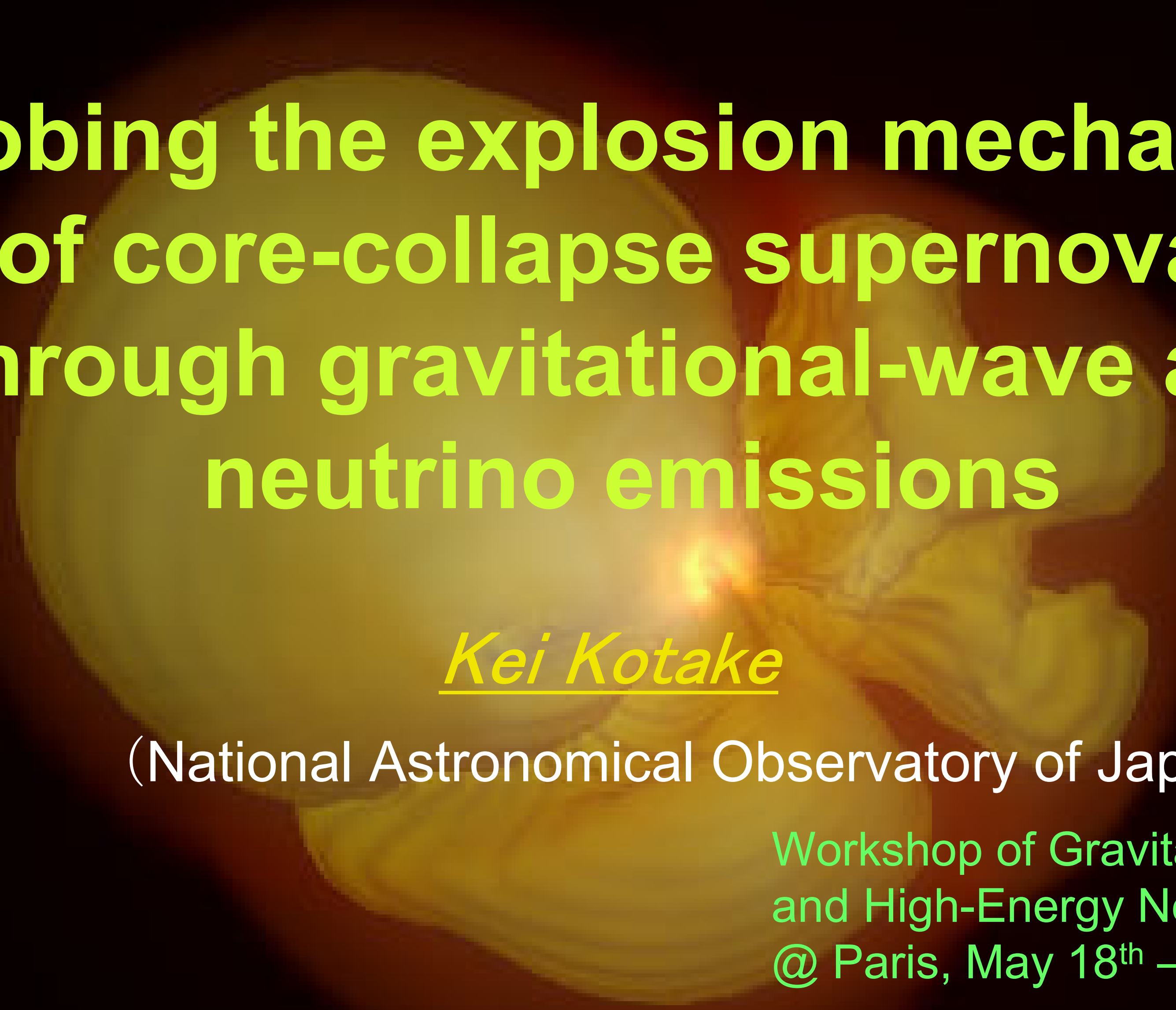
Probing the explosion mechanism of core-collapse supernovae through gravitational-wave and neutrino emissions



Kei Kotake

(National Astronomical Observatory of Japan)

Workshop of Gravitational Waves
and High-Energy Neutrinos
@ Paris, May 18th – 20th

Outline

- ✓ Introduction
  :Current status of multi-dimensional supernova models

- ✓ Gravitational waves from
  neutrino-driven supernova explosions in 3D
  (KK, Iwakami, Ohnishi, Yamada, ApJL 2009)

- ✓ Magnetically-driven supernova explosions
  -- signatures of GWs and neutrinos
  (Takiwaki, KK, Sato, ApJ,09,
  Harikae, Takiwaki, KK, submitted to ApJ,
  Kawagoe, Takiwaki, KK, submitted)

Core-collapse Supernovae

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

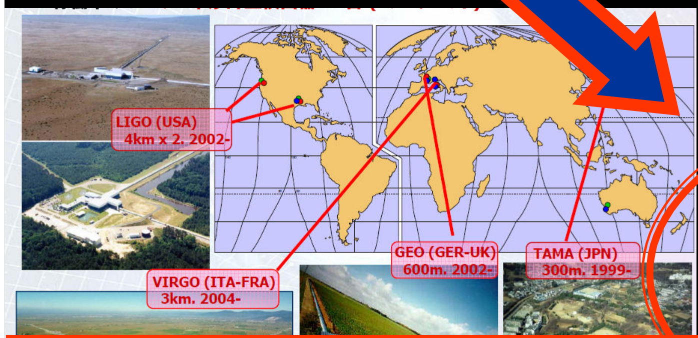
Not yet !
A kind of Rosseta stone

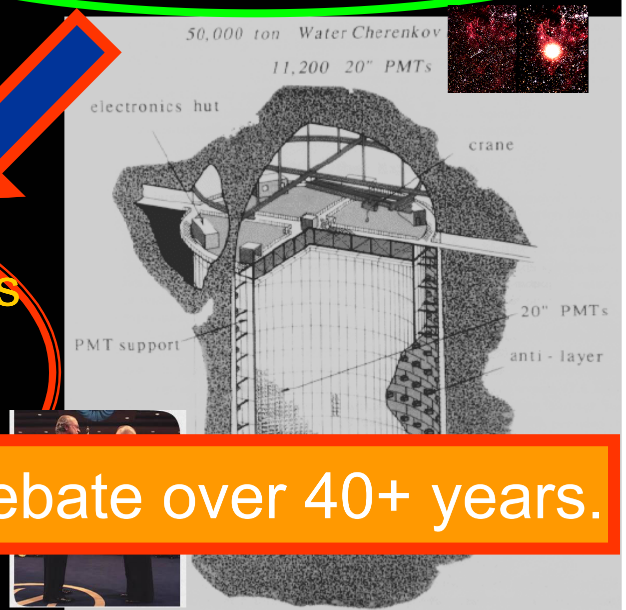
Up to now
only SN1987A

GW astronomy

Relevance to

Neutrino Astronomy





Neutron stars/Black holes
Magnetars
Gamma-ray bursts

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

Neutrino heating mechanism

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

(Wilson ´82, Bethe & Wilson '85)

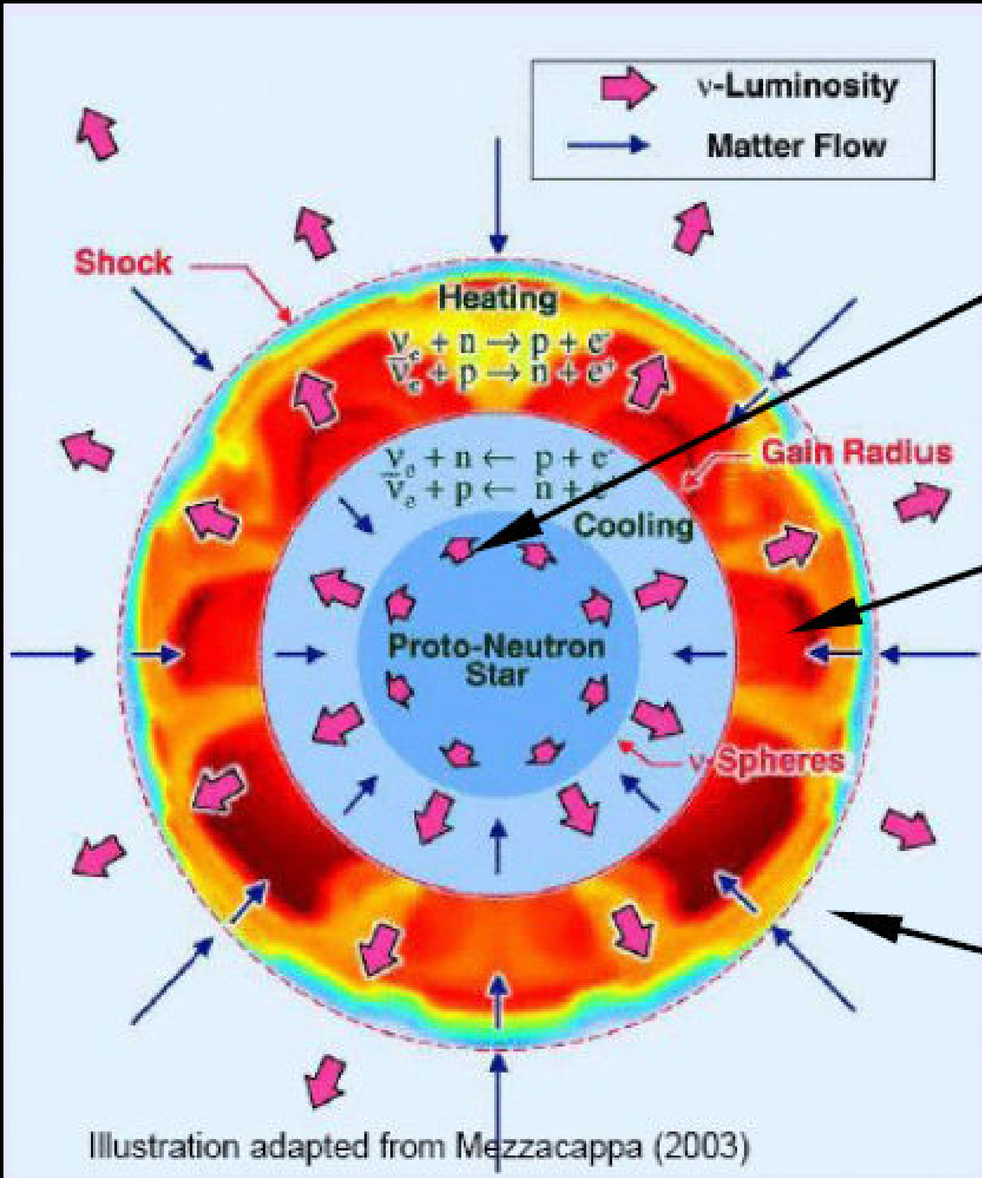


Illustration adapted from Mezzacappa (2003)

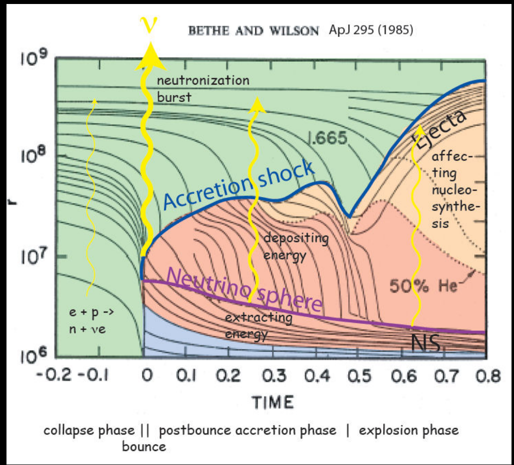
neutrinos diffuse out of opaque proto-neutron star ($\tau_\nu \sim 1$)

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

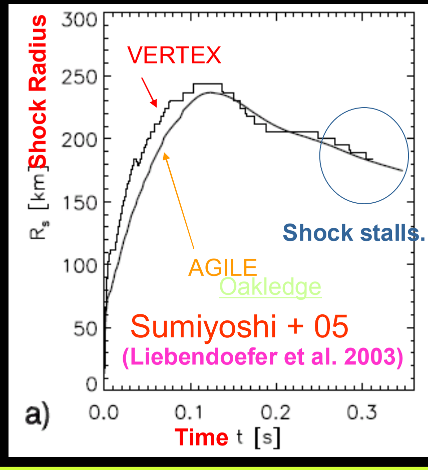
neutrinos stream freely through stellar envelope ($\tau_\nu << 1$)

Looking back 20+ Years of Modeling & Theory

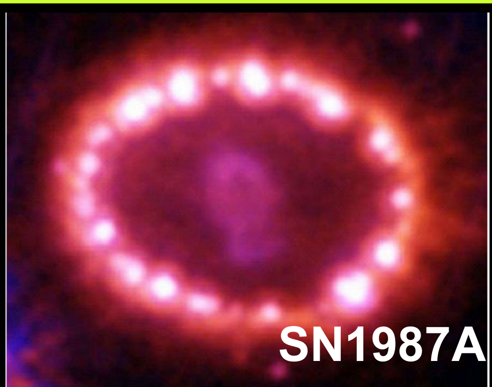
- Neutrino-heating mechanism (Wilson '82,Bethe'85) in spherical symmetry (may work for lower mass progenitors with O-Ne-Mg cores) (Kitaura et al.2006) fails to explode massive stars with iron cores.



~20 years



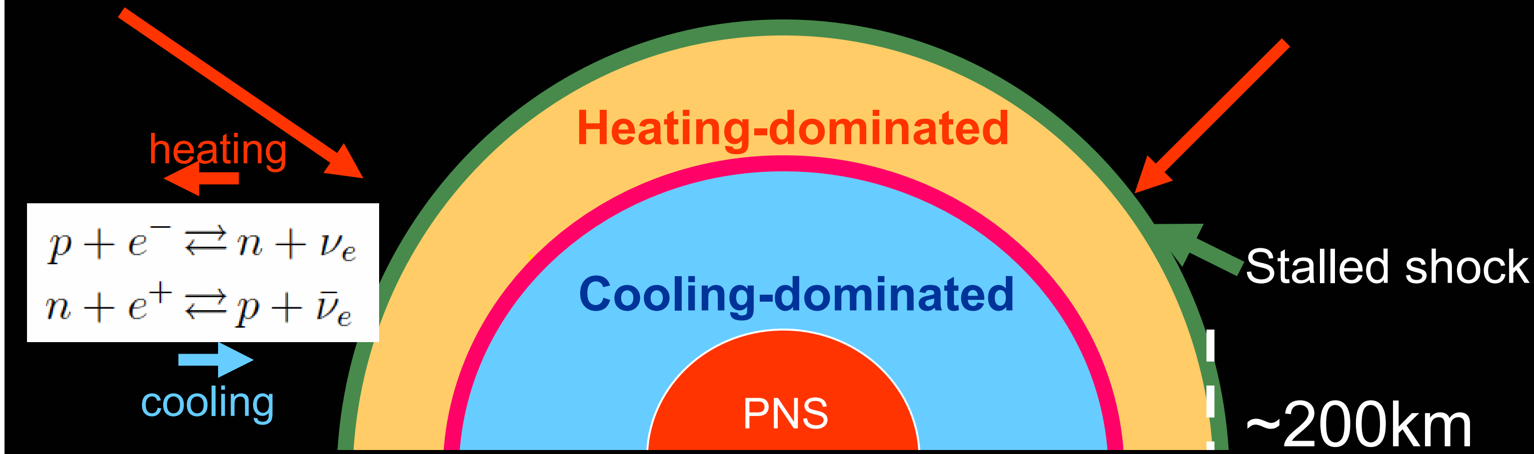
Doing-best simulations, but..



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

Multidimensional modeling is crucial !

Why no explosion in 1D ?



Advection timescale

$$\tau_{\rm adv}(t) = -\int_{r_{\rm gain}(t)}^{r_{\rm sh}(t)} \frac{1}{v_r(r,t)} dr$$

Neutrino heating timescale

$$\tau_{\rm heat}(t) = \frac{4\pi \int_{r_{\rm gain}(t)}^{r_{\rm sh}(t)} \varepsilon_{\rm bind}^{\rm shell}(r,t)\rho(r,t) r^2 dr}{4\pi \int_{r_{\rm gain}(t)}^{r_{\rm sh}(t)} Q(r,t) r^2 dr}$$

In spherical symmetry

$$\tau_{\rm adv}(t) < \tau_{\rm heat}(t)$$

No explosion!!

In multi-dimensional simulations（convection、SASI）

$$\tau_{\rm adv}(t) > \tau_{\rm heat}(t)$$

could be satisfied

A garden variety of multi-D SN models

Energy-drivers for explosions:

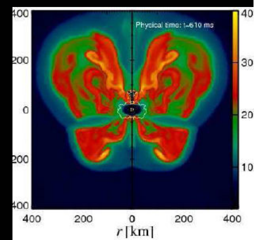
☆Neutrino

✓ Neutrino-heating mechanism + convection/SASI

SASI: Low modes oscillatory instability of standing accretion shock

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

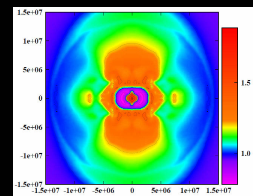
: Onset of SASI-aided neutrino driven explosion of 15 Ms star **(Marek & Janka 09)**



(Marek & Janka 07)

✓ Rotation & anisotropic neutrino radiation:

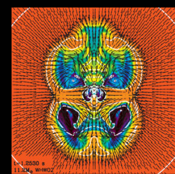
(KK+03～, Walder+05,Ott+08)



(KK+07)

☆Acoustic-power

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

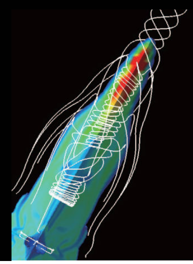


(Burrows+06)

☆ Extraction of rotational energy via B-fields

MHD mechanism:

(Yamada & Sawai04, KK+04, Takiwaki+05 Shibata+06, Obergaulinger+06,Fujimoto + 07, Cerda Duran+07, Burrows+07, Suwa+07, Takiwaki+08, Ono+09 ....)



(Takiwaki+08)

SASI-aided neutrino-heating explosions (Tokyo-Basel)

Suwa, KK, and Liebendoerfer + in prep
: MGFLD transport (IDSA)

- ✓ One of the longest-term evolution covering till 800 ms after bounce

Time for Animation

Preliminary results!
- ✓ Coarse resolutions
- ✓ Treating only electron/anti-electron neutrinos

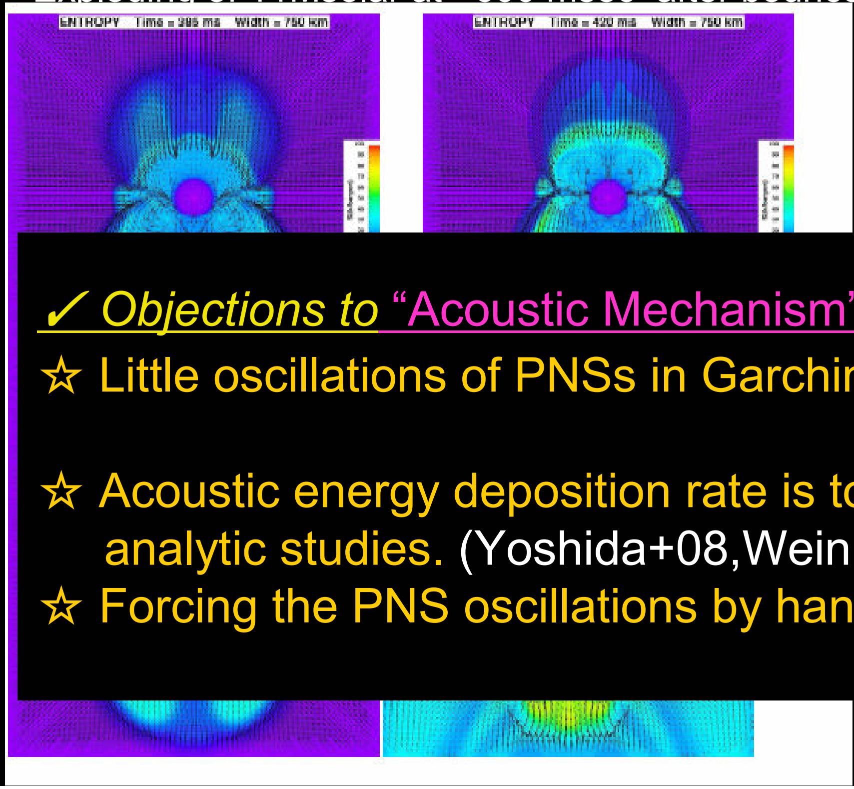
- ✓ **The outcome will be obtained within the next 2 months !**

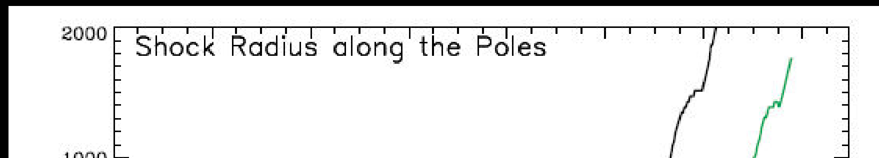
Acoustic Mechanism (Arizona)

Burrows et al. 2005,6~

- Long after bounce, the protoneutron(PNS) star begins to oscillate triggered by SASI. The PNS emits acoustic waves.
- Acoustic waves heat the matter behind the shock waves, leading to strong explosion ~ 10^{51}erg of 25 Ms progenitor stars.

Exploding of 11Msolar at ~600 msec after bounce





✓ *Objections to* "Acoustic Mechanism"

☆ Little oscillations of PNSs in Garching & Tokyo simulations (Marek & Janka 09, Suwa+ in prep)

☆ Acoustic energy deposition rate is too large in comparison with analytic studies. (Yoshida+08,Weinberg+08)

☆ Forcing the PNS oscillations by hand, no acoustic-driven explosions ! (Ohnishi, KK, Yamada 2009)

Summary of current status of SN models

Energy-drivers for explosions:	Explosion
☆Neutrino Neutrino-heating mechanism + convection/SASI **(Marek & Janka 09, Suwa, KK, Liebendoerfer in prep)**	Likely !
Rapid Rotation & anisotropic neutrino radiation: **(KK+03～, Walder+05,Ott+08)**	Not yet known ! Multi-angle Boltzmann sim. is needed.
☆Acoustic-power Acoustic mechanism: **(Burrows+. 2005,6, Ott+07)**	Strong explosion! but remains

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

・Gravitational-wave signatures from SASI/Convection-aided neutrino-driven explosion in 3D

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)

- ☆**Contracting neutron star interior is replaced by the fixed boundary.**
- ☆**Changing the neutrino luminosity, we hope to study qualitatively how the GW waveforms change with the explosion dynamics.**
  (This is ...)
- ☆ **Curren... s (Heger+ 05), which is in favor of SASI simulation. No GWs inside spherical PNSs!**

Animation for SASI in 2D.

Gravitational Waves (GWs) from Core-Collapse SNe

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

$$T^{\mu\nu} = T^{\mu\nu}_{\rm matter} + T^{\mu\nu}_{\rm neutrino}$$

Matter origin

$$h^{\rm TT}_{i,j}(R) = \frac{2G}{c^4}\frac{1}{R}\frac{d^2}{dt^2} I^{\rm TT}_{i,j}\left(t - \frac{R}{c}\right)$$

Quadrupole moment

$$I_{i,j} = \int \rho(x)(x_i x_j - \frac{1}{3}x^2\delta_{i,j})d^3x$$

Neutrino origin

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

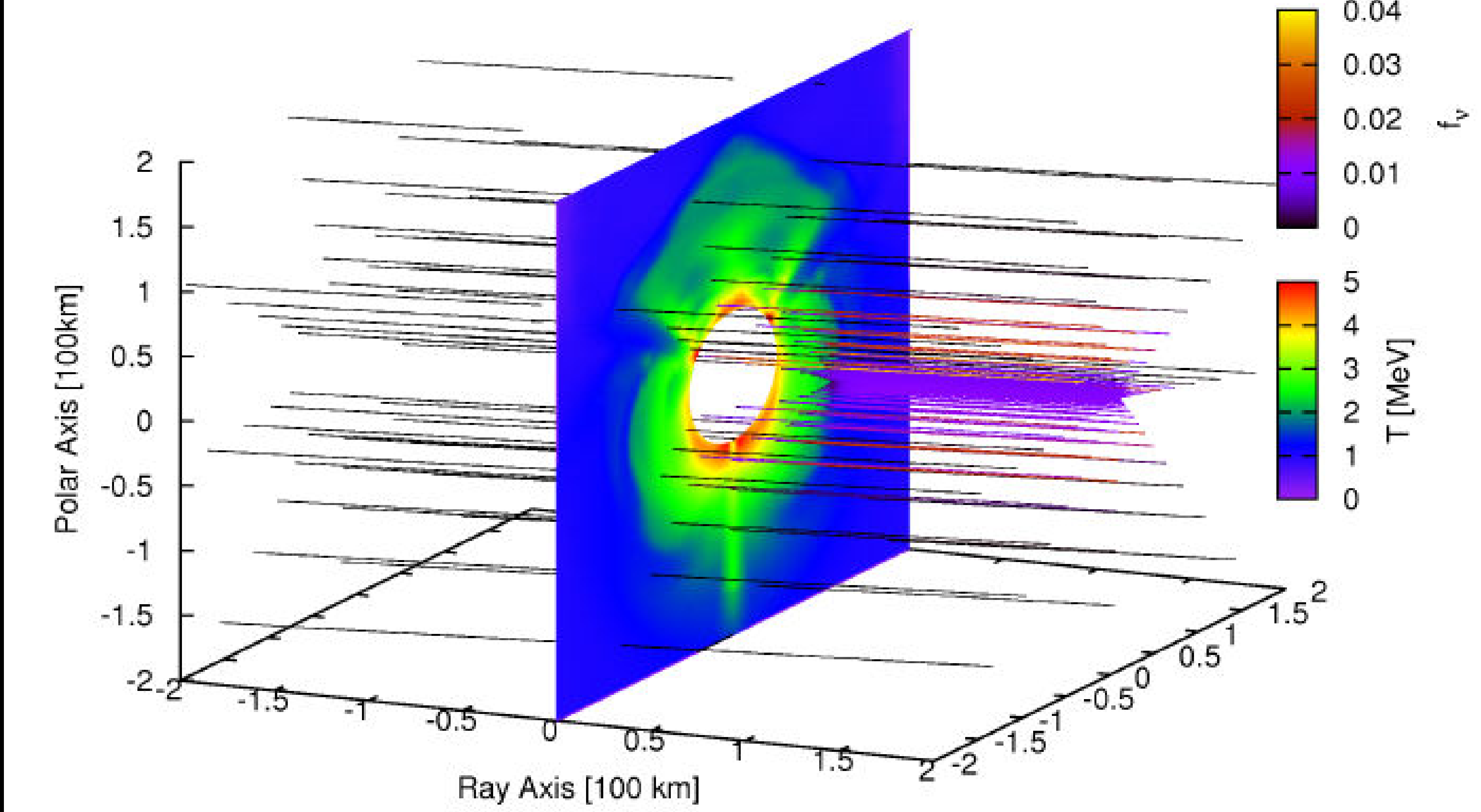
$$h_\nu(t) = \frac{2G}{c^4 R}\int_0^t dt L_\nu(t')\alpha(t')$$

Neutrino anisotropy:
Degree of anisotropic
neutrino radiation

✓ **So far, all the previous studies assumed the ray-by-ray transfer for simplicity.**
(Burrows & Hayes 96, Mueller & Janka '97, Fryer+04, KK+07)

✓ A ray-tracing neutrino transport becomes possible recently.
(KK+, 09 in press)

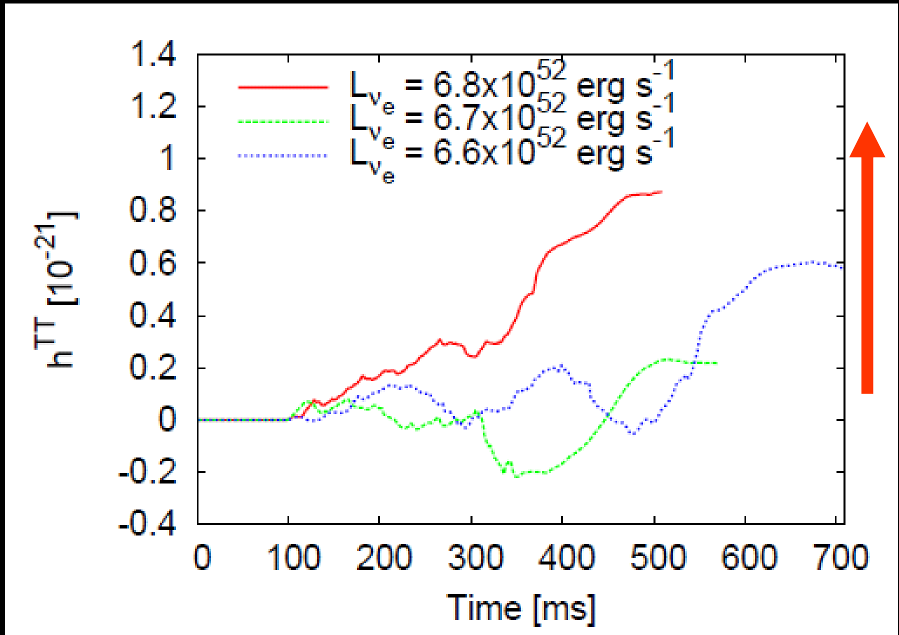
One example of ray-tracing calculations

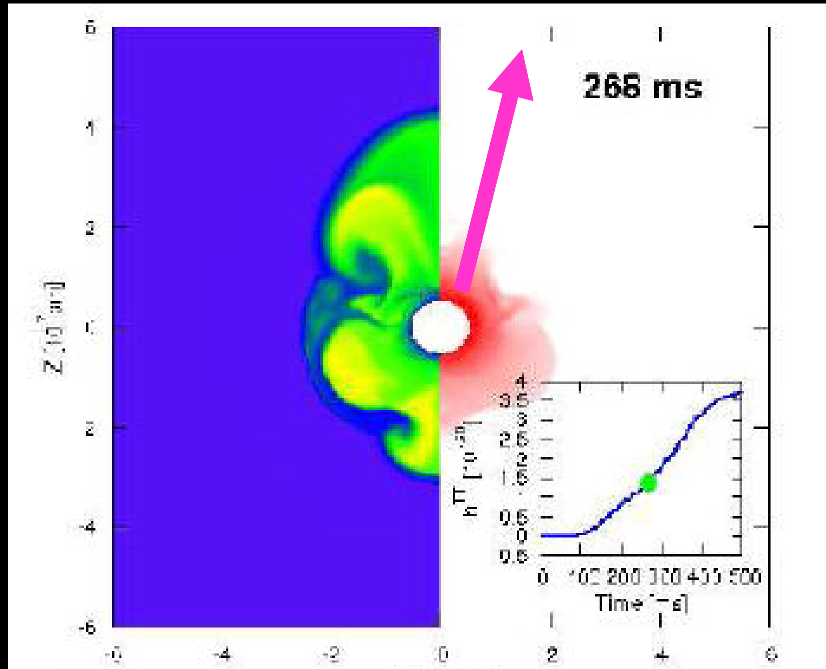


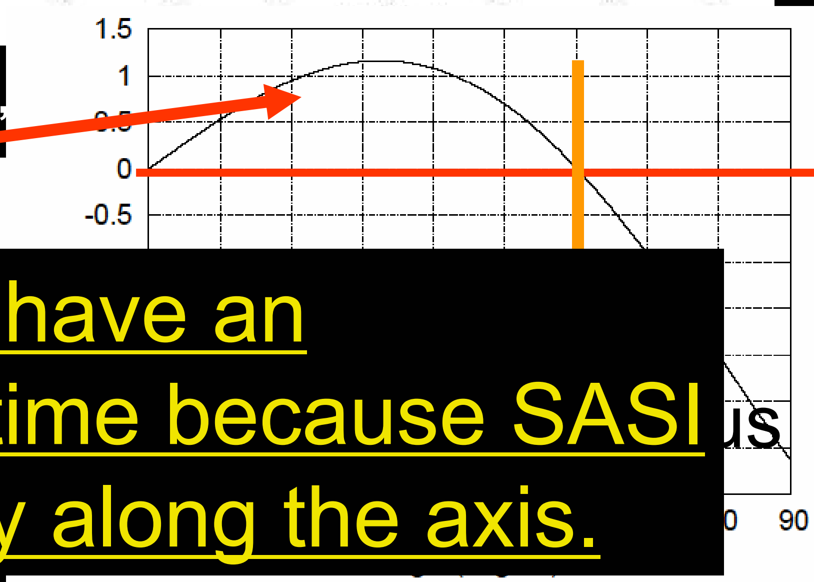
Features of neutrino-originated GWs in 2D

KK et al. 09

Waveform







GWs from anisotropic neutrino radiation in 2D (Epstein78,Mueller&Janka97)

$$h_\nu^{\rm TT} = \frac{8G}{\ldots} \int^{t-R/c} dt' \int^{\pi/2} d\theta' \, \Phi(\theta' \ldots \frac{dL_\nu(\theta', t')}{\ldots}$$

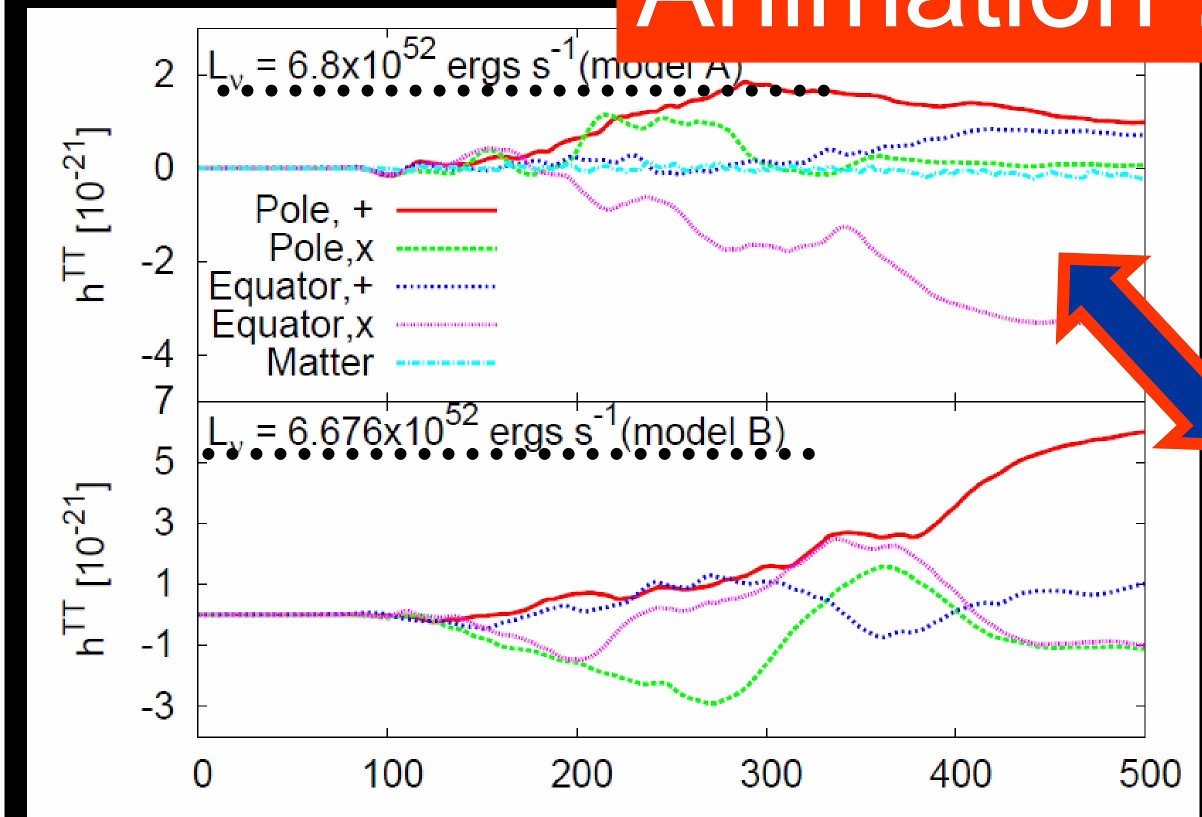
・angle

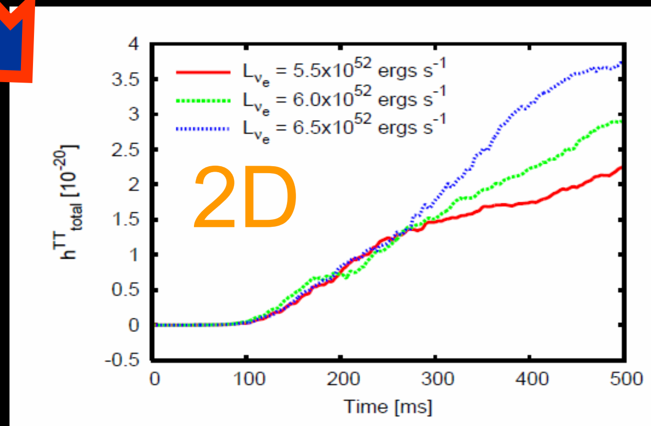
The waveforms in 2D have an increasing trend with time because SASI develops preferentially along the axis.

3D SN explosion models aided by SASI

KK et al. (2009) ApJL

The neutrino luminosity



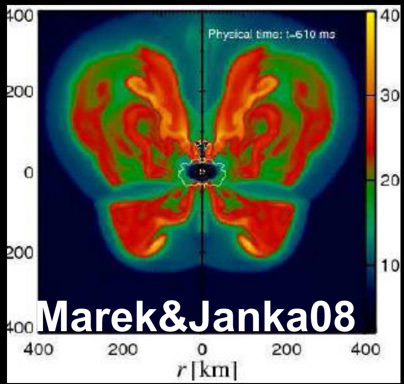


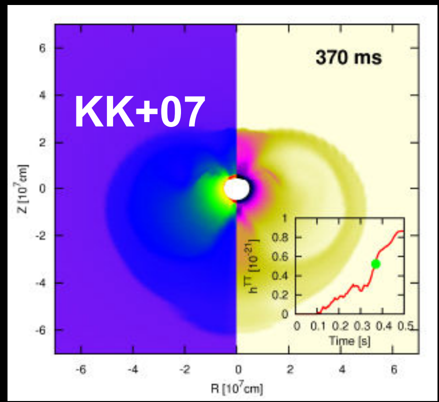
The waveforms vary much stochastically in 3D than for 2D because SASI can grow chaotically in all directions.

GWs from the two scenarios

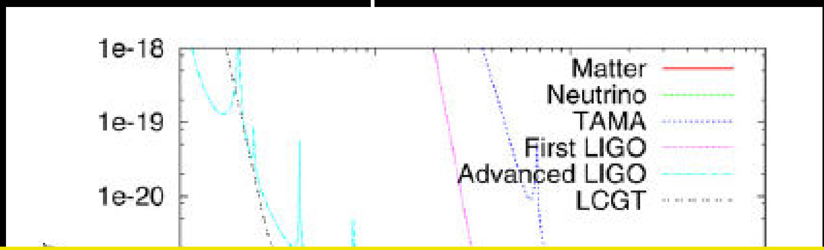
KK et al. (2009) ApJL

Neutrino heating with SASI

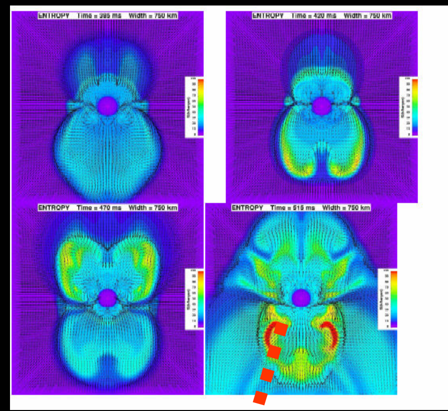




GW spectrum

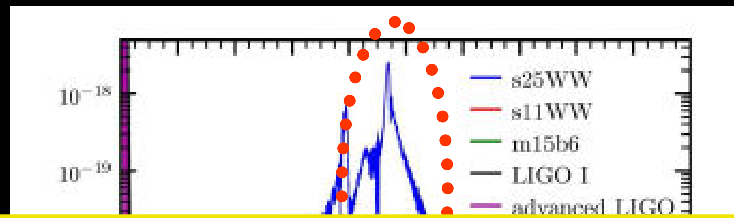


Acoustic-wave heating

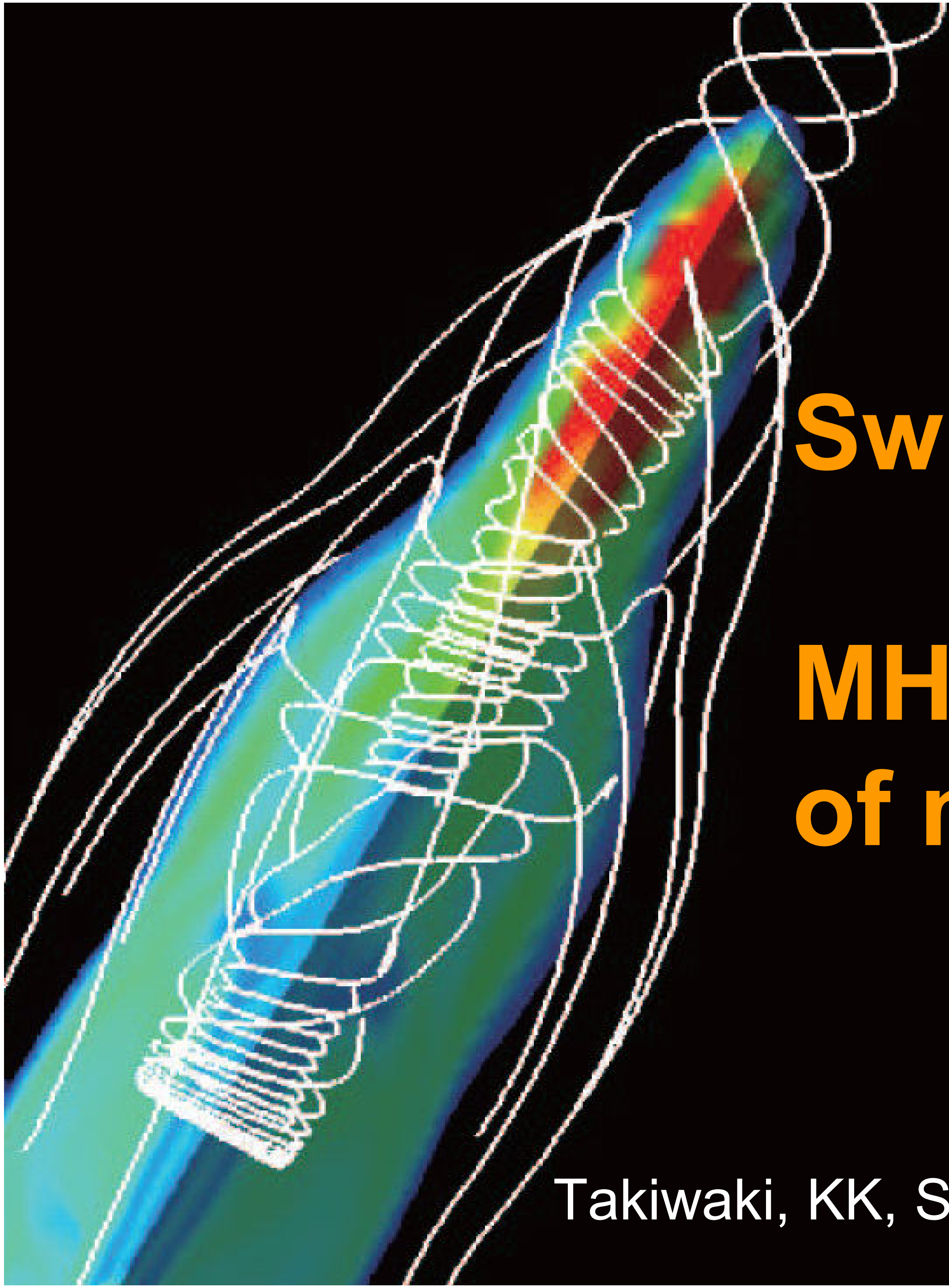


Burrows+06

~



- ☆GW signals, SASI-neutrino heating .vs acoustic mechanisms, are so different.
- ☆Thus could a clue to the explosion mechanism.
- ☆The horizon extends to ~1 Mpc for next gen. detectors.



Switching gears to MHD explosions of massive stars

Takiwaki, KK, Sato, ApJ in press

Histrory of Magnetized Supernovae

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)

LeBlanc & Wilson
Bisnovati-Kogan et al
Mueller & Hillebrandt
Ohnishi et al.
Symbalisty et al.

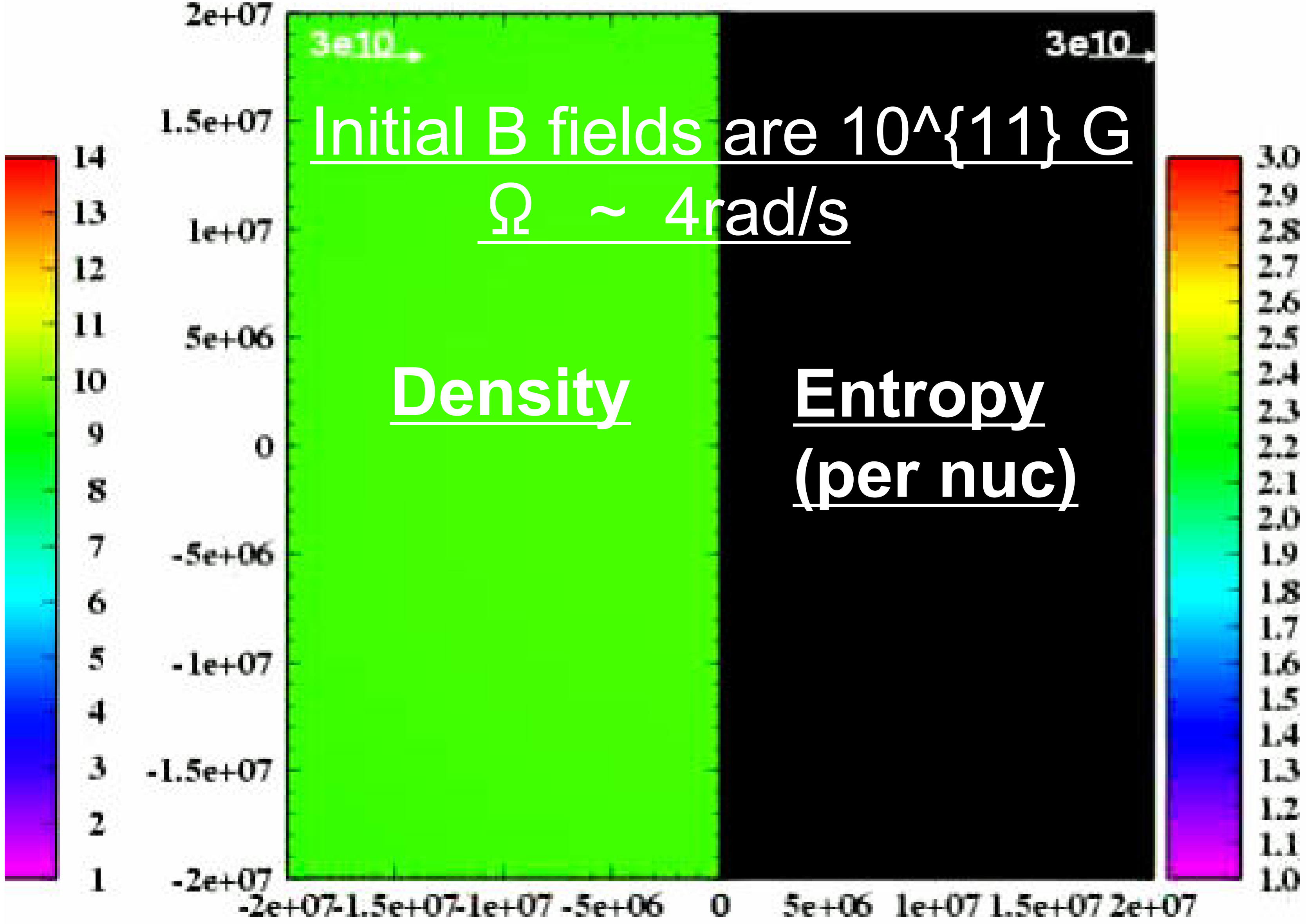
Yamada et al.
KK et al.
KK et al.
Takiwaki et al.
Ardeljan et al.
KK et al.
Obergaulinger
Sawai et al.
Suwa et al.
Liebendoefer et al
Burrows et al.
Dessert et al.
Scheidegger et al
Pablo Cerda Duran et al
Takiwaki et al.

1970 1976 1979 1983 1984 . . . 2004 2005 year

20year

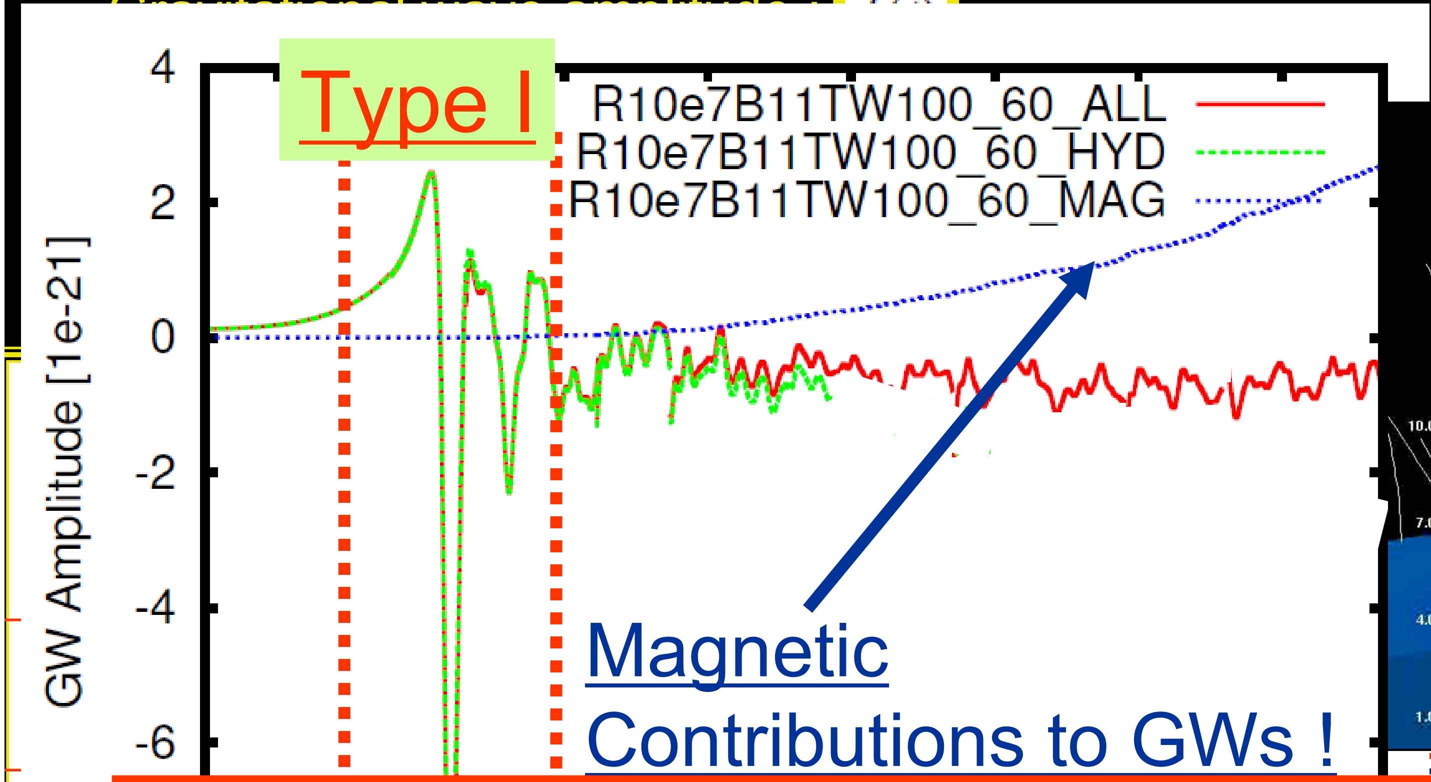
The first MHD simulation from onset of collapse to jet propagation based on special relativistic MHD simulations

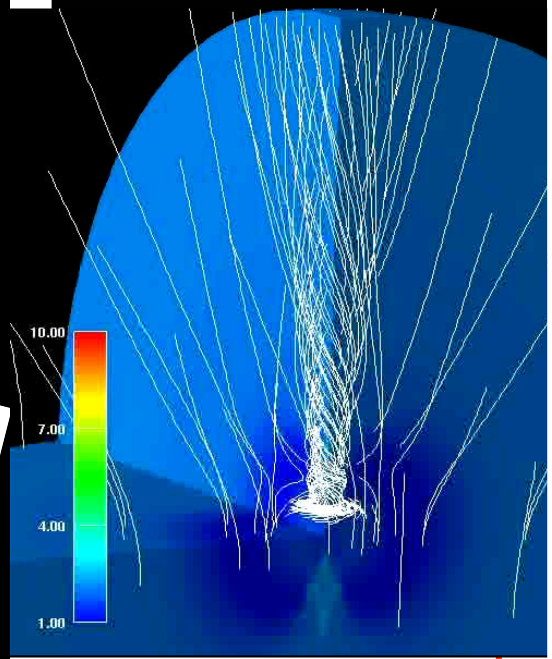
(Takiwaki, KK, Sato, ApJ09)



Gravitational Waveforms from Magneto-Driven Explosions

Takiwaki, KK, Sato ApJ 09,
Takiwaki, KK in prep





- In the MHD exploding models, waveforms can show an increasing trend due to the magnetic contributions.
- An indicator of the B fields deep inside central cores.

Neutrino oscillations in MHD explosion of supernovae

Kawagoe, Takiwaki, KK submitted.

Neutrino oscillation in stellar core-collapse

- Important probe into neutrino oscillation parameters.

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

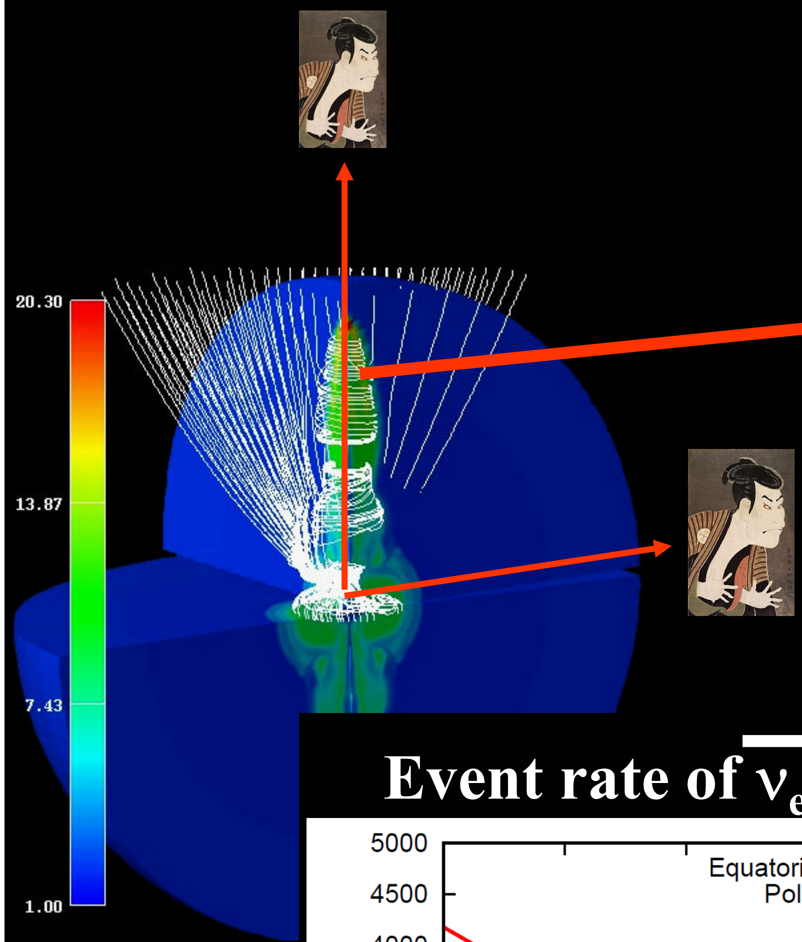
  K.Takahashi, M. Watanabe, K. Sato, T. Totani (2001)
  K.Takahashi & K. Sato (2002)
  K.Takahashi, K.Sato, A. Burrows, T.D. Thompson (2003)
  S. Ando & K. Sato (2004)
  Tomas et al. (2004)
  Ando et al (2005)
  Fogli et al (2005)
  Kachelrieß_et al (2005)
  Fogil et al. (2007)
  Choubey et al. (2007)
  Kisler et al. (2008)
  Luaridini et al. (2008)

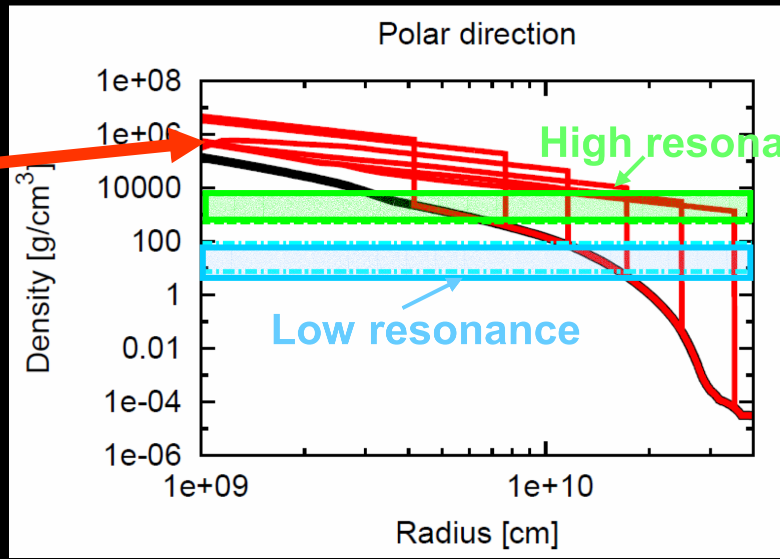
  but, basically based on spherical supernova models.

Neutrino oscillations in MHD explosion of supernovae

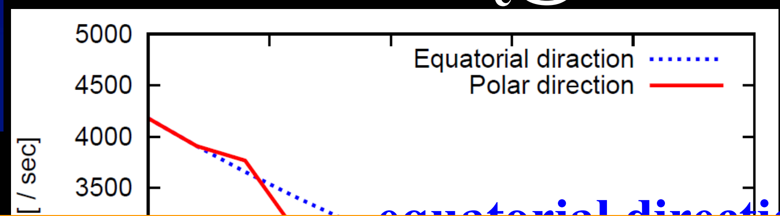
Kawagoe, Takiwaki, KK submitted.

(see also Tomas et al. 2004)

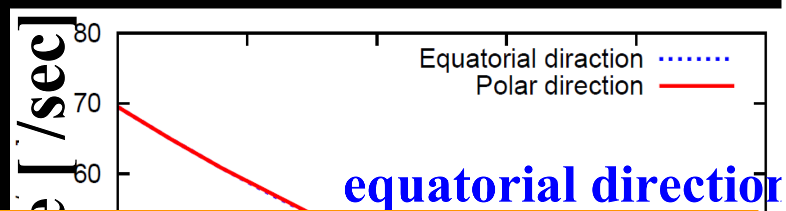




Event rate of $\bar{\nu}_e$ @ SK

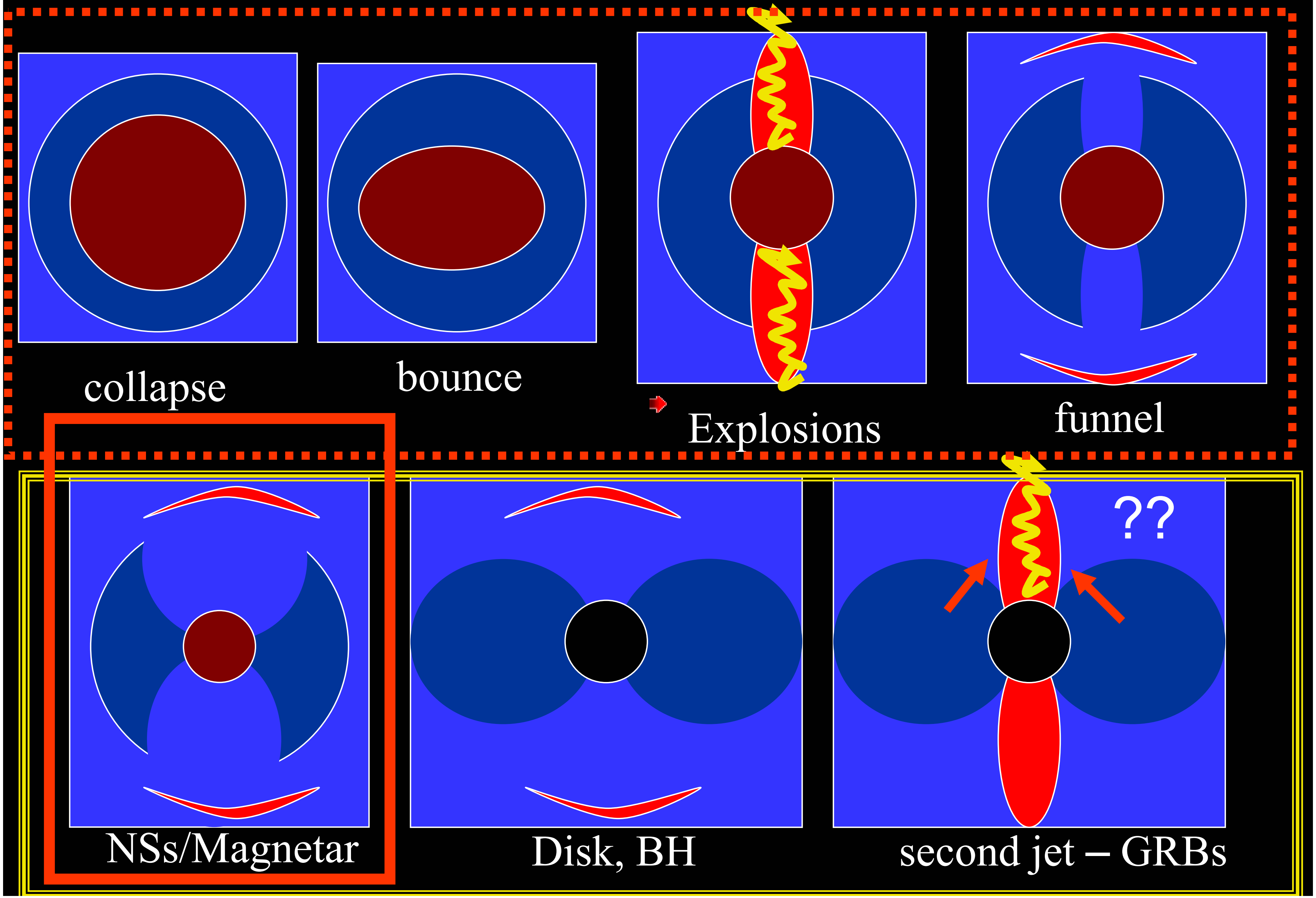


Event rate of ν_e @SK



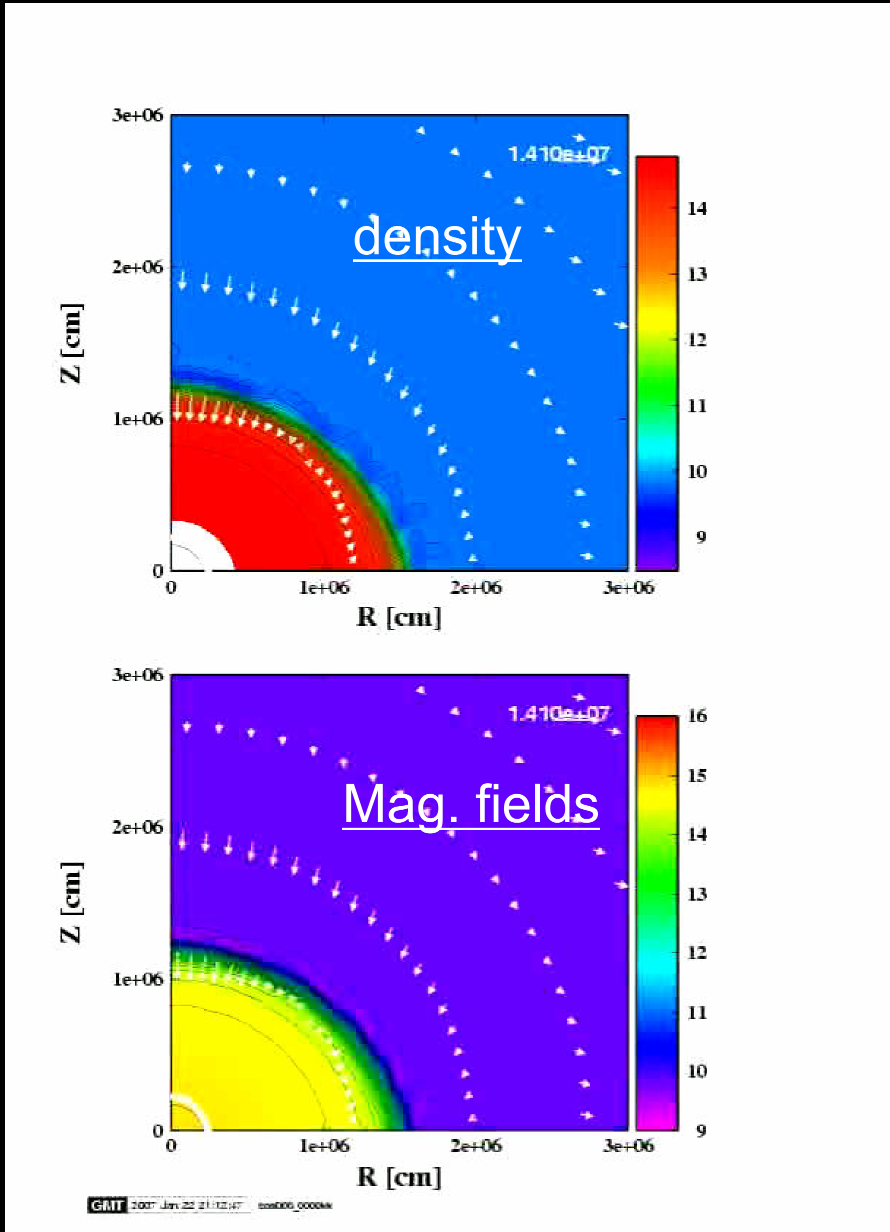
- The two signatures of high/low resonance, possibly visible to Super-Kamiokande for a Galactic source, could be an evidence for highly aspherical MHD explosions.

After SN explosions: A route to **HEN** production



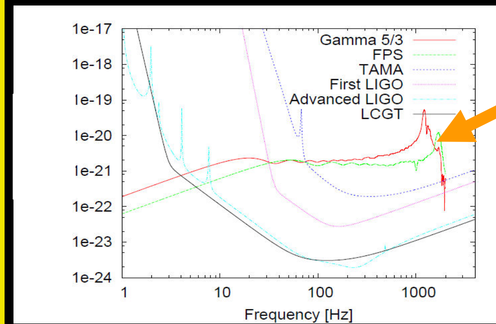
QCD Phase transition in Neutron stars/Magnetars

Kiuchi & KK, MNRAS (2008)
Kiuchi, KK, Yoshida ApJ in press
Yasutake, Kiuchi, KK, submitted



At the phase transition,

☆ Vast energy of 10^{52} erg will be released with burst-like gravitational waves visible to 10 Mpc scales.



Peak in GW induced by phase -transition induced collapse

☆ A clue to the phase transition physics

✓ Possible production of UHE neutrinos in the expanding blobs is left for us to be studied. (through photo-pion reactions).

Summary

If core-collapse supernovae are triggered by

☆Neutrino heating mechanism aided by SASI,

- ✓ Waveforms change stochastically due to chaotically growing SASI in all directions.
- ✓ Gravitational-wave spectra peak generally near 100 Hz, reflecting the SASI-induced matter overturns of 10 ms.
  - ☆Possibly visible to the first-LIGO-class detectors for a galactic supernova.
  - ☆ An important key to distinguish from the acoustic mechanism.

☆MHD mechanisms,

- ✓ The waveforms will be burst-like near bounce, with an increasing trend which should be an evidence of MHD explosions.
- ✓ Changes in the Superkamokande events both in th … teristic.
- ✓ HEN … be studied.

Thank you very much !