Probing the nuclear symmetry energy at supra-saturation densities

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Outline:

1. $E_{sym}(\rho_0)$ and L from the isospin dependence of the nucleon global optical potentials

2. Why is the $E_{sym}(\rho)$ so uncertain at supra-saturation densities?
   ……., role of the short-range tensor force, ……….

3. How can neutron stars be stable with super-soft symmetry energies?

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

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

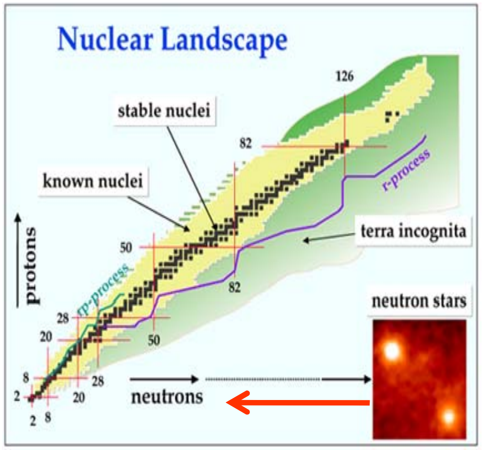
symmetry energy

Isospin asymmetry δ

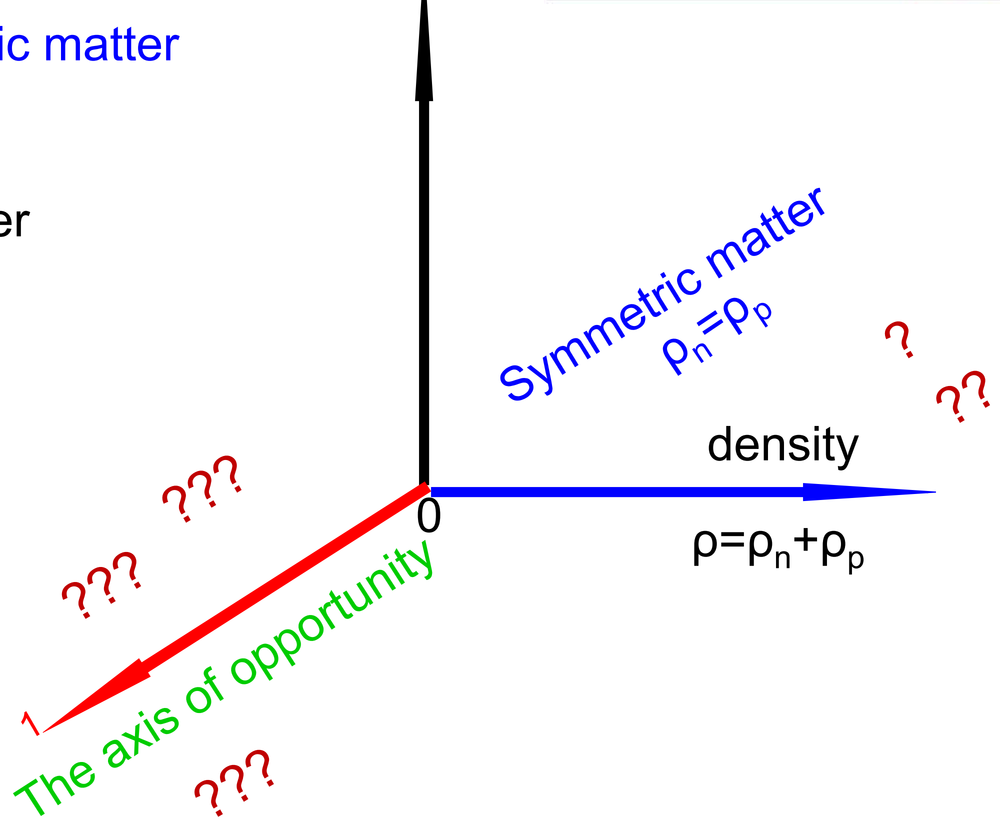
$$E(\rho_n, \rho_p) = E_0(\rho_n = \rho_p) + E_{sym}(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 + o(\delta^4)$$

Energy per nucleon in symmetric matter

Energy per nucleon in asymmetric matter

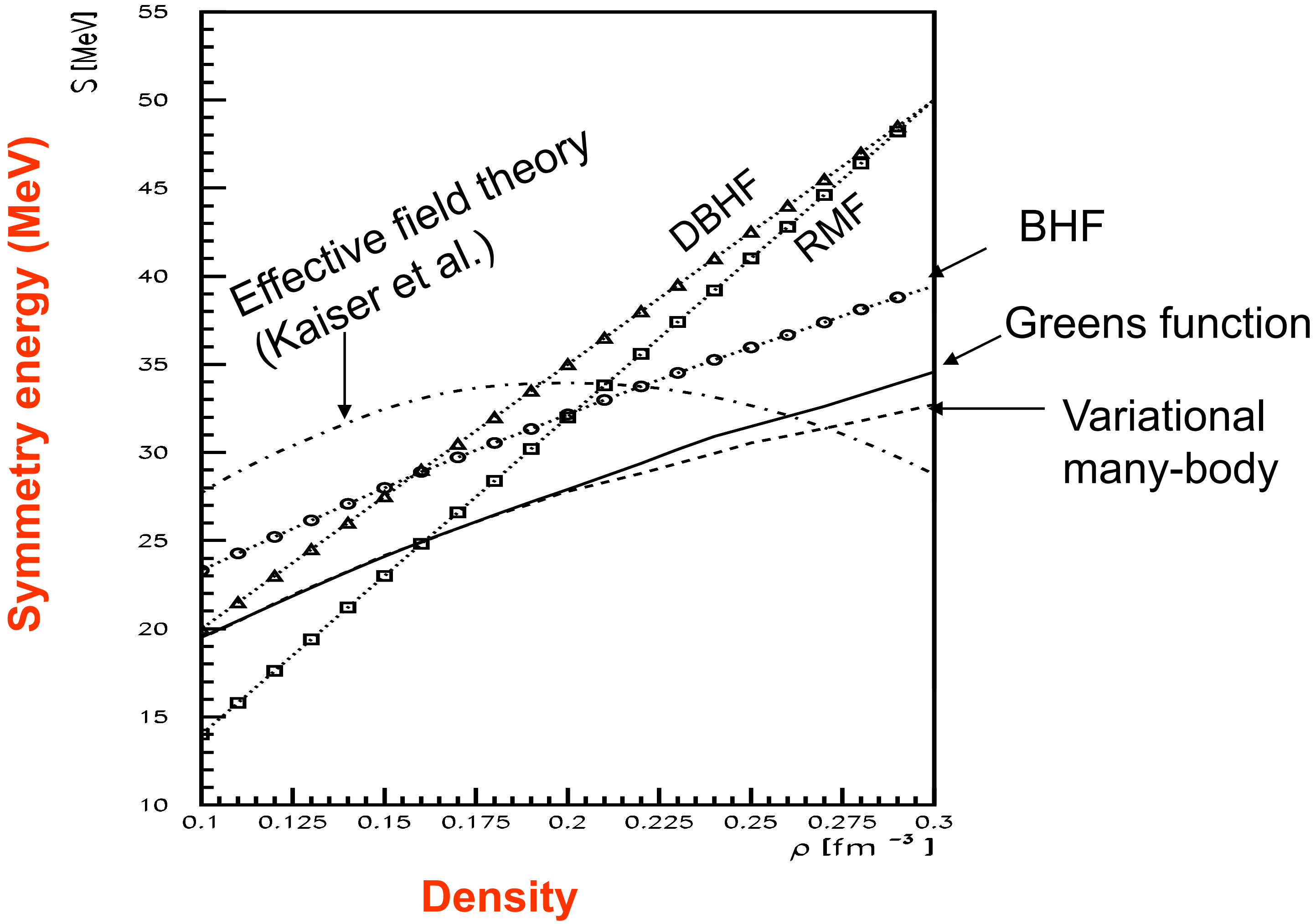


$E(\rho_n, \rho_p)$



Isospin asymmetry

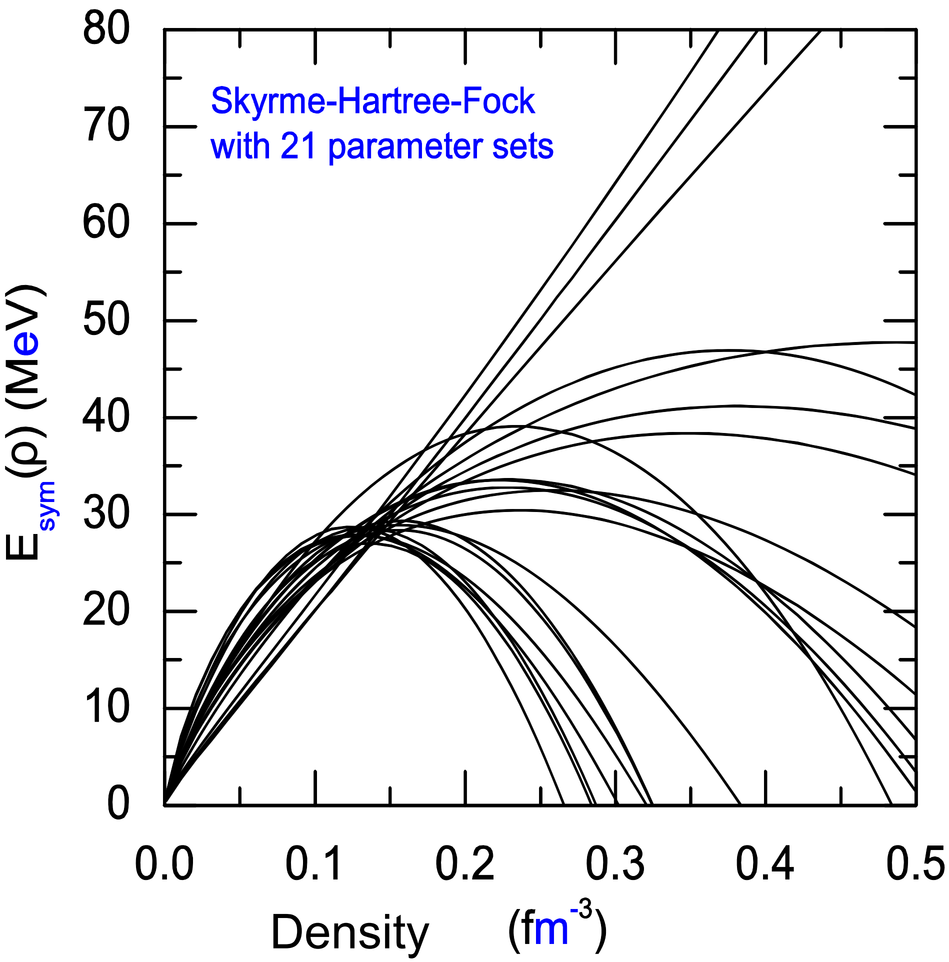
E_{sym} (ρ) predicted by microscopic many-body theories

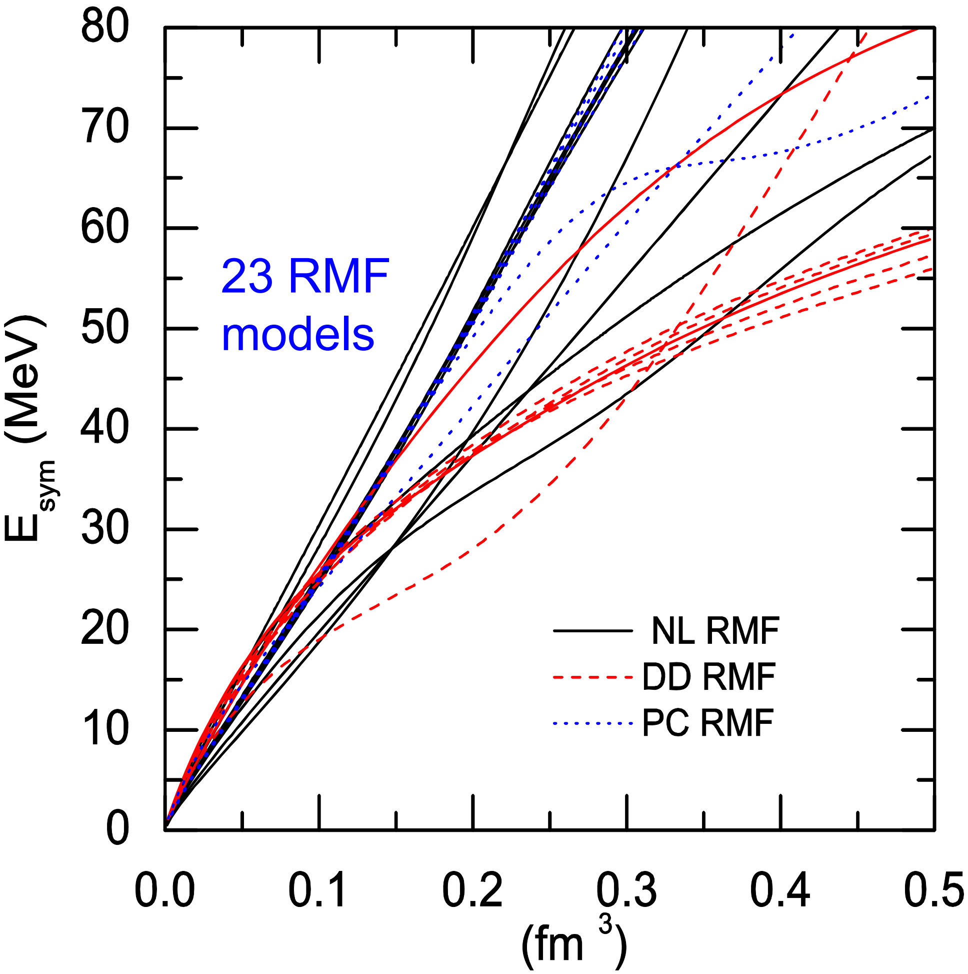


A.E. L. Dieperink et al., Phys. Rev. C68 (2003) 064307

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

Examples:



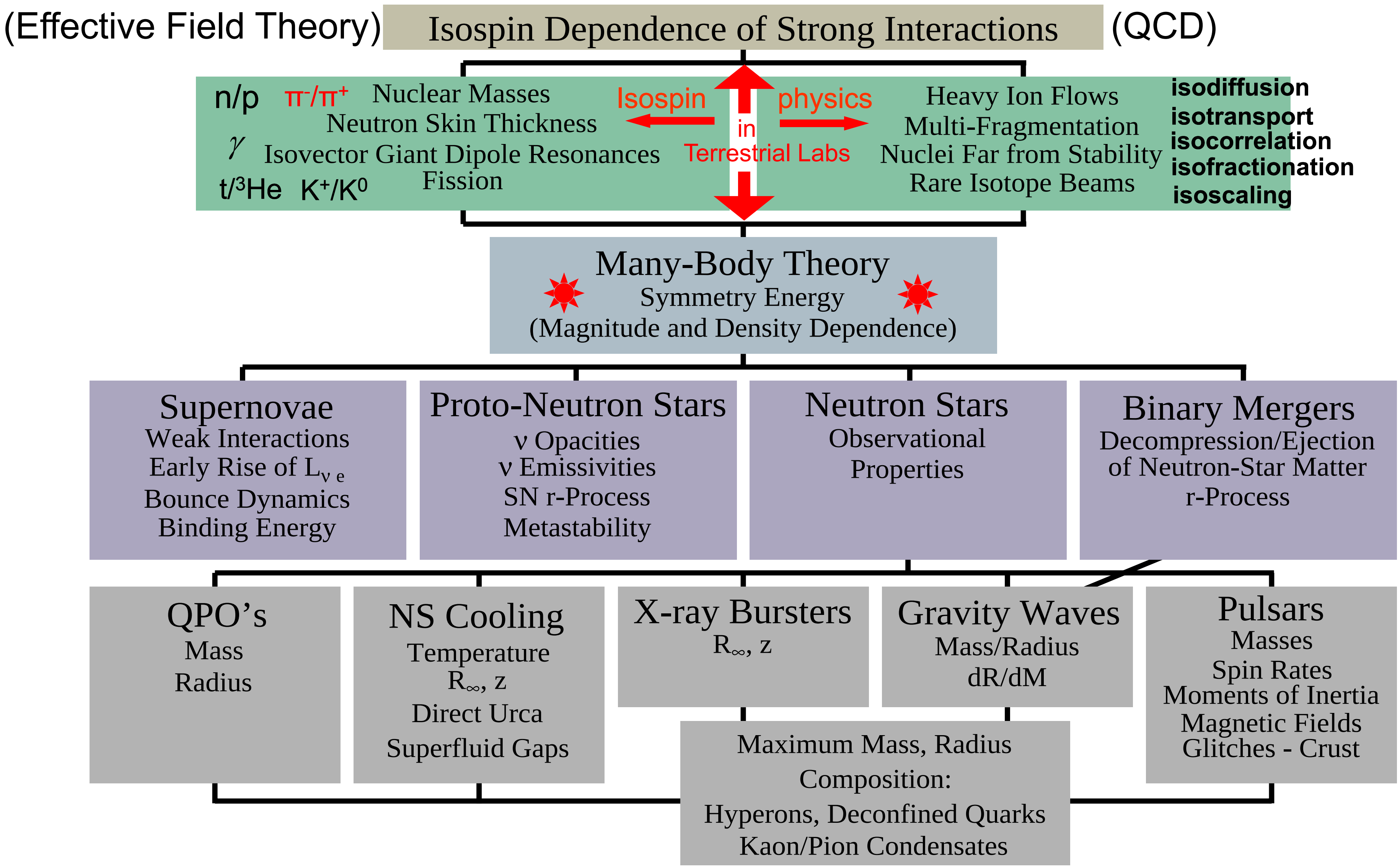


L.W. Chen, C.M. Ko and B.A. Li, Phys. Rev. C72, 064309 (2005); C76, 054316 (2007).

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).*



(Effective Field Theory) Isospin Dependence of Strong Interactions (QCD)

n/p π^-/π^+ Nuclear Masses
Neutron Skin Thickness
γ Isovector Giant Dipole Resonances
$t/^3$He K^+/K^0 Fission

Isospin physics
in
Terrestrial Labs

Heavy Ion Flows
Multi-Fragmentation
Nuclei Far from Stability
Rare Isotope Beams

isodiffusion
isotransport
isocorrelation
isofractionation
isoscaling

Many-Body Theory
Symmetry Energy
(Magnitude and Density Dependence)

Supernovae
Weak Interactions
Early Rise of L_{ν_e}
Bounce Dynamics
Binding Energy

Proto-Neutron Stars
ν Opacities
ν Emissivities
SN r-Process
Metastability

Neutron Stars
Observational
Properties

Binary Mergers
Decompression/Ejection
of Neutron-Star Matter
r-Process

QPO's
Mass
Radius

NS Cooling
Temperature
R_∞, z
Direct Urca
Superfluid Gaps

X-ray Bursters
R_∞, z

Gravity Waves
Mass/Radius
dR/dM

Pulsars
Masses
Spin Rates
Moments of Inertia
Magnetic Fields
Glitches - Crust

Maximum Mass, Radius
Composition:
Hyperons, Deconfined Quarks
Kaon/Pion Condensates

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

At sub-saturation densities

- Global nucleon optical potentials from n/p-nucleus and (p,n) reactions

- **Sizes of n-skins of unstable nuclei from total reaction cross sections**
- **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

- **$\underline{\pi^-/\pi^+}$ 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 Reports 464, 113 (2008)*

Symmetry energy and the isospin-dependence of strong interaction

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

Symmetry energy $$E_{sym}(\rho) = \frac{1}{6}\frac{\partial(\overset{\text{kinetic}}{t} + \overset{\text{isoscalar}}{U_0})}{\partial k}|_{k_F} k_F + \frac{1}{2}\overset{\text{isovector}}{U_{sym}}(\rho, k_F)$$

Effective mass $$m^*/m = [1 + \frac{m}{k_F}\frac{\partial U_0}{\partial k}|_{k_F}]^{-1}$$

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

J. Dabrowski, Physics Letters 8, 90 (1964)

K. A. Brueckner and J. Dabrowski, Phys. Rev. **134**, B722 (1964); J. Dabrowski and P. Haensel, Phys. Lett. B **42**, 163 (1972); Phys. Rev. C **7**, 916 (1973); Can. J. Phys. **52**, 1768 (1974).

Symmetry energy and its density slope at arbitrary density based on the Hugenholtz-Van Hove (HVH) theorem

N. M. Hugenholtz, L. Van Hove, Physica **24**, 363 (1958)

Single-particle potential

Fermi momentum

Kinetic energy

Energy density

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

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

$$k_F^n = k_F(1+\delta)^{1/3}, k_F^p = k_F(1-\delta)^{1/3}$$

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

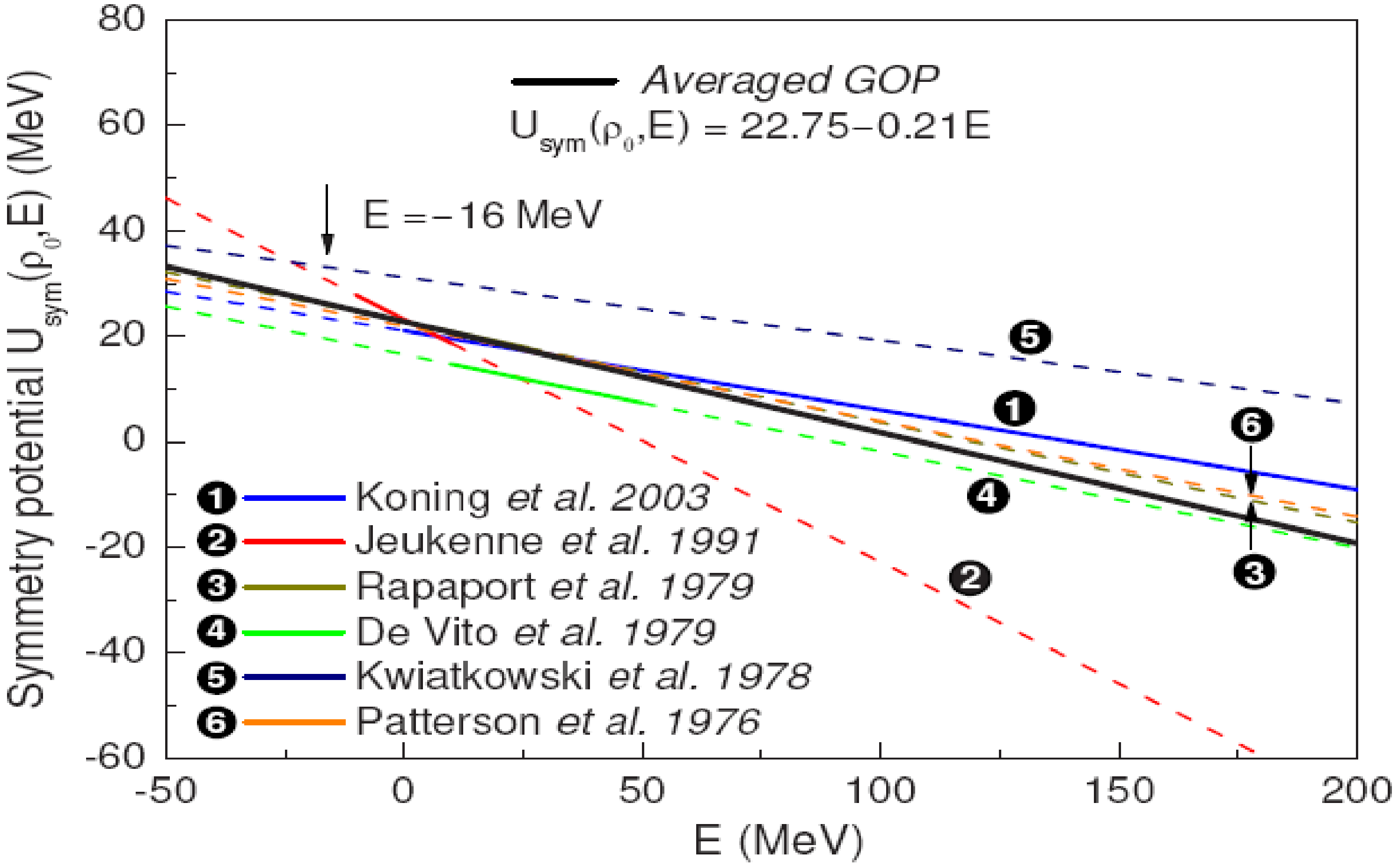
$$L(\rho) = \frac{2}{3}\frac{\hbar^2 k_F^2}{2m^*} + \frac{3}{2}U_{sym}(\rho, k_F) + \frac{\partial U_{sym}}{\partial k}|_{k_F} k_F$$

C. Xu, B.A. Li and L.W. Chen arXiv:1006.4321

Symmetry potential at saturation density from global nucleon optical potentials

Systematics based on world data accumulated since 1969:

(1) Single particle energy levels from pick-up and stripping reaction
(2) Neutron and proton scattering on the same target at about the same energy
(3) Proton scattering on isotopes of the same element
(4) (p,n) charge exchange reactions

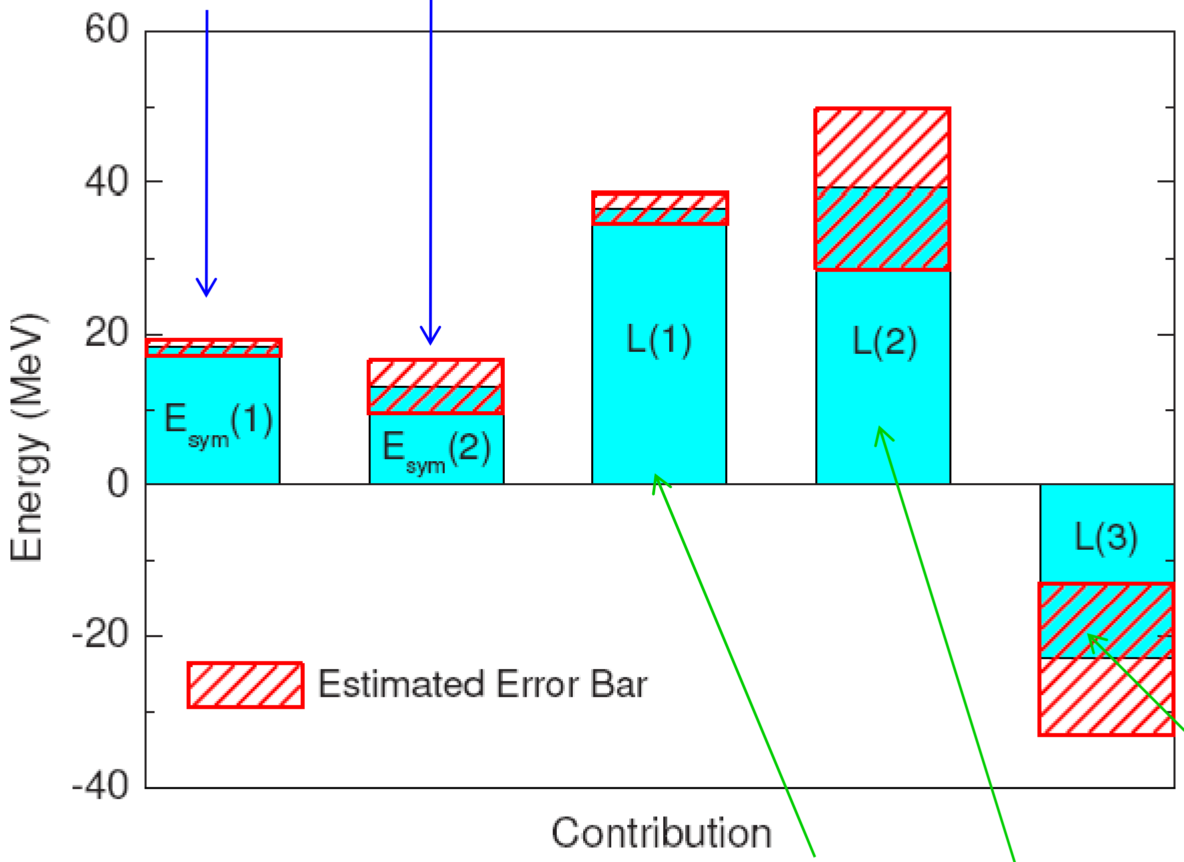


Constraining the symmetry energy near saturation density using global nucleon optical potentials

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

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

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

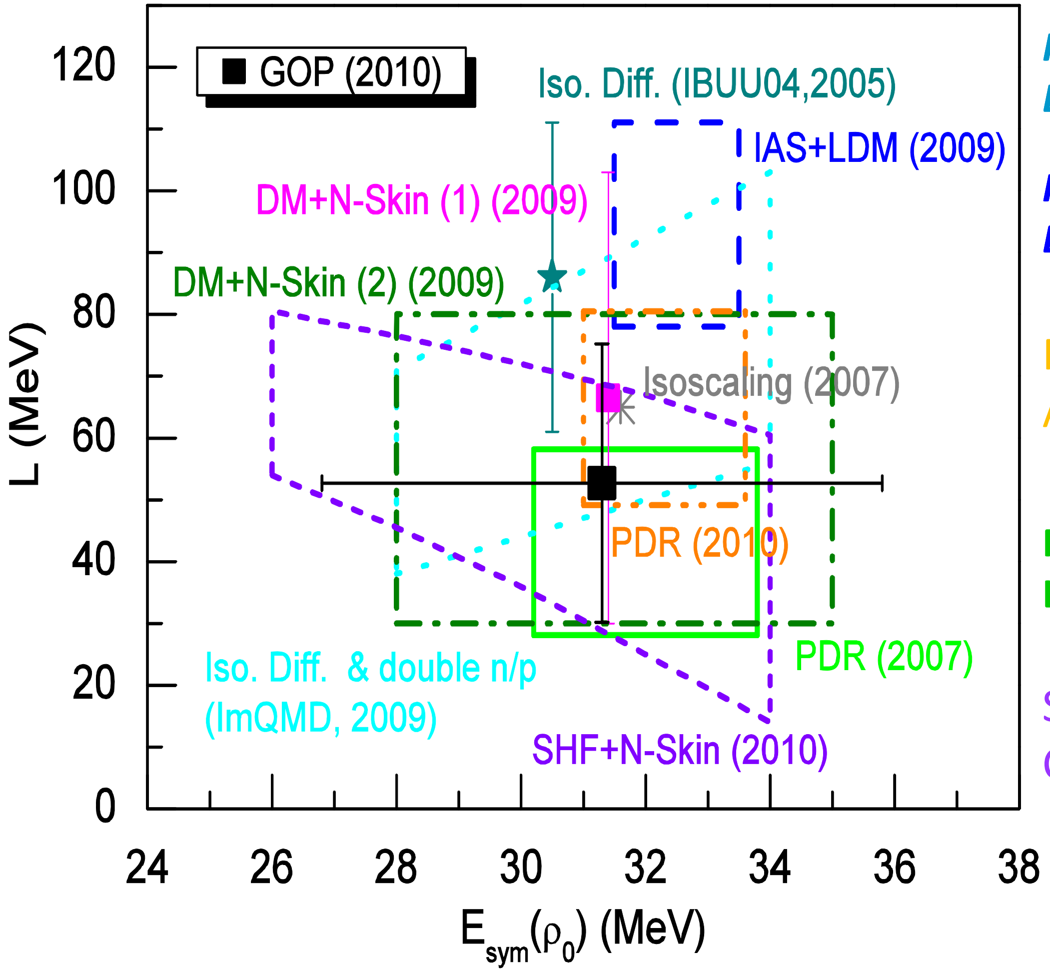


$$L(\rho_0) = 52.7 \text{ MeV} \pm 22.5 \text{ MeV}$$

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

Latest constraints on the symmetry energy and its density slope at saturation

GOP: global optical potentials (Lane potentials)
C. Xu et al., arxiv:1006.4321



Iso. Diff & double n/p (ImQMD, 2009),
M. B. Tsang et al., PRL92, 122701 (2009).

Iso Diff. (IBUU04, 2005),
L.W. Chen et al., PRL94, 32701 (2005)

IAS+LDM (2009),
Danielewicz and J. Lee, NPA818, 36 (2009)

PDR (2010) of ^{68}Ni and ^{132}Sn,
A. Carbone et al., PRC81, 041301 (2010).

PDR (2007) in ^{208}Pb
Land/GSI, PRC76, 051603 (2007)

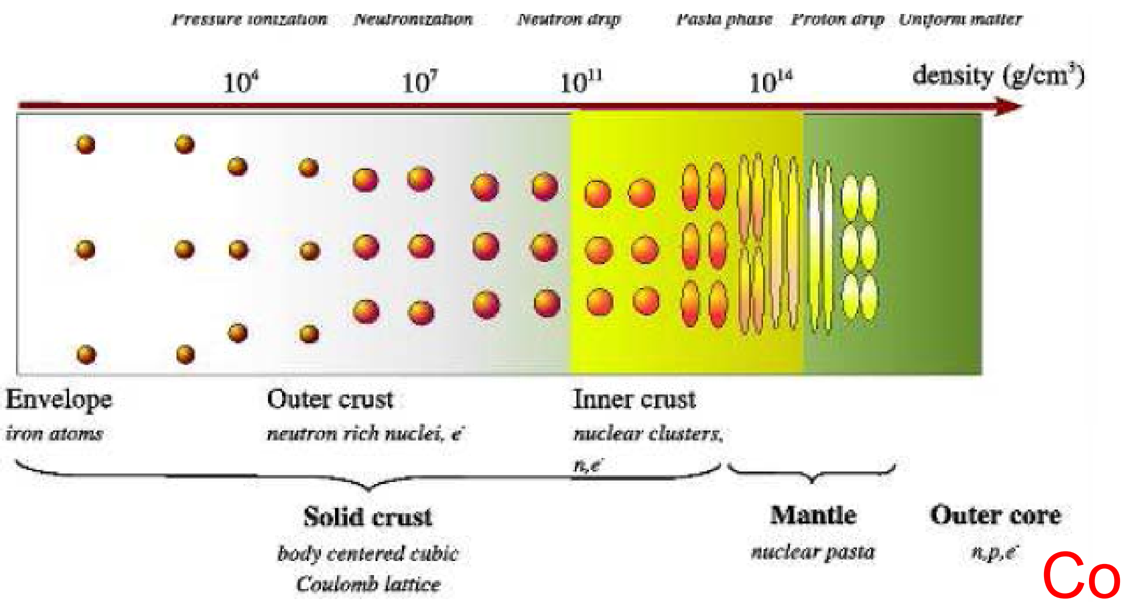
SHF+N-skin of Sn isotopes,
Chen et al., arxiv:1004.4672

Isoscaling (2007),
D.Shetty et al. PRC76, 024606 (2007)

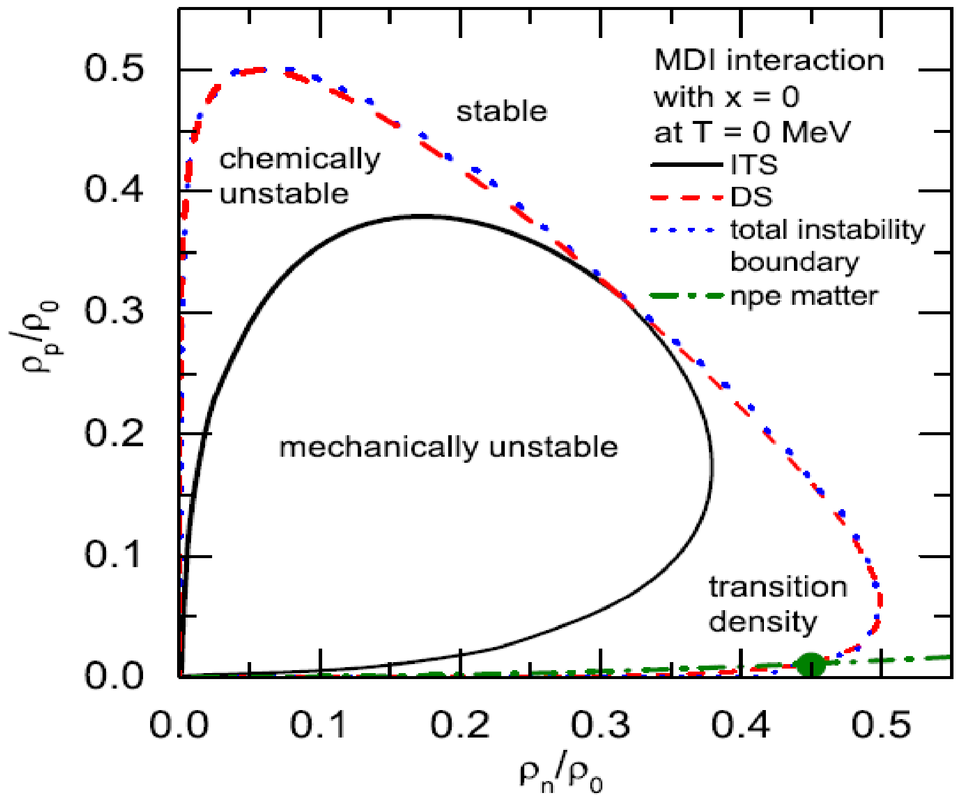
DM+N-Skin (1): M. Centelles et al., PRL102, 122502 (2009)

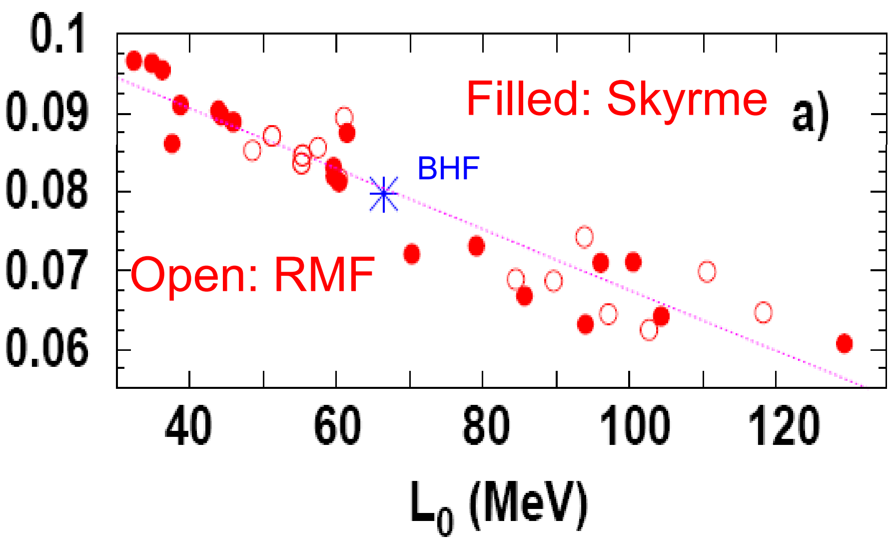
DM+N-Skin (2): M. Warda et al., PRC80, 024316 (2009)

Core-crust transition density in neutron stars



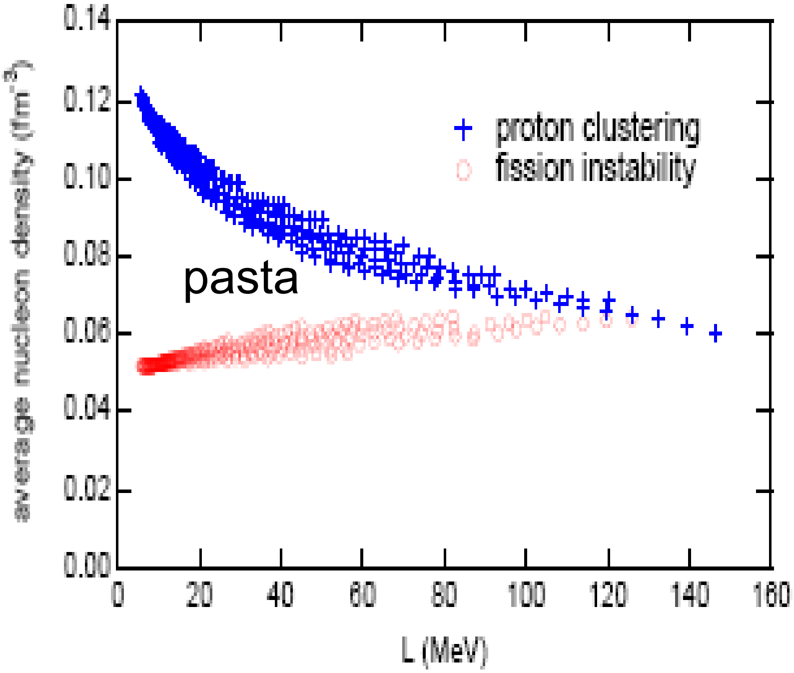
With L=40~90 MeV,
ρ_t =0.07~0.09 fm^{-3}





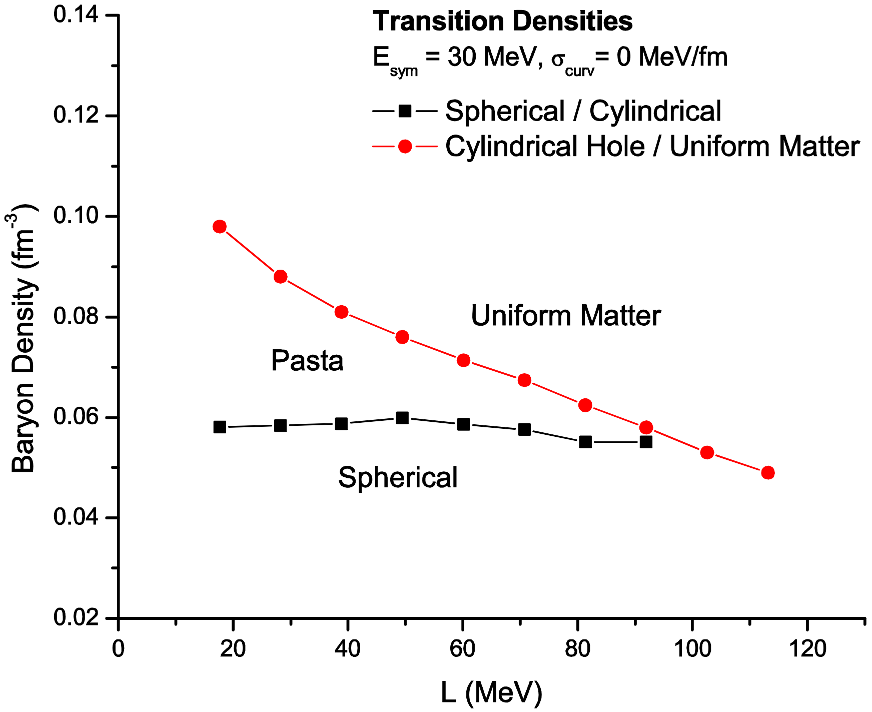
Camille Ducoin, Jérôme Margueron, Constança Providência, arXiv:1004.5197

Effects of the symmetry energy on the pasta phase in neutron star crust



Kazuhiro Oyamatsu, Kei Iida

Phys. Rev. C75 (2007) 015801



W.G. Newton et al., 2010

Liquid drop model + Wigner-Seitz approximation
including dripped neutrons and the electrons at beta equilibrium

Symmetry (isovector) potential and its major uncertainties

- Isospin-dependence of NN correlations and the tensor force

Experimental indication: BNL (p,p'pp) and (p,p'pn) and JLab (e,e'pp) and (e,e'pn) experiments,
A. Tang et al., PRL 90, 042302 (2003); E. Piasetzky et al., PRL97, 162504 (2006);
B. R. Subedi et al. Science 320,1476 (2008)………………

Theories: MANY papers,
R. Schiavilla et al., PRL 98, 132501 (2007); M. Alvioli et al., PRL 100, 162503 (2008);
L. Frankfurt, M. Sargsian and M. Strikman; T. Neff, H. Feldmeier; W. Dickhoff, Wiringa, ………………

Within an interacting Fermi gas model:
Structure of the nucleus, M.A. Preston and R.K. Bhaduri (1975)

NN correlation functions

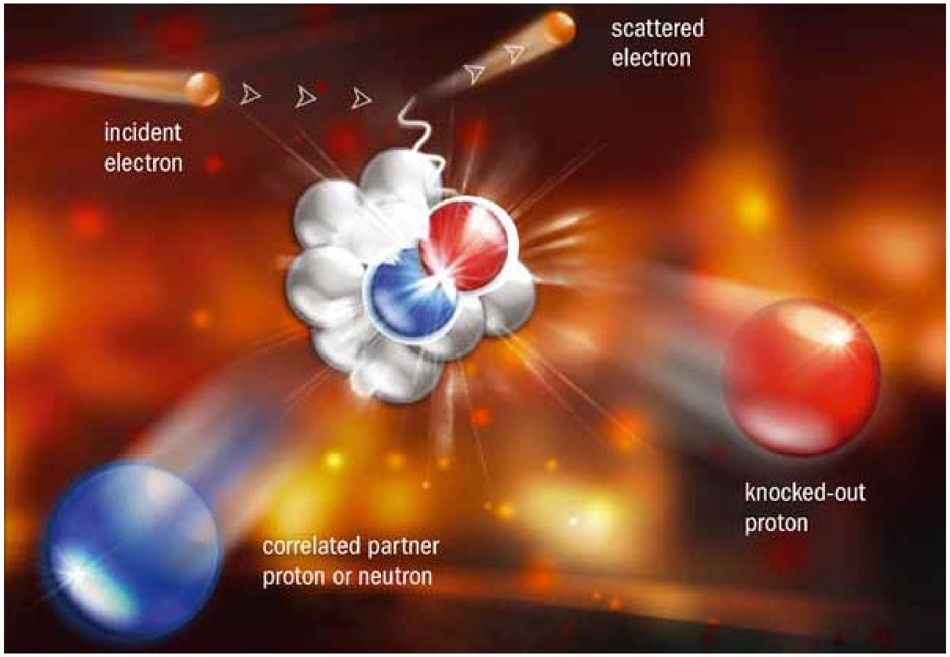
$$U_{sym}(k_F,\rho)=\frac{1}{4}\rho\int[V_{T1}(r_{ij})f^{T1}(r_{ij})-V_{T0}(r_{ij})f^{T0}(r_{ij})]d^3r_{ij}$$

- Spin-isospin dependence of 3-body forces
- Short-range tensor force due to rho meson exchange

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

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

Isospin-dependence of Short Range NN Correlations and Tensor Force



Two-nucleon knockout by an electron

R Subedi et al. Science 320, 1475 (2008)
CERN Courier Jan 27, 2009

Theory explains the pn pair dominance in terms of the tensor force:

Schiavilla, Wiringa, Pieper and Carlson,
Phys. Rev. Lett. 98, 132501 (2007)

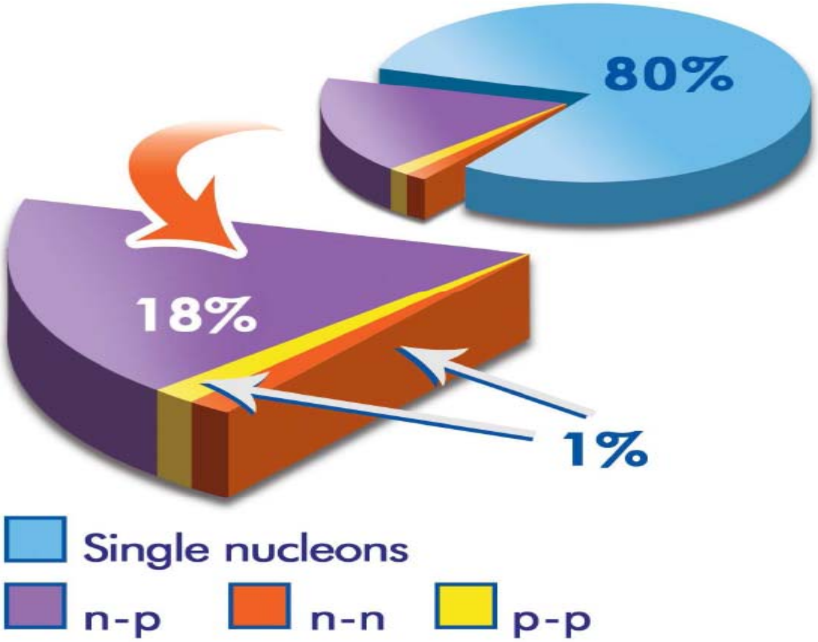
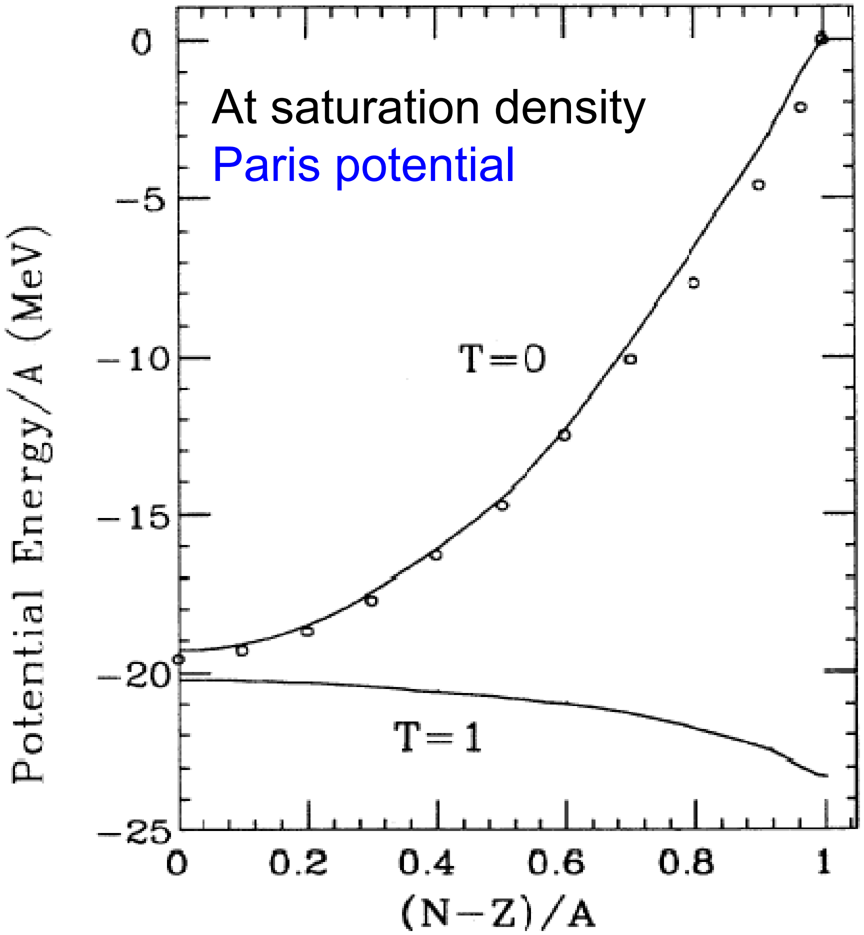


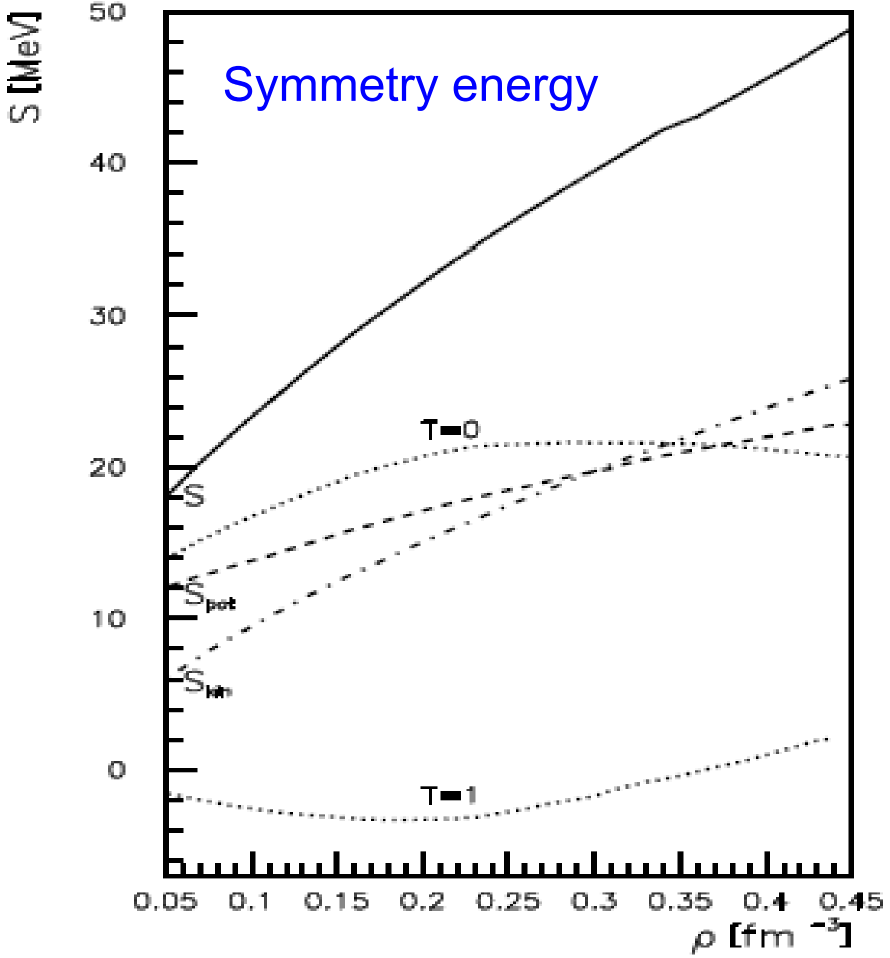
Figure 3: The average fraction of nucleons in the various initial state configurations of ^{12}C.

Dominance of the isosinglet (T=0) interaction


At saturation density

Paris potential

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

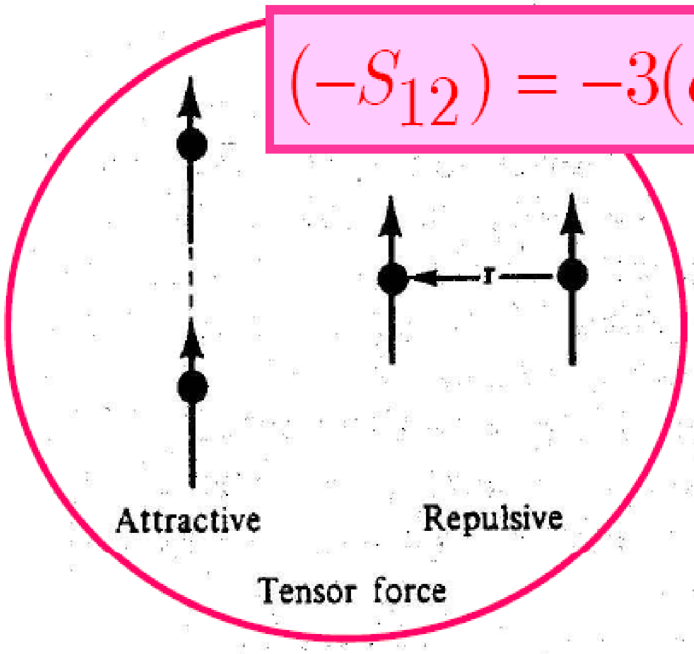

Symmetry energy

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

PRC68, 064307 (2003)

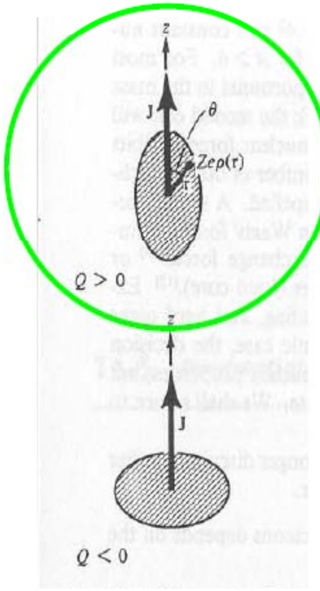
$$E_{sym}(\rho) = \frac{1}{2}\frac{\partial^2 E}{\partial \delta^2} \approx E(\rho)_{\text{pure neutron matter}} - E(\rho)_{\text{symmetric nuclear matter}}$$

$$(-S_{12}) = -3(\vec{\sigma}_1 \cdot \hat{r})(\vec{\sigma}_2 \cdot \hat{r}) + \vec{\sigma}_1 \cdot \vec{\sigma}_2$$



$S_{12}=2$

Tensor Force: First evidence from the deuteron

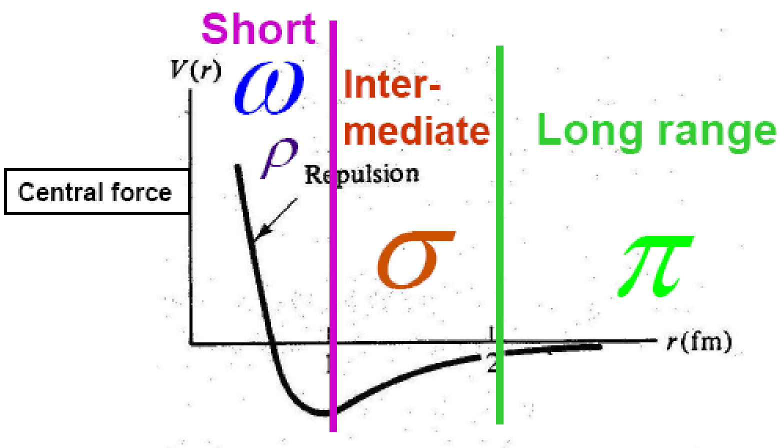


Deuteron

S=1, T=0

The short and long range tensor force

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



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

PHYSICAL REVIEW C VOLUME 21, NUMBER 3 MARCH 1980

Parametrization of the Paris N-N potential

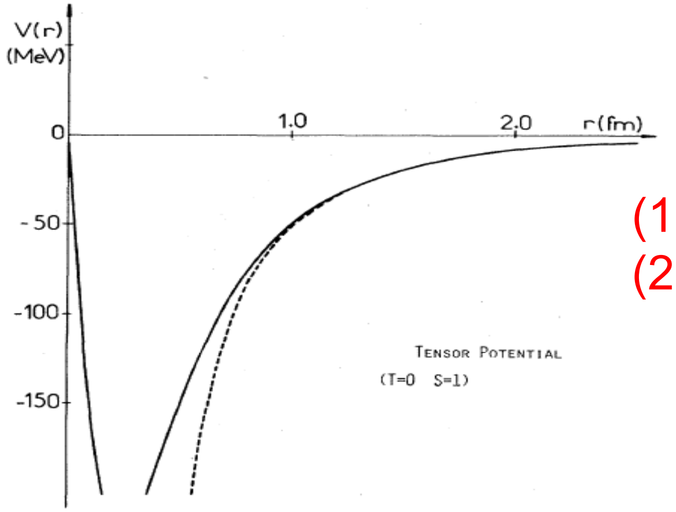
M. Lacombe, B. Loiseau, J. M. Richard, and R. Vinh Mau
Division de Physique Théorique, Institut de Physique Nucléaire, Orsay 91406, France
and LPTPE, Université Pierre et Marie Curie, Paris 75230, France

J. Côté, P. Pirès, and R. de Tourreil
Division de Physique Théorique, Institut Physique de Nucléaire, Orsay 91406, France

(Received 27 July 1979)

small values of r, there is no compelling theoretical reason to believe the validity of our potential in the region $r \lesssim 0.8$ fm since the short range (SR) part of the interaction is related to exchange of heavier systems and/or to effects of subhadronic constituents such as quarks, gluons, etc. At pres-

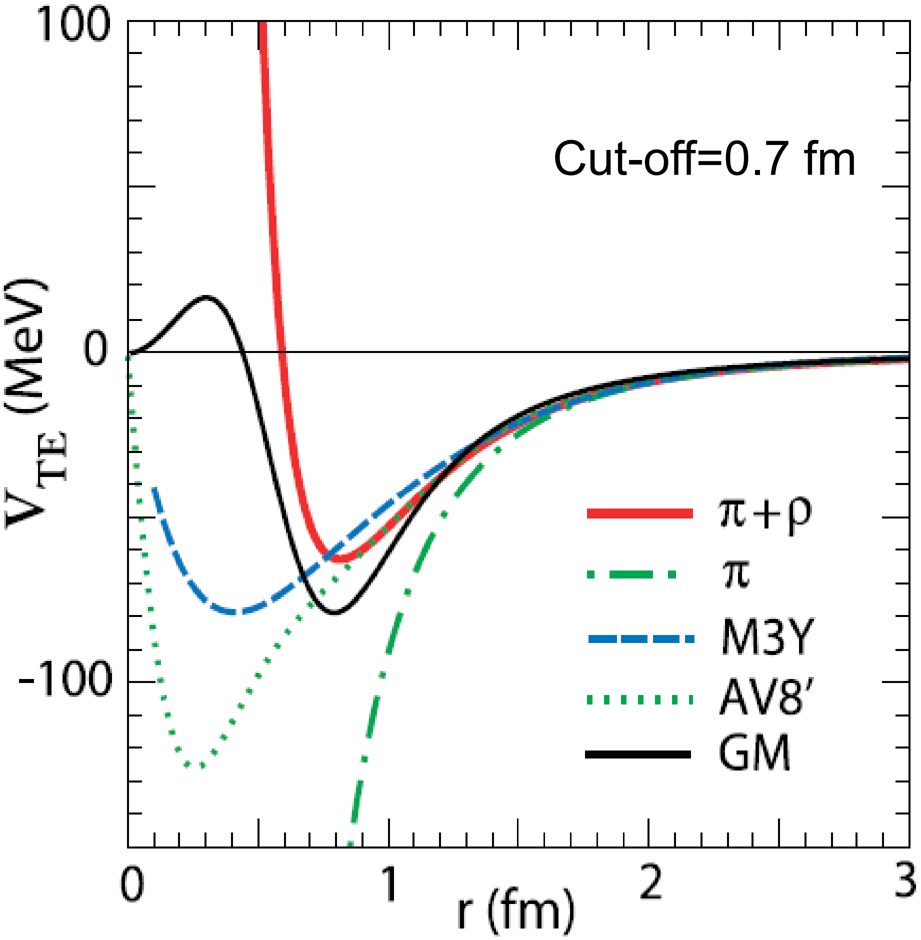
few degrees of freedom. Along this line, we proposed[3] to describe the core with a very simple phenomenological model; namely, the long and intermediate range $(\pi+2\pi+\omega)$ potential is cut off rather sharply at internucleon distance $r \sim 0.8$ fm and the short range ($r \lesssim 0.8$ fm) is described simply by a constant soft core. This introduces the



(1) including only pion contribution to the tensor force
(2) using a hard-core cut-off distance of 0.8 fm

Uncertainty of tensor force at short distance

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



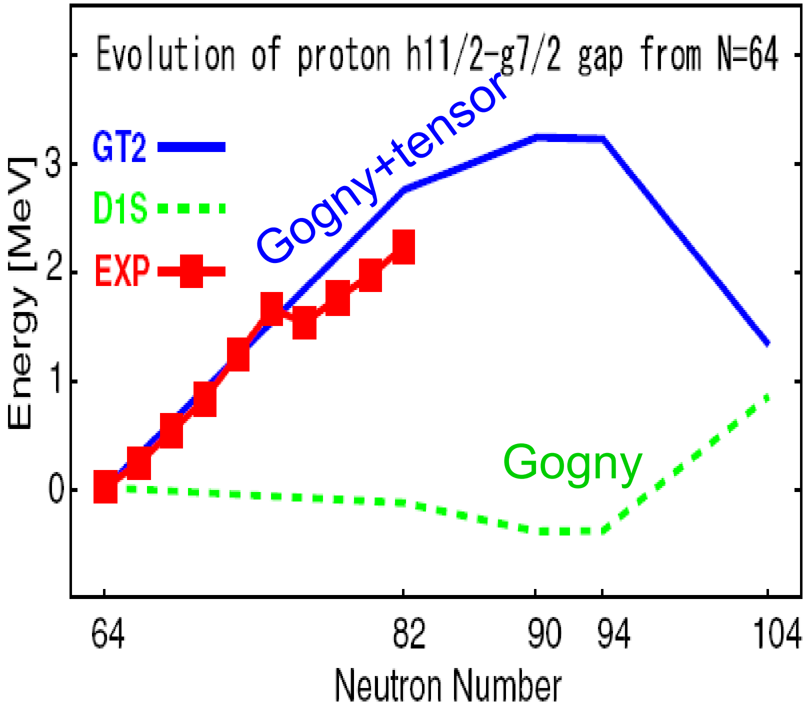


FIG. 4 (color online). Evolution of $1h_{11/2}$-$1g_{7/2}$ energy gap. The difference from the value of $N = 64$ is plotted for experimental data [21] and calculated results with GT2 and D1S interactions.

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

In-medium properties of the short-range tensor force

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

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

G.E. Brown and Mannque Rho,
PLB 237, 3 (1990)

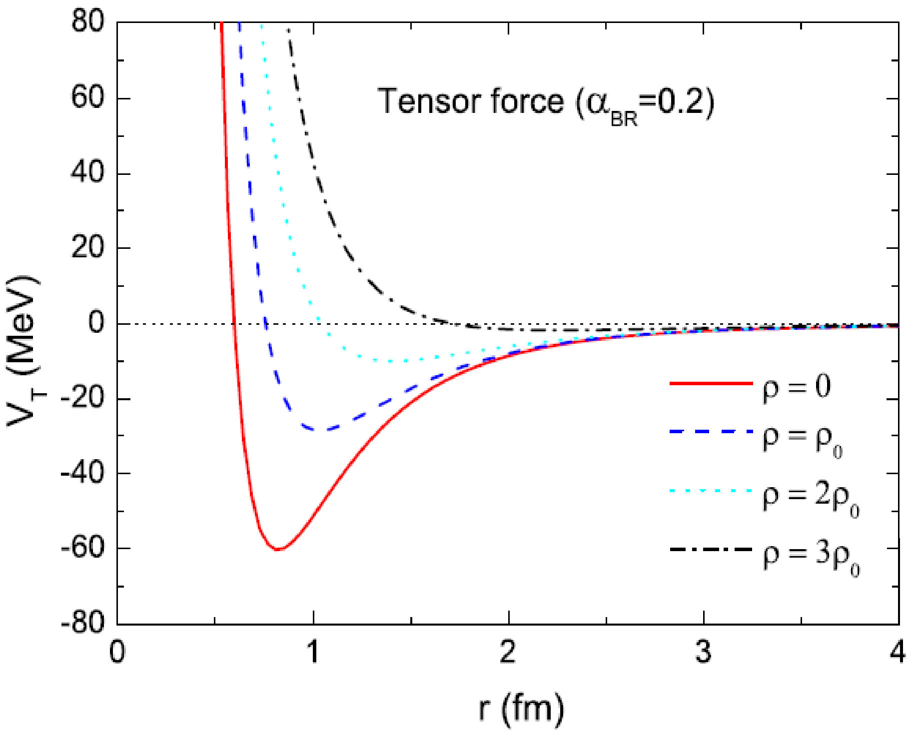
Brown-Rho scaling (BRS)

$$\frac{m_\rho^\star}{m_\rho} = 1 - \alpha_{BR} \cdot \frac{\rho}{\rho_0}$$

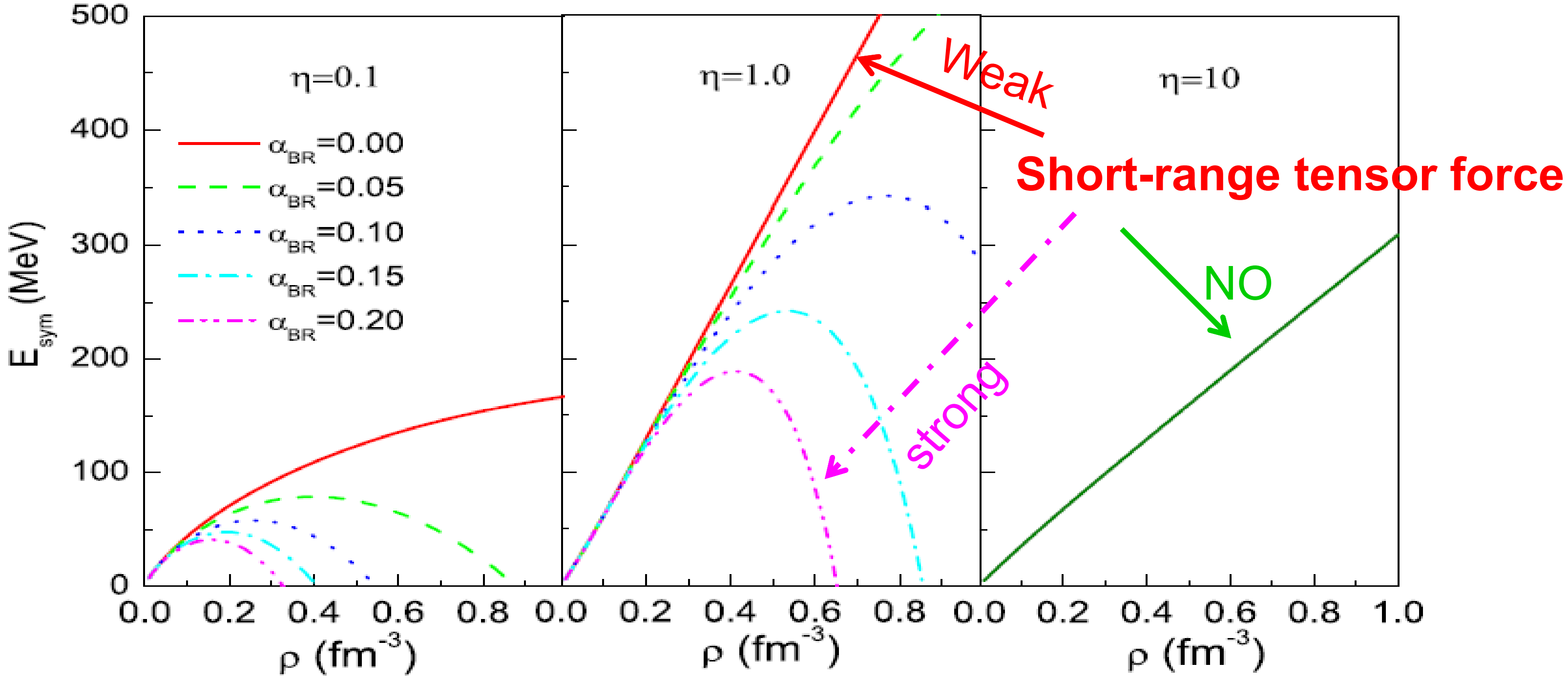
Pion mass unchanged

G.E. Brown and Mannque Rho,
PRL 66, 2720 (1991); Phys Rep. 396, 1 (2004)

Strength of the total tensor force



Short-range properties of tensor force and the high-density behavior of nuclear symmetry energy



Weak

Short-range tensor force

NO

strong

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

$$f(r_{ij})=0, r_{ij}<r_c \text{ and } f(r_{ij})=1, r_{ij}\geq r_c \text{ with } r_c=\eta(\frac{3}{4\pi\rho})^{1/3}$$

Chang Xu and Bao-An Li, Phys. Rev. C81, 064612 (2010).

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:

$$n+(n,p)\rightarrow p+(n,p)+e^-+\bar{\nu}_e$$

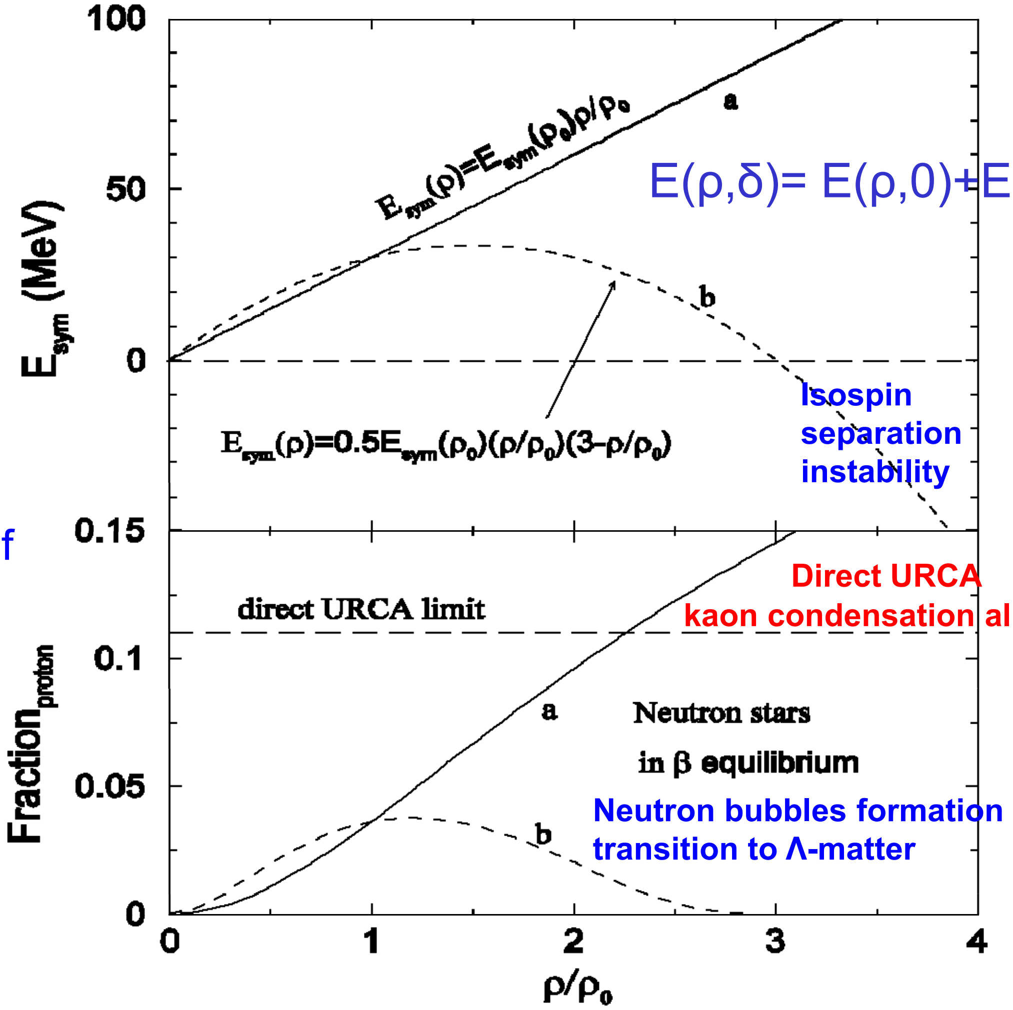
$$p+(n,p)\rightarrow n+(n,p)+e^++\nu_e$$

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

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

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

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



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

Isospin separation instability

Direct URCA kaon condensation allowed

Neutron bubbles formation transition to Λ-matter

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

Can the symmetry energy become negative at high densities?

Yes, it happens when the tensor force due to rho 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

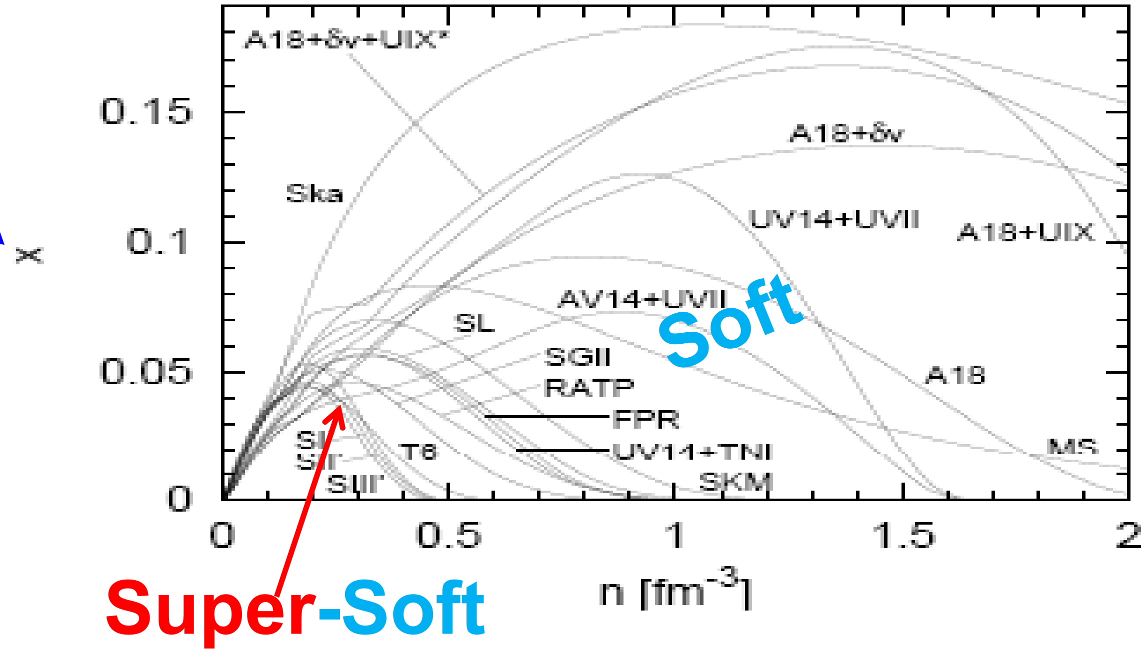
Wiringa R B, Fiks V and Fabrocini A 1988 *Phys. Rev.* C **38** 1010

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)

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

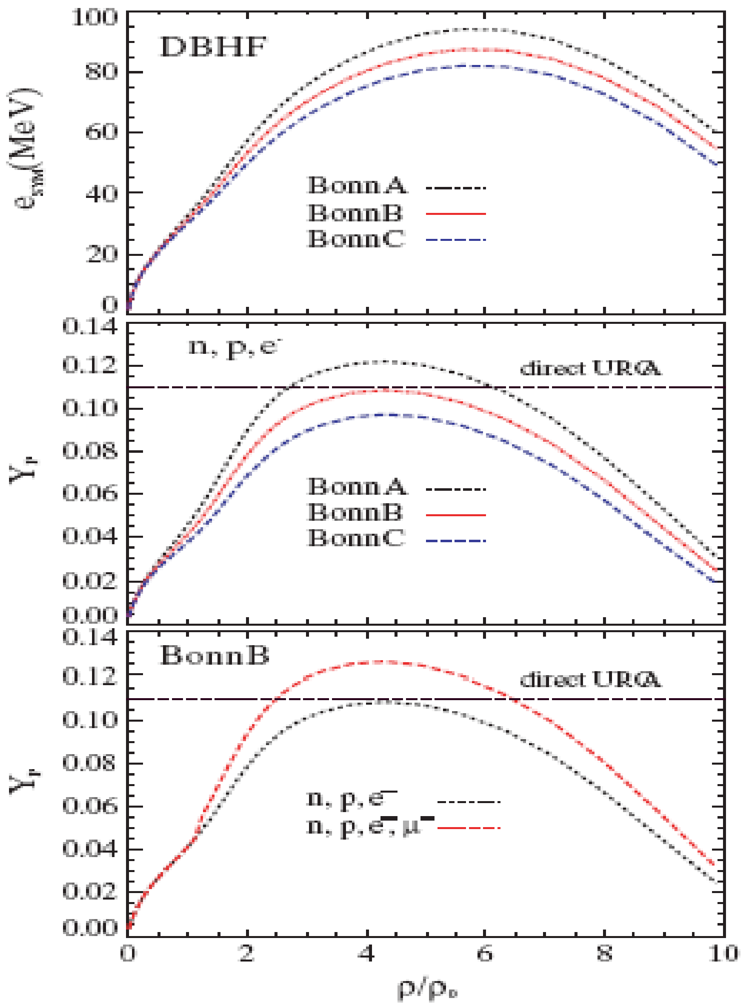


Soft

Super-Soft

Dirac-Brueckner-Hartree-Fock Calculations

P. G. KRASTEV AND F. SAMMARRUCA PHYSICAL REVIEW C 74, 025808 (2006)



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)

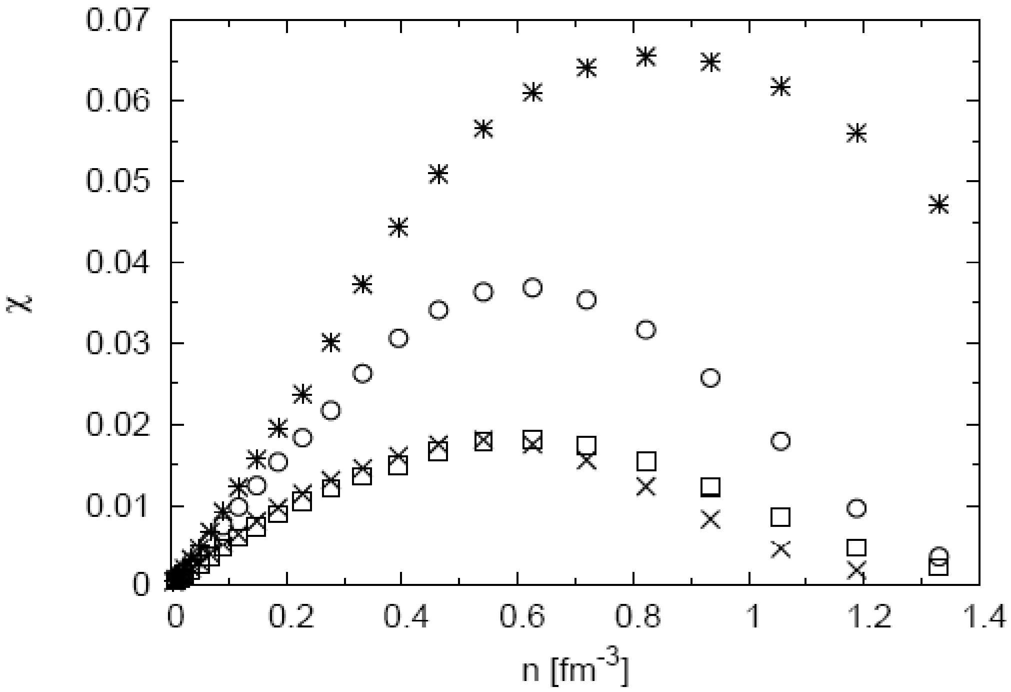
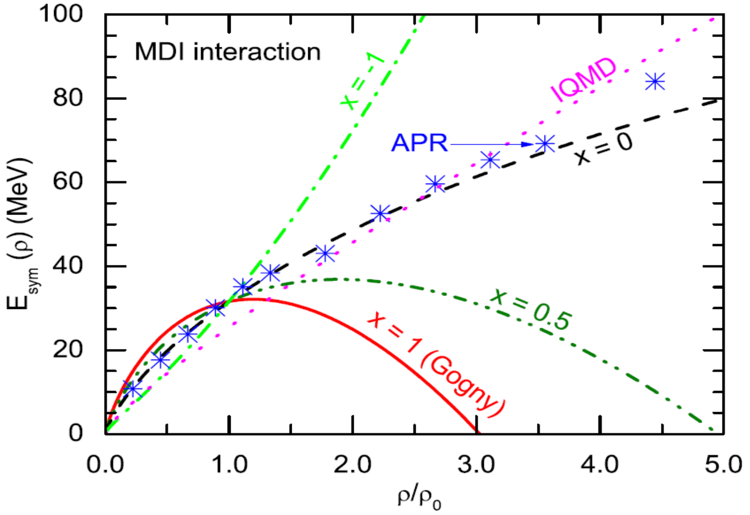


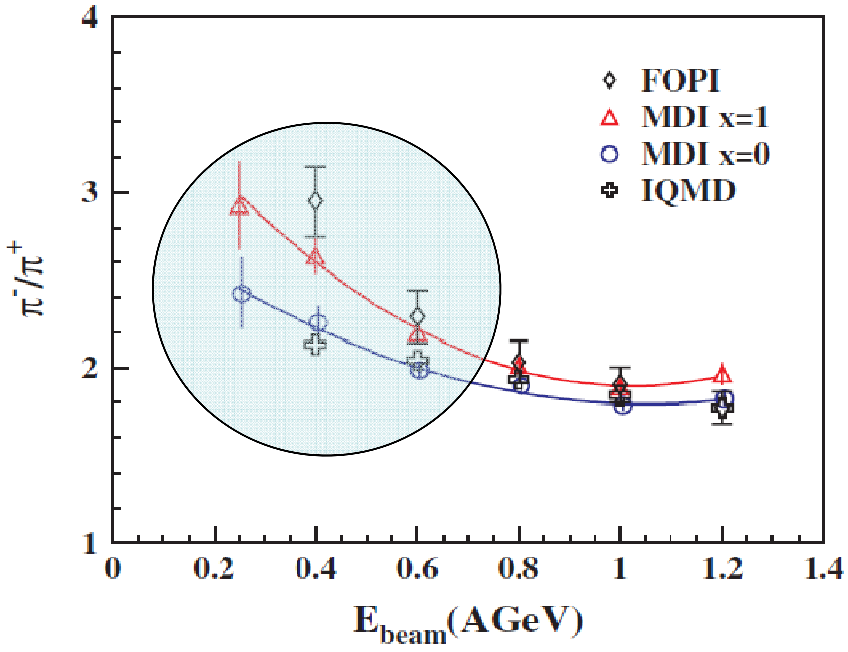
FIG. 9: Proton fraction of β-stable neutron star from realistic NN potentials. Symbols are BonnA($*$), CDBonn($\circ$), Argonne V18 ($\square$) and Nijemgen ($\times$). The interaction 'V_{low-k} plus TBF' is used.

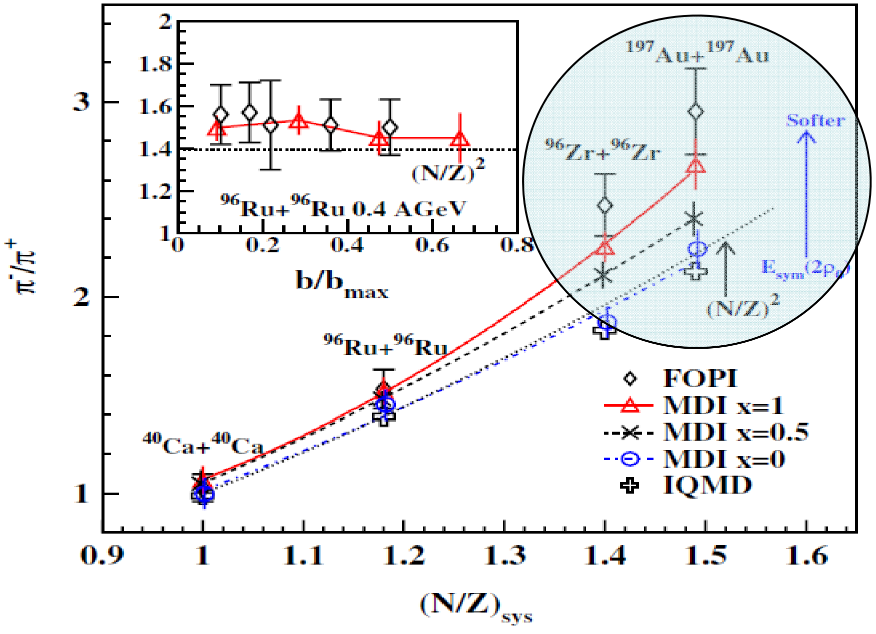
Circumstantial Evidence for a Super-soft Symmetry Energy at Supra-saturation Densities

Data: **W. Reisdorf et al.**
NPA781 (2007) 459

Calculations: IQMD and IBUU04







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

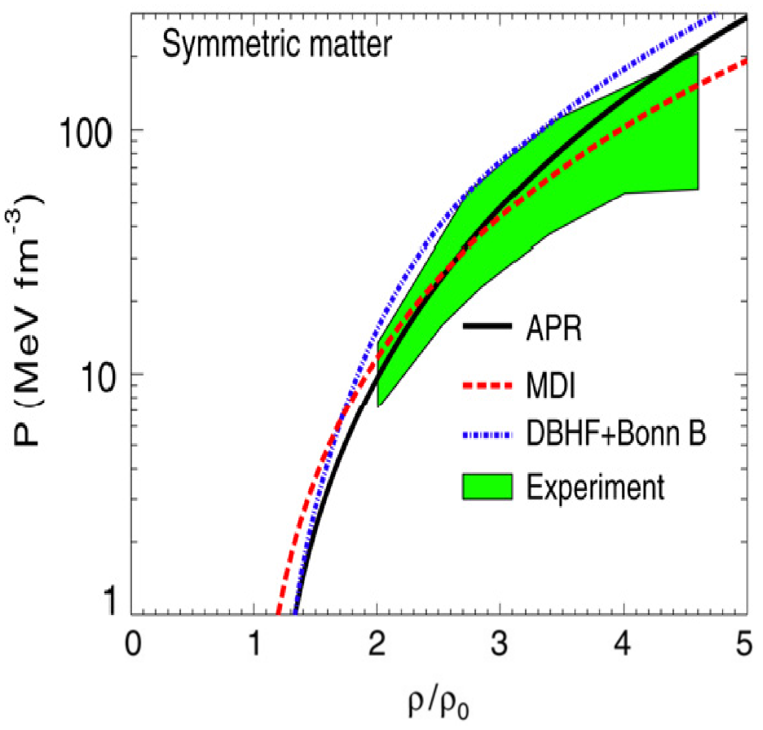
Z.G. Xiao, B.A. Li, L.W. Chen, G.C. Yong and M. Zhang, Phys. Rev. Lett. 102 (2009) 062502

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

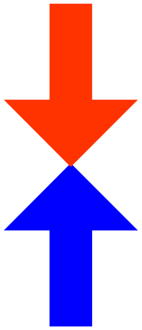
If the symmetry energy is too soft, then a mechanical instability will occur when dP/dρ is negative, neutron stars will then all collapse while they do exist in nature

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

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

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

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

Comments about the super-soft symmetry energy

Unpleasant, unwelcome, annoying !

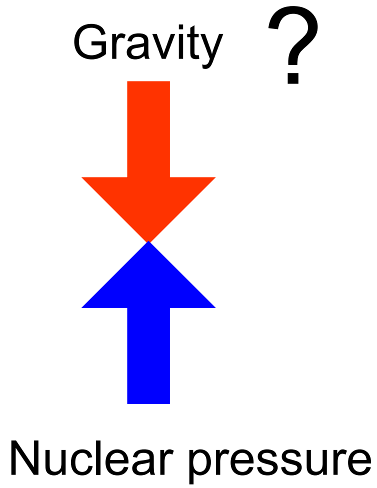
E. Chabanat, P. Bonche, P. Haensel, J. Meyer, and R. Schaeffer,
NPA627, 710 (1997); NPA635, 231 (1998).

Repeated by several others in some other papers

Unphysical !

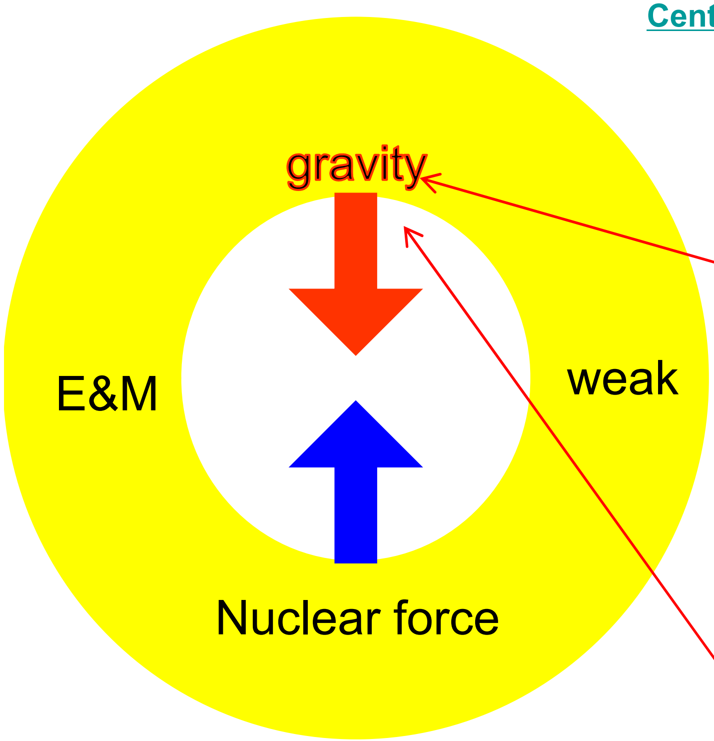
Norman Glennding, Compact Stars, Springer, ISBN: 0387989773.

Quoted by several people in a number of papers



Neutron stars as a natural testing ground of grand unification theories 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



Stable neutron star
@
β-equilibrium

- 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?

Composition and structure determined by the 4 forces TOGETHER

Do we really know gravity at short distance?

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 proposed in the super-symmetric extension of the standard model, 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).

TESTS OF THE GRAVITATIONAL INVERSE-SQUARE LAW

E.G. Adelberger, B.R. Heckel, and A.E. Nelson
Department of Physics, University of Washington, Seattle, Washington 98195-1560;

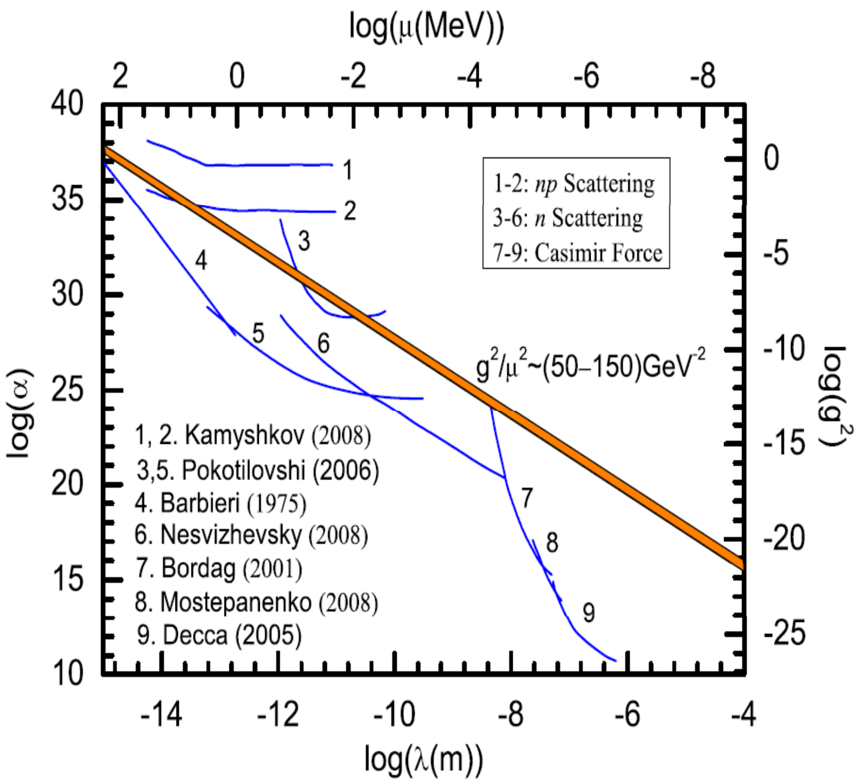
Annu. Rev. Nucl. Part. Sci. 53 (2003) 77
Prog. In Part. and Nucl. Phys., 62 (2009) 102

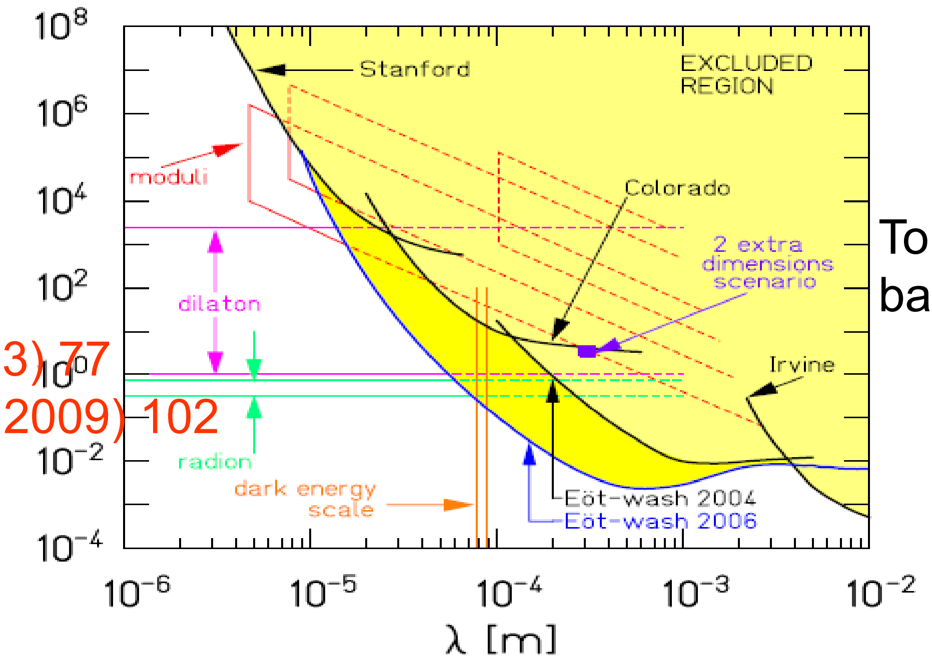
Upper limits on the strength α and range λ of the Yukawa term

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)

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

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





3) 77
2009) 102

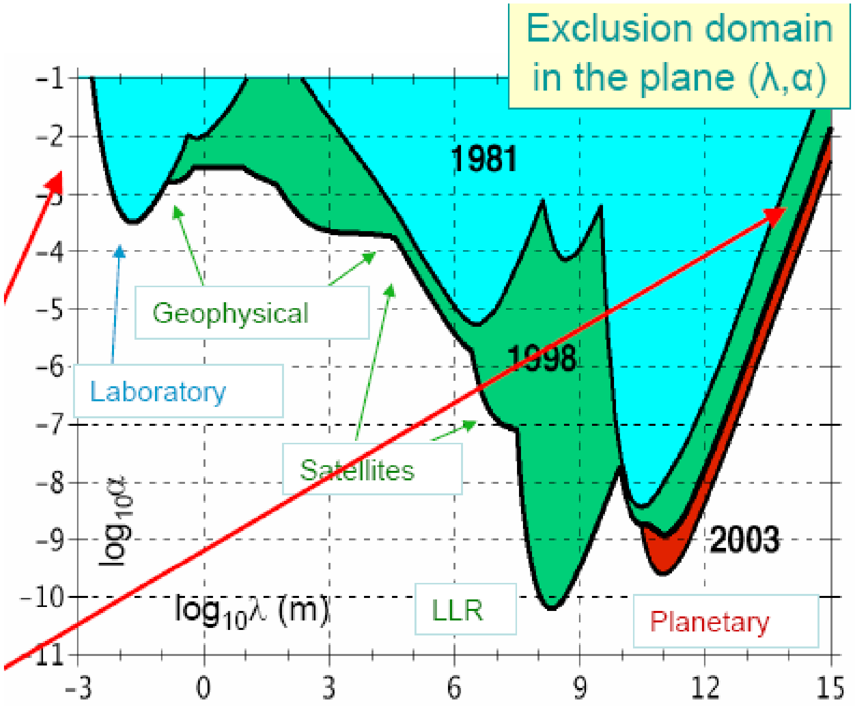
Torsion balance

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)

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

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



A motivation of the deep space gravity probe

Influences of the Yukawa term on Neutron Stars

Yasunori Fujii *J. Audouze et al. (eds.), Large Scale Structures of the Universe, 471–477.*
© 1988 by the IAU.

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]

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

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

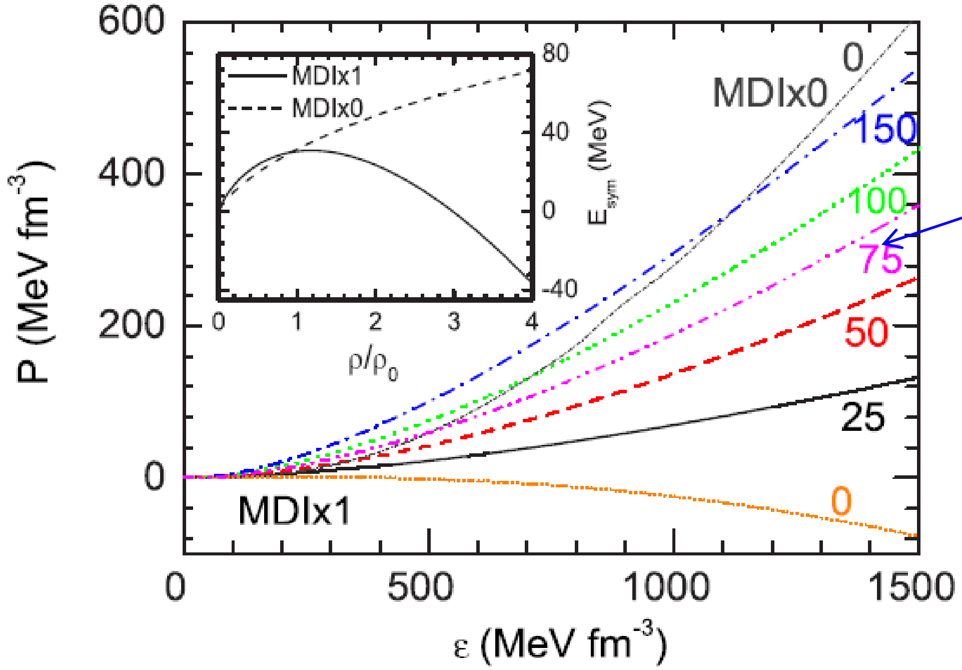
Assuming a constant boson mass independent of the density, the extra pressure is then

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

Supersoft Symmetry Energy Encountering Non-Newtonian Gravity in Neutron Stars

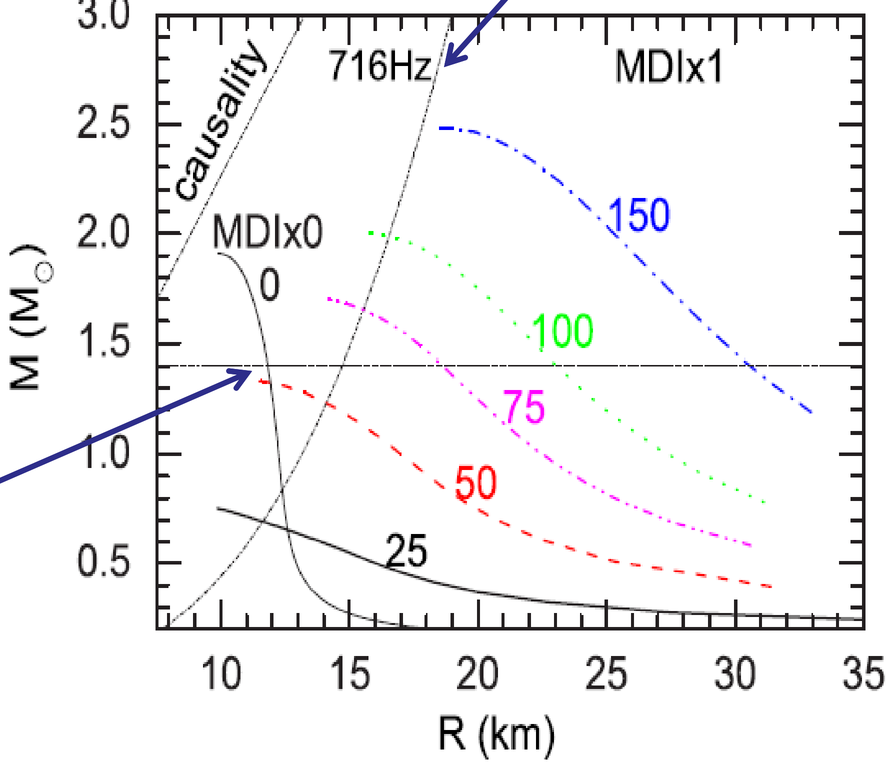
De-Hua Wen, Bao-An Li and Lie-Wen Chen, PRL 103, 211102 (2009)

EOS including the Yukawa contribution



g^2/μ^2

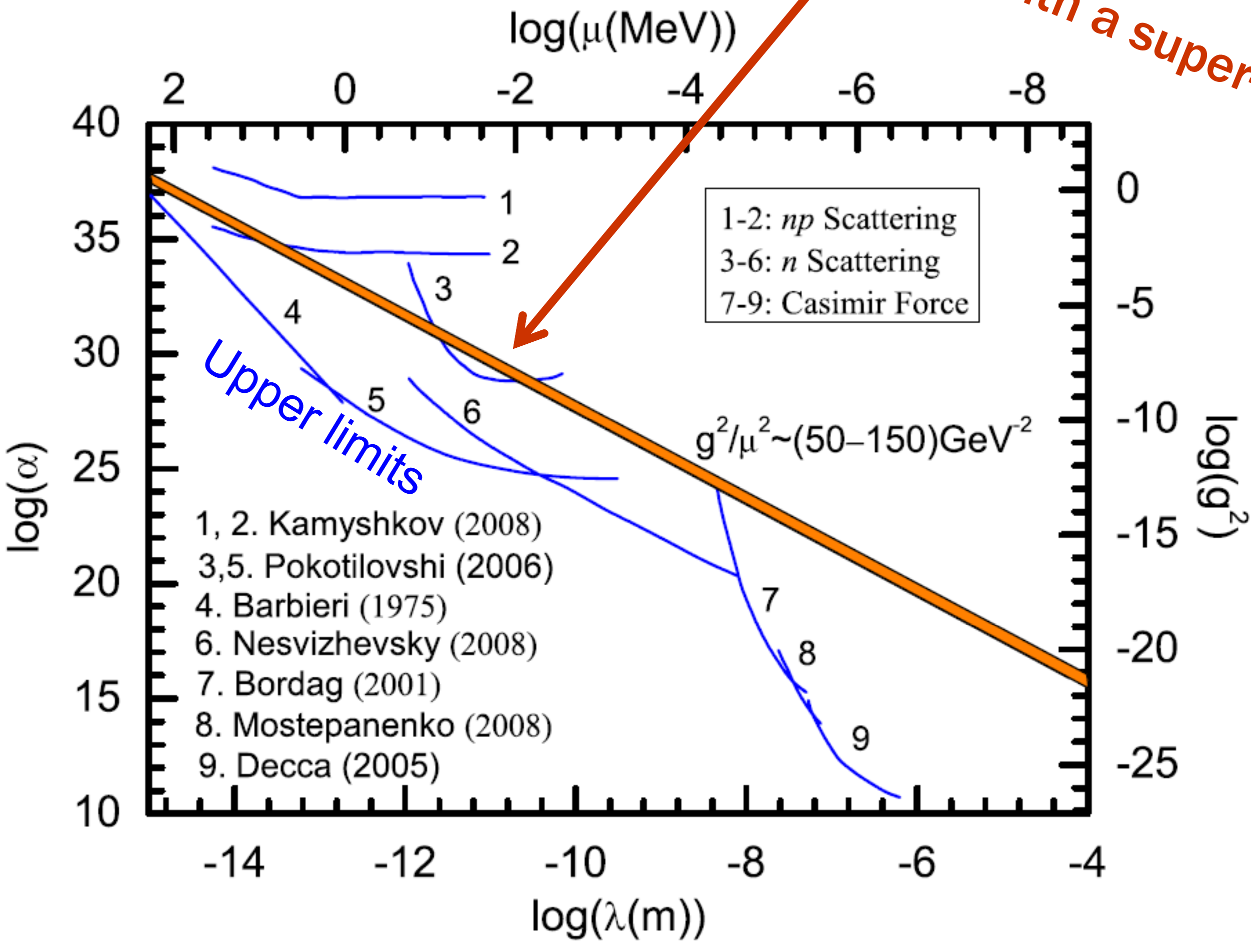
Mass-shedding limit



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

a NS of 1.4Msun and R = 12 km

Lower limit to support neutrons stars with a super-soft symmetry energy



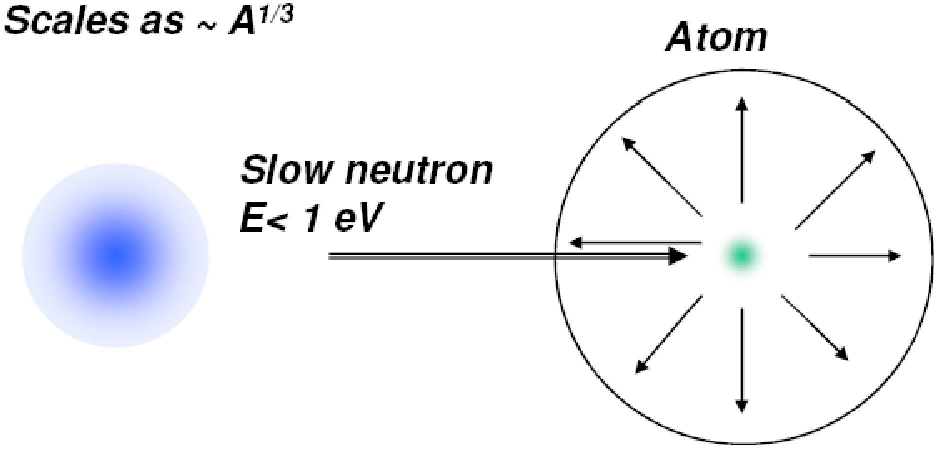
Slow neutron scattering and extra interactions

V.V.N., G. Pignol, and K.V. Protasov (2008). Physical Review D 77(3): 034020(8).

$$\begin{aligned} f(\mathbf{q}) &= f_{\rm nucl}(\mathbf{q}) + f_{\rm extra}(\mathbf{q}) \\ &= -b - A\,\frac{g^2}{4\pi}\,\hbar c\,\frac{2m\lambda^2/\hbar^2}{1+(q\lambda)^2} \end{aligned}$$

Coherent scattering length (Fermi)
- Isotropic
- Energy independent
- Scales as ~ $A^{1/3}$

- Not isotropic
- Energy dependent
- Scales as ~ A


Atom

Slow neutron
E< 1 eV

In the center of mass reference system

-Values of the scattering lengths for different atoms (nuclei) are not calculated precisely from "first principles" because of complexity of the corresponding nuclei models

Gravitationally bound quantum states of neutrons

V.V. Nesvizhevsky et al., Nature-Physics 6, 114 (2010)

Summary

- **The nuclear symmetry energy is still very uncertain especially at high densities due to mainly (1) 3-body force, (2) short-range tensor force and (3) short-range nucleon-nucleon correlation functions**

- **Symmetry energy affects many properties of neutron stars**

- **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 and have to be considered simultaneously.**

Gravity is least known among all 4 forces despite being the first force discovered
----- C.D. Hoyle, Nature 421, 899 (2003)

A lot more manuscripts on gravity than nuclear theory are posted at Arxiv every day

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,
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