Core-Collapse Simulations of Very Massive Star: Gravitational Collapse, Black-hole Formation, and Beyond

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Motivation

- Gravitational wave (GW150914) produced by merger of $35 M_\odot$ and $30 M_\odot$.
- Very massive stars (VMS; $\simeq 100\ \mathrm{M}_\odot$, Vink 2015) end their life possibly as pulsational pair-instability supernovae and produce BH.
- VMS produces a pre-collapse core of around 30-50$M_\odot$.
- Result of VMS core-collapse, shock revival? Final remnant? BH or NS?

Very massive stars and Pulsational pair-instability supernova

- 80-150$M_\odot$ ZAMS.
- Can encounter the "pulsational pair-instability supernova".
- Several pulse occurs and reduces He and heavy element core mass and outer H envelop is blown away.
- Final core mass $30 - 50 M_\odot$.

Figure 1: Eta Carinae. Credit NASA

Core-Collapse Supernova Physics

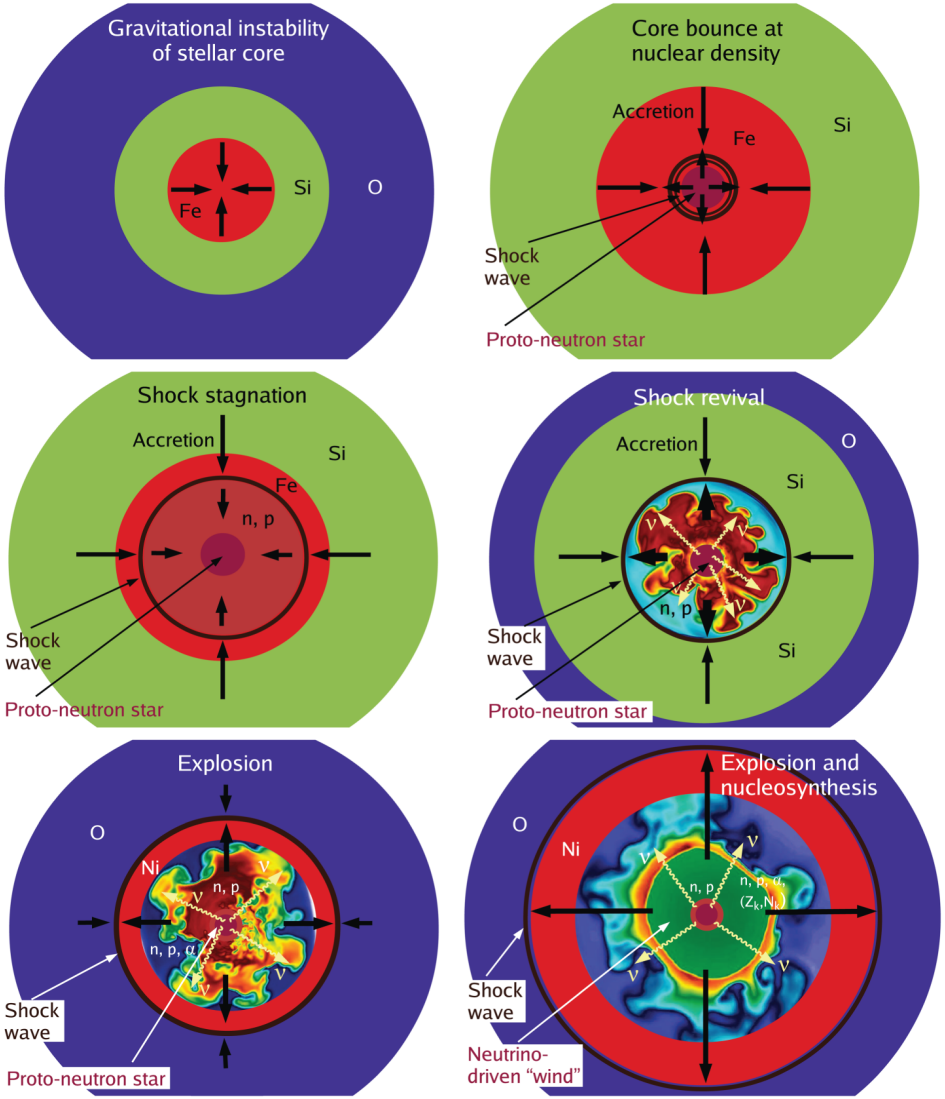


Figure 2: Different stage of core-collapse to onset of supernova (Janka et al. 2012).

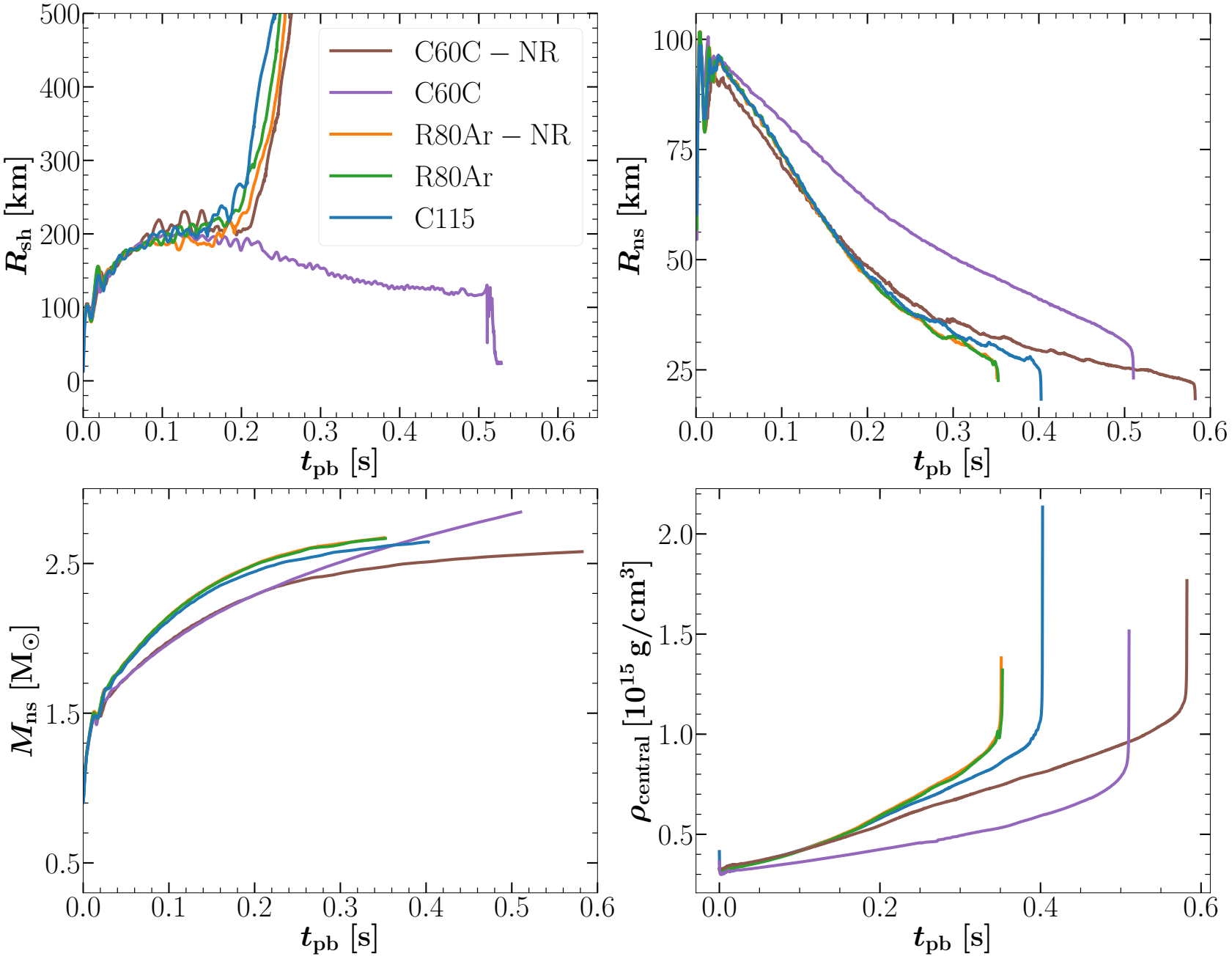
VMS - Progenitor and Setup

Model	M_{ZAMS} (M_{prog})	M_{Fe}	J_{prog} (a_{prog})	t_{sh-rev}	t_{BH}
	$[M_\odot]$	$[M_\odot]$	$[10^{50}$ erg s$]$	[s]	[s]
C60C-NR	60 (41.54)	2.37		0.250	0.580
C60C	60 (41.54)	2.37	105 (0.55)		0.510
R80Ar-NR	80 (47.64)	2.72		0.246	0.350
R80Ar	80 (47.64)	2.72	14 (0.07)	0.237	0.350
C115	115 (45.50)	2.46		0.222	0.400

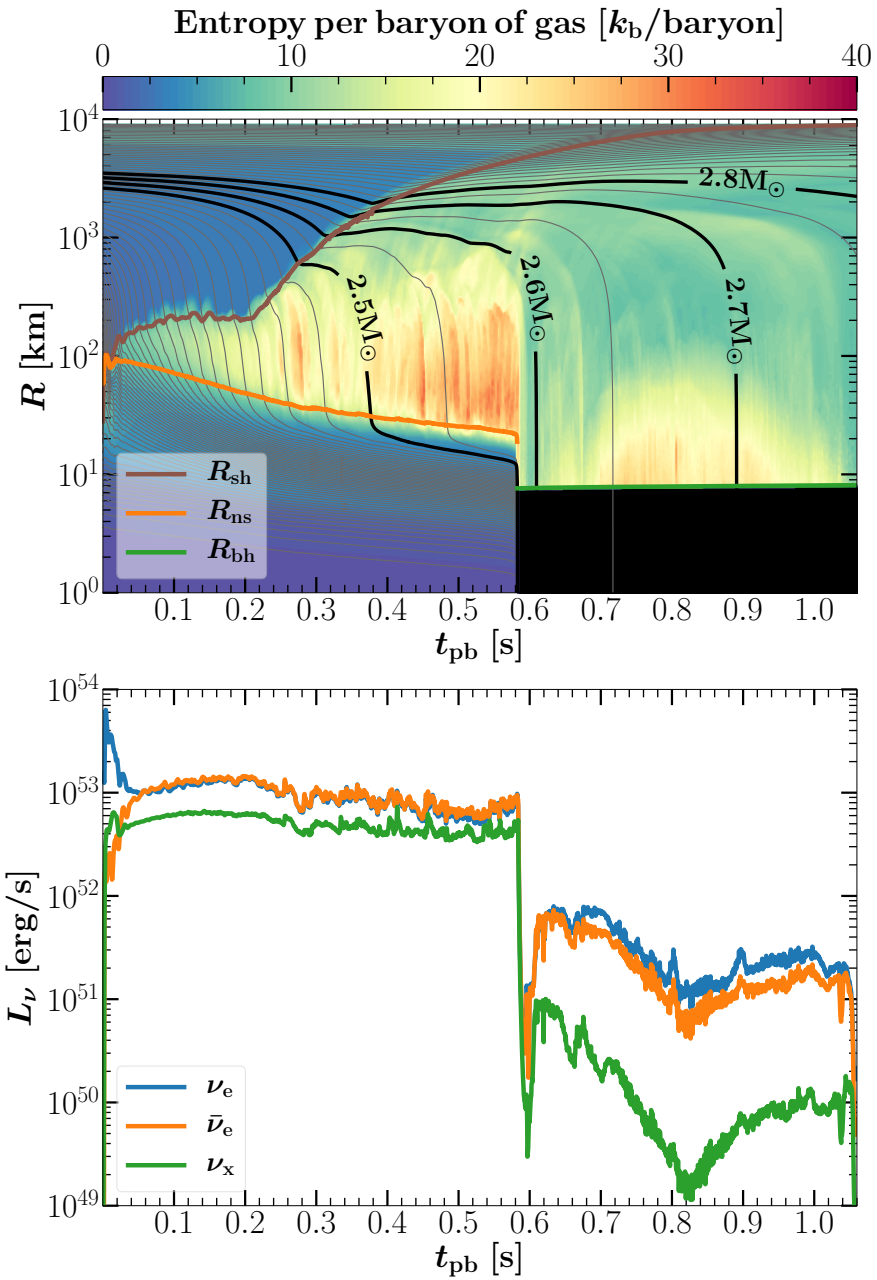
Table 1: Progenitor properties. All models have zero-age-main-sequence (ZAMS) metallicity of 10% $Z_\odot$.

- 2D GR-Hydro-Transport simulation.
- Radial grid points = 500. Angular resolution = 1.4°.
- Nuclear EOS SFHo (Steiner et al. 2012).

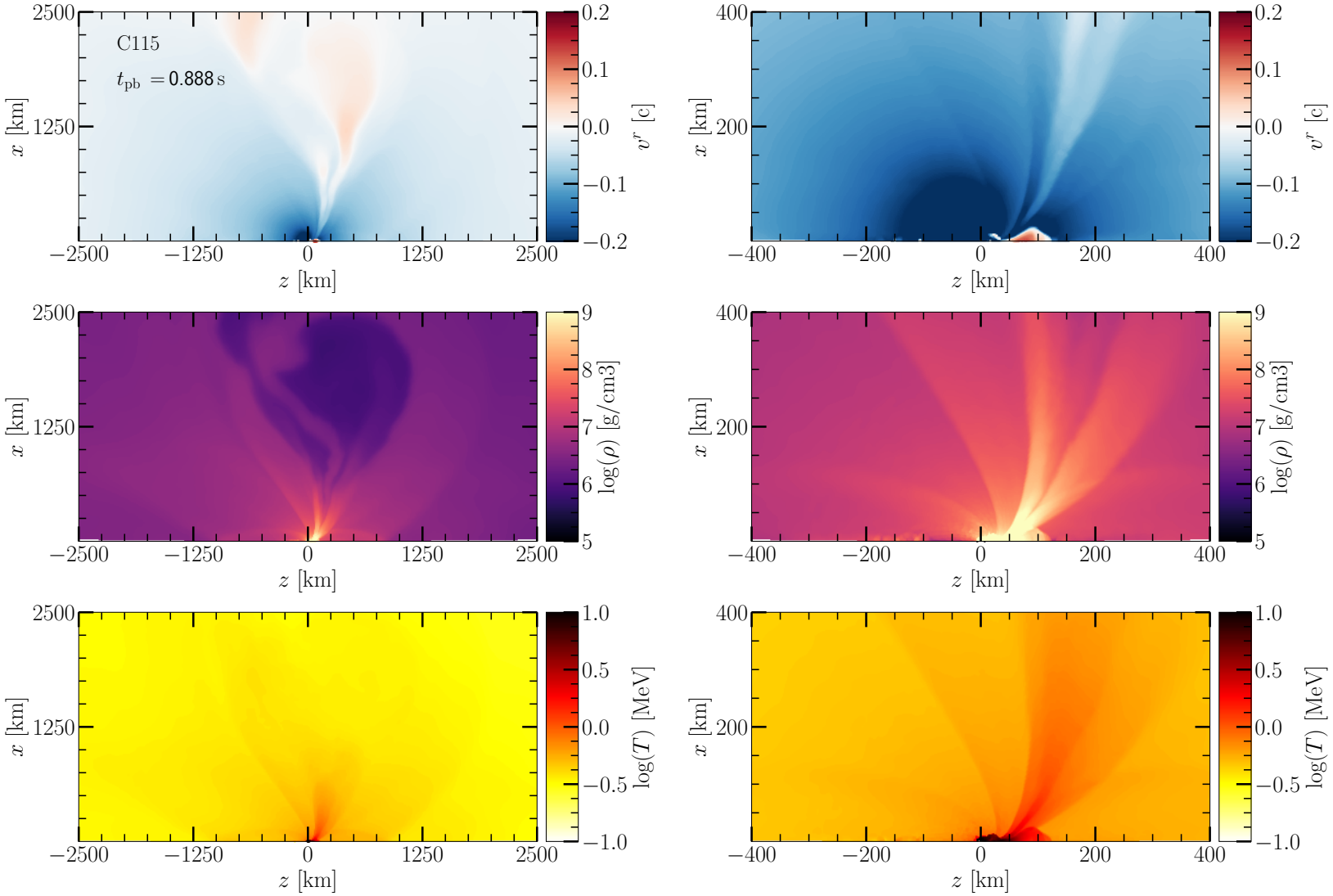
VMS Results


C60C − NR
C60C
R80Ar − NR
R80Ar
C115
R_{sh} [km]
R_{ns} [km]
M_{ns} [$M_\odot$]
$\rho_{central}$ [10^{15} g/cm^3]
t_{pb} [s]

VMS Results-After BH formation-C60C-NR model



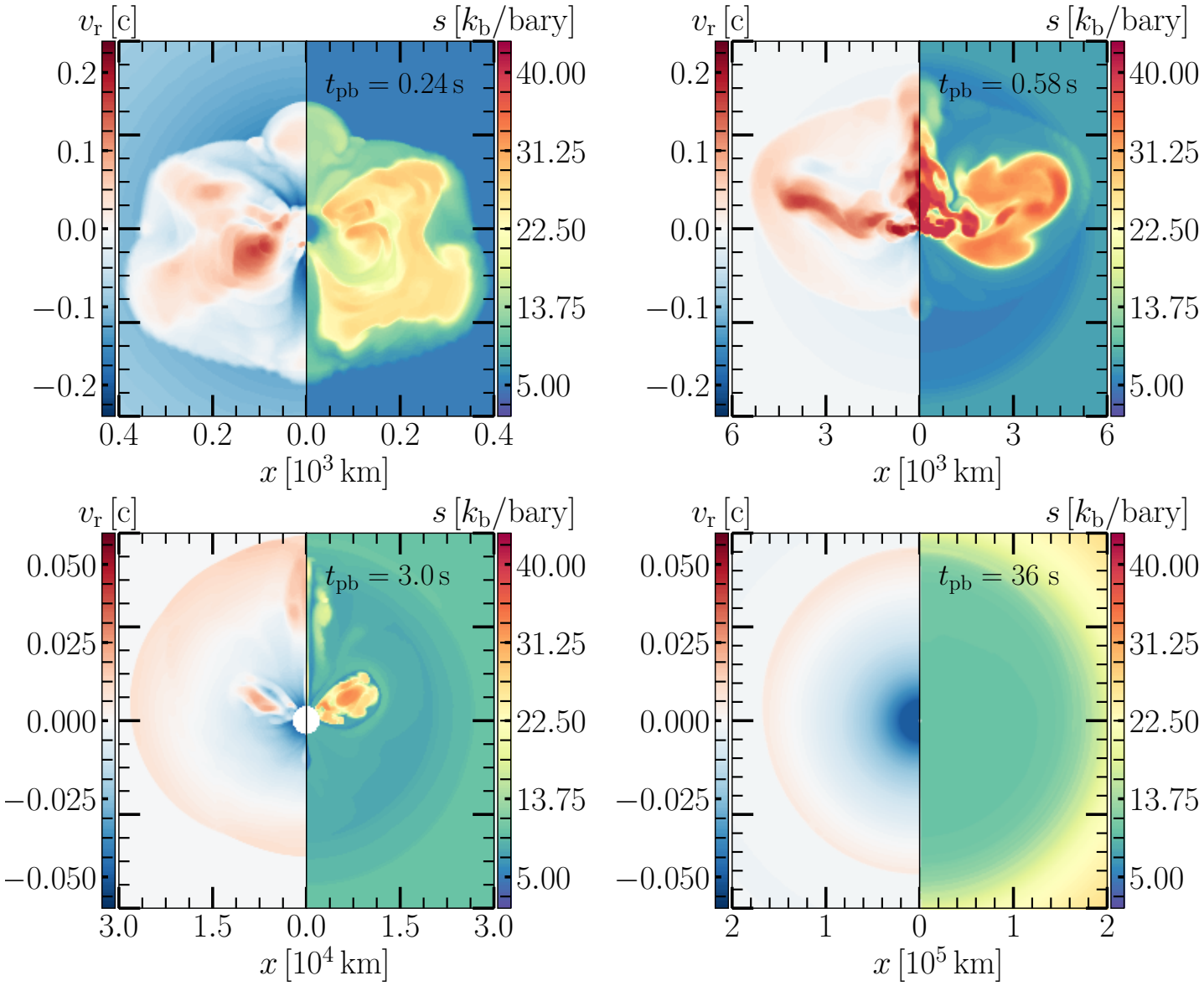
VMS Results-After BH formation-hotspot



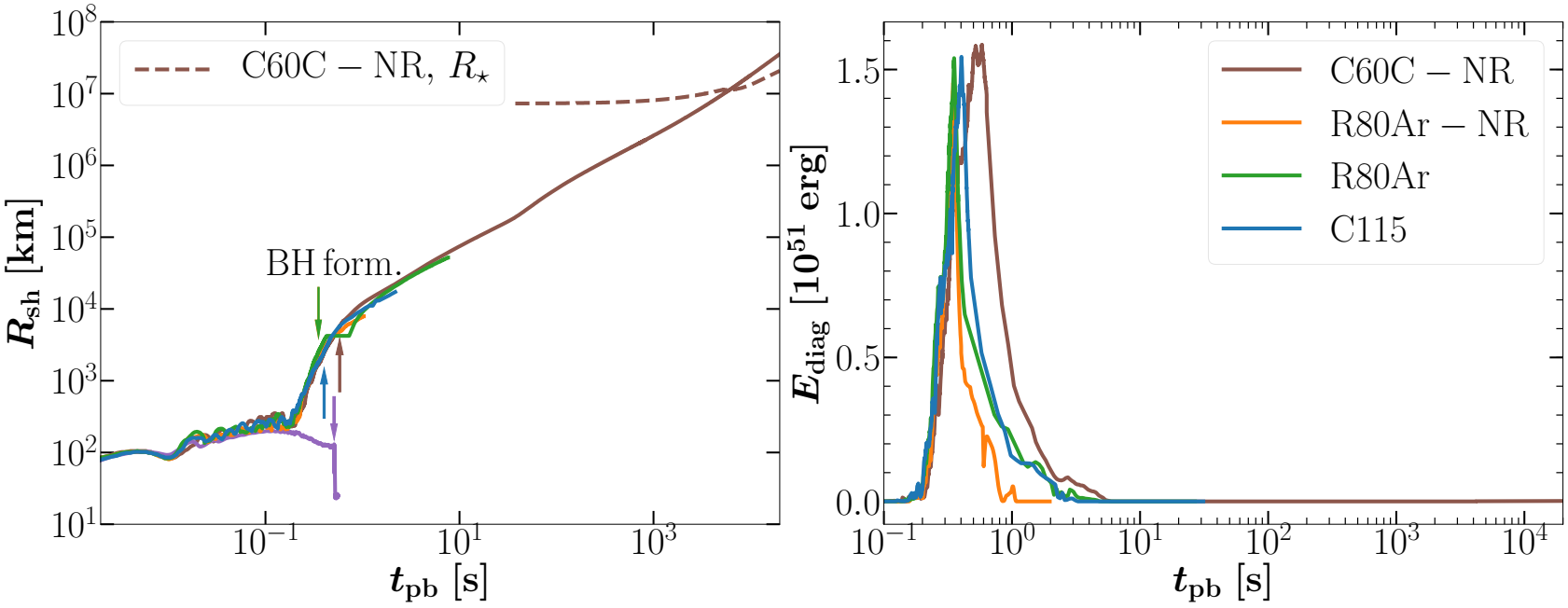
Longterm simulation after BH formation

- Hydrodynamical data was mapped from general relativistic NADA-FLD code to Newtonian Prometheus code.
- Excise the inner 400 km containing BH.
- Ensured the accretion on to BH is supersonic at a radius of 400km at the time of mapping.

VMS Results (Longterm)-C60C-NR



VMS Results (Longterm)-After BH formation



Model	Mode	Upper bound of ejecta mass [$M_\odot$]
C60C-NR	shock	0.14
R80Ar-NR	shock → sonic pulse	1.1
R80Ar	shock → sonic pulse	3.5
C115	shock → sonic pulse	0.07

Table 2: Upper bound of ejecta mass (for detail, see, e.g. Matzner and Ro 2020).

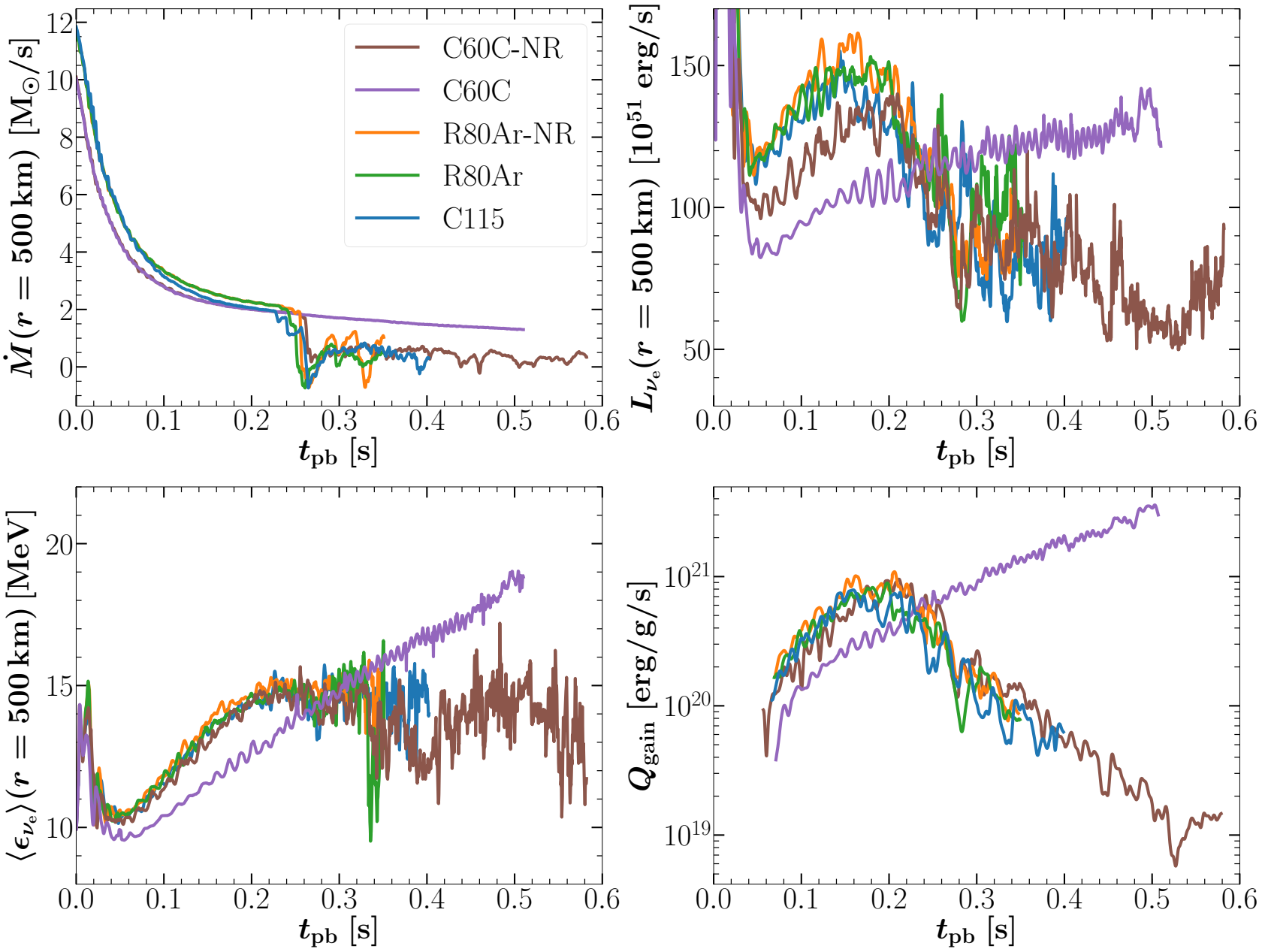
Conclusion

- Studied CCSN simulation of VMSs.
- High neutrino heating leads to shock revival (aided by hydrodynamical instabilities) for all models except rapidly rotating C60C model.
- We evolved beyond BH formation.
- We observe continuation of shock expansion after BH formation, however, only for C60C-NR model shock reaches stellar surface.
- We predict ν properties after BH formation.

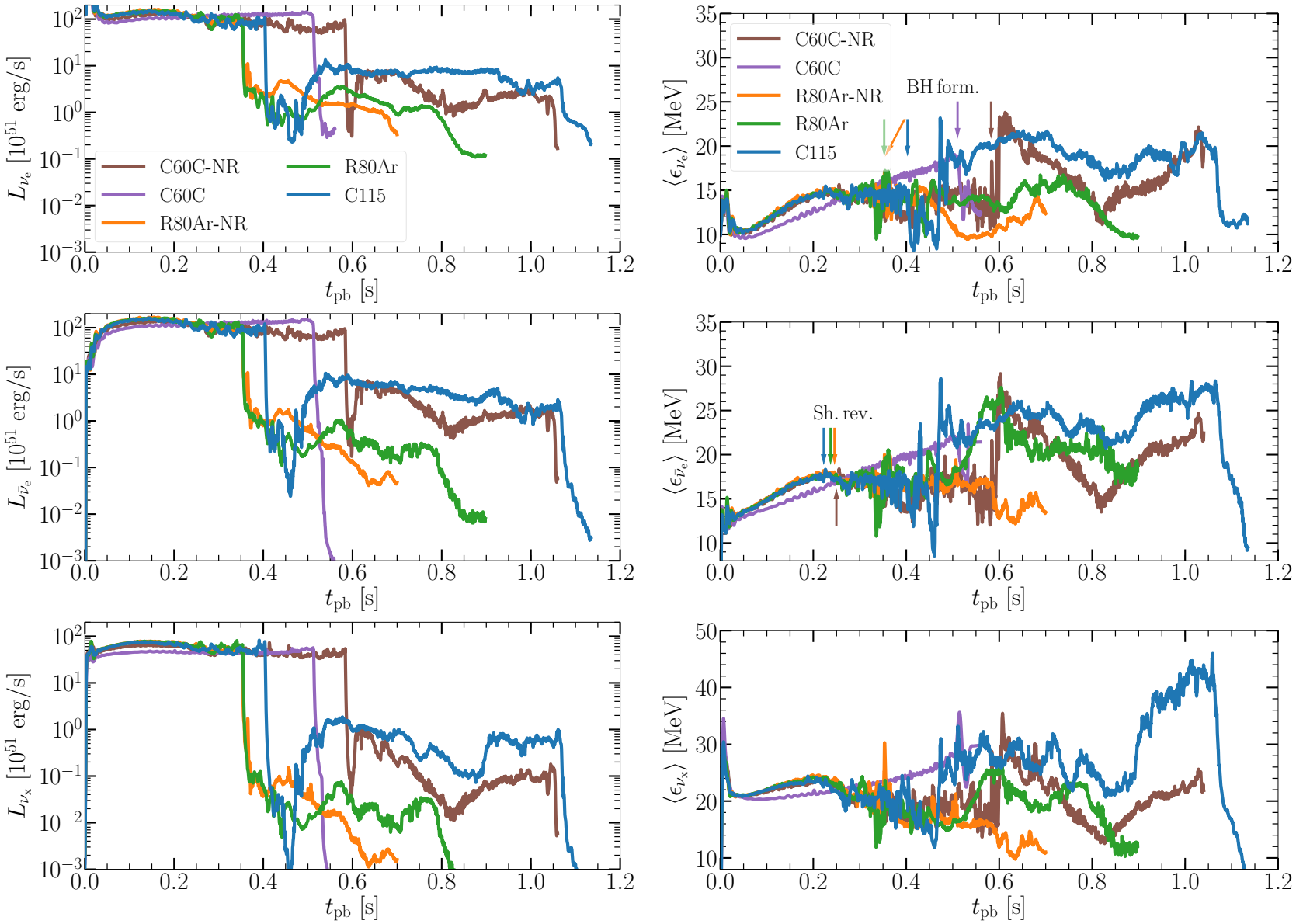
Drawbacks+Improvements

- 2D simulations (inverse cascade turbulence, toroidal geometry).
- In 3D, additional hydrodynamics instabilities (spiral SASI, triaxial spiral waves) may aid shock revival.
- Magnetic fields might play a non-negligible role in the rapidly rotating model.

VMS Results-Before BH formation



VMS Results-After BH formation-Neutrinos



Explosion or Shock expansion

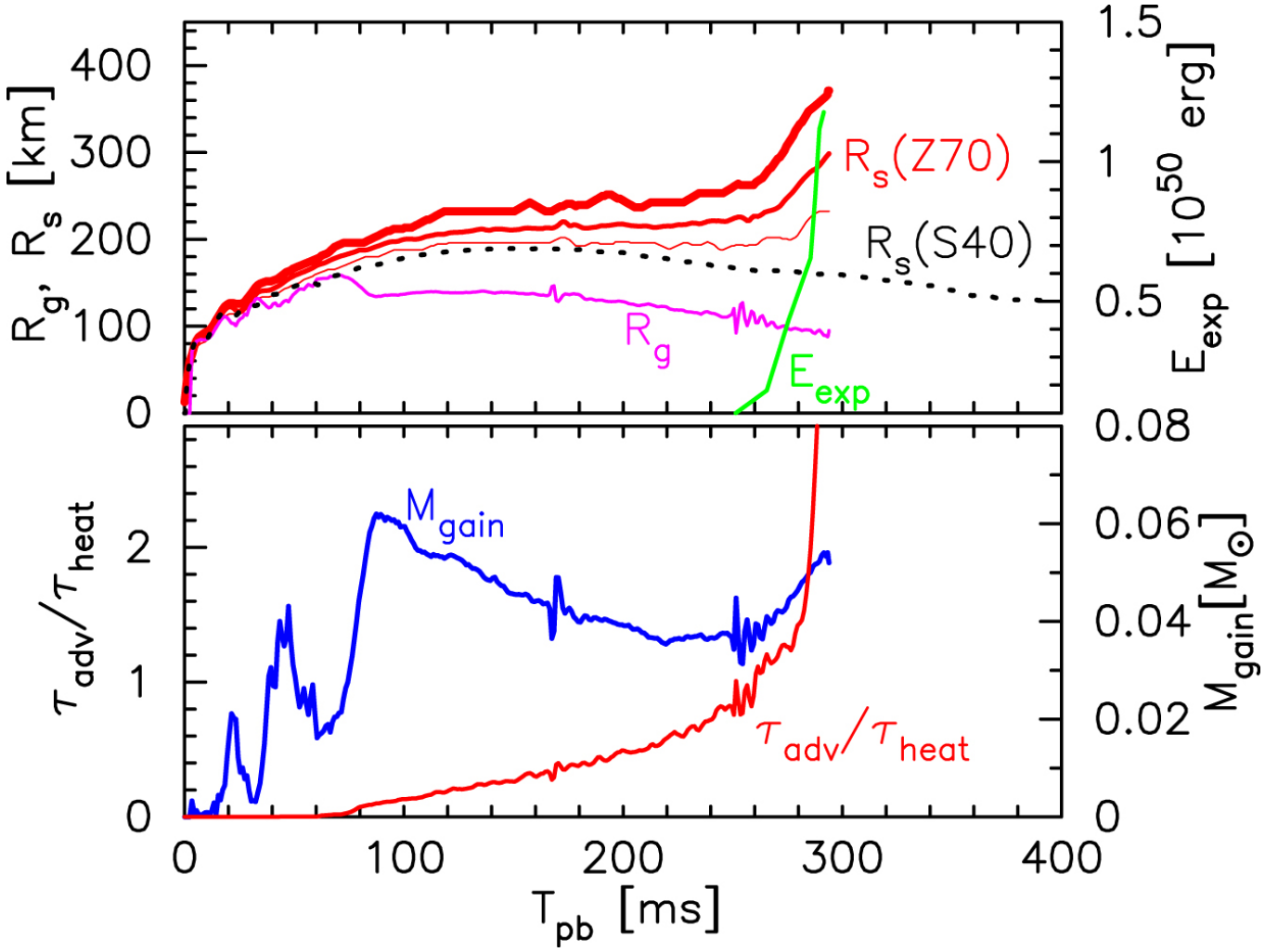
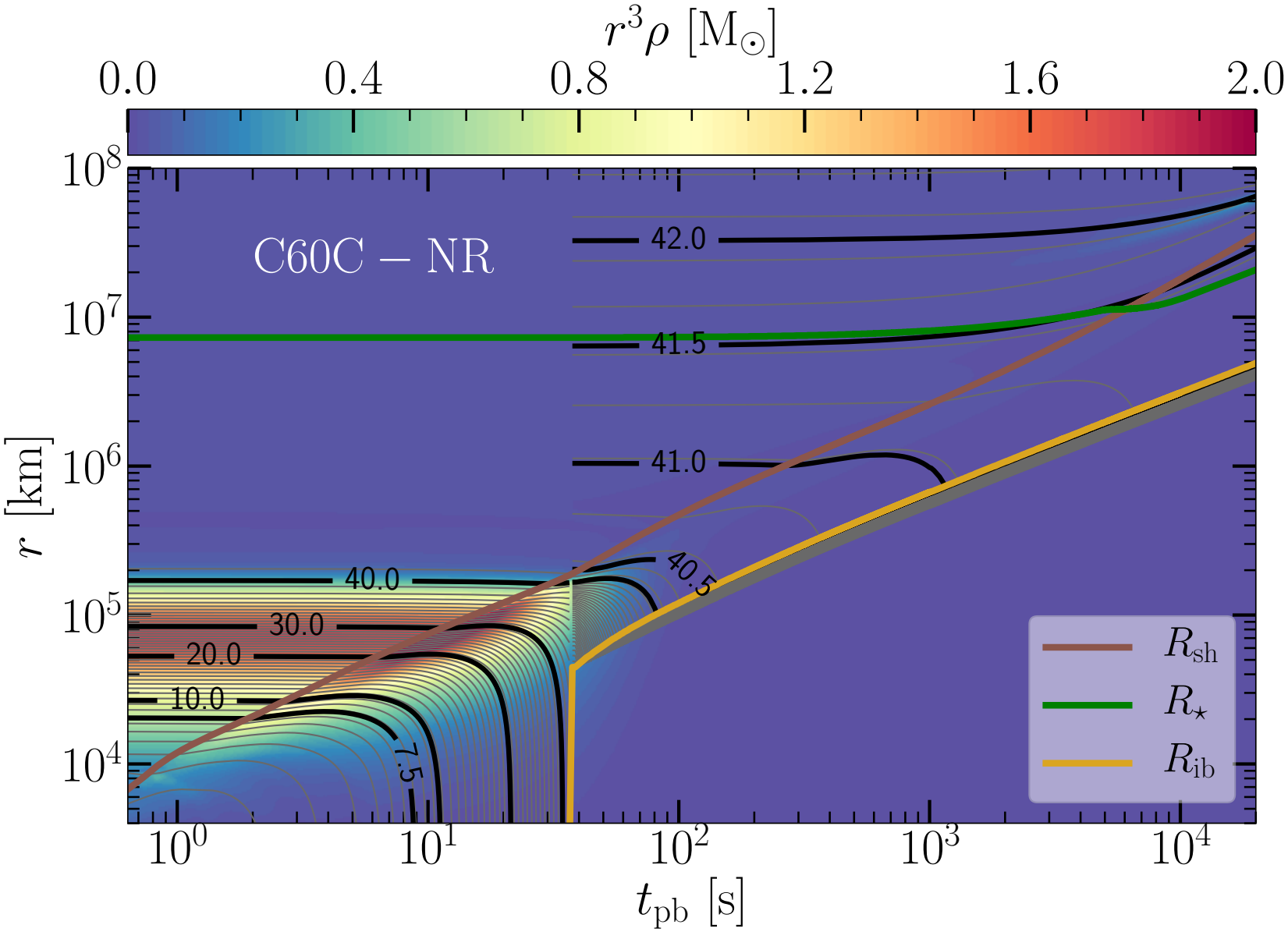
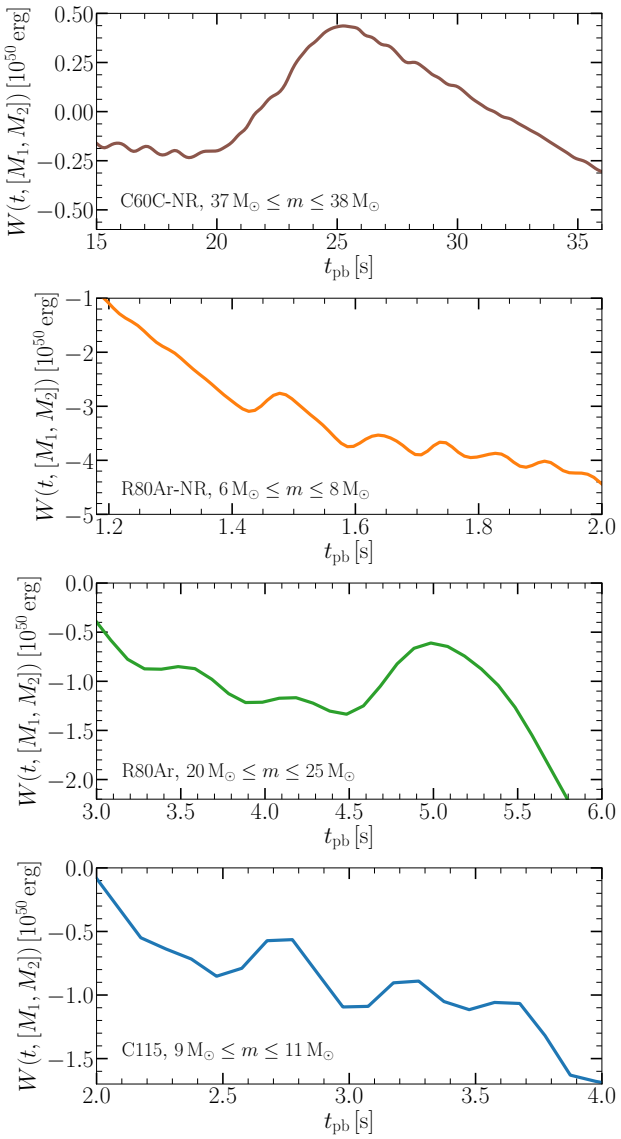
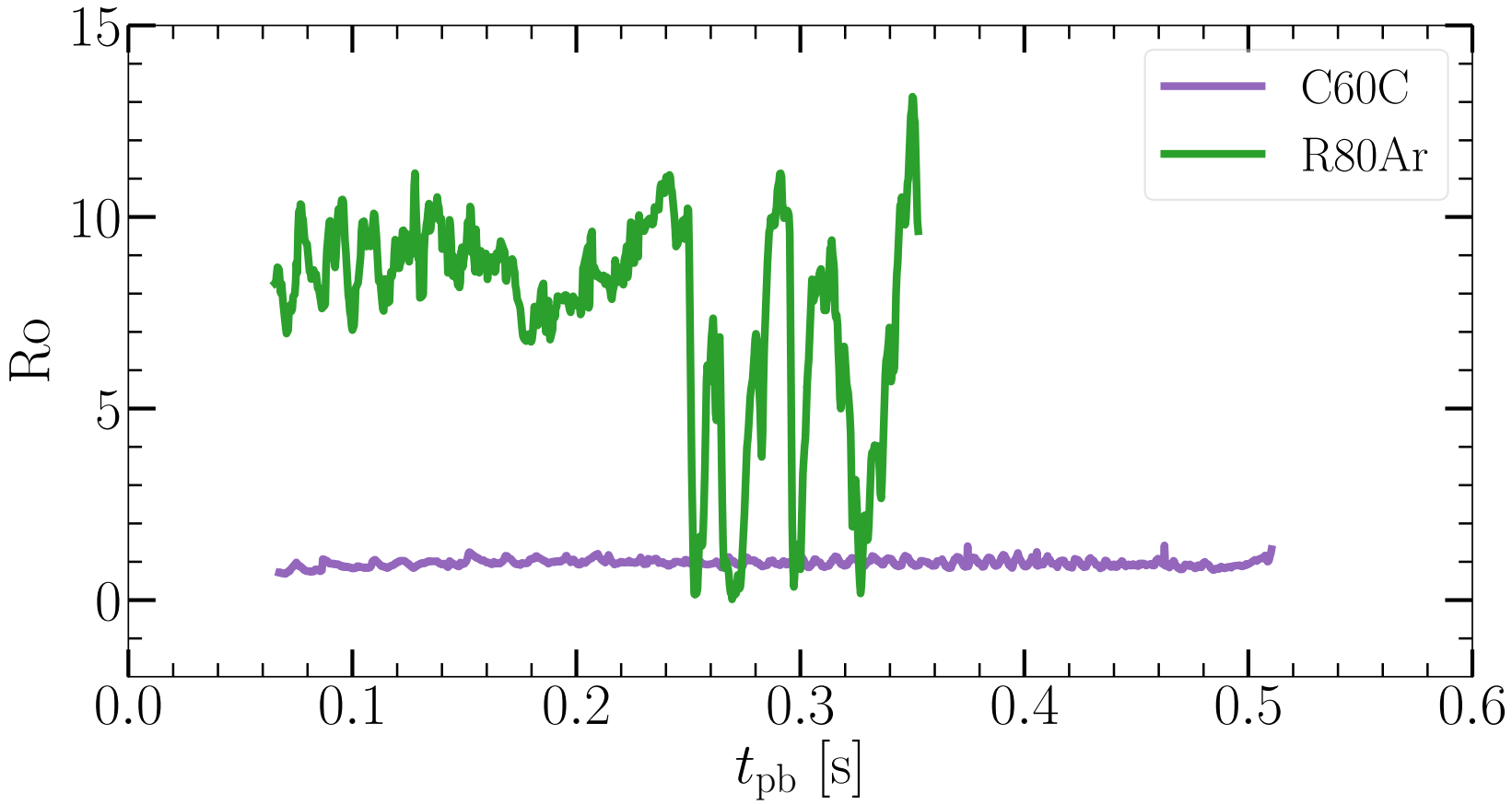


Figure 3: Explosion claim of very massive star (Kuroda et al. 2018). Also Pan et al. 2018, Chan et al. 2018, Summa et al. 2018, Ott et al. 2018, Chan & Müller, Pan et al. 2021, and Powell et al. 2021.

VMS Results (Longterm)-Mass shell plot



VMS Results-Sonic Pulses



VMS Results-Rossby Number