Collective Modes in Nuclei

Hans Emling, ANUP, Goa, Nov. 2011

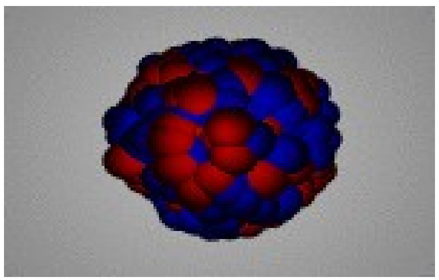
Unstable neutron-rich nuclei and dipole response

– neutron skins and halos

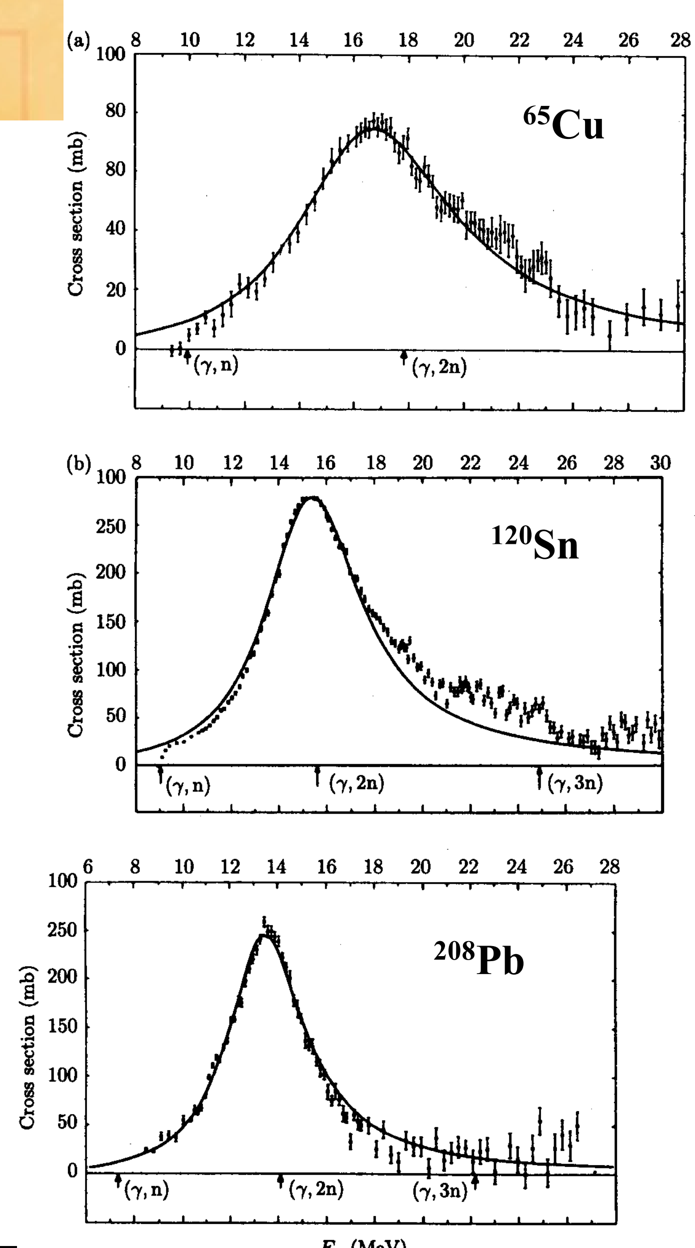
+

– pygmy resonances and soft modes

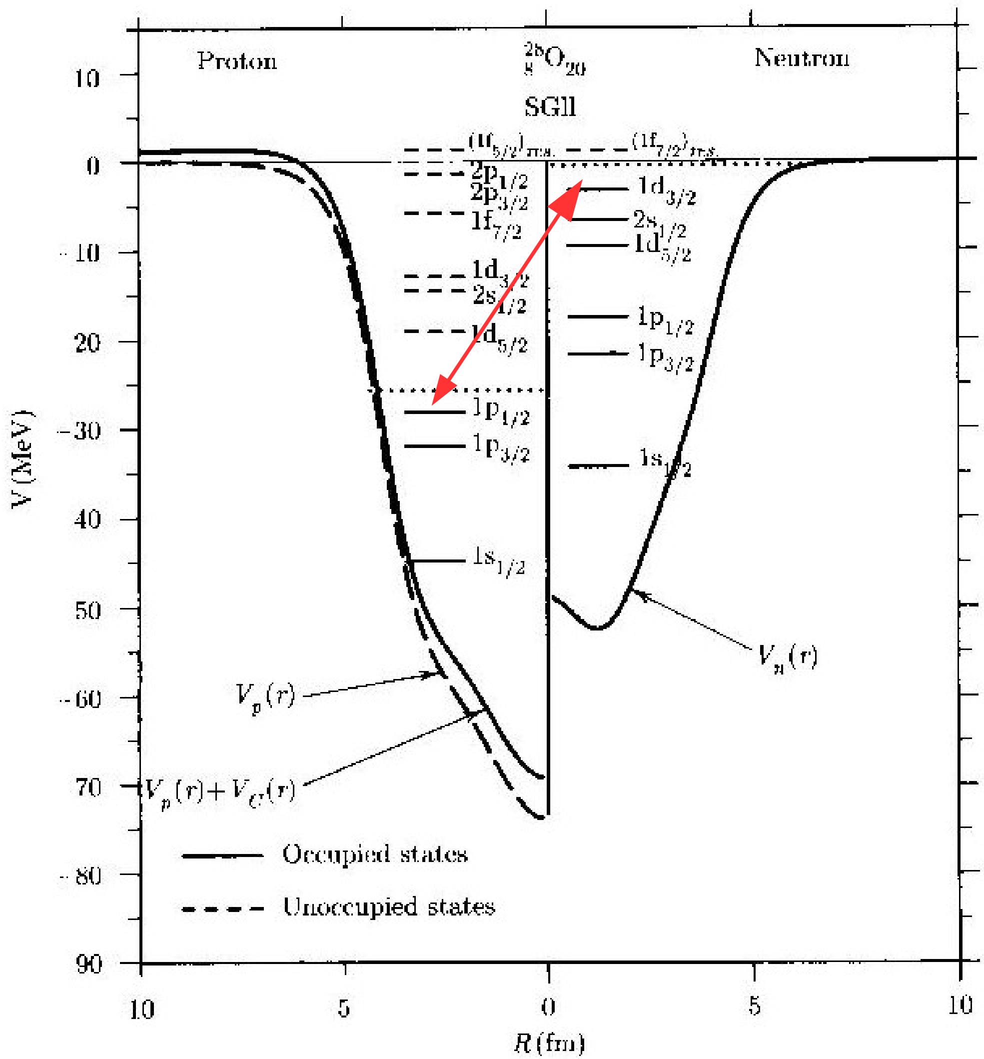
the neutron matter EoS and neutron stars

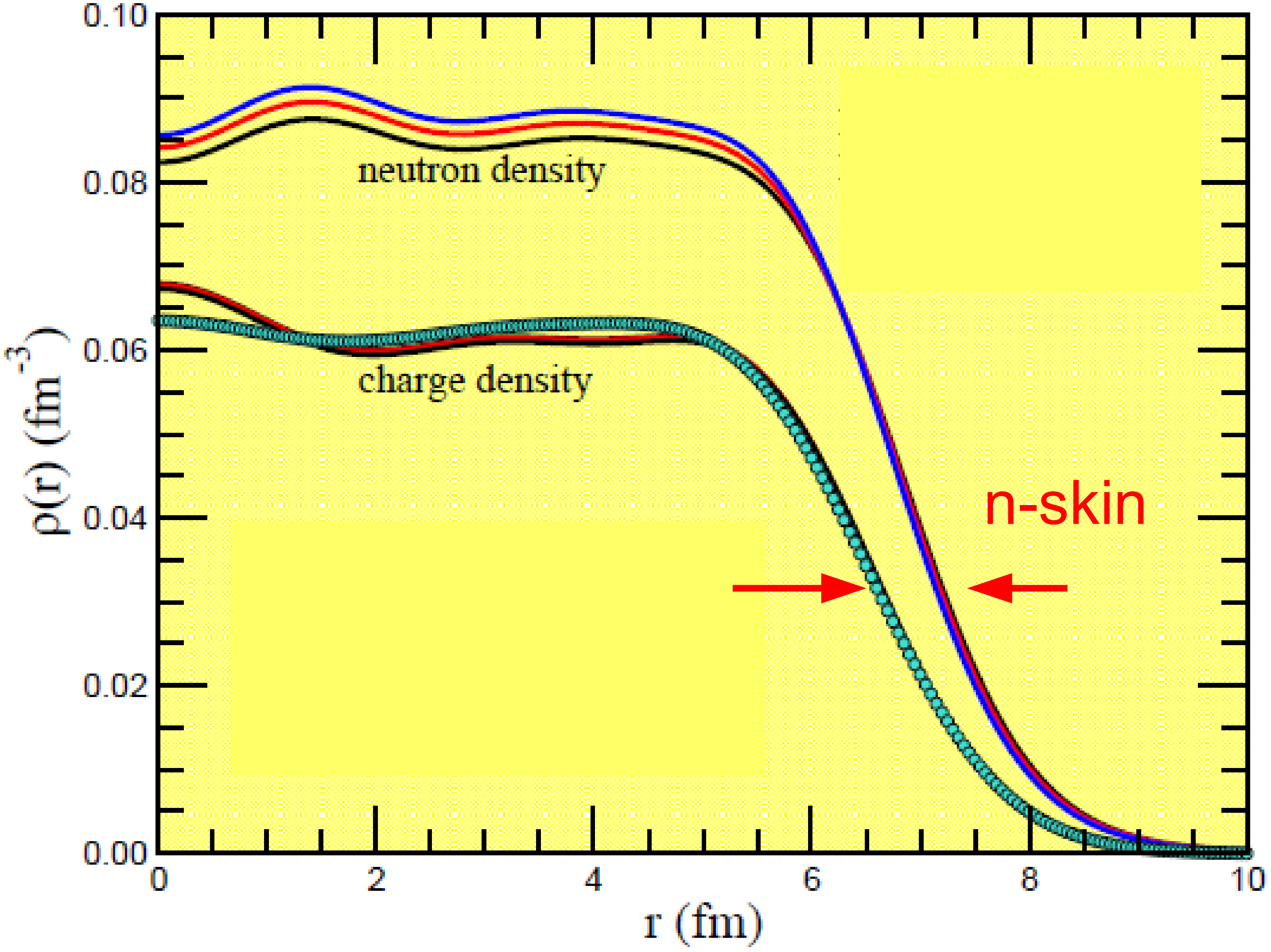


Berman and Fulz, Rev. Mod. Phys. 47 (1975) 47



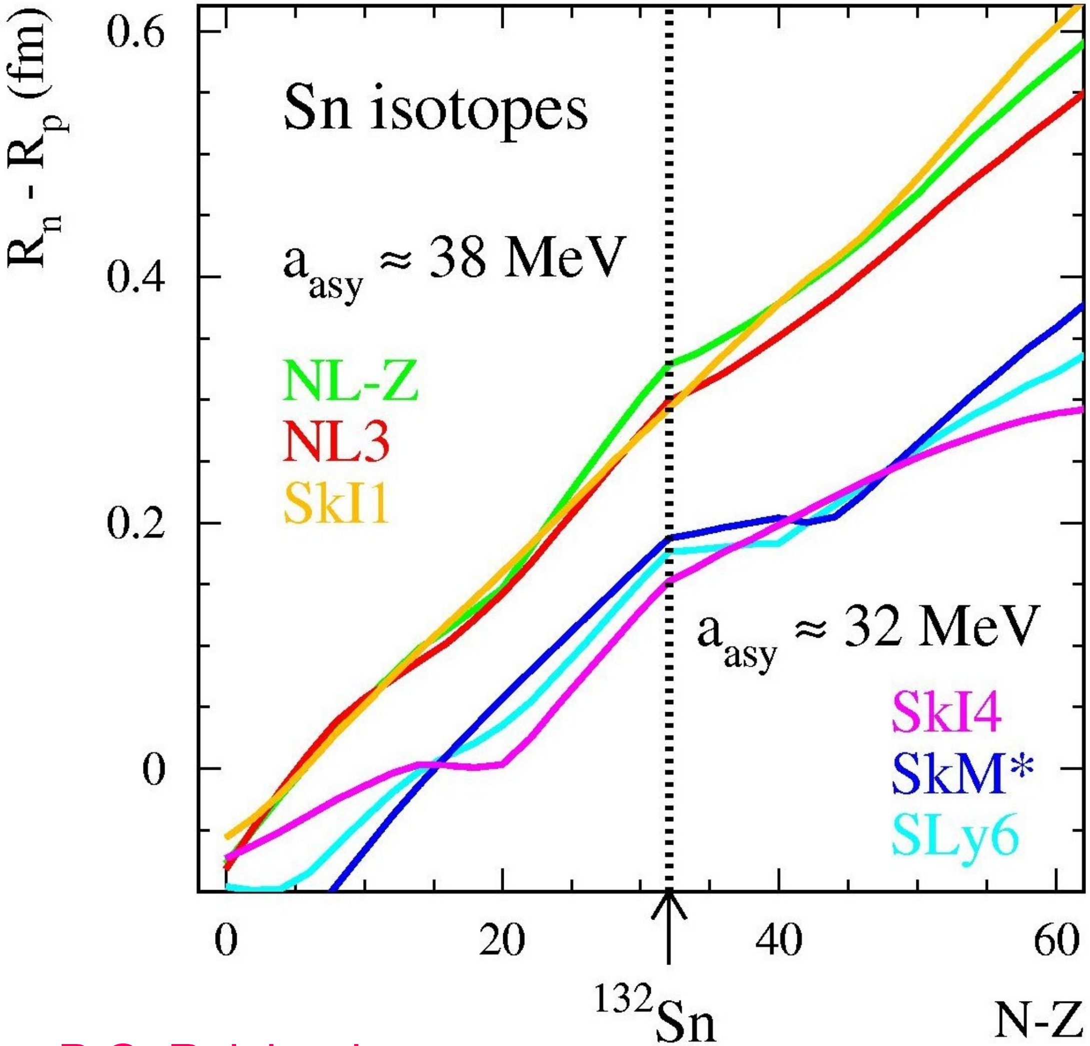
neutron-rich nuclei





0.10
0.08
0.06
0.04
0.02
0.00
ρ(r) (fm-3)
neutron density
charge density
n-skin
0
2
4
6
8
10
r (fm)

neutron skins – numerous calculations



skins are related to

– the nuclear symmetry energy

– the neutron-matter equation-of-state (EoS)

P.G. Reinhard

EoS and symmetry energy

the total (binding) energy **E** in **infinite nuclear matter** depends on the nucleon density **ρ**
and the proton-neutron ratio **α = (N-Z)/A**

$$E(\rho,\alpha) = E(\rho,0) + S(\rho)\alpha^2 + O(\alpha^4),\ \alpha = \frac{N-Z}{A}$$

Taylor expansion

N=Z symmetric matter

symmetry energy

for Z = 0 → α = 1

→ **S(ρ)** = symmetry energy in **neutron matter** neutron matter EoS

the nuclear matter symmetry energy,

particularily its density dependence,

is not well under control

SATOSHI YOSHIDA AND HIROYUKI SAGAWA
PHYSICAL REVIEW C 69, 024318 (2004)

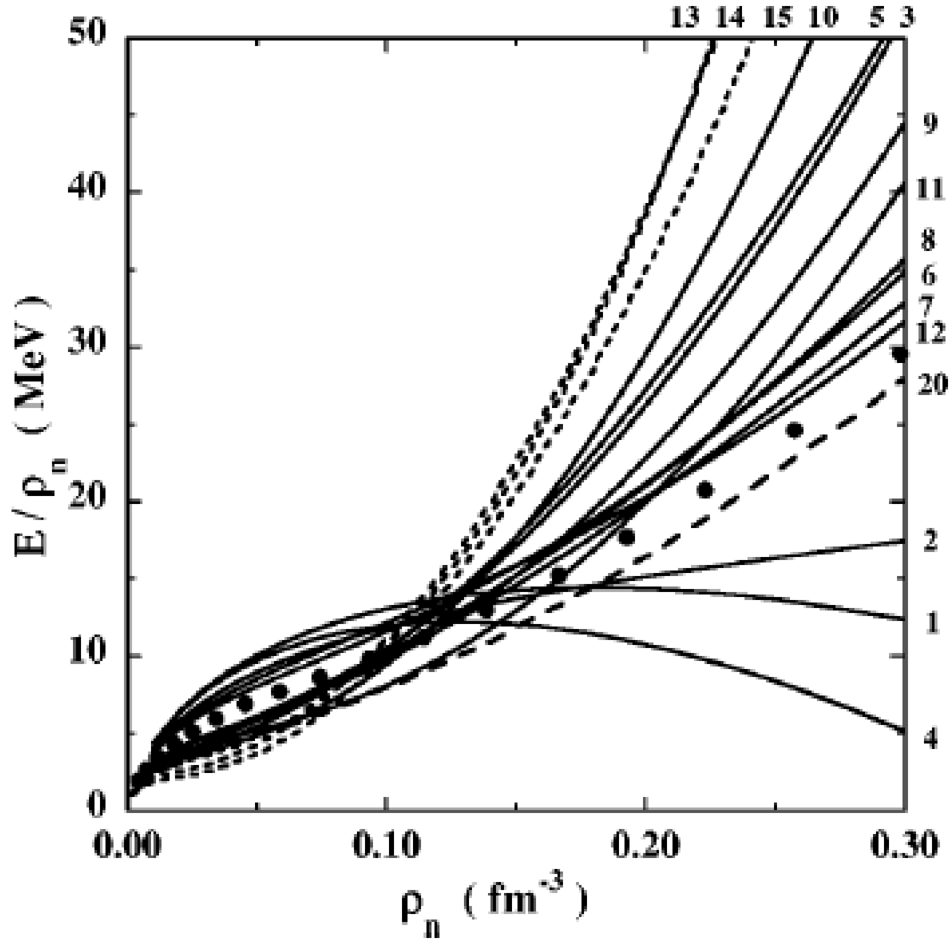
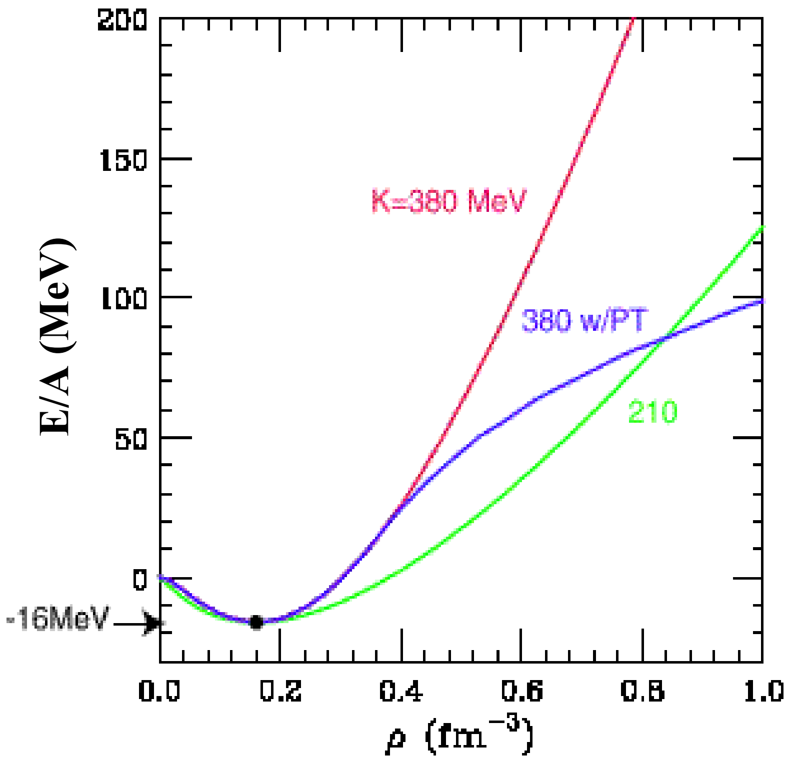


FIG. 3. The neutron equations of state are shown for the 12 parameter sets of the SHF model (solid lines) and 3 parameter sets of the RMF model (dashed lines) which in Figs. 1 and 2 were

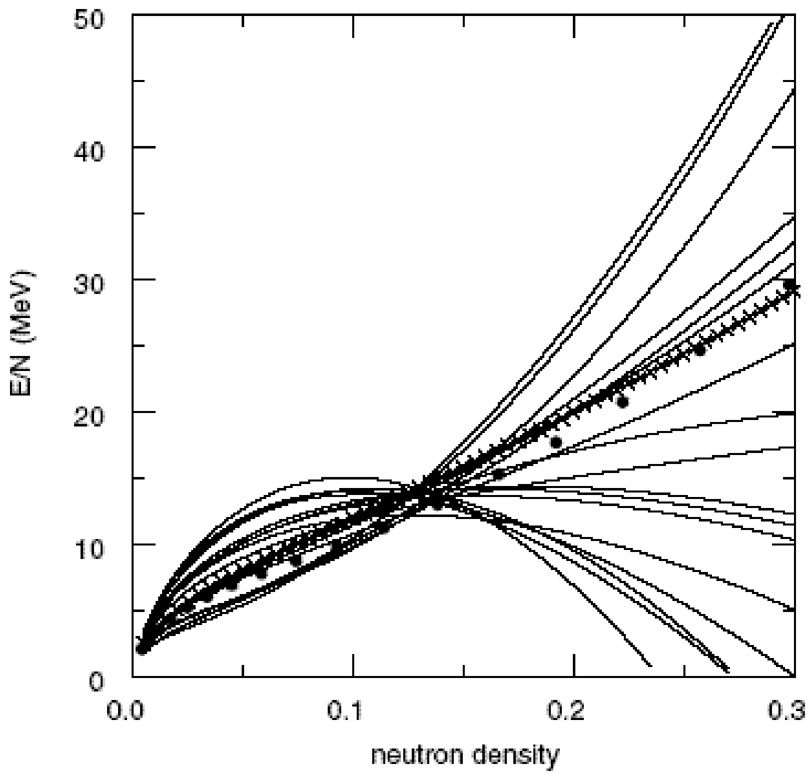
EoS

symmetric N=Z matter



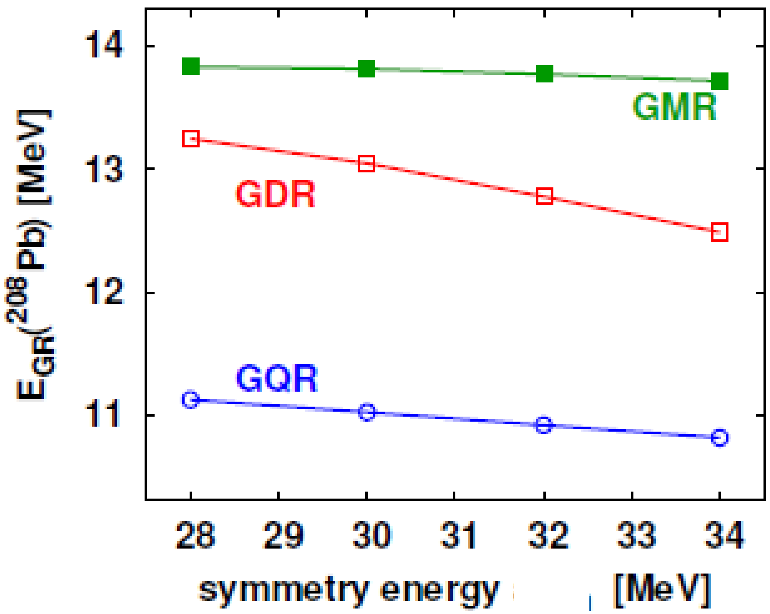
P.Danielewicz

neutron matter



B.Alex Brown
PRL 85(2000)5296

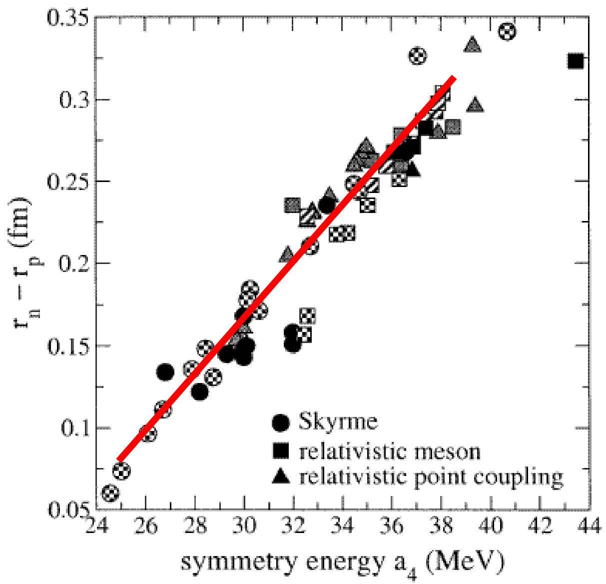
Systematic variation of Skyrme forces



GDR resonance energy depending
on symmetry energy

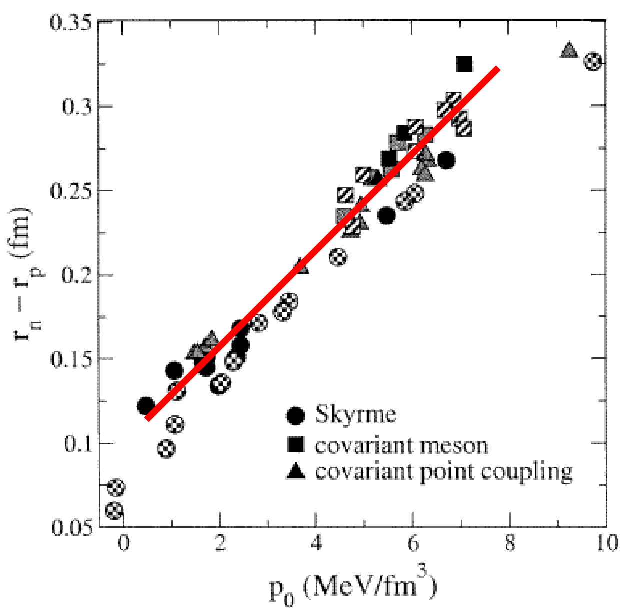
but, not very sensitive, keeping the GDR width in mind

symmetry energy and neutron skin in ^{208}Pb

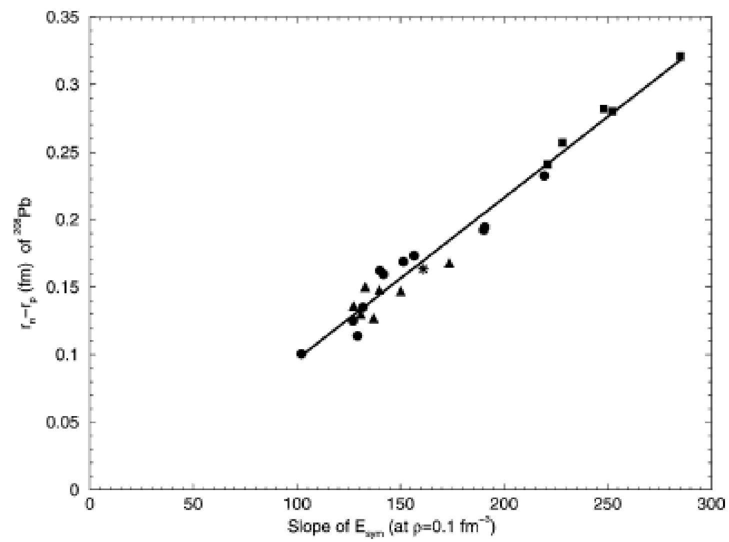


strong <u>linear</u> correlation between neutron skin thickness and sym. energy (slope)

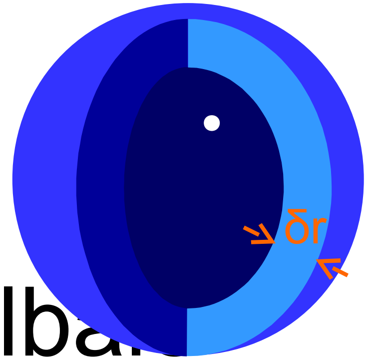
→ **precise measurement of the neutron skin (even for a single nucleus) delivers constraint on the symmetry energy**



250 *M. Baldo et al. / Nuclear Physics A 736 (2004) 241–254*

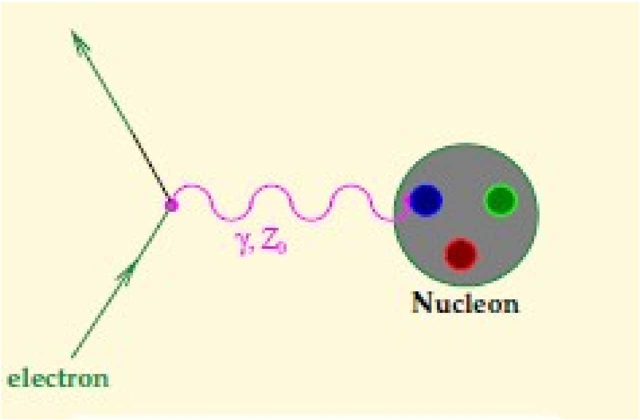


R.J.Furnstahl NPA 706(2002)85-110



<u>problem:</u>

no precise exp. skin data availbale



presently, major efforts ,
e.g., 'parity-violation' PREX experiment at JLAB
(neutron skin in ^{208}Pb)

Alternatives ?

theoretical predictions of
(collective ?) low-lying multipole sthrength
in N/Z asymmetric nuclei

link to nuclear skin and neutron matter ?

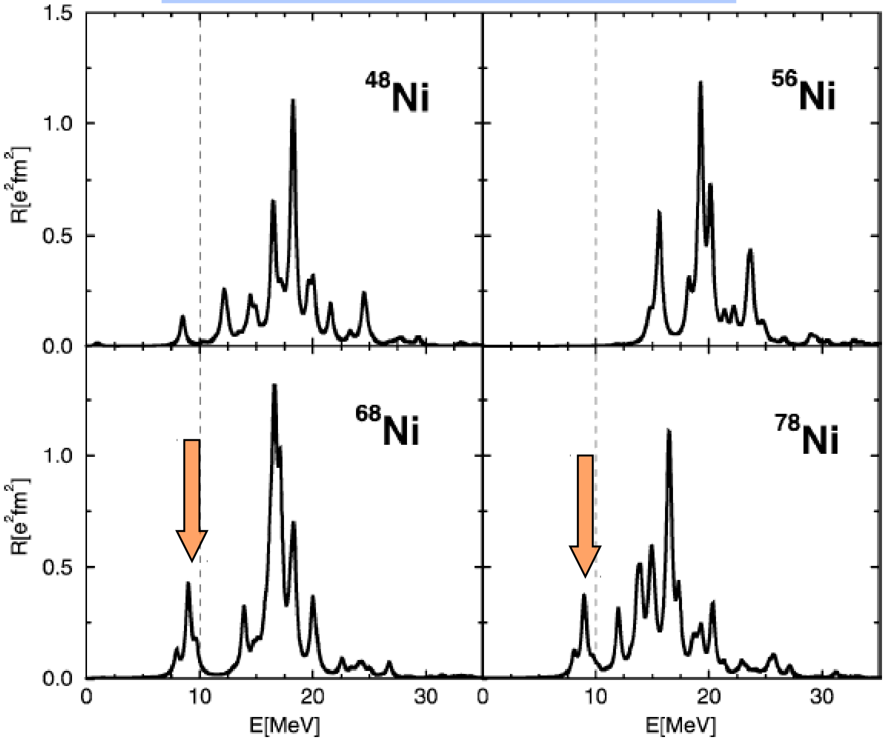
discussed here:

soft modes (light nuclei, halo's)
pygmy dipole resonance

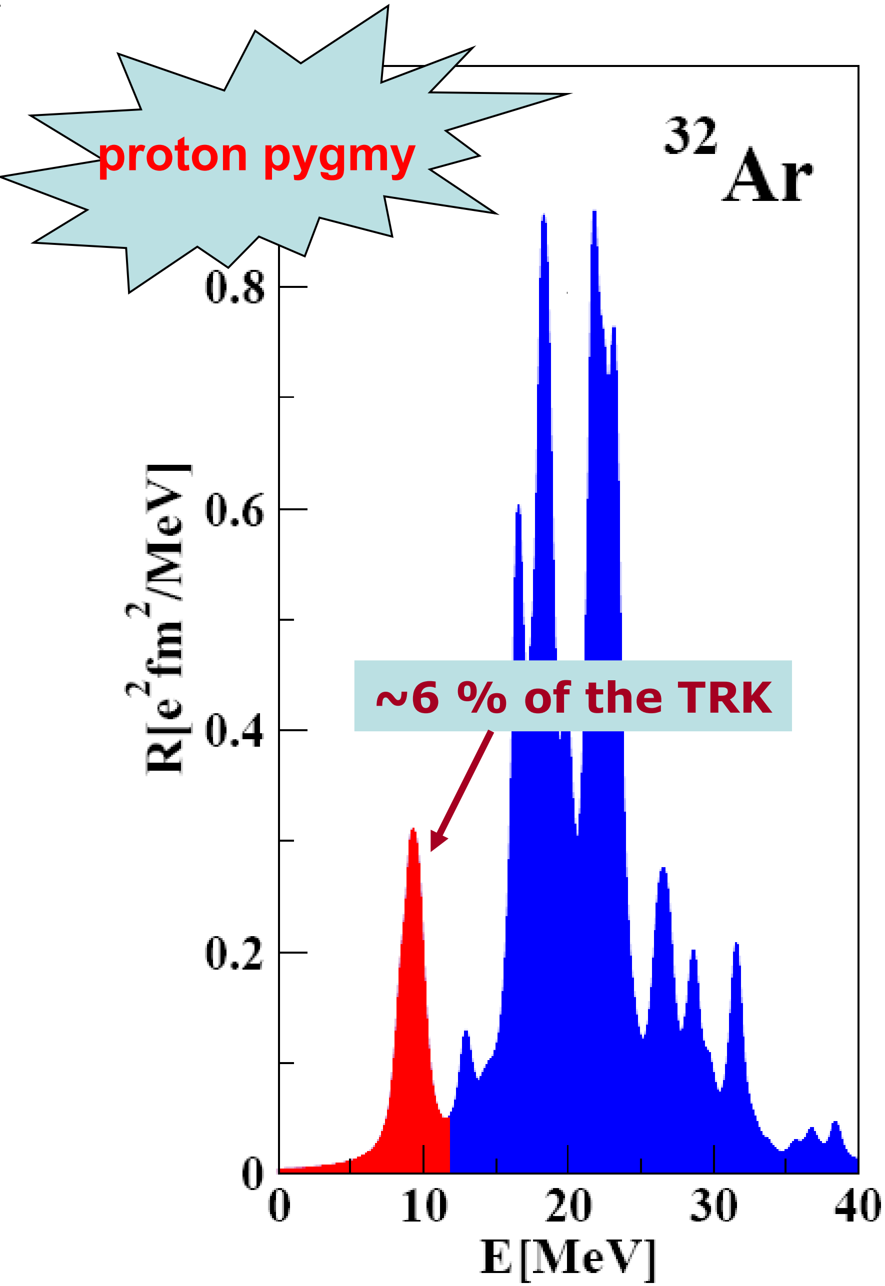
numerous theoretical calculaions

Here: relativistic mean field calculations: Vretenar et al. (NPA 692 (2001) 496)

Dipole strength functions



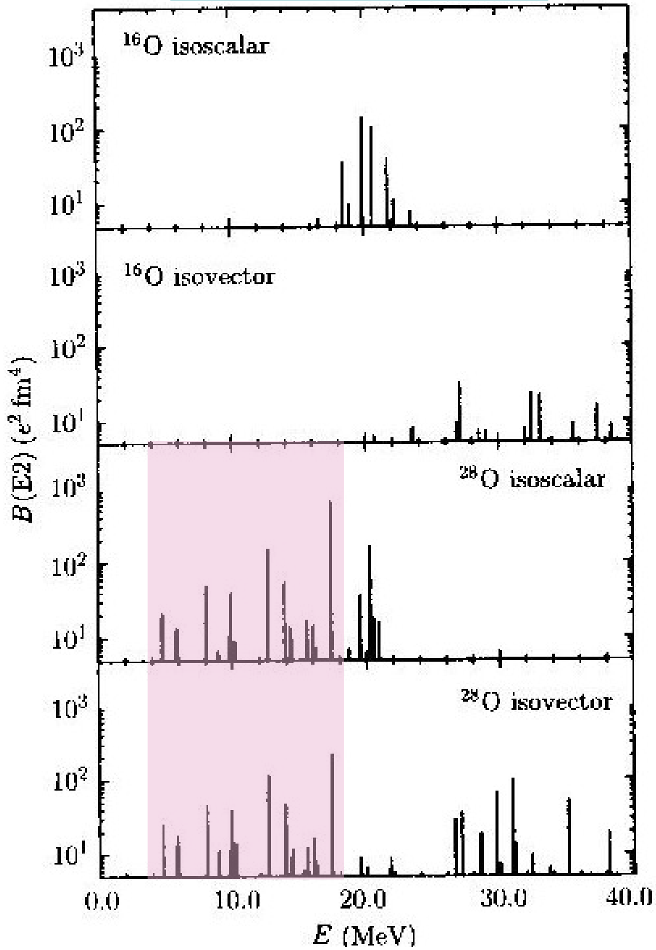
Collective low-energy state at 9 MeV characterized by a coherent superposition of many ph configurations exhausting 5% of the EWSR



Paar, Vretenar, Ring, Phys. Rev. Lett. 94, 182501 (2005)

light nuclei

E2 response



^{16}O

^{28}O

E < 18 MeV

neutron excitations only

→

no clear separation of

isoscalar and isovector

excitations

Lanza et al.

Vitturi et al.

giant resonances in unstable nuclei - experimental status -

- information on isovector Dipole strength only
- limited statistics
- limited resolution

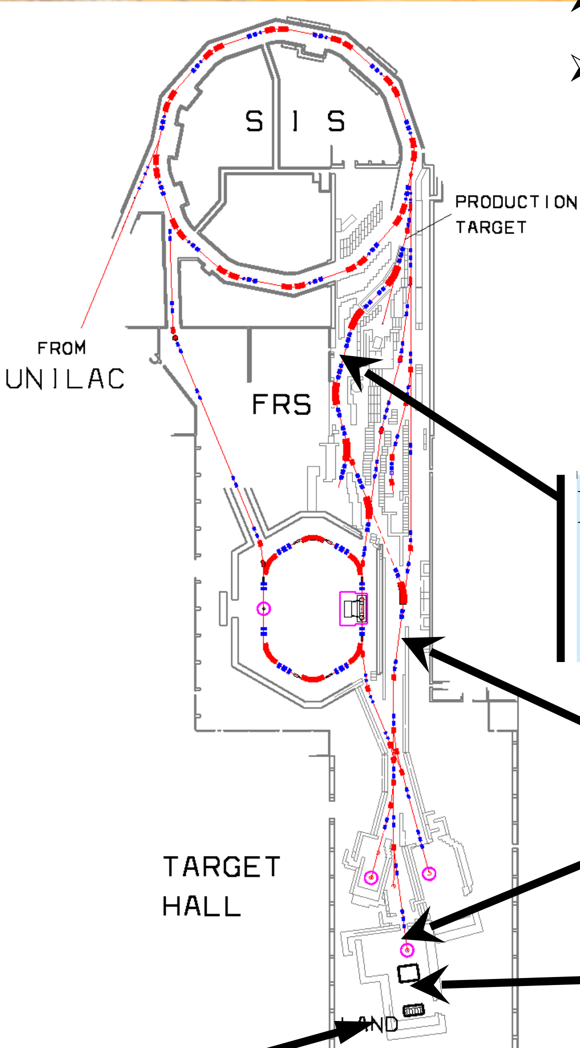
below, results from LAND@GSI presented

results for light (halo) nuclei obtained as well at GANIL, RIKEN; MSU..

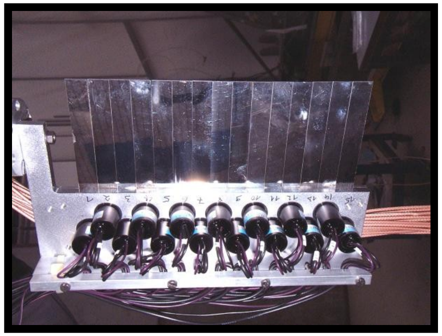
Experimental setup&method

Beam production and identification

- **Primary: $3 \cdot 10^8$ ^{238}U/spill @550Mev/u**
- **Secondary (mixed): ~ 10 ions ^{132}Sn/s**



$$\frac{A}{Z} = \frac{m_u c}{e} \frac{B\rho}{\beta\gamma}$$

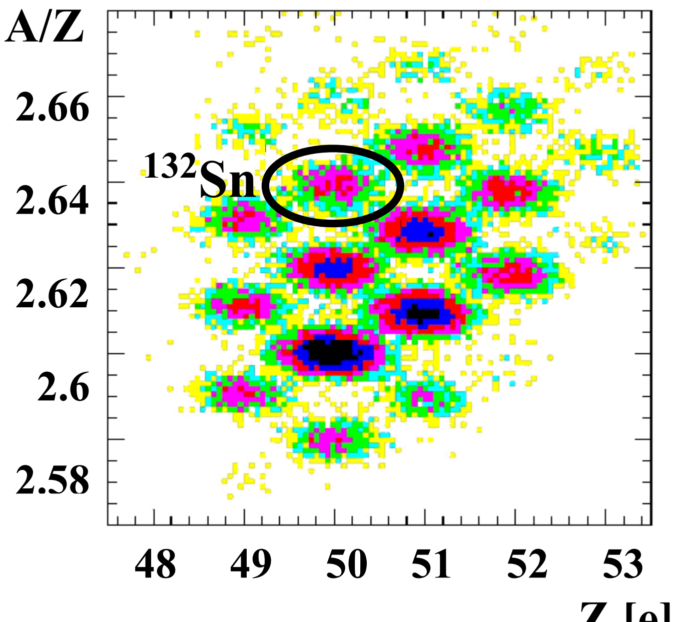


Bρ – from position at middle focal plane of the FRS

β – from TOF

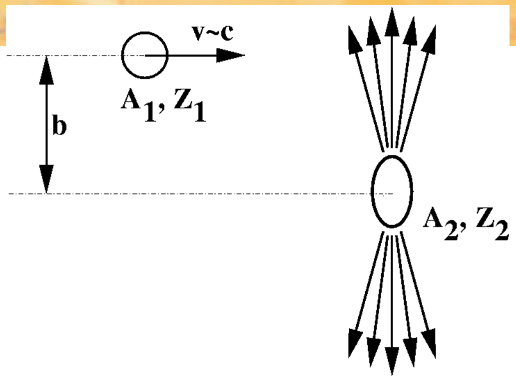
Z – from ΔE

LAND

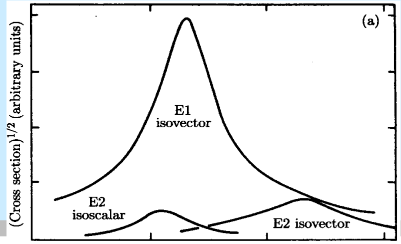


Experimental setup&method

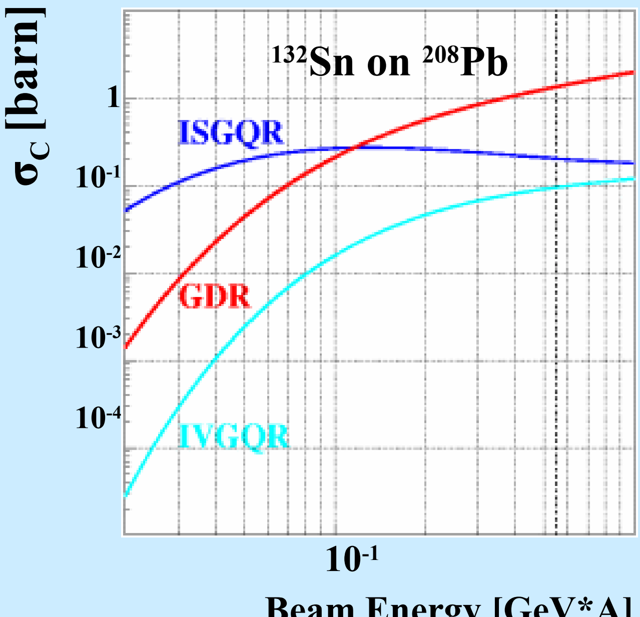
Coulomb excitation in relativistic pheripheral collision



- Selective excitation of E1 transitions (crucial since different resonances overlap in energy)



- Large cross sections: $\sigma_C \sim Z^2$



- Well understood:

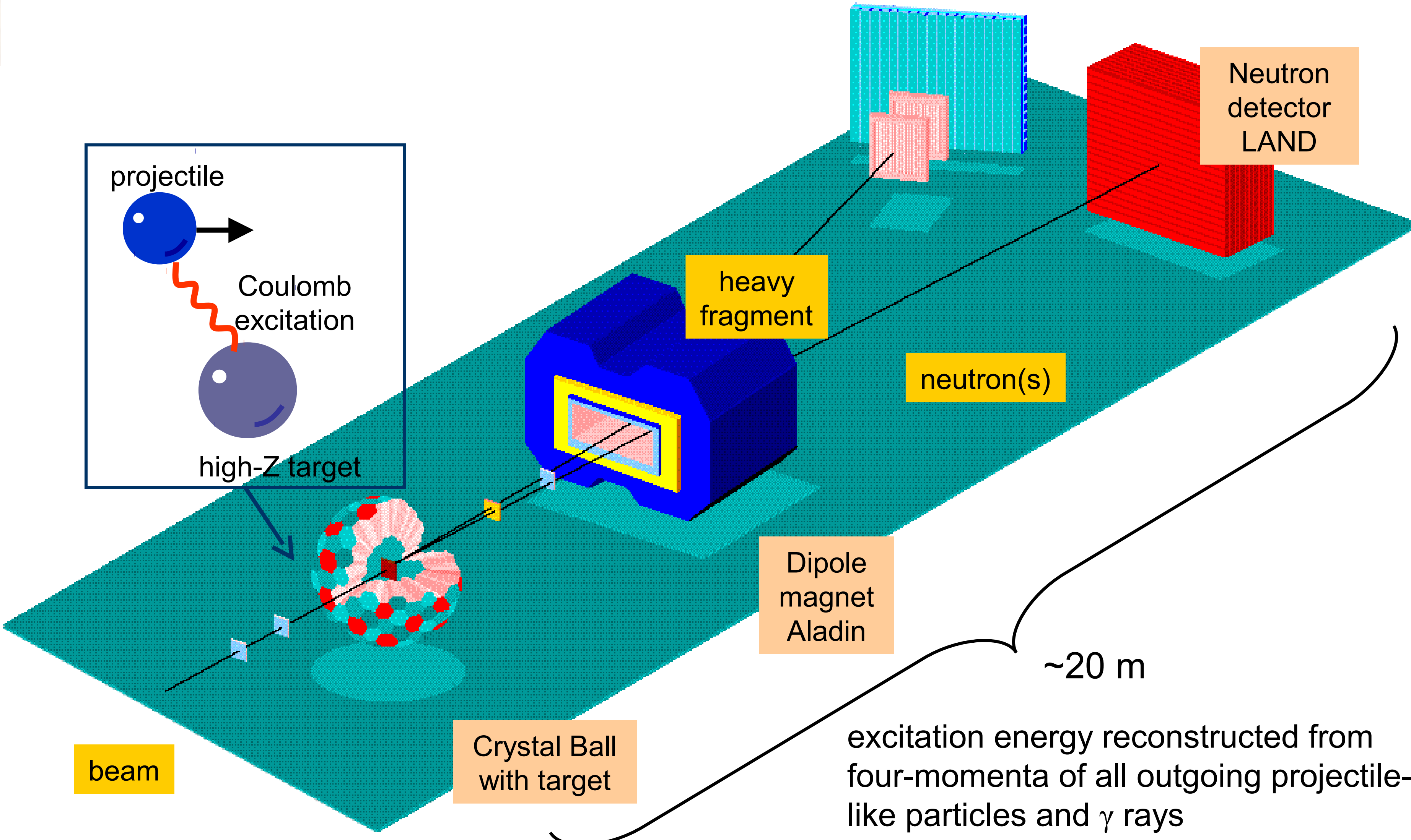
Absorbtion of virtual photons

Semi-classically:

$$\frac{d\sigma_C(E)}{dE} = \sum_{E\lambda} \frac{n_{E\lambda}(E)}{E} \sigma^{\gamma}_{E\lambda}(E)$$

C.A.Bertulani and G.Baur, Phys. Rep. 163 (1988) 299-408

LAND setup



excitation energy reconstructed from four-momenta of all outgoing projectile-like particles and γ rays

$$\left(M_{proj} + E^{*}\right)^{2} = P^{\mu} P_{\mu}$$

Dipole Sum Rule

Energy-weighted dipole sum rule

' Thomas-Reiche-Kuhn' (**TRK**) sum rule

$$\int E_{GDR} \cdot dB(E1, 0 \rightarrow E_{GDR})$$

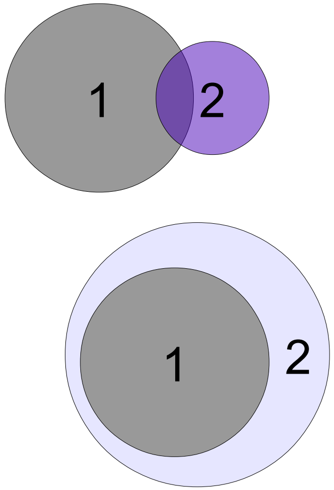
Photo-absorption cross section :

$\sigma_\gamma(E) \sim E_\gamma \cdot dB(E1, 0 \rightarrow E)/\, dE$

GDR:

TRK : $\int \sigma_\gamma(E)\, dE = 60\, \mathbf{N\, Z / A}\ MeV\, fm^2$

' Cluster dipole sum rule '



Cluster 1 + 2

Core + skin/halo

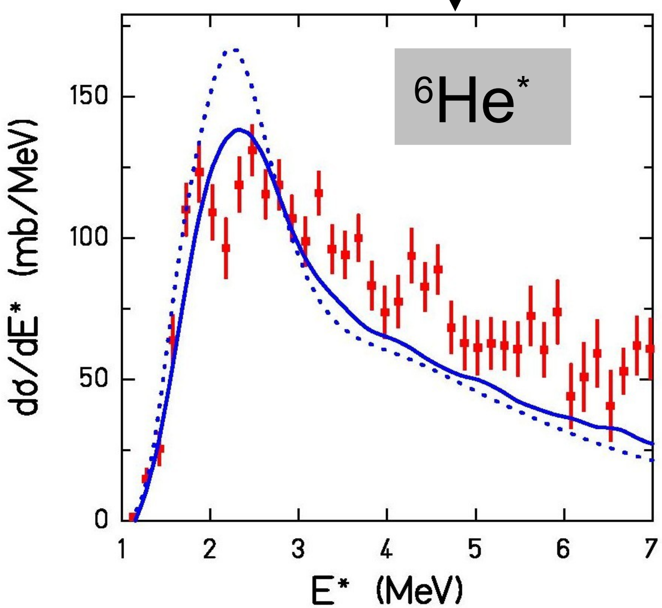
$$TRK_{total} = TRK_1 + TRK_2 + TRK_{rel.}$$

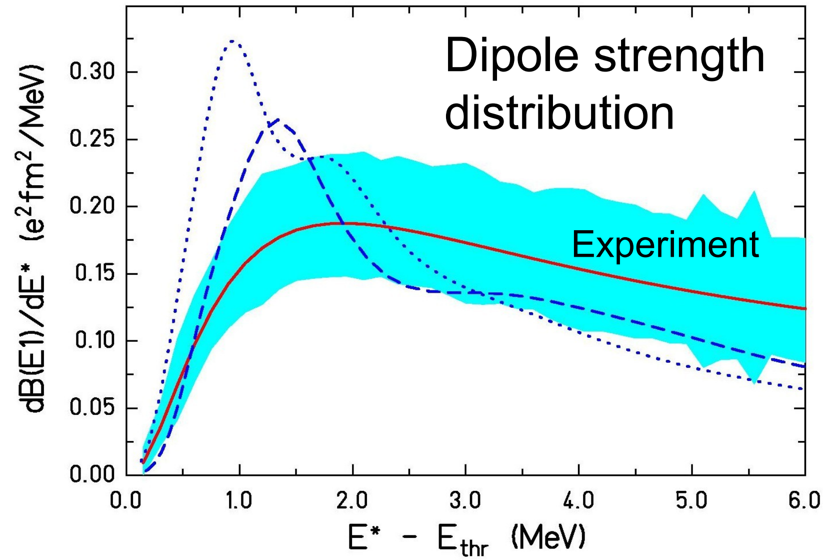
relative motion 1 ↔ 2

Electromagnetic excitation of ^{6}He

$^{6}He + Pb \rightarrow {}^{4}He + 2n$

Invariant Mass





Strength below 10 MeV fully exhausts the energy-weighted cluster sum rule

Non-energy-weighted dipole sum rule:

$$S_{NEW} = 3/4\,\pi\, Z^2 e^2 (N_h/A_c)^2 \langle R_{cm-h}{}^2 \rangle$$

Spatial correlation from dipole strength:

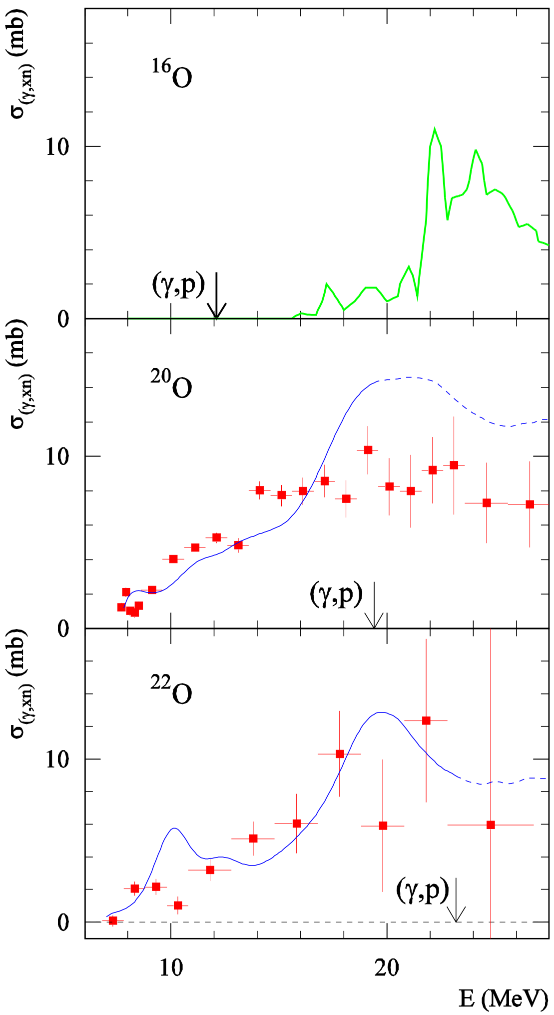
$$\langle R_{cm-halo}{}^2 \rangle^{1/2} = 2.24 \pm 0.26 \text{ fm}$$

From 3-body models:
2.3 – 2.8 fm

T. Aumann et al., PRC 59 (1999) 1252

Dipole strength – light n-rich

Photo-neutron cross sections from Coulomb breakup



Shell model (WPB10),

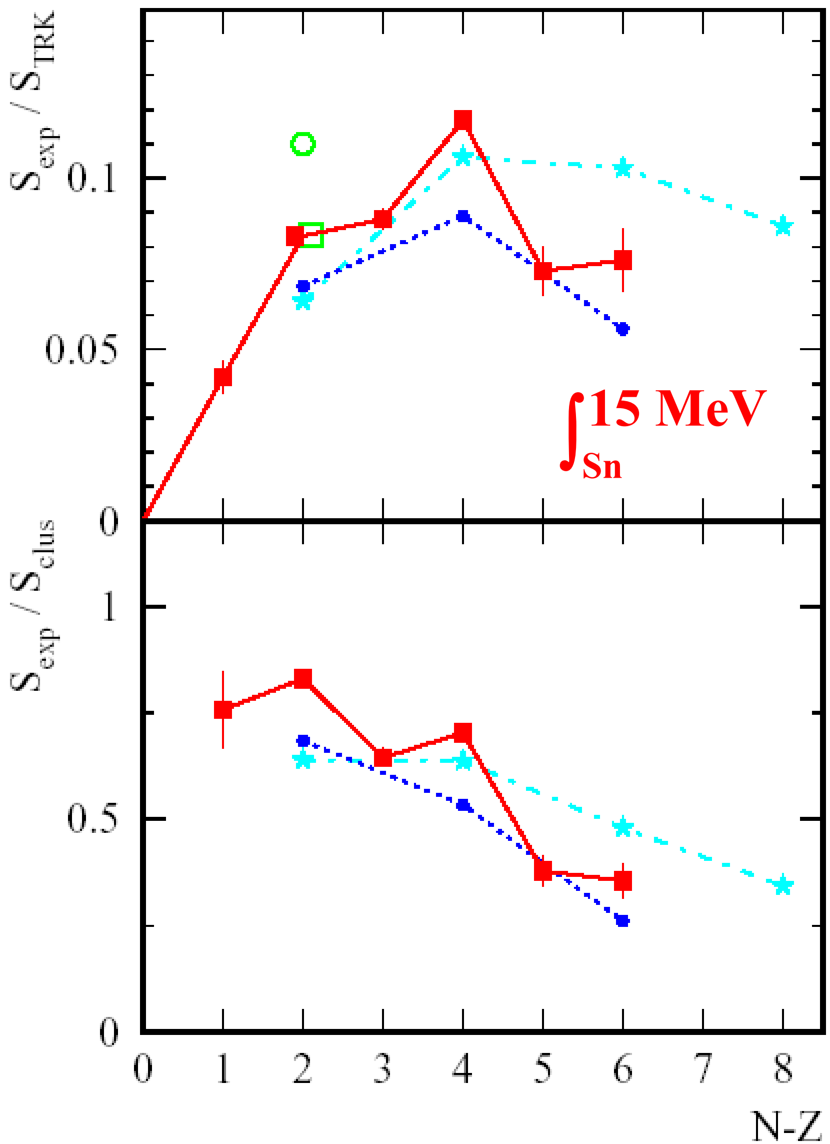
T. Suzuki, H. Sagawa , PRC 2003

A. Leistenschneider et al., PRL 2001

GSI

Low-Lying E1 Strength of n-Rich Oxygen Isotopes

⇒ Integrated strength below the GDR



Energy-weighted classical dipole sum rule (Thomas Reiche Kuhn)

$$S_{TRK} = 60\ NZ/A\ \text{mb MeV}$$

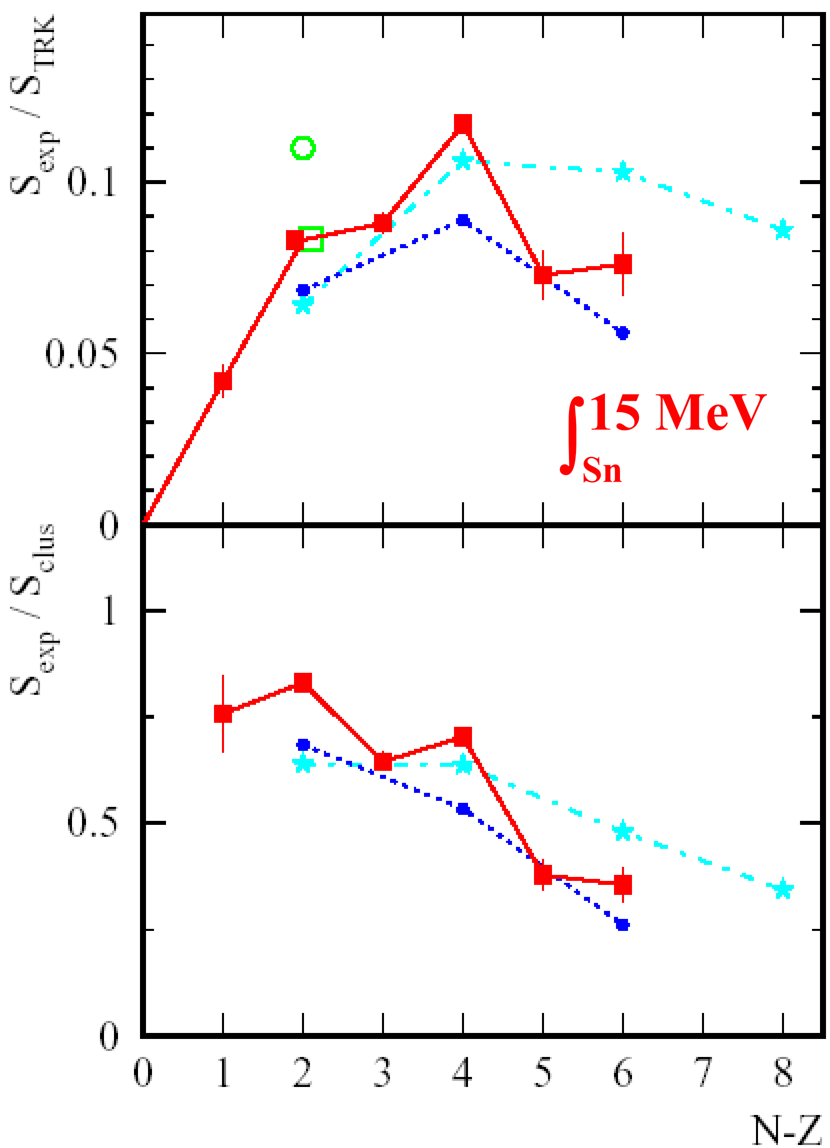
"Cluster" sum rule (valence neutrons ⇔ core)

$$S_{clus} = Z_c / A_c\ N_h / N \times S_{TRK}$$

Data: LAND-FRS@GSI

A. Leistenschneider et al., PRL 86 (2001) 5442

⇒ Integrated strength below the GDR



Collective soft-dipole vibration ?

* QRPA plus phonon coupling

(Colò and Bortignon)

only a small number of components in the wave functions of the low-lying structures

* Relativistic mean field

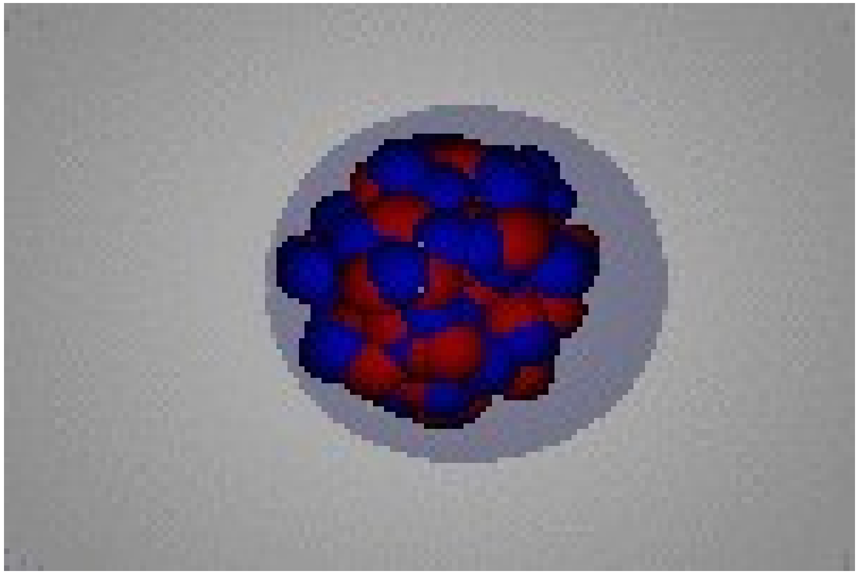
(Vretenar, Paar, Ring, and Lalazissis)

low-lying strength mainly related to single neutron particle-hole excitations

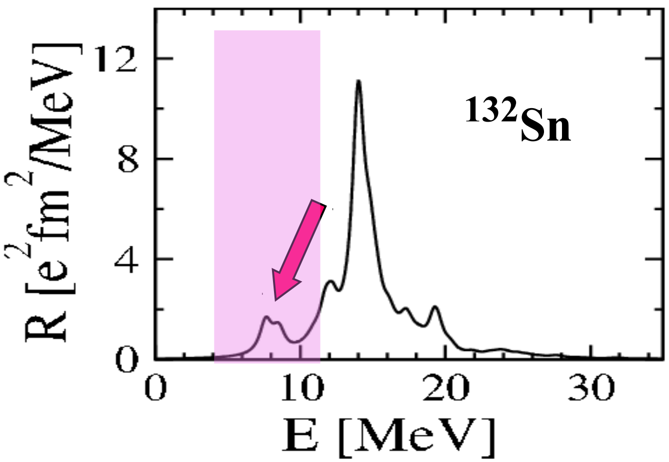
→ but: **collective soft mode predicted for heavier nuclei, e.g., Ni and Sn isotopes**

Heavy nuclei : Sn isotopes

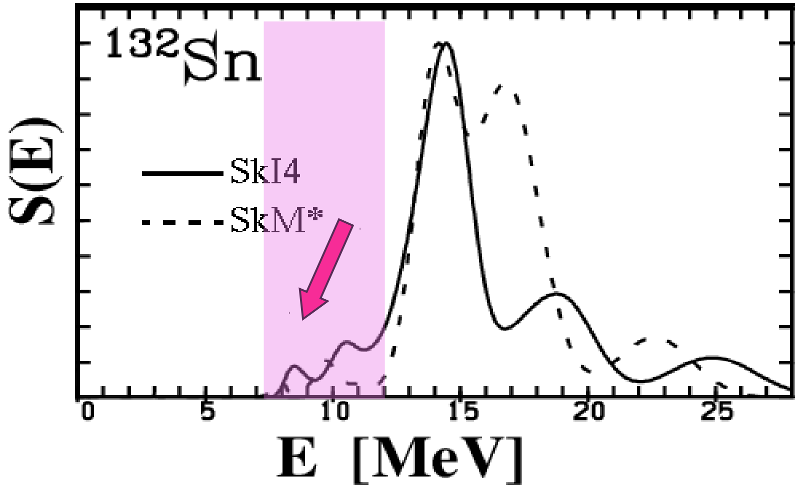
Do we find a
collective
Pygmy resonance ?



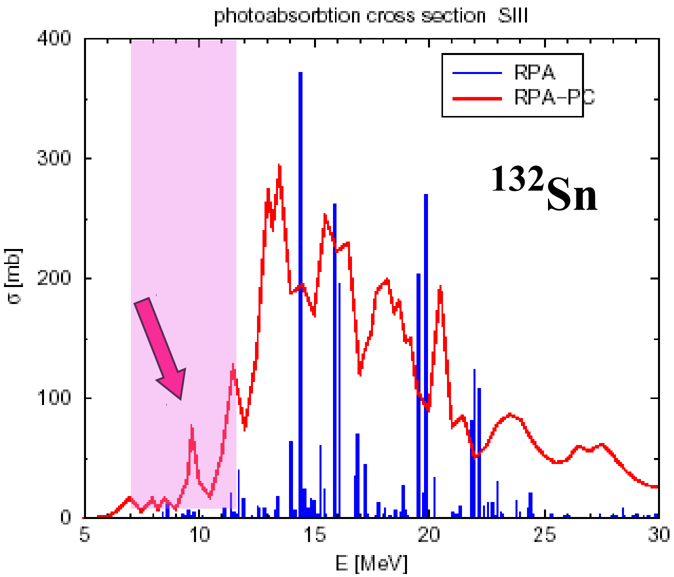
Calculations for ^{132}Sn : Pygmy at ~ 8 – 12 MeV



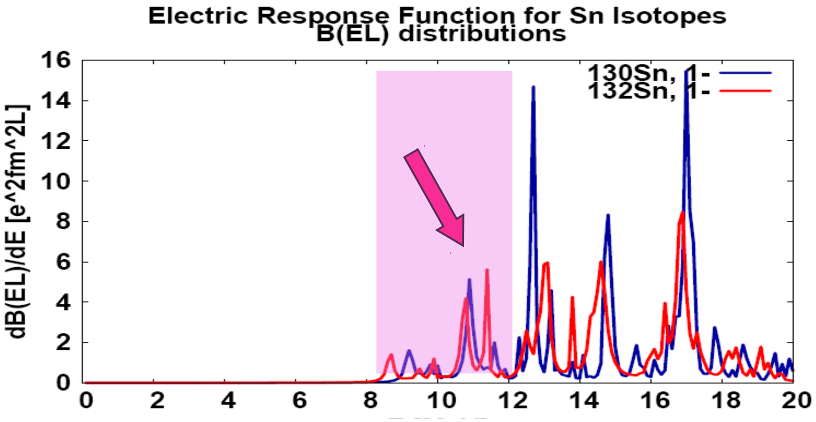
N.Paar et al, Phys.Rev. C67(2003)34312



P.G.Reinhard, Nucl.Phys. A649(1999)305c

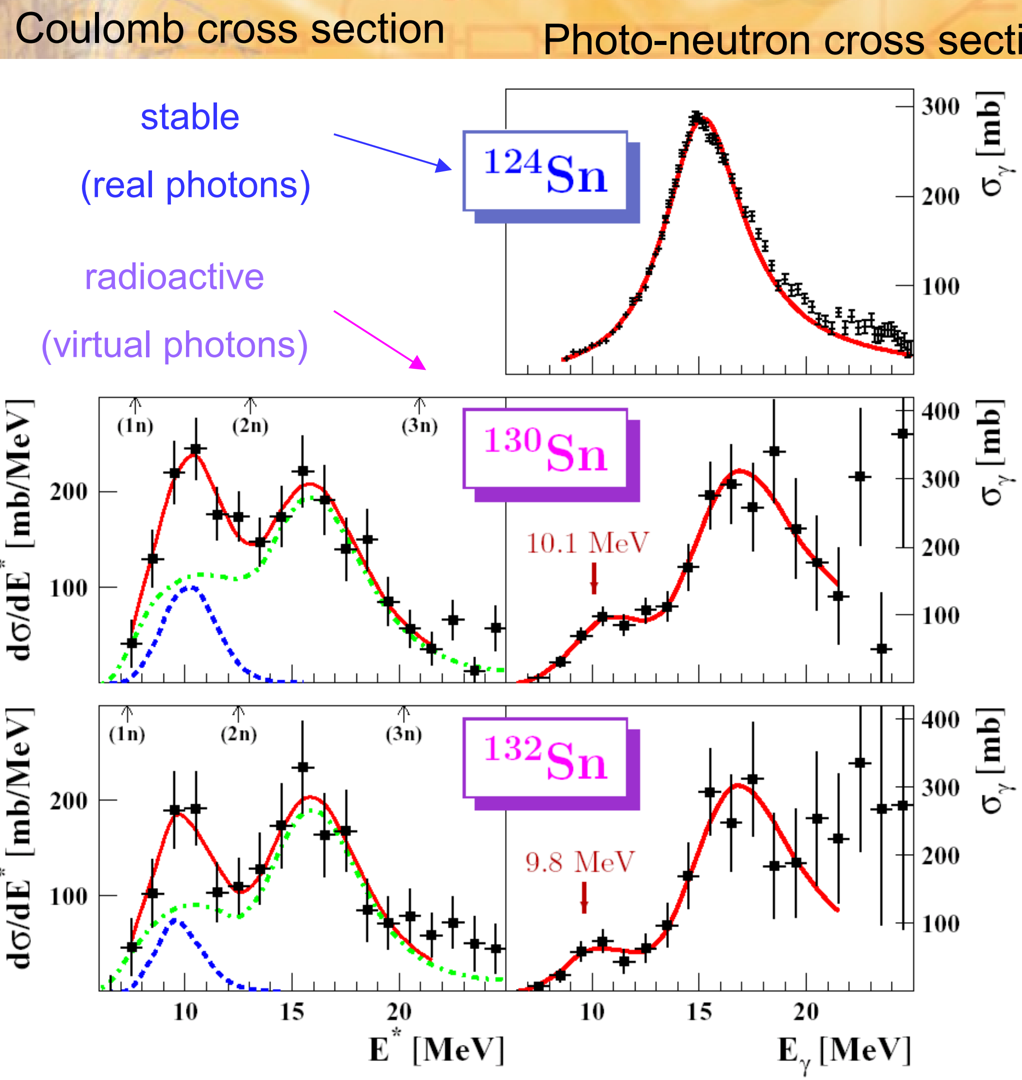


Sarchi,Bortignon,Colo



H. Lenske et al.

Results for neutron-rich even Sn isotopes



A	PDR		GDR		
	E_{centr} [MeV]	sum rule fraction [%]	E_{centr} [MeV]	Γ [MeV]	sum rule fraction [%]
^{124}Sn	-	-	15.3	4.8	116
^{130}Sn	10.1 (0.7)	7.0 (3.0)	15.9 (0.5)	4.8 (1.8)	145 (19)
^{132}Sn	9.8 (0.7)	4.0 (3.1)	16.1 (0.8)	4.7 (2.2)	125 (32)

PDR

- located at 10 MeV
- exhausts a few % TRK sum rule

GDR

- no deviation from systematics

P. Adrich *et al*., PRL 95 (2005)132501

^{130,132}Sn results
PDR compared to theoretical calculations

Sum rule exhaustion EWSR(PDR) / EWSR(GDR)			
	This experiment	RQRPA N. Paar et al., PRC 67 (2003) 34312	RPA-PC D. Sarchi et al., PLB 601 (2004) 27
^{130}Sn	0.05(2)	0.055	-
^{132}Sn	0.03(2)	0.05	0.04

However :
Conflicting interpretations of the nature of the low-lying strength:

RQRPA – coherent superposition of many particle-hole configurations.
Dynamics of skin vibration.

RPA-PC – no evidence for transitions involving more than one or two particle-hole configurations.

PHYSICAL REVIEW C **73**, 044325 (2006)

Pygmy dipole resonance as a constraint on the neutron skin of heavy nuclei

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Pygmy – Dipole

↕

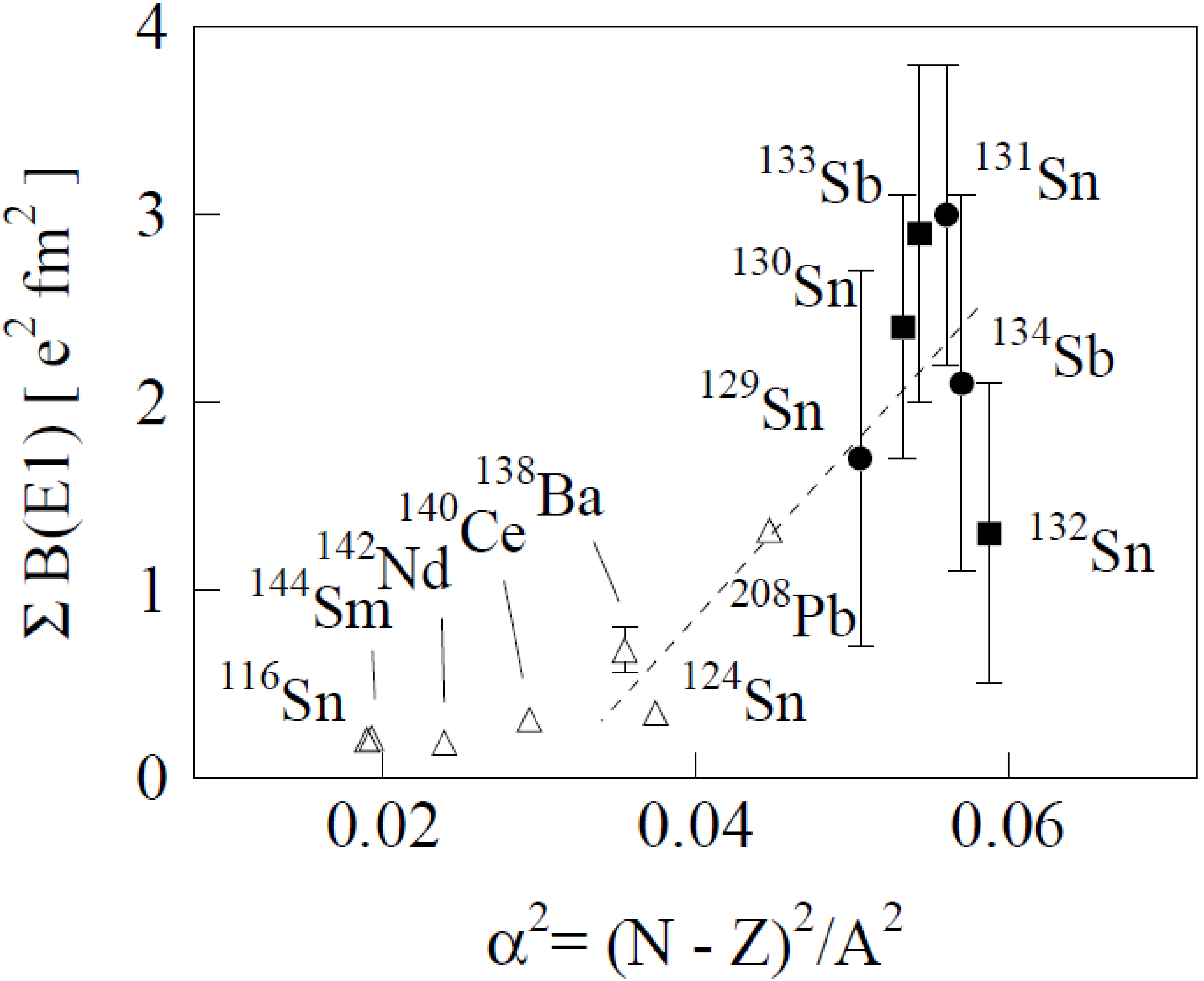
Neutron Skin

↕

Neutron Matter EoS
(Symmetry Energy)

???

GSI



4
3
2
1
0
0.02
0.04
0.06
Σ B(E1) [e² fm²]
α² = (N - Z)²/A²
133Sb
131Sn
130Sn
134Sb
129Sn
138Ba
140Ce
142Nd
144Sm
116Sn
208Pb
124Sn
132Sn

EoS:

$$E(\rho,\alpha) = E(\rho,0) + S\,(\rho)\alpha^2 + \ldots$$

Taylor exp. in α= (N-Z)/A

Symmetry energy:

$$S\,(\rho) = a_4 + \frac{p_o}{\rho_o^2}(\rho - \rho_o) + \ldots,$$

Taylor exp. in *ρ*

symmetry energy at saturation density ρ_o

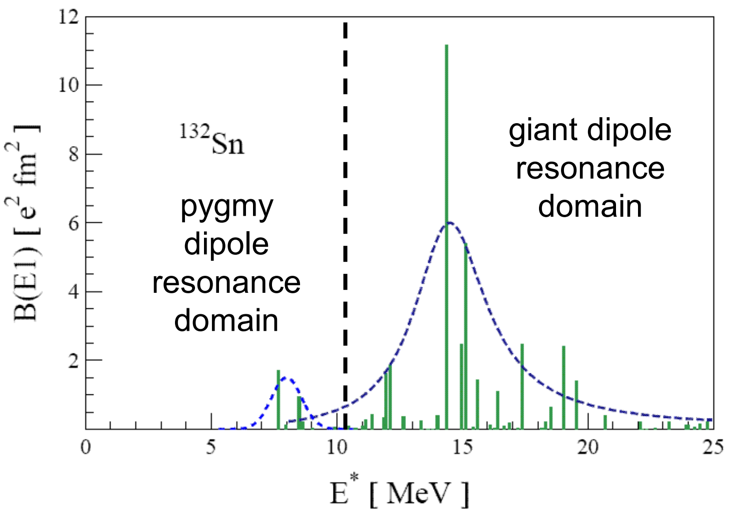
i.e., in ' normal' nuclei

$$S'(\rho)|_{\rho=\rho_0} = \frac{L}{3\rho_0}$$

slope; symmetry energy ' pressure'

GSI

Extraction of a_4 and slope parameter from $^{130,132}Sn$ experimental results

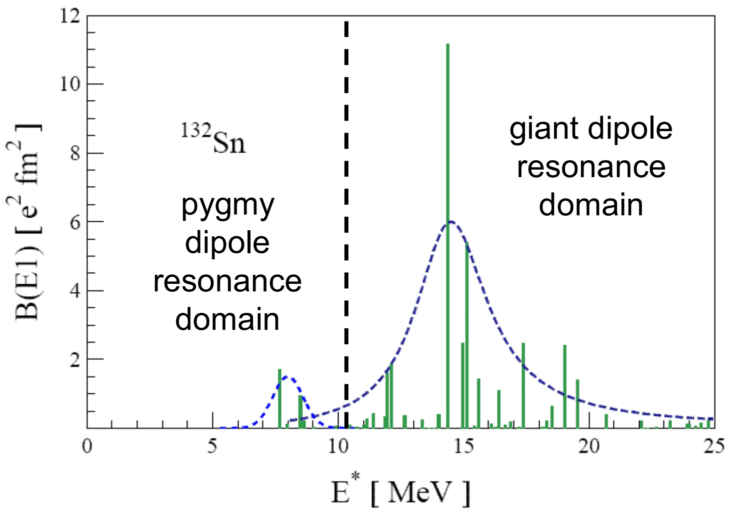


for following analysis see
A. Klimkiewicz et al., PRC 2008

RQRPA calculations therein by N. Paar

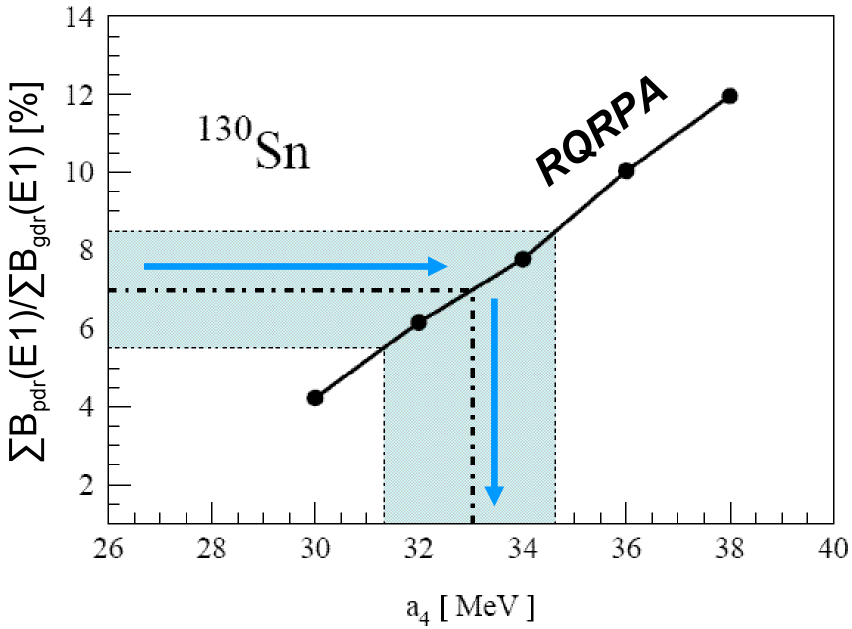
- Calculation of Pygmy strength within relativistic QRPA model
- therein, systematic variation of symmetry energy parameter
  (readjusting other model parameters to fit binding energies, radii etc.)
- comparison of pygmy strength to experiment

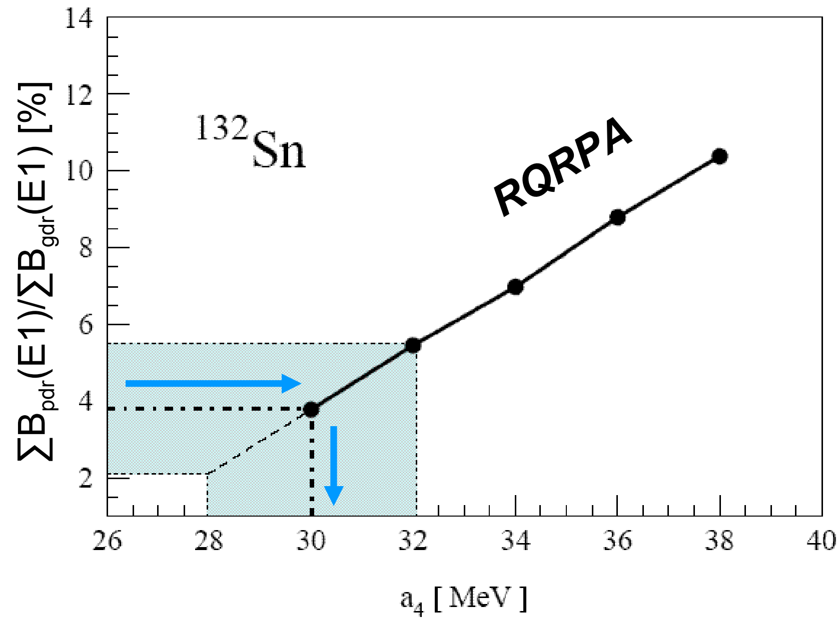
Extraction of a_4 parameter



$$a_4 = 32.0 \pm 1.8 \ \text{MeV}$$

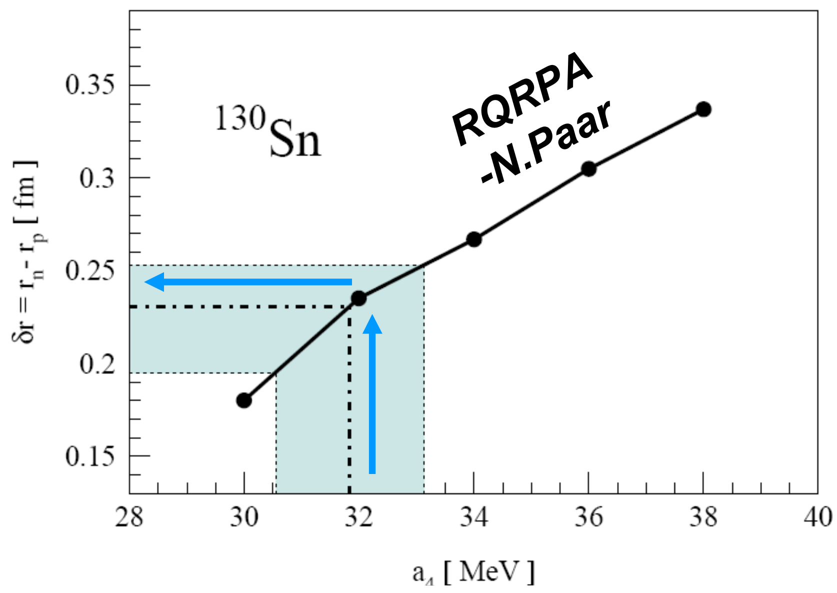
(averaged $^{130,132}Sn$)

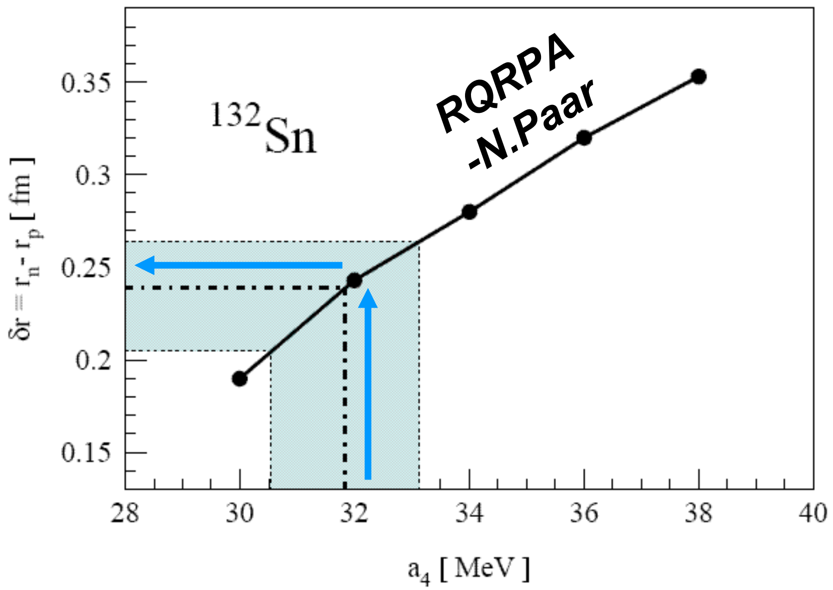


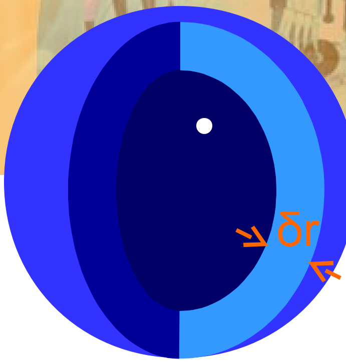


GSI

Neutron skin thickness



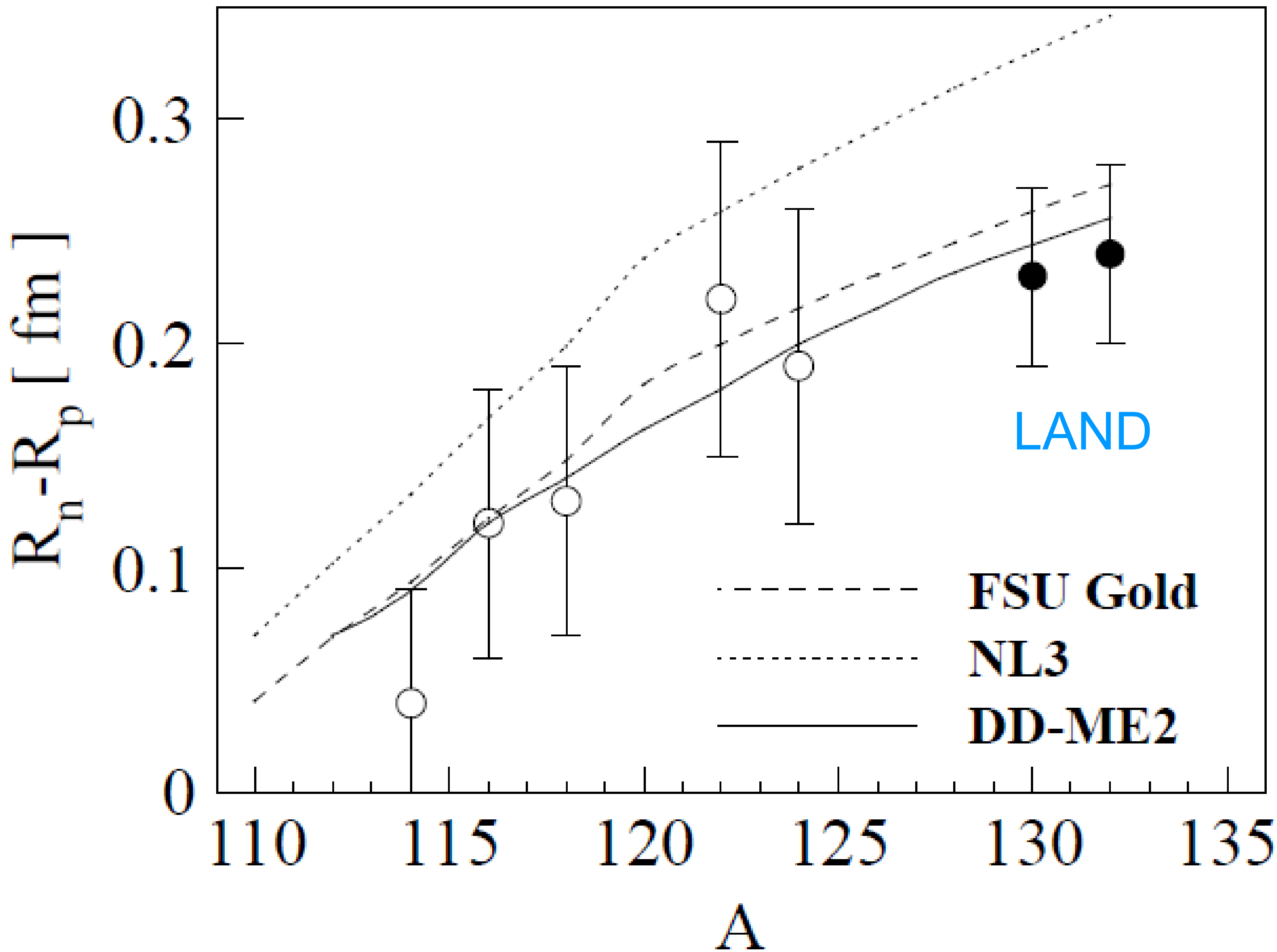




$$^{130}\mathrm{Sn}\ \delta r = 0.23 \pm 0.03\left(^{+0.02}_{-0.05}\right)\,[\mathrm{fm}]$$

$$^{132}\mathrm{Sn}\ \delta r = 0.24 \pm 0.03\left(^{+0.02}_{-0.05}\right)\,[\mathrm{fm}]$$

Neutron skin thickness in Sn isotopes



Stable isotopes:

A.Krasznahorkay et al., PRL 82(1999)3216

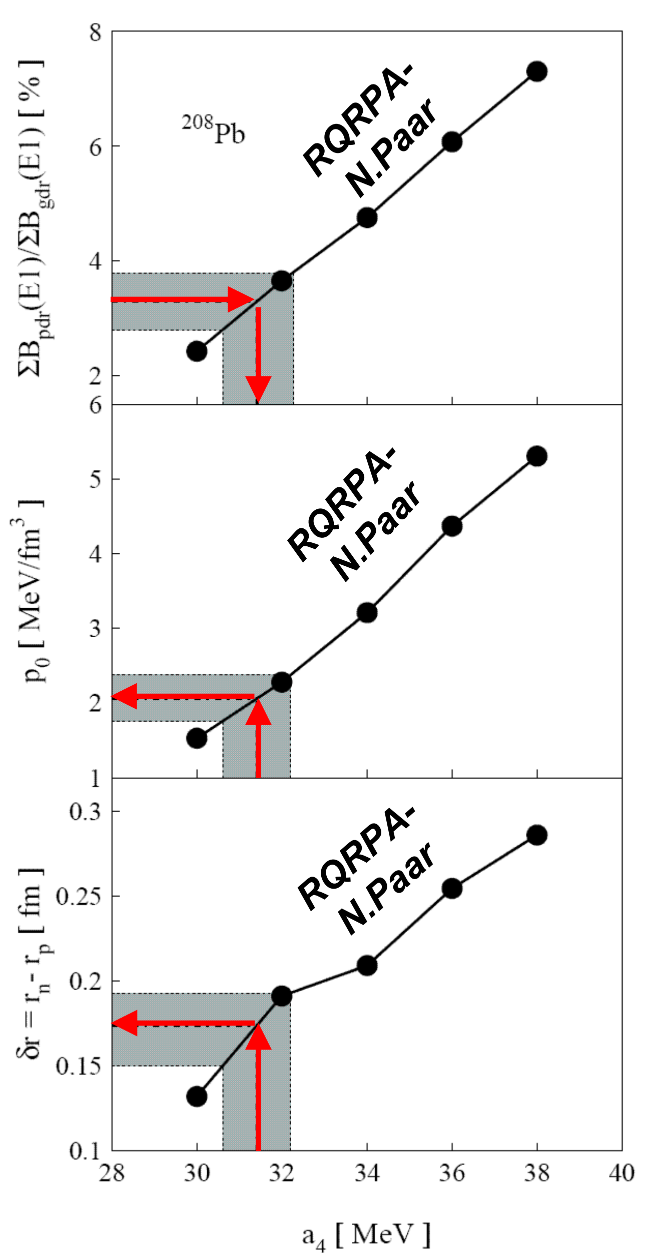
^{208}Pb analysis

$\sum B_{pdr}(E1) = 1.98\ e^2\ fm^2$

from N.Ryezayeva et al., PRL 89(2002)272501

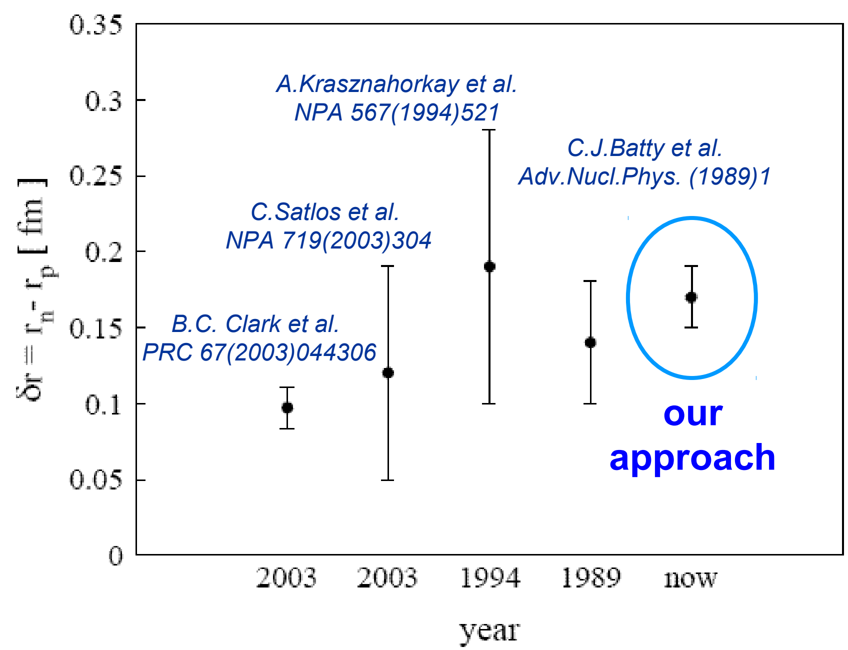
$\sum B_{gdr}(E1) = 60.8\ e^2\ fm^2$

from A.Veyssiere et al.,NPA 159(1970)561

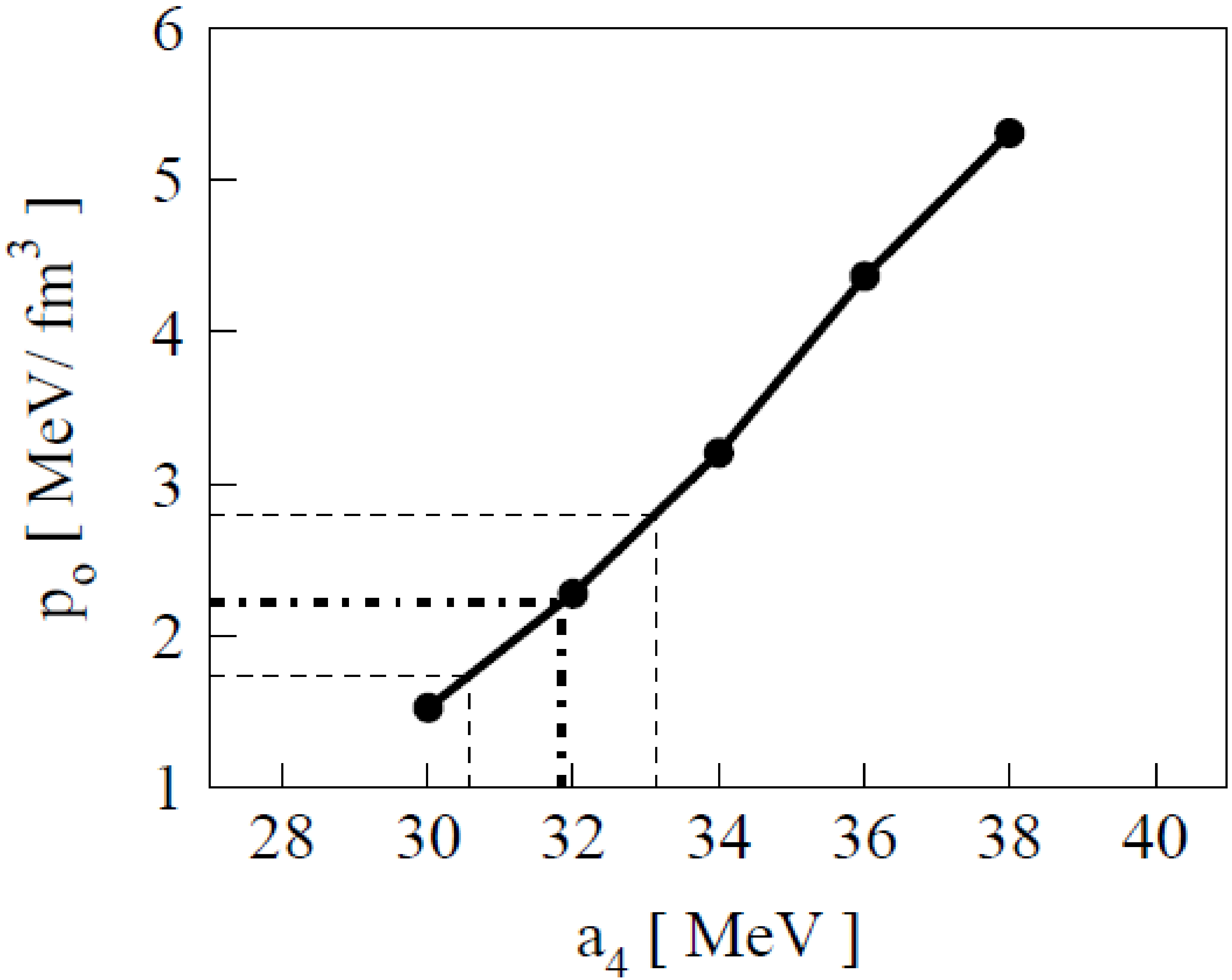


$a_4 = 31.4 \pm 0.8$ MeV

$\delta r = 0.17 \pm 0.02$ fm



GSI



6
5
4
3
2
1
28
30
32
34
36
38
40
p_o [MeV/ fm^3]
a_4 [MeV]

The information content of the nuclear neutron skin

P.–G. Reinhard[1] and W. Nazarewicz[2,3,4]

arXiv:1002.4140v1 [nucl-th] 22 Feb 2010

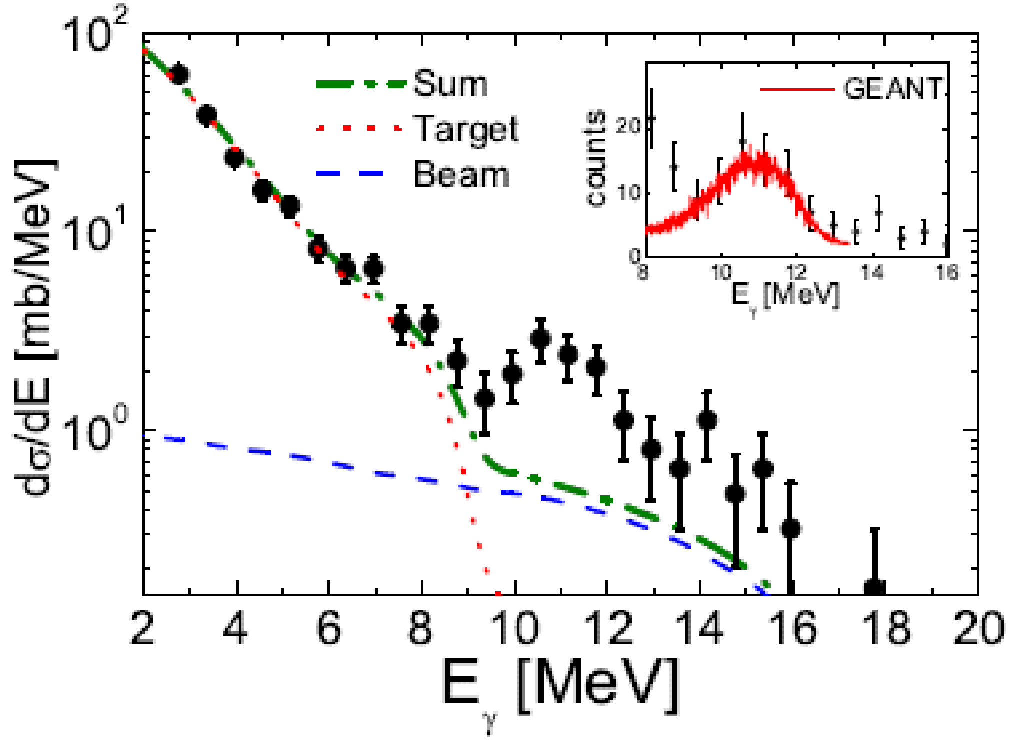
from (specific) Skyrme-RPA calculation:
- Pygmy resonances essentially of 1p-1h type and
- not strongly correlated to neutron skin

?

RISING @ GSI experiment

Search for Pygmy Dipole Resonance in ^{68}Ni at 600 MeV/nucleon

O.Wieland[1], A.Bracco[1], F.Camera[1], G.Benzoni[1], N.Blasi[1], S.Brambilla[1], F.C.L.Crespi[1], S.Leoni[1], B.Million[1], R.Nicolini[1], A.Maj[2], P.Bednarczyk[2], J.Grebosz[2], M.Kmiecik[2], W.Meczynski[2], J.Styczen[2], T.Aumann[3], A.Banu[3], T.Beck[3], F. Becker[3], L.Caceres[3,♯], P.Doornenbal[3,⋆], H.Emling[3], J.Gerl[3], H.Geissel[3], M.Gorska[3], O.Kavatsyuk[3], M.Kavatsyuk[3], I.Kojouharov[3], N.Kurz[3], R.Lozeva[3], N.Saito[3], T.Saito[3], H.Schaffner[3], H.J.Wollersheim[3], J.Jolie[4], P.Reiter[4], N.Warr[4], G.de Angelis[5], A.Gadea[5], D.Napoli[5], S.Lenzi[6], S.Lunardi[6], D.Balabanski[7], G.Lo Bianco[7], C.Petrache[7,†], A.Saltarelli[7], M.Castoldi[8], A.Zucchiatti[8], J.Walker[9], A.Bürger[10,△]



E ~ 11 MeV

5% – 9 % TRK

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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]

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[2]*INFN, Sezione di Milano, via Celoria 16, I-20133 Milano, Italy*
[3]*Institute of Modern Physics, Chinese Academy of Science, Lanzhou 730000, People's Republic of China*
[4]*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator of Lanzhou, Lanzhou 730000, People's Republic of China*

(Received 6 November 2009; published 2 April 2010)

Correlations between the behavior of the nuclear symmetry energy, the neutron skins, and the percentage of energy-weighted sum rule (EWSR) exhausted by the pygmy dipole resonance (PDR) in ^{68}Ni and ^{132}Sn are investigated by using different random phase approximation (RPA) models for the dipole response, based on a representative set of Skyrme effective forces plus meson-exchange effective Lagrangians. A comparison with the experimental data has allowed us to constrain the value of the derivative of the symmetry energy at saturation. The neutron skin radius is deduced under this constraint.

Analysis extended to a variety of non-relativistic Skyrme RPA and relativistic RPA calculations

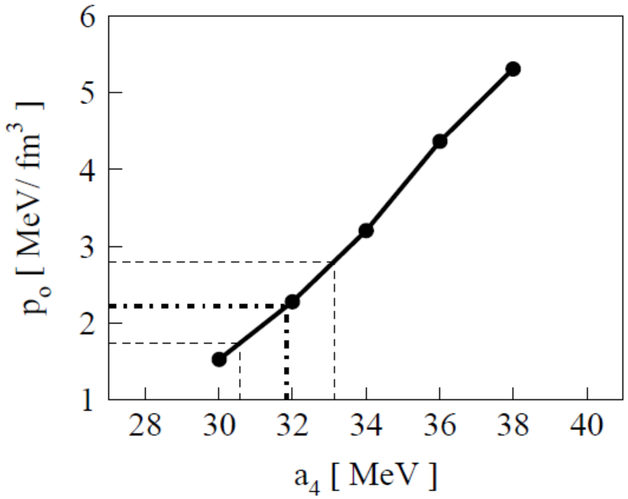
EoS:

$$E(\rho,\alpha) = E(\rho,0) + S\ (\rho)\alpha^2 + \ldots$$

Symmetry energy

$$S'(\rho)|_{\rho=\rho_0} = \frac{L}{3\rho_0}$$

slope; symmetry energy ' pressure'



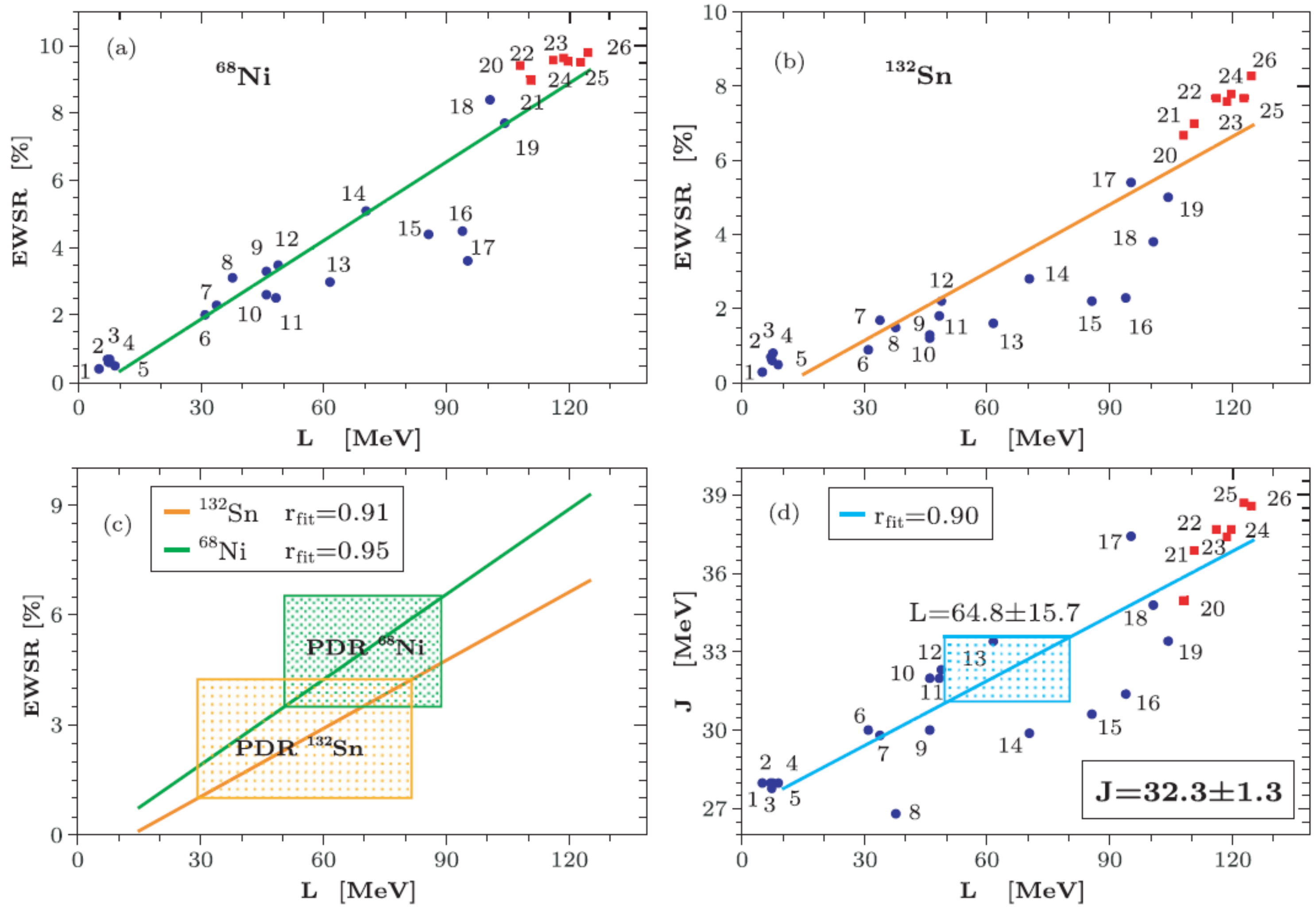
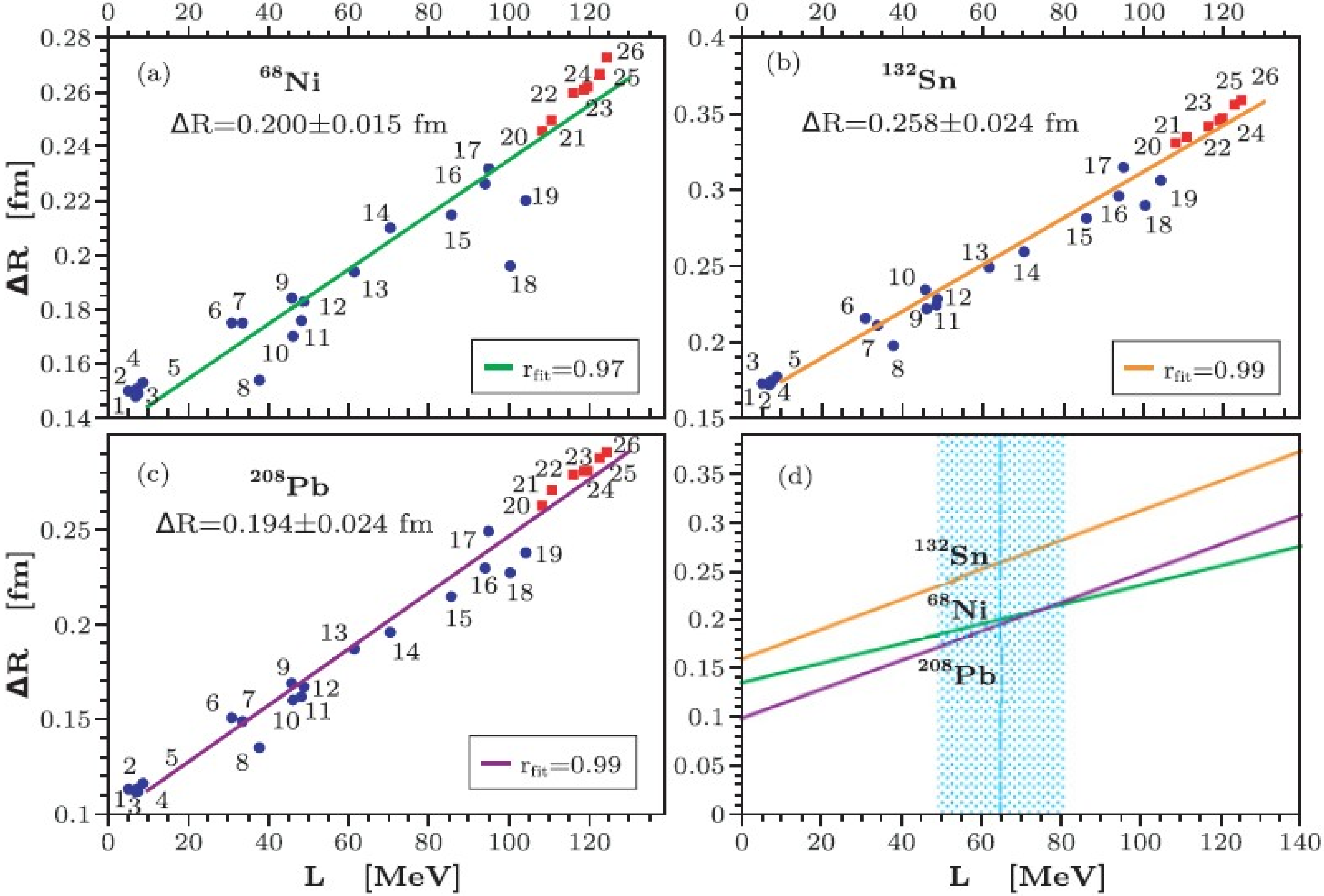
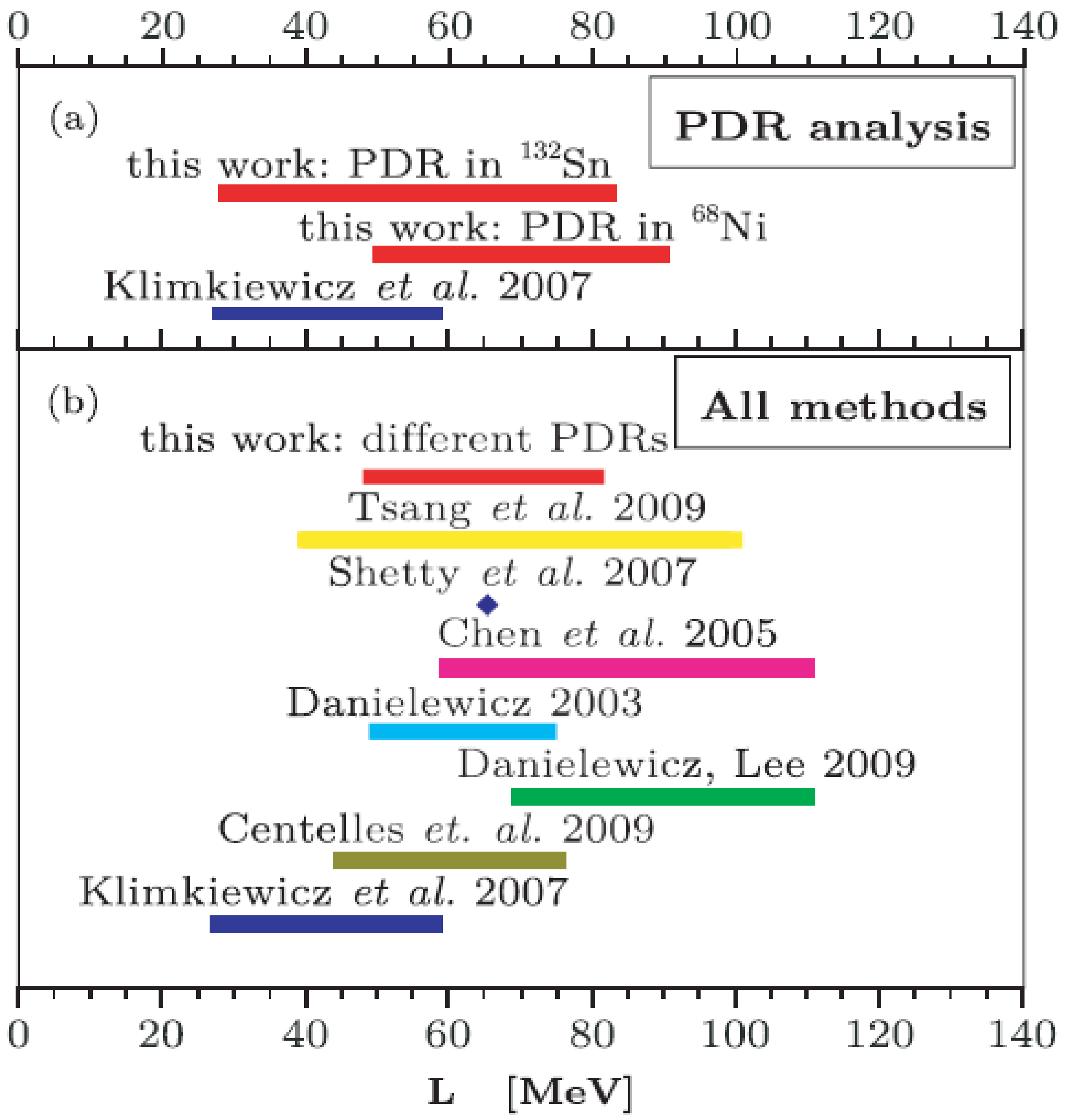


FIG. 2. (Color online) In panels (a) and (b), the correlation between L and the percentage of TRK sum rule exhausted by the PDR in ^{68}Ni and ^{132}Sn, respectively, is displayed. The computed data points are labeled, here and in what follows, by numbers. The correspondence with the parameter sets used is: 1 = v090, 2 = MSk3, 3 = BSk1, 4 = v110, 5 = v100, 6 = SkT6, 7 = SkT9, 8 = SGII, 9 = SkM*, 10 = SLy4, 11 = SLy5, 12 = SLy230a, 13 = LNS, 14 = SkMP, 15 = SkRs, 16 = SkGs, 17 = SK255, 18 = SkI3, 19 = SkI2, 20 = NLC, 21 = TM1, 22 = PK1, 23 = NL3, 24 = NLBA, 25 = NL3+, and 26 = NLE. The straight lines correspond to the results of the fits. In panel (c) we show the same straight lines displayed in (a) and (b), together with the correlation coefficient r and the constraints from the experiments [6,14]. In panel (d) the correlation between L and J is shown. The box corresponds to the value of L deduced from the weighted average of the two values extracted from ^{68}Ni and ^{132}Sn.


(a)
^{68}Ni
ΔR=0.200±0.015 fm
r_{fit}=0.97
(b)
^{132}Sn
ΔR=0.258±0.024 fm
r_{fit}=0.99
(c)
^{208}Pb
ΔR=0.194±0.024 fm
r_{fit}=0.99
(d)
^{132}Sn
^{68}Ni
^{208}Pb
ΔR [fm]
L [MeV]



0 20 40 60 80 100 120 140
(a)
PDR analysis
this work: PDR in 132Sn
this work: PDR in 68Ni
Klimkiewicz et al. 2007
(b)
All methods
this work: different PDRs
Tsang et al. 2009
Shetty et al. 2007
Chen et al. 2005
Danielewicz 2003
Danielewicz, Lee 2009
Centelles et. al. 2009
Klimkiewicz et al. 2007
0 20 40 60 80 100 120 140
L [MeV]

Neutron Star Structure and the Neutron Radius of ^{208}Pb

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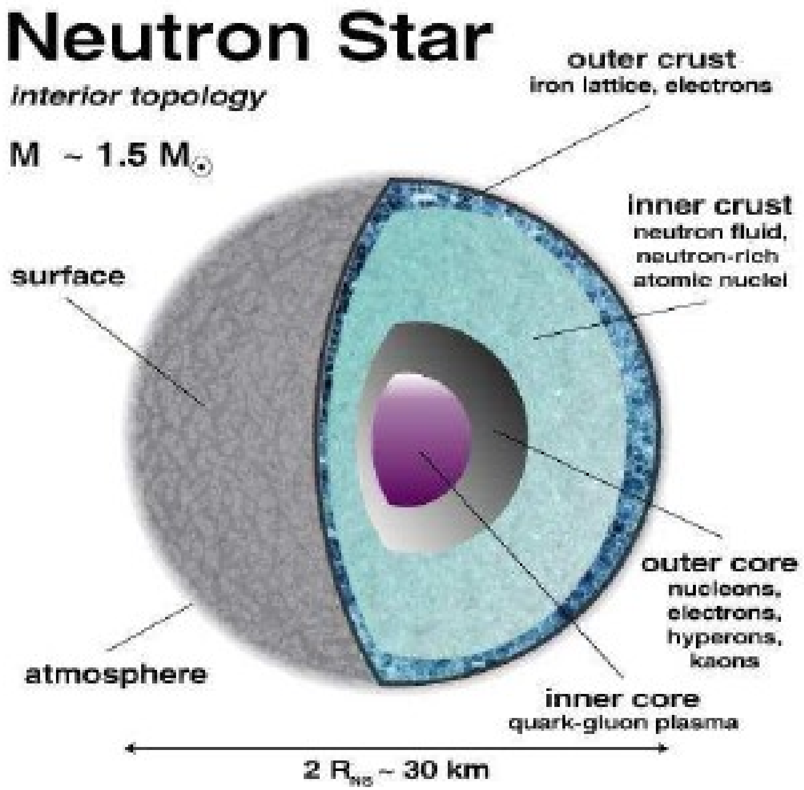
(Received 2 October 2000)

We study relationships between the neutron-rich skin of a heavy nucleus and the properties of neutron-star crusts. Relativistic effective field theories with a thicker neutron skin in ^{208}Pb have a larger electron fraction and a lower liquid-to-solid transition density for neutron-rich matter. These properties are determined by the density dependence of the symmetry energy which we vary by adding nonlinear couplings between isoscalar and isovector mesons. An accurate measurement of the neutron radius in ^{208}Pb—via parity violating electron scattering—may have important implications for the structure of the crust of neutron stars.

see also subsequent papers

Neutron skin in ^{208}Pb vs neutron star



Neutron star ↔ ^{208}Pb

x 10^{18} radius

x 10^{55} weight

Symmetry Energy Pressure

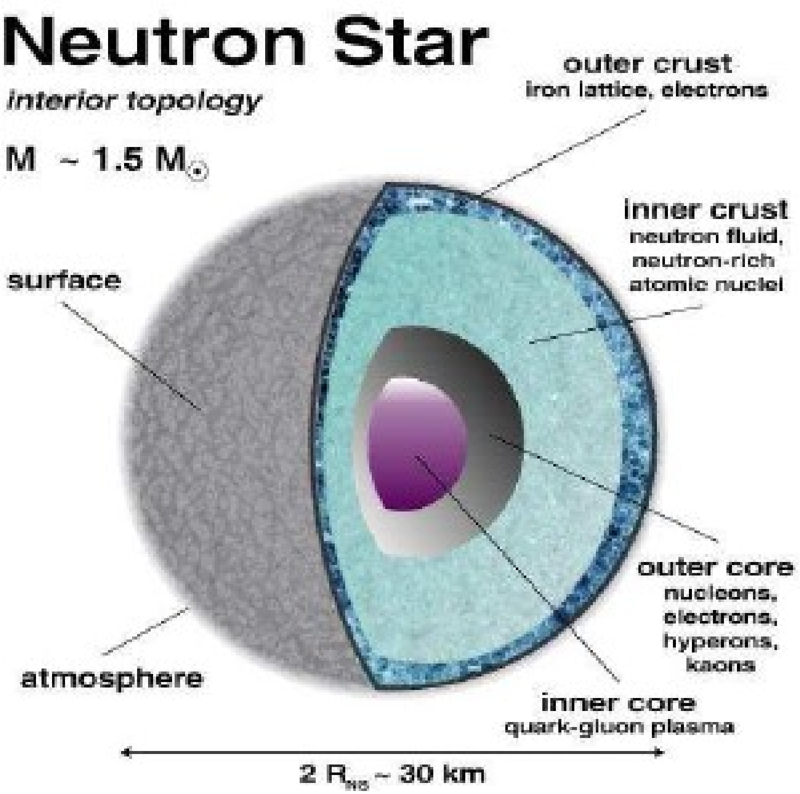
→ drives neutron skin in Pb

→ stabilizes n-star against gravitational collapse

Neutron skin in ^{208}Pb vs neutron star

a_4 = 31.4 ± 0.8 MeV

δr = 0.17 ± 0.02 fm



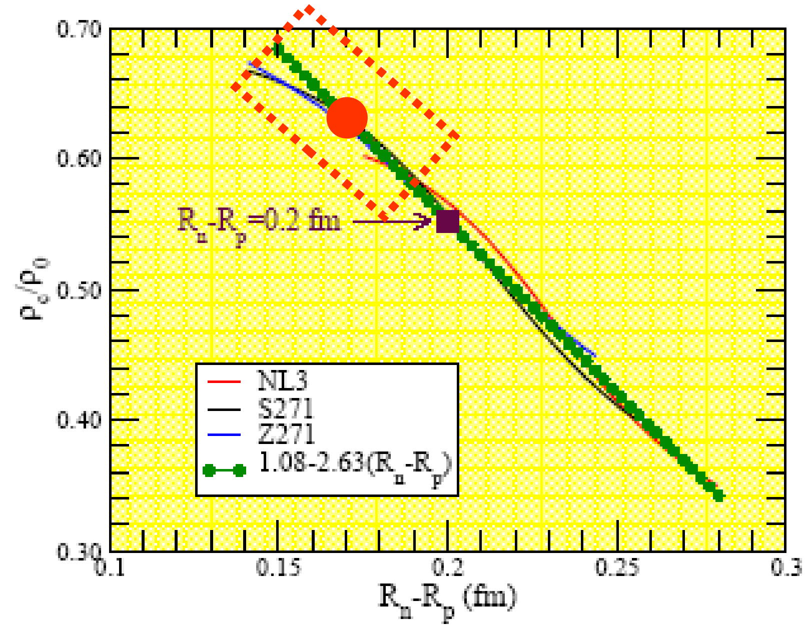


Fig. 4. Transition density from the uniform liquid mantle to the non-uniform solid crust as a function of the neutron skin of ^{208}Pb. Different models are used to show the largely model independent relation between these two observables.

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GSI

Neutron skin in ^{208}Pb vs neutron star

a_4 = 31.4 ± 0.8 MeV

δr = 0.17 ± 0.02 fm

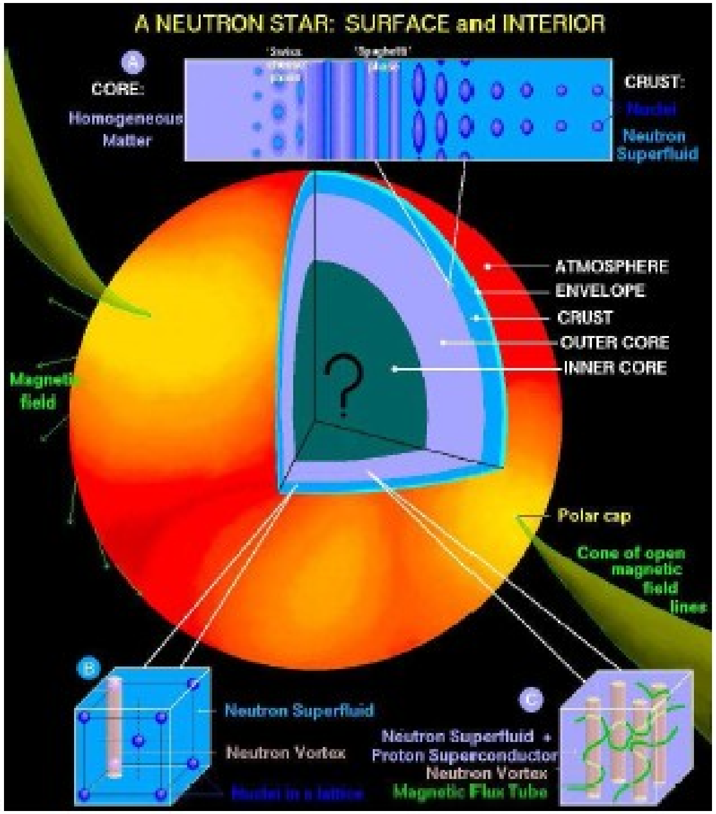

Fig. 3. State-of-the-art rendition of the structure of a neutron star (courtesy of Dany Page).

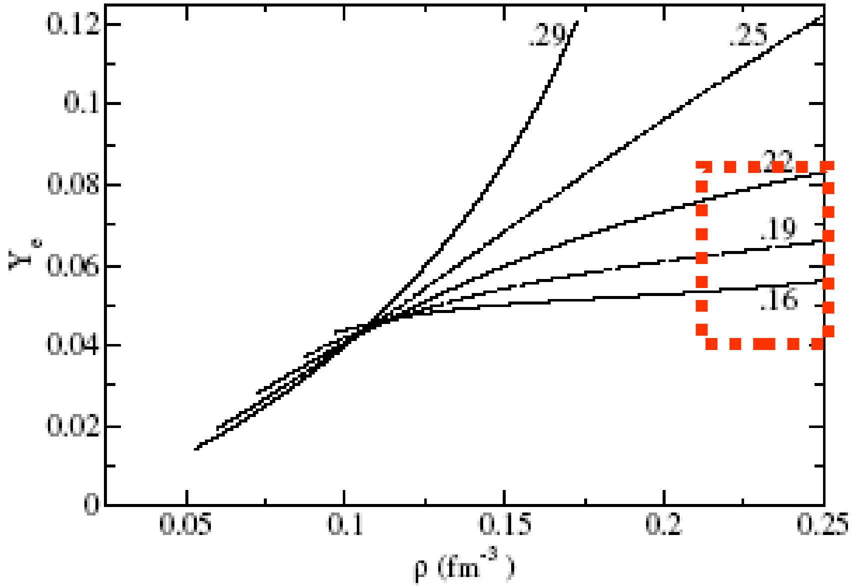

FIG. 2. Electron fraction Y_e versus baryon density for uniform neutron-rich matter in beta equilibrium using the S271 parameter set (other sets yield similar results). The curves are for different values of Λ_v that predict the indicated values of $R_n - R_p$ for ^{208}Pb, in fm.

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systematic studies of skins and pygmy's in more neutron-rich nuclei in the future $\rightarrow$ RIB experiments, for an outlook see tomorrow