Nuclear symmetry energy from microscopic calculations of the dipole response in finite nuclei

International Symposium on Nuclear Symmetry Energy (NuSYM10)

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RIKEN NISHINA CENTER

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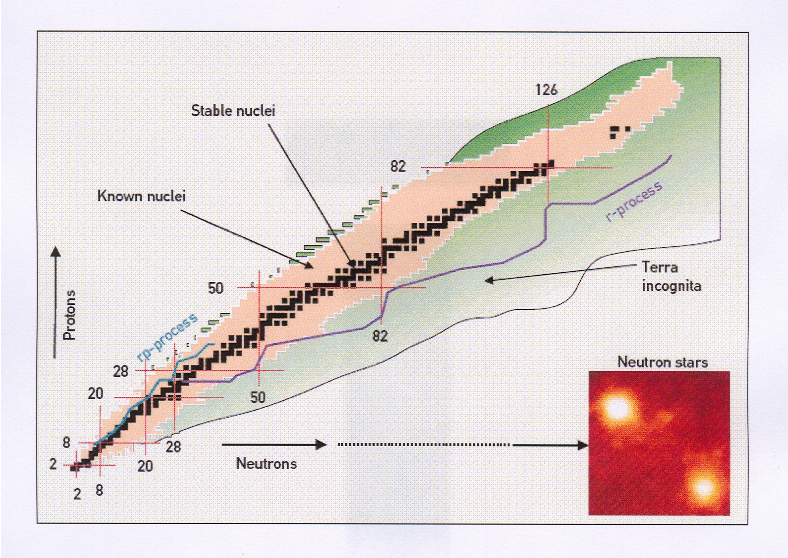
Phys. Rev. C77, 061304(R) (2008)

Phys. Rev. C81, 041301(R) (2010)

Nuclear theory and EDFs

Strong uncertainties affect *at the same time* the nuclear effective Hamiltonian and the many-body correlations. This naturally generates complementary nuclear models.

Models based on the **energy density functionals** (self-consistent mean field and extensions) allow systematic exploration of the nuclear chart – they also provide links with the **equation of state (EOS) of uniform matter**.



EDF parametrization

Finite nuclei

Nuclear EOS and astrophysics

From the functional $E[\rho_n,\rho_p]$ to the EOS

In uniform matter, spatial densities are simple numbers. If we translate E[ρ] into P[ρ] we have the Equation Of State.

Nuclear matter EOS

Symmetric matter EOS

Symmetry energy S

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,\delta=0) + S(\rho)\,\delta^2$$

where $\delta = (\rho_n - \rho_p)/\rho$.

Around saturation: the symmetric matter EOS is reasonably known.

The asymmetric matter is not !

Symmetric matter incompressibility:

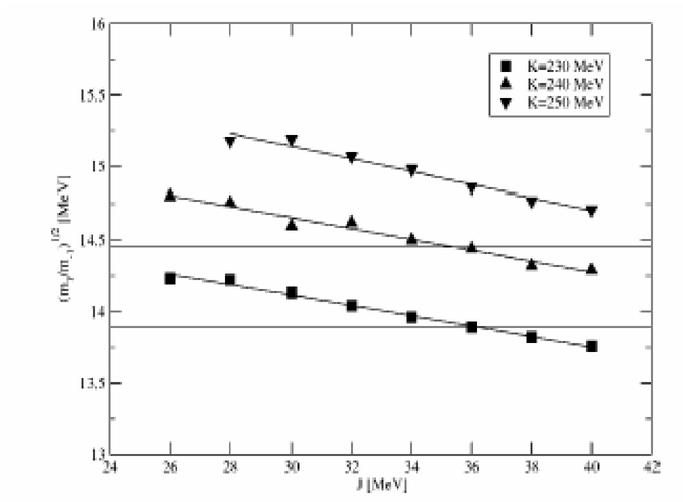
$$K_\infty = 9\rho_0^2 \frac{d^2(E/A)}{d\rho^2}\bigg|_{\rho_0}$$

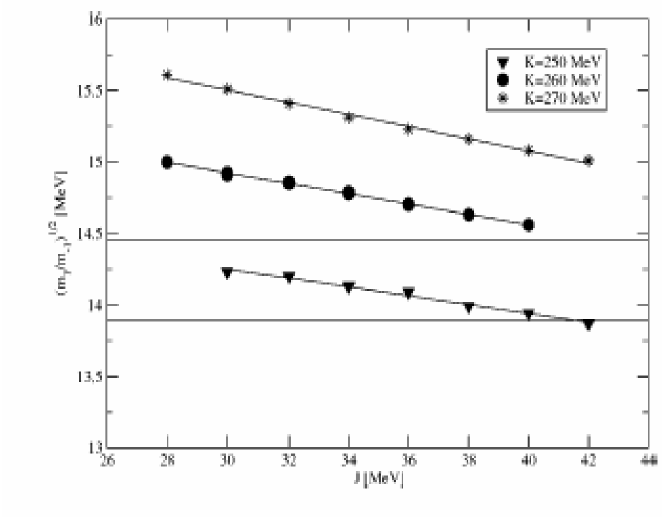
Uncertainty:
240 ± 20 MeV

Larger uncertainty on:

$$\begin{aligned} S(\rho_0) &= J \\ S'(\rho_0) &= L/3\rho_0 \\ S''(\rho_0) &= K_{\rm sym}/9\rho_0^2 \end{aligned}$$

$J \equiv S(\rho_0)$





α = 1/6 implies K around 230-240 MeV

α = 1/3 implies K around 250 MeV

G.C., N. Van Giai, J. Meyer, K. Bennaceur, P. Bonche, *Phys. Rev.* **C70**, 024307 (2004)

Constraint from the ISGMR in ^{208}Pb :

E_{GMR} constrains K_∞ = 240 ± 20 MeV. The error comes from the choice of the density dependence, not from the relativistic or nonrelativistic framework.

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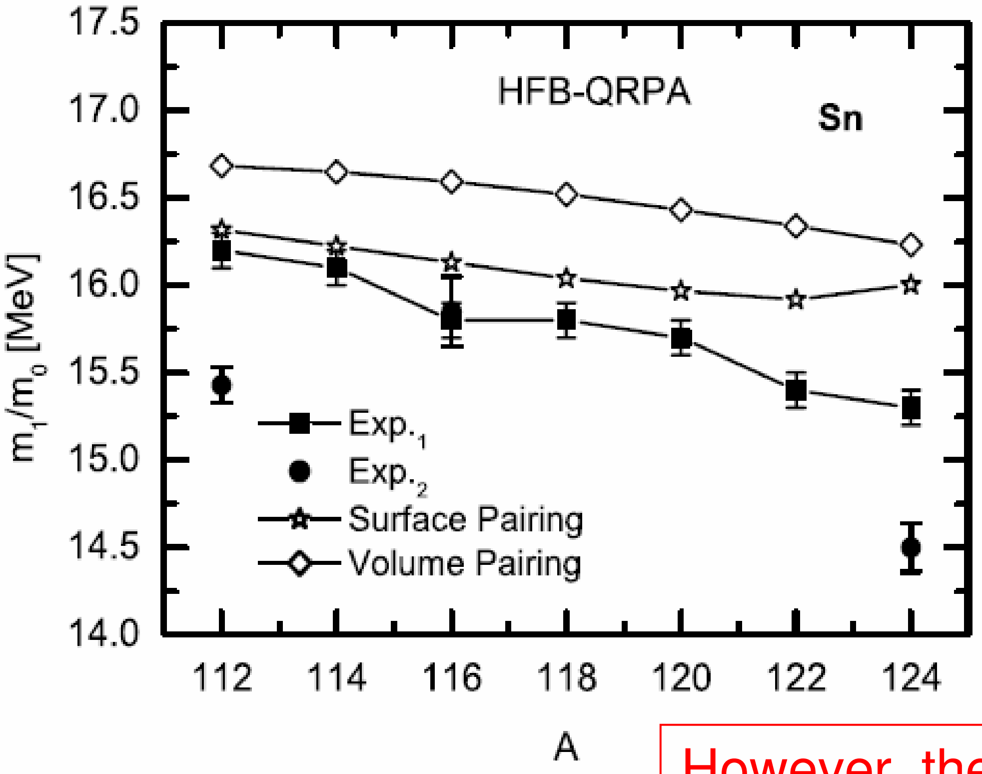
S. Shlomo, V.M. Kolomietz, G.C., *Eur. Phys. J.* **A30**, 23 (2006)

Pairing and nuclear incompressibility: pairing does have a non-negligible effect on the GMR energies in Sn. Values of nuclear matter incompressibility exctracted from Pb and Sn differ by about 10% if this is taken into account. One should compare K_∞=217 MeV (SkM*) with 240±20 MeV.



J. Li, G.C., J. Meng, Phys. Rev. C68 (2008) 064304

However, the whole trend is not optimal.
Does pairing depend on isovector density ?

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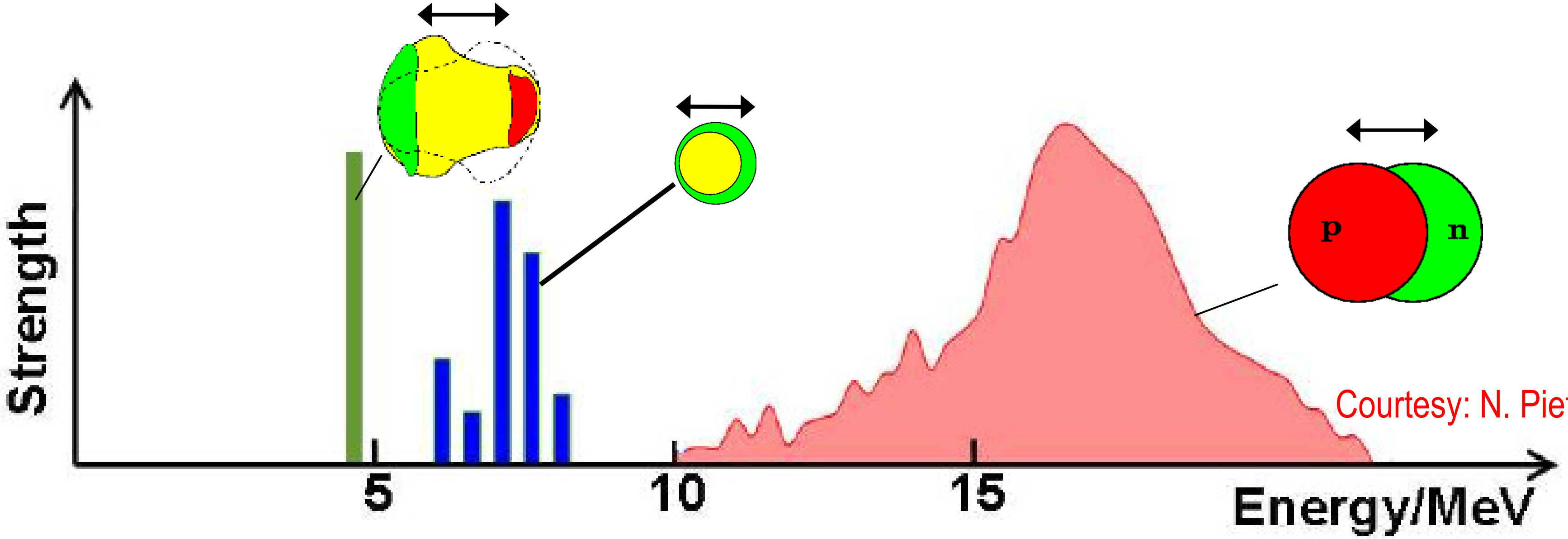
Electromagnetic field → Dipole modes → Symmetry energy



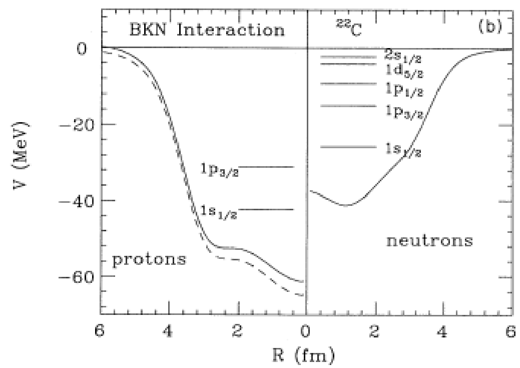
Giant Dipole Resonance (GDR) ↔ S[ρ]

Pygmy Dipole Resonance (PDR) ?

Two-Phonon excitation ($2^+ \otimes 3^-$) Unrelated with S[ρ]

In light nuclei low-lying dipole strength may be due to continuum transitions of weakly bound orbitals. No collective oscillation !

In medium-heavy nuclei the collectivity of the PDR should be assessed.



What **precisely** is the GDR correlated with ?

In the case in which the GDR exhausts the whole sum rule, its energy can be deduced following the formulas given by E. Lipparini and S. Stringari [Phys. Rep. 175, 103 (1989)]. Employing a simplified, yet realistic functional they arrive at

$$E_{-1} \equiv \sqrt{\frac{m_1}{m_{-1}}} = \sqrt{\frac{3\hbar^2}{m\langle r^2\rangle}\frac{b_{\rm vol}}{\left[1+\frac{5}{3}\frac{b_{\rm surf}}{b_{\rm vol}}A^{-\frac{1}{3}}\right]}(1+\kappa)}.$$

Cf. also G.C., N. Van Giai, H. Sagawa, PLB 363 (1995) 5.

$$EWSR = \frac{60NZ}{A}(1+\kappa)$$

$$E = \int d_3r\ \mathcal{E}\left[\rho(\vec{r})\right]$$

LDA

$$\int d_3r\ S(\rho)\frac{(\rho_n(\vec{r})-\rho_p(\vec{r}))^2}{\rho} \leftrightarrow b\frac{(N-Z)^2}{A}$$

If only volume, b is only b_{vol} and equals $S(\rho_0)$=J.

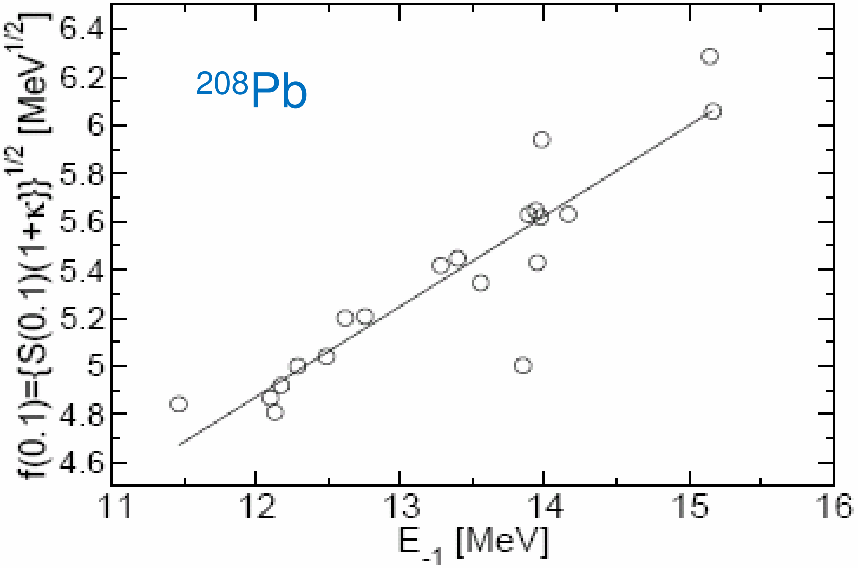
The surface correction is not strictly analytic but several results agree in stating that it produces b_{eff} = S(0.1 fm^{-3}) !

The Giant Dipole Resonance as a quantitative constraint on the symmetry energy

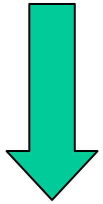
Luca Trippa, Gianluca Colò and Enrico Vigezzi

Phys. Rev. C77, 061304(R) (2008)

It is assumed that the previous formula holds for S at some sub-saturation density. The best value comes from χ^2_{min}.



- x-axis: $E_{\rm GDR}$ from RPA;
- y-axis: $\left[S(\rho = 0.1 \text{ fm}^{-3})(1+\kappa)\right]^{1/2}$; κ is the enhancement factor.



23.3 < S(0.1) < 24.9 MeV

This result, namely 24.1 ± 0.8 MeV is based on an estimate of κ. Most of the error is coming from the uncertainty on this quantity.

Another way to understand GDR ↔ S[ρ]

If one builds dipole excitations with the Goldhaber-Teller model, by starting from

$$\rho(\vec{r}, R_i) = \frac{\rho_0 i}{1 + exp[(r - R_i)/a]}$$

and shift these densities by separating p and n,

$$\rho(\vec{r} + z\vec{e}_z, R_i) = \left(1 + z\frac{d}{dz} + \frac{1}{2}z^2\frac{d^2}{dz^2}\right)\rho(\vec{r}, R_i)$$

then by calculating the energy change we arrive at

$$\delta E = 2\pi \int dr\ r^2 \frac{2S(\rho)}{\rho}\left(\rho_n - \rho_p\right)\left(\delta\rho_n - \delta\rho_p\right)$$

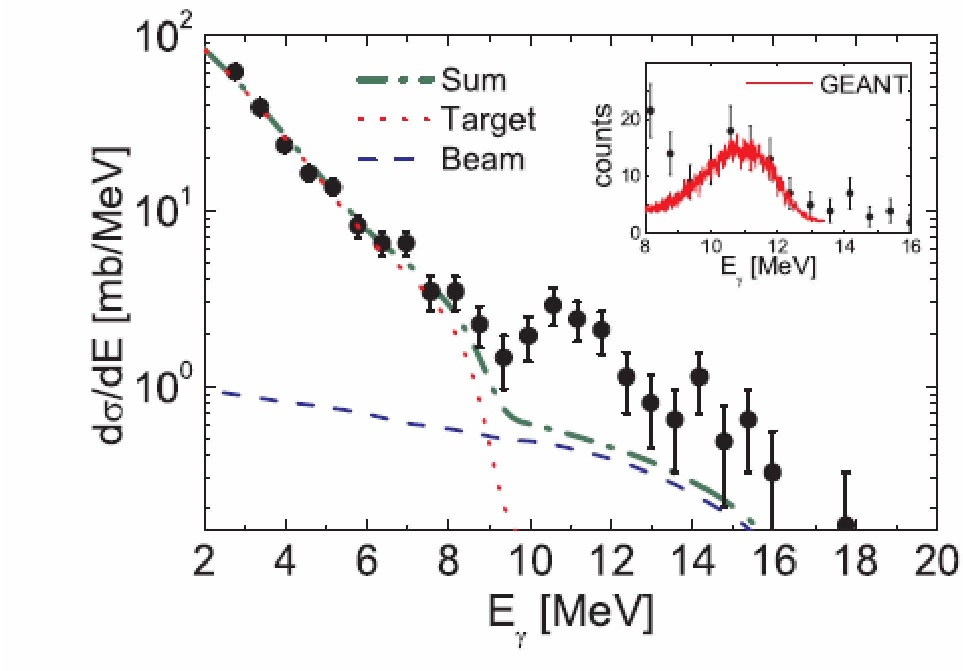
This is an effective average of S which is peaked around 0.1 fm^{-3}. (As stated above !)

We would need (although we still miss) a similar kind of physical understanding for the case of the PDR !

Recently, a Coulomb excitation measurement has been carried out by the experimental group of Milano U.: ^{68}Ni at 600 MeV/A on a Au target. Low-lying (or “pygmy”) dipole strength has been found around 11 MeV. O.Wieland *et al.*, PRL 102, 092502 (2009)

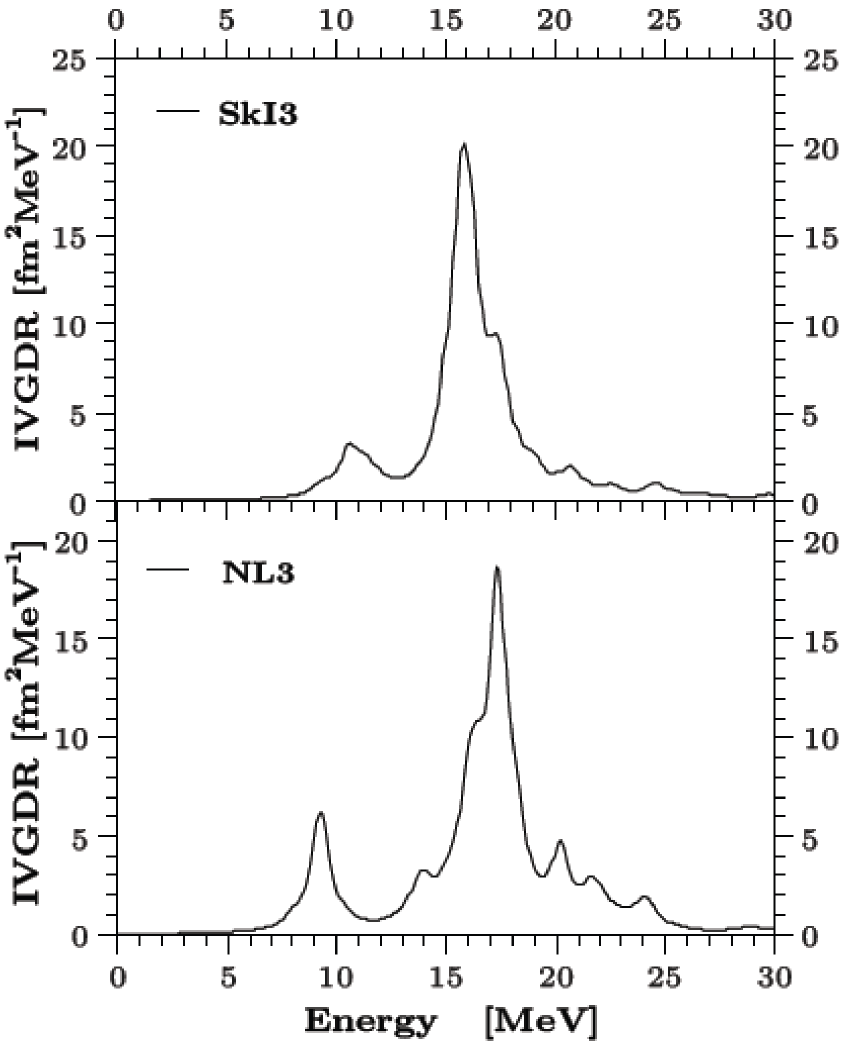
RISING

The Gamma ray spectrum shows an excess with respect to statistical emission



Dipole strength in ^{68}Ni

- Theoretical calculations show also a well-defined PDR !
- Several configurations that originate from neutron hole states $f_{5/2}$, $p_{1/2}$ and $p_{3/2}$ contribute.
- Interactions characterized by larger values of the symmetry energy seem to produce a state that is (a) more collective and (b) more decoupled from the GDR.



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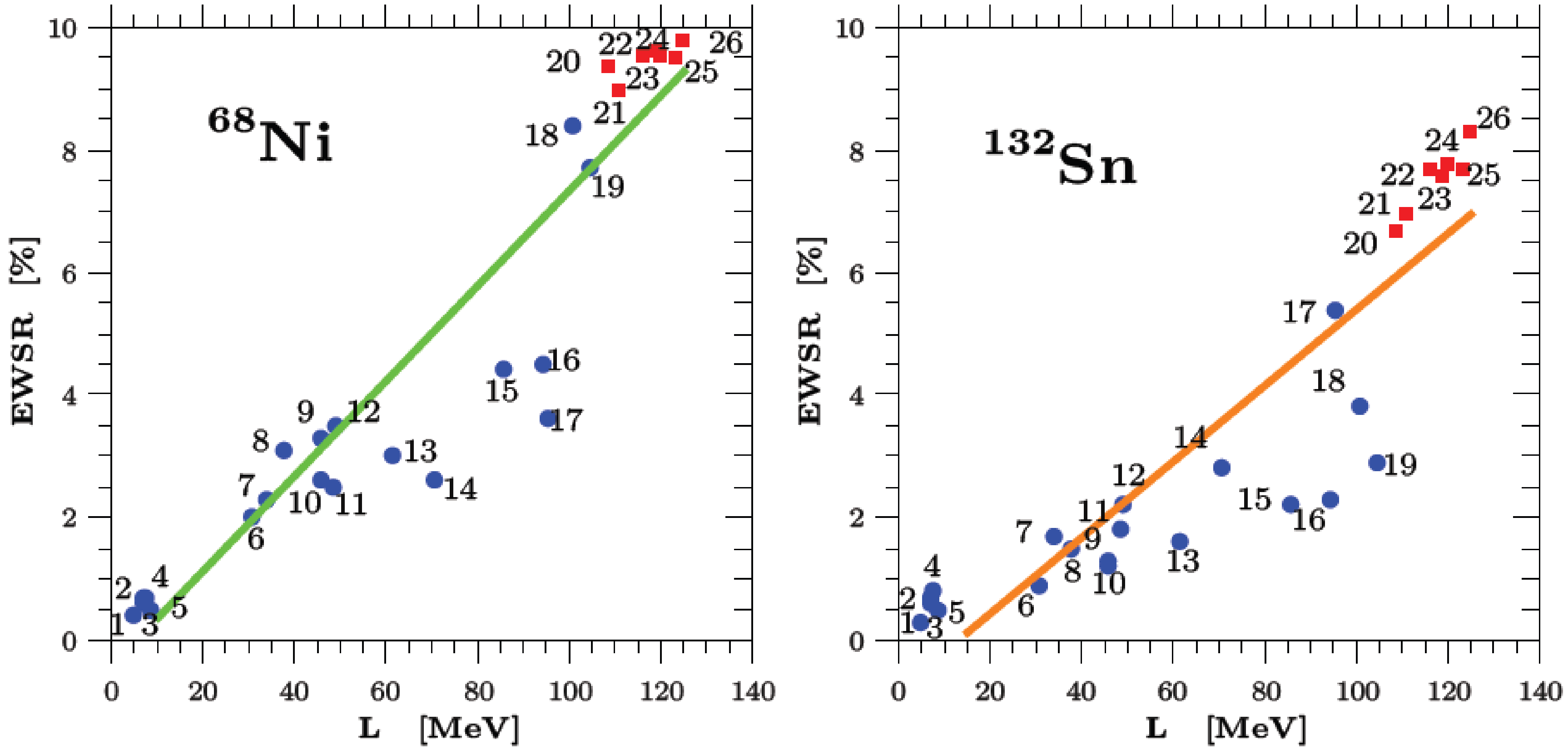
Correlation between L and the PDR



For the first time the approach has been pursued with different nuclei and different classes of EDFs. Blue=Skyrme; red=RMF.

Using experimental data → L = 65.1 ± 15.5 MeV

Skyrme forces:

1=v0902, 2=MSk3, 3=BSk1, 4=v110, 5=v100, 6=Tond6, 7=Tond9, 8=SGII, 9=SkM*, 10=SLy4, 11=SLy5, 12=SLy230a, 13=LNS, 14=SkMP, 15=SkRs, 16=SkGs, 17=SK255, 18=SkI3, 19=SkI2

RMF (meson exchange) Lagrangians:

20=NLC, 21=TM1, 22=PK1, 23=NL3, 24=NLBA 25=NL3+ 26=NLE.

PHYSICAL REVIEW C 76, 051603(R) (2007)

Nuclear symmetry energy and neutron skins derived from pygmy dipole resonances

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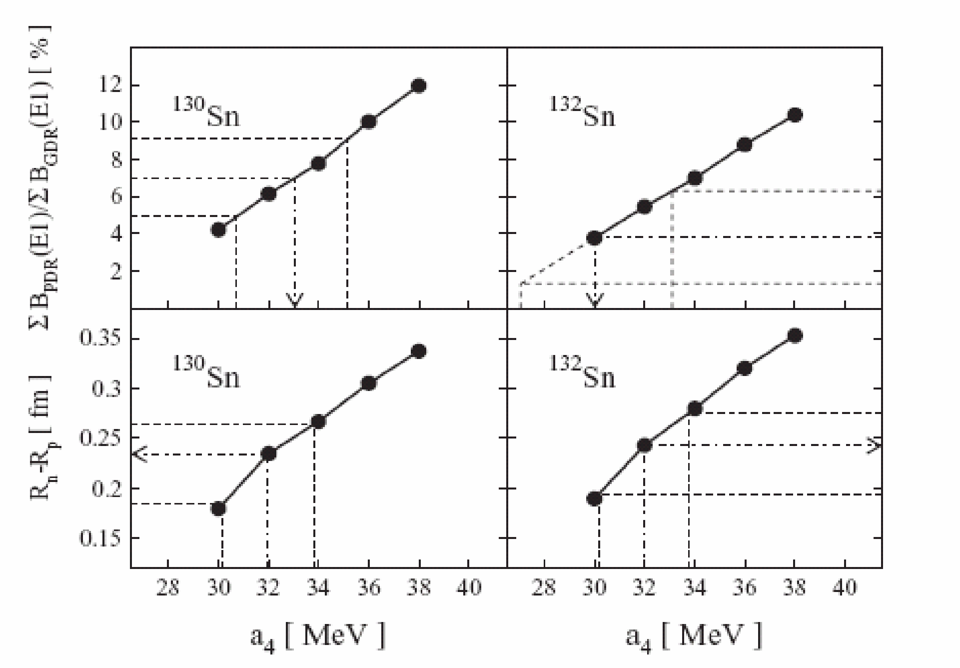
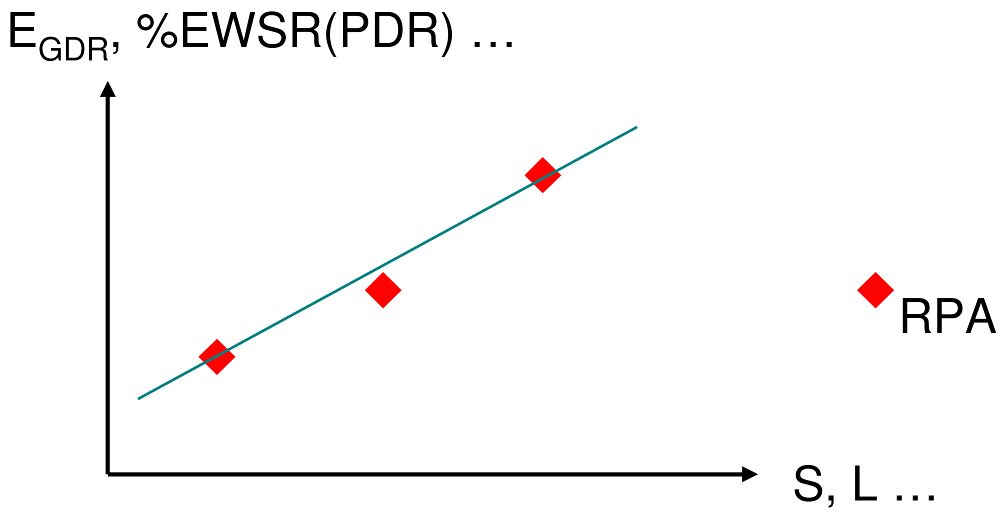
(LAND Collaboration)



- Few interactions (all belonging to the same “class”) have been used to check correlations.

- Pairing in ^{130}Sn ?

- Other pygmy dipole states in different mass regions should be looked at.



These kind of correlations should be shown using the same model for finite nuclei and infinite matter.

If pairing is inserted, it should be in both cases

Effect of pairing correlations on incompressibility and symmetry energy in nuclear matter and finite nuclei

E. Khan,[1] J. Margueron,[1] G. Colò,[2] K. Hagino,[3] and H. Sagawa[4]

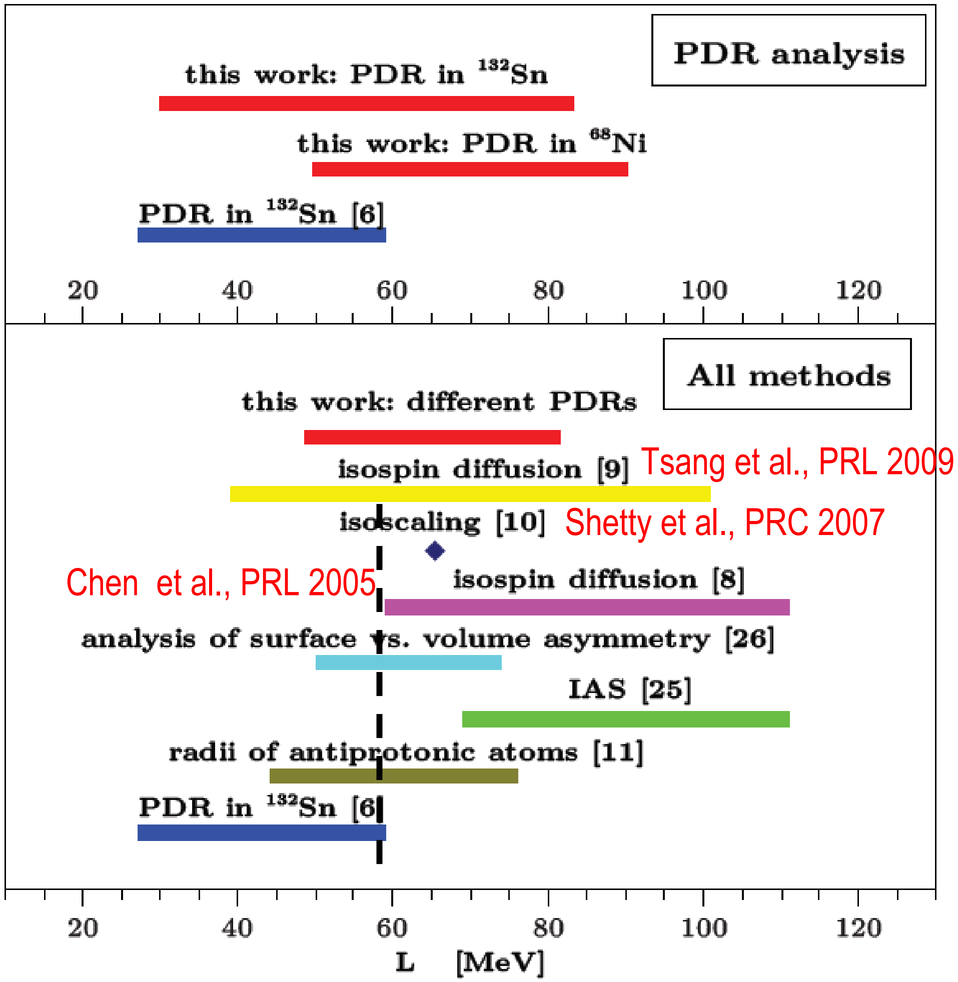
Use of phenomenological, zero-range (IS or IV) density-dependent pairing interactions.

Pairing	ρ_0 [fm^{-3}]	E/A(ρ_0) [MeV]	K_∞ [MeV]	J [MeV]	L [MeV]	K_{sym} [MeV]
no pairing	0.1604	-15.999	230.2	32.03	48.25	-112.3
IS η=0.35	0.1601	-15.998	227.3	31.93	48.49	-129.7
IS η=0.65	0.1603	-15.998	228.1	32.02	48.30	-113.7
IS η=1.00	0.1604	-15.999	230.1	32.03	48.25	-112.3
MSH	0.1599	-15.998	223.9	31.33	55.77	-139.7
YS	0.1602	-15.998	227.0	31.39	52.04	13.2

PHYSICAL REVIEW C 81, 041301(R) (2010)

Constraints on the symmetry energy and neutron skins from pygmy resonances in ^{68}Ni and ^{132}Sn

Andrea Carbone,[1] Gianluca Colò,[1,2] Angela Bracco,[1,2] Li-Gang Cao,[1,2,3,4] Pier Francesco Bortignon,[1,2]
Franco Camera,[1,2] and Oliver Wieland[2]

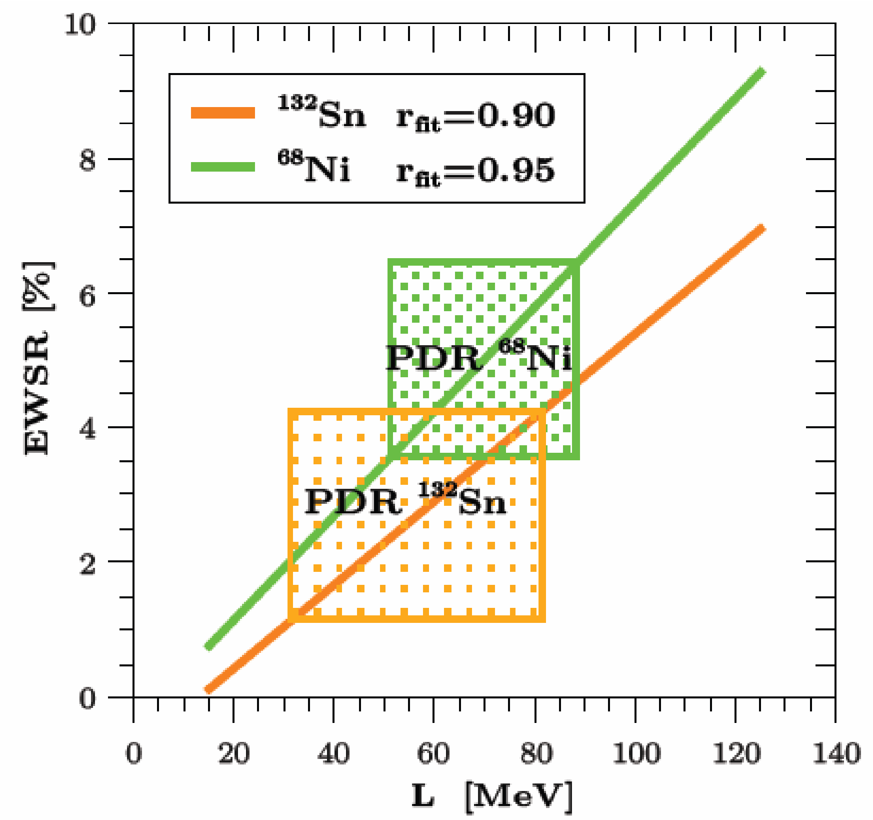


- Generalizing the approach to extract L from the PDR makes its value (more) compatible with those from analysis of HI collisions.

Please, specify clearly soft or stiff…

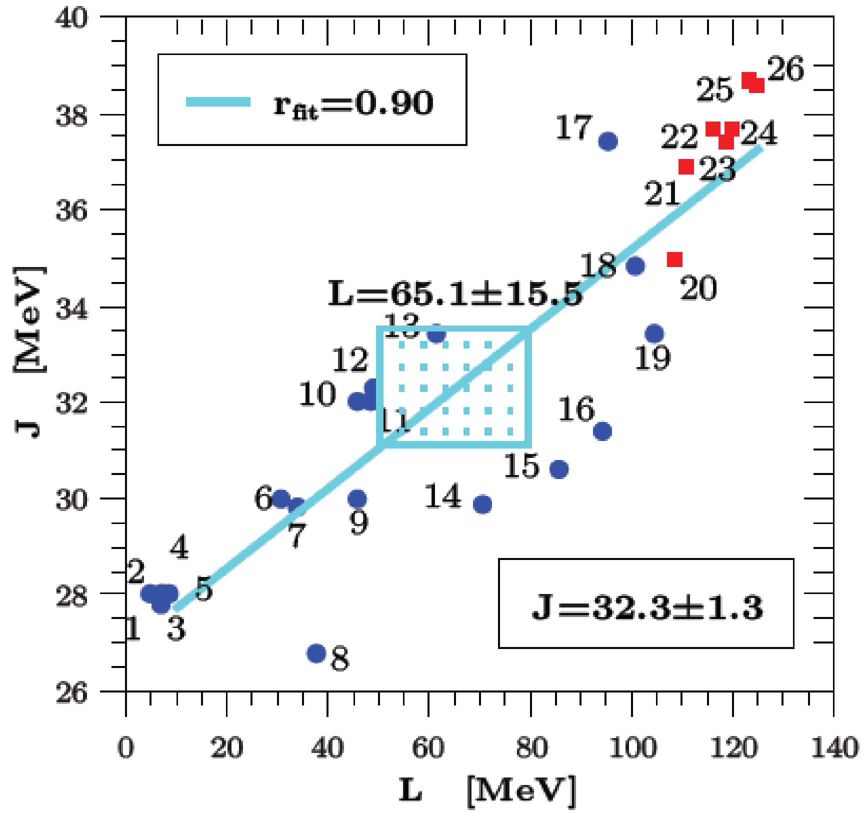
Constraint on J and L

Exp. values from O. Wieland *et al.*, PRL 102, 092502 (2009); A. Klimkiewicz *et al.*, PRC 76, 051603(R) (2007).



We deduce the weighted average

L = 65.1 ± 15.5 MeV →
J = 32.3 ± 1.3 MeV



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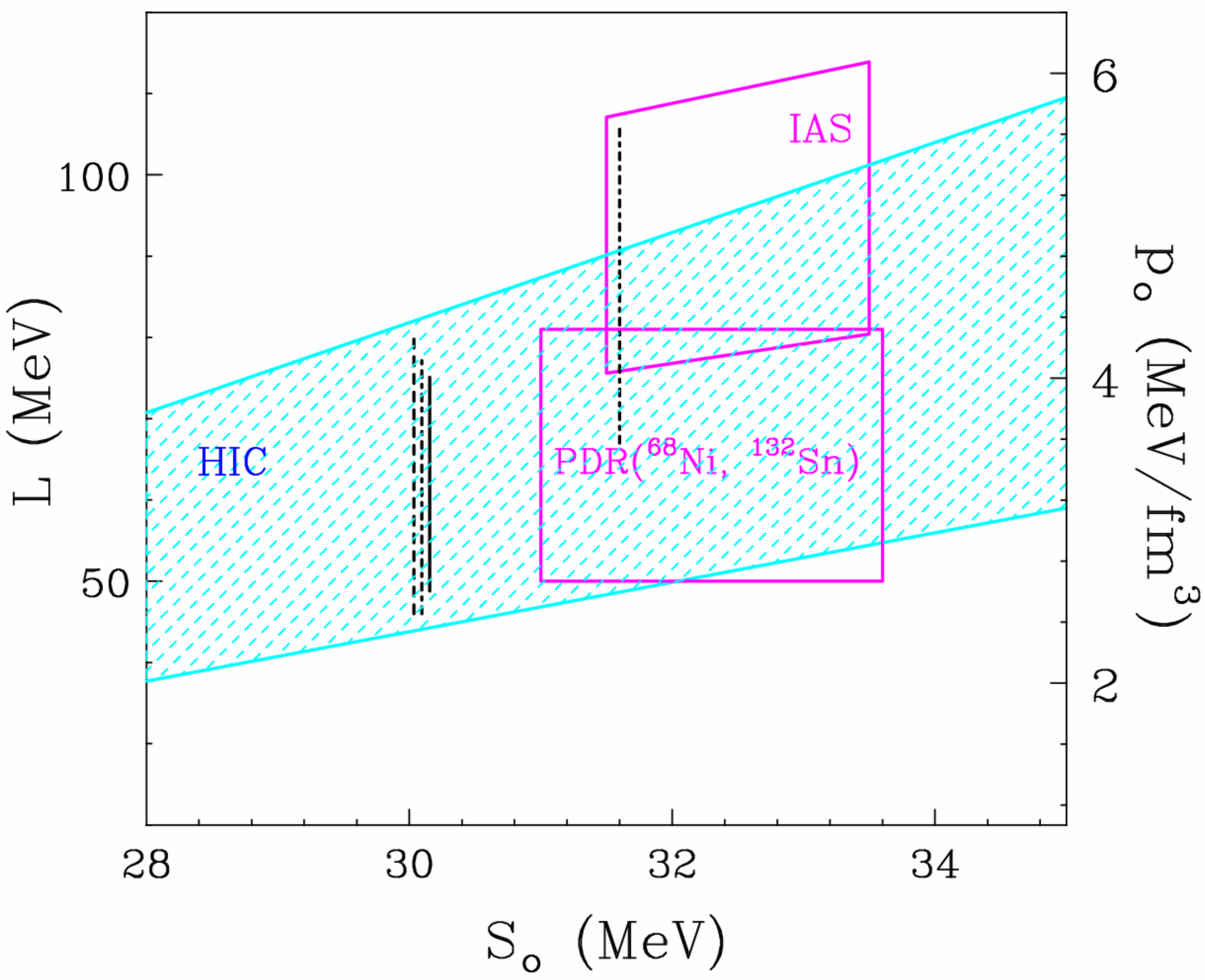
Courtesy: B. Tsang



PHYSICAL REVIEW C **80**, 045806 (2009)

Density dependence of the nuclear symmetry energy: A microscopic perspective

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(Received 29 July 2009; published 23 October 2009)

We perform a systematic analysis of the density dependence of nuclear symmetry energy within the microscopic Brueckner-Hartree-Fock (BHF) approach using the realistic Argonne V18 nucleon-nucleon potential plus a phenomenological three-body force of Urbana type. Our results are compared thoroughly with those arising from several Skyrme and relativistic effective models. The values of the parameters characterizing the BHF equation of state of isospin asymmetric nuclear matter fall within the trends predicted by those models and are compatible with recent constraints coming from heavy ion collisions, giant monopole resonances, or isobaric analog states. In particular we find a value of the slope parameter $L = 66.5$ MeV, compatible with recent experimental constraints from isospin diffusion, $L = 88 \pm 25$ MeV. The correlation between the neutron skin thickness of neutron-rich isotopes and the slope L and curvature K_{sym} parameters of the symmetry energy is studied. Our BHF results are in very good agreement with the correlations already predicted by other authors using nonrelativistic and relativistic effective models. The correlations of these two parameters and the neutron skin thickness with the transition density from nonuniform to β-stable matter in neutron stars are also analyzed. Our results confirm that there is an inverse correlation between the neutron skin thickness and the transition density.

Extraction of the neutron radii from L

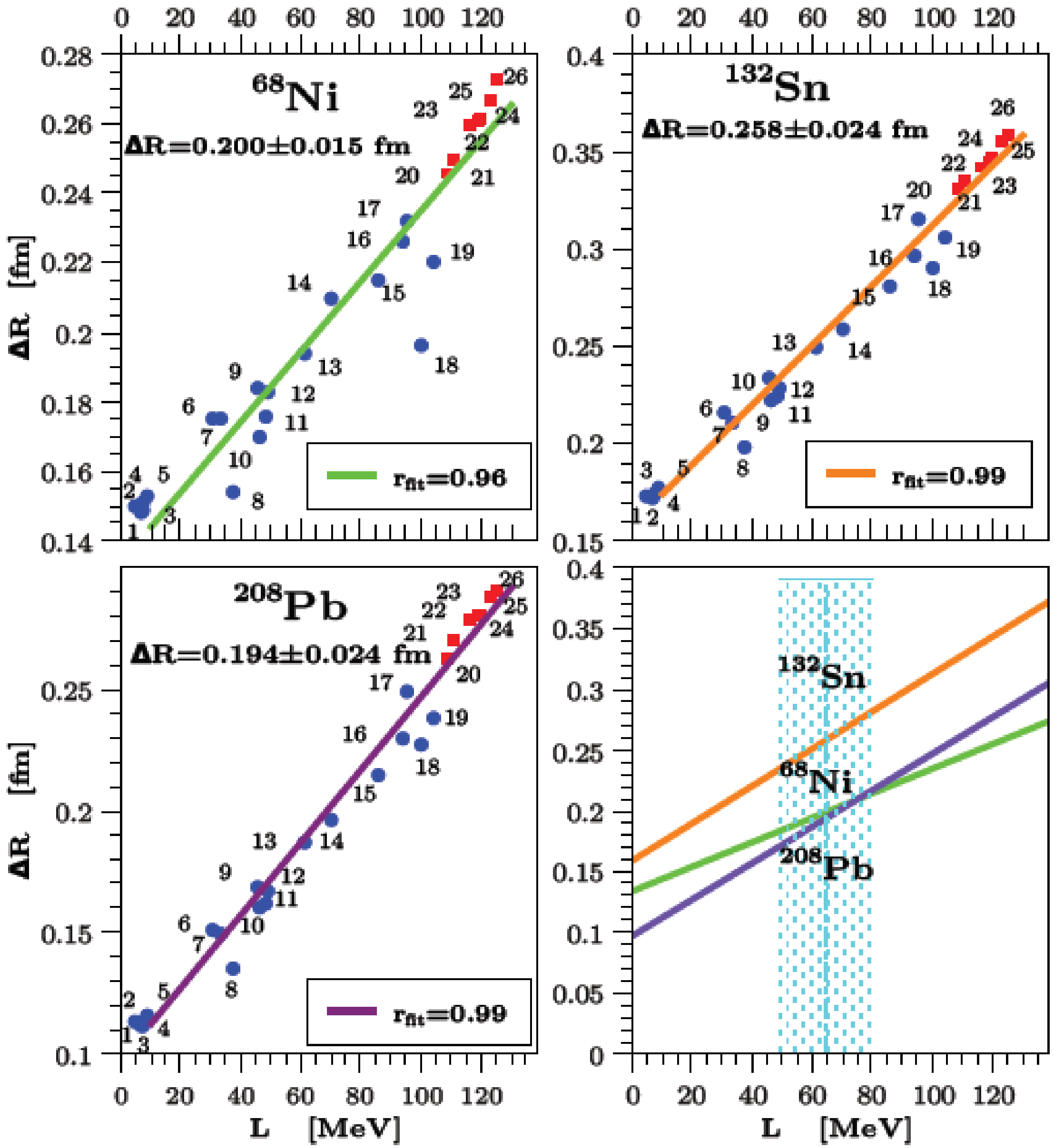
Strong correlations between L and ΔR (the neutron skin thickness) have been noticed previously.

B.A. Brown, PRL 85, 5296 (2000); S. Typel and B.A. Brown, PRC 64, 027302(R) (2001).
R.J. Furnstahl, NPA 706, 85 (2002);
S. Yoshida and H. Sagawa, PRC 69, 024318 (2004).

By using our range for L, we find ΔR with its error.

^{68}Ni: 0.200 ± 0.015 fm

^{132}Sn: 0.258 ± 0.024 fm



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Conclusions

- Mean field models allow correlations between nuclear structure and the nuclear EOS – and consequently, with nuclear astrophysics.

- Within these models one can find a correlation between the PDR strength and one of the important parameters governing the density dependence of the symmetry energy, namely the slope at ρ_0.

- In this way one can extract a constraint on this slope, namely $L = 65.1 \pm 15.5$ MeV.

- GDR had provided a constraint on S at density 0.1 fm^{-3}, namely 24.1 ± 0.8 MeV.

- There are open questions, of course …