Dear friends and colleagues of George Bertsch--

I regret I can not attend this symposium because of the much less pleasurable task of having to attend an NSAC subcommittee meeting this weekend, but I want to tell you all what a great pleasure it is having a colleague I can respect as much as I respect George, for his curiosity and interest in so many branches of physics, for his deep insights, and for his unwavering scientific integrity.

I also remember fondly that couple of time we have skied down Mt. Rainier together from Camp Muir!

Happy Birthday, George! -David Kaplan

SAVING THE SUPERNOVA R-PROCESS: CAN NUCLEAR PHYSICS INTERVENE AT LATE TIME ?

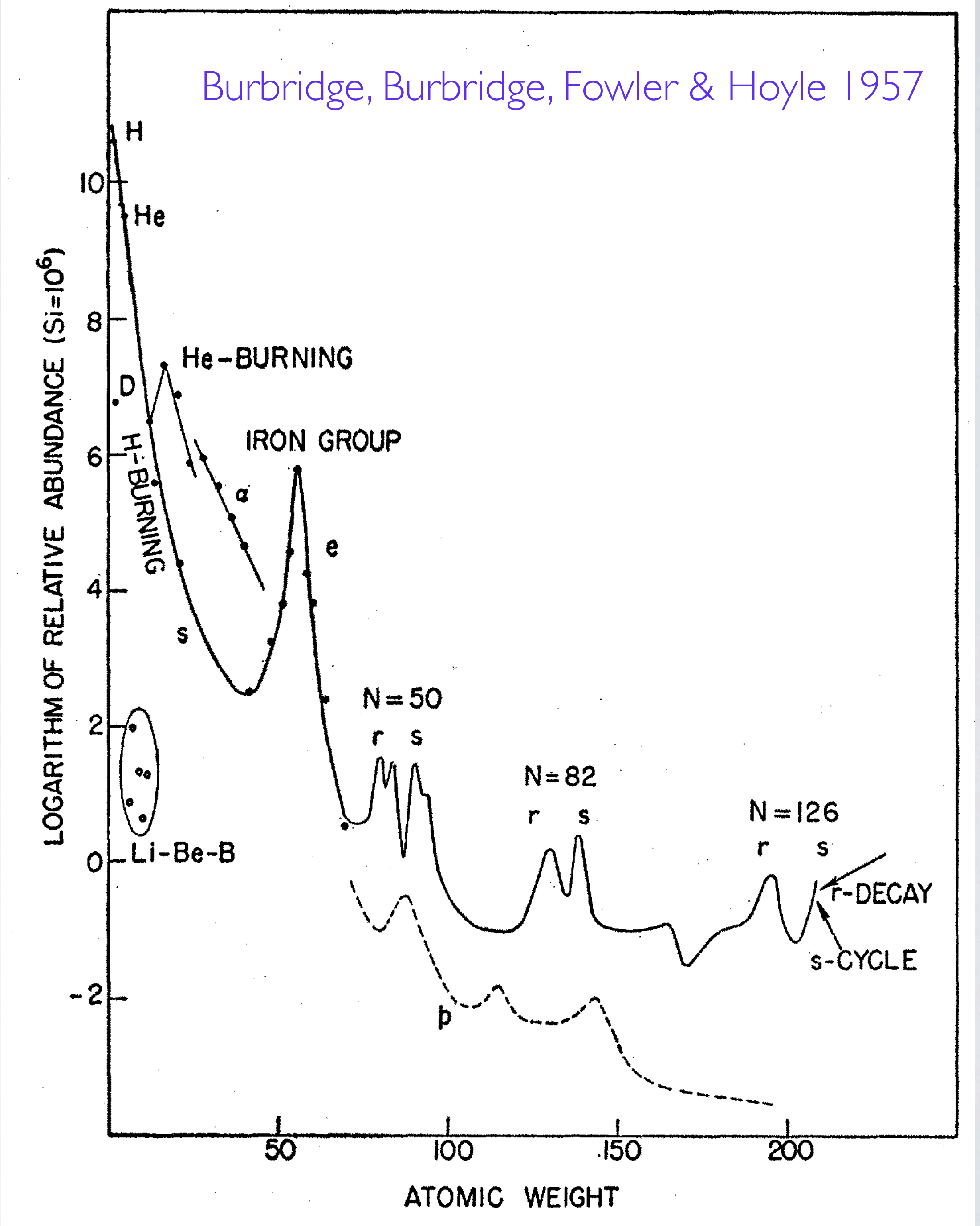
Sanjay Reddy (INT)

Collaborators:

Luke Roberts

(UCSC, now Caltech)

Gang Shen (INT)



George Fest, Seattle, Sept. 7-9 (2012)

ITS ABOUT THE $\sigma\tau$ RESPONSE OF NUCLEAR MATTER !

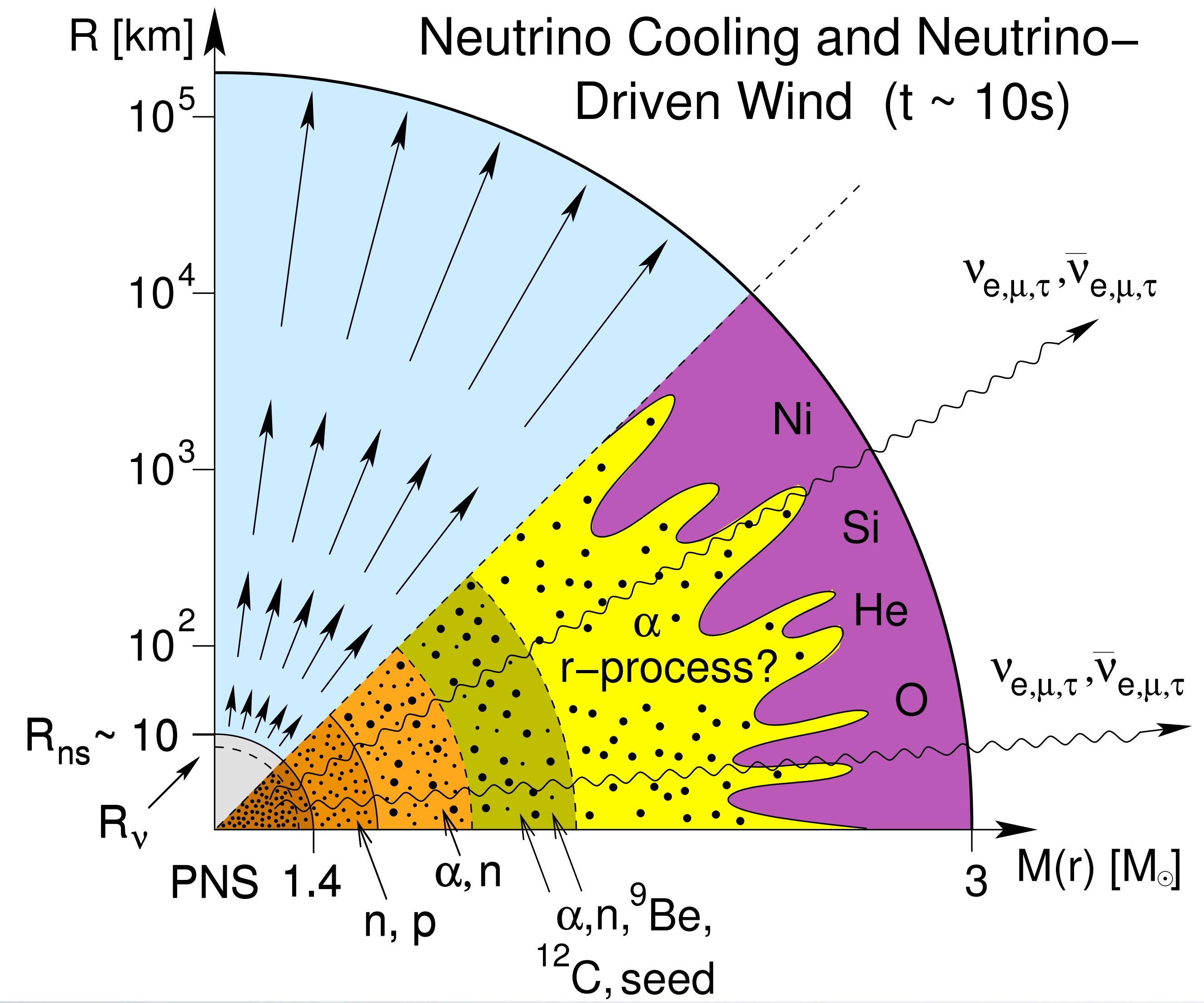
1975PhR....18..125B	202.000 05/1975
Bertsch, G. F.;Tsai, S. F.	A study of the nuclear response function
1975NuPhA.243..507S	158.000 05/1975
Shlomo, S.;Bertsch, G.	Nuclear response in the continuum
1984PhLB..146..138S	88.000 10/1984
Sagawa, H.;Bertsch, G. F.	Self-consistent calculations of finite temperature nuclear response function
1984AnPhy.157..255E	76.000 10/1984
Esbensen, H.;Bertsch, G. F.	Surface response of Fermi liquids
1999PhRvA..60.3809Y	46.000 11/1999
Yabana, K.;Bertsch, G. F.	Optical response of small silver clusters
1974AnPhy..86..138B	36.000 07/1974
Bertsch, G. F.	Elasticity in the response of nuclei
1985PhRvC..31.1816E	35.000 05/1985
Esbensen, H.;Toki, H.; Bertsch, G. F.	Surface effects on the isovector spin response induced by high energy protons
1985PhRvB..32.7659B	31.000 12/1985
Bertsch, G.;Ekardt, W.	Application of sum rules to the response of small metal particles
2006PSSBR.243.1121Y	25.000 00/2006
Yabana, K.;Nakatsukasa, T.; Iwata, J.;Bertsch, G. F.	Real-time, real-space implementation of the linear response time-dependent density-functional theory
1997ZPhyD..42..219Y	20.000 00/1997
Yabana, K.;Bertsch, G. F.	Optical response of small carbon clusters
1973PhRvL..31..121B	14.000 07/1973
Bertsch, G. F.	Nuclear Response Function
1983PThPS..74..115B	13.000 00/1983
Bertsch, G. F.	The Nuclear Response Function
1985PhLB..161..248B	12.000 10/1985
Bertsch, G.;Esbensen, H.	The classical limit of the surface response in Fermi liquids
1999CoPhC.120..155J	7.000 08/1999
Johnson, C. W.;Bertsch, G. F.; Hazelton, W. D.	Lanczos algorithm and energy-weighted sum rules for linear response

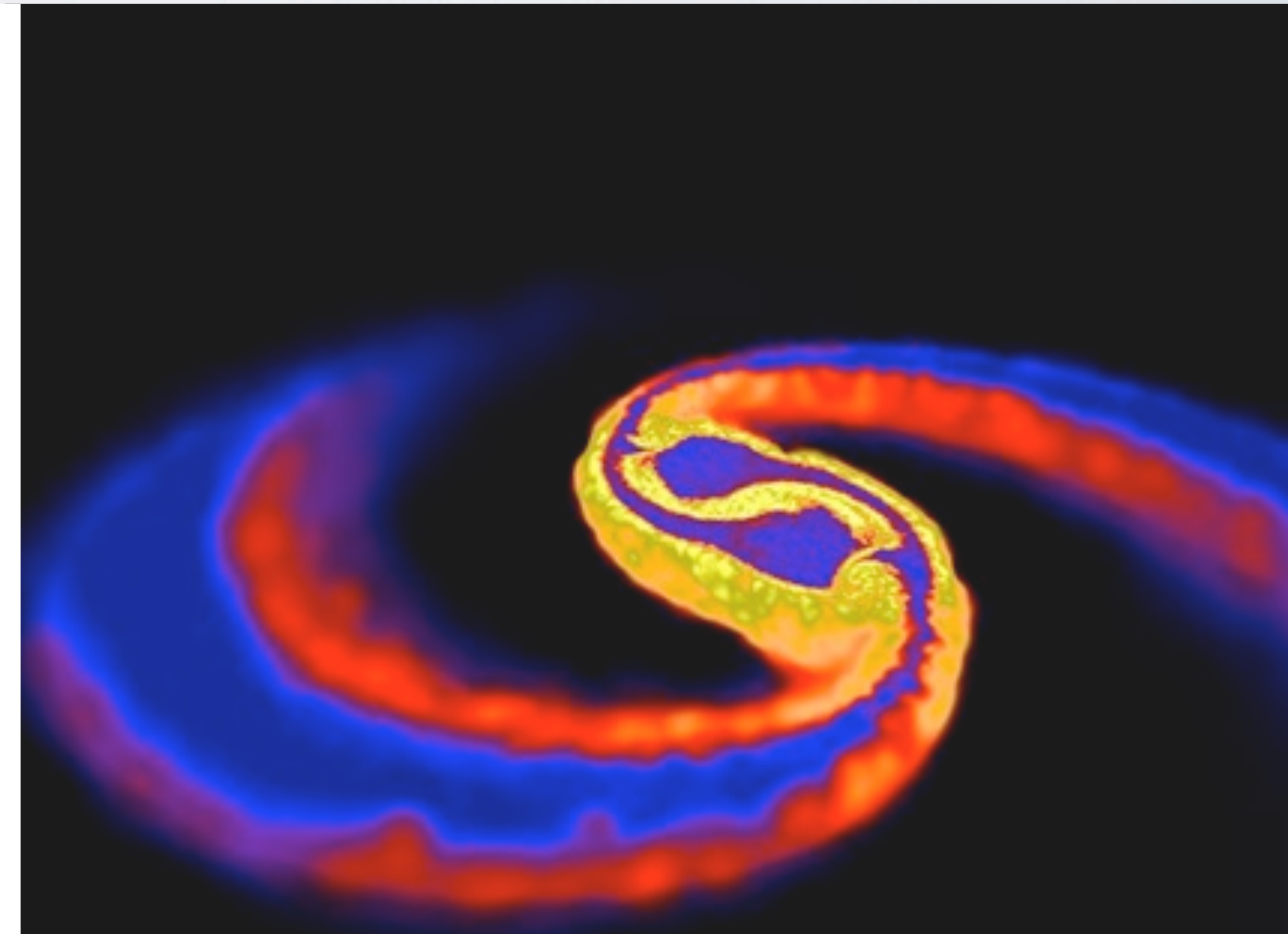
George made pioneering contributions to address this issue in nuclei more than 30 years ago !

WHERE ARE THE HEAVY (A>90) ELEMENTS MADE ?

There is general consensus that it involves either one or two neutron stars:

- The one neutron star scenario: Neutrino driven wind in a core-collapse supernova. **[Fragile]**
- The two neutron star scenario: Dynamical ejection of matter in binary neutron star mergers. **[Robust]**





Neutron-star merger simulation (S. Rosswog)

NECESSARY CONDITIONS

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.

} Hydrodynamics, Magnetic Fields, etc

- Low Y_e .

} Neutrino Spectra

What is the physics that determines the neutrino spectra emerging from the proto-neutron star ?

Y_e in the Neutrino Driven Wind

Is set by the reactions in two regions.

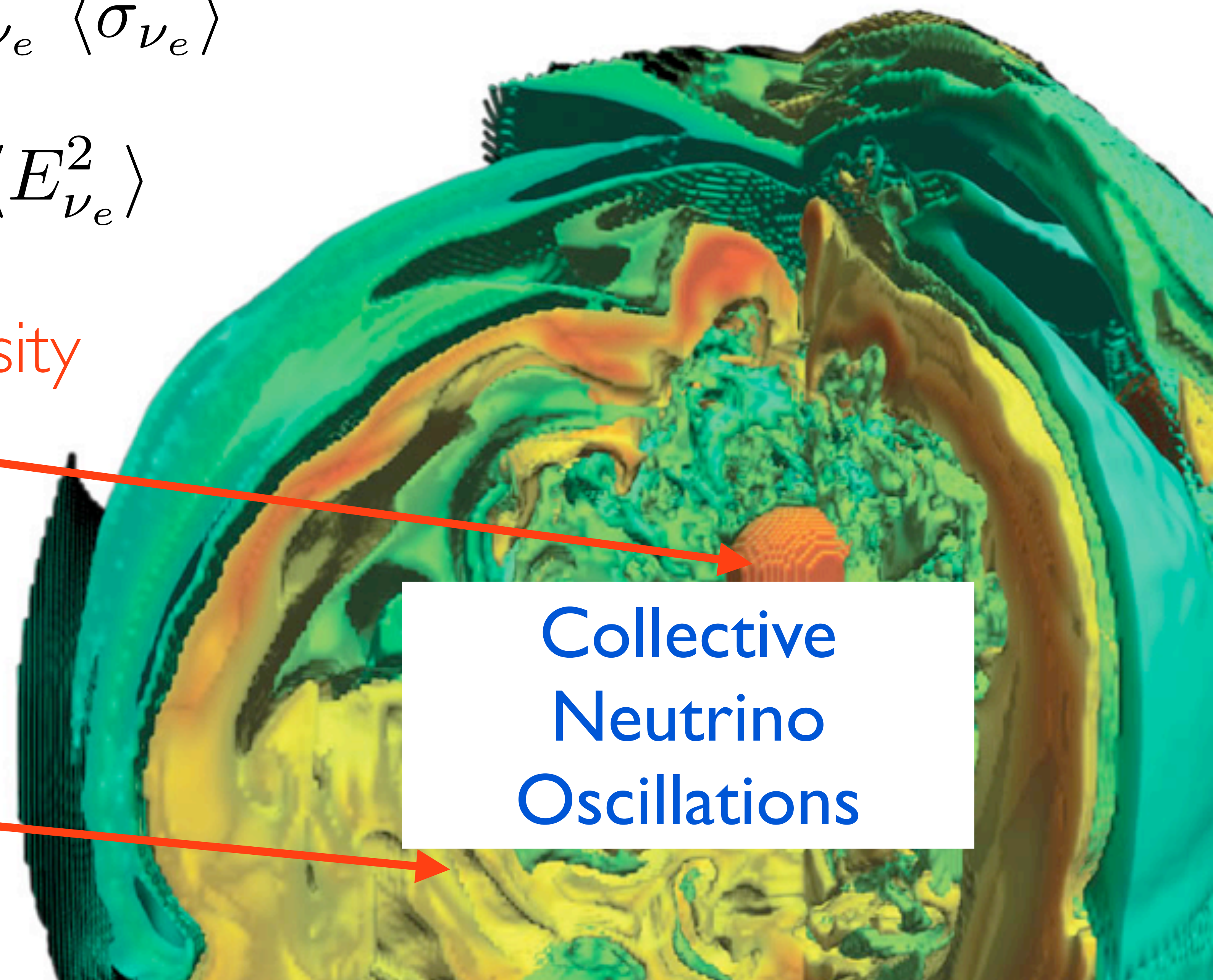
$$\begin{cases} \bar{\nu}_e + p \rightarrow n + e^+ \\ \nu_e + n \rightarrow p + e^- \end{cases}$$

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

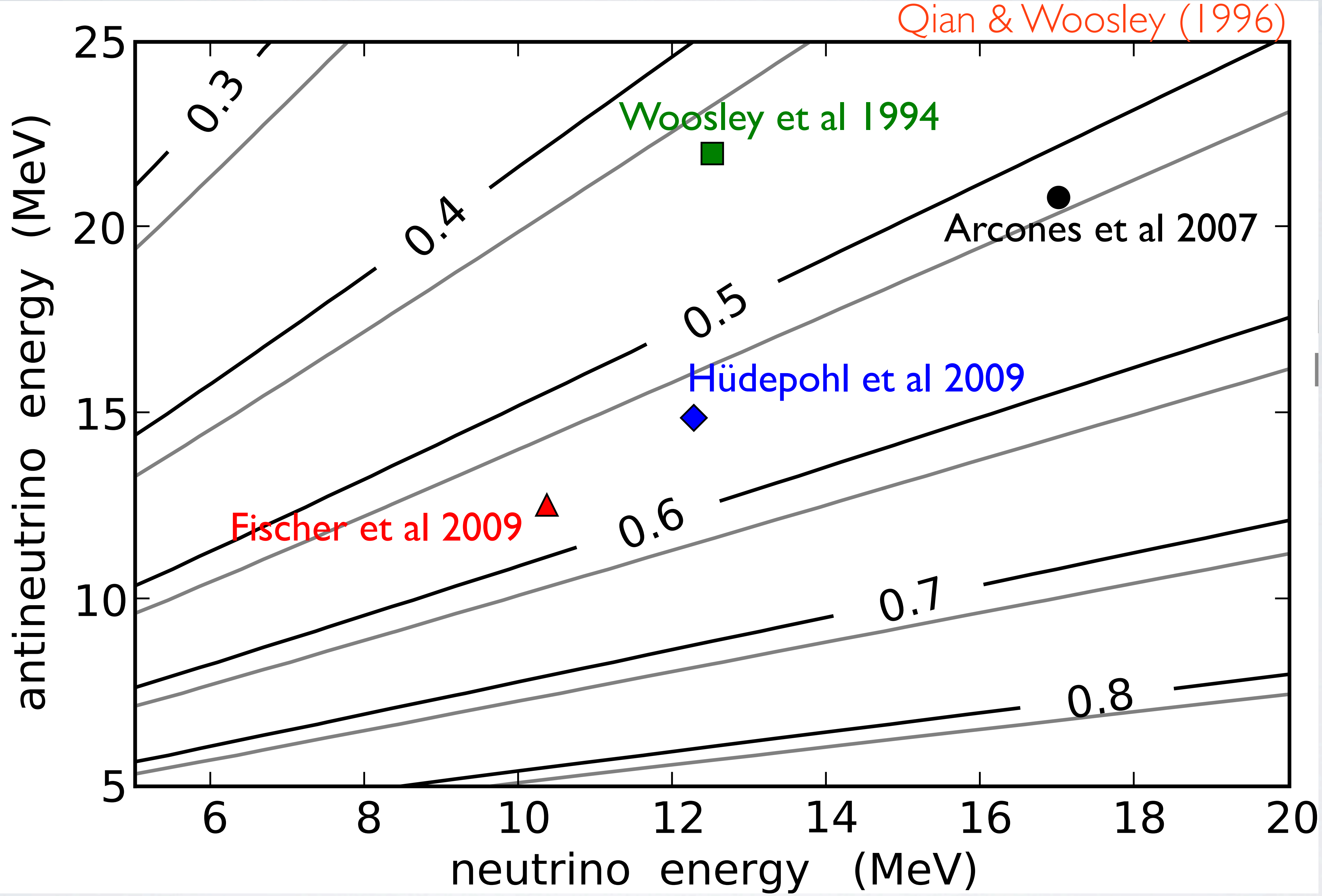
$$\langle \sigma_{\bar{\nu}_e} \rangle \propto \langle E^2_{\bar{\nu}_e} \rangle \qquad \langle \sigma_{\nu_e} \rangle \propto \langle E^2_{\nu_e} \rangle$$

Neutrino-sphere at high density and moderate entropy.
$R \sim 10\text{-}20$ km

Neutrino driven wind at low-density and high entropy.
$R \sim 10^3\text{-}10^4$ km

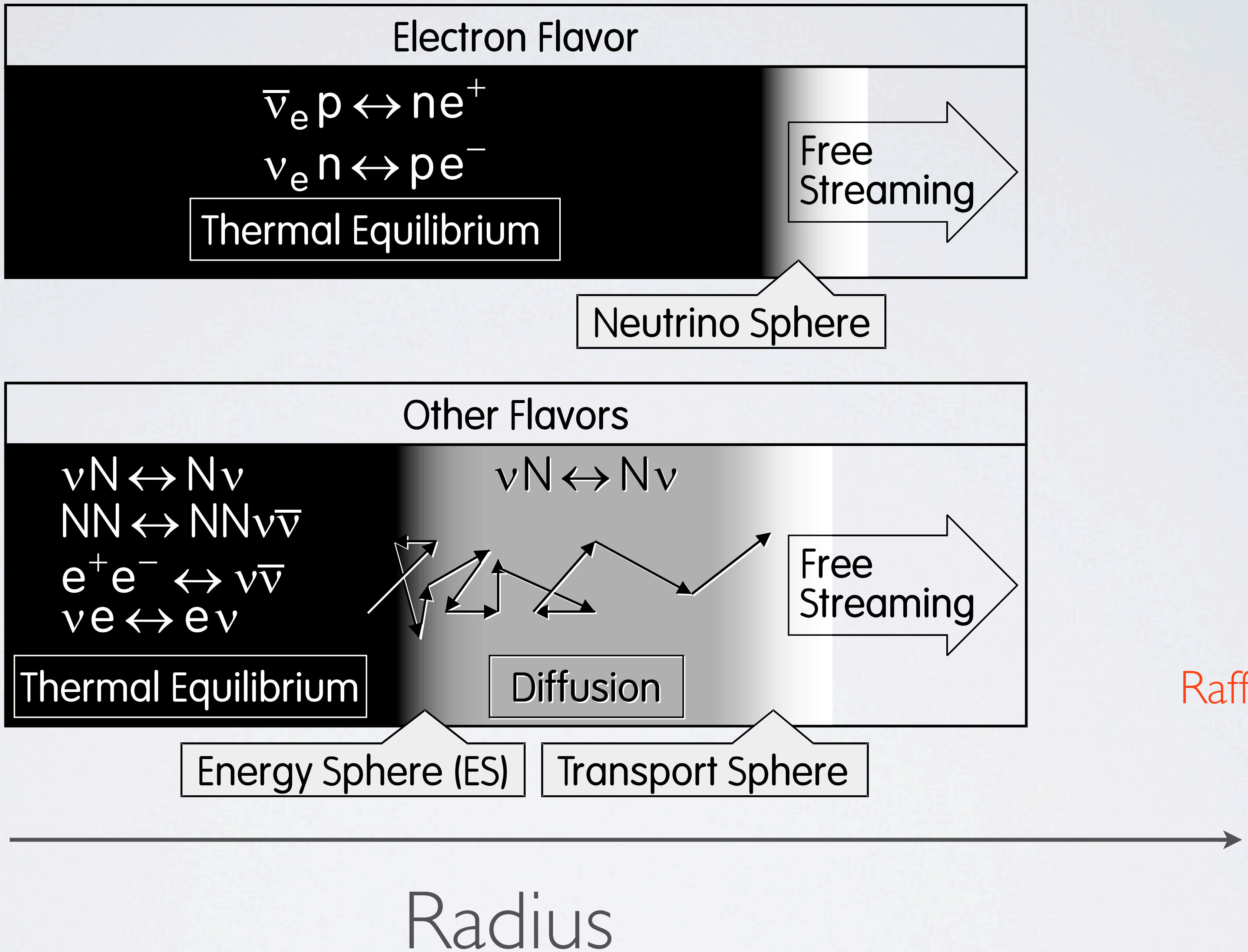


Y_e & Neutrino Spectra



Larger spectral differences imply lower Y_e

Reactions in the Neutrinosphere



Raffelt (2001)

RESPONSE OF AN IDEAL GAS

- Process involves excitation of single (uncorrelated) particles. Total response is the (incoherent) sum over individual species.

- For nucleons and electrons final state blocking is important. Matter is partially degenerate for typical supernova conditions.

- **Nucleons are heavy and recoil energy is small. Response lies at small** $|\omega| < q\, v$. Where $v \sim p_F/M$ or $\sqrt{T/M}$.

Transition rate ($\Gamma = c/\lambda$) in a Fermi Gas.

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

$$\approx G_F^2 \int \frac{d^3k_3}{(2\pi)^3}\; [C_V^2(1+\cos\theta) + C_A^2(3-\cos\theta)]\; S_{\rm FG}(q_0, q)(1 - f_3(E_3))$$

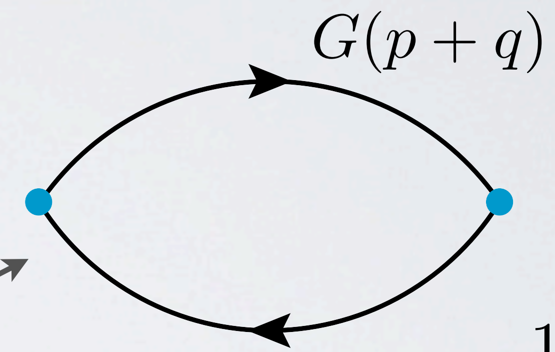
$$S(q_0, q) = 2\int \frac{d^3p_2}{(2\pi)^3}\int \frac{d^3p_4}{(2\pi)^3}(2\pi)^4\delta^4(P_1 + P_2 - P_3 - P_4)\; \times f_2(E_2)(1 - f_4(E_4))$$

RANDOM PHASE APPROXIMATION (RPA)

- An approximate method to include correlations in the response function. Required for consistency with the mean field equation of state.

$$S_{\mathrm{RPA}}(q_0, q) = \frac{1}{1 - \exp\left(-\beta\omega\right)} \; \mathrm{Im}[\Pi^{\mathrm{RPA}}]$$

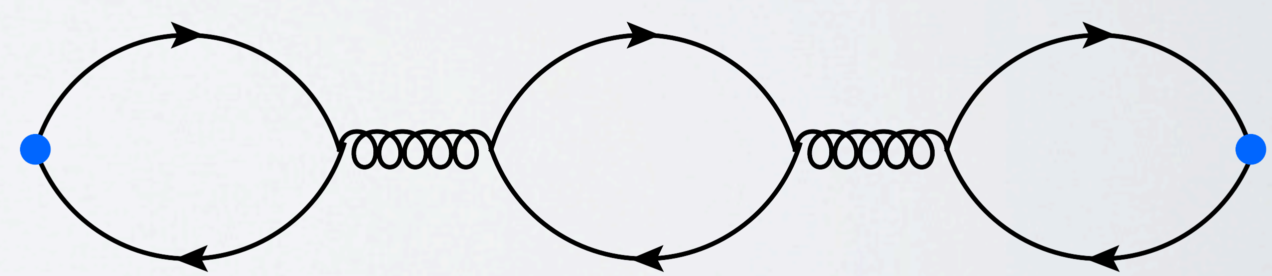
$$\Pi^{\mathrm{RPA}} = \left[\frac{\Pi^0(q_0, q)}{1 - V_c(q)\; \Pi^0(q_0, q)}\right]$$



$$G(p) = \frac{1}{p_0 - \mu - (p^2/2M)}$$

$$\Pi^0(q_0, q) = i \int \frac{d^4p}{(2\pi)^2}\; G(p)\; G(p+q)$$

$$\Pi^{\mathrm{RPA}} = \Pi^0 + \Pi^{\mathrm{RPA}}\; V_c\; \Pi^0$$



- Provides a fair qualitative description of response in nuclei. Mean field models with consistent residual p-h interactions.

THE RESIDUAL INTERACTION IN RPA

Very simple s-wave interaction is used

p-h interaction obtained from the equation of state.

$$\langle k_1 k_3^{-1} | V_{\rm ph} | k_4 k_2^{-1} \rangle = \frac{\delta^2 \langle V \rangle}{\delta n_{k_3 k_1} \delta n_{k_4 k_2}}$$

$$f_{nn} = \frac{\delta U_n}{\delta n_n}, \quad f_{pp} = \frac{\delta U_p}{\delta n_p}, \quad f_{np} = \frac{\delta U_n}{\delta n_p} = \frac{\delta U_p}{\delta n_n}$$

Or from Fermi Liquid parameters from microscopic theories.

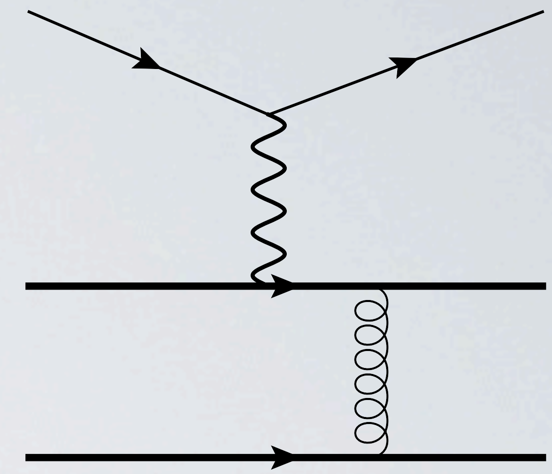
$$f_{nn} = \frac{F_0 + F_0'}{N_0}, \quad f_{np} = \frac{F_0 - F_0'}{N_0}.$$

$$g_{nn} = \frac{G_0 + G_0'}{N_0}, \quad g_{np} = \frac{G_0 - G_0'}{N_0}$$

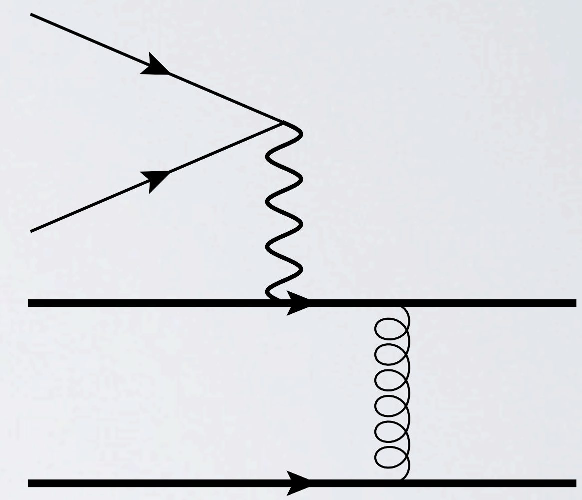
- The residual interaction for density and isospin density fluctuations obtained from the EoS is consistent.
- Important feedback may exist in SN simulations.
- The more important spin-flip interaction strength is chosen from phenomenology of response in nuclei.

MULTI-PARTICLE EXCITATIONS

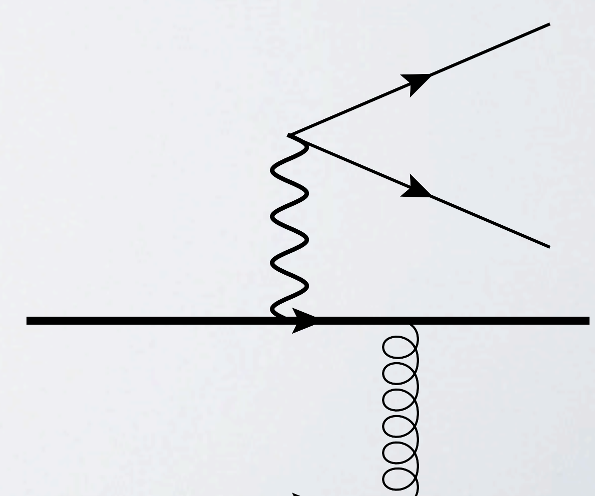
- Excitation of 2 particle-2 hole states enables pair-processes and larger energy transfer during scattering.
- In strongly coupled systems leads to significant smearing of the single particle and collective strength.
- Especially important for the spin response because spin is not conserved in nuclear interactions.
- Can enhance the charged current rate at small Y_e.



$$\nu + n + n \rightarrow n + n + \nu$$



$$\nu + \bar{\nu} + n + n \rightarrow n + n$$



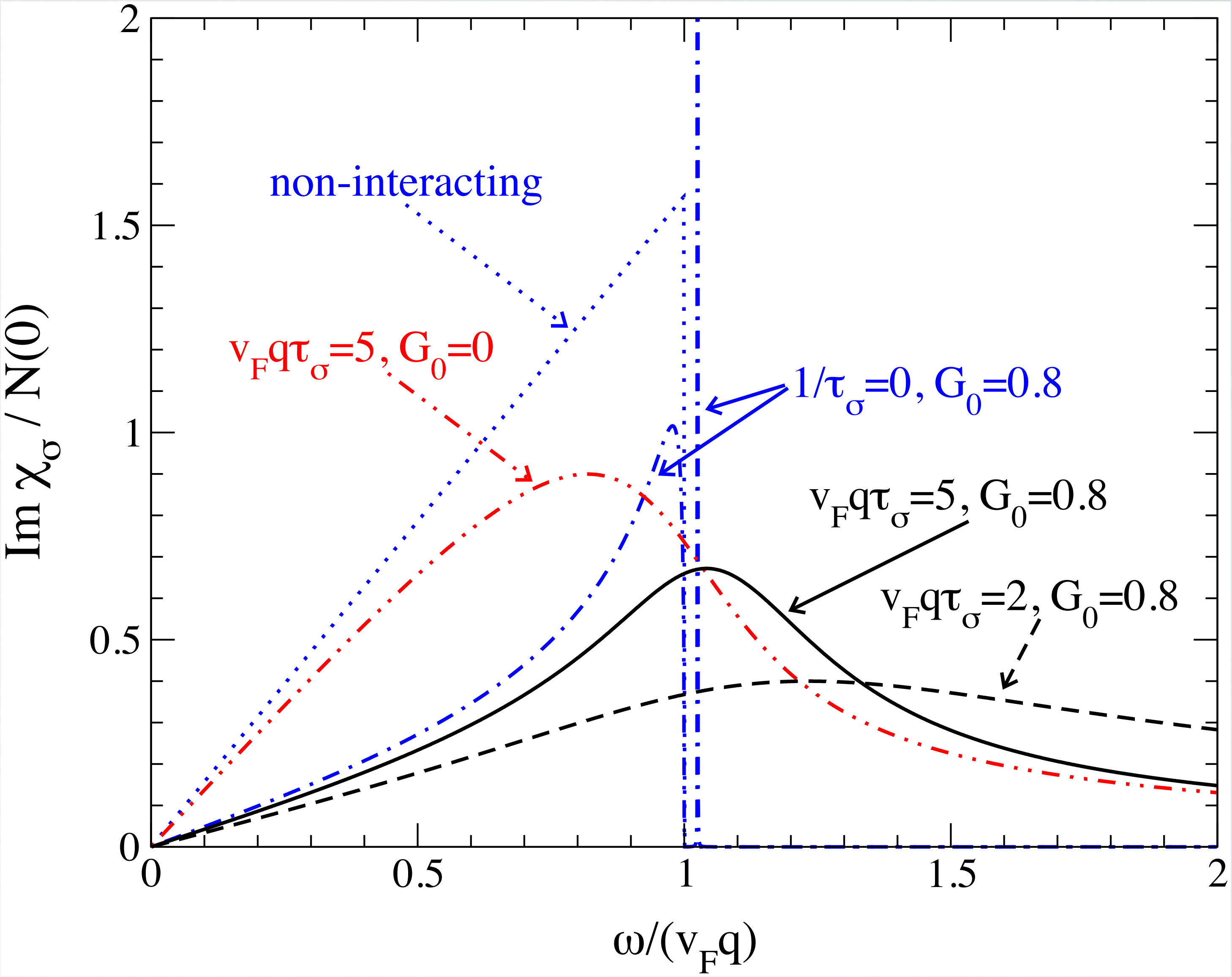
$$n + n \rightarrow n + n + \nu + \bar{\nu}$$

Raffelt & Seckel (1995)

UNIFIED TREATMENT OF SPIN RESPONSE

Lykasov, Olsson, Pethick (2005)
Lykasov, Pethick, Schwenk (2006)

- 2p-2h response is incorporated through a finite quasi-particle lifetime correction in RPA. Combines single-pair and multi-pair excitations and RPA correlations.
- Captures key aspects of the response (screening, damping and collectivity).
- Quasi-particle life-times have been calculated using realistic and modern nucleon-nucleon interactions.



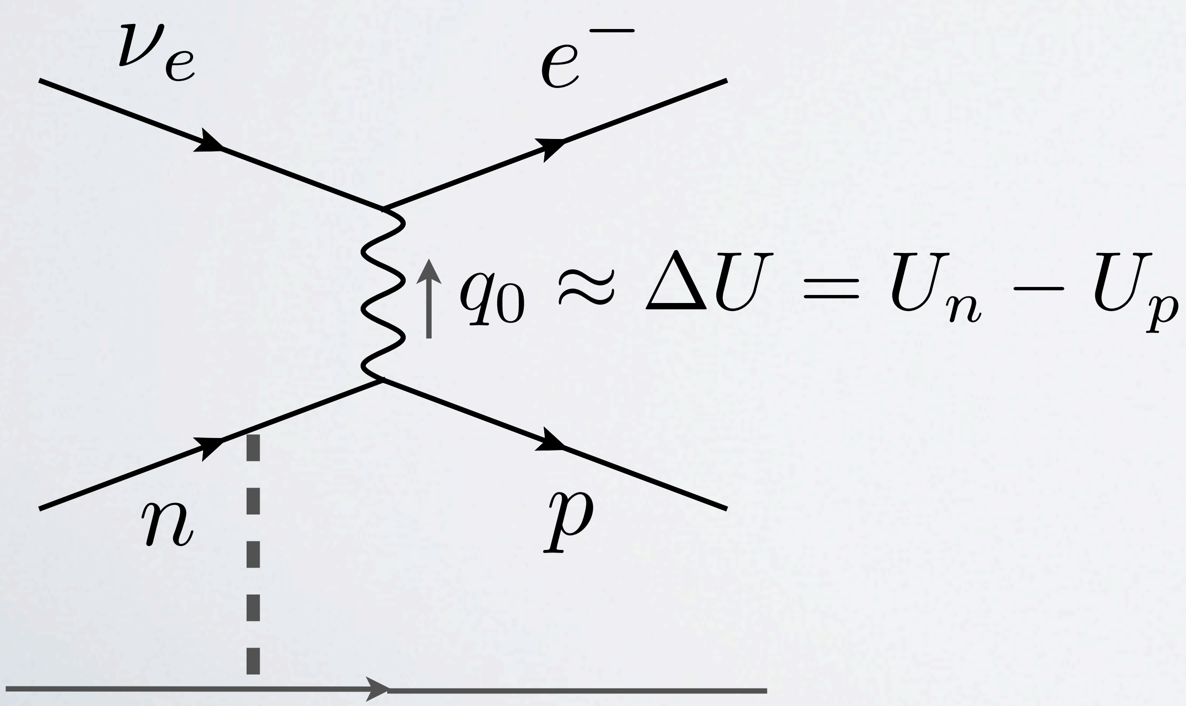
$$\mathrm{Im}\tilde{\chi}_\sigma(\omega, q \to 0) = \frac{\omega\tau_\sigma}{(1+G_0)^2 + (\omega\tau_\sigma)^2}$$

$$S_\sigma(q \to 0, \omega) = \frac{\mathrm{Im}\tilde{\chi}_\sigma(\omega)}{1 - \exp(-\beta\omega)}$$

CHARGED CURRENT OPACITY

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

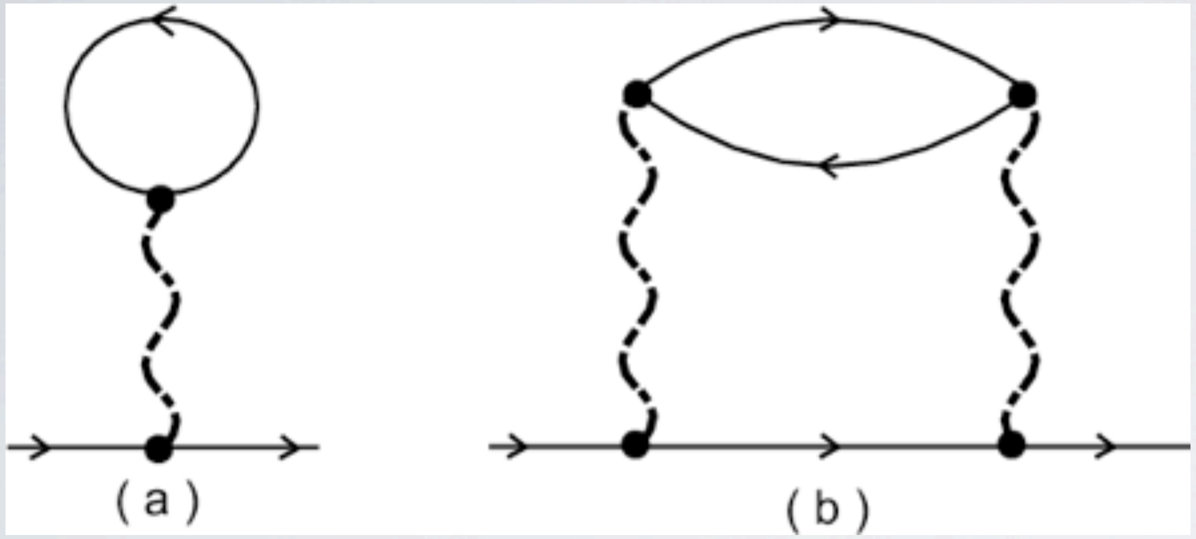
- Final state electron blocking is strong for electron neutrino absorption reaction.
- Asymmetry between mean field energy between neutrons and protons alters the kinematics.
- Multi-particle initial and final states can also move response to high energy.



Large q_0 crucial to overcome blocking

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

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:

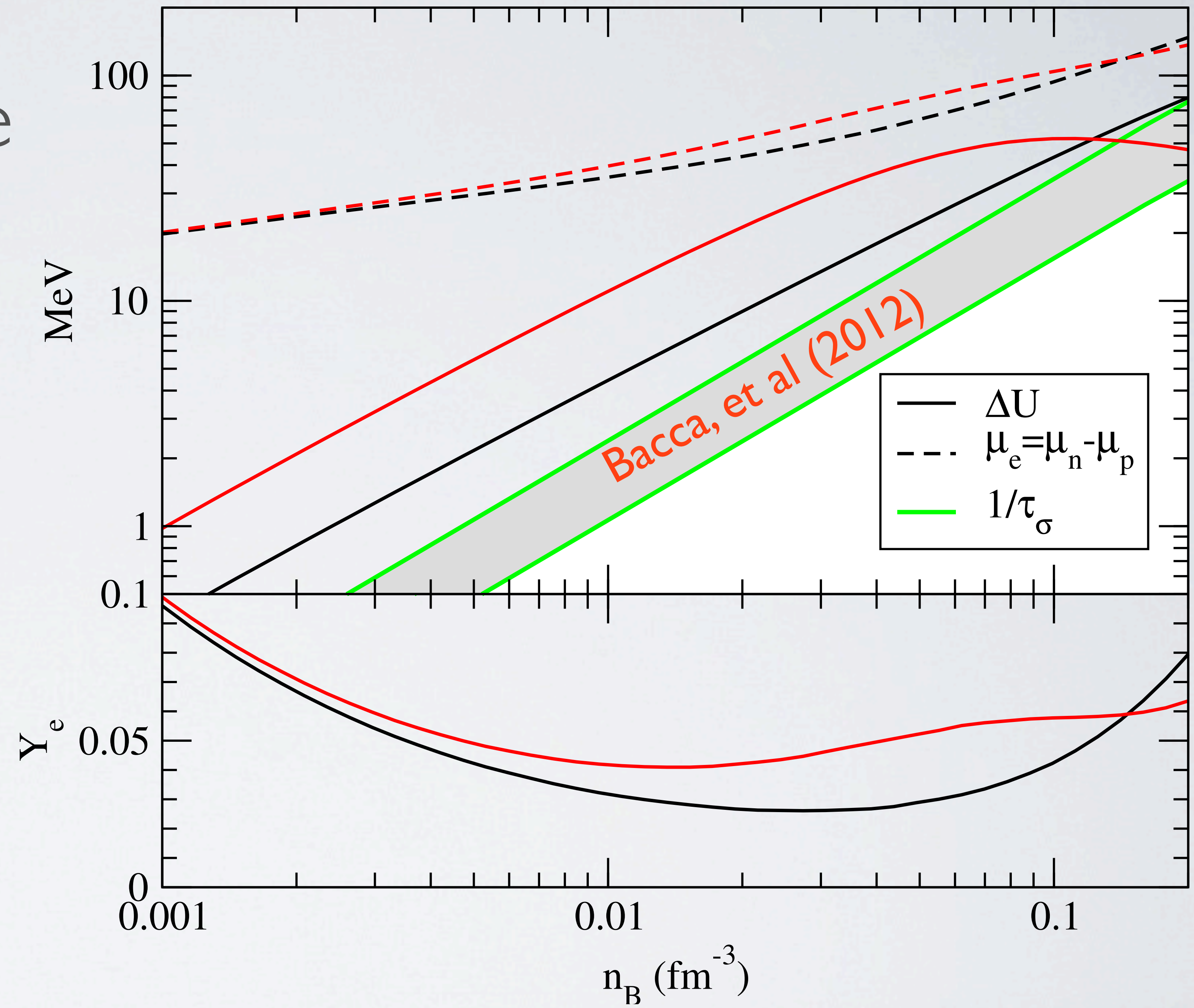
$$q_0 = E_n(p) - E_p(p+q) \simeq \frac{pq}{2m_n^*} + (m_n - m_p) + (U_n - U_p)$$

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

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

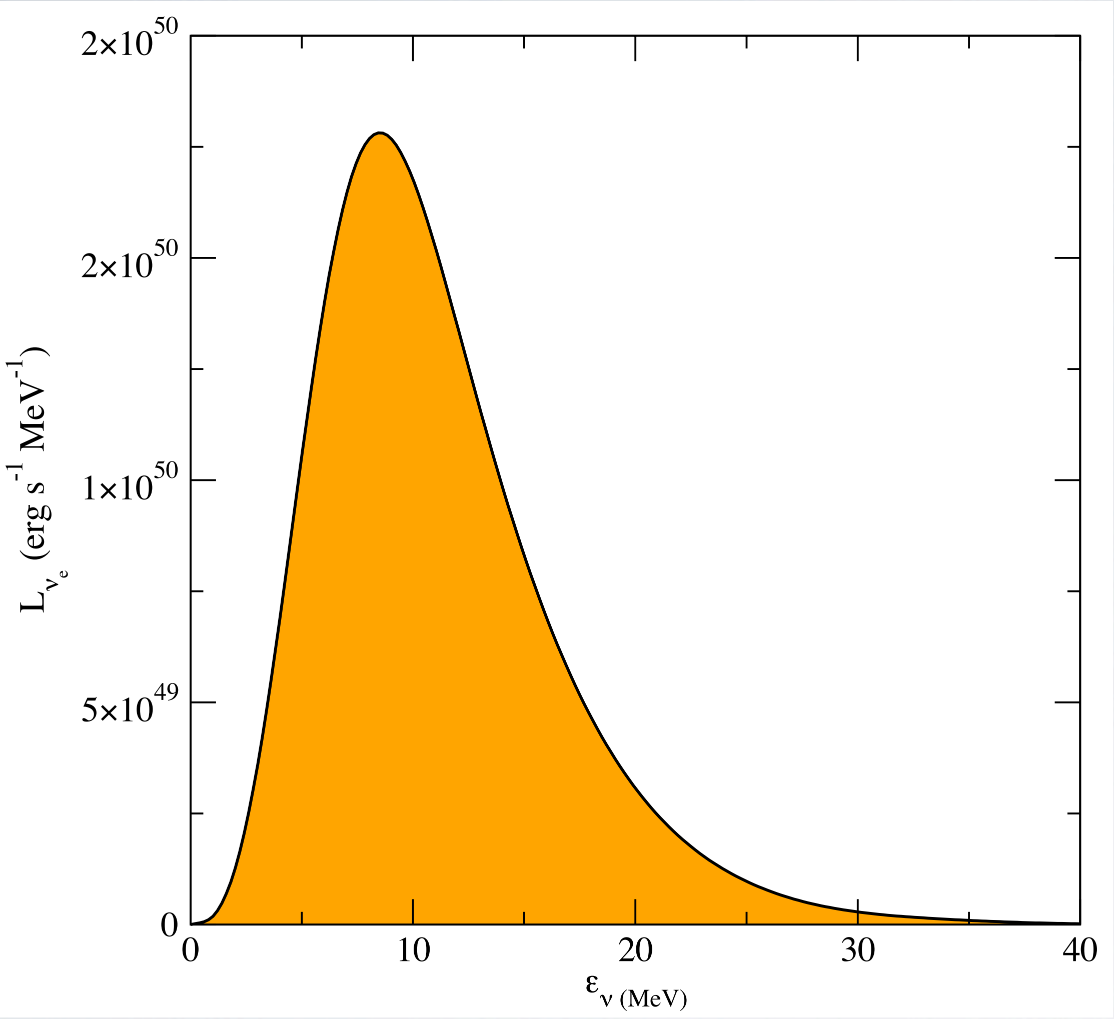
MEAN FIELD SHIFT & QP LIFE TIMES

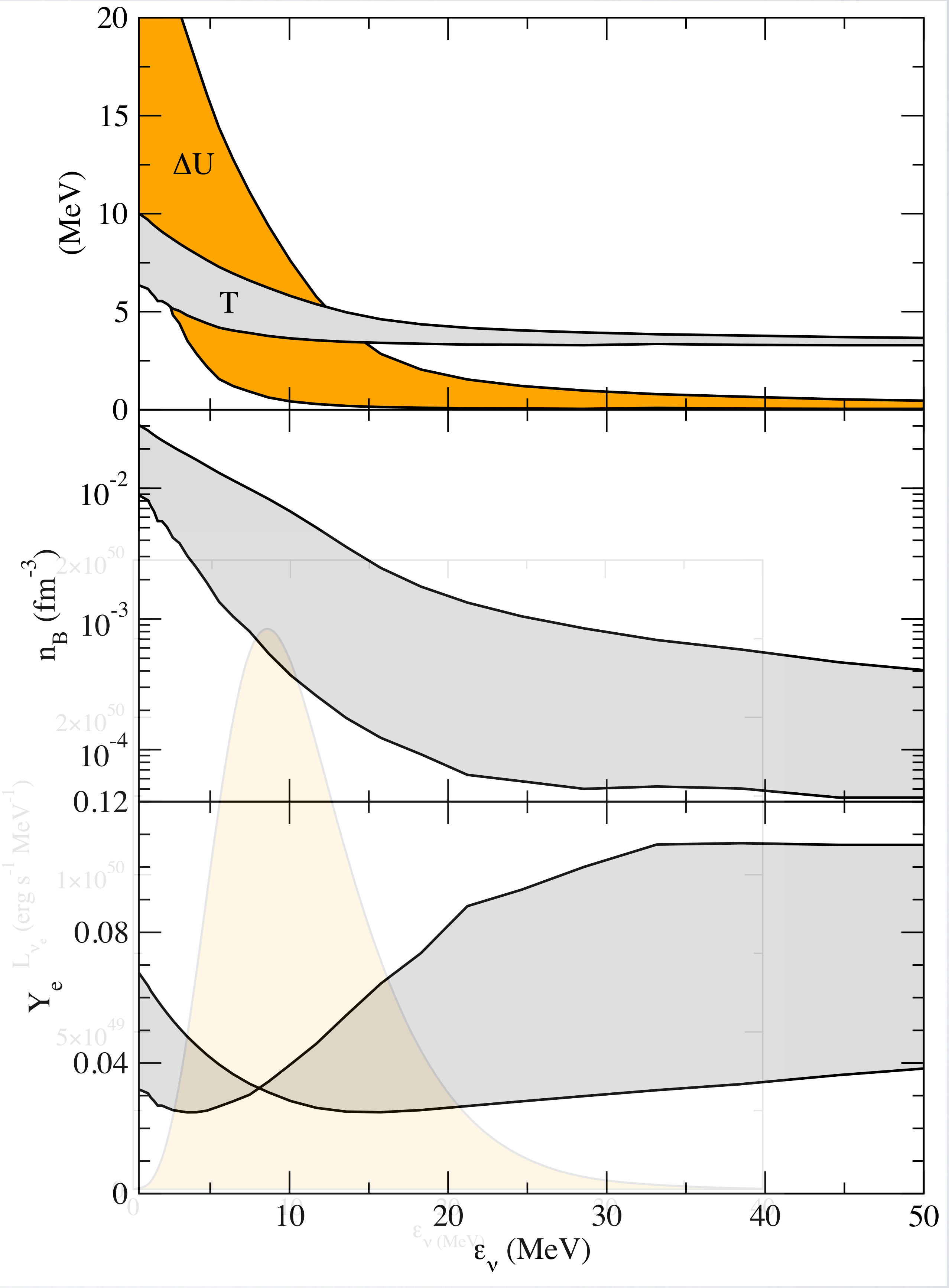
- After a few seconds, the density at the neutrino sphere is large. $\sim n_0/20 - n_0/4$.
- Nucleon propagation is affected by mean fields and collisions.
- Sensitive to the low-density behavior of the symmetry energy.



Roberts, Reddy Shen (2012)

SPECTRA AT LATE TIMES





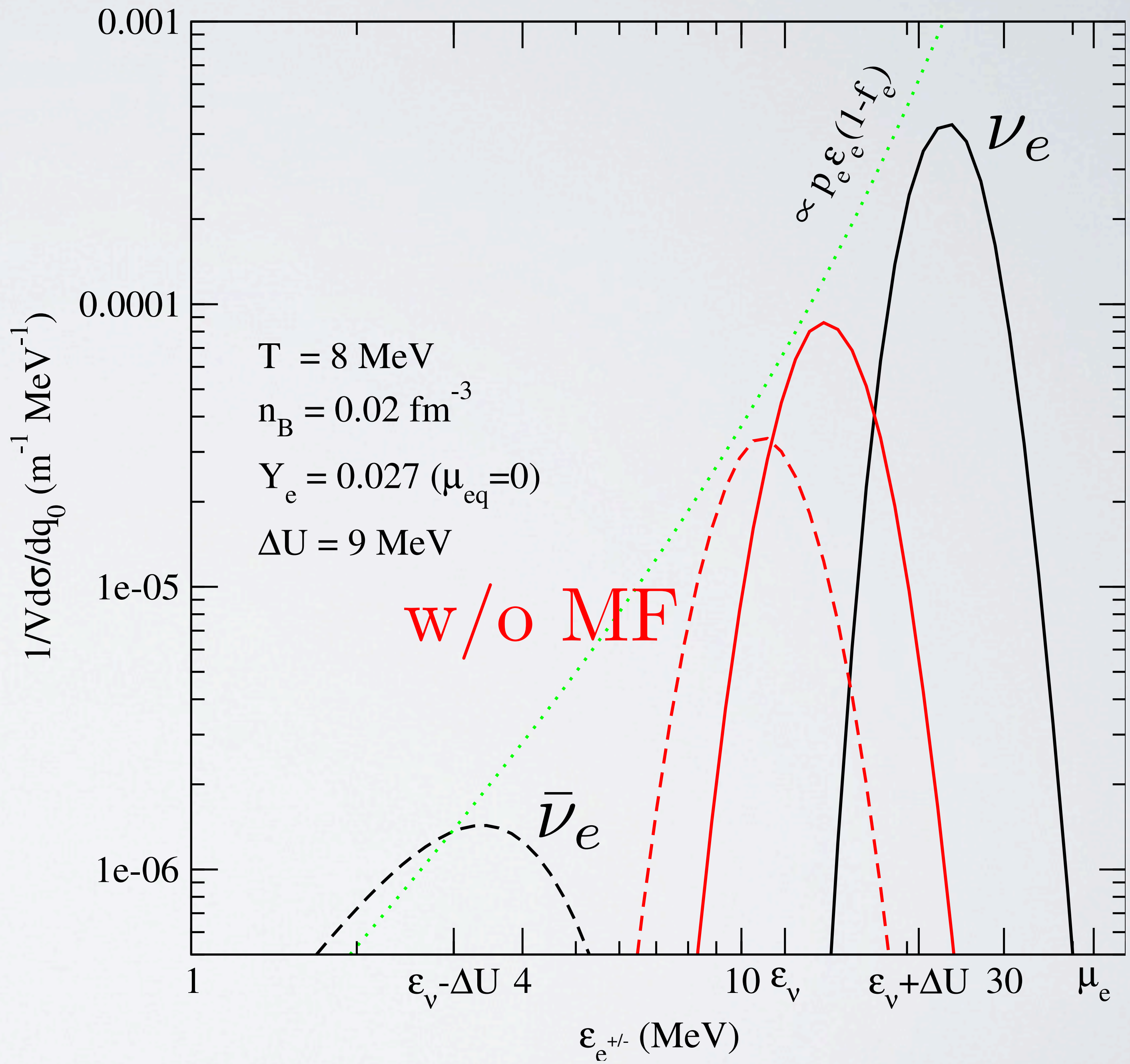
- Decoupling occurs at relatively high density.
- Spectra influenced by nuclear correlations.

Figures from PNS simulations by Roberts (2012)

ABSORPTION RATES

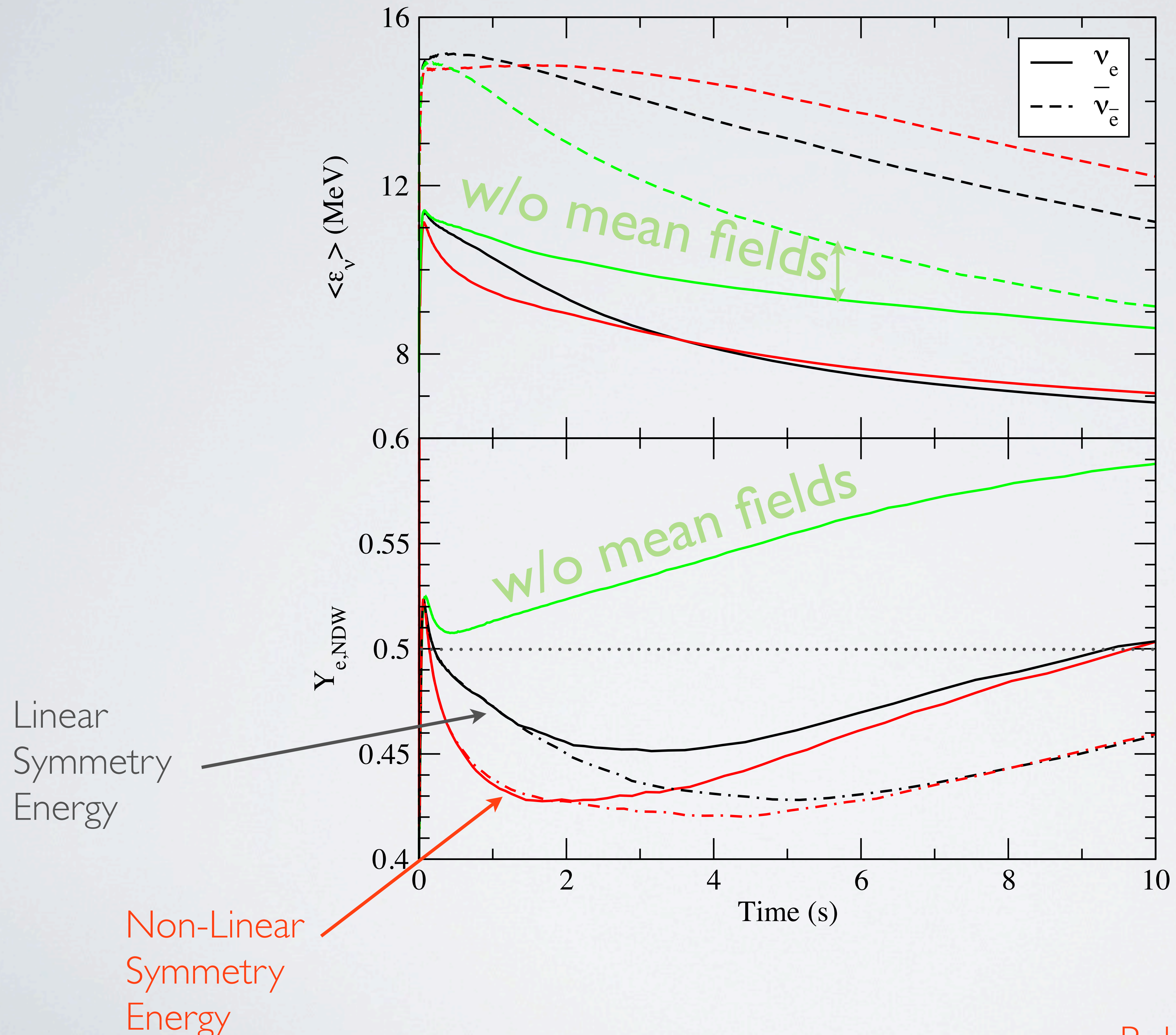
$$\frac{d\Gamma}{\cos\theta dE_e} = \frac{G_F^2}{2\pi} p_e \; E_e \left(1 - f_e(E_e)\right) \times \left[(1+\cos\theta) S_\tau(q_0, q) + g_A^2 (3 - \cos\theta) S_{\sigma\tau}(q_0, q)\right]$$

- 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



Roberts, Reddy & Shen (2012)

MEAN FIELD & COLLISIONAL BROADENING

Ansatz for the spin-isospin charge-exchange response function:

$$S_{\sigma\tau^-}(q_0, q) = \frac{1}{1 - \exp\left(-\beta(q_0 + \mu_n - \mu_p\right)} \mathrm{Im}\left[\frac{\tilde{\Pi}(q_0, q)}{1 - V_{\sigma\tau}\tilde{\Pi}(q_0, q)}\right]$$

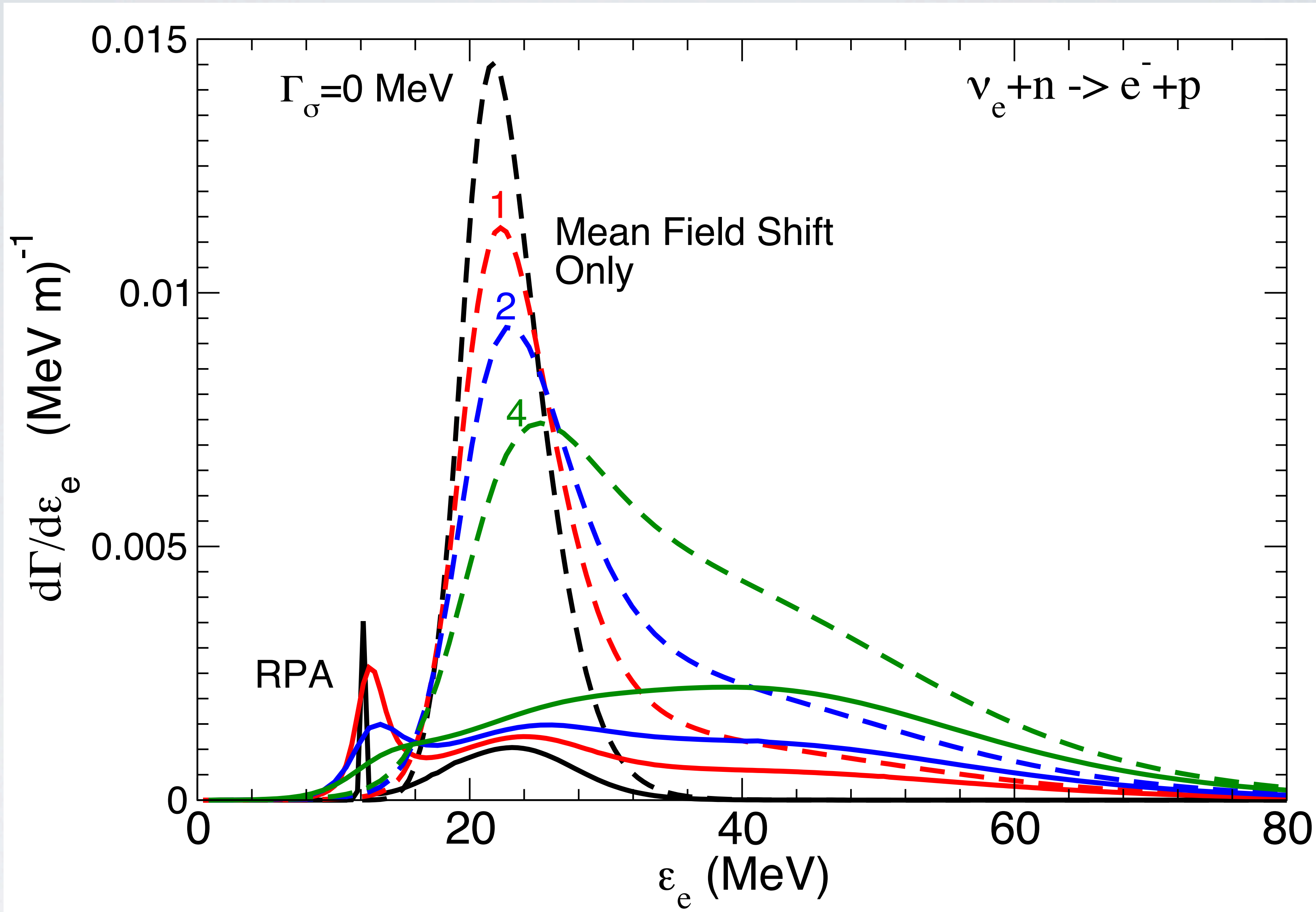
Collisional broadening (finite lifetime) introduced in the relaxation time approximation: $\Gamma = \tau_\sigma^{-1}$

$$\mathrm{Im}\tilde{\Pi}(q_0, q) = \frac{1}{\pi}\int \frac{d^3p}{(2\pi)^3} \frac{f_p(\epsilon_{p+q}) - f_n(\epsilon_p)}{\epsilon_{p+q} - \epsilon_p + \hat{\mu}} \mathcal{I}(\Gamma)$$

$$\mathcal{I}(\Gamma) = \frac{\Gamma}{(q_0 + \Delta U - (\epsilon_{p+q} - \epsilon_p))^2 + \Gamma^2}$$

$V_{\sigma\tau} \simeq 200 - 220\ \mathrm{MeV/fm}$ G. Bertsch, D. Cha, and H. Toki (1984)

SCREENING & DAMPING



$1/\lambda$ in m^{-1} for matter in beta-equilibrium at $T = 8$ MeV and various densities and $E_{\nu_e} = E_{\bar{\nu}_e} = 12$ MeV.

Density (fm^{-3})	$1/\lambda$ (m^{-1}):	no MF	MF ($\Gamma = 0$)	RPA ($\Gamma = 0$)	MF ($\Gamma > 0$)	RPA ($\Gamma > 0$)
$n_B = 0.020$	$1/\lambda_{\nu_e}$:	5.89×10^{-4}	5.22×10^{-3}	2.11×10^{-3}	7.52×10^{-3}	3.91×10^{-3}
	$1/\lambda_{\bar{\nu}_e}$:	3.54×10^{-4}	2.73×10^{-5}	6.46×10^{-5}	4.47×10^{-5}	6.03×10^{-5}

Energy Shift is Crucial

CONCLUSIONS

- Difference between electron and anti-electron neutrino spectra is larger, time dependent and depends on the density dependence of the symmetry energy.

- Mean fields alter the kinematics and energy transfers associated with charged current reactions. Increase the ν_e cross-section and reduce the $\bar{\nu}_e$ cross-section

- The $Y_e < 0.5$ in the wind for several seconds.

- Other nuclear effects that could play a role: bound states, two-body currents, bound-free and free-bound transitions.