Cutting-edge issues in the explosion theory of core-collapse supernovae

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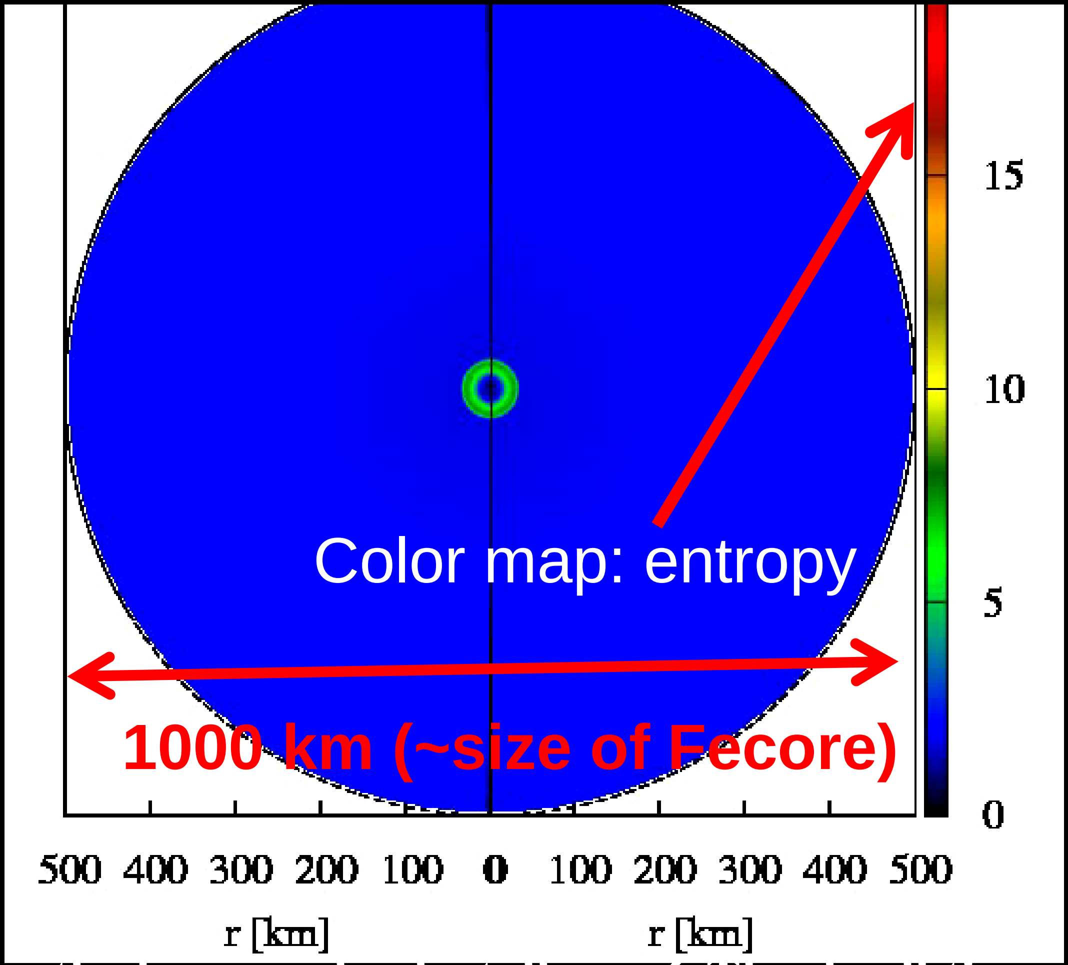
IAU Symposium 279: Death of Massive Stars:
Supernovae and Gamma-ray bursts
at Nikko, March 2012

Current paradigm: multi-D neutrino heating mechanism (1/2)

(Marek & Janka 09, Foglizzo+07, Suwa + 09, Burrows + 08, Bruenn+10)

Current paradigm: multi-D neutrino-heating mechanism (2/2)

(Marek & Janka 09, Foglizzo+07, Suwa + 09, Burrows + 08, Bruenn+10)


Color map: entropy

1000 km (~size of Fecore)

Suwa + (09)
15 solar mass:
2D rad. Hydro core-collapse simulation with spectral neutrino transport : Lattimer-Swesty (K=180MeV)
✓ only electron/anti electron neutrinos

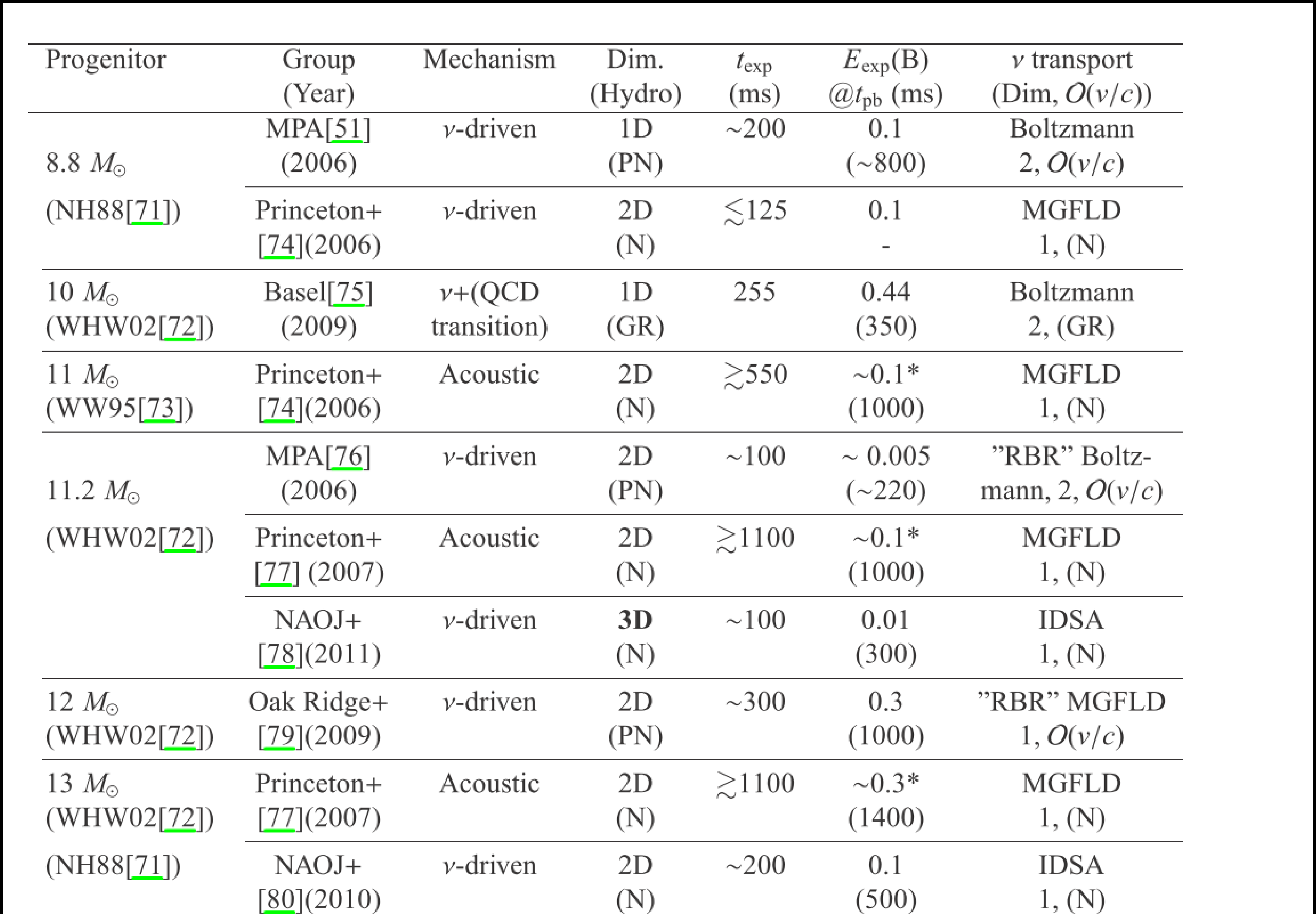
- ✓ After bounce, the bounce shock stalls.
- ✓ "Standing Accretion Shock Instability (SASI)" develops.

See talk by T. Foglizzo for in-depth story !

- ✓ The dwell timescales of matter in the gain region gets longer due to non-radial motions.
- ✓ At around O(100)s ms after bounce, the neutrino-driven explosion occurs.

List of recent milestones reported “explosions”

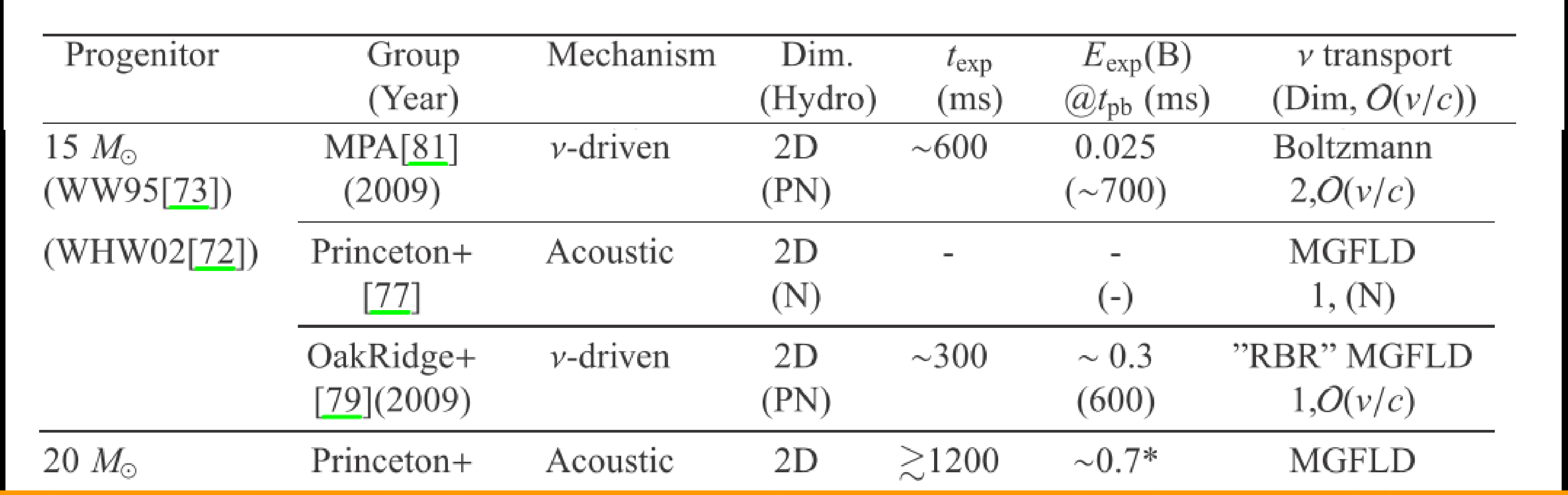
Kotake arXiv:110.5107 Comptes Rendus Physique in press



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

List of recent milestones reported "explosions"

Kotake arXiv:110.5107 Comptes Rendus Physique in press



Progenitor	Group (Year)	Mechanism	Dim. (Hydro)	$t_{\rm exp}$ (ms)	$E_{\rm exp}$(B) @$t_{\rm pb}$ (ms)	ν transport (Dim, $O(v/c)$)
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 $M_\odot$	Princeton+	Acoustic	2D	$\gtrsim$1200	~0.7*	MGFLD

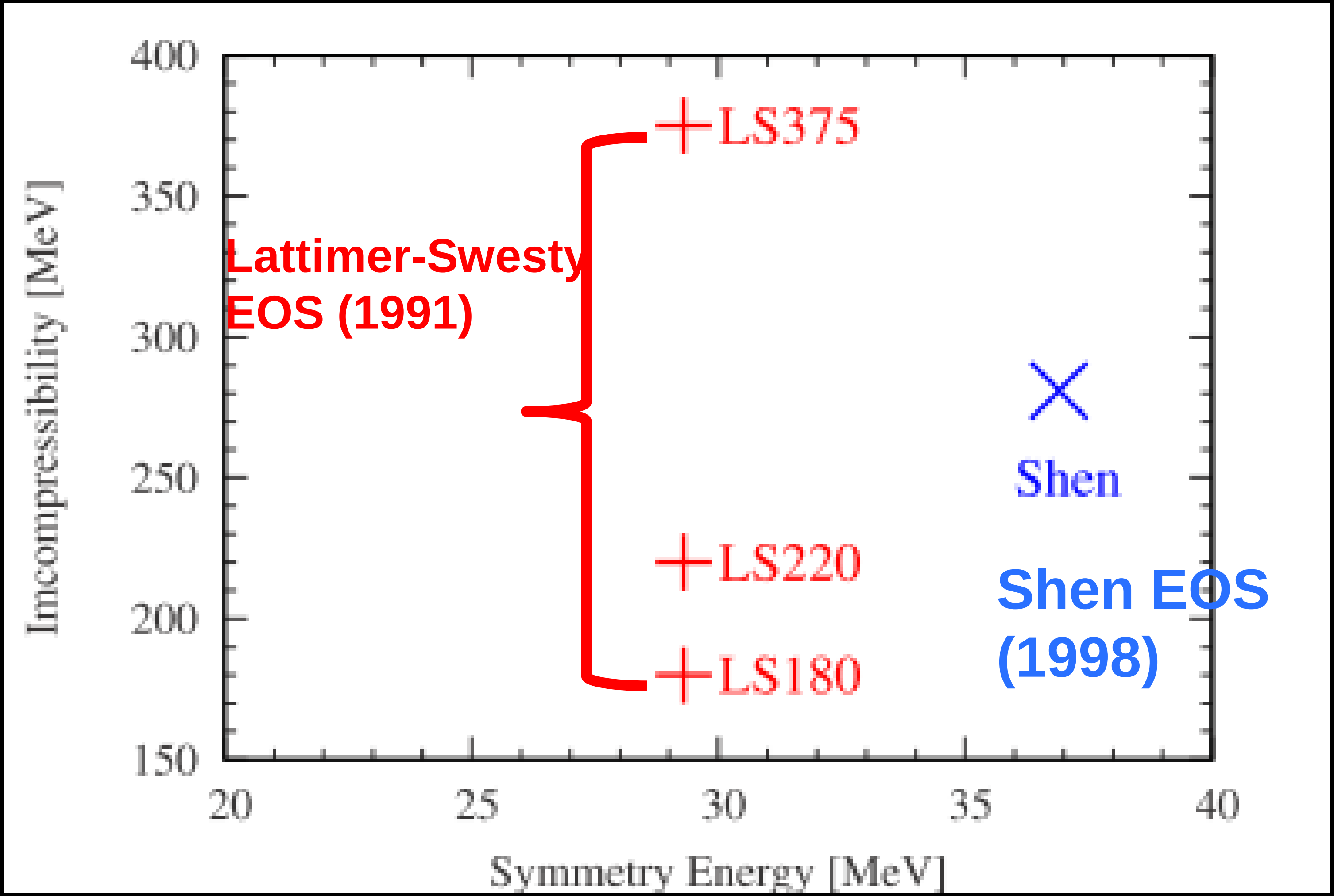
☆ Fundamental problems remained !

- ✓ **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 assume a very soft nuclear EOS (K=180 MeV).
  (K>220 MeV to explain the 2 Msun NS (e.g., Demorest+2011))

Impacts of nuclear EOS

Suwa, Takiwaki, KK+ submitted to ApJ

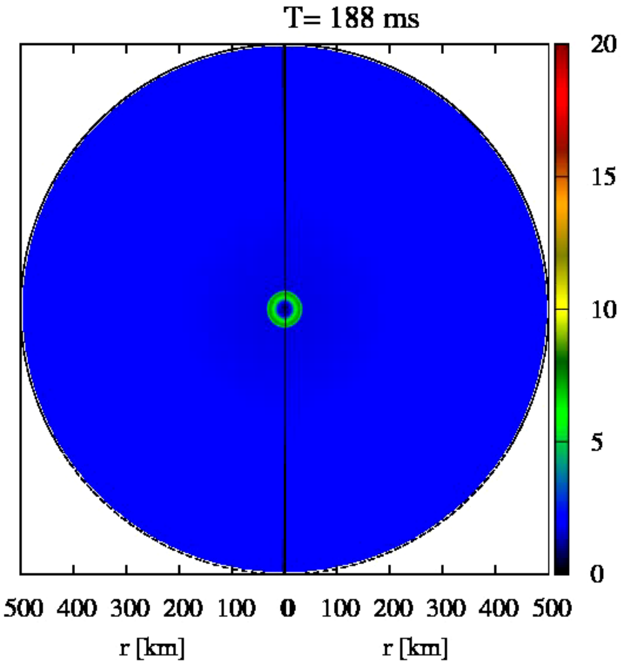
Features of SN EOS



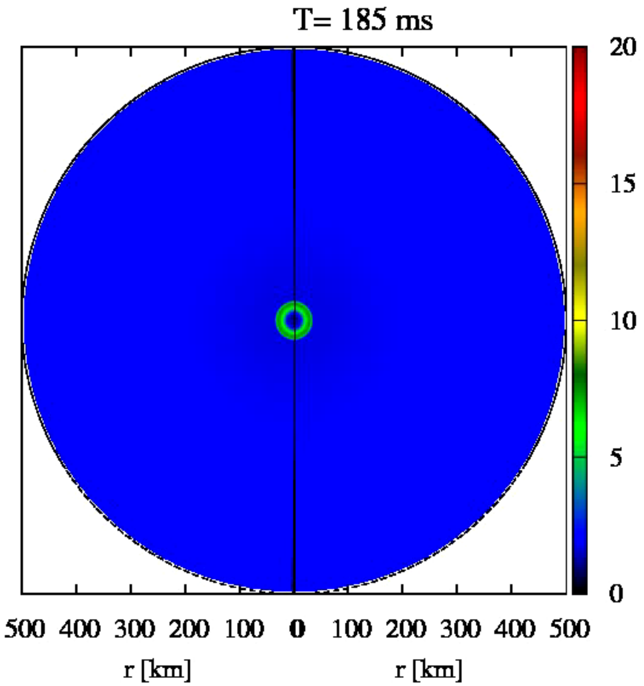
Lattimer-Swesty EOS (1991)

Shen EOS (1998)

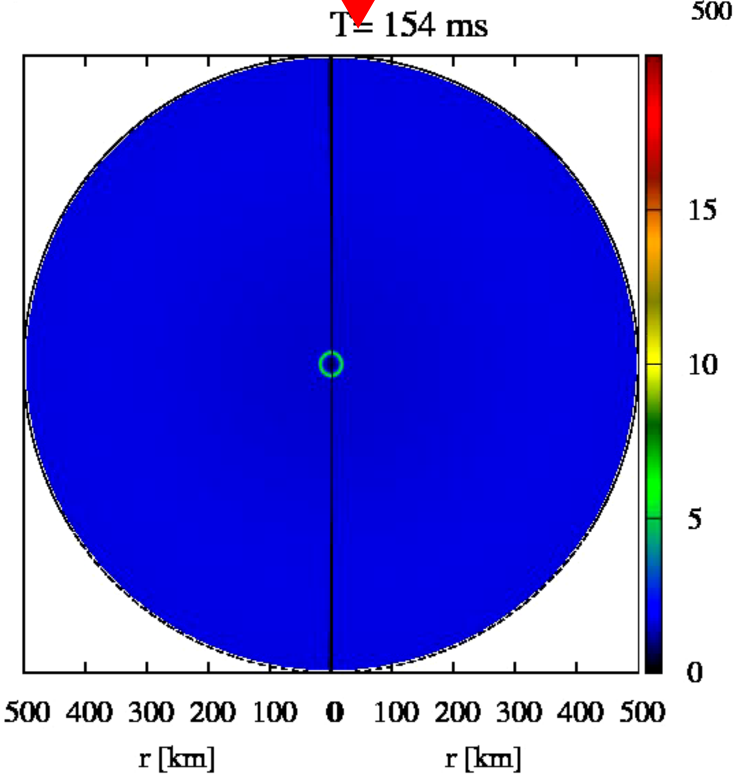
LS180



LS375



Shen



- ✓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!

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

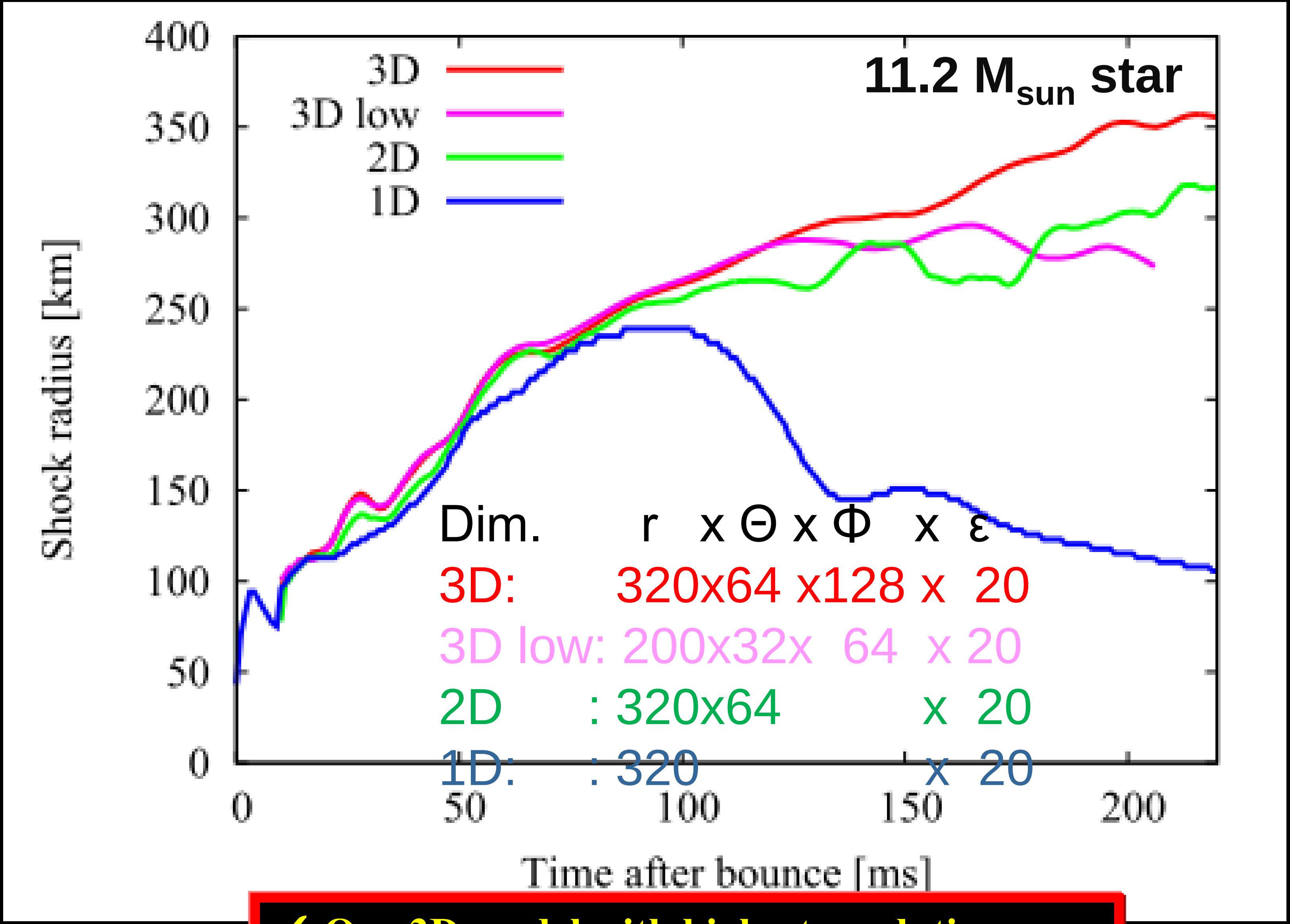
Is it easier to obtain explosions in 3D than in 2D !?

- ✓ 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 (See poster by T. Takiwaki !)
Takiwaki, KK, and Suwa (2012) ApJ in press

- ✓ **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)**
- ✓ **4096CPUs x 1 CPU month ~ It cost us 30,000 EUROs.**
- ✓ **T2K-Tsukuba**

Comparison of average shock radii



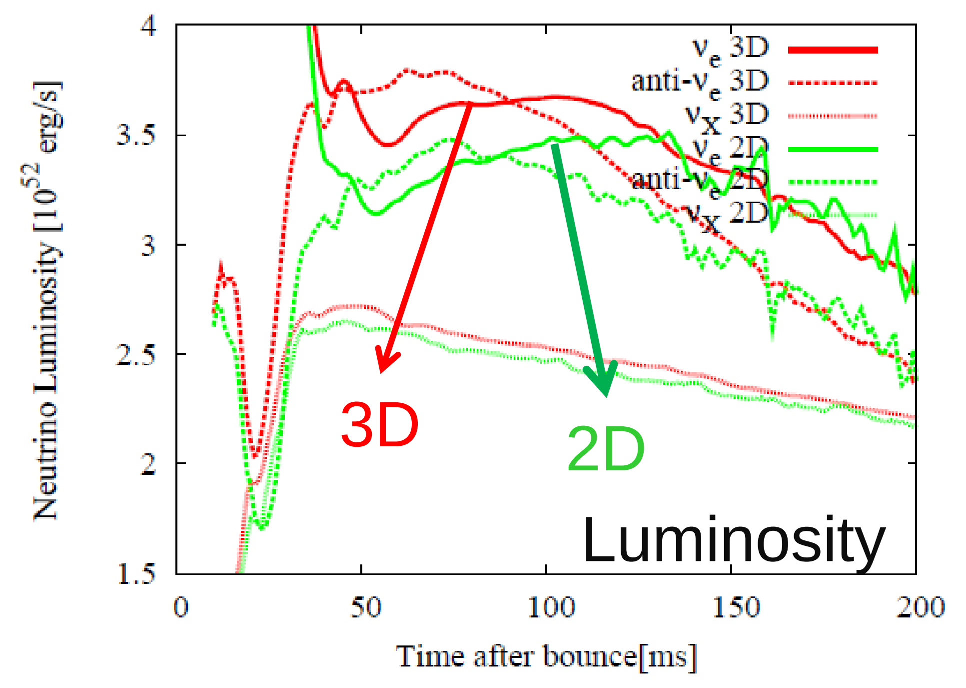
11.2 M_{sun} star

Dim.	r	x Θ	x Φ	x ε
3D:	320	x64	x128	x 20
3D low:	200	x32	x 64	x 20
2D :	320	x64		x 20
1D: :	320			x 20

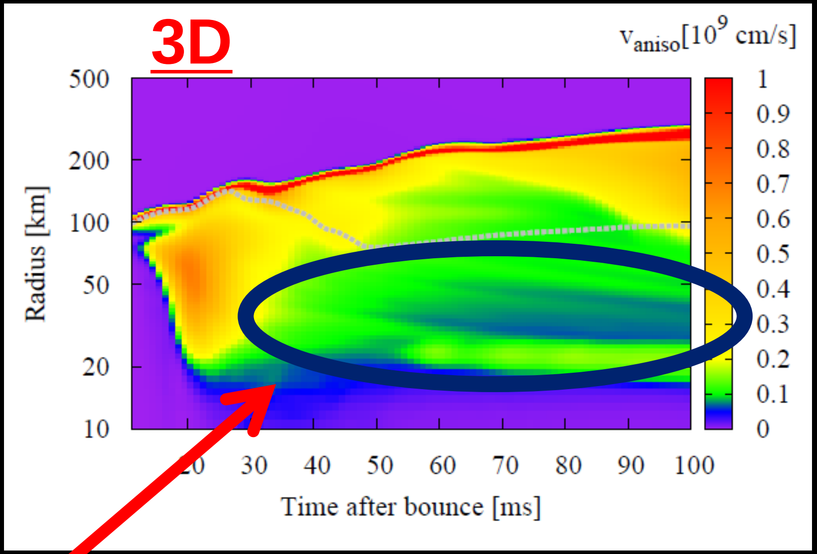
✓ Our 3D model with highest resolution :
the most energetic shock propagation.

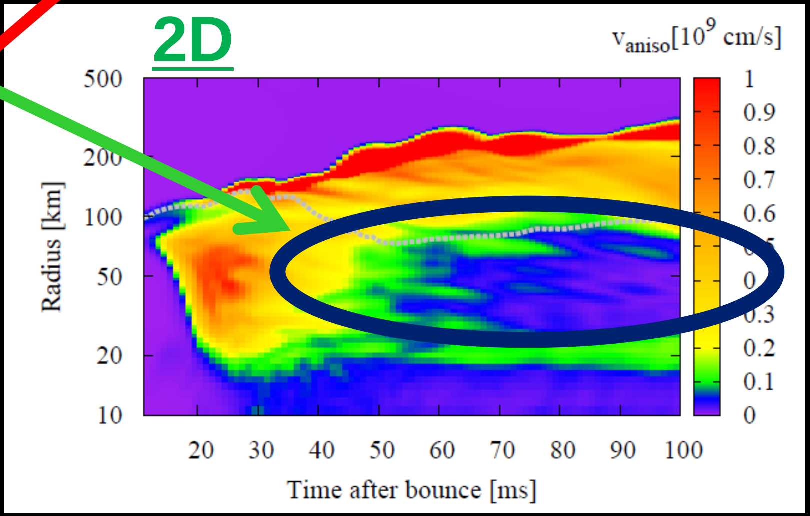
Why 3D is supportive to produce explosions ?

(Advantage 1) Higher neutrino luminosity in 3D



Turbulent velocity

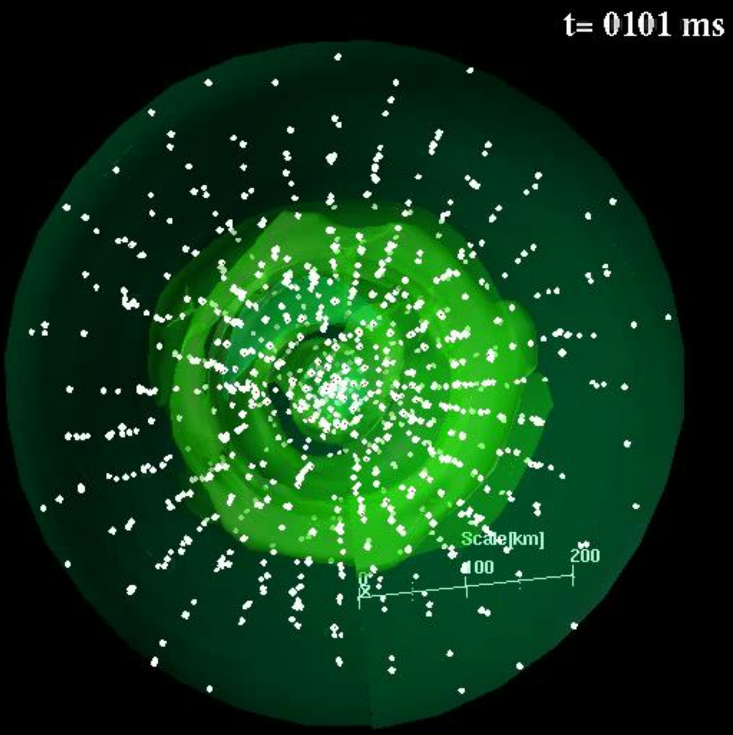




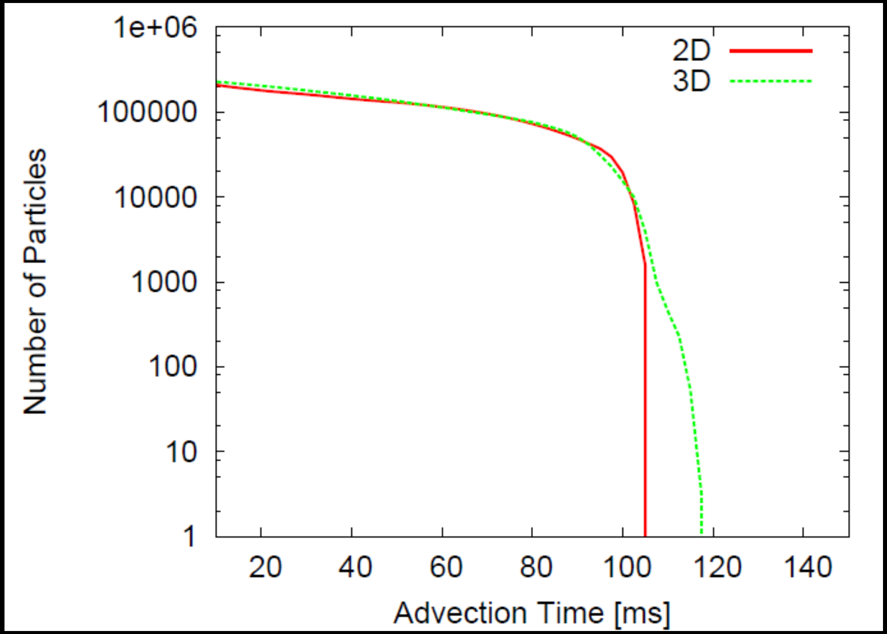
In 3D, convective flows cascade down to much smaller scale, leading to enhance convective activities below neutrino sphere ⇒ luminosity ↑

Why 3D is supportive to produce explosions ?

(Advantage 2) Longer residency timescale in the gain region



Number of particles vs.advection timescale in the gain region



✓ Due to non-axisymmetric motion, maximum residency timescale becomes longer in 3D than in 2D.

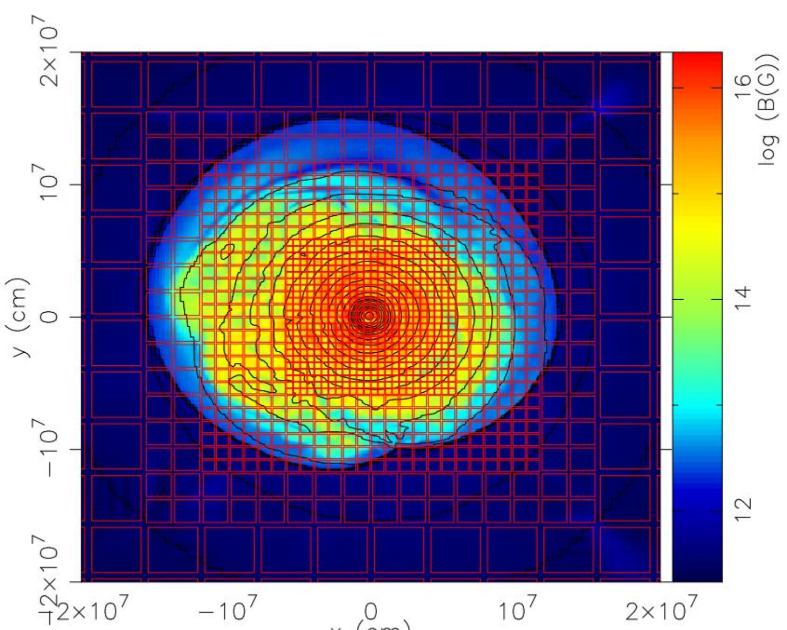
⇒ Longer exposure to the irradiation of hot streaming neutrinos is also supportive !

3rd cutting-edge issue: Is general relativity (GR) helpful for explosions !?

Kuroda, KK, Takiwaki submitted

- ✓ 3D full GR simulation with approximate neutrino transport
- ✓ The space-time is evolved by the BSSN formalism. Adaptive-mesh-refinement approach is taken. (according to Kuroda and Umeda (ApJS 2010))

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



Postl

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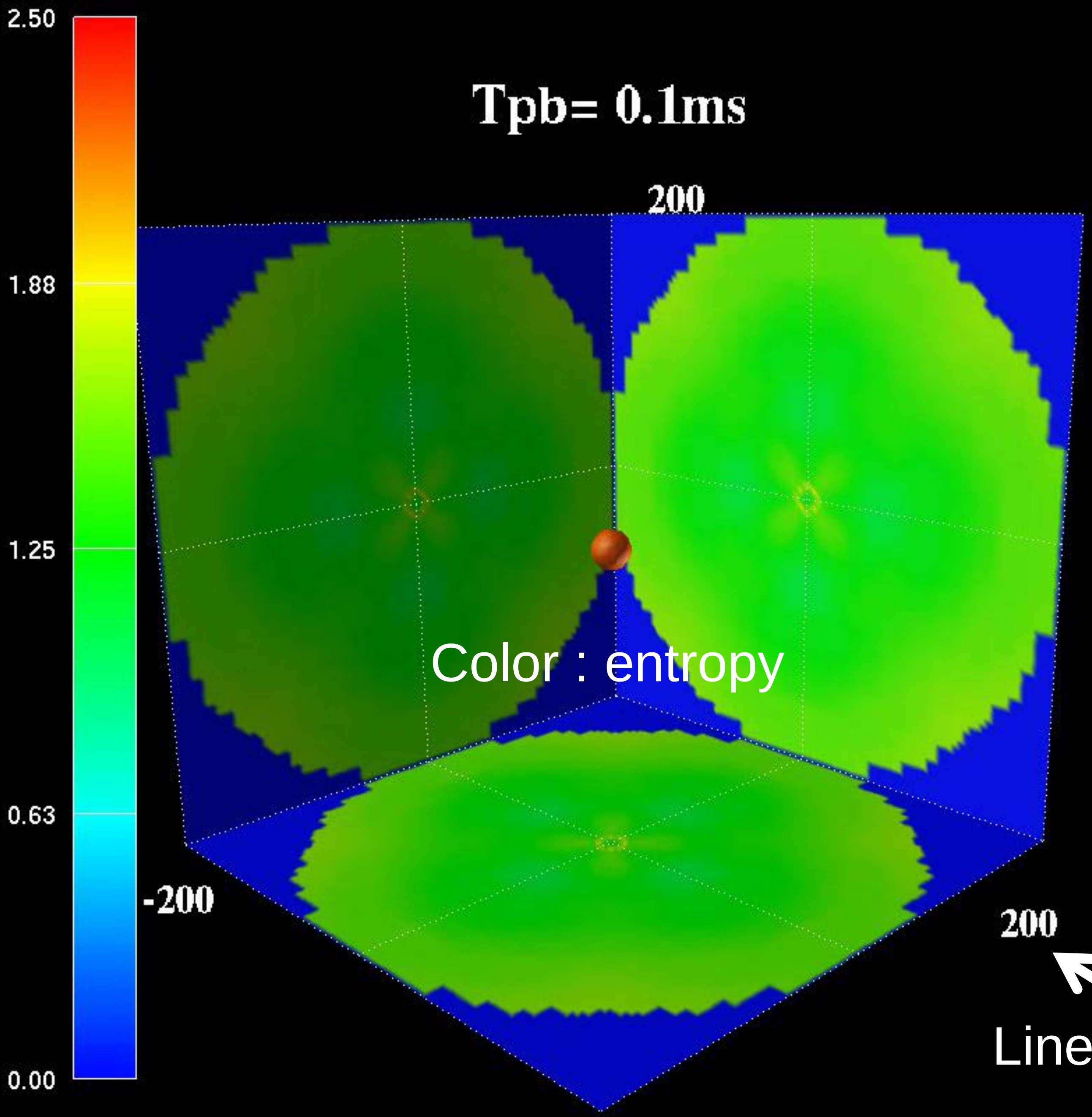
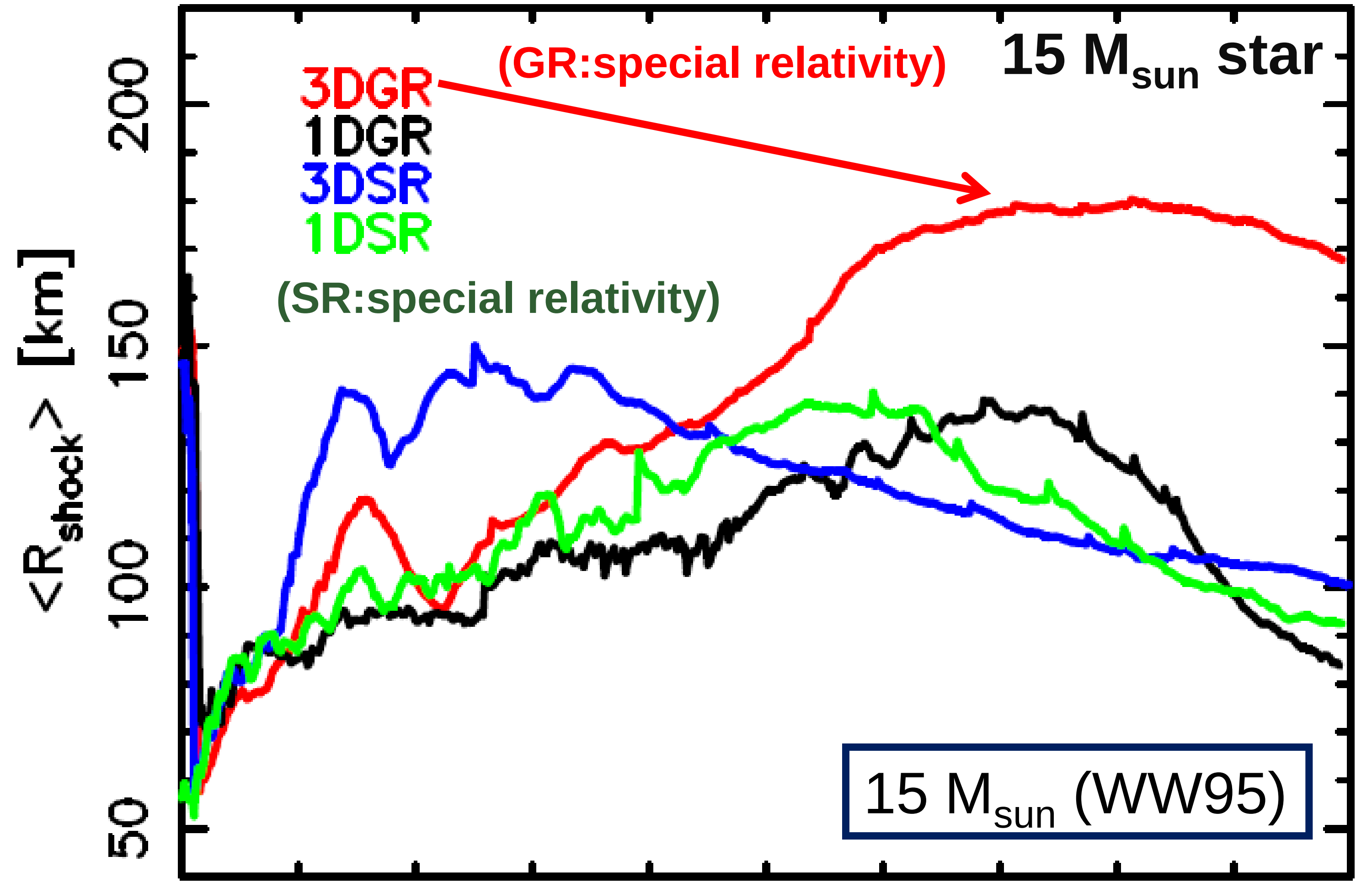


Color : entropy

Linear scale

Comparison of average shock radii



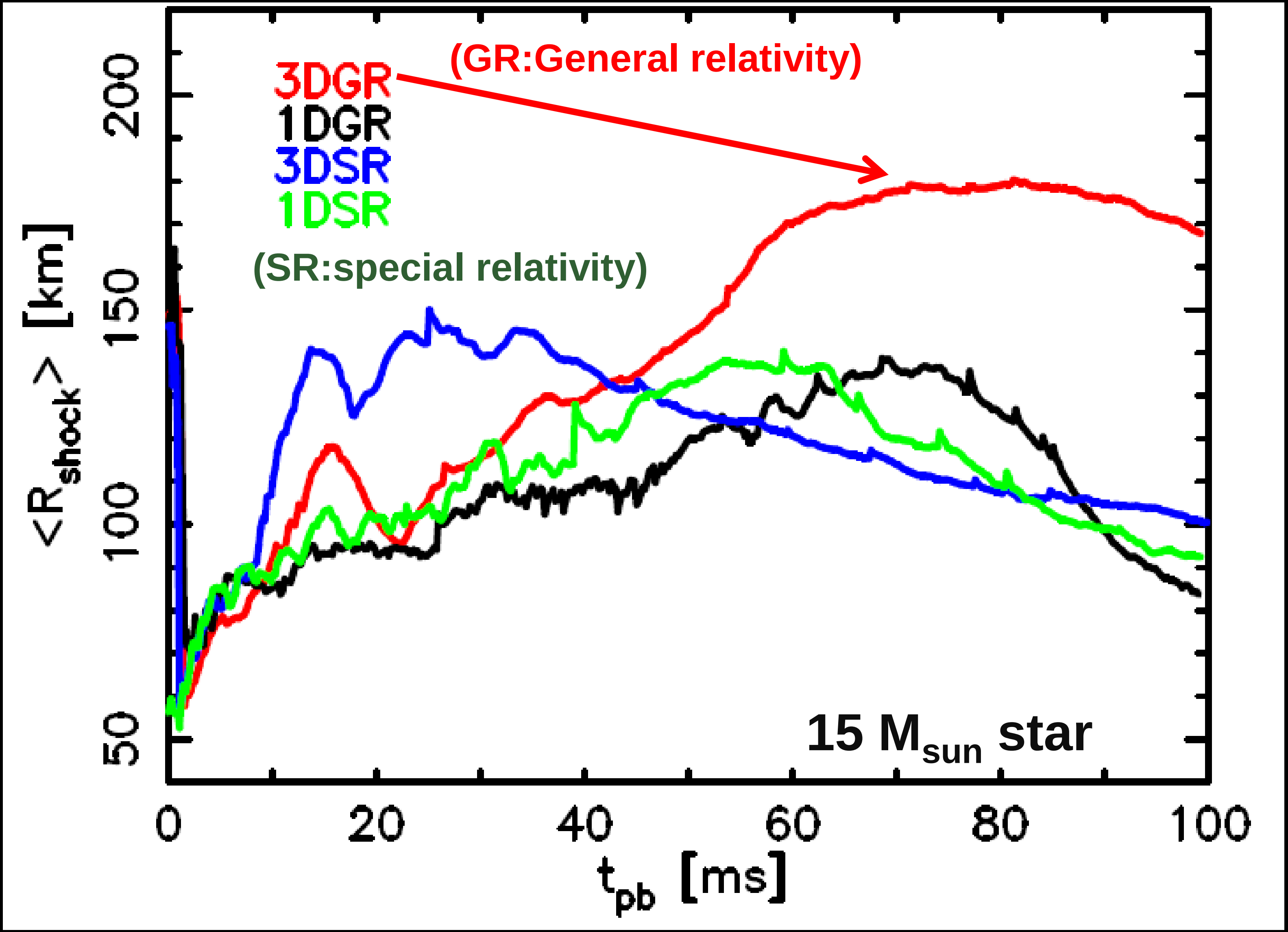
(GR:special relativity)

15 M_{sun} star

(SR:special relativity)

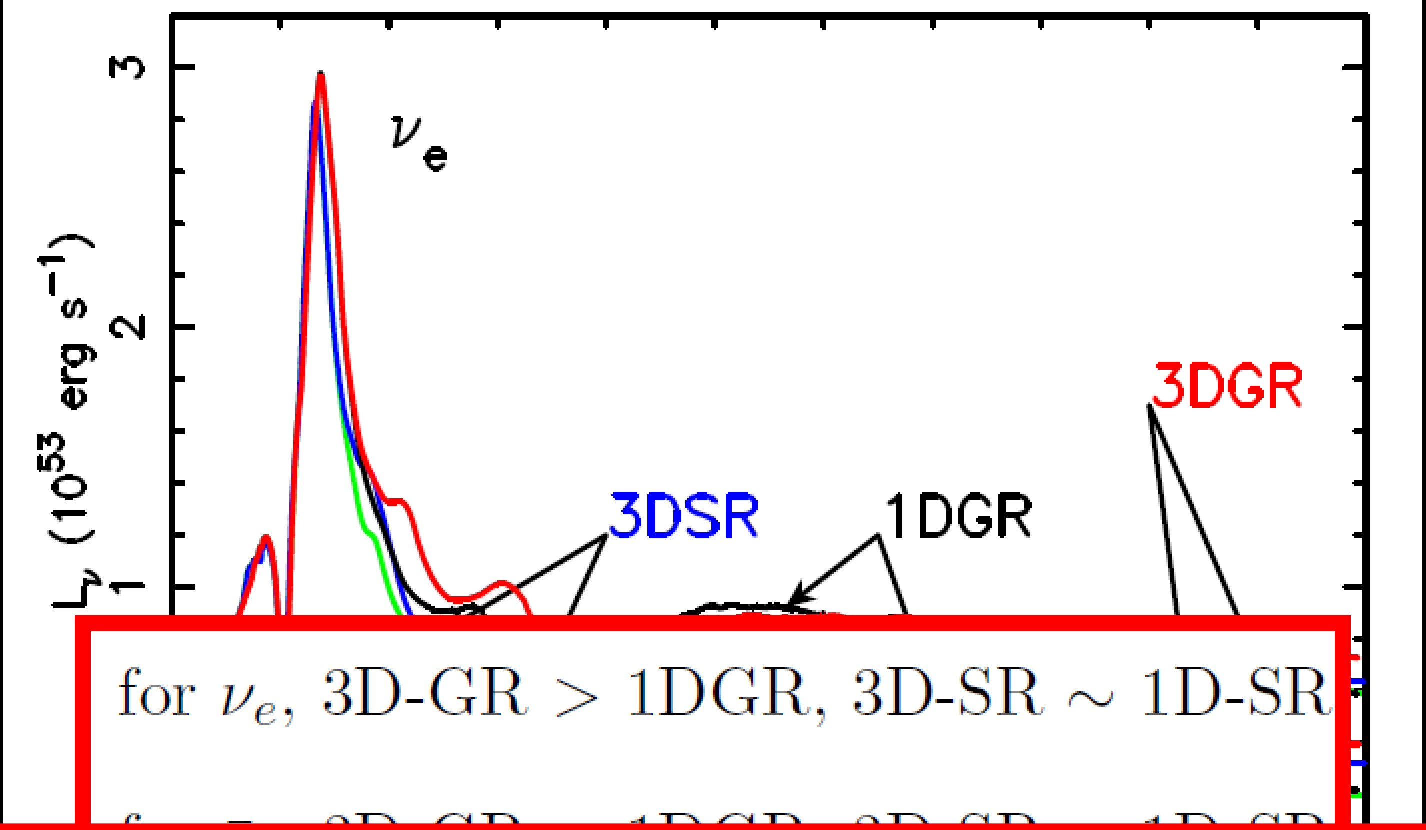
The shock goes further out for the 3D-GR model, while the shock in other models has already shown a trend of rapid recession.

Comparison of average shock radii



Why GR is supportive to produce explosions ?

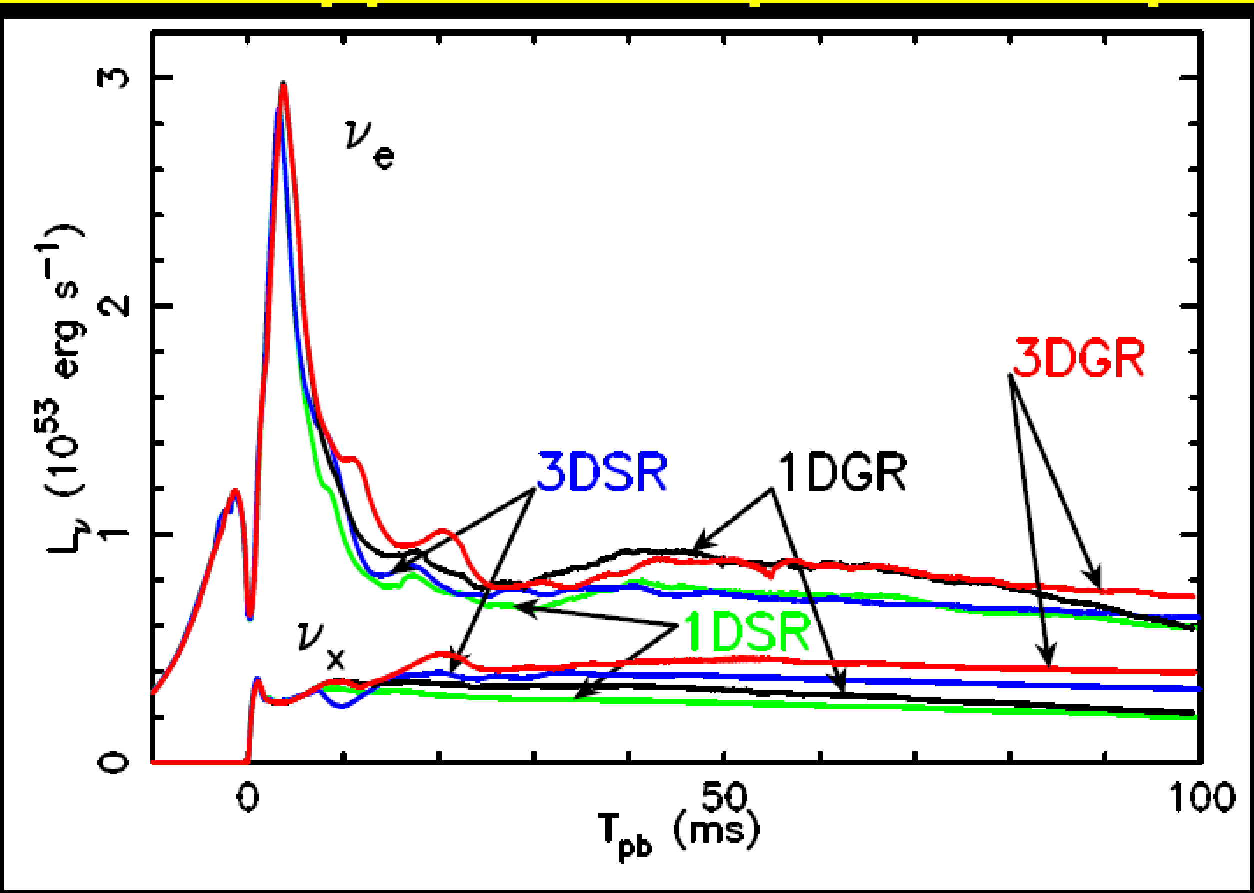
(Advantage) Higher neutrino luminosity due to GR



for ν_e, 3D-GR > 1DGR, 3D-SR ~ 1D-SR

Neutrino luminosity generally becomes higher in 3D than in1D.
always higher in GR than in SR
(stronger pull of GR ⇒positions of neutrino sphere ↘
⇒neutrino energy ↗

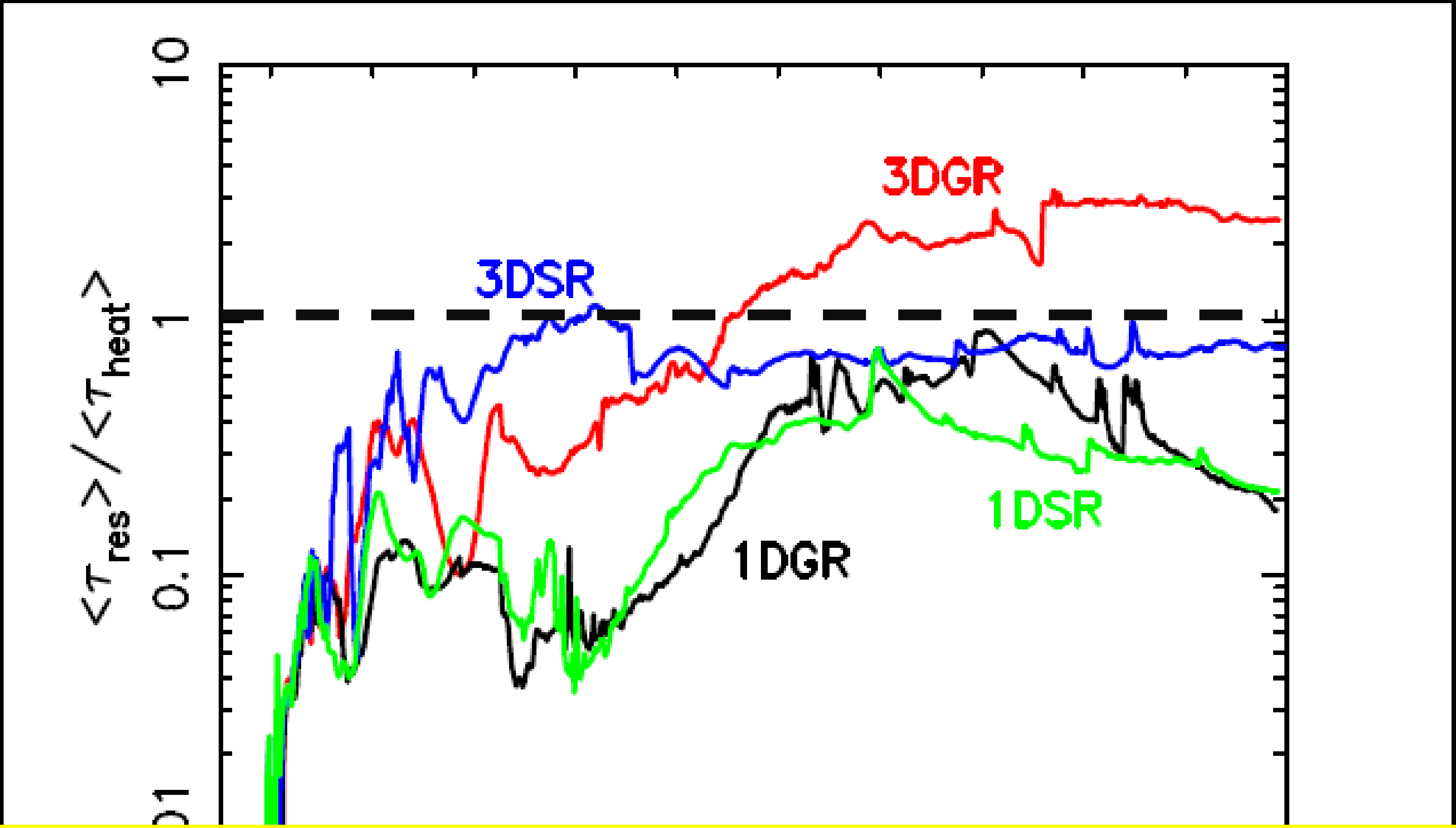
Why GR is supportive to produce explosions ?



Neutrino luminosity **always** become higher in GR than in SR.
(stronger pull of GR ⇒positions of neutrino sphere ↘
⇒neutrino energy ↗

The combination of GR and 3D: the most favorable !

Diagnostic of explosion : residency timescale/heating timescale

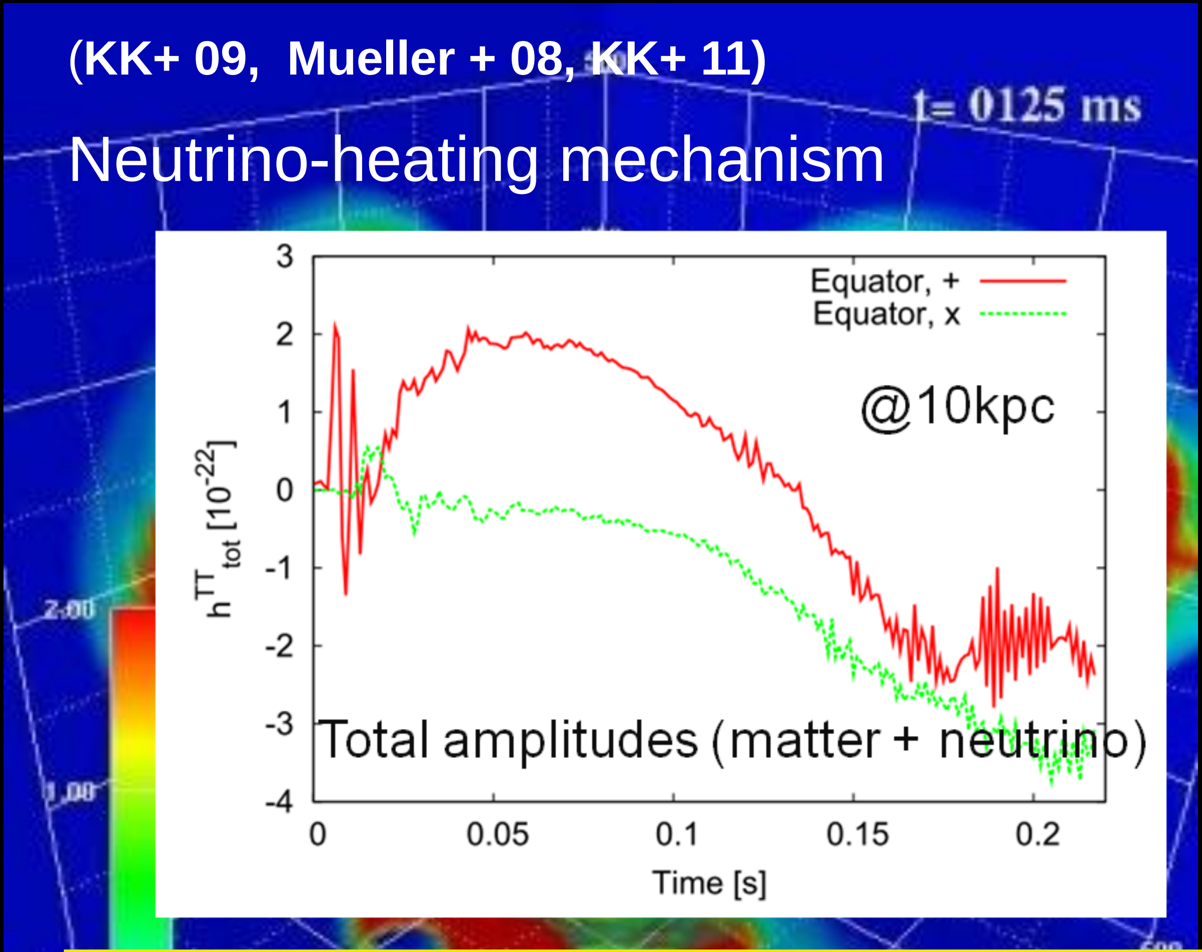


- ✓The combination of 3D and GR provides the most supportive condition of explosions !
- ✓1000ms/(2ms per day) ~ 500 days…

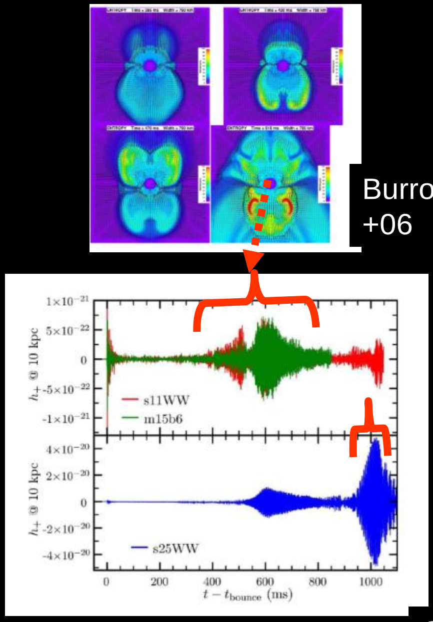
Gravitational waveforms between candidate mechanisms

(KK+ 09, Mueller + 08, KK+ 11)

Neutrino-heating mechanism



Acoustic-wave mechanism

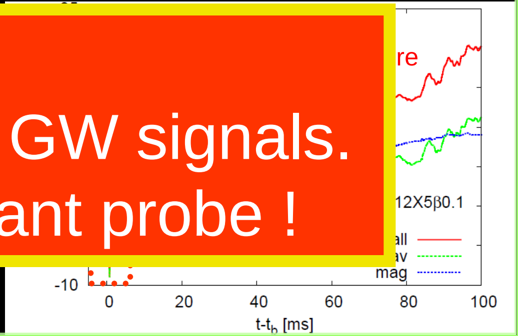


Burrows +06

Ott+06

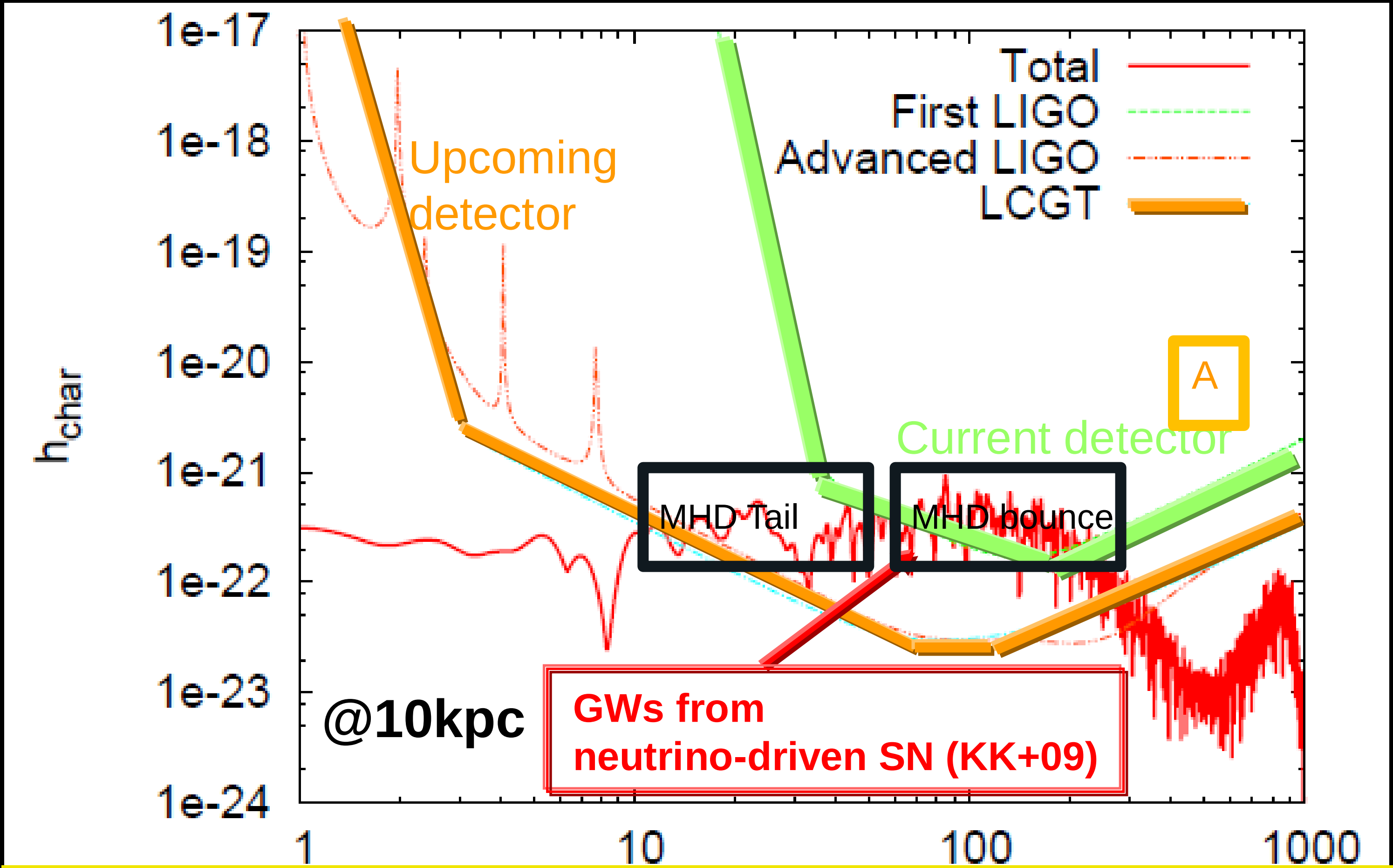
MHD mechanisms

(Takiwaki and KK 10)



- ✓A clear correlation:
  between the explosion mechanism and the GW signals.
- ✓ Detection of GWs should provide an important probe !

Detectability of GW signals



- ✓ To detect GW signals, next-generation detectors (adv. LIGO, LCGT(KAGRA)) are needed.
- ✓ By only by GWs, difficult to tell the difference one to another.
- ✓ Detailed analysis of SN multi-messengers (GWs, neutrinos, photons) is needed (a vast virgin territory awaited to be studied!)

Summary and Outlook

Cutting-edge issues:

☆ **Nuclear EOS:** Symmetry energy s
But.. impacts of EOS are non-trivial.

☆ **3D :** The most recent models with sp
transport predict that 3D is really sup
explosions.

☆ **General relativity**: also helps becau
luminosity due to a more hotter neutr
smaller radii.

from this October !

Caution: Current results depend on the next-generation
calculations with much more detailed transport in full GR.
: Update theoretical modeling of GWs, neutrinos, photons !
⇒ Need peta- or exa-scale supercomputers

Numerics(6D-GR), nuclear physics, multi-messenger astronomy
: progress understanding of CCSN theory!

On-going collaborators:

Shoichi Yamada	**(Waseda Univ.)**
Kohsuke Sumiyoshi	**(Numazu College)**
Matthias Liebendoerfer	**(Univ. Basel)**
Katsuhiko Sato	**(IPMU, NINS)**

Naofumi Ohnishi	(Tohoku Univ.)
Seiji Harkiae	(NAOJ)
Shinichiro Fujimoto	(Kumamoto college)
Tobias Fischer	(GSI, Darmstadt)
Sergey Moissenko	(Space Research institute, Russia)
Kosuke Shaku	(NAOJ)
Nobutoshi Yasutake	(Univ. Tokyo)
Sawai Hidetomo	(Tokyo U. Science)
Masaomi Ono	(Kyoto Univ.)
Nobuya Nishimura	(Univ. Basel)
Hiroyuki Takahashi	(NAOJ)