Multi-D Core-Collapse Supernova Models and the Multi-messenger Observables

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Recent *milestone* progress in the CCSN theory (and around)

(see Foglizzo + (2015), Mezzacappa + (2015), Janka (2012), Burrrows (2013), Kotake + (2012) for reviews)

Keys : Progenitor structures, Core-collapse modeling/physics, Comparison with observations

1st topic: Presupernova studies:

Systematics : Sukhbold & Woosley (2014), Jones et al. (2015), Woosley et al. (2002)…

Rotation: Fuller et al. (2015) Belyaev, Quataert, Fuller et al. (2015), Georgy et al. (2013)…

Multi-D : Arnett and Meakin (2011), Couch et al. (2015), A[illegible] et al. (2015)….

2nd topic: Core-Collapse SN theory/Modeling / [illegible]crophysics:

Compactness/derivatives : O'Connor & Ott (2011), Ugliano et al. (2012),

2D Nakamura et al. (2014), Ertl et al. (2015), Pejcha & Thompson(2015)

Accretion history: Suwa et al. (2014), Dolence et al. (2015), Ertl et al. (2015)…

Density inhomogeneity: Couch & Ott (2013), Müller & Janka (2015)…

SASI: Fernández (2015), Handy et al. (2014), Fernández et al. (2014), Hanke et al. (2012) …

Turbulence: Murphy and Meakin (2011), Murphy et al. (2013),

Dolence et al. (2013), Abdikamanov et al (2014), Couch & Ott (2015)…

Weak interactions: Grabowska et al. (2015), Rrapaj et al. (2015), Horowitz et al. (2012)…

CC simulations: Melson et al. (2015a,b), Lentz, Bruenn, Hix et al. (2015), Pan et al. (2015)…

3rd topic: Prediction of CCSN Muti-Messengers:

Neutrinos: Tamborra et al. (2013,2014), Patton, Kneller & McLaughin (2014), Scholberg (2012)..

Gravitational waves: Kuroda et al. (2014), Fuller et al. (2014), Yokozawa et al. (2014), KK(2013)

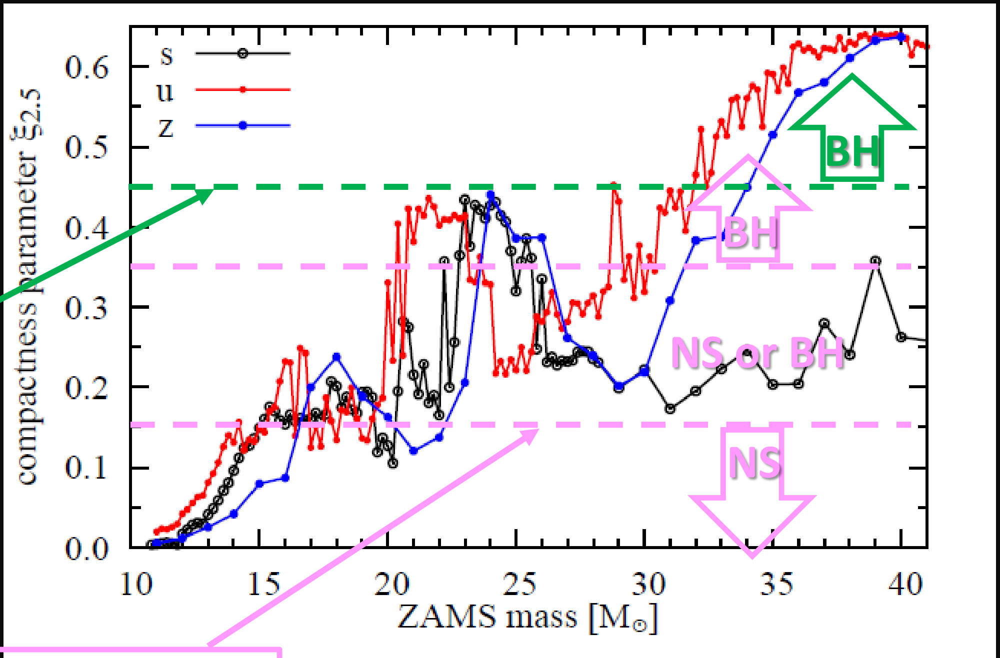
Constraint from electromagnetic waves: Gerke+(2015), Kochanek (2015), Horiuchi +(2014)..

✓"Progenitor Compactness" Parameter
as an explosion diagnostics

(O'Connor and Ott (2011))

$$\xi_{2.5} \equiv \frac{M/M_\odot}{R(M)/1000\,\mathrm{km}}$$ @ $M = 2.5\,M_\odot$

(the choice is arbitrary)



✓ Previous 1D models

O'Connor & Ott (2011); the BH formation requires $\xi_{2.5} > 0.45$

Ugliano et al. (2012); explosion $\xi_{2.5} < 0.15$, BH $\xi_{2.5} > 0.35$

378 models (101 solar(s), 247 ultra-metal poor ($Z = 10^{-4}$), 30 zero metal, Woosley et al. (2002), hereafter WHW02).

How about in multi-D self-consistent models ?

Numerics in both our 2D and 3D models (e.g., **Suwa** et al. (2011,2012,2013) for details, code comparisons)

✓IDSA spectral transport (Liebendoerfer+09) with the Bruenn-type rates (Bruenn 1985).

✓Lattimer-Swesty (1991) EOS (K=220 MeV) /Nuclear burning by alpha-network calculations.

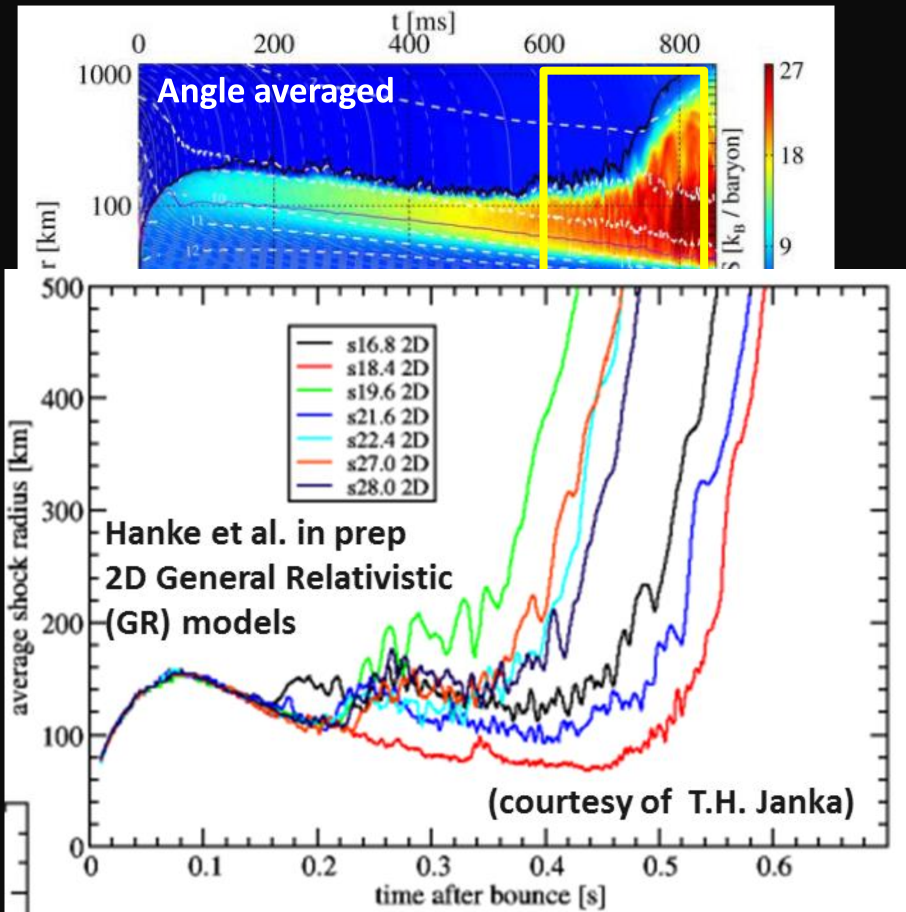
Note : Newtonian, velocity-dependent terms, energy-coupling reactions are currently off.

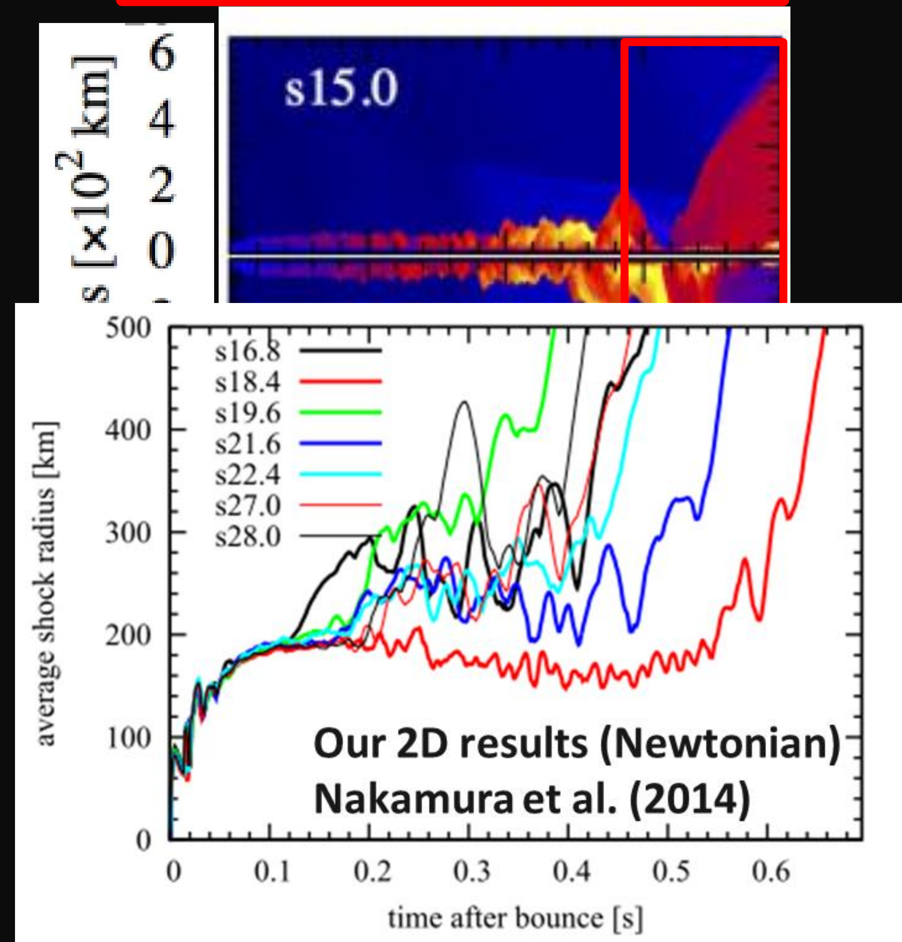
Comparison of 2D results between different CCSN codes ?

Using the same progenitor model (15_{sun} star (WHW02)).....

Obergaulinger et al. (2014) MNRAS
2D Post-Newtonian with LS220 EOS,
M1, two species ν

Nakamura, Takiwaki, Kuroda, KK (2014)
2D Newtonian with LS220 EOS,
IDSA (two species ν) + leakage for ν_x

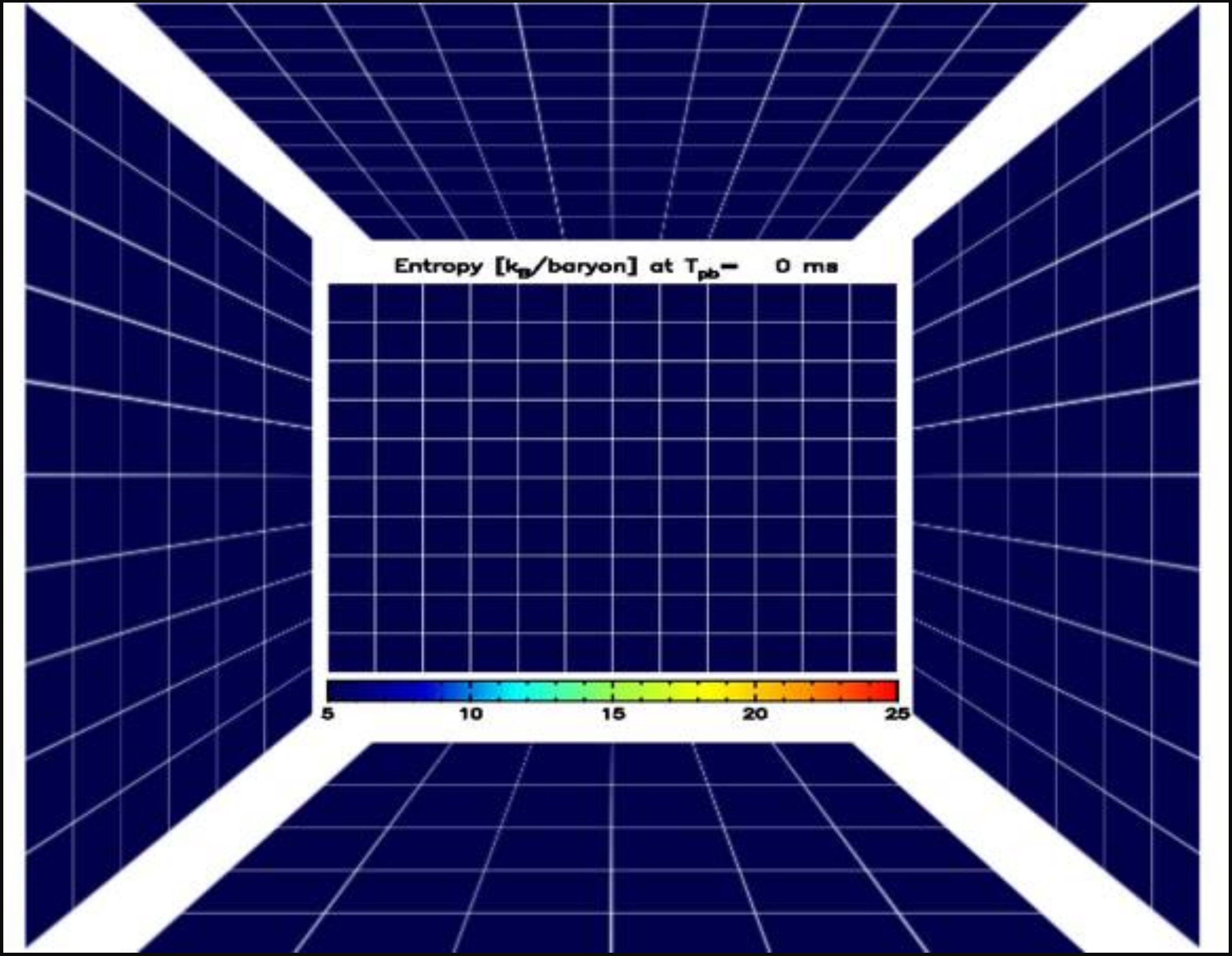




- ✓ (Mainly) due to the omission of neutrino electron scattering, the bounce shock at larger radii in our model.
- ✓ Due to the omission of GR, PNS contraction/shock recession weaker in our models.
- ✓ My take: "relatively similar" (e.g., shock trajectory, revival time) between the Valencia code , VERTEX PROMETHEUS/COCONUT, and our IDSA-ZEUS code.
  Reflecting the stochastic nature of explosion, the post-bounce evolution not exactly the same !
- ✓ Detailed comparison needed ! (FOE2015 is a good start !!)

2D-IDSA simulations for the 378 progenitors (WHW02)

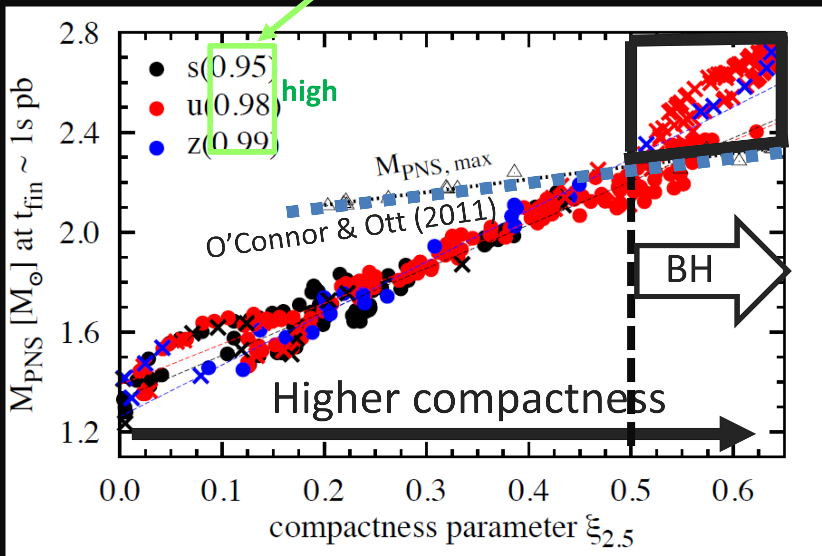
Nakamura et al. (2015)

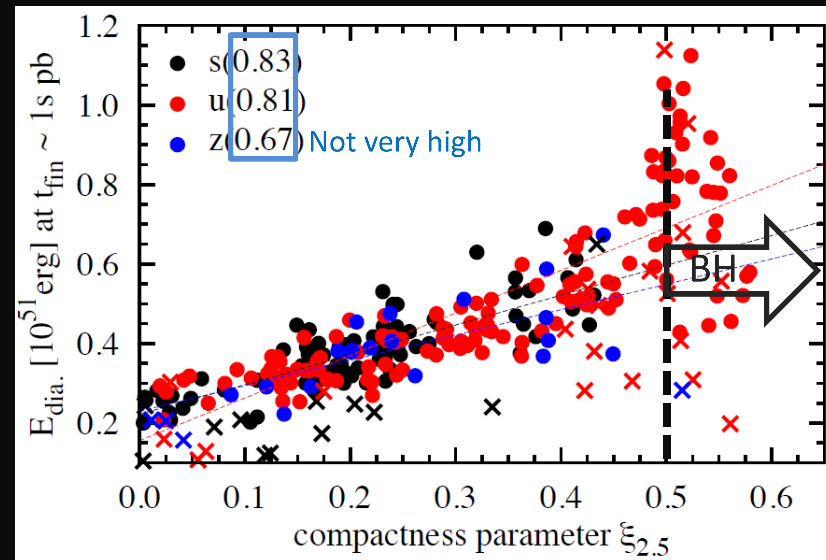


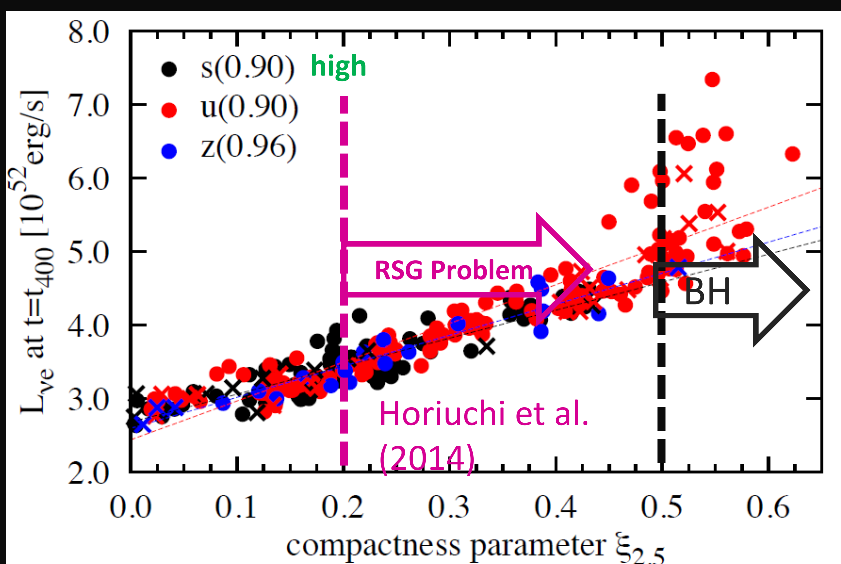
Systematics on the Progenitor Compactness (ξ) and the Explodability connections

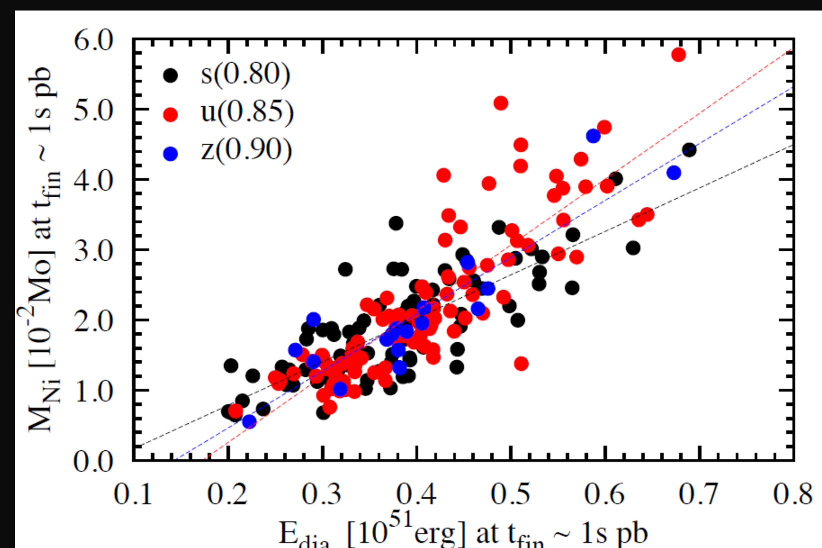
Correlation coefficients

Nakamura et al. (2015)







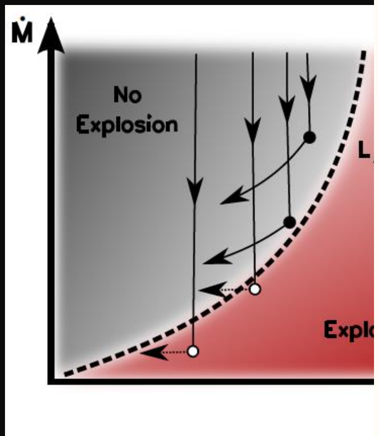


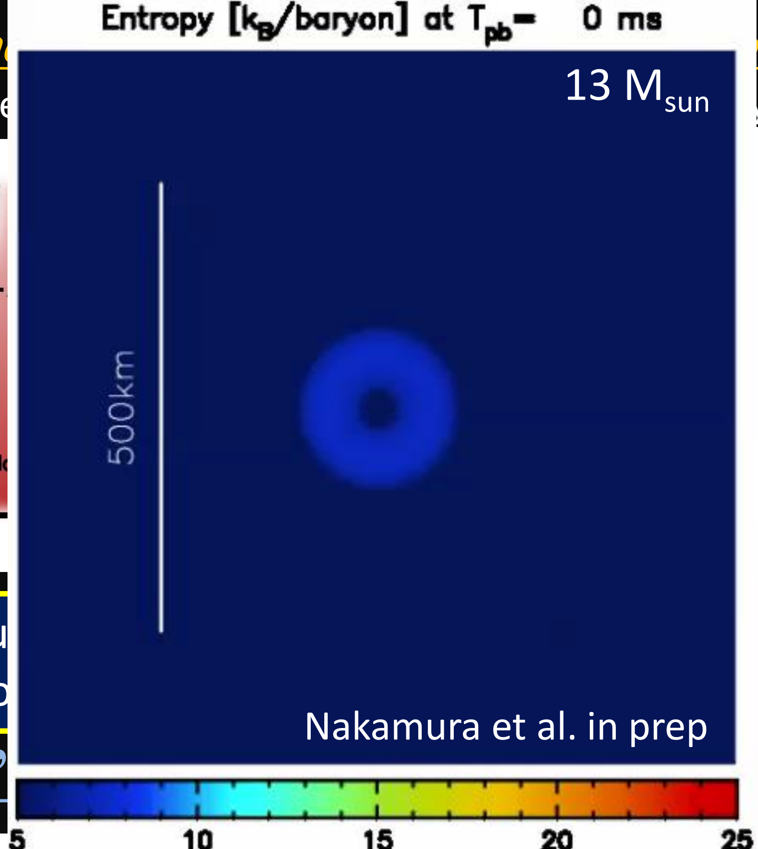
✓ Higher Compactness ⇒ Higher mass accretion to PNS ⇒ Heavier PNS ⇒ Higher neutrino luminosity aided by multi-D fluid motions ⇒ Diagnostic exp. energy and Nickel mass higher (for the NS forming case)

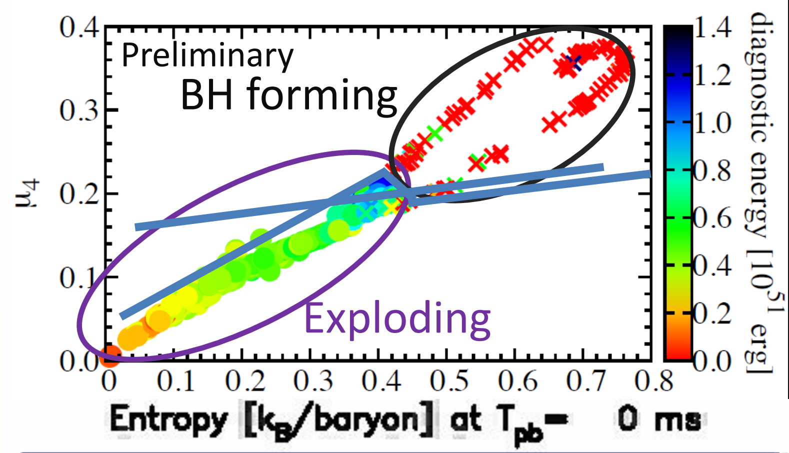
✓ General Relativistic (GR) simulations needed for BH forming (fall-back) CCSNe ✓ 2D explodability may be too high.

Is the compactn… sion diagnostics ?

The critical-curve … y + (2008), Dolence + (2015), Suwa + (2014))

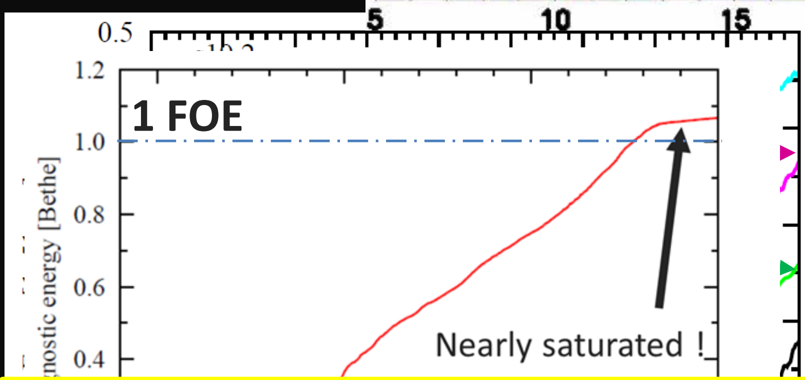


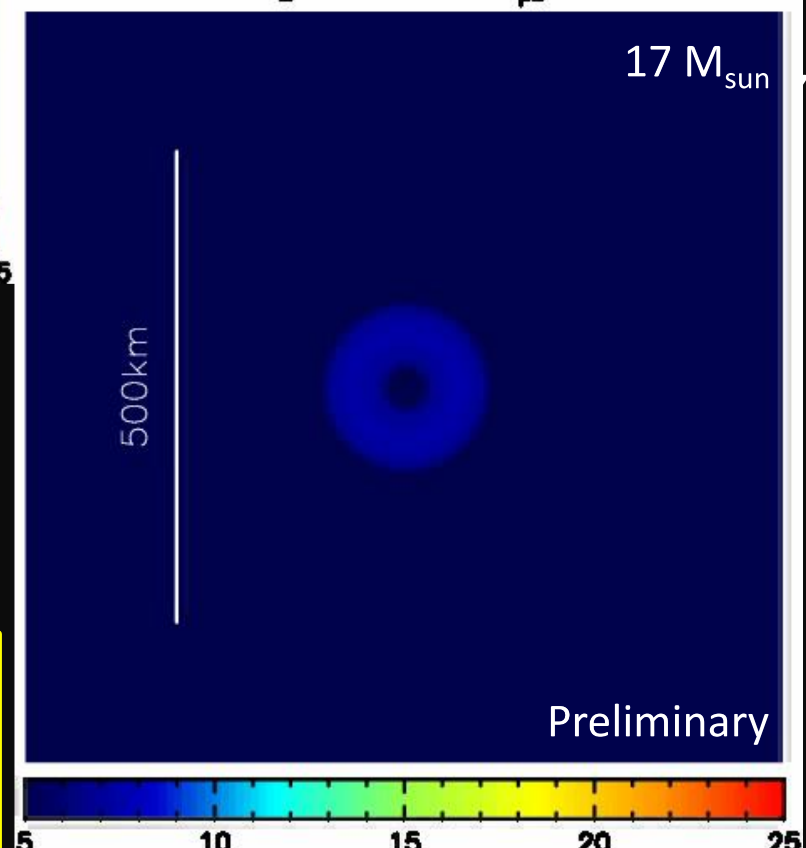




Our results are su…
but the separatio…

“Diagnostic”

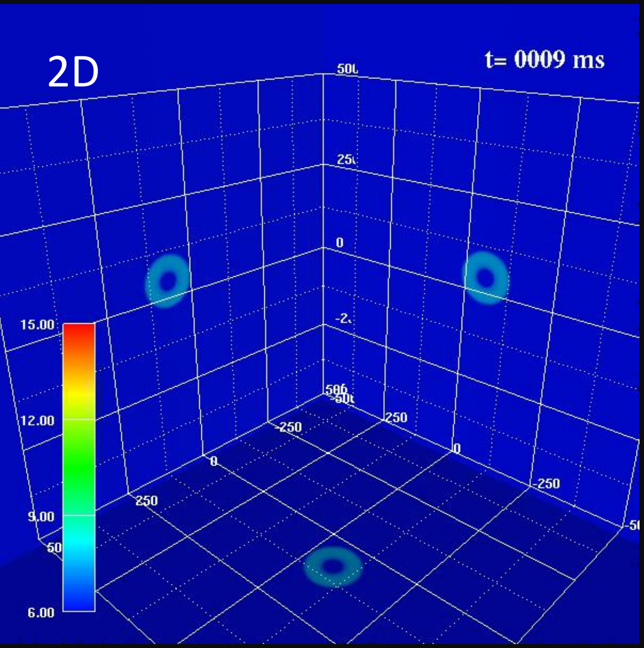




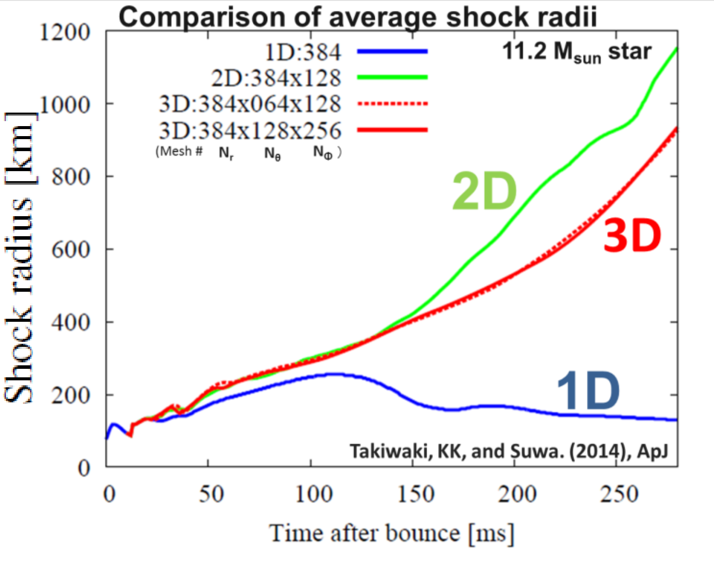
✓ **The saturation timescales: sensitive to the progenitor structures**
→ Need to perform long-term evolutions for > 378 models !
(Nakamura et al. in prep)

✓ ***Must go to 3D* !**

3D vs. 2D

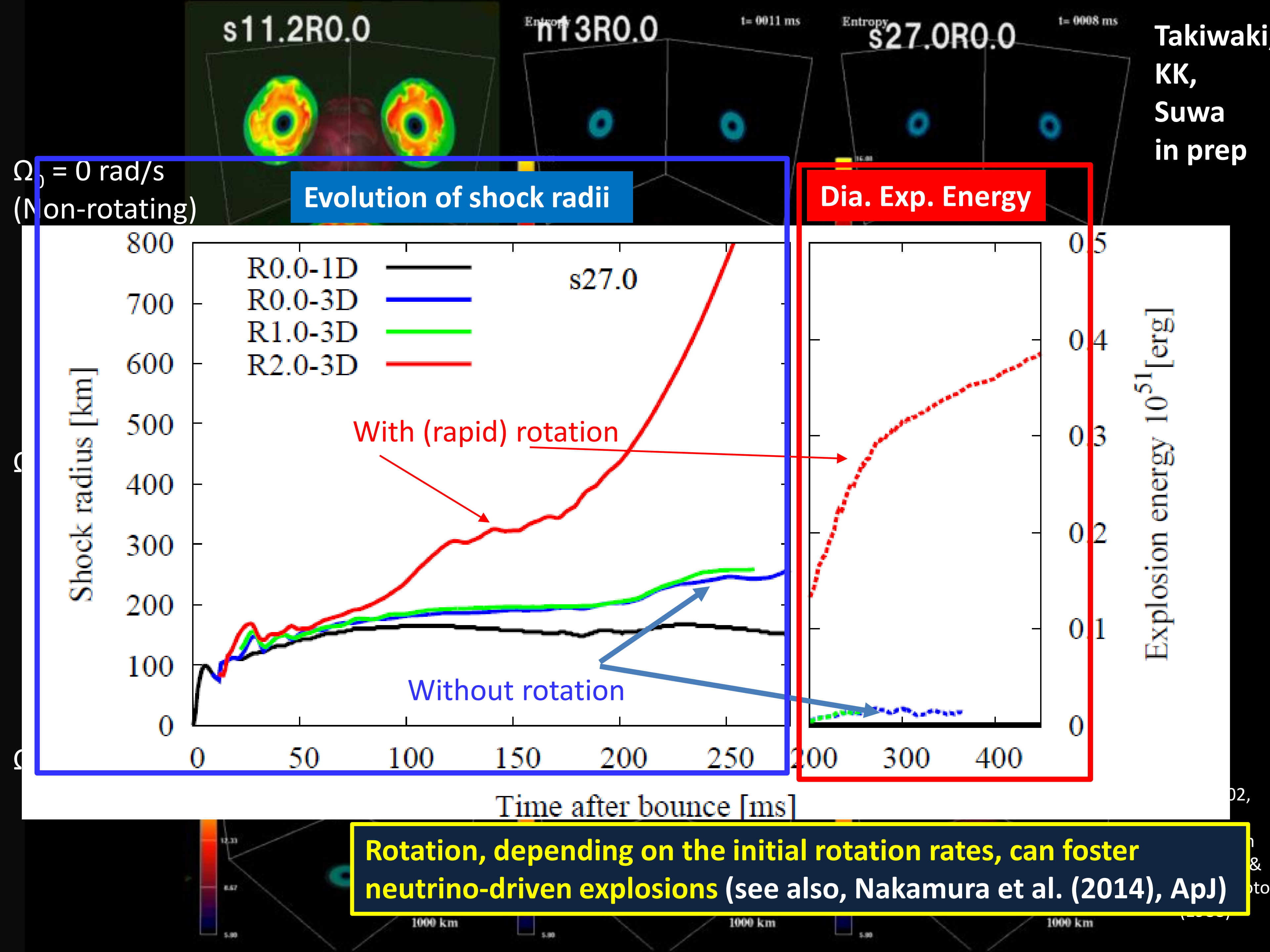


(e.g., Takiwaki + (2012,2014), ApJ)



✓ 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.
(see talk by R. Fernández !)

✓ No "FOE" models obtained in 3D.
Need to find ingredients to foster 3D explosions !



s11.2R0.0
n13R0.0
s27.0R0.0
Entropy
t= 0011 ms
t= 0008 ms
Takiwaki,
KK,
Suwa
in prep
Evolution of shock radii
Dia. Exp. Energy
s27.0
R0.0-1D
R0.0-3D
R1.0-3D
R2.0-3D
Shock radius [km]
Time after bounce [ms]
Explosion energy 10^{51}[erg]
With (rapid) rotation
Without rotation
1000 km
Rotation, depending on the initial rotation rates, can foster neutrino-driven explosions (see also, Nakamura et al. (2014), ApJ)

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

(Deeper potential well : core structures smaller ⇒making both <E_ν> 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

Expensive...

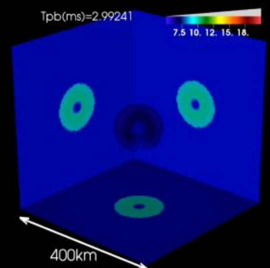
Kuroda, Takiwaki, and KK, submitted to ApJS. (arXiv:1501.06330)

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)

✓ **Results from gray (energy-averaged) version of FUGRA**
(e.g., Kuroda, Takiwaki and KK, 2012, ApJ, 2014, PRD)

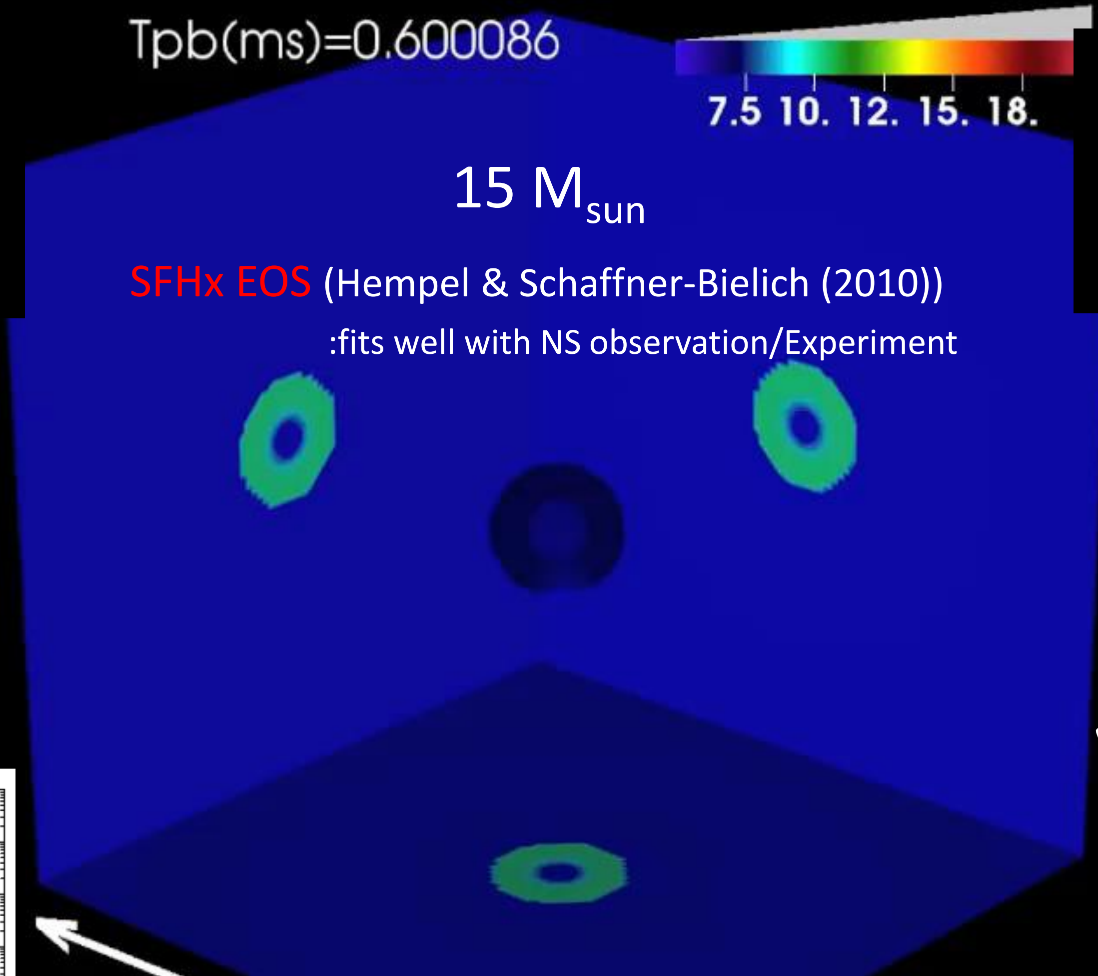
Today

Kuroda et al. (2012, 2014)



11.2 M_{sun}

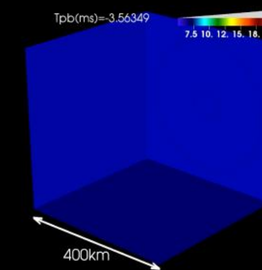
Convection-driven



15 M_{sun}

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

:fits well with NS observation/Experiment

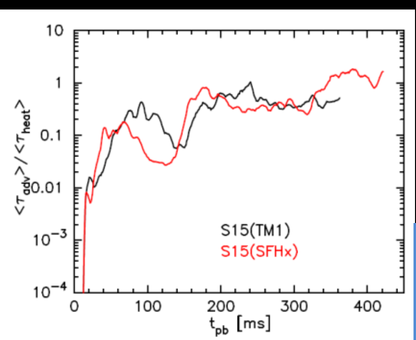


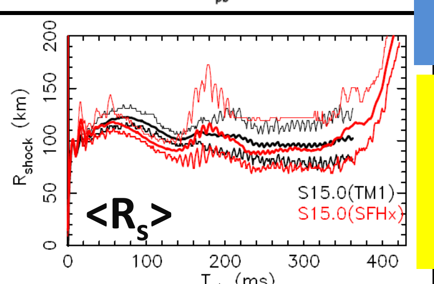
27 M_{sun}

SASI-driven:
Consistent with Hanke + 2013, Abdikamanov+2014

✓ SASI activity higher for softer EOS

τ_{adv}/τ_{heat}

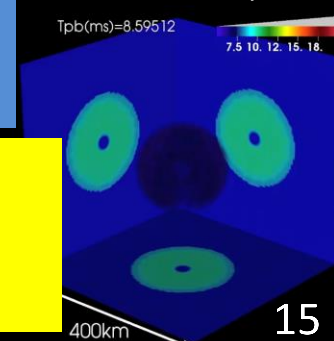




✓ 1000ms/(4 ms (gray FUGRA) per day @4096 processors)
~ 250 days …. (R_{shock} > R_{iron})
> 2500 days … (R_{shock} > R_{star});

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

EOS : Stiff (Shen+98)

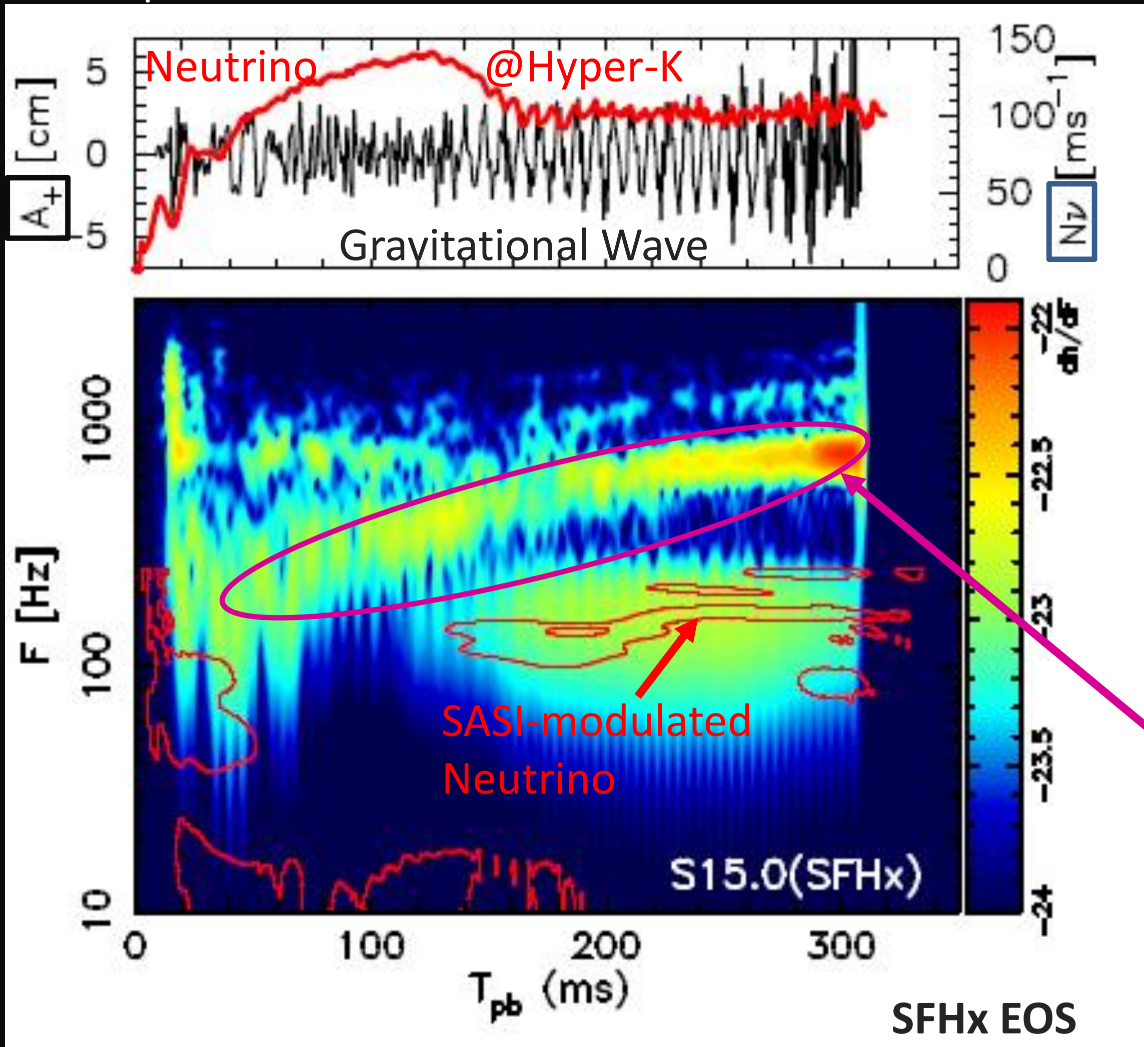


15 M_{sun}

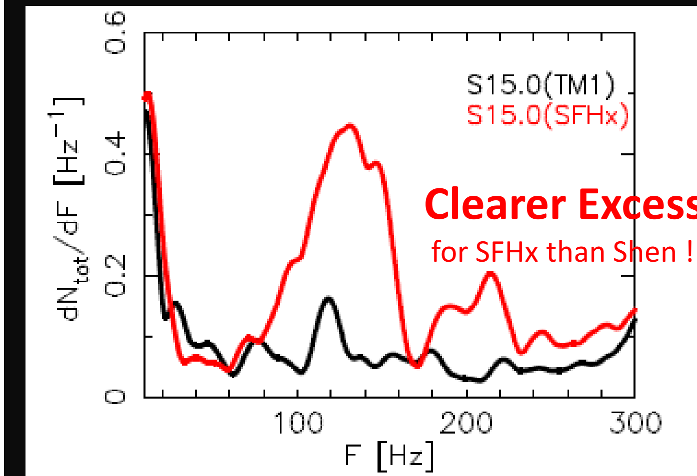
Neutrino and Gravitational-Wave signatures from 15 M_{sun} with SFHx (or SHEN EOS)

Kuroda, KK, & Takiwaki (in prep)

@ 10 kpc



✓ Typical neutrino mod. frequency



✓ Blue-shift of peak GW frequency: violent downdraft to PNS

Murphy et al. (2009), Mueller et al. (2013)

☆ Increase of typical frequency ⇒ the buoyancy frequency

$$f_p = \frac{N}{2\pi} = \frac{1}{2\pi}\frac{GM}{R^2}\sqrt{\frac{(\Gamma-1)m_n}{\Gamma k_b T}}\left(1-\frac{GM}{Rc^2}\right)^{3/2}$$

M, R, T : mass, radius, & temperature of PNS, Γ : stiffness of EOS

(see also Lentz et al. (2015) !)

✓**Hyper-Kamiokande**: back-ground free, likely to detect SASI-mod. signals for a Galactic event!

✓**Collective neutrino oscillations in 3D turbulent environment needed. Any idea ?!**

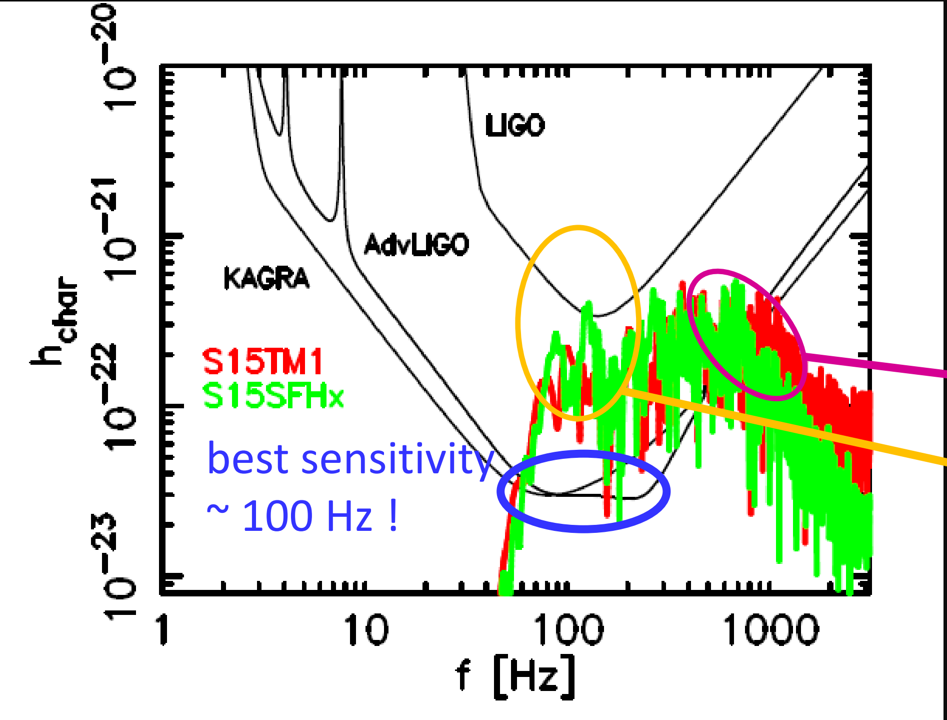
Patton, Kneller, and McLaughlin, 2015, 2014, PRD , Kneller and Mauney, 2013, PRD)

GW signal reconstruction by Coherent Network Analysis

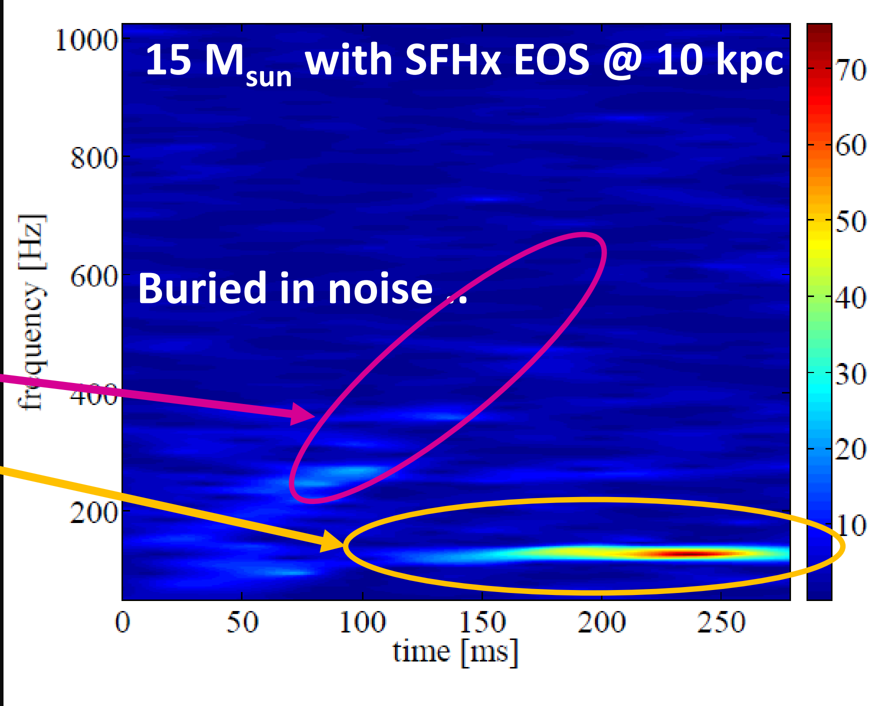
✓LIGOx2, VIGRO, KAGRA

Hayama, Kuroda, KK, & Takiwaki (2015) & in prep

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).

Summary

1. "Compactness ξ (and its derivative)" is (one of) the key(s) to characterize diversity of 2D neutrino-driven explosions.

2. For high compact progenitors,
   ✓ 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. Detailed correlation analysis of neutrino and GWs signatures mandatory.
   : provide information to break the degeneracy (M_{PNS}, R_{PNS}, T_{PNS}, R_{shock}, EOS etc.) ⇒ important probe to the explosion physics!

Many thanks!