Probing the Symmetry Energy of Dense Neutron-Rich Matter with Terrestrial Experiments and Astrophysical Observations

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- What do we currently know about $E_{sym}(\rho)$?
- How to probe the $E_{sym}(\rho)$?
- How does the $E_{sym}(\rho)$ impact the speed of sound at high ρ?
- Why is the $E_{sym}(\rho)$ still so uncertain especially at high ρ?

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

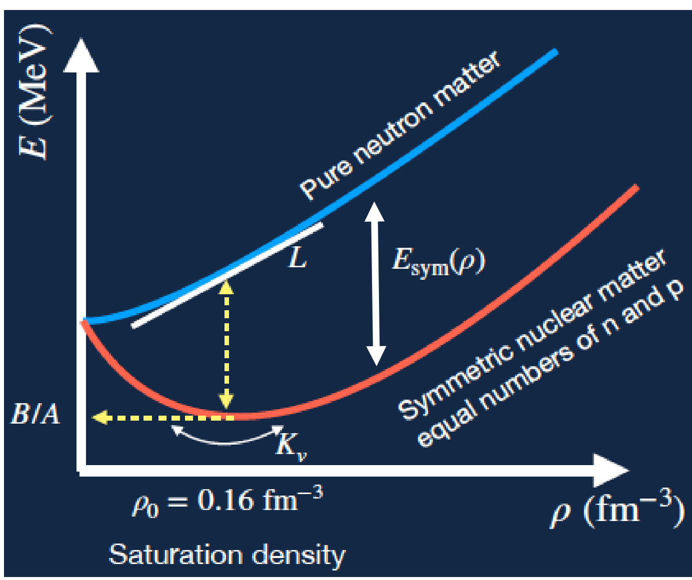
symmetry energy

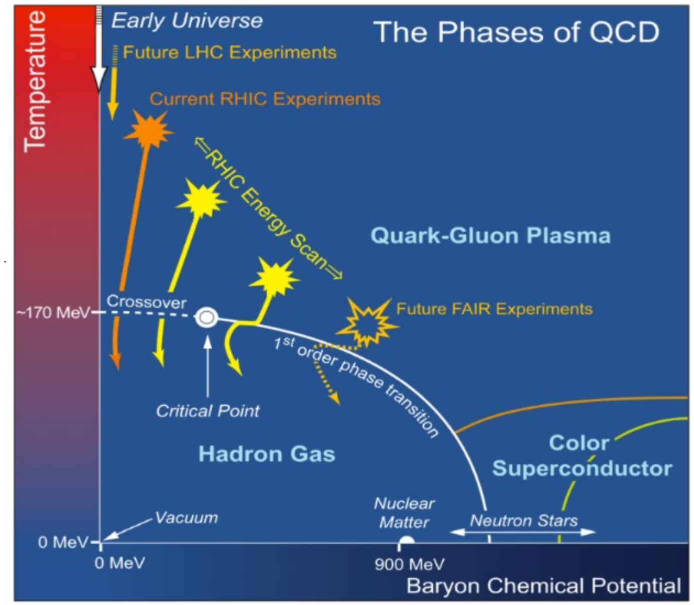
Isospin asymmetry

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

Energy per nucleon in symmetric matter

Energy in asymmetric nucleonic matter





density

New opportunities

Isospin asymmetry

$\delta = (\rho_n - \rho_p)/\rho$

Isospin effects in observables of structures & collisions of neutron stars & heavy nuclei

$P_{asy}(\rho)$

$$E_{sym}(\rho)=E_{sym}(\rho_i)+\int_{\rho_i}^{\rho}\frac{P_{PNM}(\rho_v)-P_{SNM}(\rho_v)}{\rho_v^2}d\rho_v$$

Fundamental Microphysics Theories underlying each term in the EOS , what …, why …., where …how

Experimental and Observational Macrophysics underlying each observable and phenomenon, what …, why …., where …how

Empirical parameterizations especially useful for meta-modeling of EOS

Transport model simulations of heavy-ion collisions, energy density functionals for nuclear structures, Bayesian inferences of EOS, properties of neutron stars, waveforms of gravitational waves, ….

$$E(\rho,\delta) = E_0(\rho) + E_{\rm sym}(\rho)\cdot\delta^2$$

Assuming no hadron-quark phase transition

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

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

Near the saturation density $\boldsymbol{\rho}_{0,}$ they are Taylor expansions, appropriate for structure studies. Just parameterizations when applied to heavy-ion collisions and the core of neutron stars

Single-nucleon potential in isospin-asymmetric nuclear matter

+ for neutrons

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

- 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.

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

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

Kinetic

Potential

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

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

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

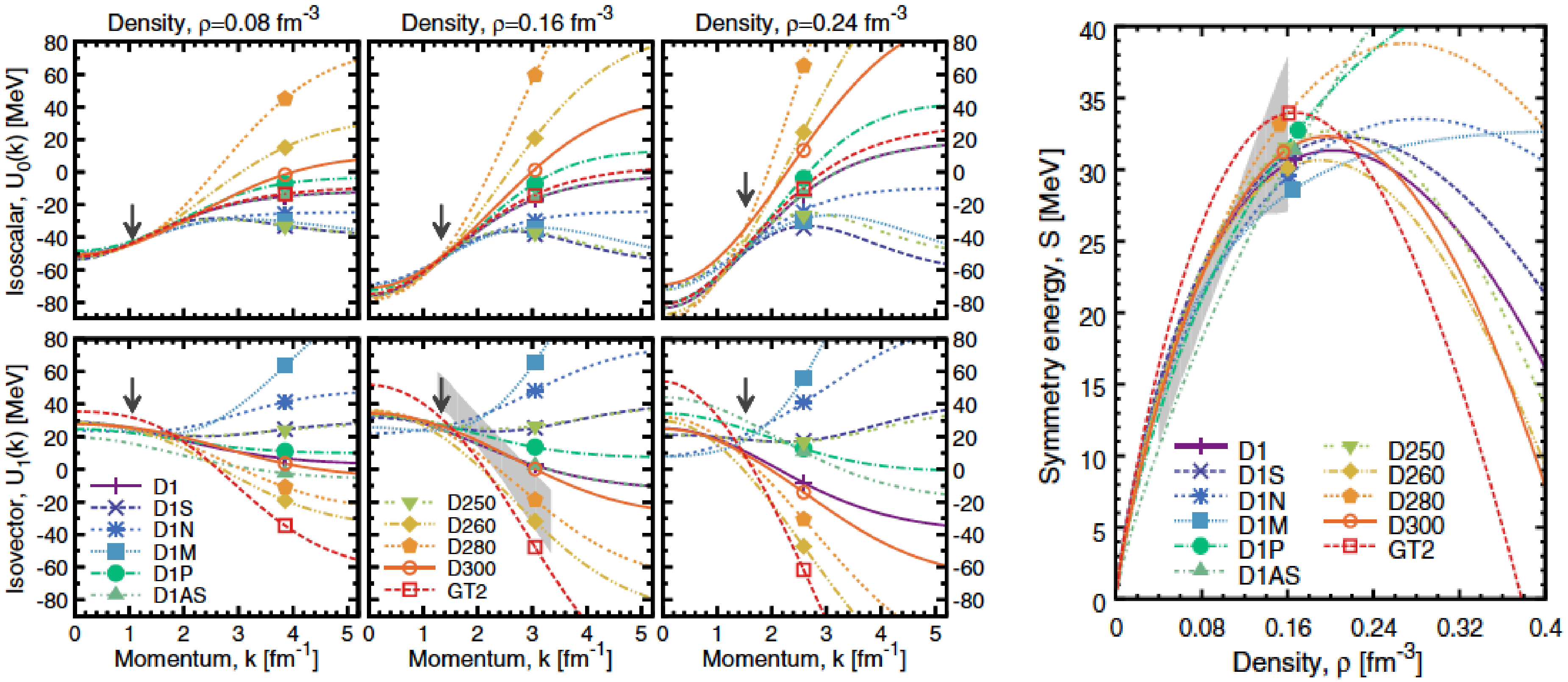
B.A. Li, B.J. Cai, L.W. Chen and J. Xu,
Progress of Particle and Nuclear Physics, 99 (2018) 29.

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

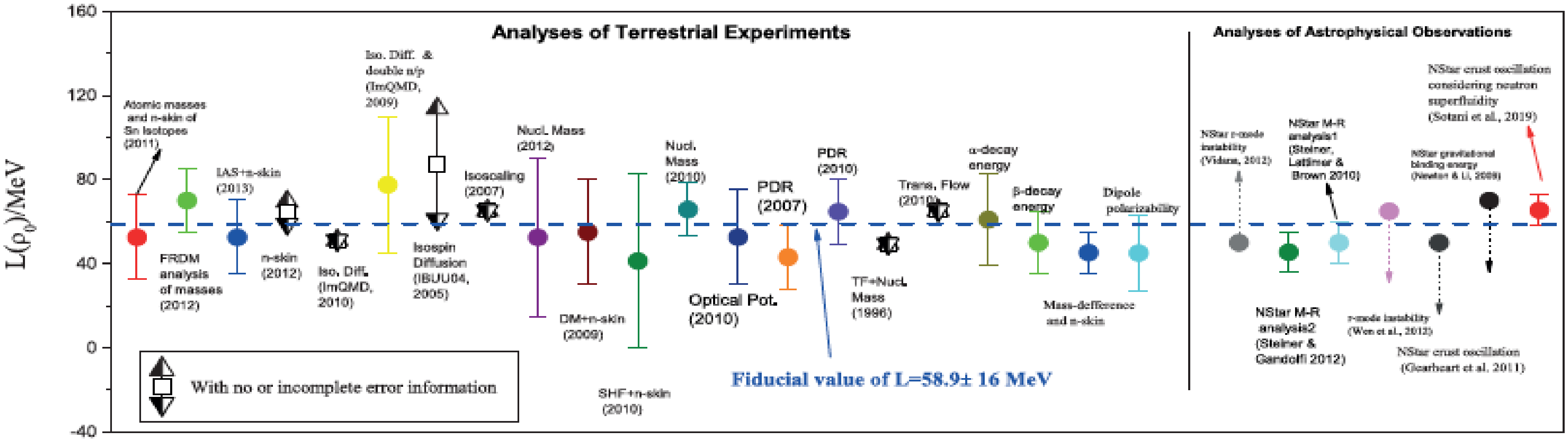
PHYSICAL REVIEW C 90, 054327 (2014)

Isovector properties of the Gogny interaction

Roshan Sellahewa and Arnau Rios



Constraints on L as of 2013 based on 29 analyses of data



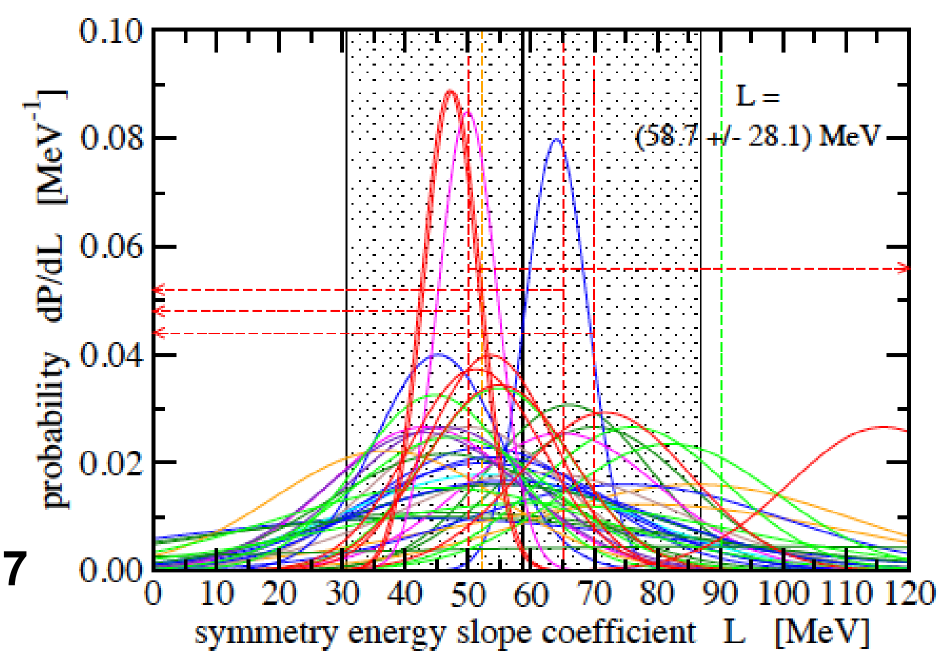
Bao-An Li and Xiao Han, **Phys. Lett. B727 (2013) 276**

L=58.7±28.1 MeV

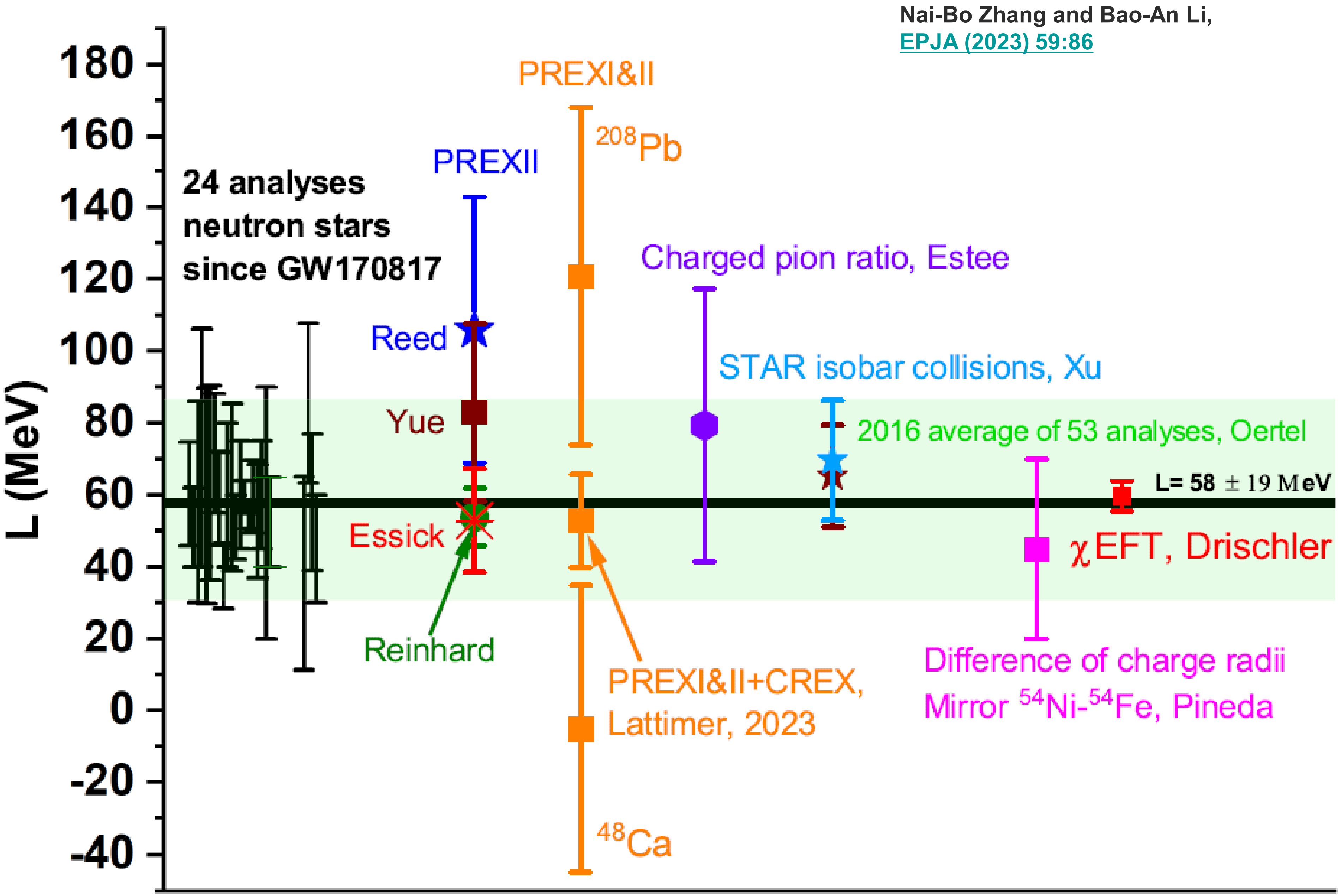
Fiducial value as of 2016 from surveying 53 analyses

M. Oertel, M. Hempel, T. Klähn, S. Typel

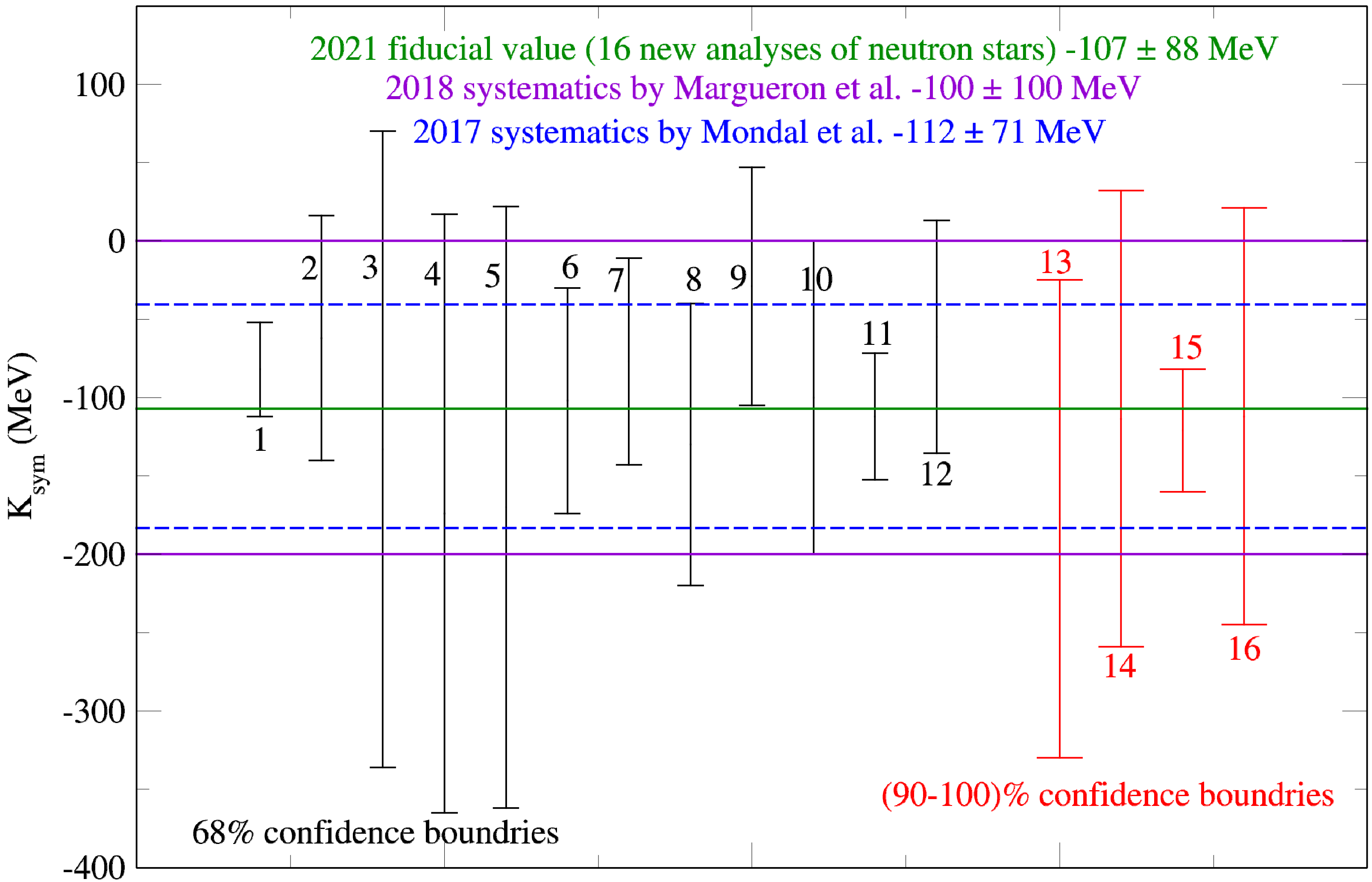
Review of Modern Physics 89 (2017) 015007



Slope L of symmetry energy as of Feb. 2023



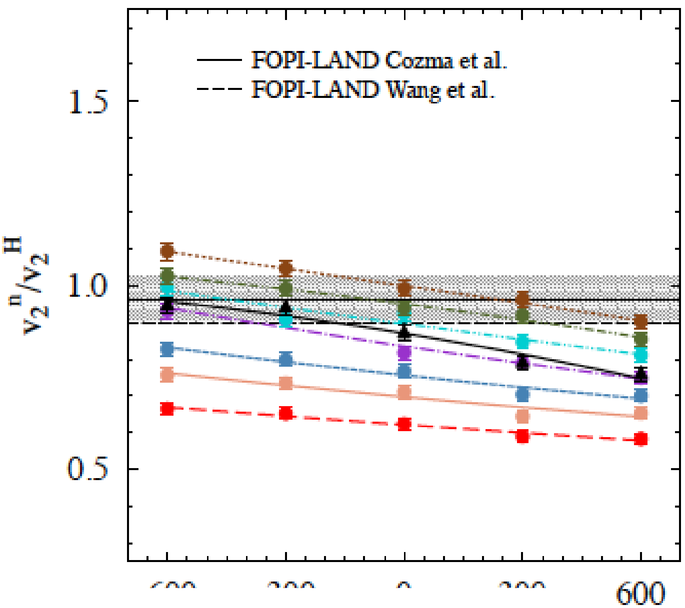
Curvature of the symmetry energy at saturation density

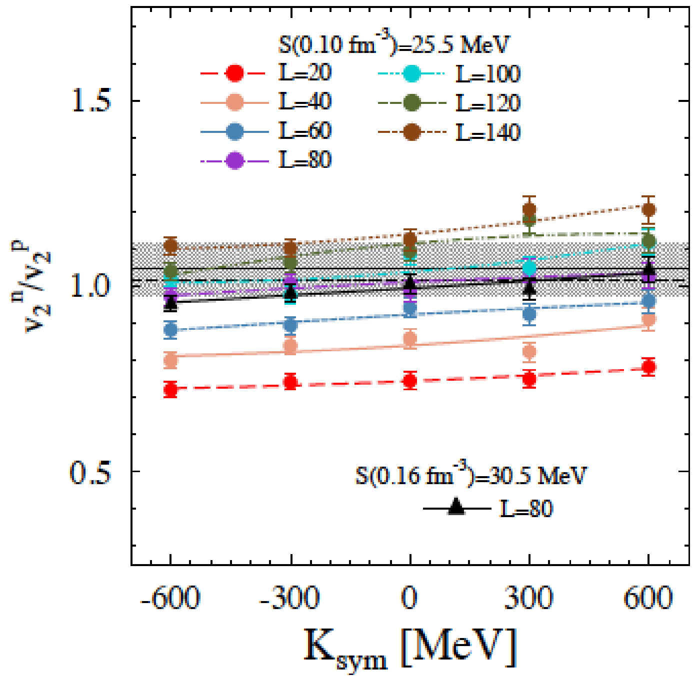


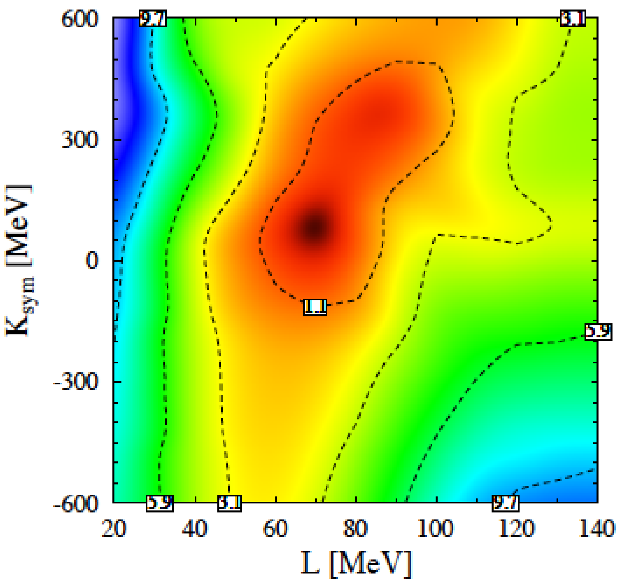
Progress in Constraining Nuclear Symmetry Energy Using Neutron Star Observables Since GW170817,
B.A. Li, B.J. Cai, W.J. Xie and N.B. Zhang, *Universe* **2021**, *7*(6), 182; **https://doi.org/10.3390/universe7060182**

Ratios of neutron to light charged particle ratios and elliptical flows from GSI

Dan Cozma, EPJA 54 (2018) 3







$$L = 85 \pm 22(\text{exp}) \pm 20(\text{th}) \pm 12(\text{sys}) \text{ MeV}$$

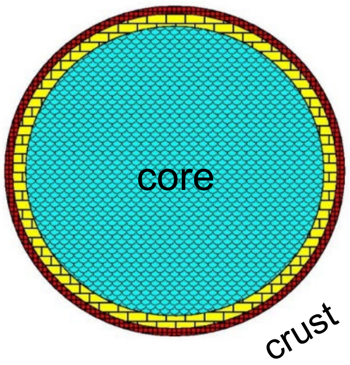
$$K_{sym} = 96 \pm 315(\text{exp}) \pm 170(\text{th}) \pm 166(\text{sys}) \text{ MeV} .$$

How does the symmetry energy affect neutron star properties?

(1) The proton fraction x 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:

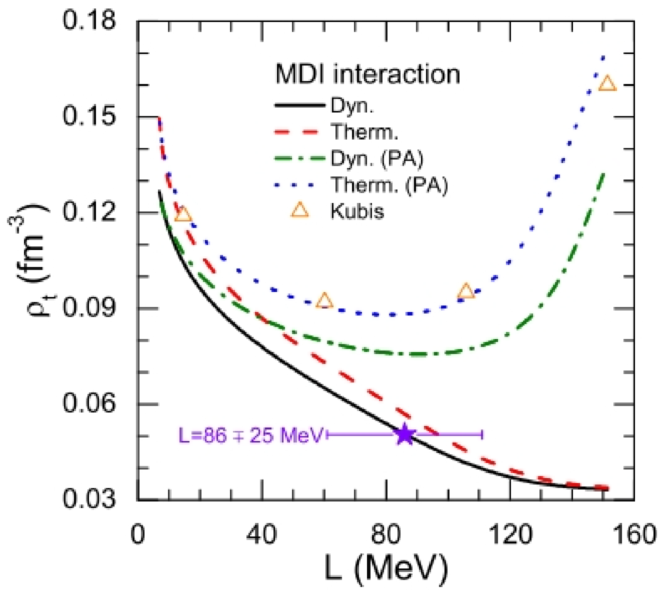
$$P(\rho,\delta) = \rho^2[\frac{dE_0(\rho)}{d\rho} + \frac{dE_{\rm sym}(\rho)}{d\rho}\delta^2] + \frac{1}{2}\delta(1-\delta)\rho E_{\rm sym}(\rho)$$

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

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

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

The crust-core transition density, pressure and isospin asymmetry are very sensitive to the fine details of the asymmetric nuclear matter EOS

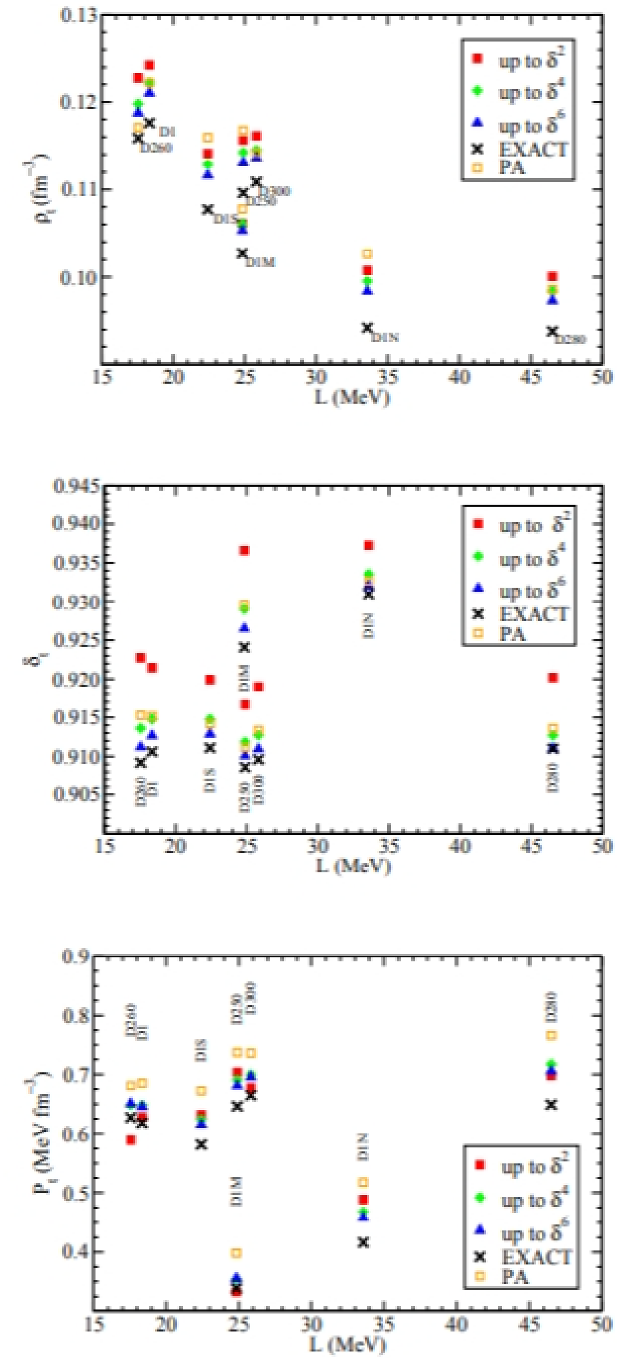


Jun Xu, L.W. Chen, B.A. Li and H.R. Ma,
***APJ* 697 (2009) 1549-1568**

PHYSICAL REVIEW C 90, 054327 (2014)

Isovector properties of the Gogny interaction

Roshan Sellahewa and Arnau Rios



Solving the NS inverse-structure problems by calling the TOV solver within 3 Do-Loops: Given an observable→ Find ALL necessary & sufficient EOSs

$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{J_0}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3, \quad (2.15)$$

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K_{sym}}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{J_{sym}}{6}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3 \quad (2.16)$$

$$E(\rho,\delta) = E_0(\rho) + E_{sym}(\rho)\cdot\delta^2$$

Fix the saturation parameters $E_0(\rho_0)$, K_0, $E_{sym}(\rho_0)$ and L at their most probable values currently known

Example:

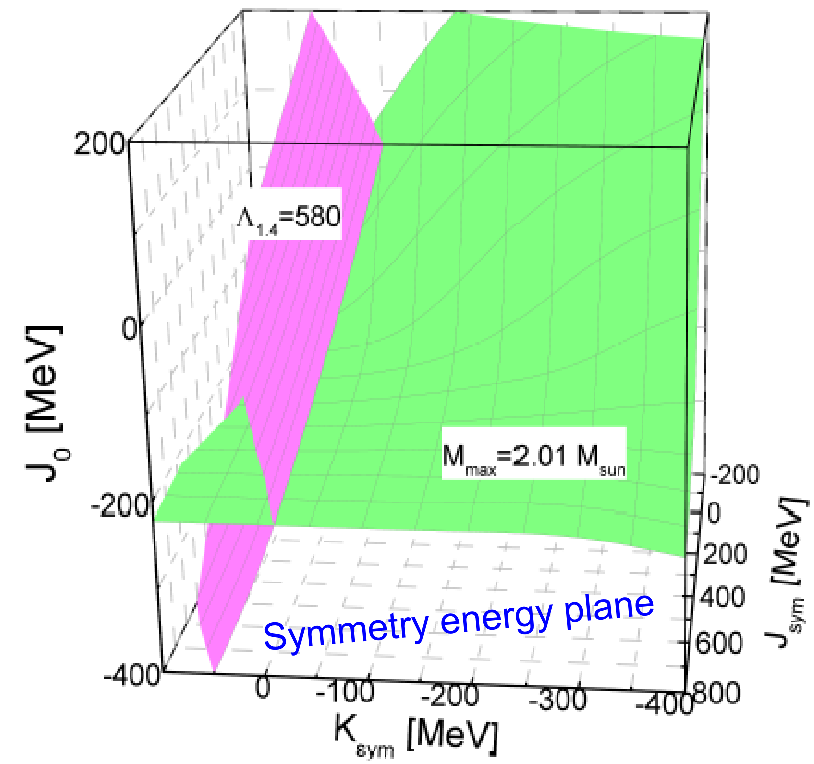
J_0=-189 is found given M_{max}=2.01M_{sun}

↑ J_0 loop

Inversion by brute force

TOV

at K_{sym}=-200 & J_{sym}=400 inside the K_{sym} and J_{sym} loops

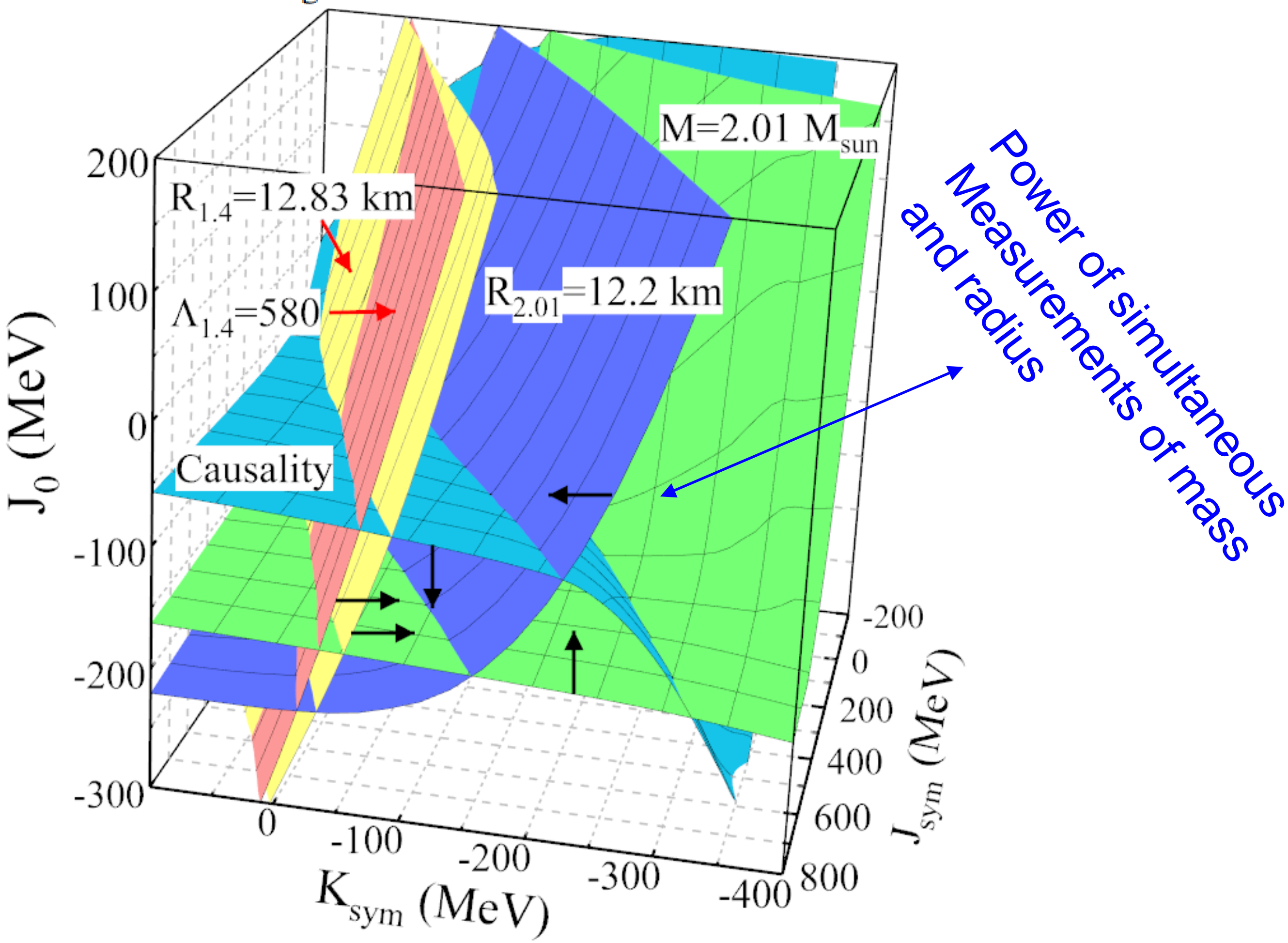


N.B. Zhang, B.A. Li and J. Xu, APJ 859, 90 (2018)

THE ASTROPHYSICAL JOURNAL, 921:111 (11pp), 2021 November 10
https://doi.org/10.3847/1538-4357/ac1e8c

Impact of NICER's Radius Measurement of PSR J0740+6620 on Nuclear Symmetry Energy at Suprasaturation Densities

Nai-Bo Zhang[1] and Bao-An Li[2]

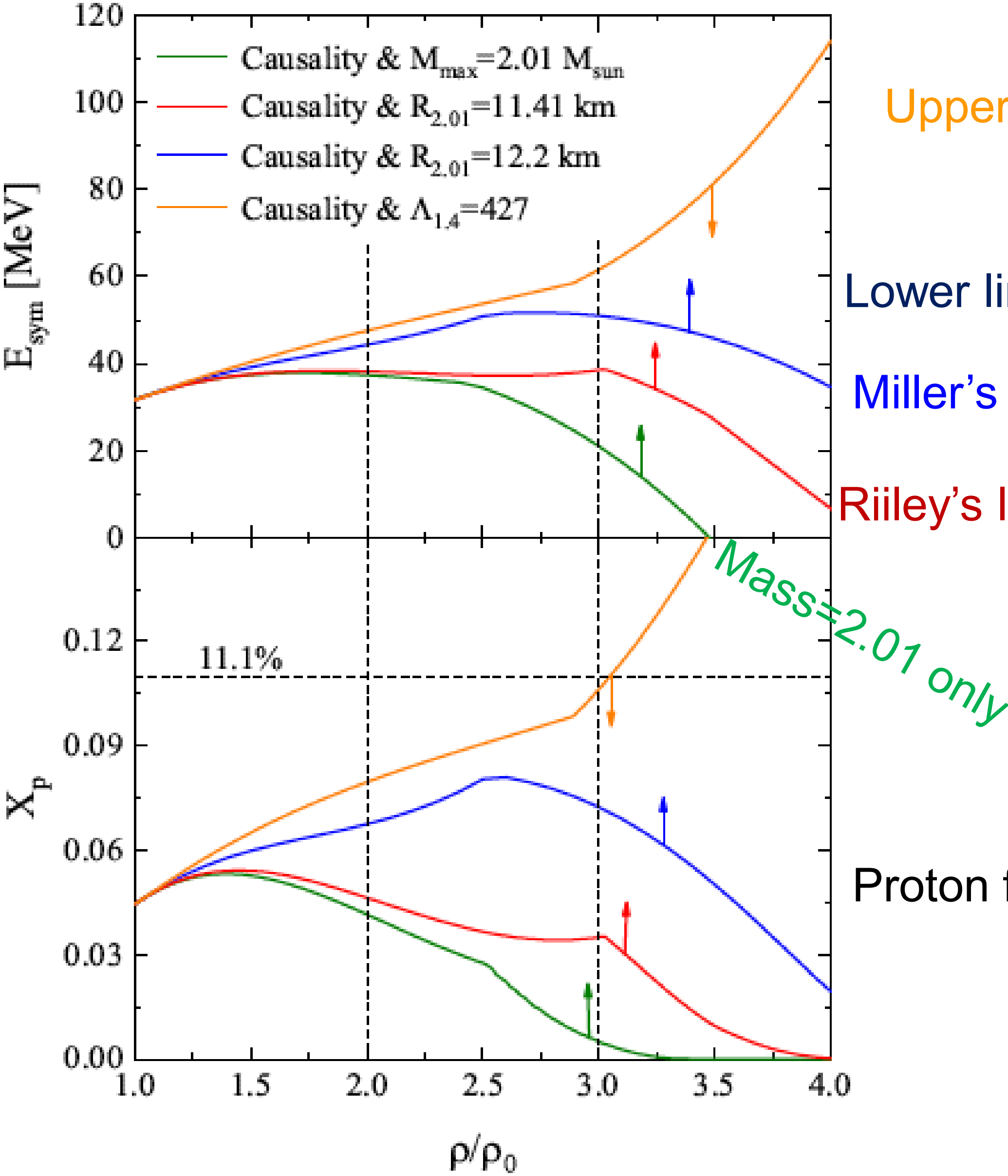


NICER results :

Mass: $2.08 \pm 0.07\, M_\odot$

Radius: $13.7^{+2.6}_{-1.5}$ km (68%) (Miller et al. 2021) or $12.39^{+1.30}_{-0.98}$ km (Riley

Constrains on the high-density symmetry energy from astrophysical observations



Upper limit on E_{sym} from GW170817

Lower limit on E_{sym} from PSR J0740+6620

Miller's lower radius

Riiley's lower radius

Proton fraction in PSR J0704+6620

N.B. Zhang and B.A Li
APJ 921, 111 (2021)

Table 1. The radius $R_{1.4}$ data used in this work.

Radius $R_{1.4}$ (km) (90% confidence level)	Source	Reference
$11.9^{+1.4}_{-1.4}$	GW170817	(Abbott et al. 2018)
$10.8^{+2.1}_{-1.6}$	GW170817	(De et al. 2018)
$11.7^{+1.1}_{-1.1}$	QLMXBs	(Lattimer & Steiner 2014)
$11.9 \pm 0.8, 10.8 \pm 0.8, 11.7 \pm 0.8$	Imagined case-1	this work
11.9 ± 0.8	Imagined case-2	this work

Wen-Jie Xie and Bao-An Li
APJ 883, 174 (2019)
APJ 899, 4 (2020)

Posterior probability distribution $$P(\mathcal{M}|D) = \frac{P(D|\mathcal{M})P(\mathcal{M})}{\int P(D|\mathcal{M})P(\mathcal{M})d\mathcal{M}},$$ **(Bayes' theorem)**

Likelihood: $$P[D(R_{1,2,3})|\mathcal{M}(p_{1,2,\cdots 6})] = \prod_{j=1}^{3} \frac{1}{\sqrt{2\pi}\sigma_{\mathrm{obs},j}} \exp[-\frac{(R_{\mathrm{th},j} - R_{\mathrm{obs},j})^2}{2\sigma^2_{\mathrm{obs},j}}],$$

Meta-modeling of nuclear EOS

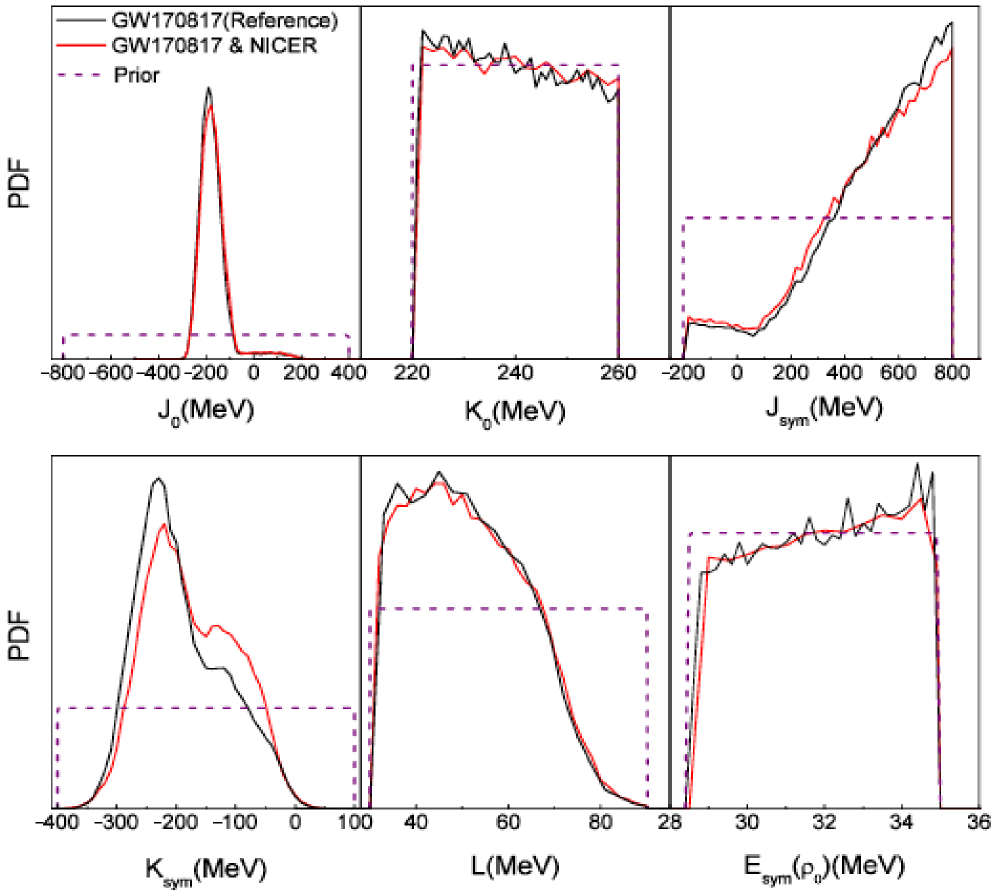
Uniform prior distribution P(M) in the ranges of

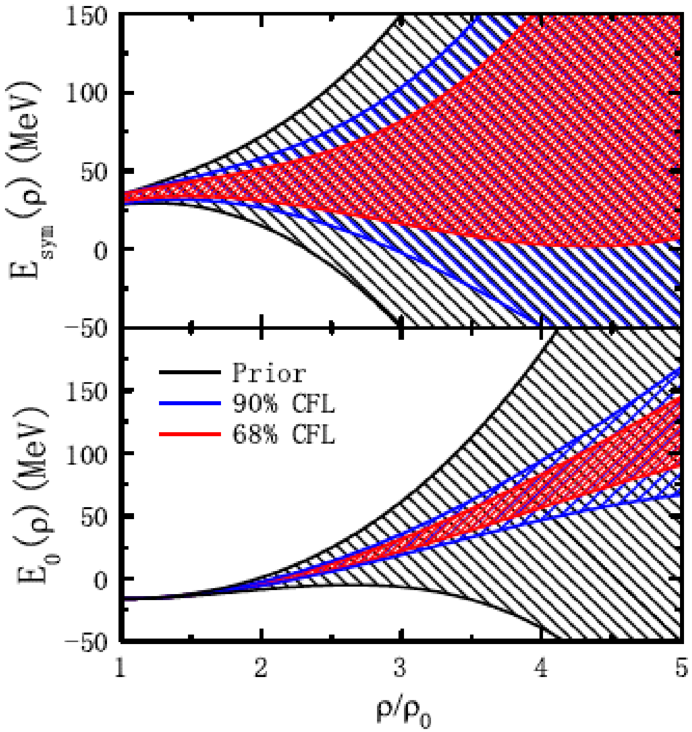
Table 2. Prior ranges of the six EOS parameters used

Parameters	Lower limit	Upper limit (MeV)
K_0	220	260
J_0	-800	400
K_{sym}	-400	100
J_{sym}	-200	800
L	30	90
$E_{\mathrm{sym}}(\rho_0)$	28.5	34.9

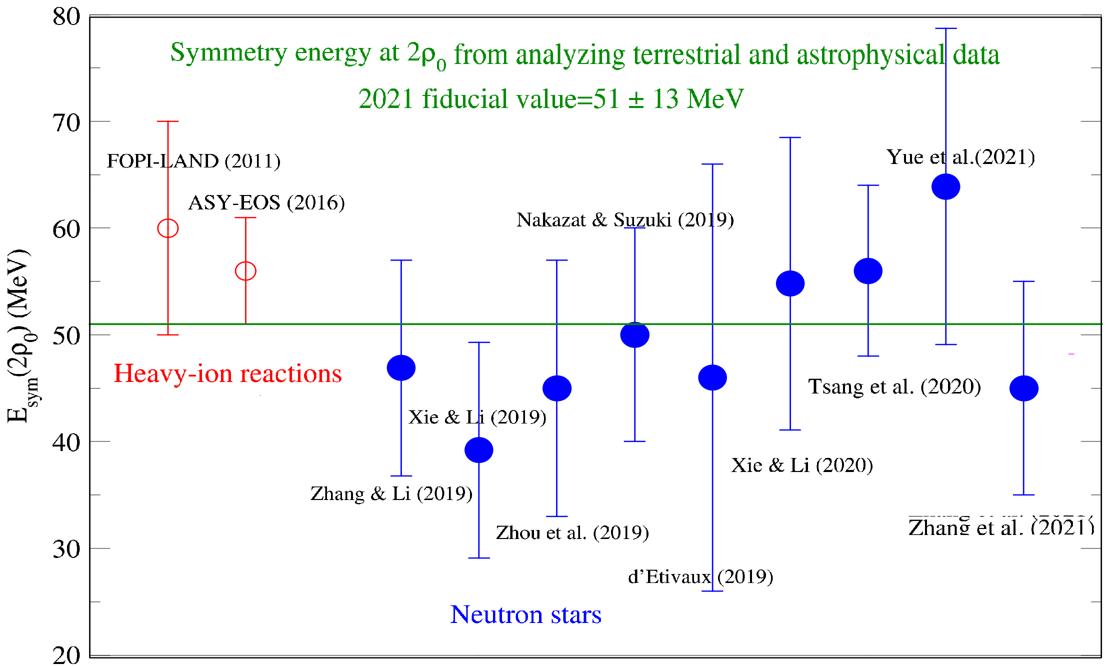
Bayesian inference of high-density E_{sym} from the radii $R_{1.4}$ of canonical neutron stars in 6D EOS parameter space

Posterior probability distribution function (PDF) of 6 EOS parameters from Bayesian analyses of GW170817 & NICER data for the canonical PSR J0030+0451 of masses around 1.4 solar mass





Wen-Jie Xie and Bao-An Li
APJ 883, 174 (2019)
APJ 899, 4 (2020)



Bao-An Li, Bao-Jun Cai, Wen-Jie Xie, Nai-Bo Zhang, **Universe 7, 182 (2021)**

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

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

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

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

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

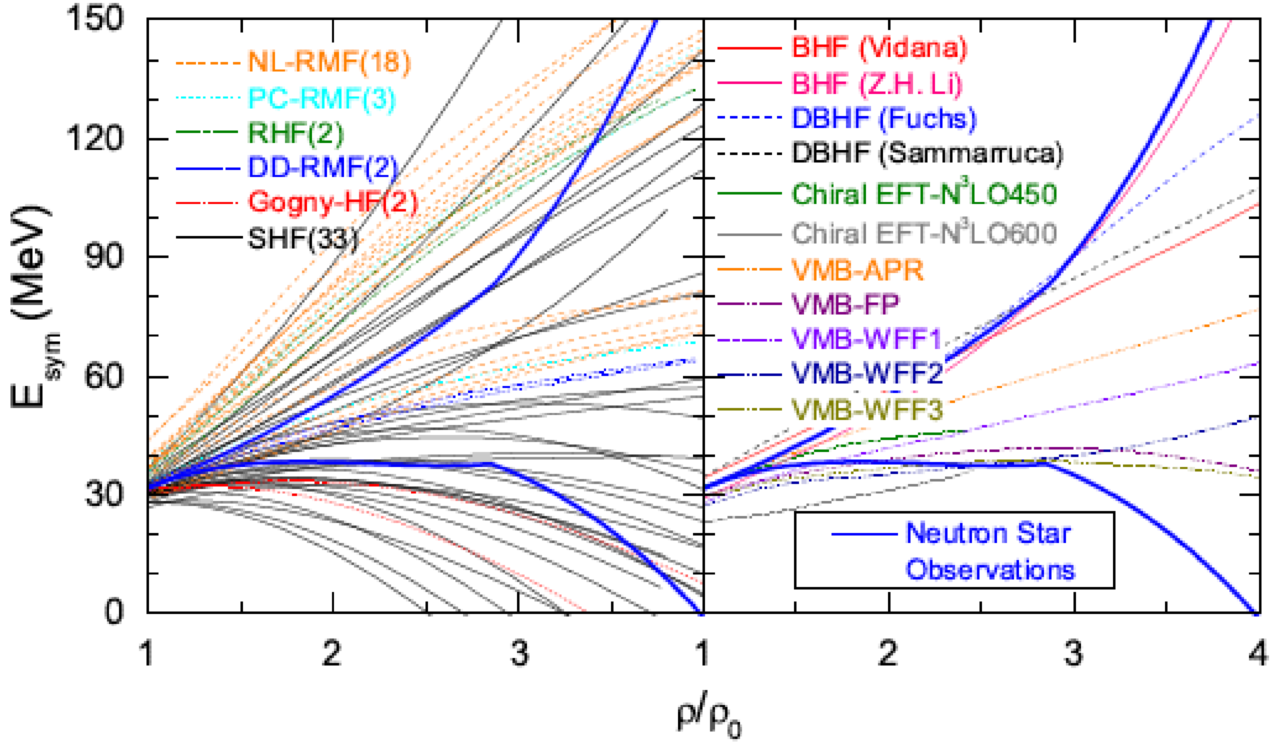
(4) Relativistic BHF: ~ 53 MeV

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

Why is the symmetry energy still so uncertain especially at high densities?

Phenomenological Models
60 examples

Microscopic & *ab initio* Theories
11 examples



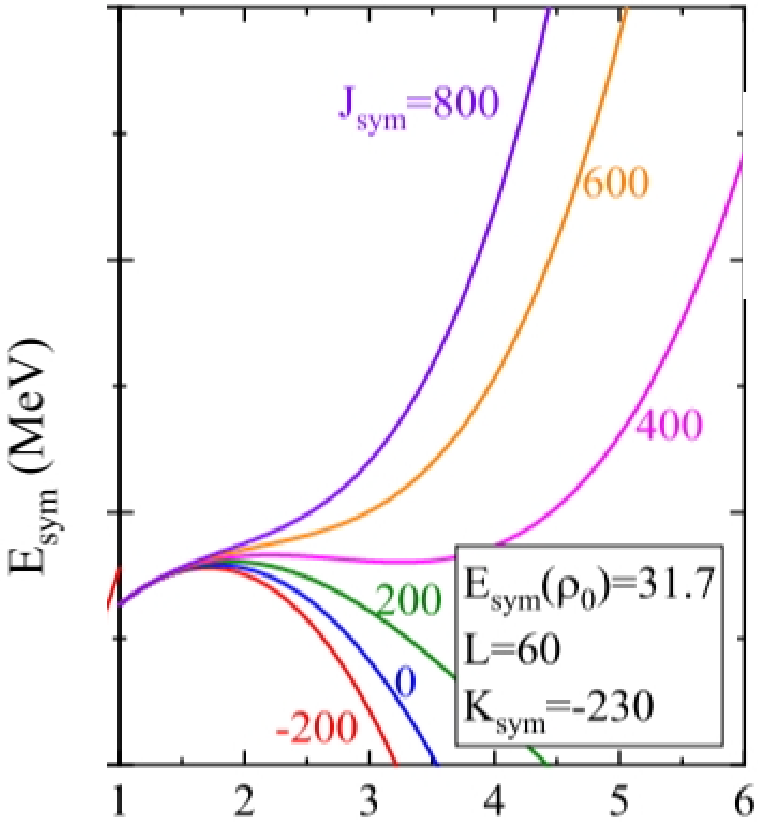
L.W. Chen, Nucl. Phys. Rev. 34, 20 (2017).
N.B. Zhang, B.A. Li, Eur. Phys. J. A 55, 39 (2019).

- E_{sym} around (1-2)ρ_0 is most relevant for determining the radii of canonical neutron stars, existing 1.4M_{sun}NS observations do NOT constrain much E_{sym} above 2ρ_0 where SRC effects are important.

Impact of symmetry energy on sound speed and spinodal decomposition in dense neutron-rich matter

Nai-Bo Zhang & Bao-An Li

The European Physical Journal A **59**, Article number: 86 (2023)



Adiabatic **Equilibrium**

$$C_{NM}^2 \equiv \left(\frac{\partial P}{\partial \epsilon}\right)_\delta \quad \text{and} \quad C_s^2 \equiv \frac{dP}{d\epsilon}.$$

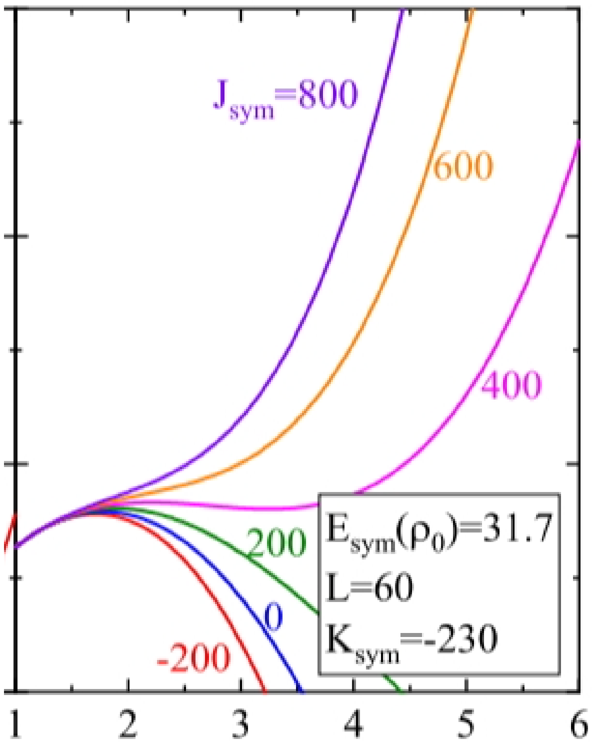
Relevant for heavy-ion reactions

Neutron stars at beta-equilibrium

$$C_{NM}^2 = \frac{K}{9(M_N + E(\rho,\delta) + P/\rho)}.$$

Adiabatic sound speed in nucleonic matter

Symmetry energy



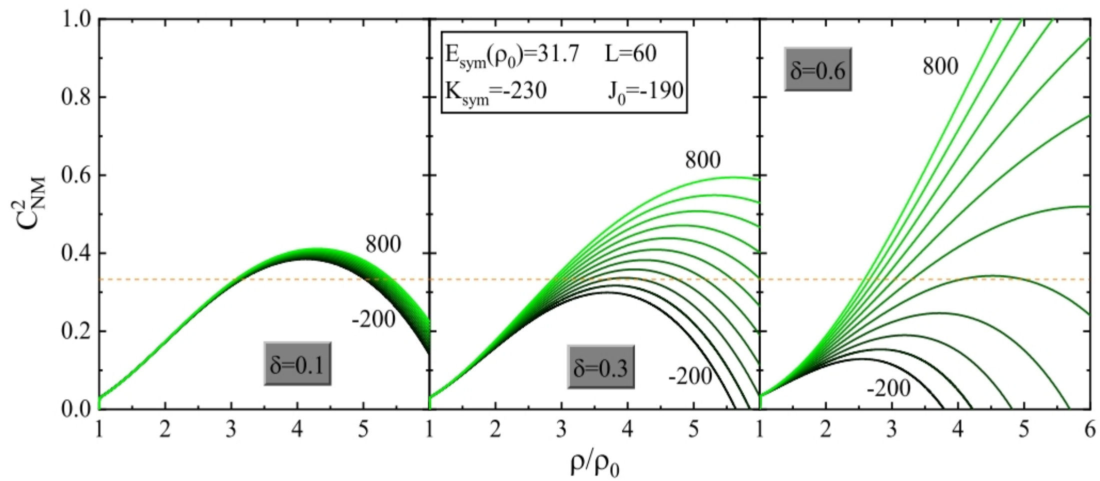


Fig. 3. The speed of sound C^2_{NM} in unit of c^2 in nucleonic matter with fixed isospin asymmetries as a function of density using the symmetry energy $E_{\rm sym}(\rho)$ functions with $J_{\rm sym}$ varying between -200 and 800 MeV as shown in the right panel of Fig. 2. The orange dashed line corresponds to the conformal limit $C^2 < 1/3$.

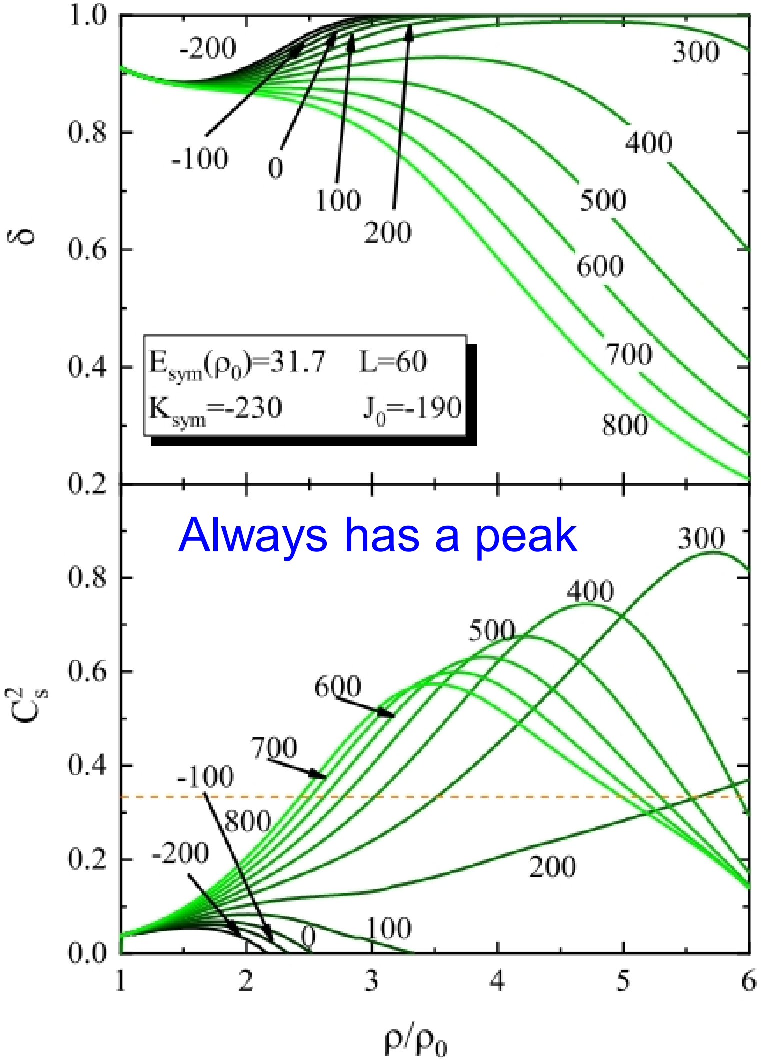
Isospin chemical potential

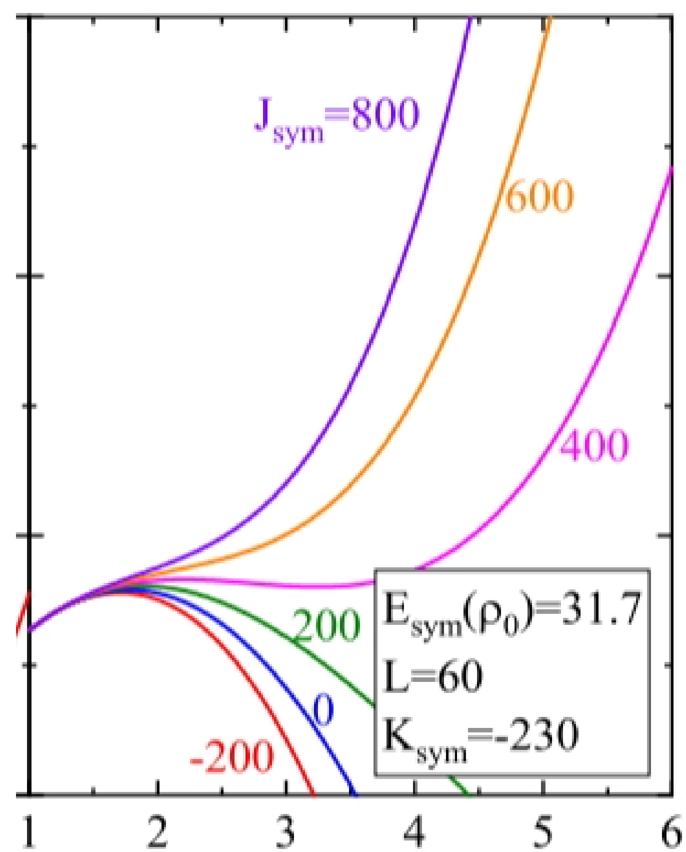
$$E_{\rm sym}(\rho_1)\delta(\rho_1) = E_{\rm sym}(\rho_2)\delta(\rho_2).$$

Equilibrium sound speed in neutron stars (n+p+e+muons) at beta-equilibrium

Physics of Isospin fractionation

$$E(\rho,\delta) = E_0(\rho) + E_{\rm sym}(\rho)\cdot\delta^2 + \mathcal{O}(\delta^4)$$





What are the fundamental physics behind the symmetry energy?

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

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

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

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

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:

Isospin-dependent correlation function

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

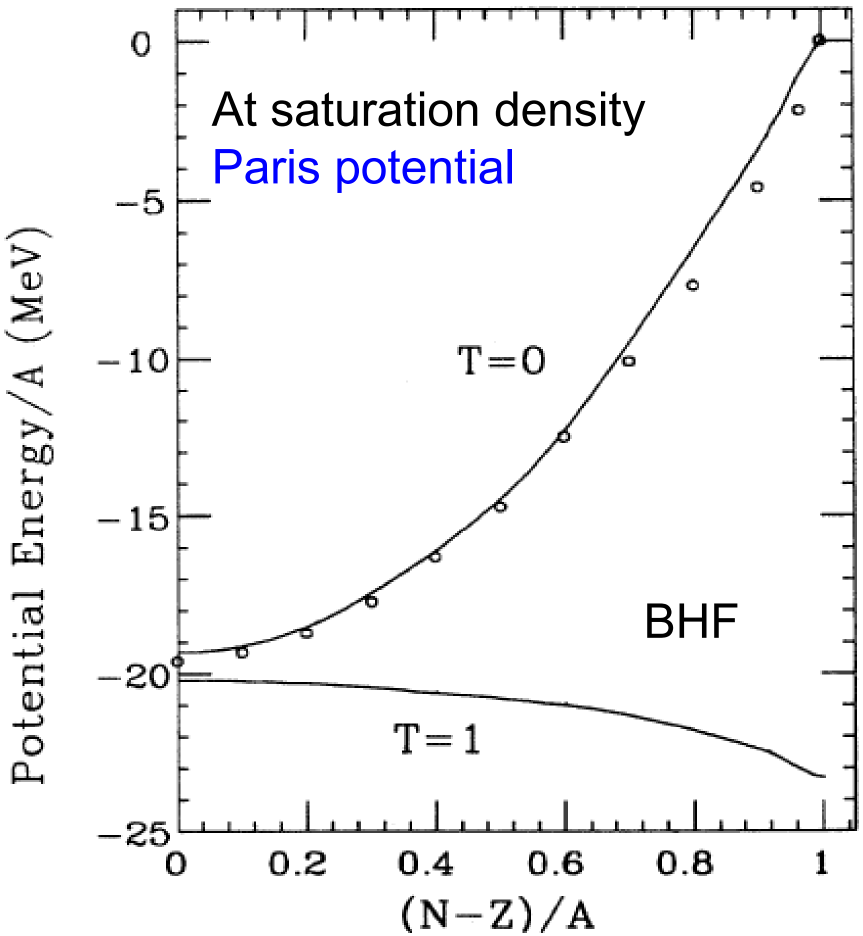
Isospin-dependent effective 2-body interaction

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

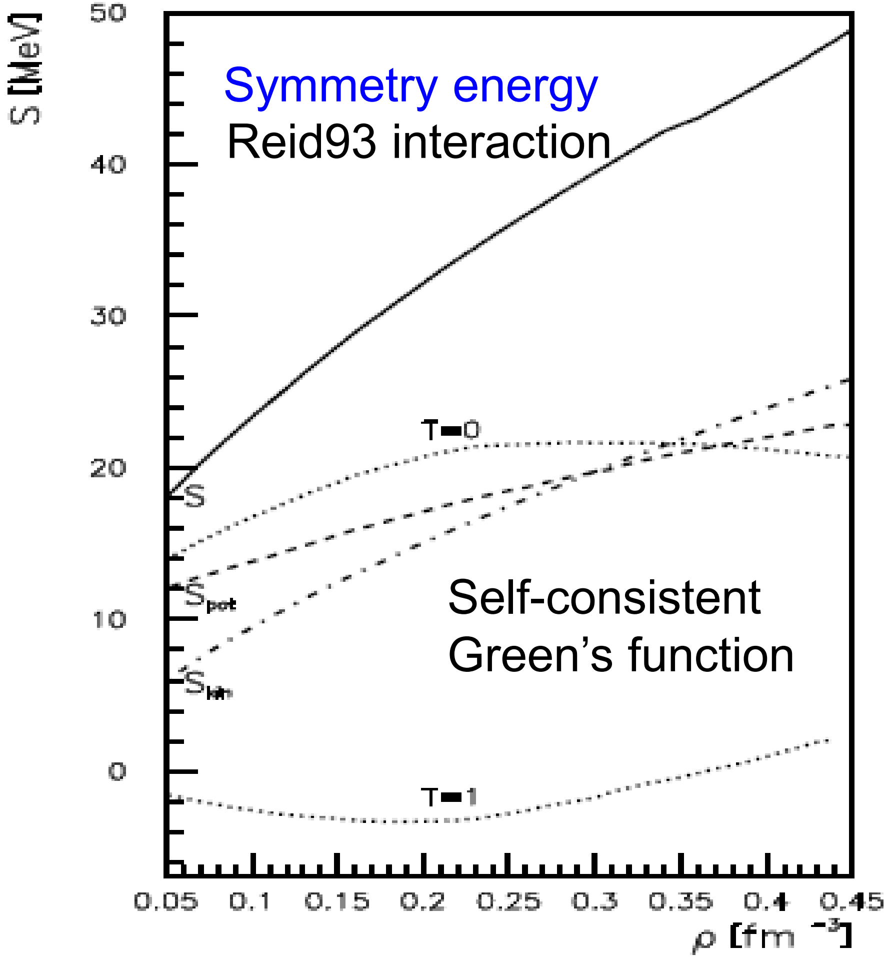
Major issues relevant to high-density E_{sym}, heavy-ion reactions and neutron stars

- **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 △(1232) resonances and their spectroscopy (mass and width)**
- **Possible sign inversion of the symmetry potential at high momenta/density**

Dominance of the isosinglet (T=0) interaction



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

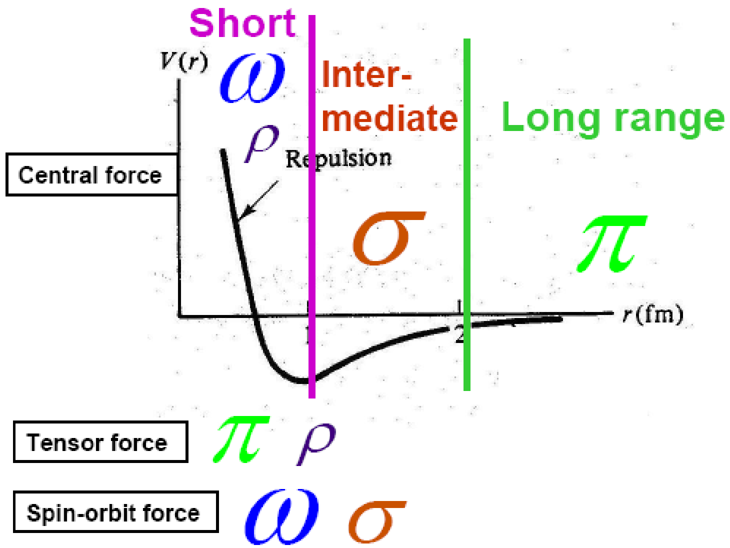


A.E.L. Dieperink,[1] Y. Dewulf,[2] D. Van Neck,[2] M. Waroquier,[2] and V. Rodin[3]

PRC68, 064307 (2003)

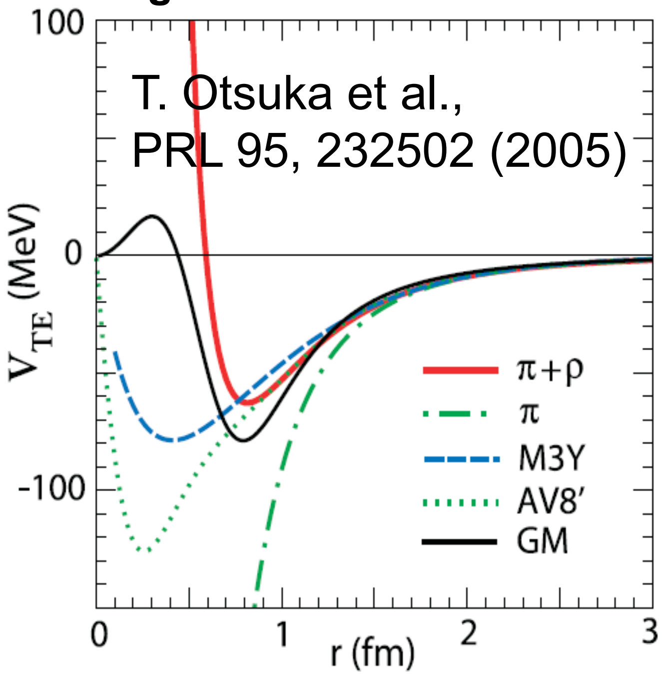
$$E_{sym}(\rho) = \frac{1}{2}\frac{\partial^2 E}{\partial \delta^2} \approx E(\rho)_{\text{pure neutron matter}} - E(\rho)_{\text{symmetric nuclear matter}}$$

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



π(138) $V_\pi = \frac{f_{\pi NN}^2}{8 m_\pi^2}\frac{\vec{q}^2}{\vec{q}^2+m_\pi^2}\left[-\vec{\sigma}_1\cdot\vec{\sigma}_2 - S_{12}(\hat{q})\right]\vec{\tau}_1\cdot\vec{\tau}_2$ — Long-ranged tensor force

σ(600) $V_\sigma \approx \frac{g_\sigma^2}{\vec{q}^2+m_\sigma^2}\left[-1 - \frac{\vec{L}\cdot\vec{S}}{2M^2}\right]$ — intermediate-ranged, attractive central force plus LS force

ω(782) $V_\omega \approx \frac{g_\omega^2}{\vec{q}^2+m_\omega^2}\left[+1 - 3\frac{\vec{L}\cdot\vec{S}}{2M^2}\right]$ — short-ranged, repulsive central force plus strong LS force

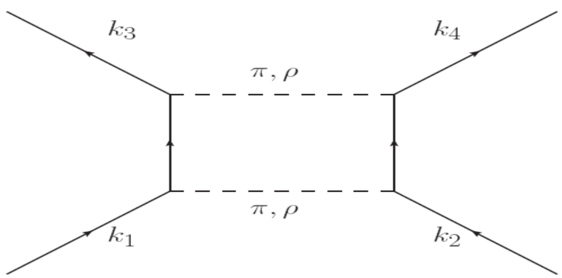
ρ(770) $V_\rho = \frac{f_\rho^2}{12M^2}\frac{\vec{q}^2}{\vec{q}^2+m_\rho^2}\left[-2\vec{\sigma}_1\cdot\vec{\sigma}_2 + S_{12}(\hat{q})\right]\vec{\tau}_1\cdot\vec{\tau}_2$ — short-ranged tensor force, opposite to pion

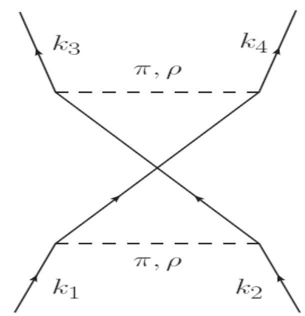
2^{nd} order tensor force contribution to the potential part of symmetry energy

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)

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



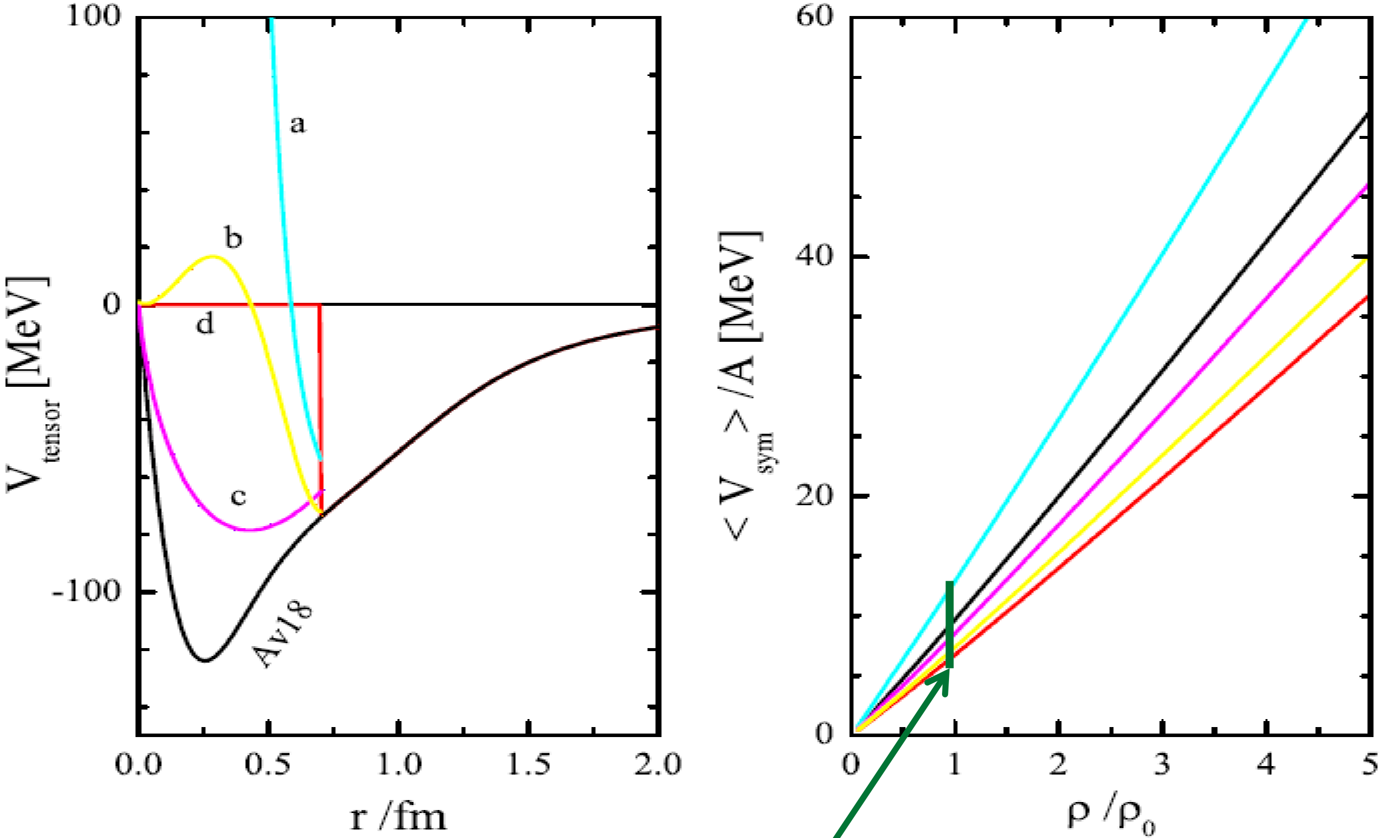


$$\frac{< V_{\rm sym} >}{A} = \frac{12}{e_{eff}} \cdot \frac{k_F^3}{12\pi^2} \{ \frac{1}{4} \int V_t^2(r) d^3r - \frac{1}{16} \int [\frac{3 j_1(k_F r)}{k_F r}]^2 V_t^2(r) d^3 r \}$$

Ang Li and Bao-An Li, arXiv:1107.0496

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

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



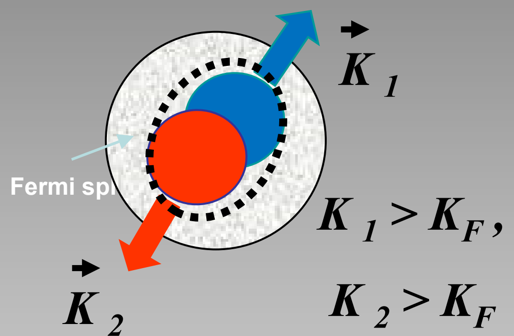
At saturation density, the 2nd order potential contribution
due to the tensor force is about 7-14 MeV, it is 9 MeV with Av18

What are the Short Range Correlations (SRC) in nuclei ?

(Modified from a slide by Eli Piasetzky)

In coordinate space:

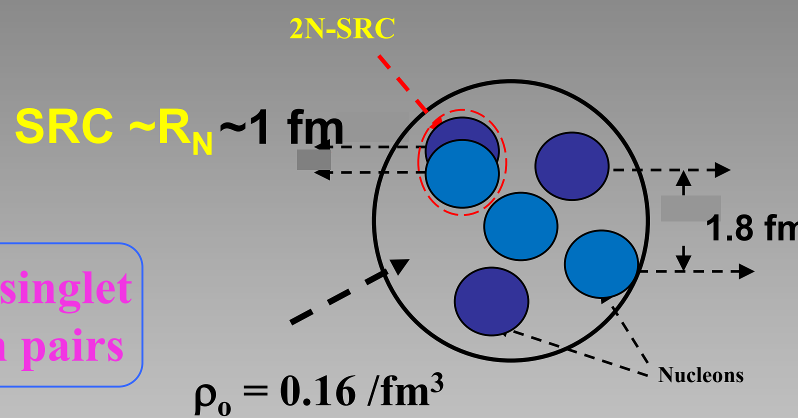
In momentum space:



High momentum tail (HMT): $(1.3 – 2.5)K_F$

In isospin space:

Dominated by the isosinglet (T=0) neutron-proton pairs



Nucleon pairs with large relative momenta and small CM momenta

Short Range Correlated pairs:
temporal fluctuations of strongly interacting nucleon pairs in close proximity

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

(1) high-momentum tail in nucleon momentum distribution

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

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

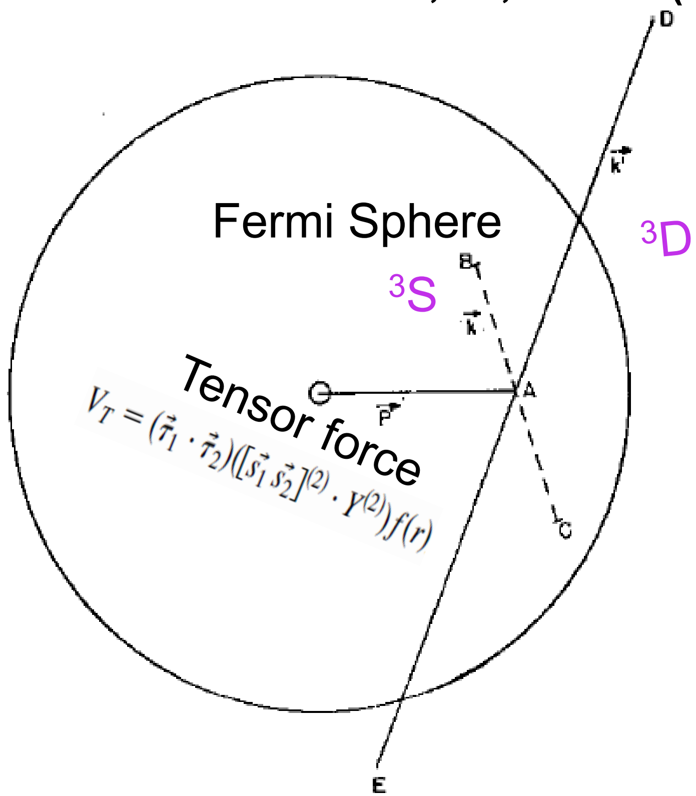
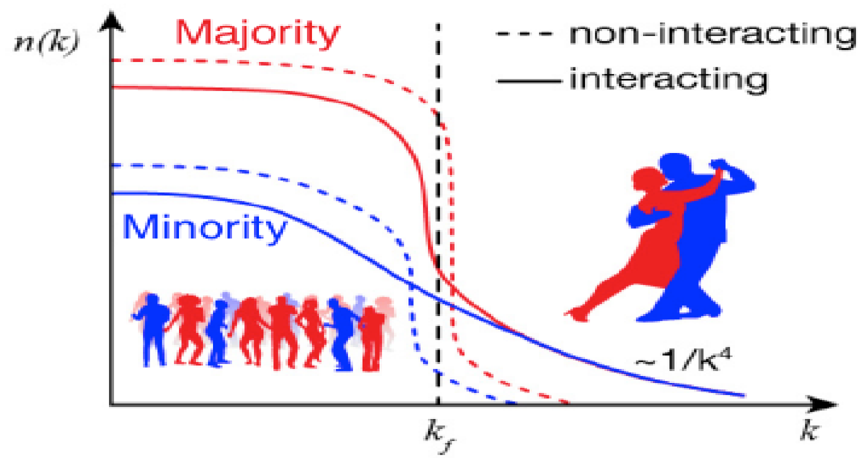
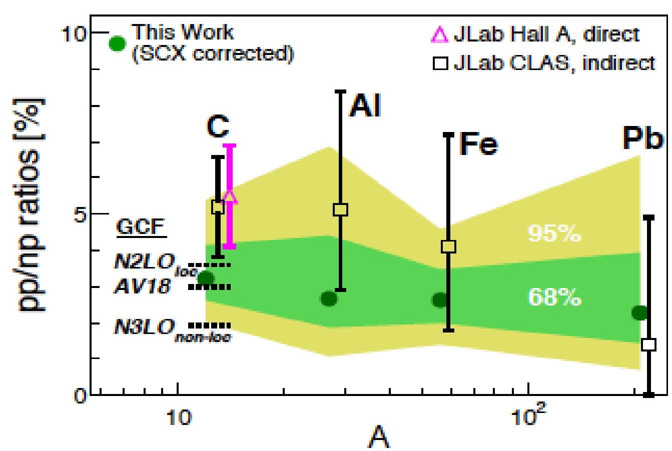


FIGURE 10. Two nucleons are initially in states B and C, having average momentum $\boldsymbol{P}$ and relative momentum $\boldsymbol{k}$. When they interact they are shifted to states D and E outside the Fermi sphere, with relative momentum $\boldsymbol{k}'$. If they are initially in a ^3S state and interact by tensor force, then they are in a $^3D_1$ state in DE.

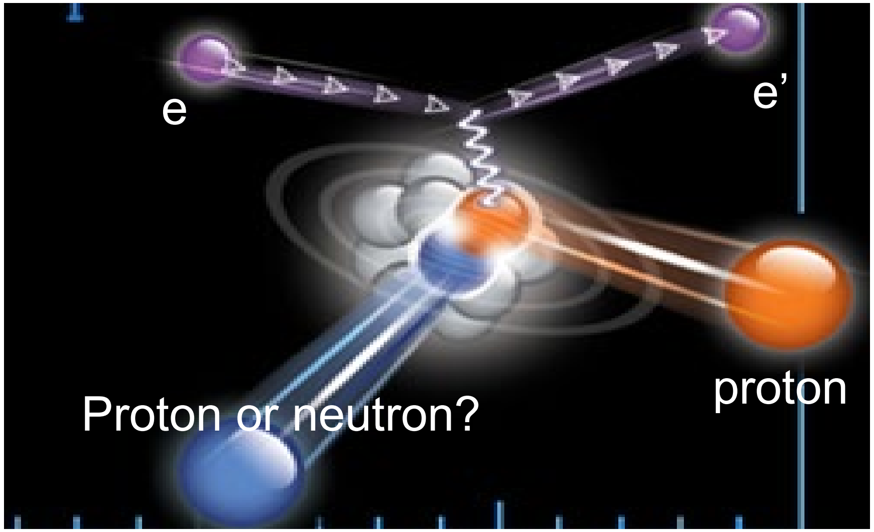
O. Hen et al. (Jlab CLAS collaboration), Science 346, 614 (2014)

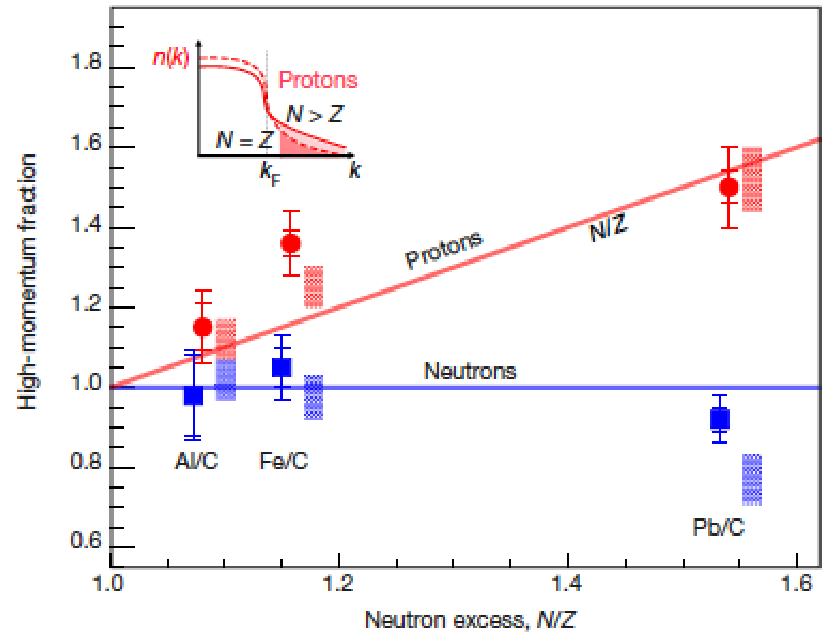


M. Duer et al., PRL 122, 172502 (2019).

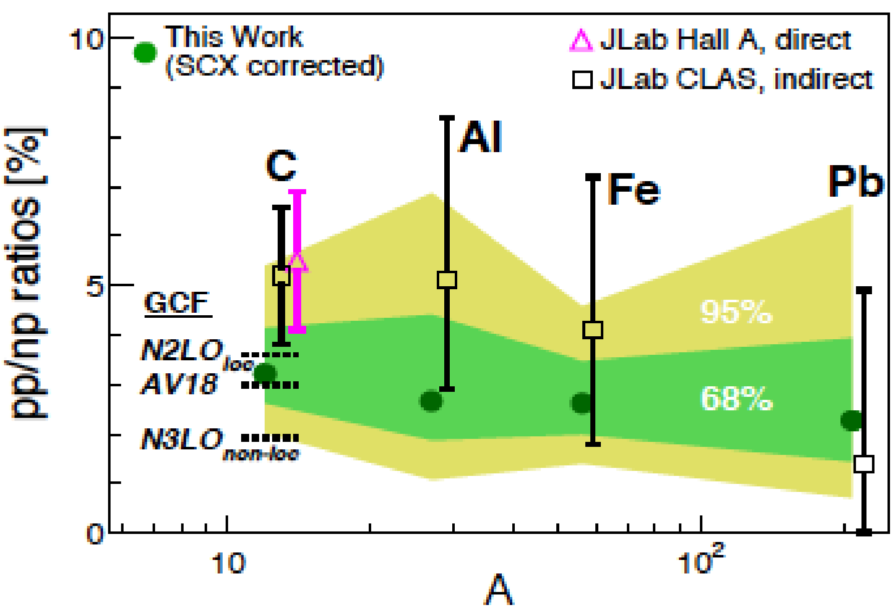


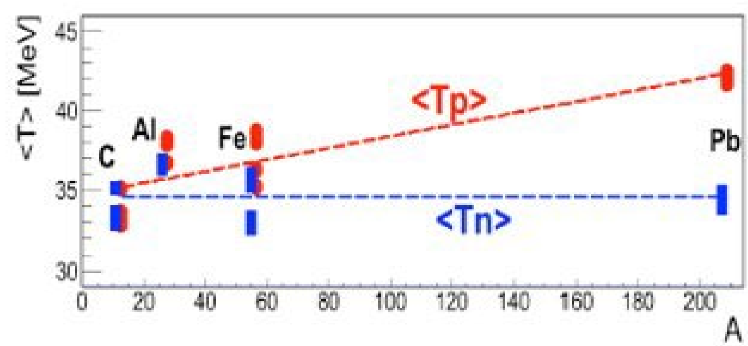
Experimental evidence of isospin-dependent nucleon momentum distribution:
Deformed-Fermi distributions in neutron-rich matter



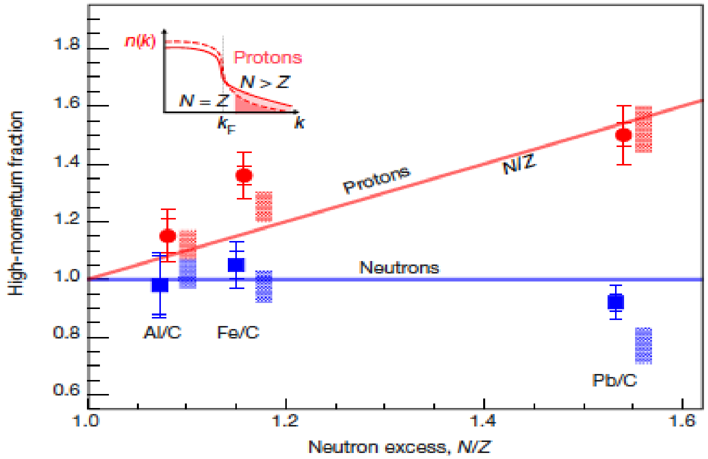


M. Duer et al., Nature 560, 617 (2018).

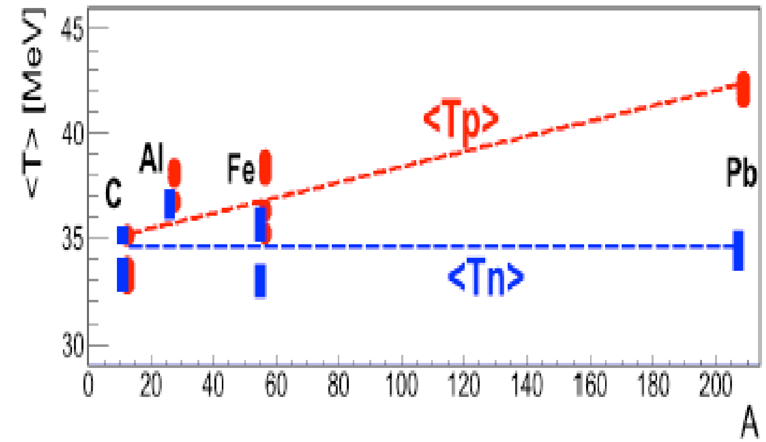




M. Duer et al., PRL 122, 172502 (2019).

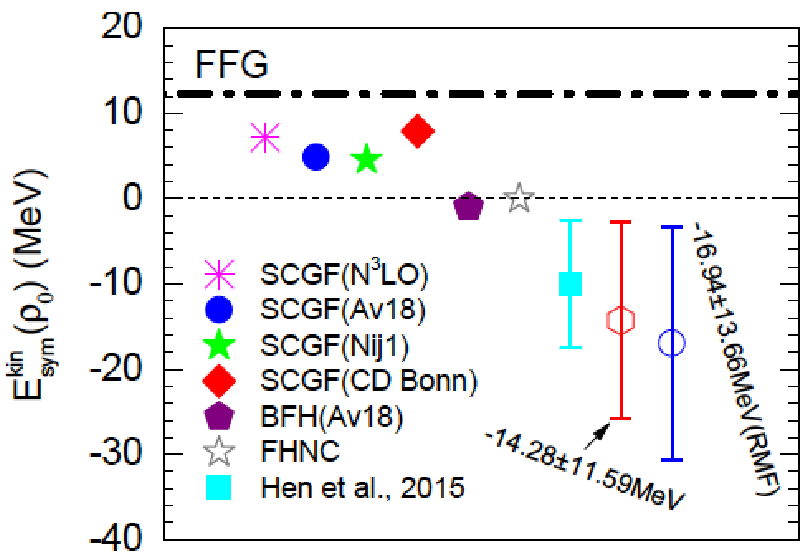


M. Duer et al., Nature 560, 617 (2018).

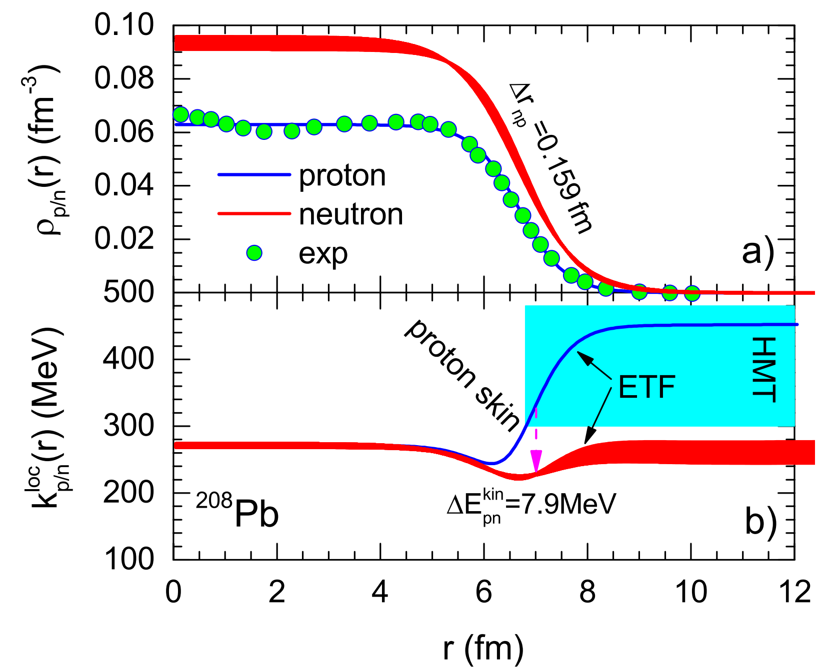


O. Hen et al., Science 346, 614 (2014).

Reduced Kinetic symmetry energy wrt free Fermi gas (FFG)



Protons move faster than neutrons in n-skin



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

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).

B.J. Cai, B.A. Li and L.W. Chen, PRC 94, 061302 (R) (2016)

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

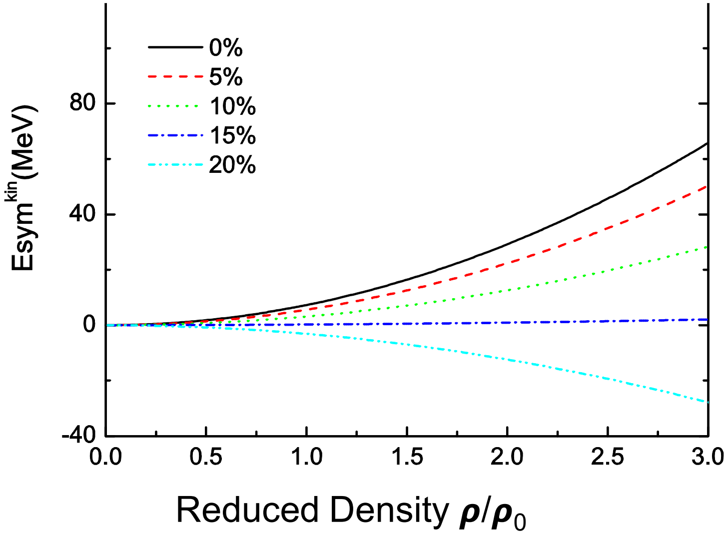
Chang Xu, Ang Li and Bao-An Li,
JPCS 420, 012190 (2013).

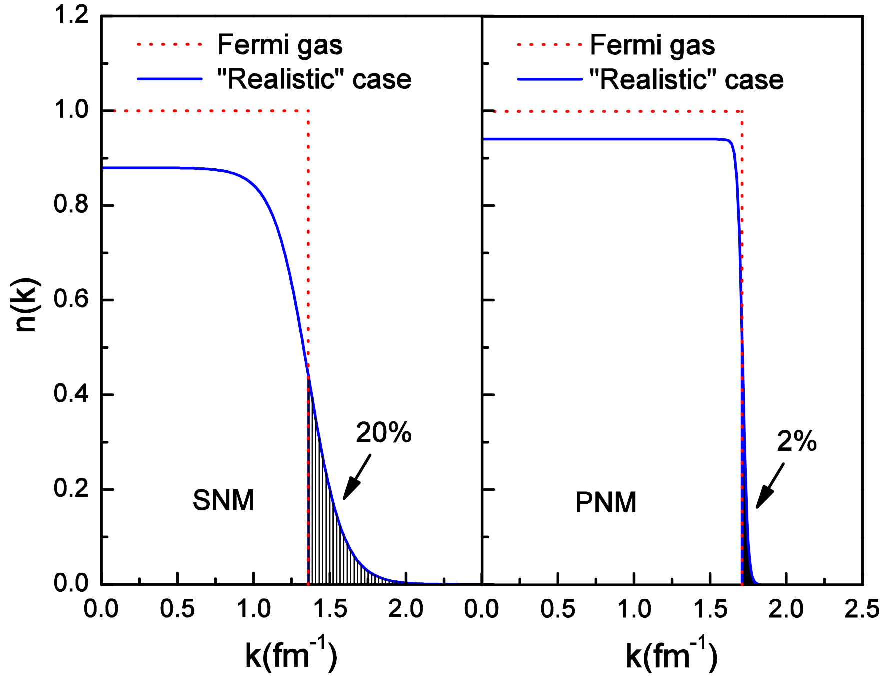
$$E_{kin} = \alpha \int_0^\infty \frac{\hbar^2 k^2}{2m} n(k) k^2 dk,$$

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

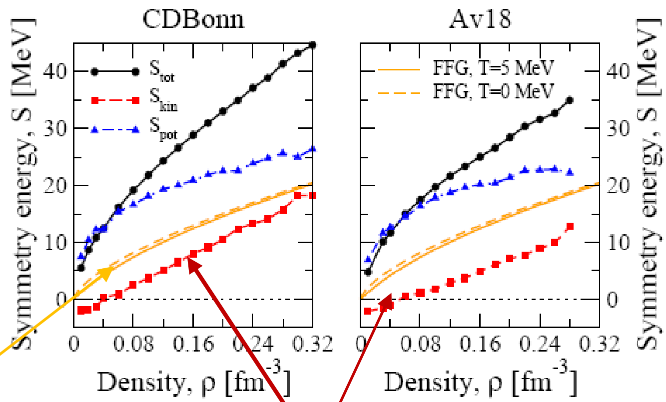
$$E^{kin}_{sym} = E^{kin}_{PNM} - E^{kin}_{SNM} < 0$$

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 (A. Rios et al.)



Free Fermi Gas

Actual kinetic symmetry E

	S_{tot} [MeV]	S_{kin} [MeV]	S_{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

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

Using the Hellmann–Feynman theorem

V18 potential plus the Urbana IX three-body force.

At saturation density,
the Free Fermi Gas (FFG) model
prediction is about 12.5 MeV

	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

EOS of dense neutron-rich matter is a major scientific motivation of

(1) High-energy rare isotope beam facilities around the world

(2) Various x-ray satellites

(3) Various gravitational wave detectors

Among the promising observables of high-density symmetry energy:

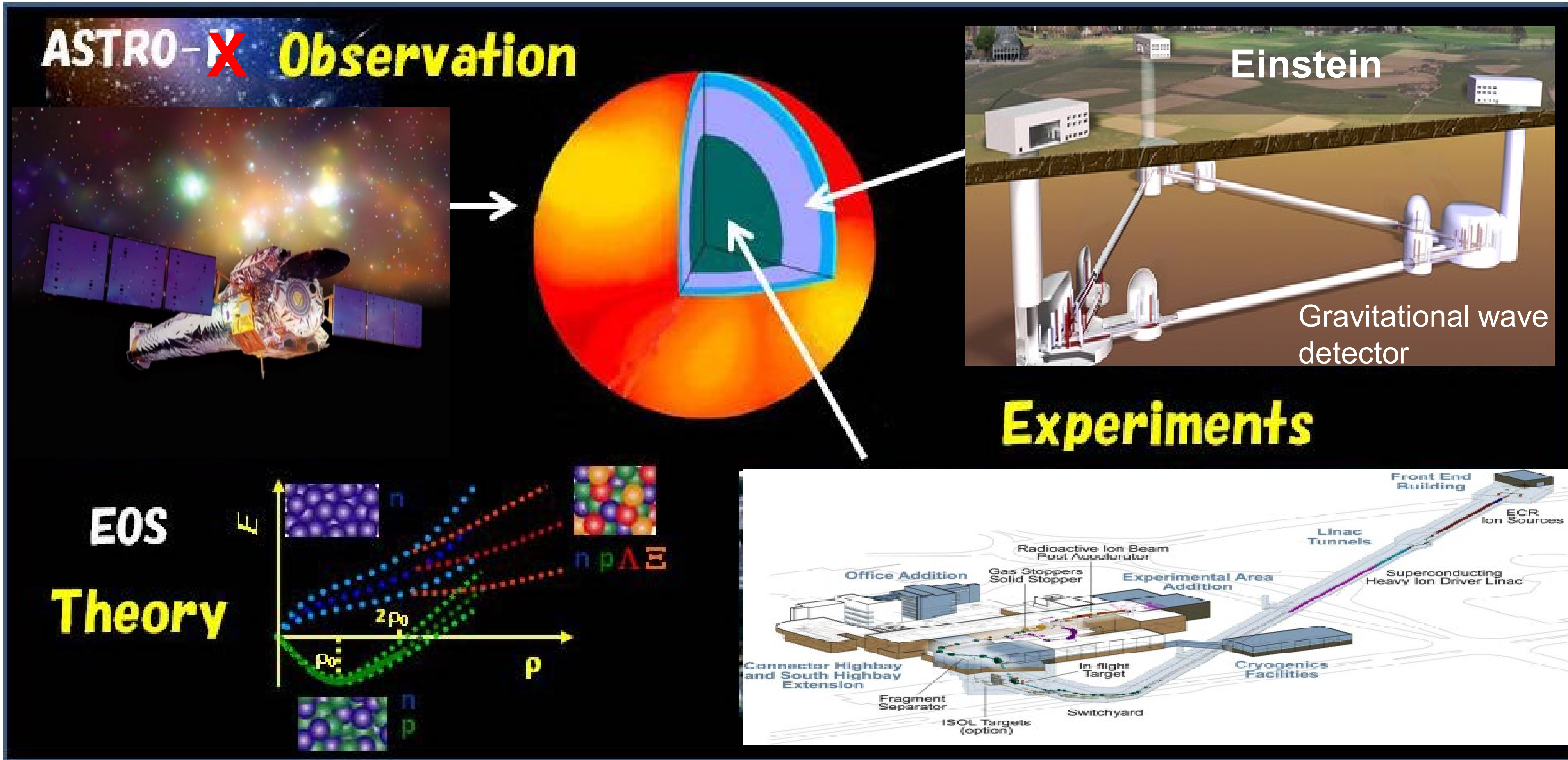
- **<u>π^-/π^+ and n/p spectrum ratio</u>, neutron-proton differential flow and correlation function in heavy-ion collisions at intermediate energies**
- **Radii of neutron stars**
- **Neutrino flux of supernova explosions**
- **Tidal polarizability in neutron star mergers, strain amplitude of gravitational waves from deformed pulsars, frequency and damping time of neutron star oscillations**

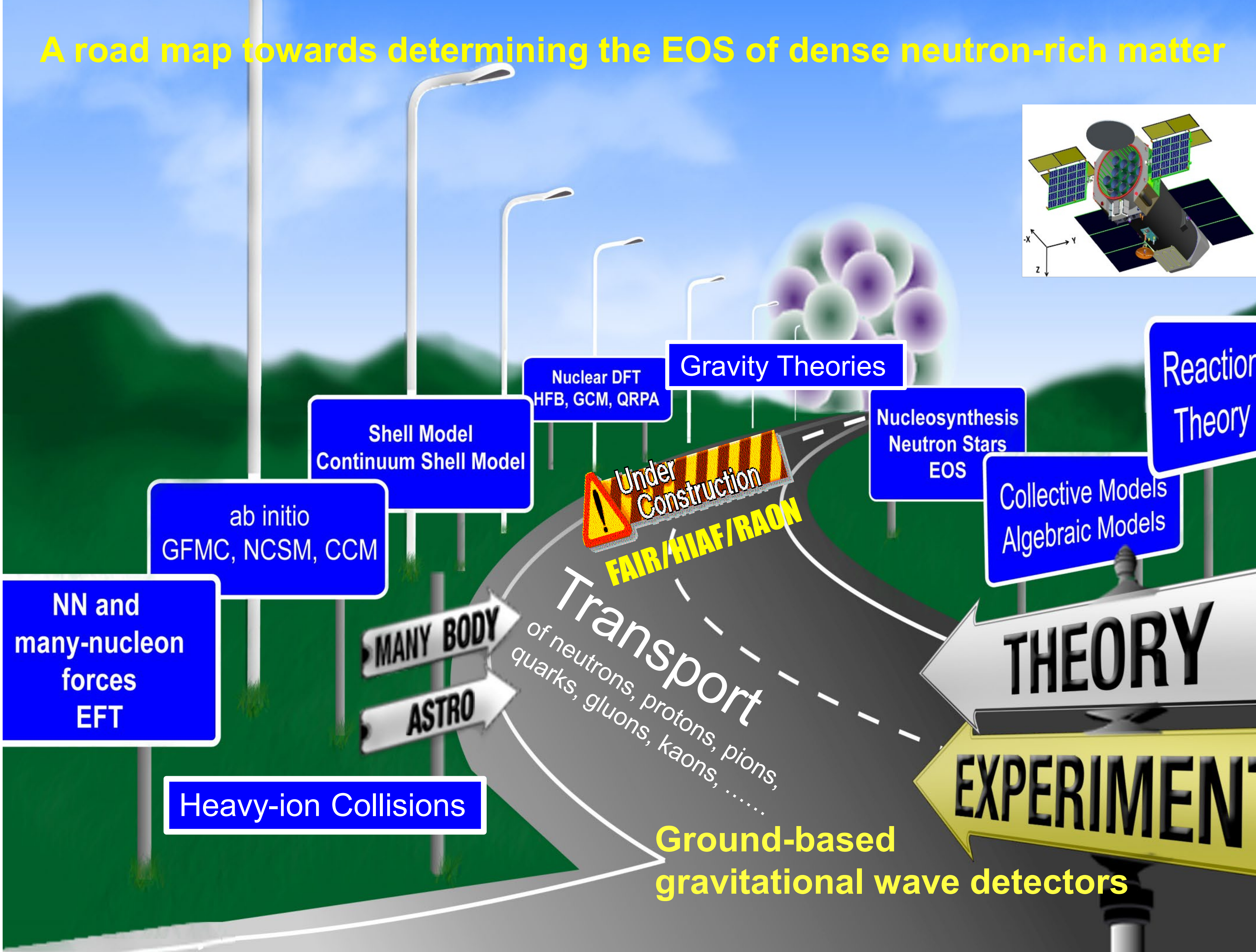
B.A. Li, L.W. Chen and C.M. Ko, Phys. Rep. 464, 113 (2008)

EPJA, Vol. 50, No. 2 (2014)

From Earth to Heaven: multi-messengers of nuclear EOS

Truly multi-messenger approach to probe the EOS of dense neutron-rich matter
= astrophysical observations + terrestrial experiments + theories + …




A road map towards determining the EOS of dense neutron-rich matter
Gravity Theories
Nuclear DFT
HFB, GCM, QRPA
Shell Model
Continuum Shell Model
ab initio
GFMC, NCSM, CCM
NN and
many-nucleon
forces
EFT
Nucleosynthesis
Neutron Stars
EOS
Reaction
Theory
Collective Models
Algebraic Models
Under
Construction
FAIR/HIAF/RAON
MANY BODY
ASTRO
Transport
of neutrons, protons, pions,
quarks, gluons, kaons, ……
THEORY
EXPERIMENT
Heavy-ion Collisions
Ground-based
gravitational wave detectors