Multidimensional modeling of core-collapse supernovae:

New challenges and perspectives

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S. Yamada and K. Kiuchi (Waseda Univ.),
W.Iwakami, N.Ohnishi (Tohoku. U),
S. Harikae and N. Yasutake (NAO).

@7th Resceu International Symposium on Astroparticle physics and Cosmology, 2008

Outline

- Introduction
  :Current status/importance of multi-dimensional SN models

- 3D Supernova Explosion Models and
  Signatures of Gravitational Waves

- MHD collapse and explosions of massive stars

- Summary (: with perspectives)

Core-collapse Supernovae

marking catastrophic ends of massive stars (> ~10 M_{solar})

Not yet !

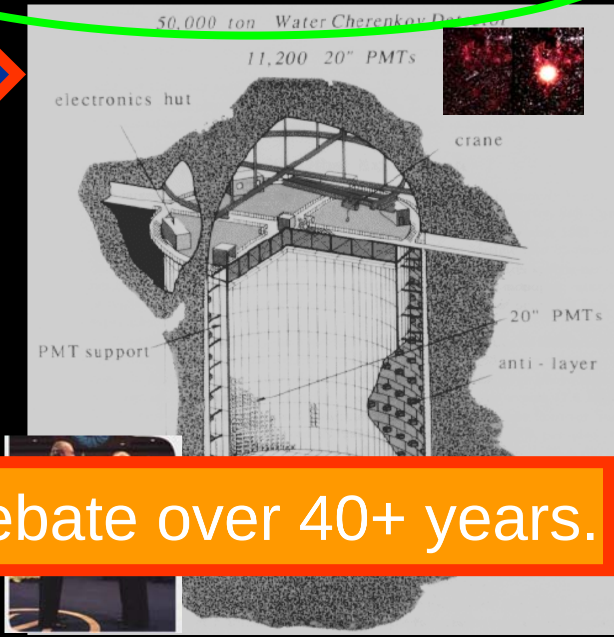
A kind of Rosseta stone

Up to now
only SN1987A

GW astronomy

Relevance to

Neutrino Astronomy



Neutron stars/Black holes
Magnetars

The explosion mechanism is still a topic of debate over 40+ years.

TAMA300

Neutrino heating mechanism

- Best-studied and most promising way to explode massive stars.

(Wilson ´82, Bethe & Wilson '85)

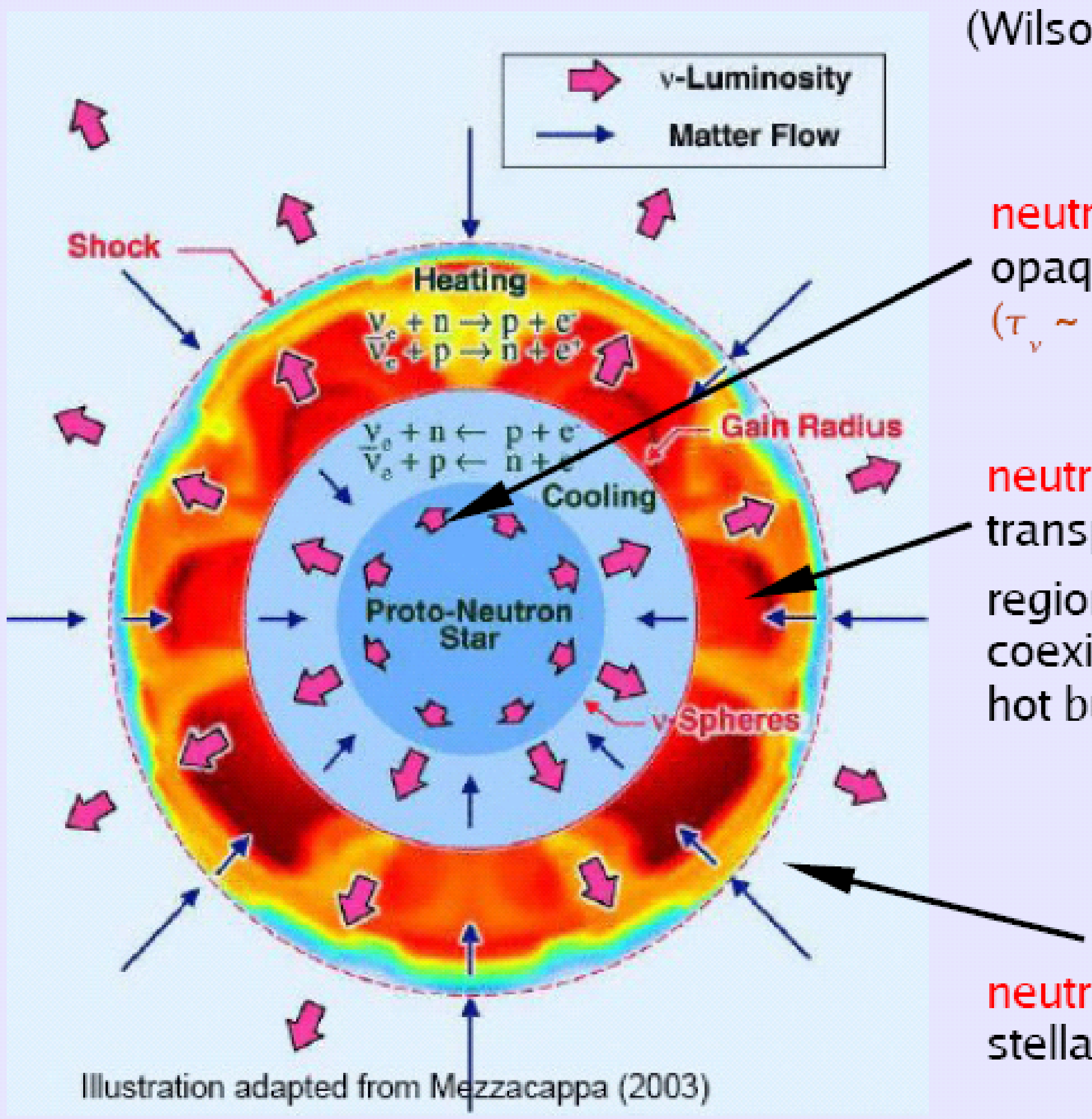


Illustration adapted from Mezzacappa (2003)

neutrinos diffuse out of opaque proto-neutron star ($\tau_\nu \sim 1$)

neutrinos heat matter in semi-transparent ($\tau_\nu \sim 1$) post-shock region ---> convection with coexisting downflows and rising hot bubbles sets in

neutrinos stream freely through stellar envelope ($\tau_\nu << 1$)

Energy budget problem

Typical observed explosion energy：

$$E_{\rm K} \sim 1 - 2 \times 10^{51} {\rm erg}$$

⇕

Releasable energy ＝ binding energy of neutron star,

$$\approx 3 \times 10^{53} {\rm erg} \left(\frac{M}{1.4 M_{\rm sol}} \right)^2 \frac{10 {\rm km}}{R}$$

essentially carried away by neutrinos.

For the neutrino heating mechanism working,

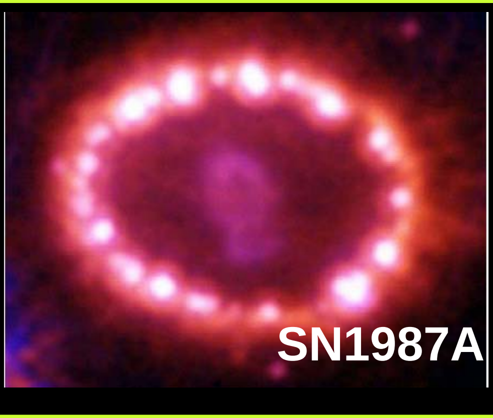
- ~1% energy transfer via neutrinos to matter.
- Energy conservations should be kept < 1%, over the entire simulations (for 2D, ~10^{20} operations, 1 CPU year/ one simulation @ 10Tflops supercomputer.)
- Supernova simulations (6D radiation-hydro problem)： Grand challenge in computational astrophysics.

Looking back 40+ Years of Modeling & Theory

- Bounce shock always stall.
  Direct "prompt" hydrodynamic explosion fails.

- Neutrino-heating mechanism (Wilson '82,Bethe'85) in spherical symmetry (may work for lower mass progenitors with O-Ne-Mg cores) (Kitaura et al.2006) fails to explode massive stars with iron cores.

  (Rampp&Janka 02,Liebendoerfer+.02,Sumiyoshi+04)



- CC SNe are generally aspherical.
  (Wang+.01,02)
- Multidimensional explosions are favorable for reproducing the synthesized elements.
  (Nagataki+.97, Maeda+.03, Kifonidius+.07,Maeda+08…)

Multidimensional modeling is crucial !

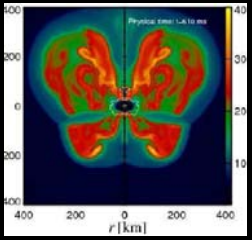
A garden variety of candidate mechanisms

○ Neutrino-heating mechanism + convection/SASI:

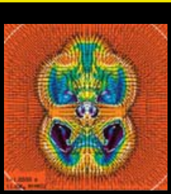
SASI: Low modes oscillatory instability of standing accretion shock

: Explosion of 2D, low-stars (11.2 Ms), **(Buras+. 2006)**

: Onset of SASI-aided neutrino driven explosion of 15 Ms star **(Marek & Janka 07)**



(Marek & Janka 07)

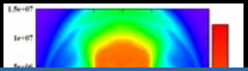


(Burrows+06)

○Acoustic mechanism: （**Burrows+. 2005,6, Ott+07)**

○Rapid Rotation & Anisotropic neutrino radiation:

(Shimizu,Sato+94, KK+ 03, Walder+05,Ott+08)



☆ Which one is the final answer ?

☆ Some 2D models show (weak) explosions, however,

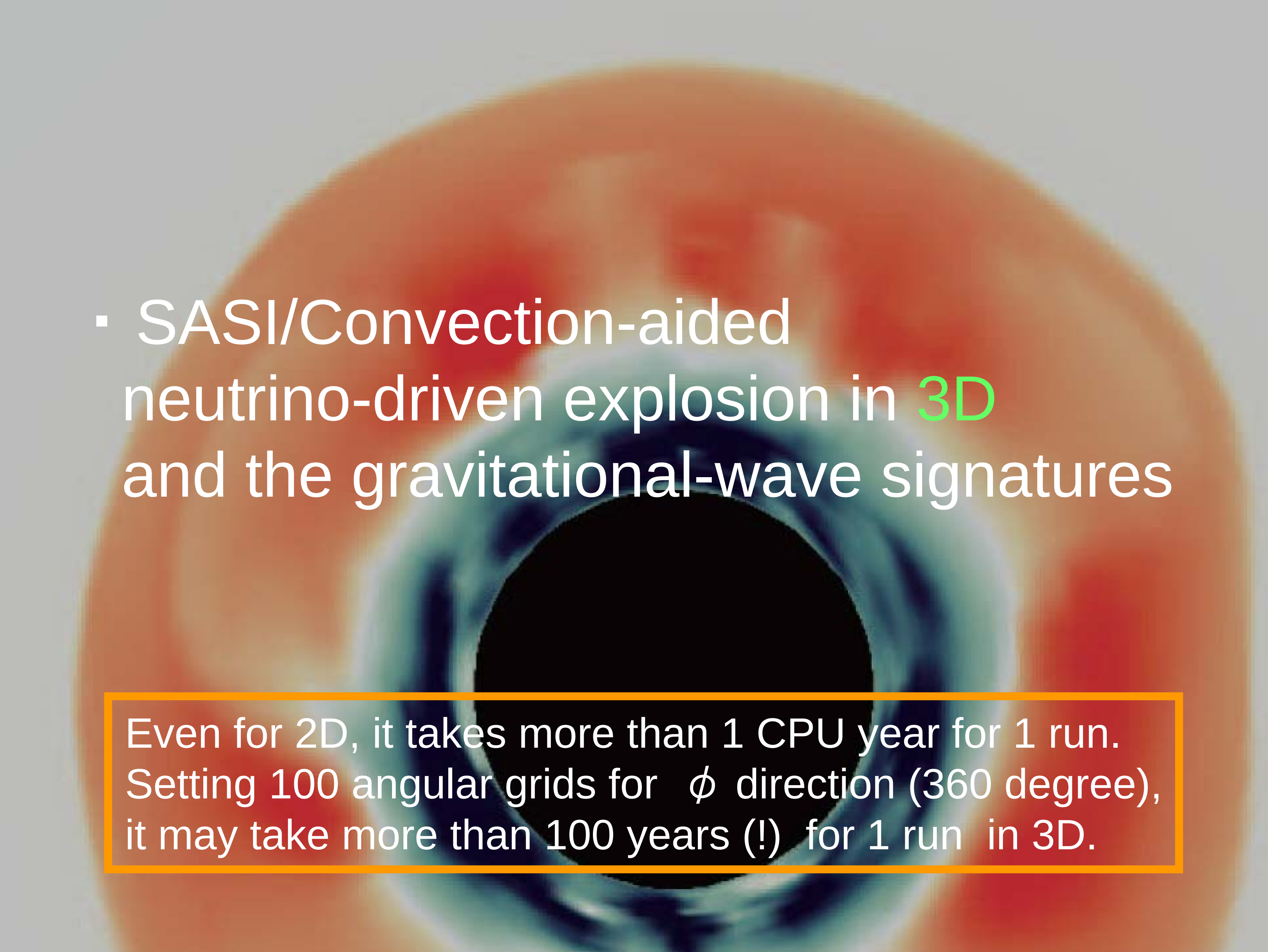
(Marek,Janka2007,Burrows+06).

do they explode in 3D ?

☆ To look into the heart of the engines : gravitational waves (GWs)

(plus neutrinos) should be helpful (albeit for a galactic source).

(Takiwaki+08)

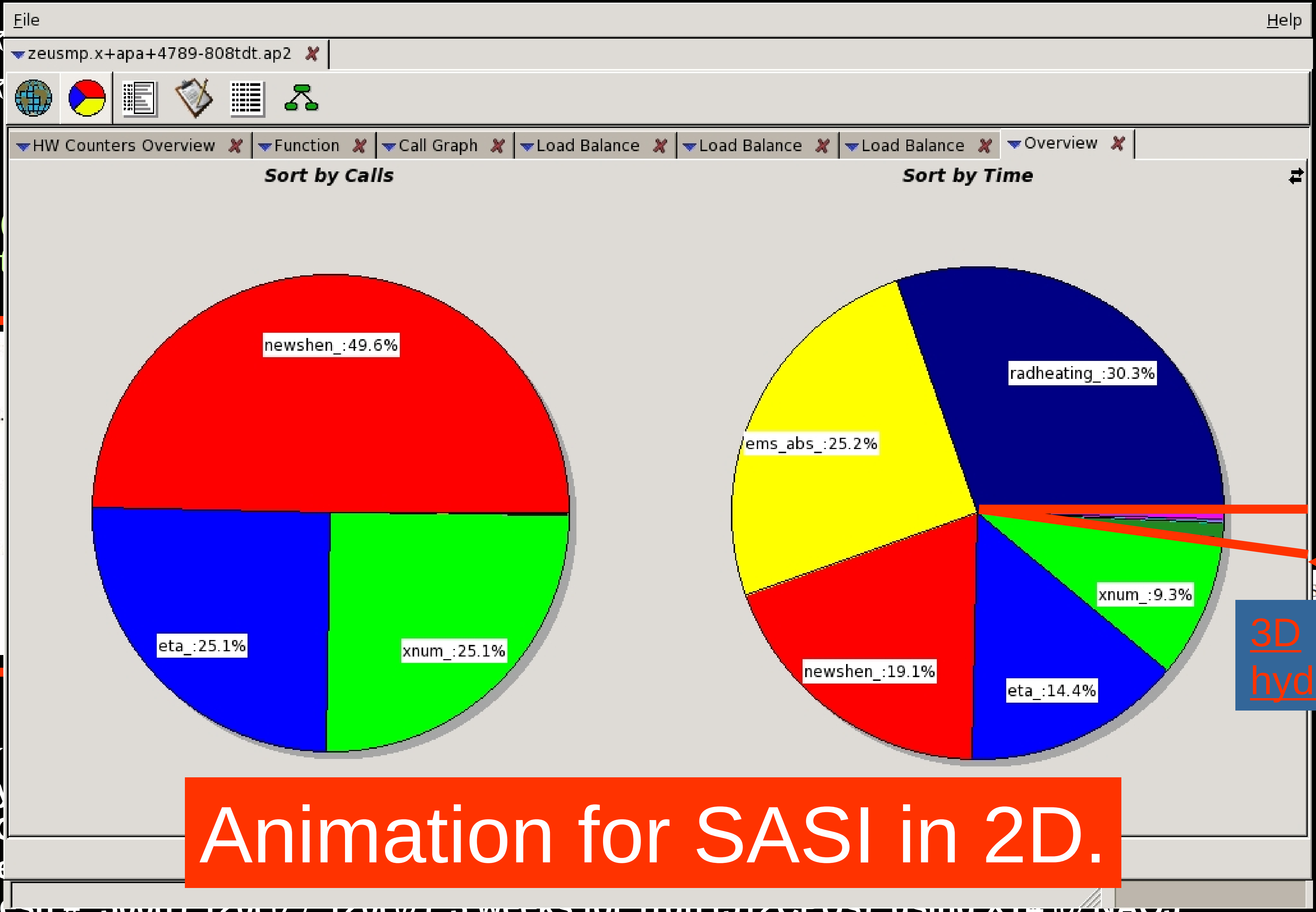


- SASI/Convection-aided neutrino-driven explosion in 3D and the gravitational-wave signatures

Even for 2D, it takes more than 1 CPU year for 1 run.
Setting 100 angular grids for ϕ direction (360 degree),
it may take more than 100 years (!) for 1 run in 3D.

Concept of the SASI simulations

(Scheck+04, 06, Ohnishi, KK, Yamada,06,07, KK+07, Blondin+07, Iwakami+08)



3D hydro

Animation for SASI in 2D.

☆

☆

☆

Hy

EC

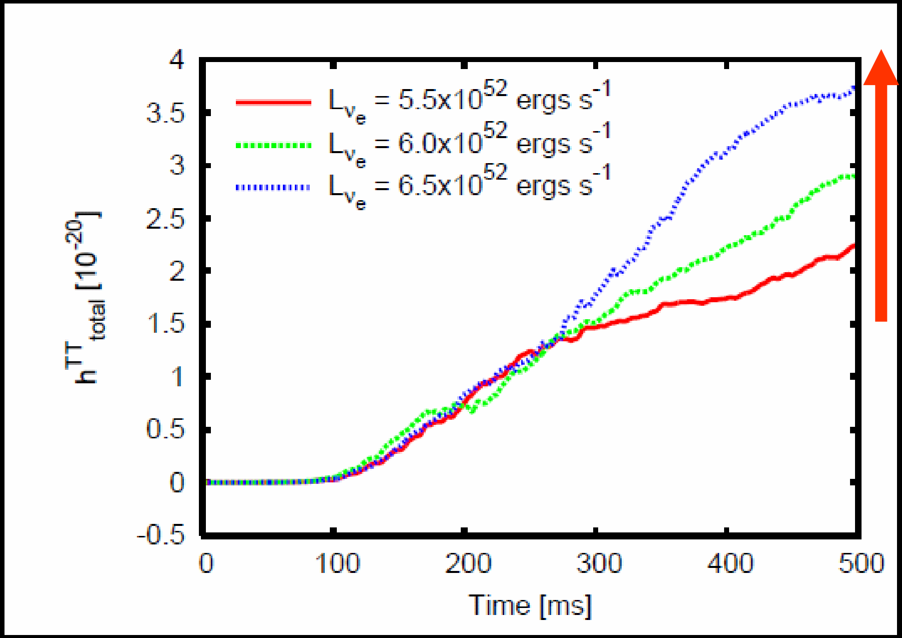
Ne

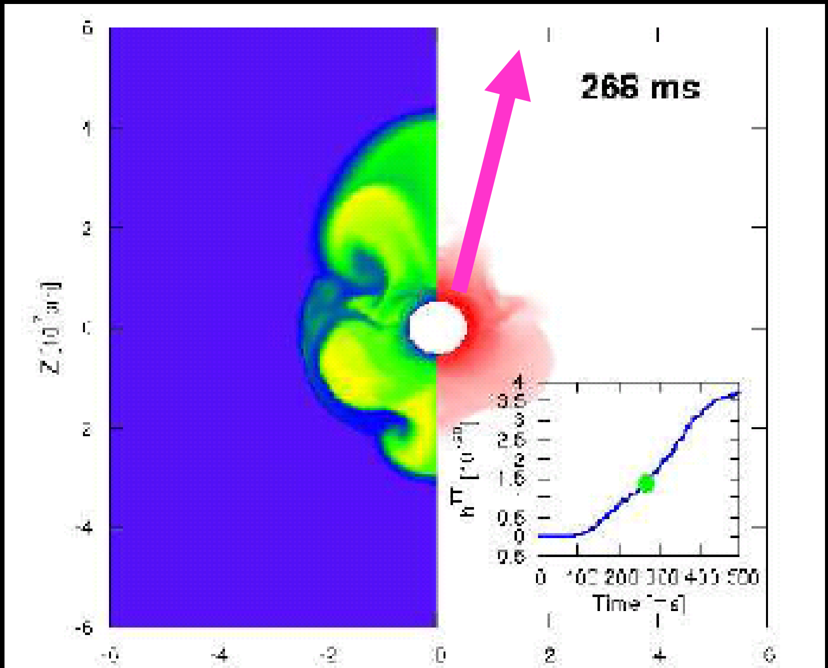
Mesh #: 300(r) 120(θ) 120(φ), 3 weeks for 1run (512CPUs), using XT4 @ NAOJ

Features of neutrino-originated GWs in 2D

KK et al. (2007)

waveform

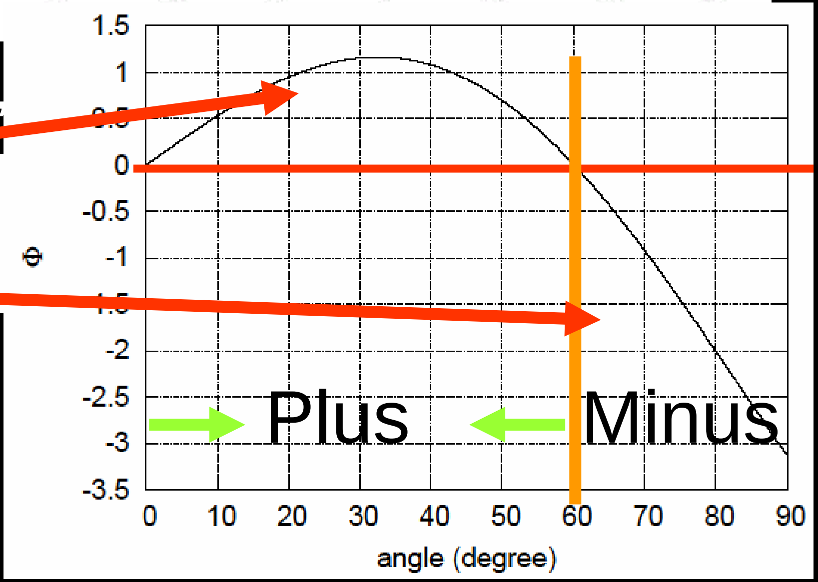




GWs from anisotropic neutrino radiation in 2D,

(Epstein78,Mueller&Janka97)

$$h_\nu^{\mathrm{TT}} = \frac{8G}{c^4 R}\int_{-\infty}^{t-R/c} dt' \int_0^{\pi/2} d\theta' \, \boxed{\Phi(\theta'} \frac{dL_\nu(\theta',t')}{d\Omega'},$$



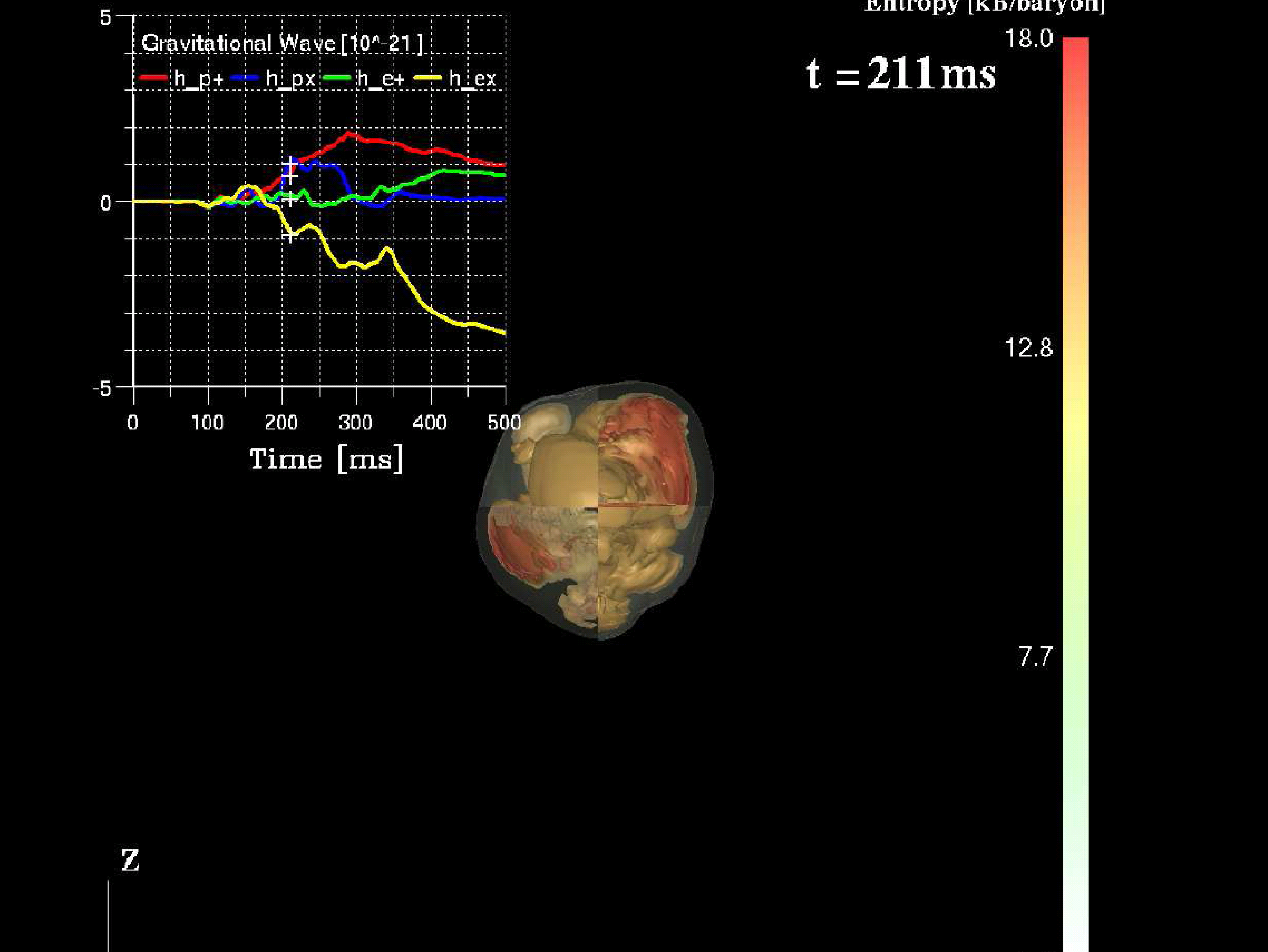
- angle dependent factor * neutrino luminosity per solid angle
- angle dependent factor is a function of the angle from the symmetry axis.

3D detailed simulations of SASI

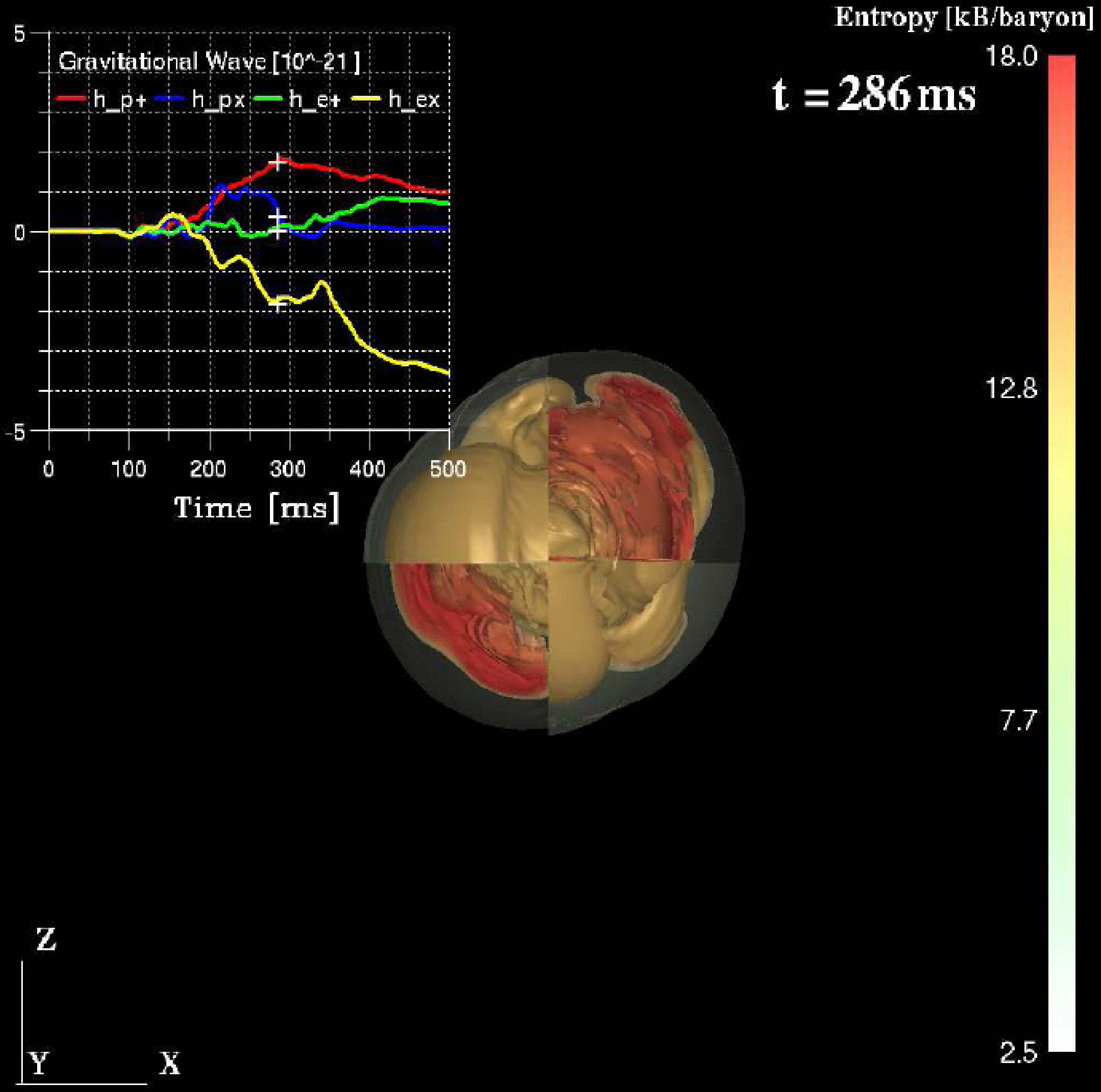
Exploding model

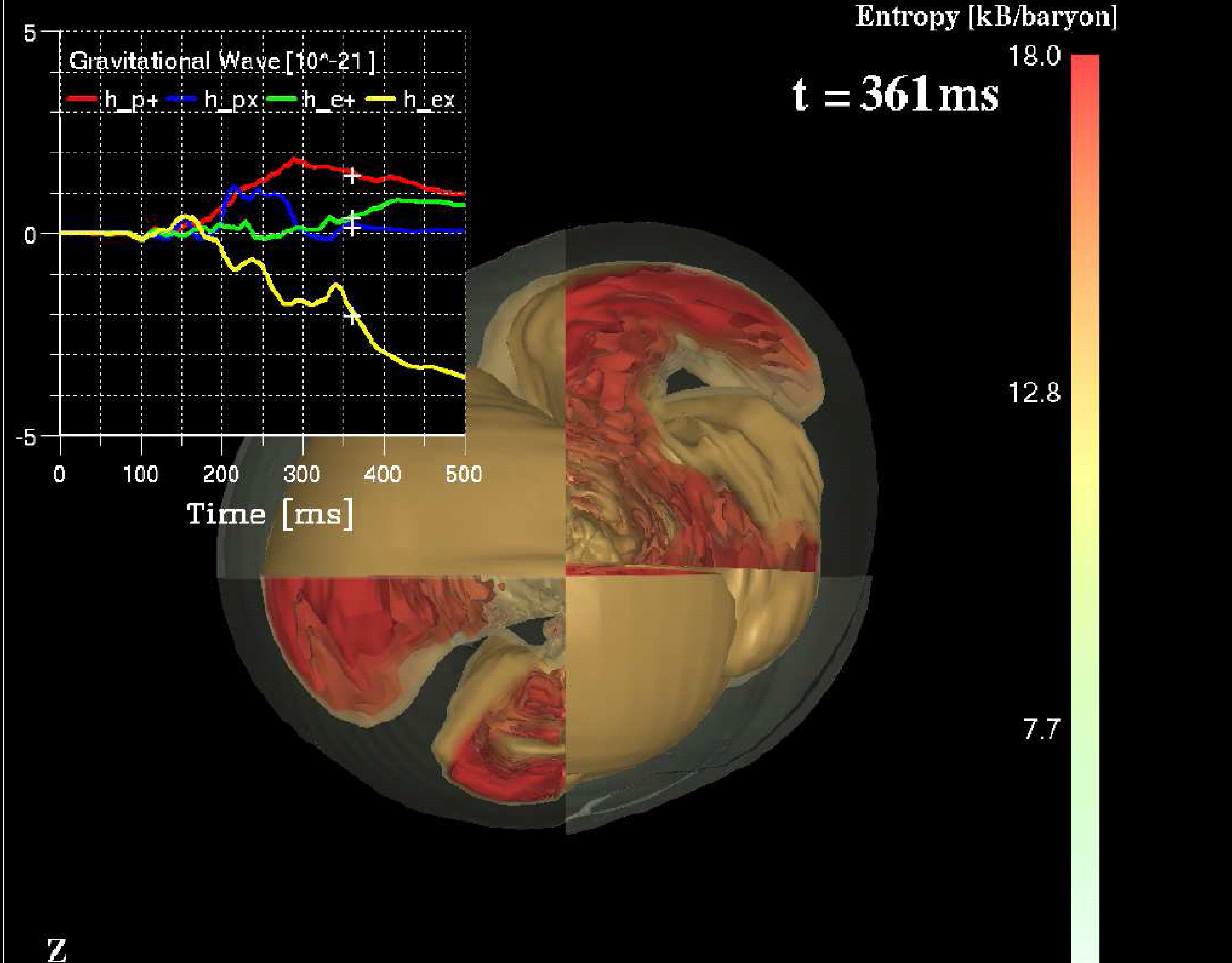
Iwakami, KK, Ohnishi, Yamada, Sawada (2008,9),
KK, Iwakami, Ohnishi, Yamada (2008)

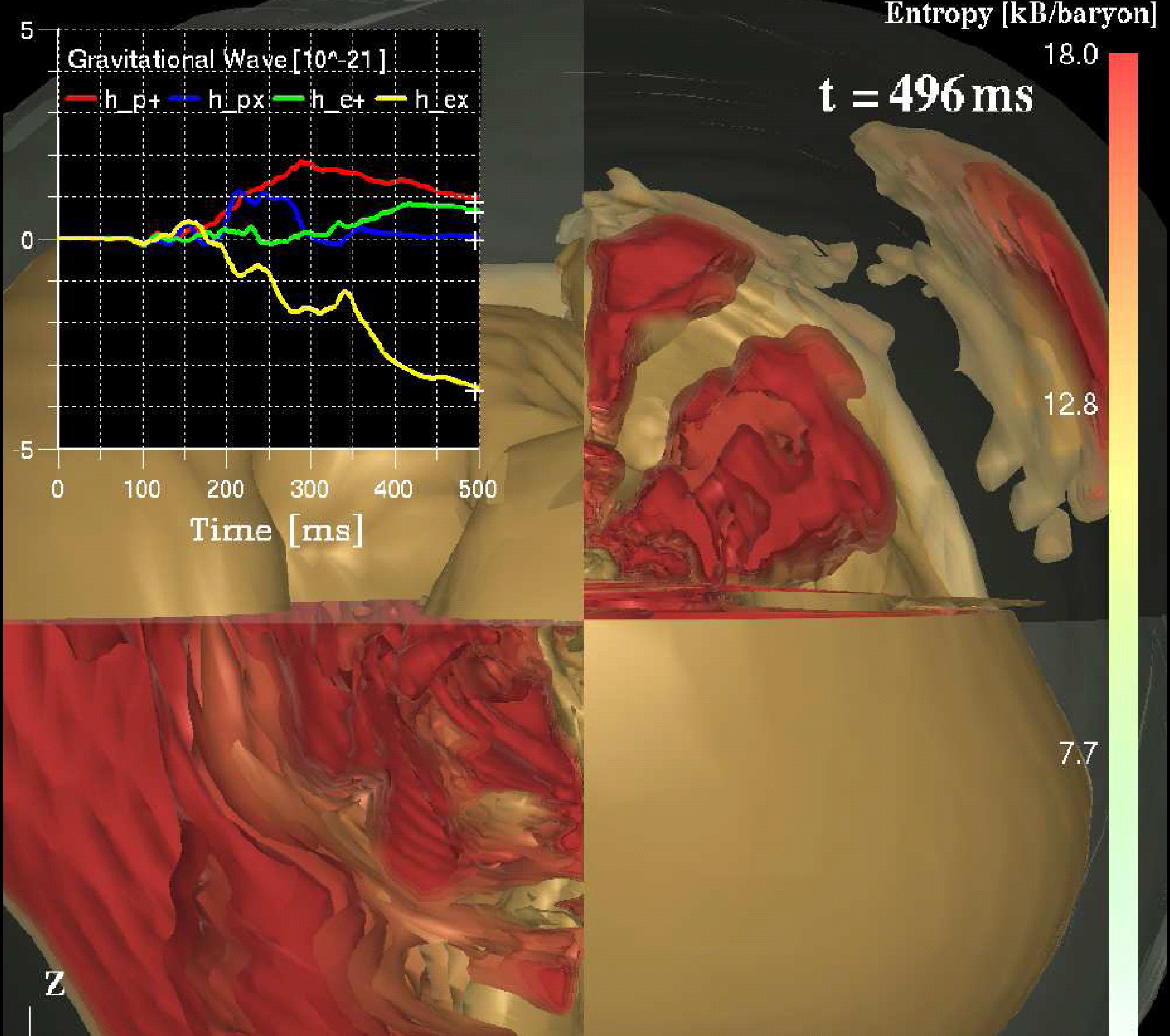
Animation !


Entropy [kB/baryon]
18.0
12.8
7.7
Gravitational Wave [10^-21]
h_p+
h_px
h_e+
h_ex
5
0
-5
0
100
200
300
400
500
Time [ms]
Z

t = 211ms


Gravitational Wave [10^-21]
h_p+
h_px
h_e+
h_ex
5
0
-5
0
100
200
300
400
500
Time [ms]
t = 286 ms
Entropy [kB/baryon]
18.0
12.8
7.7
2.5
Z
Y
X

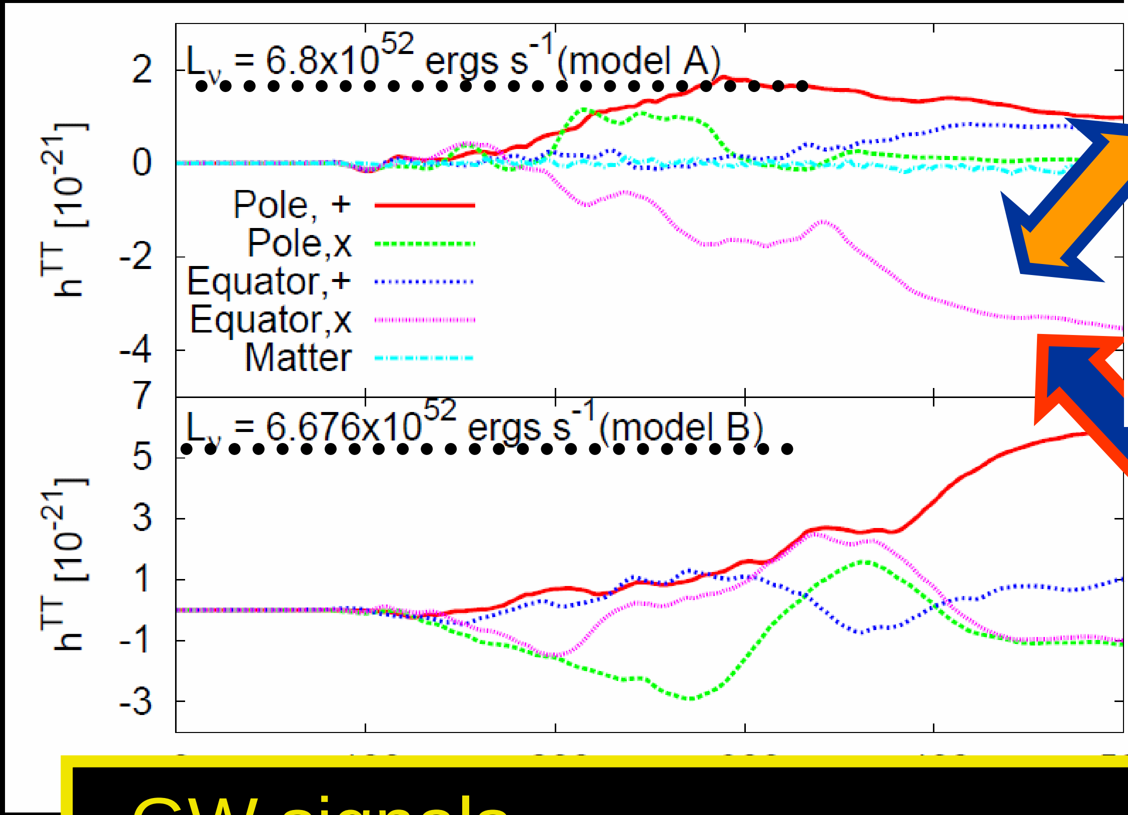

Entropy [kB/baryon]
18.0
12.8
7.7
t = 361ms
Gravitational Wave [10^-21]
h_p+
h_px
h_e+
h_ex
5
0
-5
0
100
200
300
400
500
Time [ms]
Z


Gravitational Wave [10^-21]
h_p+
h_px
h_e+
h_ex
5
0
-5
0
100
200
300
400
500
Time [ms]
Entropy [kB/baryon]
18.0
12.8
7.7
t = 496 ms
Z

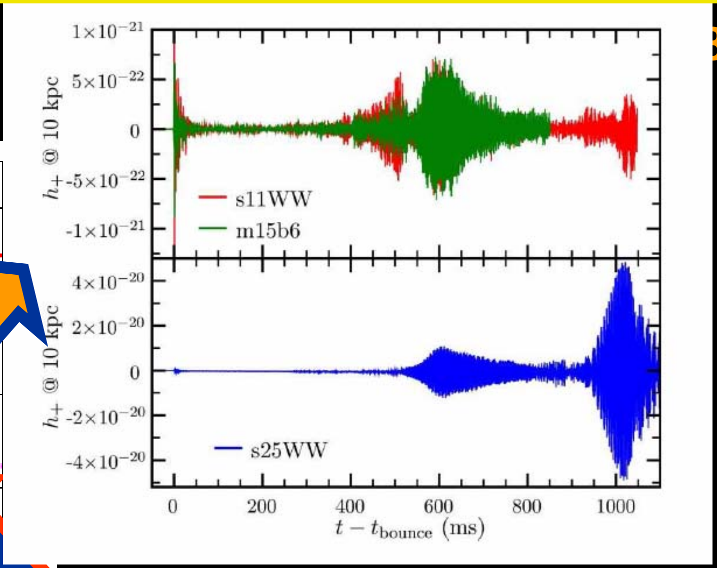
Details in the Waveforms a

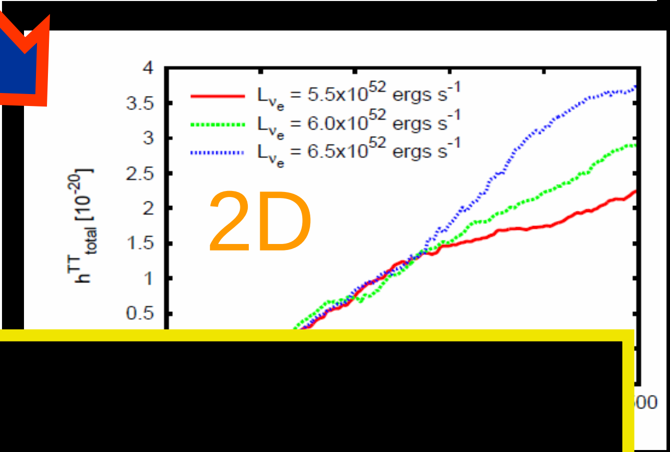
3)

The neutrino luminosity differs only 0.5 %.



GW from acoustic mechanism (Ott + 07)





- GW signals,
  SASI-neutrino heating .vs acoustic mechanisms,
  a clue to the explosion mechanism.

Estimation of Neutrino Anisotropy using Ray Tracing Methods

KK+ in prep.

- **Degree**

amics).

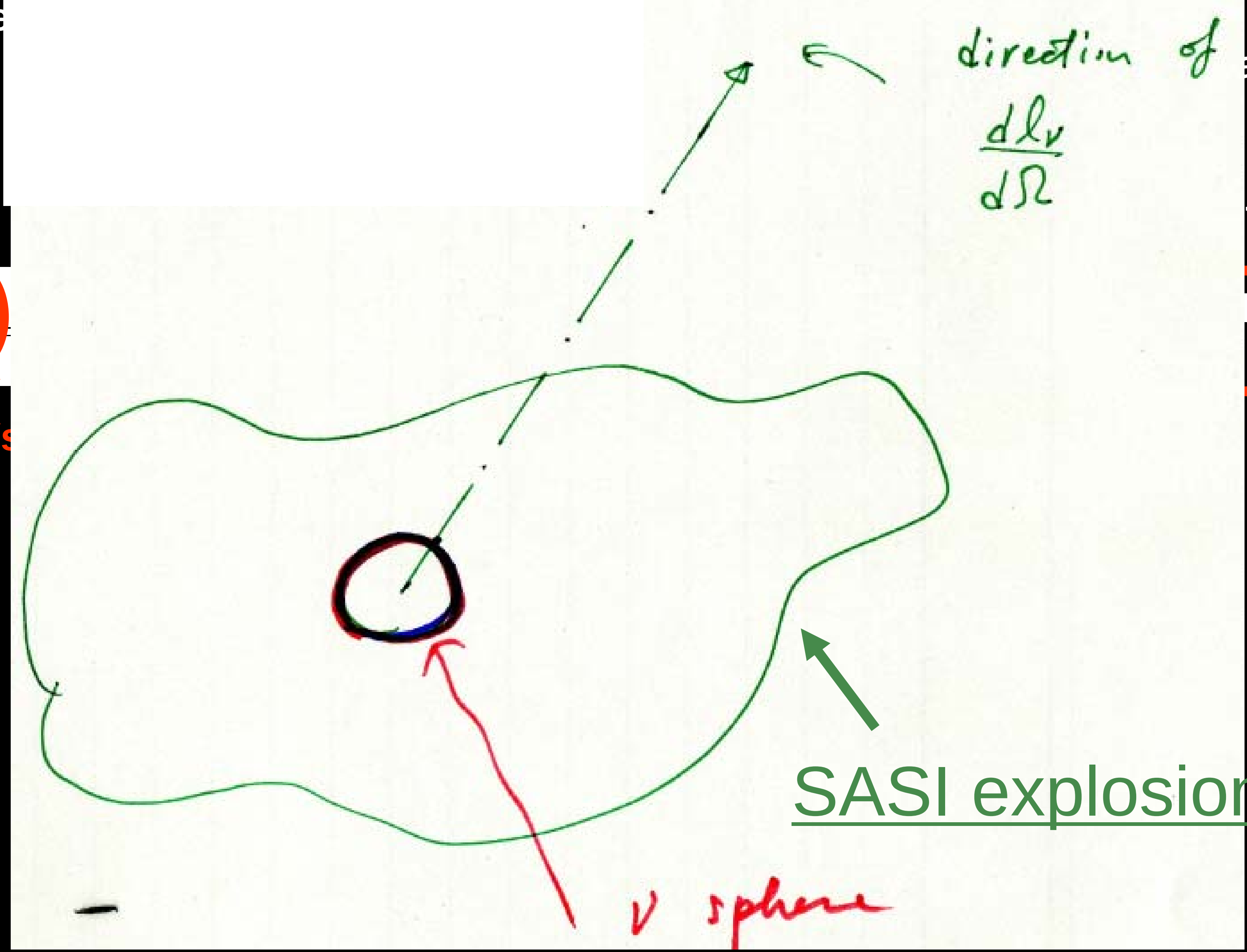
- **So far,**

+07)

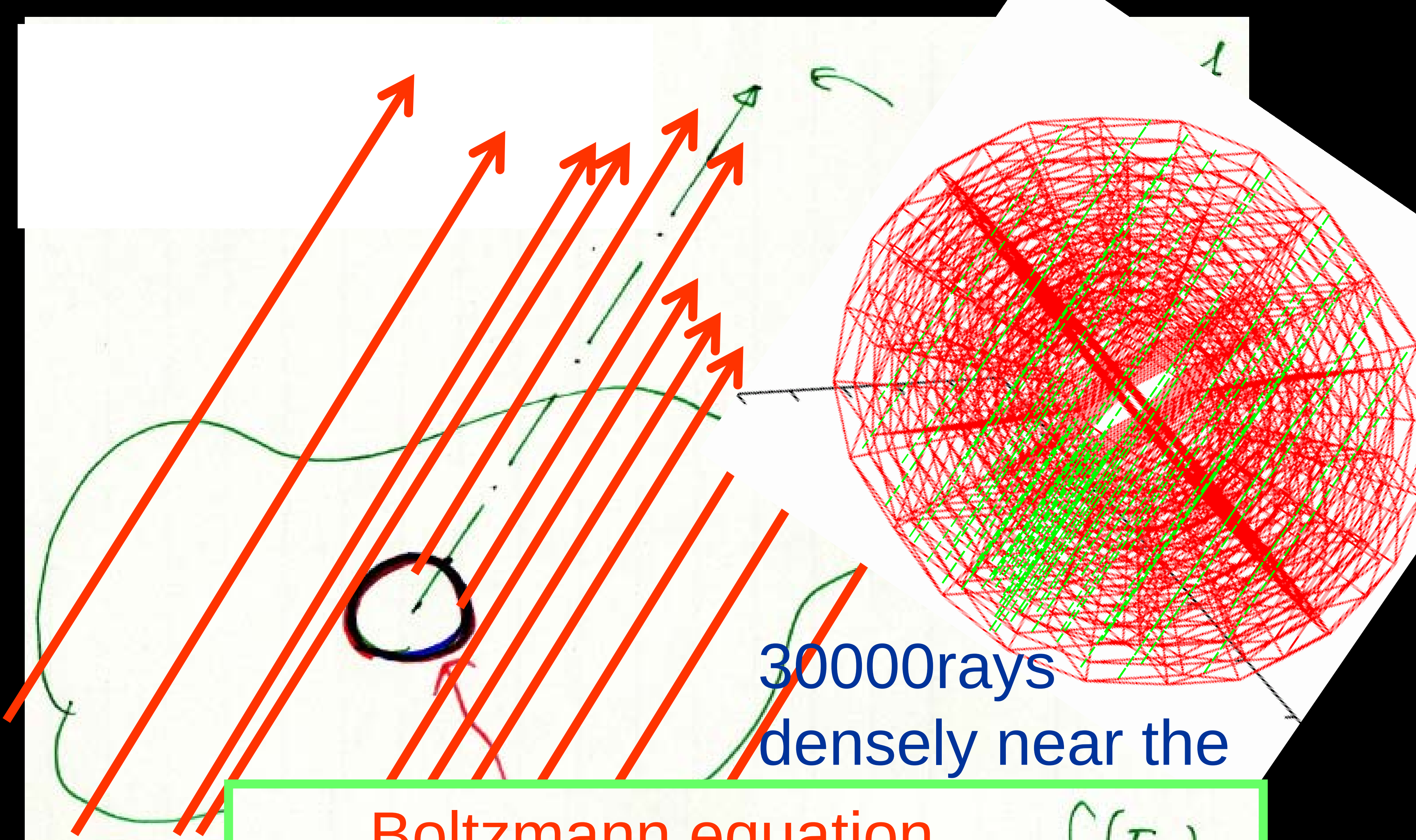
h_+^e

le

GWs



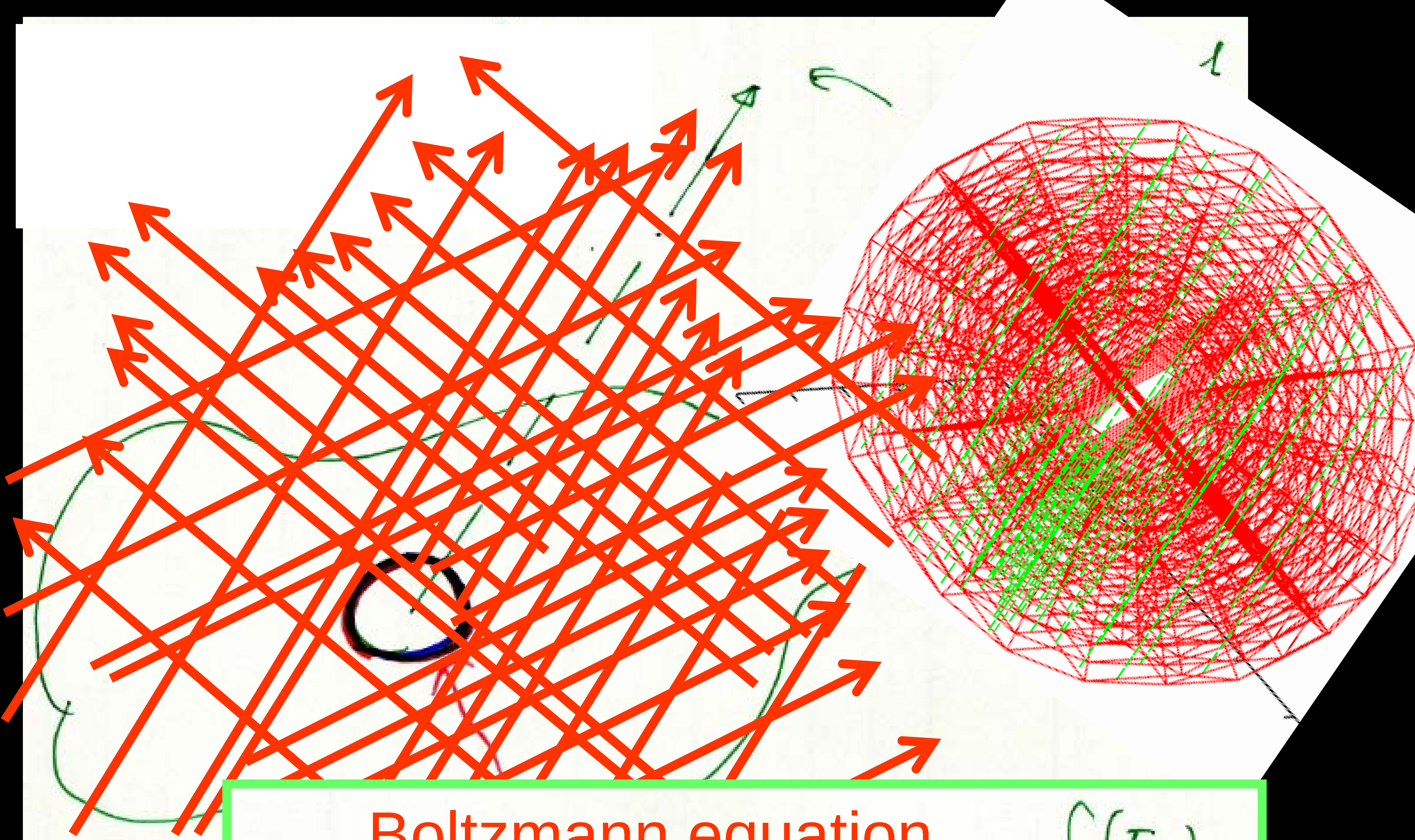
SASI explosion



30000rays densely near the

Boltzmann equation

$$\frac{\partial f}{\partial S} = j(E_\nu)(1 - f(E_\nu)) - \frac{f(E_\nu)}{\lambda(E_\nu)}$$

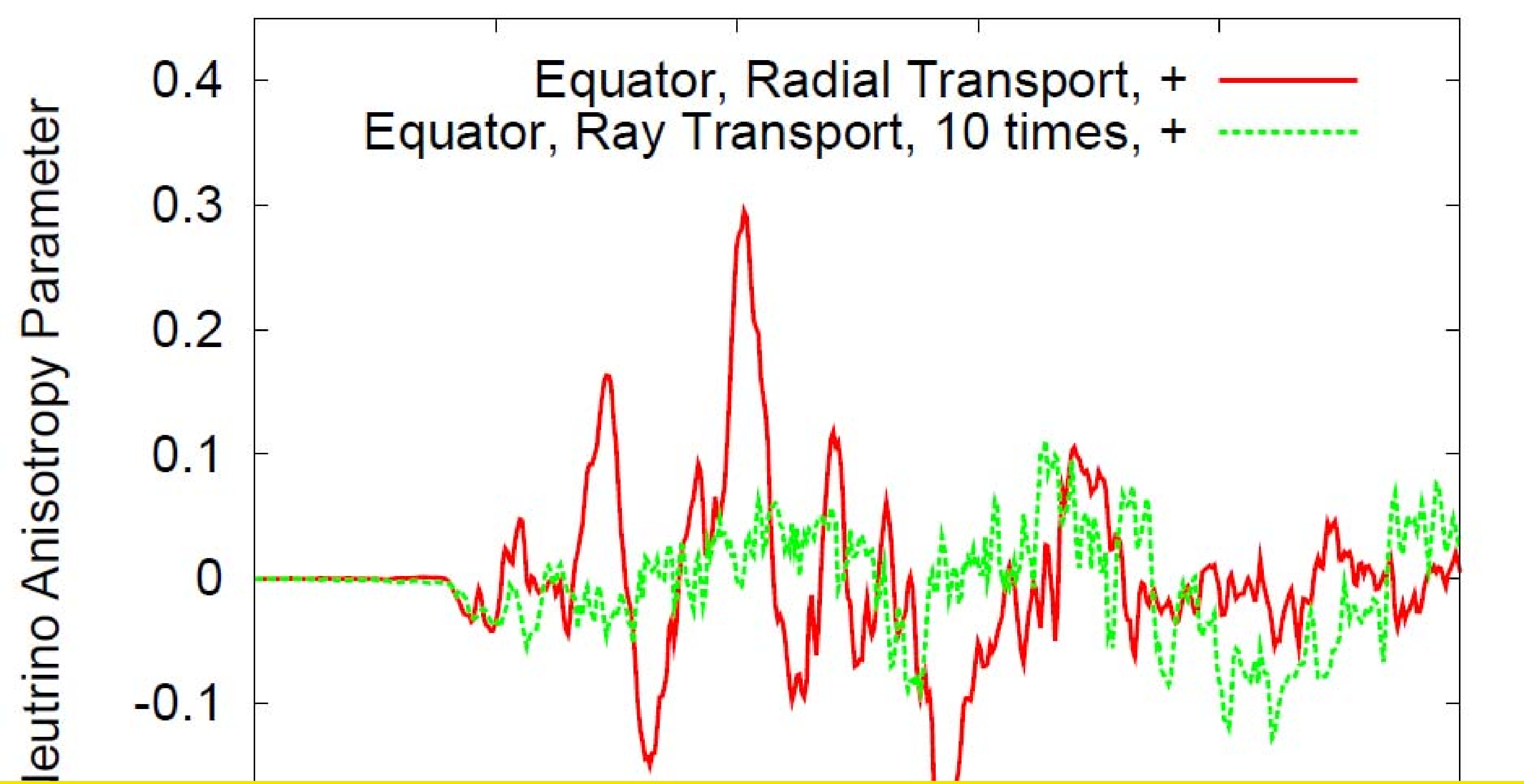


Boltzmann equation

$$\frac{\partial f}{\partial S} = j(E_\nu)\left(1 - f(E_\nu)\right) - \frac{f(E_\nu)}{\lambda(E_\nu)}$$

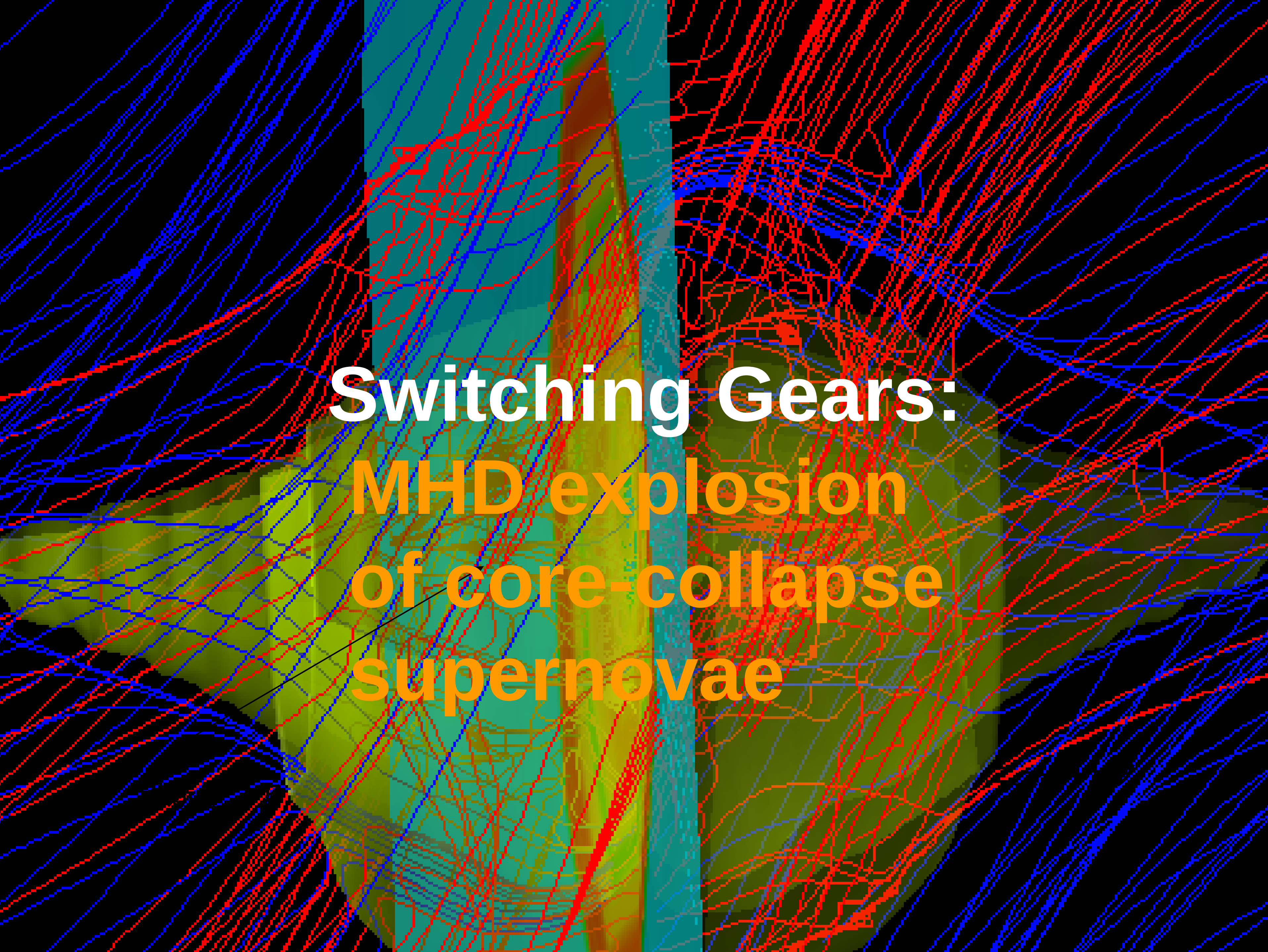
Neutrino anisotropy using Ray Tracing methods vs. Radial transport

KK+ in prep.



☆ Neutrino anisotropy becomes one-order-of magnitude smaller, thus the GW amplitudes are also…

☆ Unfortunately… 3rd generation GW detectors are needed to tell the difference between two mechanisms.

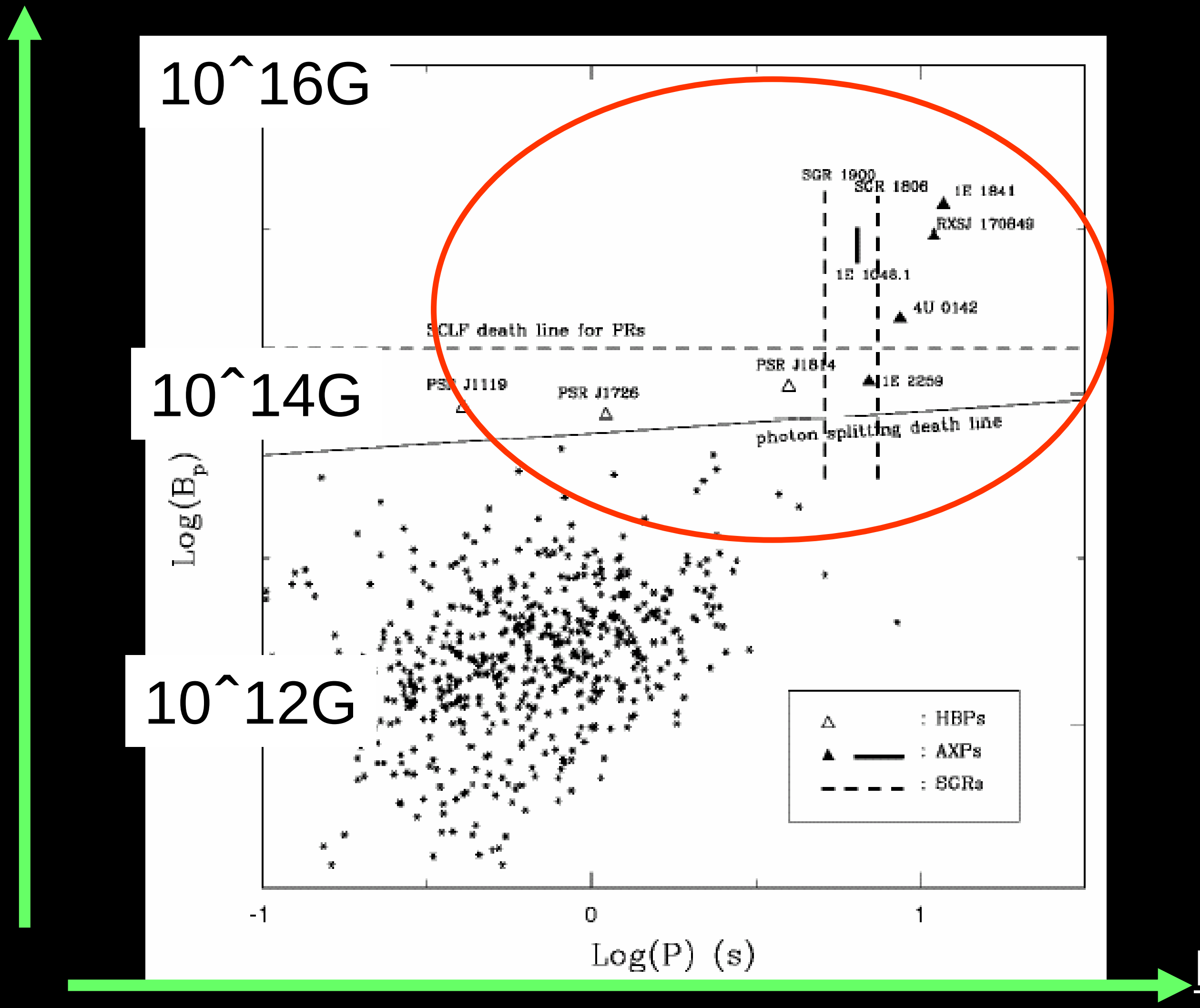


Switching Gears:

MHD explosion of core-collapse supernovae

Since “Magnetars” are minor…

Surface
B fields



Log(periods)

Zhang et al. 00

Histrory of Magnetized Supernovae

Takiwaki et al.

Pablo Cerda Duran et al

Scheidegger et al

Dessert et al.

Burrows et al.

Liebendoefer et al

Suwa et al.

Sawai et al.

Obergaulinger

KK et al.

Ardeljan et al.

Takiwaki et al.

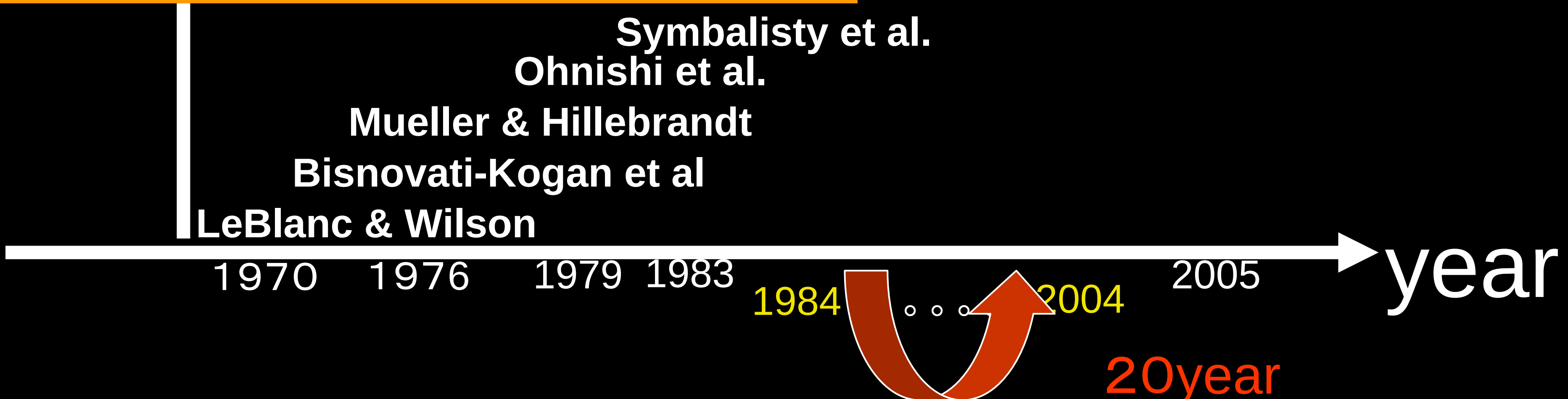
KK et al.

KK et al.

Yamada et al.

Numer of papers

- MHD supernovae : Renaissance !
- Relevant to magnetars and GRBs.
- Combination of rapid rotation & strong B fields, often called as unrealistic, are considered to be possible for the rapidly rotating metal poor stars. (Yoon & Langer 06, Woosley & Heger 06)



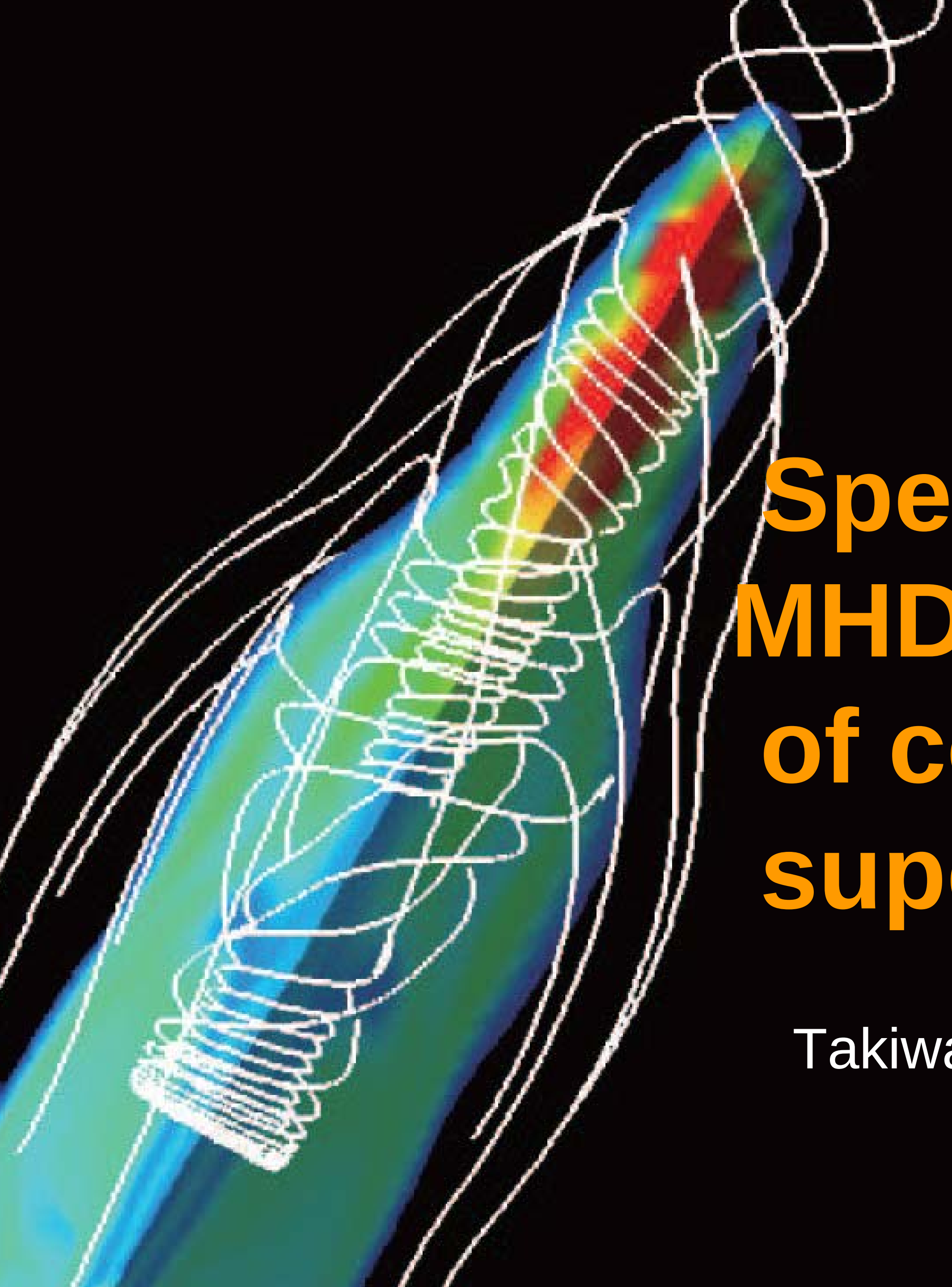
Symbalisty et al.

Ohnishi et al.

Mueller & Hillebrandt

Bisnovati-Kogan et al

LeBlanc & Wilson

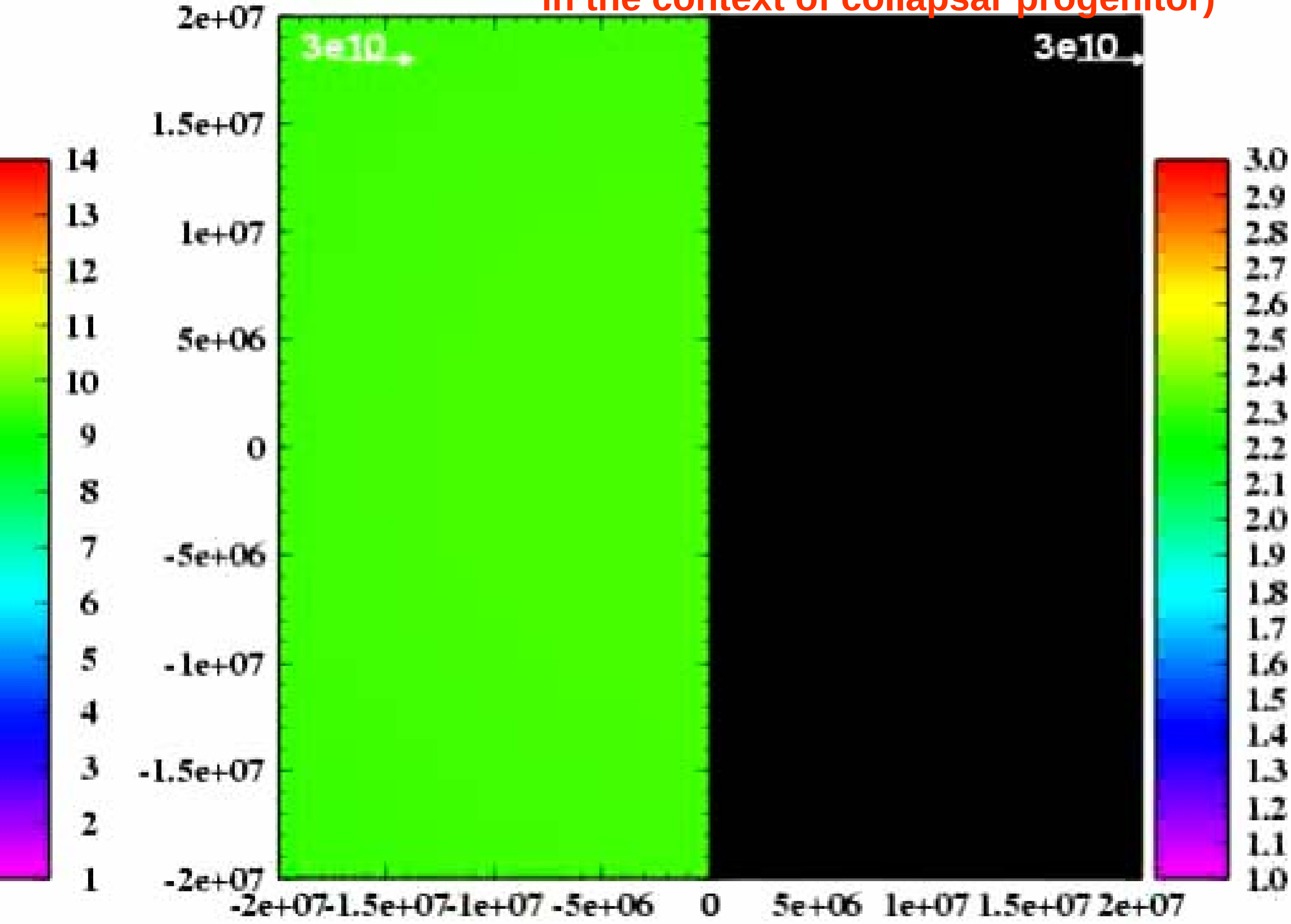


Special Relativistic MHD computations of core-collapse supernovae

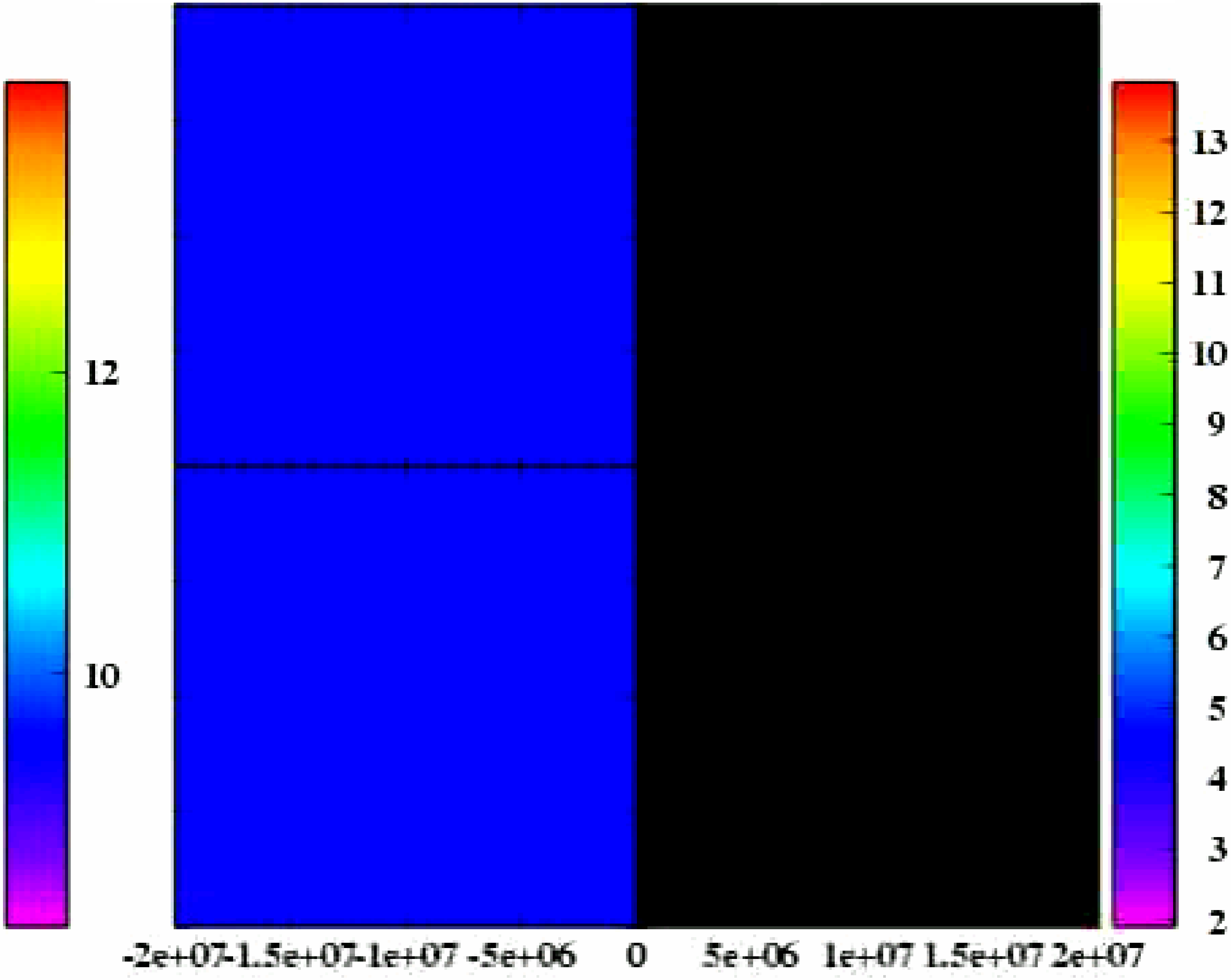
Takiwaki, KK, Sato, ApJ in press

The first MHD simulation from onset of collapse to jet propagation.

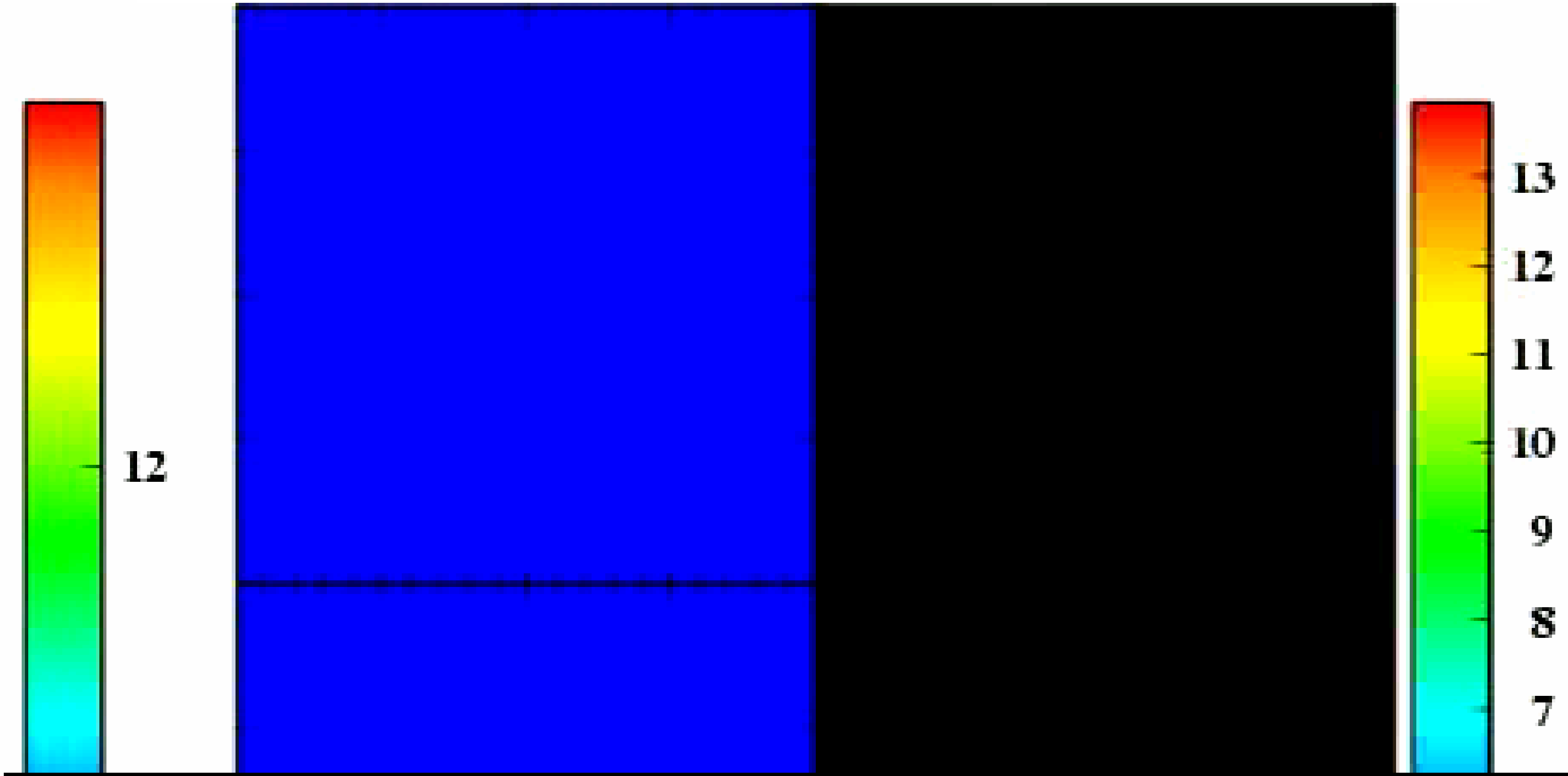
: Prompt MHD explosions (strong B~10^{12} G, rapid rotation T/|W| ~ 2 %
in the context of collapsar progenitor)



Delayed MHD Explosions (recent collapsar progenitor model; weak B, slow Ω)



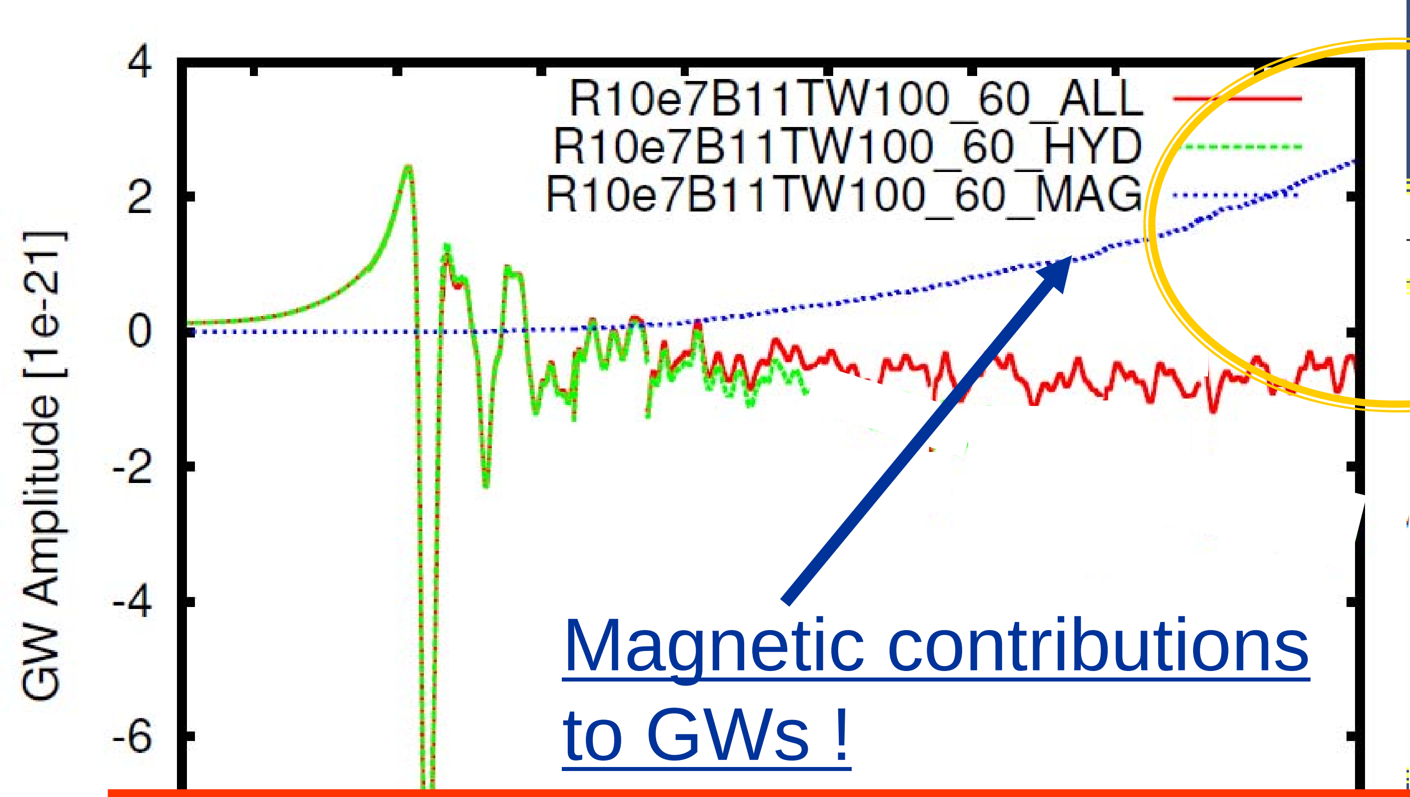
Delayed MHD Explosions (recent collapsar progenitor model; weak B, slow Ω)



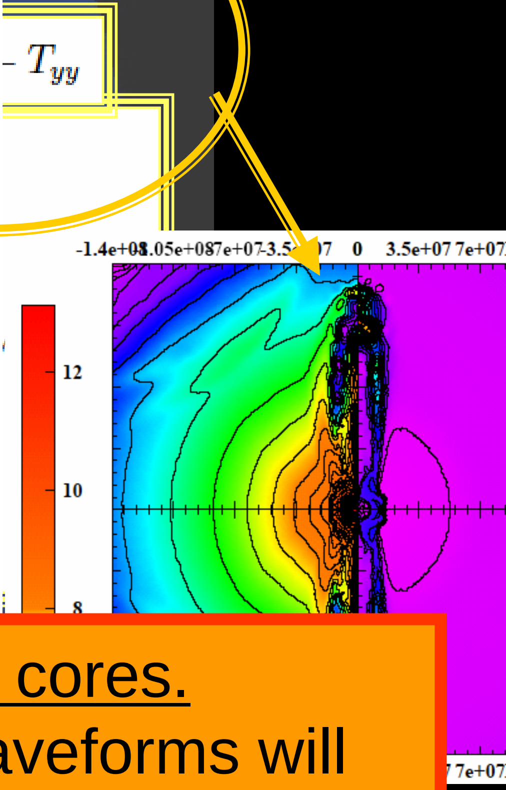
- Magnetic shock revival occurs when the magnetic pressure becomes strong, due to the field wrapping, enough to overwhelm the ram pressure of the accreting matter. The epoch is delayed here for the slow rotation.
- It's found that the magnetic shock revival can blow up the canonical collapsar progenitors.

Gravitational Waveforms from Magneto-Driven Explosions

Takiwaki, KK, Sato in prep



Magnetic contributions to GWs !



- An indicator of the B fields deep inside the cores.
- In the MHD exploding models, ***Type IV*** waveforms will be emitted (see also Obergaulinger et al. 06).

Neutrino oscillation in stellar core-collapse

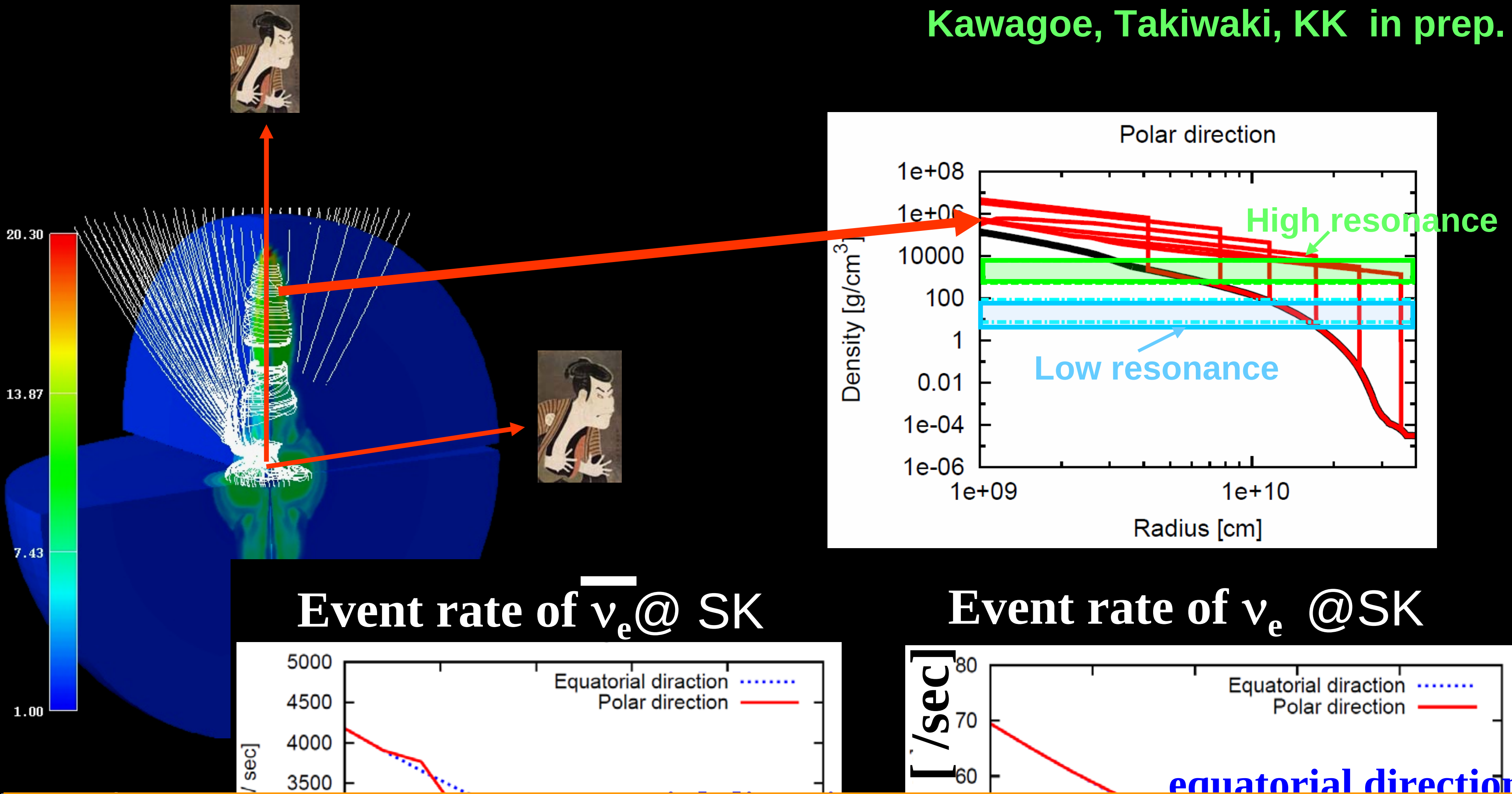
- Important probe into neutrino oscillation parameters.

  (mixing angles, mass squared differences and mass hierarchy).

  K.Takahashi, M. Watanabe, K. Sato, T. Totani (2001)
  K.Takahashi & K. Sato (2002)
  K.Takahashi, K.Sato, A. Burrows, T.D. Thompson (2003)
  S. Ando & K. Sato (2004)….

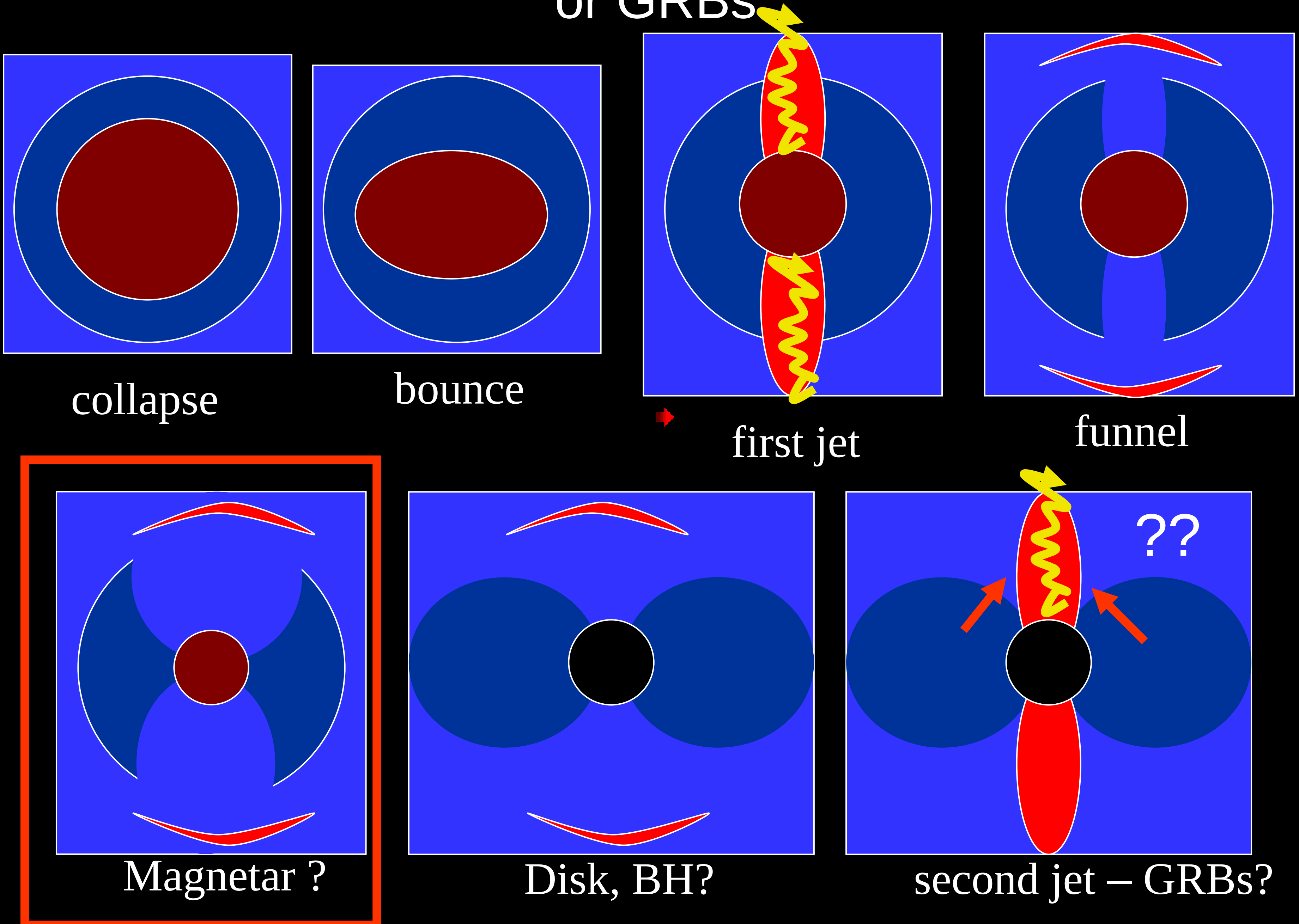
Neutrino oscillations in MHD explosion of supernovae

Kawagoe, Takiwaki, KK in prep.



- Signature in SK events, especially from the L resonance, could be a characteristic feature for the MHD explosions. (∵ shock reaches much earlier than the usual ν-heated models)
- For details, see poster (A27) by Shiou Kawagoe.

After the MHD explosions: the route to magnetar or GRBs



collapse

bounce

first jet

funnel

Magnetar ?

Disk, BH?

second jet – GRBs?

Equilibrium configurations of Magnetars

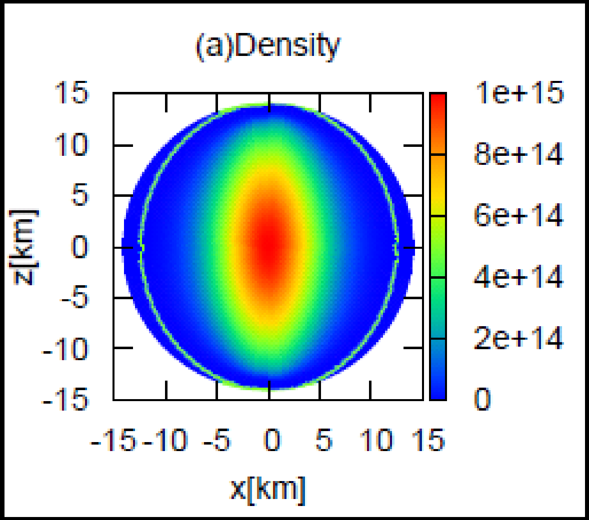
☆Kiuchi & KK, MNRAS (2008)

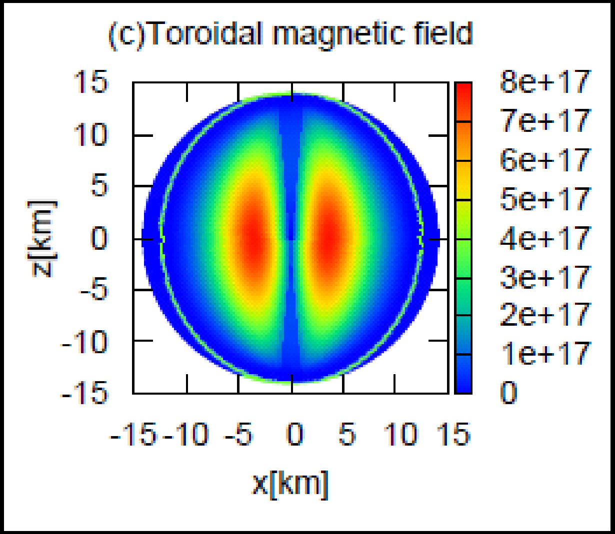
Mixed poloidal and toroidal fields : Pseudo GR gravity with realistic EOSs

☆Kiuchi, KK, and Yoshida, submitted to ApJ

full GR + Purely toroidal magnetic fields with realistic EOSs

(From core-collapse sim, toroidal fields are up-to 2 orders of mag. > the poloidal ones.)





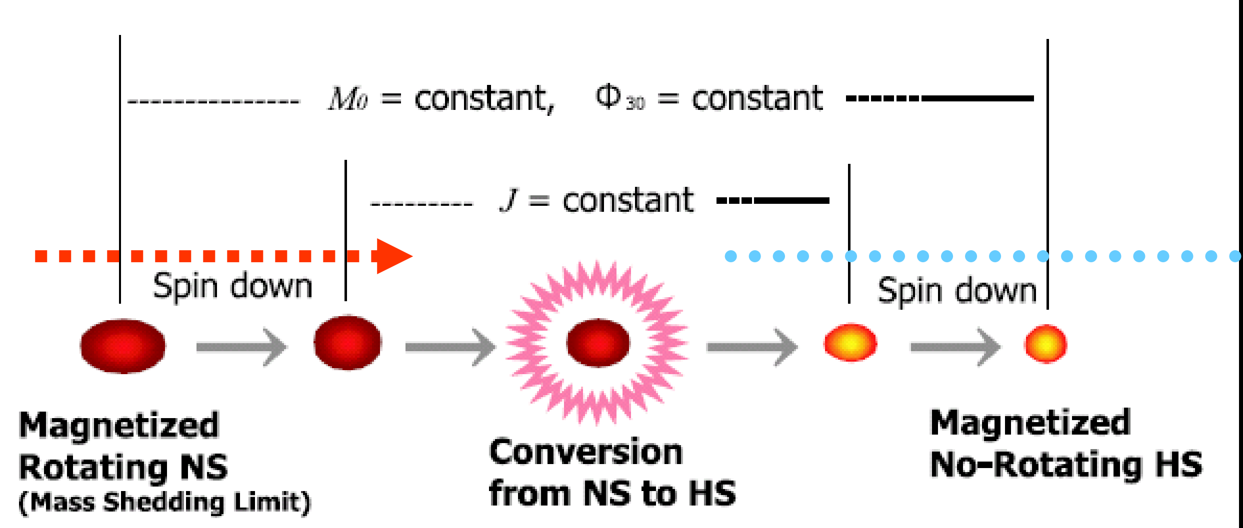
rather
from
an academic
interest …

- Strong toroidal B fields (10^{18} G), like a rubber belt, can distort magnetars prolately.

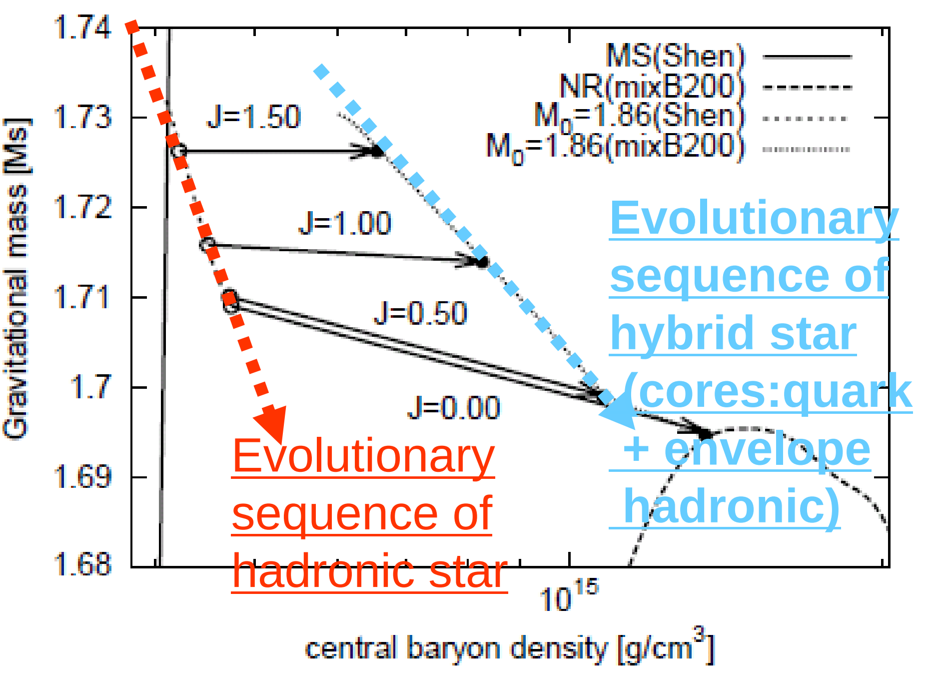
  (・ Given the same mass and the same magnetic flux, the deformation becomes higher for the softer EOS.)

Evolutions of neutron stars/magnetars to strange stars

Yasutake, Kiuchi, and KK (2009)



Fixing baryon mass,



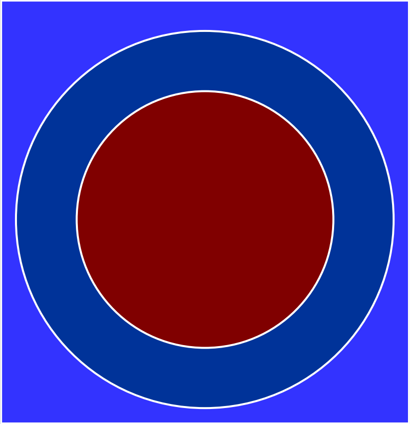
Evolutionary sequence of hadronic star

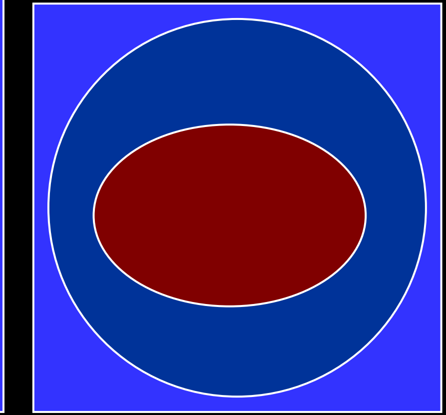
Evolutionary sequence of hybrid star (cores:quark + envelope hadronic)

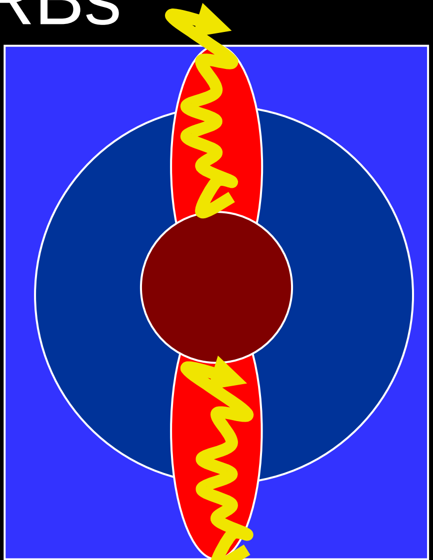
At the phase transition,
: the vast energy release of 10^{52} ergs
accompanied by
the burst-like emissions of
gravitational waves and neutrinos.

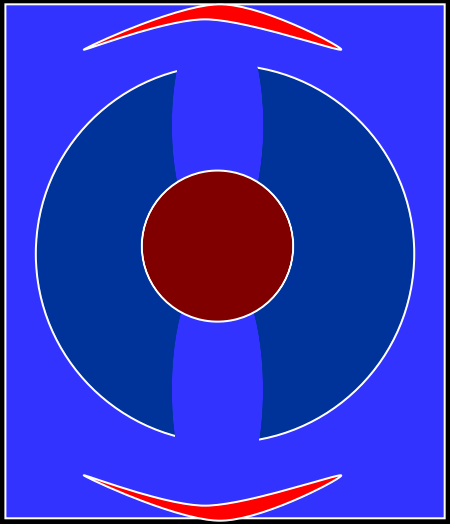
☆ a clue to the phase transition physics (albeit very speculative).

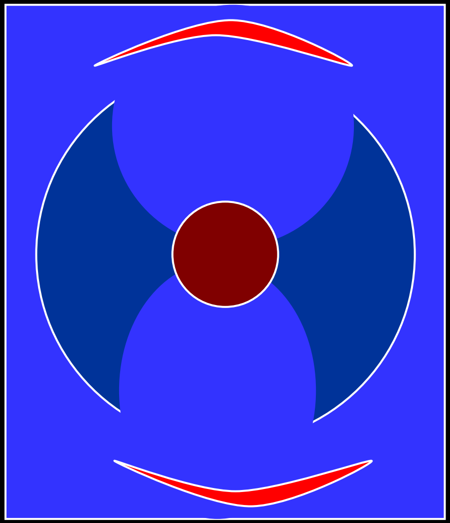
After MHD explosions: the route to magnetar or GRBs

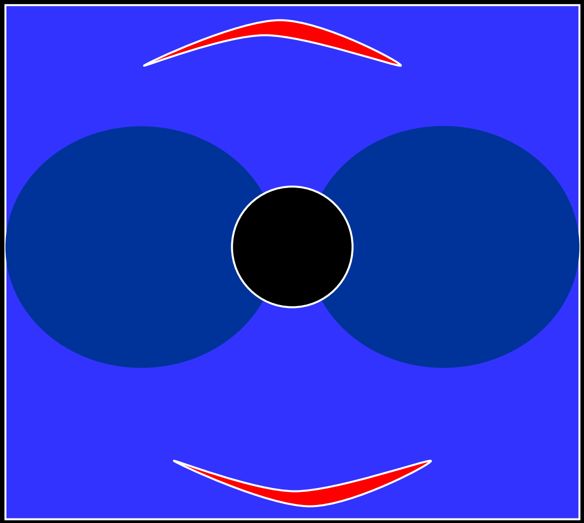

collapse

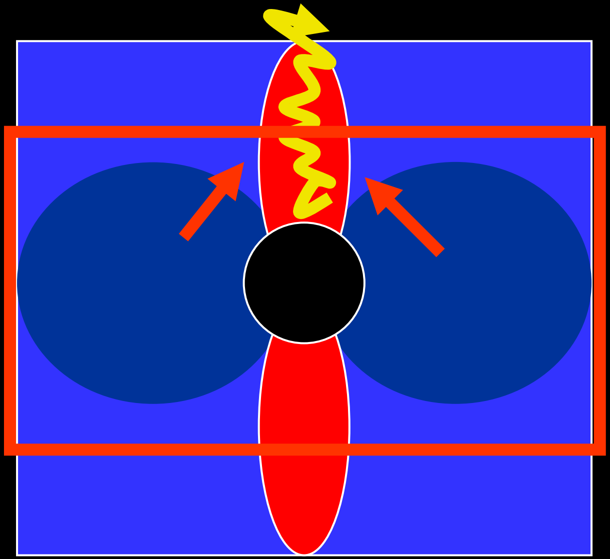

bounce


first jet


funnel


Magnetar ?


Disk, BH?

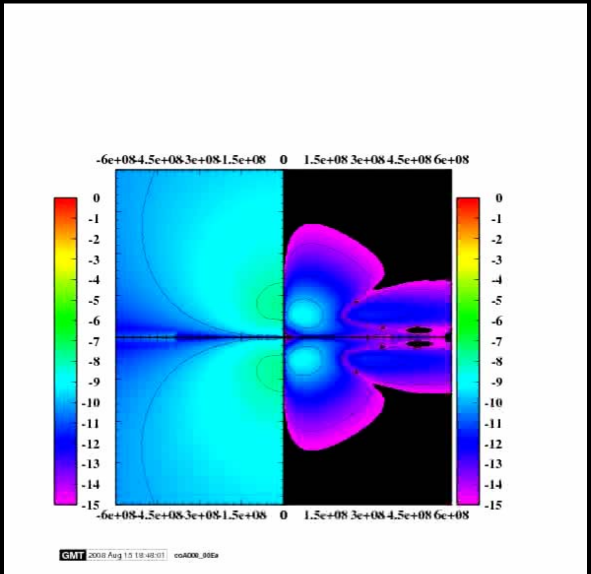

Collapsar – GRBs?

Collapsar simulation in SRMHD

Harikae, Takiwaki, KK in prep.

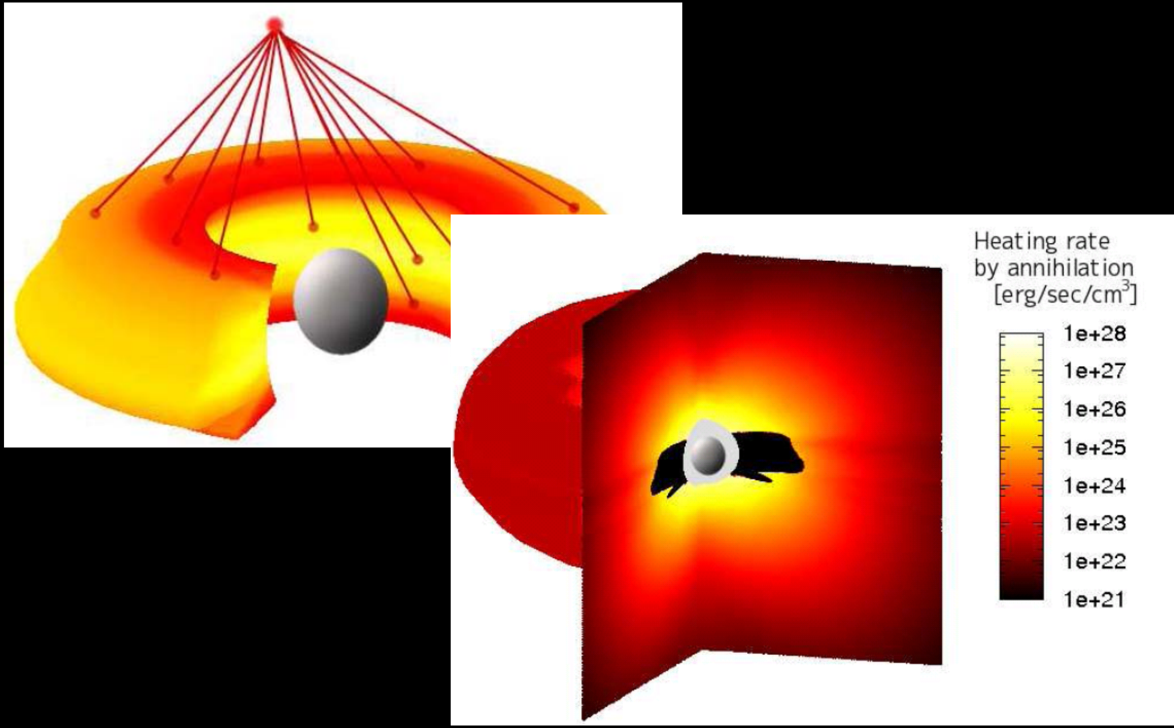
- Based on a recent collapsar progenitor (Woosley & Heger 06), much slower rotation with weaker B fields of 10^{11} G than previously assumed (Proga+03, MacFadyen & Woosley 1993).

Moderate



~5.6 sec

Neutrino pair annhilation using ray methods



☆ We do observe the launch of MHD jets in much later phase than previous study (~ 2 sec).
(note that for the stable simulations, SR is important !)

Origin of large magnetic fields

Two candidate scenarios

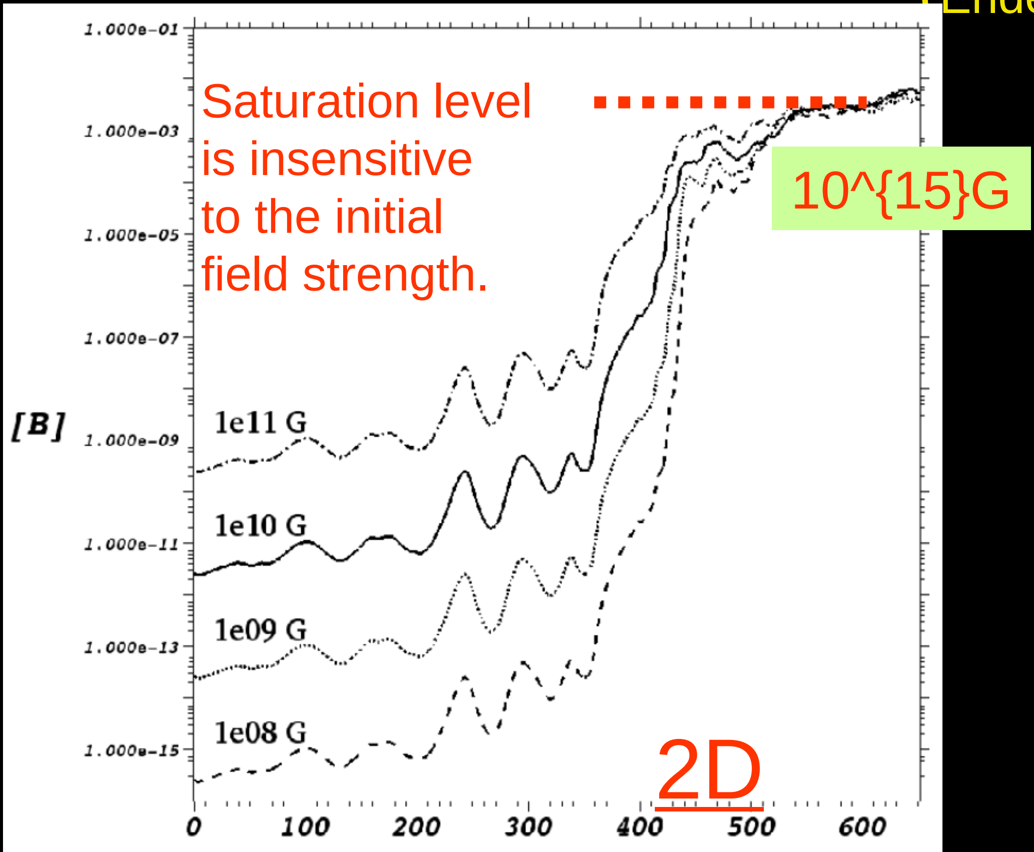
: **Fossil hypothesis** by Ferrario et al. (2004)

: **Dynamo** processes in rapidly rotating proto-neutron stars.

(Thompson & Duncan 1993)

: Generation of large magnetic fields by SASI.

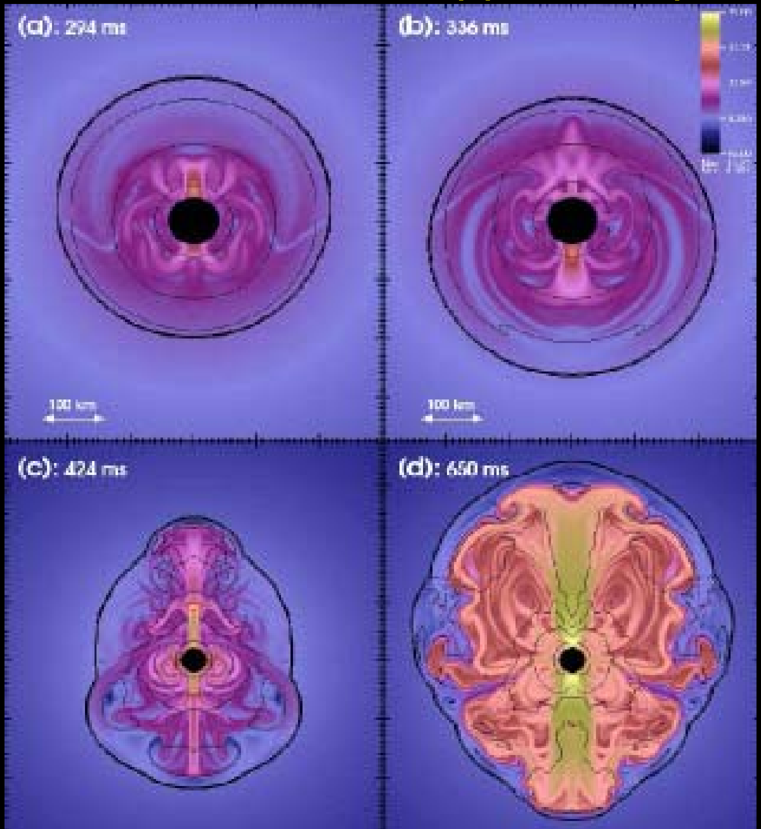
(Endeve, Cardall, Mezzacappa,astro-ph 2008)



Saturation level is insensitive to the initial field strength.

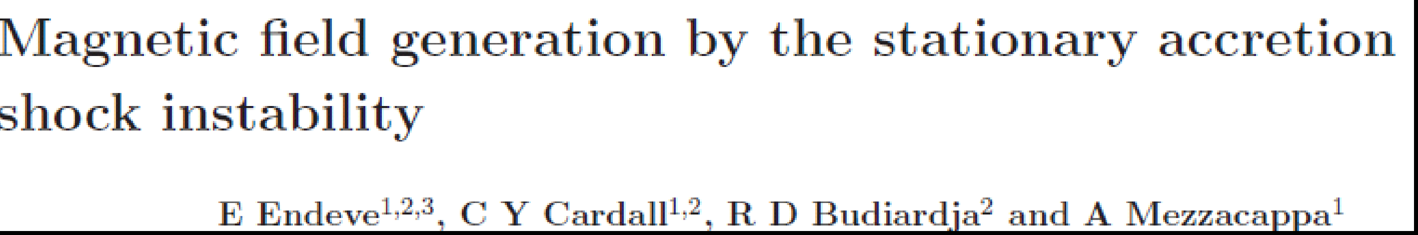
10^{15}G

2D



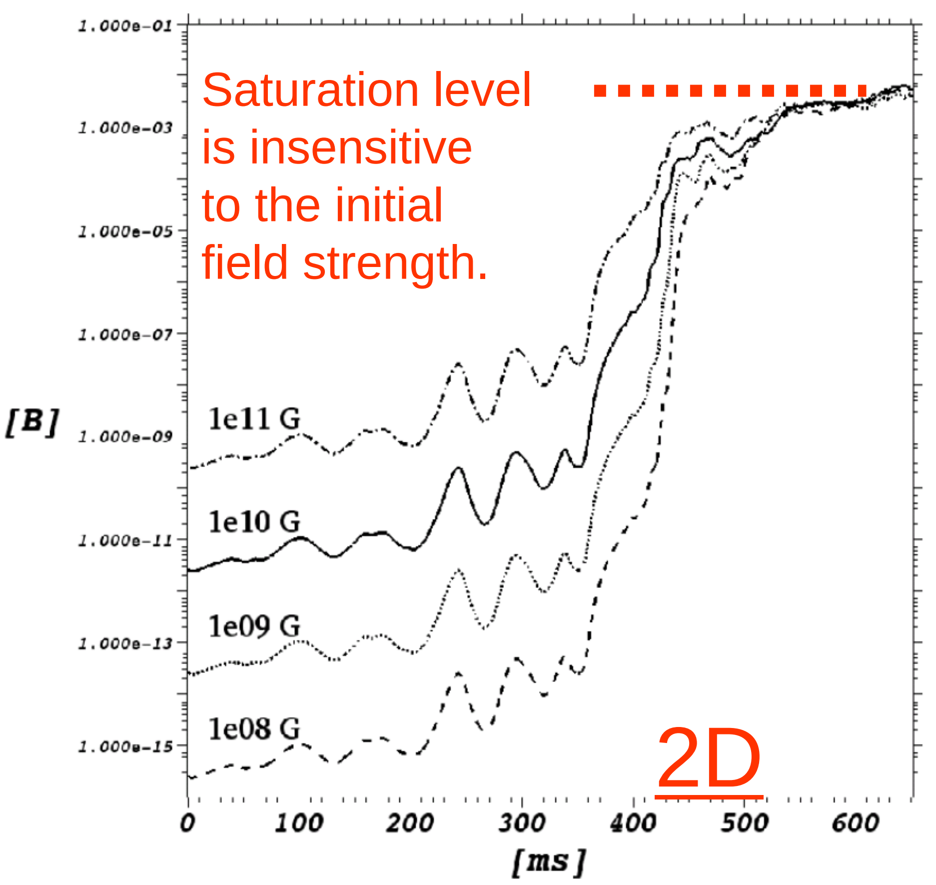
SASI in MHD

Iwakami,
KK+ in prep.



Magnetic field generation by the stationary accretion shock instability

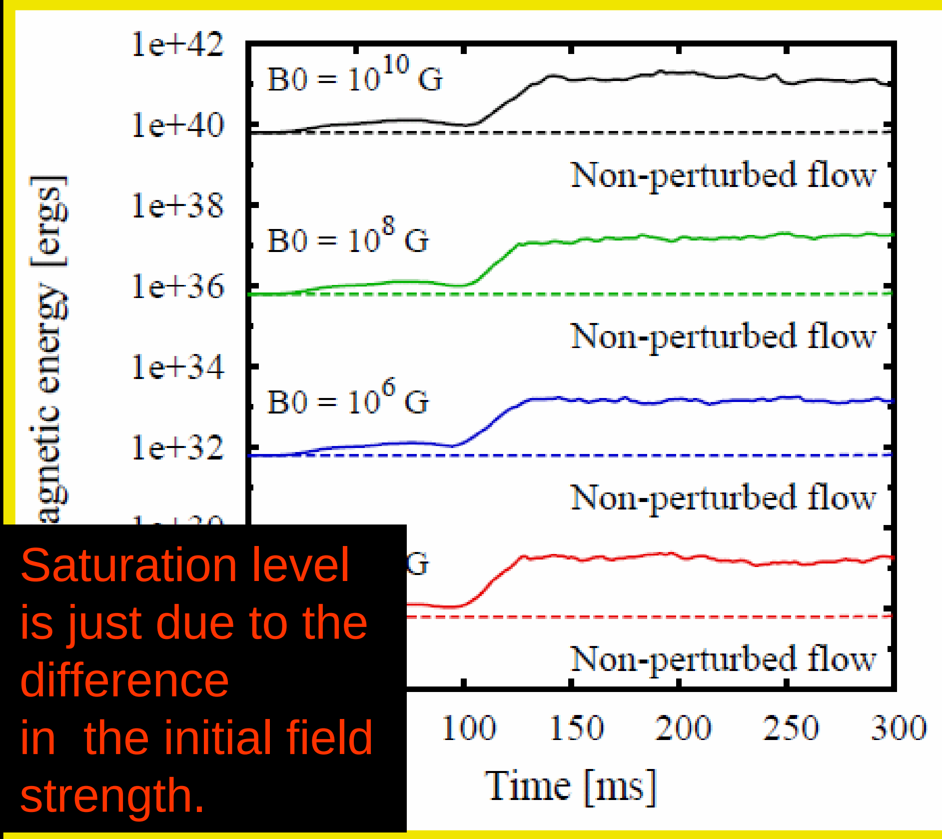
E Endeve[1,2,3], C Y Cardall[1,2], R D Budiardja[2] and A Mezzacappa[1]



Saturation level is insensitive to the initial field strength.

2D

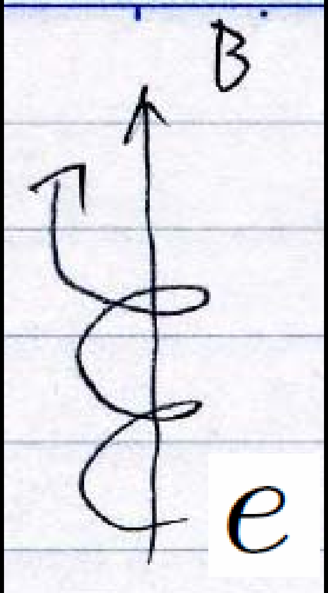
Our 3D



Saturation level is just due to the difference in the initial field strength.

Magnetic effects are not only through…

$$\rho\frac{d\boldsymbol{v}}{dt} = -\nabla \boxed{p} - \rho\nabla\Phi + \boxed{\frac{1}{4\pi}(\nabla\times\boldsymbol{B})\times\boldsymbol{B}} - \nabla\cdot\left[\sum_f\int d\omega\,(P(\omega)+\bar{P}(\omega))\right]$$



☆Lorentz force

☆Equation of state

The onset of Landau quantization of electrons occurs for the field strength larger than B_{QED},

$$\boxed{B_c = \frac{m_e^2 c^3}{e\hbar} = 4.414\times10^{13}\ \mathrm{G},}$$

(e.g., Lattmier & Prakash 07)

Such circumstances can be satisfied for (any!) MHD explosion models.

Construction of EOS tables including magnetic effects

KK, Ichikawa, Sumiyoshi in prep

- We derived analytic formulae for the expressions of pressure, number density, etc, which helps a lot to reduce the computational time for constructing a EOS table with wide density, Ye, temperature range.

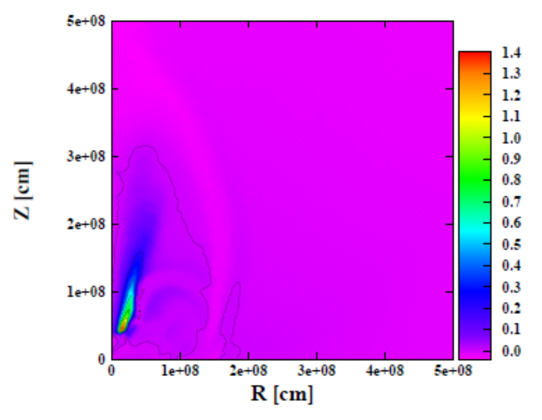
$$\begin{aligned}\frac{\rho Y_e}{m_N} &= n_{e^-}(B) - n_{e^+}(B) = \\ &= 2\frac{eB}{2\pi^2}\sum_{n=0}^{\infty} g_n m_*(n) \sum_{k=1}^{\infty} \\ &= \frac{eB}{\pi^2}\sum_{n=0}^{\infty} g_n m_*(n) \sum_{k=1}^{\infty}(-\end{aligned}$$

$$\begin{aligned}\epsilon_{\rm tot}(B) &= \epsilon_{e^+}(B) + \epsilon_{e^-}(B) \\ &= \frac{eB}{2\pi^2}\sum_{n=0}^{\infty} g_n m_*^2 \sum_{k=1}^{\infty} 2\cosh k\phi_e\ (\\ &= \frac{eB}{\pi^2}\sum_{n=0}^{\infty} g_n m_*^2 \sum_{k=1}^{\infty} \cosh k\phi_e\ (K_0\end{aligned}$$

$$\begin{aligned}P_{\rm tot}(B) &= P_{e^-}(B) + P_{e^+}(B) \\ &= \frac{eB}{2\pi^2}\sum_{n=0}^{\infty} g_n m_*^2 \sum_{k=1}^{\infty}(2\cosh kz)\frac{1}{kz}K_1(kz) \\ &= \frac{eB}{\pi^2}\sum_{n=0}^{\infty} g_n m_*^2 \sum_{k=1}^{\infty}(\cosh kz)\frac{1}{kz}K_1(kz).\end{aligned}$$

- **Difference of pressure with B from without.**

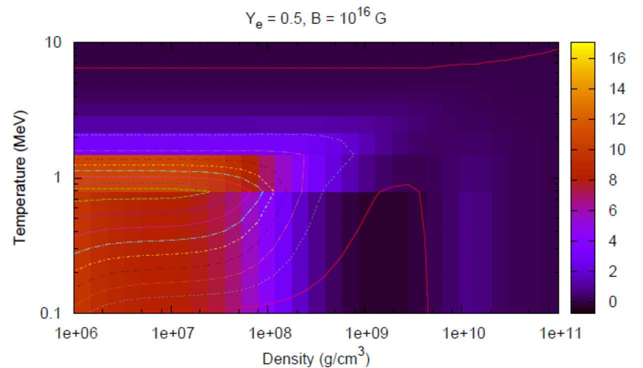
$(P_{B\neq 0} - P_{B=0})/P_{B=0}$



The pressure including the B-fields contributions can be ~2 times larger behind the shock.

☆This might affect the MHD explosions.

- Phase diagram of $(P_{B\neq 0} - P_{B=0})/P_{B=0}$



Putting things together……
Summary,
new challenges and perspectives

Summary

☆ 3D SASI-aided neutrino-driven core-collapse supernovae:
with idealized situations (e.g., excision of the PNS and
approximate neutrino transport),
to study the explosion dynamics and gravitational waves.

☆ MHD mechanism of core-collapse supernovae:
characteristic signatures in gravitational-waves and neutrinos.

☆ As a remnant of the MHD explosions, evolution of
magnetars/neutron stars (with some exotic flavors).

☆ Applications of MHD simulations : collapsar simulations
(: collapse of Pop III stars)

Suwa+07,08

Relevance with each study ? Where is our study towards ?
Do we choose the research themes, out of whim ?

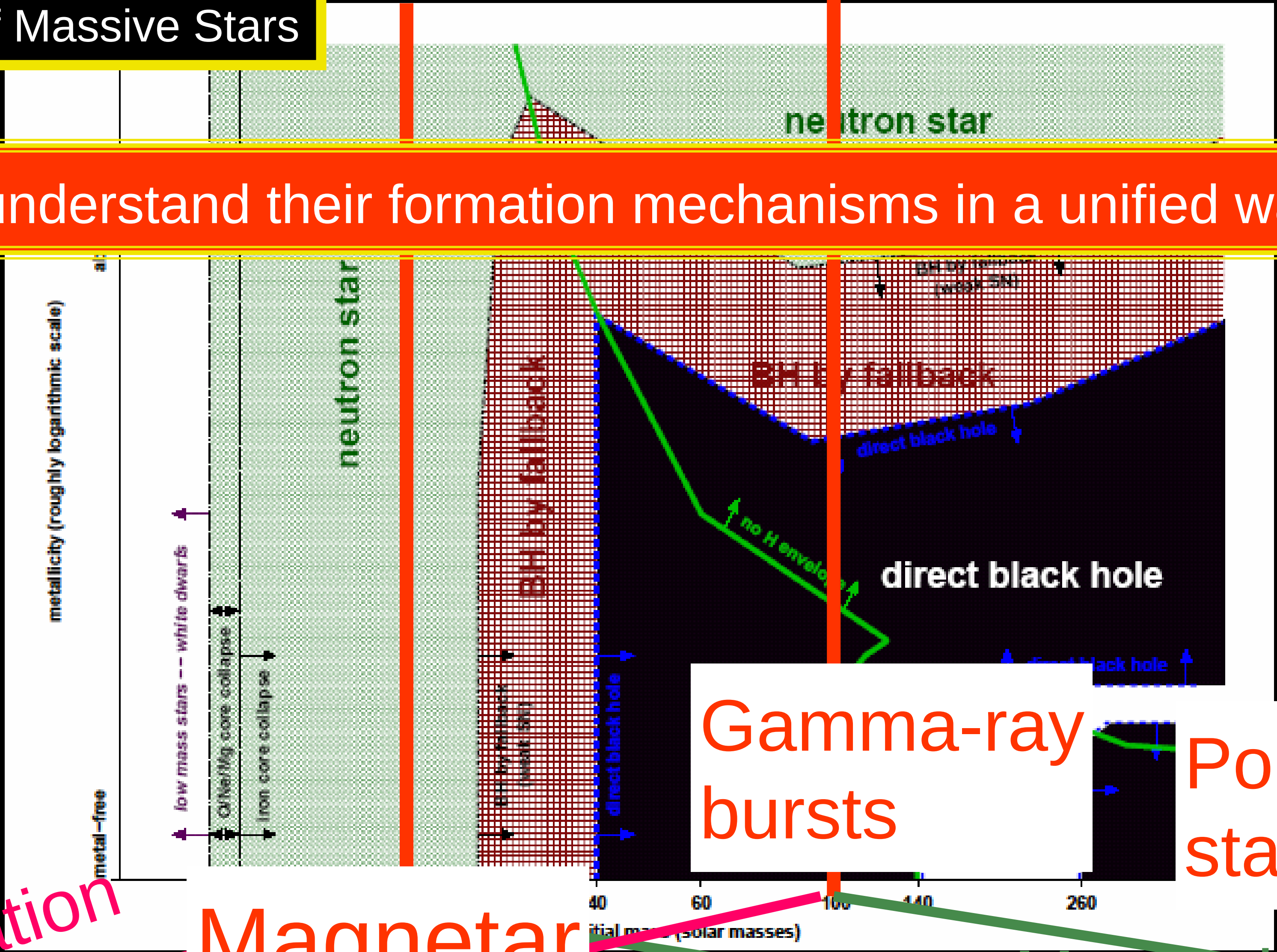
（気まぐれに）

NO !!

Perspectives

Heger+(2003)

Fate of Massive Stars



To understand their formation mechanisms in a unified way !

Metalicity

Progenitor’s mass

rotation

Magnetic field

Magnetar

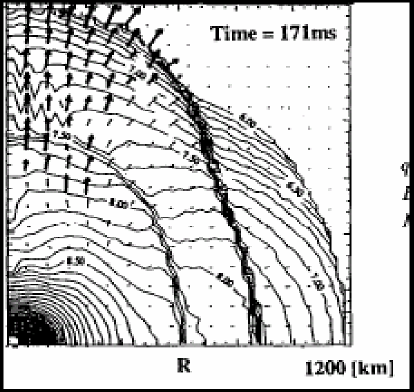
Gamma-ray bursts

Pop III stars

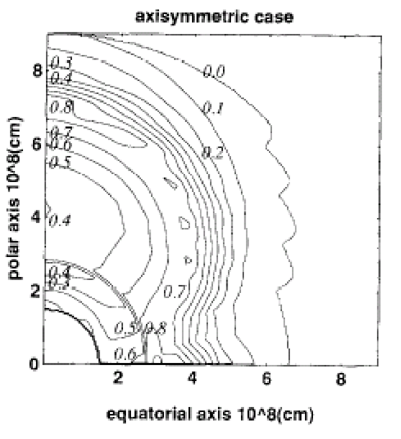
To put the cards on the table… (種を明かせば)

The policy of division of SN research of K. Sato’s group ,

☆Clarifying the roles of rotation and magnetic fields,
is a (kind of) tradition.



Yamada & Sato ApJ, 1994,



Nagataki et al. ApJ, 1997 ~

☆Studying the neutrino and GW signals is also a best subject.

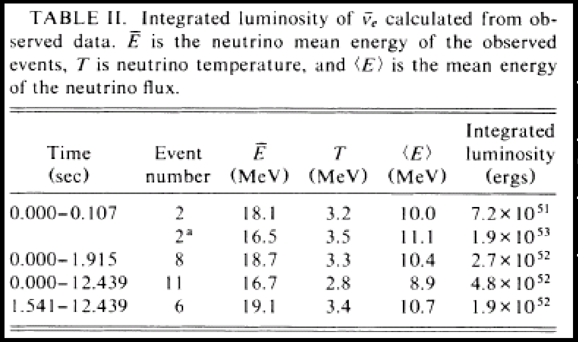
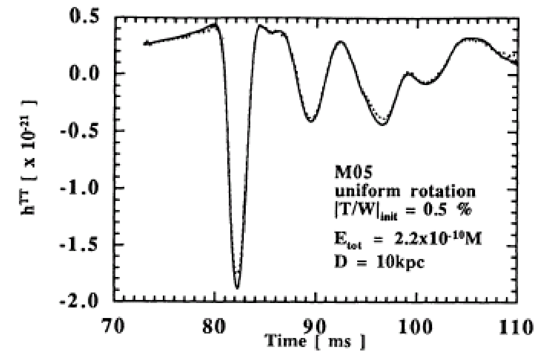


TABLE II. Integrated luminosity of $\bar{\nu}_e$ calculated from observed data. $\bar{E}$ is the neutrino mean energy of the observed events, T is neutrino temperature, and $\langle E \rangle$ is the mean energy of the neutrino flux.

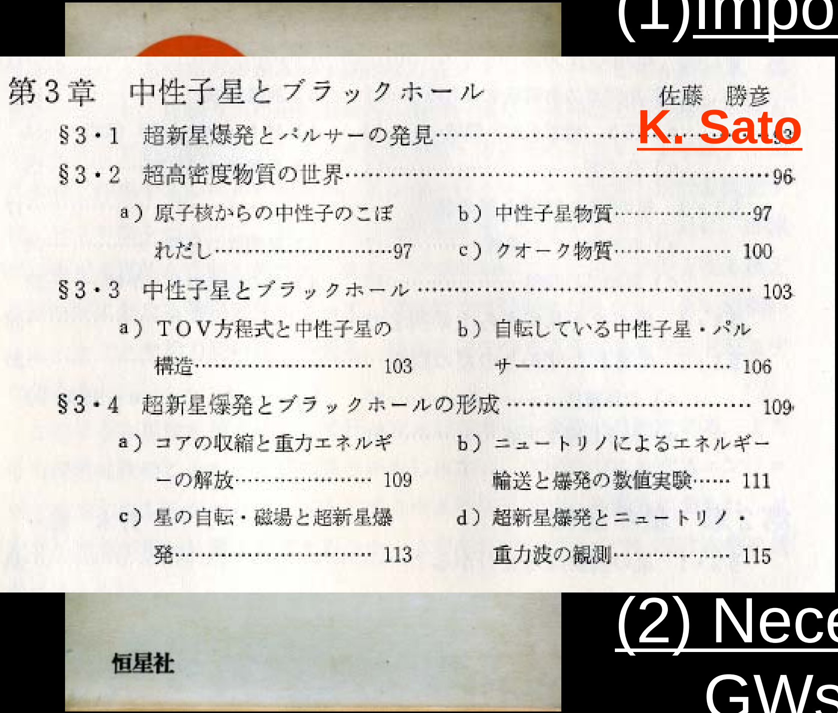
Time (sec)	Event number	$\bar{E}$ (MeV)	T (MeV)	$\langle E \rangle$ (MeV)	Integrated luminosity (ergs)
0.000–0.107	2	18.1	3.2	10.0	7.2×10^{51}
	2[a]	16.5	3.5	11.1	1.9×10^{53}
0.000–1.915	8	18.7	3.3	10.4	2.7×10^{52}
0.000–12.439	11	16.7	2.8	8.9	4.8×10^{52}
1.541–12.439	6	19.1	3.4	10.7	1.9×10^{52}

Sato & Suzuki, PRL 1987
Totani & Sato ApJ 1995



Yamada & Sato ApJ 1995

@ A used book store

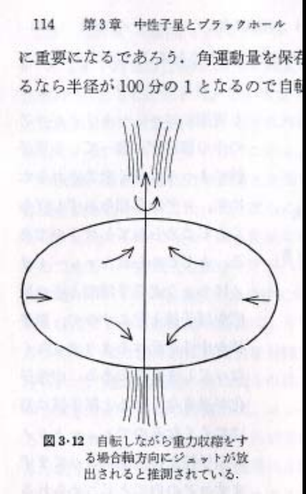


第３章　中性子星とブラックホール　佐藤　勝彦

K. Sato

恒星社

(1)Importance of rotation & magnetic fields



114　第３章　中性子星とブラックホール

に重要になるであろう．角運動量を保存
るなら半径が100分の１となるので自転

図３・12　自転しながら重力収縮をする場合軸方向にジェットが放出されると推測されている．

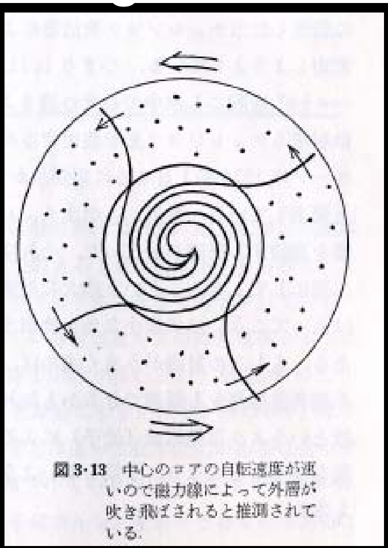


図３・13　中心のコアの自転速度が速いので磁力線によって外層が吹き飛ばされると推測されている．

(2) Necessity of coincident analysis between GWs and neutrino detections

ｄ）　超新星爆発とニュートリノ・重力波の観測

（２）や（３）の場合であっても我々の銀河内で起こる場合その検出は可能であり，ニュートリノ検出との同時観測を通じて爆発機構の解明にきわめて重要である．

Stellar evolutions
and their fate:

1979年７月

杉本大一郎

Time changes, the policy kept unchanged!

On-Going Numerical Challenges:

The ultimate tool needed,

3D full GRMHD with spectral neutrino transport simulations

: Hydro

1D Lagrangian: Sato & Takahara (1984~)
2D Newtonian HD : Yamada, Shimizu, Nagataki (1991~)
2D Newtonian MHD : KK & Yamada (2003~)
2D SRMHD: Takiwaki (2007~)
3D MHD Newtonian: Iwakami, KK, Ohnishi (2008~)
3D full GR hydro codes : Kiuchi, KK, Yamada in prep

Mariage

: Neutrino transport

1D: Boltzmann: Suzuki(1987~), Yamada(1997~), Sumiyoshi(2004~)
2D: MGFLD: KK & Ohnishi(2006~)
3D: IDS (Suwa, KK with Basel group), Sn methods: Sumiyoshi, KK, Ohnishi
Yamada et al. in prep

Q: How long will it take for the mariage ?

A: Within this 5 years (of course, with a few approximations in the transport)

Q: Are you serious ??

A: Yes, we can !

Thank you very much !