Symmetry energy systematics and its high density behavior

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- The symmetry energy (Esym)
- Systematics of the Esym
- Density curvature K_{sym} and the high density Esym
- Quark matter symmetry energy
- Summary

International Workshop on Multi facets of Eos and Clustering (IWM-EC 2014), May 6-9, 2014, Catania, Italy

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Outline

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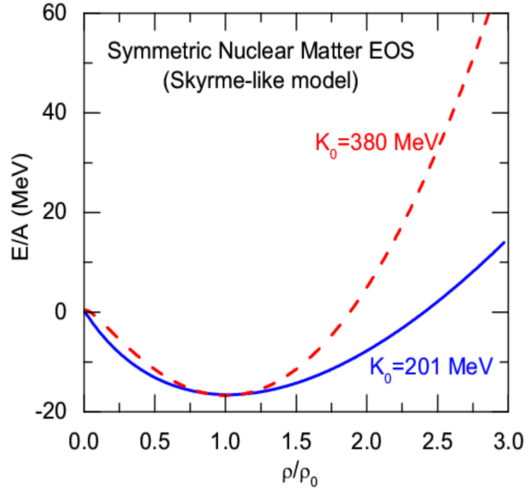
Nuclear Matter EOS

The energy of per nucleon in a nuclear matter with density ρ, temperature T, and isospin asymmetry δ ($\equiv \frac{\rho_n - \rho_p}{\rho}$) can be expressed as

$$E/A = \varepsilon = \varepsilon(\rho, T, \delta) \text{ (Nuclear Matter EOS)}$$

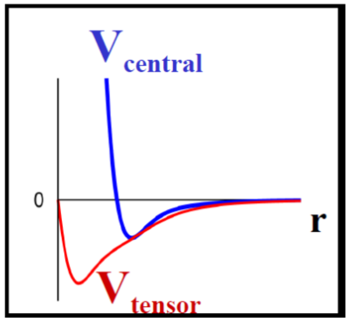


The pressure P of the nuclear matter can be expressed as

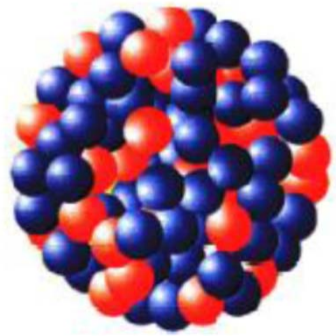
$$P(\rho, T, \delta) = \rho^2 \left(\frac{\partial \varepsilon}{\partial \rho} \right)_{T,N=\text{constant}}$$

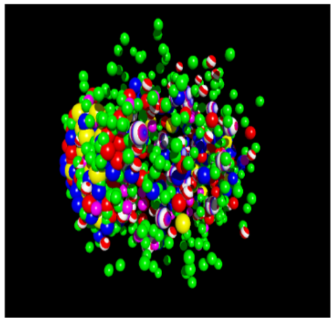
The incompessibilty K of the nuclear matter can be expressed as

$$K(\rho, T, \delta) = 9 \left(\frac{\partial P}{\partial \rho} \right)_{T,N=\text{constant}}$$



Nature of the nuclear force?


Structure and stability of nuclei?


Dynamics of heavy ion collisions?


Nature of compact stars and dense nuclear matter?

The Symmetry Energy

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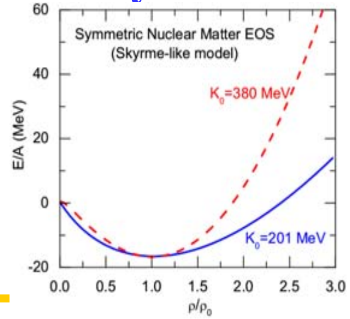
EOS of Isospin Asymmetric Nuclear Matter (Parabolic law)

$$E(\rho,\delta) = E(\rho,0) + E_{\rm sym}(\rho)\delta^2 + O(\delta^4), \quad \delta = (\rho_n - \rho_p)/\rho$$

Symmetric Nuclear Matter (relatively well-determined)

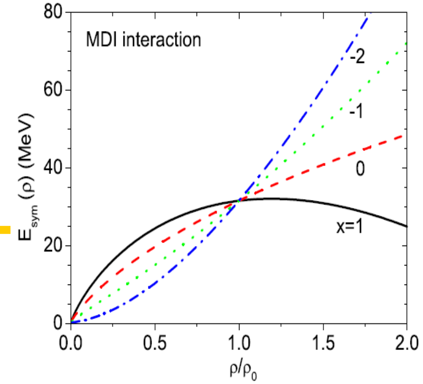
Symmetry energy term (poorly known)

Isospin asymmetry



The Nuclear Symmetry Energy

$$E_{\rm sym}(\rho) \equiv \frac{1}{2}\frac{\partial^2 E(\rho,\delta)}{\partial \delta^2}$$



$$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{\rm sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \cdots\cdots, \quad (\rho \sim \rho_0)$$

$E_{\rm sym}(\rho_0) \approx 30$ MeV (LD mass formula: *Myers & Swiatecki, NPA81; Pomorski & Dudek, PRC67*)

$$L \equiv 3\rho_0 \left.\frac{\partial E_{\rm sym}(\rho)}{\partial \rho}\right|_{\rho=\rho_0}$$

(Many-Body Theory: L : –50 ~ 200 MeV; Exp: ???)

$$K_{\rm sym} \equiv 9\rho_0^2 \left.\frac{\partial^2 E_{\rm sym}(\rho)}{\partial \rho^2}\right|_{\rho=\rho_0}$$

(Many-Body Theory: $K_{\rm sym}$: –700 ~ 466 MeV; Exp: ???)

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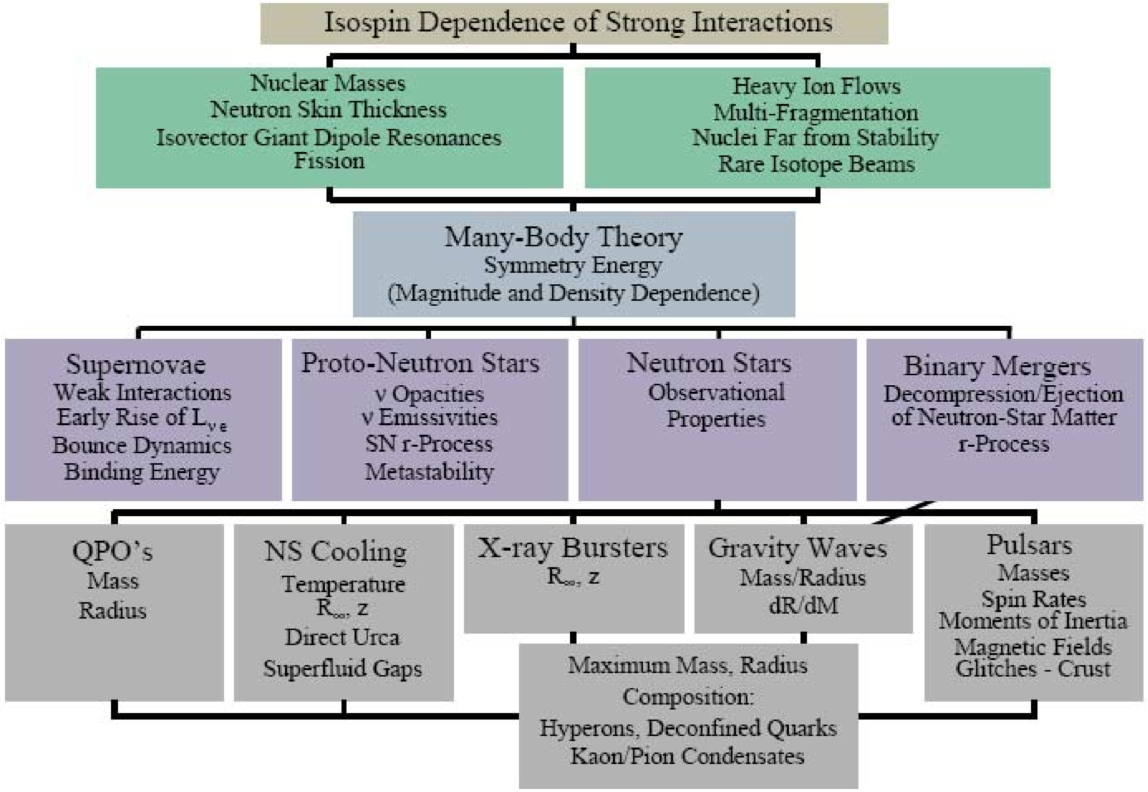
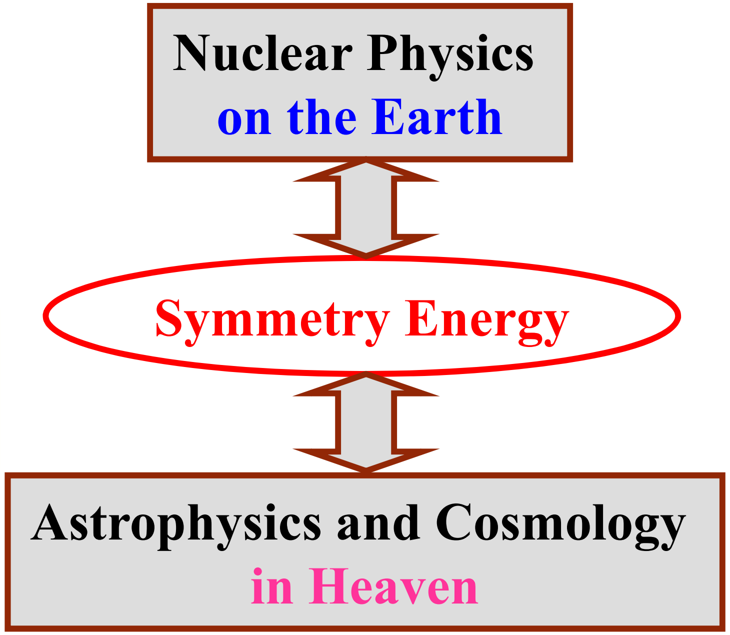
Why Symmetry Energy?

21.65.Ef

The multifaceted influence of the nuclear symmetry energy

A.W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, ***Phys. Rep. 411, 325 (2005).***





The symmetry energy is also related to some issues of fundamental physics:

1. **The precision tests of the SM through atomic parity violation observables (Sil et al., PRC05)**
2. **Possible time variation of the gravitational constant (Jofre et al. PRL06; Krastev/Li, PRC07)**
3. **Non-Newtonian gravity proposed in the grand unified theories (Wen/Li/Chen, PRL09)**
4. **Dark Matter Direct Detection (Zheng/Zhang/Chen, arXiv:1403.5134)**

Phase Diagram of Strong Interaction Matter

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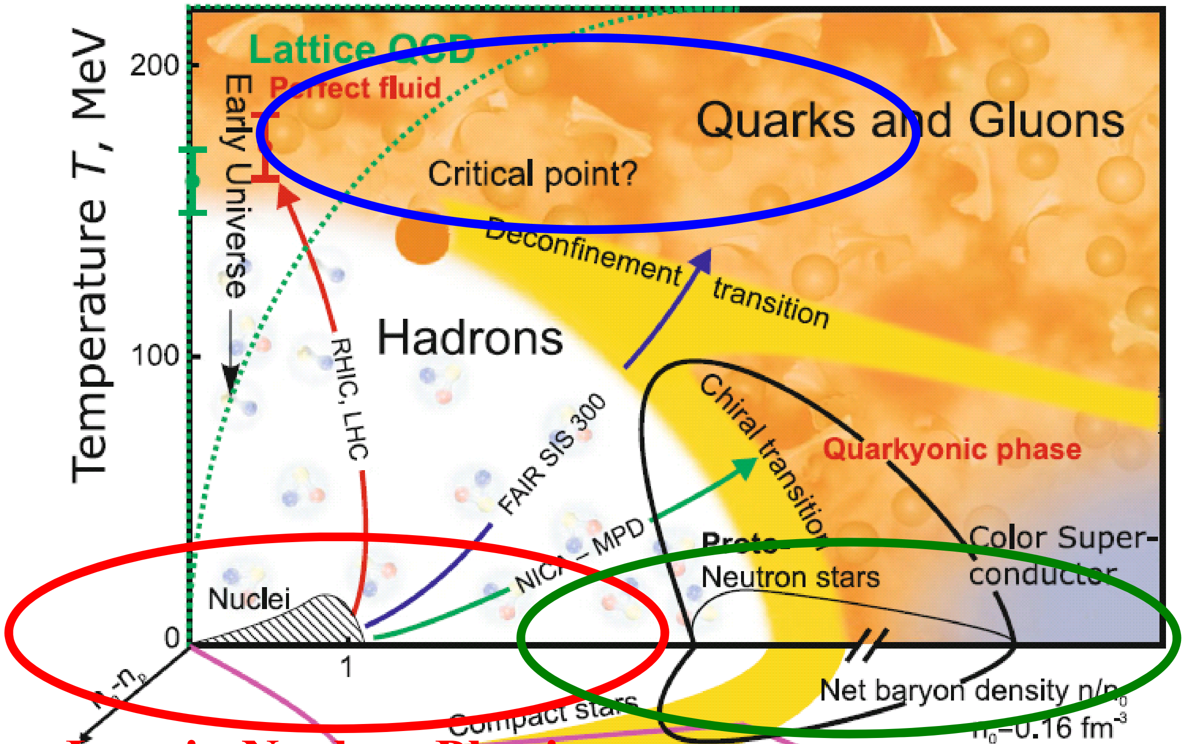
QCD Phase Diagram in 3D: density, temperature, and isospin

V.E. Fortov, Extreme States of Matter – on Earth and in the Cosmos, Springer-Verlag Berlin Heidelberg 2011

Physics of QGP



Isospin Nuclear Physics **Compact Stars**

Holy Grail of Nuclear Physics

EOS (of HM/QM) is one of most important aspects for QCD Phase Diagram, it provides basic information on strong interaction and QCD phase transitions

1. **Heavy Ion Collisions (Terrestrial Lab); 2. Compact Stars(In Heaven); …**

Facilities of Radioactive Beams

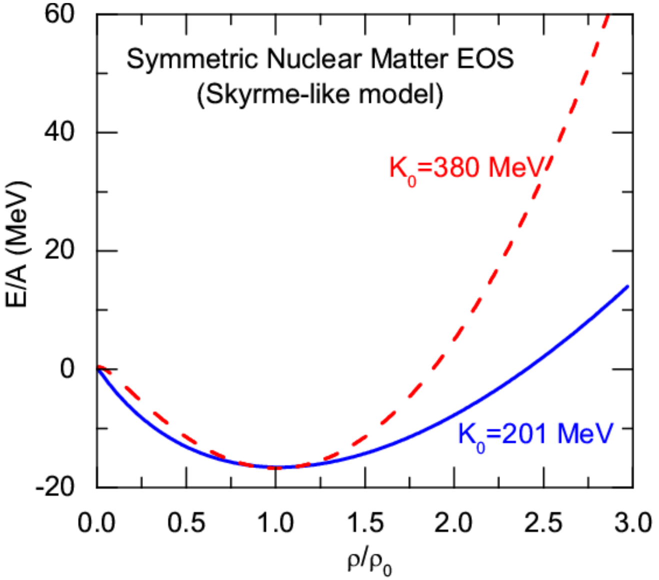
- Cooling Storage Ring (CSR) Facility at HIRFL/Lanzhou in China (2008)
  up to 500 MeV/A for ^{238}U
  http://www.impcas.ac.cn/zhuye/en/htm/247.htm
- Beijing Radioactive Ion Facility (BRIF-II) at CIAE in China (2012)
  http://www.ciae.ac.cn/
- Radioactive Ion Beam Factory (RIBF) at RIKEN in Japan (2007)
  http://www.riken.jp/engn/index.html
- Texas A&M Facility for Rare Exotic Beams -T-REX (2013)
  http://cyclotron.tamu.edu
- Facility for Antiproton and Ion Research (FAIR)/GSI in Germany (2016)
  up to 2 GeV/A for ^{132}Sn (NUSTAR - NUclear STructure, Astrophysics and Reactions)
  http://www.gsi.de/fair/index_e.html
- SPIRAL2/GANIL in France (2013)
  http://pro.ganil-spiral2.eu/spiral2
- Selective Production of Exotic Species (SPES)/INFN in Italy (2015)
  http://web.infn.it/spes
- Facility for Rare Isotope Beams (FRIB)/MSU in USA (2018)
  up to 400(200) MeV/A for ^{132}Sn
  http://www.frib.msu.edu/
- The Korean Rare Isotope Accelerator (KoRIA-RAON(RISP Accelerator Complex) (Starting)
  up to 250 MeV/A for ^{132}Sn, up to 109 pps

……

EOS of Symmetric Nuclear Matter

(1) EOS of symmetric matter around the saturation density ρ_0

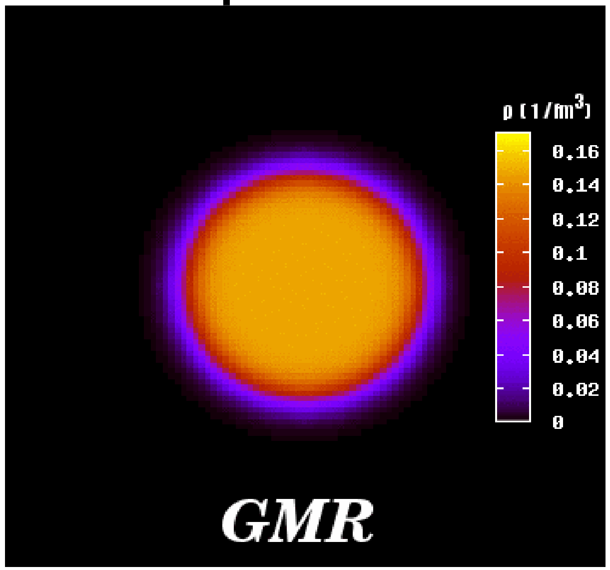
$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2!}\chi^2 + \frac{J_0}{3!}\chi^3 + \mathcal{O}(\chi^4) \quad \chi = \frac{\rho - \rho_0}{3\rho_0}$$



Incompressibility:

$$K_0 = 9\rho_0^2 \left(\frac{d^2E}{d\rho^2}\right)_{\rho_0}$$

Giant Monopole Resonance



Frequency $f_{GMR} \propto \sqrt{K_0}$

$K_0 = 231 \pm 5$ MeV

Youngblood/Clark/Lui, PRL82, 691 (1999)

Recent results:

$K_0 = 230 \pm 20$ MeV

U. Garg et al.

S. Shlomo et al.

G. Colo et al.

J. Piekarewicz et al.

Uncertainty of the extracted K_0 is mainly due to the uncertainty of *L* (slope parameter of the symmetry energy) and m^*_0 (isoscalar nucleon effective mass)

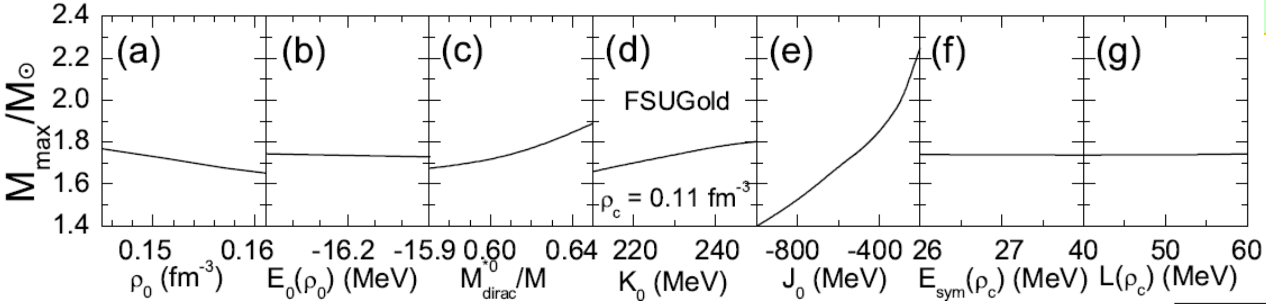
(See, e.g., L.W. Chen/J.Z. Gu, JPG39, 035104(2012))

EOS of Symmetric Nuclear Matter

(2) EOS of symmetric matter at supra-saturation density: Skewness J_0

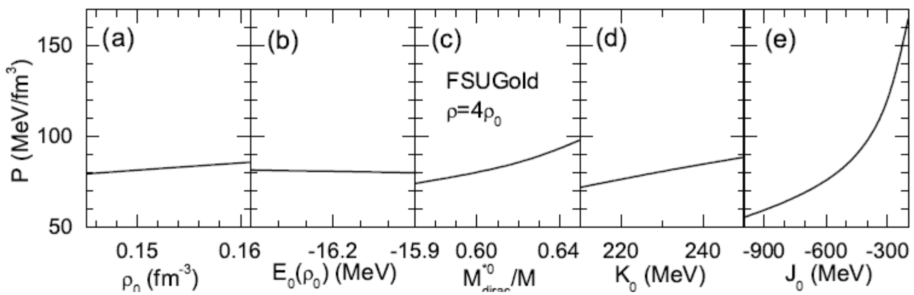
$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2!}\chi^2 + \frac{J_0}{3!}\chi^3 + \mathcal{O}(\chi^4) \quad \chi = \frac{\rho - \rho_0}{3\rho_0}$$

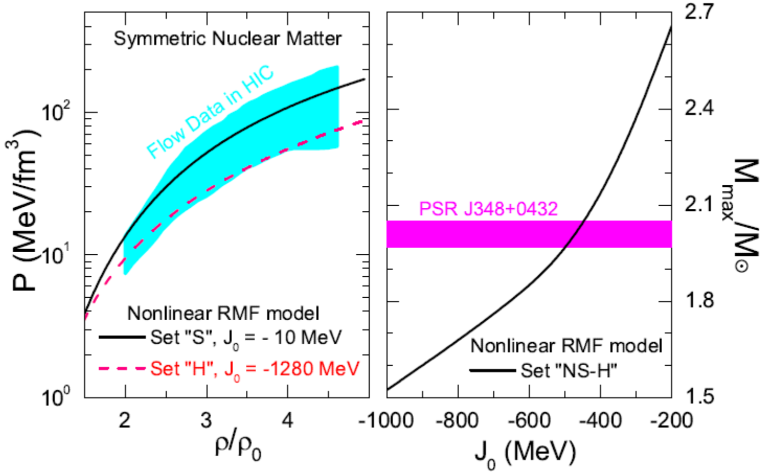
Skewness Coefficient: $J_0 = 27\rho_0^3 \left(\frac{d^3E}{d\rho^3}\right)_{\rho_0}$



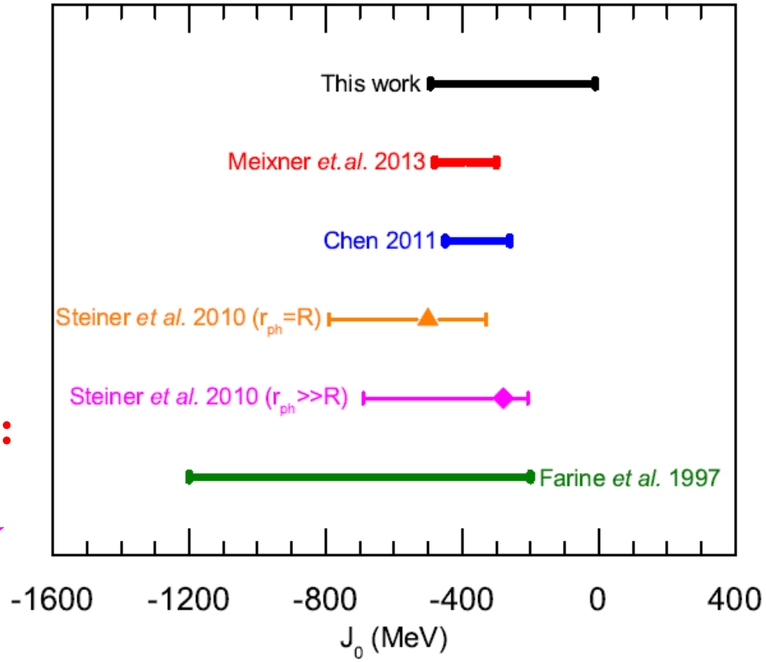
J_0 probes:

- **Mass of neutron stars**
- **Pressure at high density**





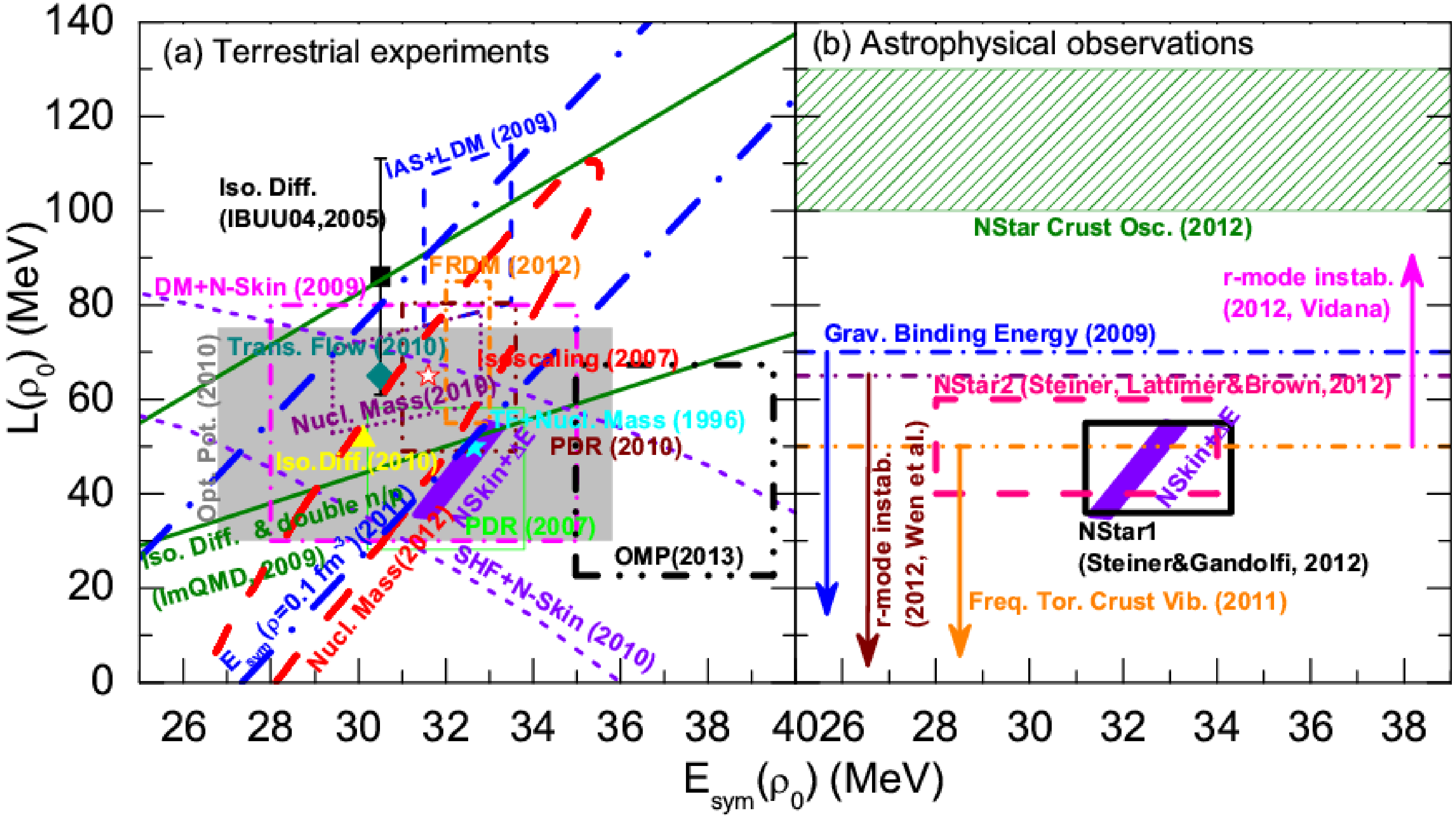
Nonlinear RMF:
J_0:
[-494, -10] MeV



B.J. Cai/L.W. Chen/, arXiv:1402.4242

E_{sym}: Around saturation density

Current constraints (An incomplete list) on E_{sym} (ρ_0) and L from terrestrial experiments and astrophysical observations



L.W. Chen, arXiv:1212.0284 $E_{sym}(\rho_0)$ = 32.5±2.5 MeV, L = 55±25 MeV

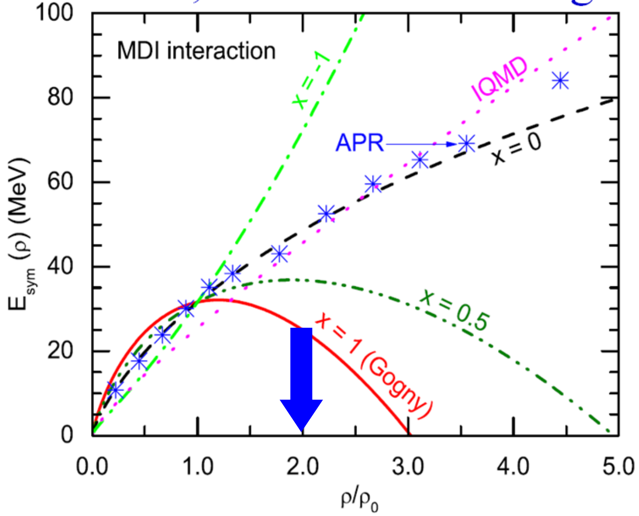
B.A. Li, L.W. Chen, F.J. Fattoyev, W.G. Newton, and C. Xu, arXiv:1212.1178

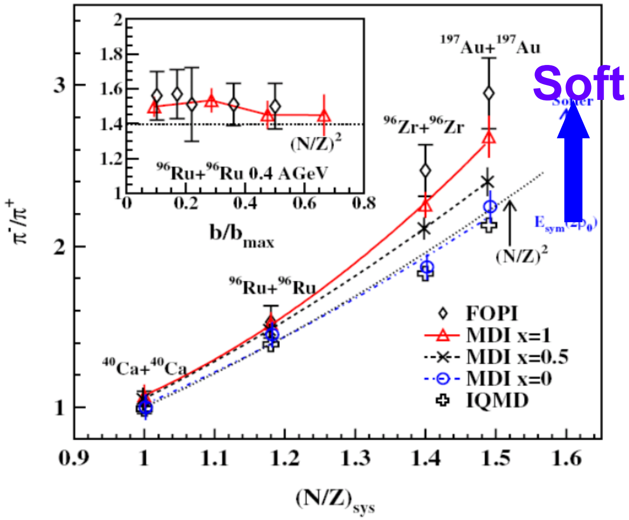
High density E_{sym}: pion ratio

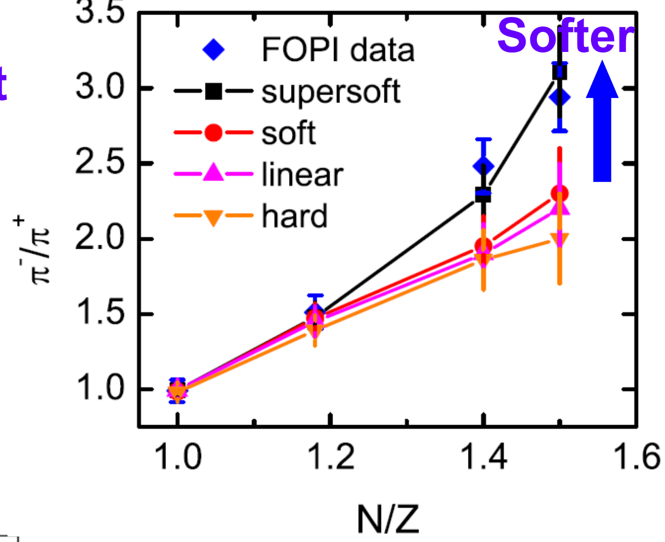
A Quite Soft Esym at supra-saturation densities ???

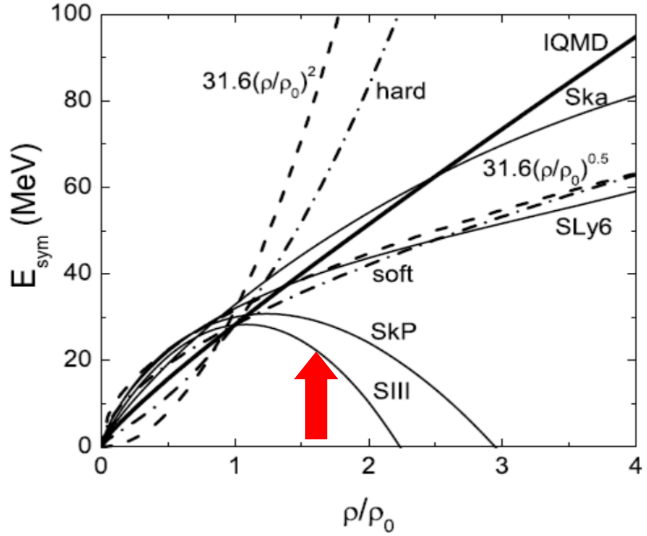
IBUU04, Xiao/Li/Chen/Yong/Zhang, PRL102,062502(2009)

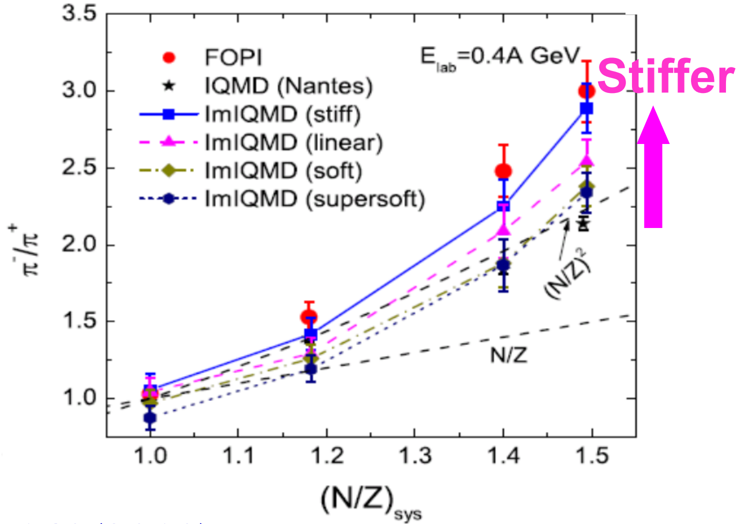
ImIBLE, Xie/Su/Zhu/Zhang, PLB718,1510(2013)











Pion Medium Effects?
Xu/Ko/Oh
PRC81, 024910(2010)

Threshold effects?
Δ resonances?
……

ImIQMD, Feng/Jin, PLB683, 140(2010)

High density E_{sym}: pion ratio

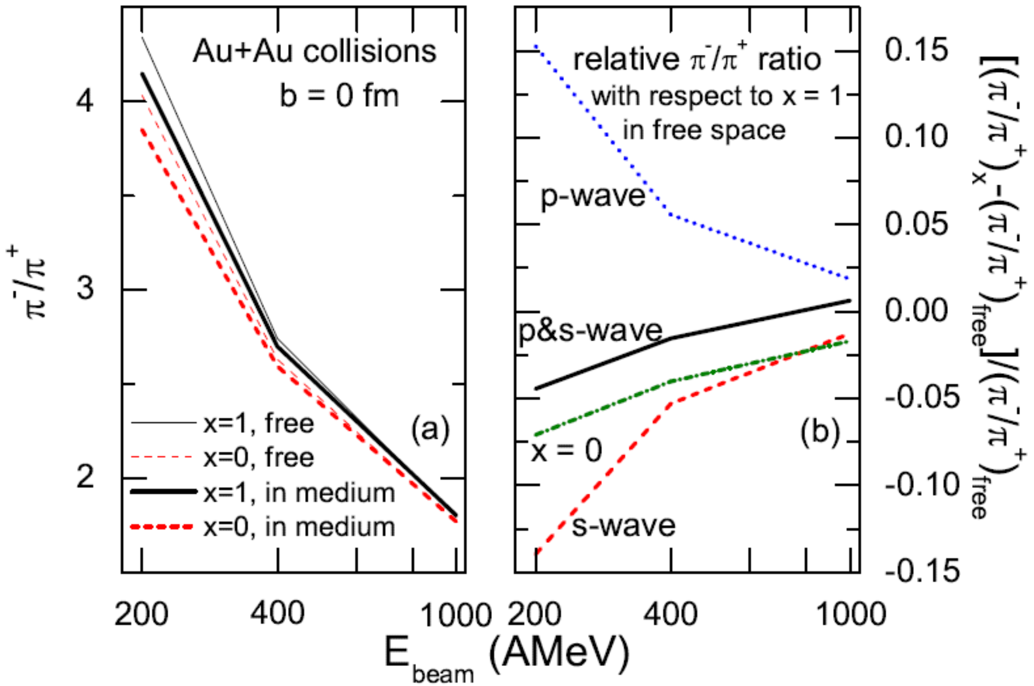
Energy dependence of pion in-medium effects on π^-/π^+ ratio in heavy-ion collisions

PRC87, 067601 (2013)

Jun Xu,[1,*] Lie-Wen Chen,[2] Che Ming Ko,[3] Bao-An Li,[4,5] and Yu-Gang Ma[1]

[1] Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

Within the framework of a thermal model with its parameters fitted to the results from an isospin-dependent Boltzmann-Uehling-Uhlenbeck (IBUU) transport model, we have studied the pion in-medium effect on the charged-pion ratio in heavy-ion collisions at various energies. We find that due to the cancellation between the effects from pion-nucleon s-wave and p-wave interactions in nuclear medium, the π^-/π^+ ratio generally decreases after including the pion in-medium effect. The effect is larger at lower collision energies as a result of narrower pion spectral functions at lower temperatures.



The pion in-meidum effects seem comparable to Esym effects in the thermal model !!!

But how about in more realistic dynamical model ???

How to treat self-consistently the pion in-medium effects in transport model remains a big challenge !!!

High density E_{sym}: pion ratio

J. Hong and P. Danielewicz, arXiv:1307.7654

$$S(\rho) = S_{kin0}\left(\frac{\rho}{\rho_0}\right)^{\frac{2}{3}} + S_{int0}\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

$$U_{\pi^{\pm}} = \pm a_T \rho_T \frac{\rho^{\gamma-1}}{\rho_0^{\gamma}}$$

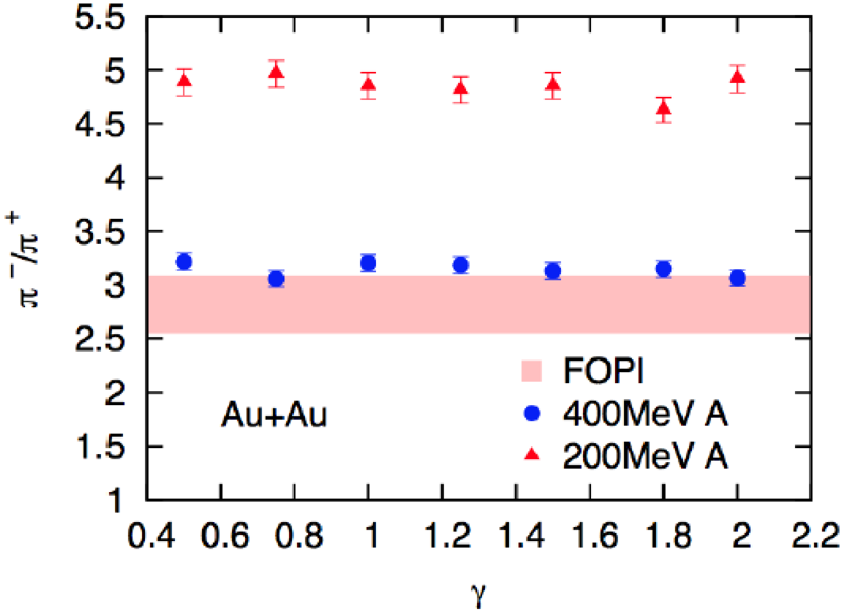


FIG. 7: Ratio of net charged pion yields in central Au+Au collisions at 400 MeV A and 200 MeV A, as a function of the stiffness of symmetry energy γ, from pBUU calculations using N_π-adjusted MF.

No Esym effects !
(no mom. dep. in sym. pot)

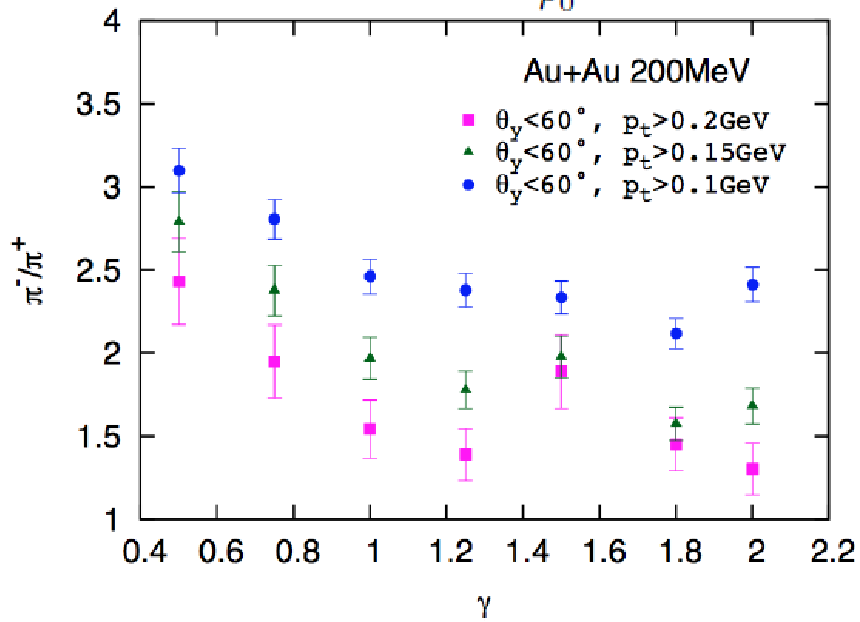
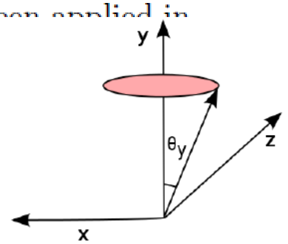


FIG. 10: Ratios of the yields of charged energetic out-of-plane pions in central Au+Au collisions at 200 MeV A, plotted as a function of γ. An angular cut of $\theta_y = 60°$ has been applied in addition to various indicated transverse momen

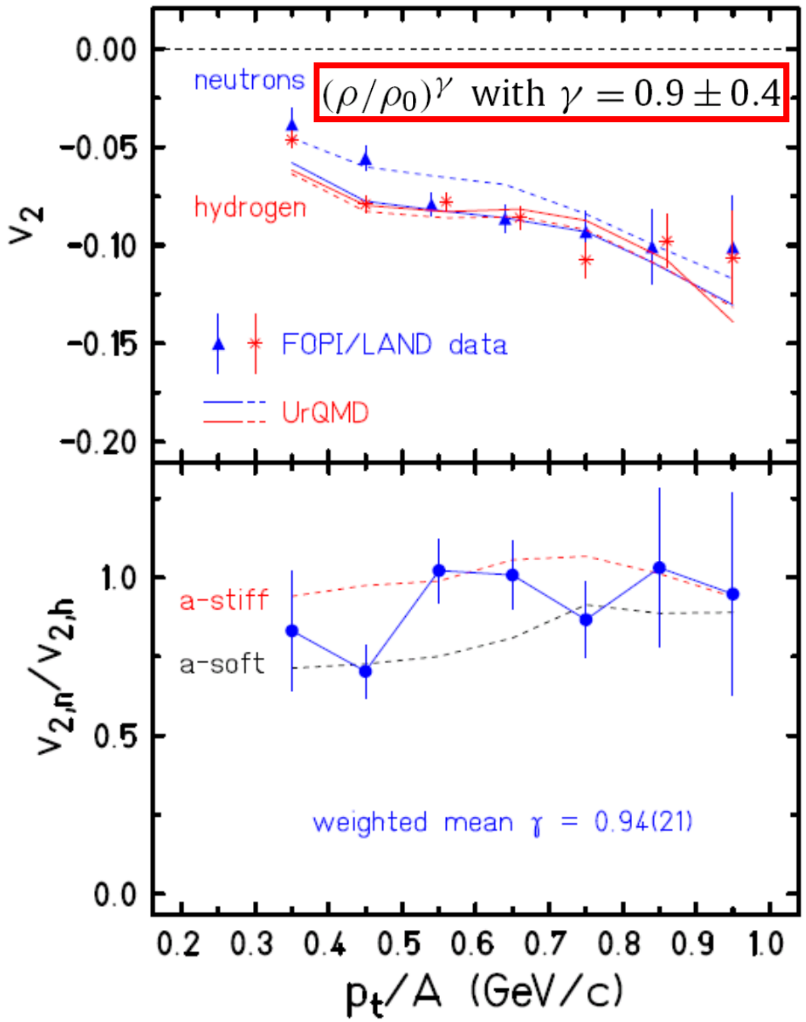


Esym effects show up for squeeze-out pions !

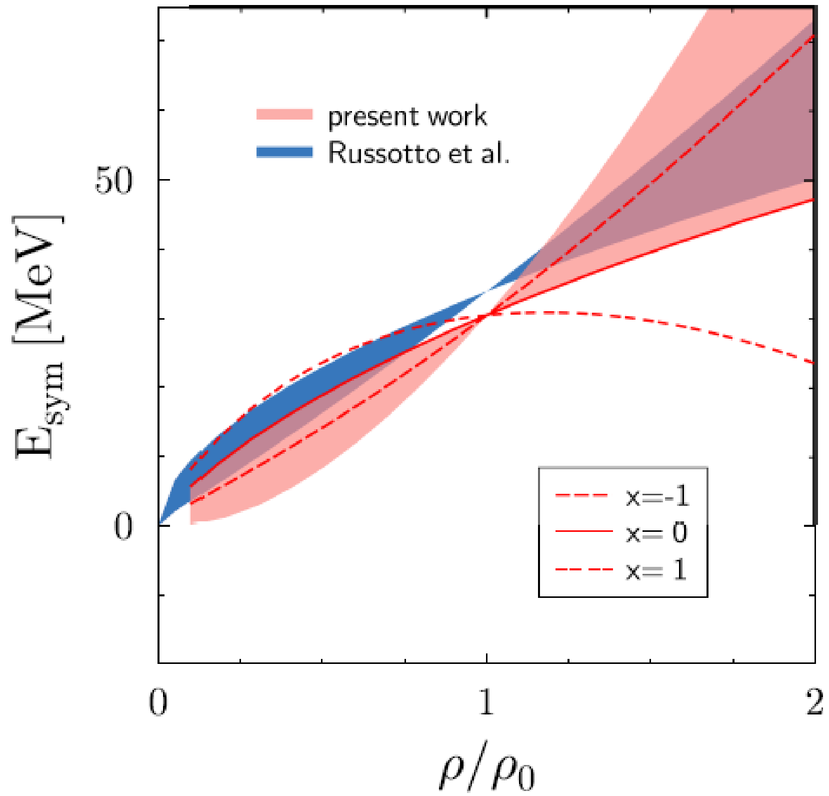
High density E_{sym}: n/p v2

A Soft or Stiff Esym at supra-saturation densities ???

P. Russotto, W. Trauntmann, Q.F. Li et al., PLB697, 471(2011) (UrQMD)



M.D. Cozma, W. Trauntmann, Q.F. Li et al., PRC88, 044912 (2013) (Tubingen QMD - MDI)



Moderately stiff to roughly linear density dependence !

E_{sym}: at supra- and saturation density

●Cannot be that all the constraints on E_{sym} (ρ_0) and L are equivalently reliable since some of them don't have any overlap. However, all the constraints seem to agree with:

$$E_{sym}(\rho_0) = 32.5 \pm 2.5 \text{ MeV}$$
$$L = 55 \pm 25 \text{ MeV}$$

●All the constraints on the high density Esym come from HIC's, and all of them are based on transport models. The constraints on the high density Esym are elusive and controversial for the moment !!!

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- The symmetry energy (Esym)
- Systematics of the Esym
- Density curvature K_{sym} and the high density Esym
- Quark matter symmetry energy
- Summary

Esym systematics and high density E_{sym}

- So far (**most likely also in future**), essentially all the constraints on Esym have been obtained based on some energy density functionals or phenomenological parameterizations of Esym. Are there some universal laws (systematics) for the density dependence of Esym within these functionals or parameterizations?
- While more high quality data and more reliable models are in progress to constrain the high density Esym, can we find other ways to get some information on high density Esym?
- Can we get some information on high density Esym from the knowledge of Esym around saturation density?

$$E_{\rm sym}(\rho) = E_{\rm sym}(\rho_0) + L\chi + \frac{K_{\rm sym}}{2!}\chi^2 + \frac{J_{\rm sym}}{3!}\chi^3 + \frac{I_{\rm sym}}{4!}\chi^4 + O(\chi^5) \quad \chi = \frac{\rho - \rho_0}{3\rho_0}$$

$E_{sym}(\rho_0)$, L, and K_{sym} ⇒ E_{sym} up to $2\rho_0$ or even higher densities!!!

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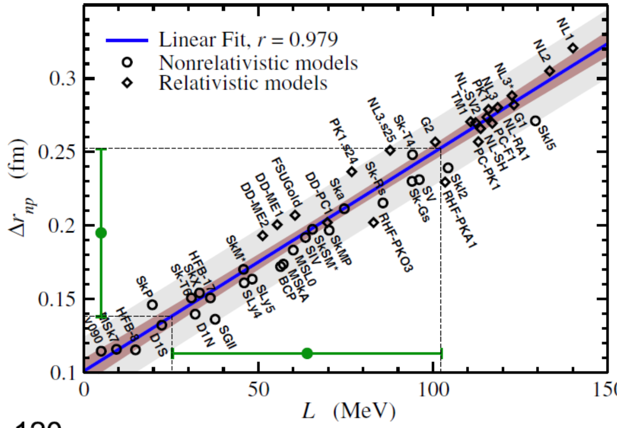
Systematics of density dependence of E_{sym}

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\chi + \frac{K_{sym}}{2!}\chi^2 + \frac{J_{sym}}{3!}\chi^3 + \frac{I_{sym}}{4!}\chi^4 + O(\chi^5) \qquad \chi = \frac{\rho - \rho_0}{3\rho_0}$$

Roca-Maza et al., PRL106, 252501 (2011)

46 interactions +BSK18-21+MSL1+SAMi +SV-min+ UNEDF0-1+TOV-min+IU-FSU+BSP+IU-FSU*+TM1*

(Totally 60 interactions in our analysis)



Skyrme (33): **v090,MSk7,BSk8,SKP,SKT6,SKX,BSk17,SGII,SKM*,SLy4,SLy5,MSkA,MSL0,SIV,SkSM*,SkMP,SKa,Rsigma,Gsigma,SKT4,SV,SkI2,SkI5,BSK18.BSK19,BSK20,BSK21,MSL1,SAMi,SV-min,UNEDF0,UNEDF1,TOV-min**

Gogny (2): D1S,D1N

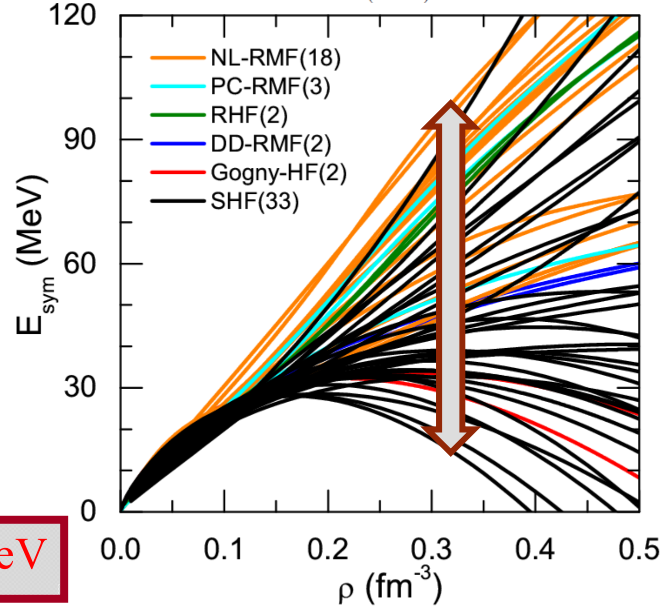
NL-RMF (18): **FSUGold,PK1s24,NL3s25,G2,TM1,NL-SV2,NL-SH, NL-RA1,PK1,NL3,NL3*,G1,NL2,NL1,IU-FSU,BSP,IUFSU*,TM1***

DD-RMF (2): DD-ME1,DD-ME2

PC-RMF (3): DD-PC1,PC-PK1,PC-F1

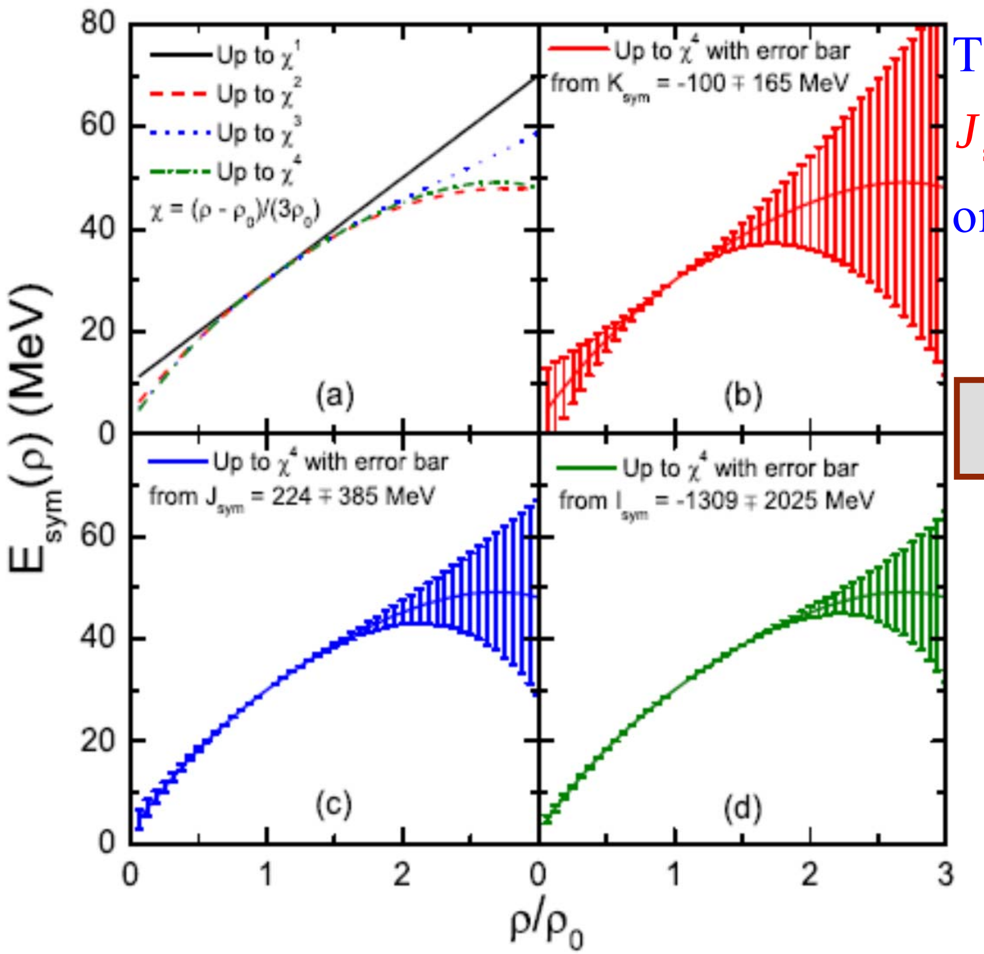
RHF (2): PKO3,PKA1

$E_{sym}(2\rho_0) \approx [15,100]$ MeV



Systematics of density dependence of E_{sym}

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\chi + \frac{K_{sym}}{2!}\chi^2 + \frac{J_{sym}}{3!}\chi^3 + \frac{I_{sym}}{4!}\chi^4 + O(\chi^5) \qquad \chi = \frac{\rho - \rho_0}{3\rho_0}$$



The higher-order chracteristic parameters J_{sym}, I_{sym} et al seem only have tiny effects on $E_{sym}(\rho)$ below about $2\rho_0$ (Based on SHF)

$E_{sym}(\rho)$ up to about $2\rho_0$ is essentially determined by three characteristic parameters: $E_{sym}(\rho_0)$, L, and K_{sym}

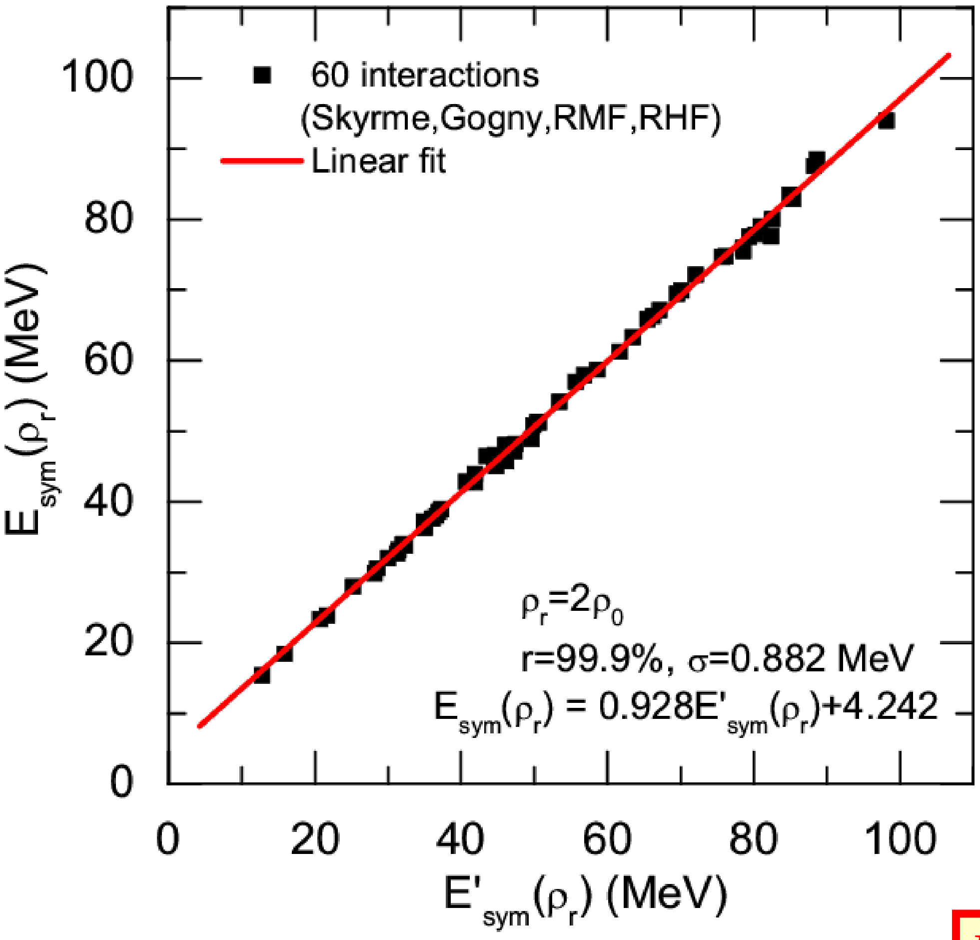
$E_{sym}(\rho_0)$, L, and K_{sym}

$E_{sym}(2\rho_0) = ?$

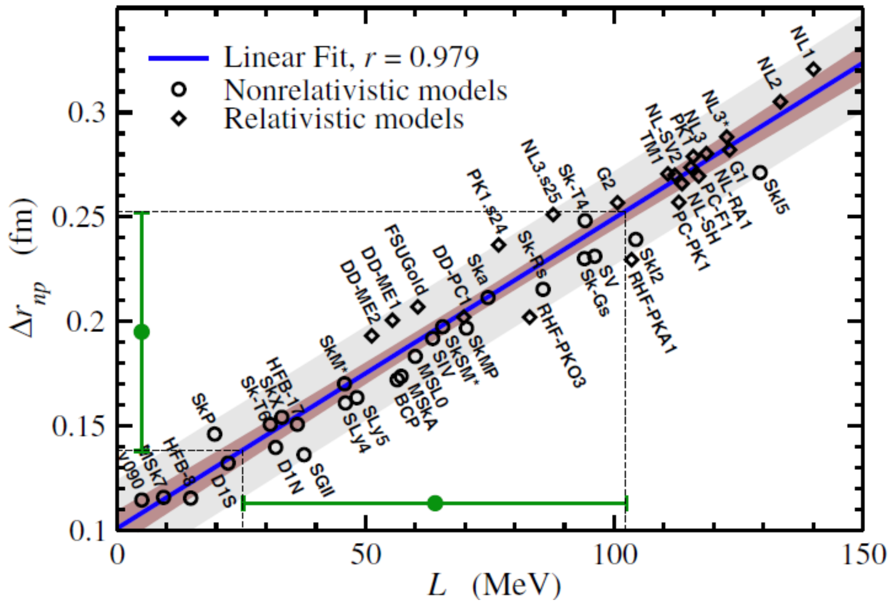
L.W. Chen, Sci. China Phys. Mech. Astron. 54, suppl. 1, s124 (2011) [arXiv:1101.2384]

Systematics of density dependence of E_{sym}

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\chi + \frac{K_{sym}}{2!}\chi^2 + \frac{J_{sym}}{3!}\chi^3 + \frac{I_{sym}}{4!}\chi^4 + O(\chi^5) \qquad \chi = \frac{\rho - \rho_0}{3\rho_0}$$



$$E'_{sym}(2\rho_0) \equiv E_{sym}(\rho_0) + L/3 + K_{sym}/18$$



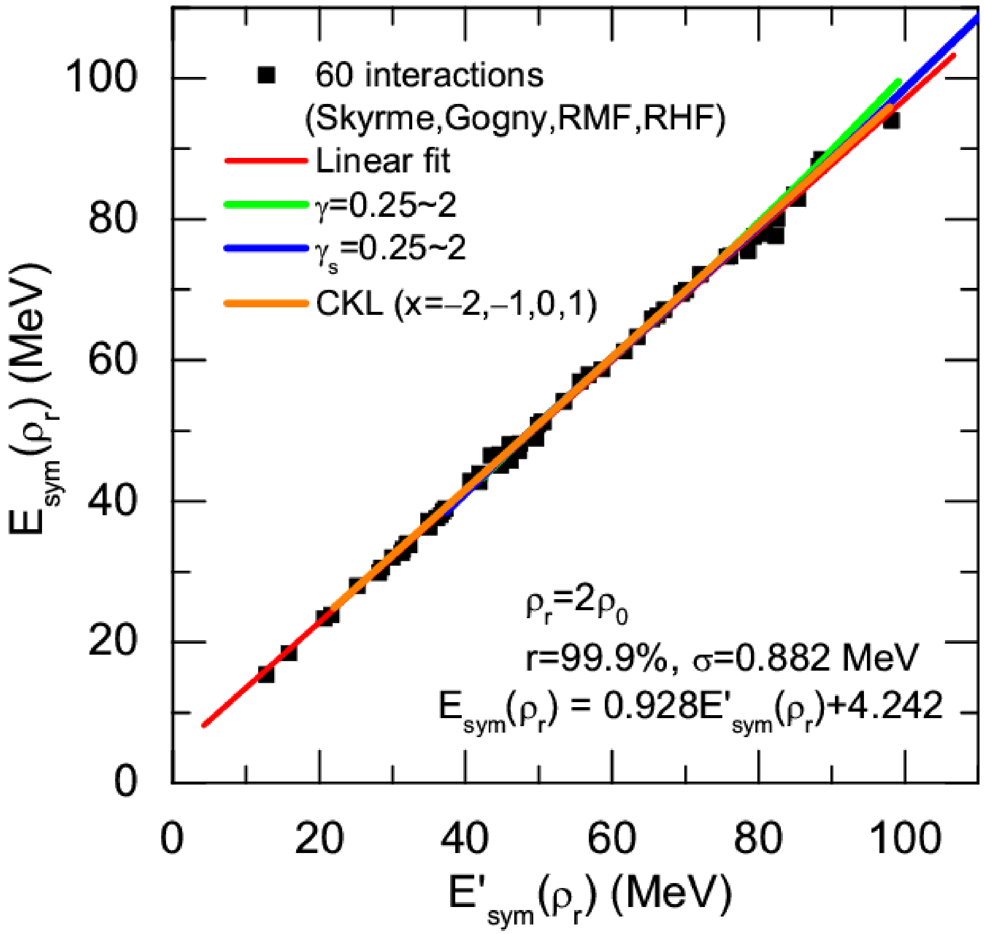
Roca-Maza et al., PRL106, 252501 (2011)

46 interactions +BSK18-21+MSL1+SAMi +SV-min+UNEDF0-1+TOV-min+IU-FSU +BSP+IU-FSU*+TM1* (Totally 60 interactions in our analysis)

$E_{sym}(\rho_0)$, L, and K_{sym} ⇒ $E_{sym}(2\rho_0) = ?$

Systematics of density dependence of E_{sym}

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\chi + \frac{K_{sym}}{2!}\chi^2 + \frac{J_{sym}}{3!}\chi^3 + \frac{I_{sym}}{4!}\chi^4 + O(\chi^5) \qquad \chi = \frac{\rho-\rho_0}{3\rho_0}$$



$$E'_{sym}(2\rho_0) \equiv E_{sym}(\rho_0) + L/3 + K_{sym}/18$$

Phenomenological parameterizations in transport models for HIC's

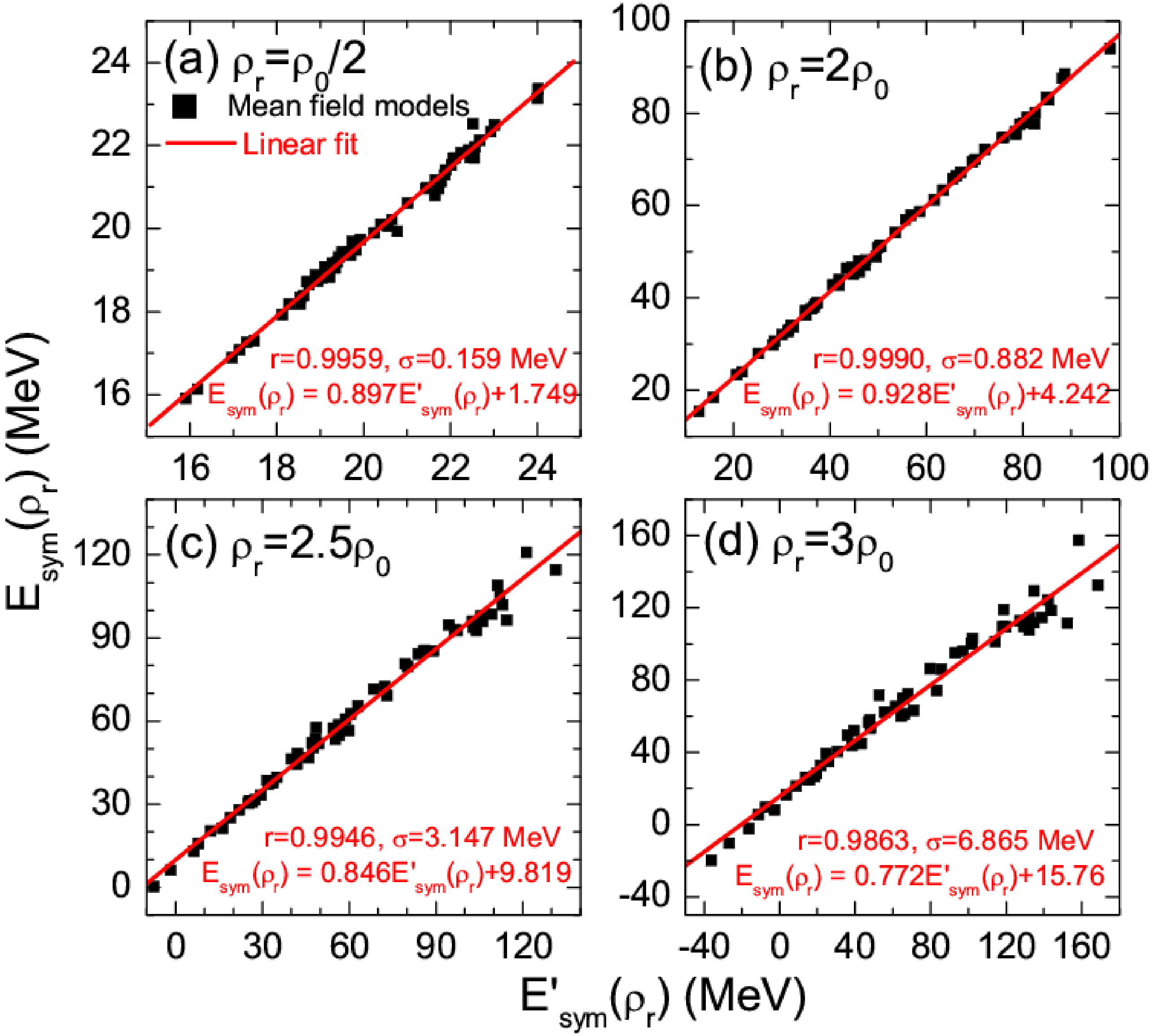
$$E_{sym}(\rho) = 12.3\left(\frac{\rho}{\rho_0}\right)^{2/3} + 20\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

$$E_{sym}(\rho) = 32.3\left(\frac{\rho}{\rho_0}\right)^{\gamma_s}$$

$$E_{sym}(\rho) = 13\left(\frac{\rho}{\rho_0}\right)^{2/3} + F(x)\left(\frac{\rho}{\rho_0}\right) + (18.6 - F(x))\left(\frac{\rho}{\rho_0}\right)^{G(x)}$$

(Chen/Ko/Li, PRL94, 032701(2005), MDI interaction)

Systematics of density dependence of E_{sym}



Magnitude of E_{sym}:

Linear correlation at different densities

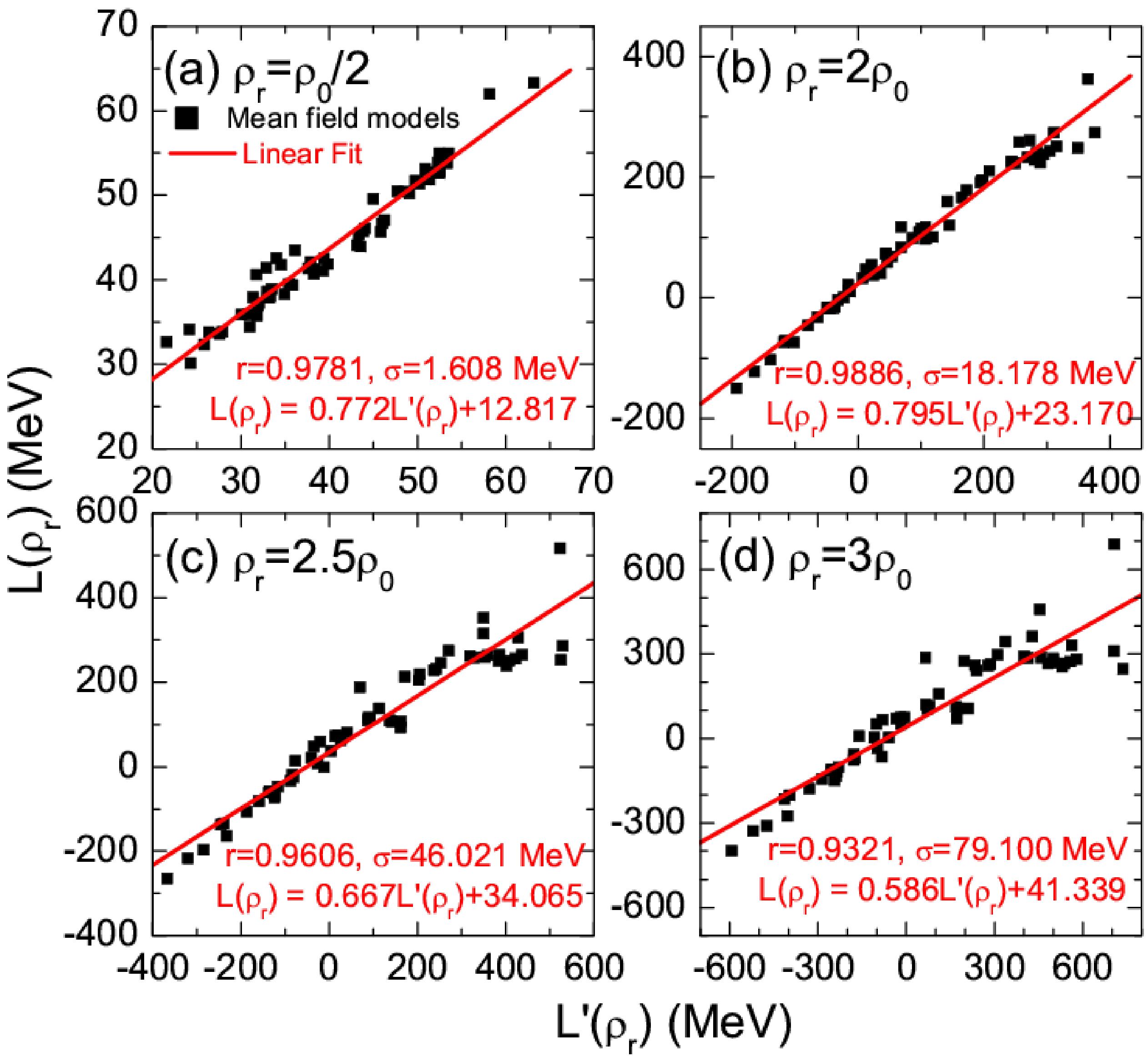
Good linear relationship between $E_{sym}(\rho)$ and $E'_{sym}(\rho)$:

$E_{sym}(\rho) \approx A + BE'_{sym}(\rho)$

(Linear correlation coeficient is larger than 96% for $0.2\rho_0 \leq \rho \leq 3\rho_0$)

$$E'_{sym}(\rho) \equiv E_{sym}(\rho_0) + L\chi + K_{sym}\chi^2/2$$

Systematics of density dependence of E_{sym}



Density slope L:

Linear correlation at different densities

Good linear relationship between $L(\rho)$ and $L'(\rho)$:

$L(\rho) \approx A + BL'(\rho)$

(Linear correlation coeficient is larger than 93% for $0.5\rho_0 \le \rho \le 3\rho_0$)

$$L'(\rho) \equiv 3\rho \frac{dE'_{sym}}{d\rho} = L\frac{\rho}{\rho_0} + K_{sym}\chi\frac{\rho}{\rho_0}$$

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Systematics of density dependence of E_{sym}

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\chi + \frac{K_{sym}}{2!}\chi^2 + \frac{J_{sym}}{3!}\chi^3 + \frac{I_{sym}}{4!}\chi^4 + O(\chi^5) \qquad \chi = \frac{\rho - \rho_0}{3\rho_0}$$

$E_{sym}(\rho_0)$, L, and K_{sym} ⟺ $E_{sym}(\rho)$ $(0.2\rho_0 \le \rho \le 3\rho_0)$ or $L(\rho)$ $(0.5\rho_0 \le \rho \le 3\rho_0)$

THREE values of $E_{sym}(\rho)$ $(0.2\rho_0 \le \rho \le 3\rho_0)$ or $L(\rho)$ $(0.5\rho_0 \le \rho \le 3\rho_0)$ essentailly determine $E_{sym}(\rho_0)$, L, and K_{sym} as well as $E_{sym}(\rho)$ $(0.2\rho_0 \le \rho \le 3\rho_0)$ and $L(\rho)$ $(0.5\rho_0 \le \rho \le 3\rho_0)$

$$E_{sym}(\rho) \approx A + BE'_{sym}(\rho)$$

$$L(\rho) \approx A_L + B_L L'(\rho)$$

Note: A and A_L are usually not zero,

B and B_L are usually not 1

(Corrections from Higher-order J_{sym}, I_{sym}, ...)

$$E'_{sym}(\rho) \equiv E_{sym}(\rho_0) + L\chi + K_{sym}\chi^2 / 2$$

$$L'(\rho) \equiv 3\rho \frac{dE'_{sym}}{d\rho} = L\frac{\rho}{\rho_0} + K_{sym}\chi\frac{\rho}{\rho_0}$$

Outline

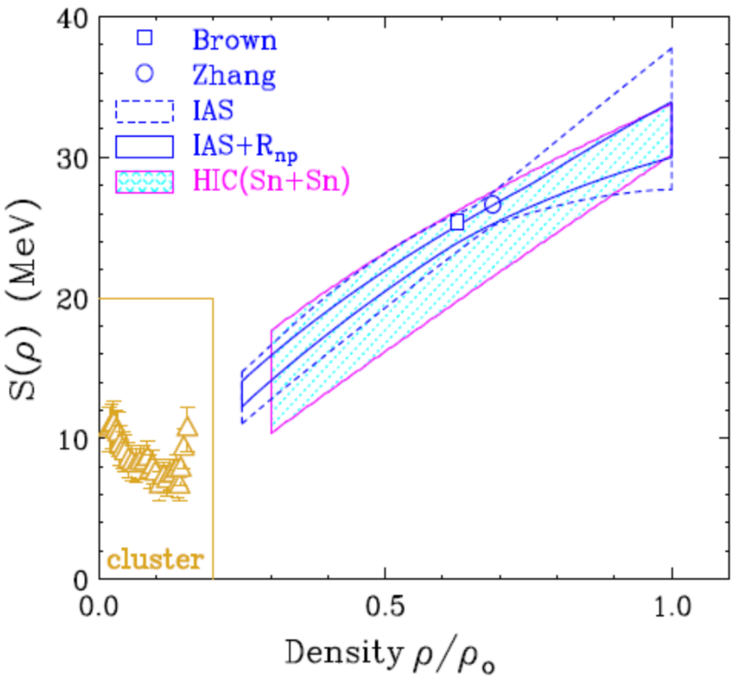
- The symmetry energy (Esym)
- Systematics of the Esym
- Density curvature K_{sym} and the high density Esym
- Quark matter symmetry energy
- Summary

Three values of $E_{sym}(\rho)$ and $L(\rho)$

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\chi + \frac{K_{sym}}{2!}\chi^2 + \frac{J_{sym}}{3!}\chi^3 + \frac{I_{sym}}{4!}\chi^4 + O(\chi^5) \qquad \chi = \frac{\rho - \rho_0}{3\rho_0}$$

THREE values of $E_{sym}(\rho)$ $(0.2\rho_0 \le \rho \le 3\rho_0)$ or $L(\rho)$ $(0.5\rho_0 \le \rho \le 3\rho_0)$

C.J. Horowitz et al., arXiv:1401.5839



Review in NuSYM2013/ICNT2013

Zhang/Chen, PLB726, 234 (2013)

Physics Letters B 726 (2013) 234–238

Constraining the symmetry energy at subsaturation densities using isotope binding energy difference and neutron skin thickness

Zhen Zhang [a], Lie-Wen Chen [a,b,*]

A B S T R A C T

We show that the neutron skin thickness Δr_{np} of heavy nuclei is uniquely fixed by the symmetry energy density slope $L(\rho)$ at a subsaturation cross density $\rho_c \approx 0.11$ fm^{-3} rather than at saturation density ρ_0, while the binding energy difference ΔE between a heavy isotope pair is essentially determined by the magnitude of the symmetry energy $E_{sym}(\rho)$ at the same ρ_c. Furthermore, we find a value of $L(\rho_c)$ leads to a negative $E_{sym}(\rho_0)$–$L(\rho_0)$ correlation while a value of $E_{sym}(\rho_c)$ leads to a positive one. Using data on Δr_{np} of Sn isotopes and ΔE of a number of heavy isotope pairs, we obtain simultaneously $E_{sym}(\rho_c) = 26.65 \pm 0.20$ MeV and $L(\rho_c) = 46.0 \pm 4.5$ MeV at 95% confidence level, whose extrapolation gives $E_{sym}(\rho_0) = 32.3 \pm 1.0$ MeV and $L(\rho_0) = 45.2 \pm 10.0$ MeV. The implication of these new constraints on the Δr_{np} of ^{208}Pb and the core–crust transition density in neutron stars is discussed.

Not only the magnitude E_{sym}, but also the density slope L at 0.11 fm^{-3} have been determined with high precision !!!

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Three values of $E_{sym}(\rho)$ and $L(\rho)$

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\chi + \frac{K_{sym}}{2!}\chi^2 + \frac{J_{sym}}{3!}\chi^3 + \frac{I_{sym}}{4!}\chi^4 + O(\chi^5) \qquad \chi = \frac{\rho - \rho_0}{3\rho_0}$$

THREE values of $E_{sym}(\rho)$ $(0.2\rho_0 \le \rho \le 3\rho_0)$ or $L(\rho)$ $(0.5\rho_0 \le \rho \le 3\rho_0)$

$E_{sym}(\rho_r)$ at ρ_r =0.11 fm^{-3} ⟺ **Binding energy difference of heavy isotope pair**

$L(\rho_r)$ at ρ_r =0.11 fm^{-3} ⟺ **The neutron skin of heavy nuclei**

$E_{sym}(\rho_r)$ at $\rho_r = \rho_0$ ⟺ **Binding energy**

Z. Zhang/L.W. Chen, PLB726, 234 (2013):

$E_{sym}(0.11\text{ fm}^{-3}) = 26.65 \pm 0.2$ MeV (Binding energy difference of heavy isotope pairs)

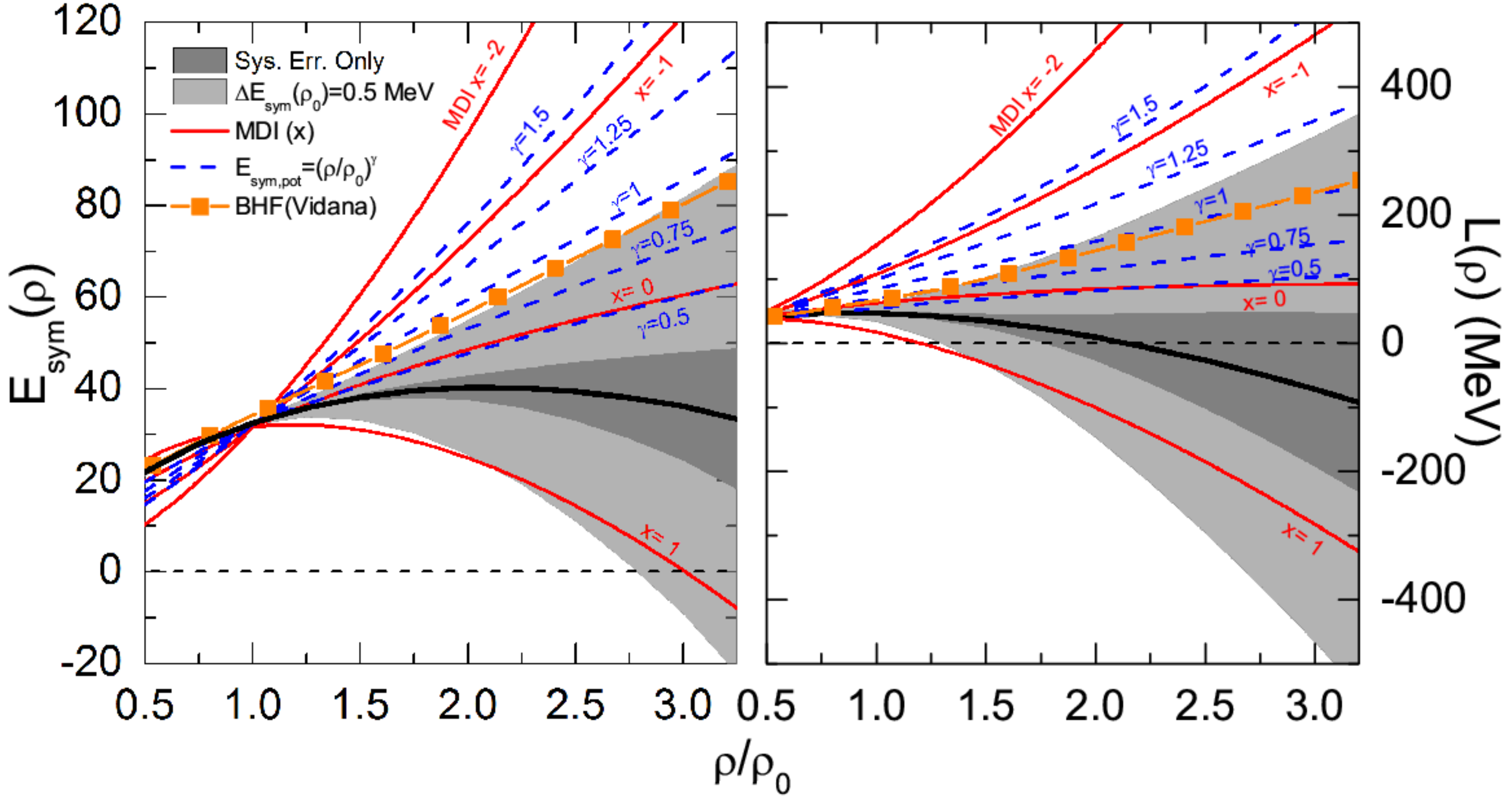
$L(0.11\text{ fm}^{-3}) = 46.0 \pm 4.5$ MeV (The neutron skin of Sn isotopes)

P. Moller et al., PRL108, 052501 (2012):

$E_{sym}(\rho_0) = 32.5 \pm 0.5$ MeV (Binding energy - FRDM)

High density E_{sym} and K_{sym} parameter

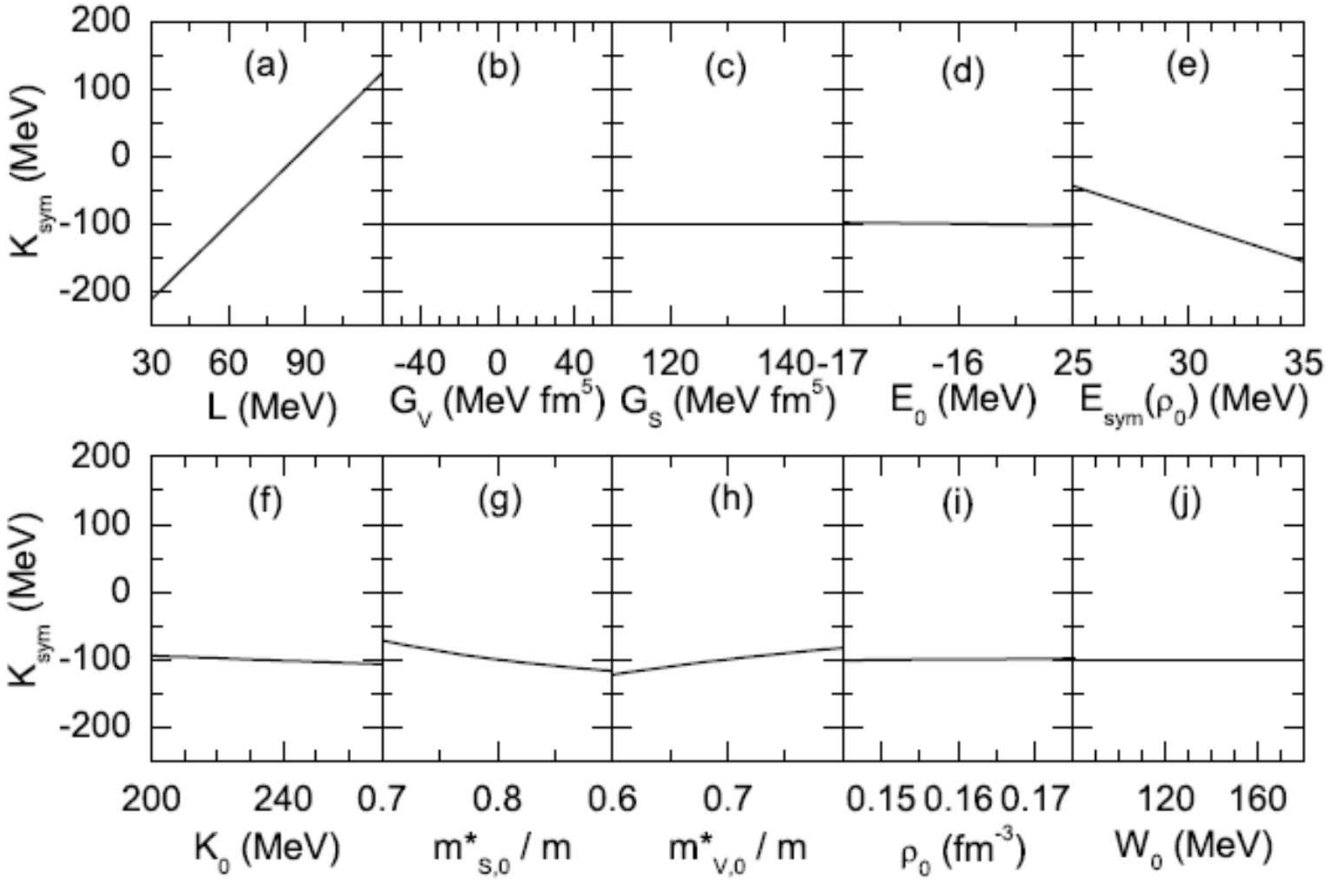
$E_{sym}(0.11\ \text{fm}^{-3}) = 26.65 \pm 0.2$ MeV, $L(0.11\ \text{fm}^{-3}) = 46.0 \pm 4.5$ MeV, $E_{sym}(\rho_0) = 32.5 \pm 0.5$ MeV



- At ρ_0 : $E_{sym}(\rho_0) = 32.5 \pm 0.5$ MeV, $L(\rho_0) = 46.7 \pm 13.4$ MeV, $K_{sym}(\rho_0) = -167.1 \pm 185.3$ MeV
- At $2\rho_0$: $E_{sym}(2\rho_0) = 40.2 \pm 14.7$ MeV, $L(2\rho_0) = 8.8 \pm 156.6$ MeV
- Soft to linear density dependence of the symmetry energy is favored: $E_{sym,pot}(\rho) \sim (\rho / \rho_0)^{\gamma}$ with $\gamma < 1$

The value of K_{sym} from SHF

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\chi + \frac{K_{sym}}{2!}\chi^2 + \frac{J_{sym}}{3!}\chi^3 + \frac{I_{sym}}{4!}\chi^4 + O(\chi^5)$$



L.W. Chen, PRC83, 044308(2011)

$$K_{sym} = 3\gamma L + E_{sym}^{kin}(\rho_0)(3\gamma - 2) + 2D(5 - 3\gamma) - 9\gamma E_{sym}(\rho_0)$$

$$K_{sym} = (-100 \pm 165)\ \text{MeV}$$

Based on SHF !

Esym systematics:
K_{sym}= -167.1±185.3 MeV

L.W. Chen, Sci. China Phys. Mech. Astron. 54, suppl. 1, s124 (2011) [arXiv:1101.2384]

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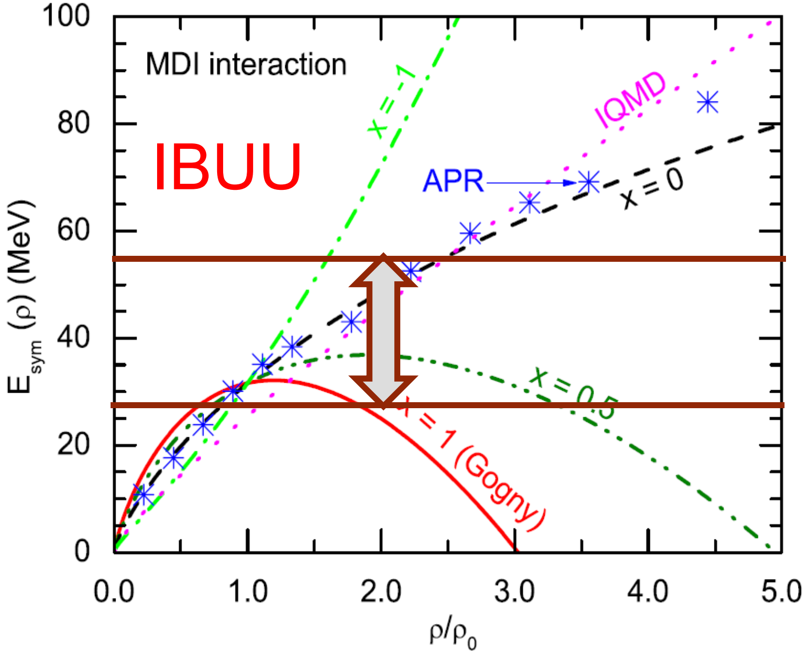
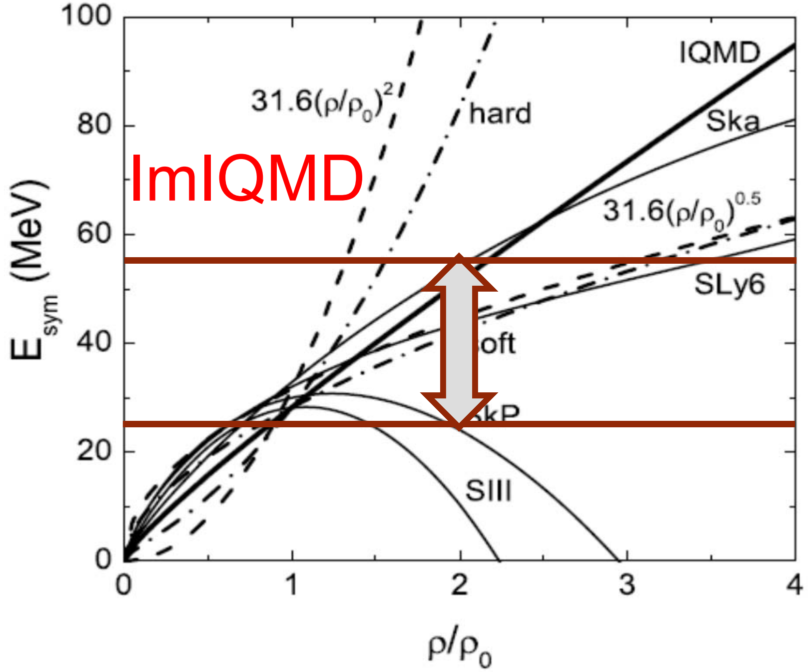
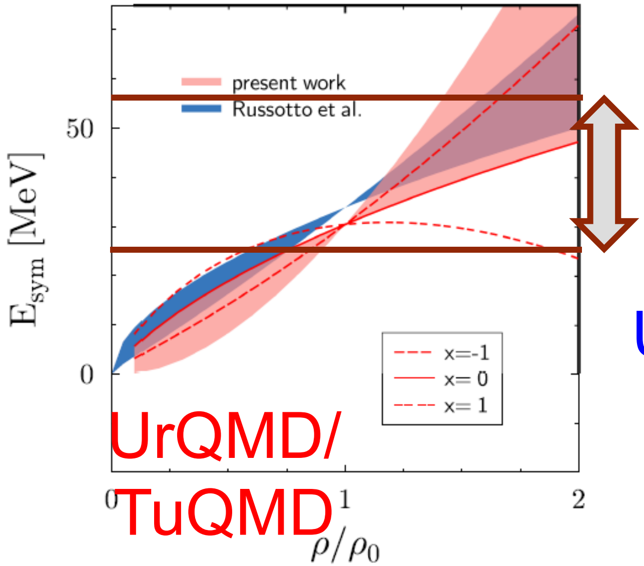
High density E_{sym} : $E_{sym}(2\rho_0)$ from HIC's





$E_{sym}(2\rho_0) \approx [25.5, 54.9]$ MeV



$$E_{sym} = E_{sym}^{pot} + E_{sym}^{kin}$$
$$= 22\text{ MeV} \cdot (\rho/\rho_0)^{\gamma} + 12\text{ MeV} \cdot (\rho/\rho_0)^{2/3}$$

UrQMD: $\gamma = 0.9 \pm 0.4$

$\gamma \leq 0.7$ (for $\rho \leq 2\rho_0$)

Soft symmetry energy ($\rho \leq 2\rho_0$) is favored !!!

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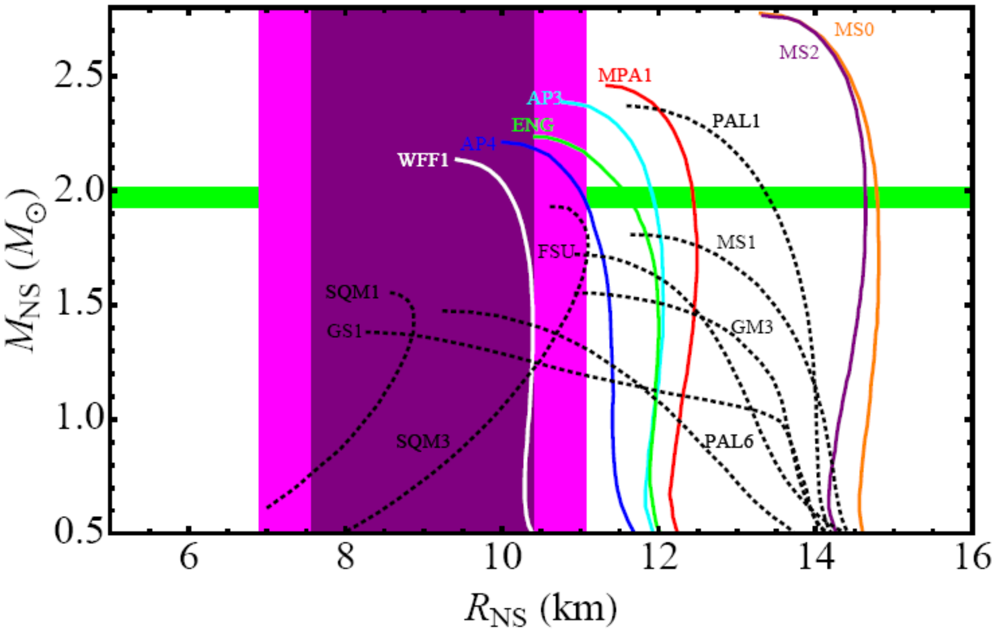
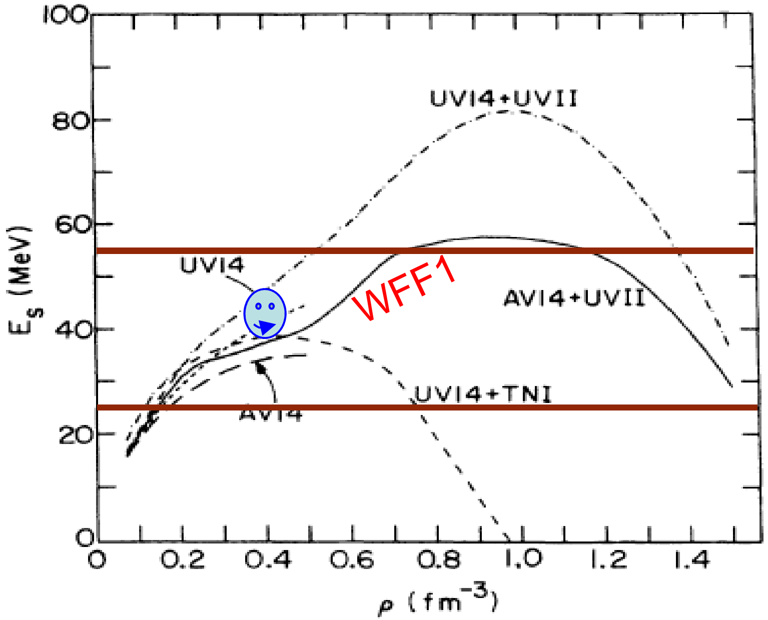
High density E_{sym} : $E_{sym}(2\rho_0)$ from R_{NS}

R_{NS}: strongly model dependent so far





$R_{NS} = 9.1^{+1.3}_{-1.5}$ km (90%-confidence)
Rutledge/Guillot, ApJ772 (2013)

WFF: Wiringa/Fiks/Fabrocini, PRC38, 1010 (1988)

- R_{NS}: Determined by Esym around 2rho0 (Lattimer&Prakash)
- WFF1 has a soft EOS: K_0=209 MeV, E_{sym} ≈26 MeV, L ≈ 60 MeV (estimates)
- WFF1 has a soft Esym around 2rho0 (Esym(2rho0)~35 MeV, L(2rho0)~20 MeV)

Our results: $E_{sym}(2\rho_0) = 40.2 \pm 14.7$ MeV, $L(2\rho_0) = 8.8 \pm 156.6$ MeV

Outline

- The symmetry energy (Esym)
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Phase Diagram of Strong Interaction Matter

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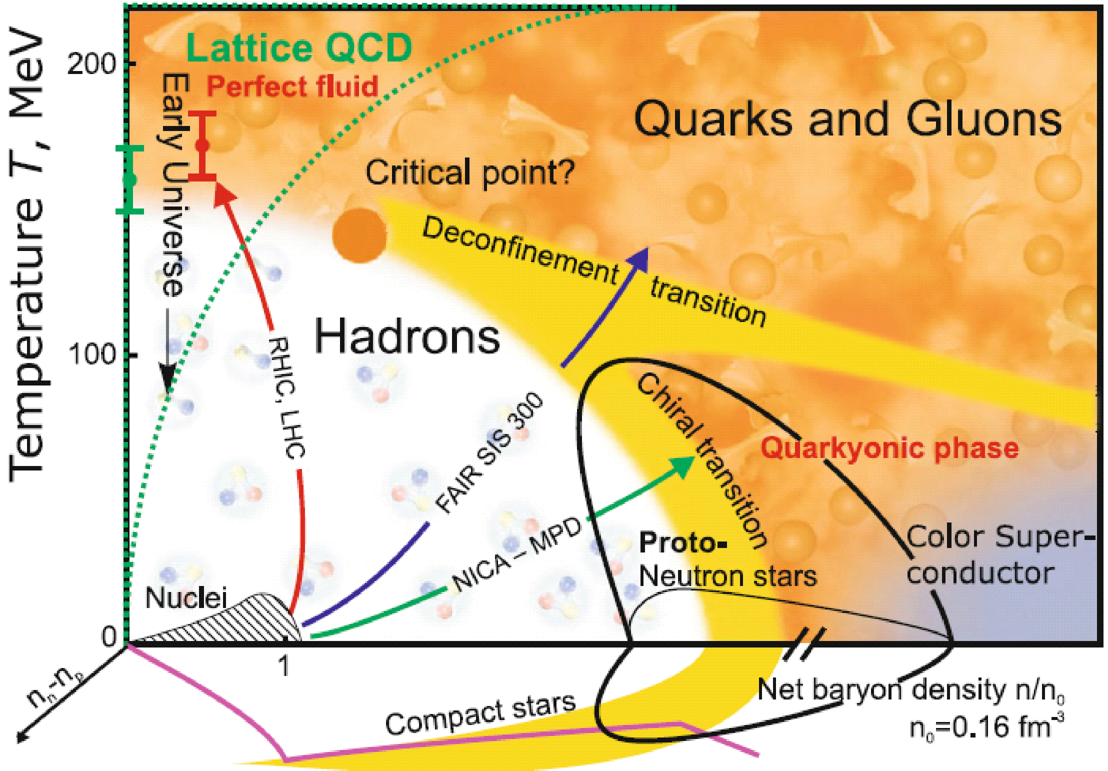
QCD Phase Diagram in 3D: density, temperature, and isospin

V.E. Fortov, Extreme States of Matter – on Earth and in the Cosmos, Springer-Verlag Berlin Heidelberg 2011



Quark Matter Symmetry Energy ?

Although we believe we have already known something about nuclear matter Esym, we know little about QM Esym !

-LQCD does not work at finite baryon density while pQCD only works at extremely high baryon density

At extremely high baryon density, the main degree of freedom could be the deconfined quark matter rather than confined baryon matter, and there we should consider quark matter symmetry energy (isospin symmetry is still satisfied). The isopsin asymmetric quark matter could be produced/exist in HIC/Compact stars

Quark Matter Symmetry Energy

P.C. Chu/L.W. Chen, ApJ780, 135(2014)

QUARK MATTER SYMMETRY ENERGY AND QUARK STARS

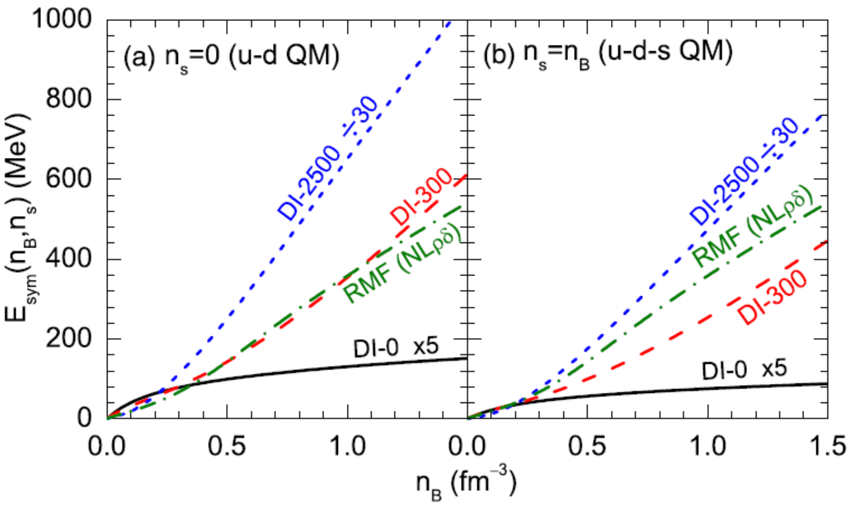
Peng-Cheng Chu[1] and Lie-Wen Chen[1,2]
[1] Department of Physics and Astronomy and Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai 200240, China; lwchen@sjtu.edu.cn
[2] Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China

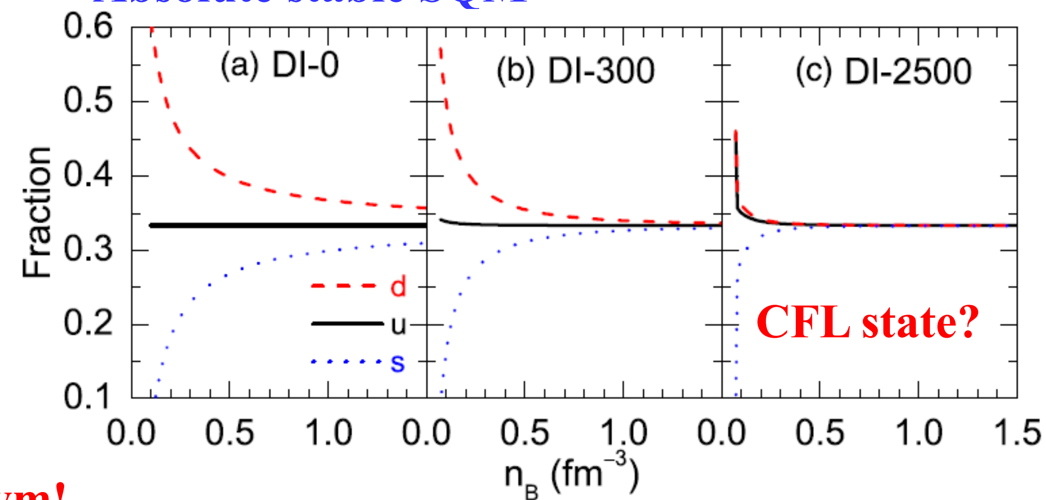
The confined-isospin-density-dependent-mass (CIDDM) model

$$m_q = m_{q0} + m_I + m_{\rm iso} \qquad \delta = 3\frac{n_d - n_u}{n_d + n_u}$$
$$= m_{q0} + \frac{D}{{n_B}^z} - \tau_q \delta D_I n_B^\alpha e^{-\beta n_B}$$

Some basic properties

- **Quark confinement**
- **Asymptotic freedom**
- **Chiral symmetry restored at high density**
- **Isospin symmetry**
- **Absolute stable SQM**

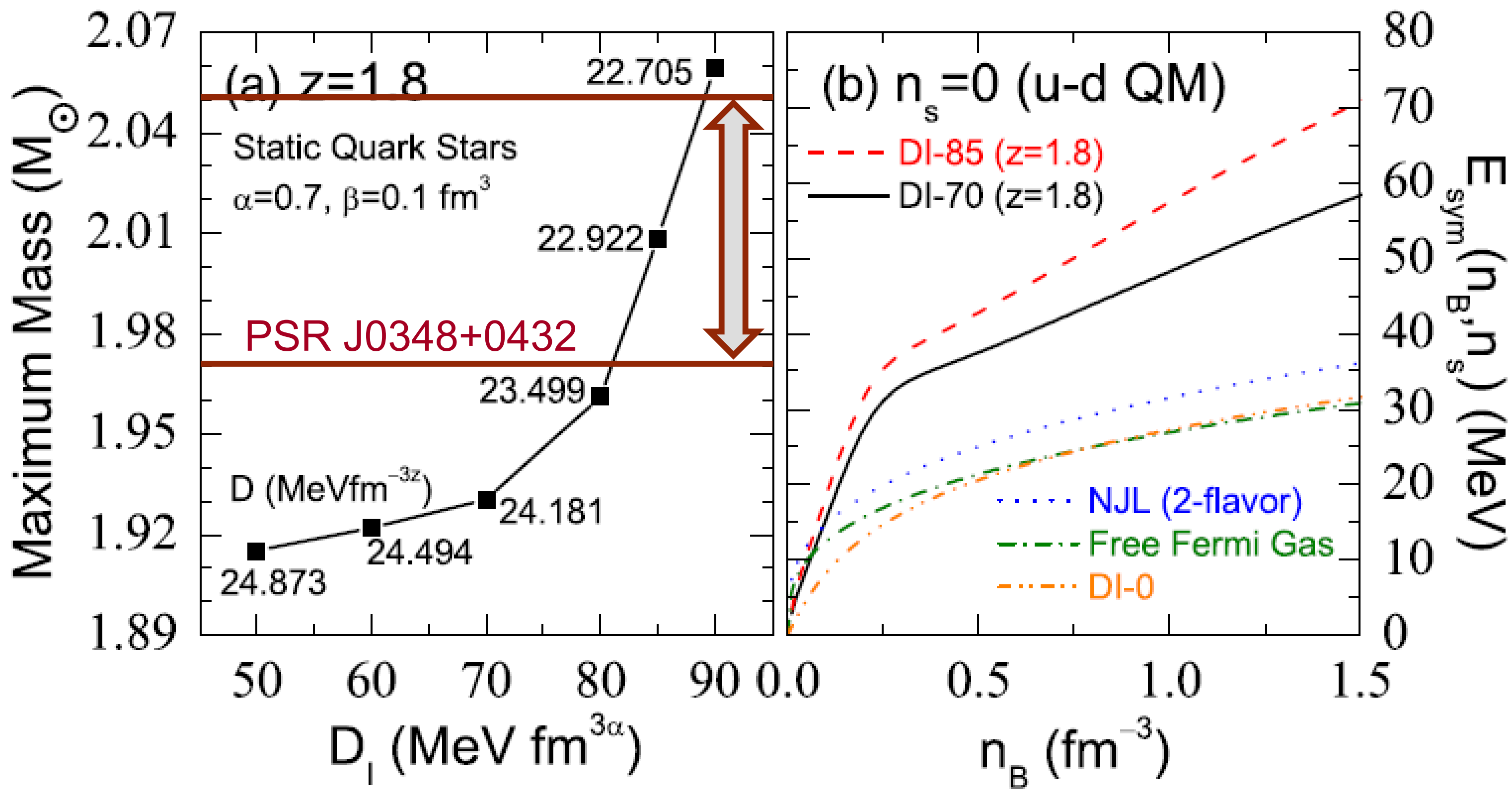




Large isospin asymmetry could exist in Quark Stars and sensitive to the QM Esym!

Quark Matter Symmetry Energy

P.C. Chu/L.W. Chen, ApJ780, 135(2014)



If the recently discovered large mass pulsar PSR J0348+0432 with a mass of 2.01+/-0.04 Msun is a quark star, then we have

Esym (QM) ~ 2 Esym of free quark gas or normal QM in NJL model

But it is still significantly smaller than NM symmetry energy from RMF model

The u and d quarks may have very different interactions in isospin asymmetric QM!

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Summary

- **The symmetry energy $E_{sym}(\rho)$ and its density slope $L(\rho)$ from sub- to supra-saturation density can be essentially determined by three parameters defined at saturation density, i.e., $E_{sym}(\rho_0)$, $L(\rho_0)$, and $K_{sym}(\rho_0)$, implying that three values of $E_{sym}(\rho)$ or $L(\rho)$ can essentially determine $E_{sym}(\rho)$ and $L(\rho)$.**
- **Using E_{sym} (0.11 fm^{-3}) =26.65±0.2 MeV and L(0.11 fm^{-3}) =46.0±4.5 MeV extracted from isotope binding energy difference and neutron skin of Sn isotopes, together with $E_{sym}(\rho_0)$ =32.5±0.5 MeV extracted from FRDM analysis of nuclear binding energy, we obtain:**

  $L(\rho_0)$ =46.7±13.4 MeV and $K_{sym}(\rho_0)$ = -167.1±185.3 MeV

  favoring soft to roughly linear density dependence of $E_{sym}(\rho)$.
- **Information of $E_{sym}(\rho)$ and $L(\rho)$ around saturation density can be very useful to extract information on high density $E_{sym}(\rho)$ and vice verse.**
- **Quark matter symmetry energy could be significantly large than the predicted in conventional models**

Probes of the Symmetry Energy

Promising Probes of the $E_{sym}(\rho)$
(an incomplete list !)

At sub-saturation densities (亚饱和密度行为)

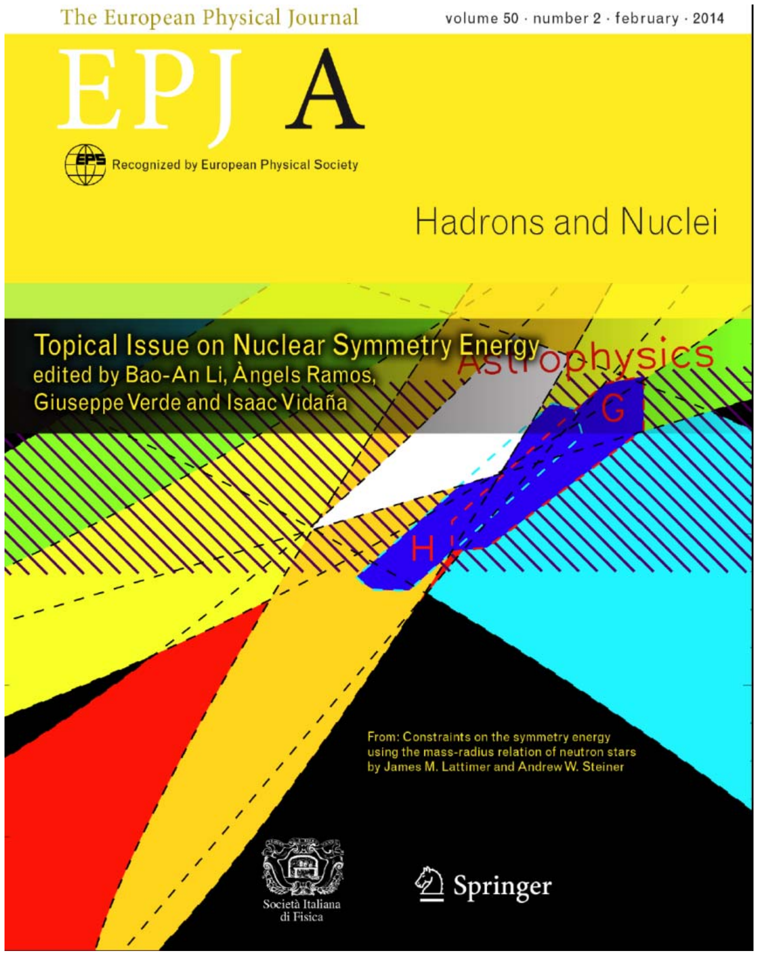
- Sizes of n-skins of unstable nuclei from total reaction cross sections
- Proton-nucleus elastic scattering in inverse kinematics
- Parity violating electron scattering studies of the n-skin in ^{208}Pb
- n/p ratio of FAST, pre-equilibrium nucleons
- Isospin fractionation and isoscaling in nuclear multifragmentation
- Isospin diffusion/transport
- Neutron-proton differential flow
- Neutron-proton correlation functions at low relative momenta
- $t/^{3}He$ ratio
- Hard photon production
- Pigmy/Giant resonances
- Nucleon optical potential

Towards high densities reachable at CSR/Lanzhou, FAIR/GSI, RIKEN, GANIL and, FRIB/MSU (高密度行为)

- π^-/π^+ ratio, K^+/K^0 ratio?
- n-p (t-He3) differential transverse flow
- n/p (t/He3) ratio at mid-rapidity
- Nucleon elliptical flow at high transverse momenta
- n/p (t/He3) ratio of squeeze-out emission

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

Probes of the Symmetry Energy



Eur. Phys. J. A (2014) **50**: 37
DOI 10.1140/epja/i2014-14037-6
THE EUROPEAN PHYSICAL JOURNAL A

Review

Probing nuclear symmetry energy at high densities using pion, kaon, eta and photon productions in heavy-ion collisions*

Zhi-Gang Xiao[1,2,a], Gao-Chan Yong[3], Lie-Wen Chen[4], Bao-An Li[5], Ming Zhang[6], Guo-Qing Xiao[3], and Nu Xu[7]

[1] Department of Physics, Tsinghua University, Beijing 100084, China
[2] Collaborative Innovation Center of Quantum Matter, Beijing, China
[3] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China

Eur. Phys. J. A (2014) **50**: 29
DOI 10.1140/epja/i2014-14029-6
THE EUROPEAN PHYSICAL JOURNAL A

Review

Probing isospin- and momentum-dependent nuclear effective interactions in neutron-rich matter*

Lie-Wen Chen[1,2,a], Che Ming Ko[3], Bao-An Li[4,5], Chang Xu[6], and Jun Xu[7]

[1] Department of Physics and Astronomy and Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai 200240, China
[2] Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China
[3] Cyclotron Institute and Department of Physics and Astronomy, Texas A & M University, College Station, TX 77843-3366, USA

While there are so many Esym probes, high quality experimental data (from both low and high incident energies) are extremely important !!!

Theoretically, the model dependence of the Esym probes is another big challenge (Transport 2014, Shanghai; ……)

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De-Hua Wen (SCUT, Guanzhou)
Zhi-Gang Xiao (Tsinghua, Beijing)
Chang Xu (NJU, Nanjing)
Jun Xu (SINAP, CAS, Shanghai)
Gao-Chan Yong (IMP, Lanzhou)
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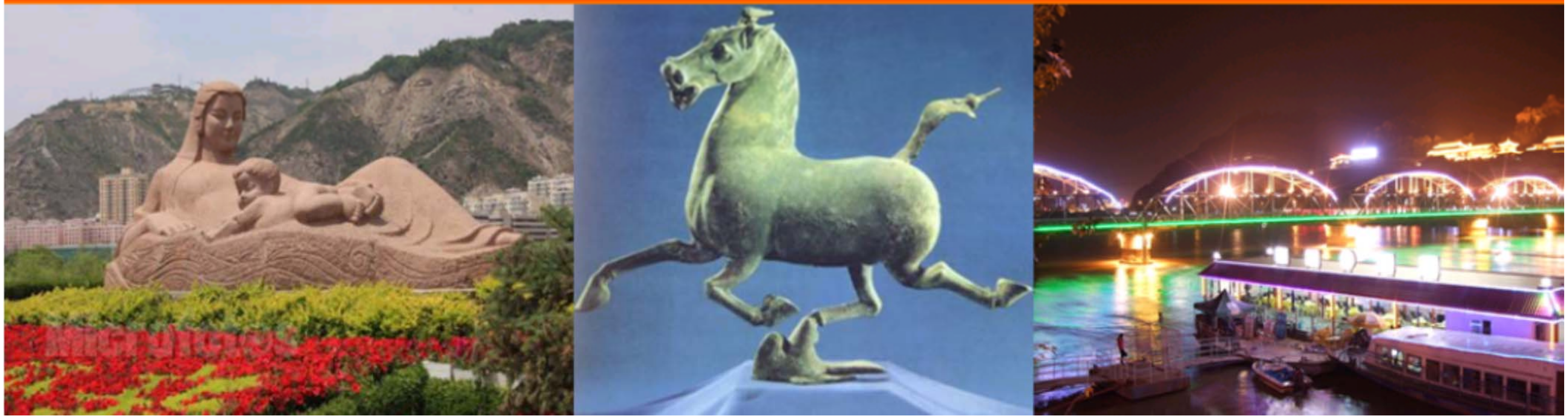
IWND2014, Lanzhou, China

The 4th International Workshop on Nuclear Dynamics in heavy-ion reactions (IWND2014) (August 15-19, 2014, Lanzhou, China)



General information

"The International Workshop on Nuclear Dynamics in Heavy-Ion Reactions (IWND2014)" will be held in Lanzhou, China, on **Aug 15-19, 2014**. The topics of this workshop include recent progress on nuclear dynamics as follows:

1. Heavy-Ion Nuclear Reaction Dynamics and Isospin Effects
2. Symmetry Energy in Nuclear Matter and Neutron Stars
3. Phase Transitions in Strongly Interacting Matter
4. Reaction Dynamics for Superheavy Elements and Weakly Bound Nuclei
5. Nuclear dynamics induced by protons (anti-protons) and mesons
6. Nuclear Astrophysics

IWND2014, Aug 15-19, 2014
Lanzhou, China

http://iwnd2014.csp.escience.cn/

谢 谢！

Thanks！