Cutting-edge issues of multi-dimensional core-collapse supernova simulations

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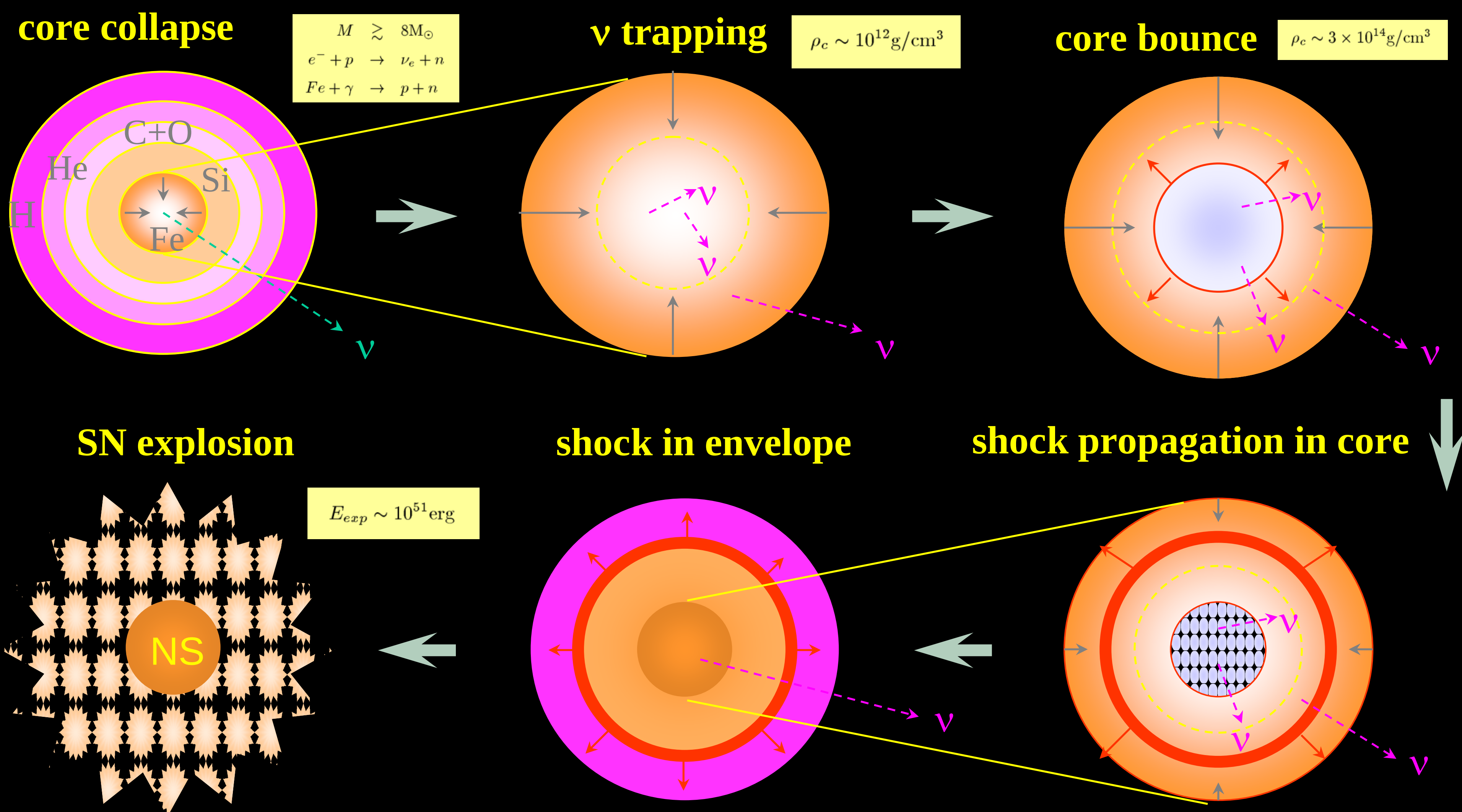
NIC XII; satellite workshop on r-process nucleosynthesis

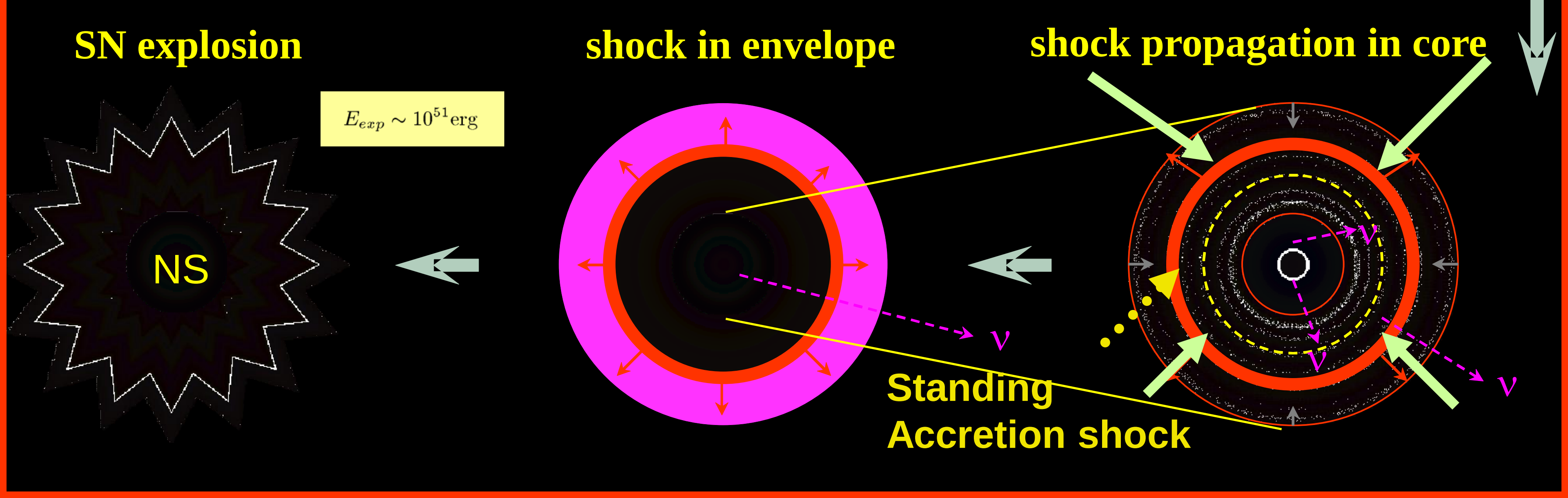
Standard scenario of core-collapse SNe

(e.g., Kotake+06, Janka+07 for a review)



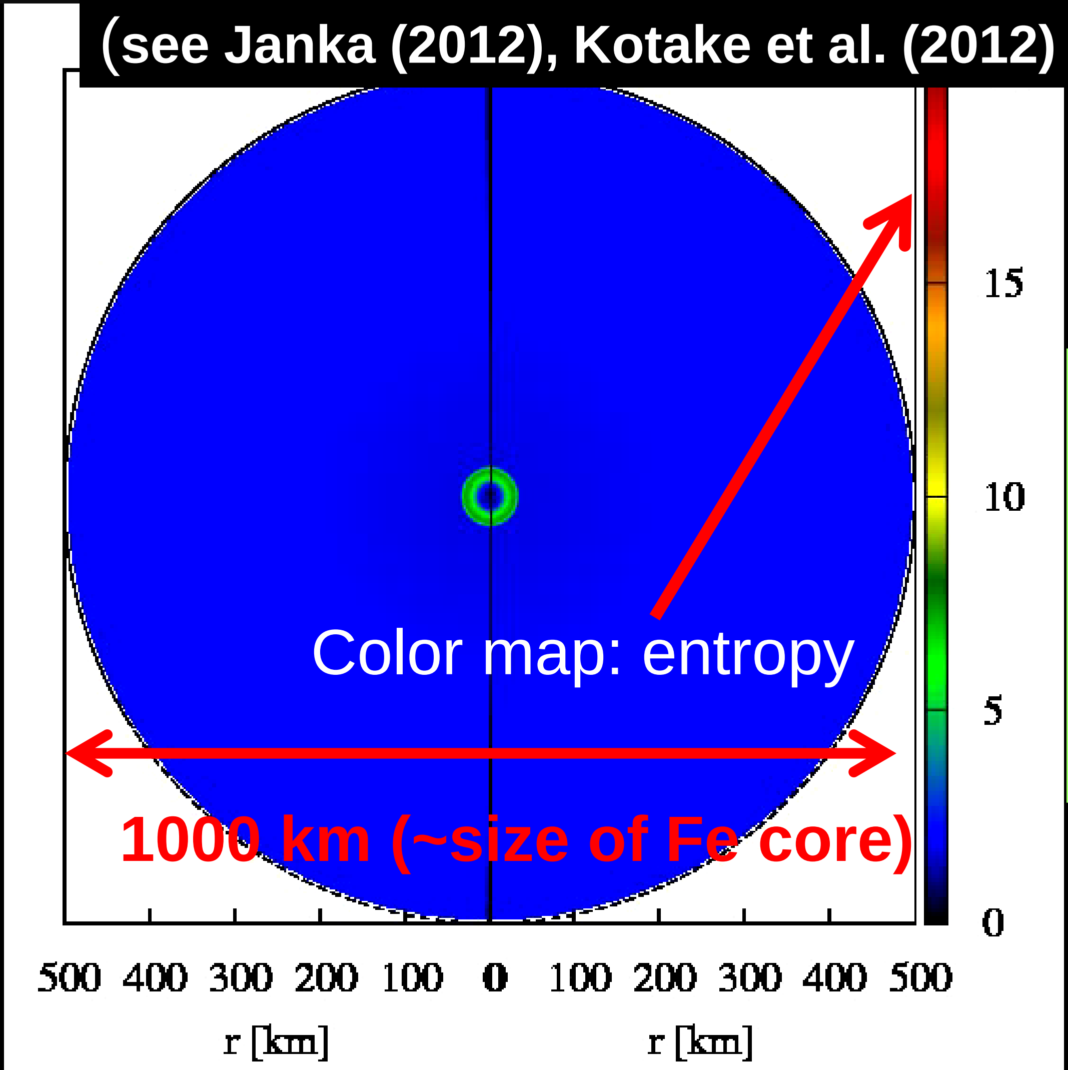
Standard scenario of core-collapse SNe

✓Have to find the way to revive the stalled bounce shock.
✓ The best-studied & most promising:
the neutrino-heating mechanism (Bethe, Wilson 1985)
: **neutrinos heat material to produce explosions.**
✓ **Except for special cases(Kitaura + (06)), the simplest, 1D form of this mechanism does not work.**
(Liebendoerfer et al. (2001), Rampp & Janka (2000), Sumiyoshi et al. (2005))



Current paradigm: multi-D neutrino-heating mechanism

(see Janka (2012), Kotake et al. (2012) for recent reviews)



Suwa, KK+ (10,11)
15 M_{sun} star (WW95)
- ✓2D rad. hydro core-collapse simulation with spectral neutrino transport
- ✓Lattimer-Swesty EOS (K=180MeV)

- ✓ After bounce, the bounce shock stalls.
- ✓ "Standing Accretion Shock Instability (SASI)" develops.
- ✓ The dwell timescales of matter in the gain region ⇒ much longer in multi-D.
- ✓ At around O(100)s ms after bounce, the neutrino-driven explosion occurs.

List of recent milestones reported **"explosions"**

Kotake arXiv:110.5107 Comptes Rendus Physique in press

Progenitor	Group (Year)	Mechanism	Dim. (Hydro)	t_{exp} (ms)	E_{exp}(B) @t_{pb} (ms)	ν transport (Dim, $O(v/c)$)
8.8 $M_\odot$	MPA[51] (2006)	ν-driven	1D (PN)	~200	0.1 (~800)	Boltzmann 2, $O(v/c)$
(NH88[71])	Princeton+ [74](2006)	ν-driven	2D (N)	$\lesssim$125	0.1 -	MGFLD 1, (N)
10 $M_\odot$ (WHW02[72])	Basel[75] (2009)	ν+(QCD transition)	1D (GR)	255	0.44 (350)	Boltzmann 2, (GR)
11 $M_\odot$ (WW95[73])	Princeton+ [74](2006)	Acoustic	2D (N)	$\gtrsim$550	~0.1* (1000)	MGFLD 1, (N)
11.2 $M_\odot$ (WHW02[72])	MPA[76] (2006)	ν-driven	2D (PN)	~100	~ 0.005 (~220)	"RBR" Boltzmann, 2, $O(v/c)$
	Princeton+ [77] (2007)	Acoustic	2D (N)	$\gtrsim$1100	~0.1* (1000)	MGFLD 1, (N)
	NAOJ+ [78](2011)	ν-driven	**3D** (N)	~100	0.01 (300)	IDSA 1, (N)
12 $M_\odot$ (WHW02[72])	Oak Ridge+ [79](2009)	ν-driven	2D (PN)	~300	0.3 (1000)	"RBR" MGFLD 1, $O(v/c)$
13 $M_\odot$ (WHW02[72])	Princeton+ [77](2007)	Acoustic	2D (N)	$\gtrsim$1100	~0.3* (1400)	MGFLD 1, (N)
(NH88[71])	NAOJ+ [80](2010)	ν-driven	2D (N)	~200	0.1 (500)	IDSA 1, (N)

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15 $M_\odot$ (WW95[73])	MPA[81] (2009)	ν-driven	2D (PN)	~600	0.025 (~700)	Boltzmann 2,$O(v/c)$
(WHW02[72])	Princeton+ [77]	Acoustic	2D (N)	-	- (-)	MGFLD 1, (N)
	OakRidge+ [79](2009)	ν-driven	2D (PN)	~300	~ 0.3 (600)	"RBR" MGFLD 1,$O(v/c)$
20 $M_\odot$ (WHW02[72])	Princeton+ [77](2007)	Acoustic	2D (N)	$\gtrsim$1200	~0.7* (1400)	MGFLD 1, (N)

☆ **Fundamental problems remained !**

✓ **The explosion energies are typically smaller by 1 or 2 orders-of-magnitudes compared to observation (SN kinetic energy of 10^{51} erg).**

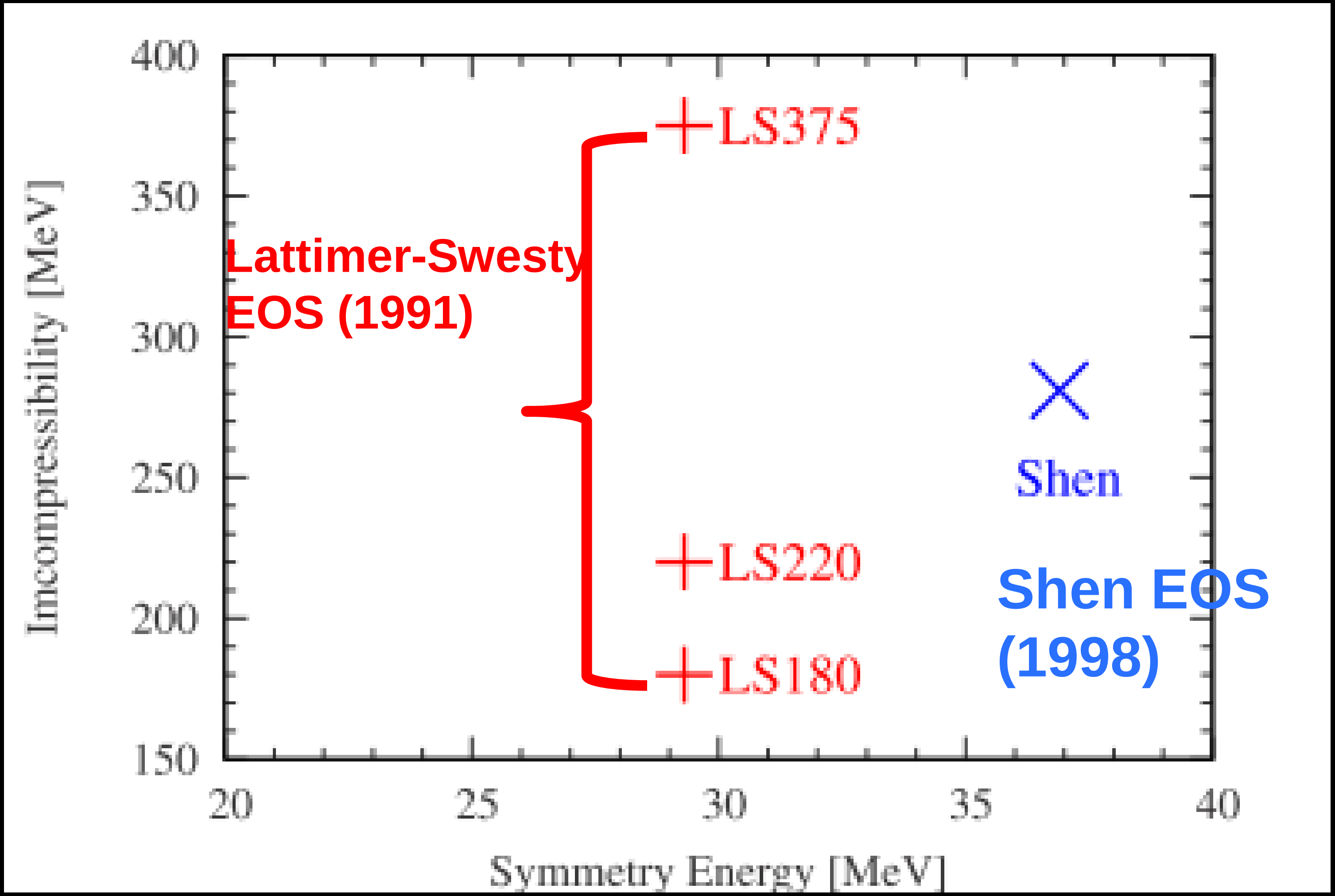
✓ Most of the neutrino-driven exploding models have employed a very soft nuclear EOS (K=180 MeV).

(K>220 MeV to explain the 2 Msun NS (e.g., Demorest+2010))

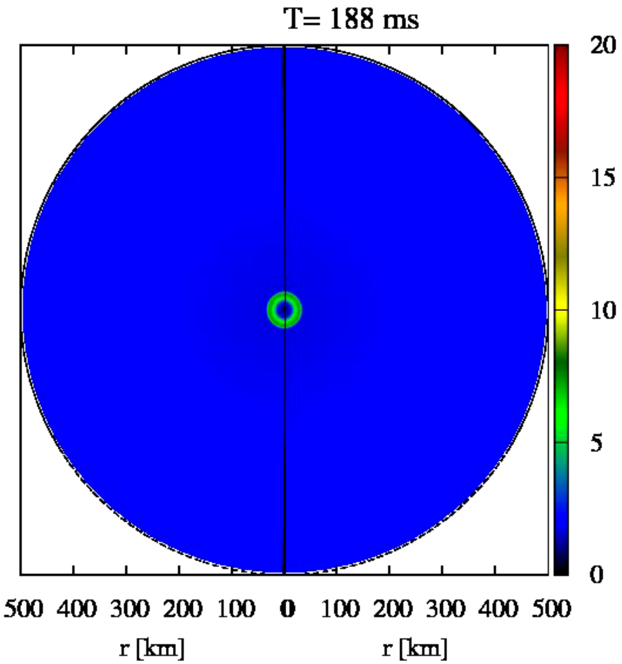
1st cutting-edge issue: Impacts of nuclear EOS

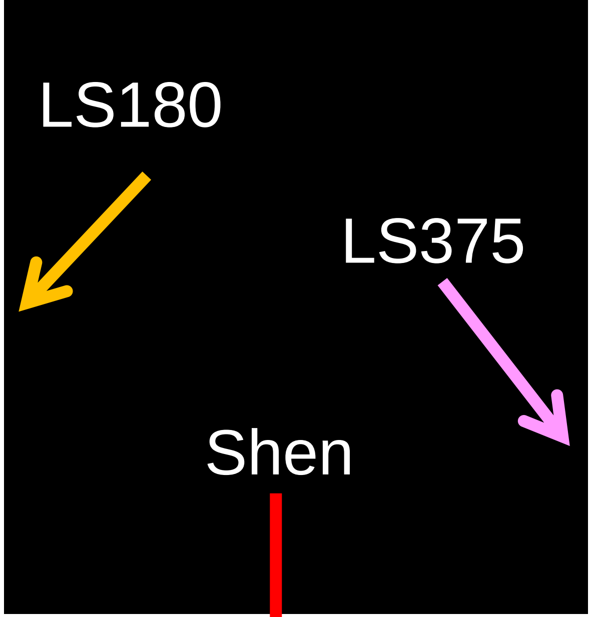
Suwa, Takiwaki, KK+ submitted to ApJ

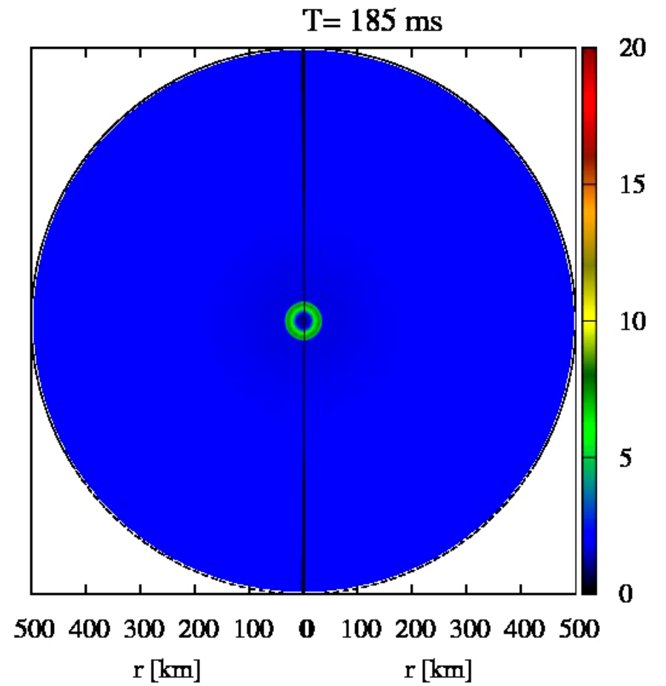
Features of SN EOS

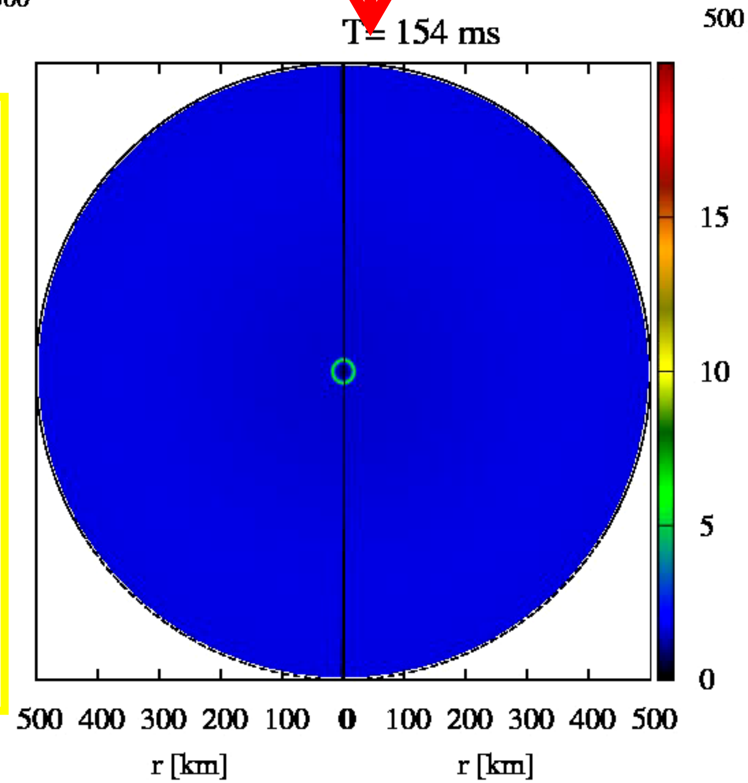


@ saturation density









- ✓ **Generally correct: easier to obtain explosions for softer EOSs.**
- ✓ **"K" is not the only quantity ! "symmetry energy" also important.**

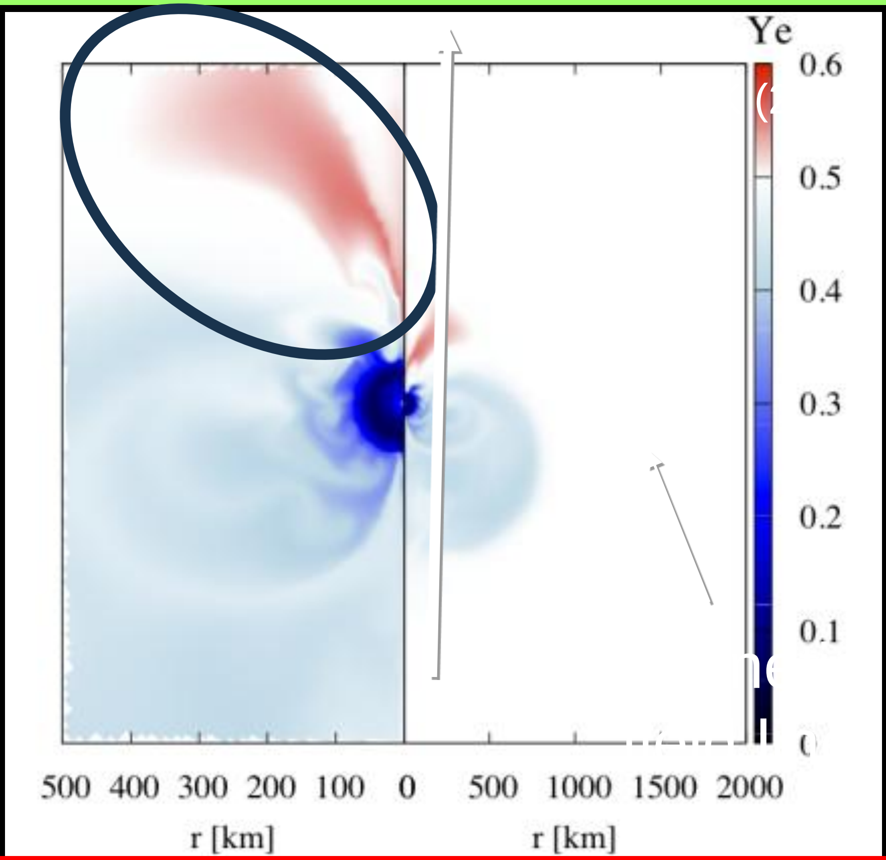
1st issue

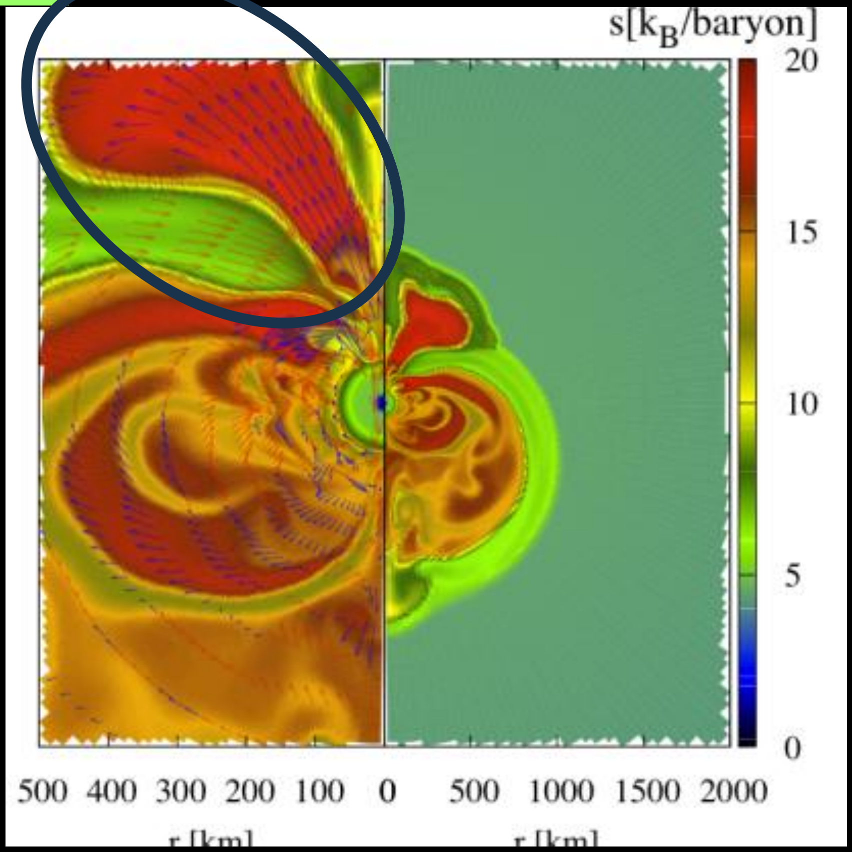
⇒ details of nuclear forces :key

✓ Need precise description of nuclear theory!

Ye profile in our 2D models (pioneered by Arcones et al. (2006) Fischer et al. (2010,2011), Arcones & Janka (2011), See talk by Arcones.)

In the beginning of the neutrino-driven wind phase (t_{pb} ~ 550 ms for 15 M_{sun} progenitor (WW95))





✓The neutrino-driven wind ⇒ proton-rich in multi-D simulations.
(Interested in our multi-D data , Emails, start collaboration !)
✓ Link of MHD models to r-process cites(see talks by Thielemann, Nobuya)

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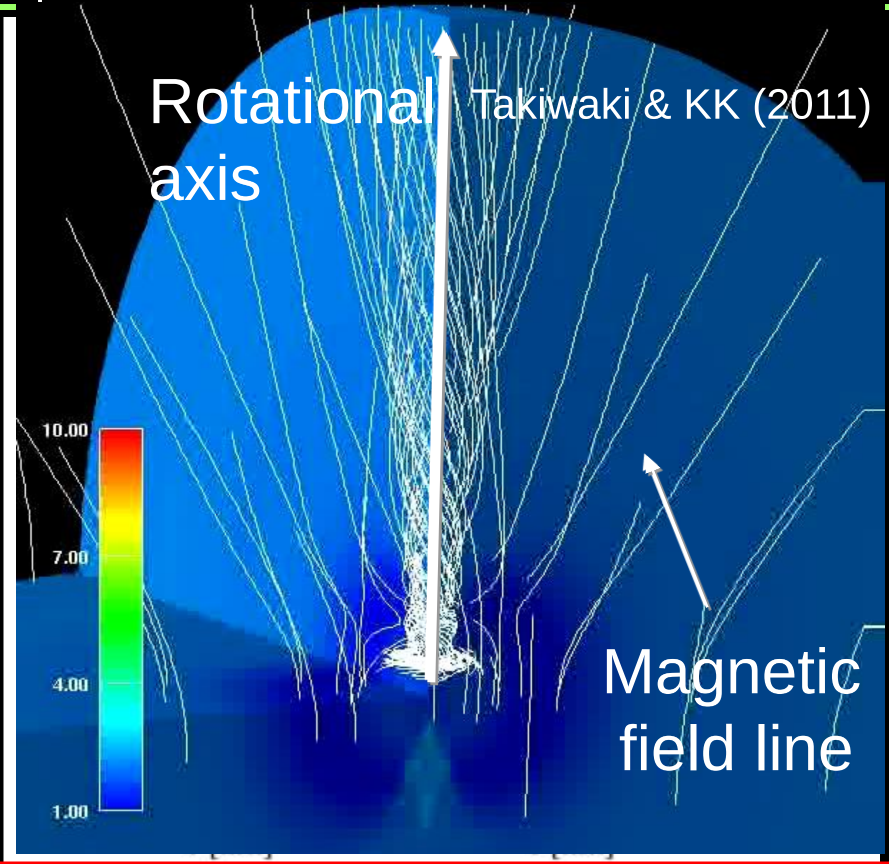

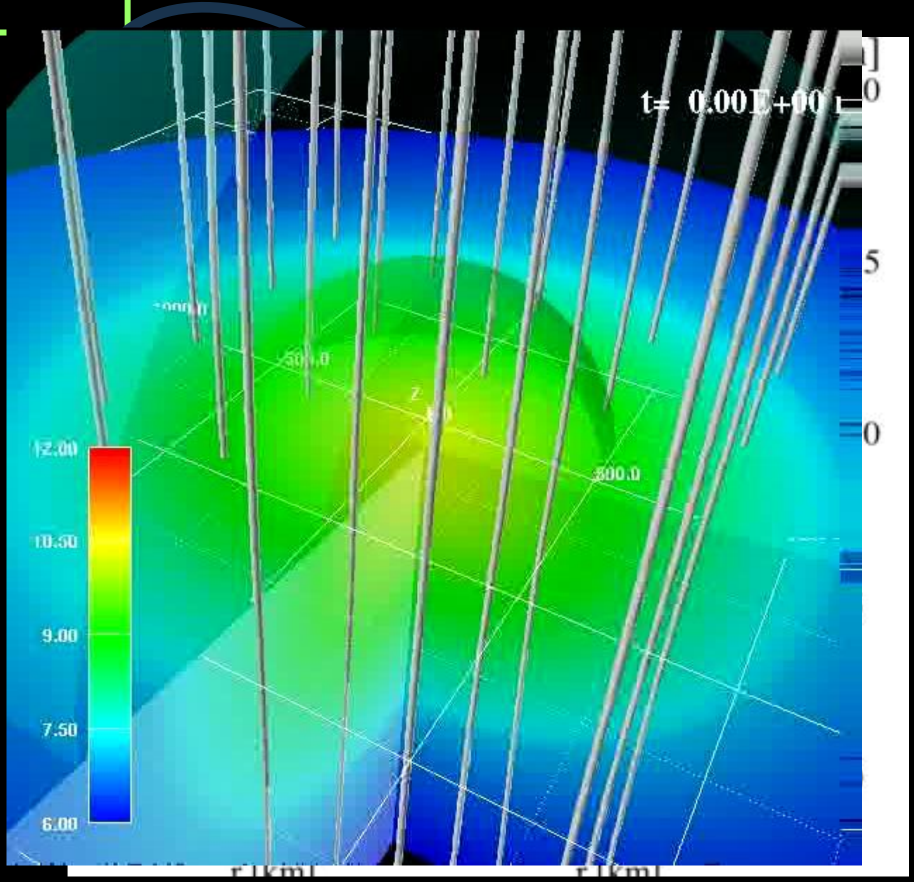

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A list of recent "rad-hydro" milestones making "explosions"

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	[80](2010)		(N)		(500)	1, (N)

✓ Still (far …) behind to successfully produce explosions as energetic as **10^{51} erg (= 1 Bethe)**

✓ **"Something" may be missing ….**

✓ **Fostering the models needs new ideas/algorithms !**

2nd cutting-edge issue: **Multidimensionality**

Is it easier to obtain explosions in 3D than in 2D !?

- ✓ 3D effects : very controversial.
  (Nordhaus+. (2010) Yes vs. Hanke+ (2011) No(so much))
- ✓ In previous 3D simulations,
  the light-bulb scheme was employed. **(L_ν = const)**
  (neutrino heating 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

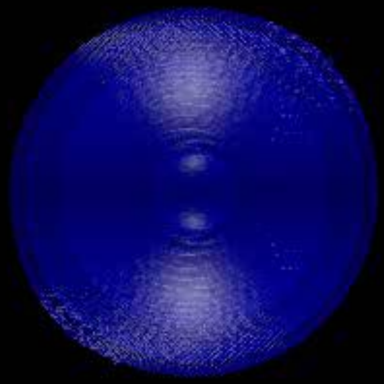
- ✓ **11.2 Msun progenitor (Woosley, Heger, Weaver (2002))**
- ✓ Spectral neutrino transport is solved (IDSA: Liebendoerfer+09)
- ✓ **320(r)x64(θ)x128(φ)x20(ε) (4 times finer than our ApJ paper)**
- ✓ **8192CPUs x 1 CPU month**
- ✓ **the world-2nd fastest "K" computers.**

Animation hidden !

Thanks to T. Wada (CfCA)

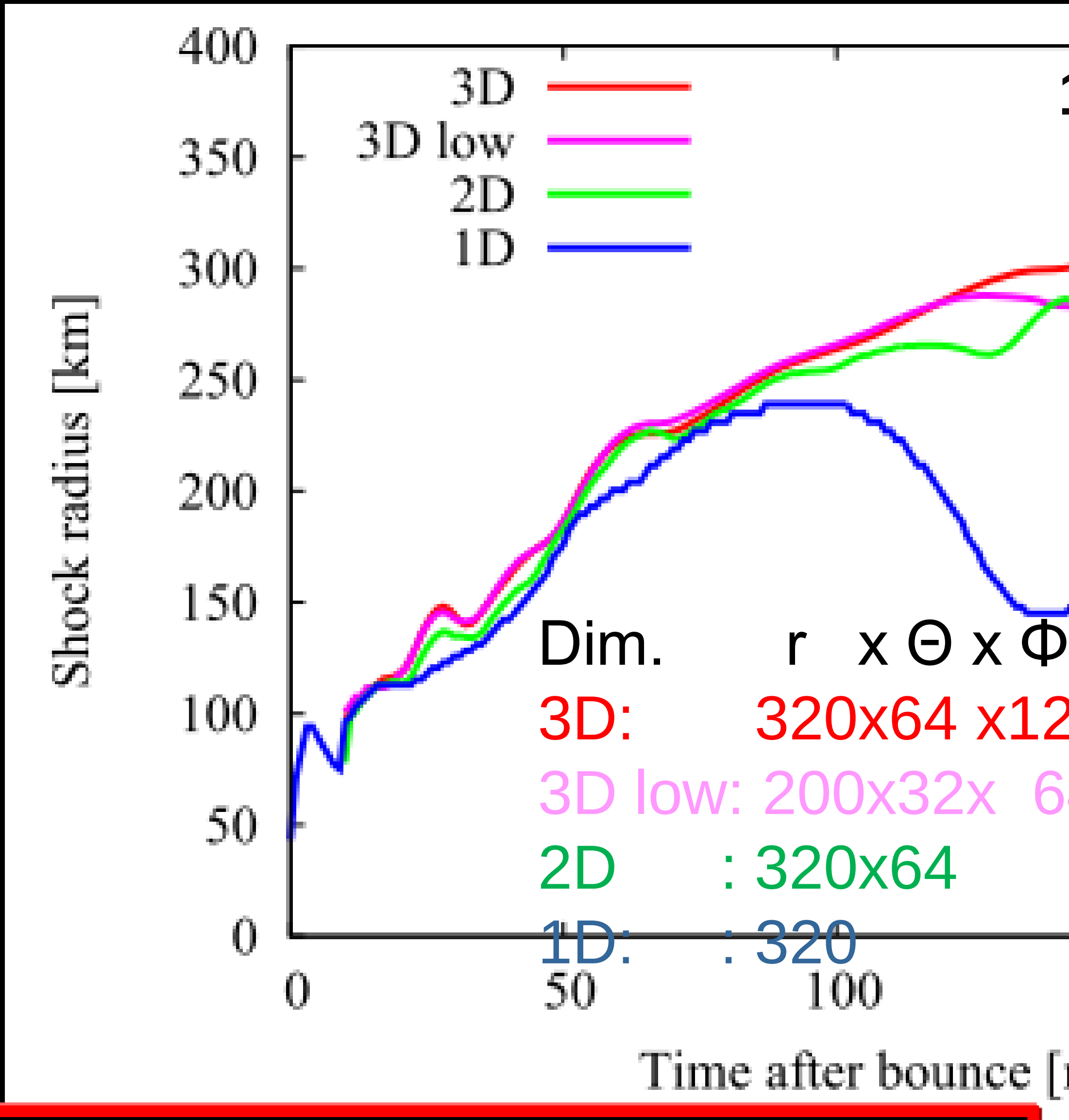
3 msec

Post-bounce time



Entropy (per baryon)

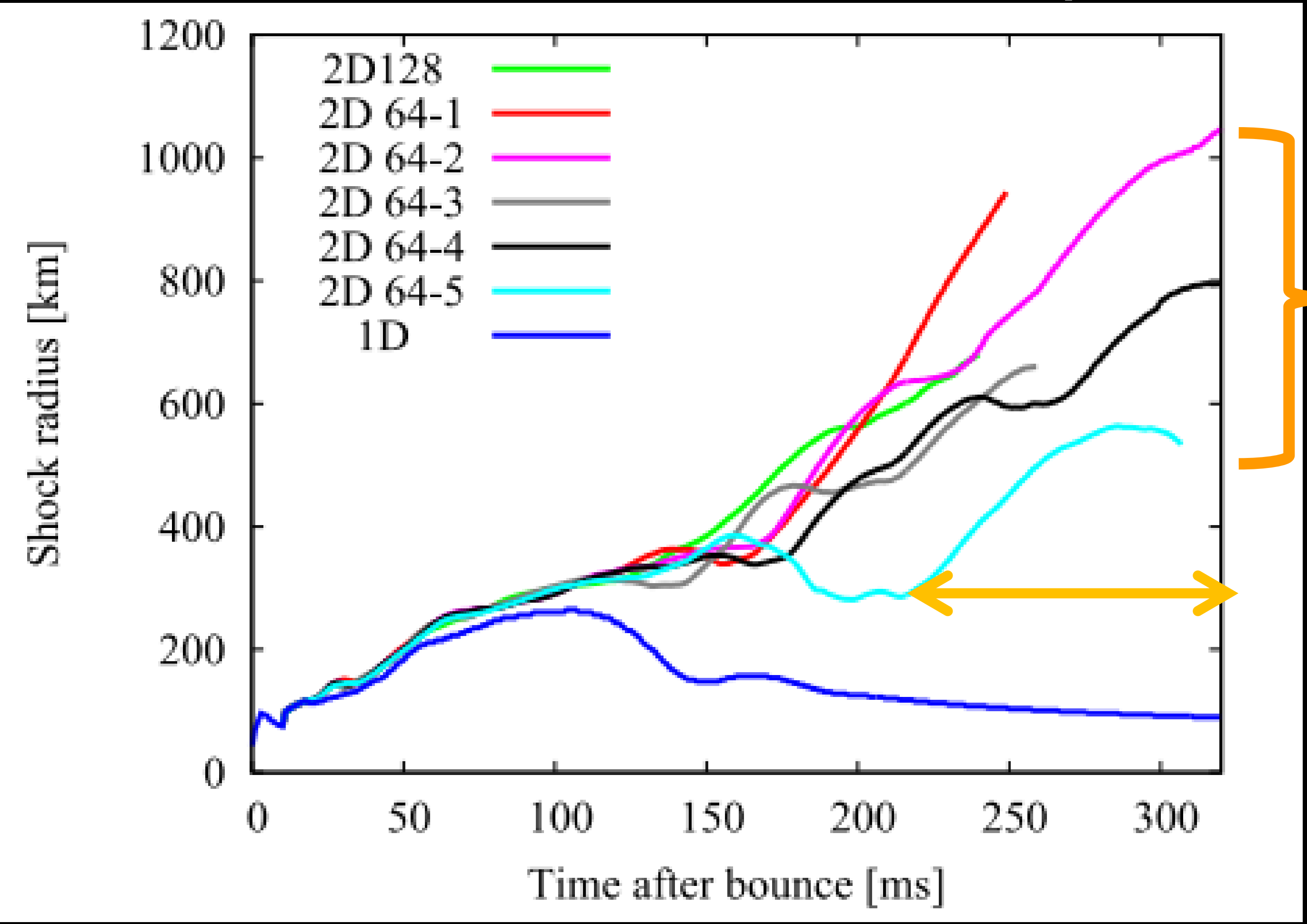
Comparison of average shock radii



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

“Stochastic Nature” of neutrino-driven explosions

(see also KK+09, Iwakami+08)

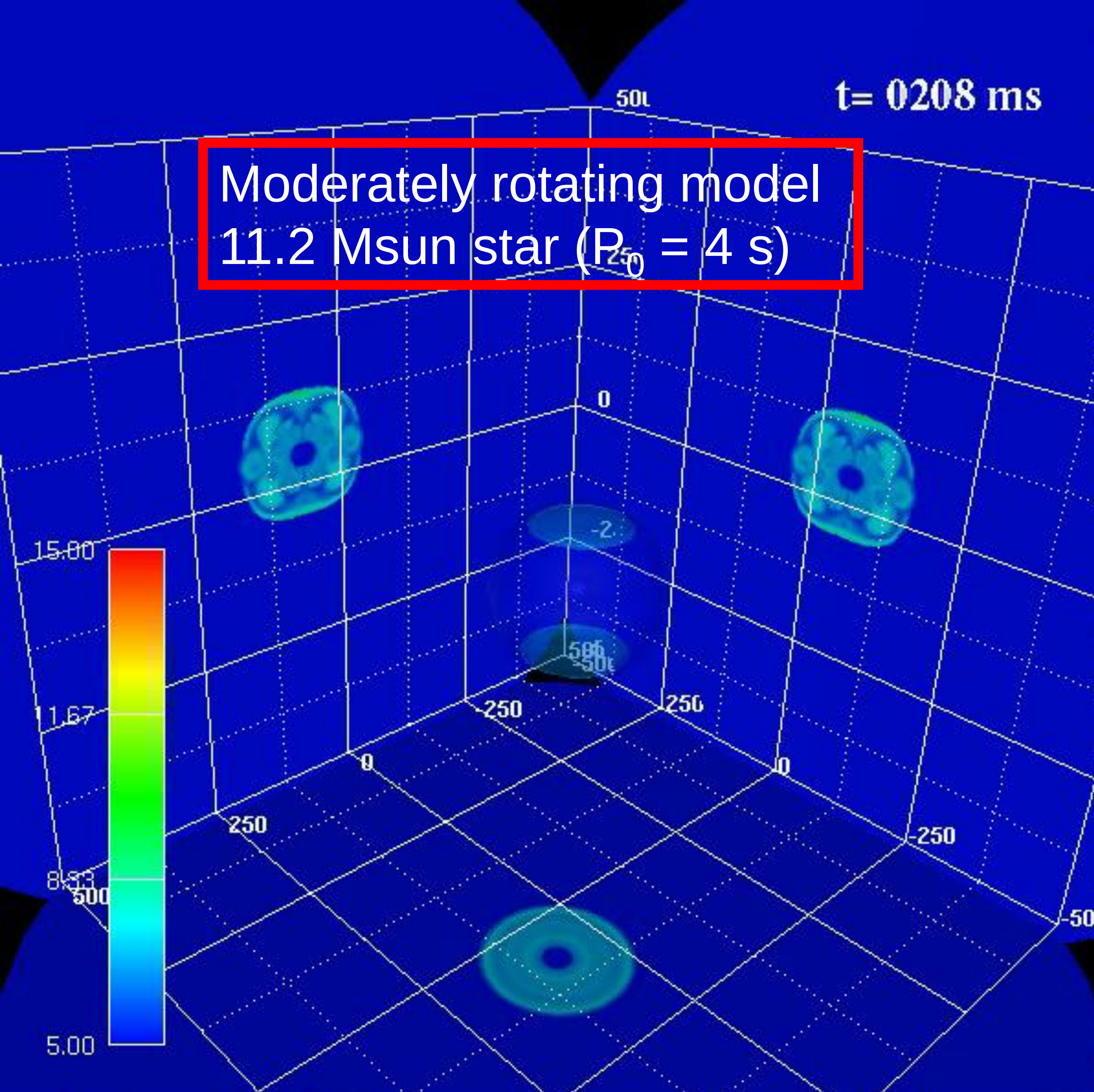


2D models with different random perturbations given after shock-stall (1% velocity perturbation)

✓From only one realization of our 3D model, we cannot clearly figure out whether 3D is really helpful to produce explosions compared to 2D.
✓ Systematic study (num. resolution, perturbation) needed.
✓ Computationally hyper-expensive !

Takiwaki, KK + in prep

Moderately rotating model
11.2 Msun star (P_0 = 4 s)



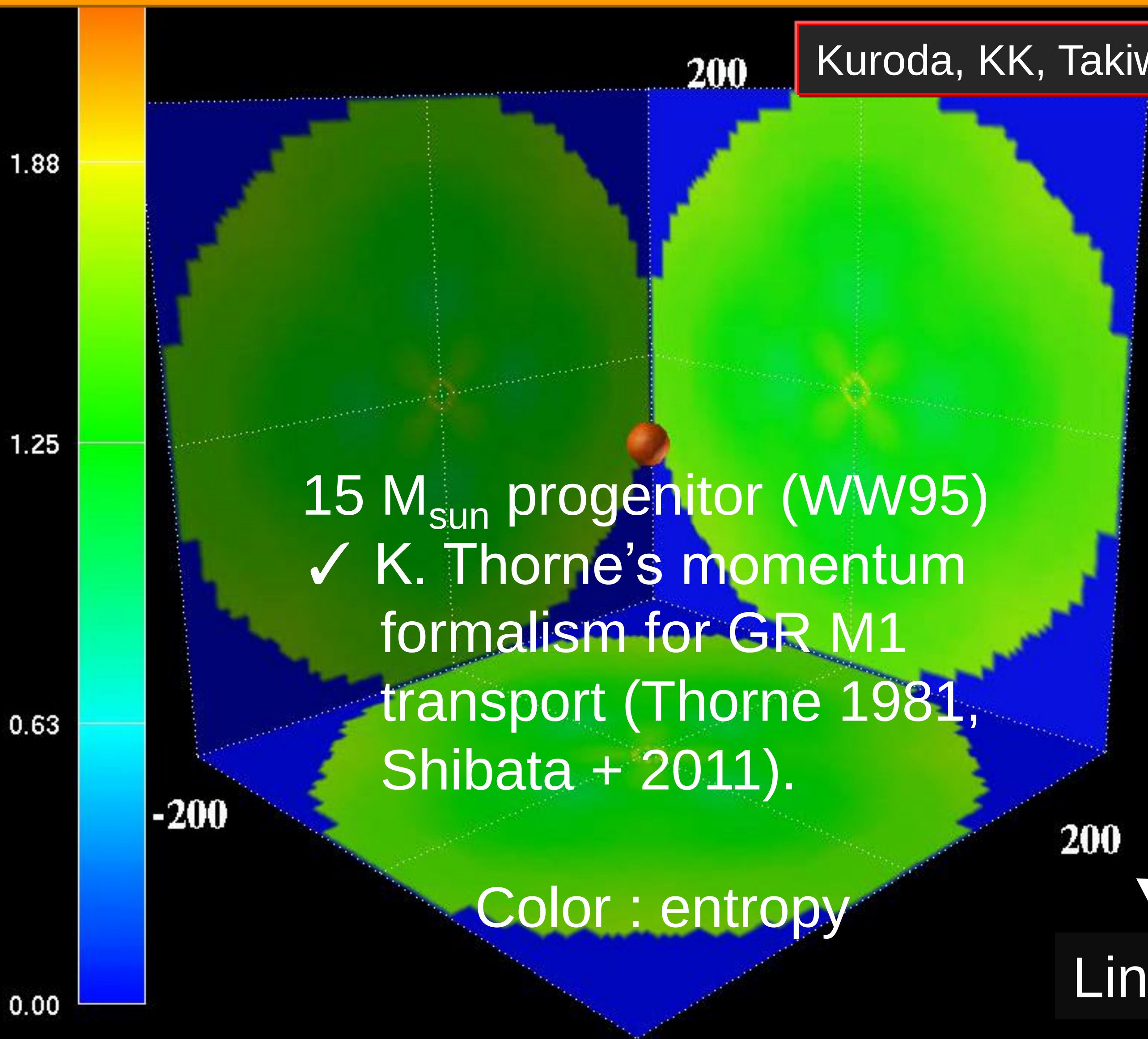
Bipolar explosions:
- ✓Explosion energy higher !
- ✓ Nucleosynthesis, neutrino, and GW signatures between rotating and non-rotating models exciting !

Sh

3rd cutting-edge issue:

Is general relativity (GR) helpful for explosions !?

Kuroda, KK, Takiwaki (2012), ApJ



15 M_{sun} progenitor (WW95)

✓ K. Thorne's momentum formalism for GR M1 transport (Thorne 1981, Shibata + 2011).

Color : entropy

Linear scale

Transp

Multi-Energy

Gray

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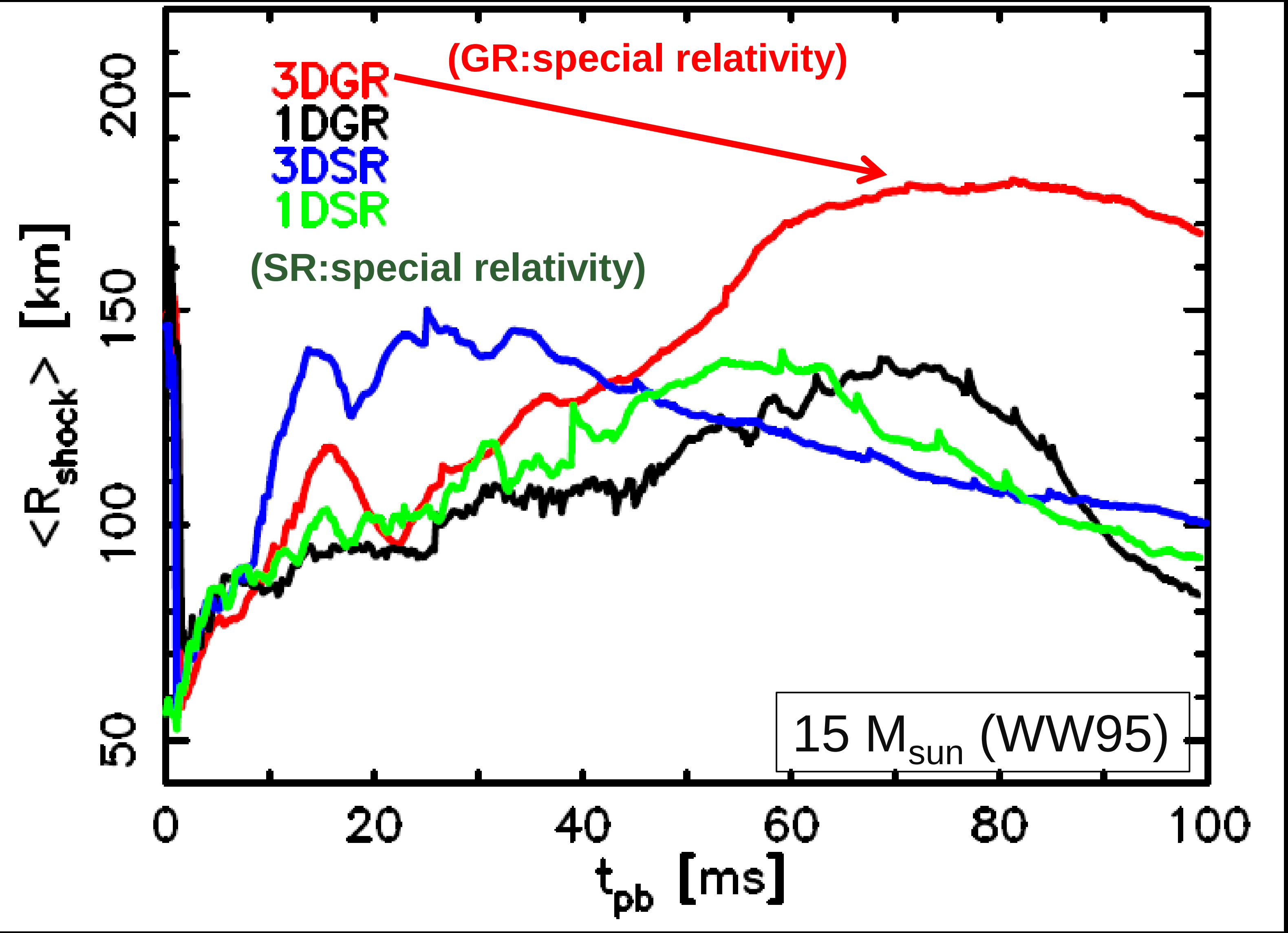
a + (2012)

3D GR

tivity

Comparison of average shock radii



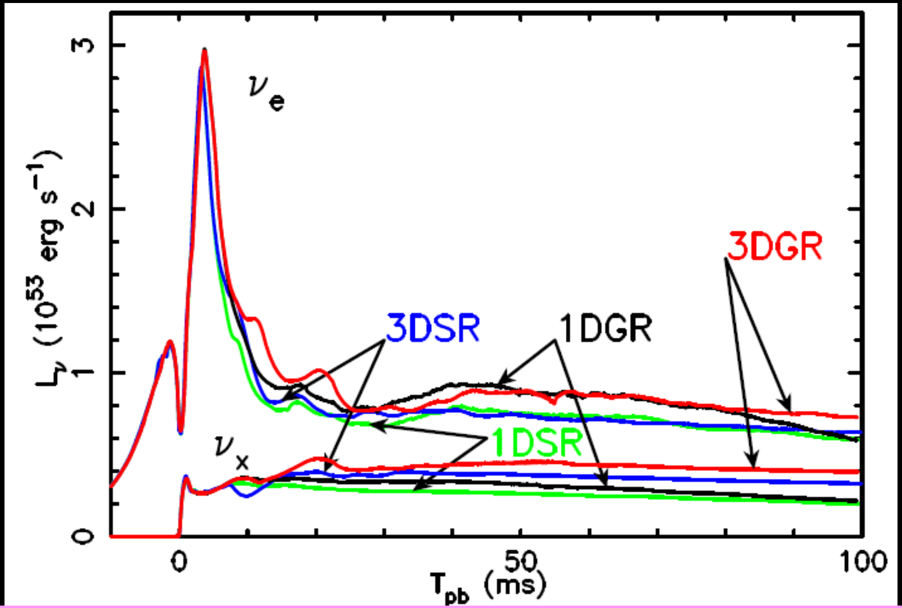
✓Except for our 3D-GR model, the shock has shown a trend of recession.

✓ Important : why the shock can reach most further out for 3D-GR ?

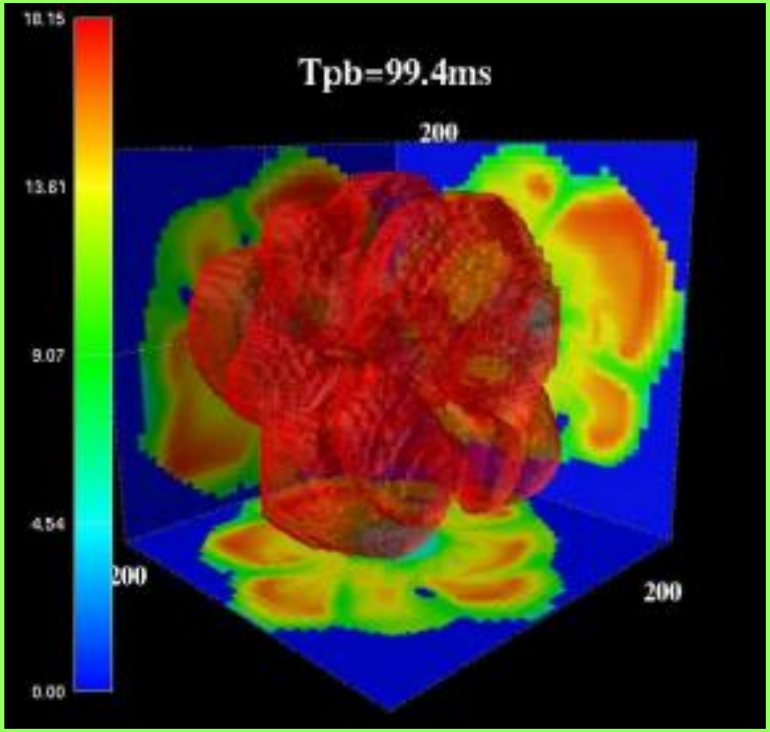
Advantages in 3D-GR model to go explosions !

Two things : GR and 3D

✓ Deeper potential well :
core structures smaller ⇒
making <E_ν> higher.

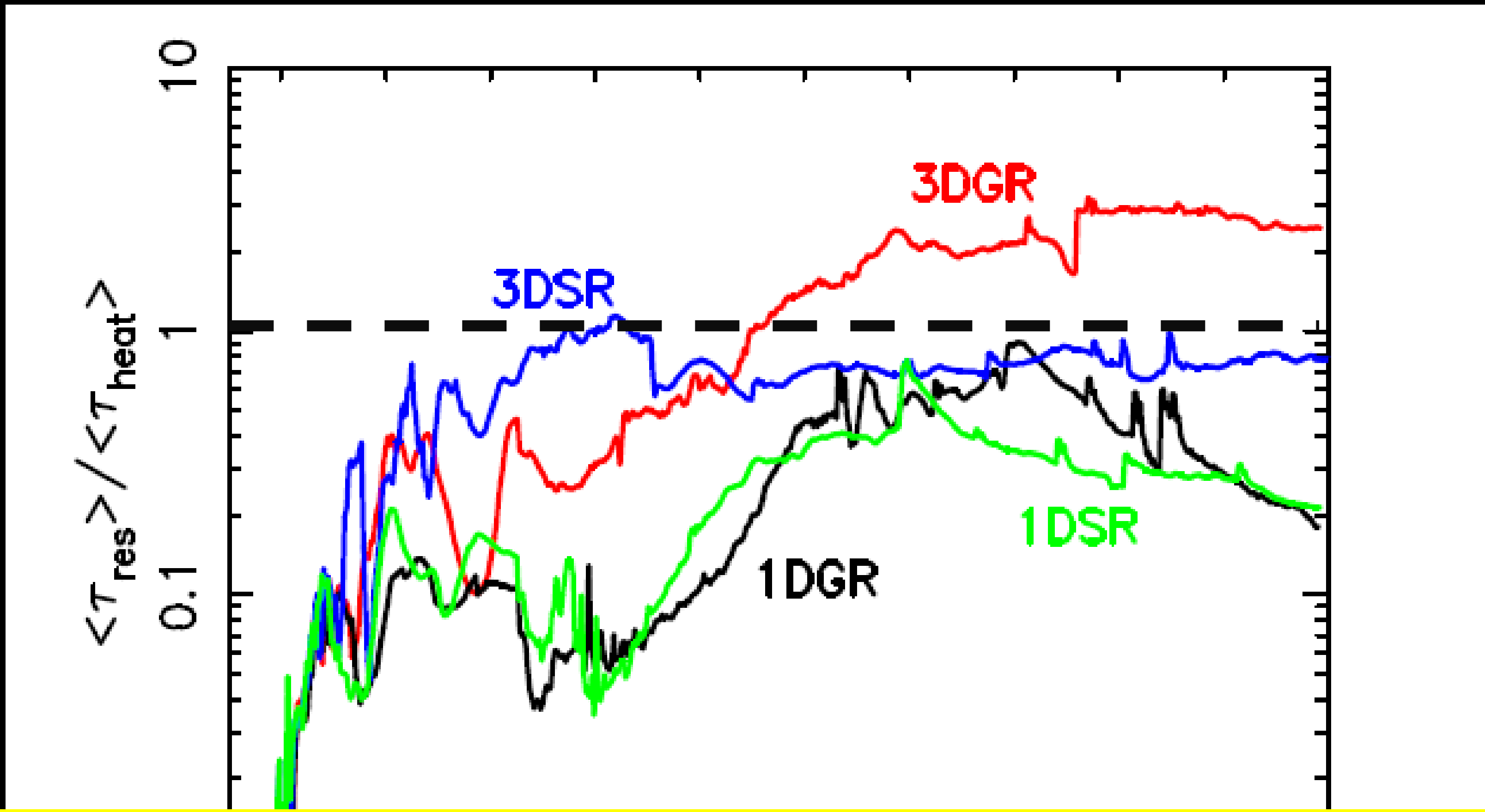


✓GR can enhance the neutrino luminosity up to 40 % comp.to the SR counterpart.



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 !
- ✓ In order to extract hydro-data for nucleosynthesis…
- ✓1000ms/(2 ms per day) ~ 500 days…

Summary and Outlook

☆ **On the 3D effects:**

we've not obtained a clear-cut answer, hampered by stochastic nature of explosions.

✓ **Systematic 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.**

☆ **Significantly further to reach the goal !**

☆ **Theoretical prediction of nucleosythesis, GWs, neutrinos will be all updated.**

✓ **More come in the "next" time !**

Thank you very much !

Summary and Outlook

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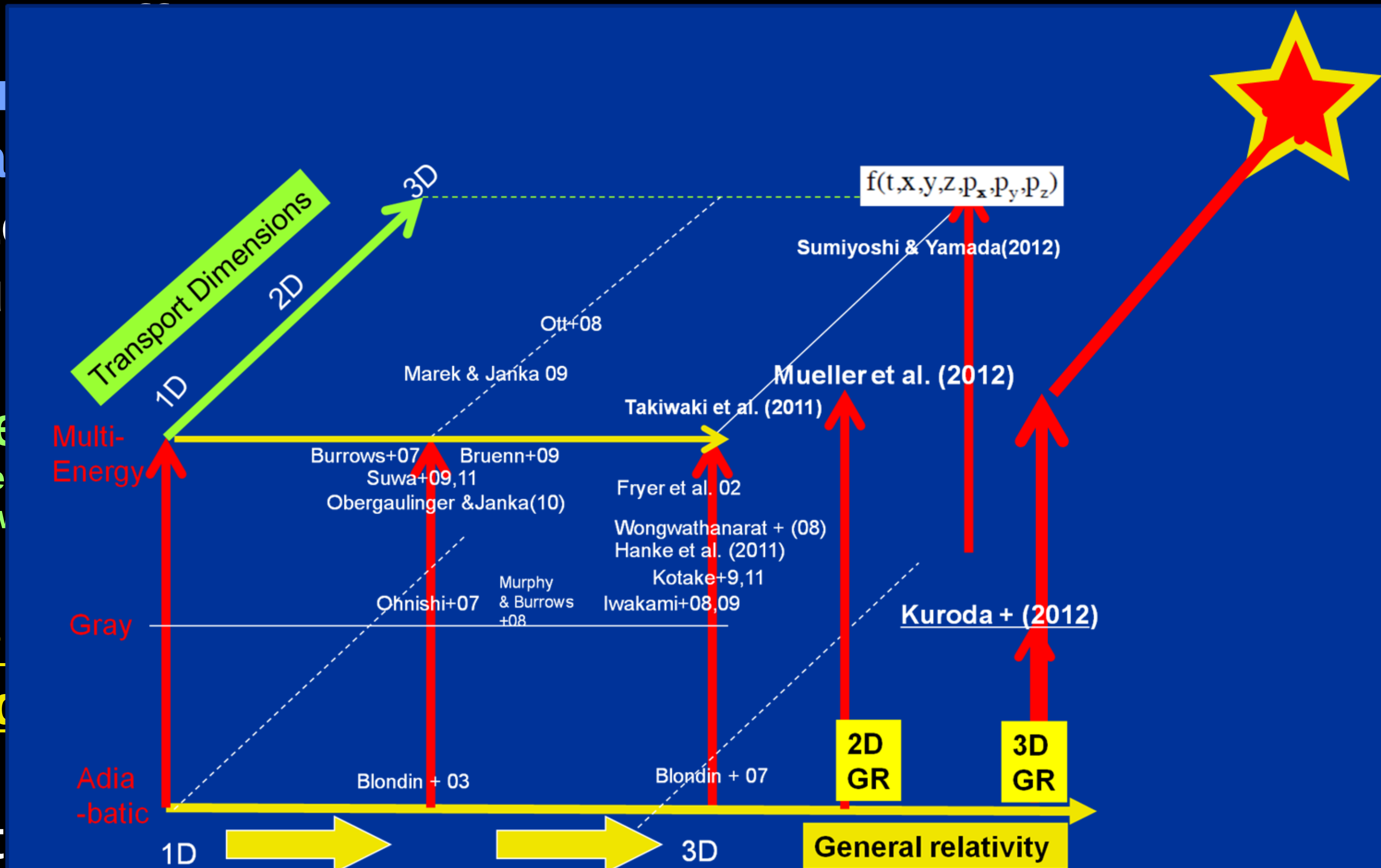

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Thank you very much !