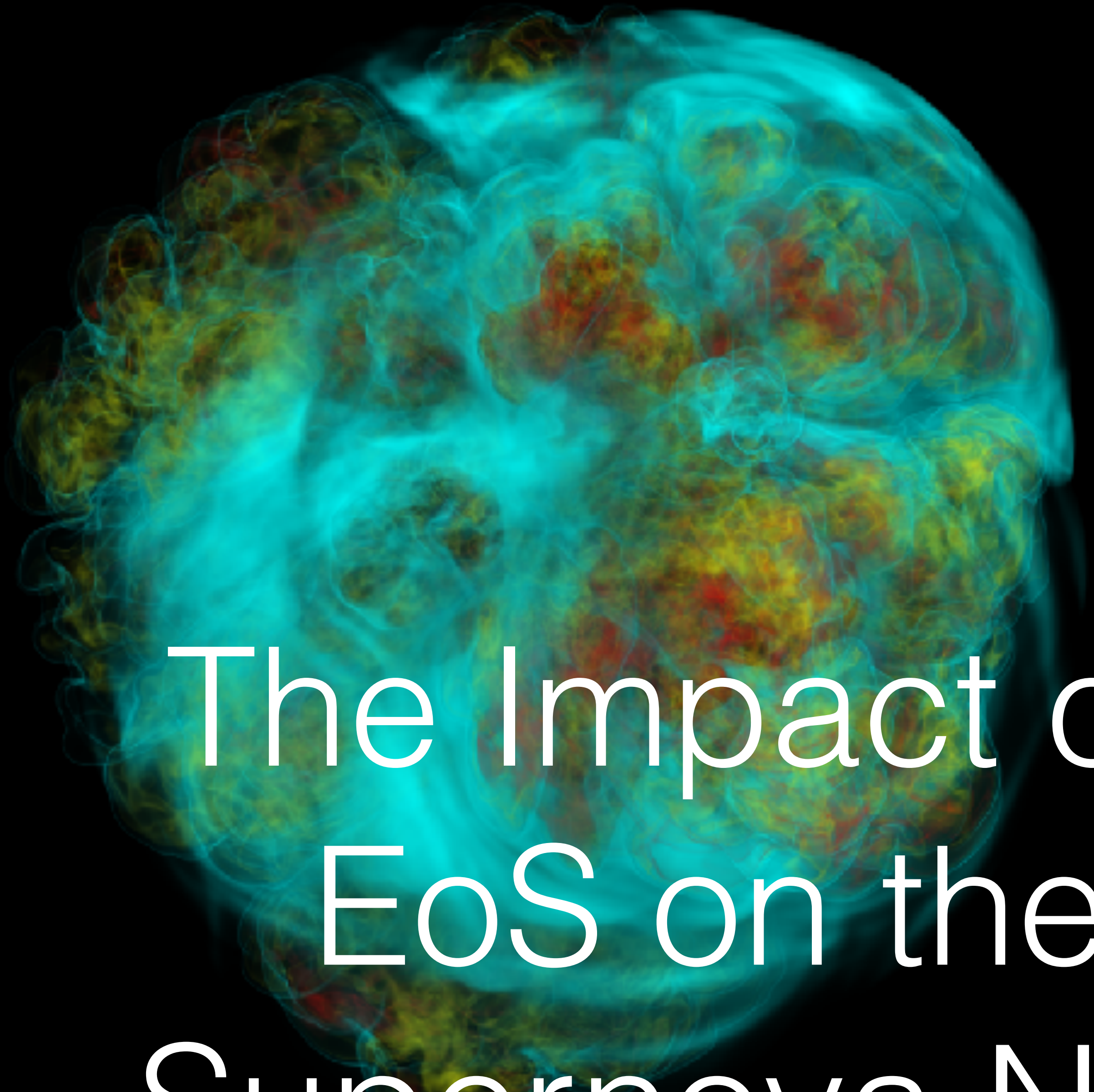


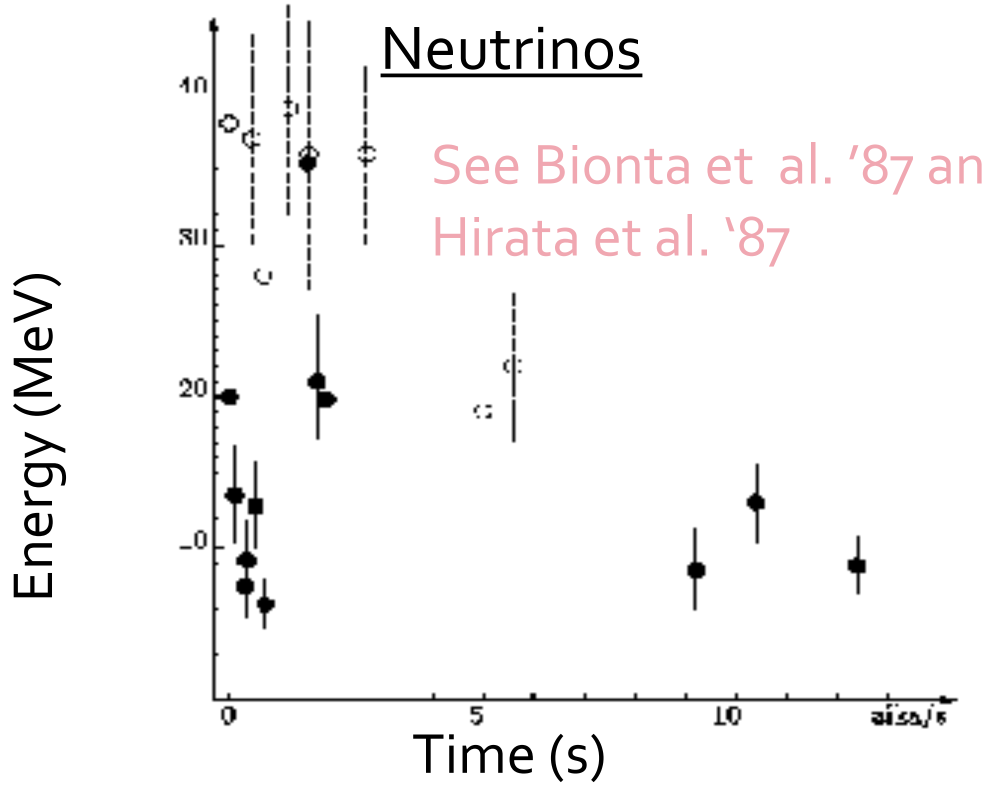
The Impact of the Nuclear EoS on the Long Term Supernova Neutrino Signal

Luke Roberts
NSCL, MSU

Collaborators: Sanjay Reddy, Andre Schneider, Gang Shen

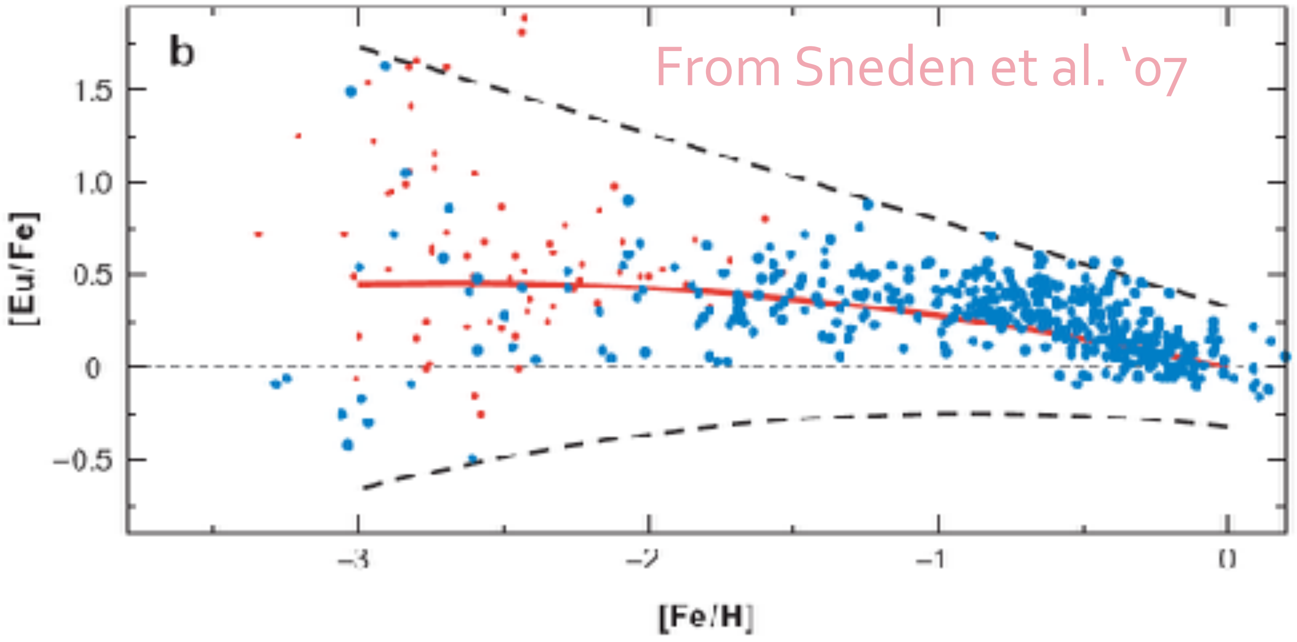
Core Collapse Supernovae: Multi-Messenger Events

Neutrinos



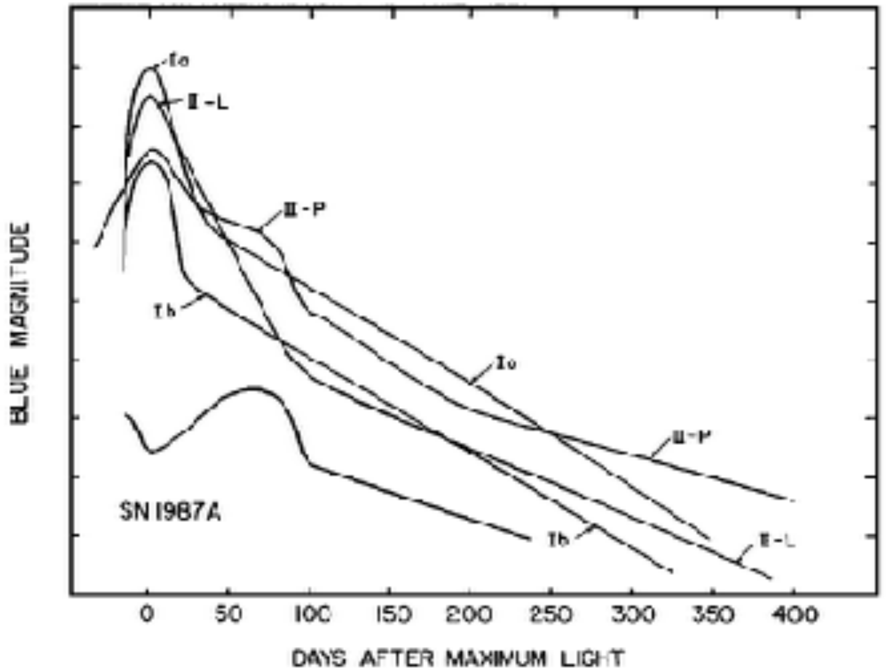
See Bionta et al. '87 and Hirata et al. '87

Nucleosynthesis



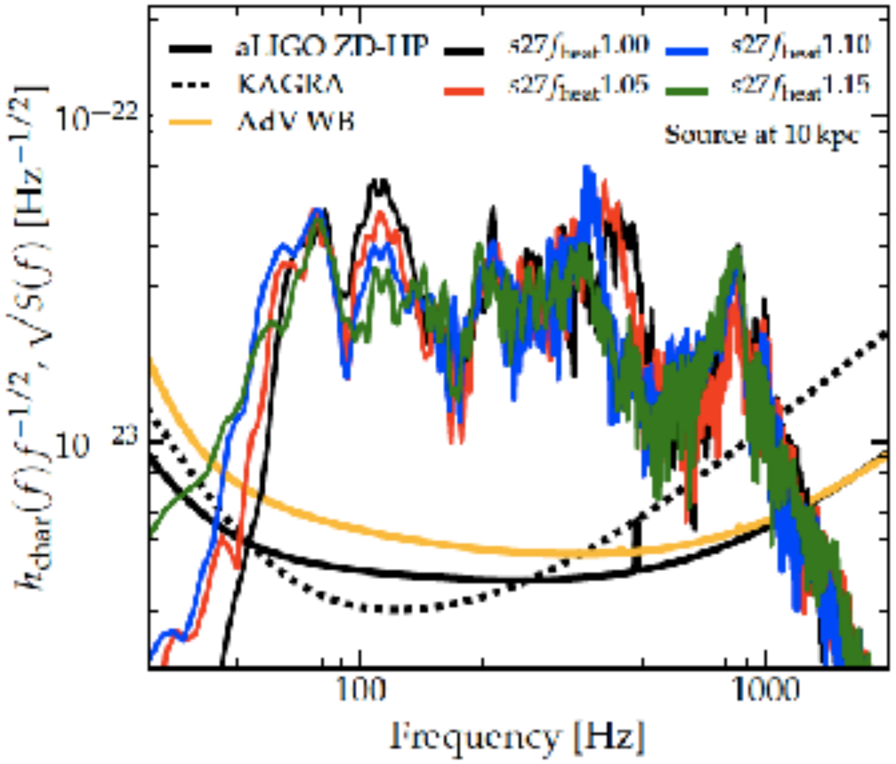
From Sneden et al. '07

Electromagnetic



From Filippenko '97

Gravitational Waves



From Ott et al. '12

Overview

- Background
- Impact of convection on neutrino emission
- Impact of opacities on neutrino emission and nucleosynthesis

Milky Way Supernova Rate

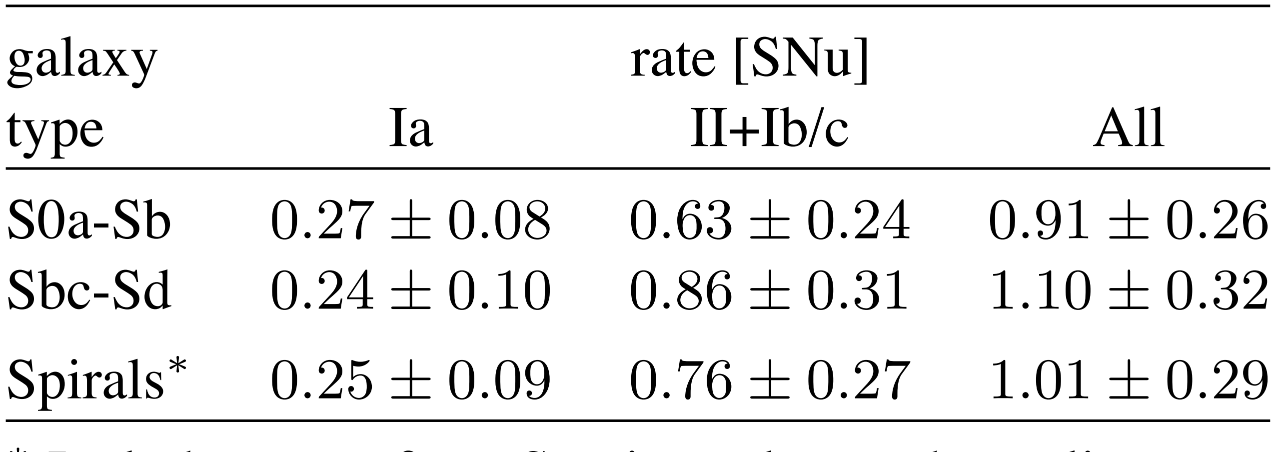
- Most recent known MW CCSN Cas A (~300 yrs)

- Look for supernovae in galaxies analogous to MW (Cappellaro et al. 1999)

- Take census of historical galactic supernovae and correct for obscuration (Tammann et al. 1994)

- Reasonably consistent

multiply by ~2.4 to get MW rate



galaxy type	rate [SNu] Ia	 II+Ib/c	 All
S0a-Sb	0.27 ± 0.08	0.63 ± 0.24	0.91 ± 0.26
Sbc-Sd	0.24 ± 0.10	0.86 ± 0.31	1.10 ± 0.32
Spirals*	0.25 ± 0.09	0.76 ± 0.27	1.01 ± 0.29

Cappellaro et al. (1999)

SN* Neutrino Detectors

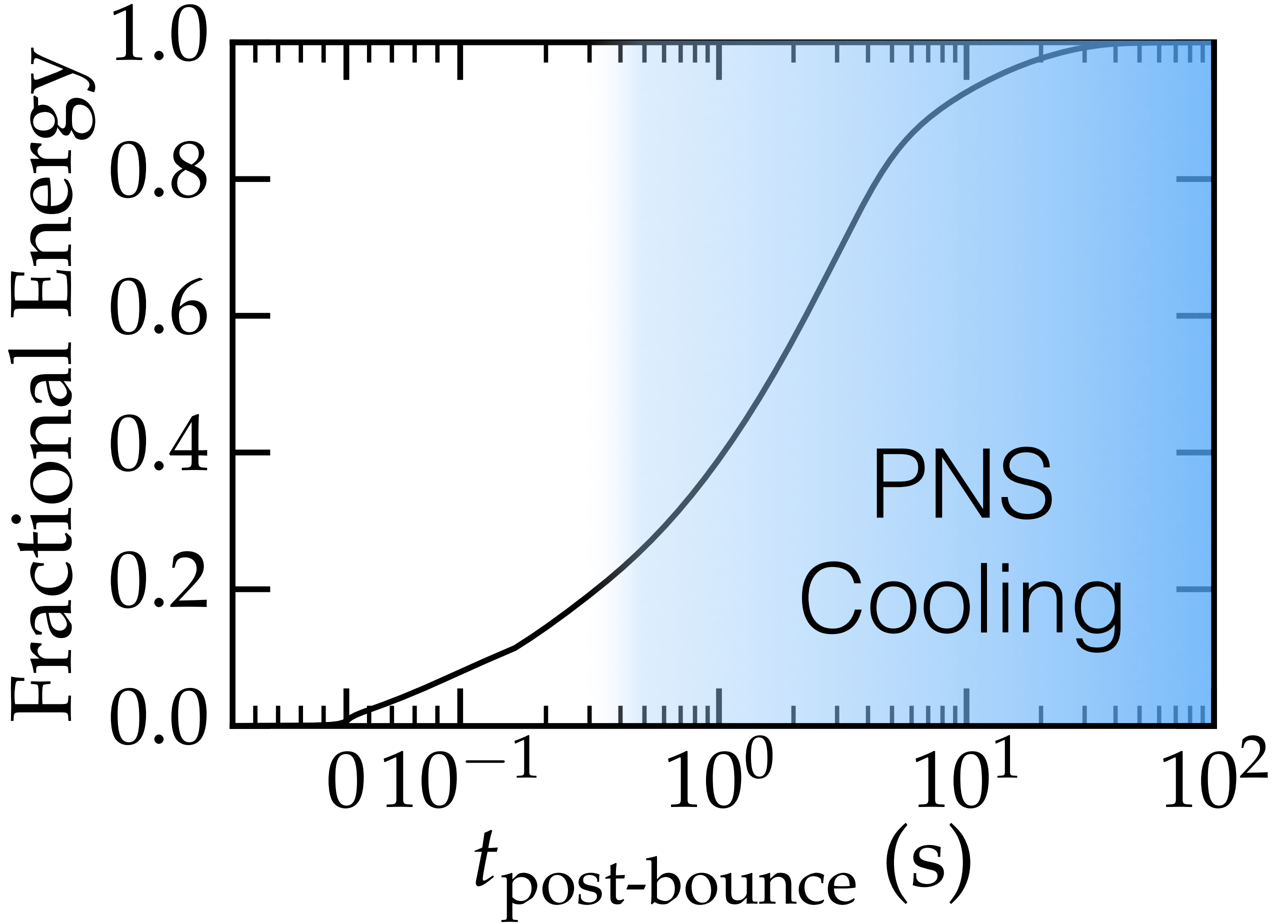
Detector	Type	Mass (kt)	Location	Events	Flavors	Status
Super-Kamiokande	H_2O	32	Japan	7,000	$\bar{\nu}_e$	Running
LVD	C_nH_{2n}	1	Italy	300	$\bar{\nu}_e$	Running
KamLAND	C_nH_{2n}	1	Japan	300	$\bar{\nu}_e$	Running
Borexino	C_nH_{2n}	0.3	Italy	100	$\bar{\nu}_e$	Running
IceCube	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Running
Baksan	C_nH_{2n}	0.33	Russia	50	$\bar{\nu}_e$	Running
MiniBooNE*	C_nH_{2n}	0.7	USA	200	$\bar{\nu}_e$	(Running)
HALO	Pb	0.08	Canada	30	ν_e, ν_x	Running
Daya Bay	C_nH_{2n}	0.33	China	100	$\bar{\nu}_e$	Running
NOνA*	C_nH_{2n}	15	USA	4,000	$\bar{\nu}_e$	Turning on
SNO+	C_nH_{2n}	0.8	Canada	300	$\bar{\nu}_e$	Near future
MicroBooNE*	Ar	0.17	USA	17	ν_e	Near future
DUNE	Ar	34	USA	3,000	ν_e	Proposed
Hyper-Kamiokande	H_2O	560	Japan	110,000	$\bar{\nu}_e$	Proposed
JUNO	C_nH_{2n}	20	China	6000	$\bar{\nu}_e$	Proposed
RENO-50	C_nH_{2n}	18	Korea	5400	$\bar{\nu}_e$	Proposed
LENA	C_nH_{2n}	50	Europe	15,000	$\bar{\nu}_e$	Proposed
PINGU	Long string	(600)	South Pole	(10^6)	$\bar{\nu}_e$	Proposed

Scholberg et al. (2015)

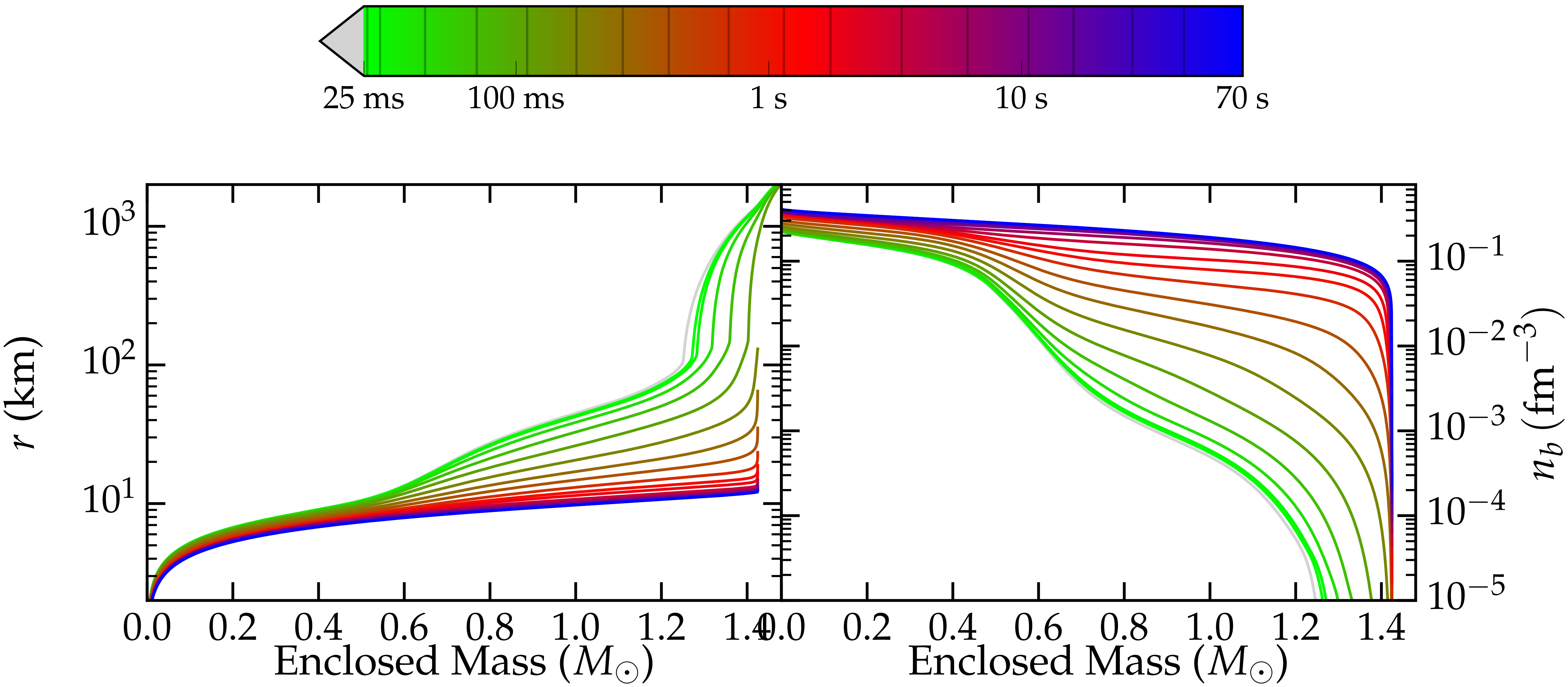
Late Time SN Neutrino Emission

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

- 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

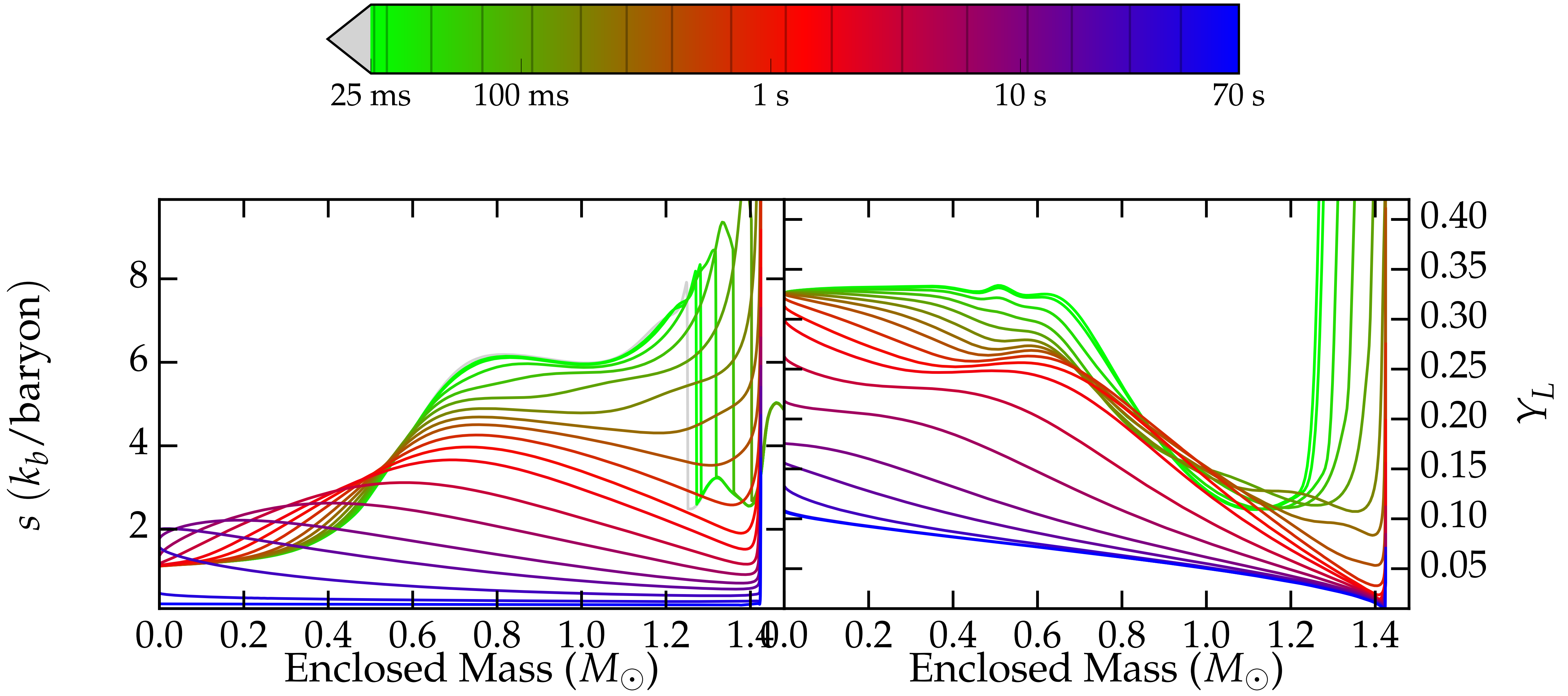


Long Term PNS Evolution



$$E_{\rm SN} \sim \frac{3GM_{\rm pns}^2}{5r_{\rm NS}} \approx 3\times 10^{53}\,{\rm erg}\left(\frac{M_{\rm pns}}{M_\odot}\right)^2\left(\frac{r_{NS}}{12\,{\rm km}}\right)^{-1}$$

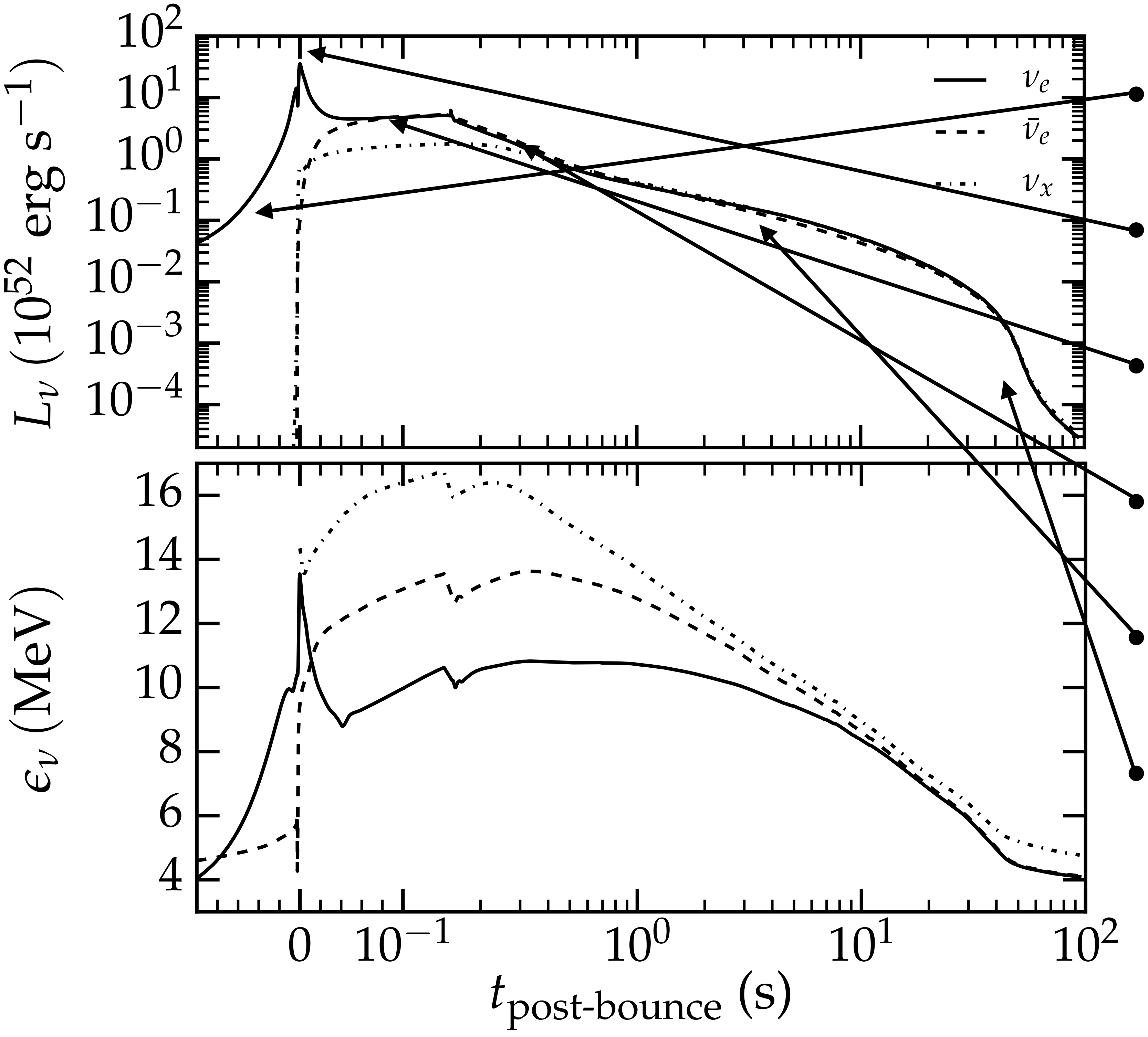
Long Term PNS Evolution



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

See Prakash et al. '97

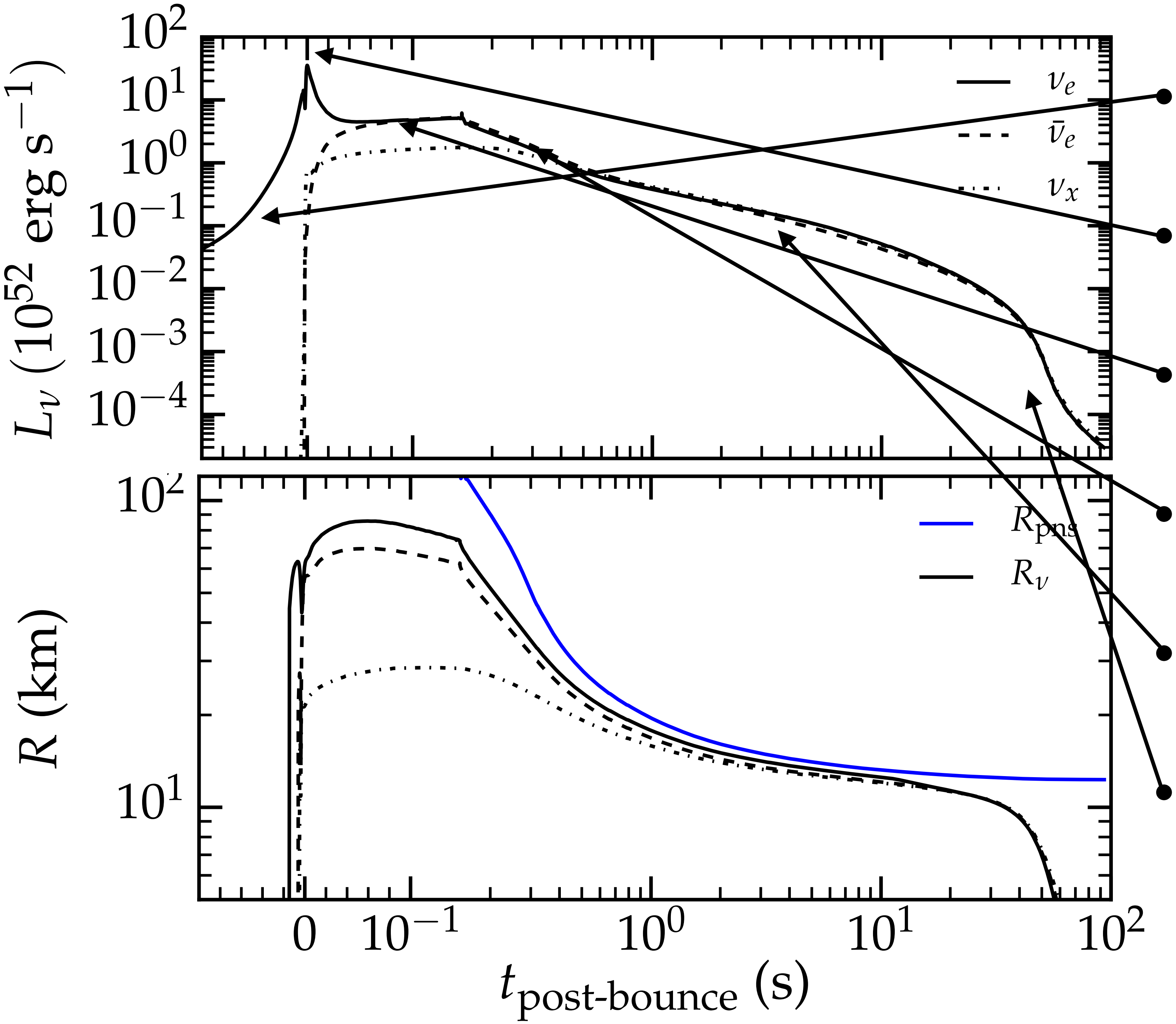
Anatomy of the Neutrino Signal



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

LR and Reddy ‘15

Anatomy of the Neutrino Signal



- Core deleptonization
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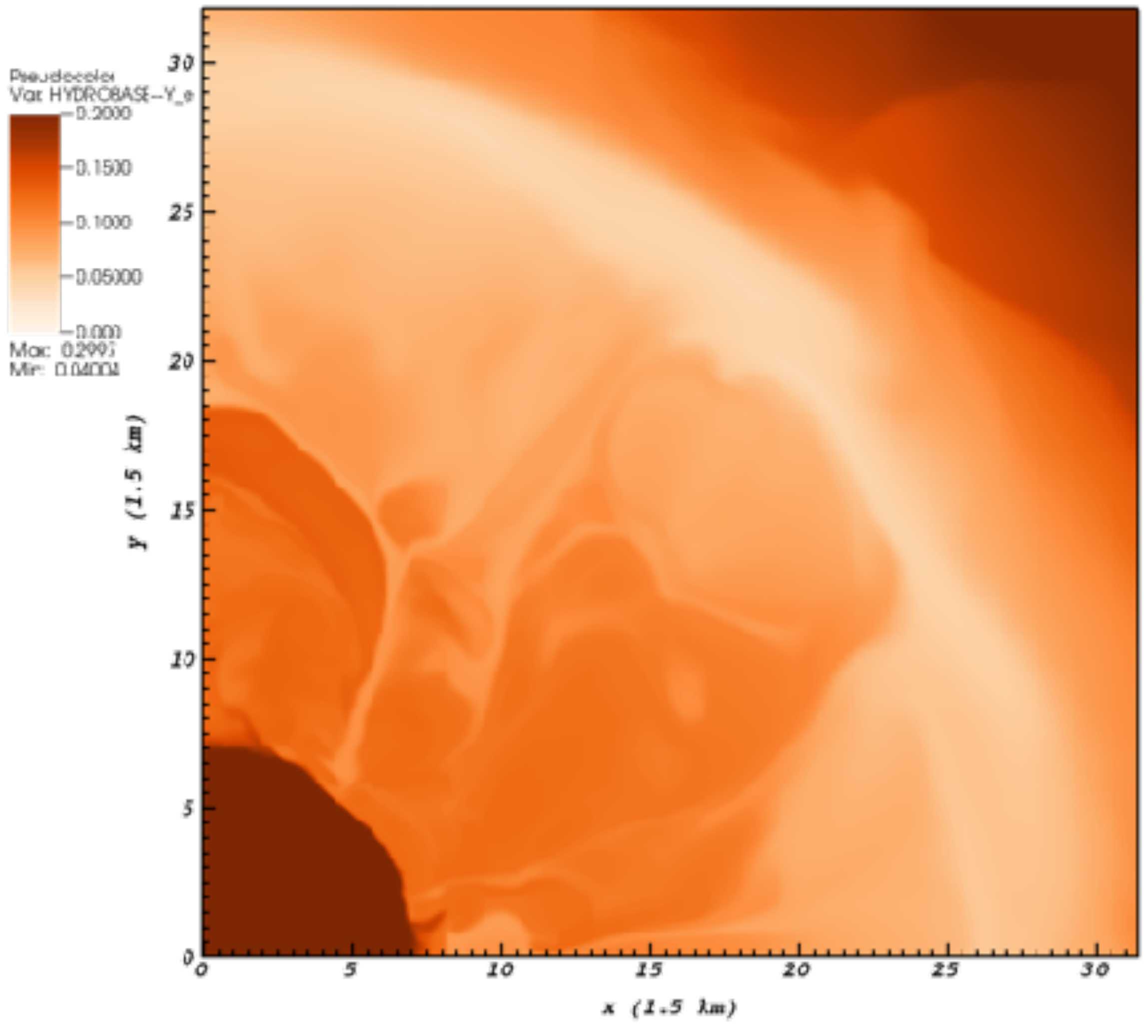
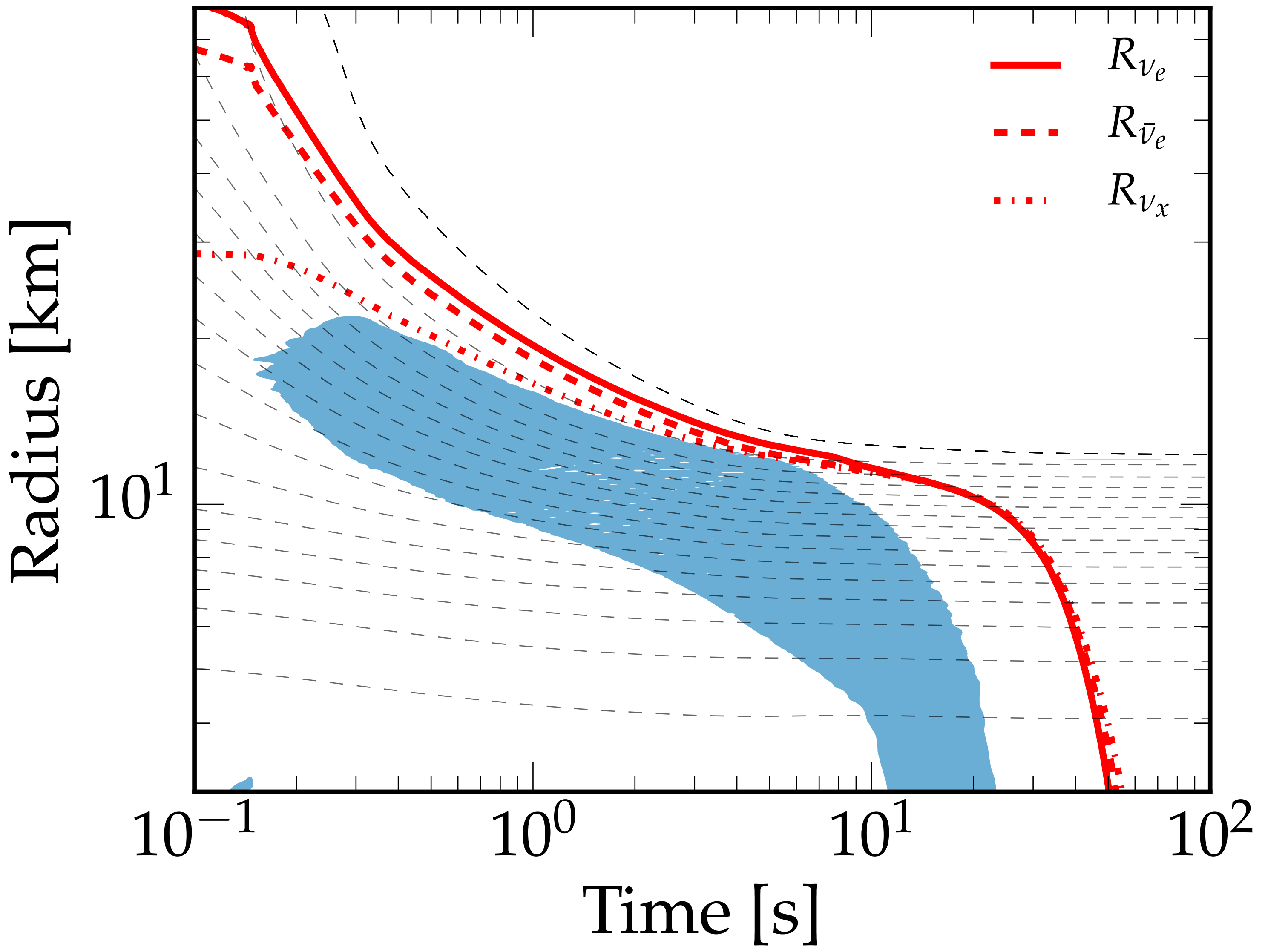
LR and Reddy ‘15

Proto-Neutron Star Convection

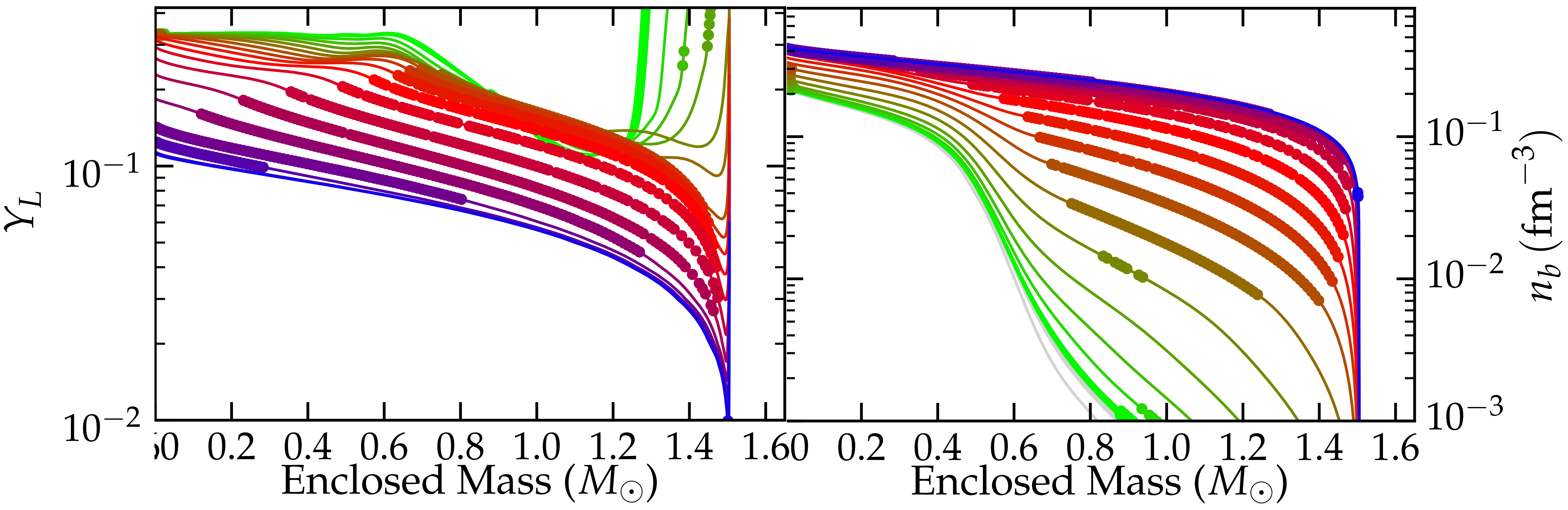




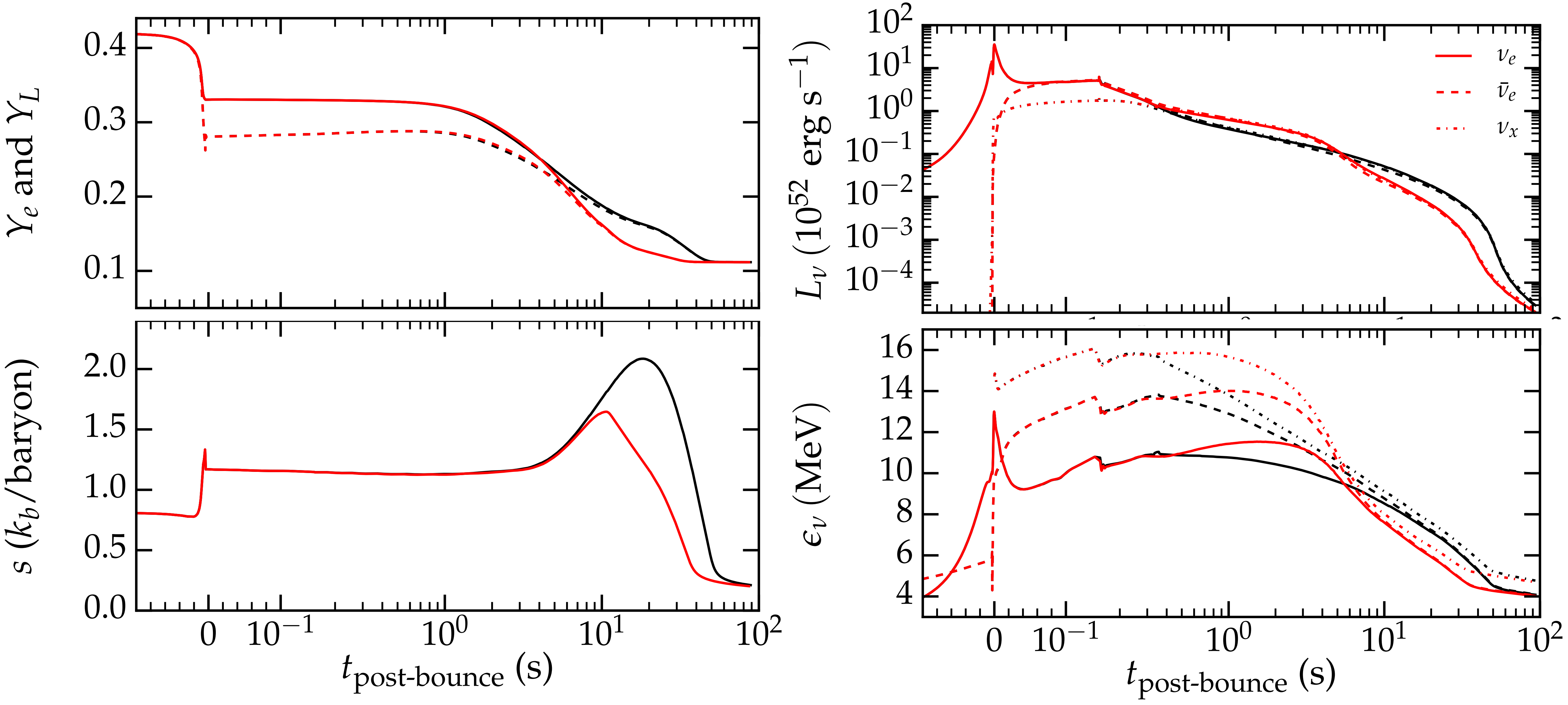
Region of convective instability determined by the Ledoux Criterion:

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

Convection Conditions



Convection



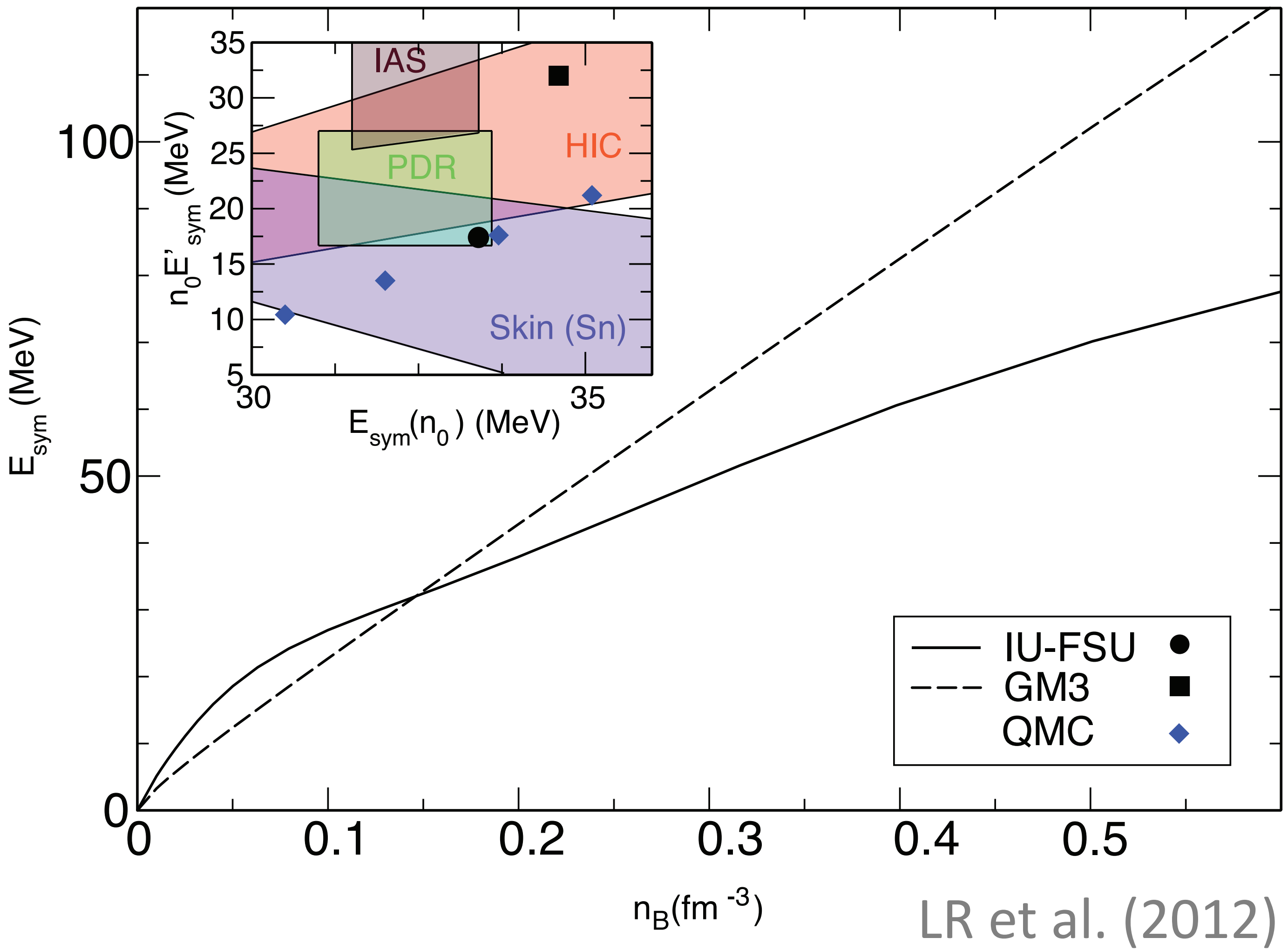
Black: No Convection

Red: Convection

See also Mirizzi et al. (2015)

Proto-Neutron Star Convection

Dependence on the EoS

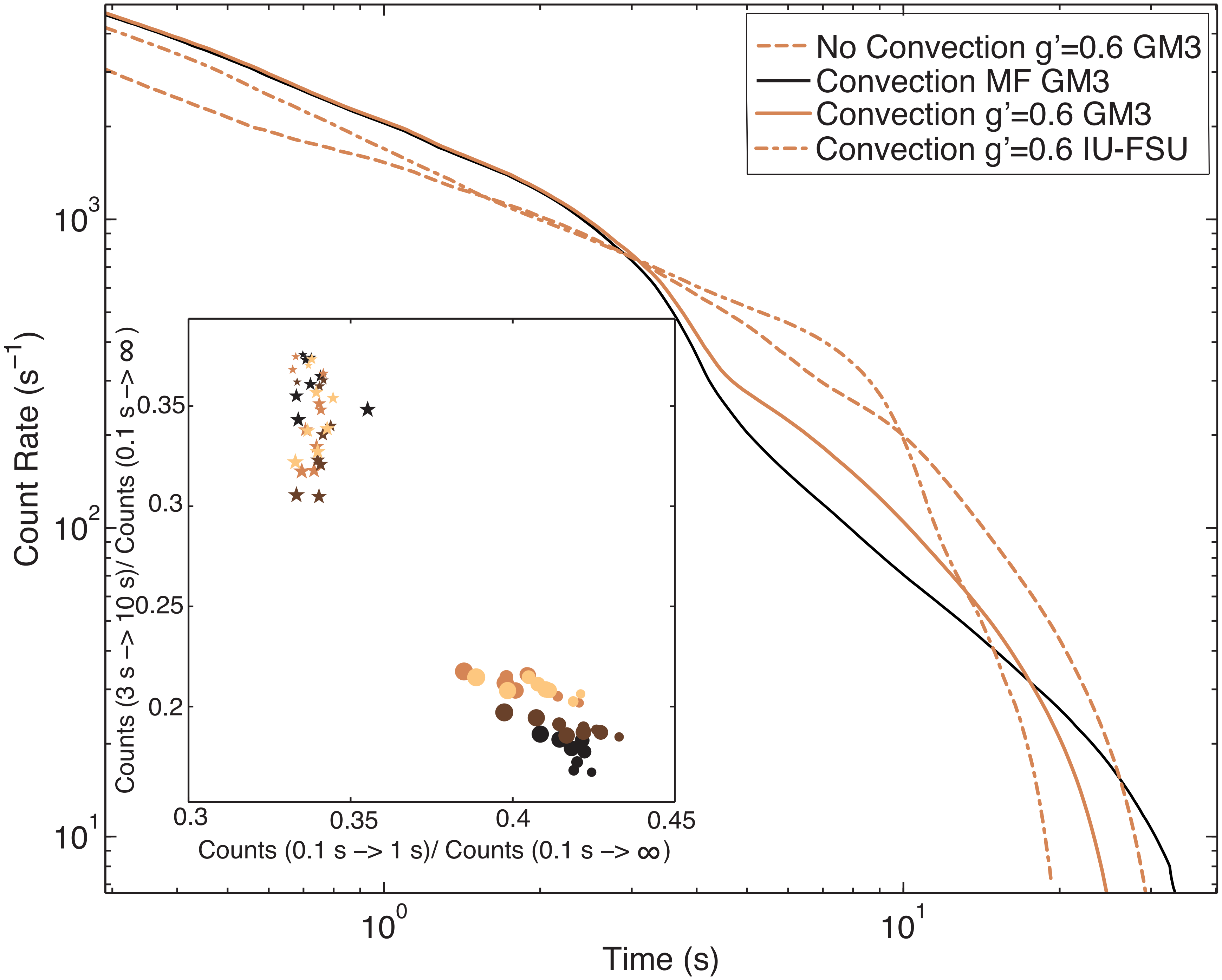


LR et al. (2012)

Pressure derivatives are sensitive to the symmetry energy derivative:

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

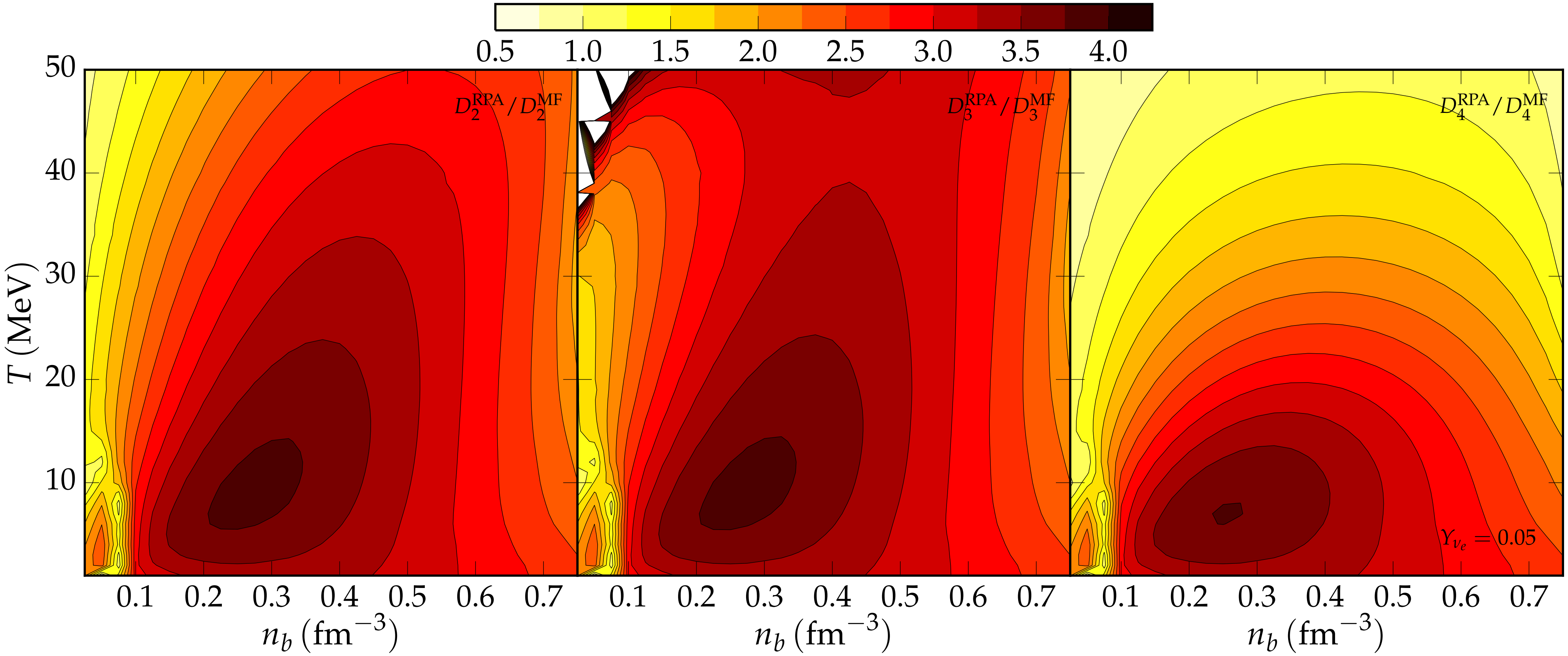
Comparison of Count Rates including Convection and Opacity Corrections



LR et al. (2012)

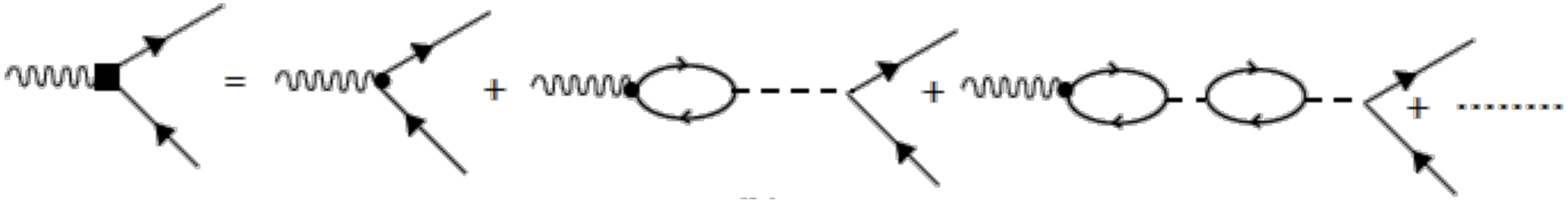
Impact of Nuclear Correlations on Neutrino Opacities

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

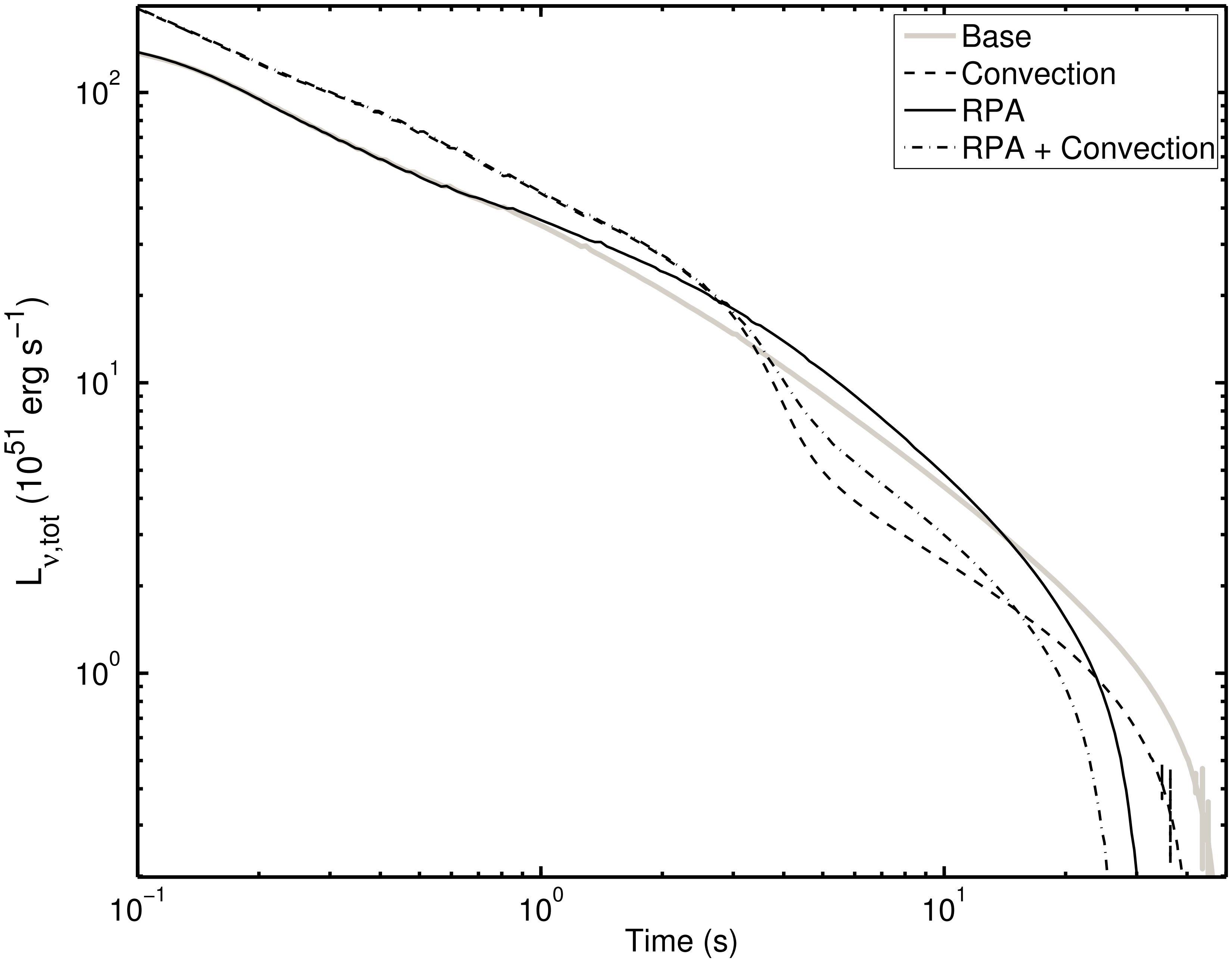


Neutrino Diffusion Coefficients

Correlations through the RPA:

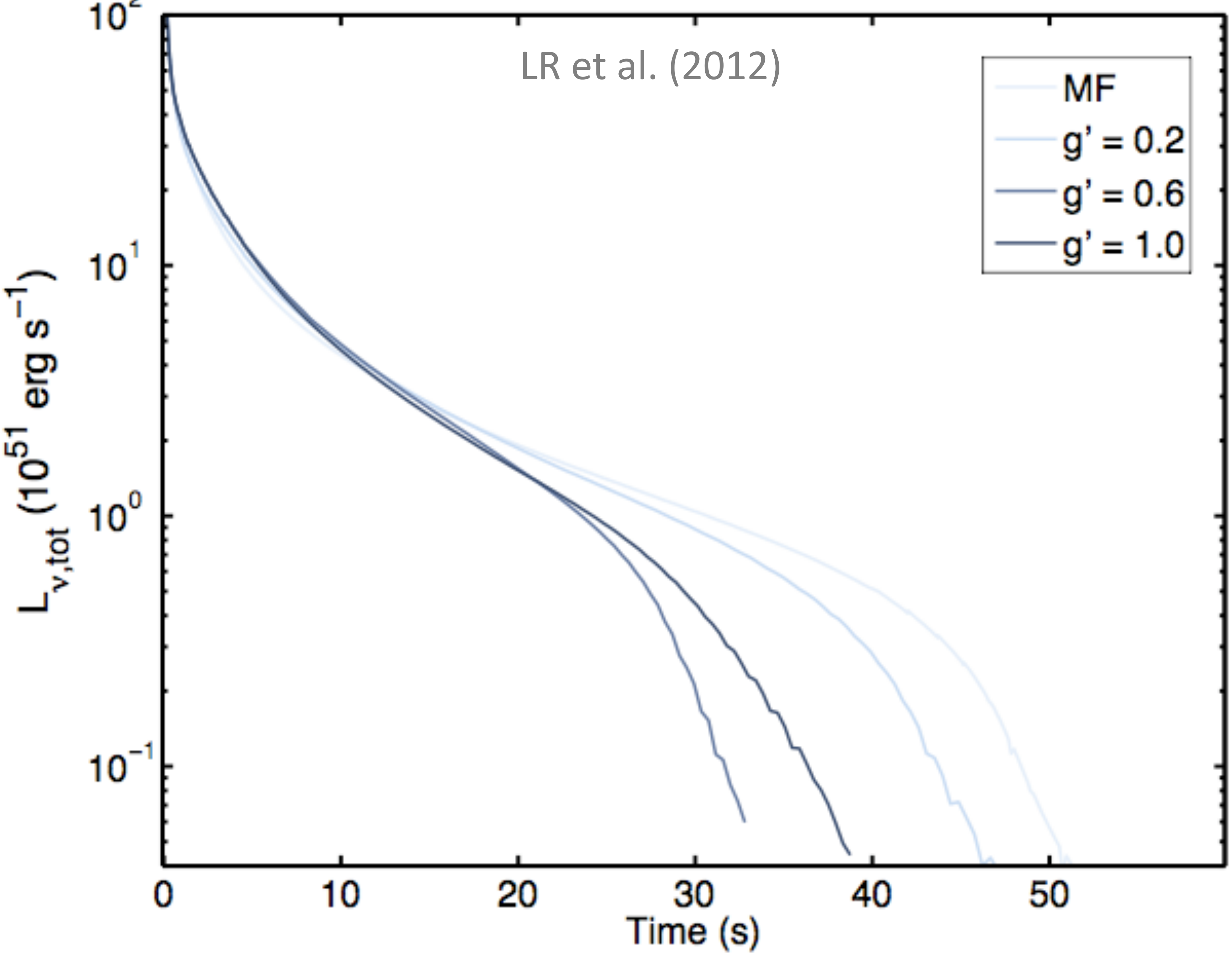


Impact of Screening



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

Variations in the Interaction

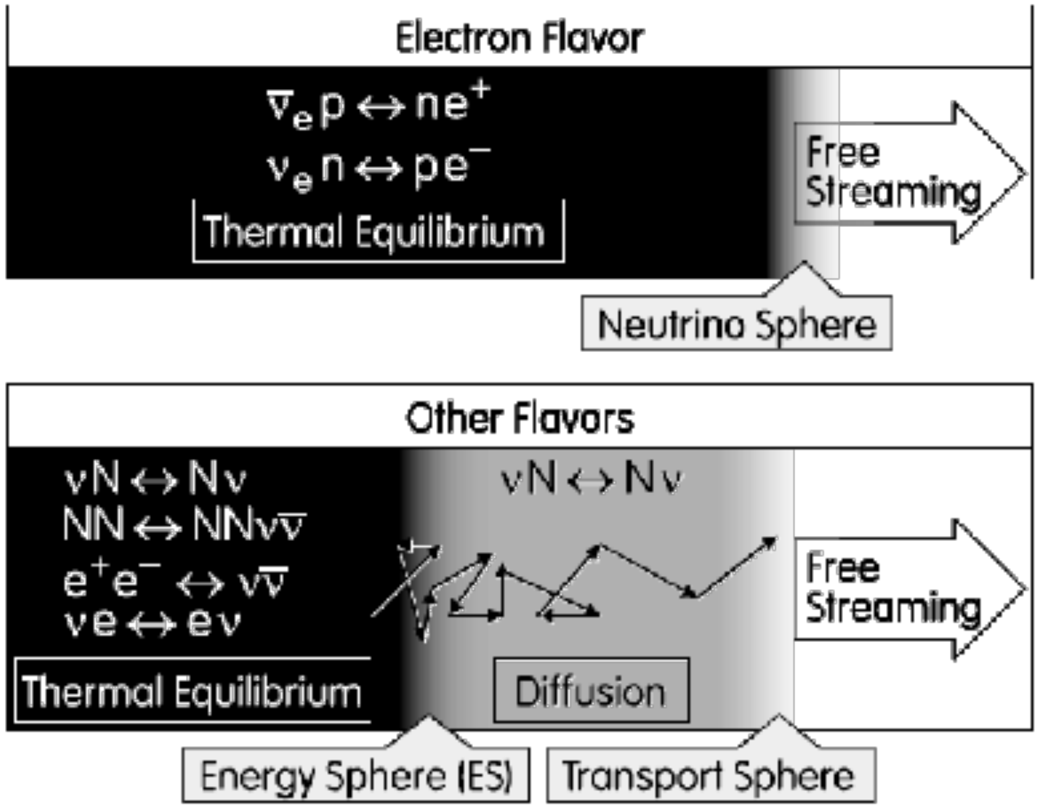


Varying the axial vector coupling

Reddy et al. (1999)

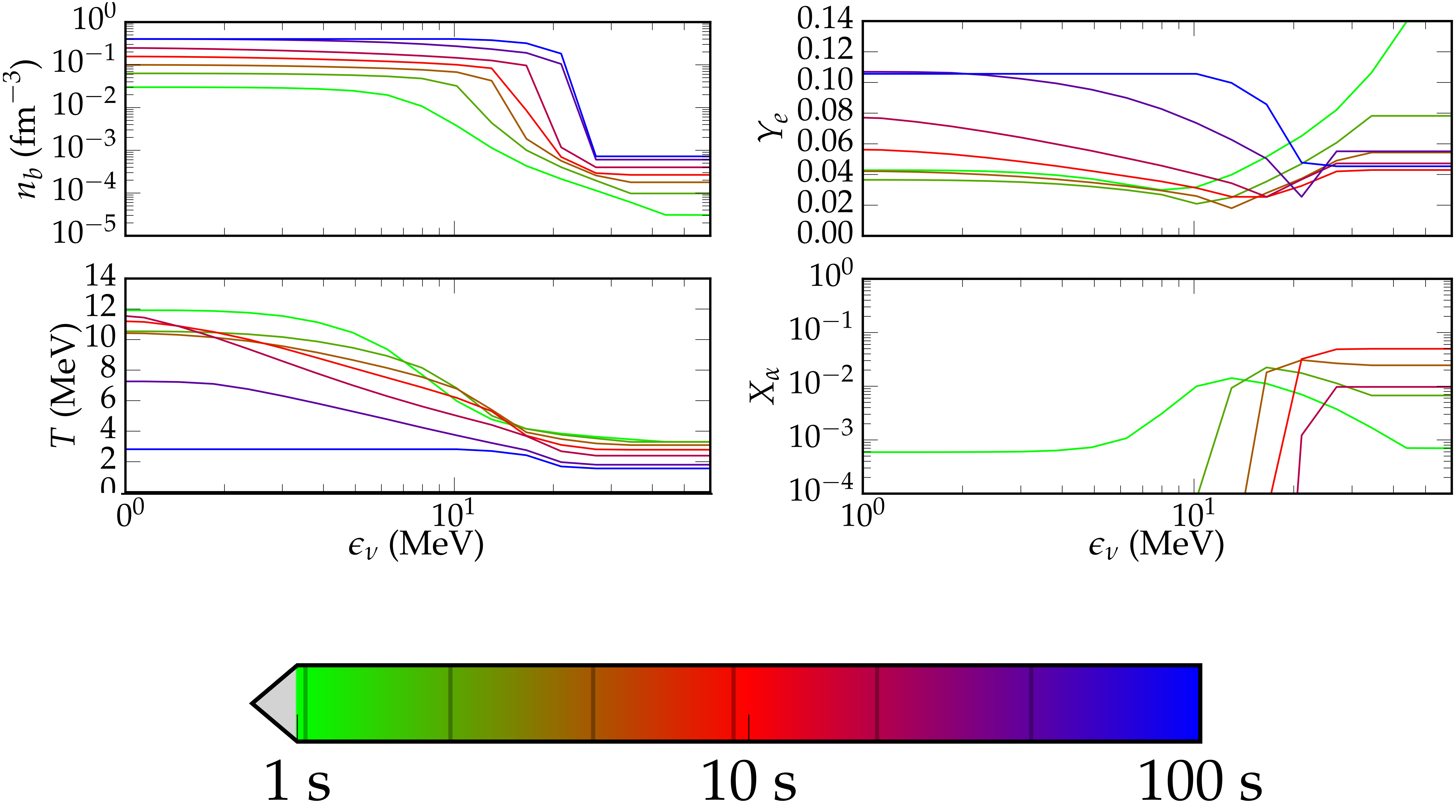
What Determines the ν_e Spectra?

- “Neutrino sphere” is not well defined, energy dependent, range of densities and temperature
- Both charged and neutral current reactions important to ν_e and anti-ν_e decoupling radii
- Charged current rates introduce asymmetry between neutrinos and antineutrinos
- Difference between ν_e and anti-ν_e spectra strongly influences electron fraction of the neutrino driven wind and the nucleosynthesis that occurs there



From Raffelt ‘01

Decoupling Conditions



Charged Current Interaction Rates in Medium

Nucleons are in an interacting medium, have altered dispersion relations:

$$E_i(k) = \sqrt{k^2 + M^{*2}} + U_i$$

Transfers potential difference to outgoing leptons:

$$\Delta U = U_n - U_p \approx 40 \times \frac{(n_n - n_p)}{n_0}\ \mathrm{MeV}$$

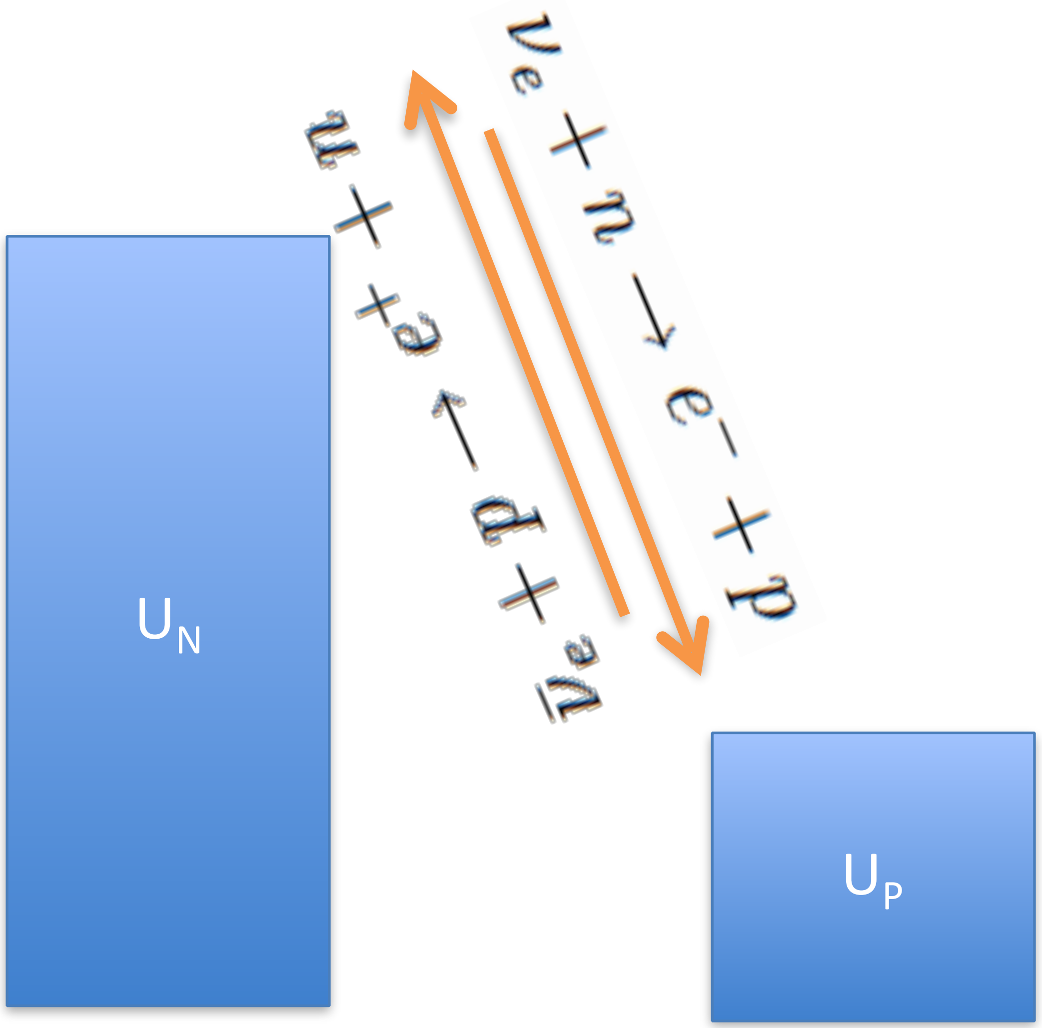
$$E_e = E_\nu + \Delta U$$

$$\frac{1}{V}\frac{d^2\sigma}{d\cos\theta\, dE_e} \propto \frac{G_F^2 \cos^2\theta_c}{4\pi^2}\, p_e\, E_e\, (1 - f_e(E_e))$$

Exponential increase in available phase space for electron neutrino capture:

$$\frac{\lambda^{-1}(\Delta U)}{\lambda^{-1}(\Delta U = 0)} \approx \frac{(\varepsilon_\nu + \Delta U)^2}{\varepsilon_\nu^2} \exp(\Delta U / T)$$

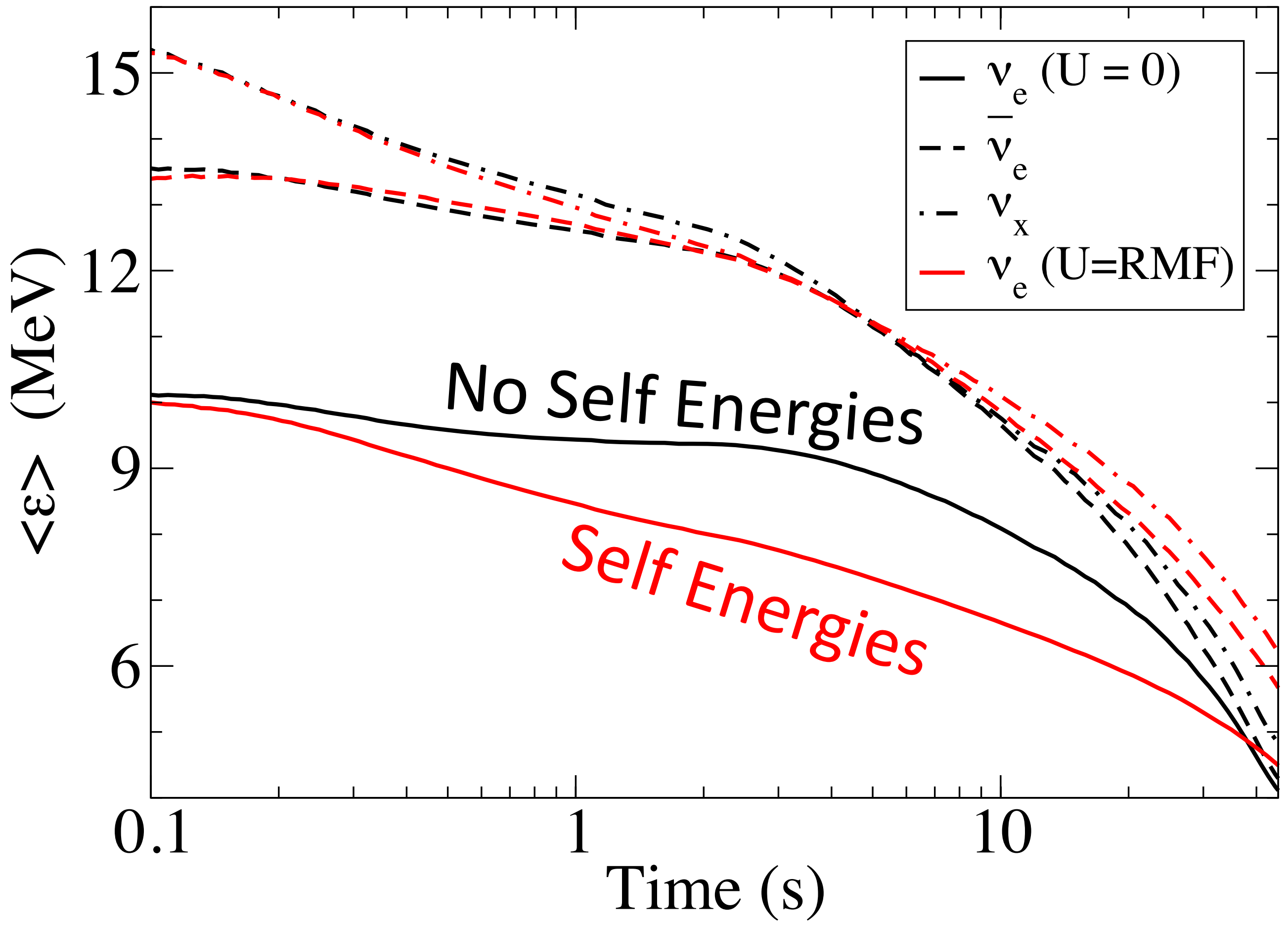
e.g. Reddy et al. 1998,
Horowitz & Perez-Garcia 2003,
LR, Reddy & Shen 2012,
LR & Reddy 2017



Neutrino emission w/ and w/o Nuclear Interactions

See LR ‘12 and Martinez-Pinedo et al. ‘12

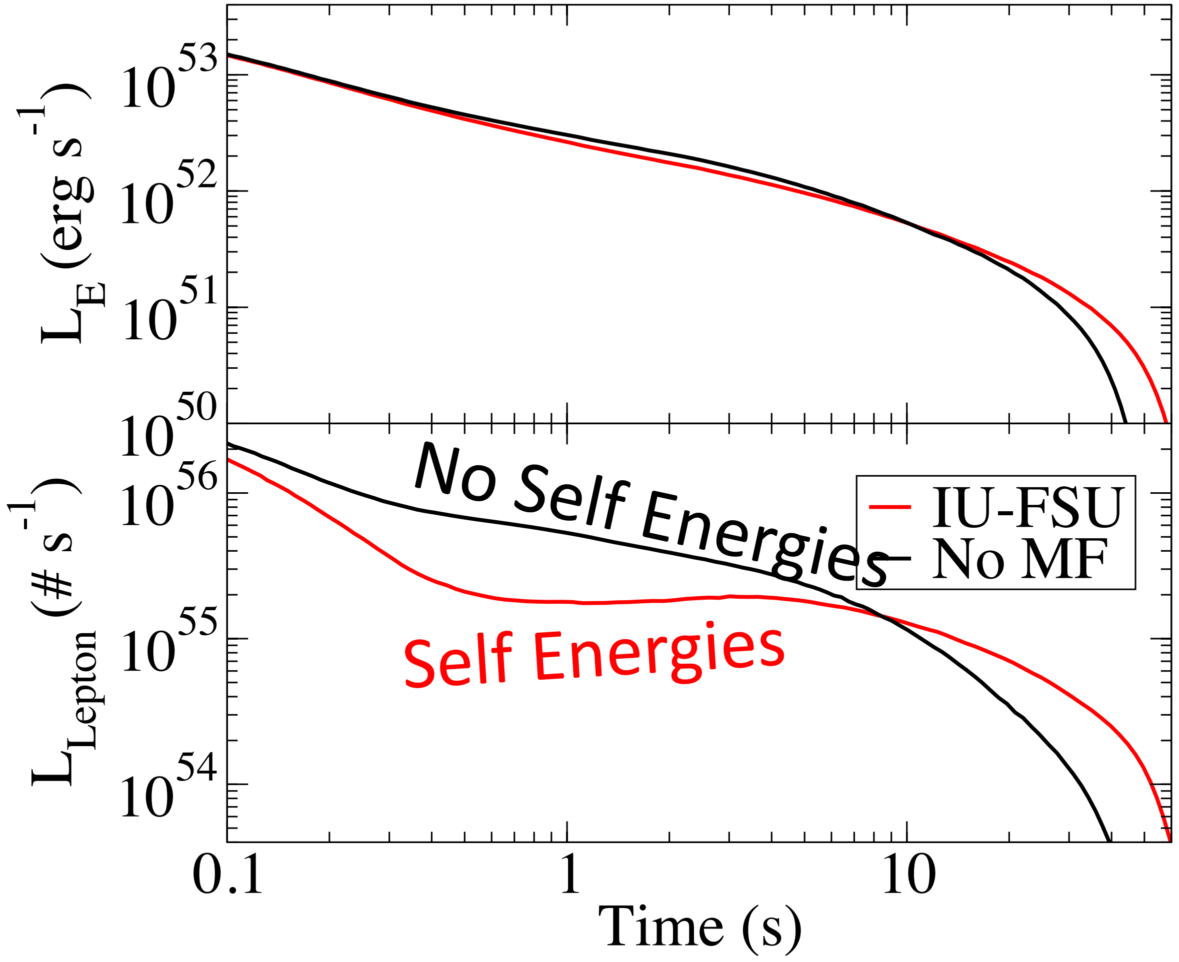
Self energies shift average neutrino energies



No Self Energies

Self Energies

Deleptonization

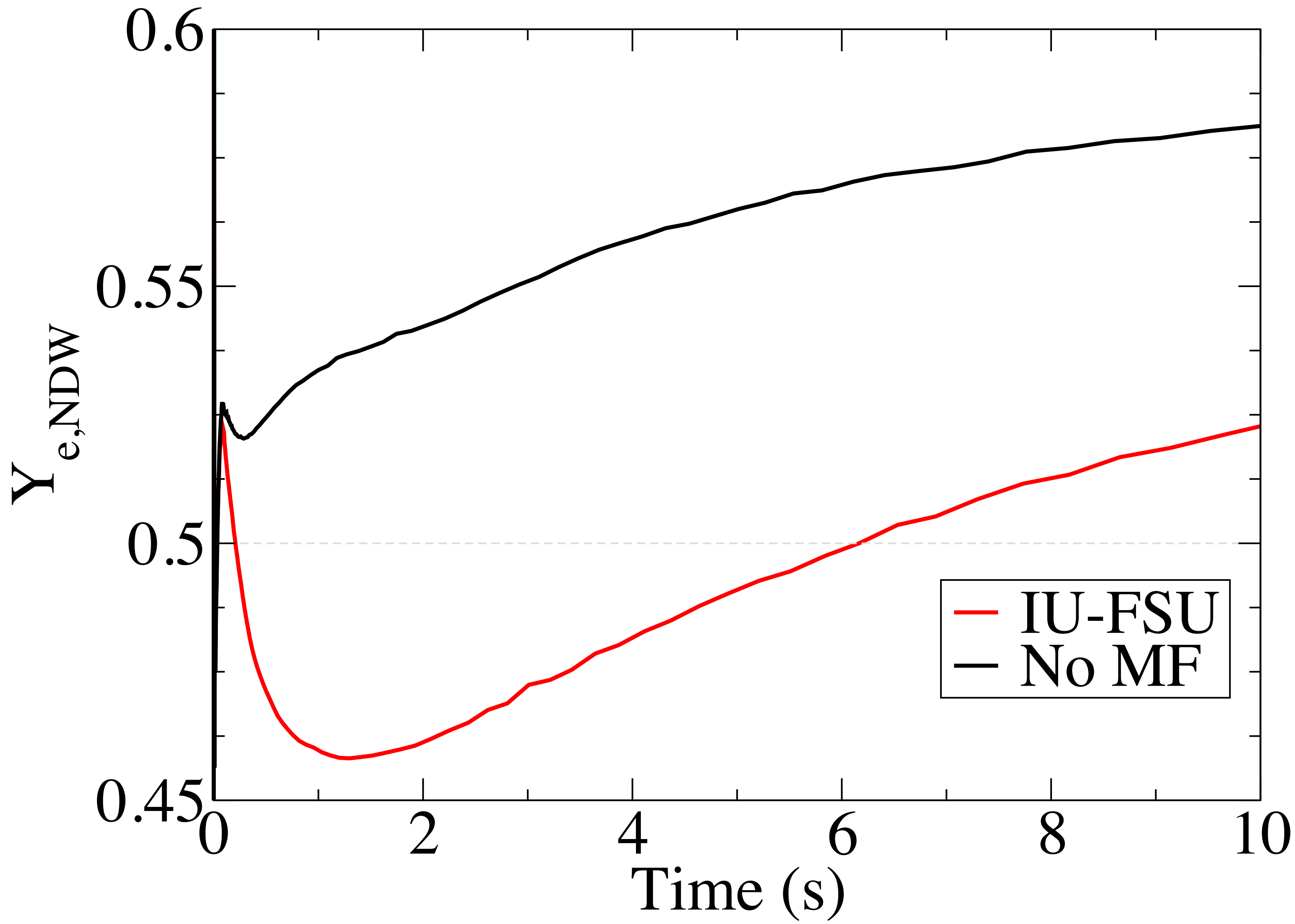


No Self Energies

Self Energies

Neutrino emission w/ and w/o Nuclear Interactions

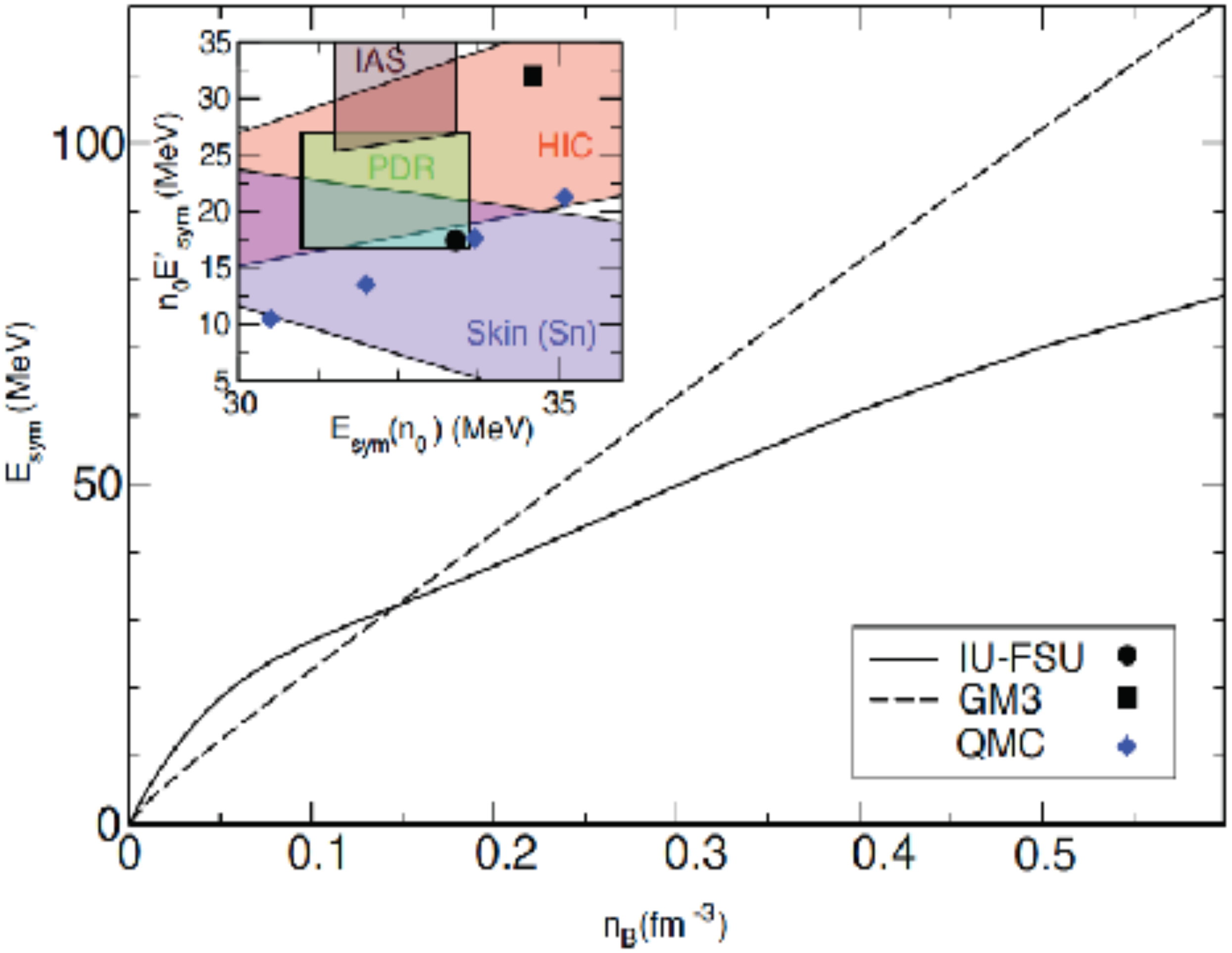
See LR '12 and Martinez-Pinedo et al. '12



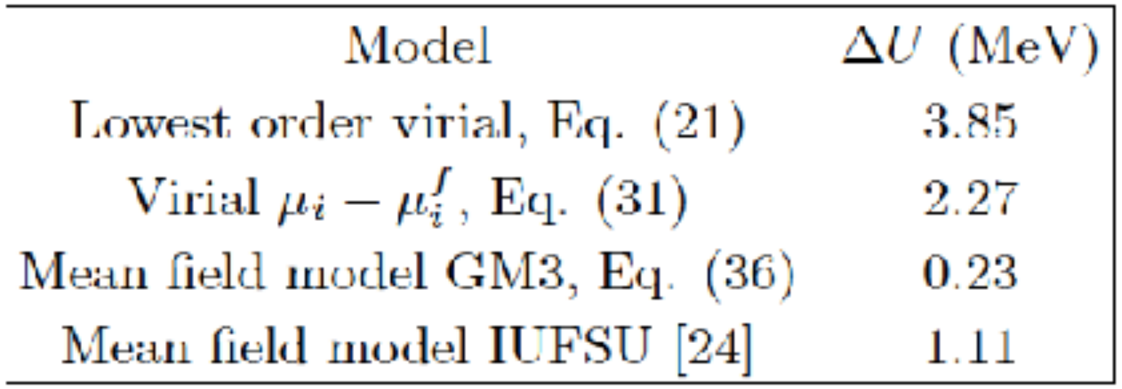
$$Y_e \approx \frac{\lambda_{\nu_e}^{-1}}{\lambda_{\nu_e}^{-1} + \lambda_{\bar{\nu}_e}^{-1}} \approx \left(1 + \frac{\dot{N}_{\bar{\nu}_e}}{\dot{N}_{\nu_e}} \frac{(\varepsilon_{\bar{\nu}_e} - \Delta)^2}{(\varepsilon_{\nu_e} + \Delta)^2}\right)^{-1}$$

Symmetry Energy Dependence

From Roberts et al. (2012)

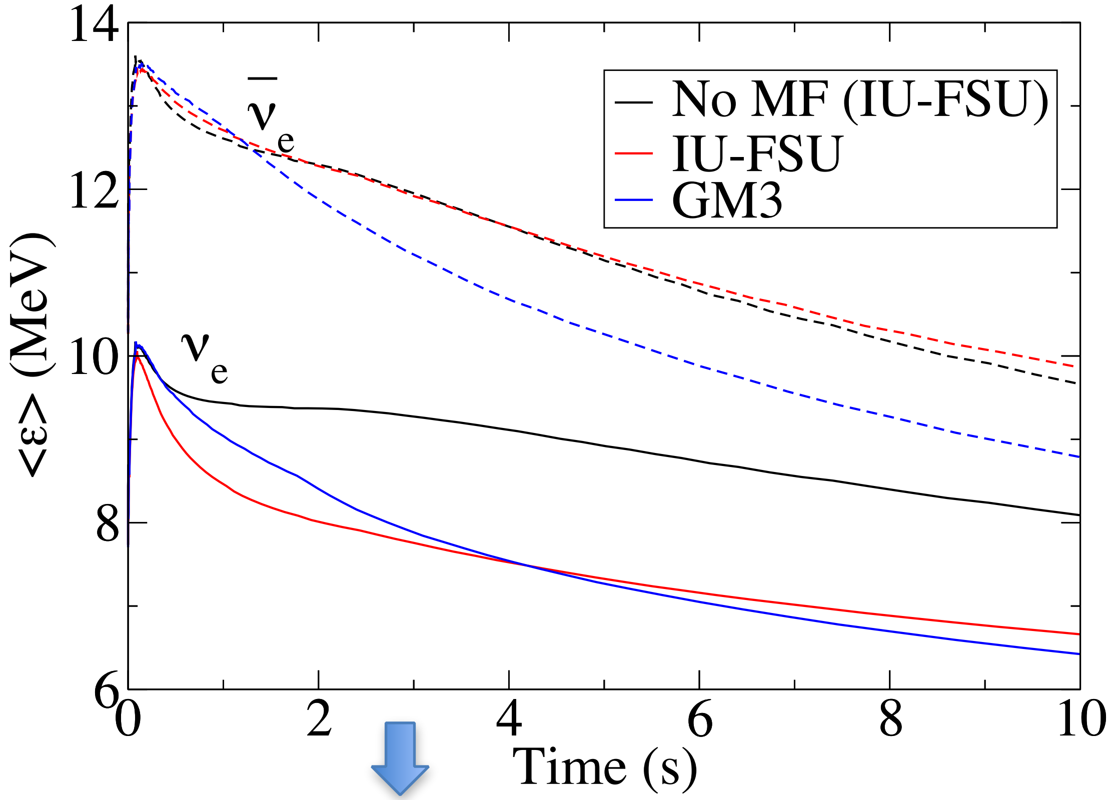


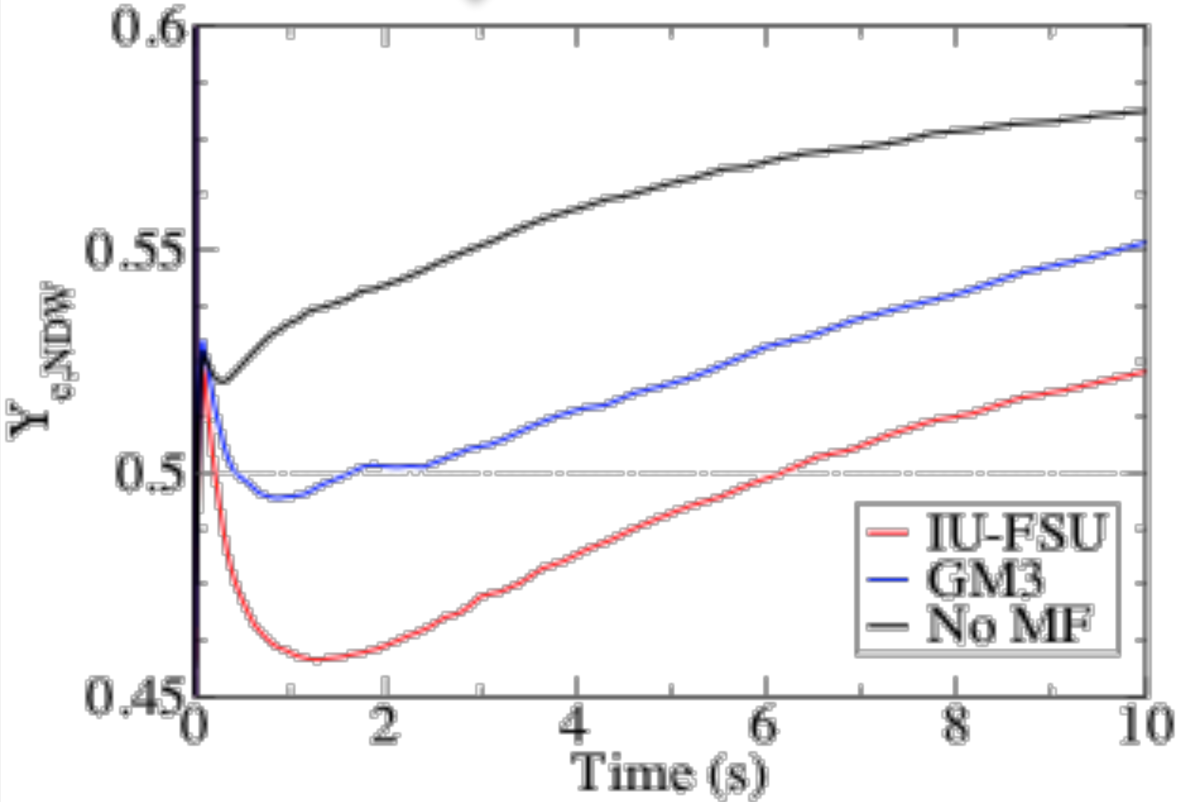
Different equations of state



Model	ΔU (MeV)
Lowest order virial, Eq. (21)	3.85
Virial $\mu_i - \mu_i^f$, Eq. (31)	2.27
Mean field model GM3, Eq. (36)	0.23
Mean field model IUFSU [24]	1.11

From Horowitz et al. (2012)





Conclusions

- 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), so constraining density dependence is important to predicting the timescale of neutrino emission

- 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.

- Properties of the neutrinos can also impact nucleosynthesis near the PNS. The nucleon self-energies play a significant role in determining neutron or proton richness of the NDW.