Supernova Neutrinos: The role of the nuclear equation of state and neutrino-matter interactions in hot and dense matter

- Introduction
- Temporal structure: Neutron star tomography
- Neutrino spectra
- Supernova cooling constraints

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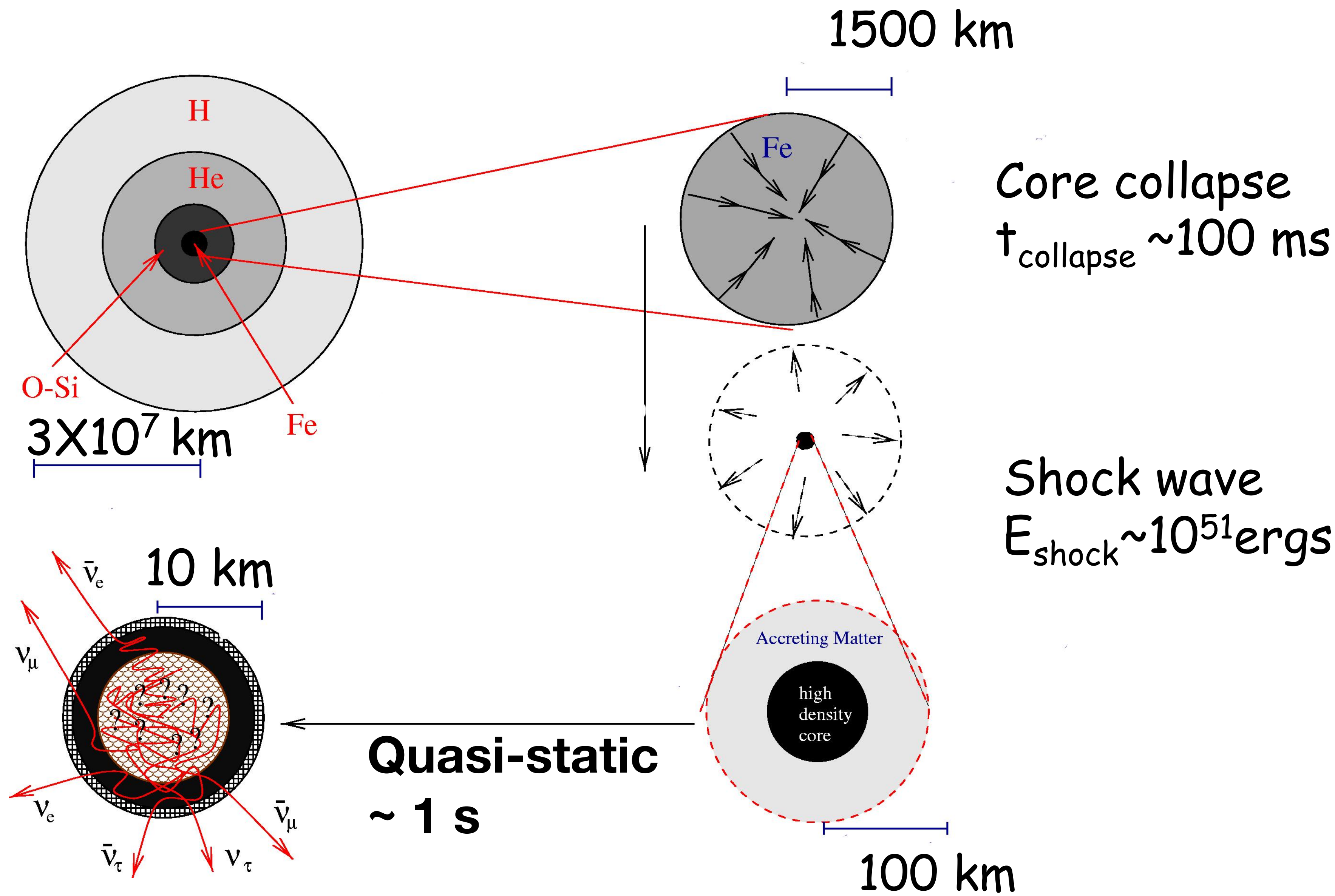
SN neutrinos at DUNE: SLAC meeting, Nov. 23-24, 2015

Supernova Neutrinos



neutrinos diffuse out of the dense newly born neutron star

carry away ~ 3 x 10^{53} ergs

- The time structure of the neutrino signal depends on how heat is transported in the neutron star core (10^{13}-10^{15} g/cm^3).
- The spectrum is set by scattering in a hot (T=5-10 MeV) and not so dense (10^{11}-10^{13} g/cm^3) neutrino-sphere.

A broad brush description of SN neutrino emission

Neutrino luminosity:

$$L_\nu(t) \approx 4\pi\sigma_\nu R_\nu^2(t)\ T_\nu^4(t)$$

Radius of the neutrino decoupling surface.

Temperature of the neutrino decoupling surface.

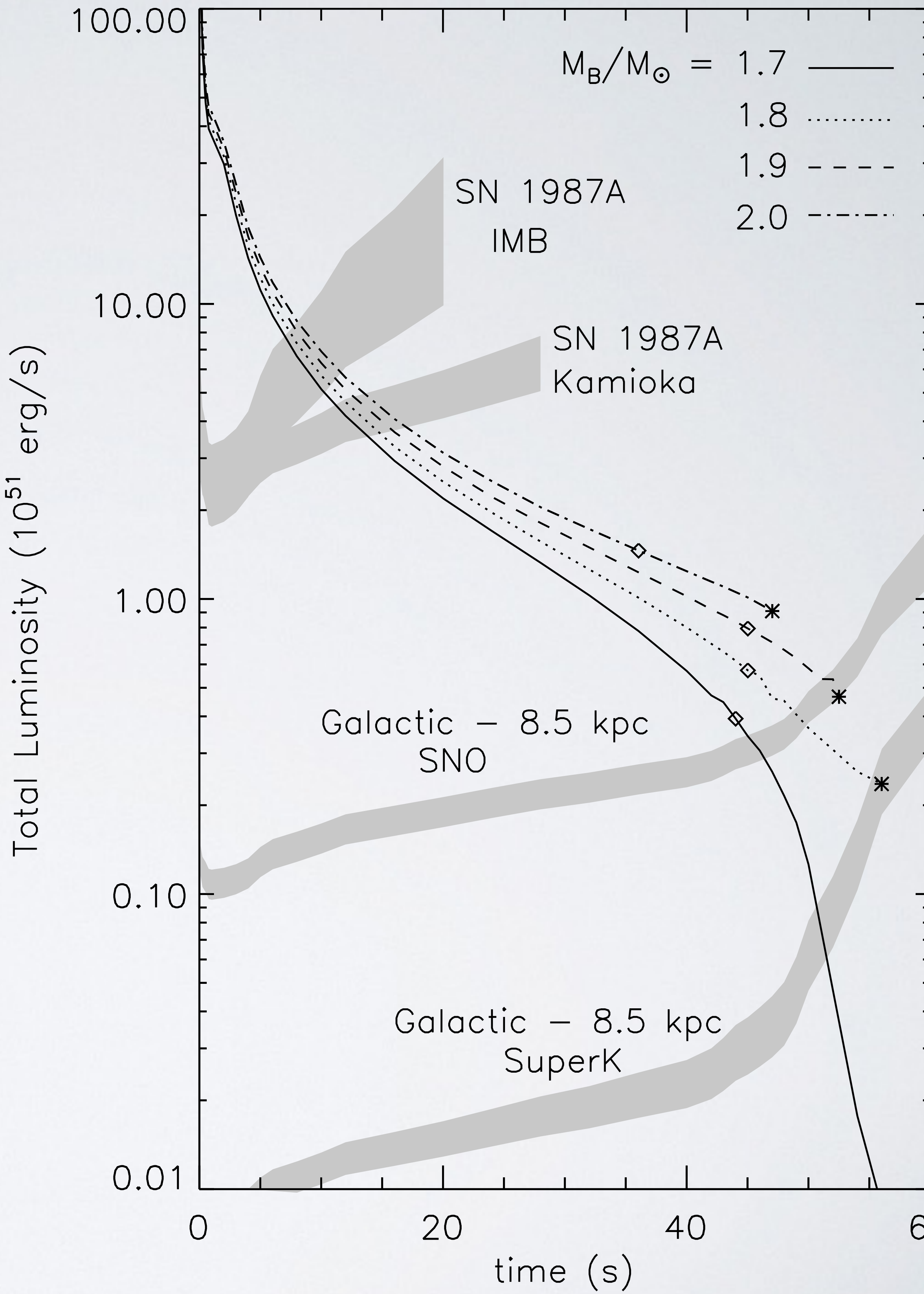
For given neutron star mass:

- The equation of state determines R.
- Neutrino interactions near the PNS surface determines T.
- Time evolution is determined by neutrino opacities in the core, equation of state of dense matter and the stability of the final neutron star.

Neutrino Emission: Baseline Model

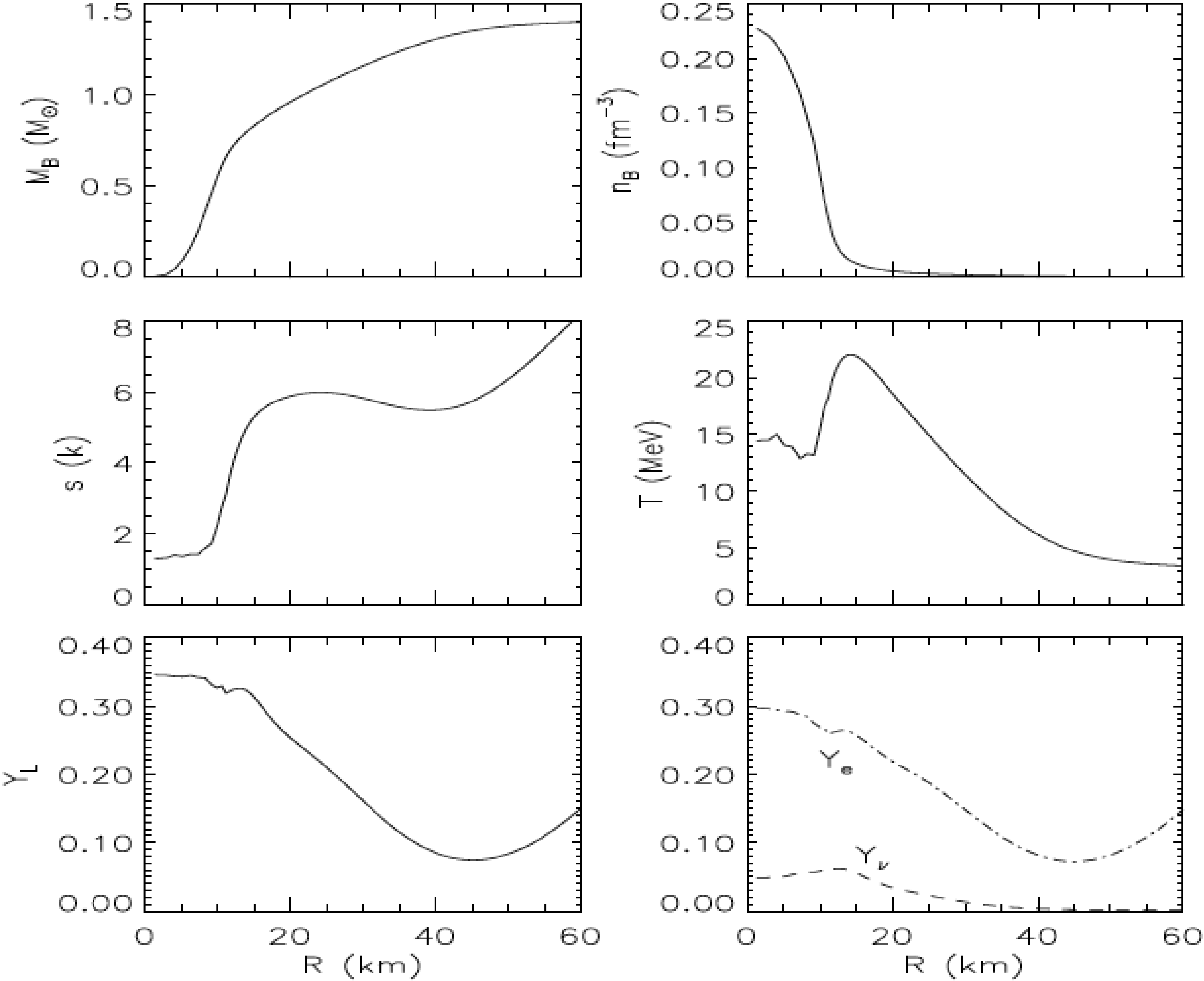
Generic expectations:

- For a galactic SN we should see neutrinos for about 40 s
- Luminosity increases with NS mass.
- Heavier masses can collapse to a black-hole if the high density equation of state is soft.



Prakash, Lattimer, Pons, Steiner and Reddy, astro-ph/0012136

Protoneutron Star Evolution

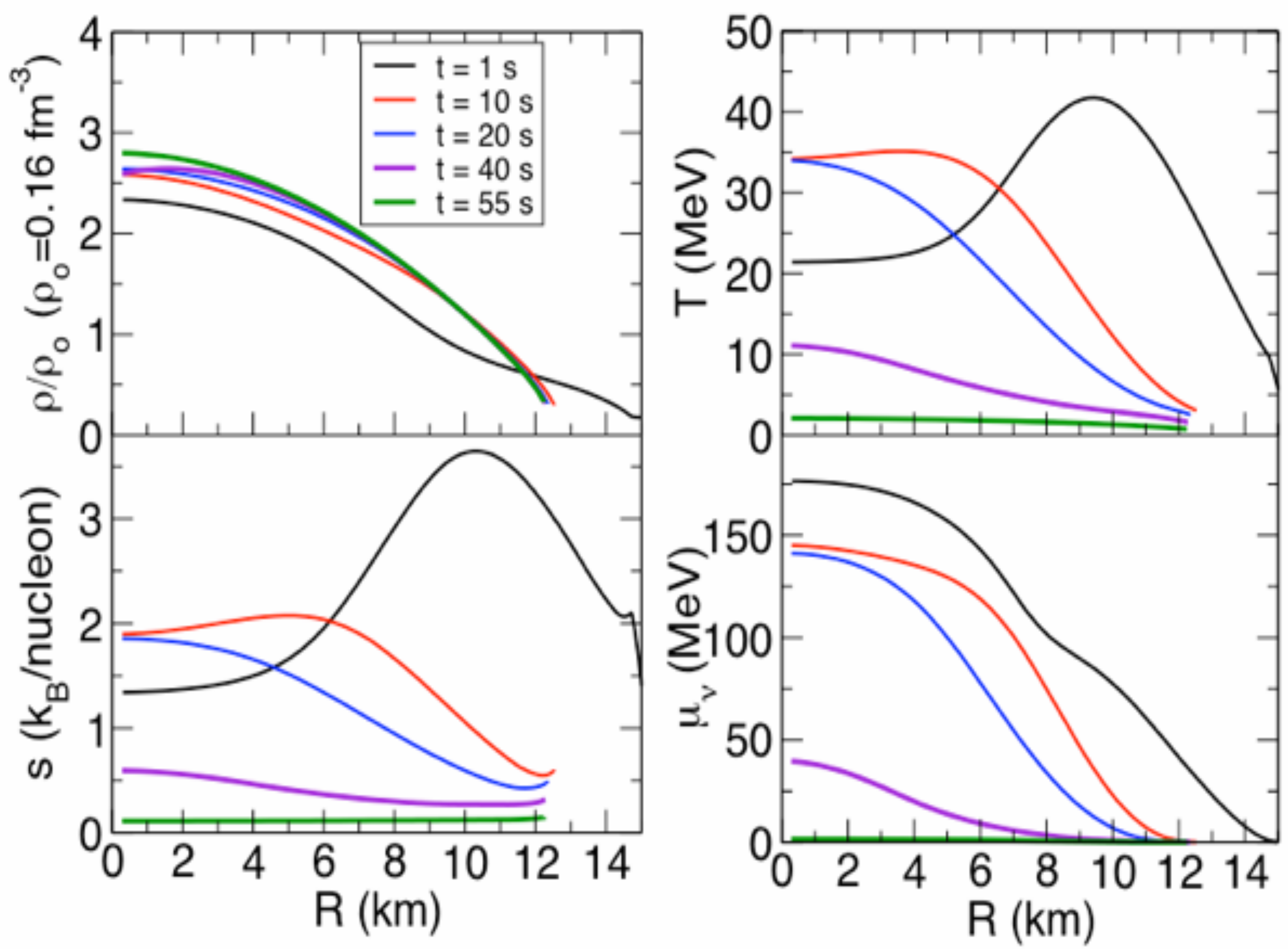


Initial state of the PNS.

Pons et al. (1999)

Neutrino diffusion cools and deleptonizes the PNS.

Time scales are set by properties of high density matter



Typical time-scales:

$$T(t) \approx T(t=0)\left(1 - \frac{t}{\tau_C}\right)$$

$$\tau_C \approx C_V \frac{R^2}{c\langle\lambda_\nu\rangle}$$

$$Y_\nu(t) \approx \frac{\mu_\nu^3}{6\pi^2}$$

$$\approx Y(t=0)\exp\left(-\frac{t}{\tau_D}\right)$$

$$\tau_D = \frac{3}{\pi^2}\frac{\partial Y_L}{\partial Y_\nu}\frac{R^2}{c\langle\lambda_{\nu e}\rangle}$$

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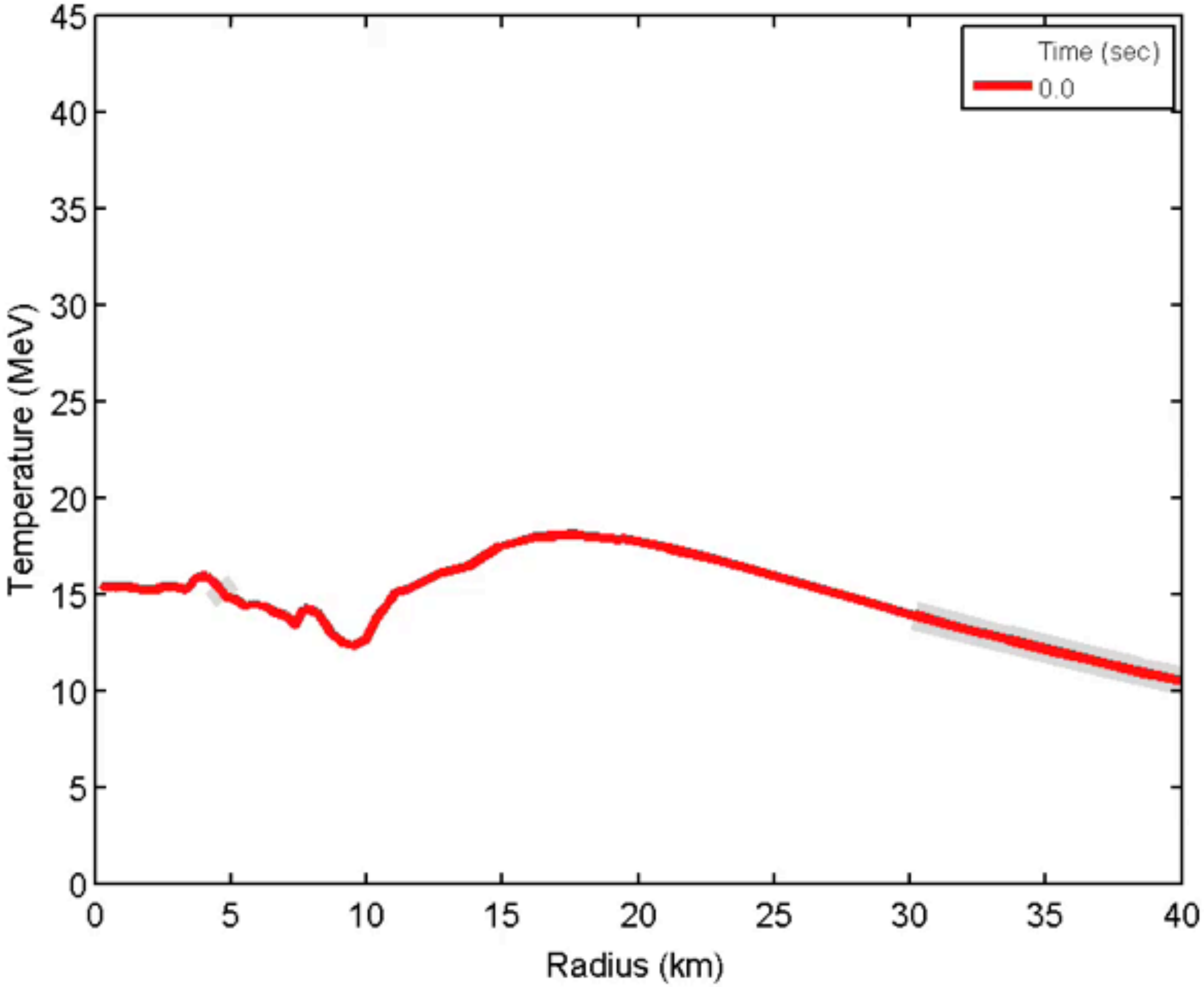

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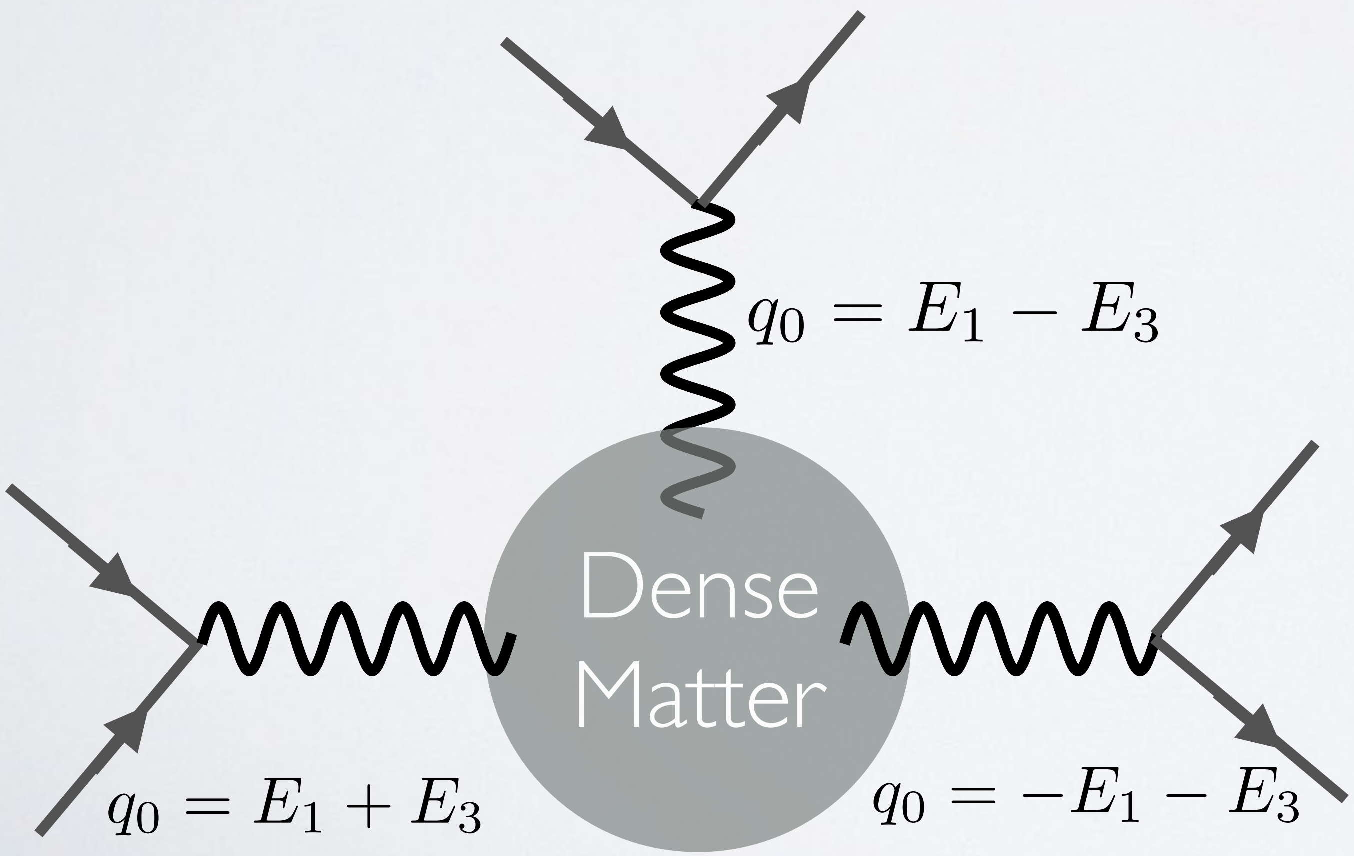
Neutrino Transport

- RHS of the Boltzmann Equation.

$$\frac{\partial f(E_1)}{\partial t} = \int \frac{d^3k_3}{(2\pi)^3} \; R(E_1, E_3, \cos\theta) \; f_3(1-f_1)$$
$$-R(E_3, E_1, \cos\theta) \; f_1(1-f_3)$$
$$+R(E_1, -E_3, \cos\theta) \; (1-f_1)(1-f_3)$$
$$-R(-E_1, E_3, \cos\theta) \; f_1 \; f_3$$



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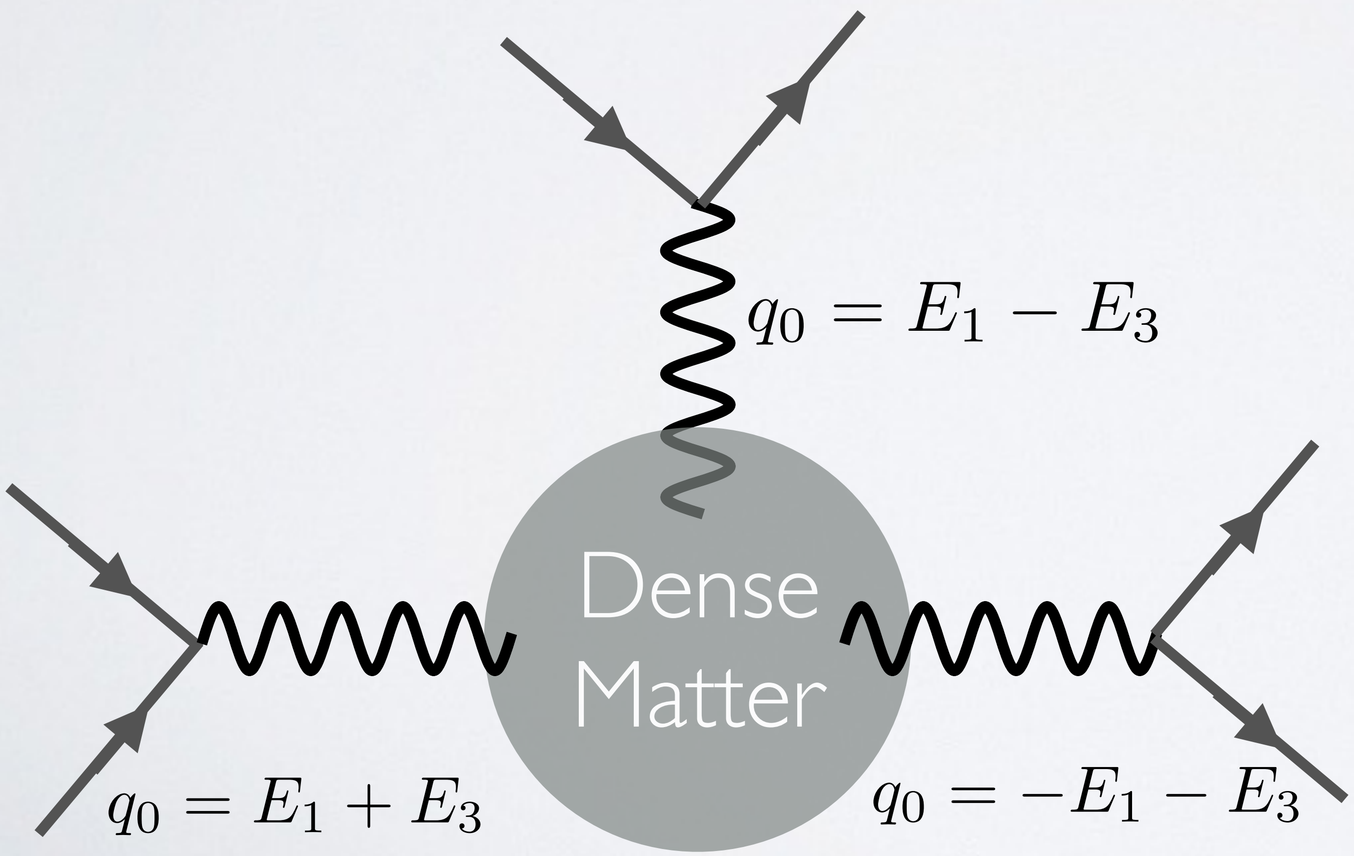
$$-R(E_3, E_1, \cos\theta) \; f_1(1-f_3) \longrightarrow \text{scattering-out}$$

$$+R(E_1, -E_3, \cos\theta) \; (1-f_1)(1-f_3) \longrightarrow \text{pair-production}$$

$$-R(-E_1, E_3, \cos\theta) \; f_1 \; f_3 \longrightarrow \text{pair-annihilation}$$



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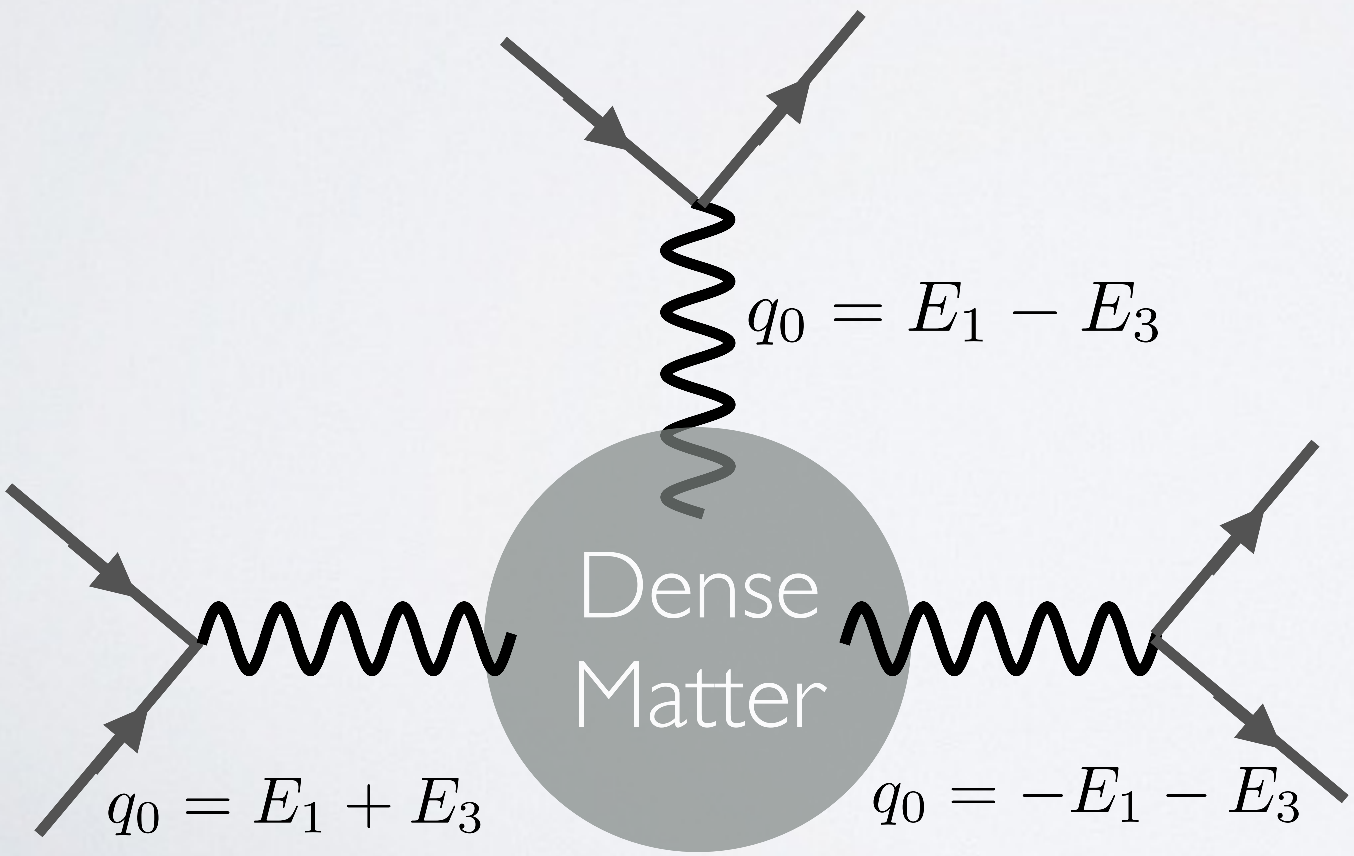

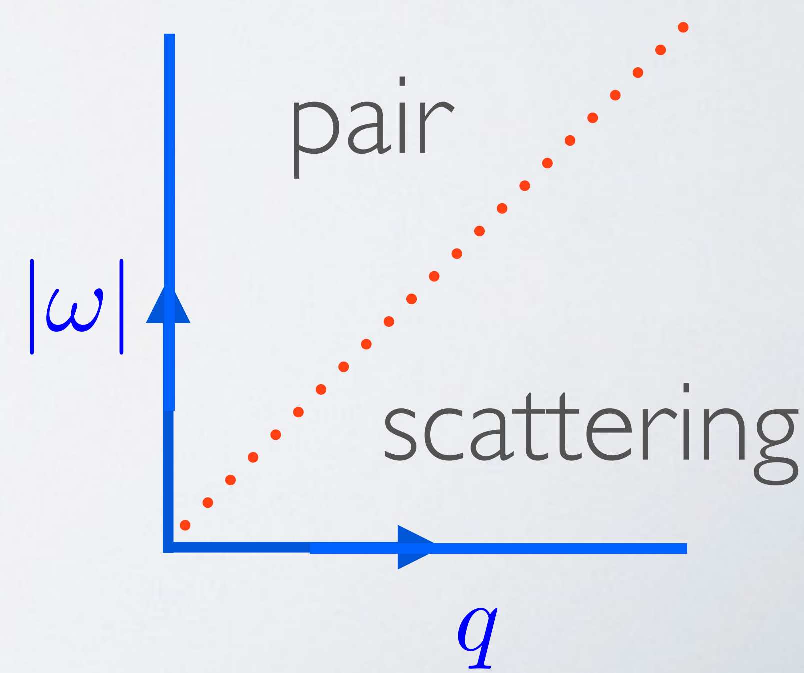

Neutrino Cross Sections

Differential Scattering/Absorption Rate:

response function of the medium

$$R(E_1, E_3, \cos\theta) = G_F^2\ L(E_1, E_3, \cos\theta)\ \times\ S_{[\rho, Y_e, T]}(q_0, q)$$

neutrino/lepton kinematic factor

- Neutral and charged current reactions contribute.

$$\mathcal{L}_{int}^{cc} = \frac{G_F}{\sqrt{2}}\ l_\mu j_W^\mu \qquad \text{for} \qquad \nu_l + B_2 \rightarrow l + B_4$$

$$\mathcal{L}_{int}^{nc} = \frac{G_F}{\sqrt{2}}\ l_\mu^\nu j_Z^\mu \qquad \text{for} \qquad \nu_l + B_2 \rightarrow \nu_l + B_4$$

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$$l_\mu = \overline{\psi}_l \gamma_\mu (1-\gamma_5)\, \psi_\nu \,, \quad j_W^\mu = \overline{\psi}_4 \gamma^\mu (g_V - g_A \gamma_5)\, \psi_2$$

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$$\mathcal{L}_{int}^{cc} = \frac{G_F}{\sqrt{2}} \; l_\mu j_W^\mu \quad \text{for} \quad \nu_l + B_2 \to l + B_4$$

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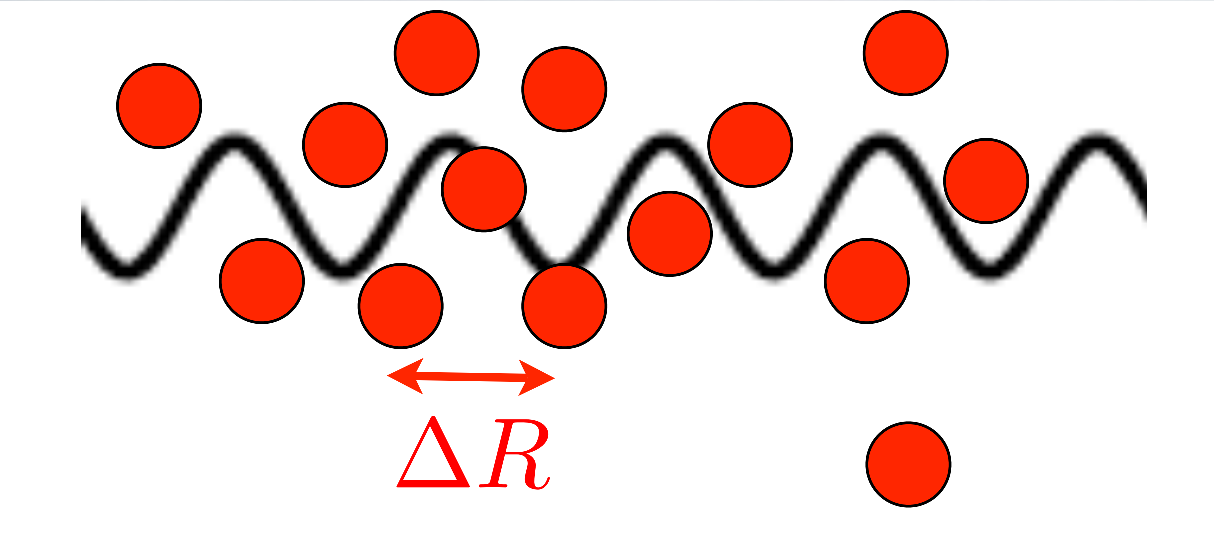
$c_V^n = -1.0,\ c_A^n = -1.26(-1.1)$
$c_V^p = 0.07,\ c_A^p = 1.26(1.4)$
$c_V^e = 1.92,\ c_A^e = 1.\ [\nu_e]$
$c_V^e = -0.08,\ c_A^e = -1.\ [\nu_X]$

Neutrino Interactions at High Density



At small q_0 and q the neutrino cannot resolve a single nucleon.

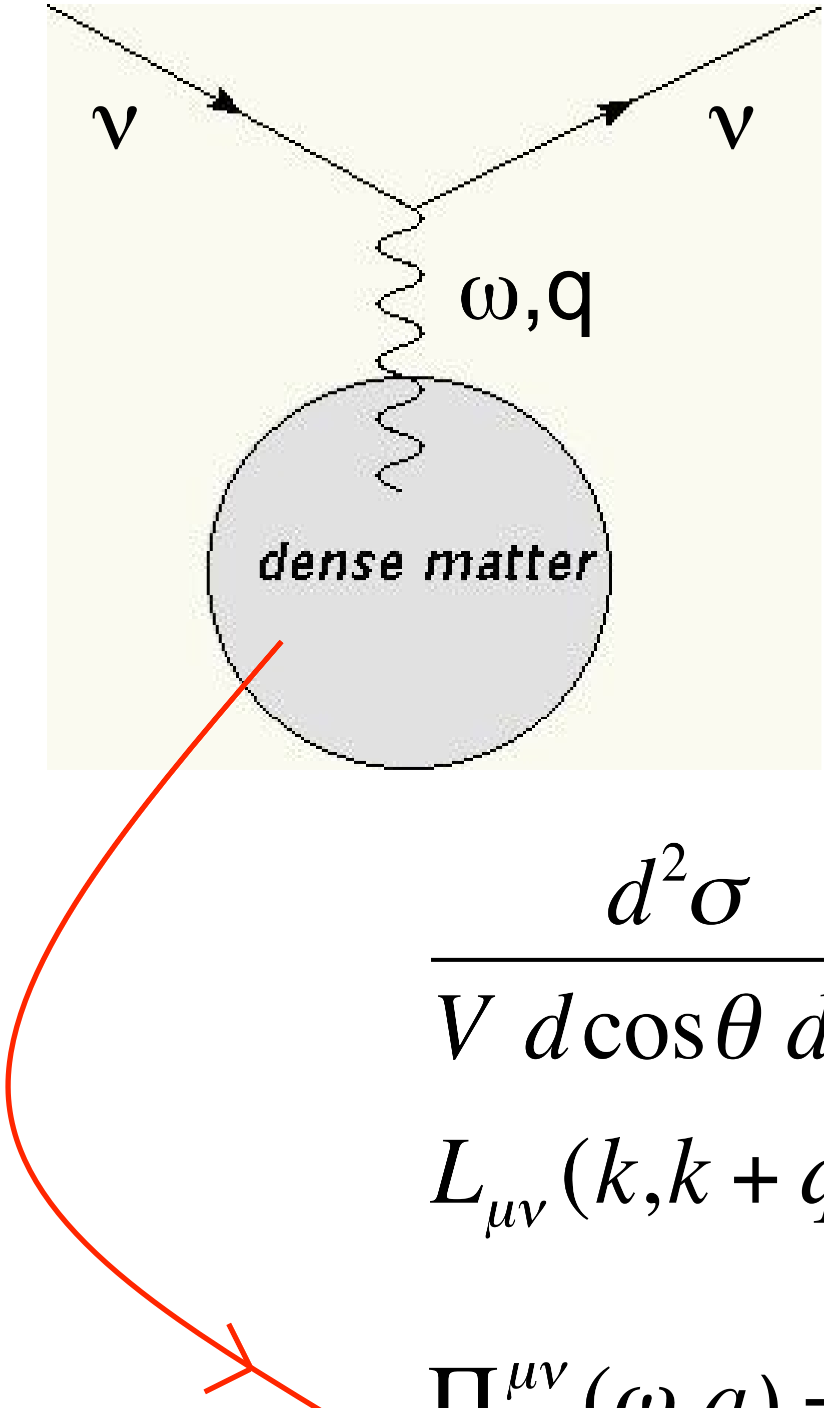
Sawyer (1975, 1989)
Iwamoto & Pethick (1982)
Horowitz & Wherberger (1991)
Burrows & Sawyer (1999)
Reddy, et al. (1998,1999,2000,2001,2002)

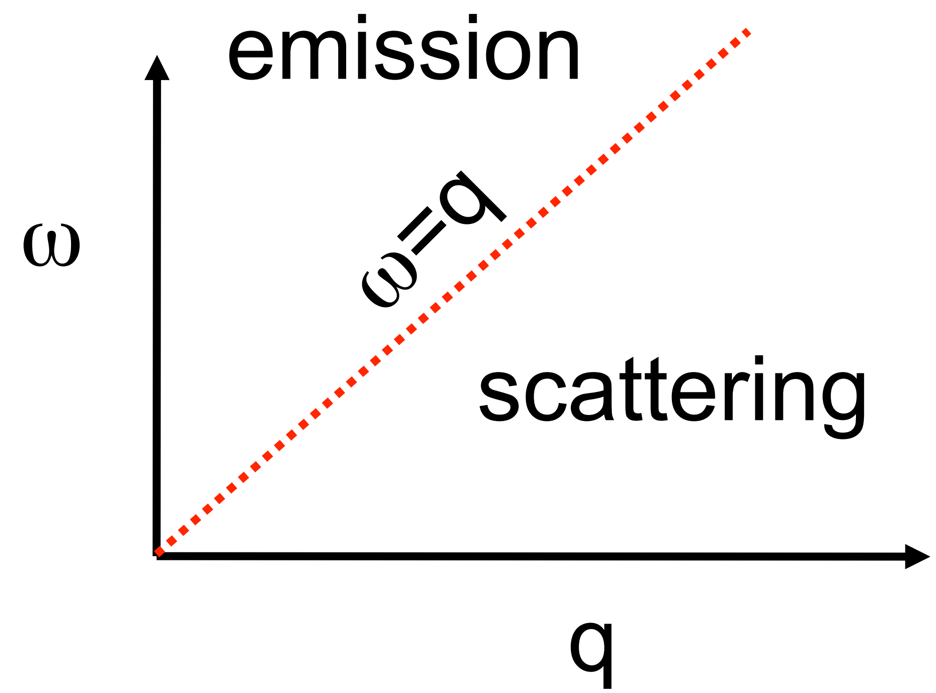
- Neutrinos "see" more than one particle in the medium.
- Nature of spatial and temporal correlations between nuclei, nucleons and electrons affect the scattering rate.
- Nucleon dispersion relation is altered. Energy shifts are important.

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

- Phase transitions to quark matter, matter with strangeness can greatly alter the neutrino mean free path.

Neutrino Rates





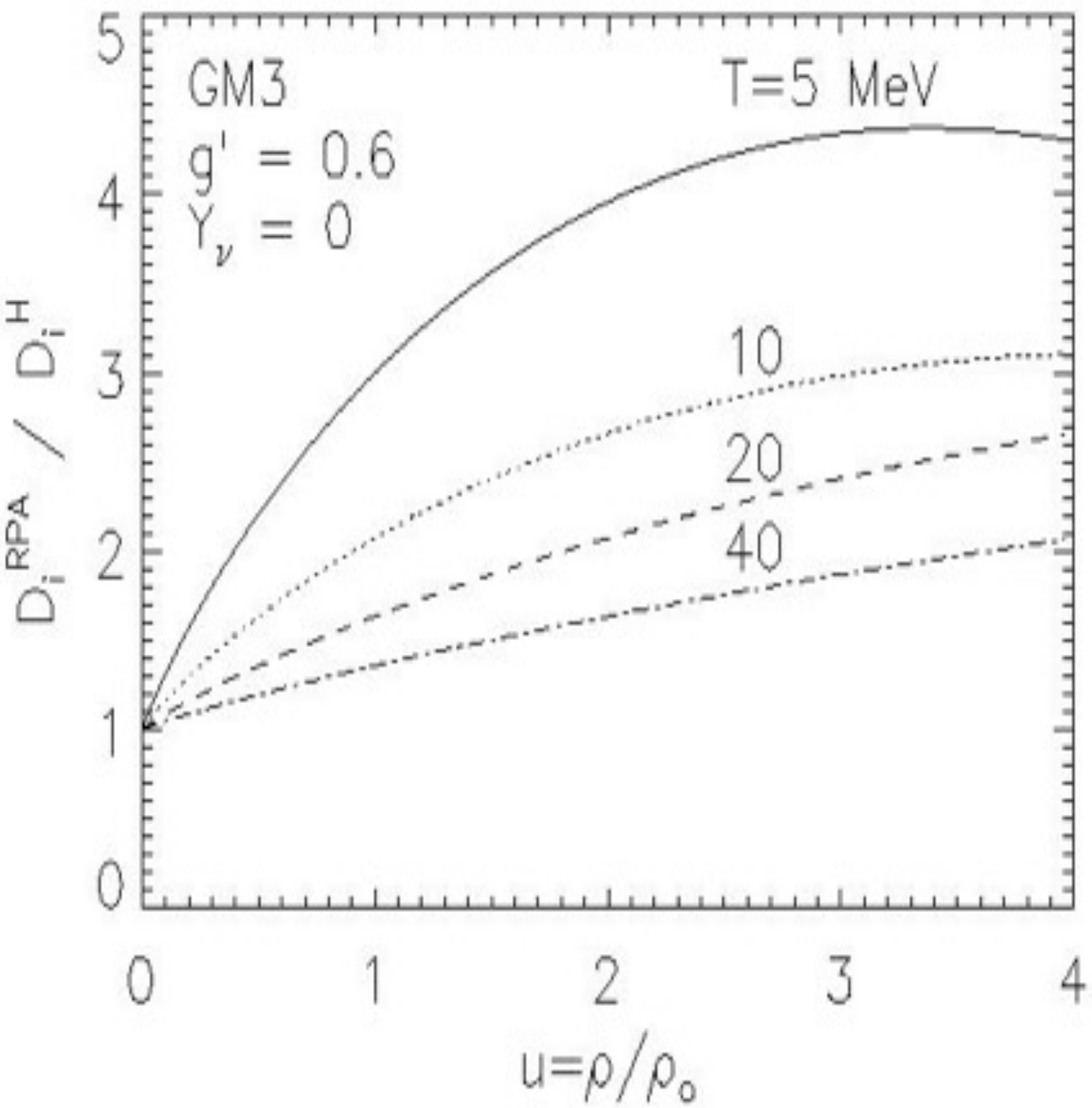
$$\frac{d^2\sigma}{V\, d\cos\theta\, dE'} \approx G_F^2 \frac{E}{E'} \mathrm{Im}\left[L_{\mu\nu}(k,k+q)\, \Pi^{\mu\nu}(q)\right]$$

$$L_{\mu\nu}(k,k+q) = \mathrm{Tr}\,[\, l_\mu(k)\; l_\nu(k+q)\,]$$

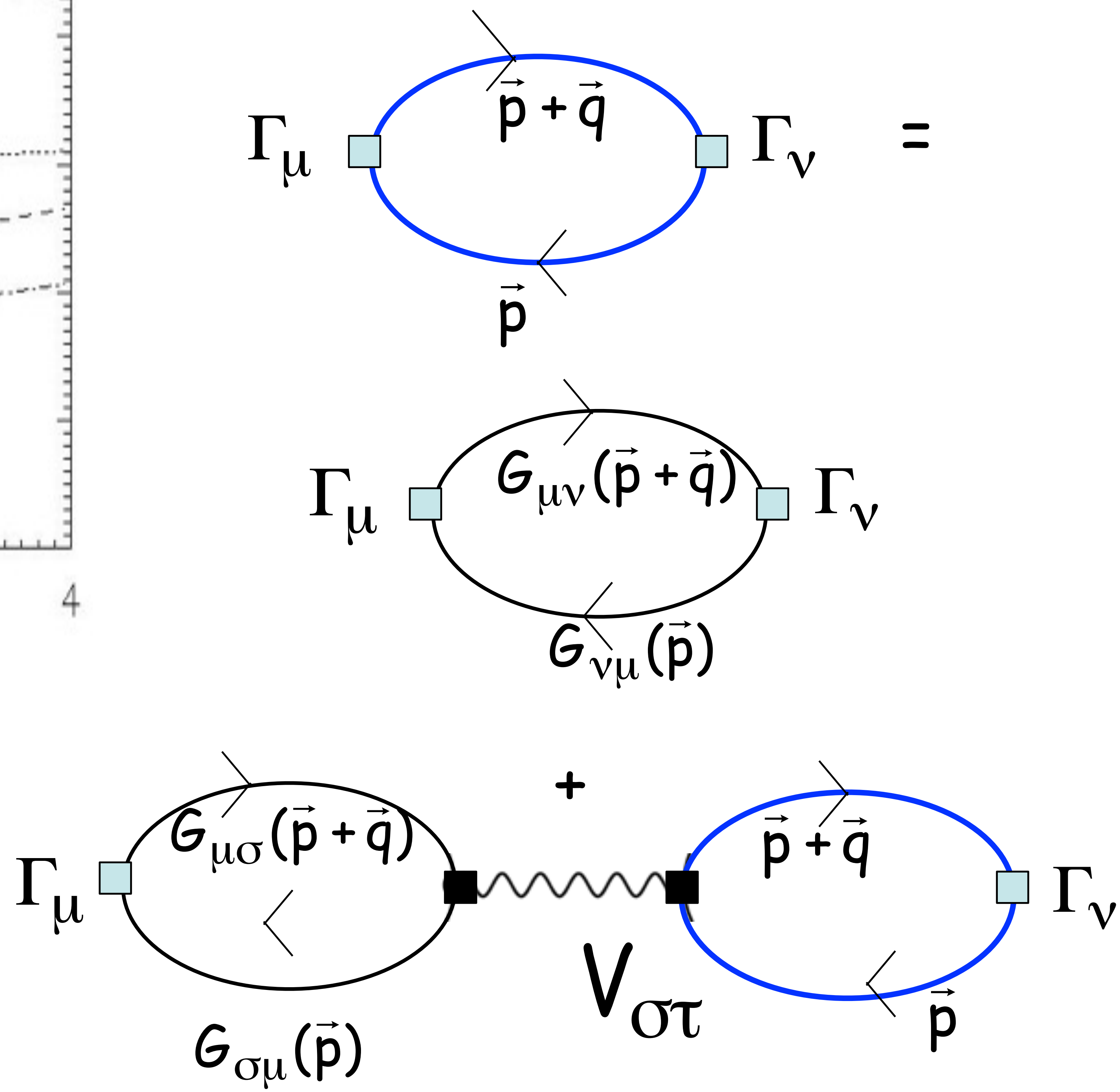
$$\Pi^{\mu\nu}(\omega,q) = \int \frac{d^4p}{(2\pi)^4}\, \mathrm{Tr}\,[\, j^\mu(p)\;\; j^\nu(p+q)\,]$$

Dynamic structure factor:
spectrum of density, spin and current fluctuations.

Neutrino Diffusion Enhanced by Nuclear Correlations

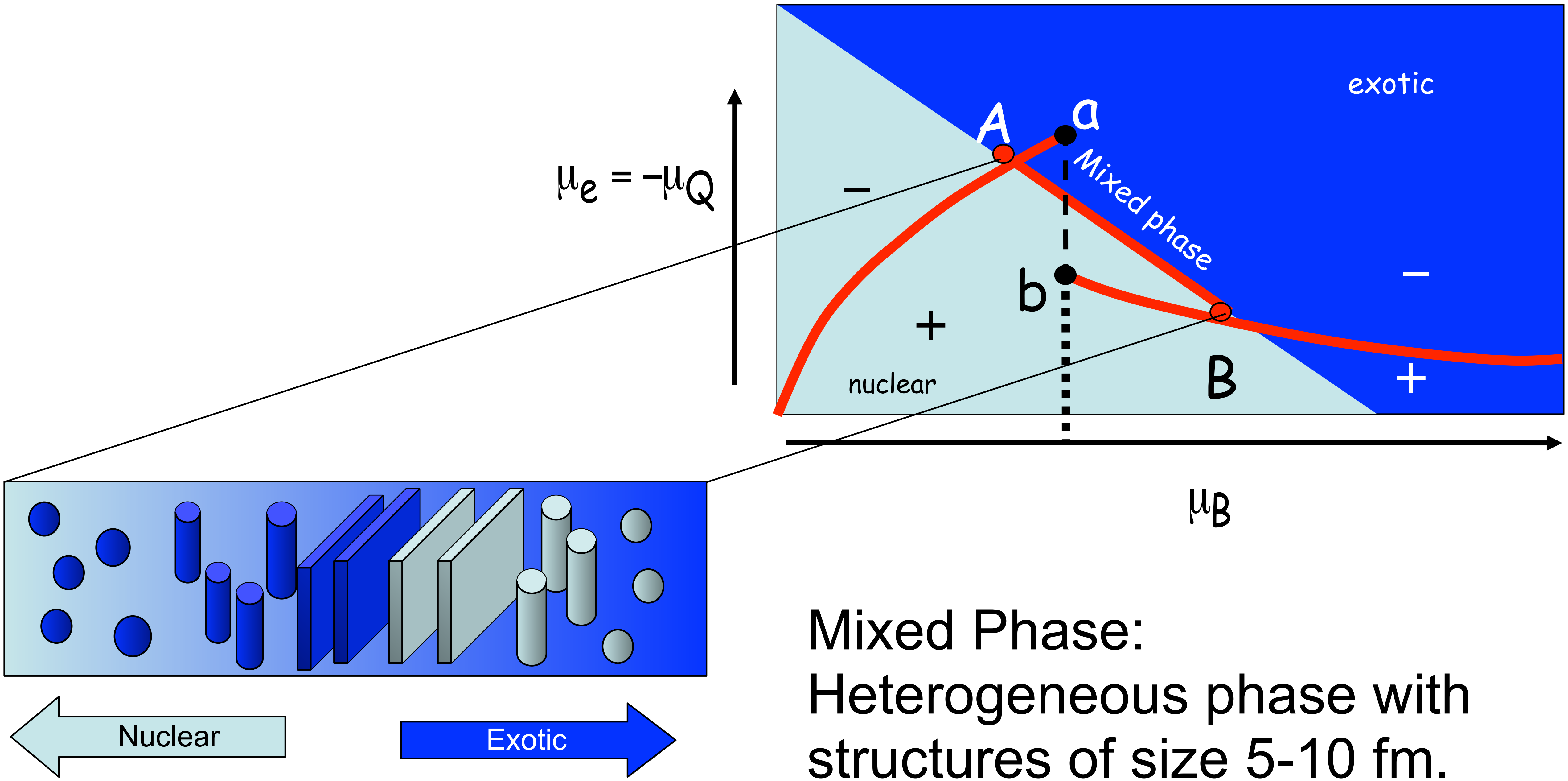


$$\Pi^{\mu\nu}(\omega, q) =$$



Horowitz & Wehrberger, (1991)
Burrows & Sawyer, (1999)
Reddy, Pons, Prakash, Lattimer, (1998,1999)

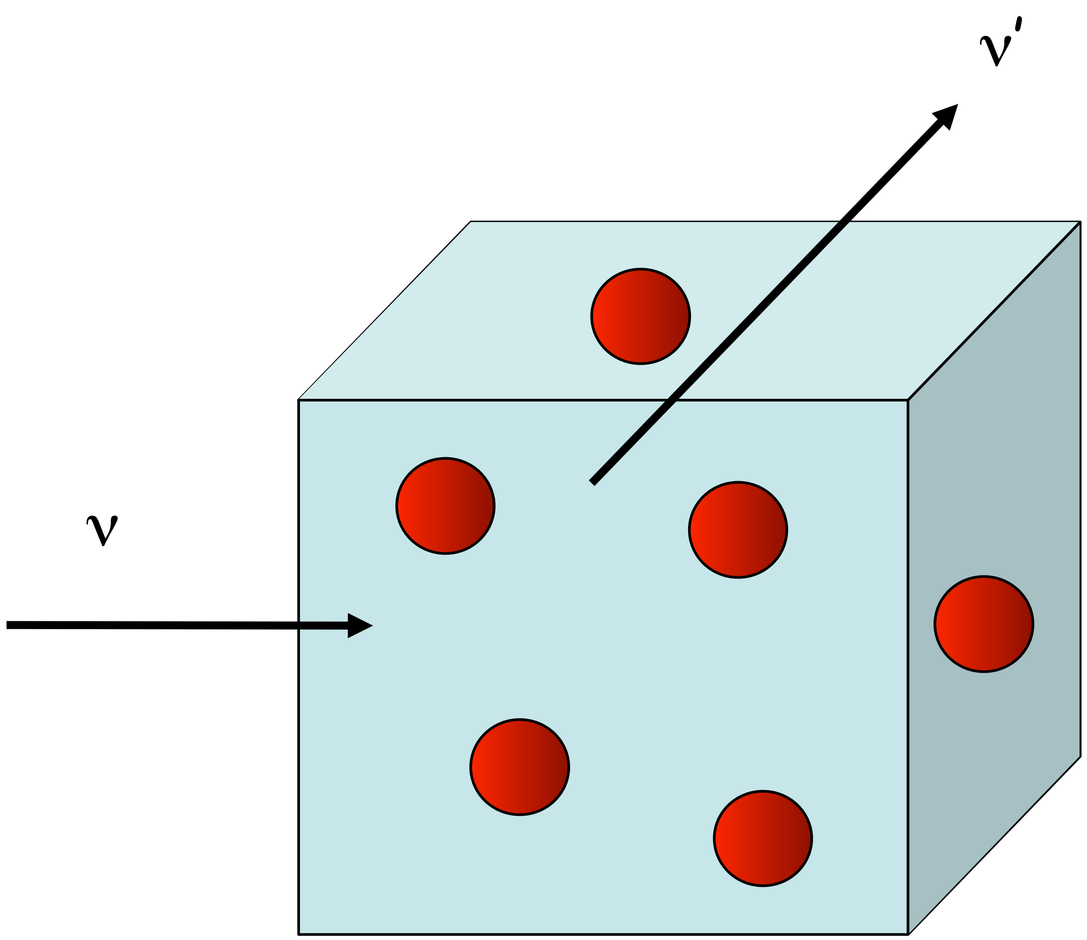
First-Order Phase Transitions in the PNS Core

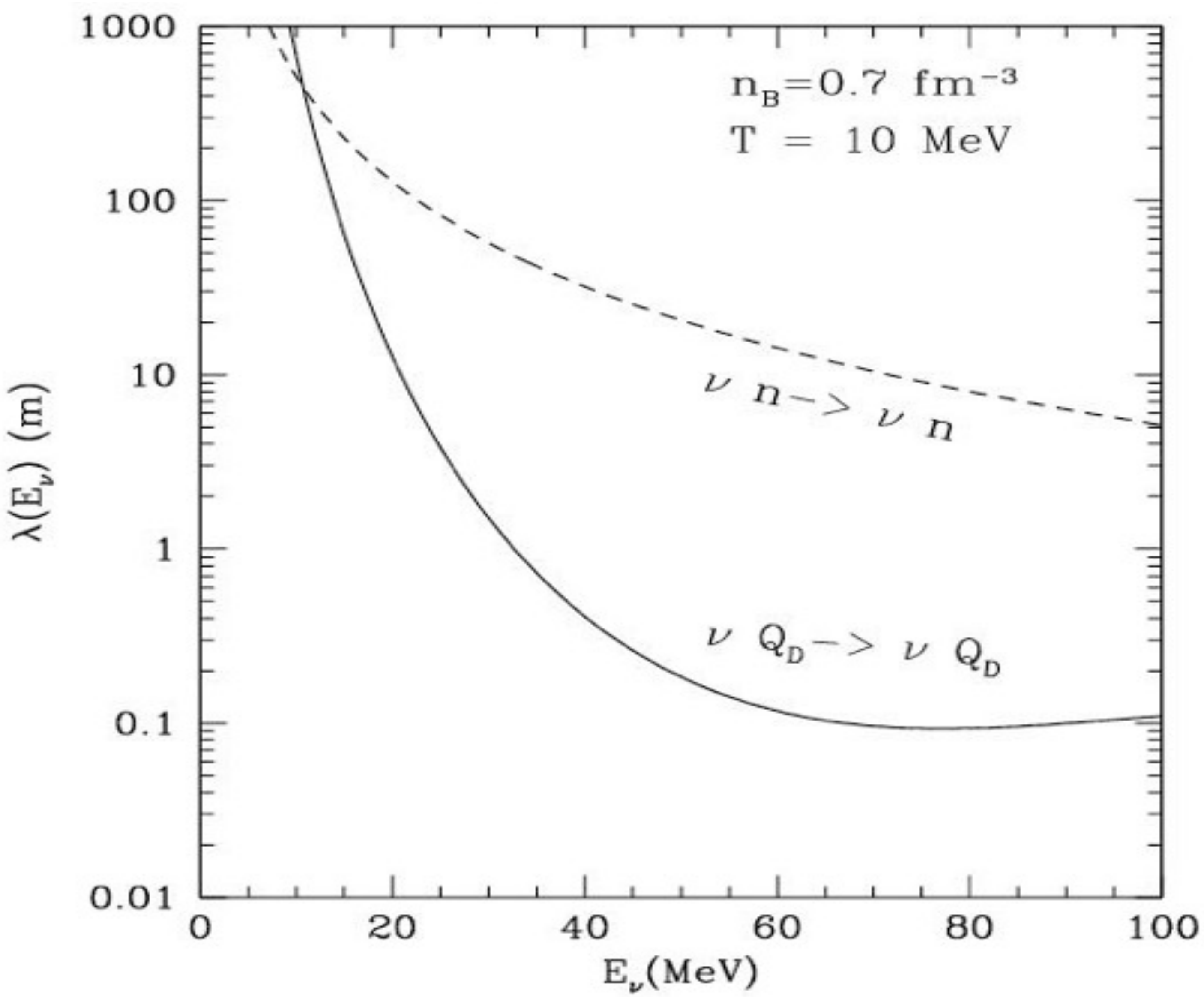


Mixed Phase:
Heterogeneous phase with structures of size 5-10 fm.

Reddy, Bertsch & Prakash, (2000)

Neutrino Mean Free Path in a Mixed Phase





Scattering from quark droplets in a quark-hadron transition.

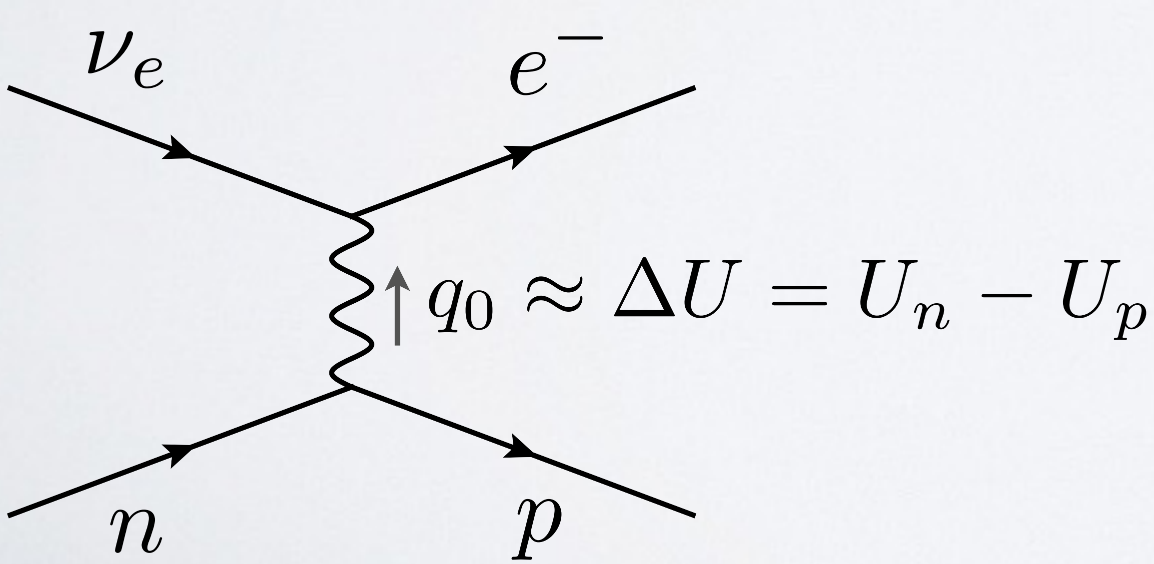
$$\frac{d\sigma}{d\cos(\theta)} = N_D \frac{G_F^2}{16\pi} S_q \, Q_W^2 E_\nu^2 (1 + \cos(\theta))$$

Reddy, Bertsch & Prakash, (2000)

Charged Current Reactions

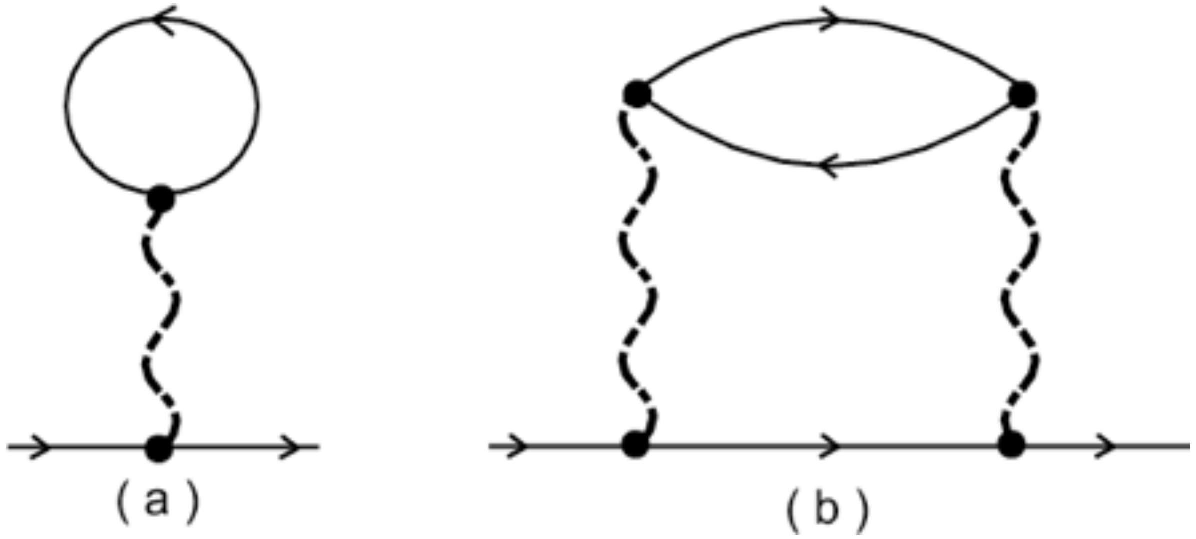
$$\begin{cases} \nu_e + n \rightarrow p + e^- \\ \bar{\nu}_e + p \rightarrow n + e^+ \end{cases}$$

- Determine the electron neutrino spectra and deleptonization times.
- Final state electron blocking is strong for electron neutrino absorption reaction.
- Asymmetry between mean field energy between neutrons and protons alters the kinematics.



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

SINGLE PARTICLE 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:

$$q_0 = E_n(p) - E_p(p+q) \simeq \frac{pq}{2m_n^*} + (m_n - m_p) + (U_n - U_p)$$

$$\approx 0 \qquad \simeq 1.3 \text{ MeV}$$

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

Y_e in the Neutrino Driven Wind

Is set by the charged current reactions in two regions.

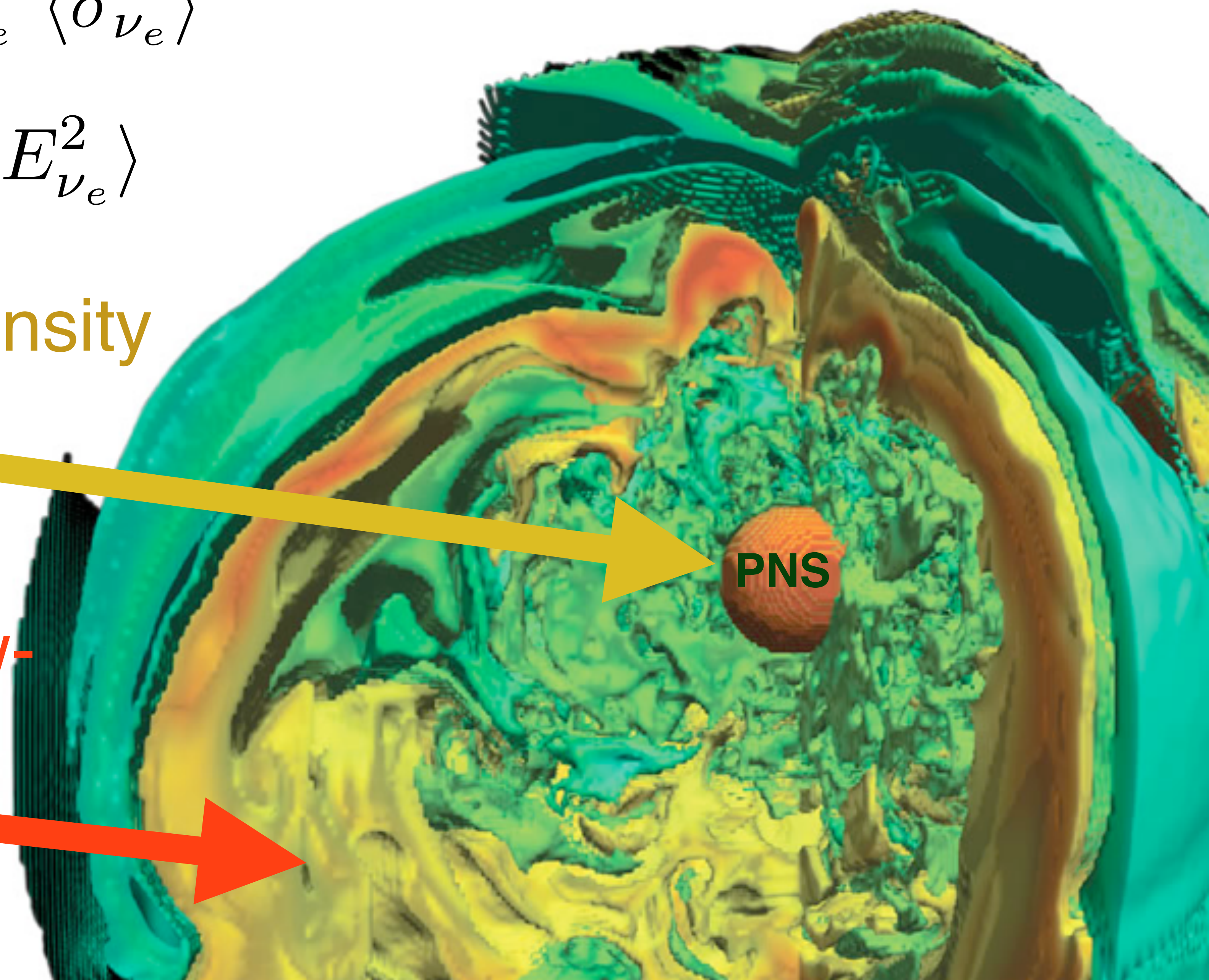
$$\left\{ \begin{array}{l} \bar{\nu}_e + p \rightarrow n + e^+ \\ \nu_e + n \rightarrow p + e^- \end{array} \right.$$

$$Y_e^{\rm NDW} \approx \frac{\dot{N}_{\nu_e} \langle \sigma_{\nu_e} \rangle}{\dot{N}_{\bar{\nu}_e} \langle \sigma_{\bar{\nu}_e} \rangle + \dot{N}_{\nu_e} \langle \sigma_{\nu_e} \rangle}$$

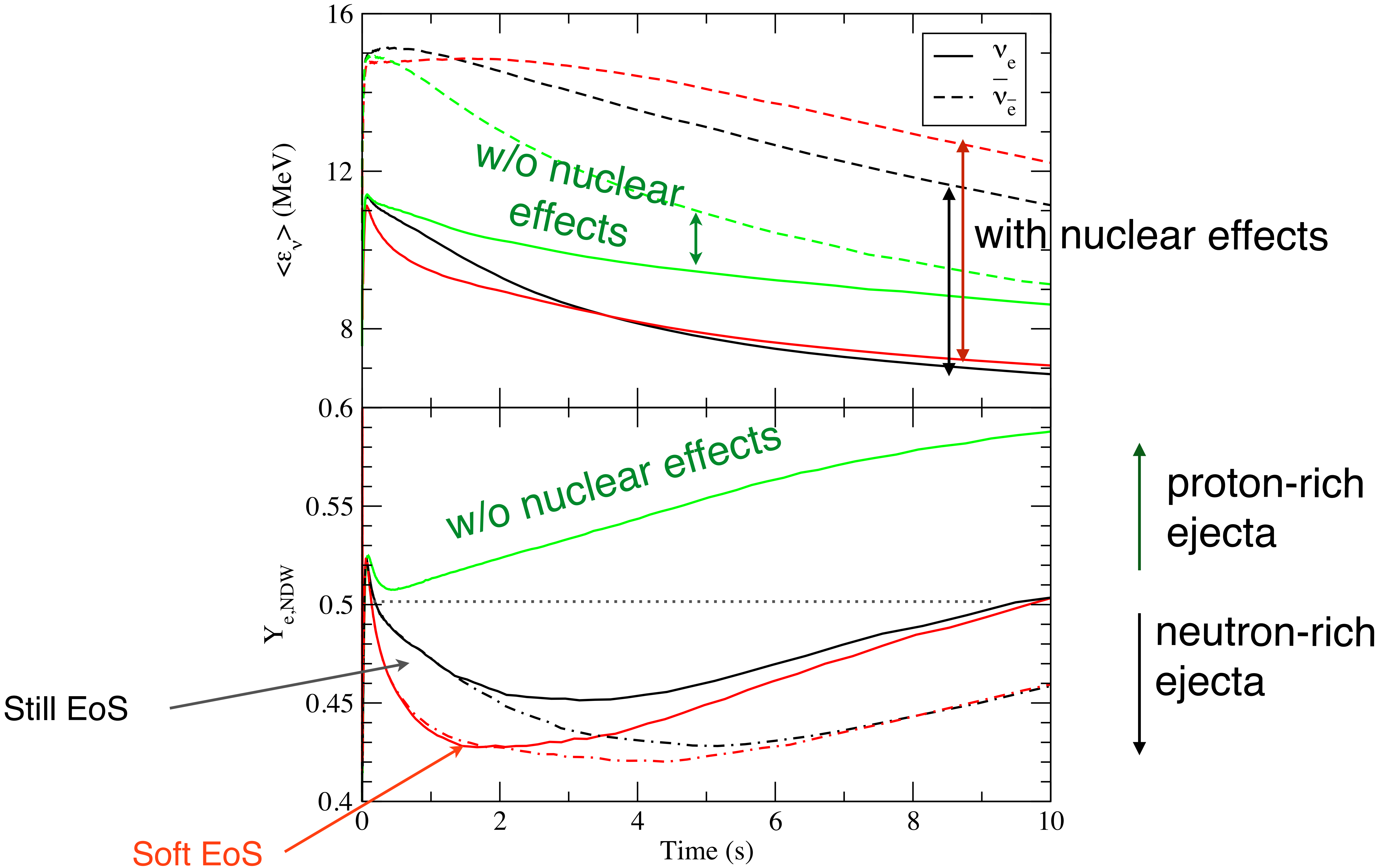
$$\langle \sigma_{\bar{\nu}_e} \rangle \propto \langle E^2_{\bar{\nu}_e} \rangle \qquad \langle \sigma_{\nu_e} \rangle \propto \langle E^2_{\nu_e} \rangle$$

Neutrino-sphere at high density and moderate entropy.
R ~ 10-20 km

Neutrino driven wind at low-density and high entropy.
R ~ 10^3-10^4 km

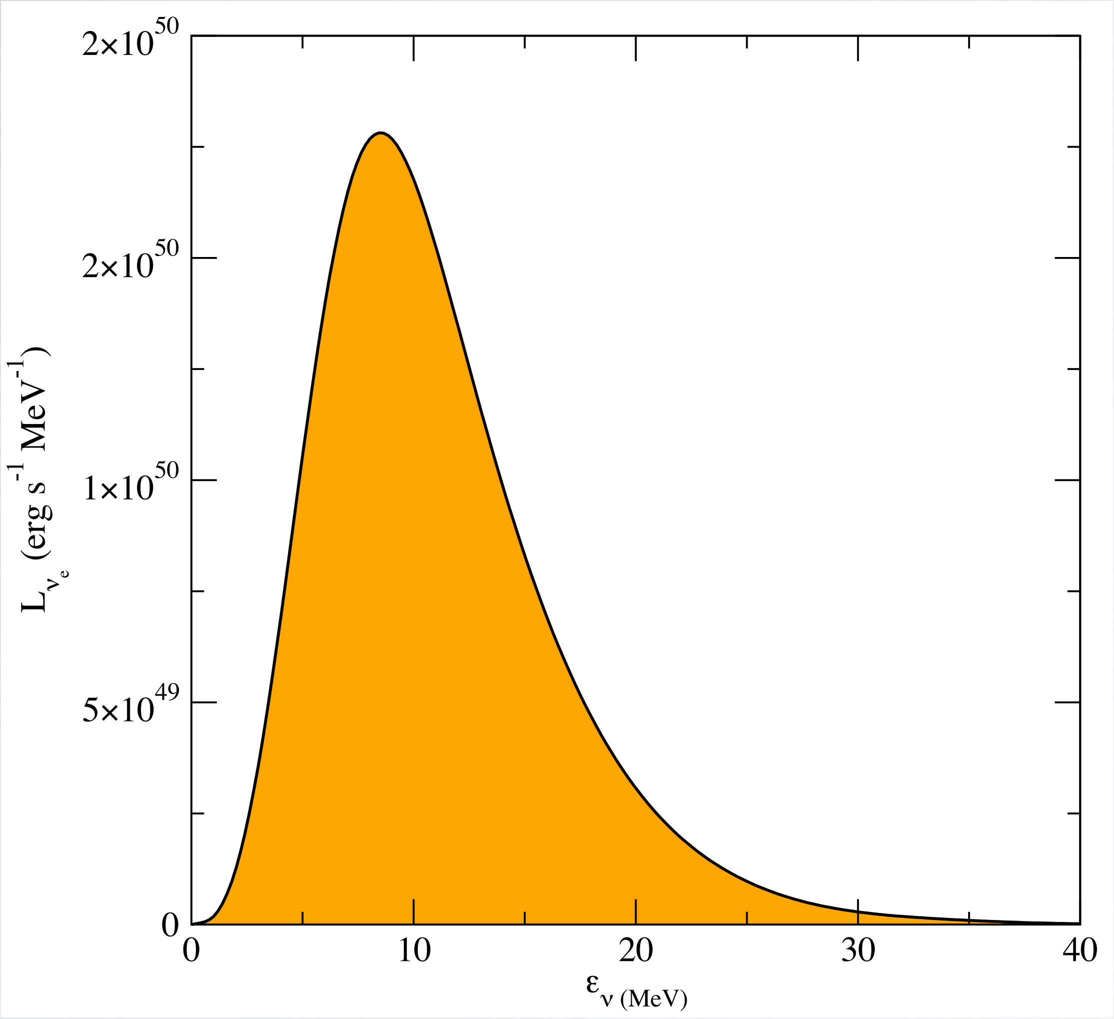


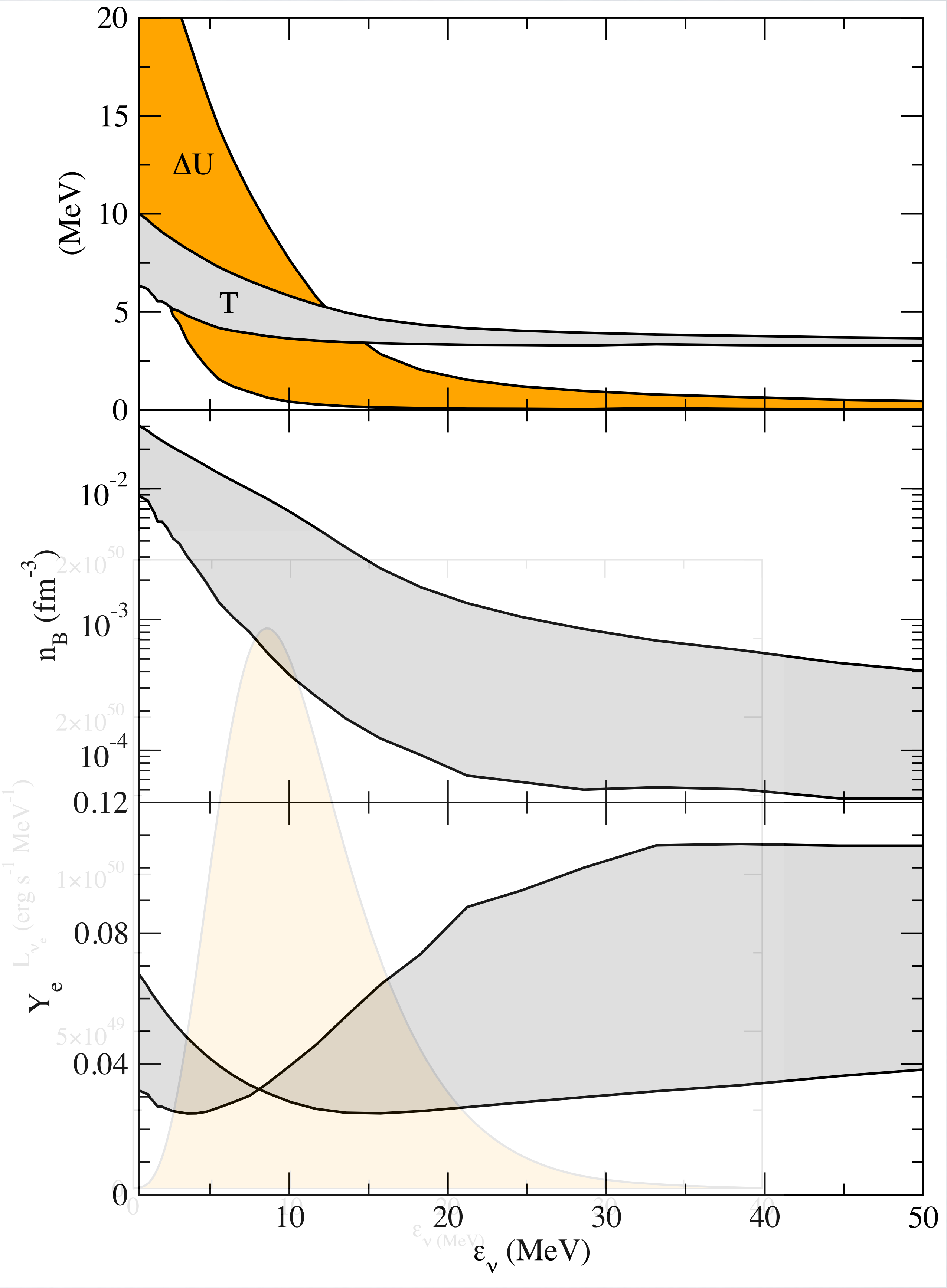
Spectra & Nucleosynthesis



Roberts, Reddy & Shen (2012)

Spectra at late times





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

Figures from PNS simulations by Roberts (2012)

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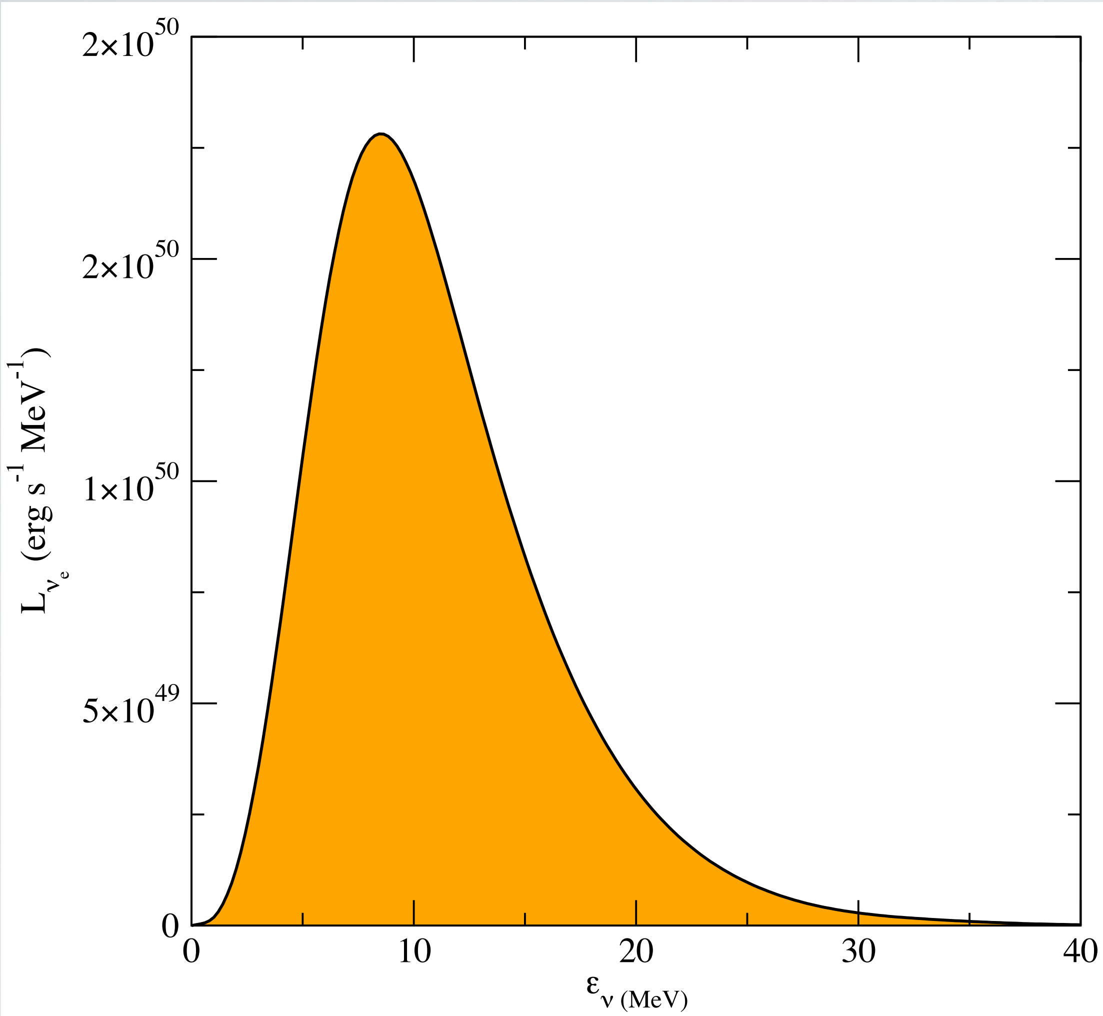

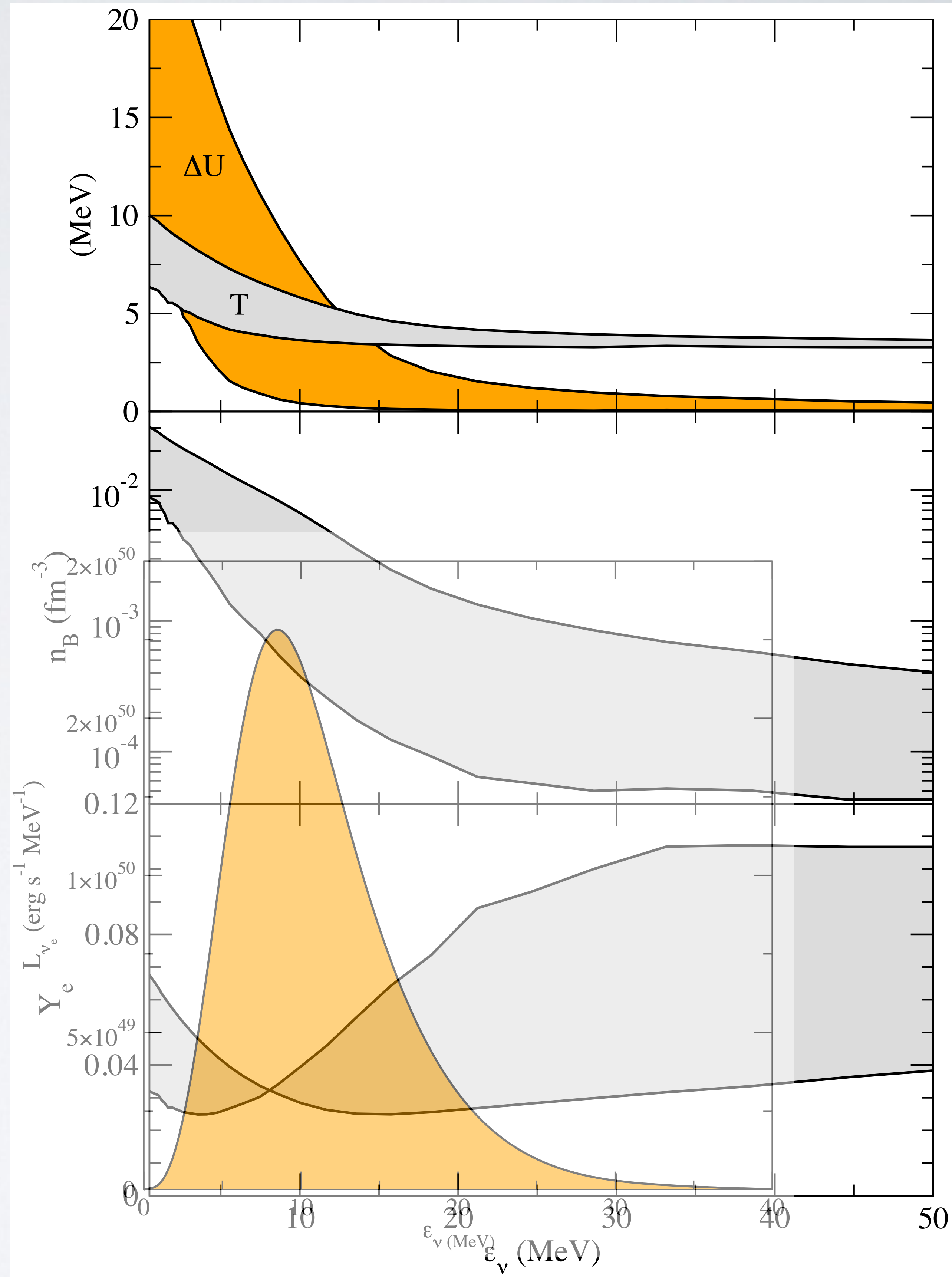

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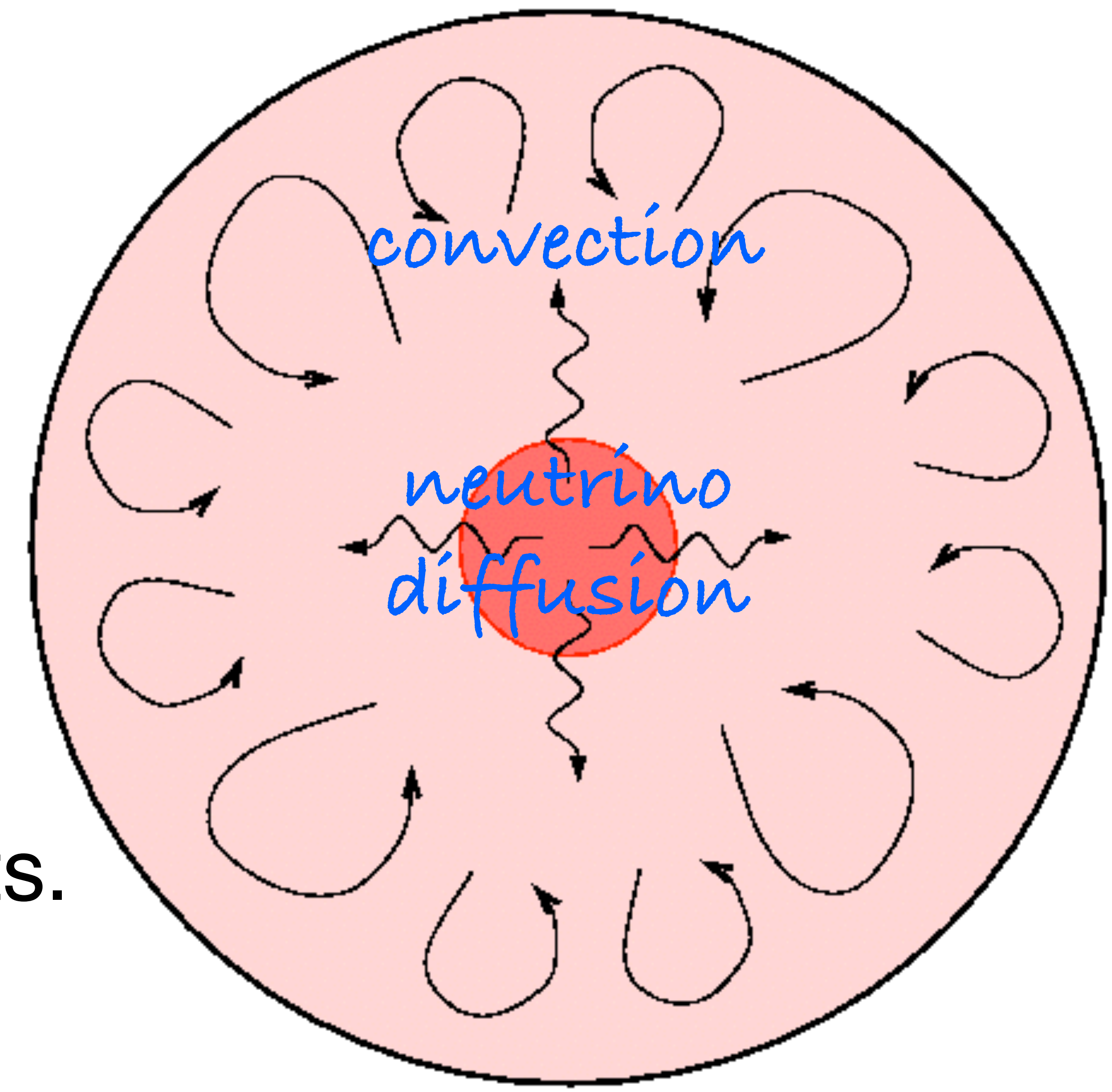
Figures from PNS simulations by Roberts (2012)

PNS evolution: Role of EoS.

Heat transport : Neutrino diffusion + convection

Diffusion:

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



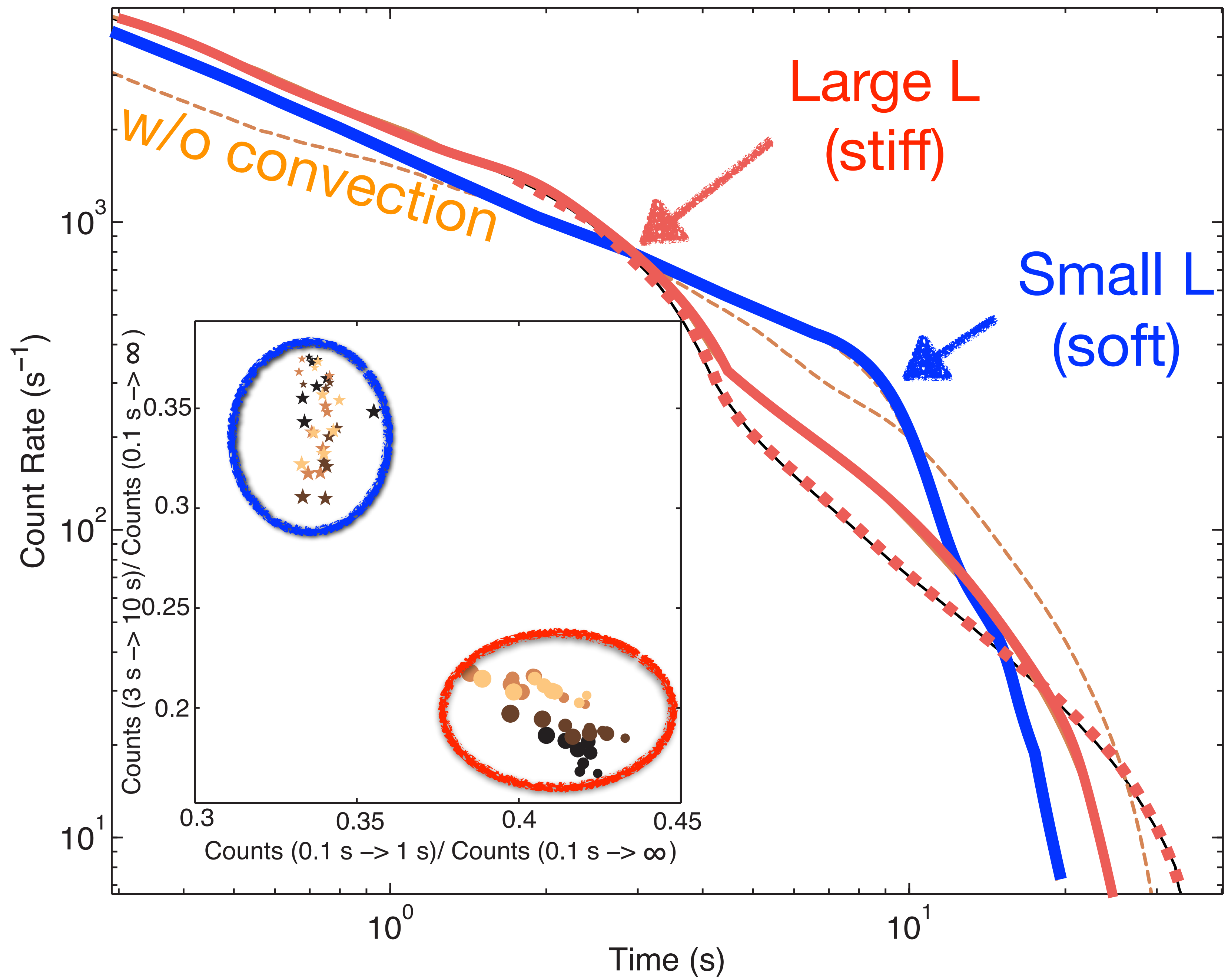
Convection:

Convection is driven by composition and entropy gradients.

The buoyancy of matter depends nuclear equation of state.

Observable signatures of convective transport

- Neutrino flux is enhanced during convection.
- There is break in the light curve (when convection ends).
- Fraction of events between 3-10 s provides good discrimination.



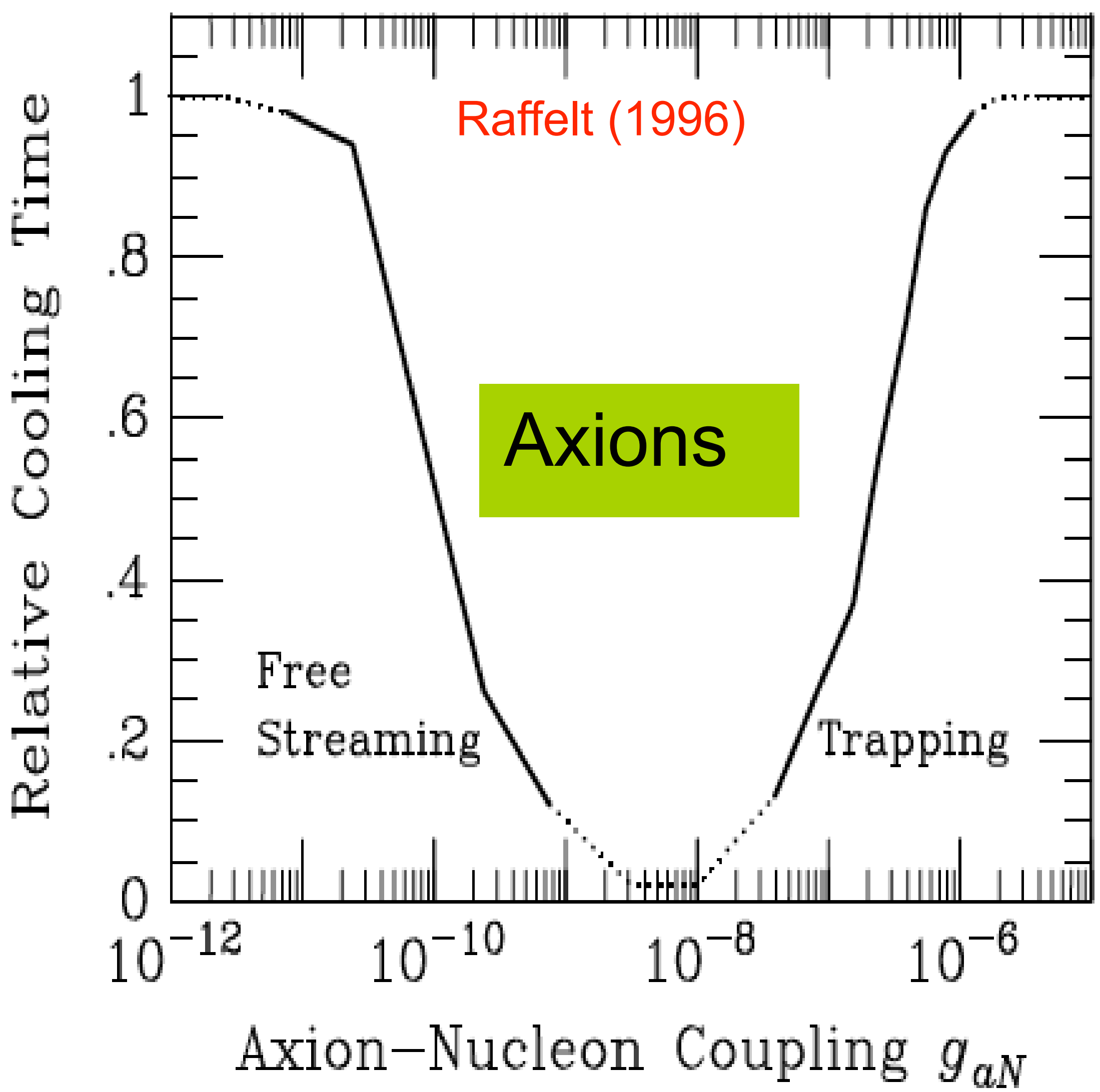
Count rate in Super-Kamiokande for galactic supernova at 10 kpc.

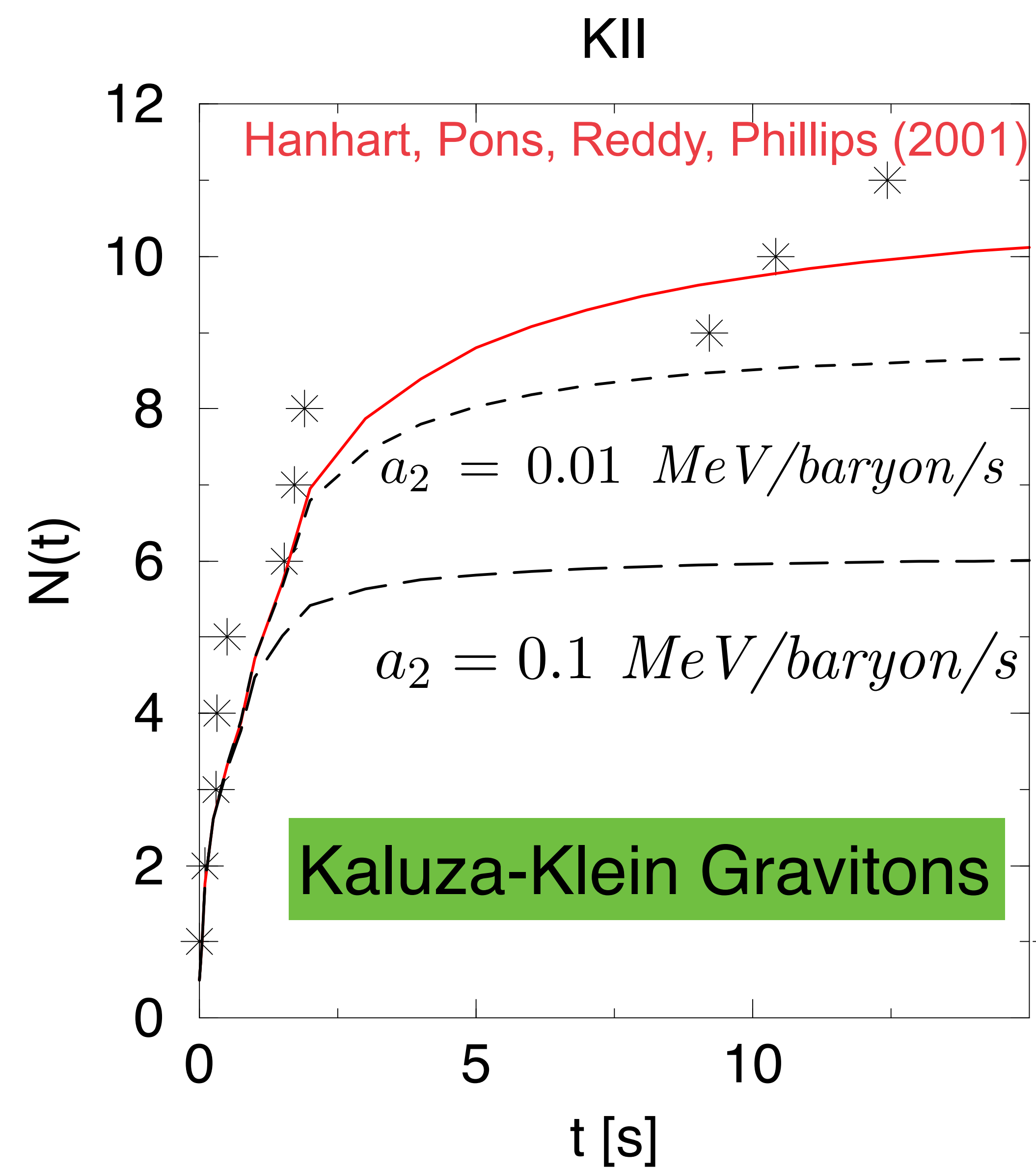
Roberts, Cirigliano, Pons, Reddy, Shen, Woosley (2012)

Hypothetical Weakly Interacting Particles

Since neutrinos are trapped for ~20 s a new particle that couples more weakly to matter can radiate away the binding energy.

When this energy loss > 10^{19} ergs/g/s it will shorten the neutrino time scale by a factor of 2.





$$\frac{dE}{dt} = a_n \left(\frac{n_B}{n_0}\right)\left(\frac{T}{10\ \mathrm{MeV}}\right)^{p_n} \chi(X_n, X_p) \quad \mathrm{MeV/baryon/s}$$

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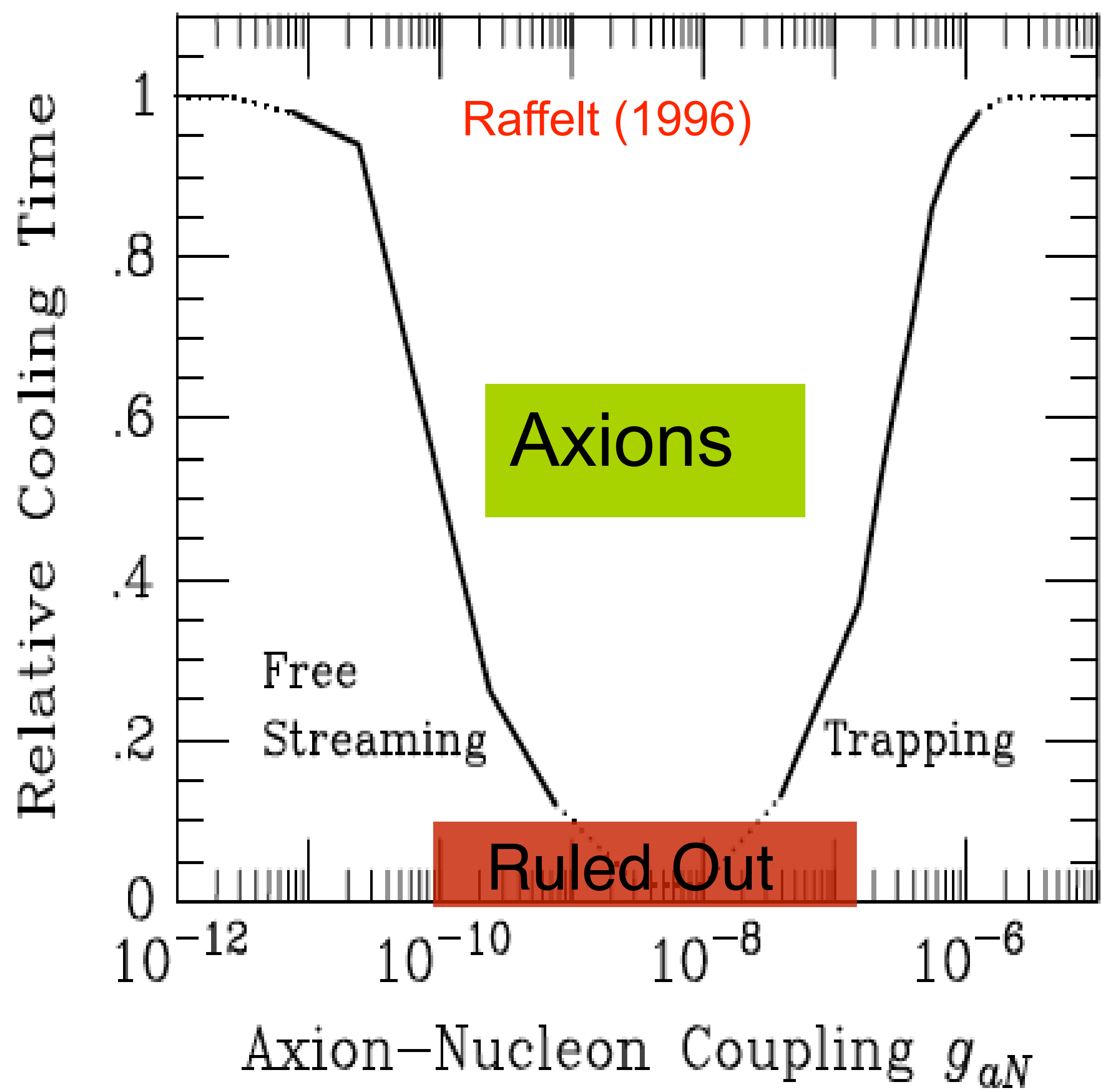

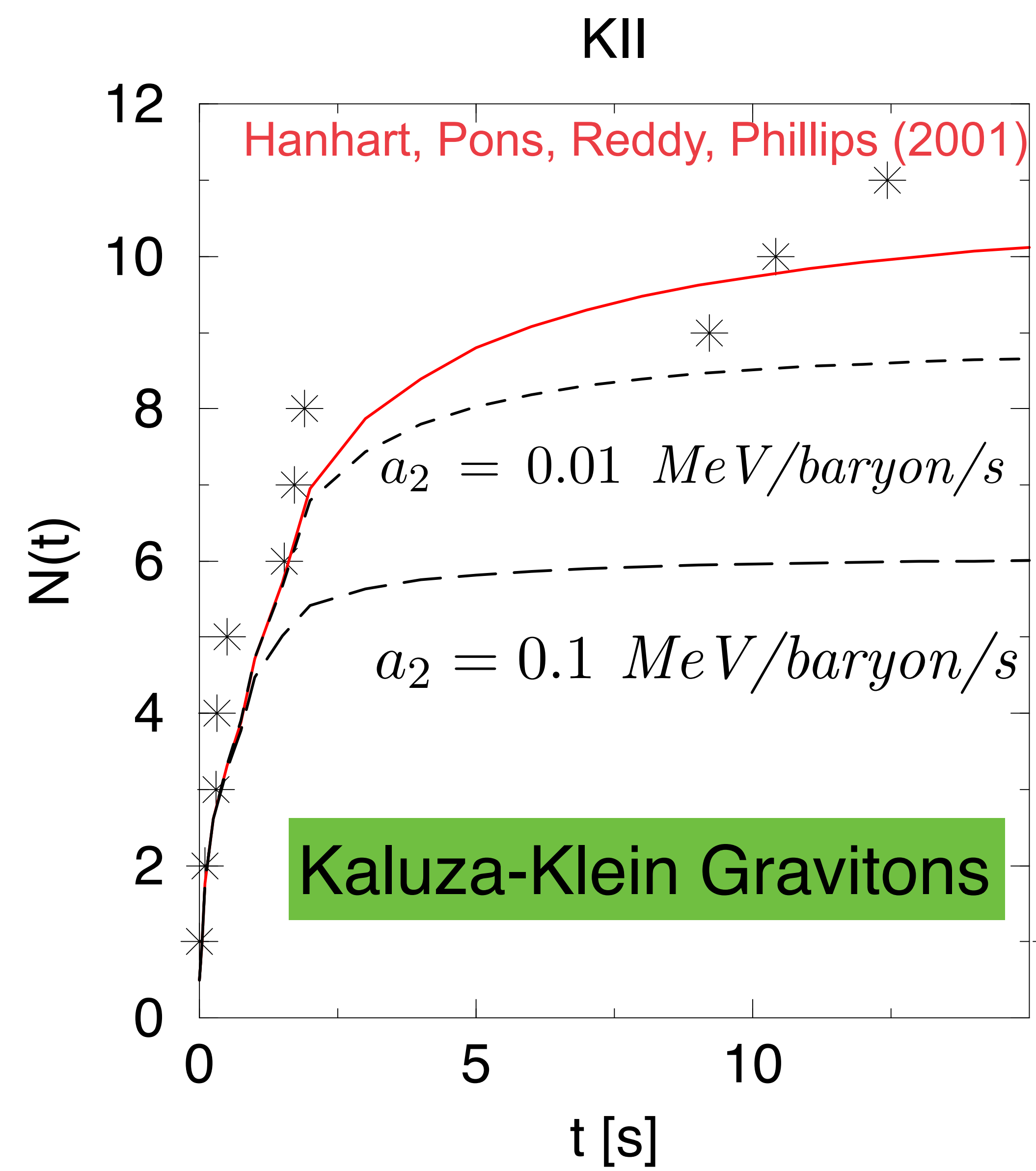

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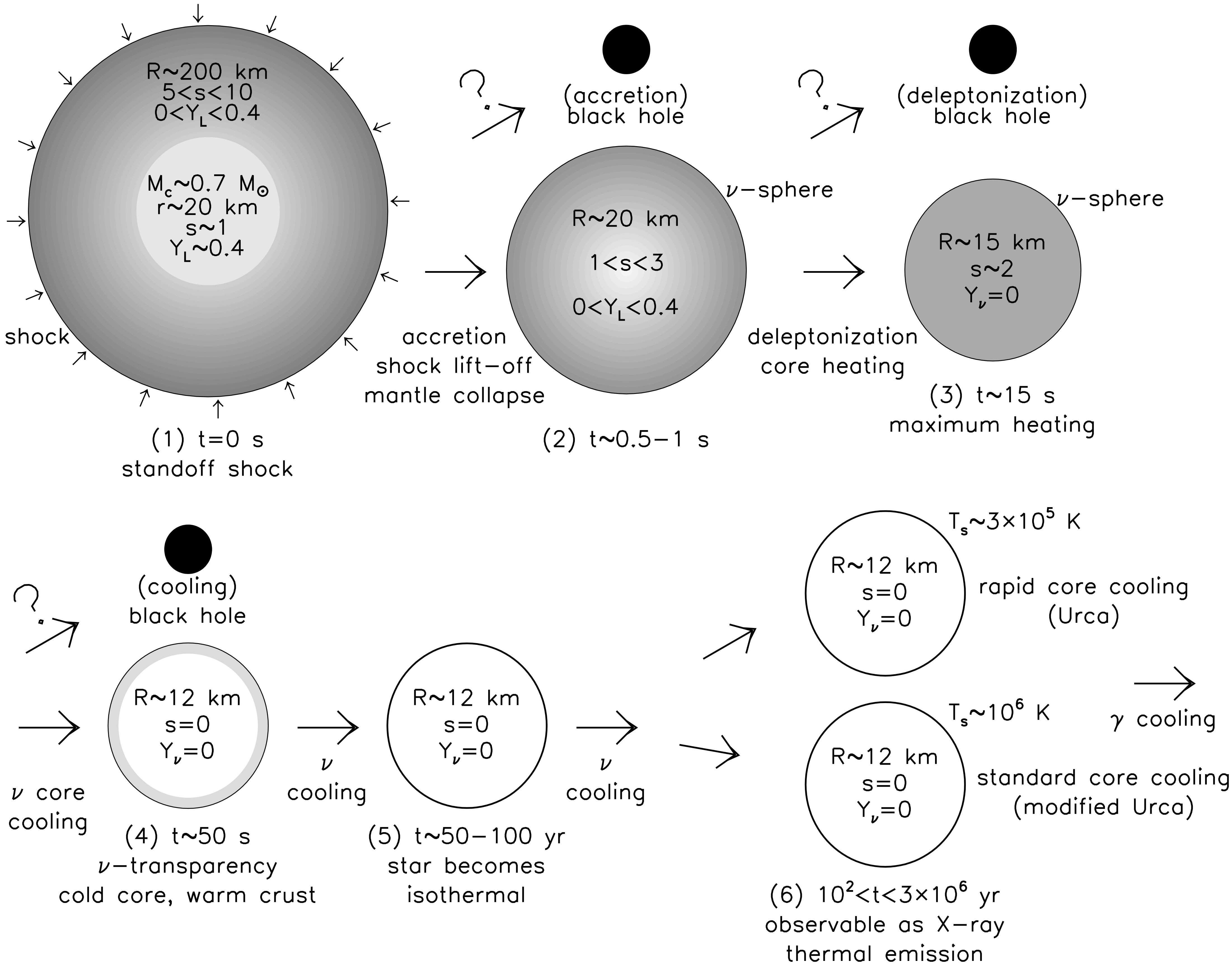
SN neutrinos can reveal early evolution of a neutron star



Prakash, Lattimer, Pons, Steiner and Reddy, astro-ph/0012136