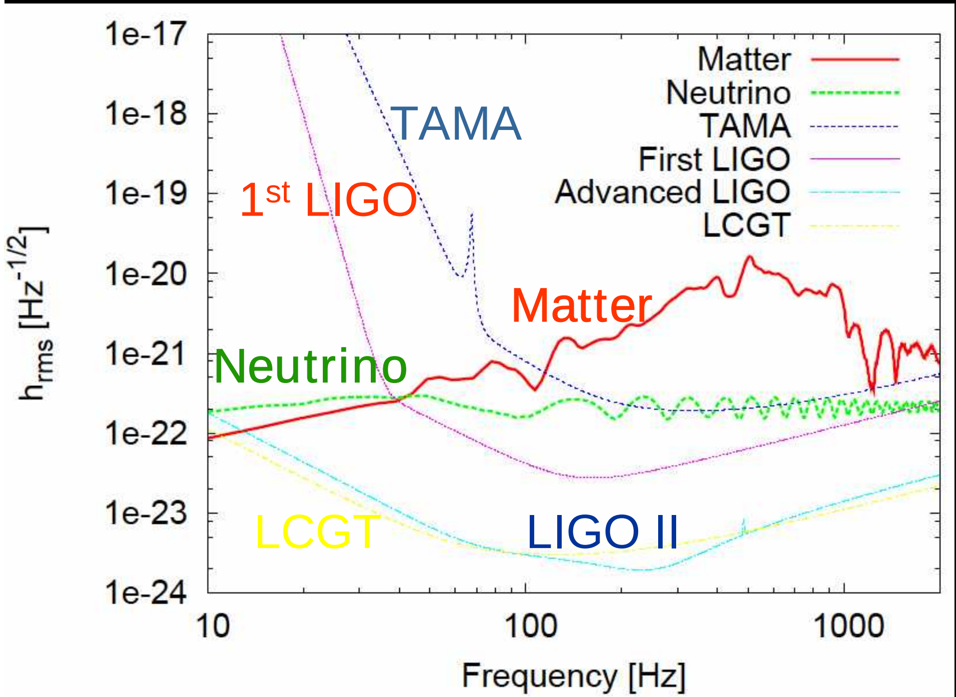


Stronger differential rotation

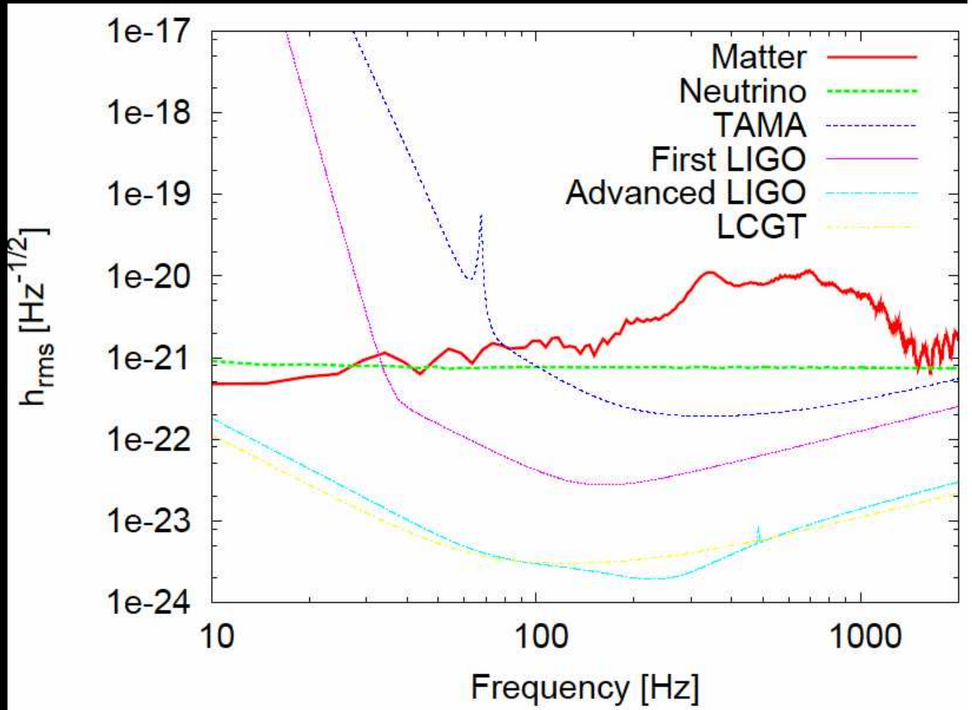
Gravitational radiation from anisotropic neutrino radiation

Spectrum Analysis

Uniform rotation model

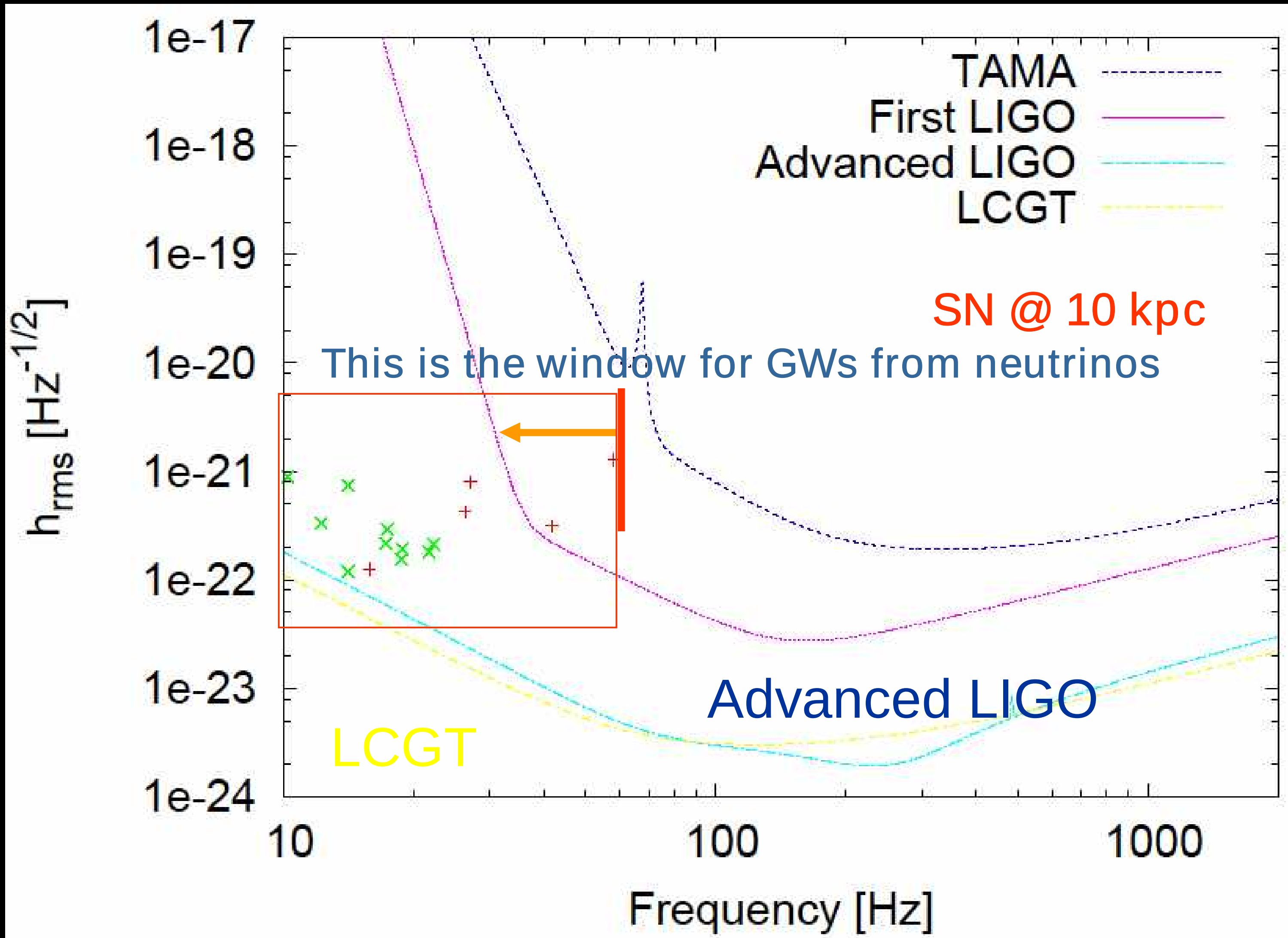


Differential rotation model



GWs from neutrinos dominate over the ones from matter at the lower frequency of ~ 100 Hz.

Detectability of GWs from neutrinos

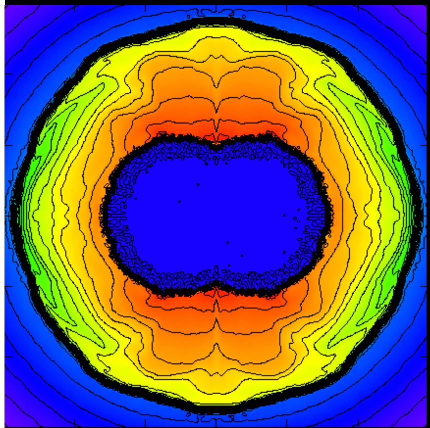


They are within the detection limits of LIGO II or LCGT.

ニュートリノ起源の重力波：爆発メカニズムへの示唆（その1）

Given 鉄コアの自転

↓



非対称なニュートリノ放射

↙ ↘

爆発メカニズムに良いセンス。

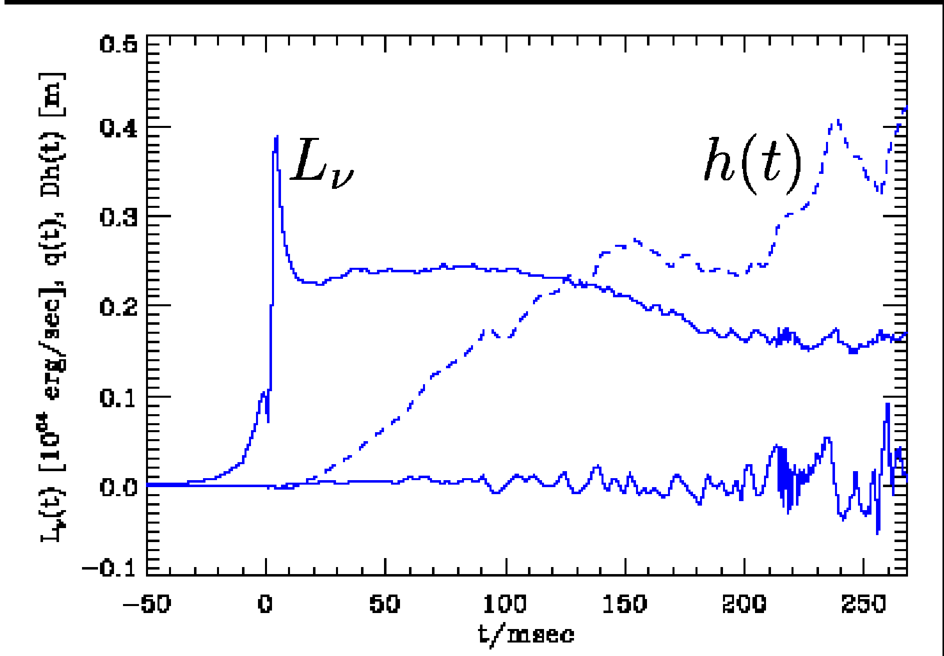
重力波

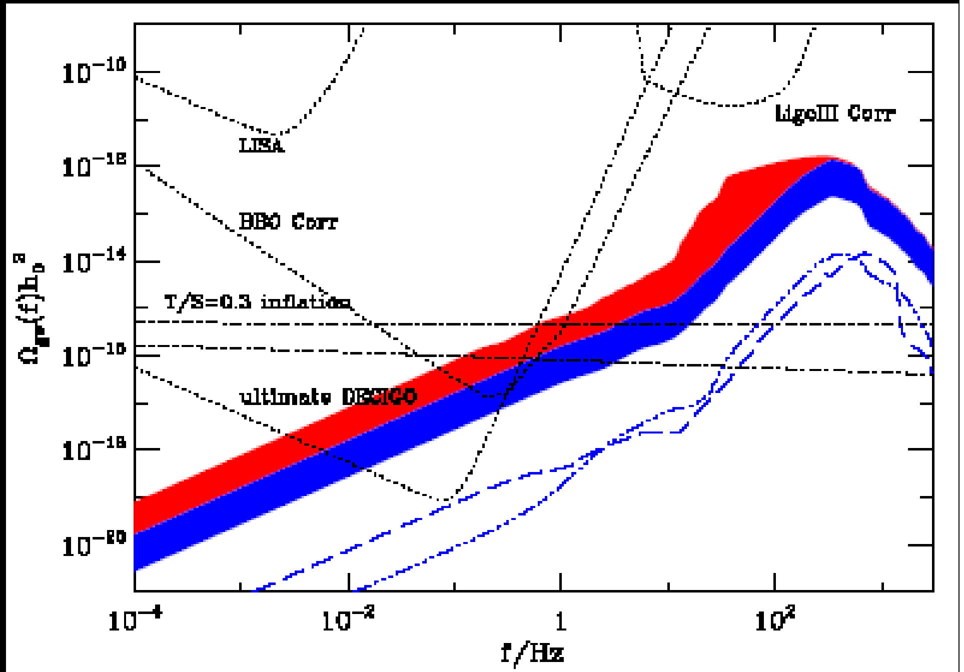
爆発メカニズムの理解の一助になるかもしれない。

ニュートリノ起源の重力波：背景重力波（その2）

Buonnanno et al. 2004

自転モデル (s15r model)
におけるニュートリノ重力波



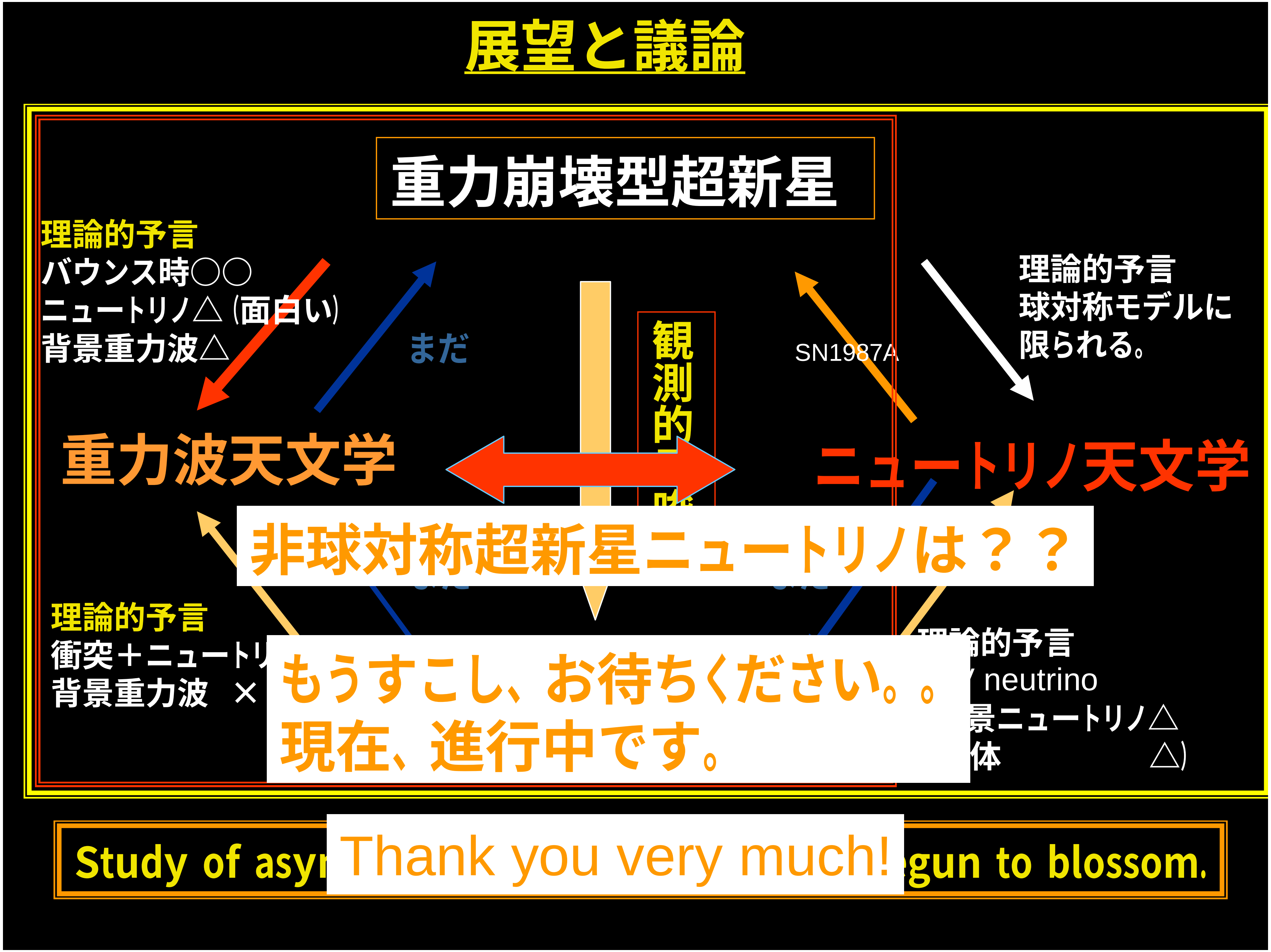


Mueller et al.（03） の数値計算

Neutrino emission
3×10^{53} erg

Convective motion

BBOなどの次世代検出器で背景重力波として観測される可能性をもつ


展望と議論
重力崩壊型超新星
理論的予言
バウンス時○○
ニュートリノ△ (面白い)
背景重力波△
まだ
観測的
SN1987A
理論的予言
球対称モデルに
限られる。
重力波天文学
ニュートリノ天文学
非球対称超新星ニュートリノは？？
理論的予言
衝突＋ニュートリ
背景重力波 ×
もうすこし、お待ちください。。
現在、進行中です。
neutrino
景ニュートリノ△
体
△)
Study of asy
gun to blossom.
Thank you very much!