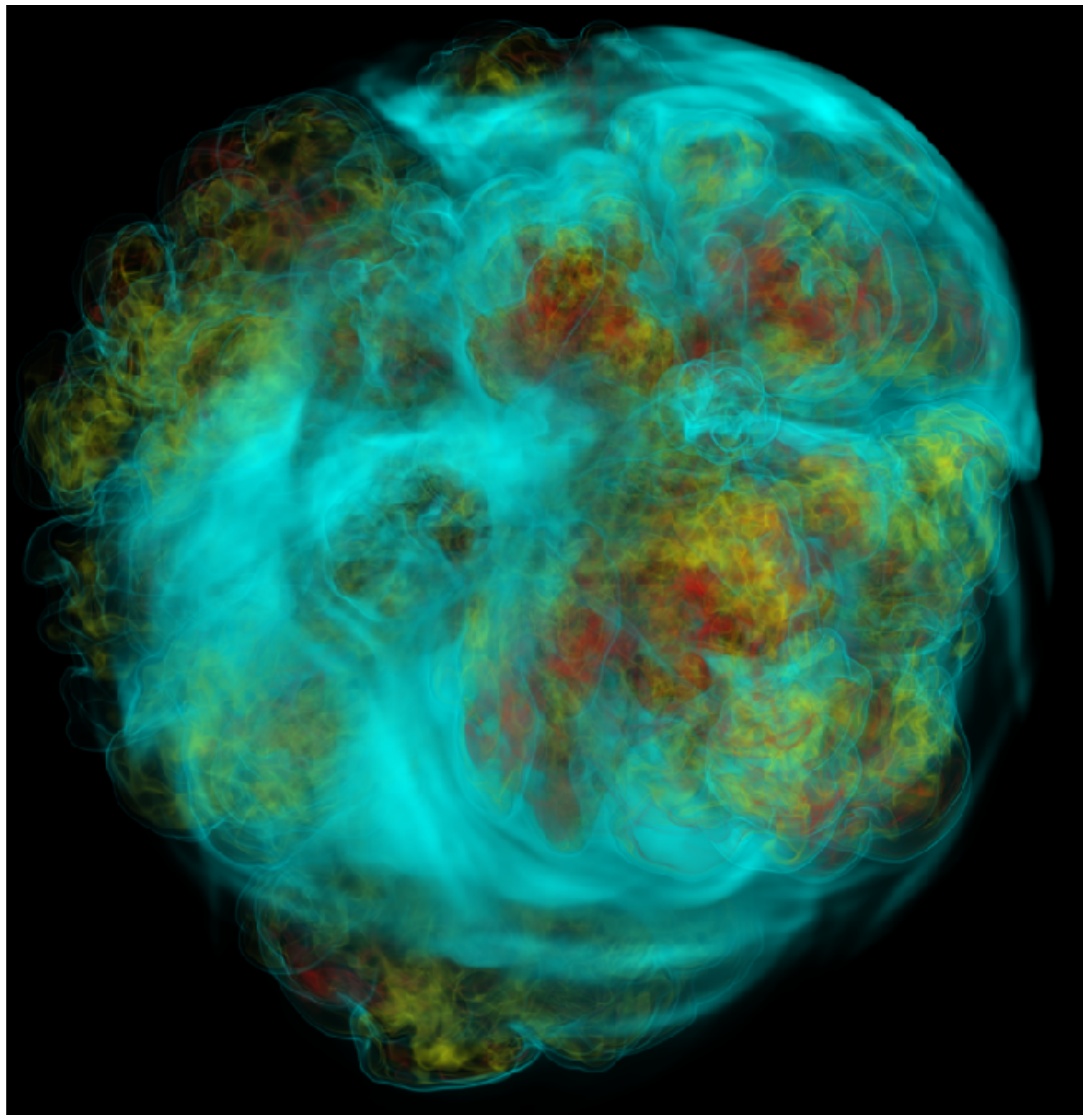
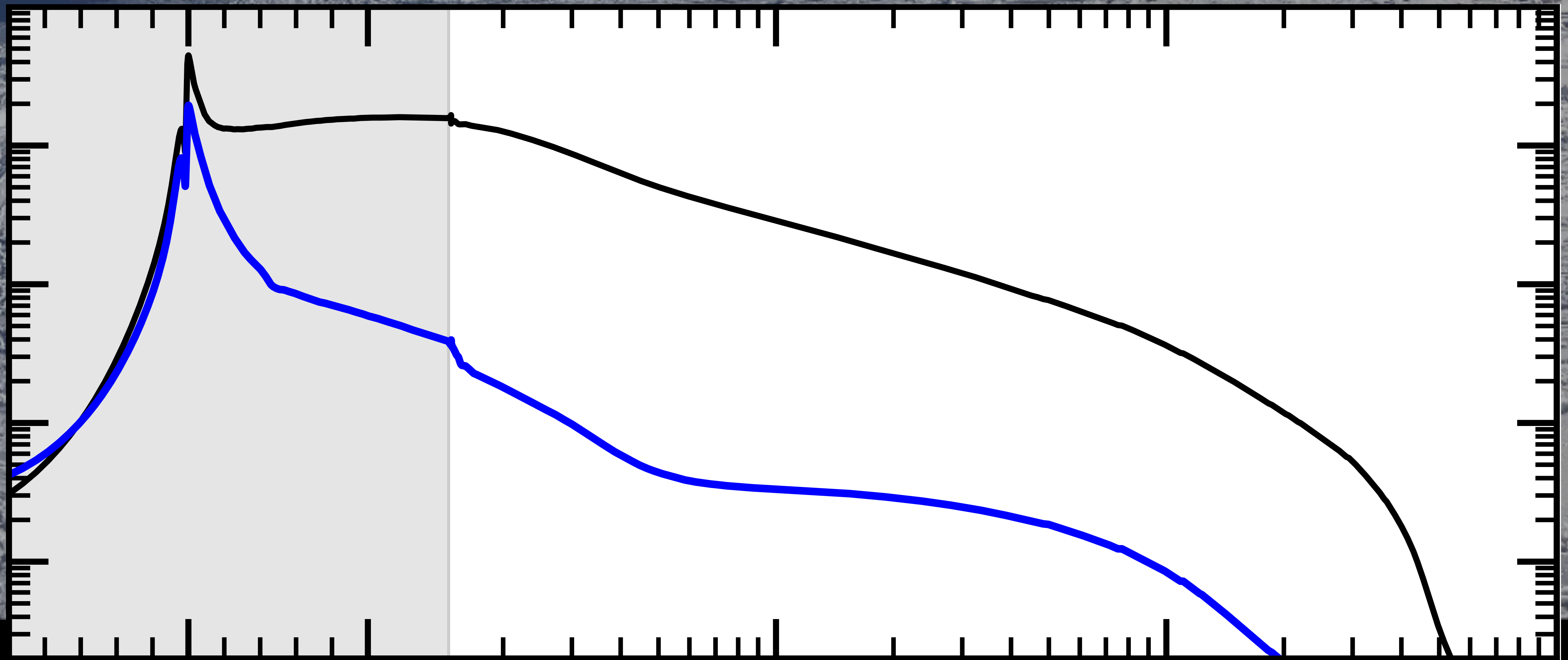


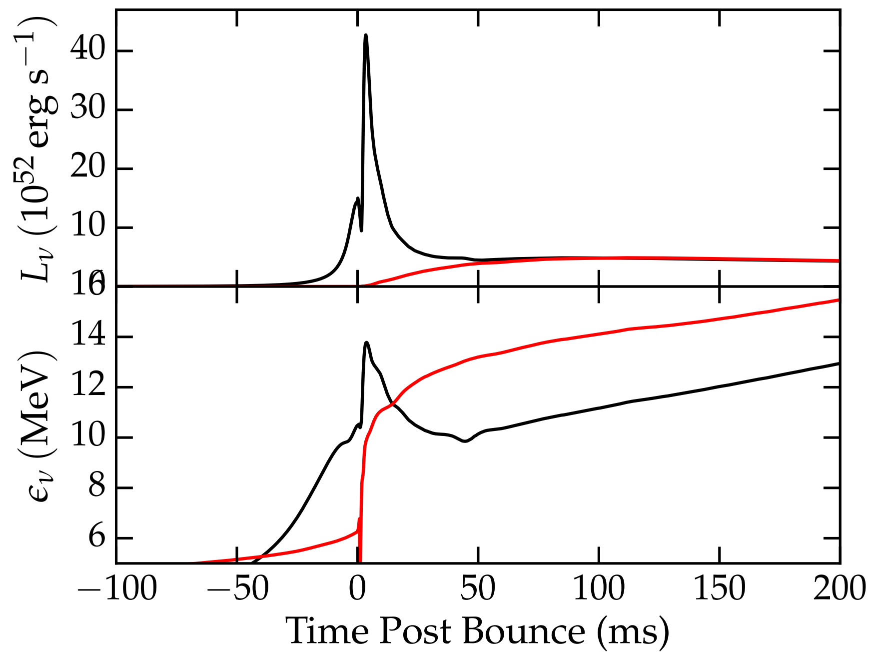
The impact of the nuclear EOS on neutrino emission from proto-neutron stars



Luke Roberts
Michigan State University

Overview

- Progenitor dependence of 3D models of CCSNe
- EOS sensitivity of CCSN explosion mechanism
- Some EOS sensitivities of long term CCSN neutrino emission



Core Collapse

- Stars with M >~ 9 M_{sun} burn their core to Fe

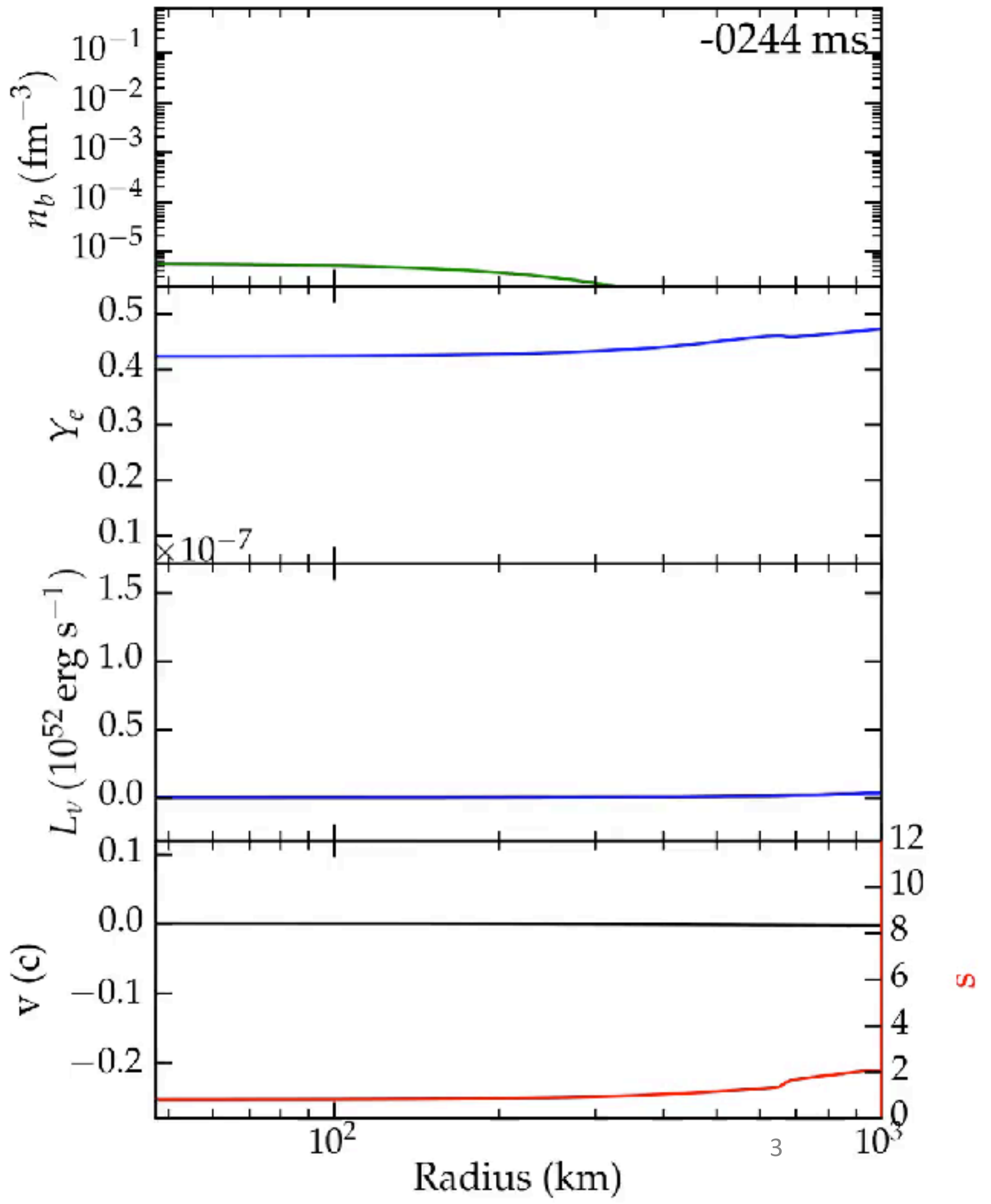
- Core exceeds a Chandrasekhar mass supersonic collapse outside of homologous core → bounce shock after ~2 x saturation density

- Gravitational binding energy of compact remnant:

$$\frac{GM_{NS}^2}{R_{NS}} \sim 3\times10^{53}\,erg$$

- Binding energy of stellar envelope:

$$\sim 10^{51}\,erg$$



Simulating the Neutrino Mechanism

Hydrodynamics

+

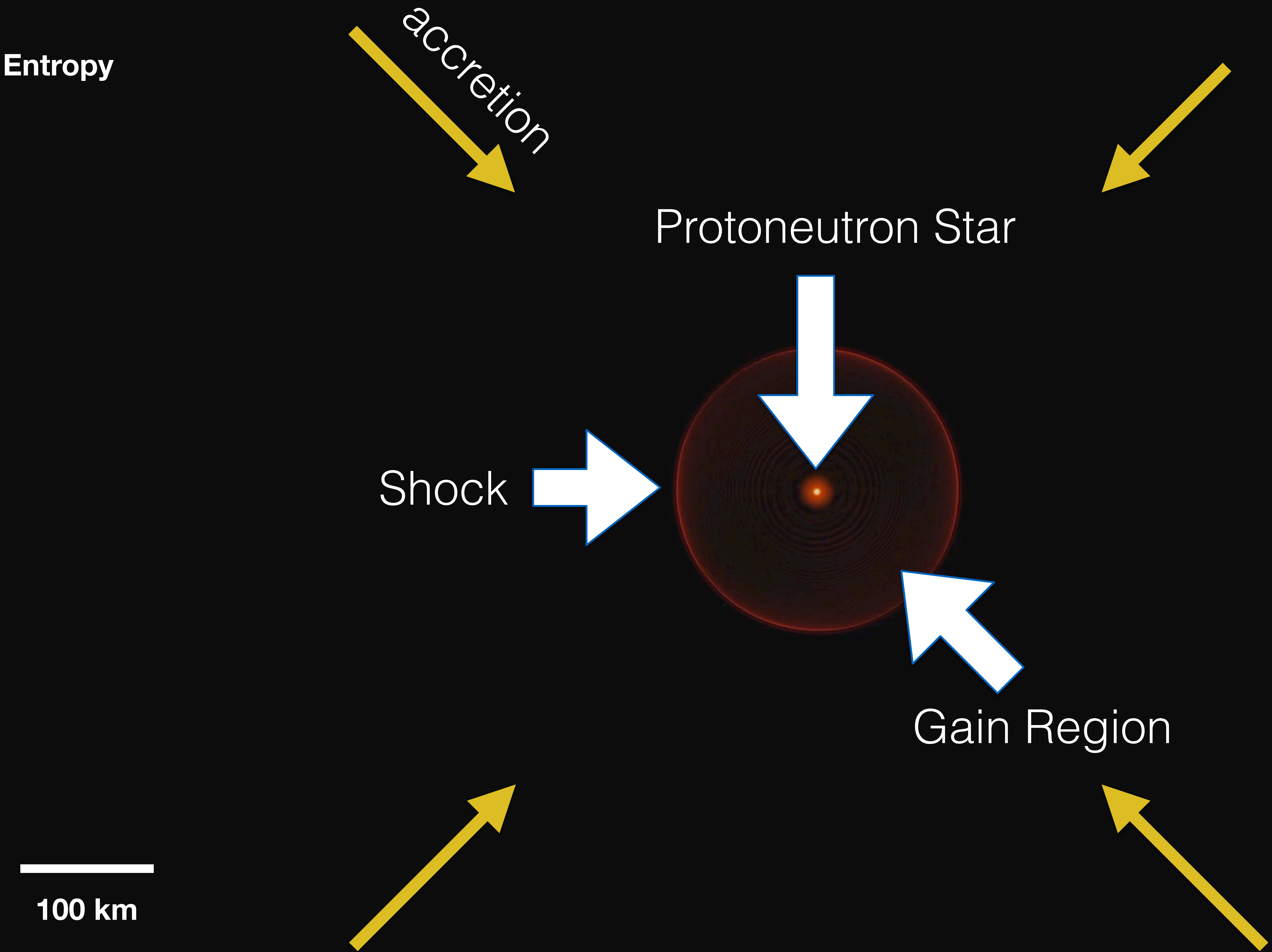
General Relativity

+

Neutrino Transport

+

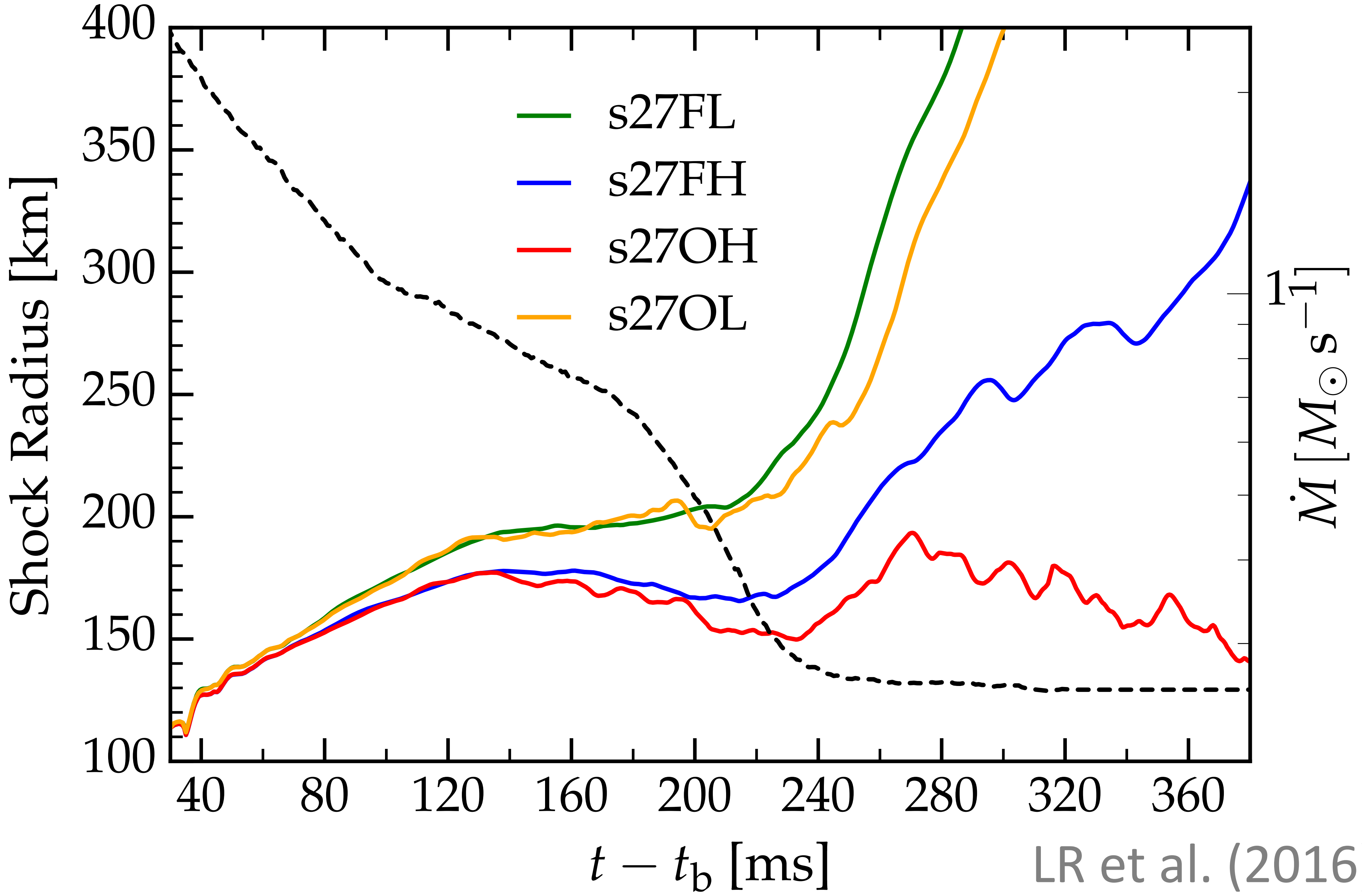
Microphysics
(EoS, ν-opacities)



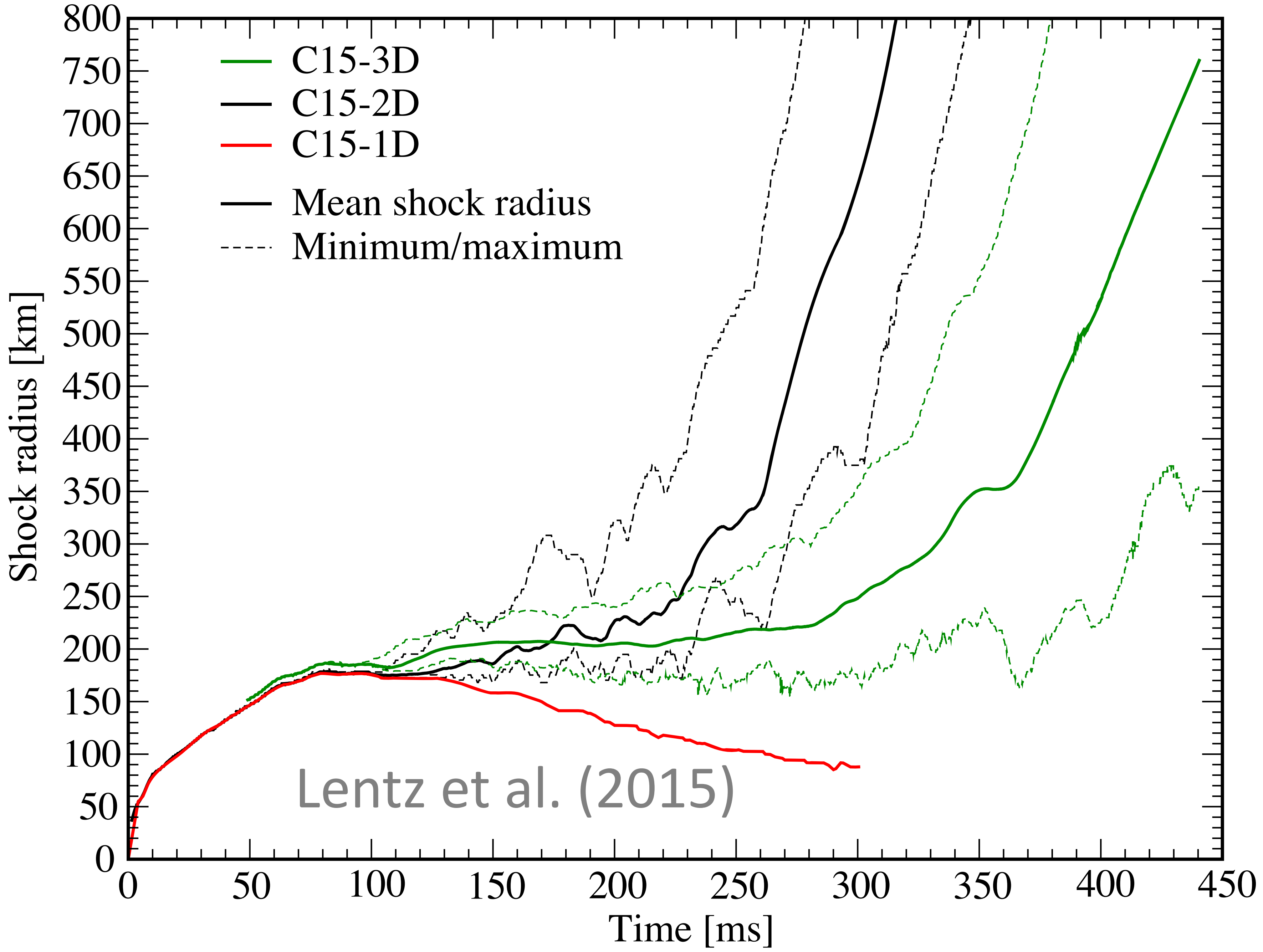
Ott, LR, et al. (2018)

3D Explosion Models

Takiwaki et al. ’12, Melson ’15, Lentz ’15, LR et al. ’16, Takiwaki et al. ’16, Ott et al. ’18, O’Connor and Couch ’18, Burrows et al. ’19



LR et al. (2016)

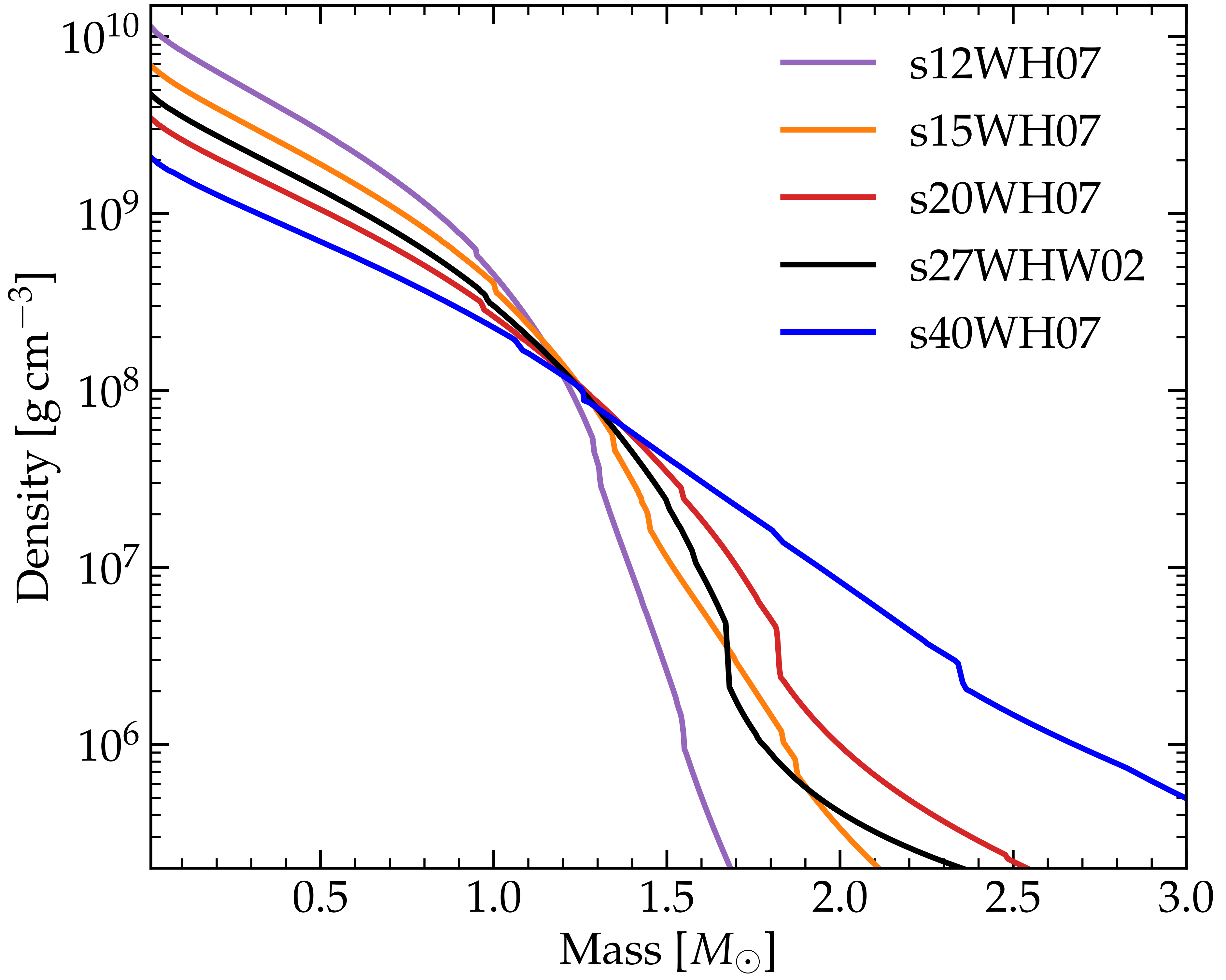


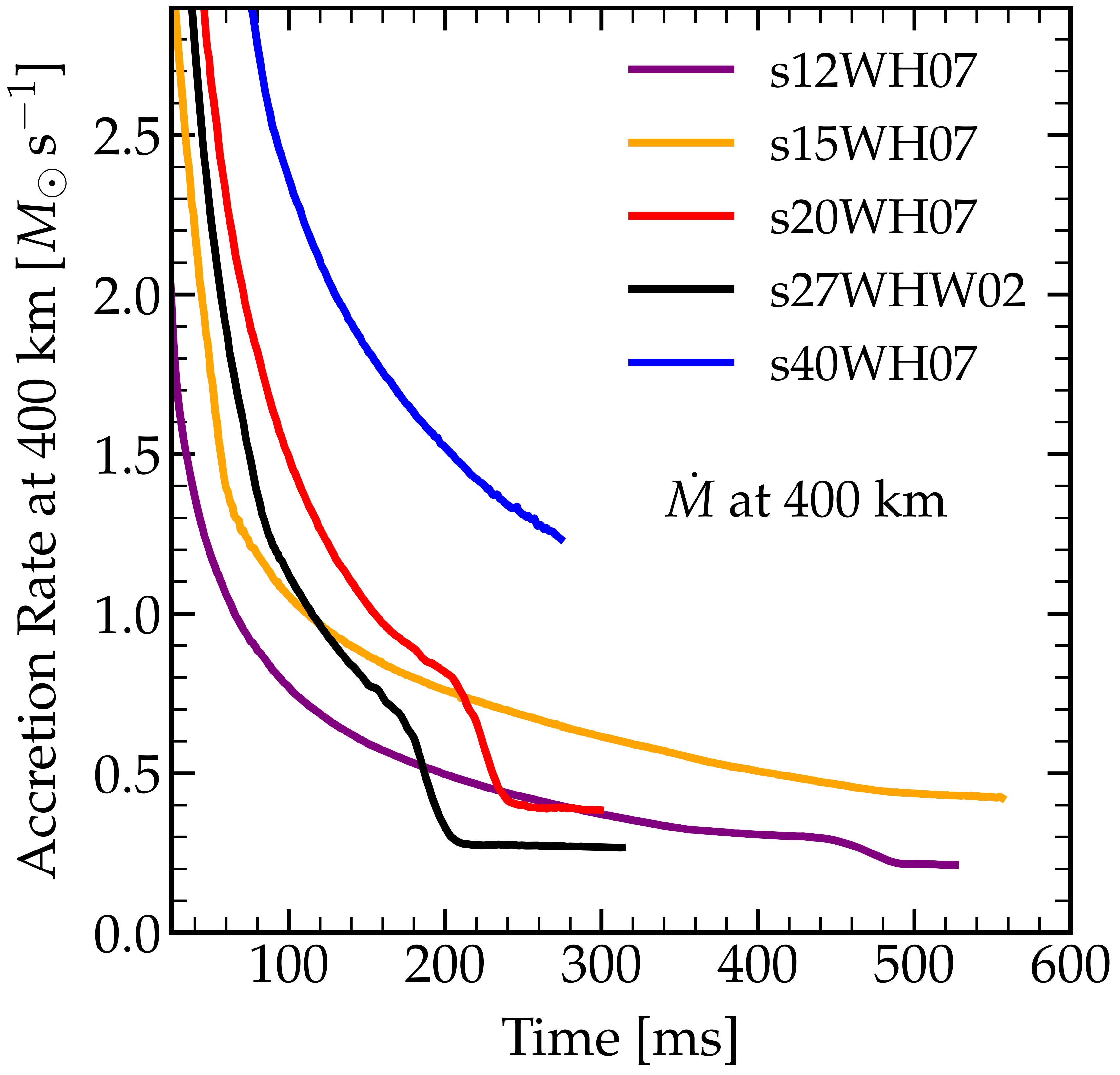
Lentz et al. (2015)

- Many groups are seeing shock runaway (although not all), but maybe not quantitative agreement
- Sensitive to input physics (e.g. Melson et al. ’15) and resolution
- Nevertheless, things look relatively positive for 3D shock runaway

Stellar Progenitor Dependence

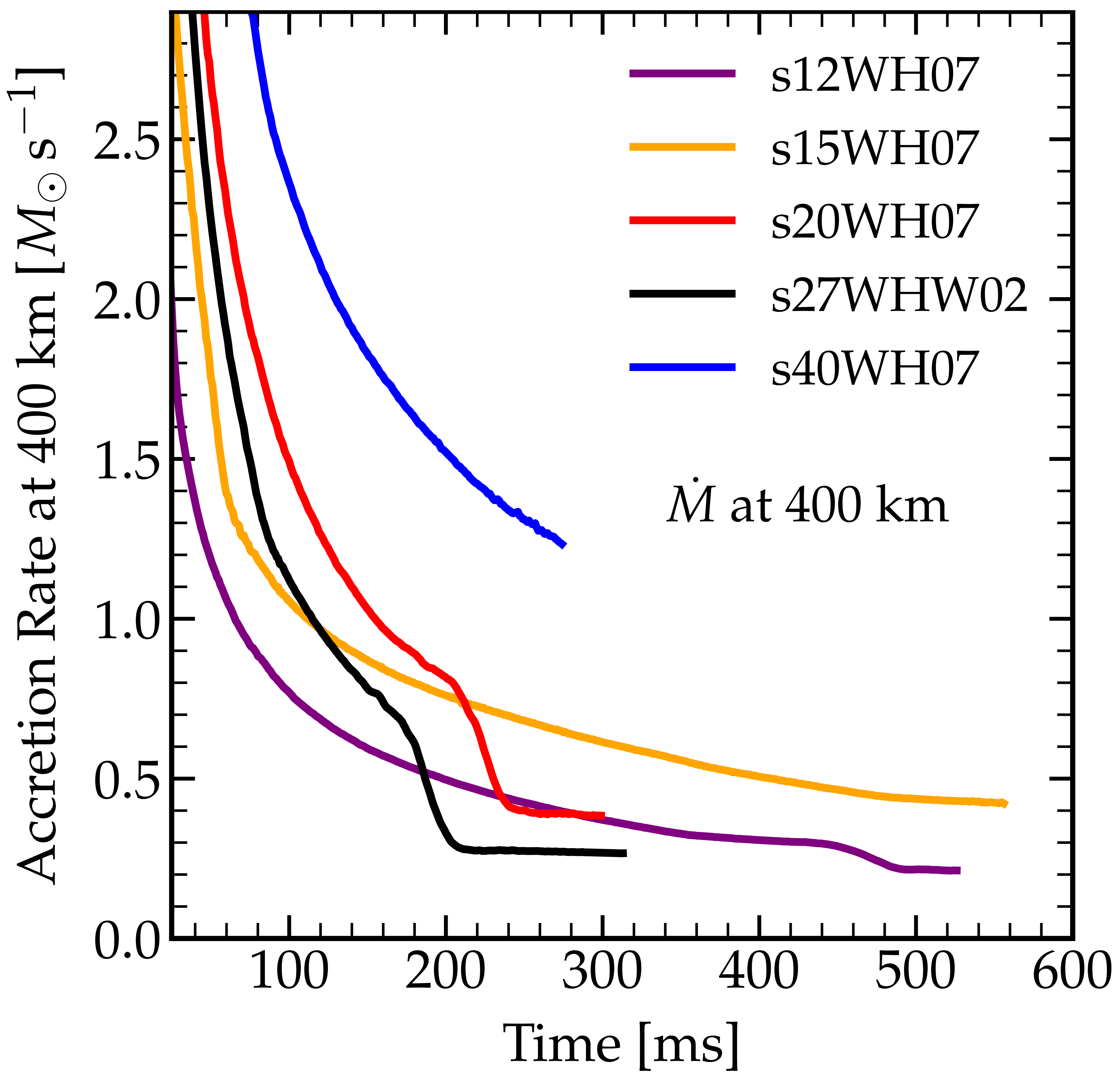
Ott, LR et al. (2018)

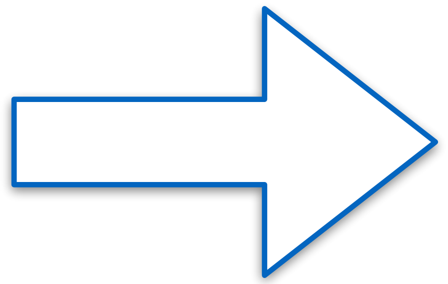


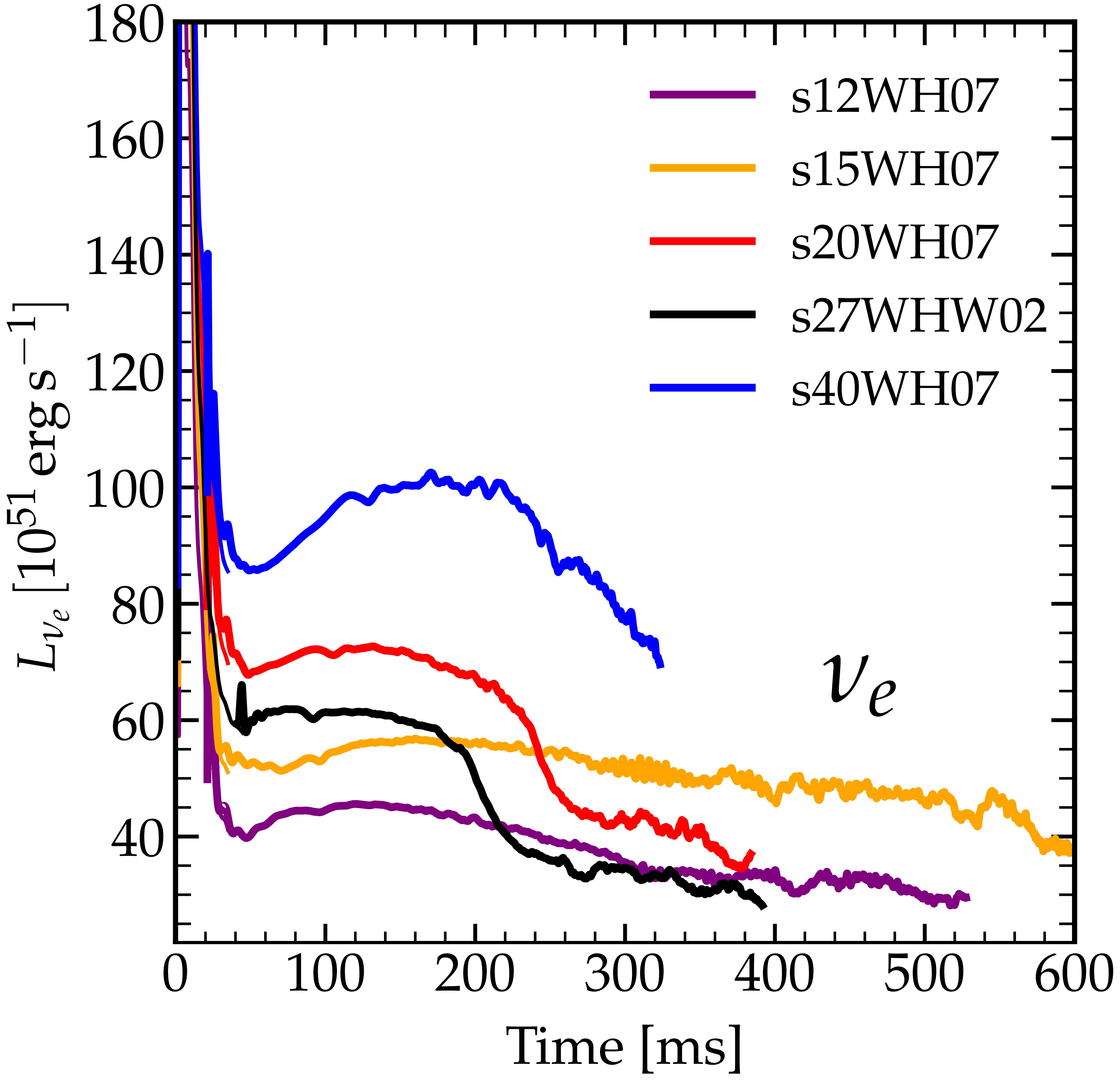


Stellar Progenitor Dependence

Ott, LR et al. (2018)







$$P_{\rm ram} = \rho v^2 \propto \dot{M} M_{\rm PNS}^{1/2} r_s^{-5/2}$$

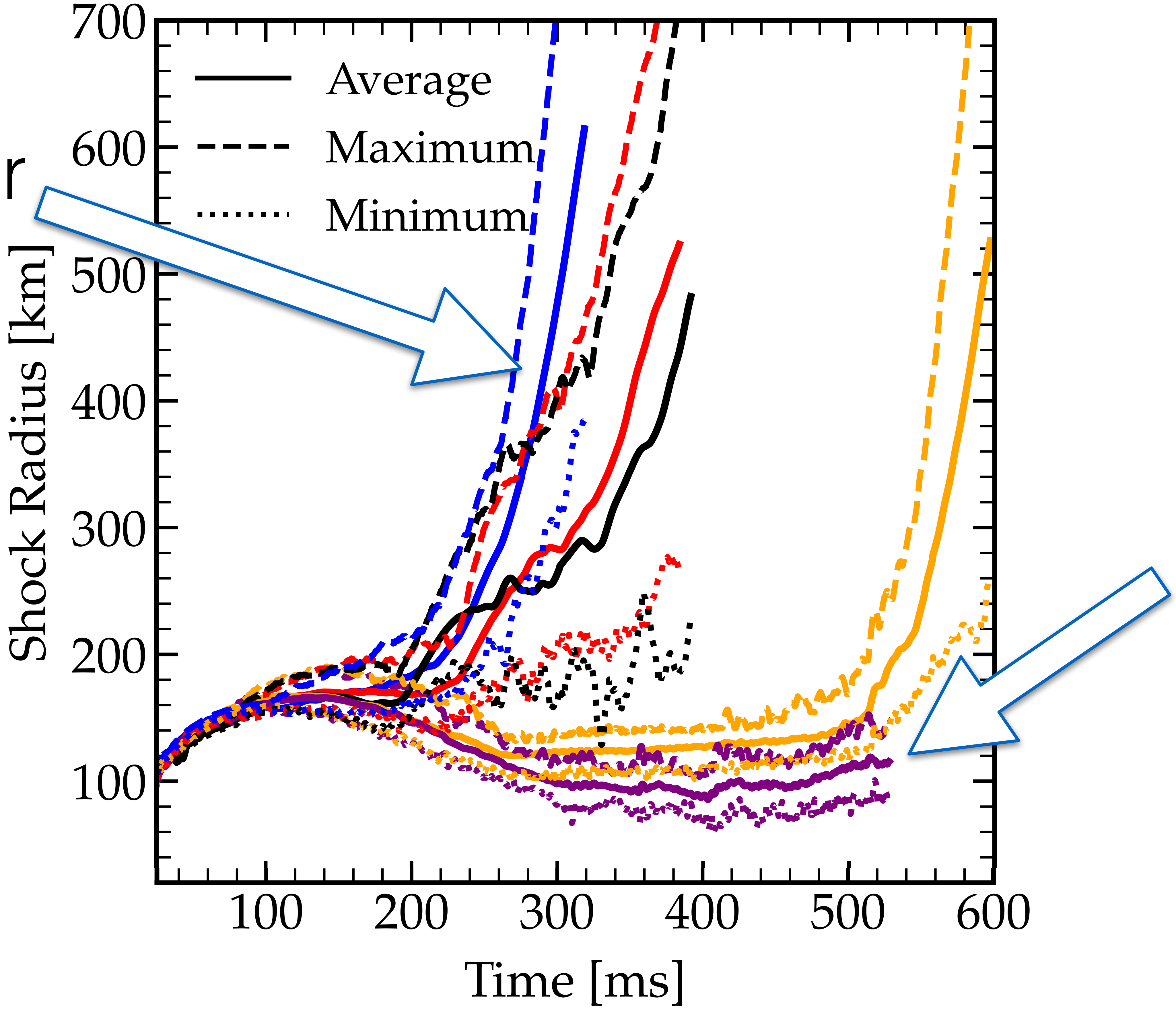
but also

$$L_{\rm acc} \propto \dot{M} M_{\rm PNS} R_{\rm PNS}^{-1}$$

Stellar Progenitor Dependence

Ott, LR et al. (2018)

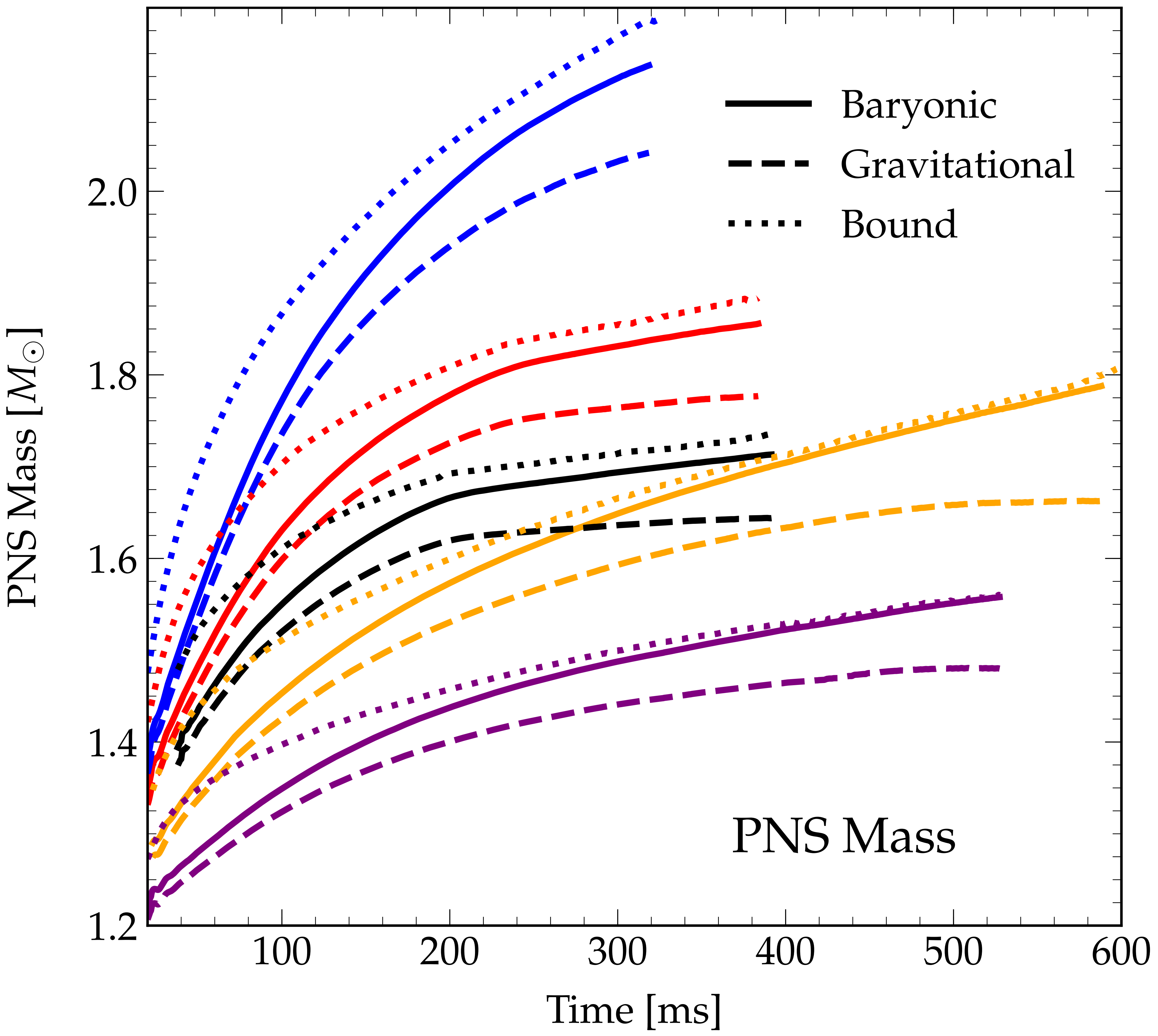
Highest mass progenitor

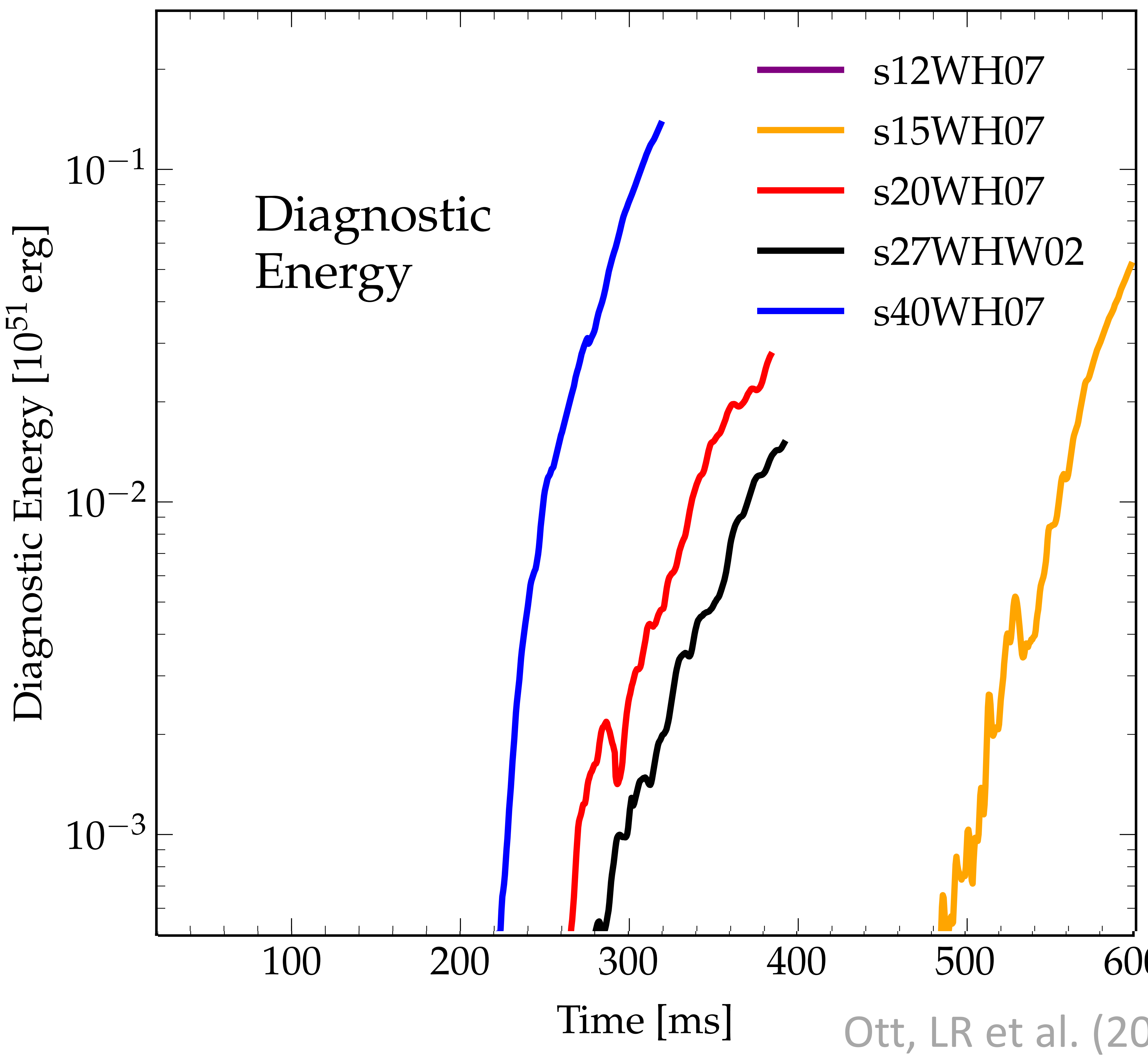


Lowest mass progenitor

$P_{\mathrm{ram}} = \rho v^2 \propto \dot{M} M_{\mathrm{PNS}}^{1/2} r_s^{-5/2}$ but also $L_{\mathrm{acc}} \propto \dot{M} M_{\mathrm{PNS}} R_{\mathrm{PNS}}^{-1}$

Final States

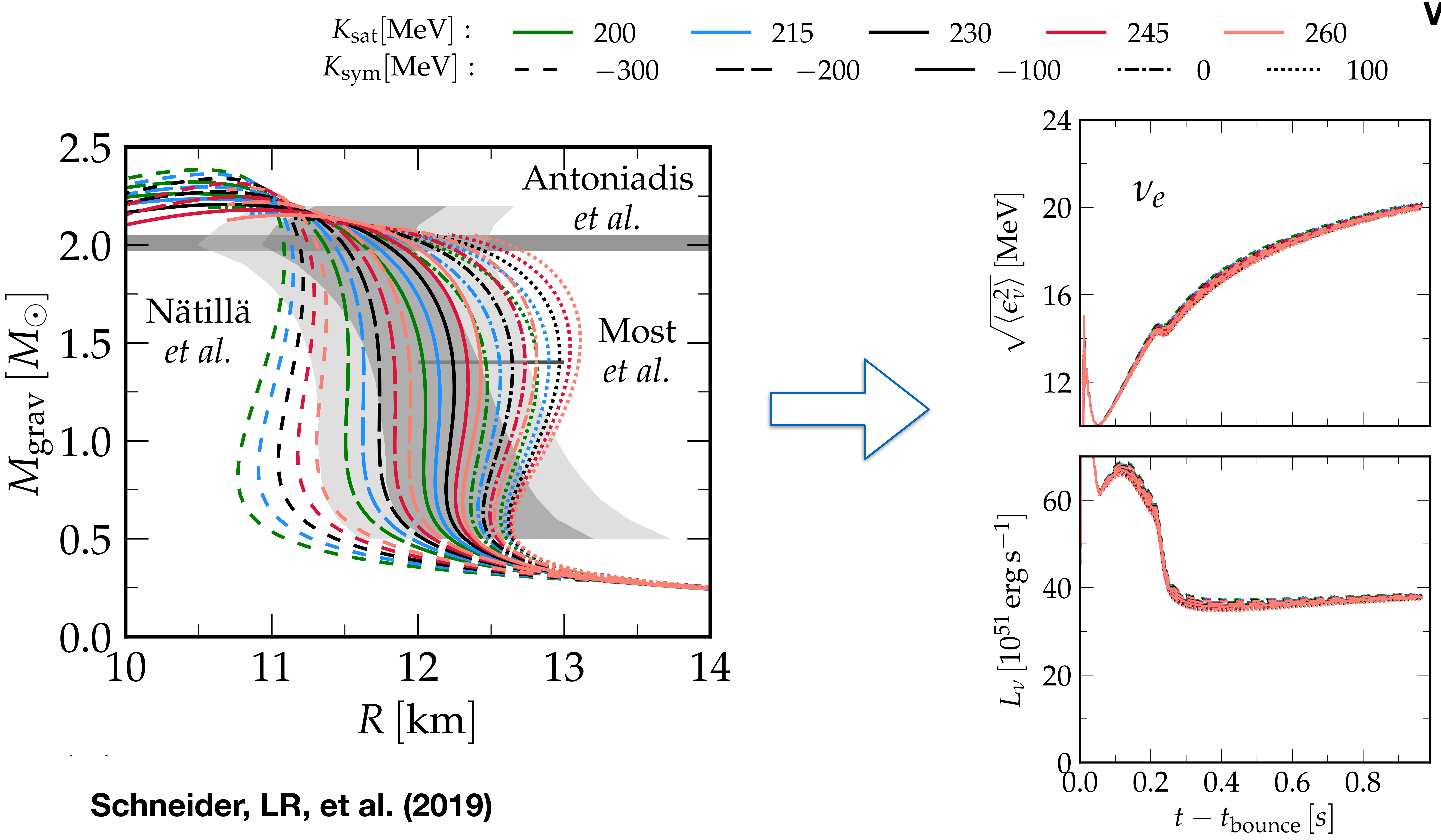




Ott, LR et al. (2018)

Equation of State Impacts

Melson et al. ’15, Bollig et al., ’17, Yassin et al. ‘19



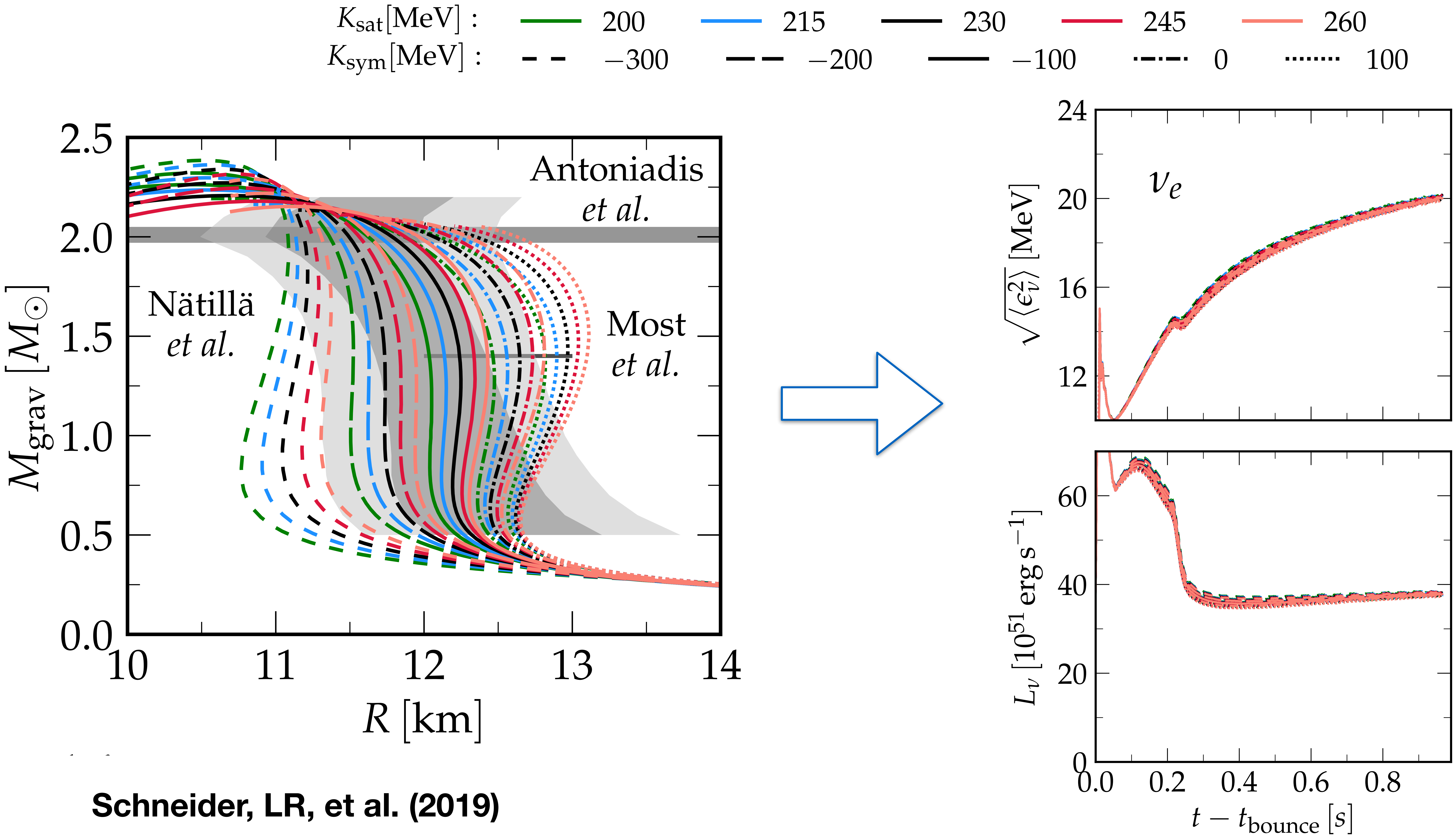
Schneider, LR, et al. (2019)

Vary within experimental constraints using Schneider ’16 EoS framework:

s_M	$m^\star$ $\Delta m^\star$
—	$n_{\rm sat}$ $\epsilon_{\rm sat}$
s_S	$\epsilon_{\rm sym}$ $L_{\rm sym}$
s_K	$K_{\rm sat}$ $K_{\rm sym}$
s_P	$P^{(4)}_{\rm SNM}$ $P^{(4)}_{\rm PNM}$

Equation of State Impacts

Melson et al. '15, Bollig et al., '17, Yassin et al. '19



Schneider, LR, et al. (2019)

Similarly small impacts for:

ϵ_{sym}

L_{sym}

K_{sat}

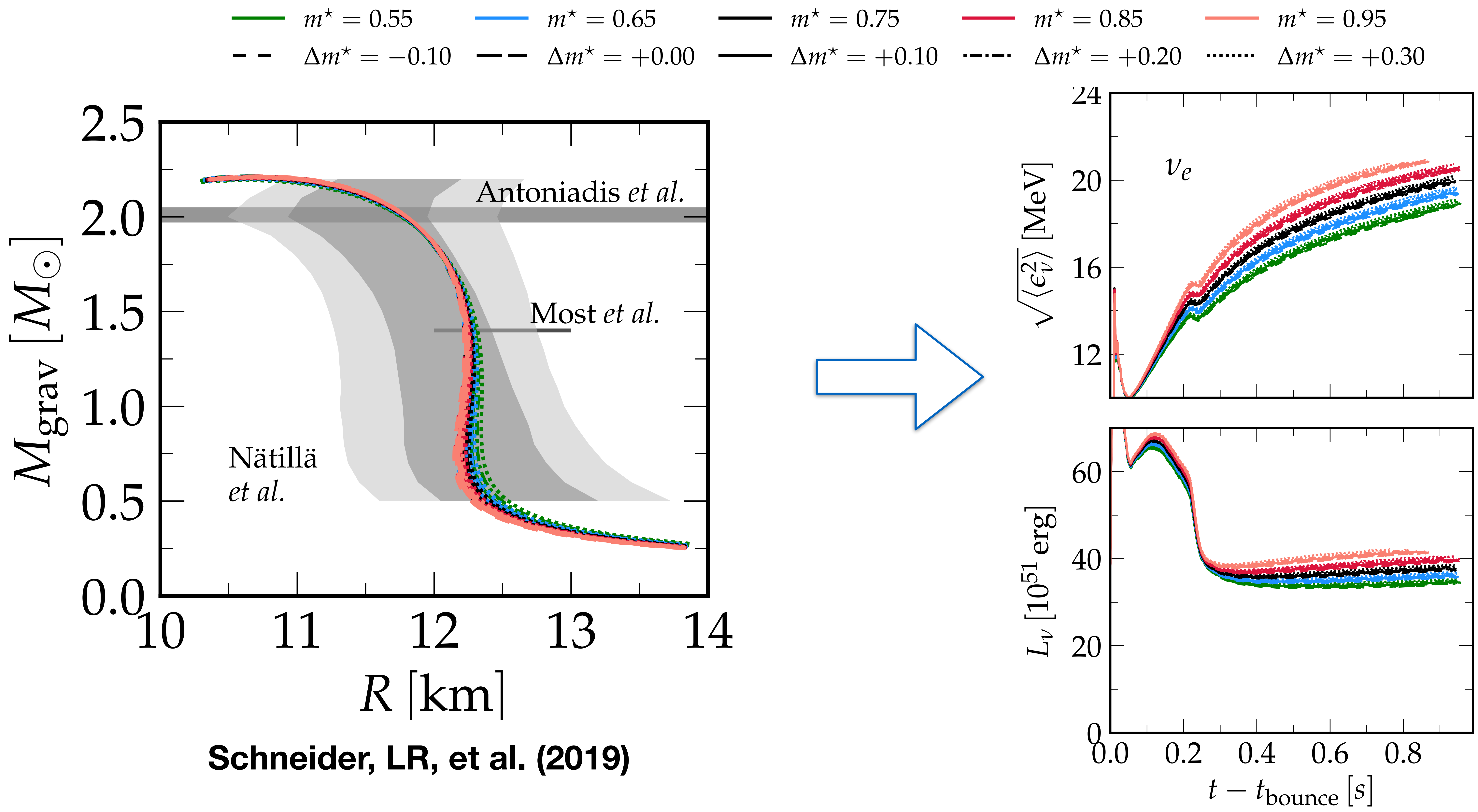
K_{sym}

$P^{(4)}_{\mathrm{SNM}}$

$P^{(4)}_{\mathrm{PNM}}$

Equation of State Impacts

Melson et al. ’15, Bollig et al., ’17, Yassin et al. ‘19



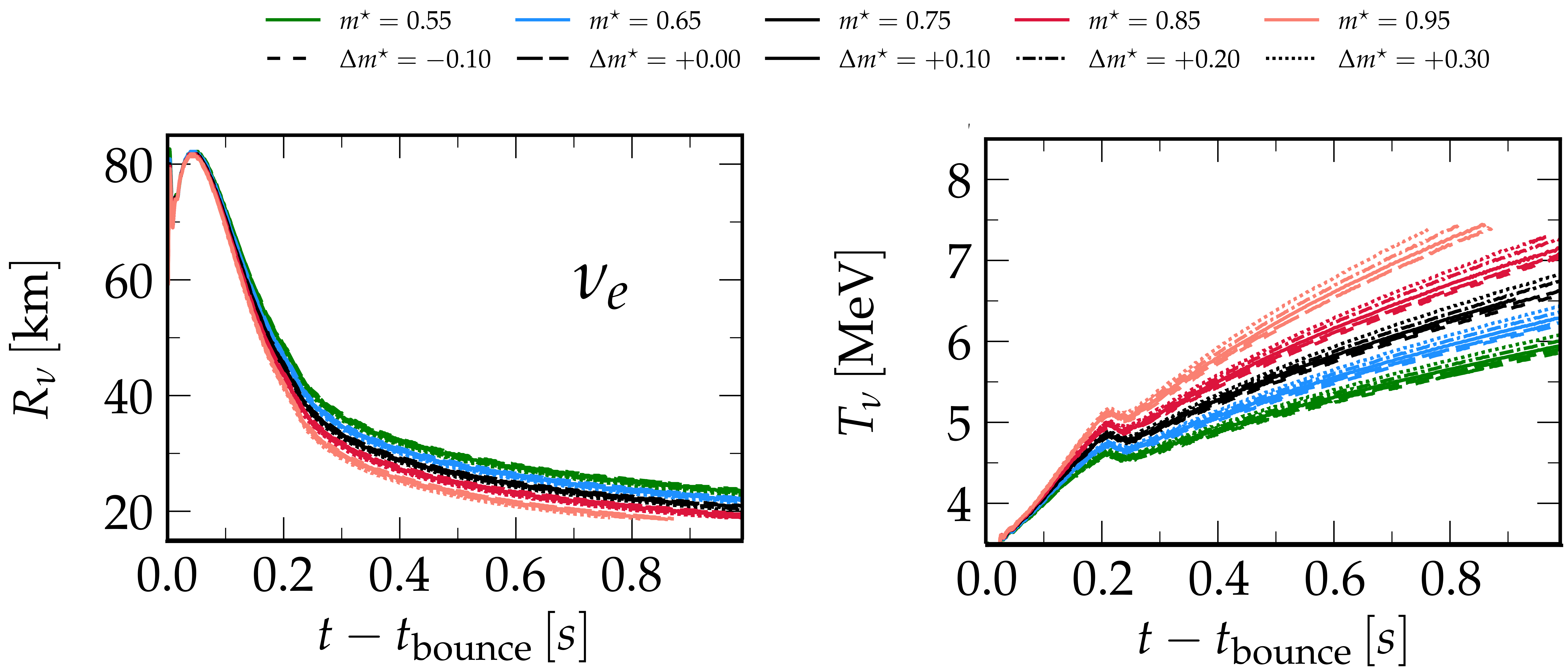
Schneider, LR, et al. (2019)

Vary the effective mass:

s_M	$m^\star$ $\Delta m^\star$
—	n_{sat} ϵ_{sat}
s_S	ϵ_{sym} L_{sym}
s_K	K_{sat} K_{sym}
s_P	$P^{(4)}_{\mathrm{SNM}}$ $P^{(4)}_{\mathrm{PNM}}$

Equation of State Impacts

Melson et al. ’15, Bollig et al., ’17, Yassin et al. ‘19

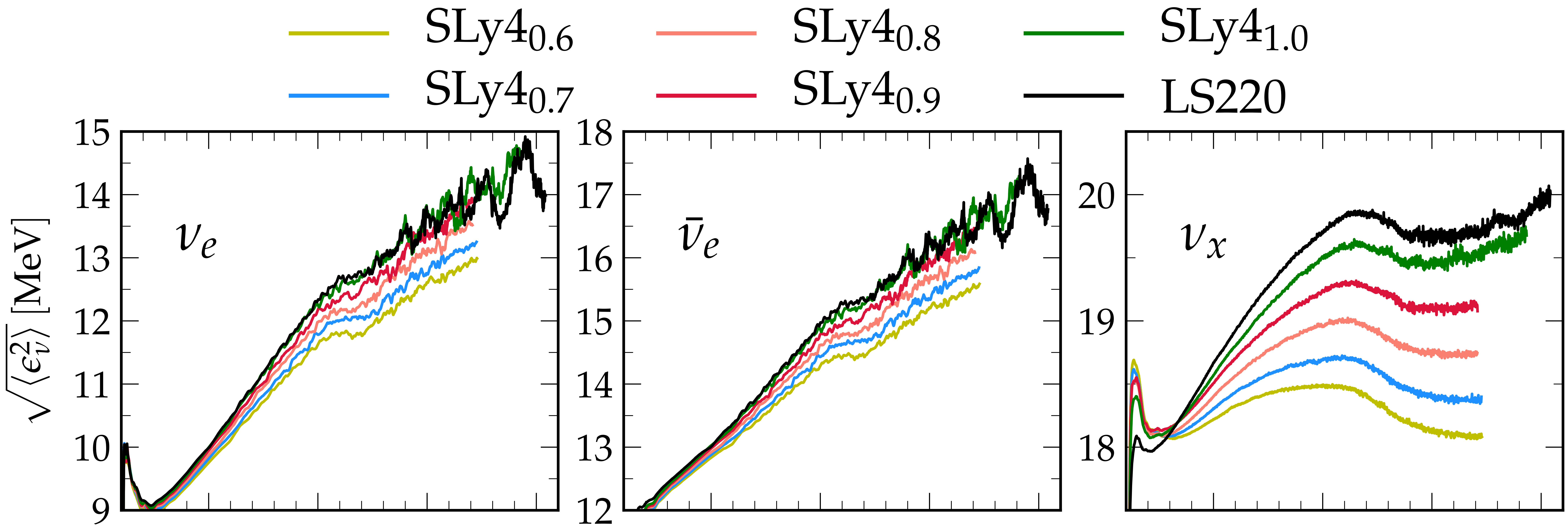


Impact on neutrino sphere properties

Schneider, LR, et al. (2019)

$$P_{th,nuc} \propto \frac{1}{m^*}$$

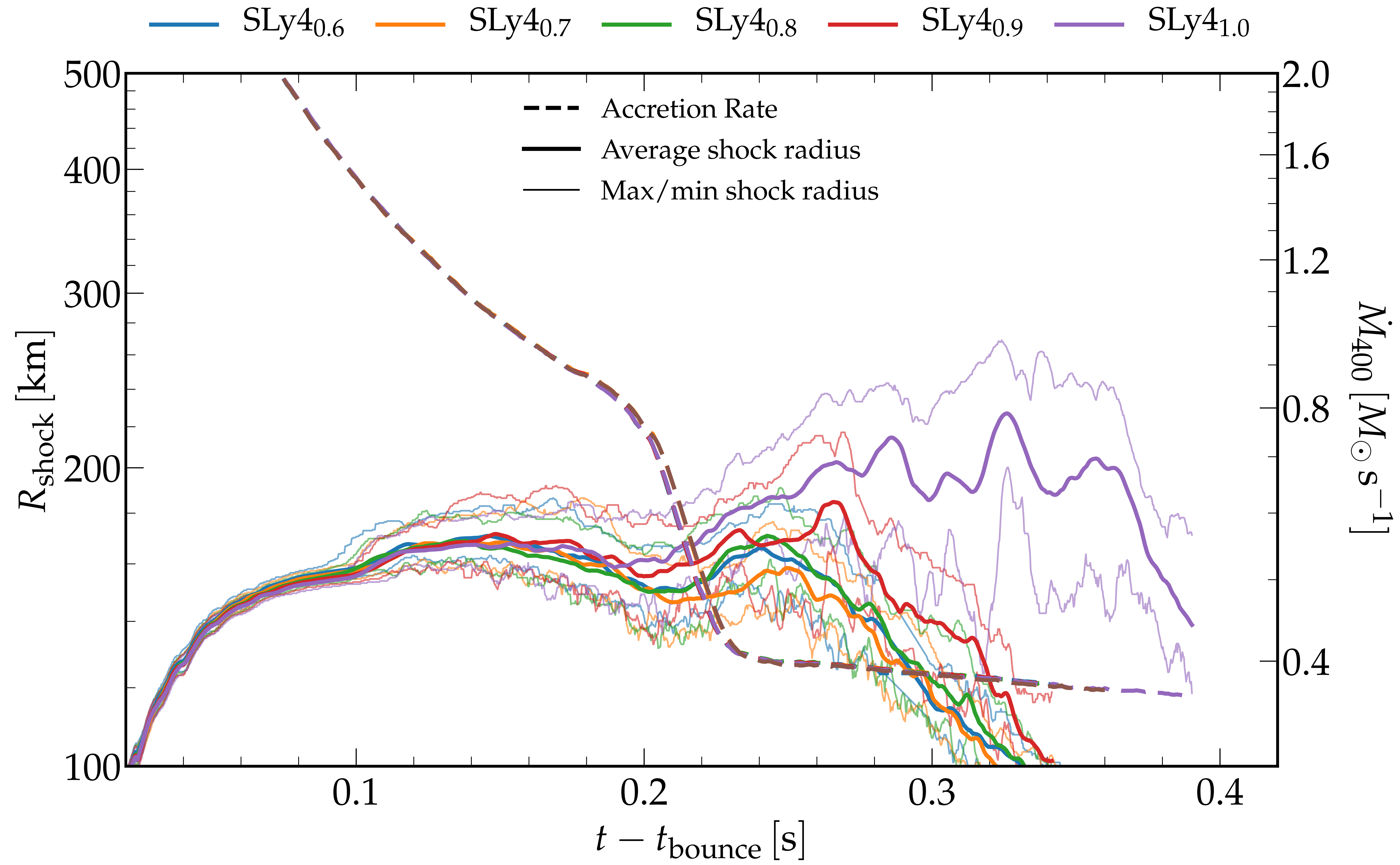
Equation of State Impacts



Schneider, LR, et al. (2019)

3D Octant simulations see similar impact of effective mass to spherically symmetric simulations

Equation of State Impacts



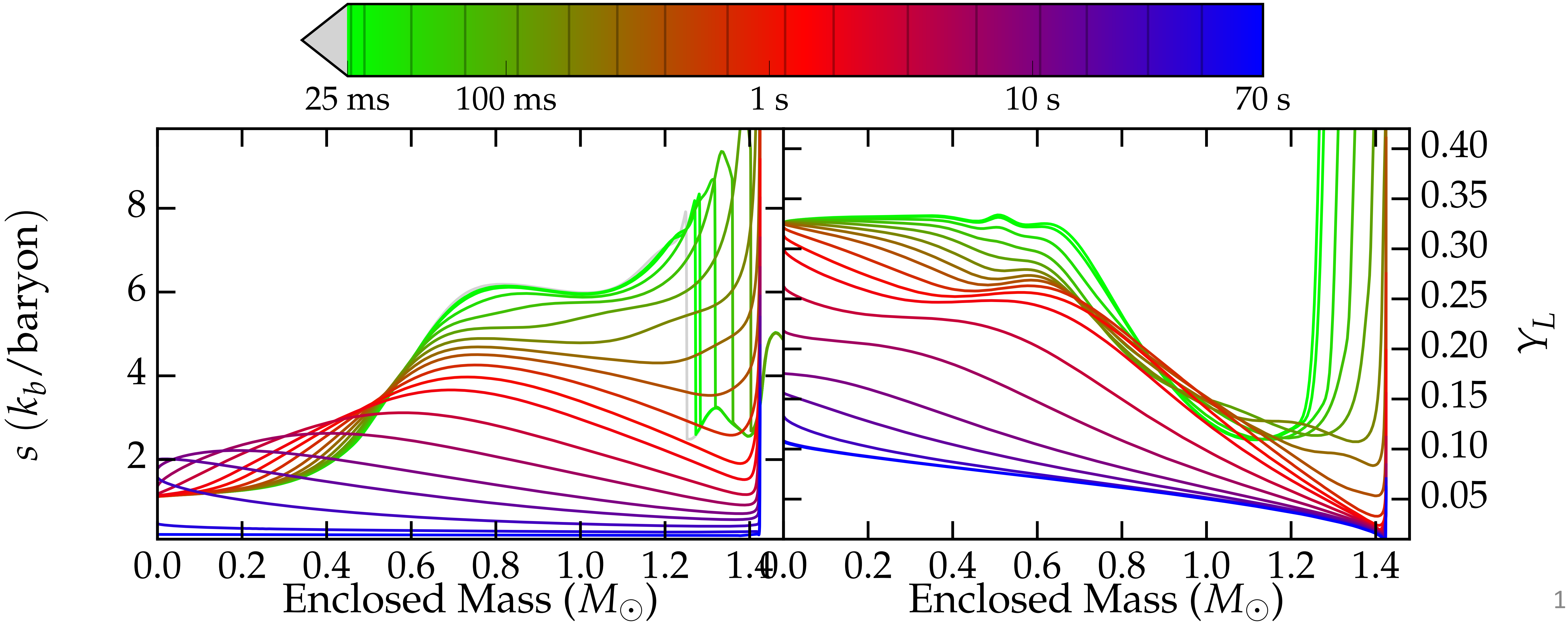
Schneider, LR, et al. (2019)

3D Octant simulations

Late Time Neutrino Emission

See e.g. Burrows & Lattimer '86, Pons et al. '99, Huedepohl et al. '10, Fischer et al. '10, LR '12, Nakazato '13

- Driven by cooling and deleptonization of the remnant
- Coupled neutron star structure and neutrino transport
- Sensitive to dense matter equation of state, neutrino opacities



Late Time Neutrino Emission

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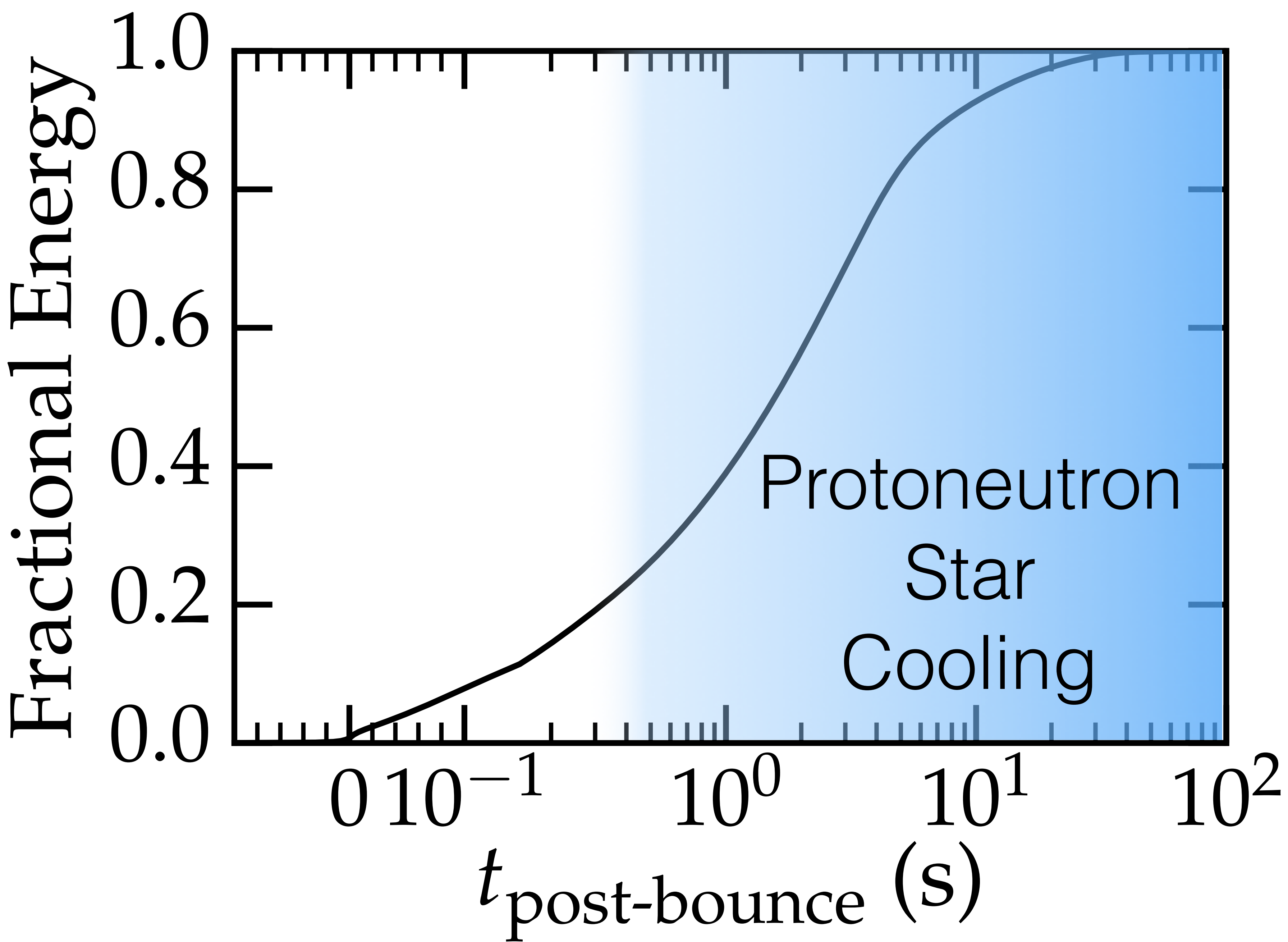
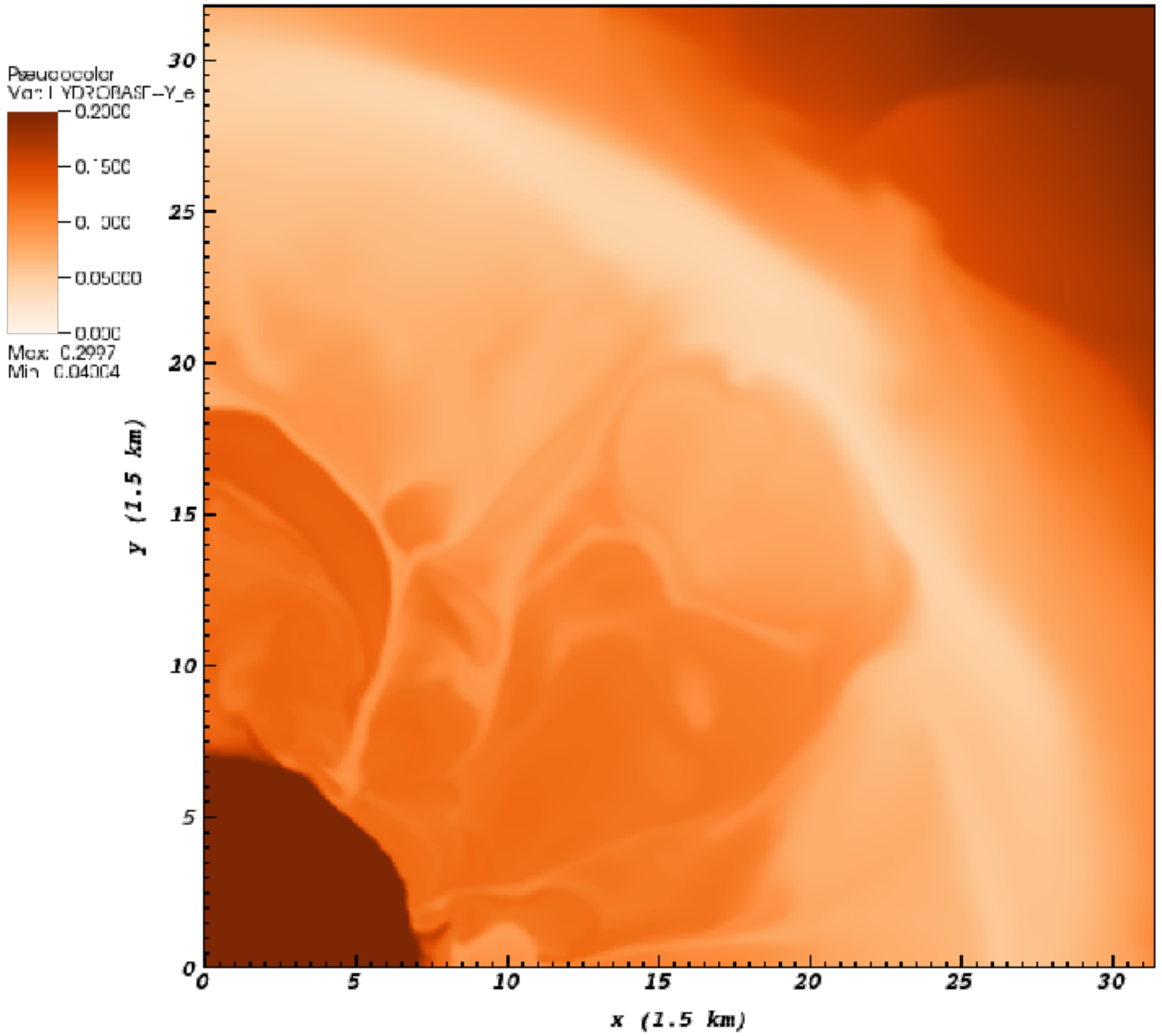
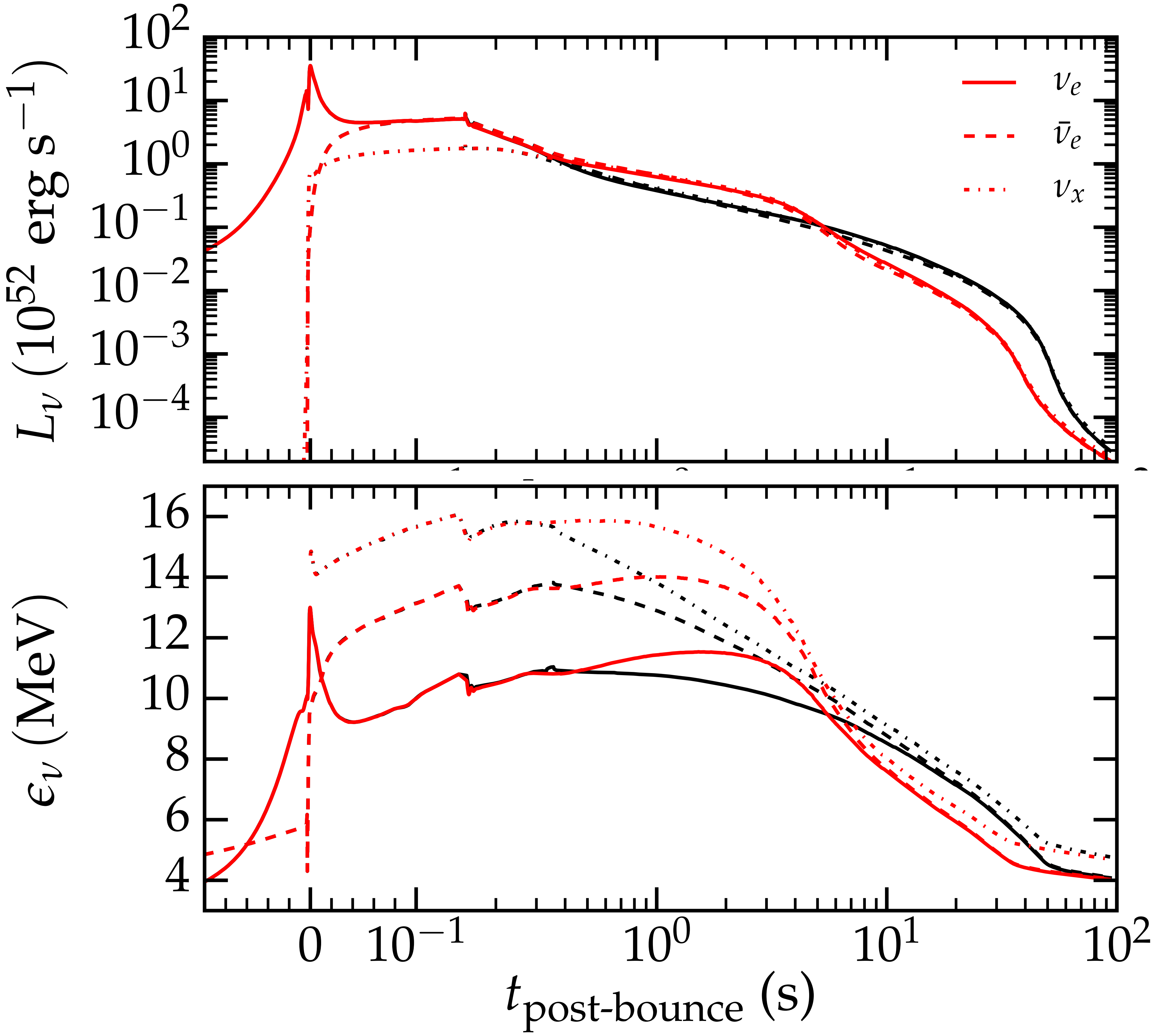


Proto-Neutron Star Convection

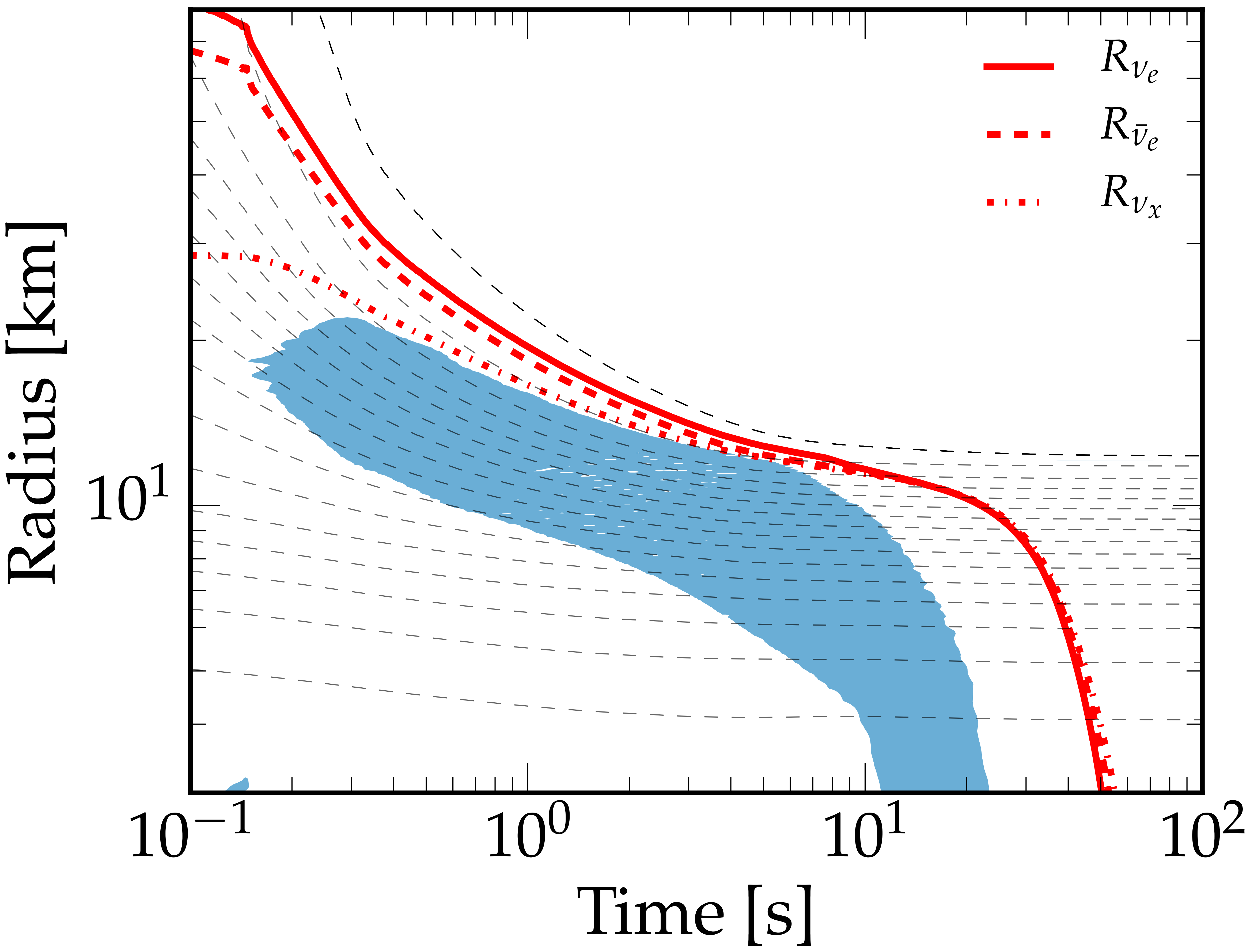




Red: Convection

Black: No Convection

Proto-Neutron Star Convection

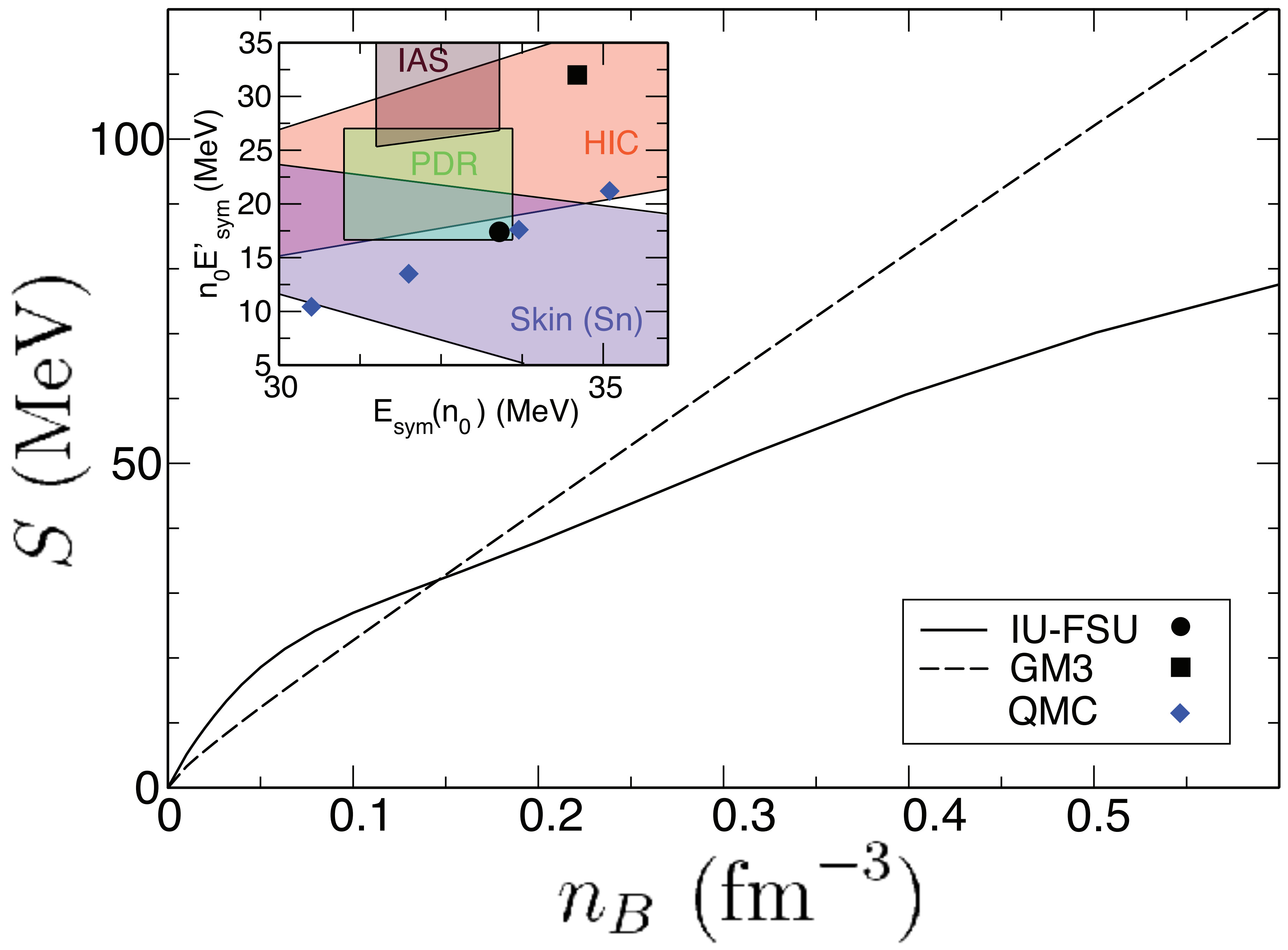


Region of convective instability determined by the Ledoux Criterion:

$$C_L = -\left(\frac{\partial P}{\partial s}\right)_{n,Y_l} \frac{ds}{dr} - \left(\frac{\partial P}{\partial Y_l}\right)_{n,s} \frac{dY_l}{dr} > 0$$

Proto-Neutron Star Convection

Dependence on the EoS

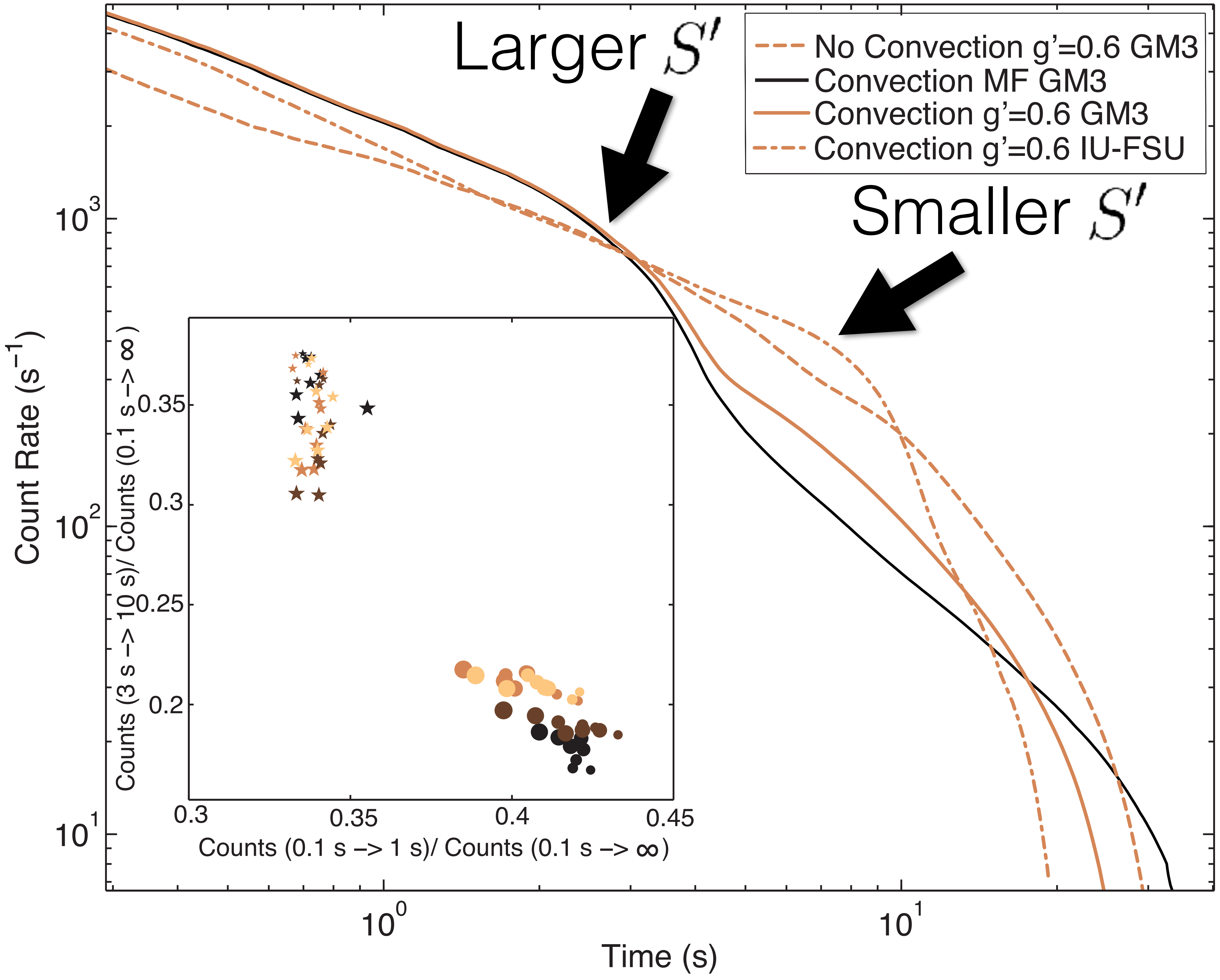


Pressure derivatives are sensitive to the symmetry energy derivative:

$$\epsilon(n_B, Y_e) = \epsilon(n_B, 1/2) + S(n_B)(1-2Y_e)^2$$

$$\left(\frac{dP}{dY_L}\right)_{n_B,s} \approx n_B^{4/3} Y_e^{1/3} - 4n_B^2 S'(1-2Y_e)$$

Proto-Neutron Star Convection



LR et al. (2012)

Conclusions

- 3D explosion models becoming available for a range of progenitors
- Early-time neutrino emission is sensitive to finite temperature properties of nuclear equation of state, larger nucleon effective masses result in conditions more favorable for explosion
- PNS convection significantly impacts the neutrino cooling timescale, produces a break in the neutrino emission, sensitive to the nuclear EoS through the density dependence of the symmetry energy
- ~~Nuclear correlations and nuclear pasta have possibility of impacting late tie cooling, but the critical temperature for pasta formation may be too low and neutrino opacity in the relevant range suppressed~~

Set	Quantity	Range	This work	Units
s_M	$m^\star$	0.75 ± 0.10	0.75 ± 0.10	m_n
	$\Delta m^\star$	0.10 ± 0.10	0.10 ± 0.10	m_n
$-$	$n_{\rm sat}$	0.155 ± 0.005	0.155	$\rm fm^{-3}$
	$\epsilon_{\rm sat}$	-15.8 ± 0.3	-15.8	$\rm MeV\ baryon^{-1}$
s_S	$\epsilon_{\rm sym}$	32 ± 2	32 ± 2	$\rm MeV\ baryon^{-1}$
	$L_{\rm sym}$	60 ± 15	45 ± 7.5	$\rm MeV\ baryon^{-1}$
s_K	$K_{\rm sat}$	230 ± 20	230 ± 15	$\rm MeV\ baryon^{-1}$
	$K_{\rm sym}$	-100 ± 100	-100 ± 100	$\rm MeV\ baryon^{-1}$
s_P	$P^{(4)}_{\rm SNM}$	100 ± 50	125 ± 12.5	$\rm MeV\ fm^{-3}$
	$P^{(4)}_{\rm PNM}$	160 ± 80	200 ± 20	$\rm MeV\ fm^{-3}$