# Proto-Neutron Star Cooling: The Late Time Supernova Neutrino Signal

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# Outline

- Review
- Modeling PNS cooling
- Neutrino opacity variations
- The effects of late time convection
- Late time neutrino spectra

# Core Collapse Supernovae

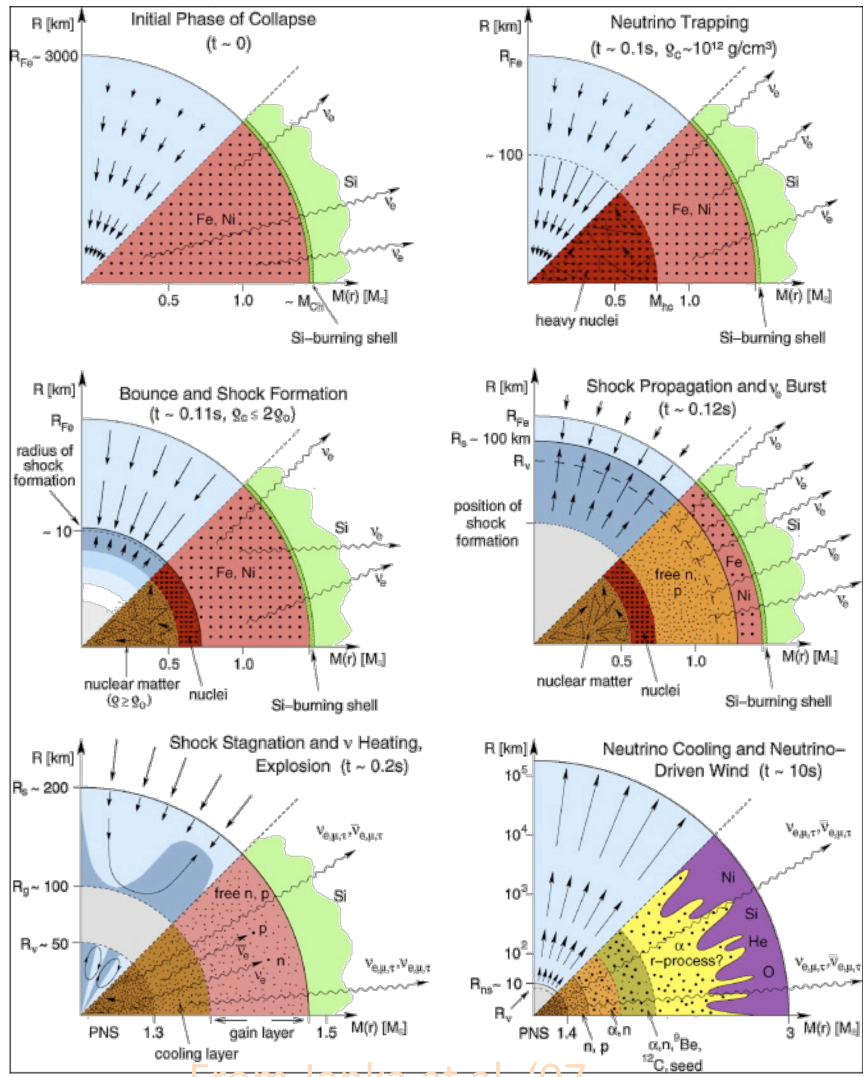
- Stars with M > 8 $M_{sun}$ burn their core to Fe
- Core exceeds a Chandrasekhar mass → supersonic collapse outside of homologous core → bounce shock after ~2 x saturation density
- Gravitational binding energy of compact remnant:

$$\frac{GM_{NS}^2}{R_{NS}} \sim 3 \times 10^{53}\, erg$$

- Binding energy of stellar envelope:

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

- Details of coupling somewhat uncertain
- Today, we will just assume that they explode




From Janka et al. '07

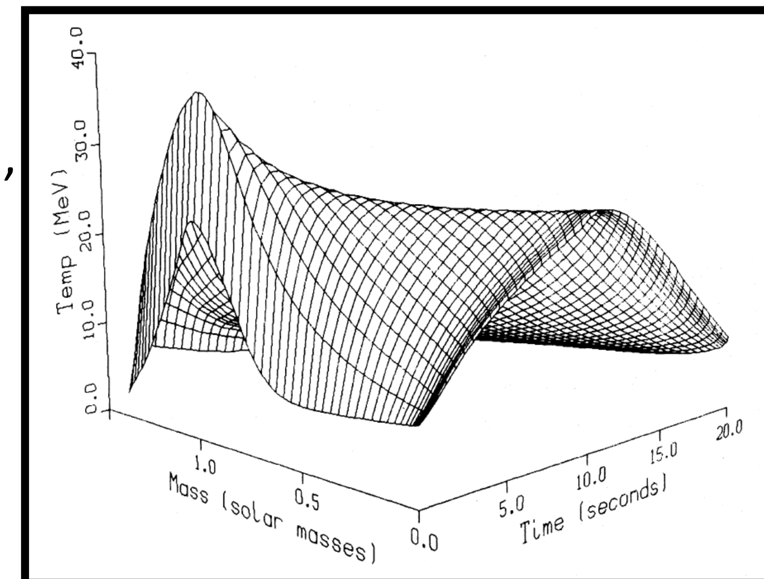
# Late Time Neutrino Signal

- Most of NSs gravitational binding energy lost in the form of neutrinos

- Late time signal *mostly* independent of hydrodynamic details of the SN mechanism, hydrostatic spherical symmetry is a reasonable approximation

- Provides a window into the properties of hot dense matter… if you can reasonably model macroscopic effects

- Reasonably described by diffusive Kelvin-Helmholtz evolution of the PNS (Burrows & Lattimer '86)




from Burrows and Lattimer '86

# Order of Magnitude PNSs

$$M_{PNS} \sim 1.4\ M_{sun}$$

$$R_{PNS} \sim 12\ km$$

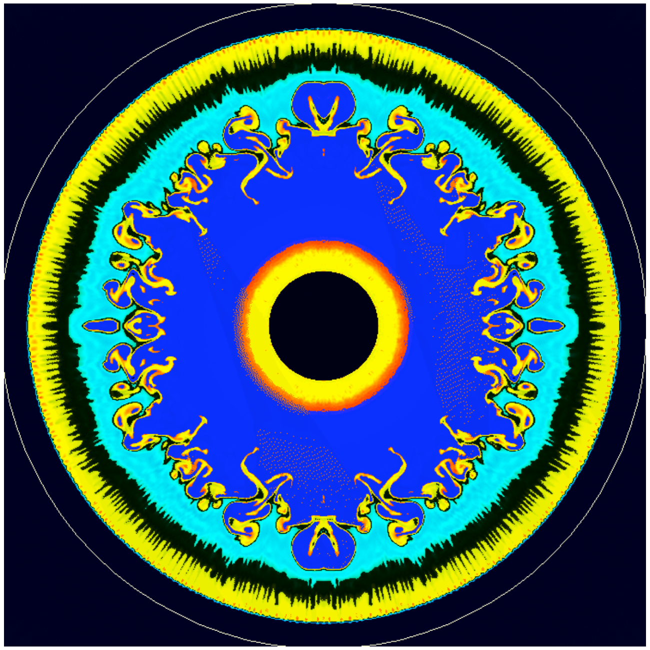
$$T_C \sim \frac{3GM_{PNS}m_b}{5\pi R_{PNS}} \sim 30\ MeV$$

$$\tau_\nu \sim n\sigma_0 \left(\frac{T_c}{2\ MeV}\right)^2 R_{NS} \sim 2\times 10^3$$

$$T_{eff} \sim \frac{T_C}{\tau_\nu^{1/4}} \sim 5\ MeV$$

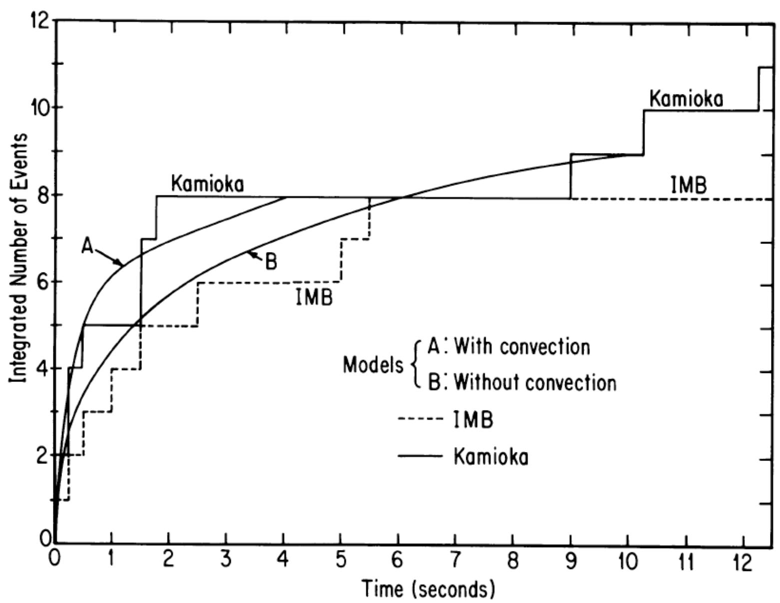
$$L_{\nu,tot} \sim 4\pi R^2 \sigma_\nu T_{eff}^4 \sim 10^{52}\ ergs\ s^{-1}$$

$$\tau_{KH} \sim \frac{3GM_{NS}^2}{5RL_{\nu,tot}} \sim 25\ s$$



From Dessart et al. '06

# Observed Neutrinos from 1987a

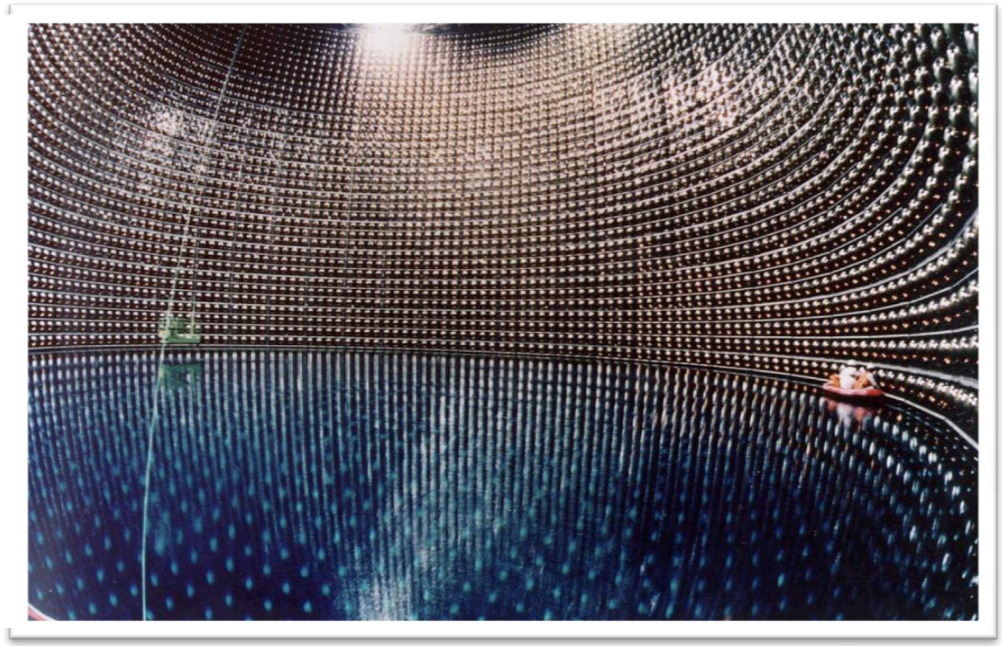



From Burrows & Lattimer '88

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

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

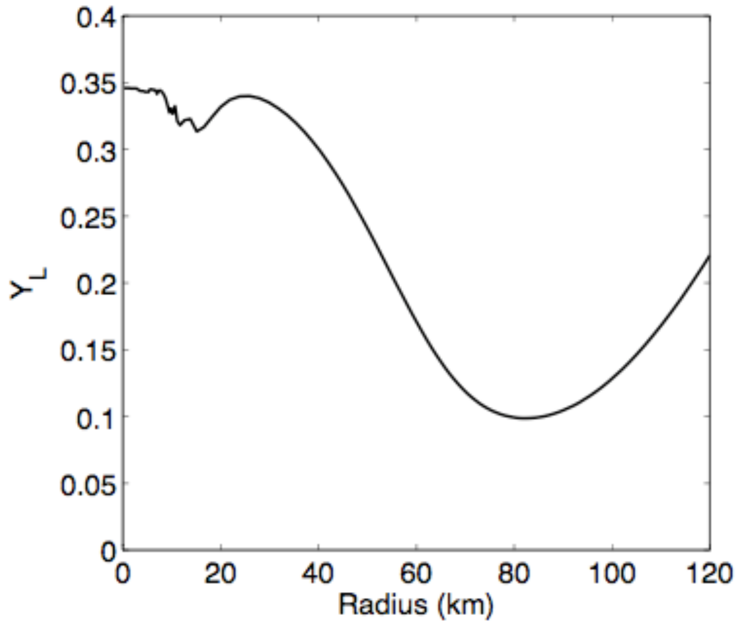
See Bionta et al. '87 and Hirata et al. '87

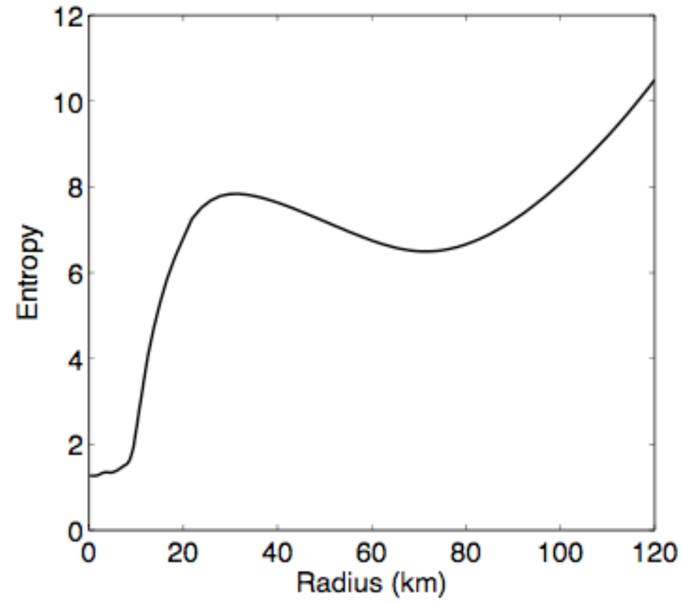


Super-Kamiokande Neutrino Detector

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

# Structure of Initial Models




Hydrostatic evolution means that only initial entropy, neutrino fraction, electron fraction, and the enclosed mass specify the initial conditions. Therefore, need data from supernova models at around the time the shock is reinvigorated (~200-300 ms).

# A Simple PNS Cooling Model

TOV Equations:

$$\begin{aligned}
\frac{dr}{da} &= \frac{\Gamma}{4\pi r^2 n_B} \\
\frac{dm}{da} &= \Gamma \frac{\rho}{n_B} \\
\frac{dP}{da} &= -(\rho + P)\frac{m + 4\pi r^3 P}{\Gamma 4\pi r^4 n_B} \\
\frac{d\phi}{da} &= \frac{m + 4\pi r^3 P}{\Gamma 4\pi r^4 n_B}
\end{aligned}$$

GR FLD Transport Equations:

$$\begin{aligned}
\frac{dY_\nu}{dt} + \frac{\partial\left(4\pi r^2 e^{\phi}\left[F_\nu + F_{\nu,c}\right]\right)}{\partial a} &= e^{\phi} S_n \\
\frac{dY_e}{dt} + \frac{\partial\left(4\pi r^2 e^{\phi} F_{e,c}\right)}{\partial a} &= -e^{\phi} S_n \\
\frac{dE}{dt} - \frac{p}{n_b^2}\frac{dn_b}{dt} + e^{-\phi}\frac{\partial\left(4\pi r^2 e^{2\phi}\left[H_\nu + H_c\right]\right)}{\partial a} &= 0
\end{aligned}$$

$$F_\nu = -\frac{\Gamma e^{-\phi} T^2}{6\pi^2}\left[D_3 \frac{\partial T e^{\phi}}{\partial r} + D_3 T e^{\phi}\frac{\partial \eta}{\partial r}\right]$$

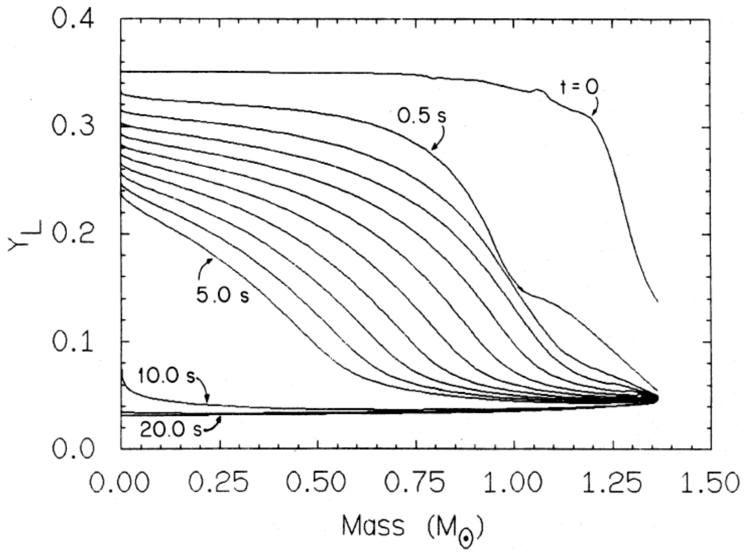
Fully Implicit Transport, Predictor-Corrector between transport and structure modules
(Similar to Burrows and Lattimer '86, Pons et al. '99)

$$D_n = \int_0^\infty dx\, x^n D(xT) f_0(xT)(1 - f_0(xT))$$

$$D(\omega) = (j_a + 1/\lambda_a + 1/\lambda_s^*)^{-1}$$

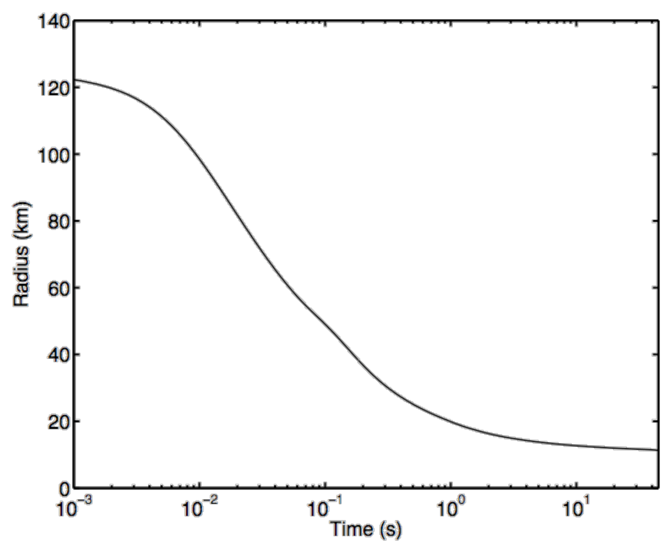
# Modeling PNS Evolution

Deleptonization:

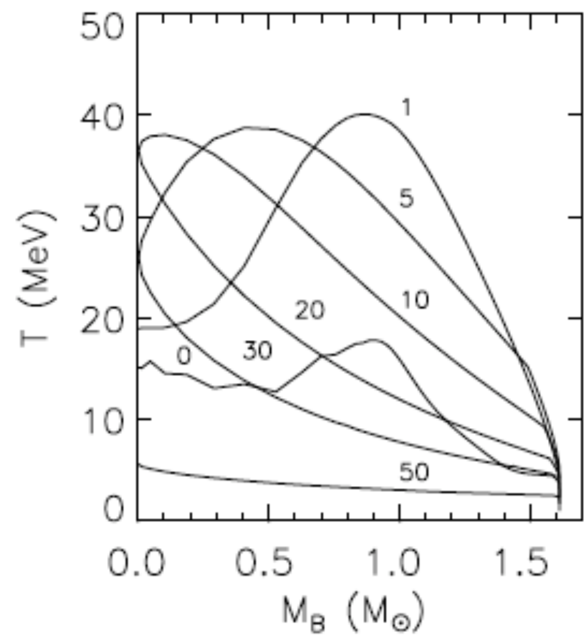



From Keil and Janka '95

Contraction:




Cooling:

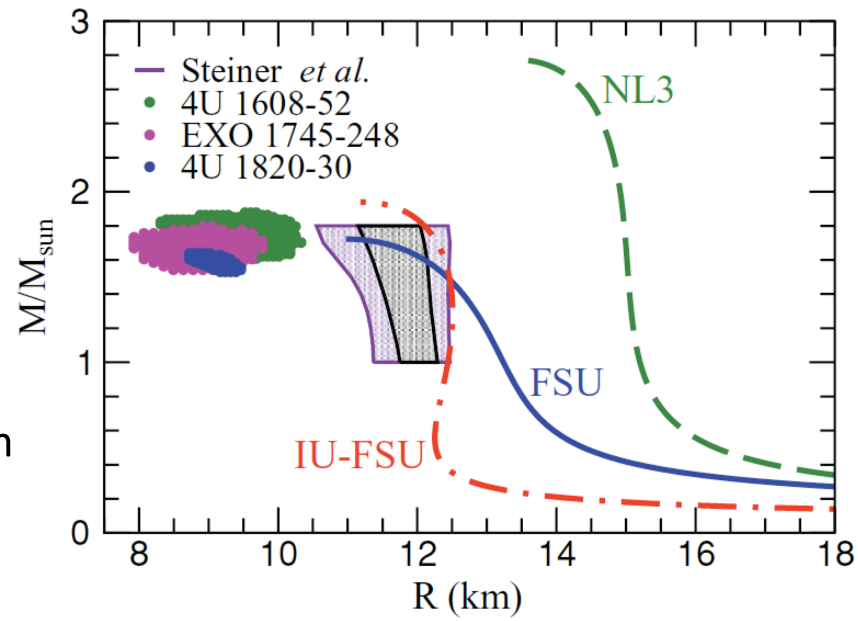



From Pons et al. '99

# Input Physics:
## Equation of State

$$\begin{aligned}\mathscr{L}_{\rm int} = \bar{\psi}\left[g_{\rm s}\phi - \left(g_{\rm v}V_\mu + \frac{g_\rho}{2}\boldsymbol{\tau}\cdot\mathbf{b}_\mu + \frac{e}{2}(1+\tau_3)A_\mu\right)\gamma^\mu\right]\psi \\ - \frac{\kappa}{3!}(g_{\rm s}\phi)^3 - \frac{\lambda}{4!}(g_{\rm s}\phi)^4 + \frac{\zeta}{4!}g_{\rm v}^4(V_\mu V^\mu)^2 \\ + \Lambda_{\rm v} g_\rho^2 \mathbf{b}_\mu\cdot\mathbf{b}^\mu g_{\rm v}^2 V_\nu V^\nu.\end{aligned}$$

An QHD mean field equation of state for uniform matter is used in our PNS simulations. We have been recently working with two parameter sets that have been fit to the known properties of bulk nuclear matter, GM3 and IU-FSU. Both give results which are reasonably consistent with current estimates of masses and radii of neutron stars. The presence of the non-linear vector/iso-vector coupling allows the high density symmetry energy to be tuned.




| Model | $\rho_0$(fm$^{-3}$) | $\varepsilon_0$ (MeV) | $K_0$ (MeV) | $J$ (MeV) | $L$ (MeV) |
|---|---|---|---|---|---|
| NL3 | 0.148 | −16.24 | 271.5 | 37.29 | 118.2 |
| FSU | 0.148 | −16.30 | 230.0 | 32.59 | 60.5 |
| IU-FSU | 0.155 | −16.40 | 231.2 | 31.30 | 47.2 |

From Fattoyev, et al. 2010

# Input Physics:
## Neutrino Opacities

$$\frac{1}{V}\frac{d^3\sigma}{d^2\Omega_3 dE_3} = -\frac{G_F^2}{128\pi^2}\frac{E_3}{E_1}\left[1-\exp\left(\frac{-q_0-(\mu_2-\mu_4)}{T}\right)\right]^{-1}$$
$$\times(1-f_3(E_3))\mathrm{Im}(L^{\alpha\beta}\Pi^R_{\alpha\beta}), \qquad (45$$

Calculated based on the underlying EoS, either in the MF approximation or MF +RPA.

Absorption Reactions:

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

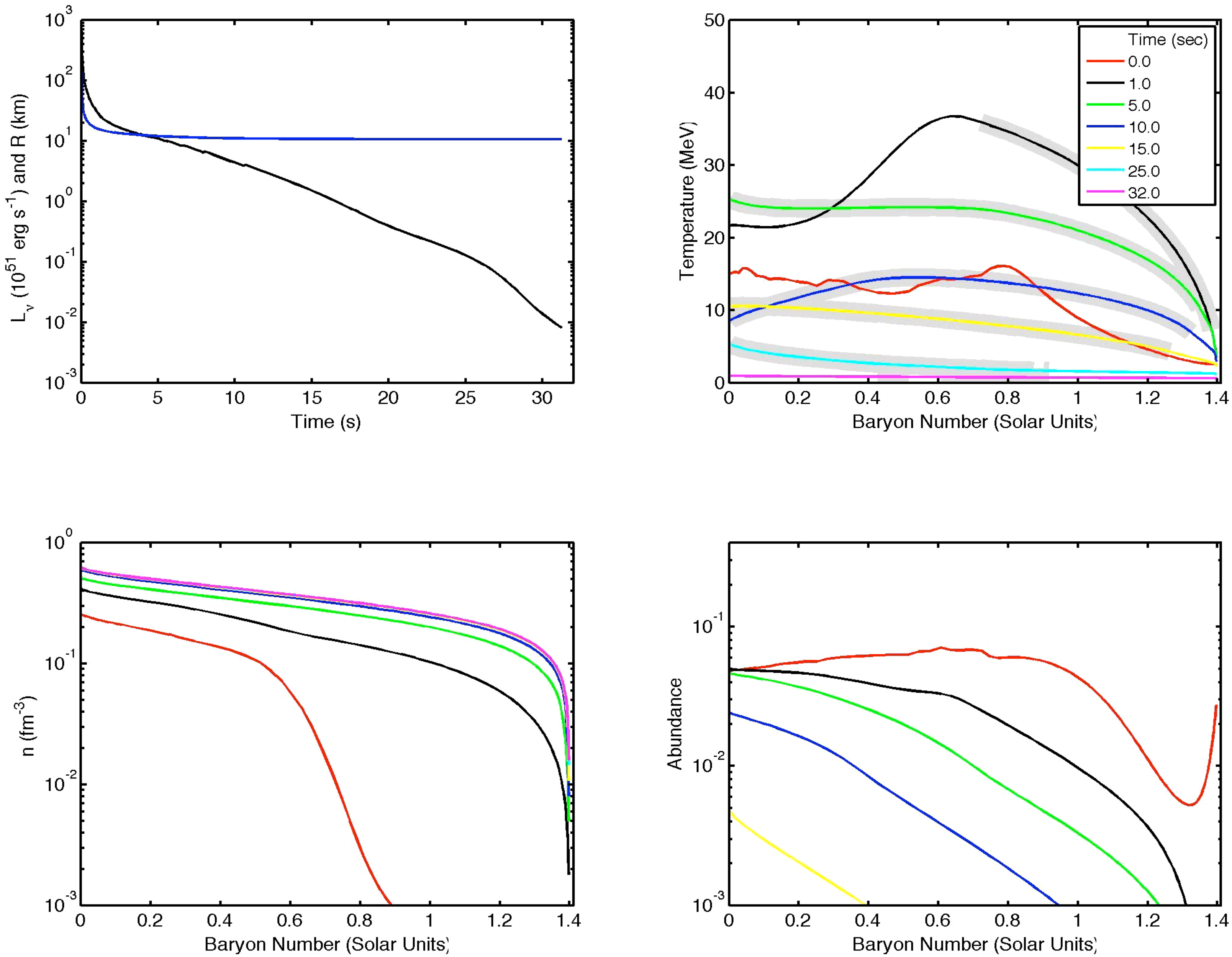
Scattering Reactions:

- $\nu + e \leftrightarrow \nu + e$
- $\nu + N \leftrightarrow \nu + N$

"Rosseland Mean" Opacities:

$$D_n = \int_0^\infty dx x^n D(xT) f_0(xT)(1 - f_0(xT))$$

$$D(\omega) = (j_a + 1/\lambda_a + 1/\lambda_s^*)^{-1}$$



$L_\nu$ ($10^{51}$ erg s$^{-1}$) and R (km)
Time (s)
Temperature (MeV)
Time (sec)
0.0
1.0
5.0
10.0
15.0
25.0
32.0
Baryon Number (Solar Units)
n (fm$^{-3}$)
Baryon Number (Solar Units)
Abundance
Baryon Number (Solar Units)

# What Affects Late Time Cooling?

- Neutrino Interaction Rates
  (see Keil et al. '95, Reddy et al. '99, Burrows & Sawyer '98)
- Convection
  (Epstein 1979, Keil et al. '96)

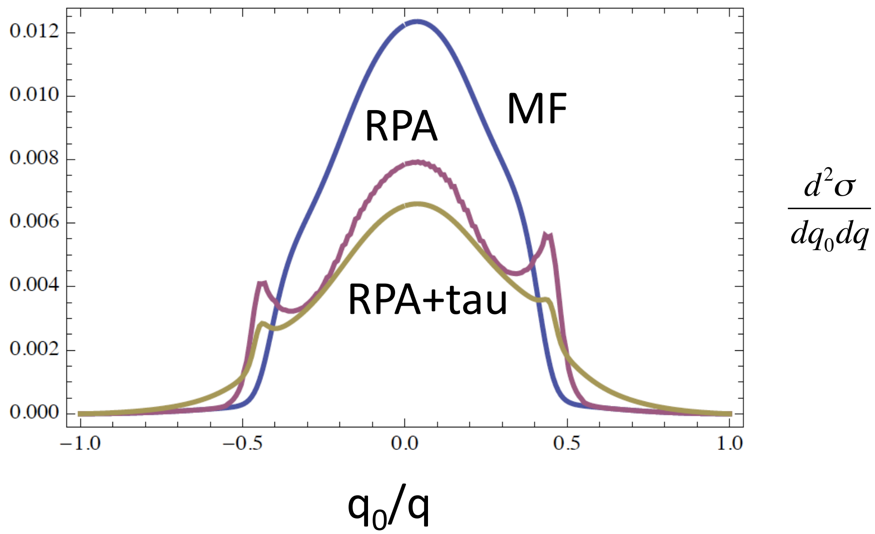
Effect $\tau_{KH}$

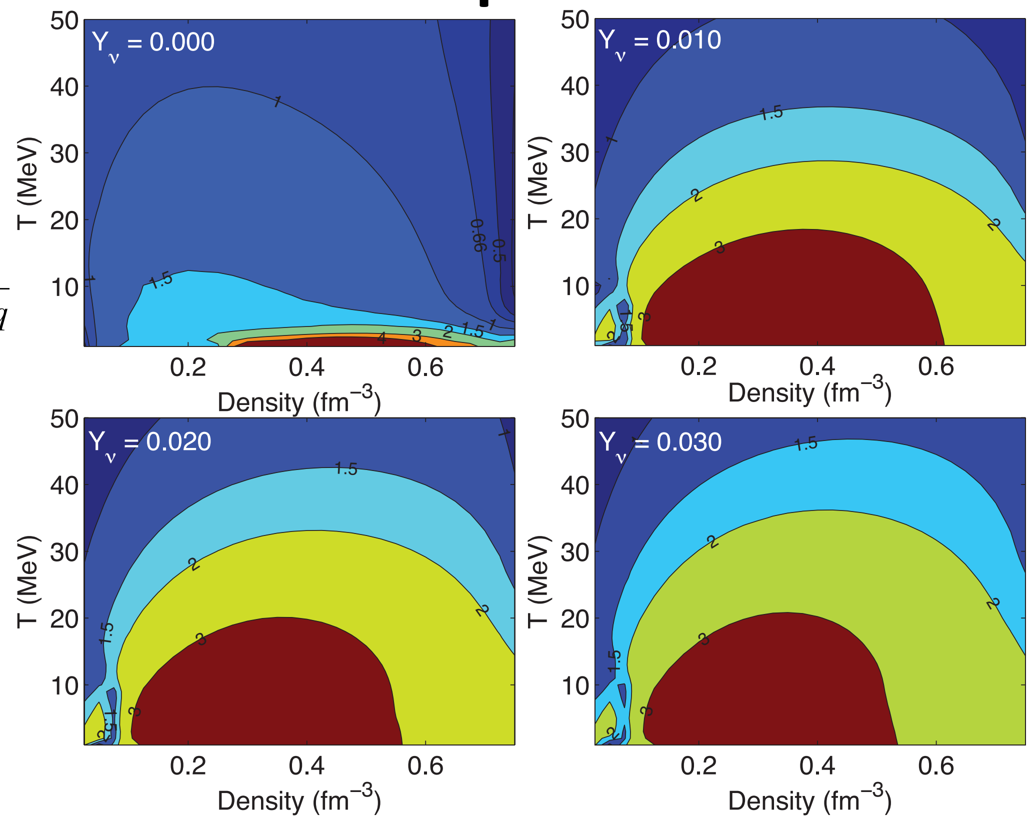
- Equation of State
  - Presence of Strangeness and Hyperons
    (see Pons et al. '99)
  - Presence of Phase Transition?
    (see Pons et al. '01a, '01b)
- Neutron Star Mass

Effect metastability and Black Hole Formation

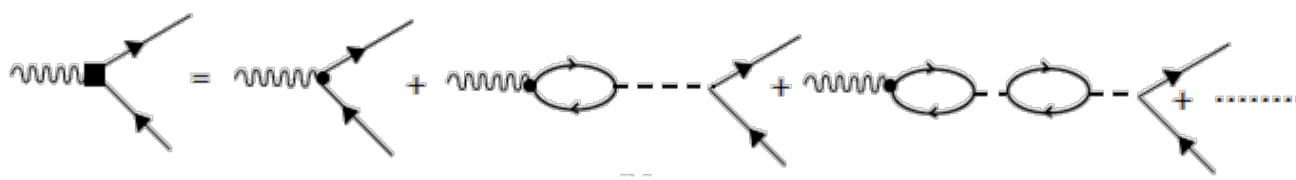
- Other Macroscopic Effects
  - Magnetic Fields
  - Rotation
  - Fallback
  - Initial Conditions

# Variations in Neutrino Opacities



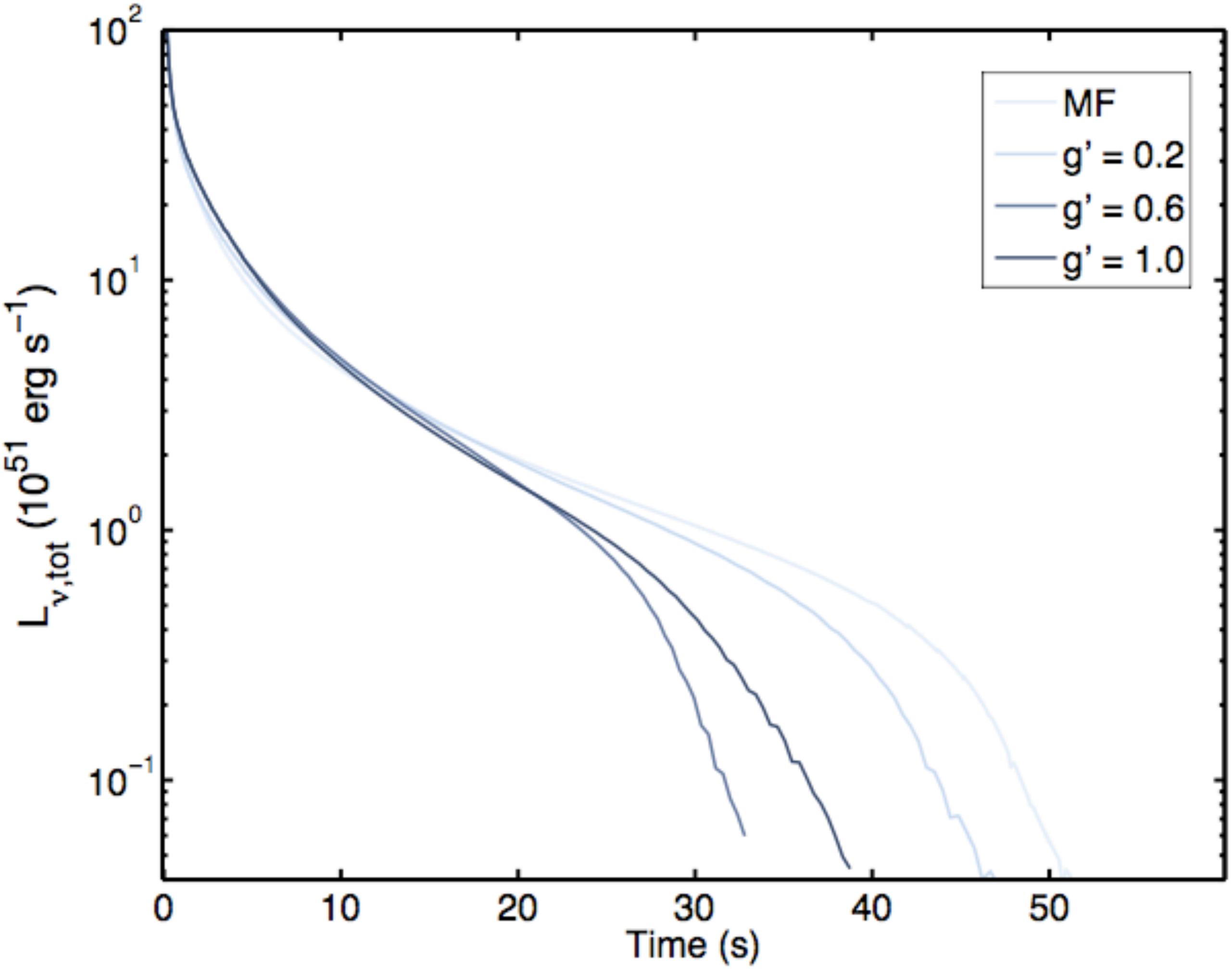

Correlations through the RPA:



Short range repulsive interaction in the axial channel introduced through:

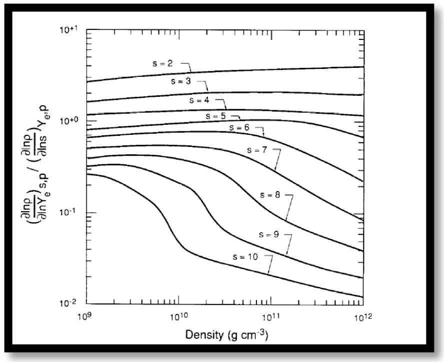
$$\frac{q_\mu q_\nu}{q_m u^2 - m_\pi^2 + i\epsilon} \rightarrow \frac{q_\mu q_\nu}{q_m u^2 - m_\pi^2 + i\epsilon} - g' g_{\mu\nu}$$

# Variations in the Opacities

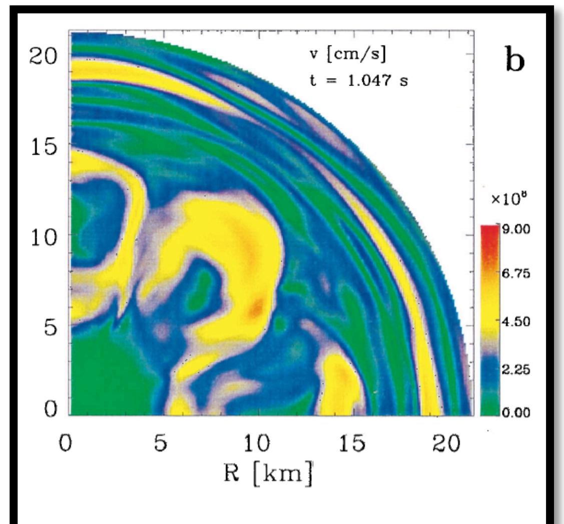


# Convection in PNS Evolution

- After shock passage, outer layers unstable by Ledoux Criterion (Epstein '79)

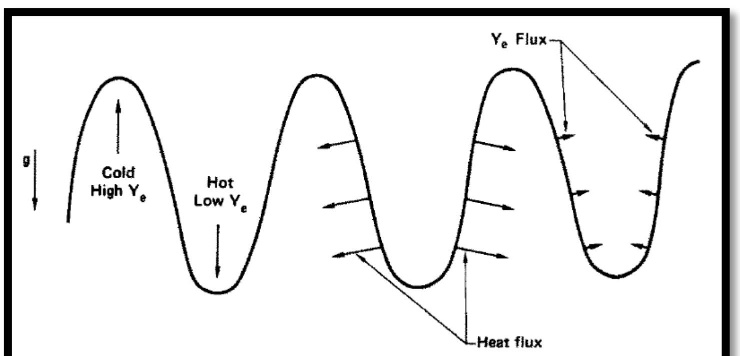



- Multi-D simulations show significant convection at early times (Keil et al. '96, Mezzacapa et al. '96, Dessart et al. '06)




from Keil et al. '96

- Possibility of secular instabilities (not seen in multi-D models, leave for a later time) (Wilson & Mayle '88, Bruenn & Dineva '96, Miralles et al. 2000 )




From Wilson et al. '88

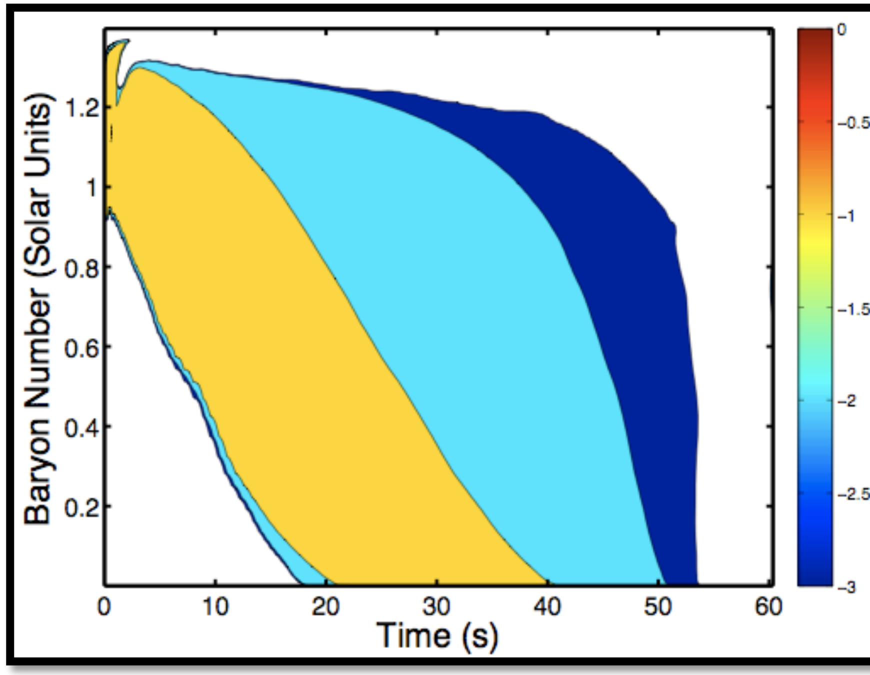
# Time Dependent Mixing Length Theory

GR Gravitational Acceleration and Pressure Scale Height:

$$g = \frac{G_N}{r^2}\left(m + 4\pi r^3 P/c_L^2\right)$$
$$H_p = \frac{P}{g(\rho + P)/c_L^2}$$

Convective "Diffusion" Coefficient from MLT:

$$D_C = \frac{V_c H_p}{3} = H_p^2 \sqrt{\frac{g}{2n_B}\left(\frac{dn_B}{dr} - \frac{dP}{dr}\left(\frac{\partial n_B}{\partial P}\right)_{s,Y_e,Y_\nu}\right)}$$




Convectively Unstable Regions of PNS

Convective Fluxes as Implemented:

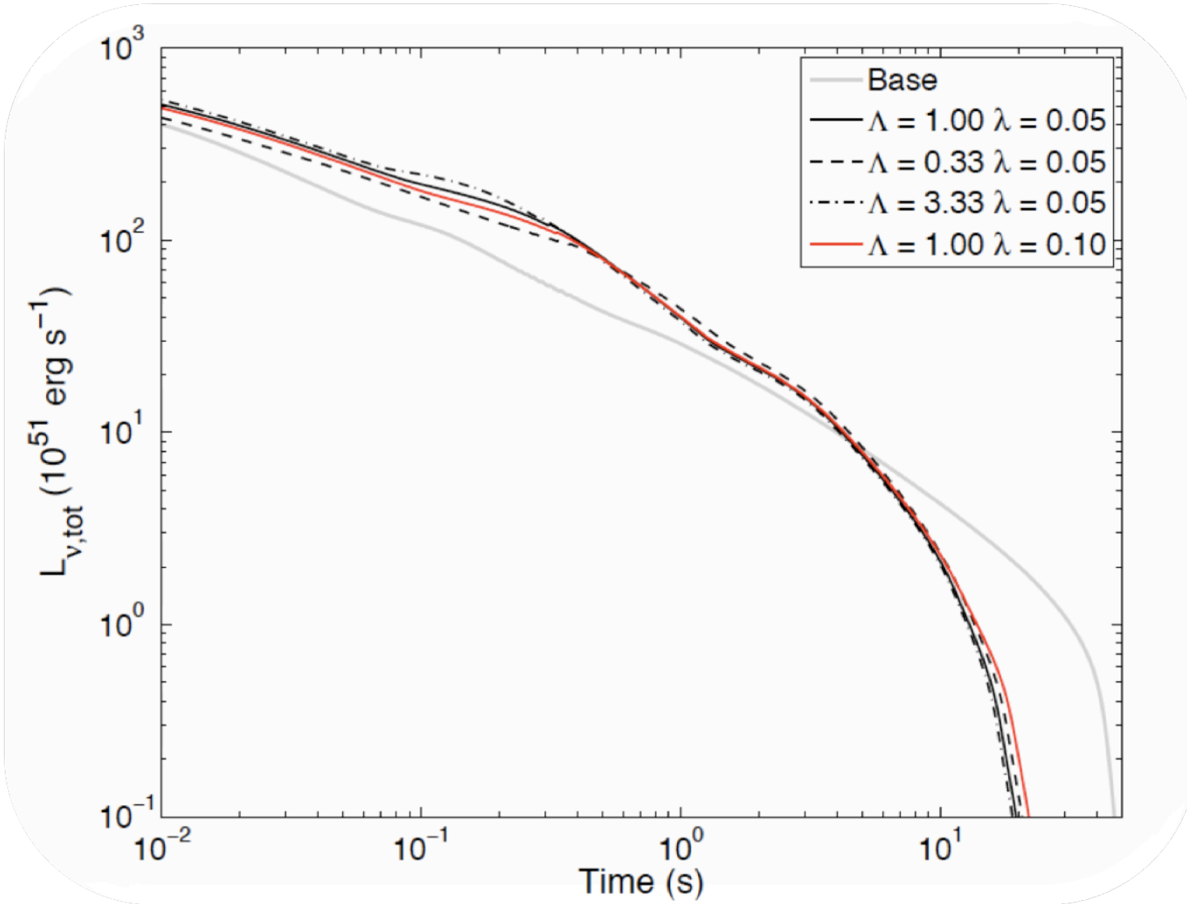
(similar to Wilson & Mayle '88)

$$H_C = -n_b D_C\ \partial e/\partial r$$
$$F_\nu = -n_b D_C\ \partial Y_\nu/\partial r$$
$$F_e = -n_b D_C\ \partial Y_e/\partial r$$

Ledoux criterion not quite accurate, should use growth rates for double diffusive instabilities. Generalize mixing length theory to:

$$D_C = \frac{H_p^2\omega}{3}$$

# How Good is TDMLT?

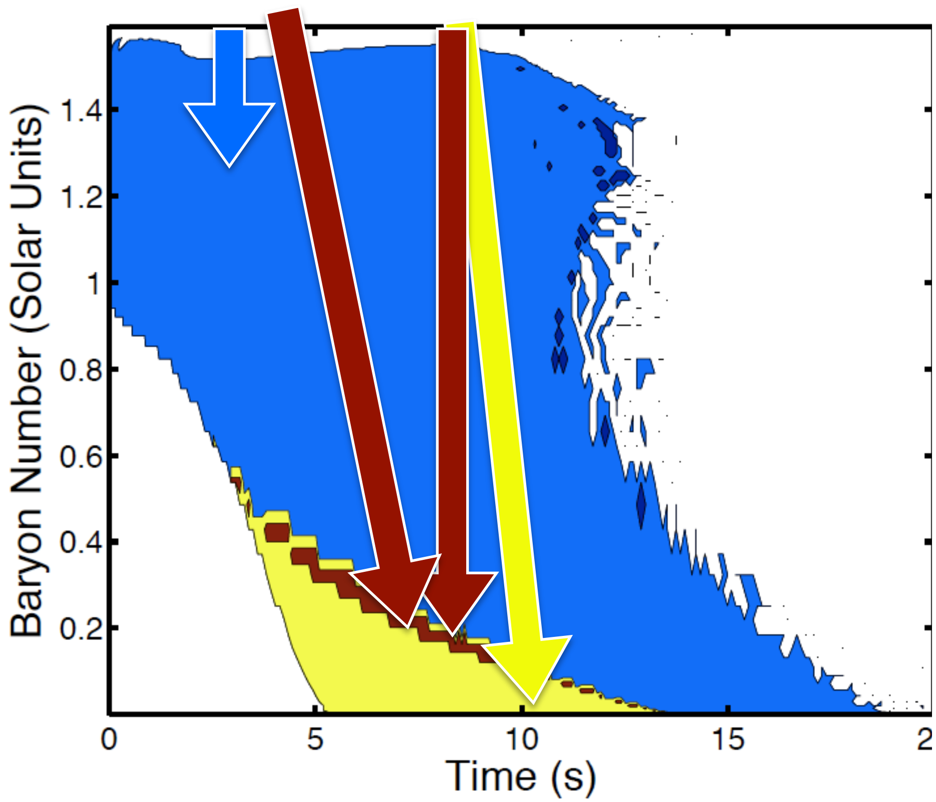



Luckily, the results are fairly insensitive to choice of the mixing length. This is because the PNS is convectively efficient throughout its evolution, which is consistent with multi-d results found in Buras et al. '06.

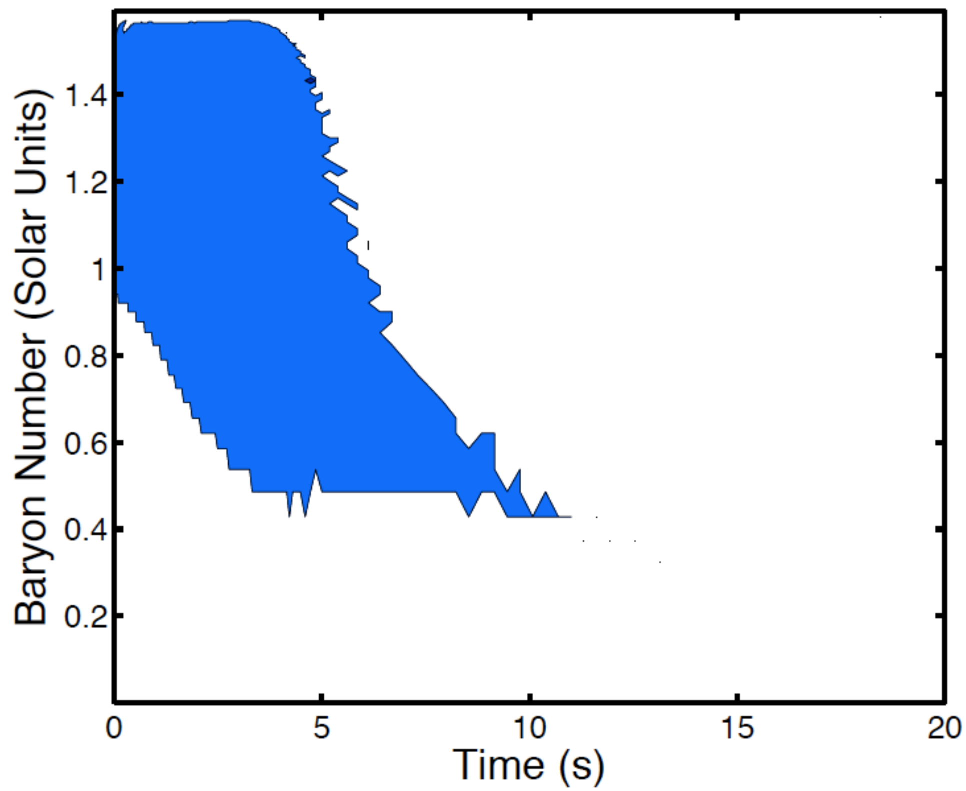
# Convective Evolution for two EoSs

Ledoux Criterion:

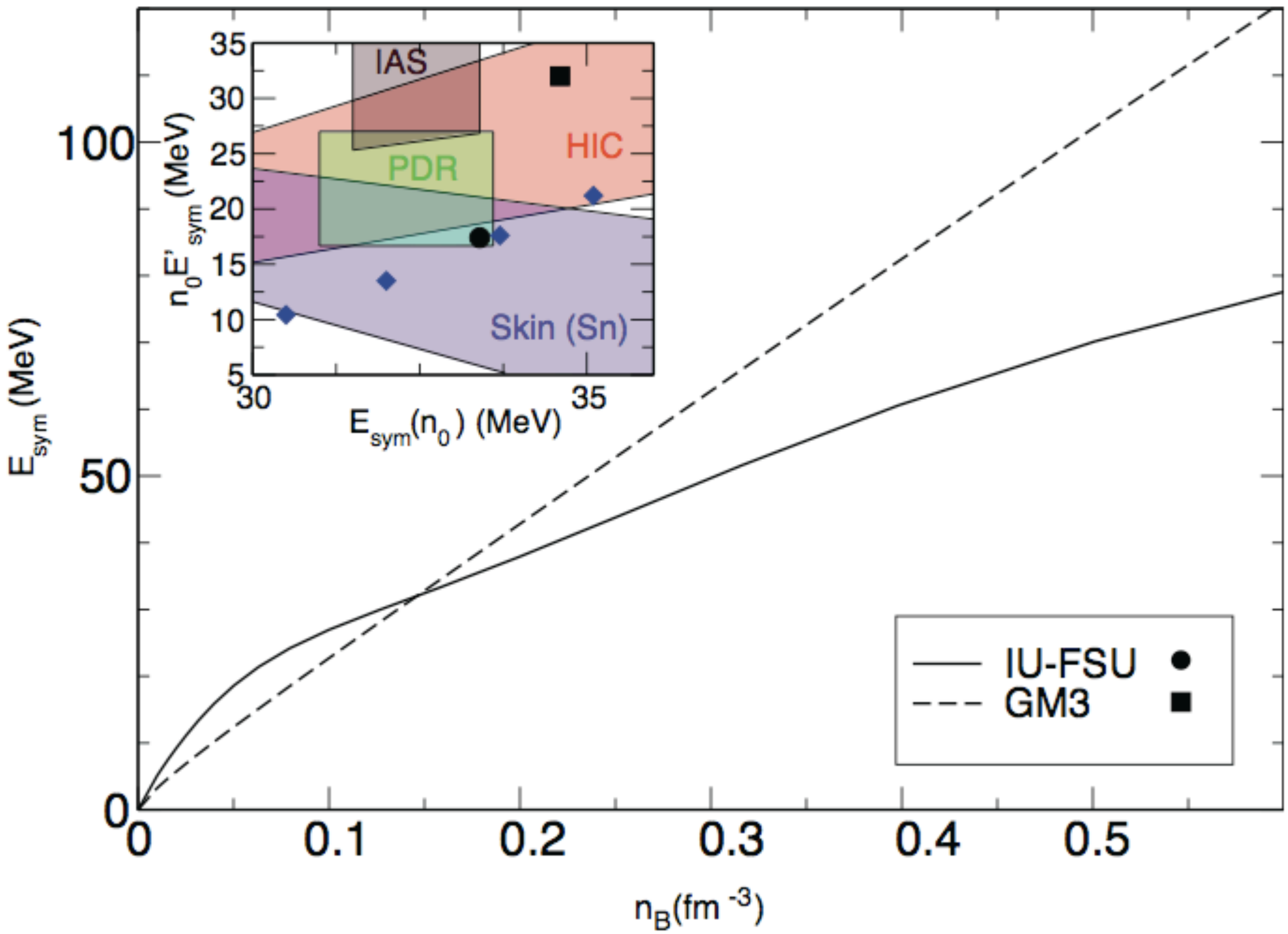
$$-\left(\frac{\partial p}{\partial s}\right)_{n,Y_L}\frac{ds}{dr}-\left(\frac{\partial p}{\partial Y_L}\right)_{n,s}\frac{dY_L}{dr}>0$$




IU-FSU

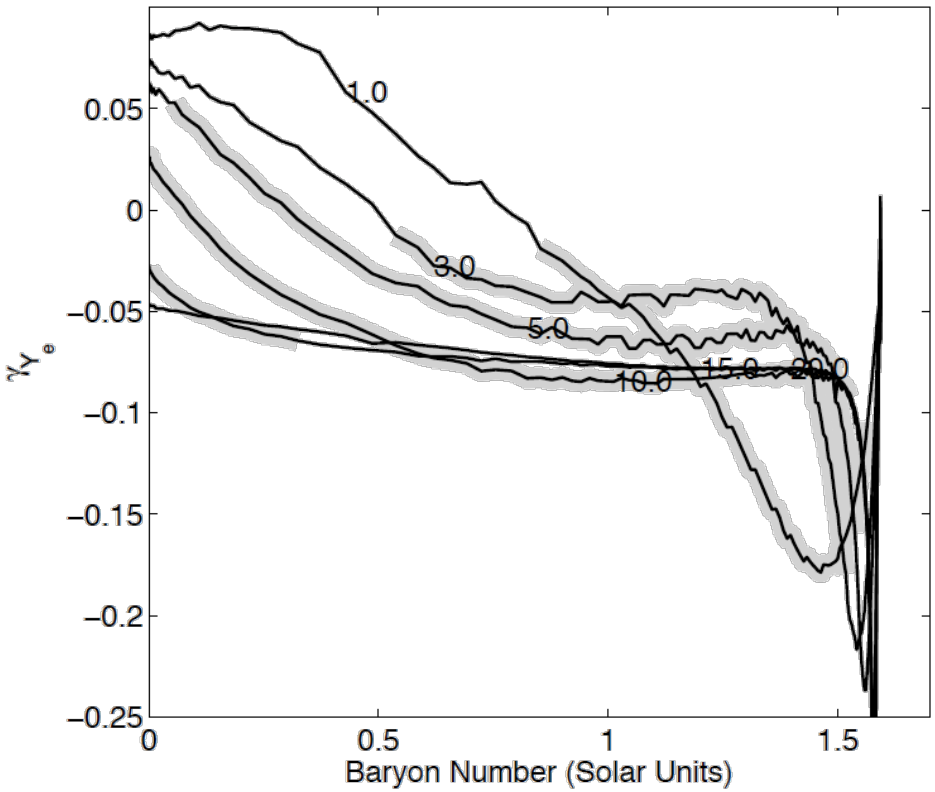



GM3

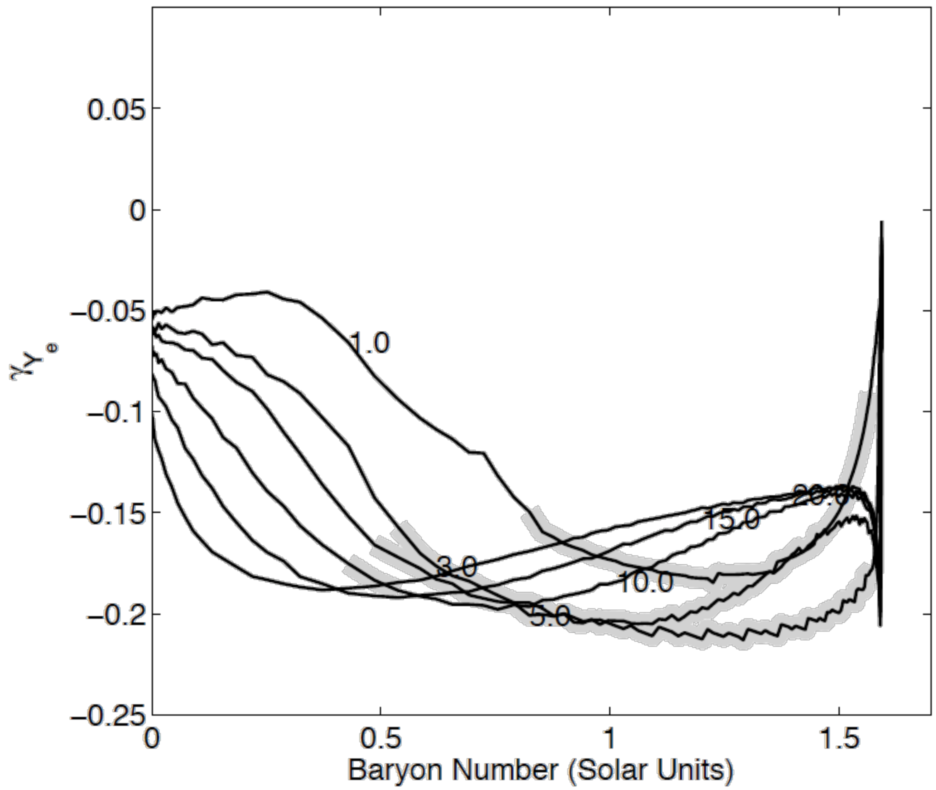



$$E(n_B, x_p) = E(n_B, x_p = 1/2) + E_{\rm sym}(n_B)\delta^2 + \cdots$$

$$\delta = (1 - 2x_p)$$

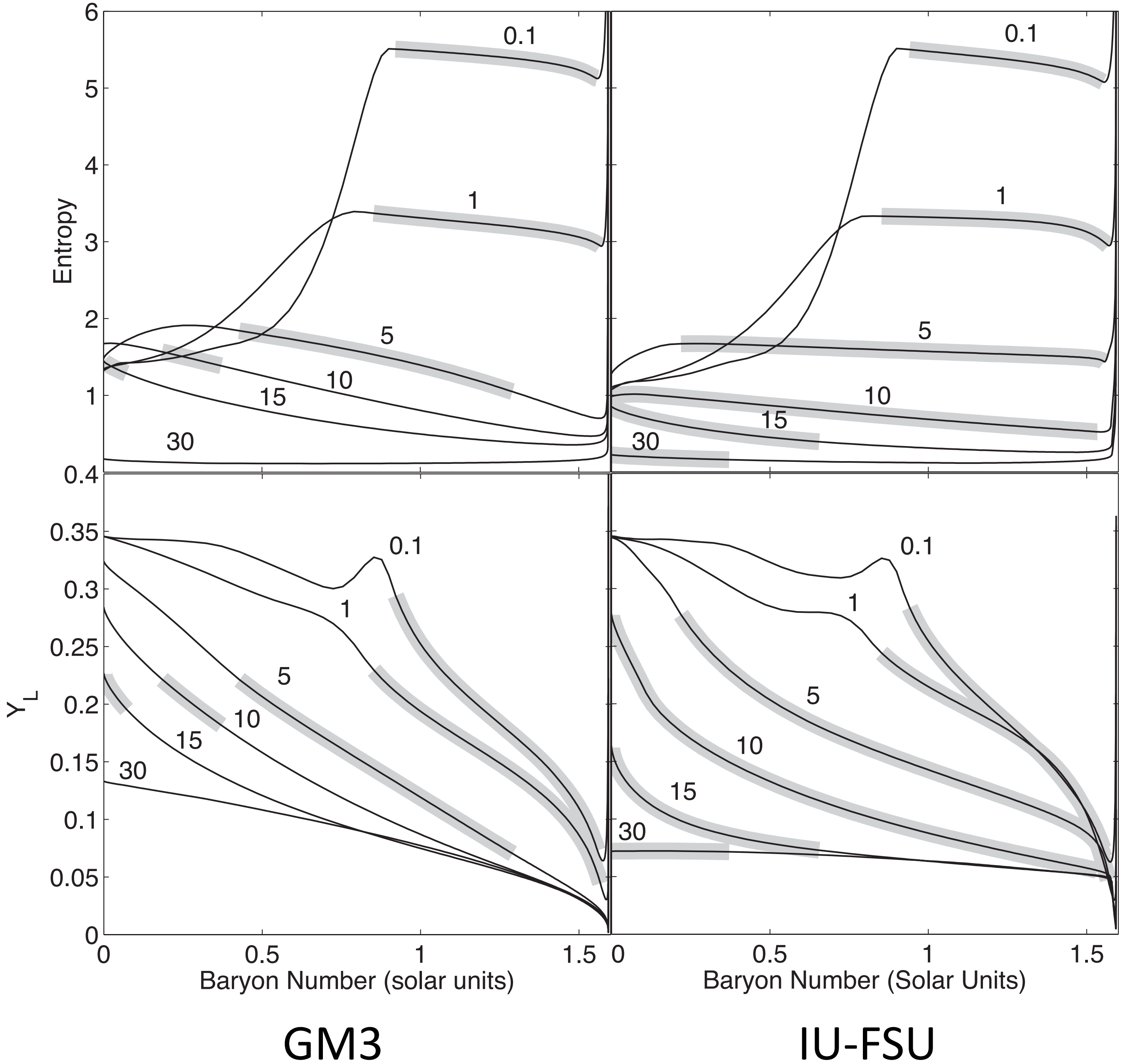



IU-FSU

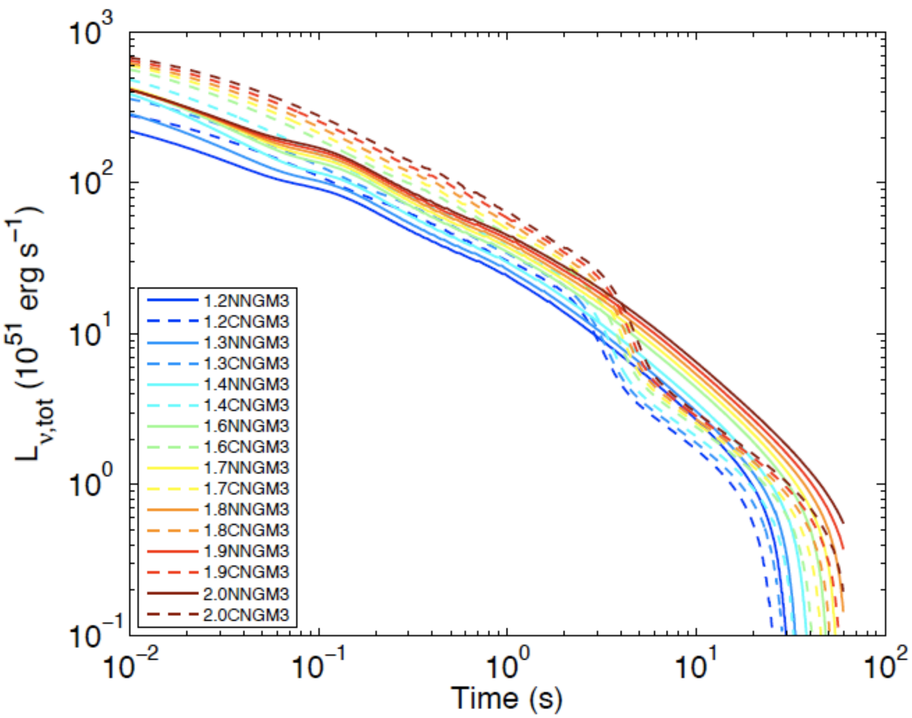



GM3

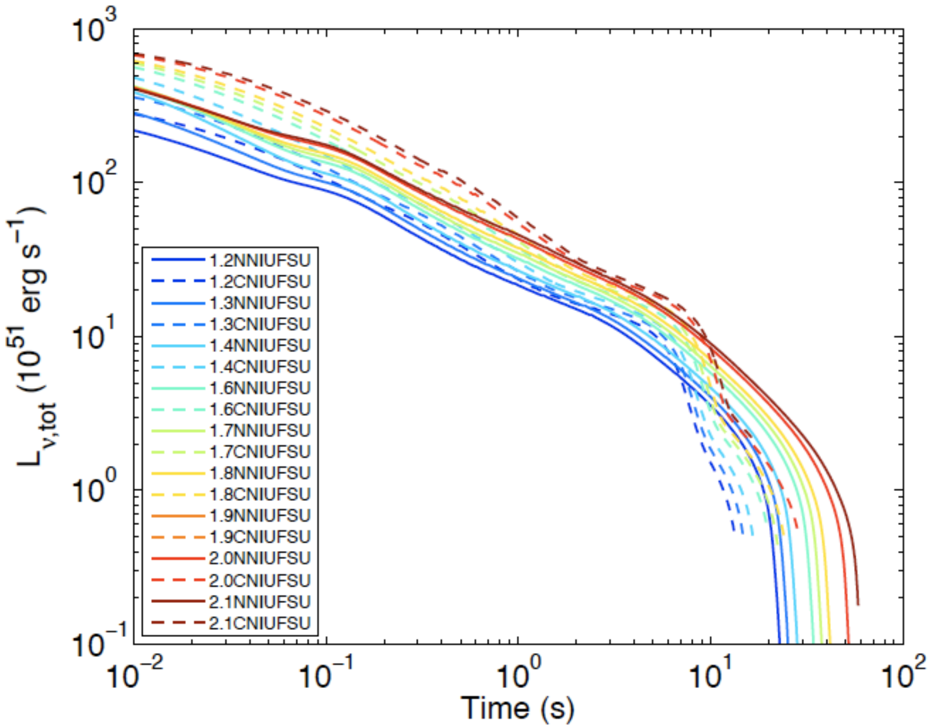
$$\left(\frac{\partial P}{\partial Y_L}\right)_{n_B} \simeq n_B^{4/3} Y_e^{1/3} - 4 n_B^2 E'_{\rm sym}(1-2Y_e)$$


Entropy
Y_L
Baryon Number (solar units)
Baryon Number (Solar Units)
0.1
1
5
10
15
30
GM3
IU-FSU

# Total Neutrino Luminosities

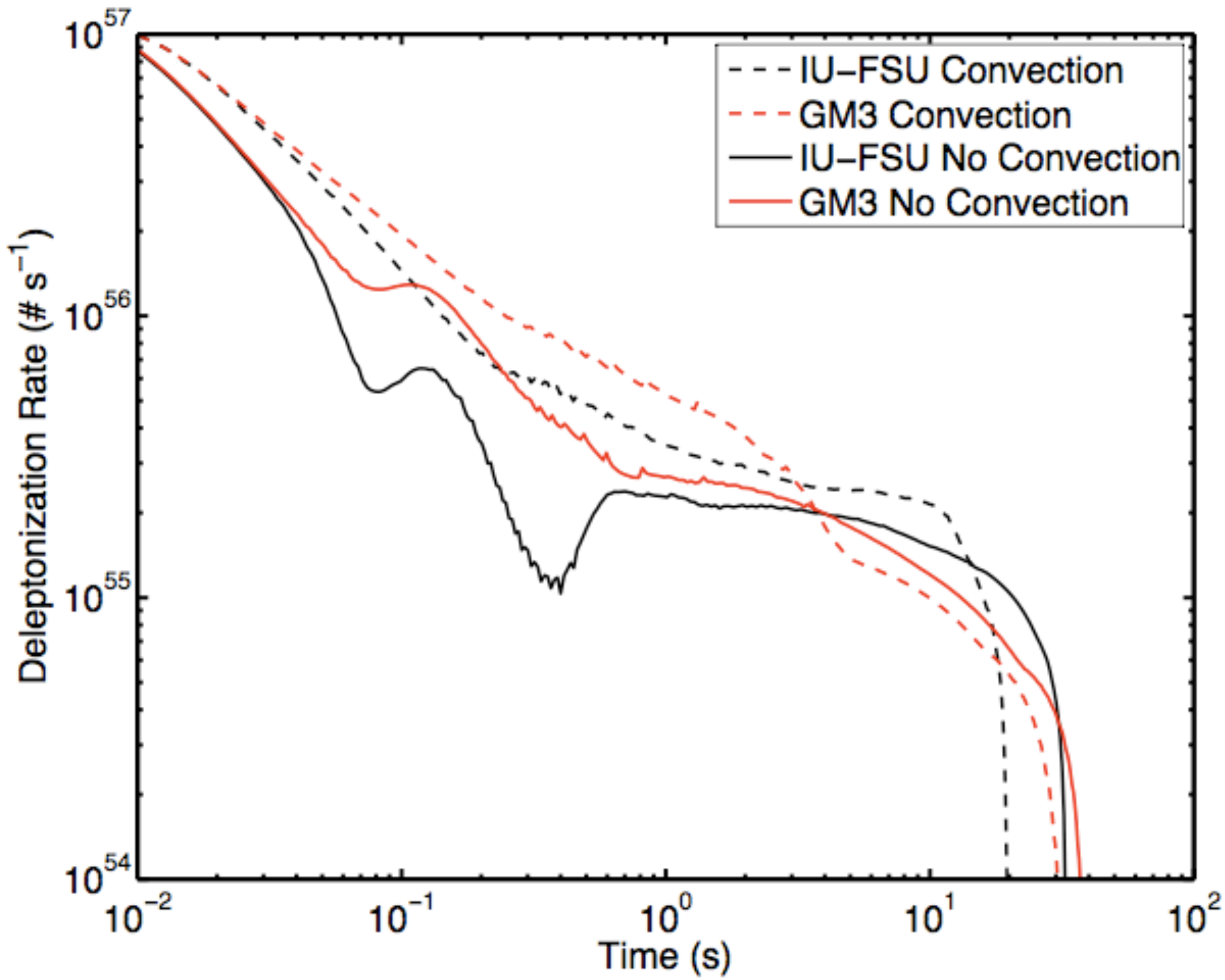


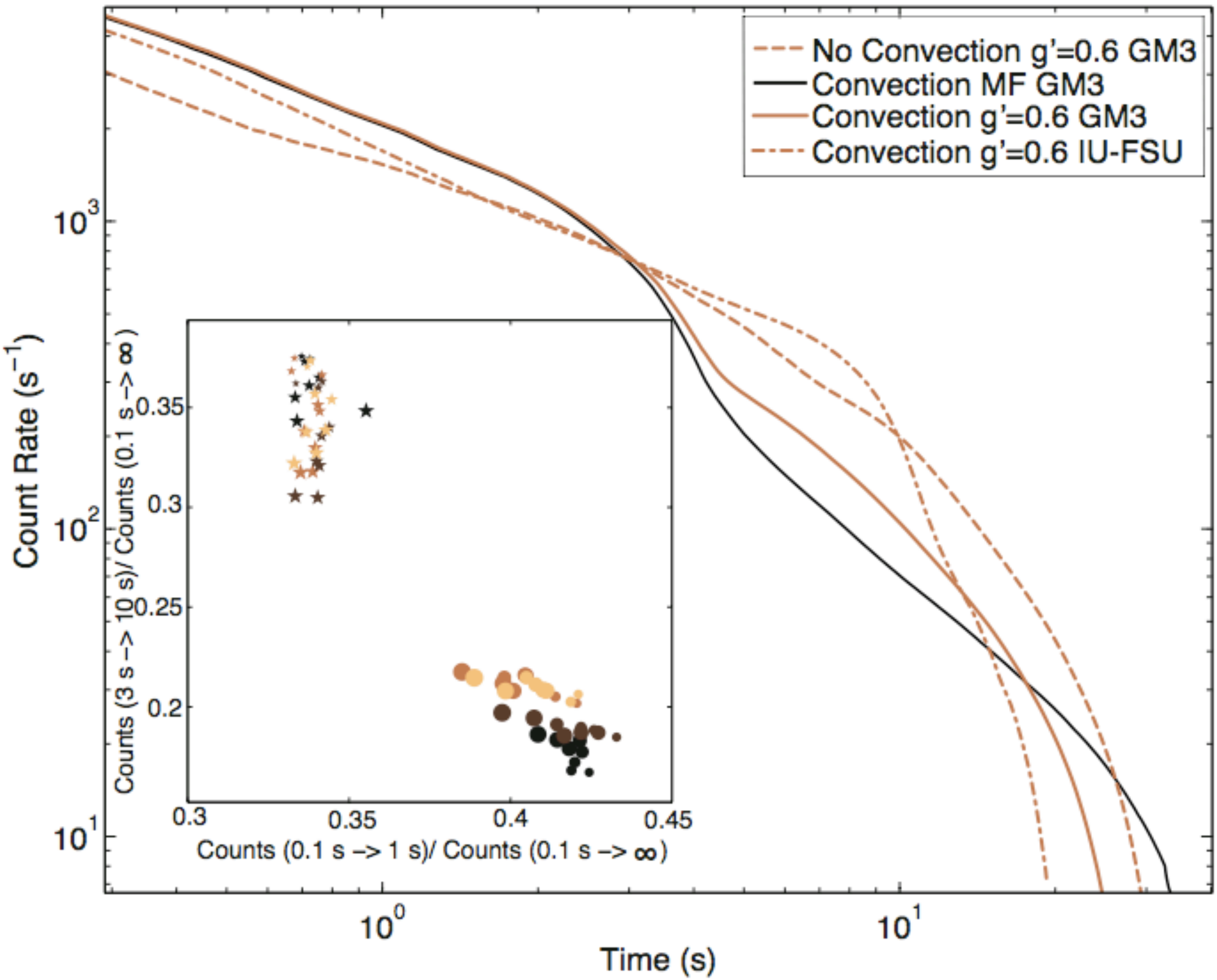

GM3




IU-FSU

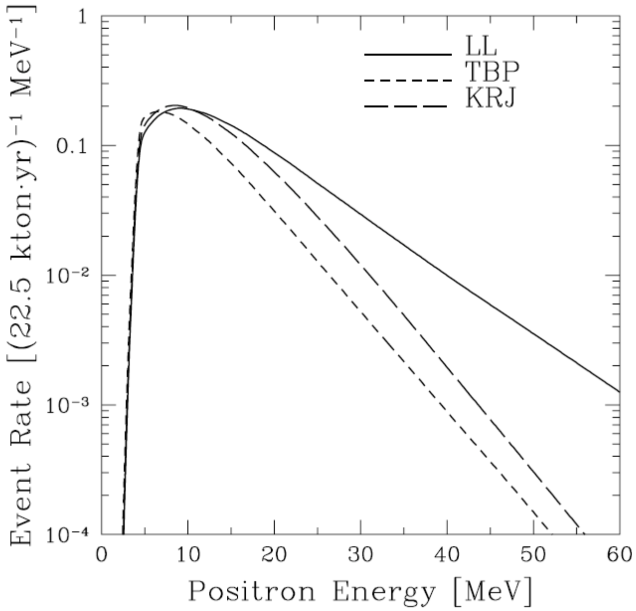
# De-leptonization Rates



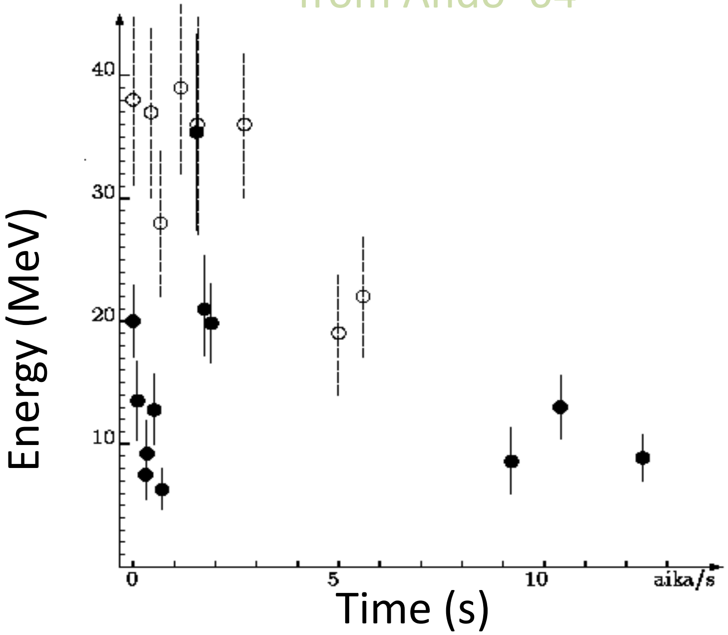


No Convection g'=0.6 GM3
Convection MF GM3
Convection g'=0.6 GM3
Convection g'=0.6 IU-FSU
Count Rate (s$^{-1}$)
Time (s)
$10^3$
$10^2$
$10^1$
$10^0$
$10^1$
Counts (3 s -> 10 s)/ Counts (0.1 s -> ∞)
Counts (0.1 s -> 1 s)/ Counts (0.1 s -> ∞)
0.35
0.3
0.25
0.2
0.3
0.35
0.4
0.45

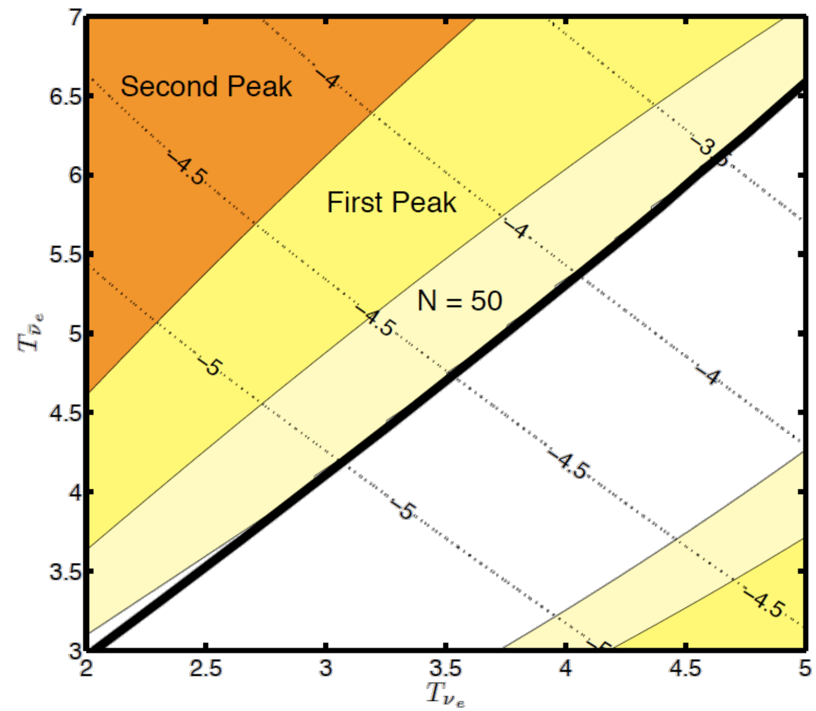
# What can accurate spectra tell us?




from Ando '04

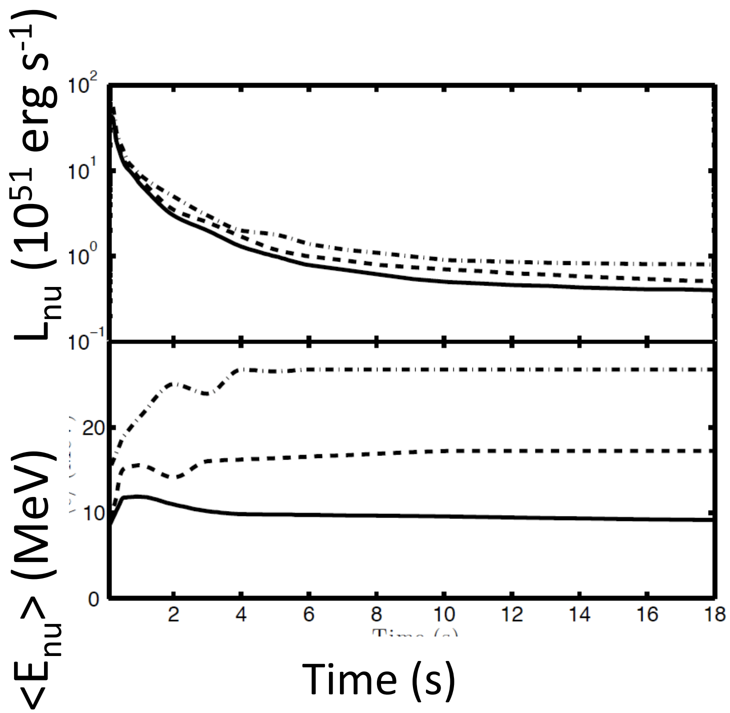


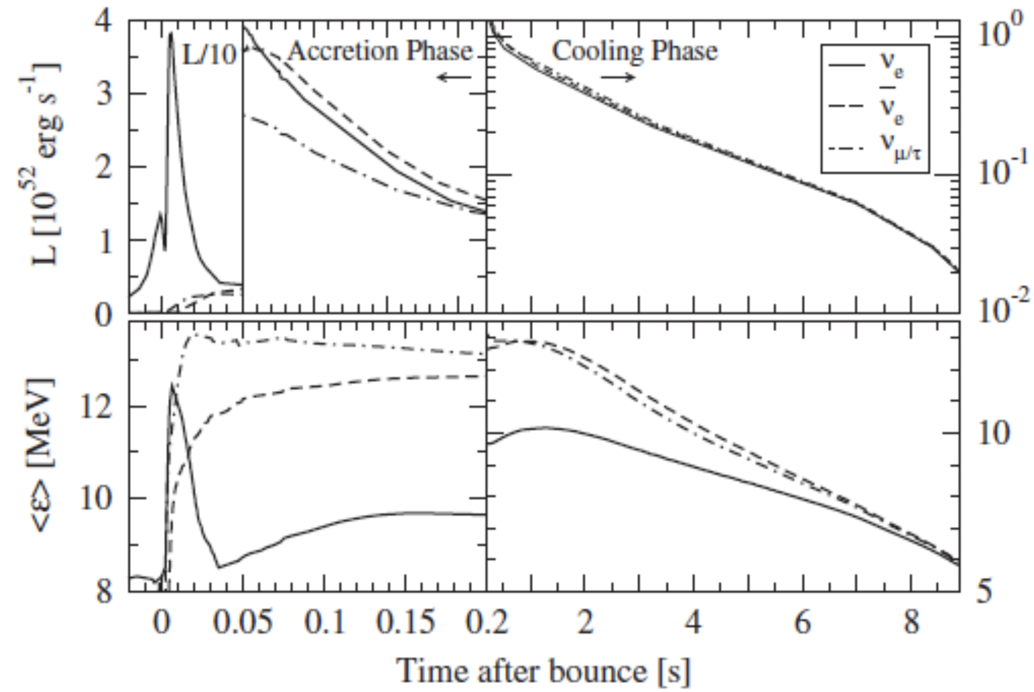

See Bionta et al. '87 and Hirata et al. '87




from Roberts et al. '10

# Calculations of Late Time Spectra

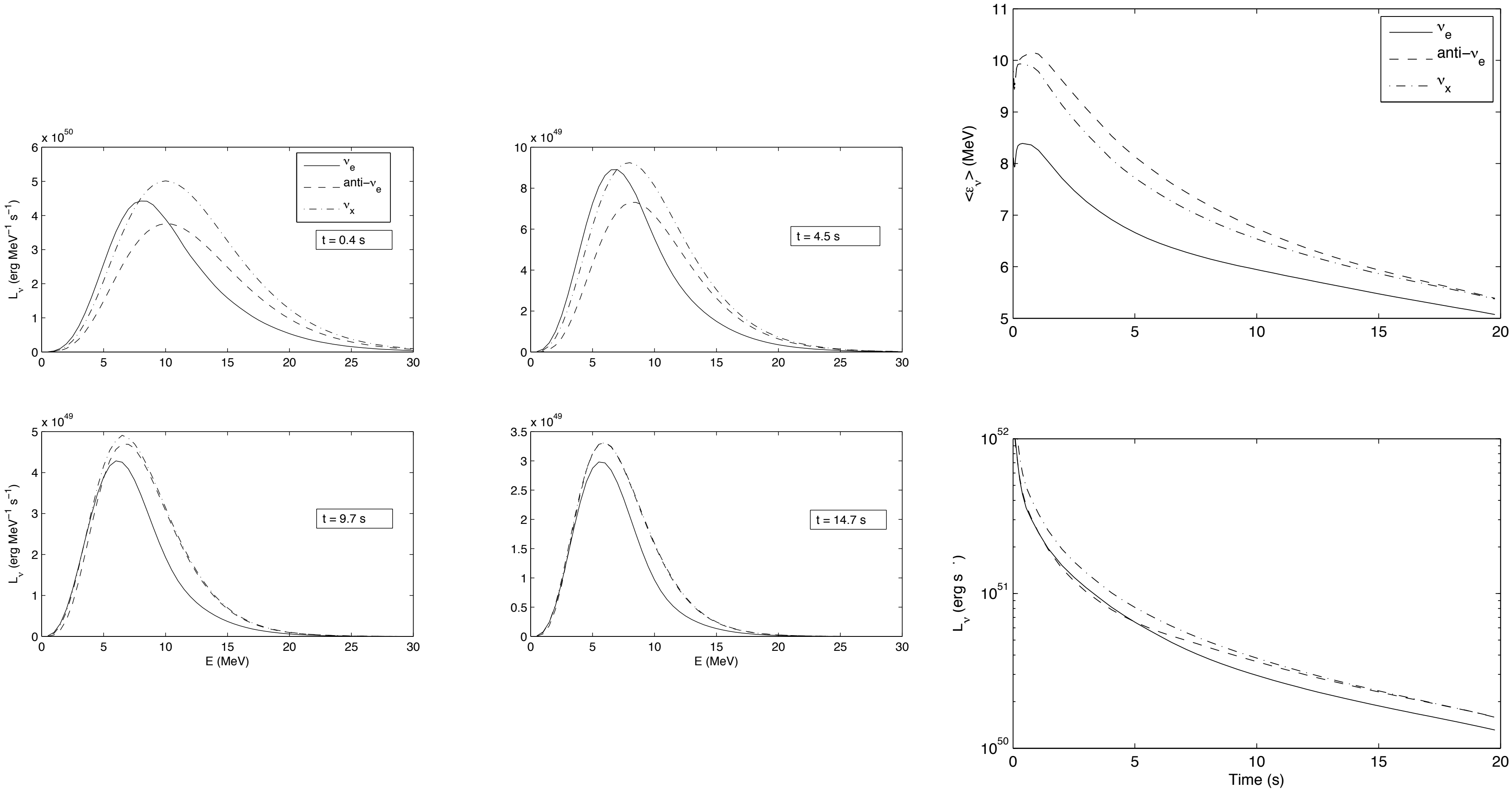



Woosley, Wilson, et al. '94

Huedepohl, et al. '94

# Spectral Evolution in Our Models



# Conclusions

- Convection significantly decreases PNS cooling timescale
- Very efficient, not so sensitive to mixing length
- Driven by competition between Leptonic and Entropy gradients
- High density behavior of symmetry energy significantly effects the time over which convection operates
- Maybe can discern between the effects convection and correlations within the neutrino signal
- Important to nail down the spectral properties of neutrinos from this phase