3D simulations of CCSNe:
a systematic investigation of NS properties

KN+(2025) MNRAS, 536, 280

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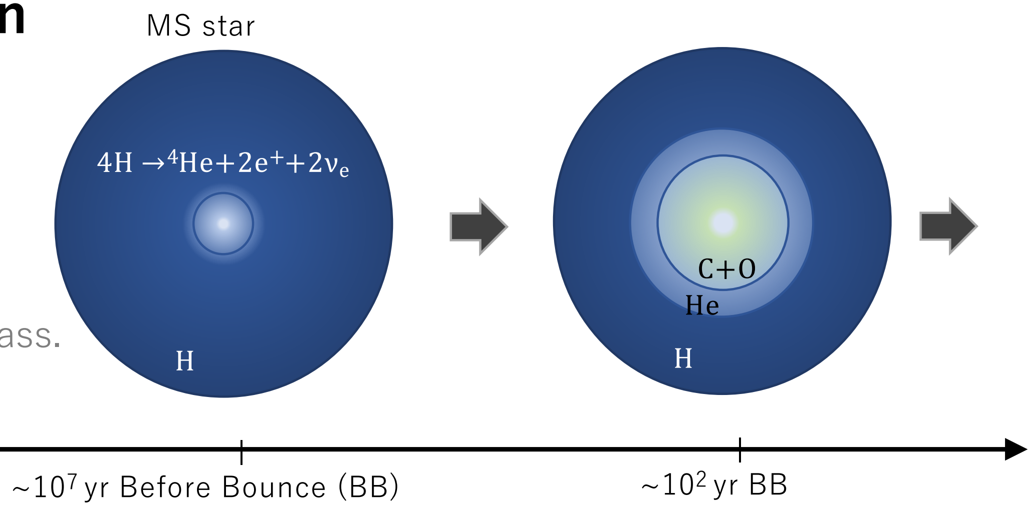
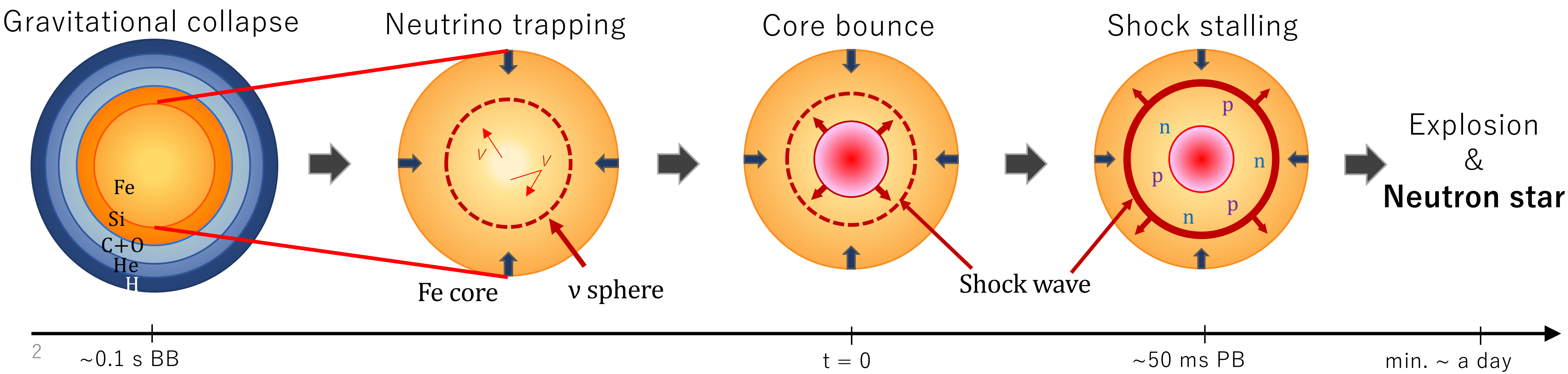
From a massive MS star to a CCSN

✓ 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.





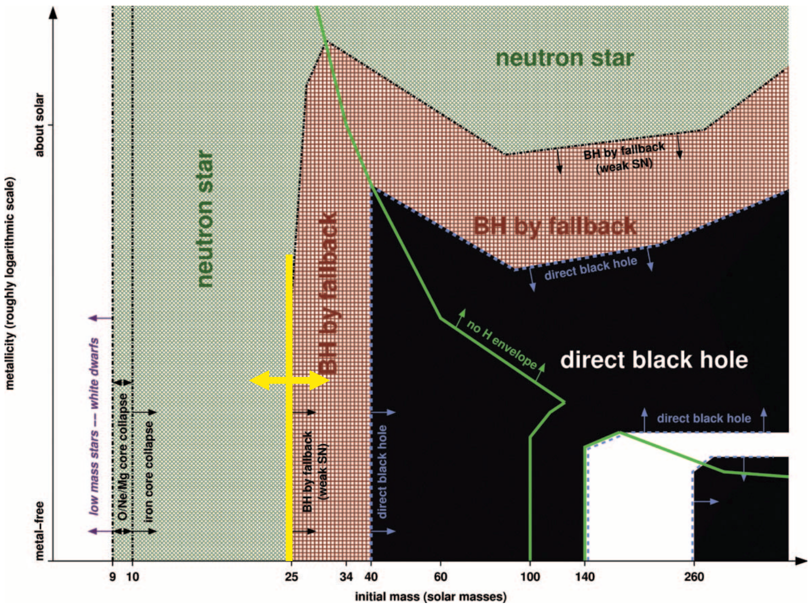
Systematic numerical simulations

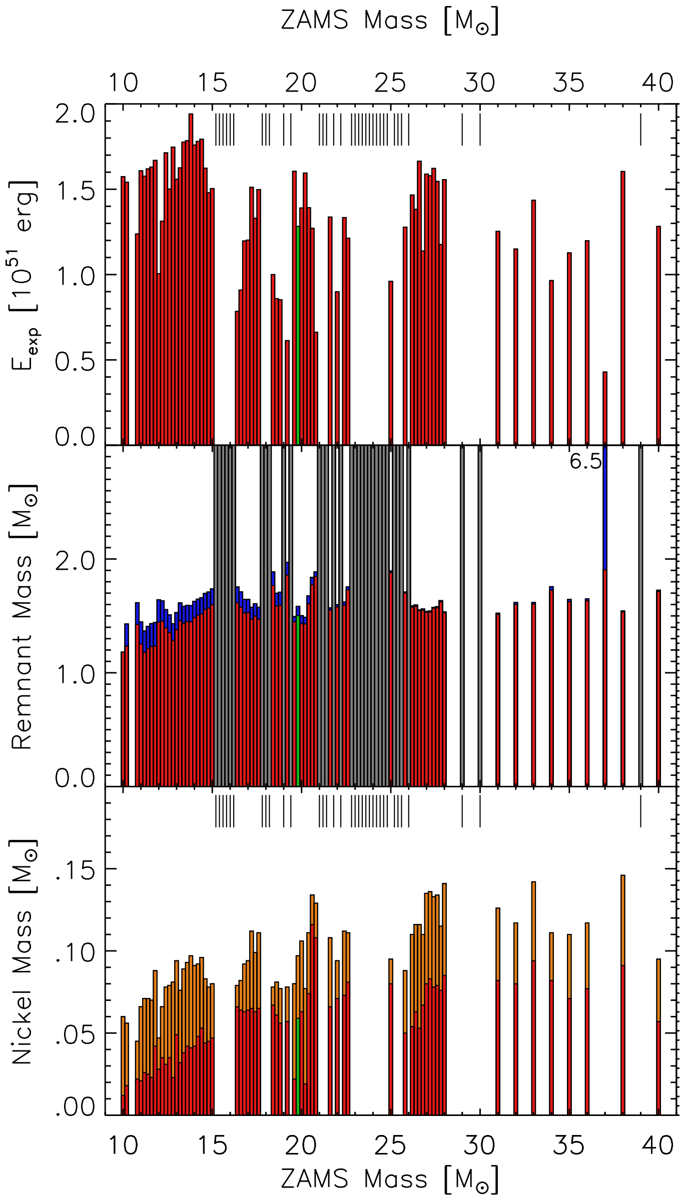
- ✓ Heger et al. (2003)

  There should be a **"critical" mass** at $M \sim 25\ M_{\odot}$, dividing NS/BH forming cases.

- ✓ O'Connor & Ott (2011); Ugliano et al. (2012)

  1D simulations with artificial explosion schemes show **non-monotonic explosion properties**.





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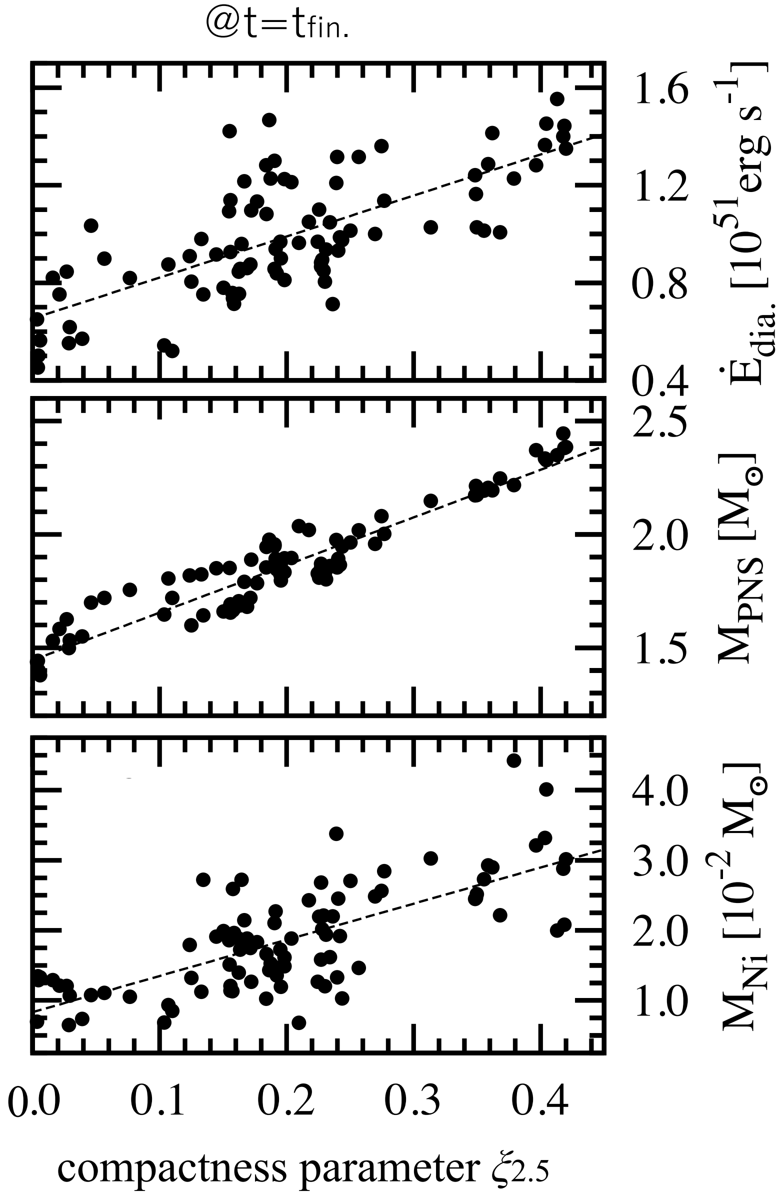
✓ KN et al. (2015); KN et al. (2019)

2D self-consistent simulations show linear relations between some explosion properties and the **compactness parameter** ξ.

$$\xi_M = M(R)\ [M_\odot]\ /\ R\ [1000\ \mathrm{km}]$$



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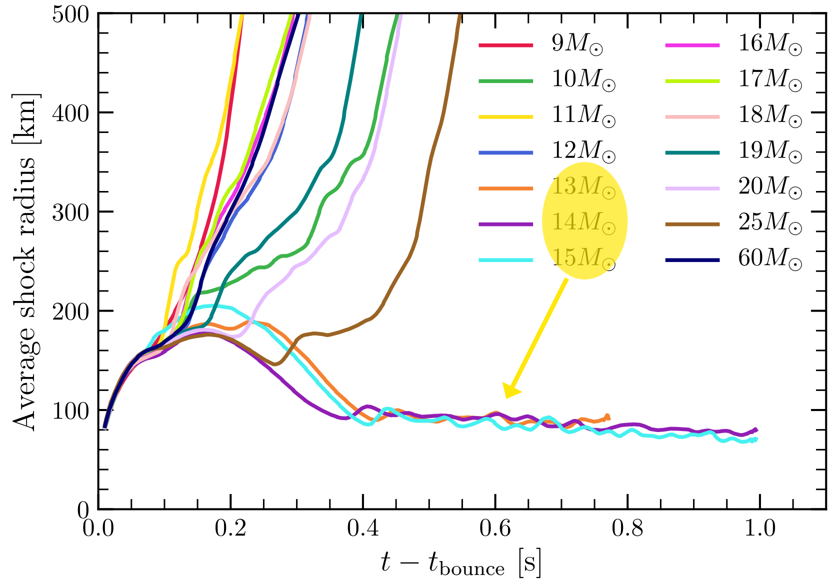
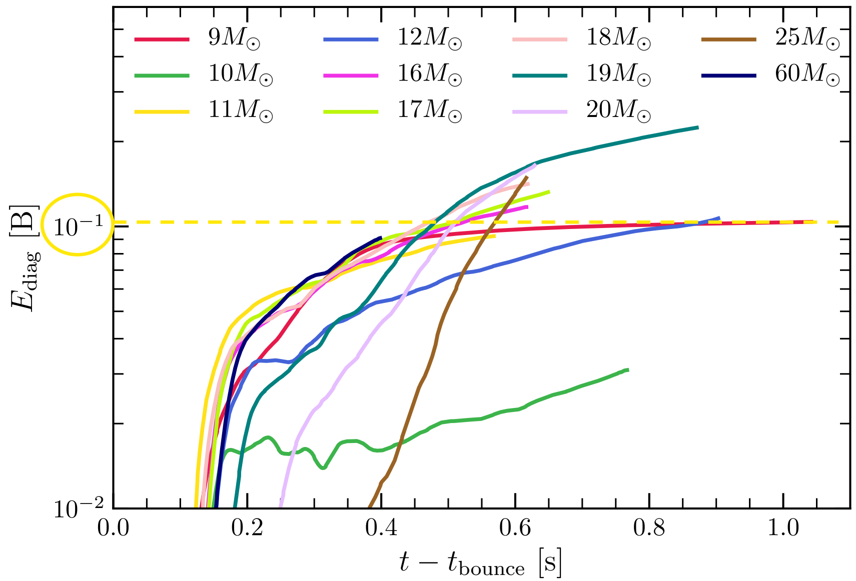
2D self-consistent simulations show linear relations between some explosion properties and the **compactness parameter** ξ.

✓ Burrows et al. (2020)

3D self-consistent simulations show low-energetic (~10^{50} erg) or failed explosions.





Systematic CCSN simulations

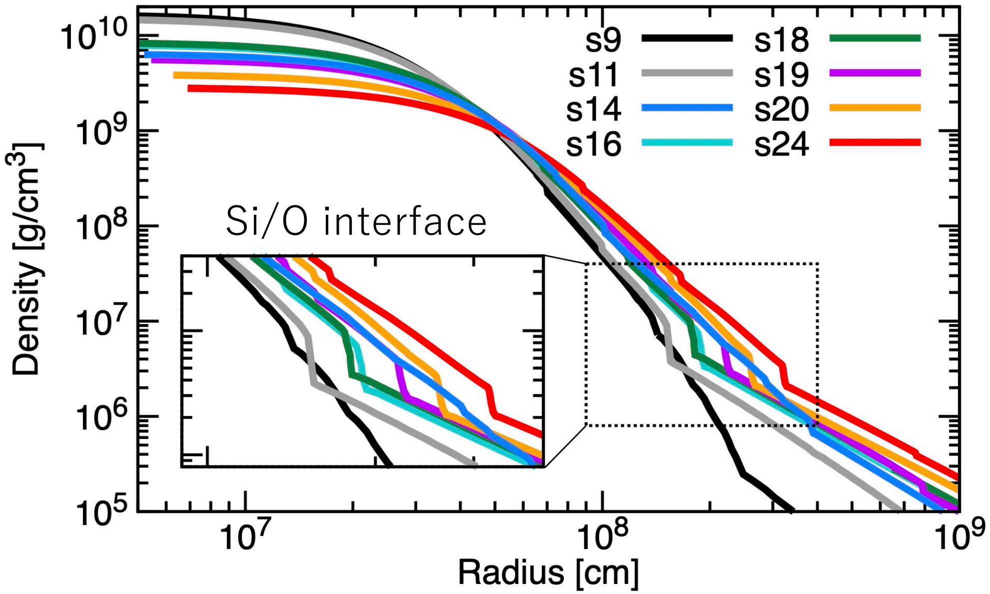
	Spatial dim.	Model #	ν heating	ZAMS M $[M_\odot]$	Z	sim. time	Summary
O'connor & Ott '11,'13	1D	~100	x *factor*	10-120	0-solar	~1s	Non-monotonic expl./BH formation.
Ugliano+'13	1D	~100	$L\nu\,(R_{NS}, t)$	10-40	solar	**~10s+**	Non-monotonic explosion properties.
KN+'15	**2D**	**~400**	**Self-consistent**	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+'25	**3D**	**16**	**Self-consistent**	9-24	solar	0.5s	**Independent 3D study, based on MHD.**

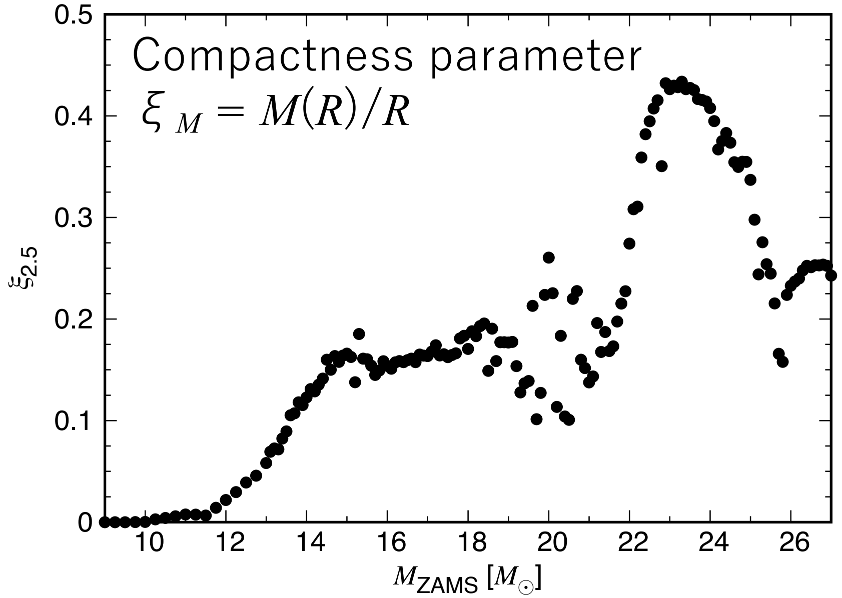
Systematic 3D MHD simulations - Numerical scheme

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

- 3D neutrino-radiation hydrodynamics code for CCSN simulations.
- Neutrino transport: 3-flavor IDSA scheme, 20 energy bins for $0 < e_\nu < 300$ MeV.
- GR effects: effective GR potential (case A in *Marek+'06*) and reddening in ν transport.
- EoS: LS220 EoS + Boltzmann gas.

✓ **16 progenitor models** covering **9-24 solar masses** (*Sukhbold+'16*)





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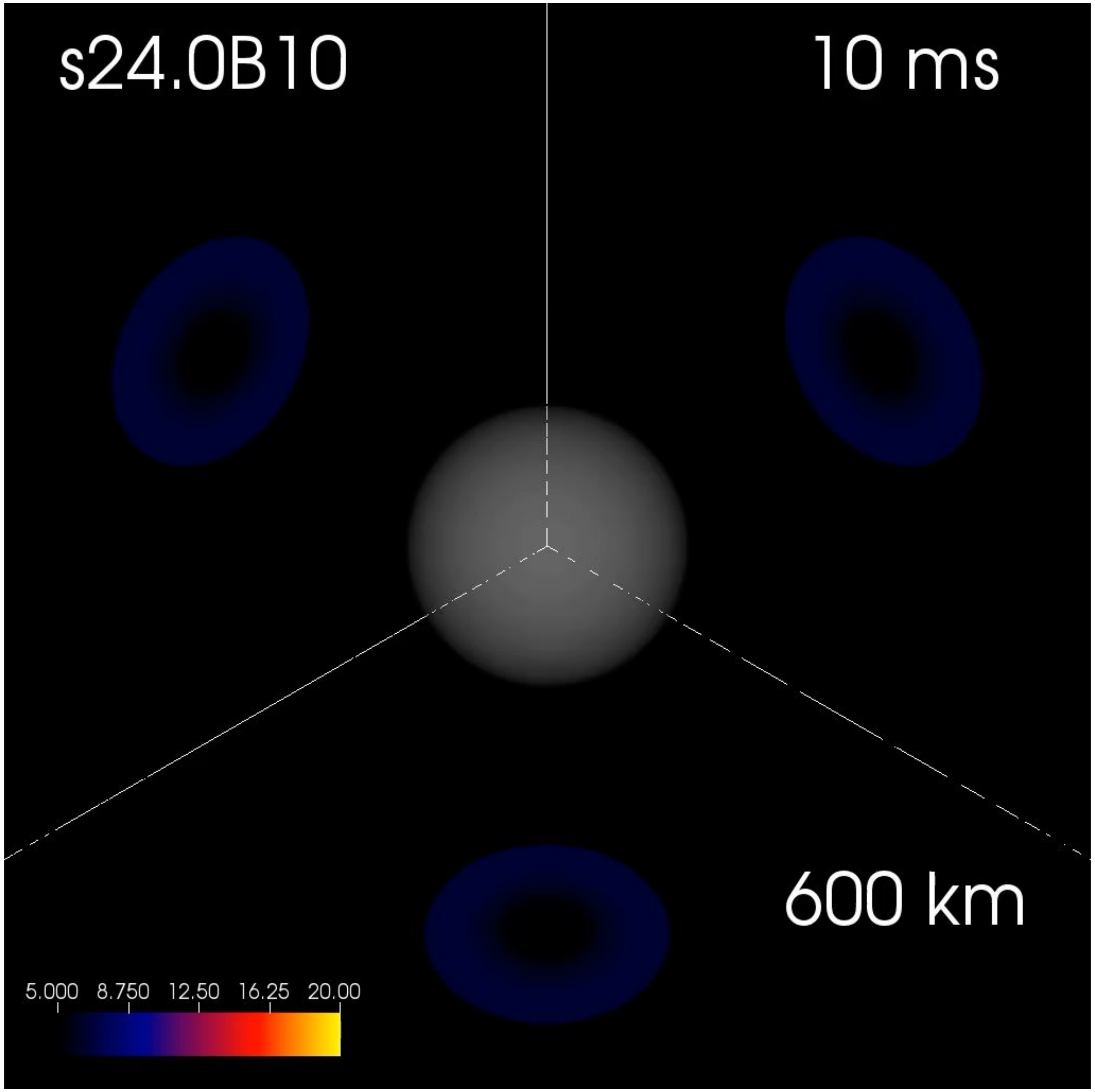
✓ Initial 2D simulation:
- No rotation, $A_\phi = \frac{B_0}{2}\frac{r_0^3}{r^3 + r_0^3} r \sin\theta$ with $\boldsymbol{B_0} = \mathbf{10^{10}}$ **[G]** (weak) and $r_0 = 10^3$ km.
- 600(r)x128(θ) grids for $0 \leqq R \leqq 10^4$ km and $0 \leqq \theta \leqq \pi$.

✓ Subsequent 3D simulation:
- 2D → 3D at 10ms after bounce.
- Random **density perturbation (≦ 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 - Overview



24 solar-mass progenitor

~2M CPU*hr / model
(~1.5 month with 2000 CPUs)

Systematic 3D MHD simulations - Shock revival

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

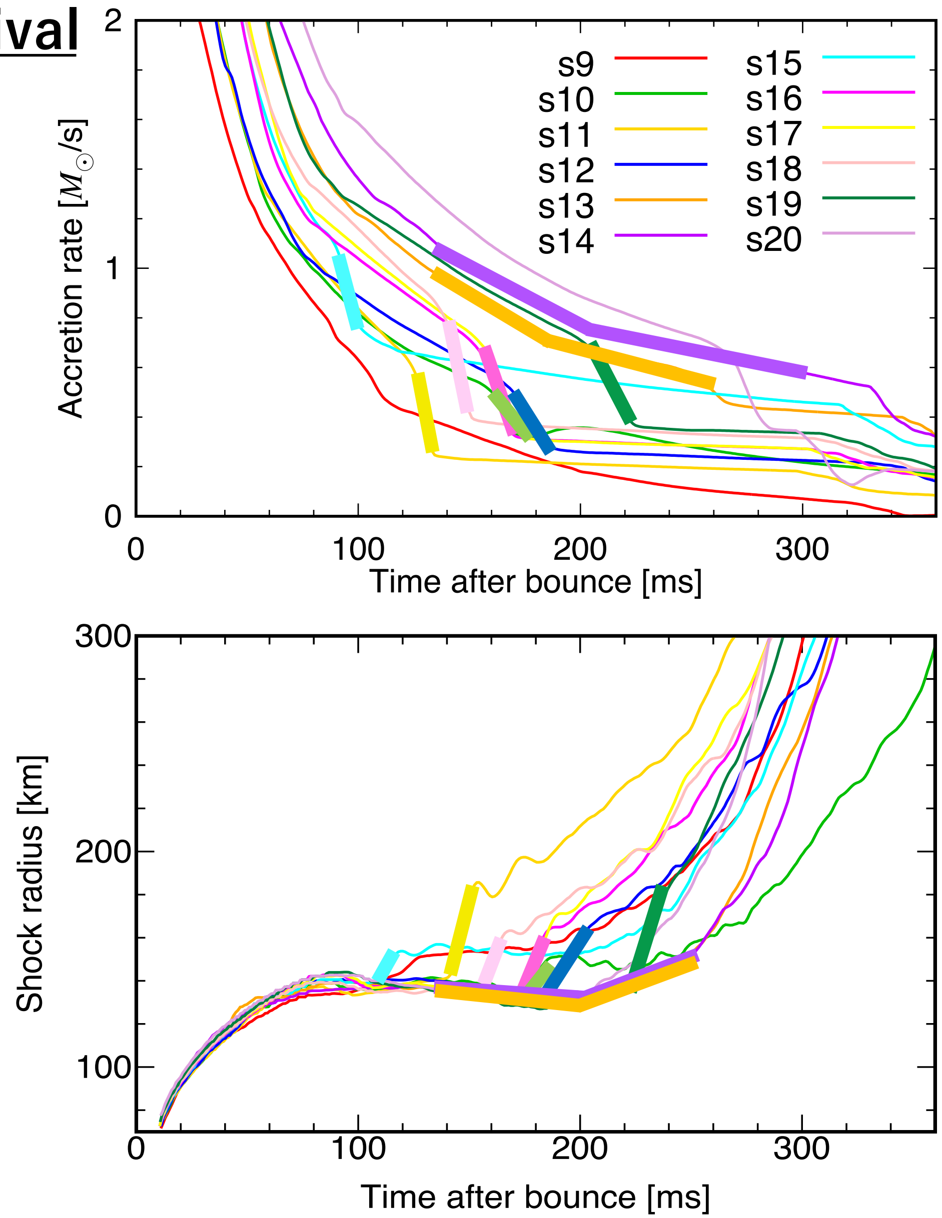
Roughly in order of ZAMS mass (or compactness) in the early phase (< 100 ms).

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.

The density jump in the progenitor structure plays a crucial role in shock revival (**explodability**).



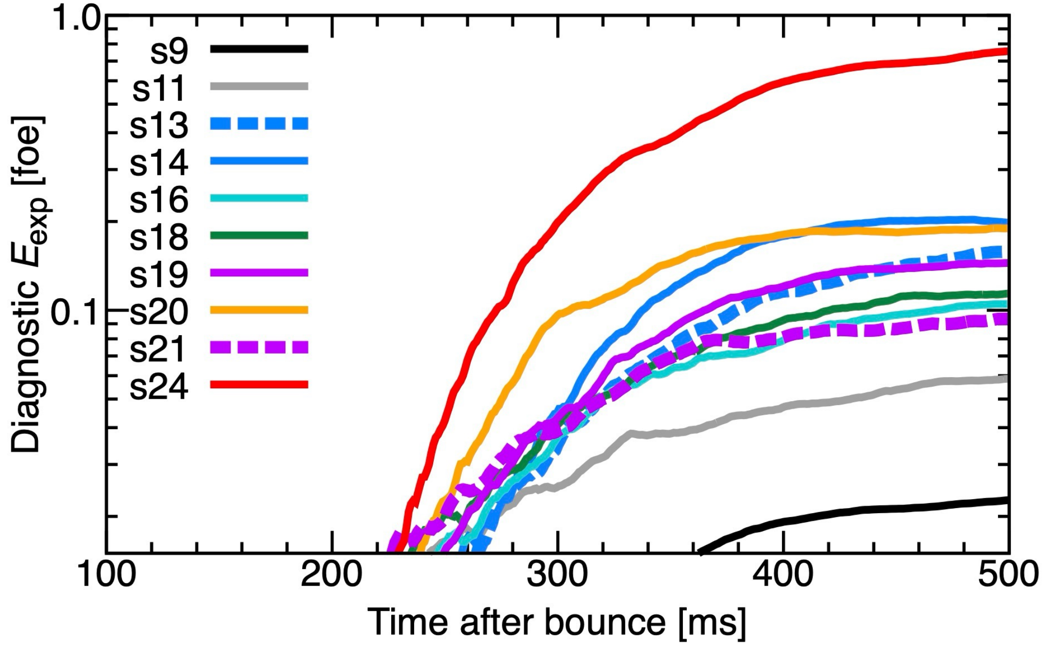
Systematic 3D MHD simulations - Explosion energy

✓ **Diagnostic explosion energy** ($E_{\rm kin} + E_{\rm int} + E_{\rm grv}$ of the ejected matter).

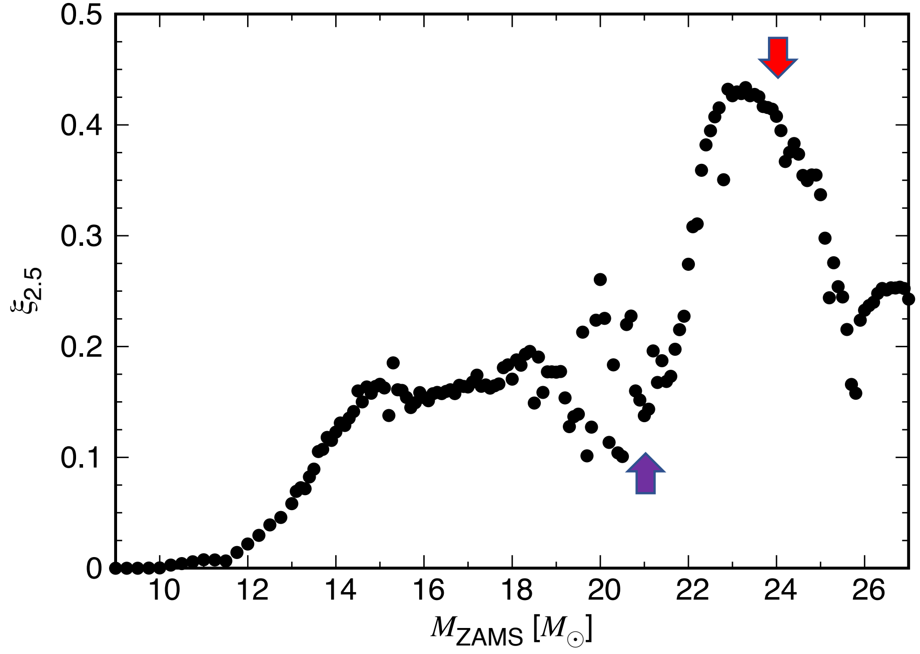
Most models show $E_{\rm exp}$ < 0.2 x 10^{51} erg @500ms, except s23 & s24 models (~ **0.8 x 10^{51} erg**).

Here overburden (negative binding energy) of the stellar envelope is not taken into account.

Explosion energy



compactness parameter $\xi_M = M(R)/R$



Multi-messenger signals from CCSN

✓ **KN+ 2016, MNRAS, 461, 3296**

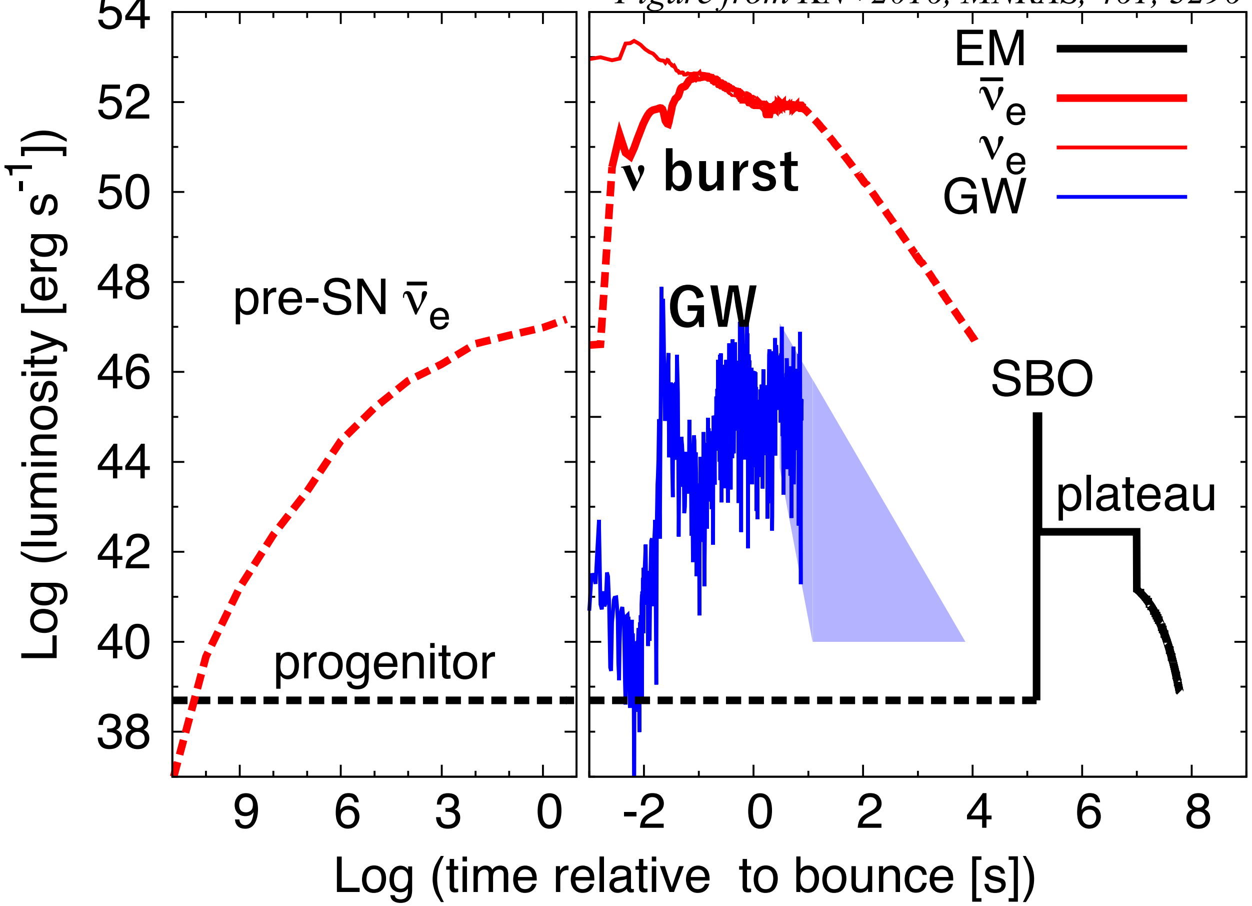
CCSNe emit neutrinos, GWs and electromagnetic waves.

Luminosity:
neutrinos & GWs >> EM

Detectability:
EM >> neutrinos & GWs

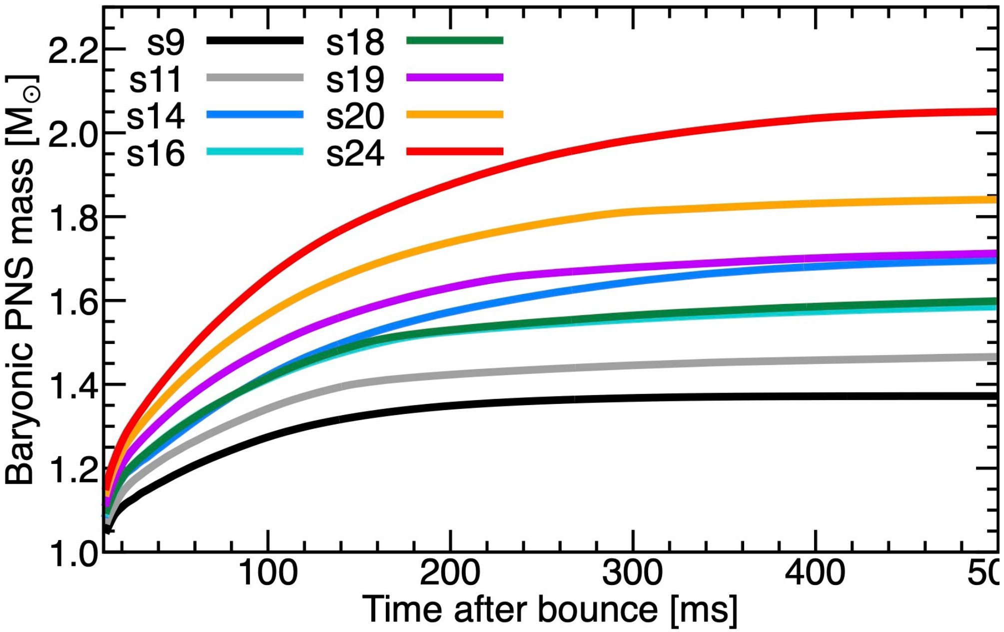
Remnant (NS/BH) information is also useful.

Figure from KN+2016, MNRAS, 461, 3296

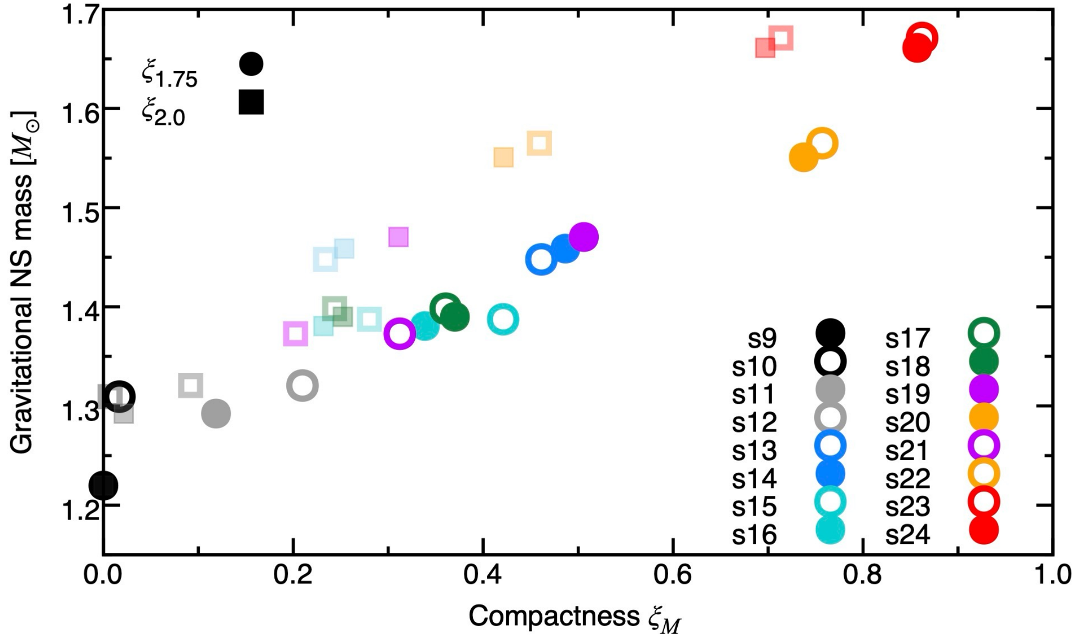


Properties of NSs - mass

Time evolution of **PNS mass**.



Correlation between $M_{\rm PNS}$ and ξ.



The mass accretion onto the central PNS almost stops within the simulation time (t_{pb}<500ms), and $\boldsymbol{M}_{\rm PNS}$ converges to **1.4-2.1 $\boldsymbol{M}_\odot$** .

$\boldsymbol{M}_{\rm PNS}$ is well correlated to the parameters characterizing mass accretion rate ($M_{\rm Si}$, ξ_M).

Compactness: $\xi_M = M[M_\odot]/R(M)[1000{\rm km}]$

Properties of NSs - mass

1) Estimate the gravitational mass of cold NSs.

Lattimer & Prakash (2001)

2) Assume that $\boldsymbol{M}_{\rm NS} = \boldsymbol{M}_{\rm PNS}$ at $t_{\rm pb}$= 500ms, and the IMF is Salpeter's one.

3) Compare with observational data.

65 NSs from Table 1 in Lattimer (2012)

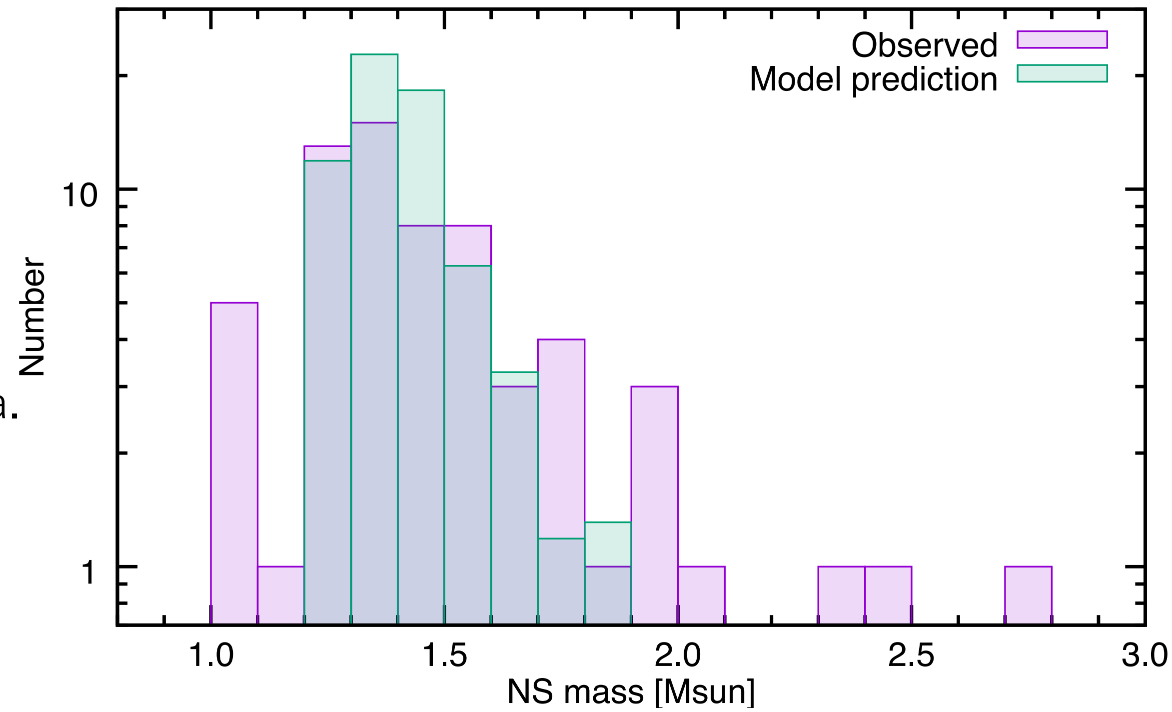
The **NS mass distribution** has a peak at $\sim 1.4\ M_\odot$ as seen in the observational data.

Light NSs coming from small-mass SNe?
Even O-Ne-Mg SNe and ultra-stripped SNe leave NSs >1.2 $M_\odot$.

Kitaura et al. (2006)
Suwa et al. (2015), Mueller et al. (2018)
Mueller, Heger, & Powell (2025)

Heavy NSs coming from binary interaction?
e.x.) Black Widow Pulsar

NS mass distribution



Properties of NSs - kick velocity

NSs are "kicked" at the explosion → correlated to anisotropic ejection of the matter and neutrino.

✓ Hydrodynamic kick.

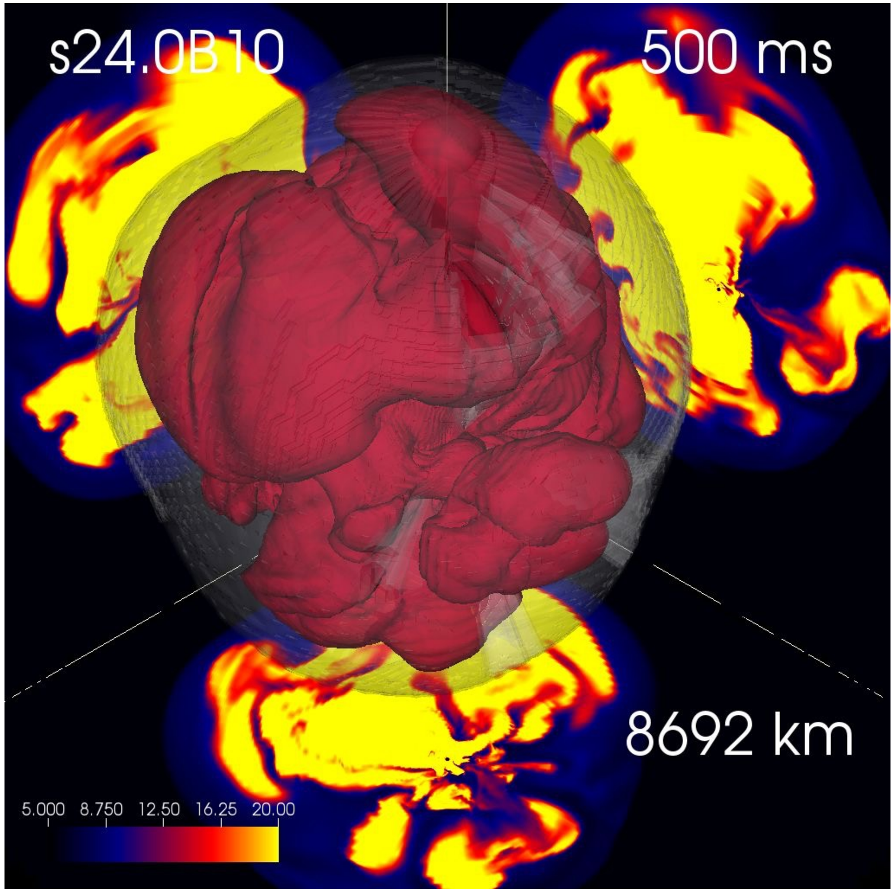
$$\mathbf{v}_{\mathrm{kick}}^{\mathrm{hydro}} = -\frac{1}{M_{\mathrm{PNS}}} \int_{\rho<10^{11}\,\mathrm{g\,cm^{-1}}} \mathbf{v}\rho \mathrm{dV},$$

assuming the conservation of the matter momentum.

✓ Neutrino-driven kick.

$$\dot{\mathbf{v}}_{\mathrm{kick}}^{\nu} = -\frac{1}{cM_{\mathrm{PNS}}} \int_{S} (\mathbf{F}^{\nu_e} + \mathbf{F}^{\bar{\nu}_e} + \mathbf{F}^{\nu_x}) \mathrm{dA},$$

assuming ray-by-ray (only radial) transport of neutrino.



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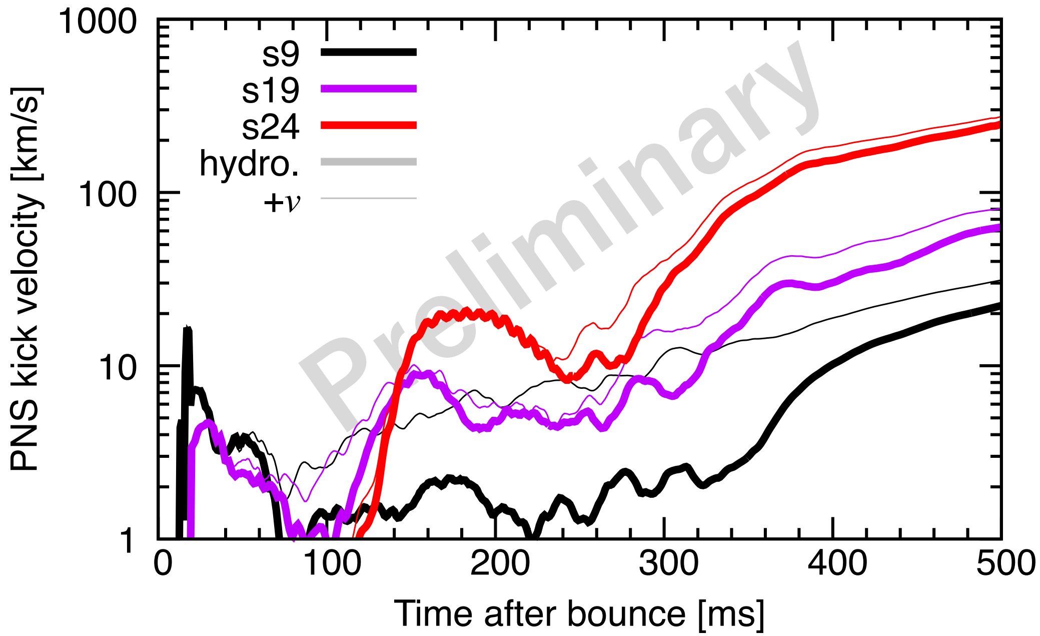
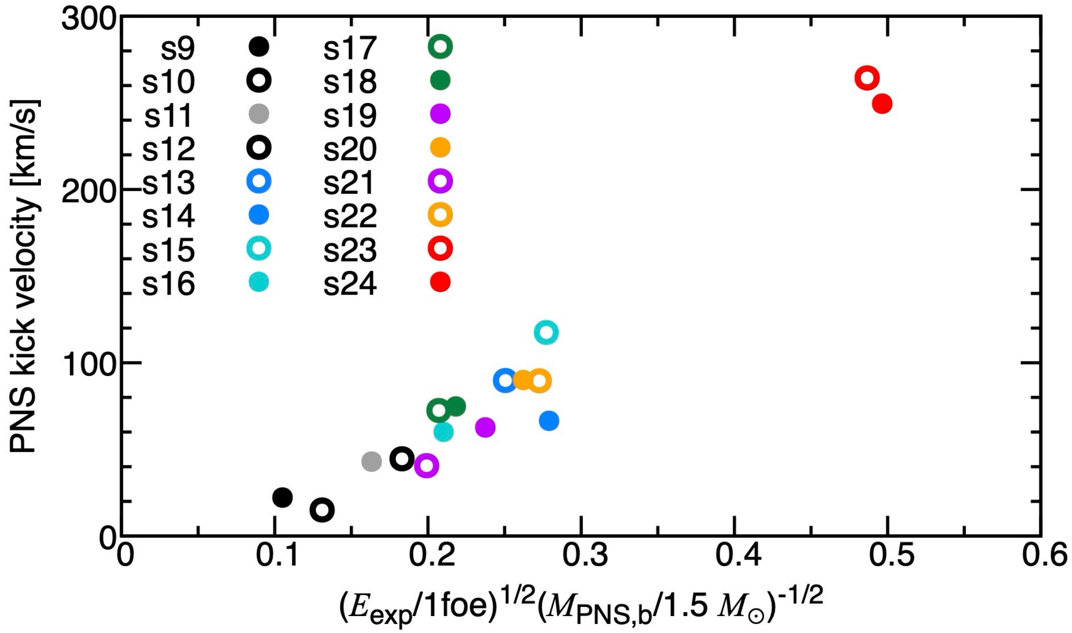
Time evolution of NS kick velocity



Correlation between $v_{\rm PNS}$ and $(E_{\rm exp}/M_{\rm PNS})^{1/2}$



Not yet converged at t_{pb} = 500ms.
→ long-term simulation is necessary.

Properties of NSs - spin

Note: our simulations start from **non-rotating** progenitor models.

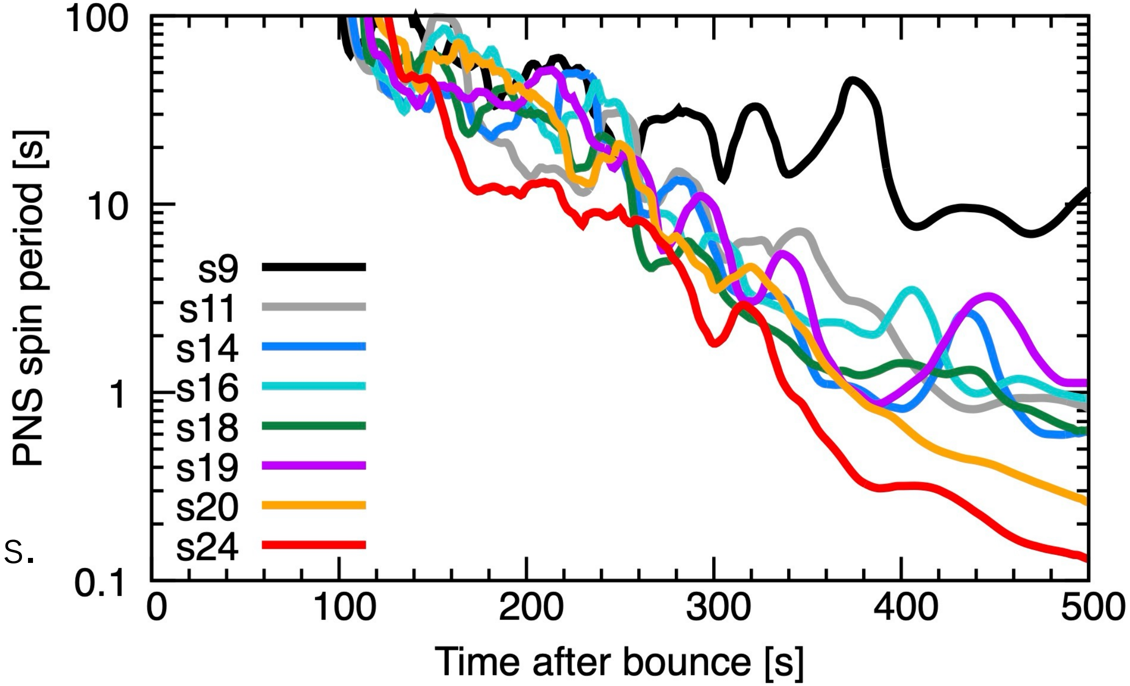
Anisotropic motions behind the shock.
→ accretion of angular momentum onto the central PNS.

NS spin period $T = 2\pi\, \mathrm{I}/\mathrm{J}$ using the total angular momentum $J = \sqrt{J_x^2 + J_y^2 + J_z^2}$.

T_{NS} = **0.1 s - 10 s** at t_{pb} = 500ms.
Heavy (large- ξ) models present short periods.

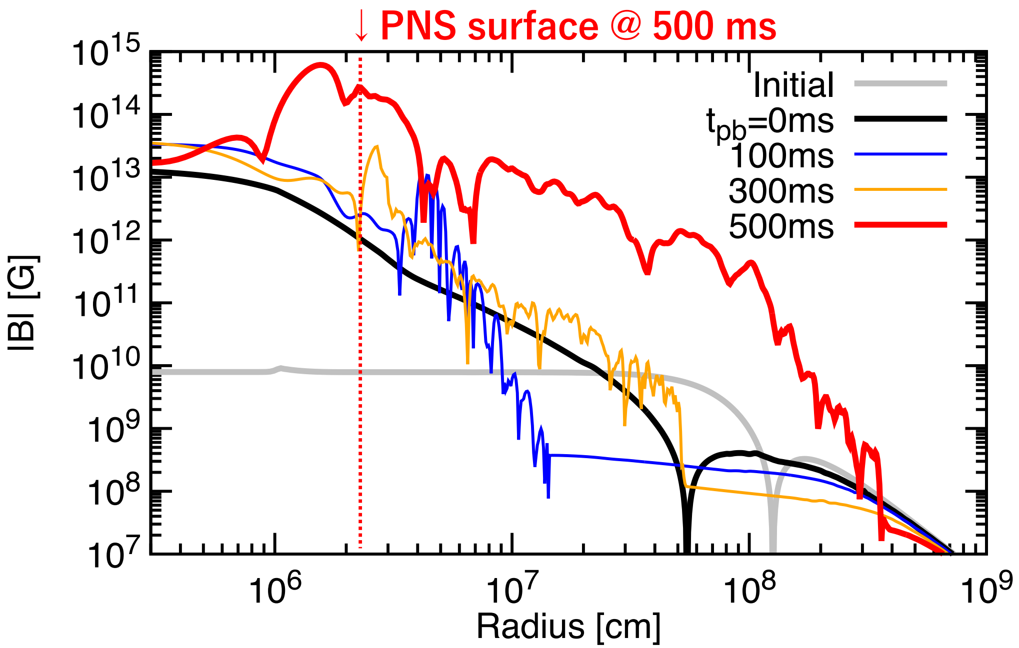
The most rapidly rotating model (s24) shows a signature of the **spiral SASI motion**.

Time evolution of NS spin period

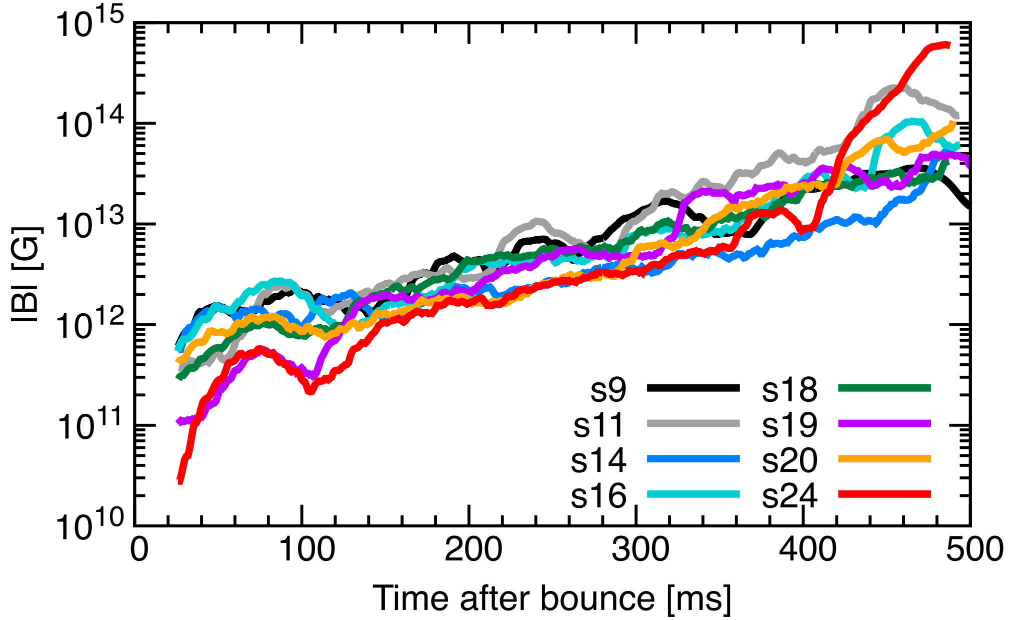


Properties of NSs - magnetic field

Radial profile of |B| for s24 model



Time evolution of |B| at PNS surface



The magnetic field strength at the center is amplified by more than 10^3 times by accumulation of magnetic field flux frozen with the accreting matter, and dynamo process in the PNS convective region.

Summary

Explodability ← fine structure of the progenitor structure (density jump).
Explosion properties ← mass accretion rate (~ ξ , M_{Si})

- ✓ 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.
  - Most models show E_{exp} < **0.2 x 10^{51} erg**, except s23 & s24 models (~ **0.8 x 10^{51} erg**).
- ✓ Our 3D models leave **NSs**:
  - **Mass** distribution well matches with observational data with a peak at 1.4 $M_{\odot}$.
  - **Kick** velocity is induced by anisotropic ejection of the matter and ν, but < 300km/s.
  - **Spin** period T_{NS} = **0.1 s - 10 s**, heavy (large- ξ) models present short periods.
  - **Magnetic field** is enhanced by the accumulation and dynamo processes.

→ **They will provide us with fruitful information on the CCSN explosion mechanism!**