Brainstorming on core-collapse supernova theory with perspectives toward multi-messenger astronomy

Kei Kotake

(National Astronomical Observatory of Japan:NAOJ)

with Tomoya Takiwaki (NAOJ),Takami Kuroda (NAOJ), Yudai Suwa (Kyoto), Ko Nakamura (NAOJ), Akihiro Suzuki (NAOJ), , and Youhei Masada (Kobe)

INT 12-2a: Core-Collapse Supernovae: Models and Observable Signals

An Analysis of Recent Research Trend of CCSN modeling in 2012

January : E.Mueller + (AA)
February: Foglizzo + (PRL), Pejcha-Thompson(A
B.Mueller+(ArXiv)
Kuroda+(ArXiv)
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Lentz + (ApJ)
Endeve + (ArXiv)x2
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Suwa+(ArXiv) (more to come…)

✓ First-principle simulations
-1D with B-transport
- 2D/3D different scheme extended to GR

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✓ Phenomenological modeling
- Liebendoerfer Ye formula
- a light-bulb scheme

for following a long-term post-bounce evolution in a qualitative/systematic manner.

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✓ **Novel approaches** proposed
- Shallow water analogue (Foglizzo)
- Ante-sonic condition (Pejcha)
- Radial instability (Fernandes)
- Theory of turbulence (Murphy)

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✓New algorithms for 6D transport ultimately in GR
- Monte Carlo (see his talk !)
- S_N method in 3D
- M1 formalism (pioneered by Shibata +11, and Kuroda, KK,Takiwaki, O'Conner, Ott (July)

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✓ Theoretical predictions of neutrino, gravitational-wave signals are updated by 3D modeling (Mueller+) with GR (Ott+) for CCNSe, (explored in collapsars by KK+).

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1. First-principle simulations
   -1D with B-transport
   - 2D/3D different scheme extended to GR

2. Phenomenological modeling
   - Liebendoerfer Ye formula
   - a light-bulb scheme

3. Novel approaches proposed

4. New algorithms for 6D transport ultimately in GR

5. Theoretical predictions of neutrino, gravitational-wave signals

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tational-wave

Explosion Mechanisms of Core-Collapse Supernovae

Hans-Thomas Janka
Max Planck Institute for Astrophysics, Karl-Schwarzschild-Str. 1, D-85748 Garching, Germany; email: thj@mpa-garching.mpg.de

Core-Collapse Supernovae as Supercomputing Science: a status report toward 6D simulations with exact Boltzmann neutrino transport in full general relativity

Kei Kotake[1,2], Kohsuke Sumiyoshi[3], Shoichi Yamada[4,5], Tomoya Takiwaki[2], Takami Kuroda[1], Yudai Suwa[6], and Hiroki Nagakura[4,6]

Multimessengers from core-collapse supernovae : multidimensionality as a key to bridge theory and observation

Kei Kotake[1,2], Tomoya Takiwaki[2], Yudai Suwa[3], Wakana Iwakami Nakano[4], Shio Kawagoe[5], Youhei Masada[6], and Shin-ichiro Fujimoto[7]

1st topic : 3D simulations with spectral transport

✓ 3D effects : very controversial.
(Nordhaus+. (2010) Yes vs. Hanke+ (2011) No(so much))

✓ Previously :the light-bulb scheme was employed.
(L_ν = const was given by hand to trigger explosions).

✓ 3D simulations with spectral neutrino transport are (at least) needed to draw a robust conclusion.

Our most up-to-date 3D results

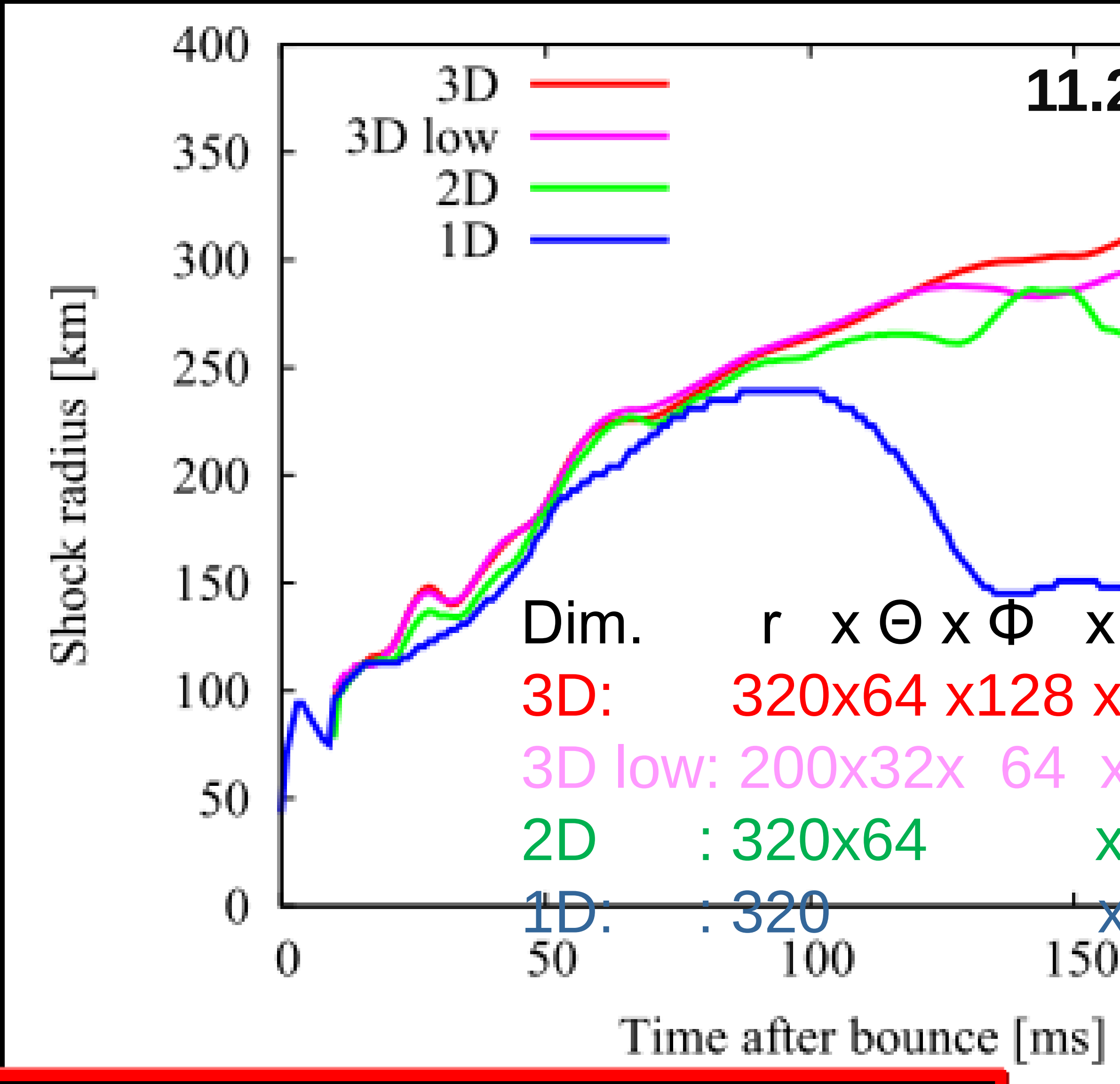
Takiwaki, KK, and Suwa (2012) ApJ

- ✓ **11.2 Msun progenitor (Woosley, Heger, Weaver: WHW (2002))**
- ✓ Spectral neutrino transport is solved (IDSA: Liebendoerfer+09)
- ✓ Cooling by mu/nu neutrinos is treated by a leakage scheme.
- ✓ **320(r)x64(θ)x128(φ)x20(ε) (x4 finer than our ApJ paper, 3 deg.)**
- ✓ **8192 cores x 1 CPU month**
- ✓ **@ the world-2nd "K" computers.**

Animation hidden !

Thanks to Tomohide Wada (CfCA)

Comparison of average shock radii



Dim.	r	x Θ	x Φ	x
3D:	320	x64	x128	x
3D low:	200	x32	x 64	x
2D :	320	x64		x
1D: :	320			x

✓ **Our 3D model with highest resolution : the most energetic shock propagation.**

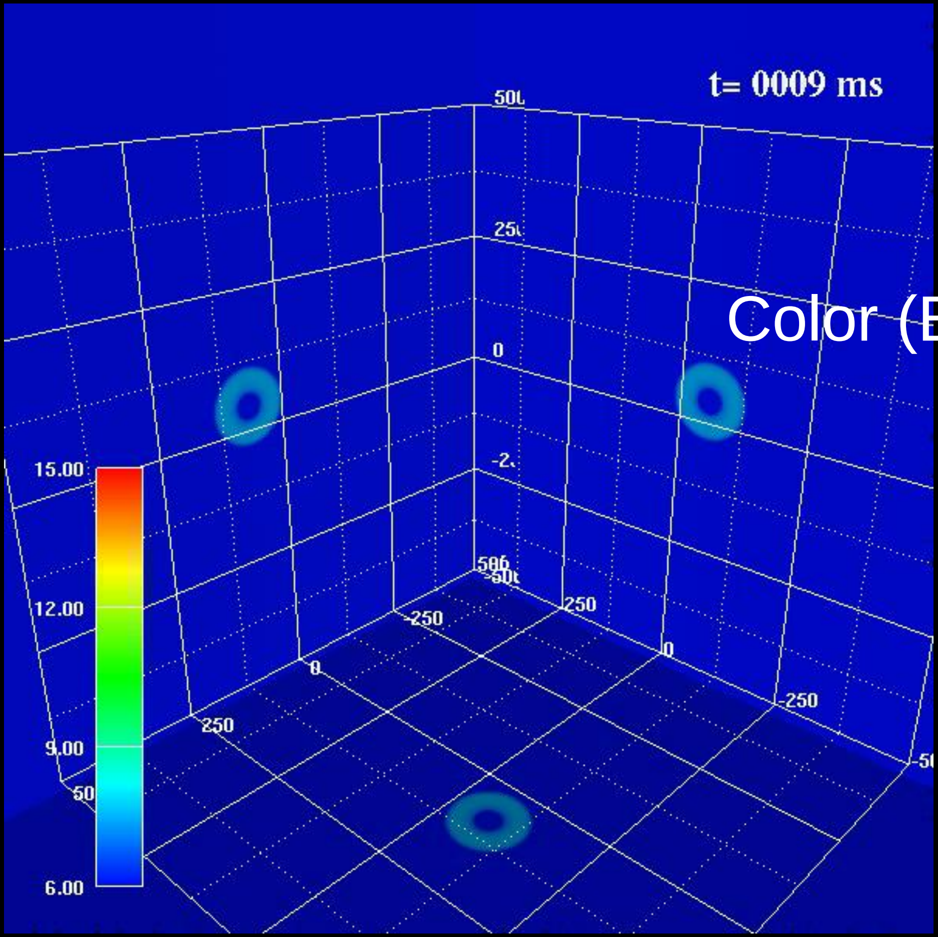
“Stochastic Nature” of neutrino-driven explosions

(e.g., KK+09, Iwakami+08)

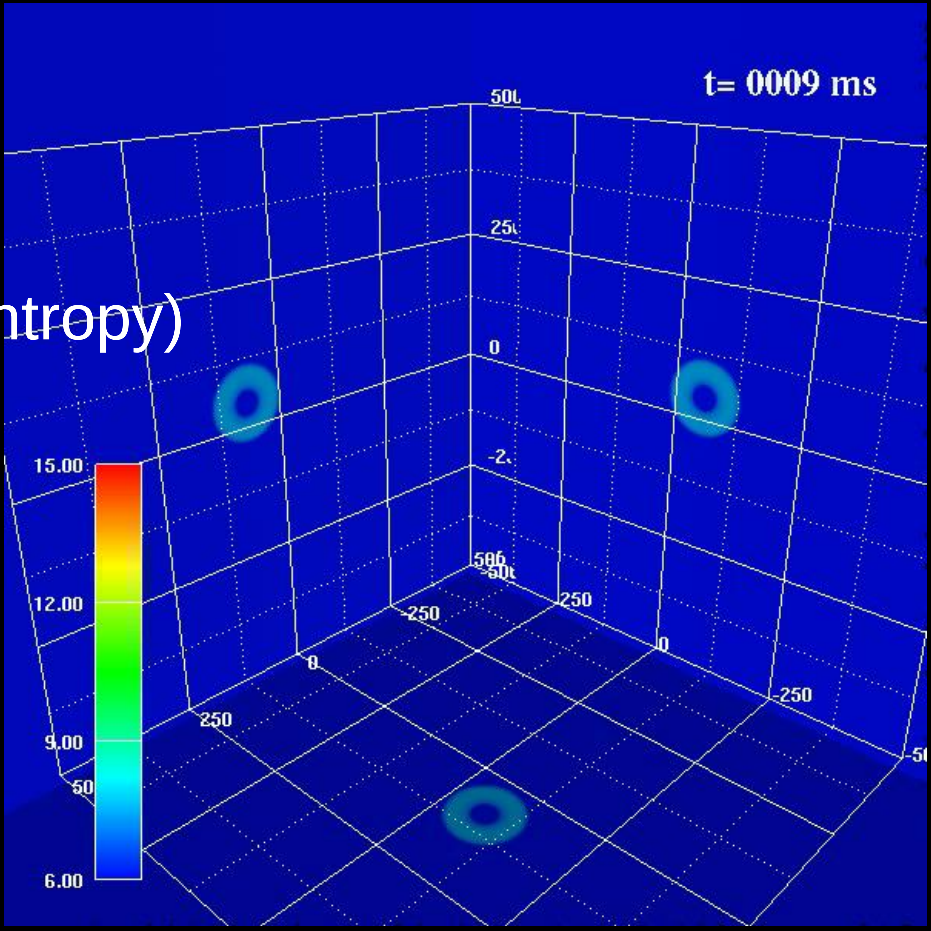
✓ 2D simulations for an 11.2 M_{sun} star (WHW02)

☆ Resolutions fixed (300(r)x128(Θ)x20(ε))

☆ The only difference : **initial random perturbation after shock-stall**

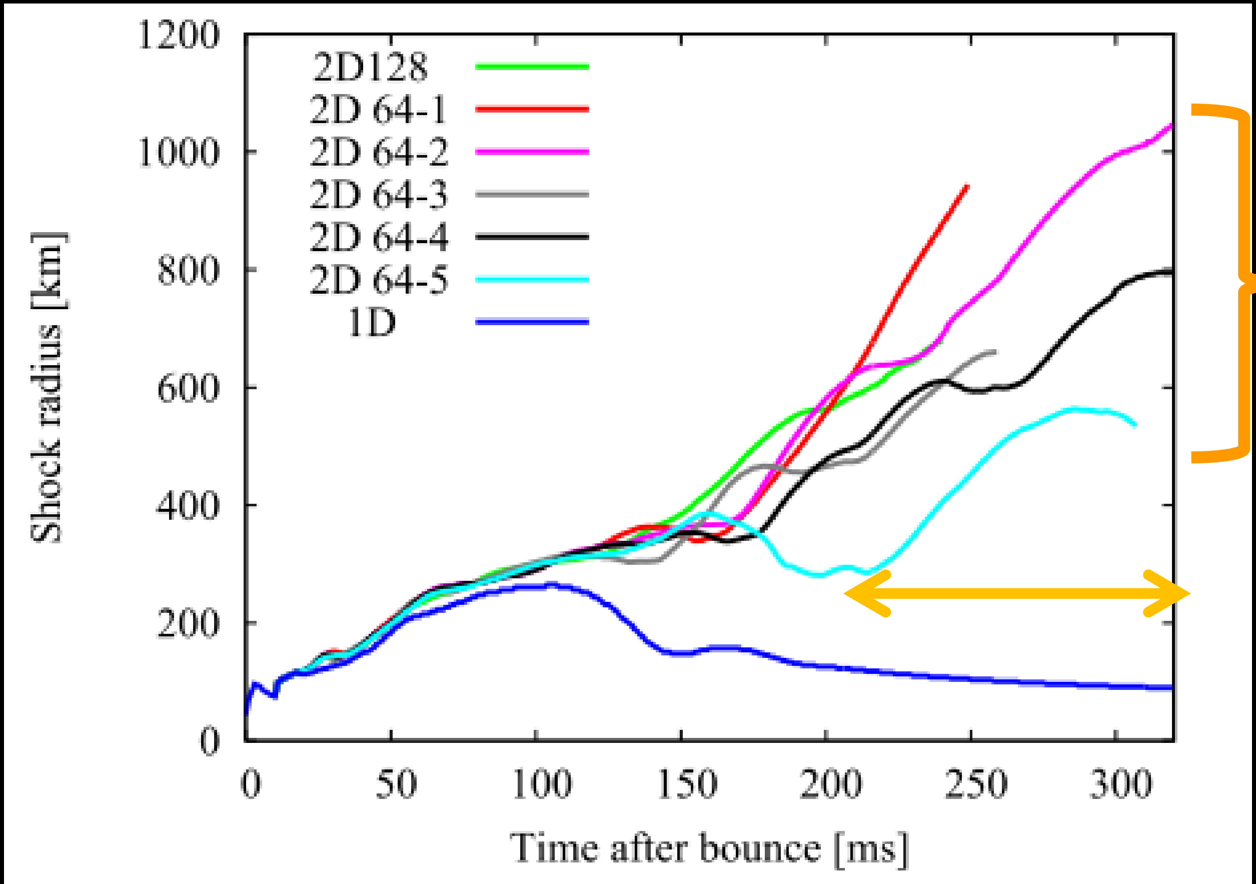


Color (Entropy)



“Stochastic Nature” of neutrino-driven explosions

(Takiwaki, KK, Suwa in prep)



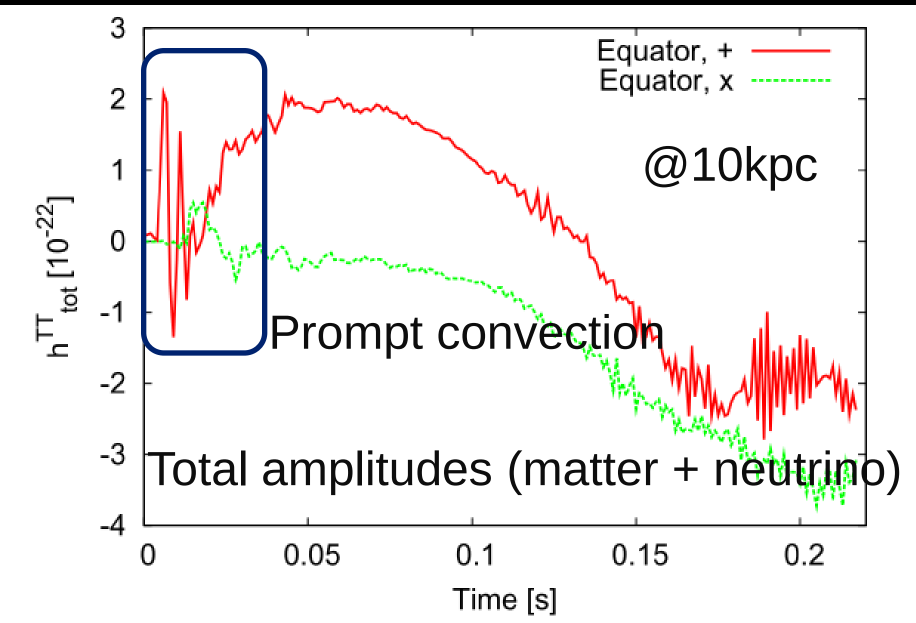
2D models with different initial random perturbations given after shock-stall

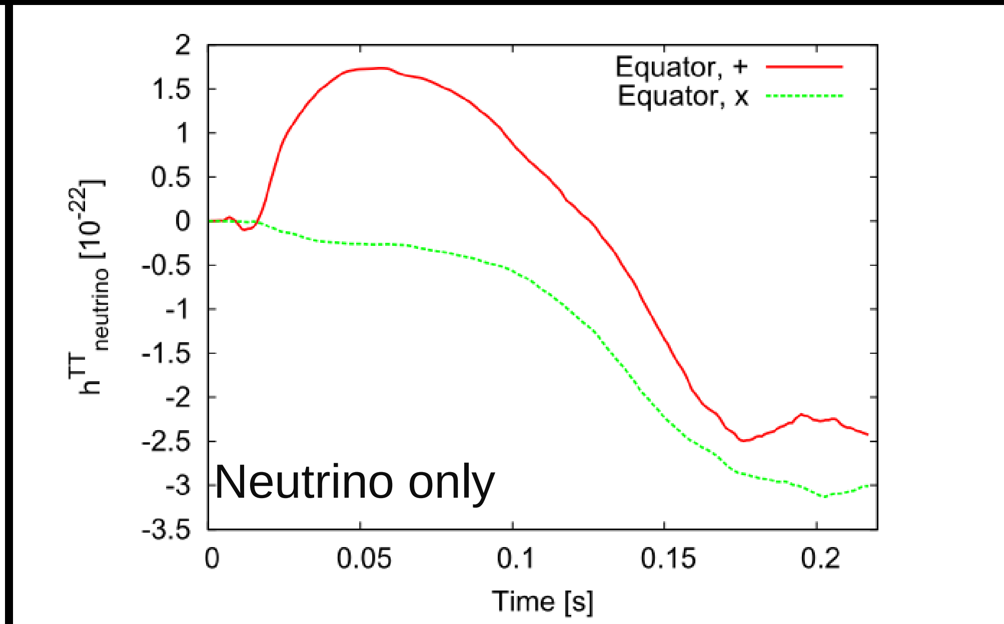
From only one realization of our 3D model, nothing solid can be deduced about the 3D effects. Systematic study needed ! (computationally hyper-expensive (Exsa-scale platforms))

Gravitational waveforms in 3D simulation with spectral transport

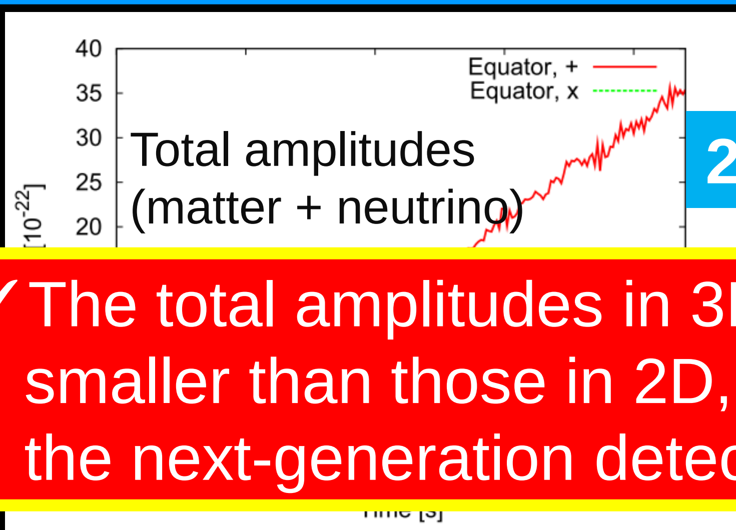
KK, Takiwaki + in prep

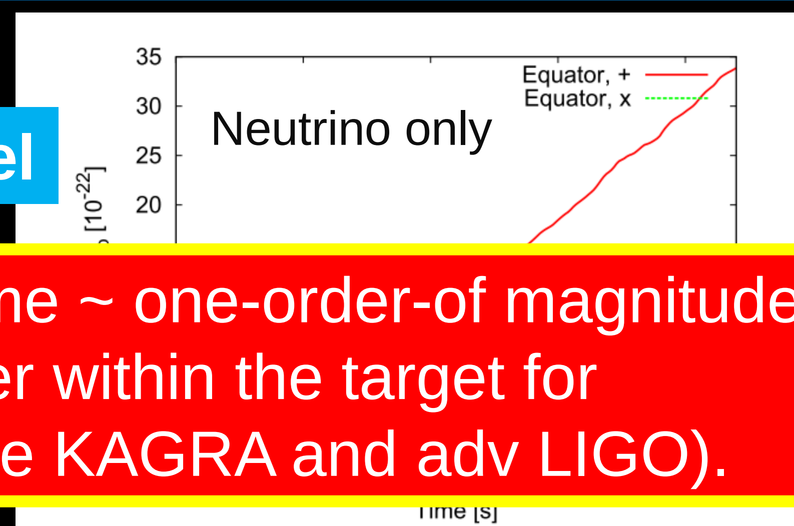
(see also, Mu”ller & Janka (1997), Ott(2009), KK et al. (09,11), Mueller et al. (2012))



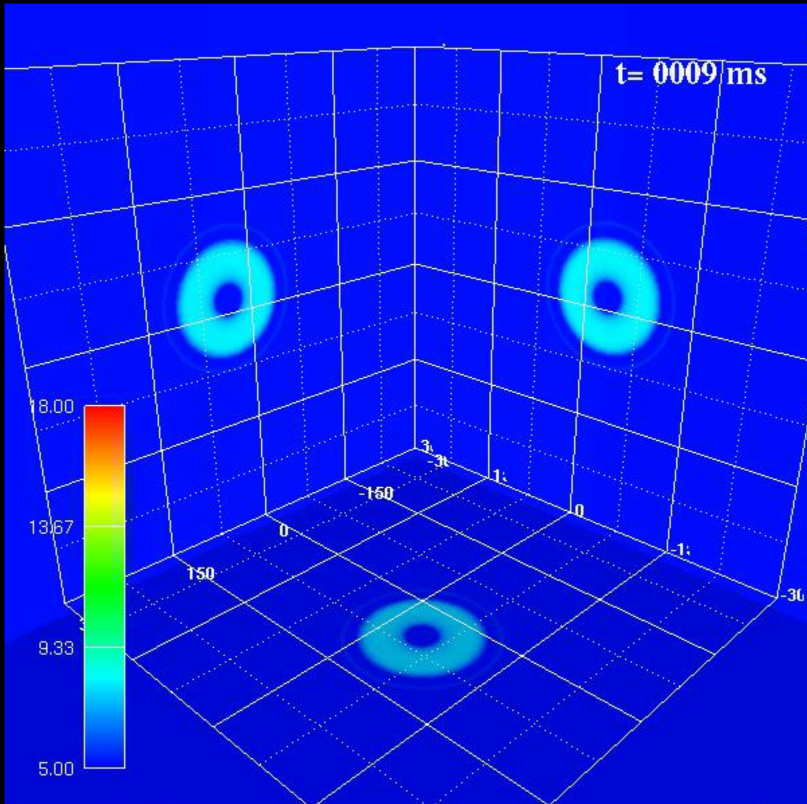


2D model





✓The total amplitudes in 3D become ~ one-order-of magnitude smaller than those in 2D, however within the target for the next-generation detectors (like KAGRA and adv LIGO).

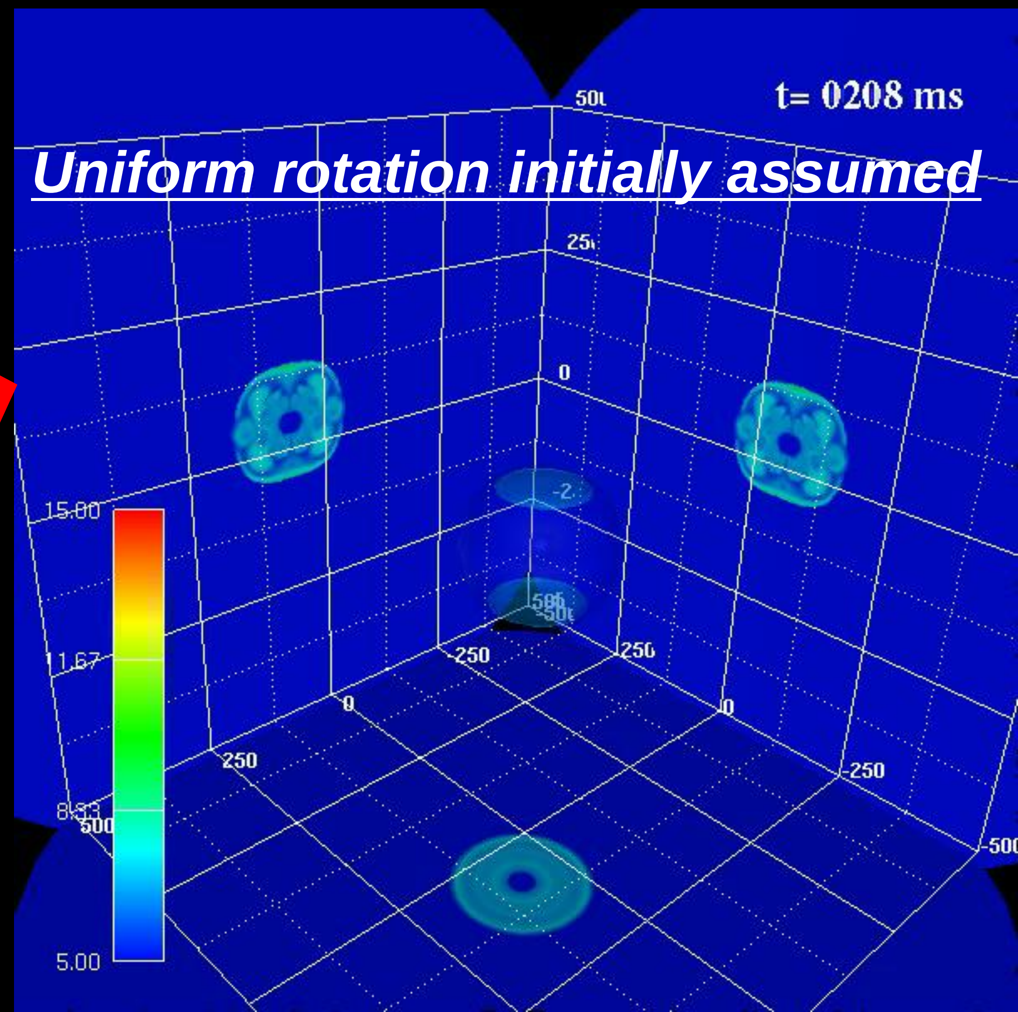


Non-rotating 11.2 Msun star (moderate resolution)

(Relatively) rapidly rotating 11.2 Msun star (P_0 = 4 rad/s)

- ✓Coherent motions in Φ reduce stochasticity
- ✓Explosion energy ↗ for a rotating model.

<u>Uniform rotation initially assumed</u>



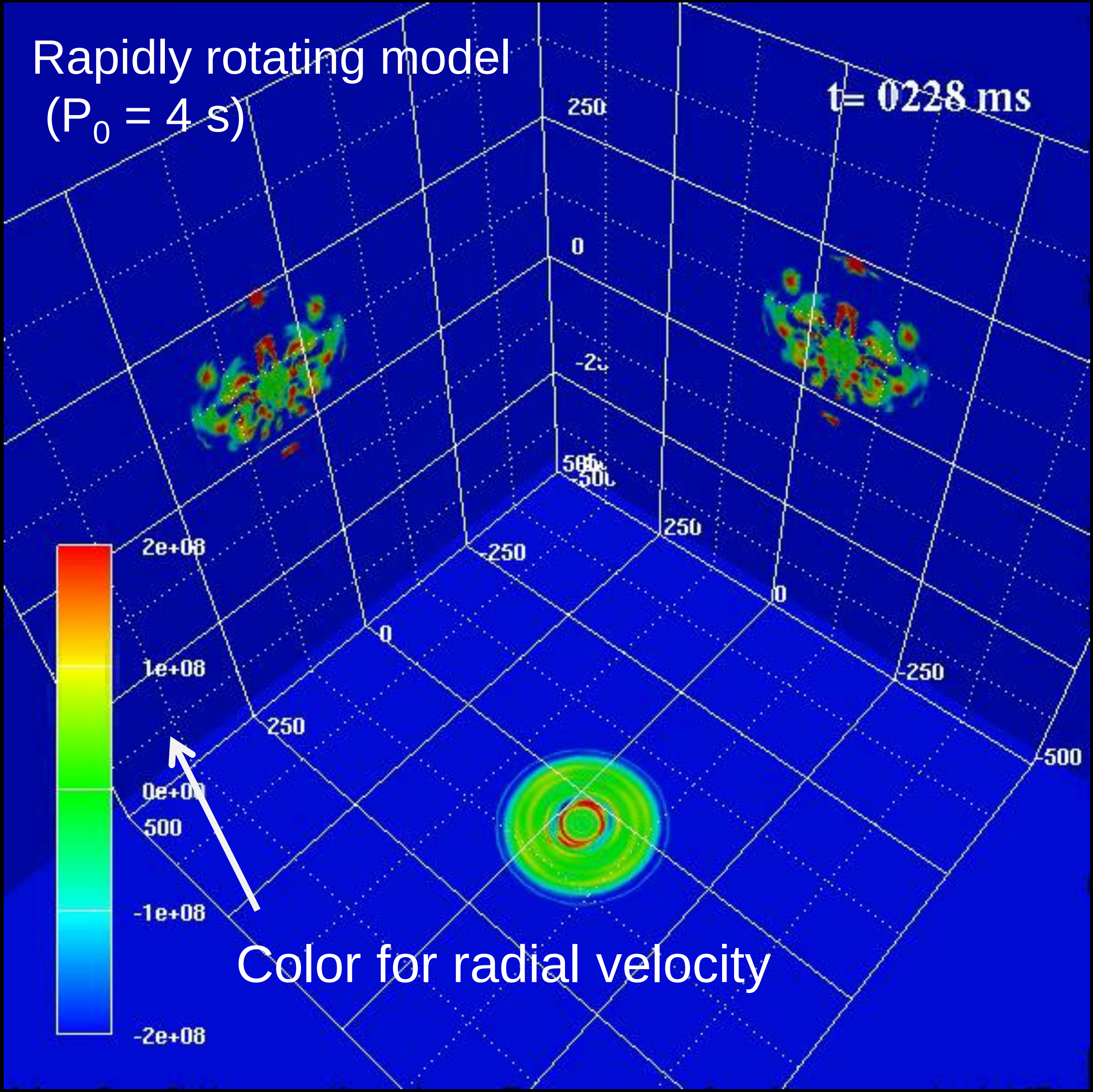
What is interesting about spiral modes ?

"*Seemingly*"….

for this model, dominant modes

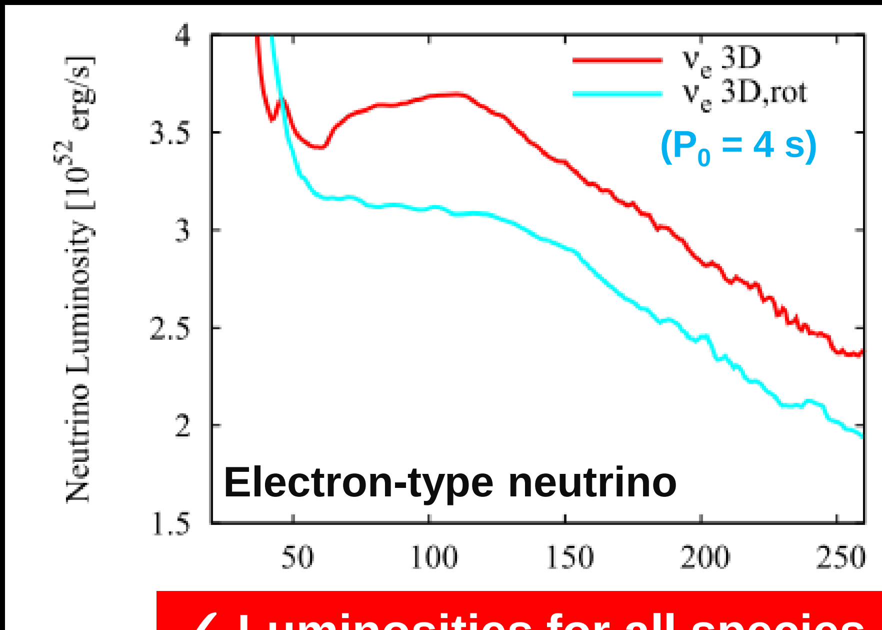
- ✓ **In the linear regime, spiral modes (e.g., Yamasaki & Foglizzo (08))**
- ✓ **in the non-linear phase, axisymmetric modes.**

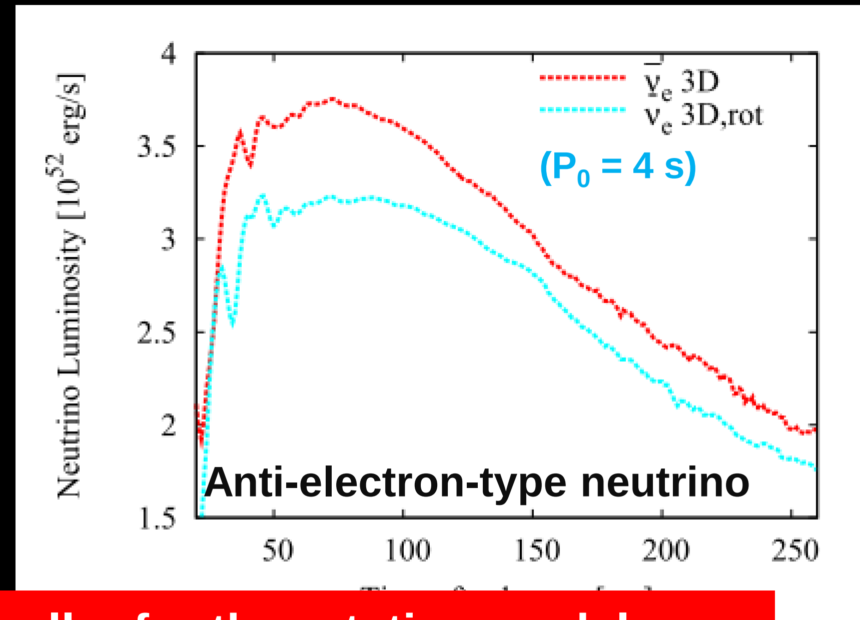
(Should depend on initial rotation rates. More careful analysis is under way !)



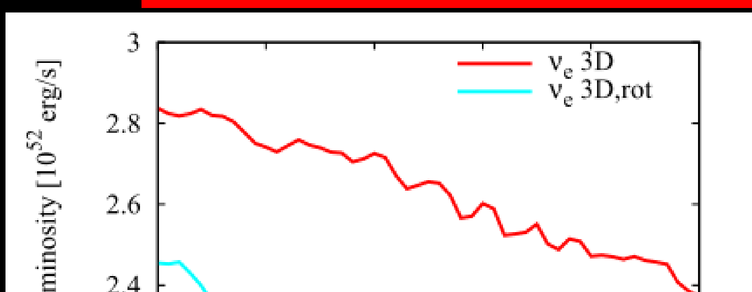
Neutrino and GW signatures between 3D models with/without rotation

Takiwaki & KK in prep

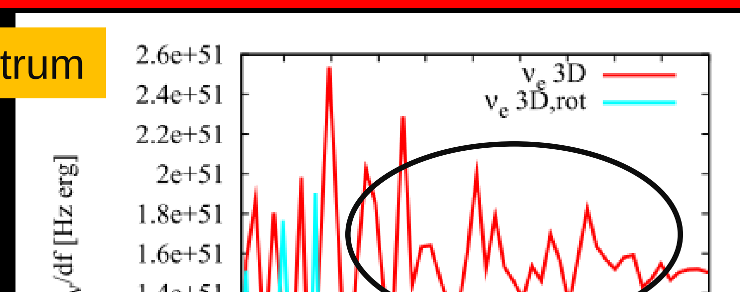




✓ Luminosities for all species get smaller for the rotating model because the centrifugal forces act against the core-contraction.



Spectrum



✓Variation timescale of neutrino signals ⇒ longer for rotating models (because the dynamical timescale longer for rotating models)

⇒would provide one additional clue : the difference between the rotating and non-rotating model (see talks by Lunardini and Lund !).

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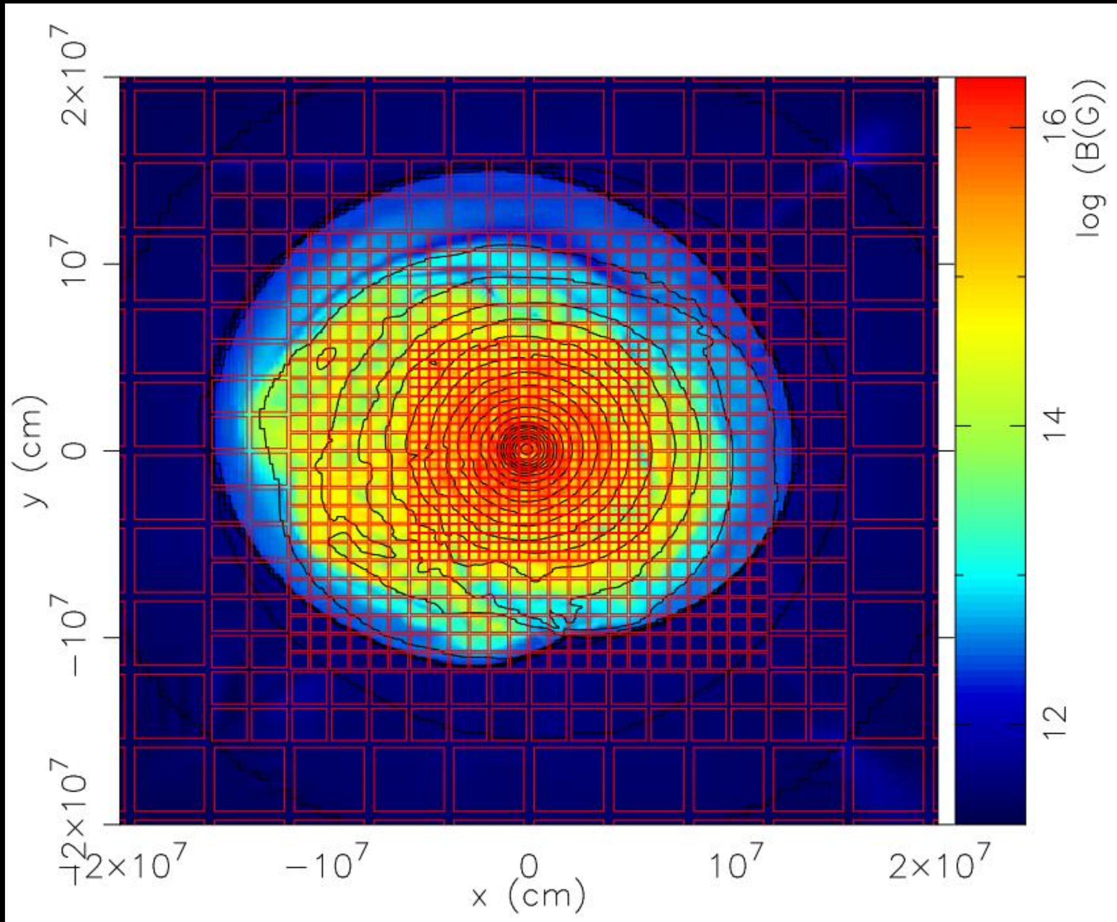
Does GR **help "multi-D" neutrino-**driven explosions?

Kuroda, KK, Takiwaki ApJ in press (see also B. Mueller et al. 2012)

- ✓ 3D full GRMHD code developed by Kuroda (NAOJ) (for more details, see Kuroda and Umeda (ApJS 2010))
- ✓ Adaptive-mesh-refinement approach is taken (δx_{min} = 450-600m).

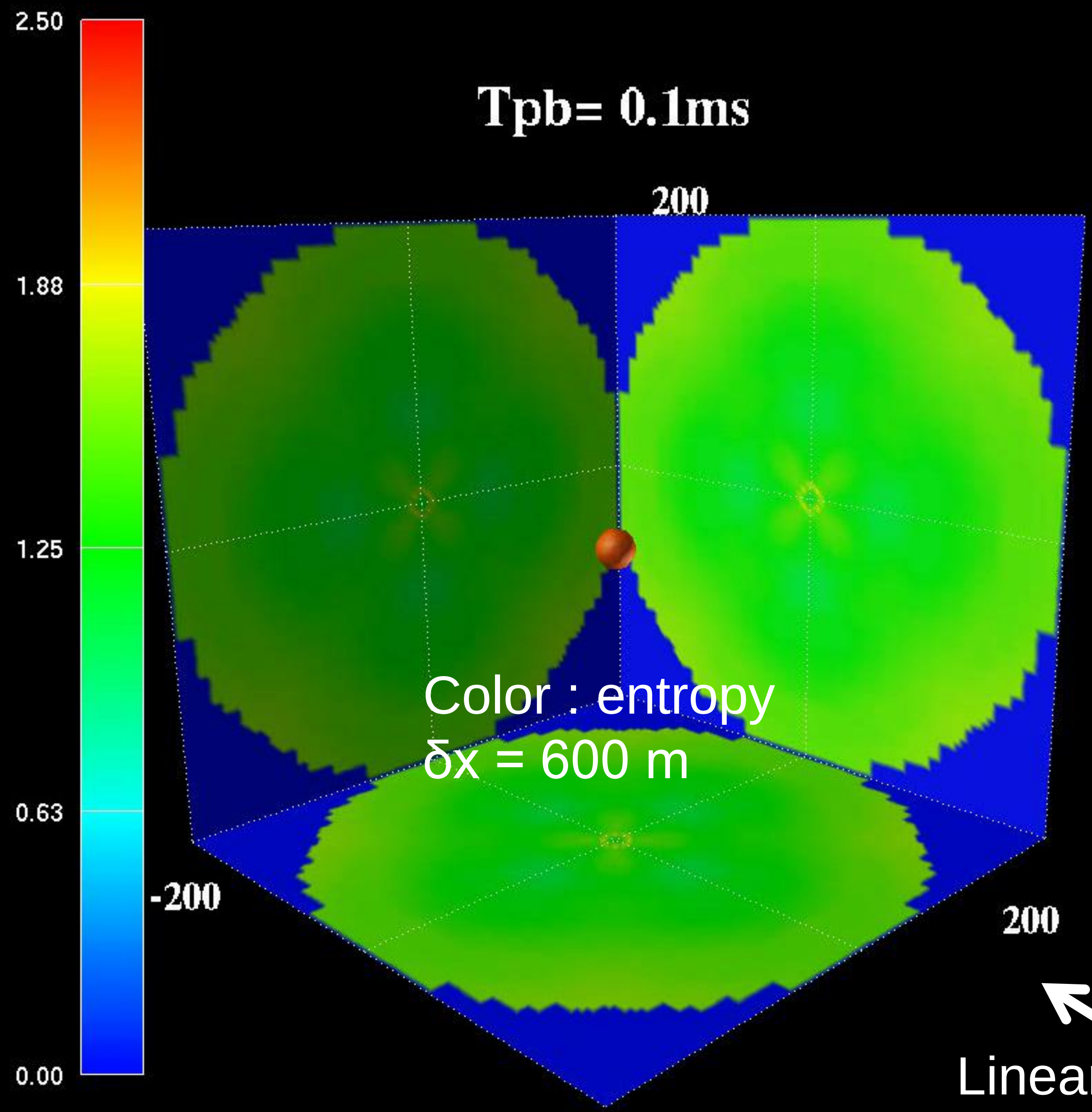
new **old**

- ✓ Neutrino cooling: multi-flavor leakage scheme.
- ✓ Neutrino heating: by a partial implementation of the Thorne's moment formalism (Shibata+11).



Post

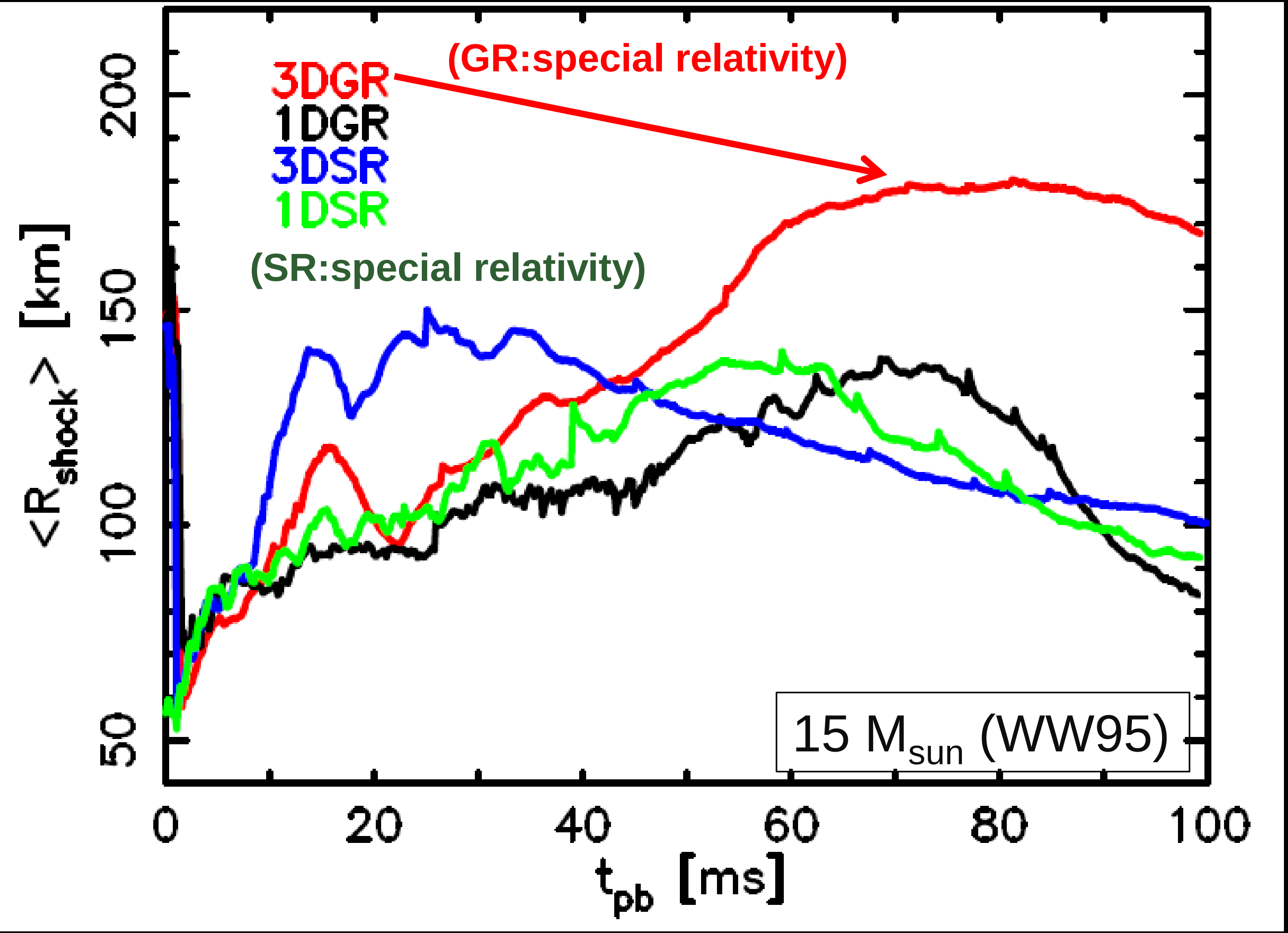
press



Linear scale (km)

3D GR rotating model
(P_0 = 4 s)
Color : entropy
δx = 450 m

Comparison of average shock radii

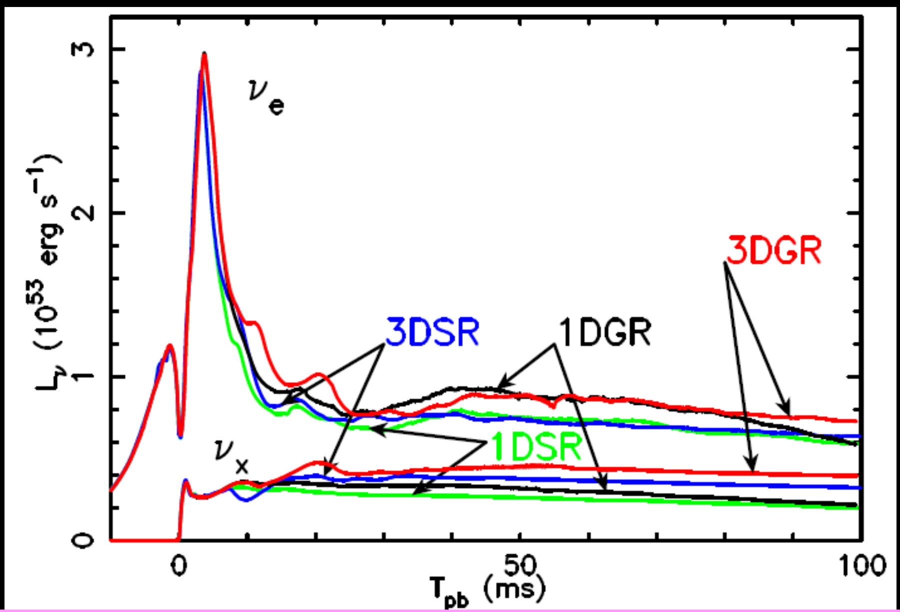


✓Except for our 3D-GR model, the shock has shown a trend of recession.
✓ Important : why the shock can reach most further out for 3D-GR ?

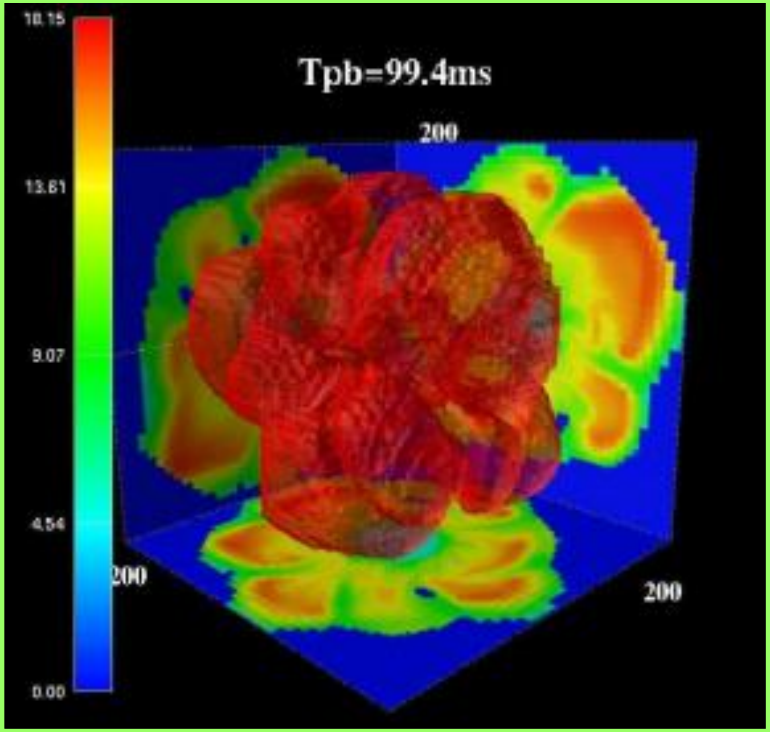
Advantages in 3D-GR model to go explosions !

Two things : GR and 3D

✓ Deeper potential well : core structures smaller ⇒ making <E$_\nu$ > higher.



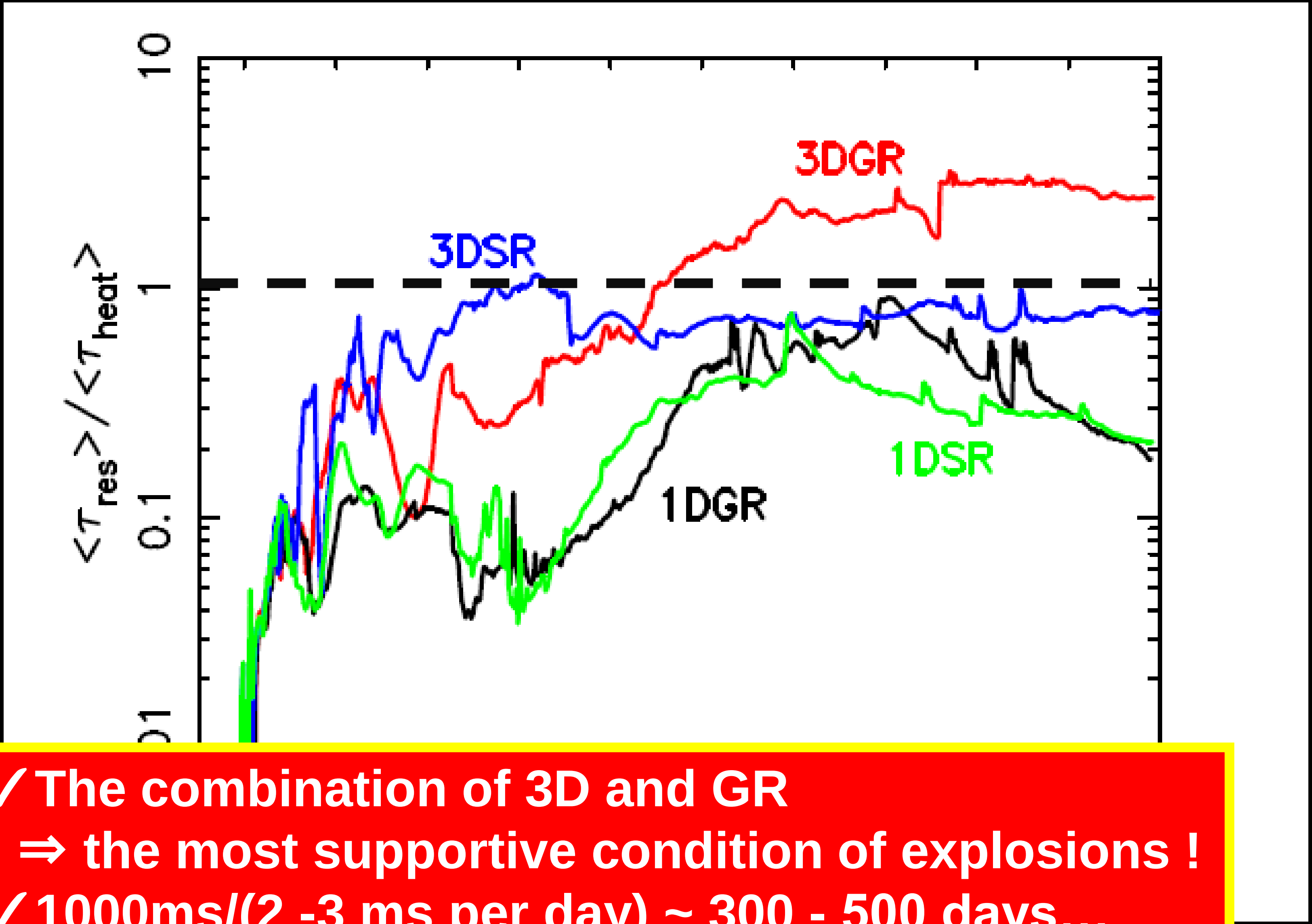
✓GR can enhance the neutrino luminosity up to 40 % comp.to the SR counterpart.



Due to non-radial motions, the residency timescale : longer in 3D than in 1D.

⇒ Essential why 3D are supportive compared to 1D

Diagnostic of explosion : residency timescale/heating timescale



✓The combination of 3D and GR

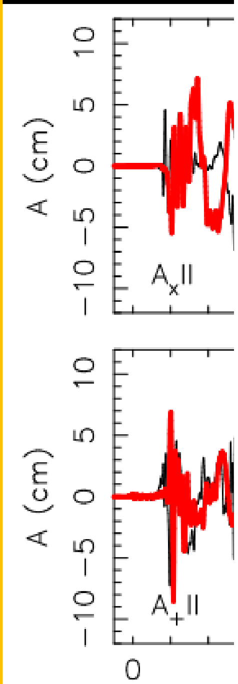
⇒ the most supportive condition of explosions !

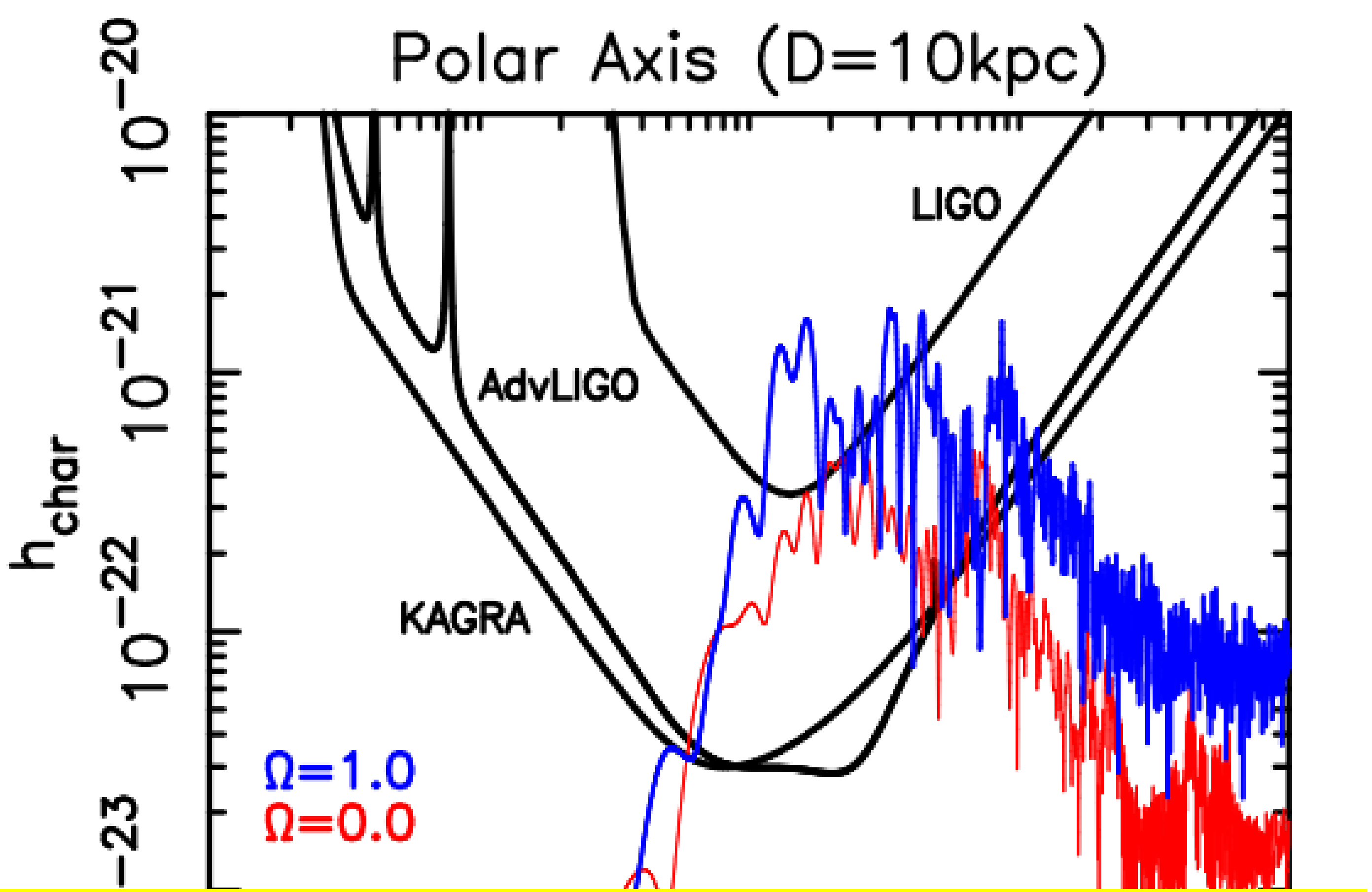
✓1000ms/(2 -3 ms per day) ~ 300 - 500 days…

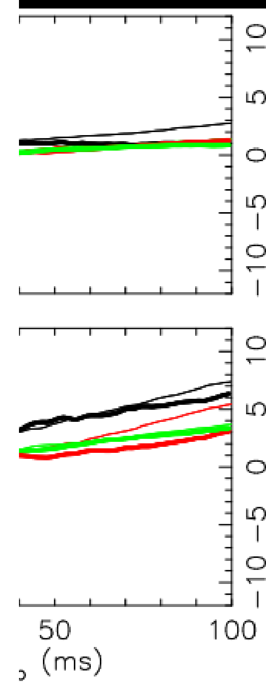
Gravitational waveforms from 3D-GR model

(Kuroda & KK in prep)

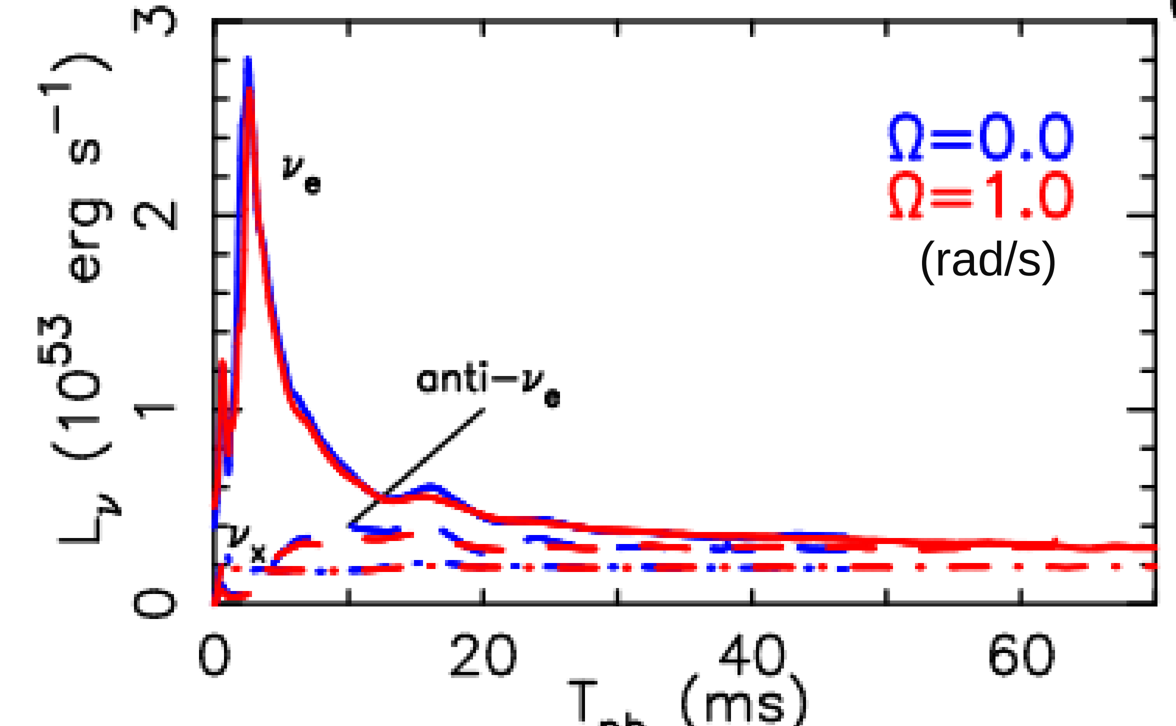
Preliminary







Rapid rotation (making core-deformation larger) leads to more easier detection for GWs !



Neutrino luminosity gets smaller for models with larger initial angular momentum.

Inverted hierarchy

$\sin^2\Theta_{13}$ =0.1

No collective effects

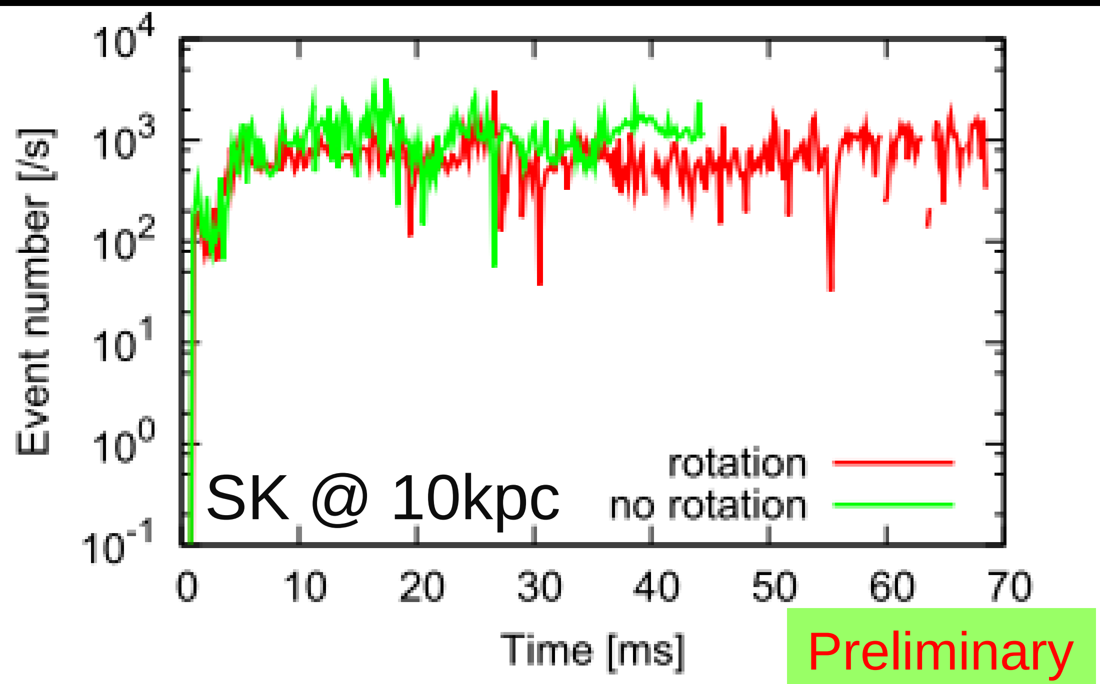
Rapid rotation

⇒ neutrino signals ↘

rms energy ↘

luminosity

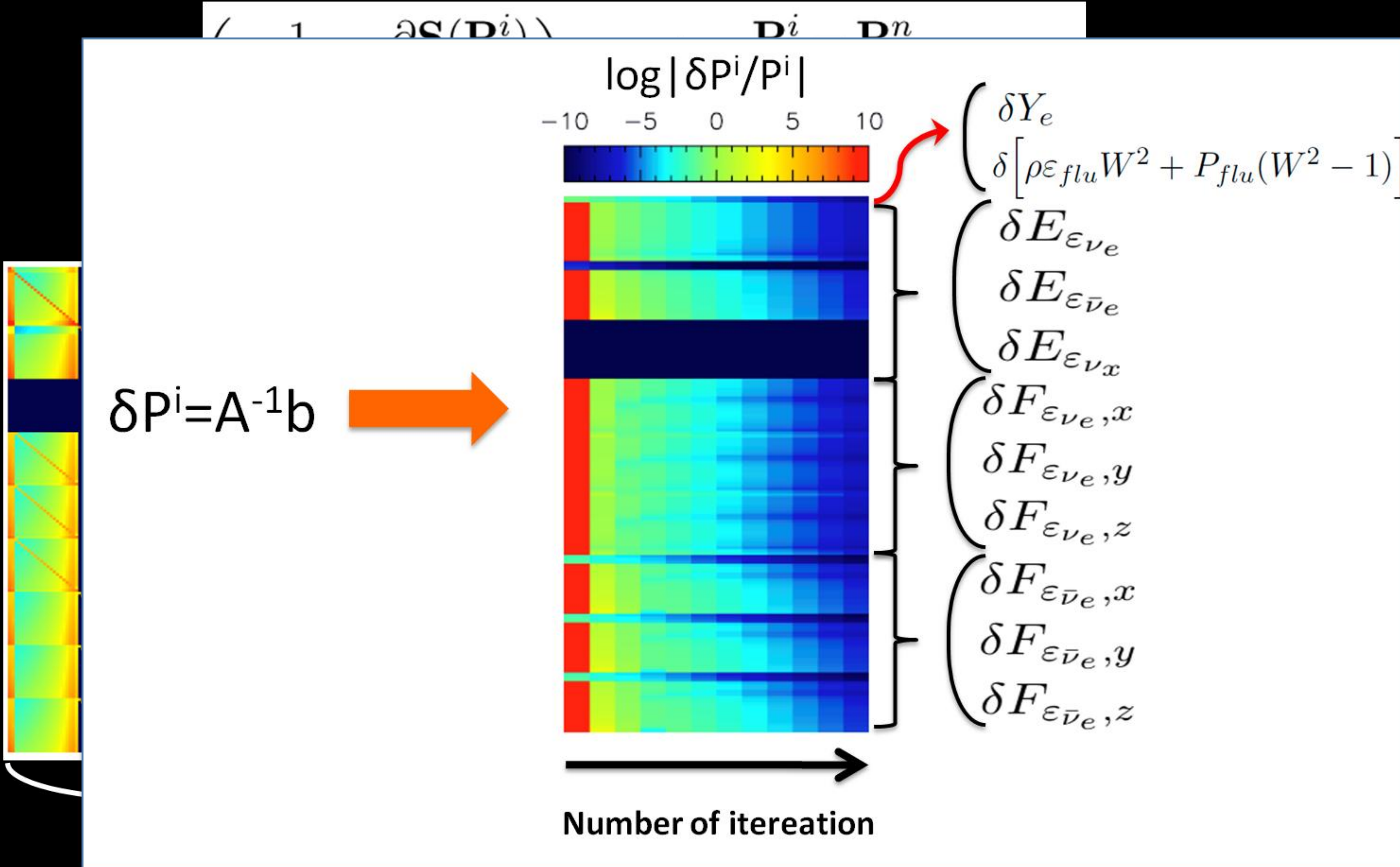
(More detailed analysis is coming ! KK et al . in prep)



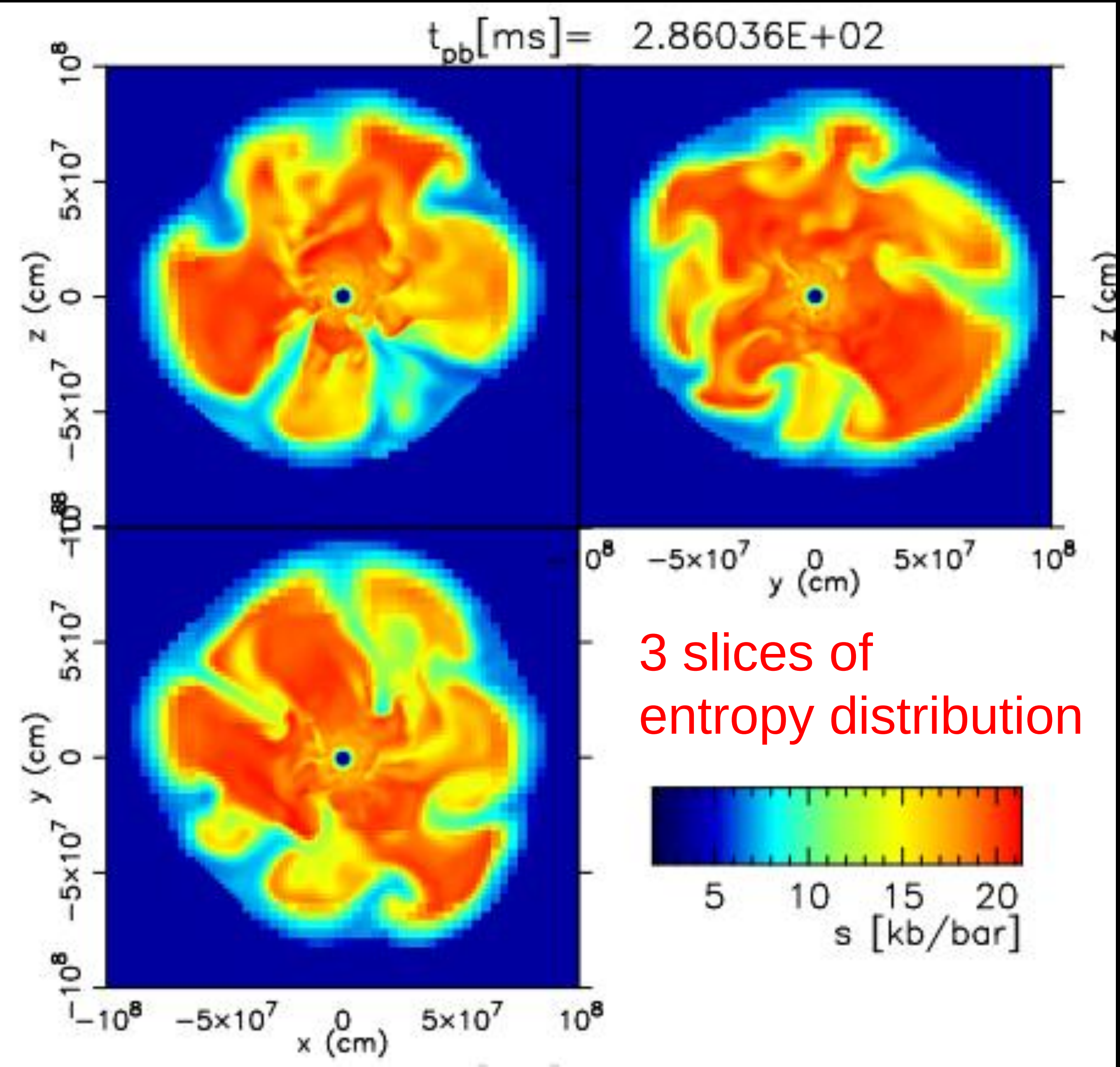
"Full GR code with *spectral neutrinos transport*(1/4)"

Kuroda, KK, Takiwaki in prep.

Newton-Raphson method



Demonstration of our newly developed code (2/4)

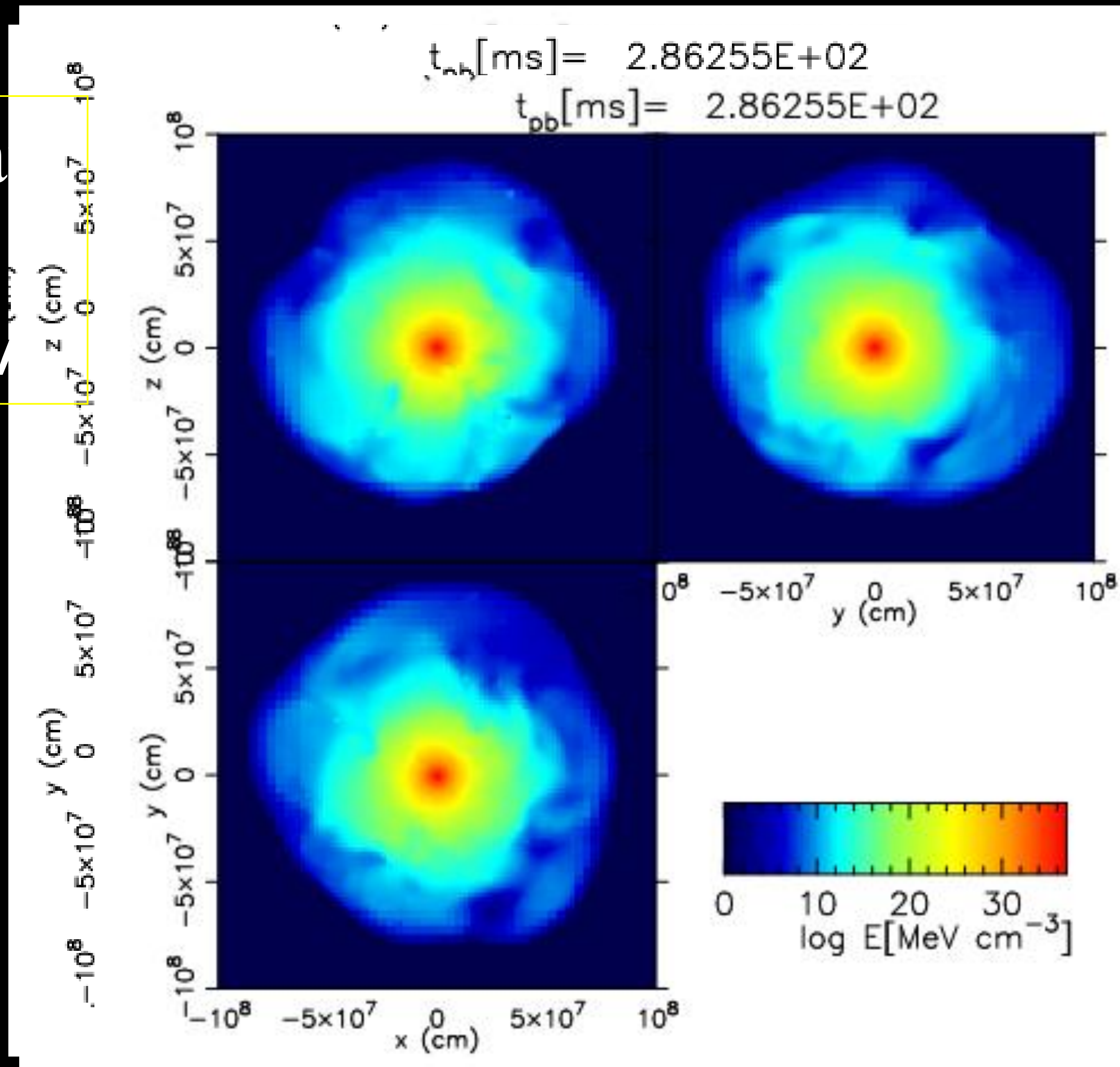


Demonstration of our newly developed code (3/4)

For lower energy bin:
E_{ν}: 3 MeV

For higher energy bin:
E_{ν}: 36 MeV

For intermediate energy bin
$<E_{\nu}>$: 18 MeV



NES/Thermal Production are being installed (4/4)

$$\partial_t(\sqrt{\gamma}E_{(\nu)}) + \partial_j[\sqrt{\gamma}(\alpha F^j_{(\nu)} - \beta^j E_{(\nu)})] + \frac{\partial}{\partial\nu}\left(\nu\alpha\sqrt{\gamma}n_\alpha M^{\alpha\beta\gamma}_{(\nu)}\nabla_\gamma u_\beta\right)$$
$$= \alpha\sqrt{\gamma}[P^{ij}_{(\nu)}K_{ij} - F^j_{(\nu)}\partial_j \ln\alpha - S^\alpha_{(\nu)}n_\alpha],$$

$$\partial_t(\sqrt{\gamma}F_{(\nu)i}) + \partial_j[\sqrt{\gamma}(\alpha P^j_{(\nu)i} - \beta^j F_{(\nu)i})] - \frac{\partial}{\partial\nu}\left(\nu\alpha\sqrt{\gamma}\gamma_{i\alpha}M^{\alpha\beta\gamma}_{(\nu)}\nabla_\gamma u_\beta\right)$$
$$= \sqrt{\gamma}\left[-E_{(\nu)}\partial_i\alpha + F_{(\nu)k}\partial_i\beta^k + \frac{\alpha}{2}P^{jk}_{(\nu)}\partial_i\gamma_{jk} + \alpha S^\alpha_{(\nu)}\gamma_{i\alpha}\right]$$

Active !

$$S^\alpha_{(\nu)} = \int \frac{d\nu'}{\nu'}\left[-\{(J_{(\nu)} - 4\pi\nu^3)u^\alpha + H^\alpha_{(\nu)}\}(4\pi\nu'^3 - \bar{J}_{(\nu')})R^{\rm pro}_0(\nu,\nu')\right.$$
$$- \frac{\bar{H}^\alpha_{(\nu')}}{\ldots}\{(4\pi\nu^3 - J_{(\nu)})R^{\rm pro}_1(\nu,\nu') + J_{(\nu)}R^{\rm ann}_1(\nu,\nu')\}$$

✓The **most conservative** way to pin-down the mechanism :
(e.g., Mueller + (2012)):
implementation of multi-energy transport in full GR
3D simulations incl. **all relevant s.o.a. interactions** !
(Horowitz (1997), Burrows Sawyer(1998), Reddy+99)

✓ A steady progress is being made ! (it takes a time …)

To obtain the unified picture in the stellar evolution theory,

A grand challenge in computational astrophysics

Time Evolution

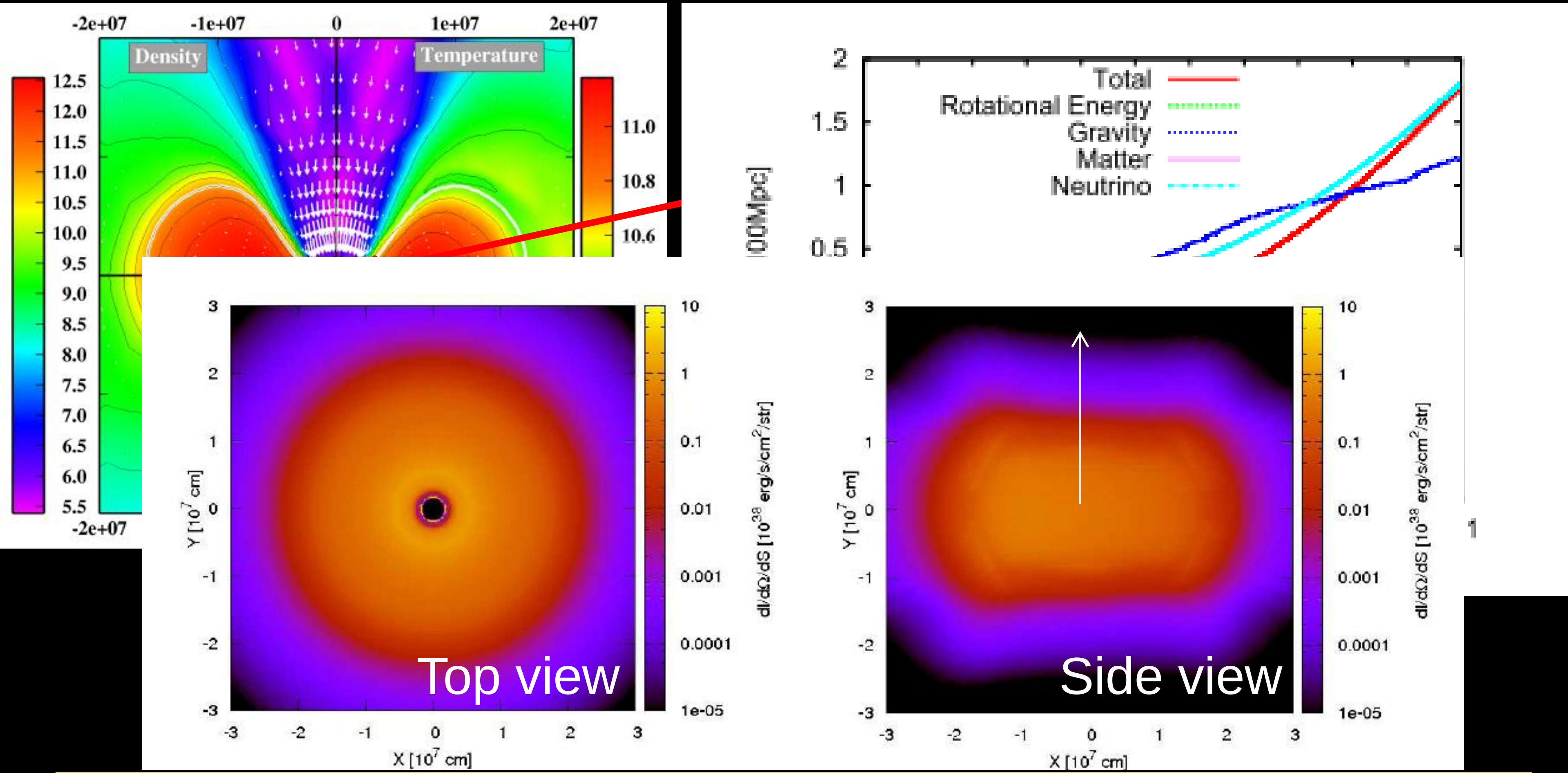
Dynamics of black hole formation

Mechanism of Hypernova & GRB

- ✓ No doubt : 3D GR neutrino rad-hydro sims. needed for handling BH formation and highly anisotropic field.
  (e.g., Ott + (2011), B.Mueller+(12), Sekiguchi-Shibata (2010), Kuroda+(2012))
- ✓ Typical duration of LGRBs ~ T_{90} > 20 s (Elena's talk !)
- ✓ Apparently beyond peta-scale platforms.
- ✓ Some approximate method is needed.
- ✓ Sitting between two chairs: Perfectionism vs. Pragmatism

Collapsar dynamics and the GW signatures

Kotake et al. (2012) ApJ in press



✓The total GW amplitude from collapsars is dominated by GWs from neutrinos.

✓Anisotropic neutrino flow from the accretion disk is the dominant source of GWs in the long-term evolution!

Collapsar dynamics and the GW signatures

Kotake et al. (2012) ApJ in press

Typical amplitude of neutrino GWs :

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

Neutrino anisotropy: degree of anisotropic neutrino radiation (zero if spherical)

$$|h| \sim 10^{-23}\left(\frac{\alpha}{\ }\right)\left(\frac{L_\nu}{\ }\right)\left(\frac{\delta t}{\ }\right)\left(\frac{R}{\ }\right)^{-1}$$

Kawagoe, KK+ in prep

Table 1: This table shows average event rate of the neutrinos from the collapsar. "with" means with the collective effects, and "without" means without the collective effects.

distance	model A		model B		model C	
	with	without	with	without	with	without
1Mpc	15.144	8.194	110.095	53.599	17.133	8.340
5Mpc	0.606	0.328	4.400	1.894	0.685	0.334
10Mpc	0.152	0.082	1.110	0.536	0.171	0.083

Hyper-Kamiokande

Neutrino astronomy of collapsars
is hard (even by next.gen. detectors.)
(the closest example:
SN'98bw-GB980425 : D ~ 40 Mpc)

ts of DECIGO and BBO !
are several/decade.
l be feasible !

An Analysis of Recent Research Trend of CCSN modeling in 2012

January : E.Mueller + (AA)
February: Foglizzo + (PRL), Pejcha-Thompson
B.Mueller+(ArXiv)
Kuroda+(ArXiv)
March : Guilet + (MNRAS)
Sumiyoshi&Yamada(ApJS)
Abdikamalov + (ArXiv)
Lentz + (ApJ)
Endeve + (ArXiv)x2
April : Takiwaki+(ApJ)
Fernandes (ApJ)
Ott+(ArXiv)
Burrows+(ArXiv)
Montero+ (ApJ)
Kotake+(ArXiv)
May : Endeve+(ApJ)
Murphy+(ArXiv)
B.Mueller+(ArXiv)
Ugliano+(Arxiv)
Kotake+(ArXiv)
Kotake+(AriXiv)
June : Nordhaus+(MNRAS)
Lentz + (ArXiv)
Couch(Arxiv),
Janka (ArXiv)
Suwa+(ArXiv) (more to come…)

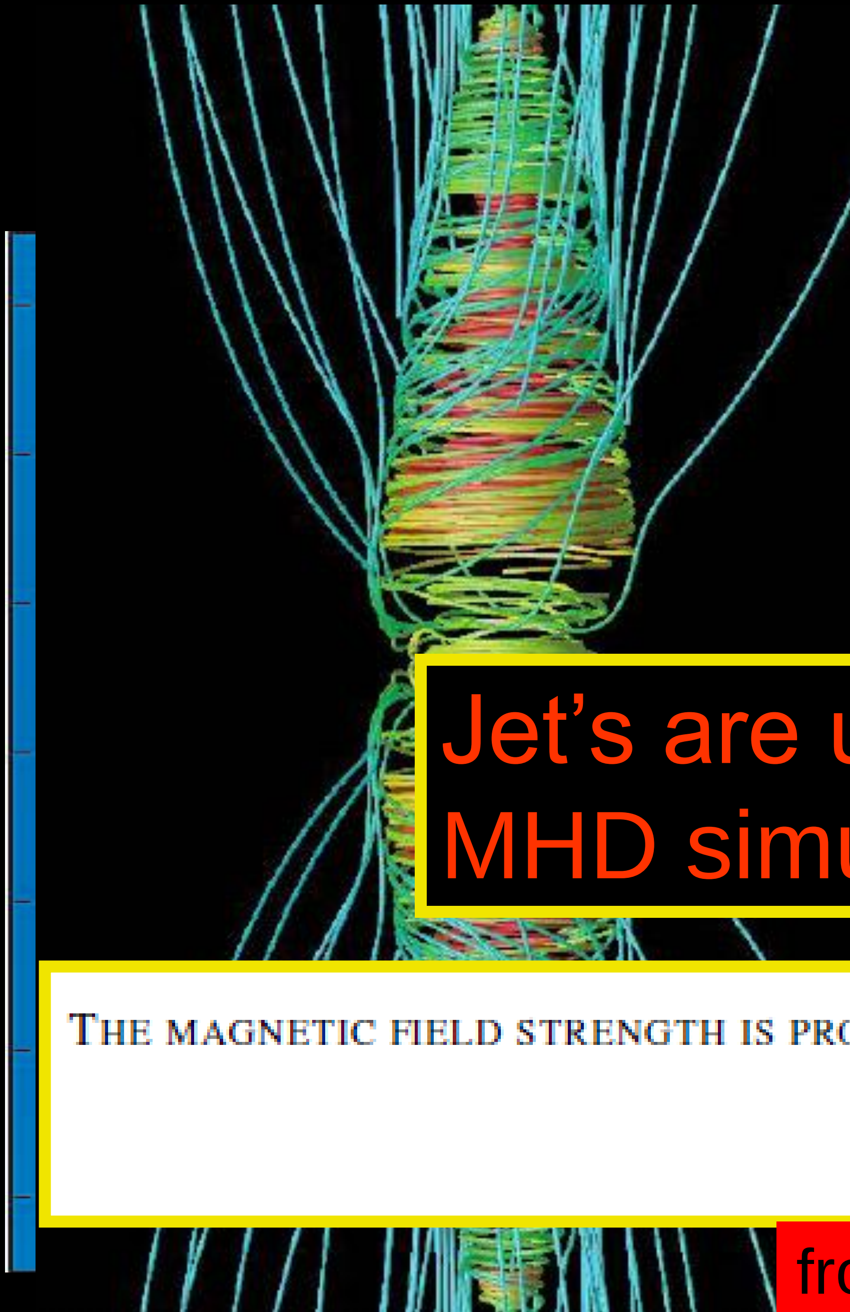
1. First-principle simulations
   - 1D with B-transport
   - 2D/3D different scheme extended to GR

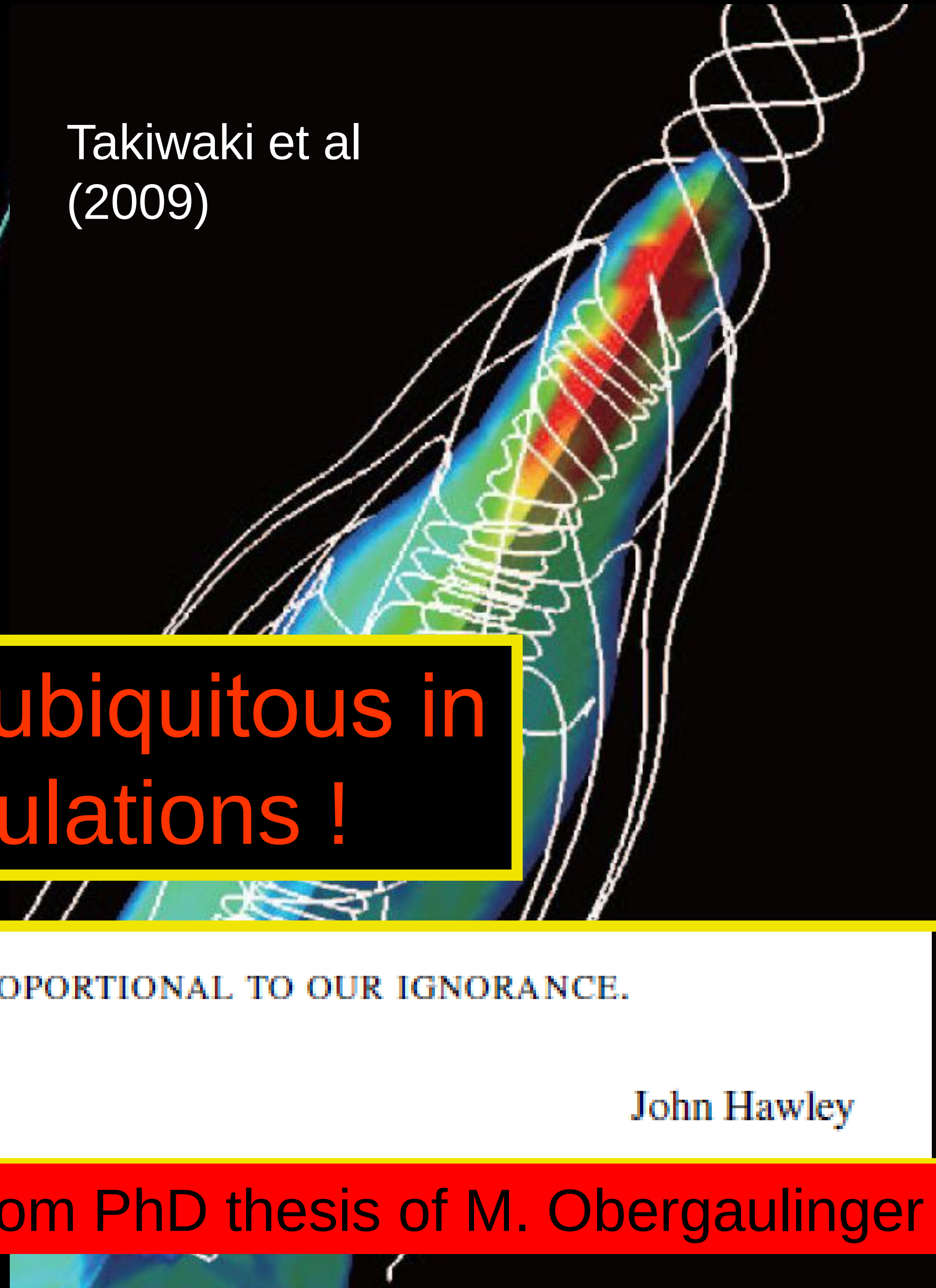
2. Phenomenological modeling
   - Liebendoerfer Ye formula
   - a light-bulb scheme

3. Novel approaches proposed

4. New algorithms for 6D transport ultimately in GR

5. Theoretical predictions of SN multi-messengers: neutrino, gravitational-wave elemag. signals





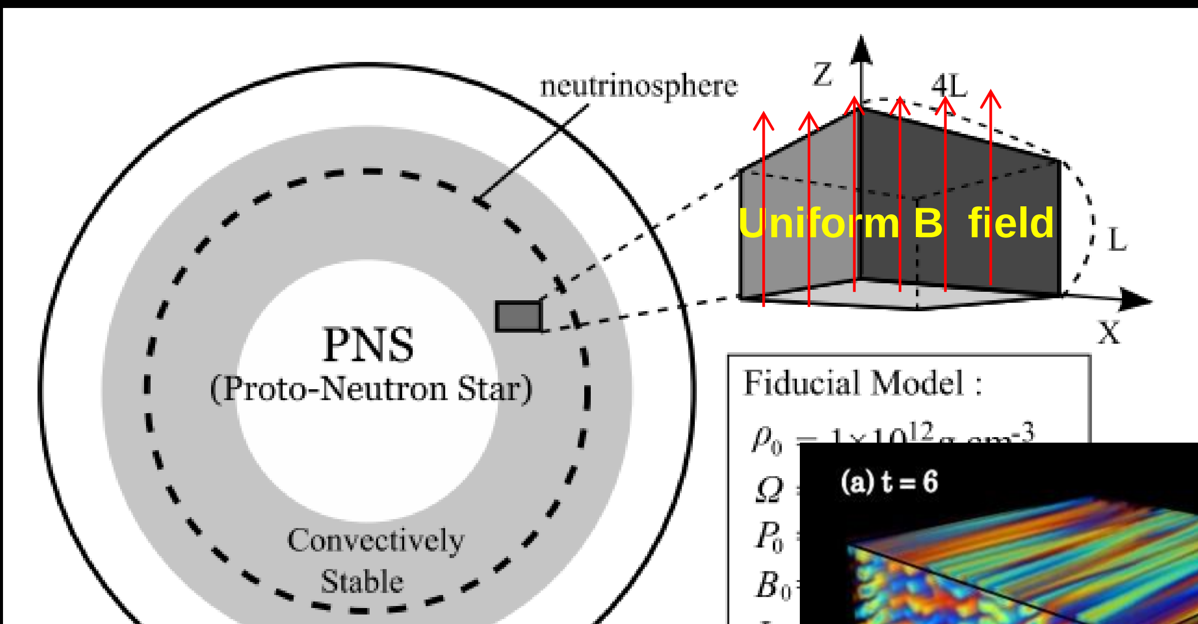
Jet’s are ubiquitous in MHD simulations !

THE MAGNETIC FIELD STRENGTH IS PROPORTIONAL TO OUR IGNORANCE.

John Hawley

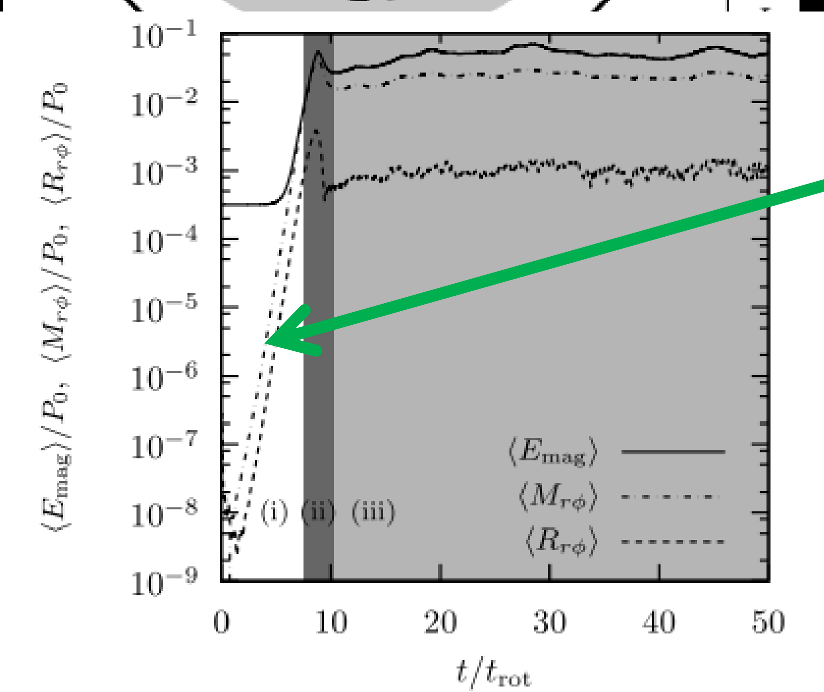
from PhD thesis of M. Obergaulinger

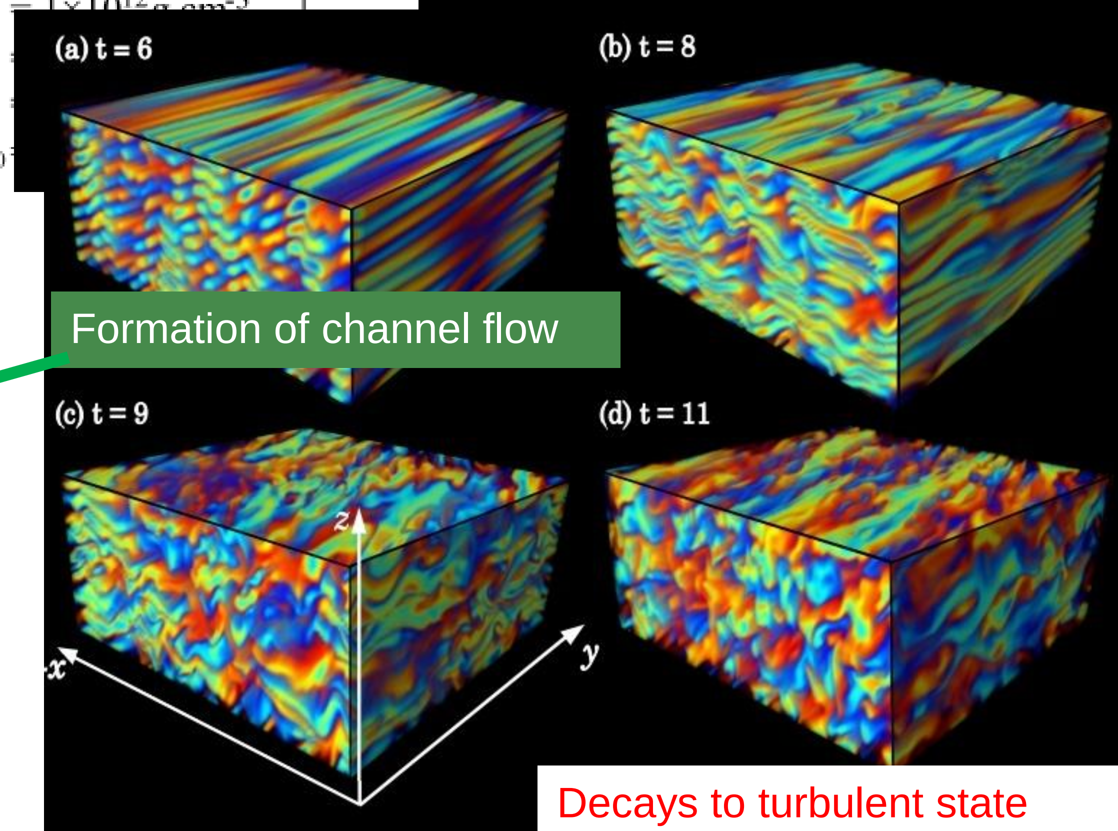
3D local simulations of MRI in the supernova cores



Masada et al. in prep.
(pioneered by
Obergaulinger +(09,10))

✓Degree of differential rotation is systematically investigated in our study.

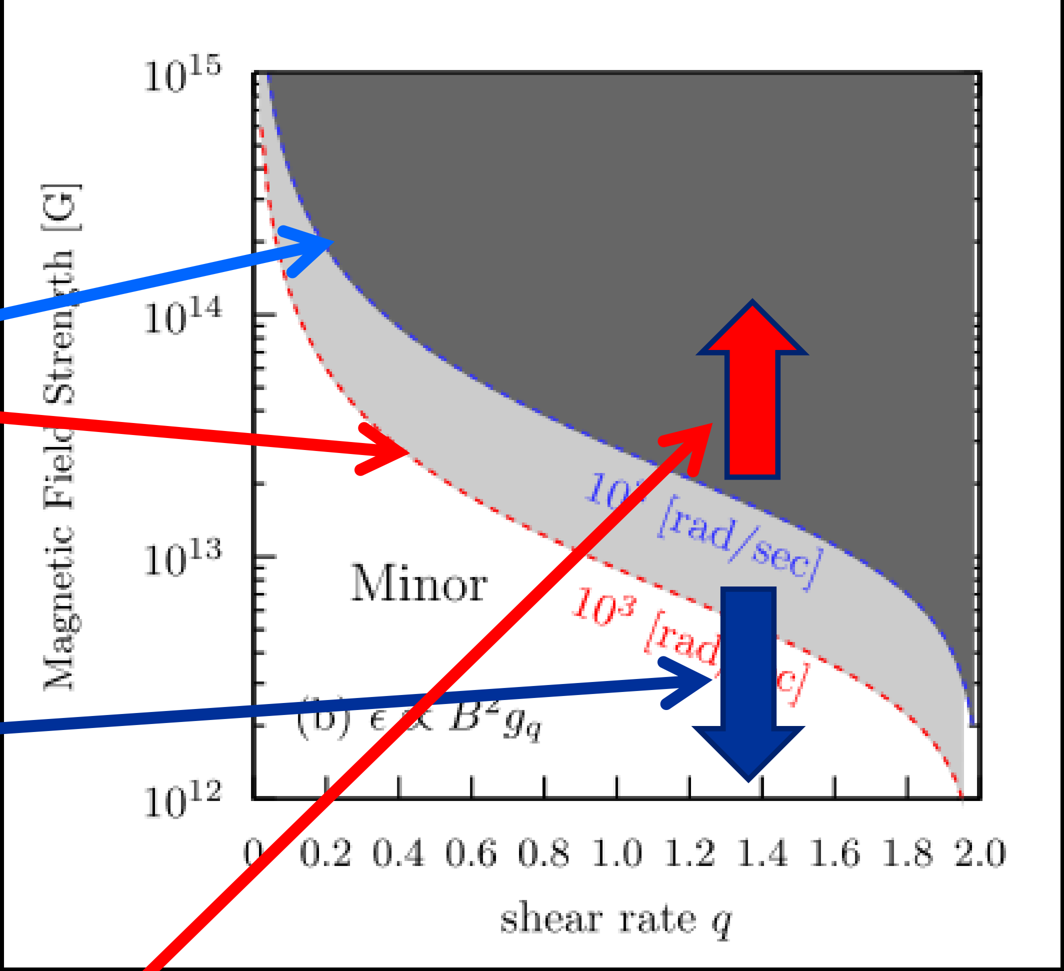




How much energy tapped as shear-rotational energy could be dissipated by MRI-driven turbulence ?

Masada, Takiwaki, KK, Sano in prep

Given a post-bounce rotation rate,
$L_{MRI} \sim 10^{51}$ erg/s



$$q \equiv -d \ln \Omega / d \ln r$$

✓ For canonical CCSN progenitors, MRI never important.

✓ For collapsars, energy supply by MRI-driven heating likely affects the outflow formations ! (Masada et al. to be submitted)

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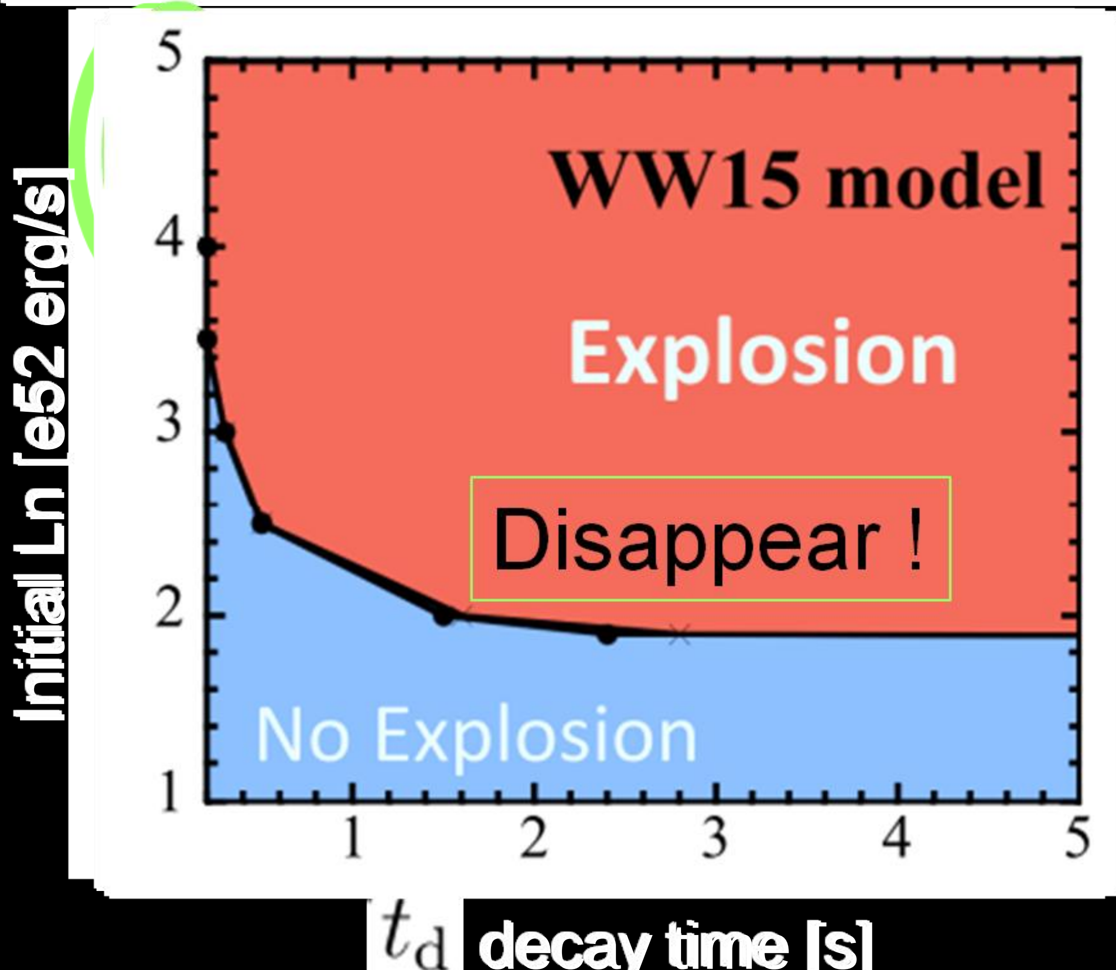
Seeking some candidates to foster explosions:

✓ Impacts of nuclear burning revisited

(e.g., Janka et al. (2001), Mezzacappa et al. (2007))

$$L_{\nu_e} = L_{\bar{\nu}_e} = L_{\nu 0}\exp(-(t - t_{\rm bounce})/t_{\rm d})$$

$L_{\nu 0}$



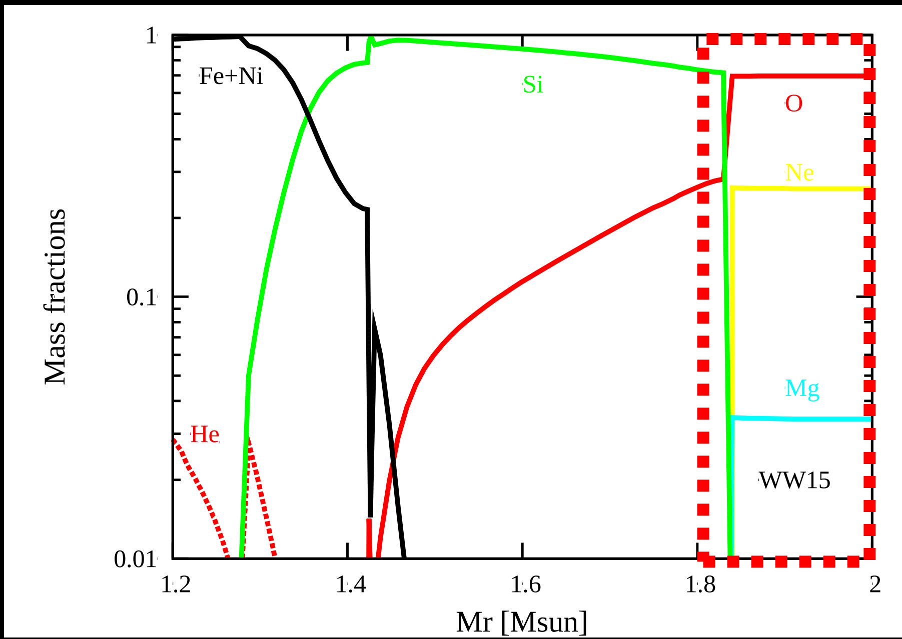
✓ 1D/2D light-bulb simulation

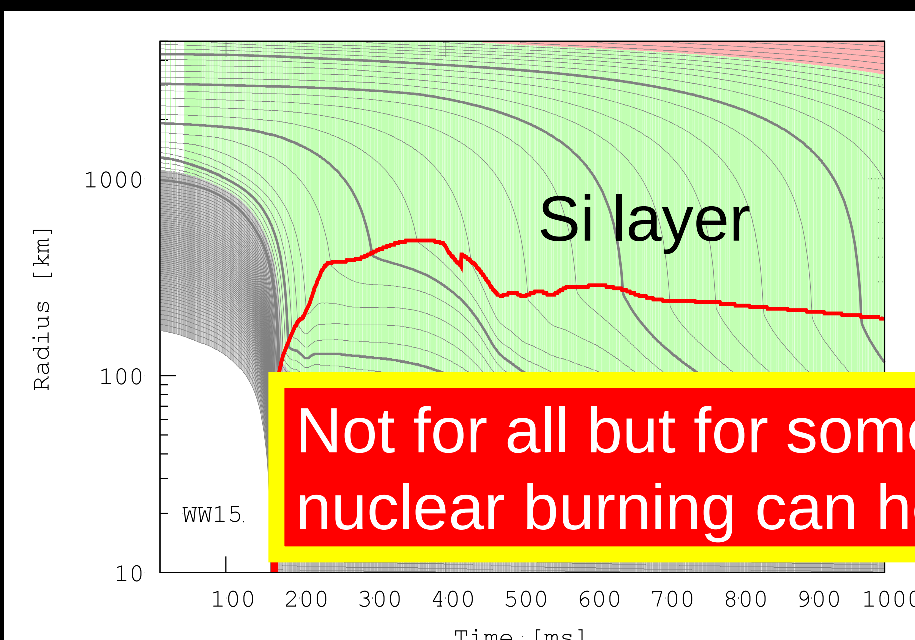
$15\ M_{sun}$

Chieff (2006)

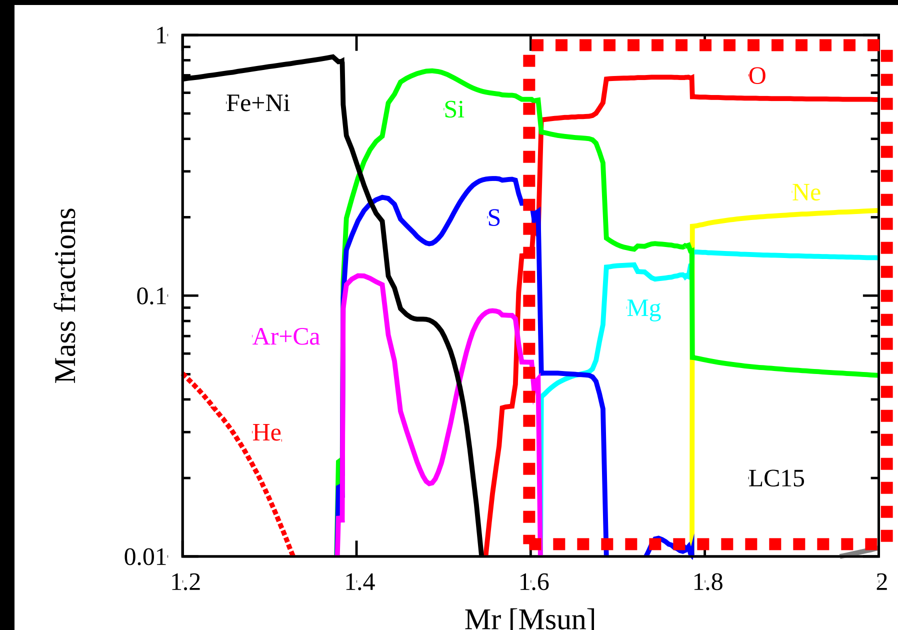
Nakamura KK+ in prep

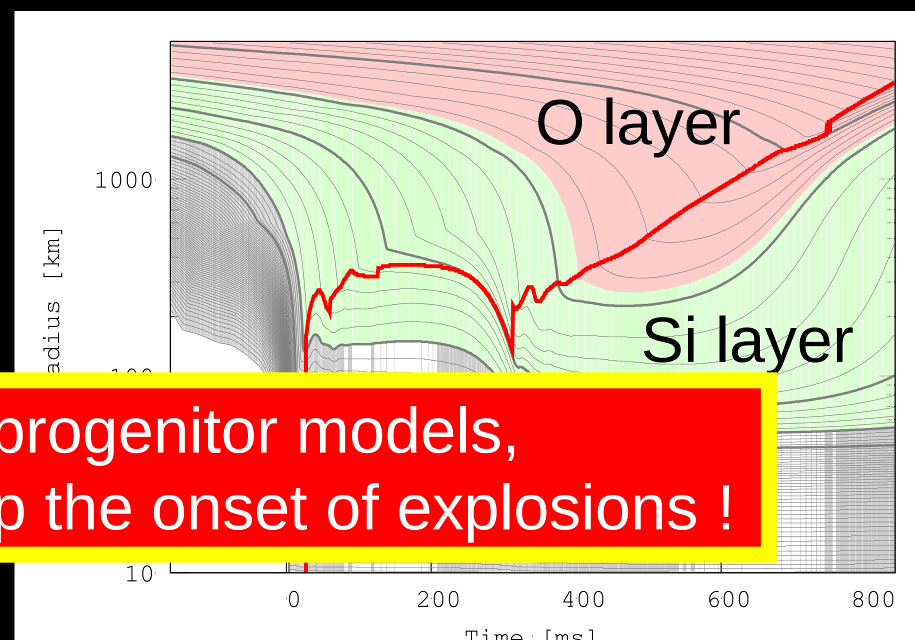
Woosley-Weaver (1995)





Limongi-Chieff (2006)



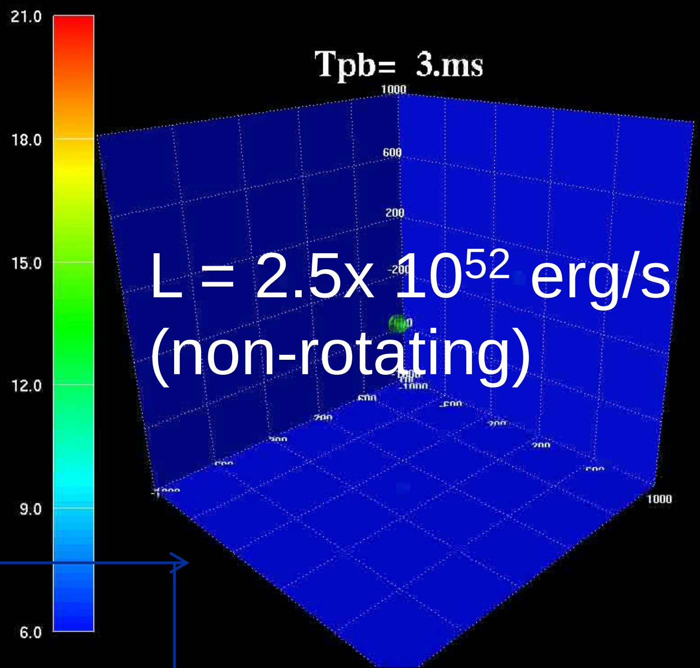


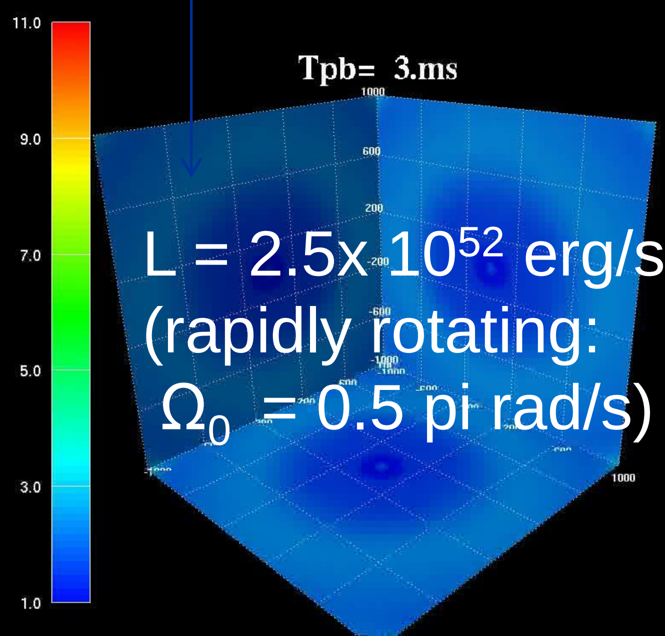
Not for all but for some progenitor models,
nuclear burning can help the onset of explosions !

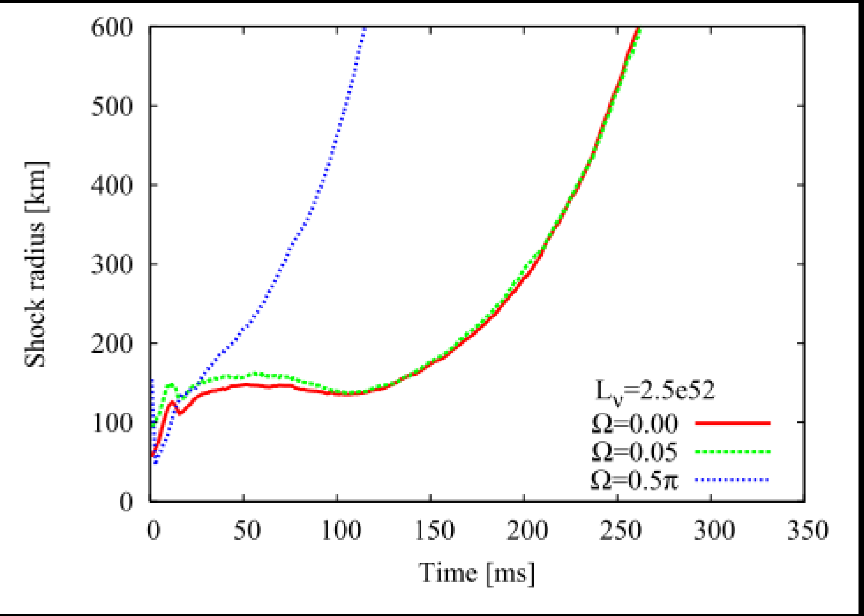
3D light-bulb simulations in progress in NAOJ

Nakamura, Kuroda, KK+ in prep

Preliminary







Very dangerous:

magnetorotational effects

by **manual explosion models.**

(especially **by pure** light-bulb).

but … **Very attractive**

✓ blast morphology

✓ light curve modeling

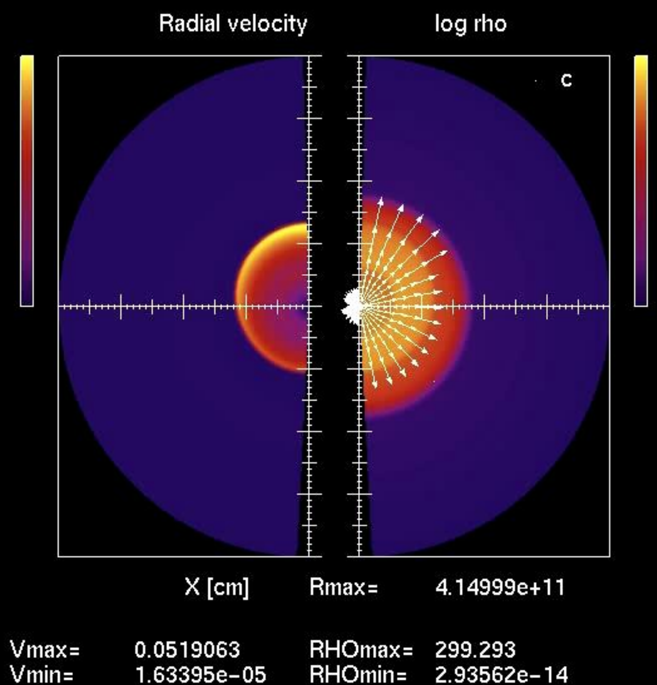
✓ spin/kick of newly-born pulsars

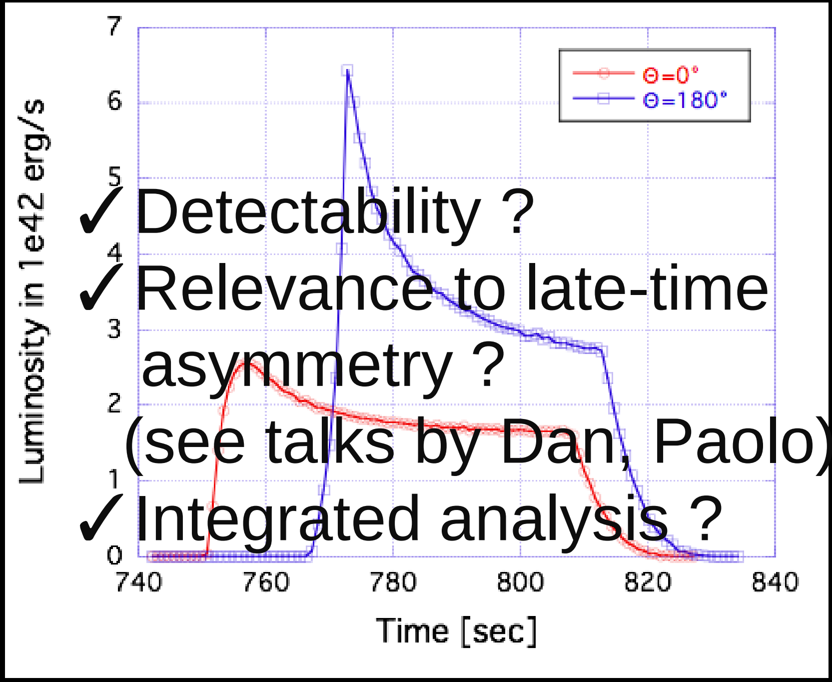
(see A.Wongwathanarat's talk for a better transport scheme!)

Light-curve asymmetry at the shock-breakout signatures

Preliminary

Suzuki, Takana, KK et al. in prep (pioneered by Kifonidis+2003, Hammer+10





- ✓Detectability ?
- ✓Relevance to late-time asymmetry ? (see talks by Dan, Paolo)
- ✓Integrated analysis ?

✓Need to list all observational signatures: to clarify links between "multi-D supernova mechanism" and "their multi-messenger signatures".

✓Not easy, but the only way to make the dream come true !

Summary and Outlook

☆ **On the 3D effects:**
we've not obtained a clear-cut answer, hampered by stochastic nature of explosions.

✓ **Parametric studies in the first-principle 3D simulations by changing resolutions, perturbations, and so on) should be done !**

⇒ **Need peta- or exa-scale supercomputers!**
(see our recent review (accepted to PTEP: Kotake et al. toward 6D simulations with exact Boltzmann transport in full general relativity !)

☆ **Our 1st generation GR results: the combination of GR and 3D provides the most favorable condition.**

✓ **Just find the way to hold the wedding between spectral neutrino transport and GR hydro-code.**

✓ **MRI should affect the MHD mechanism especially for collapsars.**

☆ **Integrated analysis between GWs, neutrinos, and photons is needed, which is a big virgin territory yet to be studied.**