SYMMETRY ENERGY IN ASTROPHYSICS

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Astrophysical Observation

Astro-structure, hydrodynamics, transport

$$\mathcal{E}[\rho_n(r), \rho_p(r), \nabla\rho_n(r), \nabla\rho_p(r); T]$$

$$\mathcal{H} = \frac{\nabla^2}{2M} + V_{\mathrm{NN}} + V_{\mathrm{NNN}} + \cdots$$

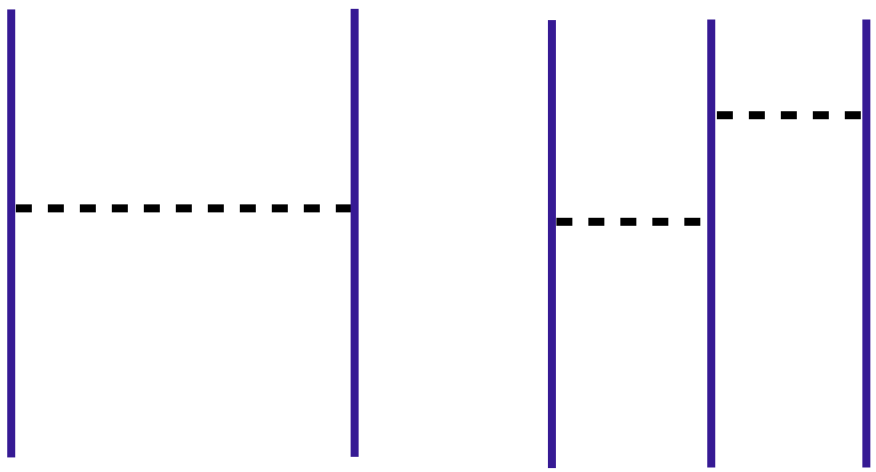
Nuclear Scattering and Structure Experiments

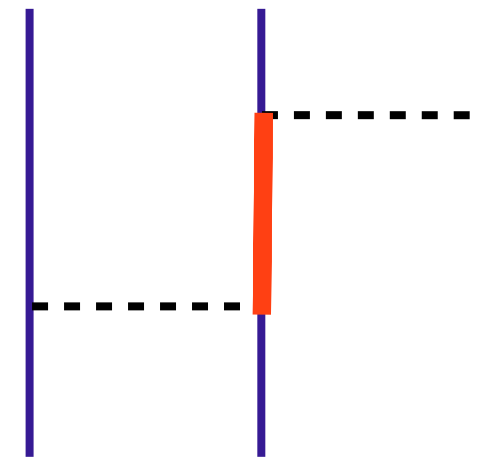
Phenomena sensitive to the symmetry energy:

- Neutron star radius
- Neutron star cooling
- Symmetry energy in Supernova

Nuclear Many Body Theory

$$H_{\text{nuclear}} = \frac{\nabla^2}{2M} + V_{\text{NN}} + V_{\text{NNN}} + \cdots$$





Phenomenological potentials (Argonne etc) tuned to fit scattering and light nuclei.

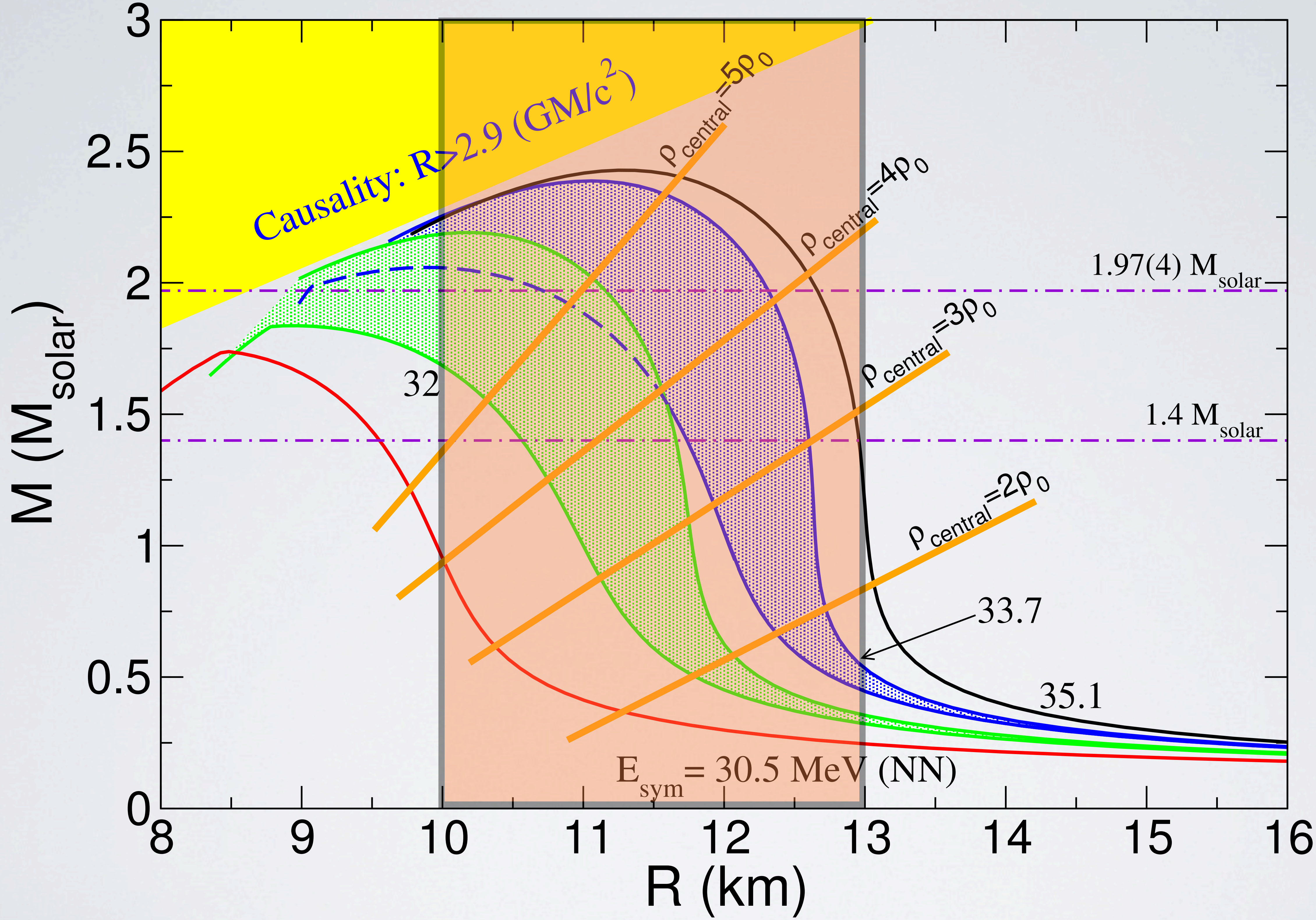
Chiral potentials and softer low energy potentials obtained using RG.

Computational Methods: Quantum Monte Carlo

Diagrammatic Methods

$$E(\rho_n, \rho_p)$$: Energy per particle

Neutron Star Radius and Symmetry Energy



INTERPRETING RADII

- Strong correlation between L and R_{NS} in most models of the neutron matter equation of state. Interesting connection to the 3-neutron force in ab intio calculations.

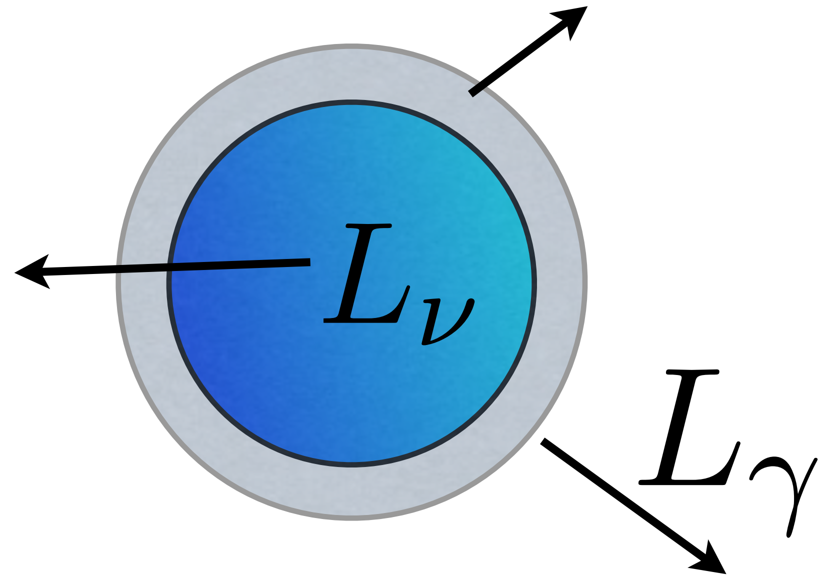
- Still much work needs to be done to understand the errors associated with the extrapolation to supra nuclear density. Chiral EFT 3n interactions will help in this regard.

- Astrophysical constraints of neutron stars have several systematic errors that need to be addressed.

Neutron Star Cooling

Crust cools by conduction

Isothermal core cools by neutrino emission



Surface photon emission dominates at late time t > 10^6 yrs

Basic neutrino reactions:

$$
\begin{aligned}
n &\rightarrow p + e^- + \bar{\nu}_e \\
e^- + p &\rightarrow n + \nu_e
\end{aligned}
$$

$$\dot{\epsilon}_\nu|_{\rho=\rho_o} \simeq 10^{25}\ T_9^6\ \frac{\text{ergs}}{\text{cm}^3\ \text{s}}$$

Fast: Direct URCA

$$
\begin{aligned}
n + n &\rightarrow n + p + e^- + \bar{\nu}_e \\
e^- + p + n &\rightarrow n + n + \nu_e
\end{aligned}
$$

$$\dot{\epsilon}_\nu|_{\rho=\rho_o} \simeq 10^{22}\ T_9^8\ \frac{\text{ergs}}{\text{cm}^3\ \text{s}}$$

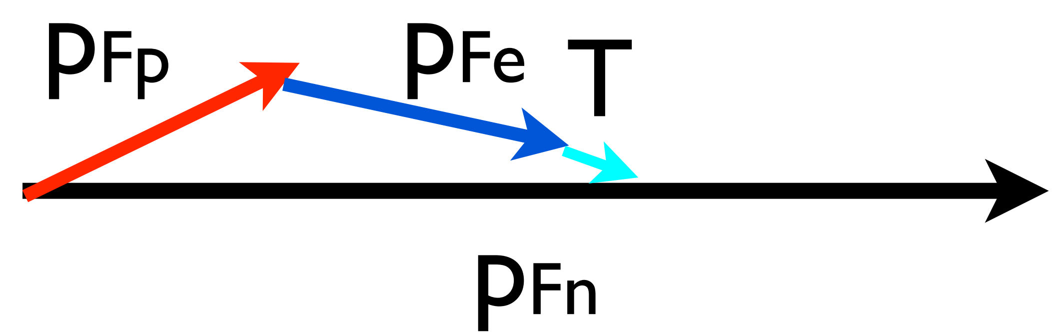
Slow: Modified URCA

Cooling and Symmetry Energy

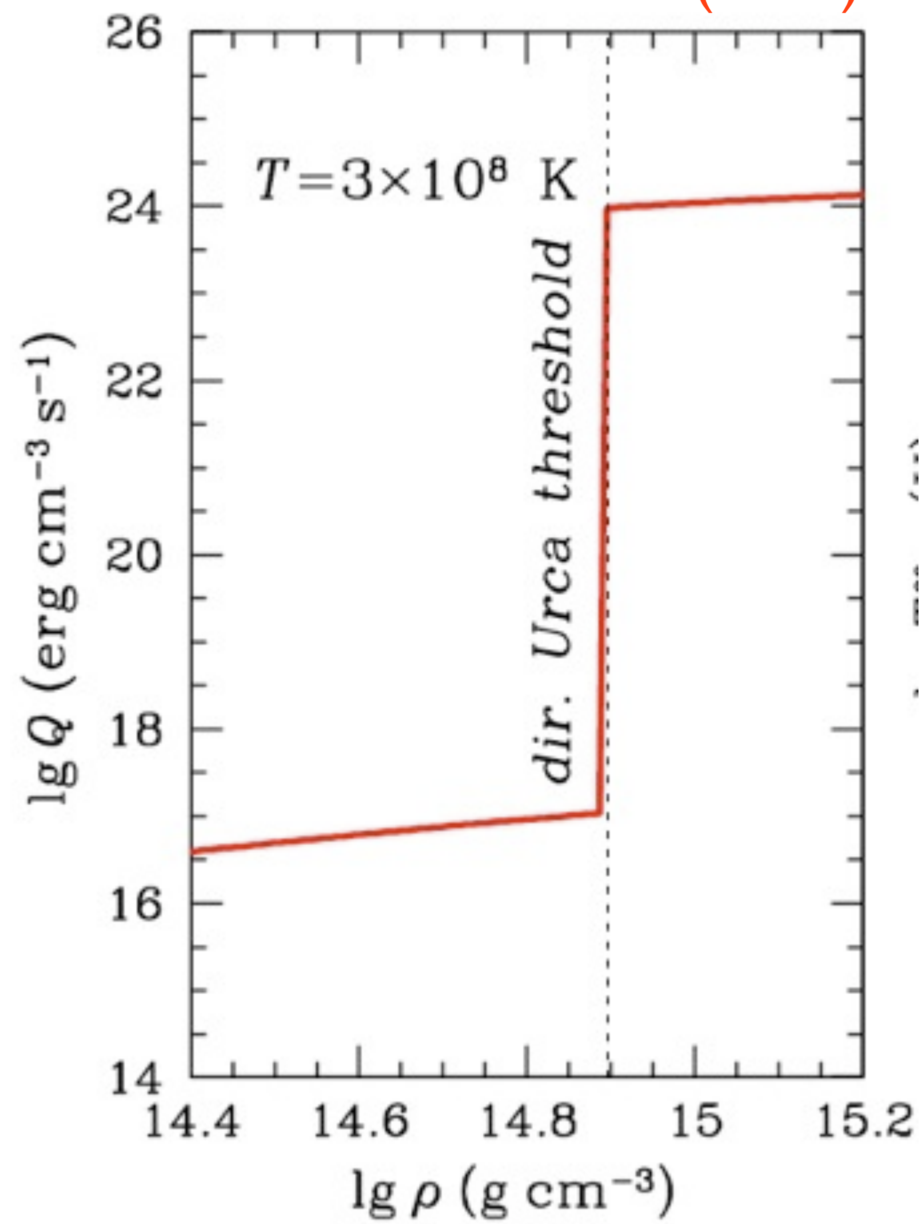
Neutron decay at the Fermi surface cannot conserve momentum if

$x_p \sim (p_{Fp} / p_{Fn})^3 < 0.12\text{-}14$

- In the standard scenario only massive stars ($M \sim 2\ M_\odot$) cool rapidly.



Yakovlev & Pethick (2004)



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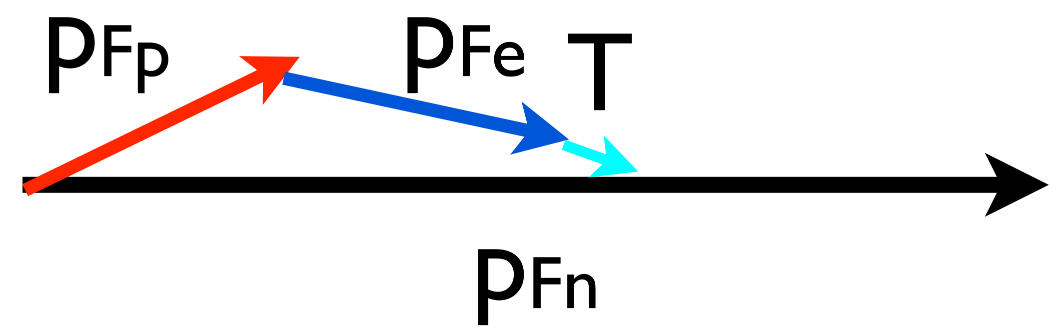
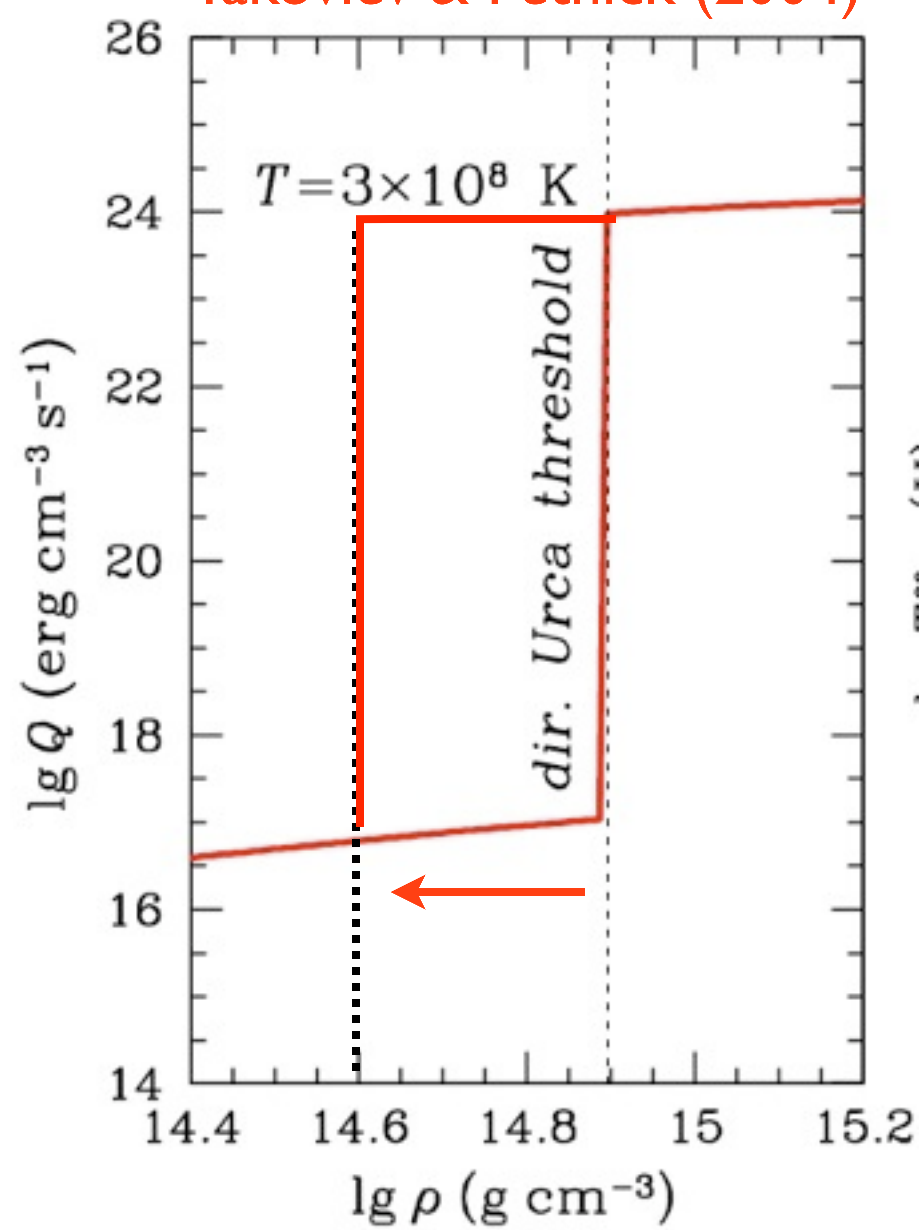


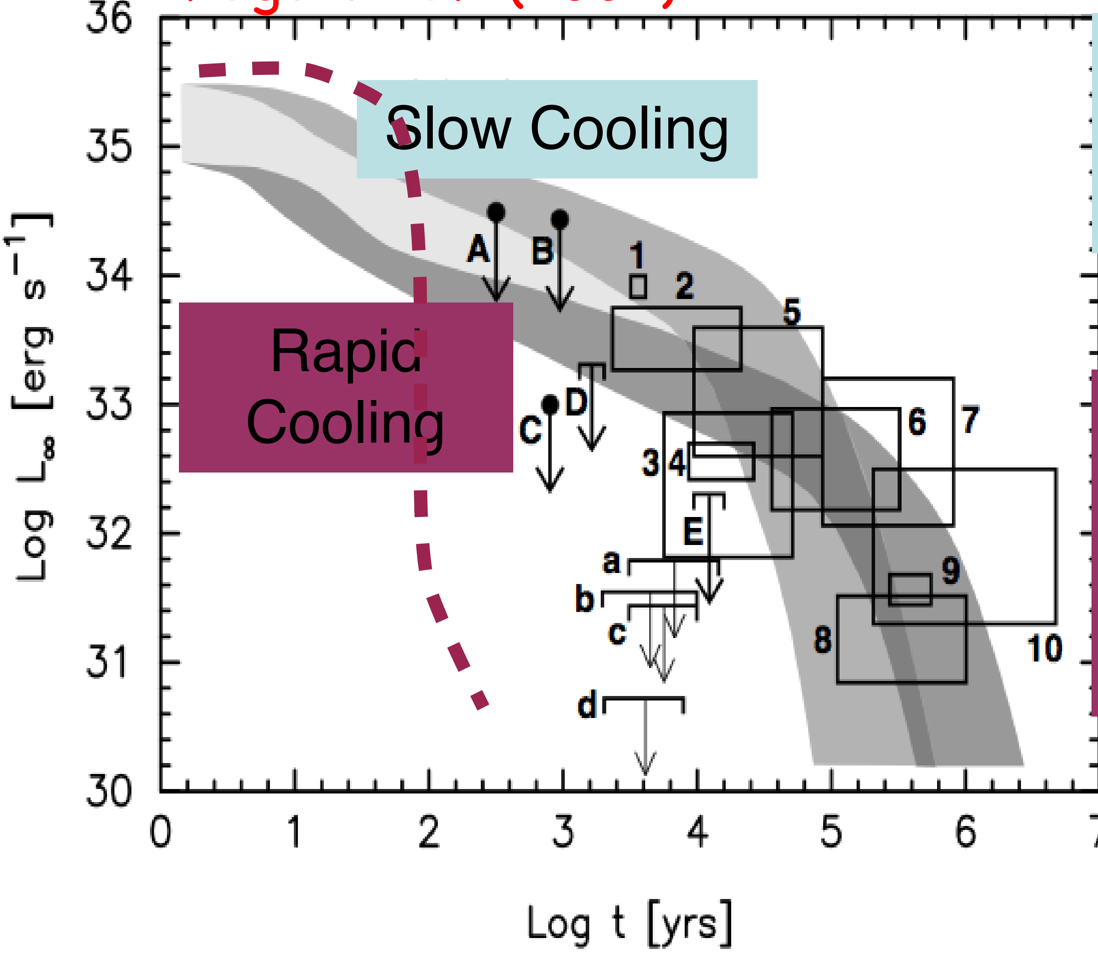
- In the standard scenario only massive stars (M ~ 2 M☉) cool rapidly.
- A large symmetry energy will allow direct URCA for typical NS (M ~ 1.4 M☉) .
- Recall large symmetry energy also favors large radii.

Yakovlev & Pethick (2004)



Neutron Star Cooling

Page et al. (2005)



Slow Cooling:
$n + n \rightarrow n + p + e^- + \bar{\nu}_e$

Standard Scenario

Rapid Cooling:
$n \rightarrow p + e^- + \bar{\nu}_e$
$X \rightarrow Y + e^- + \bar{\nu}_e$

Needs high (>10%) Proton fraction or a phase transition

- Most neutron stars compatible with slow cooling.
- Notable exceptions exist.

Cooling in Accreting Stars

During accretion heating will heat up the core.
Core temperature set by balance between heating and neutrino cooling.

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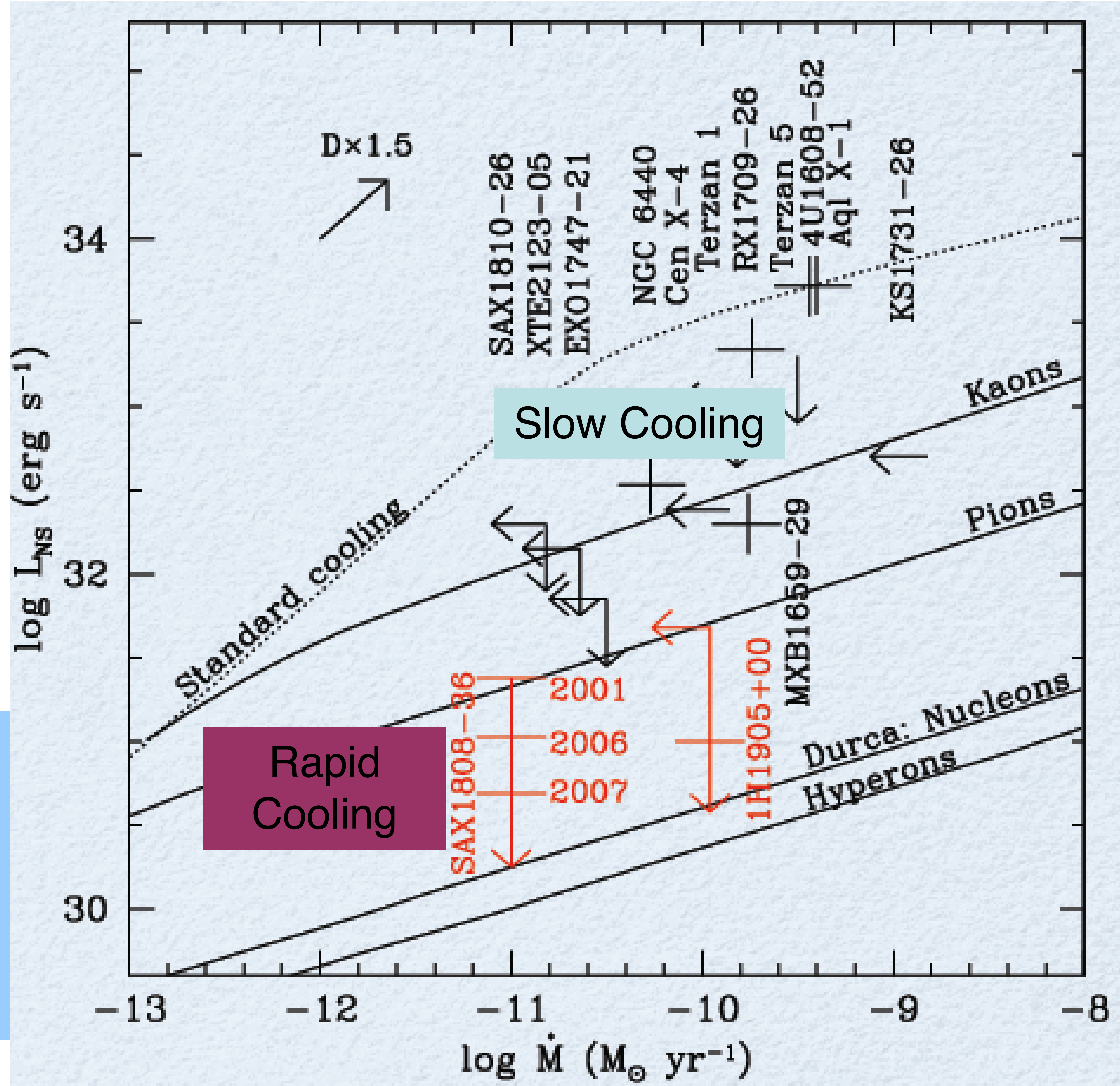
Quiescent emission after periods of bursting in accreting neutron stars (SXRT)



Rutledge (2004) Yakovlev (2006) Heinke (2007)

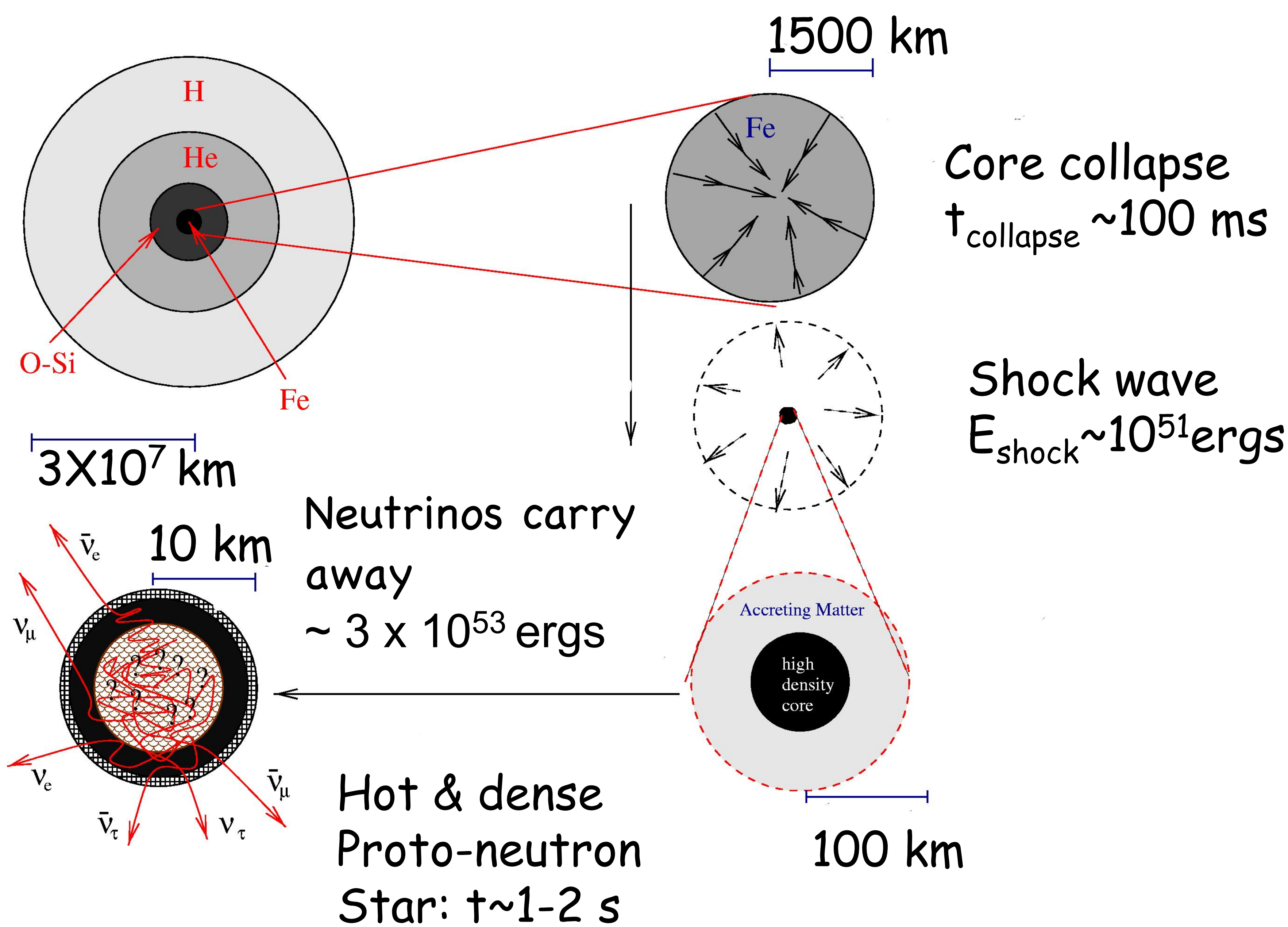
INTERPRETING COOLING

- The vast majority of neutron stars are cooling slowly, but this does not imply that the proton fraction is small. Neutron and proton superfluidity can suppress the neutrino emission rates.

- No correlation between mass and cooling has yet been established.

- Difficult to draw definitive insights on the symmetry energy.

Symmetry Energy and Supernova Neutrinos



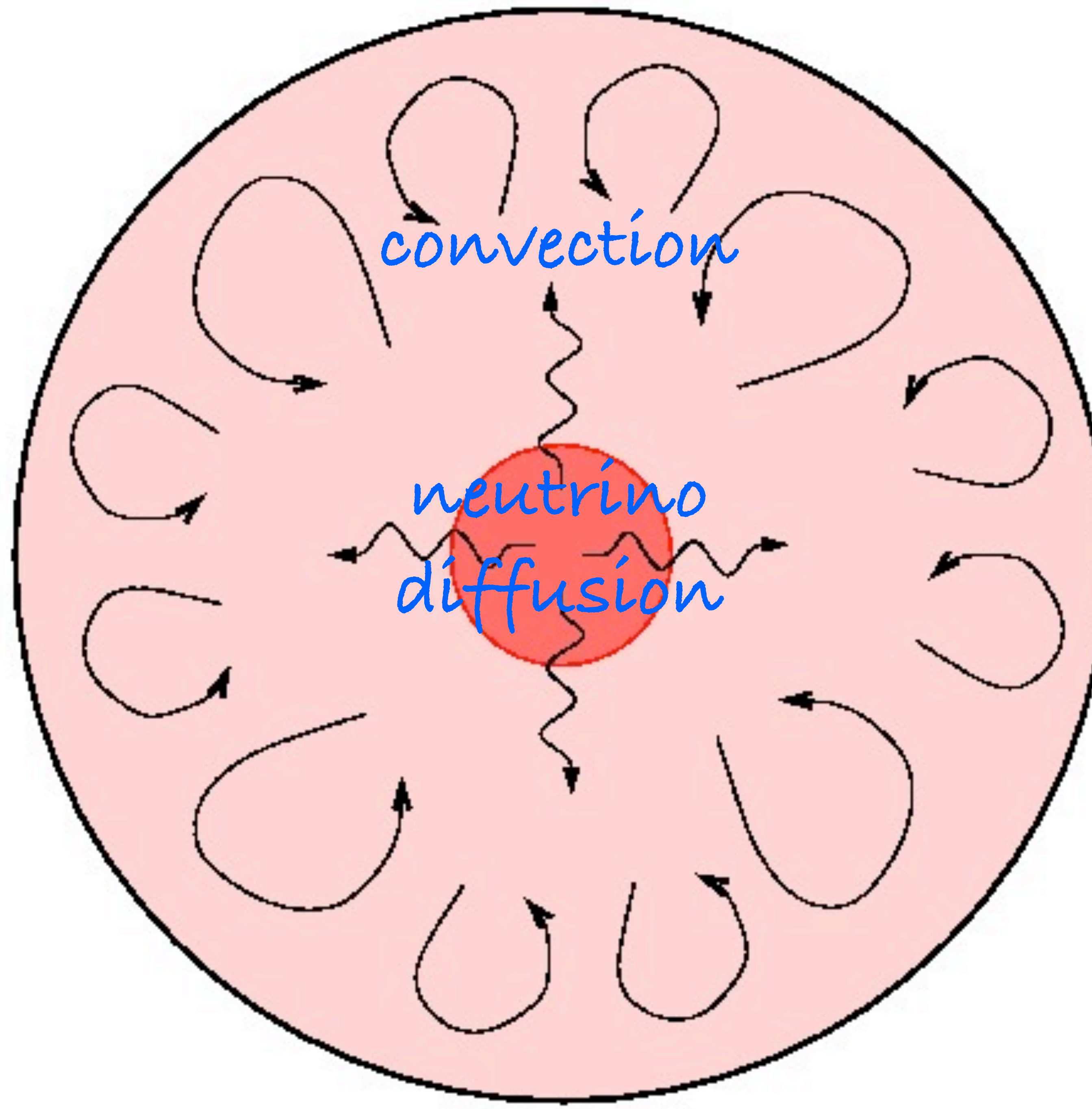
Neutrino flavor and energy distribution can impact explosion mechanism and r-process nucleosynthesis.

Modeling PNS evolution with different EoS.

Heat transport : Neutrino diffusion + convection

Neutrino Diffusion:

$$\tau_{\rm diff} \simeq \frac{R^2}{c\ \lambda_\nu} \approx 3 - 5\ {\rm s}$$



Convection:

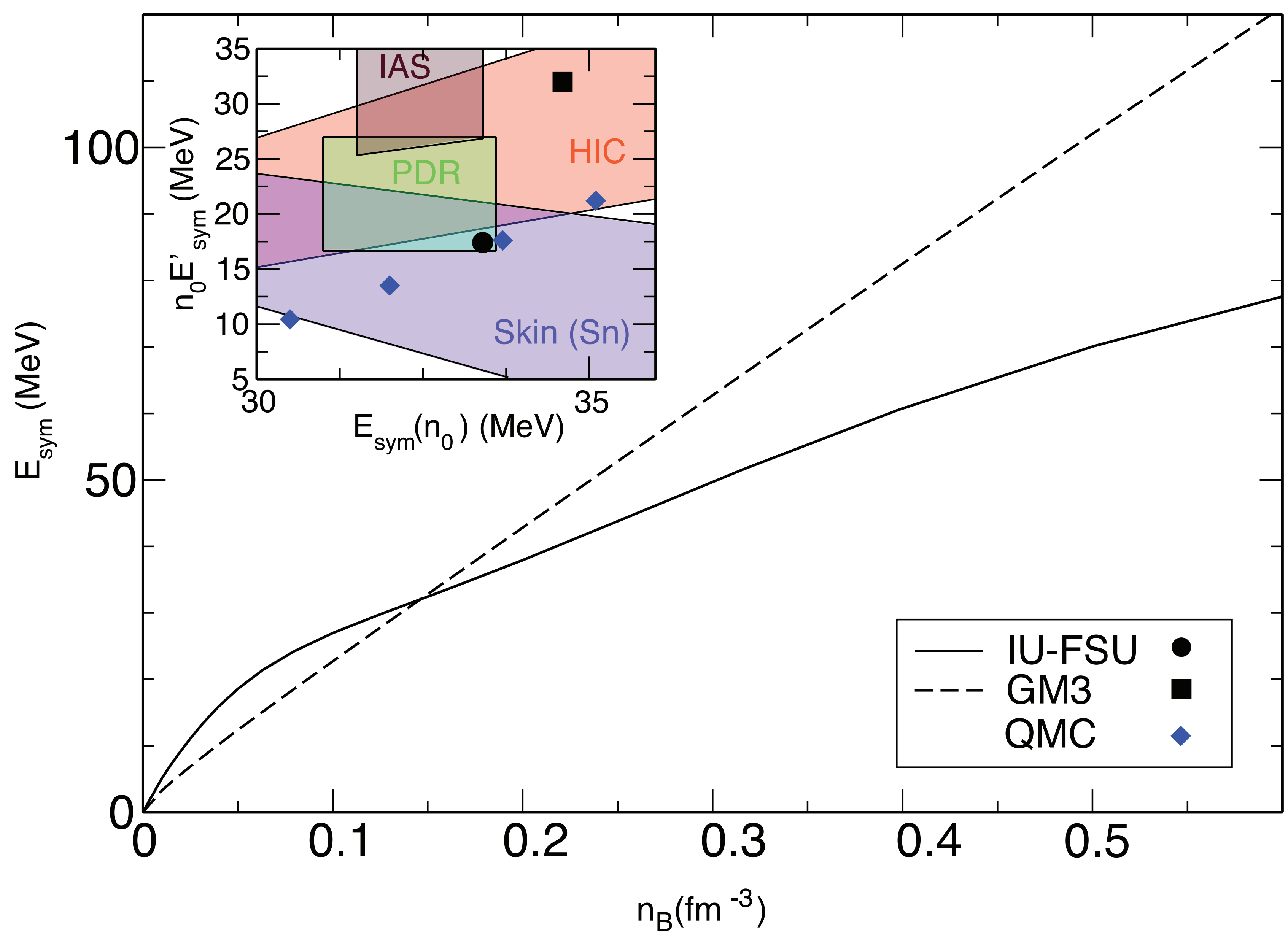
Convection is driven by composition gradients.

Different EoS could have distinct convective instabilities.

Modeling PNS evolution with different EoS.

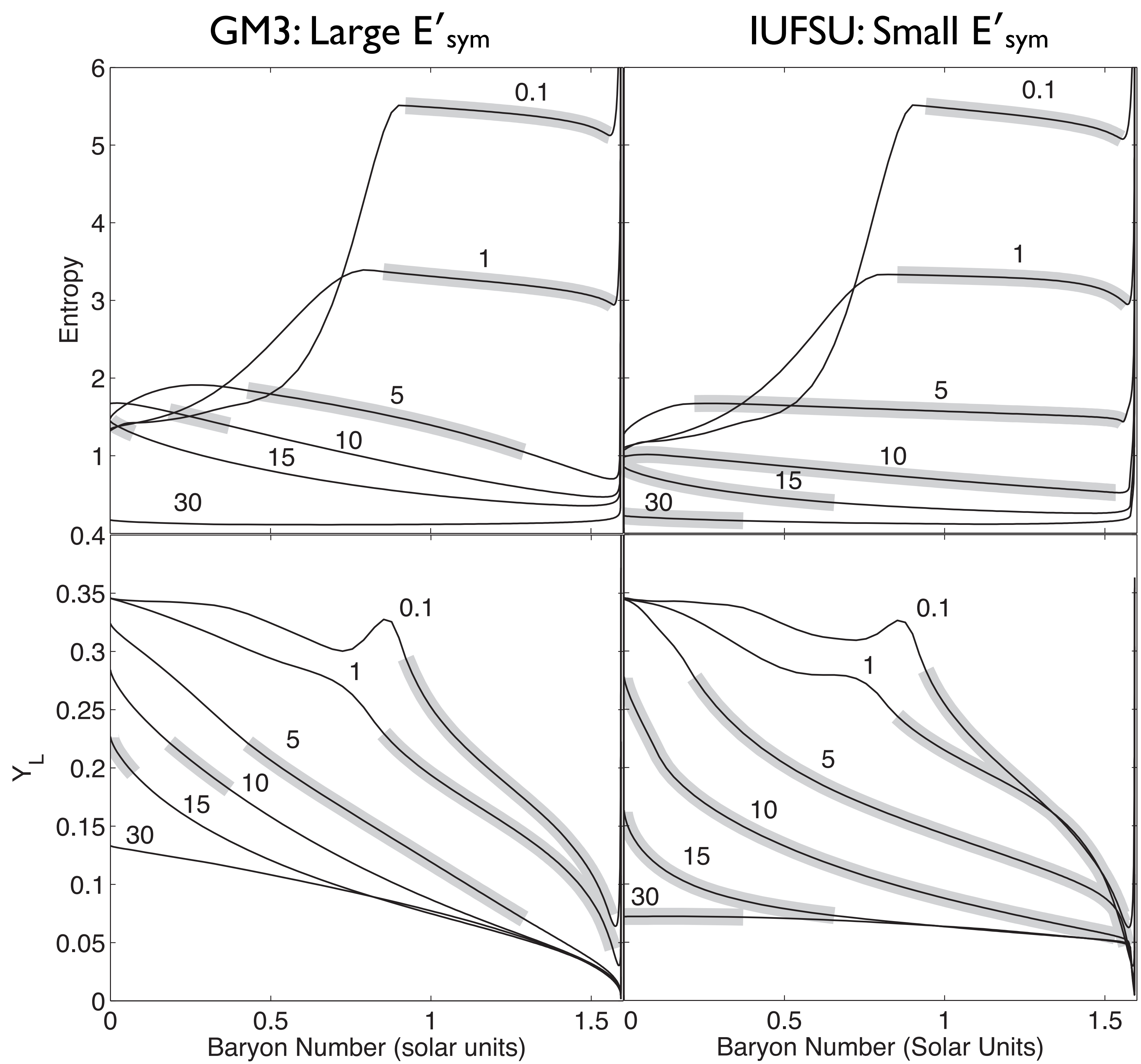
$$
\begin{aligned}
\mathscr{L}_{\mathrm{int}} &= \bar{\psi}\left[g_{\mathrm{s}}\phi - \left(g_{\mathrm{v}}V_{\mu} + \frac{g_{\rho}}{2}\boldsymbol{\tau}\cdot\mathbf{b}_{\mu} + \frac{e}{2}(1+\tau_3)A_{\mu}\right)\gamma^{\mu}\right]\psi \\
&- \frac{\kappa}{3!}(g_{\mathrm{s}}\phi)^3 - \frac{\lambda}{4!}(g_{\mathrm{s}}\phi)^4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

- At finite temperature only mean field calculations exist.
- Can tune parameters to mimic different symmetry energies.



An intense neutrino source

- Protoneutron star evolution time scale is set by neutrino diffusion and convection.
- It is imprinted on the temporal structure of the neutrino signal - tomography ?



Roberts, Shen, Cirigliano, Pons, Reddy, Woosley (2011)

Convection is driven by unstable gradients in entropy and lepton number. Convective growth rate:

$$\omega^2 = -\frac{g}{\gamma_{n_B}} \left(\gamma_s \nabla \ln(s) + \gamma_{Y_L} \nabla \ln(Y_L)\right)$$

$$\gamma_{n_B} = \left(\frac{\partial \ln P}{\partial \ln n_B}\right)_{s,Y_L} \gamma_s = \left(\frac{\partial \ln P}{\partial \ln s}\right)_{n_B,Y_L} \gamma_{Y_L} = \left(\frac{\partial \ln P}{\partial \ln Y_L}\right)_{n_B,s}$$

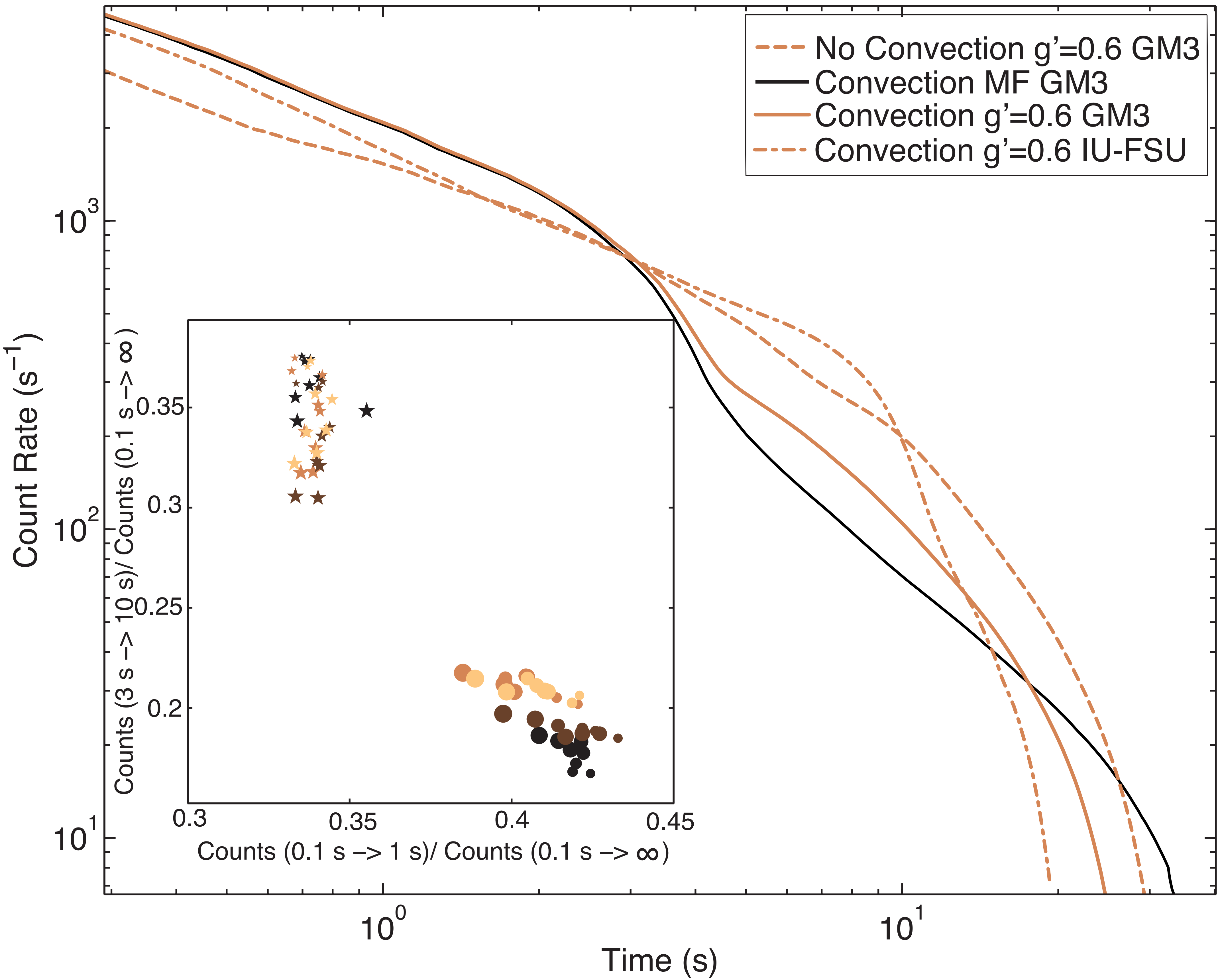
The nuclear symmetry energy is key to understanding composition driven convective instabilities:

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

Roberts, Shen, Cirigliano, Pons, Reddy, Woosley (2011)

Observable signatures of convective transport

Count rate in Super-Kamiokande for galactic supernova at 10 kpc.



NECESSARY CONDITIONS FOR R-PROCESS
(in supernova)

High neutron to seed ratio is needed to populate the observed A~130 and A ~ 190 peaks.

This requires:

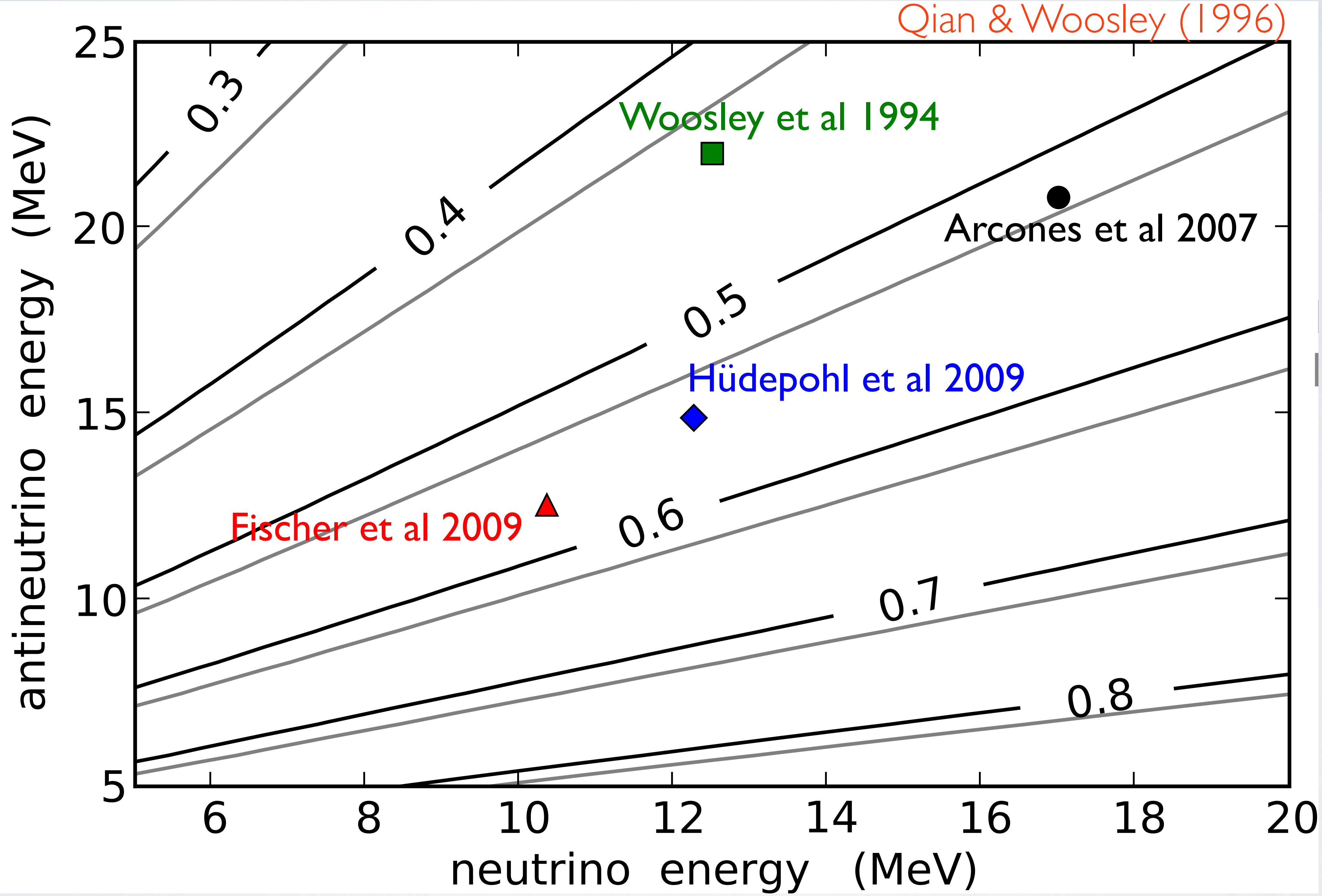
- High entropy per baryon.
- Short expansion time.
- Low Y_e .

} Hydrodynamics, Magnetic Fields, etc

} Neutrino Spectra

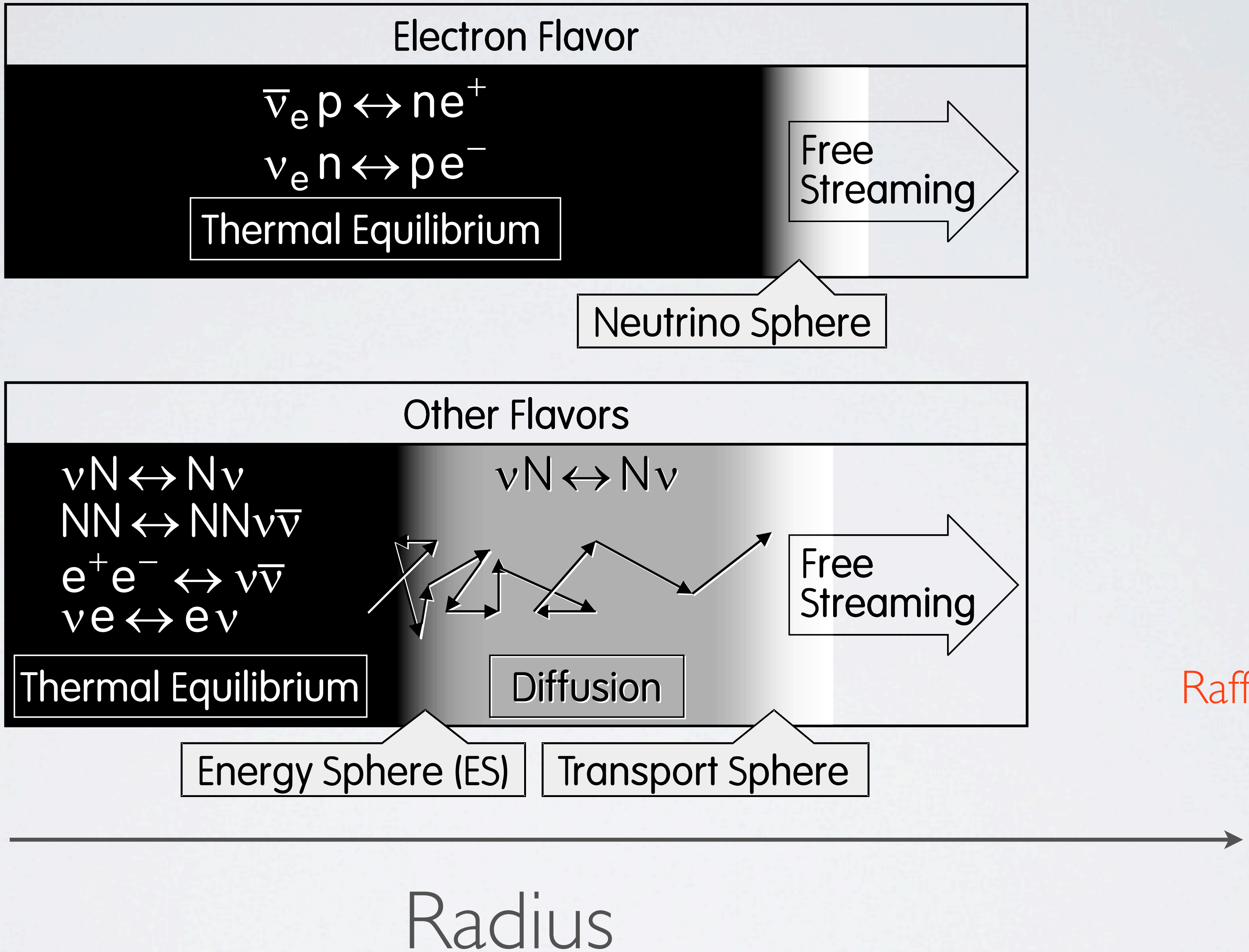
Neutrino spectra emerging from the proto-neutron star are sensitive to the nuclear symmetry energy at low density?

Y_e & Neutrino Spectra



Larger spectral differences imply lower Y_e

Reactions in the Neutrinosphere

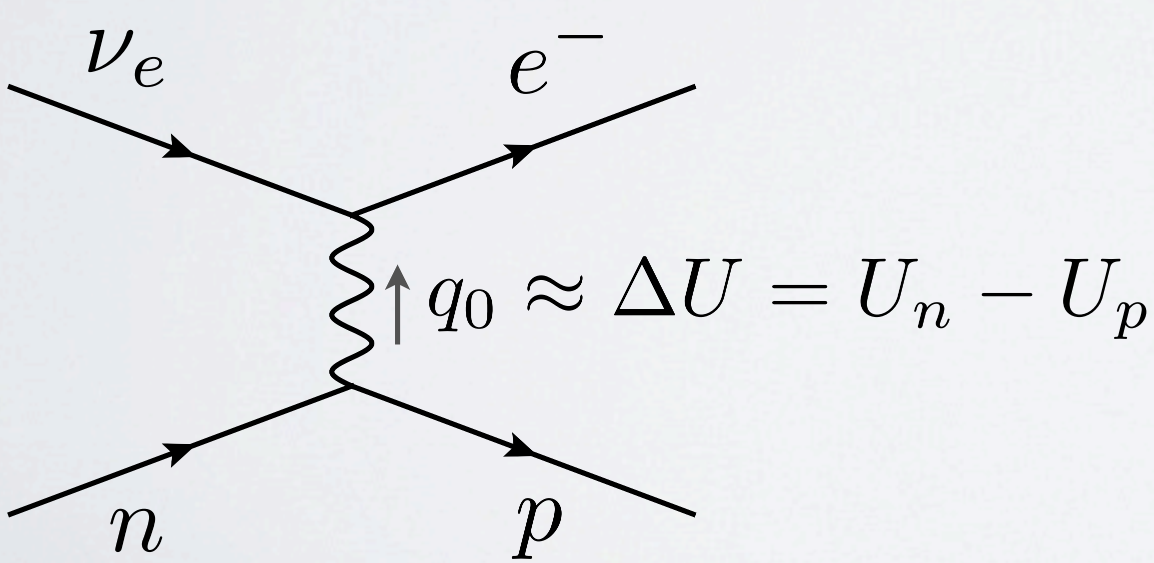


Raffelt (2001)

CHARGED CURRENT OPACITY

$$\begin{cases} \nu_e + n \to p + e^- \\ \bar{\nu}_e + p \to n + e^+ \end{cases}$$

- Final state electron blocking is strong for electron neutrino absorption reaction.
- Asymmetry between mean field energy between neutrons and protons alters the kinematics.
- Multi-particle initial and final states can also move response to high energy.



Large q_0 crucial to overcome blocking

Reddy, Prakash & Lattimer (1998)
Roberts (2012)
Martinez-Pinedo et al. (2012)
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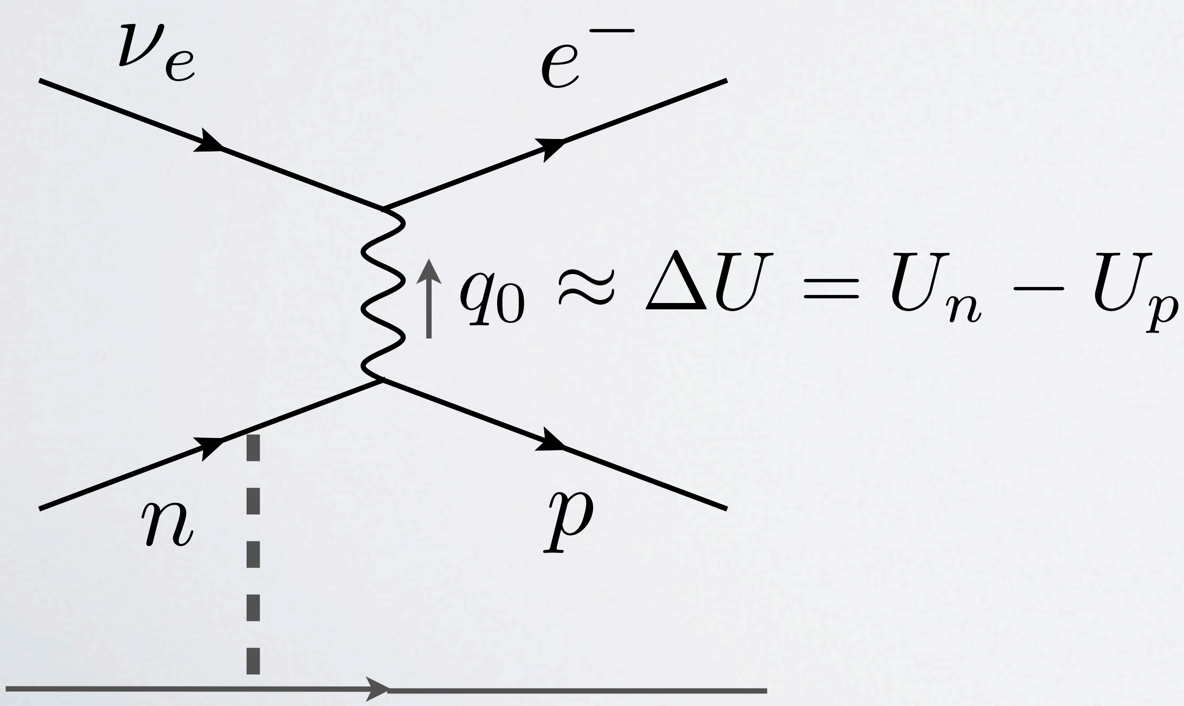

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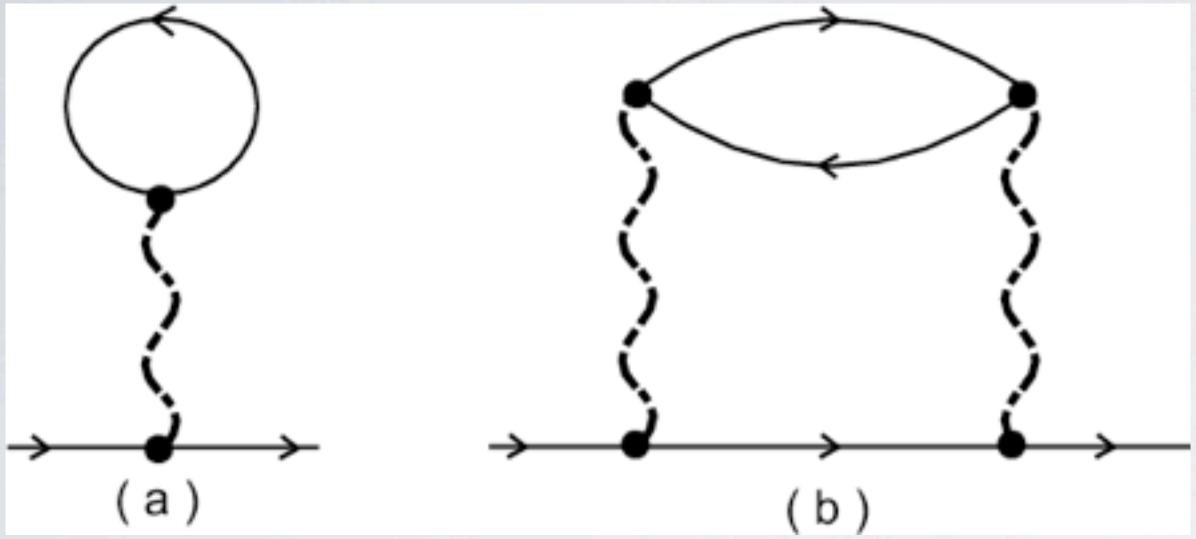
MEAN FIELD ENERGY SHIFT & DAMPING



$$E_n(p) \approx m_n + \frac{p^2}{2m_n^*} + U_n + i\,\Gamma_n$$

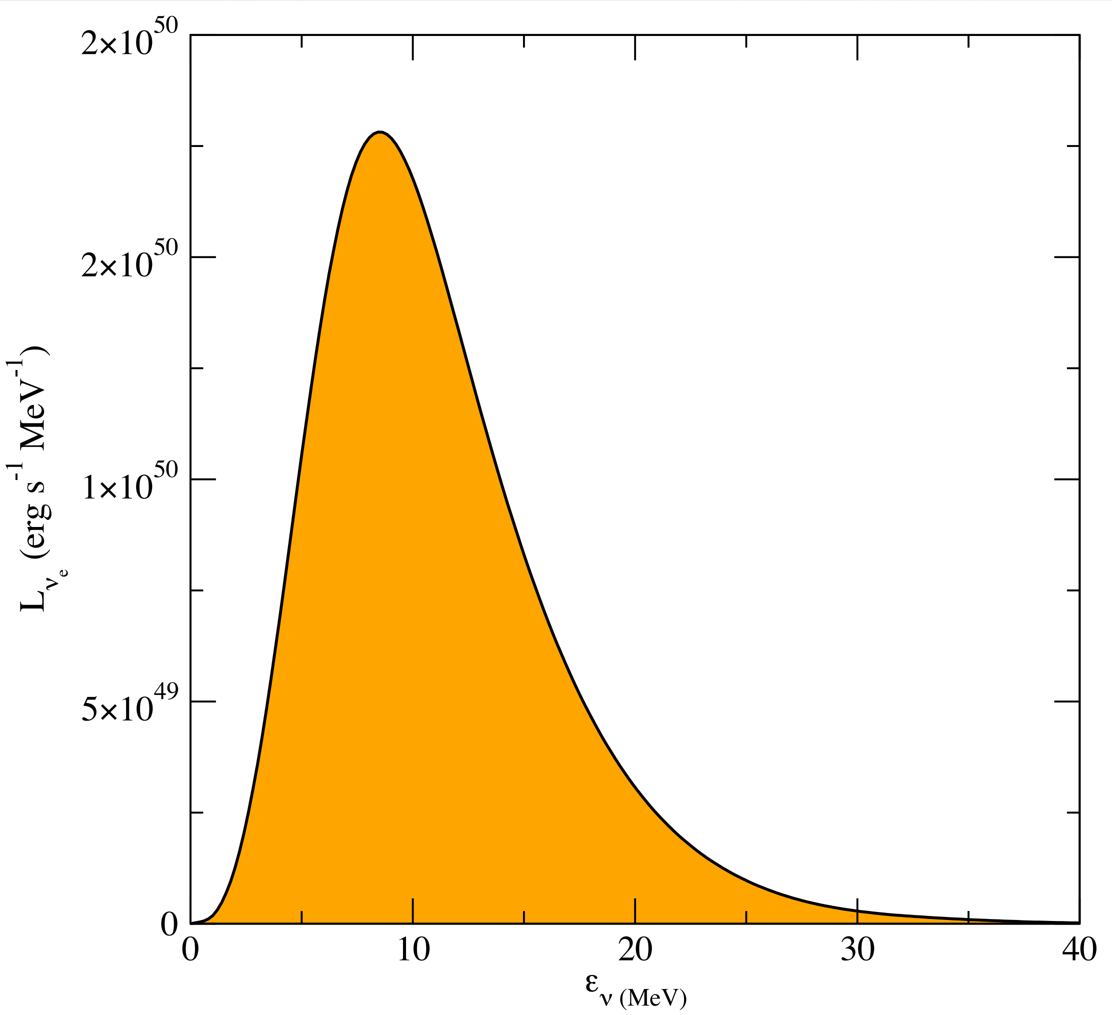
$$E_p(p+q) \approx m_p + \frac{(p+q)^2}{2m_n^*} + U_p + i\,\Gamma_p$$

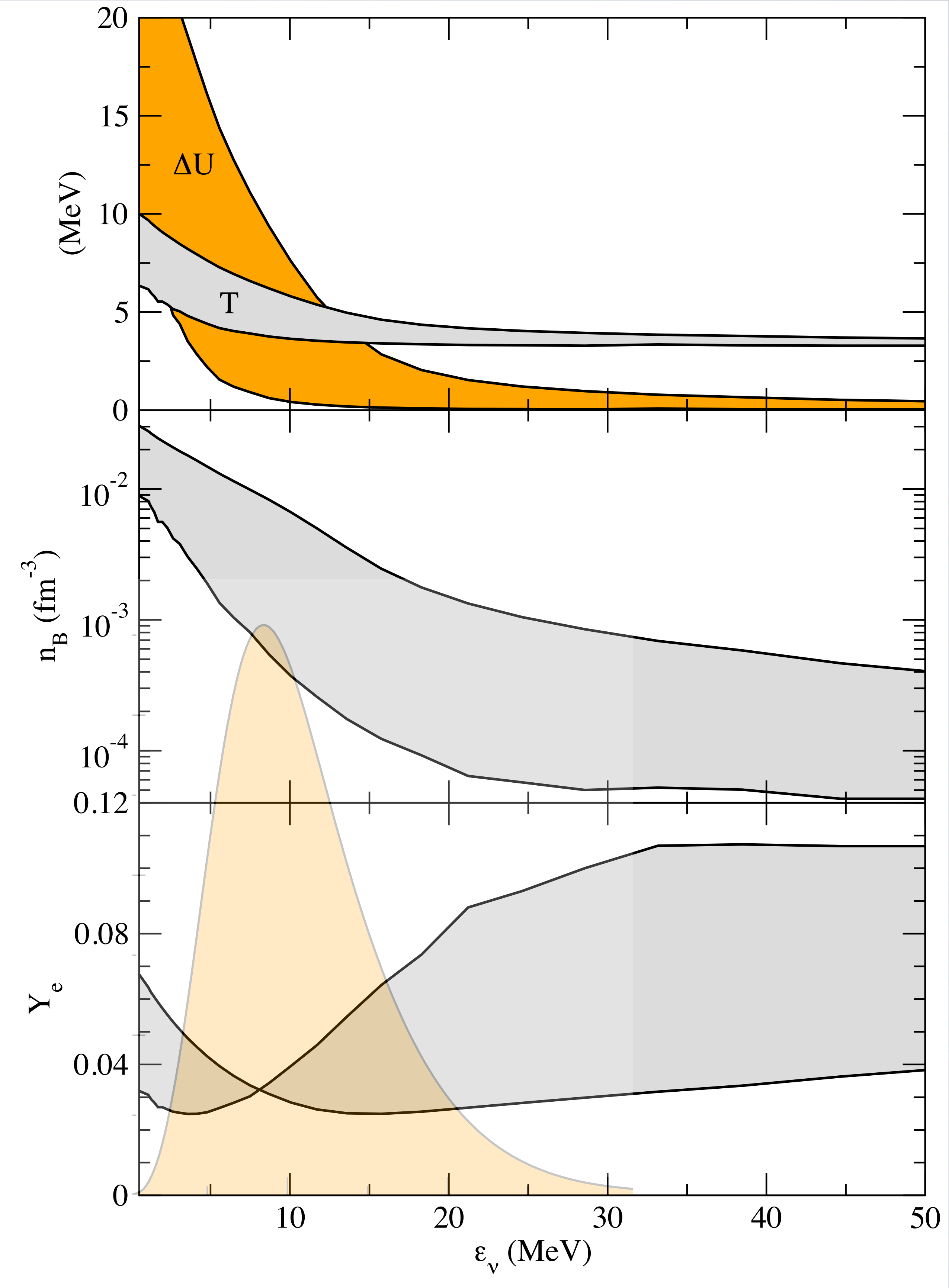
Energy Transfer in the Charged Current Process:

$$q_0 = E_n(p) - E_p(p+q) \simeq \underbrace{\frac{pq}{2m_n^*}}_{\approx 0} + \underbrace{(m_n - m_p)}_{\simeq 1.3 \text{ MeV}} + (U_n - U_p)$$

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

SPECTRA AT LATE TIMES





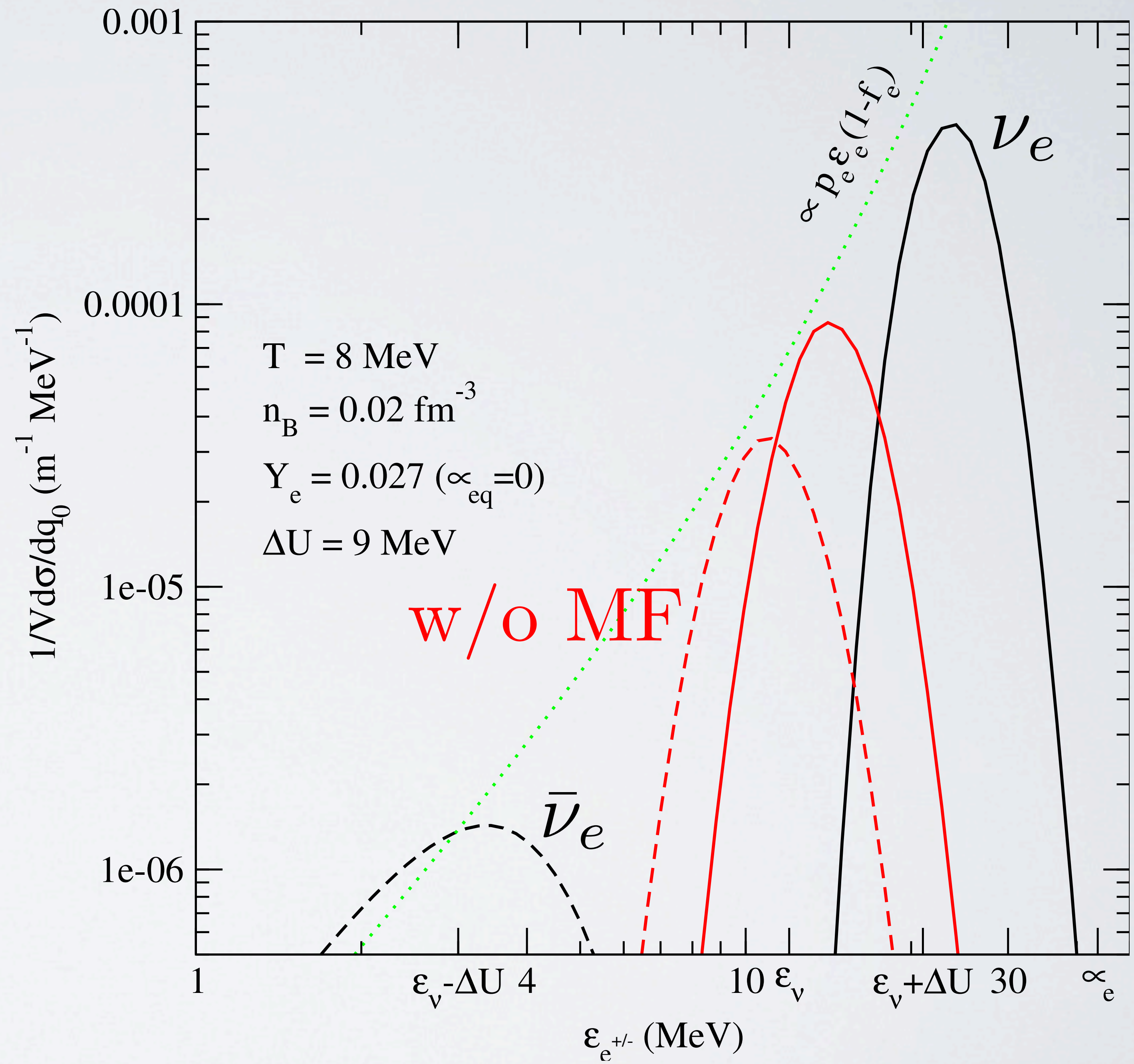
- Decoupling occurs at relatively high density.
- Spectra influenced by nuclear correlations.

Figures from PNS simulations by Roberts (2012)

ABSORPTION RATES

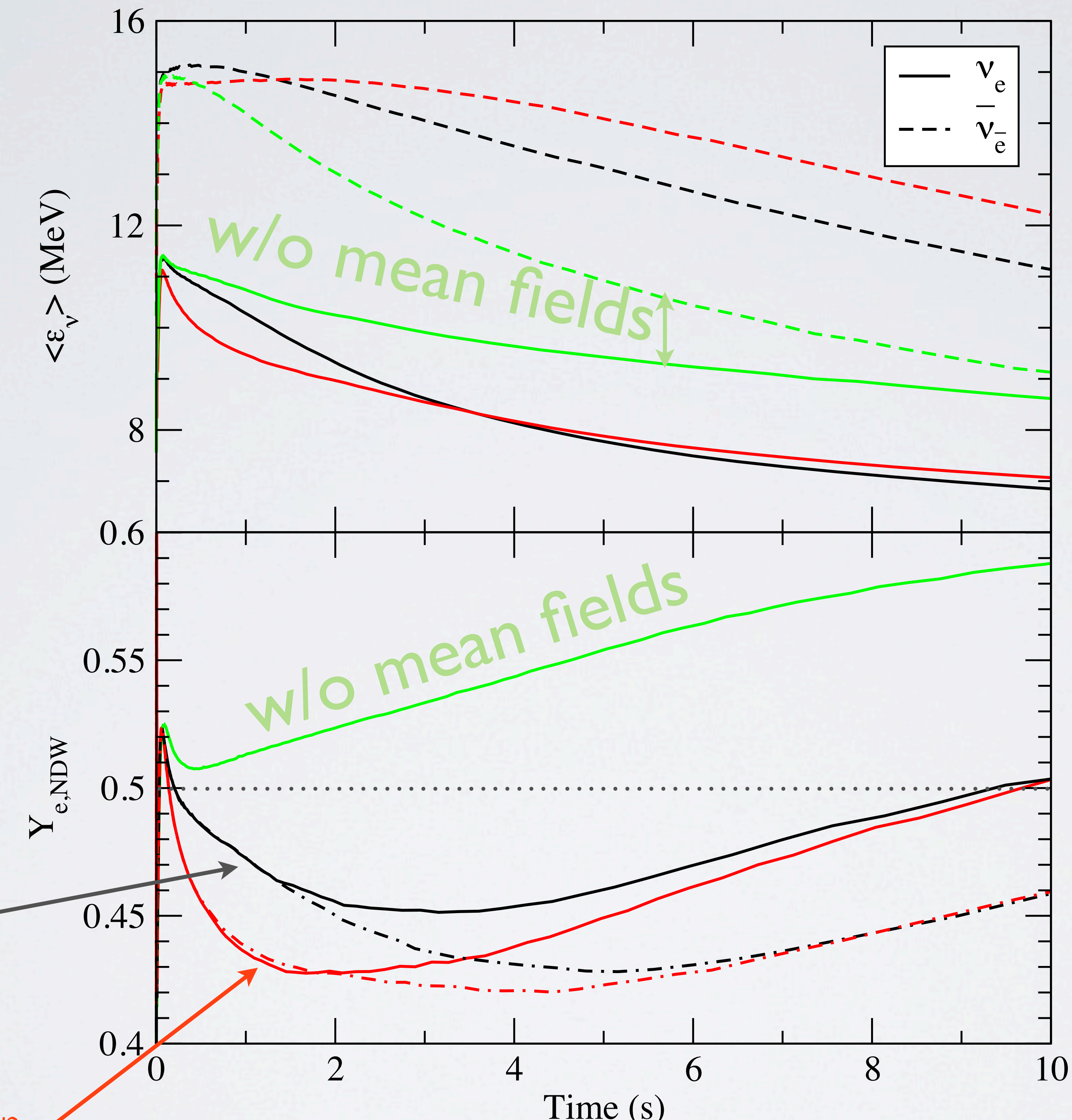
$$\frac{d\Gamma}{\cos\theta dE_e} = \frac{G_F^2}{2\pi} p_e \ E_e \left(1 - f_e(E_e)\right) \times \left[(1+\cos\theta)S_\tau(q_0,q) + g_A^2(3-\cos\theta)S_{\sigma\tau}(q_0,q)\right]$$

- Mean field energy shift helps overcome electron final state blocking.
- Enhances ν_e absorption
- Larger energy needed to produce neutrons suppresses anti-ν_e absorption.



Roberts, Reddy & Shen (2012)

EMERGENT SPECTRA & Y_e



Linear Symmetry Energy

Non-Linear Symmetry Energy

Roberts, Reddy & Shen (2012)

CONCLUSIONS

- Several neutron star and supernova observables are sensitive to the density dependence of the symmetry energy.
- We already have some hints from astrophysics about the behavior of the neutron matter EoS.
- Extrapolations to relevant densities will rely on our understanding of many-body forces.
- Key aspects of neutrino emission from supernova depend on the symmetry energy at relatively low density.