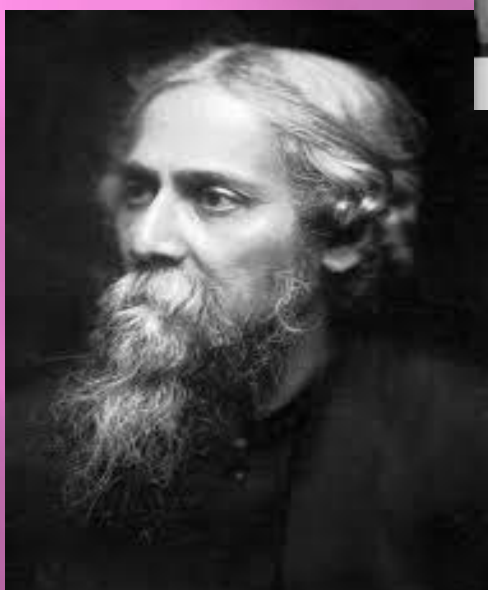
Madame Irene Curie-Joliot Opening the Institute



Rabindranath Tagor C. V. Raman

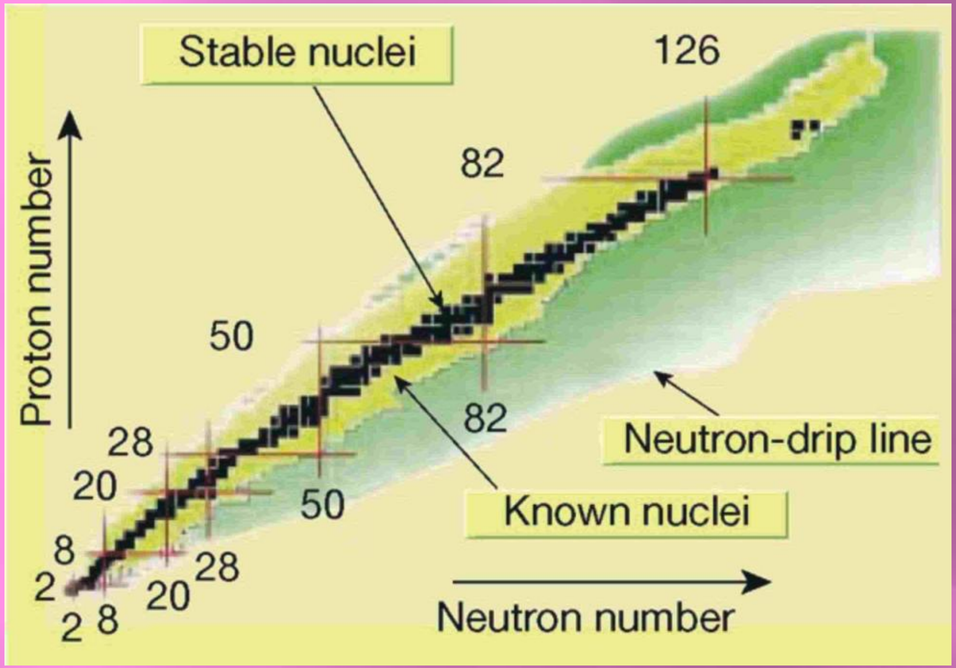
NUCLEAR SYMMETRY ENERGY FROM NUCLEAR OBSERVABLES

Bijay K. Agrawal
Saha Institute of Nuclear Physics
Kolkata, India

SINP

Outline of talk

- ✓Introduction /Motivation
- ✓Nuclear energy density functional
- ✓Probes for nuclear symmetry energy
- ✓Results
- ✓Conclusions

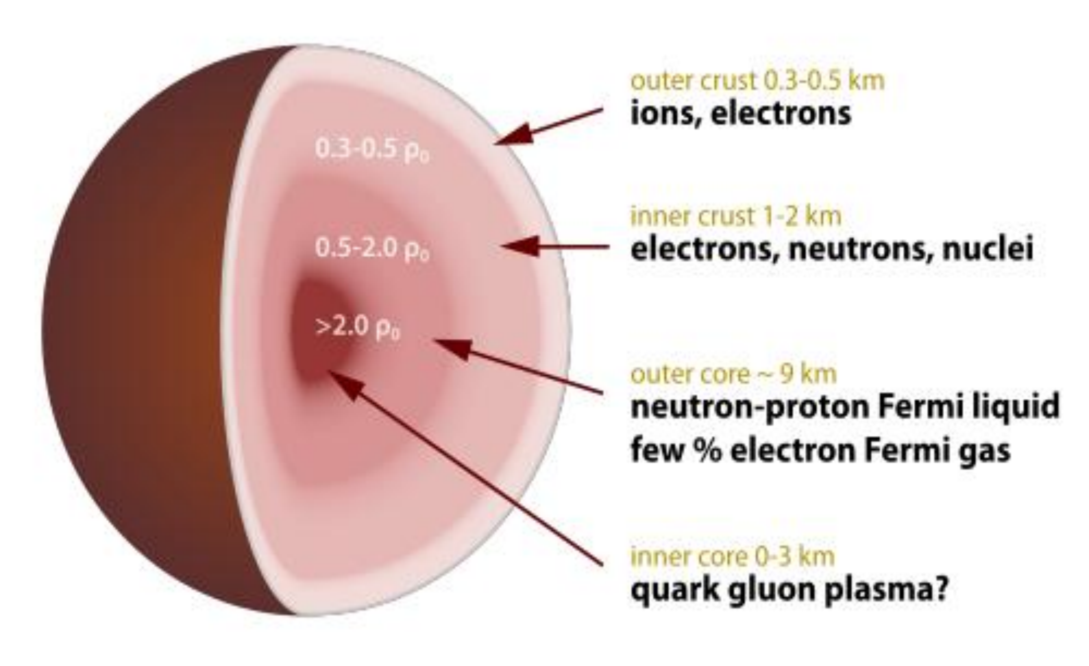


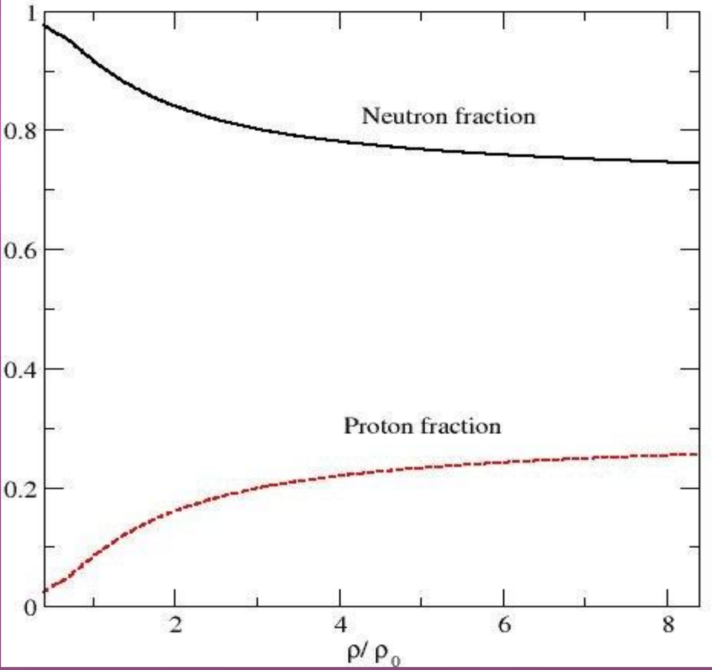
- Giant resonances
- Neutron rich nuclei
- Neutron drip line

$$B = a_V A - a_S A^{2/3} - a_C Z^2 A^{-1/3} - (J - J_S A^{-1/3}) A I^2 + \dots$$

$$I = \frac{N - Z}{N + Z}$$

Neutron star internal structure





Structure Equations

$$\frac{dP}{dr} = -G\frac{\varepsilon\mathcal{M}}{r^2c^2}\left[1+\frac{P}{\varepsilon}\right]\left[1+\frac{4\pi r^3 P}{\mathcal{M}c^2}\right]\left[1-\frac{2G\mathcal{M}}{rc^2}\right]^{-1}$$

$$\frac{d\mathcal{M}}{dr} = 4\pi r^2\frac{\varepsilon}{c^2}$$

Equation of State (EOS) for Asymmetric nuclear matter

$$E(\rho, I) = E(\rho,0) + J(\rho)I^2 + \ldots$$

$$E(\rho,0) = E(\rho_0,0) + \frac{1}{2}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 K + \ldots$$

$$J(\rho) = J(\rho_0) + \left(\frac{\rho-\rho_0}{3\rho_0}\right)L(\rho_0) + \ldots$$

$$\rho_0 = 0.16\ \mathrm{fm}^{-3}$$

$$E(\rho_0,0) = -16\ \mathrm{MeV}$$

$$\mathrm{K} = 220\ \mathrm{MeV}$$

$$J(\rho_0) \approx 32\ \mathrm{MeV}$$

$$\mathrm{L}(\rho_0) = 20\text{-}120\ \mathrm{MeV}\ ?$$

Proton fraction at β equilibrium x_β

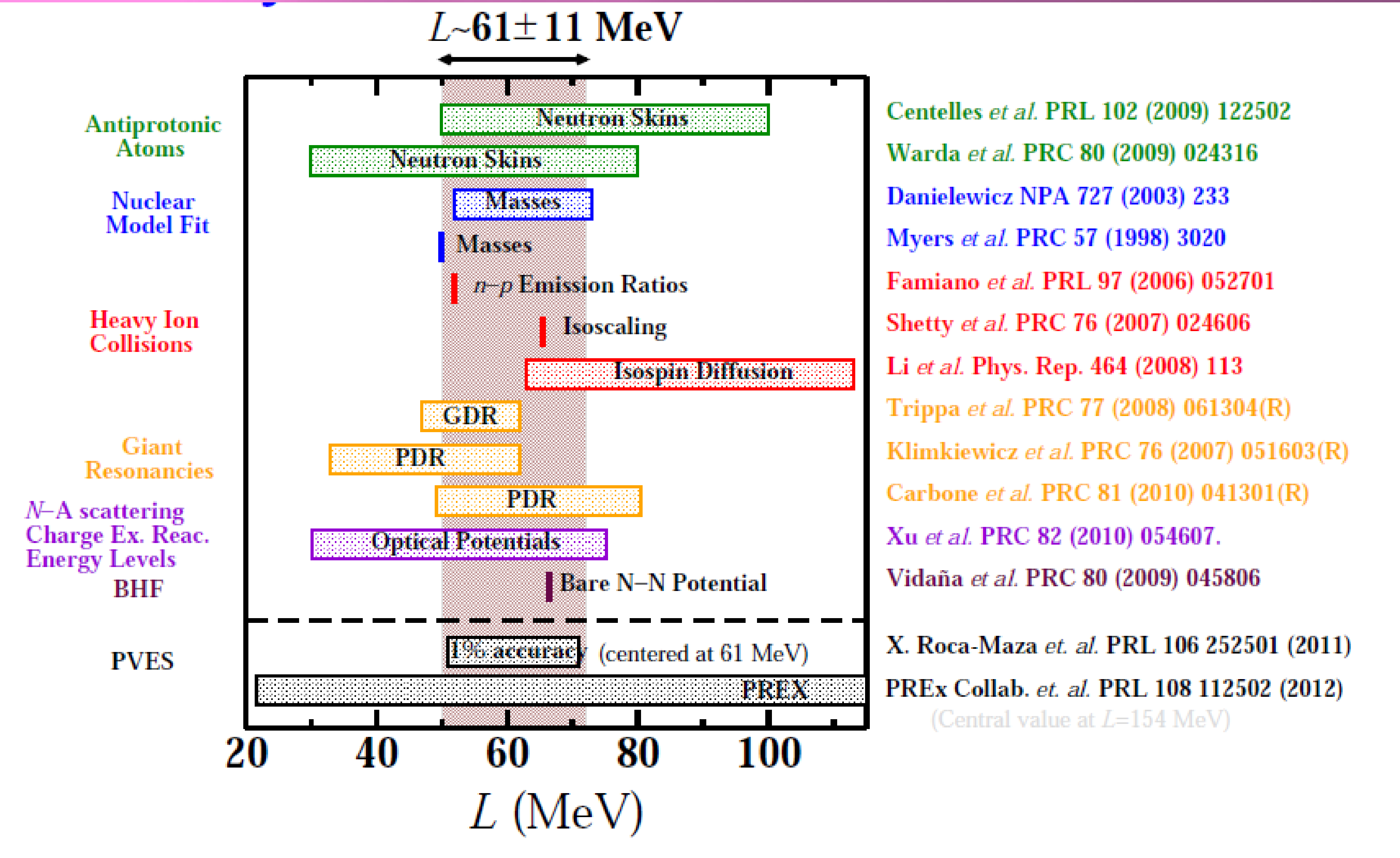
$$\hbar c(3\pi^2 \rho x_\beta)^{1/3} = 4(1-2x_\beta)J(\rho)$$

Neutron star properties

- Core-crust transition properties
- Cooling
- Composition
- Mass-radius relation ship

Knowledge of $J(\rho_0)$ and $L(\rho_0)$ is indispensable !!

Status of L



L~61±11 MeV
Antiprotonic Atoms
Nuclear Model Fit
Heavy Ion Collisions
Giant Resonancies
N–A scattering
Charge Ex. Reac.
Energy Levels
BHF
PVES
Neutron Skins
Neutron Skins
Masses
Masses
n–p Emission Ratios
Isoscaling
Isospin Diffusion
GDR
PDR
PDR
Optical Potentials
Bare N–N Potential
1% accuracy (centered at 61 MeV)
PREX
20
40
60
80
100
L (MeV)
Centelles et al. PRL 102 (2009) 122502
Warda et al. PRC 80 (2009) 024316
Danielewicz NPA 727 (2003) 233
Myers et al. PRC 57 (1998) 3020
Famiano et al. PRL 97 (2006) 052701
Shetty et al. PRC 76 (2007) 024606
Li et al. Phys. Rep. 464 (2008) 113
Trippa et al. PRC 77 (2008) 061304(R)
Klimkiewicz et al. PRC 76 (2007) 051603(R)
Carbone et al. PRC 81 (2010) 041301(R)
Xu et al. PRC 82 (2010) 054607.
Vidaña et al. PRC 80 (2009) 045806
X. Roca-Maza et. al. PRL 106 252501 (2011)
PREx Collab. et. al. PRL 108 112502 (2012)
(Central value at L=154 MeV)

Definitions

Symmetryenergy

$$J(\rho) = \frac{1}{2}\left(\frac{\partial^2 E(\rho, I)}{\partial I^2}\right)_{I=0}$$

$$\approx E(\rho,1) - E(\rho,0)$$

Slope parameter

$$L(\rho) = 3\rho \frac{dJ}{d\rho}$$

$$J \equiv J(\rho_0)$$

$$L \equiv L(\rho_0)$$

Nuclear energy density functional

1. Non-Relativistic mean field model

2. Relativistic mean field model

3. Density dependant meson exchange model

Non-Relativistic mean field model : Skyrme type

$$\varepsilon = \varepsilon_{kin} + \varepsilon_0 + \varepsilon_3 + \varepsilon_{eff}$$

$$\varepsilon_{kin} = \left(\frac{\hbar^2}{2m}\right)\tau$$

$$\varepsilon_0 = \frac{1}{4} t_0 \left[(2 + x_0)\rho^2 - (2x_0+1)(\rho_p^2 + \rho_n^2)\right]$$

$$\varepsilon_3 = \frac{1}{24} t_3 \rho^{\alpha} \left[(2 + x_3)\rho^2 - (2x_3+1)(\rho_p^2 + \rho_n^2)\right]$$

$$\varepsilon_{eff} = \frac{1}{8}\left[t_1(2 + x_1) + t_2(2 + x_2)\right]\tau\rho + \frac{1}{8}\left[t_2(2x_2 + 1) - t_1(2x_1 + 1)\right](\tau\rho_p + \tau\rho_n)$$

$\tau \Rightarrow$ kinetic energy density, $\rho \Rightarrow$ number density

m $\Rightarrow$ nucleon mass,

$t_i x_i$ (i = 0,1,2 and 3) determined from finite nuclei properties.

Relativistic mean field model

$$\varepsilon = \varepsilon_{kin} + \varepsilon_{lin} + \varepsilon_{\sigma} + \varepsilon_{\omega} + \varepsilon_{\rho} + \varepsilon_{\sigma\omega\rho}$$

$$\varepsilon_{lin} = \sum_{J=n,p} \overline{\psi}_J \left[i\gamma^{\mu}\partial_{\mu} + (g_{\sigma}\sigma - M) + \left(g_{\omega}\gamma^{\mu}\omega_{\mu} + \frac{1}{2} g_{\rho}\gamma^{\mu}\tau.\rho_{\mu} \right) \right] \psi$$

$$\varepsilon_{\sigma} = -\tfrac{1}{2} m_{\sigma}^2 \sigma^2 - \frac{k_3}{6M} g_{\sigma} m_{\sigma}^2 \sigma^3 - \frac{k_4}{24M^2} m_{\sigma}^2 \sigma^4$$

$$\varepsilon_{\omega} = \frac{1}{2} m_{\omega}^2 \omega^2 + \frac{1}{24} \zeta_0 g_{\omega}^2 \omega^4$$

$$\varepsilon_{\rho} = \frac{1}{2} m_{\rho}^2 \tilde{\rho}^2$$

$$\varepsilon_{\sigma\omega\rho} = \frac{\eta_1}{2M} g_{\sigma} m_{\omega}^2 \sigma \omega^2 + \frac{\eta_2}{4M^2} g_{\sigma}^2 m_{\omega}^2 \sigma^2 \omega^2 + \frac{\eta_{\rho}}{2M} g_{\sigma} m_{\rho}^2 \sigma \tilde{\rho}^2$$

$$+ \frac{\eta_{1\rho}}{4M^2} g_{\sigma}^2 m_{\rho}^2 \sigma^2 \tilde{\rho}^2 + \frac{\eta_{2\rho}}{4M^2} g_{\omega}^2 m_{\rho}^2 \sigma^2 \omega^2 \tilde{\rho}^2$$

Density dependant meson exchange model DDME

$$g_i(\rho) = g_i(\rho_{sat}) f_i(x) \text{ for i} = \sigma, \omega$$

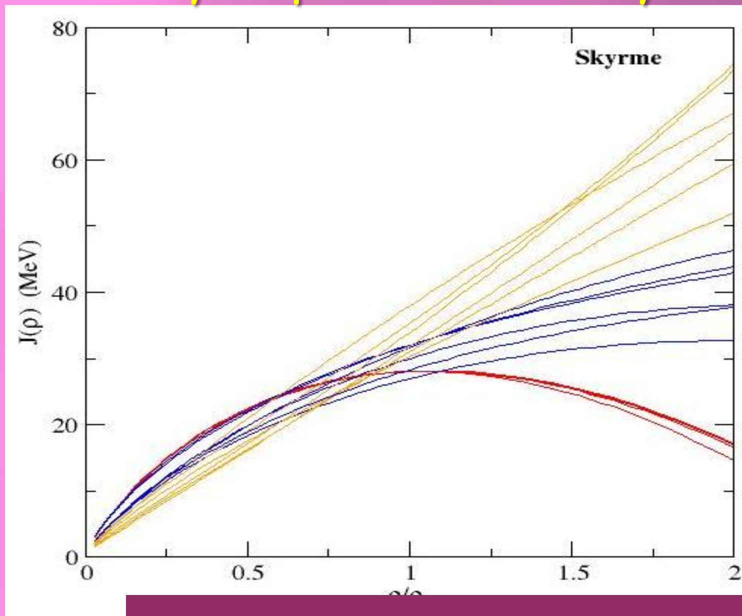
$$g_\rho(\rho) = g_\rho(\rho_{sat}) \exp[-a_\rho (x-1)]$$

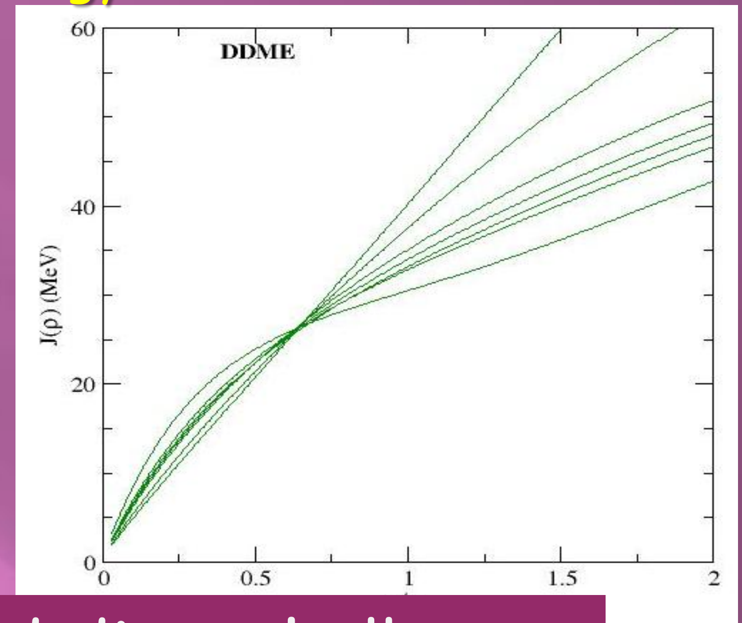
$$x = \frac{\rho}{\rho_{sat}},$$

$$f_i(x) = a_i \frac{1 + b_i (x + d_i)^2}{1 + c_i (x + d_i)^2}$$

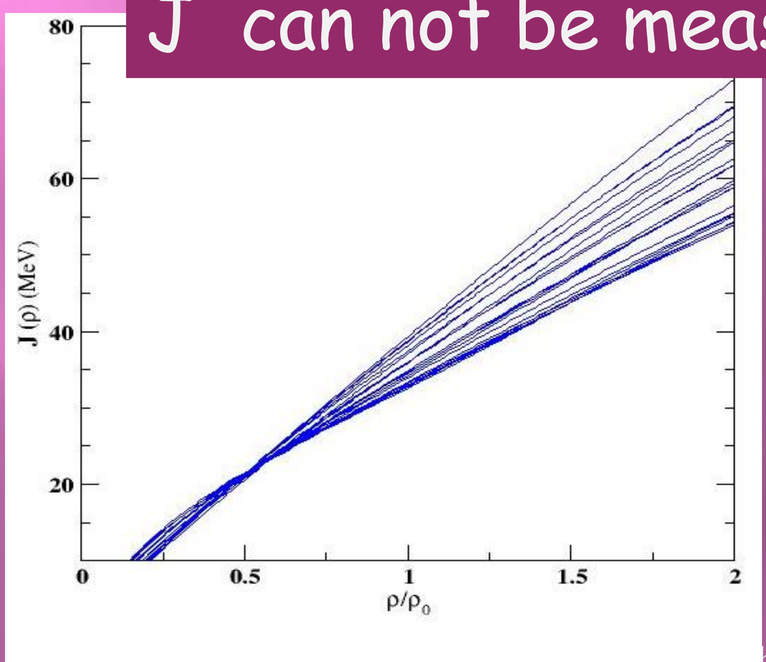
$$f_i(1) = 1$$

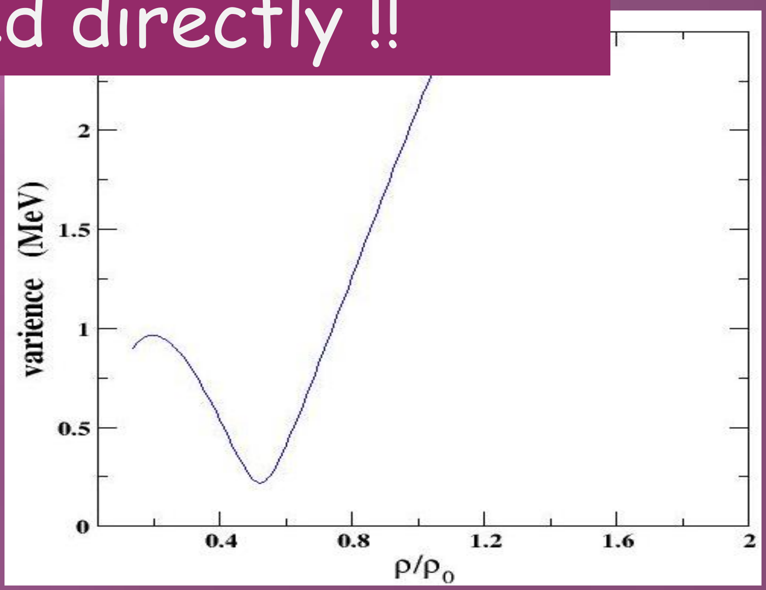
Density dependence of symmetry energy





J can not be measured directly !!

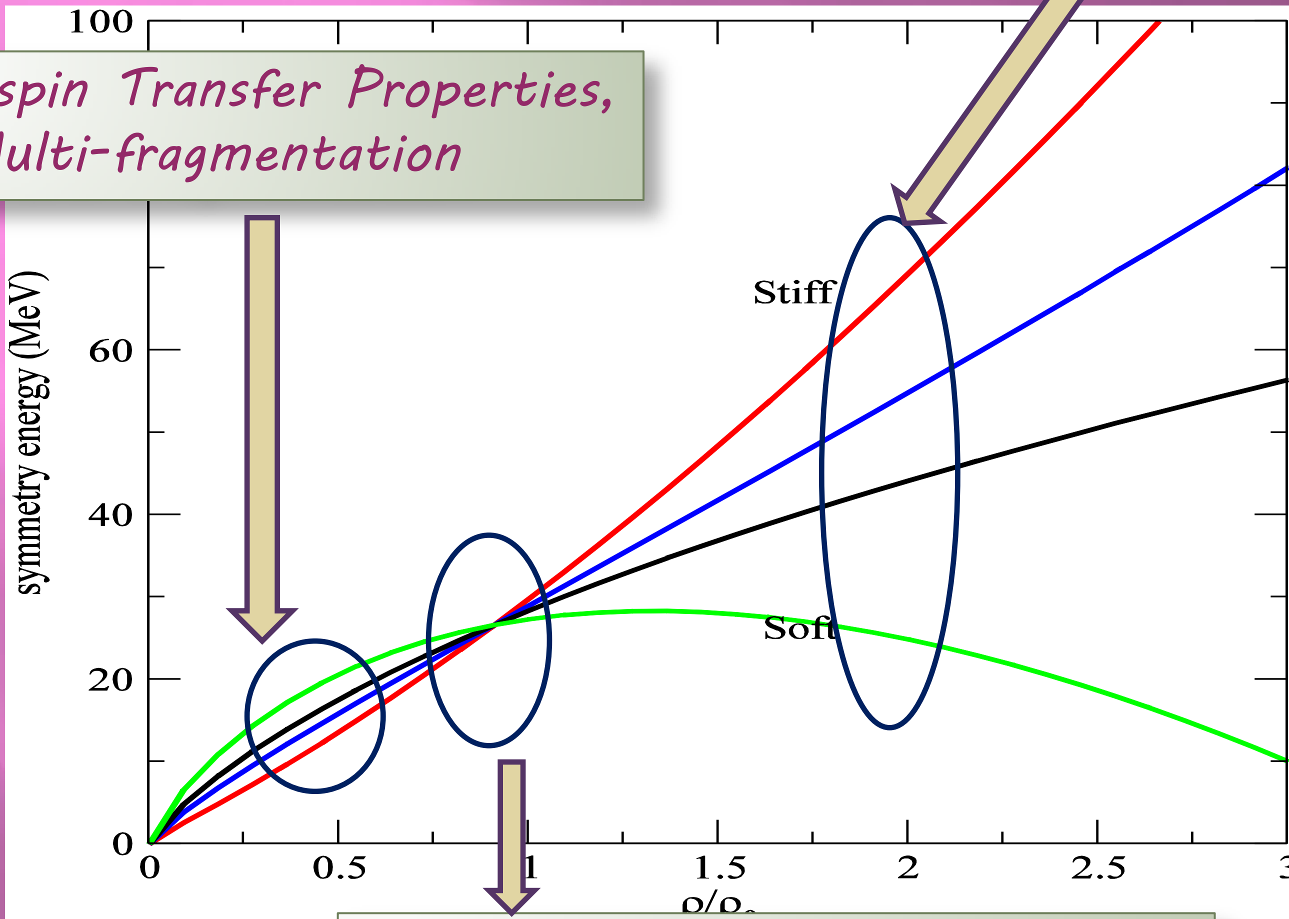




Probes for the nuclear symmetry energy

Supra saturation densities Supernovae, Nucleosynthesis, Rel. HIC, Neutron Stars

Isospin Transfer Properties, Multi-fragmentation



$\rho = \rho_0$ structure and low energy excitations of asymmetric nuclei, skin thickness, Isovector giant resonances

Nuclear Structure: Neutron-skin, Giant resonance

Probes at ρ_0

- Neutron skin thickness
- Giant dipole resonance
  i)Pigmy dipole resonance
  ii)Dipole polarizability
- Giant quadrupole resonance
- Nuclear binding energies

Covariance Analysis

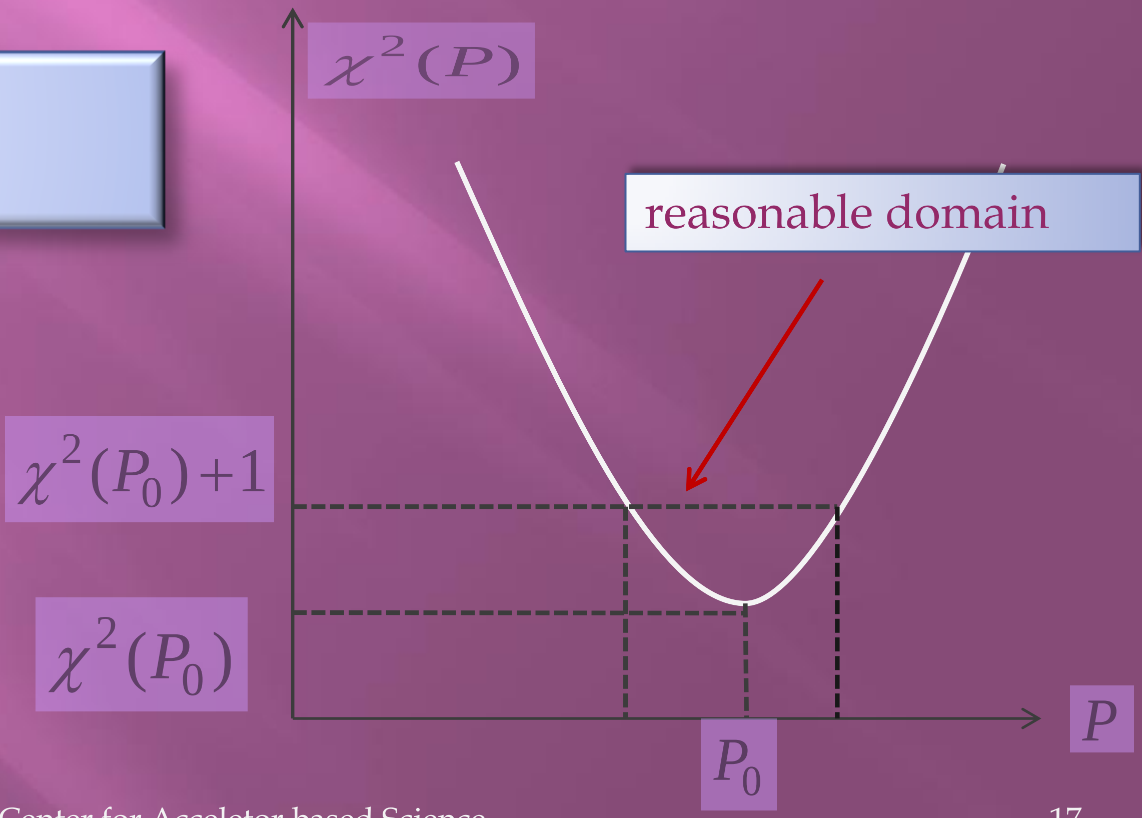
Consider a model described by coupling constants: $(P_1, P_2, \ldots, P_N)$

At the optimum parameter set P_0

$$\chi^2(P_0) = \chi^2_{min}$$

Reasonable domain of parameter satisfy:

$$\chi^2(P) - \chi^2(P_0) \leq 1$$



$$C_{AB} = \frac{\overline{\Delta A \Delta B}}{\sqrt{\overline{\Delta A^2}\,\overline{\Delta B^2}}}$$

$|c_{AB}| = 1$: Fully correlated

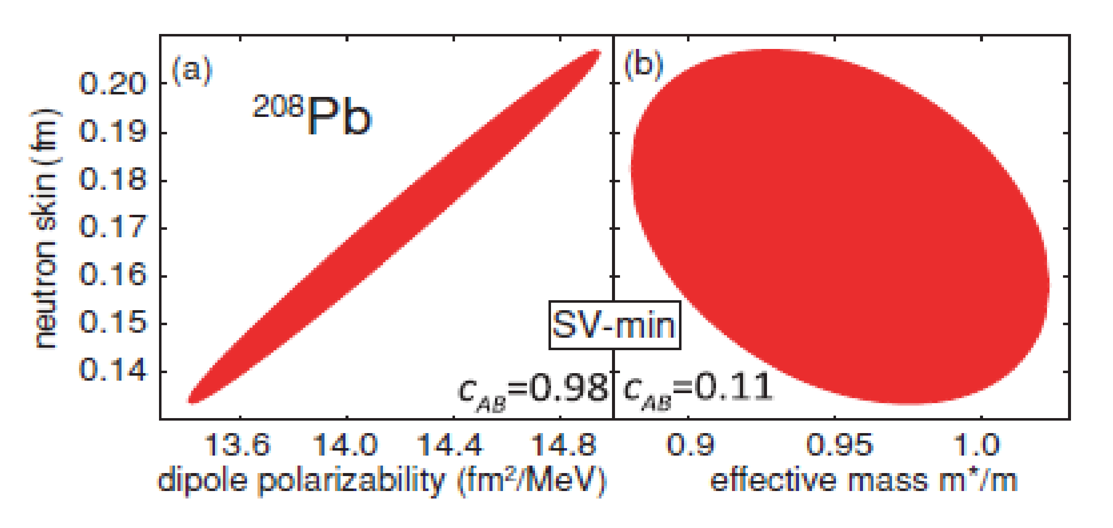
$c_{AB} = 0$: Uncorrelated or Statistically independent

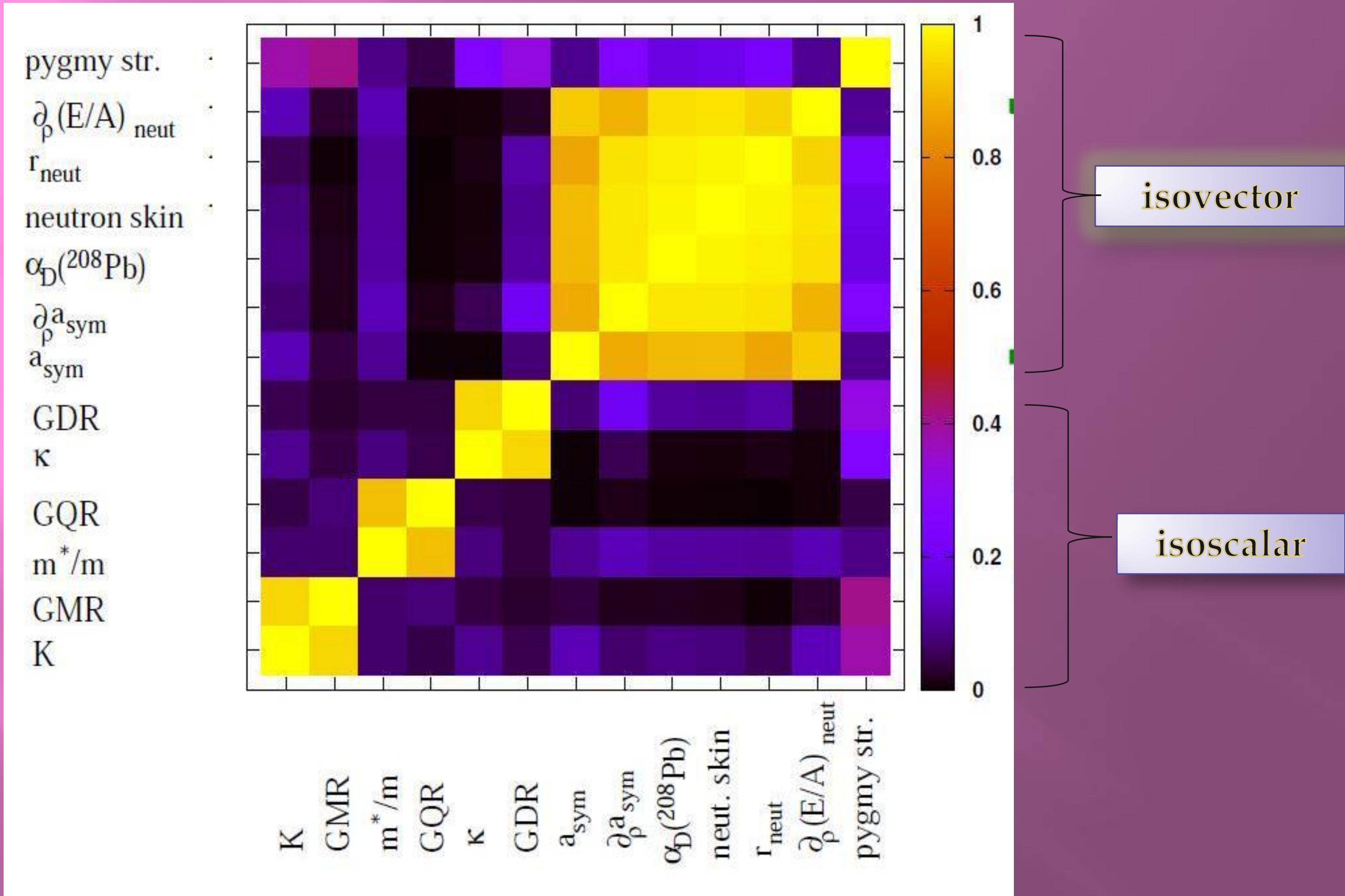
$$\overline{\Delta A \Delta B} = \sum_{ij} \partial_{pi} A (\mathrm{M}^{-1})_{ij} \partial_{pj} B$$

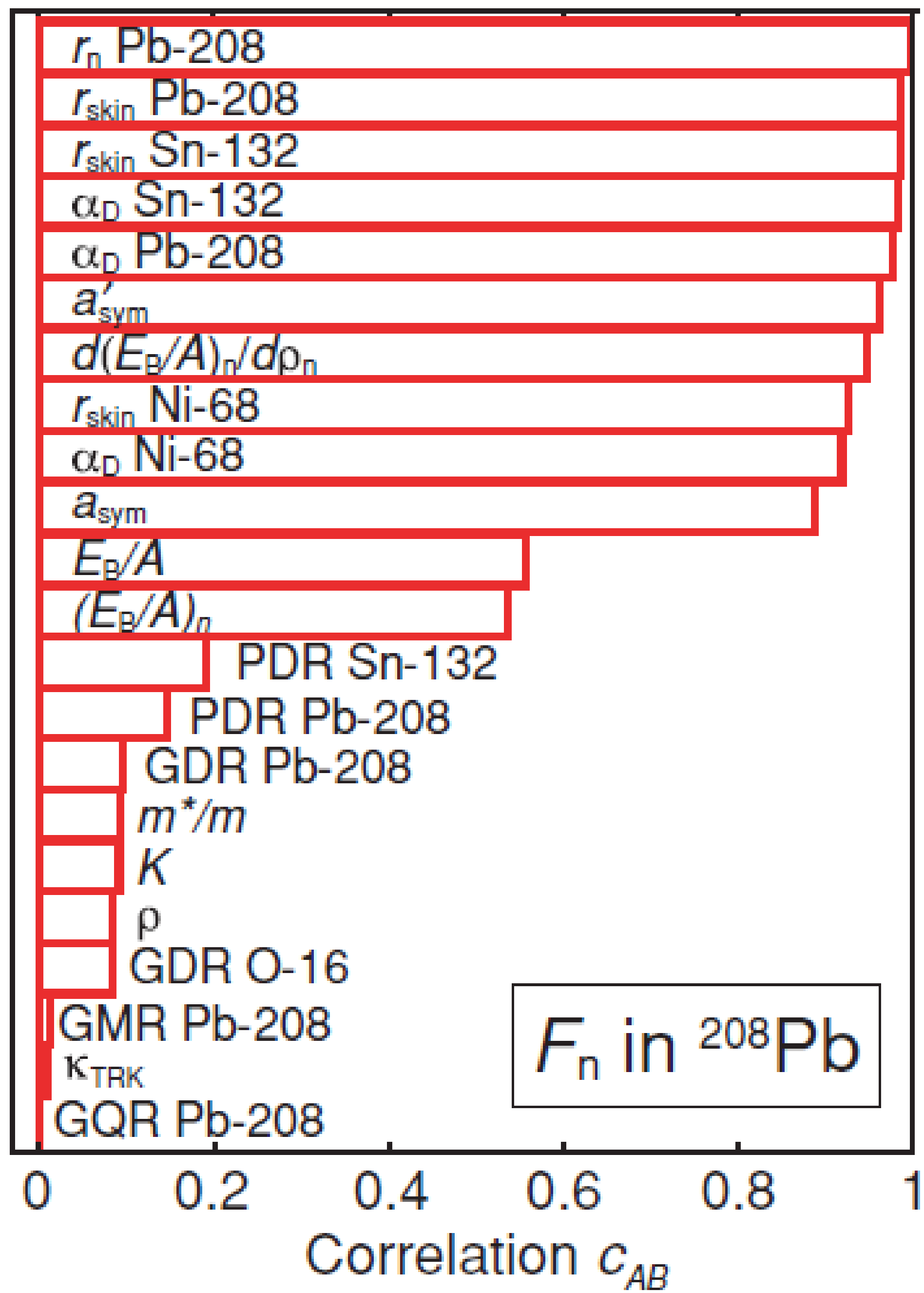
$$\overline{\Delta A^2} = \sum_{ij} \partial_{pi} A (\mathrm{M}^{-1})_{ij} \partial_{pj} A$$

$$M_{ij} = \partial_{pi} \partial_{pj} \chi^2 \Big|_{P_0}$$

$$\partial_{pi} A = \frac{\partial A}{\partial pi}\Big|_{P_0}$$



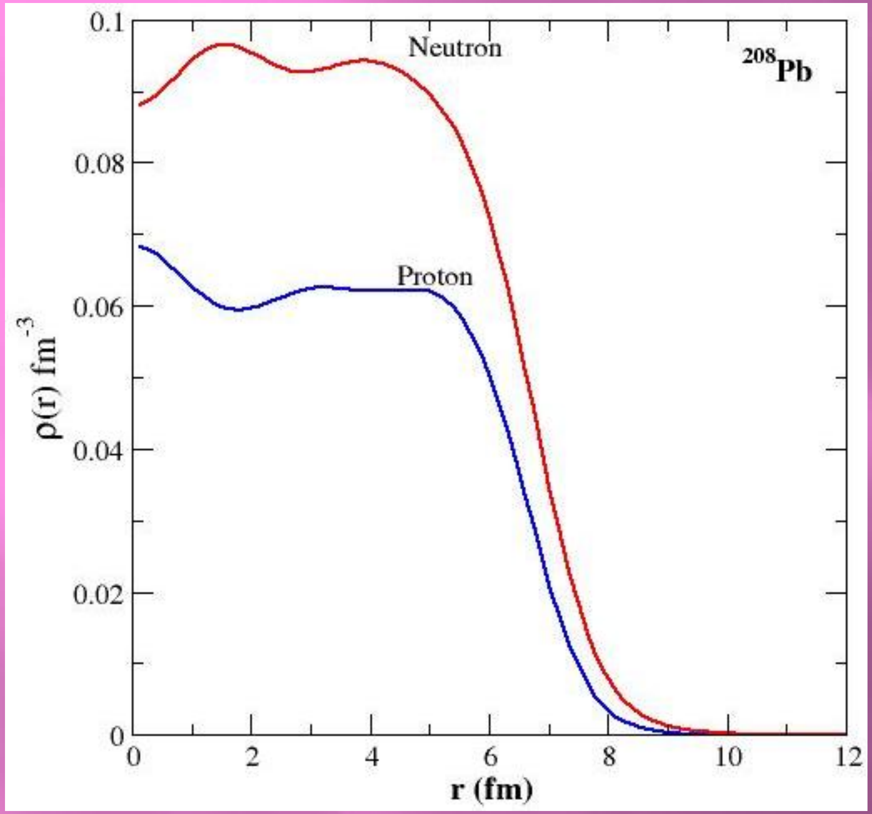

pygmy str.
$\partial_\rho(E/A)_{neut}$
r_{neut}
neutron skin
$\alpha_D(^{208}Pb)$
$\partial_\rho a_{sym}$
a_{sym}
GDR
κ
GQR
m^*/m
GMR
K
1
0.8
0.6
0.4
0.2
0
isovector
isoscalar



Good isovector indicators

Poor isovector indicators

Neutron skin thickness

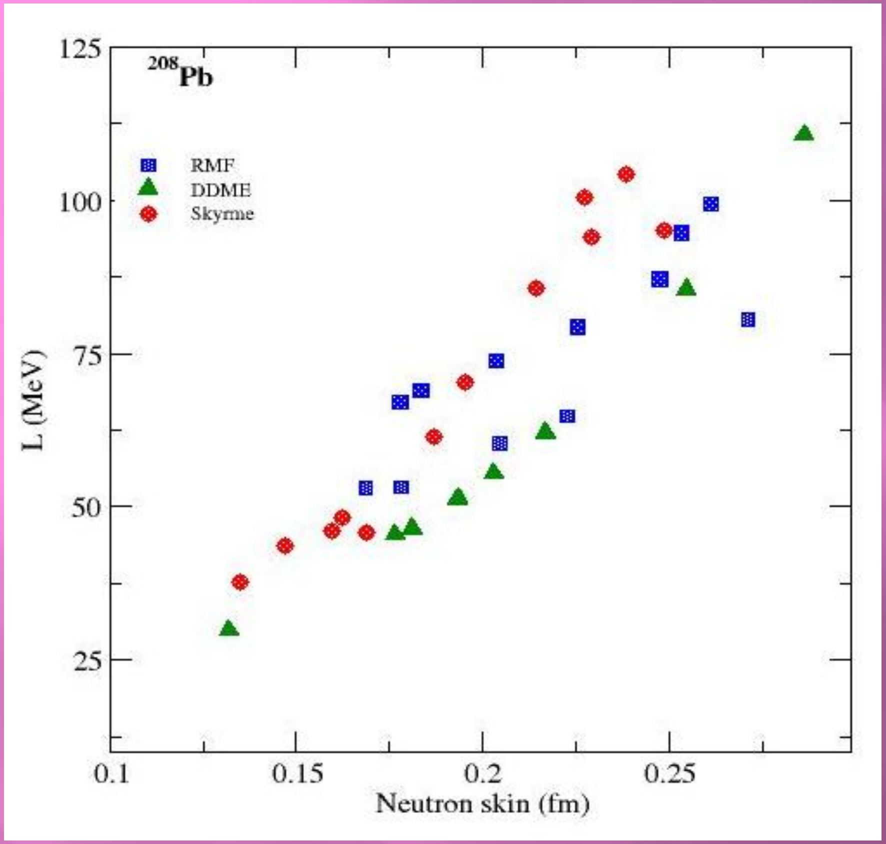


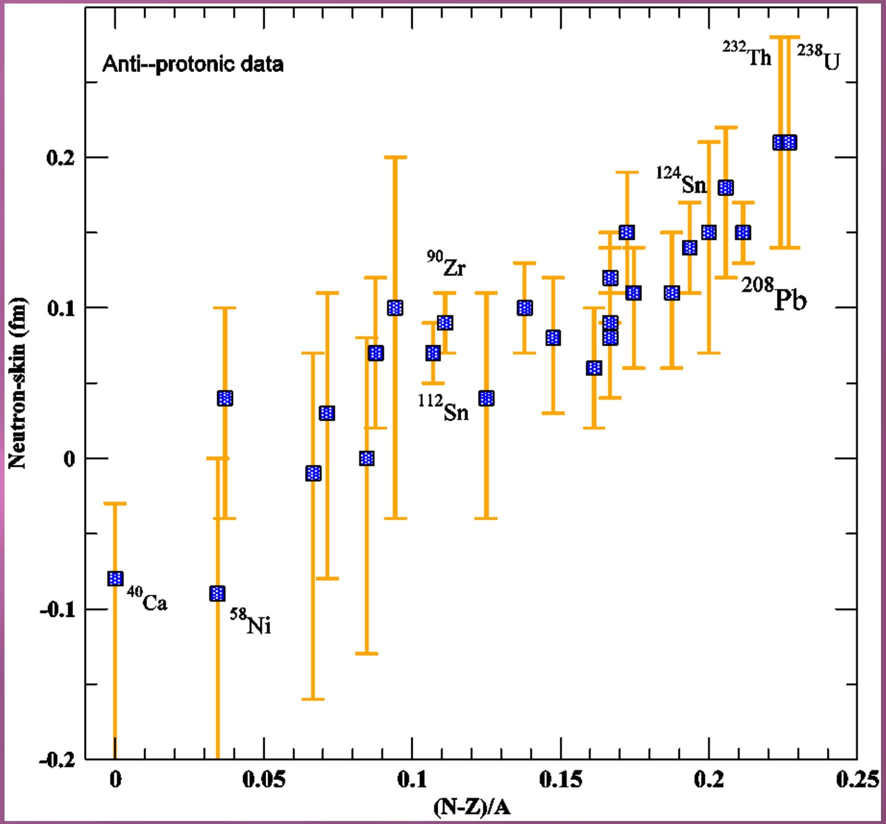
$$R_{skin} = \langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2}$$

$$\langle r_q^2 \rangle = \frac{\int r^2 \rho_q(r) d^3 r}{\int \rho_q(r) d^3 r}$$

$$q = p, n$$

L from neutron skin thickness (R_{skin})





L= 75±25MeV

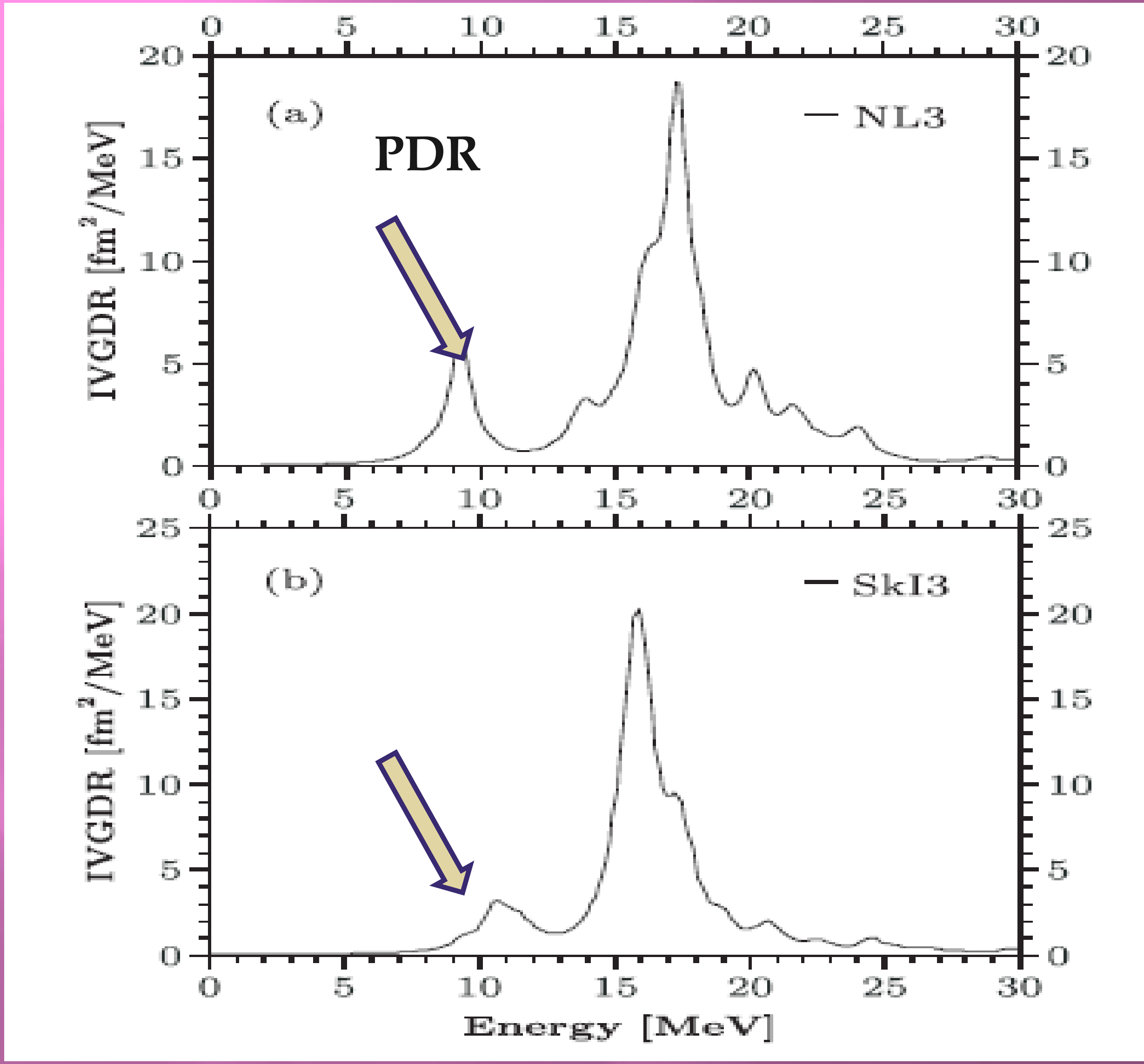
M. Centelles et.al PRL 102,122502 (2009)

First PREX data PRL 108, 112502 (2012)

$$R_{skin} = 0.33^{+0.16}_{-0.18}\ \text{fm}$$

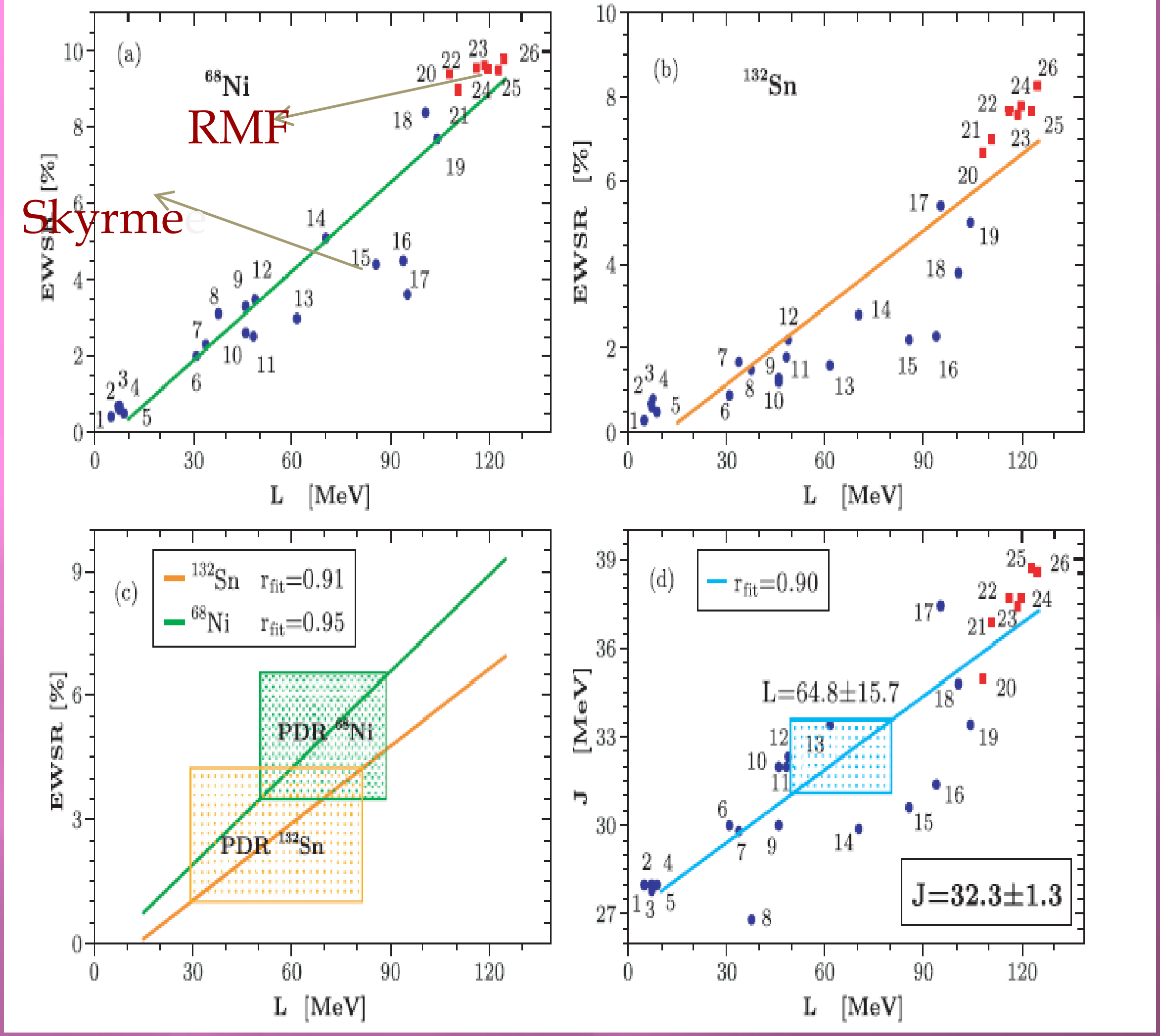
PREX II DATA awaited!!

Pigmy Dipole Resonance (PDR)



A. Carbon et.al
PRC 81,041301 (2010)

Pigmy Dipole Resonance (PDR)



$$EWSR = \int_{E_1}^{E_2} ES(E)dE$$

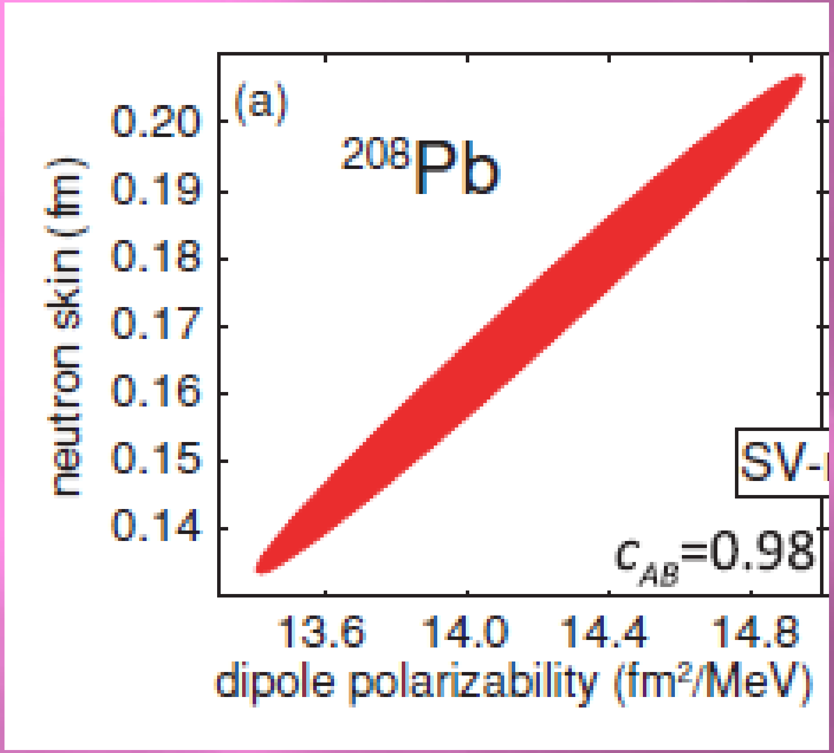
$$L(\rho_0) = 64.8 \pm 15.7$$

$$J(\rho_0) = 32.3 \pm 1.3$$

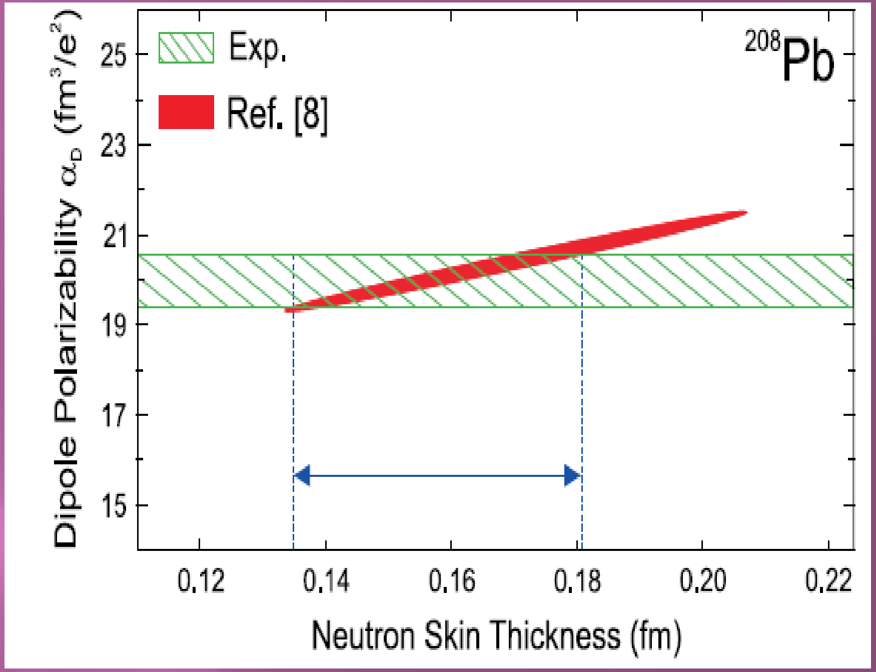
L=64.8 ± 15.7 MeV

A. Carbon et.al
PRC 81,041301 (2010)

L and R_{skin} from Diapole polarizability



Reinhard *et.al*, PRC 81, 051303 (R) 2010

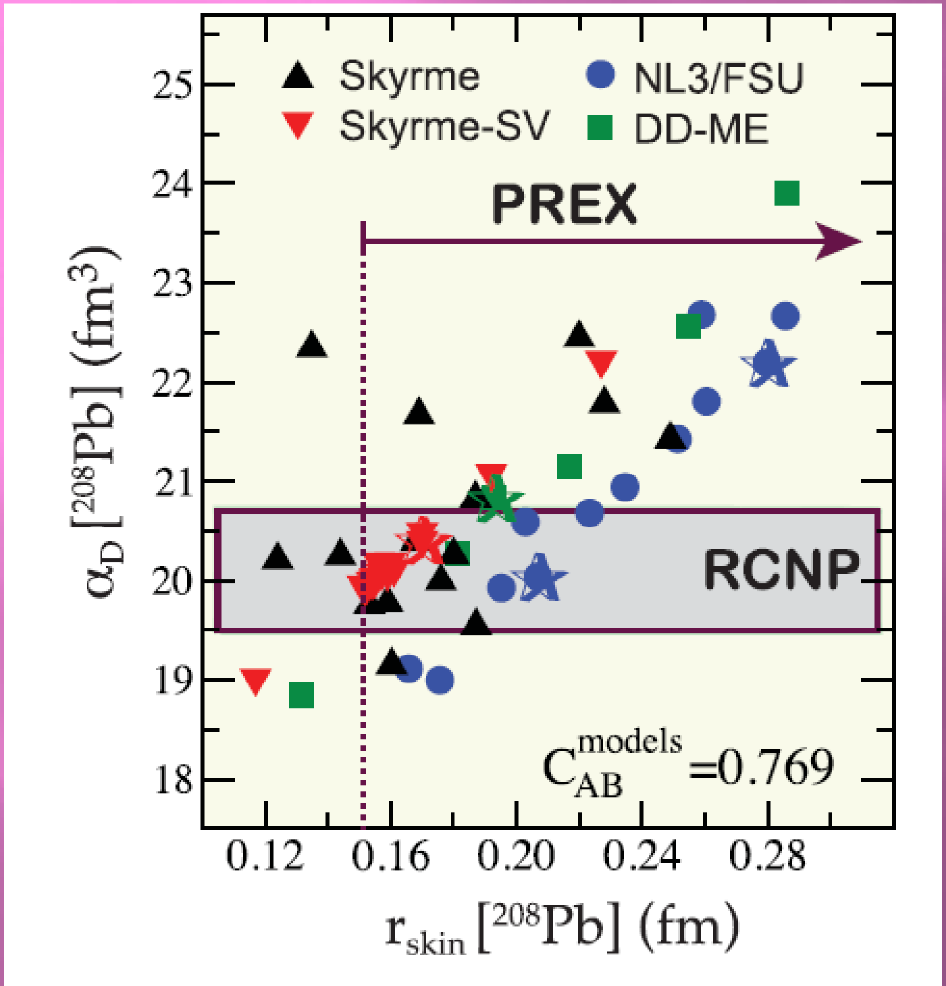


High resolution (p,p′) measurement of $\alpha_{D.}$
Tamii *et. al* PRL 107 (2011)

$$R_{skin} = 0.156^{+0.025}_{-0.021}\,\mathrm{fm}$$

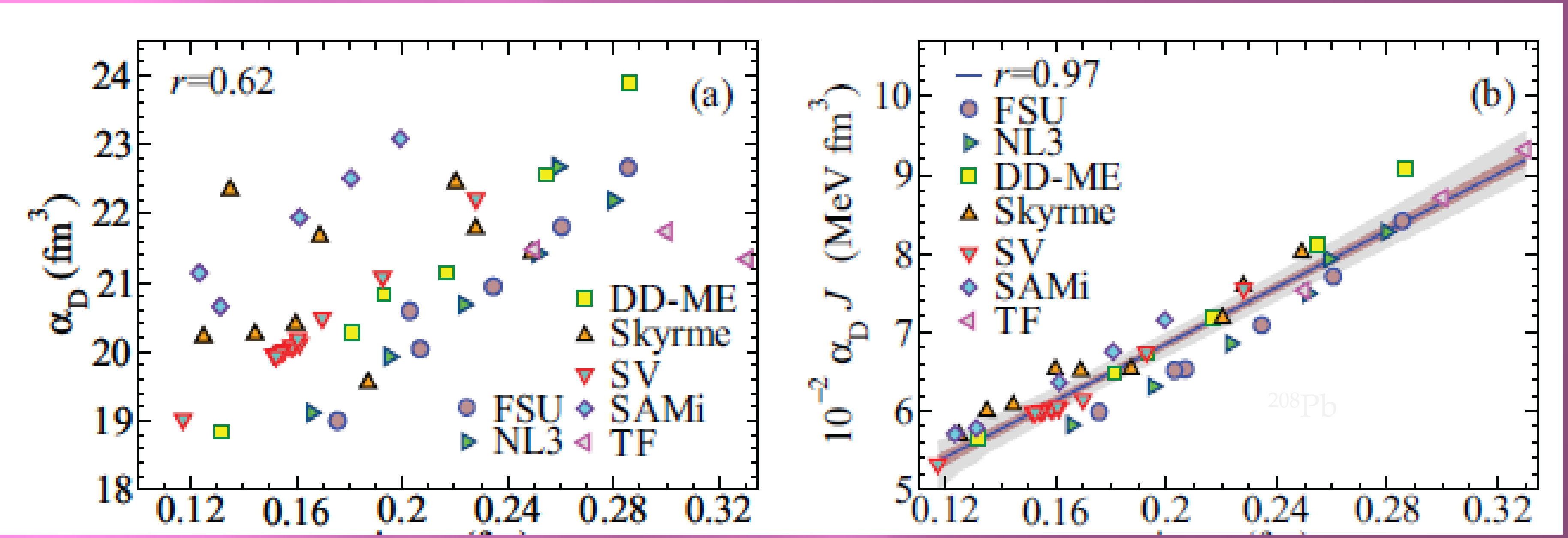
$$L = 41 \pm 14\,\mathrm{MeV}$$

L and R_{skin} from Diapole polarizability



R_{skin}= 0.168 ±0.022 fm
L= 47 ±12 MeV

Piekarewicz , B.K. Agrawal, et.al PRC (R) 2012



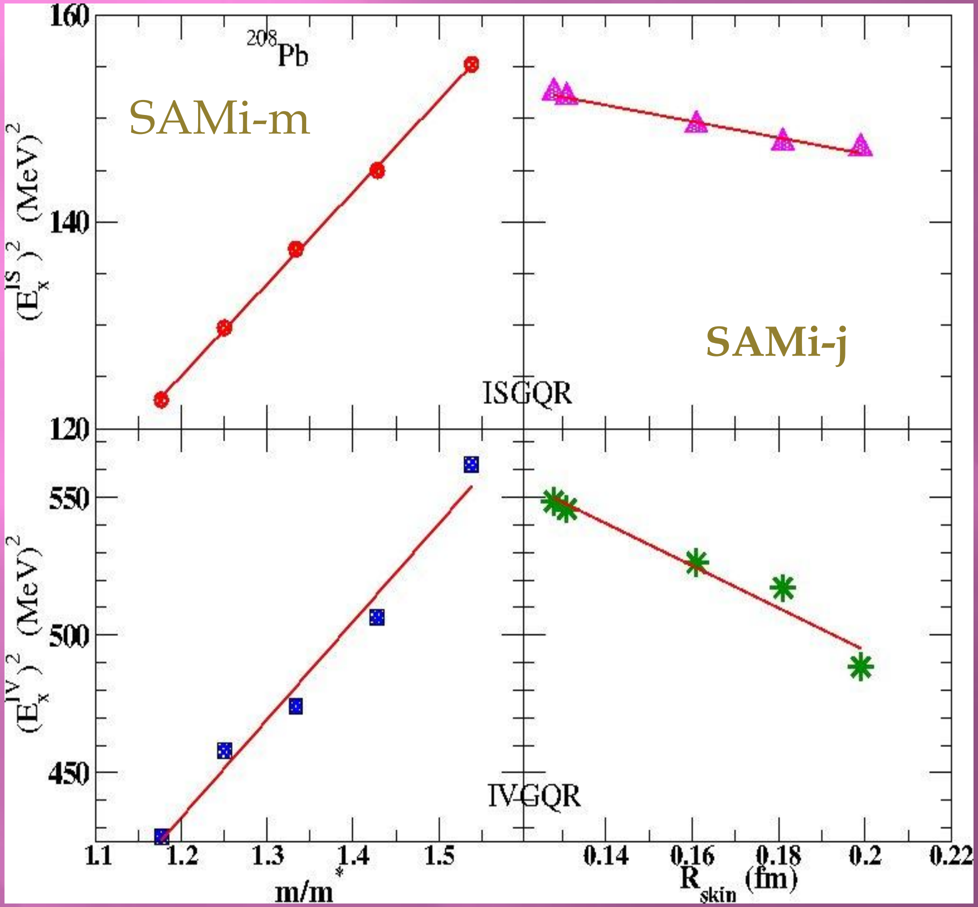
neutron skin (fm) neutron skin (fm)

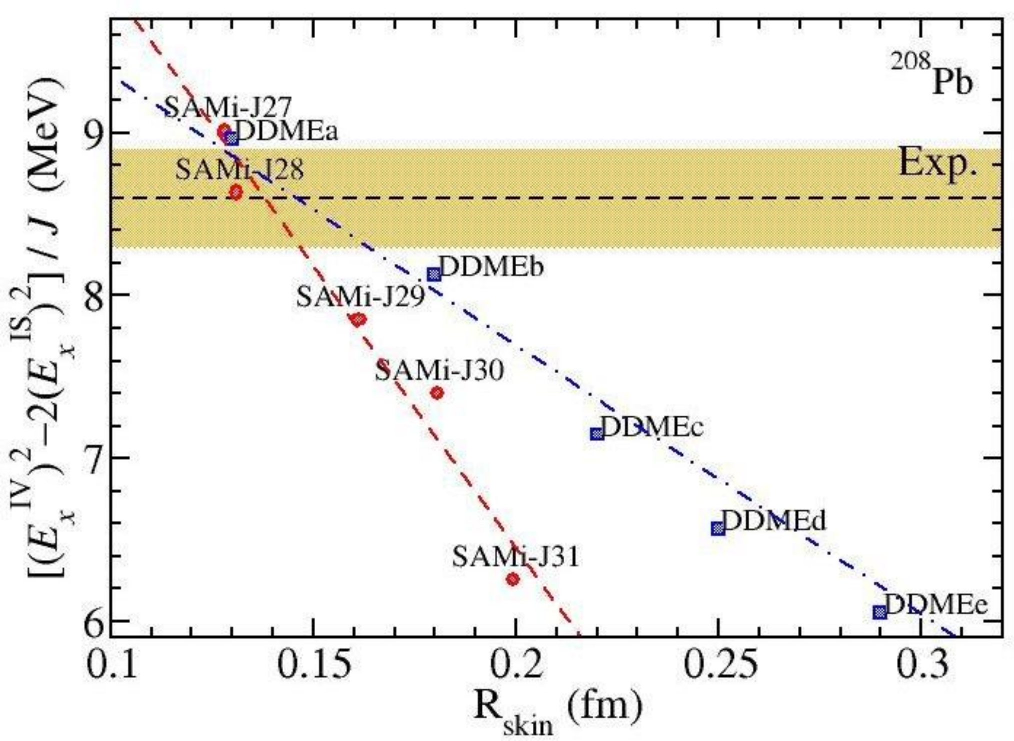
Using α_D = 20.1 ±0.6 fm^3 † in ^{208}Pb and J= 31± 2 MeV††
Neutron skin = 0.165 ± 0.043 fm
L= 43 ± 26 MeV

Agrawal, *et. al* PRC 88, 024316 (2013)

† A. Tamii et. al, PRL 107, 062502 (2011) †† Lattimer et. al, Annu.Rev. Nucl.Part.Sci., 62,485(2012)

L and R_{skin} from Giant Quadrupole Resonances





R_{skin} = 0.14 ± 0.03 fm
L = 37 ± 18 MeV

Xavi , Marco, Agrawal et.al PRC 87, 034301 (2013)

L & R_{skin} from nuclear binding energy

$$B = a_v A - a_s A^{2/3} - \left(J - J_s A^{-1/3} \right) A I^2 - a_c \frac{Z^2}{A^{1/3}} + \ldots$$

$$J = 32.10 \pm 0.31$$

$$J_s = 58.91 \pm 1.08$$

Arima et, al. PRC 85,2012

$$J(\rho) = J(\rho_0)\left(\frac{\rho}{\rho_0}\right)^{\gamma}, \quad L = 3\gamma J(\rho_0)$$

$$a_{sym}(A) = J(\rho_A) = J(\rho_0)\left(\frac{\rho_A}{\rho_0}\right)^{\gamma}$$

$$J(\rho_0) - J_s A^{-1/3} = J(\rho_A) = J(\rho_0)[1 - 3\gamma\varepsilon_A + \frac{9}{2}\gamma(\gamma - 1)\varepsilon_A^2]$$

$$\rho_A = \text{effective nucleon density}$$

L & R_{skin} from Nuclear binding energy

$$\rho_A^\gamma = \frac{1}{X_0^2}\int d^3r\,\rho(r)\rho(r)^\gamma X(r)^2$$

$$J_s = 3J(\rho_0)A^{1/3}[\gamma\varepsilon_A - \tfrac{3}{2}\gamma(\gamma-1)\varepsilon_A^2]$$

$$X_0 = \frac{N-Z}{N+Z},$$

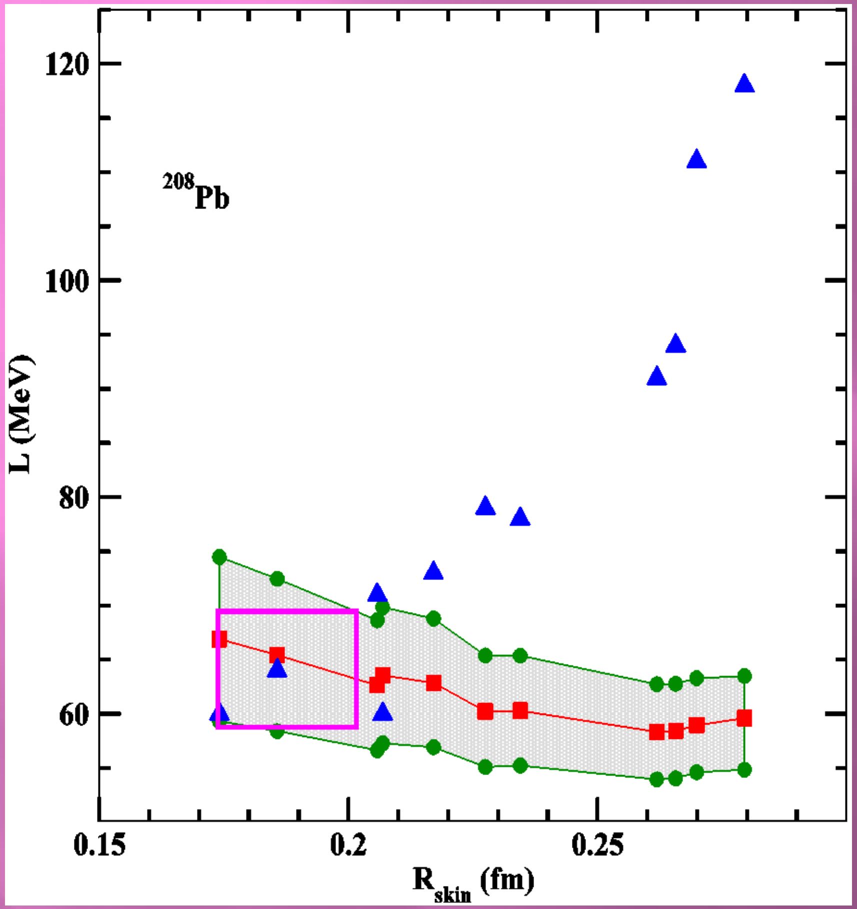
$$X(r) = \frac{\rho_n(r)-\rho_p(r)}{\rho_n(r)+\rho_p(r)},$$

$$\varepsilon_A = \frac{\rho_0-\rho_A}{3\rho_0}$$

$$\rho_0 = 0.155 \pm 0.008\,\mathrm{fm}^{-3}$$

$\rho(\mathrm{r}) \rightarrow$ mean field models

L & R_{skin} from nuclear binding energy



R_{skin}= 0.188 ± 0.014 fm
L = 64 ±5 MeV

Agrawal ,De and Samaddar PRL 109,2012

L & R_{skin} from nuclear masses

$$J(\rho) = J(\rho_0)(\frac{\rho}{\rho_0})^{\gamma} \quad \Rightarrow \text{I}$$

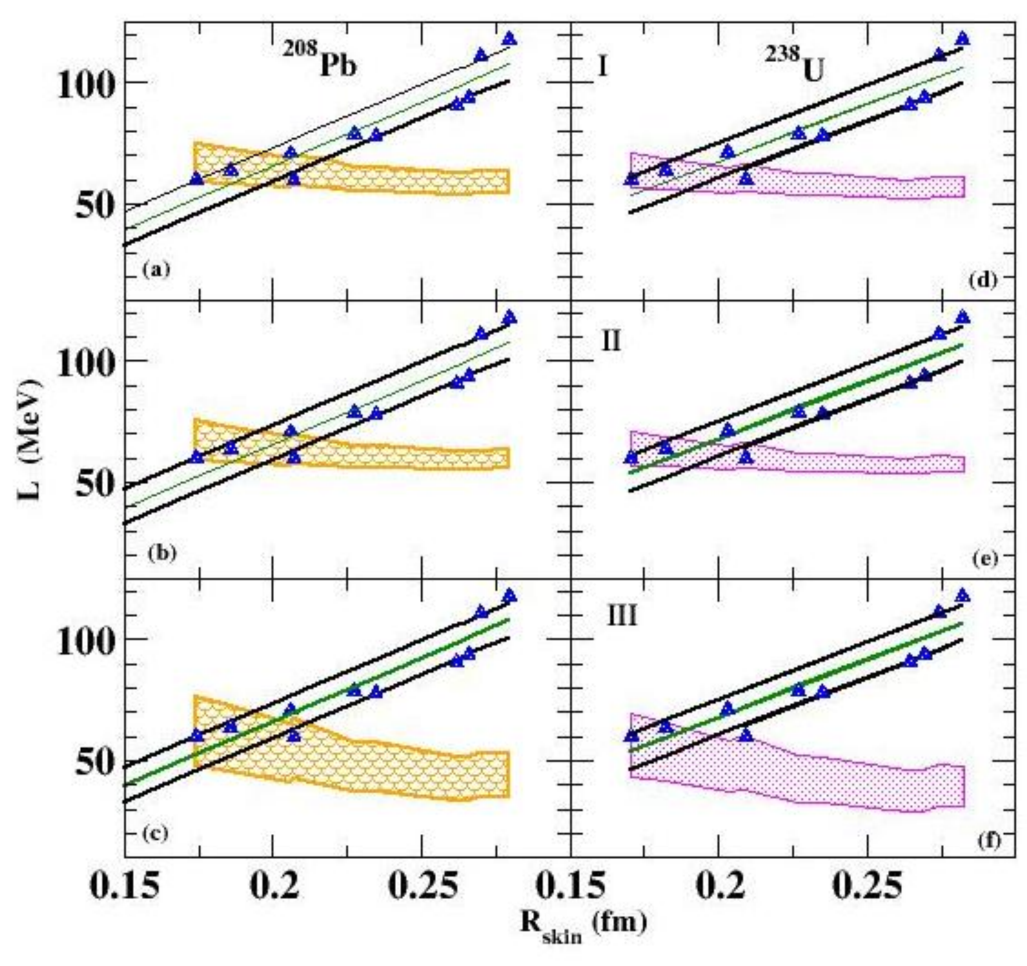
$$J(\rho) = C_k(\frac{\rho}{\rho_0})^{2/3}$$

$$+(J(\rho_0) - C_k)(\frac{\rho}{\rho_0})^{\gamma}) \quad \Rightarrow \text{II}$$

$$J(\rho) = C_k(\frac{\rho}{\rho_0})^{2/3} + C_1(\frac{\rho}{\rho_0})$$

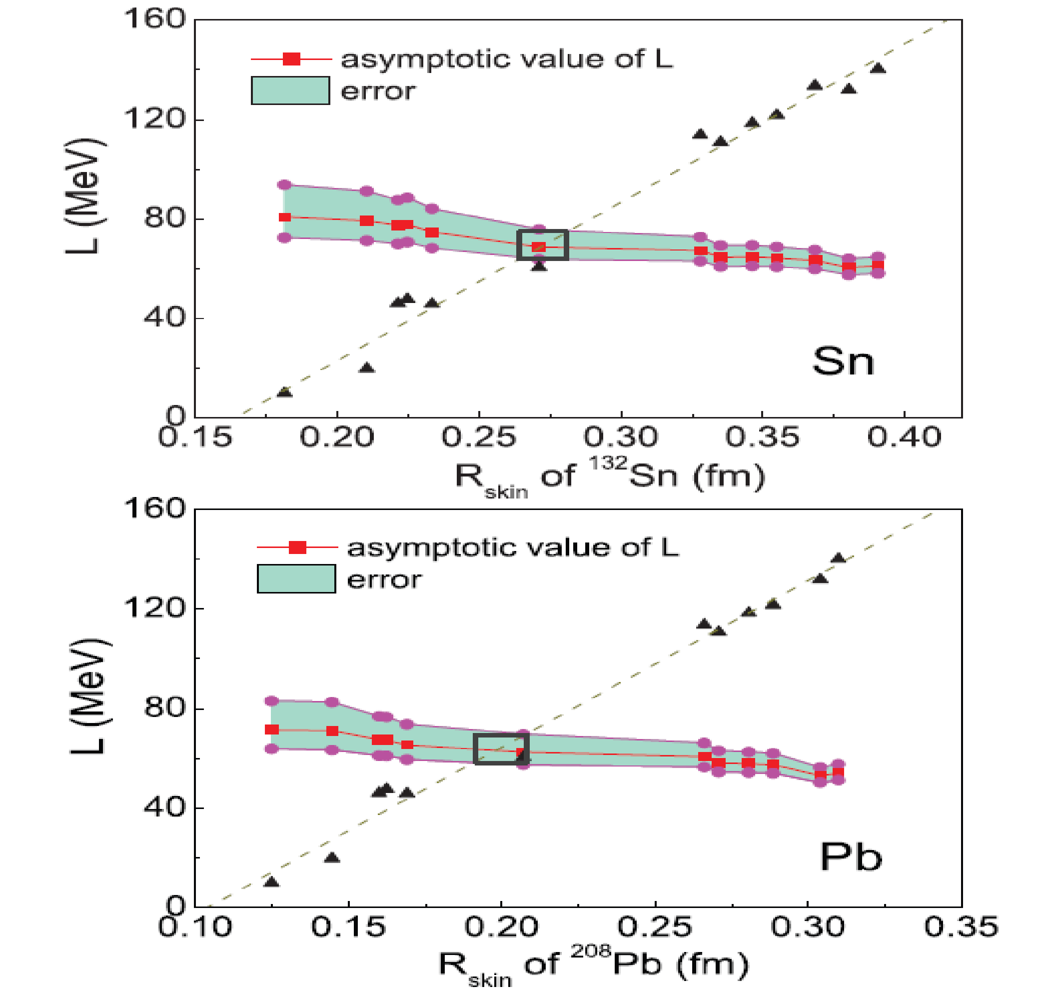
$$+(J(\rho_0) - C_k - C_1)(\frac{\rho}{\rho_0})^{5/3} \quad \Rightarrow \text{III}$$

$$C_k = 13\frac{m}{m^*}$$



R_{skin}= 0.190 ± 0.016 fm
L = 56 ±12 MeV

B. K. Agrawal, *et. al* PRC 87, 051306 (R) (2013)



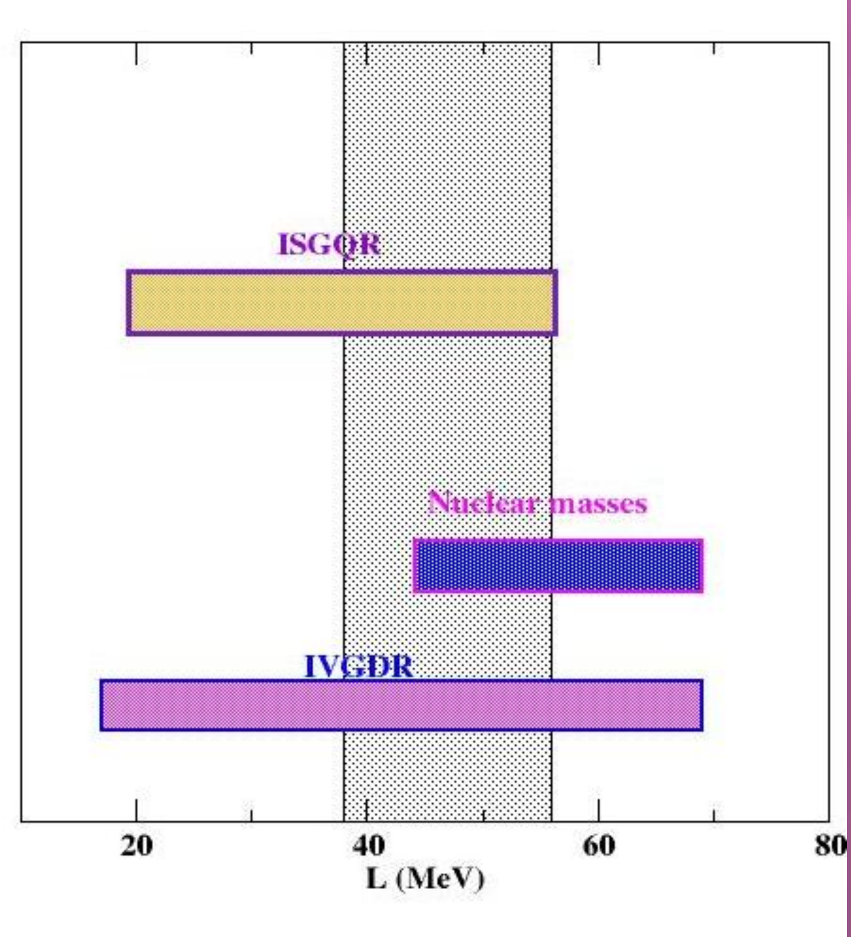
L = 66 ±7 MeV

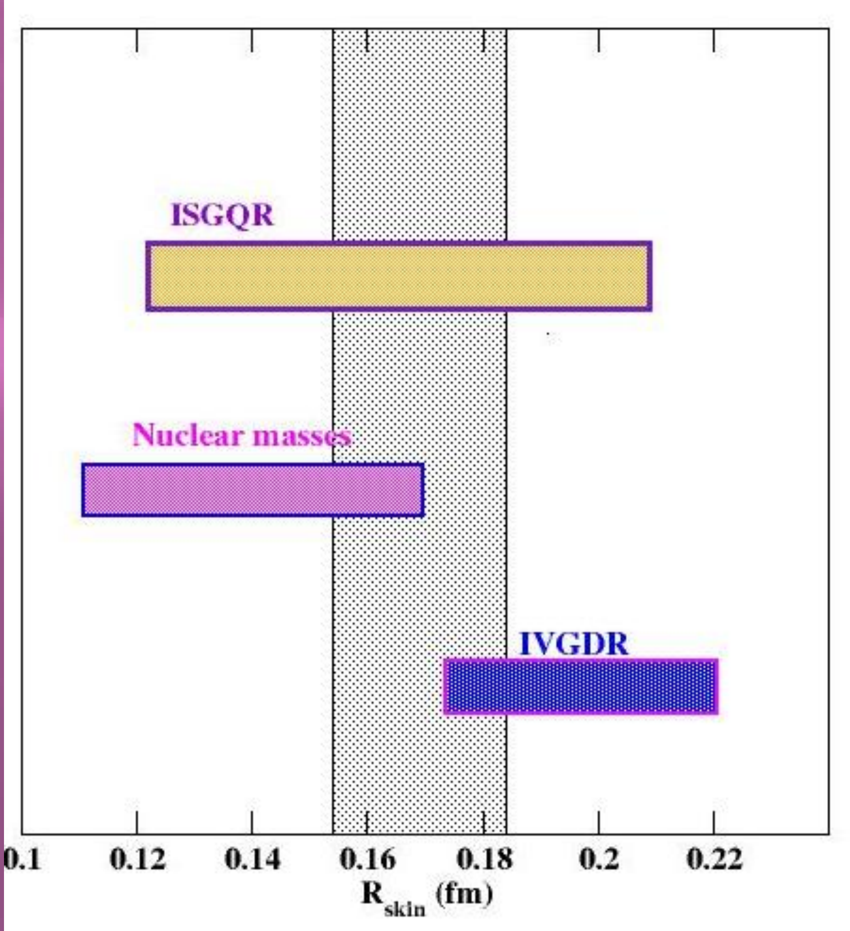
Jian Liu, et. Al Phys. Rev. C 88, 024324 (2013)

Our results

L = 47± 9 MeV

R_{skin} = 0.17± 0.02 fm





Conclusions

- Large no of the nuclear energy density functional are employed to understand the density dependence of the nuclear symmetry energy around the saturation density.

- Neutron-skin in ^{208}Pb nucleus and the symmetry energy slope parameter $L(\rho_0)$ are extracted using experimental data on giant resonances and the nuclear masses.

- Our results: R_{skin} = 0.17 ± 0.02 fm $L(\rho_0)$ = 47± 9MeV

- More accurate data for the dipole polarizability and the neutron-skin thickness in ^{208}Pb needed to constraint in a narrow window the value of the symmetry energy slope parameter.

Collaborators

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- N. Paar (Phys. Dept. Croatia)
- M. Brenna (INFN, Italy)
- Li-Gang Cao (IMP China)

Thank you !