NEUTRINO OPACITIES IN DENSE MATTER:

AN APPRAISAL OF PAST AND RECENT RESULTS

- Introduction and motivation.
- Cross-sections and correlation functions.
- Mean field theory, multi-particle excitations.
- Charged current rates.
- Benchmarks and sum rules.
- Summary and outlook.

Sanjay Reddy INT, Univ. of Washington, Seattle

Core-Collapse Supernova: Models and Observable Signals (2012)

STIVATION

• Supernova neutrinos are detectable.

- Neutrino luminosity and spectra influence the explosion mechanism and nucleosynthesis.
- Temporal and spectral features of the supernova neutrino signal is an unique probe of physics/astrophysics under extreme conditions, neutrino properties and exotic light weakly interacting particles.

NEUTRINO TRANSPORT

• RHS of the Boltzmann Equation.

NEUTRINO TRANSPORT

• RHS of the Boltzmann Equation.

NEUTRINO TRANSPORT

• RHS of the Boltzmann Equation.

NEUTRINO CROSS SECTIONS

Differential Scattering/Absorption Rate: response function of the medium

 $N = N - N^2 I(T - T)$ 5. Inelastic Neutrino Interactions with $R(E_1, E_3, \cos \theta) = G_F^2 L(E_1, E_3, \cos \theta) \times S_{[\rho, Y_e, T]}(q_0, q)$

> R_{max} We now the nonneutrino/lepton kinematic factor

• Neutral and charged current reactions contribute. For neutrino energies of interest to supernova, which are less than

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

NEUTRINO CROSS SECTIONS NEUTRINO OPOSOPHISTIC

ntial Scattering/Al For neutrino energies of interest to supernova, which are less than response function of the me terms of Fermi's effective Lagrangian and Differential Scattering/Absorption Rate: Relativistic Nucleons and Leptons We now the normalism of the first response function of the medium

scattering processes in nuclear matter. In this section, we address the

 $N = N - N^2 I(T - T)$ 5. Inelastic Neutrino Interactions with R_{max} We now the non- $S(\theta) = G_F^2 L(E_1, E_3, \cos \theta) \times S_{\ln V} \eta$ $\sqrt{ }$ √2 l ν µj $\frac{1}{3}$ is the Fermi constant of the Fermi with $\frac{1}{3}$ is the Fermi with $\frac{1}{3}$ non-interacting nucleon case. F_2 , $\cos \theta$) = $G_{\overline{D}}^2$, $L(E_1, E_2, \cos \theta) \times S_{\text{L}}$, while and \mathbf{r} interaction interaction interaction interaction interaction interaction interaction interaction in terms of Fermi's effective Lagrangian and the California effective Lagrangian and ϵ √2 201 NITCHROUGHCLOT neutrino/lepton kinematic factor $R(E_1, E_3, \cos \theta) = G_F^2 L(E_1, E_3, \cos \theta) \times S_{[\rho, Y_e, T]}(q_0, q)$

• Neutral and charged current reactions contribute. For neutrino energies of interest to supernova, which are less than and baryon weak charged currents are: charg \overline{d} d current reactions contribute.

> $I = \overline{a}$ (1 αr) a/r in \overline{a} if \overline{a} in αr in αr in αr) a/r $\partial \mu$ γ μ \leftarrow β γ ψ γ Lcc int = G_F √ 2 $l_{\mu}j^{\mu}_{W}$ for $\nu_{l} + B_{2} \rightarrow l + B_{4}$ $\mathcal{L}_{int}^{nc}\;\;=\;\;$ G_F $\frac{G_F}{\sqrt{2}}$ $\int_{\mu}^{\nu} j_Z^{\mu}$ for $\nu_l + B_2 \rightarrow \nu_l + B_4$ $l^{\nu} = \overline{\psi} \propto (1 - \gamma_{\epsilon}) \psi$, $i^{\mu}_{\tau} = \overline{\psi} \sqrt{\psi} (\gamma_{V} - \gamma_{A} \gamma_{\epsilon}) \psi_{0}$ $u_{\mu} - \varphi_{\nu} \gamma_{\mu} (1 - \gamma_5) \varphi_{\nu}$, $J_Z - \varphi_4 \gamma (\varepsilon_V - \varepsilon_{A} \gamma_5) \varphi_2$ $l_\mu = \overline{\psi}_l \gamma_\mu \left(1-\gamma_5 \right) \psi_\nu \, , \quad j_W^\mu = \overline{\psi}_4 \gamma^\mu \left(g_V - g_A \gamma_5 \right) \psi_2$ Similarly, the baryon and neutrino neutral currents are given by $\mathcal{L}_{int} = \frac{V \mu J W}{\sqrt{2}}$ ($\mu J W$ for $\mathcal{L}_{1} + \mathcal{L}_{2} \rightarrow \mathcal{L}_{1} + \mathcal{L}_{4}$ $\mathcal{L}_{int}^{nc} = \frac{G_F}{\sqrt{2}} l^{\nu}_{\mu} j^{\mu}_{Z}$ for $\nu_l + B_2 \rightarrow \nu_l + B_4$ V^2 The vector and axial-vector and axial-vector coupling constants (cV α , gA) are called constants (cV α , gA) are called constants (cV α $l^{\nu}_{\mu}=\psi_{\nu}\gamma_{\mu}\left(1-\gamma_{5}\right) \psi_{\nu}\,,\quad j^{\mu}_{Z}=\psi_{4}\gamma^{\mu}\left(c_{V}-c_{A}\gamma_{5}\right) \psi_{2}$ N typical energy and momentum involved in the reaction are action and momentum involved in the reaction are action are action are action and momentum involved in the reaction are action are action are action are action G_F and G_F $\mathcal{L}_{int}^{cc} = \frac{1}{\sqrt{2}} l_{\mu} j_{W}^{\mu}$ for Similarly, the baryon and neutrino neutral currents are given by l_{μ}^{ν} $\frac{\nu}{\mu}=\overline{\psi}_{\nu}\gamma_{\mu}\left(1-\gamma_{5}\right)\psi_{\nu}\,,\quad\overline{j}{}^{\mu}_{Z}=\overline{\psi}_{4}\gamma^{\mu}\left(c_{V}-c_{A}\gamma_{5}\right)\psi_{2}\,,$

NEUTRINO CROSS SECTIONS NEUTRINO OPOSOPHISTIC

ntial Scattering/Al For neutrino energies of interest to supernova, which are less than response function of the me terms of Fermi's effective Lagrangian and Differential Scattering/Absorption Rate: Relativistic Nucleons and Leptons We now the normalism of the first response function of the medium

scattering processes in nuclear matter. In this section, we address the

 $N = N - N^2 I(T - T)$ 5. Inelastic Neutrino Interactions with R_{max} We now the non- $\sigma(\theta) =$ $G_F^2 L(E_1, E_3, \cos \theta) \times S_{\log V}$ τ ¹(*e*) G^F √2 l ν µj $\frac{1}{3}$ is the Fermi constant of the Fermi with $\frac{1}{3}$ is the Fermi with $\frac{1}{3}$ non-interacting nucleon case. F_2 , $\cos \theta$) = $G_{\overline{D}}^2$, $L(E_1, E_2, \cos \theta) \times S_{\text{L}}$, while and \mathbf{r} interaction interaction interaction interaction interaction interaction interaction interaction in terms of Fermi's effective Lagrangian and the California effective Lagrangian and ϵ √2 201 NITCHROUGHCLOT neutrino/lepton kinematic factor $R(E_1, E_3, \cos \theta) = G_F^2 L(E_1, E_3, \cos \theta) \times S_{[\rho, Y_e, T]}(q_0, q)$

• Neutral and charged current reactions contribute. For neutrino energies of interest to supernova, which are less than and baryon weak charged currents are: charg \overline{d} d current reactions contribute.

> $\overline{a} = \overline{a}$, \overline{a} (1 \overline{a}) \overline{a}), \overline{a} if $\overline{a} = \overline{a}$, \overline{a}) \overline{a} (\overline{a} , \overline{a} , \overline{a} , \overline{a}) \overline{a} (\overline{a} , \overline{a}) \overline{a} $\partial \mu$ γ μ \leftarrow β γ ψ γ Lcc int = G_F √ 2 $l_{\mu}j^{\mu}_{W}$ for $\nu_{l} + B_{2} \rightarrow l + B_{4}$ $\mathcal{L}_{int}^{nc}\;\;=\;\;$ G_F $\mathcal{L}_{int}^{nc} = \frac{G_F}{\sqrt{2}} l^{\nu}_{\mu} j^{\mu}_{Z} \quad \text{for} \quad \nu_l + B_2 \rightarrow \nu_l + B_4 \quad {}_{c^{\prime \prime}_V} = -1.$ $l^{\nu} = \overline{\psi} \propto (1 - \gamma_{\epsilon}) \psi$ $\mu = \psi_V \gamma \mu (1 - \gamma_5) \psi_V, \quad J_Z - \psi_4 \gamma (\epsilon_V - \epsilon_A \gamma_5) \psi_2$ $l_{\mu} = \overline{\psi}_l \gamma_{\mu} (1 - \gamma_5) \psi_{\nu} \, , \quad j_W^{\mu} = \overline{\psi}_4 \gamma^{\mu} (g_V - g_A \gamma_5) \psi_2 \qquad g_V = 1, g_A = 1.26$ Similarly, the baryon and neutrino neutral currents are given by $\frac{1}{2}$ $int \frac{1}{\sqrt{2}} u \mu J W$ for $\nu_l + D_2 \rightarrow \nu + D_4$ $\sqrt{2}$ $\frac{c_V = -1}{n}$ $C_V = 0.07$ $l_\mu^\nu = \psi_\nu \gamma_\mu \left(1-\gamma_5 \right) \psi_\nu \, , \quad j_Z^\mu = \psi_4 \gamma^\mu \left(c_V - c_A \gamma_5 \right) \psi_2 \qquad \qquad c_V = 1.925$ $\epsilon_V=-0.$ N typical energy and momentum involved in the reaction are action and momentum involved in the reaction are action are action are action and momentum involved in the reaction are action are action are action are action G_F and G_F $\mathcal{L}_{int}^{cc} = \frac{1}{\sqrt{2}} l_{\mu} j_{W}^{\mu}$ for Similarly, the baryon and neutrino neutral currents are given by l_{μ}^{ν} $\frac{\nu}{\mu}=\overline{\psi}_{\nu}\gamma_{\mu}\left(1-\gamma_{5}\right)\psi_{\nu}\,,\quad\dot{\vec{j}}_{Z}^{\mu}=\overline{\psi}_{4}\gamma^{\mu}\left(c_{V}-c_{A}\gamma_{5}\right)\psi_{2}\qquad\qquad\frac{c_{V}^{e}}{c^{e}}=1.92,$ $c_V^n = -1.0, \ c_A^n = -1.26(-1.1)$ $c_V^p = 0.07, \ c_A^p = 1.26(1.4)$ $c_V^e = 1.92, \ c_A^e = 1. [\nu_e]$ $c_V^e = -0.08, \ c_A^e = -1. \ [\nu_X]$

RESPONSE FUNCTIONS Sawyer (1975), Iwamoto & Pethick (1982)

 $j^{\mu}(x) = \overline{\psi}(x) \gamma^{\mu}(c_V - c_A \gamma_5) \psi(x)$ *NR* \rightarrow $c_V \psi^+ \psi \delta^{\mu 0} - c_A \psi^+ \sigma^i \psi \delta^{\mu i}$ Neutrinos couple to density and spin

 $\times [C_V^2(1+\cos\theta)S_\rho(q_0, q) + C_A^2(3-\cos\theta)S_\sigma(q_0, q)]$ $d\Gamma(E_1)$ $d\cos\theta\,\, dq_0$ \approx $\frac{G_F^2}{4\pi^2}\,\left(E_1-q_0\right)^2\,\left(1-f_\nu(E_1-q_0)\right)$

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

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

f

RESPONSE FUNCTIONS Sawyer (1975), Iwamoto & Pethick (1982)

 $j^{\mu}(x) = \overline{\psi}(x) \gamma^{\mu}(c_V - c_A \gamma_5) \psi(x)$ *NR* \rightarrow $c_V \psi^+ \psi \delta^{\mu 0} - c_A \psi^+ \sigma^i \psi \delta^{\mu i}$ Neutrinos couple to density and spin $\mathbf{F} \cdot \mathbf{n} = \mathbf{n} \cdot \mathbf{n}$ ψ or $-c_A \psi \sigma \psi$

 $\times [C_V^2(1+\cos\theta)S_\rho(q_0, q) + C_A^2(3-\cos\theta)S_\sigma(q_0, q)]$ $d\Gamma(E_1)$ $d\cos\theta\,\, dq_0$ \approx $\frac{G_F^2}{4\pi^2}\,\left(E_1-q_0\right)^2\,\left(1-f_\nu(E_1-q_0)\right)$ $d\Gamma(E_1)$ G_F^2 $\sqrt{C_1^2(1+\cos\theta)}S(\cos\theta)+C_1^2(3-\cos\theta)S(\cos\theta)$ $\mathcal{P}_\mathcal{V}$ (i) the dense medium, and $\mathcal{P}_\mathcal{V}(10, 1)$ kinematical factors and coupling $\mathcal{P}_\mathcal{V}(20, 1)$ constants associated with neutrino currents. The latter are well-known and relatively simple functions of the neutrino $= q_0$) in contrast, the spin-dimensional function functions are complex functions are complex functions are complex functions of q_0 in q_1 \mathbf{r} $g_1(3-\cos\theta)S_\sigma(q_0,q)$

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

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

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

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

 $\bm \sigma_i$

3*n*

f

RESPONSE OF AN IDEAL GAS *V* $C₁$ *d*2,*dE*³ |
|- \sum ²-!*V*2"3*A*2""1# *^f* ³!*E*3"…*S*!*q*⁰ ,*q*", $DTCDONICF$ the most control in the most control of A rium. In some astrophysical situations, such as in the late *d*2,*dE*³

- Process involves excitation of single (uncorrelated) particles. Total response is the (incoherent) sum over individual species. $\frac{1}{2}$ esponse is the (inconerent) sum over individual spe response is the (incoherent) sum over dependence in the matter of the called the matter with w erechted norticles- τ \overline{a} \overline{b} alcu) particios. Total
Unⁱ energiae *S*(*q*⁰ ,*q*), the so-called dynamic form factor or structure
- For nucleons and electrons final state blocking is important. Matter is partially degenerate for typical supernova conditions. !%*q* !%, and the energy transfer *q*0!*E*1#*E*3. The function • For nucleons and electrons final state blocking is important. Matter is equilibrium is established among the baryons and leptons. In / ab₈ end ace ion of predication inc transfer energy α and momentum α that the differential cross section is needed in multi-energy
- Nucleons are heavy and recoil energy is small. Response lies at small $|\omega|$ < q v. Where $v \sim p$ F/M or $\sqrt{T/M}$. Nucleons are heavy and recoil energy is small Respo $\frac{1}{\sqrt{10}}$ • INUCIEONS are heavy and recoil energy i group neutrino transport codes. However, more approximate nall. Response lies at small

transition rate (Γ=c/λ) in a Fermi Gas.

\n
$$
\Gamma(E_1) = \int \frac{d^3 k_3}{(2\pi)^3} R(E_1, E_3, \cos \theta) (1 - f_3(E_3))
$$
\n
$$
\approx G_F^2 \int \frac{d^3 k_3}{(2\pi)^3} [C_V^2 (1 + \cos \theta) + C_A^2 (3 - \cos \theta)] S_{FG}(q_0, q) (1 - f_3(E_3))
$$

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

ANALYTIC FORMULA EXIST *S*FG(*q*0*,q*) = $\overline{}$ $\overline{}$.
F *<i>d* $PRMUI$ \land $FXIST$ medium is *q*² = *E*² ^ν + *E*² *^e* − 2*E*ν*Ee* cosθ. The free particle re- $A N A$ ∆*M* = *Mn* − *Mp* increases the *Q* value for this reaction and a L A L X D I A I VTIC EODMI II A EVICT relation for nucleons is given by *E*(*p*) = *M* + *p*²*/*2*M*, and ne-

• Closed form expressions for the scattering and absorption rates including effects of relativistic kinematics and weak magnetism exist in the literature. [Reddy, Prakash, Lattimer 1998, Horowitz, Perez-Garcia 2003] tion in expressions for the seattering and absorptive rates including effects of relativistic kinematics and weak $\overline{\Omega}$ For *d*³ *p*2δ(*q*⁰ +*E*² −*E*4)*f*2(1 − *f*4)*,* (4) magnoticm oviet in the literature relation for nucleons is given by *E*(*p*) = *M* + *p*²*/*2*M*, and neing and absorption \ddotsc $\frac{1}{2}$ rela $line(1 + e^{\alpha t} - e^{\alpha t})$ istic kine *P* matics and \geq *,*

$$
S_{FG}(q_0, q) = \frac{M^2 T}{\pi q (1 - e^{-z})} \ln \left[\frac{\exp \left[(e_{\min} - \mu_2) / T \right] + 1}{\exp \left[(e_{\min} - \mu_2) / T \right] + \exp \left[-z \right]} \right]
$$

where where outgoing nucleons, *M* is the nucleon mass, and

$$
z = \frac{(q_0 + \mu_2 - \mu_4)}{T} \qquad e_{\min} = \frac{M}{2q^2} \left(q_0 - \frac{q^2}{2M} \right)^2
$$

*µ*² and *µ*⁴ are the chemical potentials of the incoming and d be desirable to use these in supernov: out we under desimple to use these in superserve simulations to *e*min = **Manufacture in the intervalse stablish baseline results.** ernova simulations energy-momentum transferred transportation ϵ sicalle to use these in supernova simulation Ω → Ω $\overline{}$ • It would be desirable to use these in supernova simulations to

MANY-PARTICLE DYNAMICS • Neutrinos see more than one particle in the medium. $IPAKIICIFIYYNAYIIC V$ driven by the nuclear symmetry energy, has a similar but \mathbf{u} so of Internating System Response of Interacting System

 \sim ispatial and temporal correlations between ieons and electrons affect the scattering rate. emporal correlation Indefections anect the scattering rat ons $\overline{+}$

 \diagdown \diagup

re matter and the dispersion relation is altered. Mean field energy Mipot and $E_i(k) = \sqrt{k^2 + M^{*2}} + U_i \equiv K(k) + U_i$ $n = 1$ ∆*R*

∆*R* $\tau_{\text{collision}}$

 $\frac{2\pi}{a} > \frac{1}{1}$ $f_1 = \frac{q-1}{\lambda}$ \wedge R \blacksquare $\bigcap_{n=1}^{\infty}$ $\bigcap_{n=1}^{\infty}$ $\bigcap_{n=1}^{\infty}$ $\bigcap_{n=1}^{\infty}$ \mathbf{v} \mathbf{v} if the difference between \mathbf{v} $\frac{1}{2}$ energy per nucleon in $\frac{1}{2}$ α clear methods using α ability α $r=\frac{2\pi}{3}$ \Rightarrow Sawyer (1975, 1989) T waggest that the symmetry of $\sqrt{2}$ energy and sub-nuclear density is larger than Ω . Horowritz & Wherberg $m_{\nu} = \frac{2\pi}{\sqrt{2}}$ Raffelt & Seckel (199 tron star studies (for a review see [23]). To highlight its im- (1991) $q =$ 2π *<u>λ</u>* | >
 λ | *ς* 1 ∆*R* \mathcal{F}^\boxplus 2π mo*<*
|
| A _{nl} $\frac{1}{r}$ ∆*R* 2π τ *>* 2π **TAPONGSTOFF** $\omega =$ 2π *<* nytz
- 2. c At small q_0 and q the neutrino cannot resolve a single nucleon. Sawyer (1975, 1989) Iwampto & Pethick (1982) Horowitz & Wherberger (1991) Raffelt & Seckel (1995)

NEUTRINO SCATTERING OFF NUCLEI We present a pedagogic review of the qualitative findings of model calcu-

• Nuclei are strongly correlated by the (screened) Coulomb force. At 10^{12} g/cm³ and $T > 1$ MeV behavior is classical many particles dynamics can be predicted exactly using $F = m$ a (Molecular Dynamics). 10^{12} g/cm³ and T $>$ 1 MeV behavior is classical - \overline{a} many particles dynamics can be predicted exactly using $F = m$ d V γ $|d$ $|$ $||c$). current interaction of low-energy neutrinos with nuclei is given by many particles dynamics can be pred a (Molecular Dynamics) a (Molecular Dynamics). effects in the internet of community in the community of the communit 25 100 $\frac{1}{2}$ 1012 $\frac{1}{2}$ $T_{\rm eff}$ system, with non-trivial many-body dynamics, which is non-trivial many-body dynamics, whi relevant in the supernova context is a plasma of heavy nuclei (like Fe) current interaction of low-energy neutrinos with nuclei is given by a series with nuclei is given by Ω g/cm³ and $T > 1$ MeV behave λ many particles dynamics can be predicted heavy, and, correspondingly, their thermal velocities are small (v ∼ = acterized only by the interesting and baryon number. In this case it is in this case it is in this case it is

buple coherently to the weak charge in the nucley apic concionity to the weak charge in the number nuclei as junior as junior as junior and write the differential scattering rate in the differential scattering rat the density of the density operator in momentum space in the density of the density $\mathfrak{p}_\mathcal{S}$ showed that the dominant source of opacity for neutrinos in such a Neutrinos couple coherently to the weak charge in the nucleus. couple coherently, via the via the vector neutral current, to the vector neutral current, to the total weak ch terms of the density operator in momentum space given by

$$
L_{\rm NC} = \frac{G_{\rm F}}{\sqrt{2}} Q_W l_\mu j^\mu \qquad j^\mu = \psi^\dagger \psi \delta_0^\mu \qquad Q_W = (2Z - A - 4Z \sin^2 \theta_W)/2
$$

where l^µ = νγµ(1 − γ5)ν is the neutrino neutral current. Nuclei are heavy, and, corresponding to the small velocities are small to the small section to the small (various are small (v \mathcal{L} , we assume that nuclei are bosons characteristics, we assume that nuclei are bosons characteristics, we are bosons characteristics, \mathcal{L} $\frac{1}{2}$ tunction number. In this case it is $\frac{1}{2}$ an excellent approximation to write the neutral current carried by the To the density-density correlation \sim 1 \sim Scattering rate is related to the densit \mathbb{R} , given by dΓ \mathcal{L} count for the presence of other nuclei, since scattering from these difed to the density-density correlation where the sum is over N particles in a volume N which are labeled in a volume N which are labeled in a volume N Scattering rate is related to the density-density correlation $s_{\rm{max}}$ and $s_{\rm{max}}$ = E^ν −ω, at an angle θ, with a momentum transfer function

$$
\frac{d\Gamma}{d\cos\theta dE'_{\nu}} = \frac{G_{\rm F}^2}{4\pi^2} Q_W^2 (1 + \cos\theta) E'_{\nu}^2 S(|\vec{q}|,\omega)
$$

$$
S(|\vec{q}|,\omega) = \int_{-\infty}^{\infty} dt \exp(i\omega t) \langle \rho(\vec{q},t)\rho(-\vec{q},0) \rangle
$$

$$
\rho(\vec{q},t) = \psi^{\dagger}\psi = \sum_{i=1\cdots N} \exp(i\vec{q}\cdot\vec{r_i}(t))
$$

SCREENING, DAMPING & COLLECTIVE MODES

- Strong repulsive Coulomb forces affect the spatial distribution.
- A collective mode exists in the system.
- Response is pushed to high energy.
- Multi-particle excitations smears the response.

Smaller cross-section & larger energy transfer.

momentum transfer |\$ $P = 11.8 \text{ F}$ $PQ(T|VVV)$, reddy α from pson (2000) Burrows, Reddy & Thompson (2006)

RESPONSE OF A CLASSICAL LIQUID

The density-density correlation for N particles is

$$
\langle \rho(\mathbf{q}, \mathbf{0}) \rho(\mathbf{q}, \mathbf{t}) \rangle = \langle \sum_{\mathbf{i} \text{ is a}} \mathbf{e}^{-i\mathbf{q} \cdot \mathbf{r}_{\mathbf{i}}} \sum_{\mathbf{j} \text{ is a}} \mathbf{e}^{-i\mathbf{q} \cdot \mathbf{r}_{\mathbf{j}}(\mathbf{t})} \rangle
$$

Need to specify equations of motion ie **r**_j(t). Classical limit:

$$
\mathbf{r}_j(\Delta t) = \mathbf{r}_j(0) + \mathbf{v}_j \ \Delta t + \frac{1}{2 \ m} \Sigma_{i \neq j} \mathbf{F}_{ij} \ t^2
$$

Tractable and could be used under non-degenerate conditions.

RANDOM PHASE APPROXIMATION (RPA)

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

$$
S_{\rm RPA}(q_0, q) = \frac{1}{1 - \exp(-\beta \omega)} \operatorname{Im}[\Pi^{\rm RPA}]
$$

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

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

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

\n
$$
\Pi^{\rm RPA} = \Pi^0 + \Pi^{\rm RPA} V_c \Pi^0
$$

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

(q_0,q) models have been constructed to gain insight into their high- \prod_{A}^{\ldots} $\left|\prod_{n=0}^{\infty} +2c_A^P c_A^R g_{np} \prod_{n=0}^{\infty}\right|$ \mathbf{d}^0 \mathbf{d}^0 \mathbf{d}^0 \mathbf{d} t_{n} on p is $n \rightarrow p$ qualitative trends may be identified. The exception is the $\lambda_{RPA}/\lambda_{M^*}$ cases with increasing density density $\begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$ pected on general grounds as the repulsive vector meson contributions dominate. The uncertainties associated with *F*⁰ are related to the model dependence of the model of the model symmetry \mathcal{A} $\begin{vmatrix} n_{\mathbf{B}} = n_{\mathbf{0}} \end{vmatrix}$ $\left[\begin{array}{ccc} 1.5 & \cdots & \cdots & \cdots \end{array}\right]$ $\begin{array}{ccc} 0 & 10 & 20 & 30 \\ \text{T (MeV)} & \end{array}$ \varDelta Γ \smile E 1, E 3, cos $\bm{\varphi}$ $\mathrm{os}\hspace{0.2mm}\theta)$ φ Ω $d q_0$ (MeV s) $\overline{}$ Integrating over the *q*0-*q* space, we obtain the total cross section per unit volume or equivalently the inverse collision mean free path. This is shown in Fig. 12. The left panels $S_{\rm V}^{\rm ncrA}(q_0,q) + (3-\cos\theta) \ S_{\rm A}^{\rm ncrA}(q_0,q) \Big]$ $S_A(q_0, q) = \frac{1}{1 - \exp(-\frac{(q_0 - T)}{T})}$ Im Π_A^{RPA} , $[(c_A^p)^2(1-g_{nn}\Pi_n^0)\Pi_n^0+(c_A^n)^2(1-g_{nn}\Pi_n^0)\Pi_n^0+2c_A^pc_A^ng_{nn}\Pi_n^0\Pi_n^0]$ $\prod_{A} RPA = \left| \frac{(c_A^p)^2 (1 - g_{nn} \Pi_n^{\circ}) \Pi_p^{\circ} + (c_A^p)^2 (1 - g_{pp} \Pi_p^{\circ}) \Pi_n^{\circ} + 2c_A^p c_A^p g_{np} \Pi_n^{\circ} \Pi_p^{\circ}}{4} \right|$ \mathcal{L}_{A} $\Lambda = \begin{bmatrix} 1-a & \Pi^0-a & \Pi^0 \end{bmatrix}$ SIMPLE RPA IN A NUCLEAR LIQUID $d\Gamma(E_1)$ $d\cos\theta\,\, dq_0$ = $\frac{d\Gamma(E_1)}{d\cos\theta \, dq_0} = \frac{G_F^2}{4\pi^2} (E_1 - q_0)^2 \, [(1 + \cos\theta) \, S_{\rm V}^{\rm RPA}(q_0, q) + (3 - \cos\theta) \, S_{\rm A}^{\rm RPA}(q_0, q)]$ $S_V(q_0, q) = \frac{1}{1 - \exp(r_0)}$ $1 - \exp(-q_0/T)$ $S_V(q_0, q) = \frac{1}{1 - \exp(-q_0/T)} \text{Im } \Pi_V^{\text{RPA}},$ $\left| \prod_{V}^{\text{RPA}} \right|$ $(c_V^p)^2(1-f_{nn}\Pi_n^0)\Pi_p^0+(c_V^n)^2(1-f_{pp}\Pi_p^0)\Pi_n^0+2c_V^pc_V^n f_{np}\Pi_n^0\Pi_p^0$ Δ _{*V*} $\left| \prod_{A}^{RPA} = \right|$ $\prod_{p=1}^{6} \prod_{p=1}^{6} f_{pp} \prod_{p=1}^{6} f_{pp}$ 11 p ' *J* pp ¹¹ p *J* nn $\Delta_V = [1 - f_{nn} \Pi_n^0 - f_{pp} \Pi_p^0 + f_{pp} \Pi_p^0 f_{nn} \Pi_n^0 - f_{np}^2 \Pi_n^0 \Pi_p^0]$ ddy, Prakash, Lattimer, Pons (1999) #2*cA* \$*^A* " , !32" $\sum_{n=1}^{\infty}$ and $\sum_{n=1}^{\infty}$ \mathbb{R} cover per unit volume is given by \mathbb{R} \$(1" *f*)!*E*3"*(!1# cos+"*SV*!*q*⁰ ,*q*" #!3" cos+"*SA*!*q*⁰ ,*q*"*, !33" \mathcal{M} and \mathcal{M} $E|$. Using Ω $-cov - \frac{1}{2}$! is related to the nuclear symmetry energy *a*⁴ !(*nB*/2),2-/,*n*³ ² , where *n*3!*nn*"*np* is the isospin density. $E = -$ **F**₀ $\lambda_{\mathbf{M}} (E = \pi T)$ 2^M /² \sim 1 \leq 1 extracting the p-h interaction potential from experimental servables such as *K* and *a*4, a consistent value of *M** must be employed, since both *F*⁰ and *F*⁰ ! depend on *M**. At nuclear saturation density, investigation of the mono- $\begin{array}{cccc} -0.3 \qquad & 0 & \qquad 0.3 & \qquad 0.6 \qquad & \ & & \ddots & \ 0.1 & \qquad & \end{array}$ pressibility *K*#240%40 MeV (38*. Information from neutron-rich nuclei and observed isovector giant dipole resonances in nuclei requires that *a*4#32%5 MeV, and empirical *SV*!*q*⁰ ,*q*"! ¹ Im #*^V* \tilde{V} ¹¹ p_0 *a*) + (3 – cos θ) $S_A^{RPA}(q_0, q)$ $1 - \exp - (q_0/T)$ ${\rm Im}\,\Pi_A^{\rm RPA}\,,$ $(c_A^p)^2(1-g_{nn}\Pi_n^0)\Pi_p^0 + (c_A^n)^2(1-g_{pp}\Pi_p^0)\Pi_n^0 + 2c_A^pc_A^ng_{np}\Pi_n^0\Pi_p^0$ $\left[\frac{(\mathcal{C}_A)^{n+1}n^{n+1}p^{n+1}(\mathcal{C}_A)^{n+1}p^{n+1}p^{n+1}p^{n+2}}{\Delta_A}\right]$ $\left[\frac{\Pi_A^{RPA}}{\Delta_A}\right]$ " , !32" respectively. In terms of these response functions, the difference $\mathcal{L}(\mathbf{Q})$ ential cross section per unit volume is given by 1 *V d*3%!*E*1" *d*&² *dq*⁰ ! *GF* ı $T=10$ MeV $\begin{bmatrix} \end{bmatrix}$ $\begin{bmatrix} n_{\text{B}}=n_{\text{o}} \end{bmatrix}$ $\begin{bmatrix} n_{\text{B}}=n_{\text{o}} \end{bmatrix}$ $\begin{bmatrix} n_{\text{B}}=n_{\text{o}} \end{bmatrix}$ \$(1" *f*)!*E*3"*(!1# cos+"*SV*!*q*⁰ ,*q*" $\mathbf{E}^{-10} \mathbf{F}^{-1}$ where the various kinematical labels appearing above are as in Eq. . Using Eq. . et al. (2) computed if the p-h interaction is specified. From the discussion is defined. From the discussion is defined. From the sion of the previous section, it is clear that the previous section, it is clear that the section of the sections of the sect are model dependent and that uncertainties are large. The uncertainties are large. The uncertainties are large. The for explore different dense matter models the interest of the interest of the interest of the interest of the i generic trends.
General trends of the second control of the second control of the second control of the second control of the *1. Particle-hole interactions in nuclear matter* \mathbf{U} \mathbf{U} , $\$ v_{L} information, the p-h interaction, the p-h interaction in nuclear matter p_{L} n/a be related to empirical values of the Fermi-liquid particle par !(*nB*/2),2-/,*n*³ ² , where *n*3!*nn*"*np* is the isospin density. $\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$ $\lambda_{\text{RPA}}/\lambda_{\text{M}}$!!!3*a*⁴ /*EF*""1, !35" with *EF*!(*kF* ² /2*M**) being the Fermi energy. Note that in extracting the potential from \mathbf{p} servables such as *K* and *a*4, a consistent value of *M** must be employed, since both *F*⁰ and *F*⁰ ! depend on *M**. At nuclear saturation density, investigation of the monopole resonances in nuclei suggests that the isoscalar compressibility *K*#240%40 MeV (38*. Information from $\sum_{i=1}^n a_i$ nances in nuclei requires that *a*4#32%5 MeV, and empirical determinations of the nucleon effective mass from level den- $\begin{array}{ccc} \n\cdot & \cdot & \cdot \n\end{array}$ typical values of *K*!240 MeV, *a*4!30 MeV, and *M**/*M* !0.75, the Fermi-liquid parameters are *F*0!"0.18, *F*⁰ !0.83, and *F*1!0.75. The spin-dependent parameter *G*0, $20 \times 30 \times 10 \times 20 \times 30$ \mathbf{g} resonances, is estimated to be small, \mathbf{g} \mathbf{h} \mathbf{g} \mathbf{h} \mathbf{g} \mathbf{h} T (MeV) T (MeV) *ginnal complete borne in the set of the set* \Box in-in-medium p-h in-medium p-h in-m $\overline{d} \Gamma(F_n)$ is a measure of the matrix element be- $\frac{dI(L_1)}{dt} = \frac{G_F}{F} (E_1 - g_0)^2 [(1 + \cos \theta)$ $d\cos\theta \, dq_0$ $4\pi^2$ $($ -1 q_0 $)$ $($ $($ $,$ cos $)$ $\frac{1}{20}$ states with indicates with indicates with $\frac{1}{20}$ $p_{V(40)}, p_{V(40)} = 1 - \exp(-q_0/T)$ Δ_V $\frac{g(x+h) - 2c}{h}$ *gpn gnn*" , "26# *RPA*#!0\$!*RPADV*!0. "27# &*^V f pn* !*^p* ⁰ !*ⁿ* ⁰ "1" *f pp* !*^p* panels, effects due to spin-dependent correlations introduced $(c_A^p)^2(1-g)$ &*^A* $\frac{1}{1}$ π^{0} $\overline{}$ g_{pp} ¹ (C_A) (1 g_{pp} ¹**_{***p*)¹**1**_n¹ 2C_AC_A} $\int_{\mathbb{R}} (c_V^p)^2 (1-f_{nn} \Pi_n^0) \Pi_p^0 + (c_V^n)^2 (1-f_{pp} \Pi_p^0) \Pi_n^0 + 2c_V^p c_V^n f_{np} \Pi_n^0 \Pi_p^0$
 $\qquad \qquad \Pi_{\mathcal{R}}$ PA $\int_{\mathbb{R}} (c_A^p)^2 (1-g_{nn} \Pi_n^0) \Pi_p^0 + (c_A^n)^2 (1-g_{pp} \Pi_p^0) \Pi_n^0 + 2c_A^p c_A^n g_{np} \Pi_n^0 \Pi_p^0$ $\Delta_A = [1 - g_{nn} \Pi_n^0 - g_{pp} \Pi_p^0 + g_{pp} \Pi_p^0 g_{nn} \Pi_n^0 - g_{np}^2 \Pi_n^0 \Pi_p^0]$ "31# for the above partnership the above polarization matrix the above polarization matrix of the above polarizatio
The above polarization matrix of the above polarization matrix of the above polarization matrix of the above p ces by the appropriate vector and axial-vector couplings for vector response functions $d\Gamma(E_1)$ G_F^2 in the polarization is obtained by G_F^2 in the polarization is obtained by D_1 in the polarization is G_F^2 in the polarization is D_1 in the polarization is G_F^2 in the polarization is G_F^2 in $\frac{d}{d\cos\theta}\frac{d}{d\alpha} = \frac{1}{4\pi^2} (E_1 - q_0)^{\frac{1}{2}} (1 + \cos \theta)$ obtain the contract of the con $\frac{f}{f}$!! "1" *f nn* !*ⁿ* #!*^p* $f(p) \prod_{p}^{0} + (c_{p}^{n})^{2} (1 - f_{pp} \prod_{p}^{0}) \prod_{n}^{0} + 2c_{p}^{p}$ $\int_0^n f_{np} \Pi_n^0 \Pi$ 3000 &*^A* | ⁰ *gnp* !*^p* ⁰ "1"*gpp* !*^p* $\mathcal{N}_{\mathcal{N}}$ &*A*#\$1"*gnn* !*ⁿ* 1 $\frac{f}{\sqrt{f}}$ ⁰ *gnn* !*ⁿ* ²!*ⁿ* ⁰ !*^p* \overline{a} $\ddot{}$ "31# $f(\alpha) = \frac{1}{\alpha} \int_{-\infty}^{\infty} \frac{1}{\alpha} e^{-\alpha t} dt$ ces by the axial-vector and axial-vector and axial-vector couplings for an axial-vector couplings for an axial $t \in \mathbb{R}$ and protons are the vector and axial-vector at the vector at the vector and axial-vector a \vec{v} and \vec{v} through the Migdal parameter *g*! are shown. The different curves correspond to the same temperature as in the left panels. Reddy, Prakash, Lattimer, Pons (1999)

calculations favor a modest increase in the nuclear symmetry

 $r_{\rm T}$ at nuclear saturation is nuclear saturation in terms in ter

fore, we explore different dense matter models to identify the

THE RESIDUAL INTERACTION IN RPA 3 !%#1" " ¹ ² #*x*³ # !1"2*x*" 5 *n*0 *˜ ^Z*!" *^Z*¹ *ⁱ*!1,2 % !2*Ci*#4*Zi*"² & *^d*3*^k* ³ *^g*!*k*,+*i*"*^f ^j*!*k*"' , !A13" '¹ *˜ ^Z*!" *^Z*¹ '¹ *^C*!*C*1#*C*² , *C˜* !" *^C*¹ Δ ($\overline{ }$ '² $\bigcap_{n=1}^{\infty}$

functional differentiation of the total potential energy, namely, #!3*Ci*"4*Zi*"² & *^d*3*^k* s used and the experiment of the explicit spin de-The form of the energy density employed in these schematic Very simple s-wave interaction is used models does not explicitly account for the explicit spin de-'¹ \mathbf{r} $\overline{2}$ used and the set

the equation of state. $f_{nn} = \frac{\delta U_n}{\delta n}$, $f_{pp} = \frac{\delta U_p}{\delta n}$, $f_{np} = \frac{\delta U_n}{\delta n} = \frac{\delta U_p}{\delta n}$ p-h interaction obtained from p endence of the nucleon-nucleon-nucleon-nucleon-nucleon-nucleon-nucleon-nucleon-nucleon-nucleon δ

Their explicit algebraic forms are algebraic forms and the second state of the sec Or from Fermi Liquid $f_{nn} = \frac{F_0 + F_0'}{V}$, $f_{nn} = \frac{F_0 + F_0'}{V}$ parameters calculated in a microscopic theories. J_{nn} F₀

$$
\langle k_1 k_3^{-1} | V_{ph} | k_4 k_2^{-1} \rangle = \frac{\delta^2 \langle V \rangle}{\delta n_{k_3 k_1} \delta n_{k_4 k_2}}
$$
\n
$$
\text{ation of state.} \qquad f_{nn} = \frac{\delta U_n}{\delta n_n}, \ f_{pp} = \frac{\delta U_p}{\delta n_p}, \ f_{np} = \frac{\delta U_n}{\delta n_p} = \frac{\delta U_p}{\delta n_n}
$$

$$
f_{nn} = \frac{F_0 + F'_0}{N_0}, \ f_{np} = \frac{F_0 - F'_0}{N_0}
$$

$$
g_{nn} = \frac{G_0 + G'_0}{N_0}, \ g_{np} = \frac{G_0 - G'_0}{N_0}
$$

rity and isosnin density sity of states at the Fermi surface. For neutron matter *F*⁰ \int *S* is consistent. sity and isospin density sity of states at the Fermi surface. For neutron matter *F*⁰ 15 *formsistent. gnp* ! lensit fluctuations obtained from the EoS is consistent. • The residual interaction for density and isospin density

- **APPENDIX BY SIMULATIONS. APPENDIX B: POLARIZATION** pedback may exist in SNI simulations • Important feedback may exist in SN simulations.
- eraction strength is $\frac{1}{\sqrt{2}}$ response in nuclei. The zerobe found in Ref. "34% and for finite temperatures in Ref. "35%. The various polarization functions required to evaluate the Hartree and RPA response functions are presented in the Hartree and RPA response functions are presented i chosen from phenomenology of response in nuclei. • The more important spin-flip interaction strength is $\mathcal{F}_{\mathcal{F}}$

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 Ye.

Raffelt & Seckel (1995) $n + n \rightarrow n + n + \nu + \overline{\nu}$

UNIFIED TREATMENT OF SPIN RESPONSE Lykasov, Olsson, Pethick (2005) $F \cap T \cap T \cap T$ of the spin relaxation rate for an excess of T IED | REATMENT OF SPIN RESPONSE 2vFq JF IN KESI \overline{a} UNSE -
-
0 Ω Γα

Lykasov, Pethick, Schwenk (2006)

- 2p-2h response is incorporated through a finite quasi-particle lifetime correction in RPA. correlations.
- Captures key aspects of the response (screening, damping and collectivity). the Landau-Pomeranchuk-Migdal effect [28, 29]. Ip tures key aspects of the $\frac{0.9}{4}$
- Quasi-particle life-times have been calculated using realistic interactions. Quasi particle life tip

been calculated using realistic
and modern nucleon-nucleon
interactions.

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

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

CHARGED CURRENT REACTIONS $\nu_e + n \rightarrow p + e^ S\left\{\frac{\nu_e + n \rightarrow p + e}{\bar{\nu}_e + p \rightarrow n + e^+}\right\}$

- 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)

SPECTRA AT LATE TIMES

0 0

0.04

 5×10^{49}

0.08

 1×10^{-1}

 Y_e

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

Figures from PNS simulations by Roberts (2012)

 $\begin{equation*} \begin{array}{ll} \varepsilon_{\mathrm{v}} \otimes \mathbb{Z}_\mathrm{v} & \mathbb{Z}_\mathrm{v} \end{array} \end{equation*}$

0 10 20 30 40

10 20 30 40 50

SPECTRA AT LATE TIMES

 \emptyset

 $\overline{\varrho}$

0.04

 5×10^{49}

0.08

 $\sum_{\mathbf{c}}$

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

Figures from PNS simulations by Roberts (2012)

 $\int_{\mathsf{V}}^{\mathcal{U}} \left(\mathrm{MeV} \right)$

0 10 30 30 40 $\epsilon_{\rm v}^{\rm \Sigma U}$ (MeV)

 $10 \t\t 20 \t 30 \t 40 \t 50$

MEAN FIELD SHIFT IN THE NEUTRINO SPHERE

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

•After a few seconds, the density at the neutrino sphere is large. ~no/50-no/10. •Nucleon propagation is affected by mean fields and collisions.

•Sensitive to the low-density behavior of the symmetry energy.

FIG. 1: *Top Panel:* The electron chemical potential (dashed lines) and ∆*U* = *Uⁿ* −*U^p* (solid lines) are shown as a function of density for the two martinez-Pinedo et al. (2012) curves and GM3: black curves and GM3: black curves and *You and You and You and You and You* and You and You and You Roberts (2012)

ABSORPTION RATES section for the process ν*^e* + *n* → *e*[−] + *p* per unit volume 1 *d*²σ the ν*^e* reaction proceeds at *q*⁰ ≈ 0 at the expense of large $\begin{bmatrix} -\zeta & \cdots & \zeta & \zeta \end{bmatrix}$ to more negative *q*⁰ can increase the electron absorption $\mathbf{I}_{\mathbf{z}}$ *F*₂

1 *V* $d^2\sigma$ d $\cos \theta dE_e$ = G_F^2 2π $[(1 + \cos \theta) + g_A^2(3 - \cos \theta)] S(q_0, q)$ Γ 1 Γ \mathcal{D}_e \mathcal{L}_e $\left[1 - \int_e \left(L_e\right)\right]$ \times p_e E_e $[1 - f_e(E_e)]$

- Mean field energy shift helps overcome electron final state blocking. where the energy transfer to the nuclear medium is q_0 and q_1 \ldots q_1 ean field energy shift for the magnitude of the magnitude of the momentum of the magnitude of the momentum of ps overcome election *^S*F(*q*0*, q*) = ¹ #
- Enhances V_e absorption $\frac{e}{r}$ $\frac{V_e = 0.01}{4V_e}$
- Larger energy needed to ² produce neutrons suppresses anti-ν^e *^S*F(*q*0*, q*) = *^M*²*^T* absorption. mass difference the integrals in Eq. 4 can be performed the performance of the performance of the performance of the performance of the integrals in Eq. 4 can be performed that the performance of the performance of the per π*q* (1 − *e*−*^z*)

Roberts & Reddy (2012)

MEAN FIELD & COLLISIONAL BROADENING

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

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

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

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

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

ABSORPTION RATES IN RPA & DAMPING

Roberts, Shen, Reddy (2012) in prep.

•RPA correlations suppress cross-section. Collisional broadening enhances it.

•Net effect mild suppression. Need further investigation.

SUM RULES From the point of view of many-body theory, neutrino interaction rates in the medium can be factored into a

Response functions are constrained by sum rules. The relatively significant relatively simple functions of the neutrino \mathbb{R} energy and momentum contrast, the spin, density and current correlations are complex functions are complex functions of \sim Response functions are constrained by sum rules

$$
S_{\sigma}^{n} = \int_{0}^{\infty} S_{\sigma}(\omega, \boldsymbol{q} = 0) \ \omega^{n} \ d\omega
$$

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

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

where s(*t, q*) = *V* [−]¹ %*^N* S_{min} and S_{min} a S pri susceptionity $\frac{1}{\sigma}$ - $\frac{1}{2n}$ State Spin Structure $S^0_\sigma = 1 + \lim_{\epsilon \to \infty} \frac{1}{2N} \sum_{i=1}^N \langle 0 | e^{-i \mathbf{q} \cdot (\mathbf{r}_i - \mathbf{r}_j)} \sigma_i \cdot \sigma_j | 0 \rangle$ $q\rightarrow 0$ 3N $\overrightarrow{i\neq j}$ is the non-relativistic field operator. The non-relativistic field operator. The normal-relativistic field operator. The normal-relativistic field operator. The normal-relativistic field operator. T ization factor 4*/*3*n* where *n* is the neutron number density ensures that the dynamic form factor is canonically Energy or F-sum Rule $S_{\sigma}^{+1} = -\frac{1}{3N} \lim_{q\to 0} \langle 0 | [H_N, s(q)] \cdot s(-q) | 0 \rangle$ S_{σ}^{-1} = χ σ $\frac{\lambda}{2n}$ $S^0_\sigma = 1 + \lim_{\sigma \to 0}$ *q*→0 4 3*N* $\sqrt{ }$ *N* $i \neq j$ Static Spin Structure $S^0_\sigma = 1 + \lim_{a \to 0} \frac{4}{3N} \sum_{i}^N \langle 0 | e^{-i \mathbf{q} \cdot (\mathbf{r}_i - \mathbf{r}_j)} \sigma_i \cdot \sigma_j | 0$ $\left.\right\rangle$ $S_{\sigma}^{+1} = -\frac{4}{3N}$ 3*N* lim *q*→0 Energy or F-sum Rule $S_{\sigma}^{+1} = -\frac{4}{3N} \lim_{a \to 0} \langle 0 | [H_N, s(\mathbf{q})] \cdot s(-\mathbf{q}) | 0$ $\left.\right\rangle$ Spin susceptibility susceptionit₎ *q*→0 3*N* S_{σ}^{-1} -1 S^0 \overline{a} $\overline{2n}$ *N* **S** F-s₁ Im ⁼ [−] ⁴ lim q $\begin{aligned} i \neq j \end{aligned}$ $\frac{u}{2}$

Shen, Gandolfi, Reddy & Carlson (2012) *n*^σ and *µ*^σ are number density and chemical potential of particles with spin σ (*±*1*/*2). Our strategy here is to evaluate

• Response function constructed to satisfy QMC sum-rules at T=0 predict significant strength at 10-50 MeV. Figure 2: (Color online) The spin response function *S*σ(*q* = 0*,* ω) of neutron matter at saturation density obtained by fitting to a function and the black solid and dashed curves. The inset curves in set compared curves. The inset compared curves the fits and dashed curves. The fits and dashed curves the fits and dashed curves. The fits and data c $T-\Omega$ correlation function and one grounds we can expect the set to be dominated by two-particle dynamics. T is the calcular significant strength at the operator formal terms using the operator product expansion of T

SUMMARY & OUTLOOK

- Formula that incorporate kinematics(recoil), full structure of the weak current(weak magnetism) and Pauli blocking exactly are available.
- Correlations are relevant. Recent progress in including damping effects beyond RPA are important.
- Charged current rates in the neutrino sphere are especially sensitive to many-body effects.
- How do we benchmark calculations of response functions?
- General trends indicate large suppression at and above nuclear density - Implications ?