Probing Symmetry Energy with Terrestrial Nuclear Reactions

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National Natural Science Foundation of China

Symmetry Energy: From Earth to Heaven

- Where does the symmetry energy come from?
- Why is it so uncertain especially at high densities?
- How to probe it with terrestrial nuclear reactions?
- How does the high-density E_{sym} relate to strong-field gravity?

What is the EOS of cold, neutron-rich nucleonic matter at varying densities and neutron-proton asymmetries?

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

symmetry energy

Isospin asymmetry δ

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

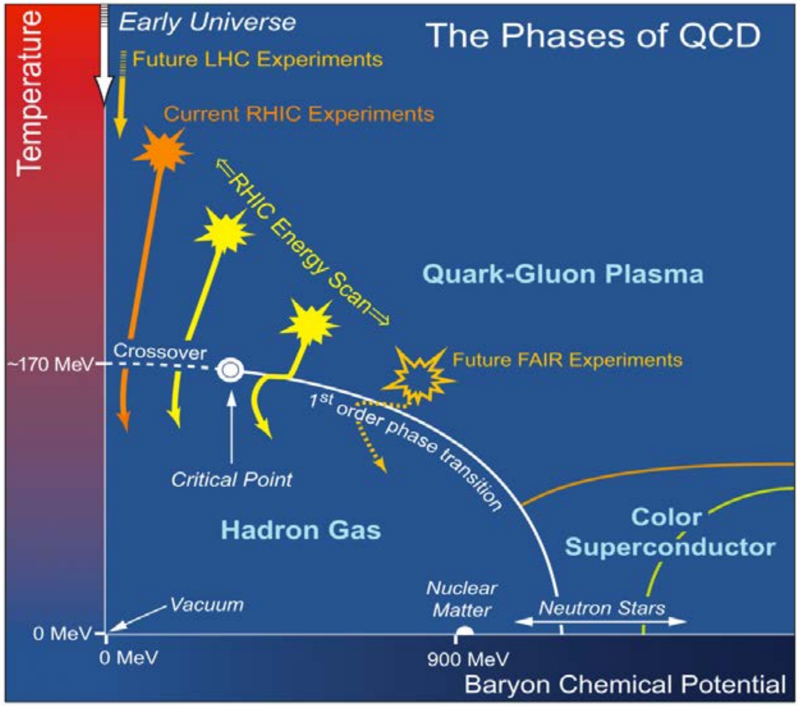
Energy per nucleon in symmetric matter

Energy in asymmetric nucleonic matter

neutrons + protons
in a large volume
of uniform matter
at density ρ and
isospin asymmetry

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

Isospin asymmetry



0

$\rho = \rho_n + \rho_p$

???

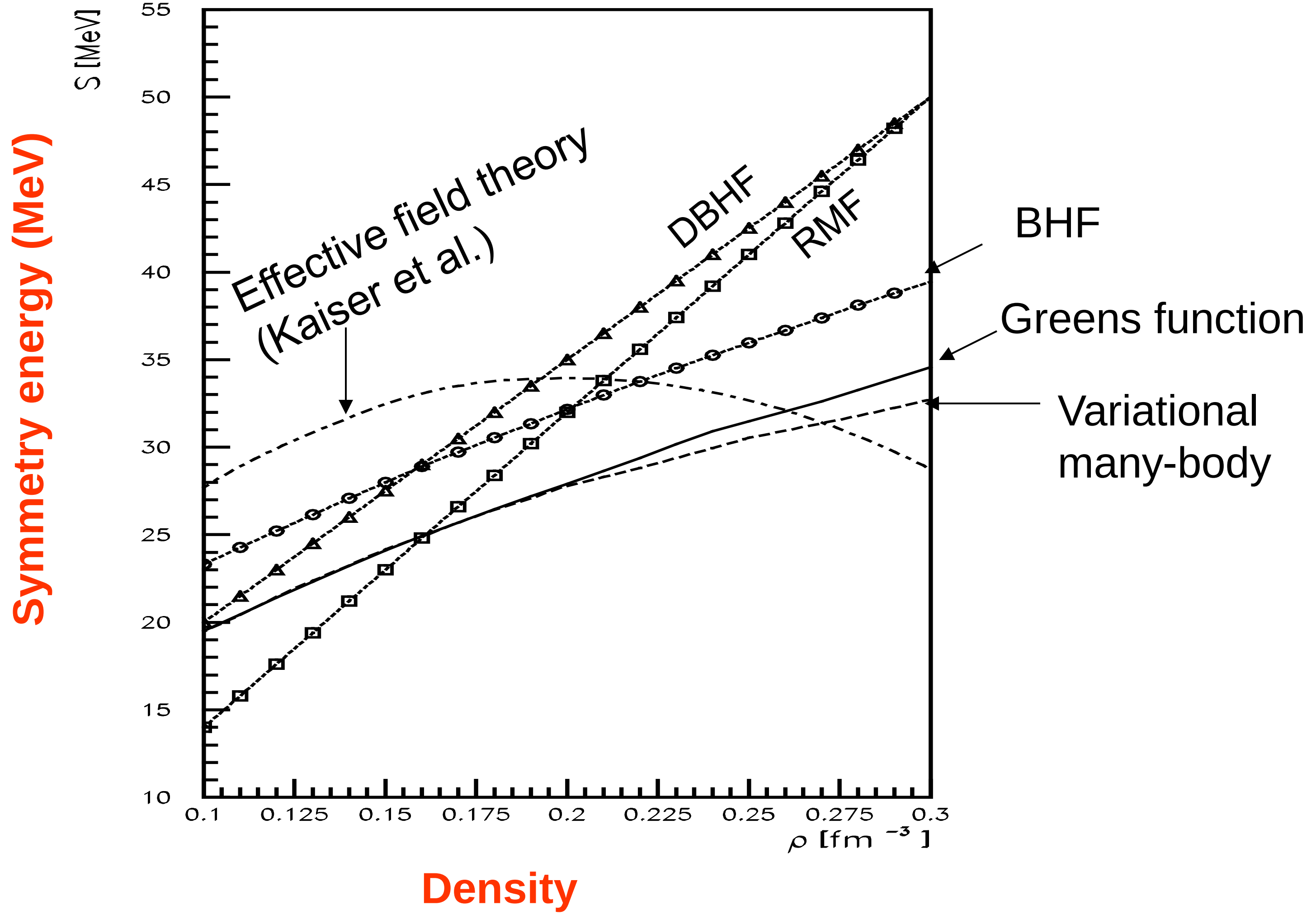
???

1

The axis of new opportunities

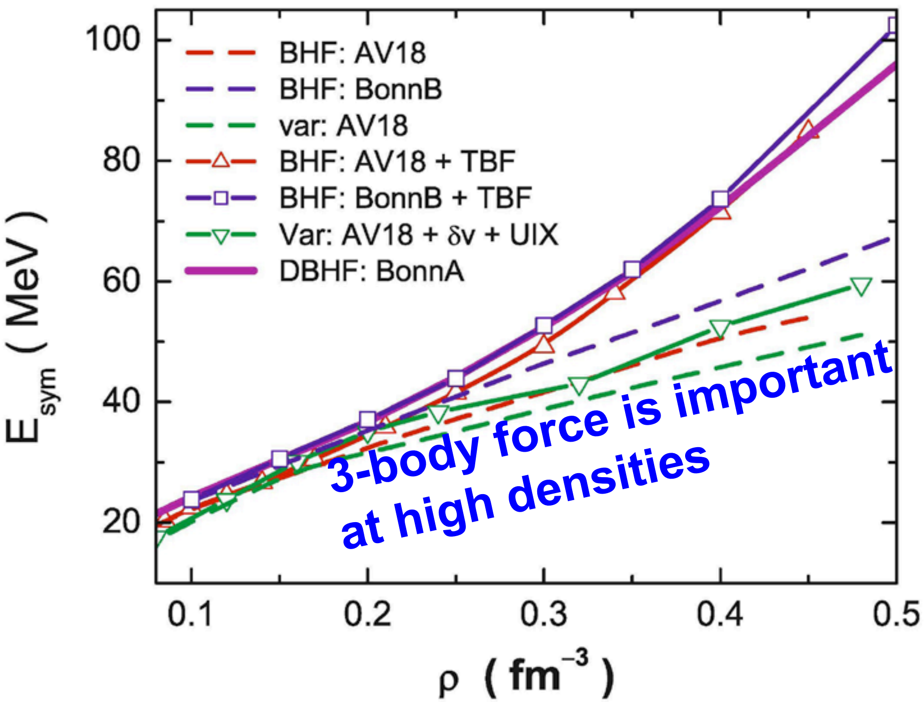
???

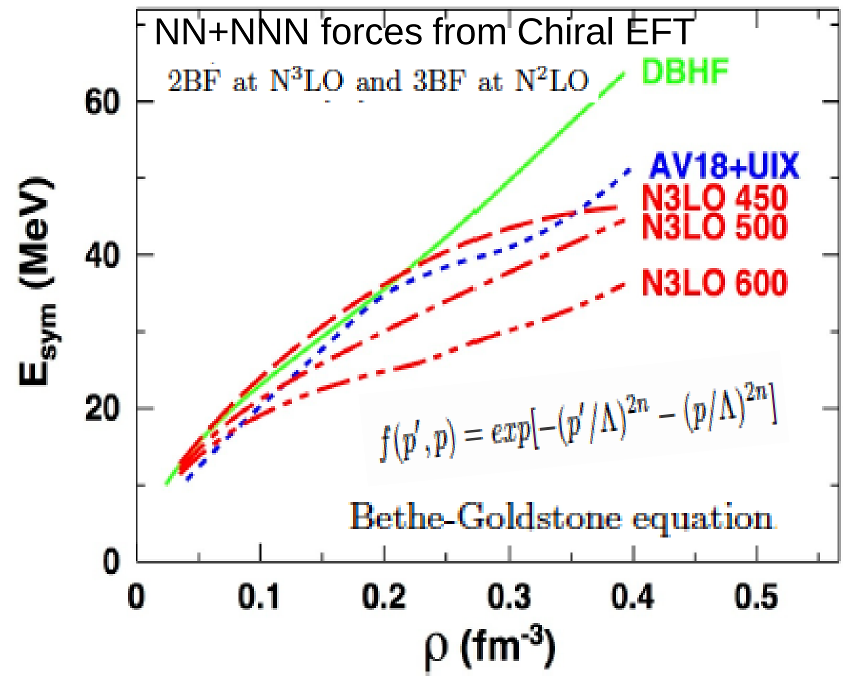
E_{sym} (ρ) predicted by microscopic many-body theories



A.E. L. Dieperink et al., Phys. Rev. C68 (2003) 064307

Examples of more recent predictions using microscopic theories





W. Zuo, I. Bombaci and U. Lombardo, Euro. Phys. J. A 50, 12 (2014).

Francesca Sammarruca, Phys. Rev. C 90, 064312 (2014)

Characterization of symmetry energy near normal density

$$E_{sym}(\rho) = E_{sym}(\rho_0) + \frac{L(\rho_0)}{3}(\frac{\rho - \rho_0}{\rho_0}) + O((\frac{\rho - \rho_0}{\rho_0})^2)$$

$$L(\rho) = 3\rho \frac{dE_{\rm sym}(\rho)}{d\rho}.$$

The physical importance of L

In npe matter in the simplest model of neutron stars at β-equilibrium

$$P(\rho, \delta) = P_0(\rho) + P_{\rm asy}(\rho, \delta) = \rho^2 \left(\frac{\partial E}{\partial \rho}\right)_\delta + \frac{1}{4}\rho_e \mu_e$$

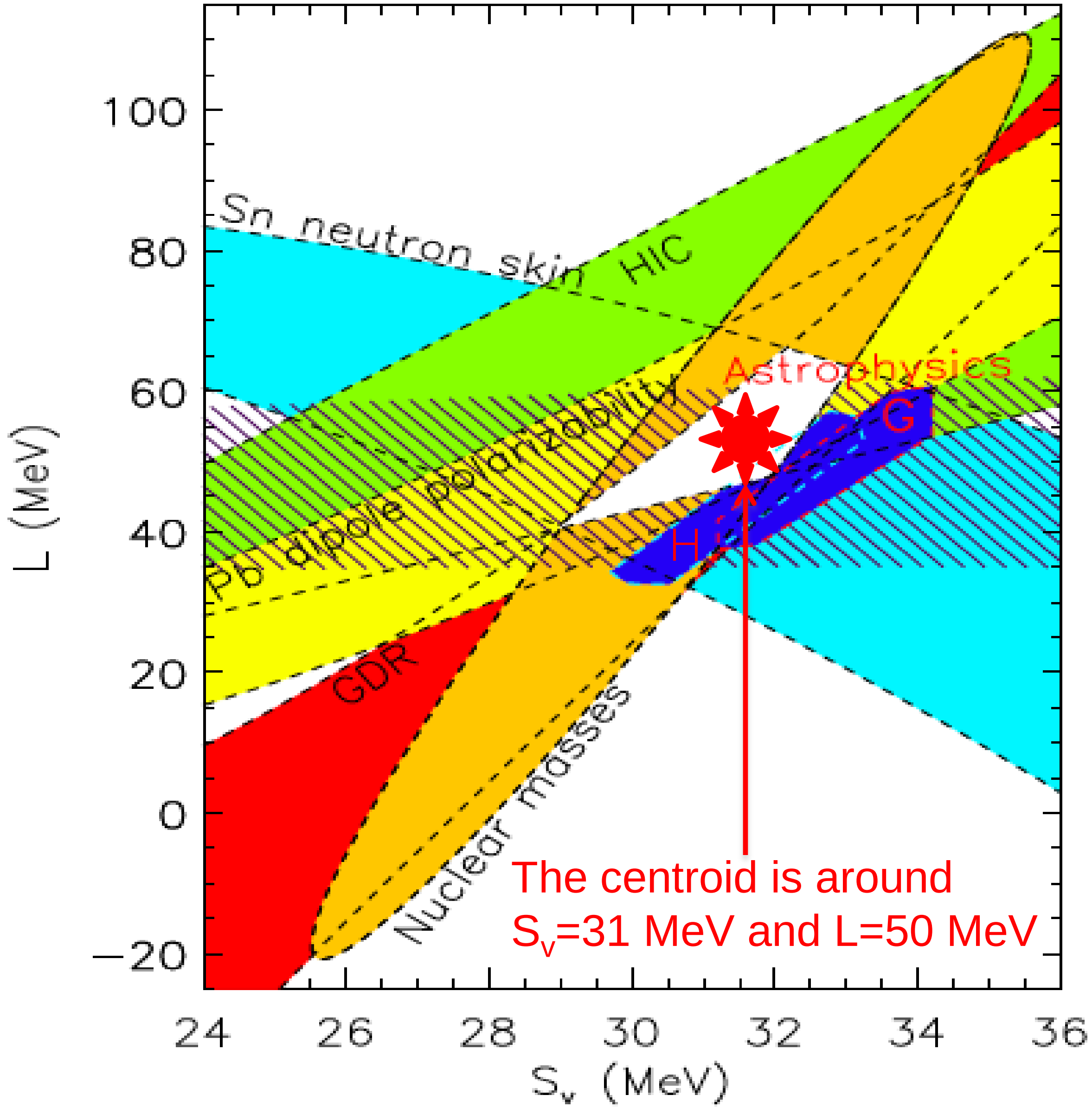
$$= \rho^2 \left[E'(\rho, \delta = 0) + E'_{\rm sym}(\rho)\delta^2\right] + \frac{1}{2}\delta(1-\delta)\rho E_{\rm sym}(\rho),$$

In pure neutron matter at saturation density of nuclear matter

$$P_{PNM}(\rho_0) = \rho_0^2 E'_{\rm sym}(\rho_0) = \frac{1}{3}\rho_0 L,$$

Many astrophysical observables, e.g., radii, core-crust transition density, cooling rate, oscillation frequencies and damping rate, etc, of neutron stars are sensitive to the density dependence of nuclear symmetry energy.

Lattimer and Steiner using 6 (2013) out of approximately 50 (2016) available constraints



Cover of the Topical Issue on Nuclear Symmetry Energy, EPJA 50, no.2 (2014)

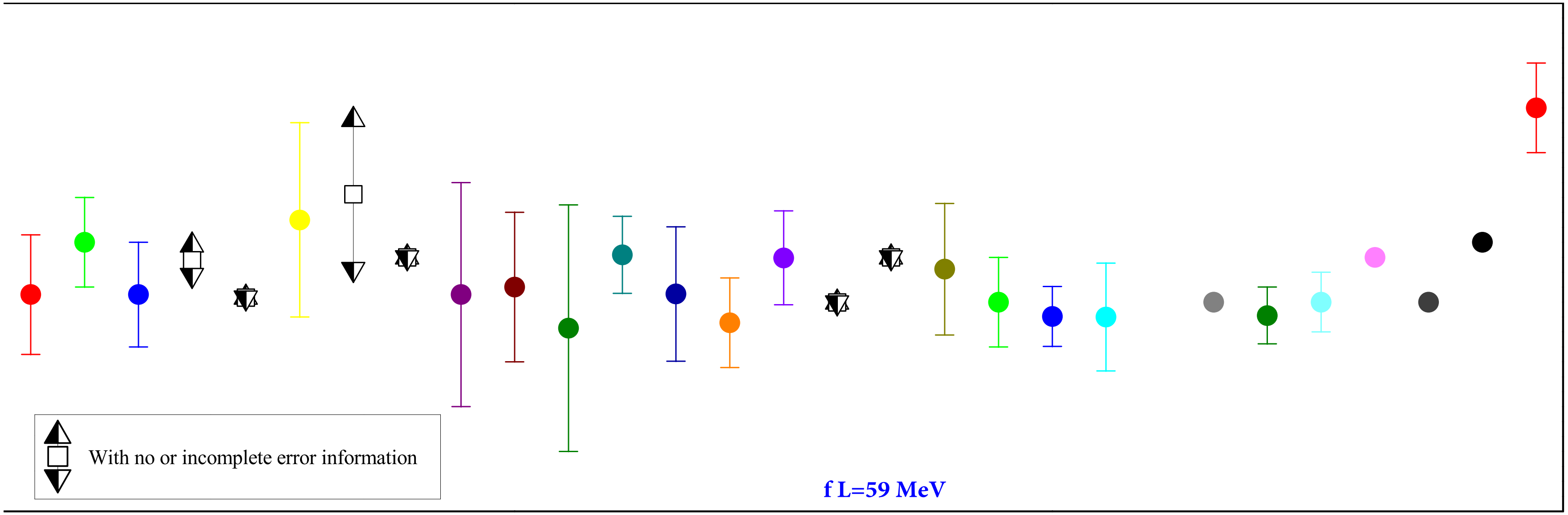
Constraints on $E_{sym}(\rho_0)$ and L based on 29 analyses of data

Fiducial values as of Aug. 2013

$$E_{sym}(\rho_0) \approx 31.6 \pm 2.66 \text{ MeV}$$

$$L \approx 2\, E_{sym}(\rho_0) = 59 \pm 16 \text{ MeV}$$

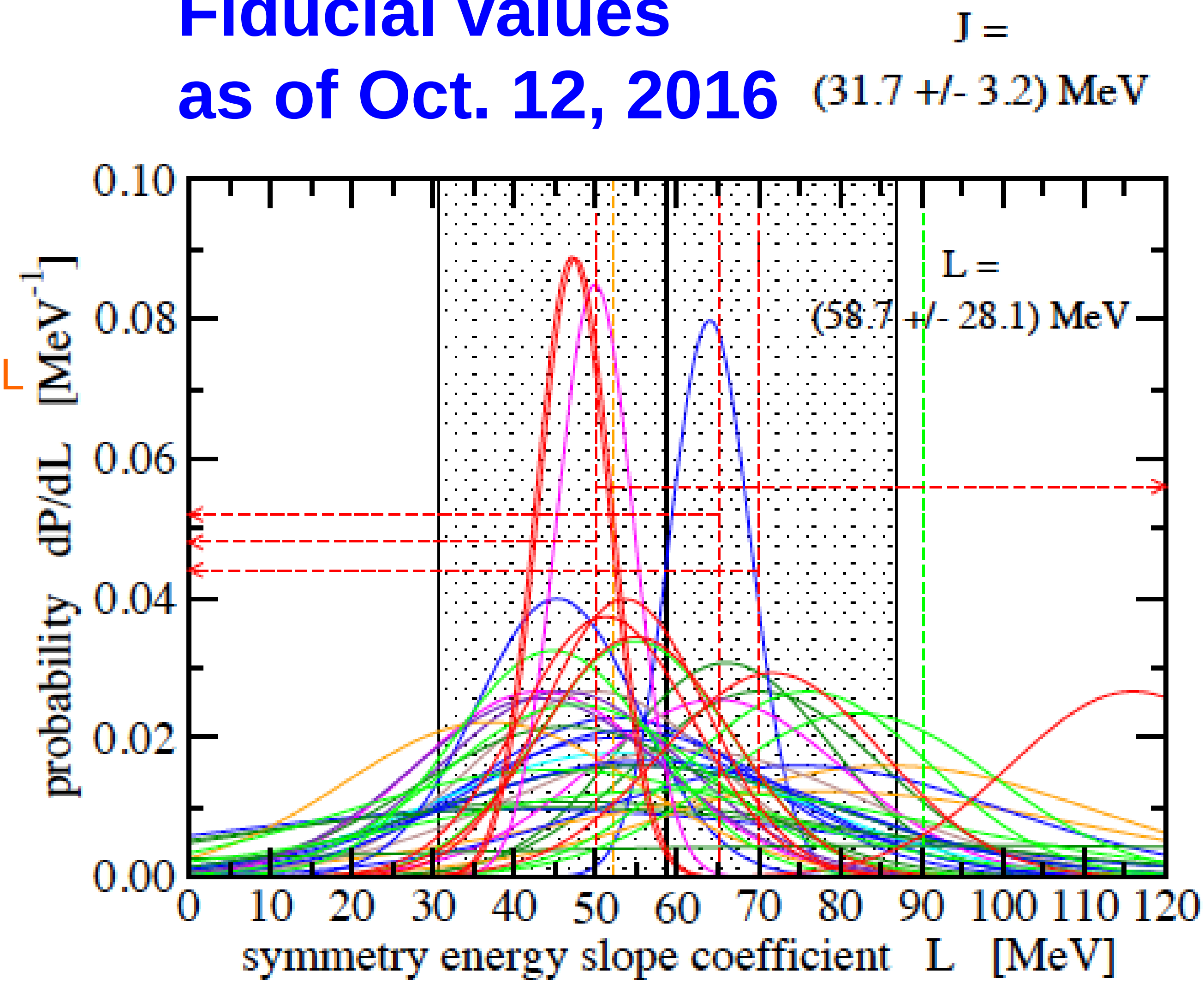
$L = 2\, E_{sym}(\rho_0)$ if $E_{sym} = E_{sym}(\rho_0)(\rho/\rho_0)^{2/3}$



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

Constraints on $E_{sym}(\rho_0)$ and L based on 53 analyses of data

Fiducial values as of Oct. 12, 2016



Assuming !
(1) Gaussian Distribution of L
(2) Democratic principle
(i.e., trust everyone)

$L \approx 2\, E_{sym}(\rho_0)$

M. Oertel, M. Hempel, T. Klähn, S. Typel arXiv:1610.03361 [astro-ph.HE]

Microphysics governing the $E_{sym}(\rho)$ and $L(\rho)$ and their correlation

at the mean - field level according to the Hugenholtz-Van Hove (HVH) theorem

$$t(k_F^n) + U_n(\rho, \delta, k_F^n) = \frac{\partial \xi}{\partial \rho_n},$$
$$t(k_F^p) + U_p(\rho, \delta, k_F^p) = \frac{\partial \xi}{\partial \rho_p}, \qquad \xi = \rho E,$$

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

$$E_{sym}(\rho) = \frac{1}{3}\frac{\hbar^2 k^2}{2m_0^*}|_{k_F} + \frac{1}{2}U_{sym,1}(\rho, k_F), \qquad m_0^*(\rho, k) = \frac{m}{1 + \frac{m}{\hbar^2 k}\frac{\partial U_0(\rho,k)}{\partial k}},$$

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

C. Xu, B.A. Li, L.W. Chen and C.M. Ko, NPA 865, 1 (2011)

Why is the symmetry energy so uncertain?
(Besides the different many-body approaches used)

- Isospin-dependence of short-range neutron-proton correlation due to the tensor force
- Spin-isospin dependence of the 3-body force
- Isospin dependence of pairing and clustering at low densities

$$E_{sym}(\rho) = \frac{1}{3}\frac{\hbar^2 k_F^2}{2m^*} + \frac{1}{2}U_{sym}(\rho, k_F)$$ (Valid only at the mean-field level)

Keith A. Brueckner, Sidney A. Coon, and Janusz Dabrowski, Phys. Rev. 168, 1184 (1968)

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

Correlation functions

Within a simple interacting Fermi gas model

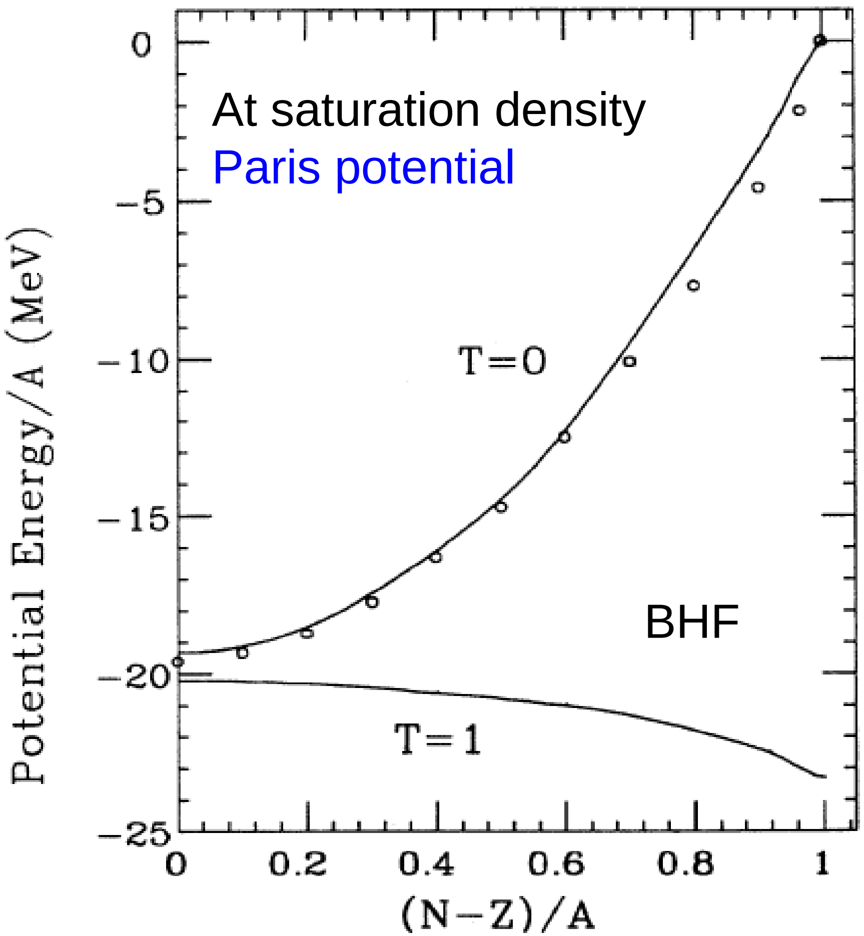
$$U_{sym}(k_F, \rho) = \frac{1}{4}\rho \int [V_{T1}(r_{ij}) f^{T1}(r_{ij}) - V_{T0}(r_{ij}) f^{T0}(r_{ij})] d^3 r_{ij}$$

V_{np}(T0) ? V_{np} (T1)
f^{T0} ? f^{T1} , the tensor force in T0 channel makes them different

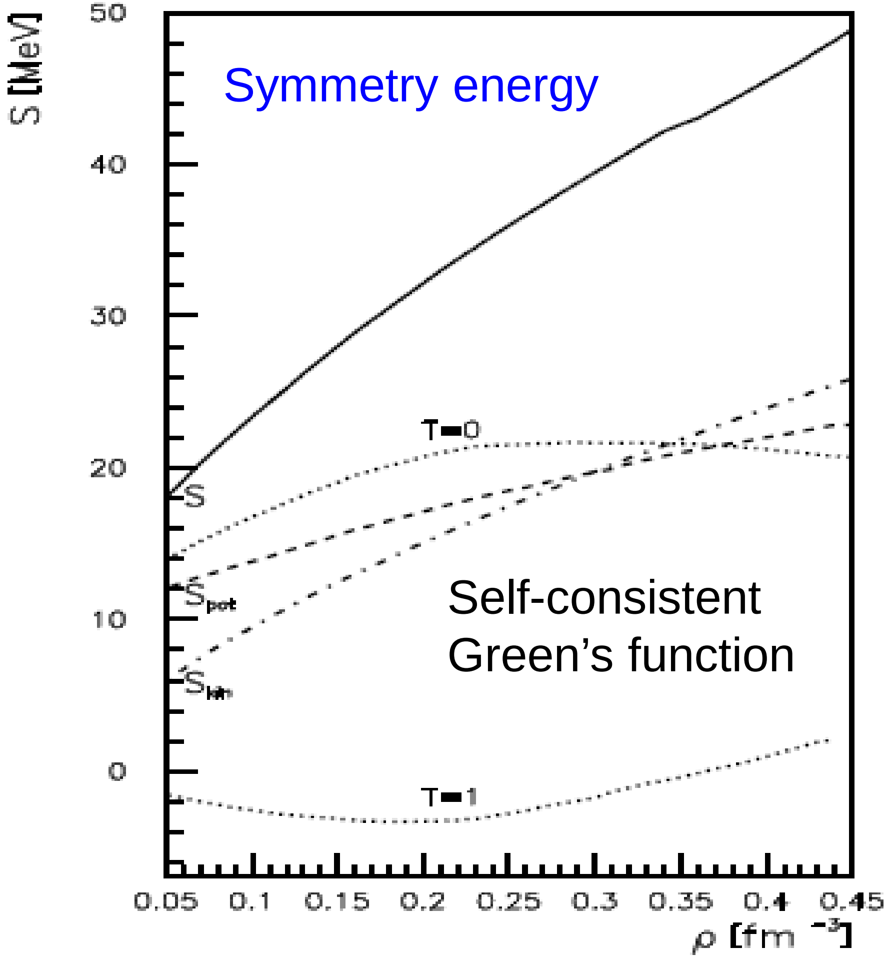
$V_{T0} = V'_{np}$ (n-p pair in the T=0 state)

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

Dominance of the isosinglet (T=0) interaction



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

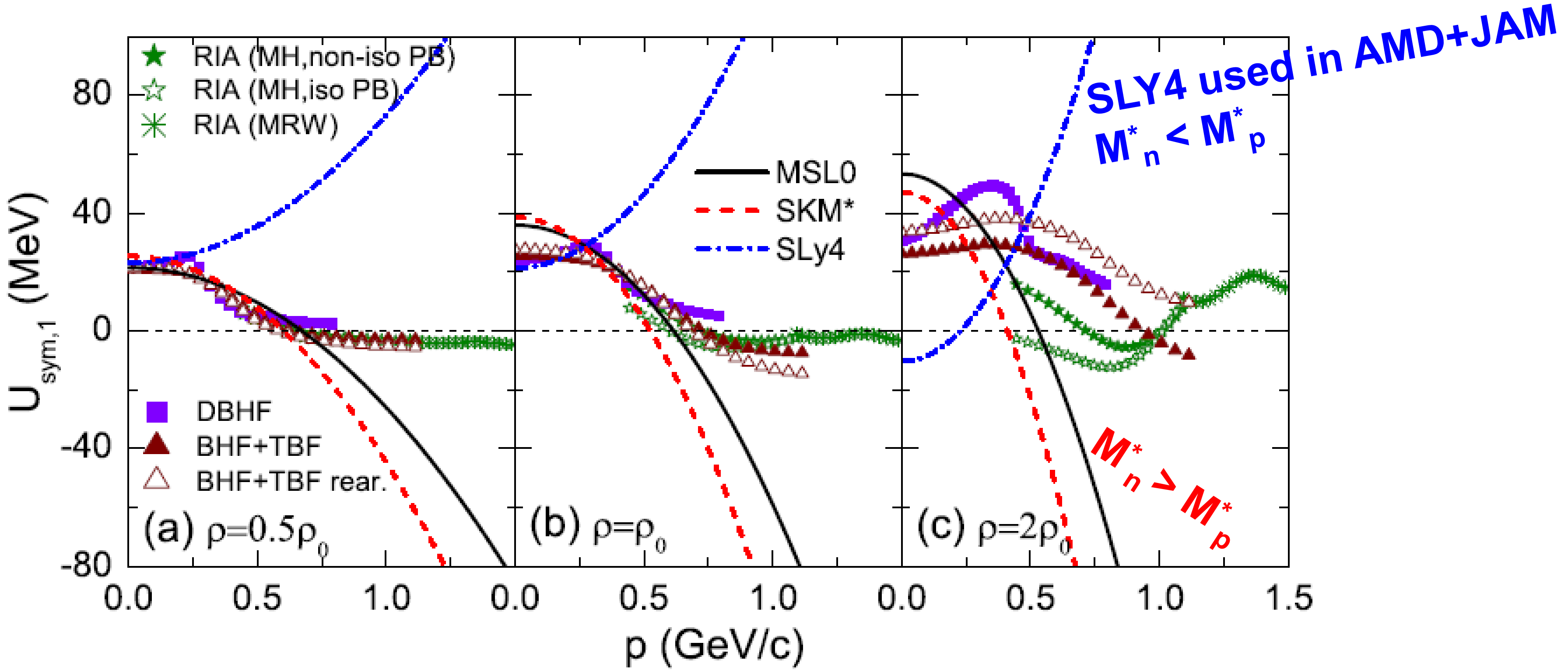


A.E.L. Dieperink,[1] Y. Dewulf,[2] D. Van Neck,[2] M. Waroquier,[2] and V. Rodin[3]

PRC68, 064307 (2003)

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

Momentum and density dependence of the symmetry potential $U_{sym,1}$

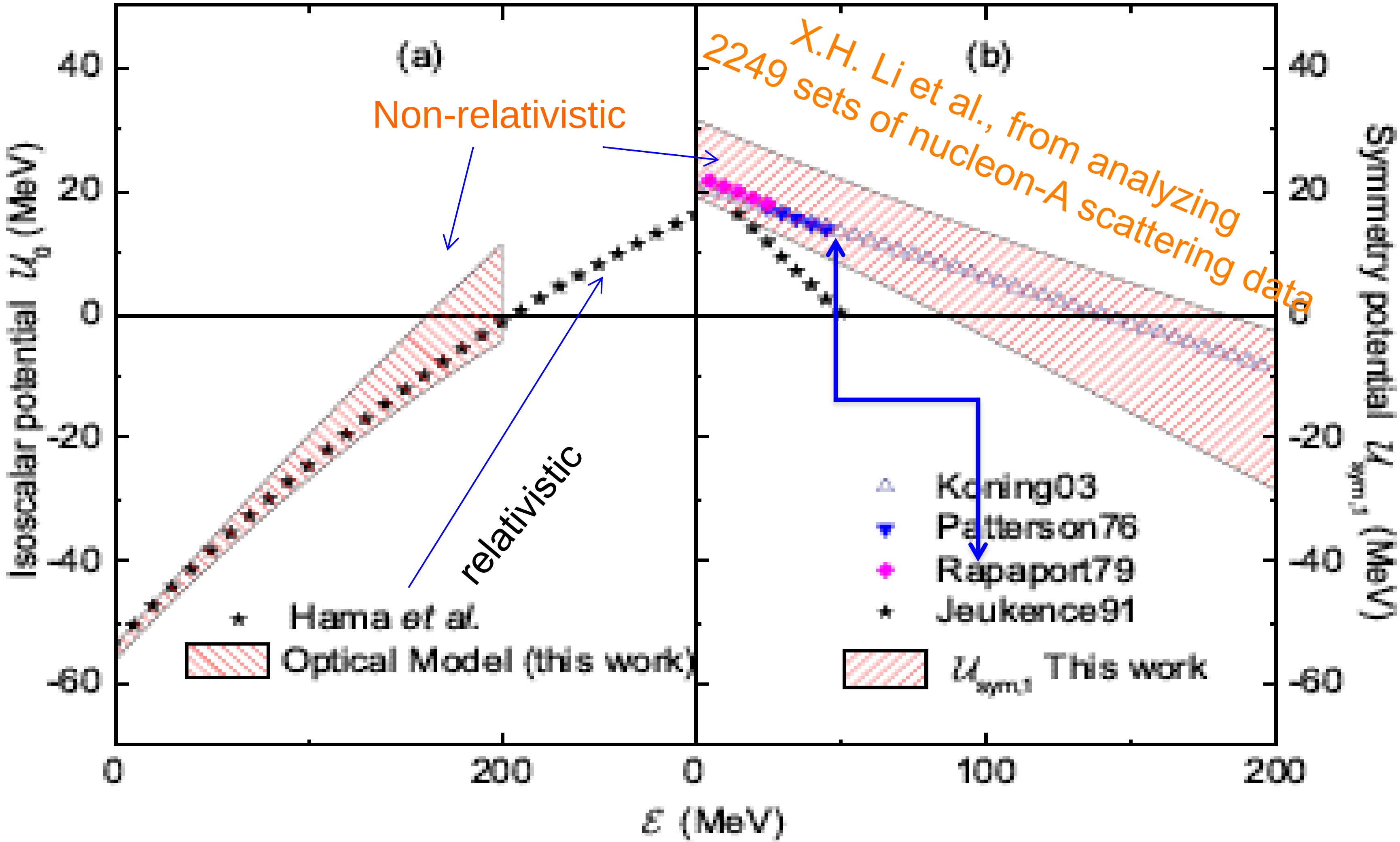


- Symmetry potential is uncertain at high density/momentum
- Isospin effects are expected to stronger at low energies where U_{sym} is larger
- Most models and nucleon-A scattering indicate a $_{Usym}$ sign inversion at high momentum

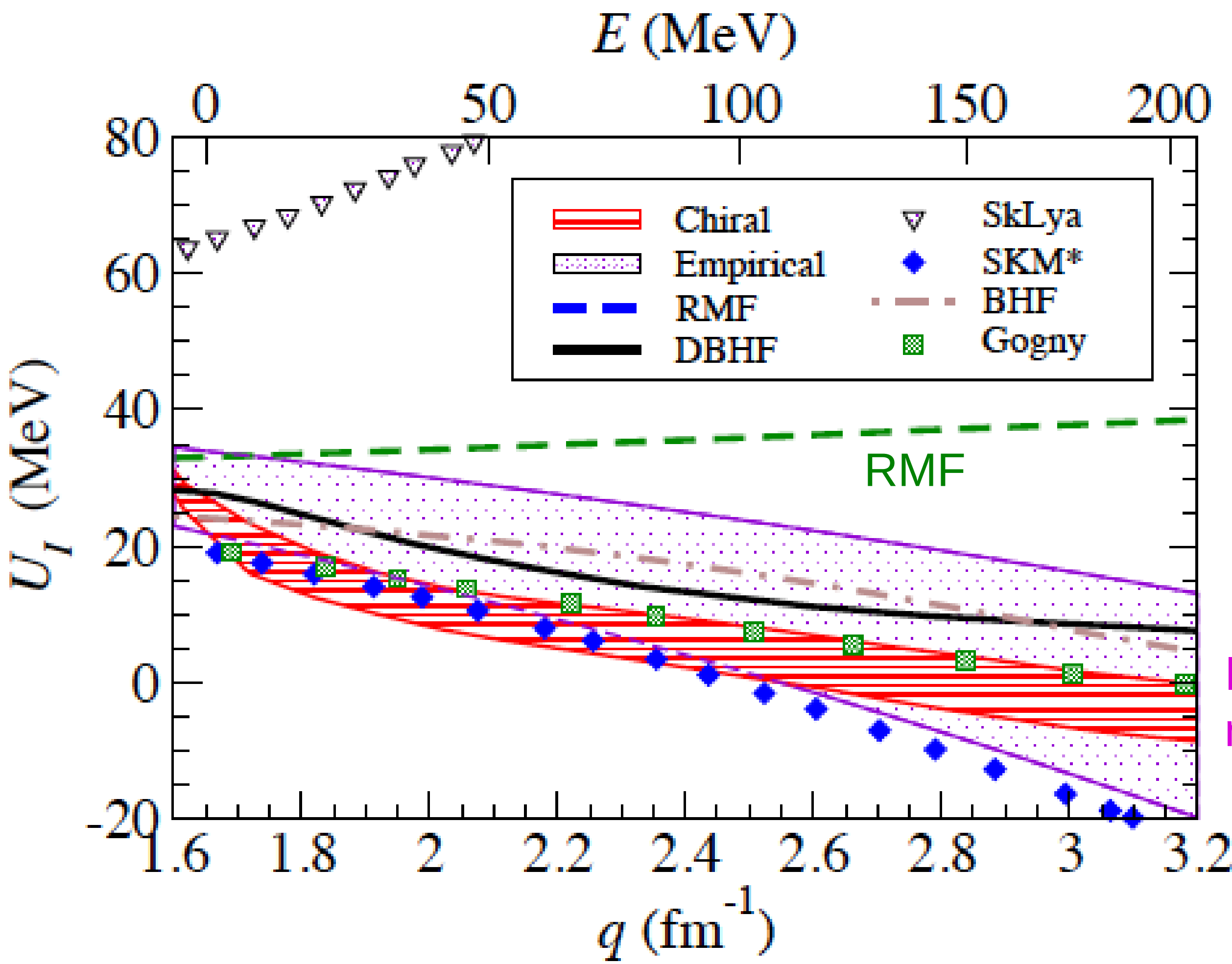
R. Chen et al., PRC 85, 024305 (2012).

Momentum dependence of the isoscalar and isovector (symmetry) potential at normal density constrained by nucleon-nucleus scattering data

Physics Letters B743 (2015) 408



Constraining the energy dependence of symmetry potential at saturation density



Isovector optical potential from nucleon-nucleus scattering

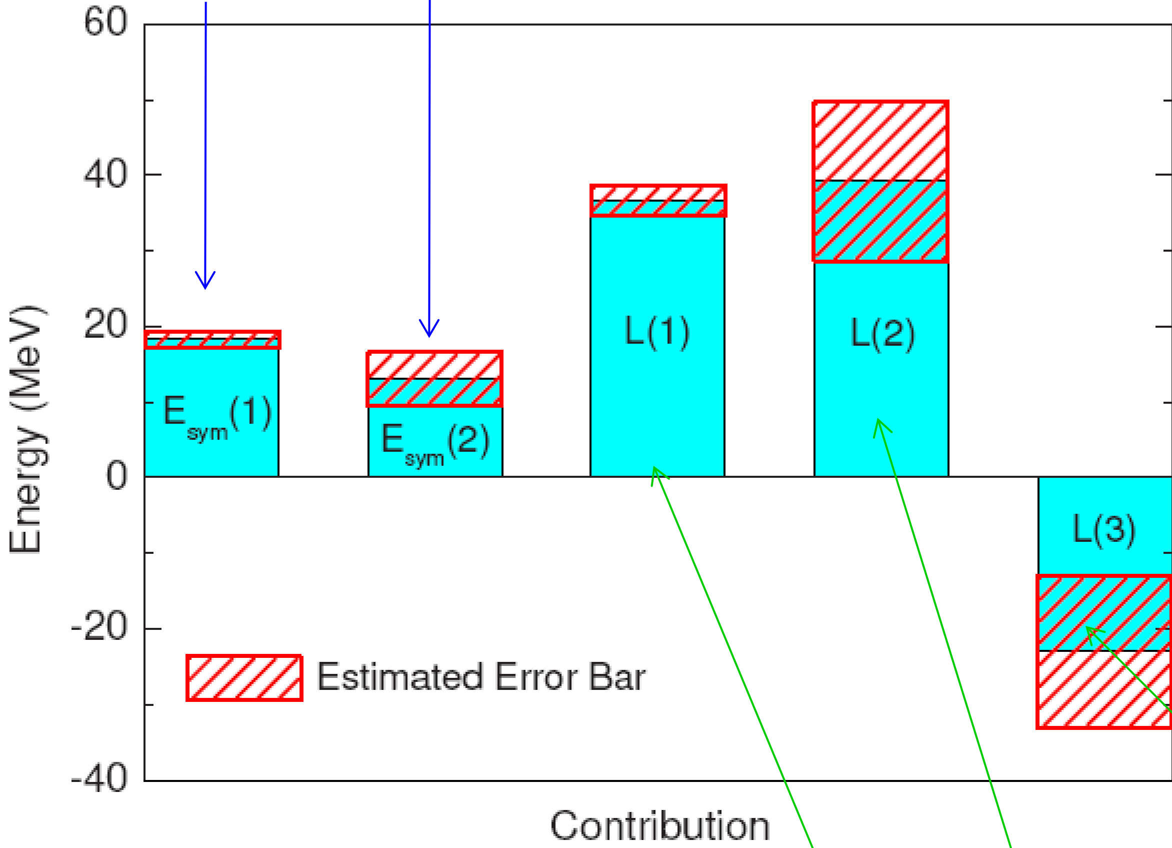
J. W. Holt, N. Kaiser, G. A. Miller
Phys. Rev. C 93, 064603 (2016)

Constraining the symmetry energy near saturation density using global nucleon optical potentials

Chang Xu, Bao-An Li, Lie-Wen Chen
Phys.Rev.C82:054607,2010

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

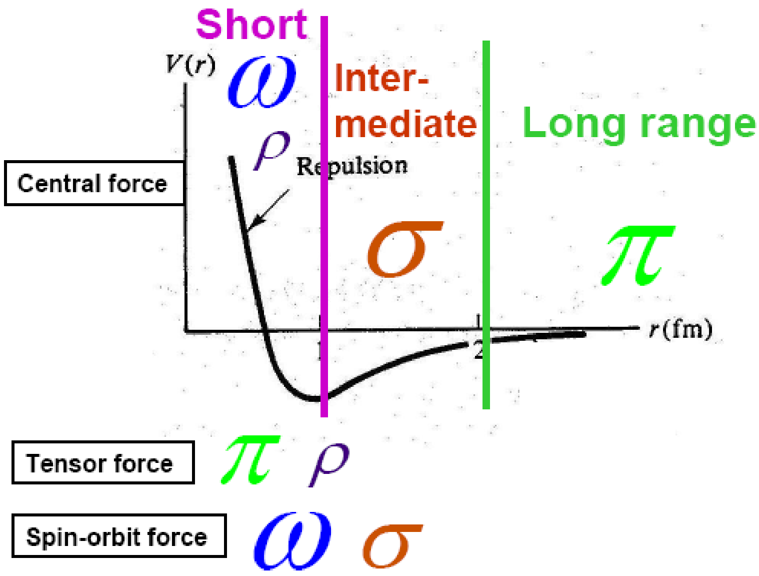
$$E_{sym}(\rho_0) = 31.3 \text{ MeV} \pm 4.5 \text{ MeV}$$



$$L(\rho_0) = 52.7 \text{ MeV} \pm 22.5 \text{ MeV}$$

$$L(\rho) = \frac{2}{3}\frac{\hbar^2 k_F^2}{2m^*} + \frac{3}{2}U_{sym}(\rho, k_F) + \frac{\partial U_{sym}}{\partial k}|_{k_F} k_F$$

The short and long range tensor force



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

$\pi(138)$

$$V_\pi = \frac{f_{\pi NN}^2}{3m_\pi^2}\frac{\vec{q}^{\,2}}{\vec{q}^{\,2}+m_\pi^2}\left[-\vec{\sigma}_1\cdot\vec{\sigma}_2 - S_{12}(\vec{q})\right]\vec{\tau}_1\cdot\vec{\tau}_2$$

Long-ranged tensor force

$\sigma(600)$

$$V_\sigma \approx \frac{g_\sigma^2}{\vec{q}^{\,2}+m_\sigma^2}\left[-1 - \frac{\vec{L}\cdot\vec{S}}{2M^2}\right]$$

intermediate-ranged, attractive central force plus LS force

$\omega(782)$

$$V_\omega \approx \frac{g_\omega^2}{\vec{q}^{\,2}+m_\omega^2}\left[+1 - 3\frac{\vec{L}\cdot\vec{S}}{2M^2}\right]$$

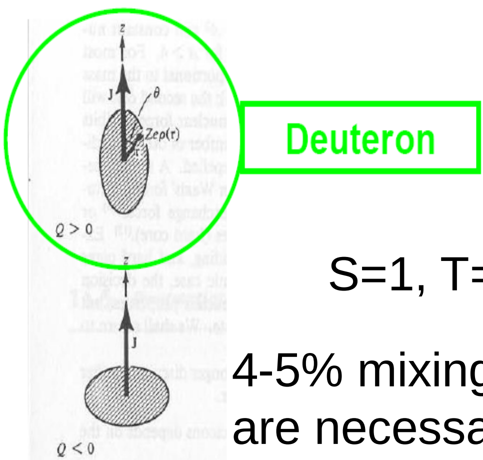
short-ranged, repulsive central force plus strong LS force

$\rho(770)$

$$V_\rho = \frac{f_\rho^2}{12M^2}\frac{\vec{q}^{\,2}}{\vec{q}^{\,2}+m_\rho^2}\left[-2\vec{\sigma}_1\cdot\vec{\sigma}_2 + S_{12}(\vec{q})\right]\vec{\tau}_1\cdot\vec{\tau}_2$$

short-ranged tensor force, opposite to pion

Tensor Force: First evidence from the deuteron

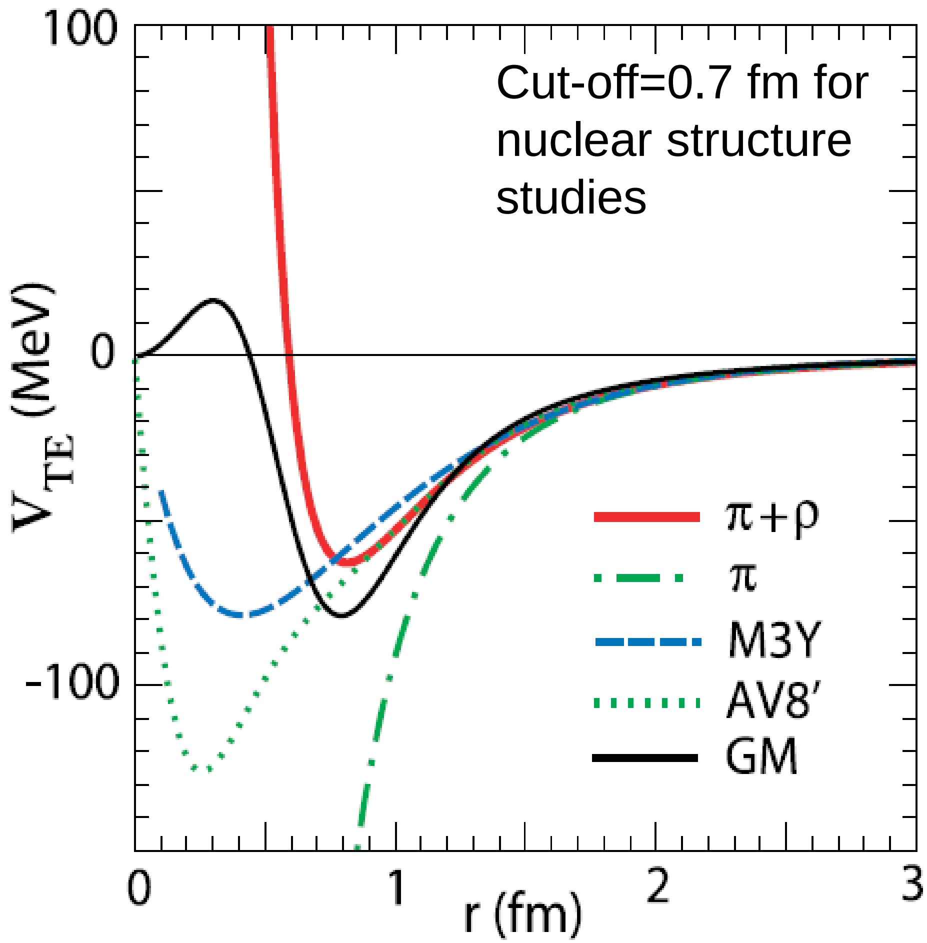


S=1, T=0

4-5% mixing of S-D waves are necessary

Uncertainty of the tensor force at short distance

Takaharu Otsuka et al., PRL 95, 232502 (2005); PRL 97, 162501 (2006)



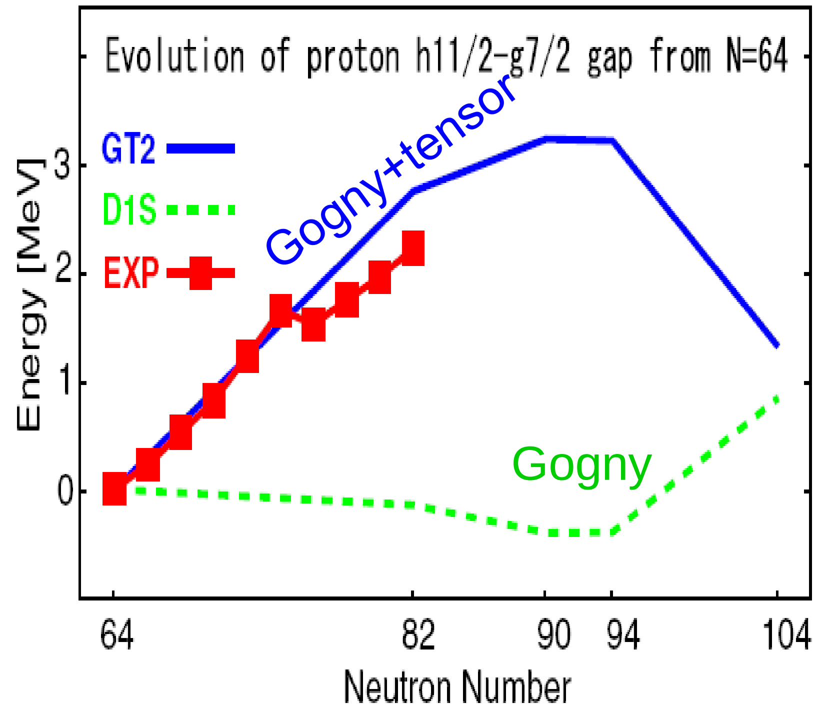


FIG. 4 (color online). Evolution of $1h_{11/2}$-$1g_{7/2}$ energy gap. The difference from the value of $N = 64$ is plotted for experimental data [21] and calculated results with GT2 and D1S interactions.

[21] J. P. Schiffer *et al.*, Phys. Rev. Lett. **92**, 162501 (2004).

Can the symmetry energy become negative at high densities?

Yes, it happens when the tensor force due to ρ exchange in the T=0 channel dominates

At high densities, the energy of pure neutron matter can be lower than symmetric matter leading to negative symmetry energy

Pandharipande V R and Garde V K 1972 *Phys. Lett.* B 39 608

Wiringa R B, Fiks V and Fabrocini A 1988 *Phys. Rev.* C 38 1010

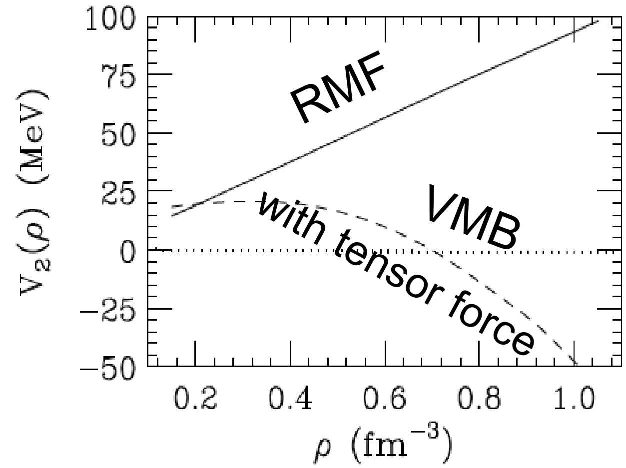
Kutschera M 1994 *Phys. Lett.* B 340 1

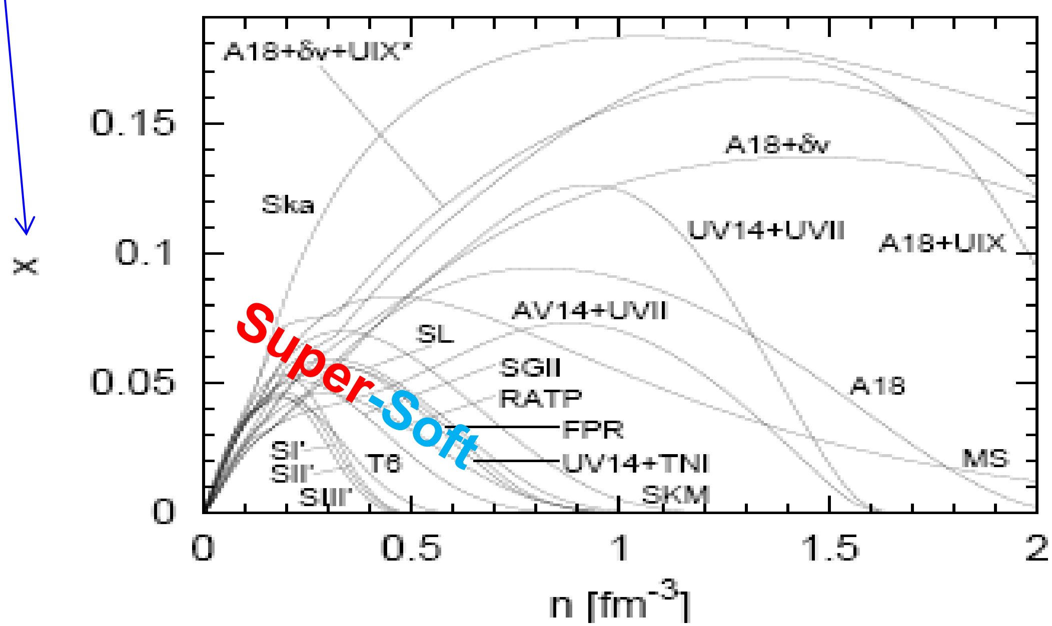
Example: proton fractions with interactions/models leading to negative symmetry energy

M. Kutschera et al., Acta Physica Polonica B37 (2006)

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

Potential part of the symmetry energy





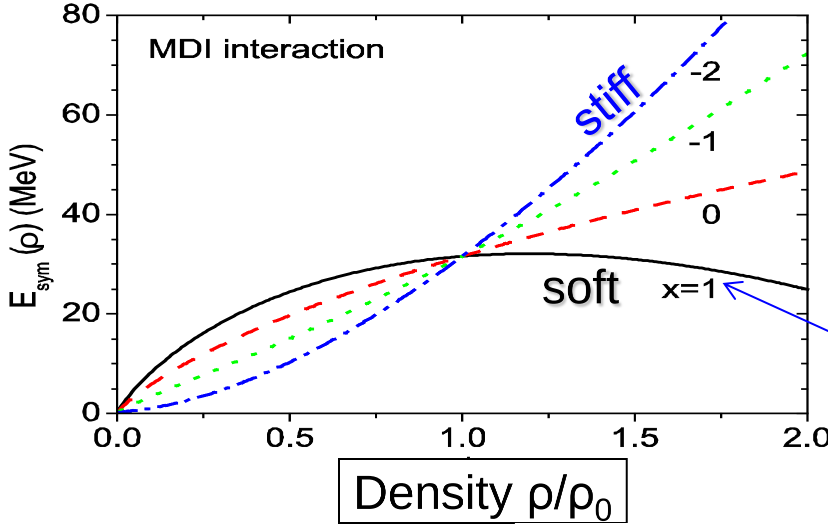
Both tensor force and/or 3-body force can make E_{sym} negative at high densities

3-body force effects in Gogny or Skyrme HF

$$V_d = t_0(1 + x_0 P_\sigma)\rho^\alpha \delta(r)$$

$$E_{sym}^{TBF} = -(1+2x_0)\frac{t_0}{8}\rho^{\alpha+1}$$

Symmetry energy and single nucleon potential MDI used in the IBUU04 transport model



The x parameter is introduced to mimic various predictions on the symmetry energy by different microscopic nuclear many-body theories using different effective interactions.

It is the coefficient of the 3-body force term

Default: Gogny force

Potential energy density

$$V(\rho,\delta) = \frac{A_1}{2\rho_0}\rho^2 + \frac{A_2}{2\rho_0}\rho^2\delta^2 + \frac{B}{\sigma+1}\frac{\rho^{\sigma+1}}{\rho_0^\sigma}(1 - x\delta^2) + \frac{1}{\rho_0}\sum_{\tau,\tau'} C_{\tau,\tau'}\int\int d^3p\,d^3p'\frac{f_\tau(\vec r,\vec p)f_{\tau'}(\vec r,\vec p')}{1+(\vec p-\vec p')^2/\Lambda^2}$$

Single nucleon potential within the HF approach using a modified Gogny force:

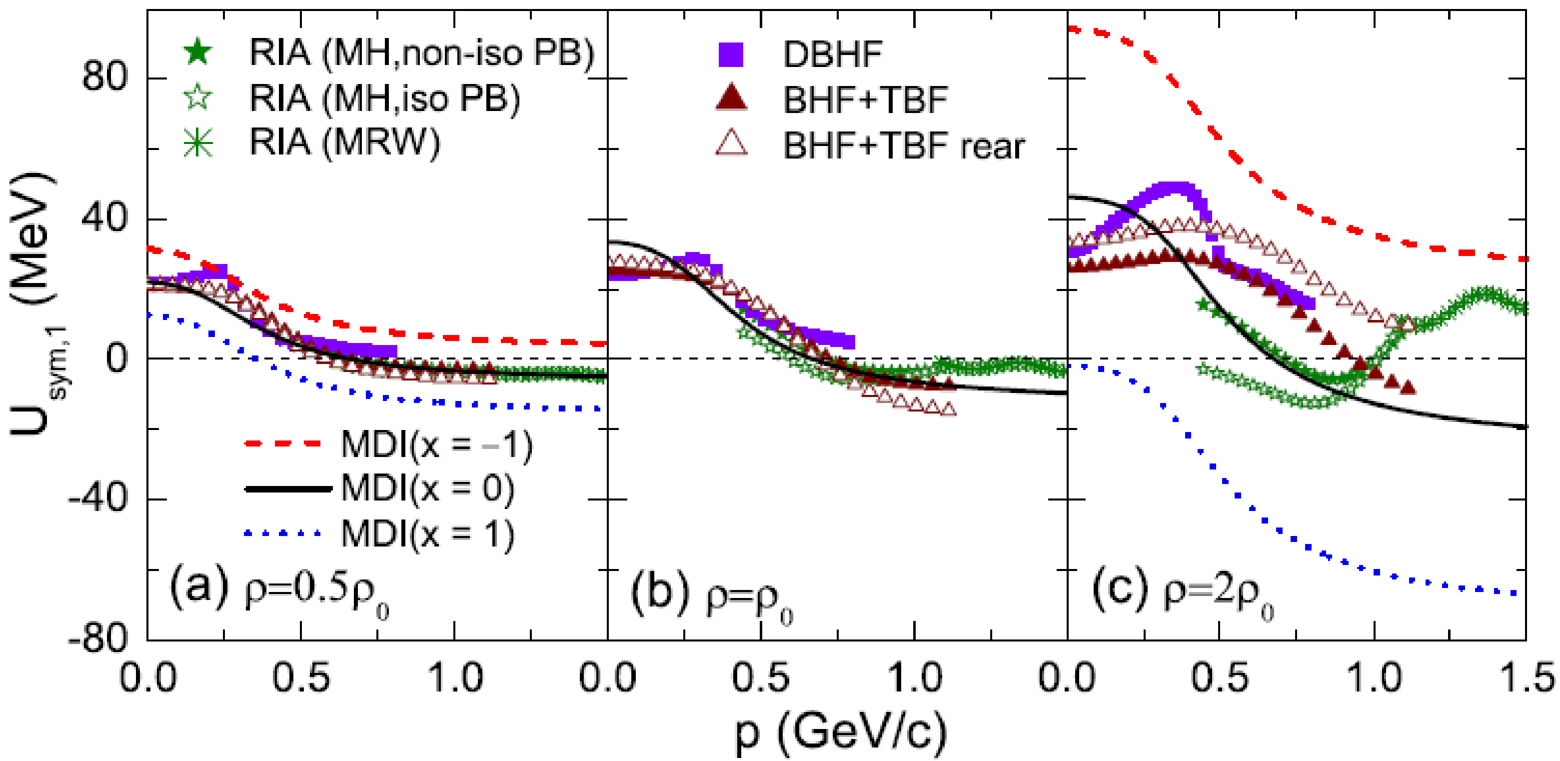
$$U(\rho,\delta,\vec{p},\tau,x) = A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^\sigma(1 - x\delta^2) - 8\tau x\frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\delta\rho_{\tau'} + \frac{2C_{\tau,\tau}}{\rho_0}\int d^3p'\frac{f_\tau(r,p')}{1+(p-p')^2/\Lambda^2} + \frac{2C_{\tau,\tau'}}{\rho_0}\int d^3p'\frac{f_{\tau'}(r,p')}{1+(p-p')^2/\Lambda^2}$$

$$\tau,\tau' = \pm\frac{1}{2},\ A_l(x) = -121 + \frac{2Bx}{\sigma+1},\ A_u(x) = -96 - \frac{2Bx}{\sigma+1},\ K_0 = 211 MeV$$

C.B. Das, S. Das Gupta, C. Gale and B.A. Li, PRC 67, 034611 (2003).

B.A. Li, C.B. Das, S. Das Gupta and C. Gale, PRC **69**, 034614; NPA **735**, 563 (2004).

$U_{sym,1}$ (ρ,p) in the MDI potential used in IBUU04 transport model

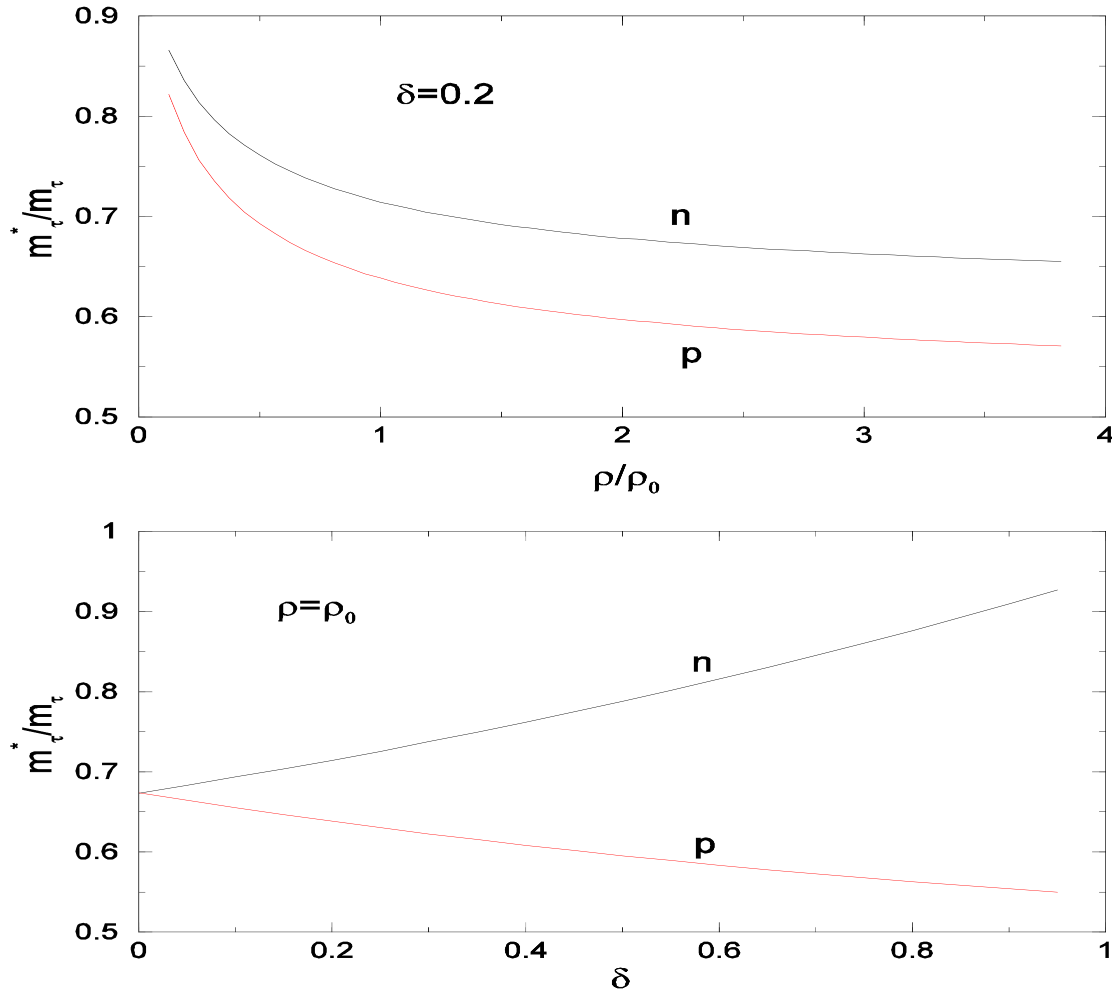


With MDI, At high densities/momentum, the neutrons (protons) feel more attractive (repulsive) potential especially with the super-soft E_{sym}

Neutron-proton effective mass splitting

in neutron-rich matter at zero temperature

$$\frac{m_\tau^*}{m_\tau} = [1 + \frac{m_\tau}{p}\frac{\partial U}{\partial p}]^{-1}_{p_F^\tau}$$



With the modified Gogny effective interaction

Isospin-dependence of nucleon-nucleon cross sections in neutron-rich nuclear matter

The effective mass scaling model:

$$\sigma_{medium} / \sigma_{free} \approx \left(\frac{\mu^*_{NN}}{\mu_{NN}} \right)^2$$

μ^*_{NN} is the reduced effective mass of the colliding nucleon pair NN

valid for $\rho \leq 2\rho_0$

according to Dirac-Brueckner-Hatree-Fock calculations
F. Sammarruca and P. Krastev, nucl-th/0506081;
Phys. Rev. C73, 014001 (2005) .

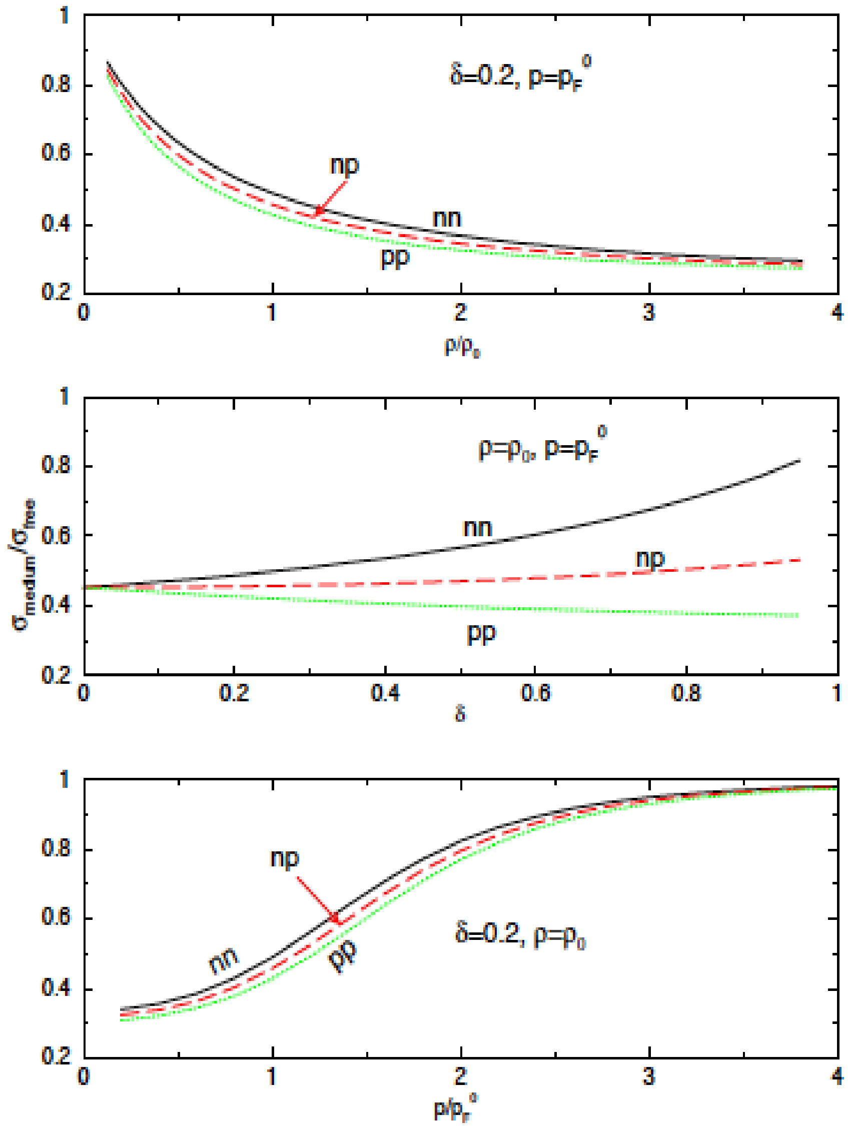
Applications in symmetric nuclear matter:

J.W. Negele and K. Yazaki, PRL 47, 71 (1981)
V.R. Pandharipande and S.C. Pieper, PRC 45, 791 (1992)
M. Kohno et al., PRC 57, 3495 (1998)
D. Persram and C. Gale, PRC65, 064611 (2002).

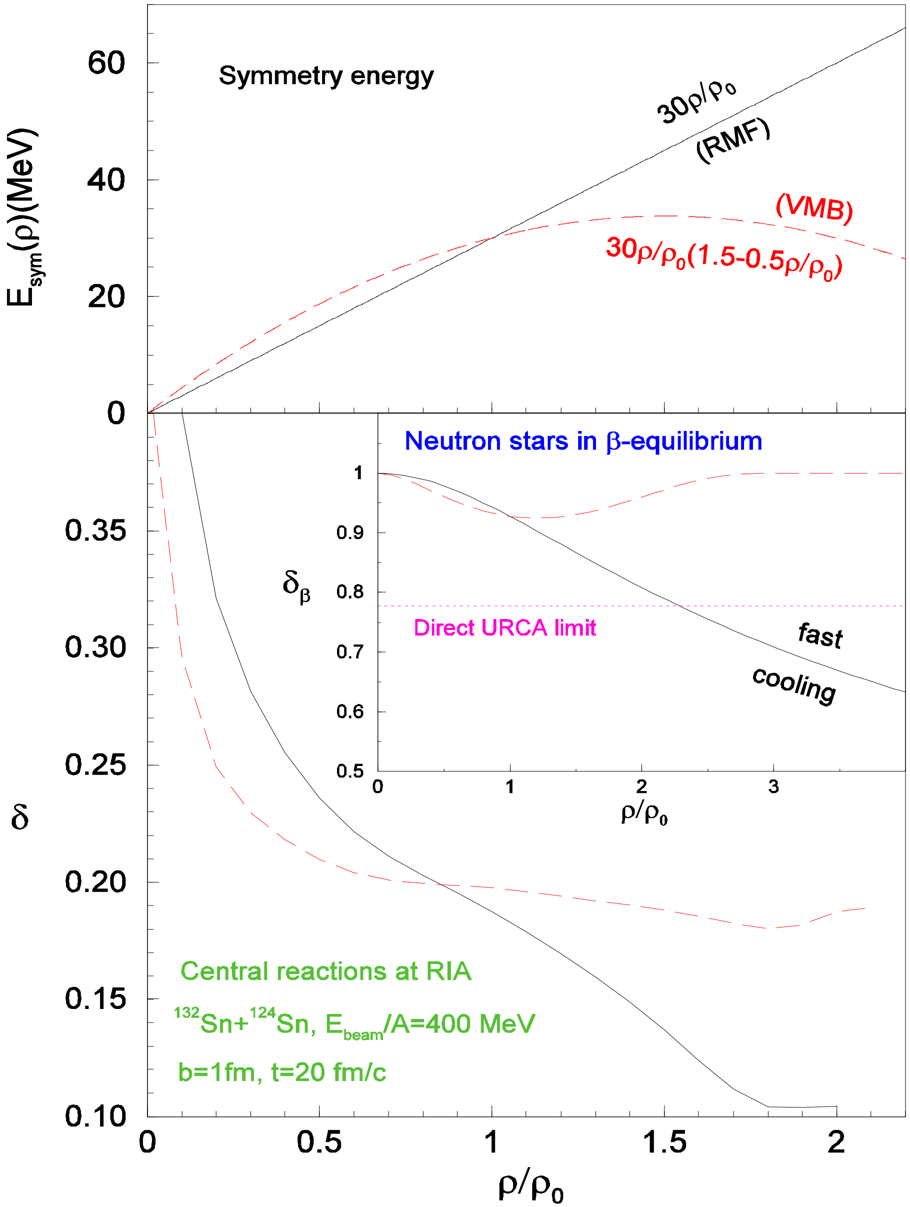
Application in neutron-rich matter:
nn and pp xsections are splitted due to the neutron-proton effective mass slitting

Bao-An Li and Lie-Wen Chen, nucl-th/0508024, Phys. Rev. C72, 064611 (2005).

$\sigma_{medium} / \sigma_{free}$ in neutron-rich matter at zero temperature



Isospin fractionation in heavy-ion reactions



$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\delta^2$$

low (high) density region is more neutron-rich with stiff (soft) symmetry energy

Bao-An Li, Phys. Rev. Lett. 88 (2002) 192701

Probing the symmetry energy at high densities

- **π^-/π^+ in heavy-ion collisions**
- **Neutron-proton differential flow & n/p ratio in heavy-ion coll.**
- **Neutrino flux of supernova explosions**
- **Strength and frequency of gravitational waves**

Where does the E_{sym} information get in, get out or get lost in pion production?

*1 Isospin fractionation, i.e., the nn/pp ratio at high density is determined by the $E_{sym}(\rho)$

***2 The isovector potential for Delta resonance is completely unknown**

$NN \leftrightarrow N\Delta$

*5.Pion mean-field (dispersion relation), S and/or P wave and their isospin dependence are poorly known, existing studies are inconclusive.

3. How to define the isospin asymmetry of the N+Δ matter?

$N+\pi$

How does the pion mean-field affect the Delta production threshold?

4. The lifetime of Δ controls the effects of its mean field on pions

Other final state interactions?

Pion ratio probe of symmetry energy at supra-normal densities

GC Coefficients²	π^+	π^0	π^-
nn	**0**	**1**	**5**
pp	**5**	**1**	**0**
np(pn)	**1**	**4**	**1**

a) Δ(1232) resonance model in first chance NN scatterings:
(negelect rescattering and reabsorption)

$$\frac{\pi^-}{\pi^+} = \frac{5N^2 + NZ}{5Z^2 + NZ} \approx \left(\frac{N}{Z}\right)^2$$

R. Stock, Phys. Rep. 135 (1986) 259.

b) Thermal model:

(*G.F. Bertsch, Nature 283 (1980) 281*; A. Bonasera and G.F. Bertsch, PLB**195** (1987) 521)

$$\frac{\pi^-}{\pi^+} \propto \exp[2(\mu_n - \mu_p)/kT]$$

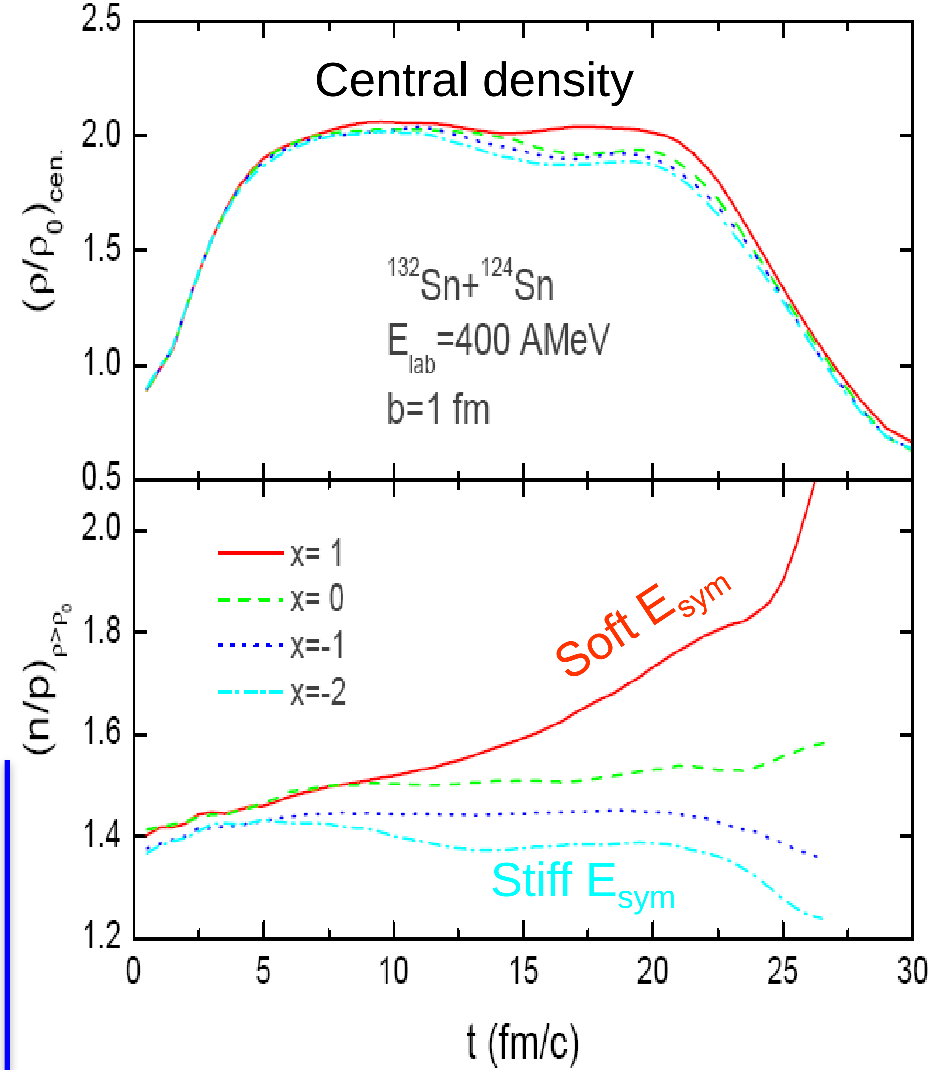
$$\mu_n - \mu_p = (V^n_{asy} - V^p_{asy})\delta - V_{Coul} + kT\{\ln\frac{\rho_n}{\rho_p} + \sum_m \frac{m+1}{m} b_m (\frac{1}{2}\lambda_T^3)^m (\rho_n^m - \rho_p^m)\}$$

H.R. Jaqaman, A.Z. Mekjian and L. Zamick, PRC (1983) 2782.

c) Transport models (more realistic approach):
Bao-An Li, Phys. Rev. Lett. 88 (2002) 192701, and several papers by others

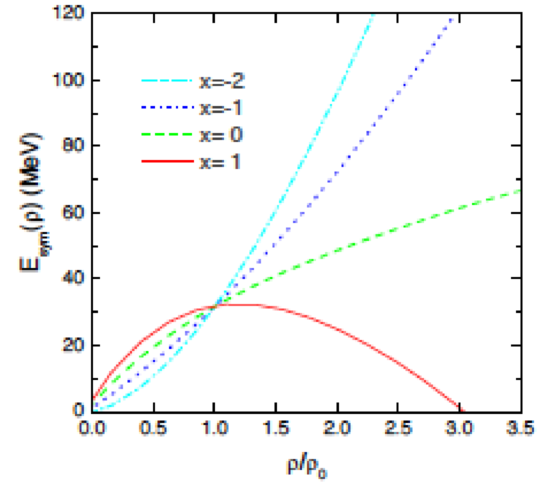
Probing the symmetry energy at supra-saturation densities

$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\delta^2$$

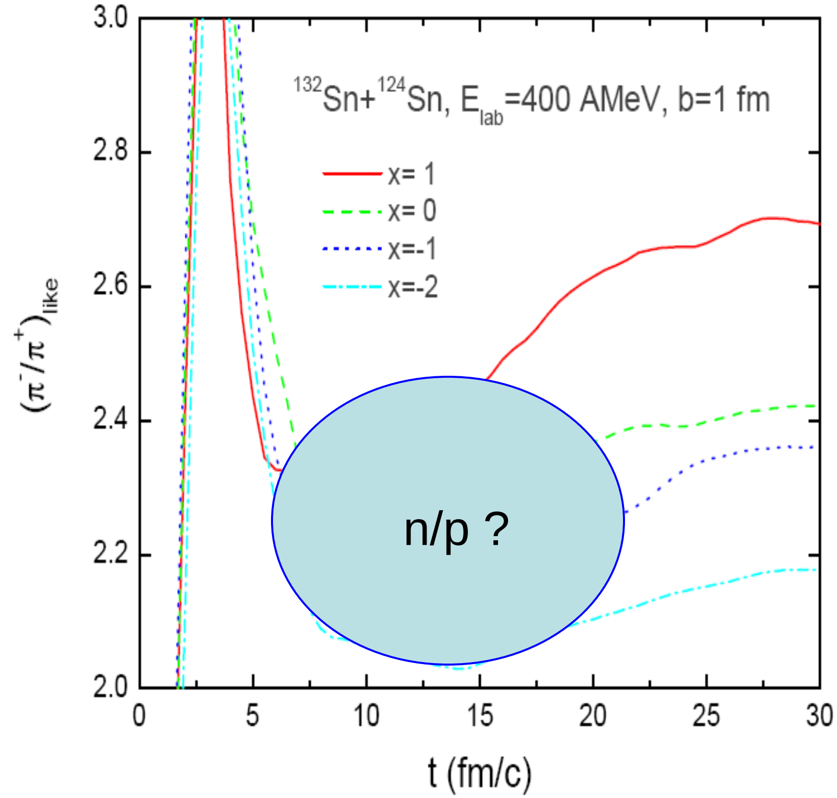


n/p ratio at supra-normal densities

Symmetry energy



π^-/π^+ probe of dense matter

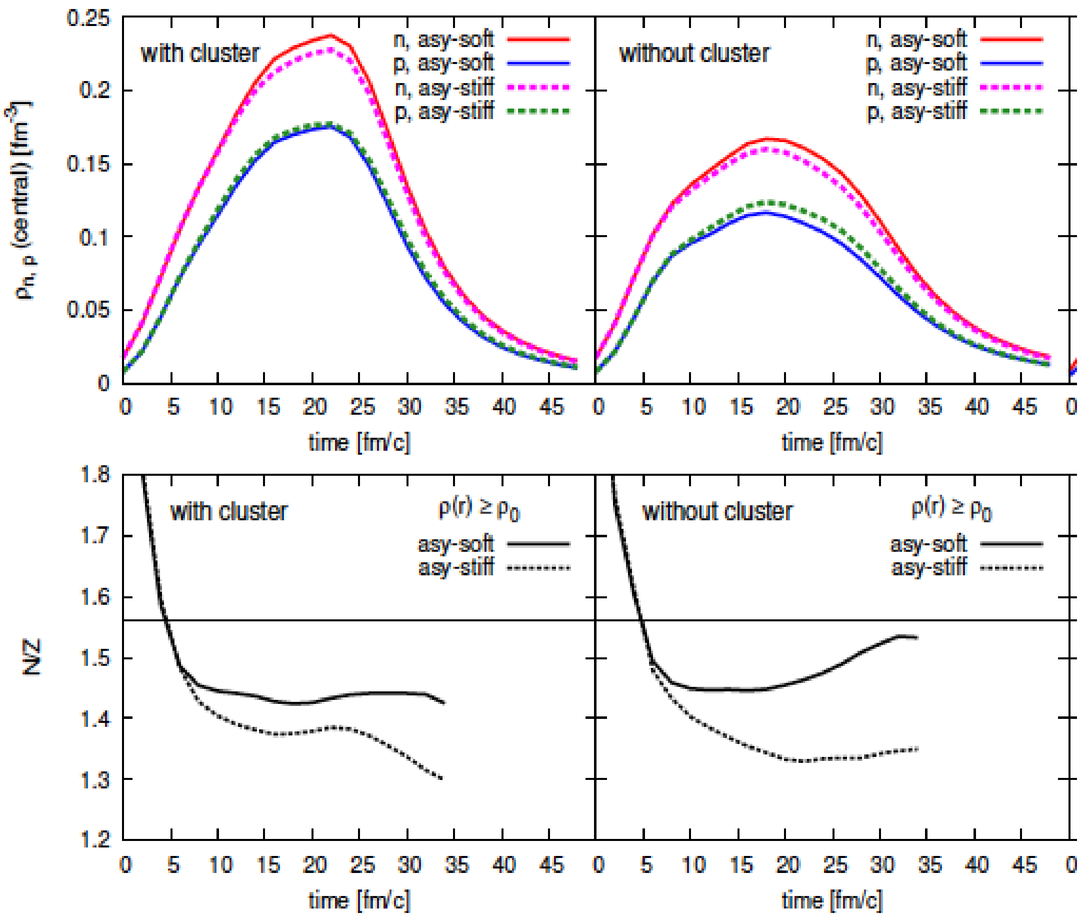


AMD+JAM

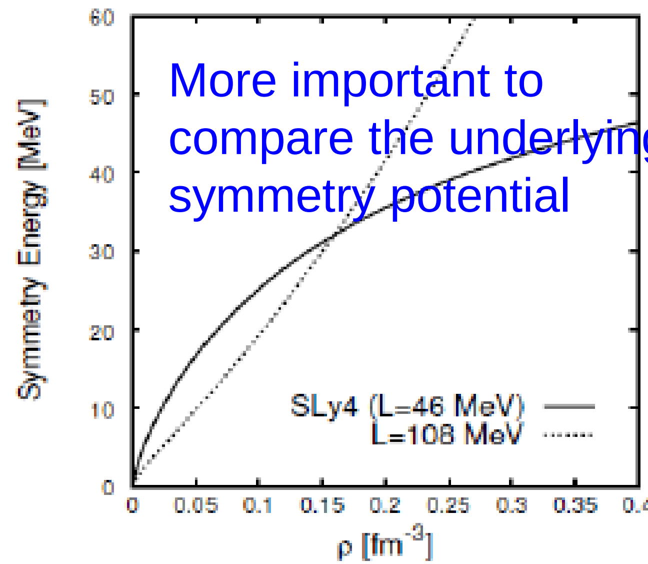
Natsumi Ikeno, Akira Ono, Yasushi Nara, Akira Ohnishi, PRC93, 044612 (2016)

Modifying the 3-body force in SLy4

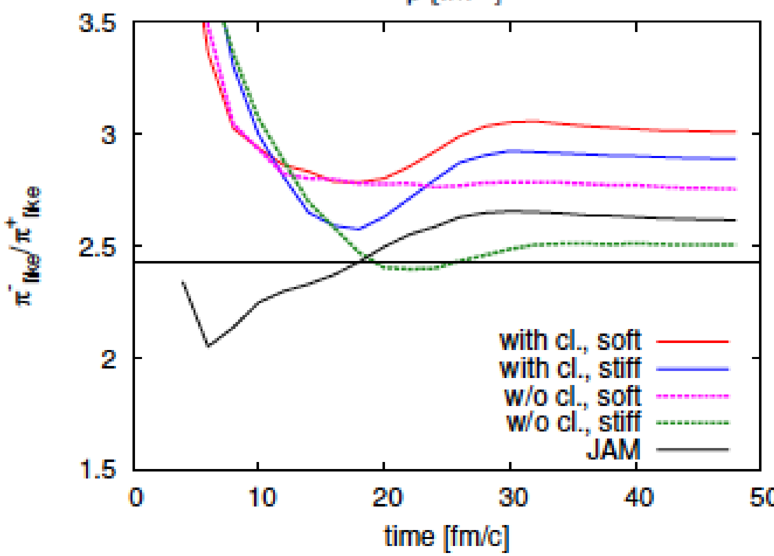
$$v_\rho^{(L=108)} = \frac{1}{6}t_3(1 + x_3' P_\sigma)\delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)\rho(\boldsymbol{r}_1)^\alpha + \frac{1}{6}t_3(x_3 - x_3')\rho_0^\alpha P_\sigma \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2).$$



$^{132}\mathrm{Sn} + {}^{124}\mathrm{Sn}$ at 300 MeV/nucleon



More important to compare the underlying symmetry potential



Comparing L with MDI and SLY4

$$L_1(\rho) = \frac{2}{3}\frac{\hbar^2 k_F^2}{2m_0^*(\rho,k_F)}$$

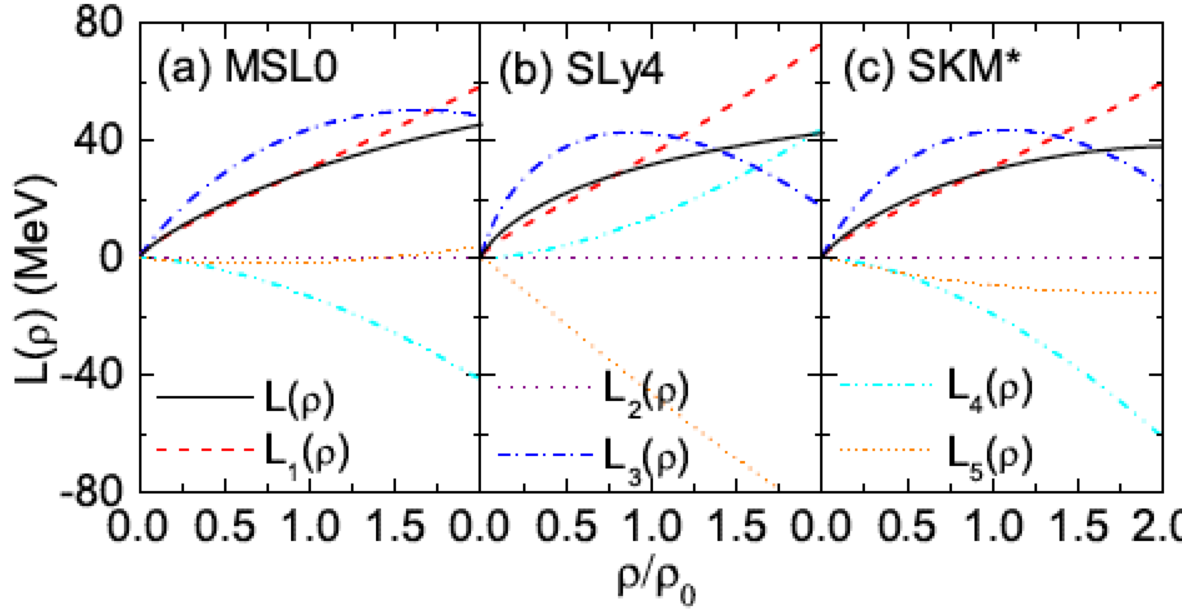
$$L_2(\rho) = -\frac{1}{6}\frac{\hbar^2 k_F^3}{m_0^{*2}(\rho,k_F)}\frac{\partial m_0^*(\rho,k)}{\partial k}|_{k_F}$$

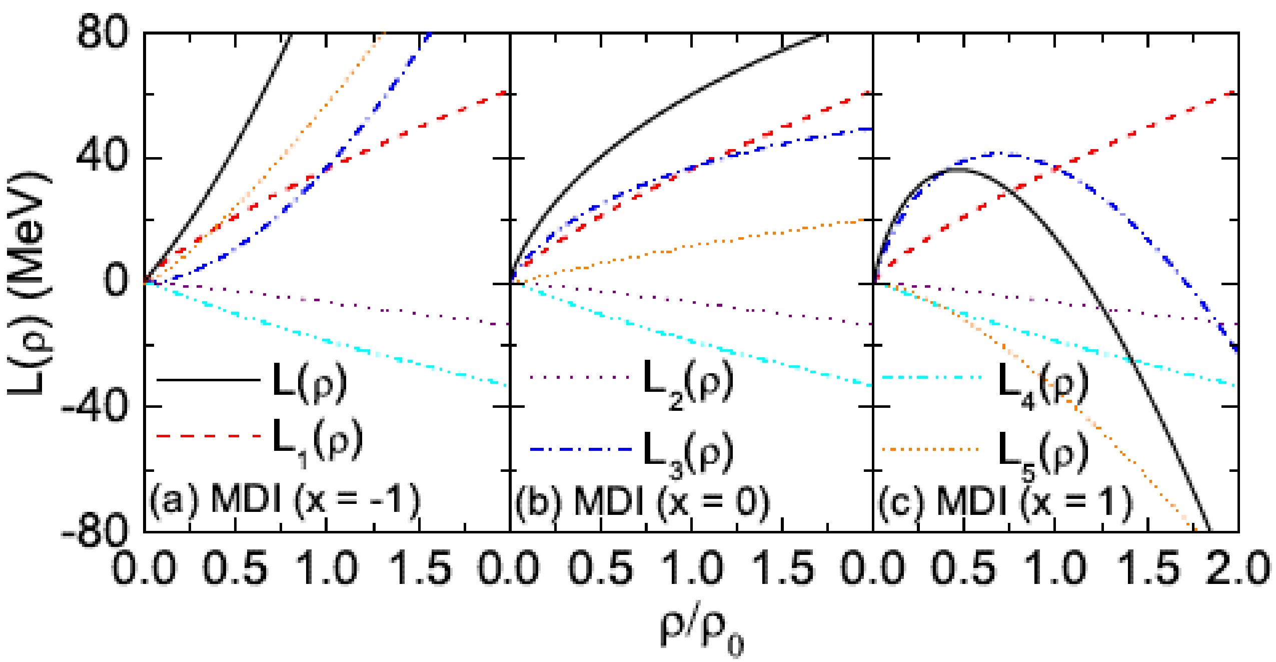
$$L_3(\rho) = \frac{3}{2}U_{sym,1}(\rho,k_F)$$

$$L_4(\rho) = \frac{\partial U_{sym,1}(\rho,k)}{\partial k}|_{k_F}\cdot k_F$$

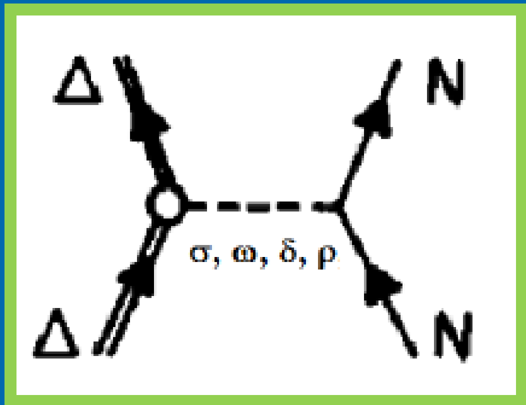
$$L_5(\rho) = 3U_{sym,2}(\rho,k_F).$$

L_4 and L_5 are the major differe

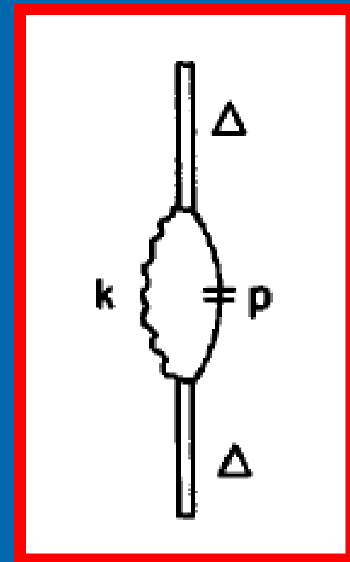




Delta Self-Energy in Nuclear Matter



+



Direct Self-energy → Hartree-Potential

$$U_\Delta^{(H)} = U_0 + U_1 \tau_\Delta \cdot \tau_N$$

$$U_\Delta^{(H)} \sim U_0 + U_1 t_z^{(\Delta)} \cdot \frac{N-Z}{A}$$

Polarization Self-Energy → dispersive (optical) potential

$$\Sigma_{\mathrm{pol}}^{(\Delta)} \sim \Sigma_0 + \Sigma_1 t_z^{(\Delta)} \frac{N-Z}{A}$$

$$\Sigma_\alpha = V_\alpha - iW_\alpha$$

...see e.g.:

E. Oset, L.L. Salcedo, NPA 468 (1987) 631; G.E. Brown, W. Weise, Phys. Rept. 22 (1975) 279

$U_0(\Delta)$ is 0-30 MeV deeper than $U_0(N)$ at ρ_0 from e+A, π+A and γ+A scattering, but nothing is known about the $U_1(\Delta)$

Critical Density and Impact of $\Delta(1232)$ Resonance Formation in Neutron Stars

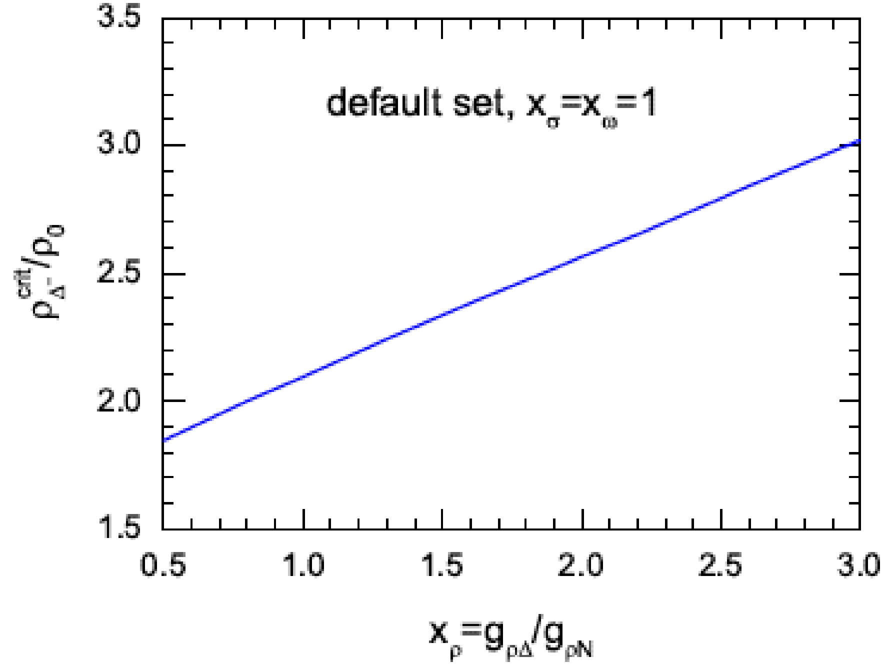
Bao-Jun Cai, F. J. Fattoyev, Bao-An Li and W.G. Newton, PRC 92, 015802 (2015).

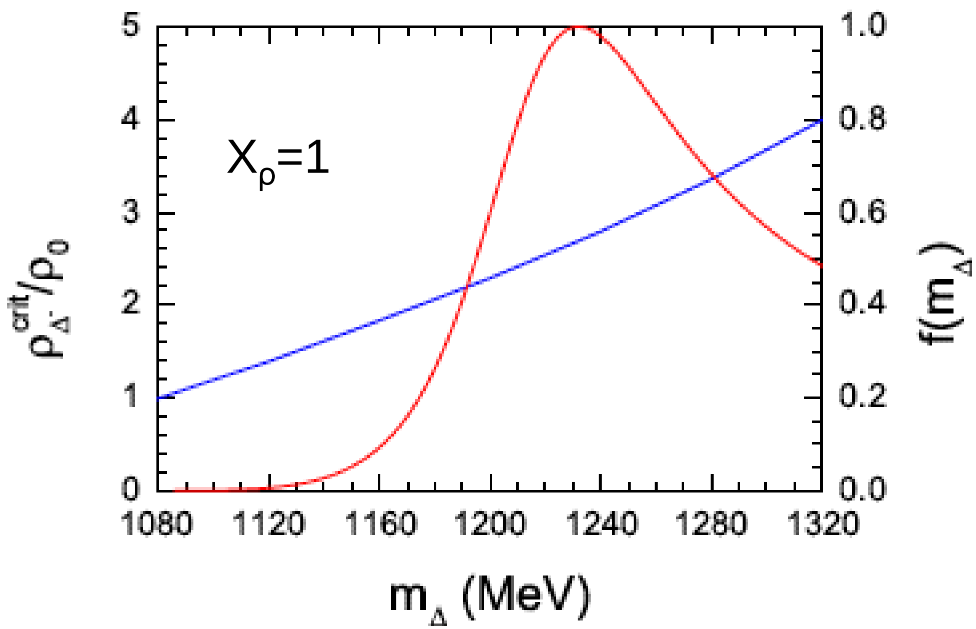
$$\Sigma_{\rm S}^{\rm N} = -g_{\sigma {\rm N}}\overline{\sigma}$$

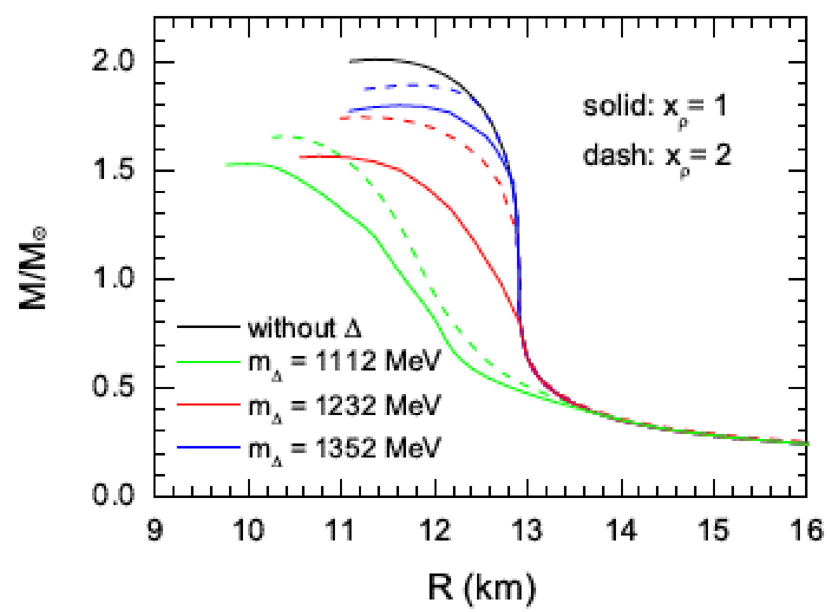
$$\text{and } \Sigma_{\rm S}^{\Delta} = -g_{\sigma\Delta}\overline{\sigma}.$$

$$\Sigma_{\rm V}^{\rm N} = g_{\omega{\rm N}}\overline{\omega}_0 + \tau_{\rm p/n}^3 g_{\rho{\rm N}}\overline{\rho}_0^{(3)}$$

$$\Sigma_{\rm V}^{\Delta} = g_{\omega\Delta}\overline{\omega}_0 + \tau_i^3 g_{\rho\Delta}\overline{\rho}_0^{(3)}$$







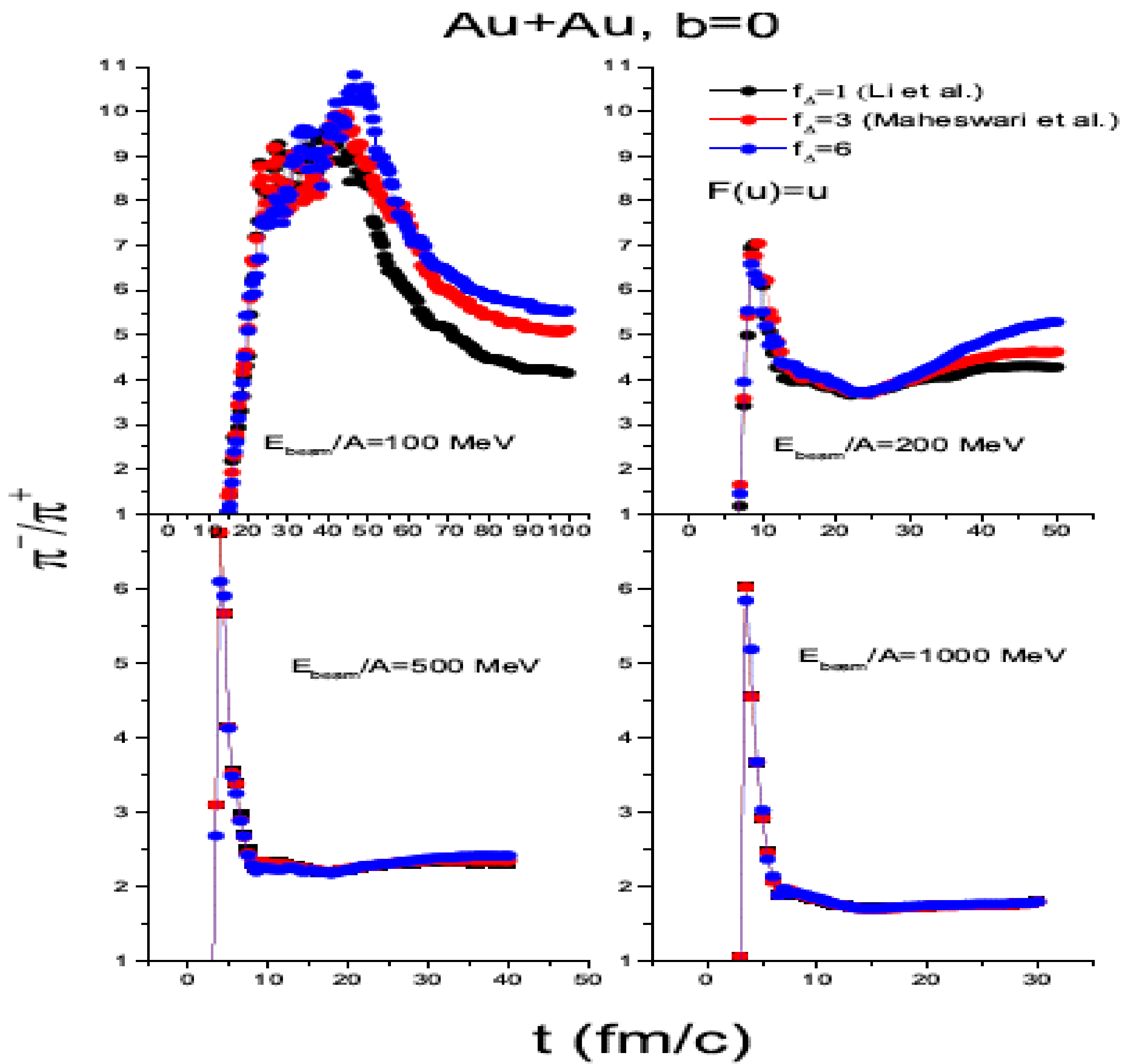
In the pi-N molecule model, assuming pions have no mean-field,the Delta isovector potential is linked to the nucleon isovector potential

Bao-An Li, PRL88, 192701 (2002) and NPA 365 (2002)

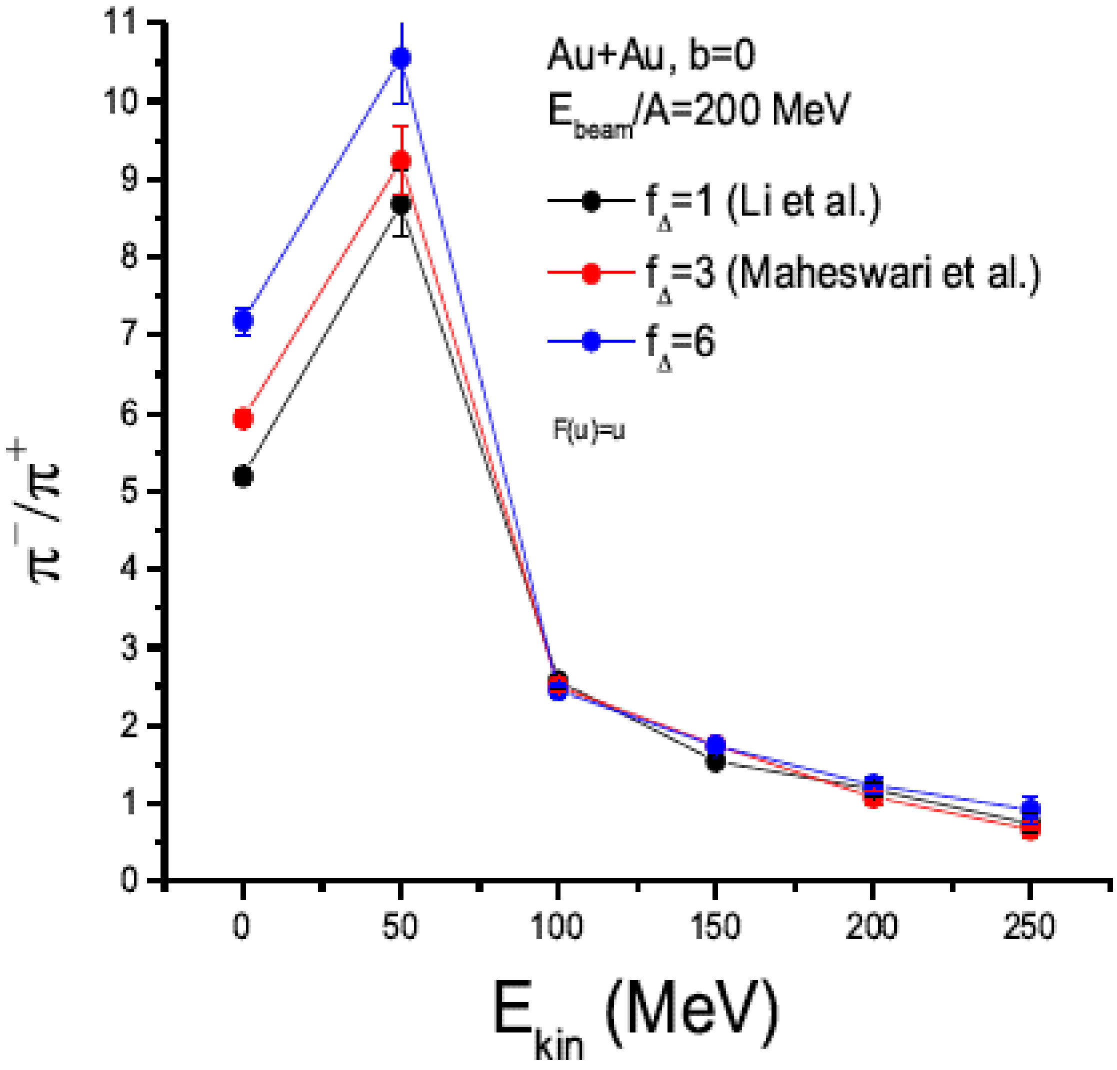
$$\begin{aligned}
v_{asy}(\Delta^-) &= v_{asy}(n), \\
v_{asy}(\Delta^0) &= \frac{2}{3}v_{asy}(n) + \frac{1}{3}v_{asy}(p) = \frac{1}{3}v_{asy}(n), \\
v_{asy}(\Delta^+) &= \frac{1}{3}v_{asy}(n) + \frac{2}{3}v_{asy}(p) = -\frac{1}{3}v_{asy}(n), \\
v_{asy}(\Delta^{++}) &= v_{asy}(p) = -v_{asy}(n).
\end{aligned}$$

To study effects of the completely unknown Delta isovector potential, multiply the above with a Delta-probing-factor:

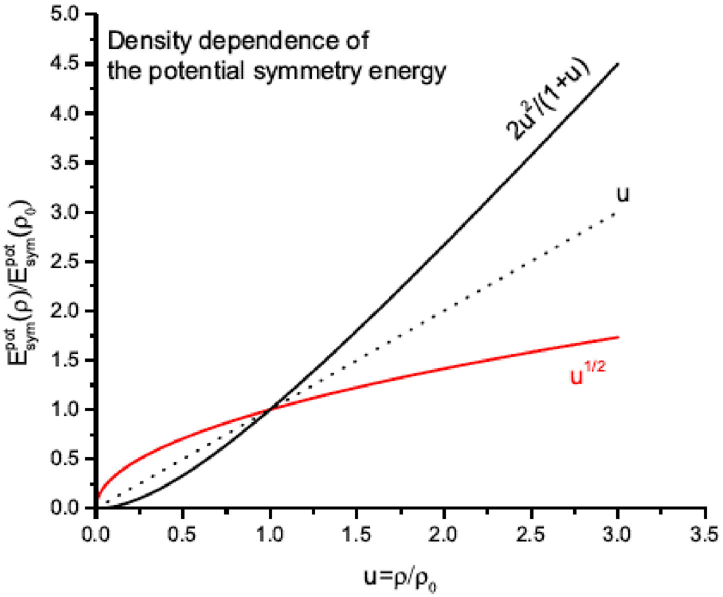
$$f_\Delta = 1,\ 3 \text{ and } 6.$$



Au+Au, b=0
f_Λ=1 (Li et al.)
f_Λ=3 (Maheswari et al.)
f_Λ=6
F(u)=u
E_beam/A=100 MeV
E_beam/A=200 MeV
E_beam/A=500 MeV
E_beam/A=1000 MeV
π⁻/π⁺
t (fm/c)



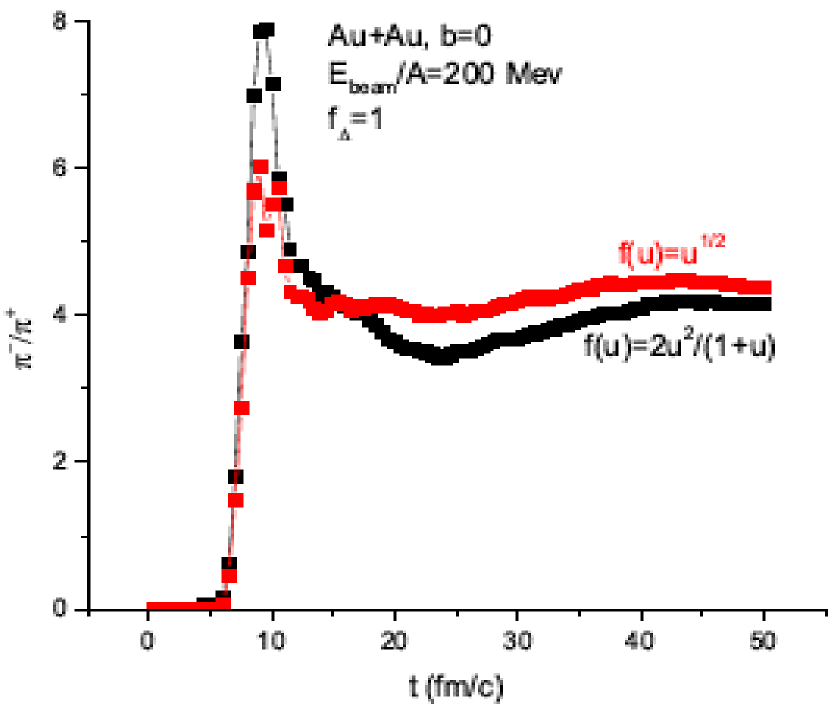
Delta isovector potential has NO effect on the high-energy spectrum!

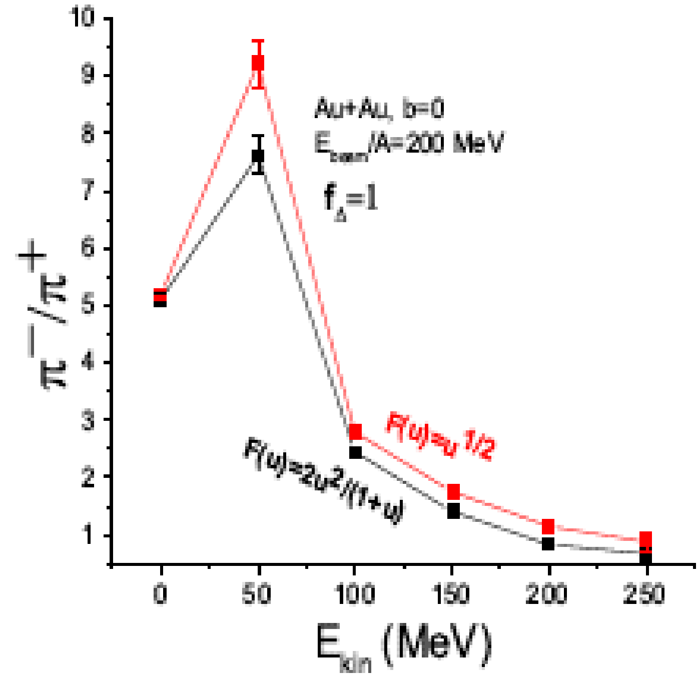


J.M. Lattimer, C.J. Pethick, M. Prakash, P. Haensel, Phys. Rev. Lett. 66, 2701 (1991).

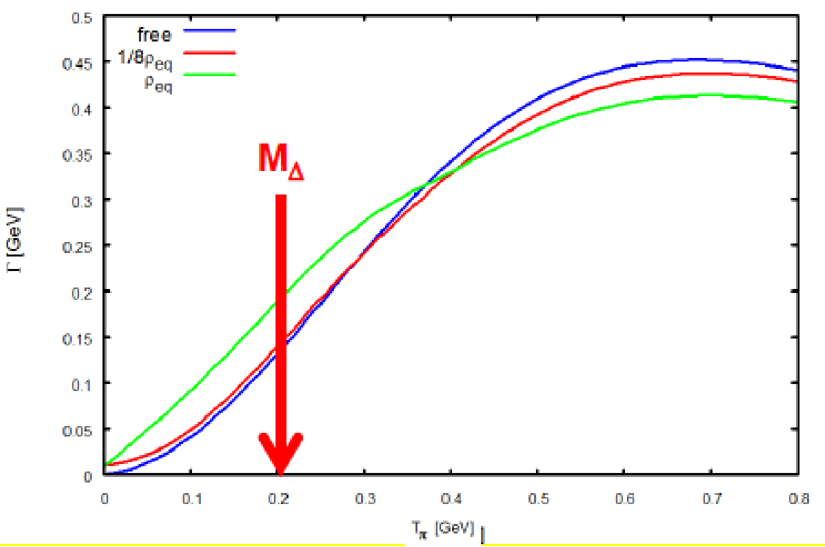
Bao-An Li, Phys. Rev. C 92, 034603 (2015)

Energetic pions are still sensitive to the $E_{sym}(\rho)$ in deeply sub-threshold collisions

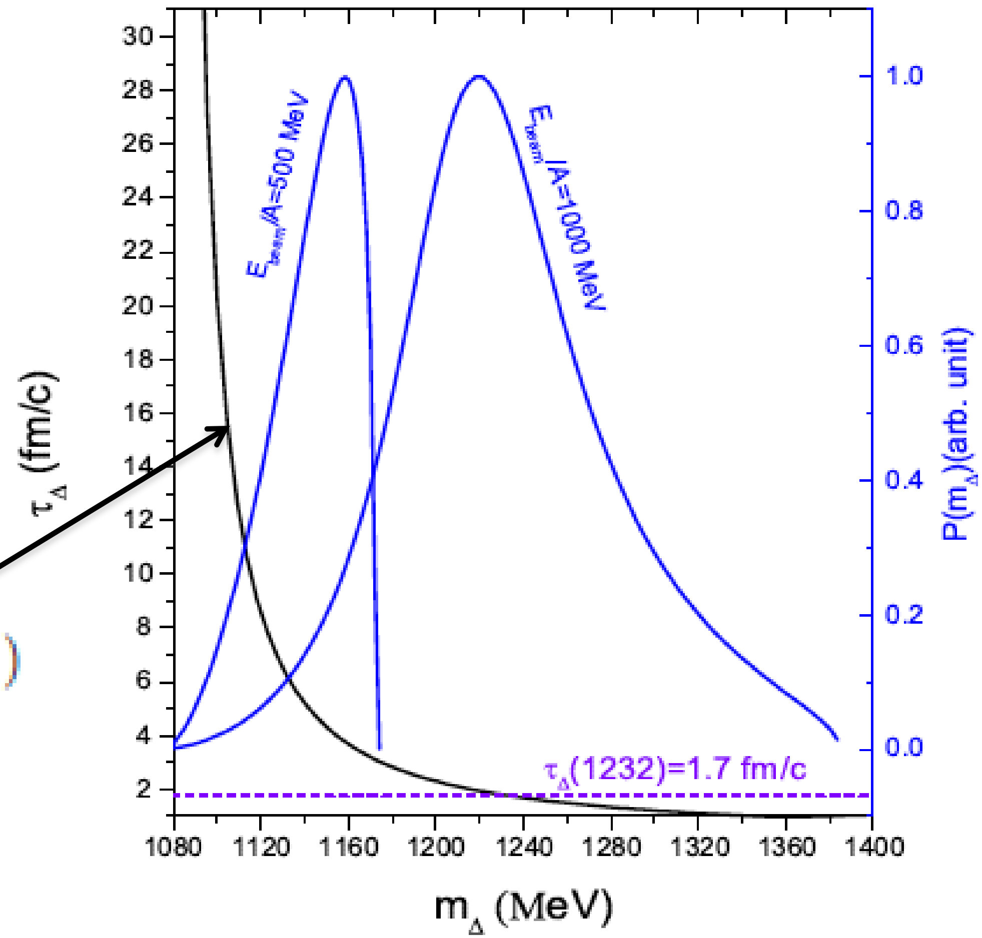




In-medium Delta width, H. Lenske et al.



Delta lifetime and mass distribution in Au+Au collisions at b=0



$$\tau_\Delta = \hbar/\Gamma(m_\Delta)$$

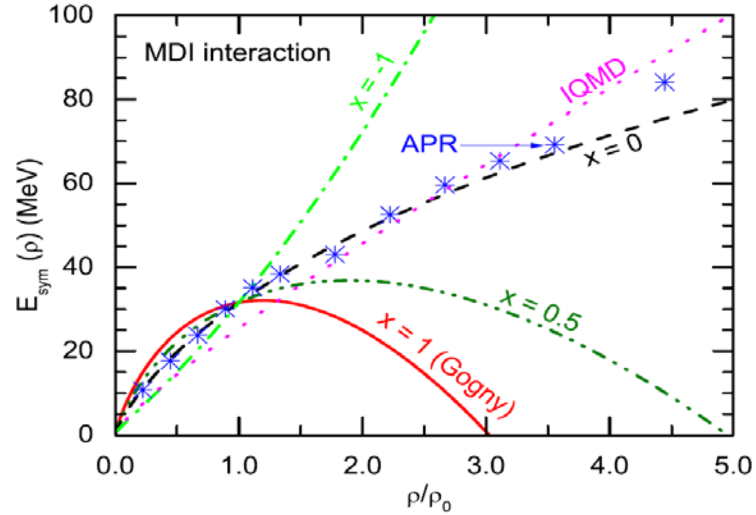
WHY?

High-mass Delta produced in energetic collisions decays too quickly to feel any mean-field effect! Only long-lived low mass Deltas have the time to feel mean-field effects.

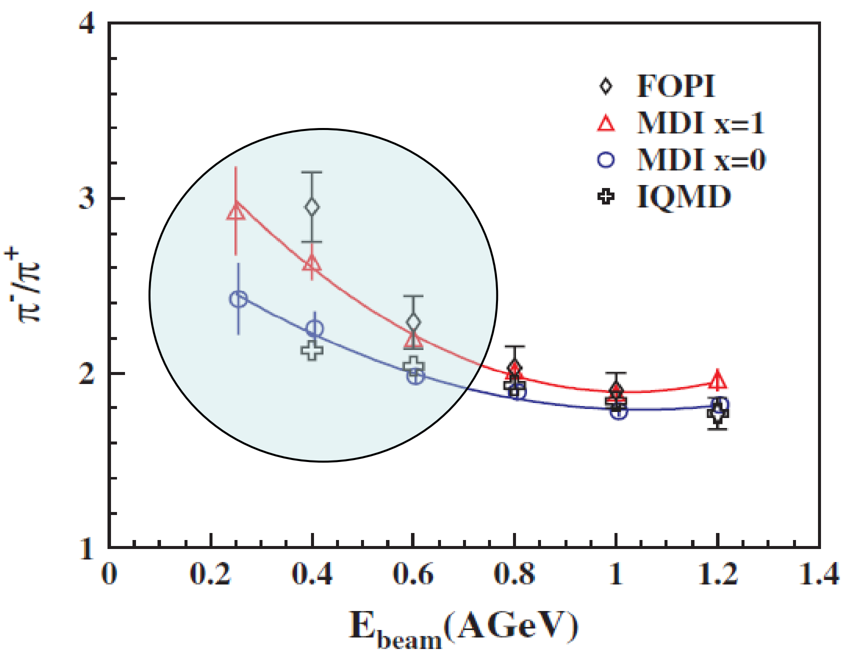
Circumstantial Evidence for a Super-soft Symmetry Energy at Supra-saturation Densities

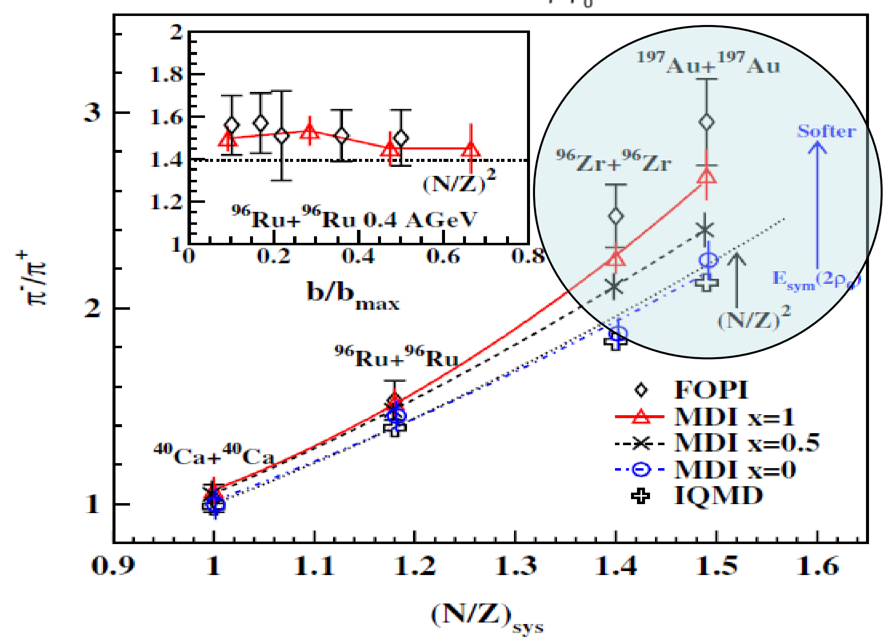
Data:

W. Reisdorf et al.
NPA781 (2007) 459



Calculations: IQMD and IBUU04





A super-soft nuclear symmetry energy is favored by the FOPI data!!!

Z.G. Xiao, B.A. Li, L.W. Chen, G.C. Yong and M. Zhang, Phys. Rev. Lett. 102 (2009) 062502

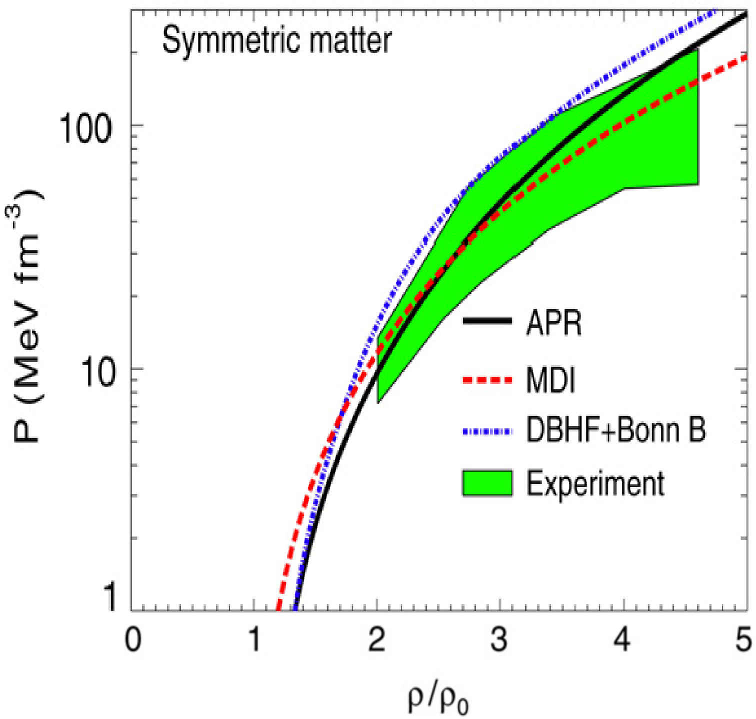
P. Russotto et al. (ASY-EOS Collaboration), Phys. Rev. C94, 034608 (2016).

A challenge: how can neutron stars be stable with a super-soft symmetry energy?

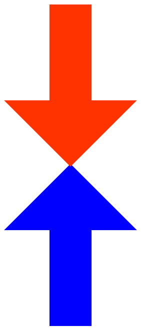
If the symmetry energy is too soft, then a mechanical instability will occur when dP/dρ is negative, neutron stars will then all collapse while they do exist in nature

TOV equation: a condition at hydrodynamical equilibrium

$$\frac{dP}{dr} = -(\epsilon + P)\frac{m_g + 4\pi r^3 P}{r(r-2m_g)}.$$



P. Danielewicz, R. Lacey and W.G. Lynch, Science 298, 1592 (2002))



Gravity

Nuclear pressure

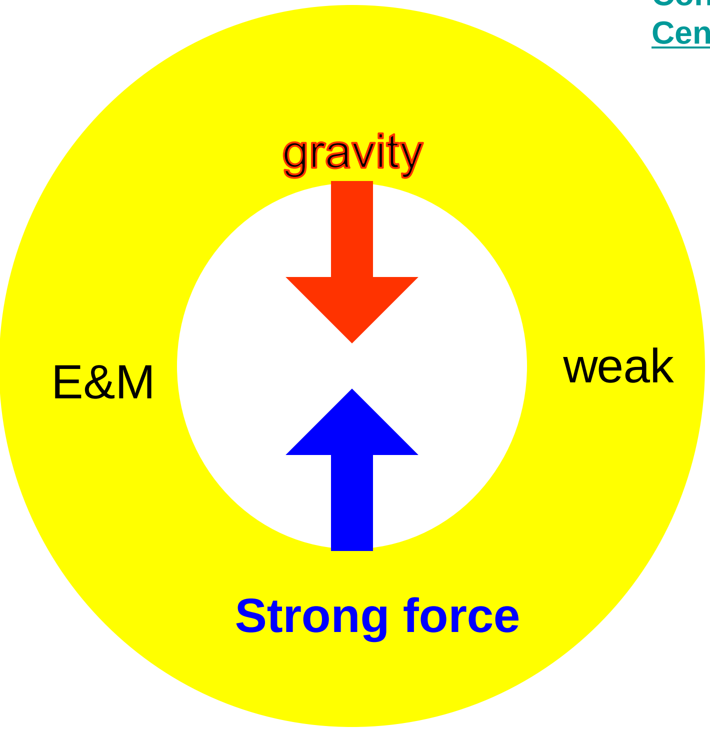
For npe matter

$$P(\rho,\delta) = P_0(\rho) + P_{asy}(\rho,\delta) = \rho^2\left(\frac{\partial E}{\partial \rho}\right)_\delta + \frac{1}{4}\rho_e\mu_e$$

$$= \rho^2\left[E'(\rho,\delta=0) + E'_{sym}(\rho)\delta^2\right] + \frac{1}{2}\delta(1-\delta)\rho E_{sym}(\rho)$$

dP/dρ<0 if E' sym is big and negative (super-soft)

Neutron stars as a natural testing ground of fundamental forces

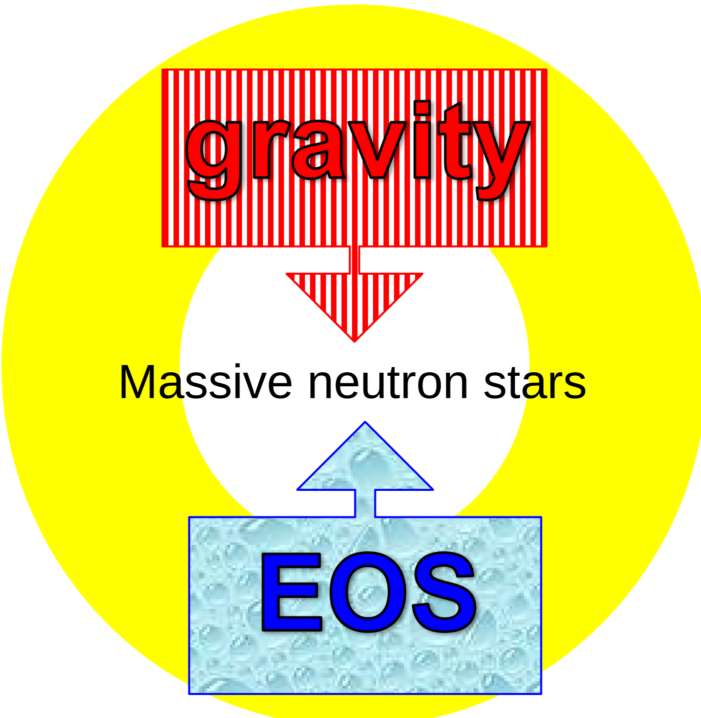


Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century, Committee on the Physics of the Universe, National Research Council

- What is the dark matter?
- What is the nature of the dark energy?
- How did the universe begin?
- What is gravity?
- Are there additional spacetime dimensions?
- What are the masses of the neutrinos, and how have they shaped the evolution of the universe?
- How do cosmic accelerators work and what are they accelerating?
- Are protons unstable?
- Are there new states of matter at exceedingly high density and temperature?
- How were the elements from iron to uranium made?
- Is a new theory of matter and light needed at the highest energies?

Gravity-EOS Degeneracy in massive neutron stars

Strong-field gravity: GR or Modified Gravity?



GR+[Modified Gravity]

$$\text{Action } S = S_{gravity} + S_{matter}$$

Matter+[Dark Matter]+[Dark Energy]

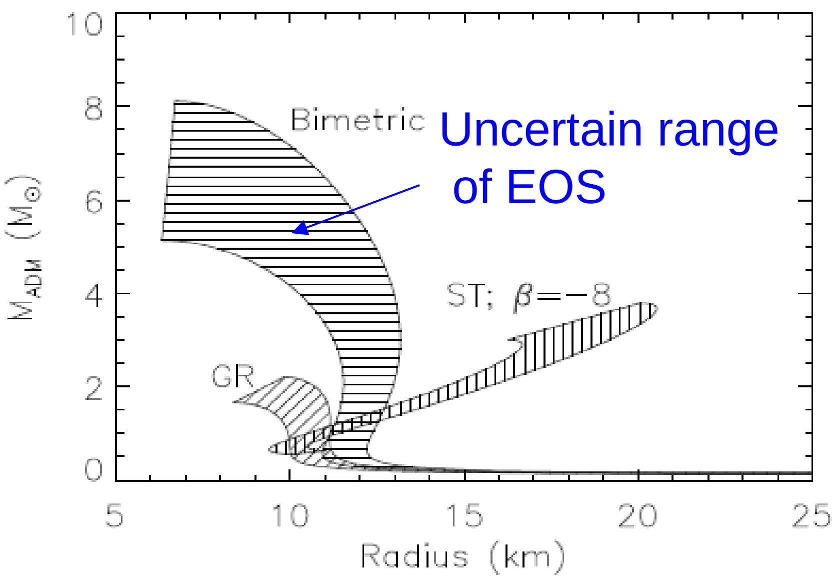
Contents and stiffness of the EOS of super-dense matter?

For high-density neutron-rich nucleonic matter, the most uncertain part of the EOS is the nuclear symmetry energy

An example of EOS-Gravity degeneracy

Simon DeDeo, Dimitrios Psaltis   Phys. Rev. Lett. 90 (2003) 141101

Dimitrios Psaltis, Living Reviews in Relativity, 11, 9 (2008)



- Neutron stars are among the densest objects with the strongest gravity
- General Relativity (GR) may break down at strong-field limit and there is no fundamental reason to choose Einstein's GR over alternative gravity theories
- Need at least 2 observables to break the degeneracy

Stiff EOS: V. R. Pandharipande, Nucl. Phys. A 174, 641 (1971).
Soft EOS: R. B. Wiringa, V. Fiks, and A. Fabrocini, Phys. Rev. C38, 1010 (1988)

Scalar-Tensor theory with quadratic coupling:

T. Damour and G. Esposito-Farèse, Phys. Rev. D 54, 1474 (1996).

$$S = \frac{c^4}{16\pi G_*}\int \frac{d^4x}{c} g_*^{1/2}\left(R_* - 2g_*^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi\right) + S_m[\psi_m; A^2(\varphi)g^*_{\mu\nu}] \; .$$

$$A(\varphi) = A_\beta(\varphi) \equiv \exp\left(\frac{1}{2}\beta\varphi^2\right)$$

Physics origin of the Yukawa term

In grand unification theories, conventional gravity has to be modified due to either geometrical effects of extra space-time dimensions at short length, a new boson or the 5th force

$$F(r) = G\frac{m_1 m_2}{r^{2+\epsilon}}.$$

String theorists have published TONS of papers on the extra space-time dimensions

N. Arkani-Hamed et al., Phys Lett. B 429, 263–272 (1998); J.C. Long et al., Nature 421, 922 (2003); C.D. Hoyle, Nature 421, 899 (2003)

In terms of the gravitational potential

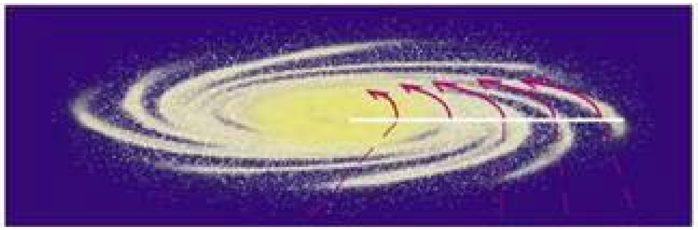
$$V(r) = -G\frac{m_1 m_2}{r}[1 + \alpha e^{-r/\lambda}].$$

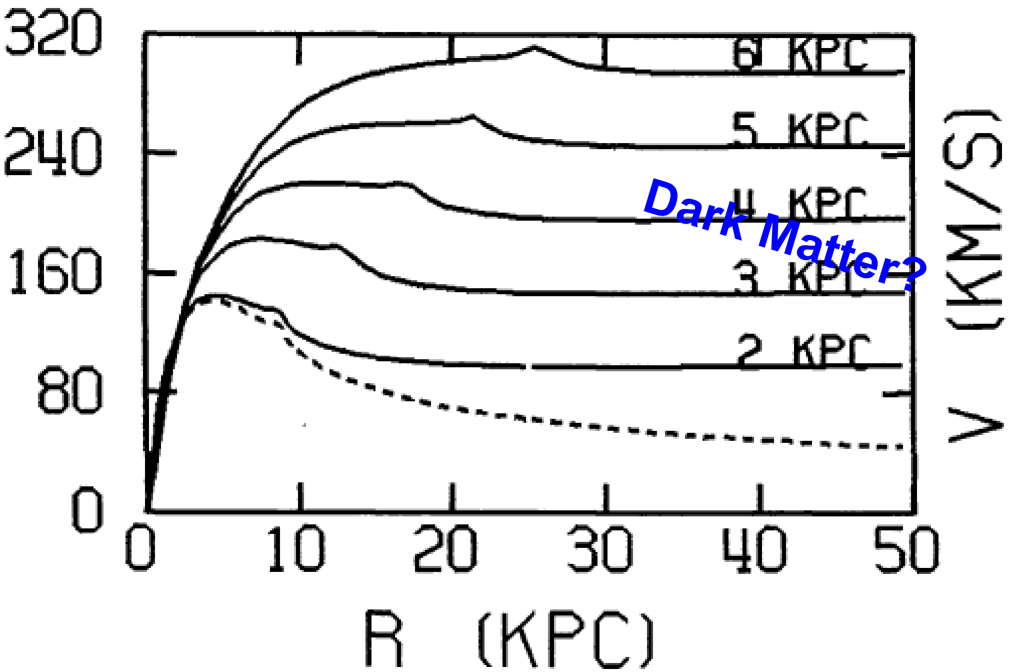
Yukawa potential due to the exchange of a new boson proposed in the super-symmetric extension of the Standard Model of the Grand Unification Theory, or the fifth force

Yasunori Fujii, Nature 234, 5-7 (1971); G.W. Gibbons and B.F. Whiting, Nature **291**, 636 - 638 (1981)

The neutral spin-1 gauge boson U is a candidate, it is light and weakly interacting,
Pierre Fayet, PLB675, 267 (2009),
C. Boehm, D. Hooper, J. Silk, M. Casse and J. Paul, PRL, 92, 101301 (2004).

Yukawa potential and galaxy rotation curves





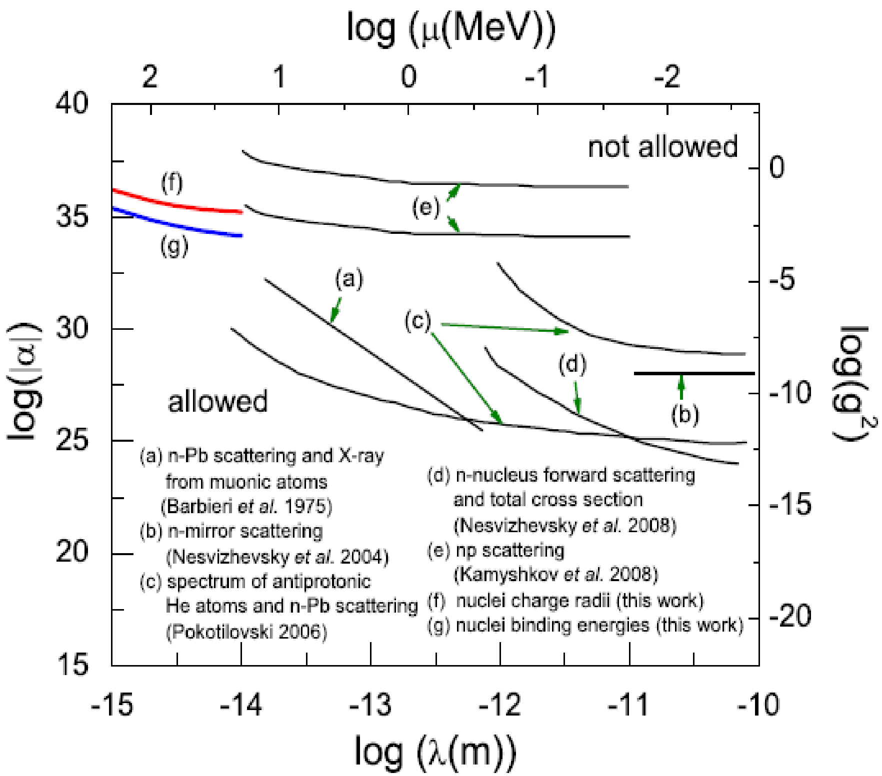
$$\frac{v^2}{r} = \frac{dU}{dr} = \frac{G_\infty M}{r^2}\left[1 + \alpha\left(1 + \frac{r}{r_0}\right) e^{-r/r_0}\right]$$

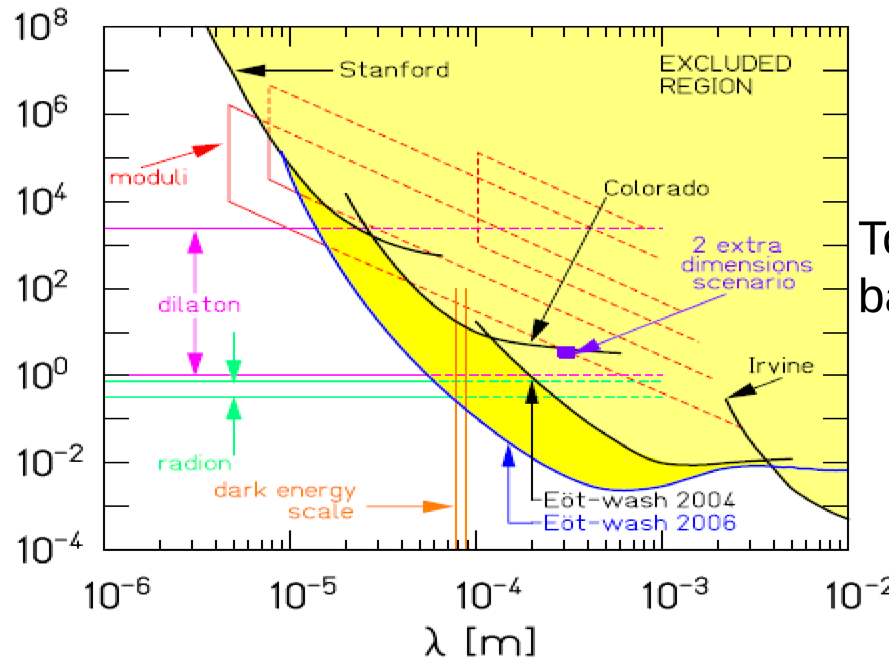
R.H. Sanders,
Astron. Astrophys. 136, L21 (1984).

Observational evidence of **Dark Matter**: rotational curve, Cluster dynamics, weak lensing, collisionless passing of Bullet cluster, ….

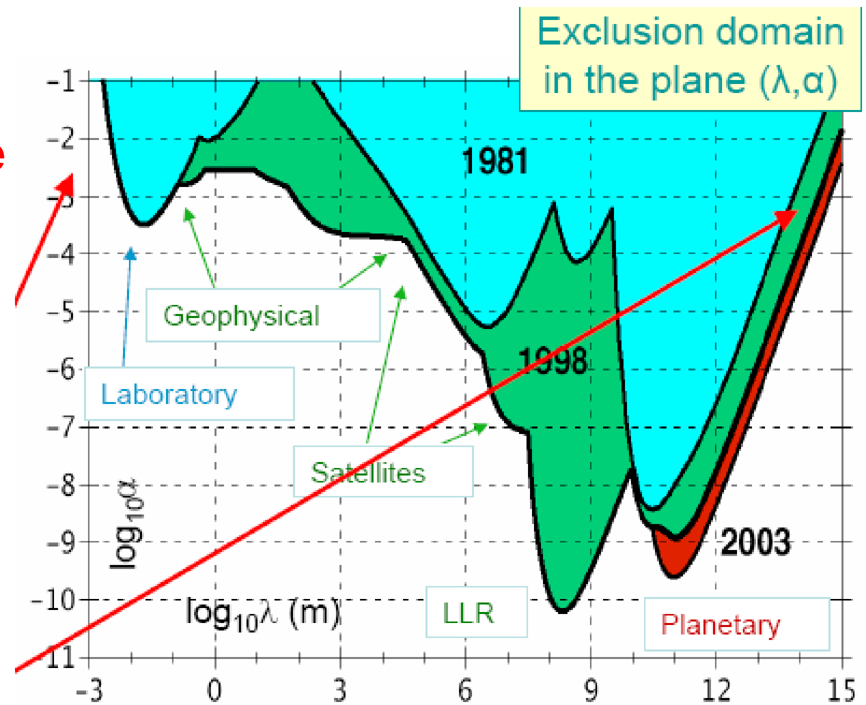
Modified gravity,
e.g., MOND and TeVeS,
pass GR test at solar scale,
can explain all observations
including the Bullet Cluster
without using Dark Matter

The Bullet Cluster 1E0657-558
Evidence shows Modified Gravity in the absence of Dark Matter
J. R. Brownstein, J. W. Moffat, MNRAS.382:29-47,2007





Torsion balance



Upper limits on the strength α and range λ of the Yukawa term

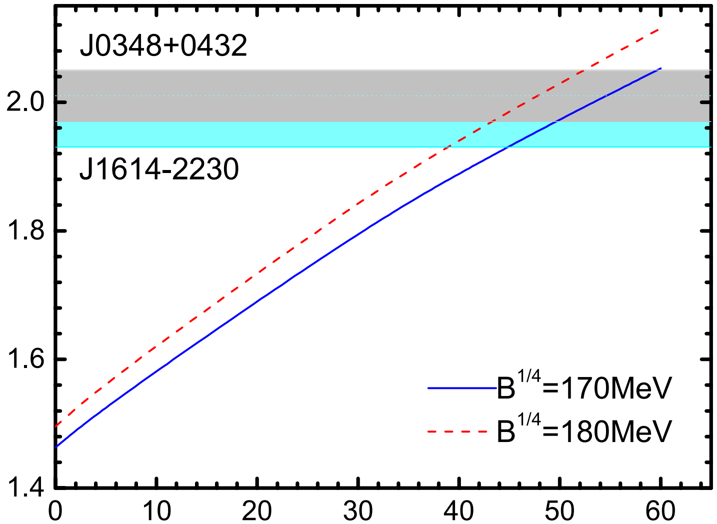
M.I. Krivoruchenko et al., PRD 79, 125023 (2009)
E.G. Adelberger et al., PRL 98, 131104 (2007)
D.J. Kapner et al., PRL 98, 021101 (2007)
Serge Reynaud et al., Int. J. Mod. Phys. A20, 2294 (2005)

$$V(r) = -G\frac{m_1 m_2}{r}[1 + \alpha e^{-r/\lambda}]$$

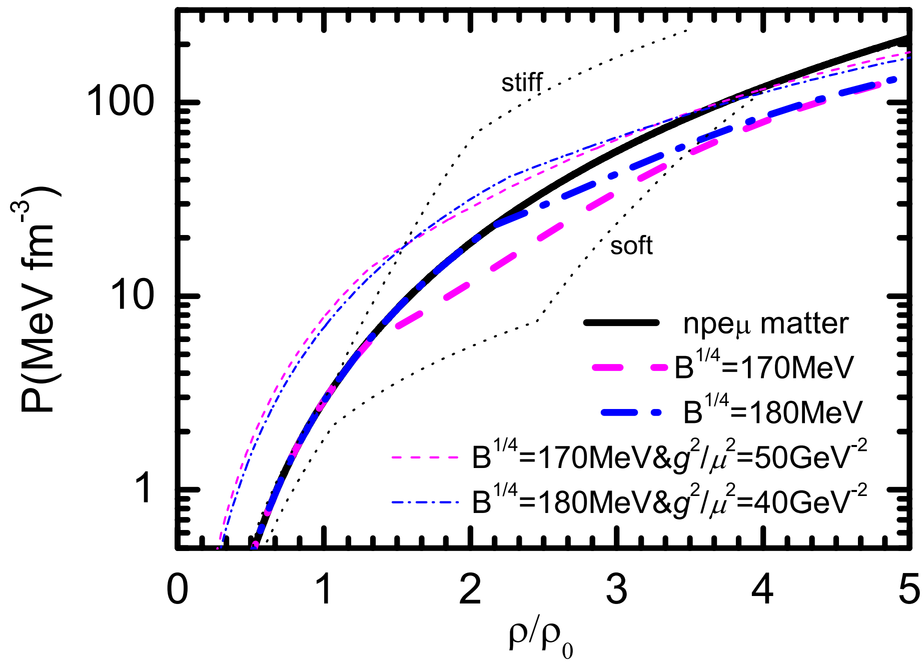
$$g^2 = \pm 4\pi G_\infty \mu^2 \alpha \text{ where } \mu = 1/\lambda$$

Supersoft Symmetry Energy Encountering Non-Newtonian Gravity in Neutron Stars

De-Hua Wen, Bao-An Li and Lie-Wen Chen, Phys. Rev. Lett. 103, 211102 (2009)



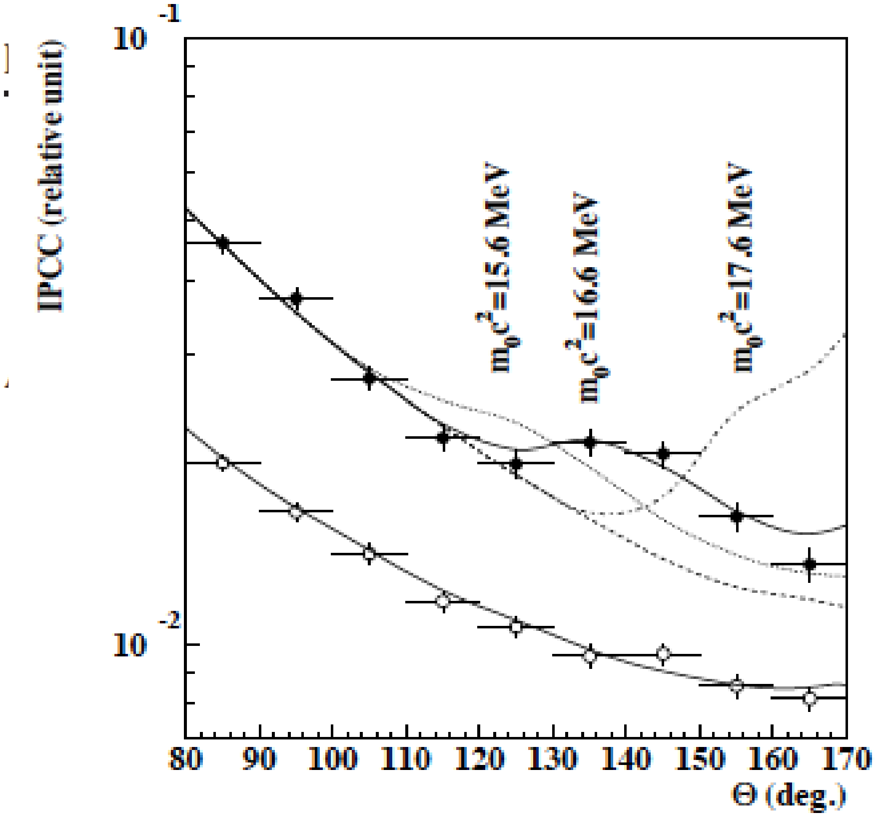
With an EOS including the Yukawa contribution



W. Lin, **Bao-An Li**, L.W. Chen, D.H. Wen and J. Xu, J. of Phys. G41, 075203 (2014).

Jun Xu, **Bao-An Li**, Lie-Wen Chen and Hao Zheng,
Journal of Physics G. 40, 035107 (2013), selected as a Research Highlight

The rise, fall and reappearing of the 5th force –
- evidence of a new (U) boson of 17 MeV



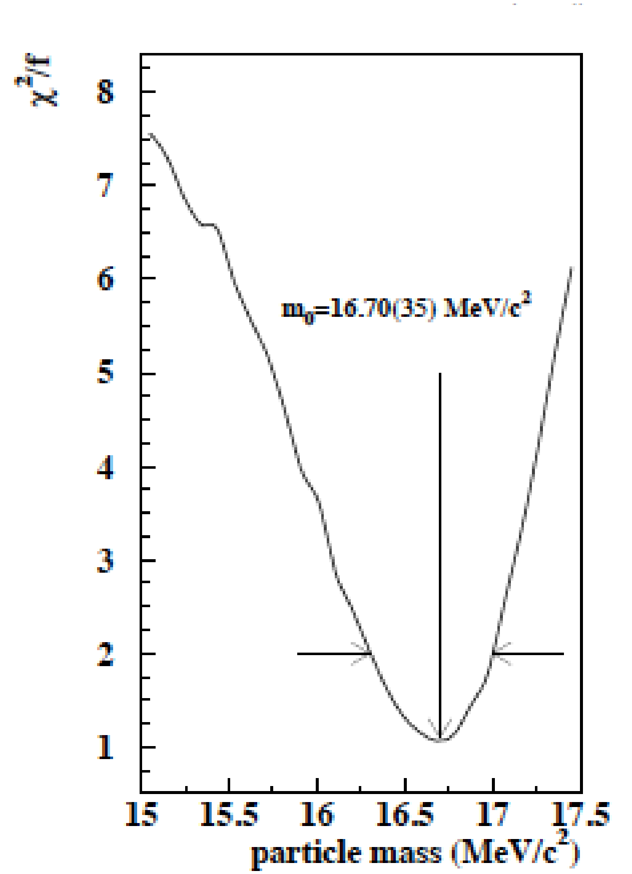


FIG. 4. *Experimental angular e^+e^- pair correlations measured in the $^7Li(p,e^+e^-)$ reaction at E_p=1.10 MeV with $-0.5 \leq y \leq 0.5$ (closed circles) and $|y| \geq 0.5$ (open circles). The results of simulations of boson decay pairs added to those of IPC pairs are shown for different boson masses as described in the text.*

Supporting theories

— nothing seems to be wrong with a U-boson of 17 MeV

PRL 117, 071803 (2016) PHYSICAL REVIEW LETTERS week ending 12 AUGUST 2016

Protophobic Fifth-Force Interpretation of the Observed Anomaly in ^{8}Be Nuclear Transitions

Jonathan L. Feng,[1] Bartosz Fornal,[1] Iftah Galon,[1] Susan Gardner,[1,2] Jordan Smolinsky,[1] Tim M. P. Tait,[1] and Philip Tanedo[1]
[1]*Department of Physics and Astronomy, University of California, Irvine, California 92697-4575, USA*
[2]*Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055, USA*

(Received 3 May 2016; published 11 August 2016)

Recently a 6.8σ anomaly has been reported in the opening angle and invariant mass distributions of e^+e^- pairs produced in ^{8}Be nuclear transitions. The data are explained by a 17 MeV vector gauge boson X that is produced in the decay of an excited state to the ground state, $^8\mathrm{Be}^* \to {}^8\mathrm{Be}\,X$, and then decays through $X \to e^+e^-$. The X boson mediates a fifth force with a characteristic range of 12 fm and has millicharged couplings to up and down quarks and electrons, and a proton coupling that is suppressed relative to neutrons. The protophobic X boson may also alleviate the current 3.6σ discrepancy between the predicted and measured values of the muon's anomalous magnetic moment.

NATURE | NEWS

Has a Hungarian physics lab found a fifth force of nature?

Radioactive decay anomaly could imply a new fundamental force, theorists say.

Edwin Cartlidge

25 May 2016

Physicists think they might have just detected a fifth force of nature

Get ready for next-level physics.

FIONA MACDONALD 26 MAY 2016

QUANTA MAGAZINE illuminating science

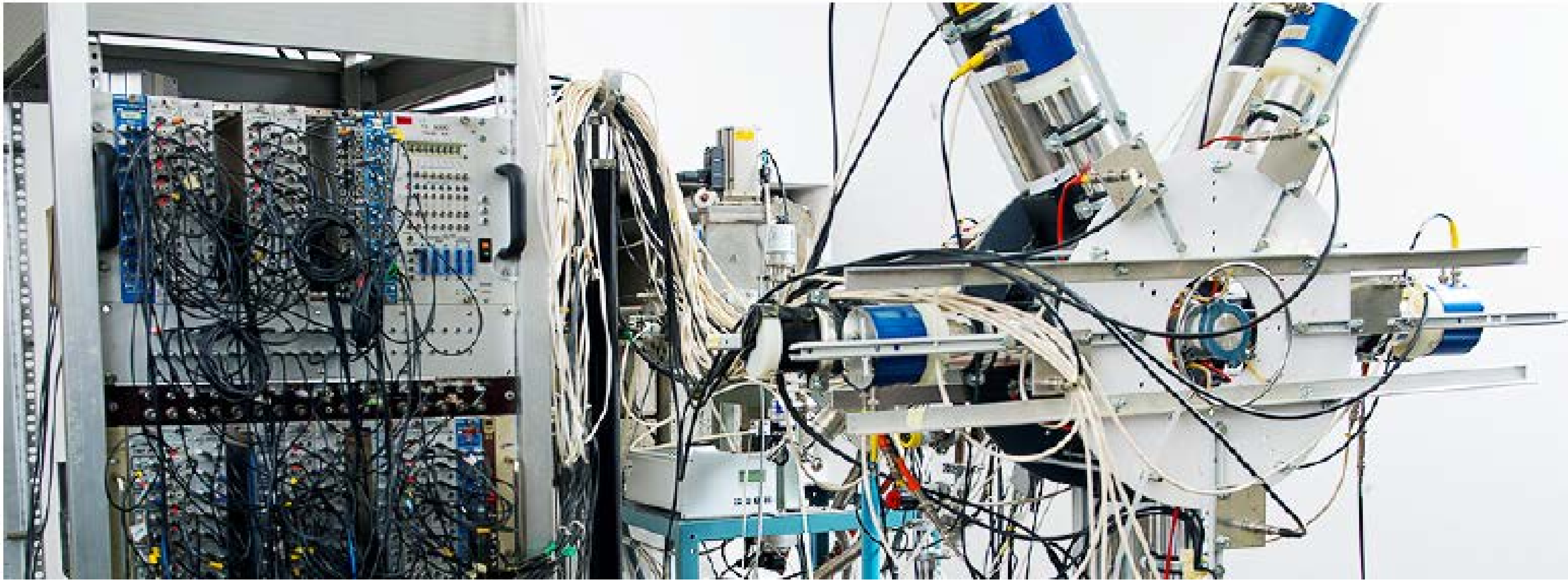
By Natalie Wolchover

June 7, 2016

NUCLEAR PHYSICS

Evidence of a 'Fifth Force' Faces Scrutiny

A lab in Hungary has reported an anomaly that could lead to a physics revolution. But even as excitement builds, closer scrutiny has unearthed a troubling backstory.




May the 5th Force be with You!
Symmetry Energy
Hard
or
Soft?
Dark Matter or Modified Gravity?