Exotic structures in the nuclear dipole spectrum

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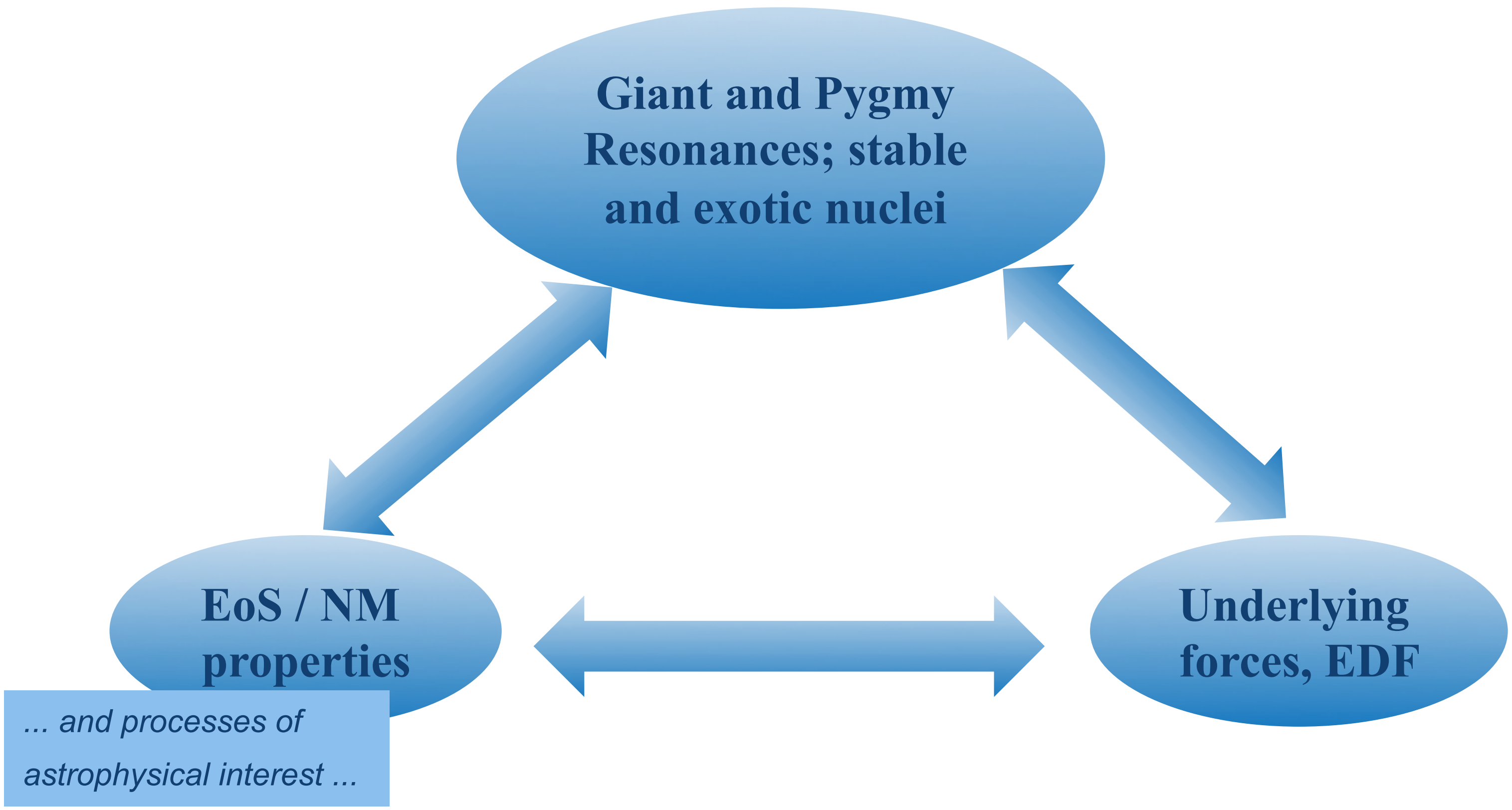
RAON at Science Day

VENI VIDI MANSI

A triangle of interests



Overview

Nuclear photoresponse / dipole response

- ❖ Ordinary and exotic features
- ❖ Focusing on:
  - Pygmy “resonance”
  - Isoscalar dipole response

Theory prospects

Summary

Overview

Nuclear photoresponse / dipole response

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- ❖ Focusing on:
  - Pygmy “resonance”
  - Isoscalar dipole response

mainly medium-mass, heavy neuclei

Theory prospects

Summary

On dipole modes in stable and exotic nuclei

- "*Proton pygmy resonances: predictions for **N=20 isotones***" Y. Kim, P. P., Eur. Phys. J. A 52 (2011) 176
- "*Isoscalar and neutron modes in the E1 spectra of **Ni isotopes** and the relevance of shell effects and the continuum*" P. P., H. Hergert, R. Roth, Phys. Rev. C 92 (2015) 034311
- "*Low-energy electric dipole response of **Sn isotopes***" P.P., H.Hergert, V.Yu.Ponomarev, R.Roth, Phys. Rev. C 89 (2014) 034306
- "*Isospin properties of electric dipole excitations in 48**Ca***" V.Derya et al., Phys. Lett. B 730 (2014) 288
- "*Low-energy dipole strength and the critical case of 48**Ca***" P.P., H.Hergert, V.Yu.Ponomarev, R.Roth, Phys. Lett. B 709 (2012) 270
- "*Isoscalar dipole coherence at low energies and forbidden E1 strength*" P.P., V.Yu.Ponomarev, R.Roth, J.Wambach, Eur. Phys. J. A 47 (2011) 14

On dipole modes in stable and exotic nuclei

RAON

- "*Proton pygmy resonances: predicti*... *0 isotones*" ... Kim, P. P., Eur. Phys. J. A 52 (2011) 176
- "*Isoscalar and ne*... *the E1 sp*... *es and the relevance of* ... *the cont*... ergert, R. Roth, Phys. R... 034311
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- ... *energy di*... *tical case of 48**Ca***" P.P., H.Hergert, V.Yu.Pon... Lett. B 709 (2012) 270
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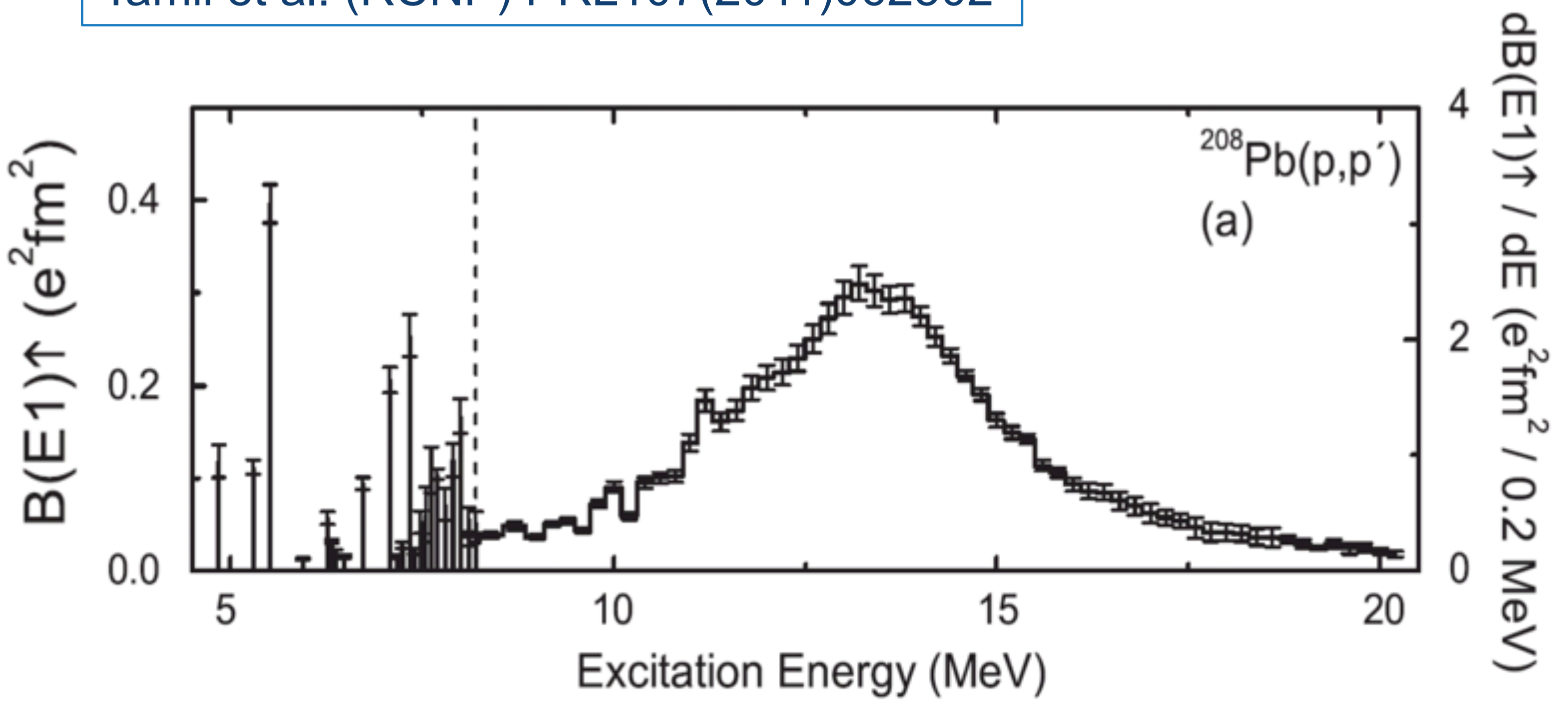
Summary:
P.P., EXON2016 Proceedings [ResearchGate]

HF(B)+(Q)RPA non-relativistic (Gogny, Skyrme)
+ data

Summary:
P.P., JPS Conf. Proc. 6 (2015) 030094
(arxiv:1408.0894)

Electric dipole spectrum of 208Pb

Tamii et al. (RCNP) PRL107(2011)062502



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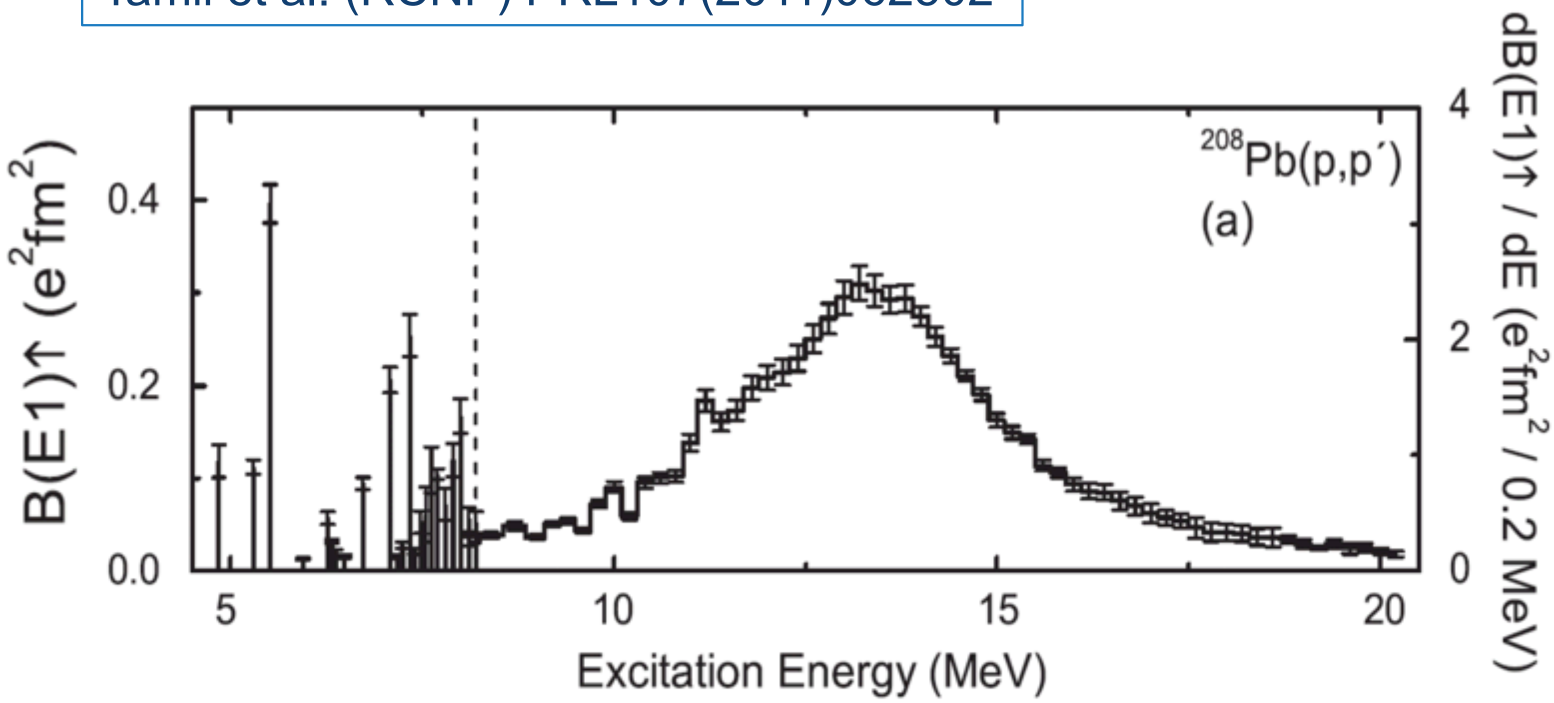

$\int \sigma_\gamma(E)dE$ nucleon forces

TRK sum

$\int \frac{\sigma_\gamma(E)}{E^2}dE$ polarizability

cf P.G.Reinhard,W.Nazarewicz, PRC87,014324
(but also: X. Roca-Maza et al., PRC92, 064304)

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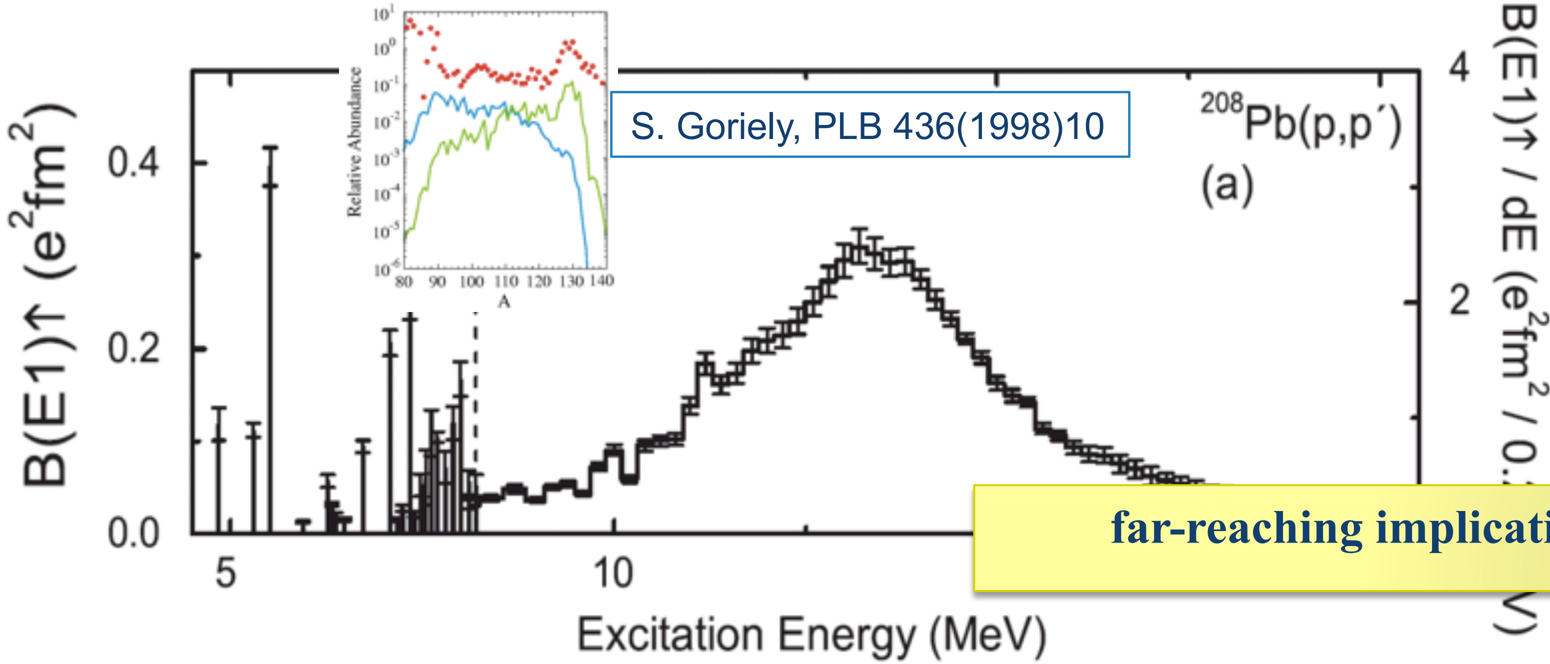


S. Goriely, PLB 436(1998)10

far-reaching implications

$\int \sigma_\gamma(E)dE$ nucleon forces

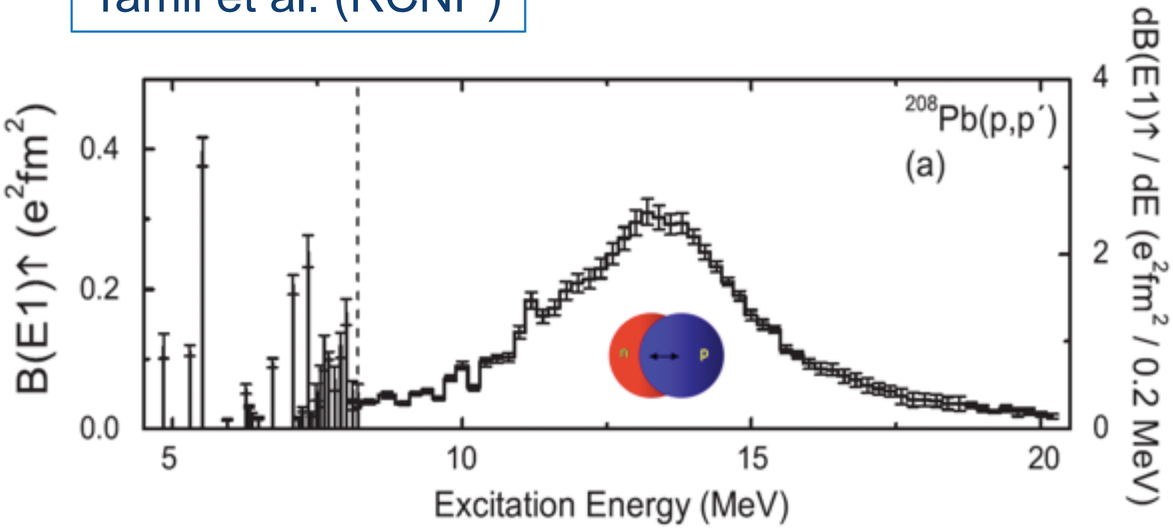
TRK sum

$\int \frac{\sigma_\gamma(E)}{E^2}dE$ polarizability

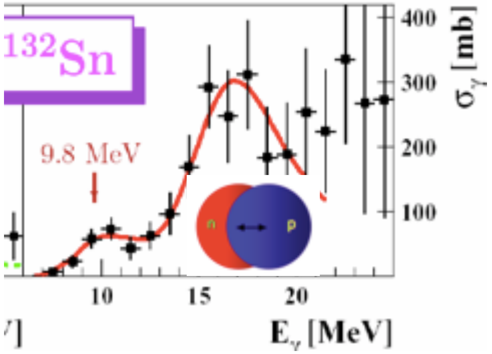
cf P.G.Reinhard,W.Nazarewicz, PRC87,014324
(but also: X. Roca-Maza et al., PRC92, 064304)

Stable vs exotic nuclei

Tamii et al. (RCNP)



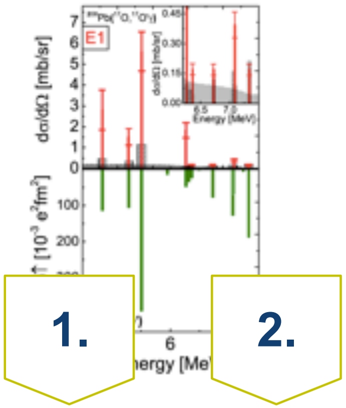
Adrich et al. (GSI)

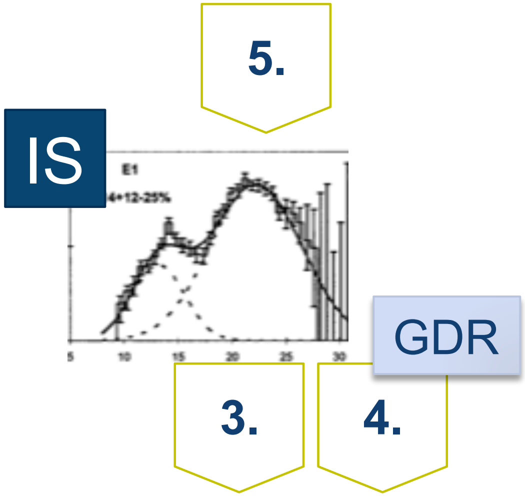


Variety of experimental methods

- Nuclear resonance fluorescence
- Coulomb excitation incl. inverse kinematics
- Alpha scattering
- Proton scattering
- Gamma-ray spectroscopy following beta decay
- ...

Electric dipole spectrum of ^{208}Pb

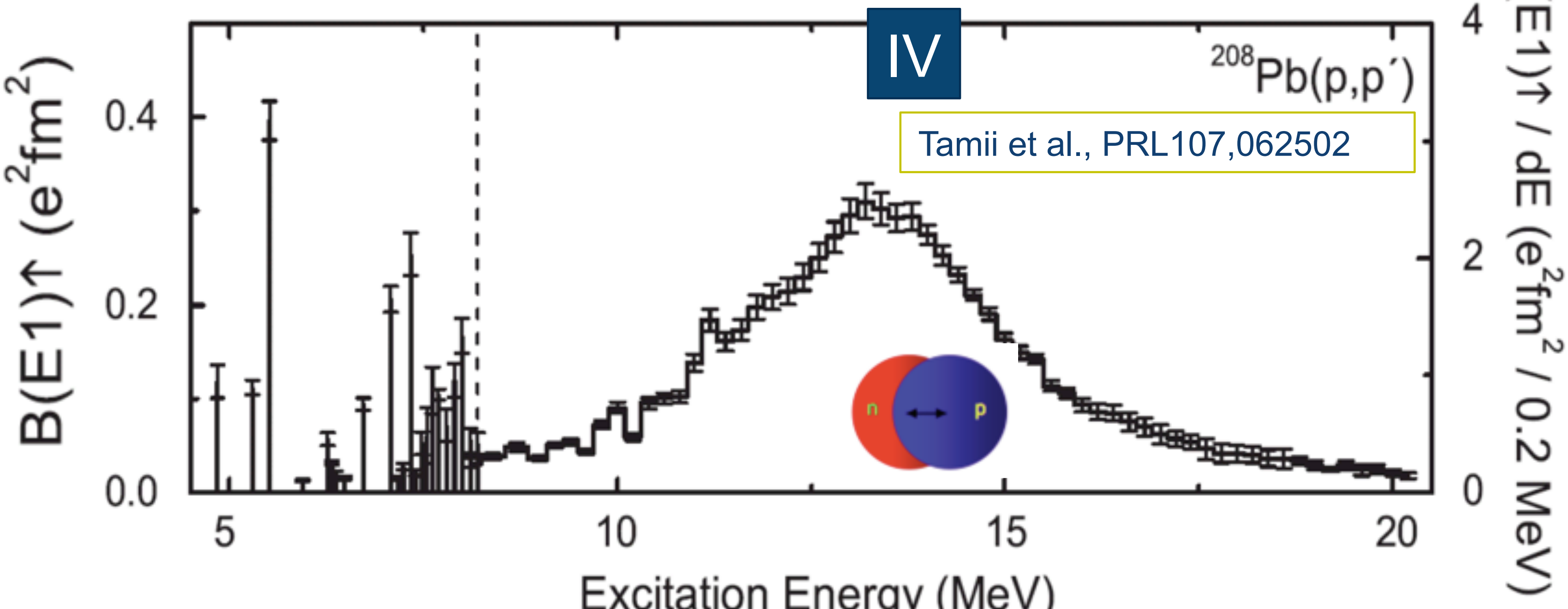




1,2: Tamii et al.,PRL107(2011)062502
Crespi et al.,PRL 113(2014)012501
Poelhakken et al., PLB278(1992)423

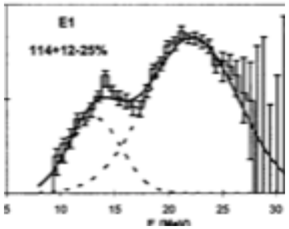
3: Youngblood et al.,PRC69(2004)034315

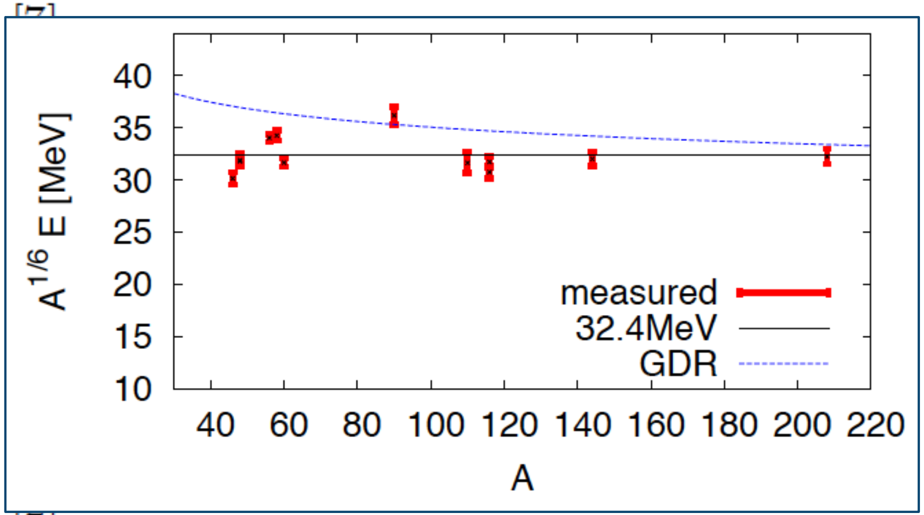
4: GDR (here: Tamii et al.)
5: IS GDR , see 3.



Isoscalar resonance near the GDR

Nucleus	$\frac{N-Z}{A}$	Energy [MeV]	% EWSR	Reference
^{24}Mg	0	[$\tilde{1}$2.5]		[6]
^{46}Ti	0.043	15.94 ± 0.31		[5]
^{48}Ti	0.083	$16.75^{+0.31}_{-0.28}$		[5]
^{48}Ca	0.167	$16.69^{+0.19}_{-0.13}$	20^{+12}_{-8}	
^{56}Fe	0.071	17.41 ± 0.20		
^{58}Ni	0.034	17.42 ± 0.25		
^{60}Ni	0.067	16.01 ± 0.20		
^{90}Zr	0.111	17.1 ± 0.4	13 ± 3	
^{110}Cd	0.127	$14.47^{+0.47}_{-0.44}$		
^{116}Cd	0.172	$13.94^{+0.30}_{-0.26}$		
^{116}Sn	0.138	14.38 ± 0.25	25 ± 15	
^{144}Sm	0.138	14.00 ± 0.30	32 ± 15	
^{208}Pb	0.211	13.26 ± 0.30	24 ± 15	

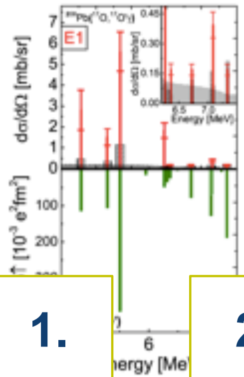


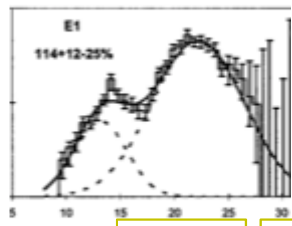


Experiments are quite ahead of theory...

Electric dipole spectrum of ^{208}Pb

5.





GDR

1. 2. 3. 4.

1,2: Tamii et al.,PRL107(2011)062502
Crespi et al.,PRL 113(2014)012501
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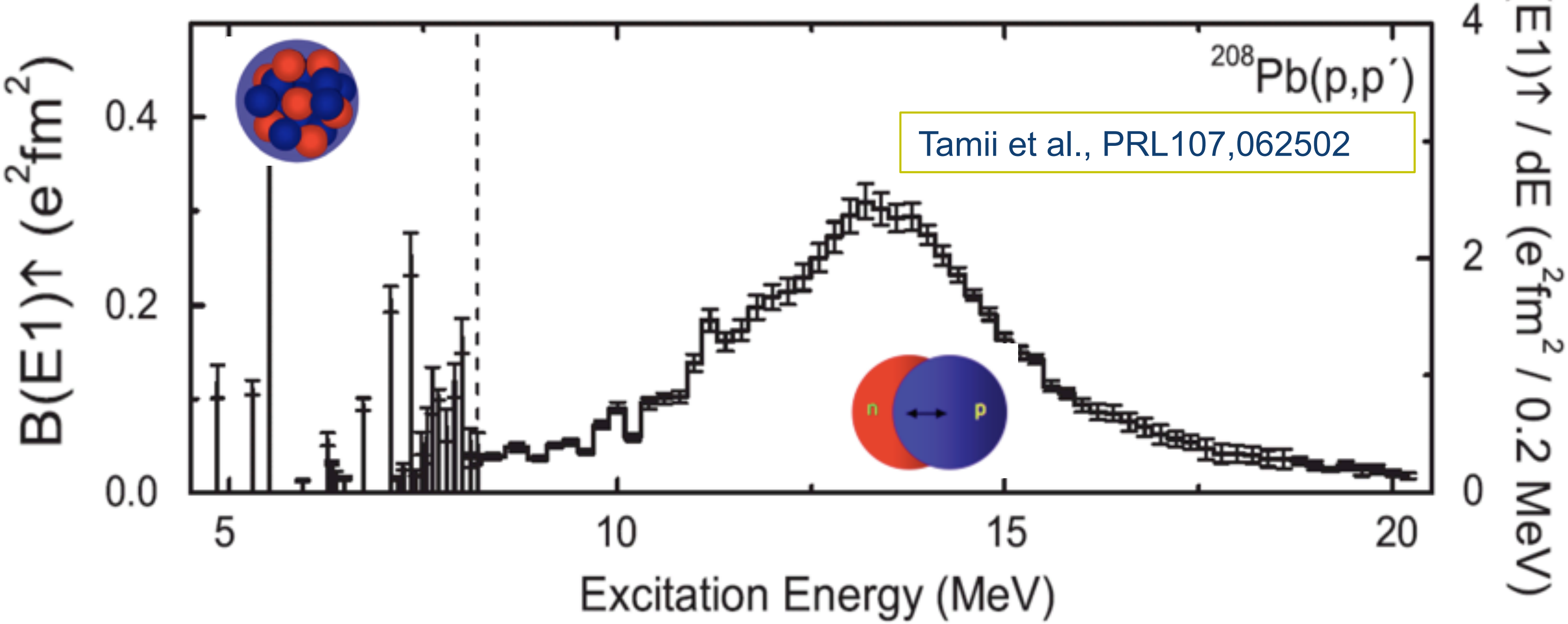
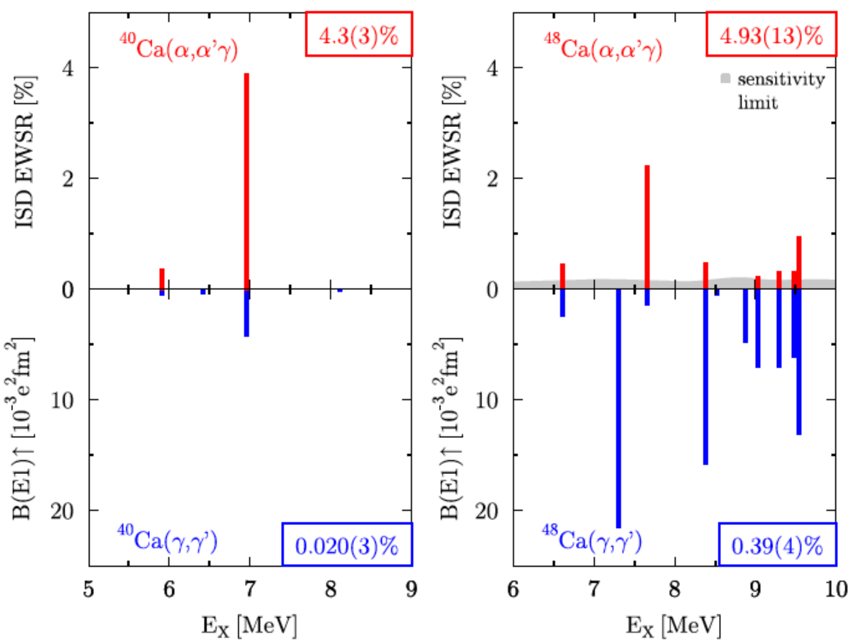


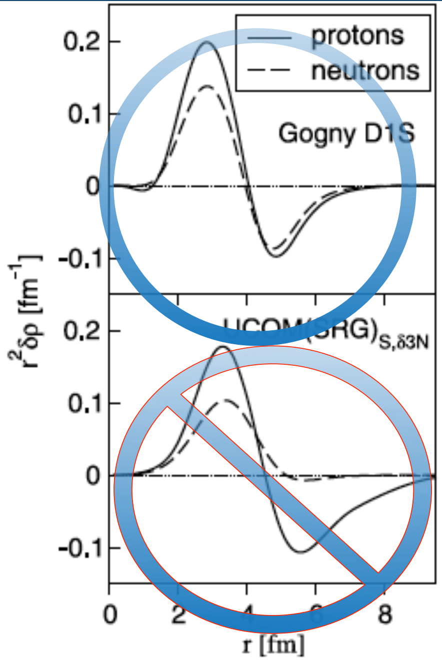
Low-energy dipole response of ^{40}Ca, ^{48}Ca

- Strong IS transitions (4-5% EWSR) below 9MeV
- **Weak E1 channel** despite large asymmetry of ^{48}Ca
- Reproduced, e.g., by the Gogny D1S interaction

V.Derya et al., PLB730,288



PP et al., PLB709,270



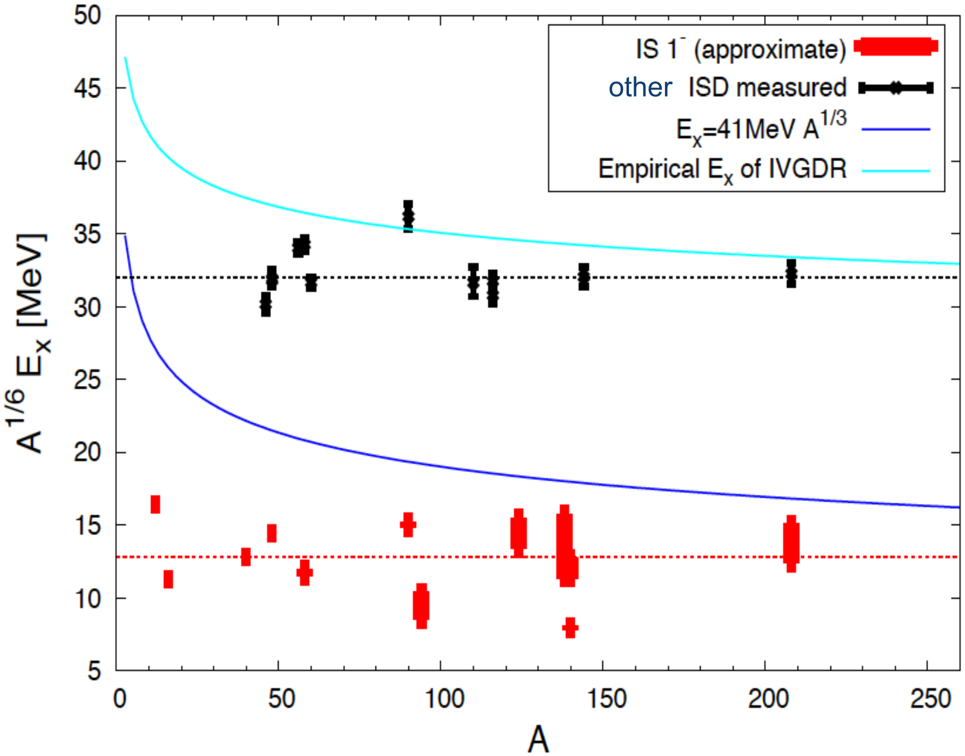
Some kind of toroidal/diffuseness oscillation

- E ~ 6-7 MeV
- B(E1)<<1W.u.

Data for IS dipole transitions from:
- Savran et al., Derya et al., Crespi et al., Poelhekken et al.,Harakeh et al

Theoretical investigations:
- [PP, H.Hergert, V.Yu.Ponomarev, R.Roth, J.Wambach + exp]:

N=Z
Ca
Sn
Ni
N=20



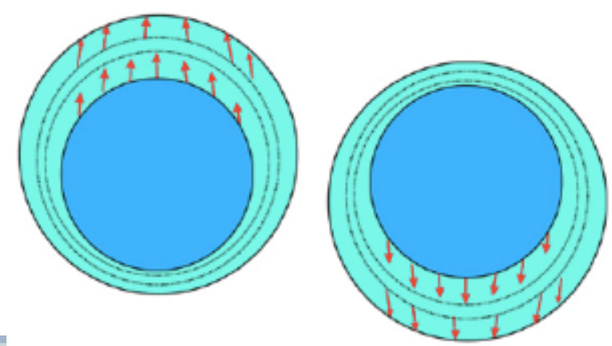


Image:PLB664,258

Electric dipole spectrum of ^{208}Pb

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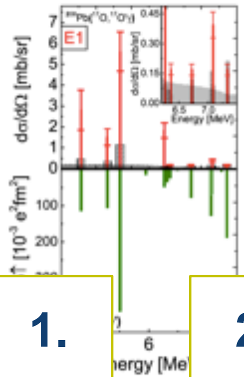
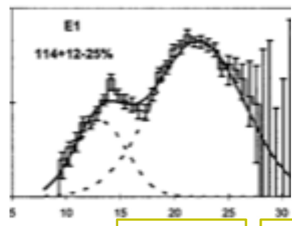




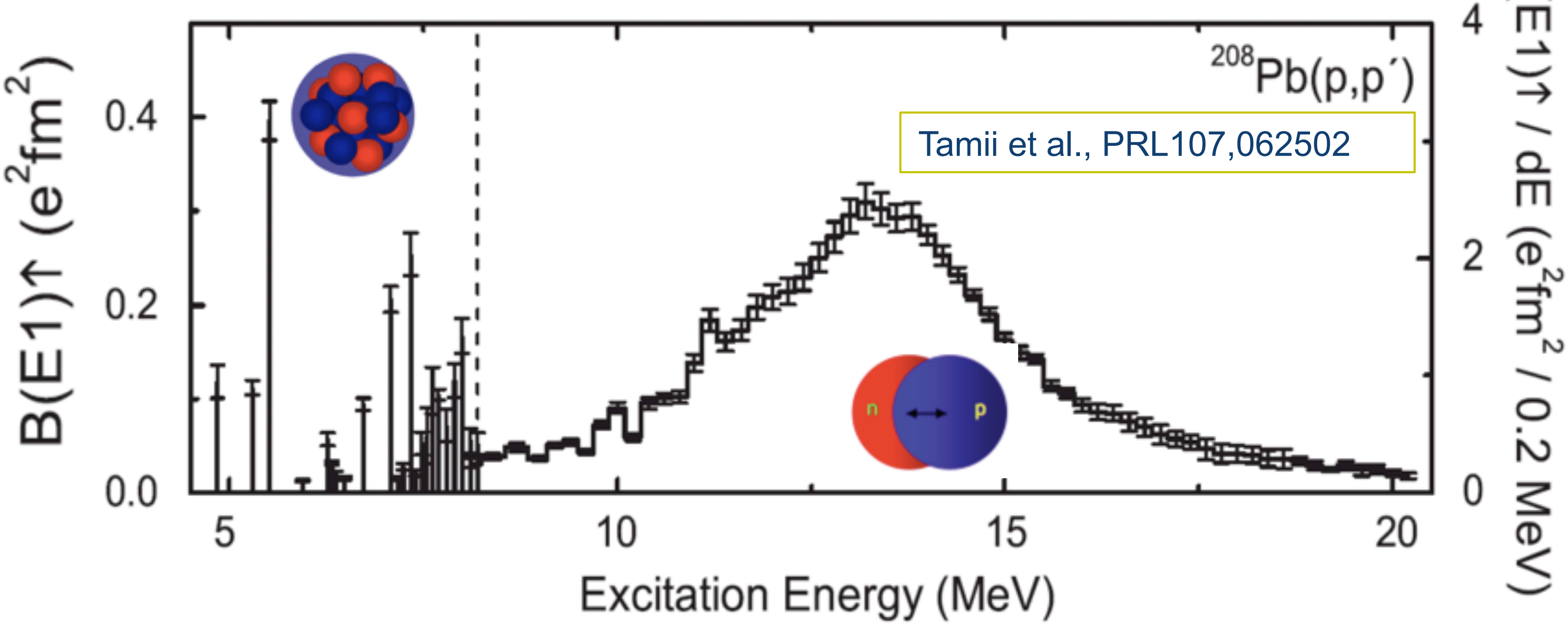
GDR

1.

2.

3.

4.



Importance of loose binding

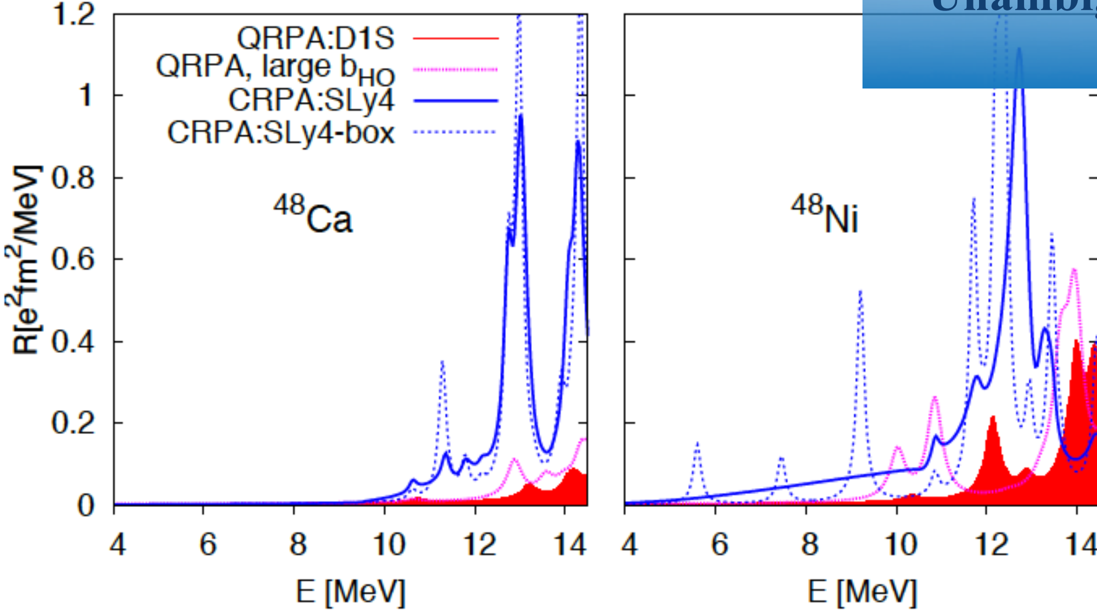
- Neutrons or protons near the Fermi surface

- Examples:
  - N=20 isotones and their mirror Ca isotopes
  - Shell closures in Ni, Ca, Sn isotopes

Proton-rich nuclei and their stable mirrors

Y.Kim,P.P, EPJA52(2016)176

Pygmies in the mirror: Unambiguous role of loose binding



	$B_{s.p}$	$B(E_1)$	$\sum_{E_i<13} B(E_i)$	$\sum_{E_i<15} B(E_i)$	$\sum_{E_i<17} B(E_i)$	$\|R_p - R_n\|$
^{40}Ca	0.188	0.004	0.008	0.117	0.179	0.042
^{42}Ti	0.177	0.008	0.116	0.249	0.361	0.106
^{44}Cr	0.166	0.009	0.189	0.320	0.576	0.159
46Fe	0.156	0.008	0.251	0.421	0.835	0.207
^{48}Ni	0.148	0.009	0.161	0.553	1.211	0.249
46Ca	0.156	0.003	0.050	0.149	0.443	0.108
^{48}Ca	0.148	0.006	0.006	0.089	0.763	0.145

candidate for proton-skin oscillation

Polarizability and shell structure in Ni

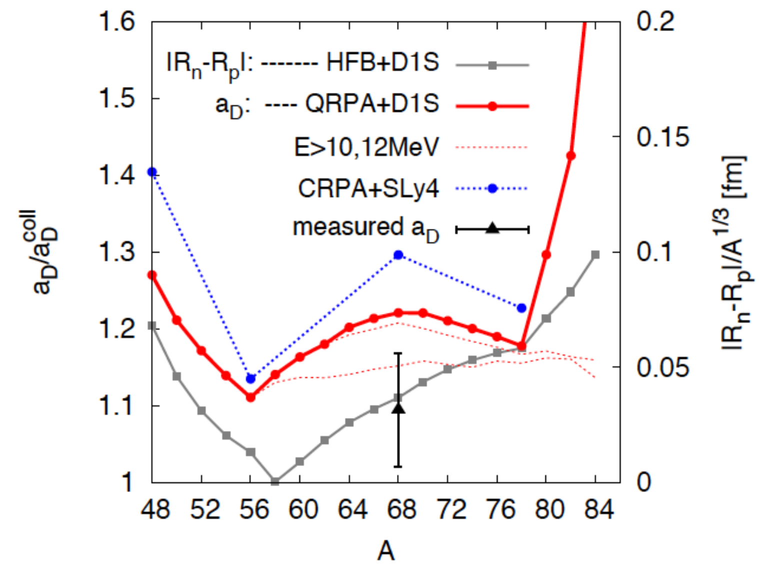
PP,H.Hergert, R.Roth, PRC92(2015)034311

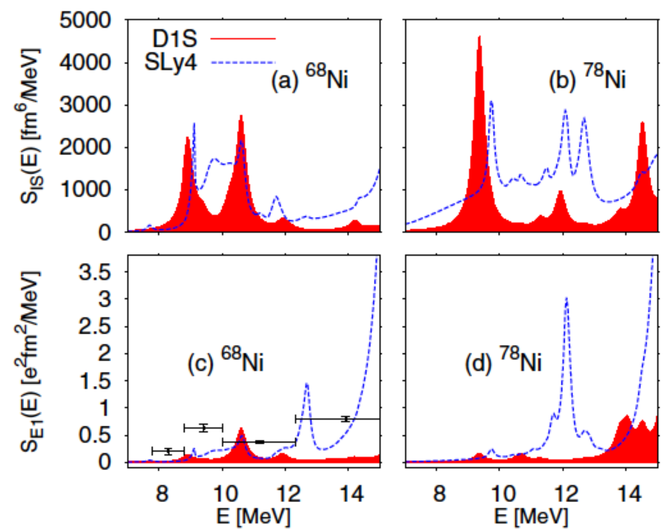
$$a_{\mathrm{D}} = \frac{\hbar c}{2\pi^2} \int \frac{\sigma_{\mathrm{abs}}}{\omega^2} d\omega$$

Reference value: assuming 100% GDR

$$a_D^{\mathrm{coll}} = \frac{\hbar c}{2\pi^2} \frac{60 N Z \mathrm{MeV mb}}{A E_{\mathrm{GDR}}^2}$$

$$E_{\mathrm{GDR}} = (31.2 A^{-1/3} + 20.6 A^{-1/6})\ \mathrm{MeV}$$



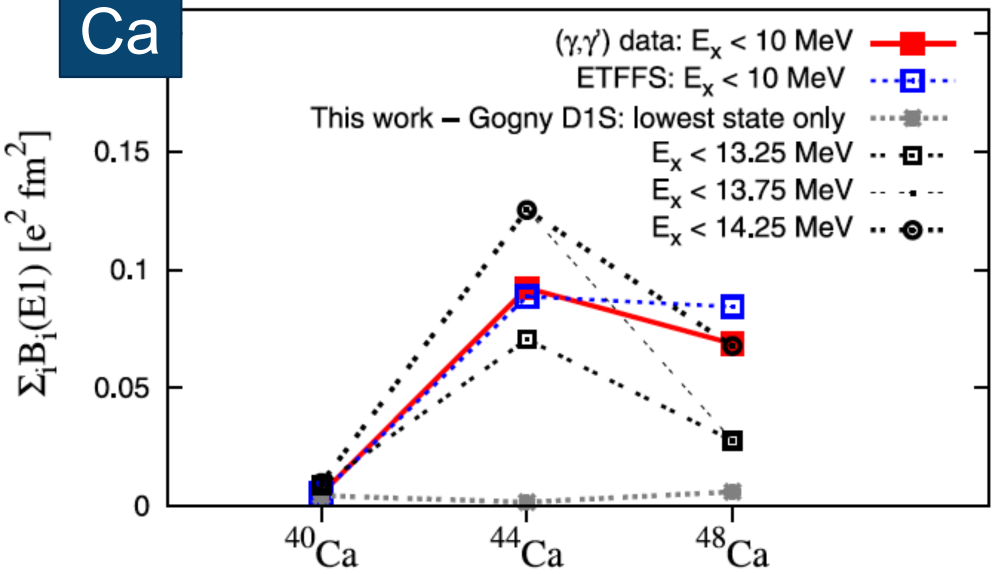


Measurement: D.Rossi et al., PLR 111,242503

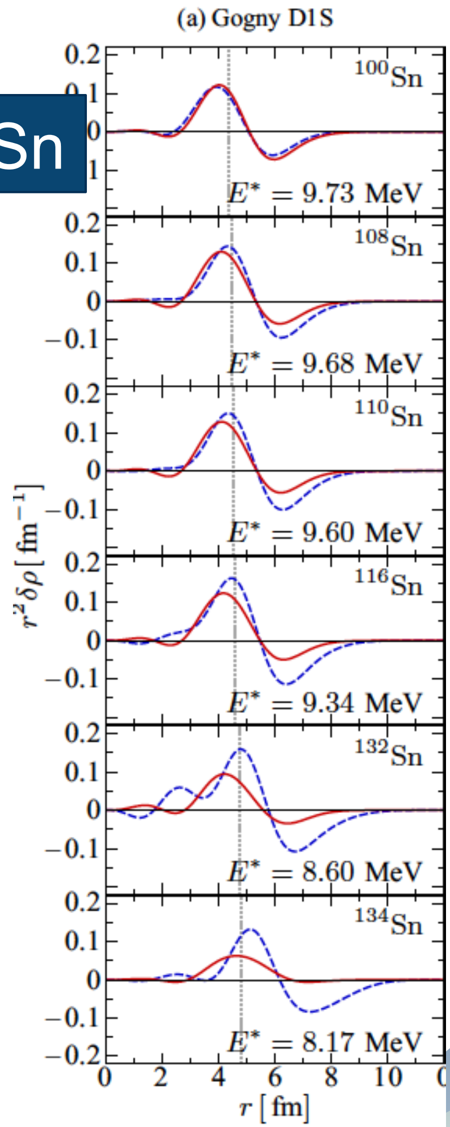
Shell structure in Ca, Sn

Weak transitions and apparent shell effect; strong neutron transitions predicted only beyond the N=28 closure

Ca

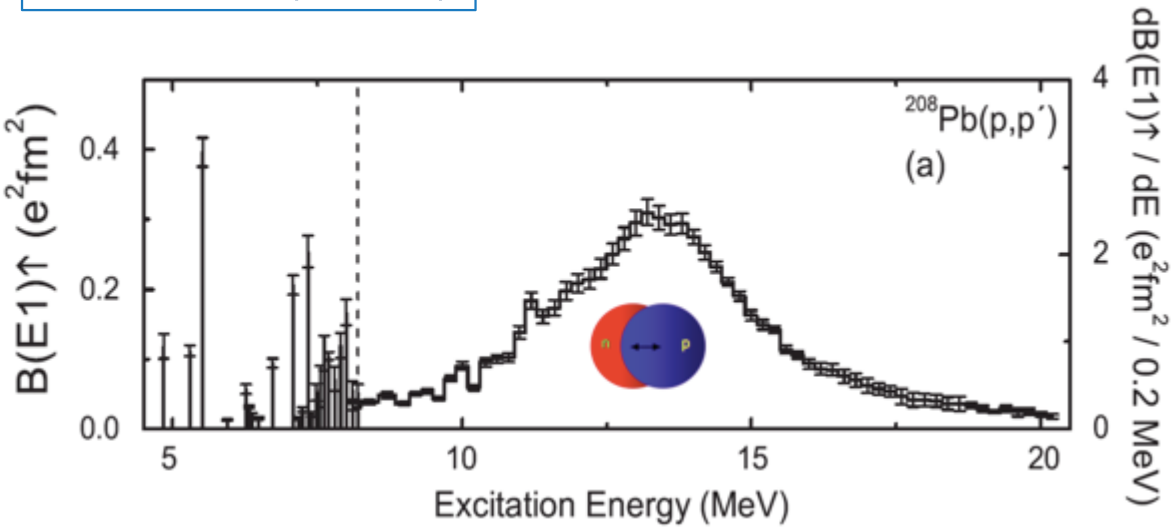


Sn

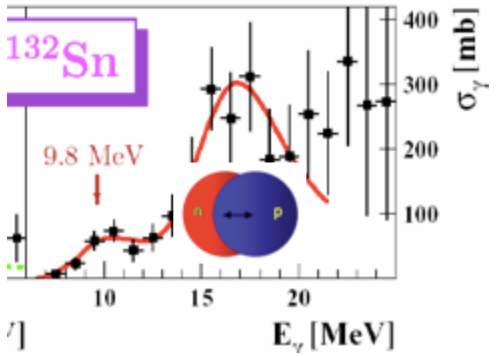


Dipoles outlook

Tamii et al. (RCNP)



Adrich et al. (GSI)



The dipole spectrum contains **a wealth of structure information** with several implications

- GDR, lowest isoscalar state: universal features
- *Neutron/proton skin modes: in very exotic nuclei or above 8-9 MeV (or both)*
- Other isoscalar resonance?
- Data on stable nuclei so far favor asysoft models
- Finite-system peculiarities must be taken into account – separation energy
- Dramatic effects at shell closure

Measurements on either side of a shell closure?

Proton pygmy resonance?

Overview

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Theory prospects

Summary

Roughly two approaches

- Given interaction + many-body method
  - Variational reference state + Equations of Motion
  - To lowest order, HF+RPA
  - Systematic inclusion of correlations / mp-mh until convergence

> - *"Wave-function approach"*
> - *Known Hamiltonian*

- Energy-density functionals + linear-response theory

> - *Kohn-Sham EDFT*
> - *E[ρ,...] known; Hamiltonian not necessarily known*
> - *"black box"*

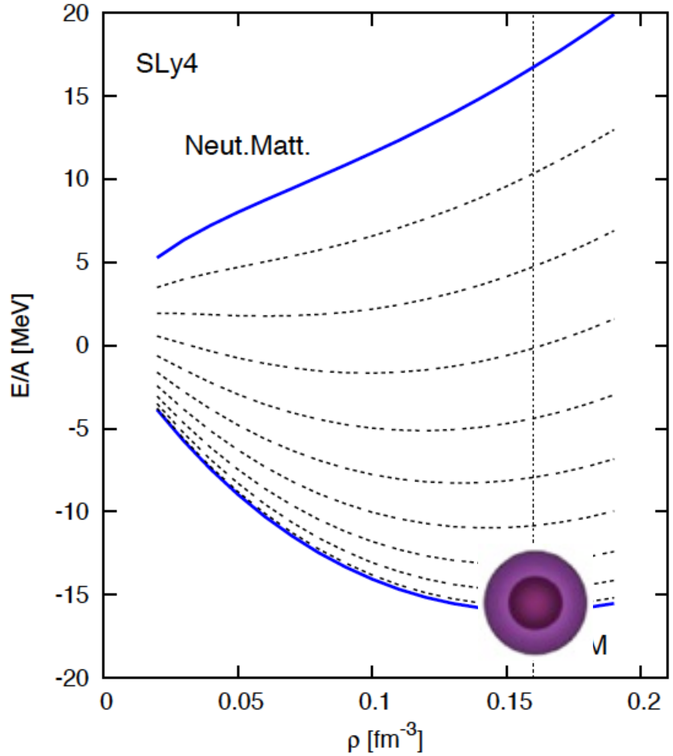
  - The order of truncation depends on the application

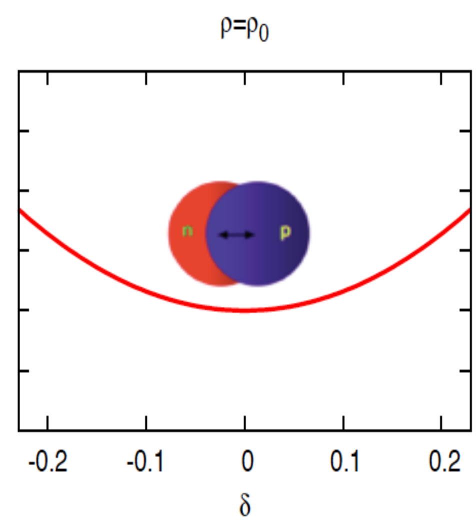
$$\frac{E}{A}(\rho,\delta^2) = \left(\frac{E}{A}\right)_{\rho=\rho_0} + \frac{(\rho-\rho_0)^2}{18}\left(\frac{\partial^2(E/A)}{\partial\rho^2}\right)_{\rho=\rho_0} + \frac{\delta^2}{2}\left(\frac{\partial^2(E/A)}{\partial\delta^2}\right)_{\delta=0}$$

K

J

absolute values vs. derivatives





Energy density functional for KIDS

❖ KIDS = Korea: IBS - Daegu – Sungkyunkwan

Ansatz

EFT/QMBT: powers of Fermi momentum

$$\mathcal{E}(\rho,\delta) = \frac{E(\rho,\delta)}{A} = \mathcal{T}(\rho.\delta) + \sum_{i=0}^{3} c_i(\delta)\rho^{1+i/3} + c_{\ln}(\delta)\rho^2 \ln[\rho/(1\mathrm{fm}^3)]$$

kinetic energy:

$$\mathcal{T} = \mathcal{T}_p + \mathcal{T}_n \,;\, \mathcal{T}_{p,n} = \frac{3}{5}\frac{\hbar^2}{2m_{p,n}} x_{p,n}^{5/3}(3\pi^2\rho)^{2/3} \,;\, x_{p,n} \equiv \rho_{p,n}/\rho$$

asymmetry:

$$c_k(\delta) = \alpha_k + \delta^2\beta_k$$

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

correspondence with Skyrme

Nuclear potential	Order	KIDS parameter	Skyrme parameter
$\mathcal{E}_0$	k_F^3	$c_0(\delta)$	(t_0, x_0)
$\mathcal{E}_1$	k_F^4	$c_1(\delta)$	$(t_3, x_3), \alpha = 1/3$
$\mathcal{E}_2$	k_F^5	$c_2(\delta)$	$(t_1, x_1), (t_2, x_2), (t_3', x_3'), \alpha' = 2/3$
$\mathcal{E}_3$	k_F^6	$c_3(\delta)$	$(t_3'', x_3''), \alpha'' = 1$

Ansatz

EFT/QMBT: powers of Fermi momentum

$$\mathcal{E}(\rho,\delta) = \frac{E(\rho,\delta)}{A} = \mathcal{T}(\rho.\delta) + \sum_{i=0}^{3} c_i(\delta)\rho^{1+i/3} + c_{\ln}(\delta)\rho^2 \ln[\rho/(1\mathrm{fm}^3)]$$

kinetic energy: $$\mathcal{T} = \mathcal{T}_p + \mathcal{T}_n \,;\, \mathcal{T}_{p,n} = \frac{3}{5}\frac{\hbar^2}{2m_{p,n}} x_{p,n}^{5/3}(3\pi^2\rho)^{2/3} \,;\, x_{p,n} \equiv \rho_{p,n}/\rho$$

asymmetry: $$c_k(\delta) = \alpha_k + \delta^2\beta_k$$

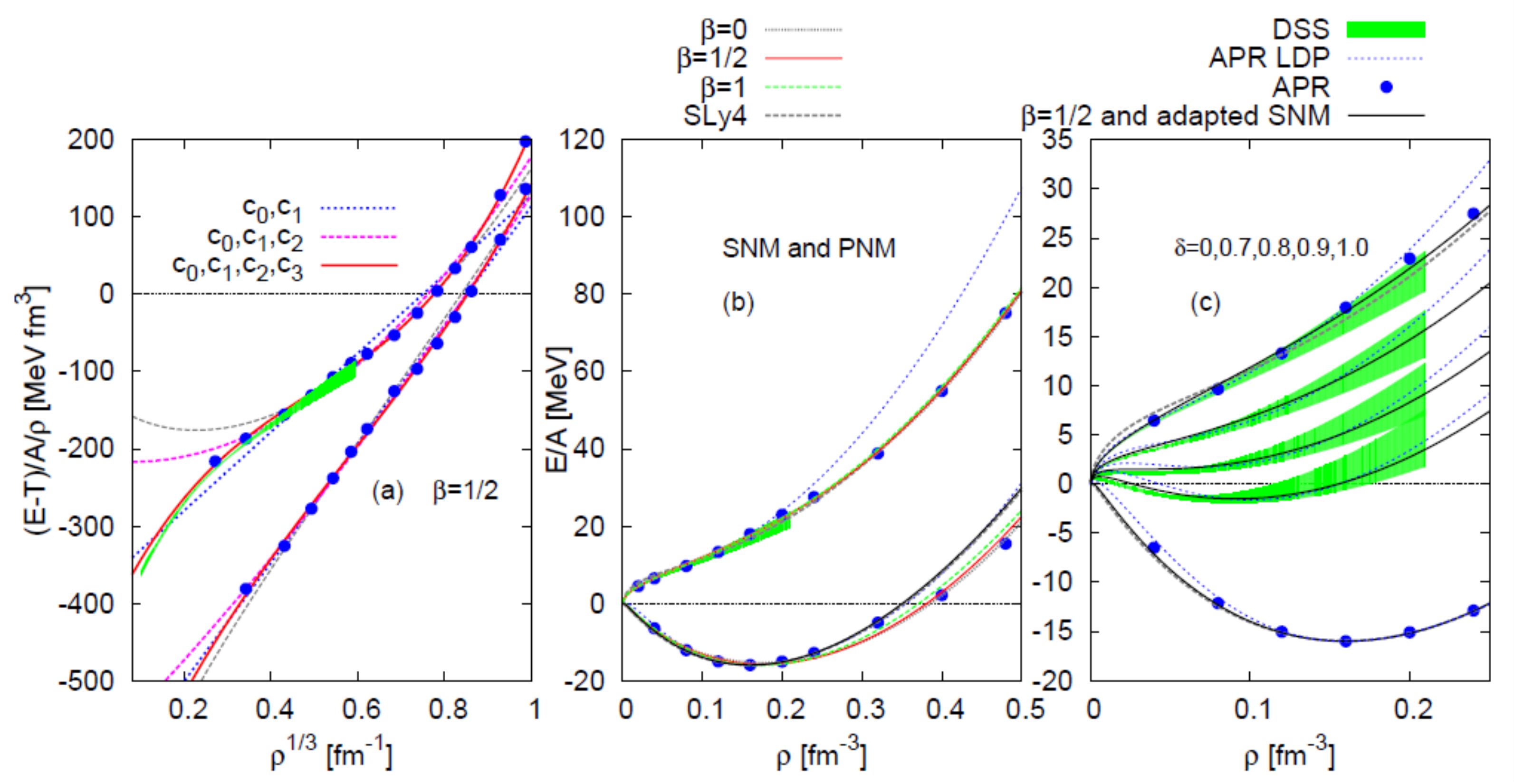
$$\delta = (\rho_n - \rho_p)/\rho$$

parameters: from fits to (pseudo-)data on homogeneous matter

microscopic calculations of symmetric and neutron matter

Results

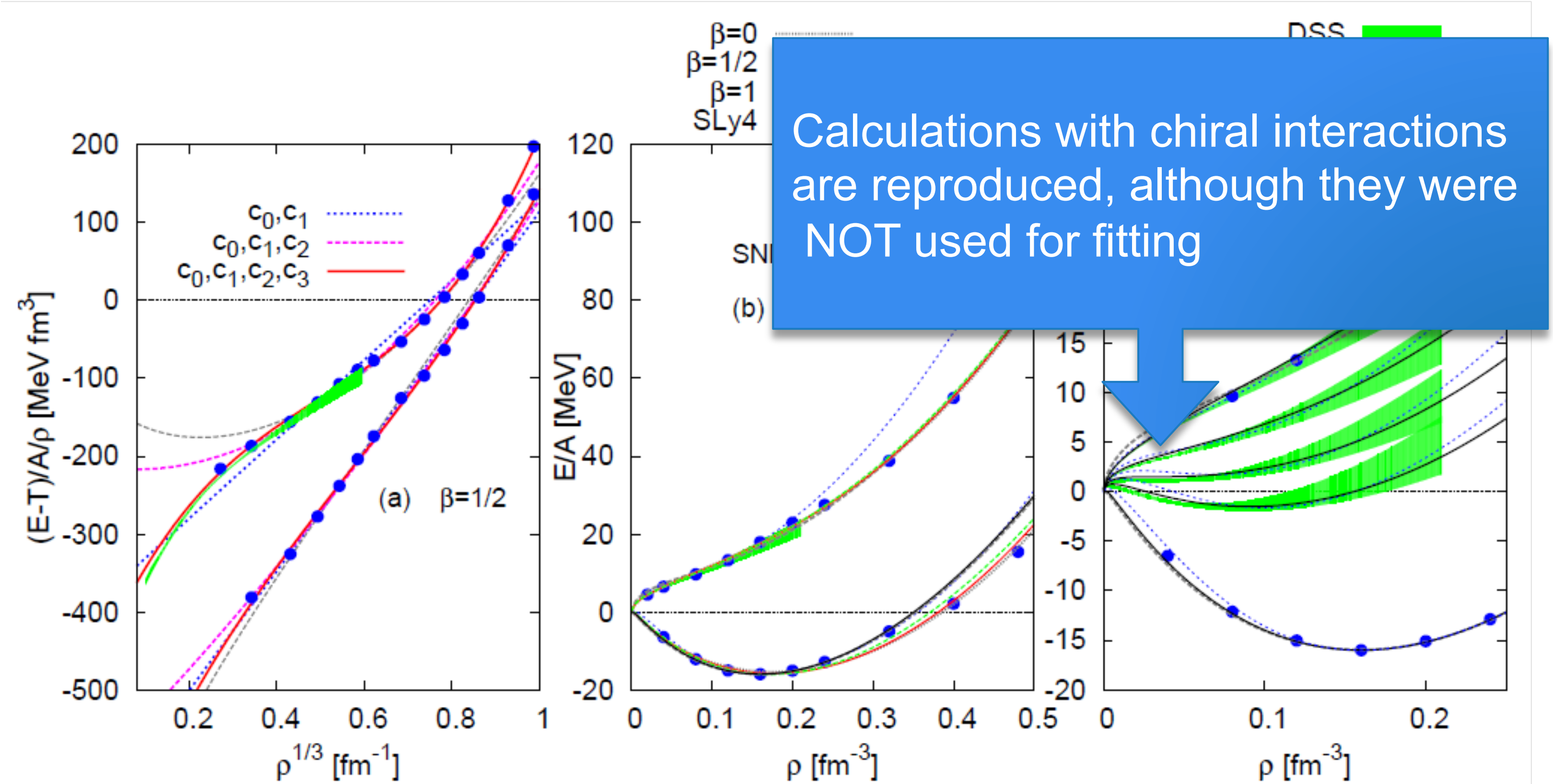
PP,Park,Lim,Hyun,arXiv:1606.04219



β: controls the weight we put on the lower-density data

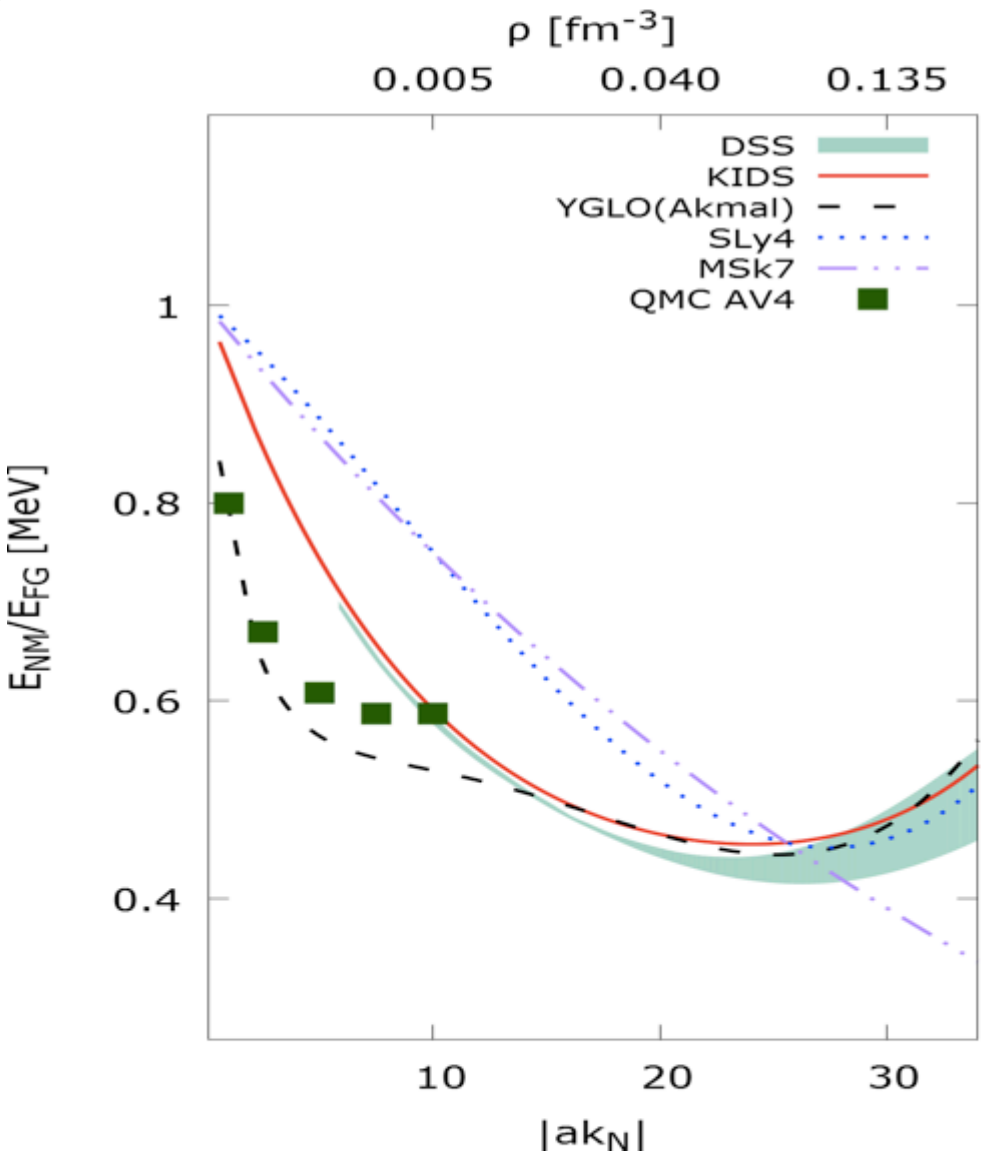
Results

PP,Park,Lim,Hyun,arXiv:1606.04219



β: controls the weight we put on the lower-density data

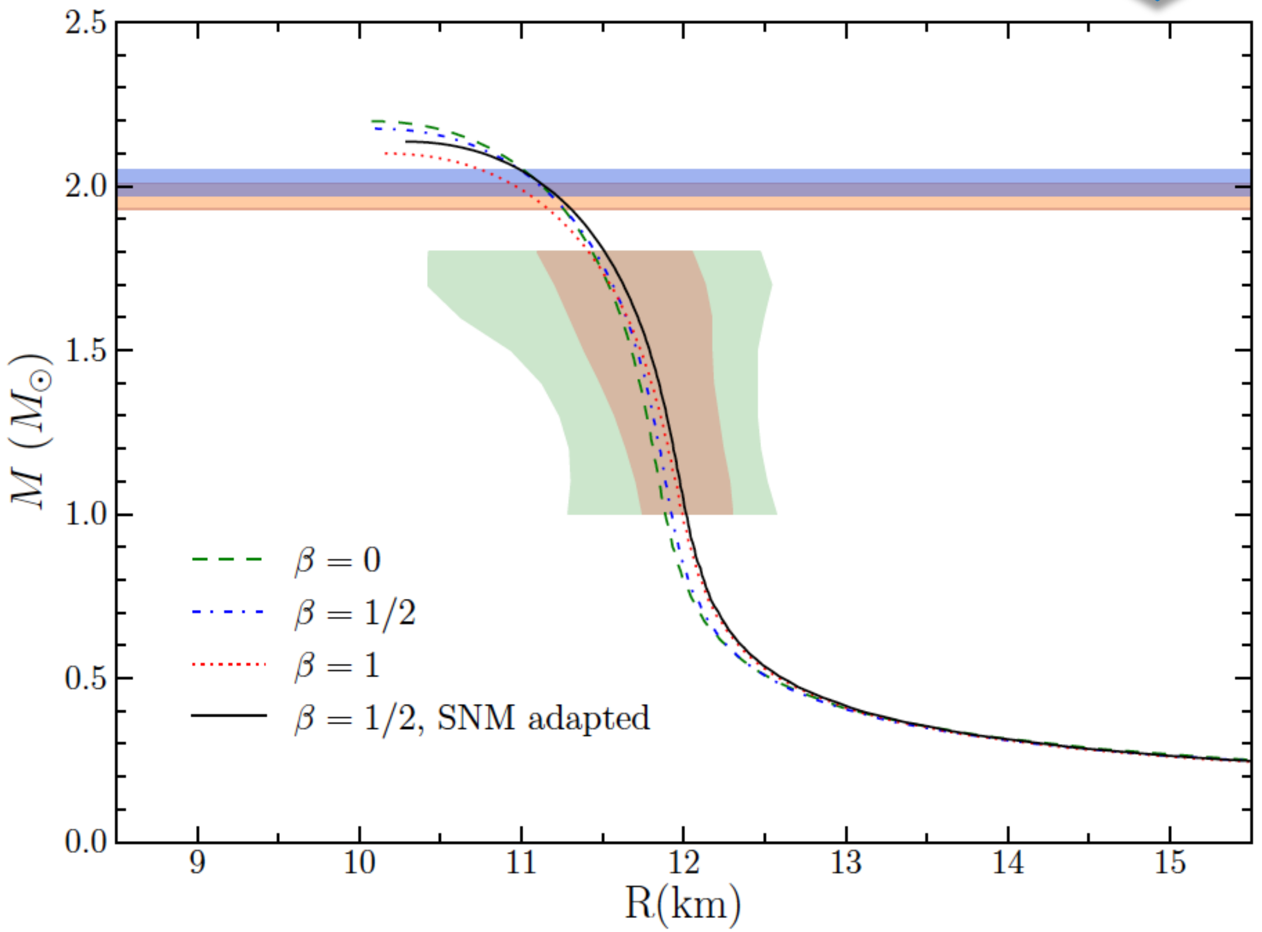
Dilute neutron matter



Dense matter: neutron stars

Agreement with observational data

PP,Park,Lim,Hyun,arXiv:1606.04219



Application in nuclei

- Skyrme-type density-dependent “interaction”
- Skyrme-Hartree-Fock equations
- Parameters already known from homogeneous matter

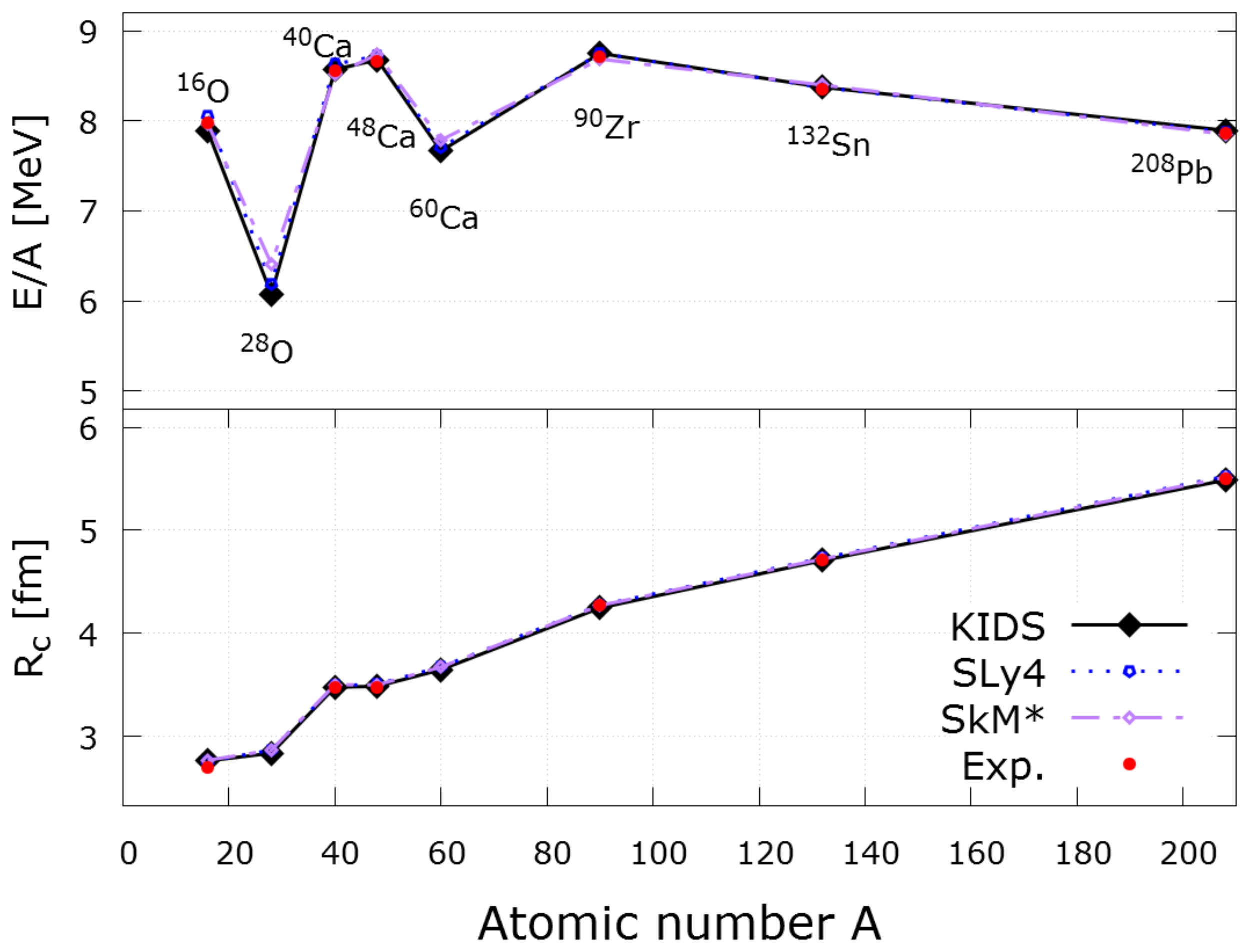
- ... except those which do not contribute to the energy of homogeneous matter:
  - Contribution of momentum-dependent terms t_1-t_2 to $c_2(\delta)$; effective mass

$$c_2(\delta) = k \cdot c_2(\delta) + (1-k) \cdot c_2(\delta) \equiv c_2^{t_3'=0}(\delta) + c_2^{t_1=t_2=0}(\delta)$$

k~0.11 reproduces the energy and radius of ^{16}O, ^{40}Ca

  - spin-orbit strength W_0 :
    W_0~ 110 from ^{48}Ca, ^{208}Pb

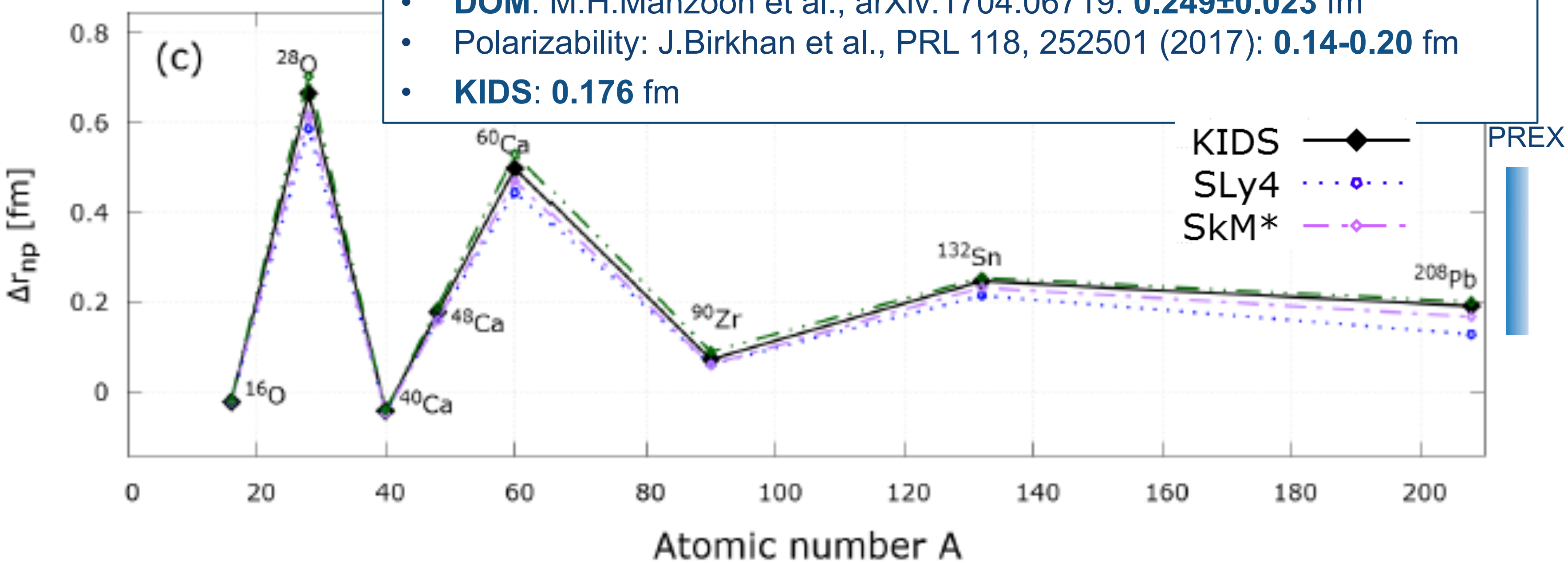
Results – proof of principle



Results- predictions

neutron skin of 48Ca:

- **CCM**: G.Hagen et al., Nature Phys. 12,186(2016) **0.12-0.15** fm
- **DOM**: M.H.Mahzoon et al., arXiv:1704.06719: **0.249±0.023** fm
- Polarizability: J.Birkhan et al., PRL 118, 252501 (2017): **0.14-0.20** fm
- **KIDS**: **0.176** fm



- **Prediction of ^{28}O and ^{60}Ca**

	^{28}O			^{60}Ca		
Model	E/A [MeV]	R_c [fm]	Δr_{np} [fm]	E/A [MeV]	R_c [fm]	Δr_{np} [fm]
SLy4	6.1925	2.8656	0.58476	7.703	3.6734	0.4435
SkM*	6.4114	2.8646	0.61631	7.7857	3.6713	0.4685
KIDS	6.0757	2.8353	0.66398	7.6652	3.6452	0.4960

AME2016: 5.988

Summary

- The dipole spectrum contains **a wealth of structure information** with several implications
  - Lowest isoscalar state: universal feature
  - Other isoscalar resonance?
  - Photoresponse: Importance of separation energy
  - Dramatic effects at shell closure
- **Measurements on either side of a shell closure?**
- **Proton pygmy resonance?**

Theory: New functionals by reverse engineering

>> *Future plans: M1, GT*

Thank you!

감사합니다~

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