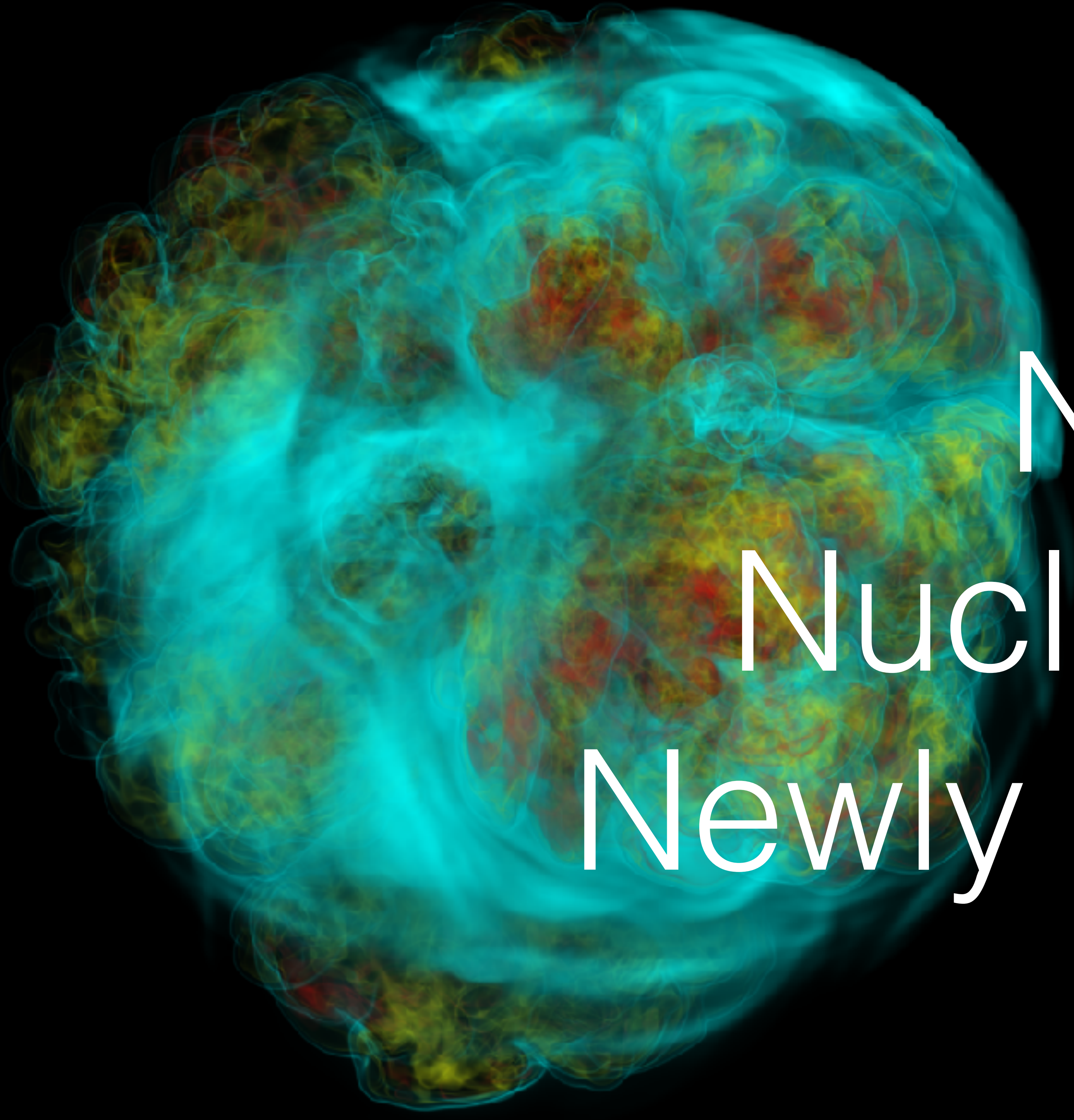
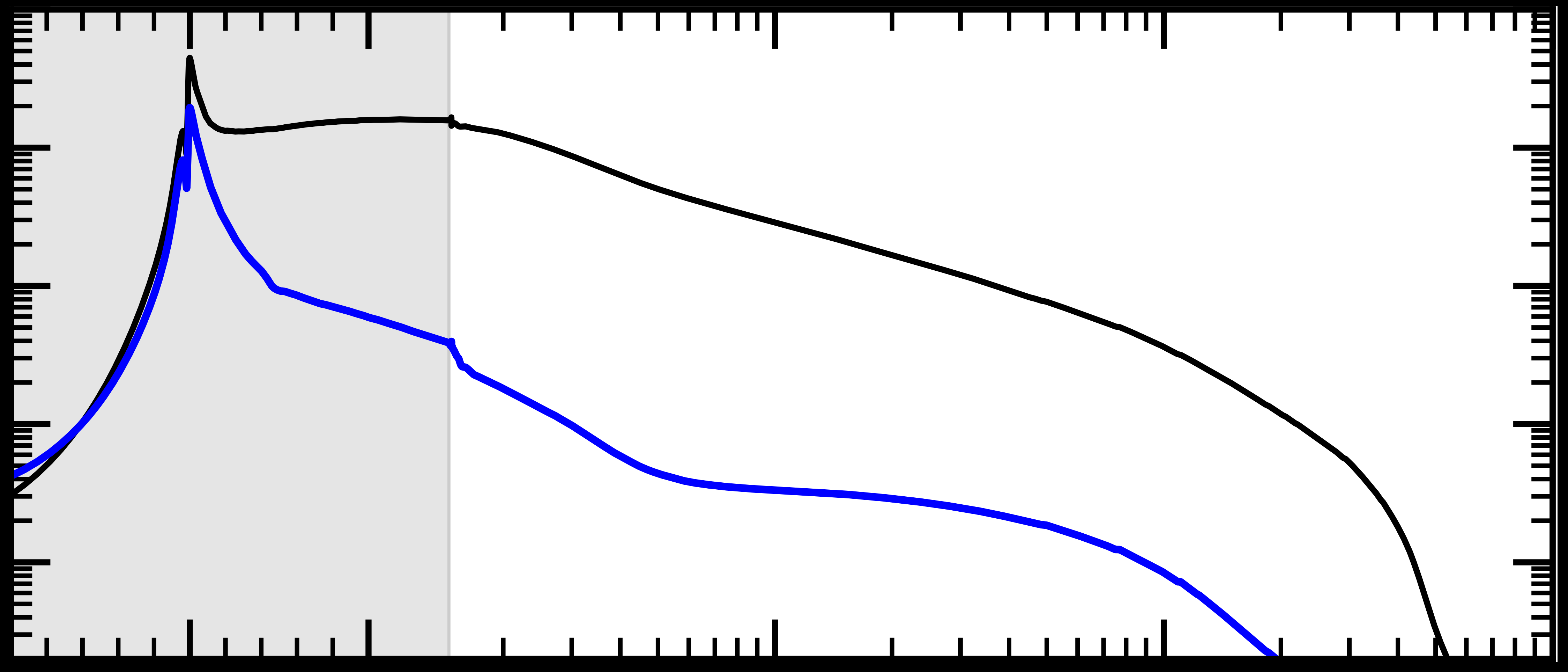


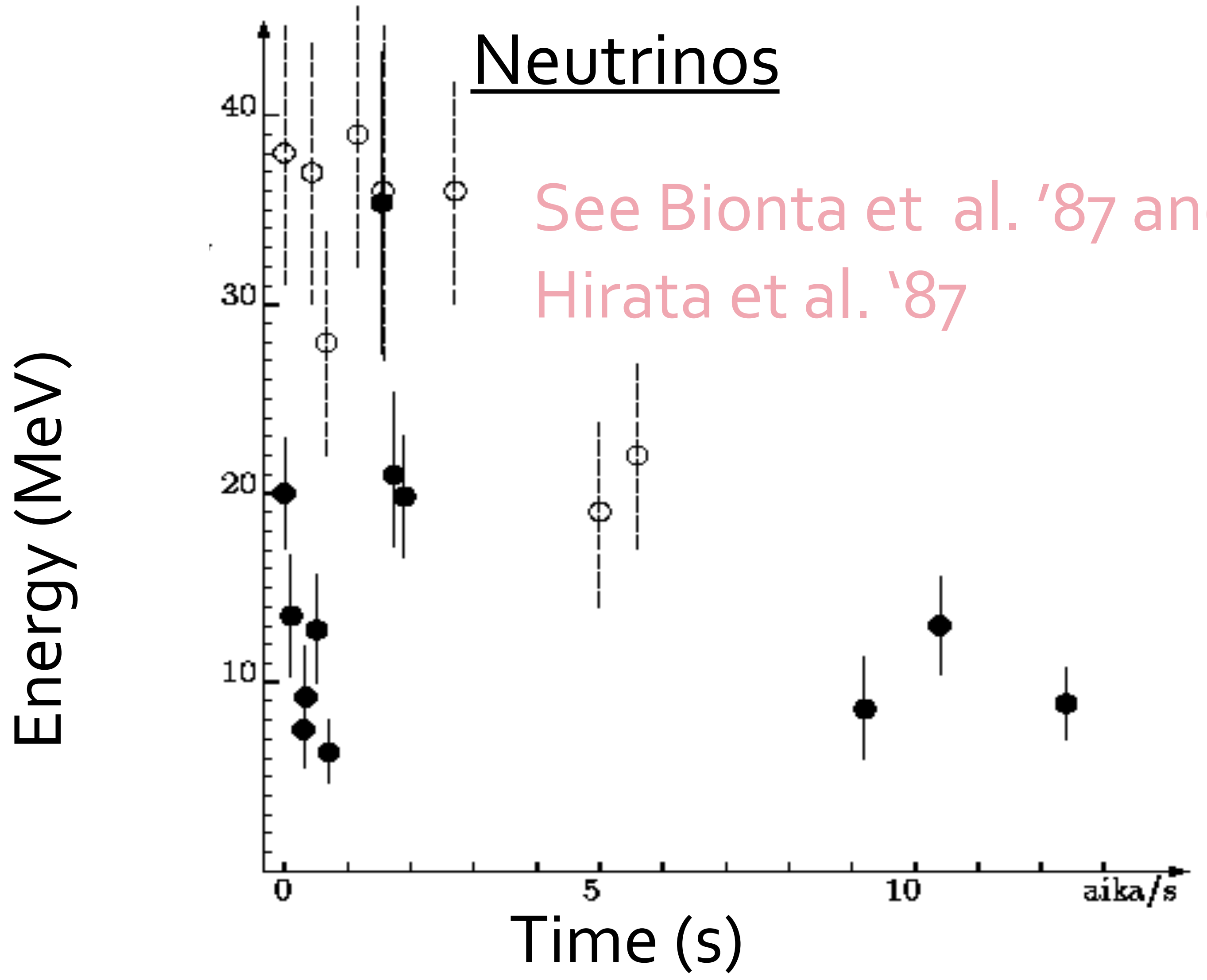
Neutrinos and Nucleosynthesis from Newly Born Neutron Stars

Luke Roberts
National Superconducting Cyclotron Laboratory
Michigan State University



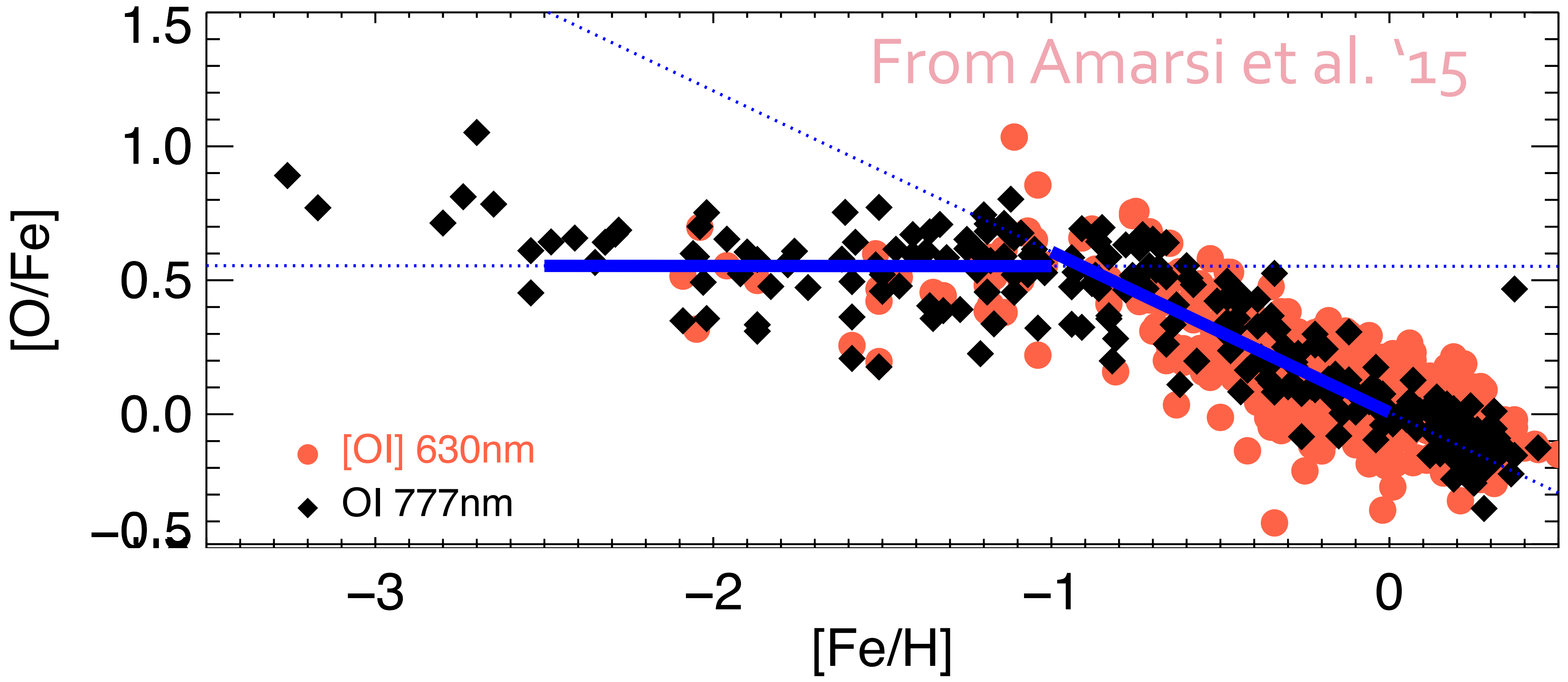
Core Collapse Supernovae: Multi-Messenger Events

Neutrinos



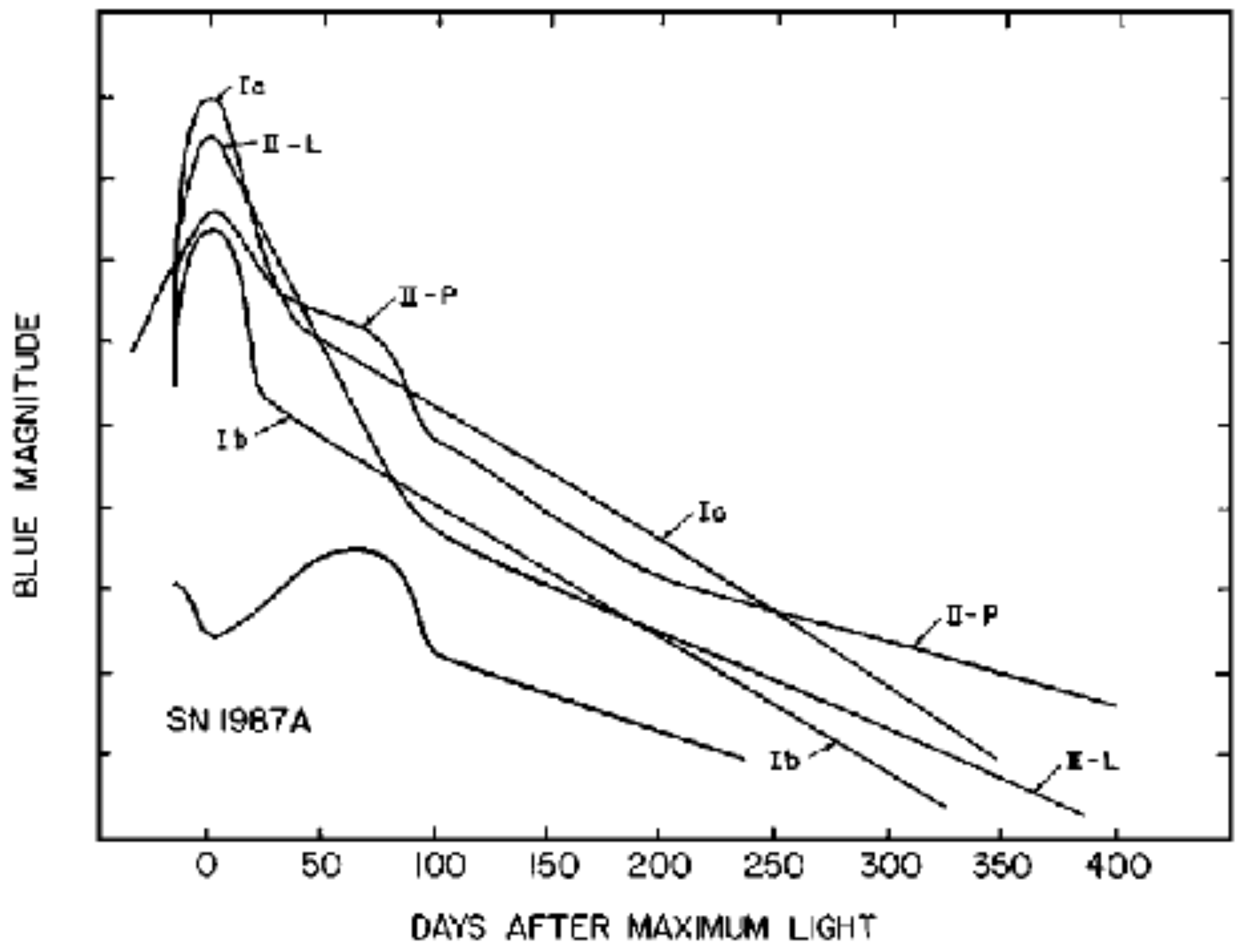
See Bionta et al. '87 and Hirata et al. '87

Nucleosynthesis



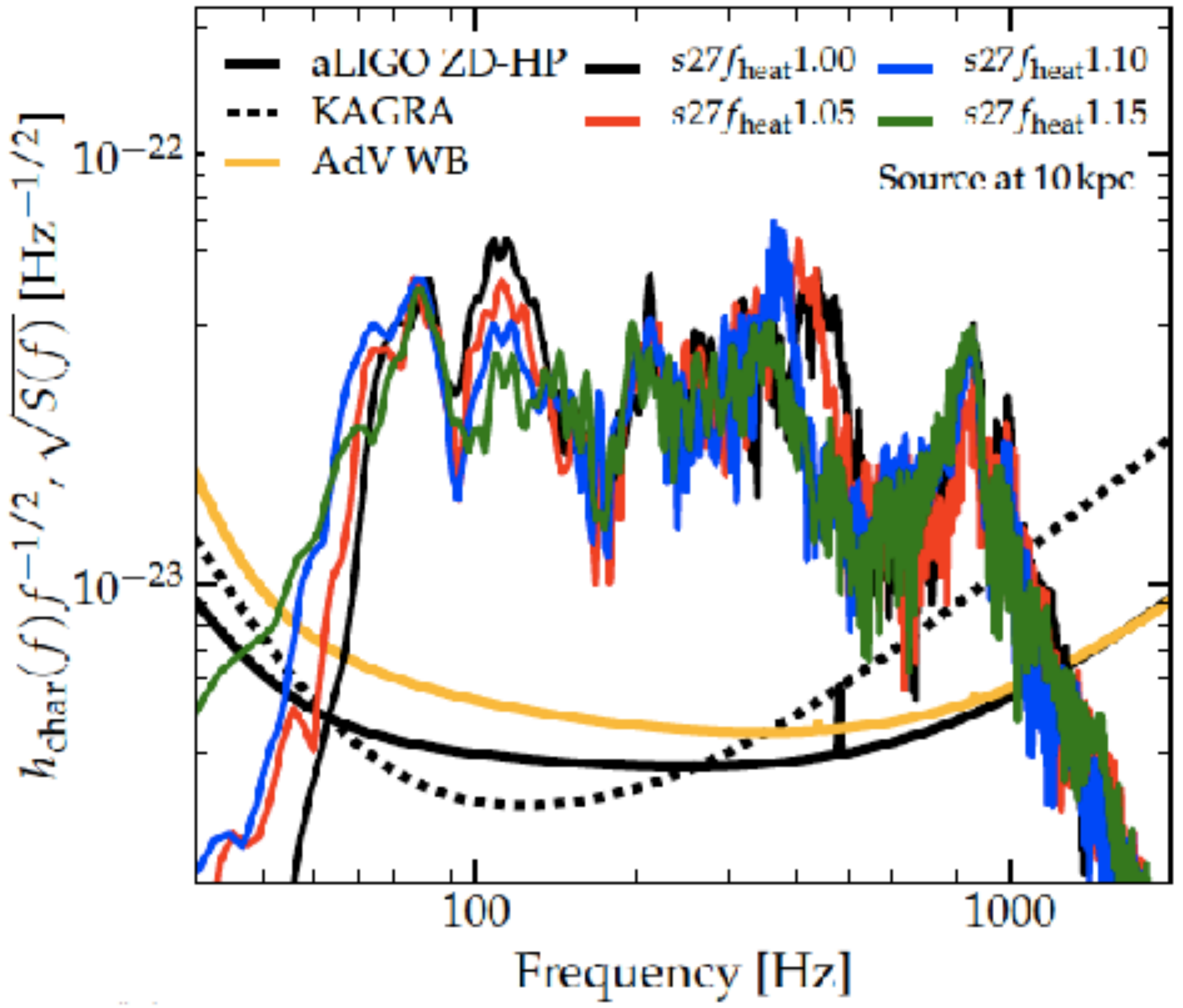
From Amarsi et al. '15

Electromagnetic



From Filppenko '97

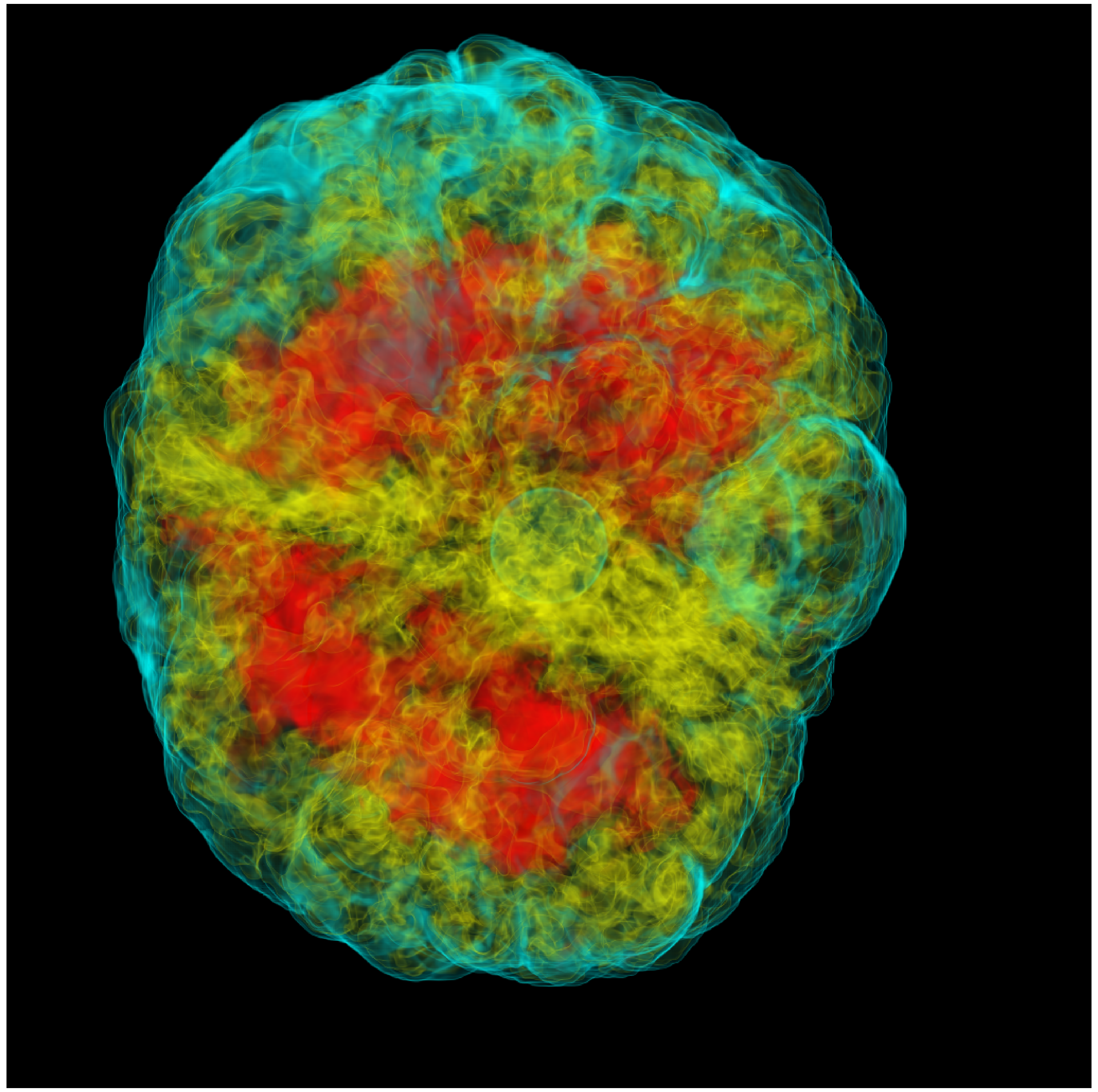
Gravitational Waves



From Ott et al. '12

Post Bounce Evolution of CCSNe

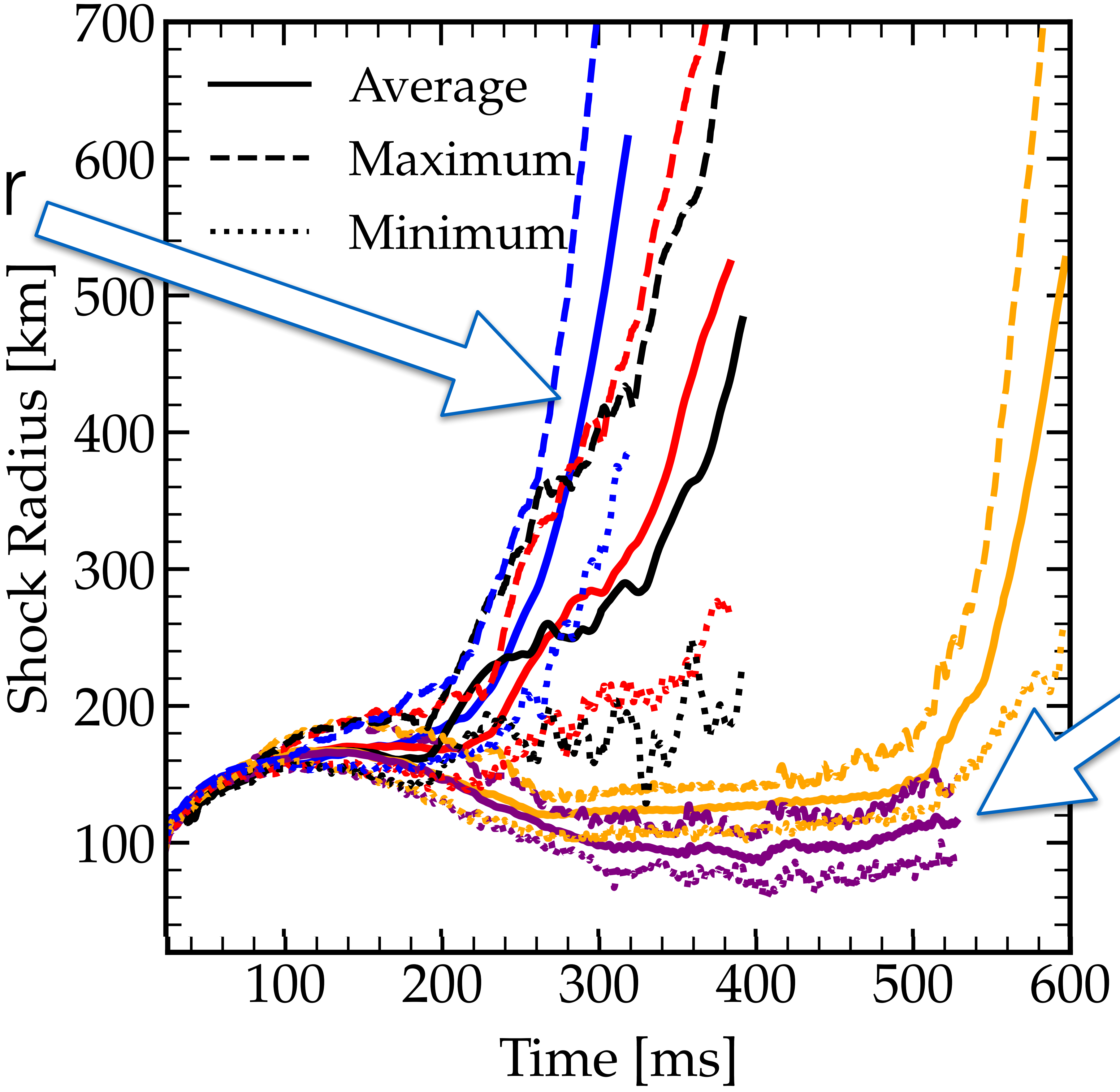
- Hydrodynamic instabilities (such as convection and SASI) can aid energy transport and shock propagation
- Many groups seeing successful explosions in 3D
- What is the fate of the remnants left behind?



Stellar Progenitor Dependence

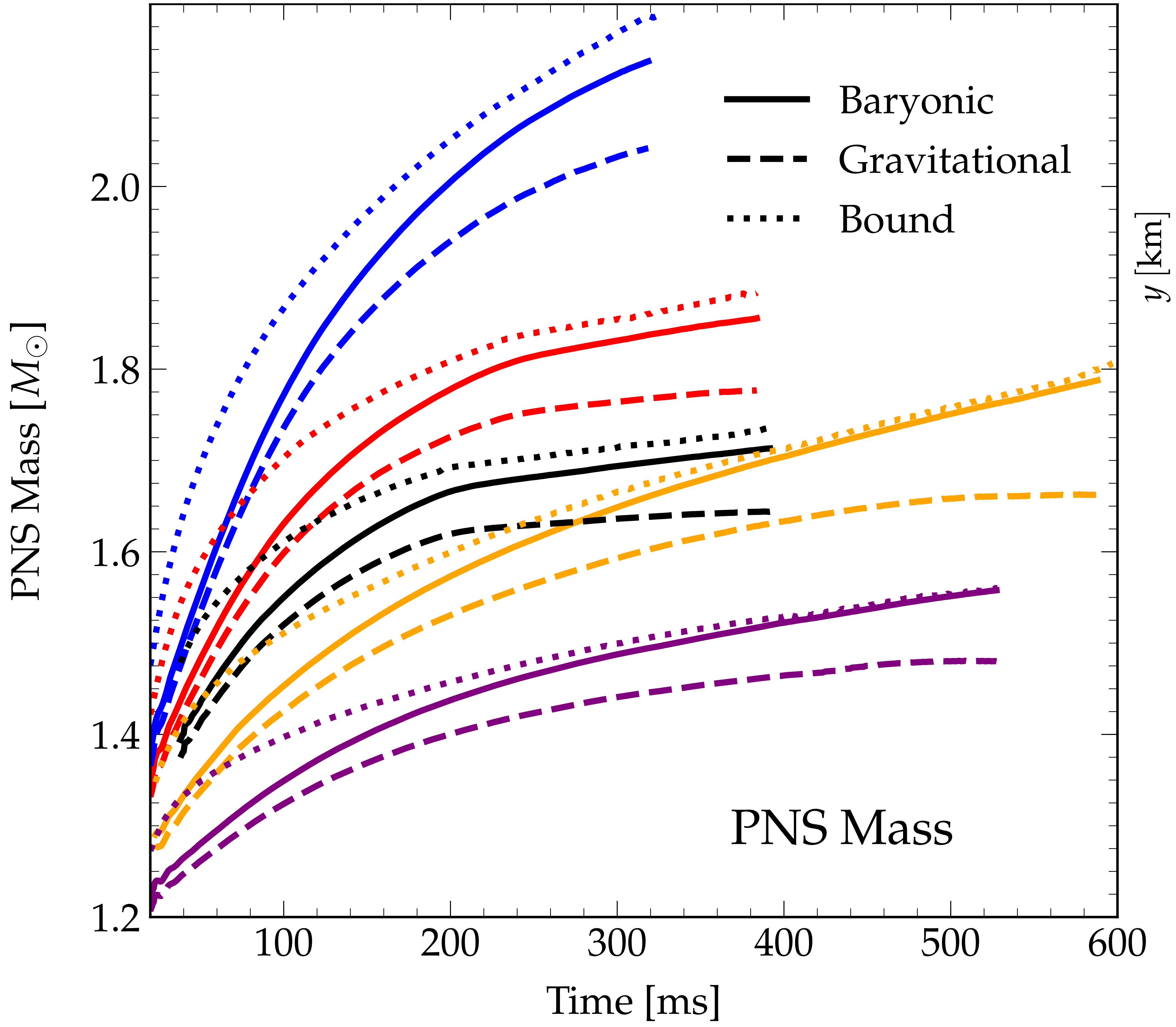
Ott, LR et al. (2018)

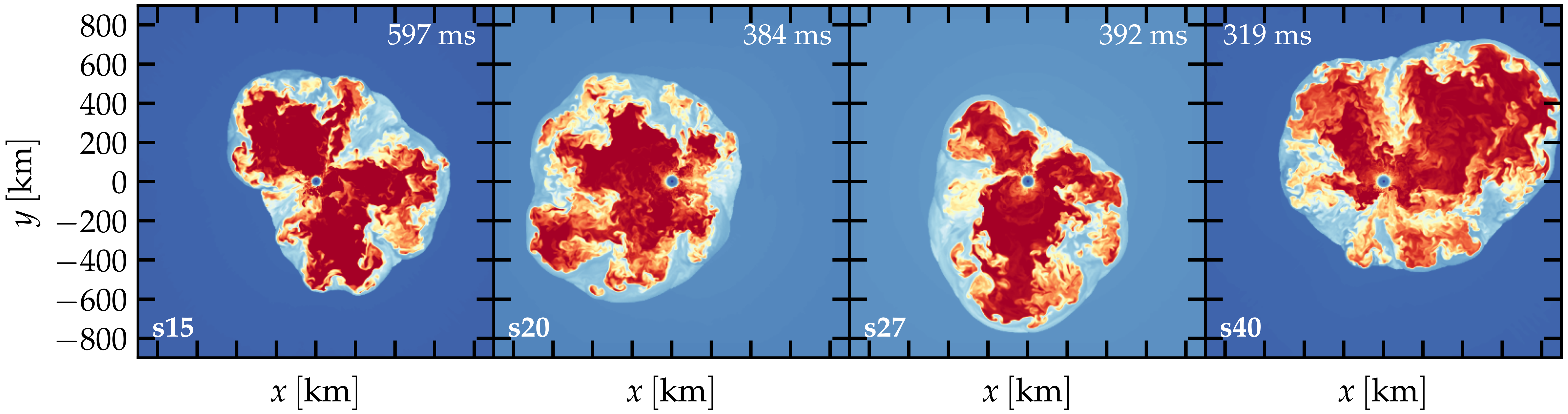
Highest mass progenitor

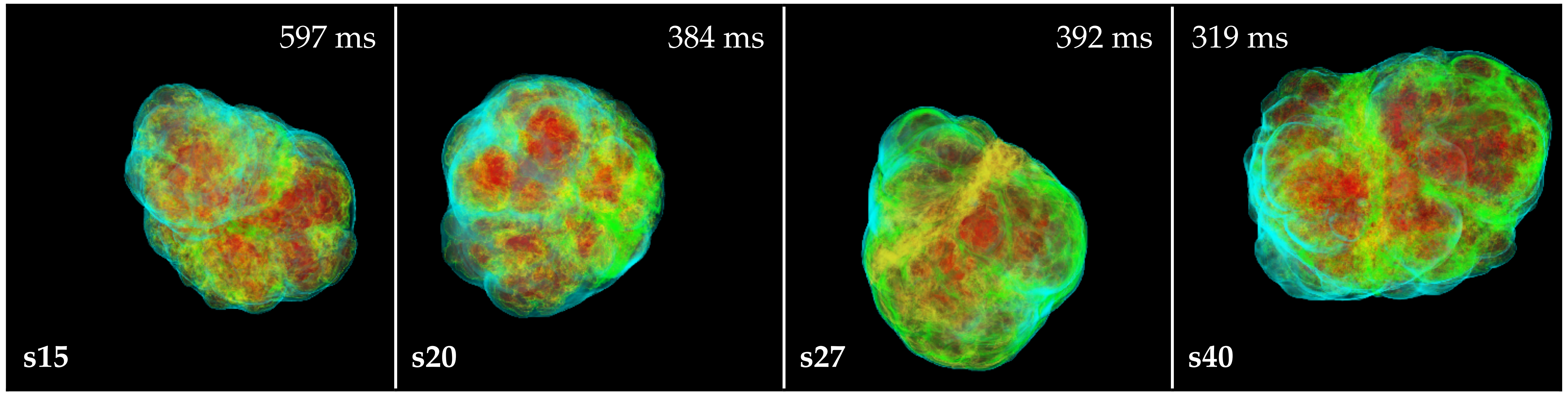


Lowest mass progenitor

Final States



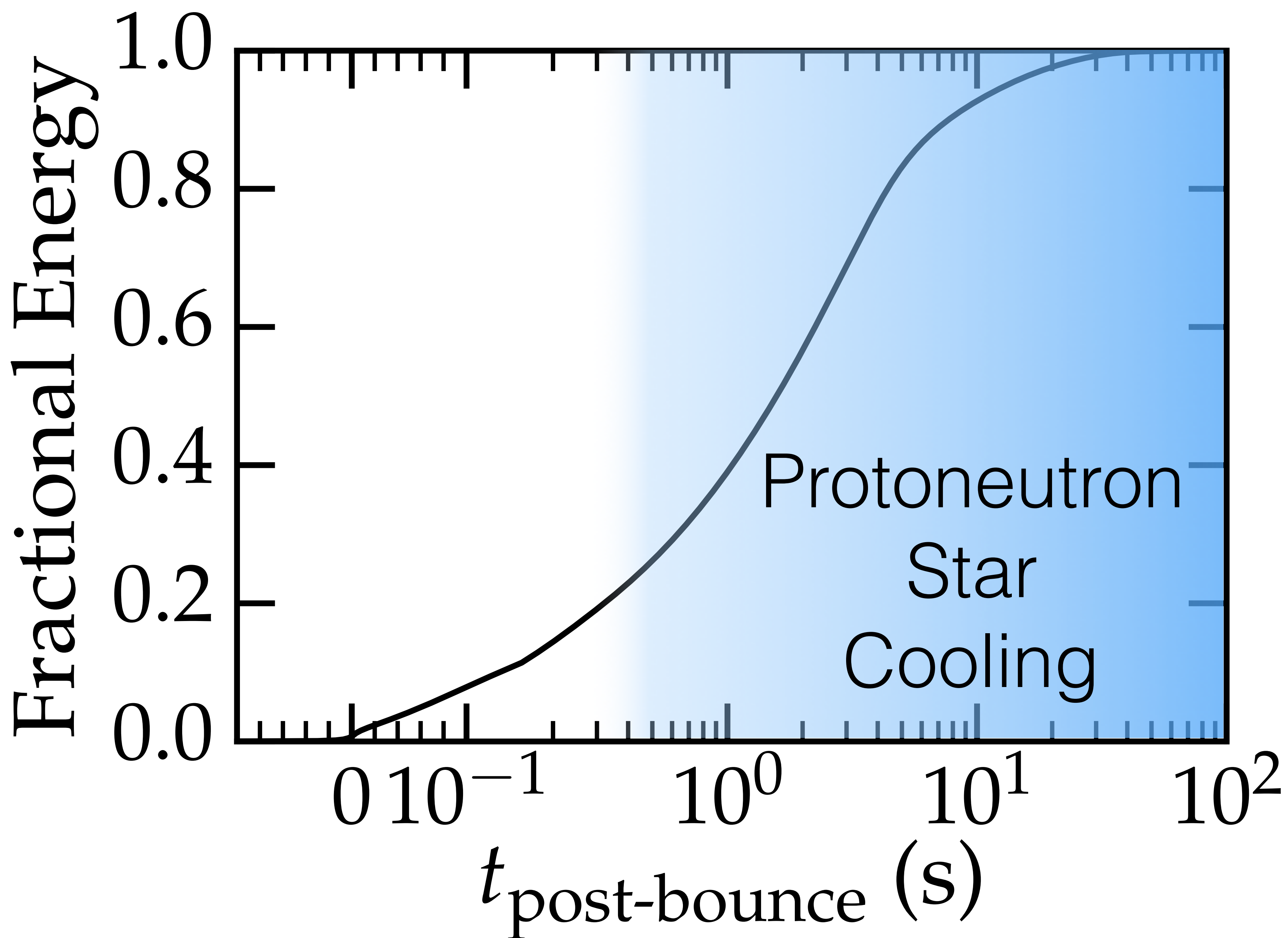




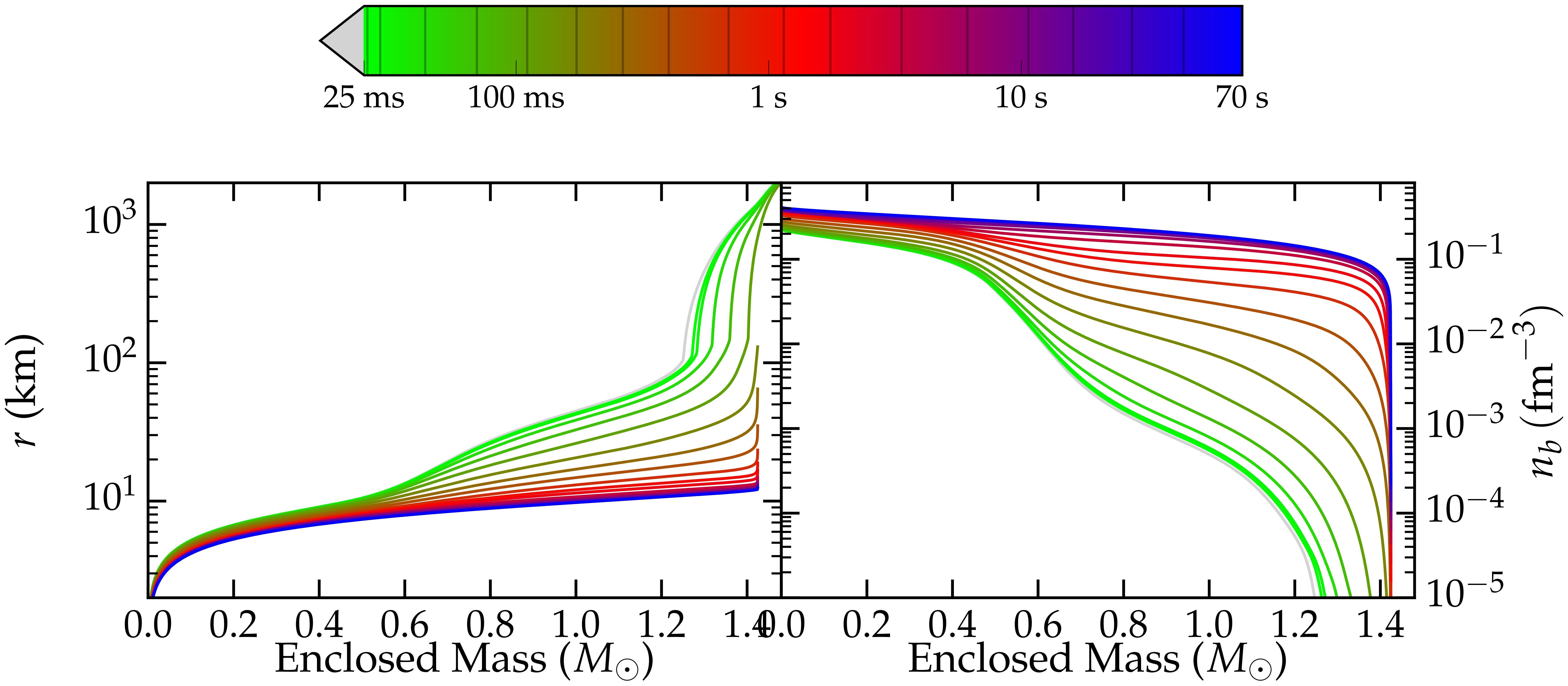
Late Time Neutrino Emission

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 oscillations
- Possibly cleaner problem than explosion mechanism

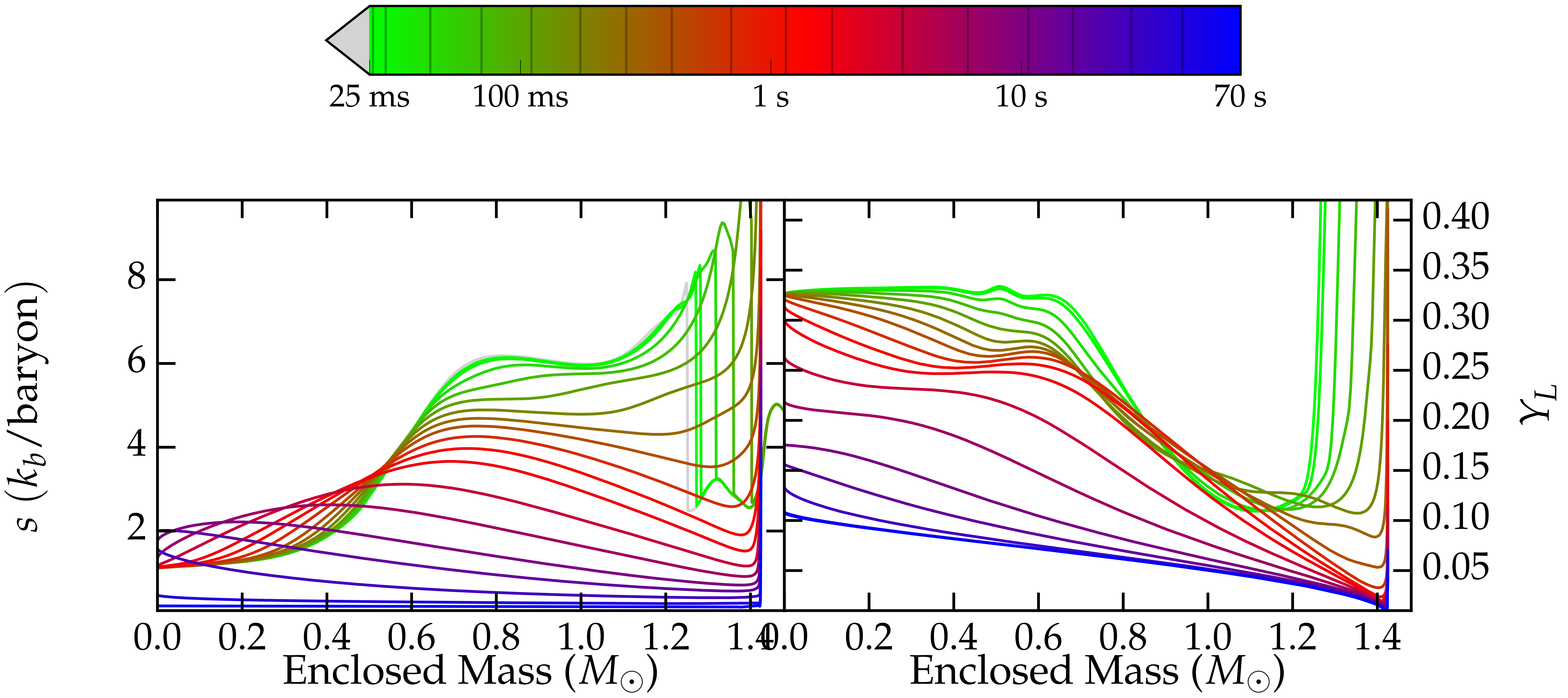


Long Term PNS Evolution



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

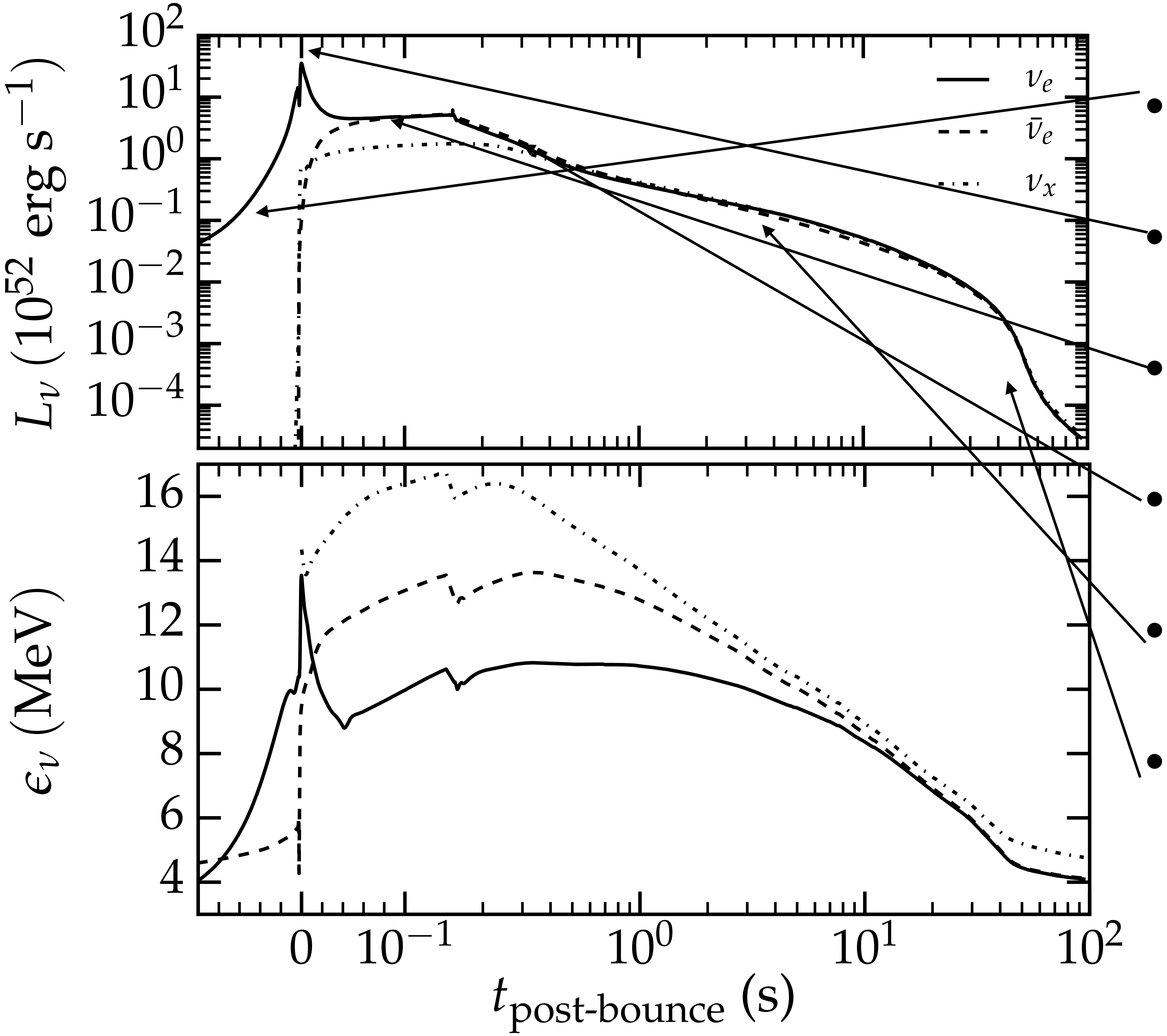
Long Term PNS Evolution



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

See Prakash et al. ‘97

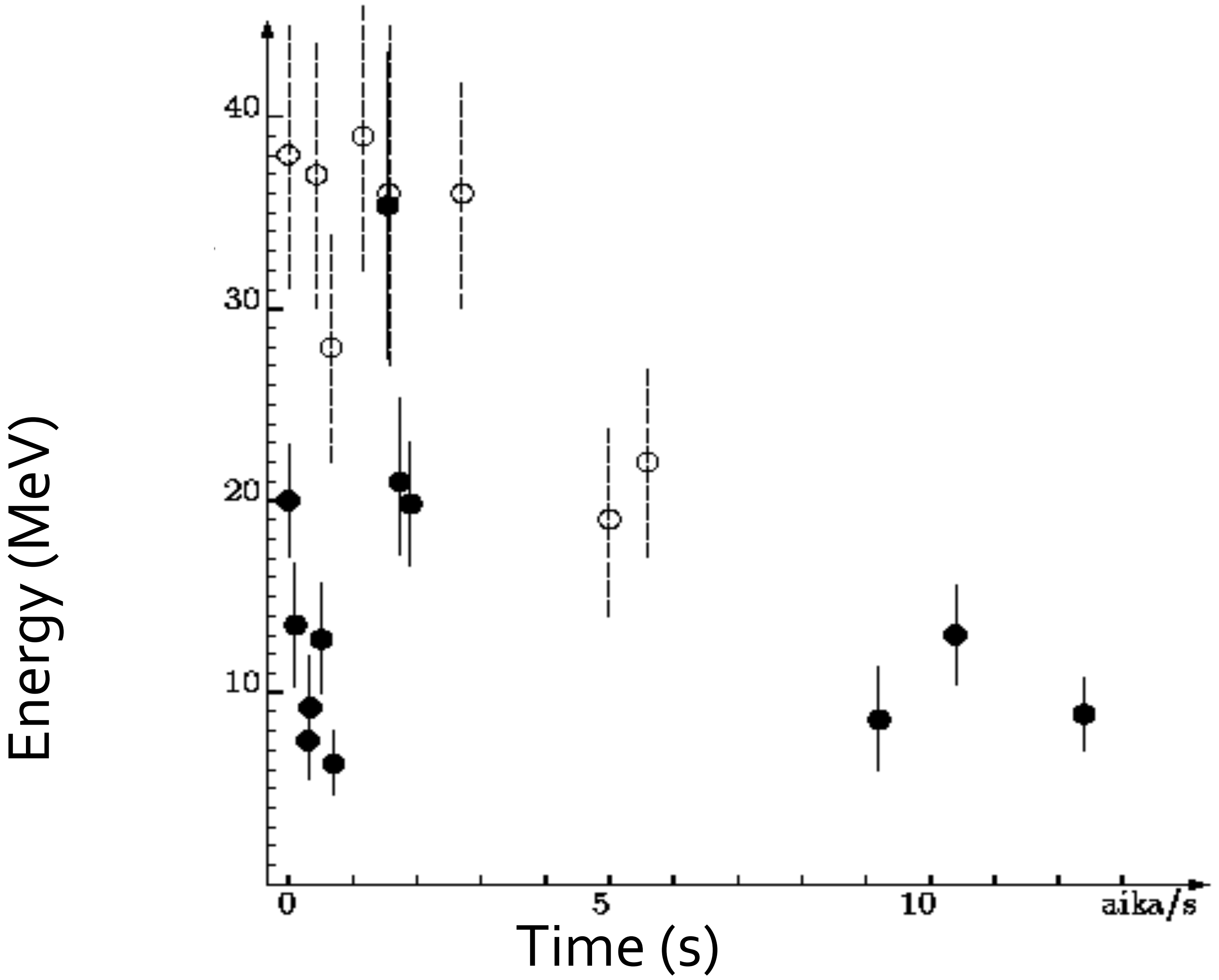
Anatomy of the Neutrino Signal



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

LR and Reddy ‘16

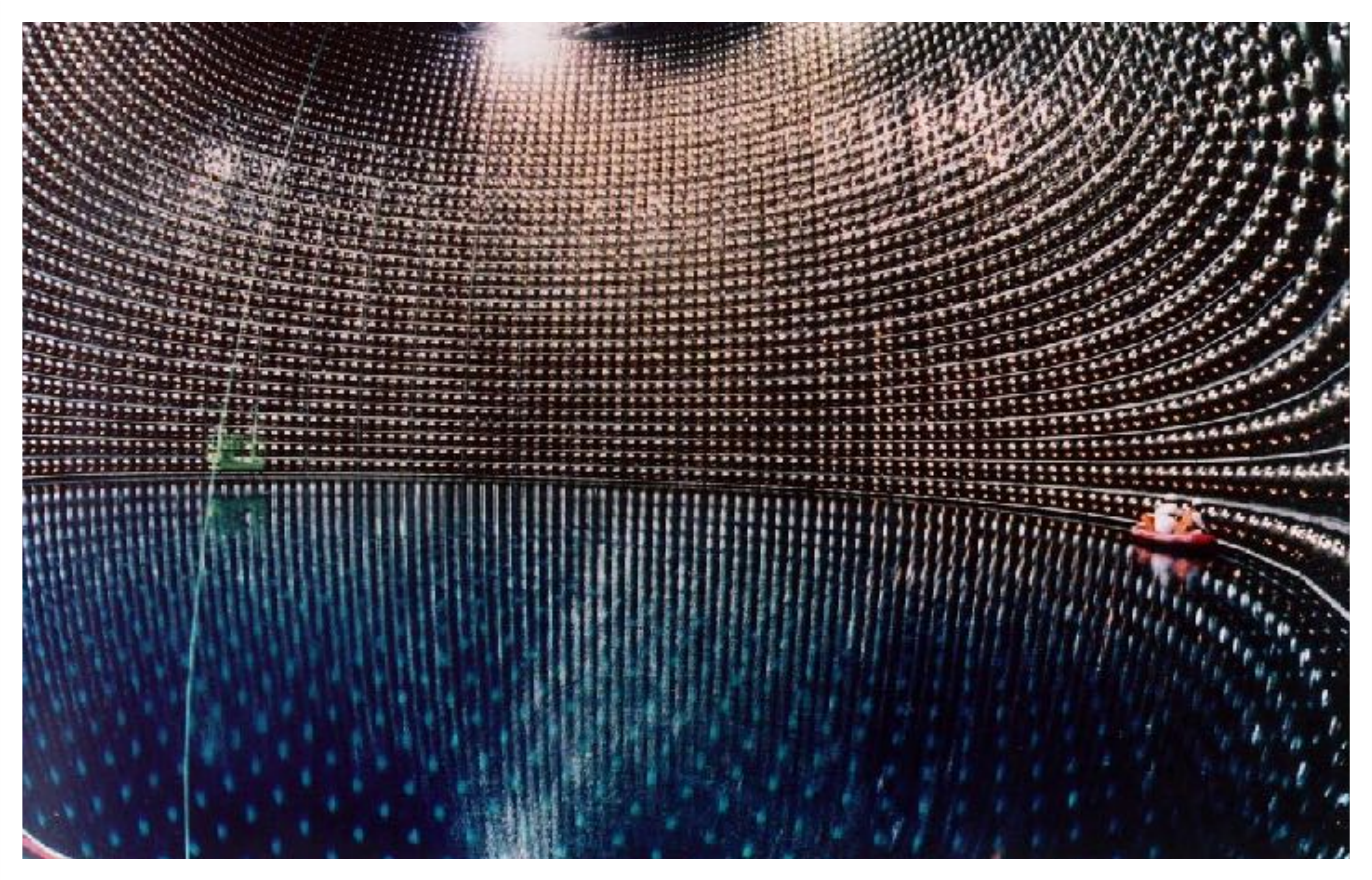
Detecting the Supernova Neutrino Signal



~20 Neutrino Events Observed from SN 1987a at two detectors via the reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

See Bionta et al. ’87 and Hirata et al. ‘87



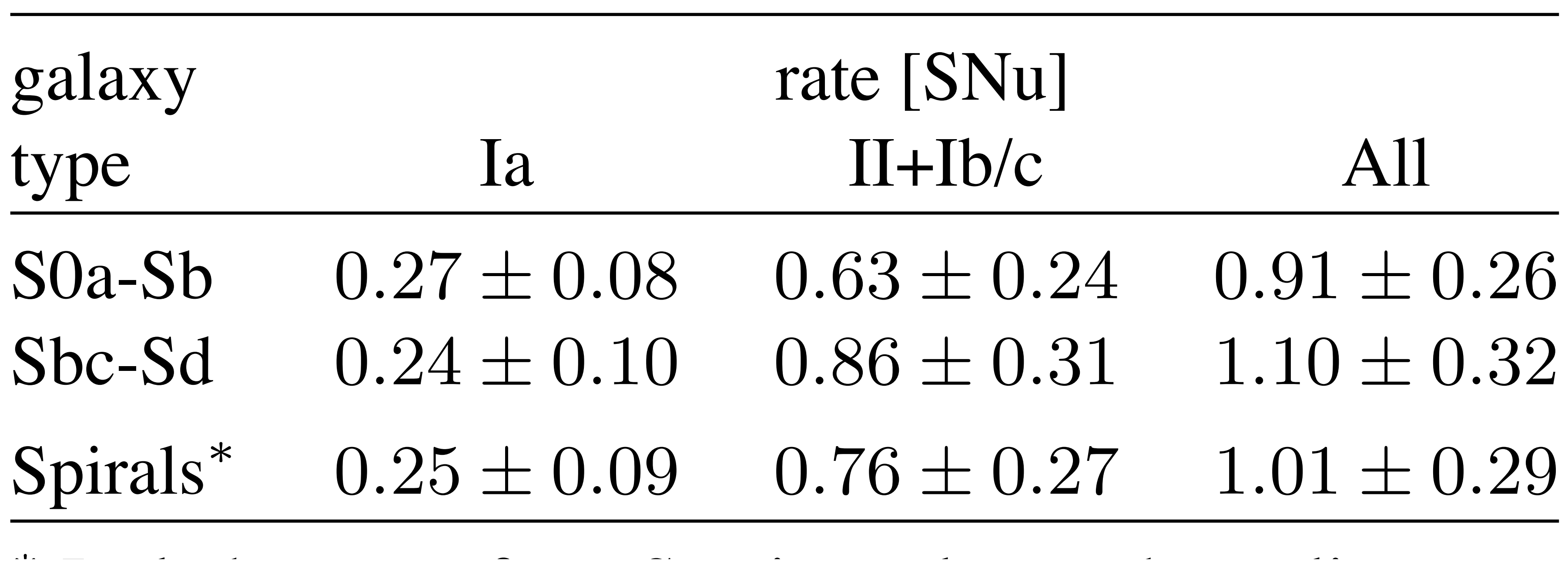
Super-Kamiokande Neutrino Detector

Larger, modern detectors will detect thousands of events from a nearby supernova, allowing us to *directly* probe the nature of the nascent neutron star

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

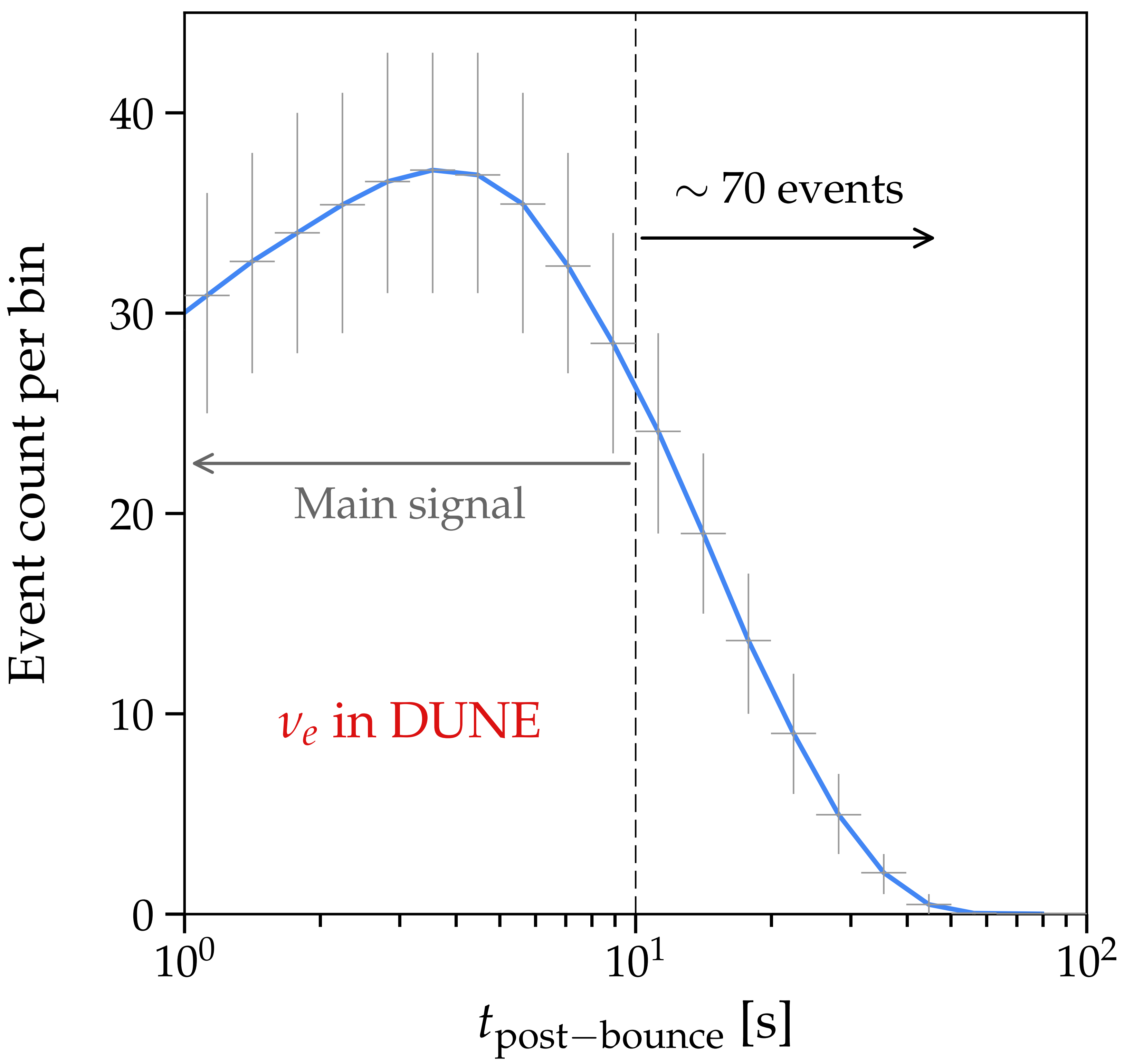
multiply by ~2.4 to get MW rate

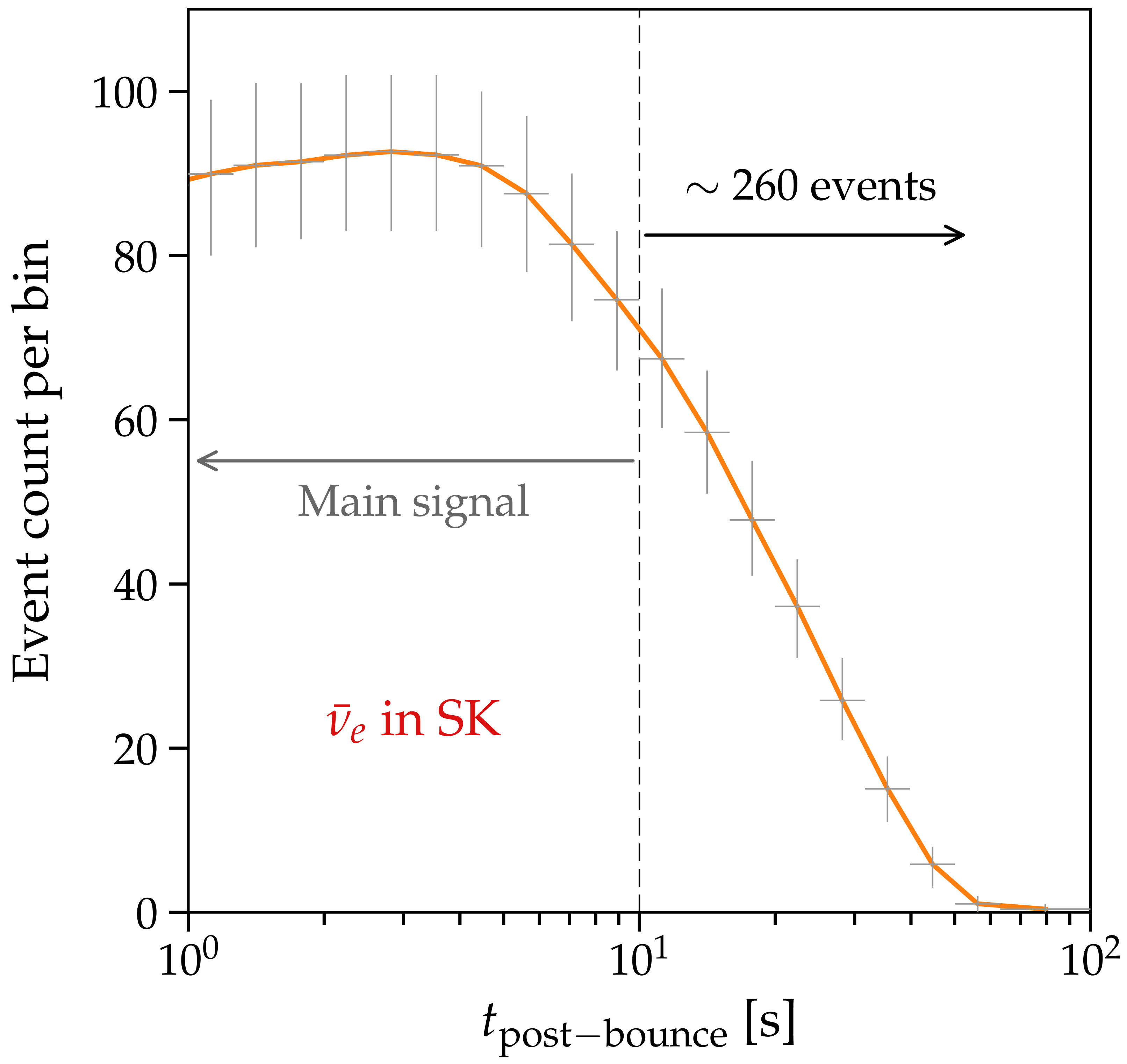


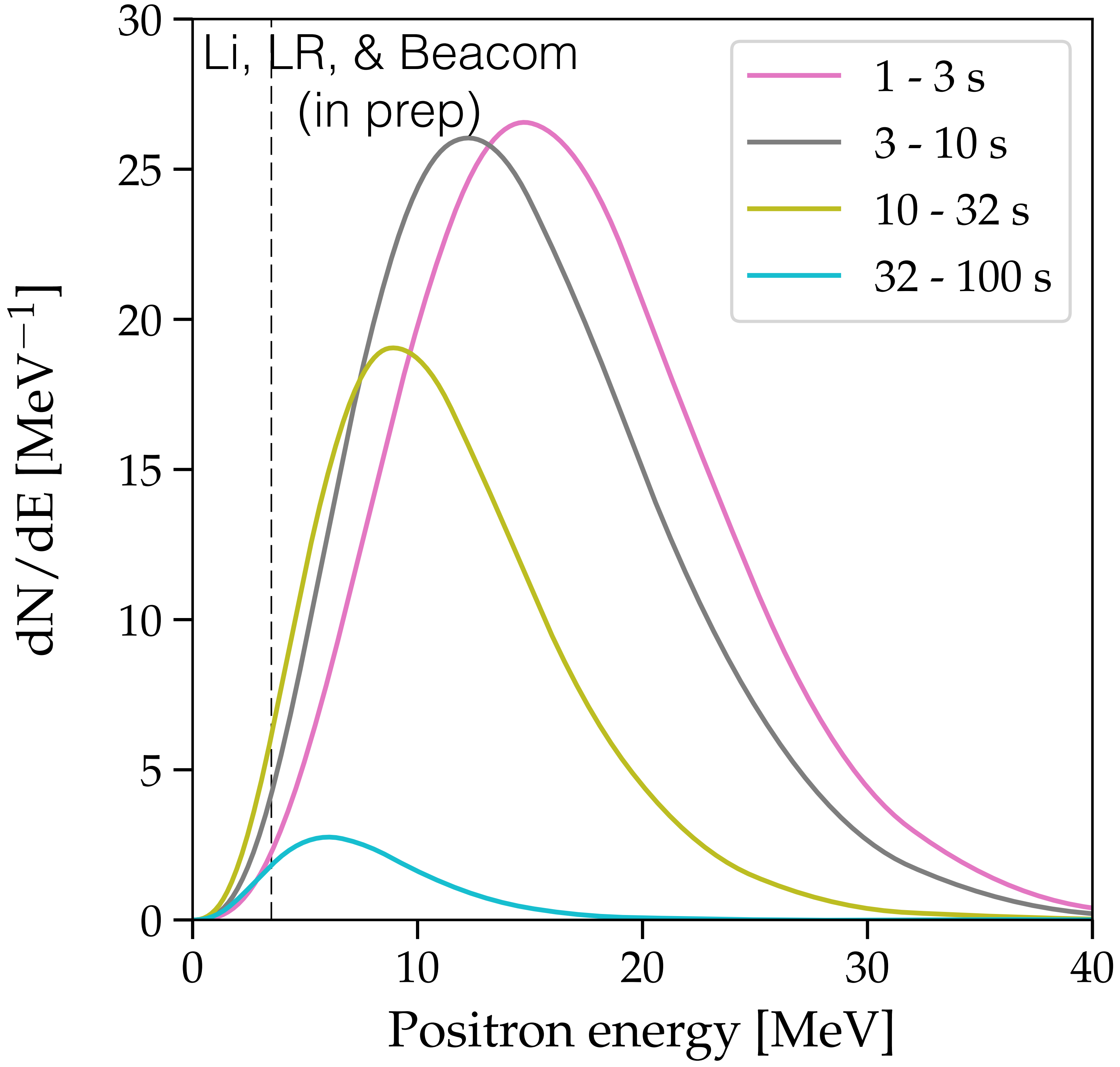
galaxy	rate [SNu]		
type	Ia	II+Ib/c	All
S0a-Sb	0.27 ± 0.08	0.63 ± 0.24	0.91 ± 0.26
Sbc-Sd	0.24 ± 0.10	0.86 ± 0.31	1.10 ± 0.32
Spirals*	0.25 ± 0.09	0.76 ± 0.27	1.01 ± 0.29

Cappellaro et al. (1999)

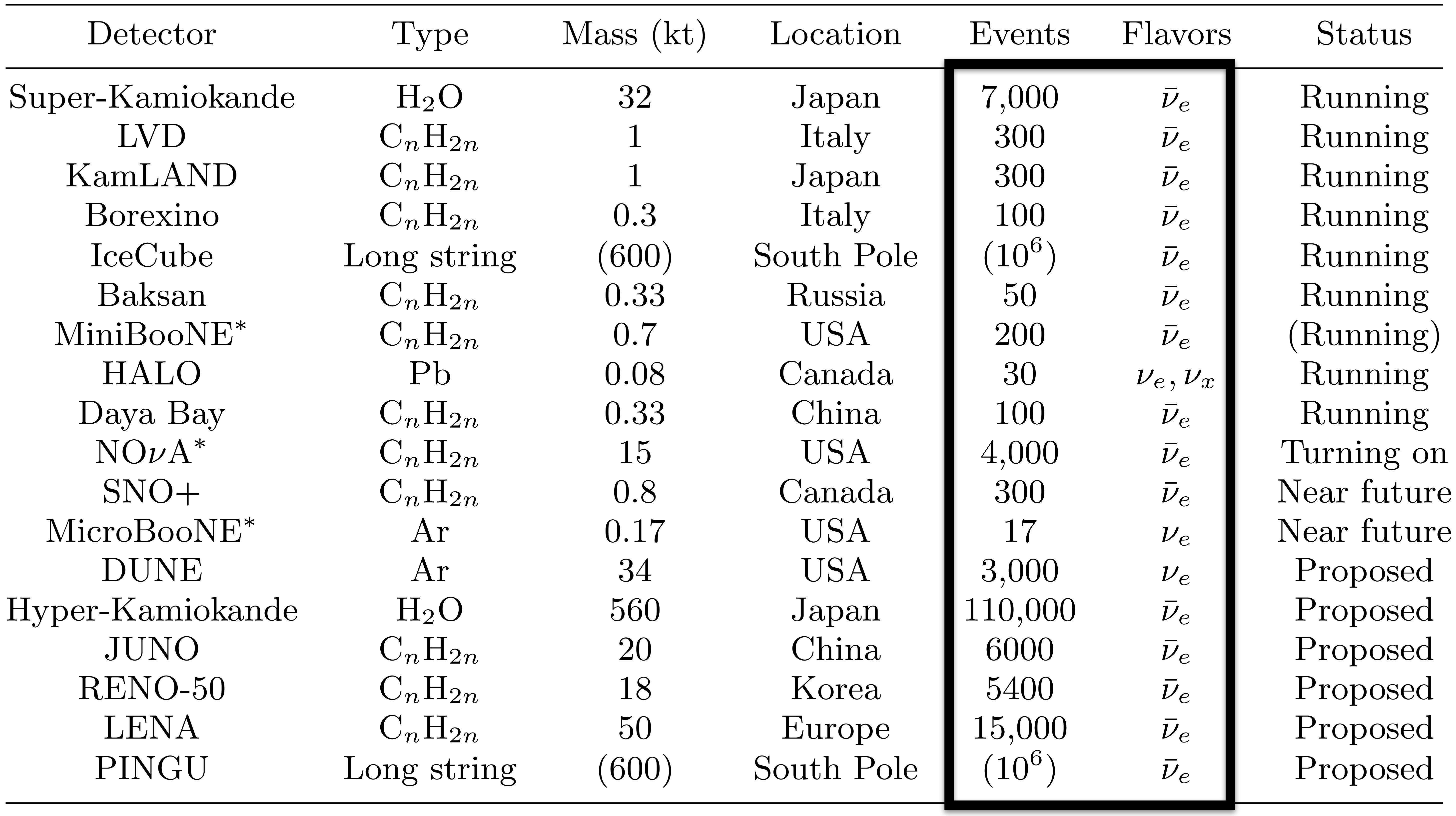
Detection Rates






Li, LR, & Beacom
(in prep)

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

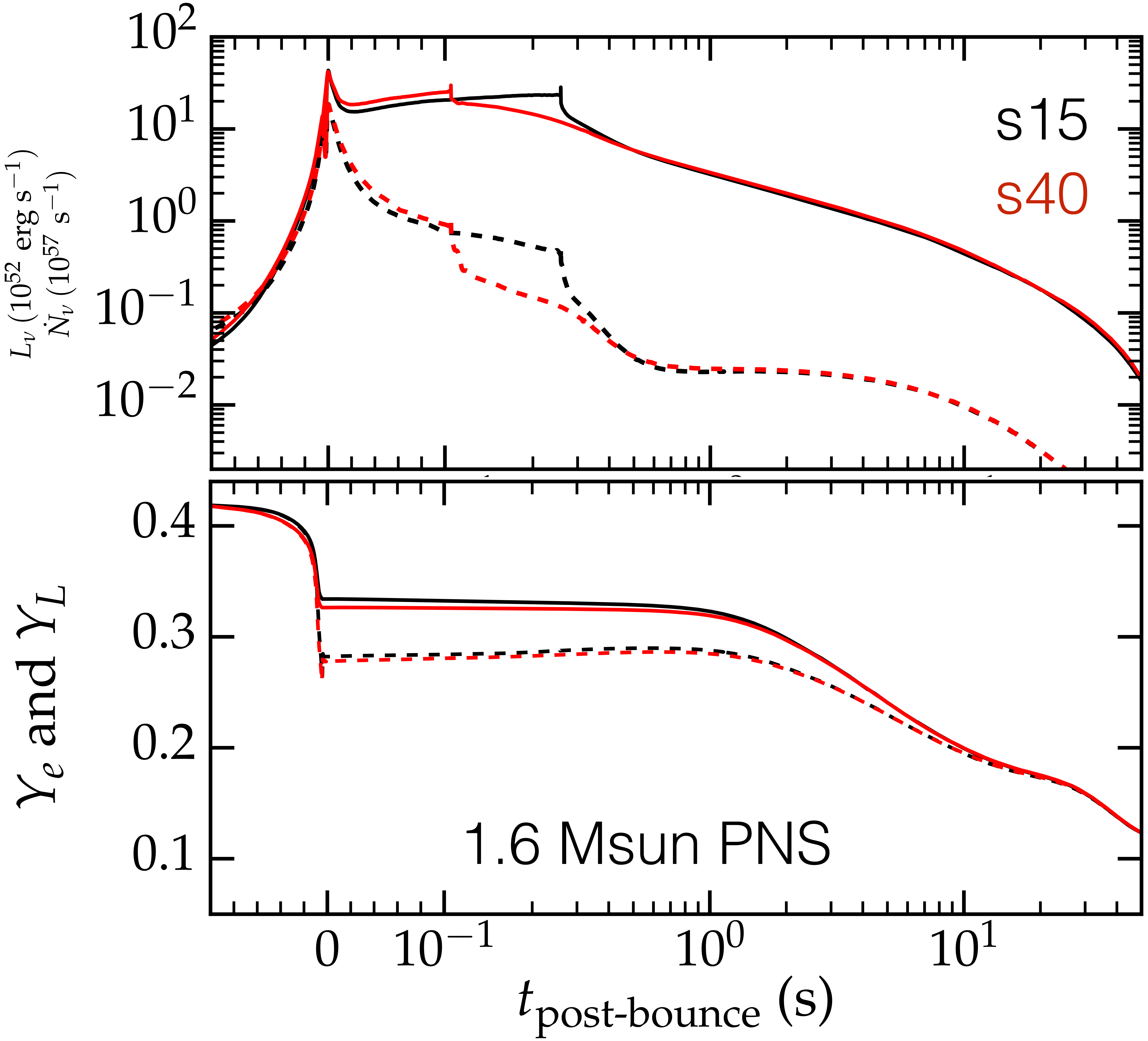
Scholberg et al. (2015)

Simple Prescription for Explosion in 1D

Perform an (inverse) mass cut

- Once supernova shock passes fixed mass shell, remove all of the overlying mass and replace with a boundary condition
- Drawback: Abrupt end to accretion
- Makes baryonic mass of remnant a free parameter, but we don't know it anyway without realistic explosion model

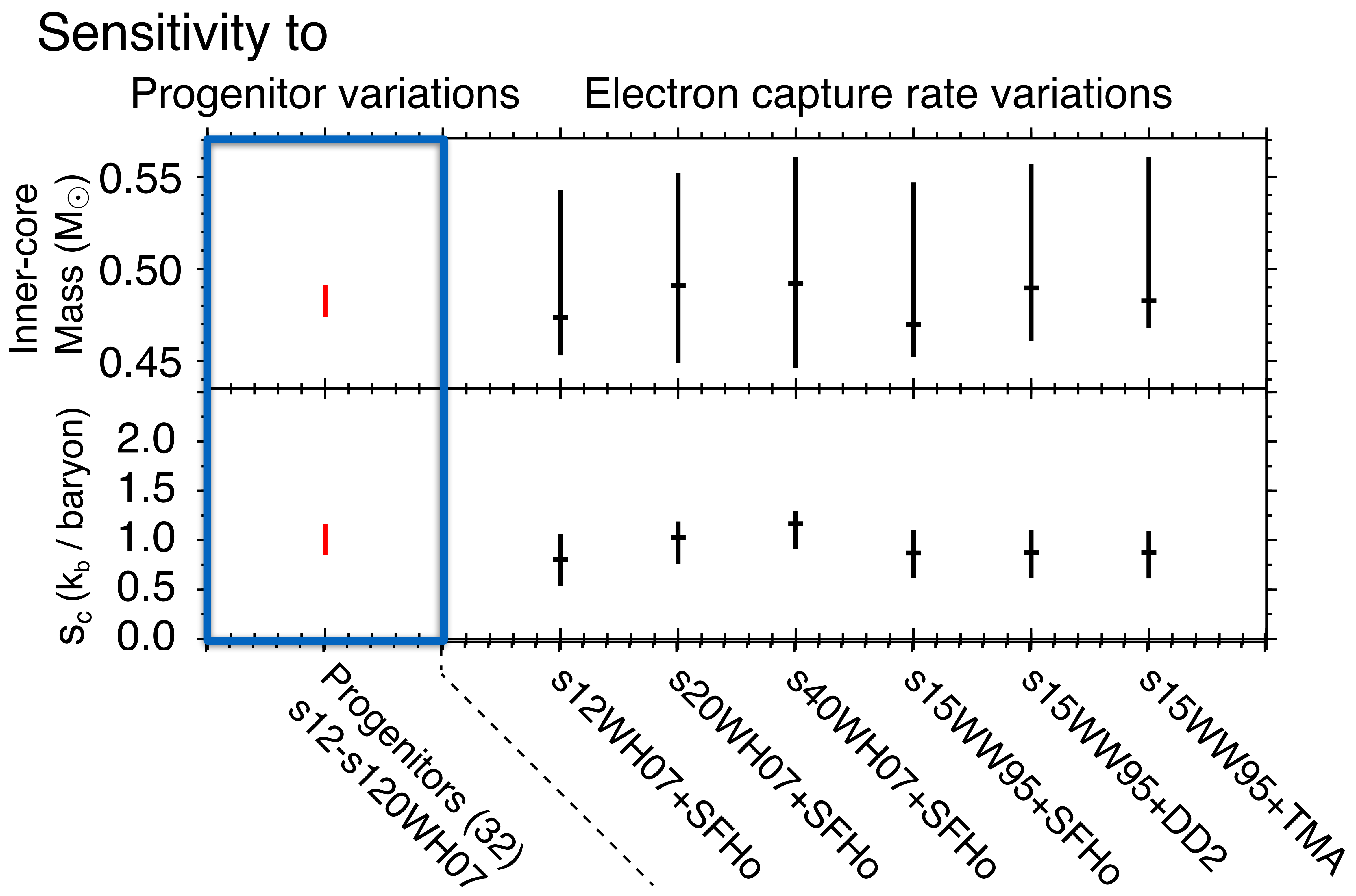
Progenitor Dependence



Progenitor Dependence

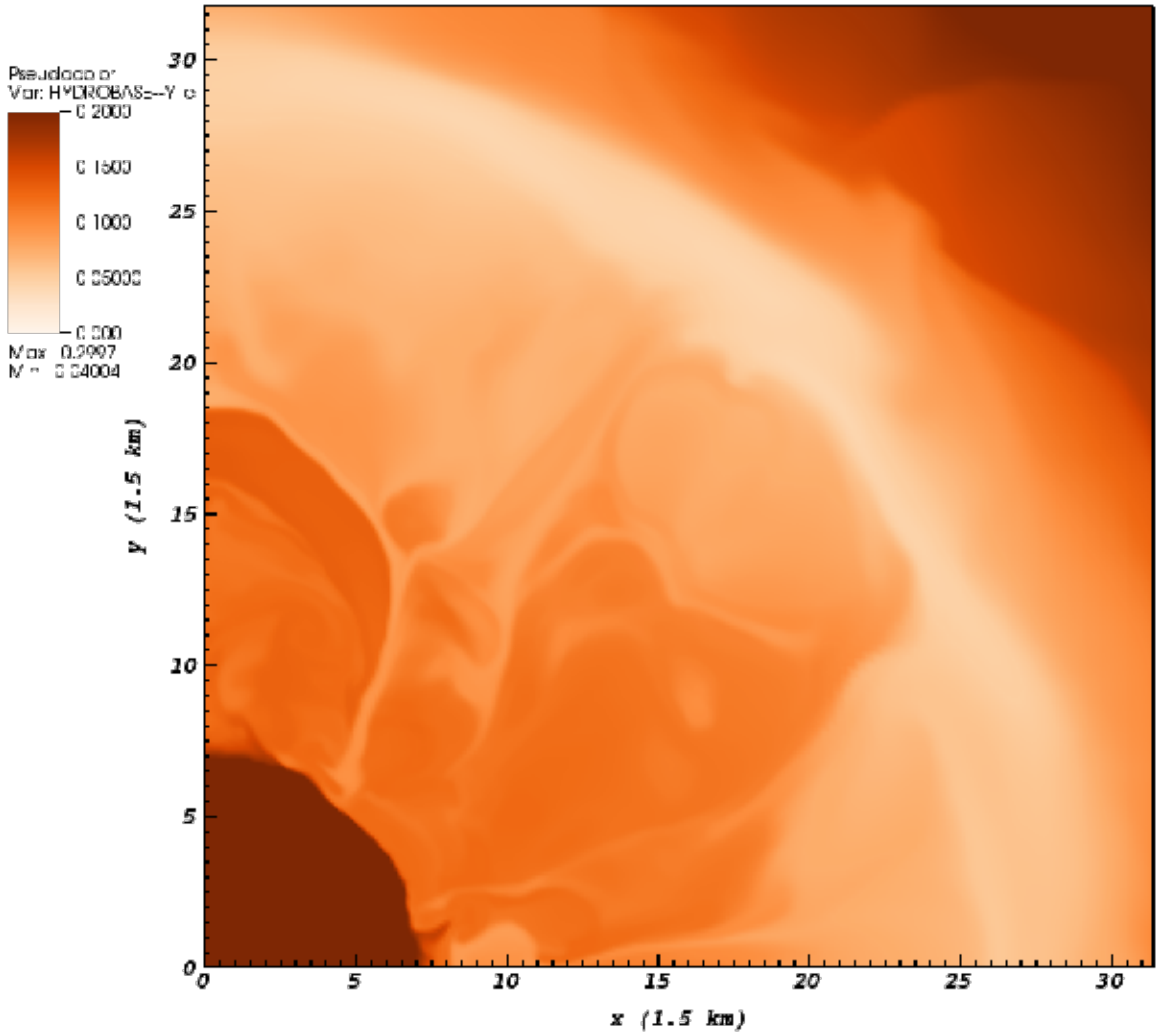
Properties of the inner core after bounce are relatively insensitive to progenitor structure

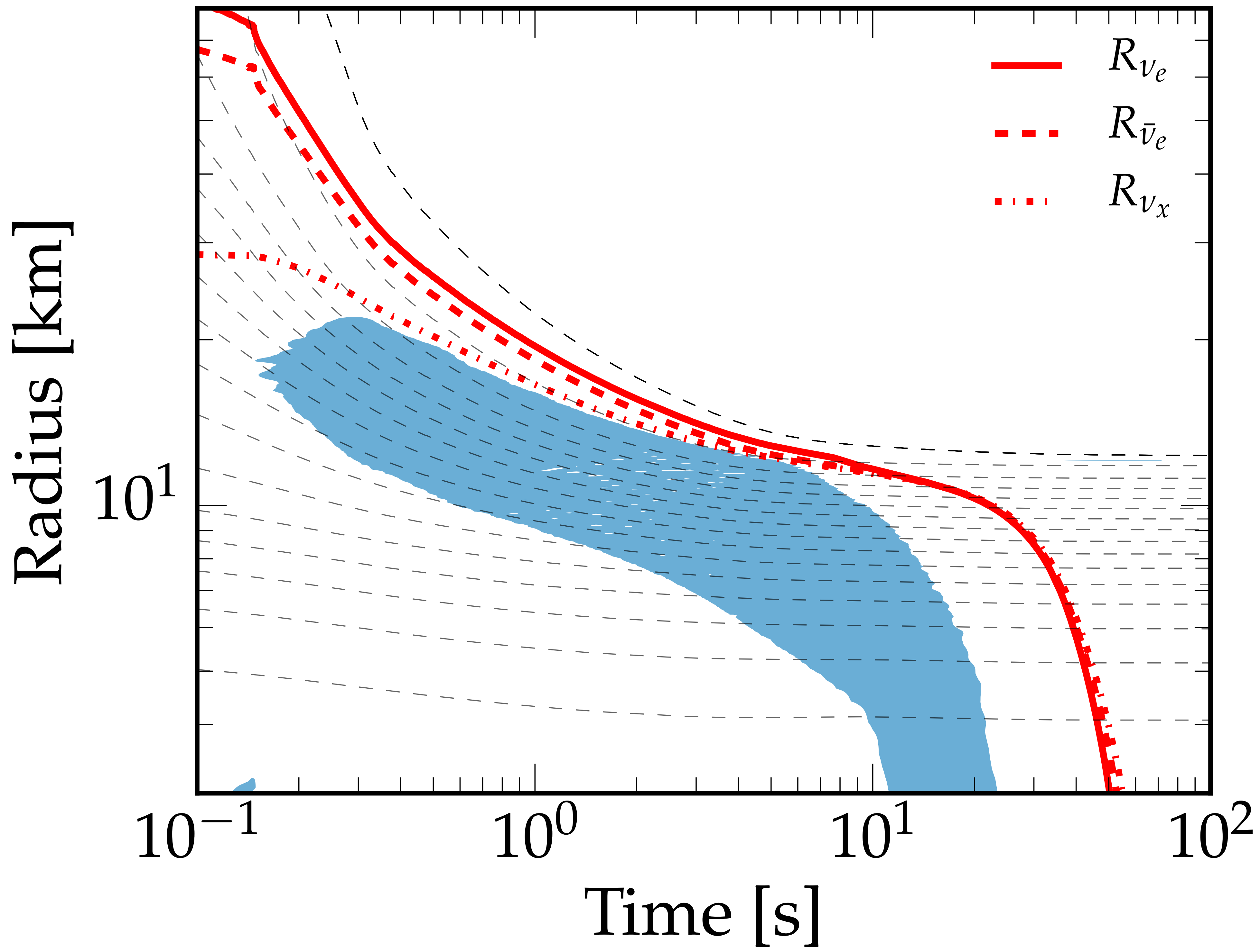
Liebendoerfer et al. 2002



From Sullivan et al. (2015)

Proto-Neutron Star Convection

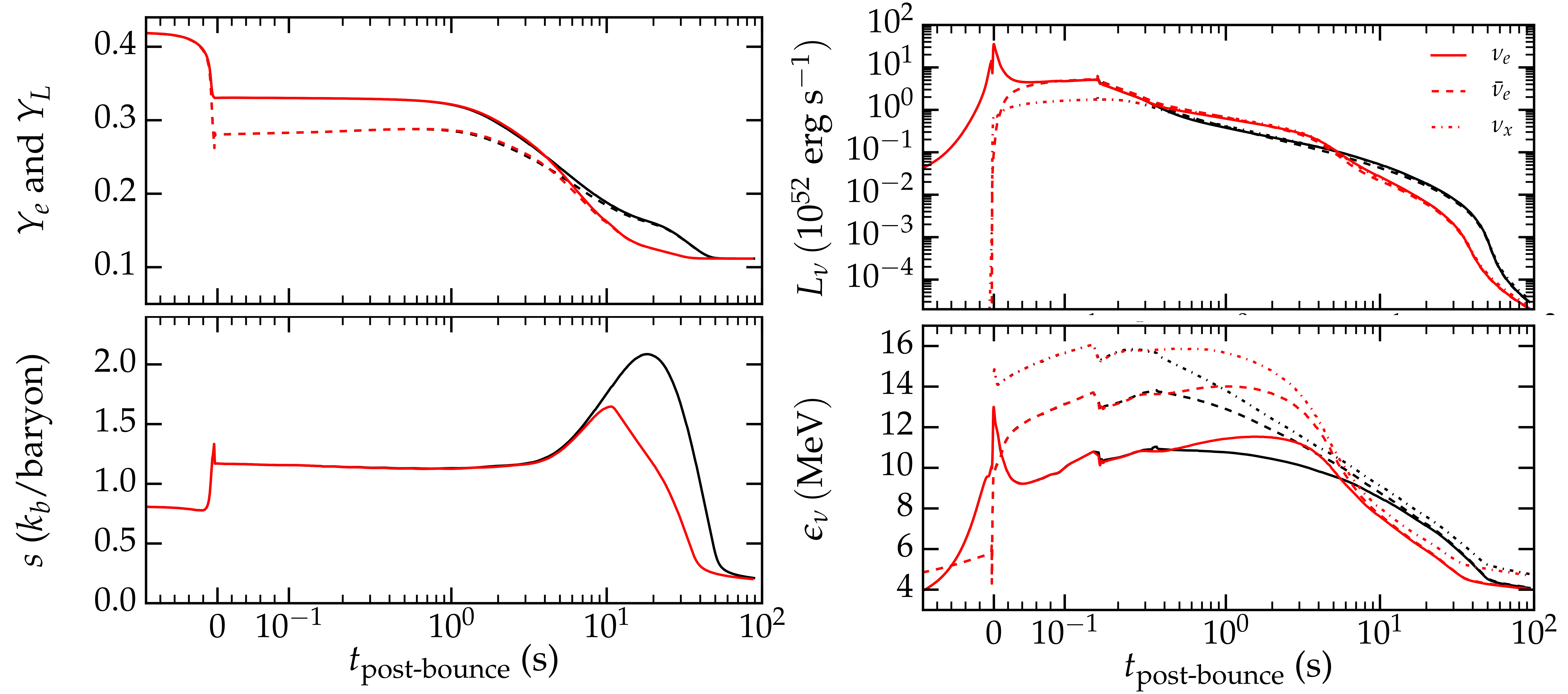




Region of convective instability determined by the Ledoux Criterion:

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

Proto-Neutron Star Convection



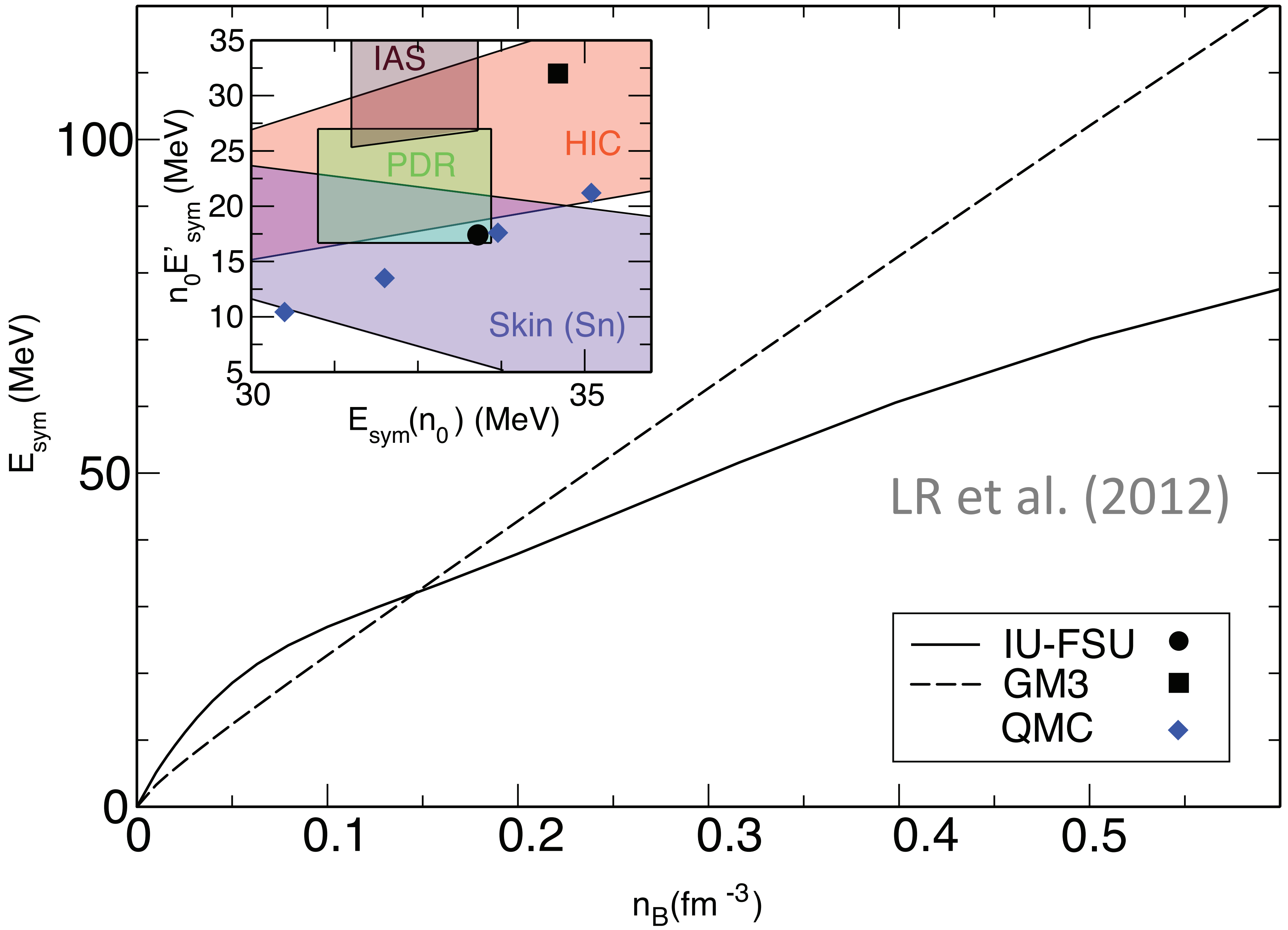
Black: No Convection

Red: Convection

See also Mirizzi et al. (2015)

Proto-Neutron Star Convection

Dependence on the EoS



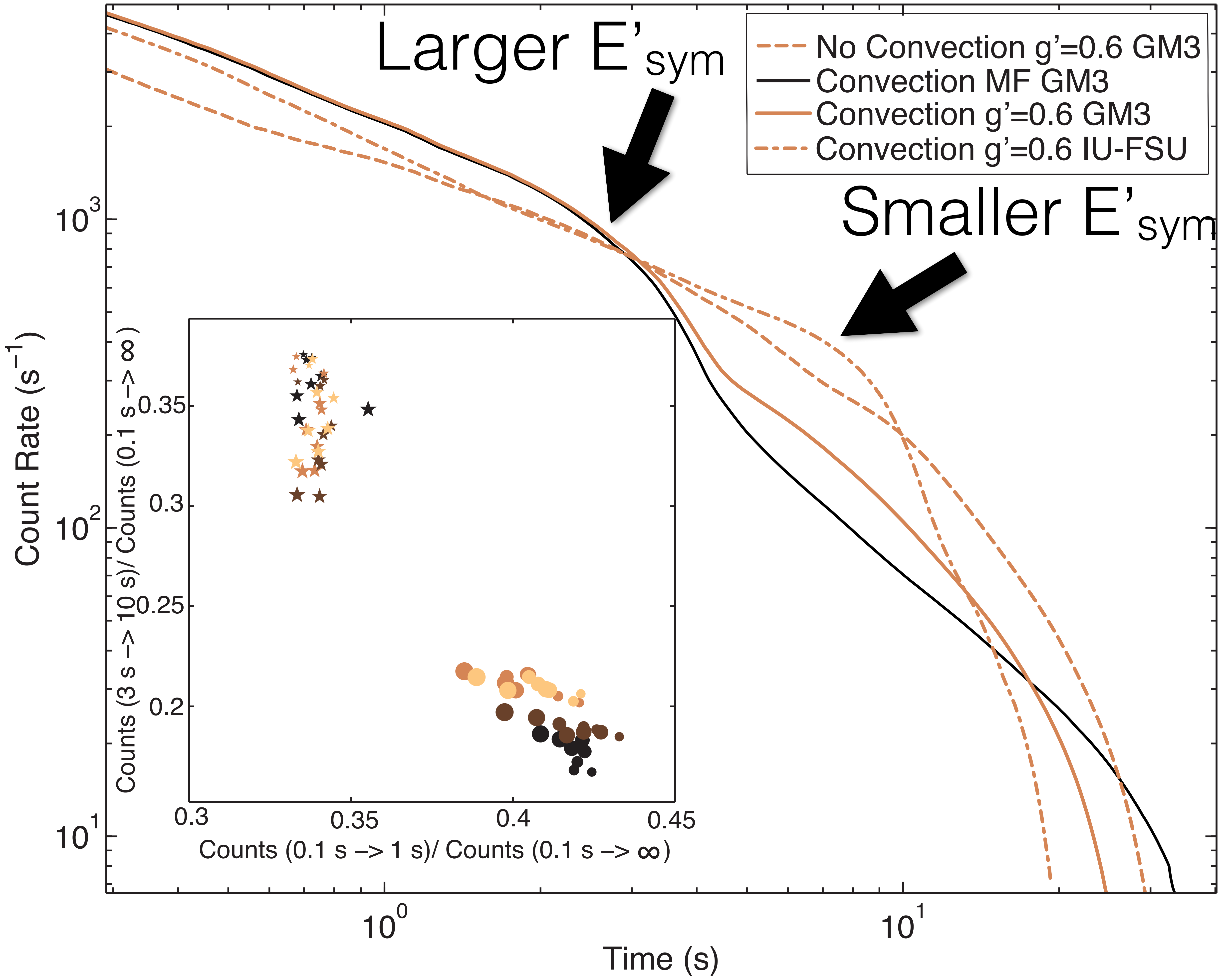
LR et al. (2012)

Pressure derivatives are sensitive to the symmetry energy derivative:

$$\epsilon(n_B, Y_e) = \epsilon(n_B, 1/2) + E_{\rm sym}(n_B)(1-2Y_e)^2$$

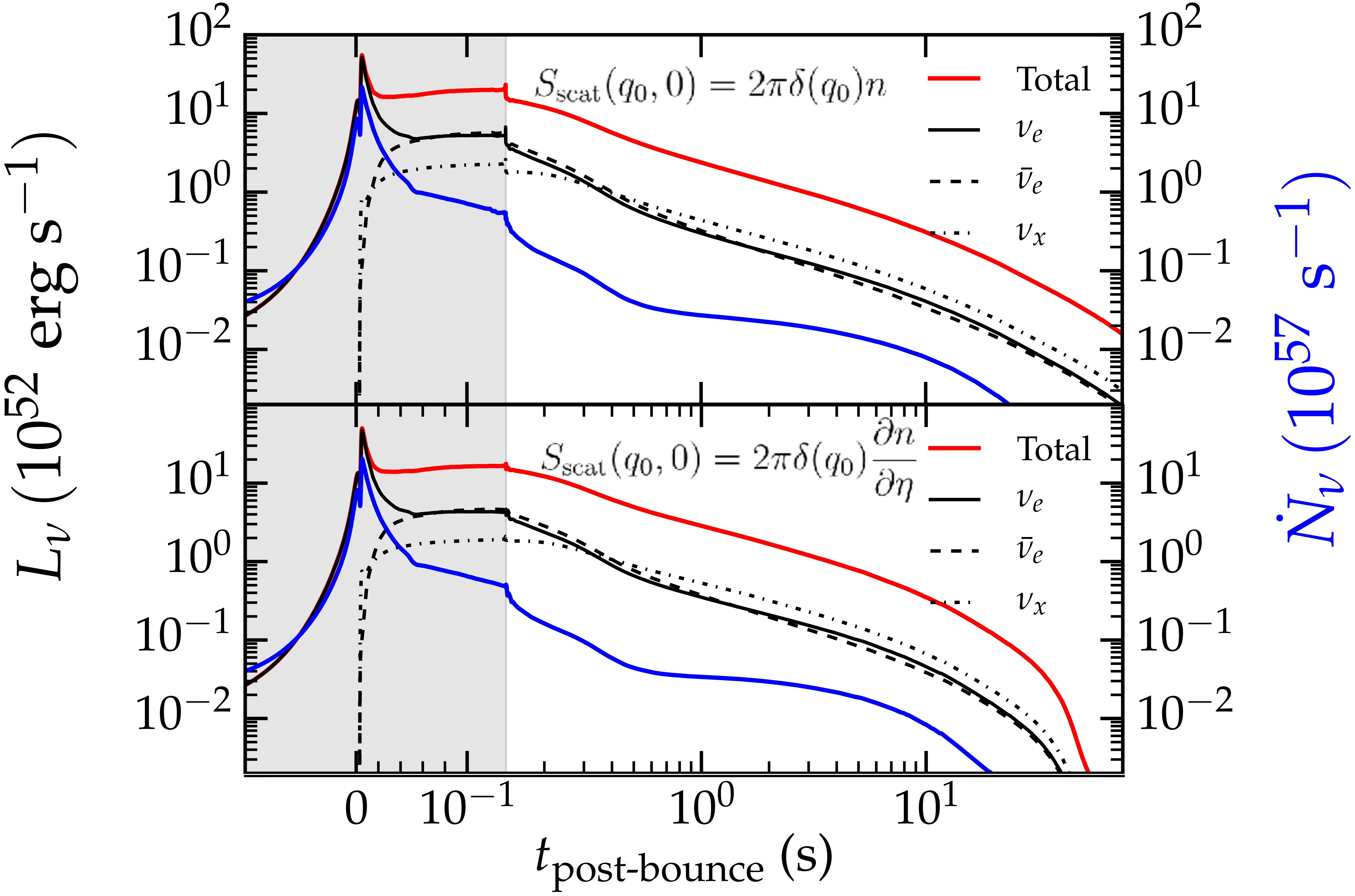
$$\left(\frac{\partial P}{\partial Y_L}\right)_{n_B} \simeq n_B^{4/3} Y_e^{1/3} - 4 n_B^2 E'_{\rm sym}(1-2Y_e)$$

Proto-Neutron Star Convection



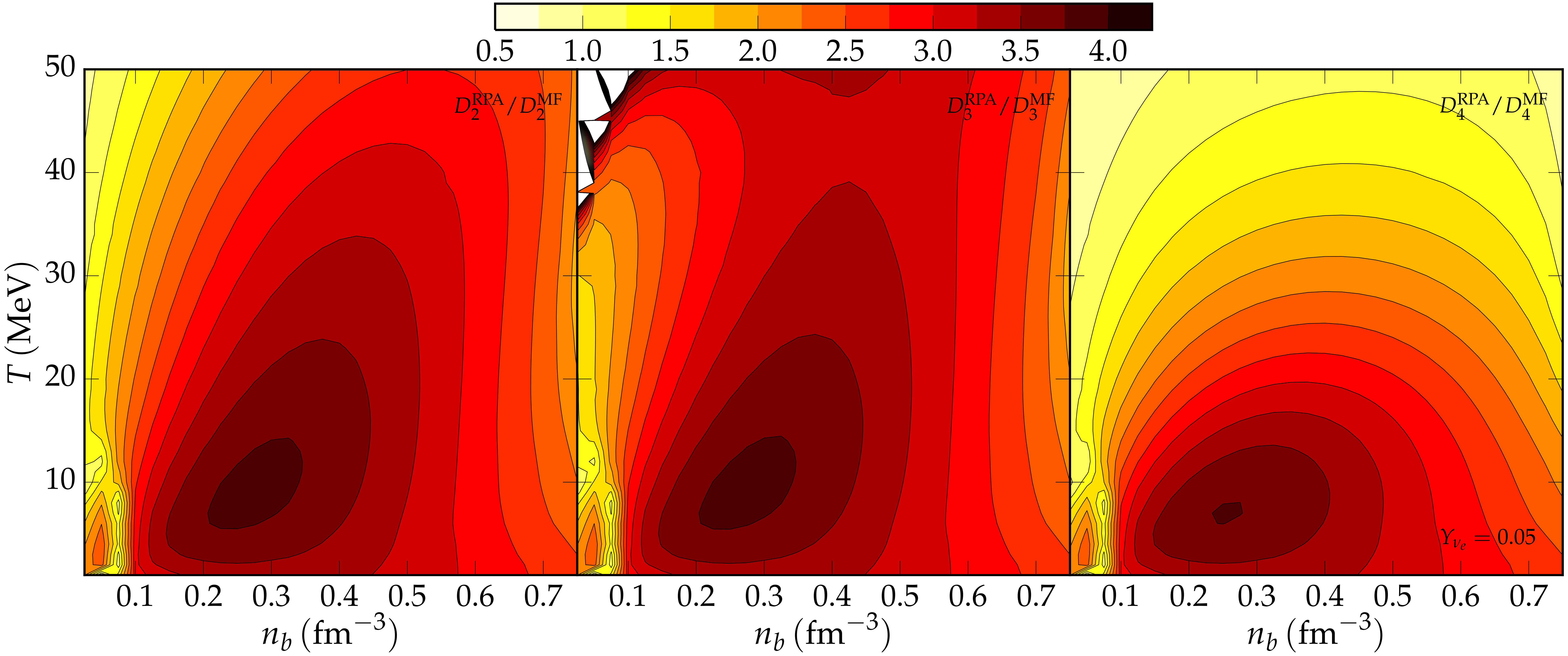
LR et al. (2012)

Opacity Dependence of Late Time Cooling



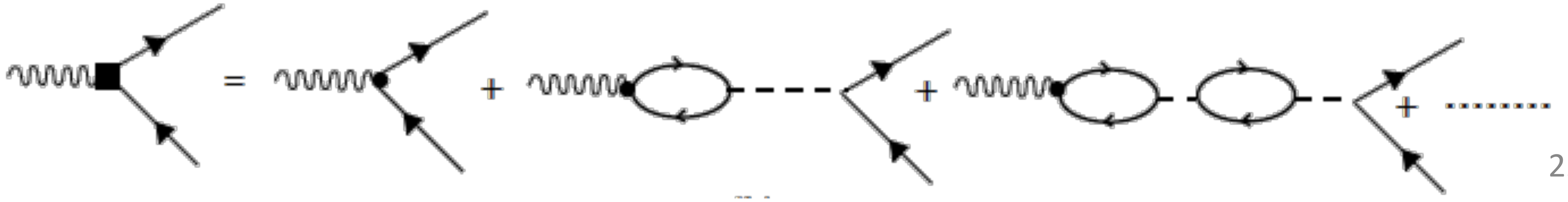
Impact of Nuclear Correlations on Neutrino Opacities

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

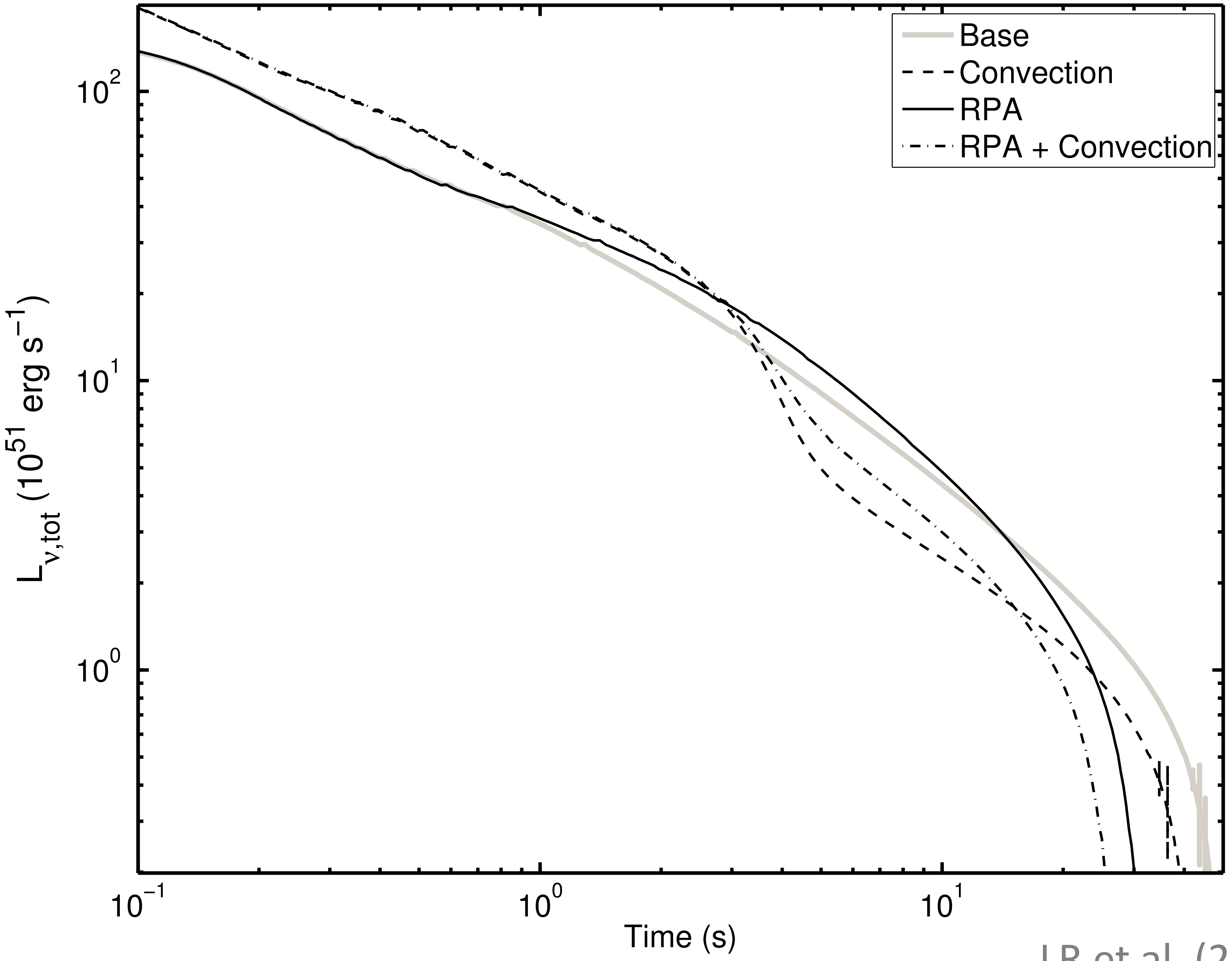


Neutrino Diffusion Coefficients

Correlations through the RPA:

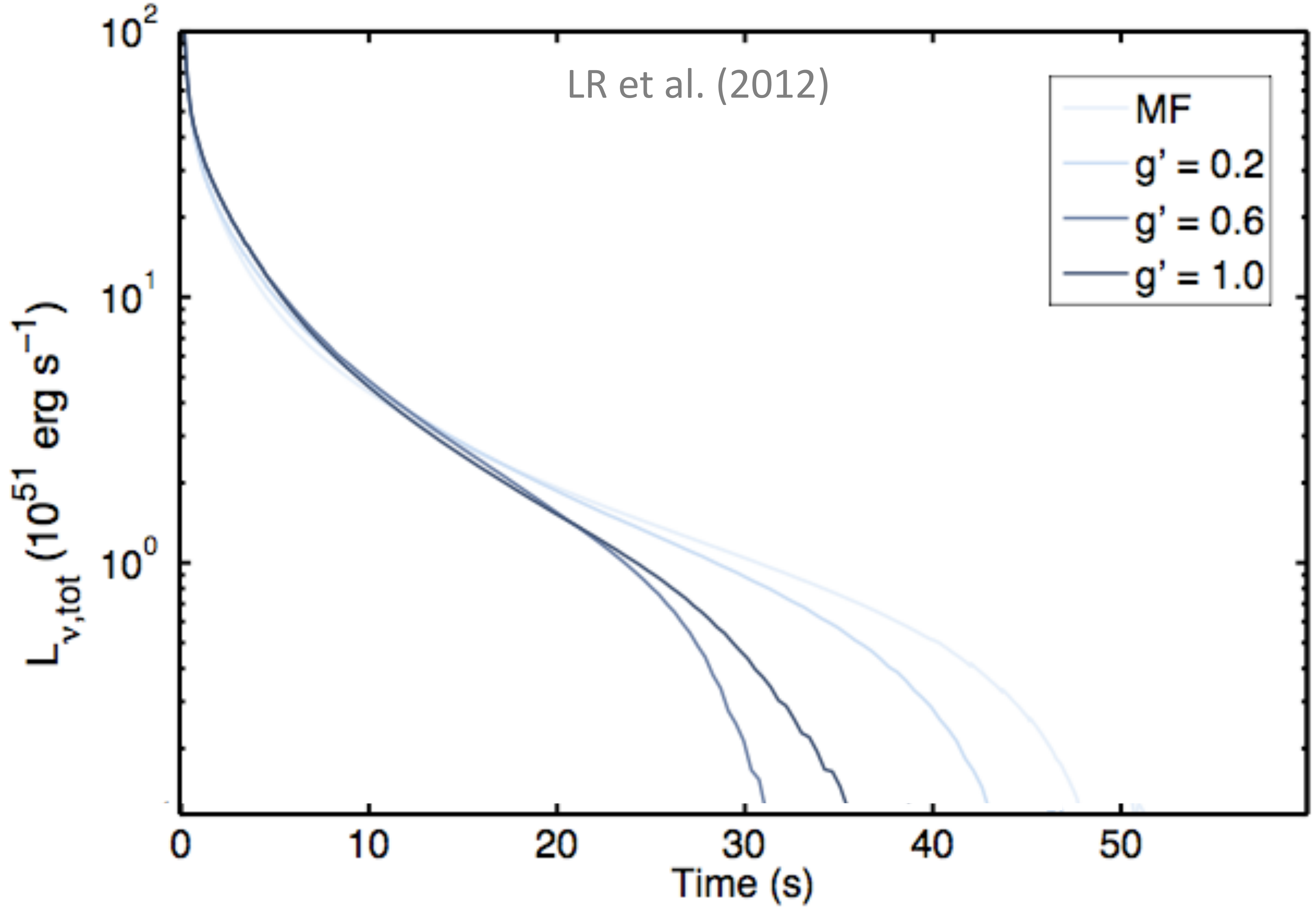


Impact of Screening



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

Variations in the Interaction



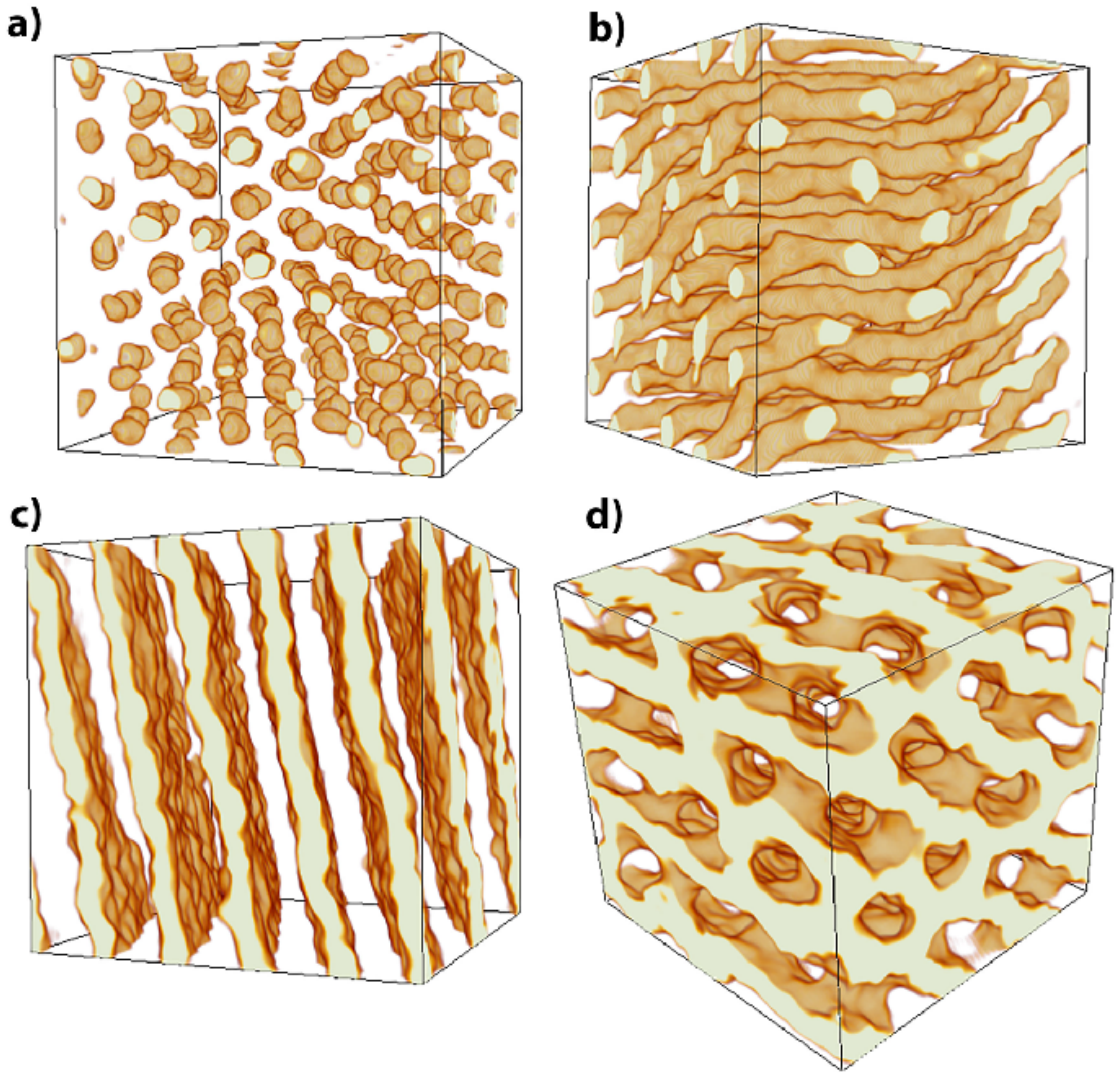
Varying the axial interaction

Reddy et al. (1999)

Nuclear Pasta and Coherent Scattering

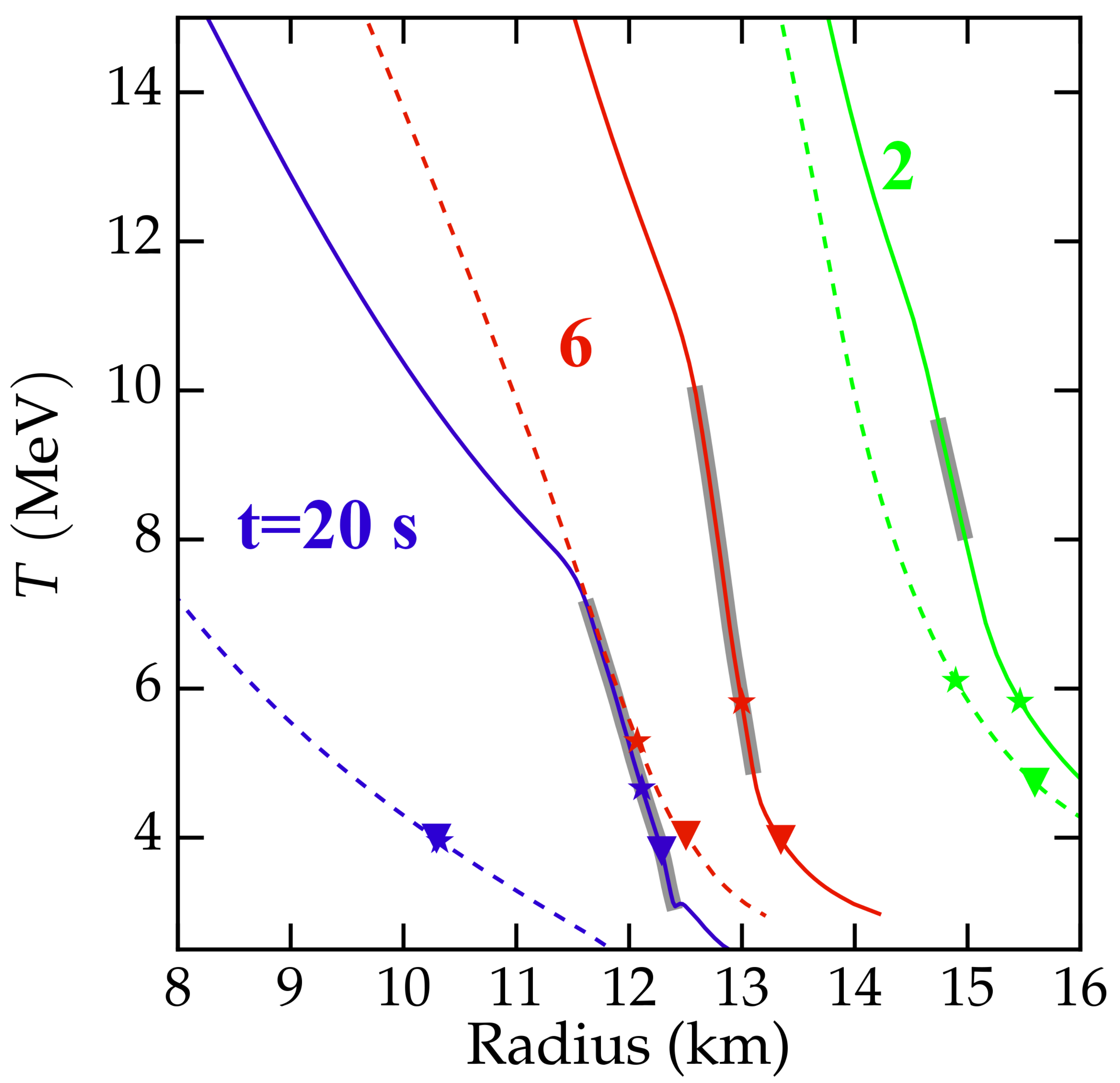
- Nuclear pasta may form below saturation density
- Competition between surface effects and Coulomb interaction
- Results in large structures for neutrinos to coherently scatter from

$$\frac{d\sigma_{\mathrm{coh}}}{dq} \propto N_w^2 \, S(q) \, F_A^2(q)$$

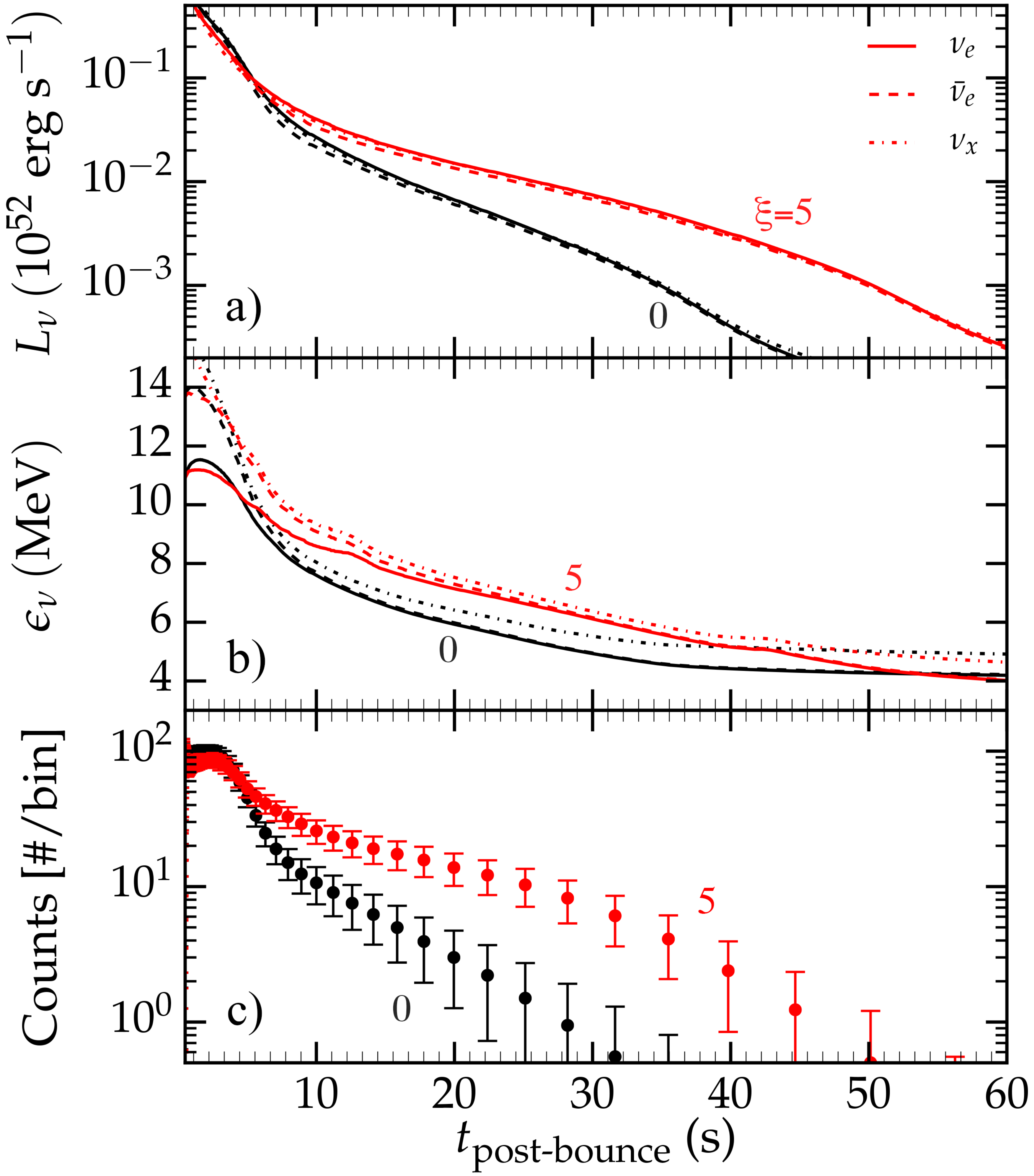


Horowitz, …, LR (2016)

Nuclear Pasta and Coherent Scattering



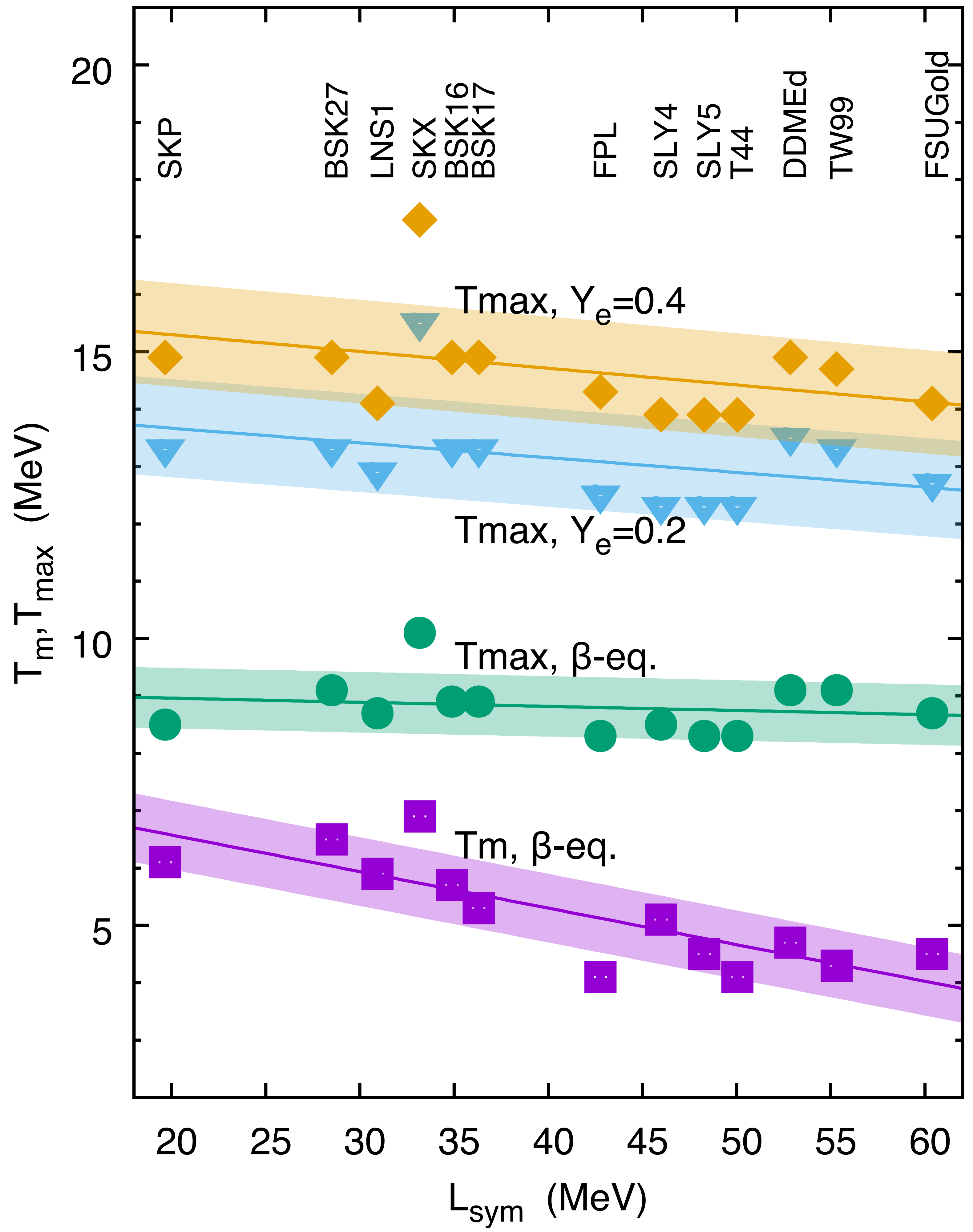
See also Nakazato et al. (2018) and Ken’ichiro’s talk



Horowitz, …, LR (2016)

Nuclear Pasta and Coherent Scattering

- Impact of pasta is sensitive to the pasta critical temperature
- This in turn is sensitive to E'_{sym}
- Actual pasta critical temperature may be too low to impact the cooling signal



Roggero, Margueron, LR, Reddy (2017)

The Neutrino Driven Wind

See Duncan et al. '86,Woosley et al. '94, Takahashi et al. '94, Thompson et al. '01, Metzger et al. '07 Arcones et al. '08, LR et al. '10, Fischer et al. '10, Huedepohl et al. '10, Vlasov '14, etc.

- After successful core collapse supernova, hot dense Protoneutron Star (PNS) is left behind

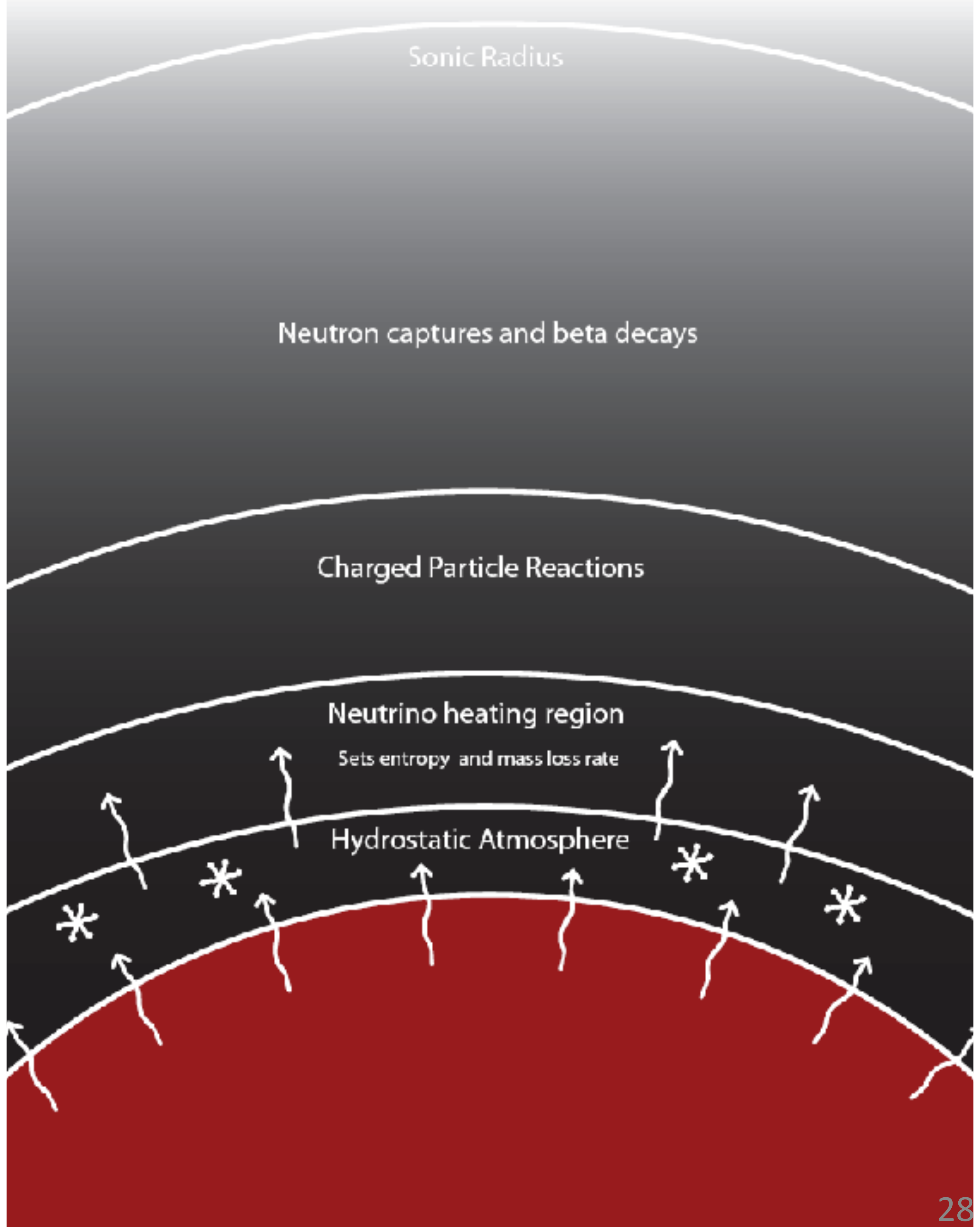
- As neutrinos leave the PNS, they deposit energy in material at the neutron stars surface

- Drives an outflow from the surface of the neutron star

- Electron fraction is determined by the neutrino interactions, some neutrons turned into protons and vice-versa

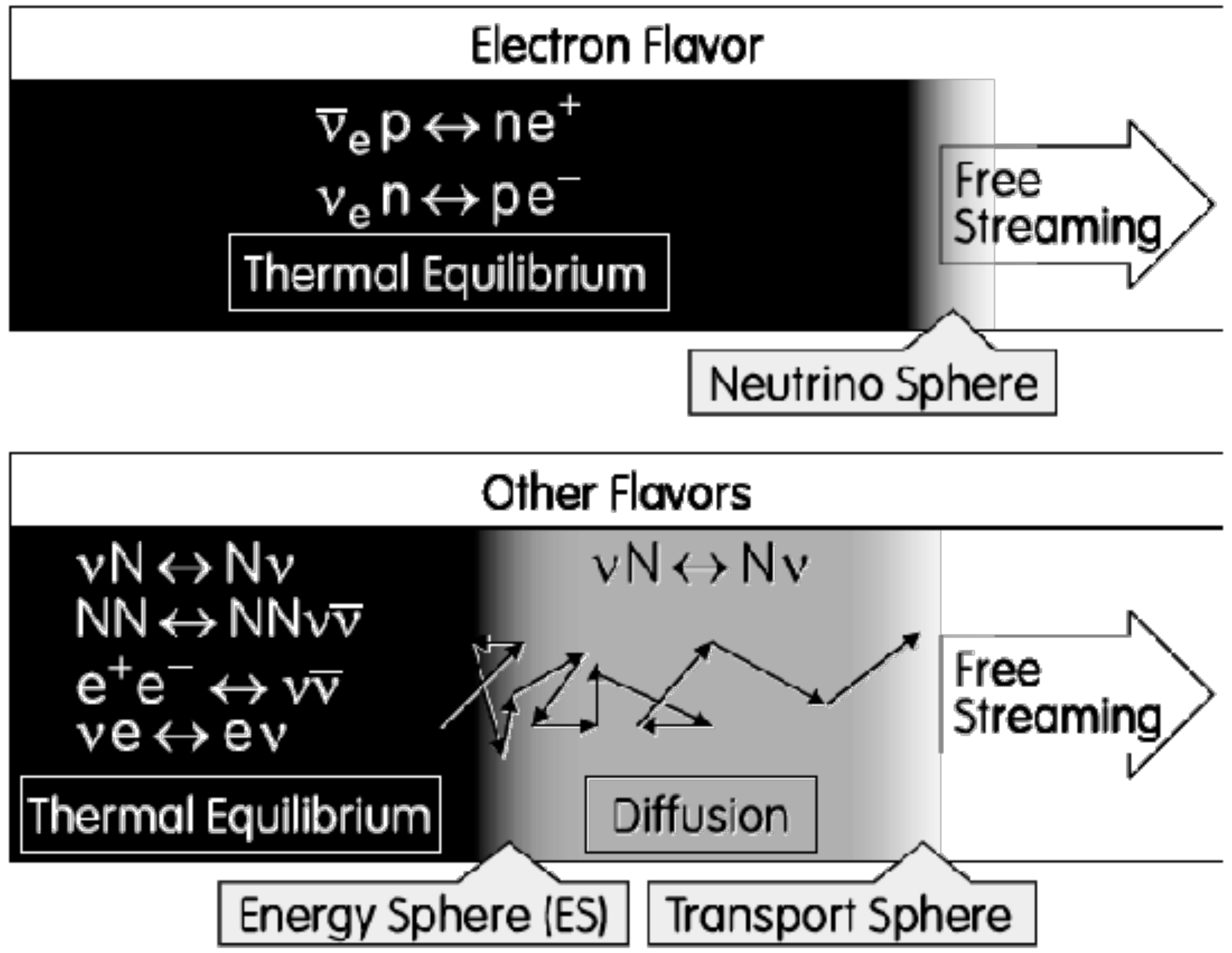
$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\nu_e + n \rightarrow e^- + p$$

- Possible site to make some interesting nuclei that are not made during normal stellar evolution: *r*-process, light *p* nuclides, N = 50 closed shell nuclei Sr, Y, Zr



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



From Raffelt ‘01

What Determines the ν_e Spectra?

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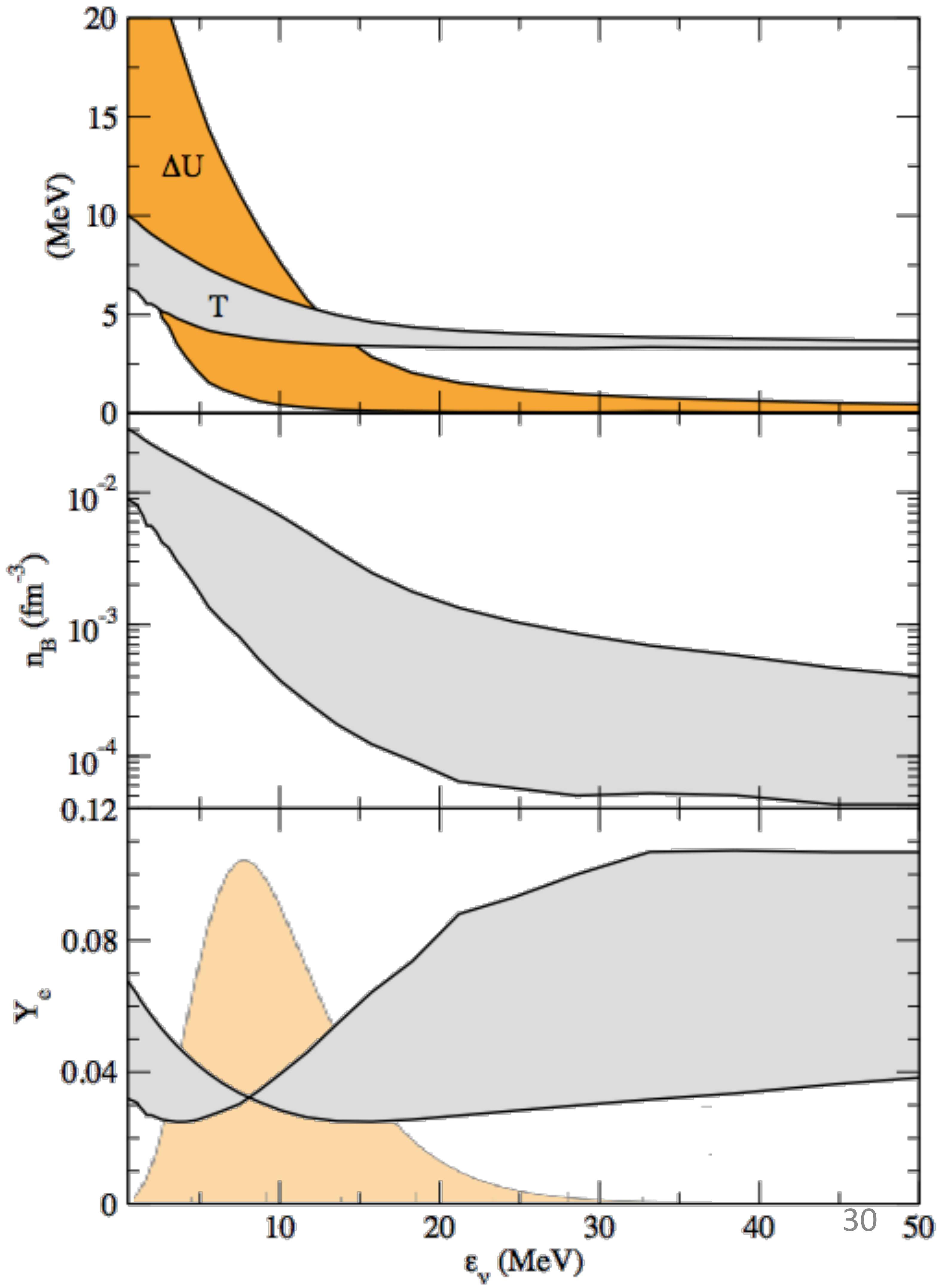


Charged Current Interaction Rates in Medium

Charged current rates introduce asymmetry between neutrinos and antineutrino interactions near the neutrinosphere

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

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:

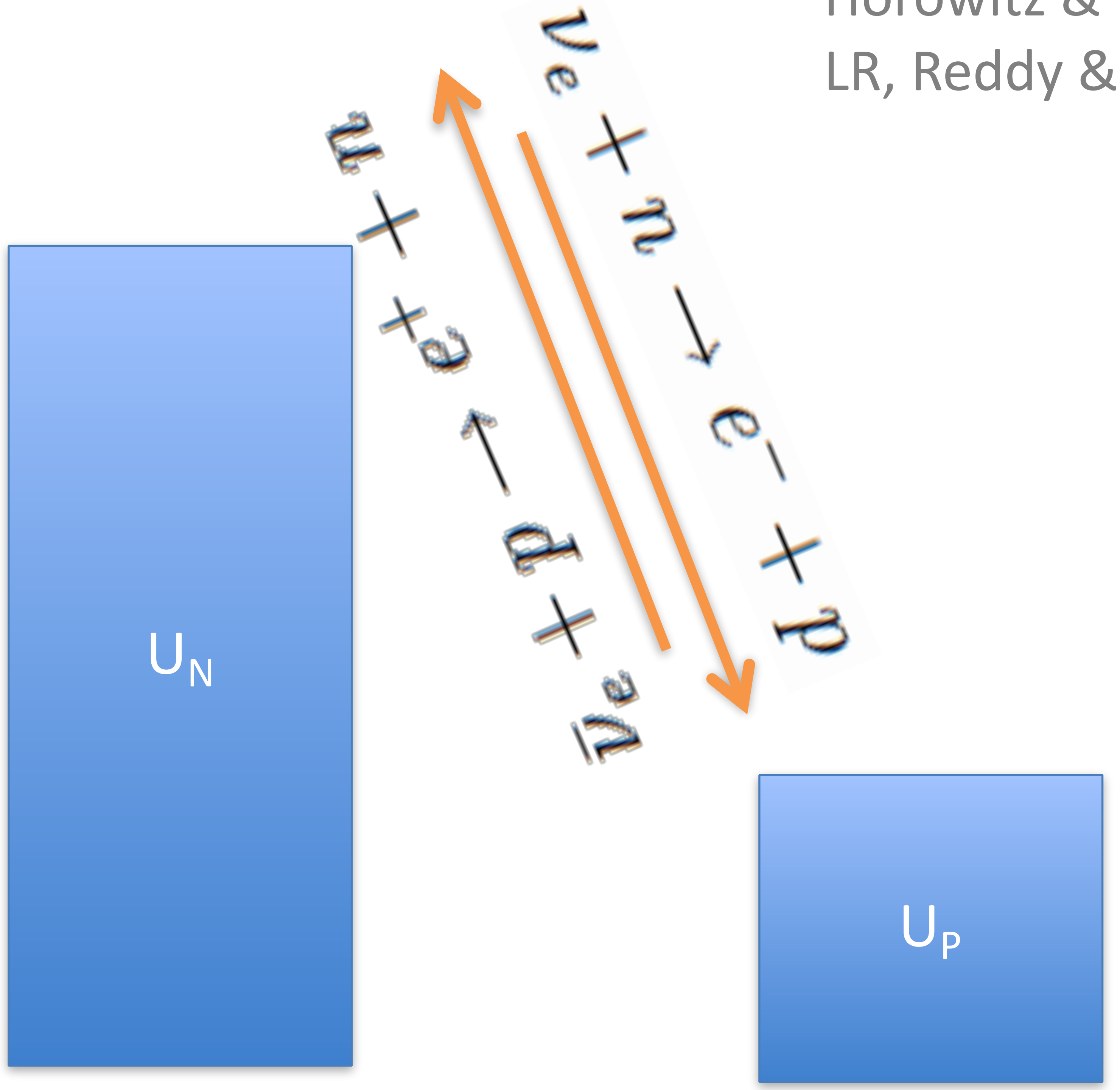
$$\Delta U = U_n - U_p \approx 40 \times \frac{(n_n - n_p)}{n_0} \text{ MeV}$$

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

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

Exponential increase in available phase space for electron neutrino capture:

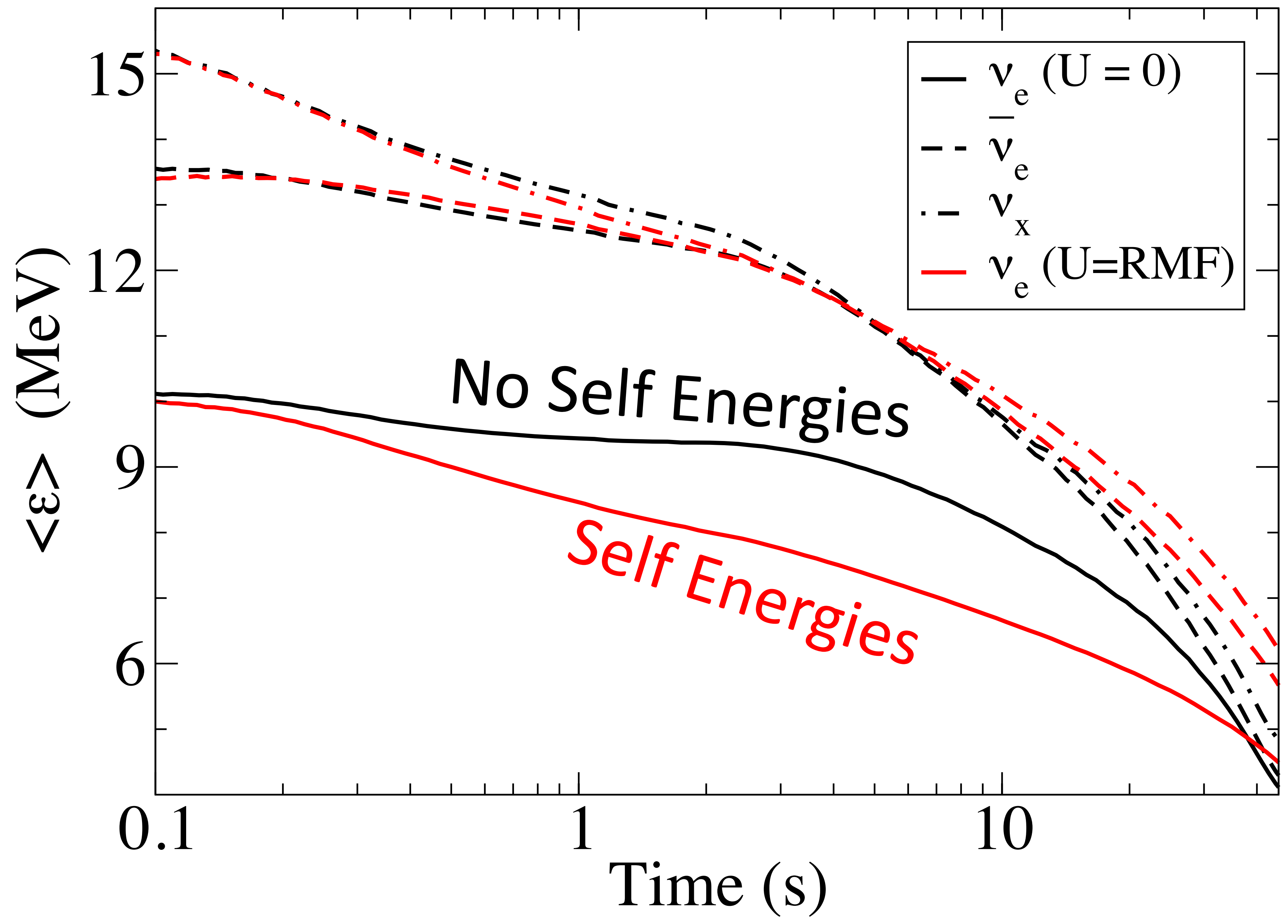
$$\frac{\lambda^{-1}(\Delta U)}{\lambda^{-1}(\Delta U = 0)} \approx \frac{(\varepsilon_\nu + \Delta U)^2}{\varepsilon_\nu^2} \exp(\Delta U / T)$$



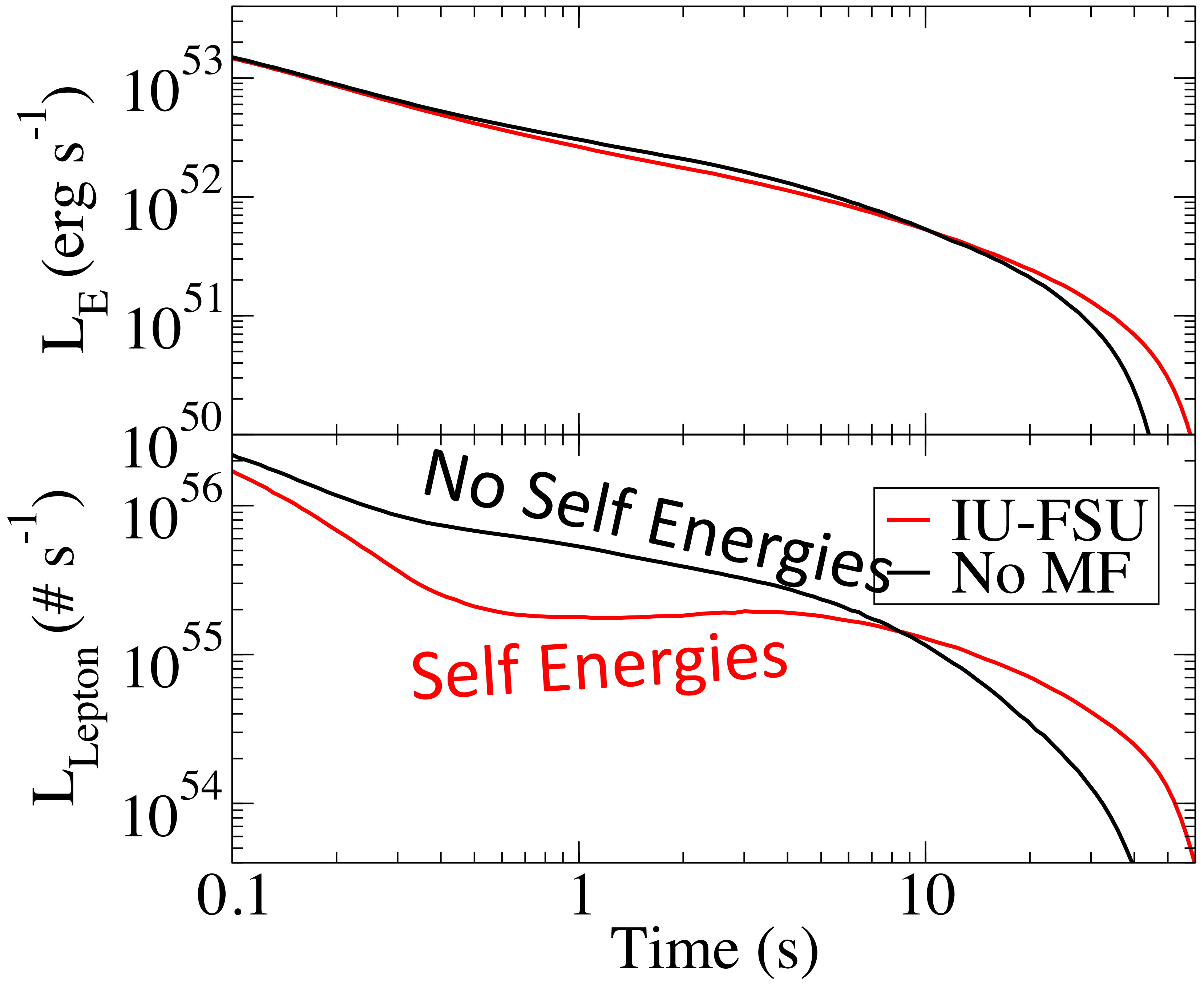
Neutrino emission w/ and w/o Nuclear Interactions

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

Self energies shift average neutrino energies

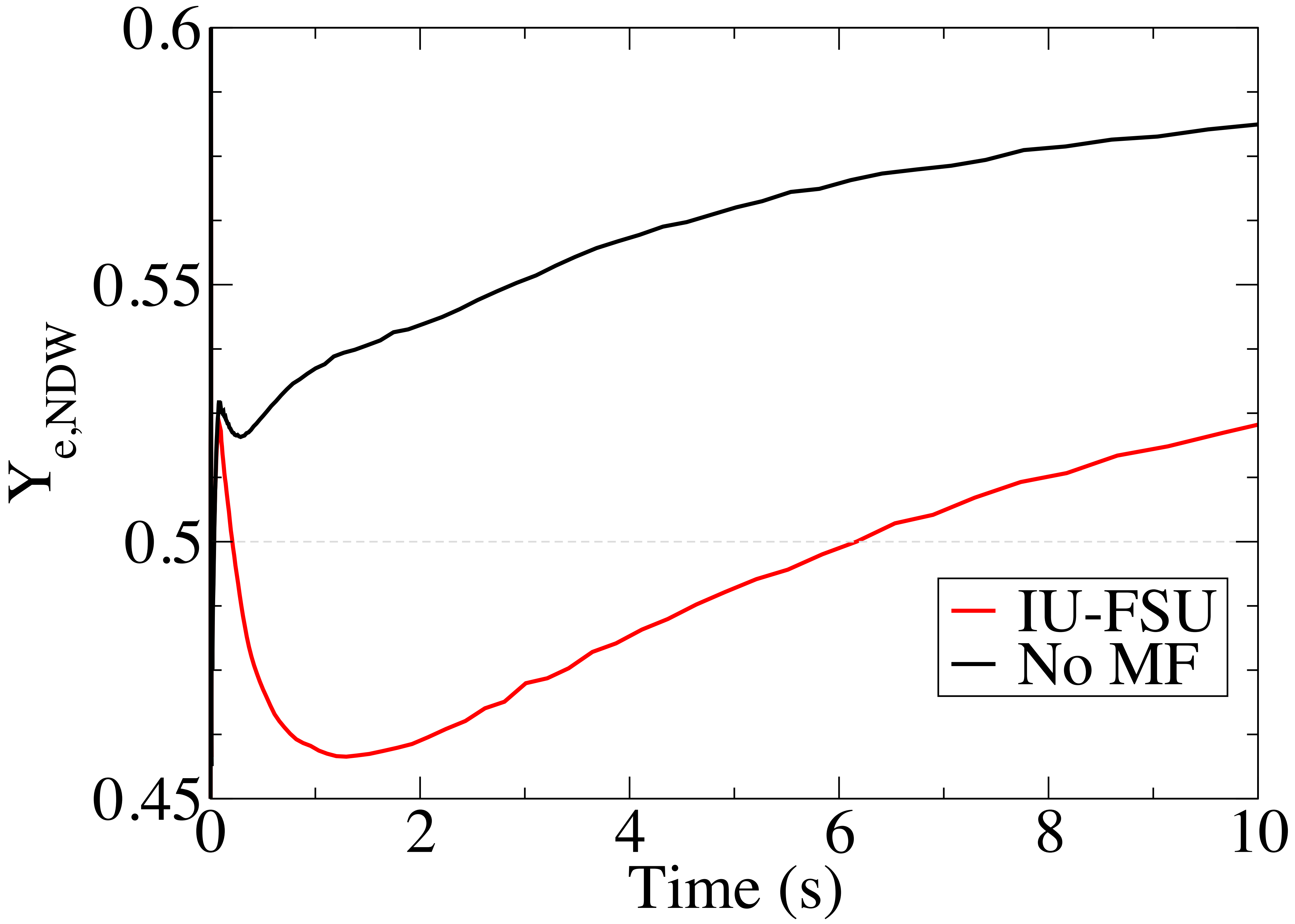


Deleptonization



Neutrino emission w/ and w/o Nuclear Interactions

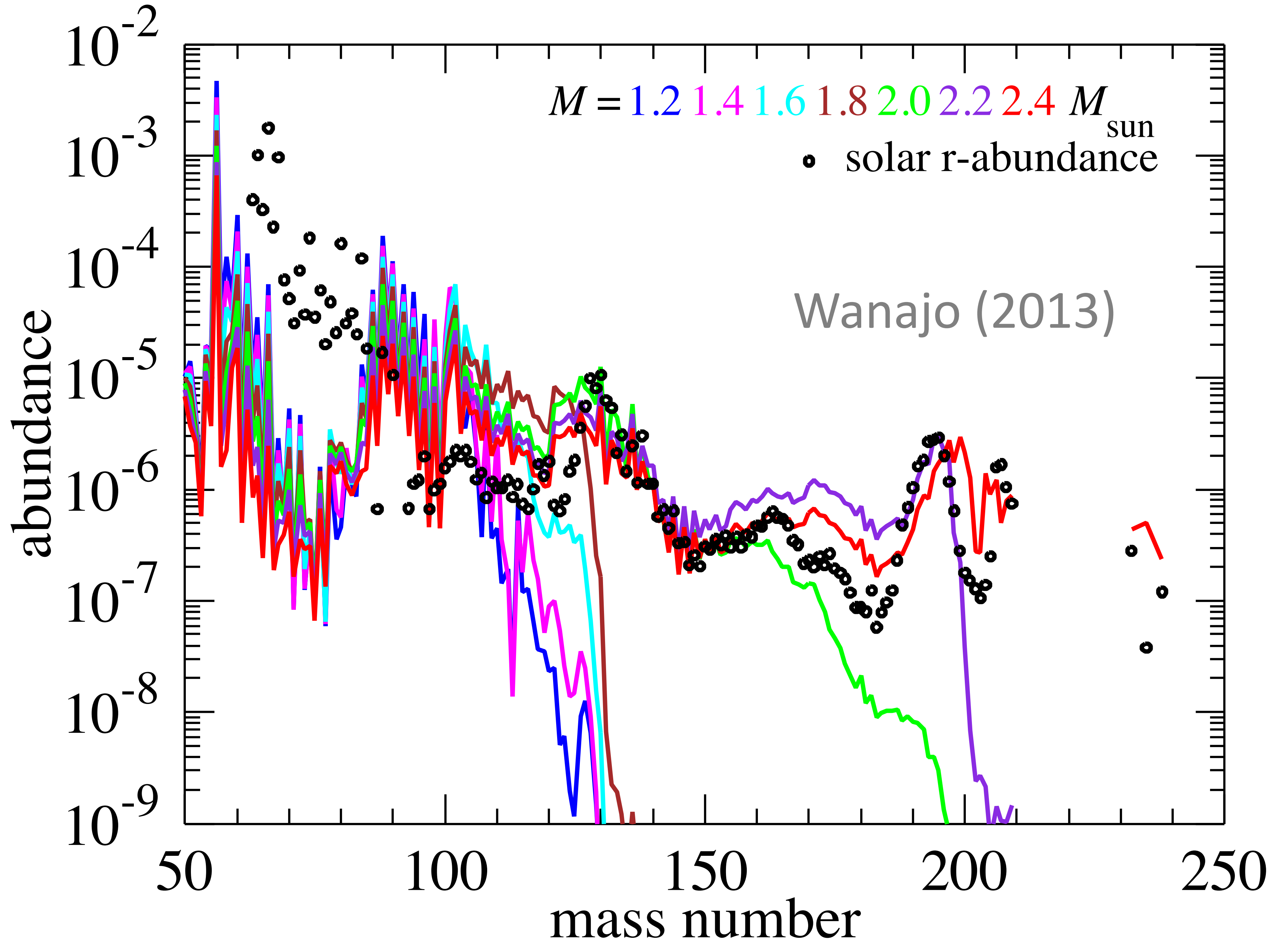
See LR ‘12 and Martinez-Pinedo et al. ‘12

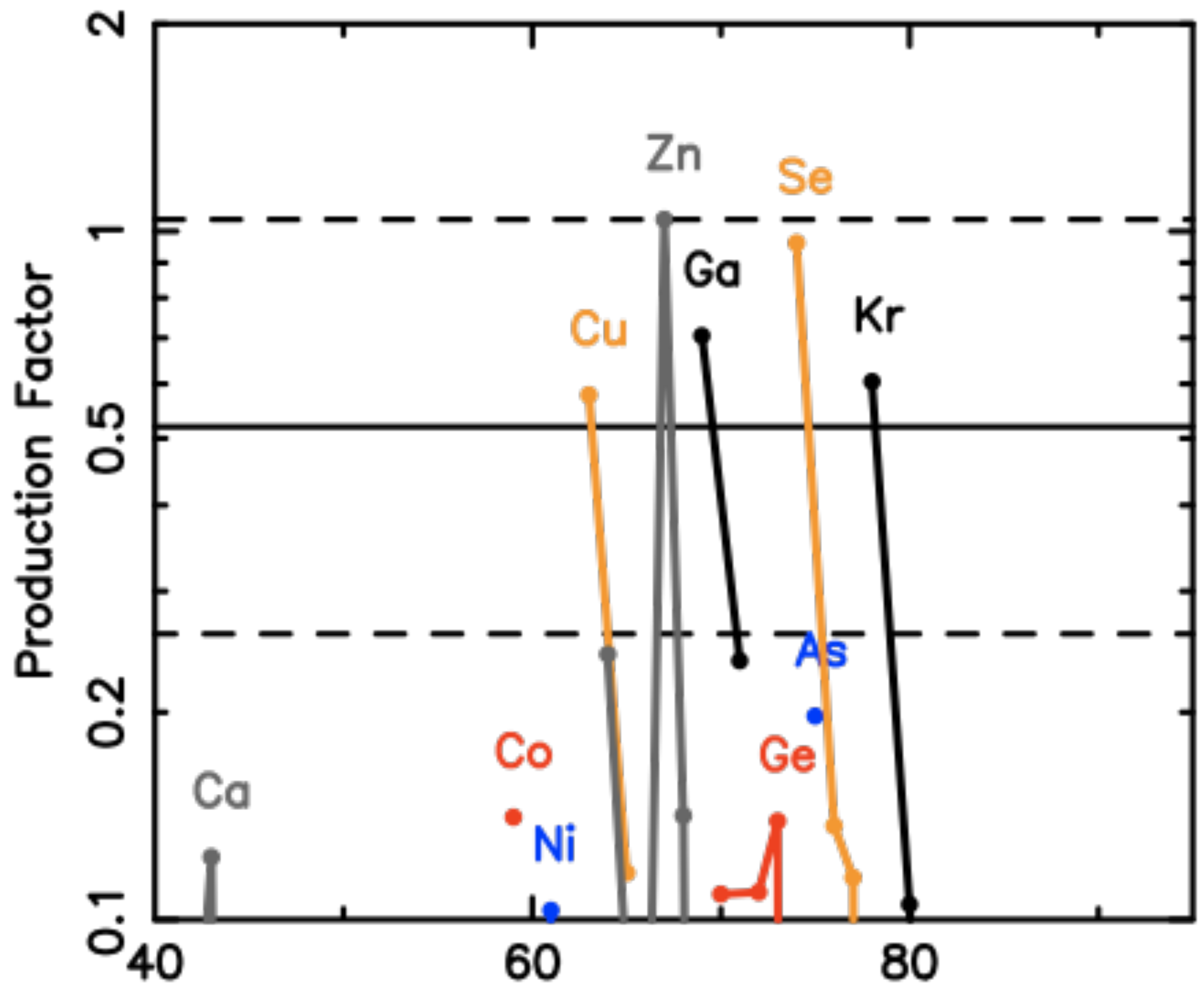


$$Y_e \approx \frac{\lambda_{\nu_e}^{-1}}{\lambda_{\nu_e}^{-1} + \lambda_{\bar{\nu}_e}^{-1}} \approx \left(1 + \frac{\dot{N}_{\bar{\nu}_e}}{\dot{N}_{\nu_e}} \frac{(\varepsilon_{\bar{\nu}_e} - \Delta)^2}{(\varepsilon_{\nu_e} + \Delta)^2}\right)^{-1}$$

Integrated NDW Nucleosynthesis

$$P_i = \frac{X_{i,w} M_w}{X_{i,\odot}(M_w + M_{\rm sn})}$$



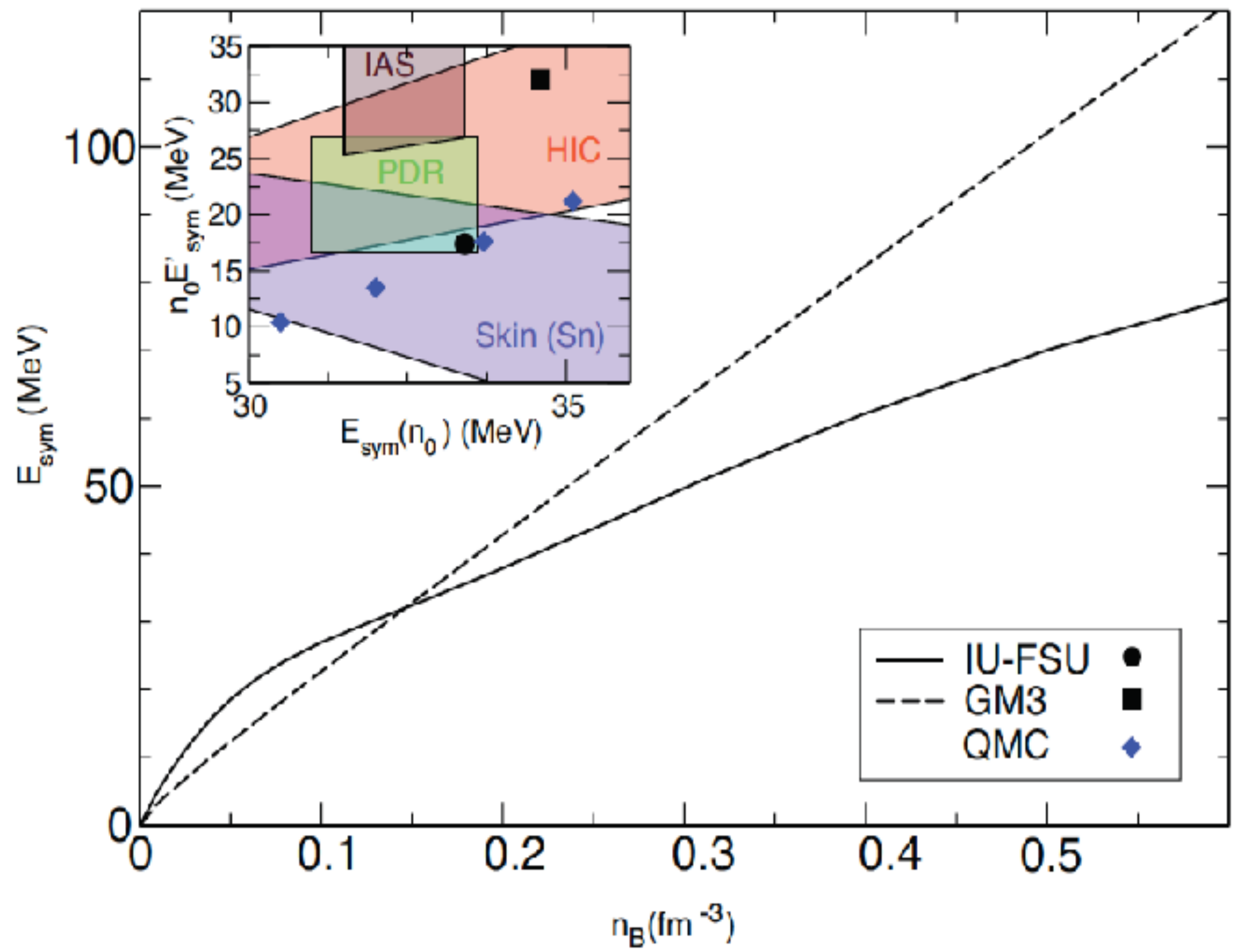


Roberts. ’12 neutrino histories. Significant N = 50 closed neutron shell production.

Huedepohl et al. ’10 neutrino histories. Very little nucleosynthesis. 7.5 $M_{\rm sun}$ ejected.

Symmetry Energy Dependence

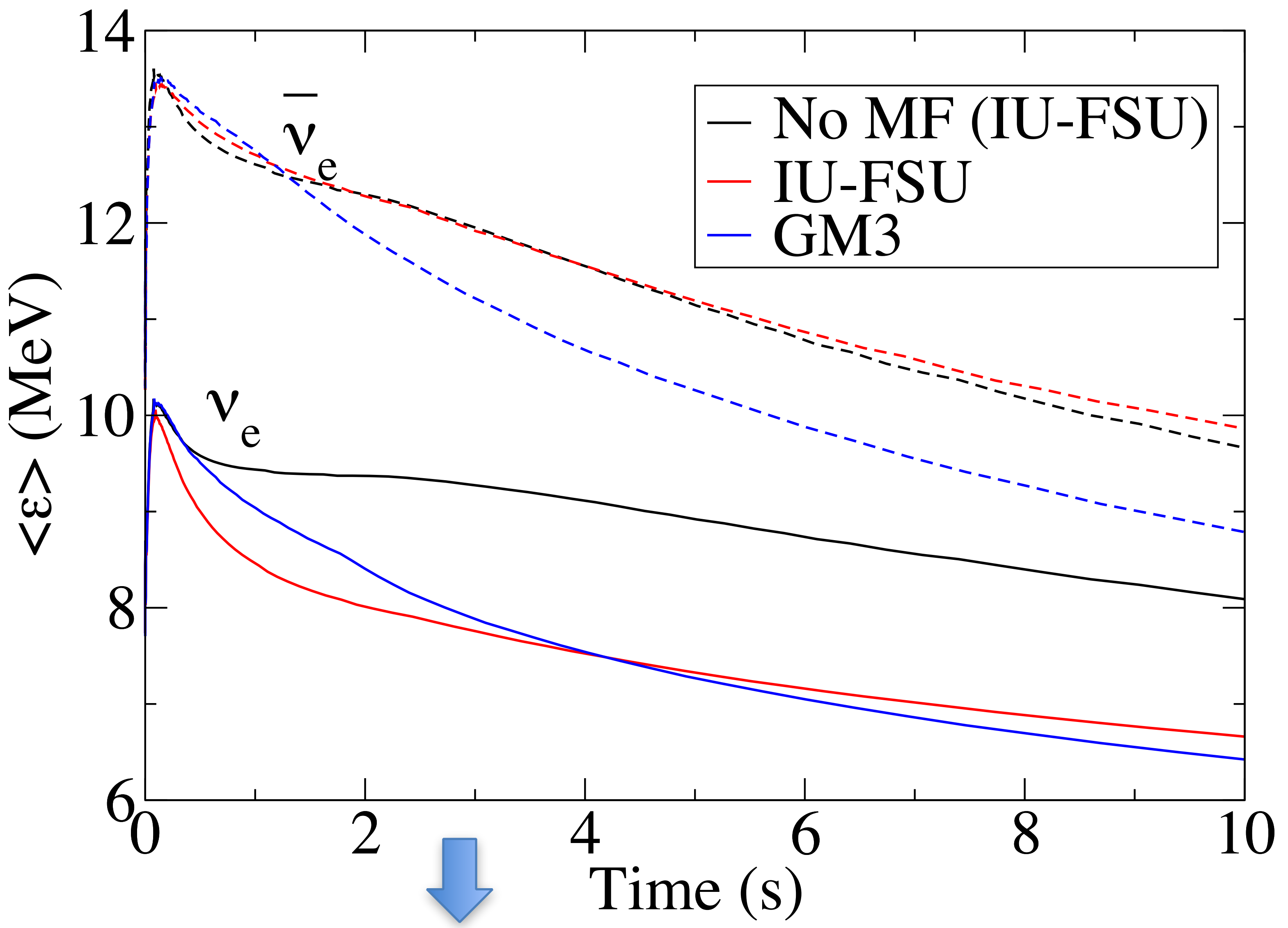
From Roberts et al. (2012)

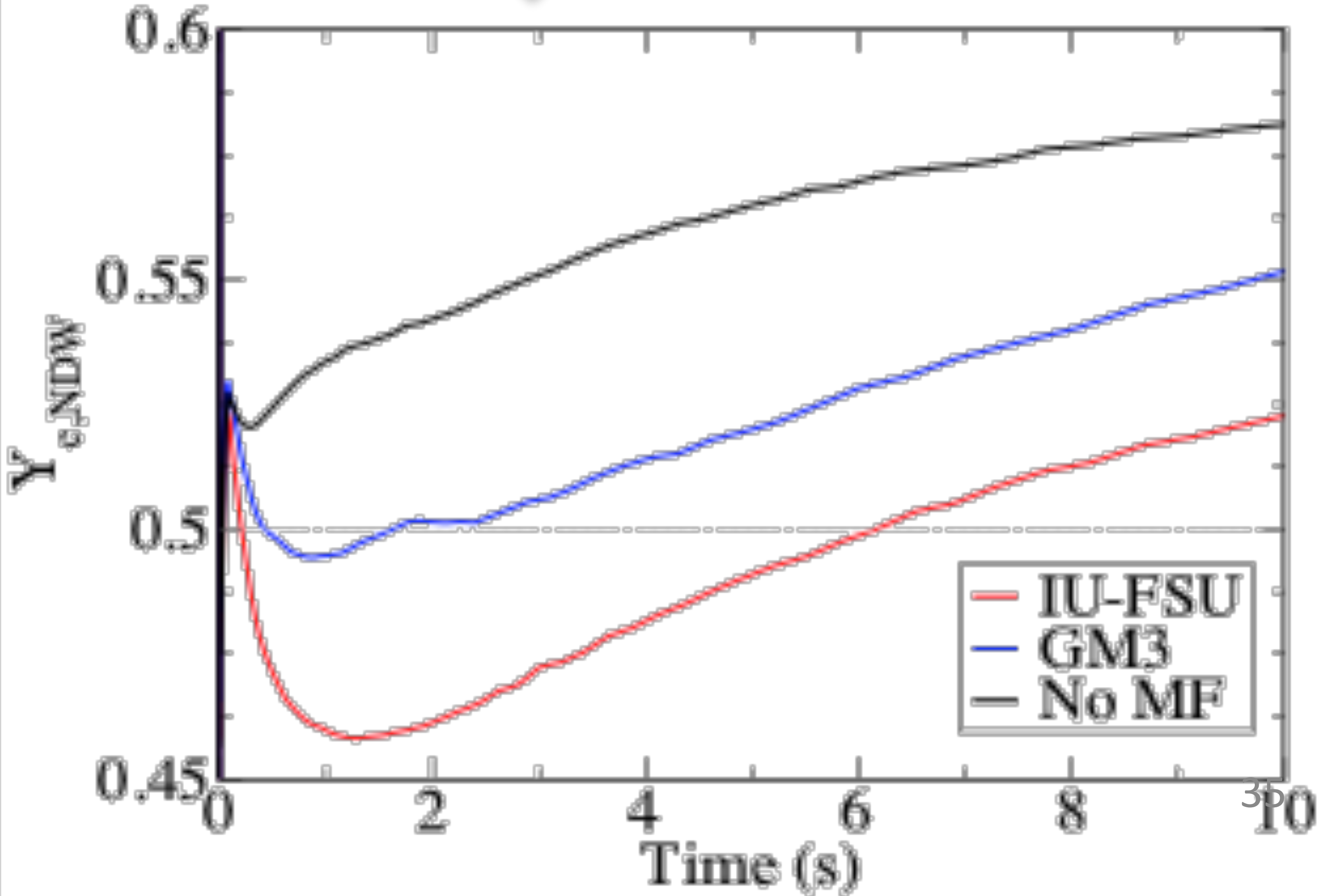


Different equations of state

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

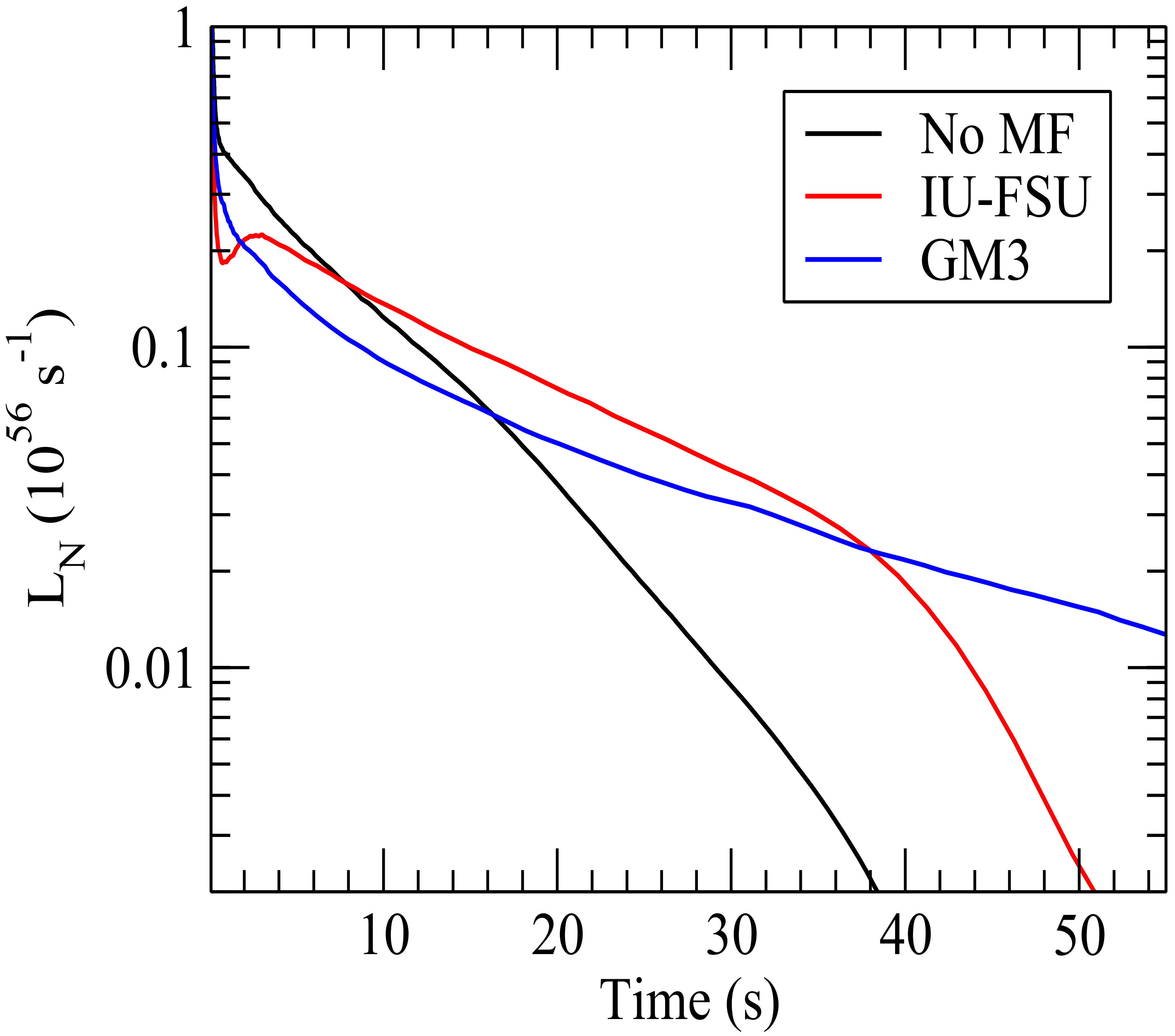
From Horowitz et al. (2012)





The Deleptonization Rate

- Nuclear symmetry energy also effects deleptonization rate of PNS (see Sumiyoshi et al. ’95)
- Inclusion of mean fields decreases deleptonization rate, which also pushes towards lower electron fraction
- Larger L results in longer deleptonization timescale



Conclusions

- 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

- Neutrino opacities especially important to the late time cooling timescale

- In particular, nuclear correlations and nuclear pasta can leave a signature on the tail of the neutrino signal

- NDW nucleosynthesis is sensitive to charged current interactions near the neutrino sphere