SRC and Nuclear Equation of State

Bao-An Li
East Texas A&M University

Collaborators: Bao-Jun Cai and Yu-Gang Ma, Fudan University

Key issues:

1. **What do we know about the EOS of neutron-rich matter?**

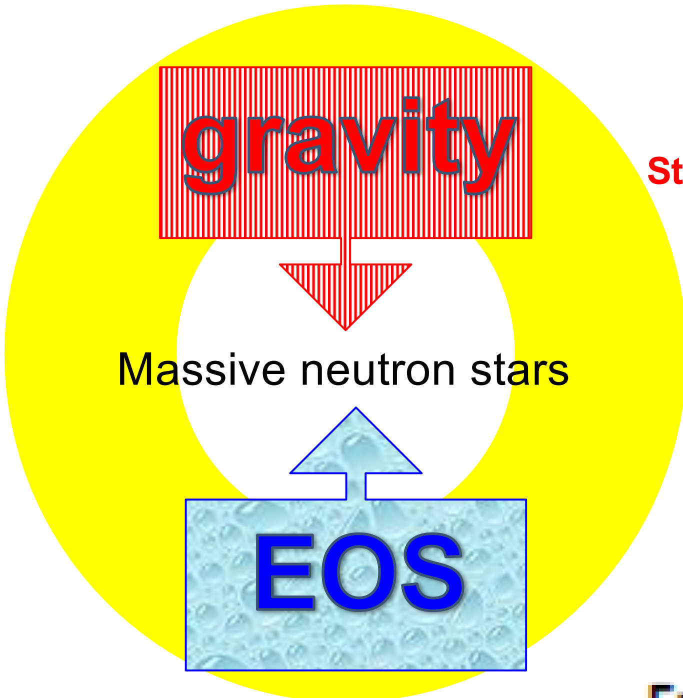
2. **How/where does the SRC affect the nuclear EOS?**

3. **What are the SRC imprints on properties of neutron stars?**

Office of Science
U.S. DEPARTMENT OF ENERGY

Gravity-EOS degeneracy

Even perfect data cannot fully disentangle gravity and EOS



2020 Astronomy & Astrophysics Decadal Survey

arXiv:1903.09221v3

Hamilton's variational principle

Strong-field gravity: Einstein's General Relativity (GR) or Modified Gravity + 5^{th} force?

Total Action $S = S_{gravity} + S_{matter}$ + their couplings

Matter [nucleons, baryon resonances, hyperons, quarks, mesons, leptons, gluons…] or +[Dark Matter] + [**X17**]?

Extreme Gravity and Fundamental Physics

- **The nature of gravity.** Can we prove Einstein wrong? What building-block principles and symmetries in nature invoked in the description of gravity can be challenged?
- **The nature of dark matter.** Is dark matter composed of particles, dark objects or modifications of gravitational interactions?
- **The nature of compact objects.** Are black holes and neutron stars the only astrophysical extreme compact objects in the Universe? What is the equation of state of densest matter?

What is the EOS?

- **Relation among P, ε, T, δ, μ**
- **Symmetry energy is a key uncertainty**

Empirical parabolic law of the EOS of cold, neutron-rich nucleonic matter

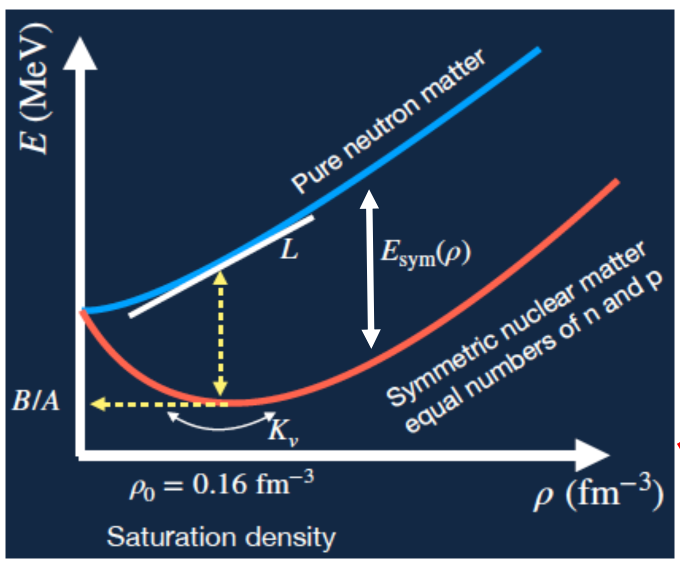
symmetry energy

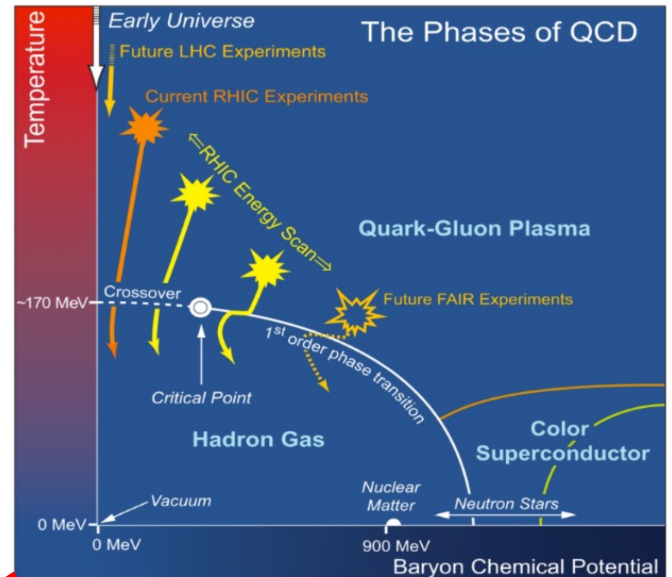
Isospin asymmetry δ

$$E(\rho_n,\rho_p) = E_0(\rho_n=\rho_p) + E_{sym}(\rho)\left(\frac{\rho_n-\rho_p}{\rho}\right)^2 + o(\delta^4)$$

Energy per nucleon in symmetric matter

Energy in asymmetric nucleonic matter





New opportunities

Isospin chemical potential

$\mu_I = E_{sym}(\rho)\cdot\delta$ in n-rich matter

Structures and collisions of heavy nuclei

Structures and mergers of neutron stars

Single-nucleon potential in isospin-asymmetric nuclear matter

+ for neutrons

A.M. Lane, PRL 8, 171 (1962)

$$U_{n/p}(k,\rho,\delta) = U_0(k,\rho) \pm U_{sym1}(k,\rho)\cdot\delta + U_{sym2}(k,\rho)\cdot\delta^2 + o(\delta^3)$$

- for protons

Isovector

According to the Hugenholtz-Van Hove (HVH) theorem: $E_F = \frac{d\xi}{d\rho} = \frac{d(\rho E)}{d\rho} = E + \rho\frac{dE}{d\rho} = E + P/\rho$

J. Dabrowski and P. Haensel, PLB 42, (1972) 163.

S. Fritsch, N. Kaiser and W. Weise, NPA. A750, 259 (2005).

C. Xu, B.A. Li, L.W. Chen, Phys. Rev. C 82 (2010) 054607.

$$E_{sym}(\rho) = \frac{1}{3}\frac{\hbar^2 k^2}{2m_0^*}|_{k_F} + \frac{1}{2}U_{sym,1}(\rho,k_F),$$

Potential

$$L(\rho) = \frac{2}{3}\frac{\hbar^2 k^2}{2m_0^*}|_{k_F} - \frac{1}{6}\left(\frac{\hbar^2 k^3}{m_0^{*2}}\frac{\partial m_0^*}{\partial k}\right)|_{k_F} + \frac{3}{2}U_{sym,1}(\rho,k_F) + \frac{\partial U_{sym,1}}{\partial k}|_{k_F}\cdot k_F + 3U_{sym,2}(\rho,k_F),$$

Kinetic

Rong Chen, Bao-Jun Cai, Lie-Wen Chen, Bao-An Li, Xiao-Hua Li, Chang Xu, PRC 85, 024305 (2012)

Nucleon effective mass in isospin symmetric matter $m_0^*(\rho,k) = \frac{m}{1 + \frac{m}{\hbar^2 k}\frac{\partial U_0(\rho,k)}{\partial k}},$

Neutron-proton effective mass splitting in neutron-rich matter

$$m^*_{n-p} \approx 2\delta\frac{m}{\hbar^2 k_F}\left[-\frac{dU_{sym,1}}{dk} - \frac{k_F}{3}\frac{d^2U_0}{dk^2} + \frac{1}{3}\frac{dU_0}{dk}\right]_{k_F}\left(\frac{m_0^*}{m}\right)^2$$

$$\approx 2\delta\left(\frac{M_s^*}{M}\right)^2\left[\frac{M}{M_v^*} - \frac{M}{M_s^*}\right]$$

B.A. Li, B.J. Cai, L.W. Chen and J. Xu, Progress of Particle and Nuclear Physics, 99 (2018) 29.

What are the fundamental physics behind the symmetry energy?

$$U_{n/p}(k,\rho,\delta) = U_0(k,\rho) \pm U_{sym1}(k,\rho)\bullet\delta + U_{sym2}(k,\rho)\bullet\delta^2 + o(\delta^3)$$

- **Isospin dependence of strong interactions and correlations**

$V_{T0} = V'_{np}$ (n-p pair in the T=0 state)

$V_{T1} = V_{nn} = V_{pp} = V_{np}$ (charge independence in the T=1 state)

Tensor force due to pion and ρ meson exchange MAINLY in the T=0 channel

$V_{np}(T0) \neq V_{np}(T1)$

In a simple interacting Fermi gas model:

The direct term

Isospin-dependent correlation function

$$U_{sym}(k_F,\rho) = \frac{1}{4}\rho \int [V_{T1}(r_{ij}) f^{T1}(r_{ij}) - V_{T0}(r_{ij}) f^{T0}(r_{ij})] d^3 r_{ij}$$

Isospin-dependent effective 2-body interaction

M.A. Preston and R.K. Bhaduri, Structure of the Nucleus, 1975

Major issues relevant to high-density E_{sym}, heavy-ion reactions and neutron stars

- **Momentum dependence of the symmetry potential due to the finite-range of isovector int.**
- **Short-range correlations due to the tensor force in the isosinglet n-p channel**
- **Spin-isospin dependence of the 3-body force**
- **Isovector interactions of Δ(1232) resonances and their spectroscopy (mass and width)**
- **Possible sign inversion of the symmetry potential at high momenta/density**

Empirical parameterizations useful for meta-modeling (template) of EOS

incompressibility

$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{J_0}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3 + \frac{Z_0}{24}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^4,$$

Relatively well-known

Poorly known

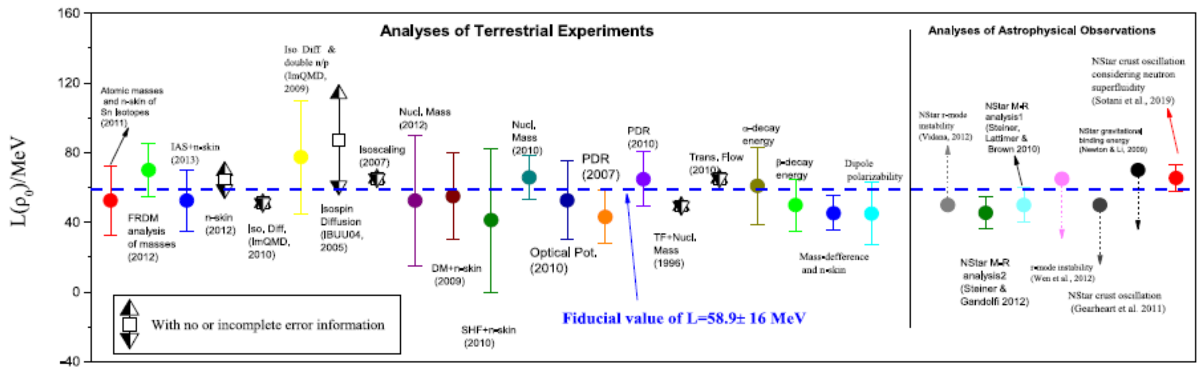
$$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho}{\rho_0}-1\right) + \frac{K_{\rm sym}}{18}\left(\frac{\rho}{\rho_0}-1\right)^2 + \frac{J_{\rm sym}}{162}\left(\frac{\rho}{\rho_0}-1\right)^3 + \mathcal{O}\left[\left(\frac{\rho}{\rho_0}-1\right)^4\right]$$

slope curvature skewness kurtosis

- Expansion near saturation density
- Uncertainties grow at high density

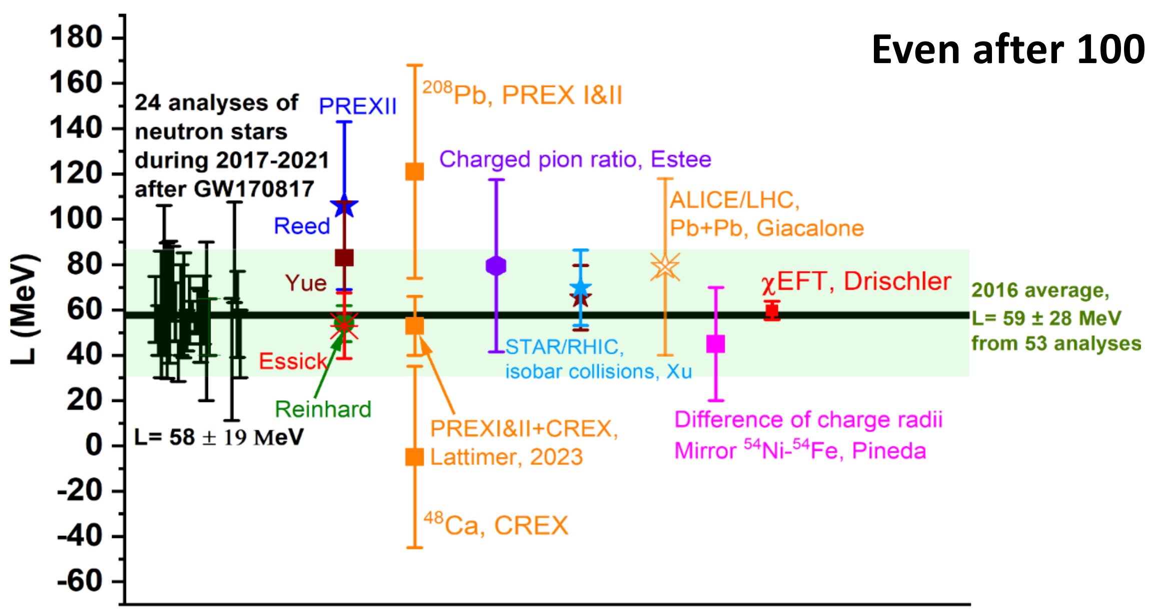
Prior on L: Broad theoretical range L ≈ 60 ± 30 MeV with a few out-standing points

As of 2013, ~30 analyses



Bao-An Li and Xiao Han,
Phys. Lett. B727 (2013) 276

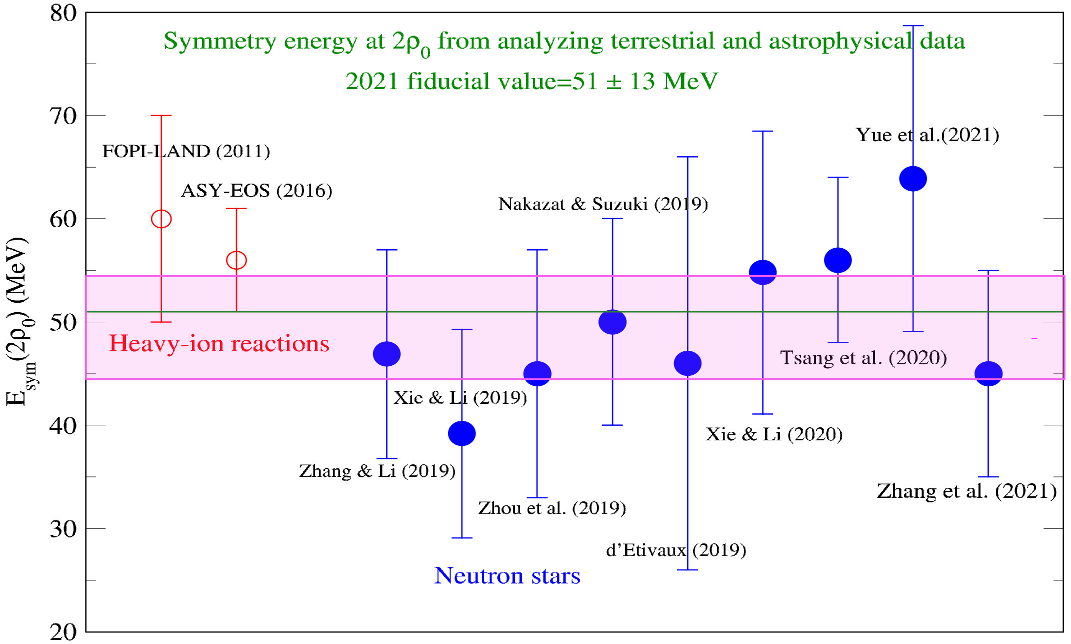
Slope L of nuclear symmetry energy as of 2023

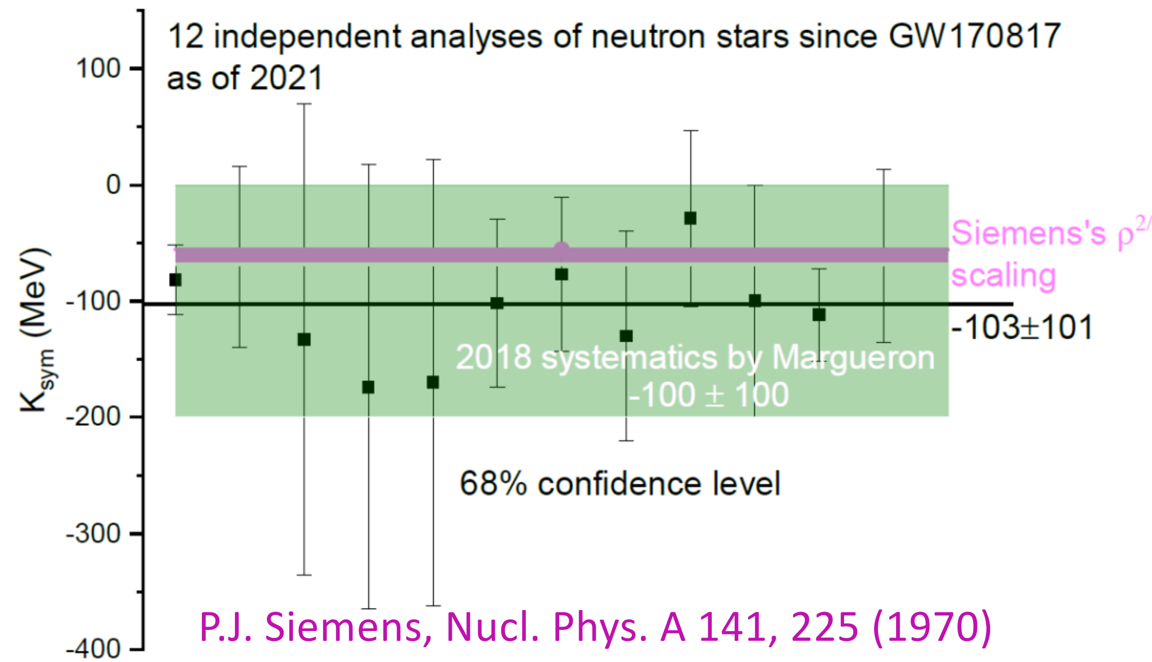


Even after 100 analyses, L remains broadly uncertain

Nai-Bo Zhang and Bao-An Li,
EPJA 59, 86 (2023)

Prior on $E_{sym}(2\rho_0)$ and K_{sym}: Despite many studies, constraints remain broad





Examples of recent theoretical predictions for $E_{sym}(2\rho_0)$:

(1) Chiral EFT, $E_{sym}(2\rho_0) \approx 45 \pm 3$ MeV

C. Drischler, R. J. Furnstahl, J. A. Melendez, and D. R. Phillips, PRL**125**, 202702 (2020)

(2) Quantum Monte Carlo, $E_{sym}(2\rho_0) \approx 46 \pm 4$

D. Lonardoni, I. Tews, S. Gandolfi, and J. Carlson, Phys. Rev. Research **2**, 022033(R) (2020)

(3) Relativistic BHF in full Dirac space: 51.6 MeV

Sibo Wang, Hui Tong, Qiang Zhao, Chencan Wang, Peter Ring, Jie Meng, PRC 106 (2022) 2, L021305

(4) Relativistic BHF: ~ 53 MeV

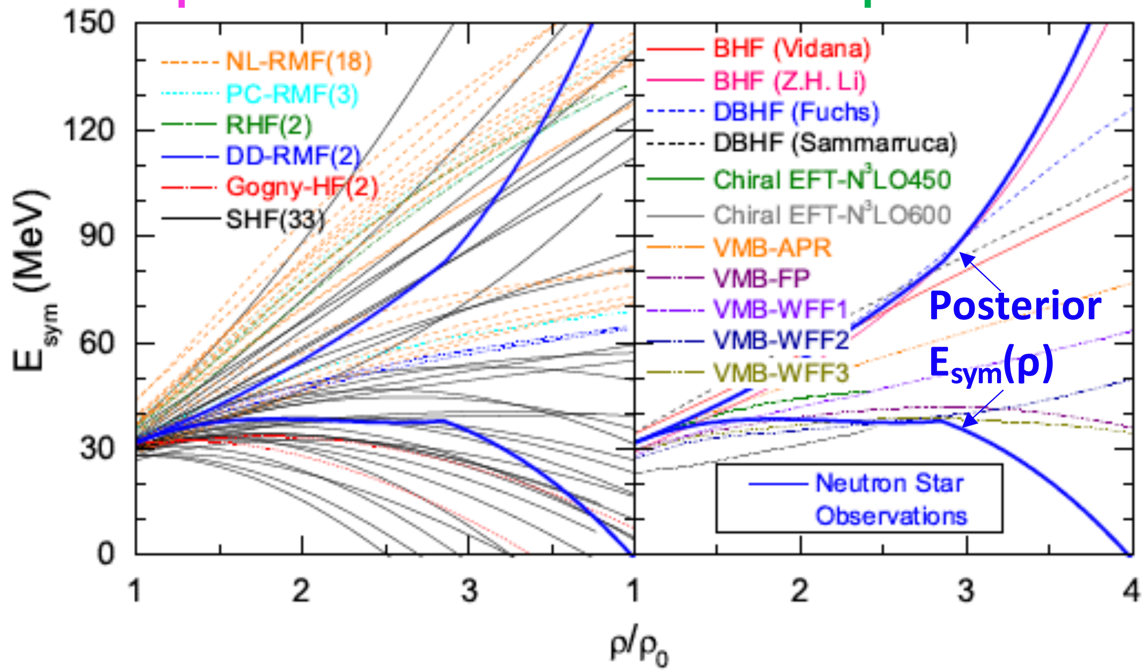
Chencan Wang, Jinniu Hu, Ying Zhang, Hong Shen, *Chin. Phys. C* 46 (2022) 6, 064108

Bao-An Li, Euro Phys. Journal Special Topic (2026)

Predictions diverge at high density

Phenomenological Models
60 examples

Microscopic & *ab initio* Theories
11 examples



L.W. Chen, Nucl. Phys. Rev. **34**, 20 (2017).
N.B. Zhang, B.A. Li, Eur. Phys. J. A **55**, 39 (2019).

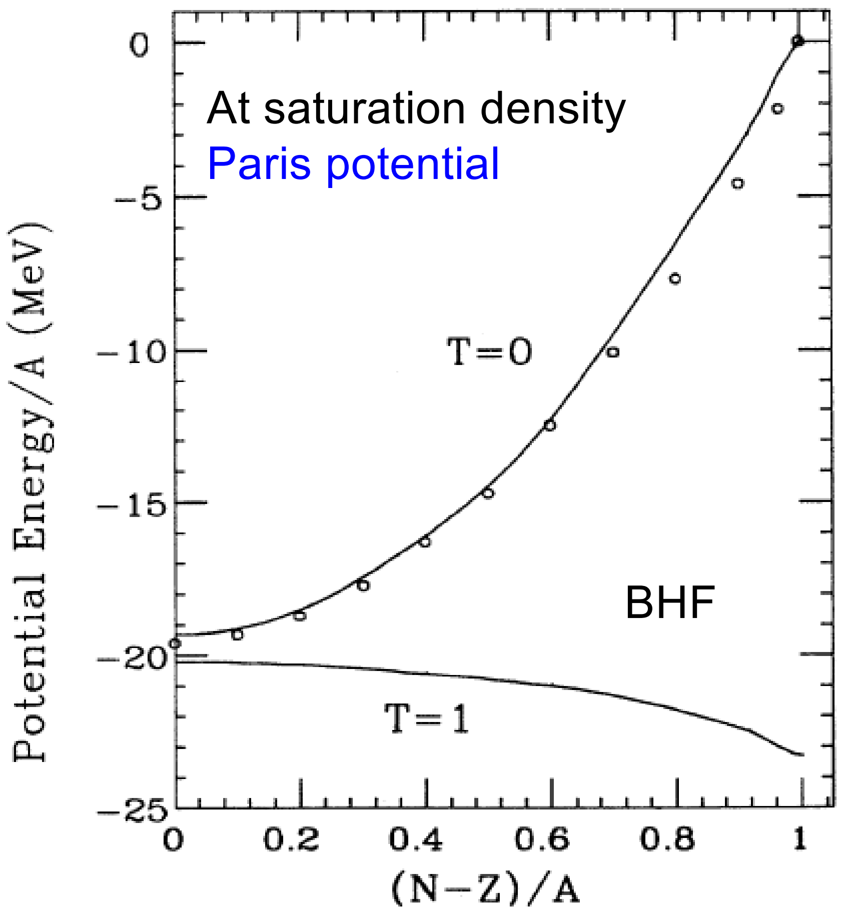
Why is the high-density symmetry energy still so uncertain?

- Isospin-spin dependent Short-Range Correlations induced by tensor forces, many-body interactions
- New particles and possible phase transitions are important but poorly known

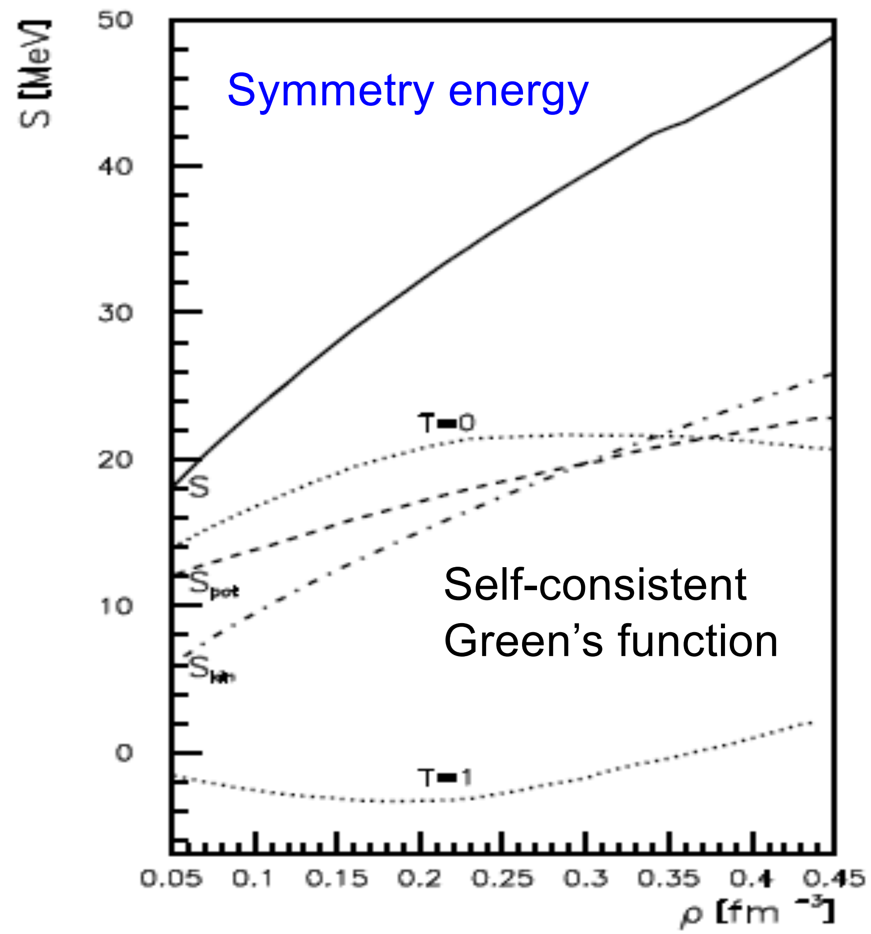
Why did the available neutron star data not help much at high densities?

- R is obtained from P®=0 at the surface, corresponding to an average density of about $2\rho_0$ where P_{sym} is larger than or compatible with $P_{SNM,}$ depending mostly on K_{sym} and L

Dominance of the isosinglet (T=0) interaction



I. Bombaci and U. Lombardo PRC 44, 1892 (1991)



A.E.L. Dieperink,[1] Y. Dewulf,[2] D. Van Neck,[2] M. Waroquier,[2] and V. Rodin[3]

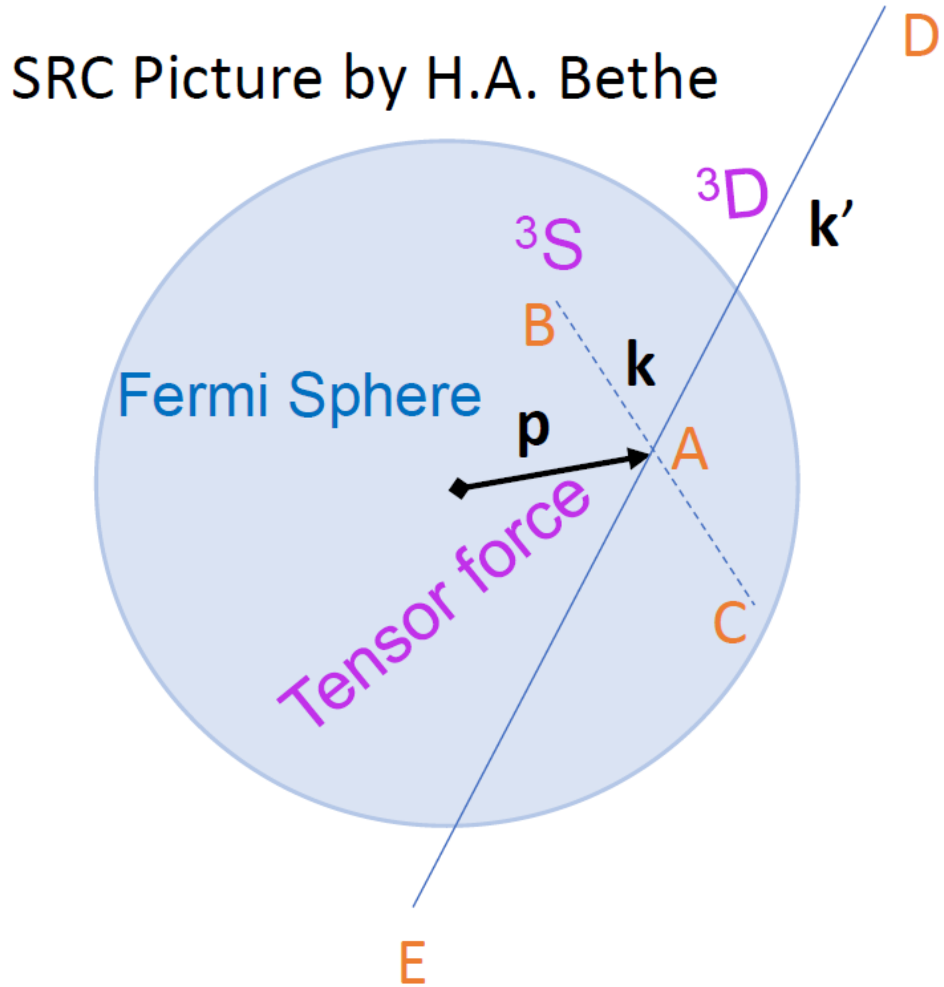
PRC68, 064307 (2003)

$$E_{sym}(\rho) = \frac{1}{2}\frac{\partial^2 E}{\partial \delta^2} \approx E(\rho)_{\text{pure neutron matter}} - E(\rho)_{\text{symmetric nuclear matter}}$$

Effects of the tensor force in T=0 neutron-proton interaction channel

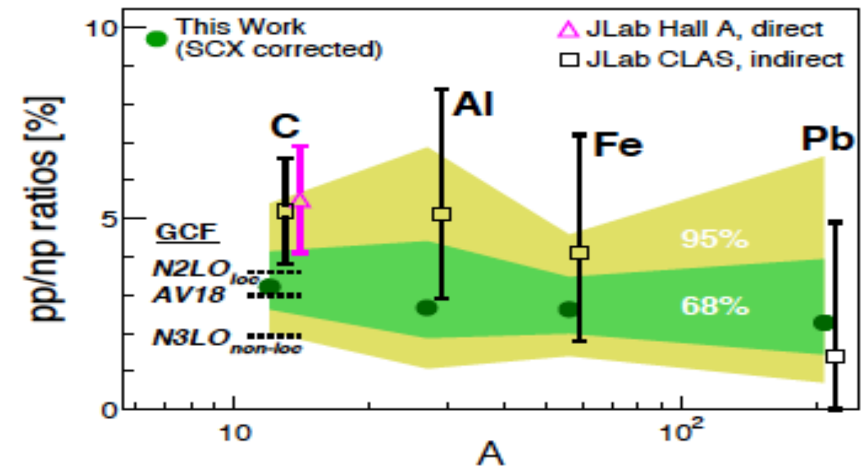
(1) High-momentum tail (HMT) in nucleon momentum distribution due to the S-D coupling induced by the tensor force

H.A. Bethe, Ann. Rev. Nucl. Part. Sci., 21, 93-244 (1971)



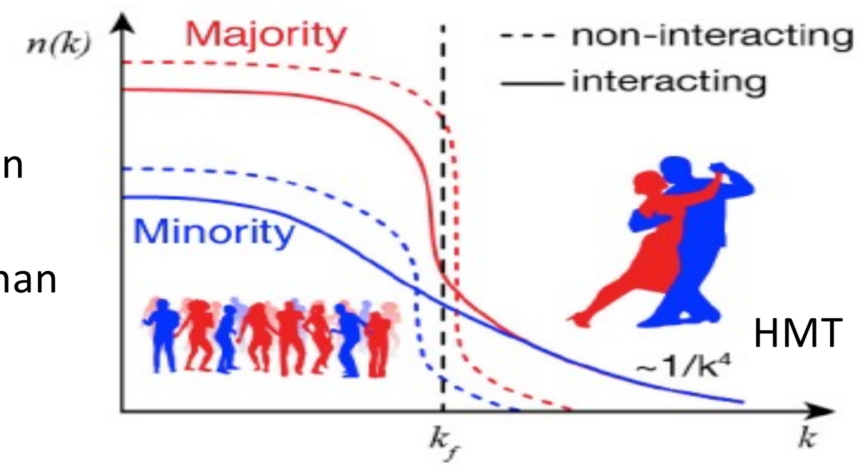
(2) isospin dependence of short-range correlation (SRC) in neutron-rich matter

M. Duer et al., PRL 122, 172502 (2019).



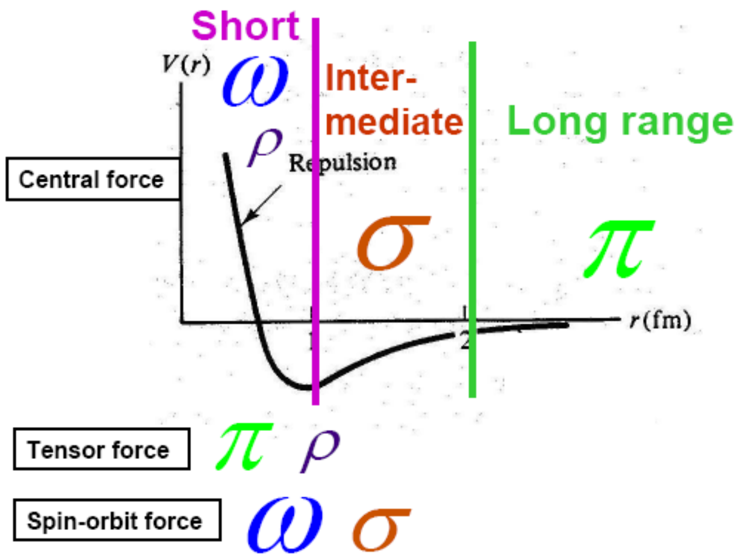
Evidence of np SRC dominance over pp (nn)

Implication: larger fraction of protons in the HMT → protons move faster than neutrons in n-rich matter



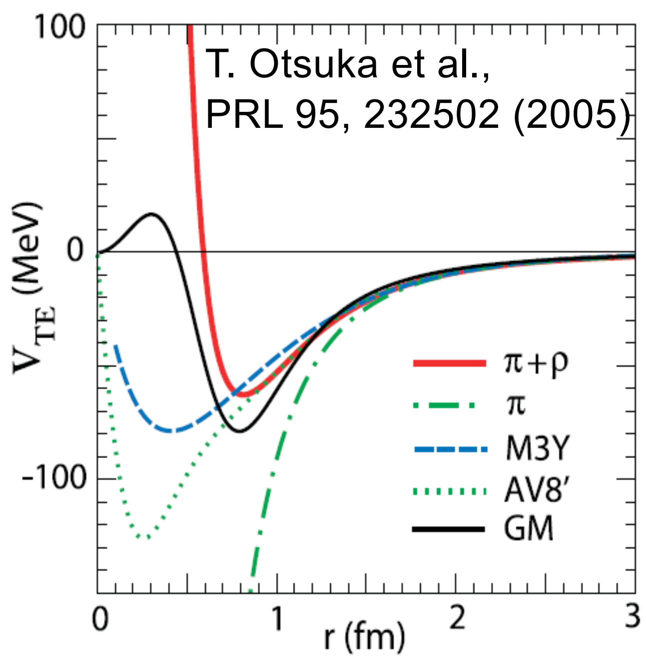
O. Hen et al., Science 346, 614 (2014)

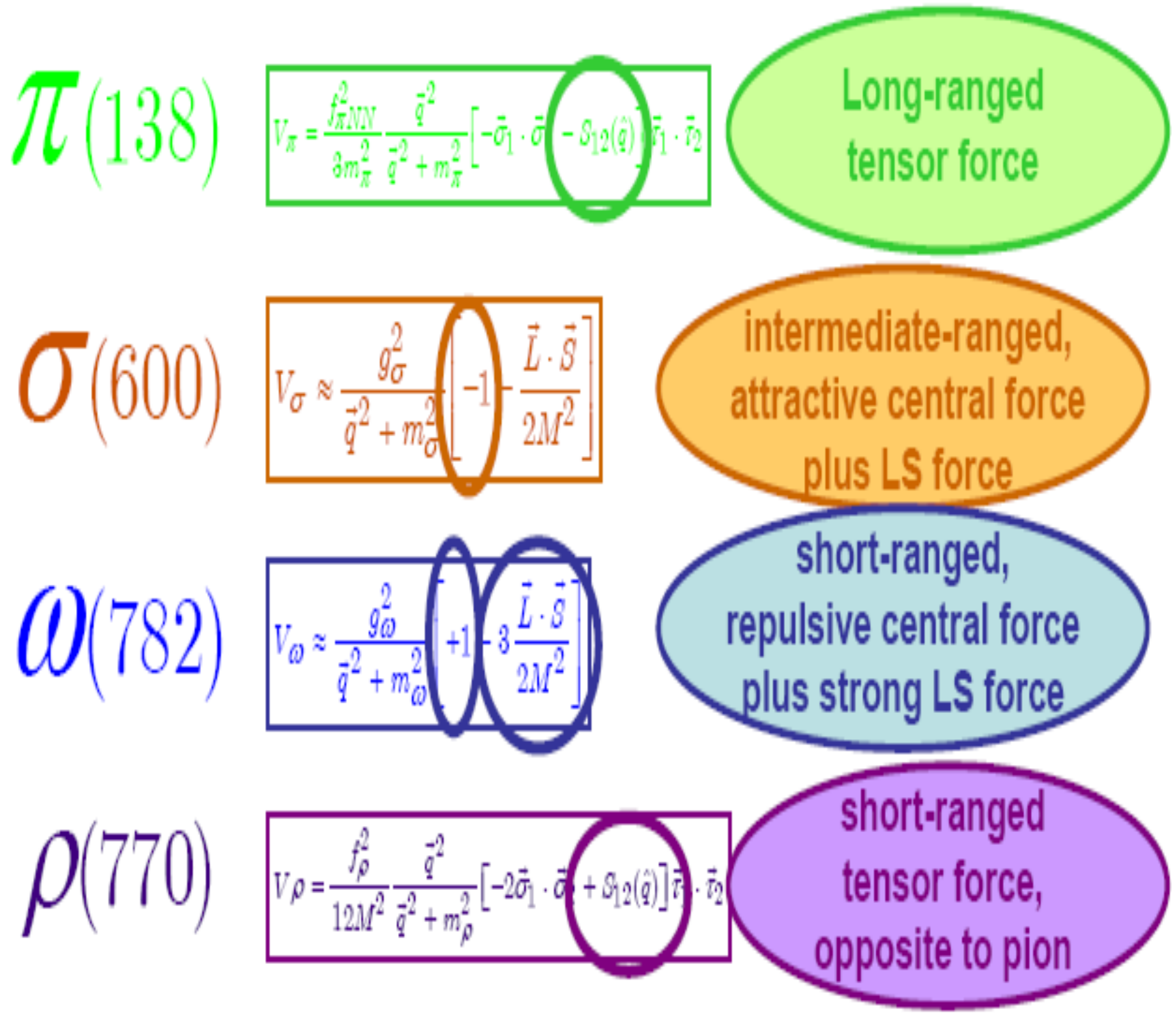
The short and long range tensor force



Lecture notes of R. Machleidt
CNS summer school, Univ. of Tokyo
Aug. 18-23, 2005

Strength of the tensor force





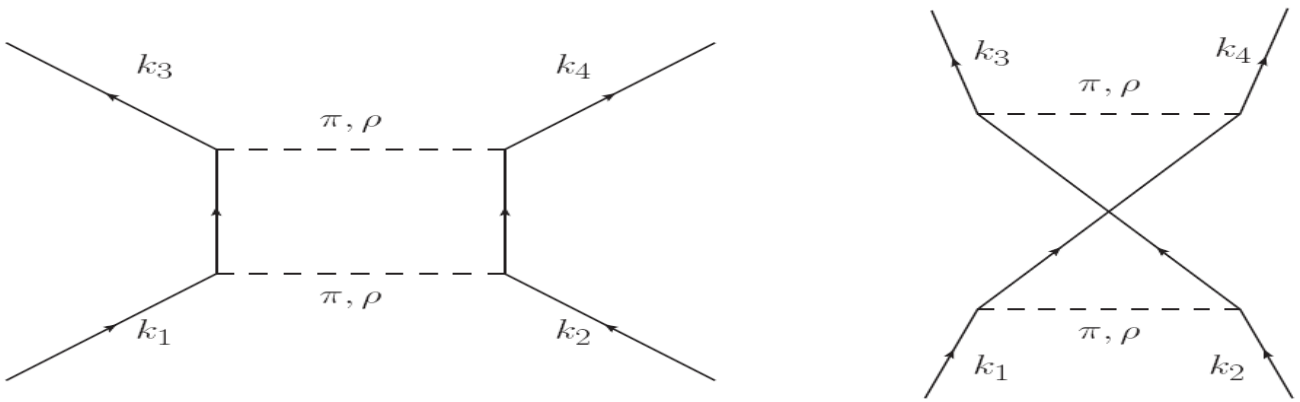
2^{nd} order tensor force contribution to the potential part of the symmetry energy

G.E. Brown and R. Machleidt, Phys. Rev. C50, 1731 (1994).

S.-O. Bacnman, G.E. Brown and J.A. Niskanen, Phys. Rep. 124, 1 (1985).

T.T.S. Kuo and G.E. Brown, Phys. Lett. 18, 54 (1965)

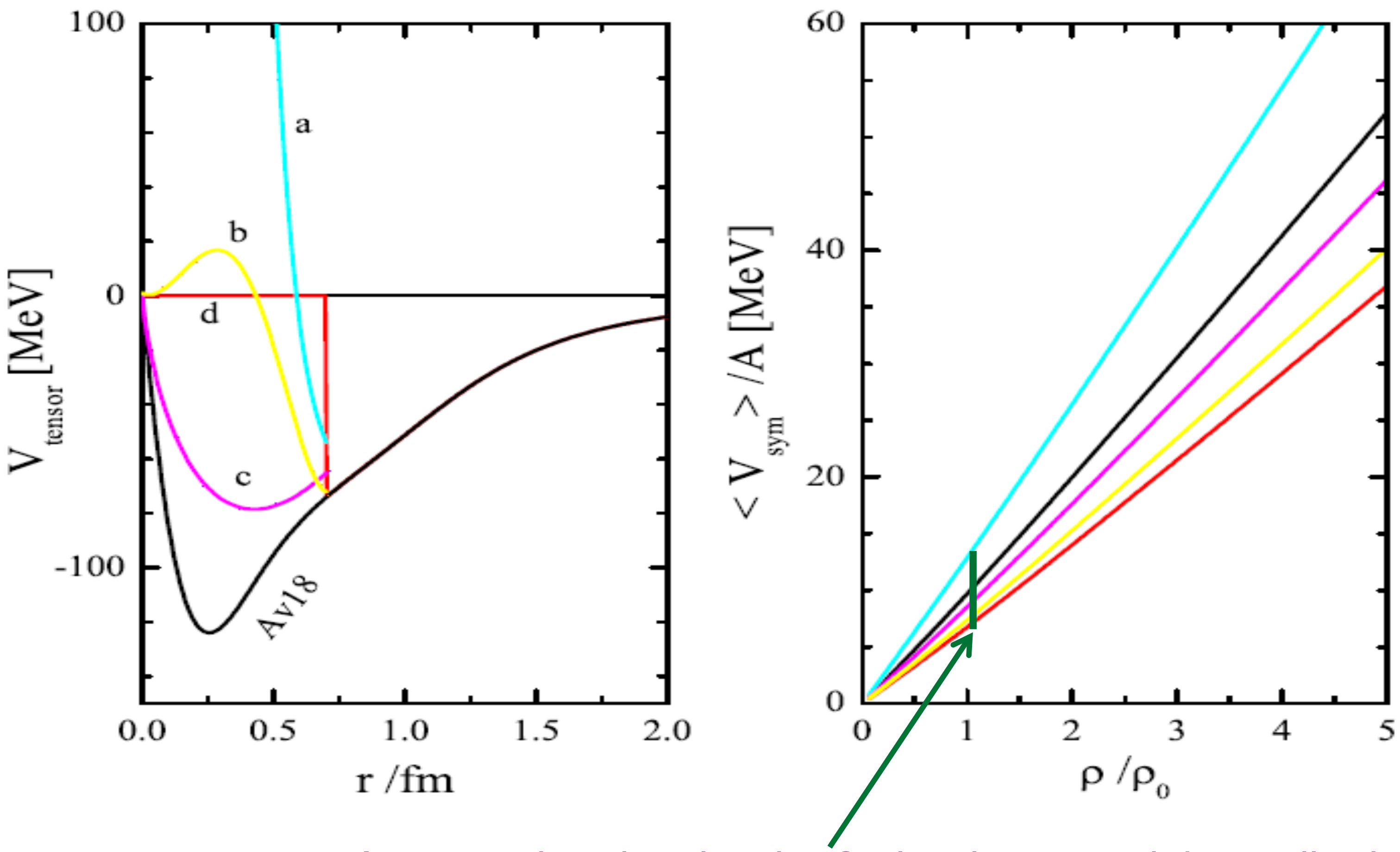
$$< V_{\rm sym} >= \frac{12}{e_{\rm eff}} < [V_t(\mathbf{r})]^2 >$$



$$\frac{< V_{\rm sym} >}{A} = \frac{12}{e_{eff}} \cdot \frac{k_F^3}{12\pi^2} \{ \frac{1}{4} \int V_t^2(r) d^3 r - \frac{1}{16} \int [\frac{3 j_1(k_F r)}{k_F r}]^2 V_t^2(r) d^3 r \}$$

Short-range tensor forces affects the high-density symmetry energy

C. Xu, A. Li and B.A. Li, Journal of Physics: Conference Series 420, 012190 (2013)



At saturation density, the 2nd order potential contribution
due to the tensor force is about 7-14 MeV, it is 9 MeV with Av18

Early microscopic calculations of SRC effects on EOS and $E_{sym}(\rho)$

EFFECT OF TENSOR FCRCES ON COMPOSITION OF DENSE MATTER Phys. Lett. B 39, 608 (1972)

V. R. PANDHARIPANDE and V. K. GARDE
Tata Institute of Fundamental Research, Bombay 5, India

Received 24 March 1972

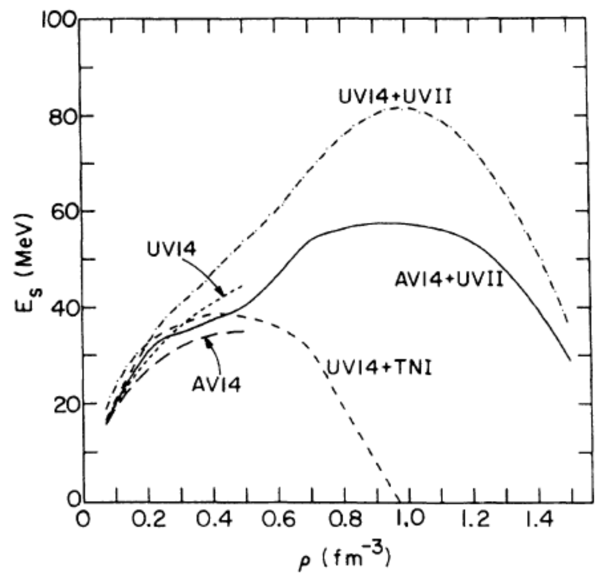
Equation of state for dense nucleon matter PRC 38, 1010 (1988)

R. B. Wiringa and V. Fiks*
Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

A. Fabrocini
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801
and Dipartimento di Fisica, Universita di Pisa, I-56100 Pisa, Italy
(Received 17 March 1988)

"**The disappearance of proton fraction (vanishing symmetry energy) at high densities is due primarily to the greater short-range repulsion in isospin singlet nucleon pairs compared to isospin triplet pairs. At high density, this short-range repulsion must dominate, and pure neutron matter is favored**."

Symmetry energy



Effects of isospin-dependent SRC on the kinetic symmetry energy of quasi-nucleons

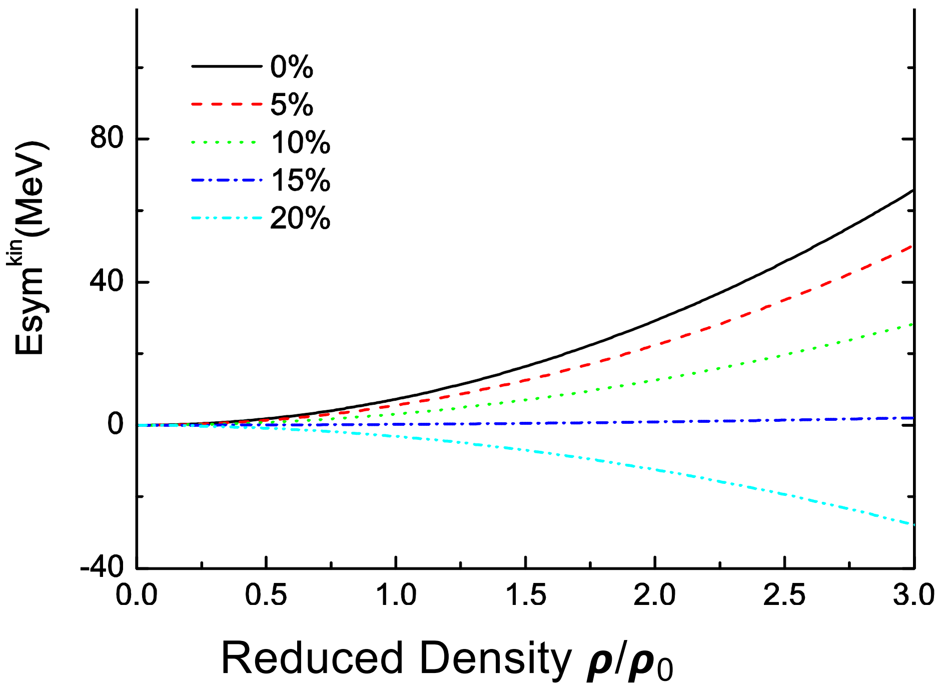
Chang Xu, Ang Li and Bao-An Li,
JPCS 420, 012190 (2013).

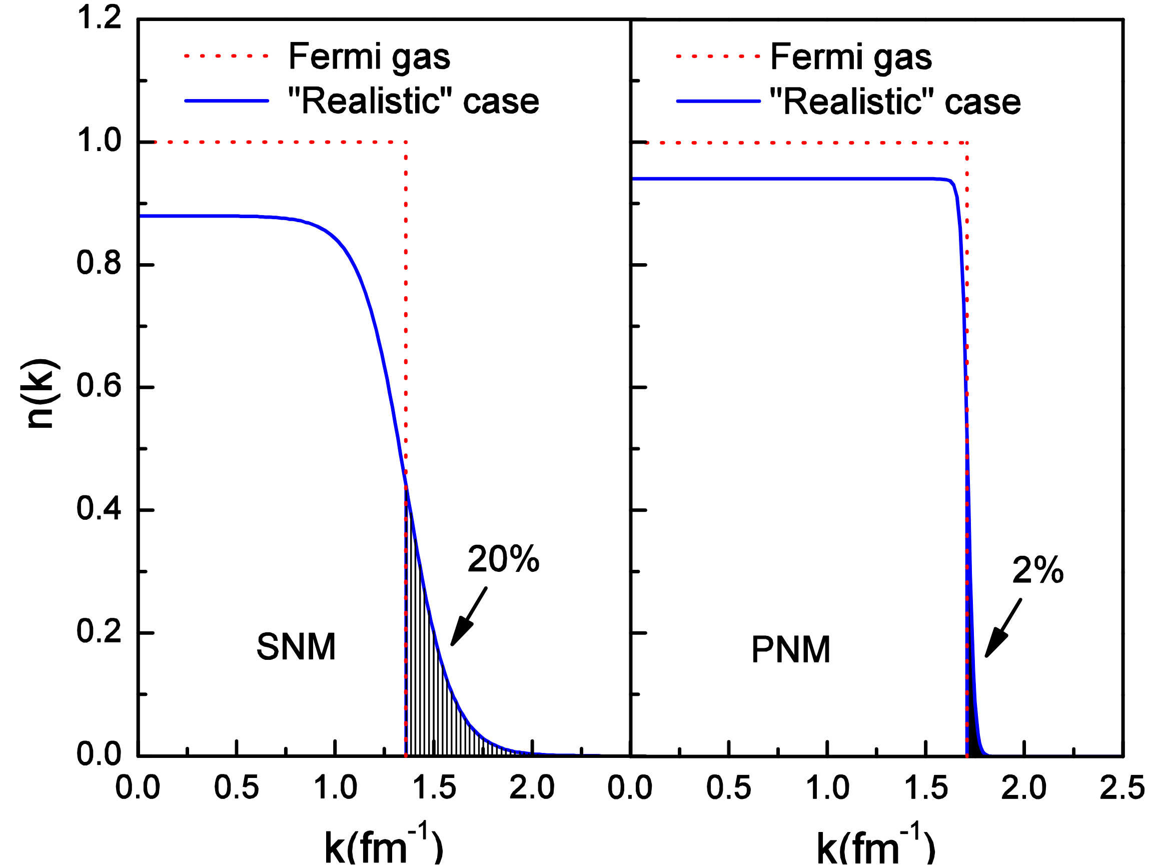
$$E_{kin} = \alpha \int_0^\infty \frac{\hbar^2 k^2}{2m} n(k) k^2 dk,$$

$$E_{sym}^{kin} = E_{PNM}^{kin} - E_{SNM}^{kin} < 0$$

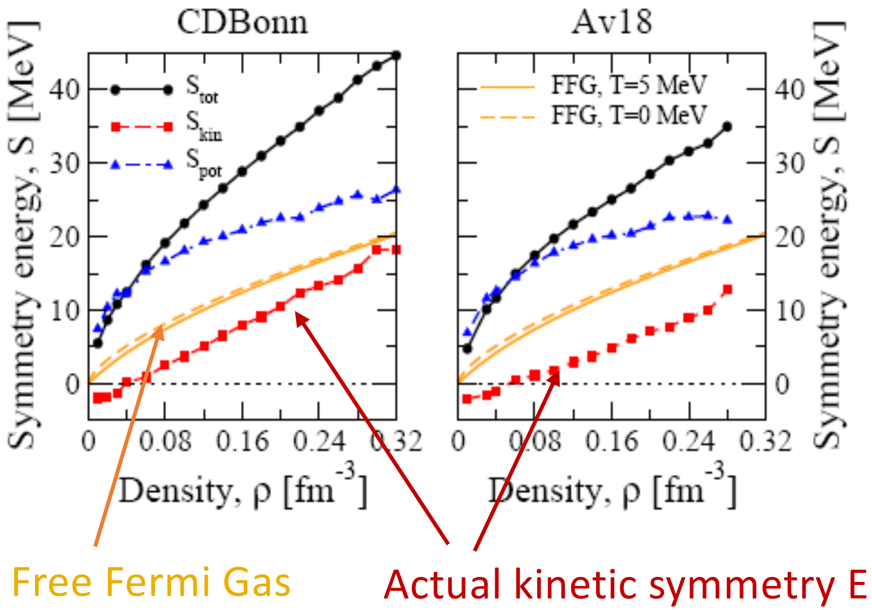
Free-Fermi Gas (FFG):
kinetic E_{sym}=12.3 MeV at ρ_0

if more than 15% nucleons are in the high-momentum tail of SNM due to the tensor force for n-p T=0 channel, the kinetic symmetry energy becomes negative





Self-Consistent Green's Function Approach



	$S_{\rm tot}$ [MeV]	$S_{\rm kin}$ [MeV]	$S_{\rm pot}$ [MeV]	L [MeV]
Av18	25.1	4.9	20.2	37.7
Nij1	27.4	4.6	22.8	48.5
CDBonn	28.8	7.9	20.9	52.6
N3LO	29.7	7.2	22.4	55.2

Arianna Carbone, Artur Polls, Arnau Rios, EPL 97, 22001 (2012)

A. Carbone, A. Polls, C. Providência, A. Rios, I. Vidaña, EPJA 50, 13 (2014)

Brueckner–Hartree–Fock approach (I. Vidana et al.)

Using the Hellmann–Feynman theorem

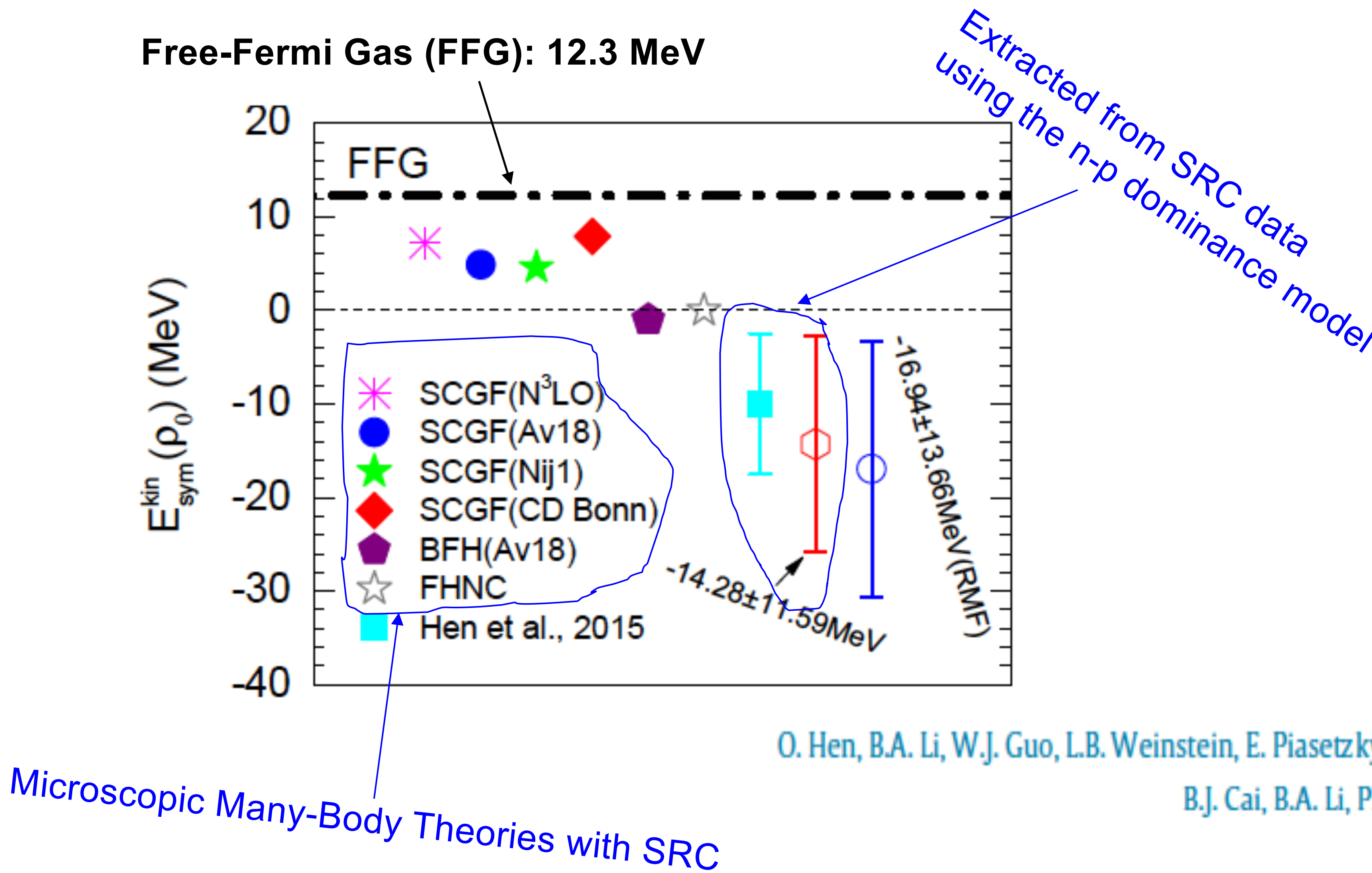
V18 potential plus the Urbana IX three-body force.

	E_{NM}	E_{SM}	E_{sym}	L
$\langle T \rangle$	53.321	54.294	−0.973	14.896
$\langle V \rangle$	−34.251	−69.524	35.273	51.604
Total	19.070	−15.230	34.300	66.500

Isaac Vidana, Artur Polls, Constanca Providencia

PRC84, 062801(R) (2011)

Reduced Kinetic symmetry energy of quasi-nucleons due to the isospin dependence of SRC

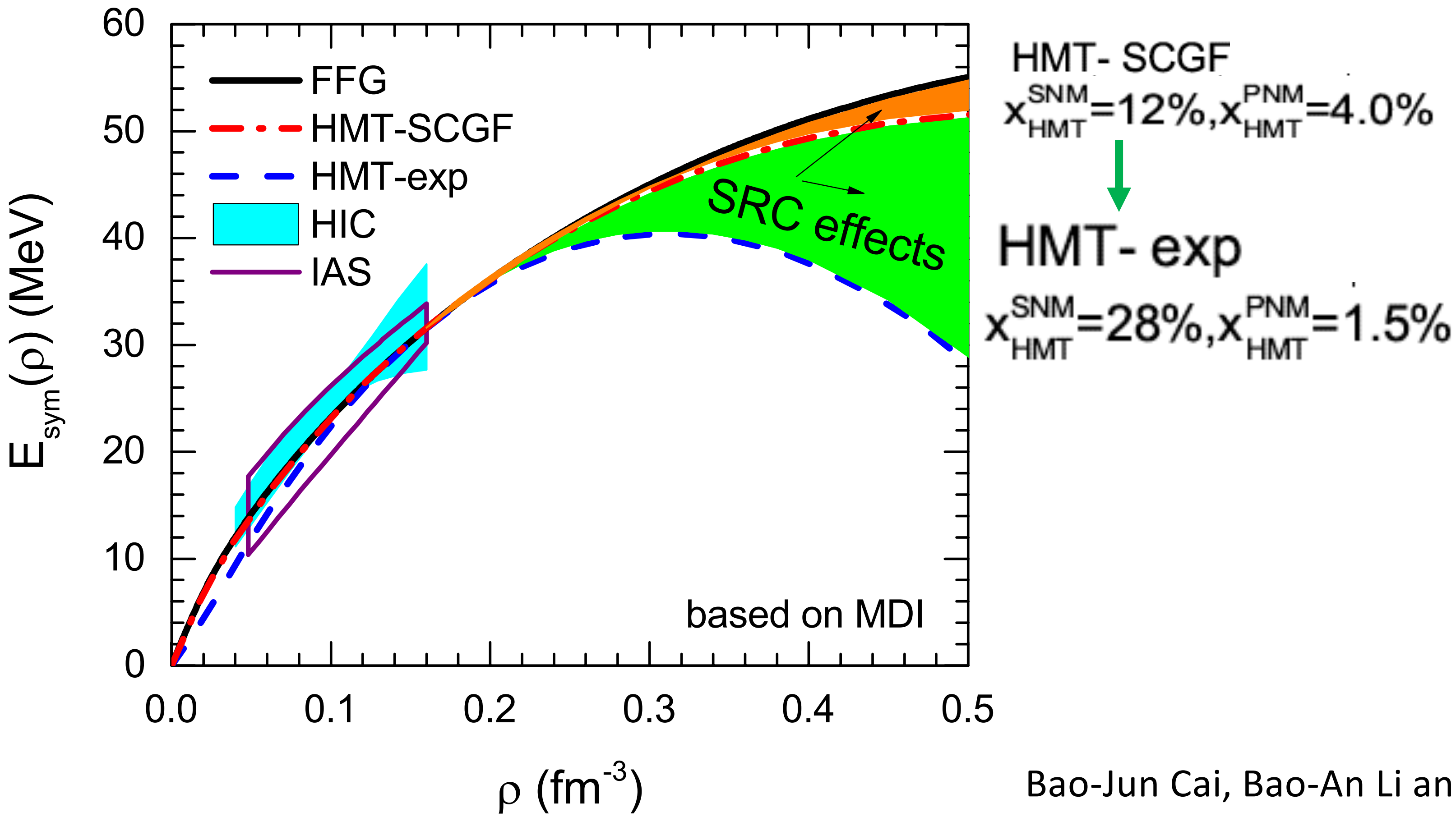


O. Hen, B.A. Li, W.J. Guo, L.B. Weinstein, E. Piasetzky, Phys. Rev. C 91 (2015) 025803.

B.J. Cai, B.A. Li, Phys. Rev. C 92 (2015) 011601(R).

Readjusting model parameters to reproduce the same saturation properties of nuclear matter as well as $E_{sym}(\rho_0)$=31.6 MeV and $L(\rho_0)$=58.9 MeV

Consequence: Symmetry energy gets softened at both low and high densities

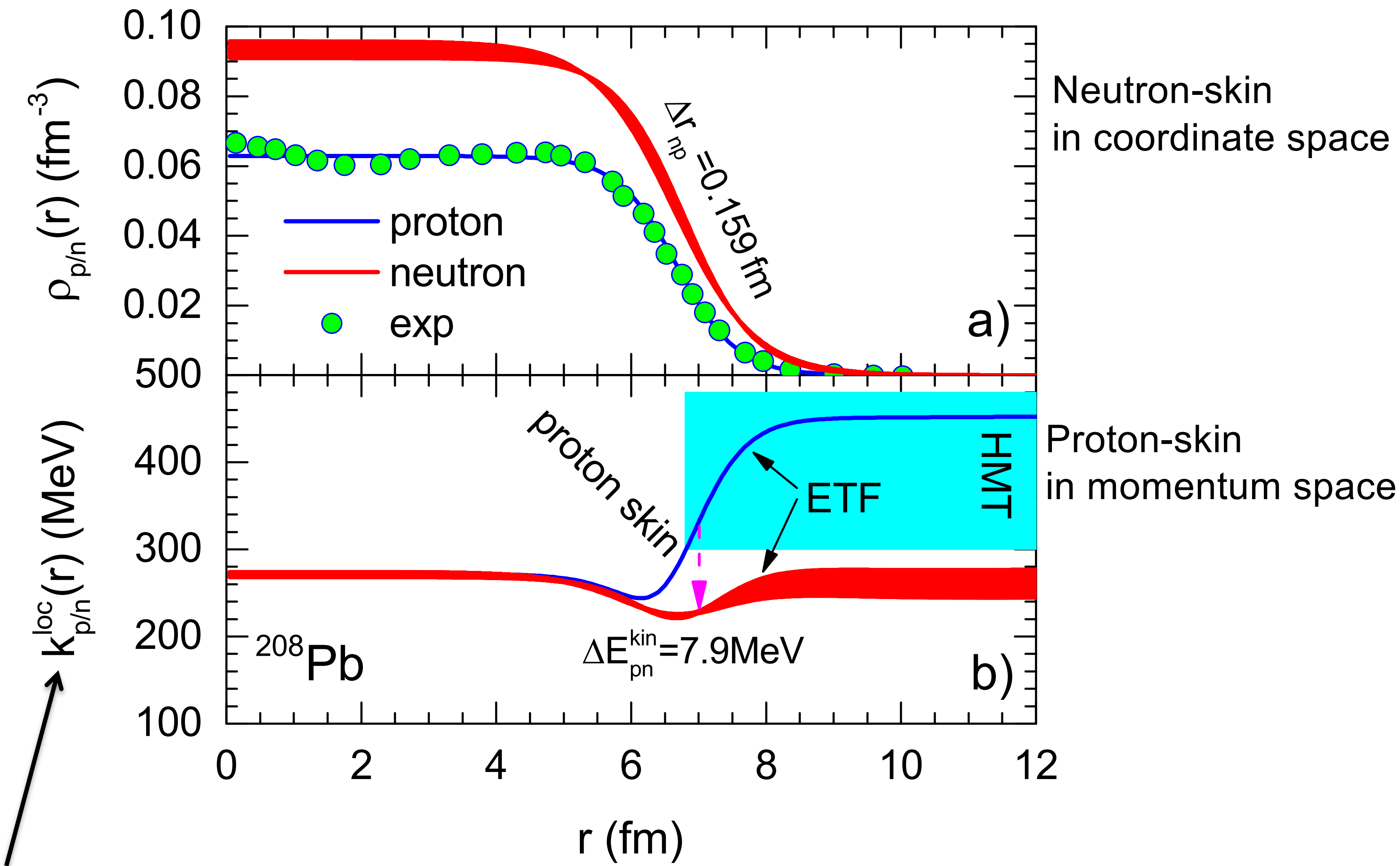


Bao-Jun Cai, Bao-An Li and Lie-Wen Chen,
AIP Conference Proceedings 2038, 020041 (2018)

Protons move much faster than neutrons in neutron-skins

--consistent with the Liouville theorem

Bao-Jun Cai, Bao-An Li and Lie-Wen Chen, PRC 94, 061302 (R) (2016)



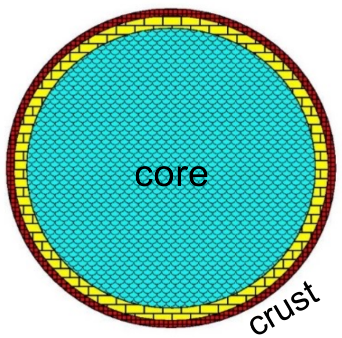
The average local momentum is defined via $k_J^{\mathrm{loc},2}(r)/2M = \varepsilon_J^{\mathrm{kin}}(r)/\rho_J(r)$

Symmetry energy controls composition and affects pressure in neutron stars

(1) The proton (electron) fraction $x(Y_e)$ is determined by the $E_{sym}(\rho)$ through charge neutrality and beta-equilibrium conditions:

$$x = 0.048[E_{sym}(\rho)/E_{sym}(\rho_0)]^3(\rho/\rho_0)(1-2x)^3$$

Critical for the cooling mechanism of protoneutron stars and associated neutrino emissions, appearance of hyperons, kaon condensation, baryon resonances…..



(2) The pressure in the npe matter at beta equilibrium:

$$P(\rho,\delta) = \rho^2\left[\frac{dE_0(\rho)}{d\rho} + \frac{dE_{\mathrm{sym}}(\rho)}{d\rho}\delta^2\right] + \frac{1}{2}\delta(1-\delta)\rho E_{\mathrm{sym}}(\rho)$$

(3) The crust-core transition density and pressure is determined by setting the incompressibility of neutron star matter =0 (speed of sound becomes imaginary):

$$K_\mu = \rho^2\frac{d^2E_0}{d\rho^2} + 2\rho\frac{dE_0}{d\rho} + \delta^2\left[\rho^2\frac{d^2E_{sym}}{d\rho^2} + 2\rho\frac{dE_{sym}}{d\rho} - 2E_{sym}^{-1}\left(\rho\frac{dE_{sym}}{d\rho}\right)^2\right] = 0$$

Lattimer & Prakash, Phys. Rep., 442, 109 (2007)

Incorporating the SRC-induced high-momentum tail in RMF

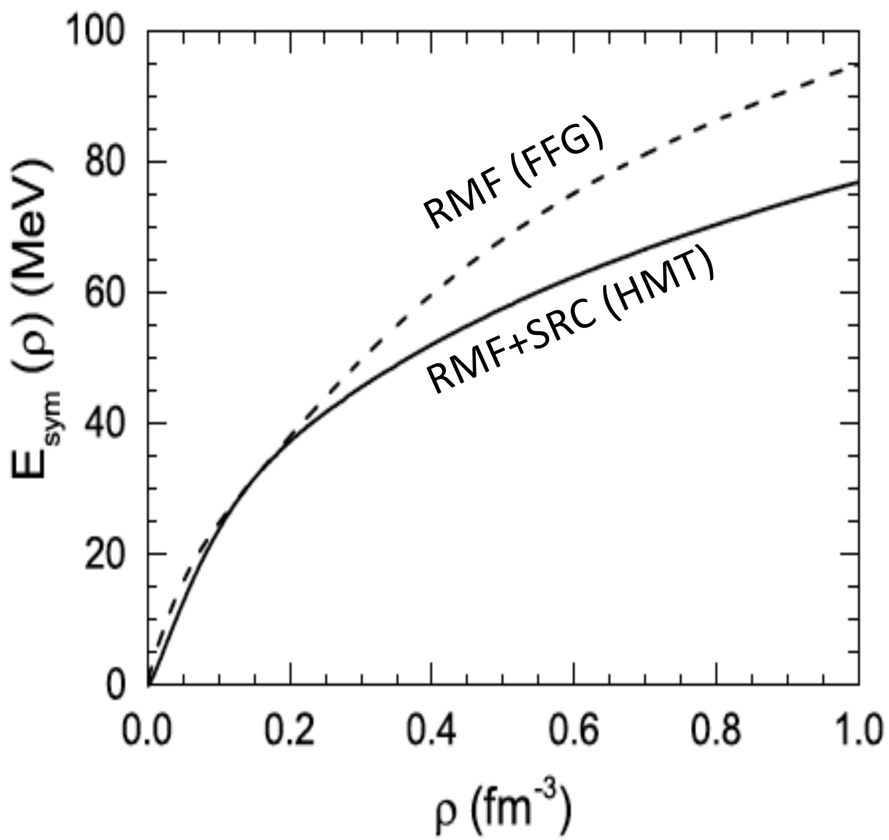
(via kinetic energy and scalar density)

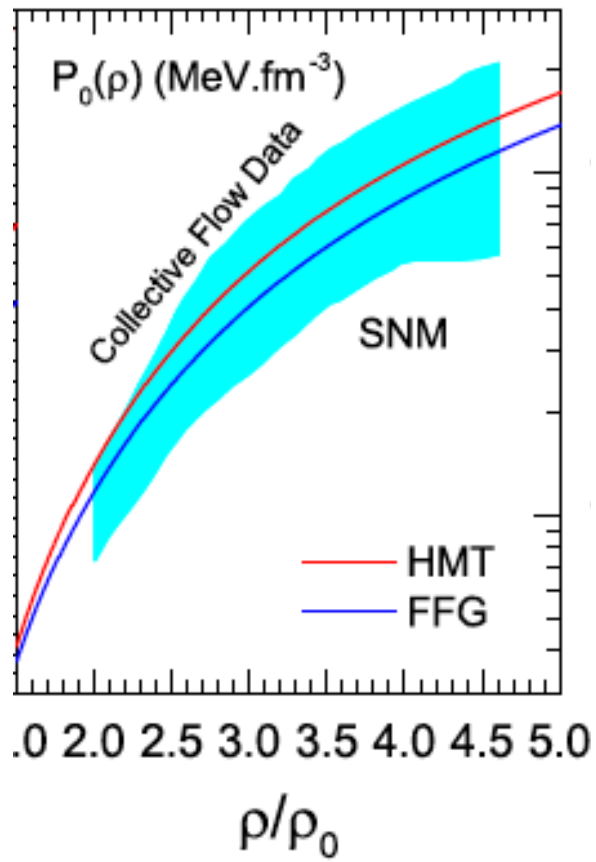
PHYSICAL REVIEW C 93, 014619 (2016)

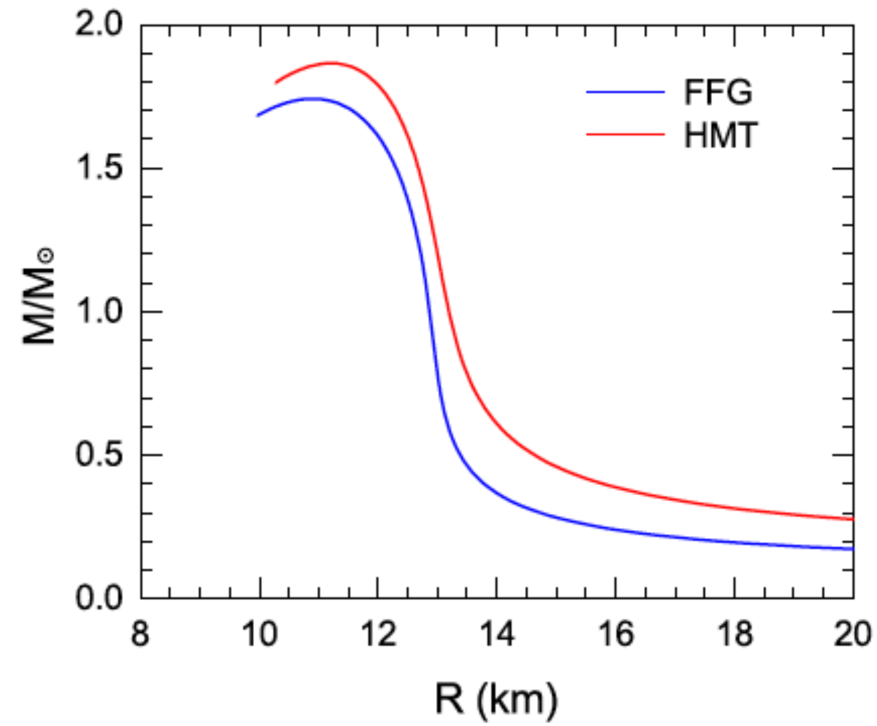
Bao-Jun Cai and Bao-An Li

$$\int_0^{k_F^J} (\text{FFG step function})\, f\, d\mathbf{k} \longrightarrow \int_0^{\phi_J k_F^J} n_{\mathbf{k}}^J\, (\text{HMT})\, f\, d\mathbf{k}.$$

e.g., scalar density: $$\rho_{S,J} = \frac{2}{(2\pi)^3} \int_0^{\phi_J k_F^J} n_{\mathbf{k}}^J d\mathbf{k} \frac{M_J^*}{\sqrt{|\mathbf{k}|^2 + M_J^{*2}}}$$

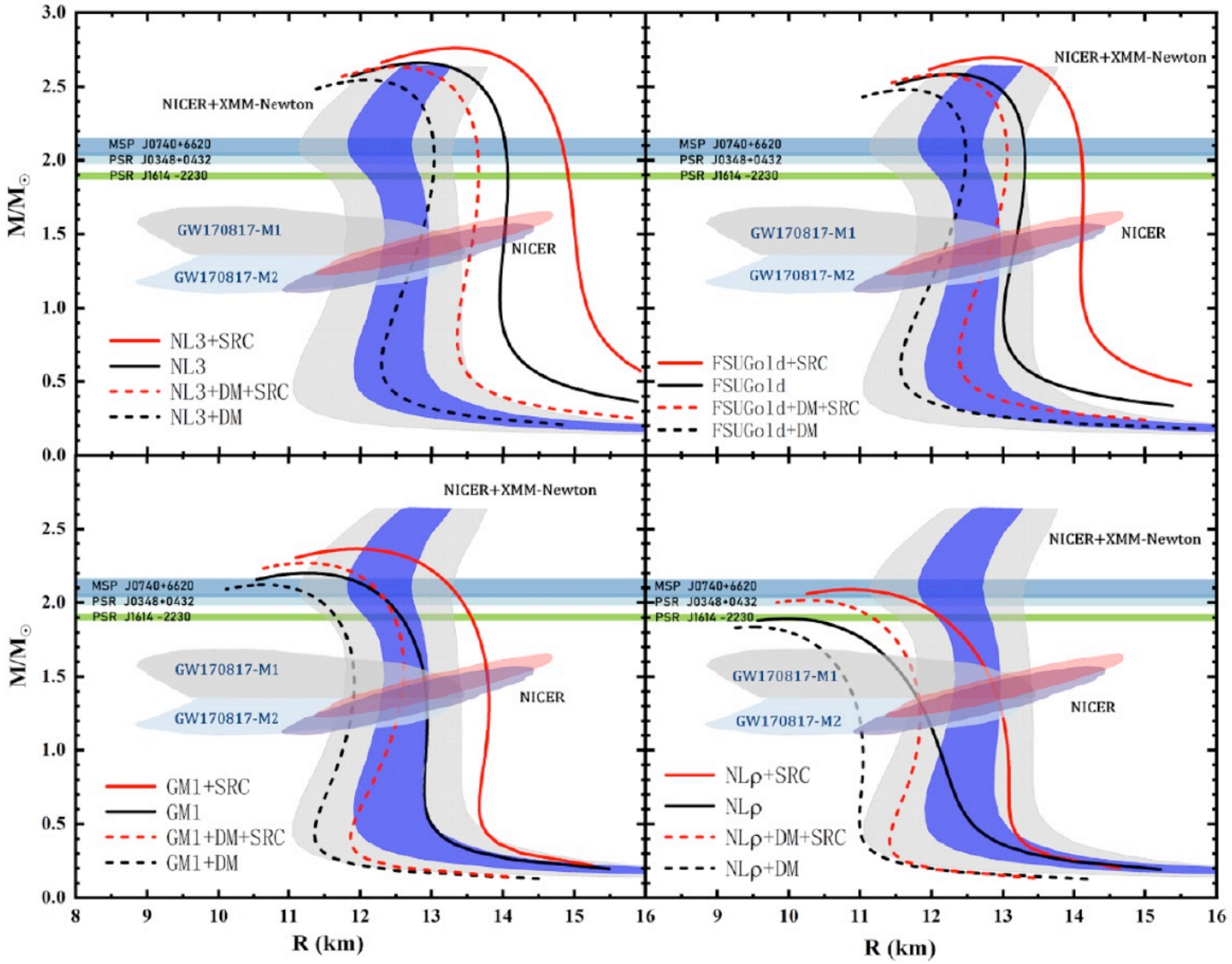






Neutron stars with short-range correlation and admixed dark matter

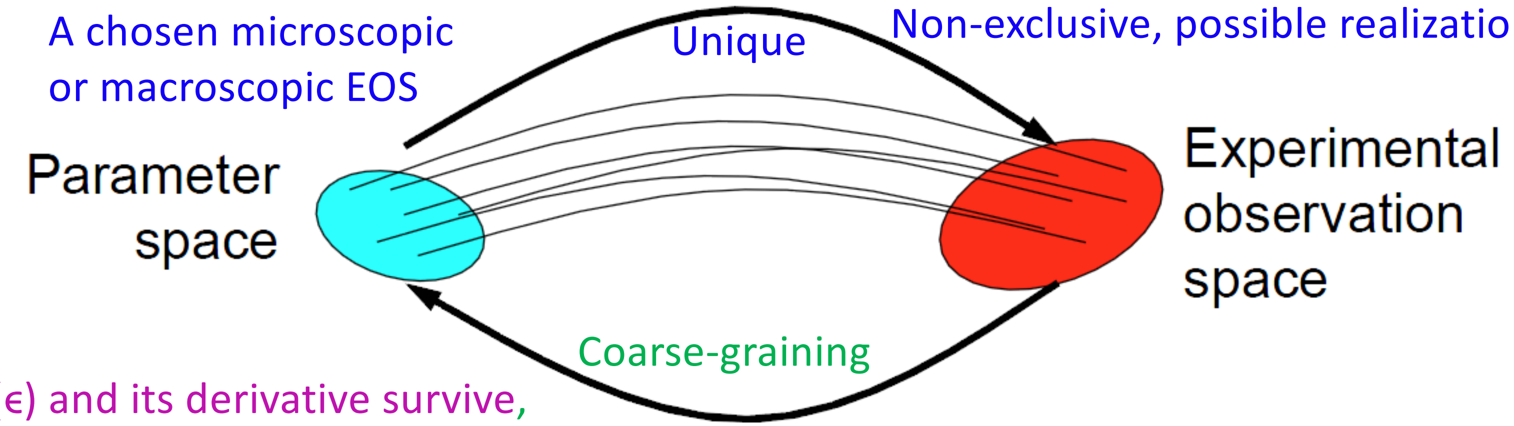
Bin Hong, ZhongZhou Ren, Chen Wu and XueLing Mu, *Class. Quantum Grav.* **40** 125007 (2023)



Forward-modeling versus backward inference

A chosen microscopic or macroscopic EOS

Non-exclusive, possible realizations consistent with experimental data



Masses, radii, tidal deformations of neutron stars

P(ϵ) and its derivative survive,

NOT a unique underlying Lagrangian or EOS model

$$
\begin{aligned}
\mathcal{L} = & \sum_{\alpha=n,p} \bar{\psi}_\alpha \Big(\gamma^\mu \Big(i\partial_\mu - g\omega\omega_\mu - \frac{1}{2} g\rho \tau_\alpha \cdot \rho_\mu \Big) - (M - g\sigma\sigma) - g\delta\tau_\alpha \cdot \delta \Big) \psi_\alpha \\
& + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{2} m_\sigma^2 \sigma^2 + \frac{\zeta_0}{4!} g^2\omega (\omega_\mu\omega^\mu)^2 - g\sigma m_\sigma^2 M \frac{k_3}{3!} + \frac{k_4}{4!}\frac{g\sigma}{M}\sigma^3 \\
& + \frac{1}{2} m_\omega^2 \omega_\mu\omega^\mu - \frac{1}{4} F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\frac{g\sigma\sigma}{M}\Big(\eta_1 + \frac{\eta_2}{2}\frac{g\sigma\sigma}{M}\Big) m_\omega^2 \omega_\mu\omega^\mu \\
& + \frac{1}{2}\eta_\rho m_\rho^2 \frac{g\sigma\sigma}{M} (\rho_\mu \cdot \rho^\mu) + \frac{1}{2} m_\rho^2 (\rho_\mu \cdot \rho^\mu) - \frac{1}{4} R_{\mu\nu}R^{\mu\nu} - \Lambda_\omega g^2\omega g^2\rho (\omega_\mu\omega^\mu)(\rho_\mu \cdot \rho^\mu) \\
& + \frac{1}{2}\partial_\mu\delta\partial^\mu\delta - \frac{1}{2} m_\delta^2 \delta^2
\end{aligned}
$$

Tolman-Oppenheimer-Volkoff (TOV) equations

$$
\frac{dP}{dr} = \underbrace{-\frac{GM\varepsilon}{r^2}}_{\text{Newtonian}} \underbrace{\overbrace{\left(1 + \frac{P}{\varepsilon c^2}\right)}^{\text{matter correction}} \overbrace{\left(1 + \frac{4\pi r^3 P}{Mc^2}\right)}^{\text{matter-geometry coupling}} \underbrace{\left(1 - \frac{2GM}{rc^2}\right)^{-1}}_{\text{geometry correction}}}_{\text{matter+geometry corrections: } \gg 1}; \quad \overbrace{\frac{dM}{dr} = 4\pi r^2 \varepsilon / c^2}^{\text{same as Newtonian}}
$$

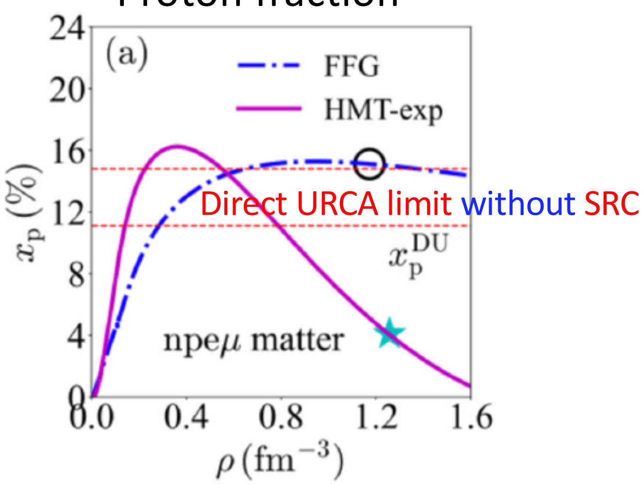
Composition blindness/degeneracy of TOV equations: Regardless how and what compositions are used, as long as the same EOS $P(\varepsilon)$ is used, the same mass-radius sequence is obtained→ EOS $P(\varepsilon)$ is necessary and sufficient to get the M and R but NOT sufficient to understand NS physics unambiguously.

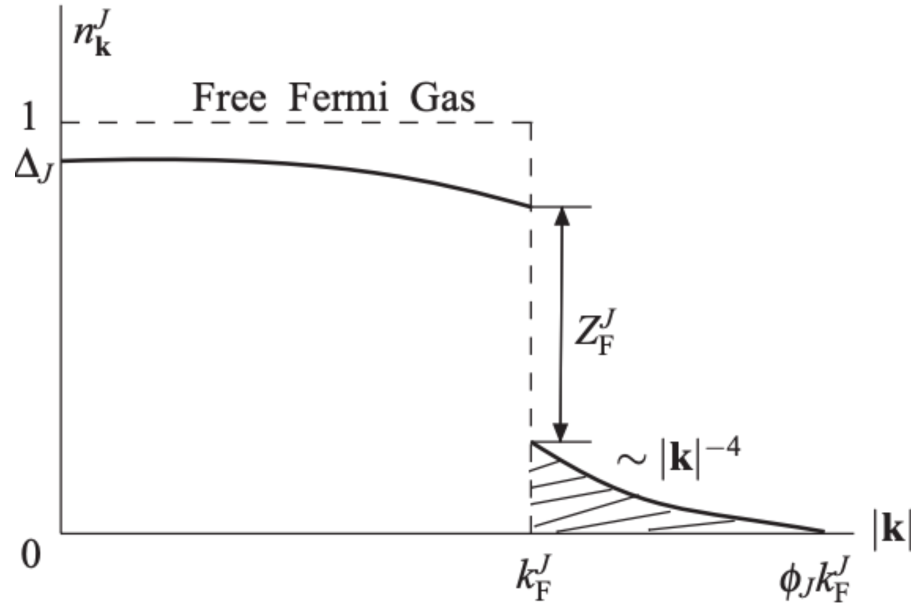
Degeneracy → Universality or consistent patterns under vastly different conditions

Cooling rates of protoneutron stars are sensitive to microscopic processes involving SRC

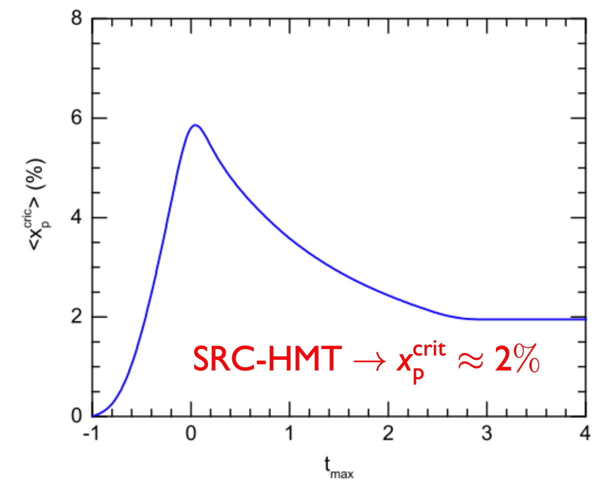
Very complicated, no self-consistent calculations including all known effects, existing cooling curves are not exclusive

Proton fraction





Direct URCA limit with SRC



Direct URCA

$$n \to p + e^- + \bar{\nu}_e \text{ and } p + e^- \to n + \nu_e$$

B.A. Li, B.J. Cai, L.W. Chen and J. Xu, Prog. Part. Nucl. Phys. 99,29 (2018)

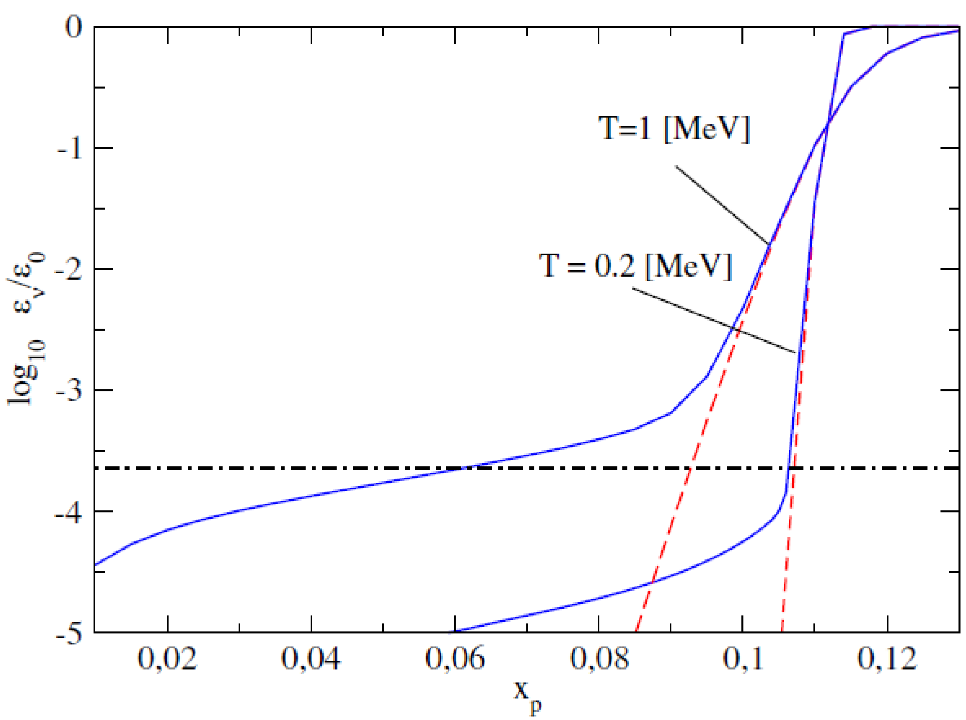
Nucleon short-range correlations and high-momentum dynamics: implications on the equation of state of dense matter
Bao-Jun Cai[1,2,a], Bao-An Li[3,b], and Yu-Gang Ma[1,2,4,c]
Eur. Phys. J. Spec. Top.
https://doi.org/10.1140/epjs/s11734-026-02227-9

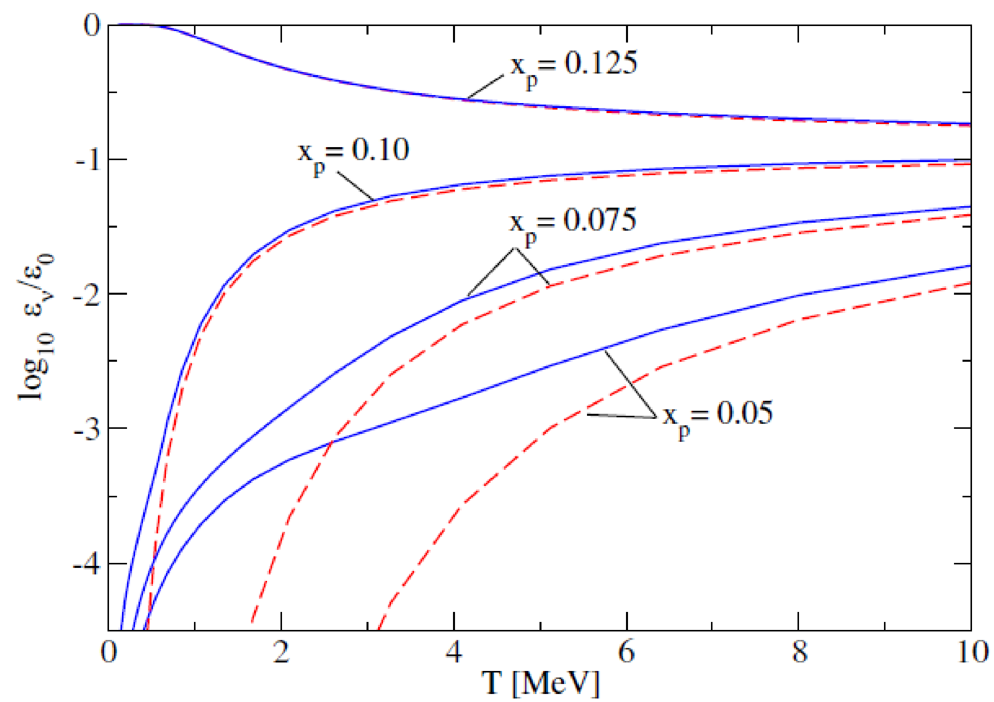
Short-Range Correlations and Urca Process in Neutron Stars

Armen Sedrakian*

PHYSICAL REVIEW LETTERS **133**, 171401 (2024)

Neutrino emissivity with and without SRC





Summary

The most fundamental but lest known physics underlying the high-density symmetry energy

Spin-isospin dependence of nucleon interactions at short distance

$$V_{np}(T_0) \neq V_{np}(T_1)$$

Tensor force and short-range repulsive core

Isospin dependent short range nucleon-nucleon correlation

(1) Modification of nucleon momentum distribution at zero temperature w.r.t. the step function for Free Fermi Gas

(2) Protons move faster than neutrons in n-rich nuclei/matter

Reduced kinetic symmetry energy w.r.t. the Free Fermi Gas

Potential symmetry energy

EOS

Structures and collisions of nuclei and neutron stars

Dynamical origin of the EMC effect

(1) Only the momentum distributions of quarks in SRC nucleon pairs in nuclei are modified w.r.t. to free nucleons

(2) Quarks in protons of n-rich nuclei are modified more

→ u quarks move faster than d quarks in n-rich nuclei

Frontiers of QCD

The flavor and spin dependent momentum distributions of quarks and gluons in nuclei and nuclear matter

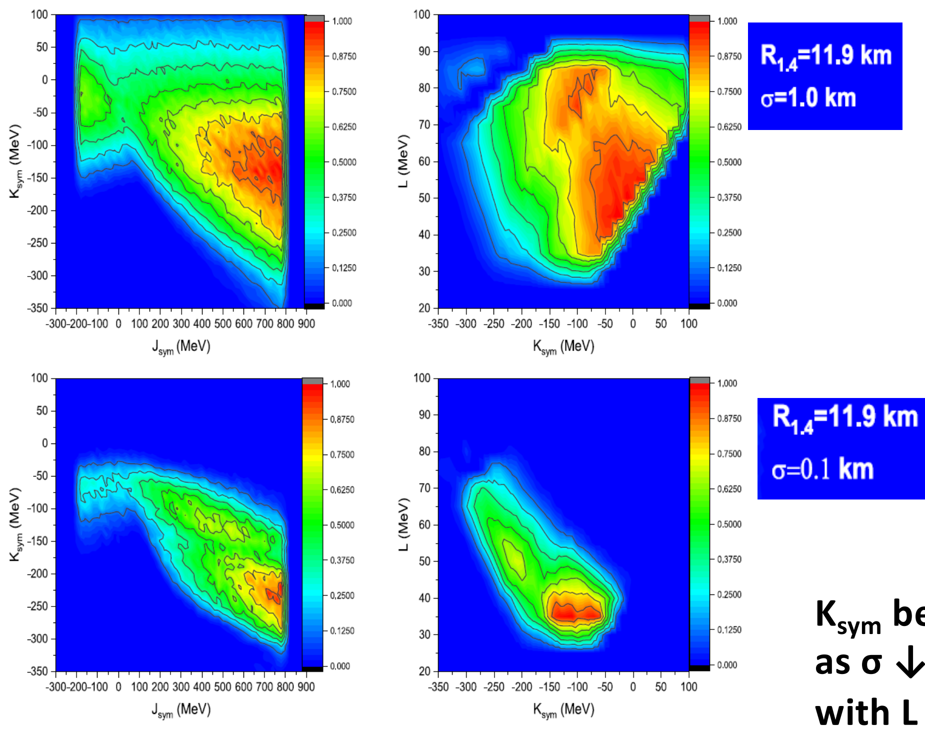
nucleons ? quarks

The proposed high-precision measurements of neutron star radii are SUPER-expensive in Time & Efforts

What do we expect high-precision R to constrain?

Bao-An Li, Xavier Grundler, Wen-Jie Xie, Nai-Bo Zhang, PRD 110, 103040 (2024)

Using mock radius data: $R_{1.4}$=11.9 ±σ

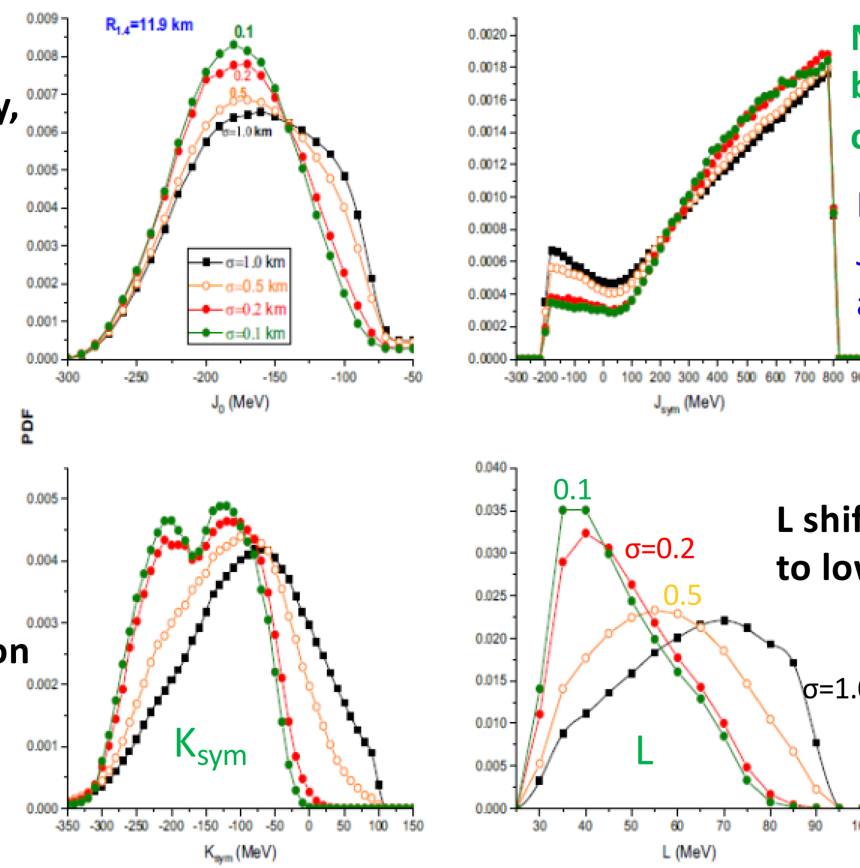


Constrained by M_{TOV} & casualty, not much by R

K_{sym} becomes bimodal as σ ↓ duo its correlation with L and J_{sym}

Strong EOS-parameter correlations appear at higher precisions

Skewness J_0 of SNM **Skewness J_{sym} of E_{sym}**



NOT constrained by R data, regardless of its precision

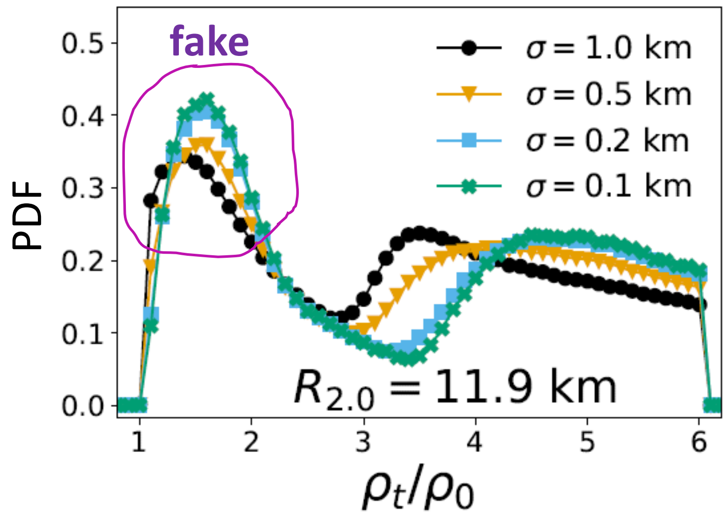
R probes EOS ~2ρ₀, J_{sym} characterizes E_{sym} at ρ>3ρ₀

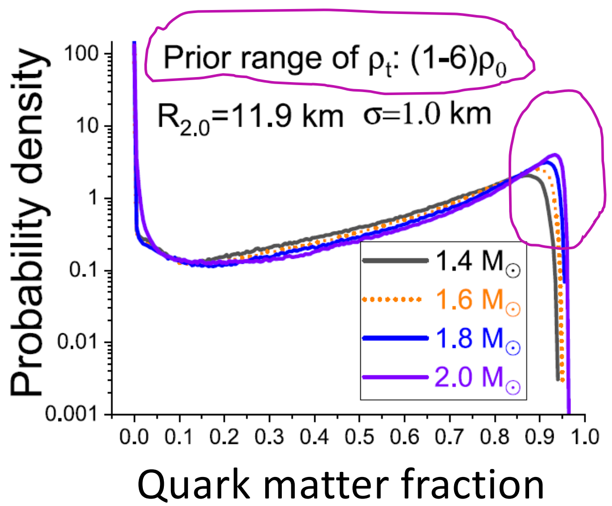
L shifts systematically to lower values as σ ↓

Can the high-precision R tell us anything new about high-density EOS?

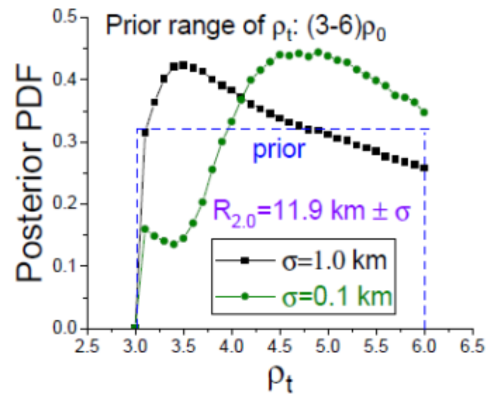
Bao-An Li, Xavier Grundler, W.J. Xie, N.B. Zhang, ApJ 998, 262 (2026)

(1) Pure statistics can NOT replace physics insight; existing NS data are not sufficient to constrain all parameters

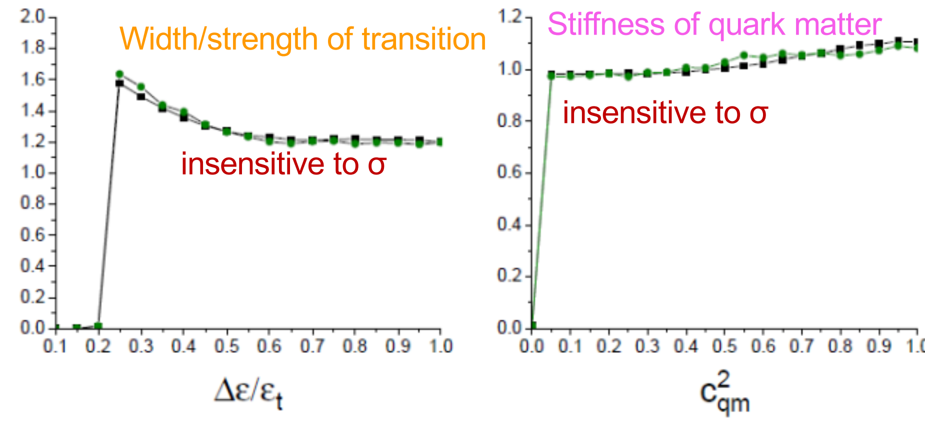




Consistent with indications of Beam Energy Scan Experiments at RHIC



(3) Deep core physics is largely invisible to R, regardless of its precision



(2) Effects on hadron-quark transition density

Low ρ_t produces strong EOS softening, large σ tolerates these softer solutions, and shifts the hadronic pressure to higher values (Jensen's bias)

High-precision R data prefer delayed quark deconfinement

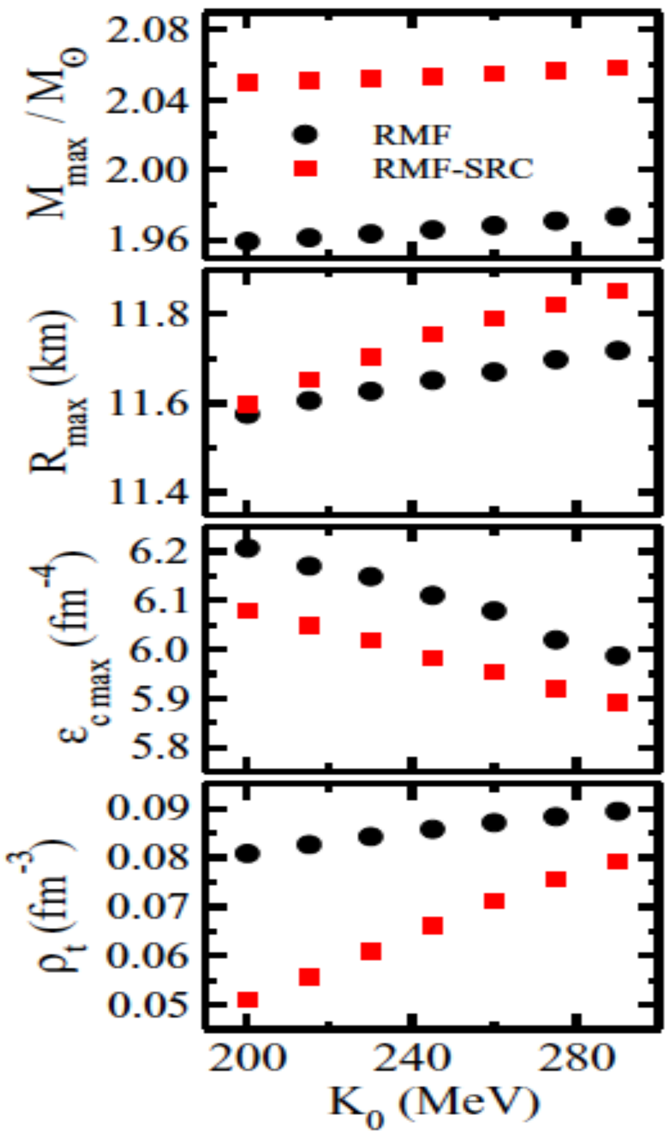
Do not probe the quark EOS itself

Effects of short-range nuclear correlations on the deformability of neutron stars

PHYSICAL REVIEW C **101**, 065202 (2020)

Lucas A. Souza, Mariana Dutra, César H. Lenzi, and Odilon Lourenço

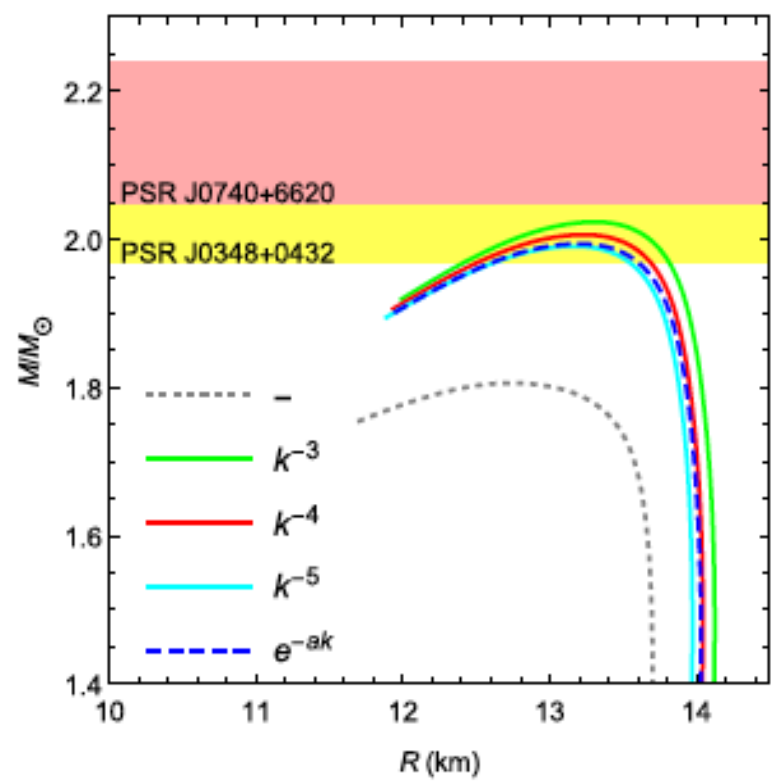
Departamento de Física, Instituto Tecnológico de Aeronáutica, DCTA, 12228-900, São José dos Campos, SP, Brazil



Impacts of nucleon-nucleon short-range correlations on neutron stars

Hao Lu [a], Zhongzhou Ren [b,c,*], Dong Bai [b]

Nuclear Physics A 1011 (2021) 122200

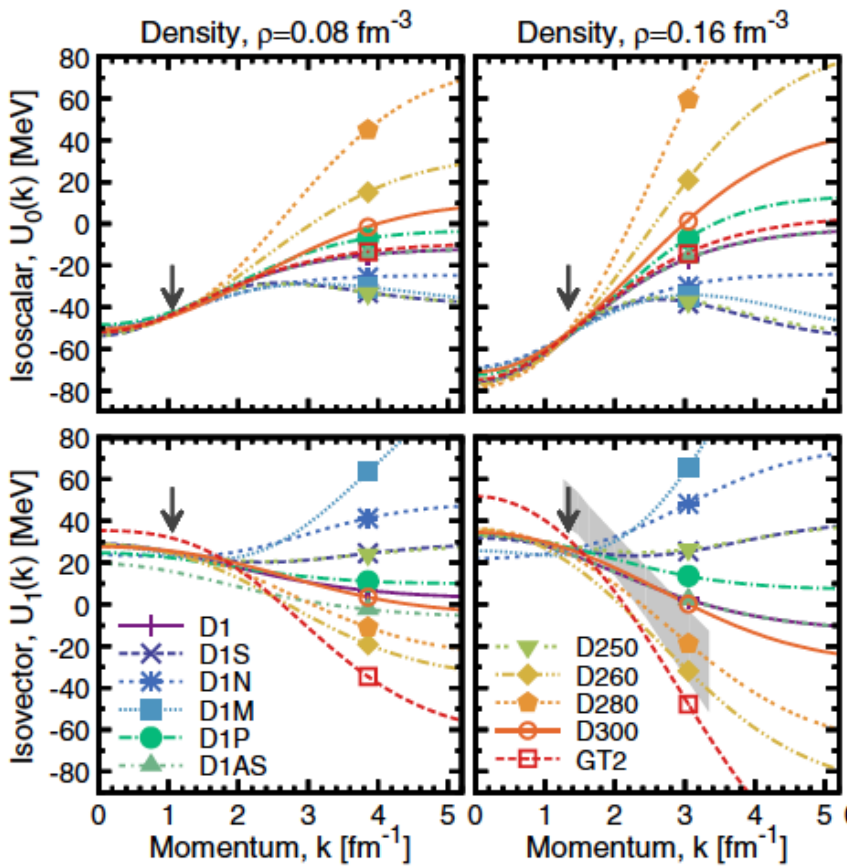


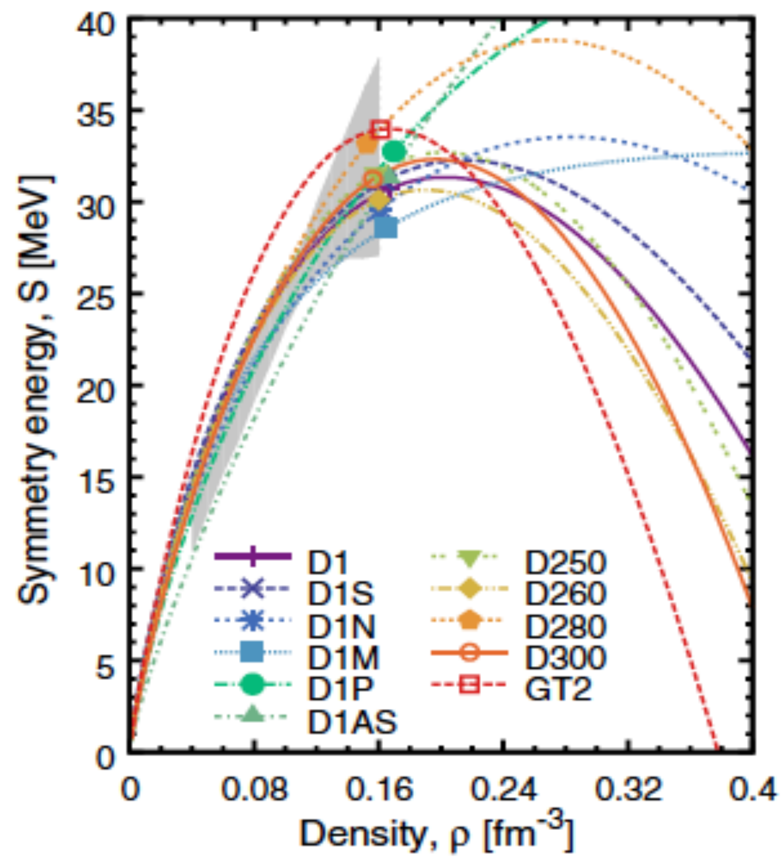
Density and momentum dependence of Isoscalar and Isovector potentials
Gogny Hartree-Fock predictions using 11 popular Gogny (finite-range) forces

PHYSICAL REVIEW C **90**, 054327 (2014)

Isovector properties of the Gogny interaction

Roshan Sellahewa and Arnau Rios





Modified Gogny Hartree-Fock energy density functional incorporating SRC-induced high momentum tail in the single nucleon momentum distribution

Kinetic — Zero-range Two-body force — Three-body force

$$E(\rho,\delta) = E^{\mathrm{kin}}(\rho,\delta) + \frac{A_\ell(\rho_{\mathrm{p}}^2+\rho_{\mathrm{n}}^2)}{2\rho\rho_0} + + \frac{A_{\mathrm{u}}\rho_{\mathrm{p}}\rho_{\mathrm{n}}}{\rho\rho_0} + \frac{B}{\sigma+1}\left(\frac{\rho}{\rho_0}\right)^{\sigma}(1-x\delta^2)$$

$$+\sum_{J,J'}\frac{C_{J,J'}}{\rho\rho_0}\int \mathrm{d}\mathbf{k}\mathrm{d}\mathbf{k}' f_J(\mathbf{r},\mathbf{k}) f_{J'}(\mathbf{r},\mathbf{k}')\Omega(\mathbf{k},\mathbf{k}'),$$

Momentum-dependent potential energy due to finite-range 2-body interaction

$$E^{\mathrm{kin}}(\rho,\delta) = \sum_{J=\mathrm{n,p}}\frac{1}{\rho_J}\int_0^\infty \frac{\mathbf{k}^2}{2M} n_{\mathbf{k}}^J(\rho,\delta)\mathrm{d}\mathbf{k}$$

$$\Omega(\mathbf{k},\mathbf{k}') = \left[1+\frac{(\mathbf{k}-\mathbf{k}')^2}{\Lambda^2}\right]^{-1}$$

SRC-induced HMT in the single-nucleon momentum distribution affects both the kinetic energy and the momentum-dependent part of the potential energy

C. B. Das, S. Das Gupta, C. Gale, Bao-An Li Phys.Rev.C67:034611,2003

Confirmation by Microscopic Many-Body Theories

1. Isaac Vidana, Artur Polls, Constanca Providencia
PRC84, 062801(R) (2011)

Brueckner--Hartree--Fock approach using the Argonne V18 potential plus the Urbana IX three-body force

2. Arianna Carbone, Artur Polls, Arnau Rios, EPL 97, 22001 (2012)
A. Carbone, A. Polls, C. Providência, A. Rios, I. Vidaña, EPJA 50, 13 (2014)
Self-Consistent Green's Function Approach with Argonne Av18, CDBonn, Nij1, N3LO interactions

3. Alessandro Lovato, Omar Benhar et al.,
extracted from results already published in
Phys. Rev. C83:054003,2011
Using Argonne V'_6 interaction
Fermi-Hyper-Netted-Chain (FHNC)
Single Operator Chains (SOC)

4. A. Rios, A. Polls, W. H. Dickhoff
PRC 89, 044303 (2014).
Ladder Self-Consistent Green Function

They all included the tensor force and many-body correlations using different techniques

Brueckner--Hartree—Fock prediction