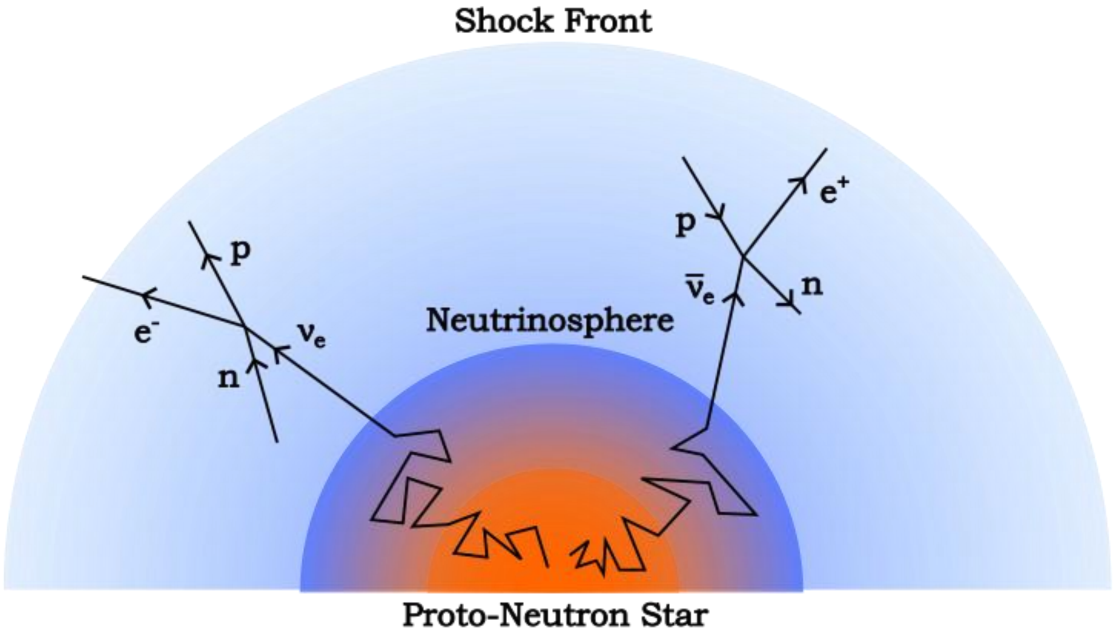
Microscopic modeling of hot, dense nuclear matter in core-collapse supernovae



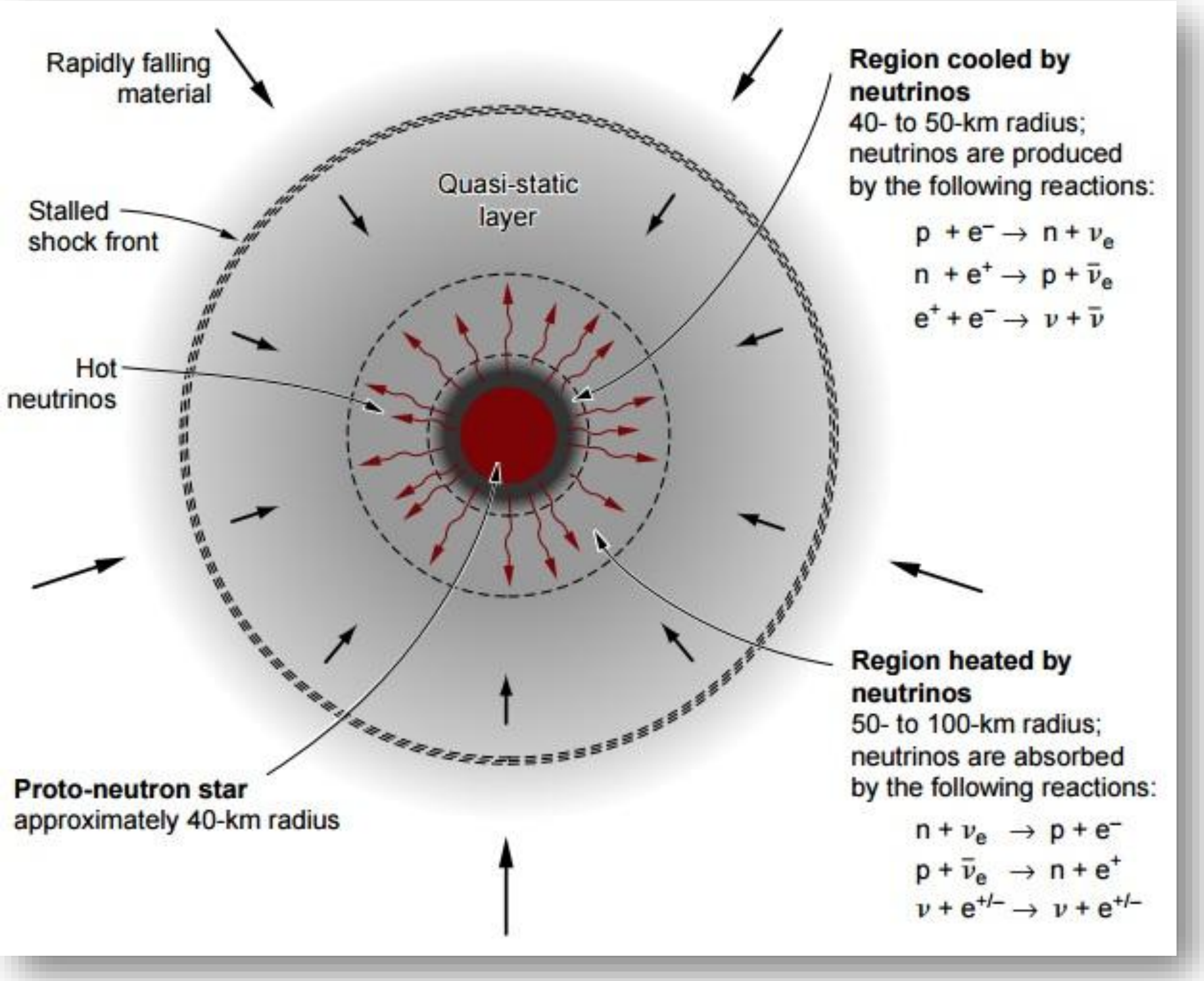
David Friedenberg, Jeremy W. Holt
Cyclotron Institute, Texas A&M University

INT Workshop 26-96W, June 16th, 2026

Outline

- **Motivation**
  - Core-Collapse Supernova
  - Proto-Neutron Stars and the nucleon effective mass
  - Neutrino opacity in the neutrinosphere
- **Methodology**
  - Chiral Effective Field Theory
  - Nucleon Self-Energy in MBPT
- **Results**
- **Outlook**
  - Urca Cooling and Nucleon Width Approximation

Core-Collapse Supernova



Region cooled by neutrinos
40- to 50-km radius; neutrinos are produced by the following reactions:

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

Region heated by neutrinos
50- to 100-km radius; neutrinos are absorbed by the following reactions:

$n + \nu_e \rightarrow p + e^-$
$p + \bar{\nu}_e \rightarrow n + e^+$
$\nu + e^{+/-} \rightarrow \nu + e^{+/-}$

Proto-neutron star
approximately 40-km radius

Image Credit: Herant et al, Los Alamos Sci. (1997)

Core-Collapse Supernova

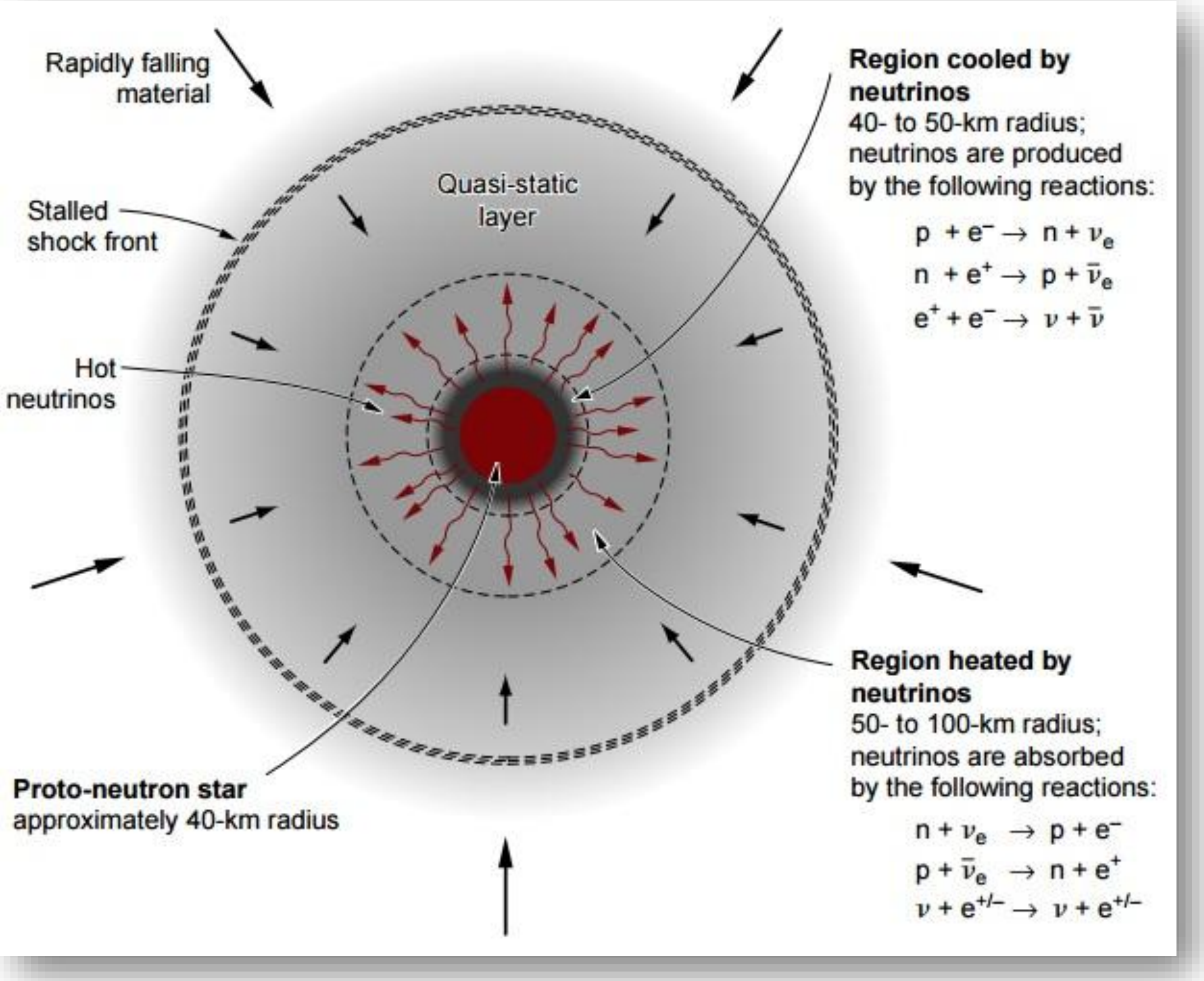
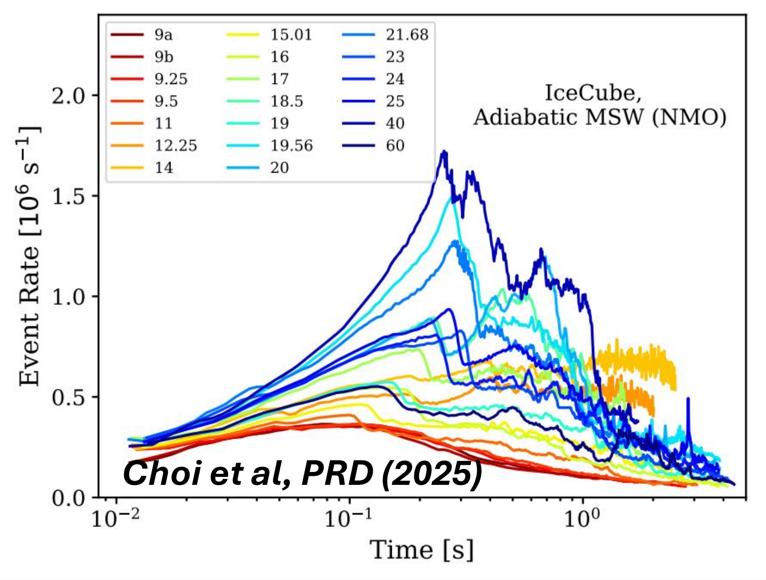
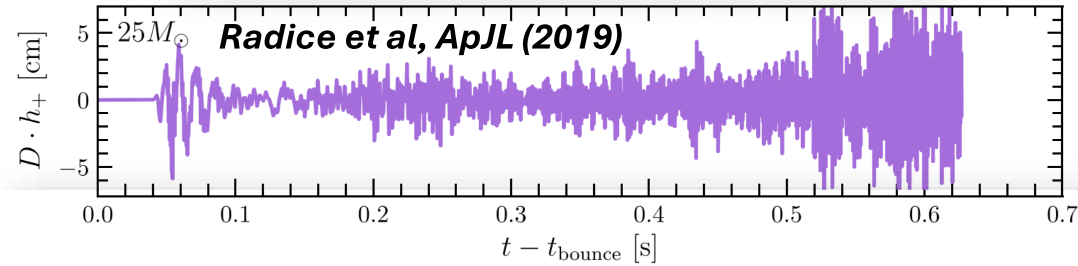


Image Credit: Herant et al, Los Alamos Sci. (1997)

The Future of Multi-Messenger Astrophysics

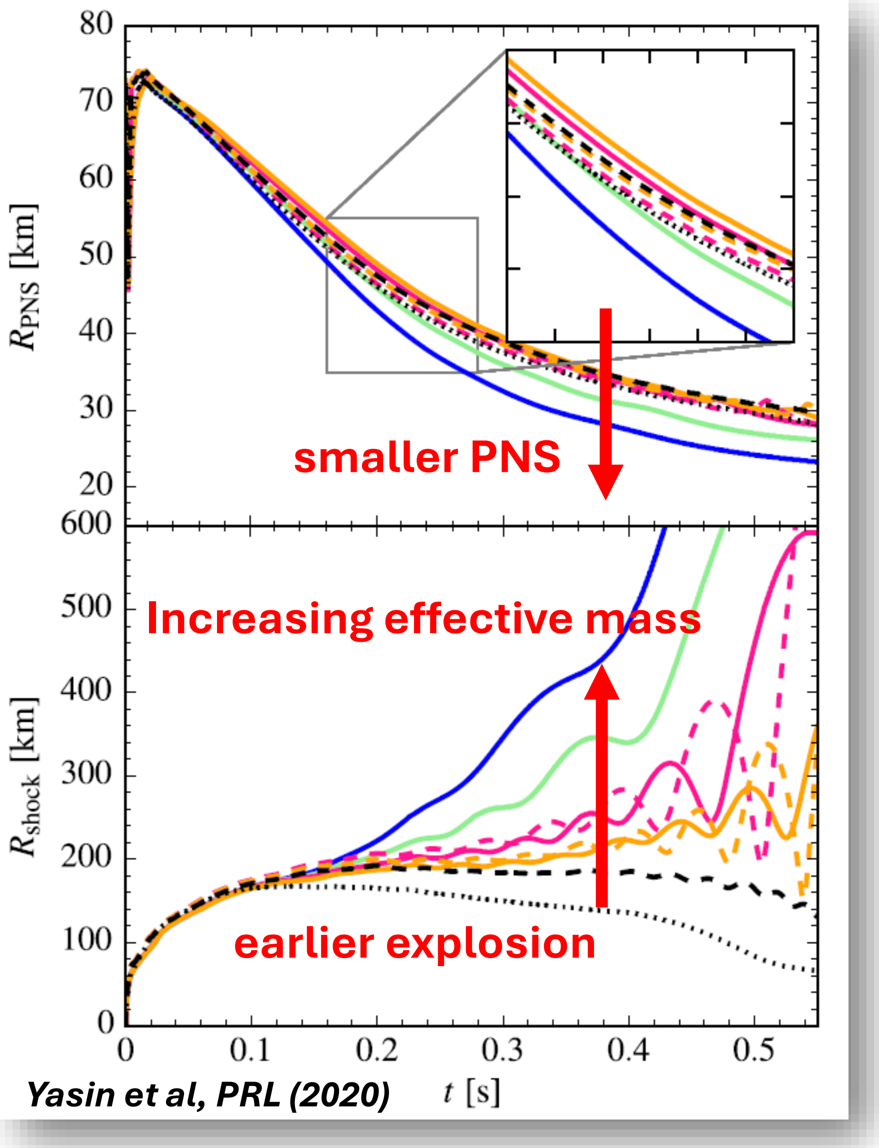


Choi et al, PRD (2025)



Radice et al, ApJL (2019)

Proto-Neutron Stars and the nucleon effective mass

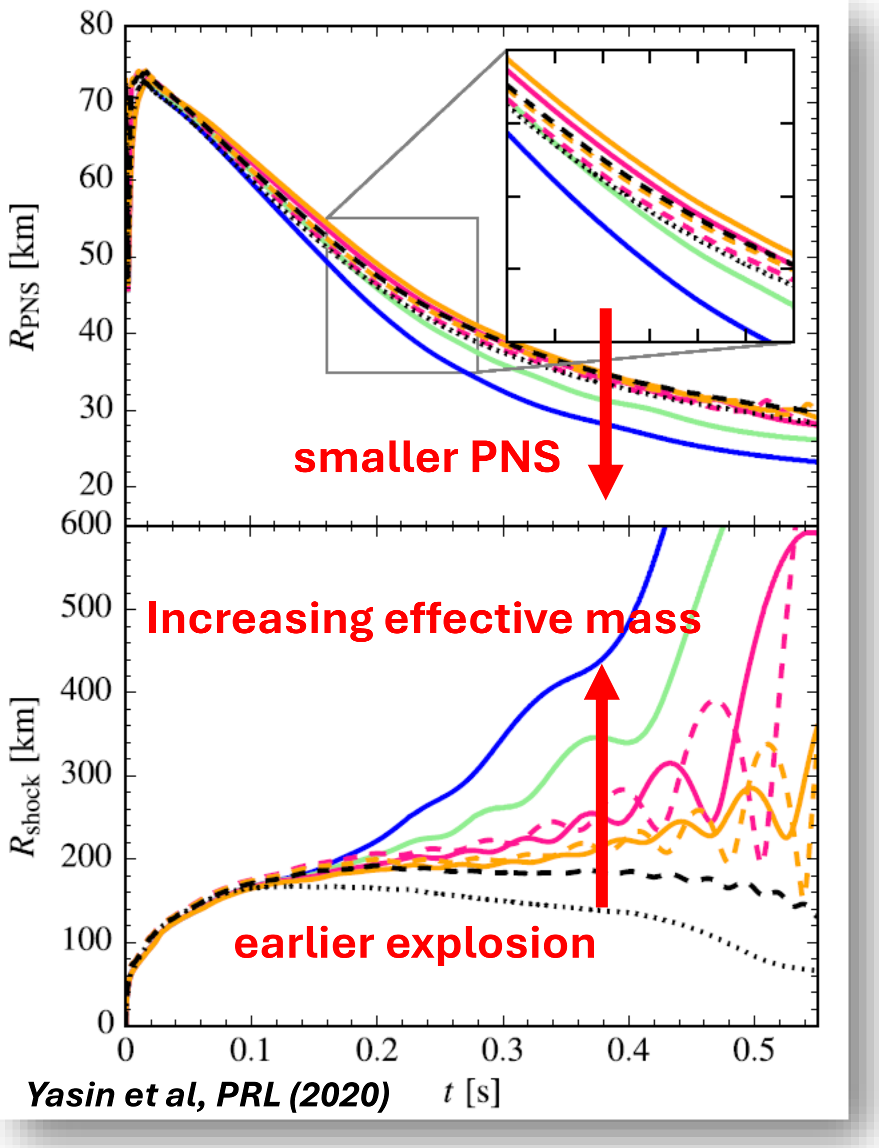


Yasin et al, PRL (2020)

Explosion dynamics are sensitive to nucleon effective mass

Schneider et al, PRC (2019); Yasin et al, PRL (2020)

Proto-Neutron Stars and the nucleon effective mass



Yasin et al, PRL (2020)

Explosion dynamics are sensitive to nucleon effective mass

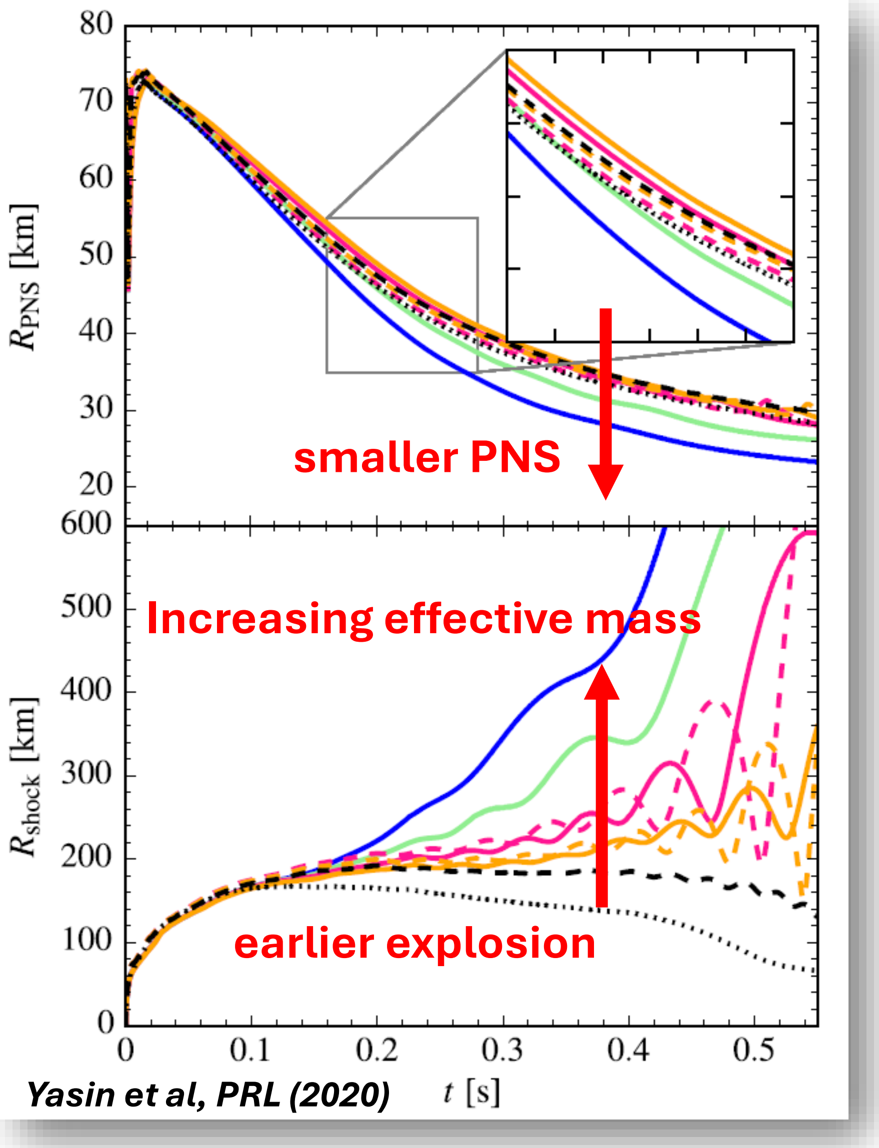
Schneider et al, PRC (2019); Yasin et al, PRL (2020)

$$P_{\mathrm{th}} \sim 1/m^*$$

(at fixed s)

- Faster PNS contraction
- Higher thermal ν energies
- Earlier explosion, larger shock radius

Proto-Neutron Stars and the nucleon effective mass



smaller PNS

Increasing effective mass

earlier explosion

Yasin et al, PRL (2020)

Explosion dynamics are sensitive to nucleon effective mass

Schneider et al, PRC (2019); Yasin et al, PRL (2020)

$$P_{\mathrm{th}} \sim 1/m^*$$

(at fixed s)

- Faster PNS contraction
- Higher thermal ν energies
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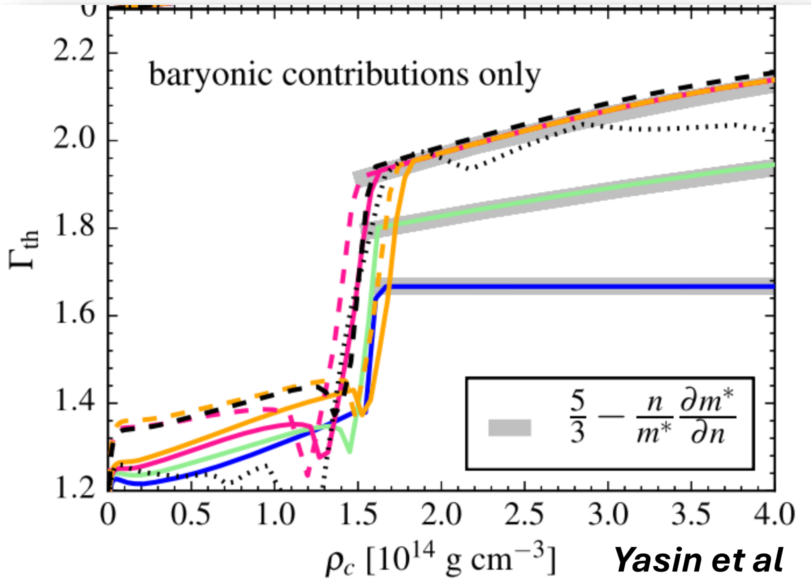
$$\Gamma_{\mathrm{th}} = 1 + \frac{P_{\mathrm{th}}}{\varepsilon_{\mathrm{th}}}$$

thermal index



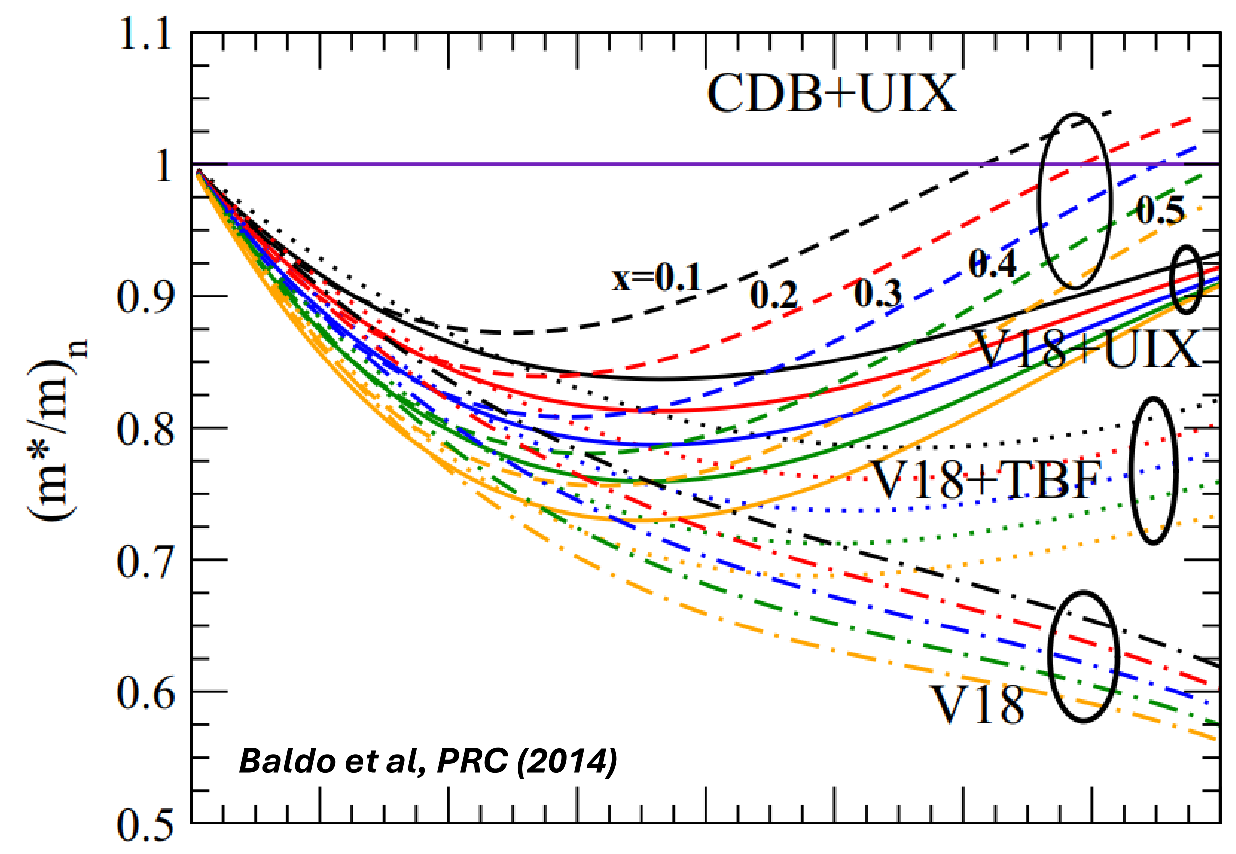
Yasin et al

Mean-field level

Nucleon Effective Mass: Mean-Field

Brueckner-Hartree-Fock

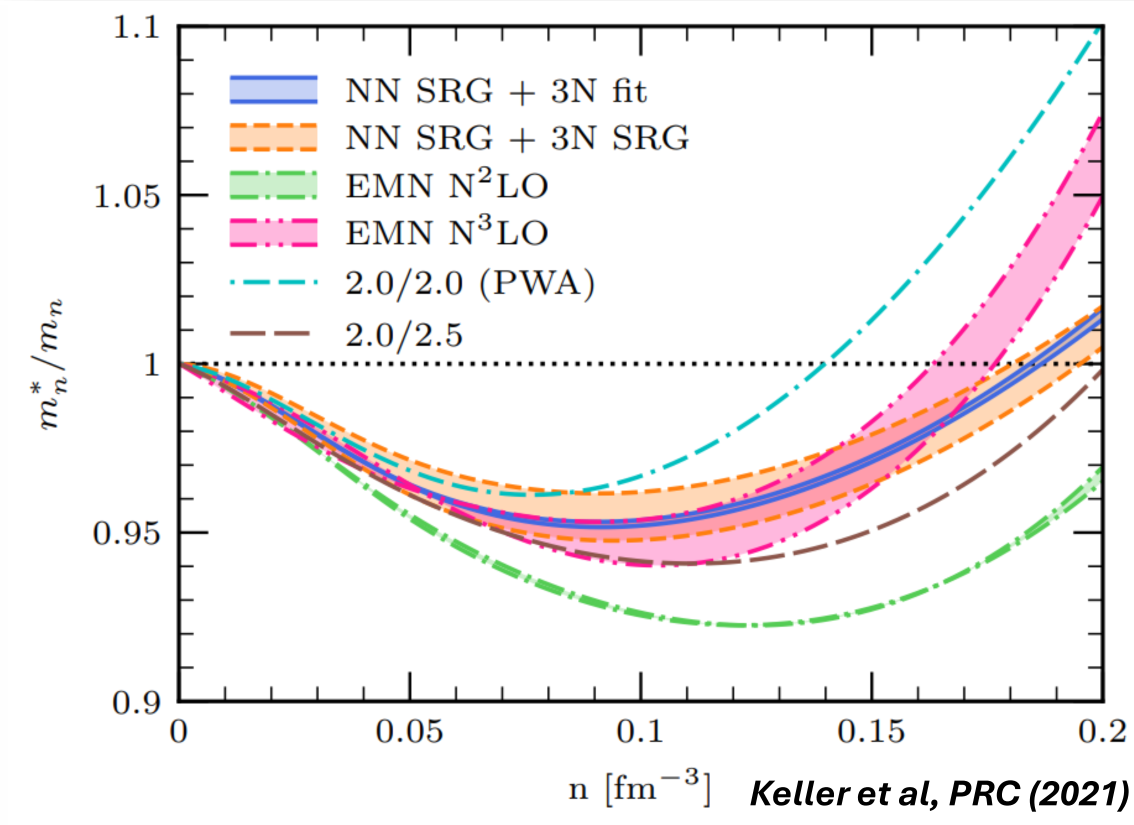
direct: $$\frac{m^*(k)}{m} = \frac{k}{m}\left[\frac{de(k)}{dk}\right]^{-1}$$



Baldo et al, PRC (2014)

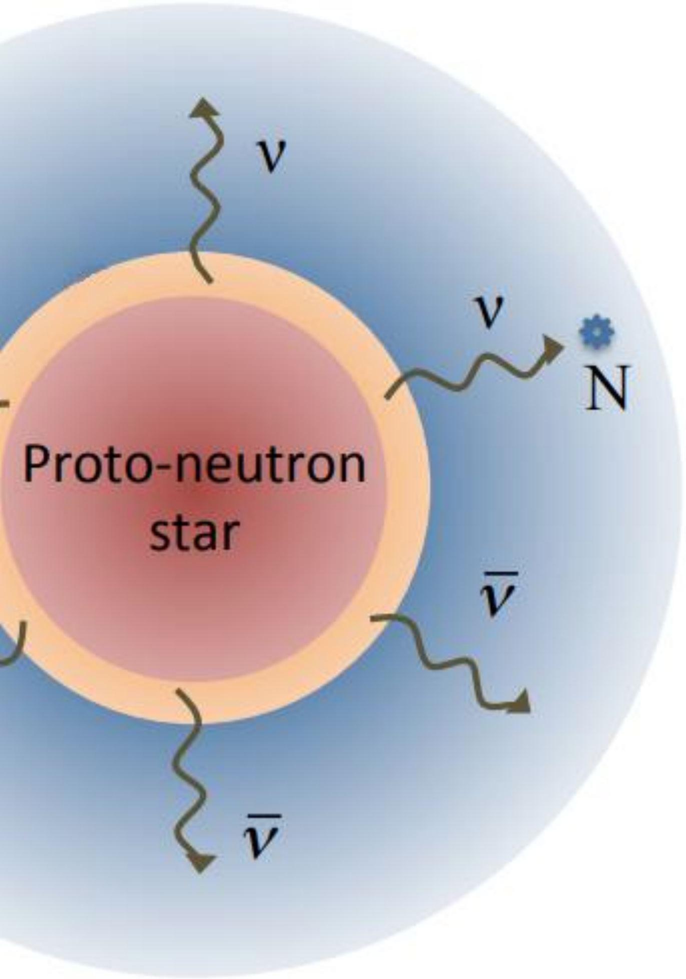
Chiral EFT + HF-MBPT

indirect: $$\Gamma^*_{\rm th}(n) = \frac{5}{3} - \frac{n}{m^*_n}\frac{\partial m^*_n}{\partial n}\,.$$



Keller et al, PRC (2021)

Supernova Neutrinos

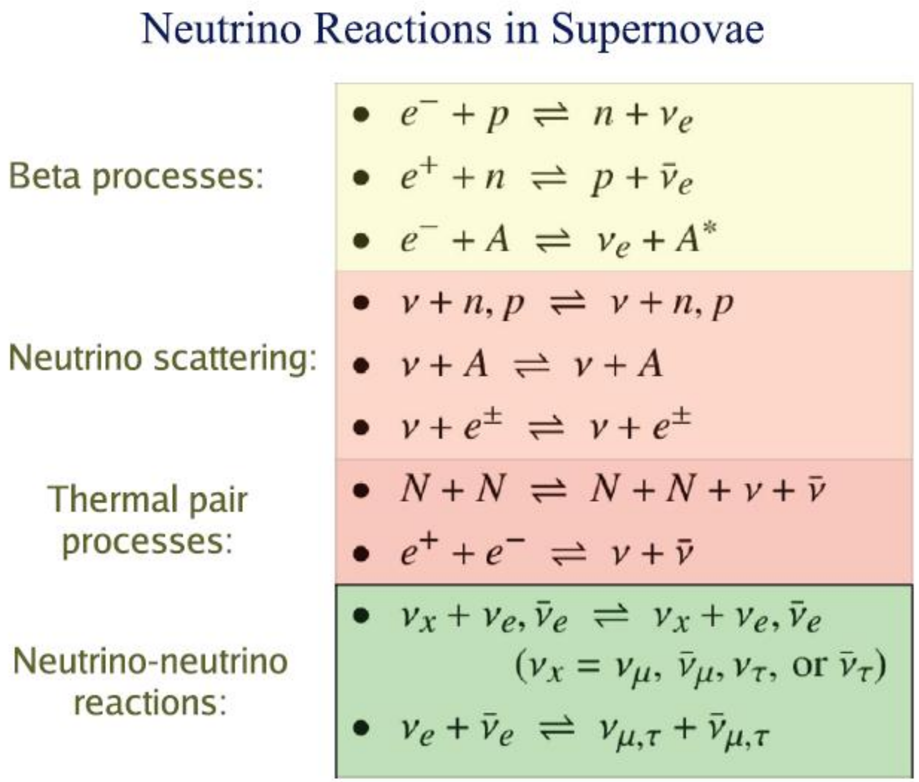


Neutrinosphere:

$T = 4 - 8\ \mathrm{MeV}$

$\rho = 10^{11} - 10^{13}\ \mathrm{g/cm^3}$

$Y_p = 0.05 - 0.10$

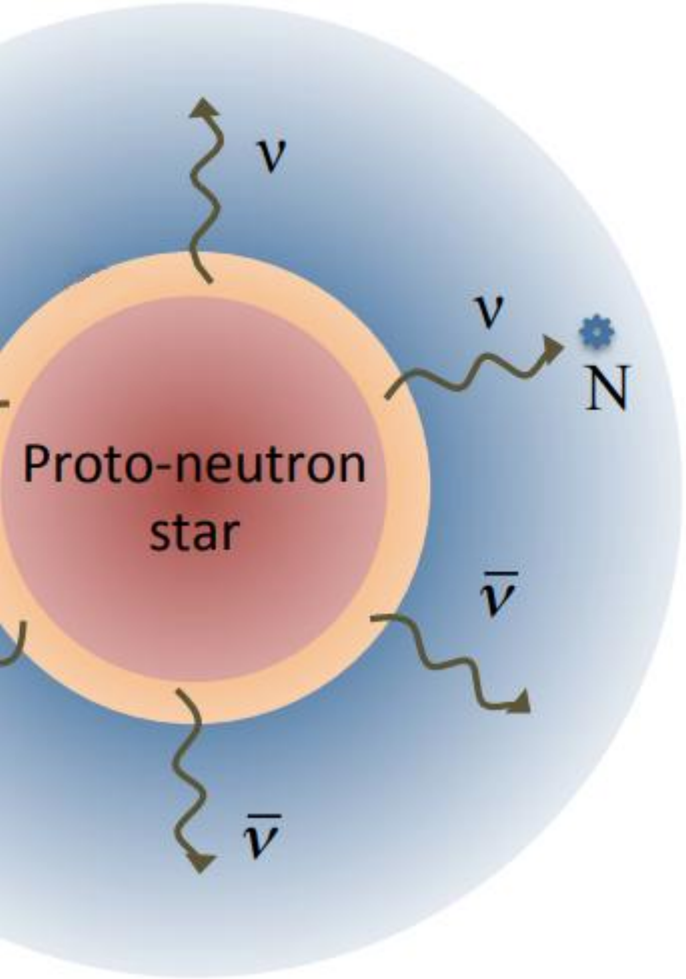


Neutrino Reactions in Supernovae

Beta processes:	$e^- + p \rightleftharpoons n + \nu_e$ $e^+ + n \rightleftharpoons p + \bar{\nu}_e$ $e^- + A \rightleftharpoons \nu_e + A^*$
Neutrino scattering:	$\nu + n, p \rightleftharpoons \nu + n, p$ $\nu + A \rightleftharpoons \nu + A$ $\nu + e^\pm \rightleftharpoons \nu + e^\pm$
Thermal pair processes:	$N + N \rightleftharpoons N + N + \nu + \bar{\nu}$ $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$
Neutrino-neutrino reactions:	$\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$ $(\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{or } \bar{\nu}_\tau)$ $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Martinez-Pinedo et al, PRL (2012)

Supernova Neutrinos



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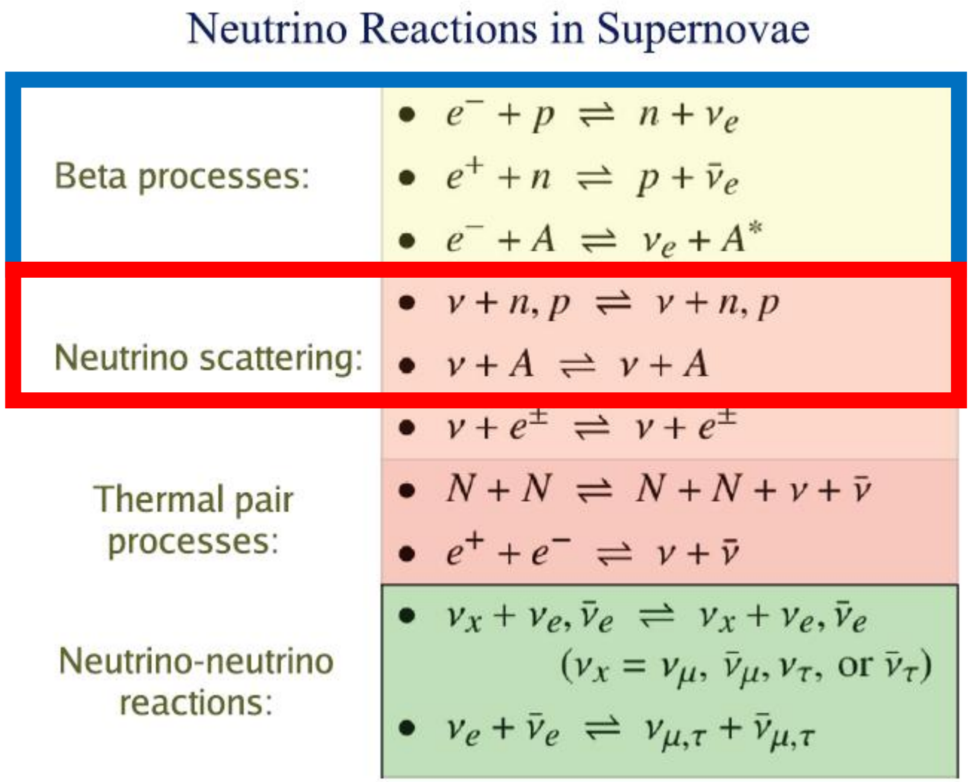
Dominated by **absorption** and **scattering** processes



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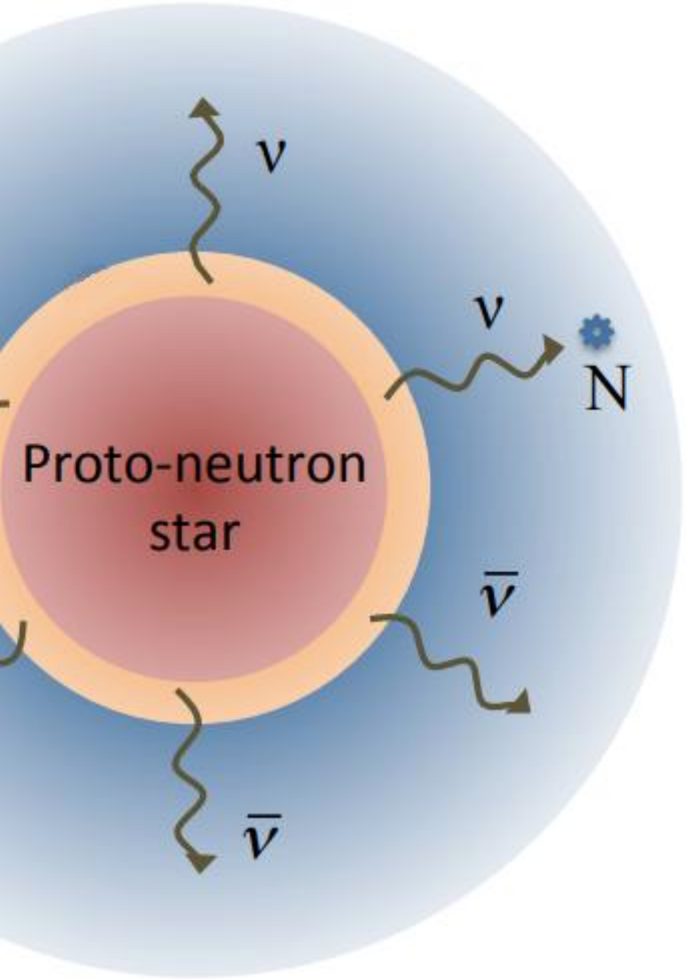
Martinez-Pinedo et al, PRL (2012)

Supernova Neutrinos



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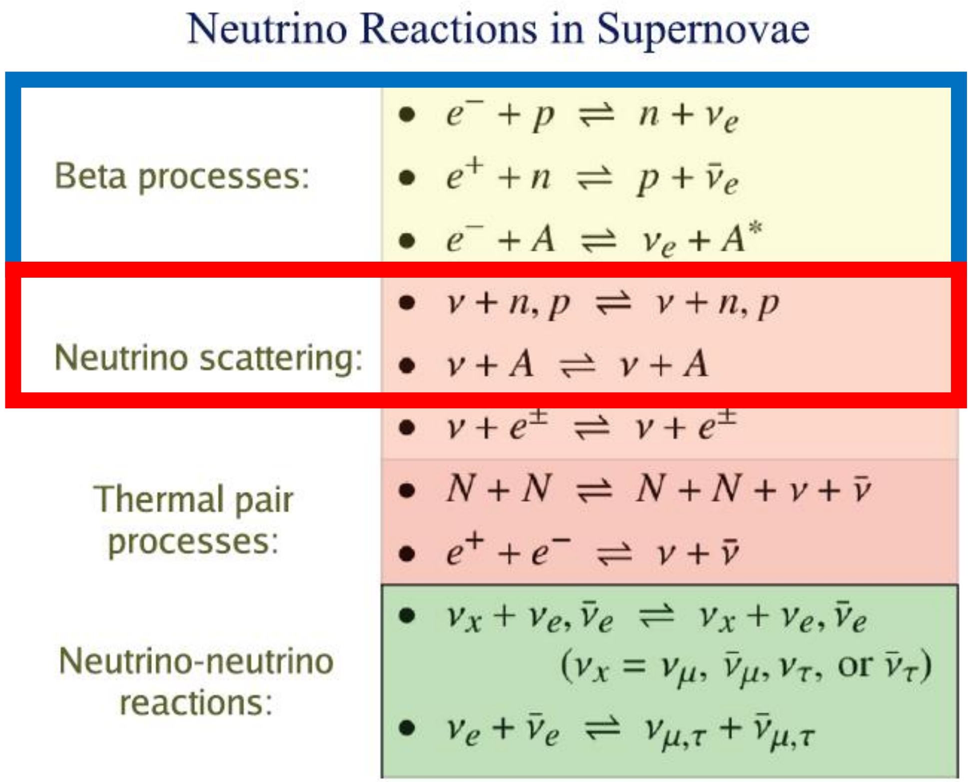
$Y_p = 0.05 - 0.10$

Dominated by **absorption** and **scattering** processes

- Controls total luminosity and average energy - *explosion mechanism*

J. A. Pons et al, ApJ (1999)

Neutrino Reactions in Supernovae



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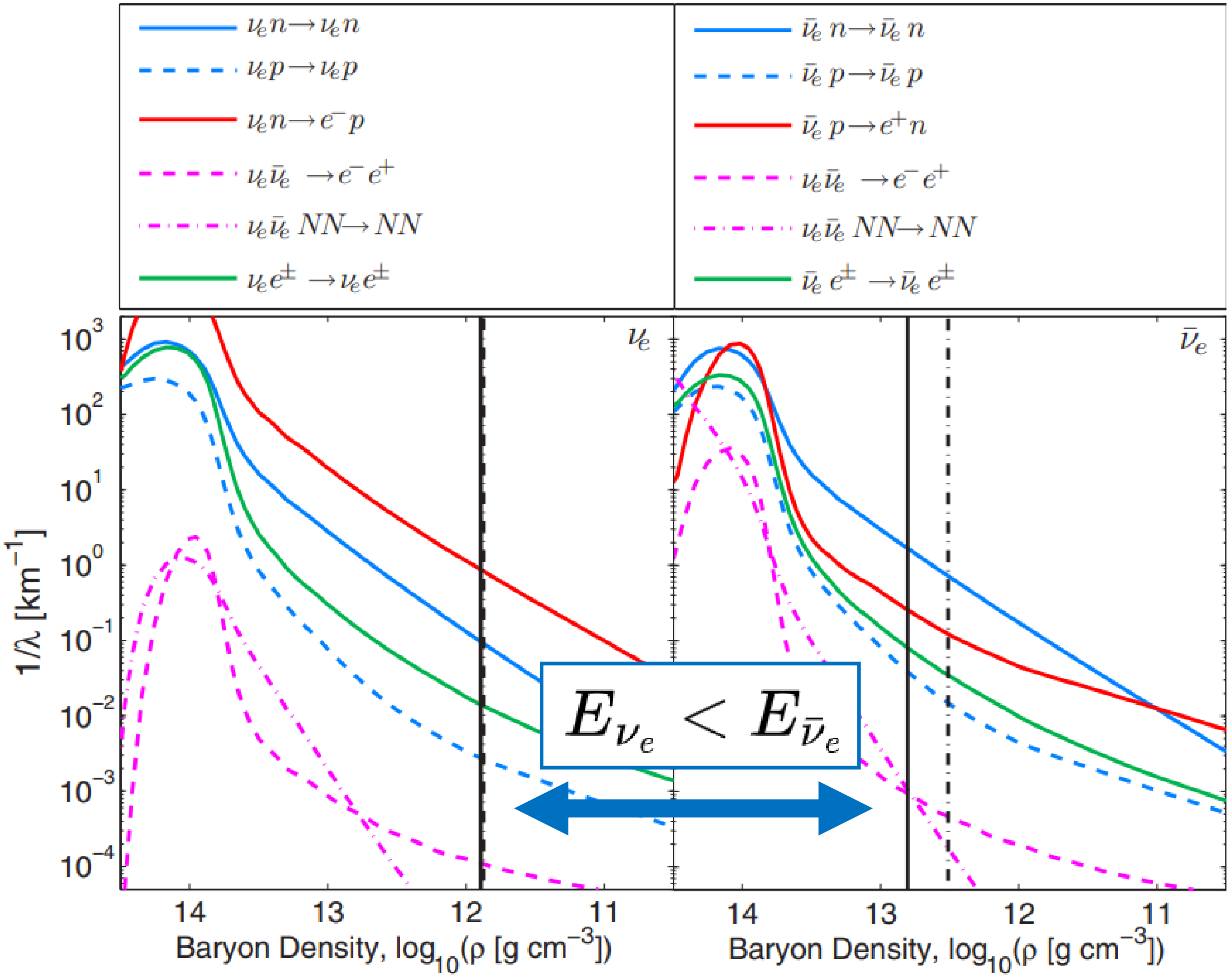
Martinez-Pinedo et al, PRL (2012)

- Governs spectral and temporal aspects of *detectable neutrino signal*

H.-T. Janka, et al, Ann. Rev. Nuc. (2016)

Neutrino opacity in the neutrinosphere



$$E_{\nu_e} < E_{\bar{\nu}_e}$$

Martinez-Pinedo et al, J Phys G (2014)

$$\boxed{\begin{aligned} \nu_e + n &\longleftrightarrow e^- + p \\ \bar{\nu}_e + p &\longleftrightarrow e^+ + n \end{aligned}}$$

charged-current reactions

Competing processes set *electron fraction* of ejected material

Neutrino-driven wind

Consequences for r-process nucleosynthesis

Martinez-Pinedo et al, PRL (2012); Roberts et al, PRC (2012)

Neutrino Absorption: Mean-Field and RPA

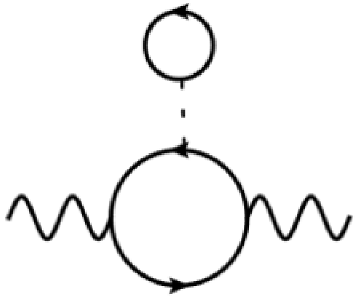
Electron phase space **Nucleon response**

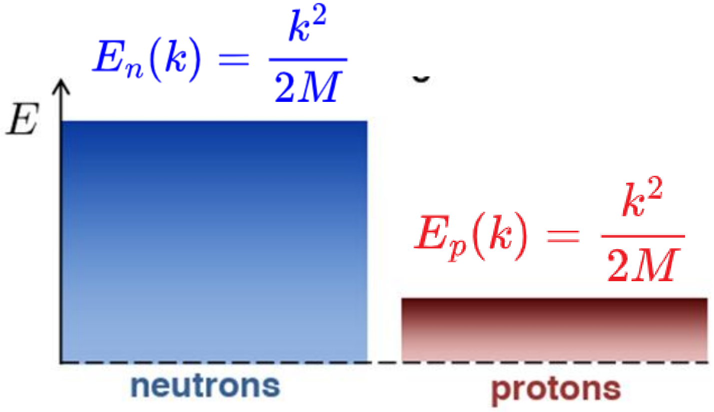
$$\frac{1}{V}\frac{d^2\sigma}{d\cos\theta dE_e} = \frac{G_F^2\cos^2\theta_c}{4\pi^2}\boxed{p_eE_e(1-f_e(E_e))}\boxed{[(1+\cos\theta)S_{\tau\rho}(\omega,q)+g_A^2(3-\cos\theta)S_{\tau\sigma}(\omega,q)]}$$

Neutrino Absorption: Mean-Field and RPA

$$\frac{1}{V}\frac{d^2\sigma}{d\cos\theta\, dE_e} = \frac{G_F^2\cos^2\theta_c}{4\pi^2}\overset{\text{Electron phase space}}{\boxed{p_eE_e(1-f_e(E_e))}}\;\overset{\text{Nucleon response}}{\boxed{[(1+\cos\theta)S_{\tau\rho}(\omega,q)+g_A^2(3-\cos\theta)S_{\tau\sigma}(\omega,q)]}}$$

Nuclear Mean-Field Effects



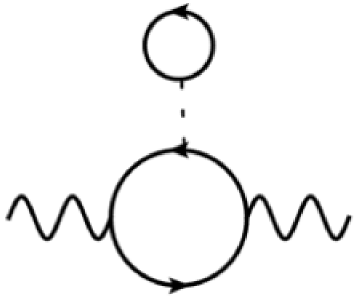


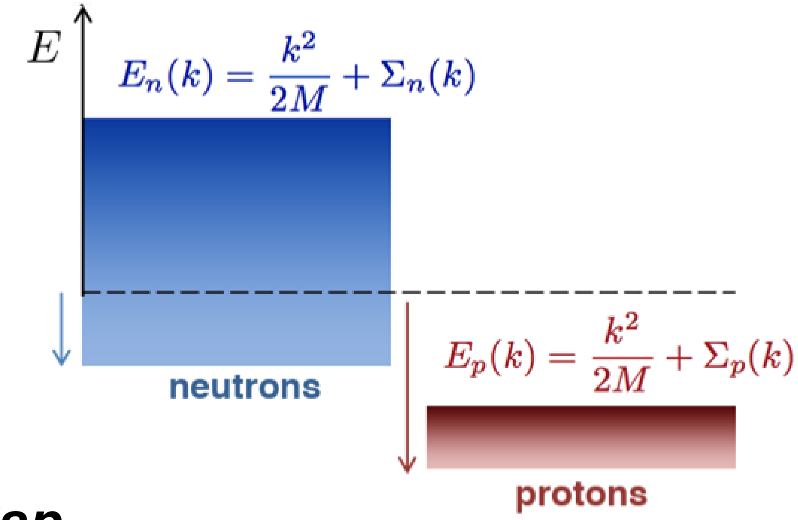
Noninteracting nucleons

Neutrino Absorption: Mean-Field and RPA

$$\frac{1}{V}\frac{d^2\sigma}{d\cos\theta\, dE_e} = \frac{G_F^2\cos^2\theta_c}{4\pi^2}\overbrace{\boxed{p_eE_e(1-f_e(E_e))}}^{\text{Electron phase space}}\overbrace{\boxed{[(1+\cos\theta)S_{\tau\rho}(\omega,q)+g_A^2(3-\cos\theta)S_{\tau\sigma}(\omega,q)]}}^{\text{Nucleon response}}$$

Nuclear Mean-Field Effects





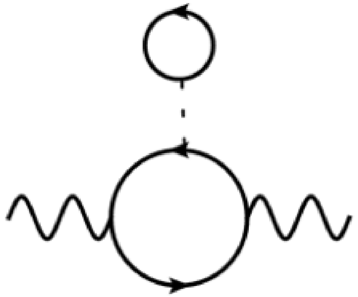
Nuclear mean fields

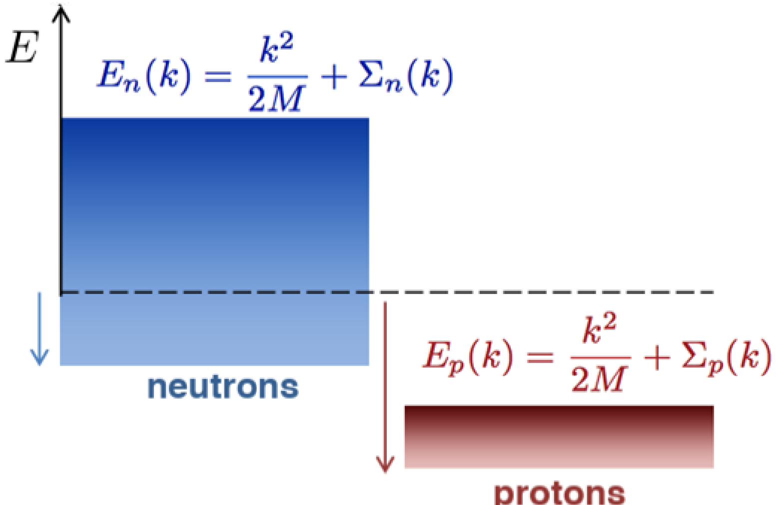
widen energy gap
between p, n

Neutrino Absorption: Mean-Field and RPA

$$\frac{1}{V}\frac{d^2\sigma}{d\cos\theta\, dE_e} = \frac{G_F^2\cos^2\theta_c}{4\pi^2}\,\overbrace{\boxed{p_eE_e(1-f_e(E_e))}}^{\text{Electron phase space}}\;\overbrace{\boxed{[(1+\cos\theta)S_{\tau\rho}(\omega,q)+g_A^2(3-\cos\theta)S_{\tau\sigma}(\omega,q)]}}^{\text{Nucleon response}}$$

Nuclear Mean-Field Effects

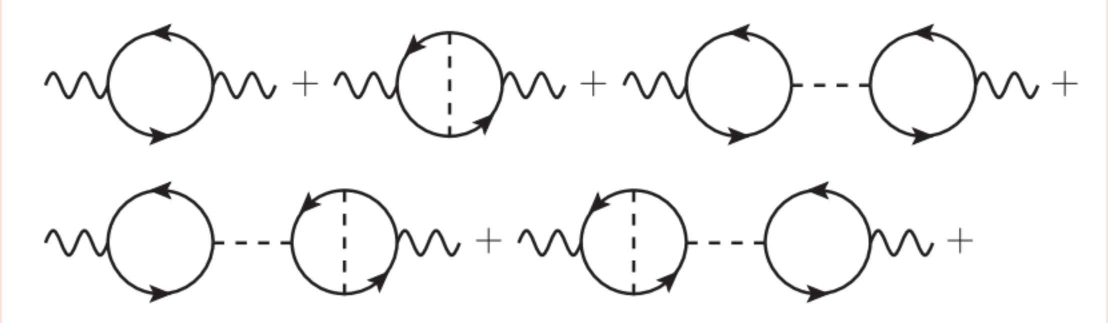




Nuclear mean fields

widen energy gap *between p, n*

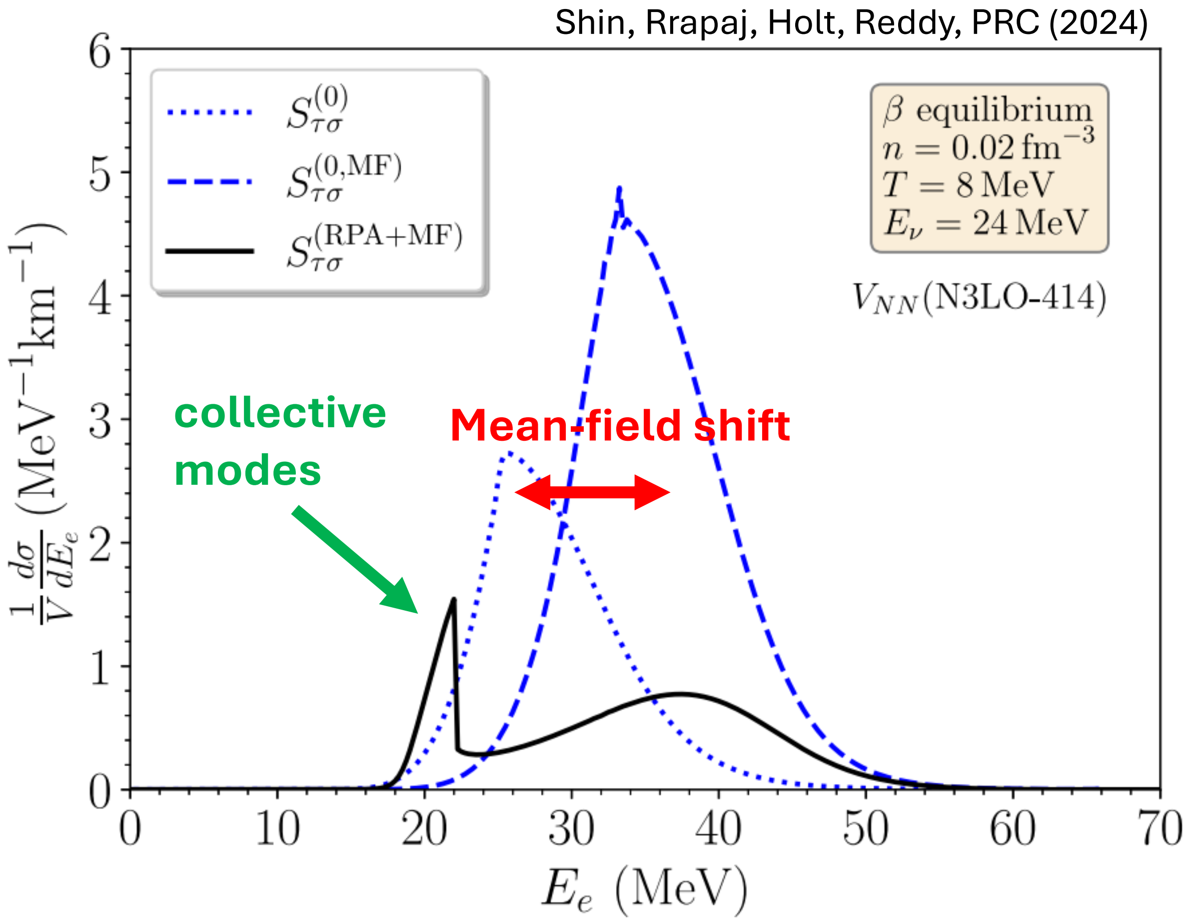
Random Phase Approximation (RPA)



- Infinite summation over “bubble” diagrams
- Conserving approximations – *sum rules*
- Mean field approach – *collective excitations*

Neutrino Absorption: Mean-Field and RPA

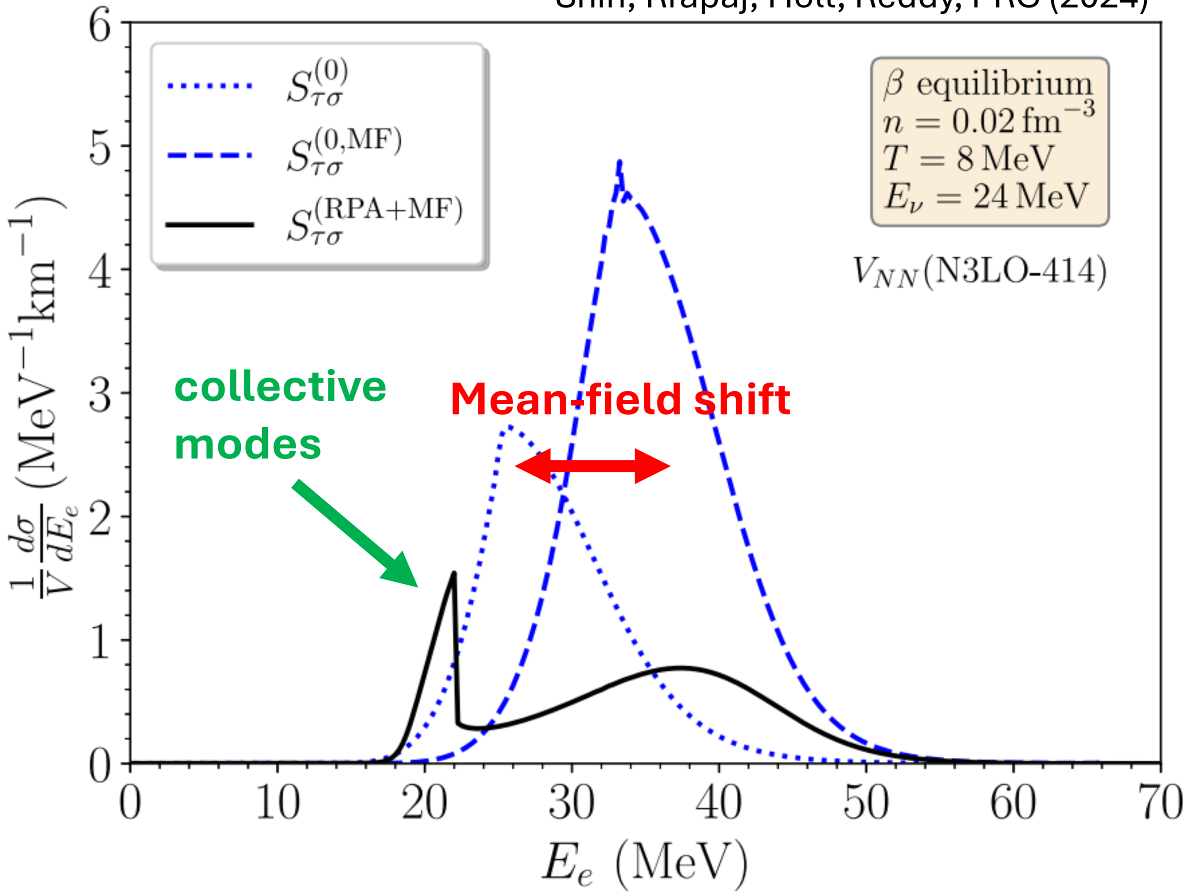
Absorption cross section


Shin, Rrapaj, Holt, Reddy, PRC (2024)

Neutrino Absorption: Mean-Field and RPA

Absorption cross section

Shin, Rrapaj, Holt, Reddy, PRC (2024)

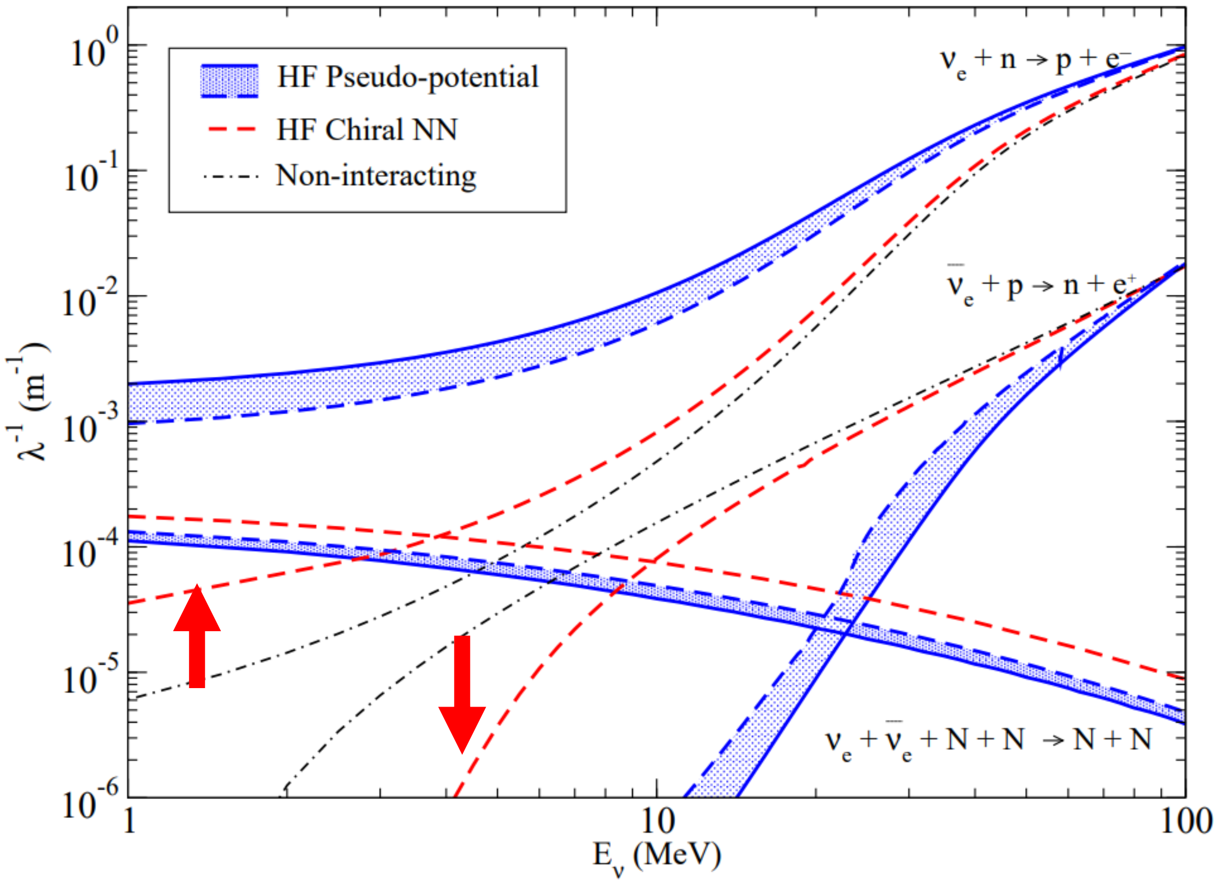


collective modes

Mean-field shift

Neutrino opacity

Rrapaj, Holt, Bartl, Reddy, et al, PRC (2015)



Neutrino Absorption: Mean-Field and RPA

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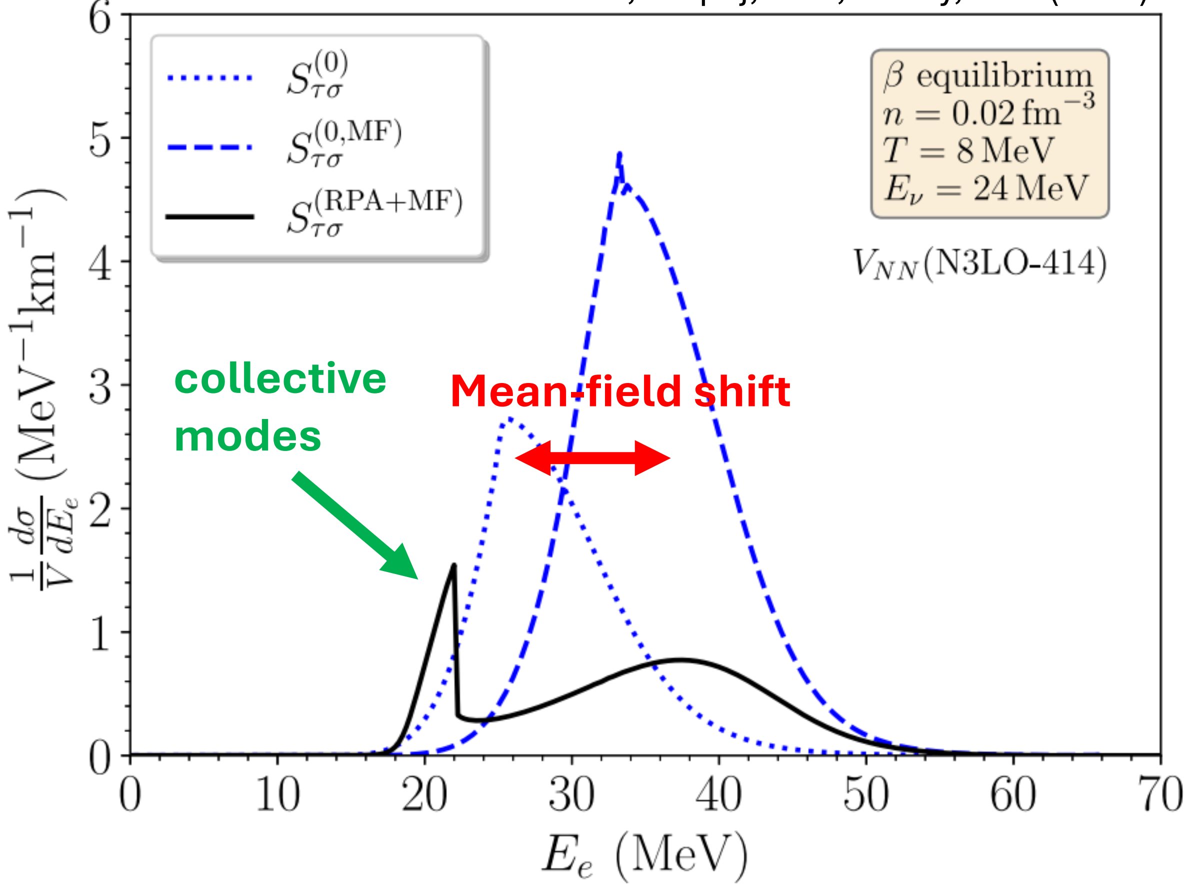
Shin, Rrapaj, Holt, Reddy, PRC (2024)



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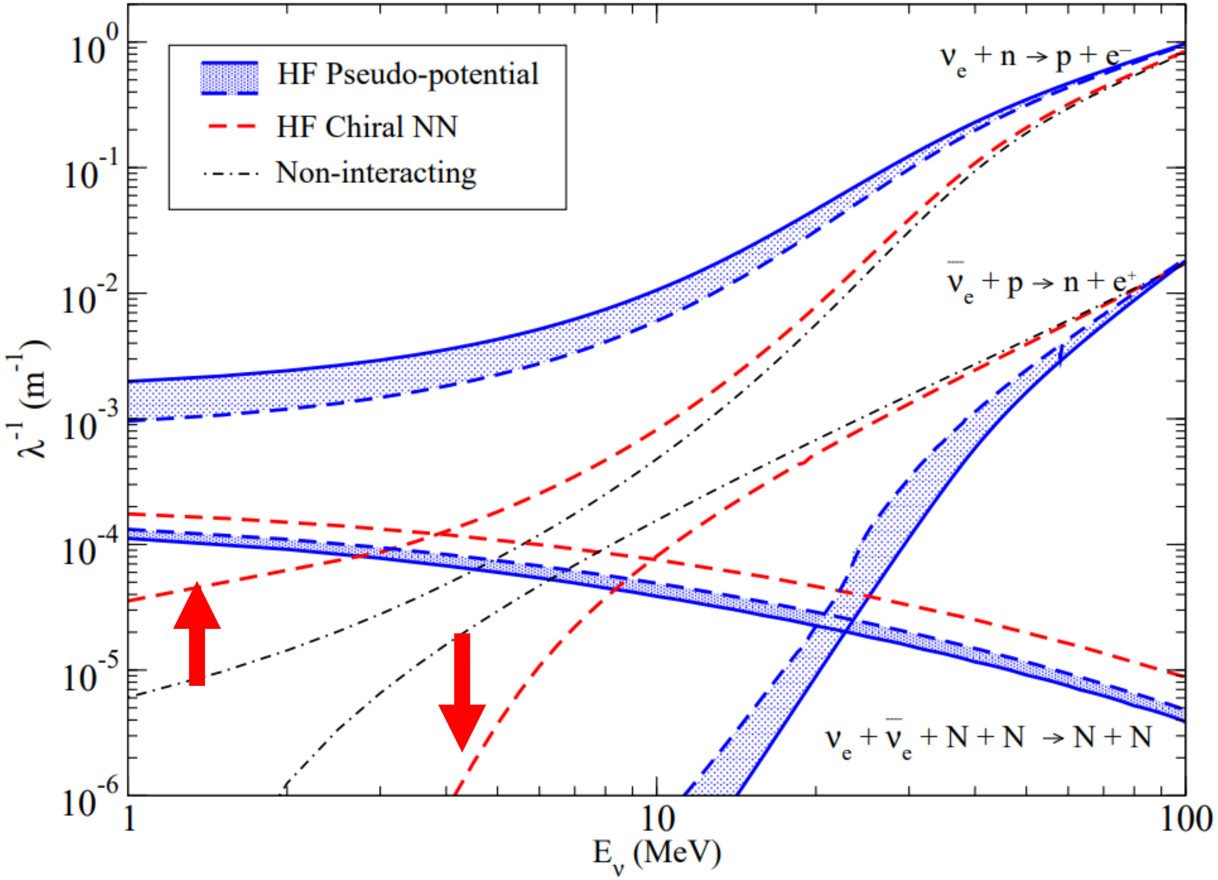


Takeaway: Nuclear mean-fields enhance neutrino absorption

Nuclear Forces from (Next-To) First Principles

Quark/gluon (high energy) dynamics

$$\mathcal{L} = -\frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu} + \bar{q}_L i\gamma_\mu D^\mu q_L$$
$$+\bar{q}_R i\gamma_\mu D^\mu q_R - \bar{q}\mathcal{M}q$$

- Approximate chiral symmetry (left and right-handed quarks approximately decouple)

Nucleon/pion (low energy) dynamics

$$\mathcal{L}_{\text{eff}} = \mathcal{L}^{(2)}_{\pi\pi} + \mathcal{L}^{(1)}_{\pi N} + \mathcal{L}^{(2)}_{\pi N} + \mathcal{L}^{(0)}_{NN} + \mathcal{L}^{(2)}_{NN} + \cdots$$

- Explicit and spontaneous **chiral symmetry breaking** → *pion mass*

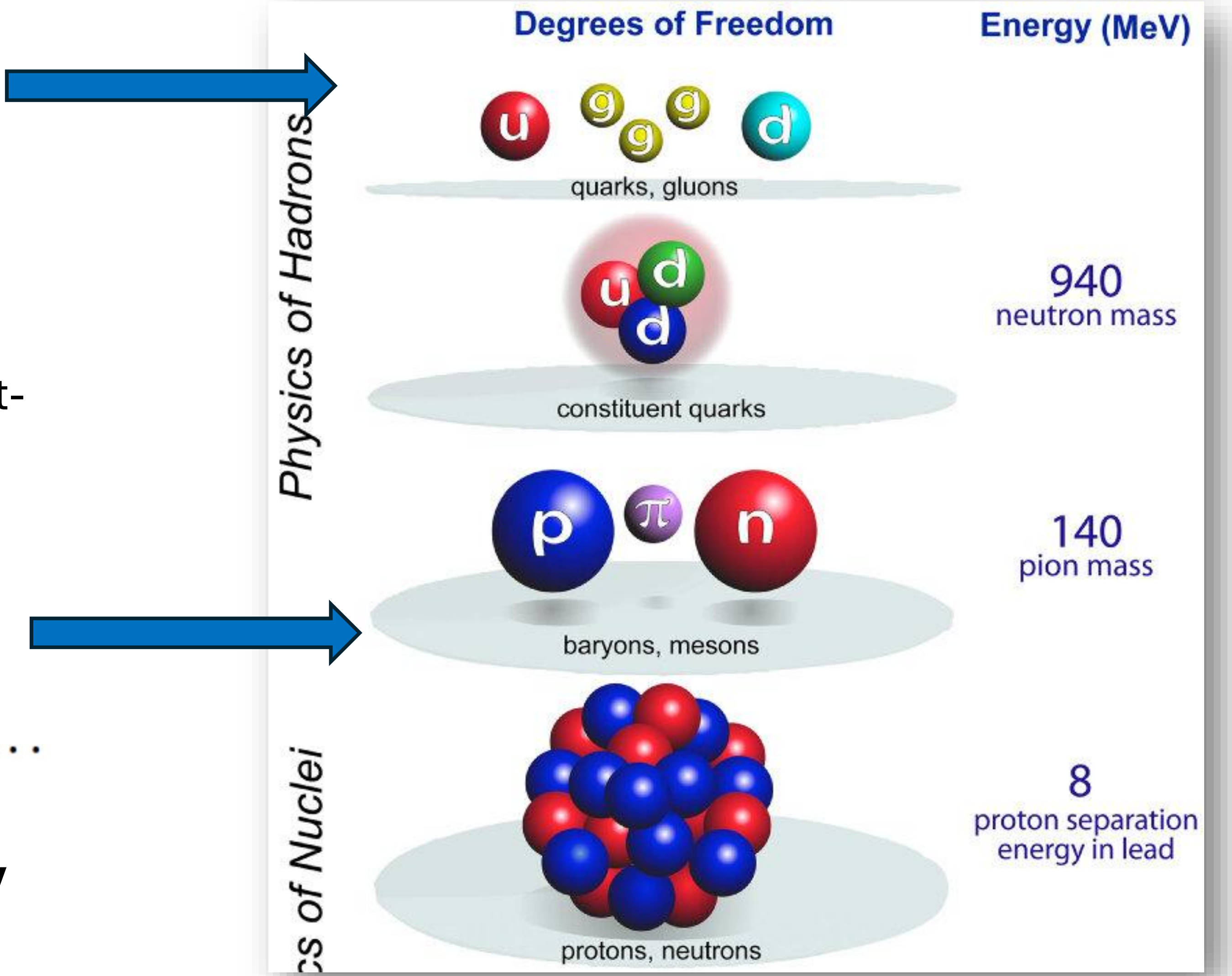
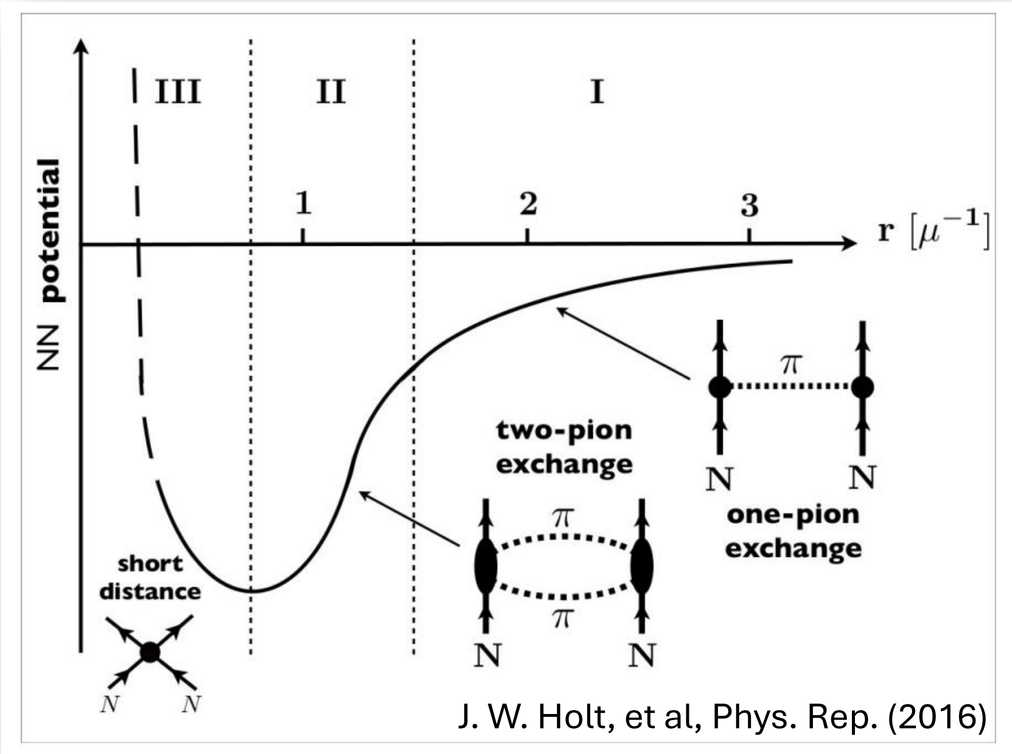


Image Credit: Oak Ridge Natl. Lab

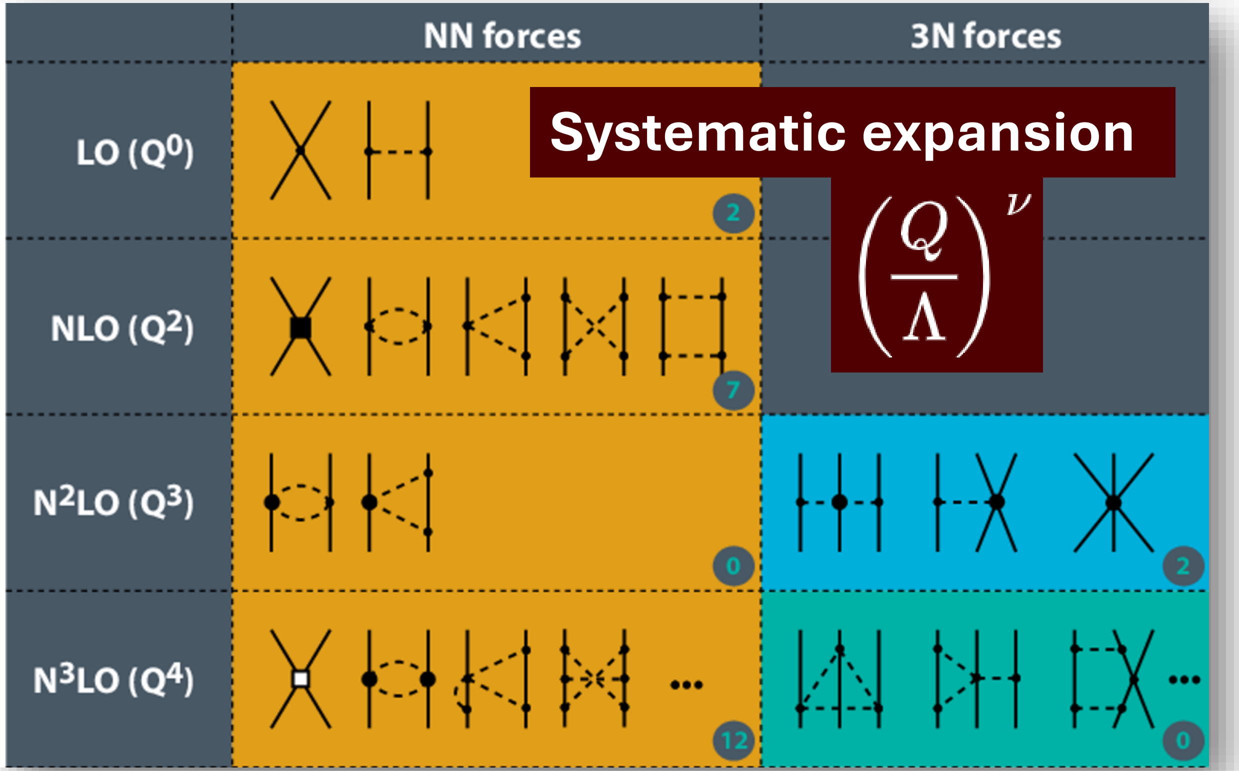
Chiral Effective Field Theory

Low energy theory of nucleons and pions

pion exchange (long range) and nucleon-nucleon contact (short range)



J. W. Holt, et al, Phys. Rep. (2016)



Systematic expansion

$$\left(\frac{Q}{\Lambda}\right)^{\nu}$$

C. Drischler, J. W. Holt, et al, Annu. Rev. Nucl. Part. Sci. (2021)

- Fit low-energy constants (πN and NN vertices) to NN scattering data and bound states (H, He, etc.)

- Naturally incorporates 3-nucleon interactions (**nuclear saturation**)

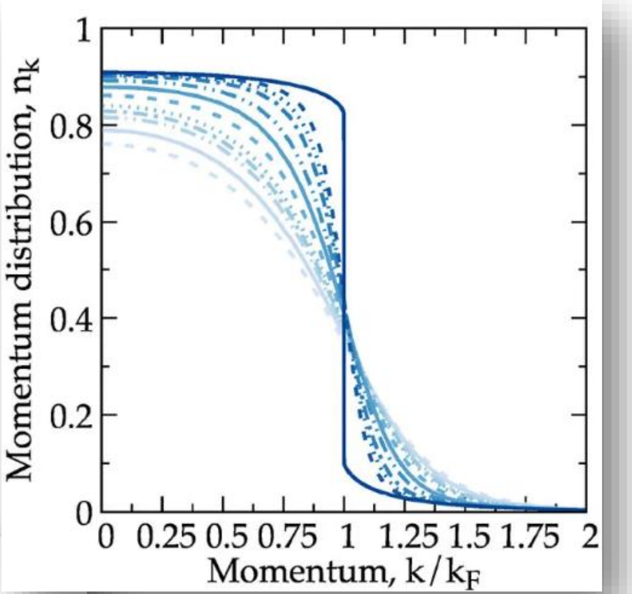
Microscopic modeling of nuclear matter

- **Many-Body Perturbation Theory** (MBPT): Perturbation series in the *grand canonical potential*

$$n_\tau = 2\int \frac{d^3\mathbf{k}}{(2\pi)^3}\, n_{k,\tau}\,(\mu_\tau, T)$$

- **Dyson Equation:** nucleon Green's functions

$$G(\mathbf{k},\omega) = G^0(\mathbf{k},\omega) + G^0(\mathbf{k},\omega)\boxed{\Sigma(\mathbf{k},\omega)}G(\mathbf{k},\omega)$$

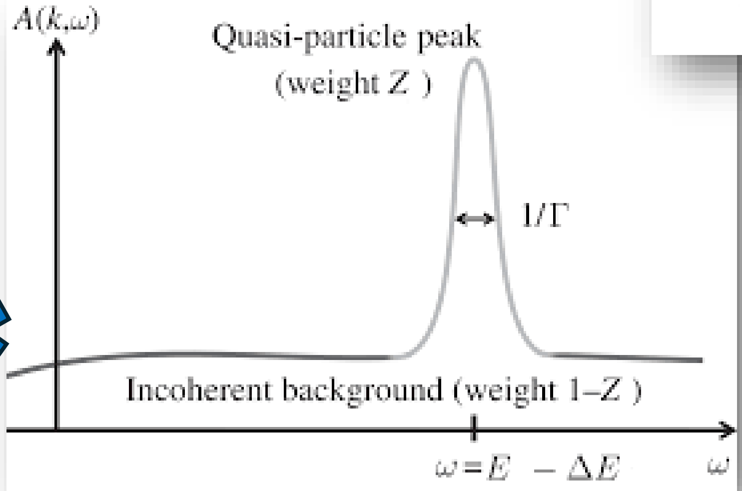


Rios, Front. Phys. (2020)

Nucleon self-energy "dresses" the particles with medium interactions – ***quasiparticle approach***

$$\varepsilon_\tau(k) = \frac{k^2}{2M_N} + \mathrm{Re}\,\Sigma_\tau(k, \varepsilon_\tau(k))$$

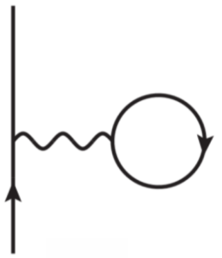
$$W_\tau(k) = -2\,\mathrm{Im}\,\Sigma_\tau(k, \varepsilon_\tau(k))$$



Nucleon Self-Energy in MBPT

- **Hartree-Fock contribution** (real, energy-independent)

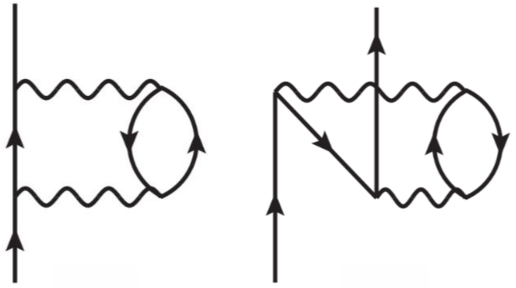
$$\Sigma_\tau^{(1)}(k;\mu_p,\mu_n,T) = \sum_{1} \langle \mathbf{k}\,\mathbf{h}_1; s\, s_1; \tau\,\tau_1 | \overline{V}_{NN} | \mathbf{k}\,\mathbf{h}_1; s\, s_1; \tau\,\tau_1 \rangle\, n_1$$



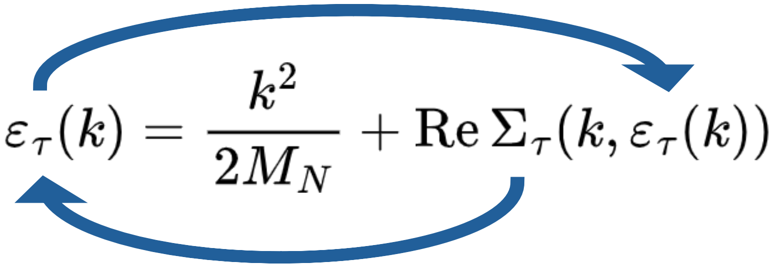
- **Second Order perturbative contributions** (complex, energy-dependent)

$$\Sigma_\tau^{(2a)}(k,\omega;\mu_p,\mu_n,T) = \frac{1}{2}\sum_{123} \frac{\left| \langle \mathbf{p}_1\,\mathbf{p}_2; s_1\, s_2; \tau_1\,\tau_2 | \overline{V}_{NN} | \mathbf{k}\,\mathbf{h}_3; s\, s_3; \tau\,\tau_3 \rangle \right|^2}{\omega + \varepsilon_3 - \varepsilon_1 - \varepsilon_2 + i\eta}$$

$$\bar{n}_1 \bar{n}_2 n_3\, (2\pi)^3\, \delta^3(\mathbf{p}_1 + \mathbf{p}_2 - \mathbf{h}_3 - \mathbf{k})$$

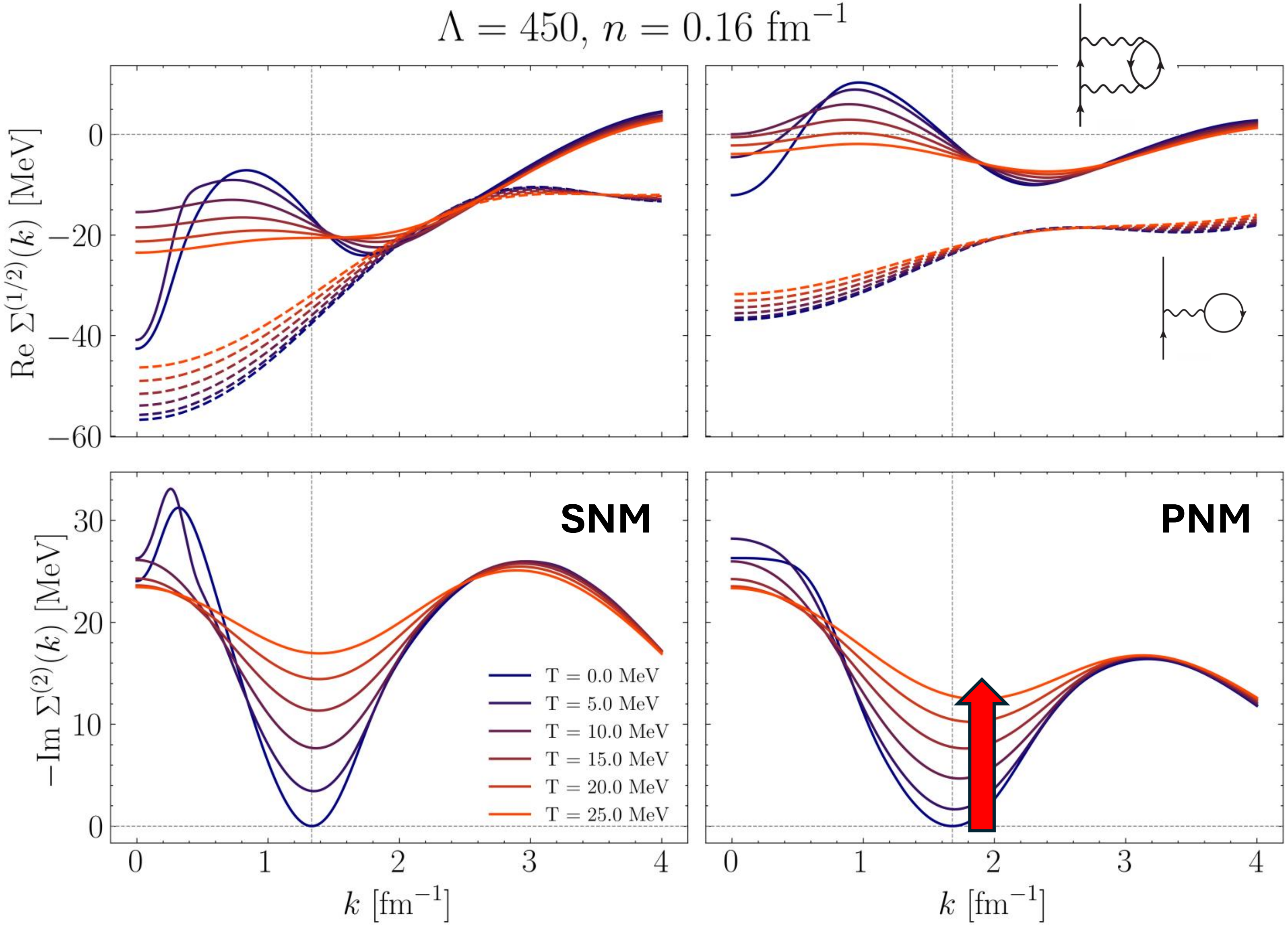


- **Self-Consistent Approach**
  (quasiparticle approximation)



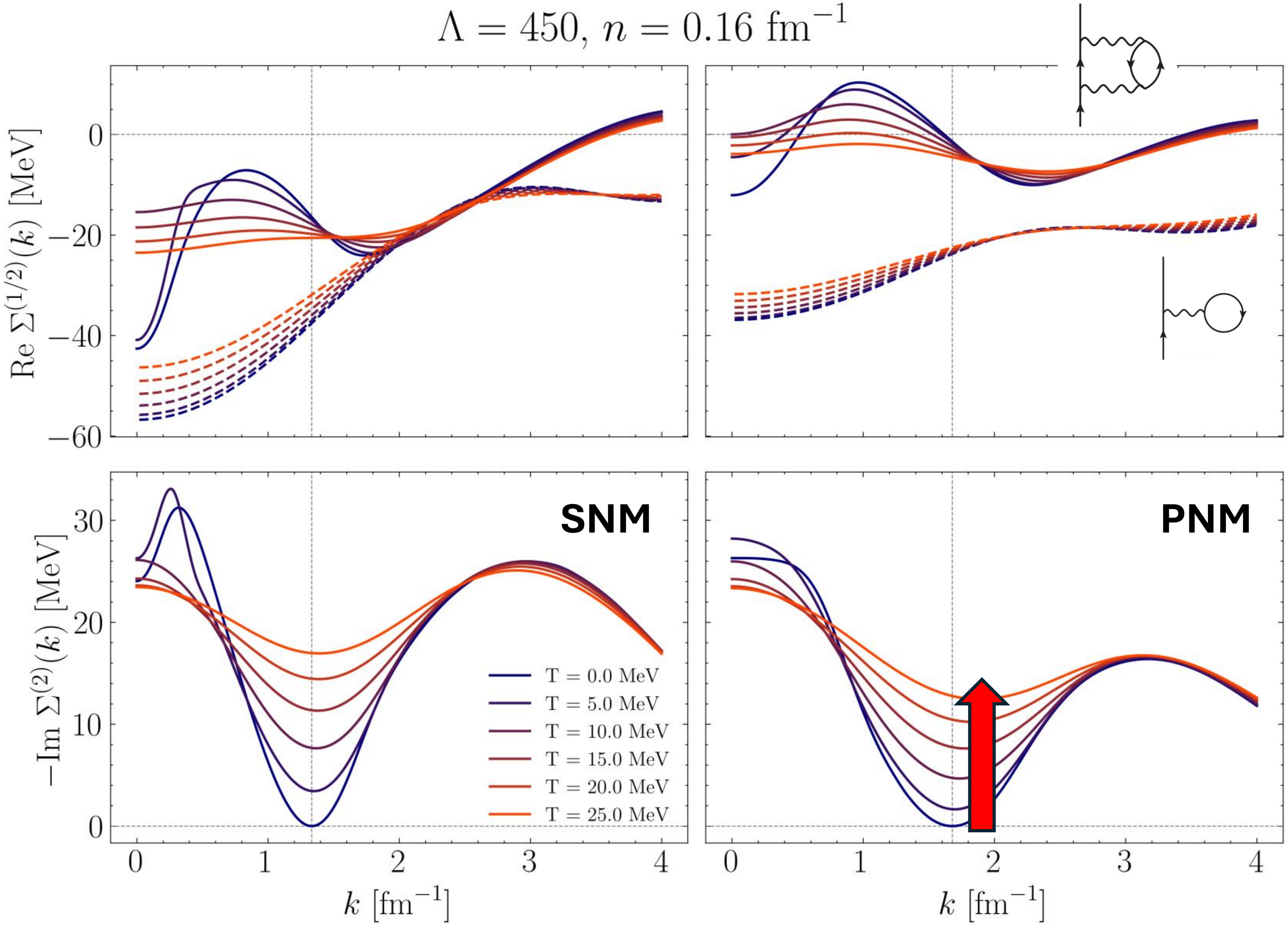
$$\varepsilon_\tau(k) = \frac{k^2}{2M_N} + \mathrm{Re}\,\Sigma_\tau(k, \varepsilon_\tau(k))$$

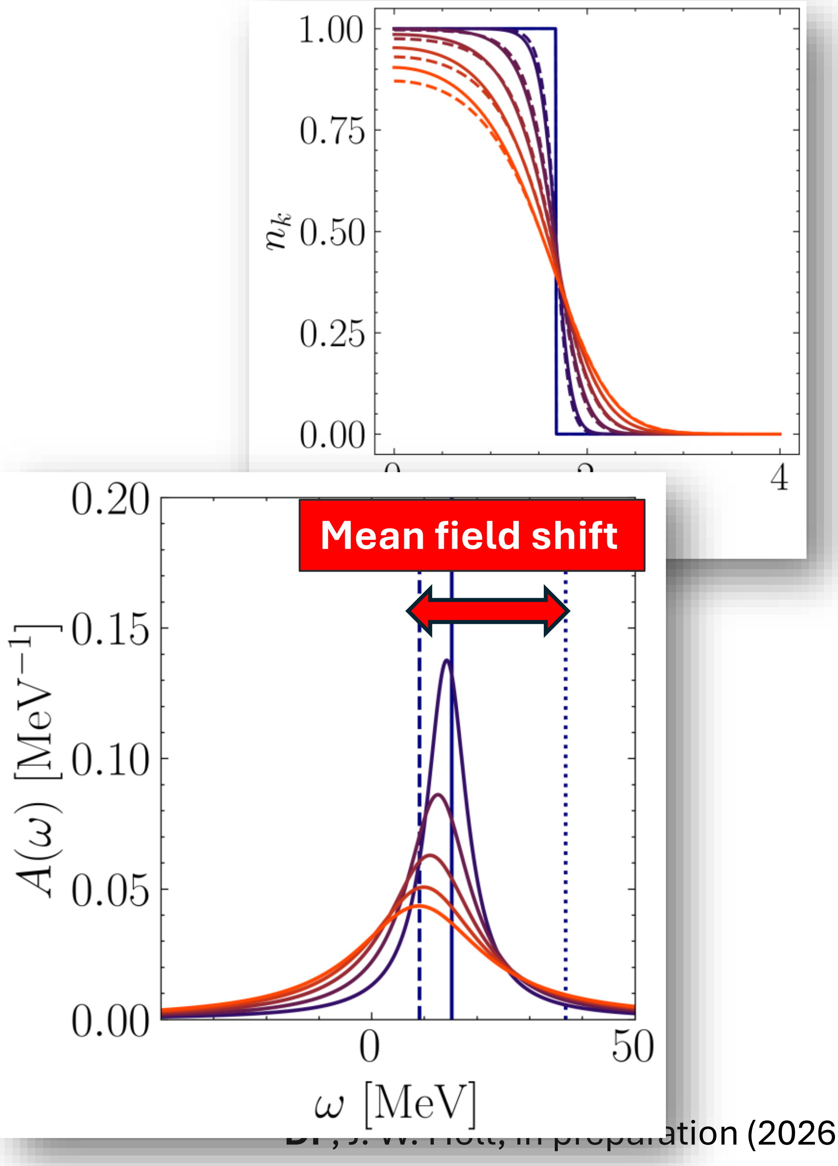
Nucleon Self-Energy: Results



DF, J. W. Holt, in preparation (2026)

Nucleon Self-Energy: Results



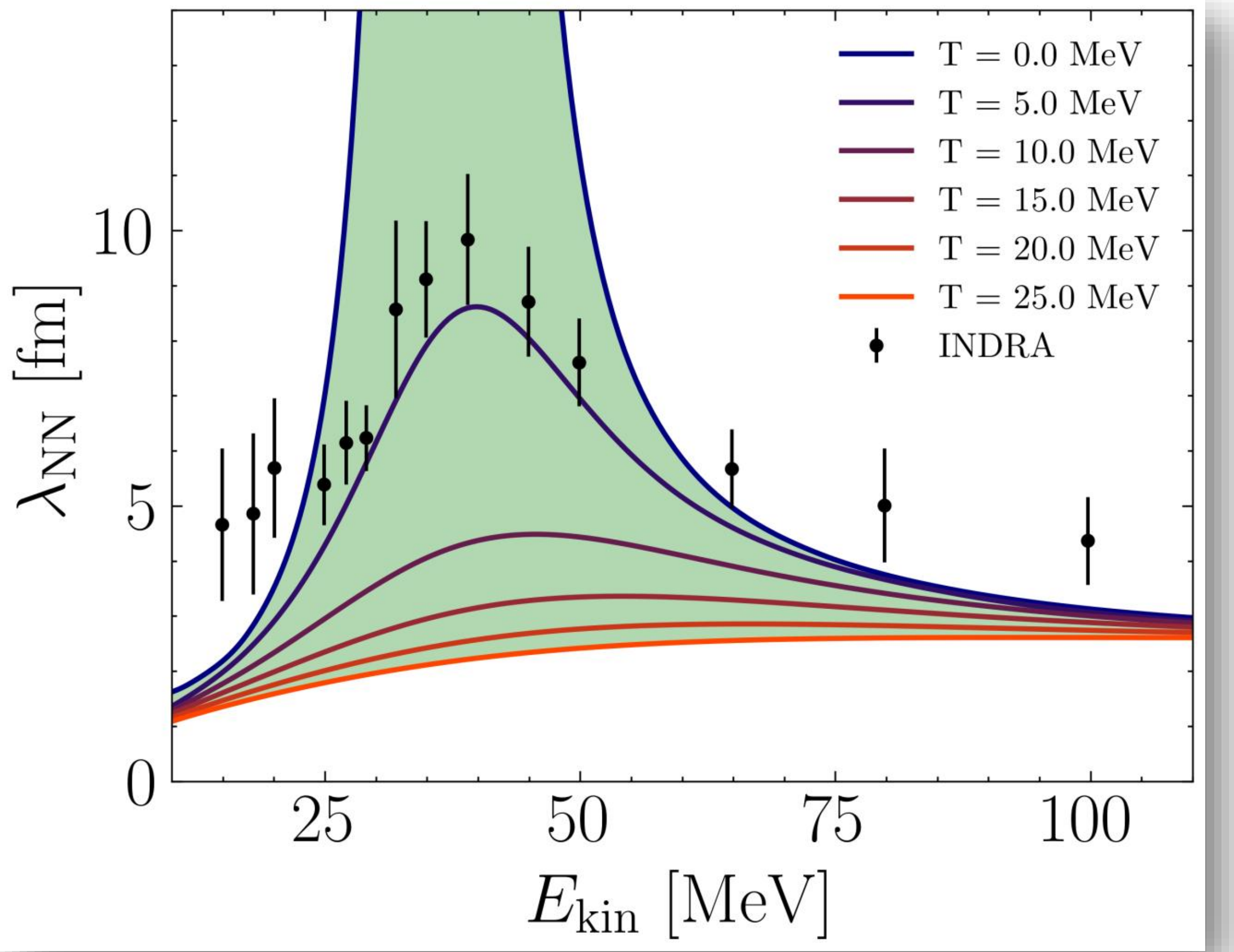


DF, J. W. Holt, in preparation (2026)

Nucleon Self-Energy: Benchmarks

Nucleon Mean-Free-Path

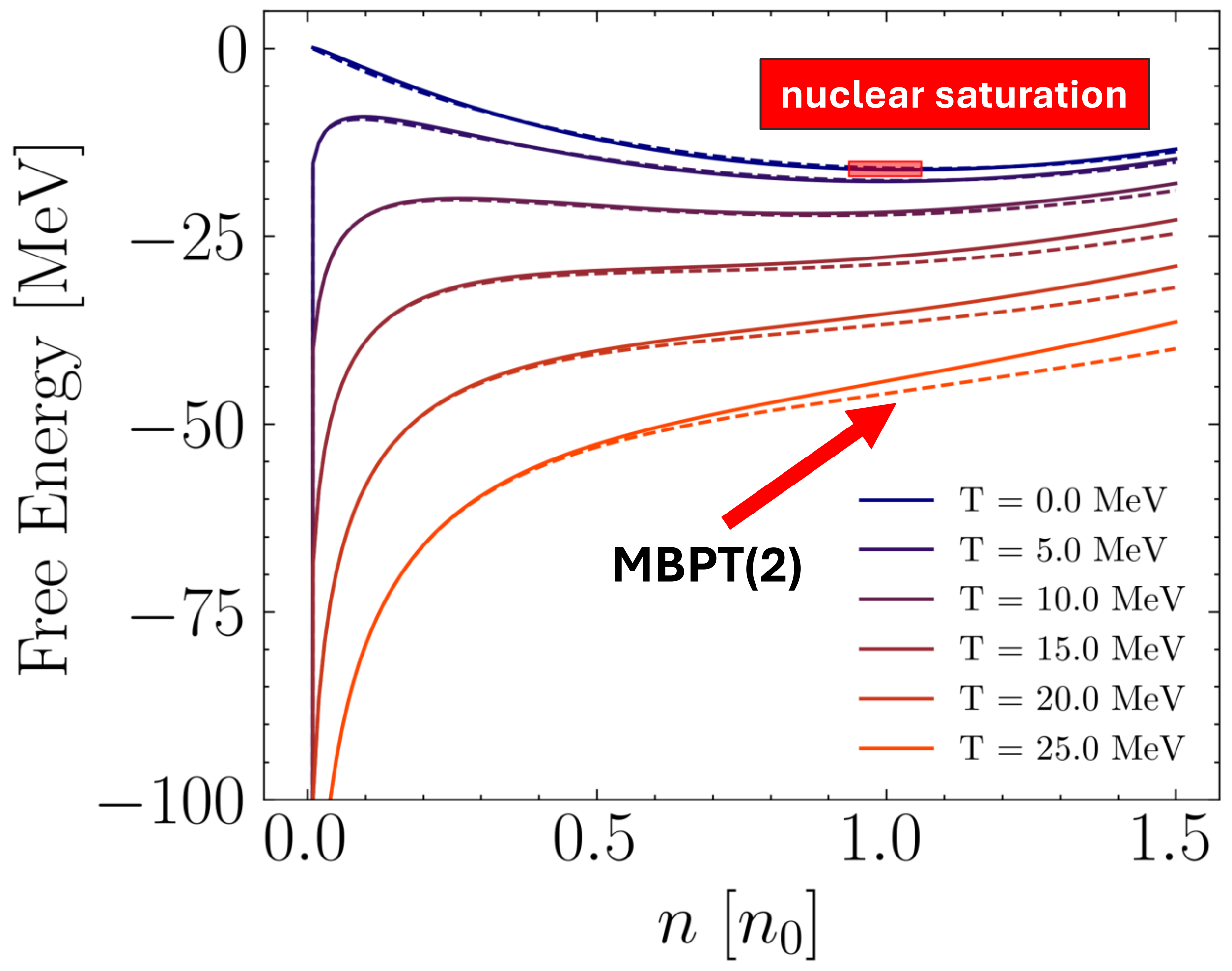
$$\lambda_{\mathrm{NN}} = v_F / W$$



INDRA Collaboration, Lopez, Durand, Lehaut, EPJ (2015)

Nuclear Matter EOS

$$x_n \, \mu_n + x_p \, \mu_p = \frac{\partial F}{\partial n_B}$$

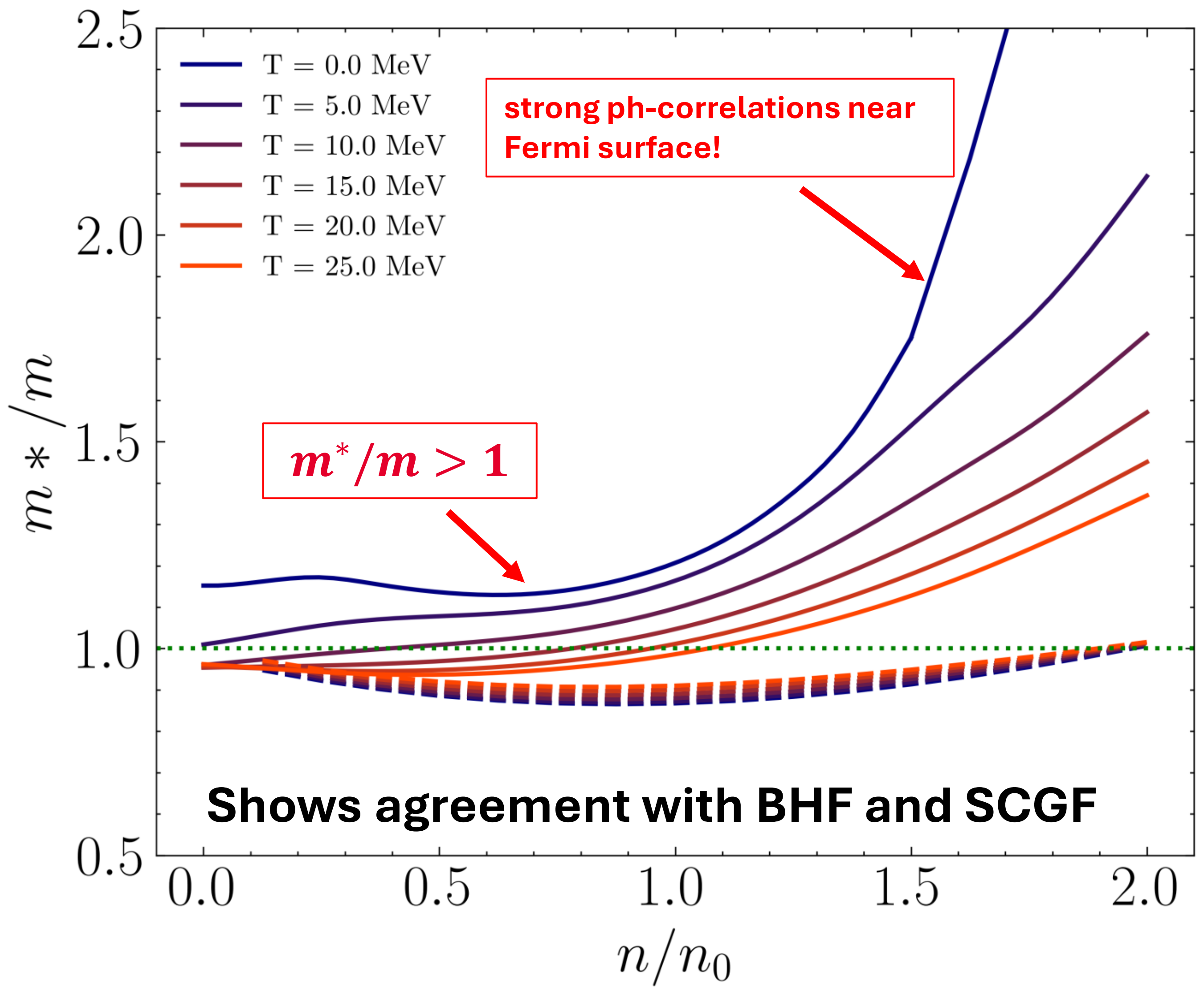


nuclear saturation

MBPT(2)

DF, J. W. Holt, in preparation (2026)

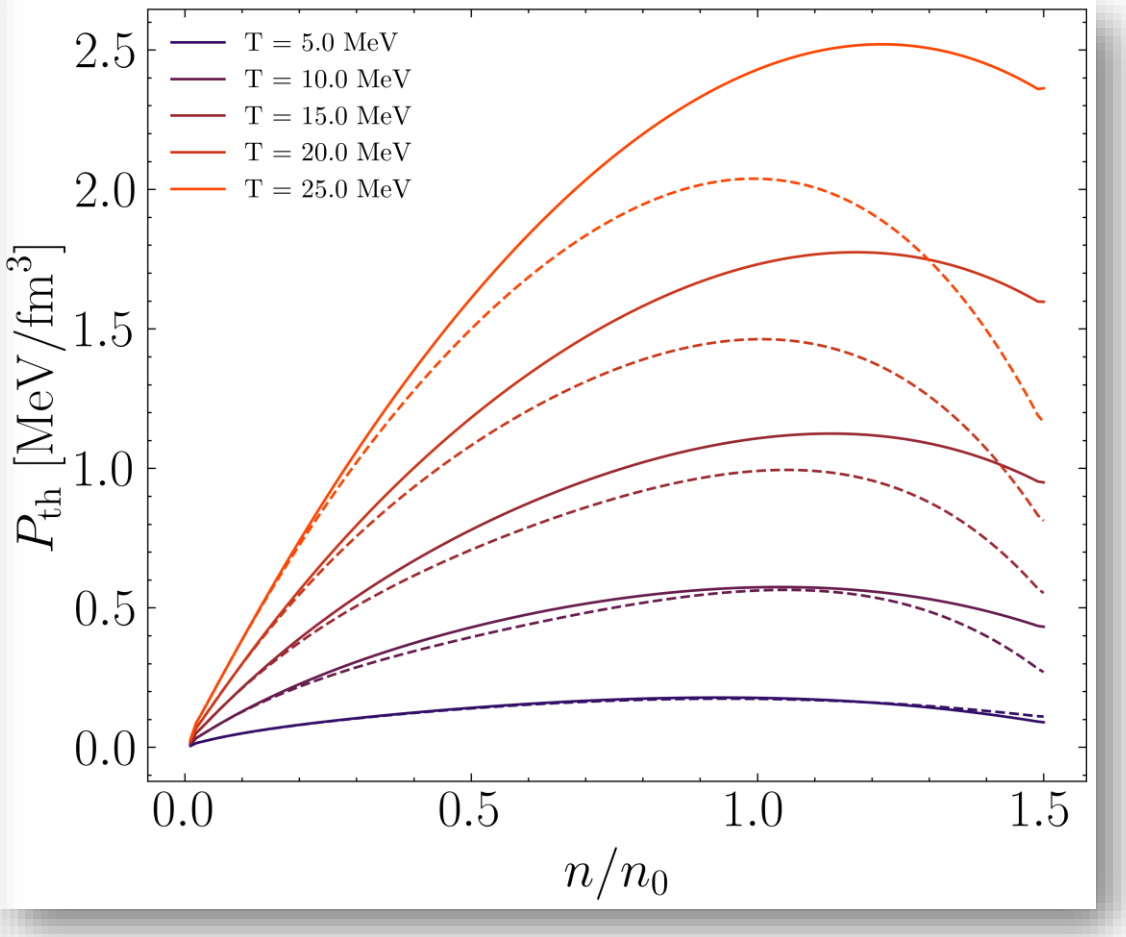
Nucleon Effective Mass



strong ph-correlations near Fermi surface!

$m^*/m > 1$

Shows agreement with BHF and SCGF

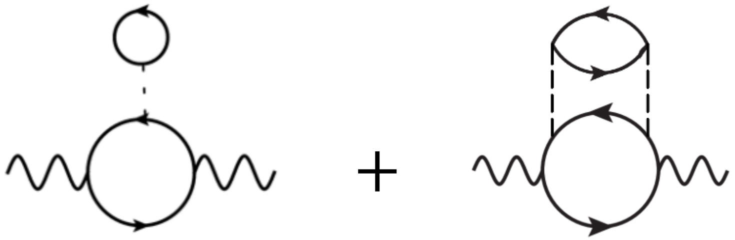


Increased thermal pressure

DF, J. W. Holt, in preparation (2026)

Neutrino Absorption: Beyond Mean Field

- Further shift in quasiparticle energy
- Stronger correlations – *two-body currents*
- **Collisional broadening**: reduced Pauli blocking

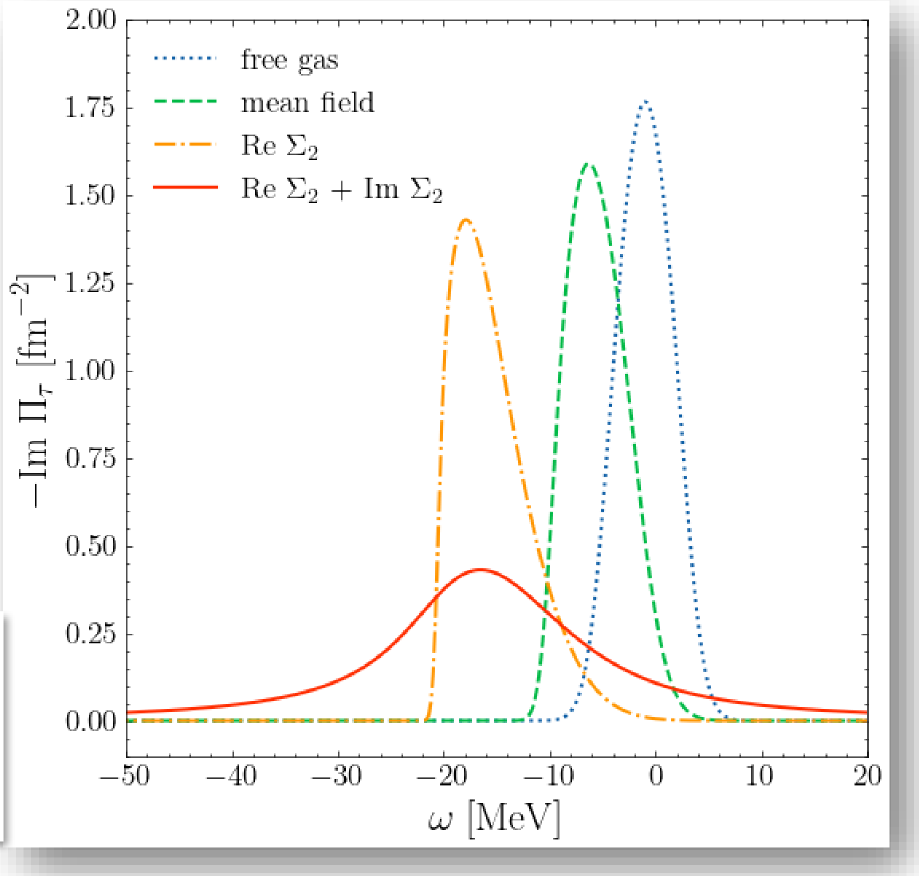


$$S_{\mathrm{F}}(q_0, q) = \frac{1}{2\pi^2} \int d^3 p_2 \boxed{\delta(q_0 + E_2 - E_4)} f_2(1 - f_4),$$

$$L(\Gamma) = \frac{1}{\pi} \frac{\Gamma}{(\tilde{q}_0 - \Delta\epsilon_{p+q})^2 + \Gamma^2},$$

Roberts, Reddy, Shen, PRC (2012)

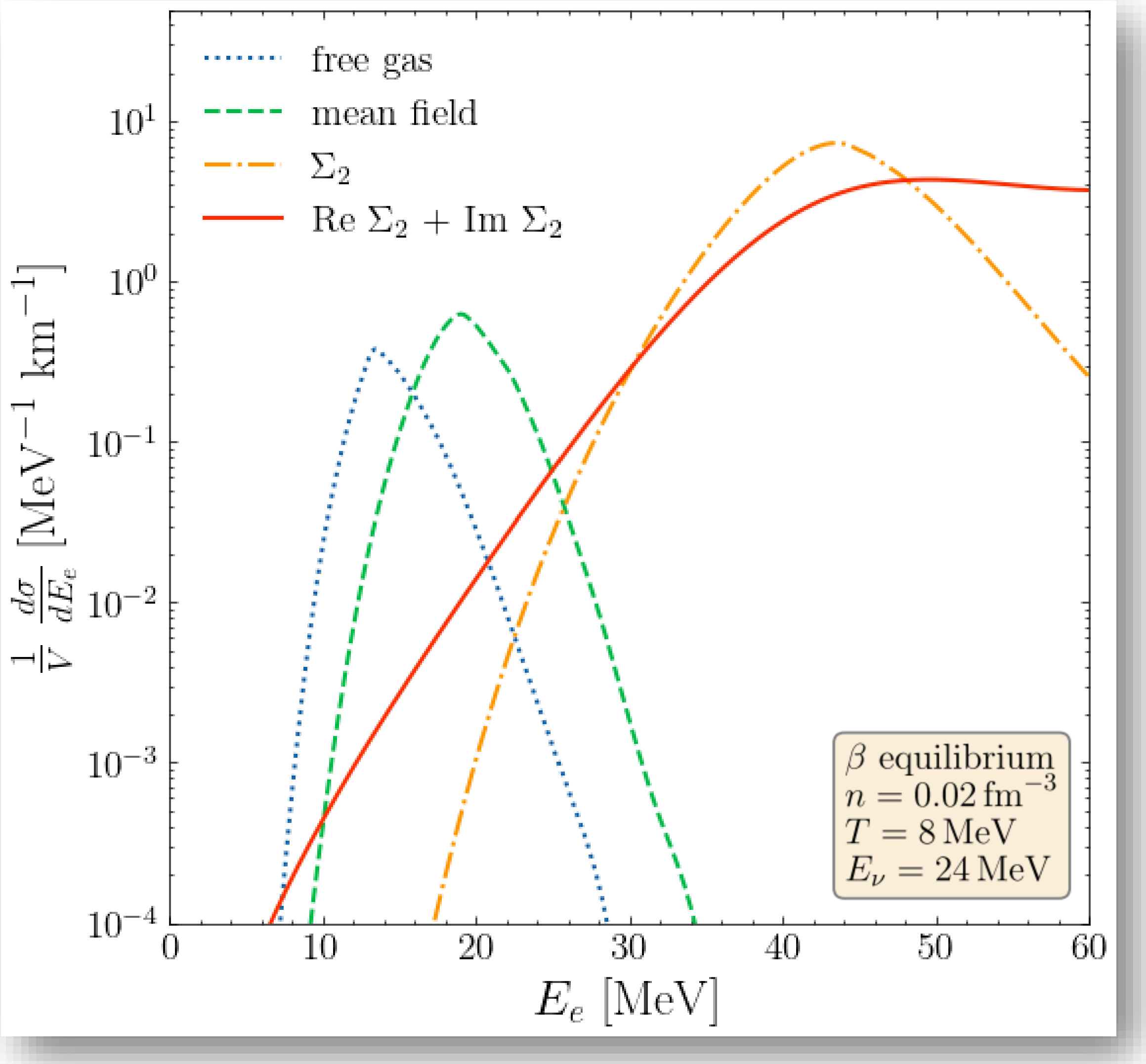
Nucleon width



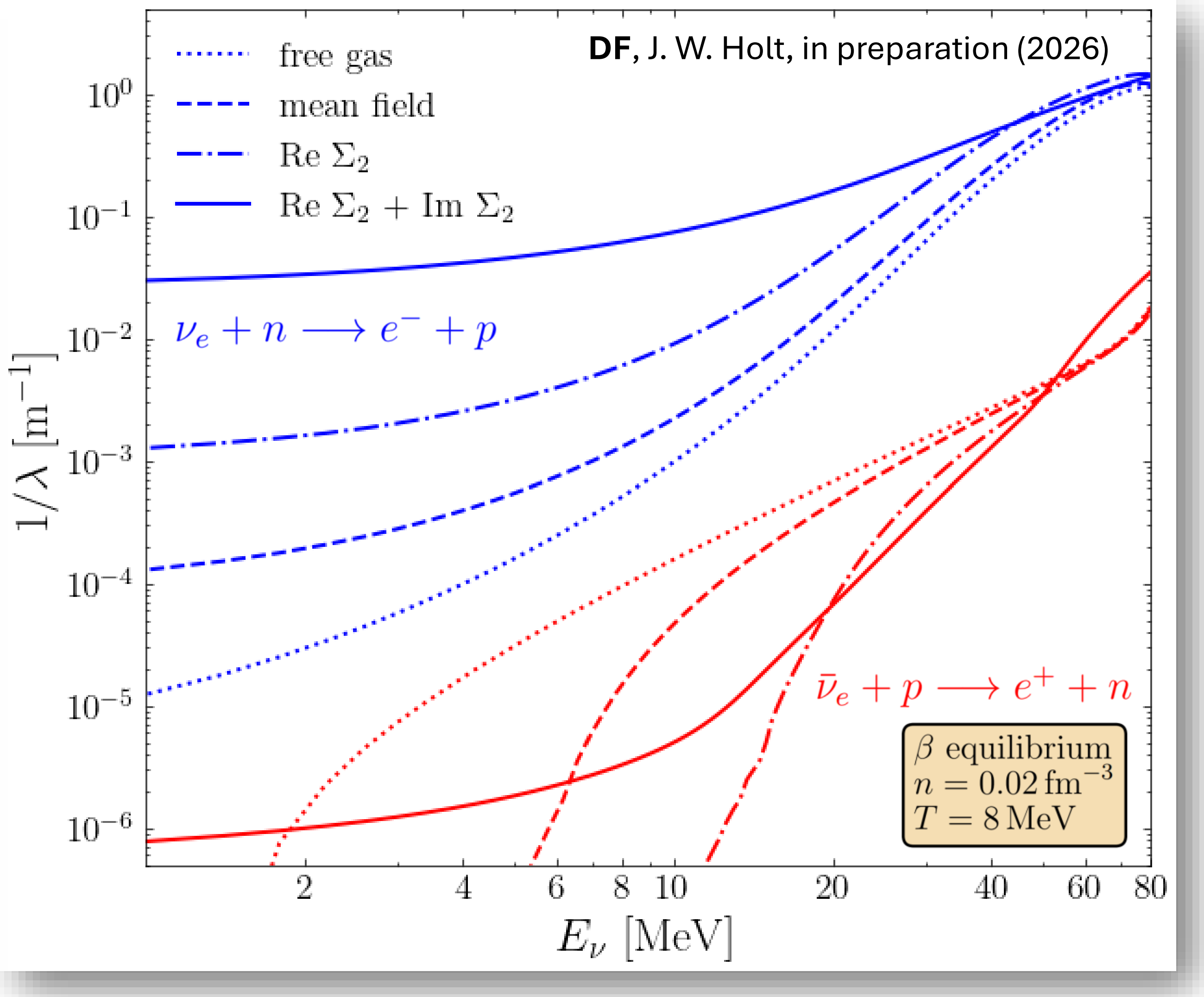
β equilibrium
$n = 0.02\mathrm{fm}^{-3}$
$T = 8\,\mathrm{MeV}$
$q = 24\,\mathrm{MeV}$

Neutrino Opacities: Beyond Mean Field

Absorption cross section



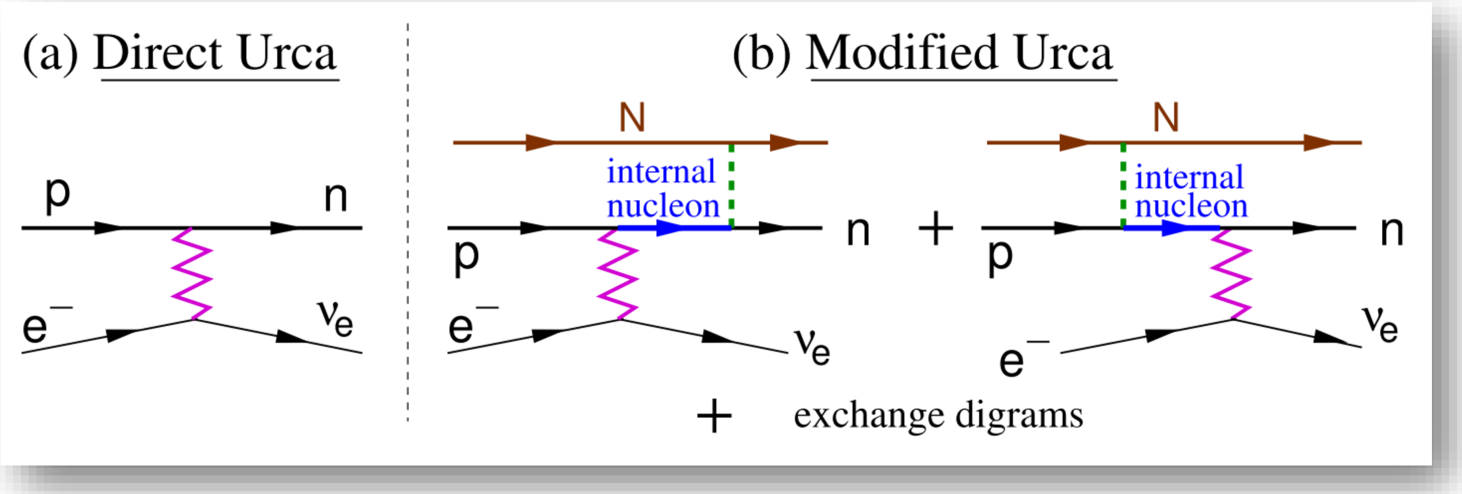
Neutrino opacity



Future Outlook: Urca Cooling

Relevant for:

- *Beta Equilibrium* – relaxation of proton fraction
- *Bulk viscosity* – damping density oscillations in NS mergers



Alford et al, PRC (2024)

Direct Urca:

- Strongly degenerate matter: dominated by Fermi surface
- Momentum conservation on Fermi surface: *heavily suppressed at low densities*

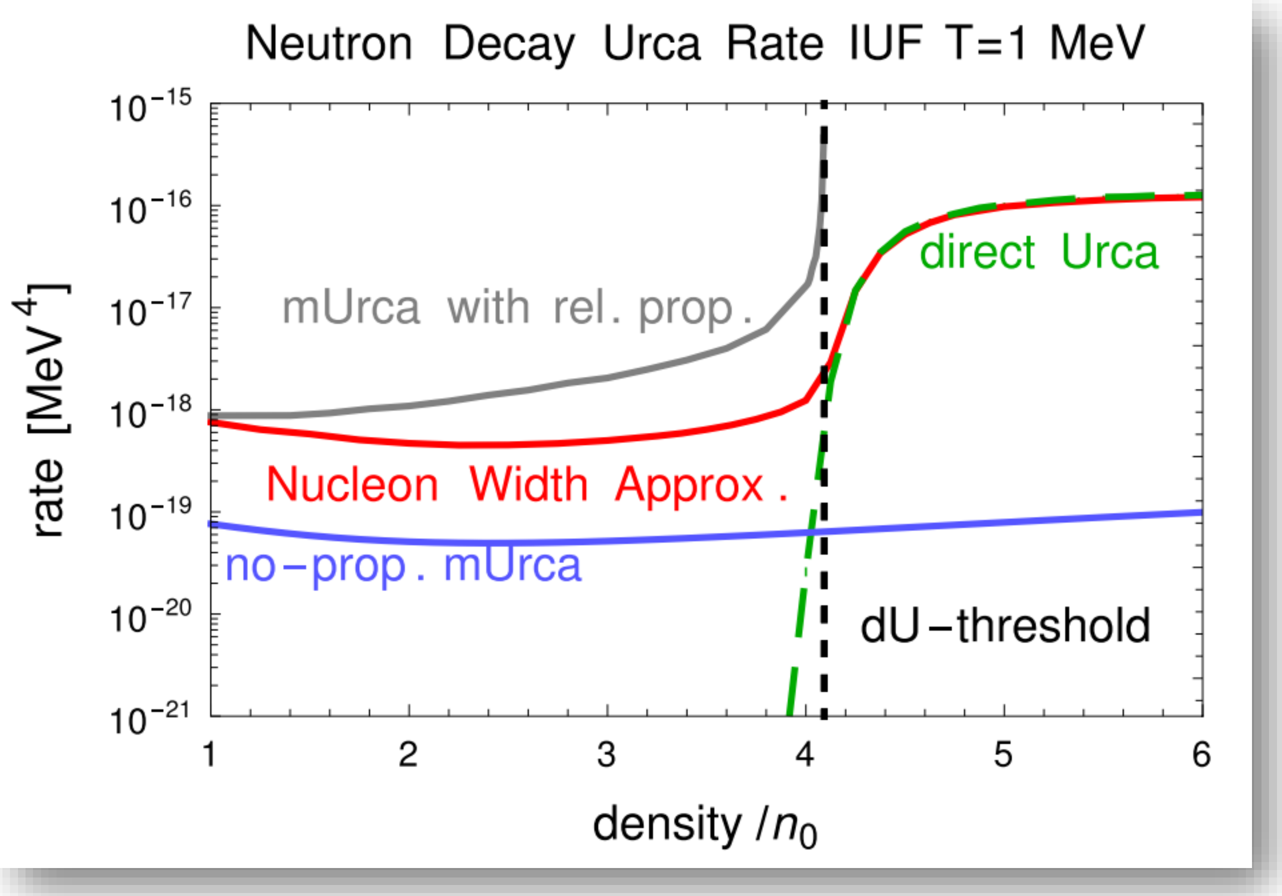
Modified Urca:

- Spectator nucleon extends kinematics at Fermi surface
- Typically approximated with constant mean-field effects (*no propagator*) or unrealistic NN interactions (F&M)

Future Outlook: Nucleon Width Approximation

$$\Gamma^{\text{NWA}} = \int_{-\infty}^{\infty} dm_{\text{n}} dm_{\text{p}} \Gamma^{\text{dUrca}}(m_{\text{n}}, m_{\text{p}}) \boxed{R_{\text{n}}(m_{\text{n}}) R_{\text{p}}(m_{\text{p}})} \,.$$

$$\xrightarrow{\quad} \quad R_a(m) \equiv \frac{1}{\pi} \frac{W_a/2}{(m - M_a^*)^2 + W_a^2/4} \,.$$

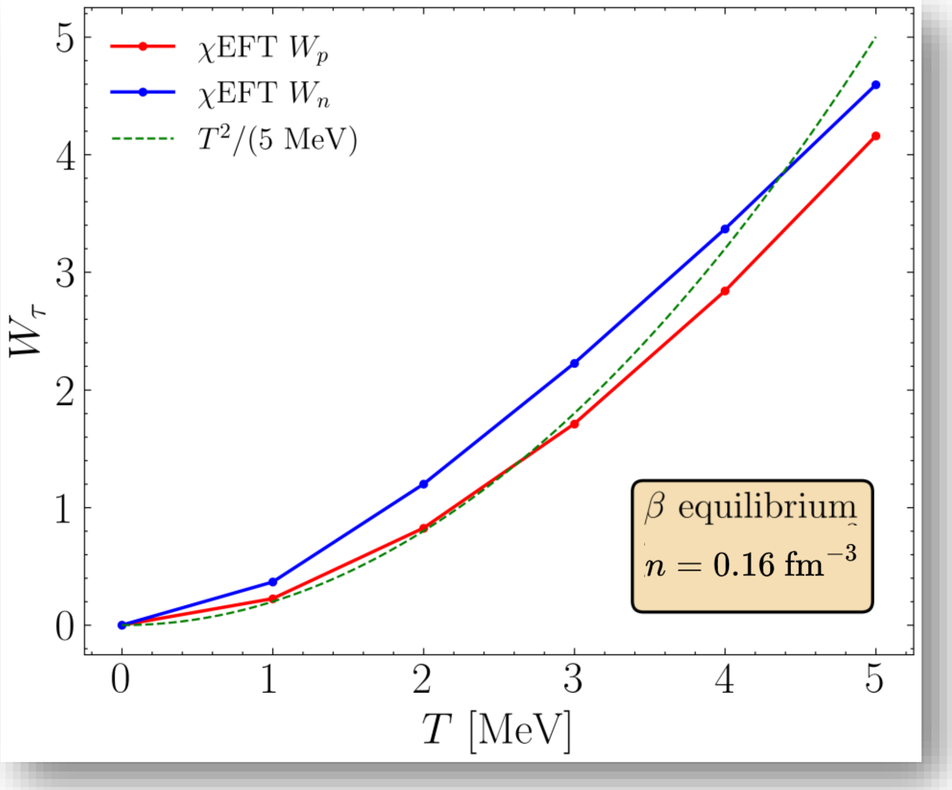


- Agreement above and below dUrca threshold
- Generalizes to higher temperatures, nonzero magnetic field, etc.
- Phenomenological width: $\Gamma_{n,p} = T^2/T_0$

Future Outlook: Nucleon Width Approximation

In progress: Use widths from Chiral EFT + MBPT2

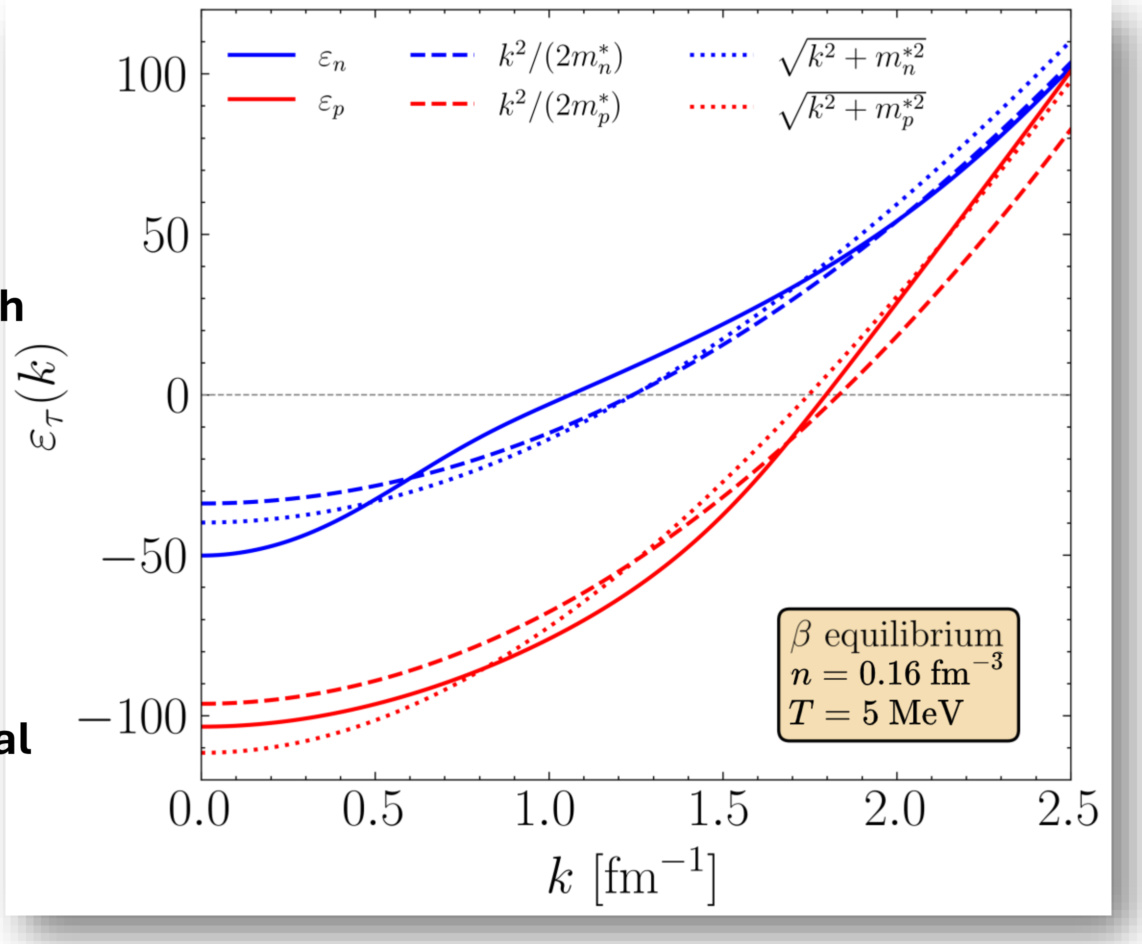
$$G_a^{\mathrm{NWA}}(k) = \frac{1}{(k_0 - U_a)\gamma^0 + k_i\gamma^i + M_a^* + iW_a/2} \,.$$



Consistent effective mass and nucleon width

Corrections to phenomenological approach

Relativistic vs. non-relativistic single-particle spectrum



Conclusions

- Effective mass of nucleons dominates thermal effects in Equation of State
- **Beyond mean field:** Larger effective masses due to correlations & 3NF ($m^*/m > 1$)!
- Charged-current reactions dominate neutrino absorption rates/opacities
- **Beyond mean field:** Wider energy shift and collisional broadening lead to larger difference in neutrino-antineutrino rates/opacities, implications for r-process in core-collapse supernovae

- **Future Outlook:** Urca cooling, flavor relaxation, uncertainty quantification, supernova simulations

Thank You!

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