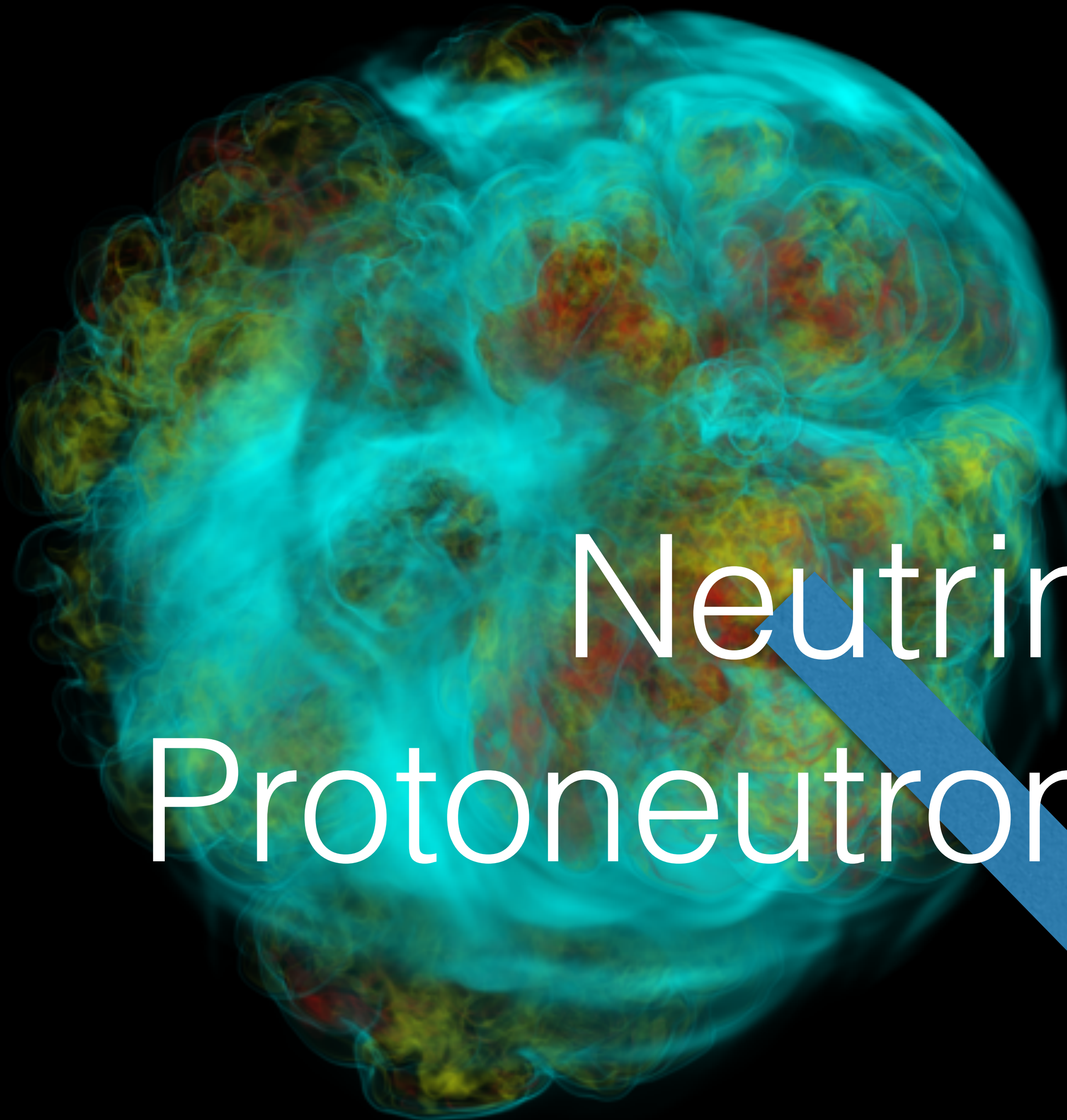
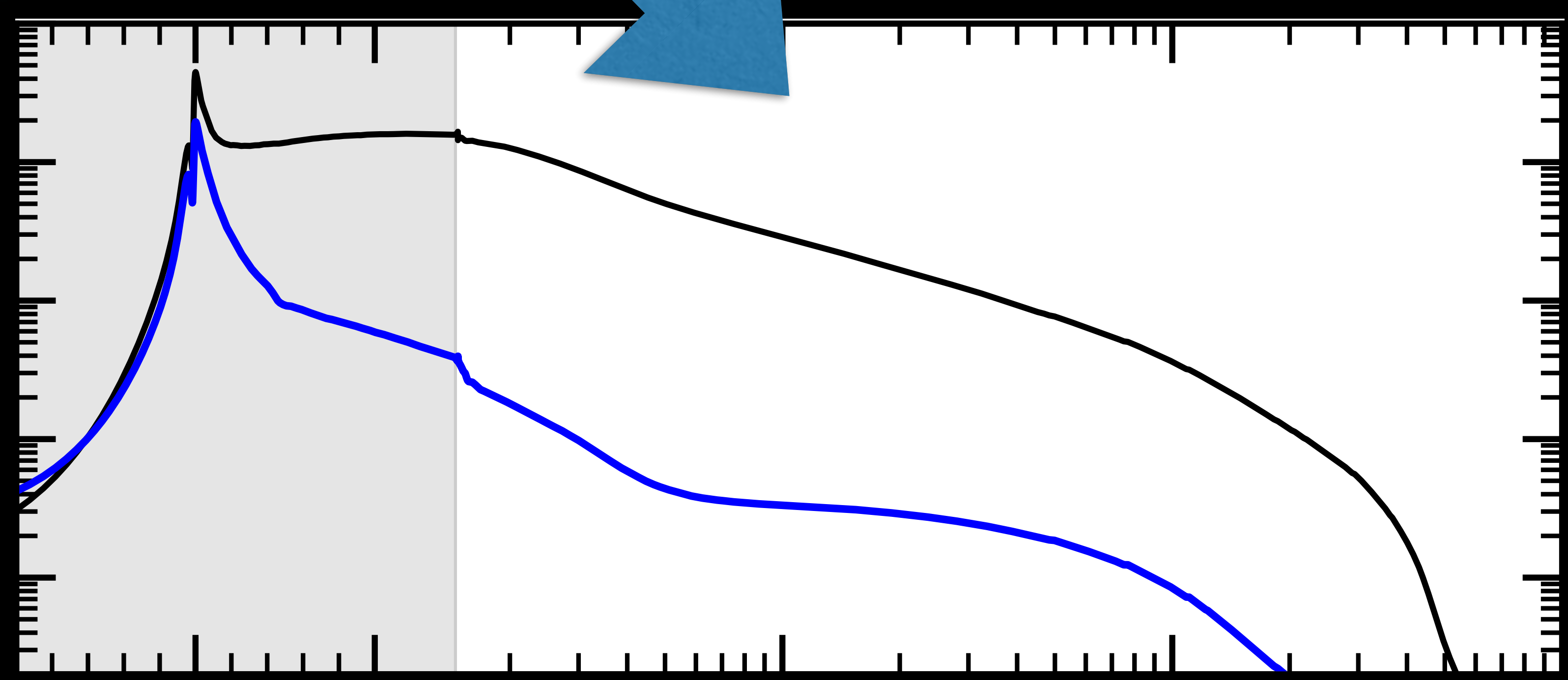


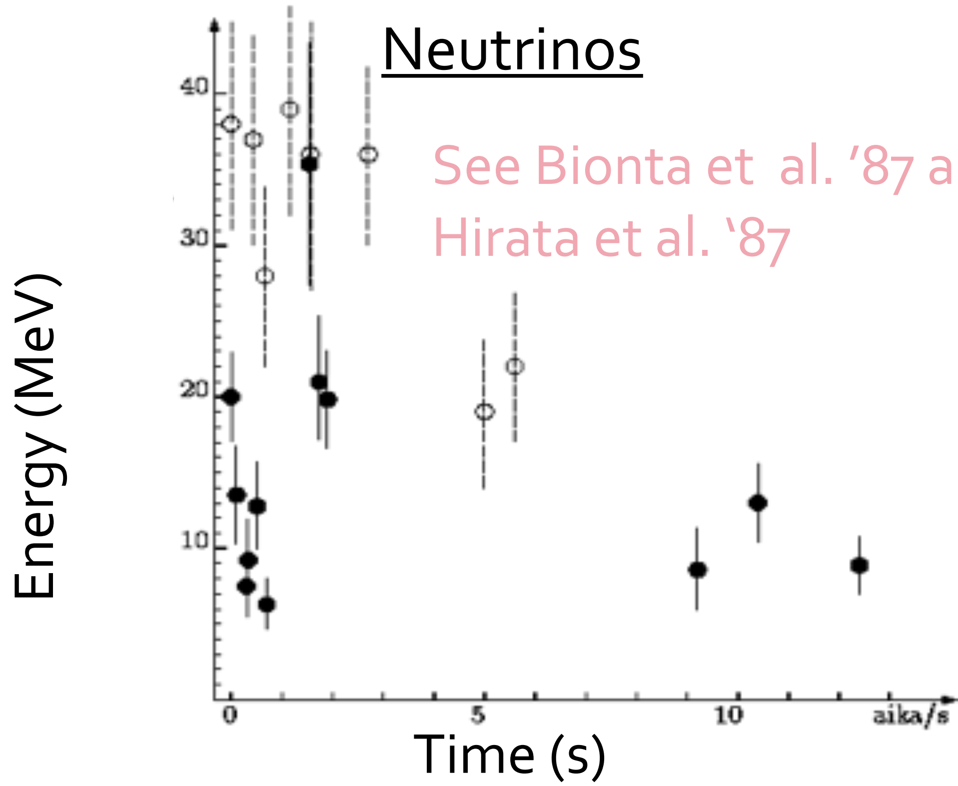
Neutrinos from Protoneutron Star Cooling



Luke Roberts
~MSU

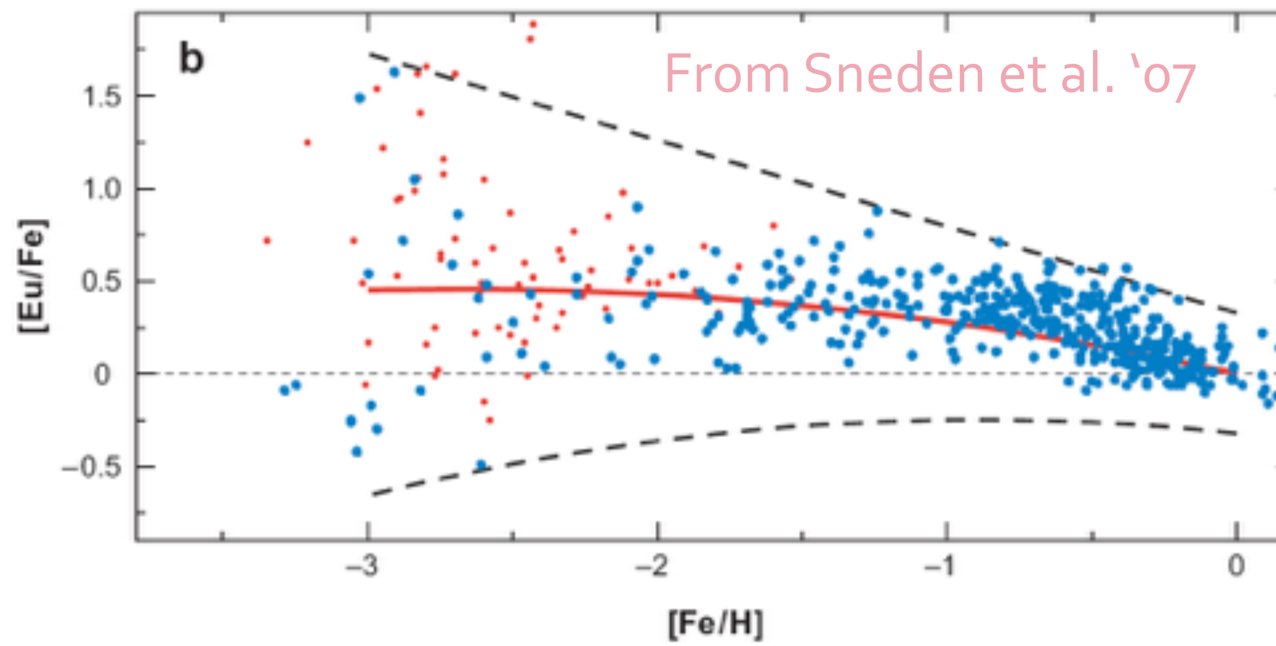
Core Collapse Supernovae: Multi-Messenger Events

Neutrinos



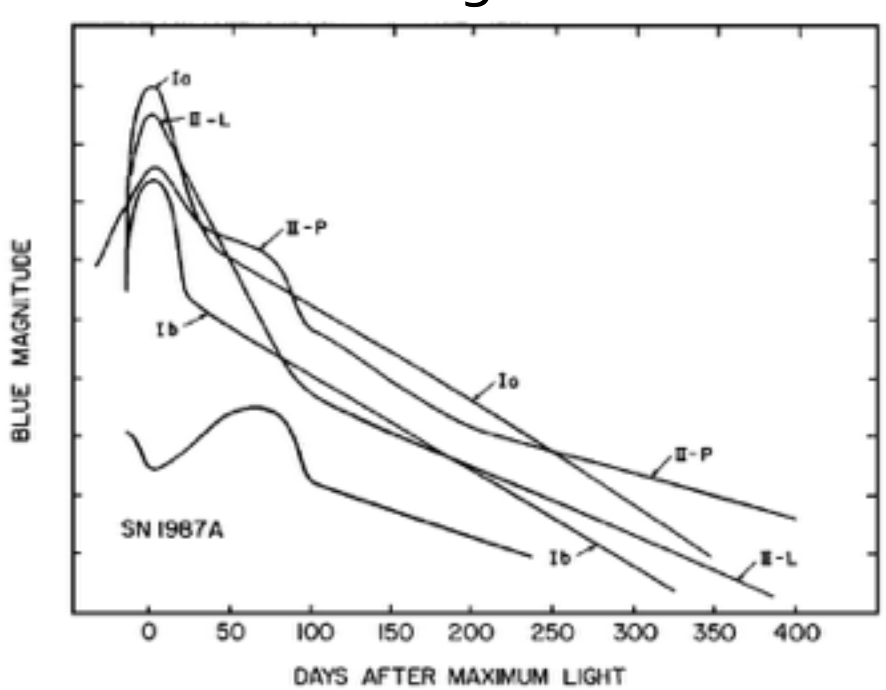
See Bionta et al. '87 and Hirata et al. '87

Nucleosynthesis



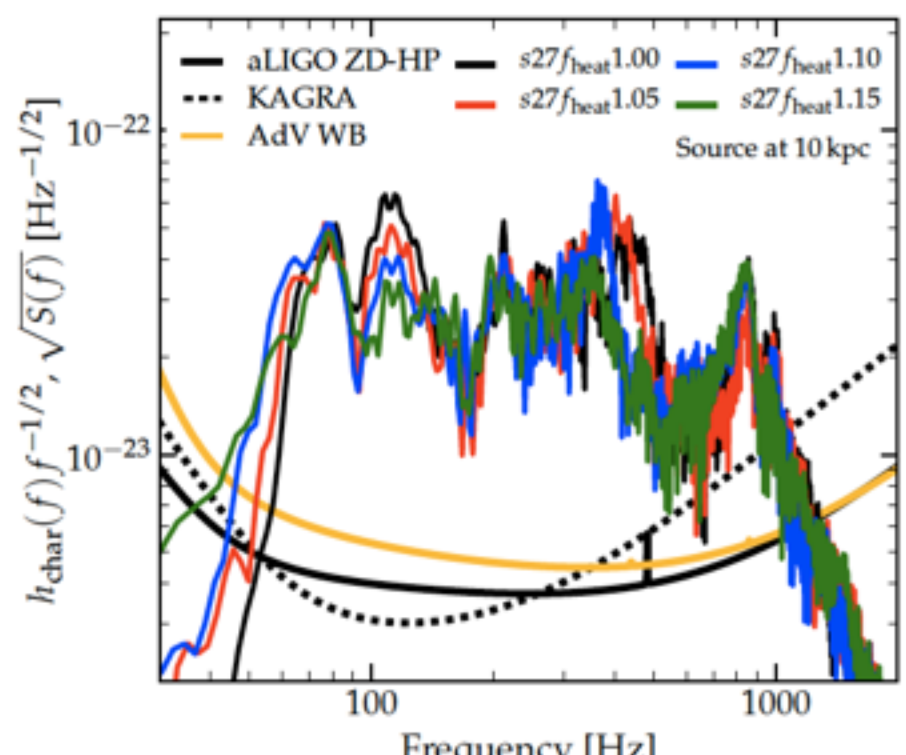
From Sneden et al. '07

Electromagnetic



From Filppenko '97

Gravitational Waves



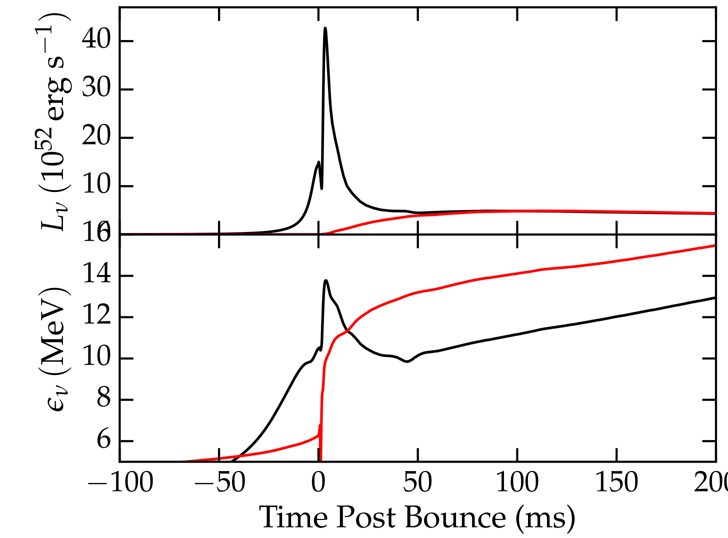
From Ott et al. '12

Overview

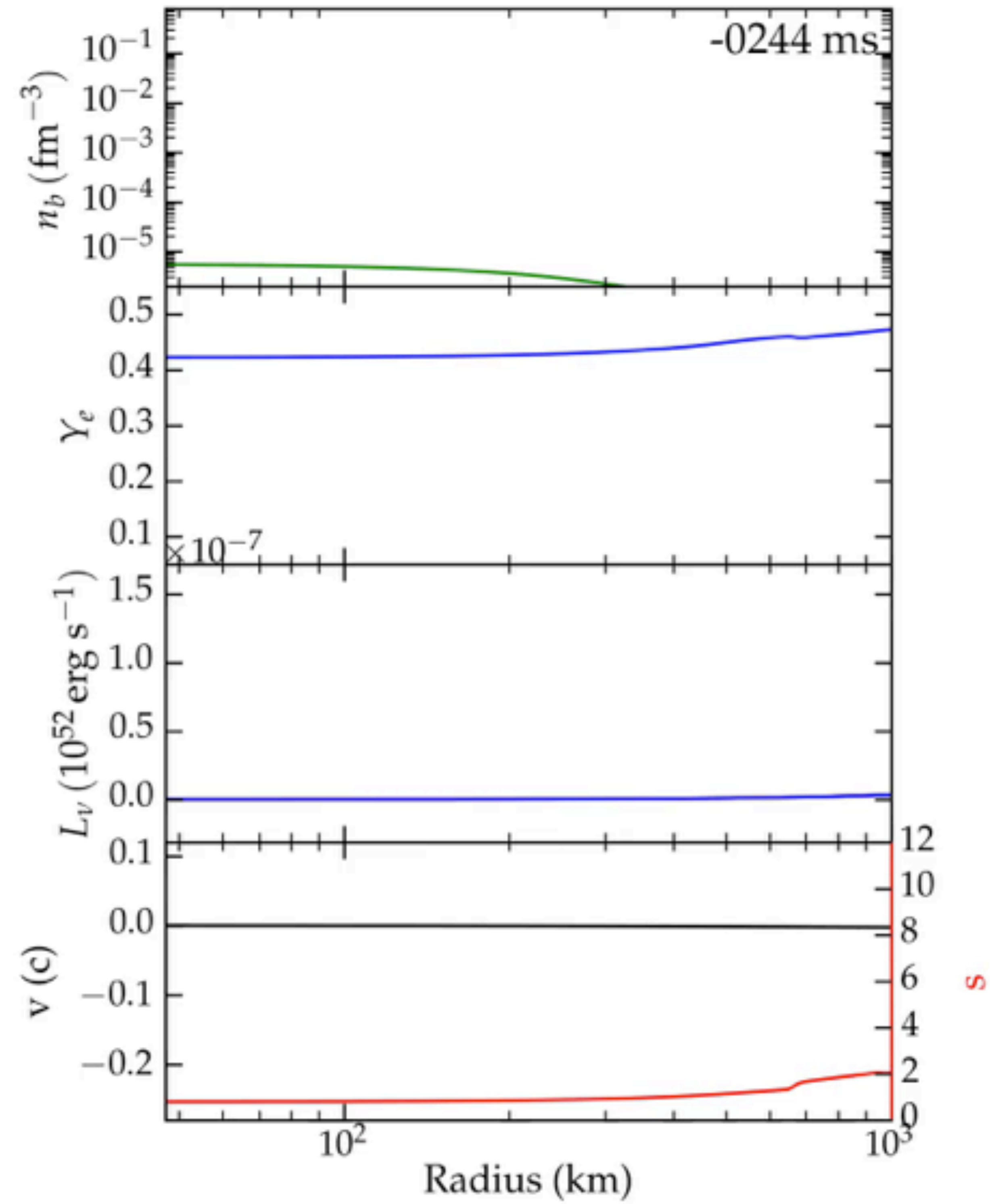
- Models of protoneutron star cooling and neutrino cooling timescales
- Impact of convection on neutrino emission
- Impact of opacities on neutrino emission

Caveat: No neutrino oscillations included

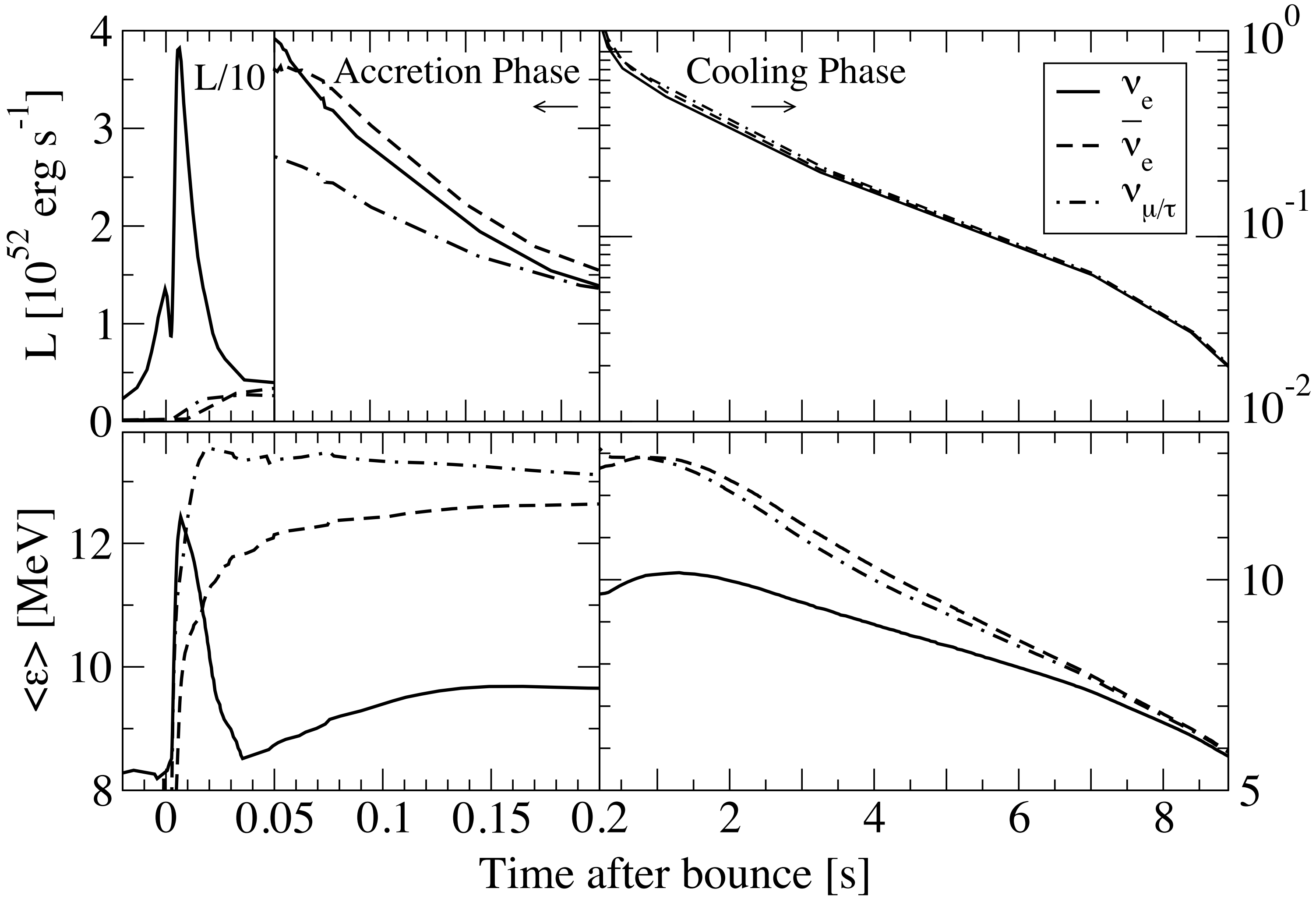
Core Collapse

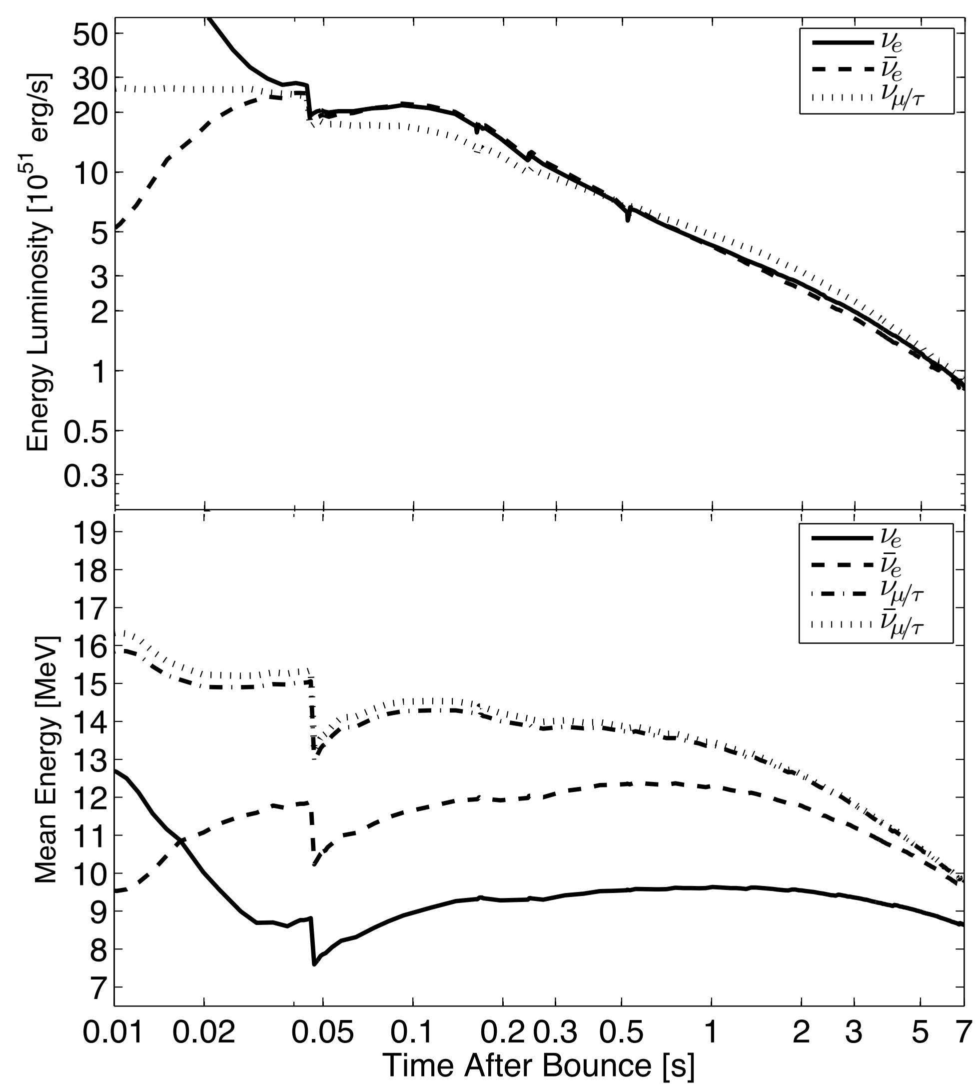


- Stars with M >~ 9 M_{sun} burn their core to Fe
- Core exceeds a Chandrasekhar mass supersonic collapse outside of homologous core → bounce shock after ~2 x saturation density
- Neutrinos trapped around 10^{11} - 10^{12} g/cc, set lepton fraction of core
- No Explosions by the neutrino mechanism in spherical symmetry for most progenitors (e.g. Liebendorfer '00)
- Just set a mass cut and evolve inner core



Self Consistent Spherically Symmetric CCSN Explosions

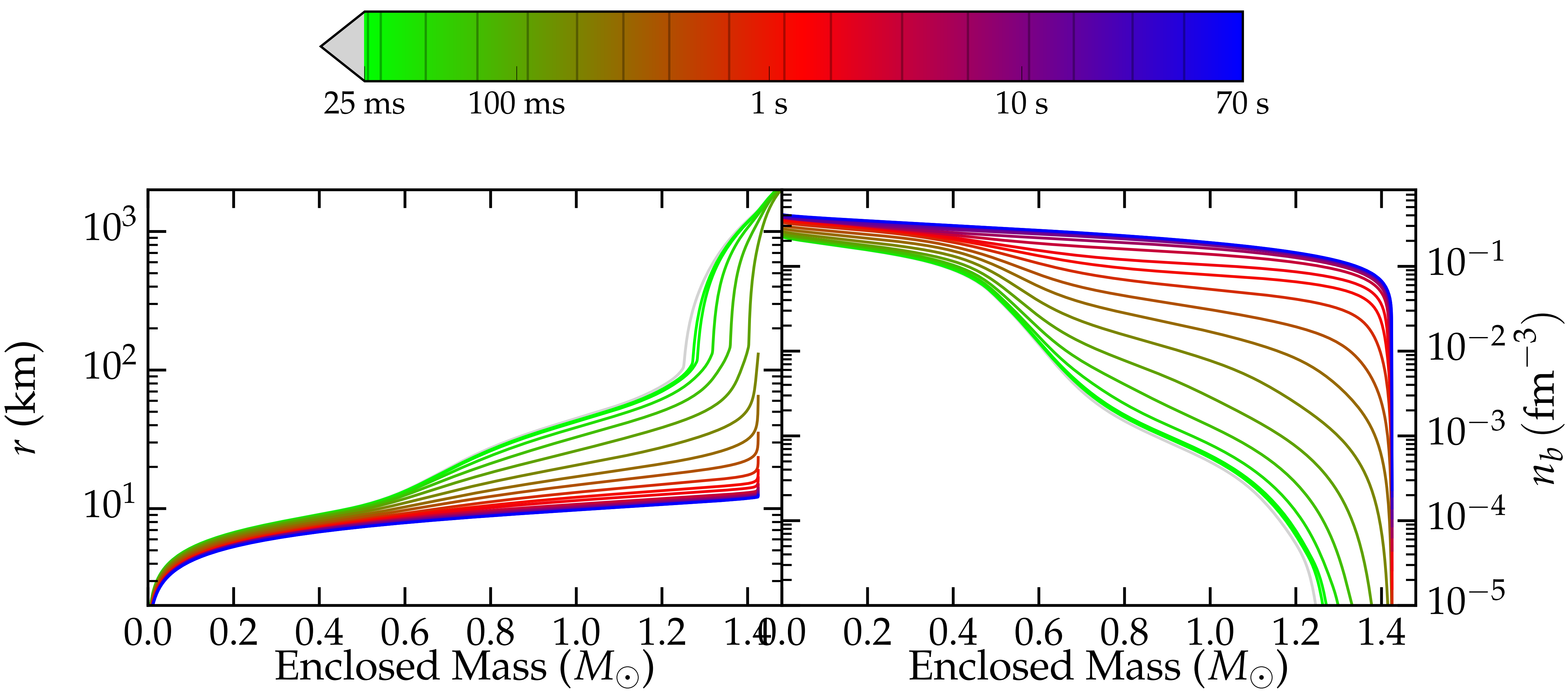




Huedepohl et al. (2010)　　Fischer et al. (2010, 2012)

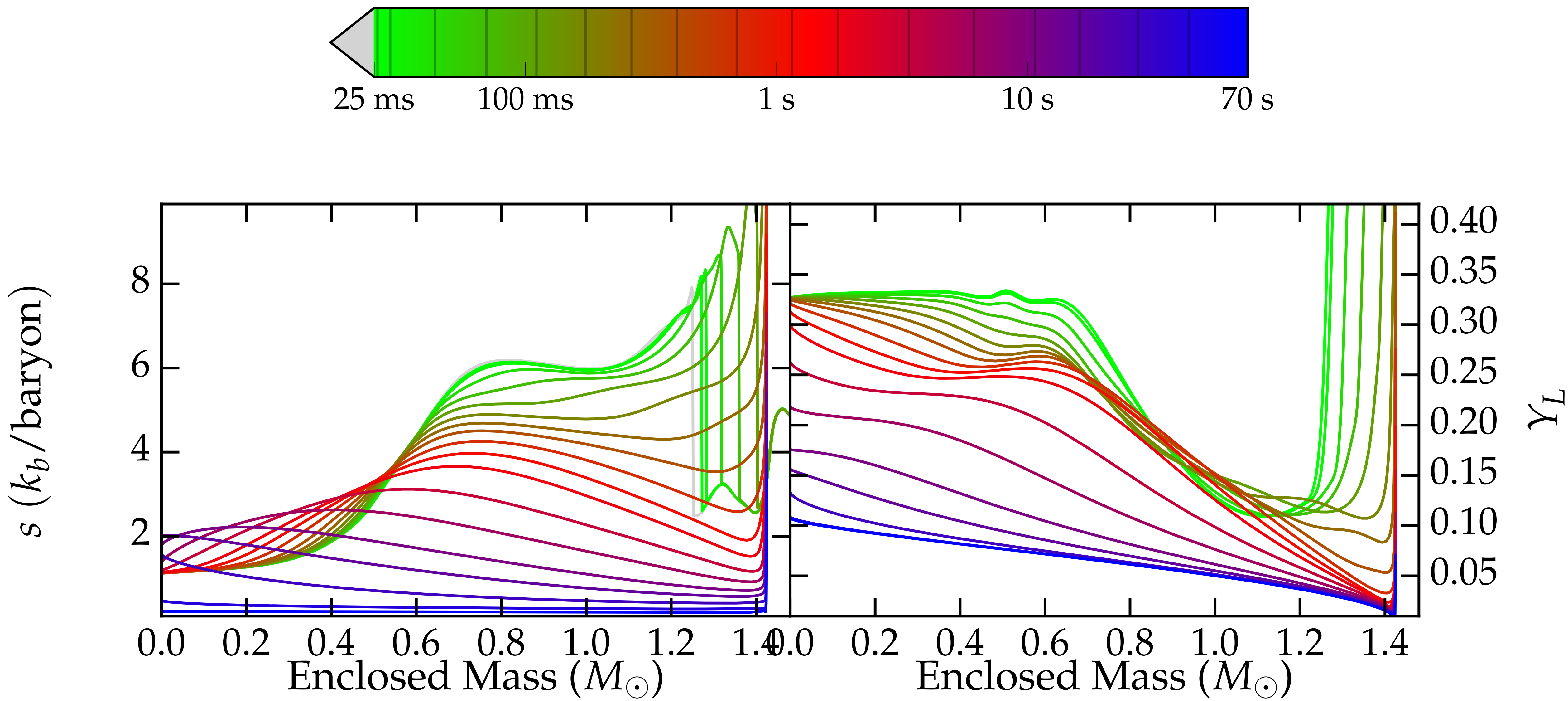
Only possible for low mass progenitors, mainly ECSN

Long Term PNS Evolution



$$E_{\rm SN} \sim \frac{3GM_{\rm pns}^2}{5r_{\rm NS}} \approx 3\times10^{53}\,{\rm erg}\left(\frac{M_{\rm pns}}{M_\odot}\right)^2\left(\frac{r_{NS}}{12\,{\rm km}}\right)^{-1}$$

Long Term PNS Evolution



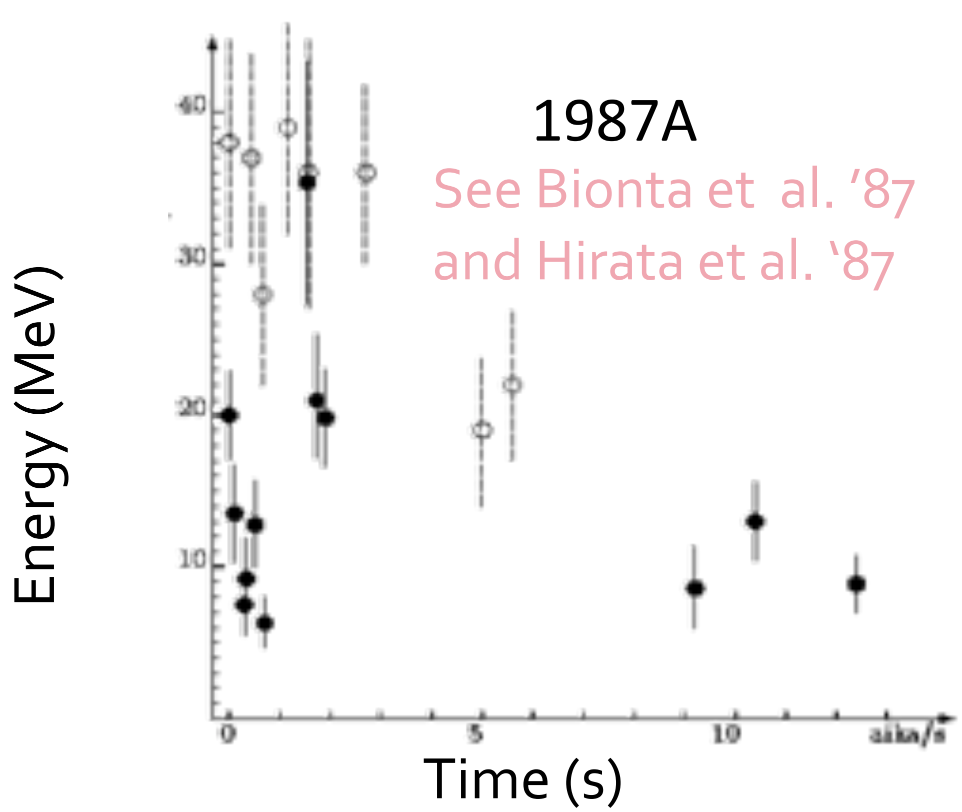
$$\tau_c \approx \frac{2\pi G_F^2 c_A^2}{\beta} \left\langle N_0 \frac{3n_b}{\pi^2} \frac{\partial s}{\partial T} \right\rangle k_B T_c \, R^2 \simeq 10 \; s \; \frac{k_B T_c}{30 \text{ MeV}} \; \frac{\langle n_b^{2/3} \rangle}{n_0^{2/3}} \; \left(\frac{R}{12 \text{ km}} \right)^2$$

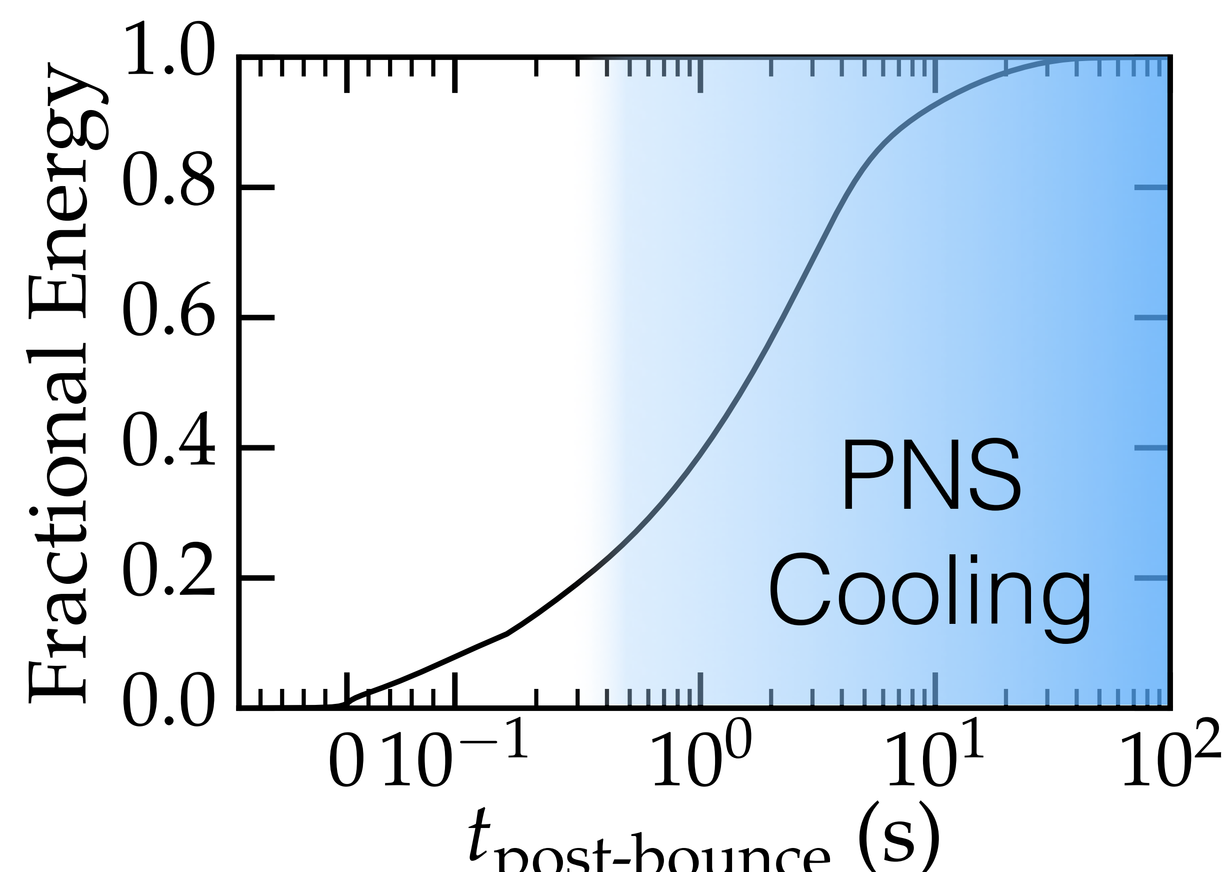
See Prakash et al. '97

Late Time Neutrino Emission

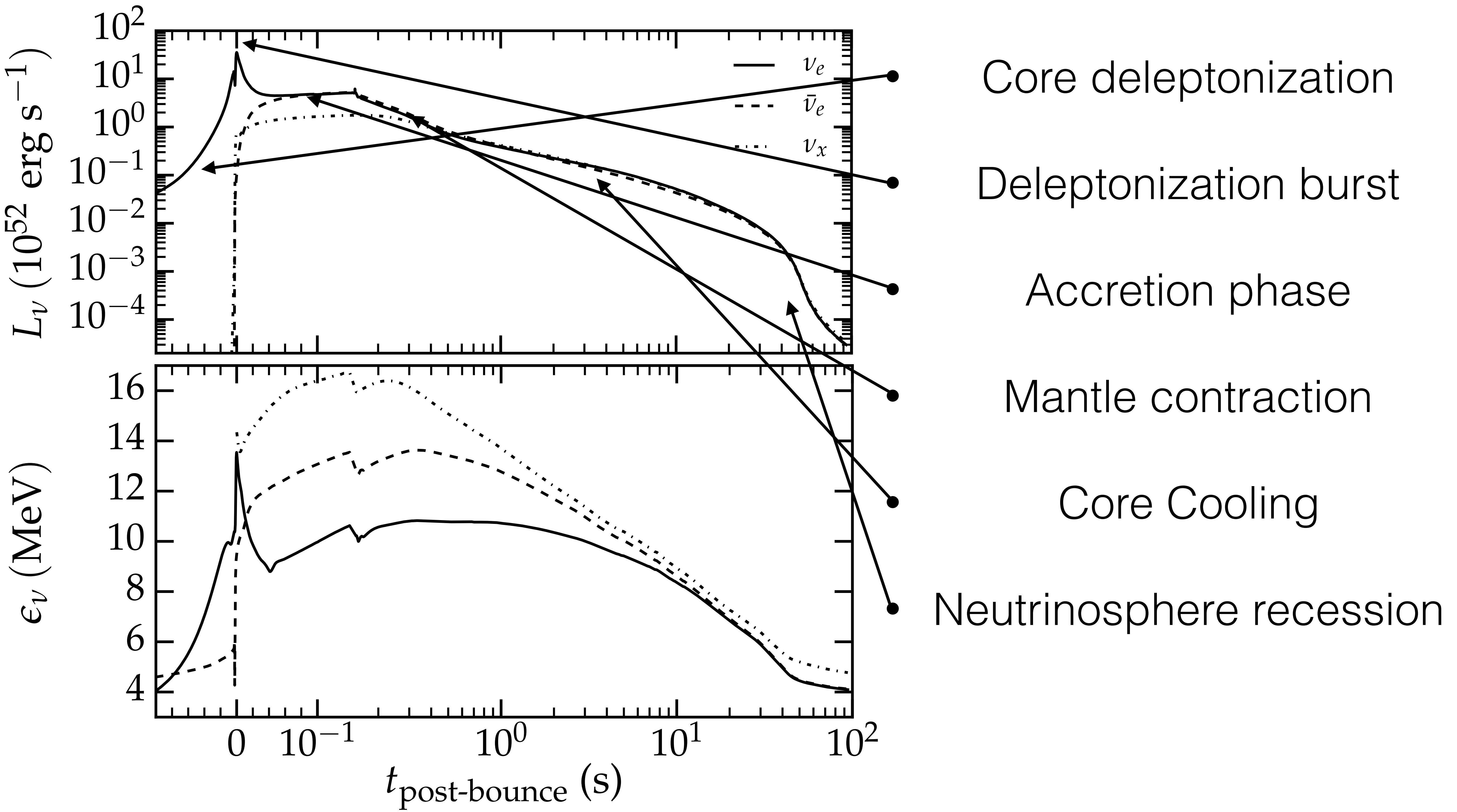
See e.g. Burrows & Lattimer ’86, Pons et al. ‘99, Huedepohl et al. ‘10, Fischer et al. ’10, LR ‘12

- Will have tens of thousands of detections from next galactic CCSN
- Kelvin-Helmholtz evolution of the neutron star mediated by neutrinos
- Coupled neutron star structure and neutrino transport
- Sensitive to dense matter equation of state, neutrino oscillations
- Possibly cleaner problem than explosion mechanism

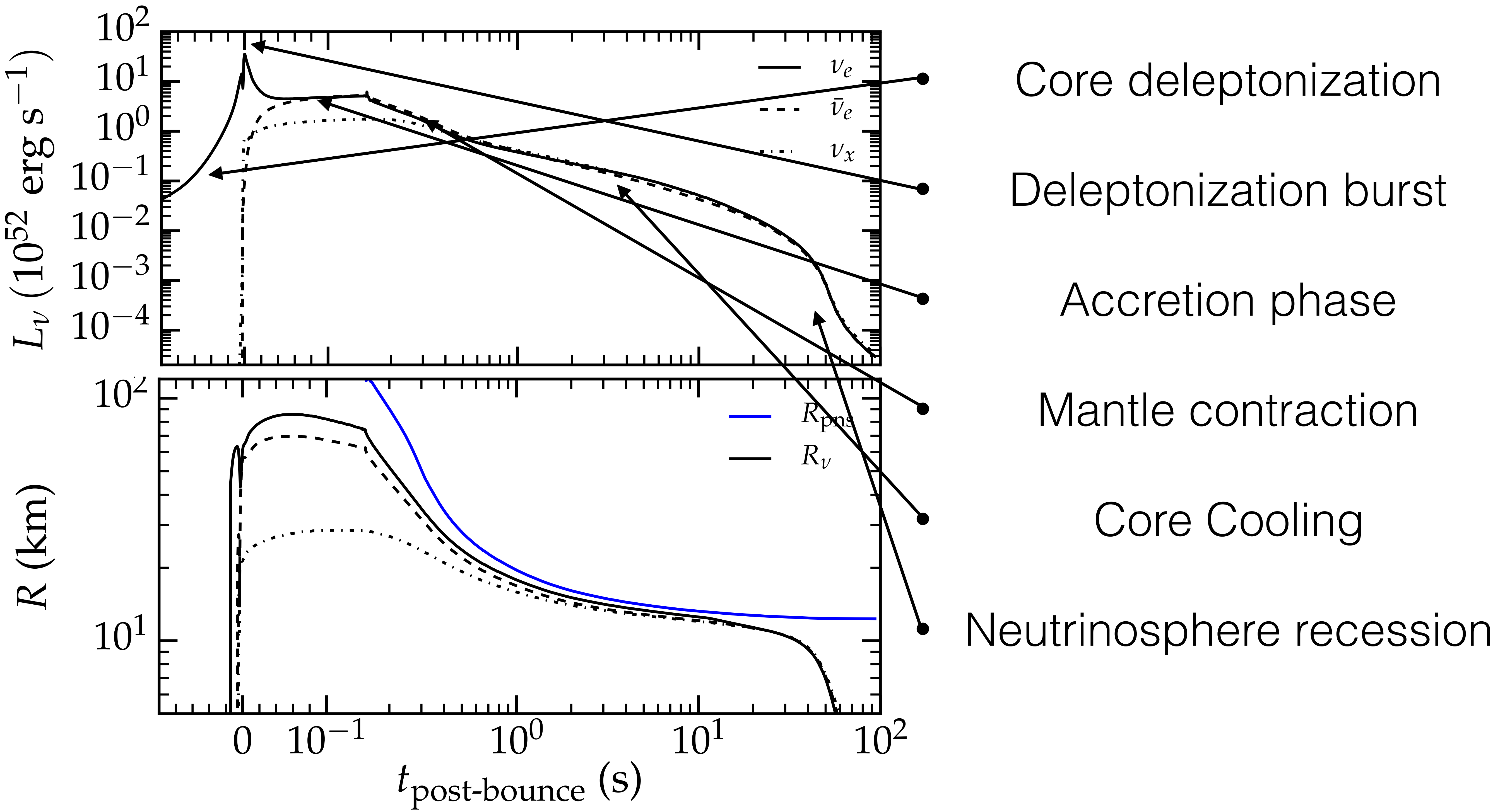




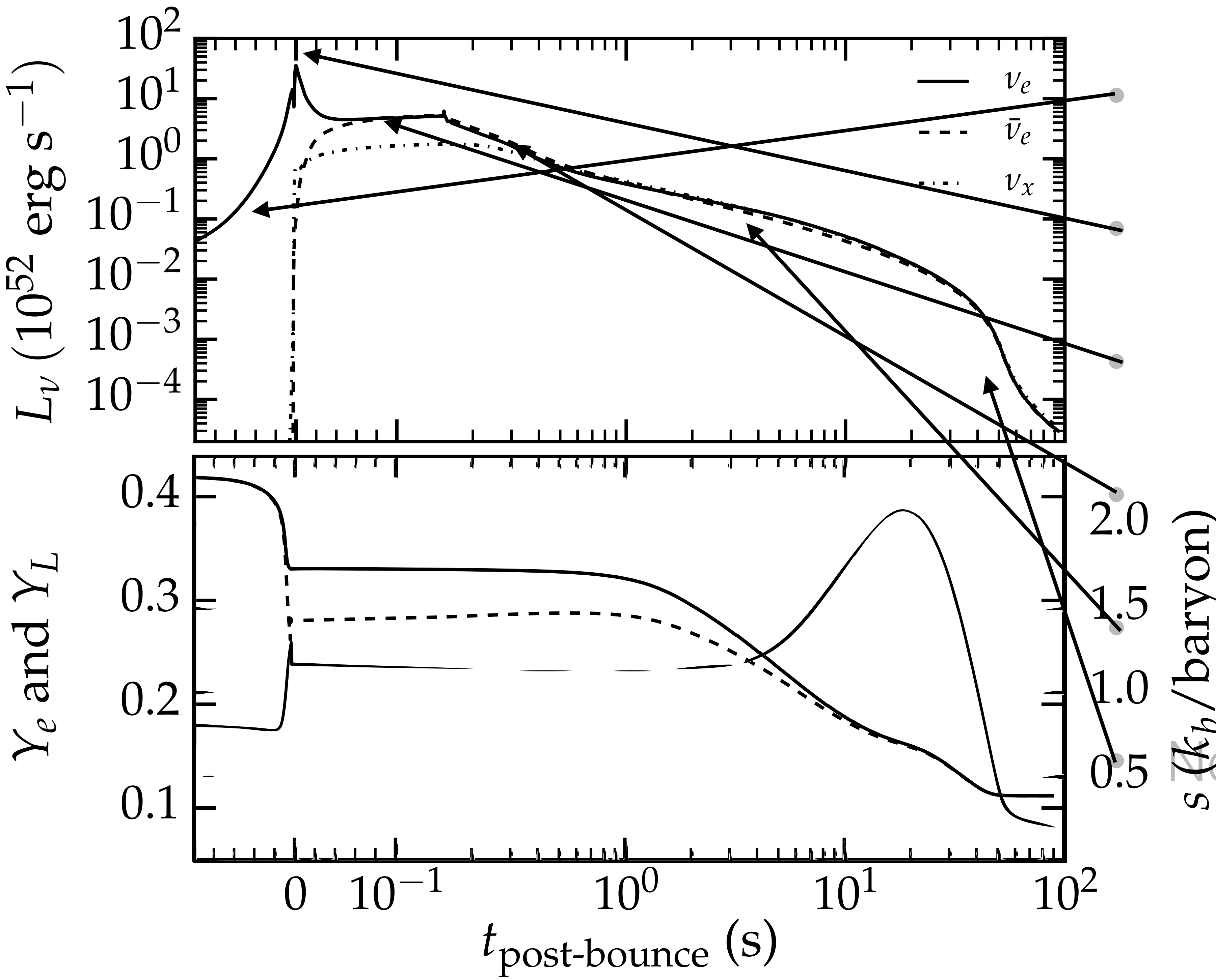
Anatomy of the Neutrino Signal



Anatomy of the Neutrino Signal

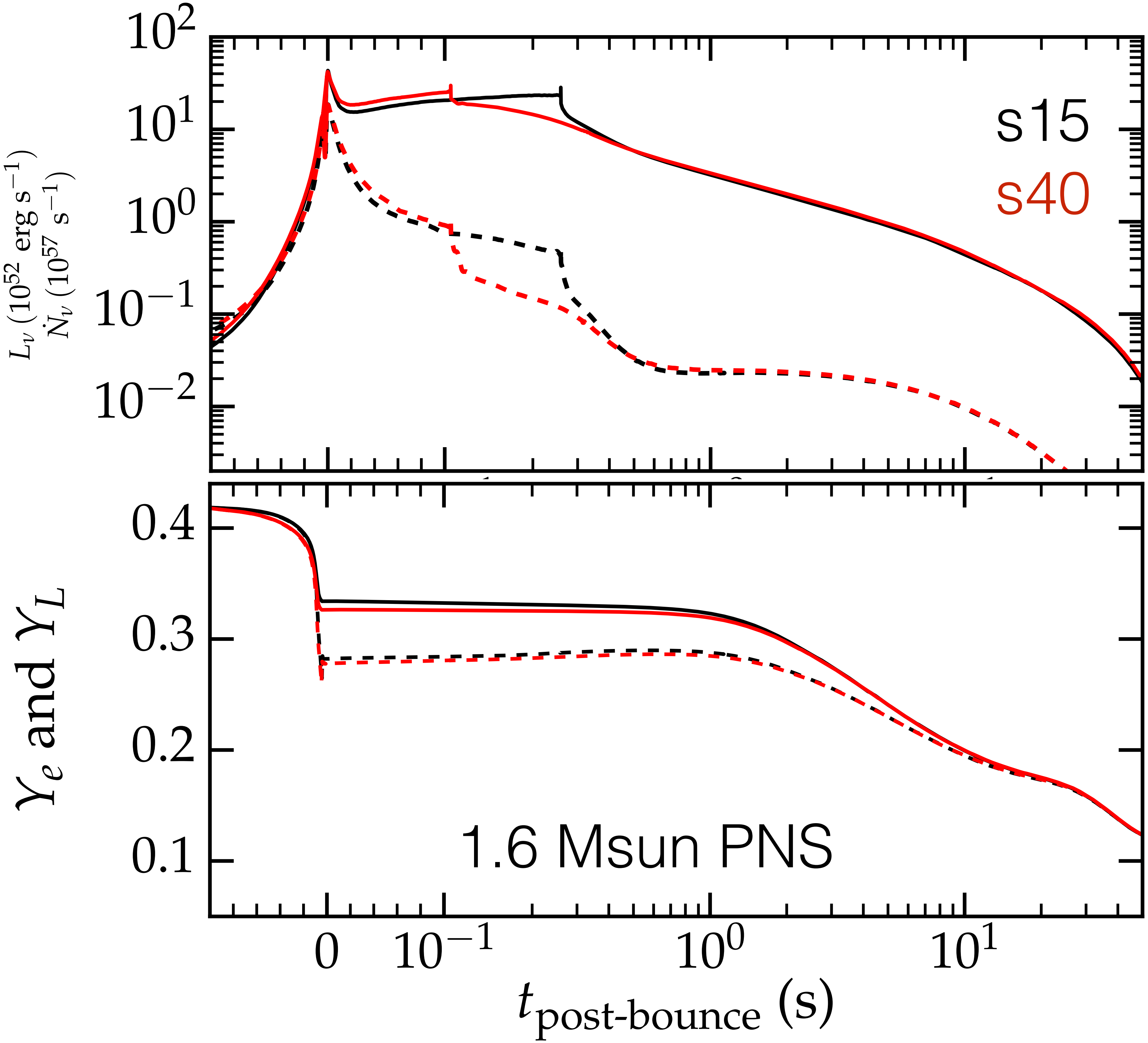


Anatomy of the Neutrino Signal

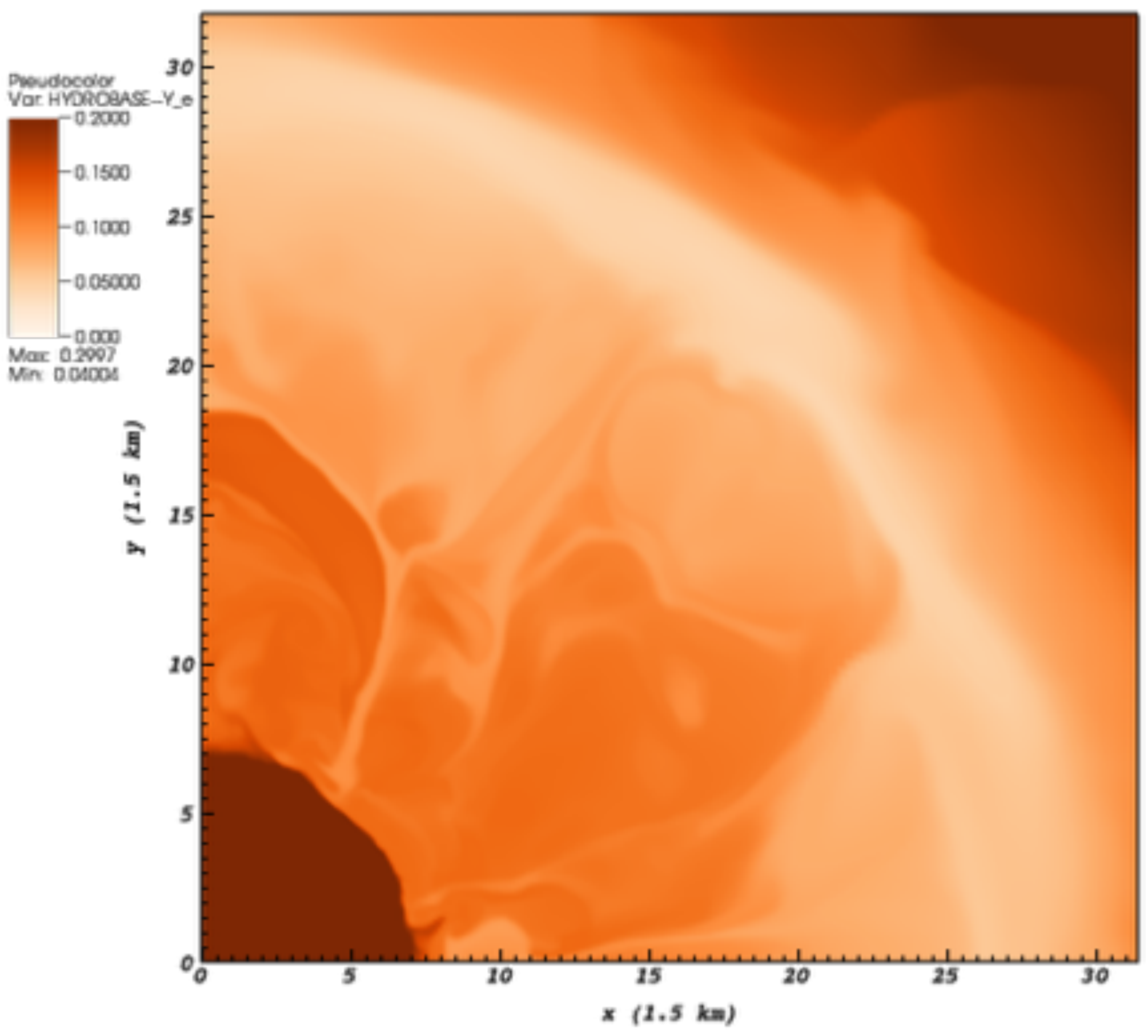


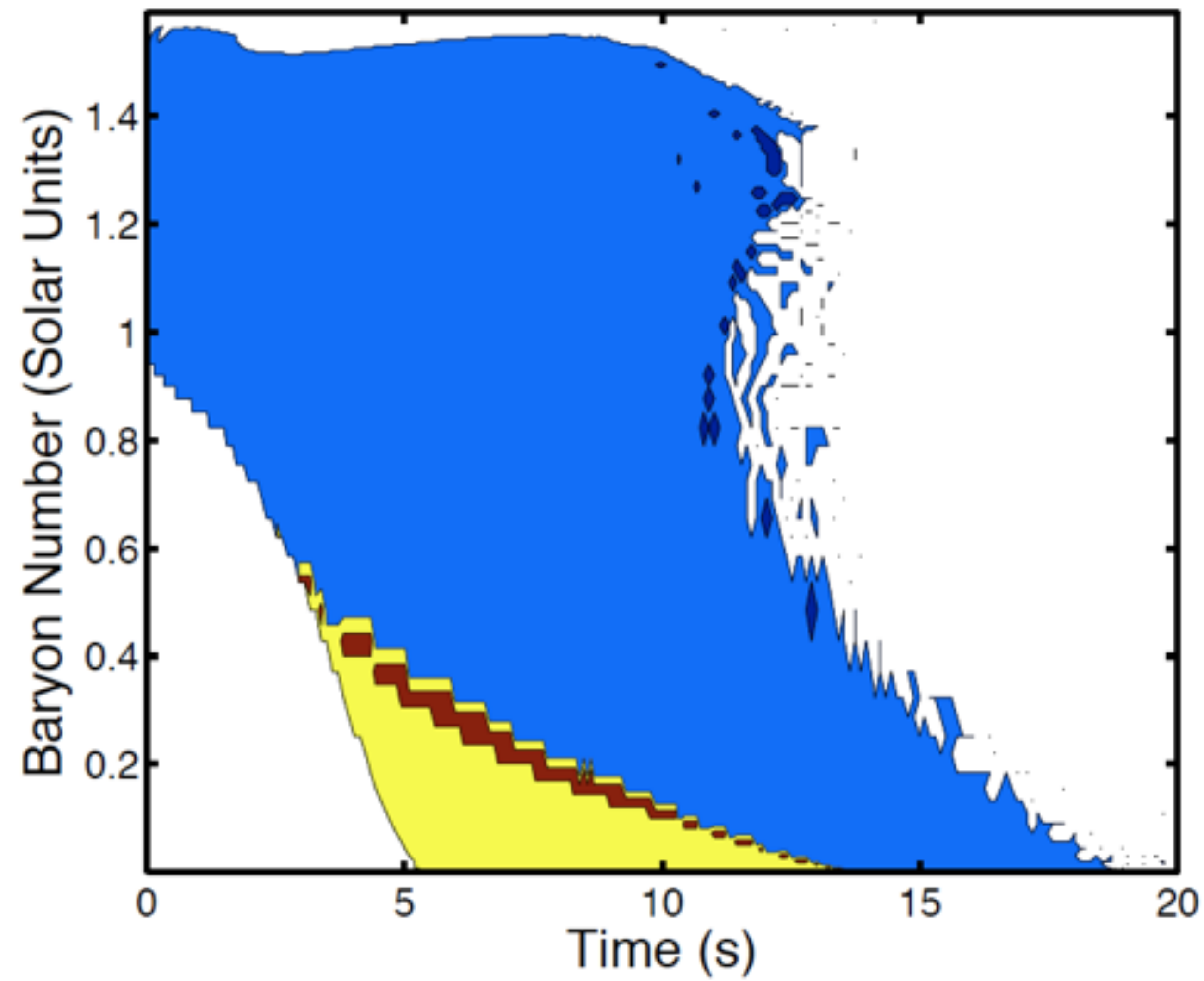
- Core deleptonization
- Deleptonization burst
- Accretion phase
- Mantle contraction
- PNS Cooling
- Neutrinosphere recession

Progenitor Dependence



Proto-Neutron Star Convection

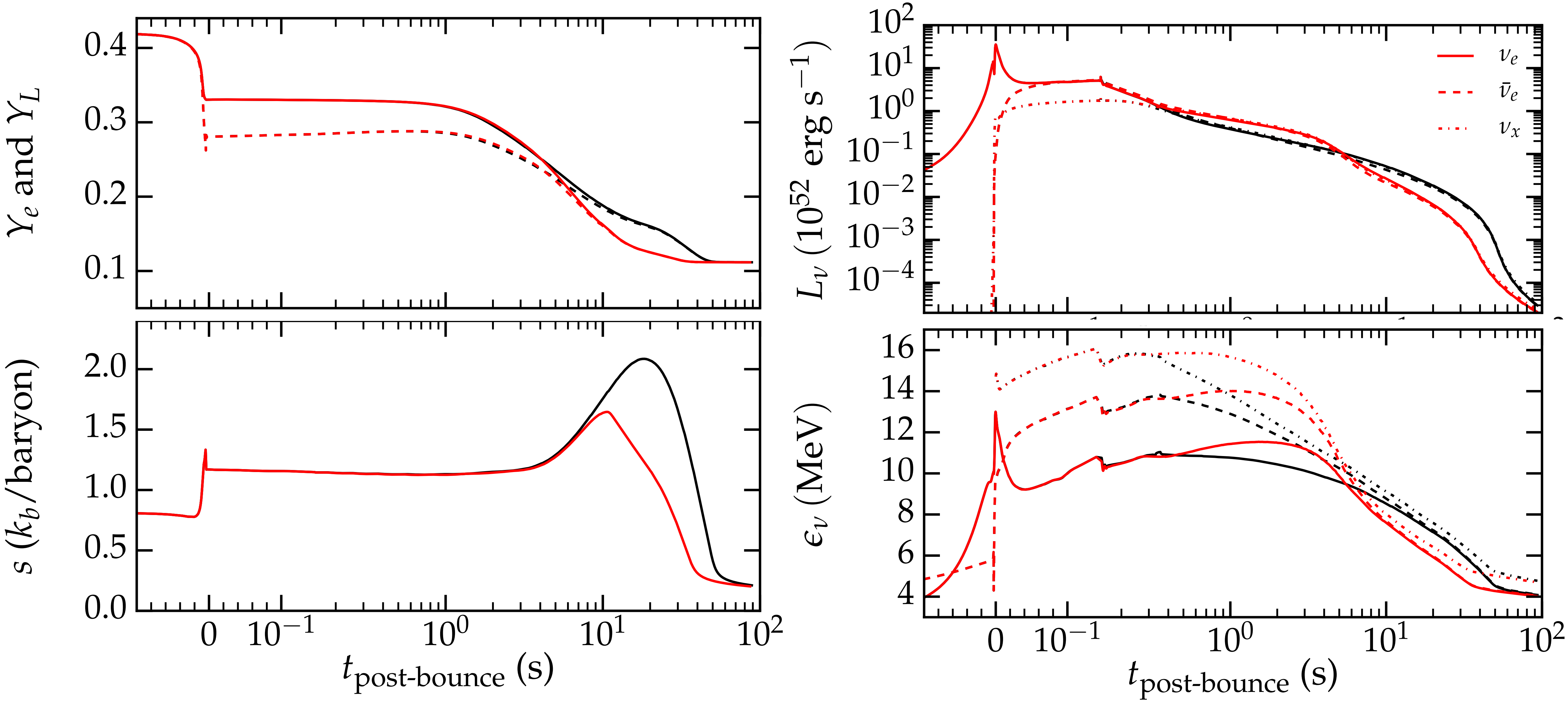




Region of convective instability determined by the Ledoux Criterion:

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

Convection



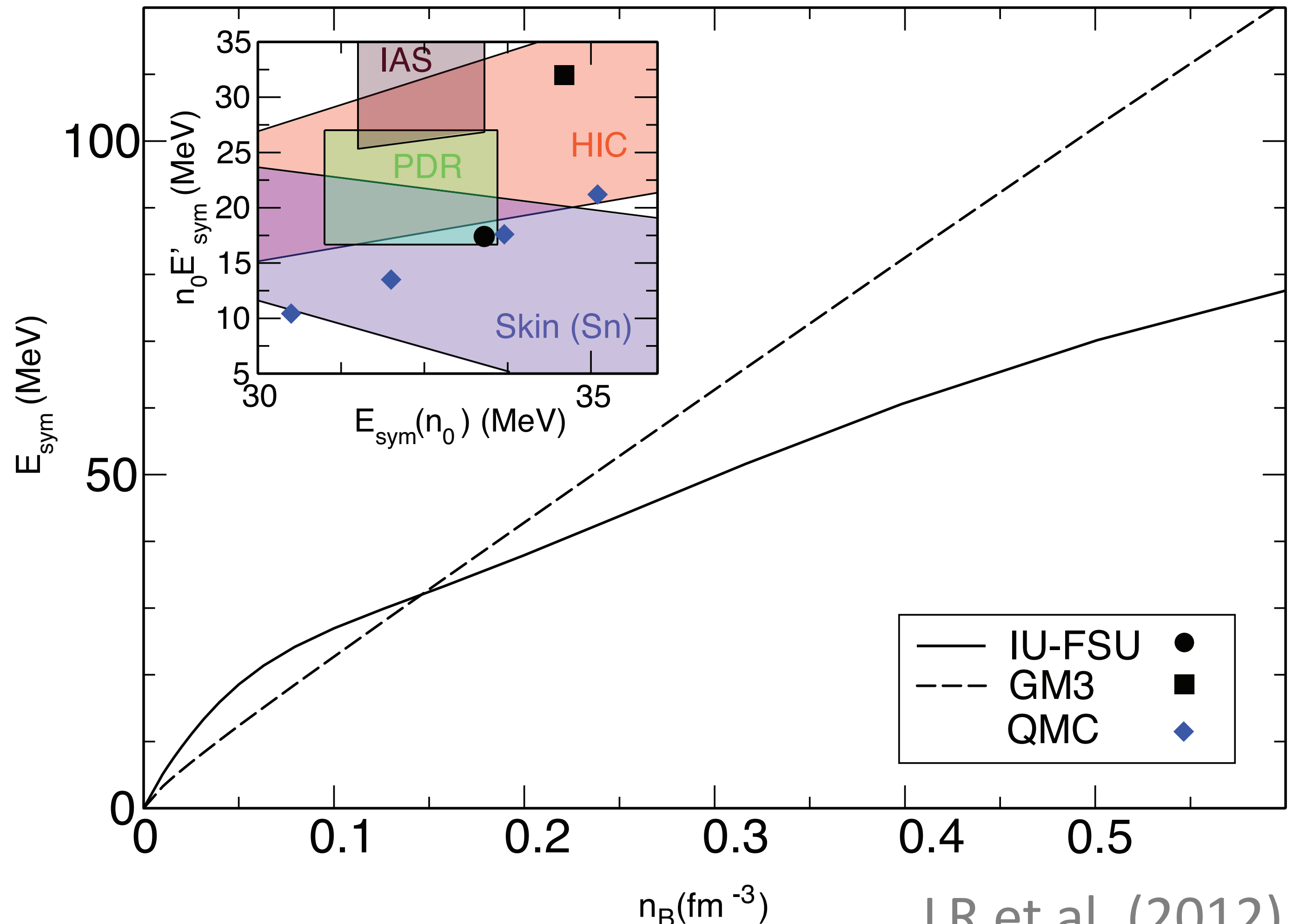
Black: No Convection

Red: Convection

See also Mirizzi et al. (2015)

Proto-Neutron Star Convection

Dependence on the EoS

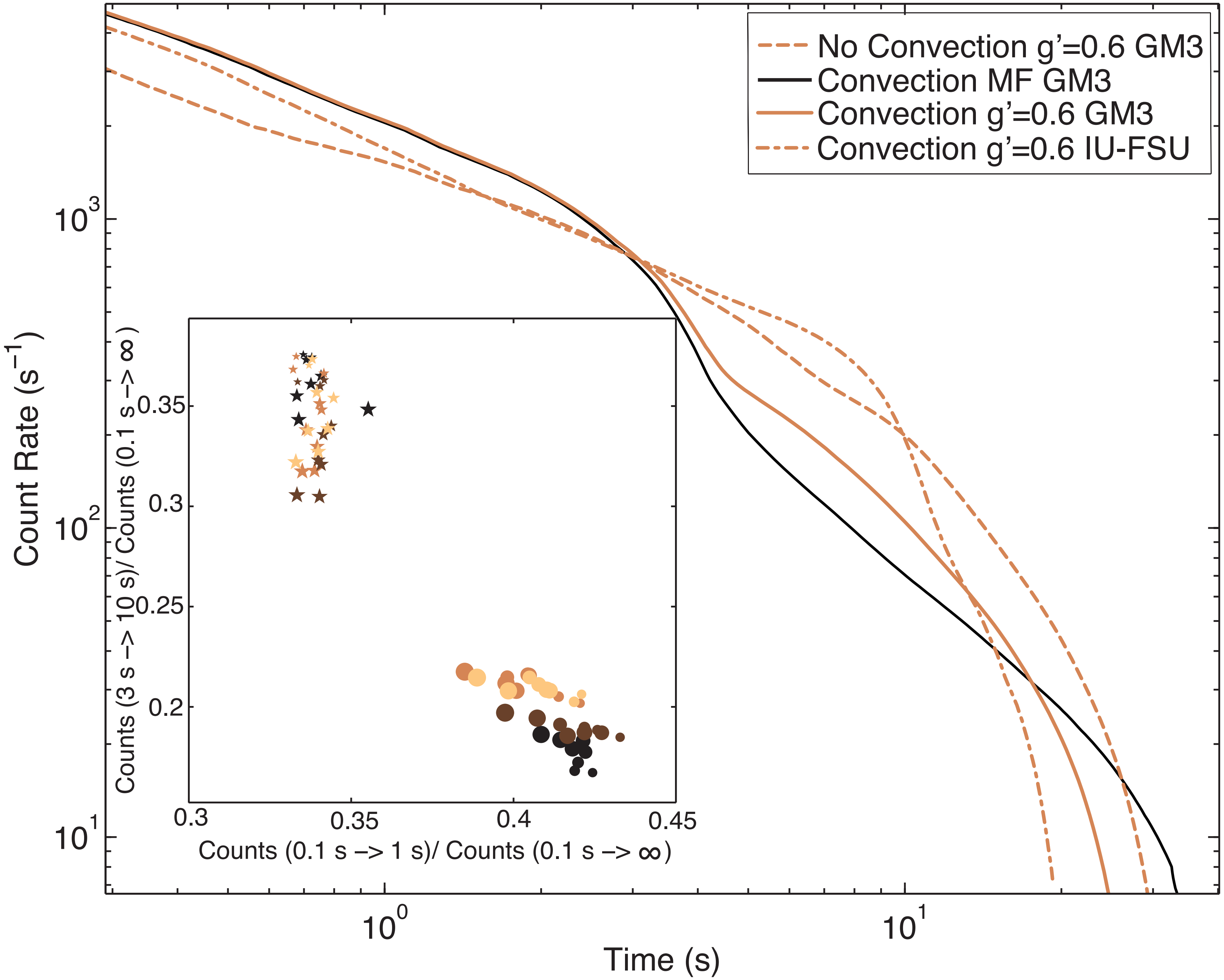


LR et al. (2012)

Pressure derivatives are sensitive to the symmetry energy derivative:

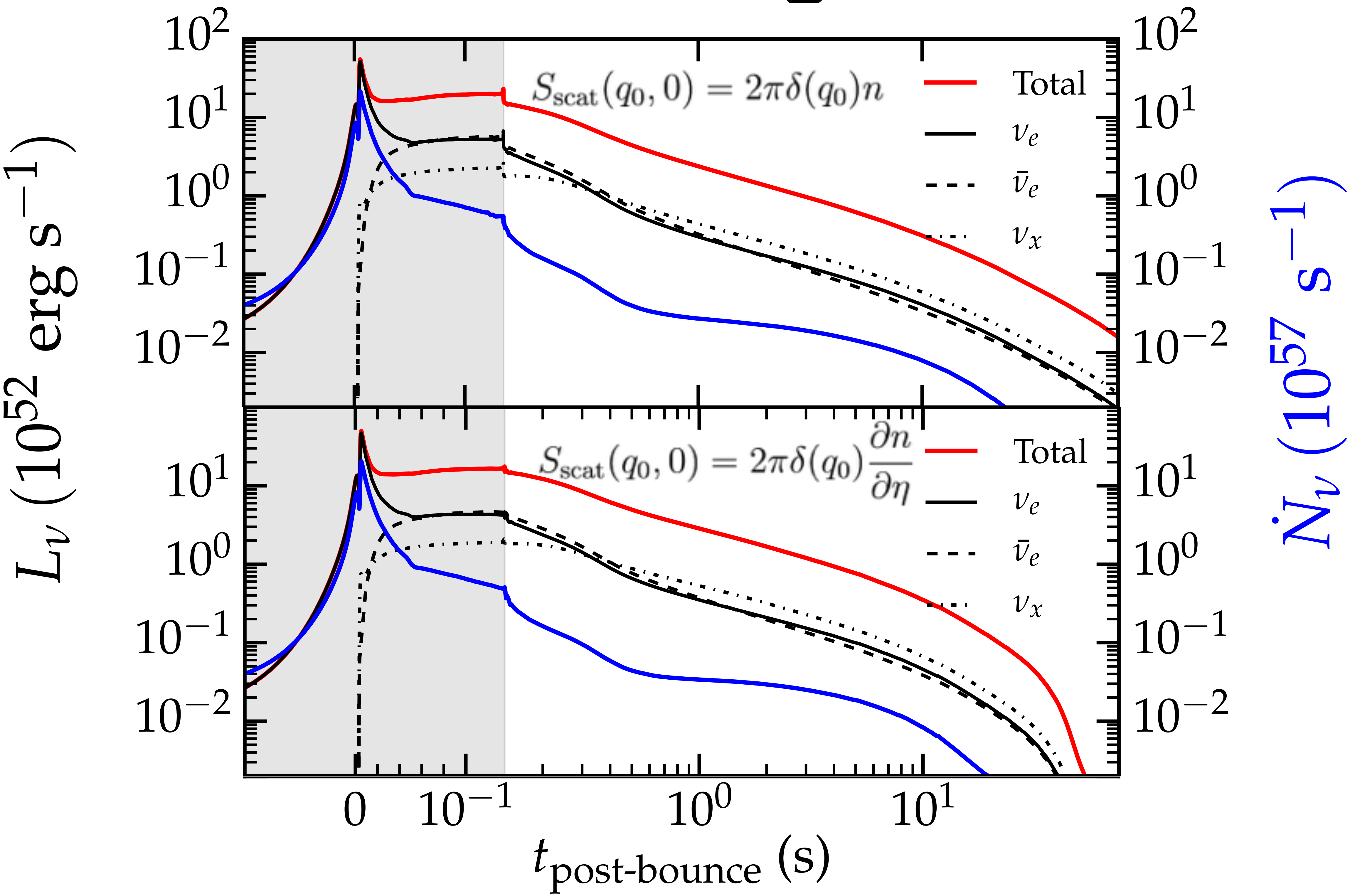
$$\left(\frac{\partial P}{\partial Y_L}\right)_{n_B} \simeq n_B^{4/3} Y_e^{1/3} - 4 n_B^2 E'_{\rm sym}(1-2Y_e)$$

Comparison of Count Rates including Convection and Opacity Corrections



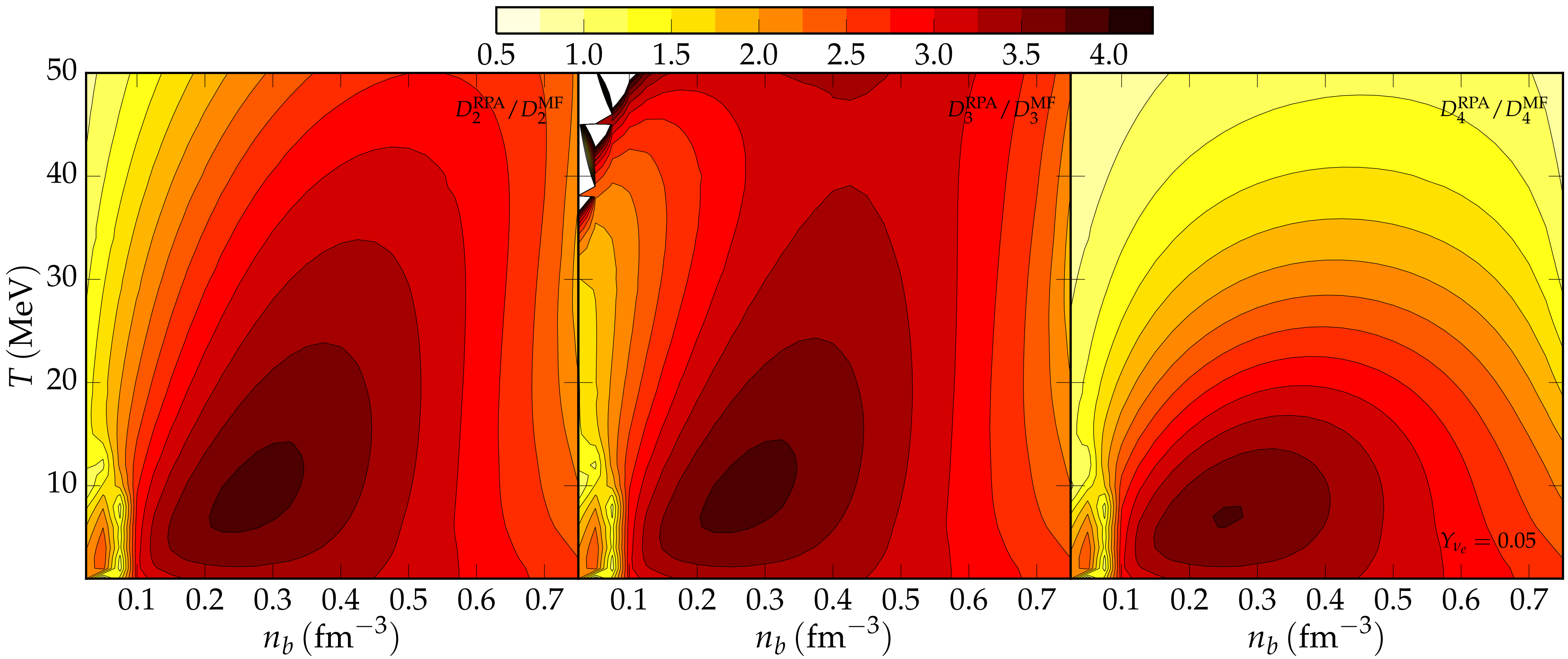
LR et al. (2012)

Opacity Dependence of Late Time Cooling



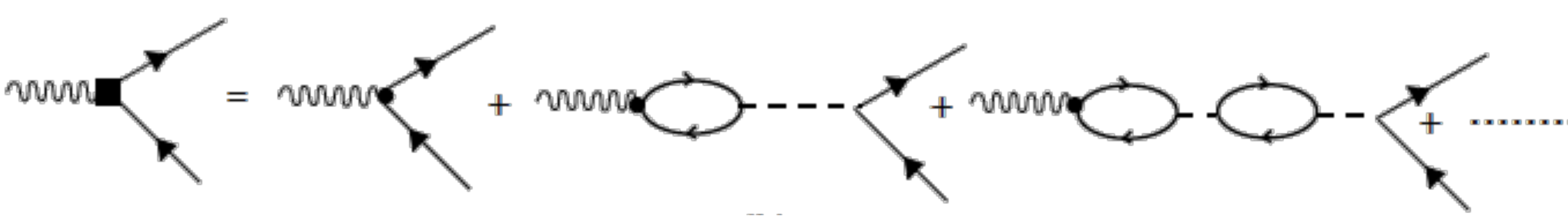
Impact of Nuclear Correlations on Neutrino Opacities

See Horowitz '93, Reddy et al. '99, and Burrows & Sawyer '99

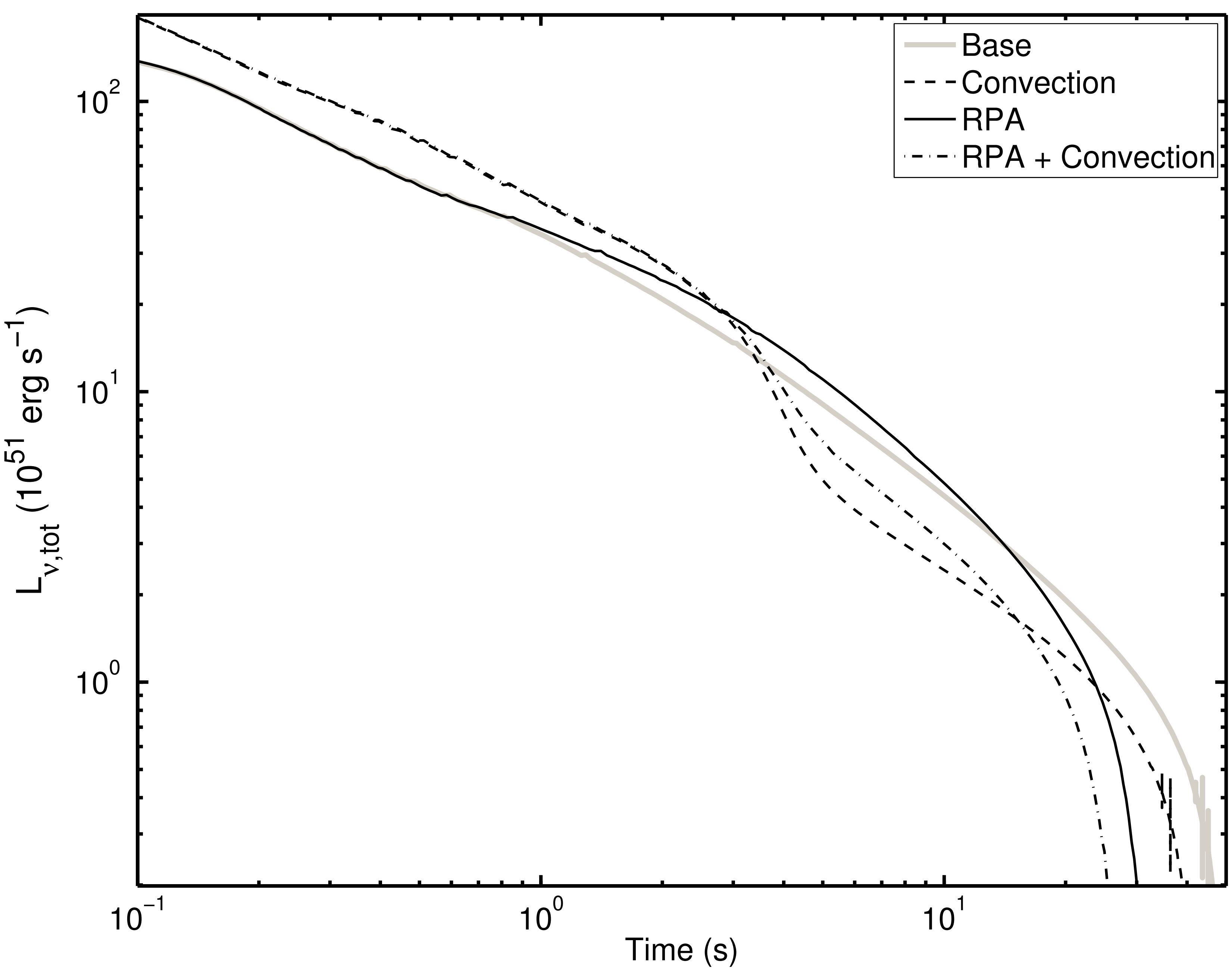


Neutrino Diffusion Coefficients

Correlations through the RPA:

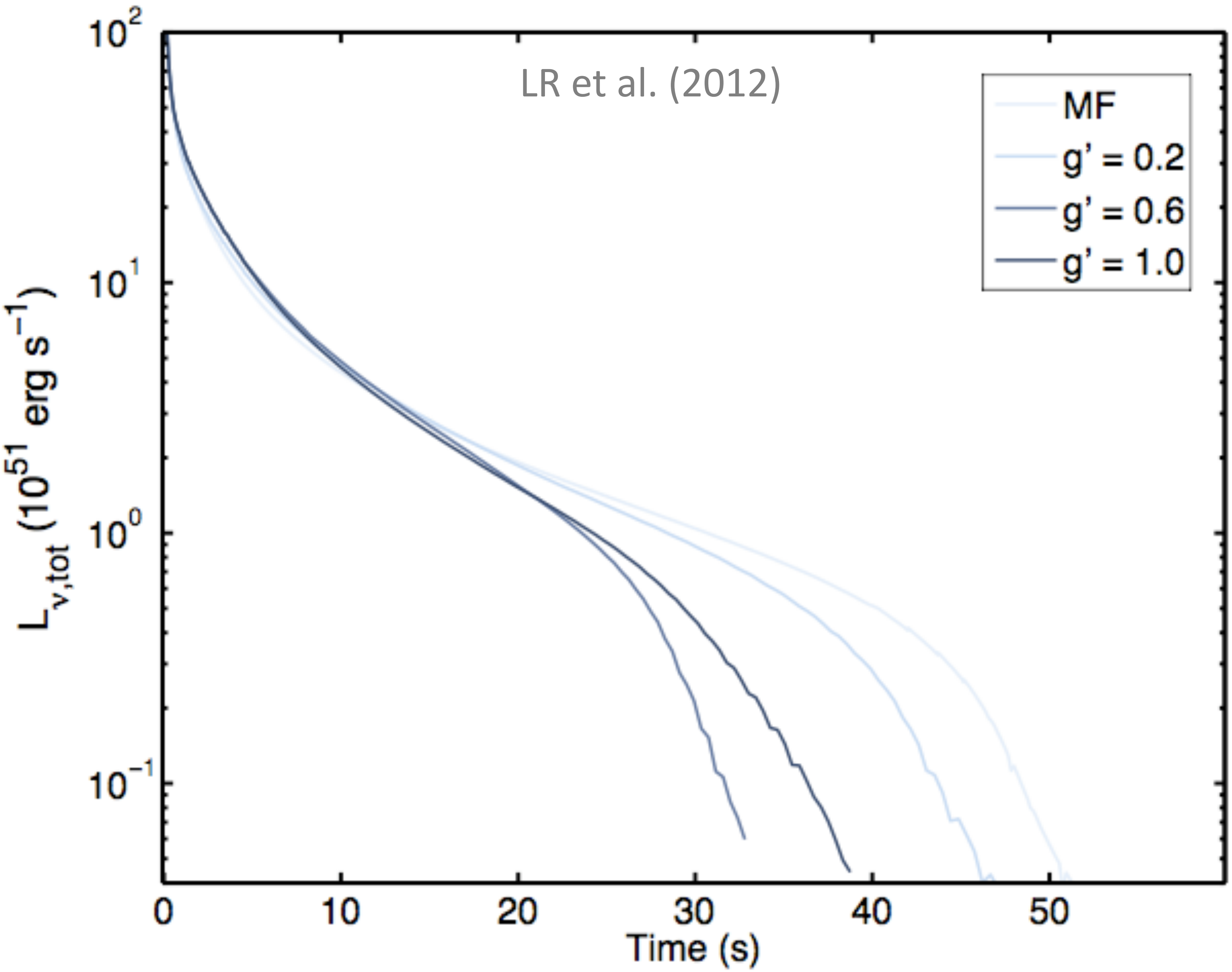


Impact of Screening



LR et al. (2012)
see also Huedepohl et al. (2010)

Variations in the Interaction

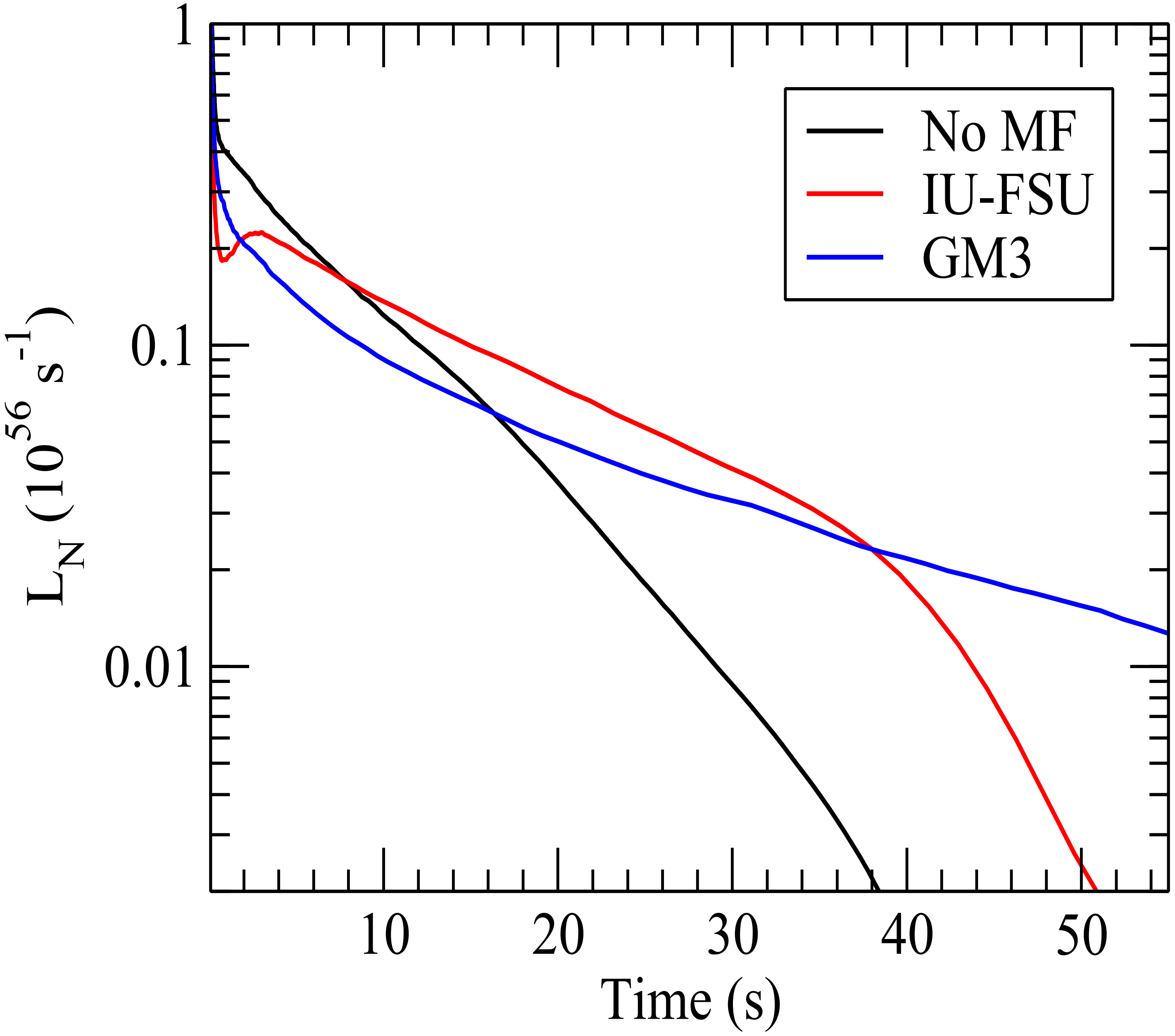


Varying the axial interaction

Reddy et al. (1999)

The Deleptonization Rate

- Nuclear symmetry energy also effects deleptonization rate of PNS
- Inclusion of mean fields decreases deleptonization rate, which also pushes towards lower electron fraction
- Larger L results in longer deleptonization timescale
- Detectable?



Conclusions

- The long term neutrino cooling signal is not particularly sensitive to progenitor structure for fixed remnant mass
- PNS convection significantly impacts the neutrino cooling timescale, produces a break in the neutrino emission
- Convection is sensitive to the nuclear EoS (mainly the symmetry energy)
- Neutrino opacities especially important to the late time cooling timescale
- In particular, nuclear correlations can also leave a signature on the tail of the neutrino signal