Inha University, Republic of Korea

Nucleon Properties in Finite Nuclei

Ulugbek Yakhshiev

9th APCTP-BLTP JINR Workshop
“Modern Problems of Nuclear and Particle Physics”
June 27 - July 4, 2015 , Almaty, Kazakhstan

Content

- Topological models and soliton
- Medium modifications
- Nucleon’s structure changes in nuclear matter
- Nuclear matter
- Consistency (difference) with (from) other soliton approaches
- Nucleon in finite nuclei and few and many body systems
- Summary and Outlook

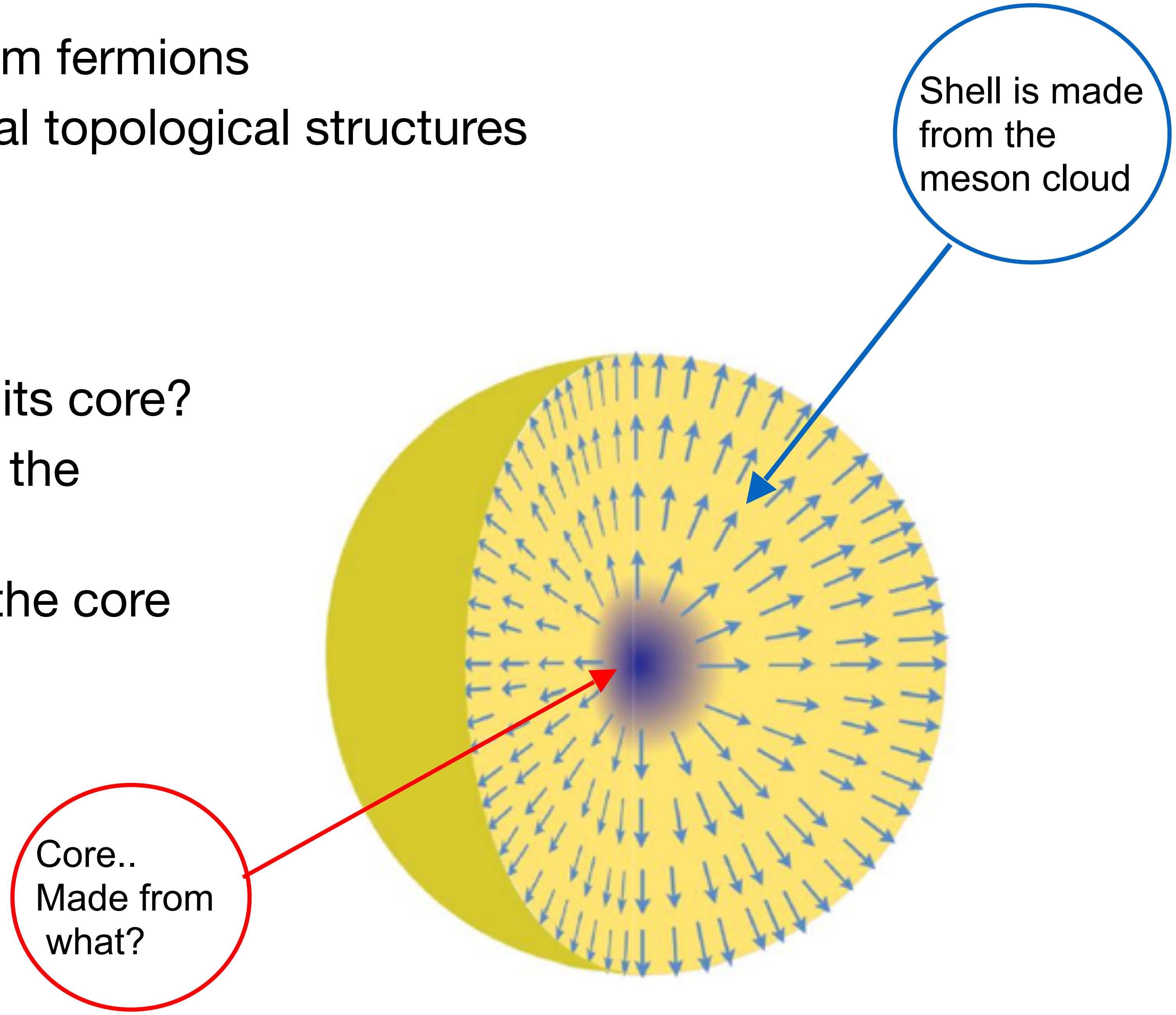
Topological models and soliton

Why topological models?

- At fundamental level we may have
  - fermions -> bosons are made from fermions
  - bosons -> fermions are nontrivial topological structures

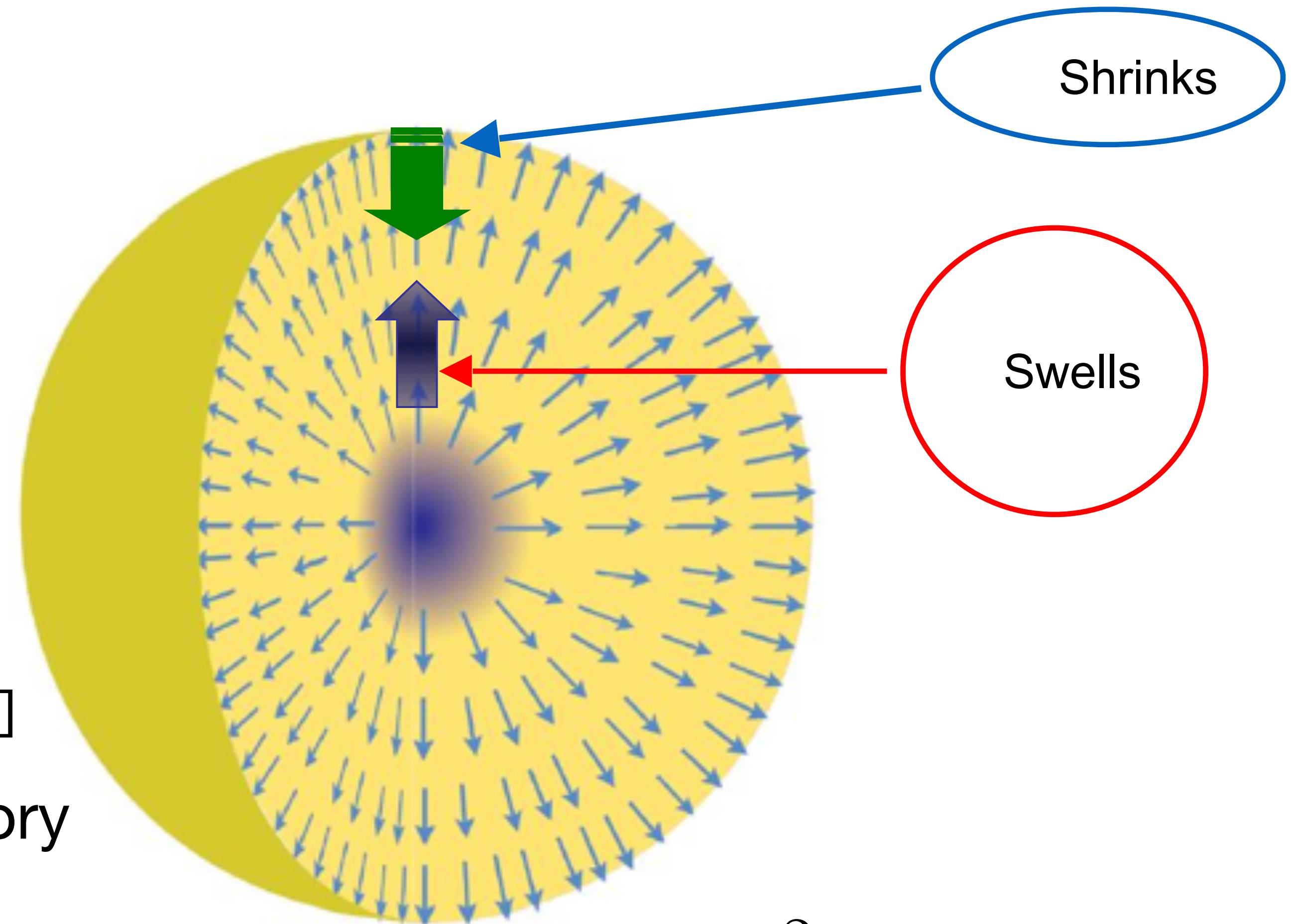
Structure

- What is a nucleon and, in particular, its core?
- The structure treatment depends on the energy scale
- At the limit of large number colours the core still has the mesonic content



Topological models and soliton

Stabilisation



- Soliton has the finite size and the finite energy
- One needs at least two terms in the effective (mesonic) Lagrangian

Prototype: **Skyrme model**

[T.H.R. Skyrme, Pros.Roy.Soc.Lond. A260 (1961)]

- Nonlinear chiral effective meson (pionic) theory

$$\mathcal{L} = \frac{F_\pi^2}{16}\,\mathrm{Tr}\left(\partial_\mu U \partial^\mu U^\dagger\right) - \frac{1}{16e^2}\,\mathrm{Tr}\,\left[U^\dagger \partial_\mu U, U^\dagger \partial_\nu U\right]^2$$

Shrinks　　　　Swells

- Hedgehog solution (nontrivial mapping)

$$U = \exp\left\{\frac{i\vec{\tau}\cdot\vec{\pi}}{2F_\pi}\right\} = \exp\{i\vec{\tau}\cdot\vec{n}F(r)\}$$

Topological models and soliton

The free space Lagrangian in use
[G.S.Adkins et al. Nucl.Phys. B228 (1983)]

$$\mathcal{L} = \frac{F_\pi^2}{16}\,\mathrm{Tr}\left(\partial_\mu U \partial^\mu U^\dagger\right) - \frac{1}{16e^2}\,\mathrm{Tr}\left[U^\dagger\partial_\mu U, U^\dagger\partial_\nu U\right]^2 + \frac{F_\pi^2 m_\pi^2}{16}\,\mathrm{Tr}\left(U + U^\dagger - 2\right)$$

- Nontrivial structure: topologically stable solitons with the corresponding conserved topological number (baryon number) ***A***

$$U = \exp\{i\bar{\tau}\,\bar{\pi}/2F_\pi\} = \exp\{i\bar{\tau}\,\bar{n}F(r)\}$$

$$B^\mu = \frac{1}{24\pi^2}\varepsilon^{\mu\nu\alpha\beta}Tr(L_\nu L_\alpha L_\beta) \qquad L_\alpha = U^+\partial_\alpha U$$

$$A = \int d^3 r B^0$$

- Nucleon is quantised state of the classical soliton-skyrmion

$$H = M_{cl} + \frac{\bar{S}^2}{2I} = M_{cl} + \frac{\bar{T}^2}{2I},$$

$$|\, S = T, s, t >= (-1)^{t+T}\sqrt{2T+1}D^{S=T}_{-t,s}(A)$$

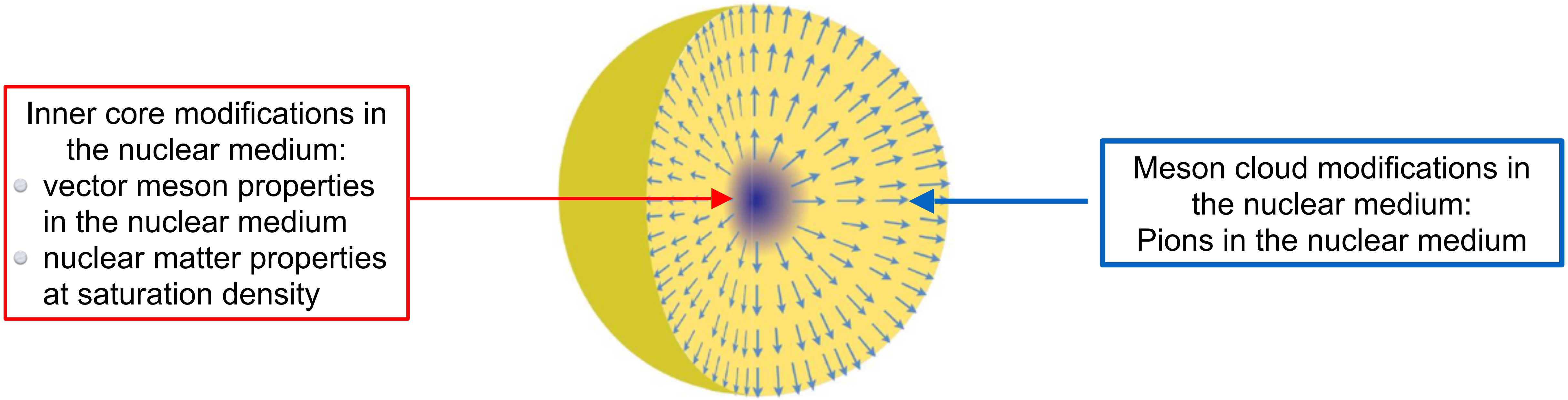
Medium modifications

What happens in the nuclear medium?

- The medium effects
  - Deformations (swelling or shrinking, multipole deformations) of nucleons
  - Possible characteristic changes: effective mass, charge distributions, form factors
  - NN interactions may change
  - etc.
- One should be able to describe all those phenomena

Soliton in the nuclear medium (phenomenological way)

- Outer shell modifications (informations from pionic atoms)
- Inner core modifications, in particular, at large densities (nuclear matter properties)



Medium modifications

"Outer shell" modifications

- In free space three types of pions can be treated separately: isospin breakin
- In nuclear matter: three types of polarization operators
- Optic potential approach: parameters from the pion-nucleon scattering, including isospin dependents

$$(\partial^\mu \partial_\mu + m_\pi^2)\vec{\pi}^{(\pm,0)} = 0$$

$$(\partial^\mu \partial_\mu + m_\pi^2 + \hat{\Pi}^{(\pm,0)})\vec{\pi}^{(\pm,0)} = 0$$

$$\hat{\Pi}^0 = 2\omega U_{\text{opt}} = \chi_s(\rho, b_0, c_0) + \vec{\nabla} \cdot \chi_p(\rho, b_0, c_0)\vec{\nabla}$$

	π-atom	$T_\pi = 50$ MeV
$b_0\ [m_\pi^{-1}]$	- 0.03	- 0.04
$b_1\ [m_\pi^{-1}]$	- 0.09	- 0.09
$c_0\ [m_\pi^{-3}]$	0.23	0.25
$c_1\ [m_\pi^{-3}]$	0.15	0.16
g'	0.47	0.47

Medium modifications

"Outer shell" modifications [U.Meissner *et al.*, EPJ A36 (2008)]

$$\mathcal{L}_2^* = \frac{F_\pi^2}{16}\alpha_\tau \mathrm{Tr}\left(\partial_0 U \partial_0 U^\dagger\right) - \frac{F_\pi^2}{16}\alpha_s \mathrm{Tr}\left(\partial_i U \partial_i U^\dagger\right)$$

$$\mathcal{L}_m^* = -\frac{F_\pi^2 m_\pi^2}{16}\alpha_m \mathrm{Tr}\left(2 - U - U^+\right)$$

- Due to the nonlocality of optic potential the kinetic term is also modified
- Due to energy and momentum dependence of the optic potential parameters following parts of the kinetic term is modified in different form:
  - Temporal part
  - Space part

$$\hat{\Pi}^0 = 2\omega U_{\mathrm{opt}} = \chi_s(\rho, b_0, c_0) + \vec{\nabla}\cdot\chi_p(\rho, b_0, c_0)\vec{\nabla}$$

	π-atom	$T_\pi = 50$ MeV
$b_0\ [m_\pi^{-1}]$	- 0.03	- 0.04
$b_1\ [m_\pi^{-1}]$	- 0.09	- 0.09
$c_0\ [m_\pi^{-3}]$	0.23	0.25
$c_1\ [m_\pi^{-3}]$	0.15	0.16
g'	0.47	0.47

Medium modifications

"Inner core" modifications
[UY & H.Ch. Kim, PRC83 (2011); UY, JKPS62 (2013); UY, PRC88 (2013)]

$$\mathcal{L}_4^* = -\frac{1}{16e^2\zeta_\tau}\,\mathrm{Tr}\,\left[U^\dagger\partial_0 U, U^\dagger\partial_i U\right]^2 + \frac{1}{32e^2\zeta_s}\,\mathrm{Tr}\,\left[U^\dagger\partial_i U, U^\dagger\partial_j U\right]^2$$

- May be related to
  - Vector meson properties in nuclear matter
  - Nuclear matter properties

$$\zeta_{\tau,s} = \zeta_{\tau,s}(\rho, \delta\rho, \mathrm{parameters})$$

Medium modifications

Final Lagrangian
[UY, JKPS62 (2013); UY, PRC88 (2013)]

- Separated into two parts

$$\mathcal{L}^* = \mathcal{L}^*_{\rm sym} + \mathcal{L}^*_{\rm asym}$$

  - Isoscalar part

$$\mathcal{L}^*_{\rm sym} = \mathcal{L}^*_2 + \mathcal{L}^*_4 + \mathcal{L}^*_m$$

  - Isovector part

$$\mathcal{L}^*_{\rm asym} = \mathcal{L}^*_{\delta m} + \mathcal{L}^*_{\delta\rho}$$

  - **Nuclear matter stabilisation** ($\rightarrow \mathcal{L}^*_2$, $\mathcal{L}^*_4$)

  - **Asymmetric matter properties** ($\rightarrow \mathcal{L}^*_{\delta\rho}$)

$$\mathcal{L}^*_2 = \frac{F_\pi^2}{16}\,\alpha_\tau {\rm Tr}\left(\partial_0 U \partial_0 U^\dagger\right) - \frac{F_\pi^2}{16}\,\alpha_s {\rm Tr}\left(\partial_i U \partial_i U^\dagger\right)$$

$$\mathcal{L}^*_4 = -\frac{1}{16e^2\zeta_\tau}\,{\rm Tr}\left[U^\dagger\partial_0 U, U^\dagger\partial_i U\right]^2 + \frac{1}{32e^2\zeta_s}\,{\rm Tr}\left[U^\dagger\partial_i U, U^\dagger\partial_j U\right]^2$$

$$\mathcal{L}^*_m = -\frac{F_\pi^2 m_\pi^2}{16}\,\alpha_m {\rm Tr}\left(2 - U - U^+\right)$$

$$\mathcal{L}^*_{\delta m} = -\frac{F_\pi^2}{32}\sum_{a=1}^{2}(m^2_{\pi^\pm} - m^2_{\pi^0}){\rm Tr}\left(\tau_a U\right){\rm Tr}\left(\tau_a U^\dagger\right)$$

$$\mathcal{L}^*_{\delta\rho} = -\frac{F_\pi^2}{16}\,m_\pi \alpha_e\,\varepsilon_{ab3}{\rm Tr}\left(\tau_a U\right){\rm Tr}\left(\tau_b \partial_0 U^\dagger\right)$$

Medium modifications

Reparametrization
[UY, PRC88 (2013)]

- Five density dependent parameters

Shell modifications:

$$F_{\pi,\tau} \to F^*_{\pi,\tau}, \quad F_{\pi,s} \to F^*_{\pi,s},$$

Core modifications:

$$e_\tau \to e^*_\tau, \quad e_s \to e^*_s$$

$$m_\pi \to m^*_\pi,$$

- Rearrangment (technical simplification)

$$1 + C_1 \frac{\rho}{\rho_0} = f_1\left(\frac{\rho}{\rho_0}\right) \equiv \sqrt{\frac{\alpha_p^0}{\gamma_s}}$$

$$1 + C_2 \frac{\rho}{\rho_0} = f_2\left(\frac{\rho}{\rho_0}\right) \equiv \frac{\alpha_s^{00}}{(\alpha_p^0)^2 \gamma_s}$$

$$1 + C_3 \frac{\rho}{\rho_0} = f_3\left(\frac{\rho}{\rho_0}\right) \equiv \frac{(\alpha_p^0 \gamma_s)^{3/2}}{\alpha_s^{02}}$$

$$\frac{\alpha_e}{\gamma_s} = f_4\left(\frac{\rho}{\rho_0}\right) \frac{\rho_n - \rho_p}{\rho_0} = \frac{C_4 \frac{\rho}{\rho_0}}{1 + C_5 \frac{\rho}{\rho_0}} \frac{\rho_n - \rho_p}{\rho_0}$$

Nucleon properties in nuclear matter

Structure: Energy momentum tensor

- It allows to address the questions like:
  - How are the total angular momentum and angular momentum of the nucleon shared among its constituents?
  - How are the strong forces experienced by its constituents distributed inside the nucleon?
- EMT form factors studied in lattice QCD, ChPT and in different models (chiral quark soliton model, Skyrme model, etc.)
- We made further step studying EMT form factors in nuclear matter

Structure: Pressure distribution inside the nucleon in free space and in symmetric matter [H.C.Kim, P. Schweitzer, UY, Phys.Lett. B718 (2012)]

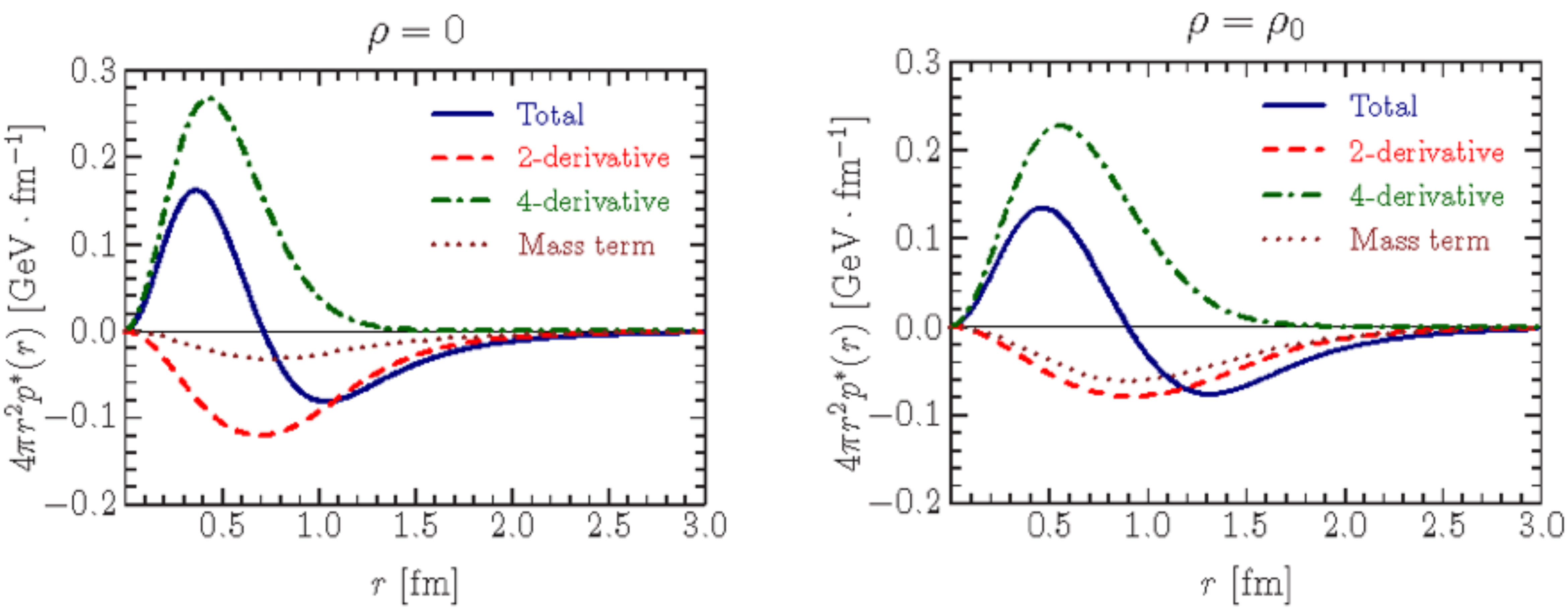


FIG. 3: (Color online) The decomposition of the pressure densities $4\pi r^2 p^*(r)$ as functions of r, in free space ($\rho = 0$) and at $\rho = \rho_0$, in the left and right panels, respectively. The solid curves denote the total pressure densities, the dashed ones represent the contributions of the 2-derivative (kinetic) term, the long-dashed ones are those of the 4-derivative (stabilizing) term, and the dotted ones stand for those of the pion mass term.

Nucleon properties in nuclear matter

Stability and applicability [H.C.Kim, P. Schweitzer, UY, Phys.Lett. B718 (2012)]

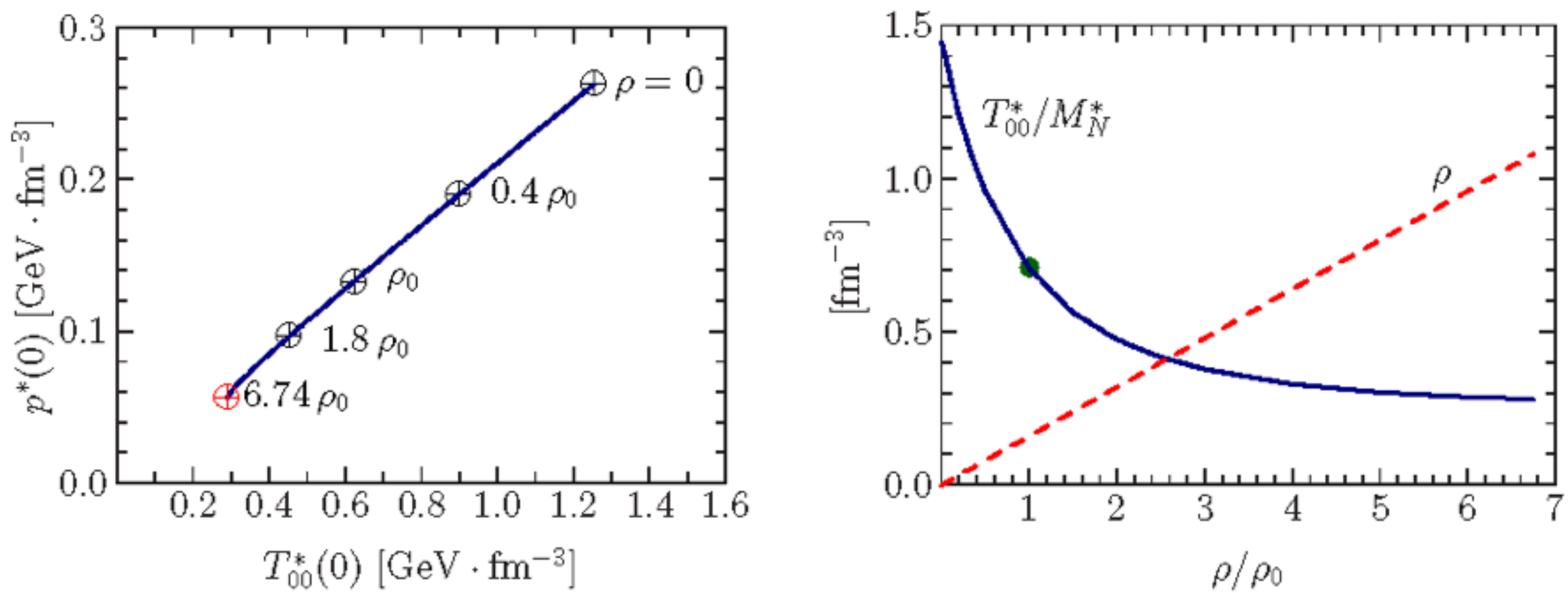


FIG. 5: (Color online) In the left panel, the correlated change of $p^*(0)$ and $T^*_{00}(0)$ drawn with ρ varied. In the right panel, the T^*_{00}/M^*_N and ρ depicted as a function of ρ/ρ_0. The maximal density is given as about $6.74\,\rho_0$, above which the Skyrmion does not exist anymore. The filled circle on the solid curve represents the value of T^*_{00}/M^*_N at normal nuclear matter density.

Nucleon properties in nuclear matter

Nucleon in nuclear matter
[UY, PRC88 (2013)]

- Isovector mass

$$m^*_{N,s} = M^*_S + \frac{3}{8\Lambda^*} + \frac{\Lambda^*}{2}\left(a^{*2} + \frac{\Lambda^{*2}_{\mathrm{env}}}{\Lambda^{*2}}\right)$$

- Isovector mass

$$\Delta m^*_{np} = a^* + \frac{\Lambda^*_{\mathrm{env}}}{\Lambda^*}$$

- Mass of the nucleon

$$m^*_{n,p} = m^*_{N,s} - \Delta m^*_{np} T_3$$

Nuclear matter

The binding-energy-formula terms in the framework of present model

$$\varepsilon(A,Z) = -a_V + a_S \frac{(N-Z)^2}{A^2} + \square$$

We are ready to reproduce

- Volume term
  - Infinite and asymmetric nuclear matter
- Asymmetry term
  - Isospin asymmetric environment
- Surface and Coulomb terms
  - Nucleons in a finite volume
- Finite nuclei properties
  - Local density approximation

Nuclear matter

The volume term and Symmetry energy

- At infinite nuclear matter approximation the binding energy per nucleon takes the form

$$\varepsilon(\lambda,\delta) = \varepsilon_V(\lambda) + \varepsilon_S\delta^2 + O(\delta^4) \equiv \varepsilon_V(\lambda) + \varepsilon_A(\lambda,\delta)$$

  - λ is normalised nuclear matter density
  - δ is asymmetry parameter
  - ε_S is symmetry energy

- In our model
  - Symmetric matter
  - Asymmetric matter

$$\varepsilon_V(\lambda) = m^*_{N,s}(\lambda,0) - m_N^{\text{free}}$$

$$\varepsilon_A(\lambda,\delta) = \varepsilon(\lambda,\delta) - \varepsilon_V(\lambda)$$

$$= m^*_{N,s}(\lambda,\delta) - m^*_{N,s}(\lambda,0) + m^*_{N,V}(\lambda,\delta)\delta$$

Nuclear matter properties

- Symmetric matter properties (pressure, compressibility and third derivative)

$$p = \rho_0 \lambda^2 \left. \frac{\partial \varepsilon_V(\lambda)}{\partial \lambda} \right|_{\lambda=1}, \quad K_0 = 9\rho^2 \left. \frac{\partial^2 \varepsilon_V(\lambda)}{\partial \rho^2} \right|_{\rho=\rho_0} \quad Q = 27\lambda^3 \left. \frac{\partial^3 \varepsilon_V(\lambda)}{\partial \lambda^3} \right|_{\lambda=1}$$

- Symmetry energy properties (coefficient, slop and curvature)

$$\varepsilon_s(\lambda) = \varepsilon_s(1) + \frac{L_s}{3}(\lambda - 1) + \frac{K_S}{18}(\lambda - 1)^2 + \square$$

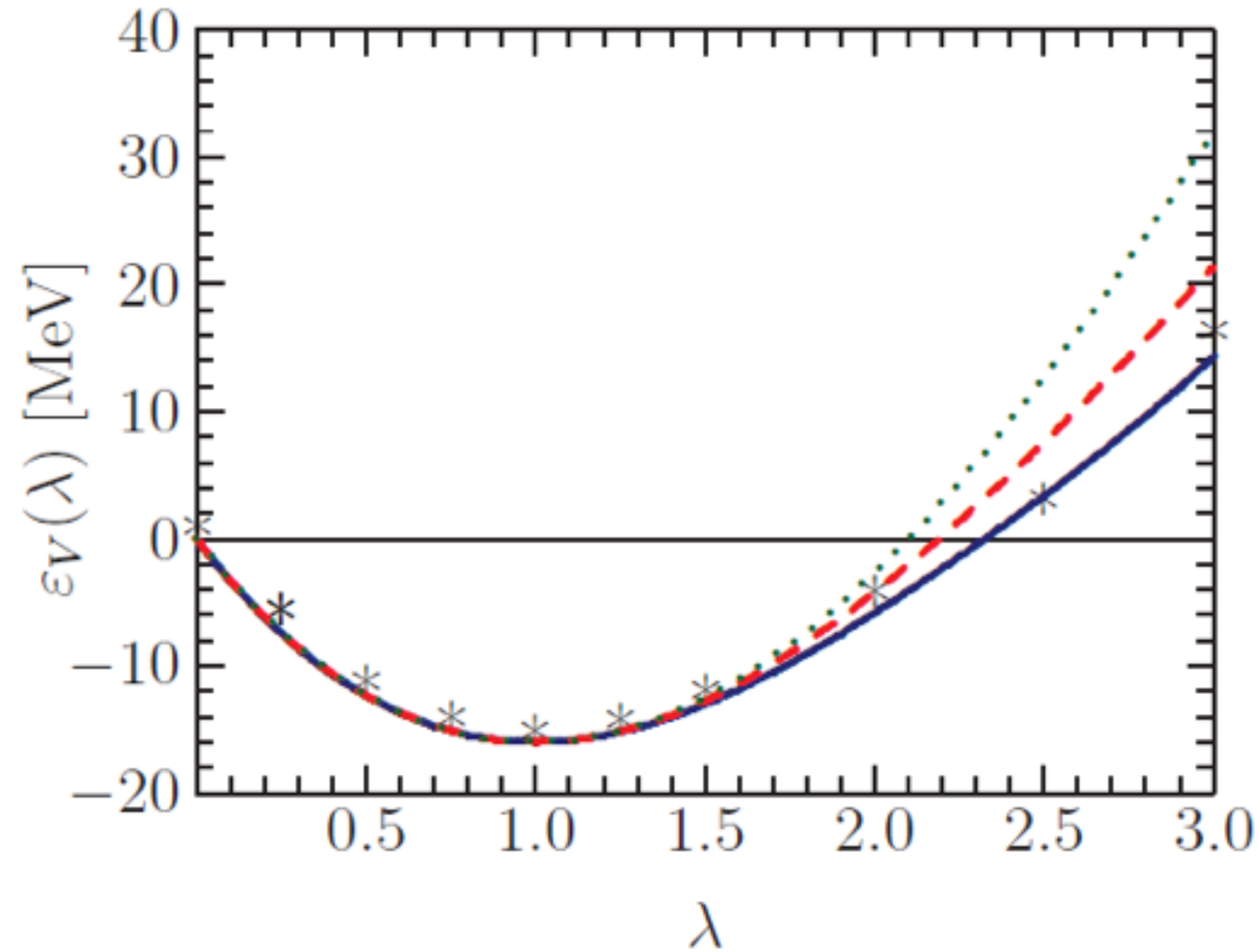
Symmetric matter

Volume energy
[UY, PRC88 (2013)]

- Set I – solid
- Set II – dashed
- Set III – dotted

For comparison: Akmal-Pandharipande-Ravenhall (APR) predictions [PRC 58, 1804 (1998)] are given by stars.

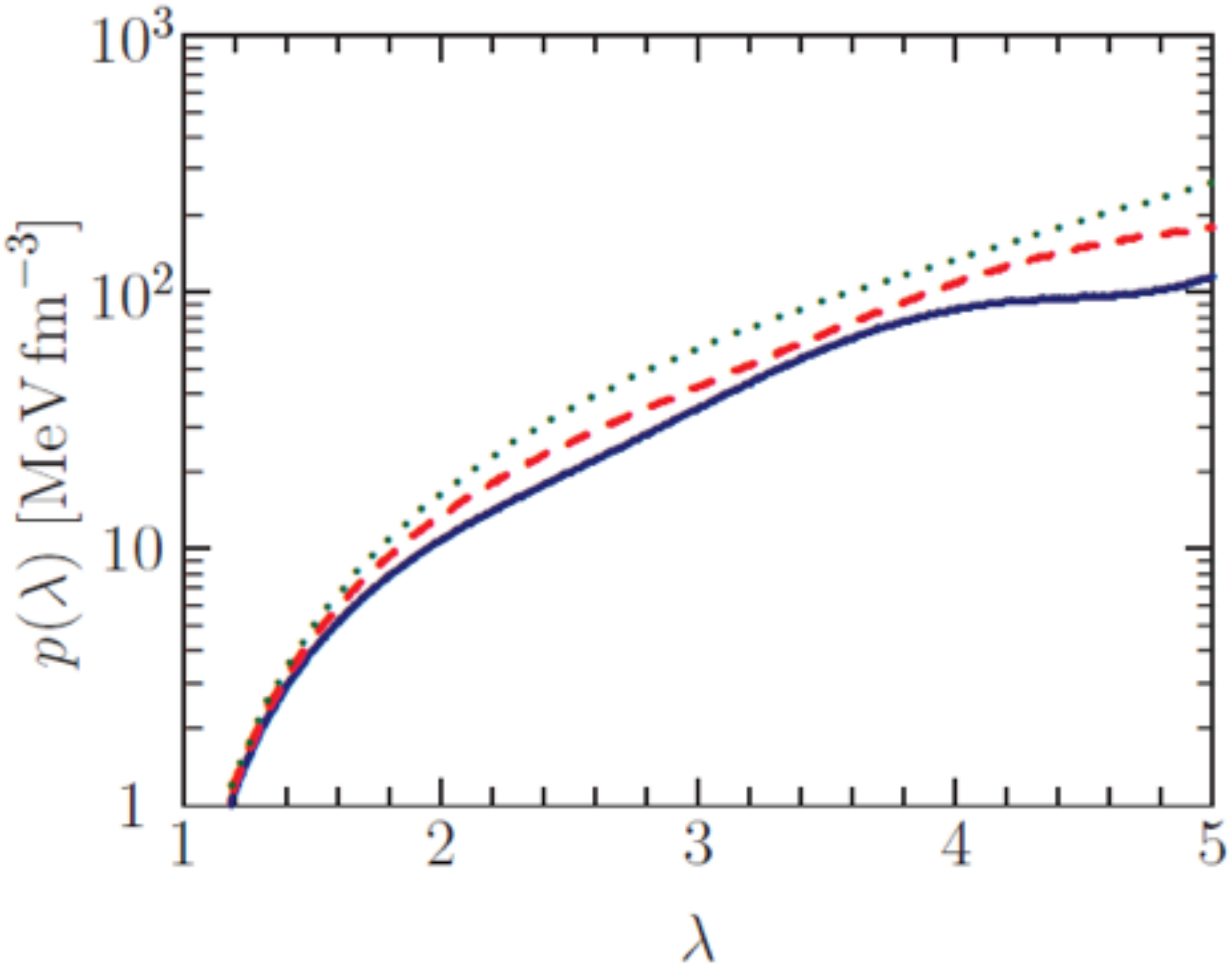
(From Arigonna 2 body interactions + 3 body interactions)

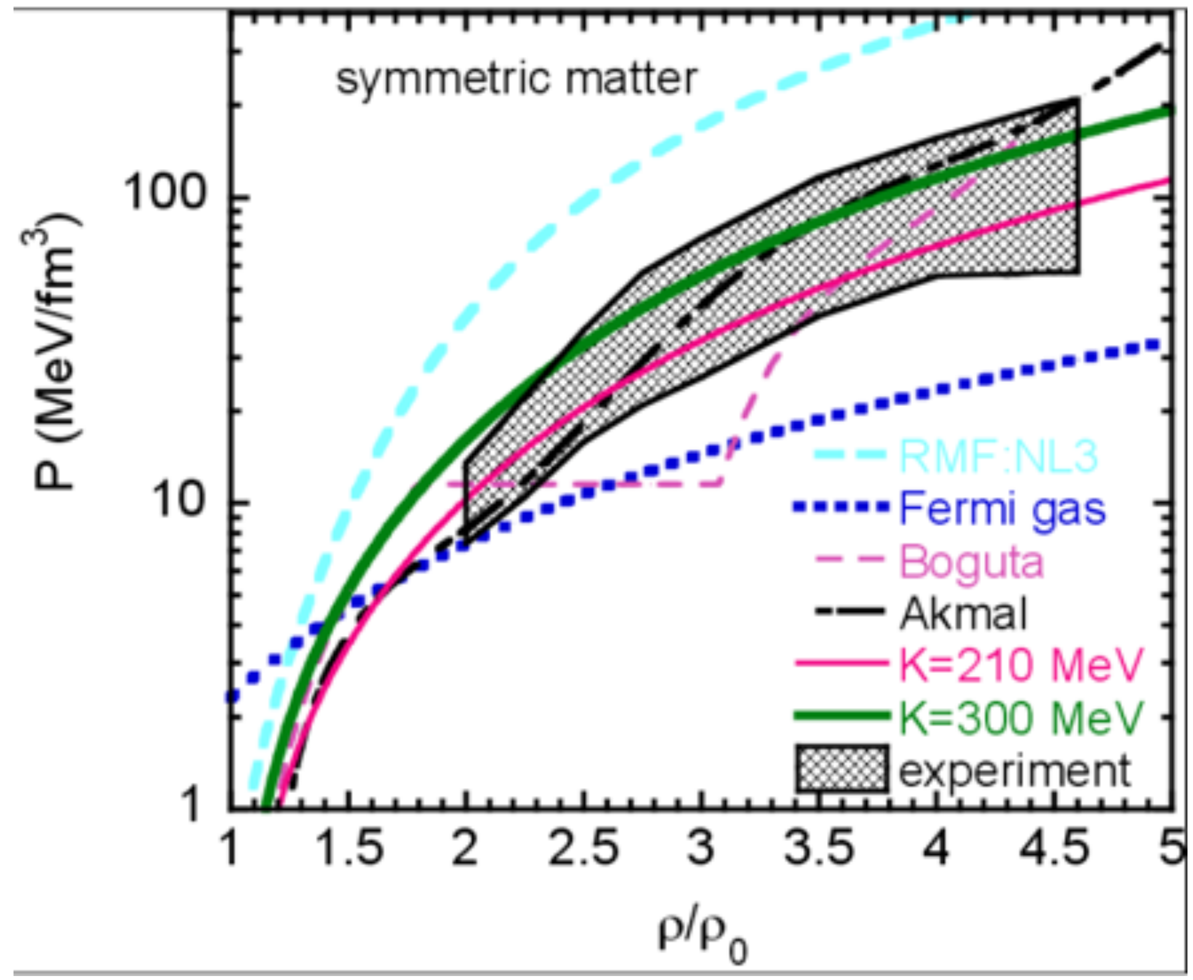


Set	C_1	C_2	C_3	$\varepsilon_V(\rho_0)$ (MeV)	K_0 (MeV)	Q (MeV)
I	−0.279	0.737	1.782	−16	240	−410
II	−0.273	0.643	1.858	−16	250	−279
III	−0.277	0.486	2.124	−16	260	−178

Symmetric matter

Pressure
[UY, PRC88 (2013)]





For comparison: Right figure from
Danielewicz- Lacey-Lynch, Science 298, 1592 (2002).
(Deduced from experimental flow data and simulations studies)

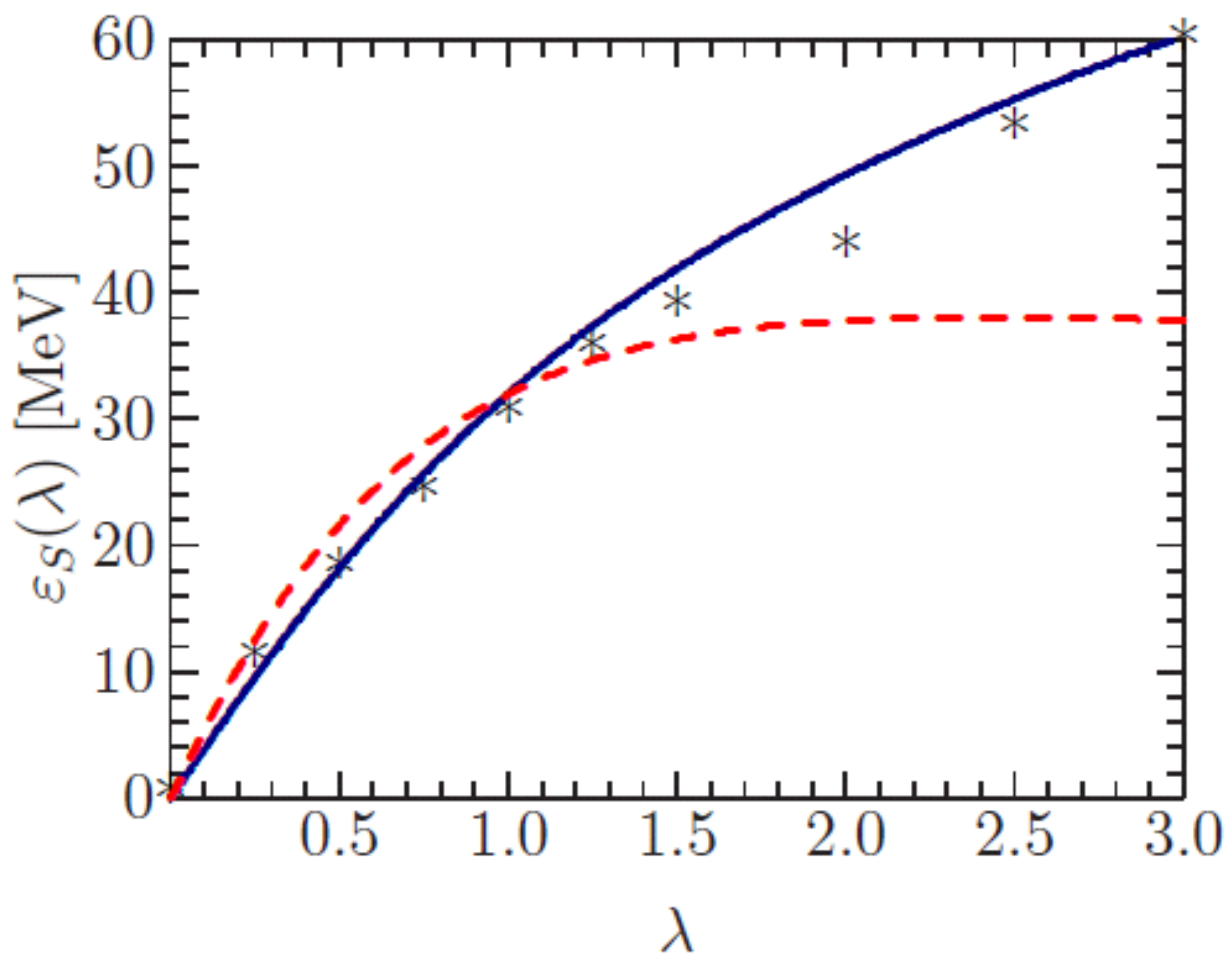
Asymmetric matter

Symmetry energy

- Solid $L_s = 70\,\mathrm{MeV}$
- Dashed $L_s = 40\,\mathrm{MeV}$

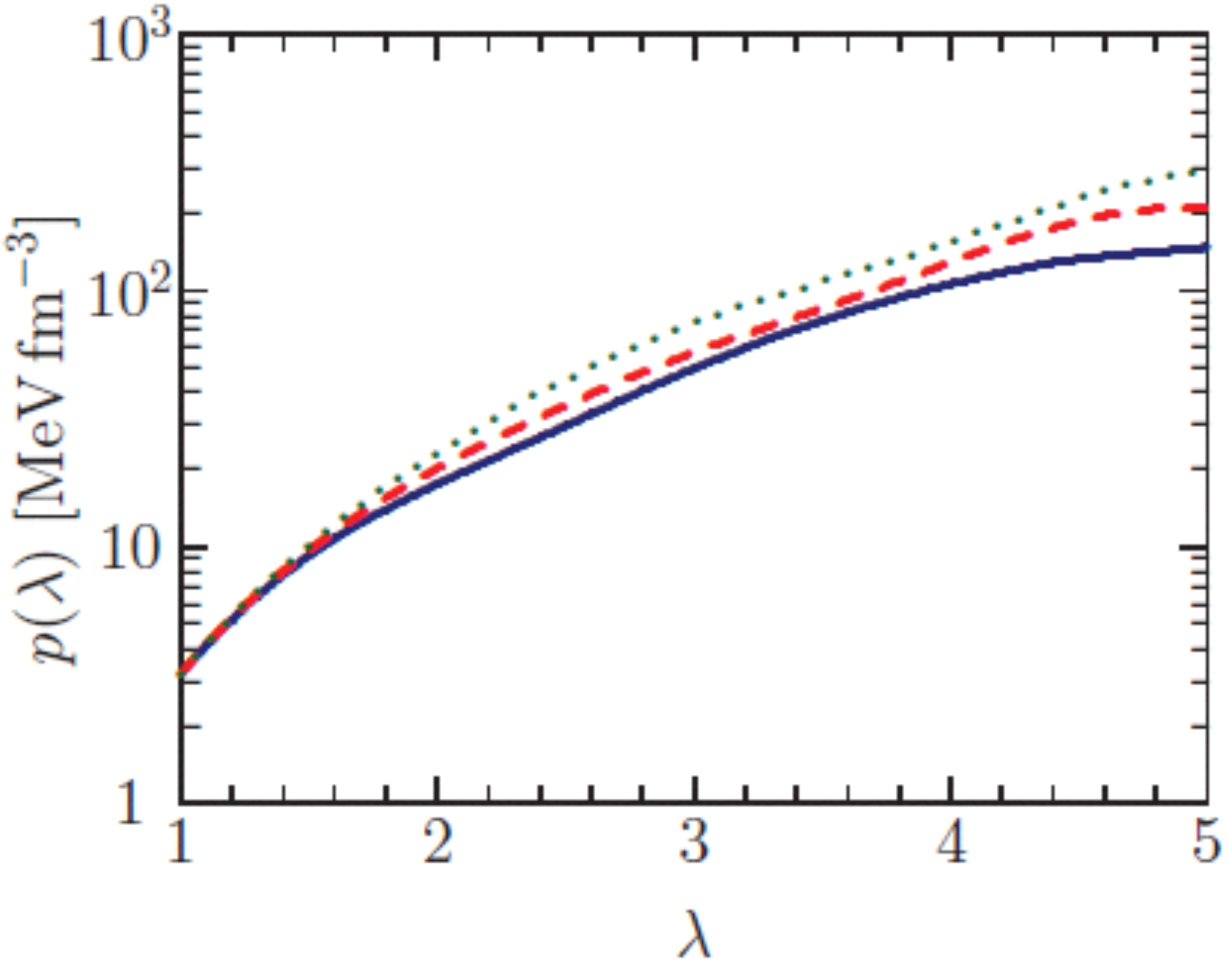
For comparison: Akmal-Pandharipande-Ravenhall (APR) predictions [PRC 58, 1804 (1998)] are given by stars.

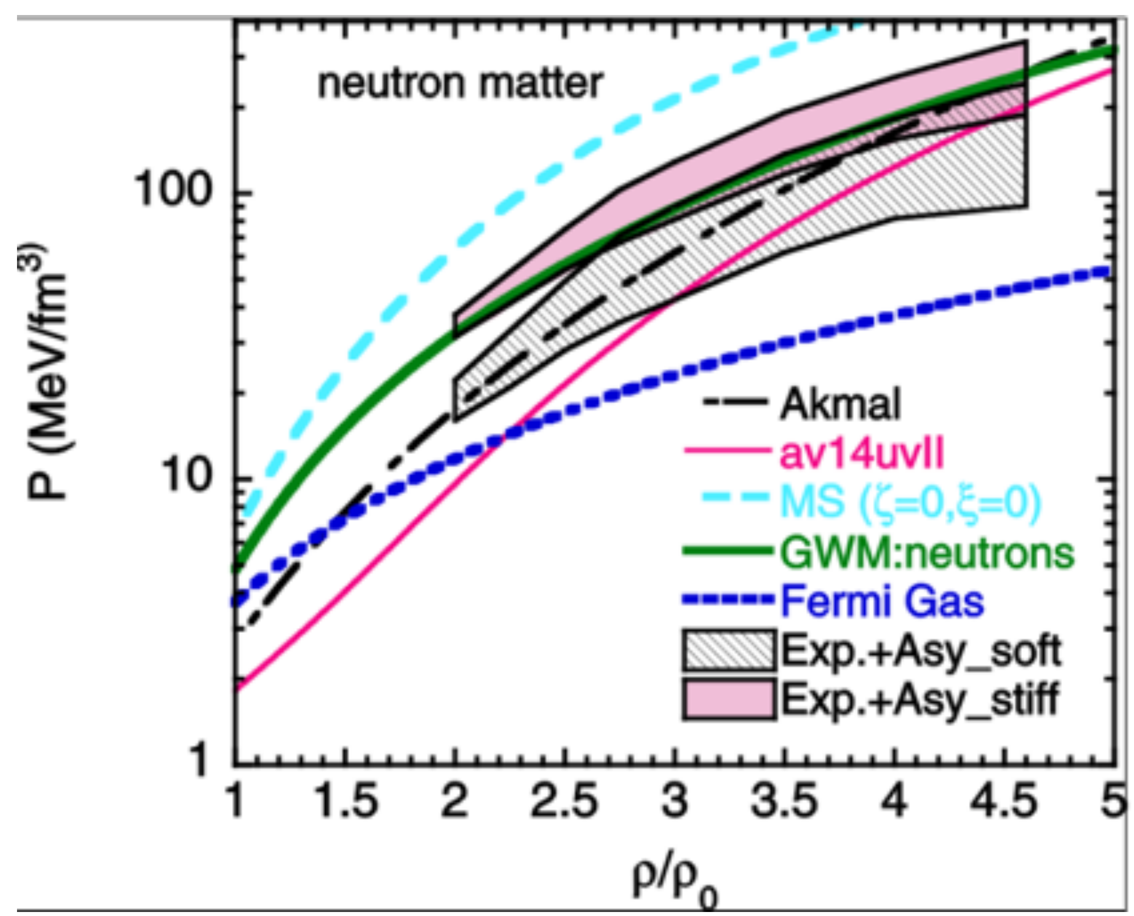
(From arigonna 2 body interactions + 3 body interactions)



Asymmetric matter

Pressure in neutron matter
[UY, PRC88 (2013)]





For comparison: Right figure from
Danielewicz- Lacey-Lynch, Science 298, 1592 (2002).
(Deduced from experimental flow data and simulations studies)

Asymmetric matter

Low density behaviour of symmetry energy

For comparison:
Trippa-Colo-Vigezzi
[PRC 77, 061304 (2008)];
From analysis of GDR
(208Pb).

$$23.3 < \varepsilon_s(\rho = 0.1\text{fm}^{-3}) < 24.9 \text{ MeV}$$

Consequently one can predict in this model:

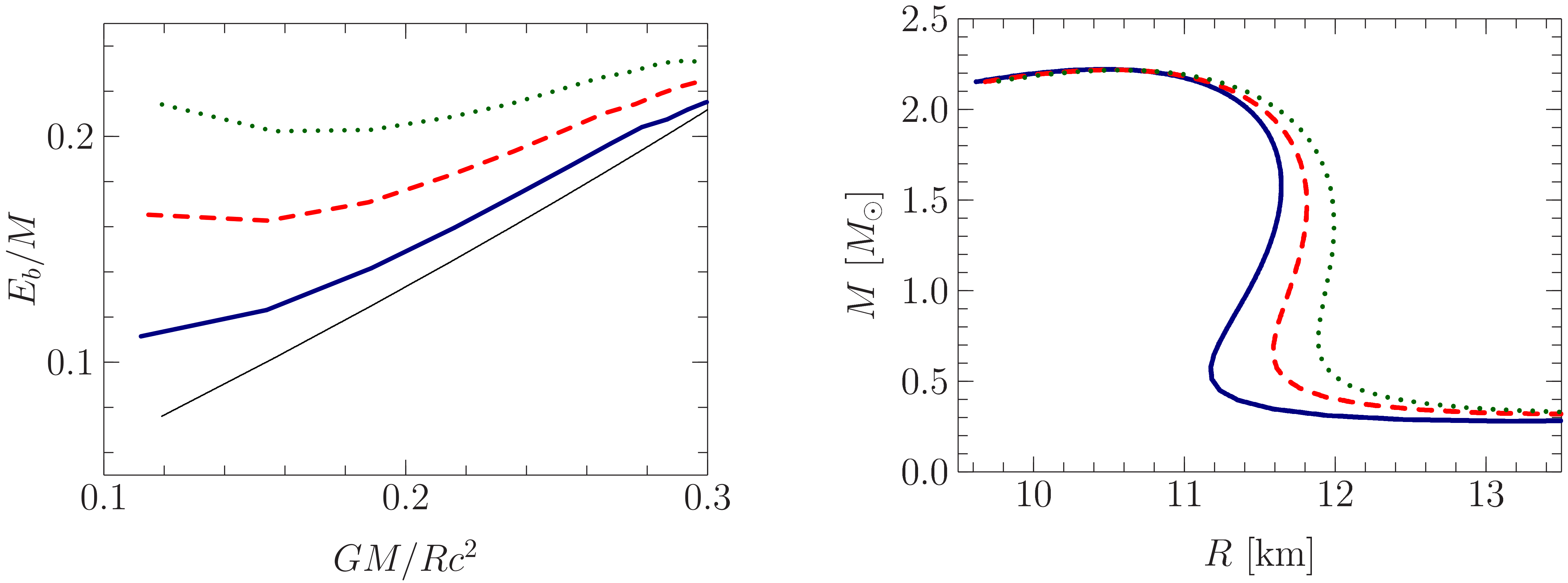
$$K_\tau = K_s - 6L_s$$

$$K_{0,2} = K_\tau - \frac{Q}{K_0} L_S$$

$\varepsilon_S(\rho_0)$ [MeV]	L_S [MeV]	K_S [MeV]	K_τ [MeV]	$K_{0,2}$ [MeV]	$\varepsilon_S(0.1\text{fm}^{-3})$ [MeV]
32	40	−181	−301	−257	25.15
32	50	−160	−310	−254	24.15
32	60	−126	−306	−239	23.22
32	70	−80	−290	−211	22.37
32	80	−21	−261	−172	21.57
32	90	50	−220	−119	20.82
32	100	134	−166	−55	20.13

Neutron stars

Neutron star properties [UY, arXiv:1506.06481[nucl-th]]



Neutron star properties [UY, arXiv:1506.06481[nucl-th]]

TABLE III: Properties of the neutron stars from the different sets of parameters (see Tables I and II for the values of parameters): n_c is central number density, ρ_c is central energy-mass density, R is radius of the neutron star, $M_{\max}$ is possible maximal mass, A is number of baryons in the star, E_b is binding energy of the star. In the left panel we represent the neutron star properties corresponding to the maximal mass $M_{\max}$ and in right panel approximately 1.4 solar mass neutron star properties. The last two lines are results from the Ref. [21].

Set	n_c [fm^{-3}]	ρ_c [10^{15}gr/cm^3]	R [km]	$M_{\max}$ [$M_\odot$]	A [10^{57}]	E_b [10^{53}erg]	n_c [fm^{-3}]	ρ_c [10^{15}gr/cm^3]	R [km]	M [$M_\odot$]	A [10^{57}]	E_b [10^{53}erg]
III-a	1.046	2.445	10.498	2.226	3.227	8.721	0.479	0.861	11.587	1.402	1.898	3.503
III-b	1.045	2.444	10.547	2.223	3.216	8.557	0.471	0.861	11.772	1.402	1.895	3.453
III-c	1.037	2.424	10.616	2.221	3.200	8.397	0.460	0.832	11.953	1.402	1.887	3.339
III-d	1.047	2.452	10.494	2.221	3.213	8.598	0.481	0.867	11.619	1.402	1.893	3.422
III-e	1.044	2.440	10.554	2.218	3.203	8.495	0.473	0.858	11.809	1.403	1.890	3.384
III-f	1.040	2.433	10.609	2.216	3.189	8.311	0.464	0.842	11.992	1.403	1.887	3.334
SLy230a [21]	1.15	2.69	10.25	2.10	2.99	7.07	0.508	0.925	11.8	1.4	1.85	2.60
SLy230b [21]	1.21	2.85	9.99	2.05	2.91	6.79	0.538	0.985	11.7	1.4	1.85	2.61

Consistency (difference) with (from) other models

One can find density functionals from the reparametrization scheme
[UY, PRC88 (2013)]

- Five density dependent parameters

Shell modifications

$$F_{\pi,\tau} \to F^*_{\pi,\tau}, \quad F_{\pi,s} \to F^*_{\pi,s},$$

Core modifications

$$e_\tau \to e^*_\tau, \quad e_s \to e^*_s$$

$$m_\pi \to m^*_\pi,$$

- Rearrangment (technical simplification)

$$1 + C_1 \frac{\rho}{\rho_0} = f_1\left(\frac{\rho}{\rho_0}\right) \equiv \sqrt{\frac{\alpha_p^0}{\gamma_s}}$$

$$1 + C_2 \frac{\rho}{\rho_0} = f_2\left(\frac{\rho}{\rho_0}\right) \equiv \frac{\alpha_s^{00}}{(\alpha_p^0)^2 \gamma_s}$$

$$1 + C_3 \frac{\rho}{\rho_0} = f_3\left(\frac{\rho}{\rho_0}\right) \equiv \frac{(\alpha_p^0 \gamma_s)^{3/2}}{\alpha_s^{02}}$$

$$\frac{\alpha_e}{\gamma_s} = f_4\left(\frac{\rho}{\rho_0}\right) \frac{\rho_n - \rho_p}{\rho_0} = \frac{C_4 \dfrac{\rho}{\rho_0}}{1 + C_5 \dfrac{\rho}{\rho_0}} \frac{\rho_n - \rho_p}{\rho_0}$$

Consistency (difference) with (from) other models

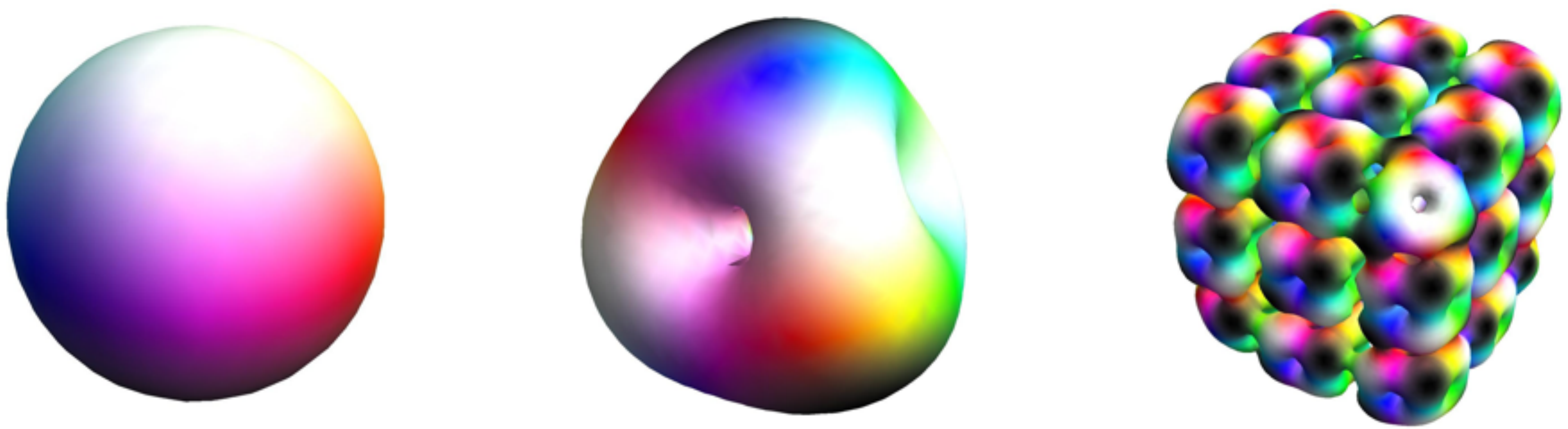
Low energy constants in nuclear at normal nuclear matter density ρ_0

	Present model	ChPT [1]	QCD sum rules [2]
$F^*_{\pi,t} / F_\pi$	0.37	0.74	0.79
$F^*_{\pi,s} / F_\pi$	0.72	< 0	0.78

[1] U. Meissner, J. Oller, A. Wirzba, Annals Phys. 297 (2002) 27.
[2] H. Kim, M. Oka, NPA720 (2003) 368.

Consistency (difference) with (from) other models

Surface of constant baryon density skyrmions [Feist, D.T.J. *et al.* Phys.Rev. D87 (2013)]



$B = 1$ $B = 3$ $B = 104$

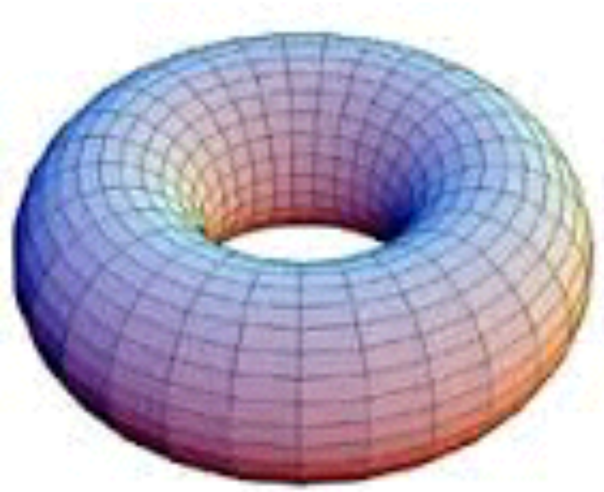
$$\mathcal{L} = \frac{F_\pi^2}{16}\,\mathrm{Tr}\left(\partial_\mu U \partial^\mu U^\dagger\right) - \frac{1}{16e^2}\,\mathrm{Tr}\left[U^\dagger \partial_\mu U, U^\dagger \partial_\nu U\right]^2$$

Changes from a nucleus to a nucleus (“calibration”)

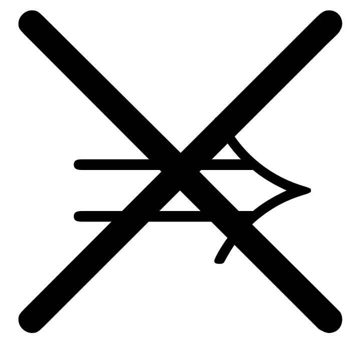
Consistency (difference) with (from) other models

?

Topological non-triviality

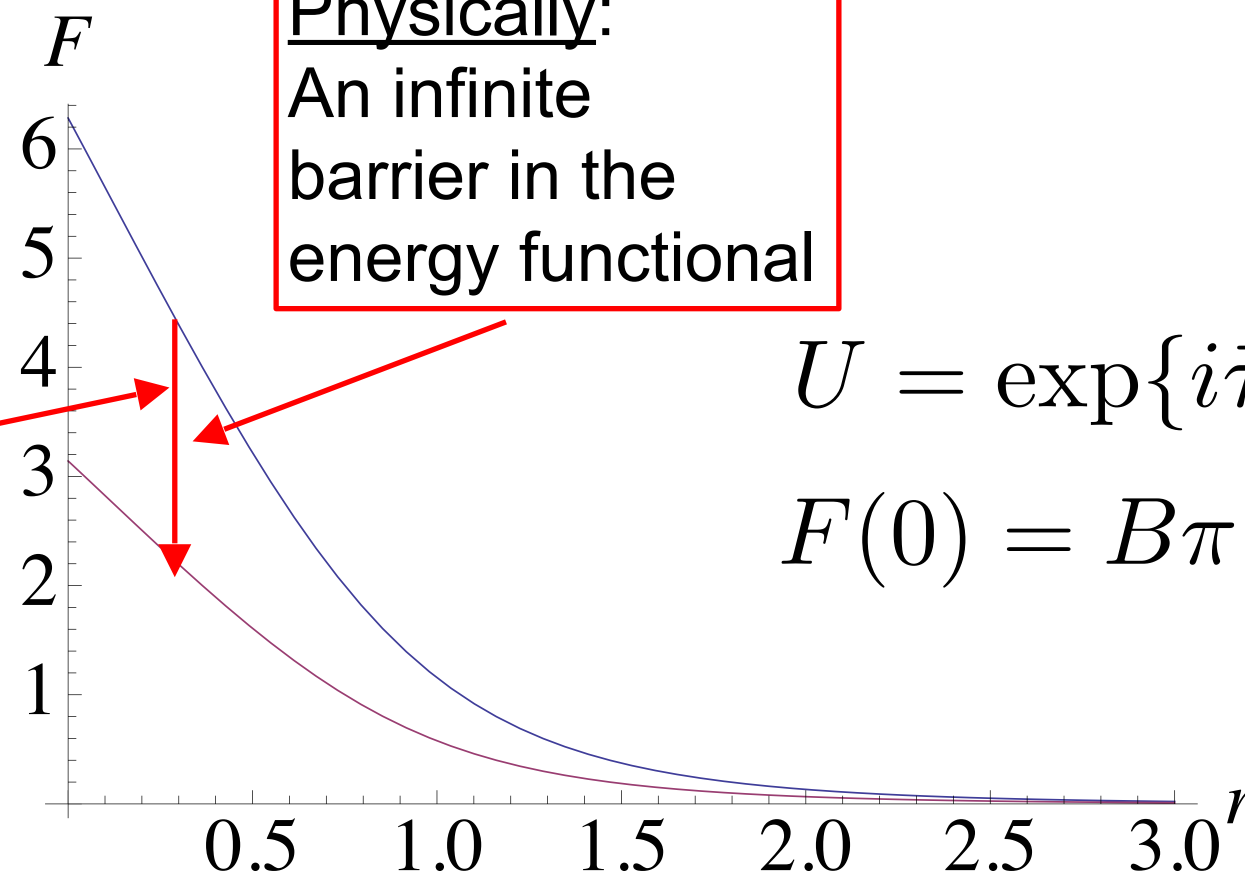


$B = 2$



$B = 1$

$B = 1$



Physically:
An infinite barrier in the energy functional

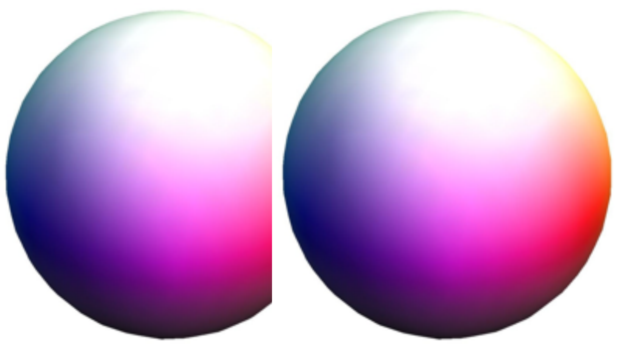
Mathematically:
There is no smooth transition between topologically distinct mappings

$$U = \exp\{i\vec{\tau}\vec{n}F(r)\}$$

$$F(0) = B\pi, \qquad F(\infty) = 0$$

Consistency (difference) with (from) other models

Physically consistent picture (ansatz product)



$$\text{Well defined} \Rightarrow$$

$B = 2$ $\qquad$ $B = 1$ $\qquad$ $B = 1$

Overlapping at small distances

Well separated at large distances

One can reproduce SS potential and project it into NN potential.

$$U_{\text{system}} = U(\vec{r}_1)U(\vec{r}_2)$$

$$U = \exp\{i\vec{\tau}\vec{n}F(r)\}$$

$$F(0) = \pi, \qquad F(\infty) = 0$$

Consistency (difference) with (from) other models

Other approaches

- Classical crystalline structures
  - Cubic structure
    [M. Kutschera *et al*. Phys. Rev. Lett. **53** (1984)]
    [I. R. Klebanov, Nucl. Phys. B **262** (1985)]
  - Phase structure analysis using FCC crystal
    [H.-J. Lee *et al.* Nucl. Phys. A **723** (2003)]
- Skyrmions in hypersphere
  - System properties from the single skyrmion in hypersphere
    [N. S. Manton and P. J. Ruback, Phys. Lett. B **181** (1986)]

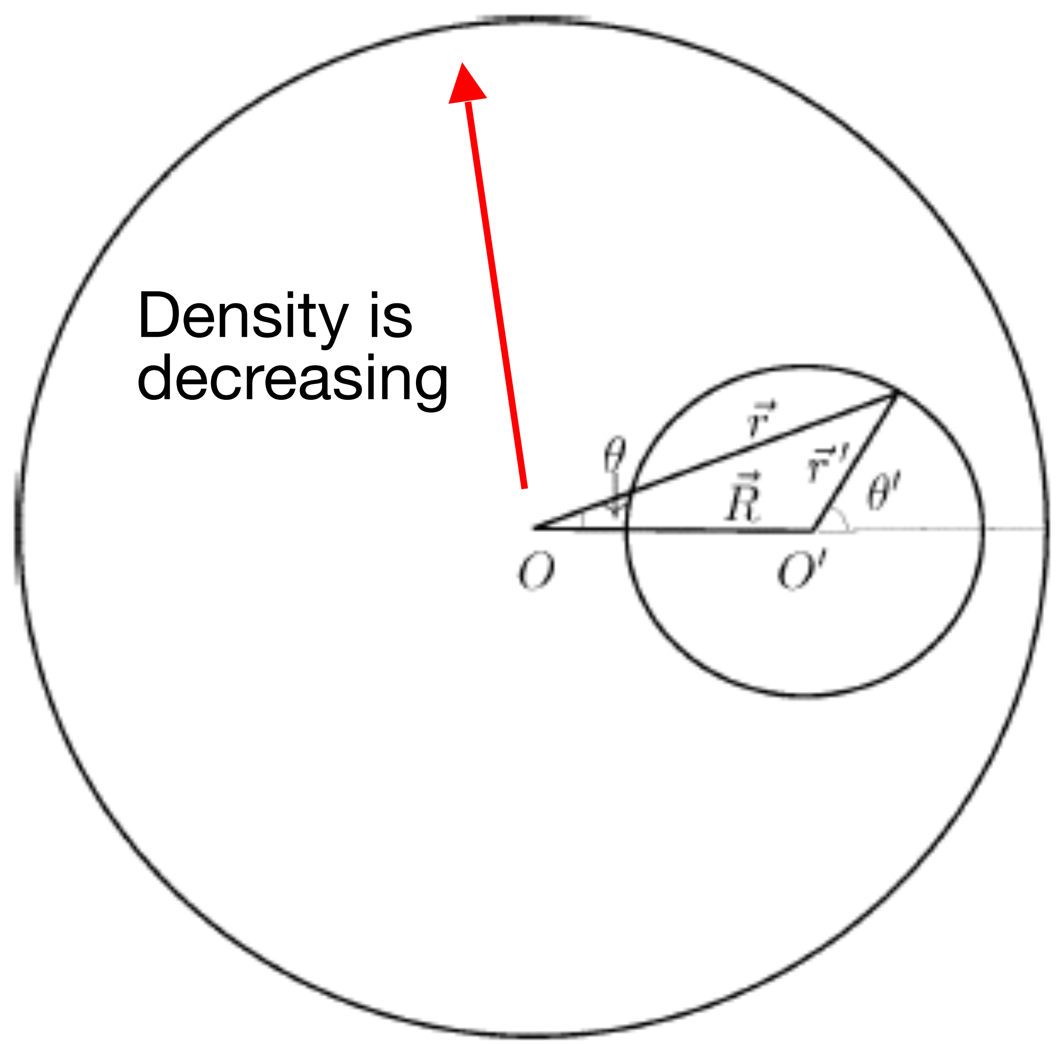
Nucleon in a nucleus (local density approximation)

- The problem is coupled partial differential equations

$$f\,(F_{\bar{r}\bar{r}},\, F_{\theta\theta},\, F_{\bar{r}},\, F_{\theta},\, \Theta_{\theta},\, F,\, \Theta) = 0,$$

$$g(\Theta_{\theta\theta},\, \Theta_{\theta},\, F_{\bar{r}},\, F_{\theta},\, \Theta,\, F) = 0,$$

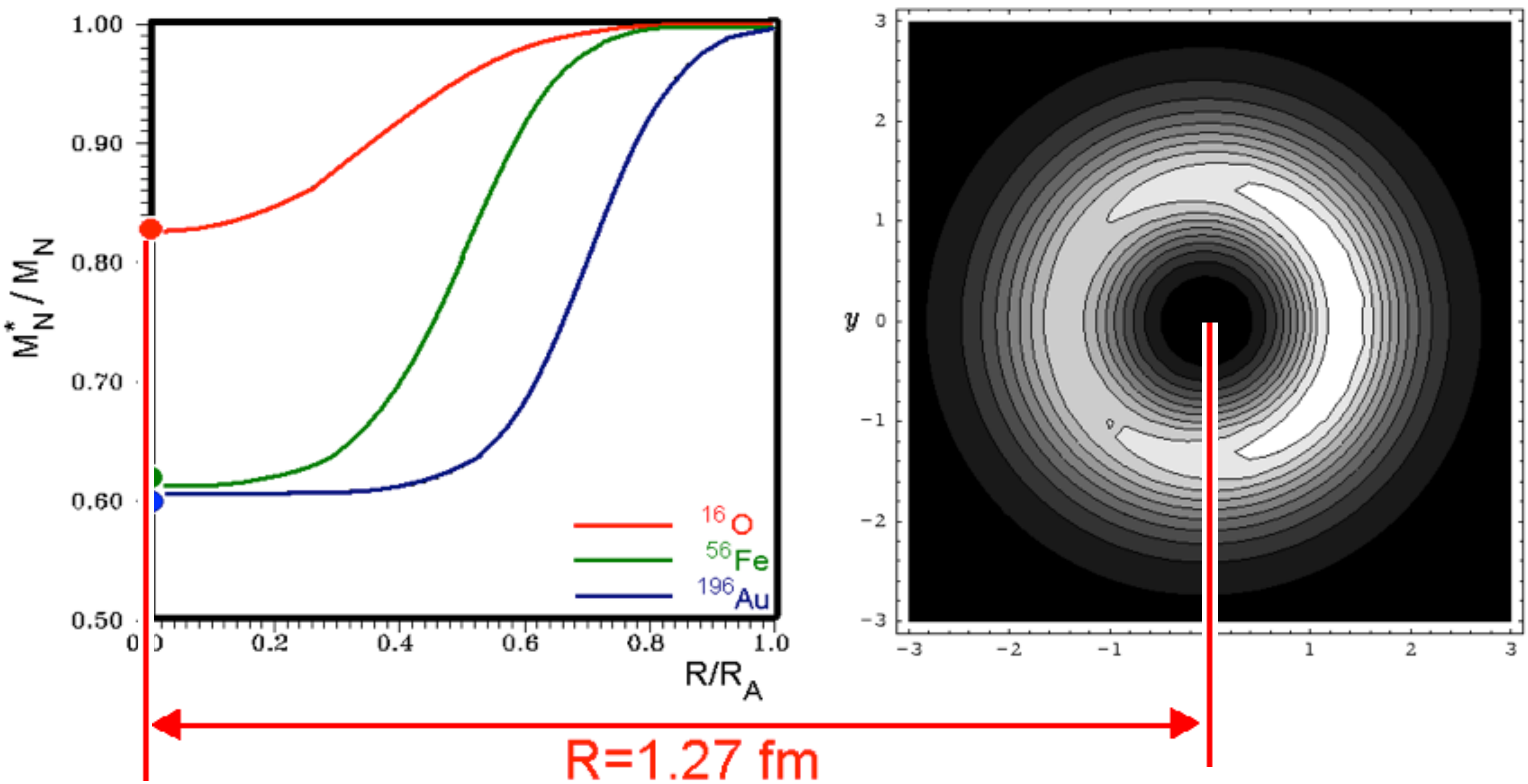
- One can formulate the minimization method



Finite nuclei

Nucleon may deform (core modification is not taken into account)
[UY, *et al.*, NPA200 (2002)]

- The single baryon density distribution in finite nuclei. Ex: Skyrmion located at distance 1.25 fm from the centre of oxygen



Summary and Outlook

- Within the applicability range, the model describes at same footing
  - the single hadrons properties
    - in separate state
    - in the community of their partners (EM and EMT form factors)
  - as well as the properties of that whole community
    - infinite nuclear matter properties (volume and symmetry energy properties)
    - matter under extreme conditions (neutron stars)
    - few and many nucleon systems (mirror nuclei, rare isotopes, halo nuclei,…)
    - nucleon knock-out reactions
    - Effective NN interactions

Summary and Outlook

Applicability and extensions of the approach

- Nucleon tomography
  - [H.Ch. Kim, UY, PLB726 (2013)]
  - [J.H.Jung, UY, H.Ch.Kim, Jour. Phys. G41 (2014)]
  - [J.H.Jung, UY, H.Ch.Kim, P. Schweitzer. PRD89 (2014)]
- Nuclear matter [UY, UY, JKPS62 (2013); UY, PRC88 (2013)]
- Neutron stars [UY, arXiv:1506.06481[nucl-th]]
- Vector mesons in nuclear matter
  - [J.H.Jung, UY, H.Ch.Kim, PLB 723 (2013)]

Thank you very much for your attention!