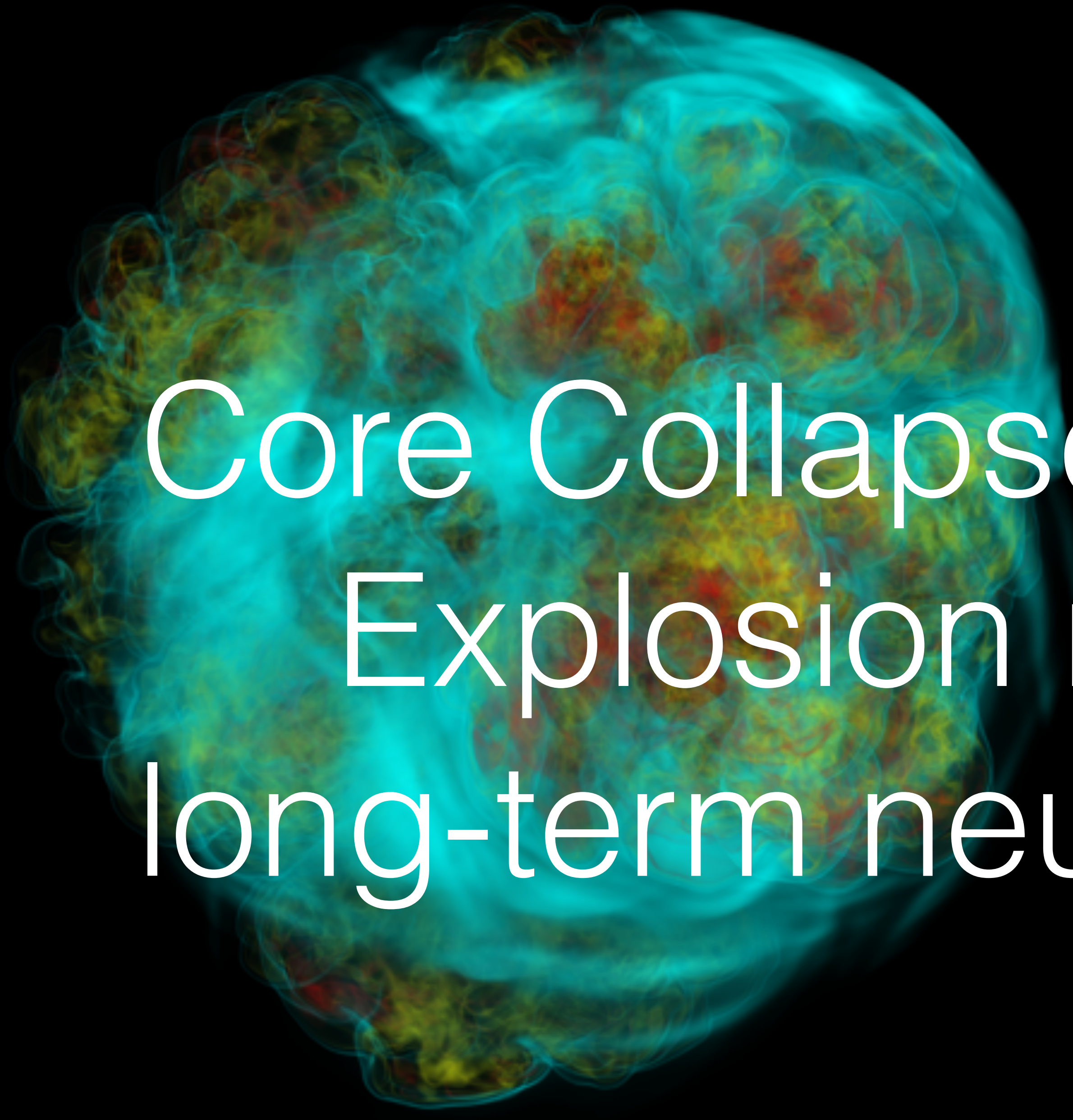
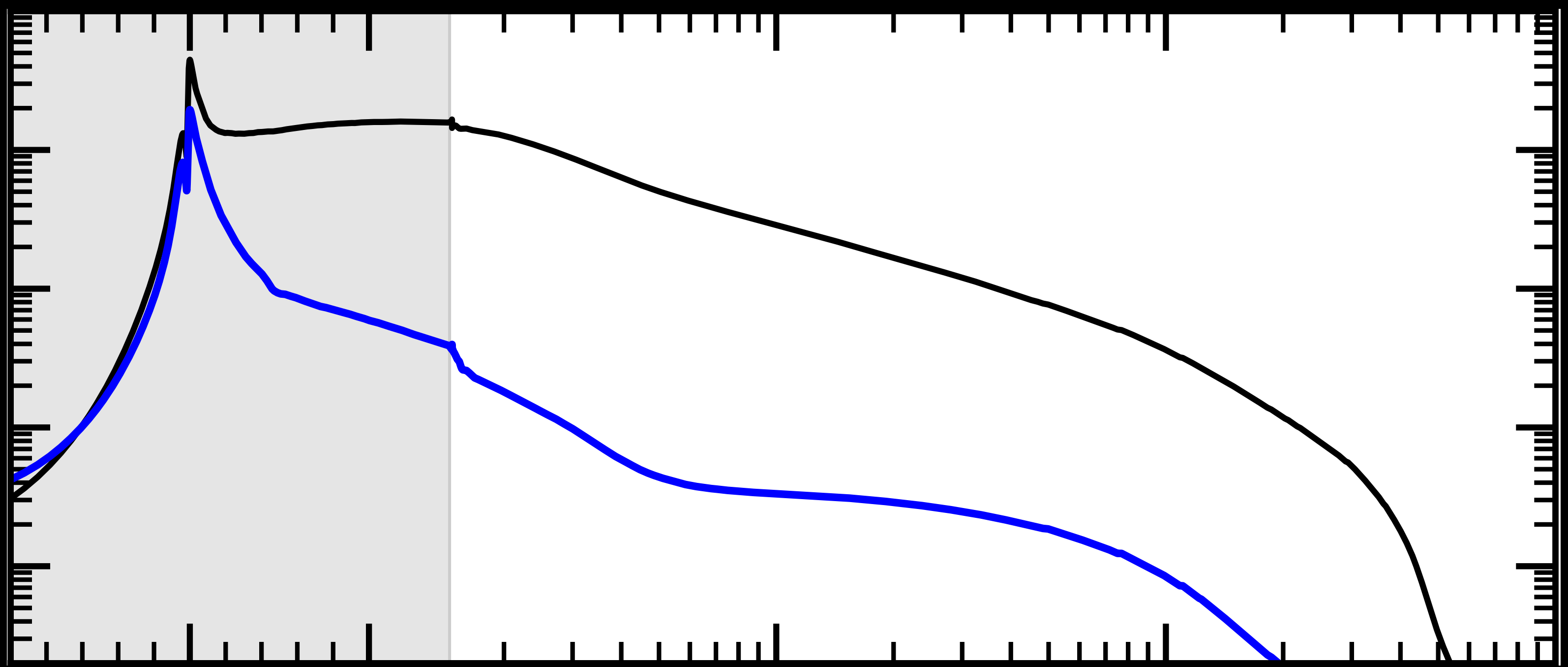


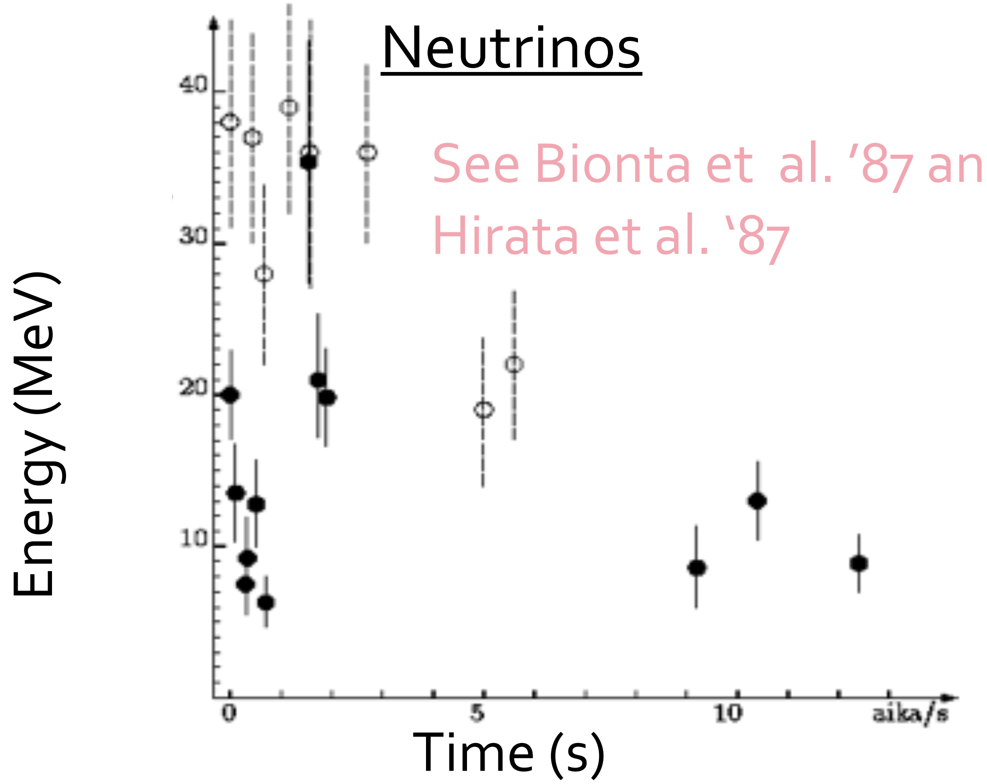
# Core Collapse Supernovae: Explosion models and long-term neutrino emission

Luke Roberts
NSCL, MSU



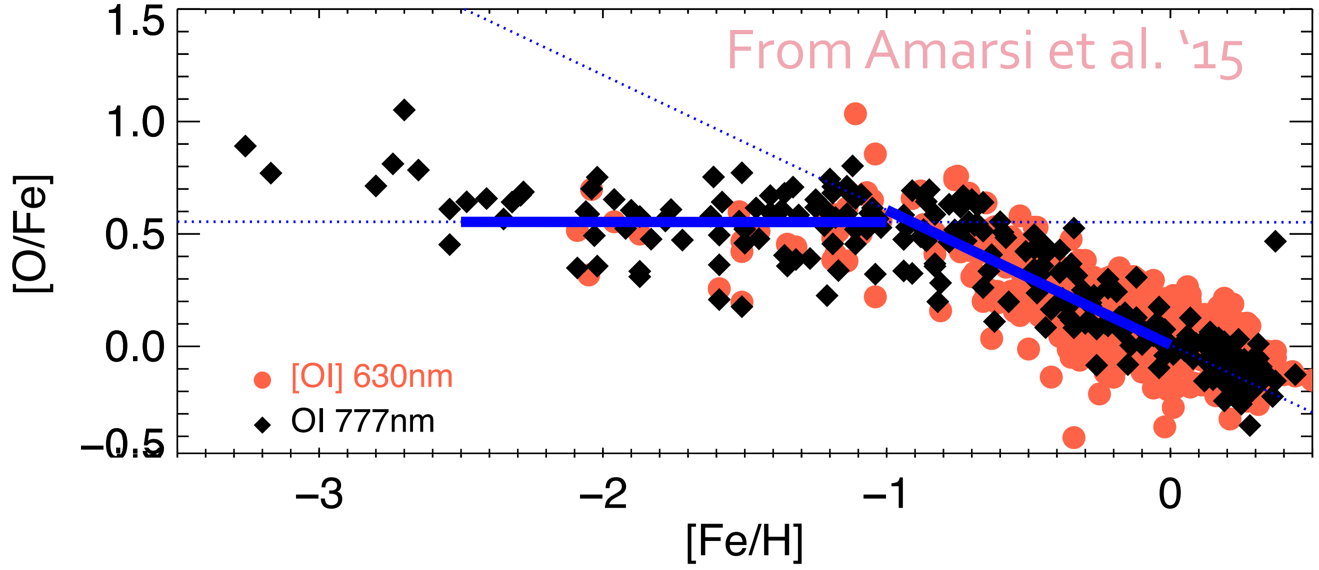
# Core Collapse Supernovae: Multi-Messenger Events

## Neutrinos



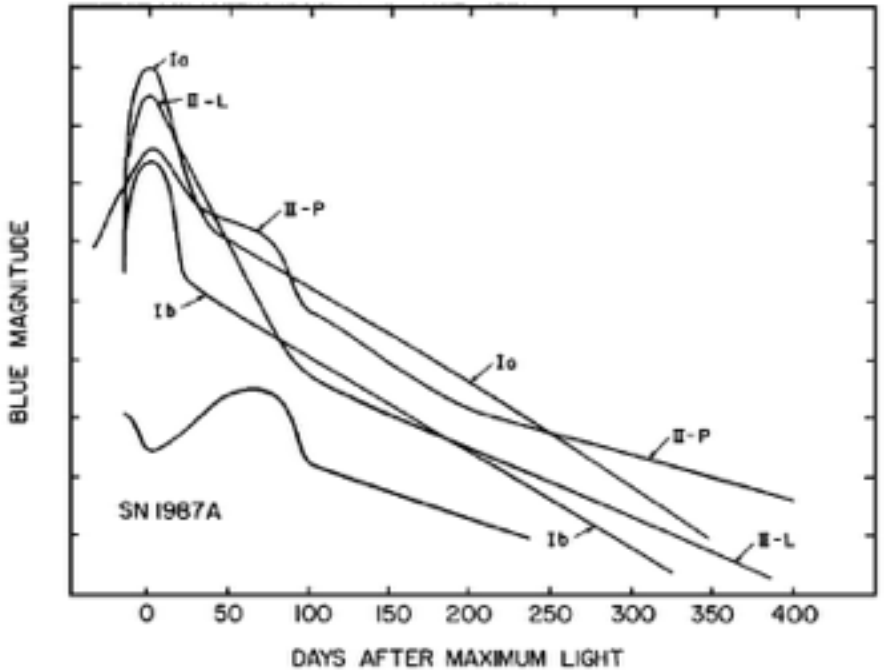
See Bionta et al. '87 and Hirata et al. '87

## Nucleosynthesis



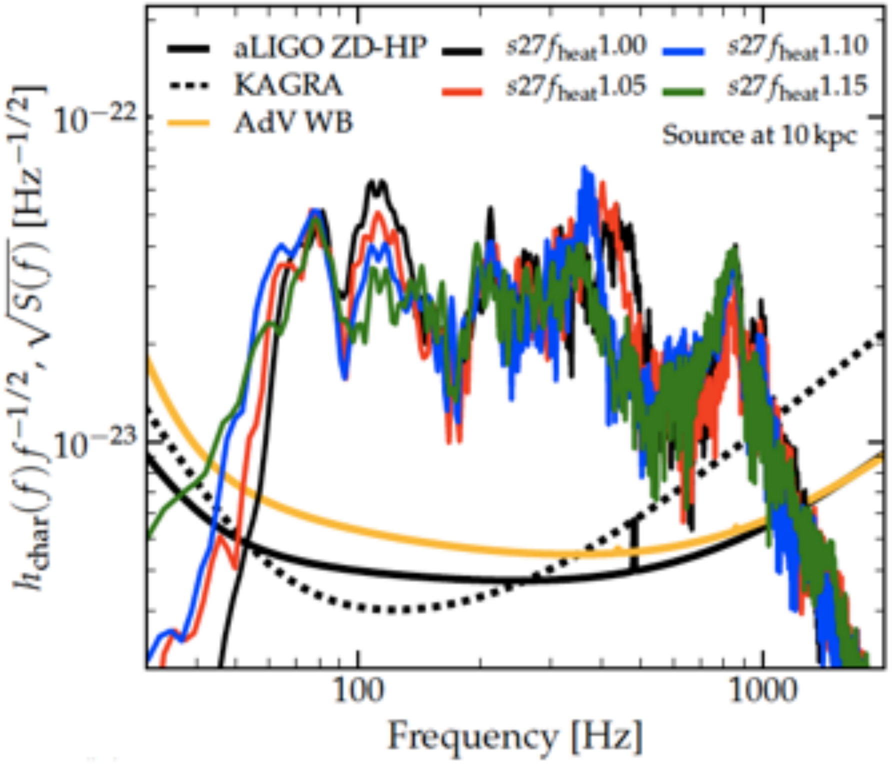
From Amarsi et al. '15

## Electromagnetic



From Filppenko '97

## Gravitational Waves

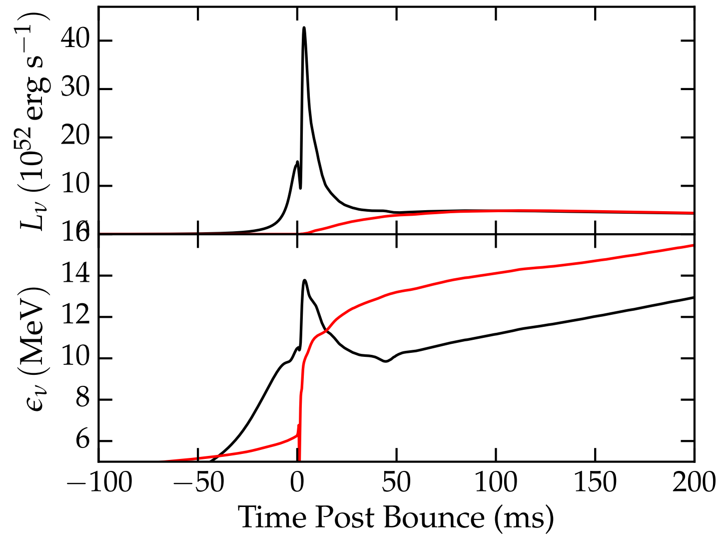


From Ott et al. '12

# Overview

- 3D Central Engine Models

- Long term CCSN neutrino emission



# Core Collapse

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

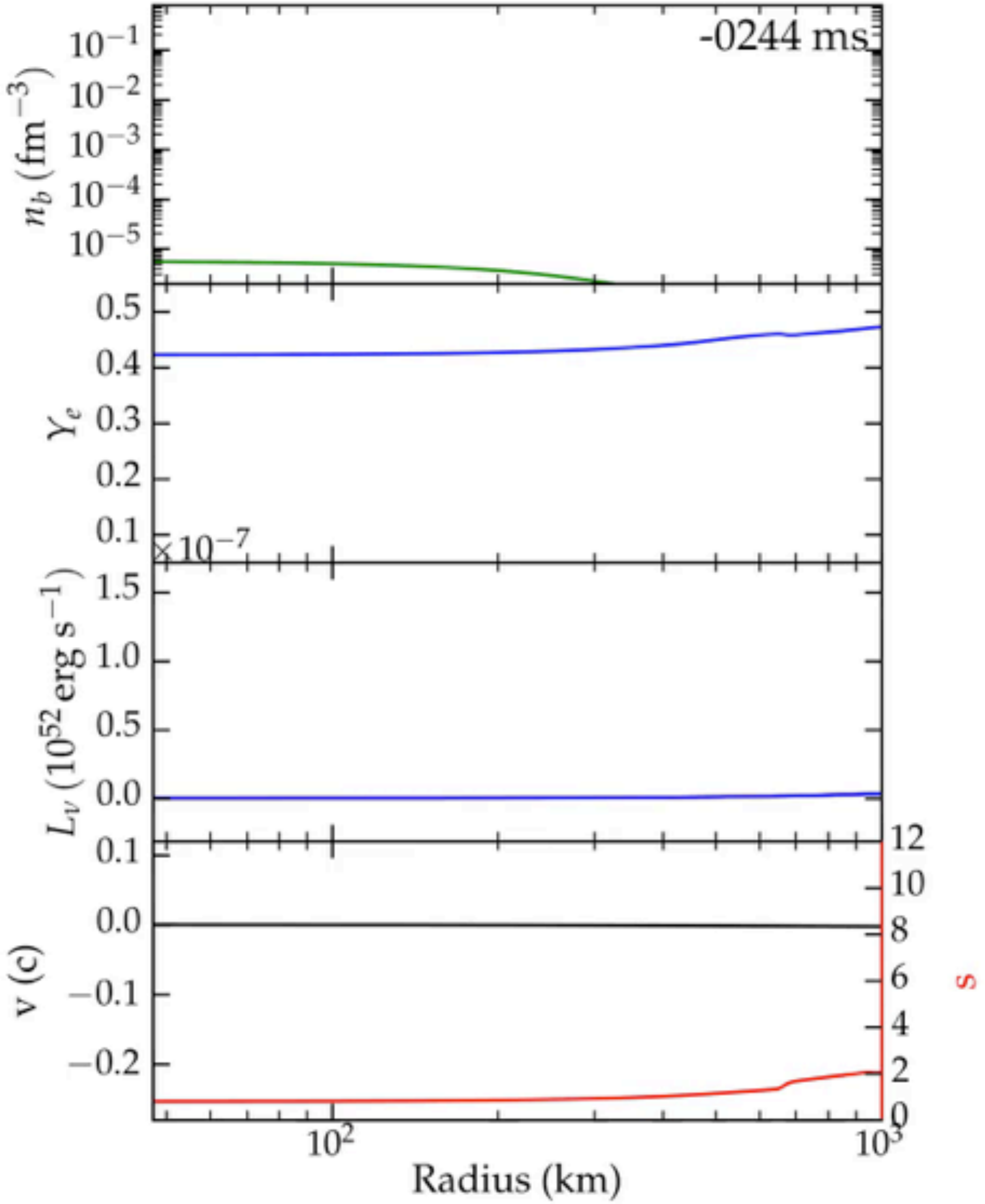
- Core exceeds a Chandrasekhar mass  supersonic collapse outside of homologous core → bounce shock after ~2 x saturation density

- Gravitational binding energy of compact remnant:

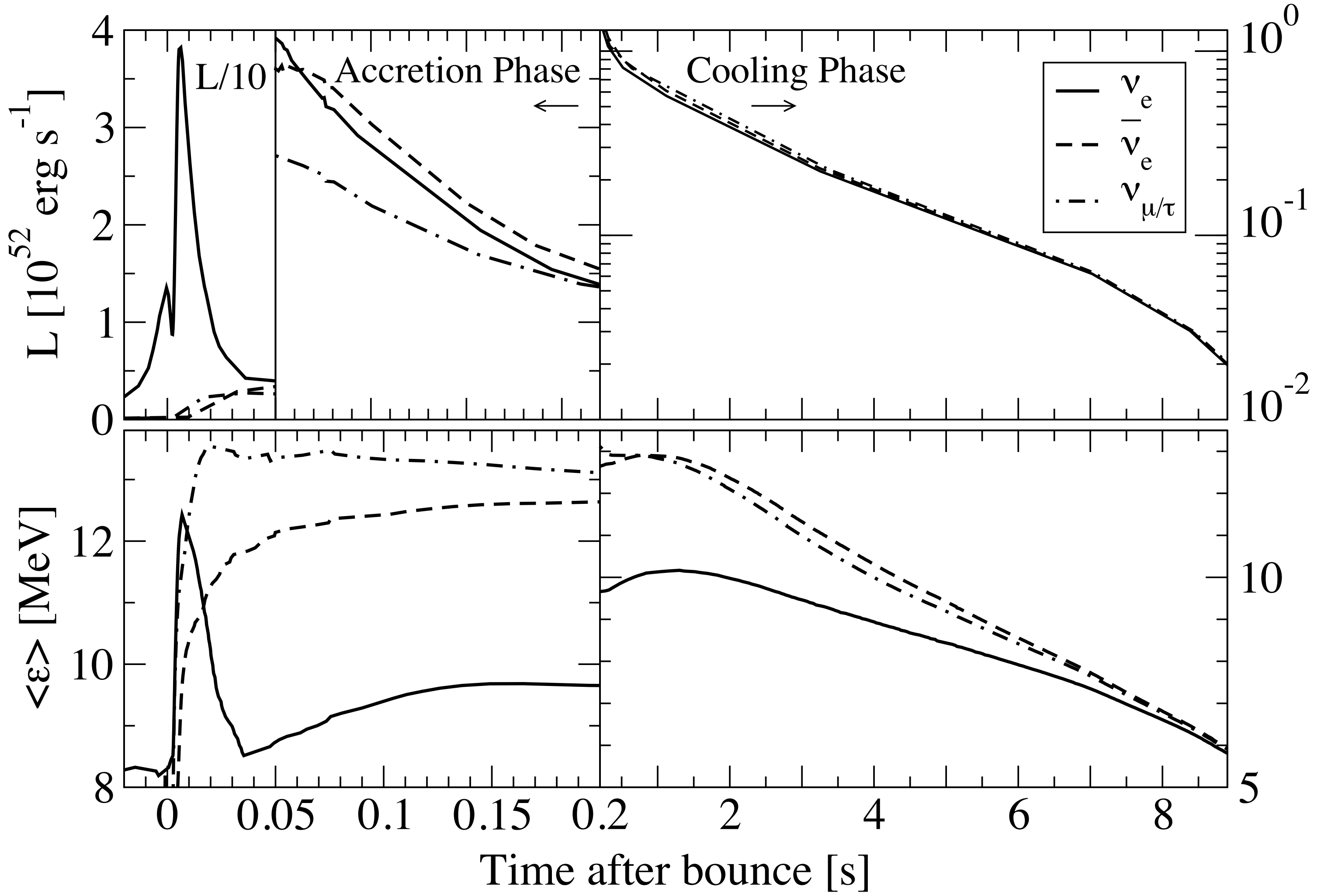
$$\frac{GM_{NS}^2}{R_{NS}} \sim 3\times10^{53}\,erg$$

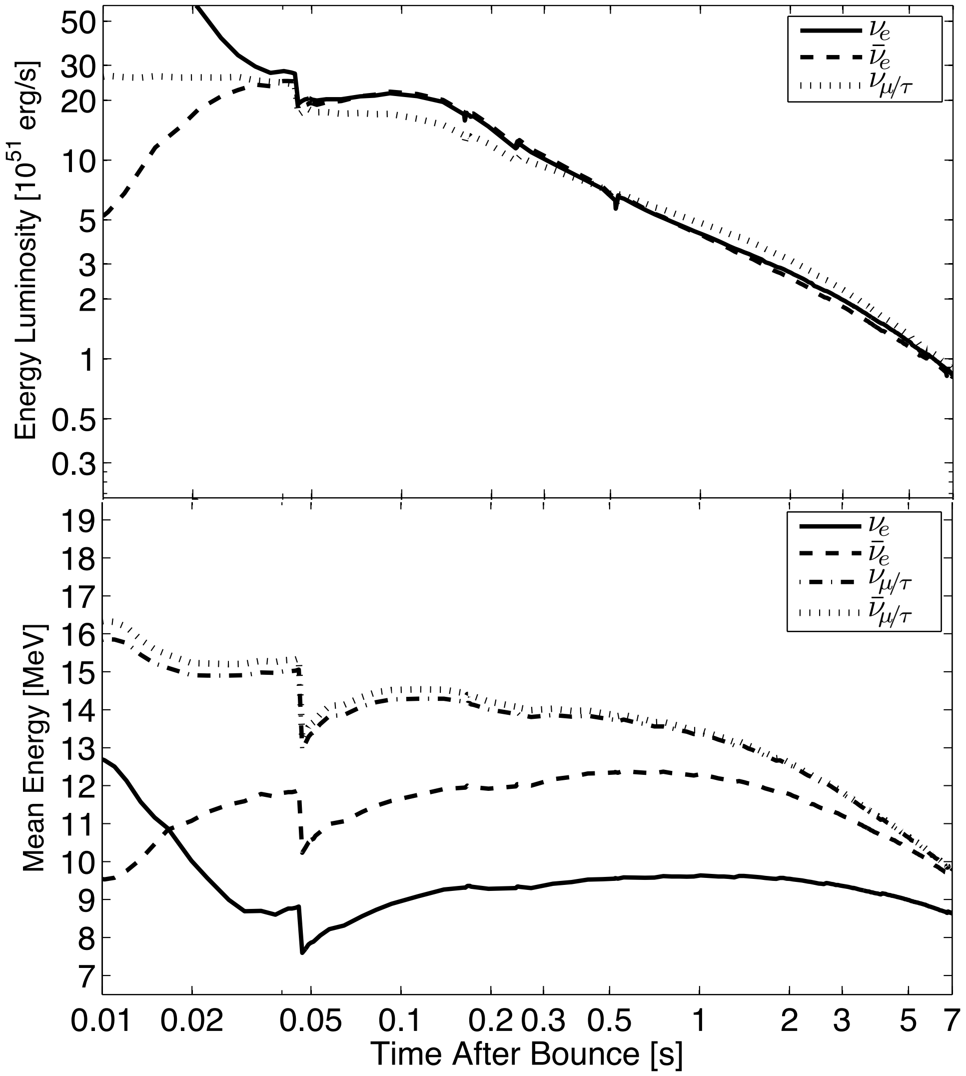
- Binding energy of stellar envelope:

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



# Self Consistent Spherically Symmetric CCSN Explosions





Huedepohl et al. (2010)

Fischer et al. (2010, 2012)

Only possible for low mass progenitors, mainly ECSN

# Simulating CCSNe

Hydrodynamics

+

General Relativity

+

Neutrino Transport

+

Microphysics

(EoS, ν-opacities, nuclear network)

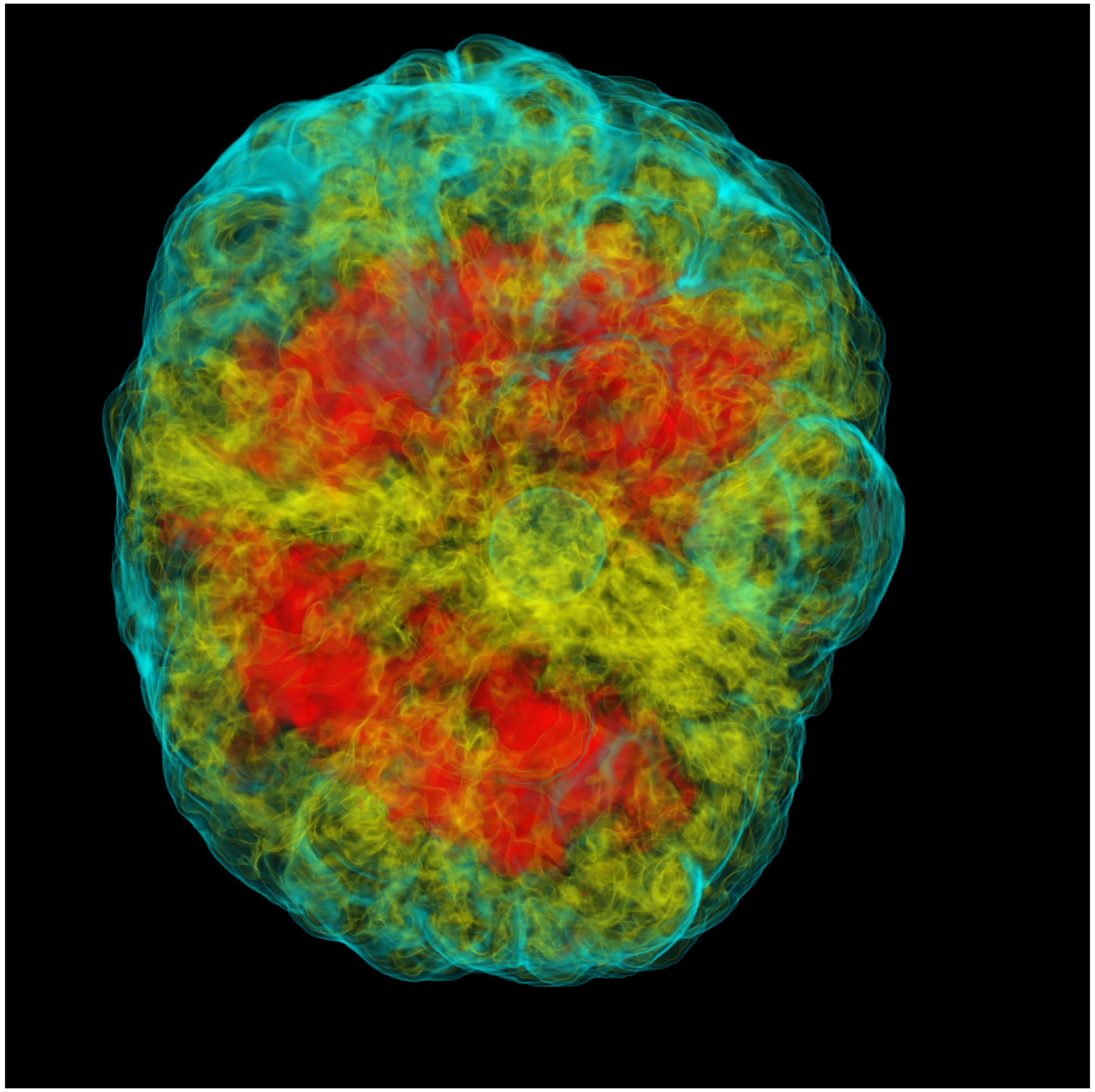
# Post Bounce Evolution of CCSNe

- Hydrodynamic instabilities (such as convection and SASI) can aid energy transport and shock propagation

- In axial symmetry, this enhances the efficacy of neutrino energy deposition and results in successful explosions (Mueller et al. ’12, Bruenn et al. ’13)

- Does the neutrino mechanism work in 3D?

- How does this depend on input physics and numerics?



# Two Moment Neutrino Transport

See e.g., Shibata et al. ’11, Cardall et al. ’13, Just et al. ’15, Kuroda et al. ’16, LR et al. ‘16

Boltzmann Equation:

$$\frac{\partial x^\alpha}{\partial \tau}\frac{\partial f(x^\mu, p^\mu)}{\partial x_\alpha} + \frac{\partial p^i}{\partial \tau}\frac{\partial f(x^\mu, p^\mu)}{\partial p_i} = \tilde{S}(x^\mu, p^\mu)$$

Take angular moments of the neutrino distribution function:

$$M^{A_k}_{(\nu)} = \int dV_p \frac{p^{\alpha_1} ... p^{\alpha_k}}{(-p_\mu u^\mu)^{k-2}} f(p^\beta, x^\beta)\delta(\nu + p_\delta u^\delta)$$

Get conservation equations for projections of the rest frame energy dependent stress tensor:

$$M^{\alpha\beta}_{(\nu)\ ;\beta}$$

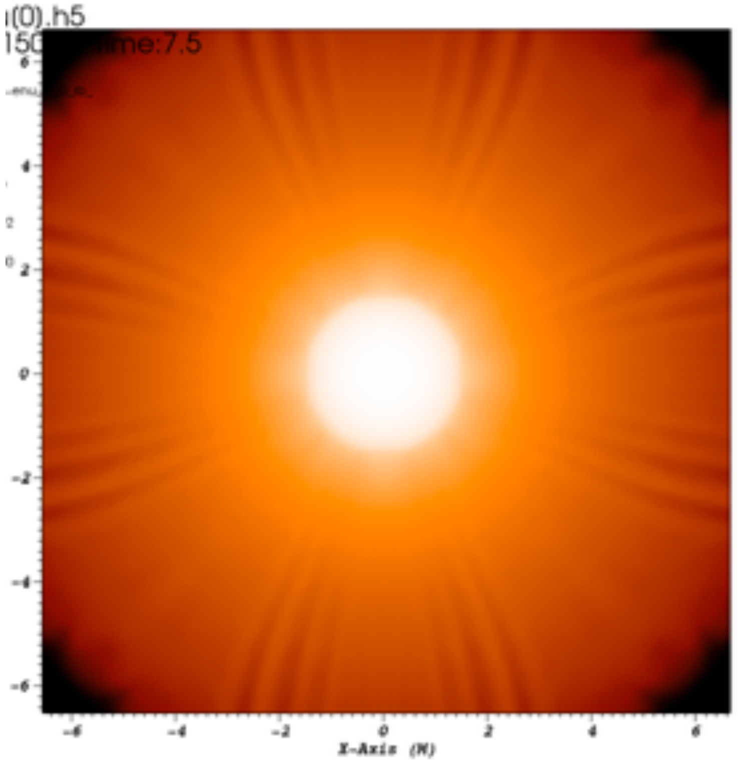
$$\partial_t \tilde{E} + \partial_j \left(\alpha \tilde{F}^j - \beta^j \tilde{E}\right) + \partial_\nu \left(\nu \alpha n_\alpha \tilde{M}^{\alpha\beta\gamma} u_{\gamma;\beta}\right) = \alpha \left[\tilde{P}^{ij} K_{ij} - \tilde{F}^j \partial_j \ln \alpha - \tilde{S}^\alpha n_\alpha\right]$$

$$\partial_t \tilde{F}_i + \partial_j \left(\alpha \tilde{P}^j{}_i - \beta^j \tilde{F}_i\right) - \partial_\nu \left(\nu \alpha \gamma_{i\alpha} \tilde{M}^{\alpha\beta\gamma} u_{\gamma;\beta}\right) = \alpha \left[\frac{\tilde{F}_k \partial_i \beta^k}{\alpha} - \tilde{E} \partial_i \ln \alpha + \frac{\tilde{P}^{jk}}{2} \partial_i \gamma_{jk} + \tilde{S}^\alpha \gamma_{i\alpha}\right]$$

Amenable to finite volume techniques and truly 3D, but

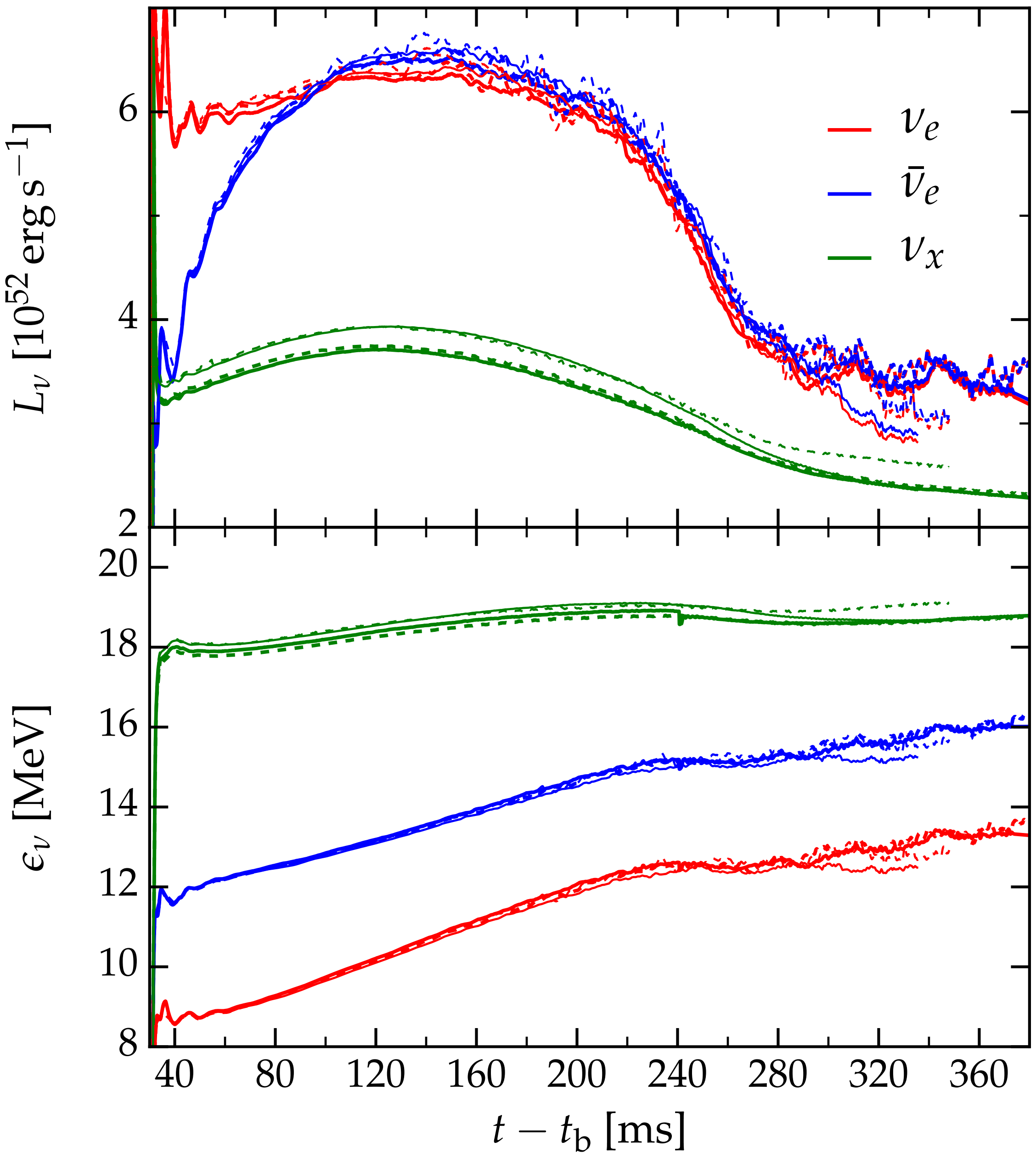
Still need to specify neutrino stress tensor:

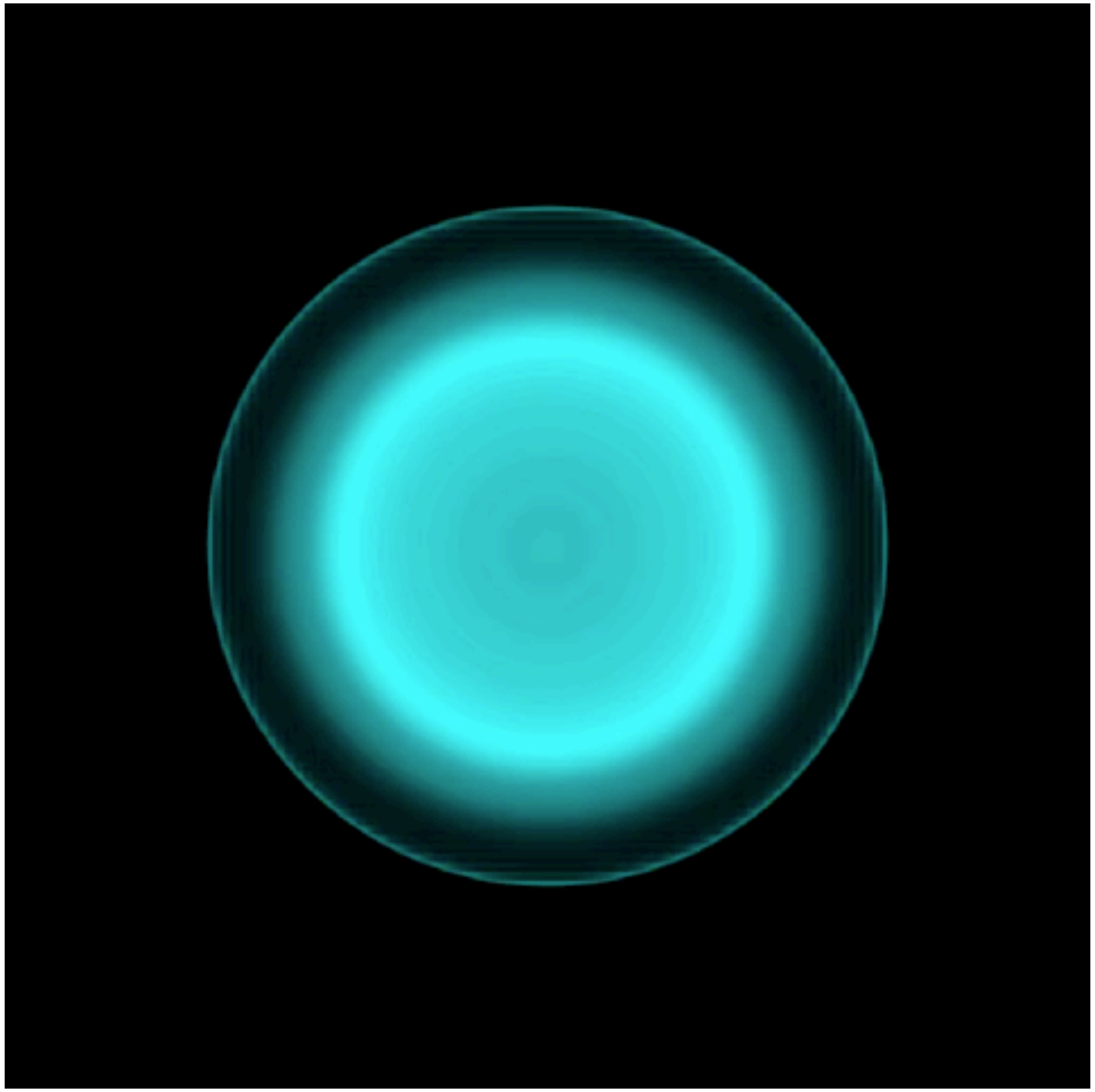
$$P^{\alpha\beta}_{(\nu)} = \frac{3\chi(\xi) - 1}{2} P^{\alpha\beta}_{(\nu),thin} + \frac{3(1 - \chi(\xi))}{2} P^{\alpha\beta}_{(\nu),thick}$$



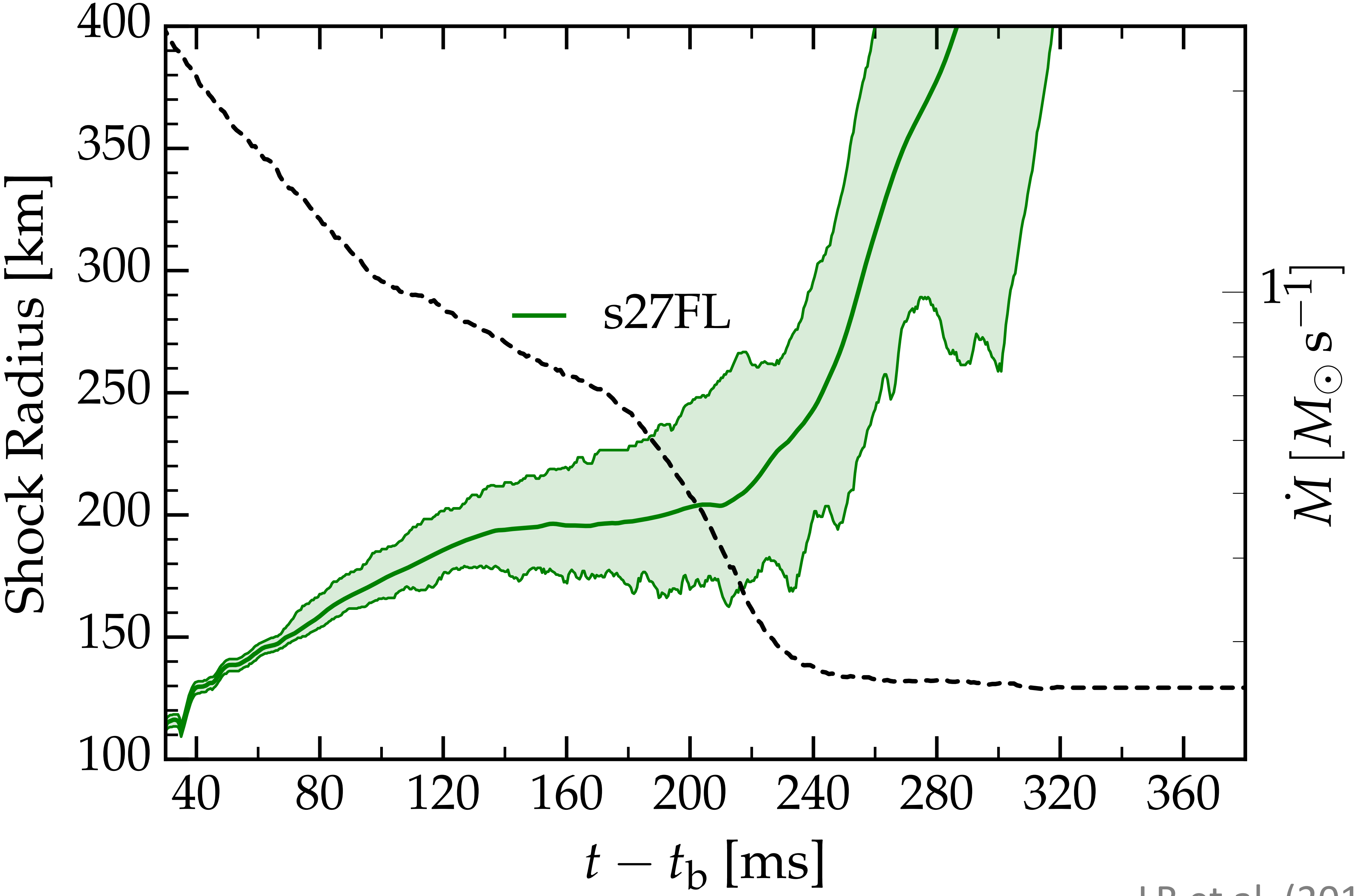
# Evolution to Explosion

LR et al. (2016)



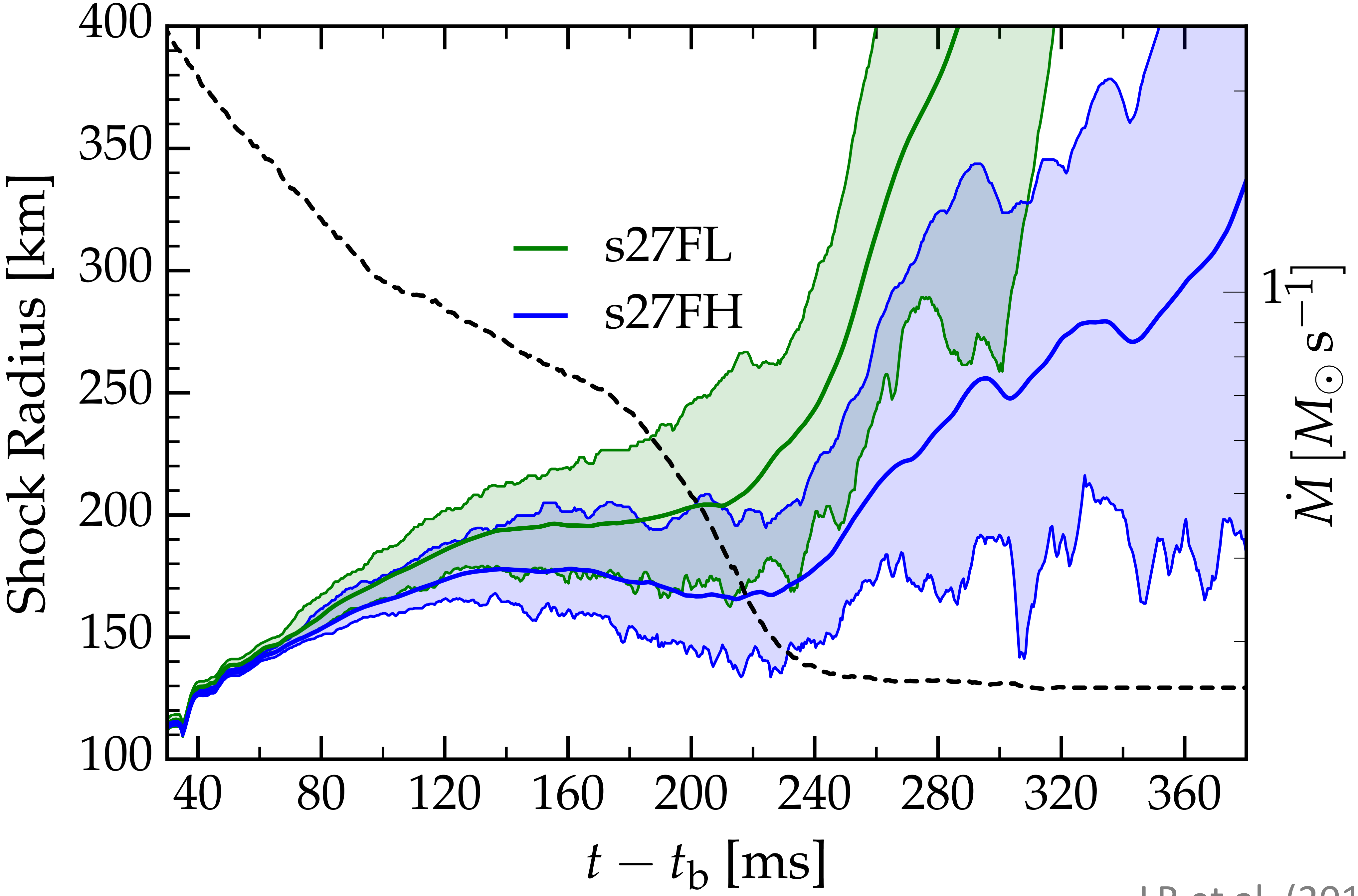


# Resolution and Symmetry Dependence of CCSNe Models



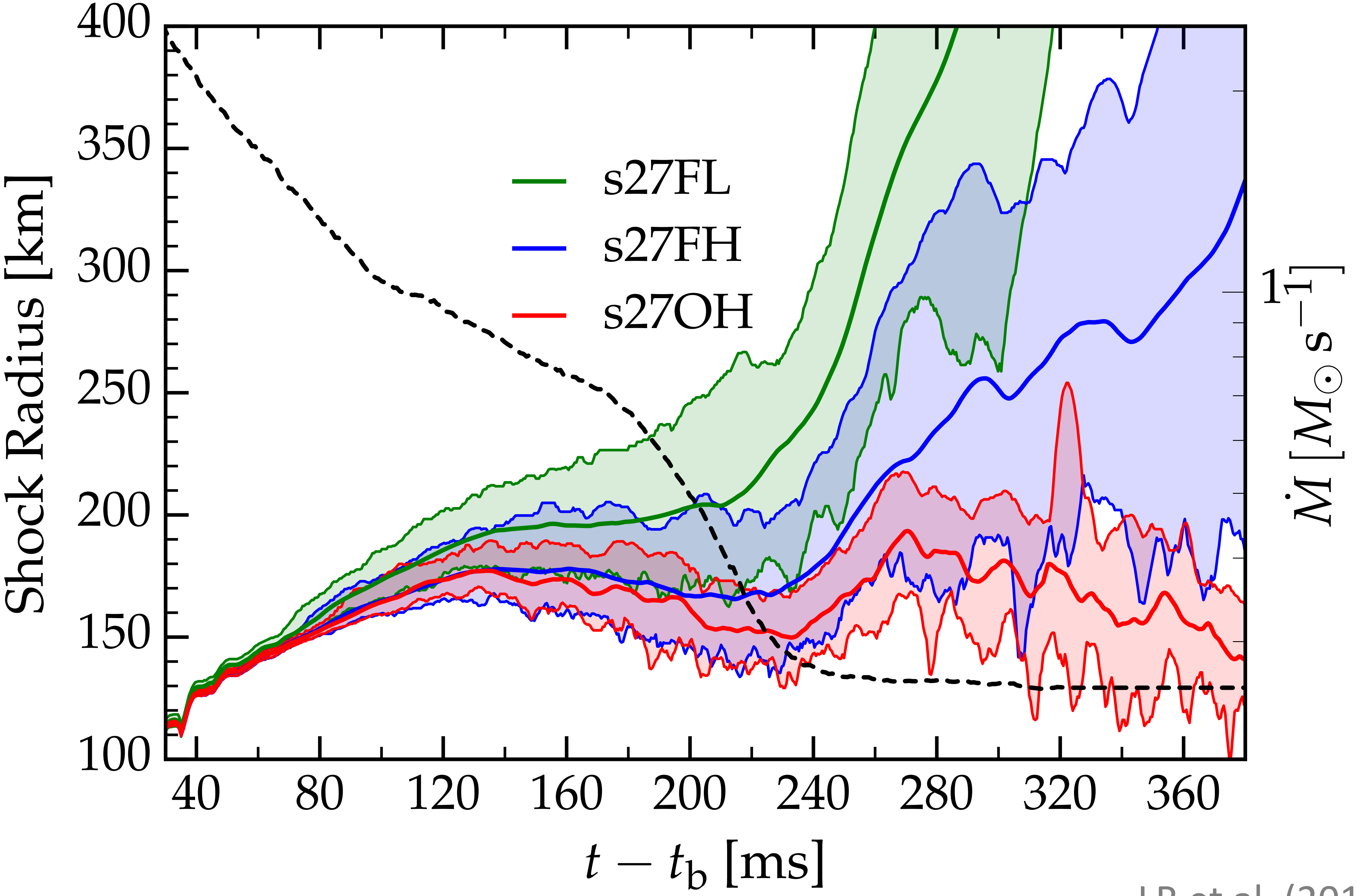
LR et al. (2016)

# Resolution and Symmetry Dependence of CCSNe Models



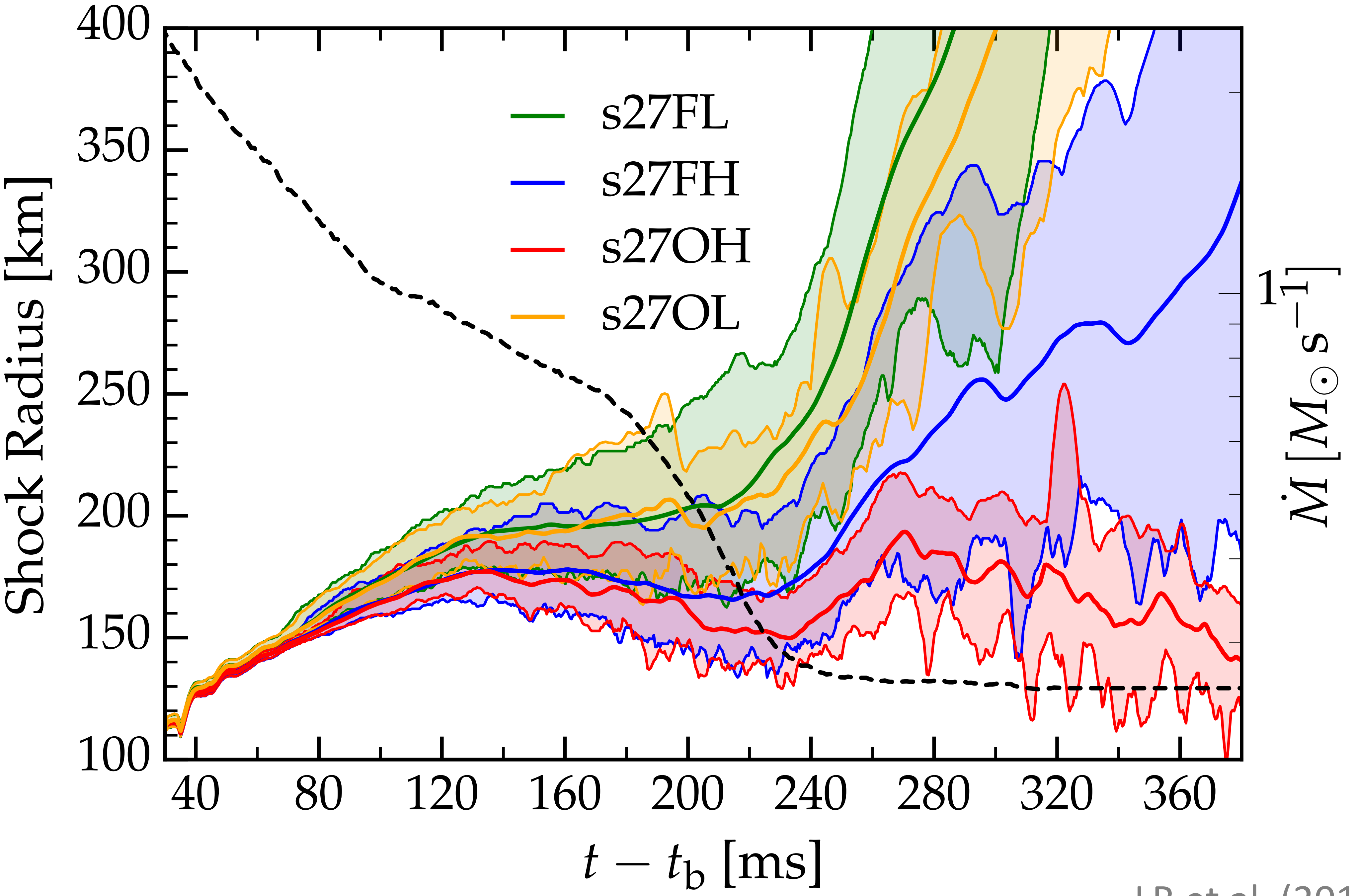
LR et al. (2016)

# Resolution and Symmetry Dependence of CCSNe Models



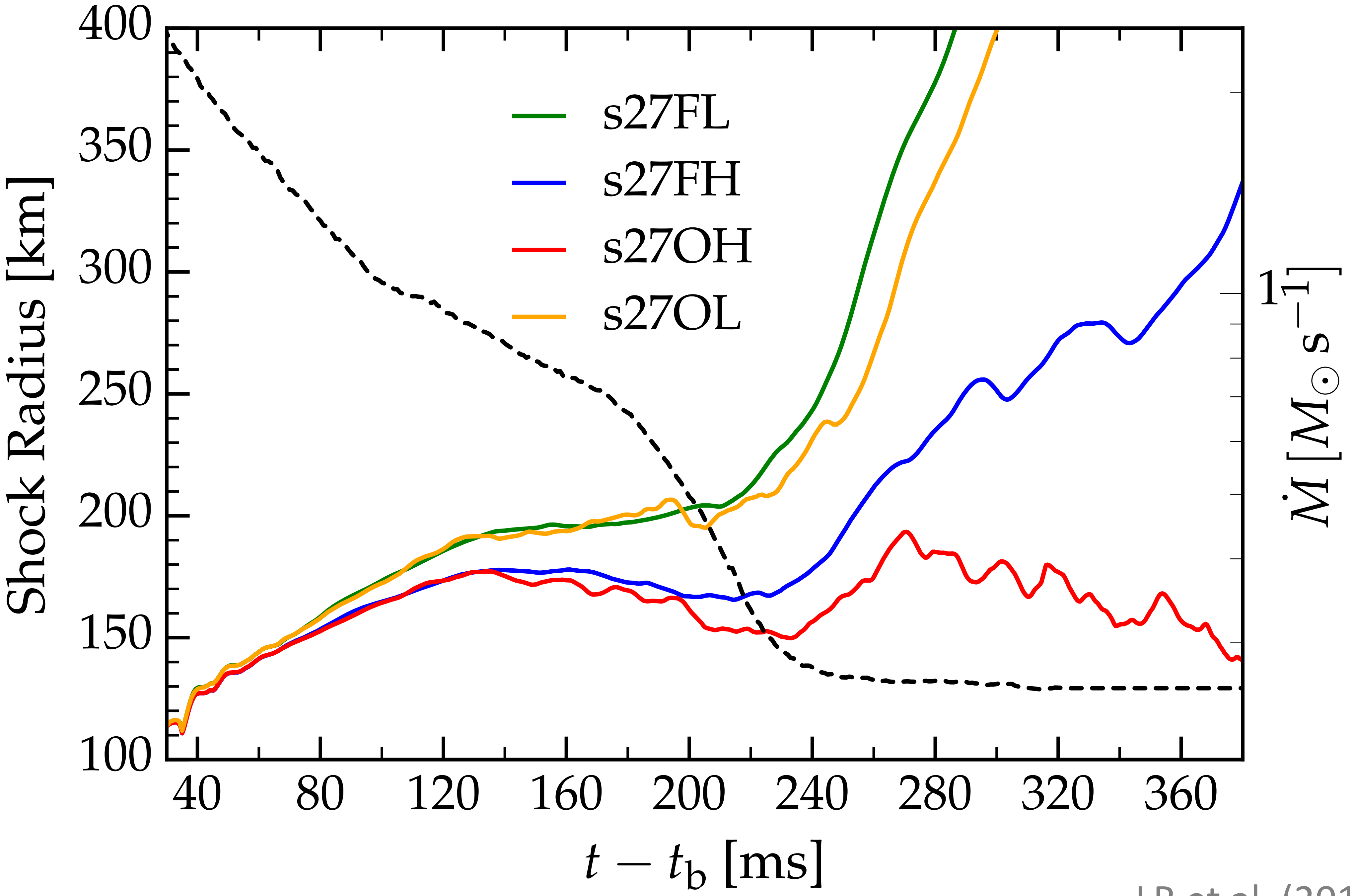
LR et al. (2016)

# Resolution and Symmetry Dependence of CCSNe Models



LR et al. (2016)

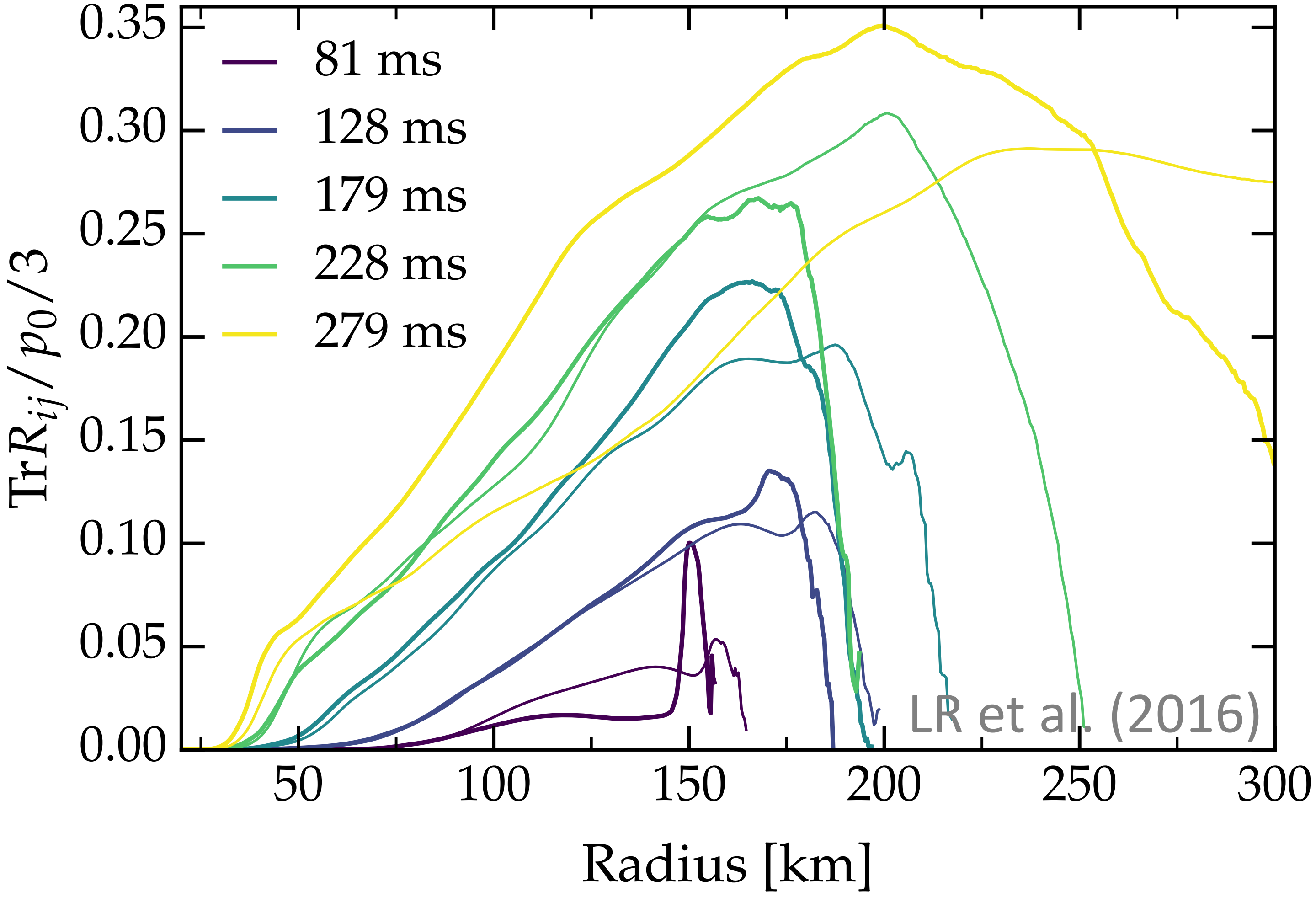
# Resolution and Symmetry Dependence of CCSNe Models



LR et al. (2016)

# Turbulent Convection

Murphy & Meakin ’11, Handy et al. ’14, Couch & Ott ‘15

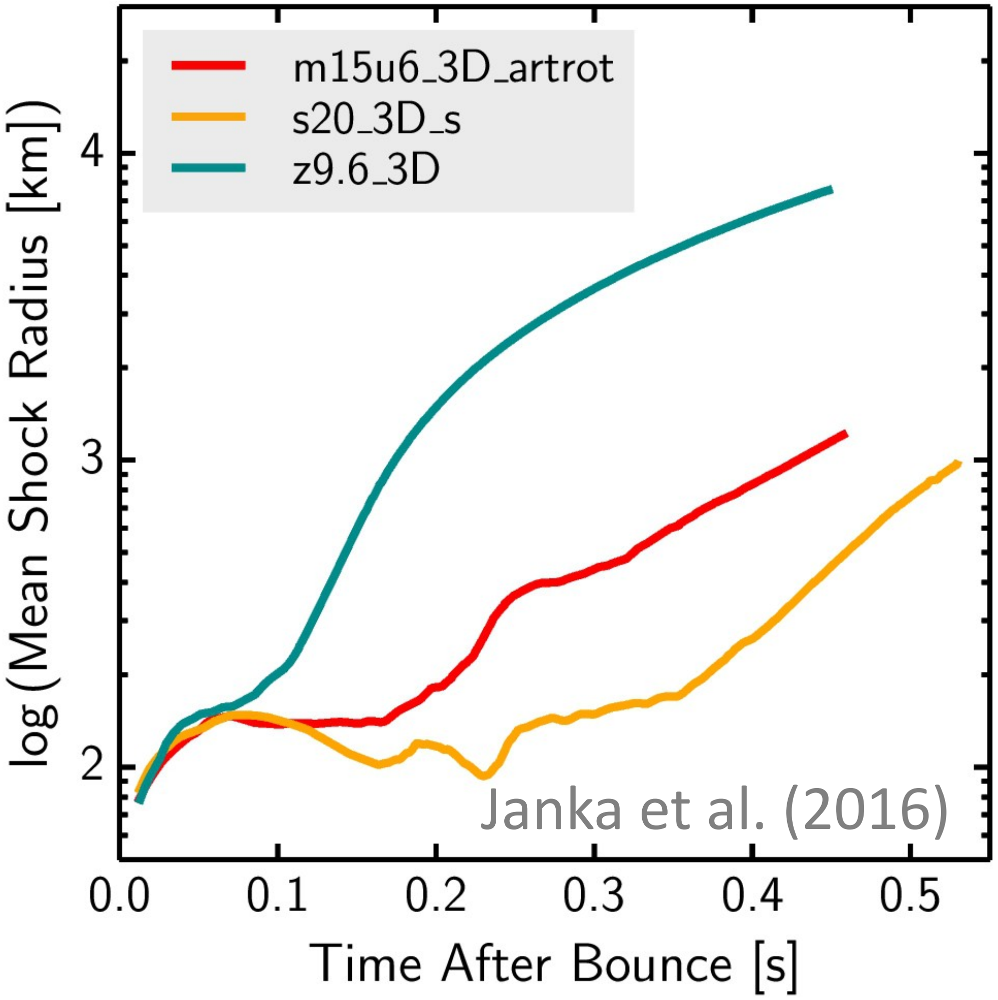


LR et al. (2016)

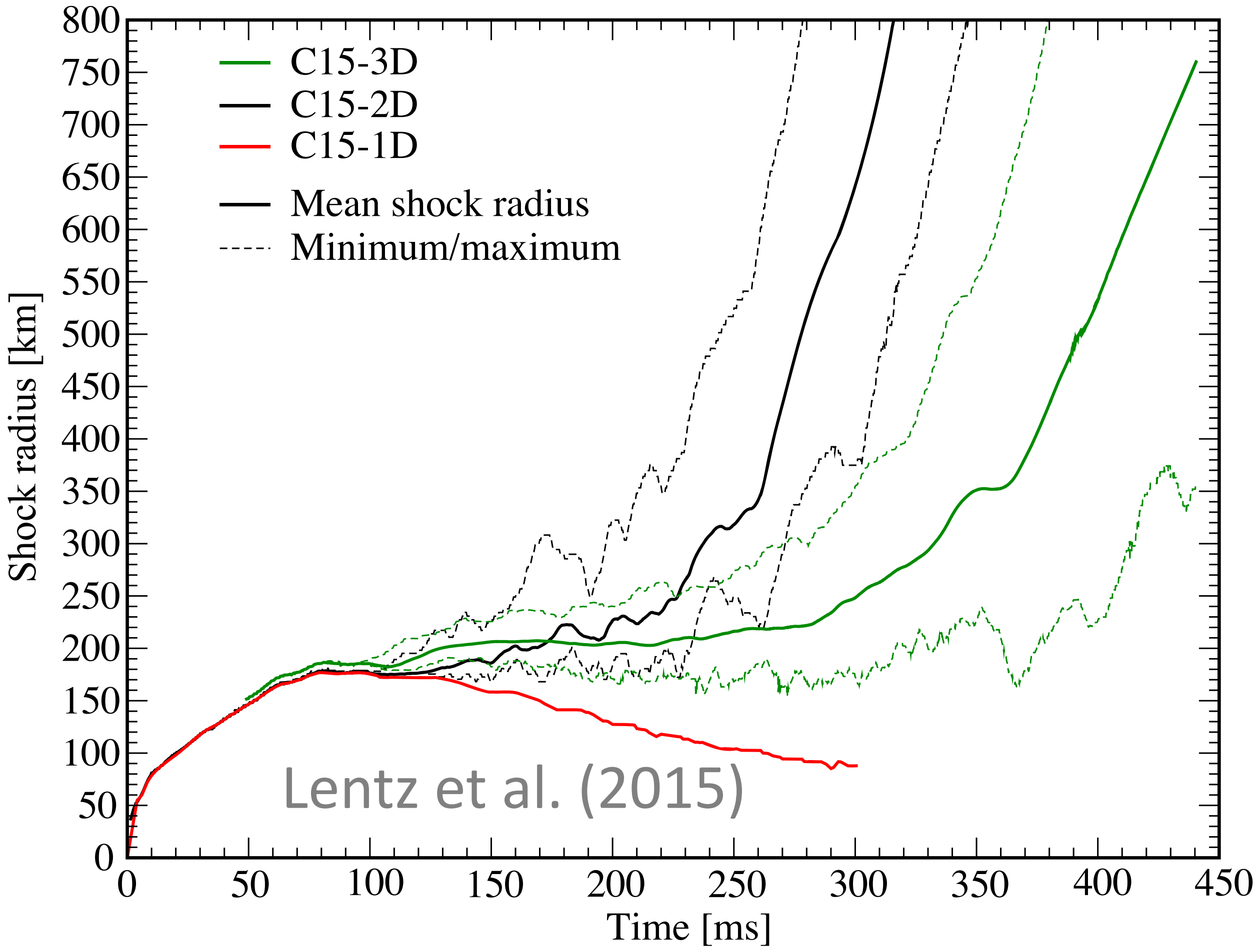
Reynolds stress can contribute significantly to the pressure in the gain region and there is some resolution dependence of the Reynolds stress

# 3D Explosion Models

Takiwaki et al. ’12, Melson ’15, Lentz ’15, LR et al. ’16, Takiwaki et al. ‘16



Janka et al. (2016)

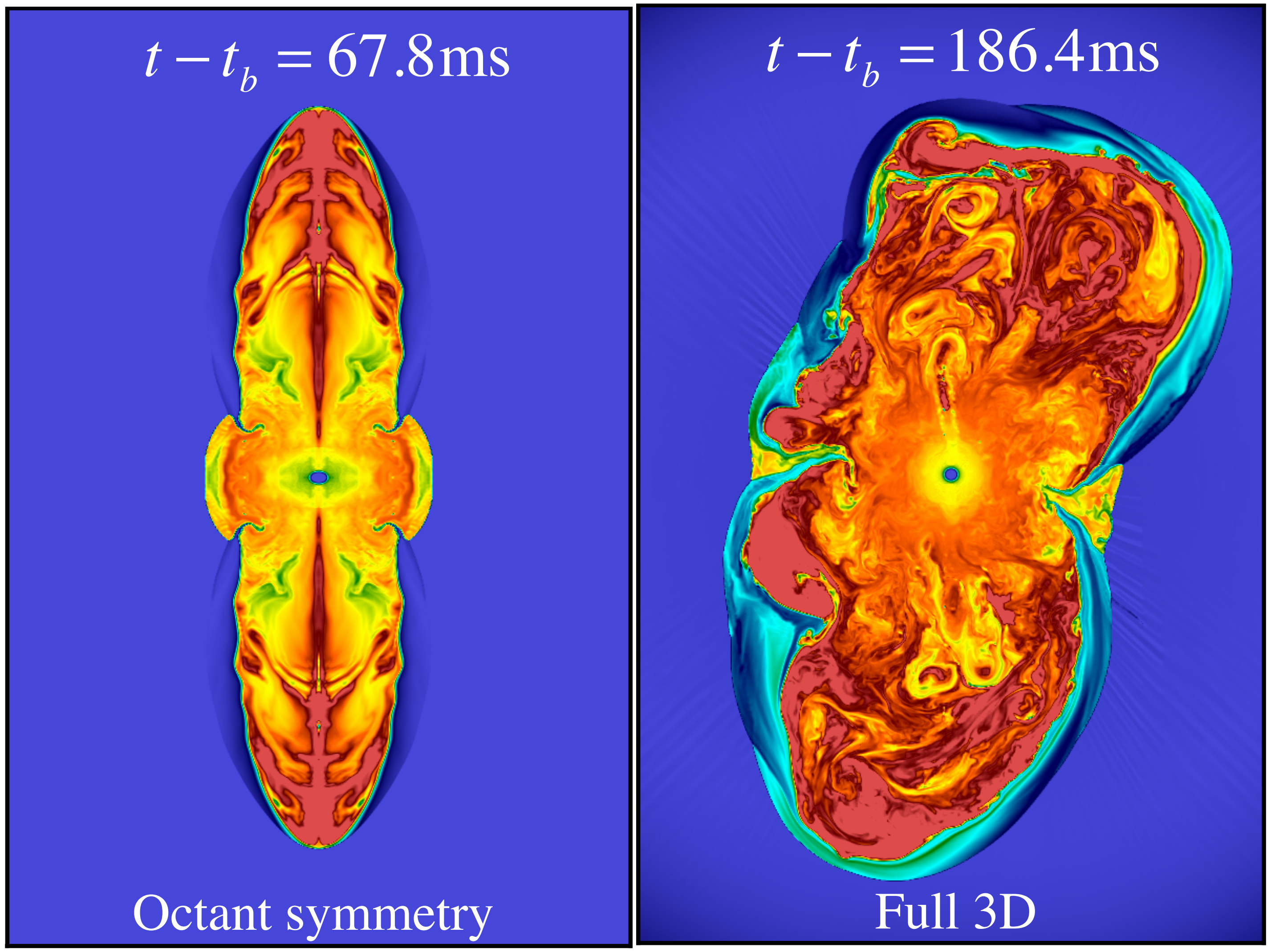


Lentz et al. (2015)

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

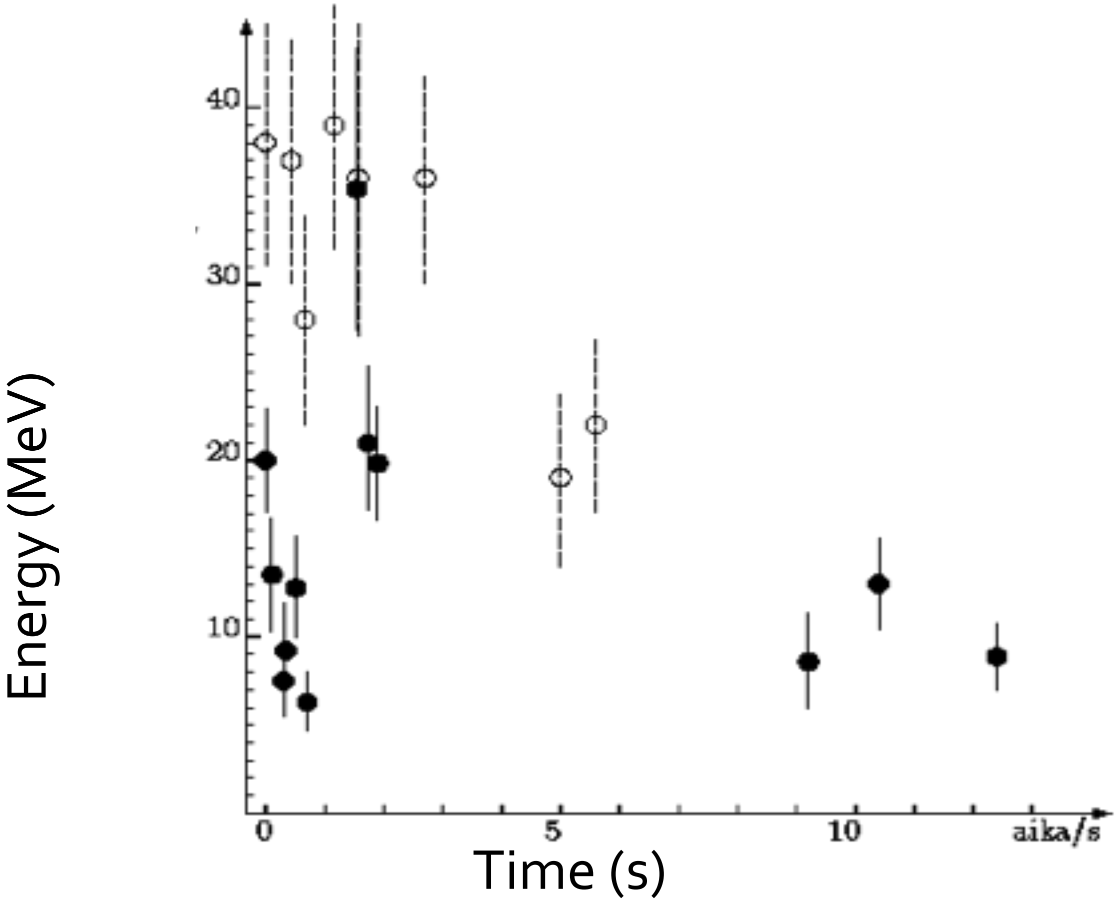
# Jet Driven Supernovae

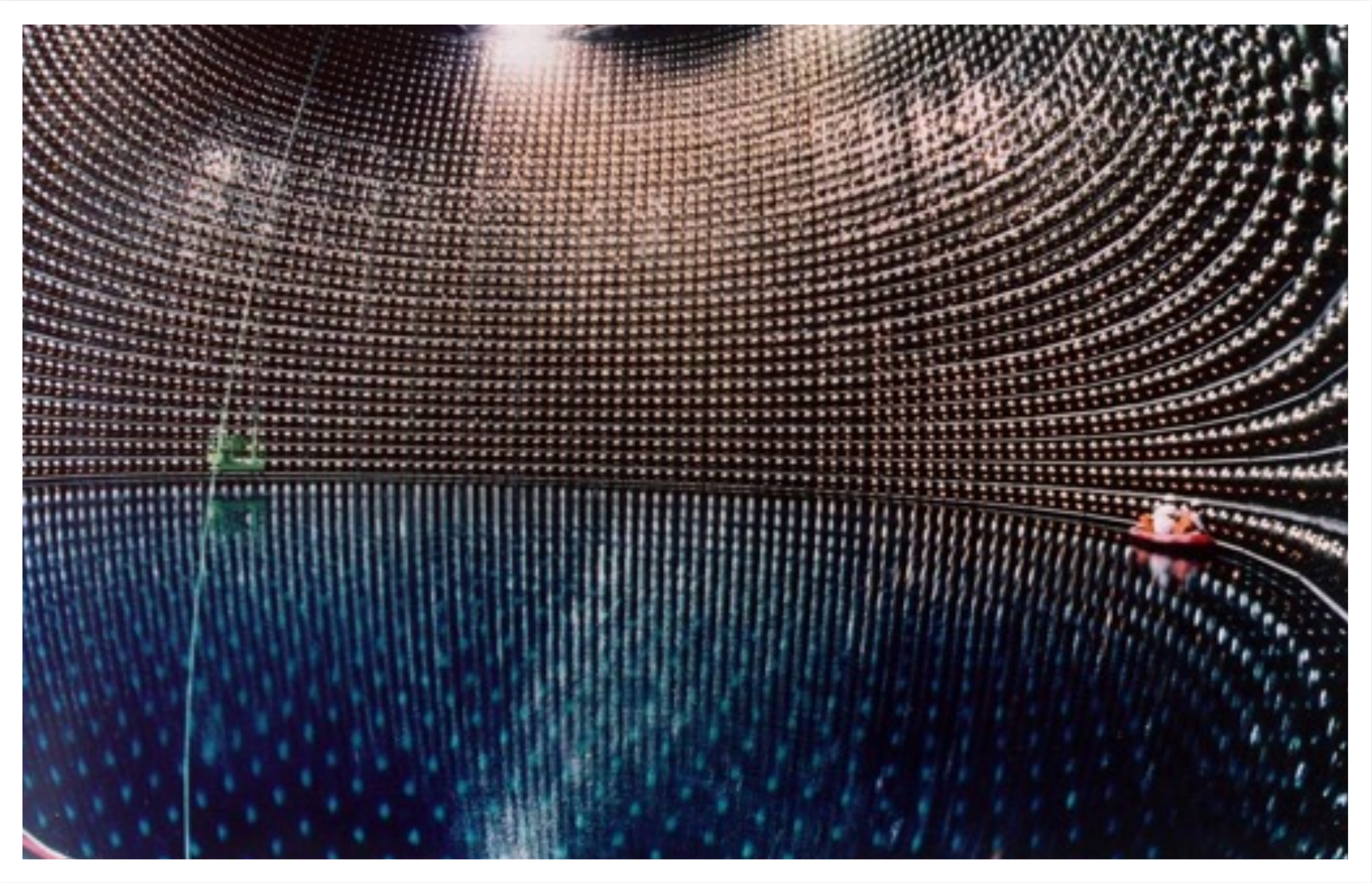
- Rapidly rotating, magnetized SNe
- Full 3D Dynamics also important here
- Kink instabilities in jet significantly change dynamics



Moesta et al. (2016)

# The Supernova Neutrino Signal





Super-Kamiokande Neutrino Detector

~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

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

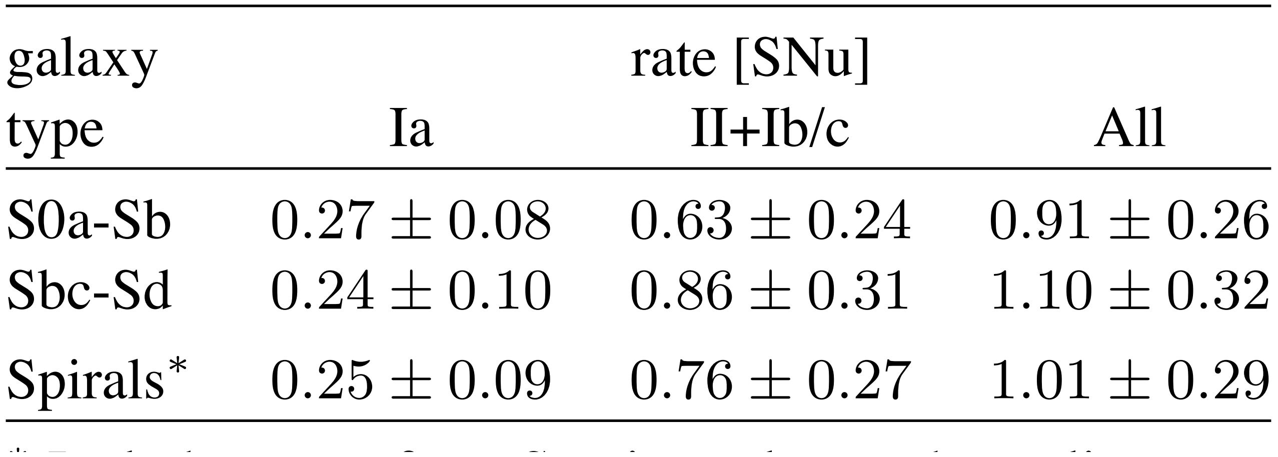
- Most recent known MW CCSN Cas A (~300 yrs)

- 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 | $0.27 \pm 0.08$ | $0.63 \pm 0.24$ | $0.91 \pm 0.26$ |
| Sbc-Sd | $0.24 \pm 0.10$ | $0.86 \pm 0.31$ | $1.10 \pm 0.32$ |
| Spirals* | $0.25 \pm 0.09$ | $0.76 \pm 0.27$ | $1.01 \pm 0.29$ |

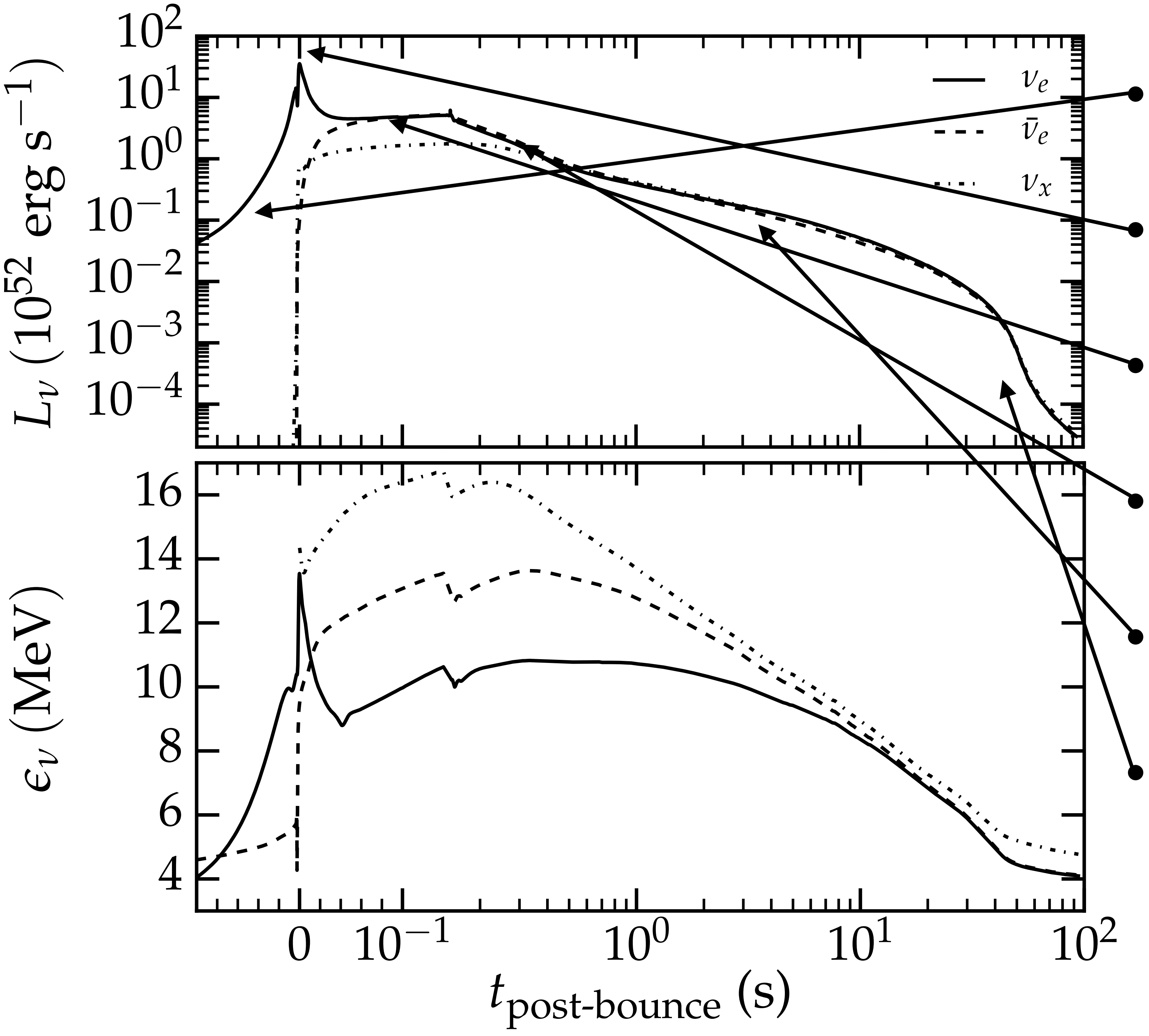
Cappellaro et al. (1999)

# 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 | $\nu_e, \nu_x$ | Running |
| Daya Bay | $C_nH_{2n}$ | 0.33 | China | 100 | $\bar{\nu}_e$ | Running |
| NO$\nu$A$^*$ | $C_nH_{2n}$ | 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 | $\nu_e$ | Near future |
| DUNE | Ar | 34 | USA | 3,000 | $\nu_e$ | 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)

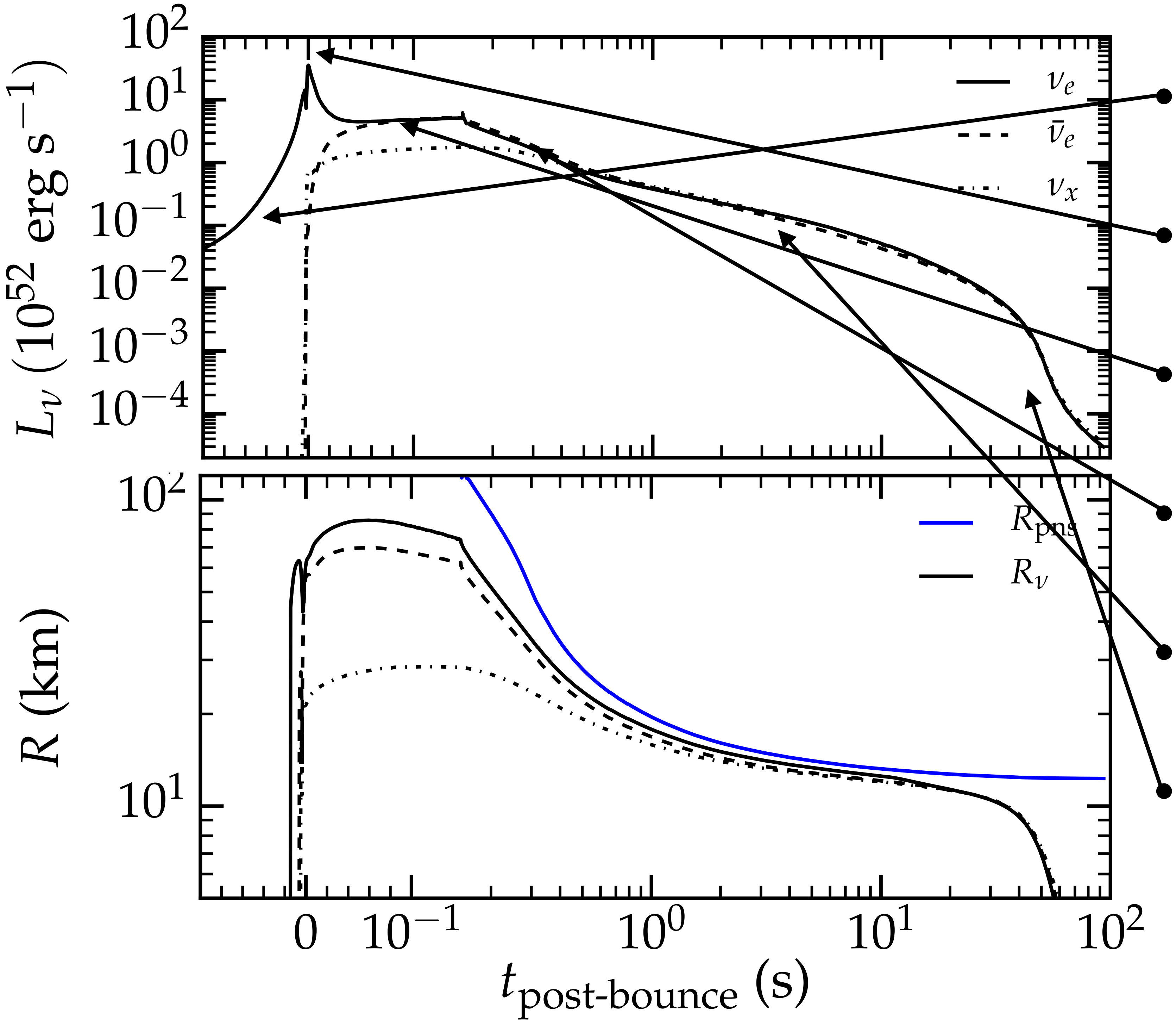
# Anatomy of the Neutrino Signal



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

LR and Reddy ‘15

# Anatomy of the Neutrino Signal



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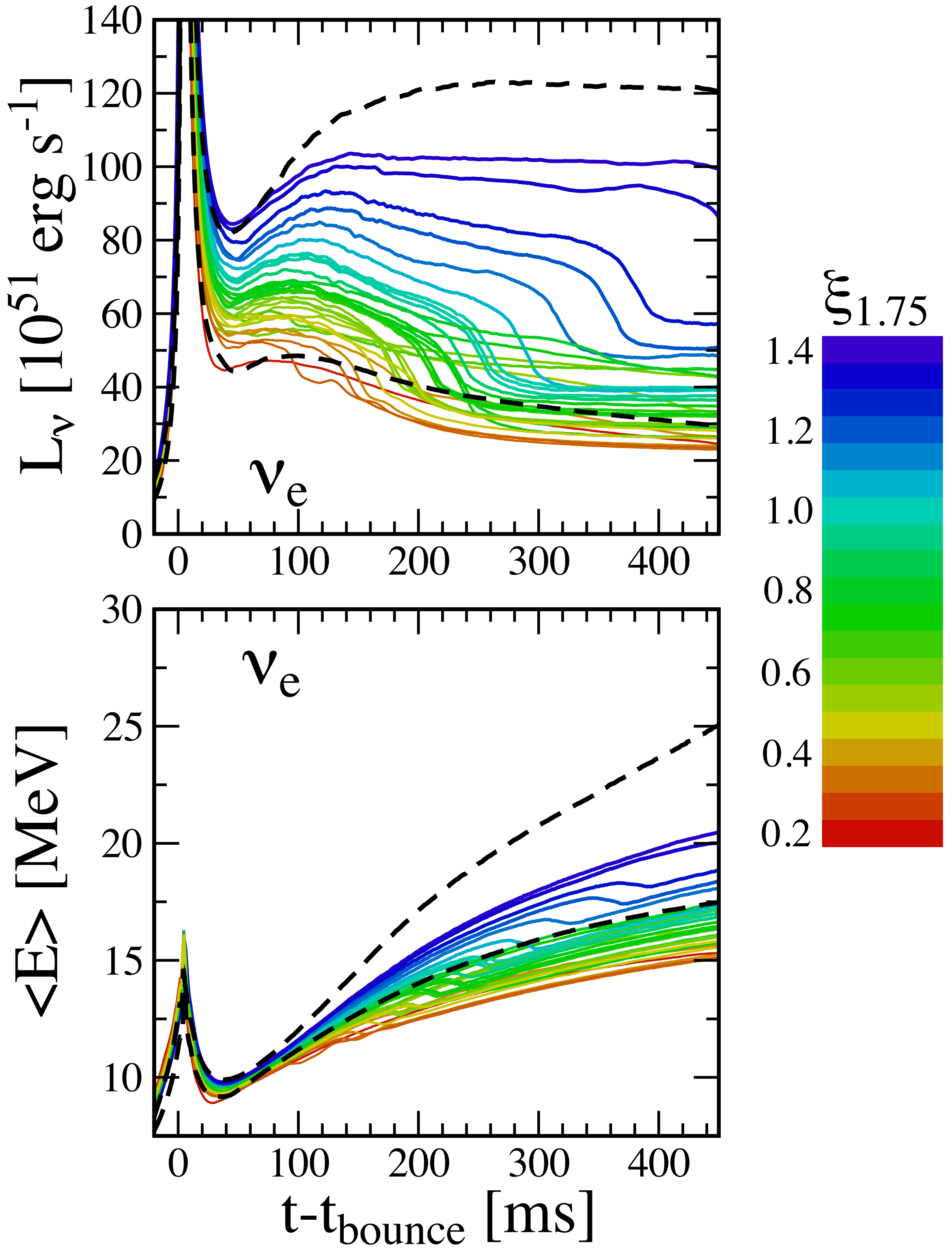
- Neutrinosphere recession

LR and Reddy ‘15

# Early Time Neutrino Emission

- 1D Study of progenitor dependence of neutrino emission
- pre-Explosion neutrino emission driven by accretion
- Progenitor core structure determines accretion rate
- Dependence on nuclear EoS via neutron star compactness

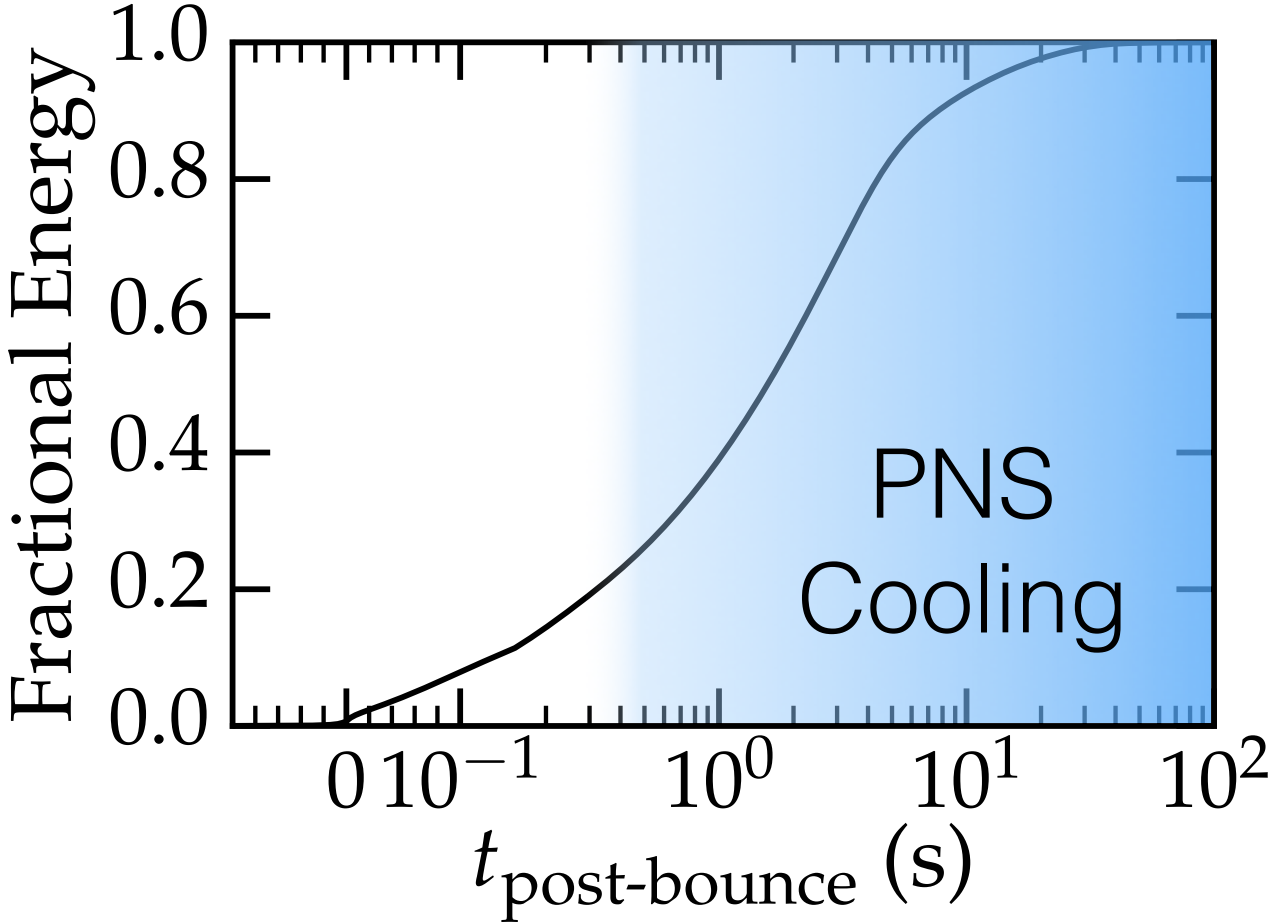


O'Connor & Ott (2013)

# 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

- 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



# Simple Prescription for Explosion in 1D

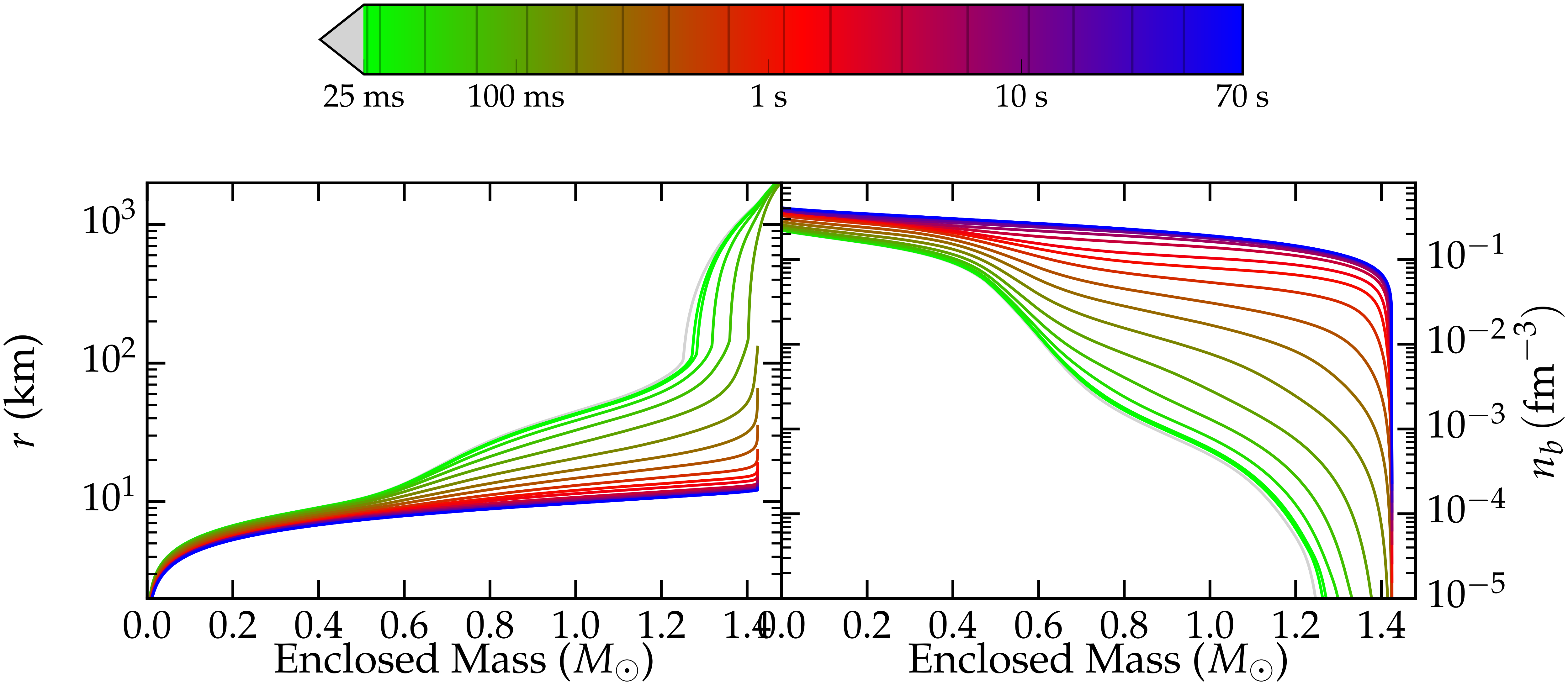
## Perform an (inverse) mass cut

- Once supernova shock passes fixed mass shell, remove all of the overlying mass and replace with a boundary condition

- Drawback: Abrupt end to accretion

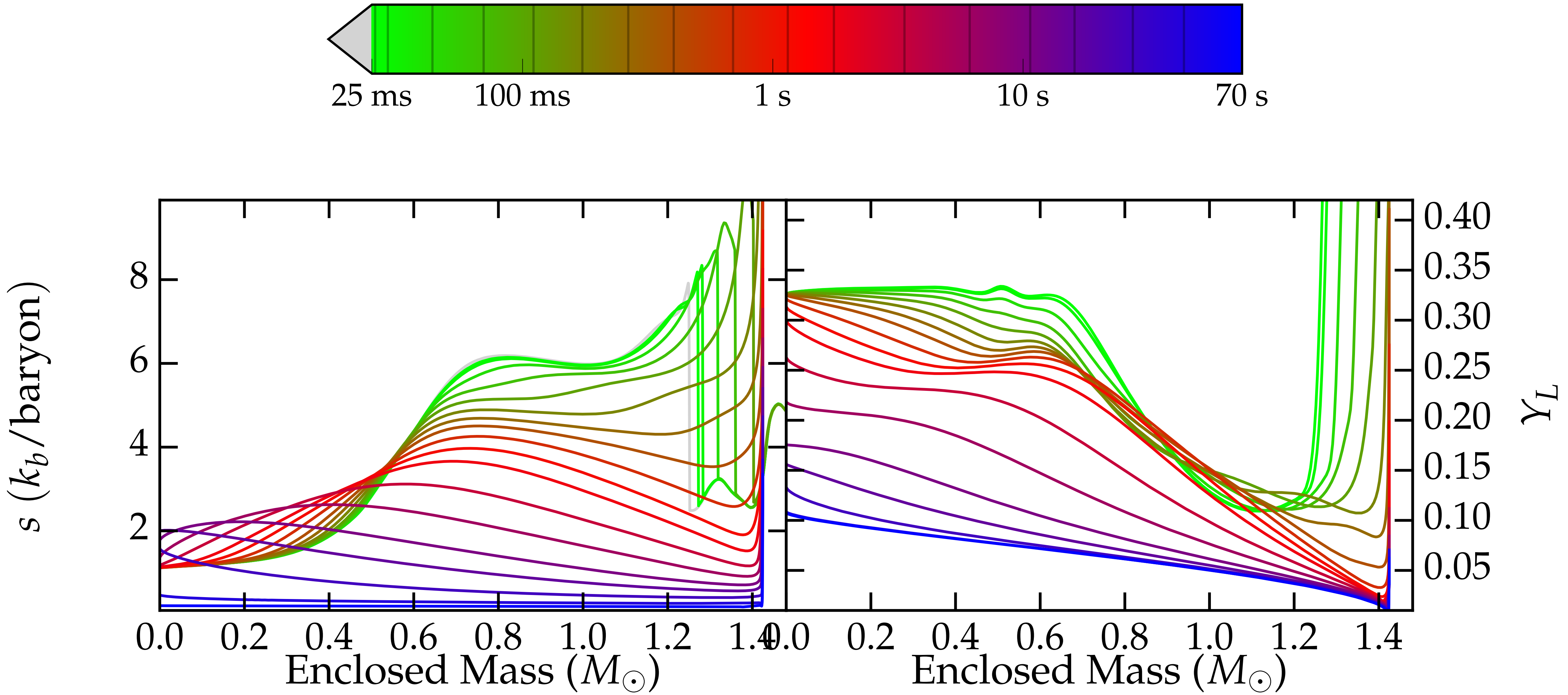
- Makes baryonic mass of remnant a free parameter, but we don't know it anyway without realistic explosion model

# Long Term PNS Evolution



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

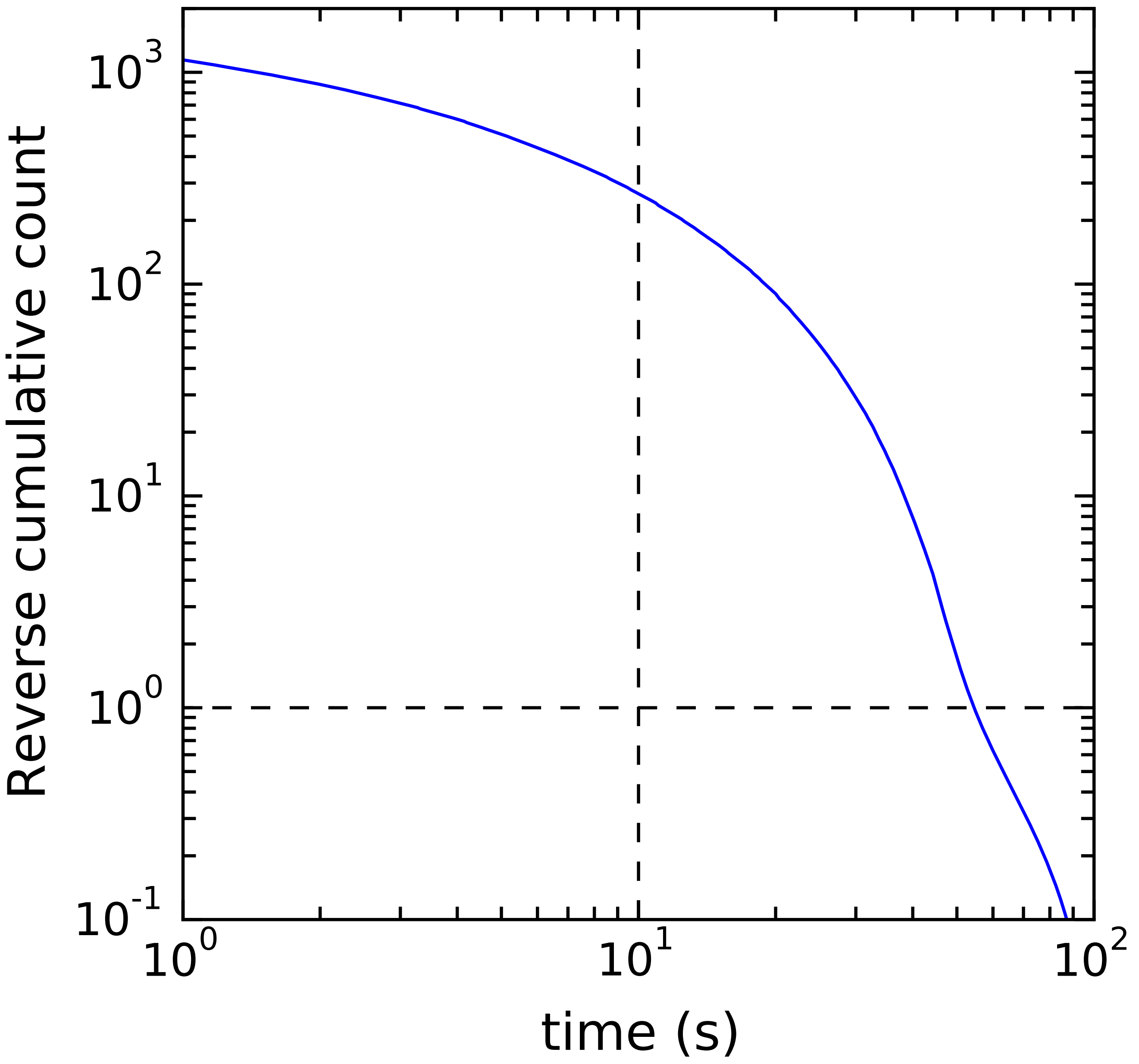
# Long Term PNS Evolution

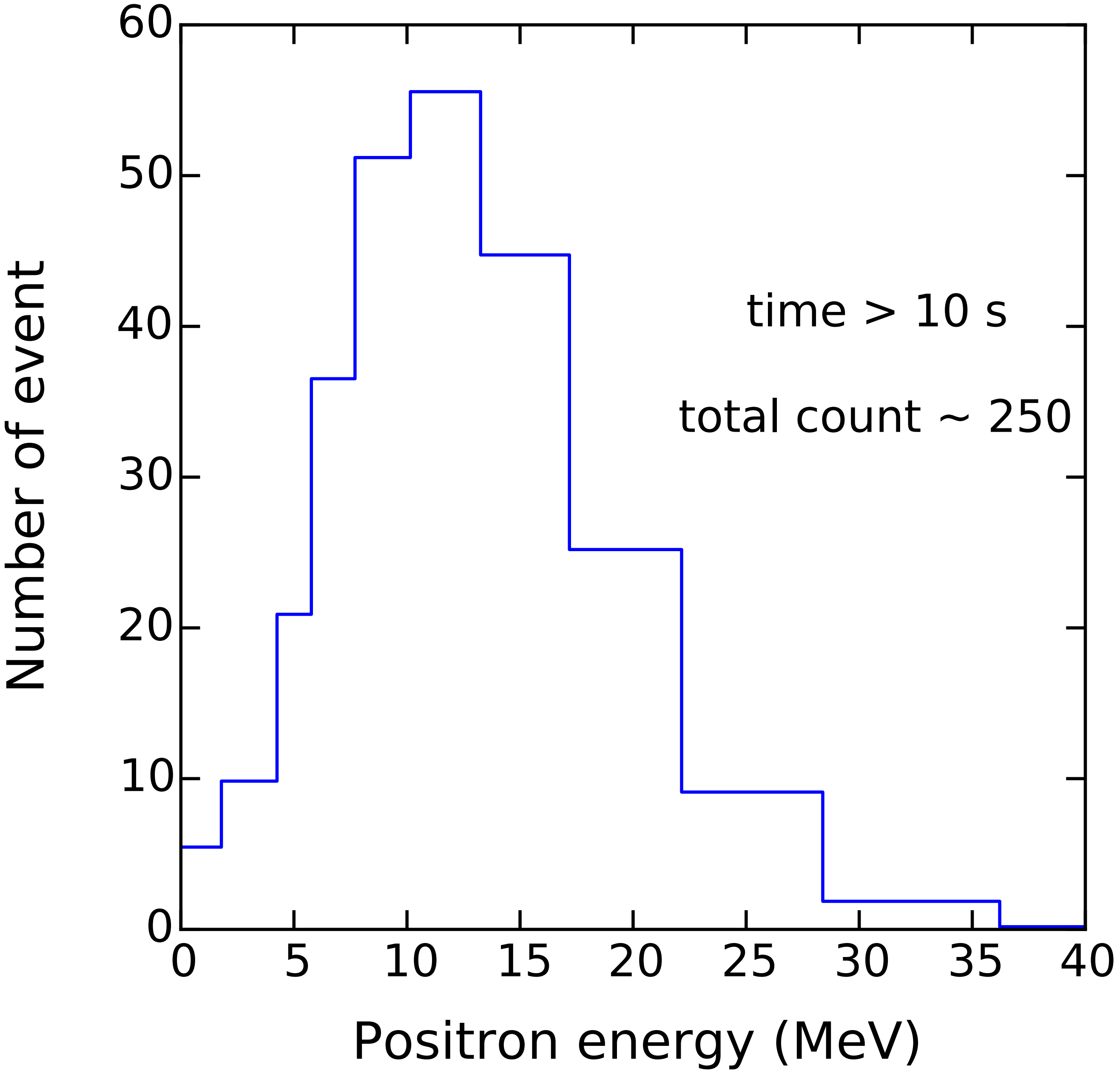


$$\tau_c \approx \frac{2\pi G_F^2 c_A^2}{\beta}\left\langle N_0 \frac{3n_b}{\pi^2}\frac{\partial s}{\partial T}\right\rangle k_B T_c\, R^2 \simeq 10\ s\ \frac{k_B T_c}{30\ \text{MeV}}\ \frac{\langle n_b^{2/3}\rangle}{n_0^{2/3}}\ \left(\frac{R}{12\ \text{km}}\right)^2$$

See Prakash et al. ‘97

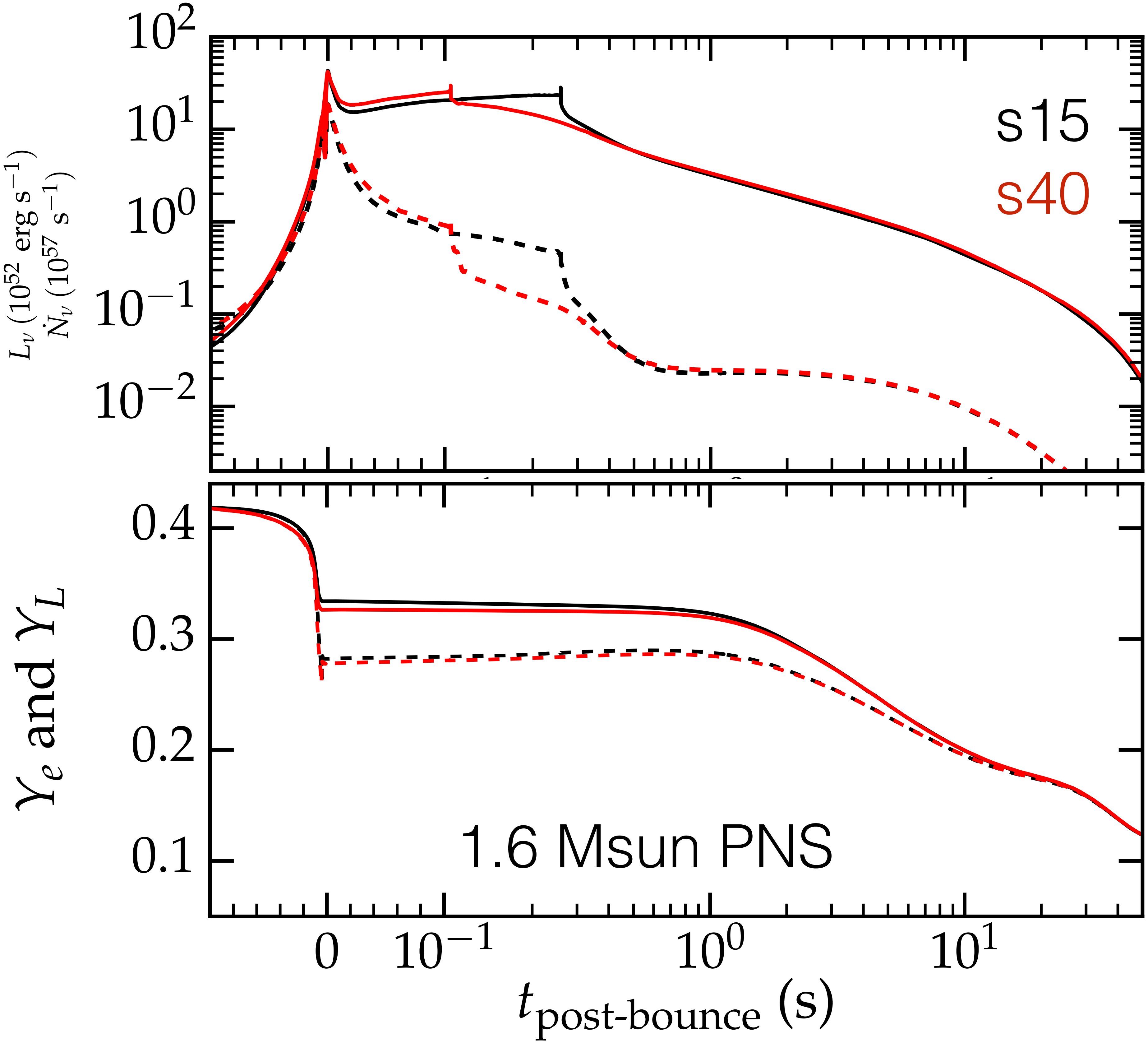
# Detection Rates





From Shirley Li

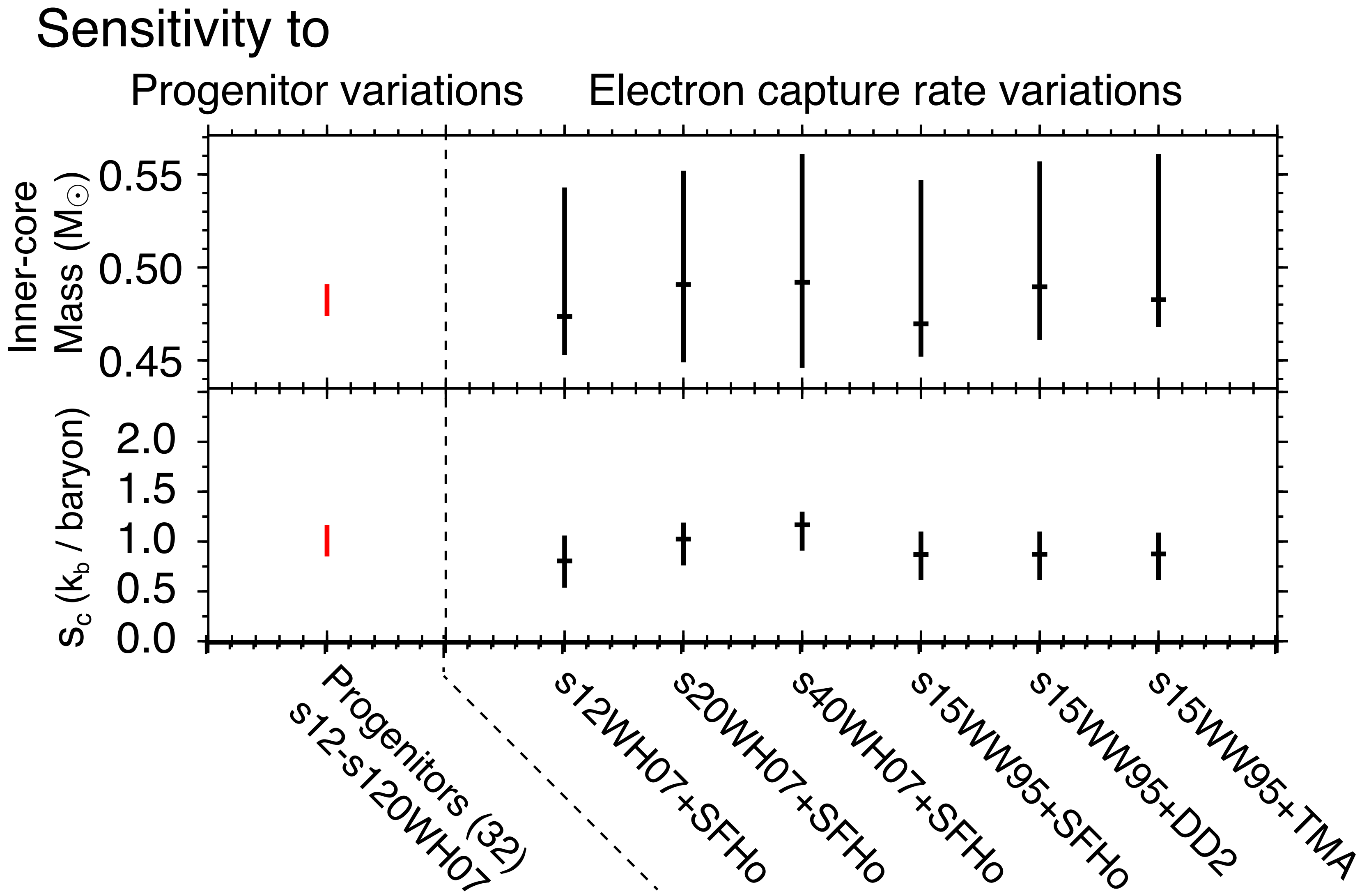
# Progenitor Dependence



# Progenitor Dependence

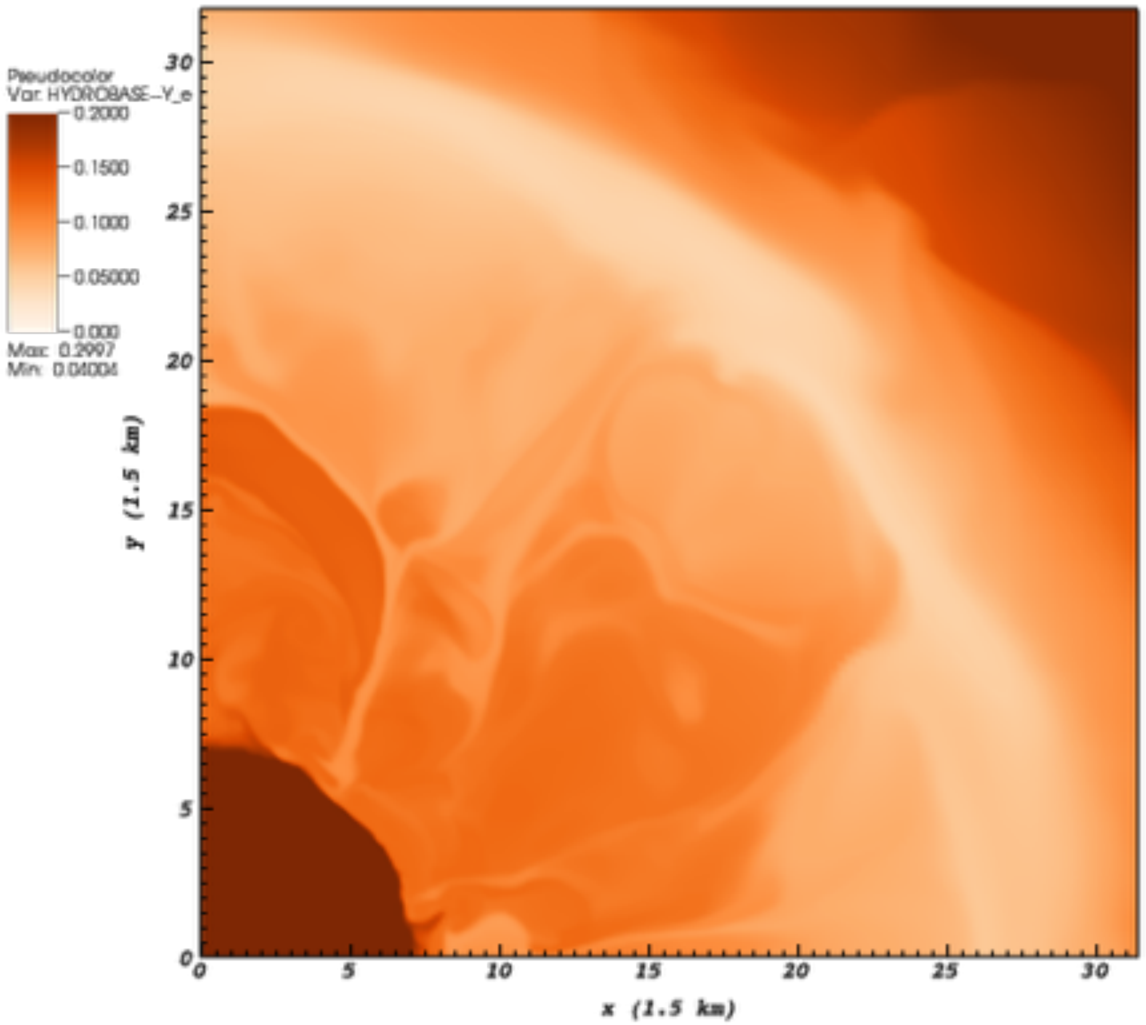
Properties of the inner core after bounce are relatively insensitive to progenitor structure

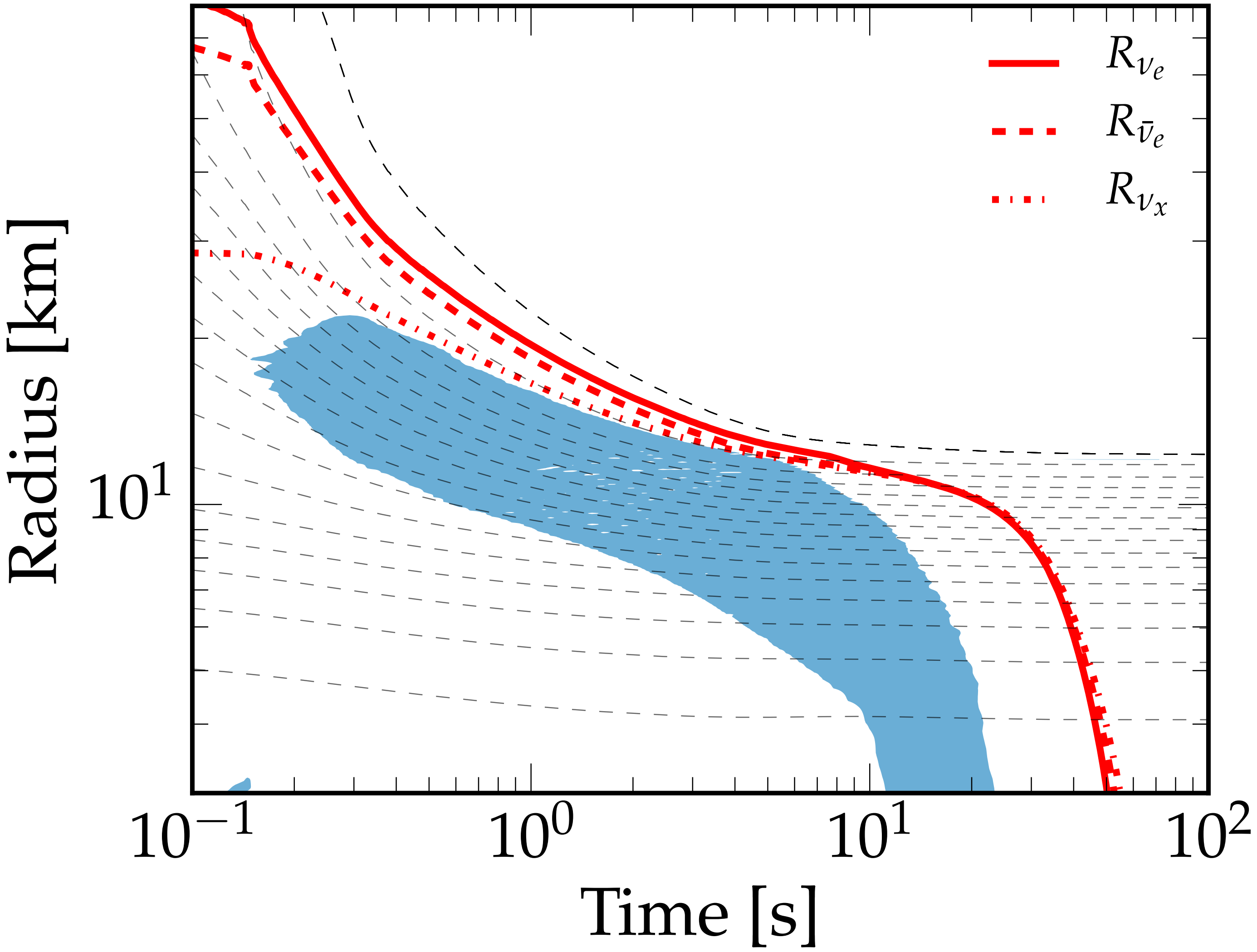
Liebendoerfer et al. 2002



From Sullivan et al. (2015)

# Proto-Neutron Star Convection

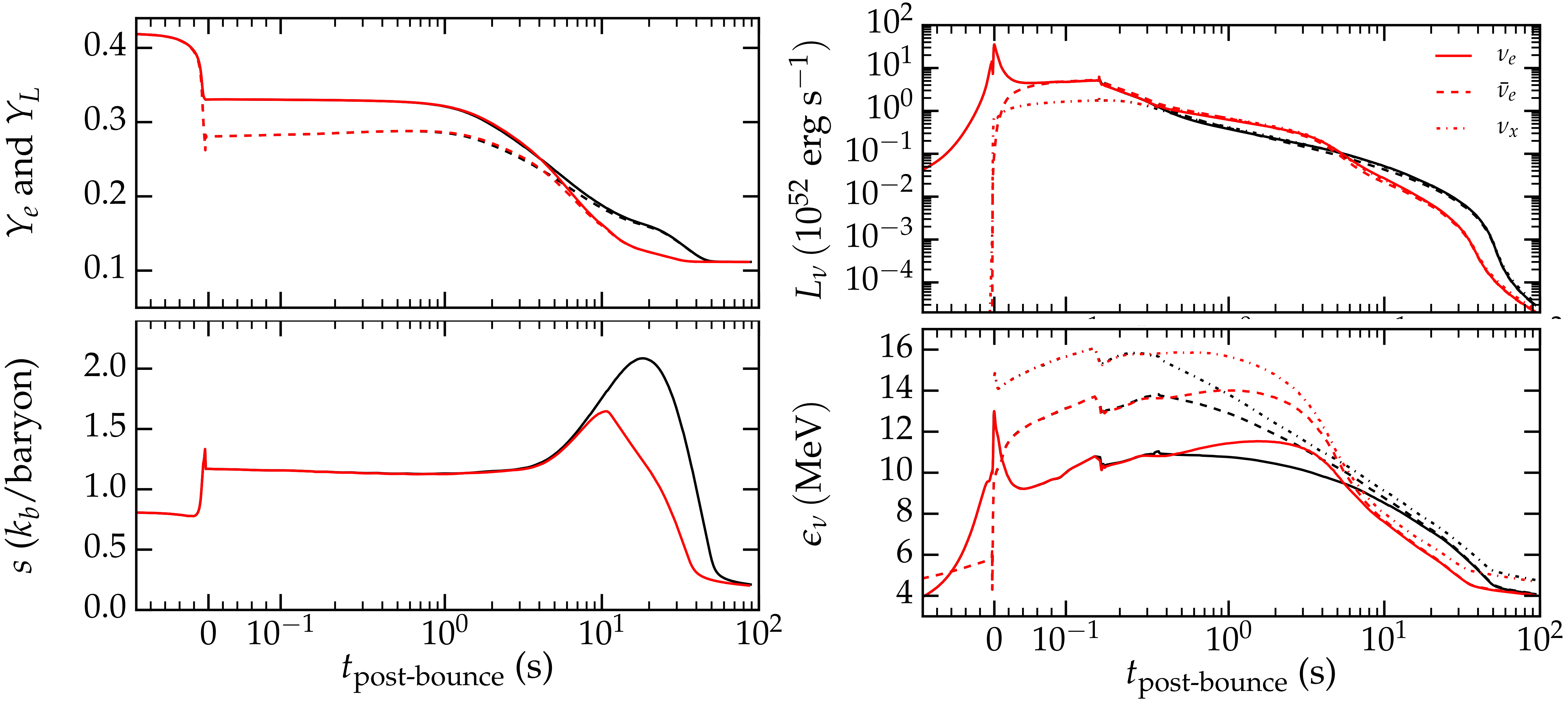




Region of convective instability determined by the Ledoux Criterion:

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

# Proto-Neutron Star Convection



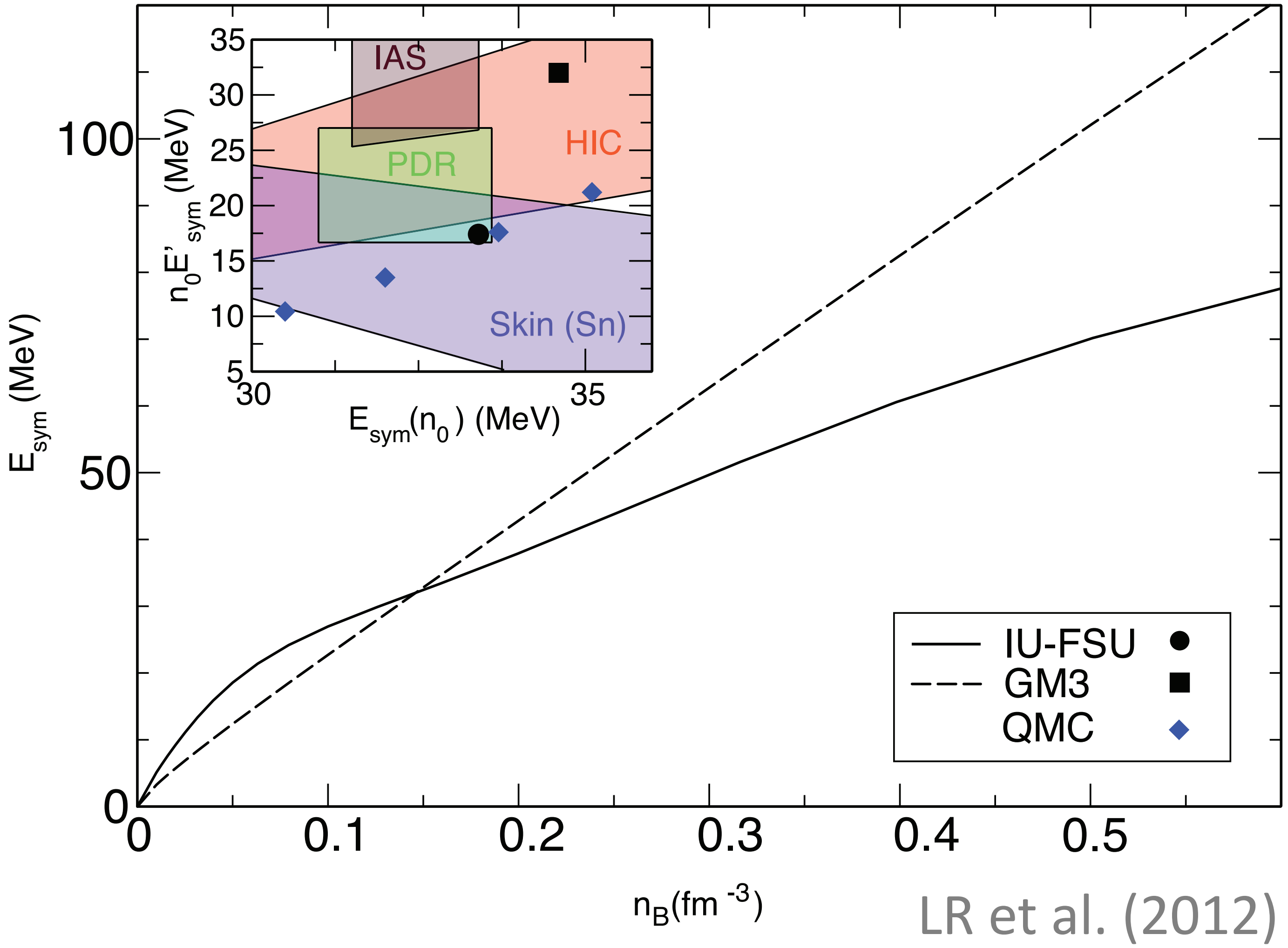
Black: No Convection

Red: Convection

See also Mirizzi et al. (2015)

# Proto-Neutron Star Convection

## Dependence on the EoS

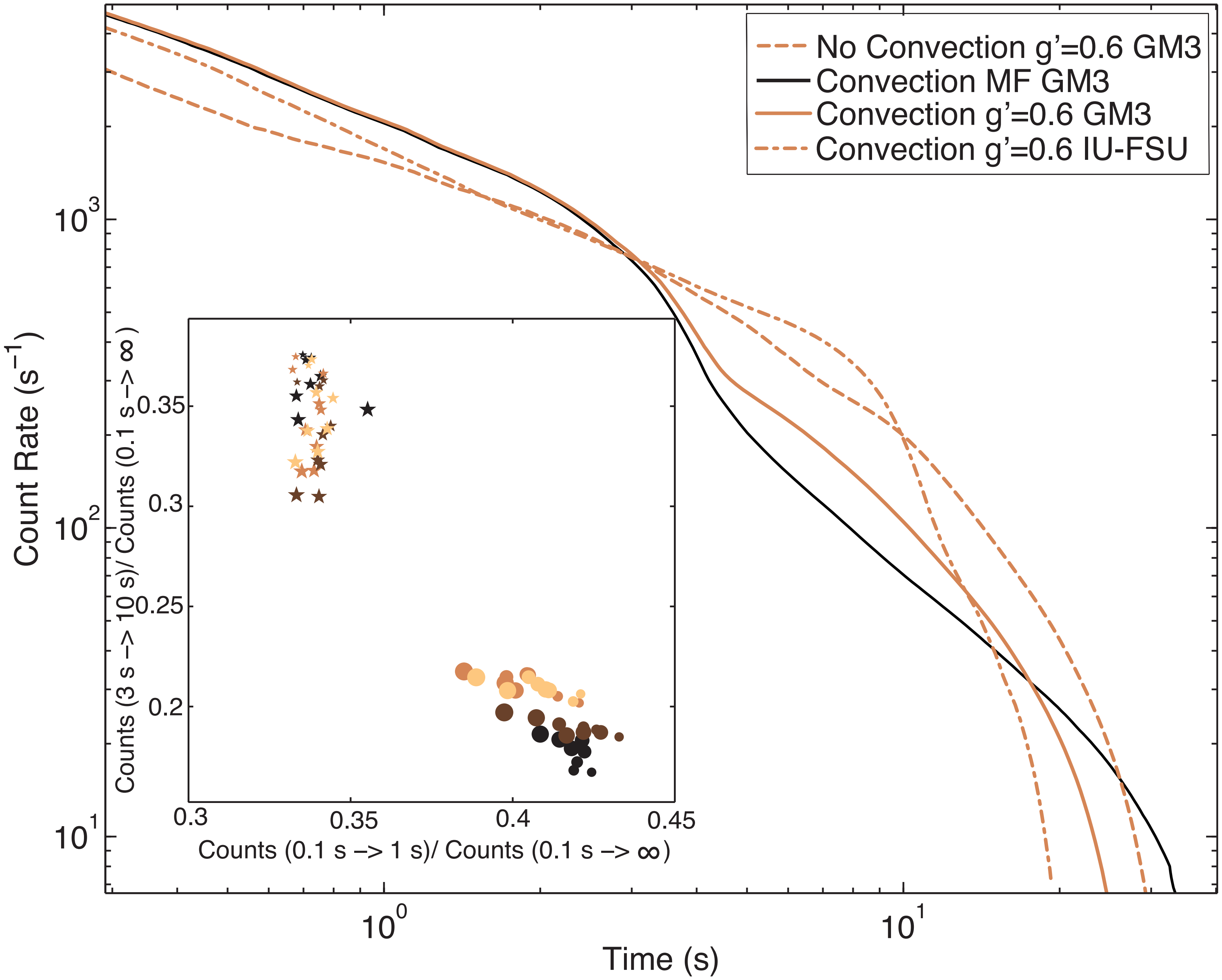


LR et al. (2012)

Pressure derivatives are sensitive to the symmetry energy derivative:

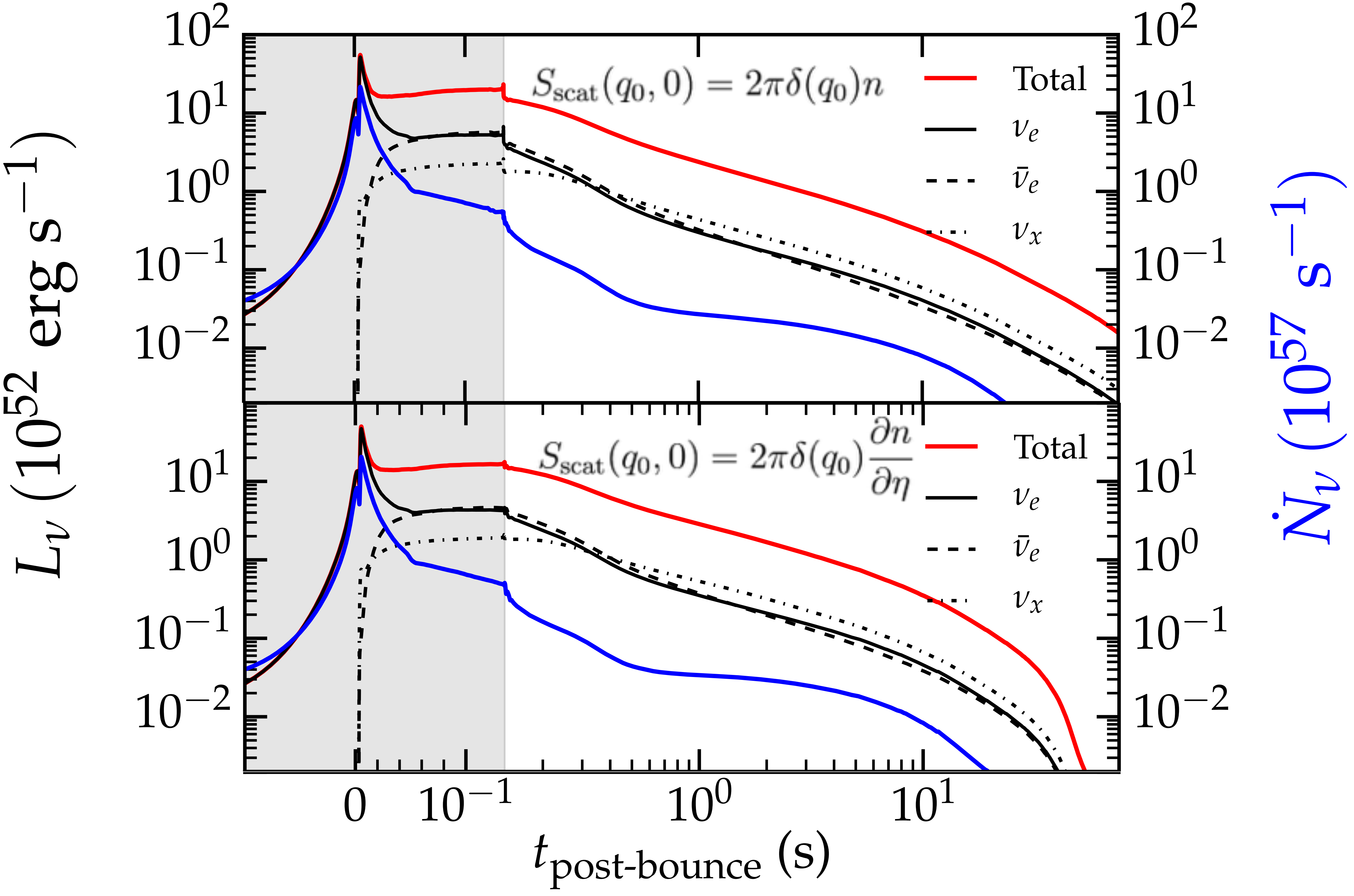
$$\left(\frac{\partial P}{\partial Y_L}\right)_{n_B} \simeq n_B^{4/3} Y_e^{1/3} - 4 n_B^2 E'_{\rm sym}(1 - 2Y_e)$$

# Proto-Neutron Star Convection



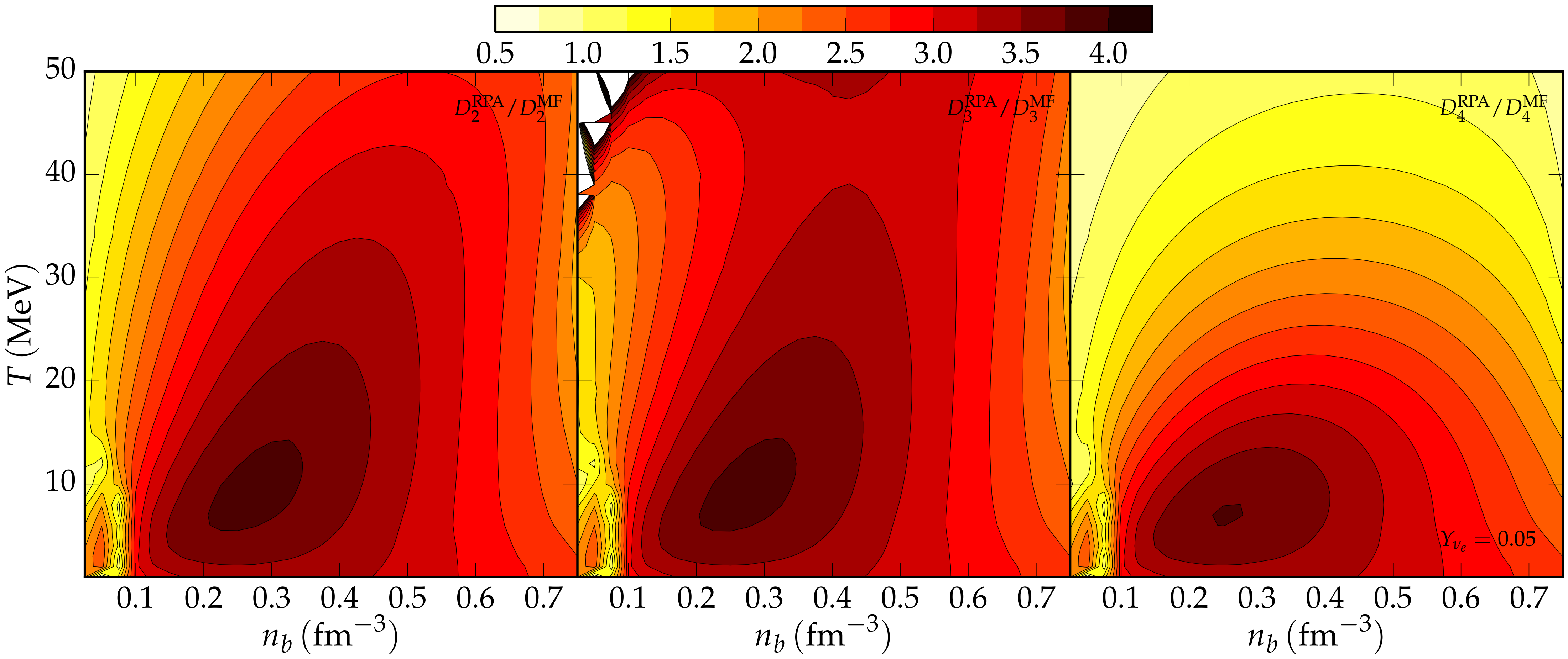
LR et al. (2012)

# Opacity Dependence of Late Time Cooling



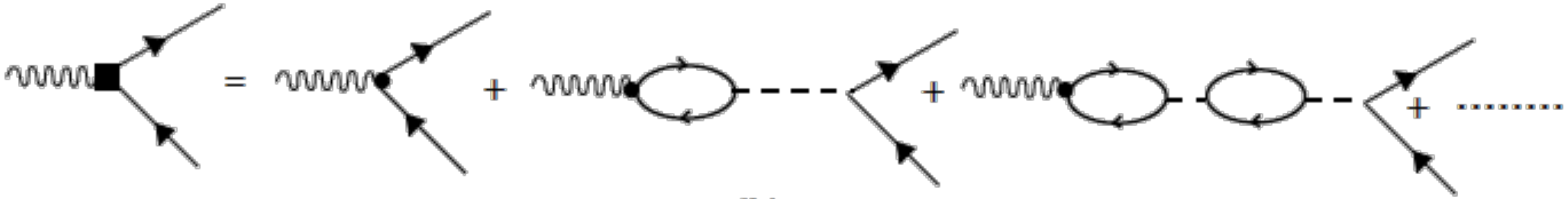
# Impact of Nuclear Correlations on Neutrino Opacities

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

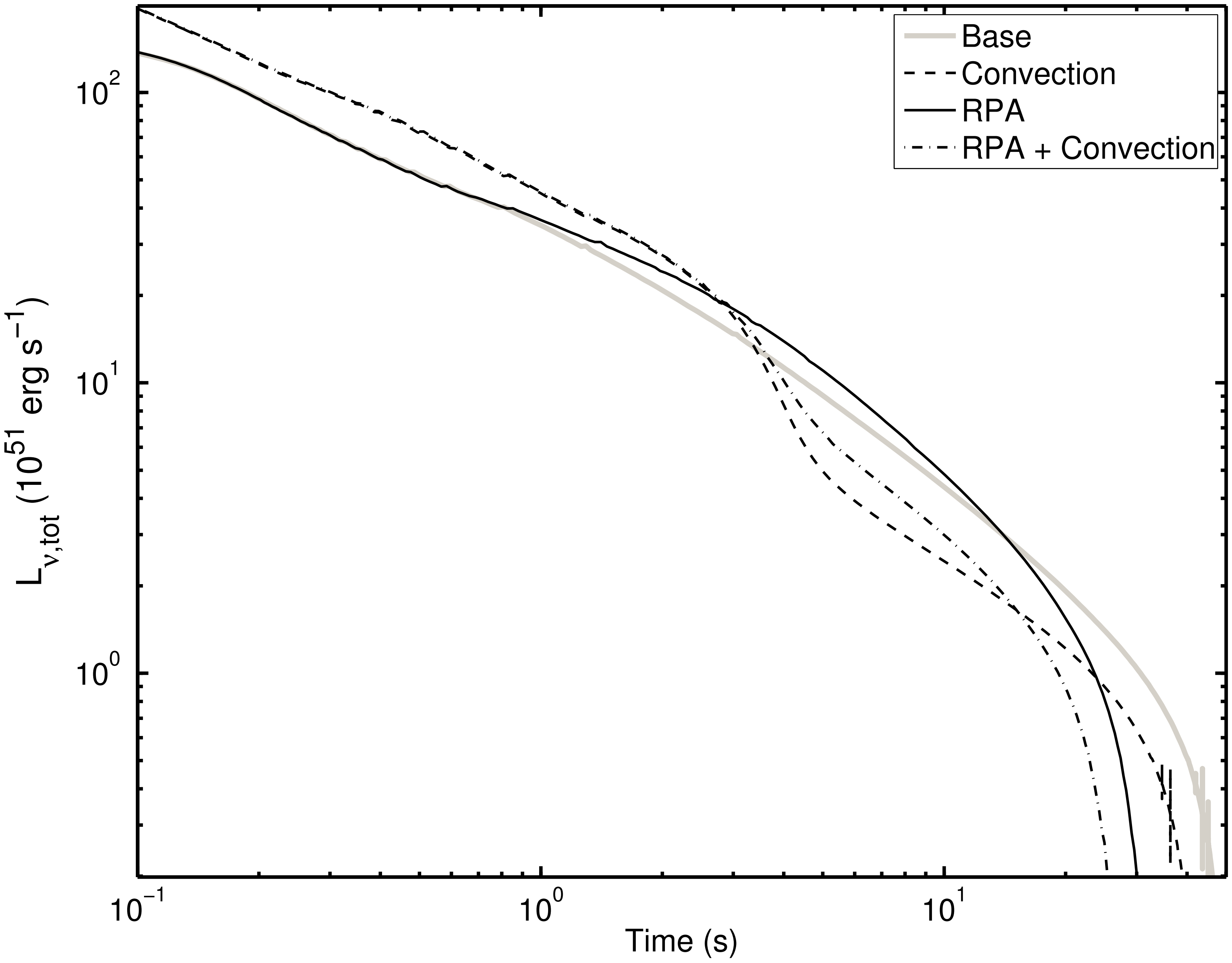


Neutrino Diffusion Coefficients

Correlations through the RPA:

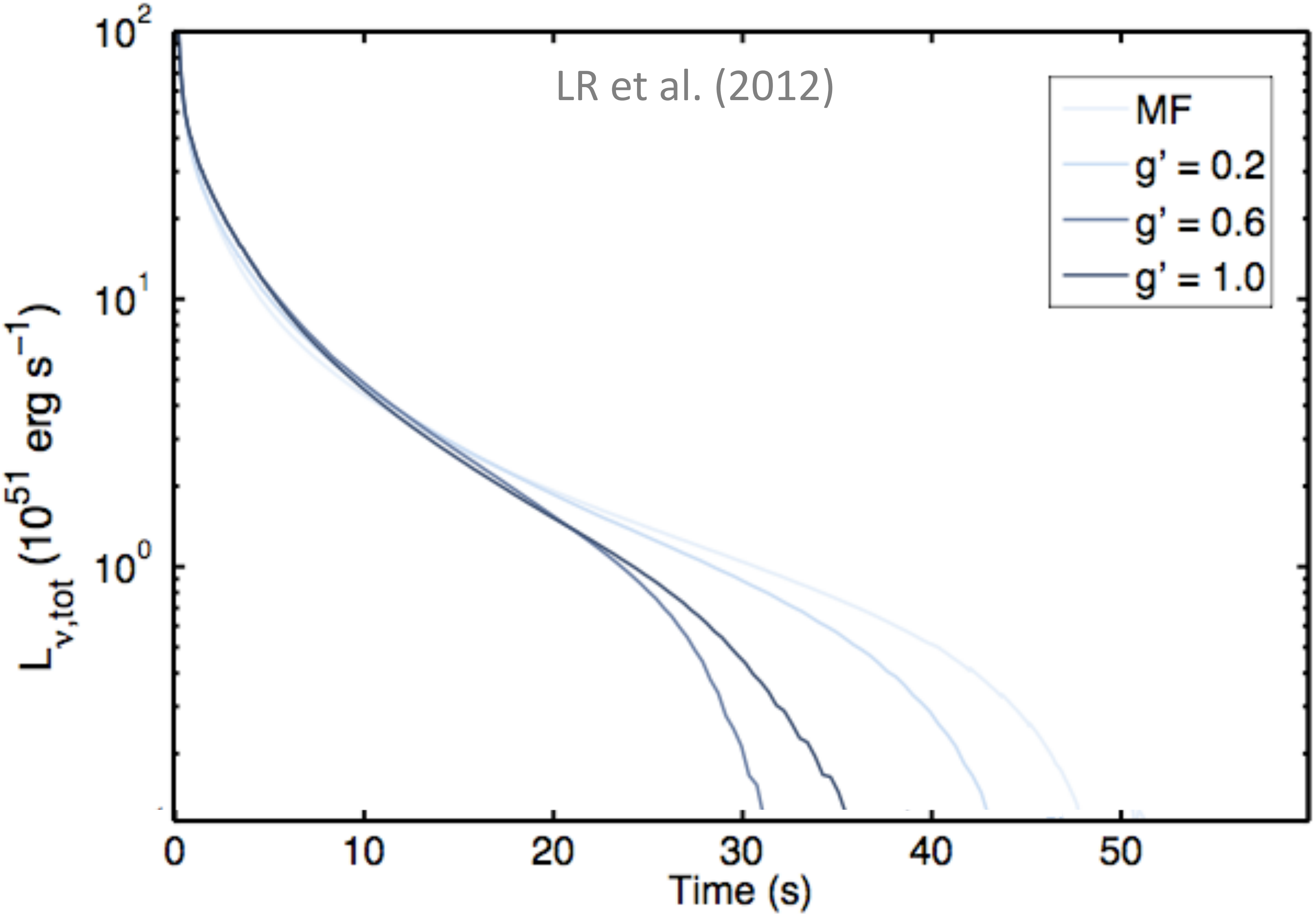


# Impact of Screening



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

# Variations in the Interaction



Varying the axial interaction

Reddy et al. (1999)

# 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

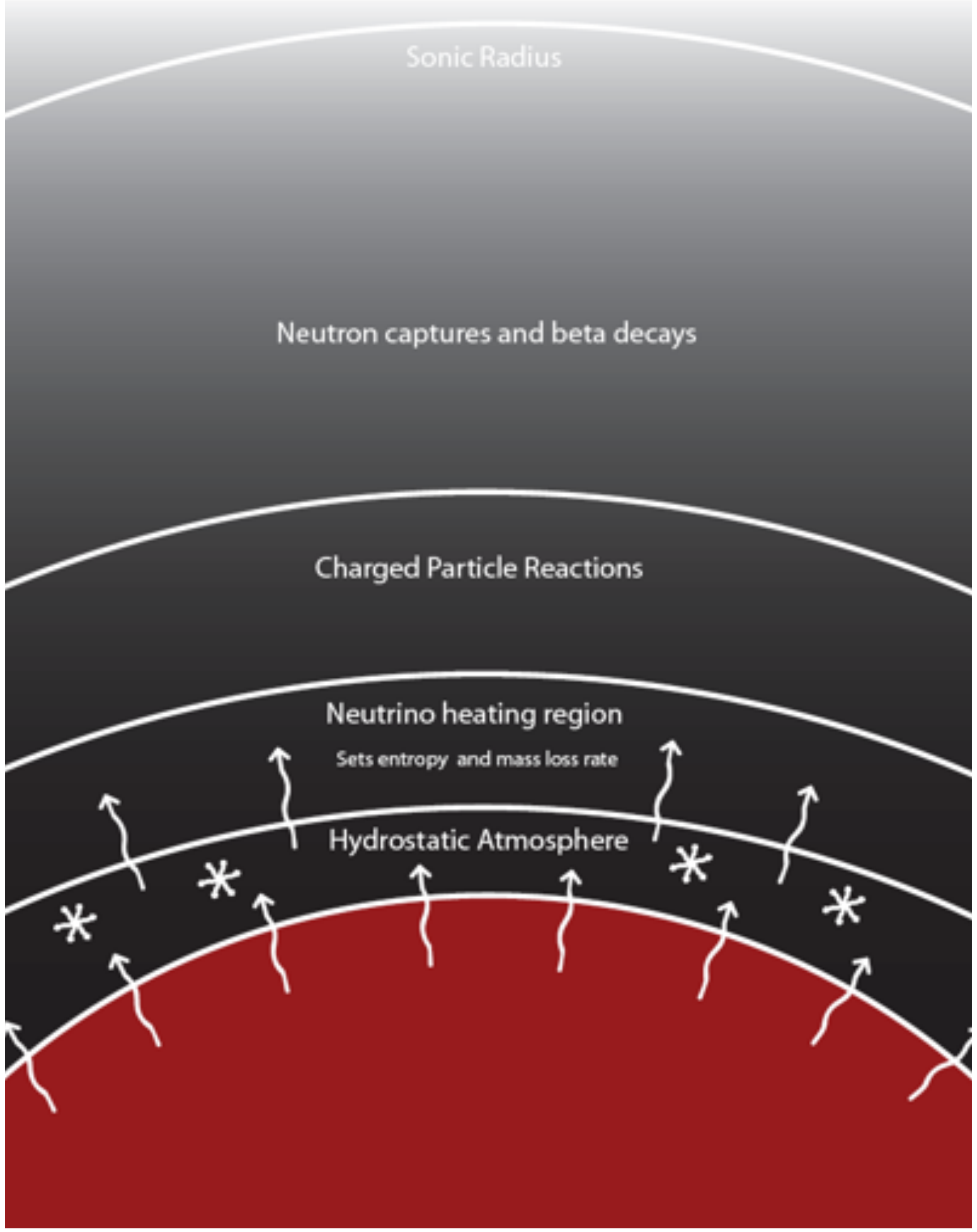
- As neutrinos leave the PNS, they deposit energy in material at the neutron stars surface

- 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

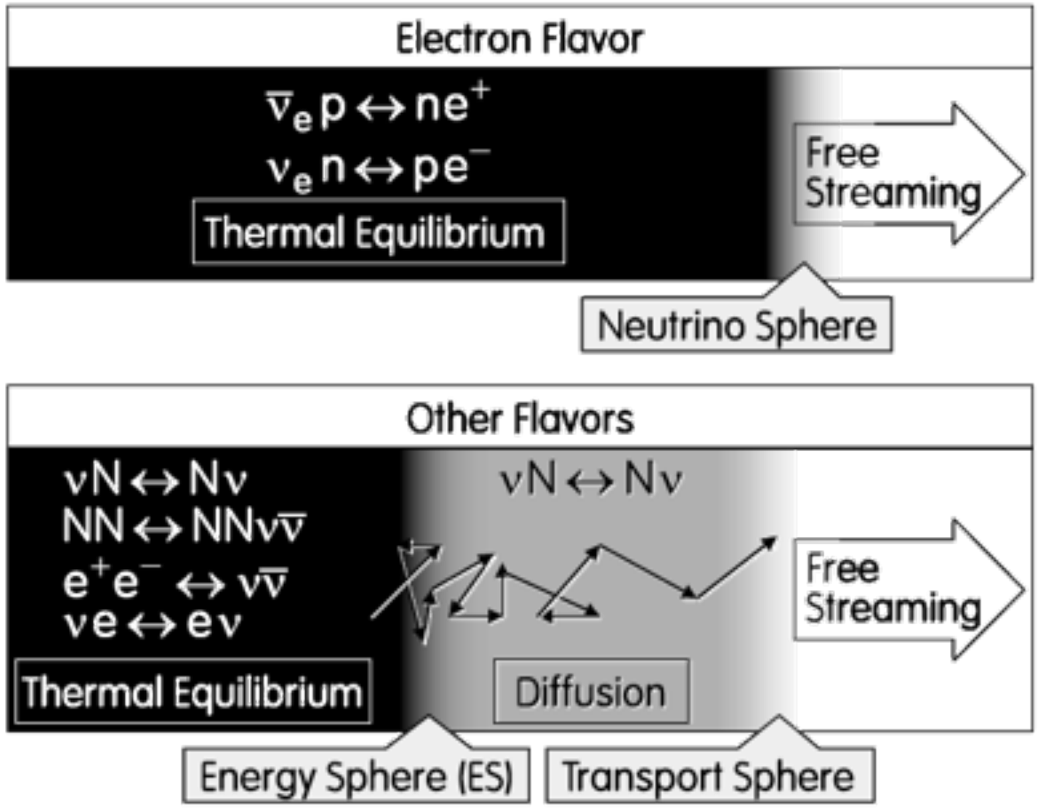
$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\nu_e + n \rightarrow e^- + p$$

- 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 $\nu_e$ Spectra?

- "Neutrino sphere" is not well defined, energy dependent, range of densities and temperature
- Both charged and neutral current reactions important to $\nu_e$ and anti-$\nu_e$ decoupling radii
- Charged current rates introduce asymmetry between neutrinos and antineutrinos

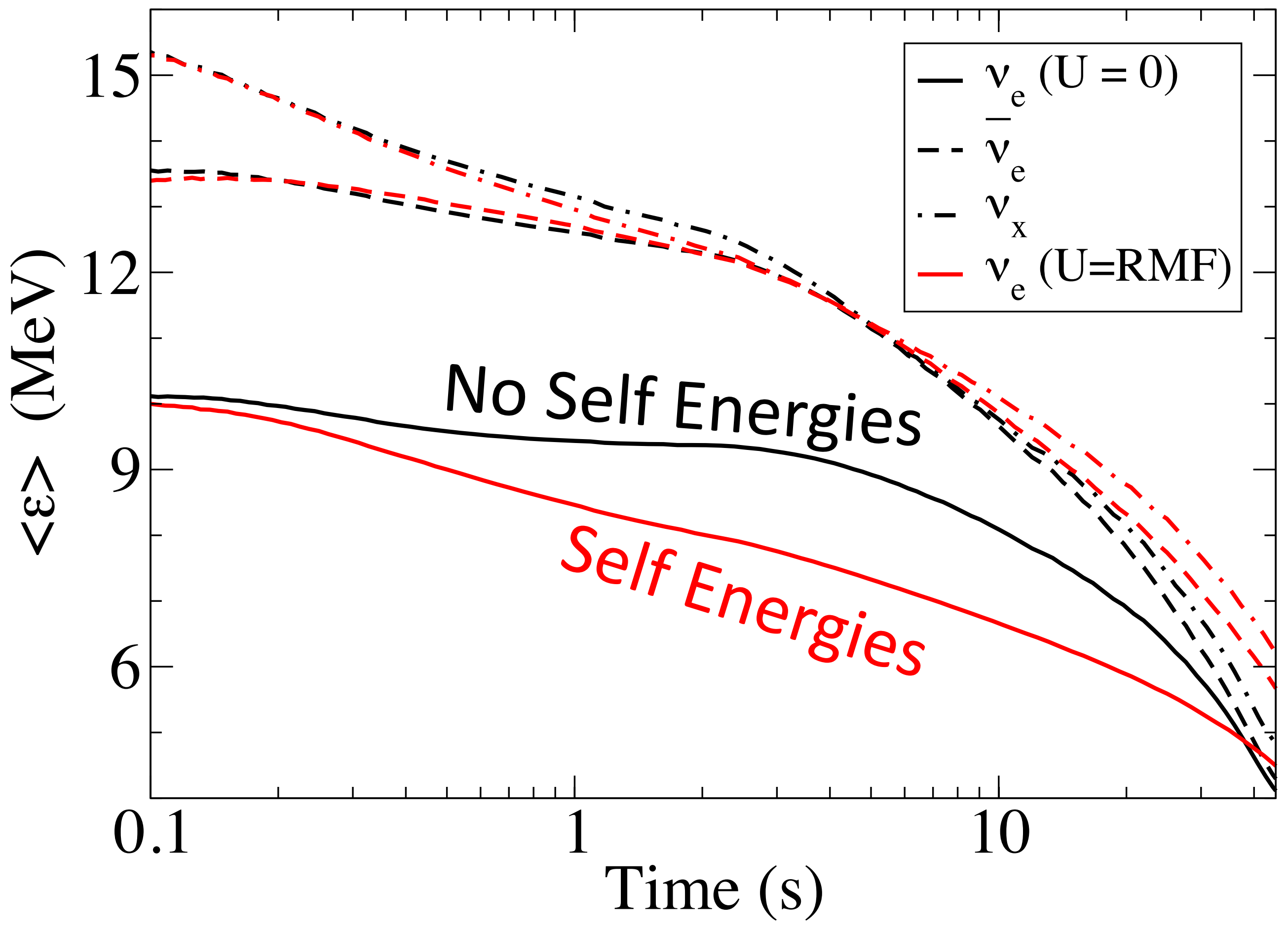


From Raffelt '01

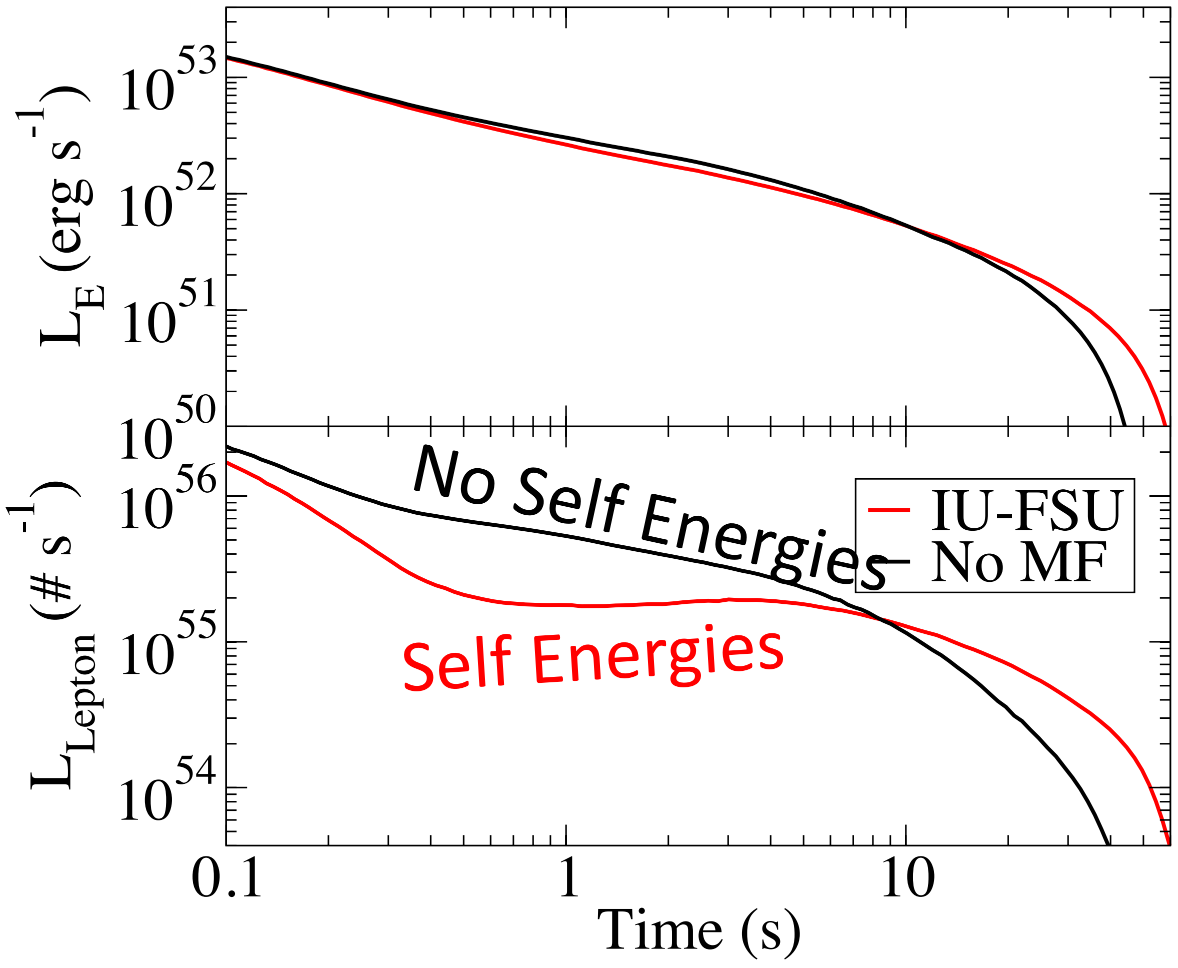
# Neutrino emission w/ and w/o Nuclear Interactions

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

## Self energies shift average neutrino energies

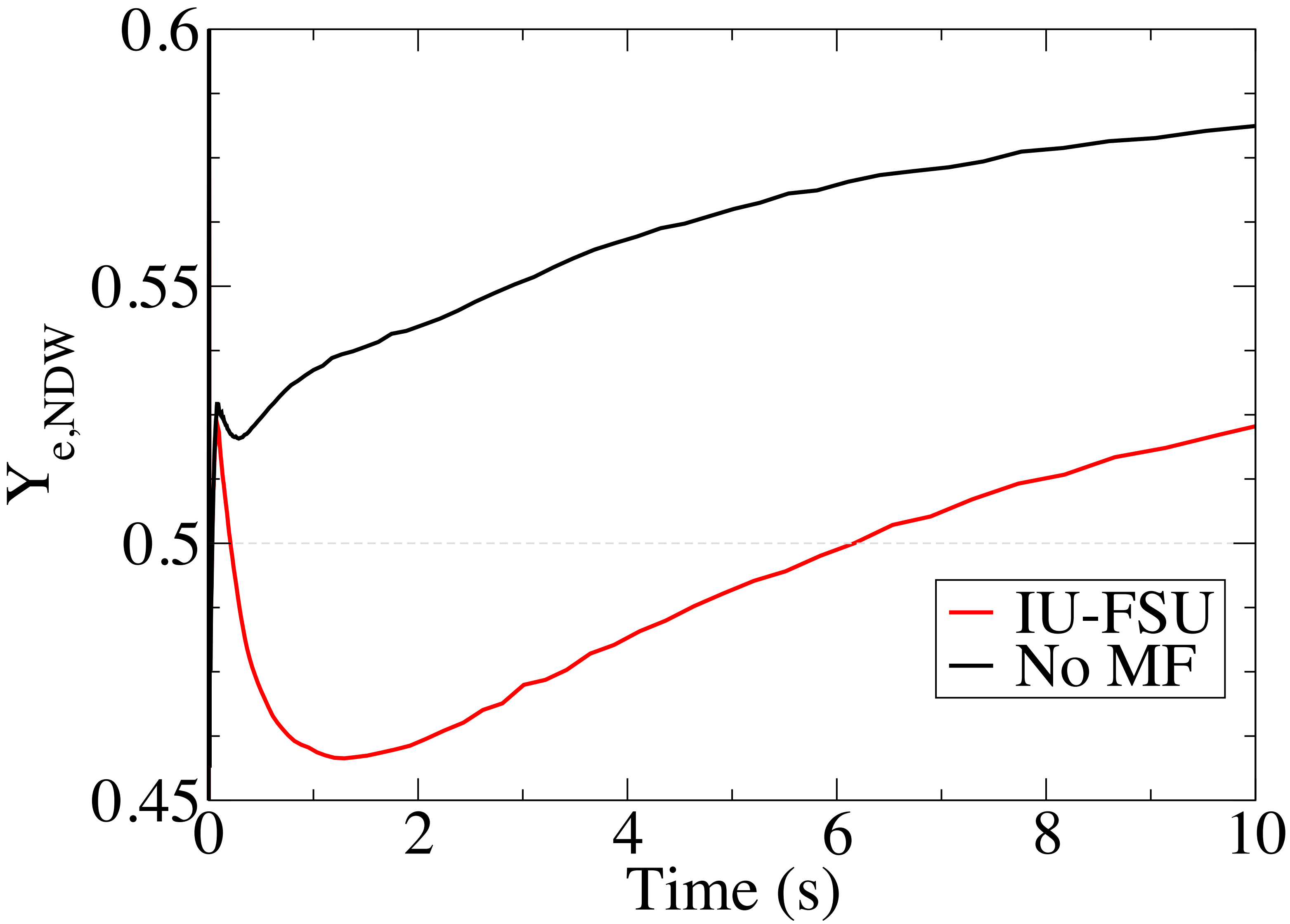


## Deleptonization



# Neutrino emission w/ and w/o Nuclear Interactions

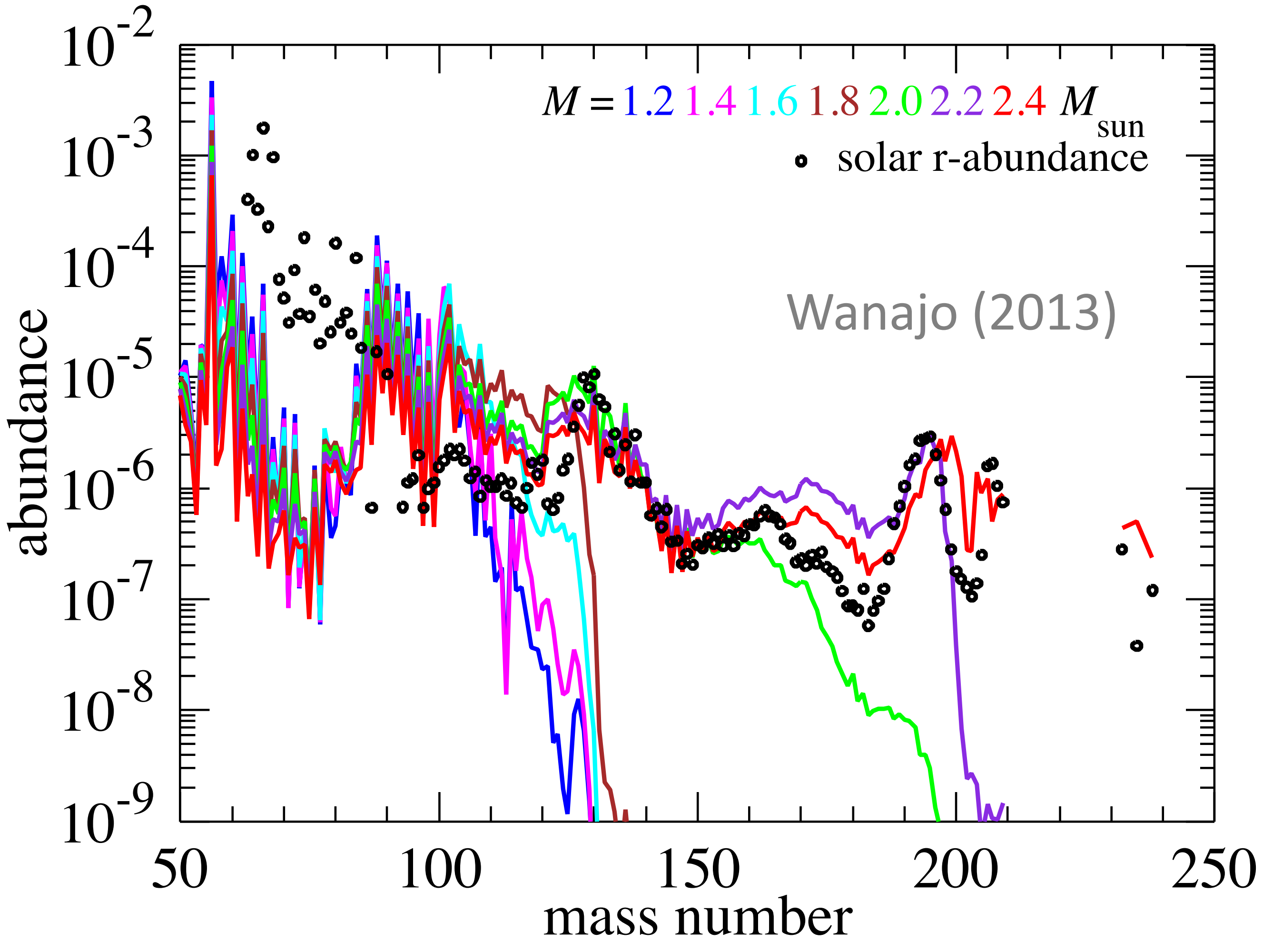
See LR ‘12 and Martinez-Pinedo et al. ‘12

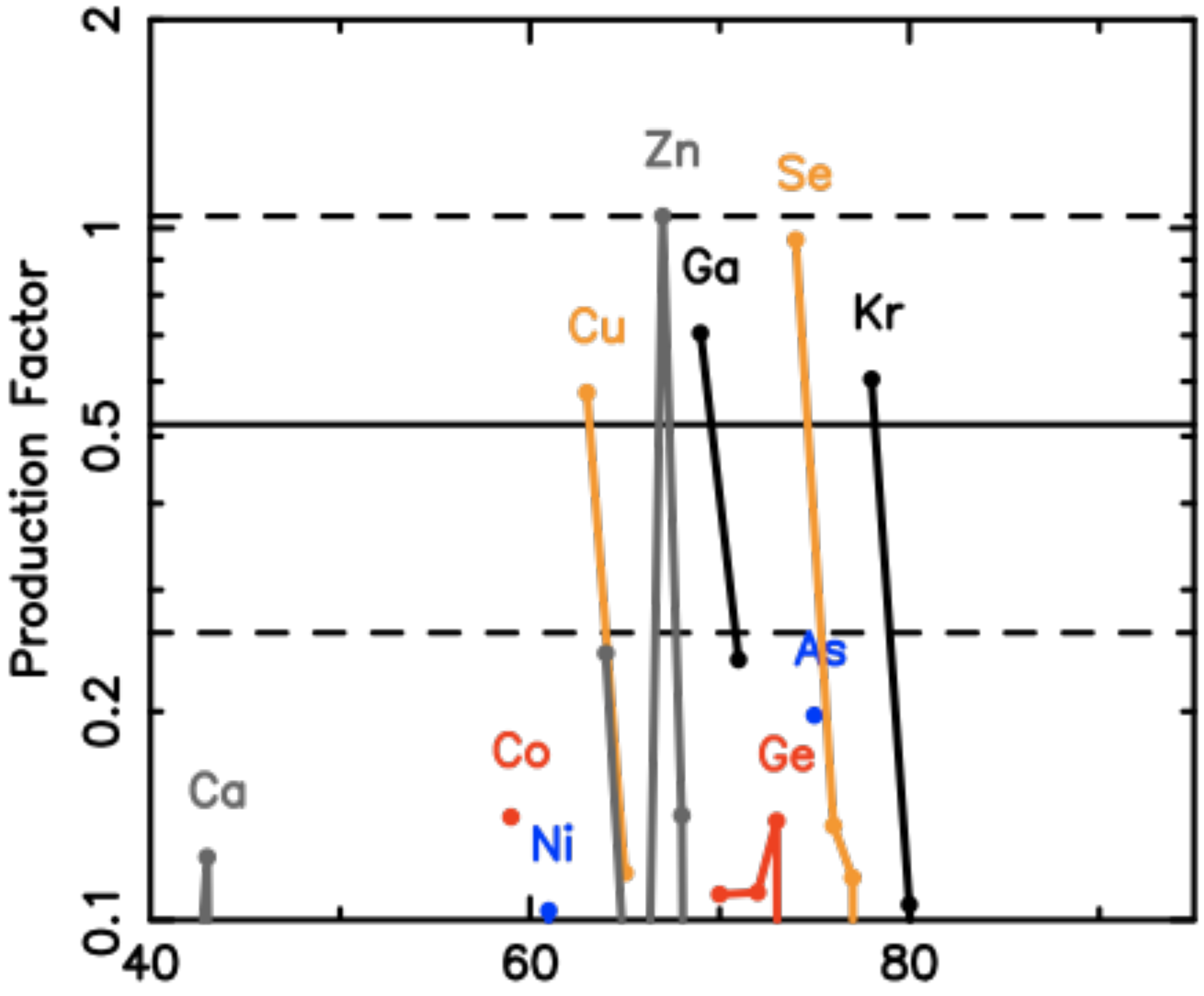


$$Y_e \approx \frac{\lambda_{\nu_e}^{-1}}{\lambda_{\nu_e}^{-1} + \lambda_{\bar{\nu}_e}^{-1}} \approx \left(1 + \frac{\dot{N}_{\bar{\nu}_e}}{\dot{N}_{\nu_e}} \frac{(\varepsilon_{\bar{\nu}_e} - \Delta)^2}{(\varepsilon_{\nu_e} + \Delta)^2}\right)^{-1}$$

# Integrated NDW Nucleosynthesis

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



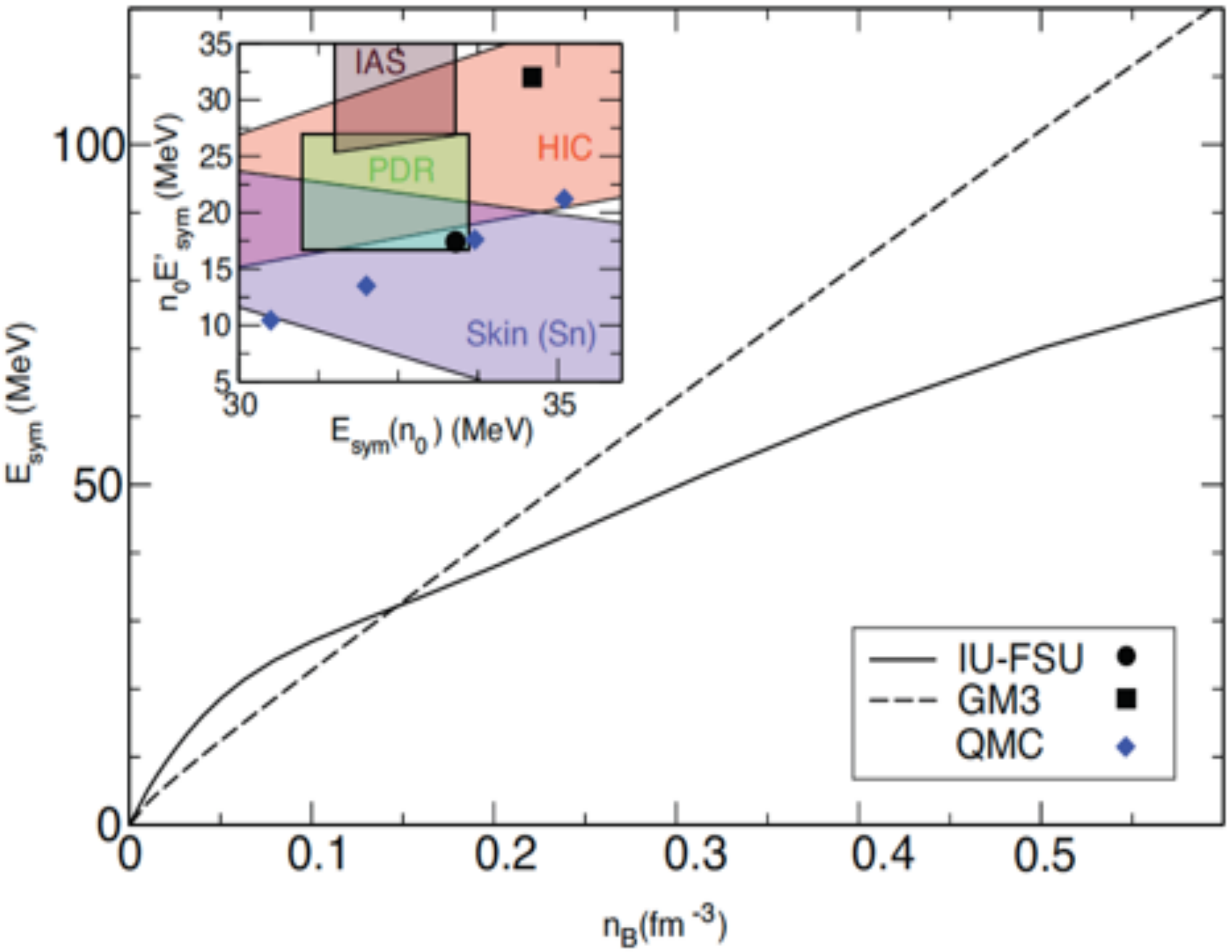


Roberts. ’12 neutrino histories. Significant N = 50 closed neutron shell production.

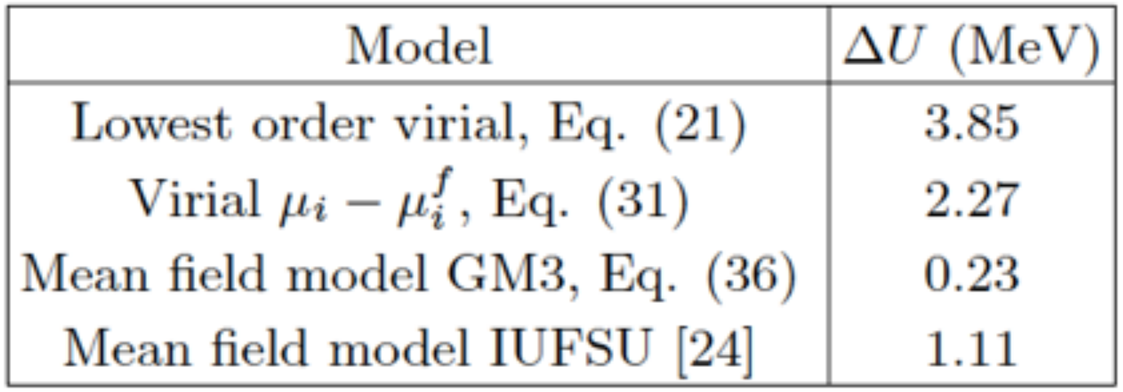
Huedepohl et al. ’10 neutrino histories. Very little nucleosynthesis. 7.5 $M_{\rm sun}$ ejected.

# Symmetry Energy Dependence

From Roberts et al. (2012)

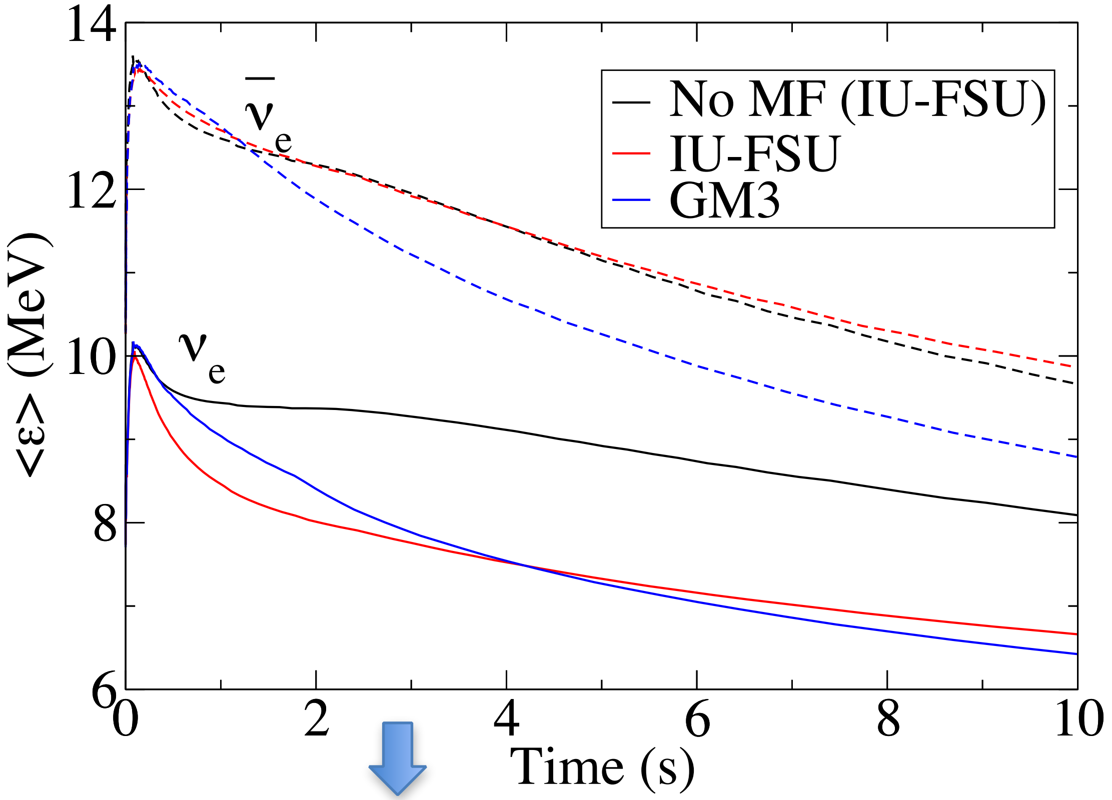


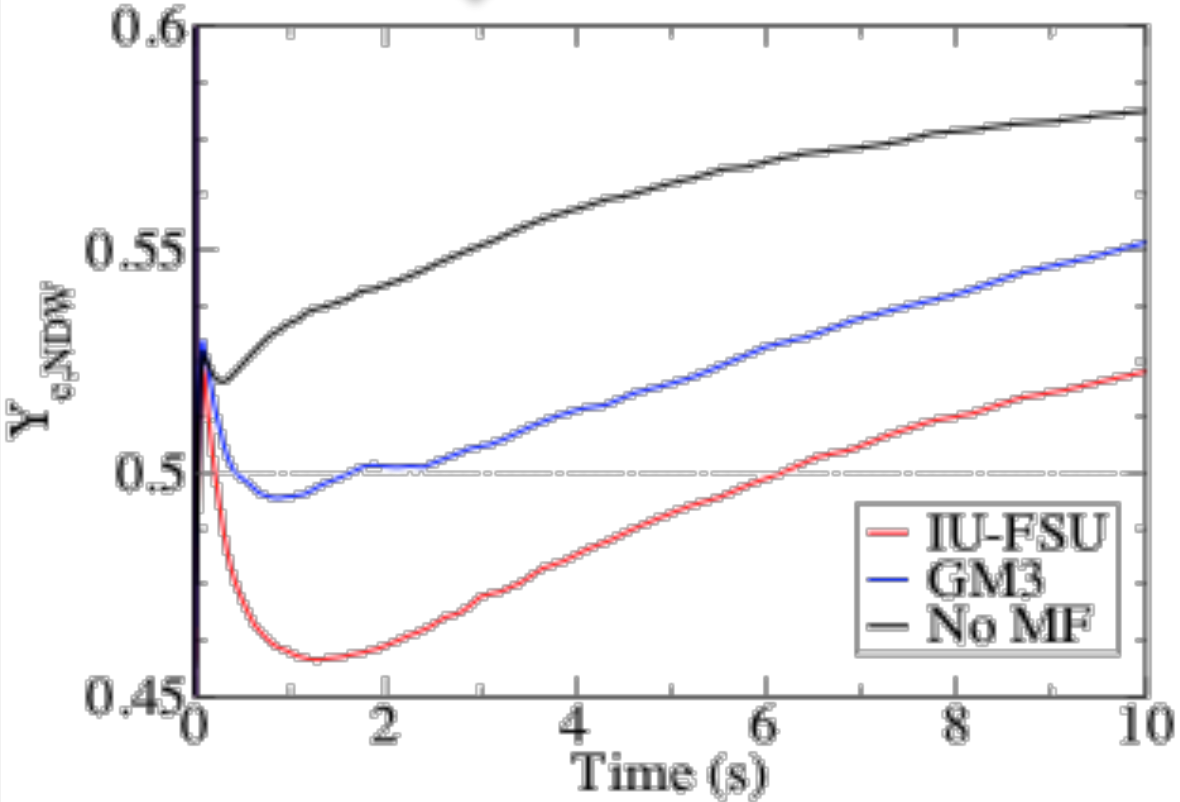
Different equations of state



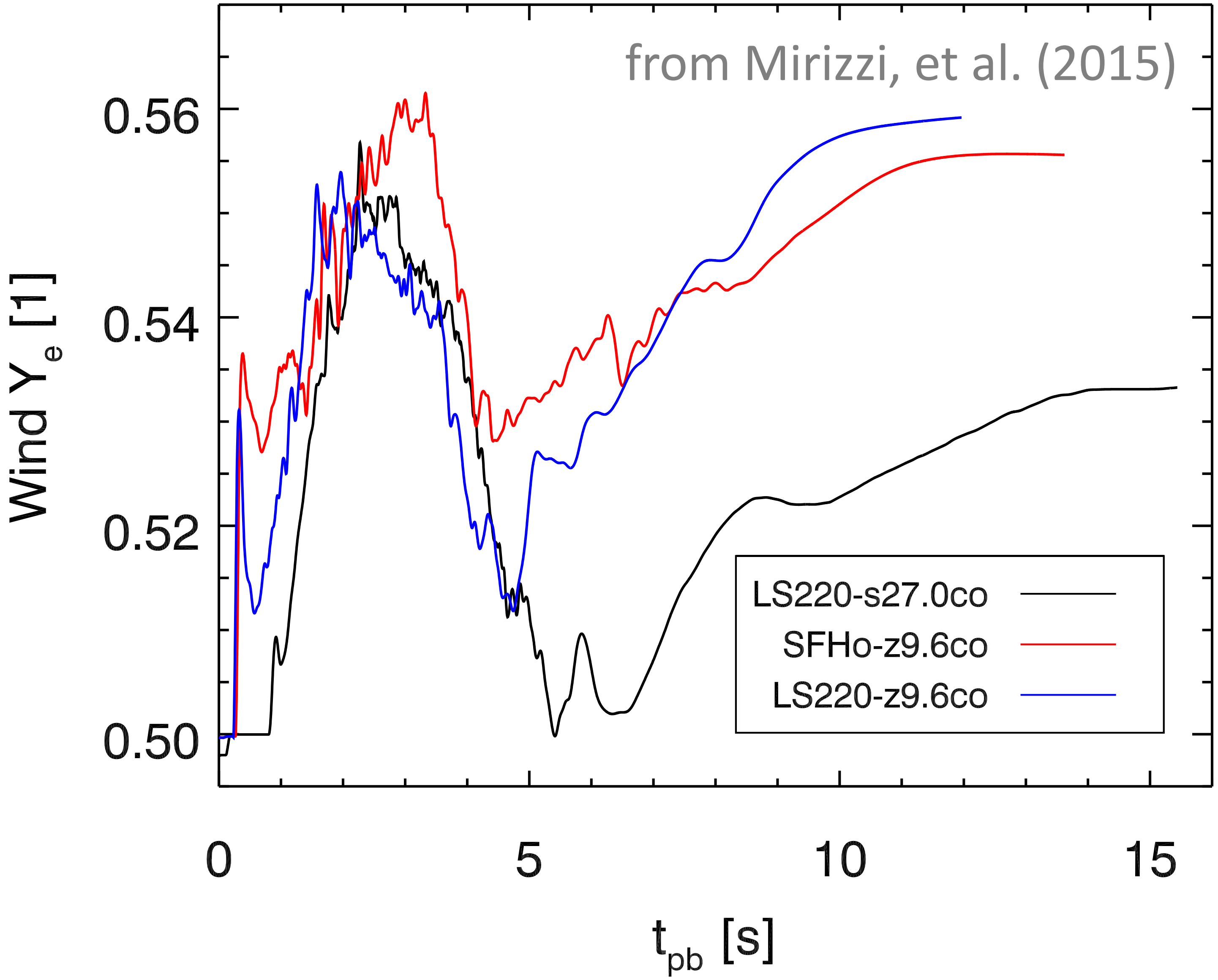
| Model | $\Delta U$ (MeV) |
|---|---|
| Lowest order virial, Eq. (21) | 3.85 |
| Virial $\mu_i - \mu_i^f$, Eq. (31) | 2.27 |
| Mean field model GM3, Eq. (36) | 0.23 |
| Mean field model IUFSU [24] | 1.11 |

From Horowitz et al. (2012)





# …Convection



- Convection increases deleptonization rate, increases $Y_e$
- Convection heats up PNS atmosphere, hotter neutrino spectra, decreases $Y_e$

# Conclusions

- 3D models of radiation hydrodynamic models of CCSNe starting to become available, producing explosions
- PNS convection significantly impacts the neutrino cooling timescale, produces a break in the neutrino emission, sensitive to the nuclear EoS
- 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

Thank you to my collaborators: S. Reddy, G. Shen, C. Ott, R. Haas, and A. da Silva Schneider