Microscopic optical potentials in neutron-rich matter from chiral EFT

Jeremy Holt

1967 - 2017
50 YEARS OF BEAM
exploring the nuclear frontier
CYCLOTRON INSTITUTE
TEXAS A&M UNIVERSITY

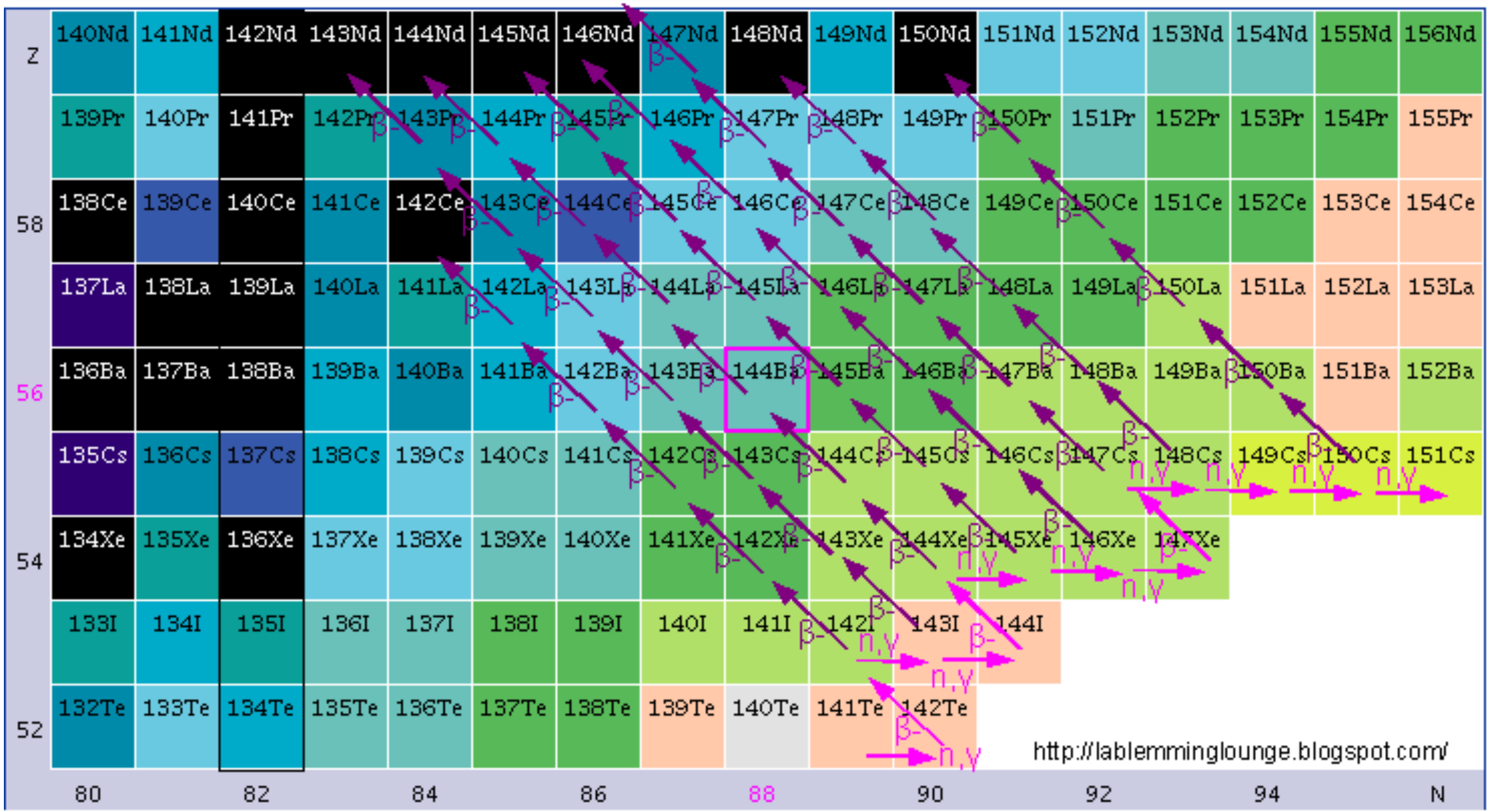
Toward predictive theories of nuclear reactions across the isotopic chart, March 10, 2017

MOTIVATION AND OUTLINE

- **R-process nucleosynthesis**
  - Neutron-capture rates in cold r-process environments
  - *Global optical potentials* from infinite matter calculations (update JLM)
  - Charged-current reactions in the supernova neutrinosphere

- **Transport model simulations of heavy-ion collisions**
  - Needed to extract equation of state at high density
  - FRIB experimental program

R-PROCESS NUCLEOSYNTHESIS

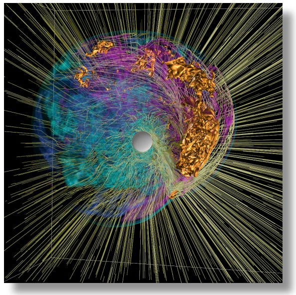


Z	140Nd	141Nd	142Nd	143Nd	144Nd	145Nd	146Nd	147Nd	148Nd	149Nd	150Nd	151Nd	152Nd	153Nd	154Nd	155Nd	156Nd
	139Pr	140Pr	141Pr	142Pr	143Pr	144Pr	145Pr	146Pr	147Pr	148Pr	149Pr	150Pr	151Pr	152Pr	153Pr	154Pr	155Pr
58	138Ce	139Ce	140Ce	141Ce	142Ce	143Ce	144Ce	145Ce	146Ce	147Ce	148Ce	149Ce	150Ce	151Ce	152Ce	153Ce	154Ce
	137La	138La	139La	140La	141La	142La	143La	144La	145La	146La	147La	148La	149La	150La	151La	152La	153La
56	136Ba	137Ba	138Ba	139Ba	140Ba	141Ba	142Ba	143Ba	144Ba	145Ba	146Ba	147Ba	148Ba	149Ba	150Ba	151Ba	152Ba
	135Cs	136Cs	137Cs	138Cs	139Cs	140Cs	141Cs	142Cs	143Cs	144Cs	145Cs	146Cs	147Cs	148Cs	149Cs	150Cs	151Cs
54	134Xe	135Xe	136Xe	137Xe	138Xe	139Xe	140Xe	141Xe	142Xe	143Xe	144Xe	145Xe	146Xe	147Xe			
	133I	134I	135I	136I	137I	138I	139I	140I	141I	142I	143I	144I					
52	132Te	133Te	134Te	135Te	136Te	137Te	138Te	139Te	140Te	141Te	142Te						
	80		82		84		86		88		90		92		94		N

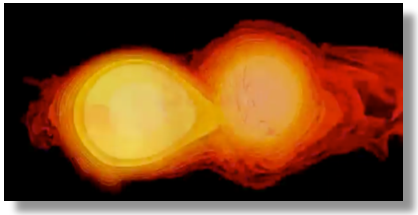
http://lablemminglounge.blogspot.com/

Astrophysical site?

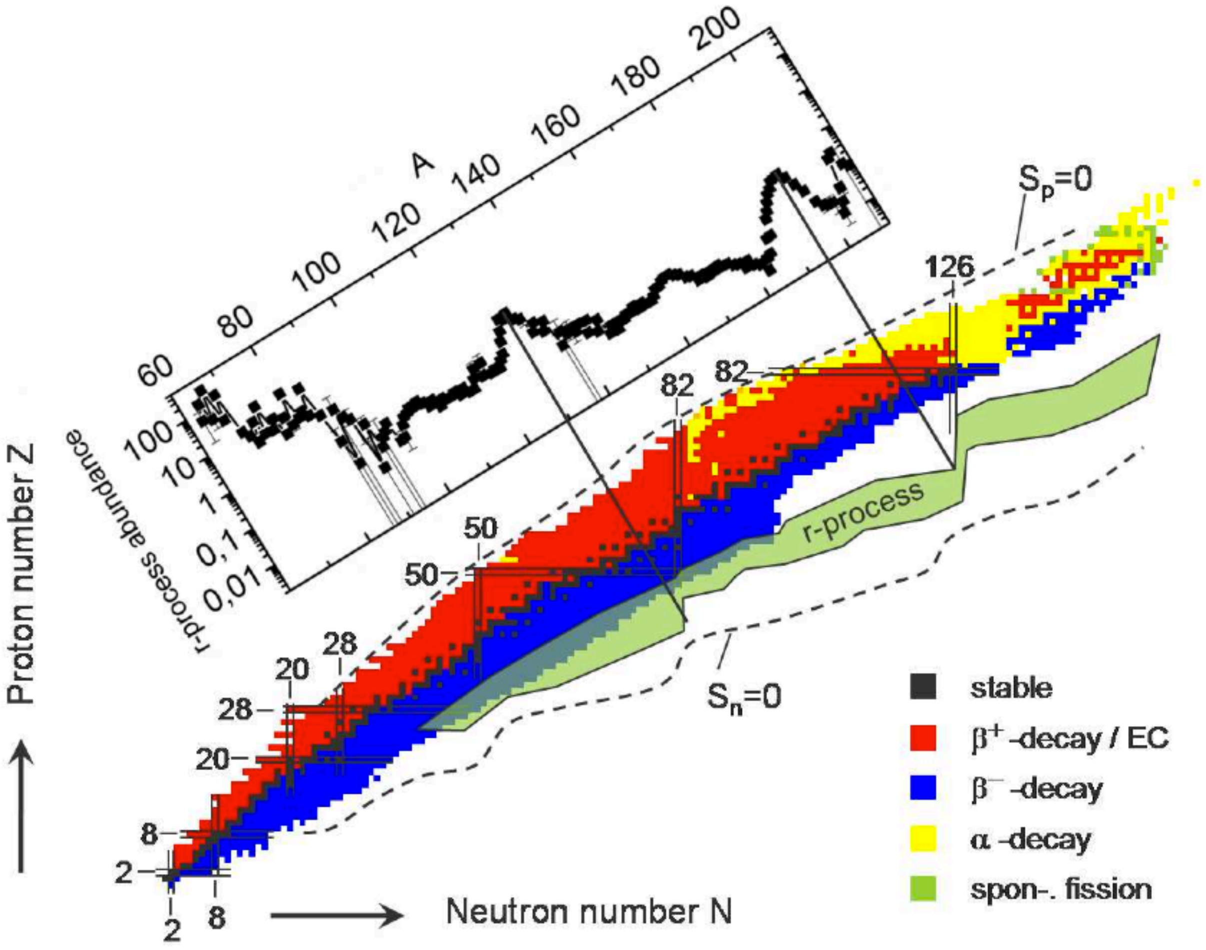
Core-collapse supernovae



Neutron-star mergers



R-PROCESS NUCLEOSYNTHESIS



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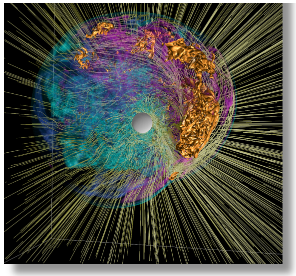
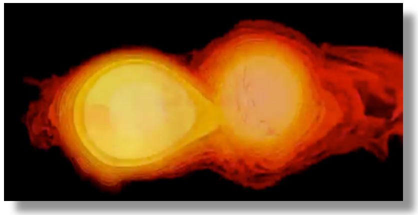


Neutron-star mergers



NUCLEAR PHYSICS INPUTS

Masses of neutron-rich nuclei

- Determine elemental abundance patterns along isotopic chains during equilibrium

$$\frac{Y(Z, A+1)}{Y(Z, A)} \sim \exp\left[\frac{S_n(Z, A+1) - S_n^0(T, \rho_n)}{kT}\right]$$

Beta-decay lifetimes

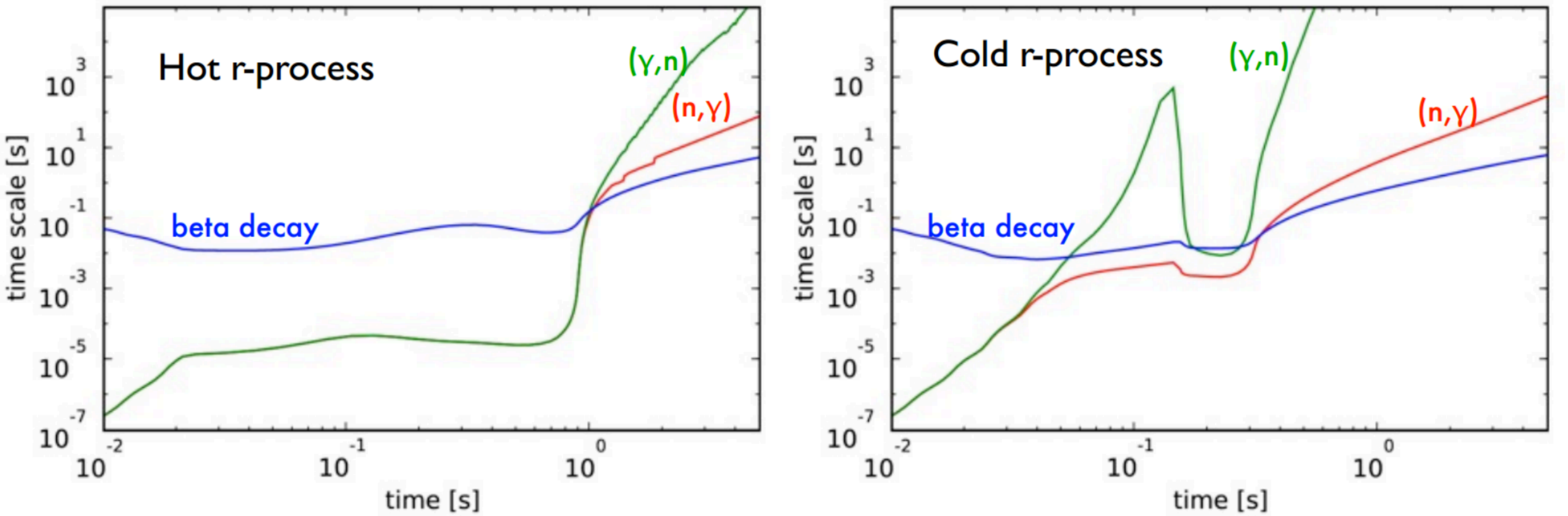
- Set timescale for formation of heavy elements from seed nuclei
- Partly responsible for peaks at A = 130 and A = 195

Neutron-capture rates

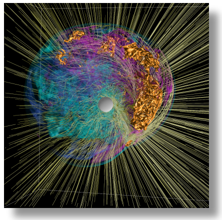
- Relevant during **late-time freeze-out phase** of the r-process
- Sensitivity studies vary capture rates over **orders of magnitude**

“HOT” VS. “COLD” R-PROCESS SCENARIOS

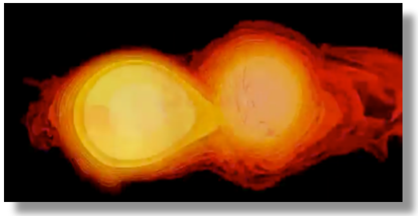
Arcones and Martinez-Pinedo, PRC (2011)



- **Hot r-process (T ~ 1 GK):** radiative neutron capture and photodissociation in equilibrium



- **Cold r-process (T ~ 0.5 GK):** radiative neutron capture and photodissociation out of equilibrium

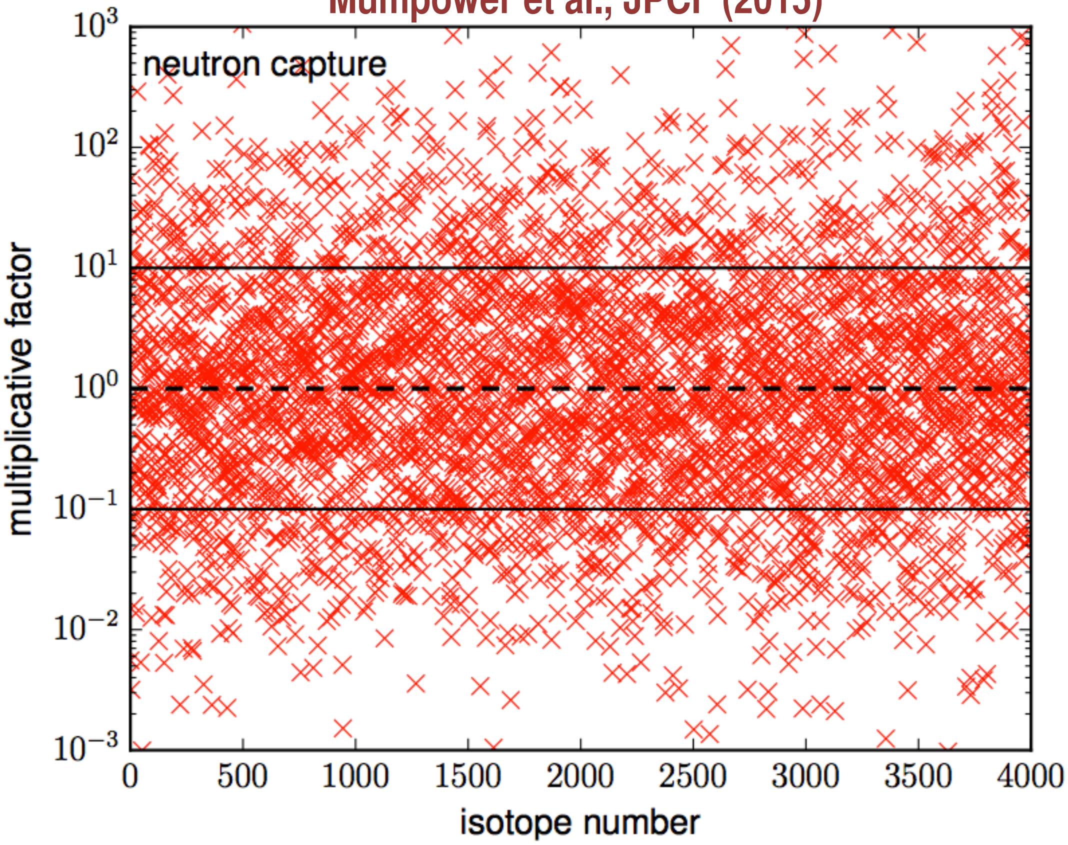


NEUTRON CAPTURE SENSITIVITY STUDIES

Uncertainties coming from:

- Nuclear level densities for Hauser-Feshbach
- γ strength functions
- **Neutron-nucleus optical potentials**

Mumpower et al., JPCF (2015)



GLOBAL OPTICAL POTENTIALS

$$\boxed{\begin{aligned}\mathcal{U}(r,E) = {} & -\mathcal{V}_V(r,E) - i\mathcal{W}_V(r,E) - i\mathcal{W}_D(r,E) \\ & + \mathcal{V}_{SO}(r,E).\mathbf{l}.\sigma + i\mathcal{W}_{SO}(r,E).\mathbf{l}.\sigma + \mathcal{V}_C(r).\end{aligned}}$$

$$\mathcal{V}_V(r,E) = V_V(E) f(r, R_V, a_V),$$

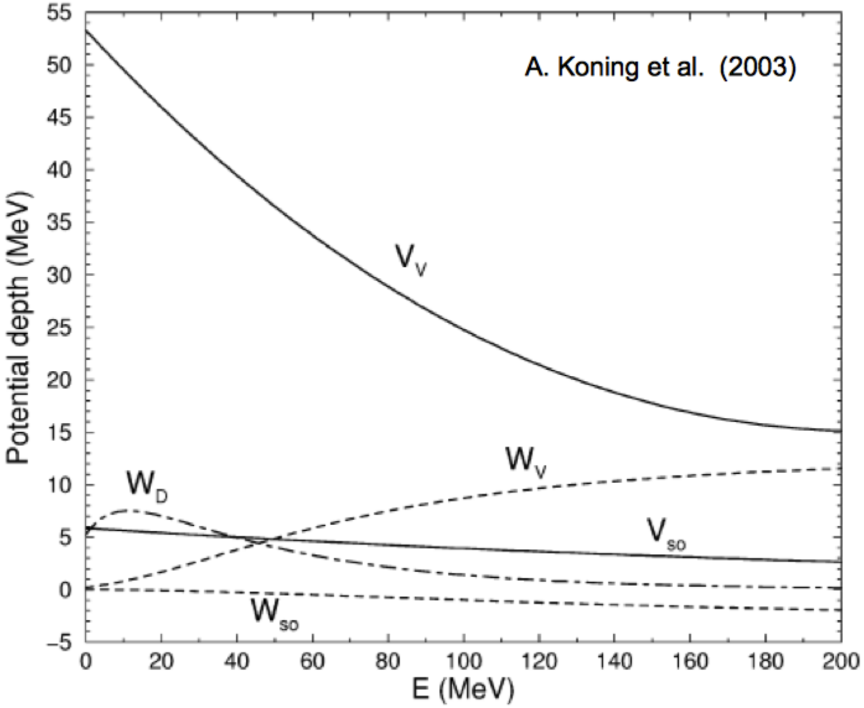
$$\mathcal{W}_V(r,E) = W_V(E) f(r, R_V, a_V),$$

$$\mathcal{W}_D(r,E) = -4a_D W_D(E) \frac{d}{dr} f(r, R_D, a_D),$$

$$\mathcal{V}_{SO}(r,E) = V_{SO}(E) \left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{r} \frac{d}{dr} f(r, R_{SO}, a_{SO}),$$

$$\mathcal{W}_{SO}(r,E) = W_{SO}(E) \left(\frac{\hbar}{m_\pi c}\right)^2 \frac{1}{r} \frac{d}{dr} f(r, R_{SO}, a_{SO}).$$

$$f(r, R_i, a_i) = \left(1 + \exp[(r - R_i)/a_i]\right)^{-1}$$



$$\left.\begin{aligned} V_V(E) &= v_1\left[1 - v_2(E - E_f) + v_3(E - E_f)^2 - v_4(E - E_f)^3\right] \\ W_V(E) &= w_1 \frac{(E - E_f)^2}{(E - E_f)^2 + (w_2)^2}, \end{aligned}\right\}$$

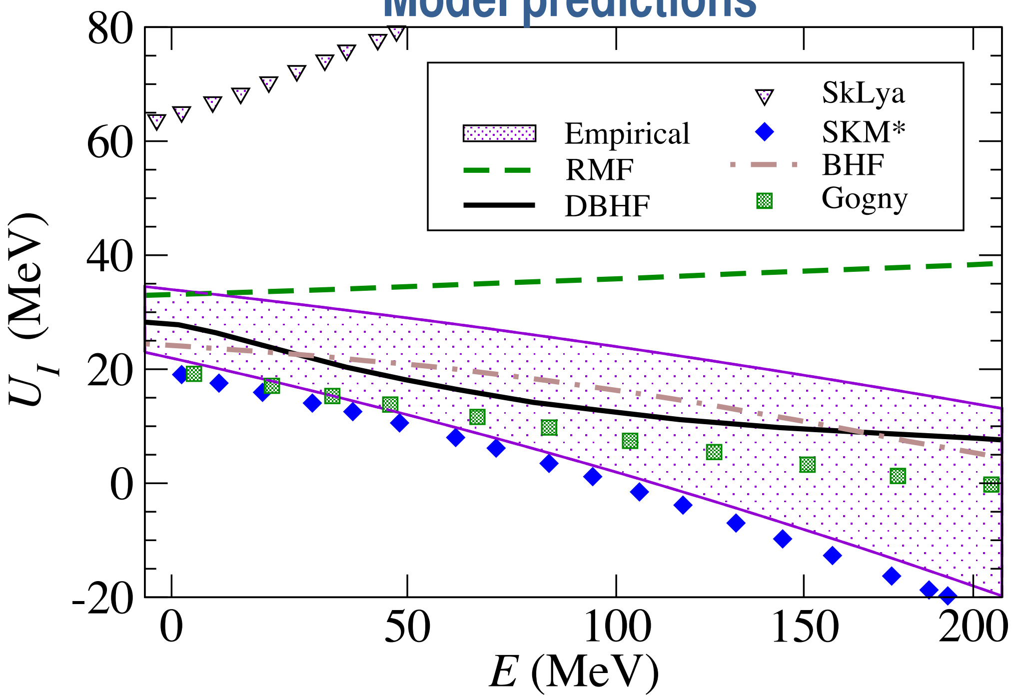
Energy dependence

ISOSPIN ASYMMETRY DEPENDENCE

- Isovector part of optical potential linear in the isospin asymmetry

$$U = U_0 - U_I \delta_{np} \tau_3 \qquad \delta_{np} = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

Model predictions

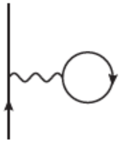


- Very little is known/predicted about **isovector imaginary part**

BULK MATTER OPTICAL POTENTIALS

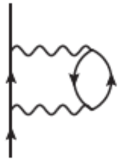
- Identified with the on-shell nucleon self-energy $\Sigma(\vec{r}_1, \vec{r}_2, \omega)$

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



$$\Sigma^{(1)}_{2N}(q;k_f) = \sum_{1} \langle \vec{q}\vec{h}_1 s s_1 t t_1 | \bar{V}_{2N} | \vec{q}\vec{h}_1 s s_1 t t_1 \rangle n_1$$

- Second-order perturbative contibutions (complex, energy-dependent):



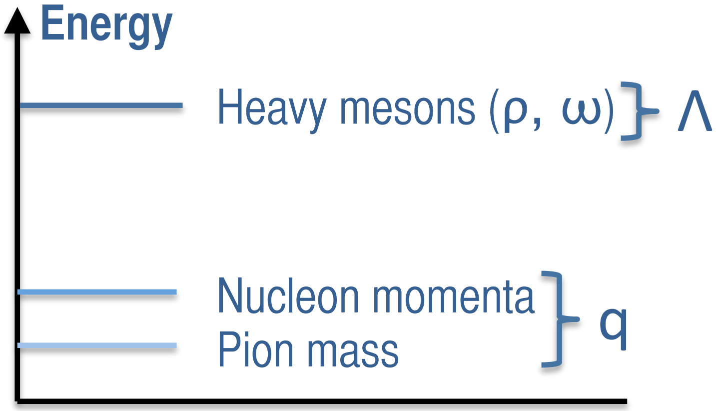
$$\Sigma^{(2a)}_{2N}(q,\omega;k_f) = \frac{1}{2}\sum_{123} \frac{|\langle \vec{p}_1\vec{p}_3 s_1 s_3 t_1 t_3 | \bar{V} | \vec{q}\vec{h}_2 s s_2 t t_2 \rangle|^2}{\omega + \epsilon_2 - \epsilon_1 - \epsilon_3 + i\eta} \bar{n}_1 n_2 \bar{n}_3 (2\pi)^3 \delta(\vec{p}_1 + \vec{p}_3 - \vec{q} - \vec{h}_2)$$

Benchmarks:

- Depth and energy dependence of phenomenological volume parts (including isospin dependence)

NUCLEAR FORCES FROM CHIRAL EFT

NATURAL SEPARATION OF SCALES



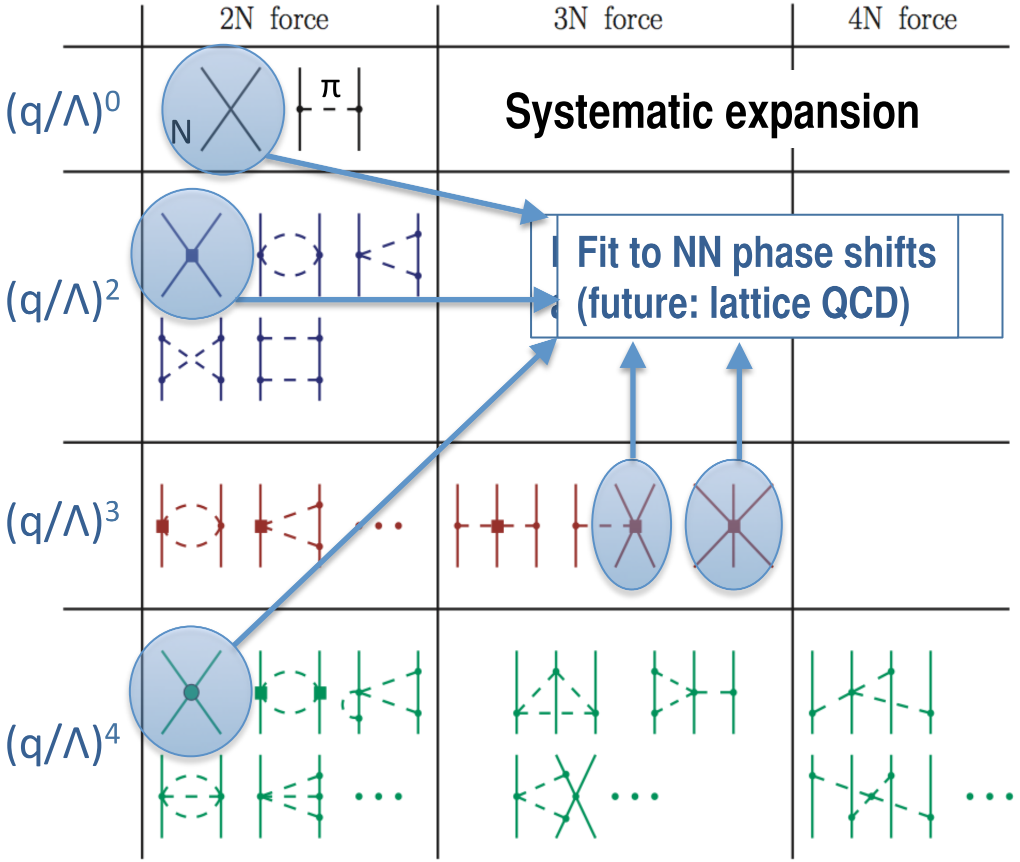
Pions weakly-coupled at low momenta

$$\mathcal{L}_{\pi\pi}^{(2)} = \frac{1}{2}\partial_\mu\vec{\pi}\cdot\partial^\mu\vec{\pi} + \frac{1}{2f_\pi^2}(\partial_\mu\vec{\pi}\cdot\vec{\pi})^2$$

$$\mathcal{L}_{\pi N}^{(1)} = \bar{N}\left(i\gamma^\mu D_\mu - m - \frac{g_A}{2f_\pi}\gamma^\mu\gamma_5\vec{\tau}\cdot\partial_\mu\vec{\pi}\right)N$$

CHIRAL EFFECTIVE FIELD THEORY

Low-energy theory of nucleons and pions



Systematic expansion

Fit to NN phase shifts (future: lattice QCD)

RESOLUTION SCALE

Regulating function

- $\langle \vec{p}\,' | V | \vec{p} \rangle \; \boxed{\exp[-(p/\Lambda)^{2n} - (p'/\Lambda)^{2n}]}$

sets resolution scale

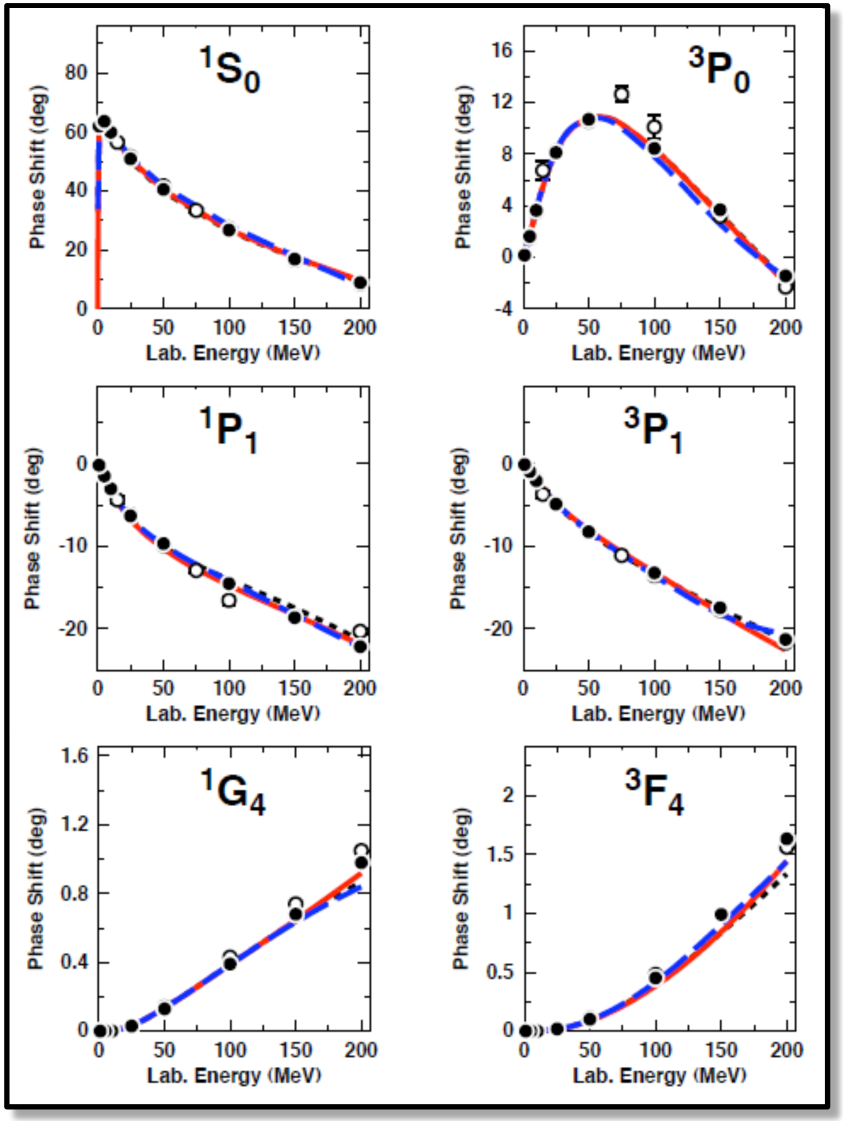
Variations in regulator

- Estimate of theoretical uncertainty

—— $\Lambda = 414\,\text{MeV}\,(\Delta x \sim 1.50\,\text{fm})$

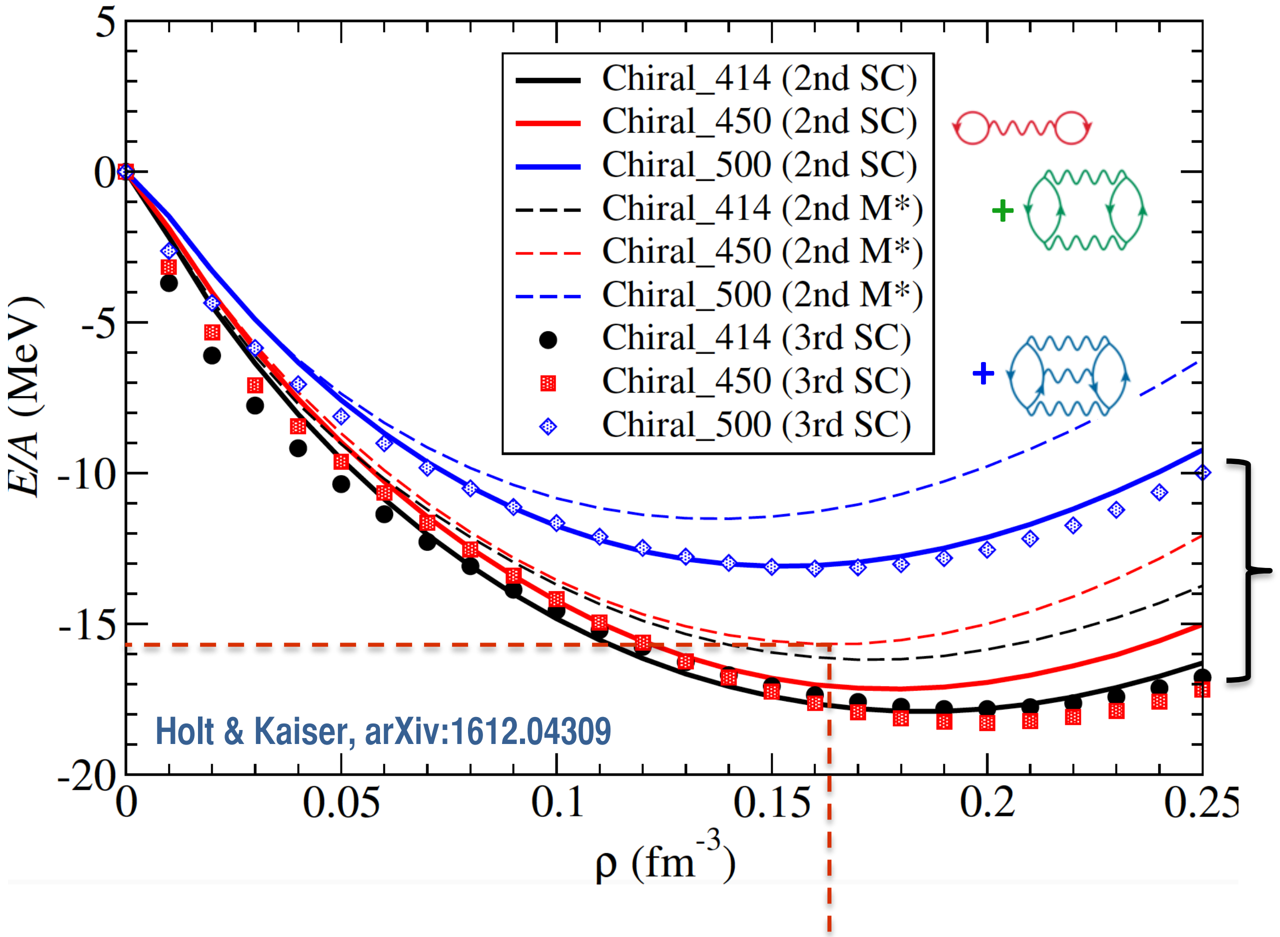
- - - $\Lambda = 450\,\text{MeV}\,(\Delta x \sim 1.38\,\text{fm})$

········ $\Lambda = 500\,\text{MeV}\,(\Delta x \sim 1.25\,\text{fm})$



Coraggio, Holt, Itaco, Sammarruca & Machleidt PRC (2013)

SYMMETRIC NUCLEAR MATTER EQUATION OF STATE

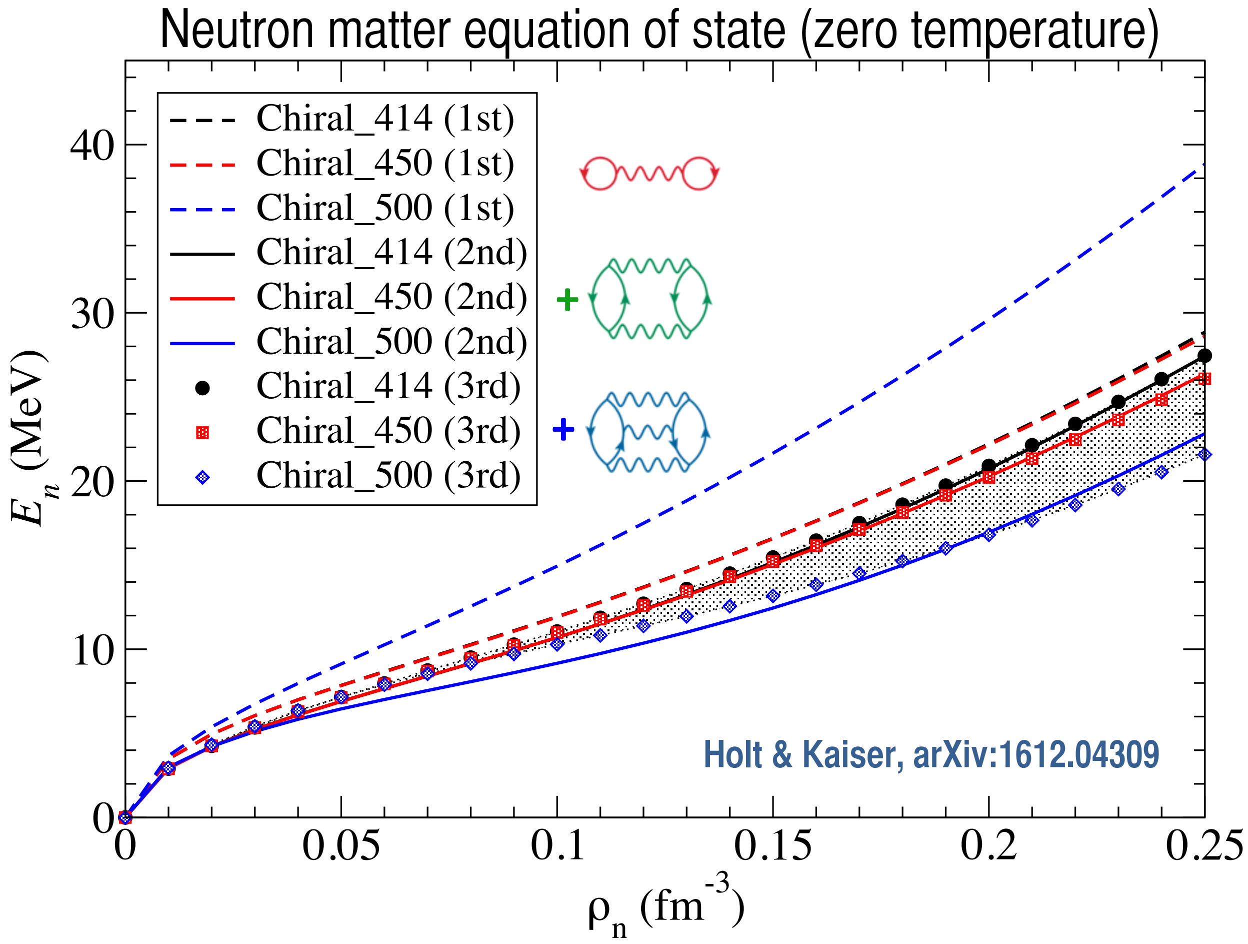


Holt & Kaiser, arXiv:1612.04309

Uncertainty grows with the density

Several approximations give good saturation properties

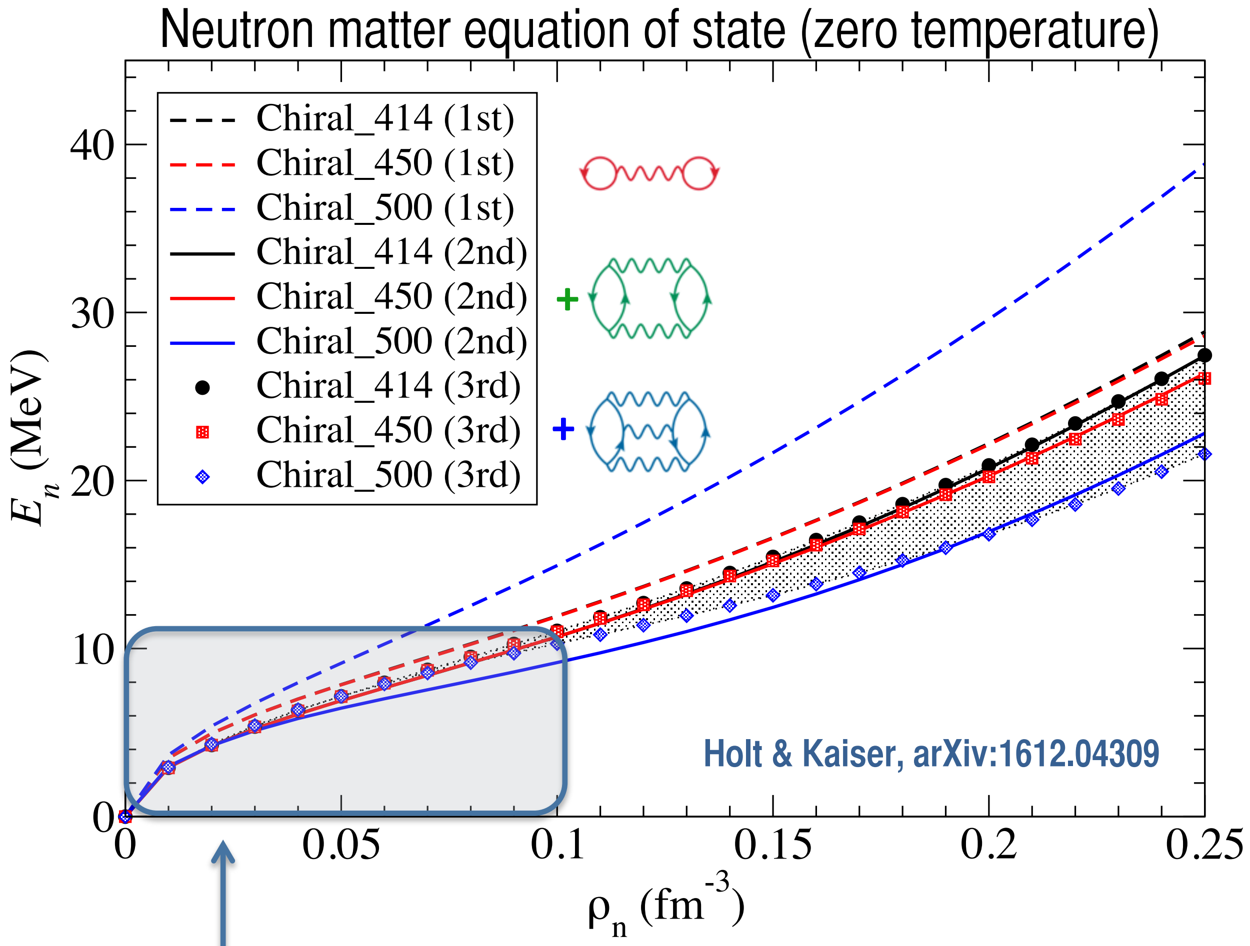
NEUTRON MATTER EQUATION OF STATE



Sources of uncertainty

- Scale dependence
- Convergence in many-body perturbation theory
- Convergence in chiral expansion

NEUTRON MATTER EQUATION OF STATE

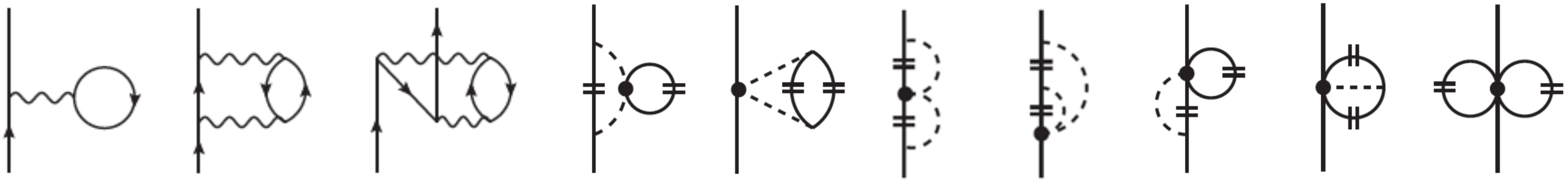


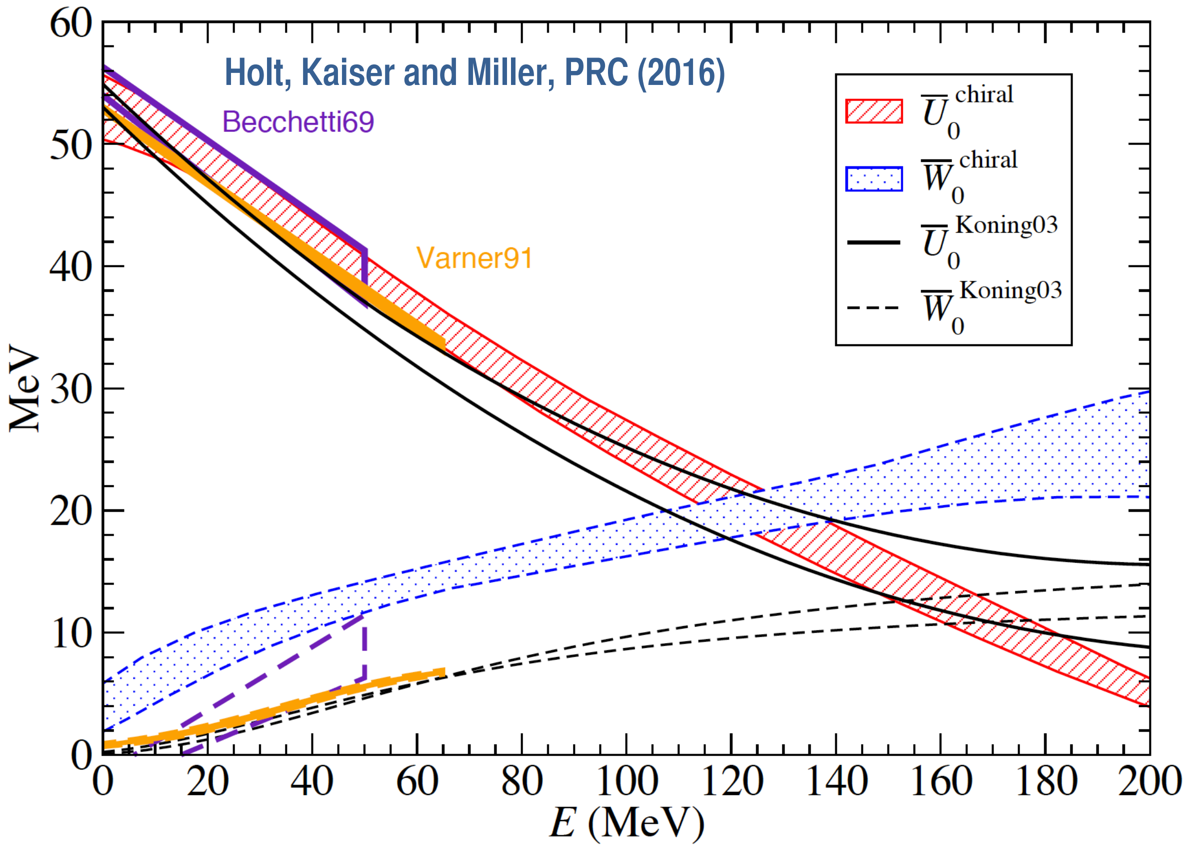
Sources of uncertainty

- Scale dependence
- Convergence in many-body perturbation theory
- Convergence in chiral expansion

Independent of resolution scale up to density 0.1 fm^{-3}

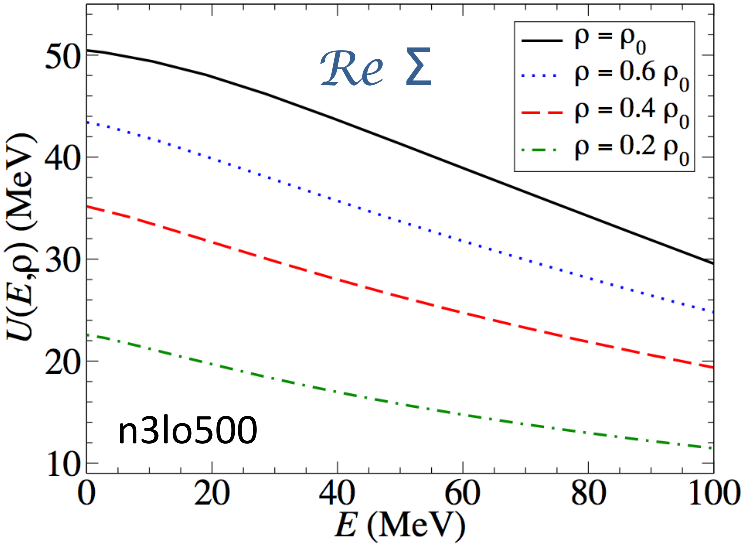
OPTICAL POTENTIAL IN SYMMETRIC MATTER

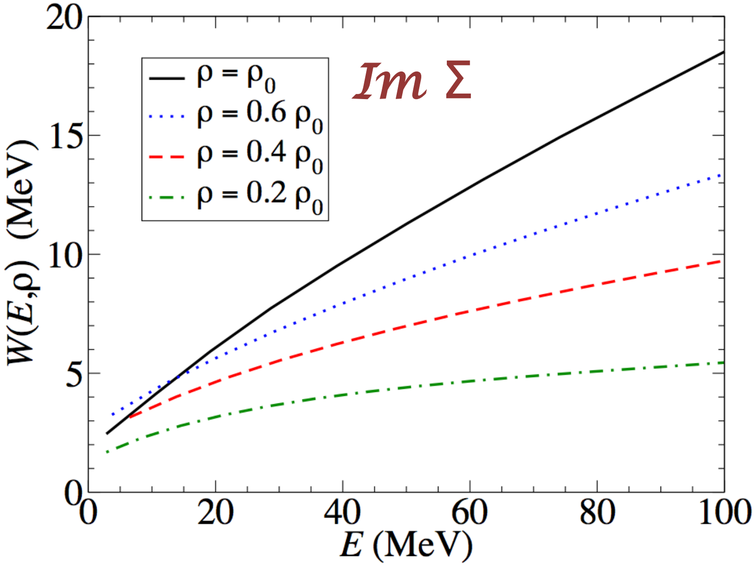




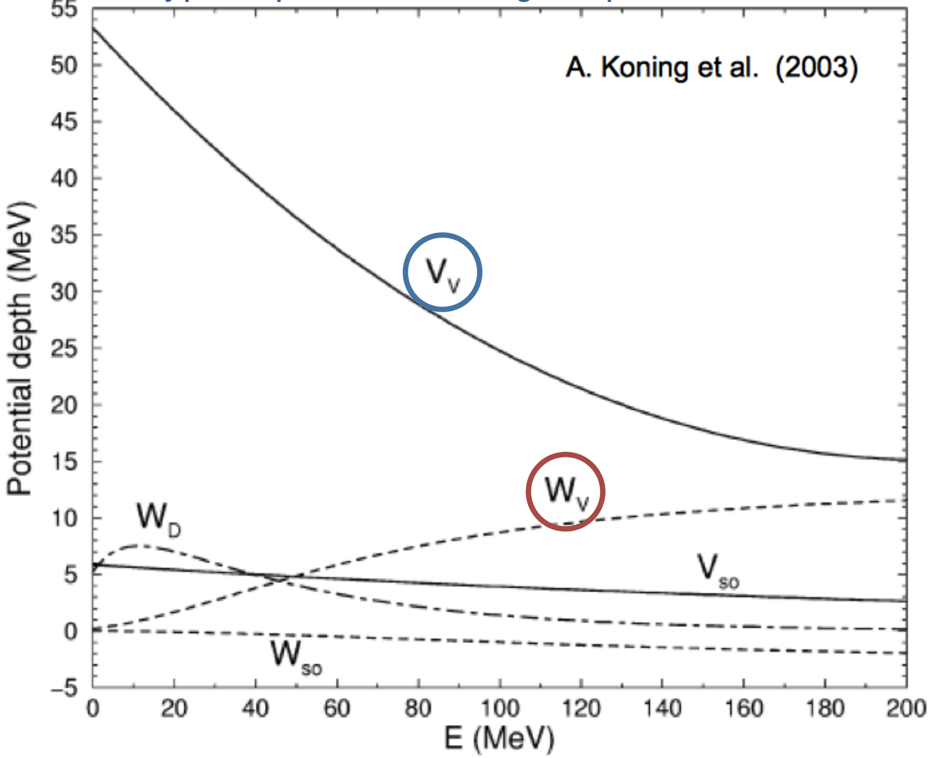
DENSITY DEPENDENCE

Holt, Kaiser, Miller & Weise, PRC (2013)





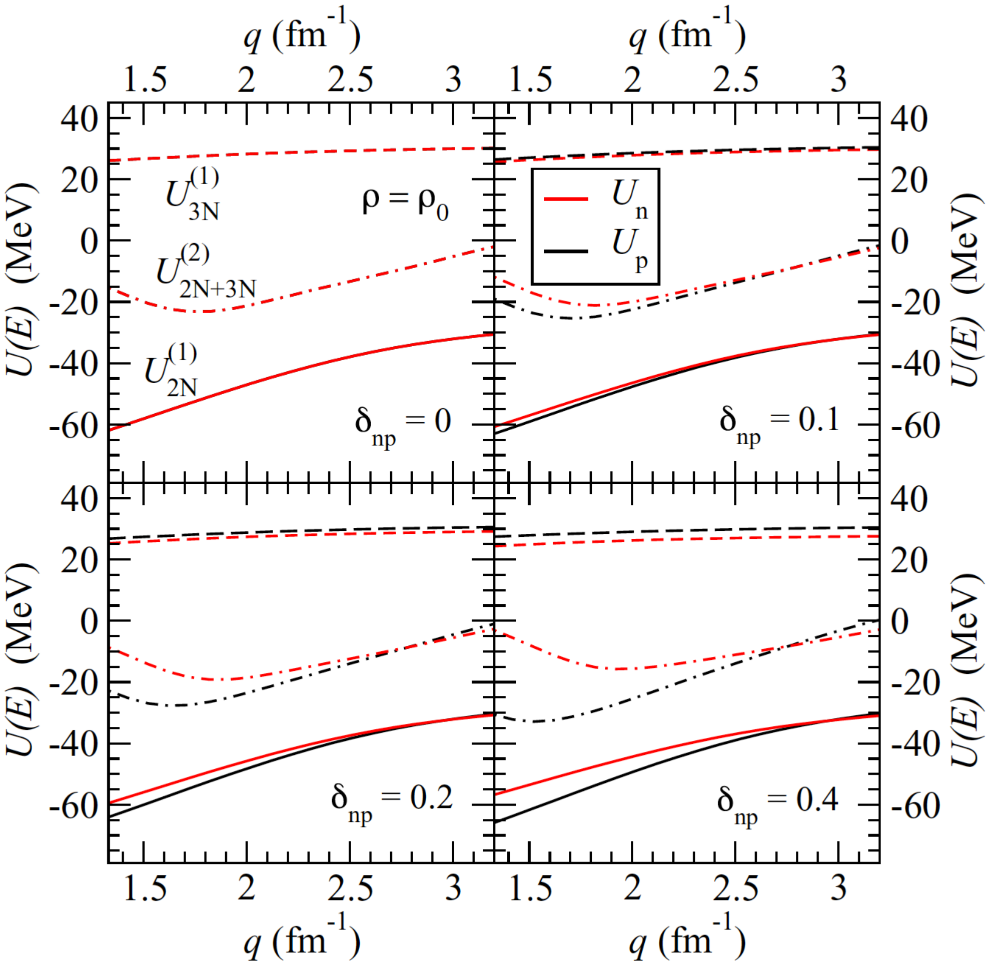
Typical phenomenological potential: ^{56}Fe



CONVERGENCE IN PETURBATION THEORY

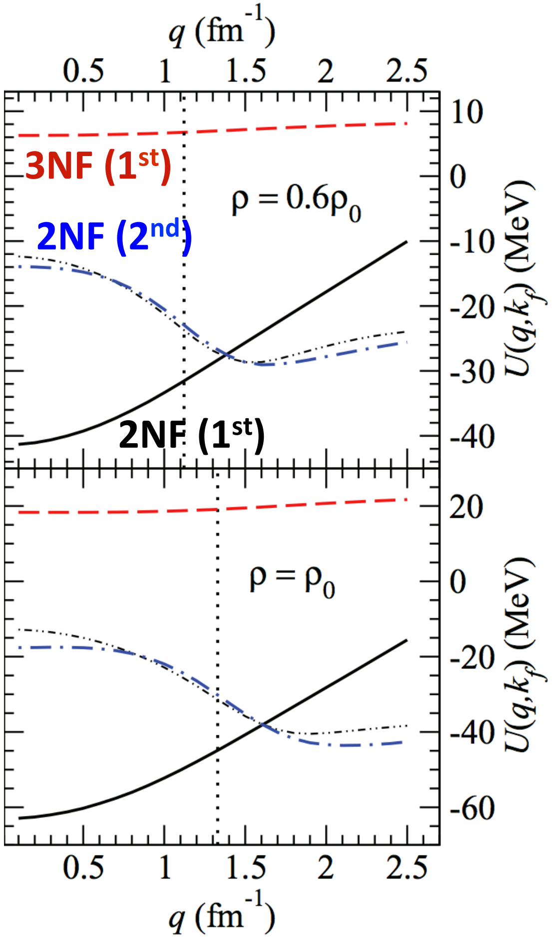
Holt, Kaiser and Miller, PRC (2016)

$\Lambda = 450$ MeV

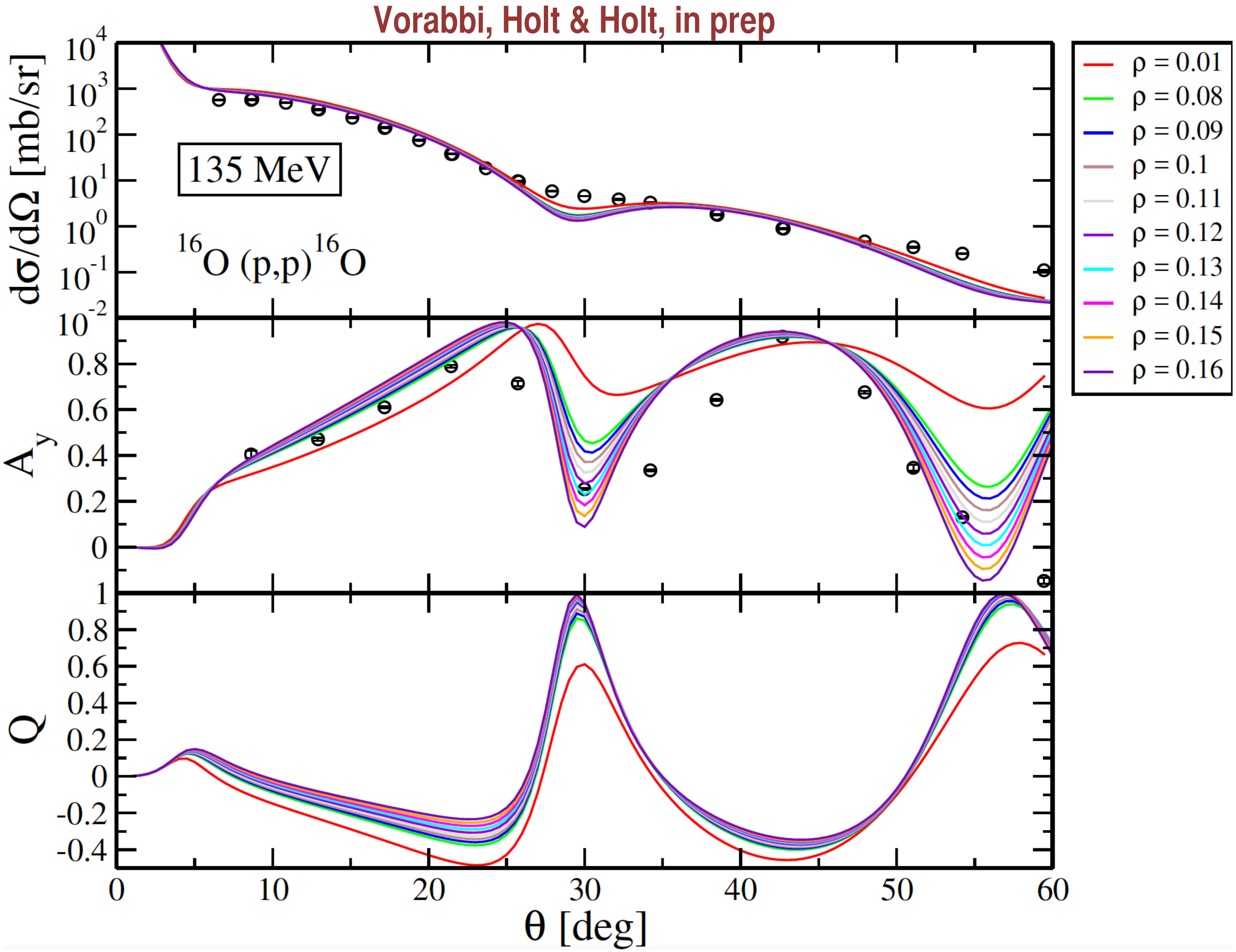


Holt, Kaiser, Miller and Weise, PRC (2013)

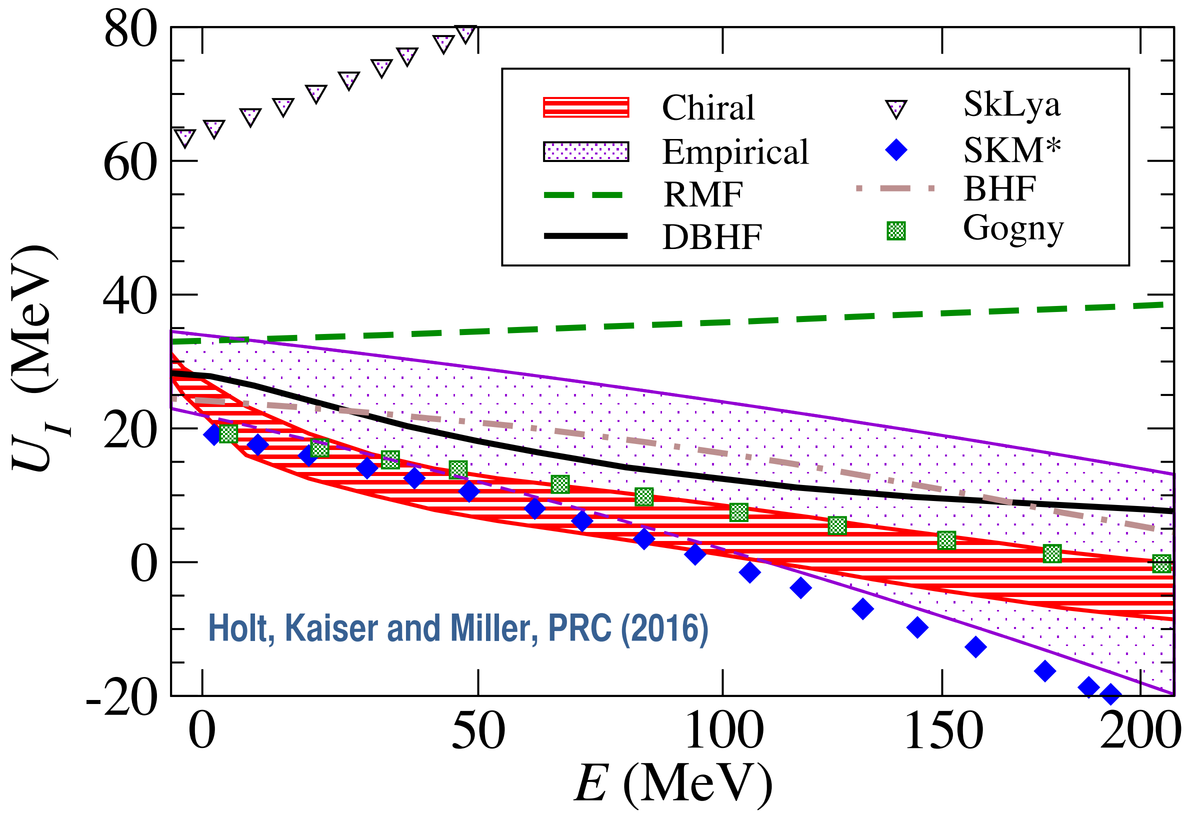
$\Lambda = 500$ MeV



PRELIMINARY CALCULATION

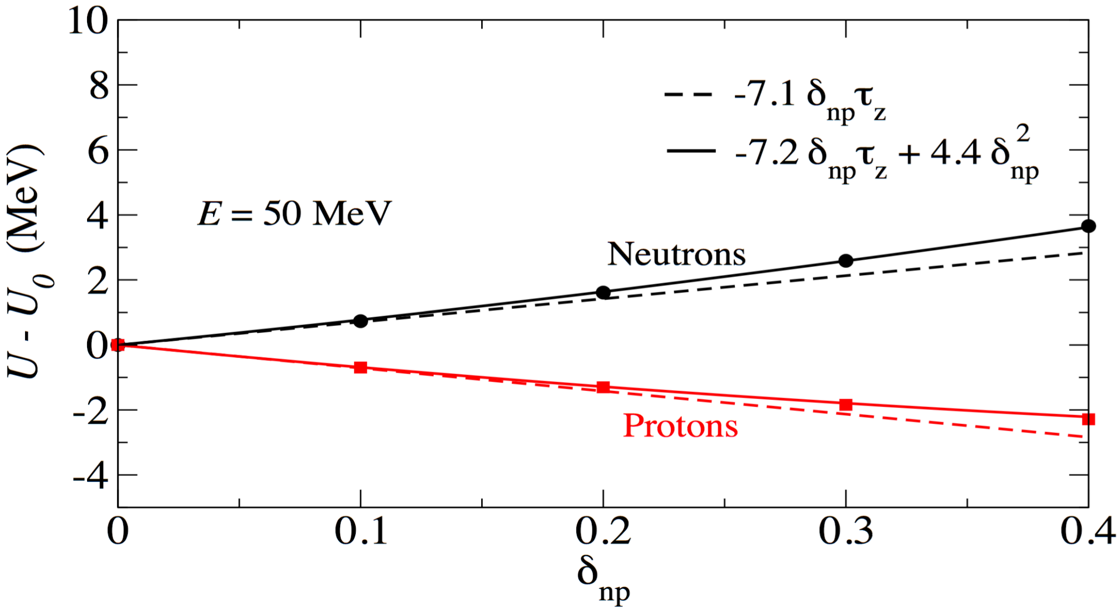


ISOVECTOR REAL OPTICAL POTENTIAL

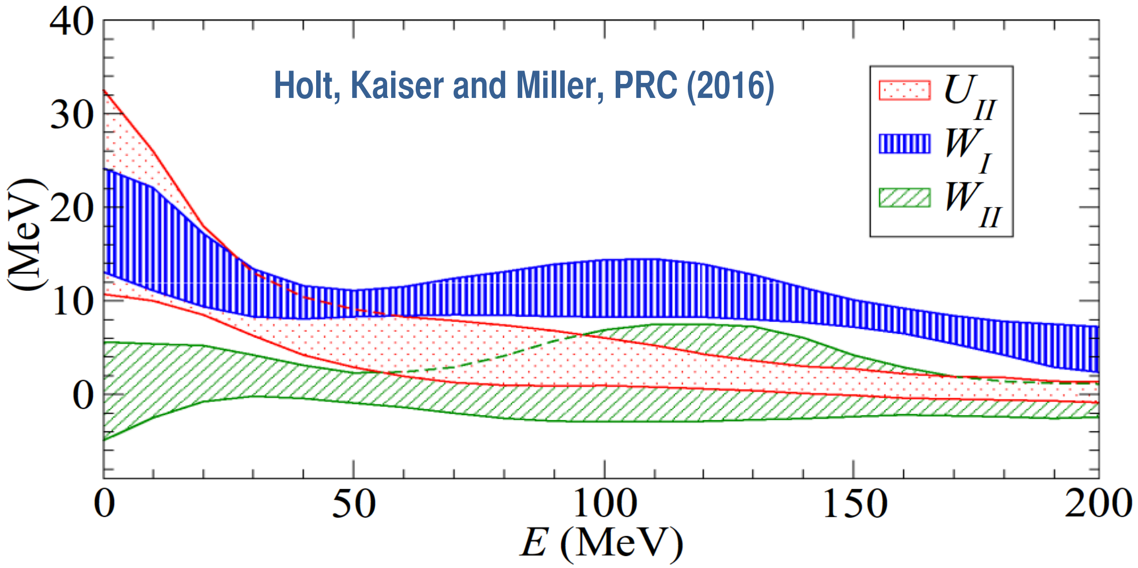


- Chiral EFT prediction consistent with broad empirical constraints

VALIDITY OF LANE APPROXIMATION

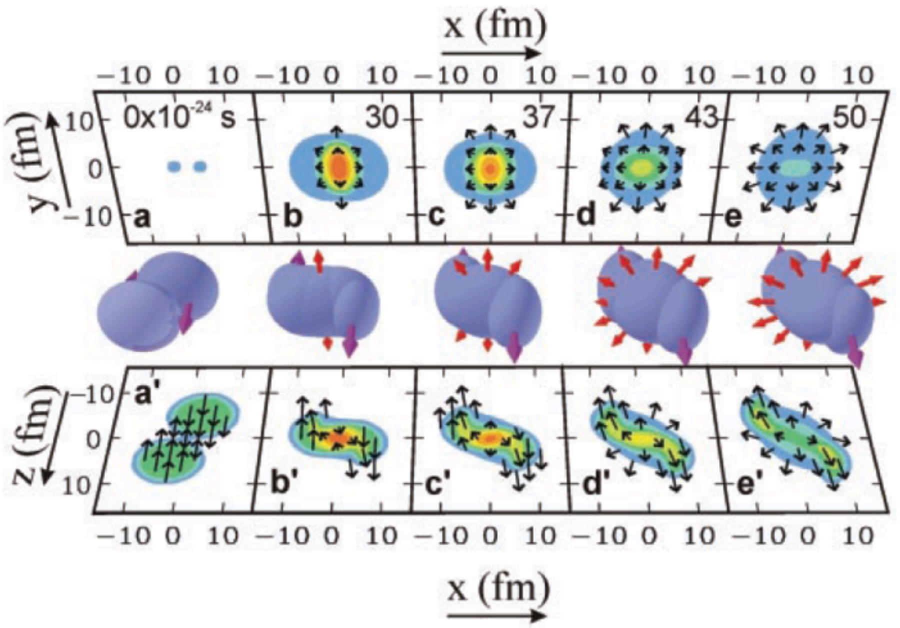


Real part has quadratic isoscalar contributions at low energies

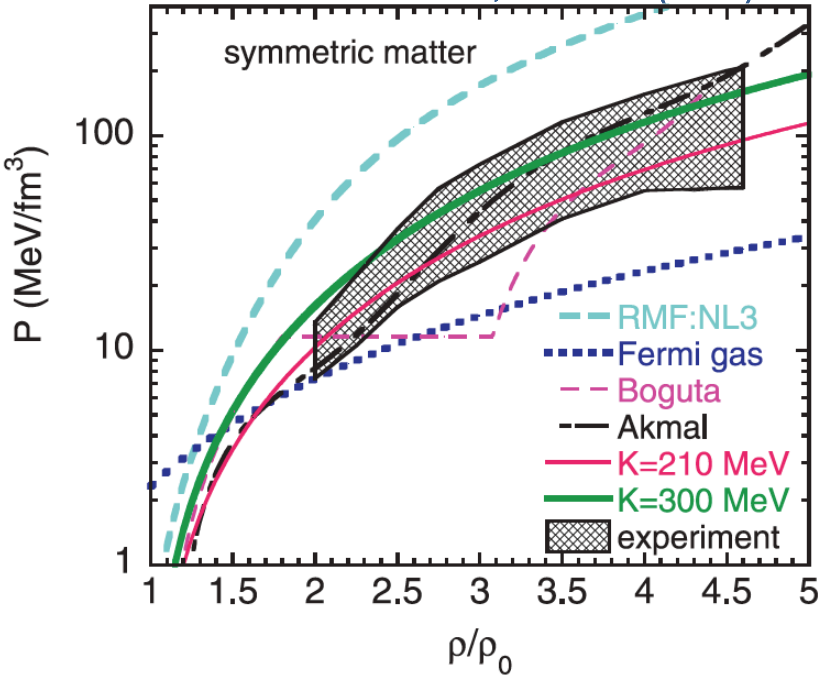

Holt, Kaiser and Miller, PRC (2016)

Imaginary part almost perfectly linear in isospin asymmetry

PROBING NUCLEAR EQUATION OF STATE IN THE LAB



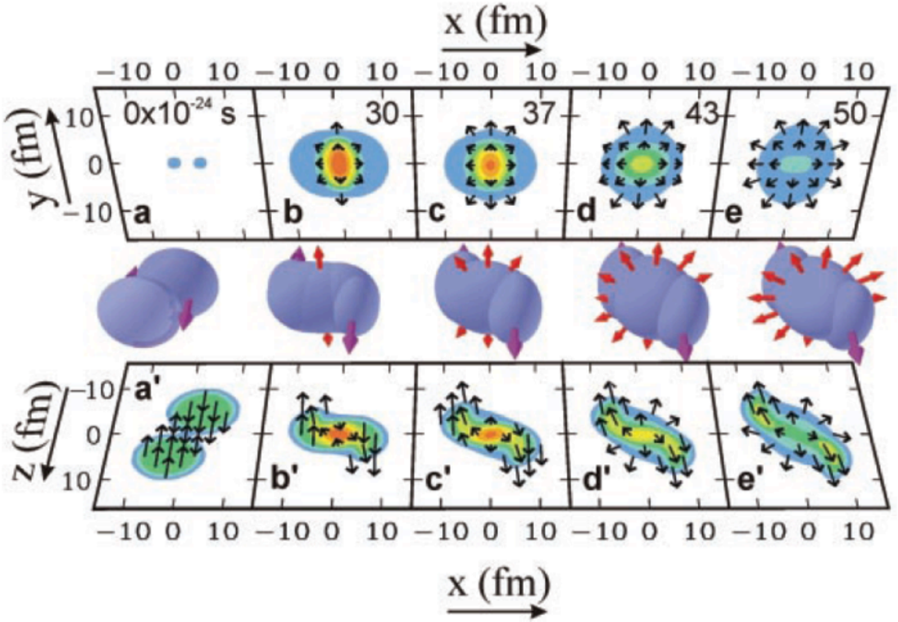
Danielewicz et al., Science (2002)



- Observables: elliptic flow, transverse flow, fragment yields
- Analyze with Boltzmann-like transport equation:

$$\frac{\partial f}{\partial t} + \nabla_p \varepsilon \cdot \nabla_r f - \nabla_r \varepsilon \cdot \nabla_p f = I$$

PROBING NUCLEAR EQUATION OF STATE IN THE LAB



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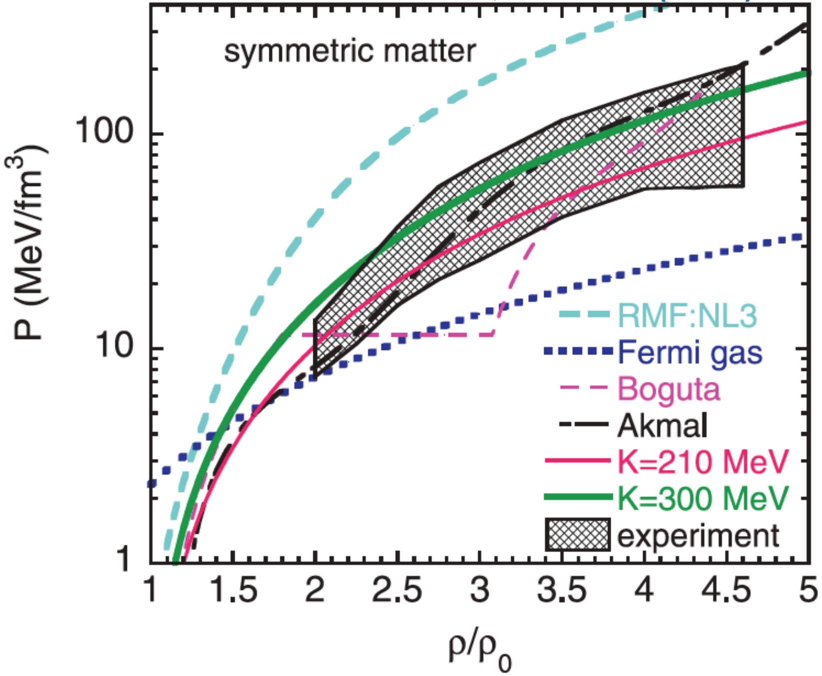
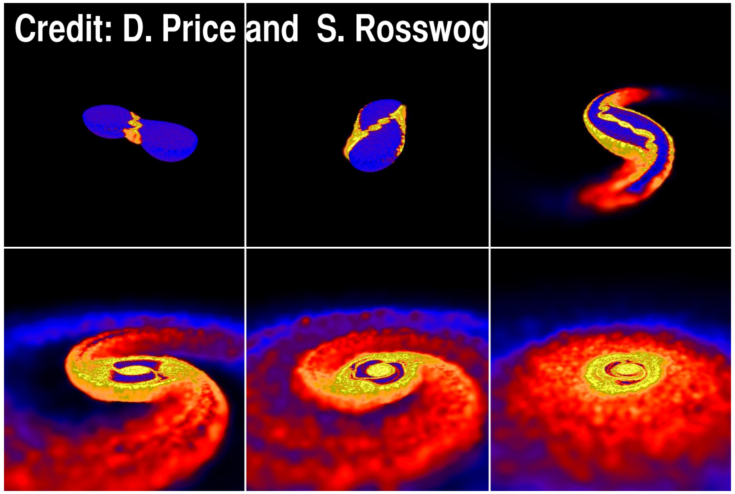


- Observables: elliptic flow, transverse flow, fragment yields
- Analyze with Boltzmann-like transport equation:

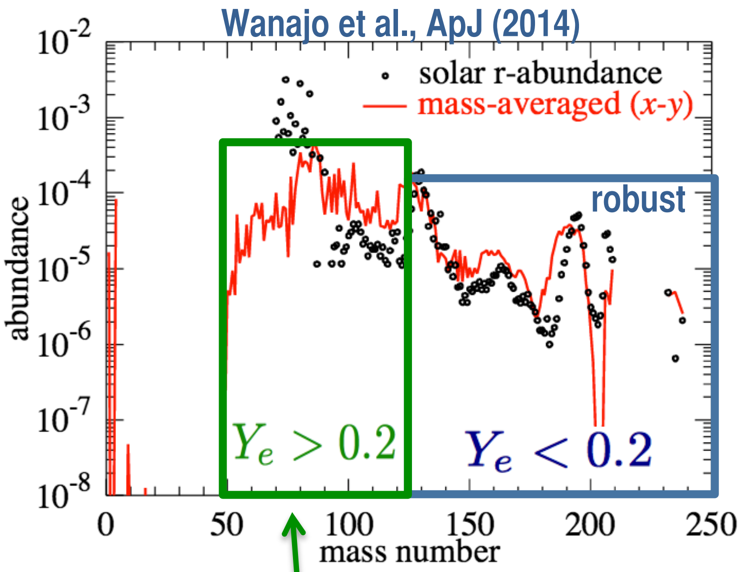
$$\frac{\partial f}{\partial t} + \nabla_p \varepsilon \cdot \nabla_r f - \nabla_r \boxed{\varepsilon} \cdot \nabla_p f = I$$

$$\varepsilon = p^2/2M + U(r,p,t)$$

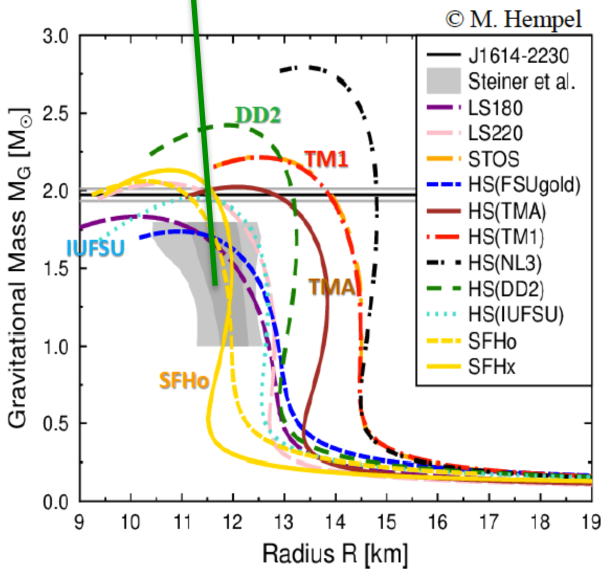
R-PROCESS IN NEUTRON STAR MERGERS



Credit: D. Price and S. Rosswog



Wanajo et al., ApJ (2014)



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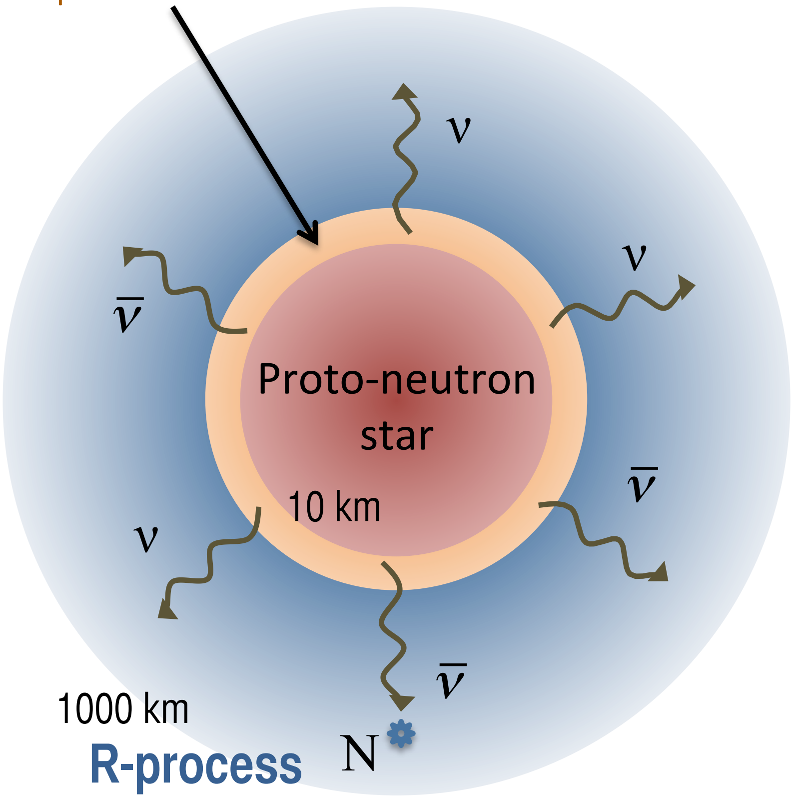
- Soft EoS (SFHo) required for favorable shock-heating in **full GR**
- Subsequent **neutrino processing** increases Y_e value for majority (60%) of ejecta

LATE-TIME SUPERNOVA NEUTRINOS

Neutrinosphere
T = 4 – 8 MeV,
$\rho = 10^{11} - 10^{13}\ \mathrm{g/cm^3}$,
$Y_p \sim 0.05 - 0.10$

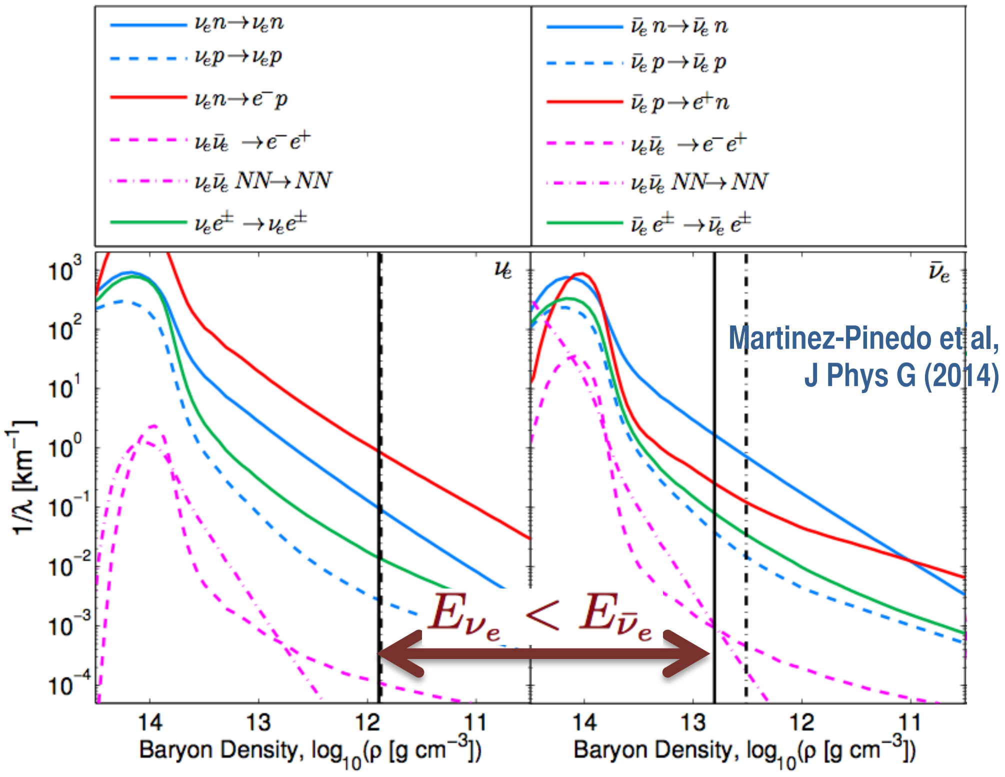


Neutrino opacity

$$\nu_e + n \longleftrightarrow e^- + p$$

Anti-neutrino opacity

$$\bar{\nu}_e + n \longrightarrow \bar{\nu}_e + n$$



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

Governs energies of free-streaming neutrinos

NUCLEAR MEAN FIELDS AND CHARGED-CURRENT REACTIONS

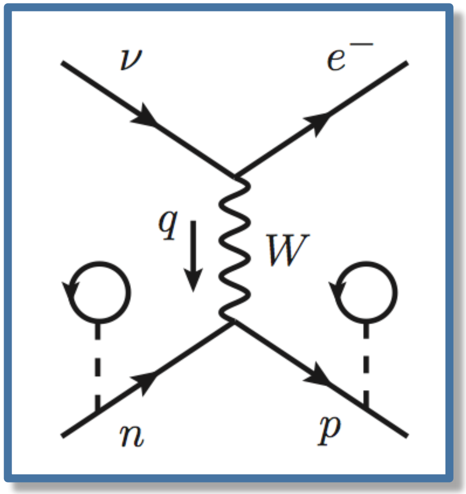
Neutrino-antineutrino spectral difference crucial for nucleosynthesis

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

Set proton fraction in
region of r-process

$$\left.\begin{aligned} N_p &\lesssim 0.4 \\ \langle E_{\bar{\nu}_e}\rangle - \langle E_{\nu_e}\rangle &> 4(m_n - m_p) \end{aligned}\right\}$$

Robust
r-process



Nuclear mean fields enhance neutrino absorption

Skyrme & RMF calculations: Martinez-Pinedo et al, PRL (2012);
Roberts et al, PRC (2012)

Resonant nucleon-nucleon interactions may enhance effect ($a_{nn} = -18\,\mathrm{fm}$)

NEUTRINO ABSORPTION CROSS SECTION

$$\frac{1}{V}\frac{d^2\sigma}{d\cos\theta\, dE_e} = \frac{G_F^2\cos^2\theta_C}{4\pi^2}\boxed{|\vec{p}_e|\, E_e\,(1-f_e(\xi_e))}$$

Electron phase space

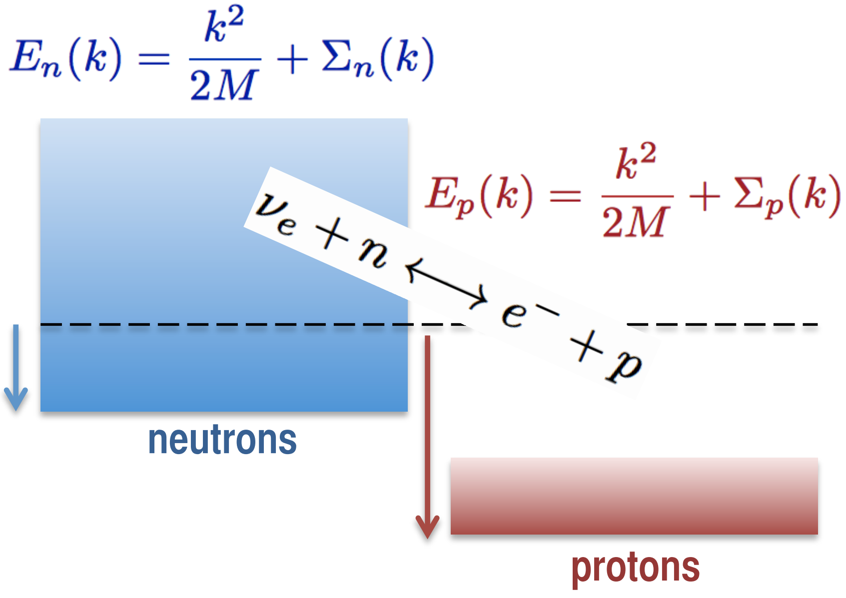
$$\boxed{\times\Big[(1+\cos\theta)S_\tau(q_0,q) + g_A^2(3-\cos\theta)S_{\sigma\tau}(q_0,q)\Big]}$$

Nucleon response

- Nuclear interactions attractive at low momenta and

$$|\langle np|V_{NN}|np\rangle| > |\langle nn|V_{NN}|nn\rangle|$$

- Mean field effects further **widen the energy gap** between protons and neutrons
- **Q-value** for neutrino absorption changes significantly



$$E_n(k) = \frac{k^2}{2M} + \Sigma_n(k)$$

$$E_p(k) = \frac{k^2}{2M} + \Sigma_p(k)$$

$$\nu_e + n \longleftrightarrow e^- + p$$

NEUTRINO ABSORPTION CROSS SECTION

$$\frac{1}{V}\frac{d^2\sigma}{d\cos\theta\, dE_e} = \frac{G_F^2\cos^2\theta_C}{4\pi^2}\boxed{|\vec{p}_e|\, E_e\,(1-f_e(\xi_e))}$$

Electron phase space

$$\boxed{\times\left[(1+\cos\theta)S_\tau(q_0,q)+g_A^2(3-\cos\theta)S_{\sigma\tau}(q_0,q)\right]}$$

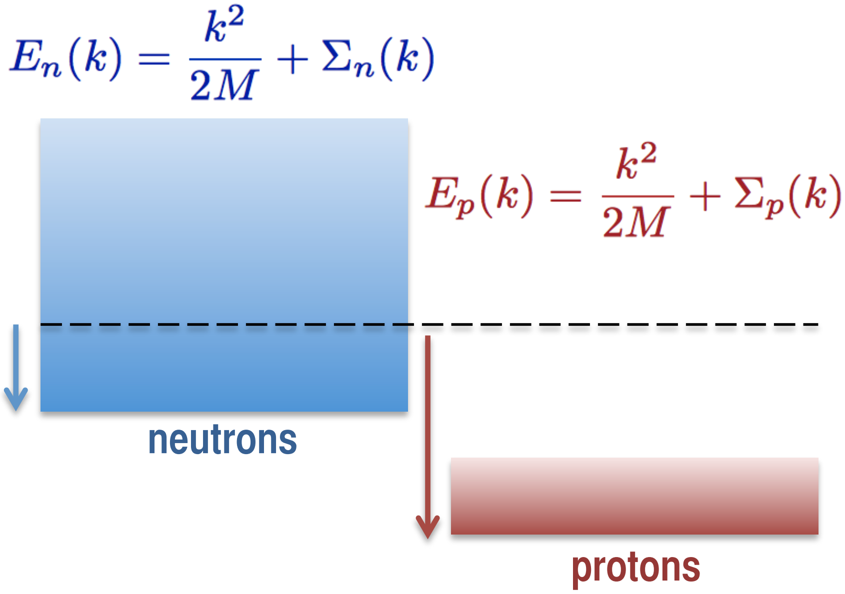
Nucleon response

- Nuclear interactions attractive at low momenta and

$$|\langle np|V_{NN}|np\rangle| > |\langle nn|V_{NN}|nn\rangle|$$

- Mean field effects further **widen the energy gap** between protons and neutrons

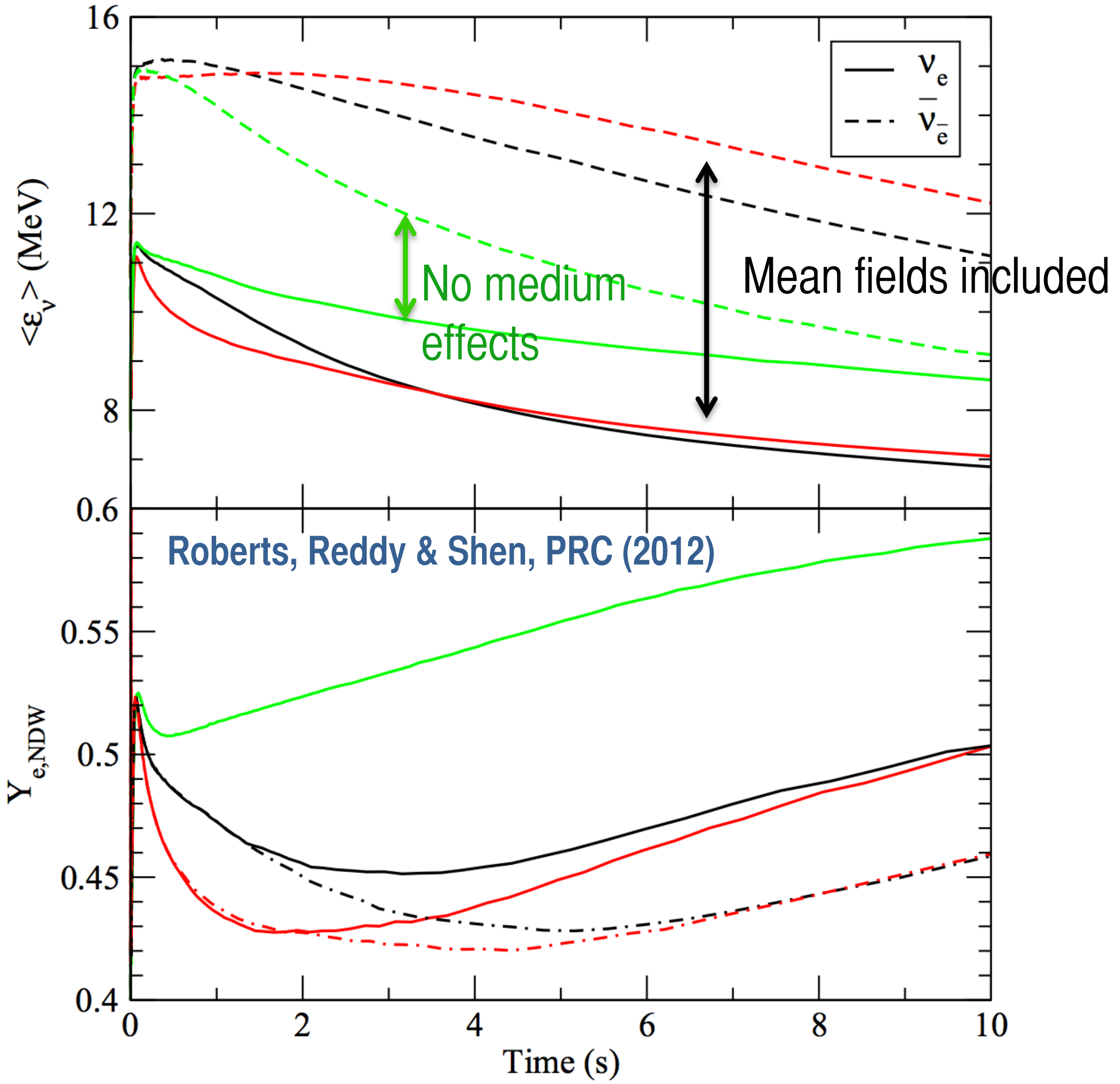
- **Q-value** for neutrino absorption changes significantly



$$E_n(k) = \frac{k^2}{2M} + \Sigma_n(k)$$

$$E_p(k) = \frac{k^2}{2M} + \Sigma_p(k)$$

MEDIUM EFFECTS ON MEAN NEUTRINO ENERGIES



Roberts, Reddy & Shen, PRC (2012)

RESONANT NN INTERACTIONS AT LOW DENSITIES

Virial expansion

Horowitz & Schwenk (2006)

- Equation of state and neutrino response for low-density, high-temperature matter

Many-body perturbation theory with chiral forces

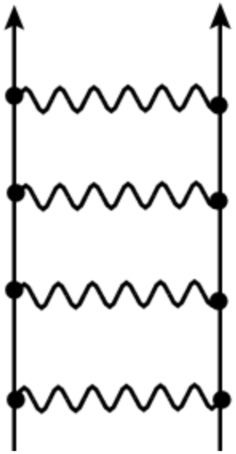
- Leading Hartree-Fock contribution likely too weak
- Second-order perturbation theory may be sufficient (work in progress…)

Nuclear pseudo-potential:

$$\langle p|V^{pseudo}_{llSJ}|p\rangle = -\frac{\delta_{lSJ}(p)}{pM_N}$$

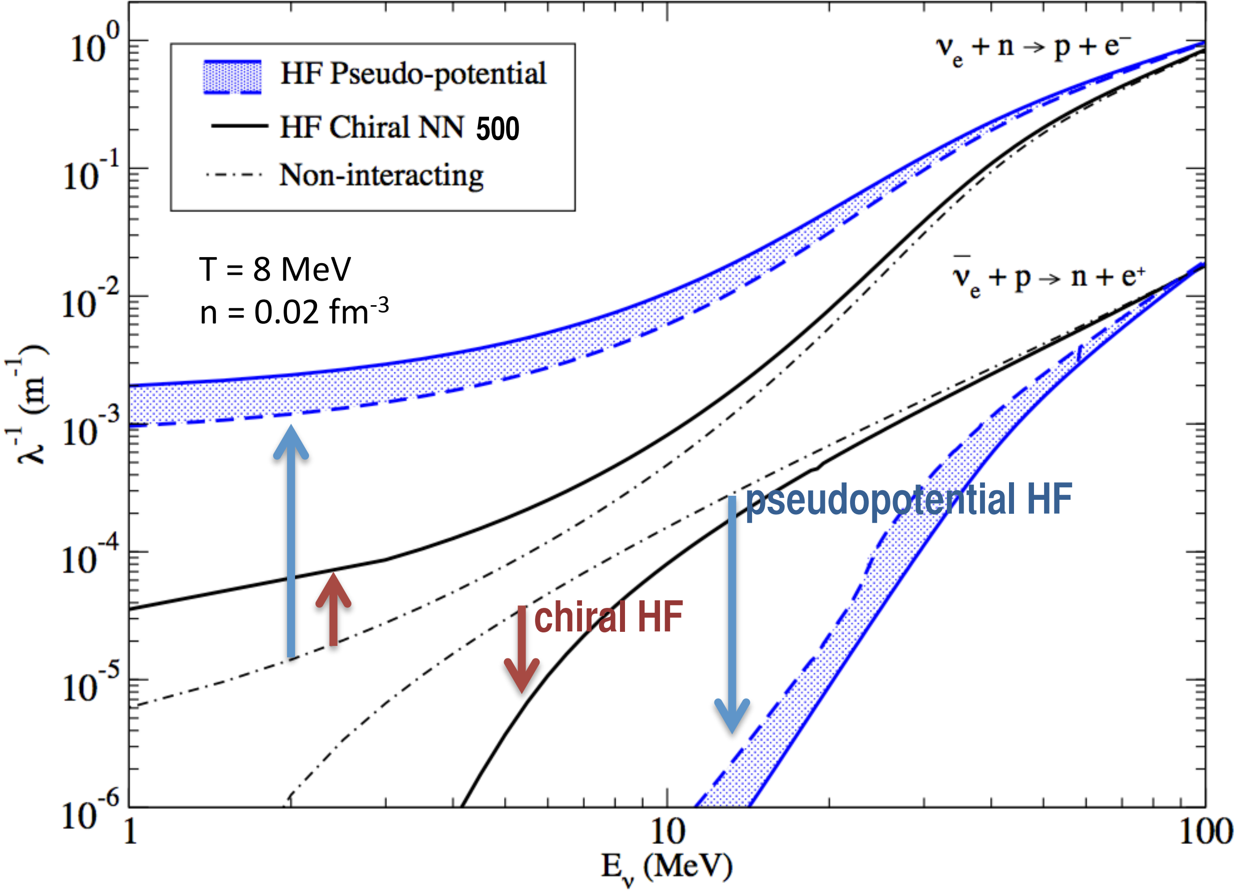
Fumi (1955),
Fukuda & Newton (1956)

$\sim$



- Designed to reproduce **exact energy shift** when used at the mean field level (valid for low-density matter)

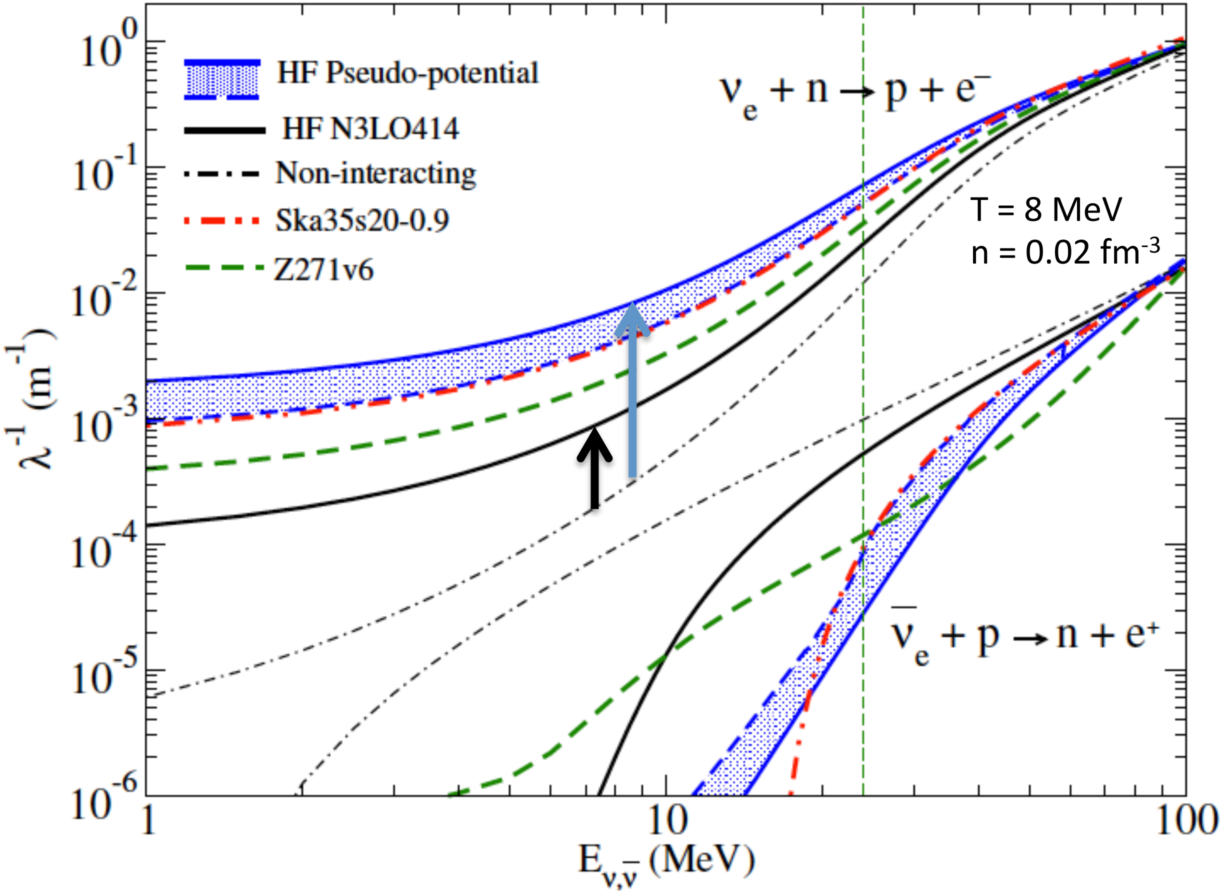
EFFECT ON MEAN FREE PATH



Rrapaj, Holt, Bartl, Reddy & Schwenk, PRC 2015

EFFECT ON MEAN FREE PATH

Rrapaj, Roggero & Holt, PRC (2016)



- Larger neutrino/antineutrino spectral difference **(may enhance r-process)**

SUMMARY & FUTURE WORK

Optical potentials for neutron-rich nuclei

- Benchmarked to phenomenological potentials (stable nuclei)
- Extended to large isospin asymmetries
- Fold with theoretical/empirical density distributions (LDA, improved LDA?)

Neutrino reactions in proto-neutron stars

- Larger neutrino opacity ⟶ more neutron-rich matter
- Higher-order contributions to nuclear response from chiral effective field theory
- Consistent equations of state & implement in simulations of supernovae, proto-neutron star evolution, neutron star mergers