The supernova shock reaches to the stellar surface somehow… with its kinetic E of 10^{51} erg (≡1 Bethe) !

Then, how do massive stars blow up ?!

Summary

✓Assuming spherical symmetry, the neutrino heating mechanism cannot explain explosions of most massive stars.

✓Many uncertainties: Go to multi-D (2D or 3D) ?, EOS/microphysics may be incomplete (needs to be improved)? → Tomorrow

Outline

1st part; Yesterday

✓ The Standard Supernova Theory

- What is missing in it ?

✓ Current Multi-D Supernova Paradigm

- status of radiation-hydrodynamics simulations

2nd ;Today

✓ Multi-messenger signatures

- Gravitational Waves and Neutrino Signals

✓ Summary with some perspectives

“90 seconds” to overview Core-Collapse Supernova physics

1 10 100 1000 1 10 100 1000

Y_e

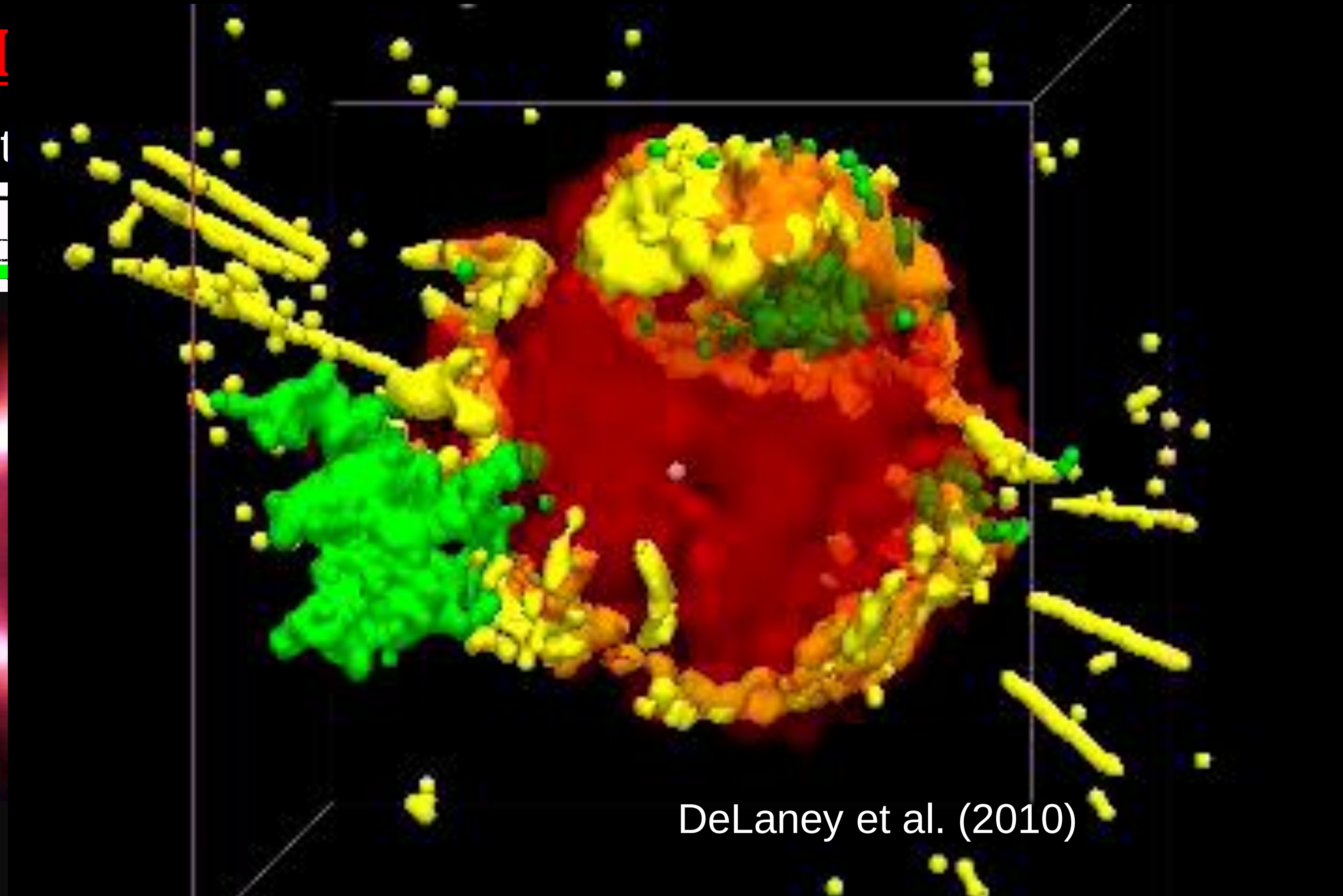
Y_{lepton}

Y_ν

10^{14}

I

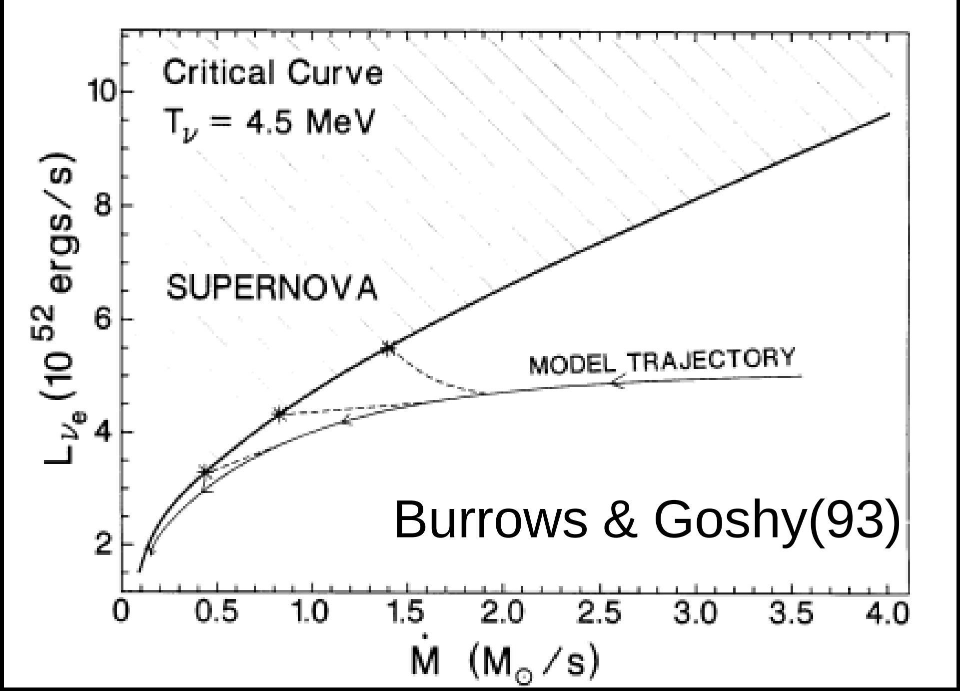
(Wilson, Bet

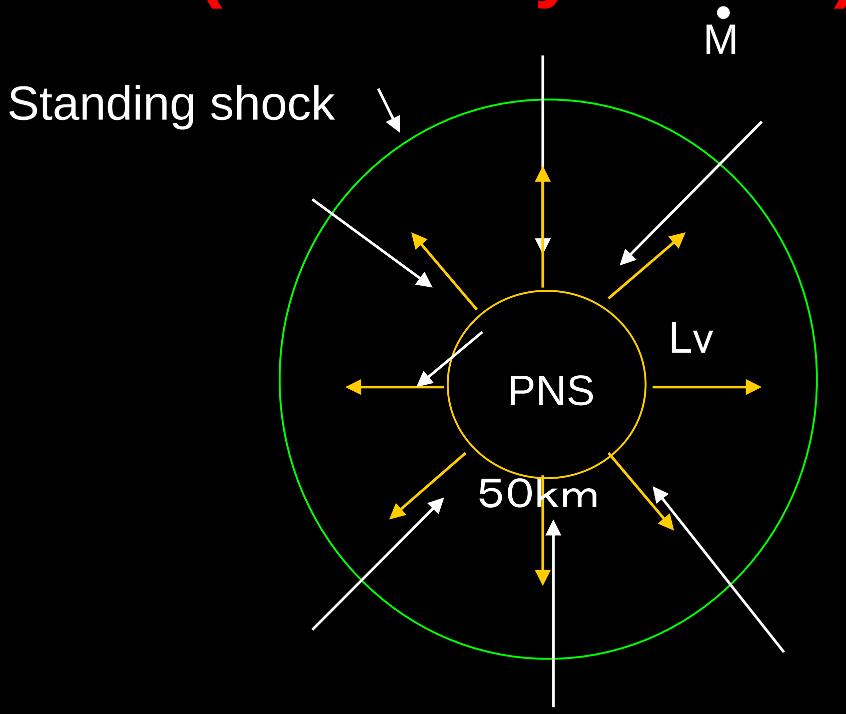


Both from theory and observation,
"Multi-D" effects are essential !

Why 1D stayed main-player (in the last 20 years?)

Tantalizing problems… (lecture by N.Paar)





Why 1D stayed main-player (in the last 20 years?)

Tantalizing problems… (lecture by N.Paar)

Neutrino reactions in the supernova core

Sophistications

Reaction	References	Good(○)or bad(×) for explosion
$\nu\, e^{\pm} \rightleftharpoons \nu\, e^{\pm}$	Mezzacappa & Bruenn (1993a)	×
	Cernohorsky (1994)	
$\nu\, A \rightleftharpoons \nu\, A$	Horowitz (1997)	×
	Bruenn & Mezzacappa (1997)	
$\nu\, N \rightleftharpoons \nu\, N$	Burrows & Sawyer (1998)	○
$\nu_e\, n \rightleftharpoons e^-\, p$	Burrows & Sawyer (1999)	—
$\bar{\nu}_e\, p \rightleftharpoons e^+\, n$	Burrows & Sawyer (1999)	
$\nu_e\, A' \rightleftharpoons e^-\, A$	Bruenn (1985), Langanke et al. (2003)	× (smaller Ye)
	Mezzacappa & Bruenn (1993b)	
$\nu\, \bar{\nu} \rightleftharpoons e^-\, e^+$	Bruenn (1985), Pons et al. (1998)	○
$\nu\bar{\nu}\, NN \rightleftharpoons NN$	Hannestad & Raffelt (1998)	○
$\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau} \rightleftharpoons \nu_e\bar{\nu}_e$	Buras et al. (2003)	○
$\overset{(-)}{\nu}_{\mu,\tau}\, \overset{(-)}{\nu}_e \rightleftharpoons \overset{(-)}{\nu}_{\mu,\tau}\, \overset{(-)}{\nu}_e$	Buras et al. (2003)	(larger Lv)

Why 1D stayed main-player (in the last 20 years?)

Tantalizing problems (lecture by N.Paar)

Energy budget crisis in the neutrino mechanism

Typical observed explosion energy:

$$E_{\mathrm{K}} \sim 1-2 \times 10^{51}\mathrm{erg}$$

Releasable energy = binding energy of PNS ~ thermal energy of PNS

$$\approx 3 \times 10^{53}\mathrm{erg}\left(\frac{M}{1.4M_{\mathrm{sol}}}\right)^2 \frac{10\mathrm{km}}{R}$$

essentially carried away by neutrinos.

For the working of the neutrino mechanism,

✓ ~1% energy transfer via neutrinos to matter.

✓ $f(t,x,y,z,p_x,p_y,p_z)$:7D Boltzmann neutrino transport.

✓ Energy conservations should be kept < 1%, over the entire simulation (for 2D, ~10^{20} , 1 year/ one simulation @ 10Tflops supercomputer.)

✓ Grand challenge in computational astrophysics !

(O) or
×) for
sion

×

×

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×

aller Ye)

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er Lv)

Multi-messenger emission cites:

Blue Giant (Red Giant: × 100)

GW

Explosion multi-dimensionality (origin of anisotropy)

Simulations

Signal Prediction

Data Analysis

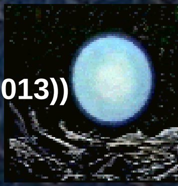
Exp. Mechanism
Dynamics
Thermodynamics

GW emission
Neutrino signals
photon

✓A final goal of SN modellers is.
"To identify the supernova mechanism from CCSN multi-messengers (GW/neutrino/EM observations) ! "

engine !

Gravitational Waves (GWs) from Stellar Collapse



(see reviews in Ott (2009), Fryer & New (2011), Kotake (2013))

GW amplitude from the quadrupole formula

$$h_{ij} = \frac{2G}{c^4 R}\frac{\partial^2}{\partial t^2}Q_{ij} \sim \frac{R_s}{R}\left(\frac{v}{c}\right)^2$$

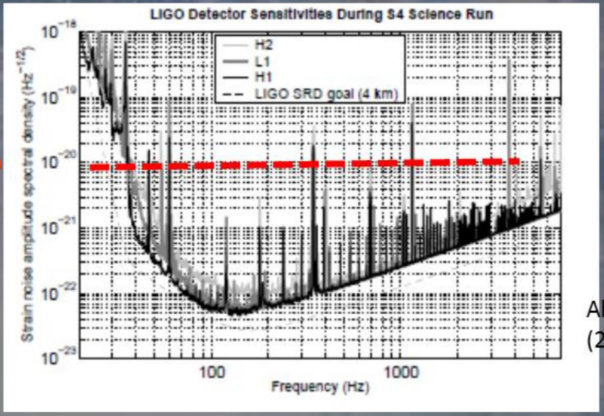
Quadrupole moment

Typical values at the formation of NS

$$R_s = 3\ \mathrm{km}\left(\frac{M}{M_\odot}\right) \quad v/c = 0.1 \quad R = 10\ \mathrm{kpc}$$

$$\boxed{h \sim 10^{-20}}$$

Sensitivity curve of LIGO



Abbot et al. (2013) PRD

✓SN in our galaxy is the target of GWs

More correctly,

$$h_{ij} = \epsilon\,\frac{R_s}{R}\left(\frac{v}{c}\right)^2$$

ϵ represents the degree of anisotropy.

If collapse proceeds spherically, $\epsilon = 0$

no GWs can be emitted.

What makes the SN-dynamics deviate from spherical symmetry is essential for the GW emission mechanism !

After +50 years of CCSN modeling : "Multi-D" neutrino mechanism

(pioneered by Colgate & White (1966), see Janka (2012), Burrrows (2013) ,Kotake et al. (2012) for review)

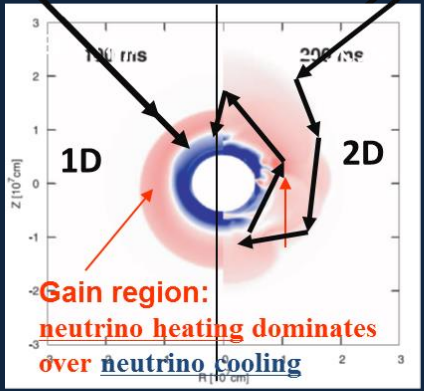
"Four steps" in neutrino-driven explosions

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

1st : After bounce, the bounce shock stalls.

2nd: Neutrino-driven convection and the SASI.
(Standing-Accretion-Shock-Instability)

3rd: In the heating region, dwell-time of material gets longer due to non-radial motions in multi-D environments. (Turbulence helps explosion).

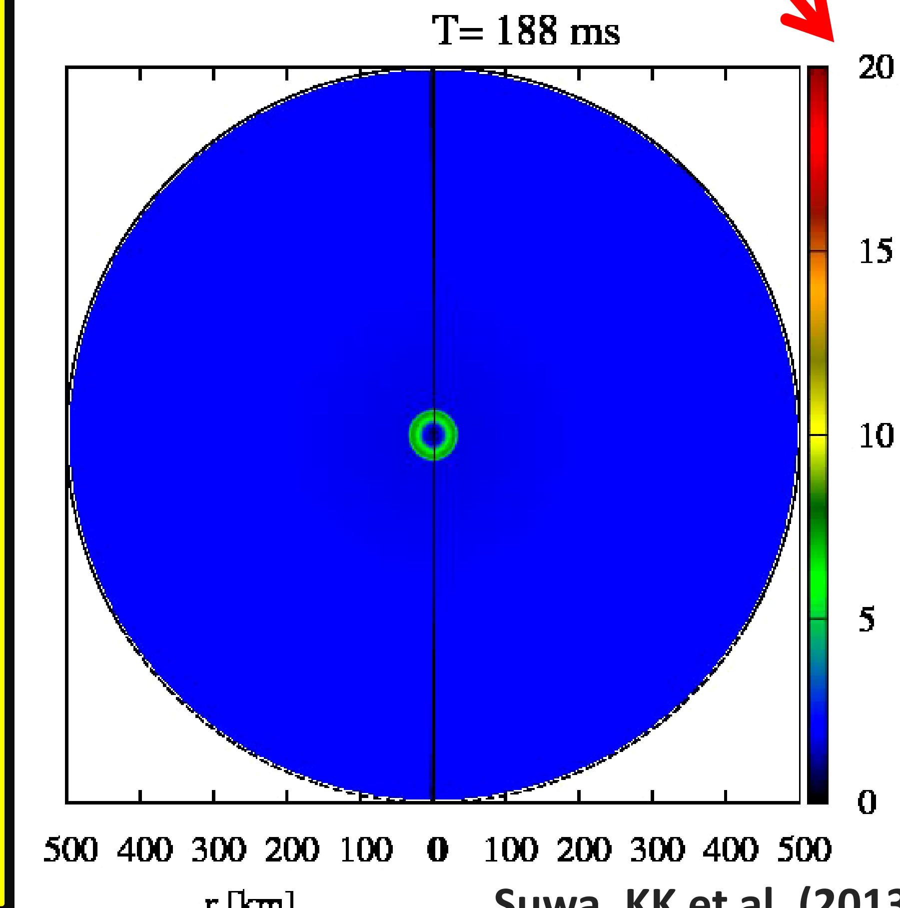


4th: At around O(100)s ms after bounce, neutrino-driven explosions set in.

2D radiation-hydro simulation of a 15 M_{sun} star

- ✓IDSA scheme for spectral neutrino transport
- ✓Lattimer-Swesty EOS (K=220 MeV)
  :compatible with 2 M_{sun} NS observation

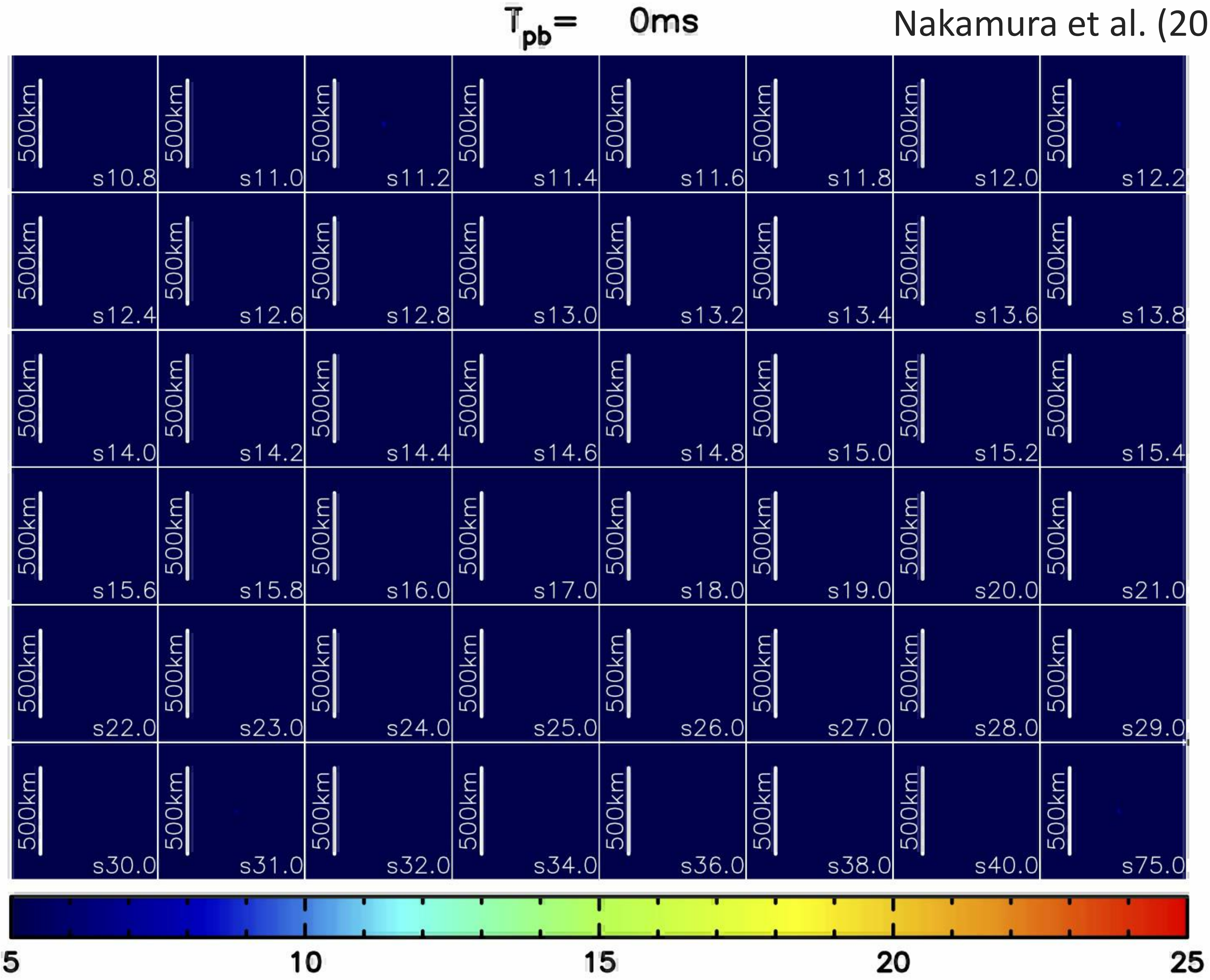
Color scale: entropy



Suwa, KK et al. (2013

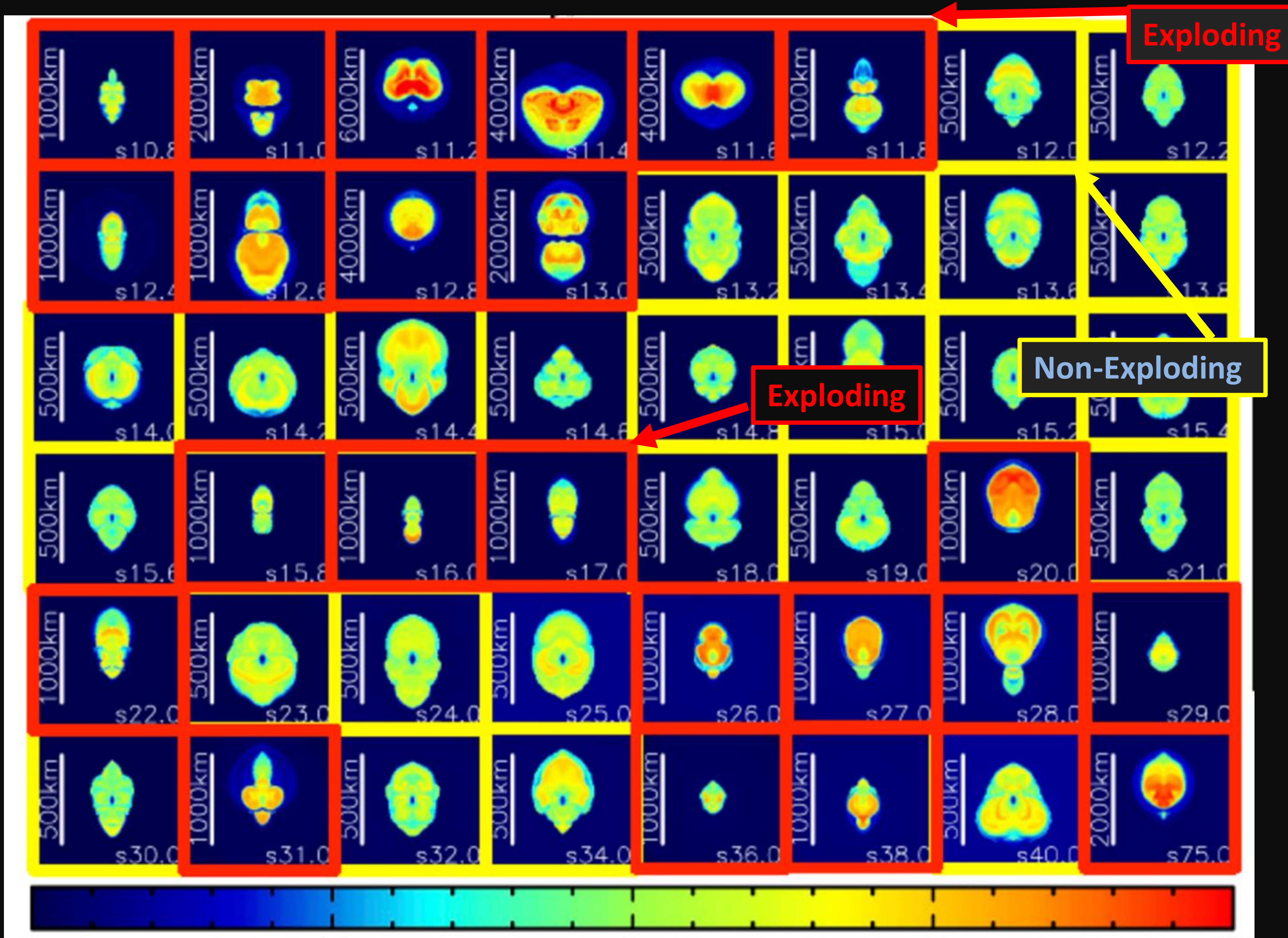
2D-IDSA simulations for 101 progenitors with solar metallicity

Nakamura et al. (2014)



“Systematics” between progenitor and explodability connections ?

Nakamura et al. (2015)



“Systematics” between progenitor and explodability connections ?

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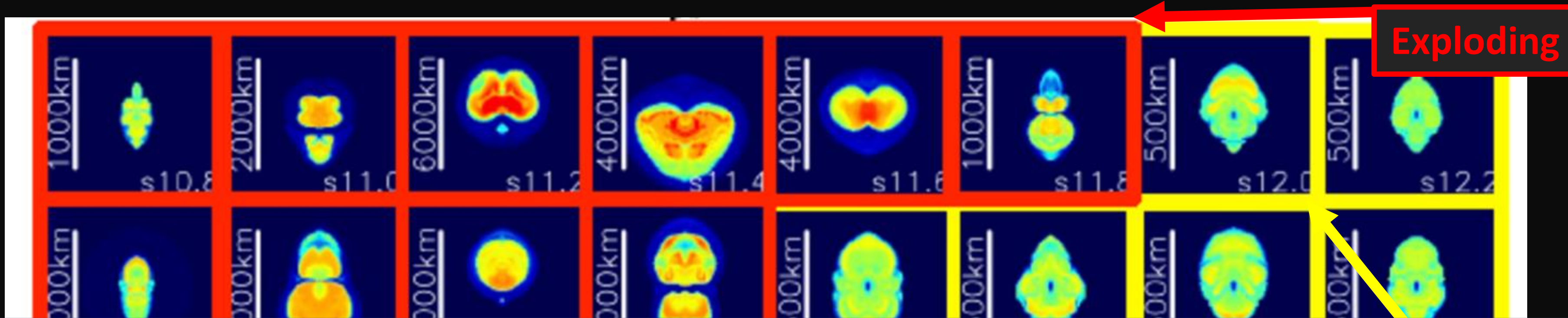
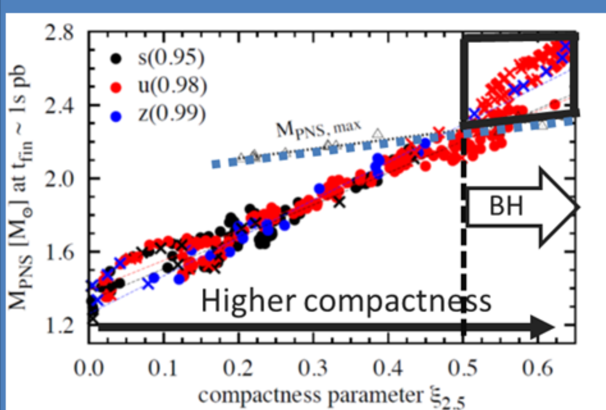
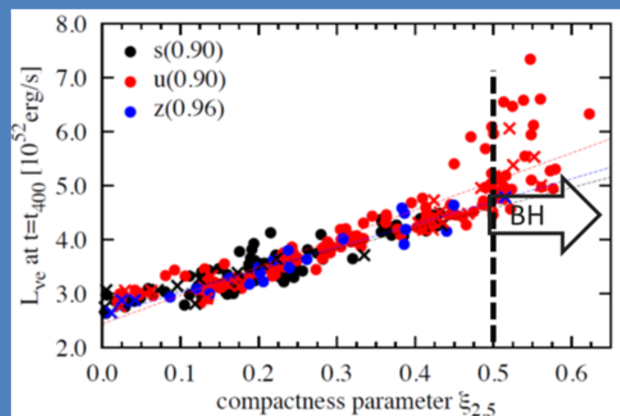


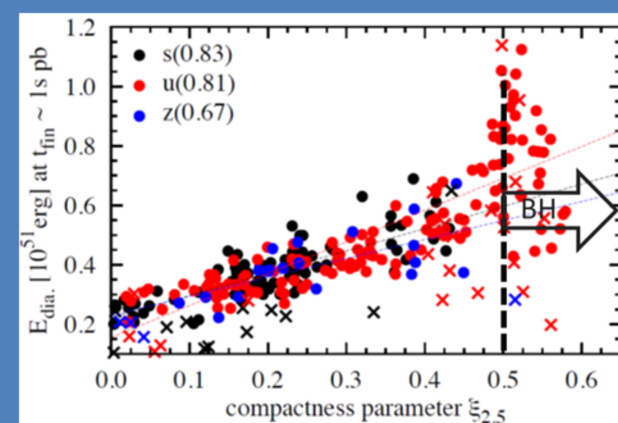
Mass accretion rate to PNS



Neutrino luminosity @ revival



Diagnostic explosion energy



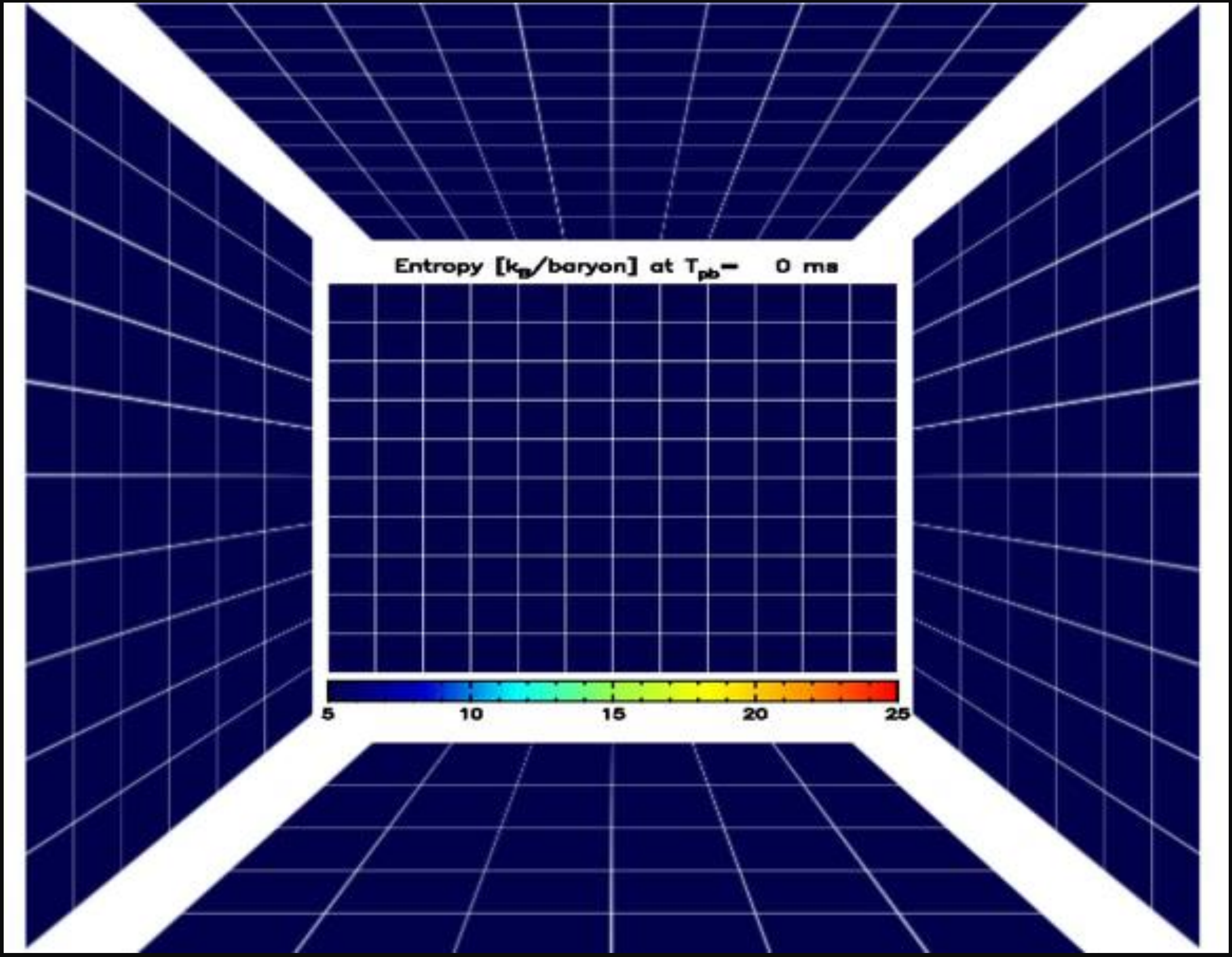
✓ “Progenitor mass” is a “not” good diagnostics for explosion.

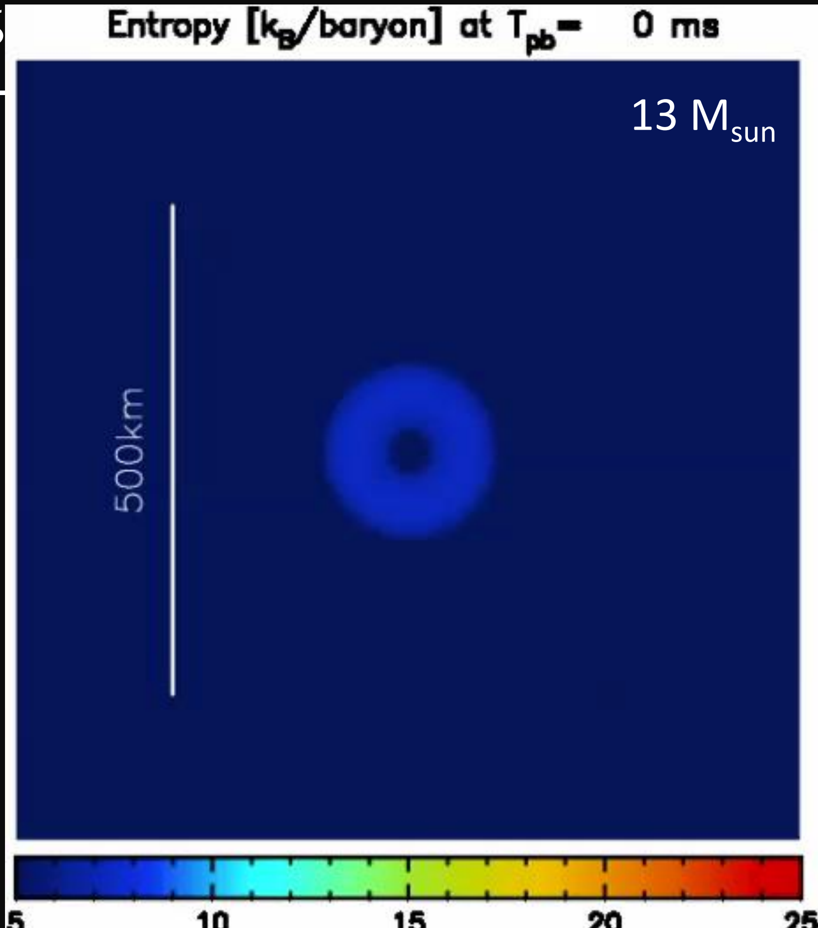
✓ **Key : “Compactness: M_{core} /R_{core}”** (O’Connor and Ott (2011))

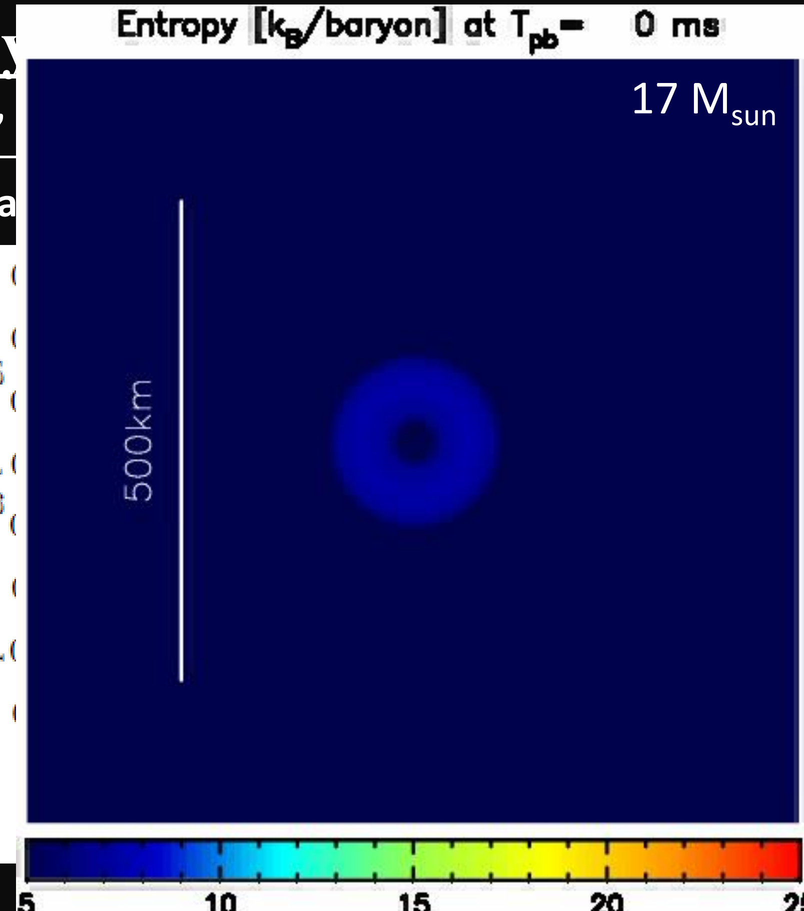
✓ Higher Compactness ⇒ Higher mass accretion to PNS ⇒ Heavier PNS ⇒ Higher neutrino luminosity ⇒ “Diagnostic” Exp. energy and Nickel mass higher (for the NS forming case) : Core-Collapse Supernova is initial value problem !

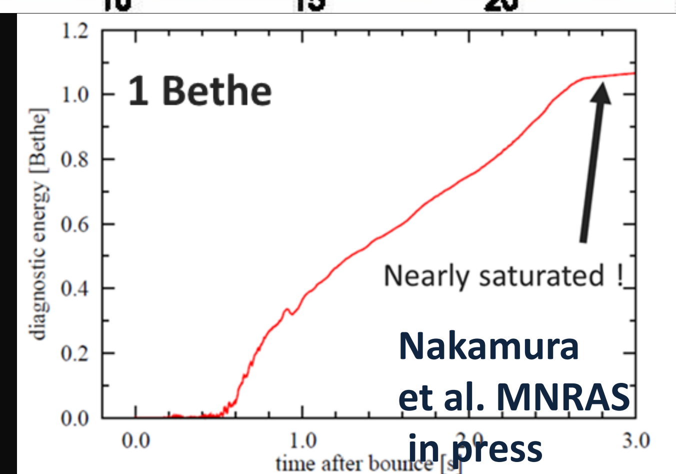
2D landscape simulations for 378 progenitors (WHW02)

Nakamura et al. (2015)







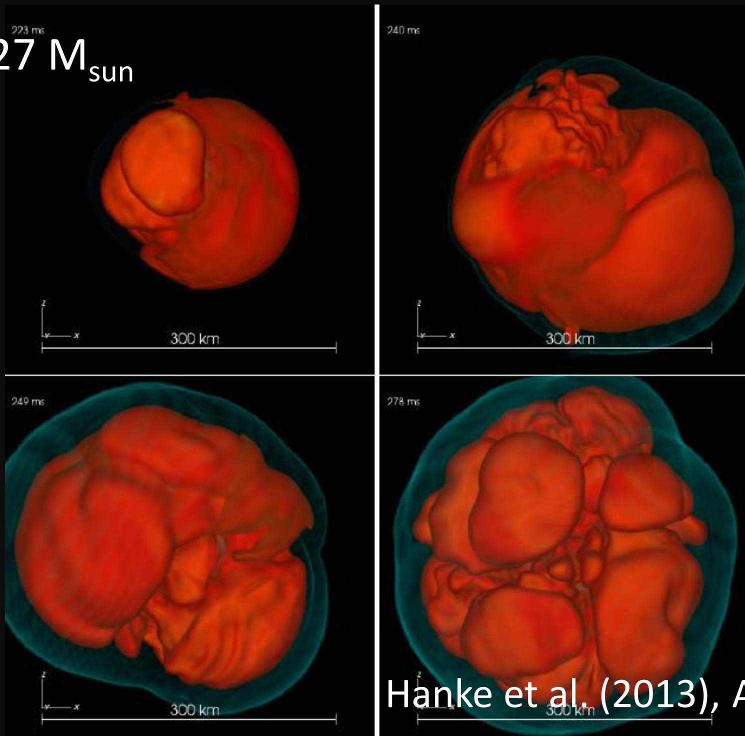


✓ The saturation timescales of explosion energy:
sensitive to the progenitor structures
→ Need to perform long-term evolutions for > 378 models !
(Nakamura et al. in prep)

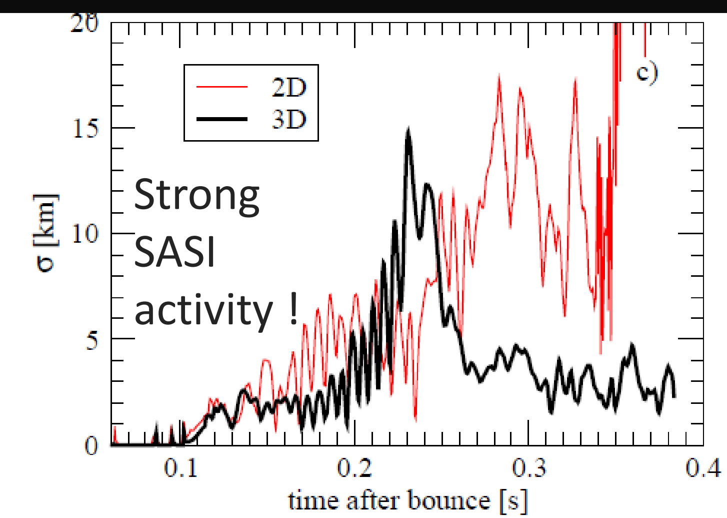
✓ ***Must go to 3D*** !

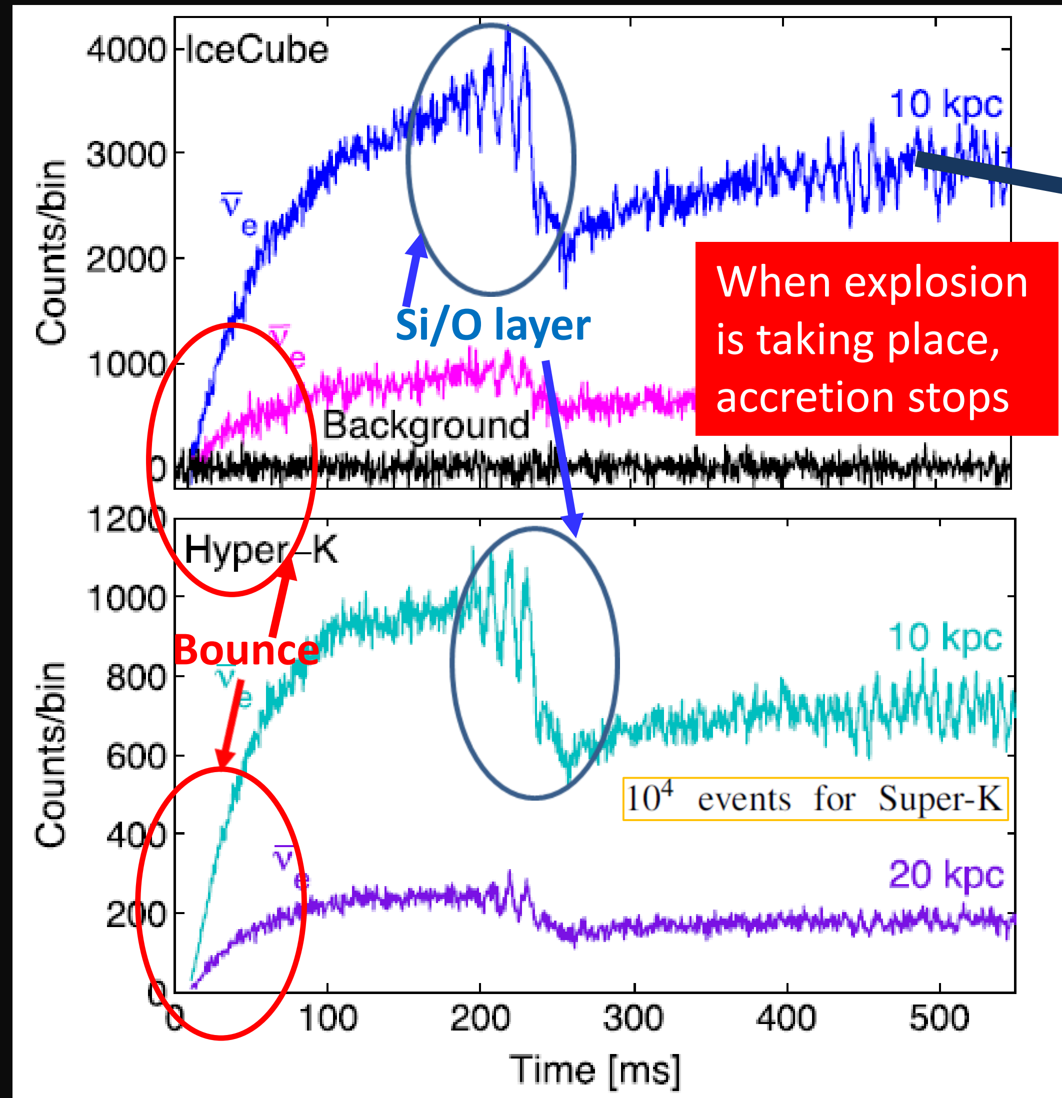
Neutrino signals from ab-initio 3D models : 27 M_{sun} (2/2)

Tamborra et al. (2013), PRL



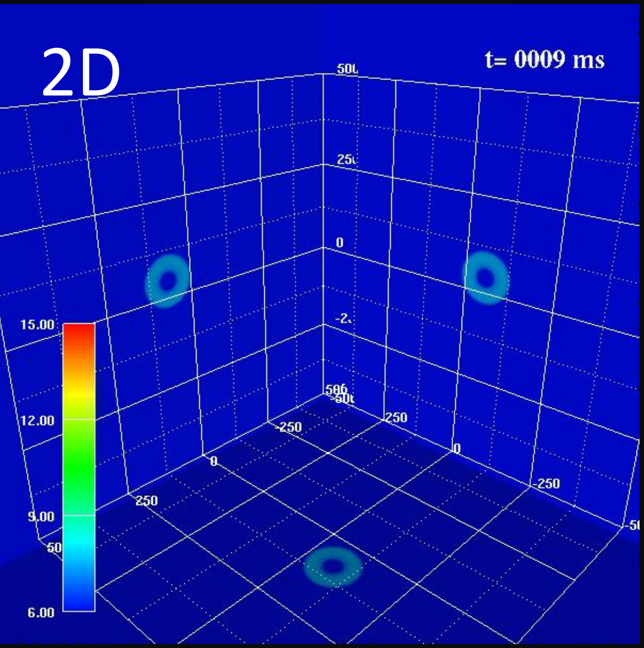
Hanke et al. (2013), ApJ



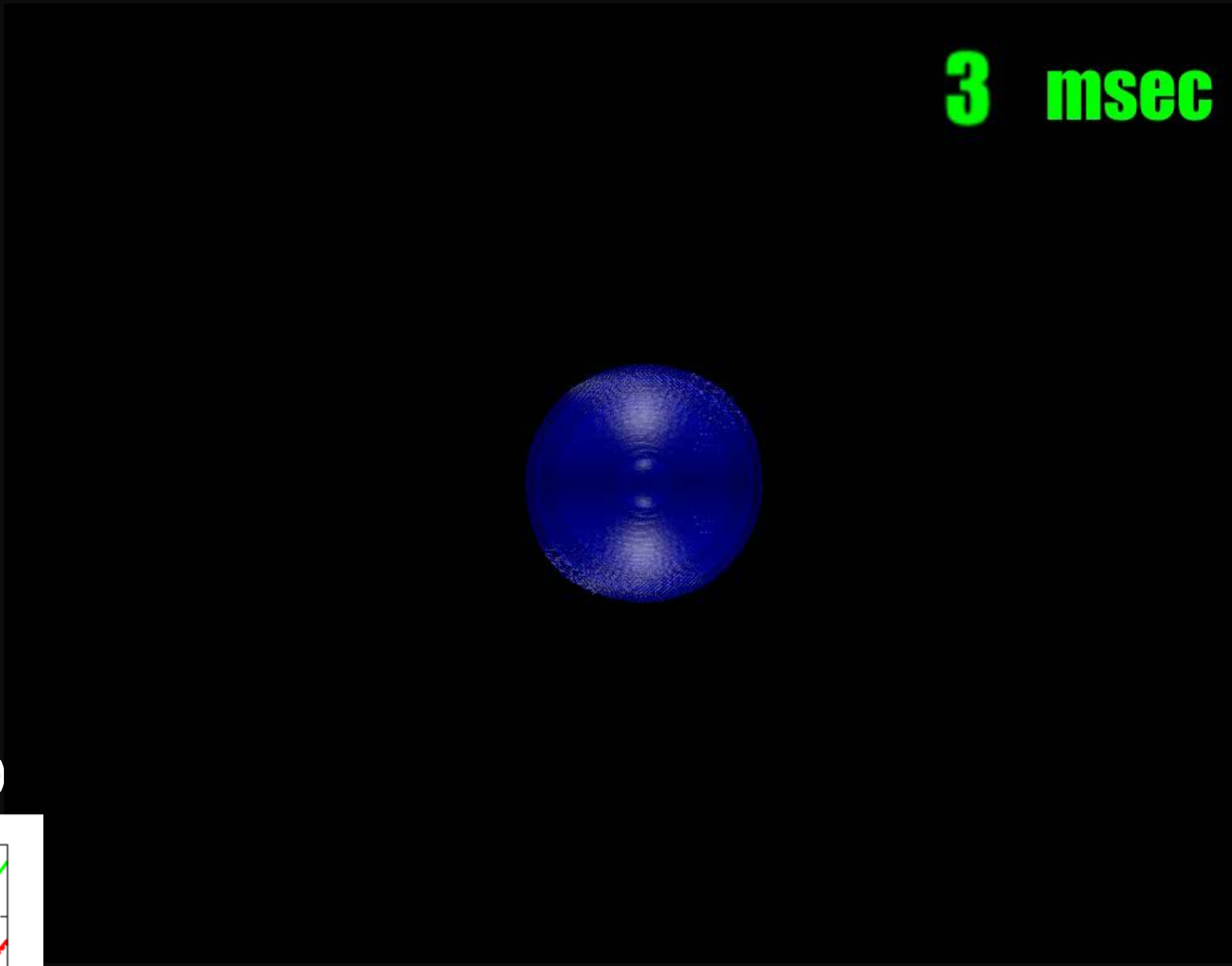


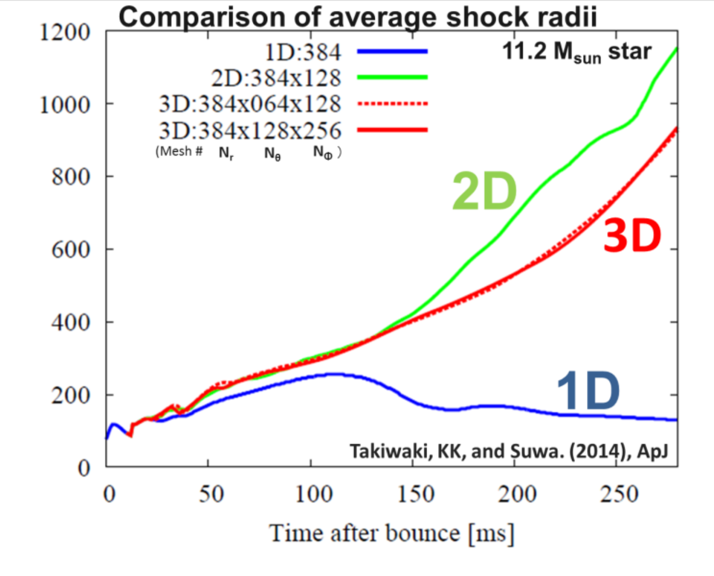
✓ **For a galactic source, we can learn much about SN physics ! (Bounce time, explosion onset/offset time, progenitor structure, SASI modulation timescales).**

3D vs. 2D



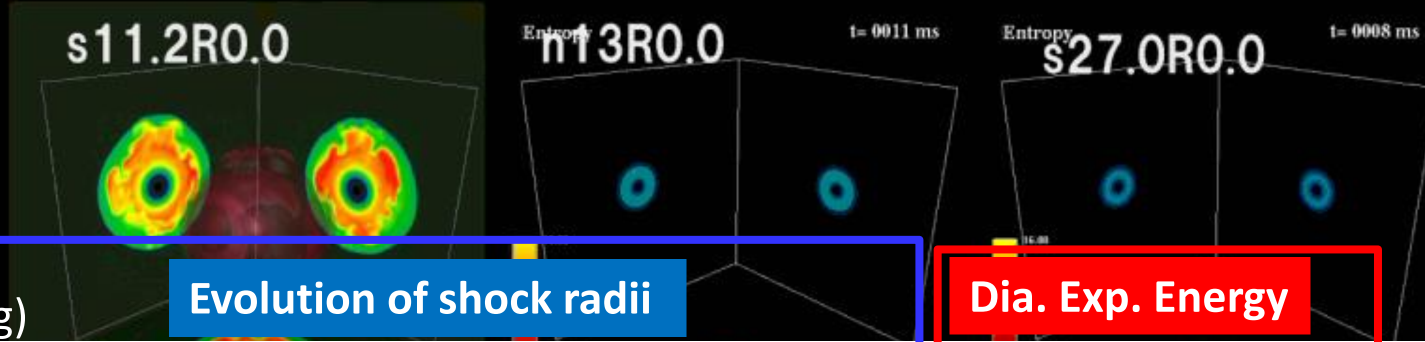
(e.g., Takiwaki,KK, Suwa (2012,2014), ApJ)





✓ For 11.2 M_{sun}, 3D explosions are weaker than 2D.
(27 M_{sun} : Hanke et al. (2014), however, not for 9.6 M_{sun} Melson et al. (2015))
⇒ The "3D vs. 2D problem" is progenitor dependent.
✓ No "Bethe" models obtained in 3D….

⇒ Need to find ingredients to foster 3D explosions !
Candidates: Rotation, General Relativity, Microphysics

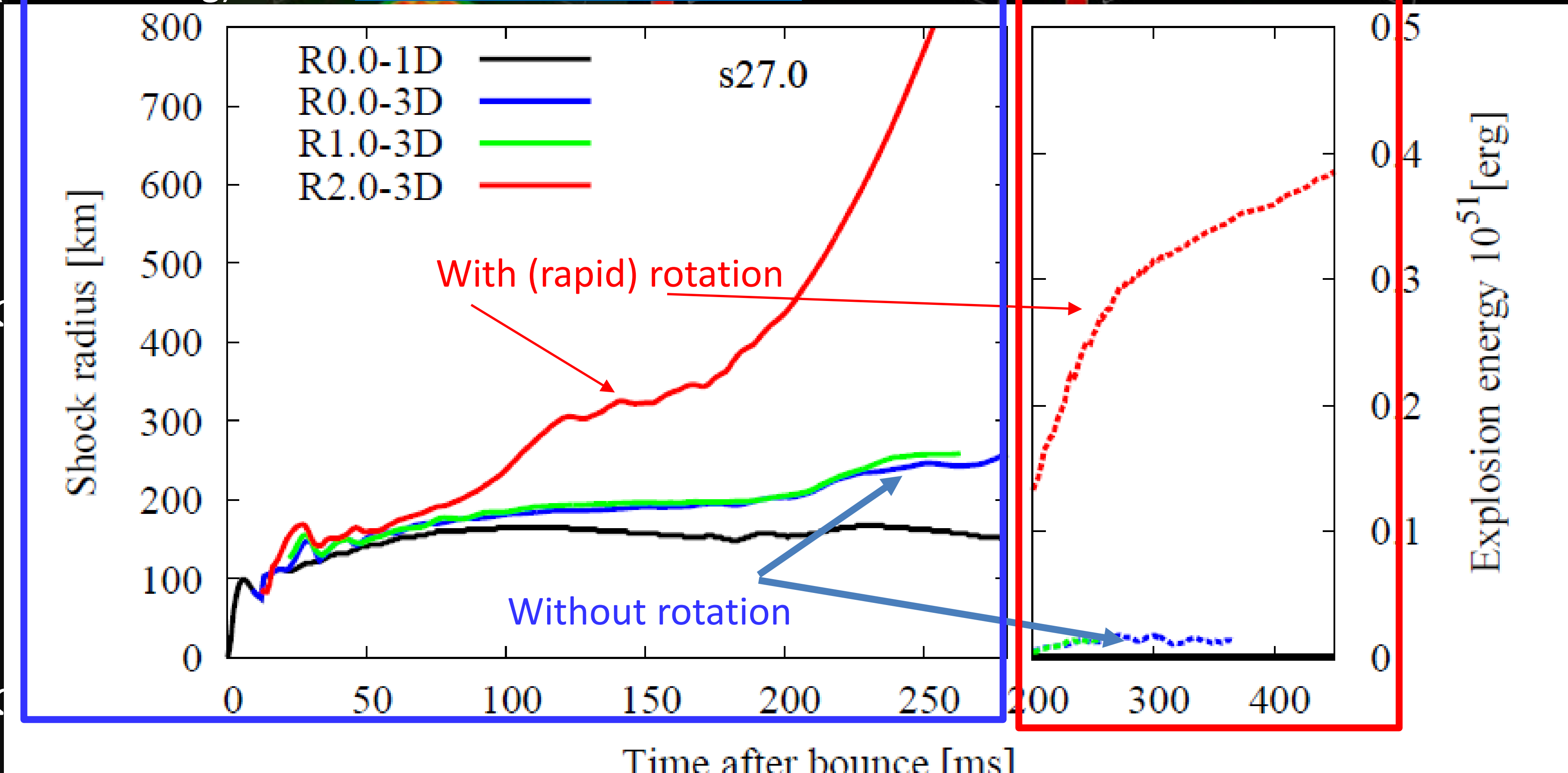


Takiwaki, KK, Suw
MNRAS Letters
In press

Ω_0 = 0 rad/s
(Non-rotating)

Evolution of shock radii

Dia. Exp. Energy

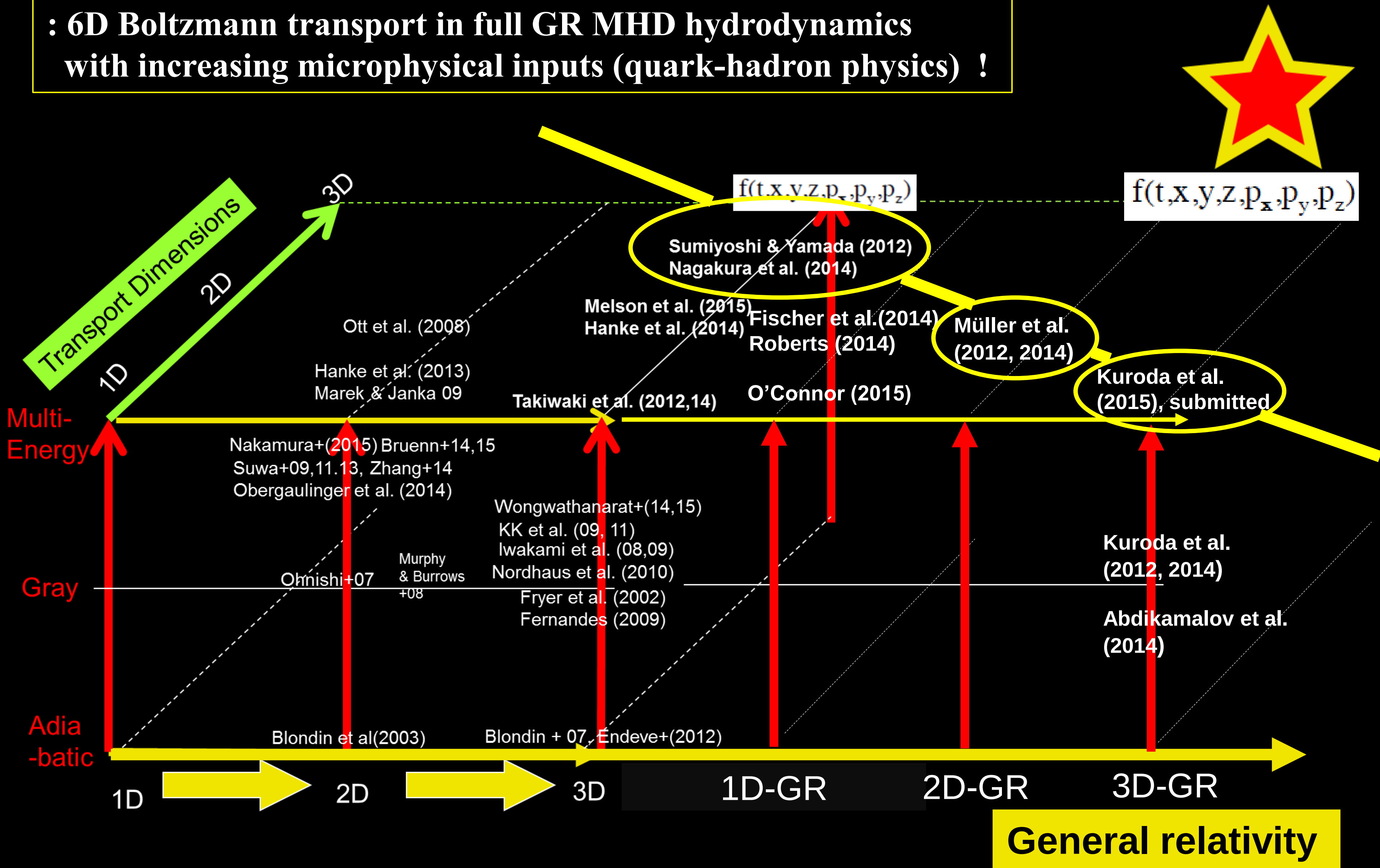


Rotation, depending on the initial rotation rates, can foster neutrino-driven explosions (see also, Nakamura et al. (2014), ApJ)

Ultimate requirement of CCSN simulations

Disclaimer: only CCSNs

: 6D Boltzmann transport in full GR MHD hydrodynamics with increasing microphysical inputs (quark-hadron physics) !



General Relativity (GR) important: Aid the onset of an explosion

(Deeper potential well : core structures smaller ⇒making both $\langle E_\nu \rangle$ and L_ν higher)

(e.g., B. Mueller et al. (2013), Kuroda et al. (2012))

✓ **3D full GR code with multi-energy neutrino transport via the M1 scheme:**

"FUGRA" : Fully General Relativistic code with neutrino transport

Kuroda, Takiwaki, and KK, ApJS. (2016)

The marriage of BSSNOK formalism (3D GR code, Kuroda & Umeda (2010, ApJS))

+ M1 scheme; Shibata+2011, Thorne 1981, (see also, Just et al. (2015), O'Connor (2015) for recent work)

$$(\partial_t - \mathcal{L}_\beta)\tilde{\gamma}_{ij} = -2\alpha \tilde{A}_{ij} \quad (11)$$

$$(\partial_t - \mathcal{L}_\beta)\phi = -\frac{1}{6}\alpha K \quad (12)$$

$$(\partial_t - \mathcal{L}_\beta)\tilde{A}_{ij} = e^{-4\phi}\left[\alpha(R_{ij} - 8\pi\gamma_{i\mu}\gamma_{j\nu}T^{\mu\nu}_{(\mathrm{total})} - D_i D_j \alpha\right]^{\mathrm{trf}} + \alpha(K\tilde{A}_{ij} - 2\tilde{A}_{ik}\tilde{\gamma}^{kl}\tilde{A}_{jl}) \quad (13)$$

$$(\partial_t - \mathcal{L}_\beta)K = -\Delta\alpha + \alpha(\tilde{A}_{ij}\tilde{A}^{ij} + K^2/3) + 4\pi\alpha\left(n_\mu n_\nu T^{\mu\nu}_{(\mathrm{total})} + \gamma^{ij}\gamma_{i\mu}\gamma_{j\nu}T^{\mu\nu}_{(\mathrm{total})}\right) \quad (14)$$

$$(\partial_t - \beta^k\partial_k)\tilde{\Gamma}^i = 16\pi\tilde{\gamma}^{ij}\gamma_{i\mu}n_\nu T^{\mu\nu}_{(\mathrm{total})} - 2\alpha\left(\frac{2}{3}\tilde{\gamma}^{ij}K_{,j} - 6\tilde{A}^{ij}\phi_{,j} - \tilde{\Gamma}^i_{jk}\tilde{A}^{jk}\right)$$

Complete set of GR-hydrodynamics equations

Solve the following equations:

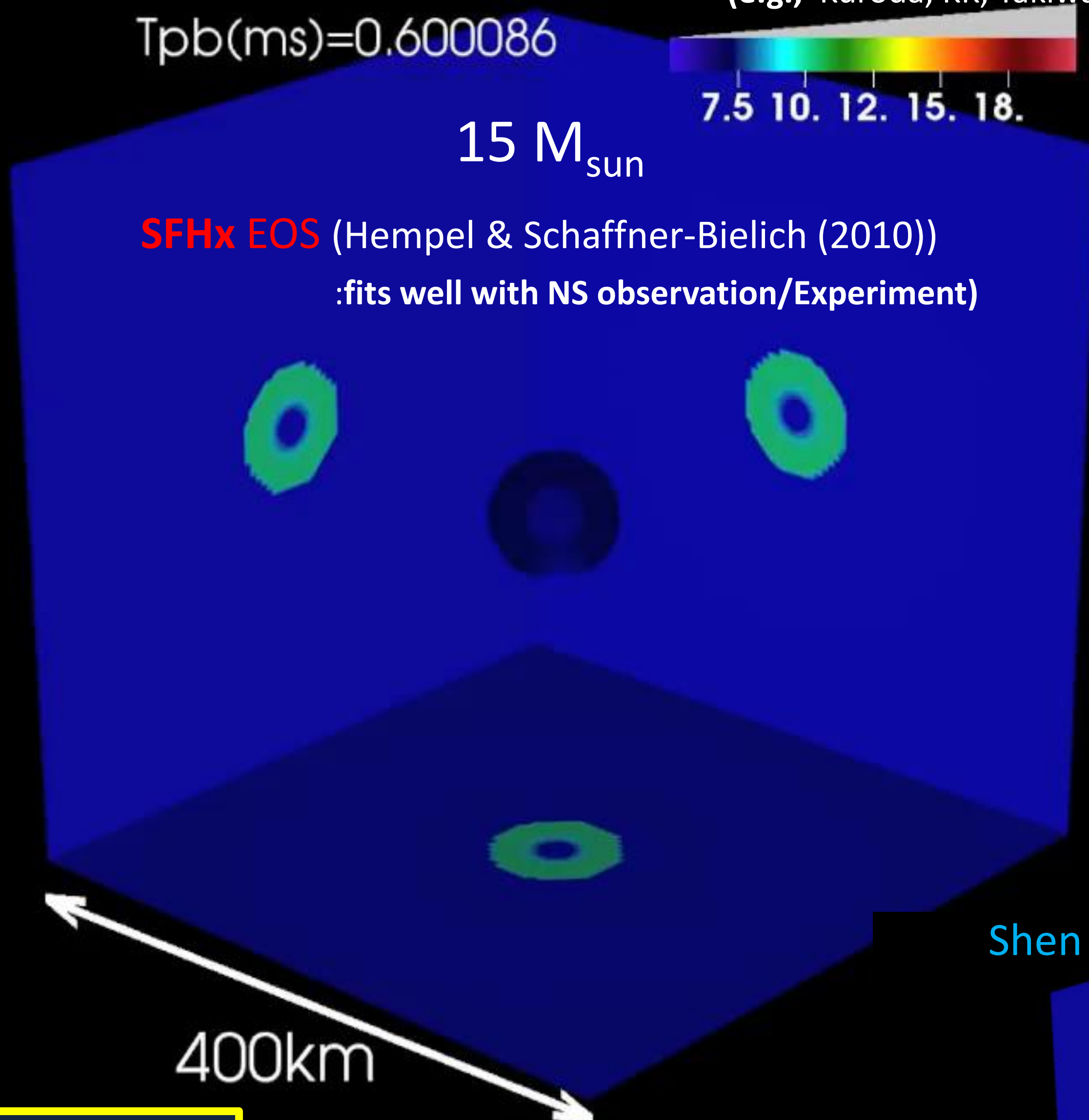
$\nabla_\mu\left(\rho u^\mu\right) = 0$	Continuity
$\nabla_\mu T^\mu_\nu = 0$ + EOS Table	HD/MHD
$\nabla_\mu\left(\rho Y_e u^\mu\right) = Q_e$	Electron fraction
$G_{\mu\nu} = \kappa T_{\mu\nu}$	
$p^\mu \frac{\partial f}{\partial x^\mu} + \dot{p}^\mu \frac{\partial f}{\partial p^\mu} = S[f, \rho, T \ldots]$	

✓ **1000ms/(4 ms (gray FUGRA) per day @4096 processors)**
~ 250 days …. ($R_{shock} > R_{iron}$)
> 2500 days … ($R_{shock} > R_{star}$);

✓ **Need next-generation (exa-scale) platforms !**
(such as the upgrade of Tianhe (China),
Titan (Oak-Ridge) /Coral (Livermore), K (Riken))

✓ **Results from gray (energy-averaged) version of FUGRA**

(e.g., Kuroda, KK, Takiwaki, 2012, ApJ, 2014, PRD)

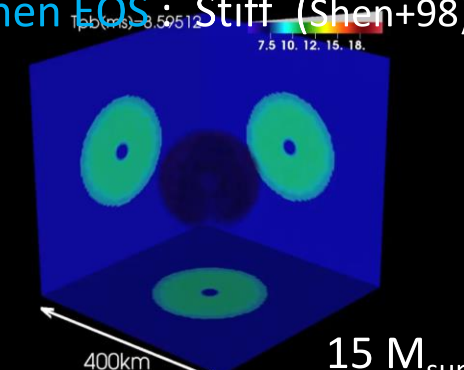


15 M_{sun}

SFHx EOS (Hempel & Schaffner-Bielich (2010))

:fits well with NS observation/Experiment)

Shen EOS : Stiff (Shen+98)



15 M_{sun}

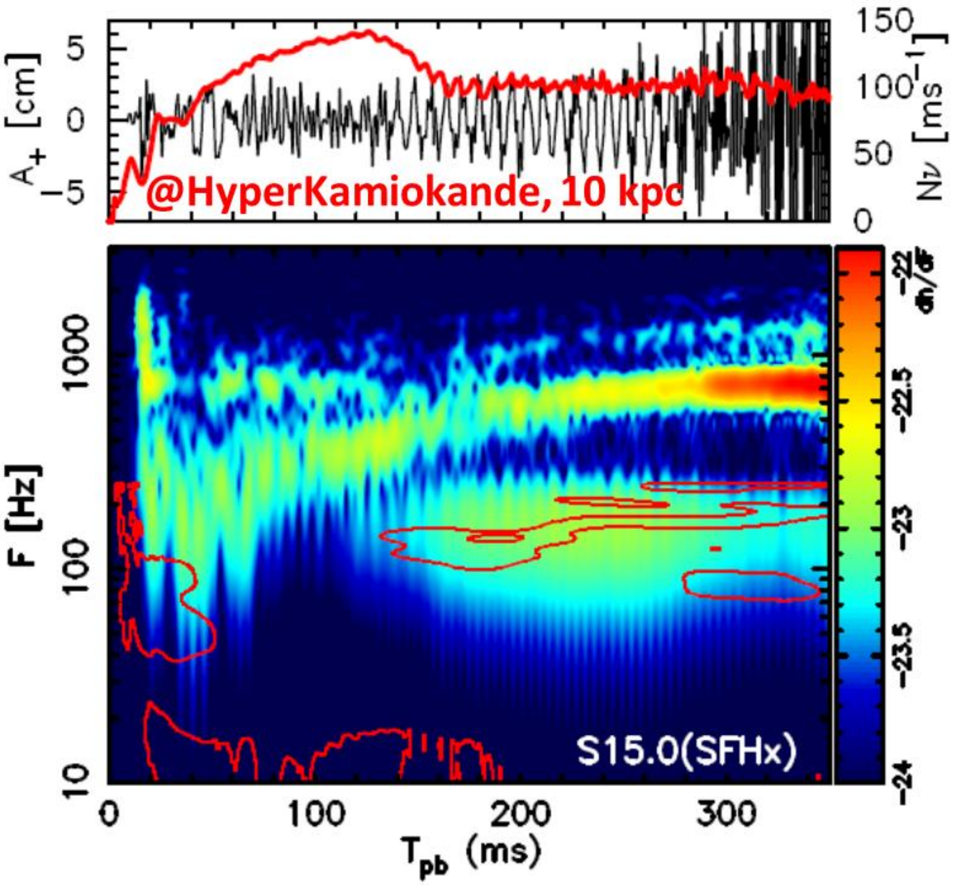
✓SASI activity higher for softer EOS

Kuroda, KK, Takiwaki (in prep)

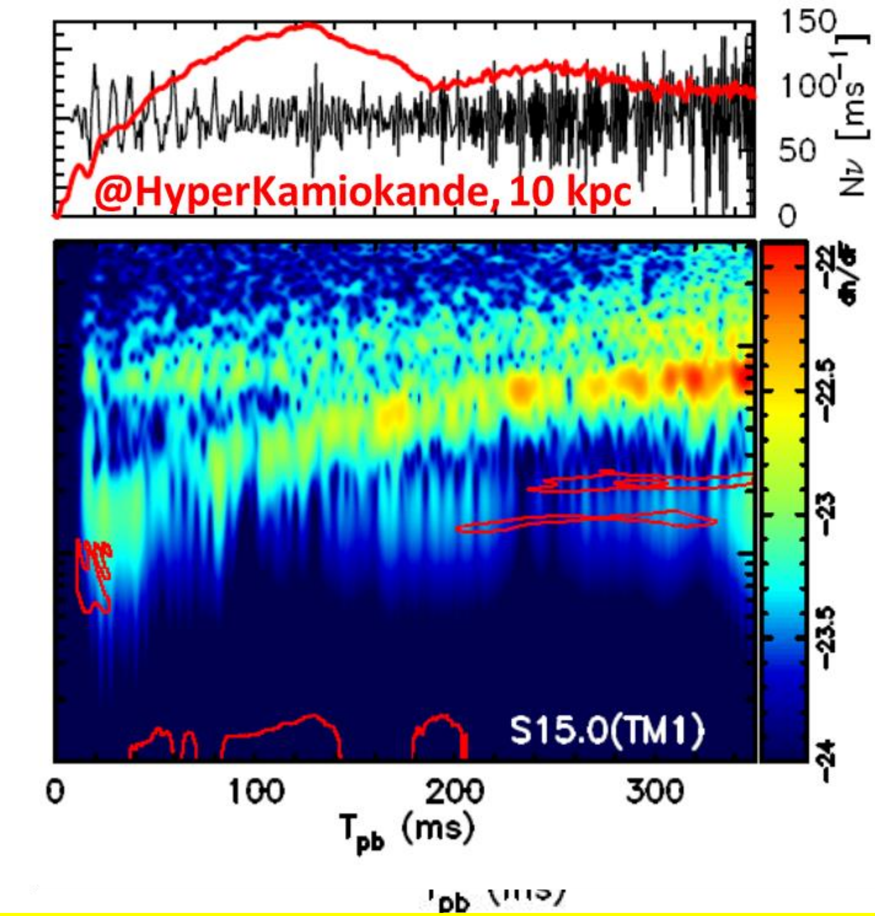
GW Spectrograms from 3D-GR model with strong SASI vs. weak SASI activity

Kuroda, KK, & Takiwaki (2016)

SFHx EOS



SHEN EOS



✓The quasi-periodic modulation of GW signals ⇒ the SASI timescales (~ 100 Hz).

✓More clearer excess for softer EOS ⇒ Possible probe to nuclear EOS.

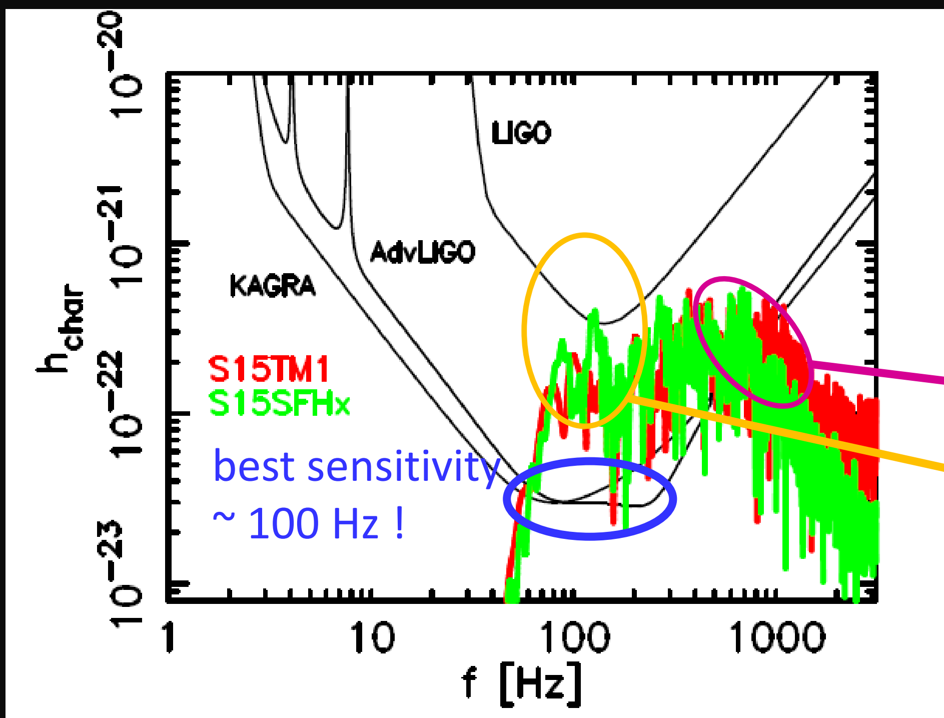
✓For neutrino signals, **Super-Kamiokande** : back-ground free (nicer than ICECUBE), can detect SASI-mod. signals for a Galactic event, Hyper-Kamiokande (2020) for an extragalactic event !

GW signal reconstruction by Coherent Network Analysis

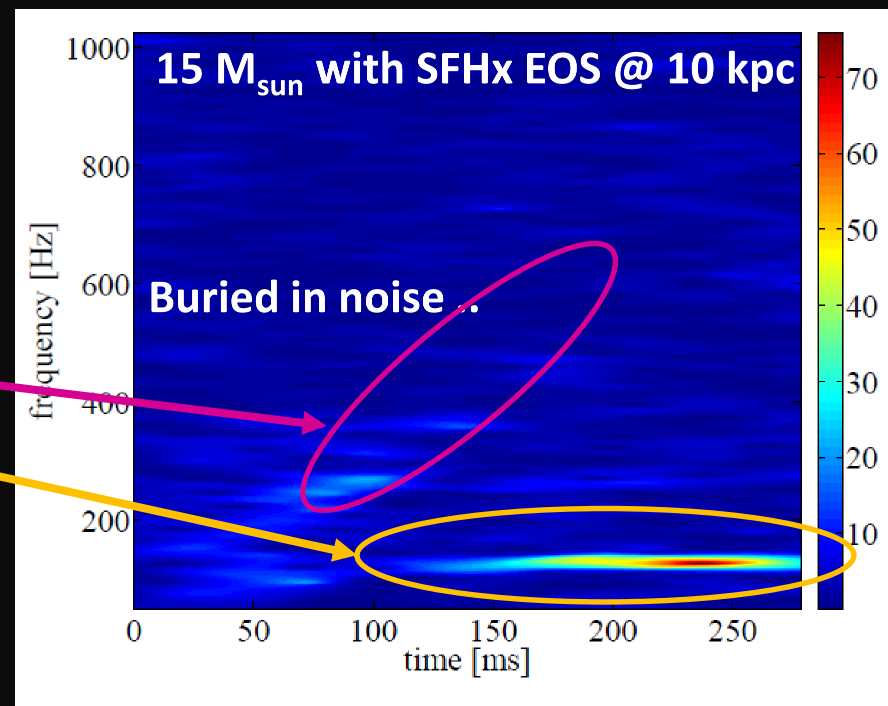
✓LIGOx2, VIGRO, KAGRA

Hayama, Kuroda, KK, & Takiwaki
PRD (2015)

Sensitivity curves and model predictions



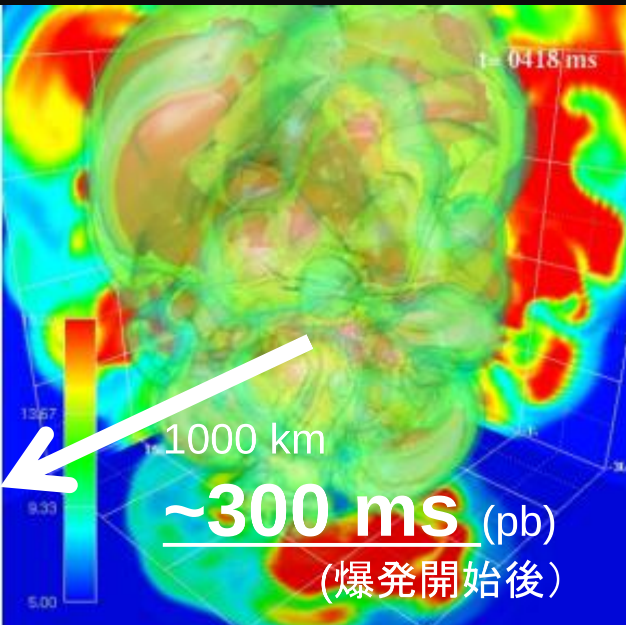
The reconstructed GW spectrogram



✓ The, quasi-periodic, SASI-modulated GW in the best sensitivity range of interferometers.
✓ Coherent network analysis: these signals detectable out to the LMC (50 kpc).

Perspectives: Where are we and where are we going ?

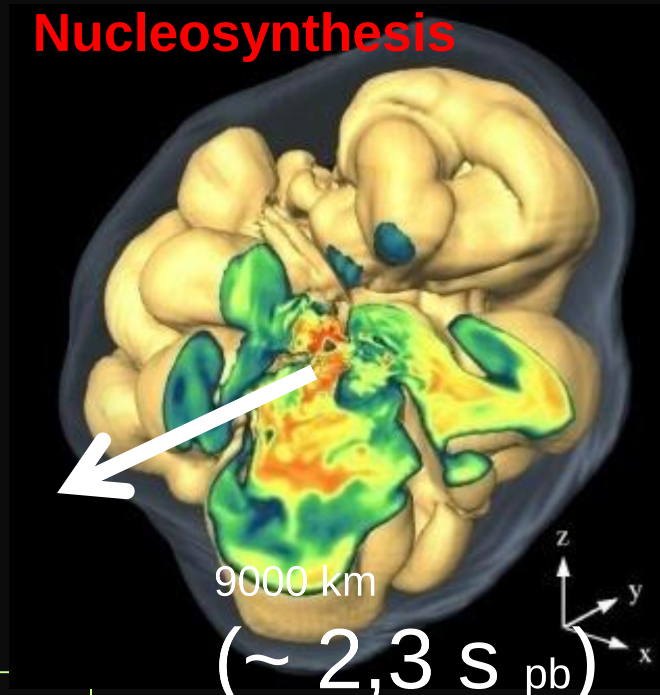
"A" self-consistent 3D model



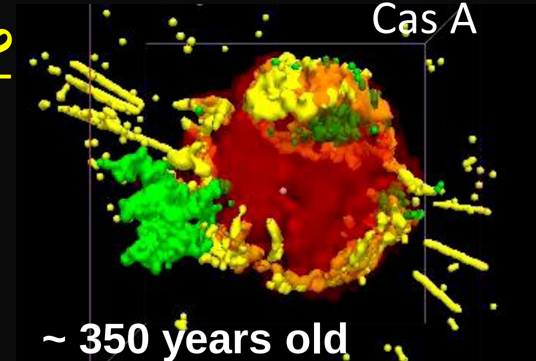
Takiwaki, KK, Suwa (2014,2012 ApJ)

For an 11.2 M_{sun} star,
the stalled shock revived !
(4D with approximate transport)

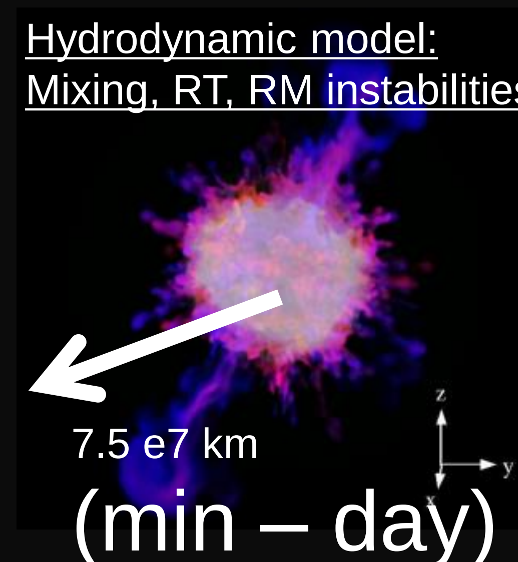
Gray-transport simulation



Wongwathanarat et al. (2012)



DeLaney et al. (2010)



(min – day)

Wongwathanarat et al. (2014)

To-do-1: Long-term evolution in self-consistent 3D (GR) models
⇒ confront CCSN theory with observation

To-do-2 : Full Boltzmann project :
⇒ ultimately test whether the stalled shock would revive.

SN 20xx ! in the Galactic center: End-to-End Bridging Simulations

sec — min — hours — day — years

- 4 — - 3 — - 2 — - 1 — 0 — 2 — >3

Log (day)

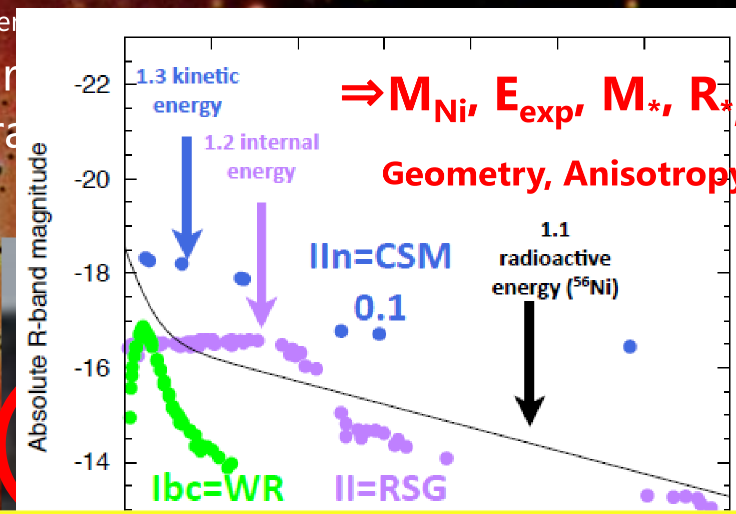
SK detects ~ 10,000 neutrinos

< 15min SURGE meeting (Supernova Urgen

< 1 hour SK provide alert: Astronomer
(onset of neutrino burst, dura

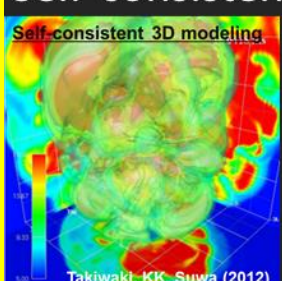
K & SK

Post-K, Hyper-K, KAGRA



Self-Cons SN Simulations

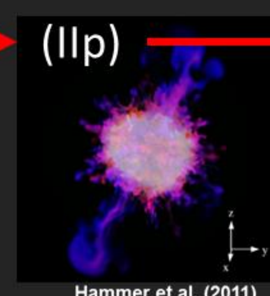
Self-consistent

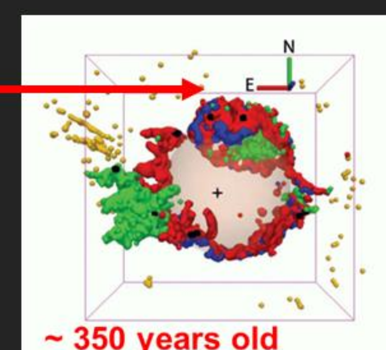


Shock-breakout

(Ib/Ic)

(IIp)





Summary

1. In 2D, a number of explosion models (> 400) obtained by independent groups.
   Some are enough energetic to account for observations (E_{exp}, Ni).

2. 3D explosions generally under-energetic than 2D.
   - progenitor dependence yet unclear.

   ✓ Need to find some ingredients to foster 3D explosions.
   - some missing neutrino physics ? (e.g., Melson et al. (2015))
   - Impacts of rotation (and magnetic fields) yet to be clarified in 3D self-consistent models.
     (e.g., MRI, Obergaulinger+2009, Masada, Takiwaki, KK, 2015, Sawai+2014))

3. 3D GR modelling has just started with increasing microphysical inputs.
   (e.g., FUGRA, it takes time … next generation machines needed !)

4. Multi-messenger analysis of neutrino and GWs are in steady progress.
   : ⇒ important probe to the explosion physics for the SN20xx !

(for reviews, google on
“Thomas Janka, Adam Burrows,
supernova review”

Many thanks!