# Hadron Properties at Finite Density (From Nucleons to Nuclei)

Ulugbek Yakhshiev
*Inha University*

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# Motivation - "Nuclear Physics"

- If there is no complete theory then what?
  - Effective theory or model is main tool
  - Some region of interest is focused
- Relation between the model and an underlying theory and the experiment
  - Retain existing symmetries
  - Include phenomenological information
- Efficiency of the model is given by
  - Less number of free parameters
  - Predictive power
  - Self-consistency

# Motivation - “Nuclear Physics”

- How well the idea of baryons as topological solutions?
- Whether is it possible to describe
  - the single hadrons properties in separate state,
  - in the community of their partners (interactions, existence as an individual…),
  - as well as the properties of that whole community in same footing?
- Can we construct some simple model to answer those questions, at least qualitatively?
- How far can we go in that direction?
- If it is far enough how well is that direction?

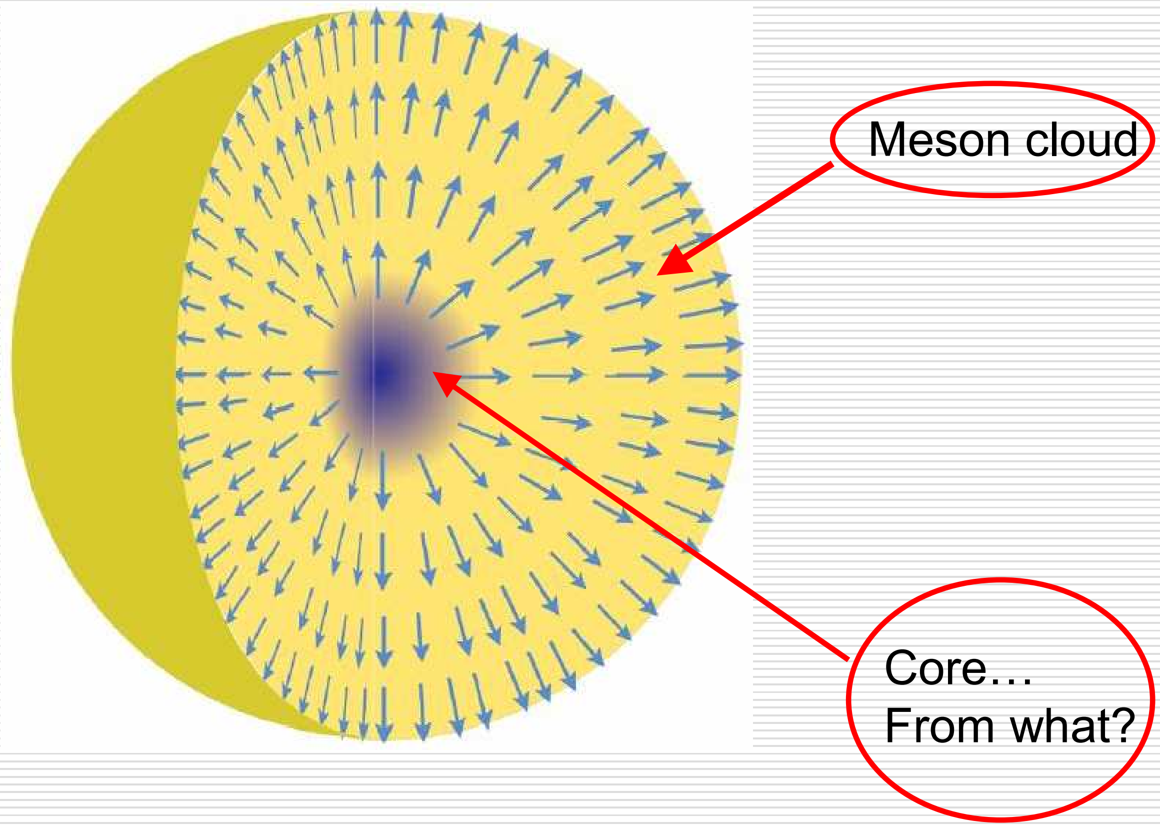
# Content

- Soliton and Topological models
- Prototype Lagrangian
- Hadrons in nuclear medium - I
  - Medium modifications
  - Effective Lagrangian - I
- Nuclear matter – I
  - Effective Lagrangian - II
  - Symmetric nuclear matter: volume energy, compressibility
- Further improvements: Effective Lagrangian - II
- Hadrons in nuclear medium – II
  - Isospin breaking
  - Nucleon in finite nuclei: deformations, neutron-proton mass difference, NS anomaly
- Nulcear matter – II
  - Symmetric nuclear matter: volume energy, pressure and compressibility
  - Asymmetric nuclear matter: symmetry energy
- Summary
- …

# Soliton and Topological models

## STRUCTURE

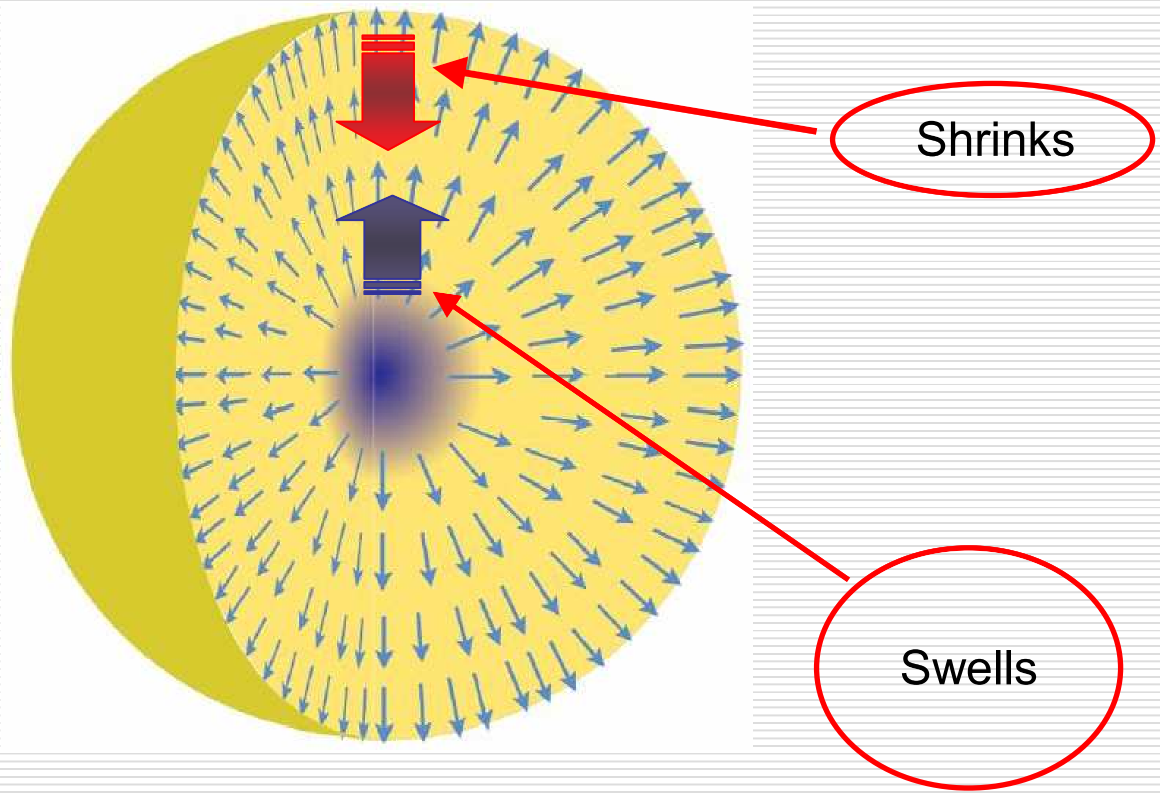
- What is a nucleon and, in particular, its core?
- At large number of colors it is still the mesonic system.



# Soliton and Topological models

## STABILIZATION

- Soliton has finite size and finite energy
- One needs at least two contrterms in the effective Lagrangian



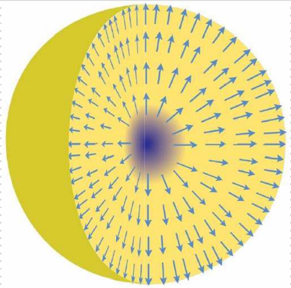
# Soliton and Topological models

- Nonlinear chiral effective meson (pionic) theory (prototype - Skyrme Model)

$$\mathcal{L} = \frac{F_\pi^2}{16}\mathrm{Tr}\left(\partial_\alpha U\right)\left(\partial^\alpha U^+\right) + \frac{1}{32e^2}\mathrm{Tr}\left[U^+\partial_\alpha U, U^+\partial_\beta U\right]^2$$

Shrinks ← → Swells

- Hedgehog soliton (nontrivial mapping)



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

# Prototype Lagrangian

$$\mathcal{L}_{\text{free}} = \frac{F_\pi^2}{16}\mathrm{Tr}\left(\partial^\alpha U\right)\left(\partial_\alpha U^+\right) + \frac{1}{32e^2}\mathrm{Tr}\left[U^+\partial_\alpha U, U^+\partial_\beta U\right]^2 + \frac{F_\pi^2 m_\pi^2}{16}\mathrm{Tr}\left(U + U^+ - 2\right)$$

- Nontrivial mapping
- It has topologically nontrivial solitonic solutions in different topological sectors with corresponding conserved topological number A
- Nucleon is quantized state of the classical soliton-skyrmion

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

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

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

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

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

# Hadrons in nuclear medium - I

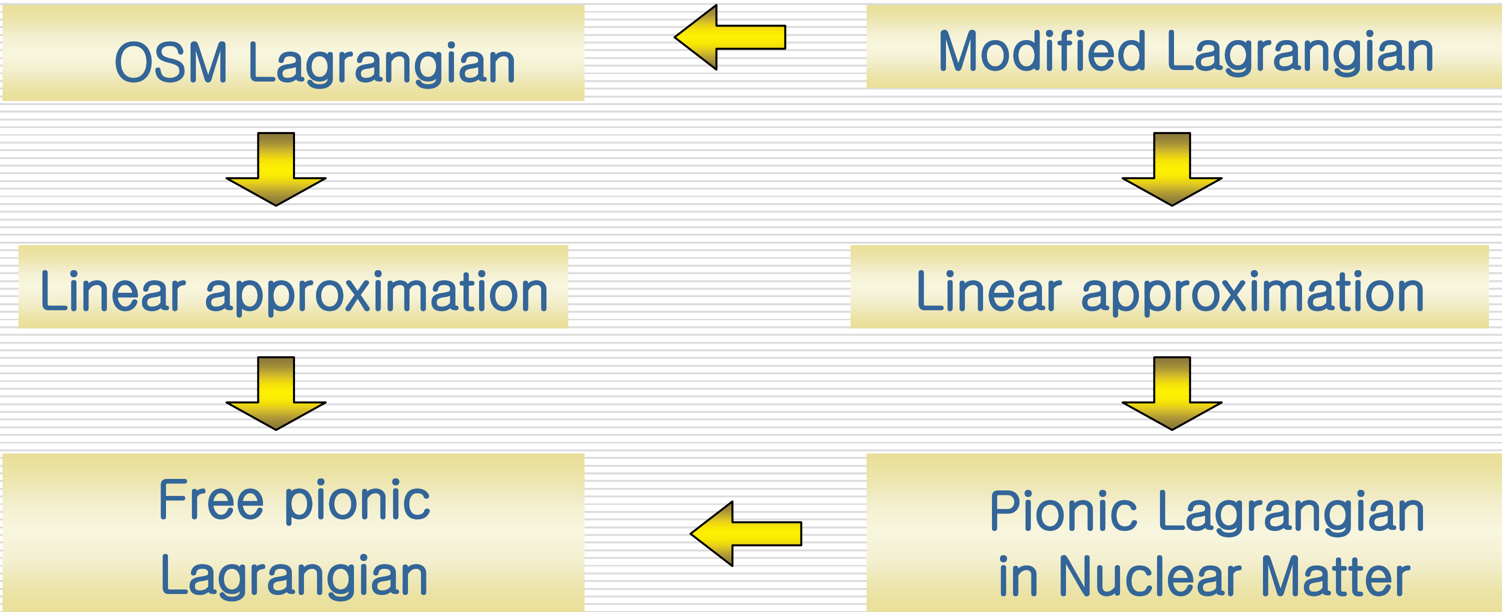
# Medium modifications

- What happens in the medium?

Possible shape change due to interactions and etc.

# Medium modifications

- Modification in the mesonic sector modifies the baryonic sector too




- How to modify the mesonic sector?

# Medium modifications

- Pion physics in nuclear matter (Optic potential approach):
  - In-medium pion equation
    $$\left(\partial^{\mu}\partial_{\mu} + m_{\pi}^{2} + \hat{\Pi}\right)\overline{\pi} = 0$$
  - Structure of the optic potential
    $$\hat{\Pi} = 2\omega U_{opt} = \chi_{s} + \vec{\nabla}\cdot\chi_{p}\vec{\nabla}$$

# In-medium modified Lagrangian – I

[Rakhimov *et al*, PRC58, 1998]

- Medium modified Lagrangian (outer shell modifications)

$$\mathcal{L}^*_{\text{stat}} = -\frac{F_\pi^2}{16}\text{Tr}\left(\vec{\nabla}U\right)\left(\vec{\nabla}U^+\right)\alpha_p + \frac{1}{32e^2}\text{Tr}\left[L_i, L_j\right]^2 + \frac{F_\pi^2 m_\pi^2}{16}\text{Tr}\left(U + U^+ - 2\right)\alpha_s$$

  - The medium functionals depend on S and P wave scattering lengths and volumes, and nuclear density

$$\alpha_s = 1 - \frac{4\pi\varsigma b_0 \rho}{m_\pi^2} \qquad \alpha_p = 1 - \frac{4\pi c_0 \rho/\zeta}{1 + 4\pi g' c_0 \rho/\zeta} \qquad \zeta = 1 + m_\pi / M_N$$

  - Scattering lengths (two parameters) are fitted from low energy pion-nucleus scattering data

# In-medium modified Lagrangian – I

[A.Rakhimov *et al*, PRC58, 1998]

- How to treat the medium changes?

$$\mathcal{L}^{*}_{\text{stat}} = -\frac{F_\pi^2}{16}\text{Tr}\left(\vec{\nabla}U\right)\left(\vec{\nabla}U^+\right)\alpha_p + \frac{1}{32e^2}\text{Tr}\left[L_i, L_j\right]^2 + \frac{F_\pi^2 m_\pi^2}{16}\text{Tr}\left(U + U^+ - 2\right)\alpha_s$$

- Effective pion decay constant $F_\pi^* = F_\pi\sqrt{\alpha_p(\rho)}$
- Effective mass of the pion $m_\pi^* = m_\pi\sqrt{1 + \frac{\alpha_s(\rho)}{\alpha_p(\rho)}}$
- Pion physics in nuclear medium $\left(\partial^\mu\partial_\mu + m_\pi^2 + \hat{\Pi}\right)\vec{\pi} = 0$

# Hadron properties in nuclear matter

[A.Rakhimov *et al*, PRC58, 1998]

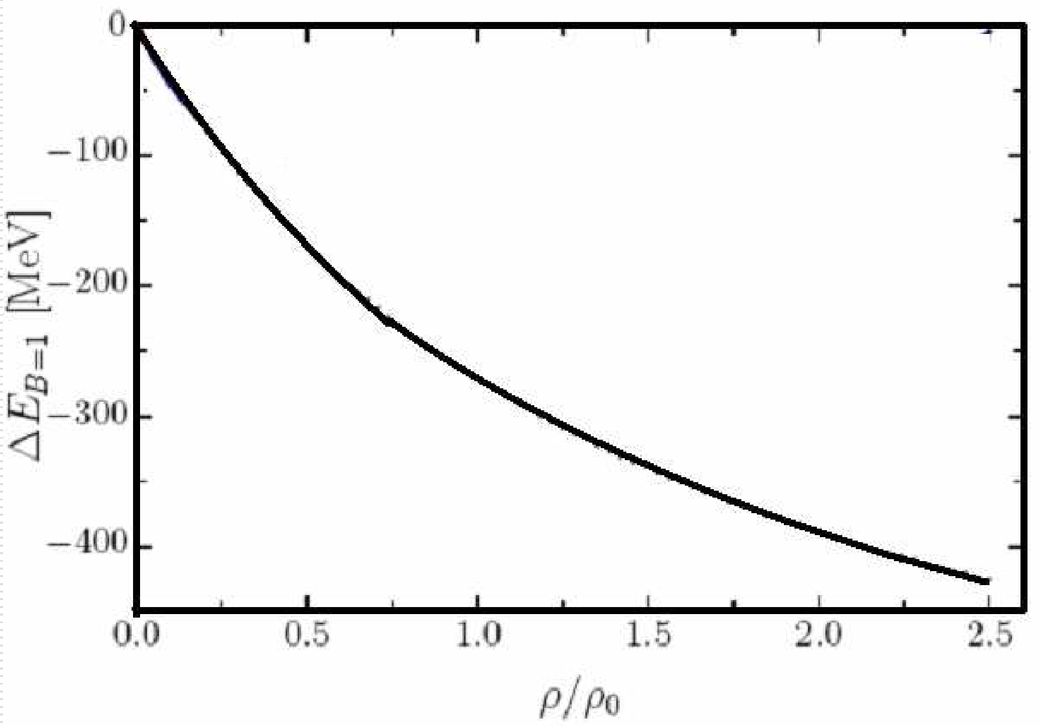
| $\rho / \rho_0$ | 0 | 0.5 | | | 1.0 | | |
|---|---|---|---|---|---|---|---|
| $g'$ | – | 0.33 | 0.6 | 1 | 0.33 | 0.6 | 1 |
| $g^*_{\pi NN}$ | 12.49 | 9.48 | 9.76 | 10.08 | 6.83 | 7.75 | 8.66 |
| $M^*_N\ (MeV)$ | 868 | 743 | 756 | 770 | 635 | 675 | 715 |
| $m^*_\pi\ (MeV)$ | 140 | 146 | 146 | 146 | 152 | 152 | 152 |
| $\Lambda^*\ (MeV)$ | 528 | 484 | 489 | 494 | 448 | 462 | 477 |
| $M^*_{\Delta N}\ (MeV)$ | 243 | 211 | 214 | 218 | 186 | 186 | 206 |

$$b_0 = b_0^{phen} = -0.024 m_\pi^{-1} \qquad c_0 = c_0^{phen} = -0.15 m_\pi^{-3}$$

Large renormalization: $$\frac{M_N^*(\rho_0)}{M_N^{\text{free}}} \approx 0.78$$

# Nuclear Matter - I

# Symmetric Nuclear Matter




$$\Delta E_{B=1}(\rho) = m_N^*(\rho) - m_N^{\text{free}}$$

# In-medium modified Lagrangian - II

[UY & HC Kim, PRC83, 2011]

- Core modifications - modification of the Skyrme term
  - May be related to vector meson properties in nuclear matter
  - May be related to nuclear matter properties

$$\mathcal{L}_4^* = \frac{1}{32e^{*2}} \mathrm{Tr}\left[L_\alpha, L_\beta\right]^2$$

$$e \to e^* = e\,\gamma^{1/2}(\rho)$$

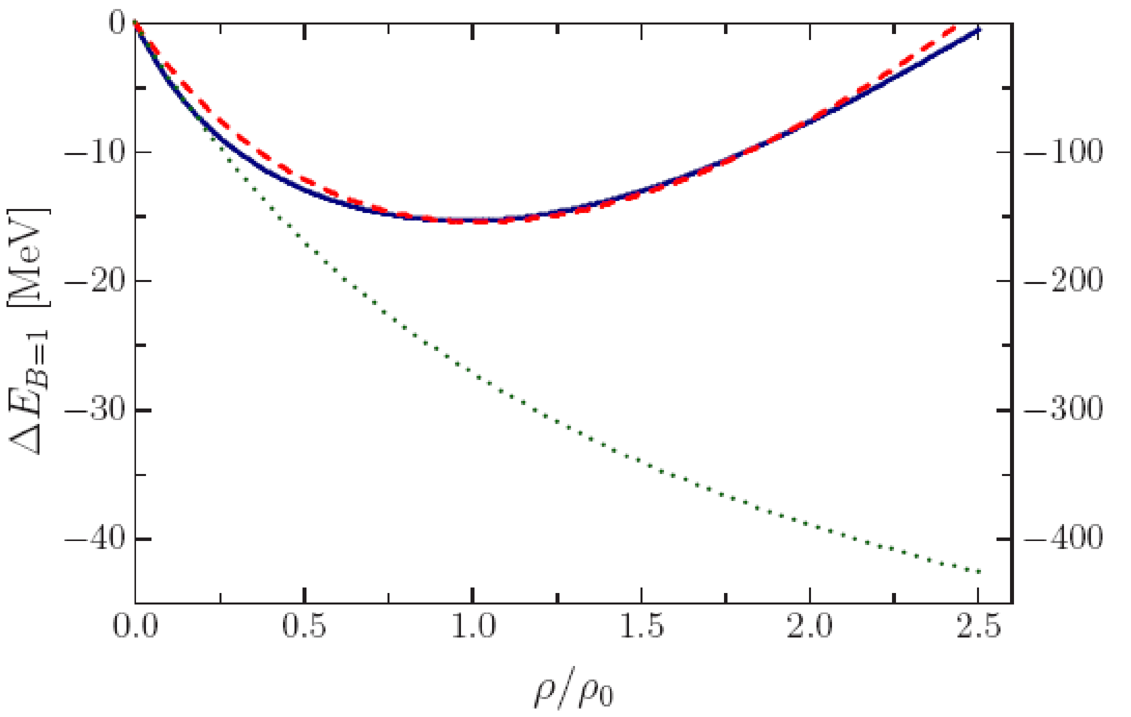
# Binding energy per nucleon (volume term)

[UY & HC Kim, PRC83, 2011]

$$\Delta E_{B=1} = m_N^* - m_N^{\text{free}}$$

$$e \to e^* = e\,\gamma^{1/2}(\rho)$$

$$\gamma = \exp\left\{-\frac{\gamma_{\text{num}}\rho}{1+\gamma_{\text{den}}\rho}\right\}$$




$$b_0 = -0.024 m_\pi^{-1}$$

$c_0 = 0.21 m_\pi^{-3}$ – solid curve

$c_0 = 0.09 m_\pi^{-3}$ – dashed curve

# Compressibility of nuclear matter

- Nuclear matter compression modulus and thermodynamic compressibility relation

$$\frac{1}{9}\rho K = \frac{1}{K^{\mathrm{th}}}$$

- Isothermal compressibility is defined as

$$\frac{1}{K^{\mathrm{th}}} = \rho \frac{\partial p}{\partial \rho} = \rho^2 \left( 2 \frac{\partial a_V}{\partial \rho} + \rho \frac{\partial^2 a_V}{\partial \rho^2} \right)$$

- At normal nuclear matter density one has expression

$$K = 9\rho^2 \frac{\partial^2 a_V}{\partial \rho^2}\bigg|_{\rho=\rho_0}$$

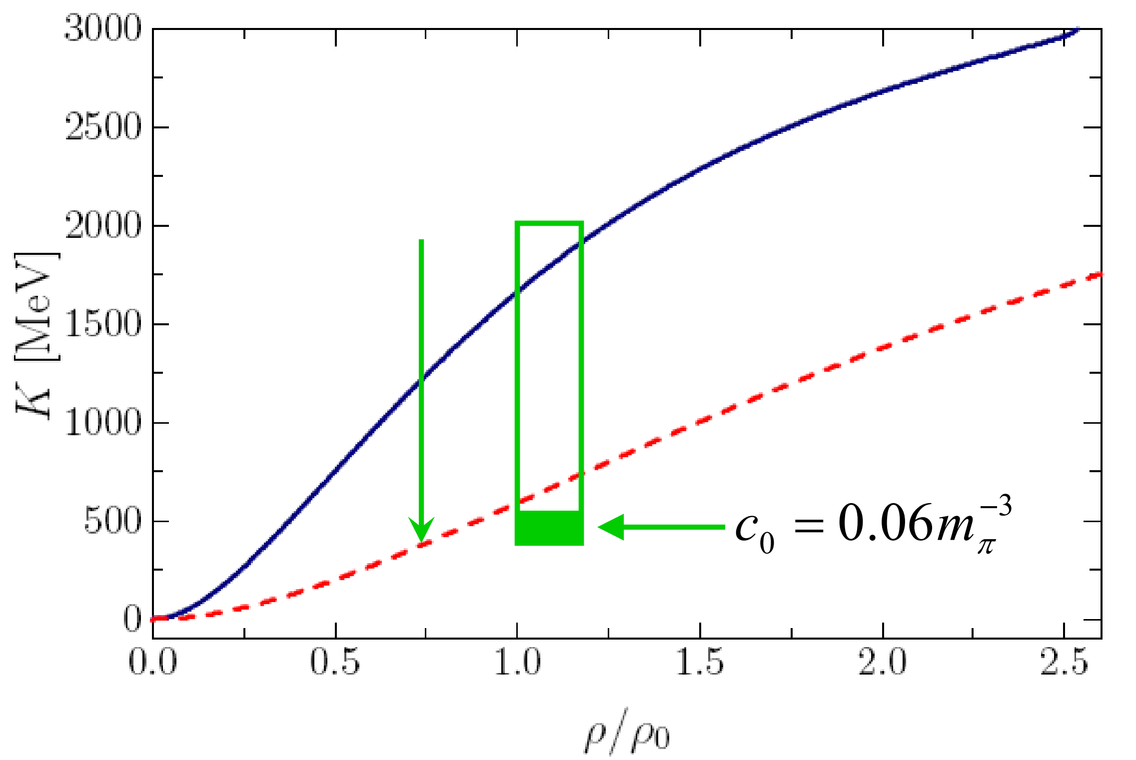
# Compressibility of nuclear matter

[UY & HC Kim, PRC83, 2011]

$$\Delta E_{B=1} = m_N^* - m_N^{\text{free}}$$

$$e \to e^* = e\,\gamma^{1/2}(\rho)$$

$$\gamma = \exp\left\{-\frac{\gamma_{\text{num}}\rho}{1+\gamma_{\text{den}}\rho}\right\}$$




$b_0 = -0.024 m_\pi^{-1}$

$c_0 = 0.21 m_\pi^{-3}$ – solid curve

$c_0 = 0.09 m_\pi^{-3}$ – dashed curve

# Compressibility of nuclear matter

[UY & HC Kim, PRC83, 2011]

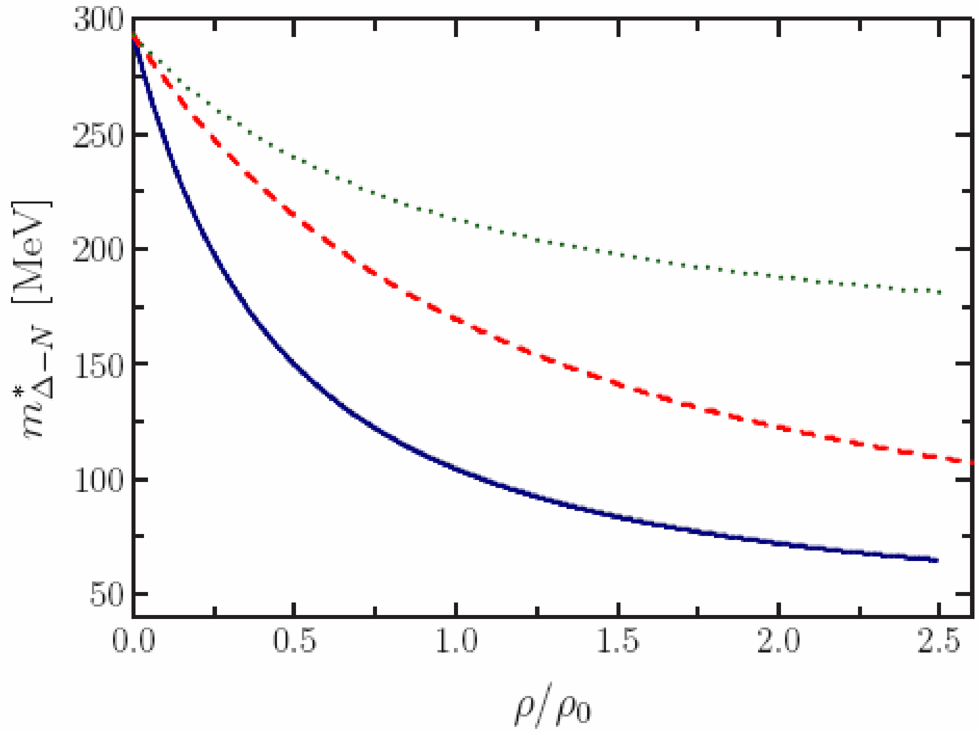
| $b_0\ [m_\pi^{-1}]$ | $c_0\ [m_\pi^{-3}]$ | $\gamma_{\rm num}\ [m_\pi^{-3}]$ | $\gamma_{\rm den}\ [m_\pi^{-3}]$ | $K$ [MeV] | $m^*_{N-\Delta}$ [MeV] |
|---|---|---|---|---|---|
| −0.024 | 0.21 | 2.098 | 1.451 | 1647.47 | 105.21 |
| −0.024 | 0.15 | 1.448 | 0.998 | 1148.18 | 129.39 |
| −0.024 | 0.09 | 0.797 | 0.496 | 582.79 | 170.34 |
| −0.029 | 0.21 | 2.106 | 1.506 | 1637.16 | 107.13 |
| −0.029 | 0.15 | 1.444 | 1.031 | 1142.00 | 131.59 |
| −0.029 | 0.09 | 0.785 | 0.502 | 580.03 | 172.91 |

$$\alpha_s(\bar{r}) = 1 - \frac{4\pi\varsigma\, b_0 \rho(\bar{r})}{m_\pi^2} \qquad \alpha_p(\bar{r}) = 1 - \frac{4\pi\, c_0 \rho(\bar{r})/\zeta}{1 + 4\pi g' c_0 \rho(\bar{r})/\zeta} \qquad \gamma = \exp\left\{ -\frac{\gamma_{\rm num}\rho}{1+\gamma_{\rm den}\rho} \right\}$$

# Symmetry energy in infinite nuclear matter approximation

- Symmetry energy can be related to Δ-N mass difference

$$E_{\rm sym} = \frac{1}{12} m^*_{\Delta-N}$$



# Further improvements

- Finite nuclei effects
  - Volume dependent part of the binding energy
  - Surface term
  - Coulomb part
- Isospin breaking effects
  - More consistent approach to symmetry energy
  - Neutron matter (applications to astrophysics)
- Finite nuclei + Isospin breaking effects
  - Mirror nuclei properties
  - Applications to the nuclei considering shell structure

# Hadrons in nuclear medium - II

# Isospin breaking effects

- Three types of pions treated separately
- In nuclear matter, one considers three types of polarization operators
- There will be some additional parameters which correspond to isospin breaking environment

$$\left(\partial^{\mu}\partial_{\mu} + m^2_{\pi^{(\pm,0)}}\right)\vec{\pi}^{(\pm,0)} = 0$$

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

| | $\pi$-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 |

# Final in-medium modified Lagrangian

- Outer&inner shell modifications + isospin breaking

$$\mathcal{L}^* = \mathcal{L}^*_{\rm sym} + \mathcal{L}^*_{\rm as}\,,$$
$$\mathcal{L}^*_{\rm sym} = \mathcal{L}^*_2 + \mathcal{L}_4 + \mathcal{L}^*_{\chi\rm SB}\,,$$
$$\mathcal{L}^*_{\rm as} = \Delta\mathcal{L}_{\rm mes} + \Delta\mathcal{L}^*_{\rm env}\,,$$
$$\mathcal{L}^*_2 = \frac{F_\pi^2}{16}\left\{\left(1+\frac{\chi_s^{02}}{m_\pi^2}\right)\mathrm{Tr}\,(\partial_0 U \partial_0 U^\dagger) - (1-\chi_p^0)\,\mathrm{Tr}(\nabla U\cdot\nabla U^\dagger)\right\},$$
$$\mathcal{L}_4 = \frac{1}{32e^2}\,\mathrm{Tr}[U^\dagger\partial_\mu U, U^\dagger\partial_\nu U]^2\,,$$

$$\mathcal{L}^*_{\chi\rm SB} = -\frac{F_\pi^2 m_\pi^2}{16}\left(1+m_\pi^{-2}\chi_s^{00}\right)\times\mathrm{Tr}\left[(U-1)(U^\dagger-1)\right],$$
$$\Delta\mathcal{L}_{\rm mes} = -\frac{F_\pi^2}{16}\sum_{a=1}^{2}\mathcal{M}_-^2\,\mathrm{Tr}(\tau_a U)\,\mathrm{Tr}(\tau_a U^\dagger),$$
$$\Delta\mathcal{L}^*_{\rm env} = -\frac{F_\pi^2}{16}\sum_{a,b=1}^{2}\varepsilon_{ab3}\frac{\Delta\chi_s+\Delta\chi_p}{2m_\pi}\times\mathrm{Tr}(\tau_a U)\,\mathrm{Tr}(\tau_b\partial_0 U^\dagger),$$

$$e \rightarrow e^* = e\,\gamma^{1/2}(\rho)$$

$\Downarrow \quad \rho \rightarrow 0$

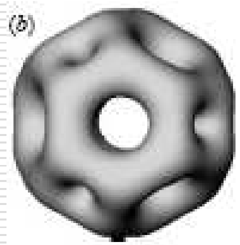
$\mathcal{L}_{\rm free}$

$\Downarrow$ Linear approx

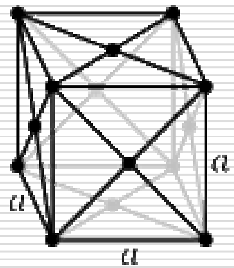
$$\left(\partial^\mu\partial_\mu + m^2_{\pi^{(\pm,0)}} + \hat{\Pi}^{(\pm,0)}\right)\vec{\pi}^{(\pm,0)} = 0$$

# Consistency with other approaches

Manton & Wood
PRD74




- Nuclear matter studies in framework of the Skyrme model (alternate approaches)
  - “Calibration” method
  - Crystalline structures
- Ideas behind




$$F_\pi \to F_\pi^*, \quad m_\pi \to m_\pi^*, \quad e \to e^*$$

e.g.
H.J.Lee
*et al*
NPA723

# Effects in finite nuclei

[UY *et al*, NPA700, 2002]

- Skyrmion deformation inside the finite nuclei
- Minimal energy configuration is not spherically symmetric

$$\vec{N} = \{\sin\Theta(r,\theta)\cos\varphi, \sin\Theta(r,\theta)\sin\varphi, \cos\Theta(r,\theta)\}$$

$$F = F(r,\theta)$$

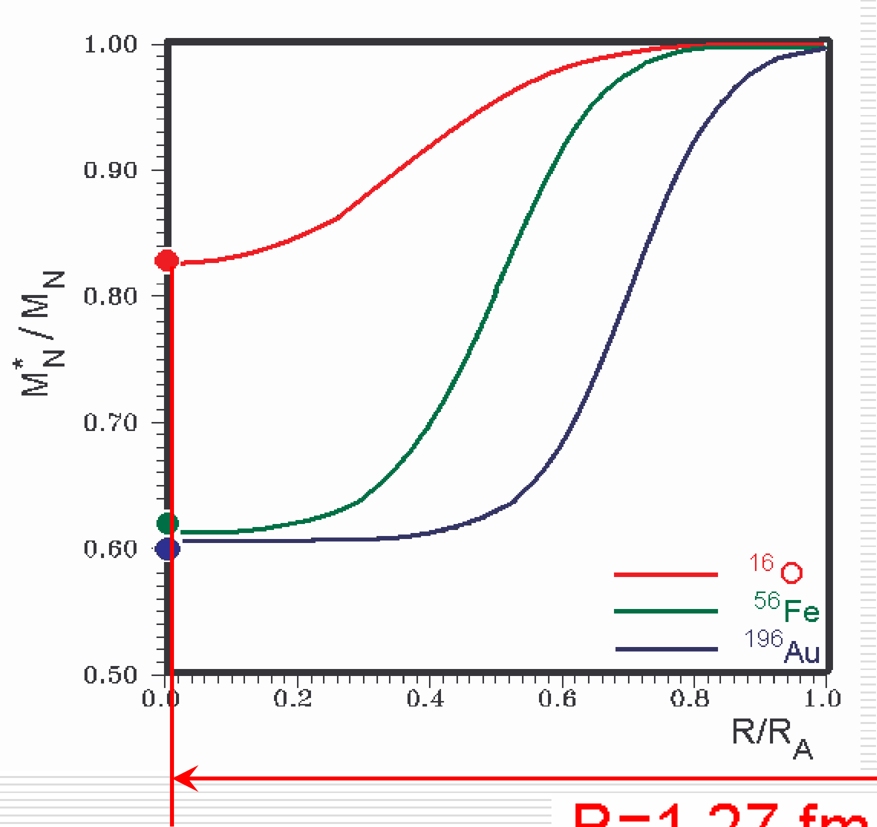
- Coupled PDE's instead of ODE

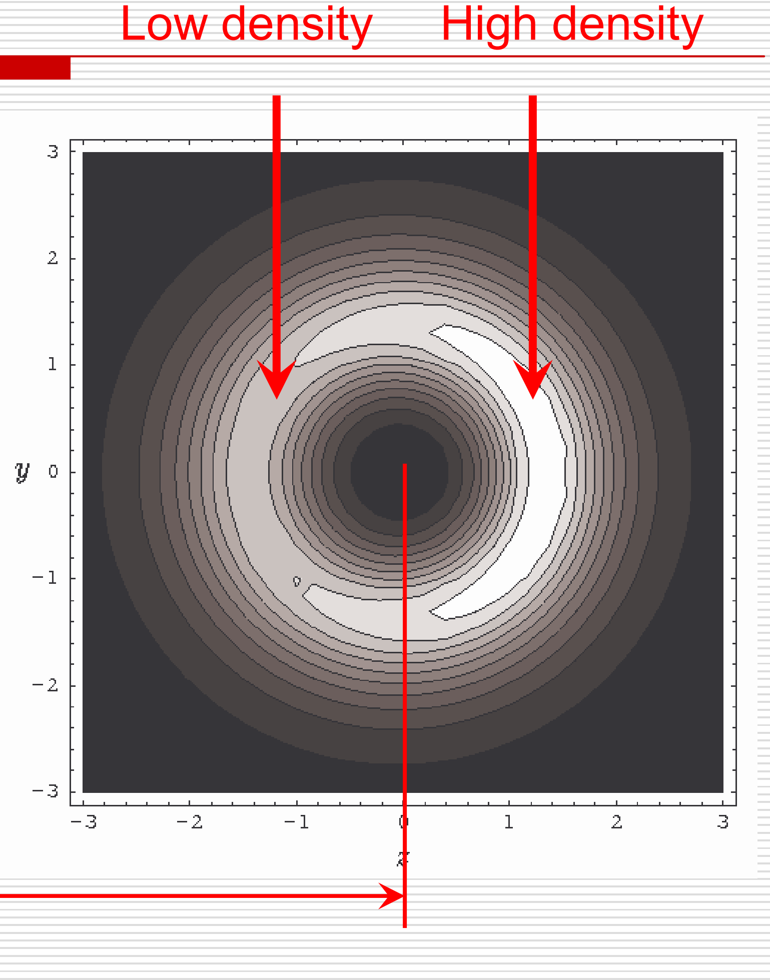
$$f(F_{rr}, F_r, F_{\theta\theta}, F_\theta, F, \Theta_r, \Theta_\theta, \Theta) = 0$$

$$g(\Theta_{rr}, \Theta_r, \Theta_{\theta\theta}, \Theta_\theta, \Theta, F_r, F_\theta, F) = 0$$

# Effects in finite nuclei

[UY *et al*, NPA700, 2002]



# Effects in finite nuclei

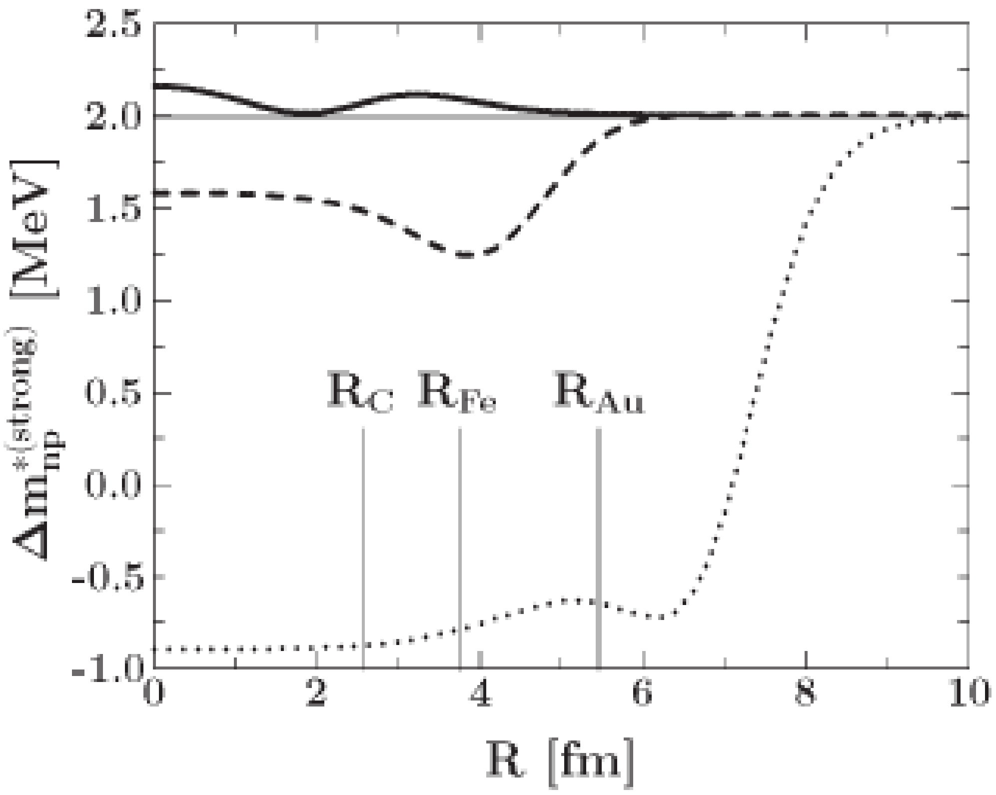
[UY, JKPS57, 2010]

| Element | $m_{p}^{*}$ [MeV] | $\Delta m_{np}^{*}$ [MeV] | $\Delta m_{np}^{*(EM)}$ [MeV] | $\mu_{p}^{*}$ [n.m.] | $\mu_{n}^{*}$ [n.m.] | $\langle r^2\rangle_{E,S}^{*1/2}$ [fm] | $\langle r^2\rangle_{E,V}^{*1/2}$ [fm] |
|---|---|---|---|---|---|---|---|
| free space | 938.81 | 1.313 | -0.687 | 1.966 | -1.241 | 0.481 | 0.739 |
| $^{12}$C | 632.37 | 1.605 | -0.558 | 2.221 | -1.185 | 0.620 | 0.785 |
| $^{48}$Ca | 568.11 | 0.367 | -0.487 | 2.548 | -1.402 | 0.711 | 0.917 |
| $^{48}$Ni | 570.75 | 3.185 | -0.485 | 2.548 | -1.388 | 0.717 | 0.914 |
| $^{56}$Fe | 564.57 | 1.104 | -0.483 | 2.570 | -1.413 | 0.719 | 0.927 |
| $^{59}$Ni | 564.18 | 1.277 | -0.481 | 2.574 | -1.416 | 0.721 | 0.930 |
| $^{132}$Sn | 575.77 | -1.689 | -0.489 | 2.555 | -1.443 | 0.702 | 0.935 |
| $^{197}$Au | 577.58 | -1.384 | -0.490 | 2.552 | -1.442 | 0.701 | 0.934 |
| $^{208}$Pb | 578.88 | -1.627 | -0.491 | 2.548 | -1.442 | 0.699 | 0.933 |

- Large renormalization of the nucleon mass

# Effects in finite nuclei

[UY, JKPS 57, 2010]



# Effects in finite nuclei (Nolen-Schiffer anomaly) [Meissner *et al*, EPJ A36, 2008]

| Nuclei | $\overline{m}_p^*$ | | Present approach | | | | | | $\overline{\Delta}_{NSA}$ | $\overline{\Delta}_{NSA}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $\alpha_{ren} = 0$ | | | $\alpha_{ren} = 0.95$ | | | ref. [16] | ref. [17] |
| | $\alpha_{ren} = 0$ | $\alpha_{ren} = 0.95$ | $\Delta\overline{m}_{np}^{*(1)}$ | $\Delta\overline{m}_{np}^{*(2)}$ | $\overline{\Delta}_{NSA}$ | $\Delta\overline{m}_{np}^{*(1)}$ | $\Delta\overline{m}_{np}^{*(2)}$ | $\overline{\Delta}_{NSA}$ | | |
| $^{15}$O-$^{15}$N | 767.45 | 928.30 | −4.27 | 1.56 | 4.02 | −0.21 | 1.33 | 0.20 | – | $0.16 \pm 0.04$ |
| $^{17}$F-$^{17}$O | 812.35 | 930.54 | −5.53 | 1.52 | 5.33 | −0.28 | 1.32 | 0.27 | 0.31 | $0.31 \pm 0.04$ |
| $^{39}$Ca-$^{39}$K | 724.78 | 926.16 | −8.11 | 1.67 | 7.75 | −0.41 | 1.33 | 0.37 | – | $0.22 \pm 0.08$ |
| $^{41}$Sc-$^{41}$Ca | 771.71 | 928.51 | −9.74 | 1.62 | 9.44 | −0.49 | 1.33 | 0.47 | 0.62 | $0.59 \pm 0.08$ |

Result "Desire" Result "Desire" Experiment

$$\overline{\Delta}_{NSA} = \Delta m_{np} - \Delta\overline{m}_{np}^*$$

$$\Delta\overline{m}_{np}^* \approx \int \left(\Delta\psi_{np}^{(2)} m_p^* + \left(\psi^{(p)}\right)^2 \Delta m_{np}^*\right) d^3R$$

- Large renormalization of the nucleon mass makes a big problem

# Nuclear Matter - II

# Symmetric nuclear matter

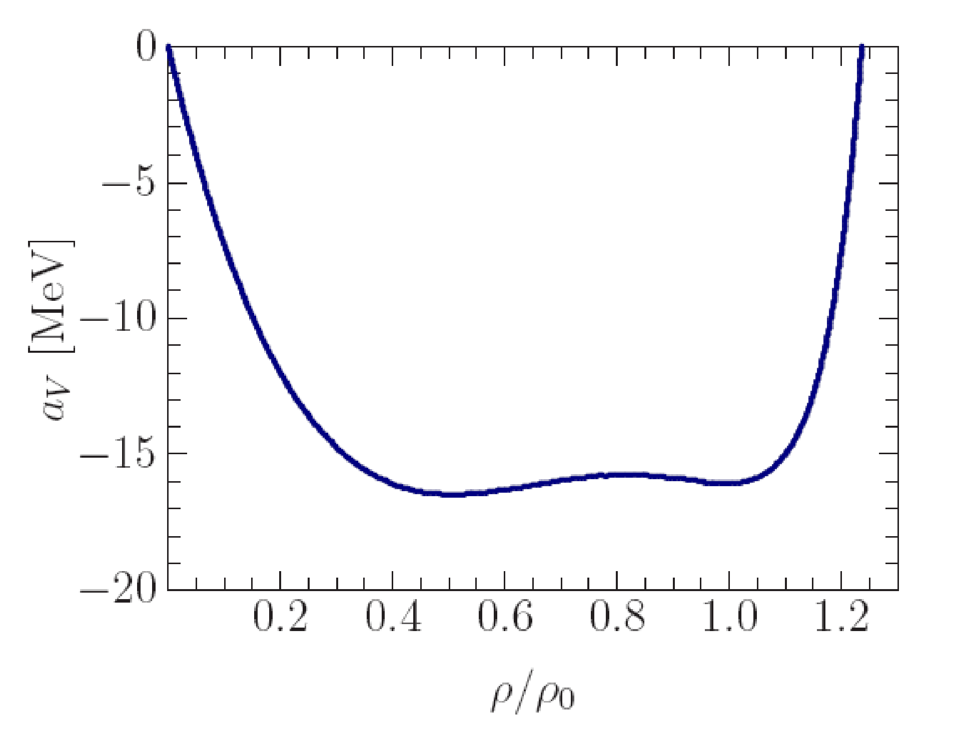
- Volume term in the binding energy formula takes into account

$$\Delta E_V = \left( \frac{m_\mathrm{p}^* + m_\mathrm{n}^*}{2} - \frac{m_\mathrm{p} + m_\mathrm{n}}{2} \right) A \equiv a_V(\rho) A$$

  - In general, isospin breaking effects - the masses of nucleons are different
  - Medium modifications – the masses are density dependent

# Binding energy per nucleon

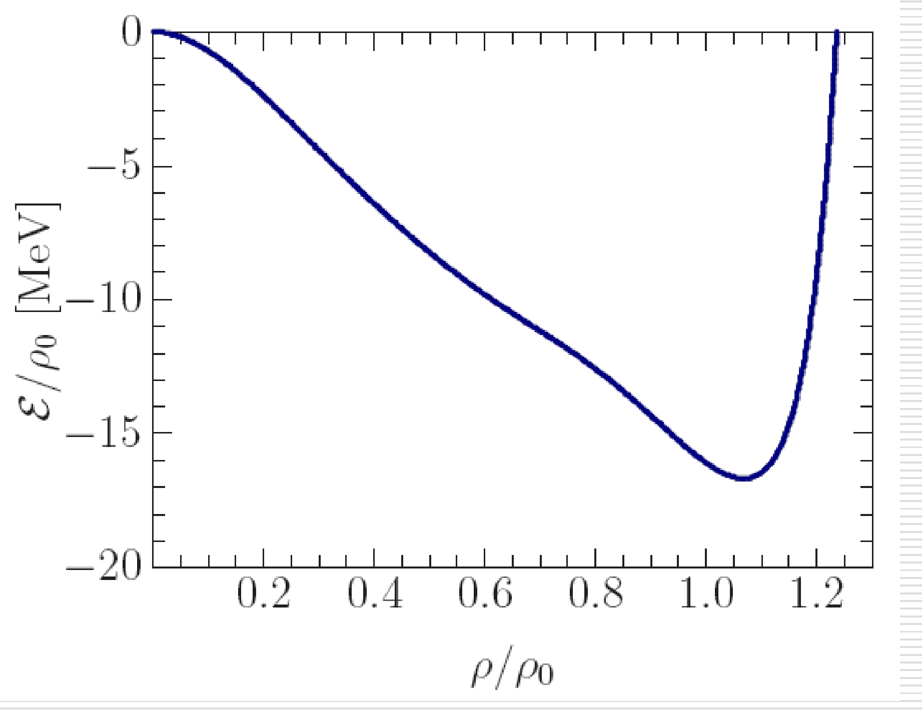
- Volume term coefficient as a function of normalized nuclear matter density



# Binding energy per nucleon

- Fraction of the binding energy per unit volume to normal nuclear matter density as a function of normalized density

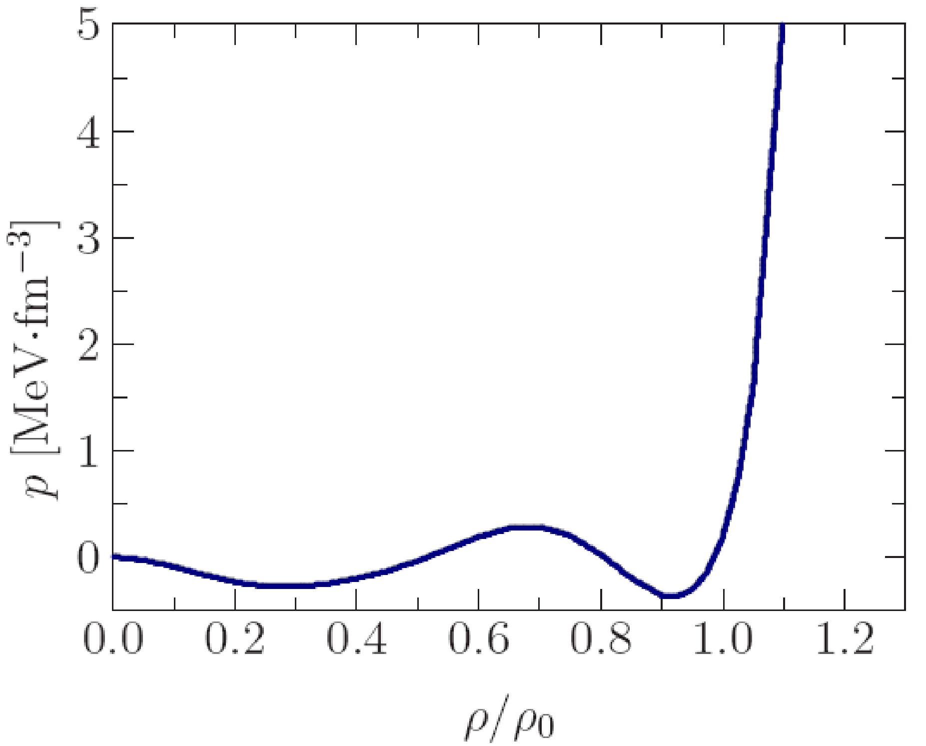
$$\mathcal{E} \equiv \frac{\Delta E}{V} = a_V \frac{A}{V} = a_V \rho$$



# Pressure

- Pressure as a function of normalized density

$$p = \rho \frac{\partial \mathcal{E}}{\partial \rho} - \mathcal{E} = \rho^2 \frac{\partial a_V}{\partial \rho}$$



# Compressibility

TABLE I: Compression modulus $K$ of nuclear matter. The variational parameters $\gamma_{\rm num}$ and $\gamma_{\rm den}$ are chosen in such a way that at $\rho = \rho_0$ the minimum of binding energy per nucleon $\Delta E/A \simeq -16$ MeV is reproduced correctly.

| $\rho_0$ [fm$^{-3}$] | $\gamma_{\rm num}$ [$m_\pi^{-3}$] | $\gamma_{\rm den}$ [$m_\pi^{-3}$] | $K$ [MeV] |
|---|---|---|---|
| 0.159 | 2.038 | 0.165 | 931 |
| 0.156 | 2.030 | 0.157 | 732 |
| 0.152 | 2.025 | 0.151 | 317 |

# Asymmetric matter

- Hamiltonian

$$\hat{H} = \hat{H}_{\rm sym} - \left( a^* - \frac{\Lambda^*_{\rm env}}{\Lambda^*_{\omega\Omega,33}} \right) \hat{T}_3$$

- Effective mass

$$m^*_{\rm n,p} = m^*_{\rm N,S} + T_3\, \Delta m^*_{\rm np}$$

- Nucleus mass

$$\begin{aligned} M(A,Z) &= Z \left( m^*_{\rm N,S} - \frac{\Delta m^*_{\rm np}}{2} \right) \\ &\quad + (A-Z) \left( m^*_{\rm N,S} + \frac{\Delta m^*_{\rm np}}{2} \right) \\ &= A m^*_{\rm N,S} + \left( \frac{A}{2} - Z \right) \Delta m^*_{\rm np}. \end{aligned}$$

# Symmetry energy

- Binding energy per nucleon

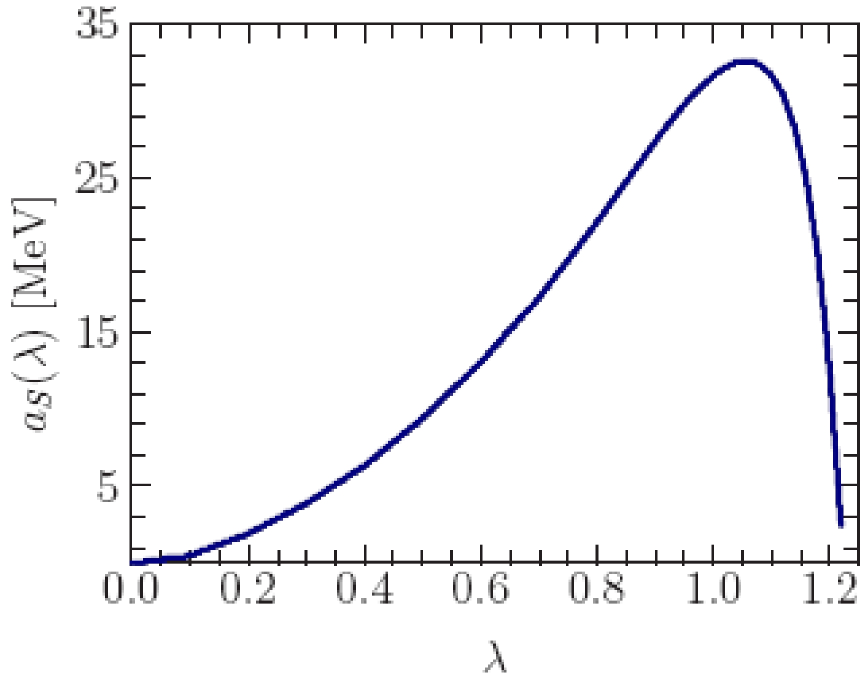
$$E_{A=1} = -\left(m_{\rm N,S}^{\rm free} - m_{\rm N,S}^{*}\right) + \frac{N-Z}{2A}\left(\Delta m_{\rm np}^{*} - \Delta m_{\rm np}^{\rm free}\right)$$

- Symmetry energy term

$$\frac{N-Z}{2A}\left(\Delta m_{\rm np}^{*} - \Delta m_{\rm np}^{\rm free}\right) \equiv a_S \beta^2$$

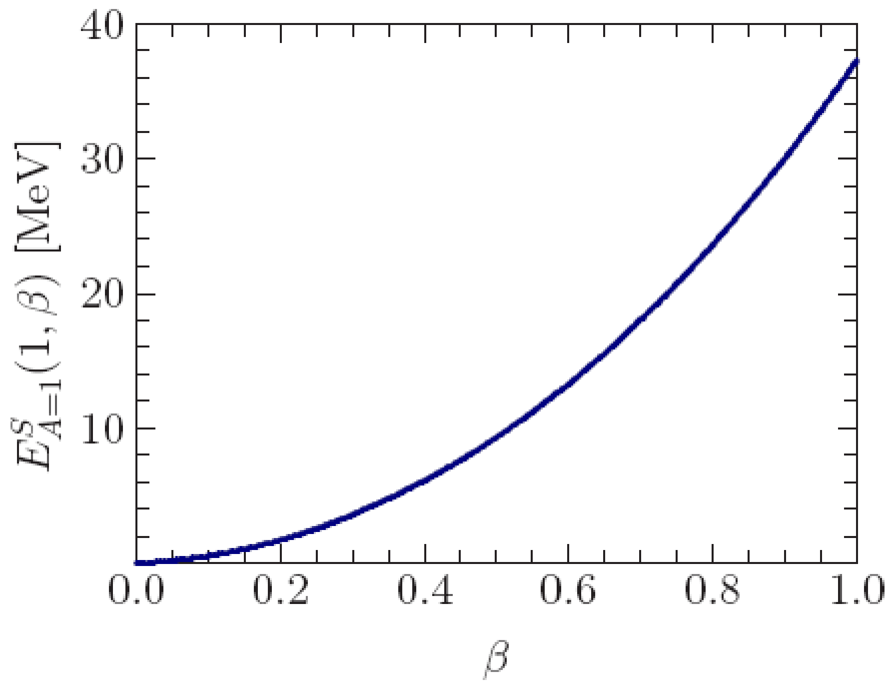
# Symmetry energy

- Symmetry energy term coefficient as a function of normalized nuclear matter density



# Symmetry energy

- Symmetry energy as a function of asymmetry parameter at normal nuclear matter density



# Summary

- How well the idea of baryons as topological solutions? It seems, not bad…
- Whether is it possible to describe
  - the single hadrons properties in separate state,
  - in the community of their partners (interactions, existence as an individual…),
  - as well as the properties of that whole community in same footing? It seems, yes.
- Can we construct some simple model to answer those questions, at least qualitatively? It seems, yes.
- How far can we go in that direction? We will see…
- If it is far enough how well is that direction? …

To be (the Skyrme model)

or not to be?

…

# Quick inspection

- Core modifications - modification of the Skyrme term
  - May be related to vector meson properties in nuclear matter
  - May be related to nuclear matter properties

$$\mathcal{L}_4^* = \frac{1}{32e^{*2}} \mathrm{Tr}\left[L_\alpha, L_\beta\right]^2$$

↑

$$e \rightarrow e^* = e\,\gamma^{1/2}(\rho)$$

# Stabilization via rho mesons

[J.Jung, UY, H.C.Kim, to be published]

- Core modifications – modified rho meson terms

$$\mathcal{L}^* = \frac{f_\pi^2}{4}\mathrm{Tr}\left(\partial_0 U \partial_0 U^\dagger\right) - \alpha_p \frac{f_\pi^2}{4}\mathrm{Tr}\left(\nabla U \cdot \nabla U^\dagger\right) - \frac{a f_\pi^2}{4}\mathrm{Tr}\left(D_\mu \xi_L \cdot \xi_L^\dagger + D_\mu \xi_R \cdot \xi_R^\dagger\right)^2$$
$$-\frac{1}{2g^2\zeta}\mathrm{Tr}\, F_{\mu\nu}^2 + \alpha_s \frac{f_\pi^2 m_\pi^2}{4}\mathrm{Tr}\left(U + U^\dagger - 2\right),$$

$$g \to g^* = g\,\zeta^{1/2}(\rho)$$

- Rho mass modification, rho-pi-pi coupling modification

$$m_\rho^2 = a\, g^2\, f_\pi^2\,, \qquad g_{\rho\pi\pi} = \frac{a}{2}\, g$$

$$m_\rho^* = \sqrt{2}\zeta^{1/2} g f_\pi\,, \qquad g_{\rho\pi\pi}^* = g\zeta.$$

# Stabilization via rho mesons

[J.Jung, UY, H.C.Kim, to be published]

- Rho mesons effective mass
  - 30% at NNM
  - 18% QCD sum rules

  [Hatsuda&Lee PRC46]