Microphysics for SN: Nuclear Equation of State, Neutrino Opacity with Medium Correction

Gang Shen

INT, University of Washington

With:
Joe Carlson, Vincenzo Cirigliano, Stefano Gandolfi (LANL)
Chuck Horowitz (Indiana), Evan O'Connor (Caltech)
Sanjay Reddy (INT/UW), Luke Roberts (UCSC)

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Outline

- Nuclear EOS
  - Overview
  - Current EOS tables
  - Further development
- Neutrino opacity: unified approach
  - Mean field effect: Charged current reactions
  - RPA correlation
  - Beyond RPA: 2-ph response
- Summary

SN EOS (T>0)

- Low density (<~ 10^12 g/cm3)
  - Single-nucleus vs multi-nuclei
  - Multi-nuclei with nucleons: NSE vs Virial+NSE

Inputs

Mass tables
Medium corrections
Correlations: NN, …

- PNS "crust" (<~ 0.5 n_0)
  - Mean field (MF) models: Skyrme vs RMF
  - Liquid drop vs Thomas-Fermi vs Hartree
  - efficiency & necessity
- Uniform matter (<~ $2n_0$)
  - MF: efficient/not systematic

Constraints on MF

- Saturation property of symmetric matter
- Stable nuclei (symmetric)
- Isovector observables
  - IVGDR
  - Neutron skin of nuclei
  - Neutron matter

- High density >~ 2 n_0
  - Skyrme vs RMF vs ??? (meson, quark,…)
  - Best parameterize uncertainties

  - Neutron star

Only a few realistic EoS used in astrophysical simulations

- most well known and widely used EoS:
  - J.M. Lattimer, F.D. Swesty LS 180, 220, 375 - non relativistic Skyrme model
  - H. Shen, H. Toki, K. Oyamatsu, K. Sumiyoshi STOS - relativistic MF model + 2nd one with hyperon (Mmax: ~1.7 solar mass)

- more recently developed EoSs:

  NSE + uniform matter at high density (RMF)

  - M. Hempel, J. Schaffner-Bielich, 2010

  Virial EOS (gas) + Hartree nonuniform (solid) + uniform (liquid) (RMF)

  - G. Shen, C.J. Horowitz, S. Teige NL3, 2011
  - G. Shen, C.J. Horowitz, E. O'Connor FSU, 2011

http://cecelia.physics.indiana.edu/gang_shen_eos/

Ensemble of nucleons and nuclei

- Grand partition function in virial expansion

$$\frac{\log Q}{V} = \frac{P}{T} = \frac{2}{\lambda_n^3}[z_n + z_p + (z_p^2 + z_n^2)b_n + 2z_p z_n b_{pn}]$$
$$+\frac{1}{\lambda_\alpha^3}[z_\alpha + z_\alpha^2 b_\alpha + 2z_\alpha(z_n + z_p)b_{\alpha n}]$$
$$+\sum_i \frac{1}{\lambda_i^3} z_i \Omega_i$$

- ➢ nucleon-nucleon
- ➢ nucleon-alpha
- ➢ nuclei

1. Nucleon and alpha: mod. ind. — Horowitz, Schwenk '05
2. Heavy species: 8980 nuclei — FRDM mass table: Moller et al '97. Δ_{rms} ~ 0.6 MeV

   Chemical equilibrium ------ $\mu_i = Z\mu_p + N\mu_n \quad z_i = z_p^Z z_n^N e^{(E_i - E_i^C)/T}.$

   Coulomb correction ------ $E_i^C = \frac{3}{5}\frac{Z_i^2\alpha}{r_A}[-\frac{3}{2}\frac{r_A}{r_i} + \frac{1}{2}(\frac{r_A}{r_i})^3]$

   Nuclear partition function Ω_i ---- eg, Fowler, Engelbrecht, Woosley, '78

   Nuclei spacing

   $$\frac{4}{3}\pi r_i^3(\sum_j Z_j n_j) = Z_i$$

3. Solving: z_n, z_p, r_i:

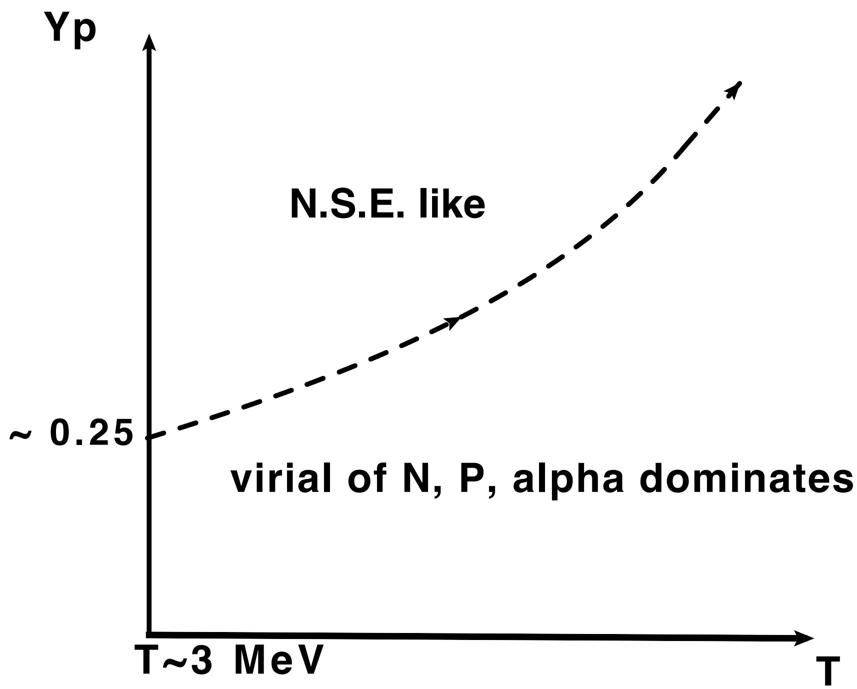
   $n_B = n_n + n_p + 4n_\alpha + \sum_i A_i n_i$ = Baryon

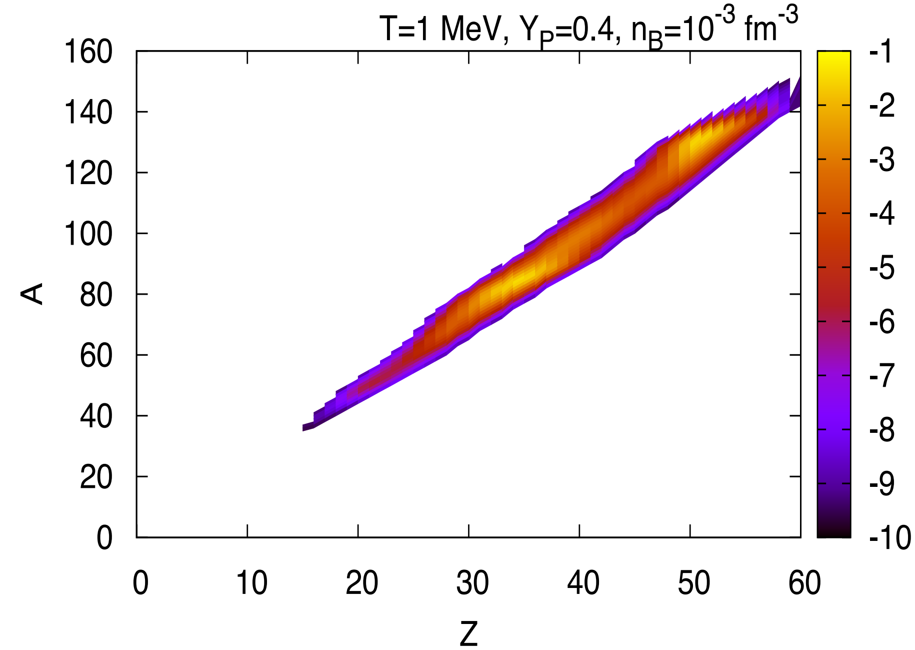
   $Y_P = (n_p + 2n_\alpha + \sum_i Z_i n_i)/n_B$ = Charge

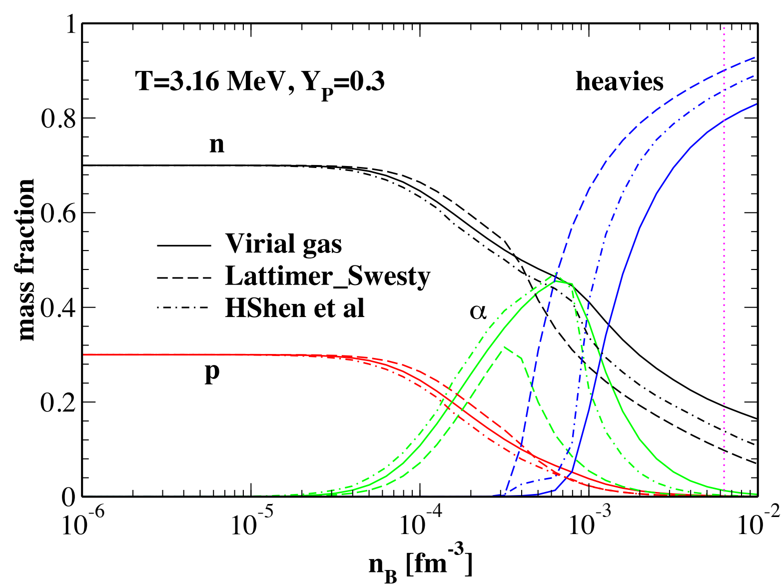
4. Mass fraction: $X_a = A_a n_a / n_B$

Mass distributions in Virial gas - multi-nuclei distribution

- $n < 0.1\text{-}0.01 n_0$
- $T < 12$ MeV







- Mass 2, 3 nuclei can be included in virial: O'Connor et al, 2008
- M. Hempel et al, 2012 partially addressed the role of multi-nuclei in 1D SN simulation

Relativistic Mean Field Theory

attractive — repulsive — Iso-vector

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

- Ψ : Nucleon fields
- Meson/photon fields: classical expectation value ➔ mean field
- 7 adjustable parameters

EoMs in real space:

Nucleon:

$$\left[\alpha\cdot\boldsymbol{p} + V(\boldsymbol{r}) + \beta\left(M + S(\boldsymbol{r})\right)\right]\psi_i = \varepsilon_i\psi_i$$

Hartree Mean fields:

$$\begin{aligned}V(\mathbf{r}) &= \beta\{g_\omega \not\omega_\mu + g_\rho\vec{\tau}\cdot\vec{\not\rho}_\mu + e\frac{(1+\tau_3)}{2}\not A_\mu + \Sigma^R\}, \\ S(\mathbf{r}) &= \Gamma_\sigma\sigma,\end{aligned}$$

Mesons and Photons:

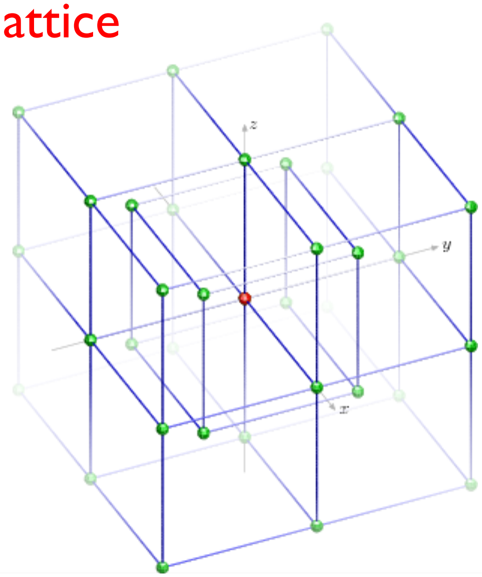
$$\begin{cases}\left(-\Delta + \partial_\sigma U(\sigma)\right)\sigma(\boldsymbol{r}) = -g_\sigma\rho_s(\boldsymbol{r}) \\ \left(-\Delta + m_\omega^2\right)\omega_0(\boldsymbol{r}) = g_\omega\rho_v(\boldsymbol{r}) \\ \left(-\Delta + m_\rho^2\right)\rho_0(\boldsymbol{r}) = g_\rho\rho_3(\boldsymbol{r}) \\ -\Delta A_0(\boldsymbol{r}) = e(\rho_c(\boldsymbol{r}) - \rho_e)\end{cases}$$

Finite temperature n_i: Fermi-Dirac stat.

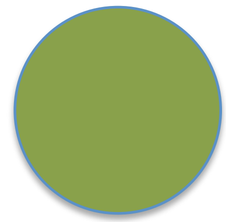
$$\begin{cases}\rho_s(\boldsymbol{r}) = \sum_{i=1}^{A}\bar{\psi}_i(\boldsymbol{r})\psi_i(\boldsymbol{r})n_i,\ \rho_3(\boldsymbol{r}) = \sum_{i=1}^{A}\psi_i^+(\boldsymbol{r})\tau_3\psi_i(\boldsymbol{r})n_i \\ \rho_v(\boldsymbol{r}) = \sum_{i=1}^{A}\psi_i^+(\boldsymbol{r})\psi_i(\boldsymbol{r})n_i,\ \rho_c(\boldsymbol{r}) = \sum_{i=1}^{A}\psi_i^+(\boldsymbol{r})\frac{1-\tau_3}{2}\psi_i(\boldsymbol{r})n_i\end{cases}$$

proto-neutron star crust (Γ>>1)

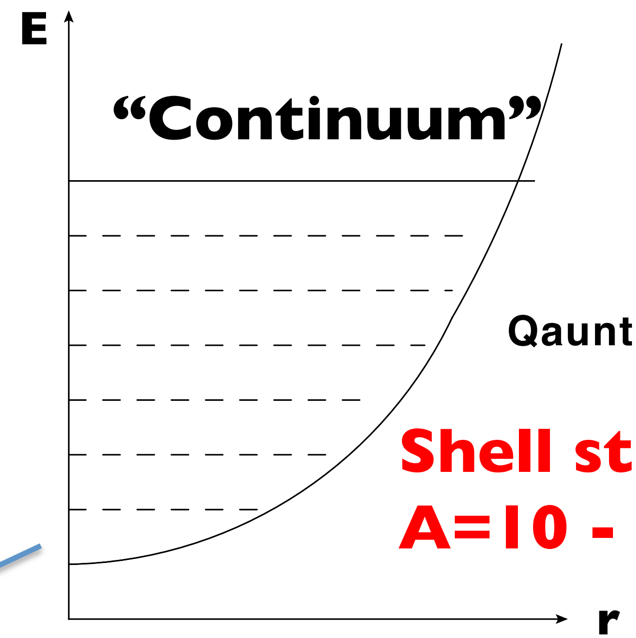
BCC lattice



$$\Gamma = (Ze)^2/ak_BT$$

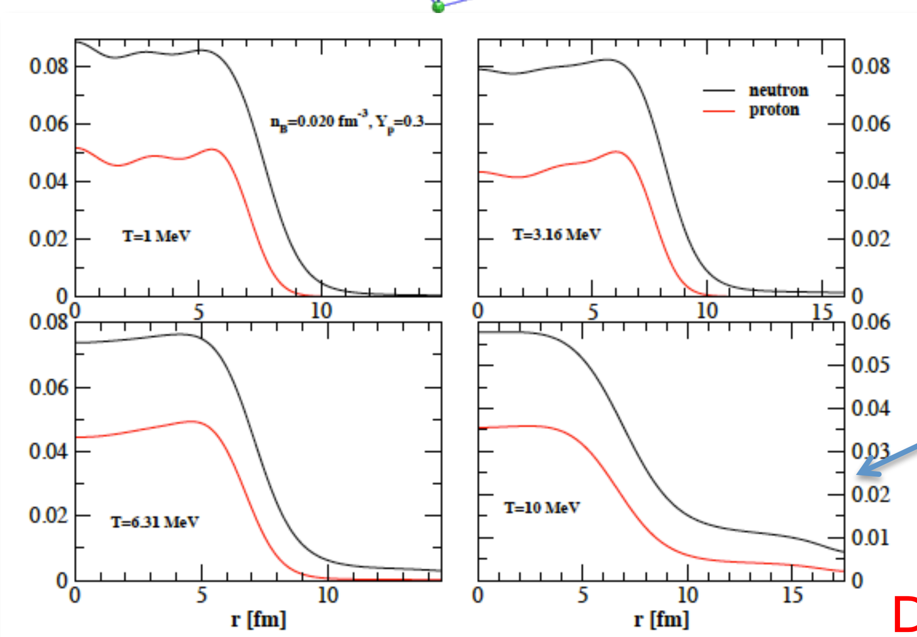


Wigner-Seitz spherical cell



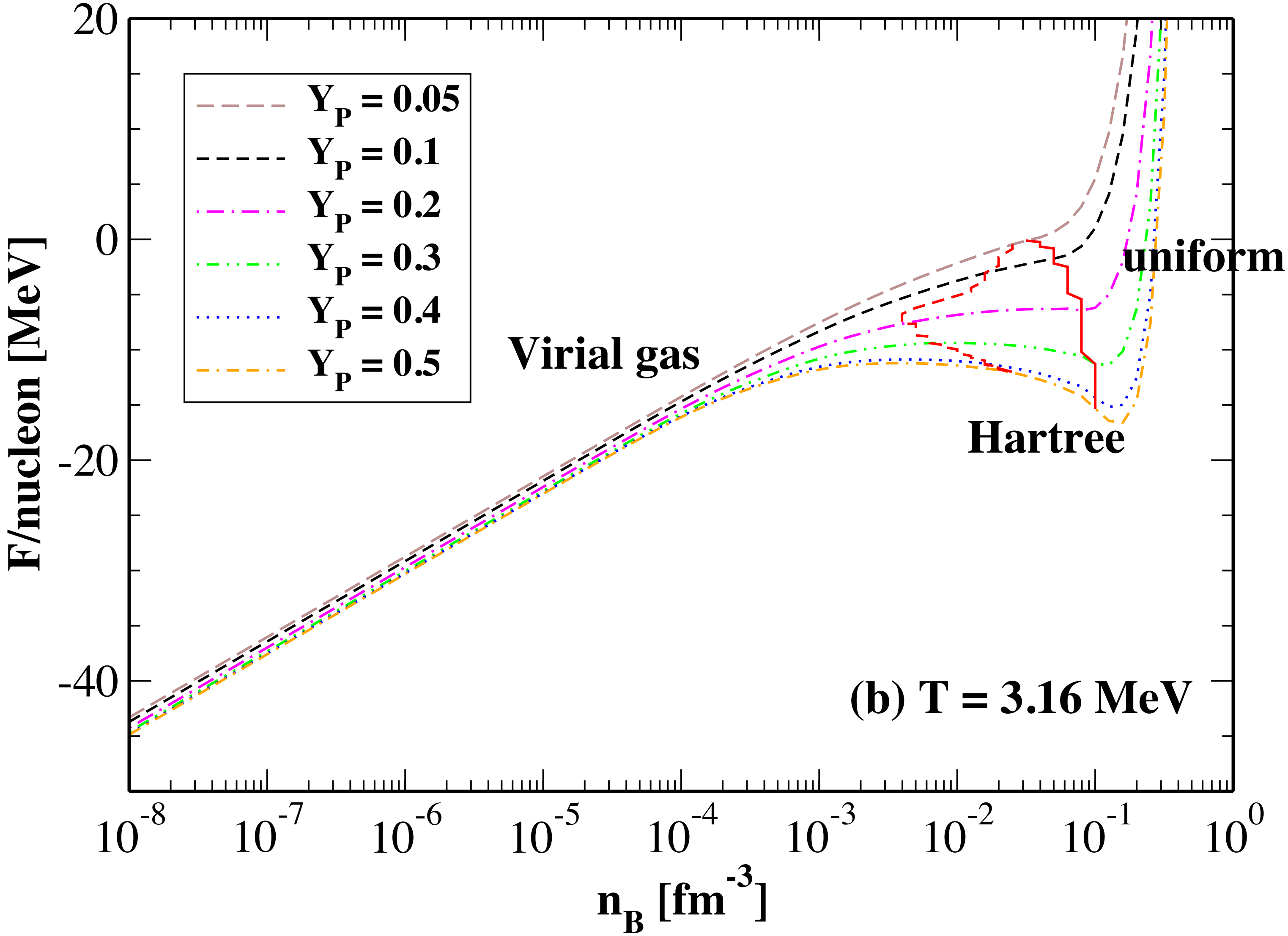
Qauntum Levels

Shell structure
A=10 - 1000



Density distribution in the unit lattice

Matching EOS from low to high densities



3-D Parameter spaces (T, ρ, Y_p) for gas-solid-liquid

	Virial Gas	Hartree	Uniform matter
Temperature [MeV]	0.1~20	0.1~12	0.1~80
Density [fm^{-3}]	1E-8~1E-1	1E-4~1E-1	1E-8~1.6
Proton fraction	0.05~0.56	0.05~0.56	0~0.56
# points in phase space	73,840	17,021	90,478
CPU time (hr)	10,000	100,000	100

- Matching them and interpolate to get thermodynamically consistent Table.

Constraints on mean fields

- Saturation of symmetric nuclear matter
  B/A, K, J
- Doubly magic nuclei: B/A, R_{ch}
- Giant/Collective resonances
  - Isoscalr Giant Monopole Resonance

Isospin ind. observables

  - Isovector Giant Dipole Resonance
- Neutron skin of nuclei
- Benchmark neutron matter: Chiral EFT, QMC
- NS observations

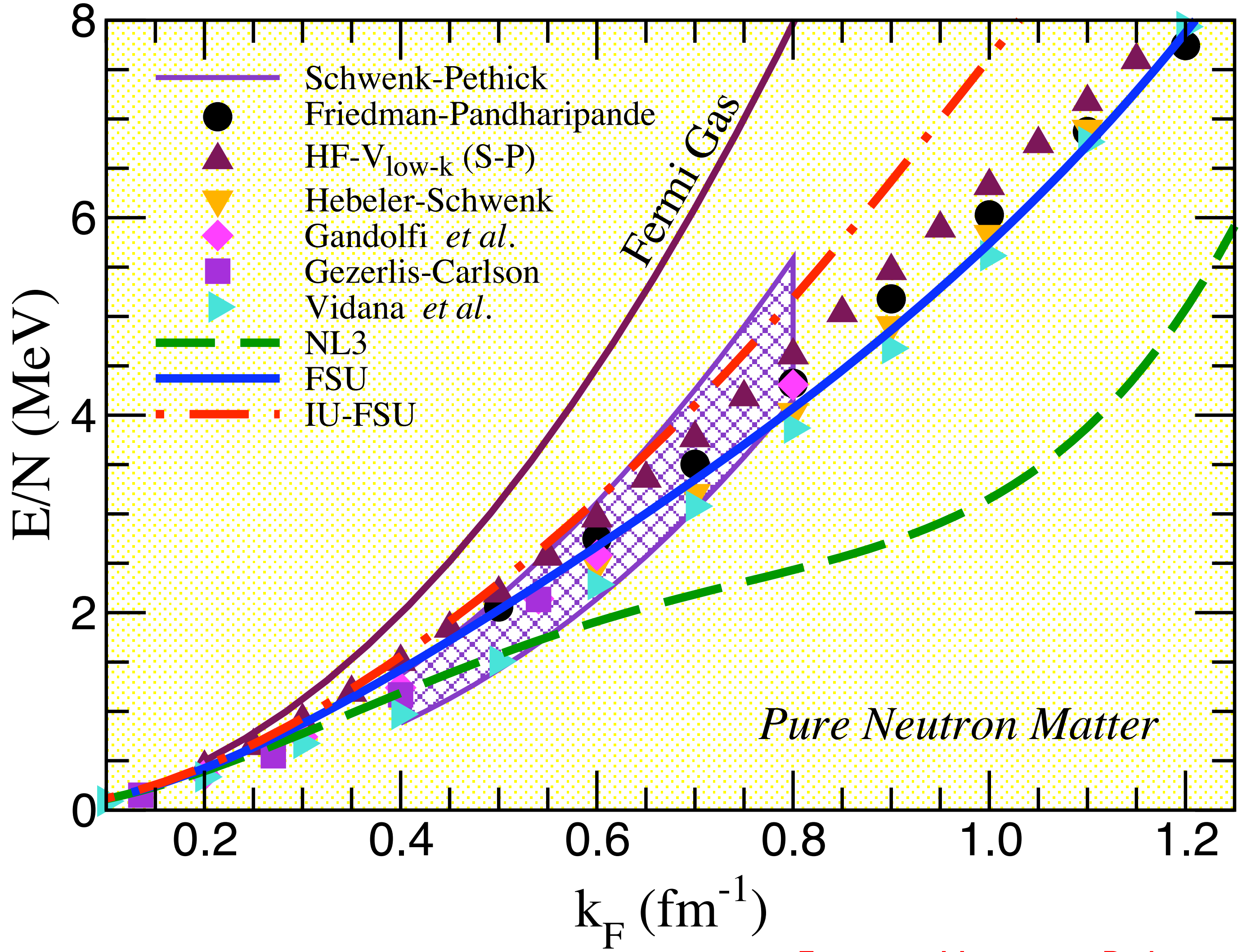
Isospin dep. observables

GMR, GDR in Pb208, Zr90

Nucleus	Observable	Experiment	NL3	FSU	IU-FSU
^{208}Pb	GMR (MeV)	14.17 ± 0.28	14.32	14.04	14.17
^{90}Zr	GMR (MeV)	17.89 ± 0.20	18.62	17.98	17.87
^{208}Pb	IVGDR (MeV)	13.30 ± 0.10	12.70	13.07	13.24

Fattoyev, Horowitz, Piekarewicz, Shen (2010)

Energy of Neutron matter



Fattoyev, Horowitz, Piekarewicz, Shen (2010)

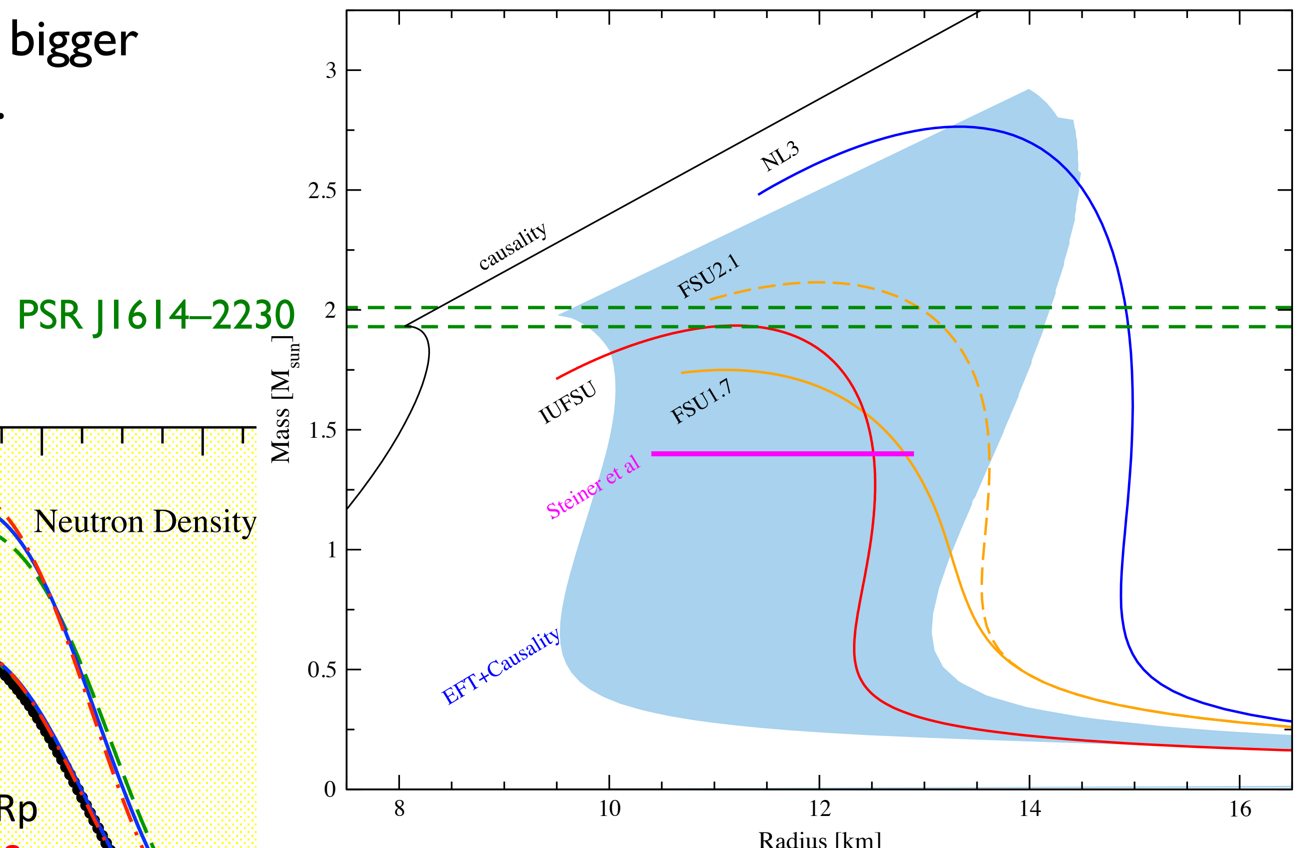
New developments:
Hebeler, Schwenk, 2010
Gandolfi, Carlson, Reddy 2011

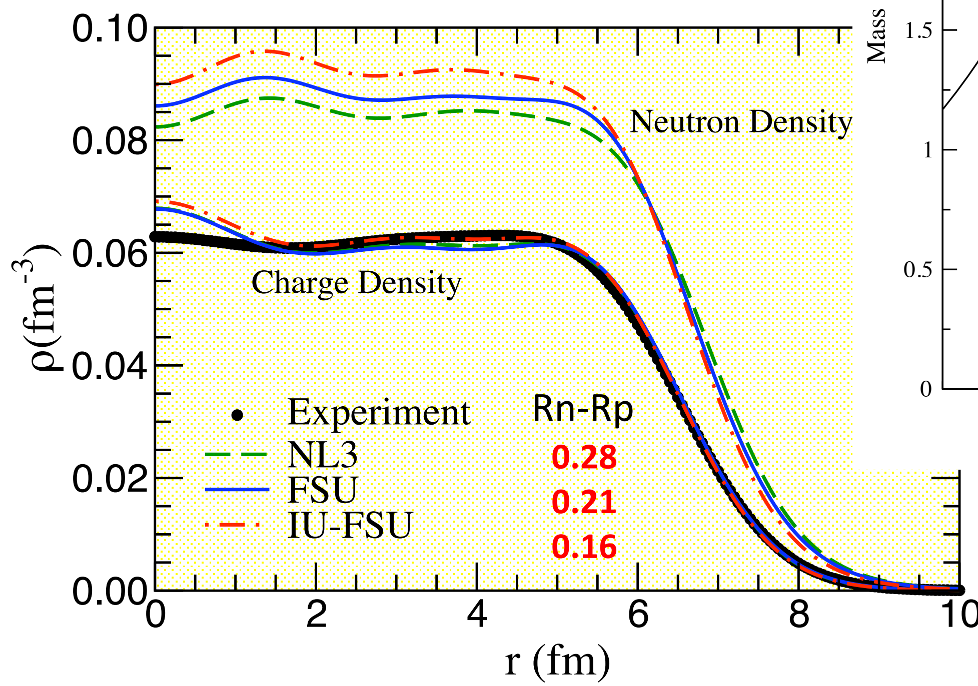
Neutron skin and NS radius

A larger $E'_{sym}(n_0)$ indicates a bigger radius for 1.4 solar mass neutron star and a bigger neutron radius in 208Pb.

$(L=3n_0E'_{sym}(n_0))$

Models	NL3	FSUGold	IU-FSU
$n_0E'_{sym}(n_0)$ [MeV]	39.4	20.2	15.7





Fattoyev, Horowitz, Piekarewicz, Shen (2010)

- Neutrino opacity: unified approach
  - Mean field effect: Charged current reactions
  - RPA correlation
  - Beyond RPA: 2-ph response

Neutrino opacity

			Corrections to ν Opacities	
✔	1.		Phase space	Model Independent
	2.		Matrix element	Model Independent
✔		a.	recoil	Model Independent
✔		b.	weak magnetism	Model Independent
		c.	form factors	~ 1%; Model Independent
		d.	strange quarks	~ 1%; Model Independent
✔	3.		Pauli blocking	Model Independent
✔	4.		Fermi/thermal motion of initial nucleons	Model Independent
✔	5.		Coulomb interactions	Model Independent
✔	6.		Mean field effects	Consistent with EOS
✔	7.		NN Correlations in RPA	Consistent with EOS
✔	8.		NN Correlations beyond RPA	
	9.		Meson exchange currents	~ 1%
	10.		Other components such as hyperons	Uncertain, Constrained by 2 Msun NS
	11.		Other phases such as meson condensates or quark matter	Uncertain, Constrained by 2 Msun NS
	12.		Corrections from superfluid/ superconductor pairing	T < 1 MeV
?????	13.		Nonuniform matter	
?????	14.		Magnetic field effects	

Cirigliano, Reddy, Roberts, Shen, 2012 (in prep.)

Neutrino cross section via response function

Neutral and charged current reactions contribute.

$$l_\mu = \overline{\psi}_l \gamma_\mu (1-\gamma_5)\psi_\nu\,, \quad j_W^\mu = \overline{\psi}_4 \gamma^\mu (g_V - g_A\gamma_5)\psi_2 \qquad g_V = 1, g_A = 1.26$$

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

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

$$l_\mu^\nu = \overline{\psi}_\nu \gamma_\mu (1-\gamma_5)\psi_\nu\,, \quad j_Z^\mu = \overline{\psi}_4 \gamma^\mu (c_V - c_A\gamma_5)\psi_2$$

Weak magnetism

$$F_2 \frac{i\sigma_{\mu\nu}q^\nu}{2M}\vec{\tau}$$

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

$$\frac{d^3\sigma}{d^2\Omega_3 dE_3} = -\frac{G_F^2}{32\pi^2}\frac{E_3}{E_1}\left[1-\exp\left(-\frac{(q_0+\hat{\mu})}{T}\right)\right]^{-1}(1-f_3(E_3))\mathrm{Im}\,(L^{\alpha\beta}\Pi^R_{\alpha\beta})\,,$$

[Reddy, Prakash, Lattimer 1998, Horowitz, Perez-Garcia 2003]

Nucleon

Retarded polarization

$$\mathrm{Im}\Pi^{\mathrm{R}}_{\alpha\beta} = \tanh((\mathrm{q}_0+\hat{\mu})/2\mathrm{T})\mathrm{Im}\Pi_{\alpha\beta}$$

Causal polarization

$$\Pi_{\alpha\beta} = -i\int\frac{d^4p}{(2\pi)^4}\mathrm{Tr}\{T[G_2(p)J_\alpha G_4(p+q)J_\beta]\}$$

Lepton tensor

$$L^{\alpha\beta} = 8[2k^\alpha k^\beta + (k\cdot q)g^{\alpha\beta} - (k^\alpha q^\beta + q^\alpha k^\beta) \mp i\epsilon^{\alpha\beta\mu\nu}k_\mu q_\nu]$$

Non-relativistic limit (simplification for discussion)

Neutrinos couple to (isospin) density
and (isospin) spin density

[Reddy, Prakash, Lattimer 1998]

$$j^\mu(x) = \bar{\psi}(x)\gamma^\mu(C_V - C_A\gamma_5)(\tau_j)\psi(x)$$

$$\text{N.R.} \rightarrow C_V\psi^+(\tau_j)\psi\delta^{\mu 0} - C_A\psi^+\sigma^i(\tau_j)\psi\delta^{\mu i}$$

$$\frac{1}{V}\frac{d^2\sigma}{d\cos\theta dE_3} = \frac{G_F^2}{4\pi^2}E_3^2(1 - f_3(E_3)) \times [C_V^2(1+\cos\theta)S_\rho(q_0,q) + C_A^2(3-\cos\theta)S_\sigma(q_0,q)]$$

Density and spin density (NC)

$$S_\rho(q_0,q) = \int dt\ e^{iq_0 t}\ \langle\rho(q,t)\ \rho(-q,0)\rangle \Rightarrow \rho = \psi^\dagger\psi = \sum_{i=1,N} e^{i\vec{q}\cdot\vec{r}_i}$$

$$= \sum_f \langle 0|\rho(q)|f\rangle\langle f|\rho(-q)|0\rangle\ \delta(q_0 - (E_f - E_0))$$

$$S_\sigma(\omega,\mathbf{q}) = \frac{4}{3n}\frac{1}{2\pi}\int_{-\infty}^{\infty} dt e^{i\omega t}\langle\mathbf{s}(t,\mathbf{q})\cdot\mathbf{s}(0,-\mathbf{q})\rangle \qquad \mathbf{s}(t,q) = V^{-1}\sum_{i=1}^N e^{-i\boldsymbol{q}\cdot\boldsymbol{r}_i(t)}\boldsymbol{\sigma}_i$$

$$= \frac{4}{3n}\sum_f \langle 0|s(\mathbf{q})|f\rangle\cdot\langle f|s(-\mathbf{q})|0\rangle\delta(\omega - (E_f - E_0))$$

Mean field shifts in charged current reactions

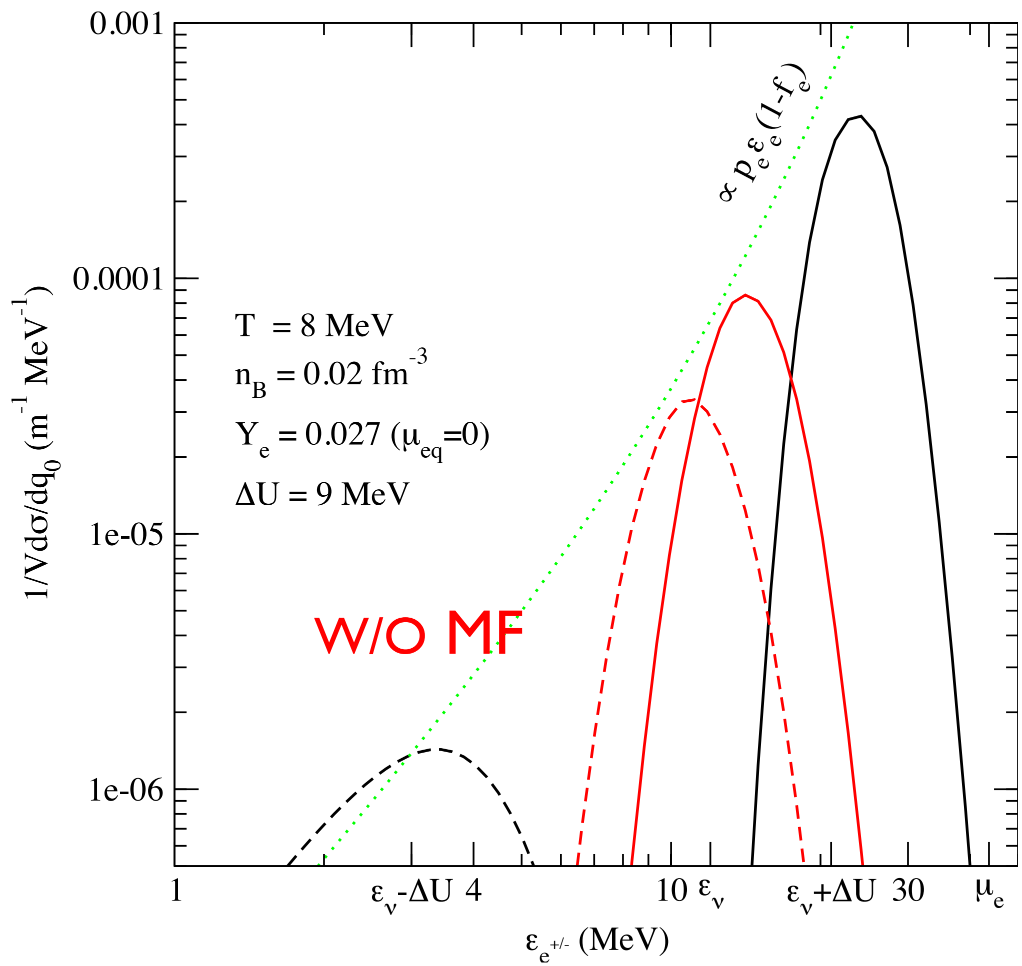
$$\mathrm{Im}\Pi^+ : \nu_e + n \to p + e^-$$
$$\mathrm{Im}\Pi^- : \bar{\nu}_e + p \to n + e^+$$

- Dispersion relation of quasi-particle from EOS:

$$E_i(k) = \sqrt{k^2 + M^{*2}} + U_i,$$
$$U_n - U_p = 40\frac{n_n - n_p}{n_0}\mathrm{MeV}$$

- Response function is peaked around $q_0 \approx U_n - U_p$

- Around neutrino sphere, mean field shift is comparable to temperature.

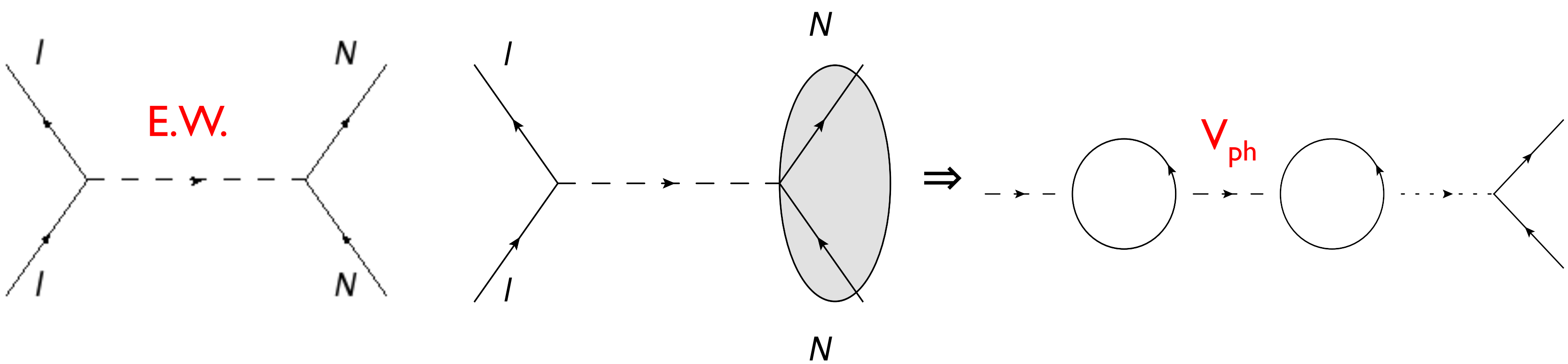


[Roberts, Reddy (2012)]

Roberts (2012)
Martinez-Pinedo et al. (2012)

Random Phase Approximation (RPA)

- An approximate method to include nuclear medium correlations in the response function: 1-ph response.



Free space In medium

⇒ Dyson Equation RPA response $$\Pi^{RPA} = \Pi^0 + \Pi^{RPA} V_{ph} \Pi^0$$

- Provides a fair qualitative description of response in nuclei. Mean field models with consistent residual p-h interactions.
- RPA preserves static sum rule and energy-weight sum rules.

Residual p-h interaction in RPA

- Relativistic field models [Reddy, Prakash, Lattimer, Pons 1999]
  - Vph is consistent with underlying nuclear mean field EOS.
  - Exception: axial vector Vph is not constrained by EOS: from study of response in finite nuclei.

- Non-relativistic Skyrme models
  - Vph from EOS, or Fermi liquid parameter calculated in a microscopic theory.
  - Residual interactions in density and isospin density fluctuations are consistent with EOS.
  - Exception: spin-flip residual interactions are obtained from study of response in finite nuclei.

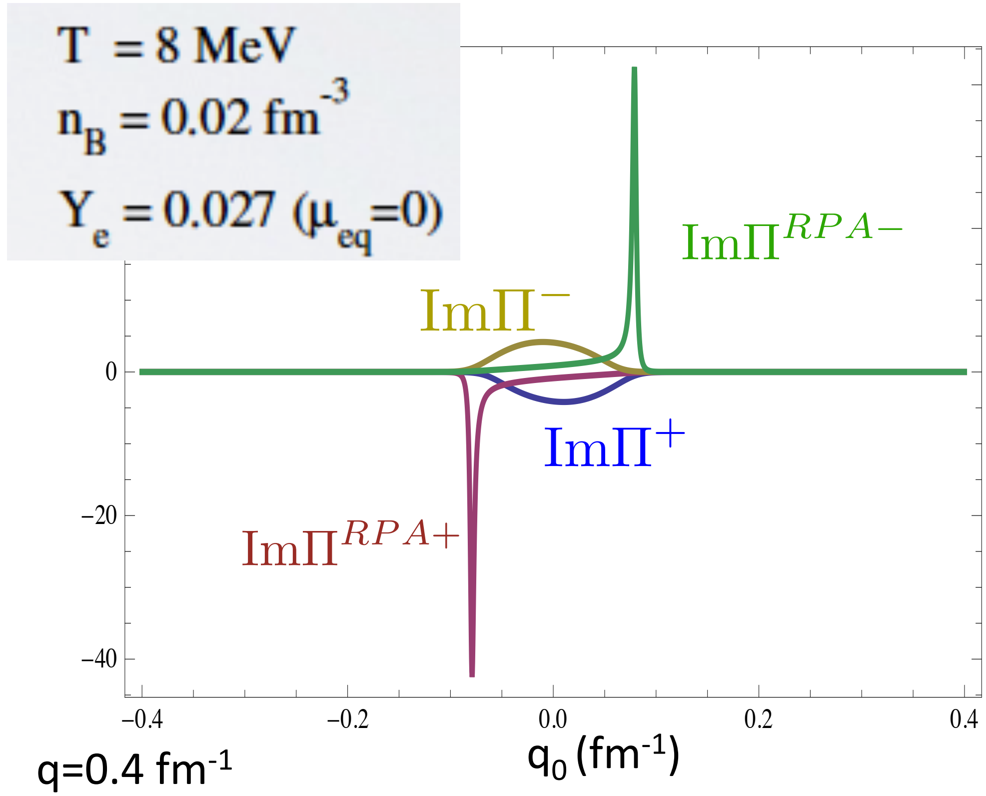
- Both axial vector or spin-flip residual interactions are more important in each model.

- Multi-component (n,p,e) matter: RPA mix various polarizations – nn, pp, ee, …

Charged current reactions in RPA

$$\mathrm{Im}\Pi^+ : \ \nu_e + n \to p + e^-$$
$$\mathrm{Im}\Pi^- : \ \bar{\nu}_e + p \to n + e^+$$

- Repulsive residual p-h interaction: favor two imbalanced fermi sea and act as restoring force.
- Collective modes (peaks): usually outside 1-ph kinematic regime.



- Ikeda sum rule

Ikeda 1964

$$\int d\omega(\mathrm{Im}\Pi^+ - \mathrm{Im}\Pi^-) \ = \ -\pi(n_2 - n_4)$$

- f-sum rule

Thouless 1961

$$\int d\omega\omega(\mathrm{Im}\Pi^+ + \mathrm{Im}\Pi^-) \ = < \psi_0|[\hat{O}^+, [H, \hat{O}]]|\psi_0 > \ + h.c.$$

Fermi/GT operators

2-ph response: beyond RPA

[Roberts, Shen, Reddy , 2012 (in prep)]

- Ansatz for spin-isospin charge-exchange response function

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

- 2PH response is included via relaxation time approximation:

$\Gamma = \tau_\sigma^{-1}$, calculated in Chiral EFT

[Bacca et al, 2009, 2011]

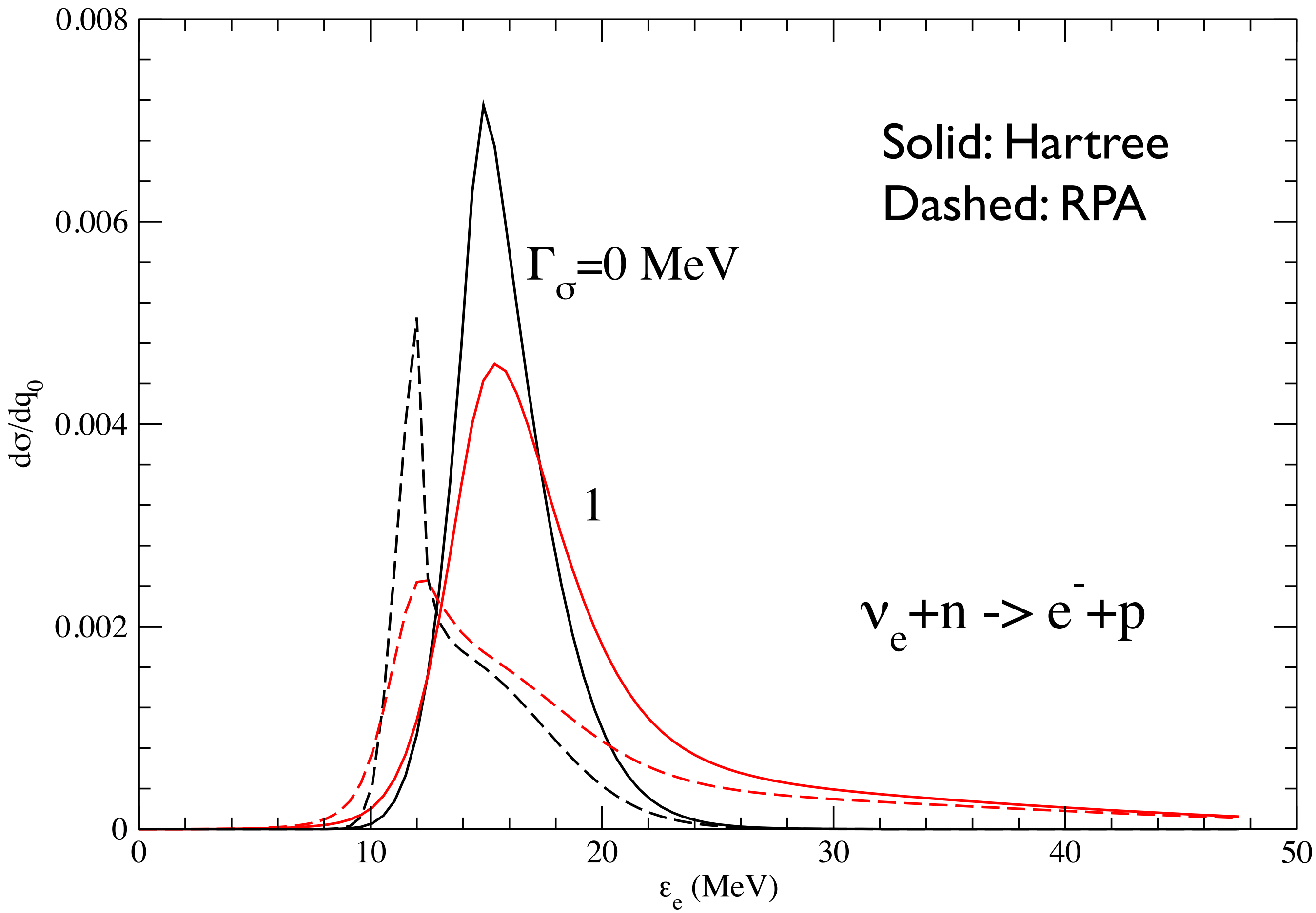
$$\mathrm{Im}\tilde{\Pi}(q_0, q) = \frac{1}{\pi} \int \frac{d^3p}{(2\pi)^3} \frac{f_p(\epsilon_{p+q}) - f_n(\epsilon_p)}{\epsilon_{p+q} - \epsilon_p + \hat{\mu}} \mathcal{I}(\Gamma)$$

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

- P-h interaction $V_{\sigma\tau}$ from GT transition of finite nuclei: 220 MeVfm^3.

Charged current reactions in RPA and beyond

T=8 MeV
N=0.006 fm-3
Ye=0.03
μ_e=30 MeV
E_ν=12 MeV



- RPA suppresses response and shifts its strength via collective mode. Multi-particle dynamics enhances it.
- Net effect mild suppression. Follow SN trajectory to study details.

Sum rules and multi-particle response

- q=0 limit, spin response comes solely from multi-particle dynamics. Density response vanishes.

$$S_\sigma(\omega, \mathbf{q}) \;=\; \frac{4}{3n}\frac{1}{2\pi}\int_{-\infty}^{\infty} dt e^{i\omega t}\langle \mathbf{s}(t,\mathbf{q})\cdot\mathbf{s}(0,-\mathbf{q})\rangle$$

- Response function is constrained by sum rules

Fermi gas

Spin susceptibility $S_{-1} = \int_0^\infty \frac{S_A(\omega,0)}{\omega} d\omega, \;\; \chi = 2nS_{-1}$ $\boxed{\chi_{FG} \;=\; mk_F/\pi^2}$

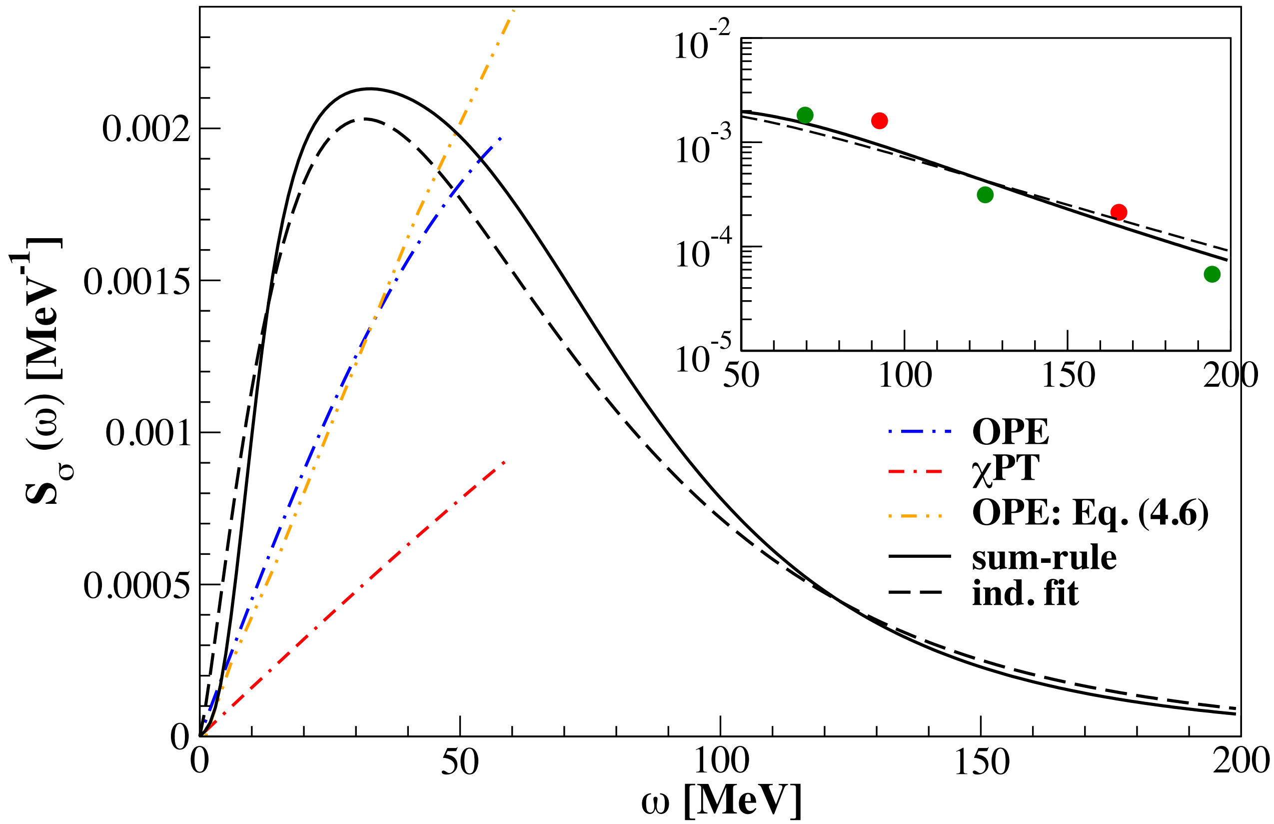
Pair correlation function $S_0 \;=\; \int_{-\infty}^{\infty} S_A(\omega,\mathbf{q})d\omega \;=\; 1 \;+\; \frac{4}{3N}\sum_{i\neq j}^{N}\langle e^{-i\mathbf{q}\cdot(\mathbf{r_i}-\mathbf{r_j})}\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j\rangle,$

Energy-weighted sum rule $S_{+1} \;=\; \int_{-\infty}^{\infty} S_A(\omega,\mathbf{q})\omega d\omega \;=\; -\frac{4}{3N}\langle [H, \boldsymbol{s}(\mathbf{q})]\cdot\boldsymbol{s}(-\mathbf{q})\rangle,$

[Shen, Gandolfi, Reddy, Carlson, 2012]

AFDMC results for the sum-rules

Density (fm^{-3})	S_σ^{-1} (MeV^{-1})	S_σ^0	S_σ^{+1} (MeV)	$\bar{\omega}_0$ (MeV)	$\bar{\omega}_1$ (MeV)
$n = 0.12$	0.0057(9)	0.20(1)	8(1)	35(9)	40(8)
$n = 0.16$	0.0044(7)	0.20(1)	11(1)	46(11)	55(8)
$n = 0.20$	0.0038(6)	0.18(1)	14(1)	47(12)	78(10)



Enhanced response at 10-50 MeV

- Low ω: from Landau Fermi liquid theory
- Corrections at intermediate ω
- High ω: reduced to 2-particle response – solved exactly from two-body Schrődinger eq.

Neutrino pair production

- $\nu_1 + \bar{\nu}_1 \rightleftharpoons \nu_2 + \bar{\nu}_2$ Buras et al, 2003
- $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$ Dicus ’72; Bruenn ’85
- $\gamma* \rightleftharpoons \nu\bar{\nu}$ Braaten & Seckel ’91, Ratkovic et al ’03
- $\gamma * + e \rightleftharpoons e + \nu\bar{\nu}$ Schinder et al ‘87, Dutta et al ‘04
- $NN \rightleftharpoons NN\nu\bar{\nu}$

- Friman & Maxwell 1979, OPE Born
- Hannestad & Raffelt 1998, OPE Born – fitting formula
- Hanhart, Philips, Reddy 1999, T-matrix – reduction compared to OPE
- Lykasov et al 2008, Bacca et al 2009, 2011: 2-body response in chiral EFT – reduction of response
- Shen, Gandolfi, Reddy, Carlson (2012): QMC sum rules – low energy enhancement

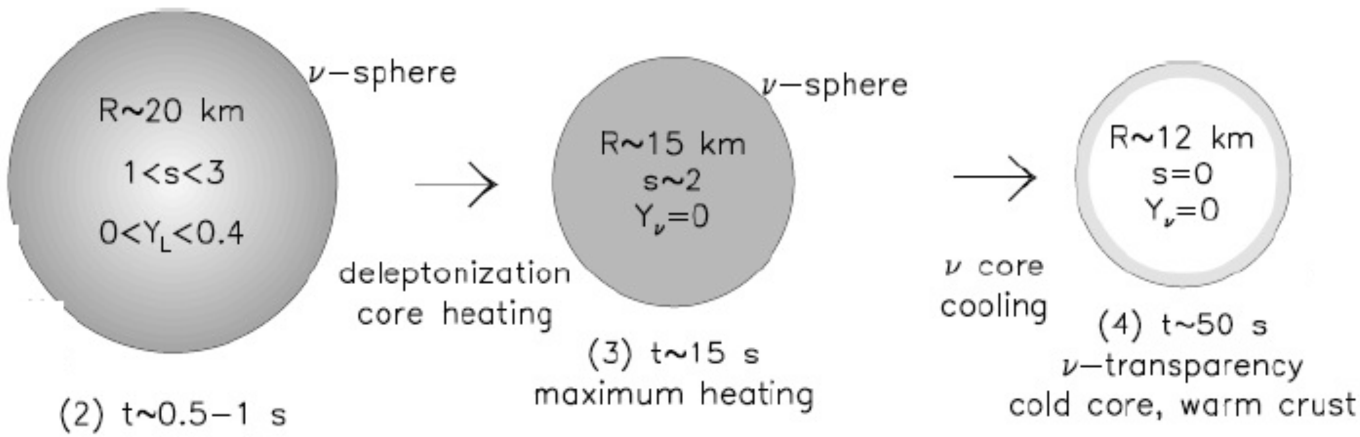
Application

- Late time supernova neutrino signal
  - Essential physics suite
  - Nuclear symmetry energy and ν convection
  - Observables

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

Late time supernova ν signal (PNS)

- Neutrino transport drives the evolution of a PNS (hot, lepton rich, SN remnant) → NS (cold, deleptonized, compact)

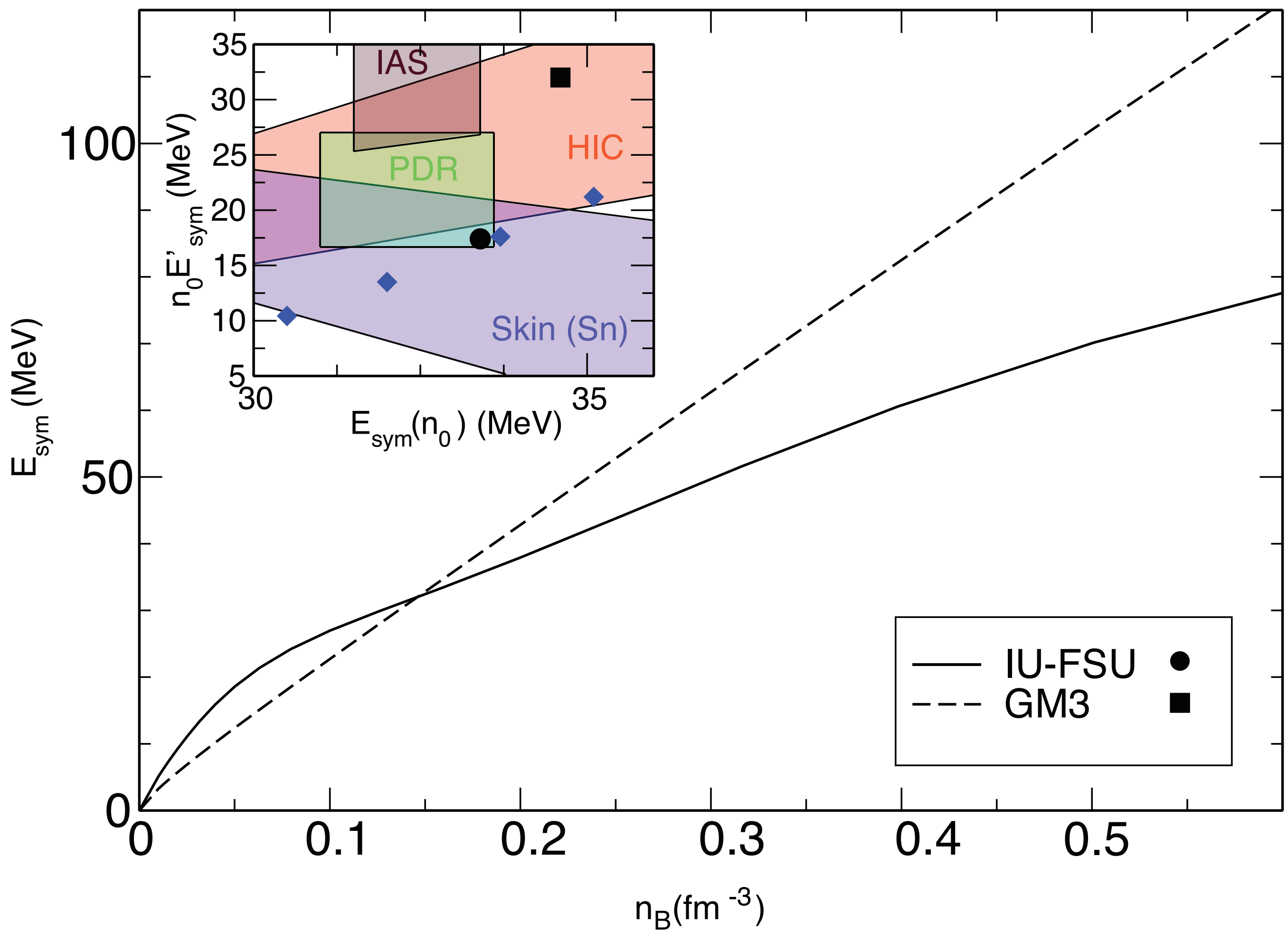


- Study the sensitivity of cooling time-scale and neutrino signal to EoS, opacities, convection

- 1d PNS model: TOV equations + diffusion transport + convection

Updates in neutrino transport: Roberts (2012)

- Use two different high density EoS with associated opacities (without and with RPA correlations)
- EoS differ in the behavior of the symmetry energy



- Large regions are convectively unstable, according to Ledoux criterion (competition of leptonic and entropy gradients)

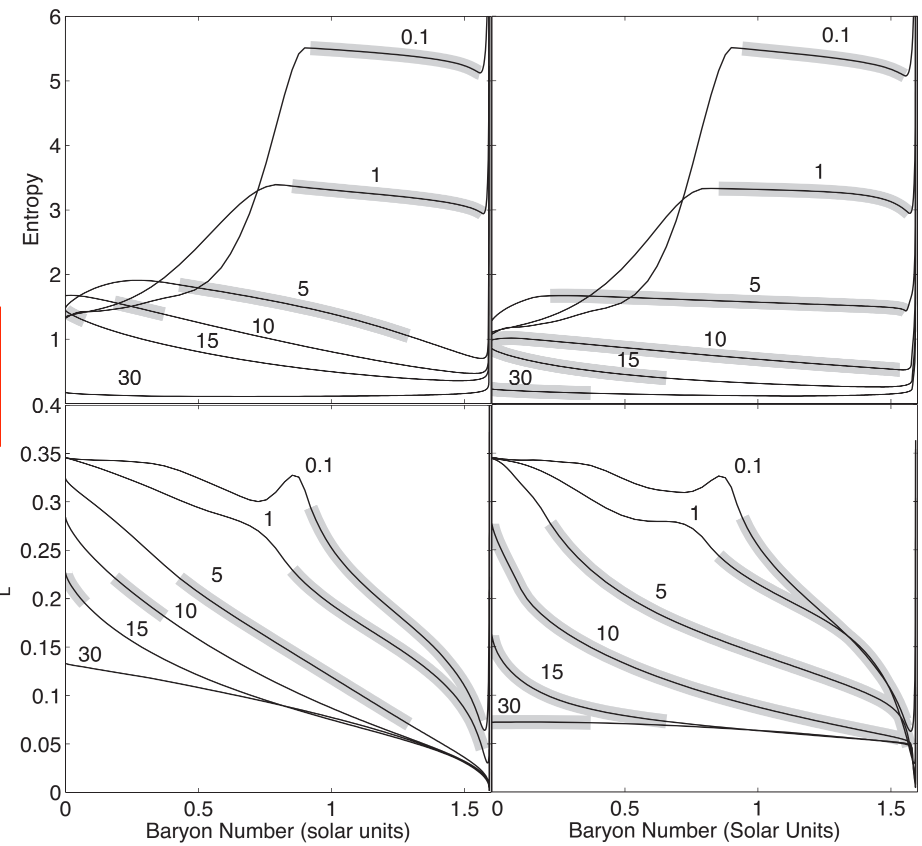
$$-\left(\frac{\partial P}{\partial s}\right)_{n,Y_L}\frac{ds}{dr}-\left(\frac{\partial P}{\partial Y_L}\right)_{n,s}\frac{dY_L}{dr}>0$$

- Density dependence of nuclear symmetry is key to understand composition driven convective instability:

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

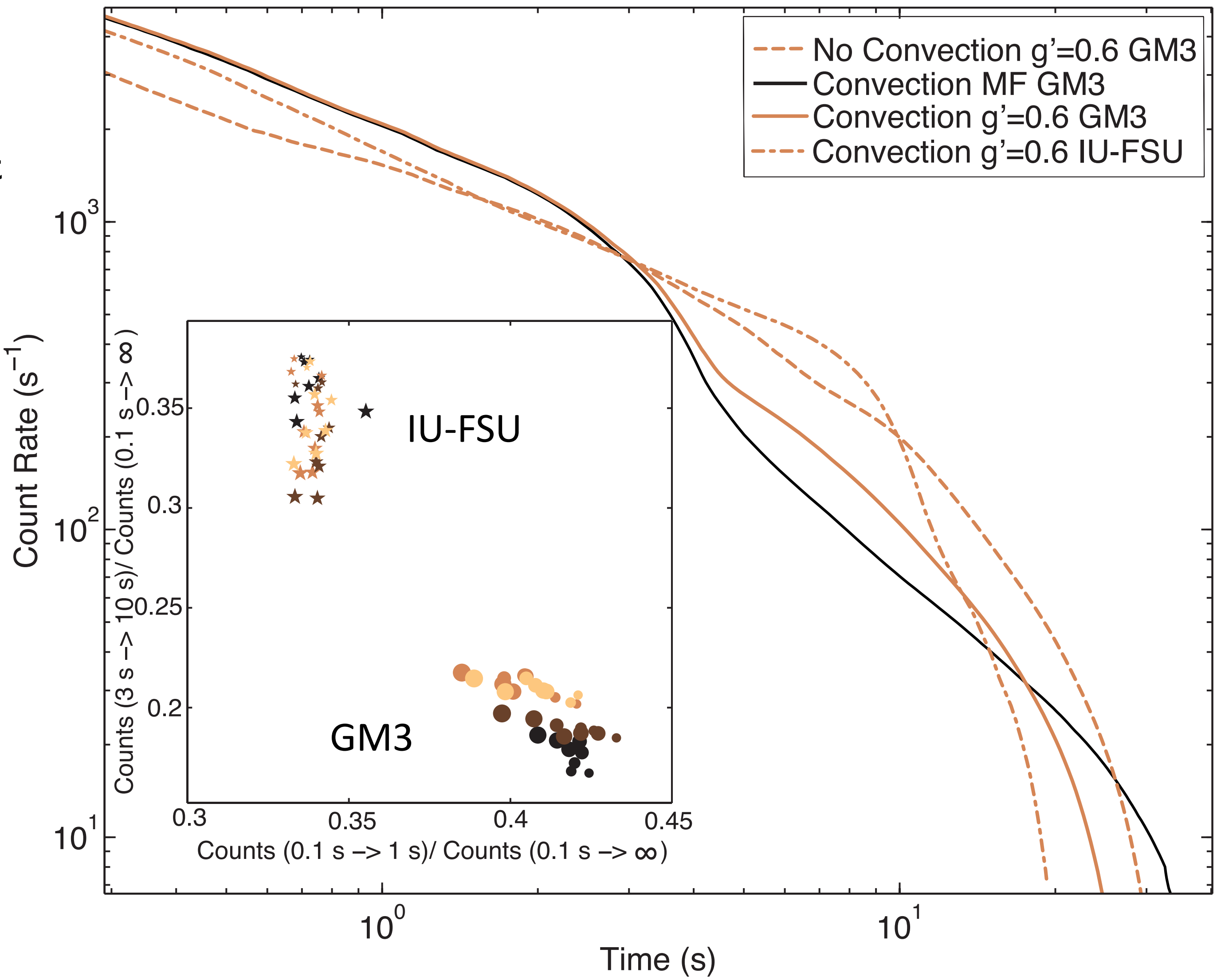
- Larger E'_{sym} stabilizes/shuts off convection at earlier time

GM3: Large E'_{sym} IUFSU: Small E'_{sym}



Observable signatures of convective transport

- Count rate in Super-K for galactic supernova at 10 kpc.
- Convection produces most dramatic features (larger luminosity and shorter cooling time scale).
- RPA opacities imply larger luminosity between 3-10 secs.



Summary

- Constraints on nuclear EOS
  - Symmetric matter: saturation, stable nuclei
  - Neutron rich matter: isovector response, neutron skin, benchmark from EFT, QMC
  - Above $2n_0$: NS observations
- Neutrino opacity
  - Kinematics
  - Mean field effects
  - NN correlations in RPA
  - NN correlations beyond RPA: 2PH
- Neutrino pair production
- Applications

Thank you !