Systematic 3D MHD simulations of core-collapse supernovae

Ko Nakamura (Fukuoka Univ.)

T. Takiwaki (NAOJ), J. Matsumoto (Keio Univ.),
S. Horiuchi (Virginia Tech.), K. Kotake (Fukuoka Univ.)

Brainstorming workshop 2022 to revolutionize the CCSN theory @ Wroclaw August 1-5, 2022

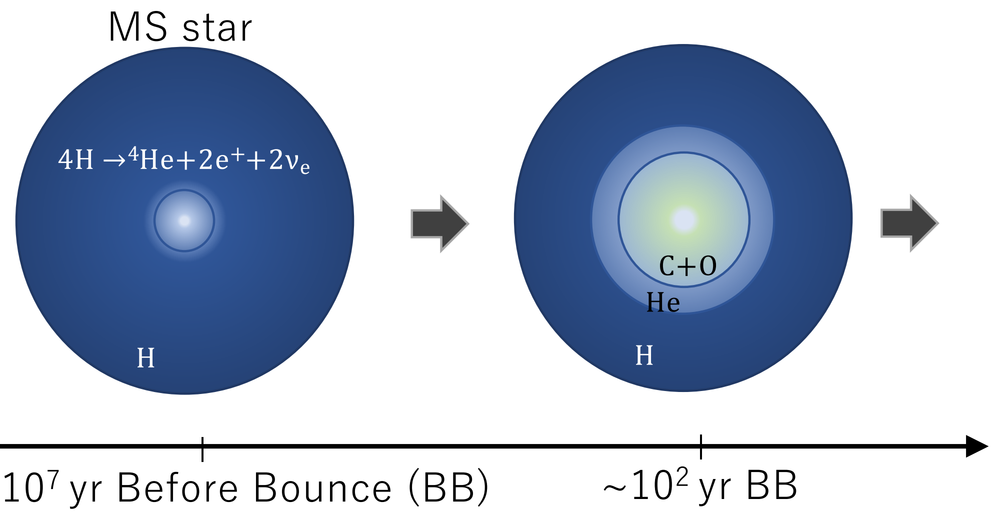
CONTENTS:

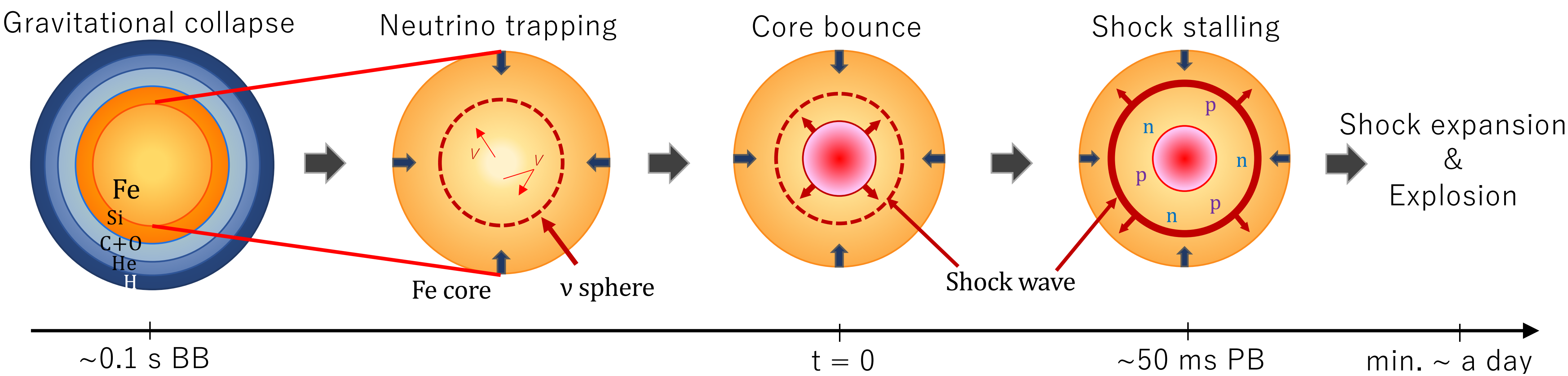
From a massive MS star to a CCSN

✓ The standard scenario toward explosion

A massive star forms iron core.
→ The core gravitationally collapses.
→ Shock stalls and revives via neutrino heating.
→ Finally the shock breaks out the stellar surface.

Note that the time scale of stellar evolution depends on its mass. Shown is the case of a ~10 solar-mass star.



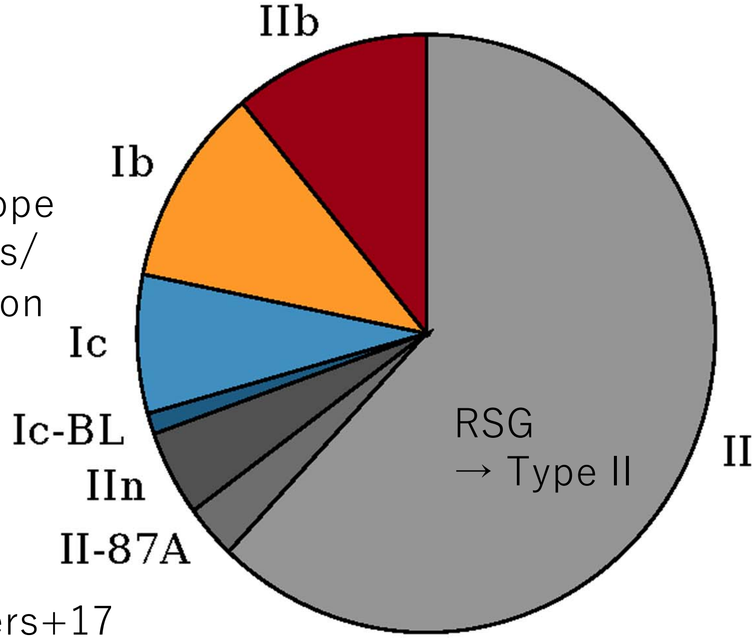


"*Standard*" CCSNe

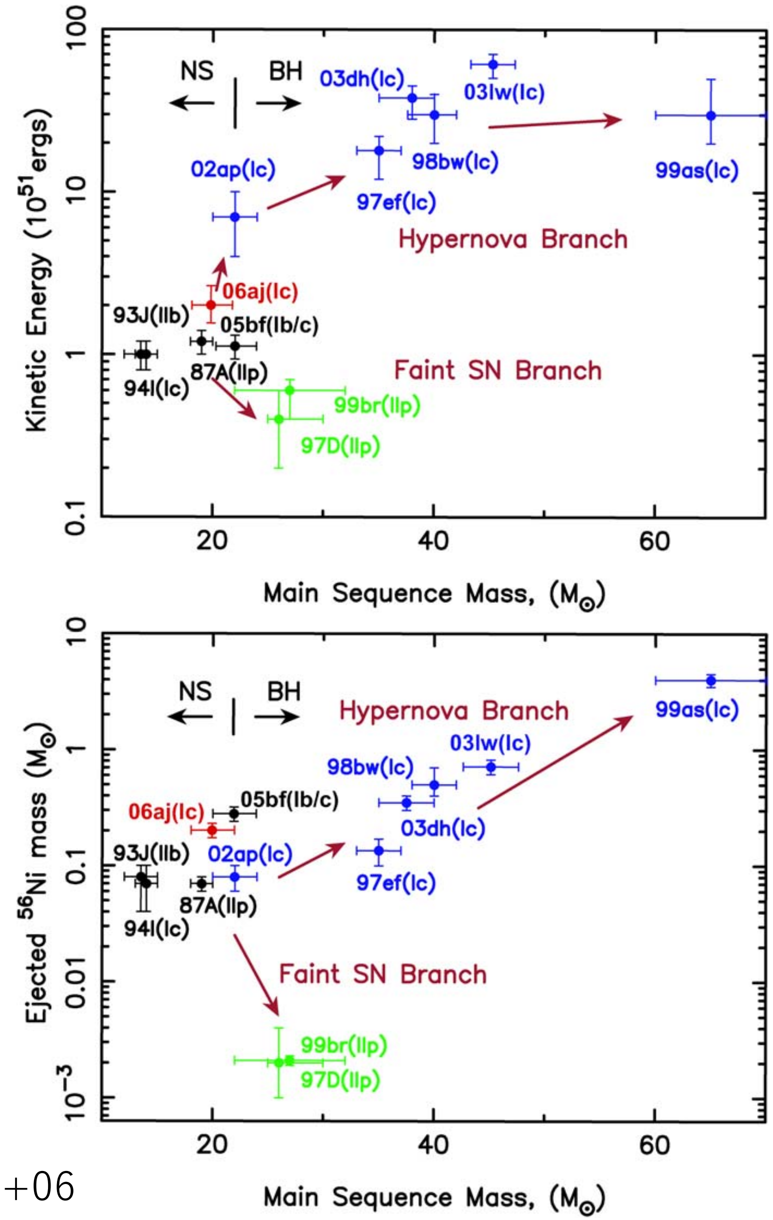
We focus on "standard" CCSNe
coming from non-extreme initial conditions (mass, rotation, B-field),
resulting in normal explosion (not GRB-HNe, not SLSNe).

What is the "standard" explosion?
$E_{\rm exp}$ = 10^51 erg? $M_{\rm Ni}$ = 0.07 solar mass?

Stripped envelope
via stellar winds/
binary interaction



Shivvers+17



Nomoto+06

Systematic CCSN studies

✓ O'Connor & Ott (2011)

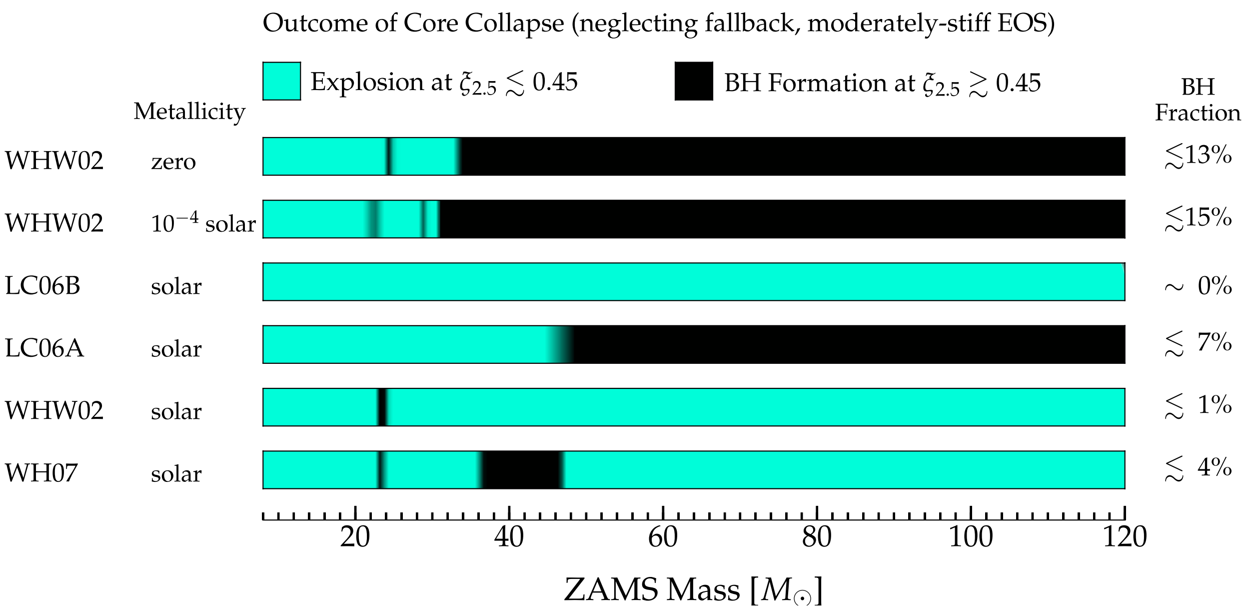
1D simulations, M = 10-120 Msun, Z = 0-Zsun.

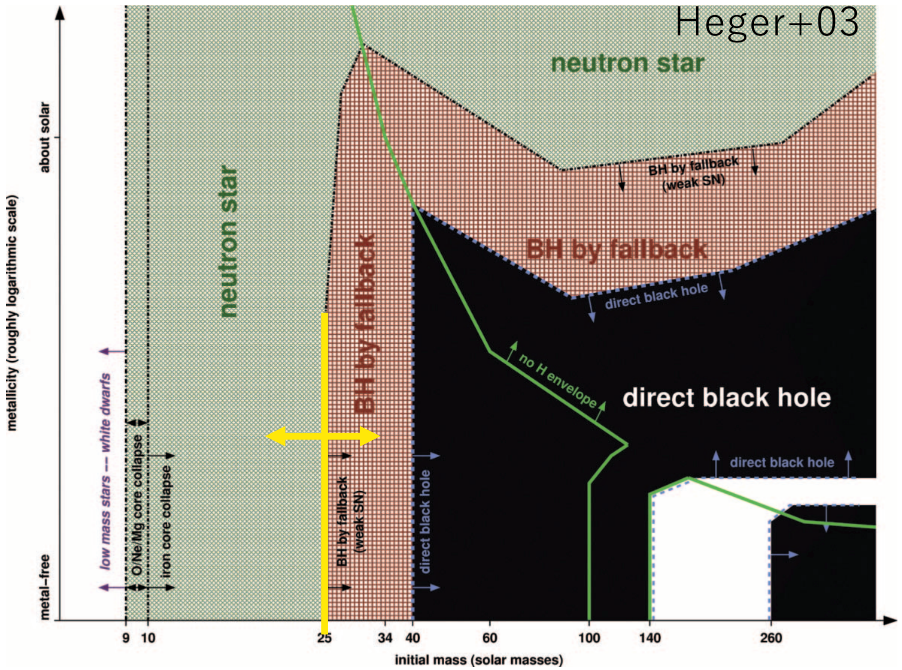
$$Q^{\rm heat}_{\nu_i}(r) = f_{\rm heat}\frac{L_{\nu_i}(r)}{4\pi r^2}\sigma_{{\rm heat},\nu_i}\frac{\rho}{m_u}X_i\left\langle\frac{1}{F_{\nu_i}}\right\rangle e^{-2\tau_{\nu_i}}$$

Compactness parameter

$$\xi_M = \frac{M/M_\odot}{R(M_{\rm bary}=M)/1000\,{\rm km}}$$

Explosion/non-explosion is non-monotonic and divided by $\xi_{2.5} \sim 0.45$.





Systematic CCSN studies

✓ Ugliano et al. (2012)

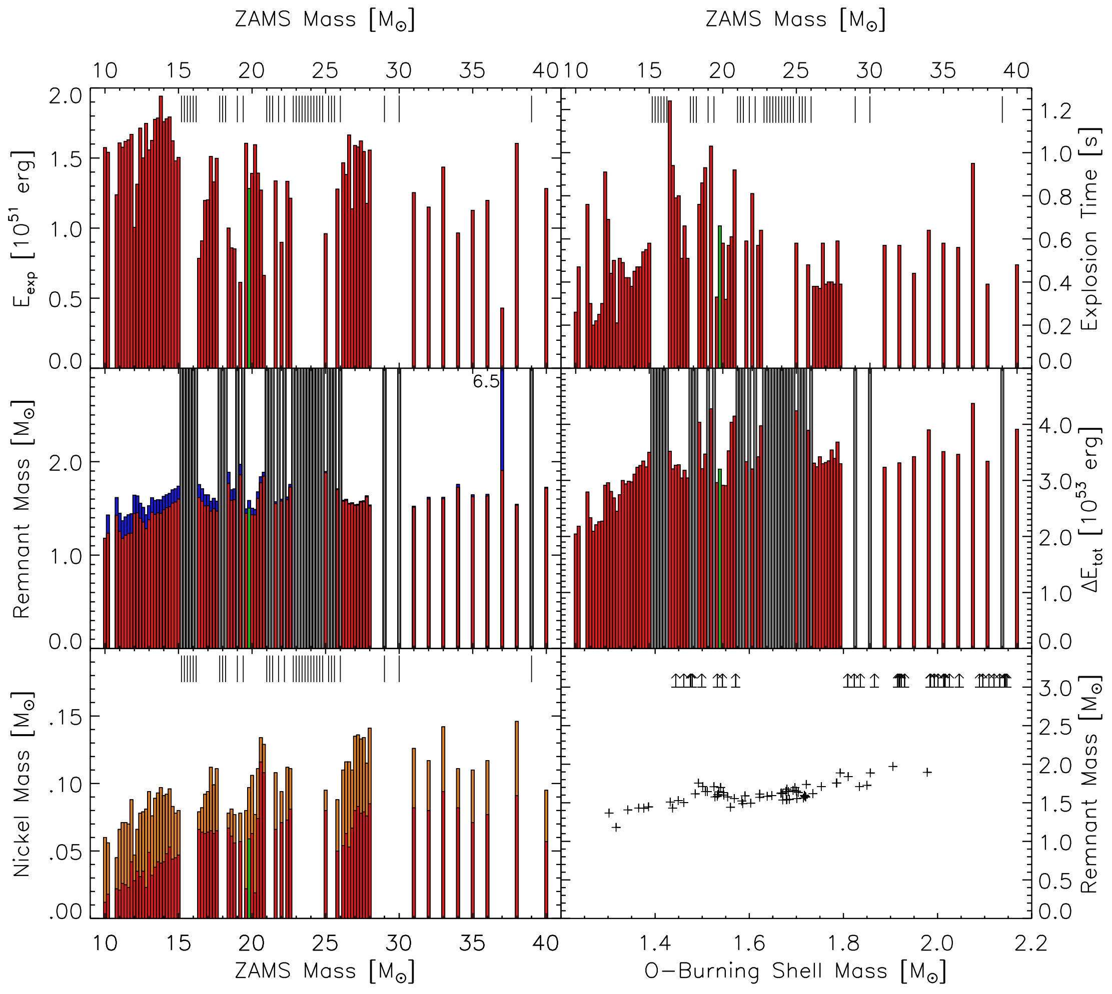
1D simulations, M = 10-40 Msun, Z = Zsun.

$$R_c(t) = R_{c,f} + (R_{c,i} - R_{c,f})/(1+t)^n$$

$$\rightarrow L\nu\,(R_c(t))$$

Explosion/non-explosion is non-monotonic, but not well correlated with the compactness.

Explosion properties are also non-monotonic.



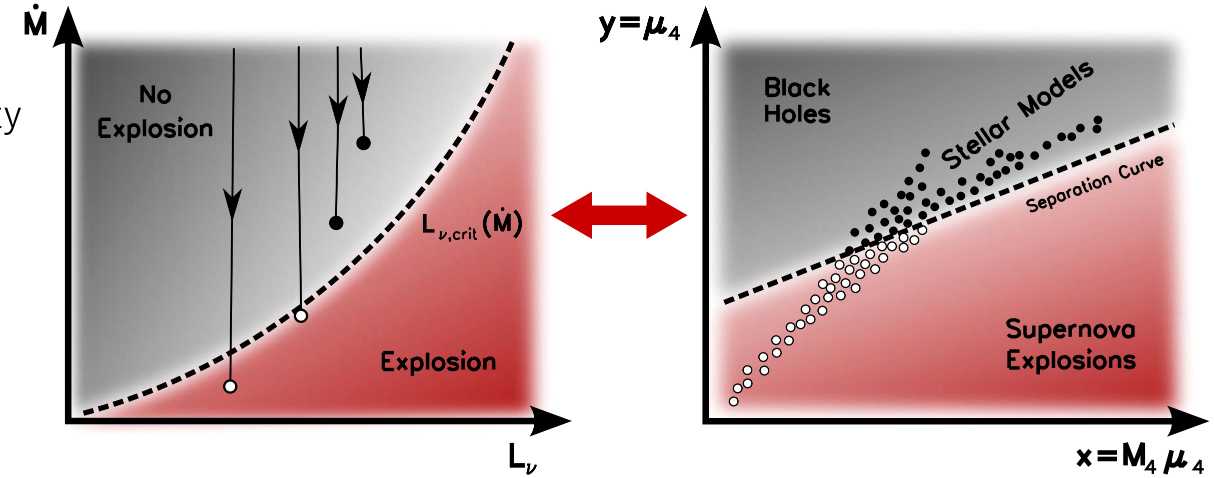
Systematic CCSN studies

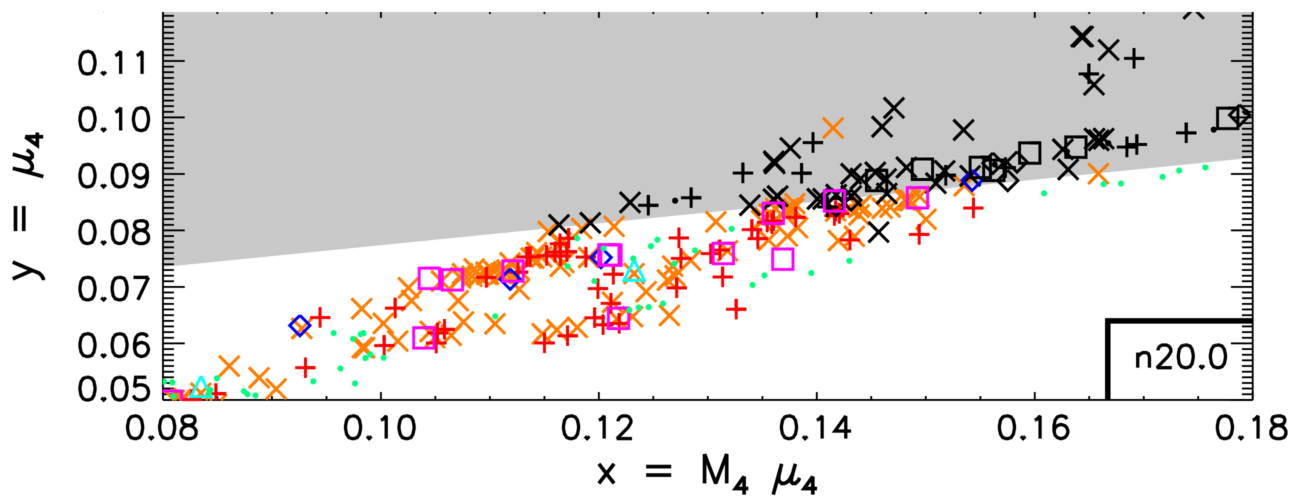
✓ Ertl et al. (2016)

Two-parameter criterion for the explodability of 1D models.

$$M_4 \equiv m(s=4)/M_\odot \sim M_{\mathrm{Si}}$$

$$\mu_4 \equiv \left.\frac{\Delta m/M_\odot}{\Delta r/1000\ \mathrm{km}}\right|_{s=4} \sim dM/dt$$

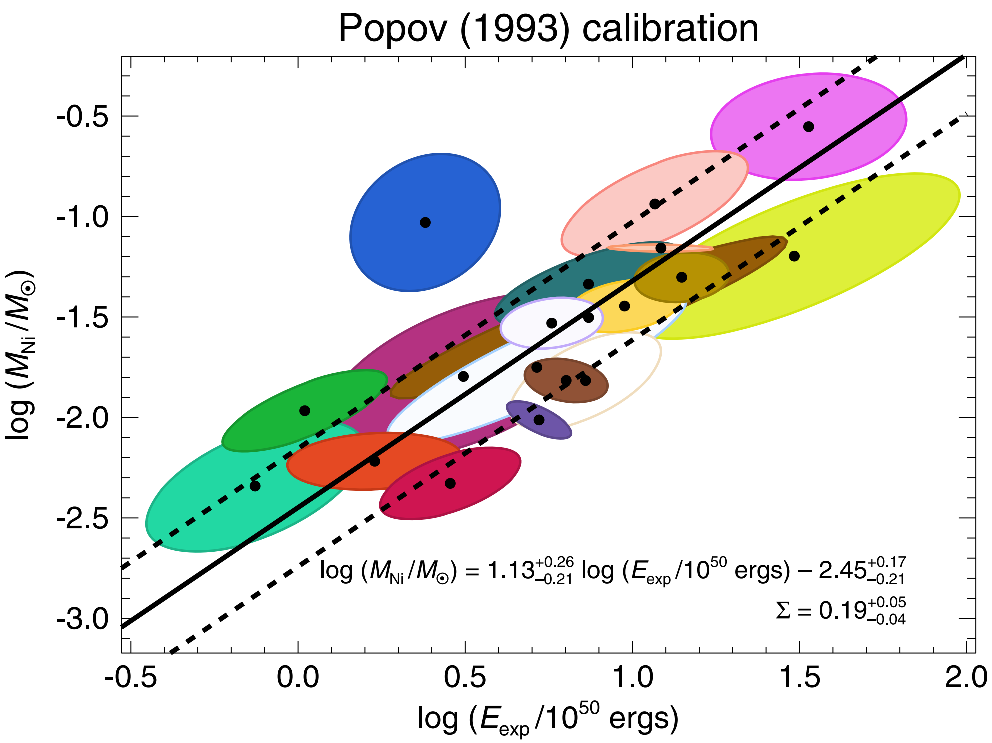


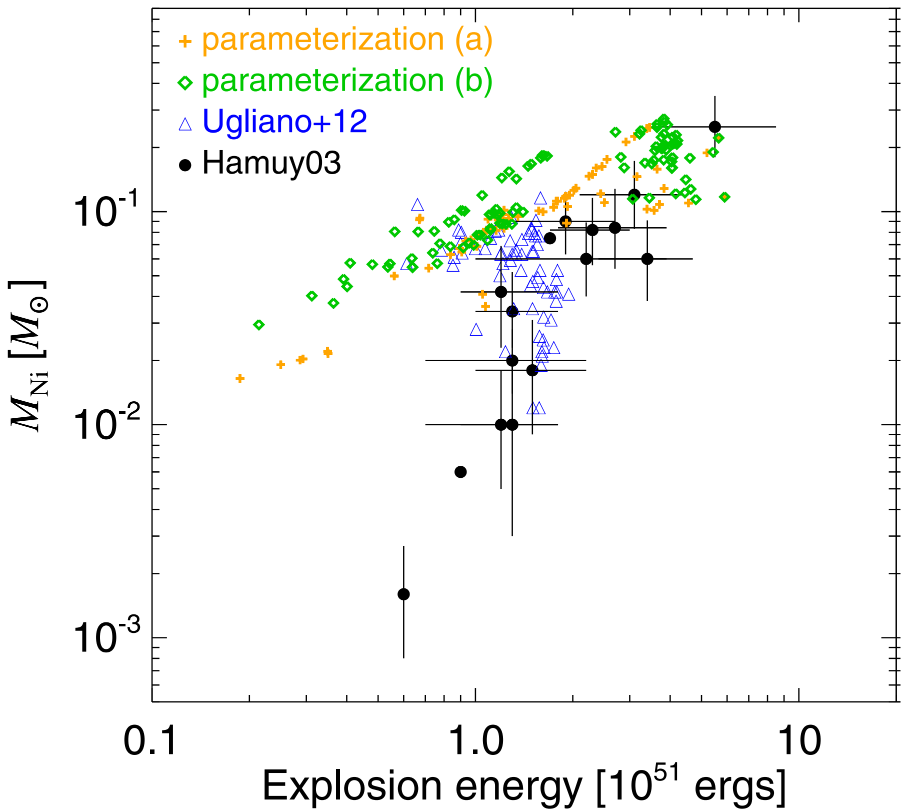


Systematic CCSN studies

✓ Pejcha & Thompson (2015); Pejcha & Prieto (2015)

Observations suggest a linear relation between E_{exp} and M_{Ni}.





Note: It's NOT easy to estimate Eexp!

✓ Popov (1993)

Time scale and luminosity at the plateau phase (Type IIP)

$$t_{\rm SN} = 100\,{\rm d} \left(\frac{\kappa}{0.34{\rm cm}^2/{\rm g}}\right)^{1/6} \left(\frac{M_{\rm ej}}{10M_\odot}\right)^{1/2} \left(\frac{E}{10^{51}{\rm erg}}\right)^{-1/6} \left(\frac{R_0}{500R_\odot}\right)^{1/6} \left(\frac{T}{5000{\rm K}}\right)^{-2/3}$$

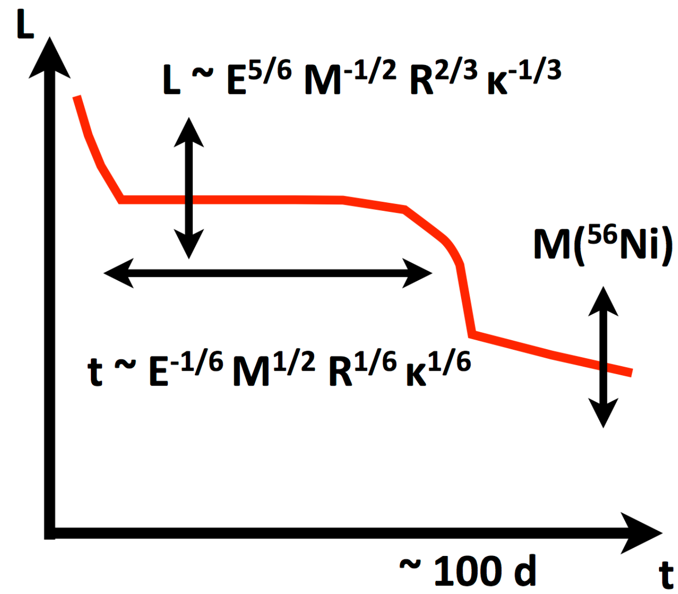
$$L = 1.5\times 10^{42}\,{\rm erg/s} \left(\frac{\kappa}{0.34{\rm cm}^2/{\rm g}}\right)^{-1/3} \left(\frac{M_{\rm ej}}{10M_\odot}\right)^{-1/2} \left(\frac{E}{10^{51}{\rm erg}}\right)^{5/6} \left(\frac{R_0}{500R_\odot}\right)^{2/3} \left(\frac{T}{5000{\rm K}}\right)^{4/3}$$

+ spectrum

$$E = \frac{1}{2}Mv^2 \rightarrow v = \left(\frac{2E}{M}\right)^{1/2}$$

Luminosity at the tail

$$\begin{aligned} L(t) &= E_{\rm Ni}\left(-\frac{dN_{\rm Ni}}{dt}\right) + E_{\rm Co}\left(-\frac{dN_{\rm Co}}{dt}\right) \\ &= \frac{E_{\rm Ni}N_{\rm Ni,0}}{\tau_{\rm Ni}}e^{-t/\tau_{\rm Ni}} + \frac{E_{\rm Co}N_{\rm Ni,0}}{\tau_{\rm Co}-\tau_{\rm Ni}}e^{-t/\tau_{\rm Co}} - \frac{E_{\rm Co}N_{\rm Ni,0}}{\tau_{\rm Co}-\tau_{\rm Ni}}\frac{\tau_{\rm Co}}{\tau_{\rm Ni}}e^{-t/\tau_{\rm Ni}} \\ &= \frac{N_{\rm Ni,0}}{\tau_{\rm Co}-\tau_{\rm Ni}}\left(\frac{(\tau_{\rm Co}-\tau_{\rm Ni})E_{\rm Ni}-\tau_{\rm Co}E_{\rm Co}}{\tau_{\rm Ni}}e^{-t/\tau_{\rm Ni}} + E_{\rm Co}e^{-t/\tau_{\rm Co}}\right) \\ &= 10^{42}{\rm erg/s}\left(6.45\,e^{-t/\tau_{\rm Ni}} + 1.45\,e^{-t/\tau_{\rm Co}}\right)\left(\frac{M_{\rm Ni}}{0.1\,M_\odot}\right) \end{aligned}$$

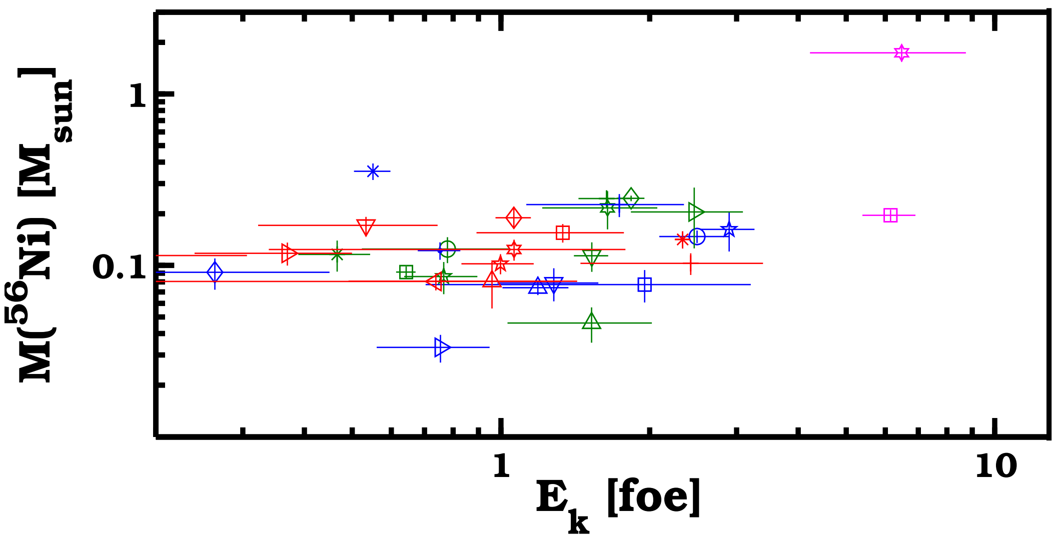


Systematic CCSN studies

✓ Taddia et al. (2018)

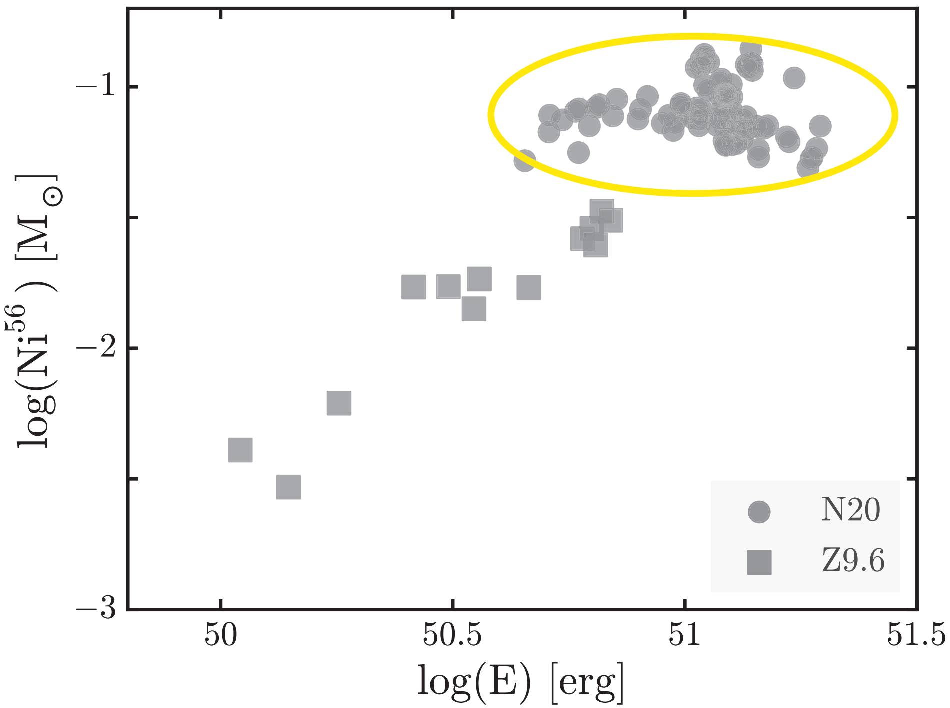
Analysis of 34 LCs from the Carnegie Supernova Project.

→ No linear relation between E_{exp} and M_{Ni}.



✓ Sukhbold et al. (2016)

1D simulation, 9-120 Msun, Z = Zsun



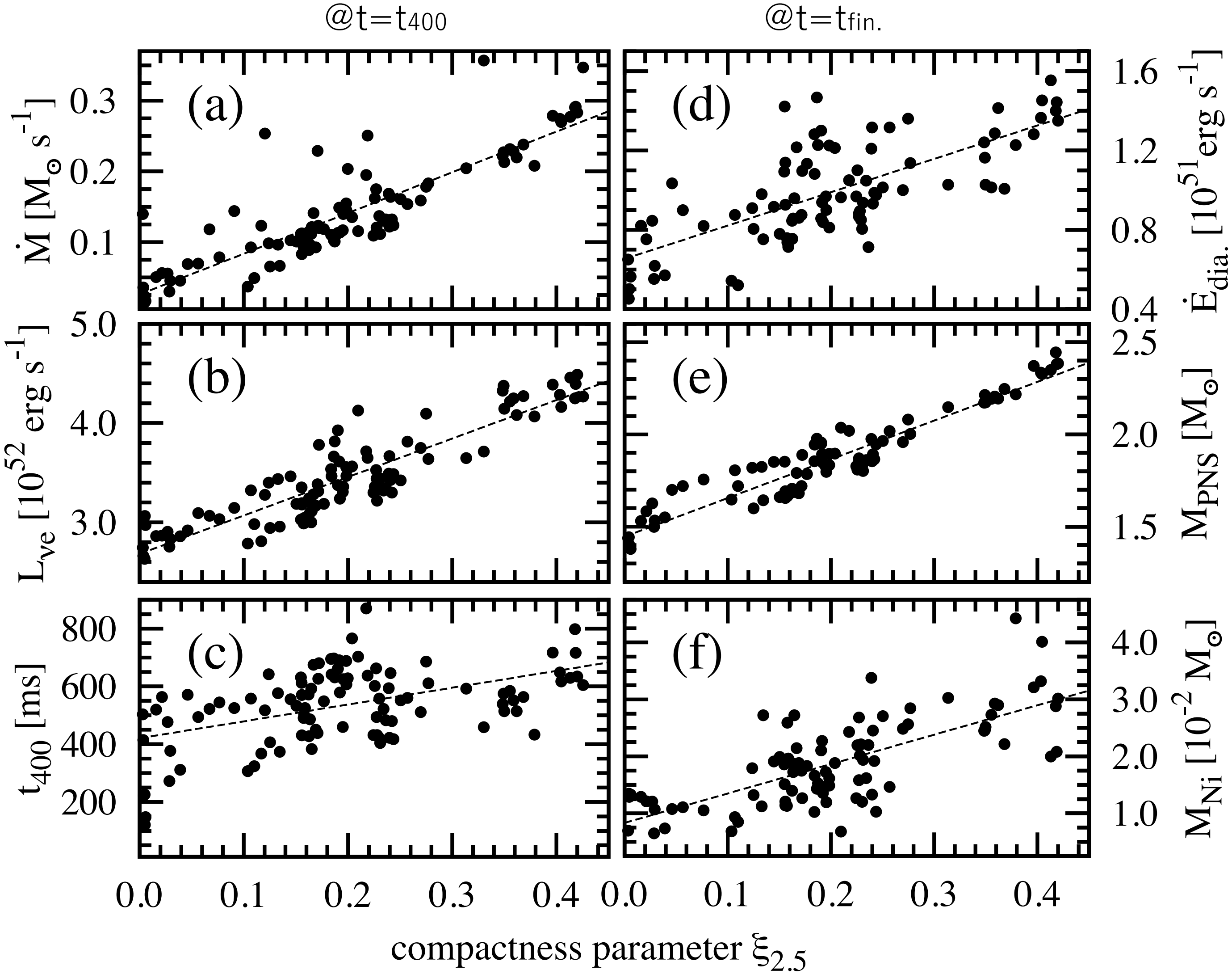
Systematic CCSN studies

✓ KN et al. (2015)

2D self-consistent simulations, M = 10.8-75 Msun, Z = 0-Zsun.

Linear relations between some explosion properties and ξ .

Simulations ended at t_pb < 1s.



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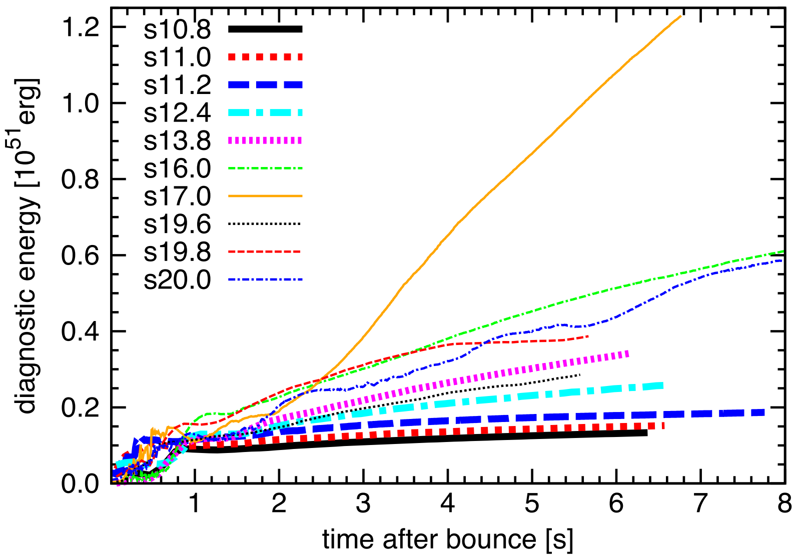
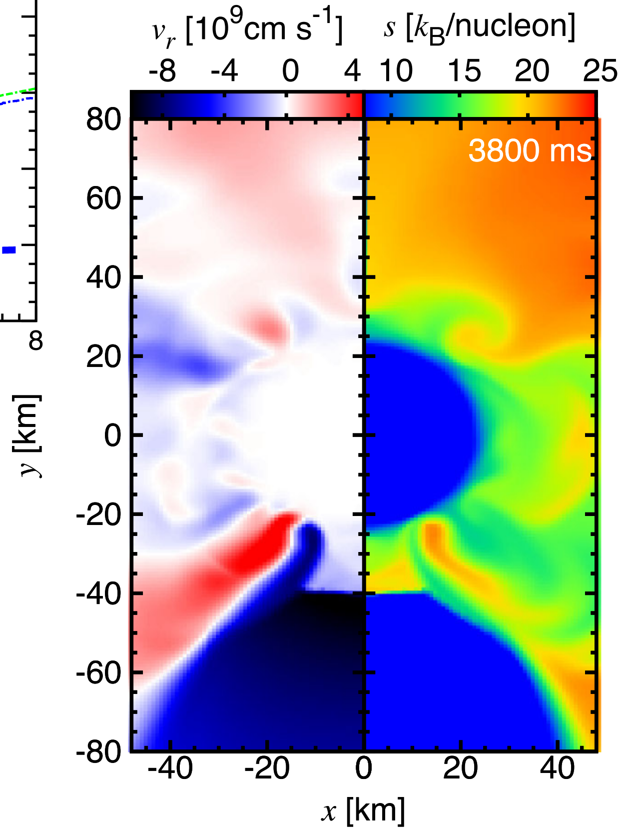




✓ KN et al. (2019)

2D long-term simulations.

One model (s17) obtains $E_{\rm exp} > 10^{51}$ erg.
← Long-lasting accretion supplies energy source & targets of neutrinos.

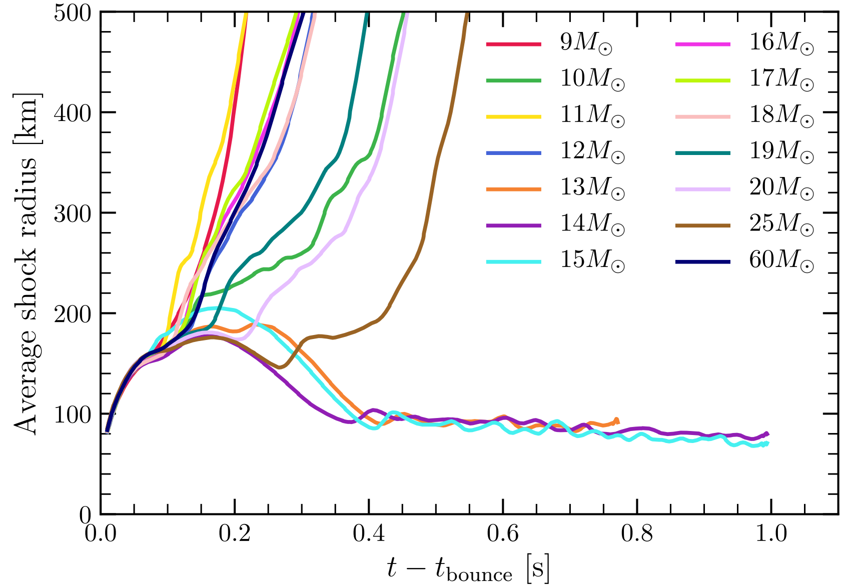
Systematic CCSN studies

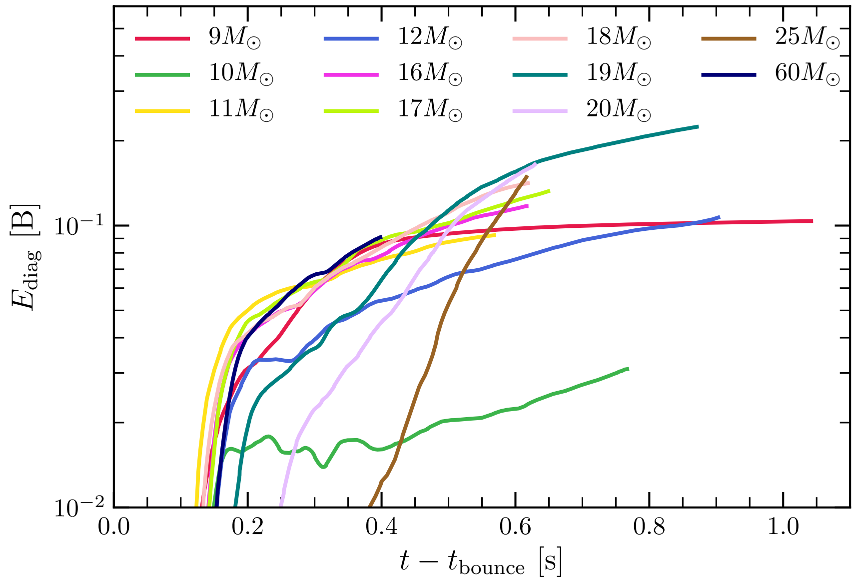
✓ Burrows et al. (2020)

3D self-consistent simulations,
M = 9-20, 25, 60 Msun, Z = Zsun.

Some models (s13,14,15) failed in explosion.

Explosion energy is ~ 10^{50} erg.





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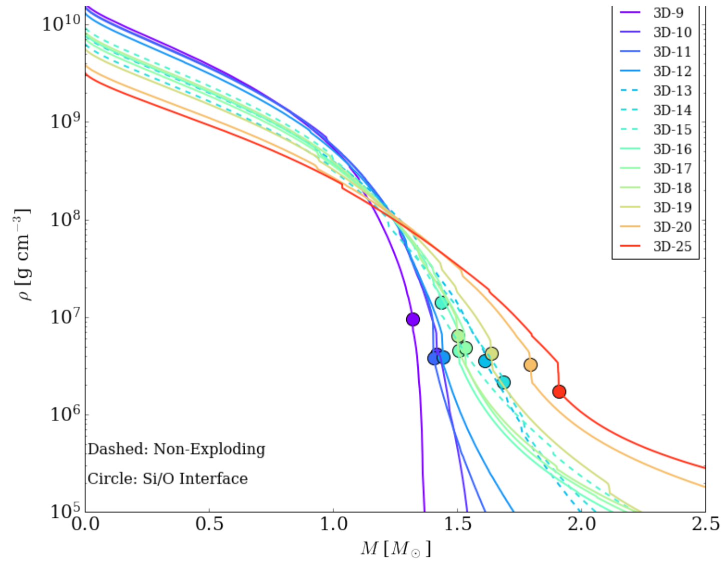
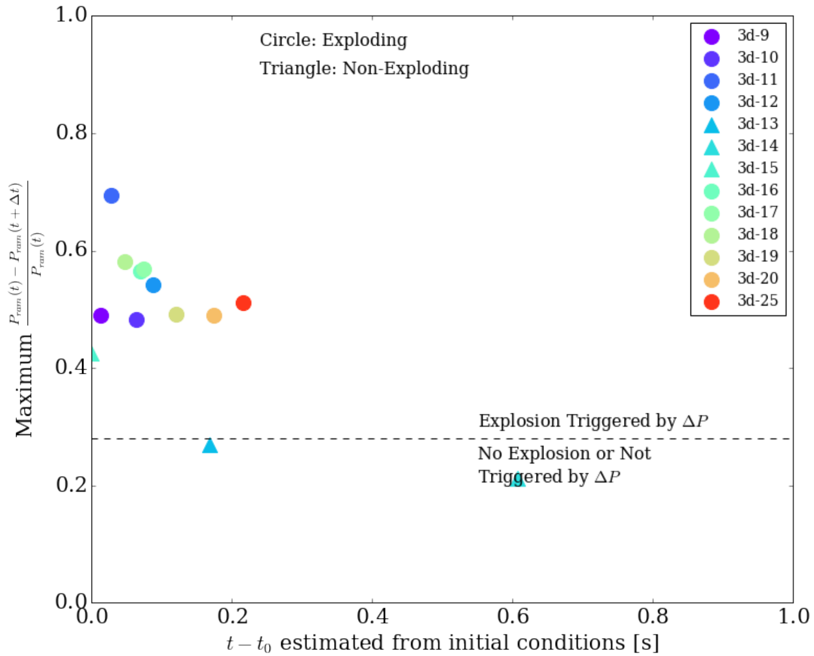


✓ Wang et al. (2022)

Compactness does NOT represent the explodability.

$$\frac{P_{\rm ram}(t) - P_{\rm ram}(t+\Delta t)}{P_{\rm ram}(t)}$$

Ram pressure jump determines the fate of a stalled shock.



Summary of the current understandings from the systematic studies

- ✓ Explosion properties are NOT a monotonic function of progenitor mass.
  $t_{\rm revival}$ (explodability), $E_{\rm exp}$, $M_{\rm NS/BH}$, L_{ν}, $M_{\rm Ni}$, ⋯

- ✓ Mass accretion onto the central core plays a dominant role.
  Parameter(s) characterizing the accretion rate (e.x., ξ) and some of the explosion properties are well correlated.

- ✓ Explodability cannot be expressed by the compactness.
  Two-parameter criterion?
  Degree of $P_{\rm ram}$ jump?

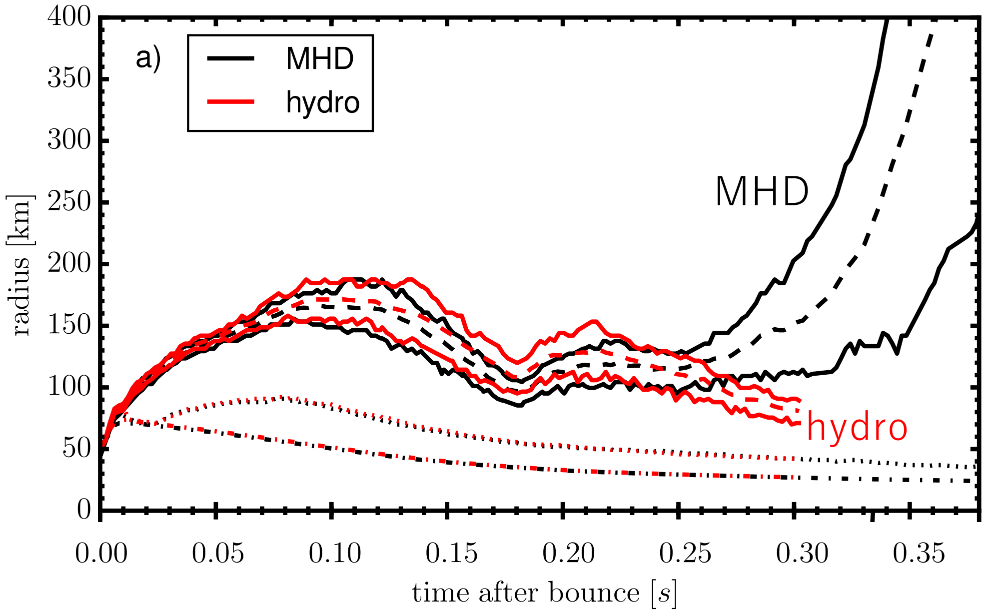
Systematic CCSN simulations

	Spatial dim.	Model #	ν heating	ZAMS M [Msun]	Z	sim. time	Summary
O'connor & Ott '11	1D	~100	x *factor*	10-120	0-solar	~1s	Non-monotonic explosion/BH formation.
Ugliano+'13	1D	~100	$L_\nu\ (R_{NS}, t)$	10-40	solar	**~10s+**	Non-monotonic explosion properties.
KN+'15	**2D**	**~400**	**Self-consistent**	10-75	0-solar	<1s	Explosion properties depend on ξ.
KN+'19	**2D**	10	**Self-consistent**	10-20	solar	**~10s**	Long-term accretion produces $E_{exp}>10^{51}$erg.
Burrows+'20	**3D**	14	**Self-consistent**	9-20,25,60	solar	<1s	E_{exp} ~ 0.1×10^{51}erg
KN+, in prep.	**3D**	16	**Self-consistent**	9-24	solar	0.5s	Independent 3D study, including $\boldsymbol{B}$.

3D CCSN simulations with magnetic field

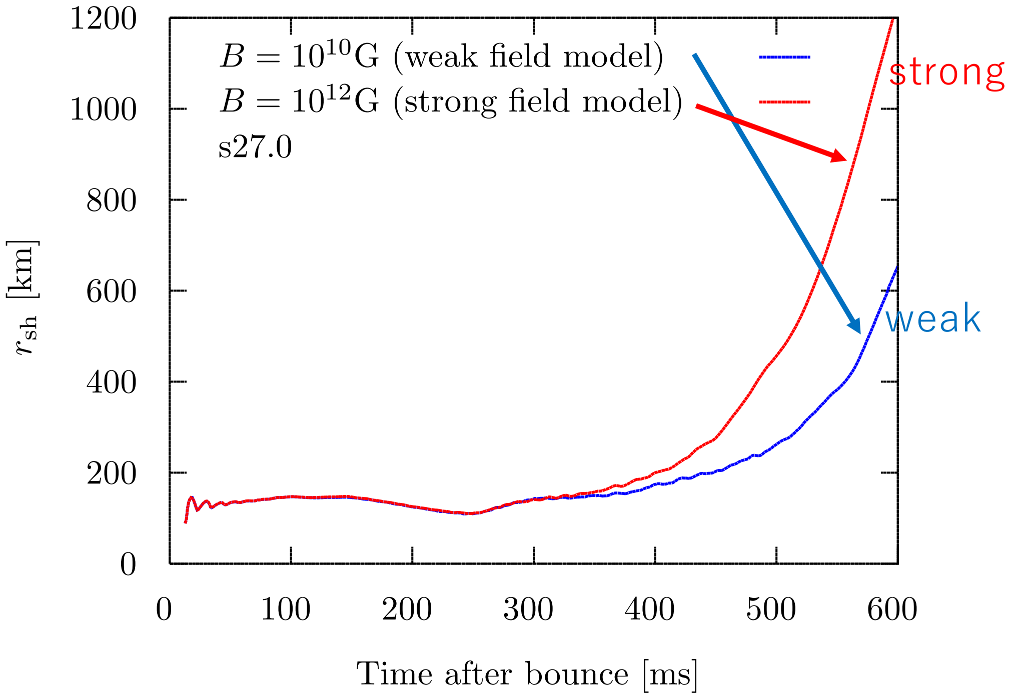
✓ Mueller & Varma (2020)

3D simulation with weak B-field.
The weak seed field is amplified and **supports** a development of a neutrino-driven explosion.



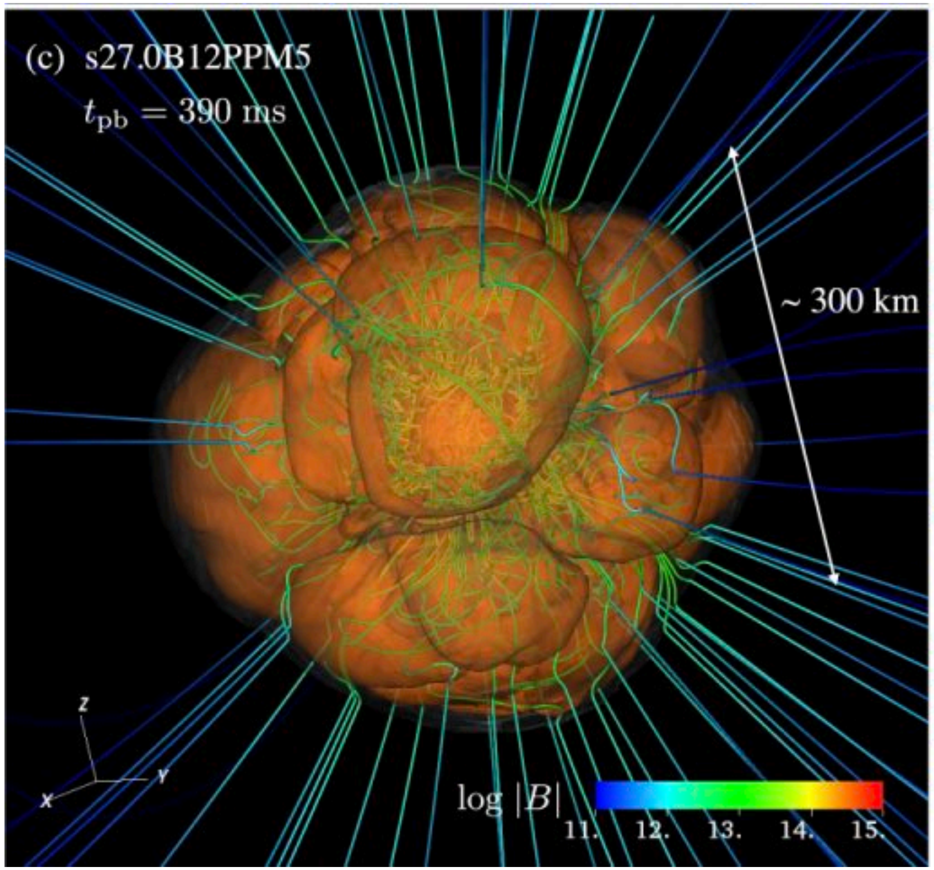
✓ Matsumoto et al. (2022)

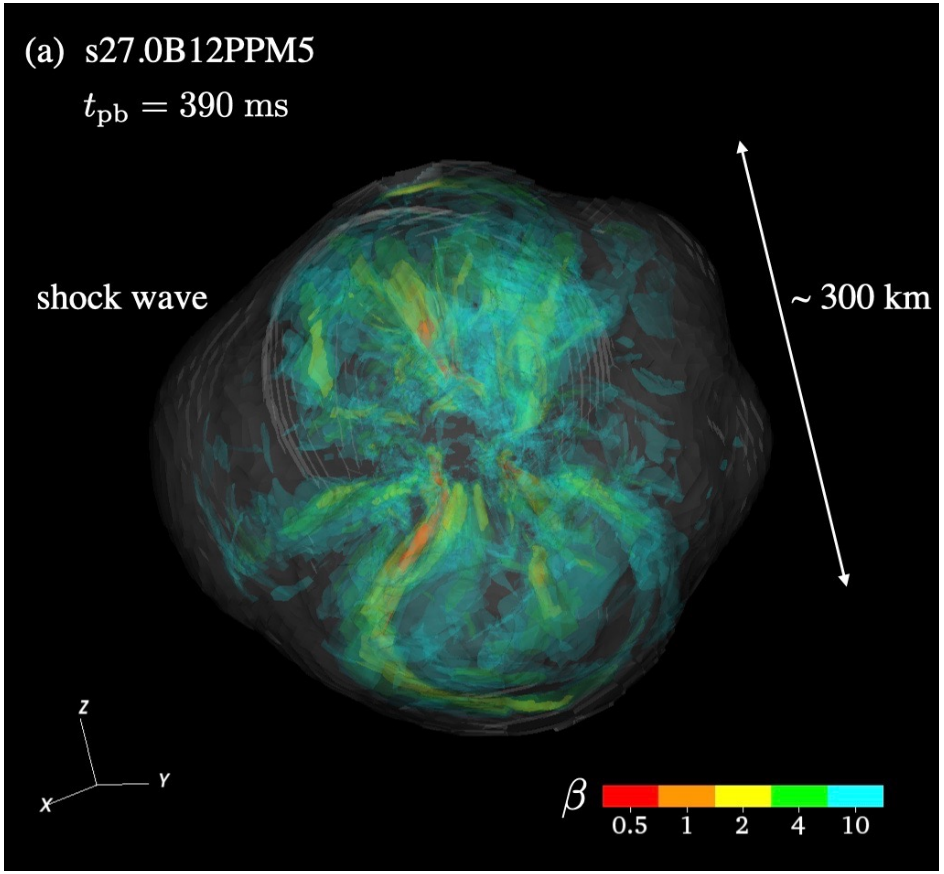
3D simulations with weak/strong B-fields.
The strong B-filed model presents **early shock revival**.



3D CCSN simulations with magnetic field

✓ Matsumoto et al. (2022)





3D CCSN simulations with magnetic field

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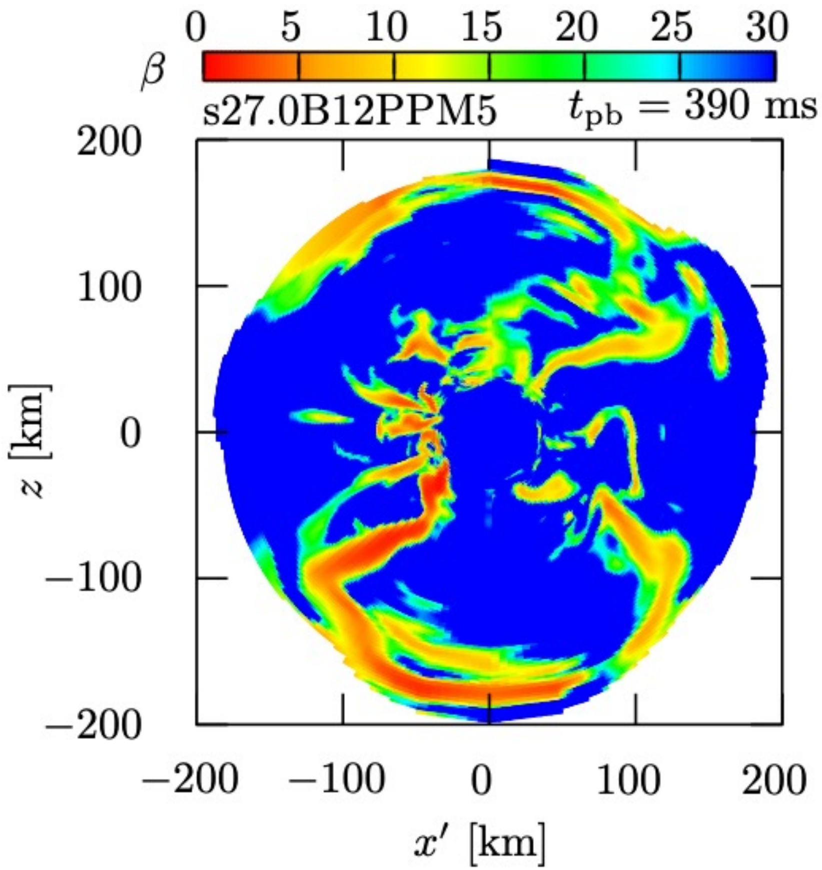
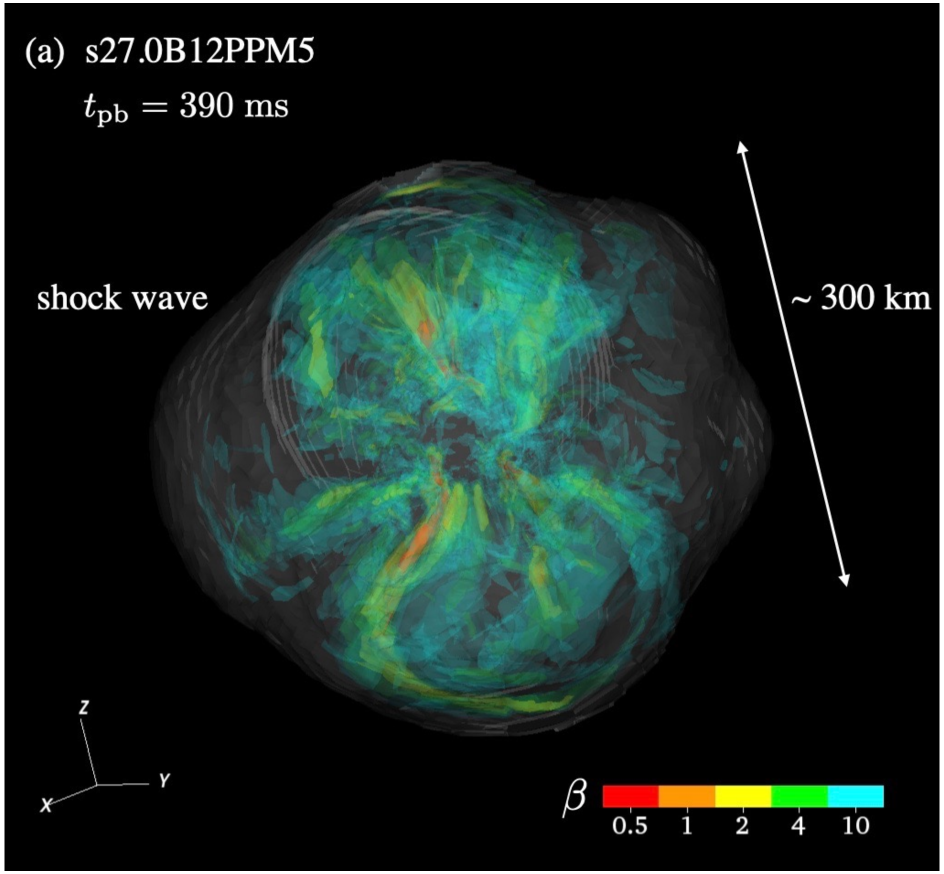




Systematic 3D MHD simulations - Numerical scheme

✓ **3DnSNe_MHD code** (*Matsumoto+'20*) based on 3DnSNe code (*Takiwaki+'16,'18*).

✓ Initial 2D simulation:

- No rotation, $A_\phi = \frac{B_0}{2} \frac{r_0^3}{r^3 + r_0^3} r \sin\theta$ with $\boldsymbol{B_0} = \mathbf{10^{10}}$ **[G]** and $r_0 = 10^3$ km.
- 600(r)x128(θ) grids for $0 \leqq R \leqq 10^4$ km and $0 \leqq \theta \leqq \pi$.

✓ Subsequent 3D simulation:

- 2D → 3D at 10ms after bounce.
- Random density perturbation ($\leqq$ 1%) is imposed in R > 100 km.
- 600(r)x64(θ)x128(ϕ) grids for $0 \leqq R \leqq 10^4$ km, $0 \leqq \theta \leqq \pi$, and $0 \leqq \phi \leqq 2\pi$.

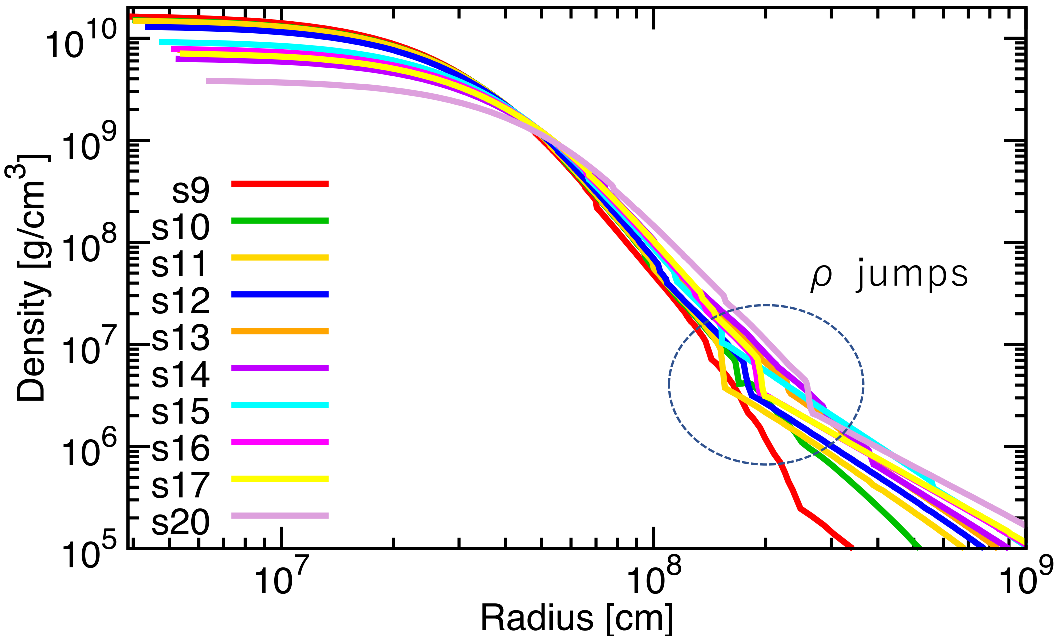
Systematic 3D MHD simulations - Progenitor models

✓ 9-24 Msun progenitors from Sukhbold et al. (2016) ApJ, 821, 38

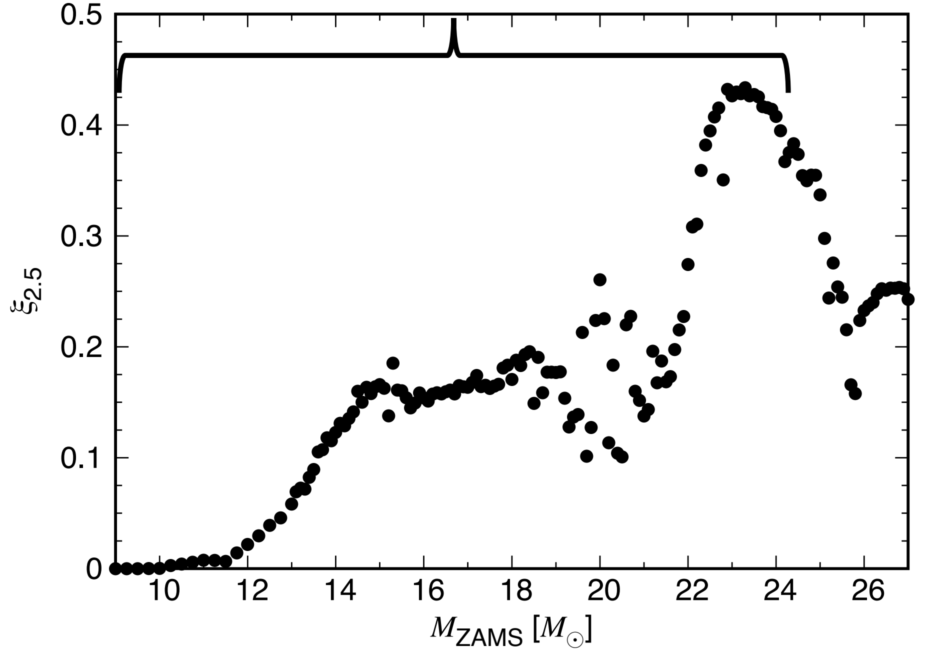
Density profiles of some models (e.x., **s10**, **s11**, **s12**) show a jump at Si/O interface.

This progenitor series have a peak (island) of compactness around M_{ZMAS} ~ 23 solar masses.

$$\xi = M(R)/R$$



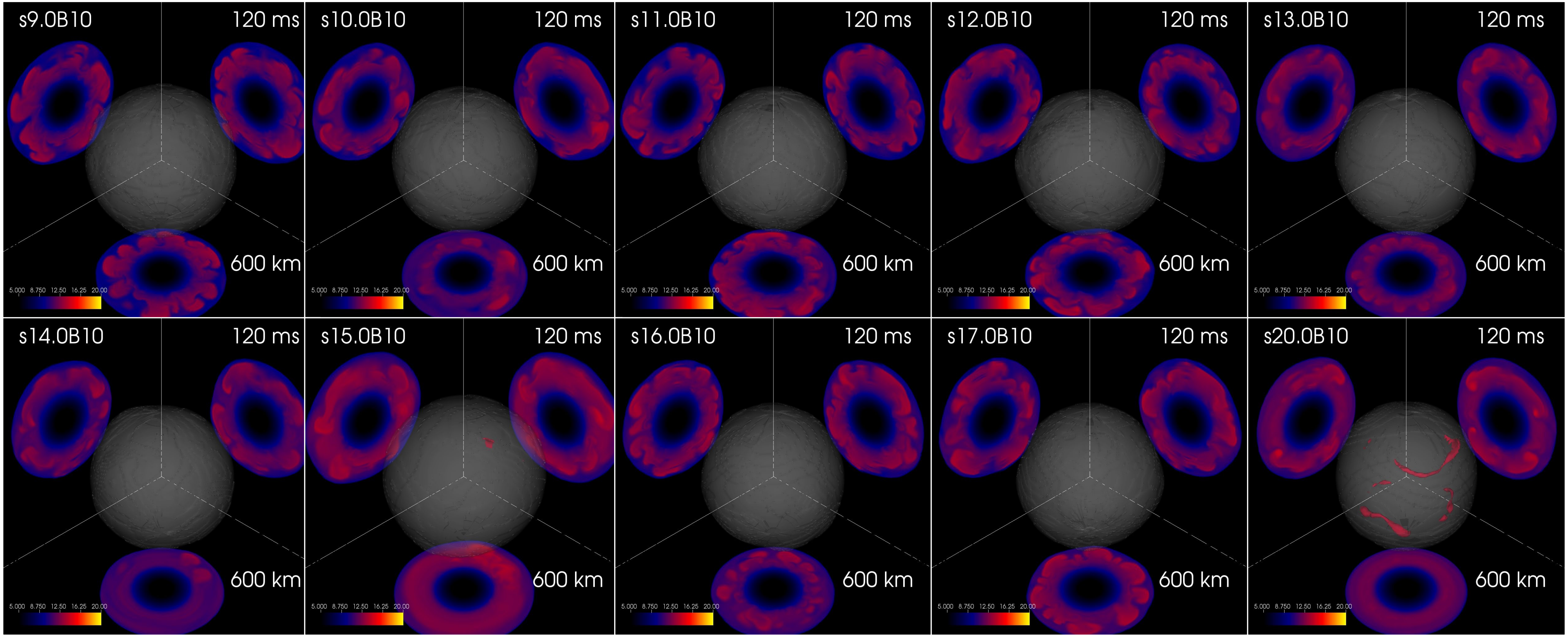
16 models in this range



Systematic 3D MHD simulations - Overview

✓ Movies show iso-surface of entropy for 10 models.
Note that spatial scale (box size) is changing as the shock waves successfully revive and expand.
The model s11 presents outstanding burst at 140 ms after bounce.

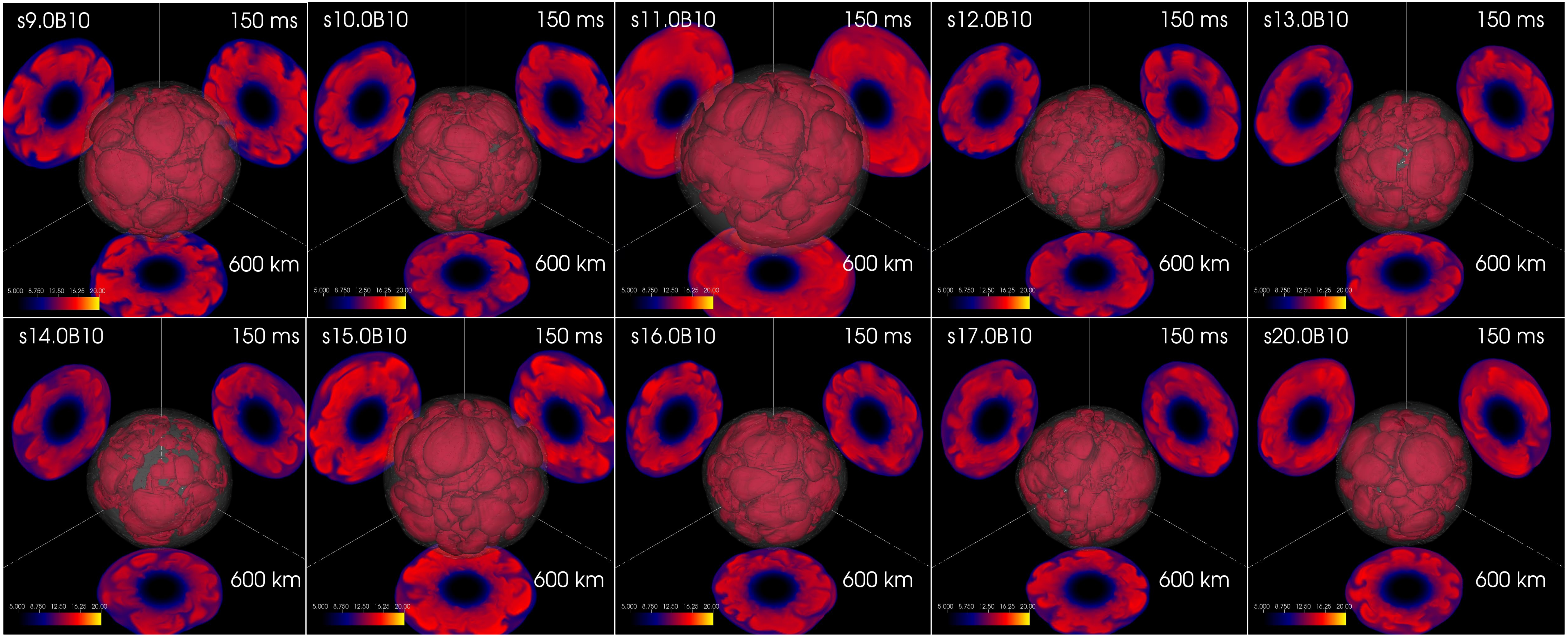
120ms after bounce.



Systematic 3D MHD simulations - Overview

- ✓ Movies show iso-surface of entropy for 10 models.
  Note that spatial scale (box size) is changing as the shock waves successfully revive and expand.
  The model s11 presents outstanding burst at 140 ms after bounce.

150ms after bounce.



Systematic 3D MHD simulations - Shock revival

✓ (Top panel) Mass accretion rate @ r = 500km.

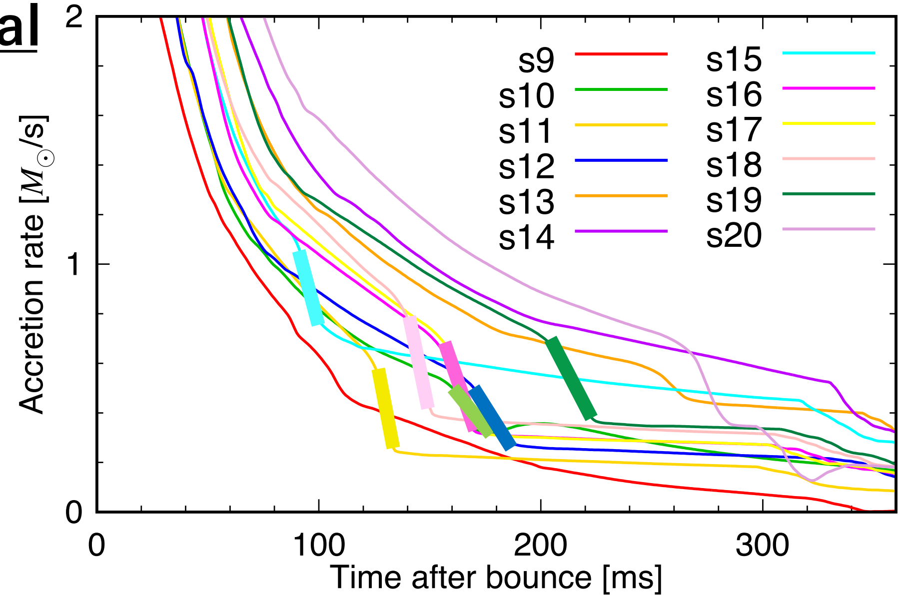
Roughly in order of ZAMS mass (or compactness) in the early phase (< 100 ms).

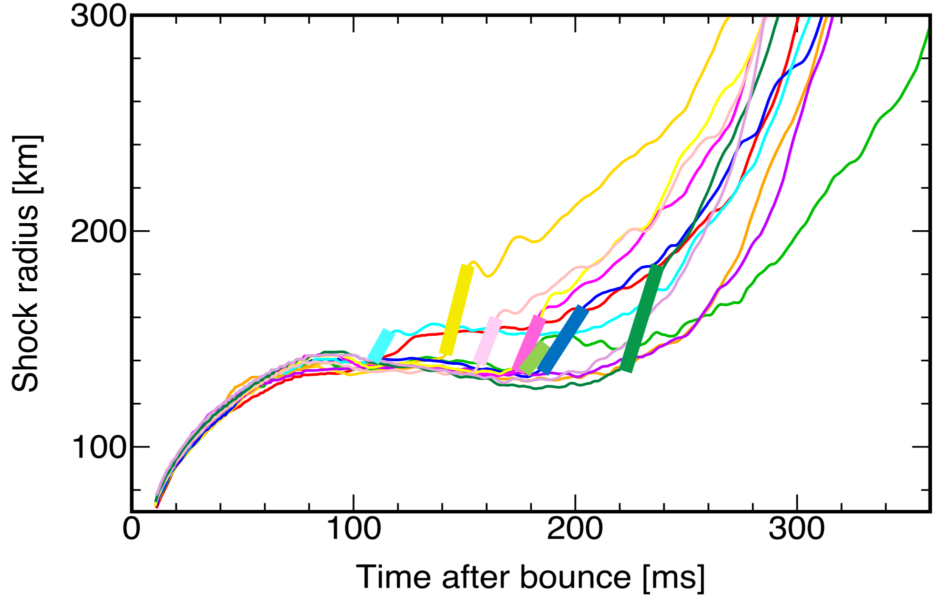
Some models show sudden drop when the Si/O interface passes through.

✓ (Bottom panel) Angle-averaged shock radius.

In some models the shock jumps when the Si/O interface falls onto the shock and ram pressure from the accreting matter is suppressed.
→ Shock revival time is not in order of ZAMS mass.

Finally all examined models successfully revive their shock wave.



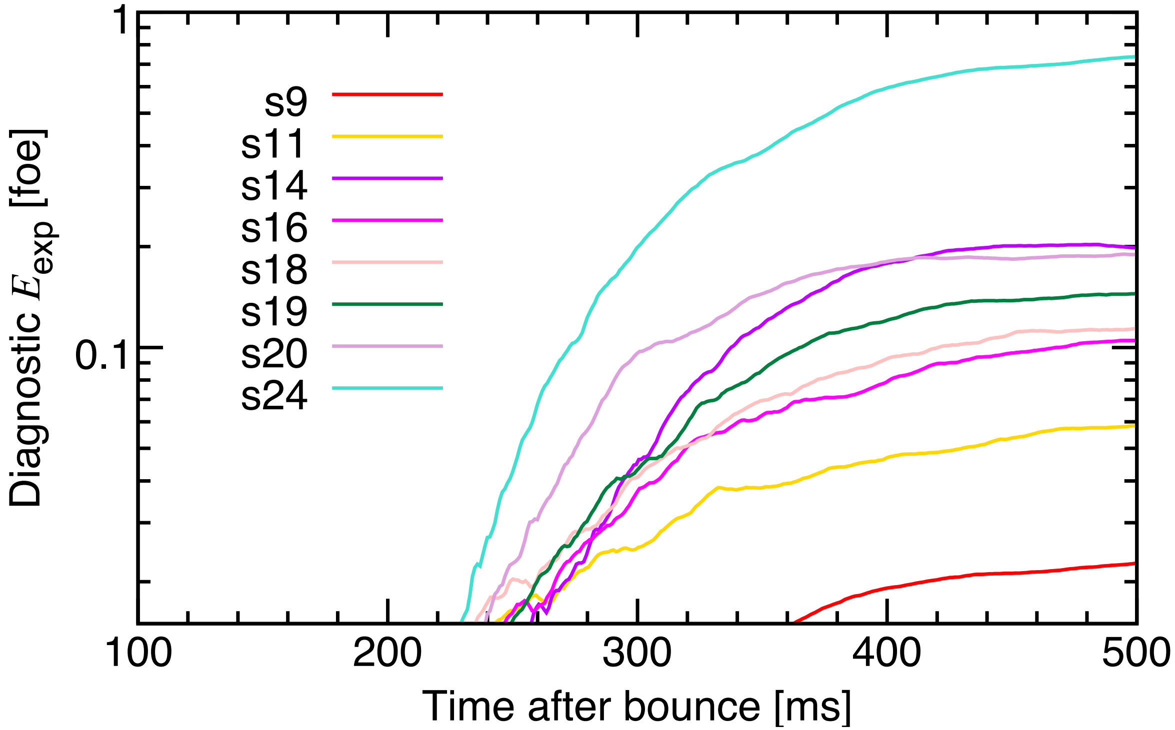


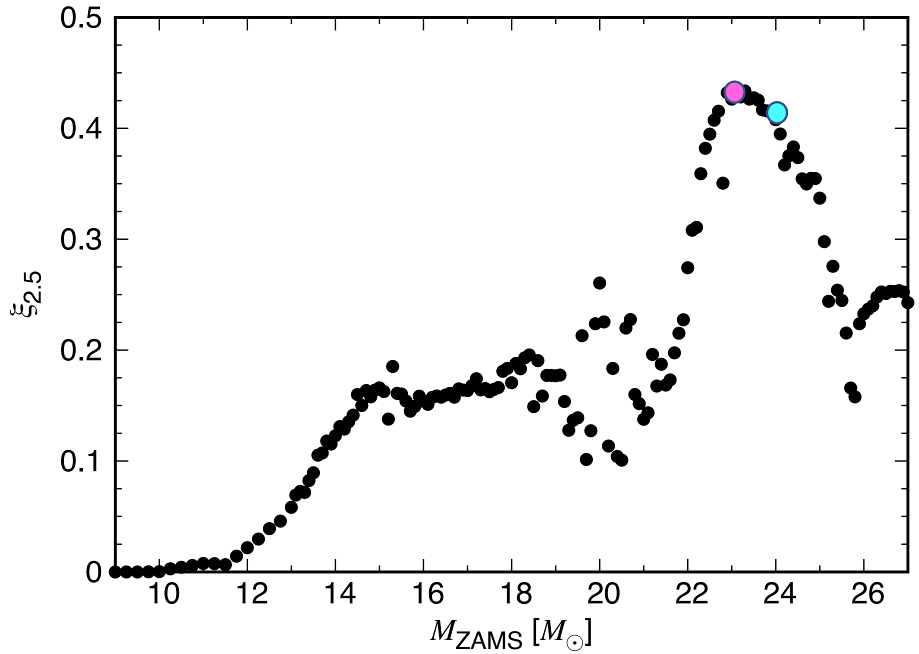
Systematic 3D MHD simulations - Explosion energy

✓ Diagnostic explosion energy

= Ekin + Eint + Egrv of ejecta (unbound & $v_r > 0$).
Here overburden of stellar envelope is not taken into account.

Most models show Eexp < 0.2 x 10^{51} erg @500ms except (s23 &) s24 model.





Multi-messenger signals from CCSN

✓ **KN+ 2016, MNRAS, 461, 3296**

CCSNe emit neutrinos, GWs and electromagnetic waves.

Luminosity:
neutrinos & GWs >> EM

Detectability:
EM >> neutrinos & GWs

GW signal from CCSN is very weak and less detectable compared with compact binary merger event.

But the GW directly brings us some information of CCSN core.

Remnant info. is also useful.

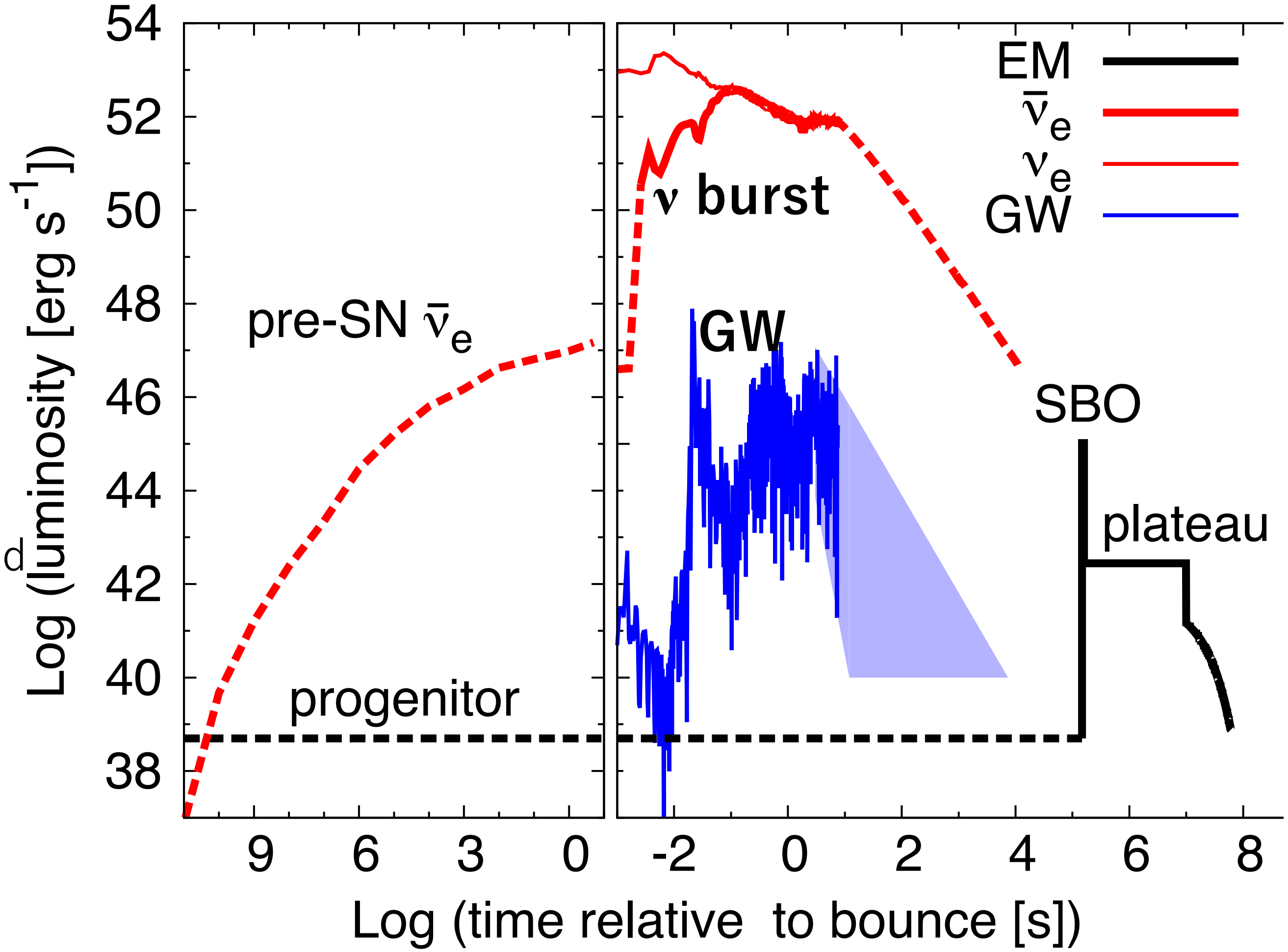


Figure from KN+'16

Systematic 3D MHD simulations - Neutrino LC

✓ （Top panel） Mass accretion rate @ r = 500km.

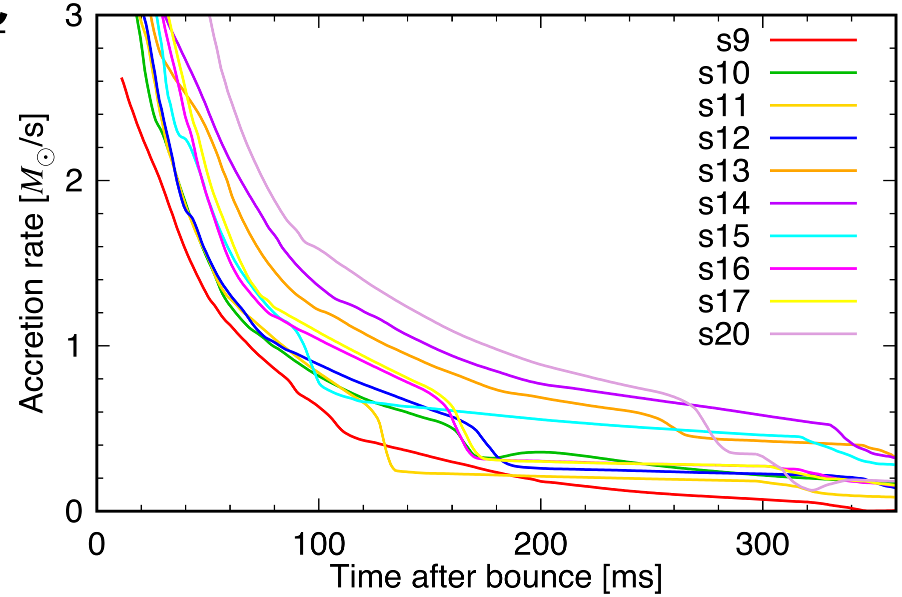
Roughly in order of ZAMS mass (or compactness) in the early phase (< 100 ms).

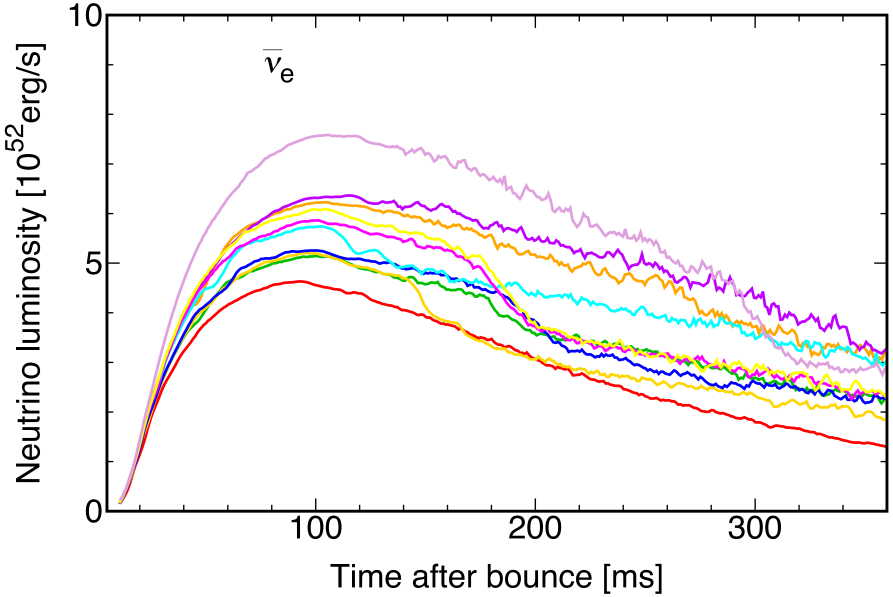
Some models show sudden drop when the Si/O interface passes through.

✓ （Bottom panel） Anti-e neutrino luminosity.

Neutrino luminosity ~ accretion rate ~ compactness.
→ Neutrino detection event number could restrict the progenitor compactness.

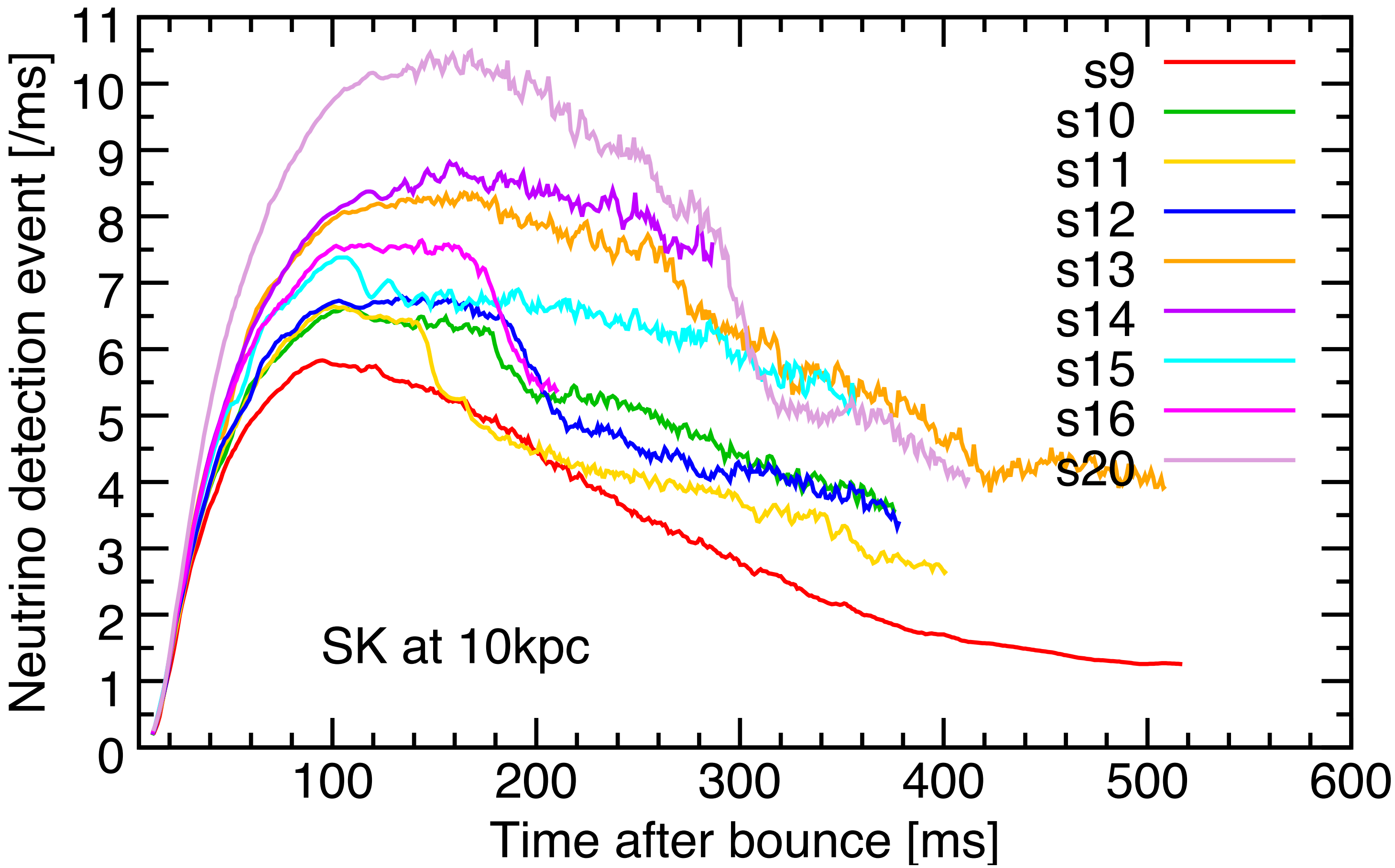
The sudden drop in mass accretion rate causes luminosity jump.
→ It tells us the density structure of the progenitor star.





Systematic 3D MHD simulations - Neutrino detection event

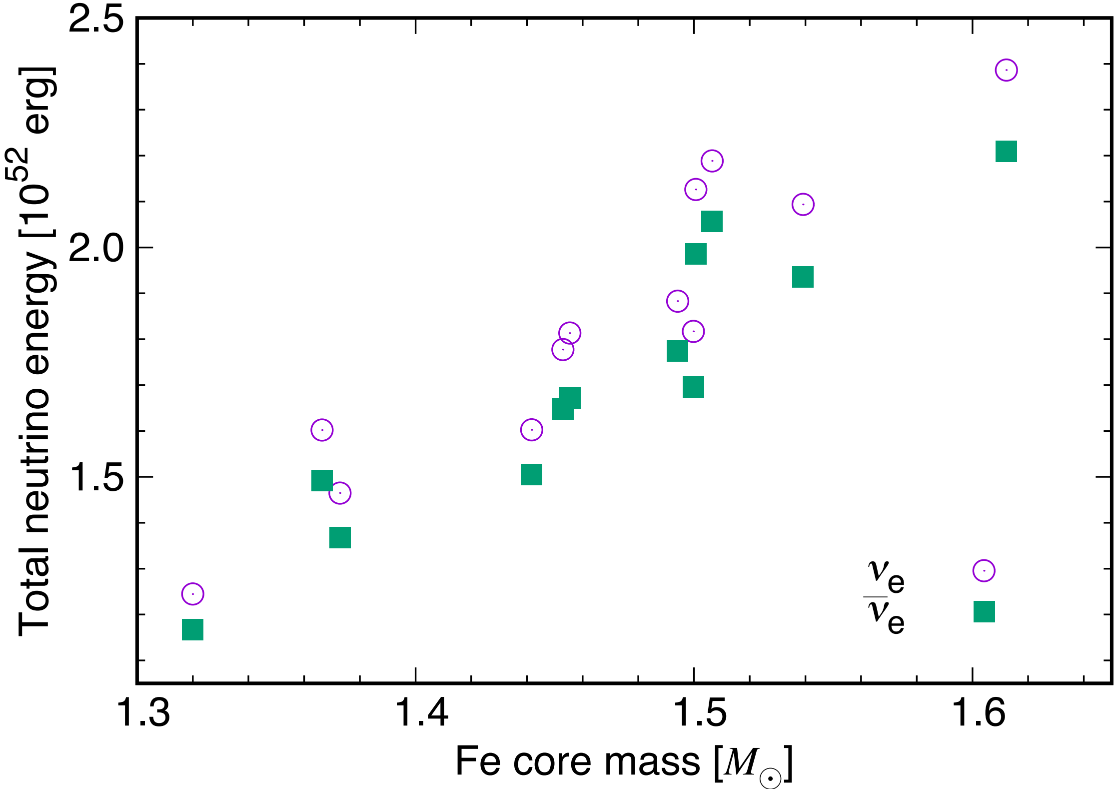
- ✓ Assuming $D = 10$ kpc.
- ✓ SK: fiducial volume = 22.5 kton, threshold energy = 7 MeV.
- ✓ Only IBD is considered. No oscillation.



Systematic 3D MHD simulations - Neutrino (3)

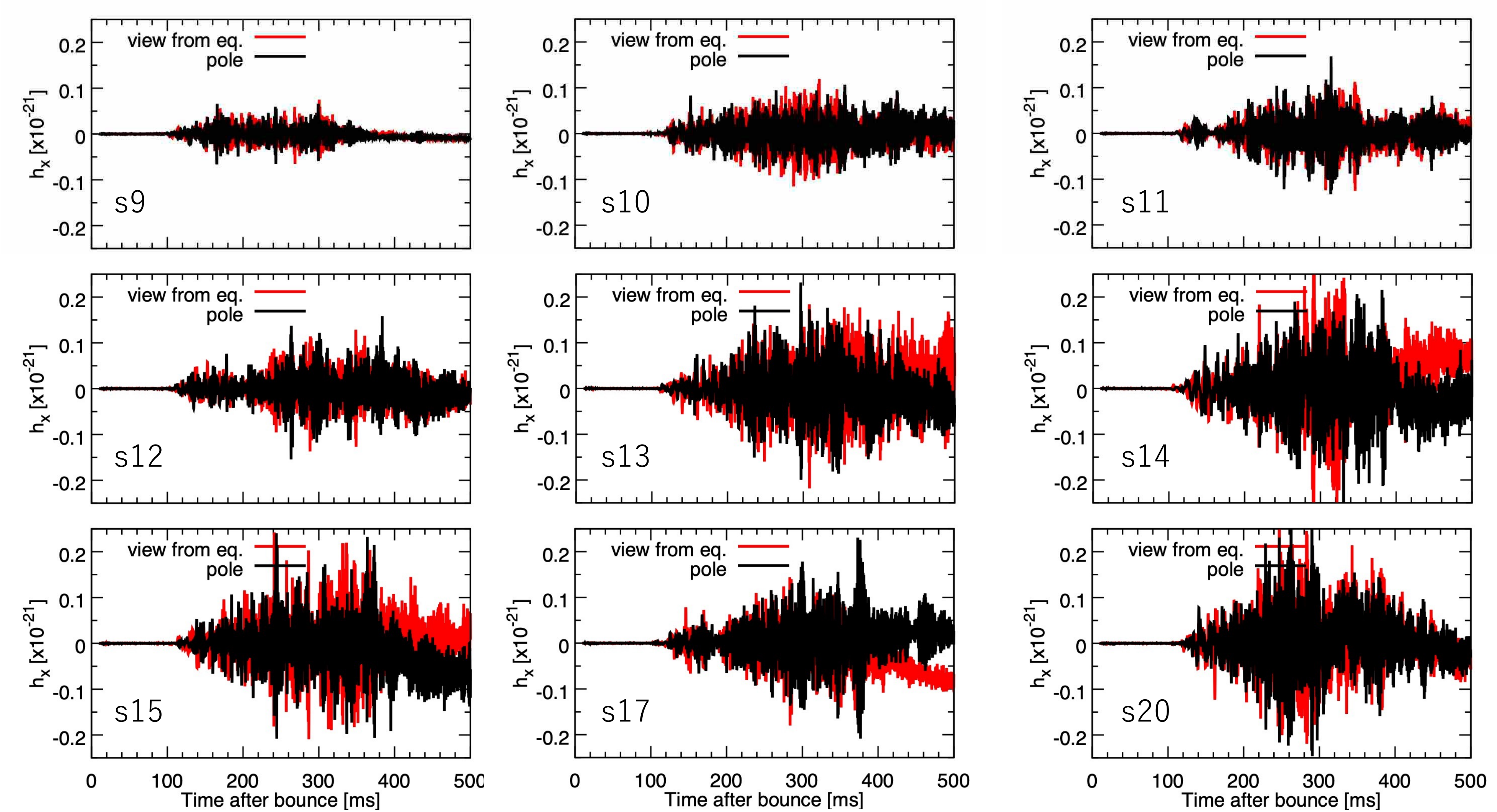
✓ Total neutrino energy emitted between 10-500 ms after bounce.

It well correlates to the gravitational potential energy released via the core collapse, which can be represented by the Fe core mass (shown below), compactness parameter, or PNS mass.



Systematic 3D MHD simulations - GW (1)

✓ GW waveforms for 9 of 12 models.

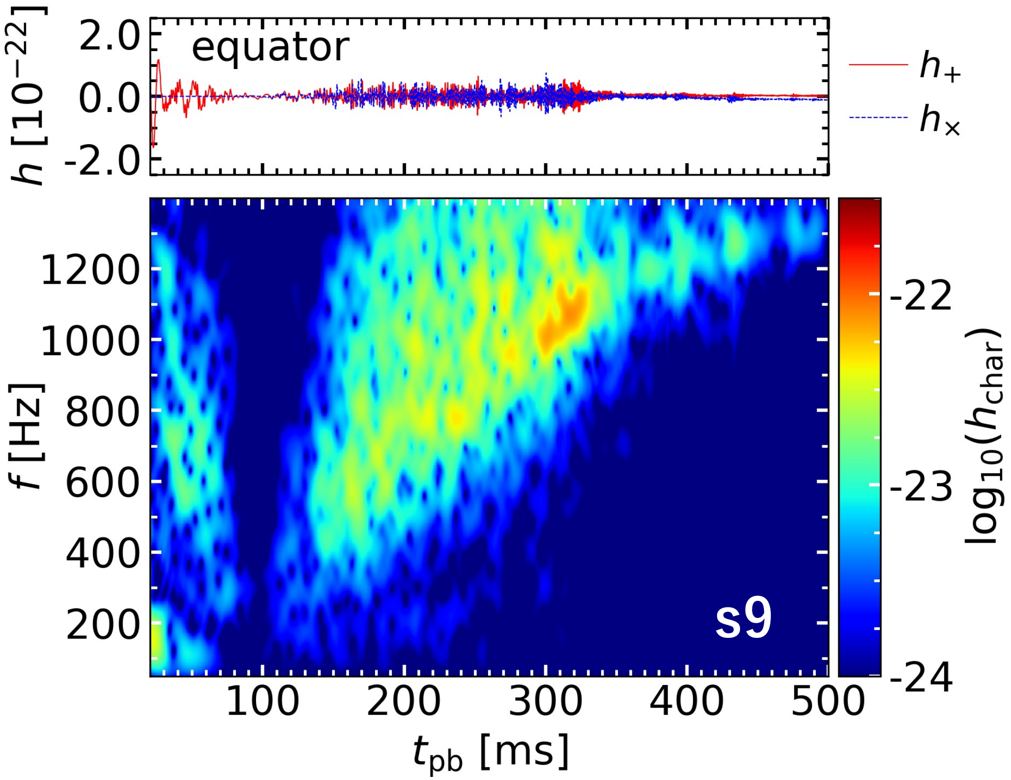


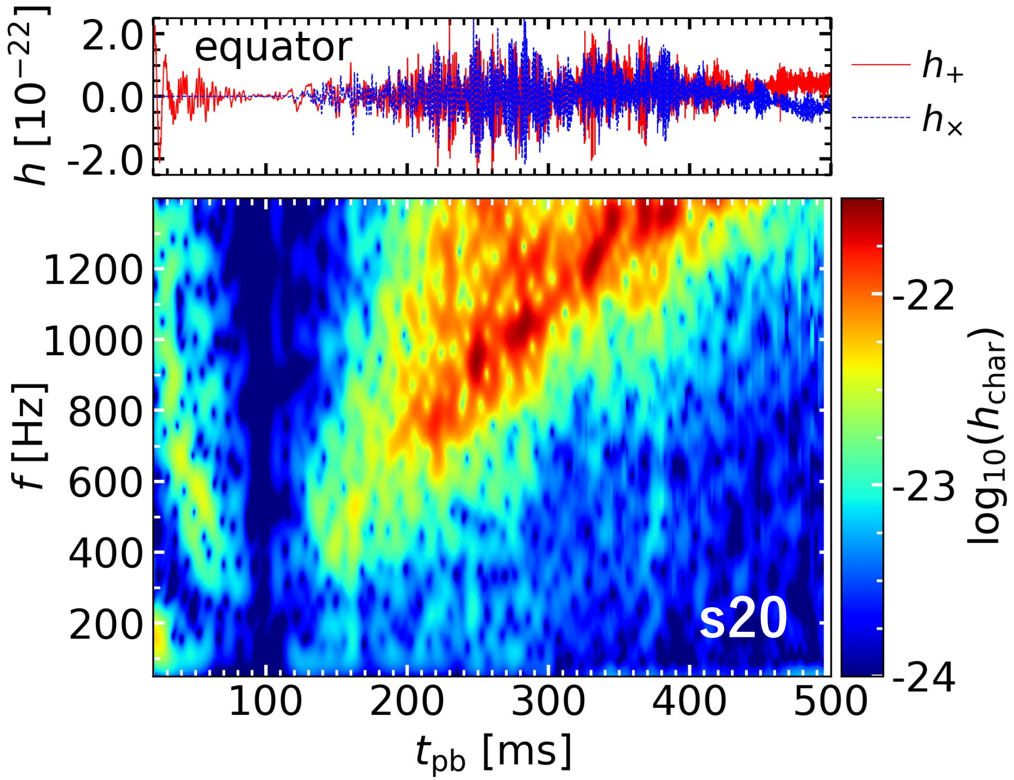
Systematic 3D MHD simulations - GW (2)

✓ GW spectrogram of s9 (left) and s20 (right).

Common features: silent phase (< 100 ms) → nonlinear phase → explosion phase.

Amplitude is correlated to the mass (~ compactness) of the progenitor stars.



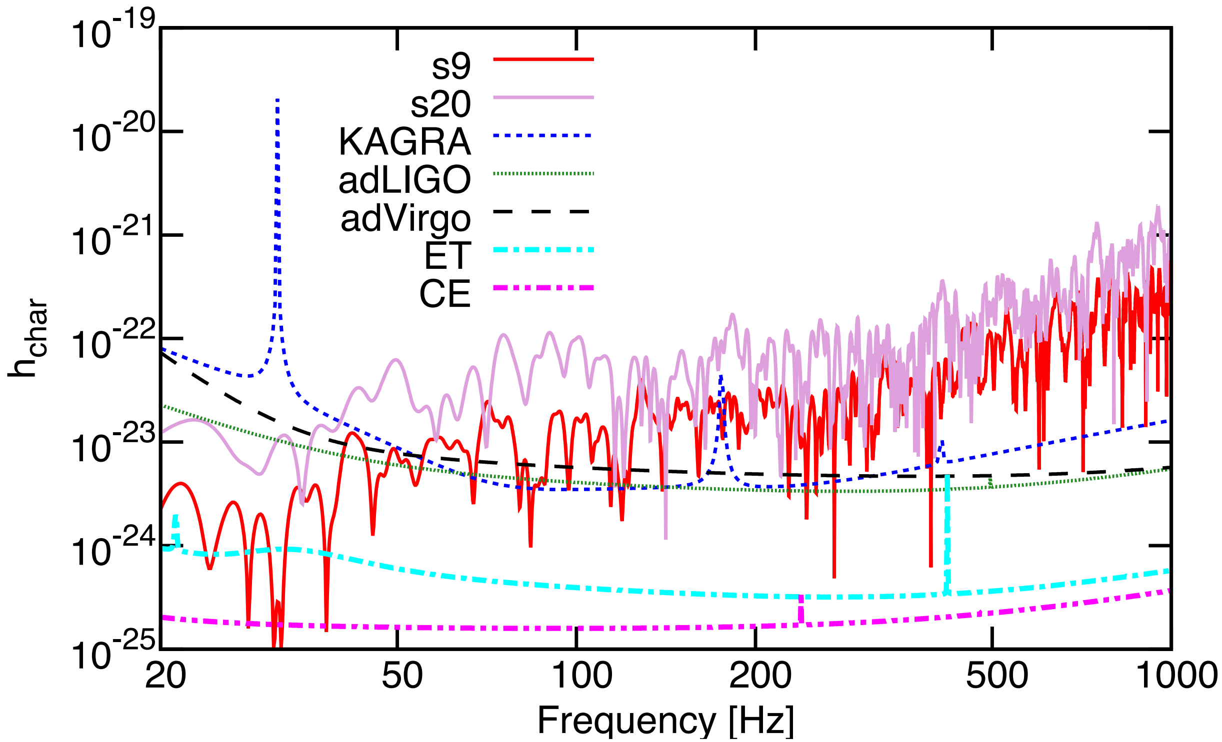


Systematic 3D MHD simulations - GW (3)

✓ GW spectra of s9 (small mass & small ξ) and s20 (high mass & high ξ), compared with sensitivity curves of some current and future GW detectors (D = 10 kpc).

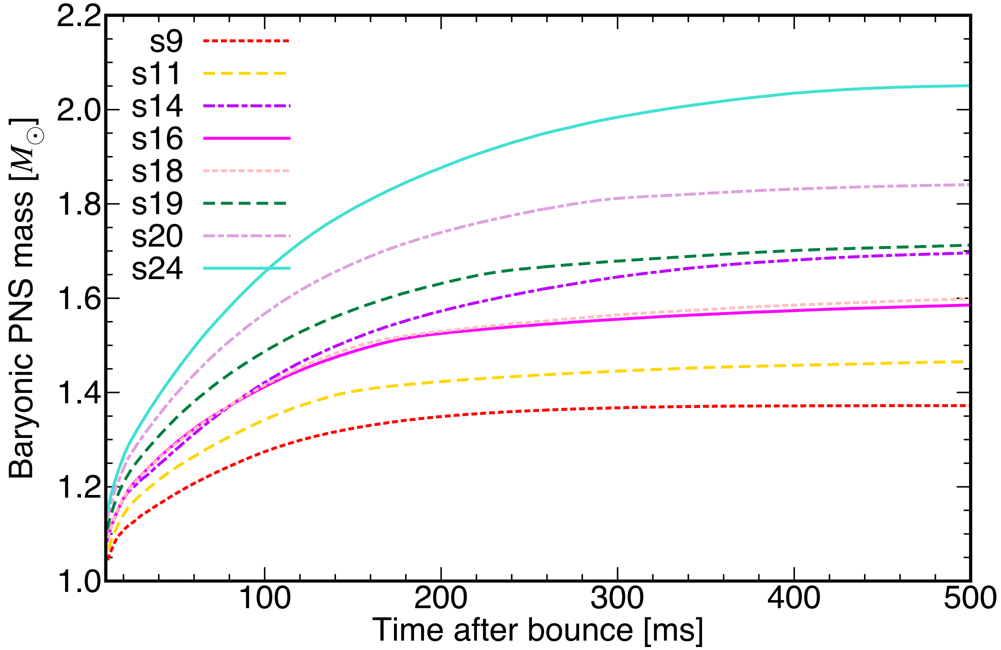
Common features:
High-frequency components coming from central region are dominant.

s9: Only $f >$ ~200 Hz is detectable.
s20: low-f signal (>~70 Hz) including PNS convection signal could be detectable.



NS properties - mass

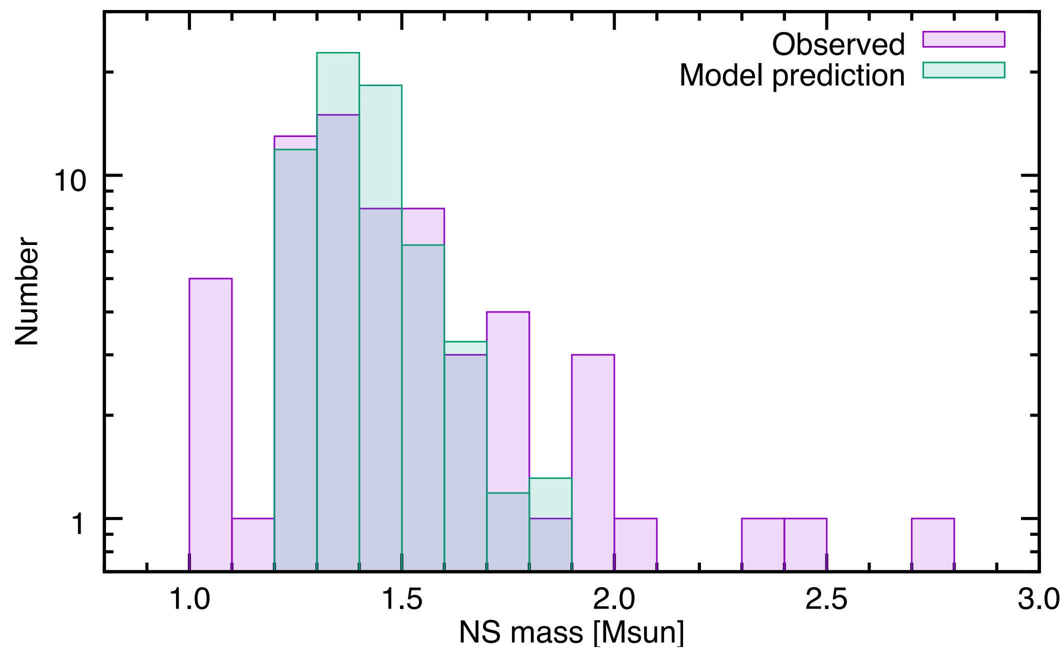
Time evolution of baryonic mass



1.4 - 2 Msun.
High accretion rate produces massive PNSs.

The time evolution is not (directly) observable.
We could guess from a ν luminosity curve.

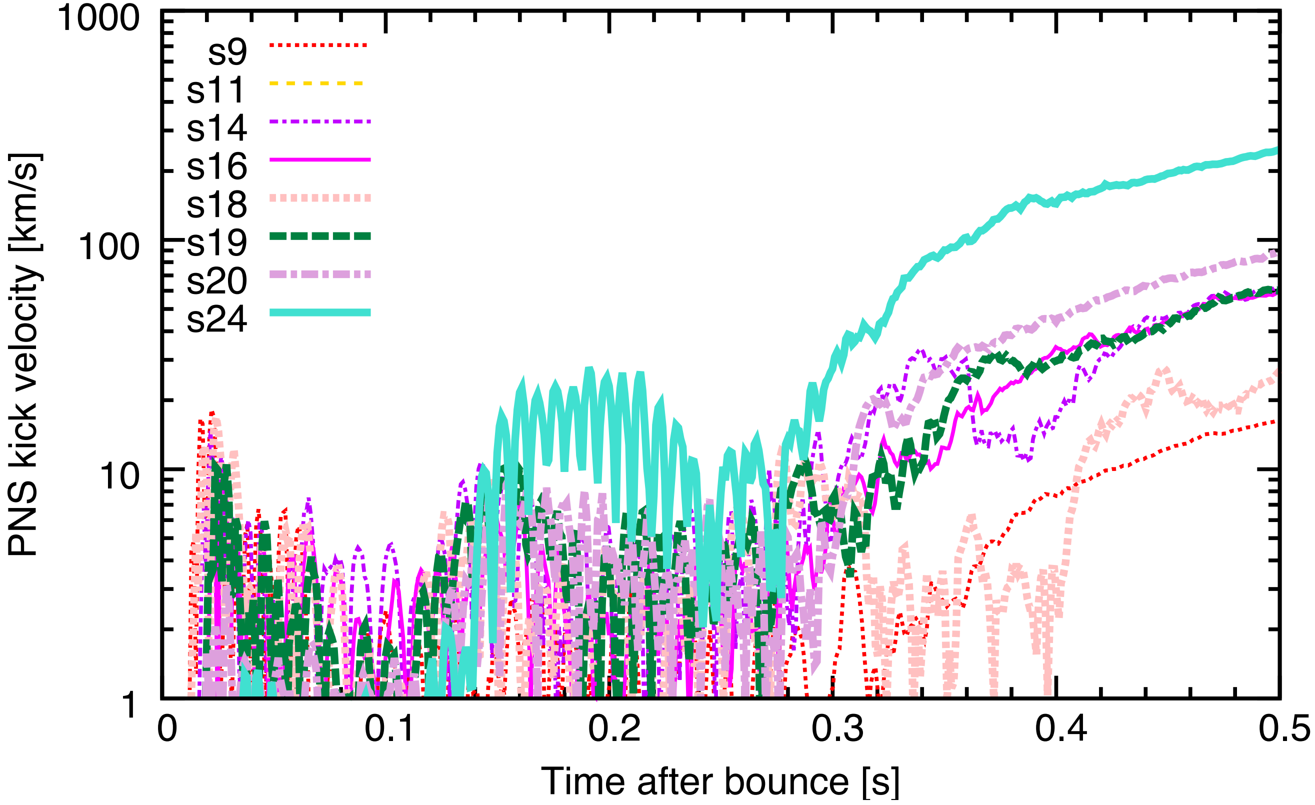
Gravitational mass distribution



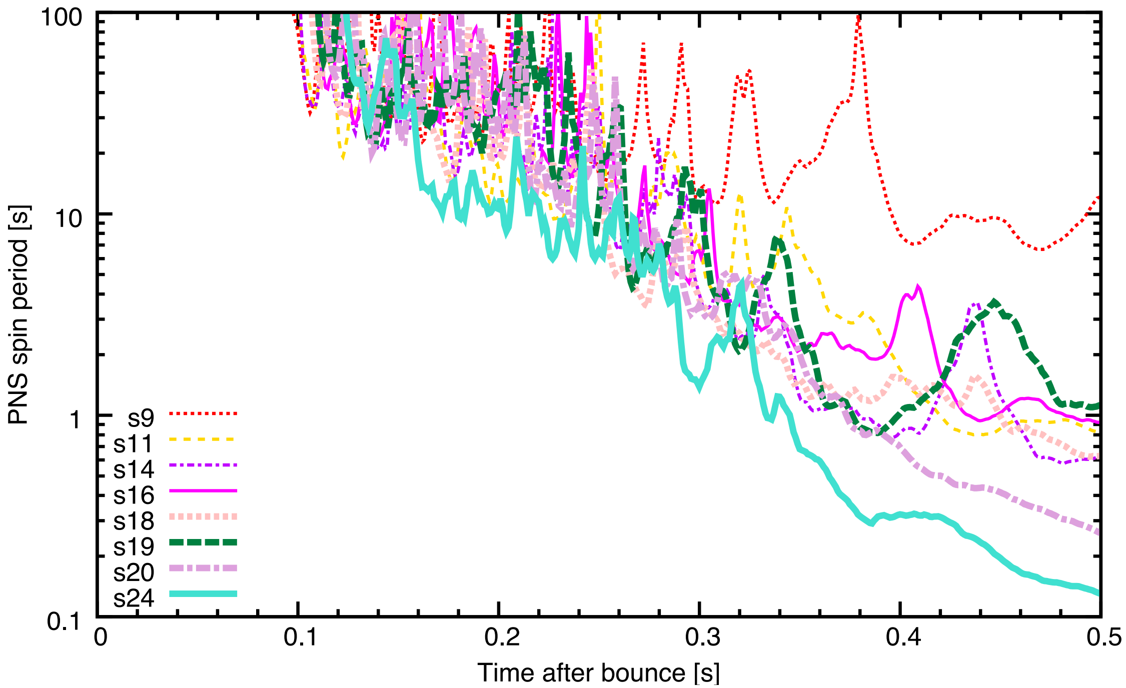
"Observed" data from Table 1 in *Lattimer (2012) Annu. Rev. Nucl. Part. Sci., 62, 485.*
"Model prediction" is IMF (Salpeter) weighted.

1.2-1.7 Msun well reproduced!
Low mass NSs from binary interaction?
High mass ones supported by rapid rotation?

NS properties - kick velocity

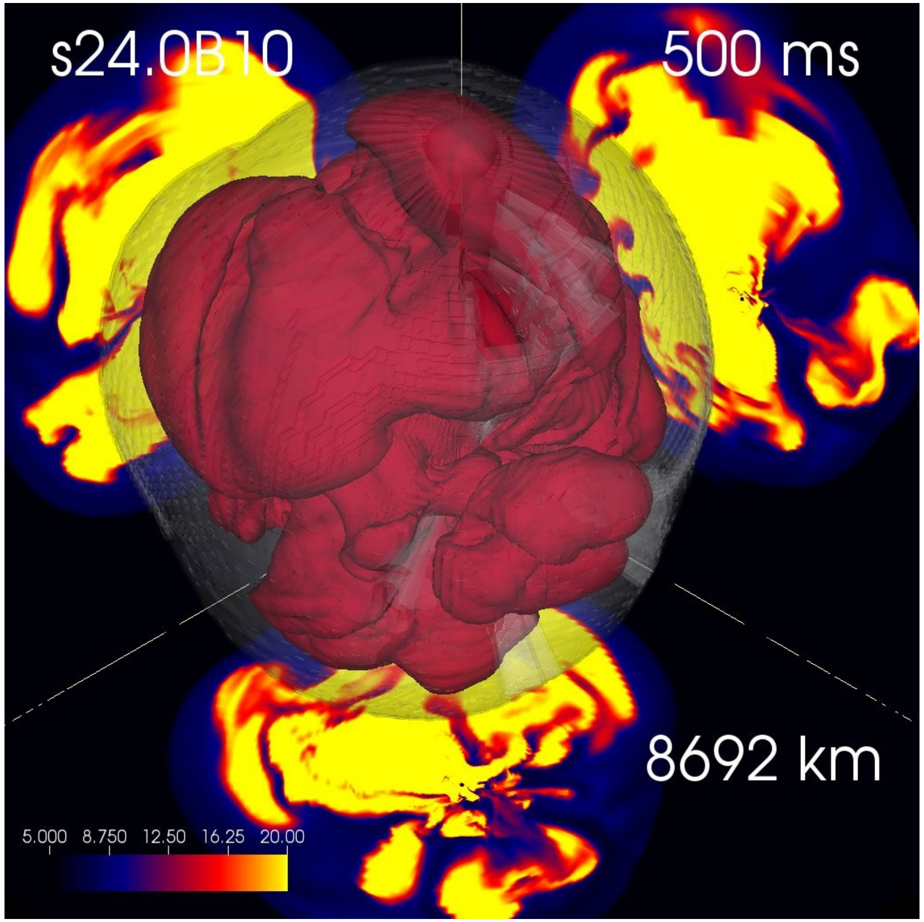


NS properties - spin

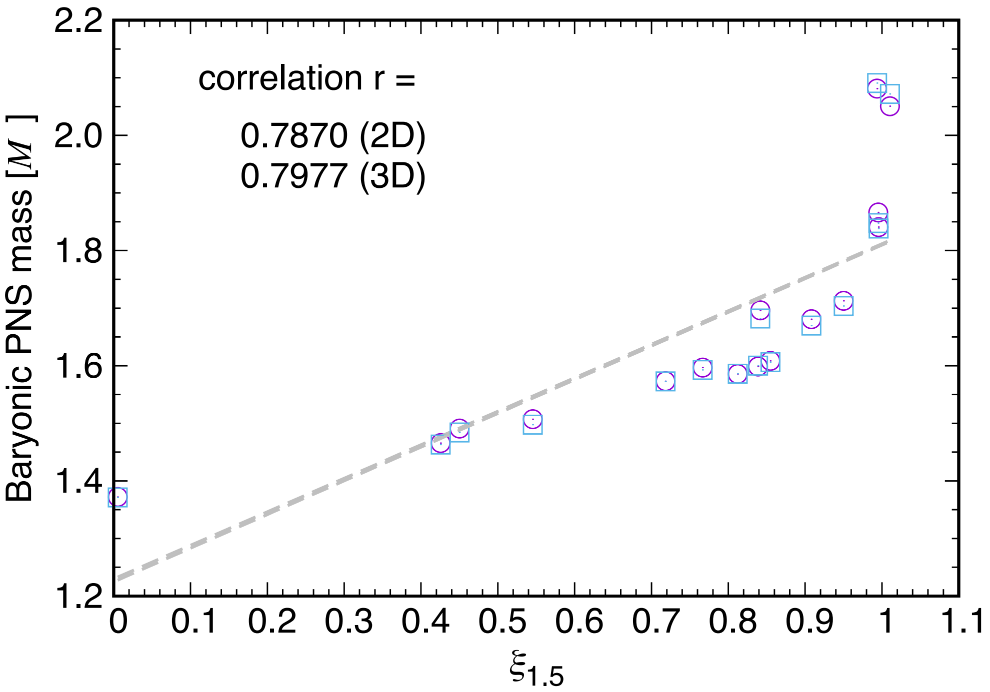


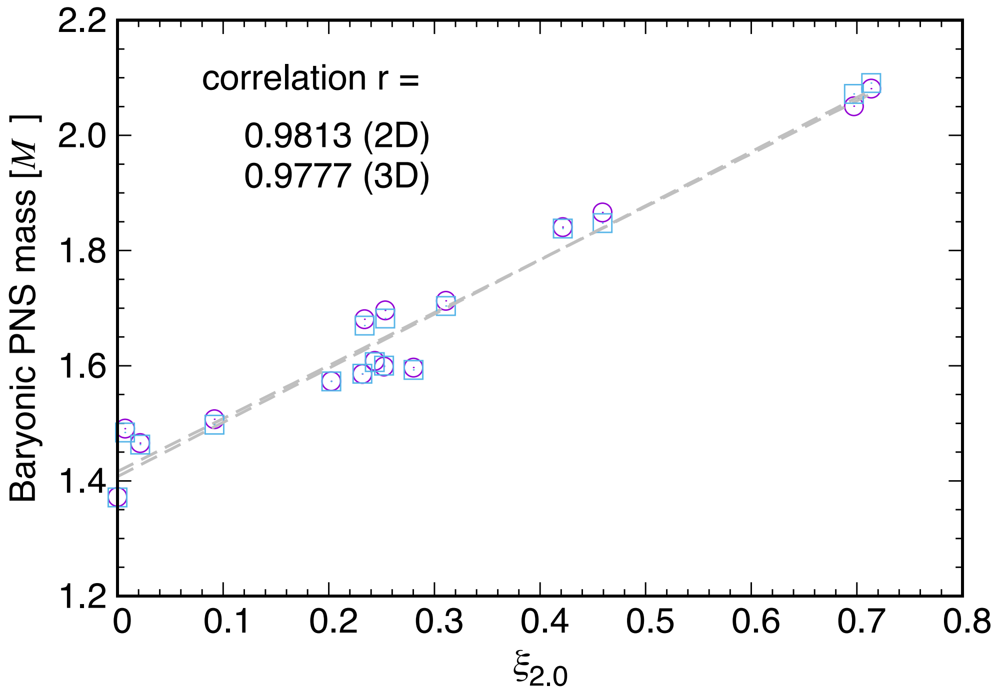
(Note: our simulations start from non-rotating progenitors.)

Spiral mode of SASI in s24 model.

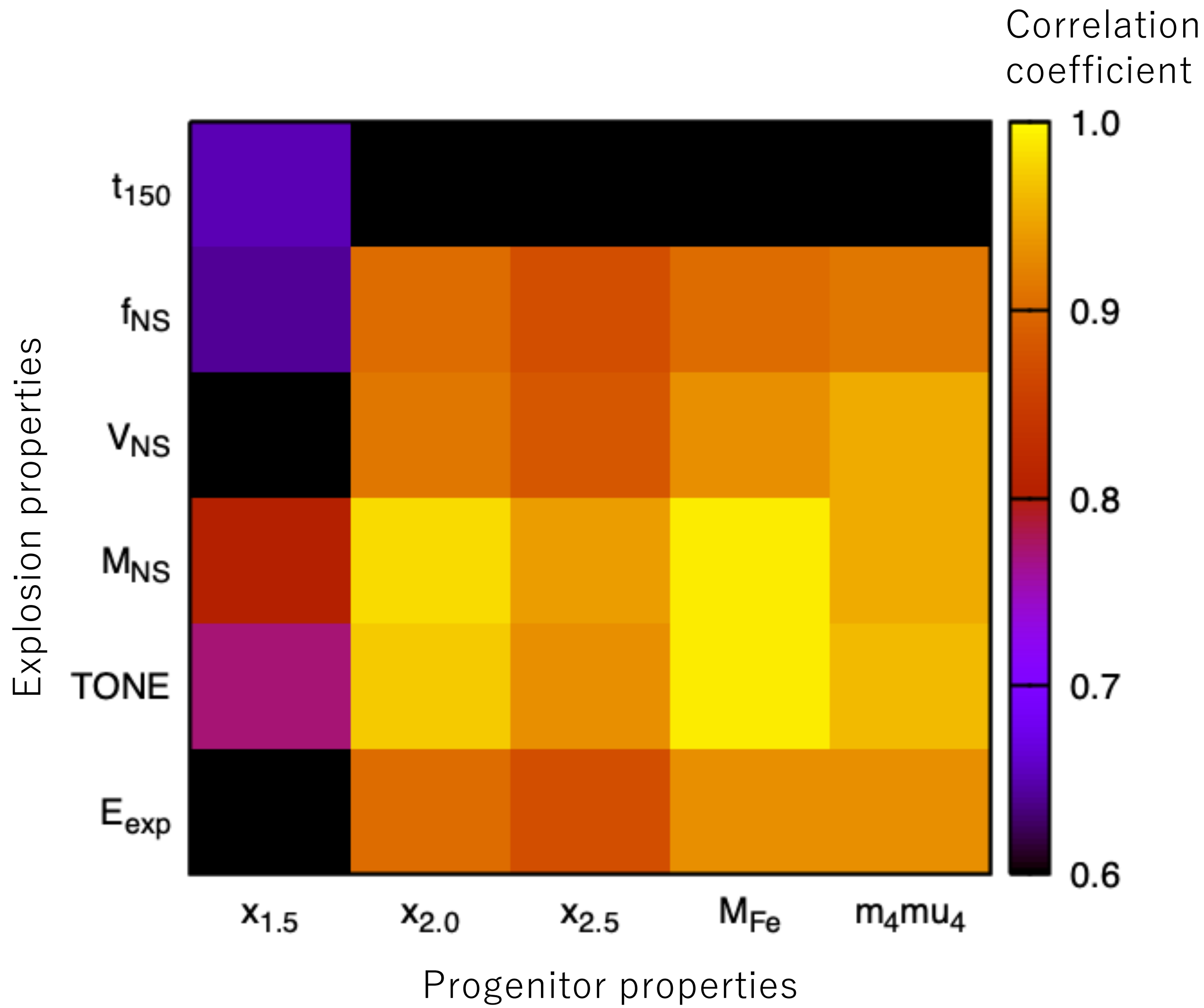


CCSN properties - what determines?





CCSN properties - what determines?



Summary

- ✓ Systematic study of 3D CCSN models is still challenging but now it’s a feasible idea.
- ✓ We demonstrate 3D MHD simulations for 9-24 solar mass progenitors (Sukhbold+’16).
- ✓ All the examined models show successful shock revival in 300 ms.
- ✓ The MM signals predicted from our 3D CCSN models confirm the previous findings in 1D/2D simulations:
  - The v luminosity and average energy differs between the models by a factor of <~2.
  - The total neutrino energy emitted during our simulations well correlates to the Fe core mass of the progenitor stars.
  - GW signals have silent phase (< 100 ms) → nonlinear phase → explosion phase.
  - High-f strong signal and low-f weak signal exist.
  - Amplitude is correlated to the mass (compactness) of progenitor stars.

→ They will provide us with fruitful information on the structure of the CCSN core!