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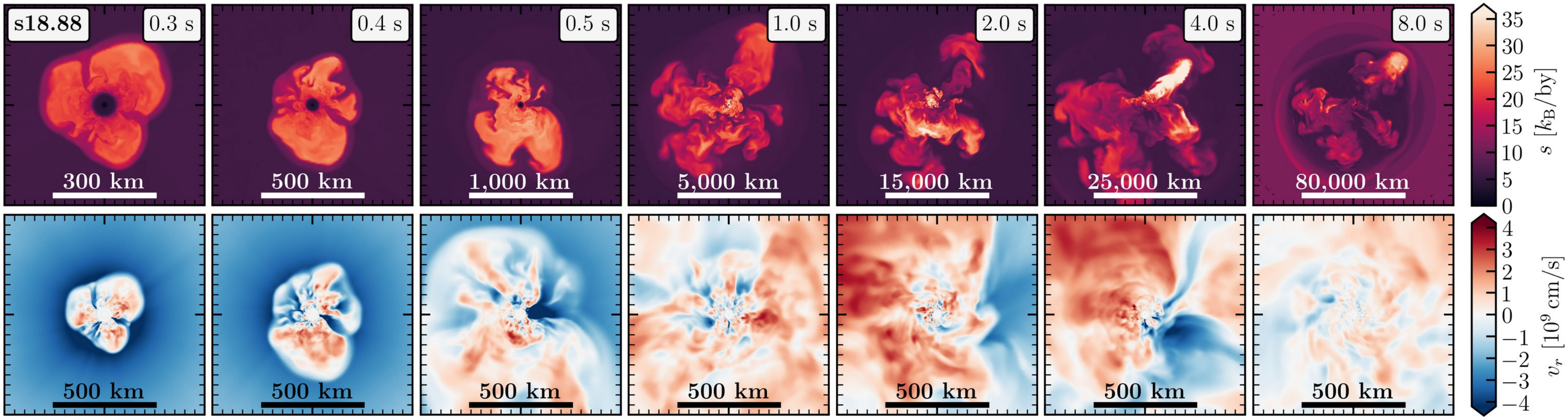
FOR ASTROPHYSICS

Post-explosion hydrodynamics in 3D neutrino-driven supernova models

SNRIII conference, 2024-06-11

arXiv:2401.13817



Collaborators: Thomas Janka, Robert Bollig, Tobias Melson, Alexander Summa, Bernhard Müller, Naveen Yadav

Characteristic properties of Core-collapse Supernovae

- **Explosion energy:** ~(0.1–1.5) x 10^{51} erg
- **Radioactive ^{56}Ni:** ~(0.01–0.1) $M_\odot$
  Radioactive ^{44}Ti: ~10^{-4} $M_\odot$
- **NS kick velocity:** ~(100–1000) km/s

Pejcha & Prieto (2015)
Martinez et al. (2022)
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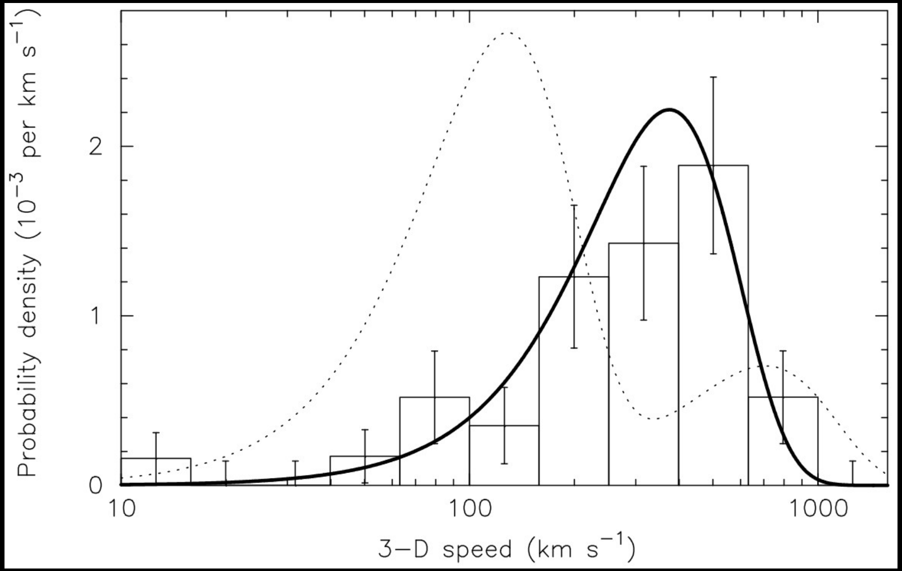

Hobbs+2005

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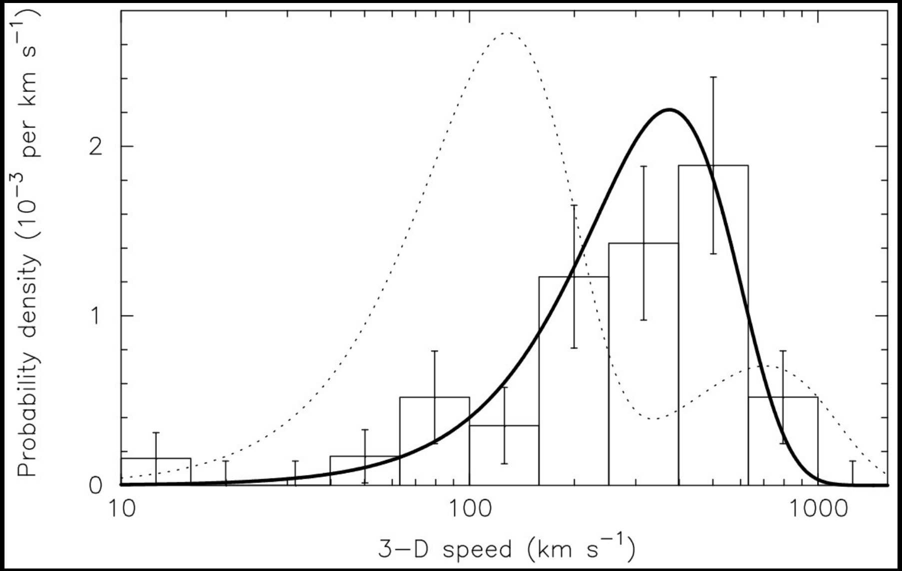
Can these SN properties be explained by self-consistent numerical simulations?



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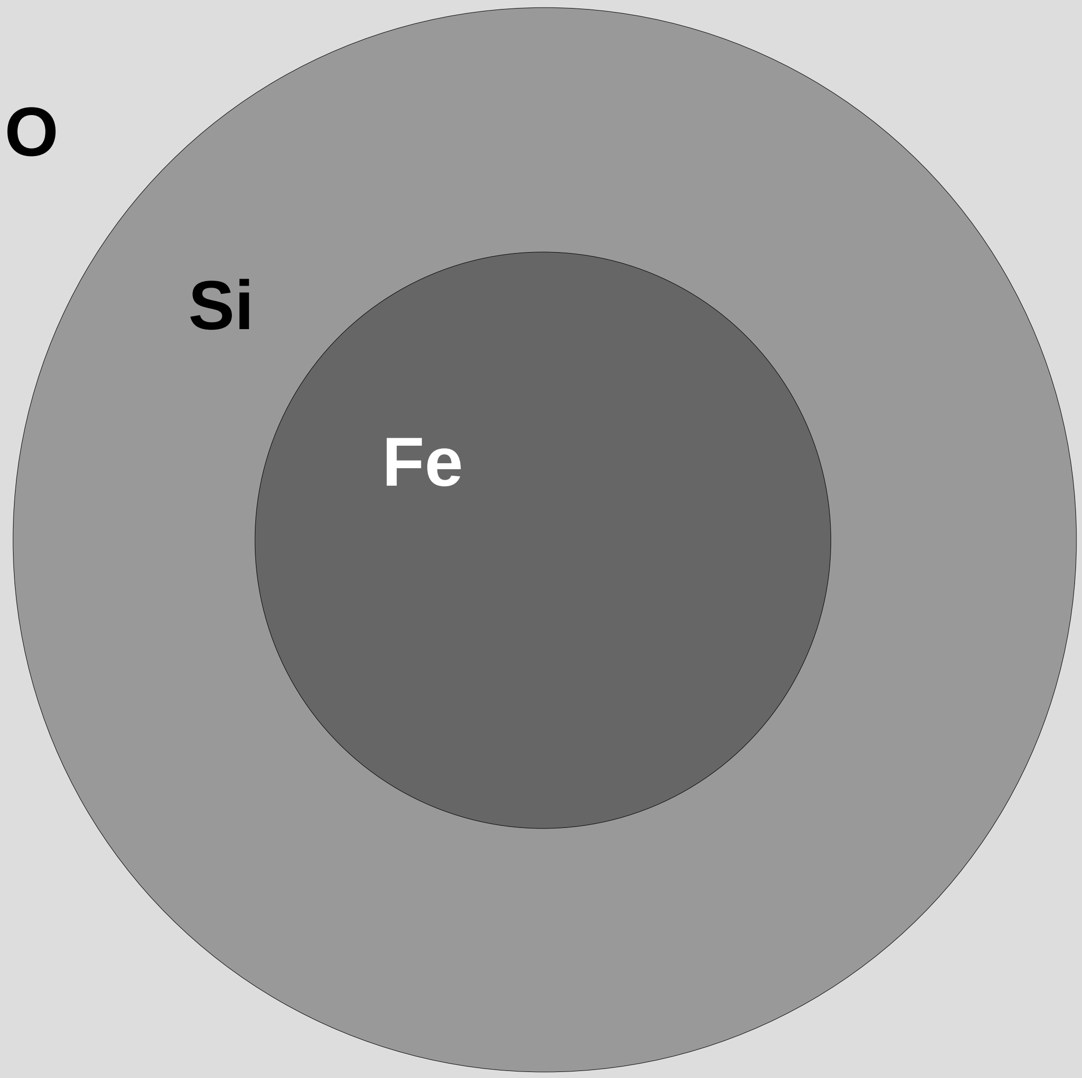
Core-collapse Supernovae in a Nutshell



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- Stellar radius: ~10^8-10^9 km
- Iron (Fe) core: ~10^3 km

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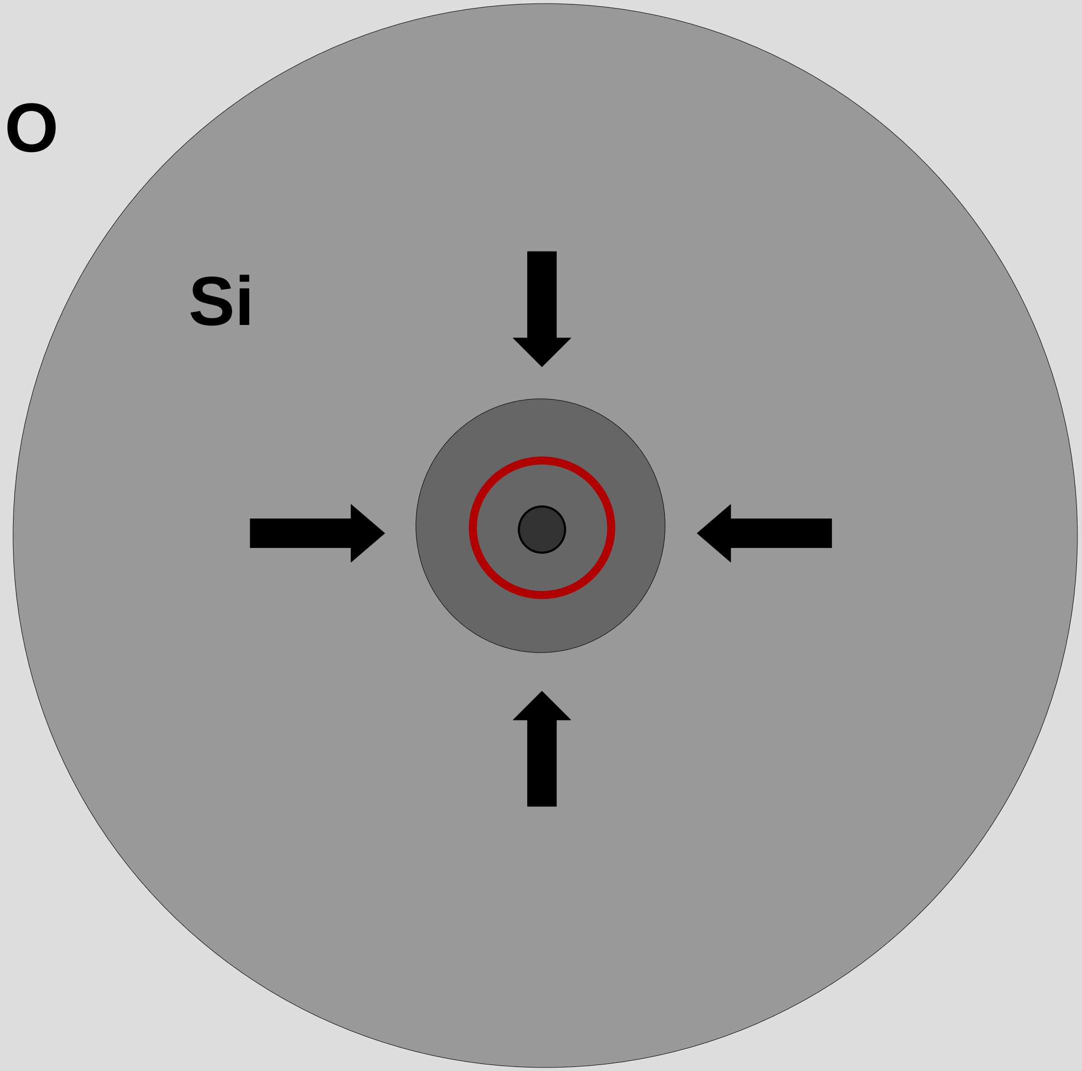

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- Stellar radius: ~10^8-10^9 km
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- Fe core collapses to a Proto-Neutron Star (PNS)
- Core bounce launches a shock wave (stagnates)

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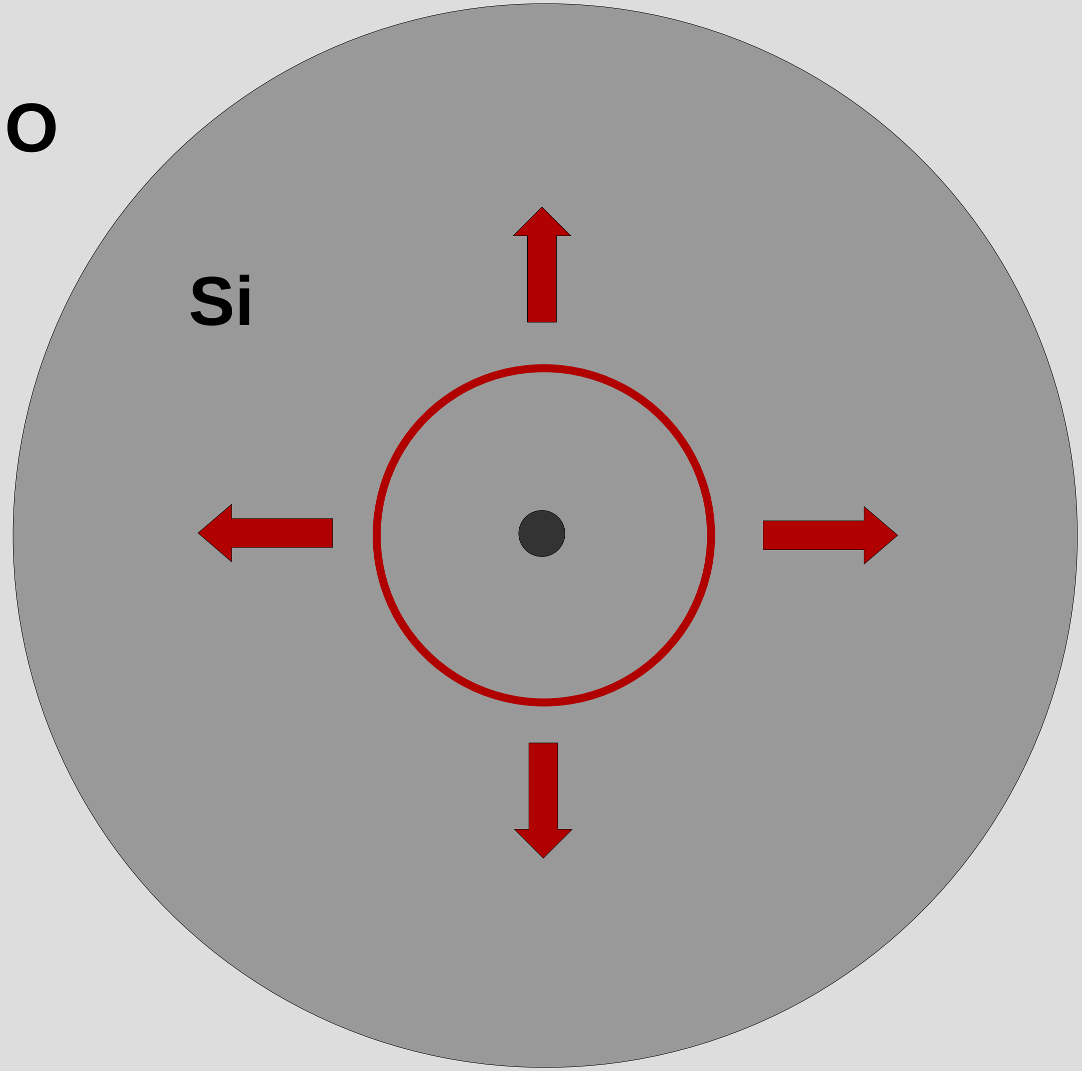

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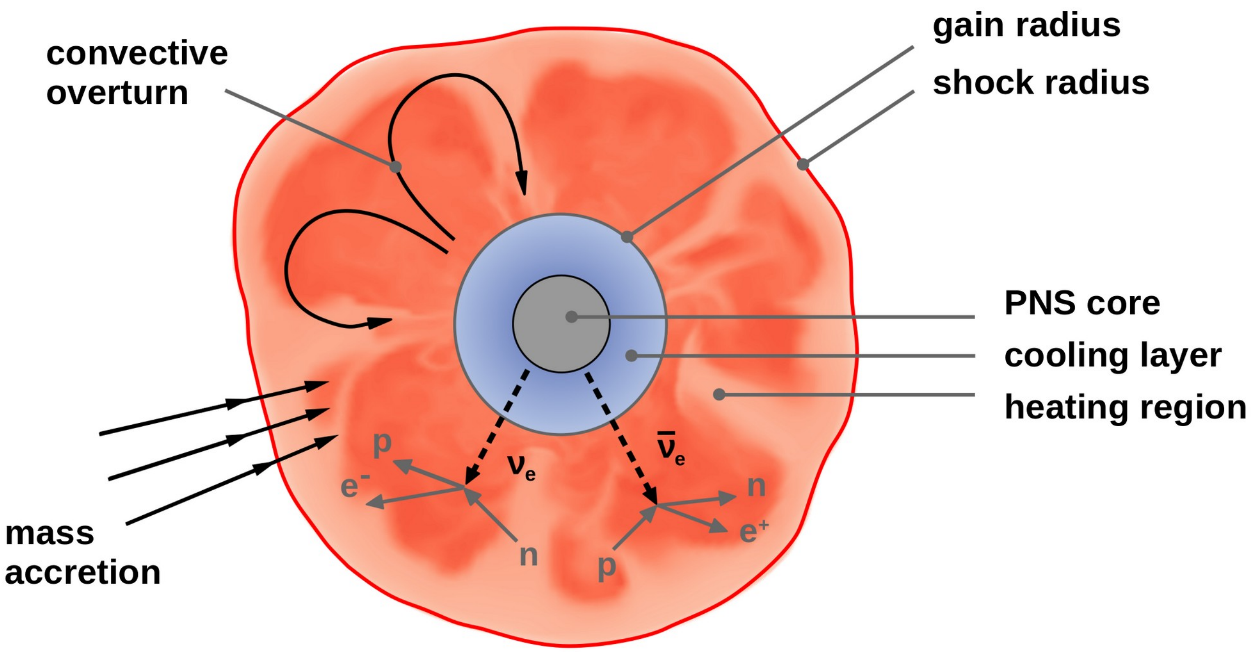
- Shock revival by neutrino energy deposition

Neutrino-driven Explosion Mechanism



Arnett (1966)
Colgate & White (1966)
Bethe & Wilson (1985)

$$\boxed{\begin{aligned} \nu_{\mathrm{e}} + \mathrm{n} &\longleftrightarrow \mathrm{p} + \mathrm{e}^- \\ \bar{\nu}_{\mathrm{e}} + \mathrm{p} &\longleftrightarrow \mathrm{n} + \mathrm{e}^+ \end{aligned}}$$

- **Gravitational binding energy of the collapsed Fe core (~3–4 x 10^{53} erg) transiently stored in a hot and inflated PNS**

- **PNS contracts and cools via neutrino emission over ~10 s**
- **~1% of neutrinos reabsorbed (in “gain layer” / heating layer)**
- **Shock revival (aided by fluid instabilities: convection & SASI)**

Status & Open Questions

- Complex interplay of stellar hydrodynamics and neutrino radiative transfer > numerical simulations (in full-3D geometry) required
- Successful shock revival by neutrino heating achieved in self-consistent 3D simulations by various groups
- However: Simulations typically until less than ~1 s due to high computational demands of neutrino-transport calculations
- Much too short for converged explosion properties!

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>> Can the neutrino-driven mechanism explain the properties of observed CCSNe (explosion energies, ^{56}Ni yields, NS kicks) ??

Goal: “Long-time” 3D simulations over several seconds until convergence of the explosion properties

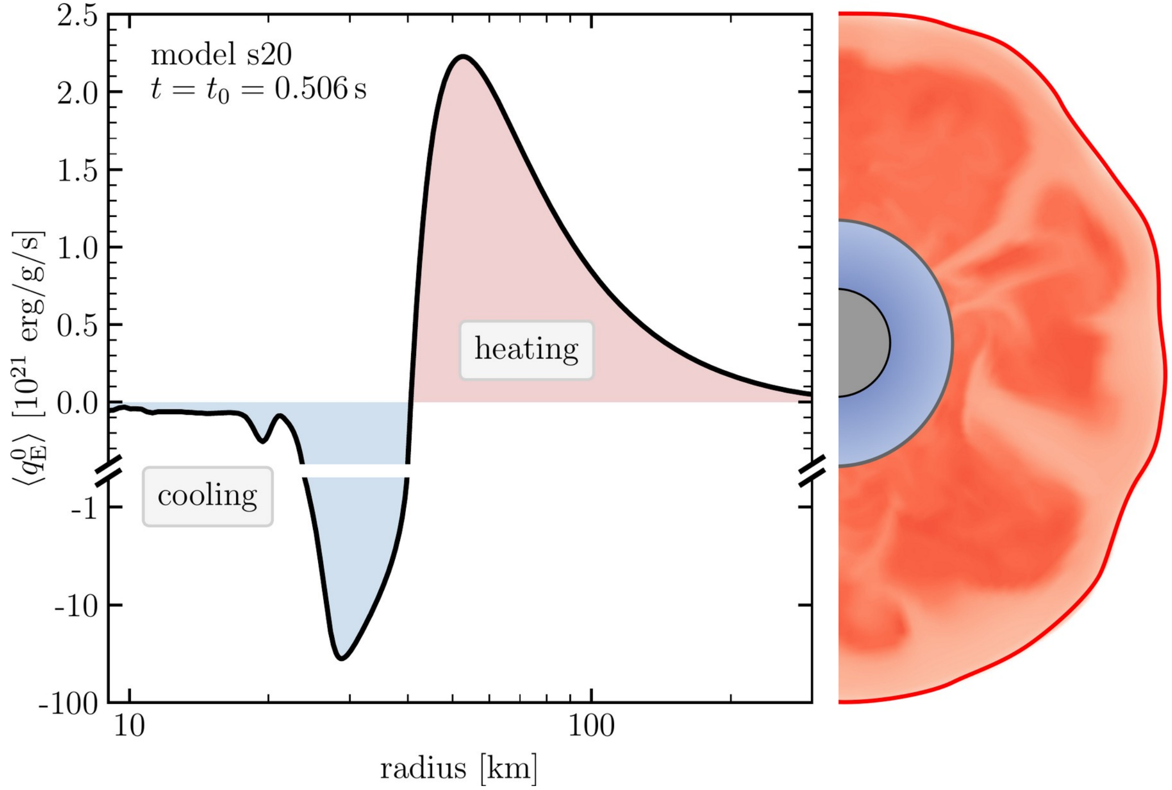
Approach:

Continue a set of fully self-consistent 3D CCSN models (simulated with the Prometheus-Vertex code) for several seconds by means of a newly implemented (computationally efficient) approximate scheme for neutrino effects (NEMESIS)

Prometheus-Vertex: Fryxell et al. (1989), Rampp & Janka (2002), Buras et al. (2006), Marek et al. (2006), Hanke (2014), Melson (2016), Bollig (2018)

NEMESIS neutrino scheme

- > neutrino cooling / neutrino heating
- > transfer of electron lepton number
- > pressure support inside the PNS



- > smoothly extends the evolution of the 3D Prometheus-Vertex models with full neutrino transport

- > time evolution of the neutrino effects guided by 1D PNS-cooling simulations with Prometheus-Vertex

Model overview

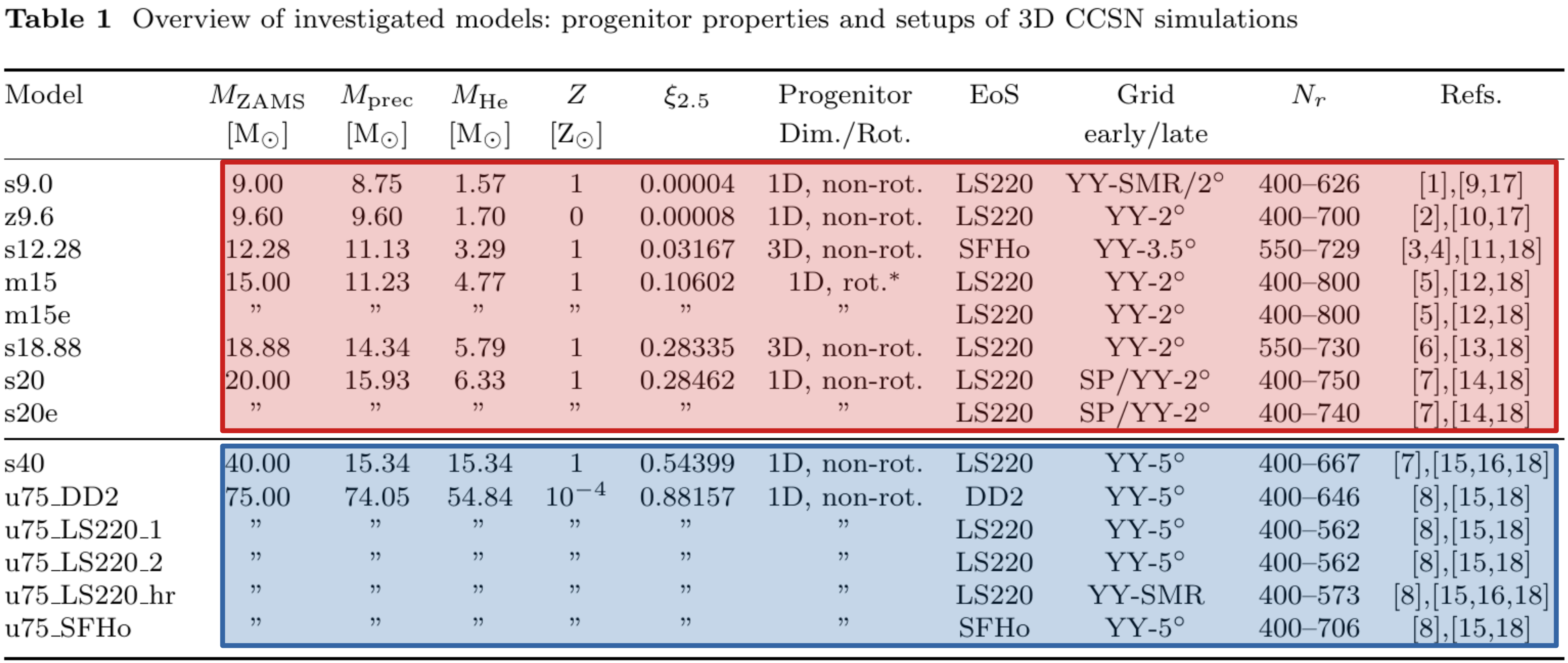
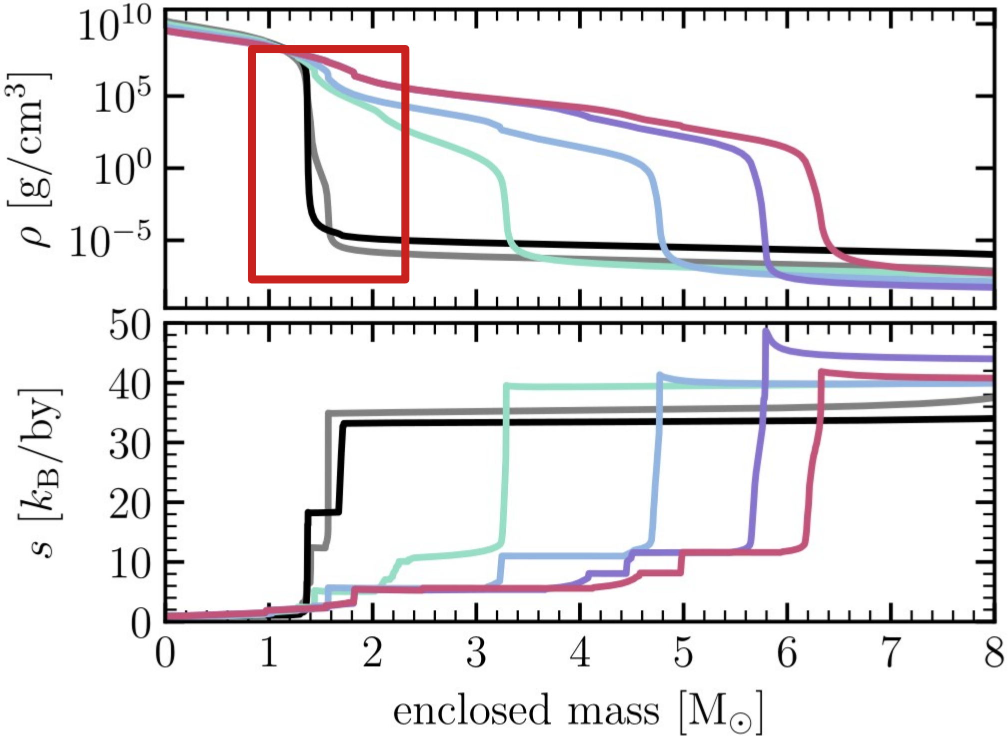


Table 1 Overview of investigated models: progenitor properties and setups of 3D CCSN simulations

Model	$M_{\rm ZAMS}$ [$M_\odot$]	$M_{\rm prec}$ [$M_\odot$]	$M_{\rm He}$ [$M_\odot$]	Z [$Z_\odot$]	$\xi_{2.5}$	Progenitor Dim./Rot.	EoS	Grid early/late	N_r	Refs.
s9.0	9.00	8.75	1.57	1	0.00004	1D, non-rot.	LS220	YY-SMR/2°	400–626	[1],[9,17]
z9.6	9.60	9.60	1.70	0	0.00008	1D, non-rot.	LS220	YY-2°	400–700	[2],[10,17]
s12.28	12.28	11.13	3.29	1	0.03167	3D, non-rot.	SFHo	YY-3.5°	550–729	[3,4],[11,18]
m15	15.00	11.23	4.77	1	0.10602	1D, rot.*	LS220	YY-2°	400–800	[5],[12,18]
m15e	”	”	”	”	”	”	LS220	YY-2°	400–800	[5],[12,18]
s18.88	18.88	14.34	5.79	1	0.28335	3D, non-rot.	LS220	YY-2°	550–730	[6],[13,18]
s20	20.00	15.93	6.33	1	0.28462	1D, non-rot.	LS220	SP/YY-2°	400–750	[7],[14,18]
s20e	”	”	”	”	”	”	LS220	SP/YY-2°	400–740	[7],[14,18]
s40	40.00	15.34	15.34	1	0.54399	1D, non-rot.	LS220	YY-5°	400–667	[7],[15,16,18]
u75_DD2	75.00	74.05	54.84	10^{-4}	0.88157	1D, non-rot.	DD2	YY-5°	400–646	[8],[15,18]
u75_LS220_1	”	”	”	”	”	”	LS220	YY-5°	400–562	[8],[15,18]
u75_LS220_2	”	”	”	”	”	”	LS220	YY-5°	400–562	[8],[15,18]
u75_LS220_hr	”	”	”	”	”	”	LS220	YY-SMR	400–573	[8],[15,16,18]
u75_SFHo	”	”	”	”	”	”	SFHo	YY-5°	400–706	[8],[15,18]

- 8 successfully exploding CCSN models > until ~10 s
- 6 black hole forming models (failed SNe) > until ~1 s

Progenitor Models



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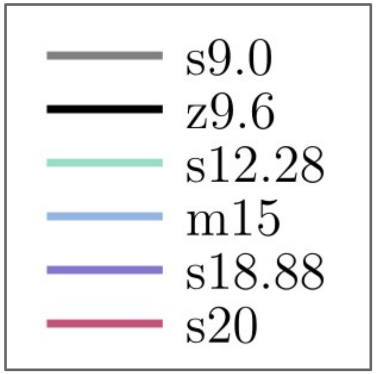
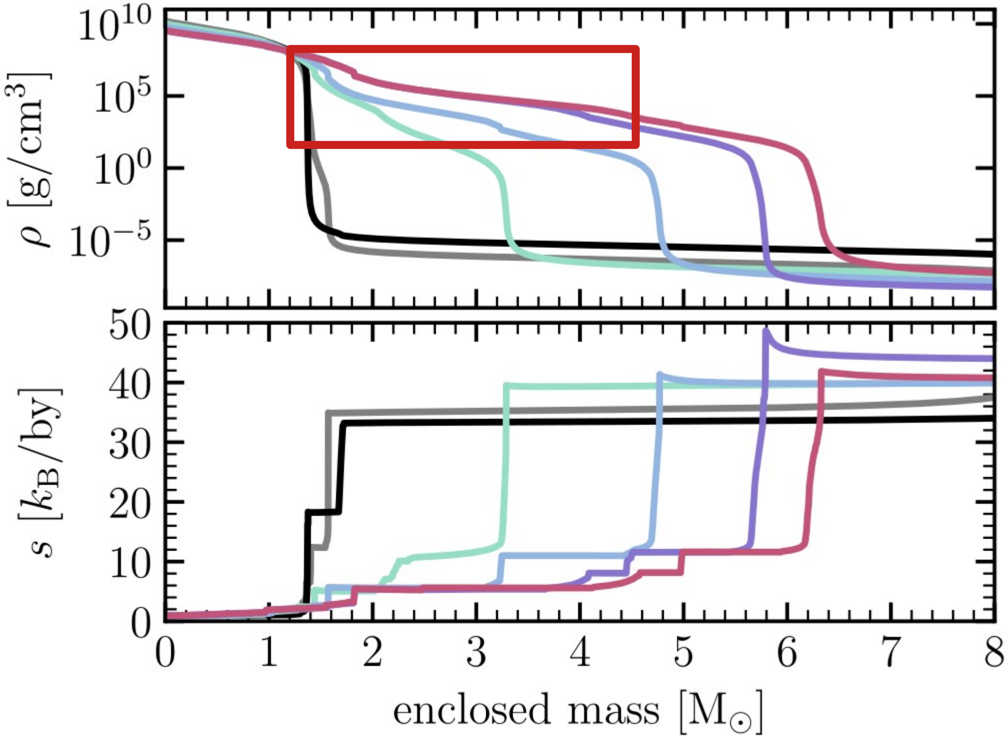
s20	20.00	15.93	6.33	1

Woosley & Heger (2007, 2015), Heger (2012), Heger et al. (2005), Sukhbold et al. (2018), Yadav et al. (2020, 2023)

> density profile outside of Fe core determines the mass accretion rate onto the PNS !!



Progenitor Models



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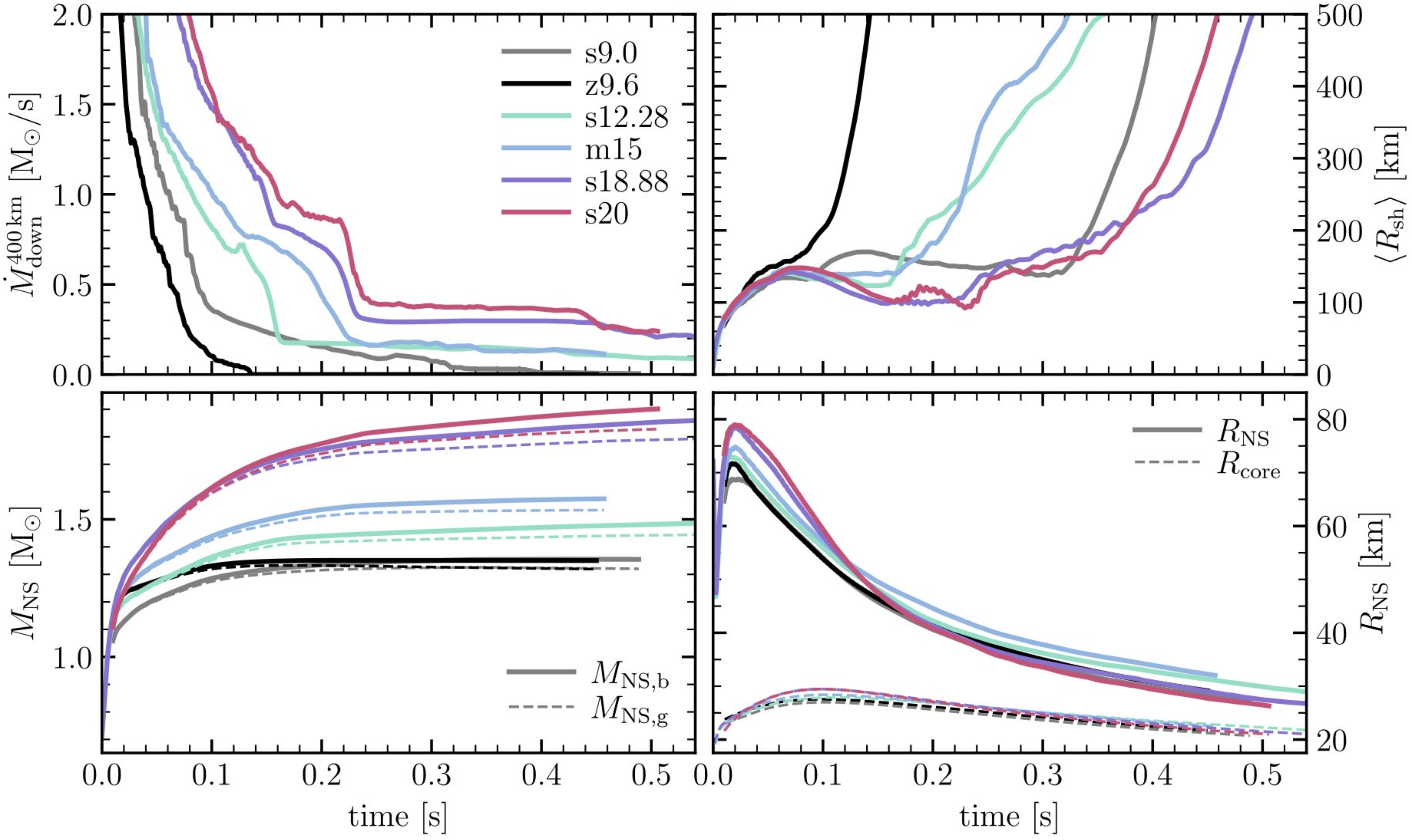
Onset of the Explosions



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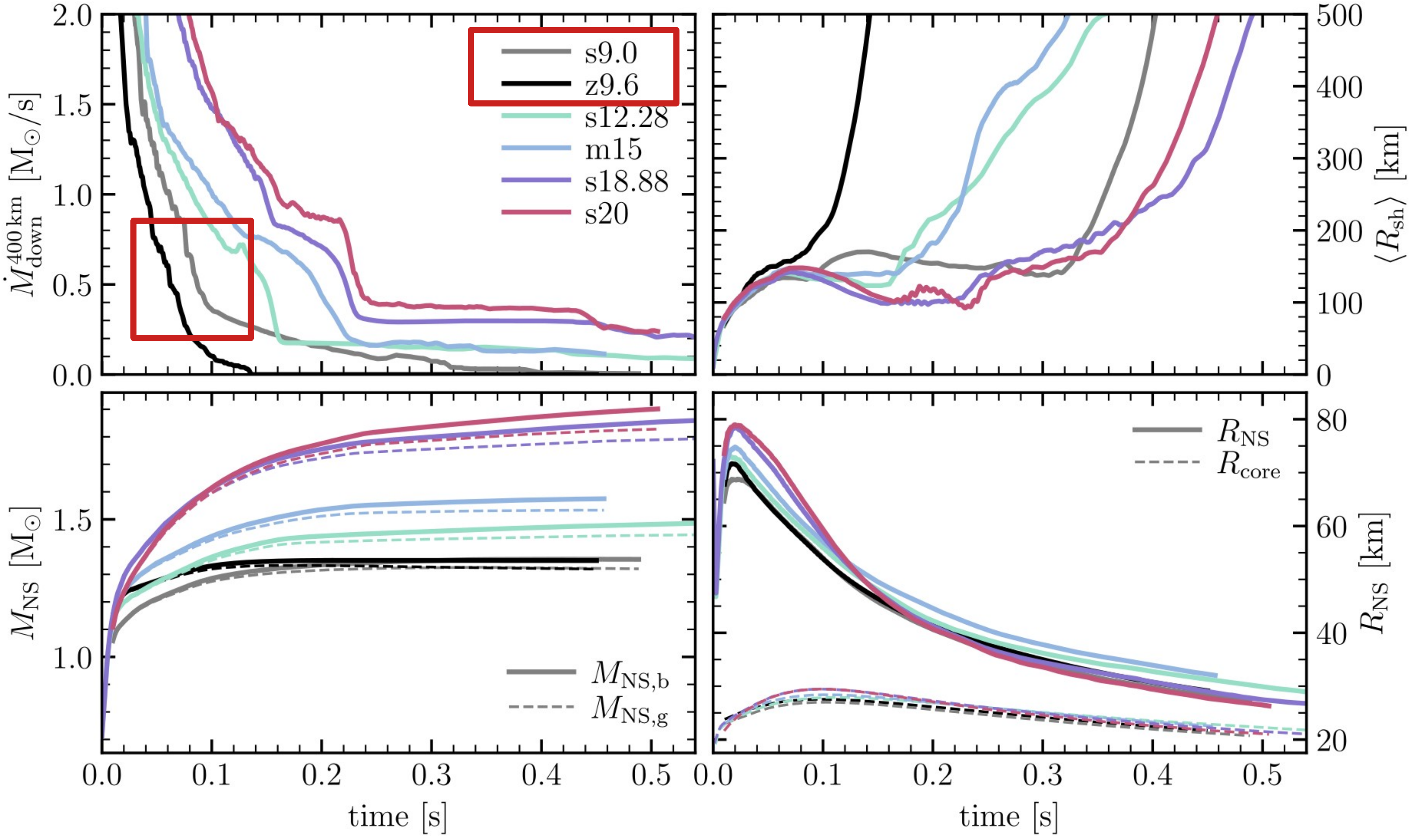
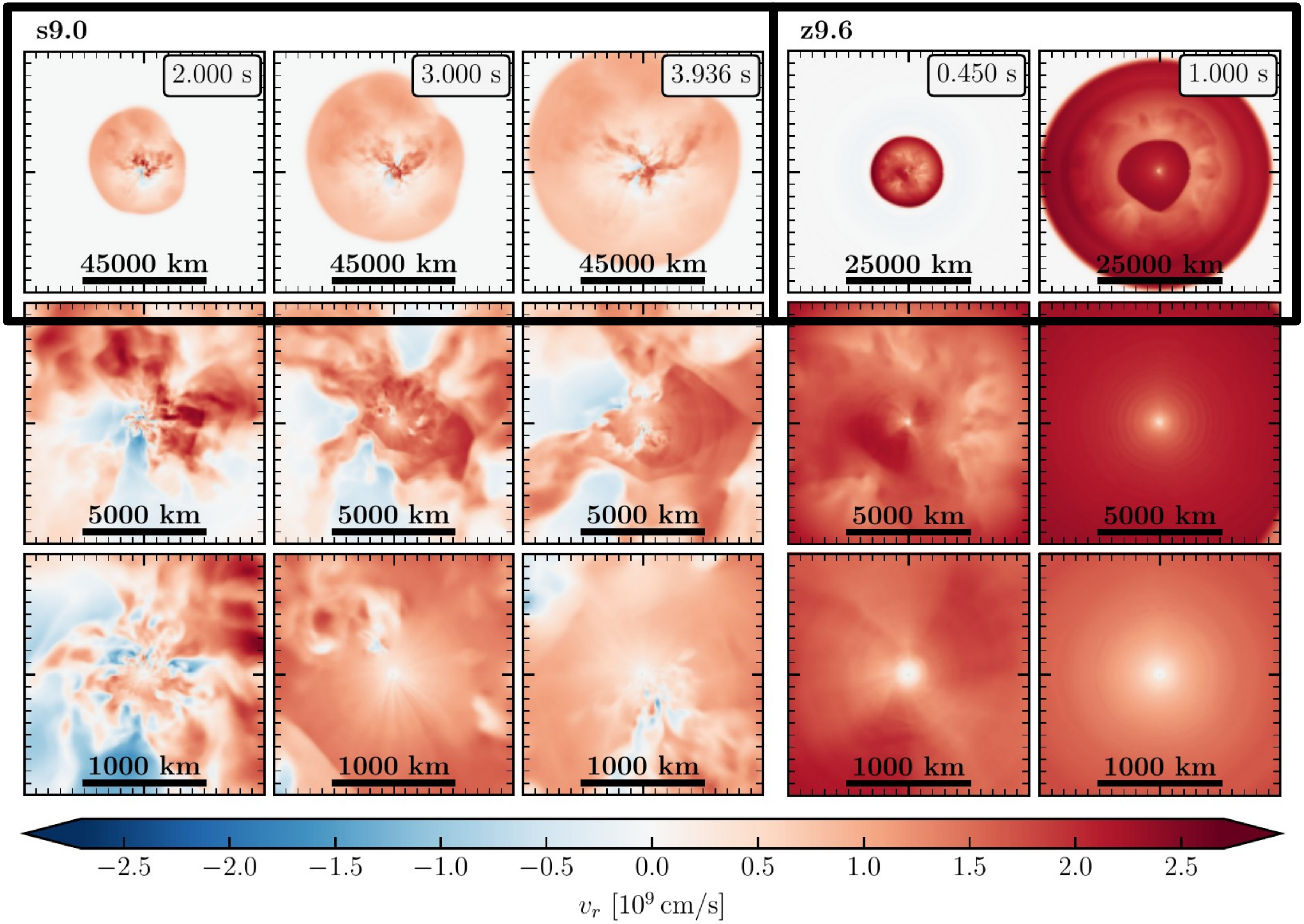


Low-mass Progenitors

(~9–10 $M_\odot$)

> explode rather "easily"
> explode quite spherical
> low mass accretion rate



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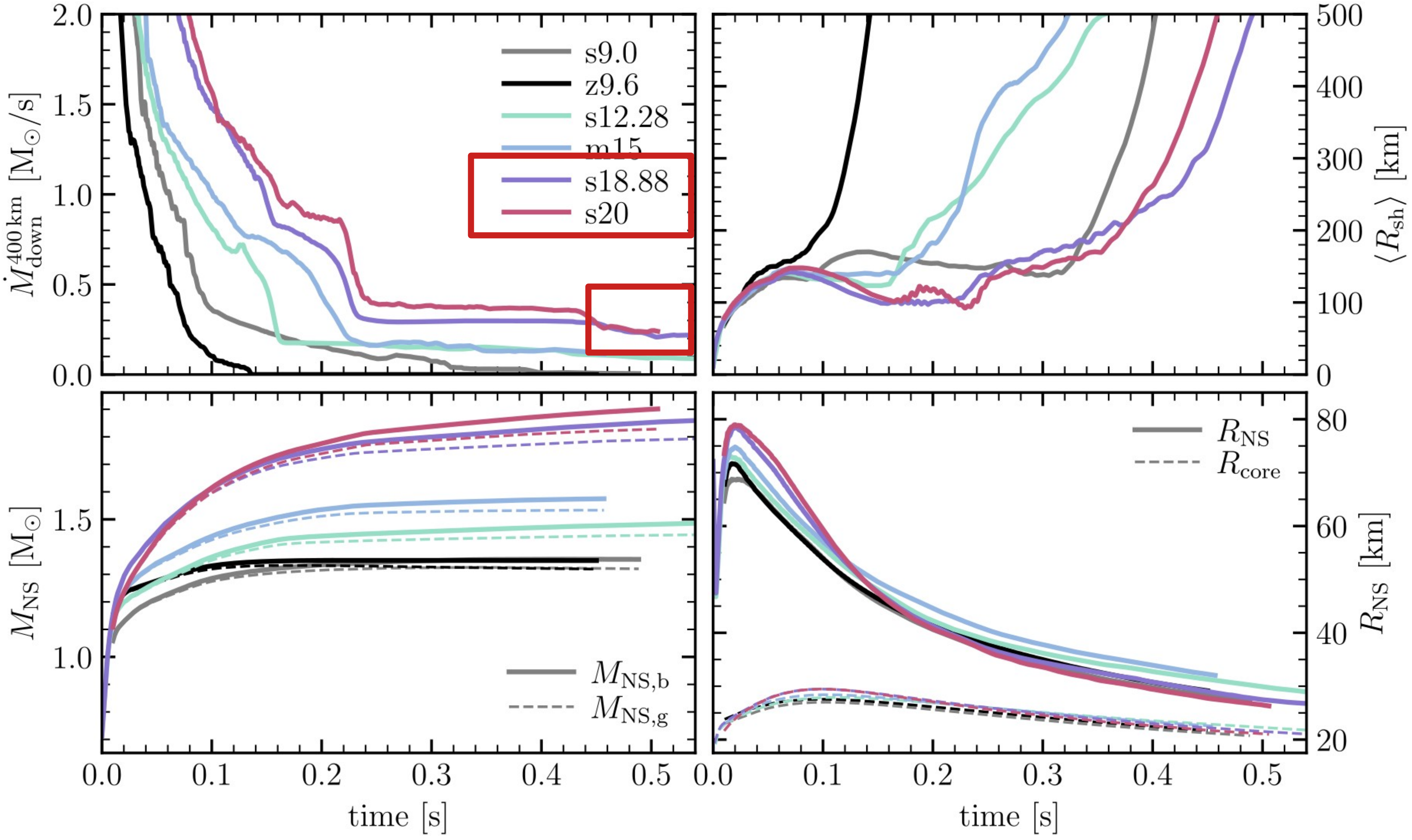
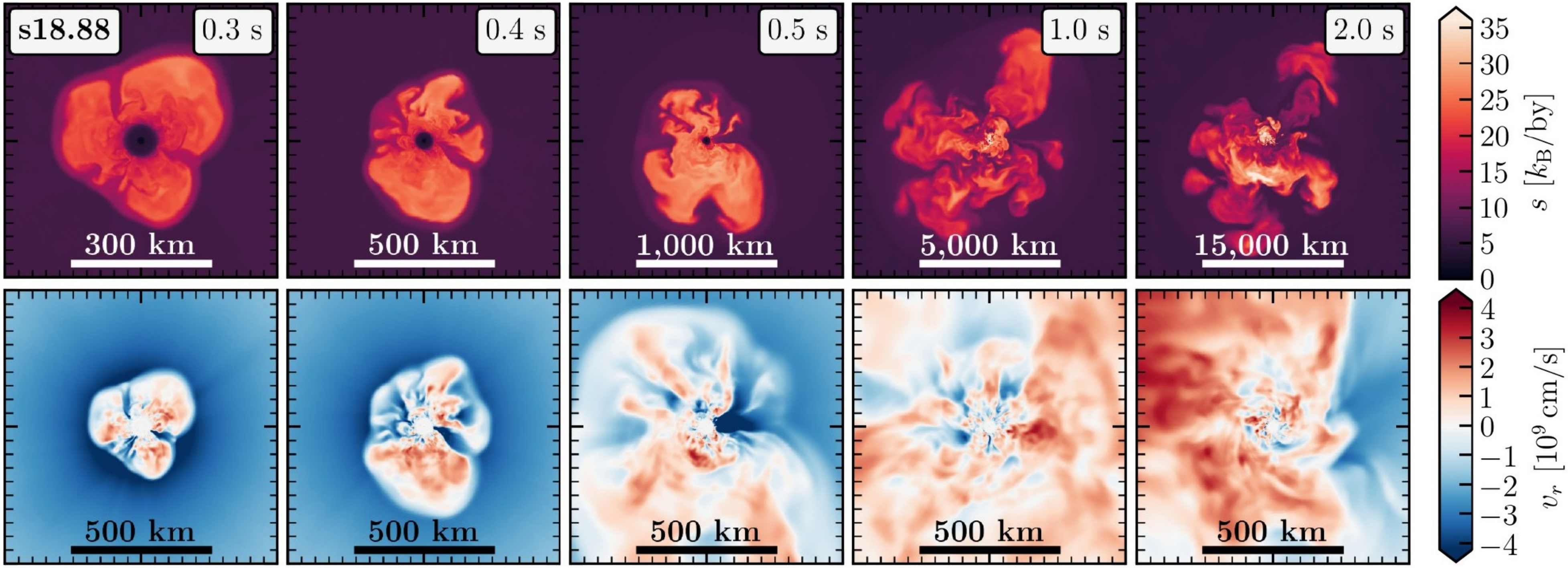


High-mass Progenitors

(~19–20 $M_\odot$)

> explode more delayed
> explode highly asymmetric
> high mass accretion rate, persistent downflows



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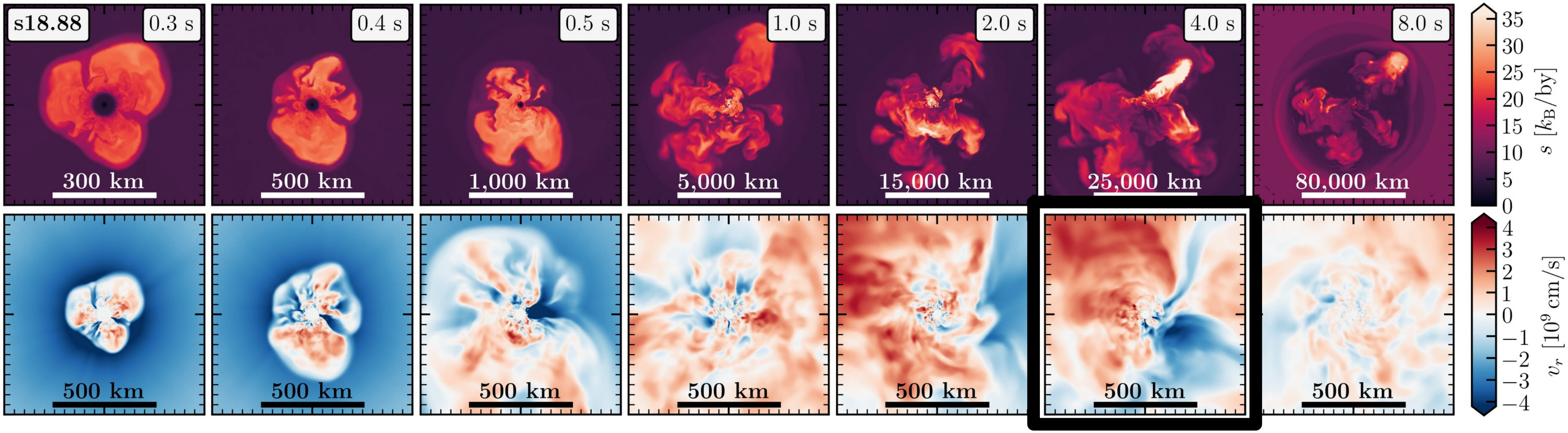
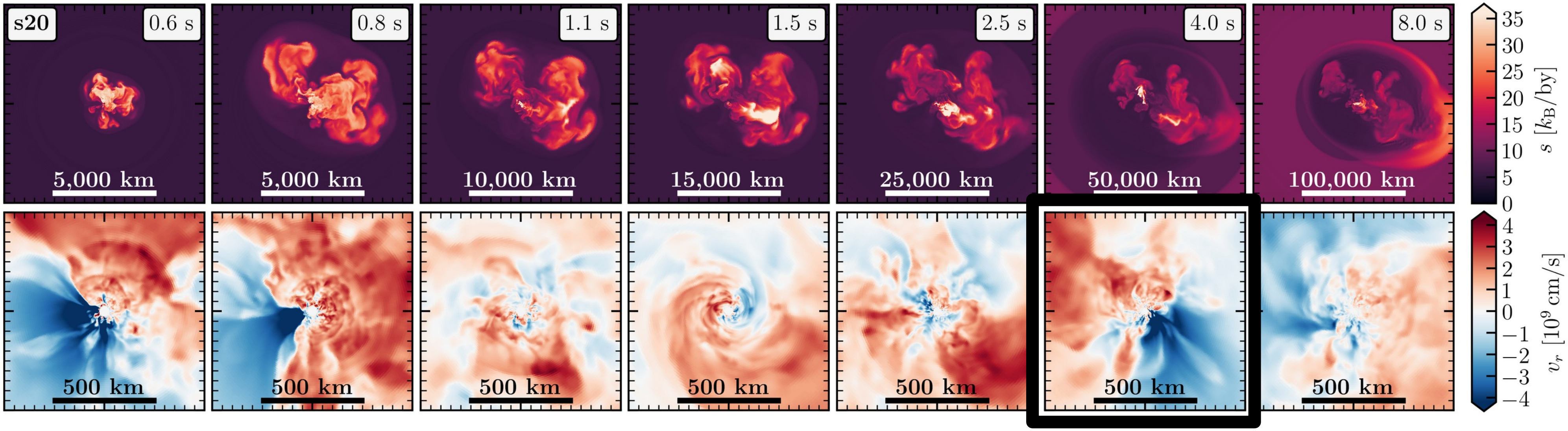
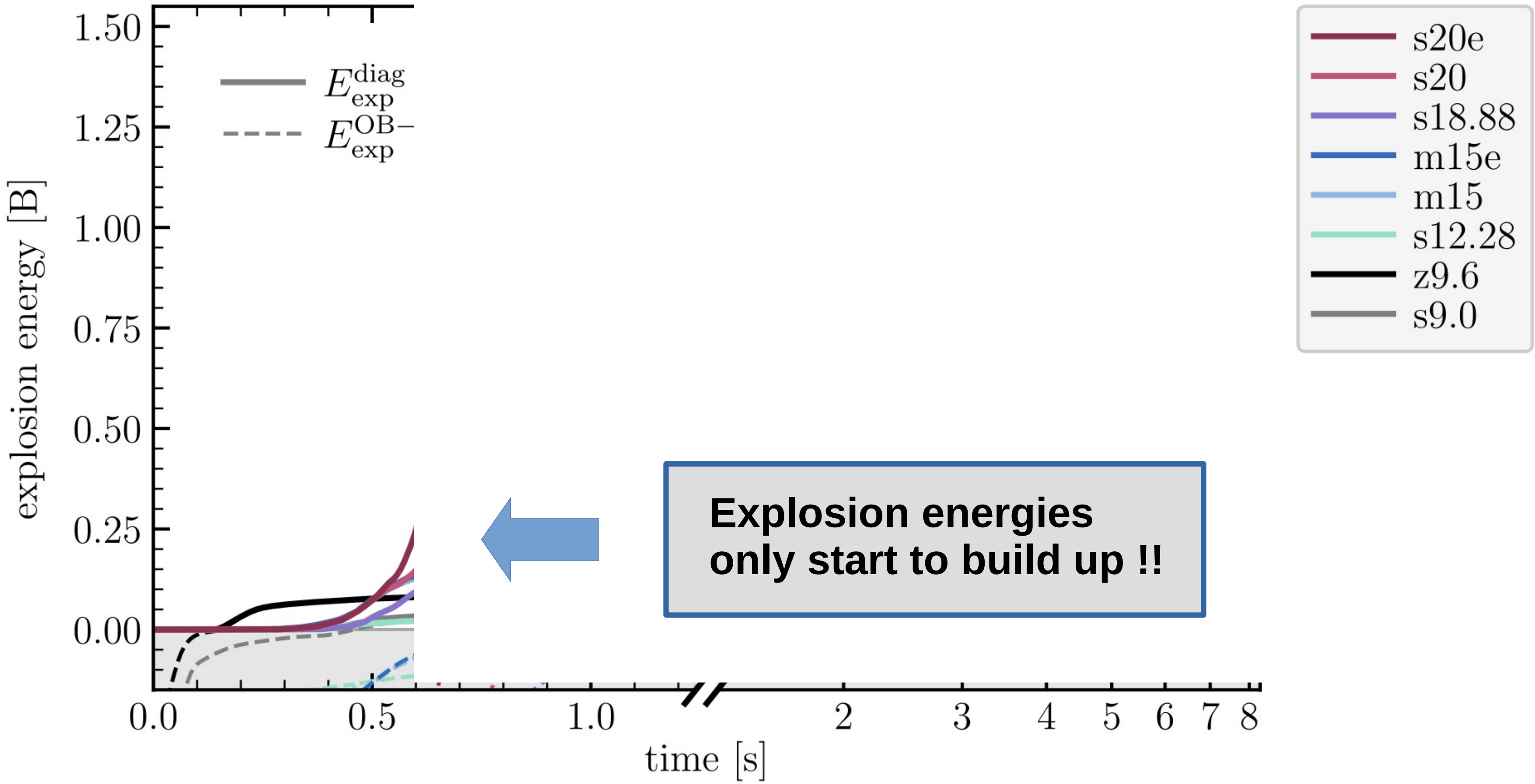


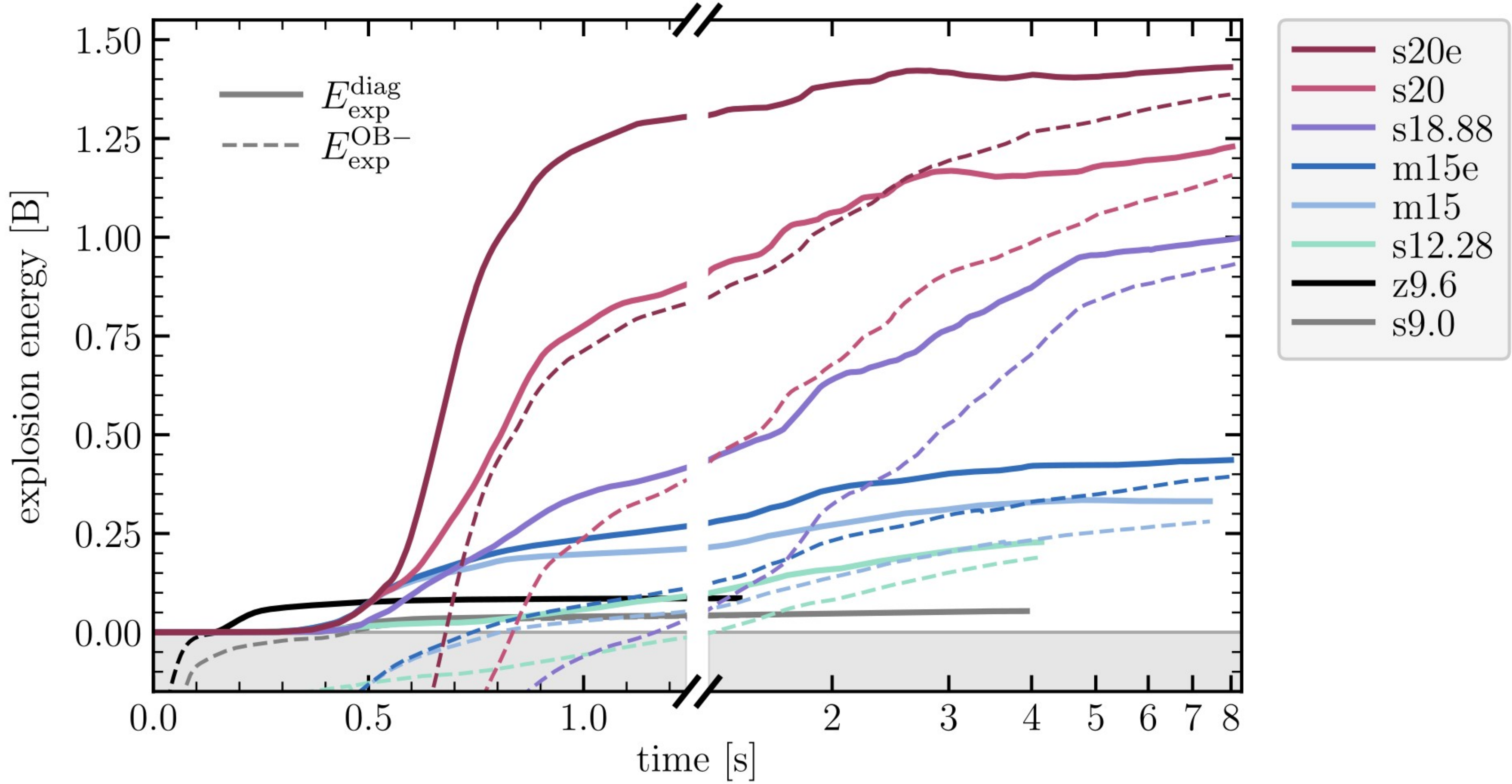


Explosion Energies



Explosion energies only start to build up !!

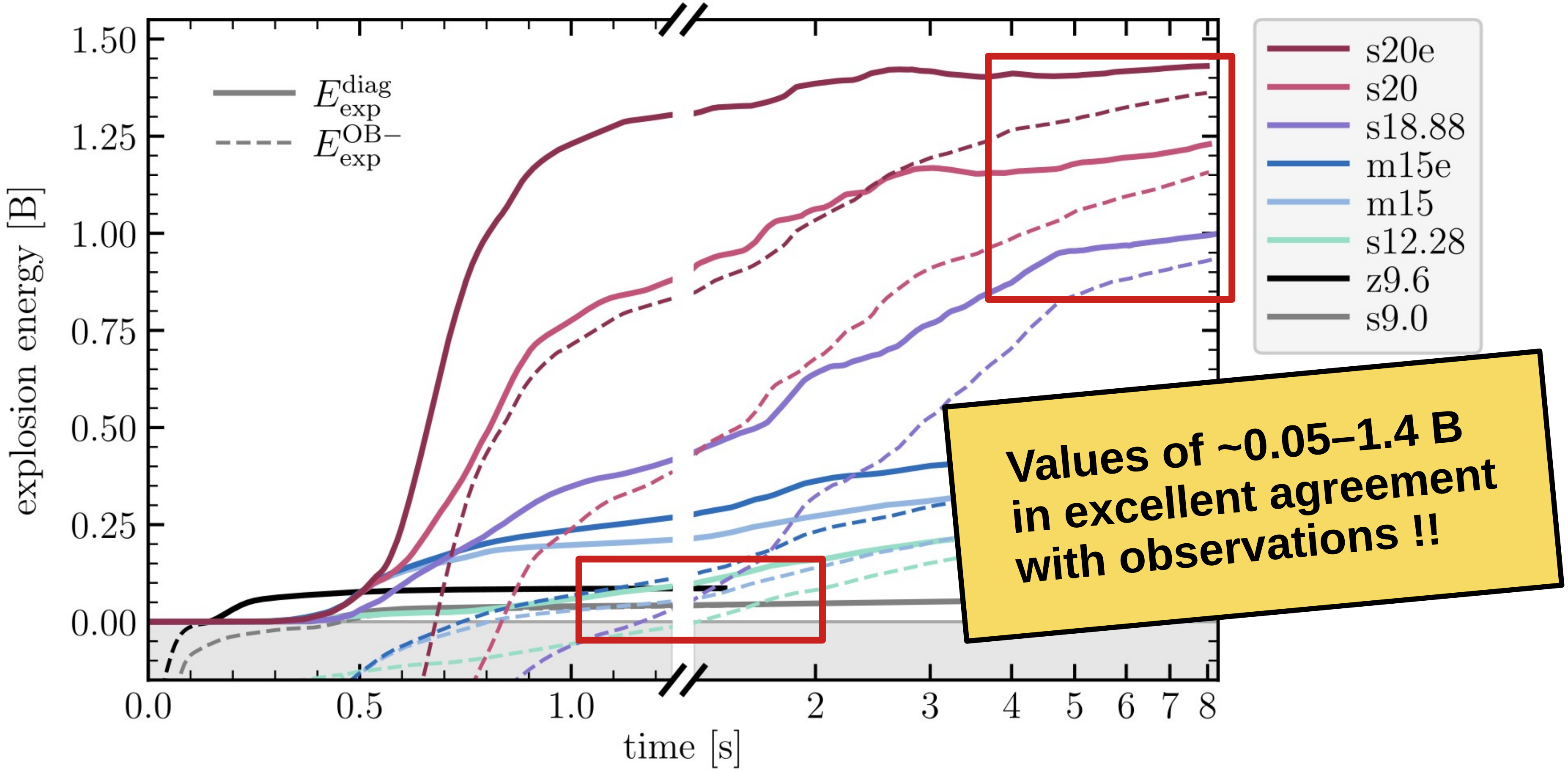
Explosion Energies



Explosion energies grow over several seconds due to:

1) continued neutrino-energy deposition ("heating")
2) supply of fresh matter close to the PNS
(long-lasting "downflows" that are re-ejected)

Explosion Energies



Values of ~0.05–1.4 B in excellent agreement with observations !!

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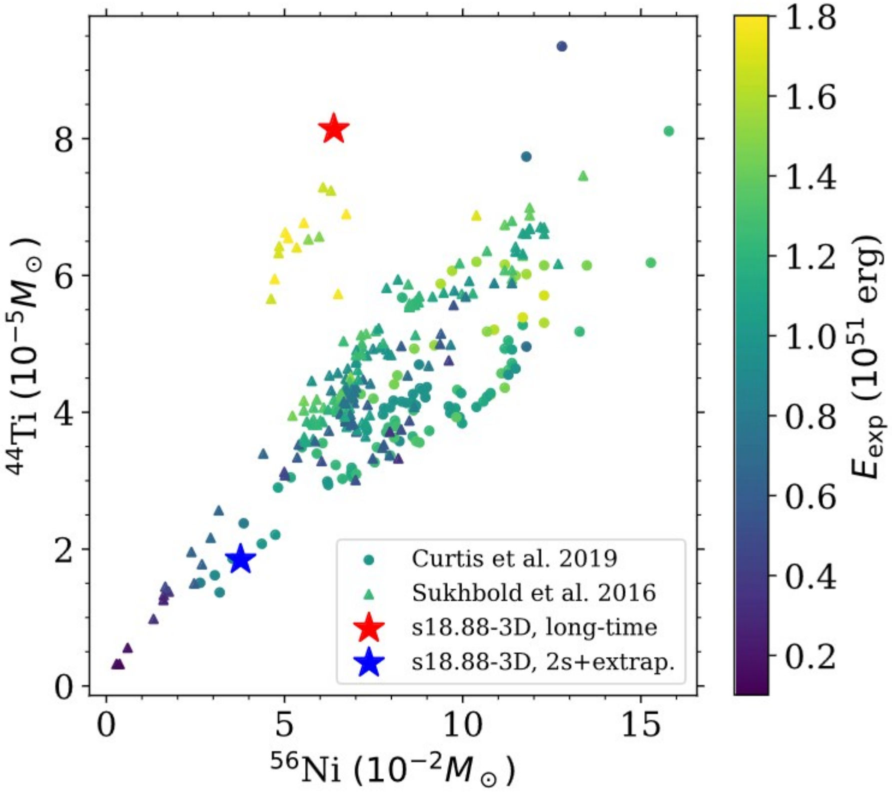
Nucleosynthesis Yields

(for model s18.88)

$M(^{56}\mathrm{Ni}) = 6.4 \times 10^{-2}\ M_\odot$
$M(^{44}\mathrm{Ti}) = 8.1 \times 10^{-5}\ M_\odot$

Sieverding, Kresse, & Janka (2023), ApJL, 957, L25, arXiv:2308.09659



Efficient production of ^{44}Ti due to non-monotonic temperature / density history of the ejecta!

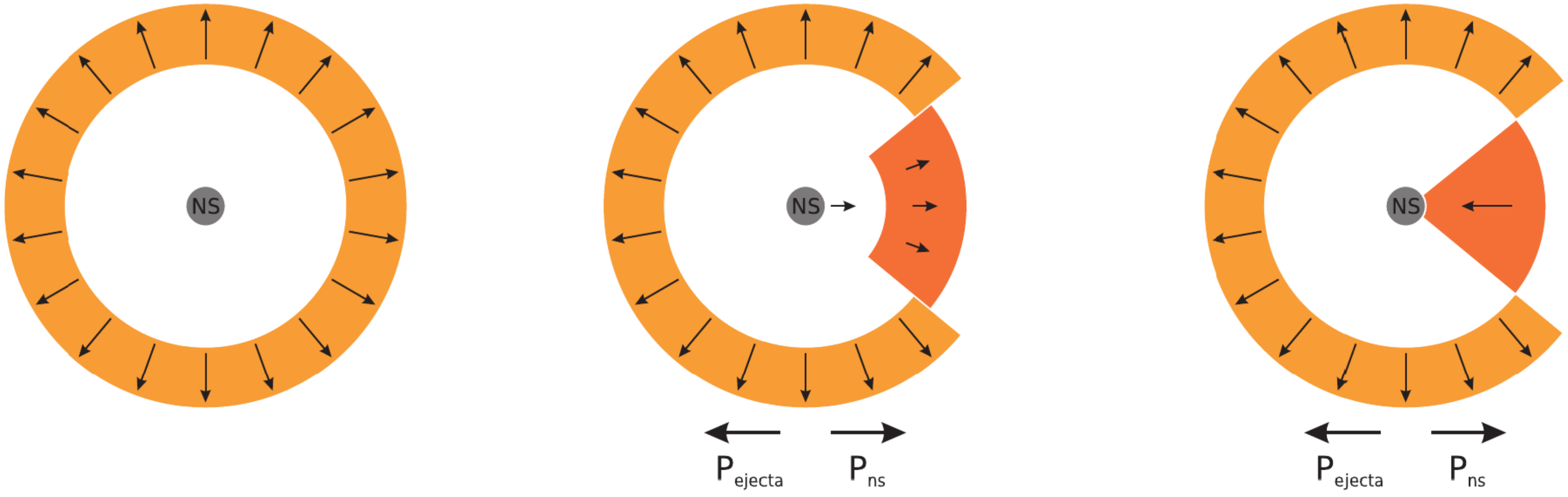
Significant enhancement of Ti / Fe yield compared to 1D models!!

Neutron Star Kicks

<u>**NS acceleration via:**</u>

1) **asymmetric ejection of matter (“hydro kick”)**
2) **asymmetric neutrino emission (“neutrino kick”)**

Janka & Kresse (2024)
arXiv:2401.13817



Scheck et al. (2006)

Asymmetric ejection of matter causes a NS kick in the direction opposite to the strongest expansion

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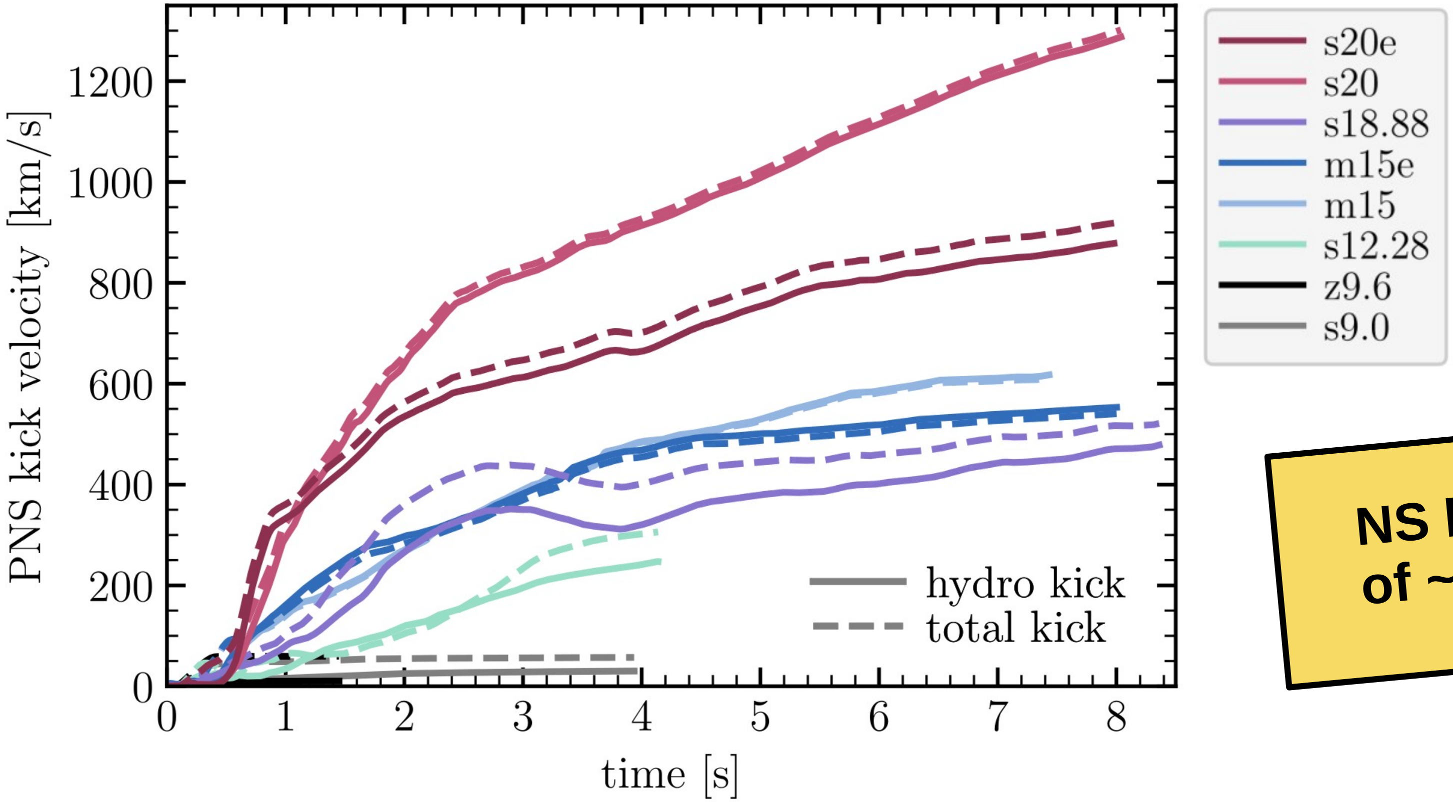

NS kick velocities of ~(50–1300) km/s

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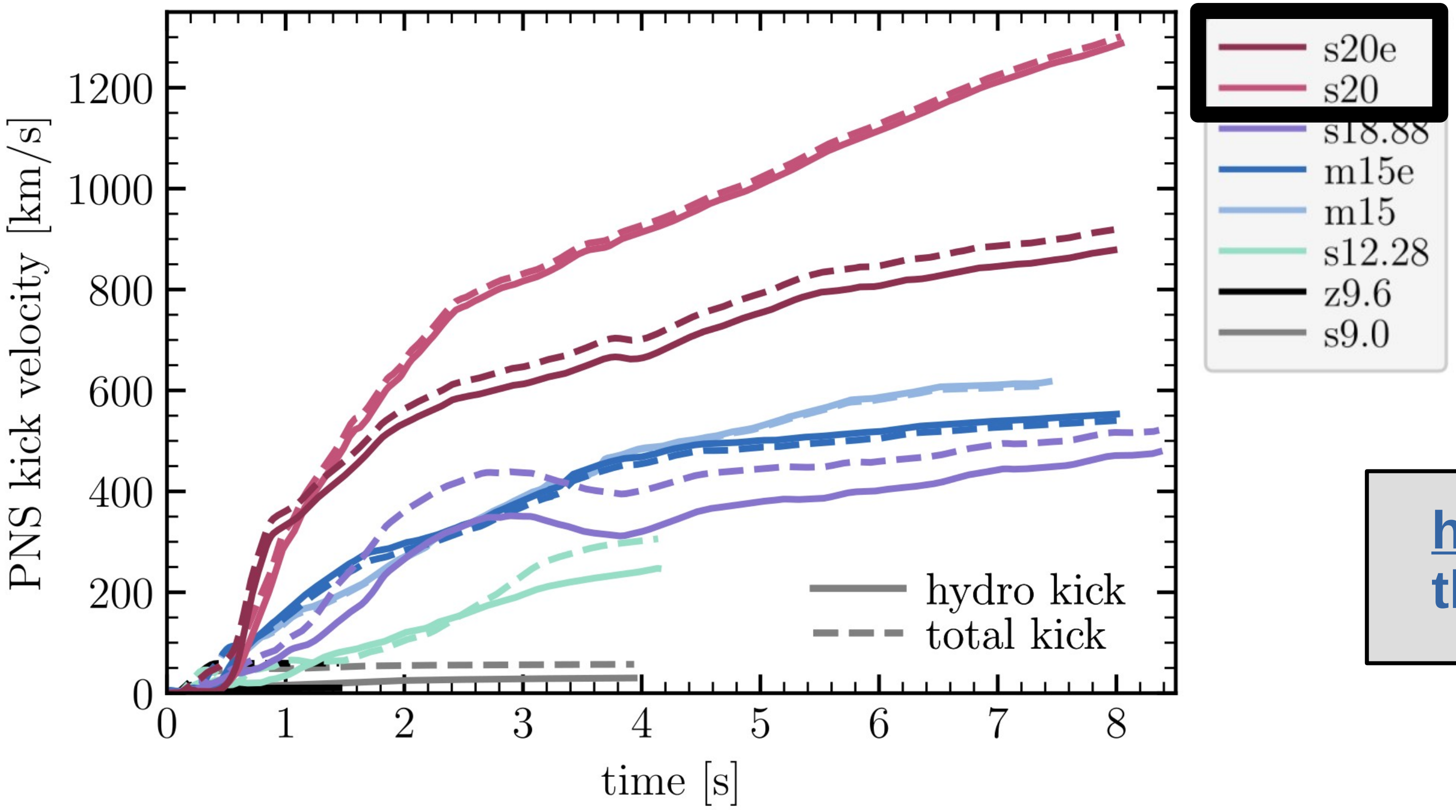
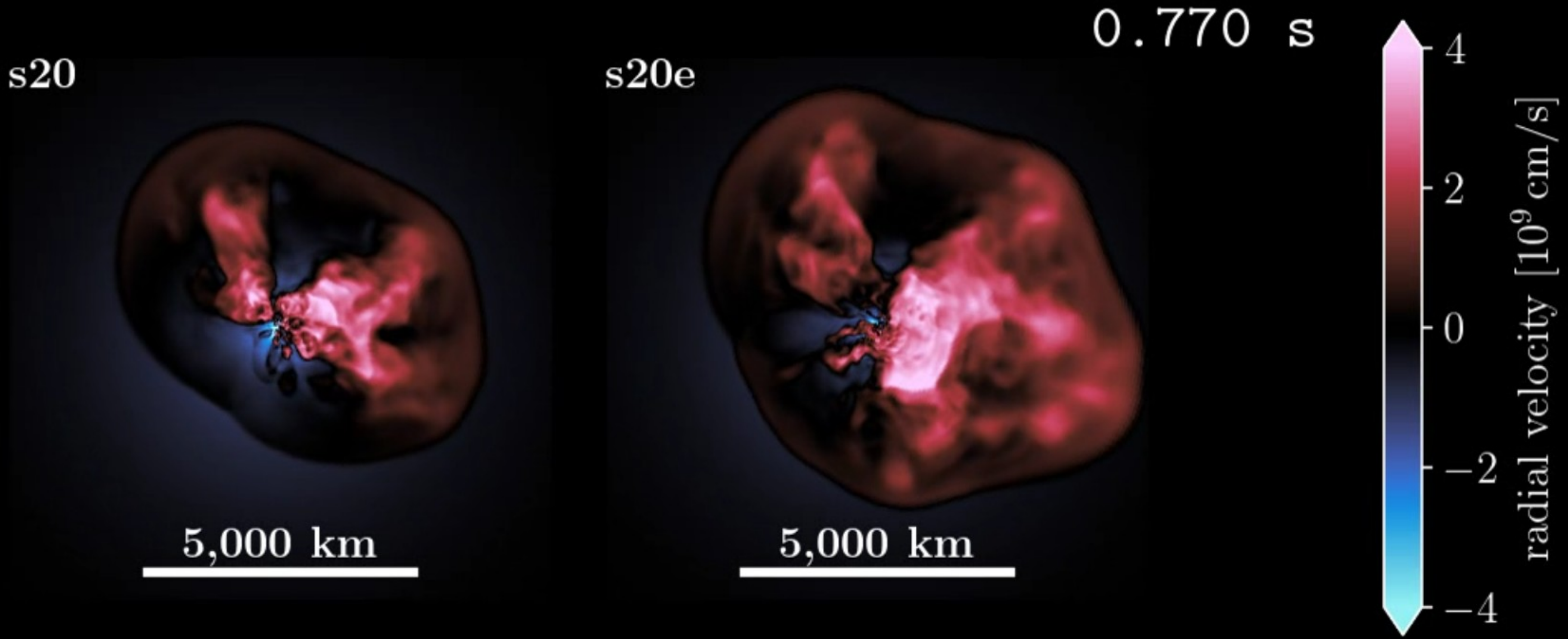


hydro kick of more than ~1000 km/s

Ejecta asymmetry matters!

$$\boxed{v_{\mathrm{NS}}^{\mathrm{hyd}} \propto \bar{\alpha}_{\mathrm{ej}}\, E_{\mathrm{exp}}}$$



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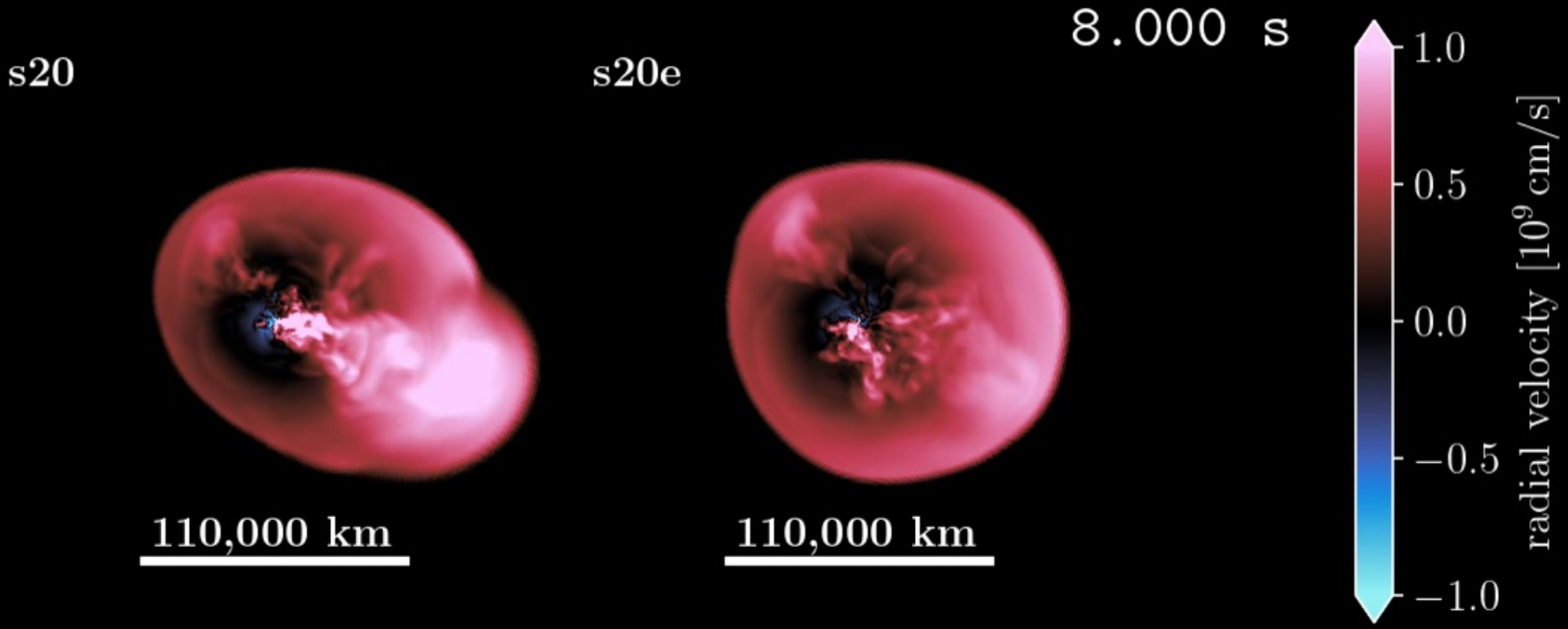

Hydro Kicks

$$v_{\mathrm{NS}}^{\mathrm{hyd}} \propto \bar{\alpha}_{\mathrm{ej}}\, E_{\mathrm{exp}}$$

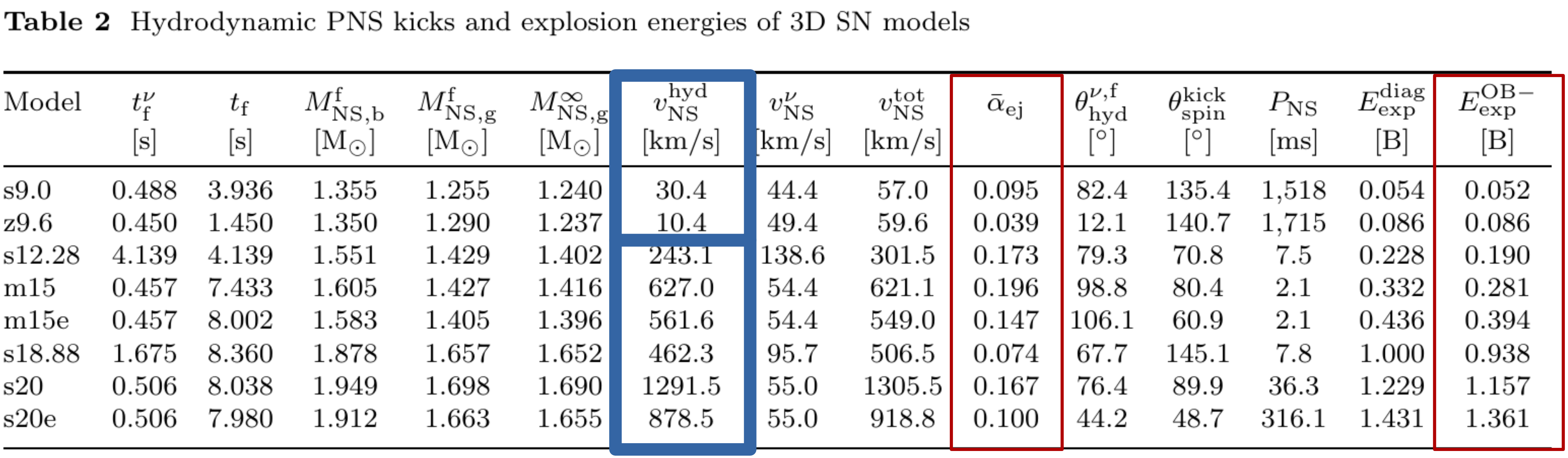

Table 2 Hydrodynamic PNS kicks and explosion energies of 3D SN models

Model	t_{f}^{ν} [s]	t_{f} [s]	$M_{\mathrm{NS,b}}^{\mathrm{f}}$ [$M_\odot$]	$M_{\mathrm{NS,g}}^{\mathrm{f}}$ [$M_\odot$]	$M_{\mathrm{NS,g}}^{\infty}$ [$M_\odot$]	$v_{\mathrm{NS}}^{\mathrm{hyd}}$ [km/s]	v_{NS}^{ν} [km/s]	$v_{\mathrm{NS}}^{\mathrm{tot}}$ [km/s]	$\bar{\alpha}_{\mathrm{ej}}$	$\theta_{\mathrm{hyd}}^{\nu,\mathrm{f}}$ [°]	$\theta_{\mathrm{spin}}^{\mathrm{kick}}$ [°]	P_{NS} [ms]	$E_{\mathrm{exp}}^{\mathrm{diag}}$ [B]	$E_{\mathrm{exp}}^{\mathrm{OB-}}$ [B]
s9.0	0.488	3.936	1.355	1.255	1.240	30.4	44.4	57.0	0.095	82.4	135.4	1,518	0.054	0.052
z9.6	0.450	1.450	1.350	1.290	1.237	10.4	49.4	59.6	0.039	12.1	140.7	1,715	0.086	0.086
s12.28	4.139	4.139	1.551	1.429	1.402	243.1	138.6	301.5	0.173	79.3	70.8	7.5	0.228	0.190
m15	0.457	7.433	1.605	1.427	1.416	627.0	54.4	621.1	0.196	98.8	80.4	2.1	0.332	0.281
m15e	0.457	8.002	1.583	1.405	1.396	561.6	54.4	549.0	0.147	106.1	60.9	2.1	0.436	0.394
s18.88	1.675	8.360	1.878	1.657	1.652	462.3	95.7	506.5	0.074	67.7	145.1	7.8	1.000	0.938
s20	0.506	8.038	1.949	1.698	1.690	1291.5	55.0	1305.5	0.167	76.4	89.9	36.3	1.229	1.157
s20e	0.506	7.980	1.912	1.663	1.655	878.5	55.0	918.8	0.100	44.2	48.7	316.1	1.431	1.361

> **small hydro kicks below ~30 km/s for low-mass progenitors**

> **large hydro kicks of up to more than ~1000 km/s for more massive progenitors (depending on the ejecta asymmetry and explosion energy)**

Neutron Star Kicks

<ins>**NS acceleration via:**</ins>

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2) **asymmetric neutrino emission (“neutrino kick”)**

Janka & Kresse (2024)
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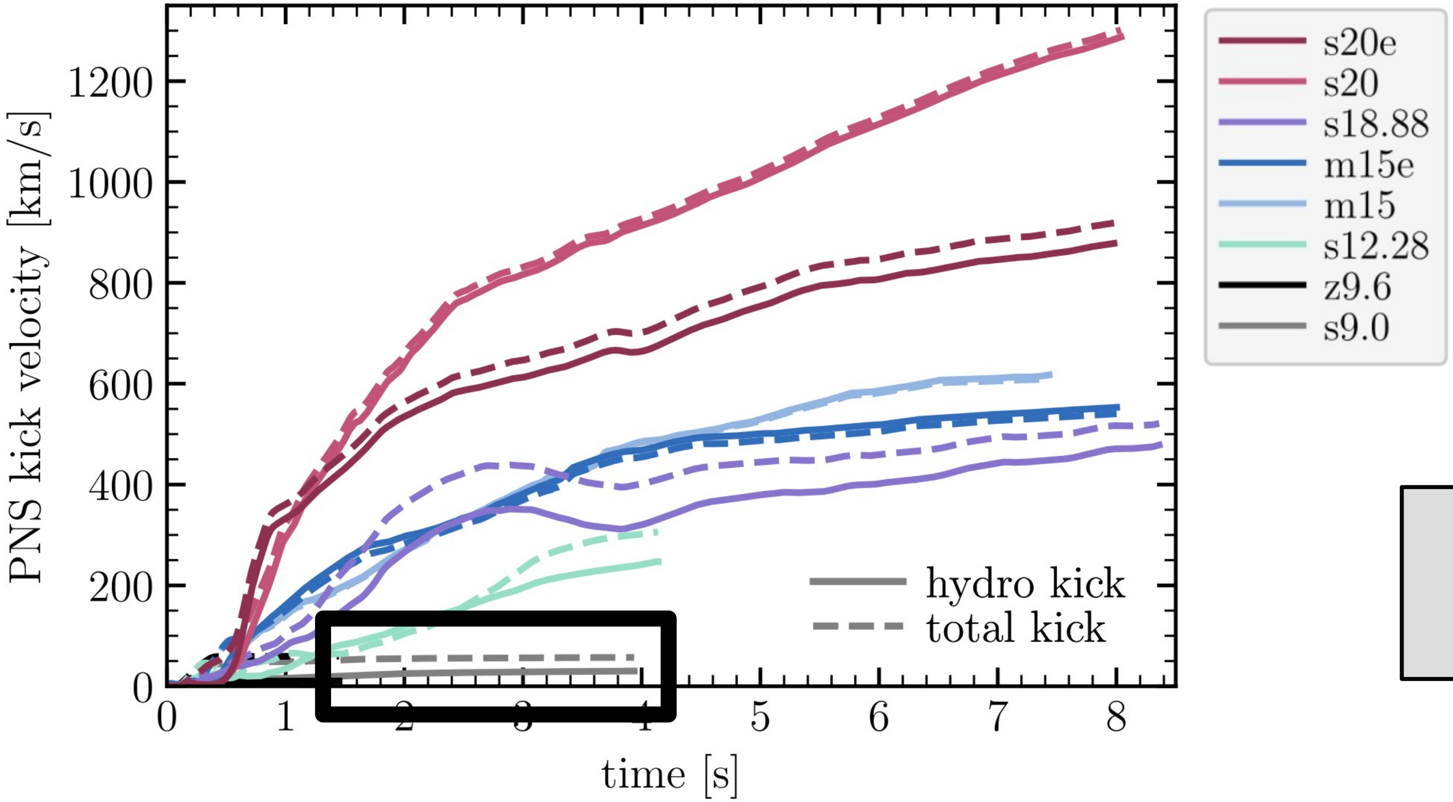

<ins>neutrino kick</ins> of
~50–200 km/s

Neutrino-induced Kicks

Reasons for asymmetric (anisotropic) neutrino emission:

1) Anisotropic neutrino emission from the PNS core (due to the LESA)

→ ν kicks of ~50 km/s

2a) Anisotropic neutrino (ν) emission from the PNS accretion mantle layer

2b) Anisotropic ν absorption/scattering in dense matter downdrafts

→ ν kicks of up to ~200 km/s

Neutrino Kicks

$$v_{\mathrm{NS}}^{\nu} \approx 167\,\frac{\mathrm{km}}{\mathrm{s}}\,\frac{\bar{\alpha}_{\nu}^{\mathrm{tot}}}{0.005}\,\frac{E_{\nu}^{\mathrm{tot}}}{3\times 10^{53}\,\mathrm{erg}}\left(\frac{M_{\mathrm{NS,b}}}{1.5\,\mathrm{M}_{\odot}}\right)^{-1}$$

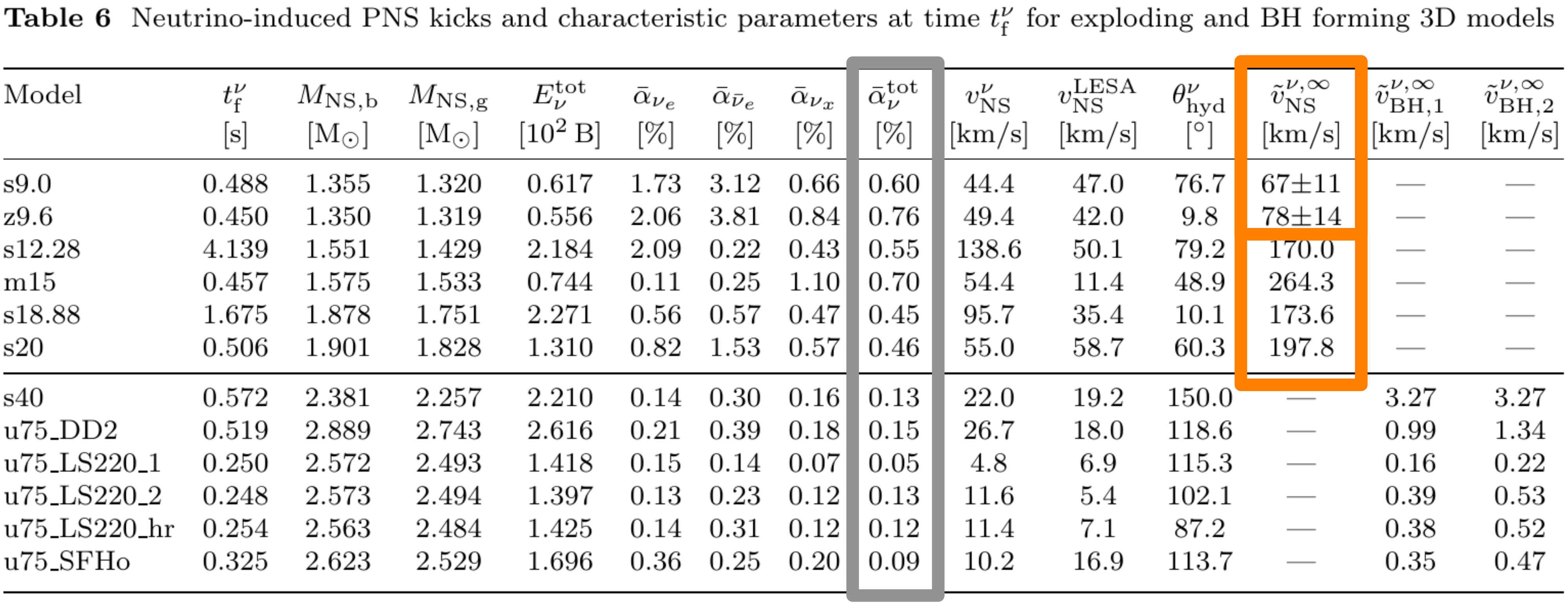

Table 6 Neutrino-induced PNS kicks and characteristic parameters at time t_{f}^{ν} for exploding and BH forming 3D models

Model	t_{f}^{ν} [s]	$M_{\mathrm{NS,b}}$ [$\mathrm{M}_{\odot}$]	$M_{\mathrm{NS,g}}$ [$\mathrm{M}_{\odot}$]	E_{ν}^{tot} [10^2 B]	$\bar{\alpha}_{\nu_e}$ [%]	$\bar{\alpha}_{\bar{\nu}_e}$ [%]	$\bar{\alpha}_{\nu_x}$ [%]	$\bar{\alpha}_{\nu}^{\mathrm{tot}}$ [%]	v_{NS}^{ν} [km/s]	$v_{\mathrm{NS}}^{\mathrm{LESA}}$ [km/s]	$\theta_{\mathrm{hyd}}^{\nu}$ [°]	$\tilde{v}_{\mathrm{NS}}^{\nu,\infty}$ [km/s]	$\tilde{v}_{\mathrm{BH,1}}^{\nu,\infty}$ [km/s]	$\tilde{v}_{\mathrm{BH,2}}^{\nu,\infty}$ [km/s]
s9.0	0.488	1.355	1.320	0.617	1.73	3.12	0.66	0.60	44.4	47.0	76.7	67±11	—	—
z9.6	0.450	1.350	1.319	0.556	2.06	3.81	0.84	0.76	49.4	42.0	9.8	78±14	—	—
s12.28	4.139	1.551	1.429	2.184	2.09	0.22	0.43	0.55	138.6	50.1	79.2	170.0	—	—
m15	0.457	1.575	1.533	0.744	0.11	0.25	1.10	0.70	54.4	11.4	48.9	264.3	—	—
s18.88	1.675	1.878	1.751	2.271	0.56	0.57	0.47	0.45	95.7	35.4	10.1	173.6	—	—
s20	0.506	1.901	1.828	1.310	0.82	1.53	0.57	0.46	55.0	58.7	60.3	197.8	—	—
s40	0.572	2.381	2.257	2.210	0.14	0.30	0.16	0.13	22.0	19.2	150.0	—	3.27	3.27
u75_DD2	0.519	2.889	2.743	2.616	0.21	0.39	0.18	0.15	26.7	18.0	118.6	—	0.99	1.34
u75_LS220_1	0.250	2.572	2.493	1.418	0.15	0.14	0.07	0.05	4.8	6.9	115.3	—	0.16	0.22
u75_LS220_2	0.248	2.573	2.494	1.397	0.13	0.23	0.12	0.13	11.6	5.4	102.1	—	0.39	0.53
u75_LS220_hr	0.254	2.563	2.484	1.425	0.14	0.31	0.12	0.12	11.4	7.1	87.2	—	0.38	0.52
u75_SFHo	0.325	2.623	2.529	1.696	0.36	0.25	0.20	0.09	10.2	16.9	113.7	—	0.35	0.47

> **neutrino-induced NS kicks:** ~50–200 km/s

Neutrino Kicks

$$v_{\mathrm{NS}}^{\nu} \approx 167\,\frac{\mathrm{km}}{\mathrm{s}}\,\frac{\bar{\alpha}_{\nu}^{\mathrm{tot}}}{0.005}\,\frac{E_{\nu}^{\mathrm{tot}}}{3\times10^{53}\,\mathrm{erg}}\left(\frac{M_{\mathrm{NS,b}}}{1.5\,\mathrm{M}_{\odot}}\right)^{-1}$$

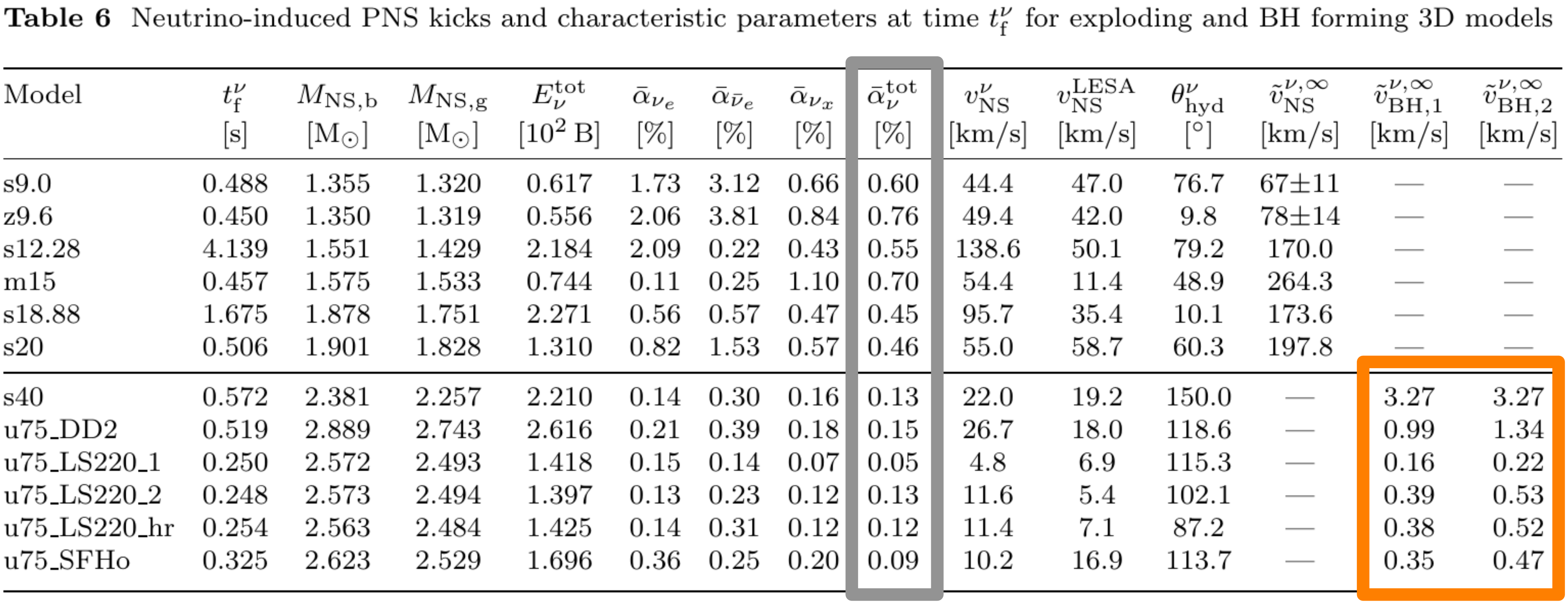

Table 6 Neutrino-induced PNS kicks and characteristic parameters at time t_{f}^{ν} for exploding and BH forming 3D models

Model	t_{f}^{ν} [s]	$M_{\mathrm{NS,b}}$ [$\mathrm{M}_{\odot}$]	$M_{\mathrm{NS,g}}$ [$\mathrm{M}_{\odot}$]	E_{ν}^{tot} [10^2 B]	$\bar{\alpha}_{\nu_e}$ [%]	$\bar{\alpha}_{\bar{\nu}_e}$ [%]	$\bar{\alpha}_{\nu_x}$ [%]	$\bar{\alpha}_{\nu}^{\mathrm{tot}}$ [%]	v_{NS}^{ν} [km/s]	$v_{\mathrm{NS}}^{\mathrm{LESA}}$ [km/s]	$\theta_{\mathrm{hyd}}^{\nu}$ [°]	$\tilde{v}_{\mathrm{NS}}^{\nu,\infty}$ [km/s]	$\tilde{v}_{\mathrm{BH,1}}^{\nu,\infty}$ [km/s]	$\tilde{v}_{\mathrm{BH,2}}^{\nu,\infty}$ [km/s]
s9.0	0.488	1.355	1.320	0.617	1.73	3.12	0.66	0.60	44.4	47.0	76.7	67±11	—	—
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s12.28	4.139	1.551	1.429	2.184	2.09	0.22	0.43	0.55	138.6	50.1	79.2	170.0	—	—
m15	0.457	1.575	1.533	0.744	0.11	0.25	1.10	0.70	54.4	11.4	48.9	264.3	—	—
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> **neutrino-induced NS kicks:** ~50–200 km/s

> **neutrino-induced BH kicks:** ~few km/s
(in failed SNe without asymmetric mass ejection)

Neutrino Kicks

$$v_{\mathrm{NS}}^{\nu} \approx 167\,\frac{\mathrm{km}}{\mathrm{s}}\;\frac{\bar{\alpha}_{\nu}^{\mathrm{tot}}}{0.005}\;\frac{E_{\nu}^{\mathrm{tot}}}{3\times 10^{53}\,\mathrm{erg}}\left(\frac{M_{\mathrm{NS,b}}}{1.5\,\mathrm{M}_{\odot}}\right)^{-1}$$

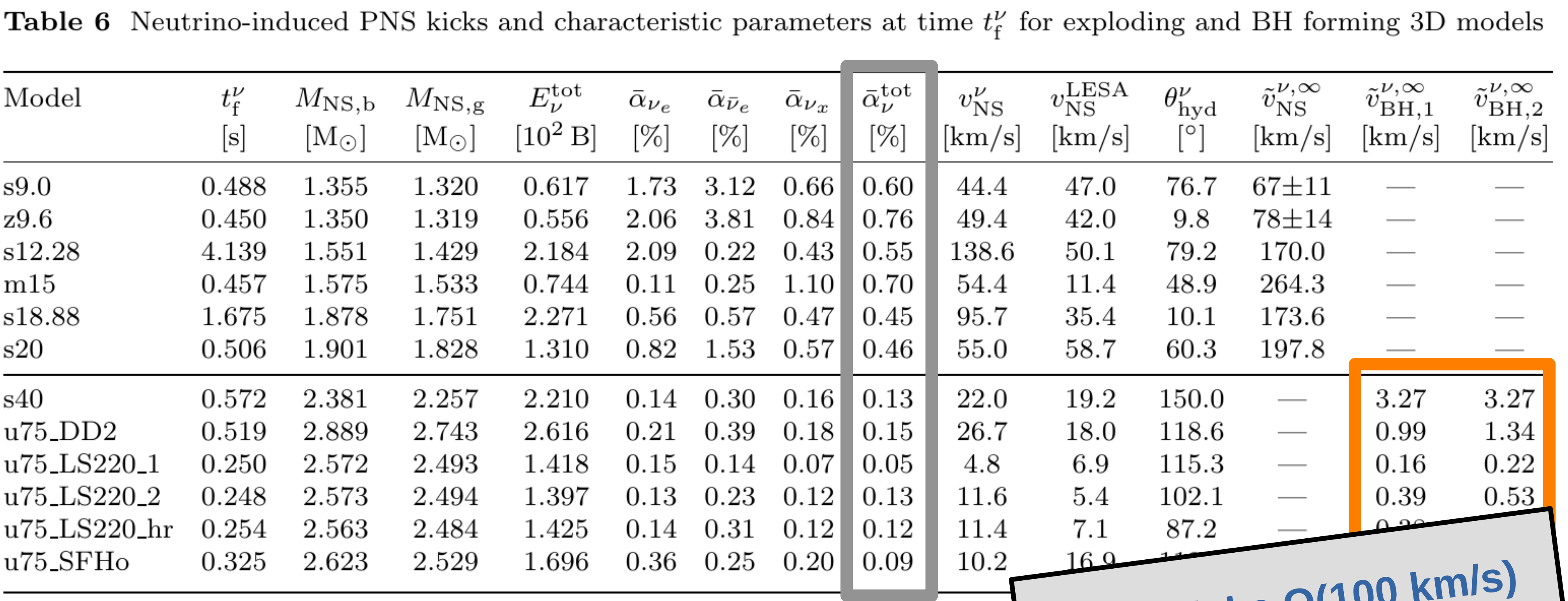

Table 6 Neutrino-induced PNS kicks and characteristic parameters at time t_{f}^{ν} for exploding and BH forming 3D models

Model	t_{f}^{ν} [s]	$M_{\mathrm{NS,b}}$ [$\mathrm{M}_{\odot}$]	$M_{\mathrm{NS,g}}$ [$\mathrm{M}_{\odot}$]	E_{ν}^{tot} [10^2 B]	$\bar{\alpha}_{\nu_e}$ [%]	$\bar{\alpha}_{\bar{\nu}_e}$ [%]	$\bar{\alpha}_{\nu_x}$ [%]	$\bar{\alpha}_{\nu}^{\mathrm{tot}}$ [%]	v_{NS}^{ν} [km/s]	$v_{\mathrm{NS}}^{\mathrm{LESA}}$ [km/s]	$\theta_{\mathrm{hyd}}^{\nu}$ [°]	$\tilde{v}_{\mathrm{NS}}^{\nu,\infty}$ [km/s]	$\tilde{v}_{\mathrm{BH,1}}^{\nu,\infty}$ [km/s]	$\tilde{v}_{\mathrm{BH,2}}^{\nu,\infty}$ [km/s]
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s12.28	4.139	1.551	1.429	2.184	2.09	0.22	0.43	0.55	138.6	50.1	79.2	170.0	—	—
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s18.88	1.675	1.878	1.751	2.271	0.56	0.57	0.47	0.45	95.7	35.4	10.1	173.6	—	—
s20	0.506	1.901	1.828	1.310	0.82	1.53	0.57	0.46	55.0	58.7	60.3	197.8	—	—
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u75_DD2	0.519	2.889	2.743	2.616	0.21	0.39	0.18	0.15	26.7	18.0	118.6	—	0.99	1.34
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u75_LS220_hr	0.254	2.563	2.484	1.425	0.14	0.31	0.12	0.12	11.4	7.1	87.2	—	[illegible]	[illegible]
u75_SFHo	0.325	2.623	2.529	1.696	0.36	0.25	0.20	0.09	10.2	16.9	[illegible]	[illegible]	[illegible]	[illegible]

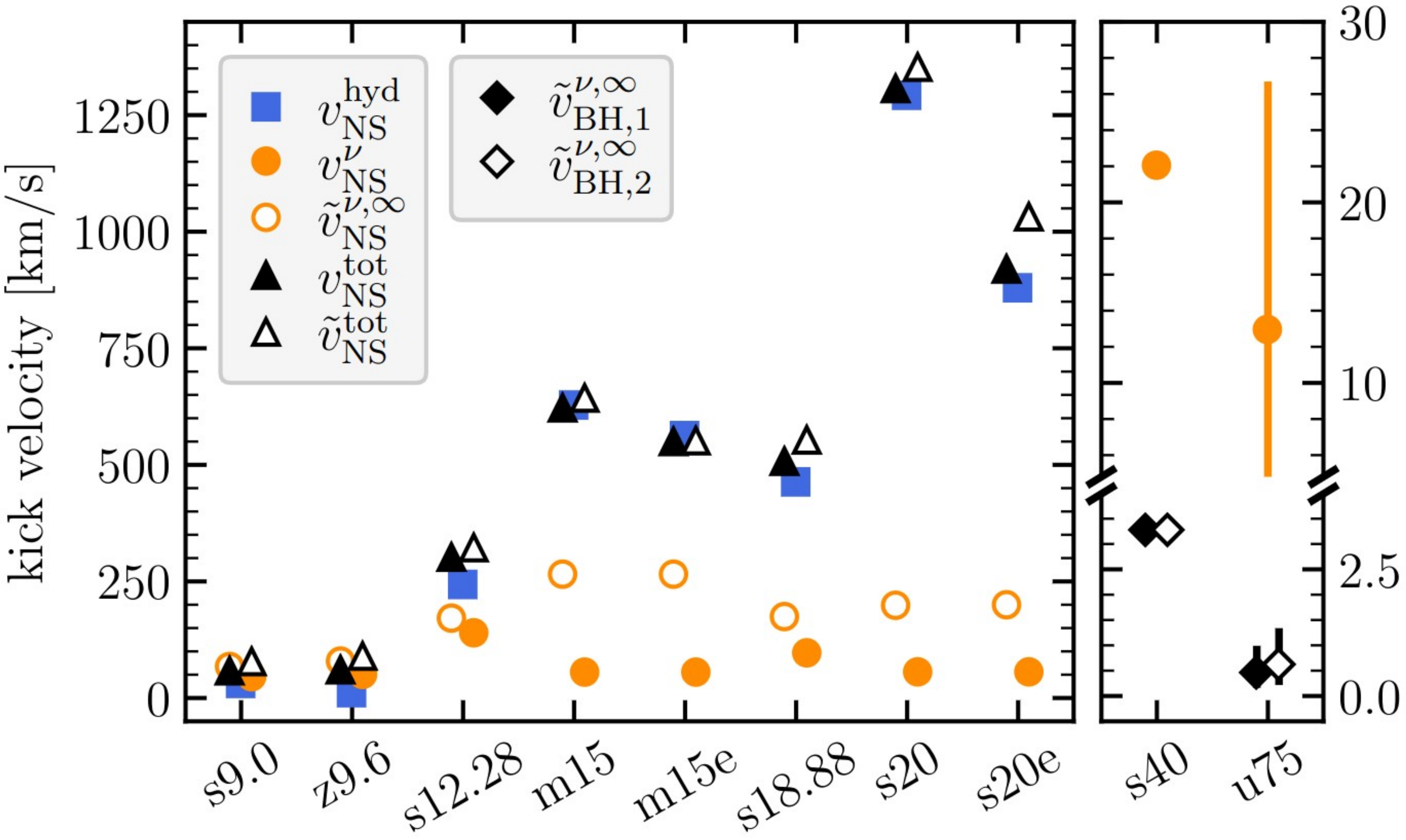
> **neutrino-induced NS kicks:** ~50–200 km/s

> **neutrino-induced BH kicks:** ~few km/s
(in failed SNe without asymmetric mass ejection)

high kicks O(100 km/s) expected for BHs from fallback SNe / BH SNe

NS and BH Kicks

Janka & Kresse (2024)
arXiv:2401.13817



NS and BH Kicks

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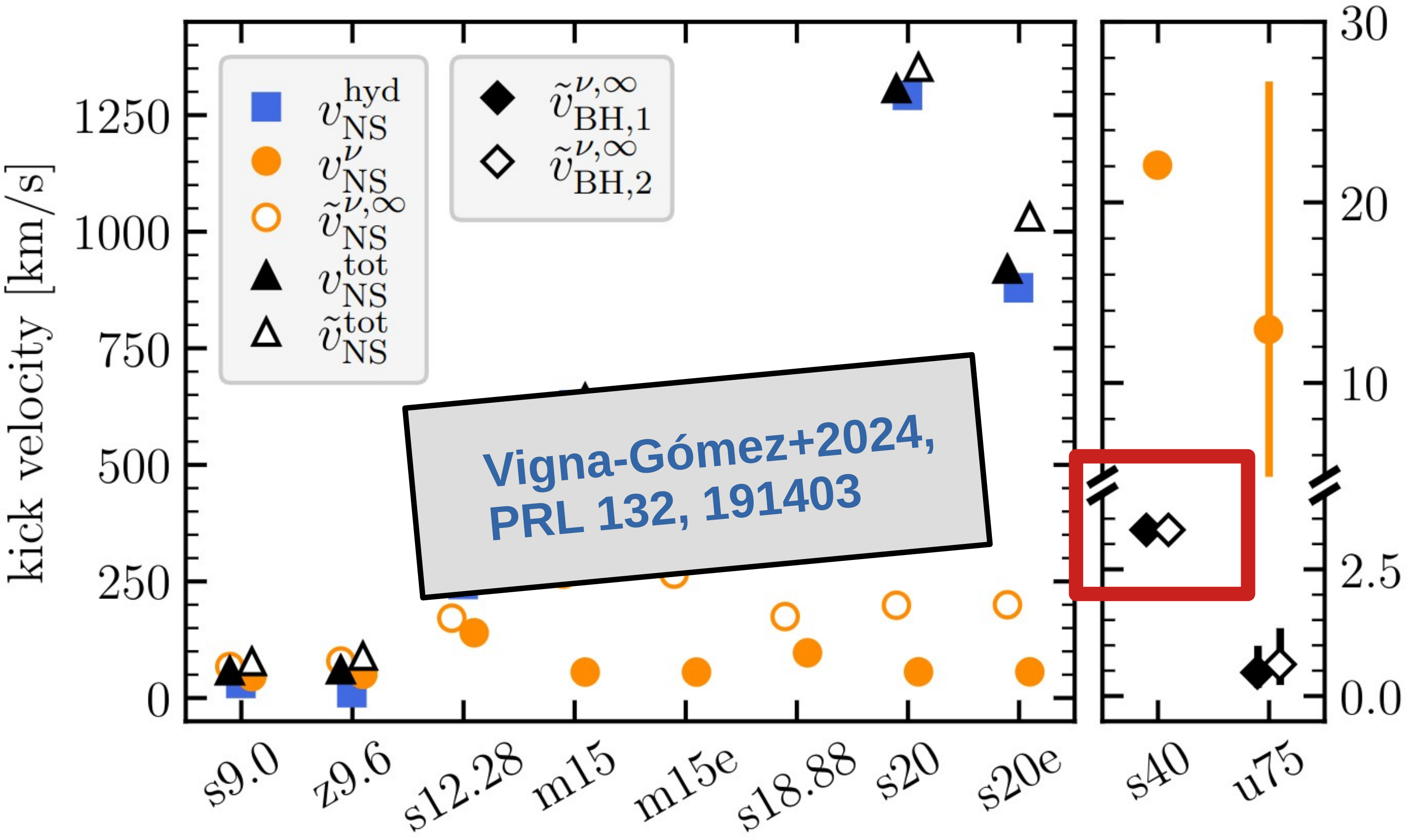

Vigna-Gómez+2024,
PRL 132, 191403

Main results:

arXiv:2401.13817

- **Explosion energy:** ~(0.1–1.5) x 10^{51} erg ✓
- **Radioactive ^{56}Ni:** ~(0.01–0.1) $M_\odot$ ✓
  Radioactive ^{44}Ti: ~10^{-4} $M_\odot$ ✓
- **NS kick velocity:** ~(100–1000) km/s ✓

References:

- Kresse et al. (2024, in prep.)
- Janka & Kresse (2024)
- Sieverding, Kresse, & Janka (2023)
- Bollig, Yadav, Kresse, et al. (2021)
- Stockinger, Janka, Kresse et al. (2020)