(some aspects of)

Nuclear Symmetry Energy & Neutron Skins of Nuclei

Advances in Nuclear Many-Body Theory

June 7th to 10th, 2011

Primosten, Croatia

M. Centelles

Barcelona University

UNIVERSITAT DE BARCELONA

ICCUB Institut de Ciències del Cosmos

CPAN Ingenio 2010

In collaboration with :

Xavier Viñas (Barcelona),

Xavi Roca-Maza (Barcelona, INFN Milano),

Michal Warda (Lublin, Poland)

INTRODUCTION – The nuclear symmetry energy: a multifaceted quantity

The nuclear symmetry energy is an important quantity in Nuclear Physics and Astrophysics that governs basic properties of both very small entities such as the atomic nucleus ($R \sim 10^{-15}$ m) and very large objects such as neutron stars ($R \sim 10^{4}$ m)

- **Nuclear Physics:**

  Binding and structure of stable neutron-rich nuclei and of isotopes far from stability, Drip lines, Neutron density distributions and neutron skin thickness of nuclei, Giant Resonances, Heavy-Ion Collisions of neutron-rich nuclei (flows, isospin diffusion, multifragmentation) . . .

- **Astrophysics:**

  Supernova explosion, Neutrino emission and cooling of protoneutron stars, Stellar nucleosynthesis (r-process), Mass-Radius relations of neutron stars, Composition of the crust of neutron stars . . .

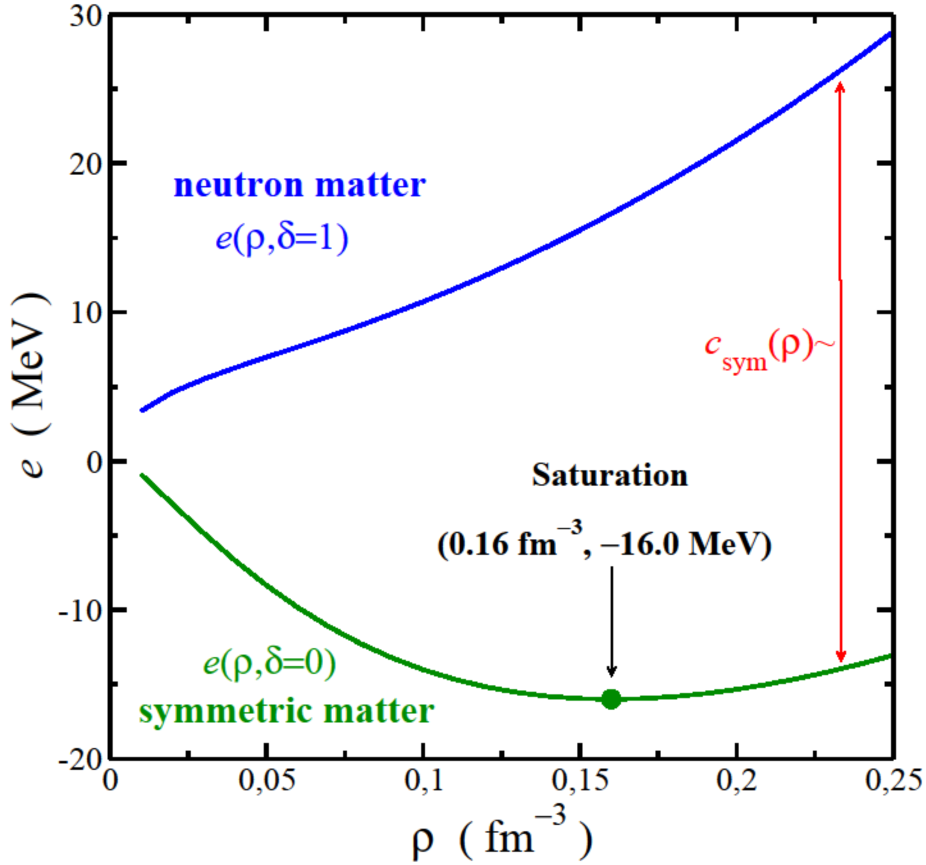
- **Interdisciplinary areas:**

  Tests of the Standard Model at low energies through atomic parity non-conservation observables

Lattimer & Prakash , Science 304, 536 (2004) ; Steiner et al, Phys Rep 411, 325 (2005) ; Baran et al, Phys Rep 410, 335 (2005) ; Li et al, Phys Rep 464, 113 (2008)

Here we will be concerned with E_{sym} at subsaturation densities

Equation of State of Neutron-Rich Matter:



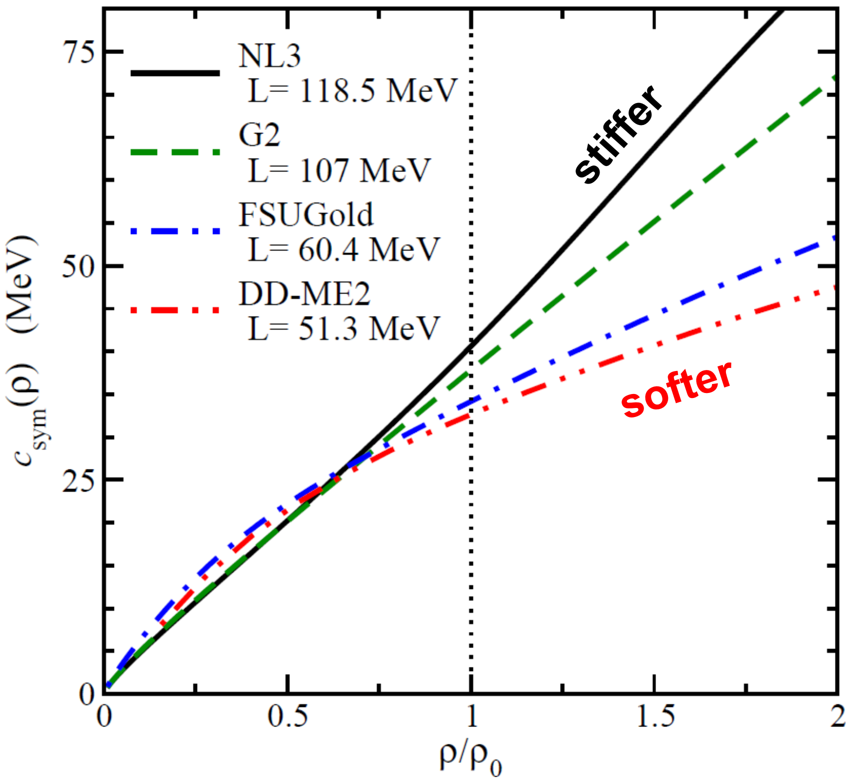
- total nucleon density: $\rho = \rho_n + \rho_p$
- isospin asymmetry: $\delta = \dfrac{\rho_n - \rho_p}{\rho}$ $(0 < \delta < 1)$
- energy per nucleon in asymmetric matter $(\rho_n > \rho_p)$:

$$e(\rho,\delta) \; = \; e(\rho,\delta=0) \; + \; c_{sym}(\rho)\,\delta^2 \; + \; \mathcal{O}(\delta^4)$$

$$c_{sym}(\rho) \equiv \frac{1}{2}\frac{\partial^2 e(\rho,\delta)}{\partial\delta^2}\bigg|_{\delta=0}$$

$$e(\rho,\delta=1)_{\text{pure neutron matter}} \approx e(\rho,\delta=0)_{\text{symmetric nuclear matter}} + c_{sym}(\rho)$$

↑ especially at subsaturation densities



- state-of-the-art models for masses and charge radii of nuclei make very different predictions for the density dependence of the nuclear symmetry energy
- currently, intense effort in theory and experiment aims to resolve better the isospin properties of the nuclear interaction

$$c_{sym}(\rho) = \boldsymbol{J} + \boldsymbol{L}\,x + \frac{1}{2}\boldsymbol{K}_{\mathbf{sym}}\,x^2 + \mathcal{O}(x^3)$$

$$x \equiv (\rho - \rho_0)/3\rho_0$$

$$\boldsymbol{J} = c_{sym}(\rho_0) \qquad \boldsymbol{L} = 3\rho_0\,\partial c_{sym}(\rho)/\partial\rho\Big|_{\rho_0} \qquad \boldsymbol{K}_{\mathbf{sym}} = 9\rho_0^2\,\partial^2 c_{sym}(\rho)/\partial\rho^2\Big|_{\rho_0}$$

❖ Parabolic expansion in density of $c_{sym}(\rho)$ is both insightful and accurate:
- differs by less than 1% from exact value at $\rho = 0.10$ fm^{-3}
- differs by less than 5% from exact value in $\sim 0.5\rho_0 < \rho < \sim 2\rho_0$

❖ $\boldsymbol{J} \approx 32$ MeV, but the values of $\boldsymbol{L}$ and $\boldsymbol{K}_{\mathbf{sym}}$ are much less certain in experiment, and the theoretical predictions vary largely among nuclear models

Some empirical constraints on the density dependence of the symmetry energy at subsaturation:

- Recent research in HIC at intermediate energies is consistent with

  $c_{sym}(\rho) = c_{sym}(\rho_0)\,(\rho/\rho_0)^{\gamma}$ at $\rho \le \rho_0$ [e.g. Li et al, Phys Rep 464]

  - Isospin diffusion (transport model simulations): $\gamma \approx 0.7–1.05$ → $L \approx 88 \pm 25$ MeV
  - Isoscaling: $\gamma \approx 0.7$ → $L \approx 65$ MeV
  - Nucleon emission ratios: $\gamma \approx 0.5$ → $L \approx 55$ MeV

- GDR in ^{208}Pb: $23.3 < c_{sym}(0.1\ \mathrm{fm}^{-3}) < 24.9$ MeV → $\gamma \approx 0.5–0.65$ [Trippa et al PRC77]

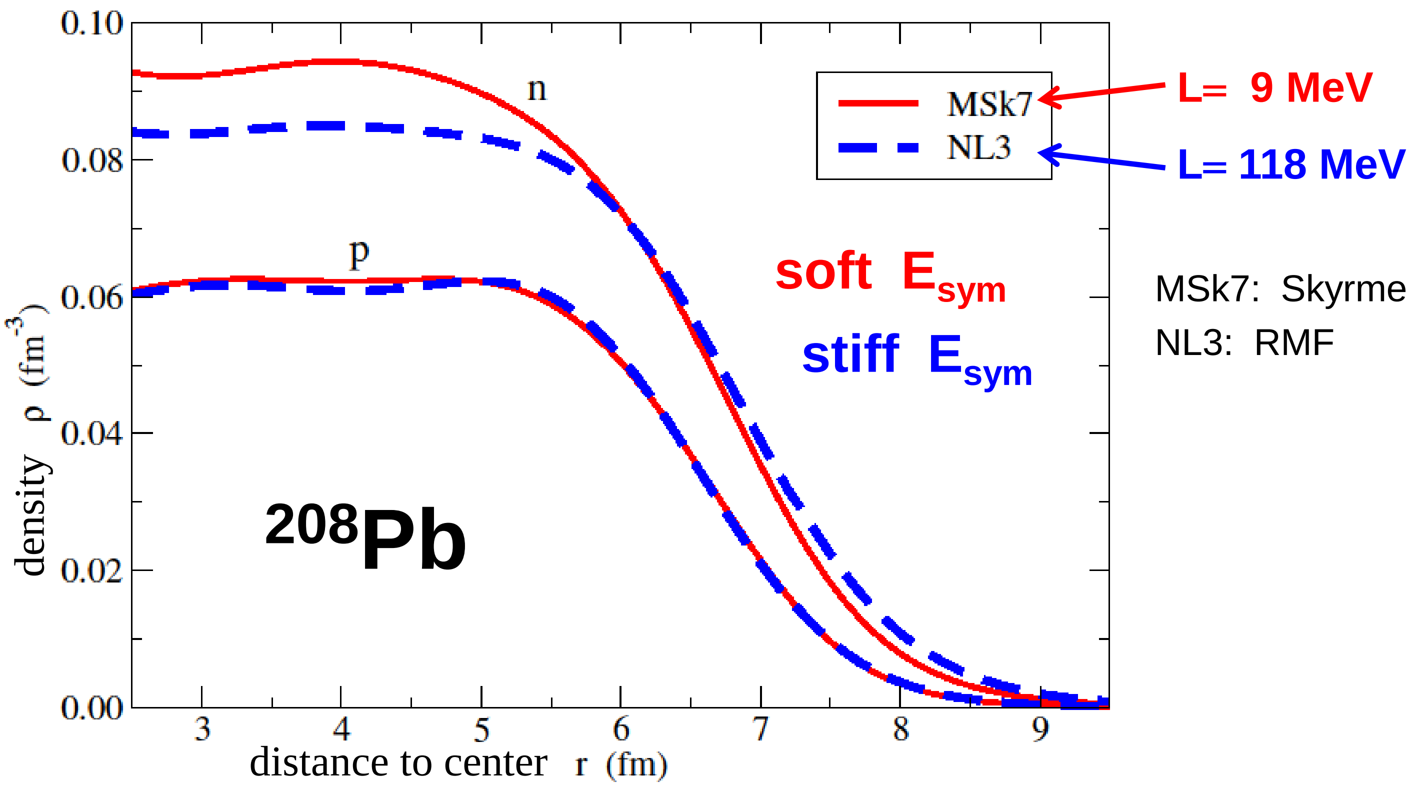
- PDR in ^{132}Sn and ^{68}Ni → $L = 65 \pm 16$ MeV [Klimkiewicz et al PRC76, Carbone et al PRC81]

- Thomas-Fermi model (Myers-Swiatecki) fitted to binding energies → $L = 50$ MeV

- … neutron skins ?

Nuclear charge densities are accurately known BUT neutron densities remain rather uncertain

➔ **theoretical nuclear models are constrained mainly by data other than neutron distributions**



MSk7: Skyrme HF-BCS

NL3: RMF

- **Fit by two-parameter Fermi shapes:**

$C_n - C_p = 0.0$ fm, $a_n - a_p = 0.10$ fm

$C_n - C_p = 0.2$ fm, $a_n - a_p = 0.12$ fm

$$\rho(r) = \frac{\rho_0}{1 + \exp\left[(r - C)/a\right]}$$

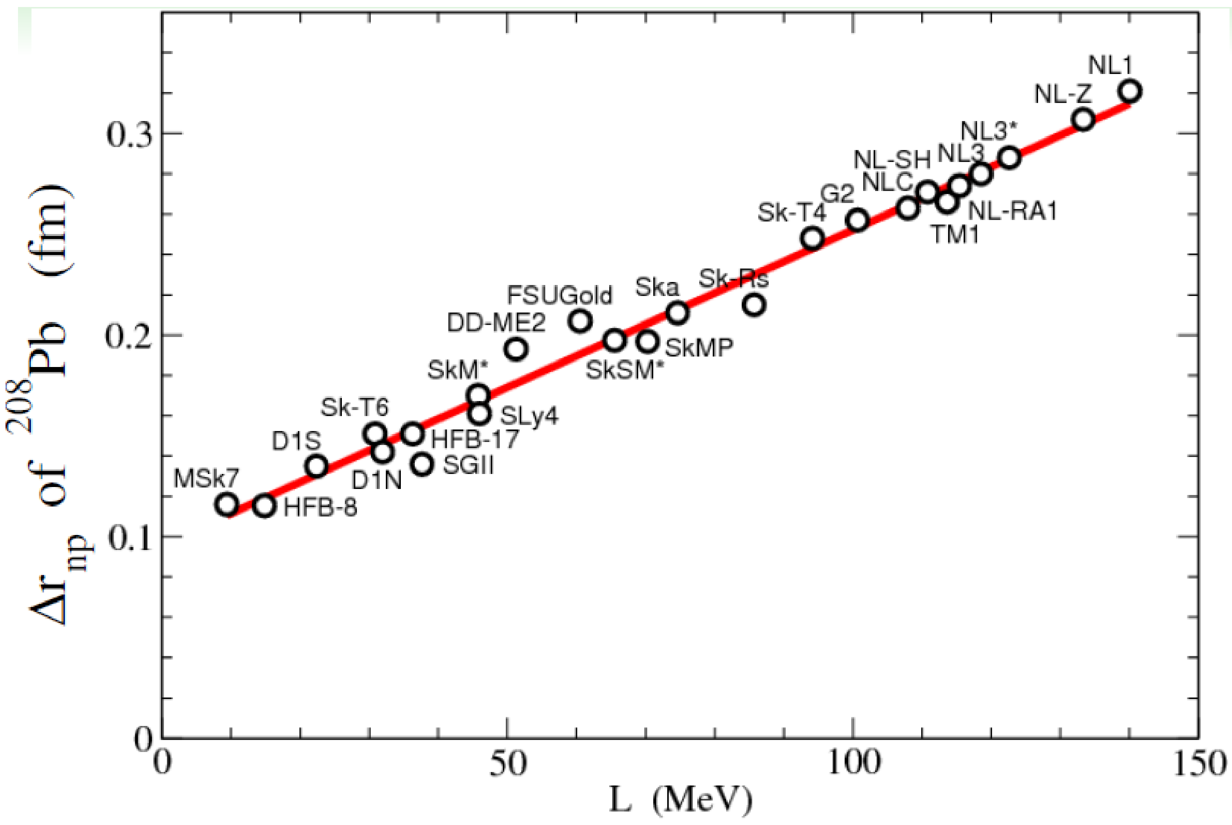
Centelles et al PRC82, 054314

Neutron skin thickness: $\Delta r_{np} = \langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2}$

- **Heavy nuclei are expected to have a neutron-rich skin (because of excess neutrons + Coulomb barrier retaining protons)**

- **Thickness of this neutron skin is very sensitive to the pressure of neutron matter and the density dependence of the symmetry energy**

(Brown PRL85, 5296; Brown, Typel PRC64, 027302; confirmed later in many studies)



Measuring neutron skins: $\Delta r_{np} = \langle r^2 \rangle_n^{1/2} - \langle r^2 \rangle_p^{1/2}$

- **Charge densities and charge radii of many nuclei are accurately known from electromagnetic probes (e.g., electron elastic scattering)**
- **Neutrons are uncharged**

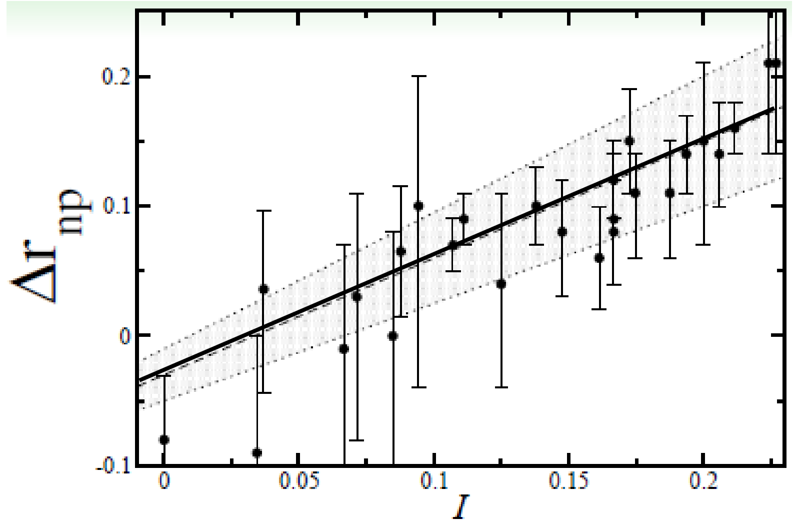
  → harder to resolve in experiment:

  usually by means of hadronic probes (strong interaction)
  - **nucleon-nucleus elastic scattering**
  - **inelastic α scattering (GDR and spin dipole resonance)**
  - **nuclear effects in exotic atoms**

Antiprotonic atoms**:** data from X rays and radiochemical analysis of the yields after the antiproton annihilation are sensitive to surface region of neutron distribution

Trzcinska et al, PRL87, 082501 (2001) :
skins of 26 stable nuclei over periodic table, from ^{40}Ca to ^{238}U

Jastrzebski et al, IJMP E13, 343 (2004)
Swiatecki et al, PRC71, 047301 (2005)
Klos et al, PRC76, 014311 (2007)



- data show overall linear trend with $I = (N-Z)/A$:

$$\Delta r_{np} = (0.9 \pm 0.15)\, I + (-0.03 \pm 0.02) \text{ fm}$$

- actually, linearity with I is predicted by the Droplet Model of Myers and Swiatecki

Symmetry energy coefficient of finite nuclei and neutron skin thickness in the Droplet Model (Myers-Swiatecki)

- Symmetry energy coefficient $a_{sym}(A)$ of the mass formula for nuclei :

$$a_{sym}(A) = \frac{J}{1+x_A}, \qquad x_A \equiv \frac{9J}{4Q} A^{-1/3} \qquad (\, a_{sym}(A) < J \,)$$

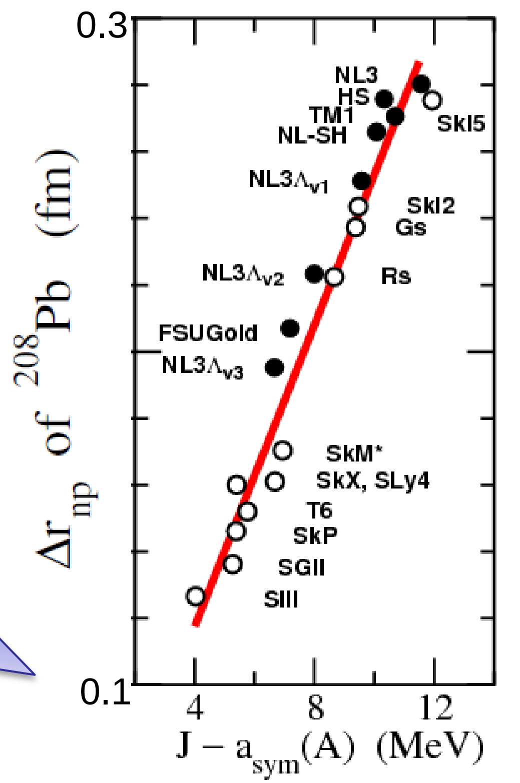
- Neutron skin thickness :

$$\Delta r_{np} = \sqrt{\frac{3}{5}} \left[t - \frac{e^2 Z}{70J} + \frac{5}{2R}(b_n^2 - b_p^2) \right]$$

$$R = r_0 A^{1/3}, \qquad I = (N-Z)/A, \qquad I_C = e^2 Z / 20JR$$

$$t = \frac{3r_0}{2} \frac{J/Q}{1+x_A} (I - I_C)$$

$$t = \frac{2r_0}{3J} \left[J - a_{sym}(A) \right] A^{1/3} (I - I_C)$$



Universal relation in MF models: "$a_{sym}(A) = c_{sym}(\rho_A)$"

The value of $a_{sym}(A)$ in finite nuclei is equal to the symmetry energy coefficient $c_{sym}(\rho_A)$ in nuclear matter at a density $\rho_A \sim 0.1\ fm^{-3}$

- representative case: $a_{sym}(^{208}Pb) \approx c_{sym}(0.10\ fm^{-3})$

Density ρ_A that *exactly* fulfils $c_{sym}(\rho_A) = a_{sym}(A)$ in various MF models:

		$A = 208$		$A = 116$		$A = 40$	
Model	J	a_{sym}	ρ	a_{sym}	ρ	a_{sym}	ρ
NL3	37.4	25.8	0.103	24.2	0.096	21.1	0.083
NL-SH	36.1	25.8	0.105	24.6	0.099	21.3	0.086
FSUGold	32.6	25.4	0.098	24.2	0.090	21.9	0.075
TF-MS	32.6	24.2	0.093	22.9	0.085	20.3	0.068
SLy4	32.0	25.3	0.100	24.2	0.091	22.0	0.075
SkX	31.1	25.7	0.102	24.8	0.096	22.8	0.082
SkM*	30.0	23.2	0.101	22.0	0.093	19.9	0.078
SIII	28.2	24.1	0.093	23.4	0.088	21.8	0.077
SGII	26.8	21.6	0.104	20.7	0.096	18.9	0.082

- density ρ_A is slightly lower in medium mass nuclei:

$a_{sym}(A{=}116) \approx c_{sym}(\rho_A = 0.093\ fm^{-3})$ $\qquad$ $a_{sym}(A{=}40) \approx c_{sym}(\rho_A = 0.08\ fm^{-3})$

($\rho_A \approx \rho_0 - \rho_0 / (1 + c A^{1/3})$ with c from $\rho_{A=208} = 0.1\ fm^{-3}$, $c \approx 1/3$)

Centelles et al, PRL102, 122502

Universal relation in MF models: "$a_{sym}(A) = c_{sym}(\rho_A)$"

- useful relation to link the isospin properties of the nuclear EOS with properties of finite nuclei that can be measured in the laboratory
- may help to constrain the density dependence of the symmetry energy at subsaturation

Case study: probing L from the neutron skin thickness of nuclei

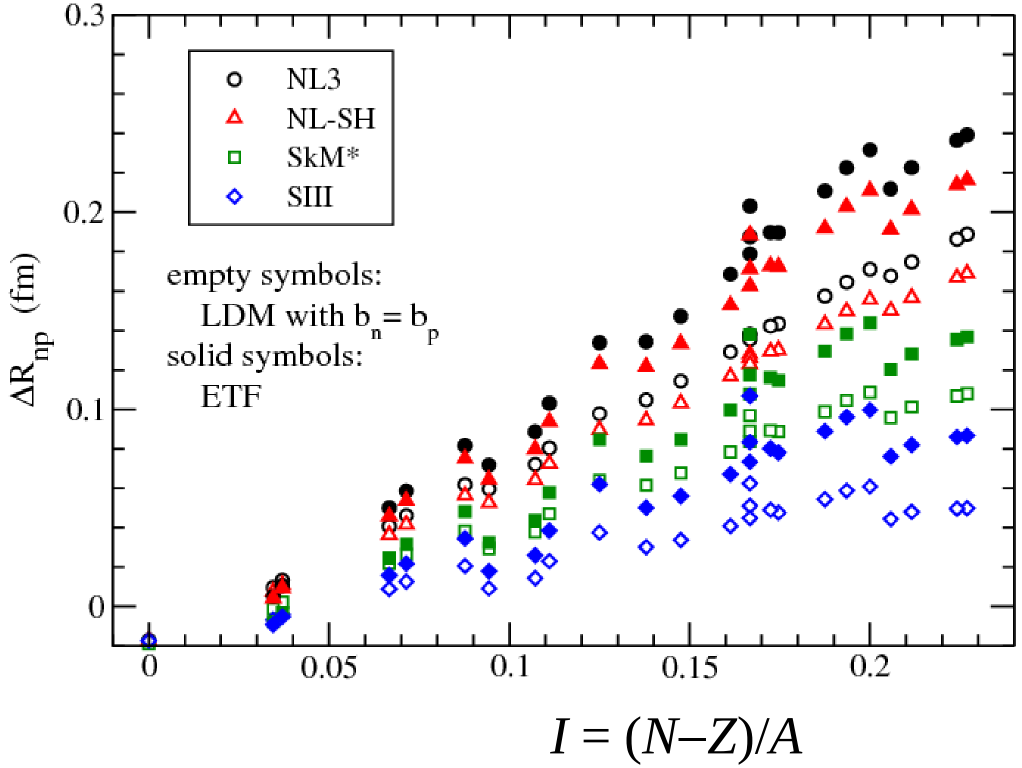
$$\Delta r_{np} = \sqrt{\frac{3}{5}}\left[\frac{2R}{3J}\,[J - a_{sym}(A)]\,(I - I_C) - \frac{e^2 Z}{70J} + \frac{5}{2R}(b_n^2 - b_p^2)\right]$$

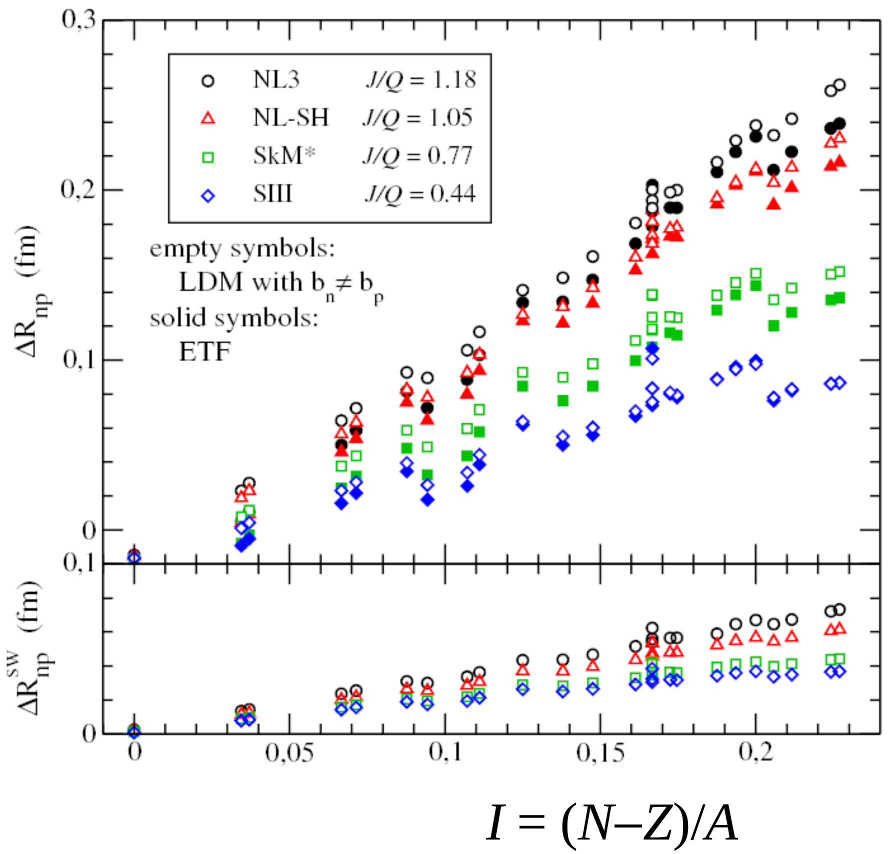
$$a_{sym}(A) \leftrightarrow c_{sym}(\rho_A) \leftrightarrow J + L\frac{(\rho_A - \rho_0)}{3\rho_0} + K_{sym}\frac{(\rho_A - \rho_0)^2}{18\rho_0^2} \rightarrow \Delta r_{np} = \Delta r_{np}(L)$$

- Surface width correction ($b_n \neq b_p$) :

$$\Delta r_{np}^{sw} = \sqrt{\frac{3}{5}}\frac{5}{2R}(b_n^2 - b_p^2) \propto I : \quad \text{from } 0.15I \text{ fm (SGII) to } 0.31I \text{ fm (NL3)}$$

Influence of the surface width correction ($b_n \neq b_p$)





$$\Delta r^{sw}_{np} = \sqrt{\frac{3}{5}}\frac{5}{2R}(b_n^2 - b_p^2) \propto I :$$ from $0.15I$ fm (SGII) to $0.31I$ fm (NL3)

b_n and b_p are obtained in ETF calculations of SINM

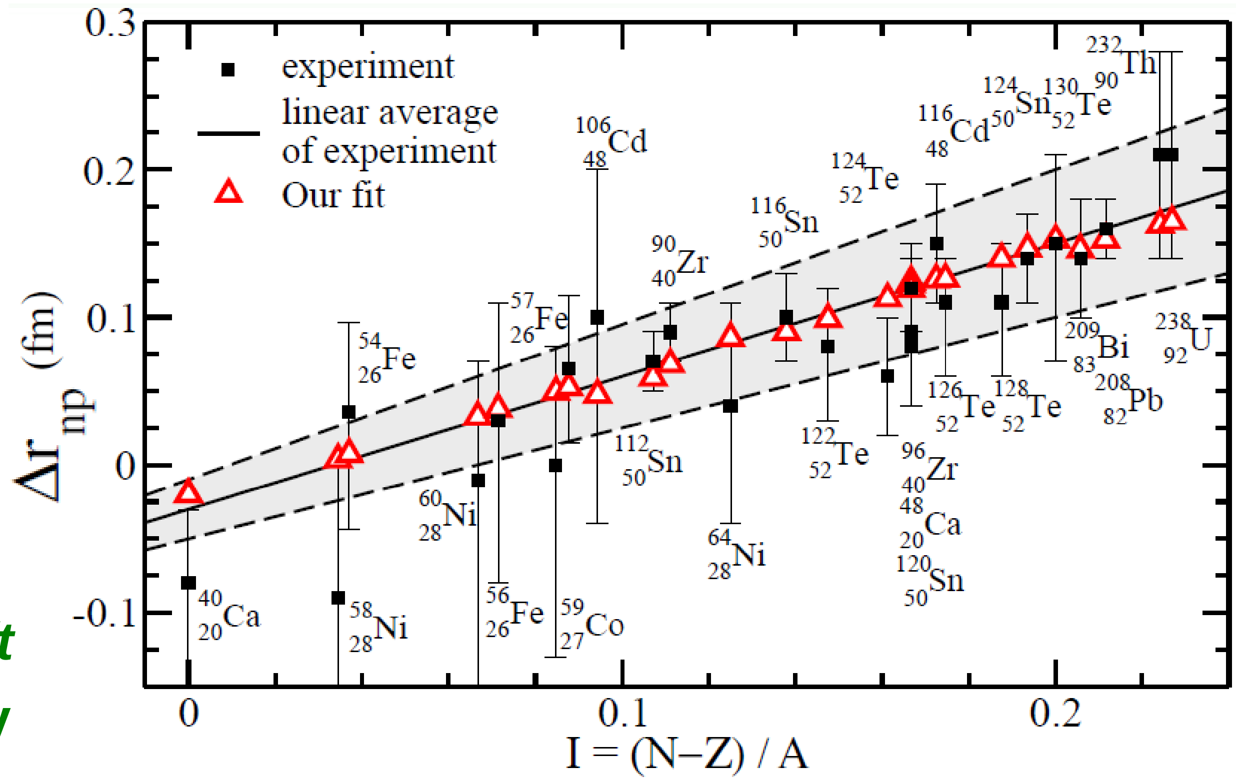
Case study: probing L from the neutron skin thickness of nuclei

- **Experimental baseline: the neutron skins measured in 26 antiprotonic atoms across the periodic table** [Trzcinska et al, PRL87, 082501 (2001)]
- $c_{sym}(\rho) = 31.6\ (\rho/\rho_0)^{\gamma}$ **MeV,** $\rho_0 = 0.16\ \text{fm}^{-3}$

Deduced constraint:

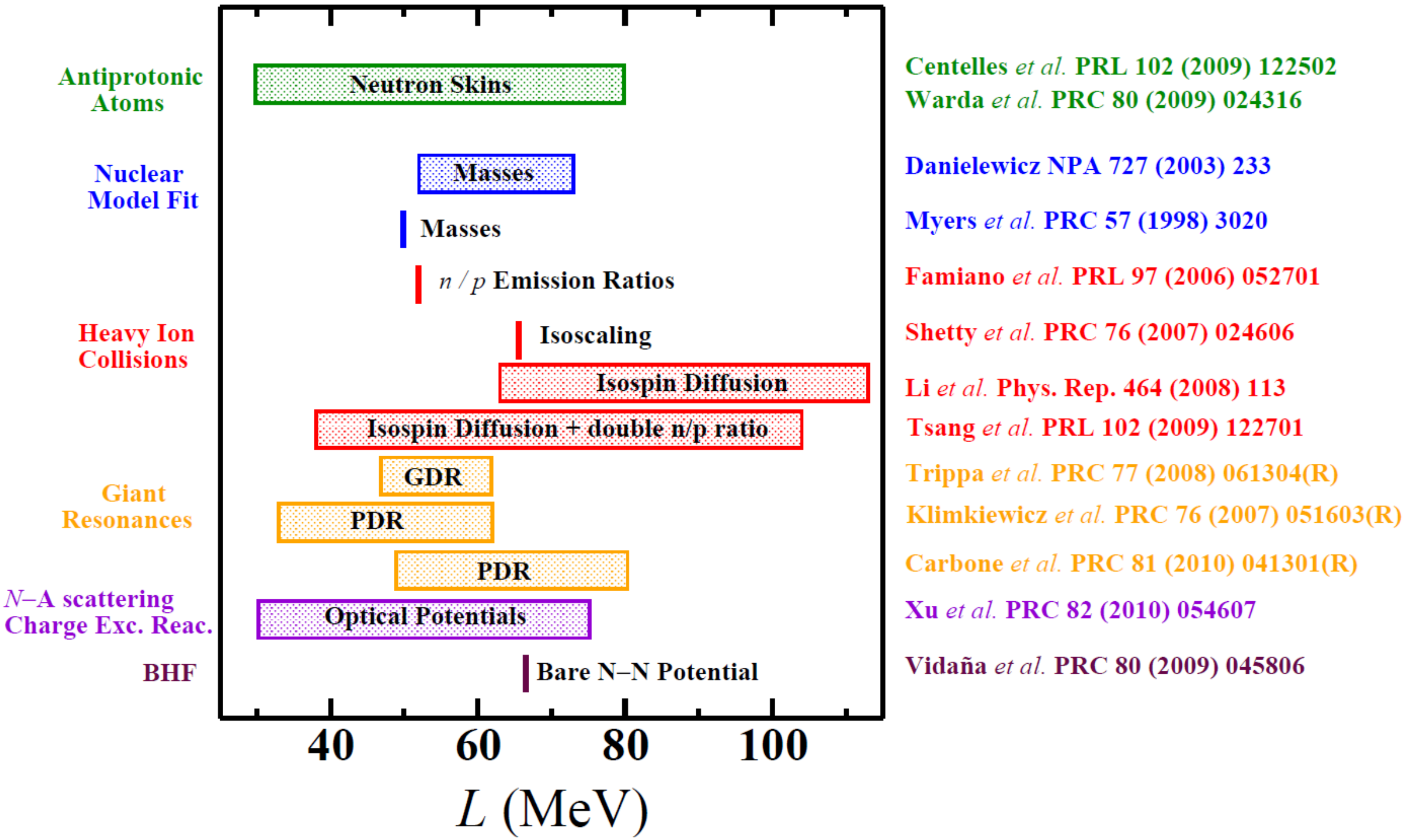
$L = 55 \pm 25$ **MeV**

in support of a rather *soft* nuclear symmetry energy



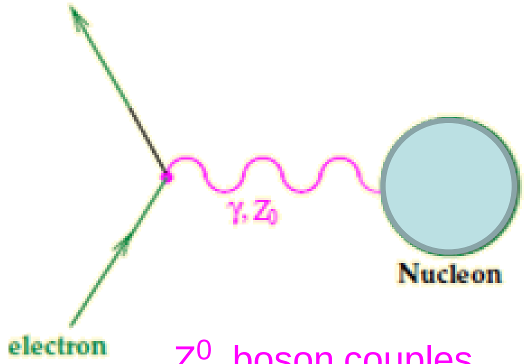
Centelles et al, PRL102, 122502; Warda et al PRC80, 024316

Recent constraints on the slope of the symmetry energy:



- ❖ Rewardingly, the recent constraints from very different observables seem to converge to a value around $L \sim 60$ MeV (± 25 MeV)
- ❖ More work needed to further narrow the constraints down with new measurements and model analyses !

Parity Violating Electron Scattering in ^{208}Pb :



Z^0 boson couples mainly to the neutron

- $A_{LR} \equiv \dfrac{\frac{d\sigma_+}{d\Omega} - \frac{d\sigma_-}{d\Omega}}{\frac{d\sigma_+}{d\Omega} + \frac{d\sigma_-}{d\Omega}}$
- $V_\pm(r) = V_{\text{Coulomb}}(r) \pm V_{\text{weak}}(r)$
- $V_{\text{weak}}(r) = \frac{G_F}{2^{3/2}}\left[(1 - 4\sin^2\theta_W) Z \rho_p(r) - N \rho_n(r)\right]$
- $A_{LR}^{\text{PWBA}} = \frac{G_F q^2}{4\pi\alpha\sqrt{2}}\left[4\sin^2\theta_W + \frac{F_n(q) - F_p(q)}{F_p(q)}\right]$

$\sin^2\theta_W \approx 0.23$

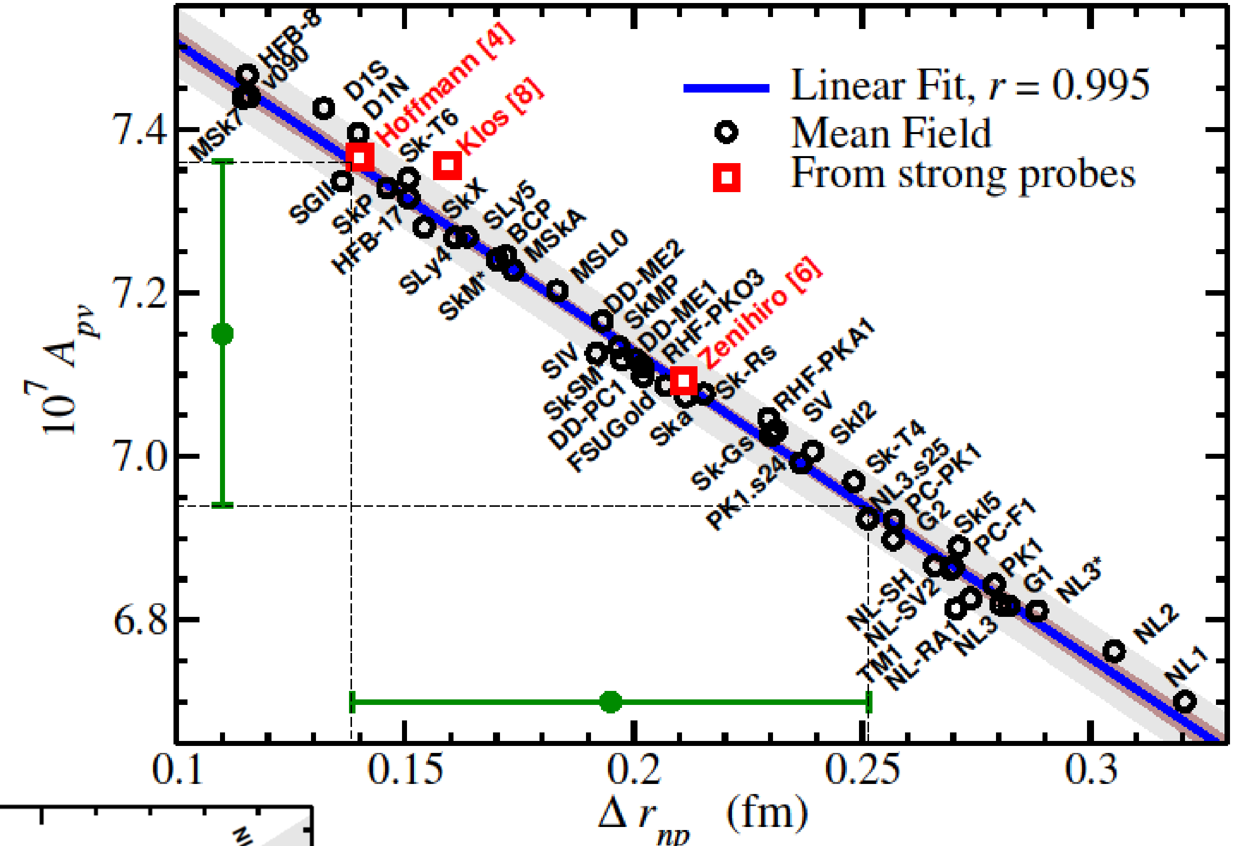
Donnelly et al NPA503, 589; Vretenar et al PRC61, 064307; Horowitz et al, PRC63, 025501

PREX experiment @ JLab:
first *electroweak* (*clean!*) measurement of the neutron radius of ^{208}Pb

~3% accuracy in A_{LR} (expected) : ~1% accuracy in neutron radius of ^{208}Pb

• Challenging experiment. A precision and clean measurement in one nucleus is complementary to more uncertain measurements by hadronic probes (but which are more common and exist for more nuclei, and which may be easier to perform in future measurements on radioactive very neutron-rich nuclei having thicker skins)

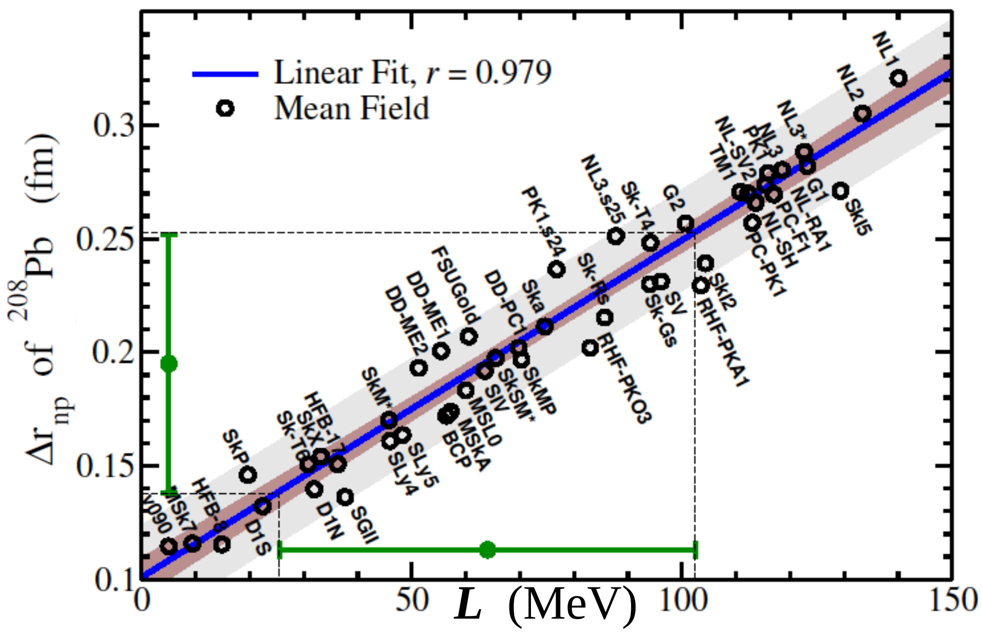
PVES on ^{208}Pb



PREX @ JLab:

E= 1.06 GeV,

θ= 5°, q_{lab}= 0.47 fm^{-1}



Fixes slope of the symmetry energy (pressure of neutron matter) around saturation density

CONCLUSIONS

- ❖ The characterization of the symmetry energy and of the equation of state of neutron-rich matter is one of the important open problems in nuclear physics

- ❖ We have described a universal relation in mean field models between the symmetry energy in finite nuclei and in nuclear matter at subnormal density

- ❖ This relation was useful to predict constraints on *L* from neutron skin data

- ❖ The results from neutron skins point to a soft nuclear symmetry energy

- ❖ The recent constraints from different observables seem to converge around a value $L \sim 60$ MeV (with about $\pm$ 25 MeV scatter)

- ❖ It is important to improve these constraints with the help of new measurements and further theoretical studies

THANKS !!