Explosion Mechanisms of Core-Collapse Supernovae and the Multi-Messenger Signatures

Kei Kotake

(Fukuoka University)

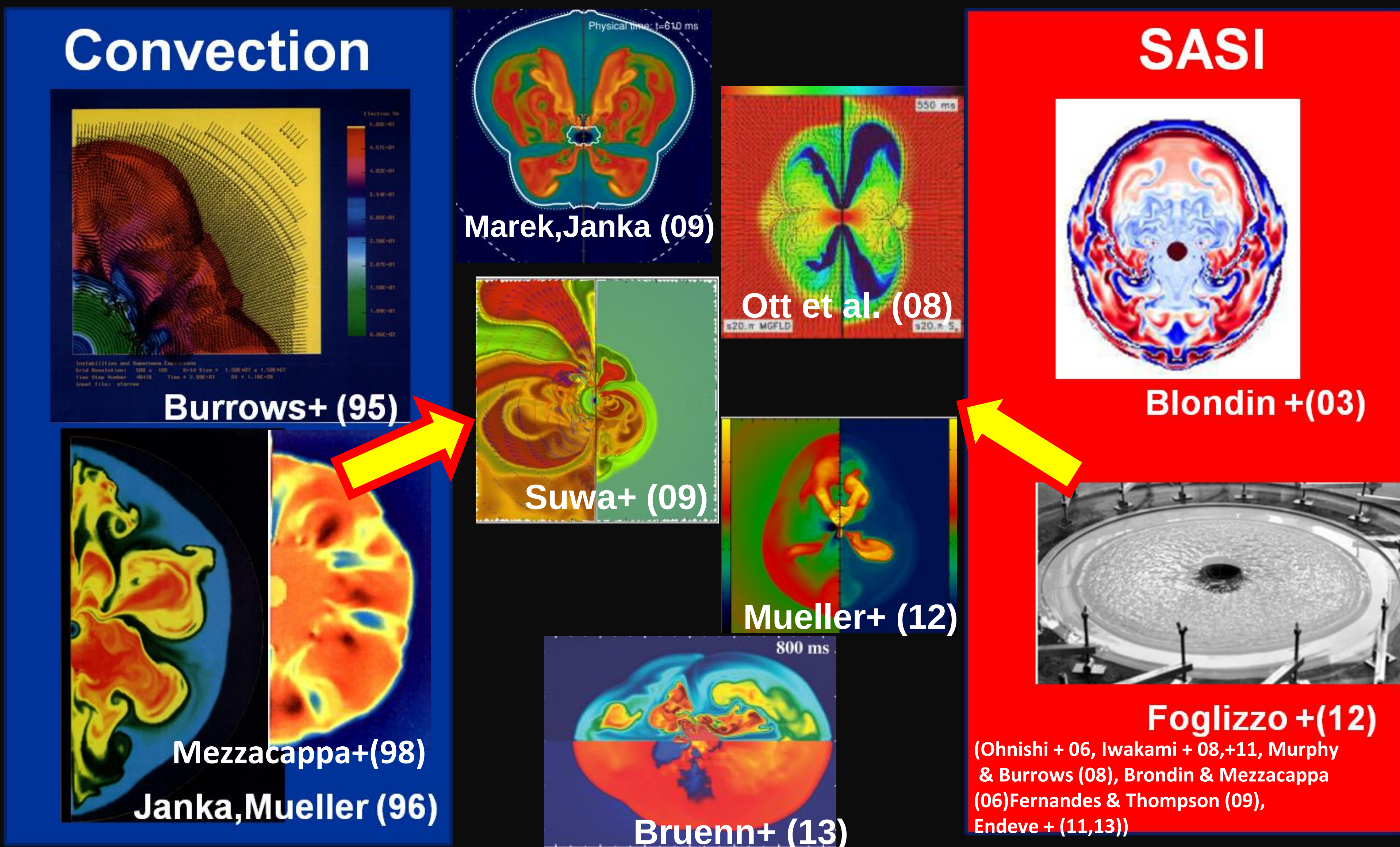
with Tomoya Takiwaki (NAOJ), Takami Kuroda (U. Basel), Ko Nakamura (NAOJ), Yudai Suwa (Kyoto U.) Kazuhiro Hayama (Osaka-city U.), Wakana Iwakami (Waseda U.) Shio Kawagoe (U. Tokyo), Tomohide Wada (NAOJ), Kohsuke Sumiyoshi (Numazu NC.), Shoichi Yamada (Waseda U.) and Katsuhiko Sato (NINS)

Supernovae and GRBs 2013

@ YITP, Kyoto Univ.

No (little!) doubt about ….. the key

(Reviews: Mezzacappa +(2005), KK+(2006), Janka 2012,+(2013), Burrows (2013), KK+ 2012, 13)



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

(e.g., KK + (2012))

Progenitor	Group (Year)	Mechanism	Dim. (Hydro)	t_{exp} (ms)	E_{exp}(B) @t_{pb} (ms)	ν transport (Dim, $\mathcal{O}(v/c)$)
8.8 $M_\odot$ (NH88)	MPA (2006,201[illegible])	ν-driven	1D(2D) (PN)	~200	0.1 (~800)	Boltzmann 2, $\mathcal{O}(v/c)$
	Princeton+ (2006)	ν-driven	2D (N)	$\lesssim$125	0.1 -	MGFLD 1, (N)
10 $M_\odot$ (WHW02)	Basel (2009)	ν+(QCD transition)	1D (GR)	255	0.44 (350)	Boltzmann 2, (GR)
11 $M_\odot$ (WW95)	Princeton+ (2006)	Acoustic	2D (N)	$\gtrsim$550	~0.1* (1000)	MGFLD 1, (N)
11.2 $M_\odot$ (WHW02)	MPA (2006,201[illegible])	ν-driven	2D (N, *C-GR*)	~100 *~200*	~ 0.005, *0.025* ~200, *900*	"RBR" Boltzmann, 2, $\mathcal{O}(v/c)$
	Princeton+ (2007)	Acoustic	2D (N)	$\gtrsim$1100	~0.1* (1000)	MGFLD 1, (N)
	Tokyo+ (2011)	ν-driven	3D (N)	~100	0.01 (300)	IDSA 1, (N)
12 $M_\odot$ (WH07)	Oak Ridge+ (2009)	ν-driven	2D (PN)	~300	0.3 (1000)	"RBR" MGFLD 1, $\mathcal{O}(v/c)$
13 $M_\odot$ (WHW02)	Princeton+ (2007)	Acoustic	2D (N)	$\gtrsim$1100	~0.3* (1400)	MGFLD 1, (N)
(NH88)	Tokyo+ (2010)	ν-driven	2D (N)	~200	0.1 (500)	IDSA 1, (N)
15 $M_\odot$ (WW95)	MPA (2009,201[illegible])	ν-driven	2D (N, *C-GR*)	~600 *~400*	0.025, *0.125* (~700, *800*)	Boltzmann 2, $\mathcal{O}(v/c)$
(WHW02)	Princeton+ (2007)	Acoustic	2D (N)	-	- (-)	MGFLD 1, (N)
(WH07)	OakRidge+ (2009)	ν-driven	2D (PN)	~300	~ 0.3 (600)	"RBR" MGFLD 1, $\mathcal{O}(v/c)$
20 $M_\odot$ (WHW02)	Princeton+ (2007)	Acoustic	2D (N)	$\gtrsim$1200	~0.7* (1400)	MGFLD 1, (N)
25 $M_\odot$ (WH07)	Princeton+ (2007)	Acoustic	2D (N)	$\gtrsim$1200	- (-)	MGFLD 1, (N)
	Oak Ridge+ (2009)	ν-driven	2D (PN)	~300	~ 0.7 (1200)	"RBR" MGFLD 1, $\mathcal{O}(v/c)$

Big breakthrough :
✓ **Success of the neutrino mechanism: (shock-revival) for 8.8 to 27 M_{sun} stars in 2D self- consistent simulations !**

~15 successful models
But still,
The neutrino mechanism:
Unexplored >90 %

Systematic study needed:
Self-consistent (in 2D, firstly) sim.
to gain a "birds-eye view" of explosion dynamics !

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(e.g., KK + (2012))

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	Oak Ridge+ (2009)	ν-driven	2D (PN)	~300	~ 0.7 (1200)	"RBR" MGFLD 1, $\mathcal{O}(v/c)$

mass (solar masses)	metallicity: solar	metallicity: 10^{-4} solar	metallicity: primordial
10.8	242 kByte	---	---
[illegible]	[illegible]	245 kByte	244 kByte
[illegible]	[illegible]	247 kByte	---
[illegible]	[illegible]	245 kByte	---
[illegible]	[illegible]	247 kByte	---
[illegible]	[illegible]	246 kByte	---
[illegible]	[illegible]	245 kByte	254 kByte
[illegible]	[illegible]	250 kByte	---
[illegible]	[illegible]	251 kByte	---
[illegible]	[illegible]	247 kByte	---
12.8	234 kByte	247 kByte	---
13.0	228 kByte	246 kByte	243 kByte
13.2	232 kByte	242 kByte	---
13.4	234 kByte	240 kByte	---
13.6	232 kByte	241 kByte	---
13.8	233 kByte	243 kByte	---
14.0	234 kByte	244 kByte	241 kByte
14.2	233 kByte	[illegible]	[illegible]
14.4	235 kByte	[illegible]	[illegible]
14.6	236 kByte	[illegible]	[illegible]
14.8	236 kByte	[illegible]	---

From 10.8 to 75 M_{sun} - star
More than 200 models
(Woosley, Heger, Weaver RMP (2002))

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1st topic: Our "birds-eye" project based on 2D rad-hyd. simulations

Nakamura et al. (2013). Suwa et al. (2013) in prep.

Numerics in both our 2D and 3D models:

✓ Spectral neutrino transport is solved by the IDSA scheme: (Liebendoerfer et al. 09)
- with "ray-by-ray" approximation (as in Garching, OakRidge group)

✓ "Standard" (Bruenn's) neutrino opacities/emissivities (Bruenn (1985)).
Cooling by mu/nu neutrinos is treated by a leakage scheme.
(Inclusion of inelastic neutrino scattering (NES) in the IDSA scheme will be installed: Takiwaki et al. in prep)

✓ Lattimer-Swesty (1991) EOS (K=220 MeV) : compati

✓ In 2D, nuclear burning included by alpha-network c

"Four steps" from collapse to explosion

(see, e.g., Suwa et al. 2010,2011,2013, ApJ)

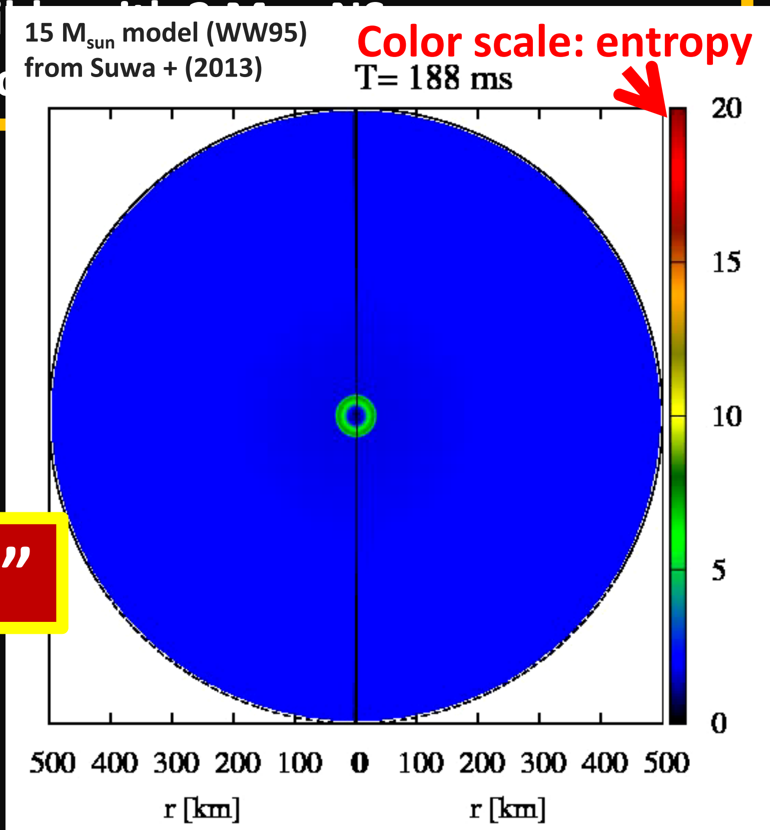
1st : After bounce, bounce shock stalls (t_{pb} < 10 ms).

2nd: Neutrino-driven convection and the SASI.

3rd: In the heating region,

Key : "initial condition" : "Progenitor"

4th: At around O(100)s ms after bounce, neutrino-driven explosions set in.



1st topic: Our "birds-eye" project based on 2D rad-hyd. simulations

Nakamura et al. (2013), Suwa et al. (2013) in prep

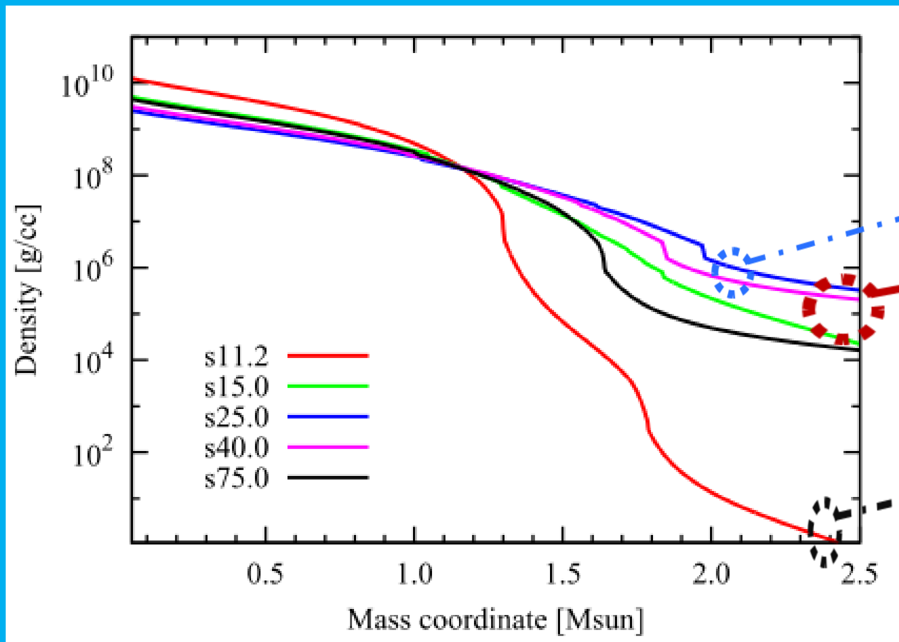
✓ "Systematics" from **100** solar-metalicity models from Woosley et al. (2002)

A Key : "Compactness: M_{core} /R_{core}"

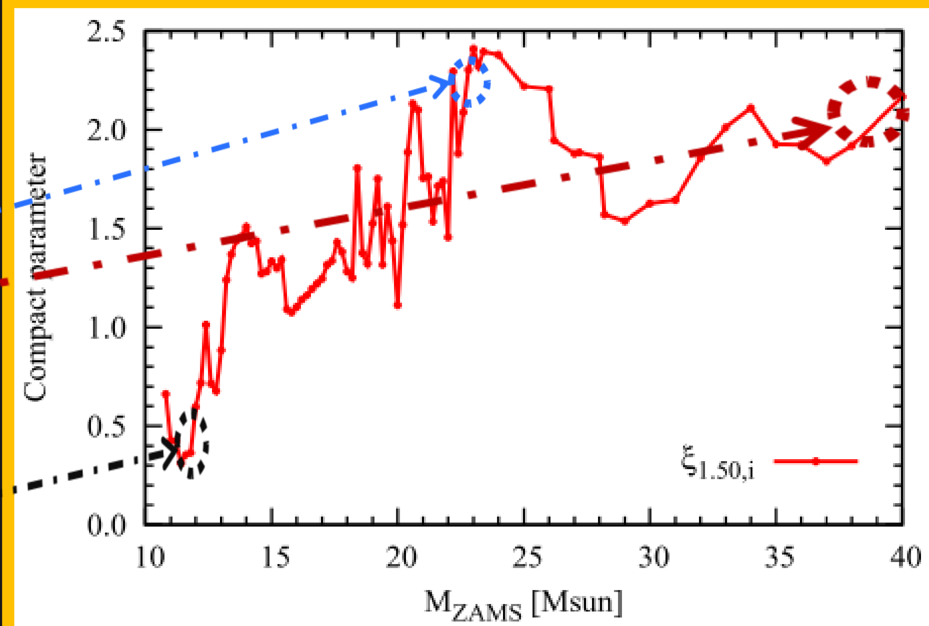
$$\xi_M = \frac{M/M_\odot}{R(M_{\rm bary} = M)/1000\,{\rm km}}\Big|_{t=t_{\rm bounce}}$$

(See also, O'Connor & Ott (2012), Ugliano et al. (2013) but in 1D results)

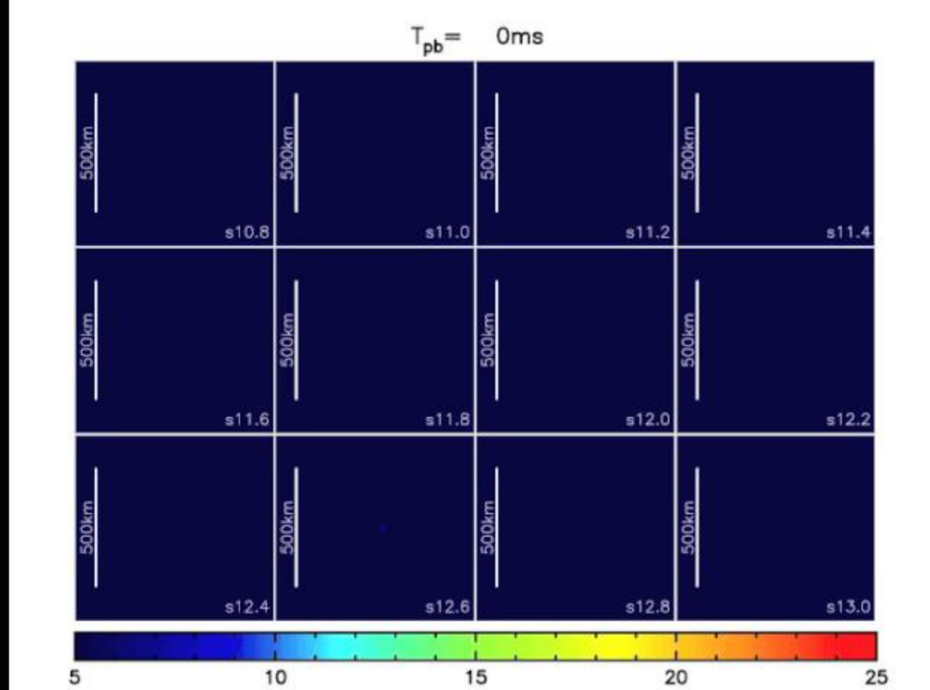
Pre-collapse density profile



Compactness parameter



✓ "Compactness" Not a monotonic function of progenitor mass !
- peaks around 20 - 30 M_{sun} models (for WHW 02 progenitor).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500km
s10.8
s11.0
s11.2
s11.4
s11.6
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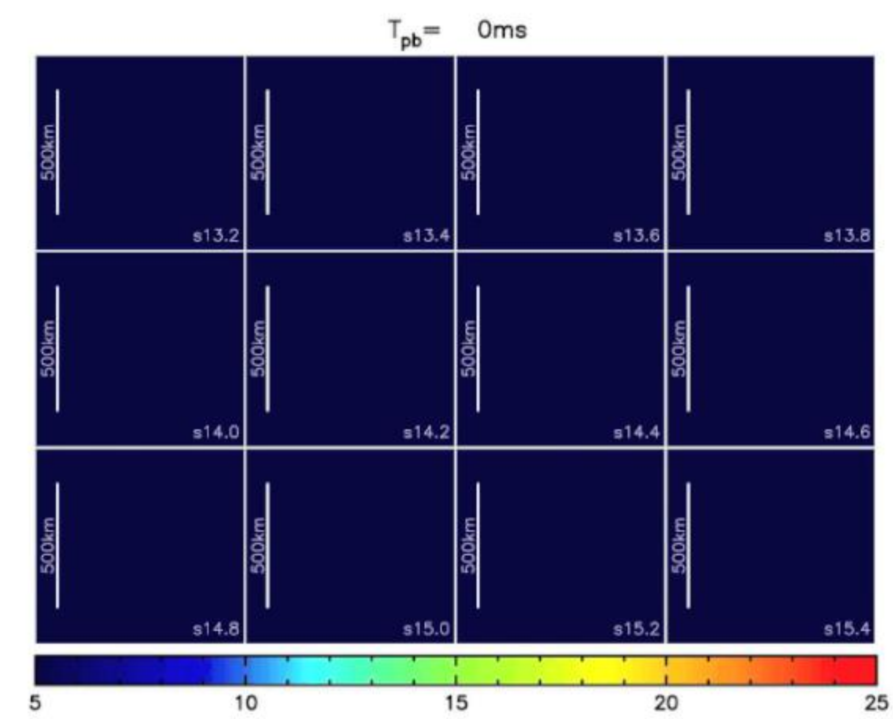
Tpb= 0ms
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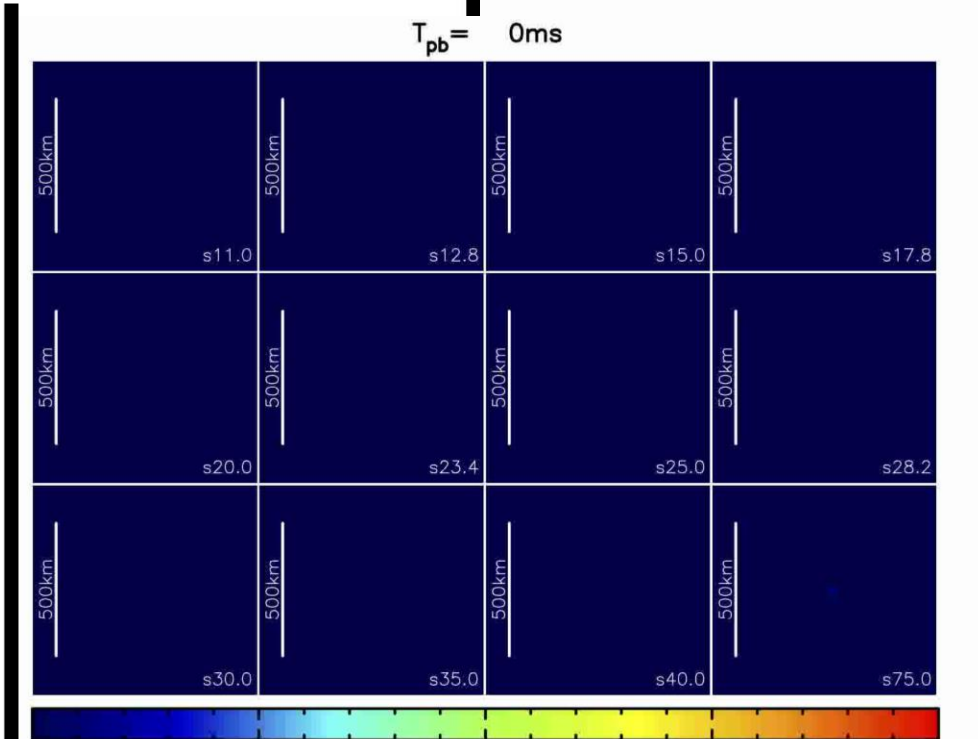
Tpb= 0ms
500km
s11.0
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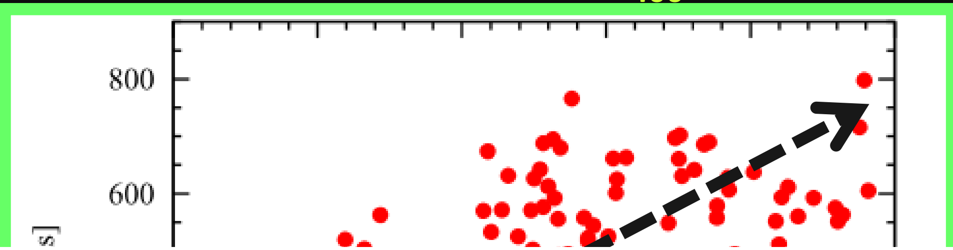
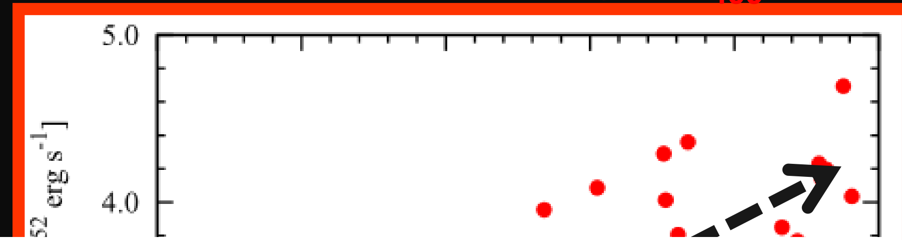
s15.0
s17.8
s20.0
s23.4
s25.0
s28.2
s30.0
s35.0
s40.0
s75.0

Onset of explosion (t_{400})

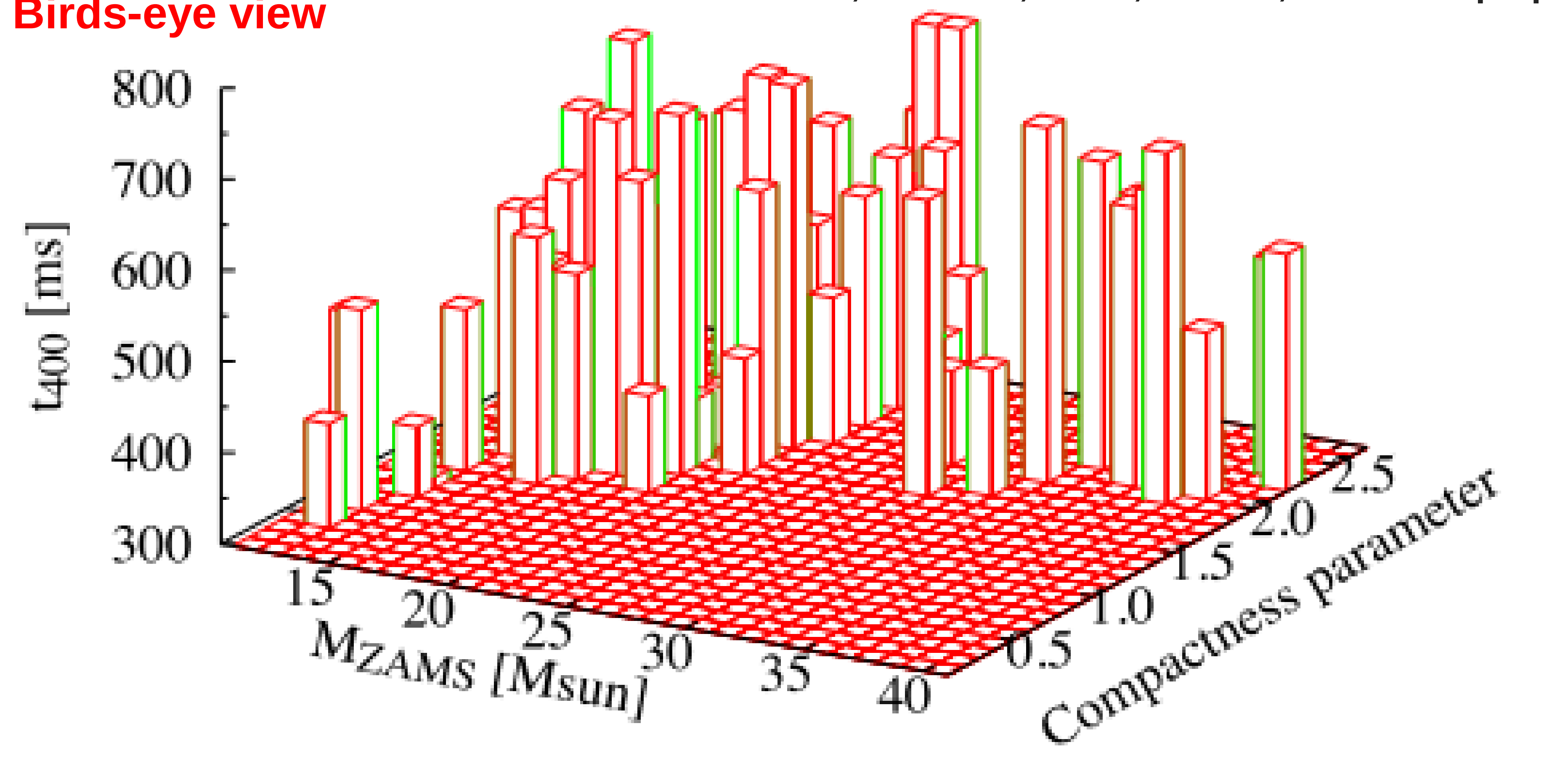


Neutrino Luminosity @ t_{400}



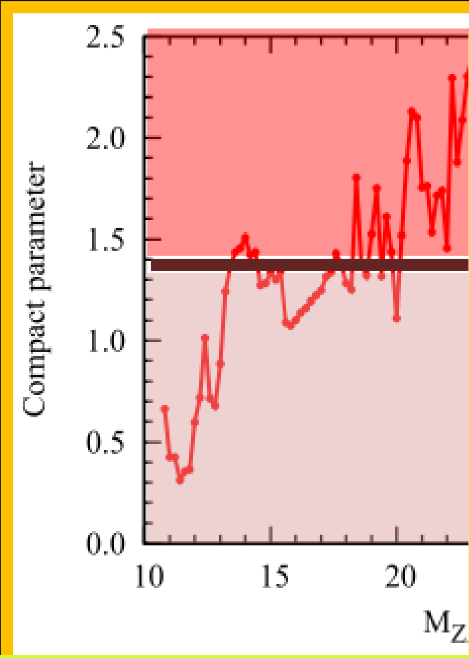
Birds-eye view

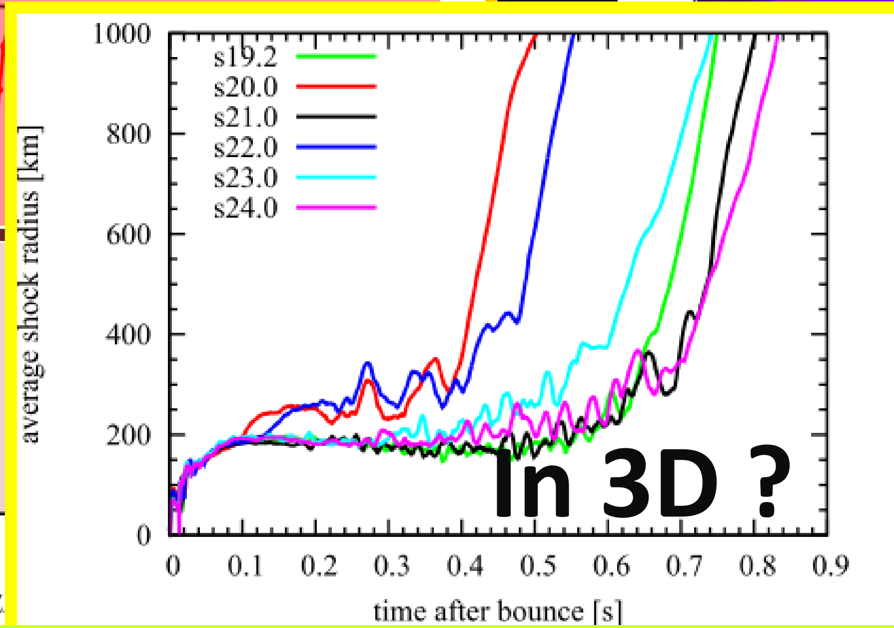
Nakamura, Takiwaki, Suwa, Kuroda, and KK in prep

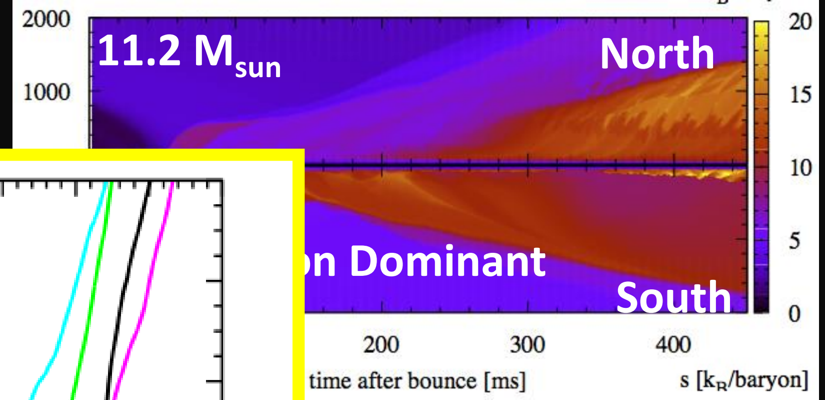


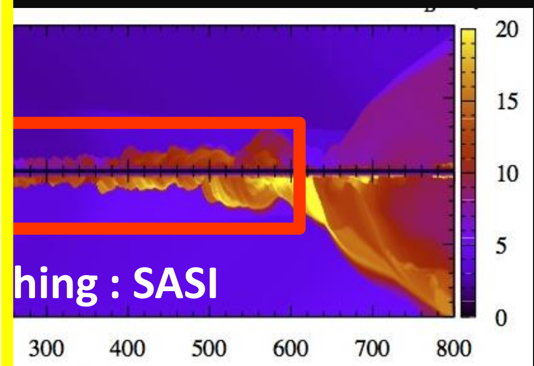
"A good indicator to diagnose multi-D explosion character !"

Convection vs. SASI in 2D









Short summary - 2D multiple progenitor models:

✓ **Core-Compactness is a key to multi-D explosion systematics (explosion time, neutrino luminosity, diagnostic energy of explosion, neutrino-convection vs. the SASI).**

✓ **~98 % of our 2D models show shock revival, leading to explosions.**
Long-term evolution : Needed to determine "final E_{exp} (increasing), final M_{rem} (NS or BH), v_{kick}, M_{Ni}, L_{ν}, h_{GW} …. etc.
(Nakamura et al (2013a,b) Suwa et al. (2013) in preparation).

(See Talks by M. Nakahata, N. Kanda, M. Was, G.McLaughlin, A. Wongwathanarat K. Maeda, S. Blinnikov, N.Tominaga, posters by V. Utrobin S. Akihiro)

2nd topic: Can the neutrino mechanism work also in 3D?

Takiwaki et al. (2012,2013)

"Low-resolution" photo

The First 3D neutrino mechanism in self-consistent CCSN simulation !

Tomoya Takiwaki

Supported by HPCI strategic program of MEXT (program number hp120285)

Special Thanks to S. Aoki (YITP, chair of Joint institute of Computational Foundation

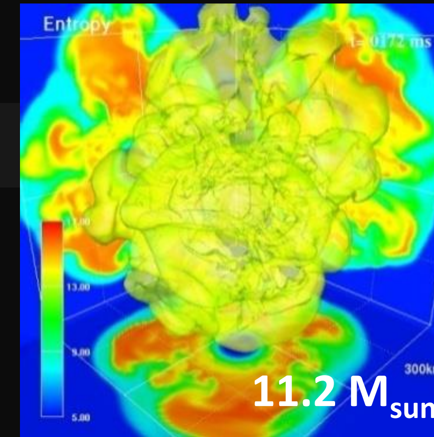
M. Shibata (YITP, chair of supercomputing committee in astrophysics)

J. Makino (Tokyo institute of technology)

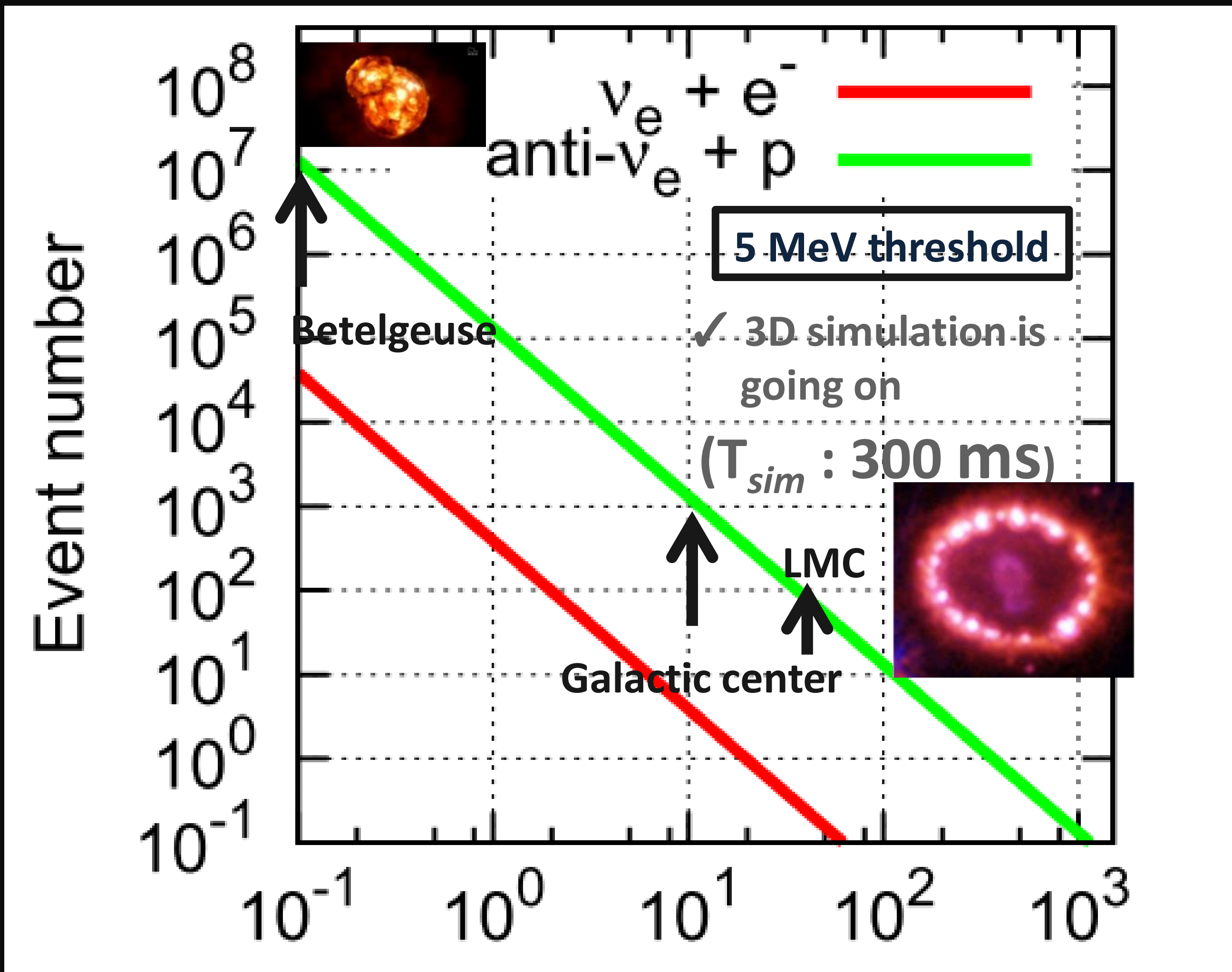
Expected number of $\bar{\nu}_e$ events at Super-K

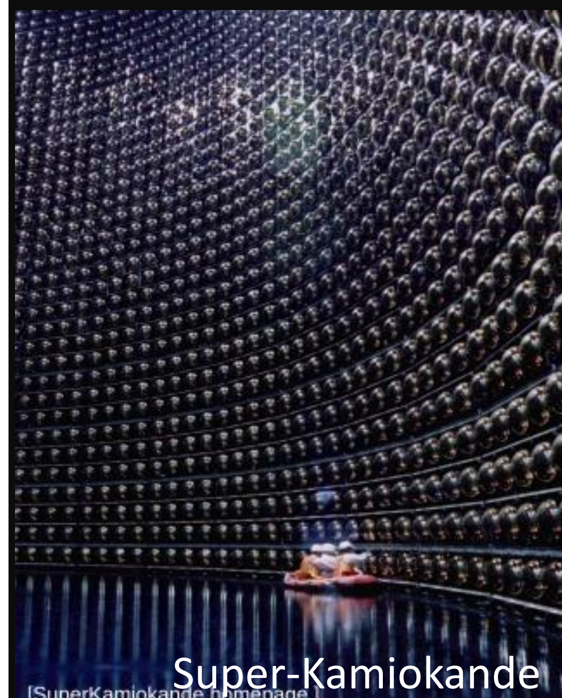
from our self-consistent 3D model (Takiwaki, Kawagoe +2013 in prep)

✓ Inverted hierarchy



$\sin^2 2\theta_{13} = 0.092$

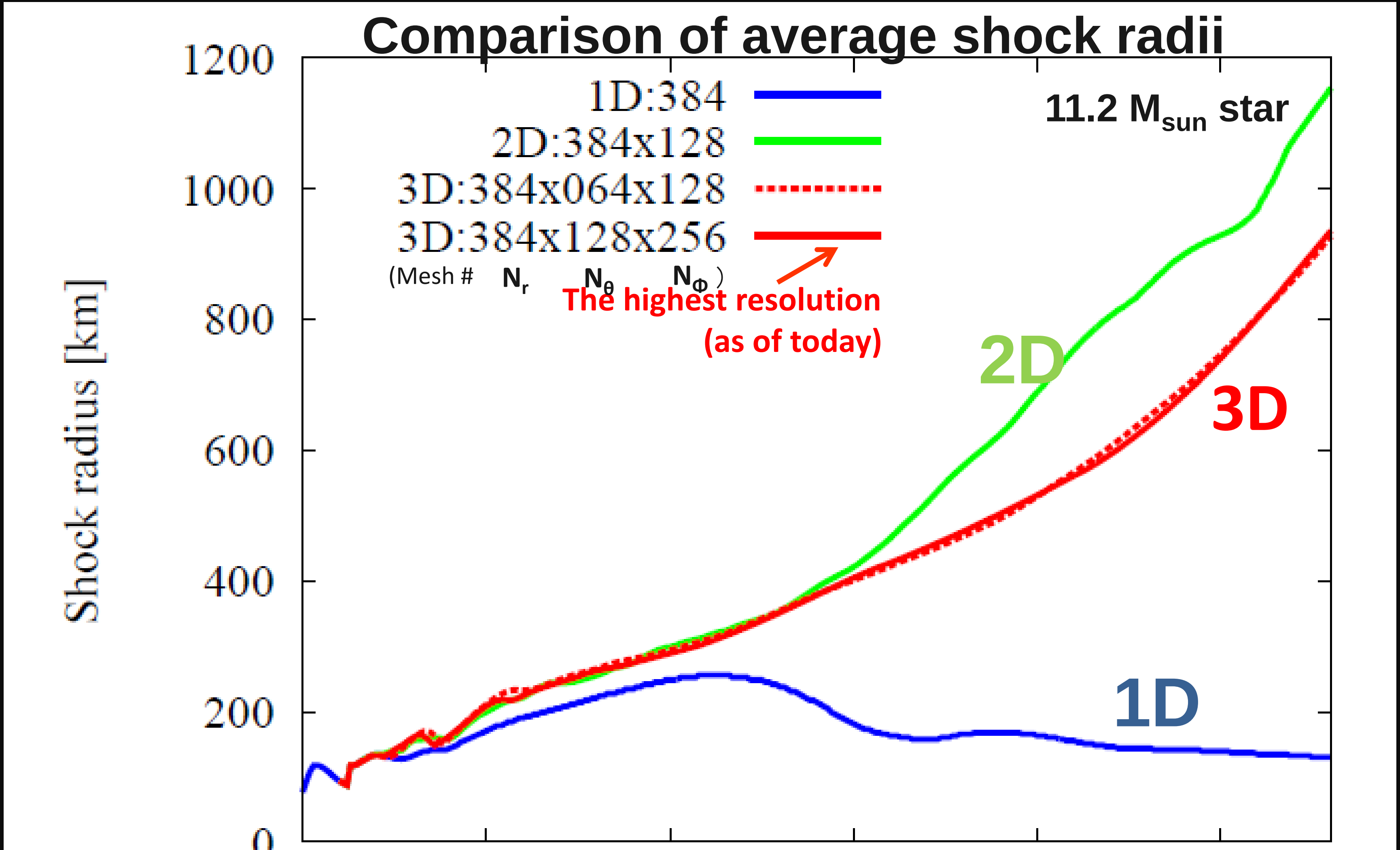




✓ Typical horizon extends (at least) out to LMC.

3D vs. 2D

✓ Update of Takiwaki et al. (2013), ApJL submiited



✓ <u>2D leads to easier explosions</u> !

(∵ In 2D, coherent motions develop along “the axis”.

In 3D, kinetic energy “cascades” via turbulence into smaller scale.)

(see also, Iwakami+(08), Hanke + (2011), Burrows+ (2012), Dolence + (2012), Couch-O’Connor (2013))

Find possible ingredients to boost explosions !

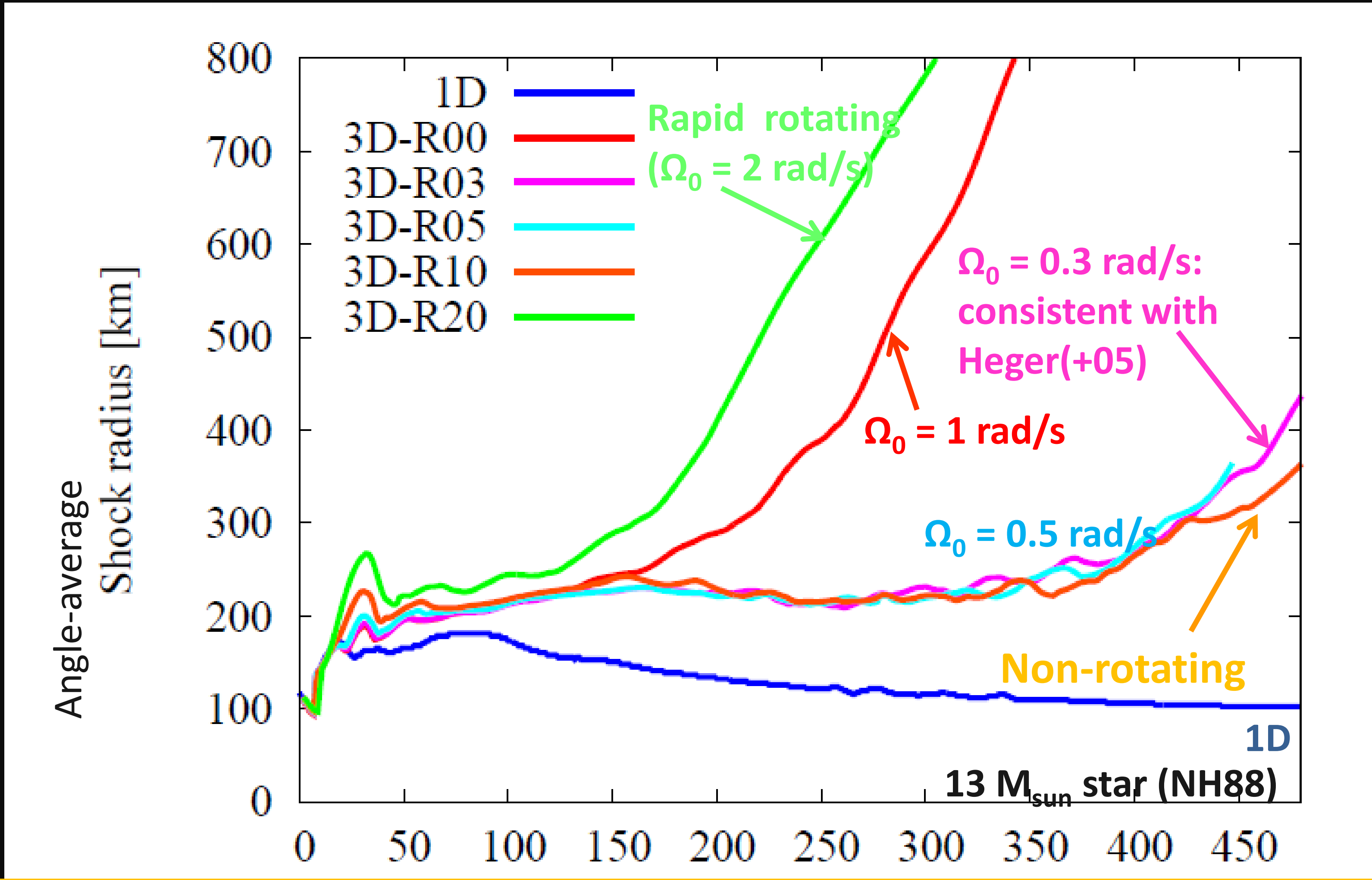
Lots of new work (but mostly in 2D) **!** (disclaimer; may be incomplete)

General Relativity (GR) : Mueller+ (2012a,b), Kuroda+ (2012)
Equation of state : Marek & Janka (2009), Suwa+ (2012), Couch (2012)
Nuclear burning : Mezzacappa+ (07), Nakamura+(2012), Yamamoto+(2013)
Microphysics missing in simulations : Sumiyoshi & Roepke (2008), Furusawa+(2013) Robert+(2012) (e.g., talks by Horowitz, Furusawa !)
Rotation : KK+(2003,2006), Marek&Janka(2009), Suwa+(2010)
Magnetic fields : Yamada &Sawai (04), KK+06, Obergaulinger+06, Suwa+07, Burrows+07, Takiwaki+09, Endeve+(10,12) , Obergauliner +(10), Obergaulinger & Janka (2013), Masada+(2012), Sawai+(2013a,b)), Moiseenko(07,13)
Collective neutrino oscillation : Suwa+(2012), Dasgupta+(2012), Pejcha+(2012
Physic of hydrodynamics & turbulence : Iwakami + (2013), Pejcha & Thompson(2012), Murphy & Meakin (2011)

See Talks by Y. Suwa, M. Obergaulinger (in this session),
posters by W.Iwakami(P03), H.Sawai (P04, S.Moiseenko(P06), O. Pejcha (P62)

Effects of rotation on neutrino-driven explosions (2/2)

Takiwaki and KK in prep



✓ Shock-revival time earlier as initial rotation rates higher.

✓ Rotation (mild as it is !) can boost neutrino-driven explosions.

✓ 3D sim. Needed because "rotation " leads to non-axisymmetric modes.

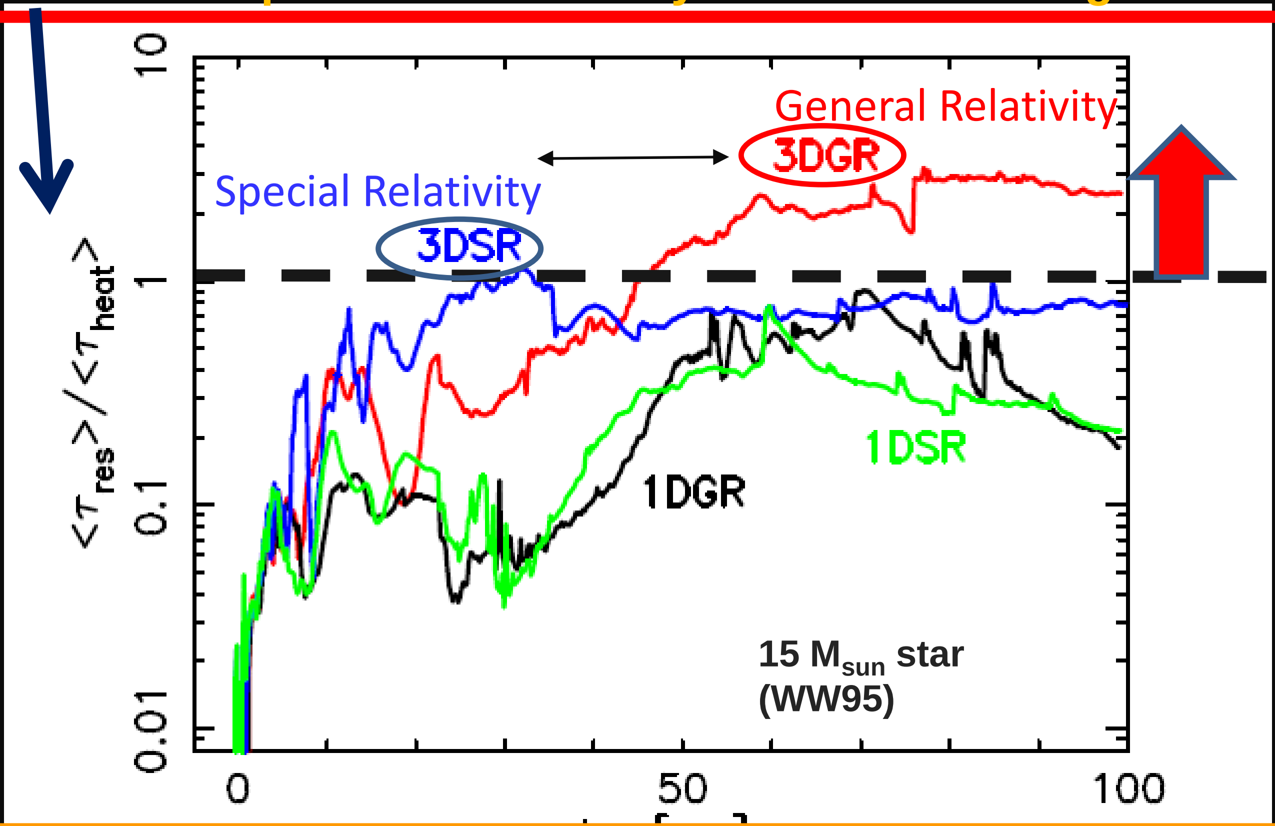
(e.g., Spiral SASI models: e.g., Blondin & Mezzacappa (2007), Iwakami et al. (2008)

Will GR help "multi-D" neutrino-driven explosions?

Kuroda, KK, Takiwaki (2012 ApJ, 2013 PRD submitted)

- ✓ 3D full GRMHD code developed by T. Kuroda (now in Basel. U)
- ✓ Three-flavor approximate neutrino transport is implemented based on the Thorne's moment formalism (Shibata+ 2011,PTP)

Diagnostic of explosion : residency timescale/heating timescale



✓ **Only "3D-GR" model satisfies a necessary condition of explosion.**

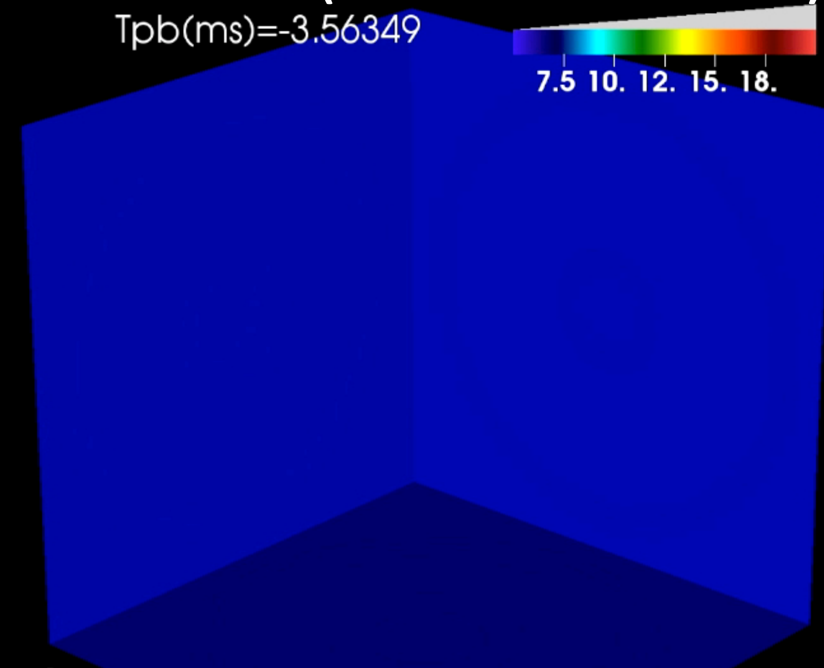
⇒ **Suggestive : GR leads to easier explosions in multi-D.**

(in line with 2D by B.Mueller et al. (2012a,b): GR with detailed transport)

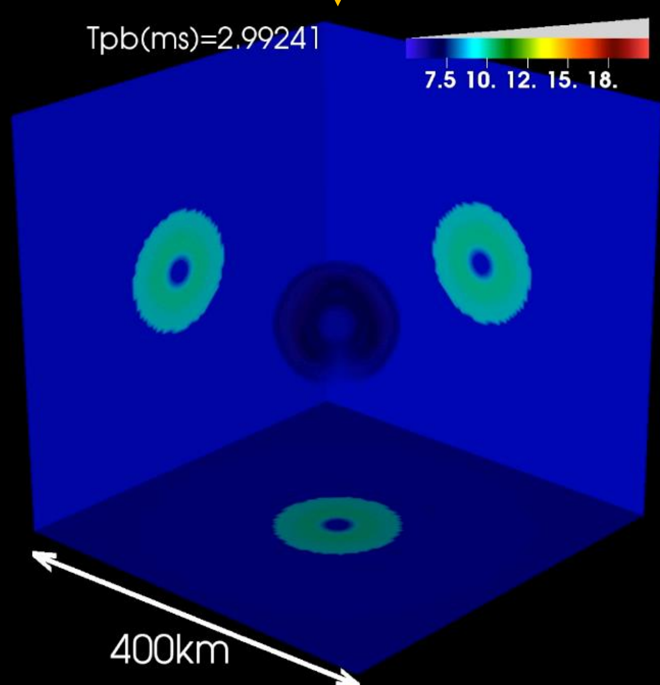
by 3D-GR simulations

Kuroda et al. (to be submitted soon)

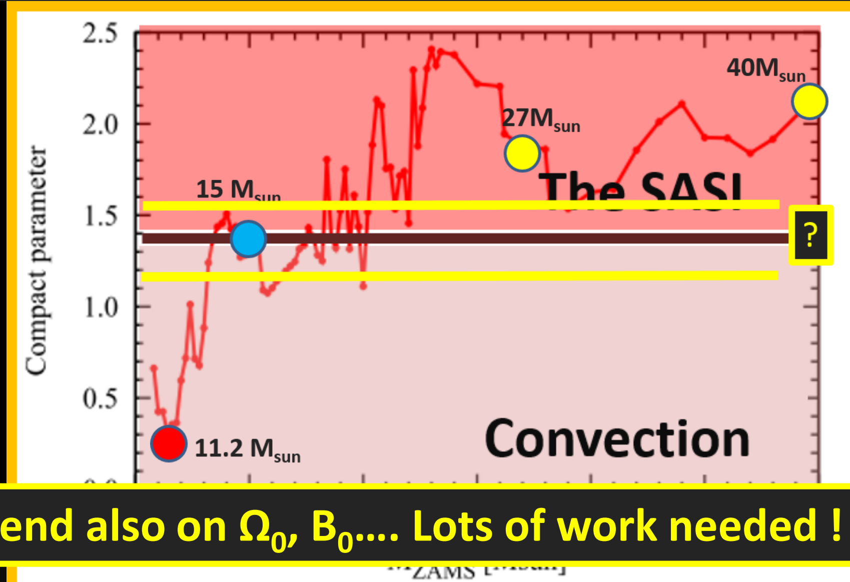
27 M_{sun} model from WHW02



11.2 M_{sun} model from WHW02

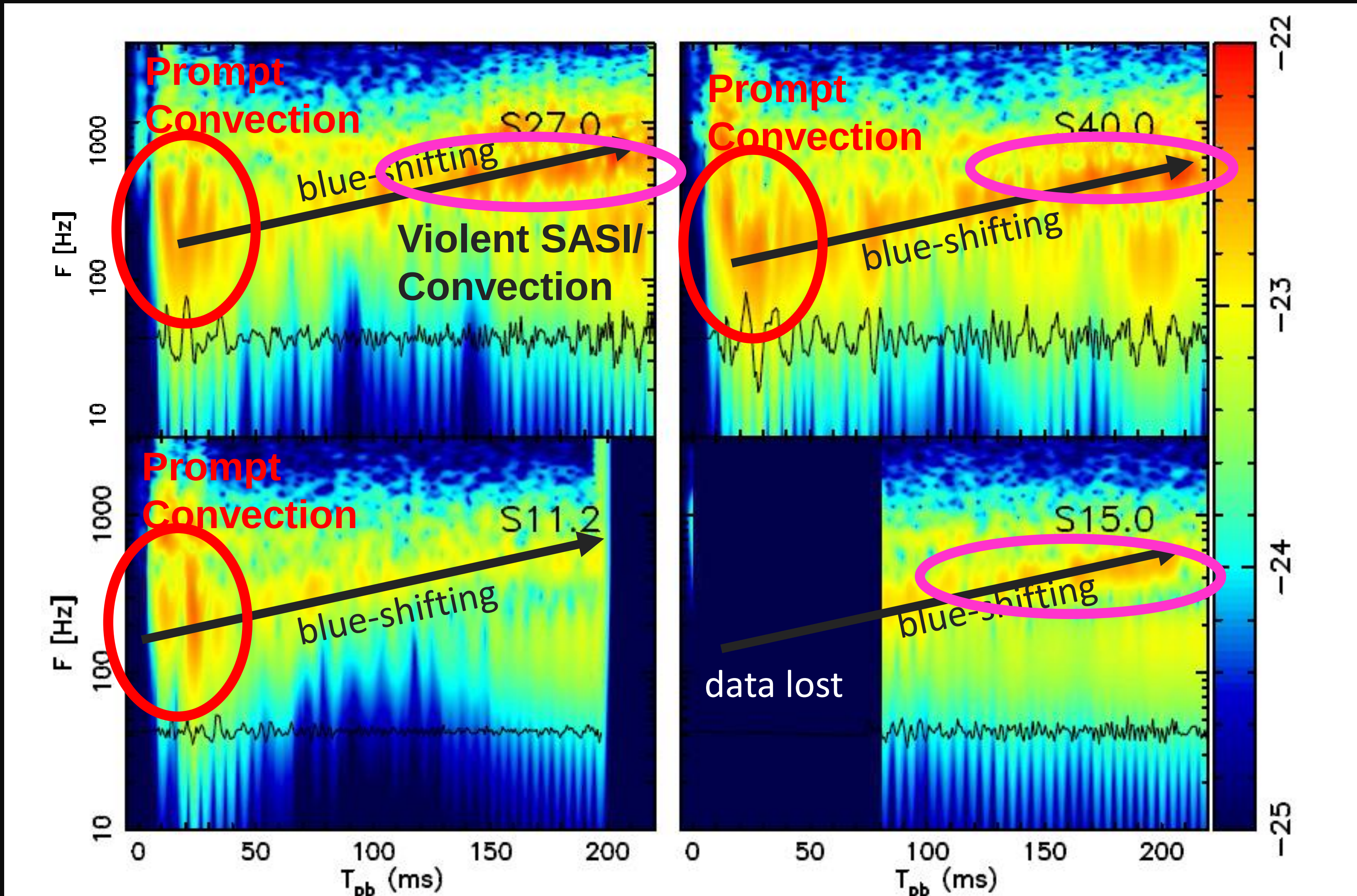


SASI vs. Convection plot in 3D-GR



Should depend also on Ω_0, B_0…. Lots of work needed !

Gravitational-Wave Spectrogram (: E_{gw} as time-frequency domain)



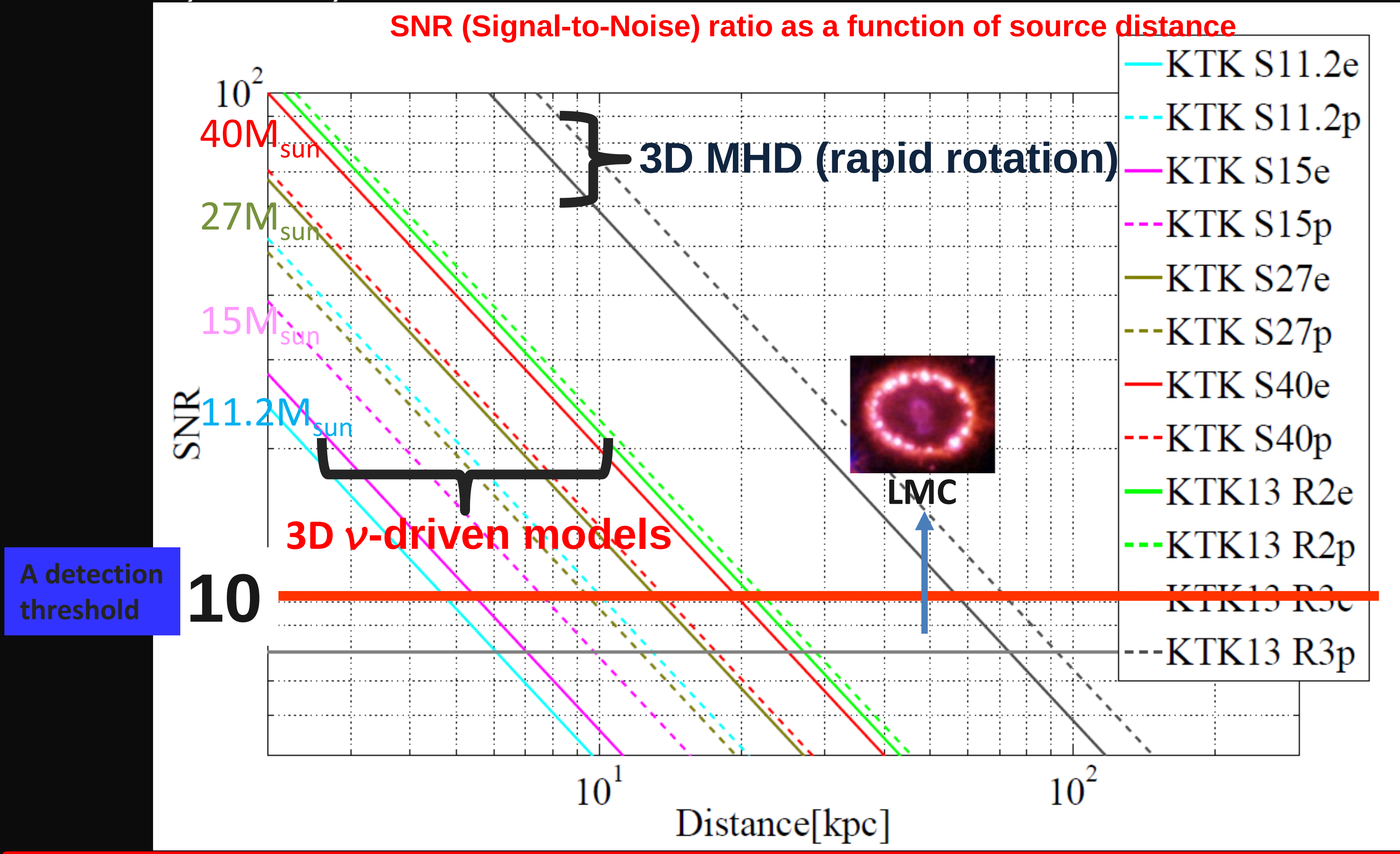
✓ "Excess power" blue-shifts with time ⇒ Traces the activity of SN engine !
(see, e.g., 2D: Murphy+(09), B.Mueller+(13), Yakunin+(09), e.g., Kotake (2013) for review)

✓ Interesting: Late-time GW signals remarkable for models with high compactness :
Expected to provide a possible hint about progenitor model !

Identifying SN mechanisms from Coherent Network Analysis

Hayama, Kuroda,Takiwaki & KK (2013a,b) in prep

✓LIGOx2, VIGRO, KAGRA



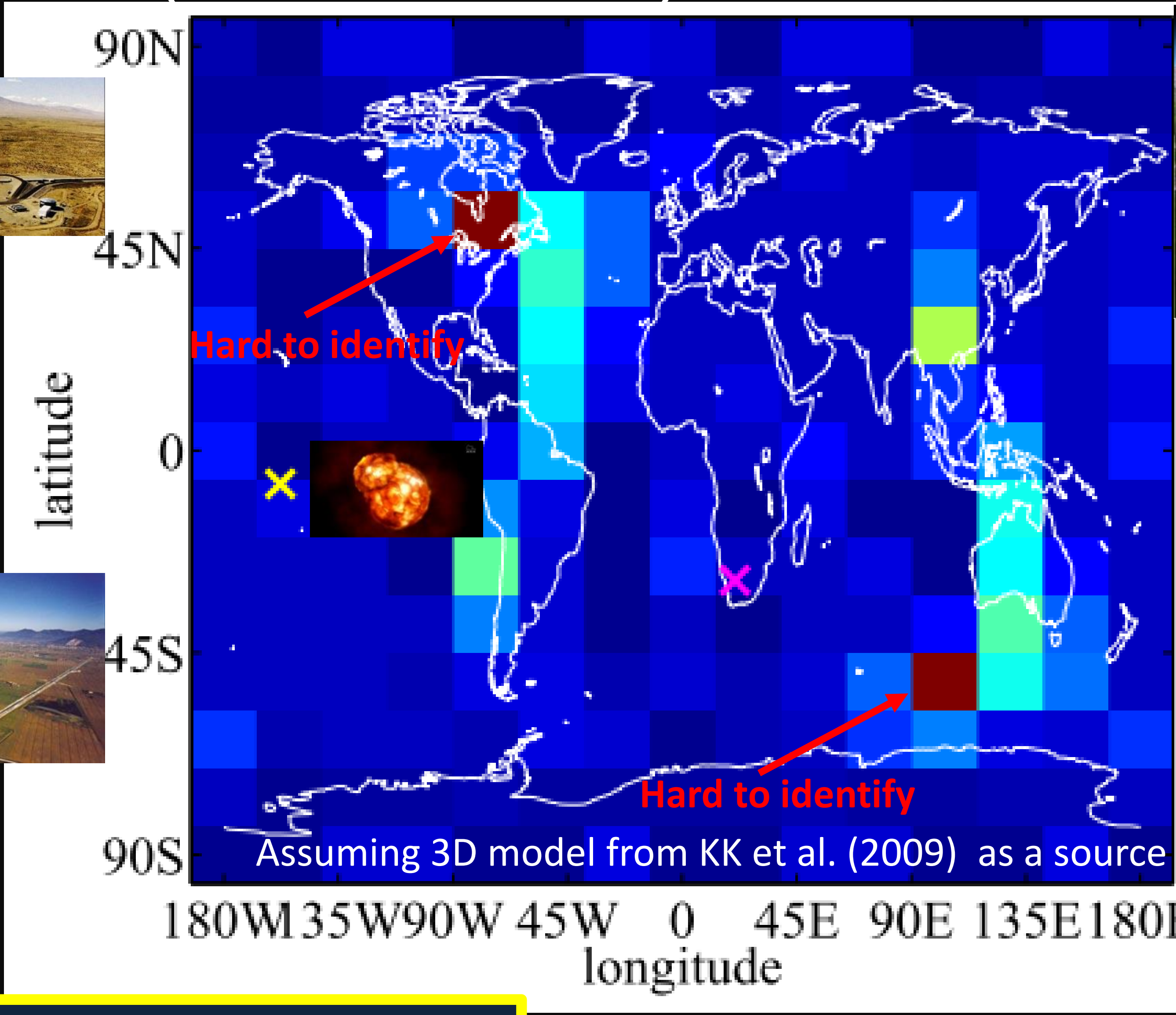
✓Method robust for *ν*-driven mechanism out to 10 kpc for massive progenitors.

✓Can identify for MHD mechanism out to LMC. (Birds-eye on GW is running !)

Source identification test (10x10 degrees)

Hayama, Kuroda, Takiwaki & KK (2013b) in prep

Spatial location (LIGOx2, VIGRO, KAGRA) relative to astrophysical source



Detectors are ready!

Summary

1 :Based 2D multiple progenitor study (98 exploding models/100),
"Compactness" is a key to characterize diversity of explosions.

2. From our 3D simulations with IDSA transport,
   - ✓ 2D leads to easier explosions than in 3D.
   - ✓ First example of 3D neutrino mechanism (still under-energetic)
   - ✓ Mild rotation boosts neutrino-driven explosions.
   - ✓ All in all, SN dynamics is of 3D nature !
3. From our 3D GR simulations with approximate transport
   - ✓ GR leads to easier explosions than Newtonian models.
   - ✓ GW spectrogram imprints the SN post-bounce activity.
4. Coherent Network Analysis is robust for neutrino-driven mechanism out to 10 kpc, and for MHD mechanism out to LMC.

Multi-messengers signatures being unveiled from first-principle 3D models:

Coincident analysis should be important !

Many thanks !