Neutrino interactions in dense matter and implications for astrophysics

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- Motivation
- Preliminaries: linear response & sum rules
- Neutrino scattering at:
	- 10¹² g/cm³ (neutrino-sphere)
	- 10¹³ g/cm³ (role of nuclei and pasta)
	- 10¹⁴ g/cm³ (spin response of nuclear matter)
- Conclusions.

 $E_{\rm SN}$ \sim $3GM^2_\mathrm{pns}$ $5r_{\rm NS}$ \approx 3 \times 10⁵³ erg $\left(\frac{M_{\rm{pns}}}{M_{\odot}}\right)$ M_{\odot} $\bigg\}^2$ / r_{NS} 12 km \setminus ⁻¹ \textsf{O} in neutrinos : $N_L\approx 3.4\times 10^{56} \left(\textcolor{blue}{\frac{14 M_{\odot}}{1.4\,M_{\odot}}} \right)$ $\langle 1.4 \dot{m}_{\odot} \rangle$ Energy radiated, mostly in neutrinos : Lepton number radiated, also in neutrinos : $N_L \approx 3.4 \times 10^{56} \left(\frac{M_{\text{pns}}}{1.4 M_{\text{e}}}\right)$ SOM_{pns}^2 SOM_{pns}^2 $O(10^{53} \text{ m/s}^2/\text{m/s}^2)^{-1}$ **n** neutrinos: $E_{SN} \sim \frac{P_{ES}}{5\pi} \approx 3 \times 10^{33} \text{ erg} \left(\frac{P_{ES}}{M}\right) \left(\frac{N}{12 \text{ km}}\right)$ $1.4M_{\odot}$ ◆

Timescale and energy spectrum of neutrinos is set by neutrino interactions thirds of the total energy, *E*SN is available during the PNS cooling phase. $\mathbf{A}(\mathbf{C})$ shock has passed the $\mathbf{C}(\mathbf{C})$ shock has passed the interior entropy varies be-Inside the PNS, a copious number of neutrinos of all flavors are produced and scattered by weak interactions in the baryons interactions presented by weak in the leptons present present pre in the hot newly born neutron star

 3×10^{53} ergs = $10^{58} \times 20$ MeV Neutrinos

SN 1987a: ~ 20 neutrinos in support of supernova theory

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Phase Diagram of Hot and Dense Matter

Neutrino Scattering in Hot Neutron Stars

Neutrino Interactions in Dense Matter **Meutrino Interactions in Dense Matter** Eq. 11 together with Eq. 12 can be used to calculate the charged current opacity. This would include corrections **Neutrino Interactions in Dense Matter** by coupling strengths *g^V* = 1, *g^A* = 1*.*26, and *F*² = 3*.*71, respectively, and *M* = (*Mⁿ* + *Mp*)*/*2 = 938*.*9 MeV and

Low energy Lagrangian:
$$
\mathcal{L} = \frac{G_F}{\sqrt{2}} l_\mu j^\mu \qquad l_1 + N_2 \rightarrow l_3 + N_4
$$

Absorption:
$$
l_\mu^{cc} = \bar{l}\gamma_\mu (1 - \gamma_5) \nu_l \qquad j_{cc}^\mu = \bar{\Psi}_p \left(\gamma^\mu (g_V - g_A \gamma_5) + F_2 \frac{i \sigma^{\mu \alpha} q_\alpha}{2M} \right) \Psi_n
$$

Scattering:
$$
l_\mu^{nc} = \bar{\nu} \gamma_\mu (1 - \gamma_5) \nu \qquad j_{nc}^\mu = \bar{\Psi}_i \left(\gamma^\mu (C_V^i - C_A^i \gamma_5) + F_2^i \frac{i \sigma^{\mu \alpha} q_\alpha}{2M} \right) \Psi_i
$$

Rate:
$$
\frac{d\Gamma(E_1)}{dE_3 d\mu_{13}} = \frac{G_F^2}{32\pi^2} \frac{p_3}{E_1} (1 - f_3(E_3)) L_{\mu\nu} S^{\mu\nu}(q_0, q)
$$

 -2 Im $\mathbf{\Pi}^{\mu\nu}(a_0, a)$ **Dynamic structure function:** $\delta^{\mu\nu}(q_0, q) = \frac{1}{1 - \exp(- (q_0 + \lambda))}$ $\frac{\nu}{\alpha}$ $q=\frac{1}{1-\exp(\alpha)}$ D $\frac{\prod^{\mu\nu}(\alpha)}{2}$ $\delta^{ \mu \nu} (\rho_0, \rho) = \frac{-2 \text{ Im } \Pi^{\mu \nu} (q_0, q)}{2 \text{ Im } \Pi^{\mu \nu} (q_0, q)}$ **absorption rate for a new index p** $(- (q_0 + \Delta \mu)/T)$ $S^{\mu\nu}(q_0, q) = \frac{-2 \text{Im } \mathbf{\Pi}^{\mu\nu}(q_0, q)}{1 - \exp\left(-\left(q_0 + \Lambda \mu\right)\right)}$ $1 - \exp(-(q_0 + \Delta \mu)/T)$ $-2 \text{ Im } \mathbf{\Pi}^{\mu\nu}(q_0, q)$ $\sum_{i=1}^n a_i$ called the dynamic response function, $\sum_{i=1}^n a_i$ Dynamic structure function:

<u>urrer</u> 1020 versions^{. $\Pi^{\mu\nu}$ (} α ^{*|}</sup> = -</sup>* $\int dt d^3x \theta(t) e^{i(q_0t-\vec{q}\cdot\vec{x})}/\|\vec{i} + (\vec{r} \cdot t) \cdot \vec{j} + (\vec{0} \cdot 0)\|$ where *v*rel is the relative velocity between particles in the initial state, *d*³⁴ = $e^{2(Q_0)}$ *d*³*p*⁴ (1 *f*3)(1 *f*4)*,* (4) $\left| \left[j_{\mu} \left(\vec{x}, t \right), j_{\nu}(0, 0) \right] \right|$ $\right\rangle$ $\mathsf{Current}\text{-}\mathsf{current} \hspace{0.05in} \mathsf{true}$ $\Pi^{\mu\nu}(q_0,q) = -i$ Z $dt \ d^3x \ \theta(t) \ e^{i(q_0t-\vec{q}\cdot\vec{x})} \langle \ |[j_\mu](\vec{x},t),j_\nu(\vec{0},0)]| \ \rangle$ Current-current correlations functions:

where $\sqrt{ }$ 10115.
Commer (1 *f*3)(1 *f*4)*,* (4) ulate in general due to the non-perturbative nature of the matrix element – averaged over initial spin states and summer α ⇧*^µ*⌫(*q*0*, q*) = *ⁱ* ^h *[|]*[*j^µ* (~*x, t*)*, j*⌫([~] *dt d*³*x* ✓(*t*) *eⁱ*(*q*0*tq*~*·*~*x*) difficult to calculate in general due to the non-perturbative nature of strong interactions.

Sawyer (1970s), Iwamoto & Pethick (1980s), ا !
. ا . is the Lorentz invariant phase were the Lorentz in Allien includes to all (1990s),
Benhar, Carlson, Gandolfi, Horowitz, Lavato, Pethick, Reddy, Roberts, Schwenk, Shen, and others (2000s) thers (2000s) nucleons in terms in the lepton terms in the lepton tensor and the lepton tensor and the baryon tensor, we find that the baryon tensor and the lepton tensor. We find the baryon tensor, we find that the baryon tensor, we fi U Strong interactions.
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Burrows & Sawyer, Horowitz & Wehrberger, Raffelt et al., Reddy et al. (1990s), Benhar, Carlson, Gandolfi, Horowitz, Lavato, Pethick, Reddy, Roberts, Schwenk, Shen, and others (2000s)

Correlations in Neutrino Interactions in Nuclear Matter & Nuclei

- At small ω response is governed by hydrodynamic.
- Single-pair response dominates for $|\omega \tau_{\text{coll}}| > 1$ and $|\omega| < qv$.
- Multi-particle response dominates for $|\omega| > qv$.
- Collective modes arise due to phase transitions or repulsive interactions.

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Linear Response

Perturbation: Response:

 $\mathcal{H}_{int}=% {\textstyle\int\nolimits_{-\infty}^{+\infty}} dt^{\prime\prime}(1-t^{\prime\prime})\left\vert \varphi_{\alpha}\right\vert$ Z $d^3x \mathcal{O}(x)$ $\phi_{ext}(x,t)$ $\delta\rho(\vec{q},\omega) = \Pi^R(\vec{q},\omega) \; \phi_{ext}(\vec{q},\omega)$

Response function: Polarization function or Generalized Susceptibility $\Pi^R(\vec{q},\omega) = \frac{-i}{\tau}$ \hbar z $dt \, e^{i \omega t} \, \theta(t) \, \langle [\mathcal{O}(-\vec{q},t) , \mathcal{O}(\vec{q},0)] \rangle$

Response to static and uniform perturbations is related to thermodynamic derivatives.

$$
\phi_{ext}(\vec{q}\rightarrow 0,\omega=0)=\delta\mu
$$

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Compressibility sum-rule:

 $\Pi^R(0,0) = \left(\frac{\partial n}{\partial u}\right)_x$ where $n = \langle \mathcal{O}(0,0) \rangle$ is the associated density. $\partial \mu$ ◆ *T*

Dynamic Structure Factor

 $\mathcal{S}(\bar{q}%)=\mathcal{S}_{m+1}(\bar{q})=\mathcal{S}_{m+1}(\bar{q})=\mathcal{S}_{m+1}(\bar{q})=\mathcal{S}_{m+1}(\bar{q})=\mathcal{S}_{m+1}(\bar{q})=\mathcal{S}_{m+1}(\bar{q})=\mathcal{S}_{m+1}(\bar{q})=\mathcal{S}_{m+1}(\bar{q})=\mathcal{S}_{m+1}(\bar{q})=\mathcal{S}_{m+1}(\bar{q})=\mathcal{S}_{m+1}(\bar{q})=\mathcal{S}_{m+1}(\bar{q})=\mathcal{S}_{m+1}(\bar{q})=\mathcal{S}_{m+1}(\bar{$ \vec{q}, ω) = *A* simpler correlation function $S(\vec{q}, \omega) = \int dt \; e^{i\omega t} \; \langle \mathcal{O}(-\vec{q}, t) \mathcal{O}(\vec{q}, 0) \rangle$

$$
=2\pi\hbar\sum_{m,n}\frac{e^{\beta K_n}}{Z}\left|\langle n|\mathcal{O}_q|m\rangle\right|^2\,\delta(K_n-K_m-\hbar\omega)
$$

where K_n are eigenvalues of $K = H - \mu N$ (grand canonical Hamiltonian)

Fluctuation-dissipation theorem:
$$
\mathcal{S}(\vec{q},\omega) = \frac{-2\hbar \operatorname{Im} \Pi^R(\vec{q},\omega)}{1 - e^{-\beta \hbar \omega}}
$$

The dynamic structure factor incorporates all of the many-body effects into the neutrino scattering and absorption rates.

Sum Rules

 $\mathcal{S}_q =$ \int_0^∞ $-\infty$ $d\omega'$ 2π Static structure factor: ${\cal S}_q = \int \frac{dS}{2\pi} S(q,\omega')$

F-sum rule:
$$
\underline{\int_{-\infty}^{\infty} d\omega' \omega' \text{ Im } \Pi^R(q, \omega') = \langle [\mathcal{H}, O_q], O_q] \rangle}
$$

Compressibility sum-rule: \Box

$$
\int_{-\infty}^{\infty} \frac{d\omega'}{\pi} \frac{\operatorname{Im} \Pi^R(0, \omega')}{\omega'} = \operatorname{Re} \Pi^R(0, 0) = \left(\frac{\partial n}{\partial \mu}\right)_T
$$

 $At T=0$:

$$
\int_{-\infty}^{\infty} \frac{d\omega'}{2\pi} \; \frac{(1-e^{-\beta\hbar\omega'})\mathcal{S}(q\rightarrow 0,\omega')}{\hbar\omega'} = \left[\int_{0}^{\infty} \frac{d\omega'}{2\pi} \; \frac{\mathcal{S}(q\rightarrow 0,\omega')}{\hbar\omega'} = \left(\frac{\partial n}{\partial\mu}\right)_{T=0} \right]
$$

At high temperature: $(1-e^{-\beta \hbar \omega'}) \simeq \beta \hbar \omega'$

$$
\mathcal{S}_{q=0} = \mathrm{lt}_{q\to 0} \int_{-\infty}^{\infty} d\omega' \ \mathcal{S}(q,\omega) = T \left(\frac{\partial n}{\partial \mu}\right)_T
$$

Neutrino-nucleon scattering

Nucleon currents simplify in the non-relativistic limit:

$$
j_{nc}^{\mu} = \Psi^{\dagger} \Psi \delta_0^{\mu} + \Psi^{\dagger} \sigma_k \Psi \delta_k^{\mu} + \mathcal{O}[\frac{p}{M}]
$$

density
spin-density

$$
\frac{d\Gamma(E_1)}{d\Omega dE_3} = \frac{G_F^2}{4\pi^2} E_3^2 \left[C_V^2 (1 + \cos\theta_{13}) S_\rho(\omega, q) + C_A^2 (3 - \cos\theta_{13}) S_\sigma(\omega, q) \right]
$$

Neutrino-nucleon scattering

Neutrino-nucleon scattering

In general
$$
\tilde{S}_{\alpha}(q) = \int_{-q}^{\omega_{max}} d\omega S_{\alpha}(\omega, q) < S_{\alpha}(q) = \int_{-\infty}^{\infty} d\omega S_{\alpha}(\omega, q)
$$

In practice for conserved currents at long-wavelengths:

At high temperature recall that $S_\rho(q \to 0) = T$

$$
\tilde{S}_{\rho}(q \to 0) = S_{\rho}(q \to 0)
$$

$$
\tilde{S}_{\rho}(q) \simeq S_{\rho}(q)
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 $\partial \mu\,/\,_{T}$

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$$

 $\partial \mu\,/\,_{T}$

Spin is not conserved by strong interactions

F-sum Rule:
$$
F_{\alpha}(q) = \int d\omega \ \omega S_{\alpha}(\omega, q) = \frac{1}{2} \langle [\mathcal{O}_{\alpha}^{\dagger}, [\mathcal{O}_{\alpha}, H]] \rangle
$$

$$
F_{\rho}(q) = n \frac{q^2}{2m} \qquad F_{\sigma}(q) = C + \tilde{n} \frac{q^2}{2m}
$$

- Thermodynamic derivates may not be adequate to accurately describe the long wavelength spin response.
- Some dynamical information is needed to calculate neutrino scattering rates in the medium.

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1p-1h contribution dominates. No time-like response.

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F_{\rho}(q) &= n \, \frac{q^2}{2m} \\
\uparrow \qquad \qquad \uparrow \qquad \qquad \uparrow \qquad \qquad \uparrow \qquad
$$

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2p-2h contribution Finite time-like response.

 \cdot (q)

$$
\tilde{S}_{\rho}(q) = \int_{-q}^{\omega_{max}} d\omega \ S_{\rho}(\omega, q) \simeq S_{\rho}(q) \qquad \qquad \tilde{S}_{\sigma}(q) = \int_{-q}^{\omega_{max}} d\omega \ S_{\sigma}(\omega, q) < S_{\sigma}
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Supernova Neutrino Spectra and Nucleosynthesis in r-process elements, the heavy elements are much harder oupeniova iveuulilo ope ra and Nucleosynthesis fusion fuel is exhausted (see figure 4). The dominant neufusion function function function function \mathbf{f} . The dominant neural neu-algebra \mathbf{f} Supernova iveutrino Spectra and ivi

with present line physics have neutrino physics have neutrino physics have not yet pro-

nism also means that we do not know the exact results are considered by the exact results and the exact results are considered by the exact results and the exact results are considered by the exact results and the exact re

Electron and anti-electron neutrinos play energy spectrum impacts: d anti-electron neutrinos
al role in supernova. Their $\qquad \qquad \int \ \overline{\nu}_e + \ p \to \ n\, + \, e^+$ The neutrino heating efficiency spectrum impacts:
The neutrino heating on convertibility in $\mathcal{V}_e + n \rightarrow p + e^$ play a crucial role in supernova. Their

- 1. Explosion mechanism
2. Nucleosynthesis 1. Explosion mechanism
- z. inucleusymmesis curve that fits the heavier elements so well.
Curve the heavier elements so well. 2. Nucleosynthesis
- The difference is suggestive. It might be telling us that the transit of neutrinos.
The actual explosion mechanism is not neglected to a set of the actual explosion mechanism is not neglected to still uncertain.7,14,15 Self-consistent supernova calculations 3. Detection

The critical parameter that determines whether the critical parameter that determines whether the critical parameter of the critical parameter of the critical parameter of the critical parameter of the critical parameter o

 $\gamma_e + p \rightarrow n + e^+$ $v_e + n \rightarrow p + e^-$ {

duced successful explosions.

PNS

stabilities and the opacity of the stellar material to the

 t transit of neutrinos. The actual explosion mechanism is \mathcal{L}_max

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with present the present of the present of the parties of the physics have not yet pro-

ployed with the effects of the effects

of stellar rotation and magnetic fields and magnetic fields and magnetic fields and magnetic fields are in

model calculations that are not restricted to spherical sym-

metry. There is also still much uncertainty in our knowledge is also still much uncertainty in our knowledge in

edge of how neutrinos interact with dense matter (and in-

deed of how they behave

understanding of the type II supernova explosion mecha-based of the type II supernova explosion mecha-

The is the new the neutrino-driven ex-

- Neutrino-sphere at high density. Neutron-rich matter at moderate entropy. $R \sim 10-20$ km yttrium, and zirconium (*Z* = 38–40) seem to have a very duced successful explosions. The contract of the O-sphere at high the neutrino-driven ex p is the construction measure to be right with the effects with $\mathcal{H}(\mathcal{C})$ oderate entropy.
The stellar rotation and magnetic fields are included in the included included in the included in the included \sim 10-20 km are not restricted to spherical sym-Neutrino-sphere at high density. Neutron-rich matter at moderate entropy. R ~ 10-20 km
- Neutrino driven wind at low **Is it always supernovae?** $\mathsf{autrino}$ driven wind at low- \blacksquare m edge of how neutrinos interact with dense m -10^{3} deed of km the lack of the lack of $\sim 10^{3}$ defined in vacuum). The lack of $\sim 10^{3}$ $\mathbf{u} = \mathbf{u} - \mathbf{u}$ Neutrino driven wind at lowdensity and high entropy. $R \sim 10^{3} - 10^{4}$ km

- •Matter is dilute, but interactions are strong and non-perturbative.
- Nucleon-nucleon scattering length is large \sim 20 fm.
- Small expansion parameter is the fugacity $z=e^{\mu/T}$ virial expansion.
- •Horowitz & Schwenk developed a virial EoS in this regime.

Long-wavelength Response using the Virial EoS

Assumes that scattering is nearly elastic to include all many-body correlations through the static structure factors.

$$
\tilde{S}_{\rho}(q) = \int_{-q}^{\omega_{max}} d\omega S_{\rho}(\omega, q) \simeq S_{\rho}(q) \qquad \qquad \tilde{S}_{\rho}(q \to 0) = S_{\rho}(q \to 0)
$$

Calculate the static structure factors using the compressibility or thermodynamic sum rule

$$
S_{\rho}(q\rightarrow 0)=T\ \left(\frac{\partial n}{\partial \mu}\right)_{T}
$$

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Sawyer (1975, 1979) 
Horowitz and Schwenk (2005), Horowitz et al. (2017)
```
This is an excellent approximation for the density response relevant to neutral current reactions in the neutrino sphere.

The spin response and charged current reactions require some dynamical input.

Pseudo-potential for Hot & Dilute Nuclear Matter

The dynamic structure factor calculable using standard diagrammatic "perturbation" theory - with a twist. Interactions represented by a pseudo-potential: $V_{ps} \propto$ $\delta(p_{rel})$ *prel M*

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Bedaque, Reddy, Sen & Warrington (2018)

Bedaque, Reddy, Sen & Warrington (2018) ³ (1 + 4*b*2*,f ree^z* ⁺ *...*)*,* (5.3)

Back-scattering is suppressed

angles : Important for transport and spectra. A reduced axial response implies a reduced scattering at backward

incoming band is a zoomed out view of the planet panel is a solution for the Bedaque, Reddy, Sen & Warrington (2018)

Charged Current Reactions in Neutron-Rich Matter

Potential energy difference between neutrons and protons is large - and related to the low density symmetry energy.

The pseudo-potential is suitable to calculate the nucleon self-energy.

Dense Medium

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

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

$$
\mathbf{Q} = \varepsilon_n(\vec{k}) - \varepsilon_p(\vec{k} - \vec{q})
$$

$$
= M_n - M_p + \Sigma_n(k) - \Sigma_n(k - q)
$$

Reddy, Prakash & Lattimer (1998), Martinez-Pinedo et al. (2012), Roberts & Reddy (2012), Rrapaj, Bartl, Holt, Reddy, Schwenk (2015)

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Mean Field & Collisional Broadening

 $S_{\sigma\tau^{-}}(q_0, q) = \frac{1}{1 - \exp(-\beta/\sigma)}$ $\text{Im} \mid$ $\tilde{\Pi}(q, q)$ $\overline{1}$ Ansatz for the spin-isospin charge-exchange response function in hot matter:

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

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

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

Charged Currents at Low Density with the Pseudo-potential

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

is the frapachule-hole polarization function. Holt, Bartl, Reddy & Schwenk (2015) T potential and pseudo-potential and pseudo-potential are both used in HF approximation. This provides a conservative and pseudo-potential are both used in HF approximation. This provides a conservative and pseudo-poten rapaj, noit, barti, neudy & Scriwerik (zu ib)

Neutrino Spectra are Sensitive to Symmetry Energy Sensitive

Time evolution of electron neutrino spectrum could be a useful diagnostic. Larger difference between electron and anti-electron neutrino energies is good for the r-process.

10¹³-10¹⁴ g/cm³ and T~3-20 MeV where ⁰ ' 1*.*2 MeV/fm² is the surface tension of sym- \sim 3-20 MeV clear saturation density. Typically we find *Z* ' 50 at

- Interesting regime where matter behaves as a dense heterogenous **in and** α and α and α functions α functions density phases, and *f*3(*u*) is the geometrical factor assopoliticated as a definer fielding control with the Wighes
- Virial expansion fails. No small expansion parameter. $\mathbf{R} \cdot \mathbf{R} \cdot \mathbf{S} = \mathbf{S} \cdot \mathbf{S} \cdot \mathbf{S} = \mathbf{S} \cdot \mathbf{S}$ • Virial expansion falls. No small phase on the surface tension $\mathbf{32}$. The surface tension $\mathbf{32}$
- Coexistence between neutron-rich nuclei and neutron-rich matter is favored at lower temperature favors large density fluctuations. angle averaged comes from rates from rodical nuclei of similar size [33]. Further, as noted earlier,
- Neutrinos can coherently scatter of the heterogenous structures. or the nuclei ogeneas phase is given by

 $d\Gamma_{\rm coh}$ $d\cos\theta$ = G_F^2 E_ν^2 8π n_A (1 + cos θ) *S*(*q*) *N*_w² *F*_A²(*q*) (5)

Pasta in Beta-Equilibrium Dissolves at Low Temperature

For large Y_e the volume fraction of nuclei denoted by **u** is large near the transition density. For small Y_e **u** decreases rapidly with T as protons leak out of nuclei. or nucler derioted by **u** is r
near the transition density **b**
 <u>I as protons loak out of pu</u>

Gibbs equilibrium is altered due to thermal protons in the lowdensity phase. rium pairs as it traverses the coexistence region. The

Pasta configurations favored at large Y_e at T=0, are not realized at $T > 1$ MeV for matter close to beta-equilibrium. rarge real red, are not re
at T > 1 MeV for matter cl

Roggero, Margueron, Reddy, & Roberts & (2017) Person Morqueren Deddy, 8 Deberte 8 (0017) \log geno, margaoron, rioady, a riodorio a (201) F M F H density phase in het-density phase in F $P(\text{loggen}, \text{mag}(\text{cm}), \text{Ricary}, \alpha)$ for the α (2017)

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Paucity of Large Nuclei & Reduced Coherent Scattering audity of Large Nuclei & Heuded Obliefein Ocaliering *^p , T*) *nf* Large Nuclei & Reduced Cohe actions and use \mathcal{L} to calculate the scattering rates the scattering rates of \mathcal{L}

Coherent scattering makes a modest contribution to the total opacity at sub-nuclear density h Coherent scattering makes a modest contribution to the total opacity at ا ا باب.
. *e*(*p*2*/*2*mµi*) rent scattering makes a modest contribution to the total opacity at

potentials which are spin dependent. The Feynman diagrams that account for screening at leading order in the nucleon 10¹⁴ g/cm³ uniform neutron-rich matter

potentials which are spin dependent. The Feynman diagrams that account for screening at leading order in the nucleon 10¹⁴ g/cm³ uniform neutron-rich matter

- Corrections due to screening, 2-body currents expansion parameter - results rely on F_{min} is a $\frac{1}{2}$ will consider the static, and momentum transfers, denoted momentum transfer, denoted mom (uncontrolled) many-body approximations. and 2p-2h excitations are all large. No
	- *C* \overline{a} \overline{b} \overline{c} $\$)ľ 11 + U • Need re-summations - Random Phase Approximation or RPA.
	- r<mark>esponse is</mark> (2⇡)³ *^V* ⁰ the density and soon response is reduced by $\mathcal{A} = \mathcal{A} \cup \mathcal{A} \cup \mathcal{A}$, $\mathcal{A} = \mathcal{A} \cup \$ • A lot of work in this direction suggests that both factors of 2-4.

potentials which are spin dependent. The Feynman diagrams that account for screening at leading order in the nucleon 10¹⁴ g/cm³ uniform neutron-rich matter

- Corrections due to screening, 2-body currents \leq expansion parameter - results rely on First, I will consider the static, long wavelength limit in which the neutrino energy and momentum transfer, denoted (uncontrolled) many-body approximations. $\bigcup_{n=1}^{\infty} V_{ni}$ and 2p-2h excitations are all large. No
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Spin-Response of Neutron Matter: Guidance from Quantum Monte Carlo and is domination pair recombination processes and the decay of finite energy collective modes α

Going beyond RPA: Sum-rules can be calculated with QMC. Coinciple Servered DDA: Cure wiles agre he soloulated with OMO energies defined by ¯!⁰ = *S*⁰

Shen, Gandolfi , Carlson, Reddy (2012)

In the vicinity of nuclear **and 10.24** for an and 0.34 for α = 0.34 α density QMC sum-rules *Facebook* α is very similar to the lowest density that α indicate significant density our result is approximately 20 per cent lower for the susceptibility. The susceptibility of the susceptibility. The susceptibility of the susceptibility. The susceptibility of the susceptibilit difference may like that the fact that the three-nucleon force used in \mathbb{R}^n is repulsive in unpolarized neutron matter, and the three-nucleon force used neutron matter, and and the three-nucleon matter, and the three strength at

 $\omega \simeq 30 - 50 \text{ MeV}$

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S

strength at

compared to

$$
\frac{q^2}{2m} \quad \text{or} \quad q \times v_F
$$

Conclusions

- Effects due nuclear interactions on the density, spin and isospin susceptibility impacts neutrino transport and spectra in supernovae and mergers. Affects SN and BNS mergers: explosion mechanism, nucleosynthesis, mass ejection, and detections.
- First steps towards an ab-inito approach to calculating the dynamic structure factors at densities and temperatures of interest to the neutrino-sphere are encouraging.
- Nuclei and coherent neutrino scattering are reduced in hot neutron-rich matter at small Y_e. Pasta dissolves rapidly.
- At high density sum rules from ab initio theory can be useful to construct reliable models for the dynamic response.
- It is essential to ensure consistency between the EoS and neutrino opacities in simulations.