High-Density Symmetry Energy and Heavy-Ion Reactions

Bao-An Li & collaborators:

Joshua Edmonson, M. Gearheart, Will Newton, Justin Walker, De-Hua Wen, Chang Xu and Gao-Chan Yong, Texas A&M University-Commerce
Lie-Wen Chen and Hongru Ma, Shanghai Jiao Tong University
Plamen G. Krastev, San Diego State University
Che-Ming Ko and Jun Xu, Texas A&M University, College Station
Wei-Zhou Jiang, Southeast University, Nanjing, China
Zhigang Xiao and Ming Zhang, Tsinghua University, China
Xunchao Zhang and Wei Zuo, Institute of Modern Physics, China
Champak B. Das, Subal Das Gupta and Charles Gale, McGill University

Outline:

1. Why is the high-density symmetry energy very uncertain? Why is it important?

2. How to probe the high-density symmetry energy with heavy-ion reactions?

3. Circumstantial evidence for a super-soft symmetry energy from the FOPI/GSI pion production data and its astrophysical implications

What is the Equation of State of neutron-rich nuclear matter?

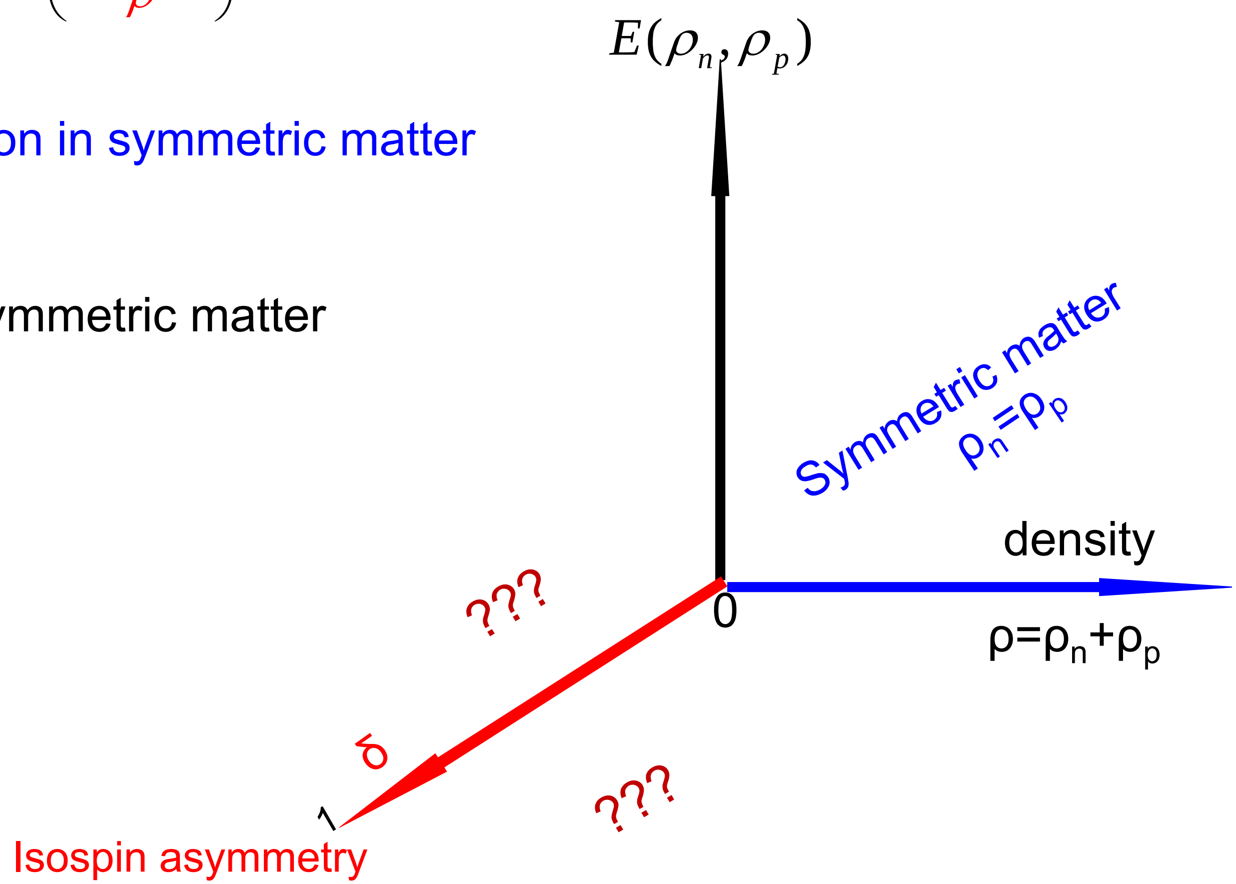
$$E_{sym}(\rho) = \frac{1}{2}\frac{\partial^2 E}{\partial \delta^2} \approx E(\rho)_{\text{pure neutron matter}} - E(\rho)_{\text{symmetric nuclear matter}}$$

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 per nucleon in asymmetric matter



What are the most important underlying physics determining the symmetry energy at high densities?

Based on the Fermi gas model (Ch. 6) and properties of nuclear matter (Ch. 8) of the textbook:
***Structure of the nucleus by M.A. Preston and R.K. Bhaduri* (1975)**

$$E_{sym}(\rho) = \frac{1}{3}t(k_F) + \frac{1}{6}\frac{\partial U_0}{\partial k}|_{k_F} \cdot k_F + U_{sym}(k_F)$$

Kinetic Isoscalar Isovector

$$U_{n/p} = U_0 \pm U_{sym}\delta$$

$$U_0 = \frac{1}{2}(U_n + U_p) = \frac{1}{4}(3u_{T1} + u_{T0}) \quad \text{(Isoscalar single particle potential)}$$

$$U_{sym} = \frac{1}{2\delta}(U_n - U_p) = \frac{1}{4}(u_{T1} - u_{T0}) \quad \text{(Isovector or Lane potential)}$$

In coordinate space, in terms of two-body interactions,

$$U_{sym}(\rho) = \frac{1}{8}\rho \int f_{cor}(r)[V_{T1}(r) - V_{T0}(r))]d^3r$$

We are probing the in-medium isospin-dependence of strong interactions

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

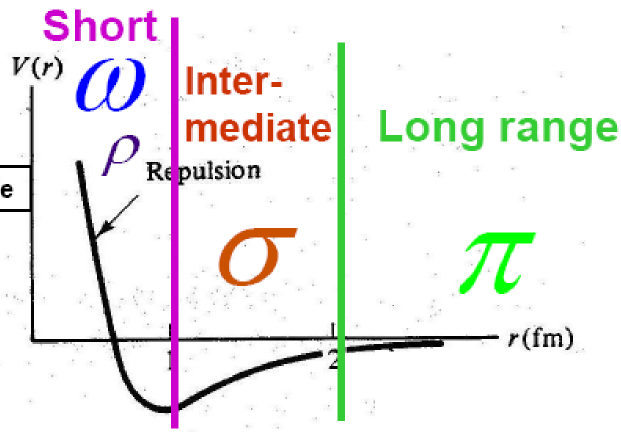
$$V_{T1} = V_{nn} = V_{pp} = V_{np} \quad \text{(charge independence in the T=1 state)}$$

Isospin dependence of the 3-body force and 2-body tensor force due to the ρ exchange

Chang Xu and Bao-An Li, ArXiv: 0910.4803

The short and long range tensor force

Lecture notes of R. Machleidt
at the 2005 RIKEN summer school



Central force

Tensor force π ρ

Spin-orbit force ω σ

$\pi(138)$ $$V_\pi = \frac{f_{\pi NN}^2}{3m_\pi^2}\frac{\vec{q}^2}{\vec{q}^2+m_\pi^2}\left[-\vec{\sigma}_1\cdot\vec{\sigma}_2 - S_{12}(\hat{q})\right]\vec{\tau}_1\cdot\vec{\tau}_2$$ 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

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

$$V_T^\rho(r) = \frac{f_{N_\rho}^2 m_\rho}{4\pi}\tau_1\cdot\tau_2(S_{12}[\frac{e^{-m_\rho r}}{(m_\rho r)^3} + \frac{e^{-m_\rho r}}{(m_\rho r)^2} + \frac{e^{-m_\rho r}}{3m_\rho r}]$$

$$V_T^\pi(r) = \frac{f_{N_\pi}^2 m_\pi}{4\pi}\tau_1\cdot\tau_2(-S_{12}[\frac{e^{-m_\pi r}}{(m_\pi r)^3} + \frac{e^{-m_\pi r}}{(m_\pi r)^2} + \frac{e^{-m_\pi r}}{3m_\pi r}].$$

TWO-BODY AND THREE-BODY EFFECTIVE INTERACTIONS IN NUCLEI †

Nuclear Physics **A301** (1978) 336–348

NAOKI ONISHI †† and J. W. NEGELE †††

D. Vautherin and D.M.Brink, Phys.Rev.C5, 626 (1972)

E. Chabanat [a], P. Bonche [b], P. Haensel [c], J. Meyer [a,1], R. Schaeffer [b]

Nuclear Physics A 627 (1997) 710–746

+ MANY other papers starting from the same 3-body force,

$$V_3(\xi_1\xi_2\xi_3) = t_3\delta(\mathbf{r}_1-\mathbf{r}_2)\delta(\mathbf{r}_2-\mathbf{r}_3)$$

Necessary to fit the saturation properties of nuclear matter in ALL many-body theories

Reduced to different 2-body force with α=1/3, 2/3, 1, etc

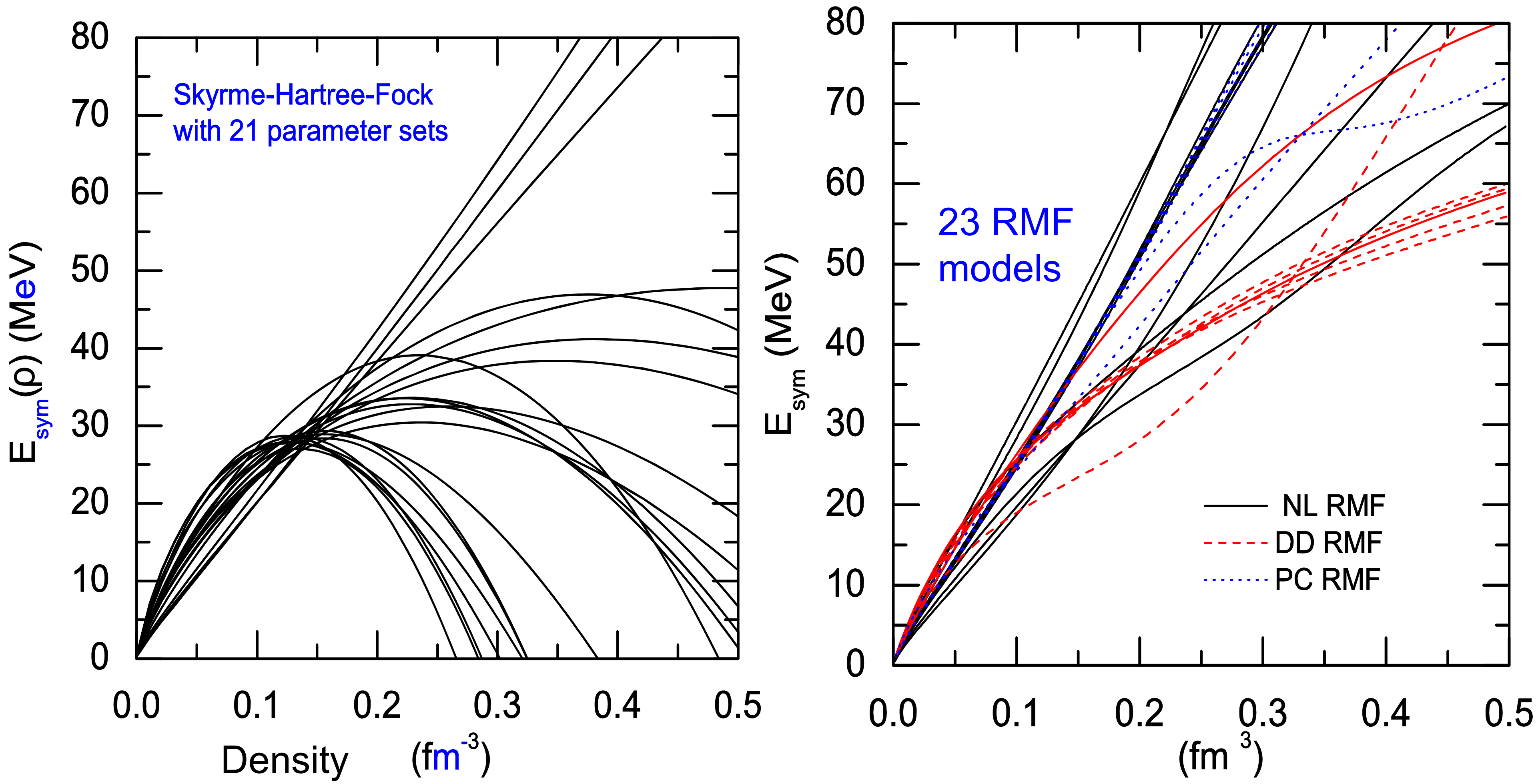
α controls the in-medium many-body effects

$$t_0(1+x_0P_\sigma)\rho^\alpha\left(\frac{r_1+r_2}{2}\right)\delta(r_1-r_2)$$

x_0 controls the mixing of different spin-isospin channels

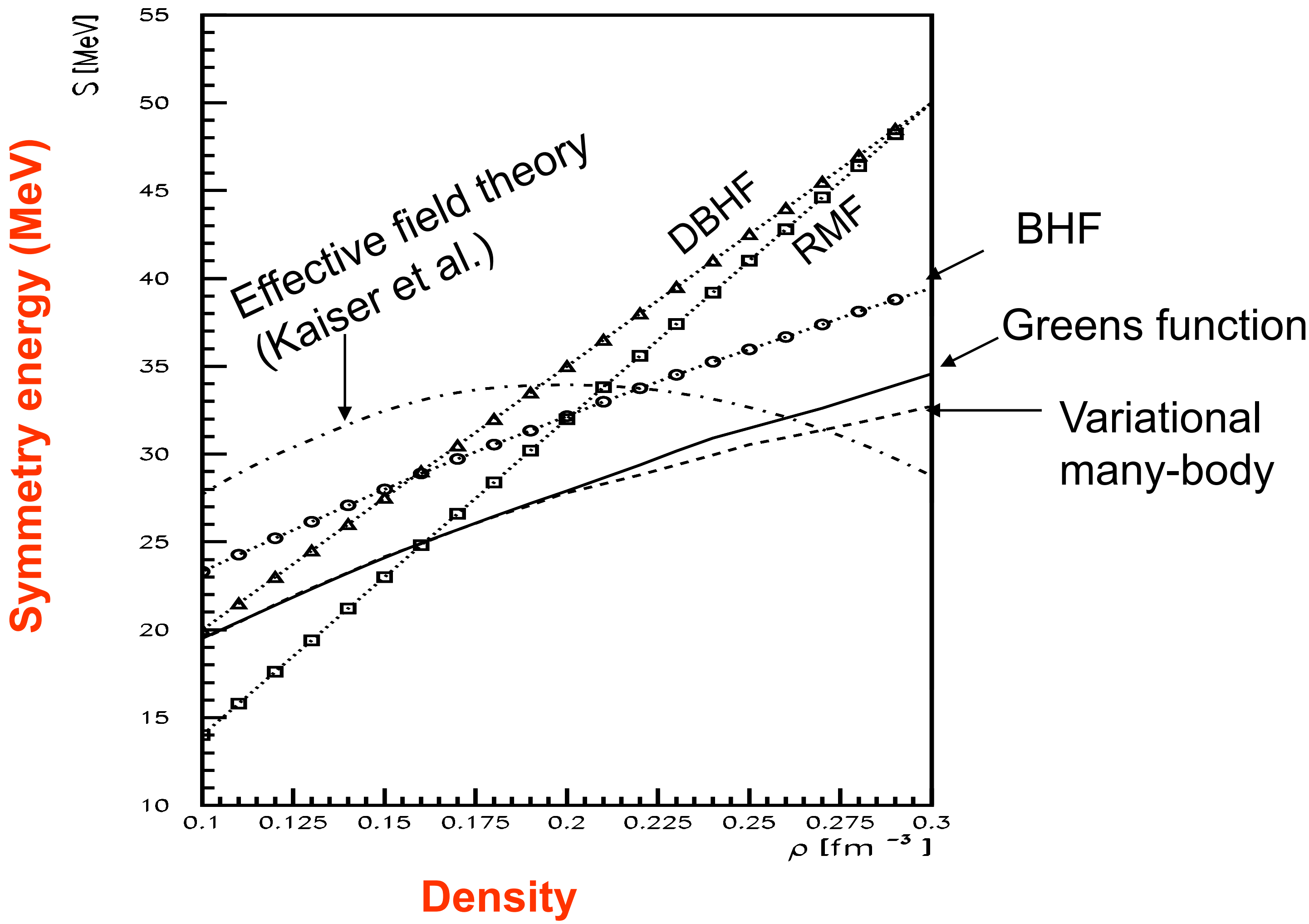
The E_{sym} (ρ) from model predictions using popular effective interactions

Examples:



L.W. Chen, C.M. Ko and B.A. Li, Phys. Rev. C72, 064309 (2005); C76, 054316 (2007).

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



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

Neutron star and β-stable ring-diagram equation of state

Huan Dong and T. T. S. Kuo
*Department of Physics and Astronomy, Stony Brook University, Stony Brook,NY 11794-3800, USA**

R. Machleidt
Department of Physics, University of Idaho, Moscow, Idaho 83844, USA

Phys. Rev. C80, 065803 (2009)

The proton fraction x at ß-equilibrium in proto-neutron stars is determined by

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

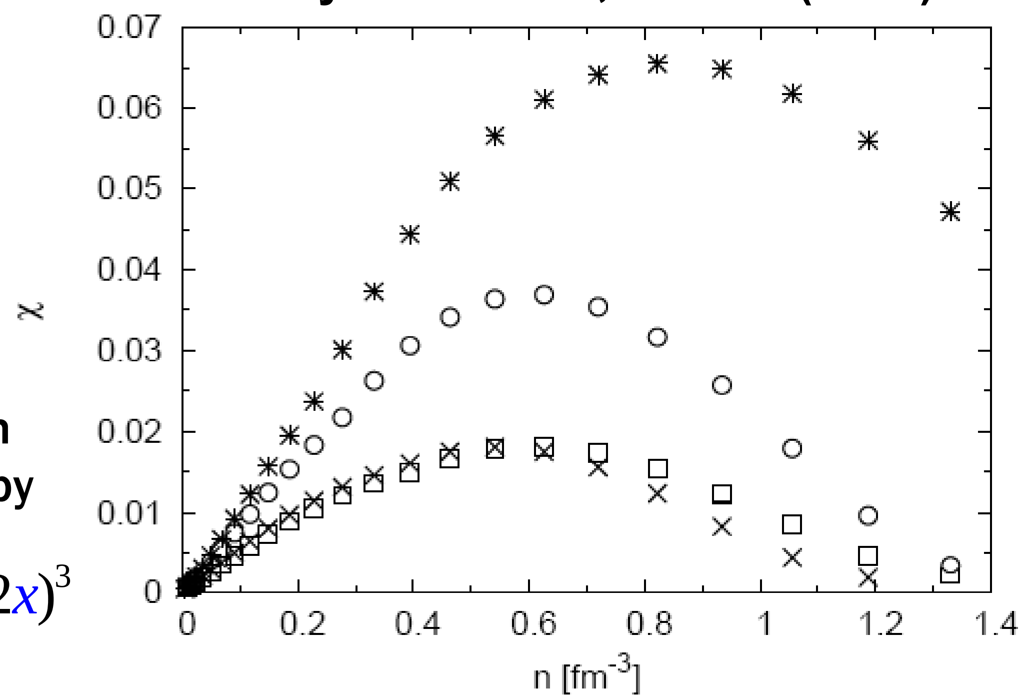
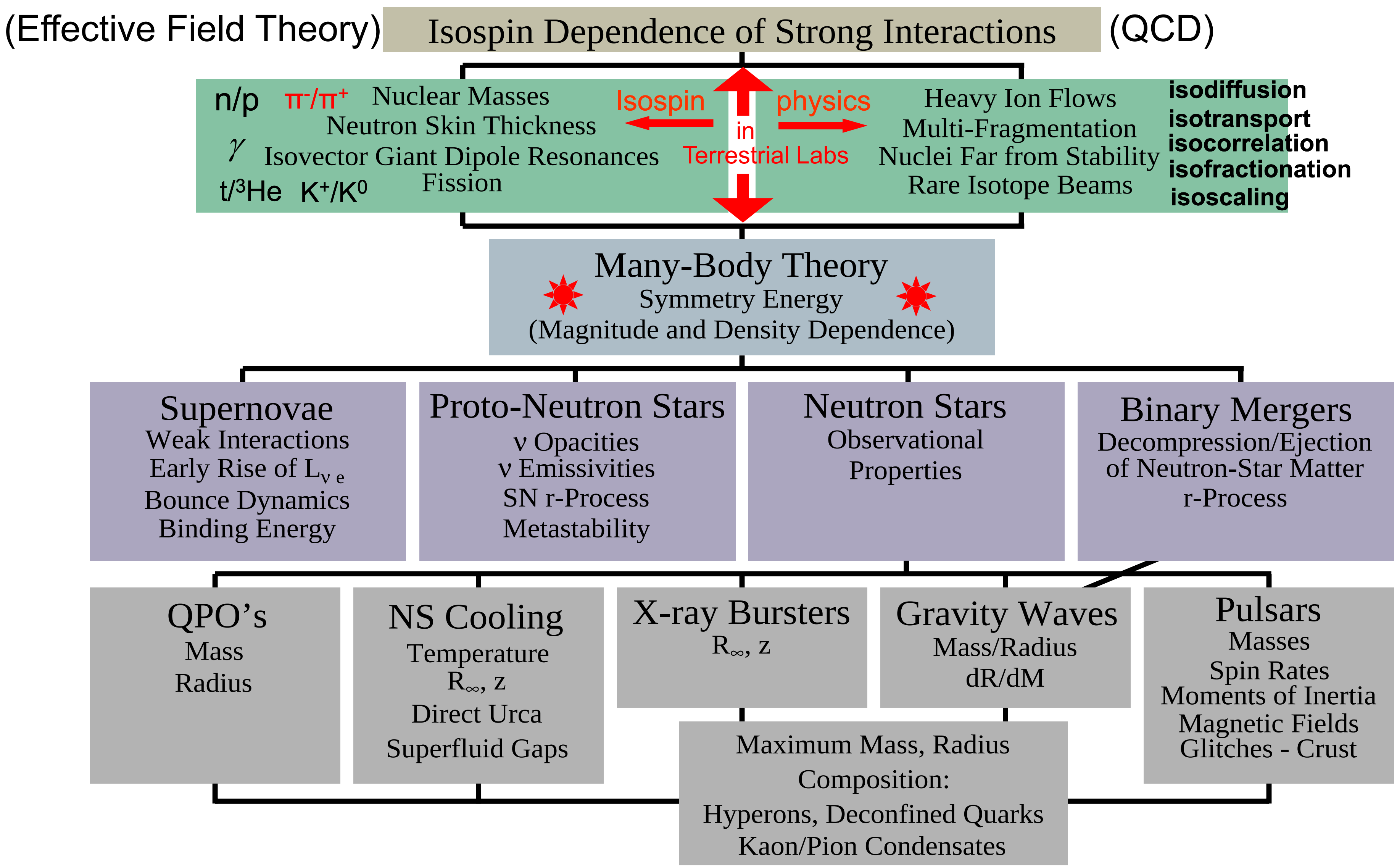


FIG. 9: Proton fraction of β-stable neutron star from realistic NN potentials. Symbols are BonnA($*$), CDBonn($\circ$), Argonne V18 ($\Box$) and Nijemgen ($\times$). The interaction 'V_{low-k} plus TBF' is used.

The multifaceted influence of the isospin dependence of strong interaction and symmetry energy in nuclear physics and astrophysics

J.M. Lattimer and M. Prakash, *Science Vol. 304 (2004) 536-542.*

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



The proton fraction x at ß-equilibrium in proto-neutron stars is determined by

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

The critical proton fraction for direct URCA process to happen is X_p=0.14 for npeμ matter obtained from energy-momentum conservation on the proton Fermi surface

Slow cooling: modified URCA:

$$n+(n,p)\rightarrow p+(n,p)+e^-+\overline{\nu_e}$$

$$p+(n,p)\rightarrow n+(n,p)+e^++\nu_e$$

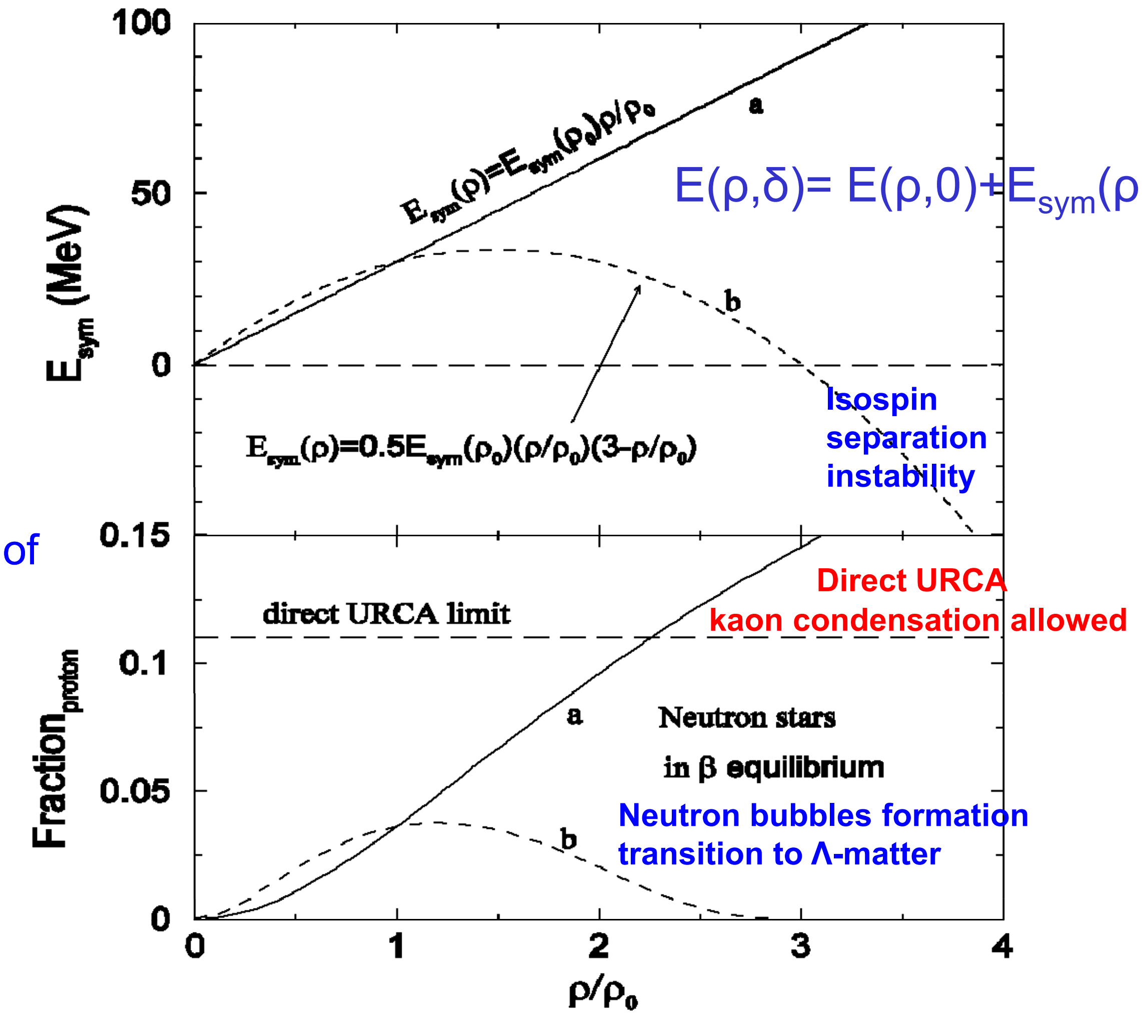
Consequence: long surface thermal emission up to a few million years

Faster cooling by 4 to 5 orders of magnitude: direct URCA

$$n \rightarrow p + e^- + \overline{\nu}_e$$

$$p \rightarrow n + e^+ + \nu_e$$

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



B.A. Li, Nucl. Phys. **A708**, 365 (2002).

Can the symmetry energy become negative at high densities?

Yes, for example, due to the isospin-dependence of the nuclear tensor force

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

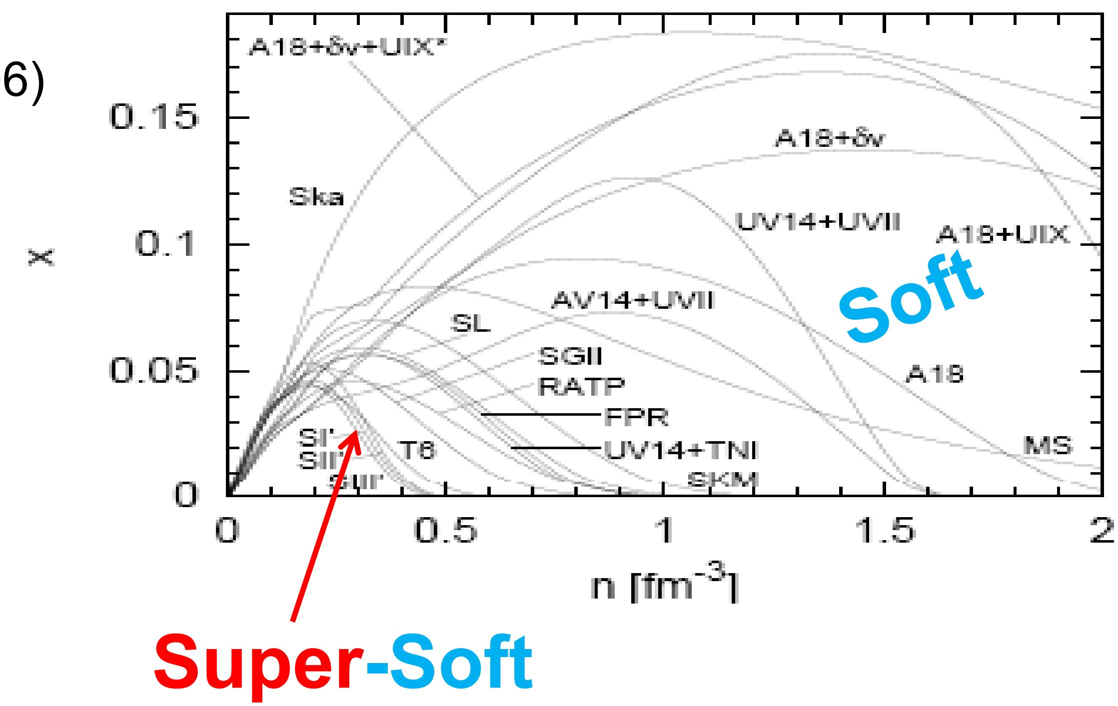
Wiringa R B, Fiks V and Fabrocini A 1988 *Phys. Rev.* C 38 1010

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

Chang Xu and Bao-An Li
ArXiv: 0910.4803

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

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



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

Promising Probes of the $E_{sym}(\rho)$ in Nuclear Reactions

At sub-saturation densities

- **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 at JLab**
- **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**

Towards supra-saturation densities

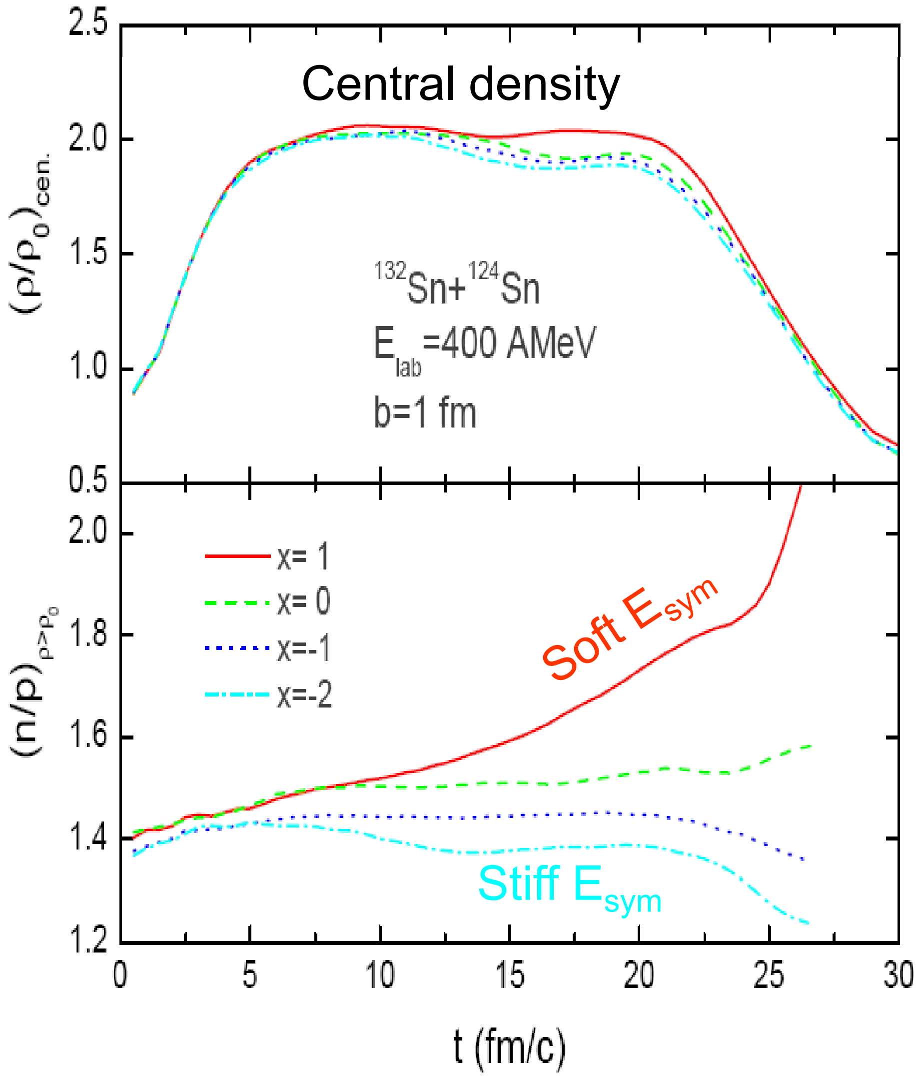
- **π^-/π^+ ratio, K^+/K^0 ?**
- **Neutron-proton differential transverse flow**
- **n/p ratio of squeezed-out nucleons perpendicular to the reaction plane**
- **Nucleon elliptical flow at high transverse momentum**
- **t-^{3}He differential and difference transverse flow**

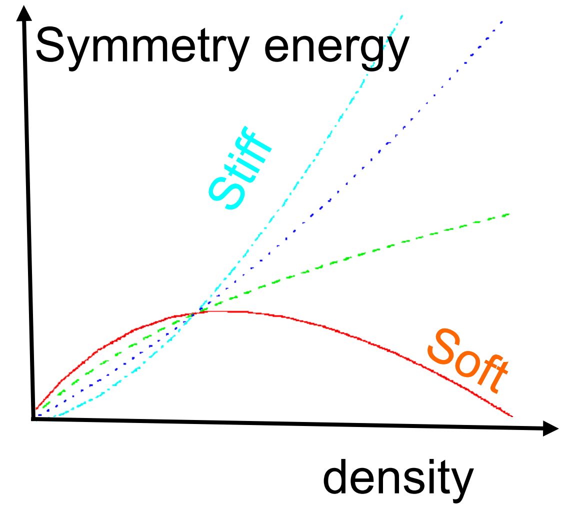
(1) Correlations of multi-observable are important
(2) Detecting neutrons simultaneously with charged particles is critical

B.A. Li, L.W. Chen and C.M. Ko, ***Physics Report 464, 113 (2008)***

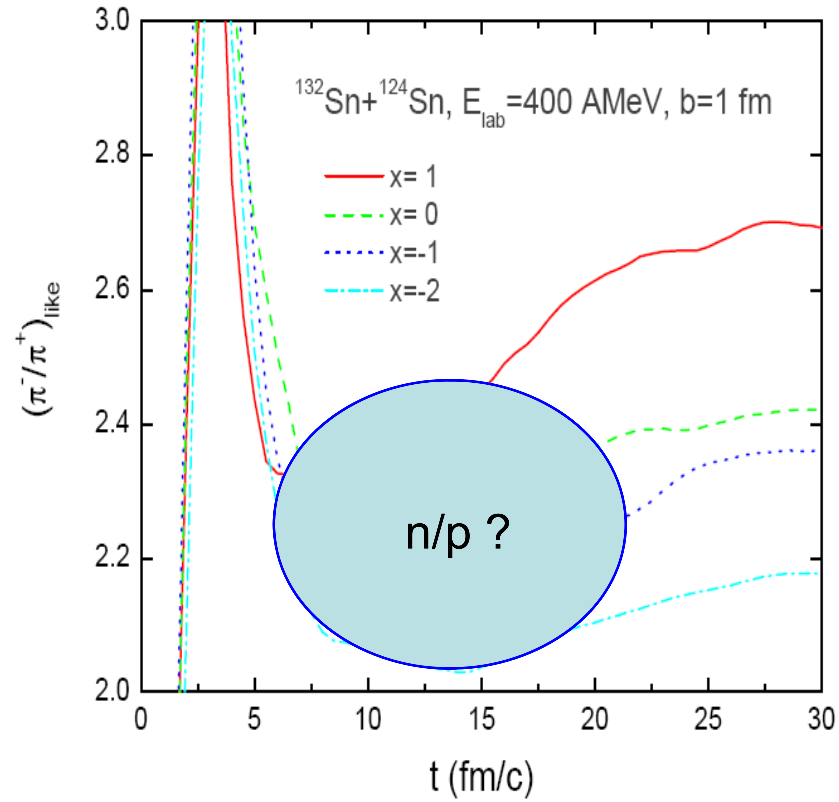
Formation of dense, asymmetric nuclear matter

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





π^-/π^+ probe of dense matter



n/p ratio at supra-normal densities

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)

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

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

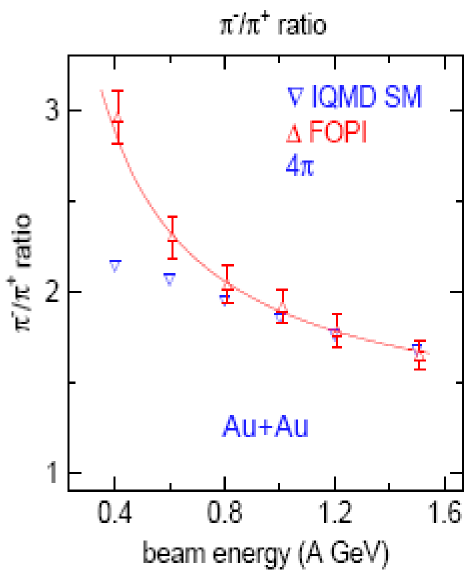
H.R. Jaqaman, A.Z. Mekjian and L. Zamick, PRC (1983) 2782.

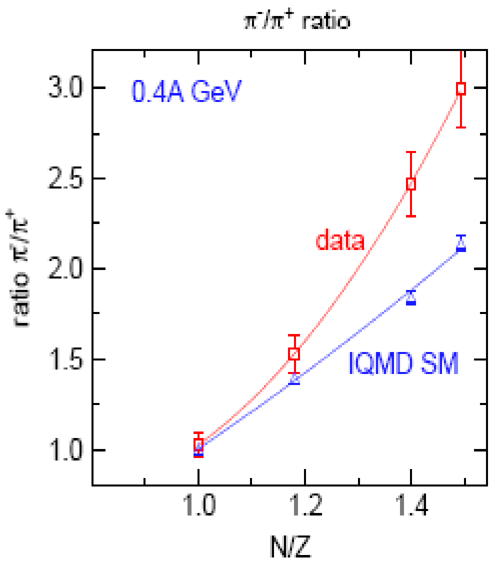
c) Transport models (more realistic approach):

Bao-An Li, Phys. Rev. Lett. 88 (2002) 192701, and several papers by others

Near-threshold π⁻/π⁺ ratio as a probe of symmetry energy at supra-saturation densities

W. Reisdorf et al. for the FOPI collaboration , NPA781 (2007) 459





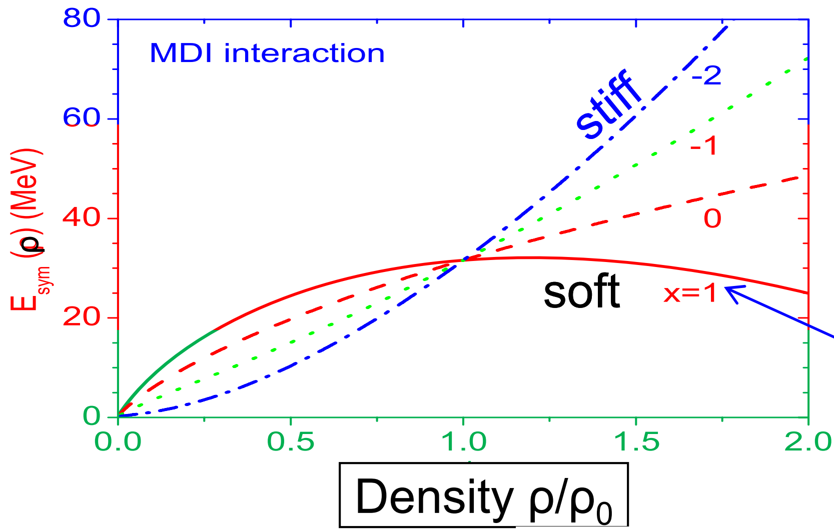
IQMD: Isospin-dependent Quantum Molecular Dynamics
C. Hartnack, Rajeev K. Puri, J. Aichelin, J. Konopka, S.A. Bass, H. Stoecker, W. Greiner
Eur. Phys. J. A1 (1998) 151-169

$$V_{sym}^{ij} = t_6 \frac{1}{\varrho_0} T_{3i} T_{3j} \delta(\vec{r}_i - \vec{r}_j) \quad t_6 = 100\,\mathrm{MeV}$$

$$\text{corresponding to } E_{sym}(\rho) = \frac{100}{8}\frac{\rho}{\rho_0} + (2^{2/3}-1)\frac{3}{5}E_F^0(\frac{\rho}{\rho_0})^{2/3}$$

Indication:
Need a symmetry energy softer than the above
to make the pion production region more neutron-rich!

Symmetry energy and single nucleon potential 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

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

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

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

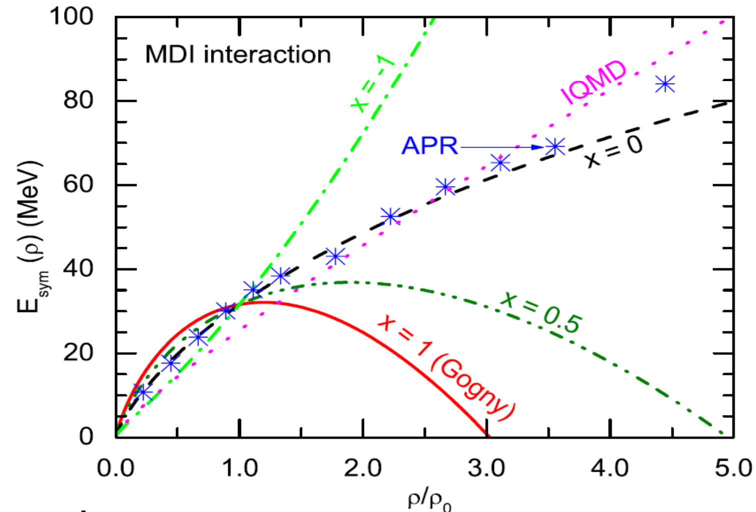
$$\tau,\tau'=\pm\frac{1}{2},\ A_l(x)=-121+\frac{2Bx}{\sigma+1},\ A_u(x)=-96-\frac{2Bx}{\sigma+1},\ K_0=211\,MeV$$

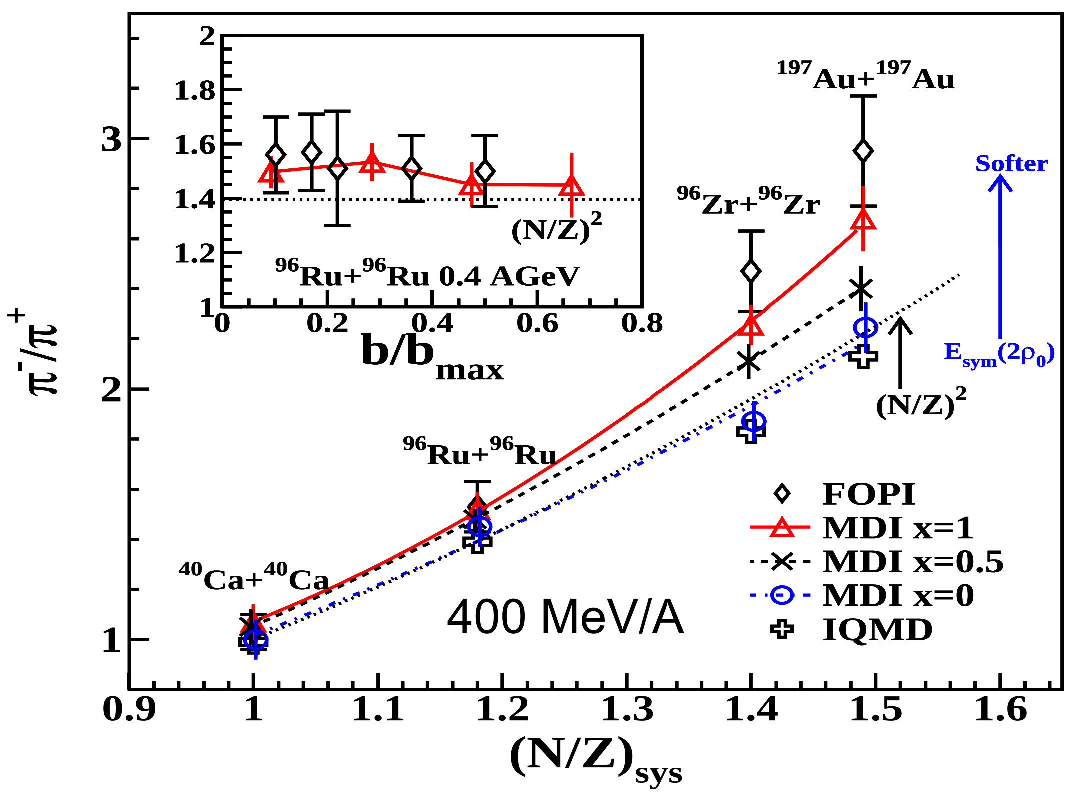
C.B. Das, S. Das Gupta, C. Gale and B.A. Li, PRC 67, 034611 (2003).

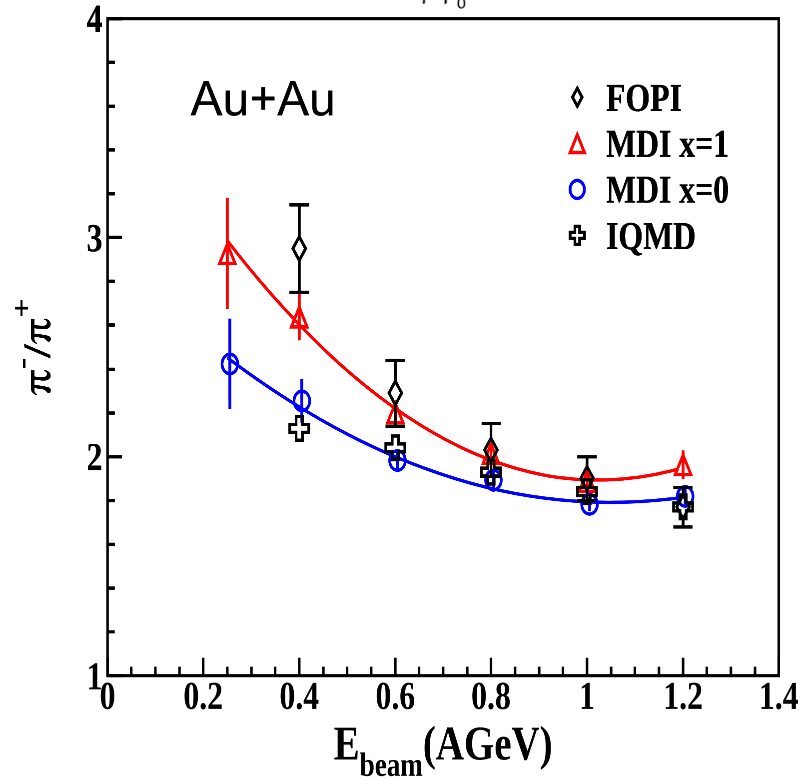
B.A. Li, C.B. Das, S. Das Gupta and C. Gale, PRC **69**, 034614; NPA **735**, 563 (2004).

Circumstantial evidence for a super-soft symmetry energy at high densities

Transport model analysis using IBUU04
Z. Xiao, B.A. Li, L.W. Chen, G.C. Yong and M. Zhang, PRL 102, 062502 (2009)





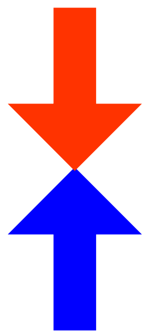


A challenge: how can neutron stars be stable with a super-soft symmetry energy?

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

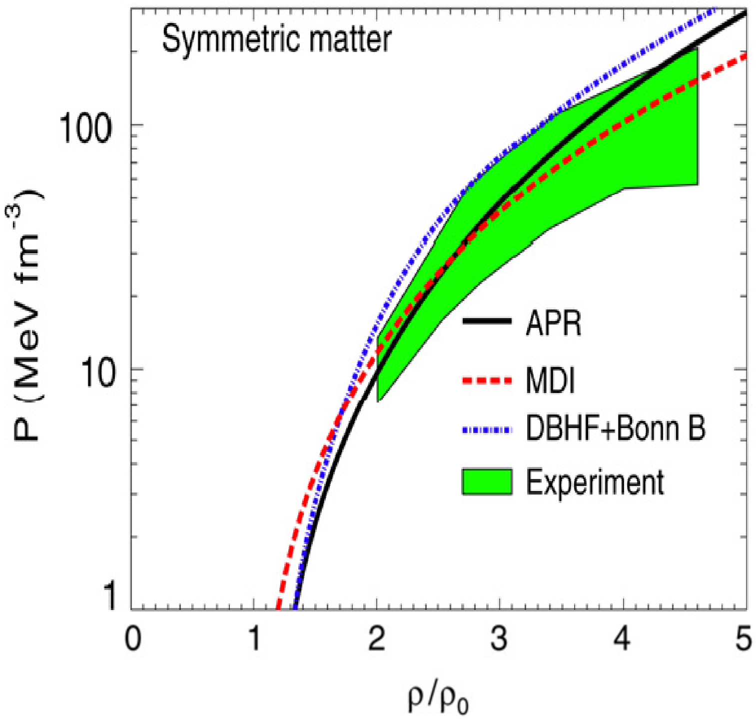
TOV equation: a condition at hydrodynamical equilibrium

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



Gravity

Nuclear pressure



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

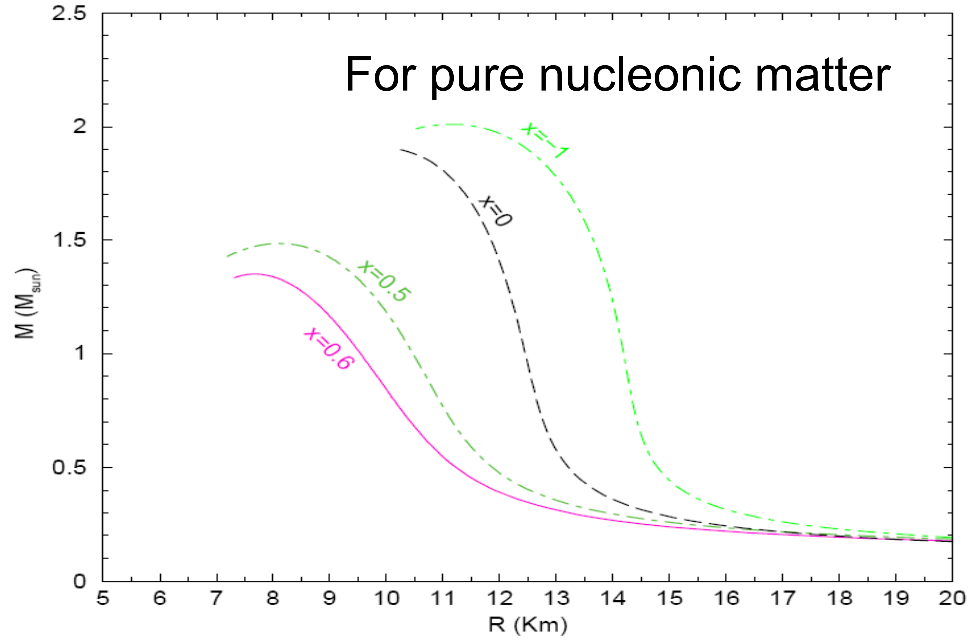
For npe matter

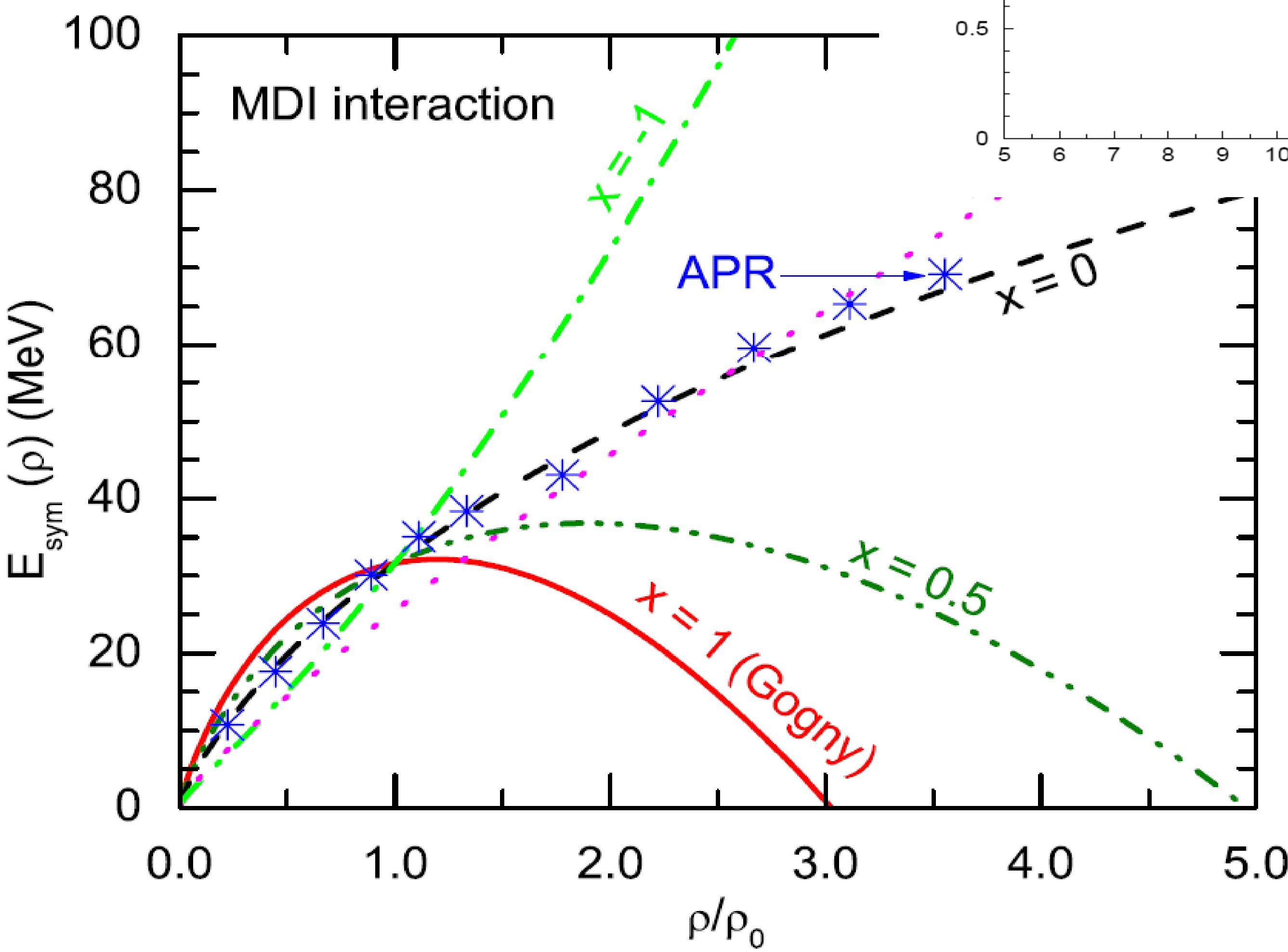
$$P(\rho,\delta) = P_0(\rho) + P_{asy}(\rho,\delta) = \rho^2\left(\frac{\partial E}{\partial \rho}\right)_\delta + \frac{1}{4}\rho_e\mu_e$$

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

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

Astrophysical implications





Using the EOS for symmetric matter consistent with the terrestrial nuclear reaction data up to 5 rho_0,
the softest symmetry energy that the TOV is still stable is x=0.93 giving M_max=0.11 solar mass and R=>28 km.

Comments about the super-soft symmetry energy

Unpleasant, unwelcome, annoying !

E. Chabanat, P. Bonche, P. Haensel, J. Meyer, and R. Schaeffer, NPA627, 710 (1997); NPA635, 231 (1998).

Repeated by several others in some other papers

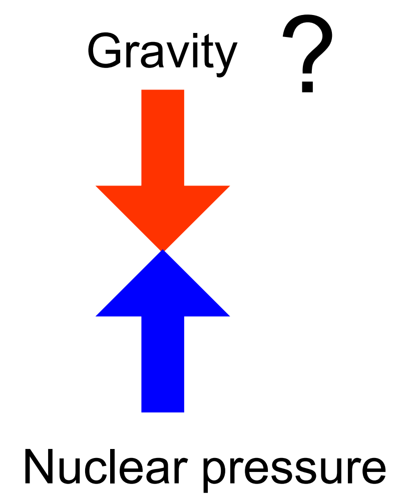
Unphysical !

Norman Glennding, Compact Stars, Springer, ISBN: 0387989773.

Quoted by several people in a number of papers

You are drunk !

Some participants of the 26th Winter Workshop on Nuclear Dynamics in Jamaica



Do we really know gravity at short distance?

Not at all!

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)

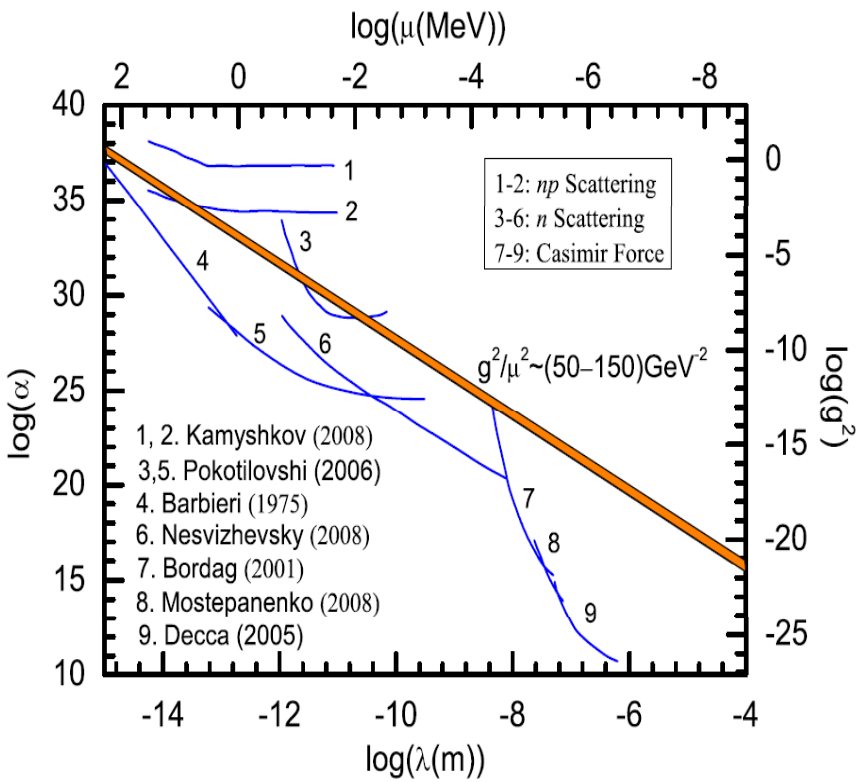
In terms of the gravitational potential

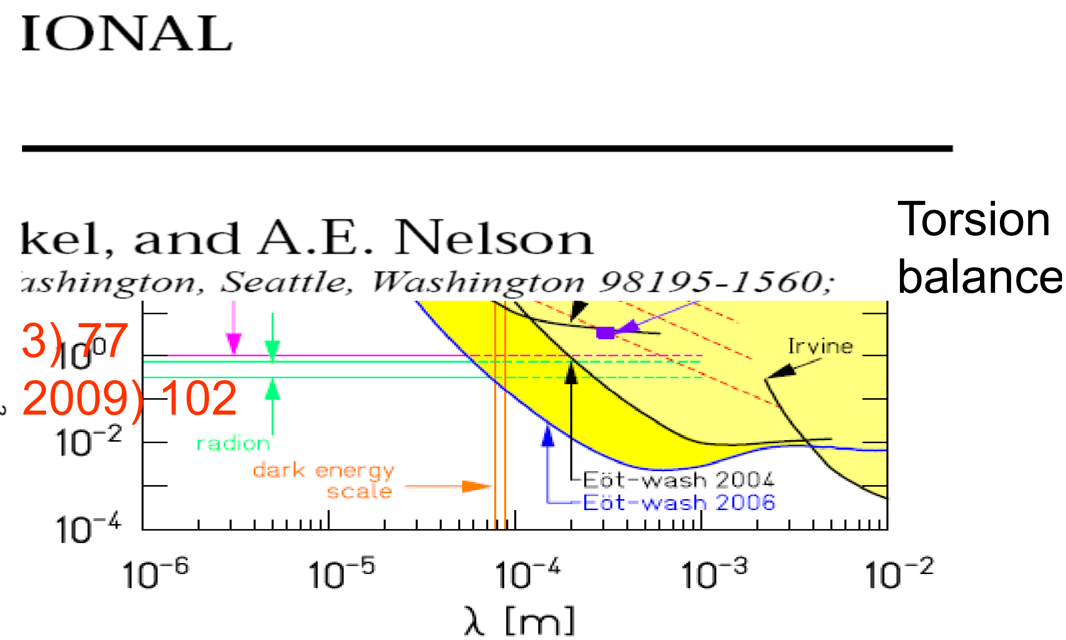
$$V(r) = -G\frac{m_1 m_2}{r}[1 + \alpha e^{-r/\lambda}].$$

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).



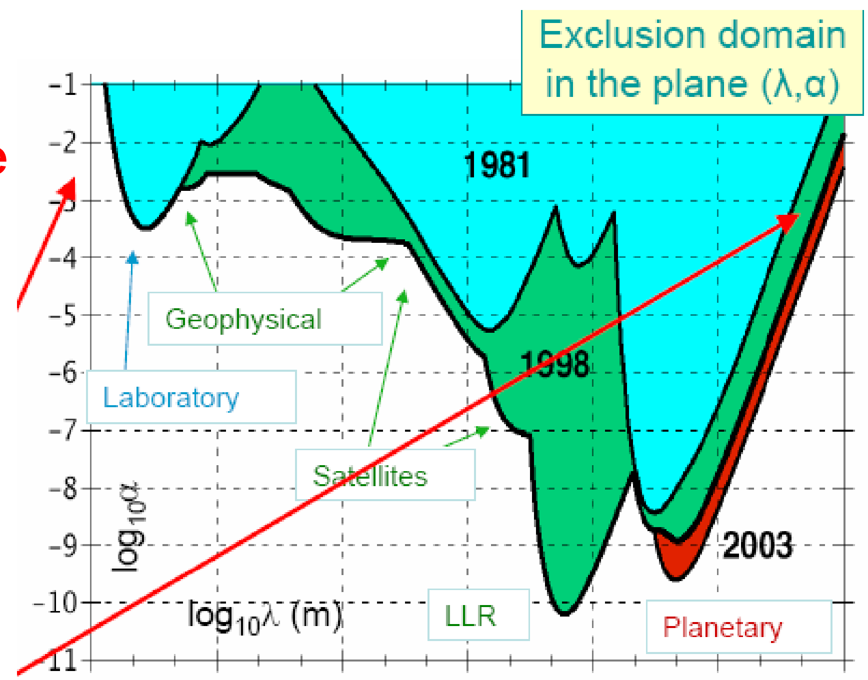


Upper limits on the strength α and range λ of the Yukawa term

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)

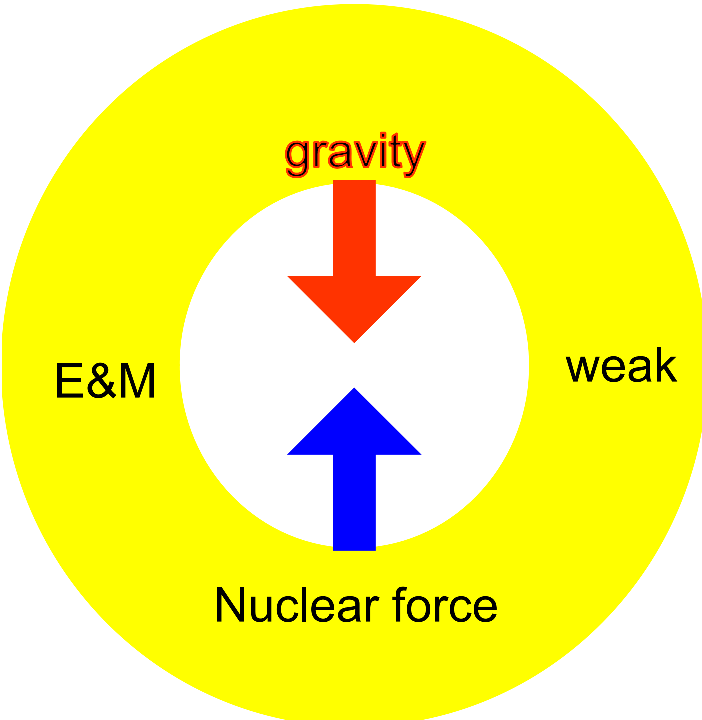
$$V(r) = -G\frac{m_1 m_2}{r}[1 + \alpha e^{-r/\lambda}]$$

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



A motivation of the deep space gravity probe

Neutron stars as a natural testing ground of grand unification theories of fundamental forces?



Stable neutron star
@
β-equilibrium

The eleven questions:

- What is the dark matter?
- What is the nature of the dark energy?
- How did the universe begin?
- What is gravity?
- 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?
- Are there additional spacetime dimensions?
- How were the elements from iron to uranium made?
- Is a new theory of matter and light needed at the highest energies?

Requiring simultaneous solutions in both gravity and strong interaction!
Grand Unified Solutions of Fundamental Problems in Nature!

Influences of the Yukawa term on Neutron Stars

Yasunori Fujii

J. Audouze et al. (eds.), Large Scale Structures of the Universe, 471–477.

I next emphasize that the 5-th force is simply part of the matter system in general relativity. Consequently Einstein's equation remains unchanged. The only change one expects to occur is in the equation of state. And probably the first reasonable thing to do is to appeal to the mean field approximation.[11]

$$\varepsilon_{\mathrm{UB}} = \frac{1}{2V}\int \rho(\vec{x}_1)\frac{g^2}{4\pi}\frac{e^{-\mu r}}{r}\rho(\vec{x}_2)d\vec{x}_1 d\vec{x}_2 = \frac{1}{2}\frac{g^2}{\mu^2}\rho^2,$$

$$P_{UB} = \frac{1}{2}\frac{g^2\rho^2}{\mu^2}\left(1 - \frac{2\rho}{\mu}\frac{\partial\mu}{\partial\rho}\right).$$

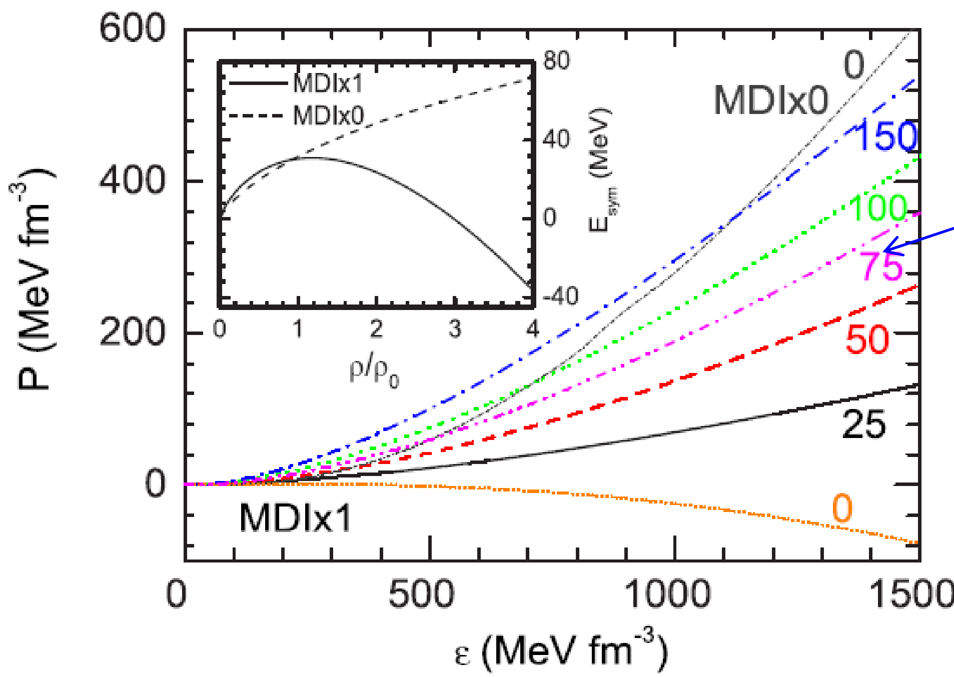
Assuming a constant boson mass independent of the density, the extra pressure is then

$$P_{UB} = \varepsilon_{UB} = \frac{1}{2}\frac{g^2}{\mu^2}\rho^2 \qquad (4)$$

Supersoft Symmetry Energy Encountering Non-Newtonian Gravity in Neutron Stars

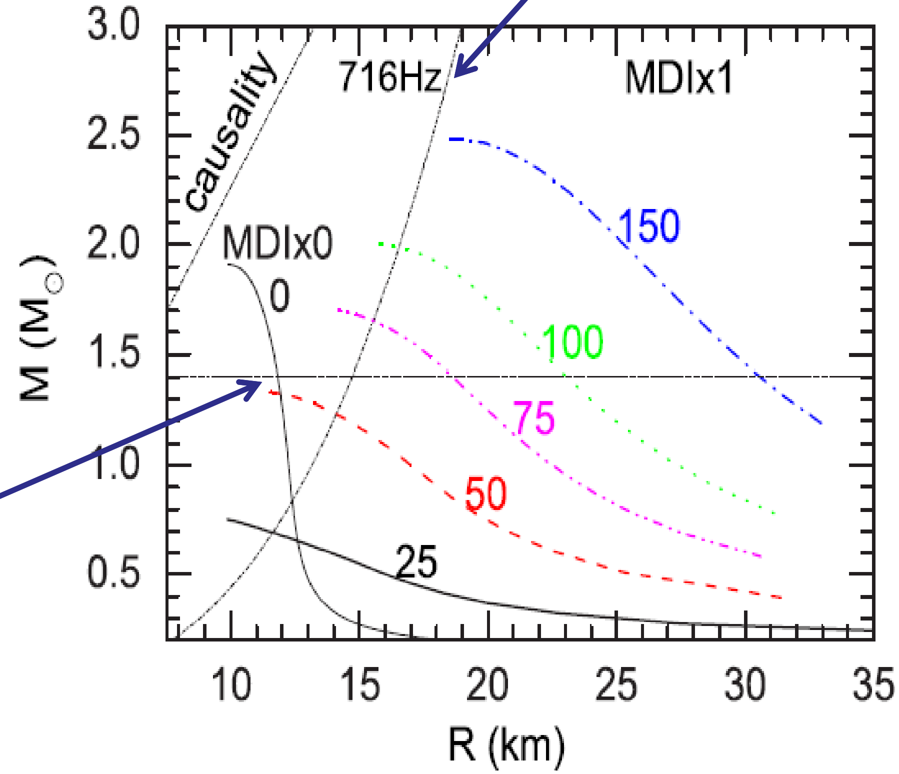
De-Hua Wen, Bao-An Li and Lie-Wen Chen, PRL 103, 211102 (2009)

EOS including the Yukawa contribution



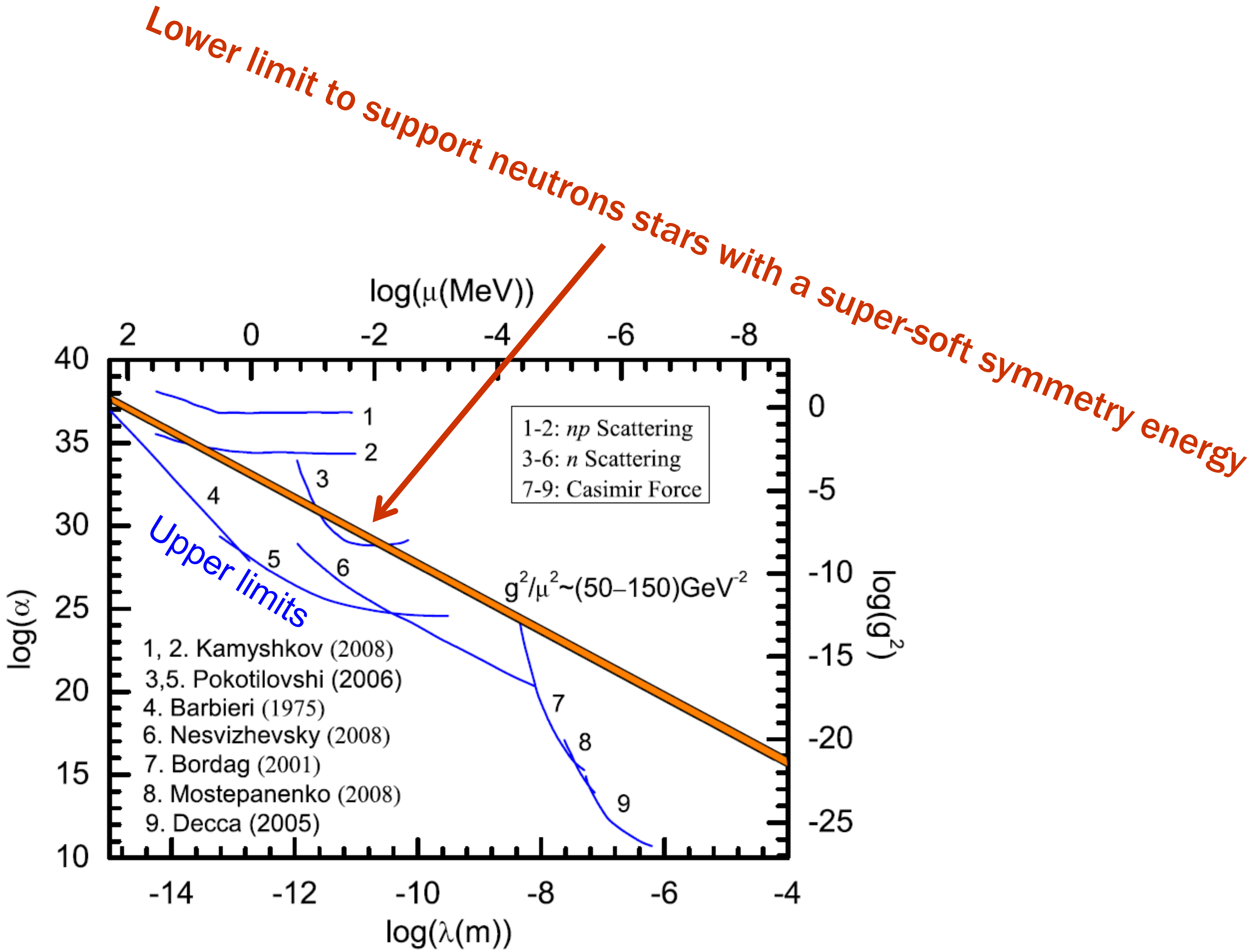
g^2/μ^2

Mass-shedding limit



$g^2/\mu^2 = 50\,\mathrm{GeV}^{-2}$ to support

a NS of 1.4Msun and R = 12 km



Lower limit to support neutrons stars with a super-soft symmetry energy
log(μ(MeV))
2
0
-2
-4
-6
-8
40
35
30
25
20
15
10
log(α)
0
-5
-10
-15
-20
-25
log(g²)
-14
-12
-10
-8
-6
-4
log(λ(m))
1-2: np Scattering
3-6: n Scattering
7-9: Casimir Force
g²/μ²~(50–150)GeV⁻²
Upper limits
1, 2. Kamyshkov (2008)
3,5. Pokotilovshi (2006)
4. Barbieri (1975)
6. Nesvizhevsky (2008)
7. Bordag (2001)
8. Mostepanenko (2008)
9. Decca (2005)

Summary

- The high-density nuclear symmetry energy is very uncertain

- Heavy-ion reactions, especially those induced by radioactive beams, are promising tools to constrain the high-density symmetry energy

- Neutron stars are natural testing ground of grand unification theories. High-density symmetry energy, gravity at short distance, possible extra space-time dimensions are all closely related.

The 11th International Conference on Nucleus-Nucleus Collisions (NN2012)

May 27-June 1, 2012
Hyatt Regency, San Antonio, Texas

Local Organizing Committee:

Carlos Bertulani, Cody Folden, Kris Hagel, John Hardy,
Bao-An Li (Co-Chair), Joseph B. Natowitz (Co-Chair),
Ralf Rapp, Livius Trache and Sherry J.Yennello