

Experiments with relativistic radioactive beams

The dipole response of neutron-rich nuclei investigated at R3B



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TECHNISCHE
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HIC
for FAIR
Helmholtz International Center



NAVI
Nuclear Astrophysics Virtual Institute



September 20th 2014

International School on Nuclear Physics 36th course

Nuclei in the Laboratory and in the Cosmos

Erice-Sicily

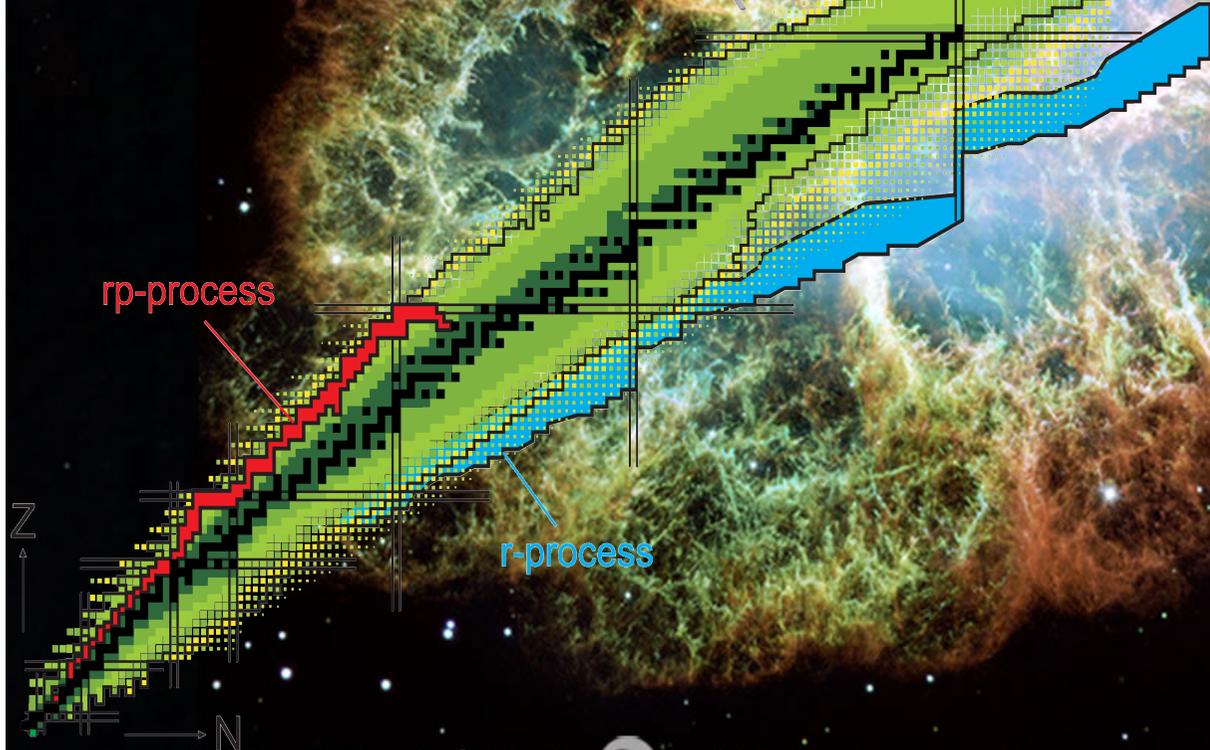
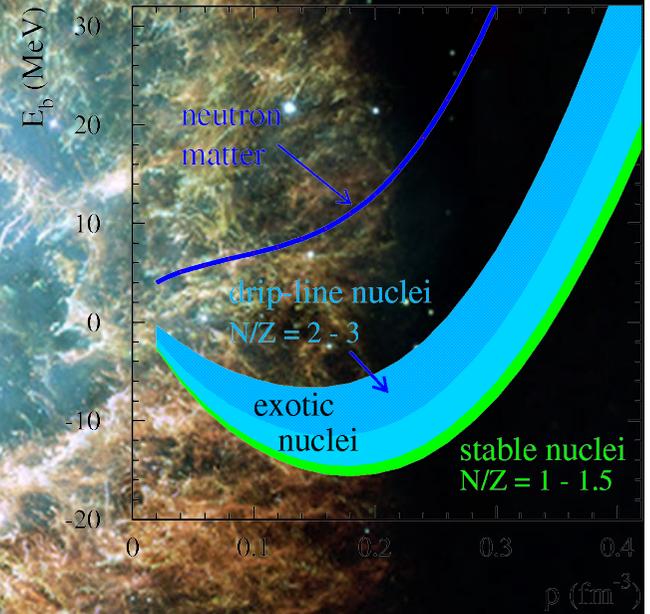
GEFÖRDERT VOM



Bundesministerium
für Bildung
und Forschung

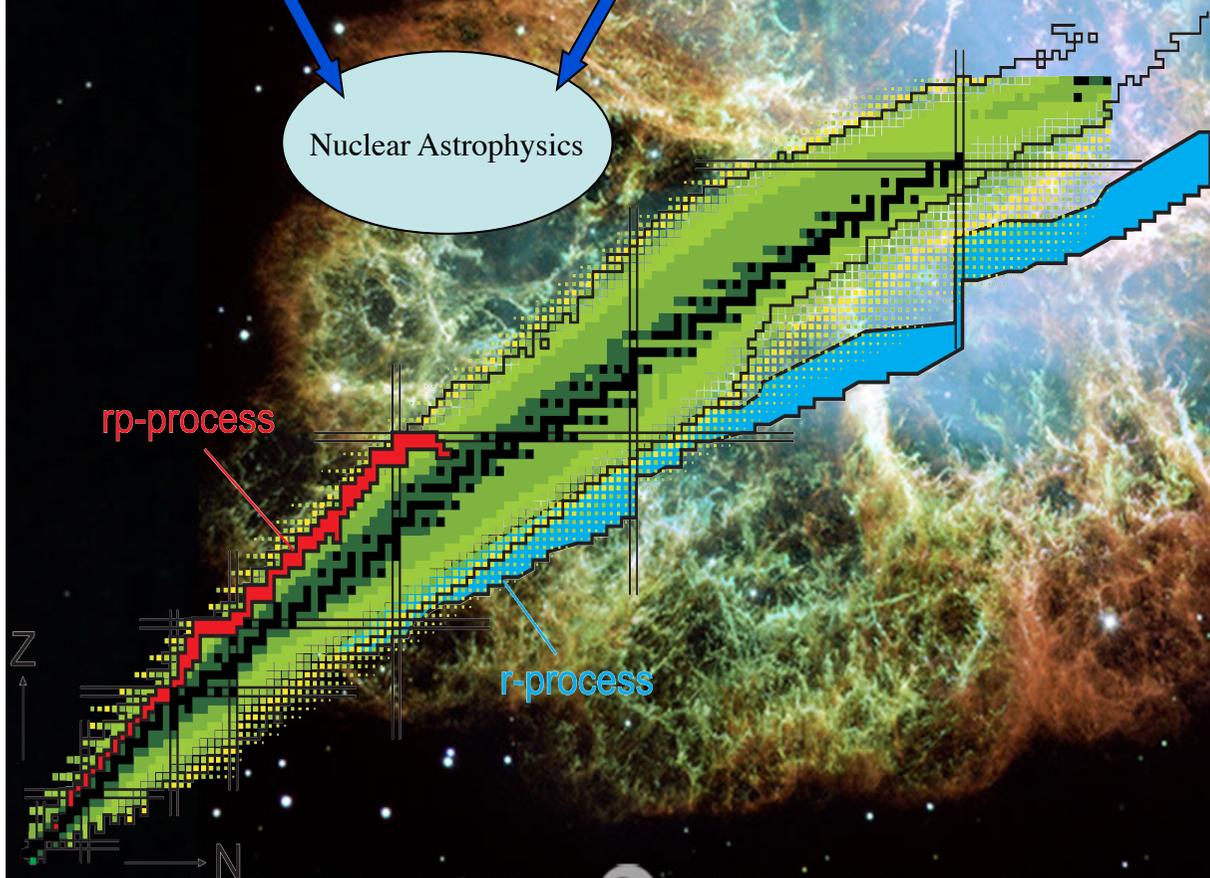
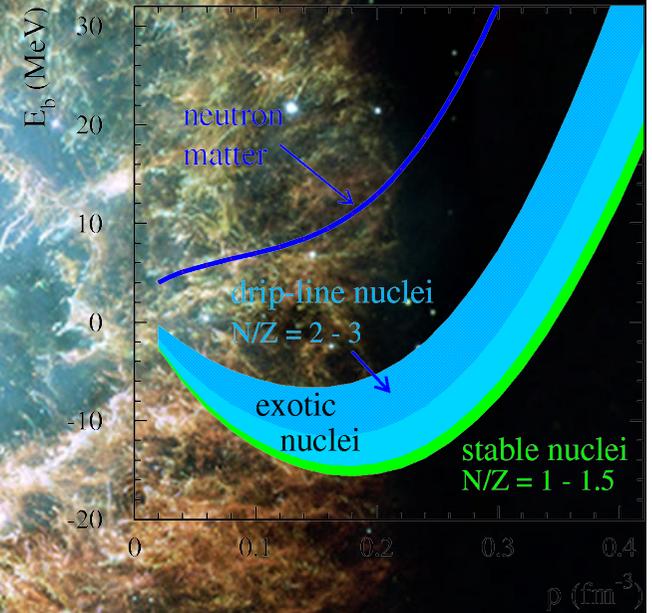
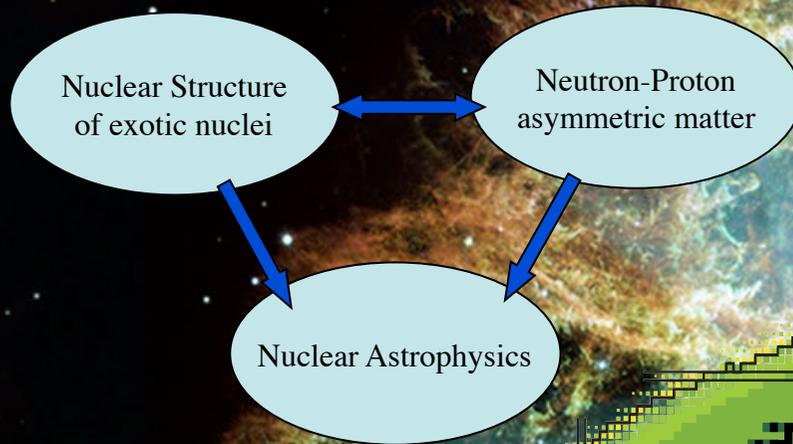
Supported by the BMBF under contract no 05P12RDFN8

Reactions with neutron-proton asymmetric nuclei



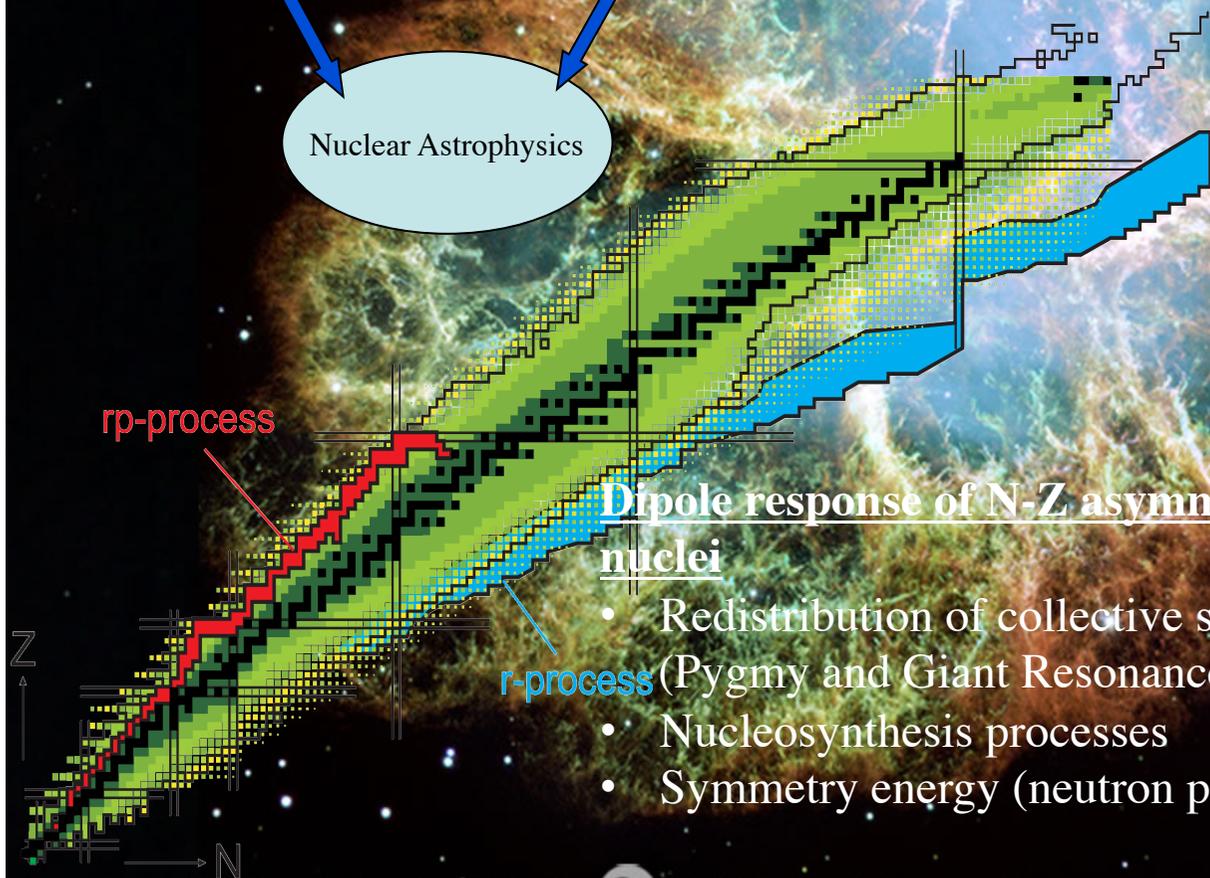
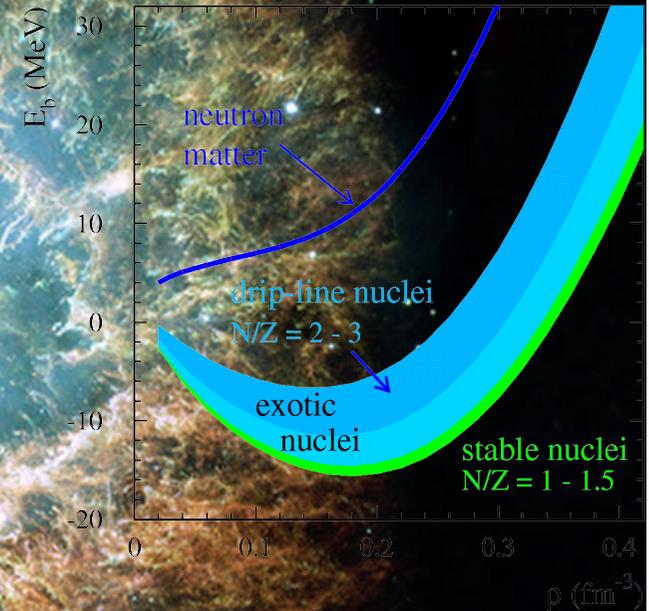
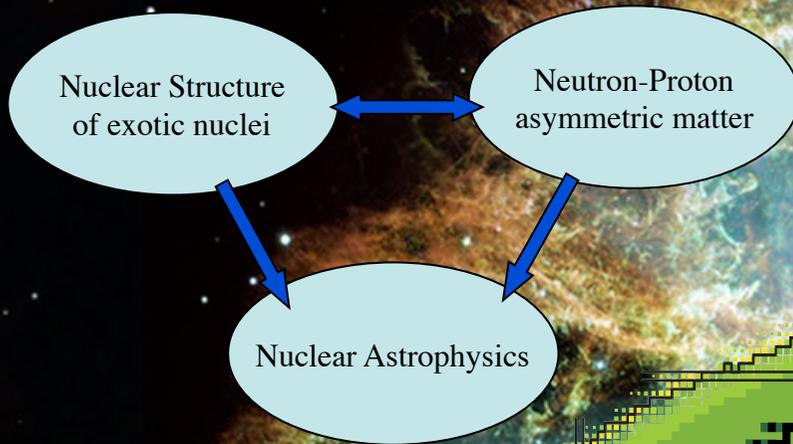
Reactions with neutron-proton asymmetric nuclei

A laboratory for studying nuclear properties as a function of isospin and density:



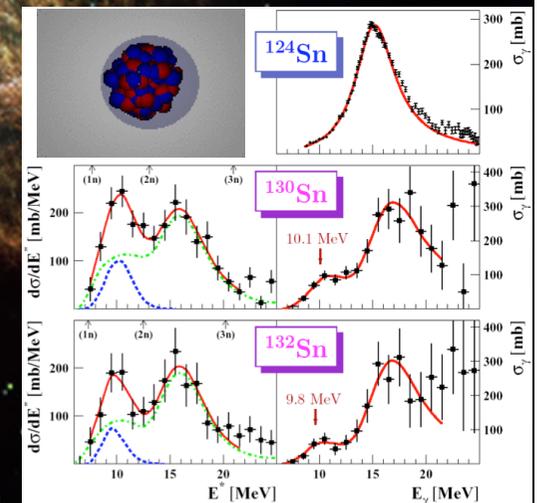
Reactions with neutron-proton asymmetric nuclei

A laboratory for studying nuclear properties as a function of isospin and density:



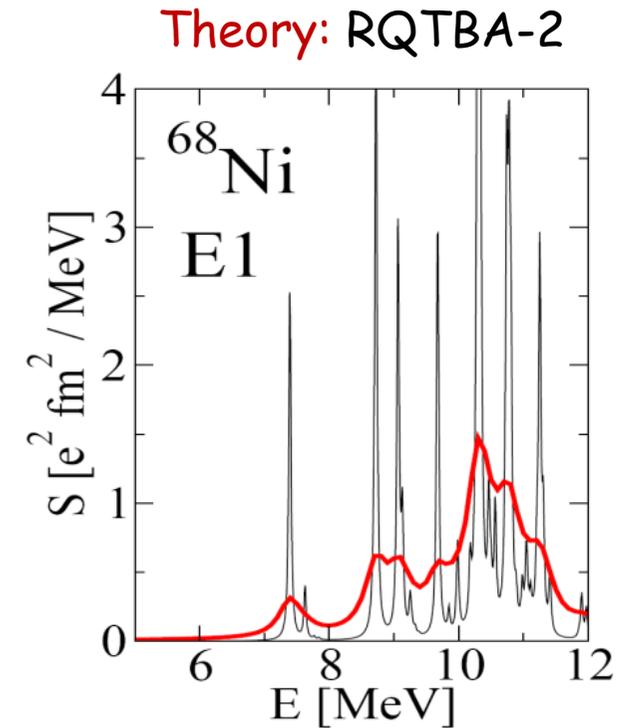
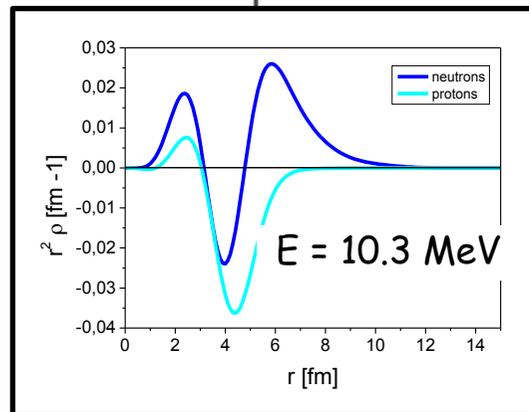
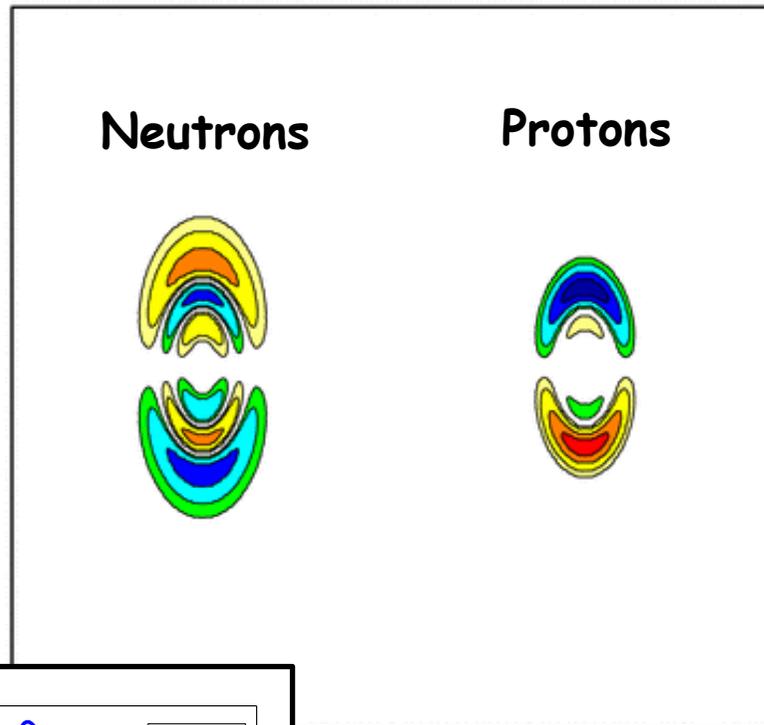
Dipole response of N-Z asymmetric nuclei

- Redistribution of collective strength (Pygmy and Giant Resonances)
- Nucleosynthesis processes
- Symmetry energy (neutron pressure)



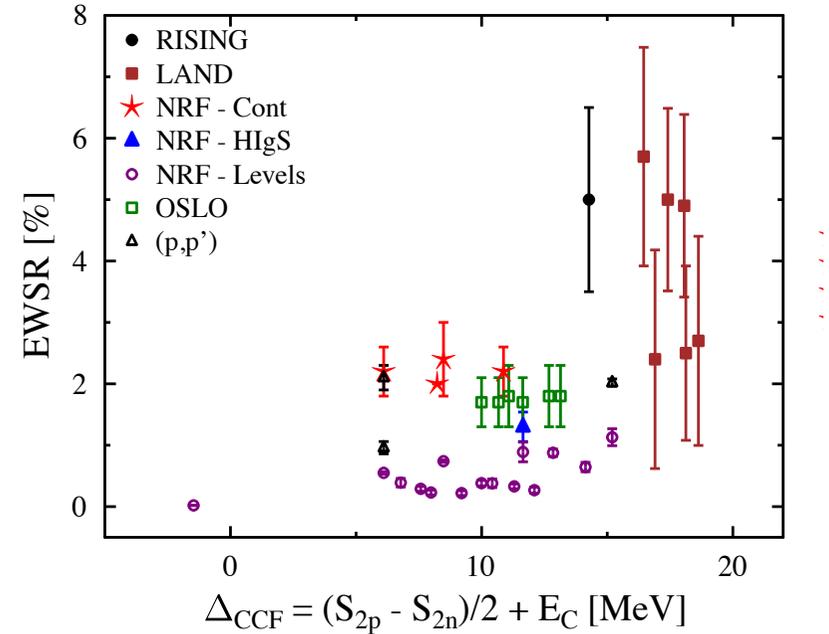
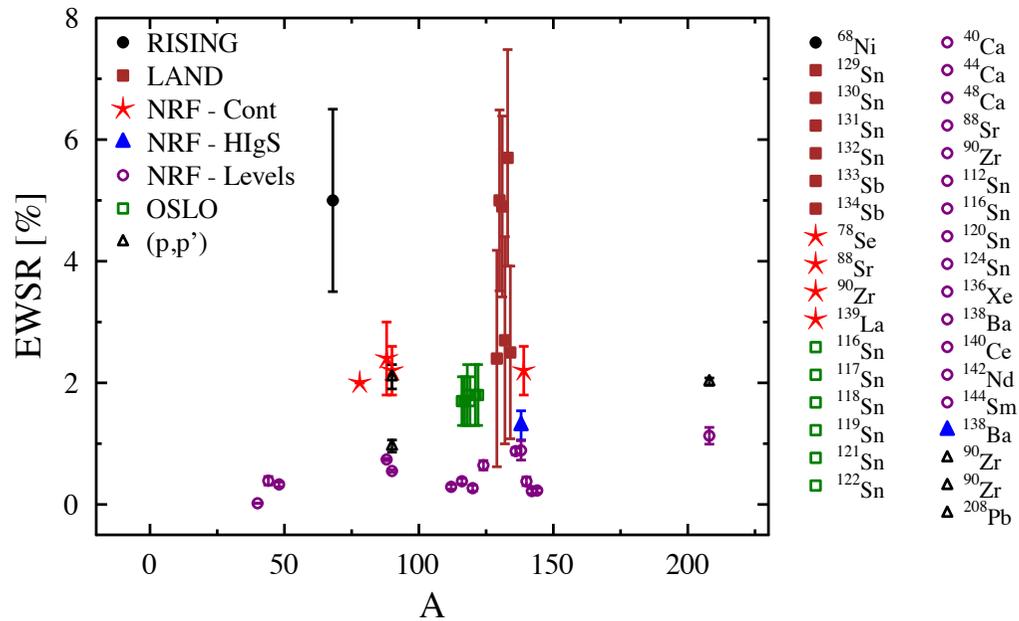
The Pygmy Dipole Resonance (PDR) Relativistic mean-field theory

RQTBA dipole transition densities in ^{68}Ni at 10.3 MeV



Theory:
Elena Litvinova (GSI, WMU&MSU)

Systematics of Pygmy dipole strength ?

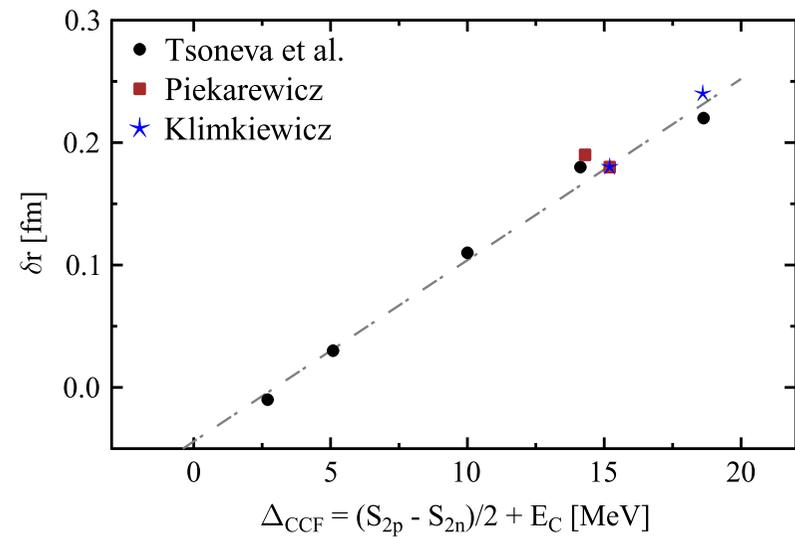


Review

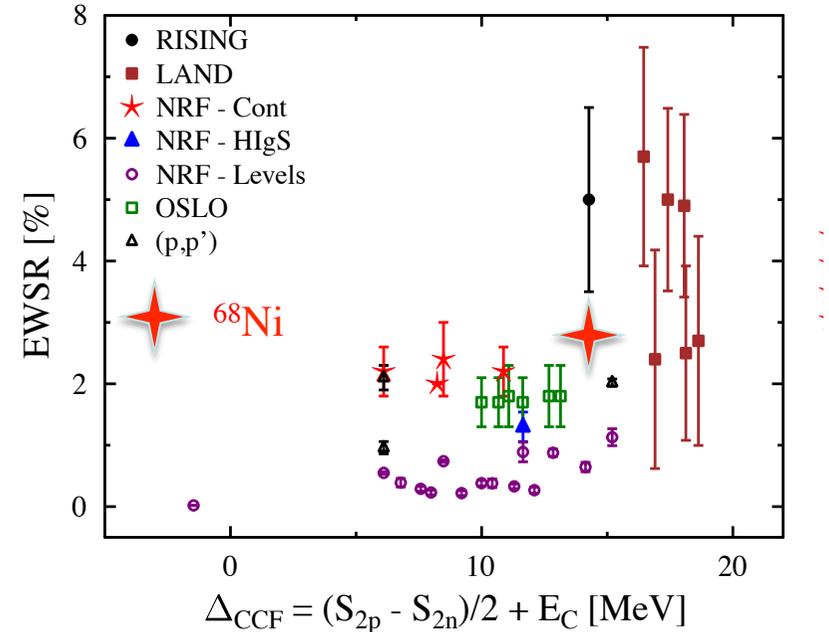
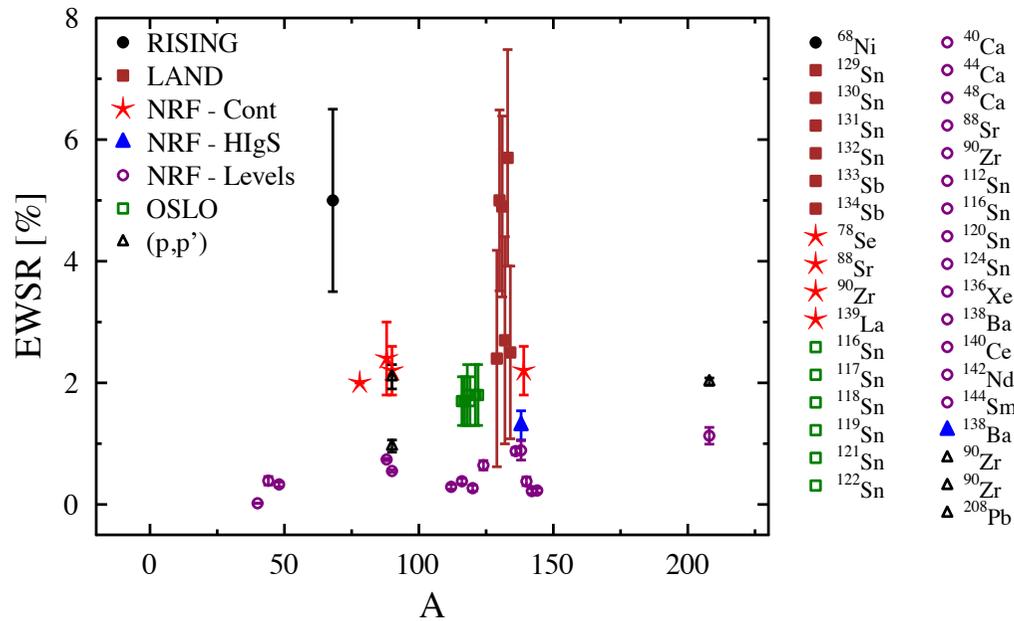
Experimental studies of the Pygmy Dipole Resonance

D. Savran ^{a,b,*}, T. Aumann ^{c,d}, A. Zilges ^e

Progress in Particle and Nuclear Physics 70 (2013) 210–245



Systematics of Pygmy dipole strength ?

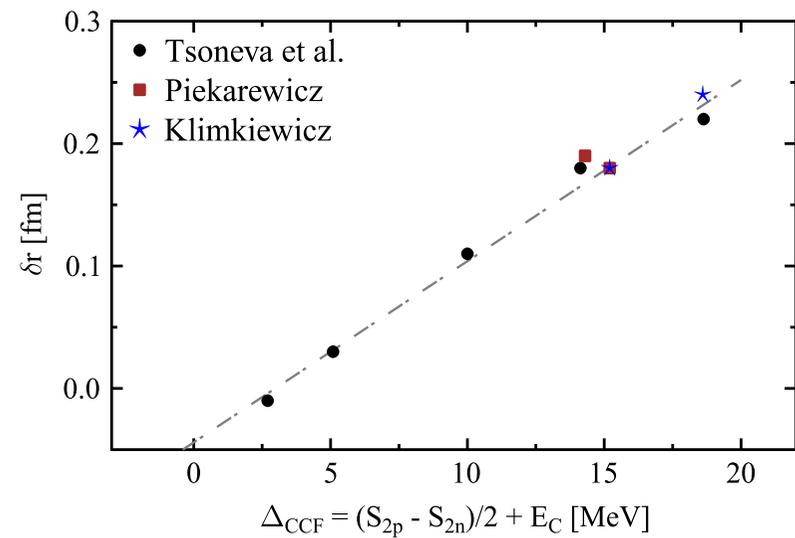


Review

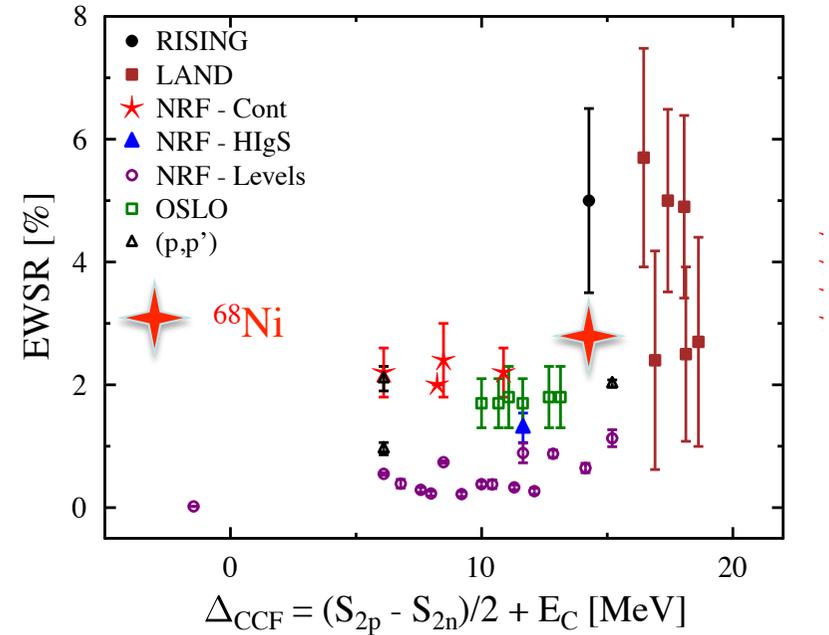
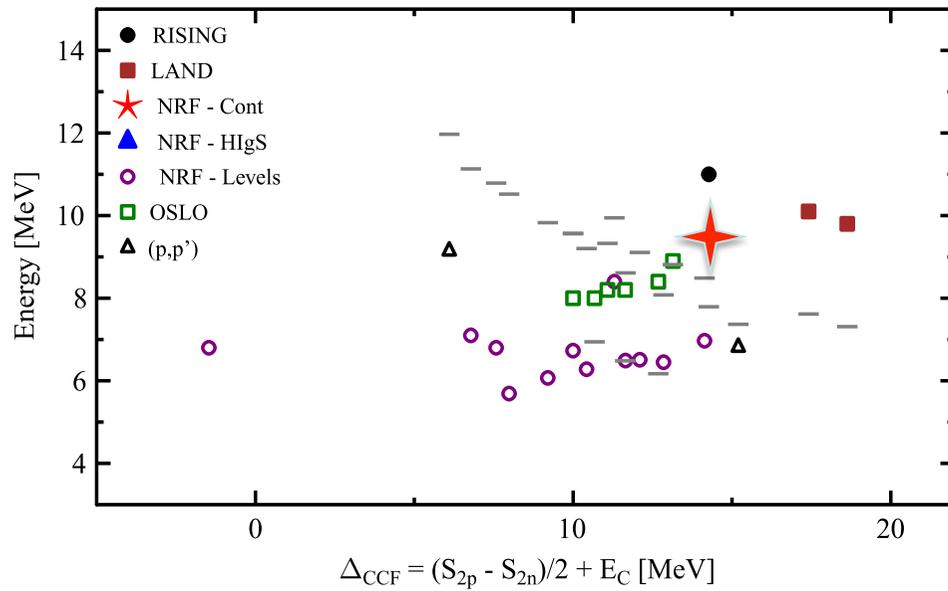
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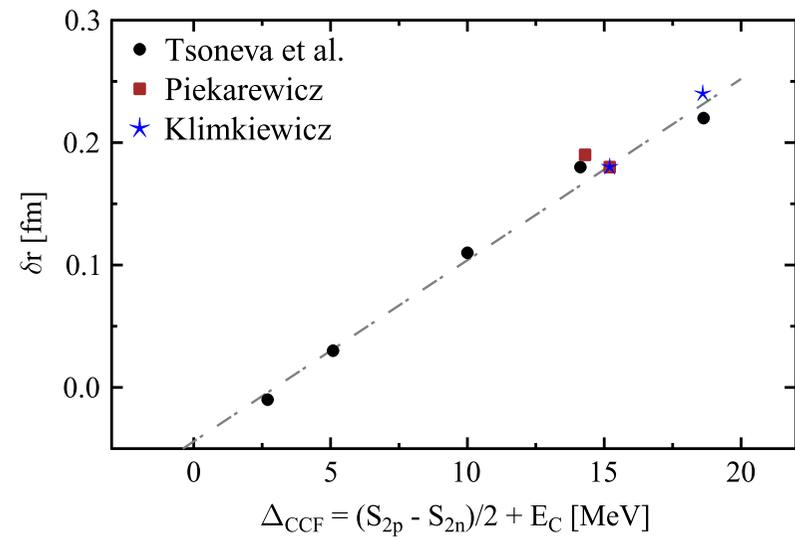


Review

Experimental studies of the Pygmy Dipole Resonance

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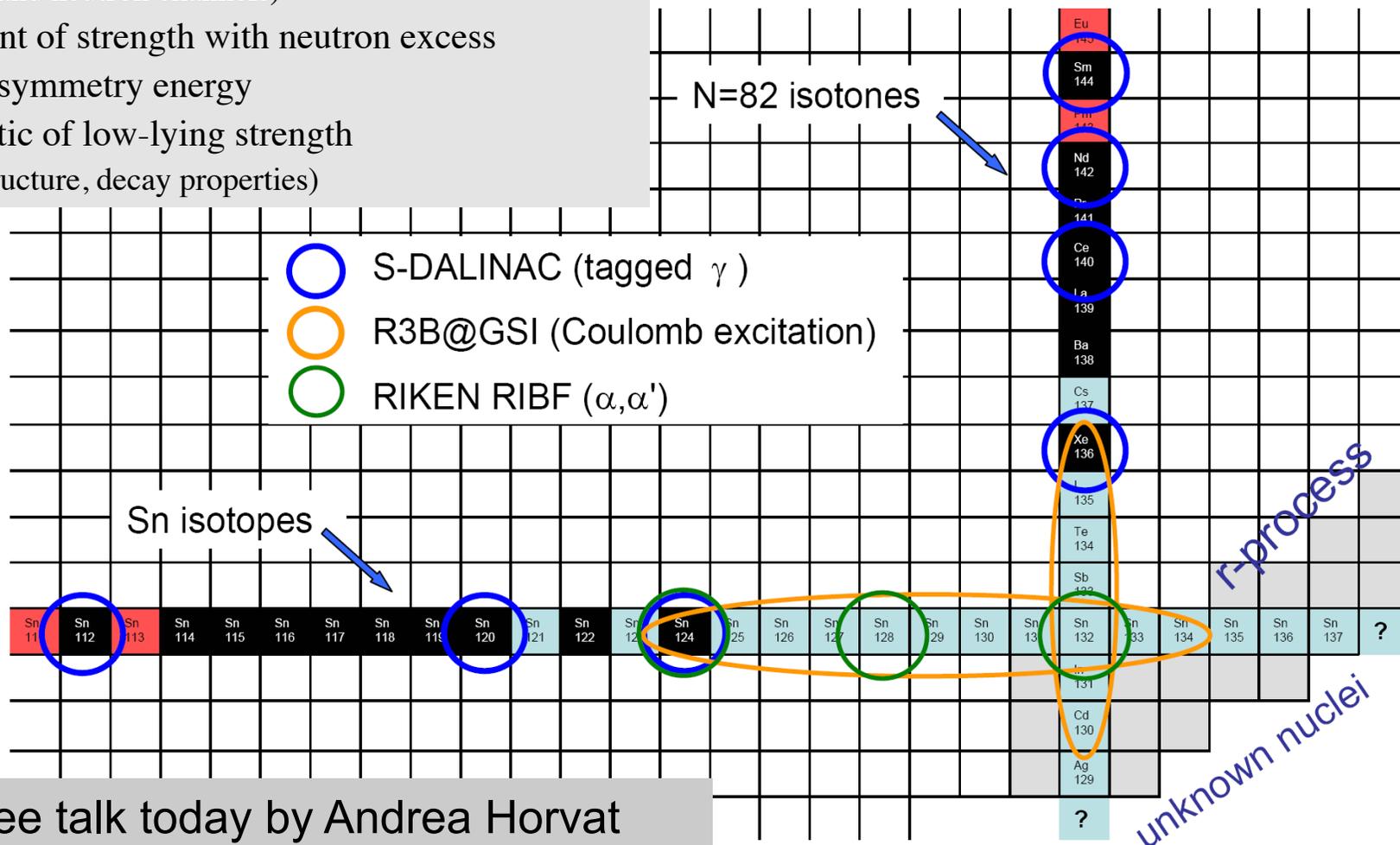
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Proposed experimental programme

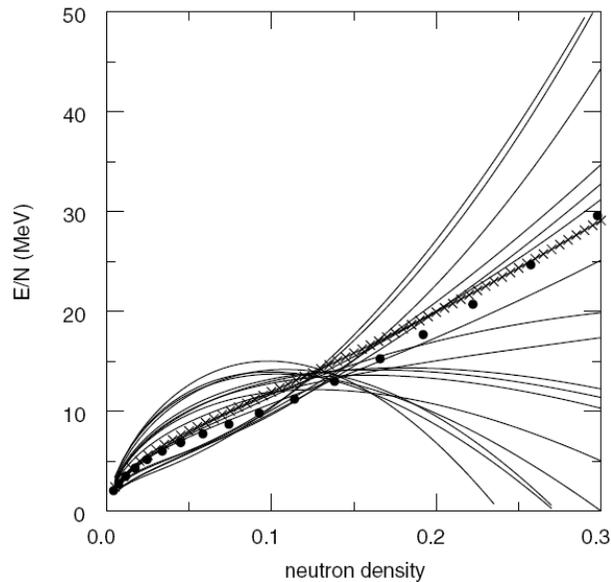
Next-generation experiments – Goals:

- extraction of full dipole strength function
(below and above threshold, extracting E2 contribution, γ (-cascade) and neutron channels)
- development of strength with neutron excess
- relation to symmetry energy
- characteristic of low-lying strength
(isospin structure, decay properties)



→ See talk today by Andrea Horvat

Symmetry energy $S_2(\rho)$ and neutron skin in ^{208}Pb

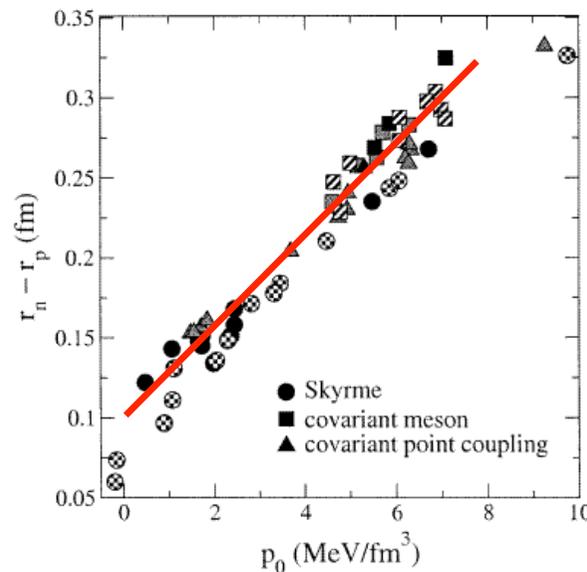
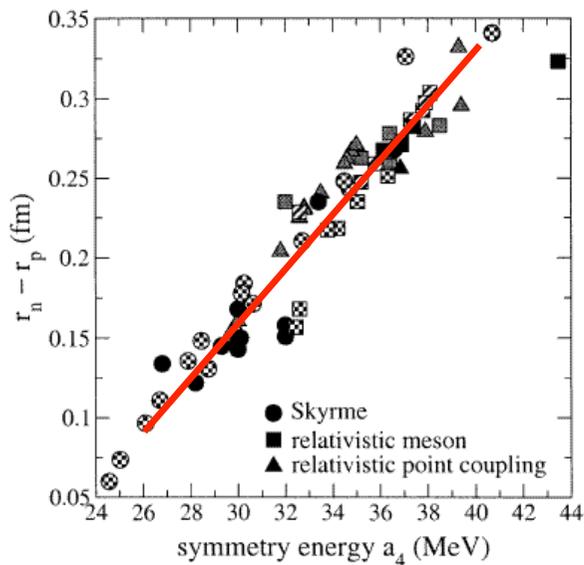


$$E(\rho, \alpha) = E(\rho, 0) + S_2(\rho)\alpha^2 + O(\alpha^4), \quad \alpha = \frac{N - Z}{A}$$

$$S_2(\rho) = \frac{1}{2} \left. \frac{\partial^2 E(\rho, \alpha)}{\partial \alpha^2} \right|_{\alpha=0} =$$

$$= a_4 + \frac{p_0}{\rho_0^2} (\rho - \rho_0) + \frac{\Delta K_0}{18\rho_0^2} (\rho - \rho_0)^2 + \dots$$

Alex Brown,
PRL 85 (2000) 5296



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

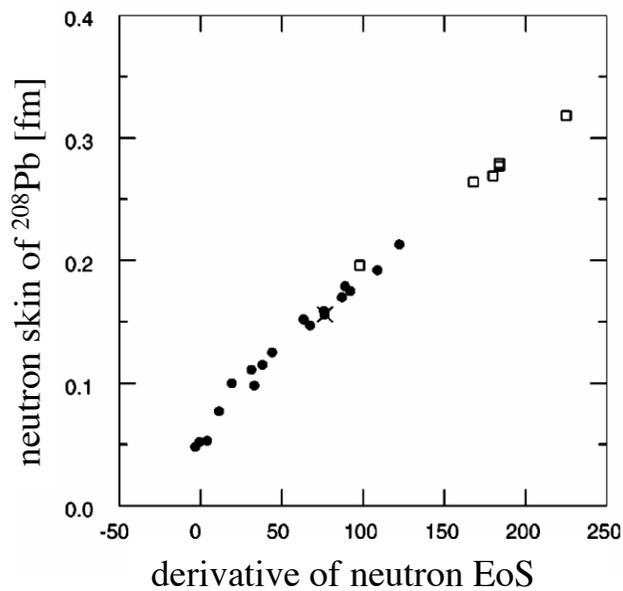
- strong linear correlation between neutron skin thickness and parameters a_4, p_0

Symmetry energy and dipole response

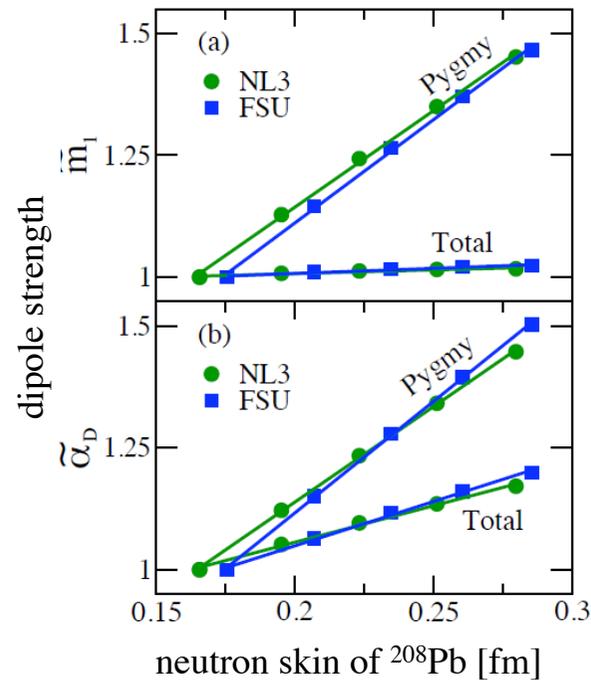
neutron-skin thickness
dipole response

density dependence of
symmetry energy

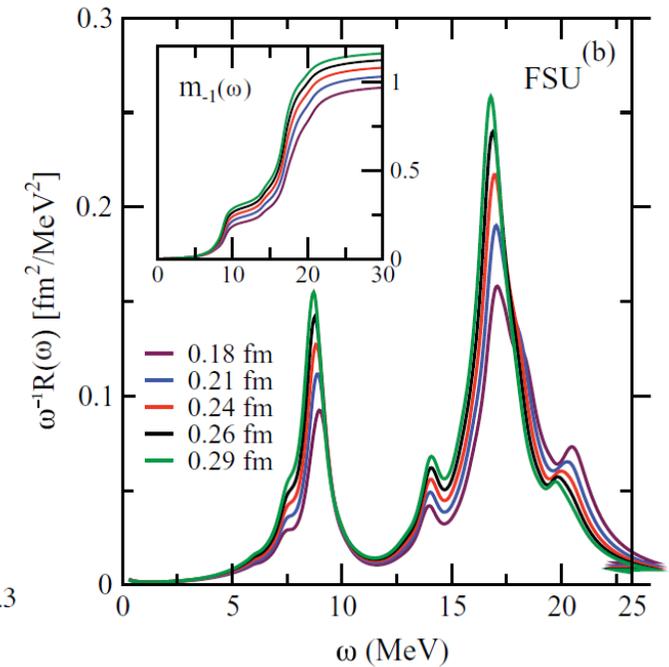
properties of
neutron-rich matter



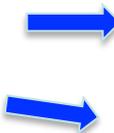
S. Typel and B.A. Brown,
Phys. Rev. C **64** (2001) 027302



J. Piekarewicz, *PRC* **83**, 034319 (2011)

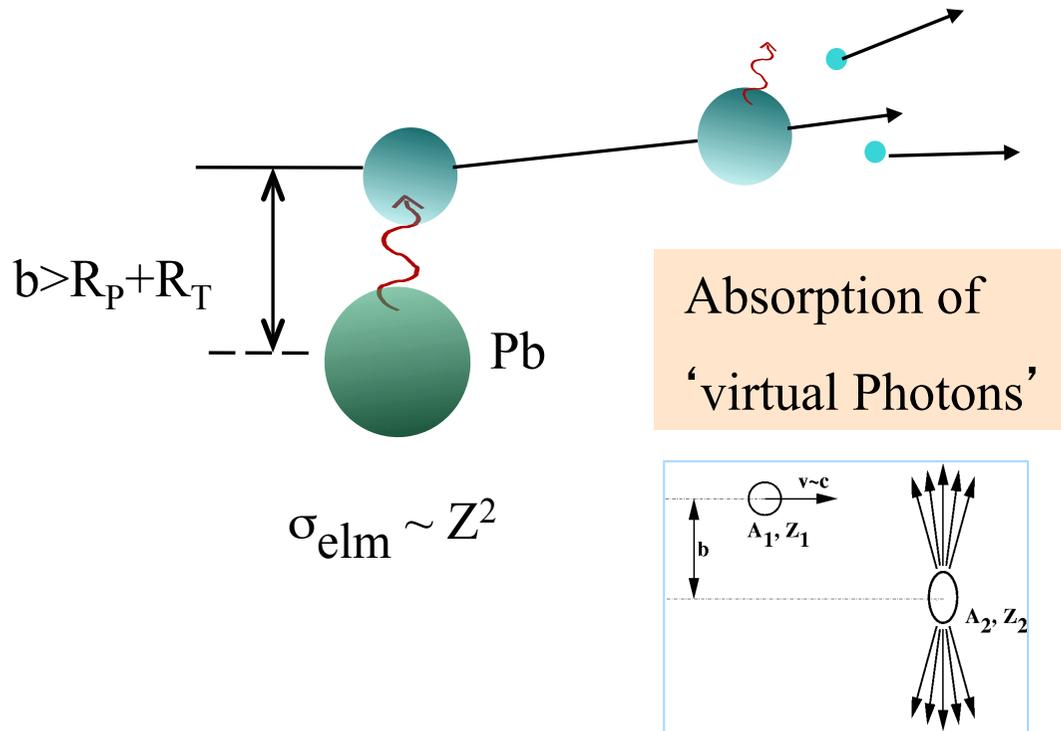


n-skin from Pygmy strength
n-skin from polarizability

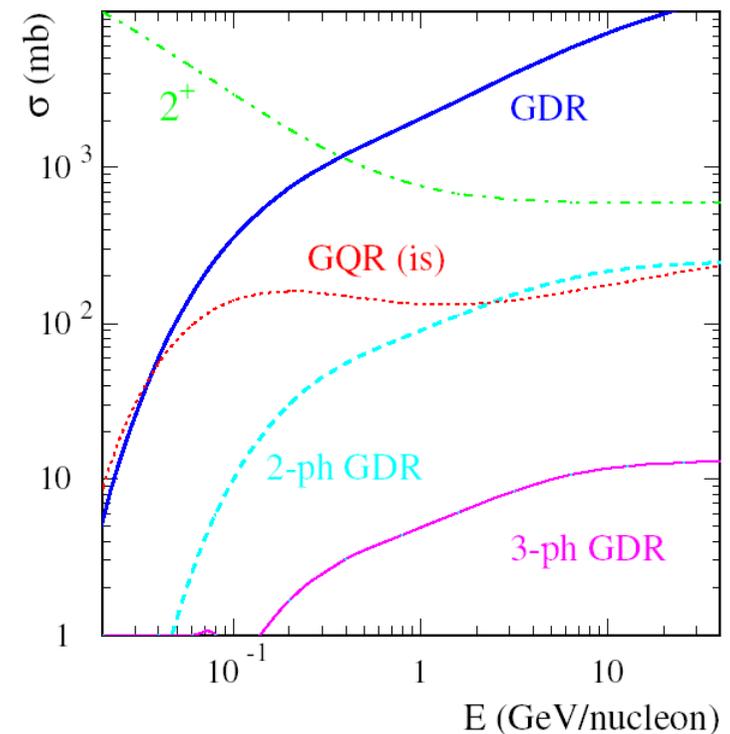


A. Klimkiewicz et al., *PRC* 76 (2007) 051603(R)
A. Carbone et al., *PRC* 81 (2010) 041301(R)
P.-G. Reinhard, W. Nazarewicz, *PRC* 81 (2010) 051303(R)
A. Tamii et al., *Phys. Rev. Lett.* 107 (2011) 062502.

Electromagnetic excitation at high energies



$$d\sigma_{\text{elm}} / dE = N_{\gamma}(E) \sigma_{\gamma}(E)$$



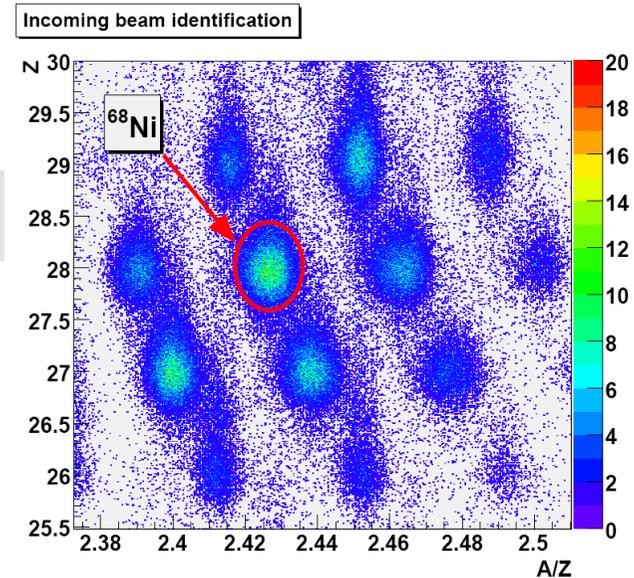
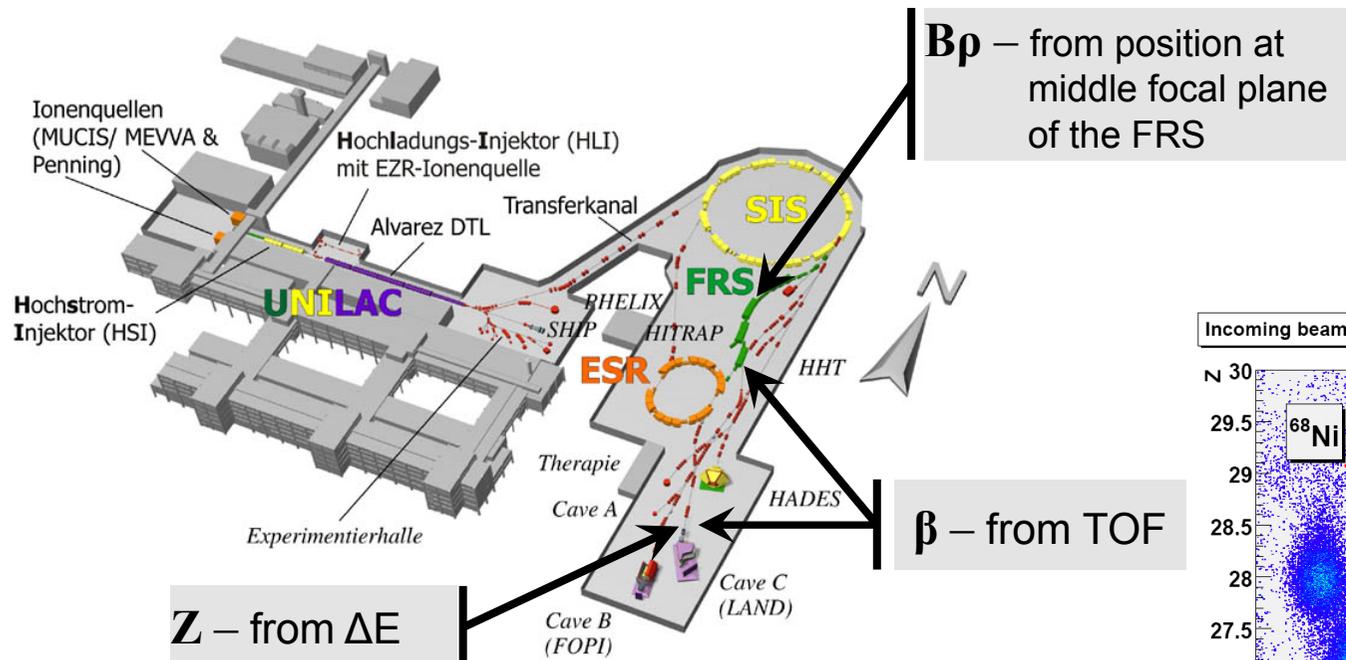
High velocities $v/c \approx 0.6-0.9$
 \Rightarrow High-frequency Fourier components

$$E_{\gamma, \text{max}} \approx 25 \text{ MeV (@ 1 GeV/u)}$$

Determination of 'photon energy' (excitation energy) via a kinematically complete measurement of the momenta of all outgoing particles (invariant mass)

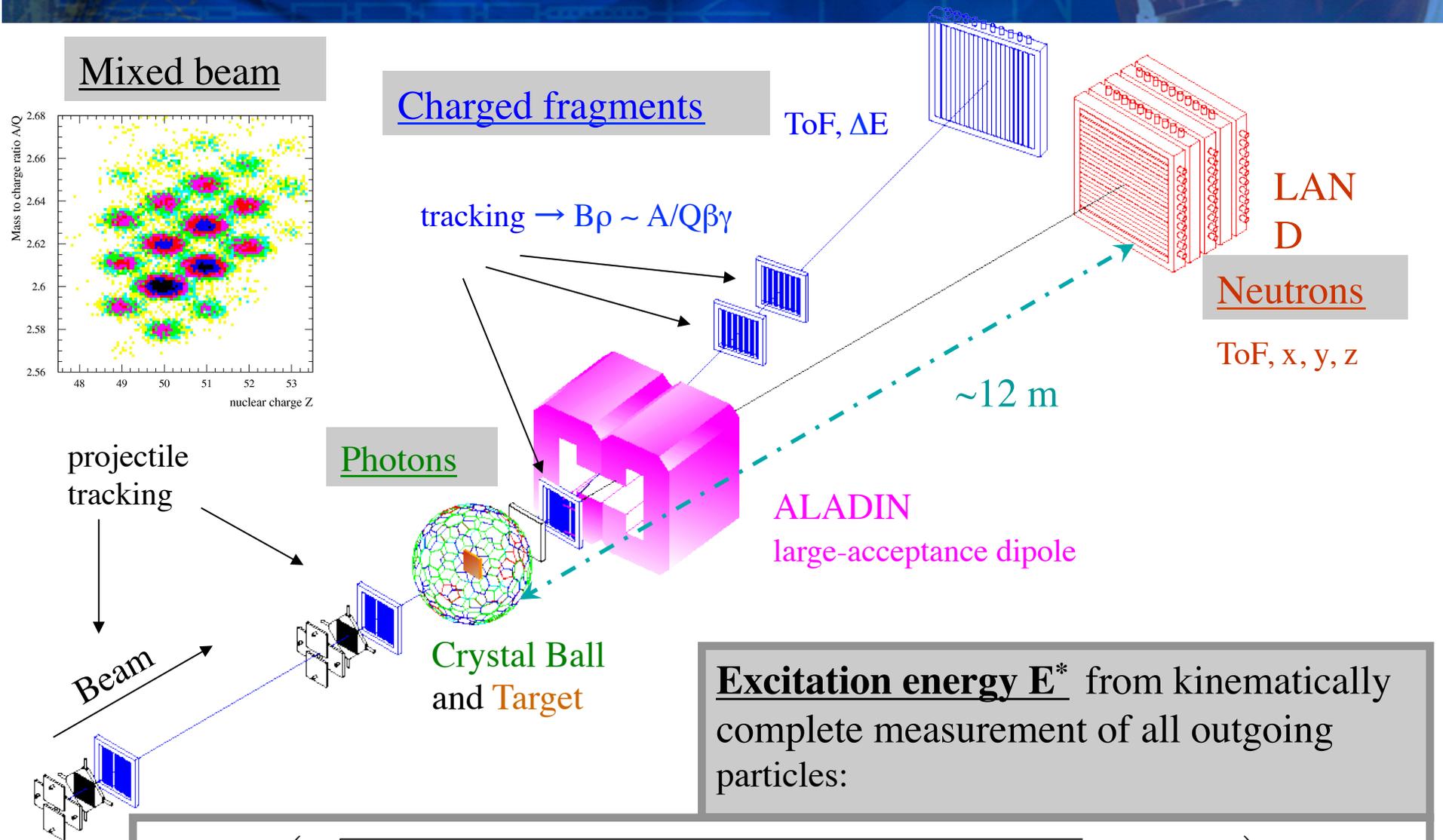
Production of fast exotic nuclei

- Stable beams from SIS, fragmentation on Be target or in-flight fission
- Selection of radioactive beams in Fragment Separator (FRS)



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

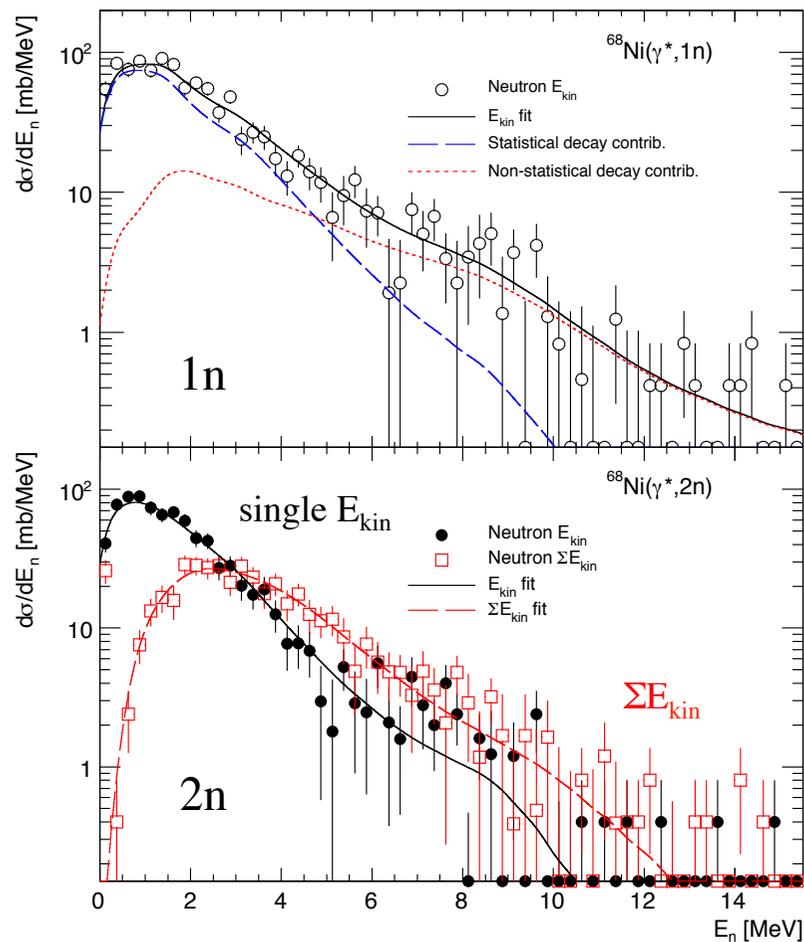
The LAND reaction setup @GSI



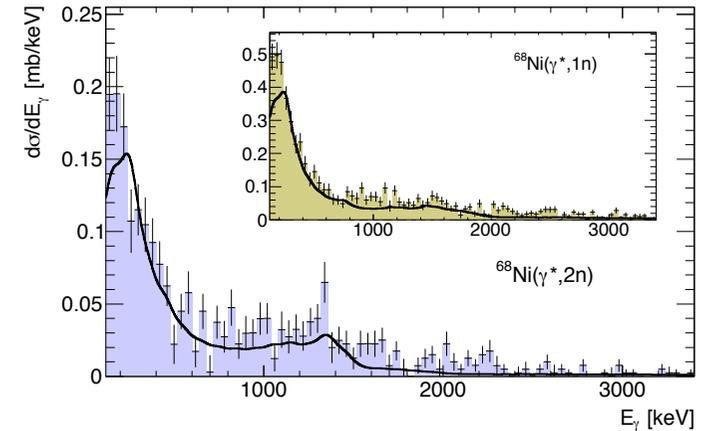
$$E^* = \left(\sqrt{\sum_i m_i^2 + \sum_{i \neq j} m_i m_j \gamma_i \gamma_j (1 - \beta_i \beta_j \cos \theta_{ij})} - m_{proj} \right) c^2 + E_\gamma$$

Analysis of ^{68}Ni : decay after Coulomb excitation

Neutron kinetic energy



gamma sum energy



$$R_{\text{direct}} = 24(4) \%$$

consistent fit taking into account:

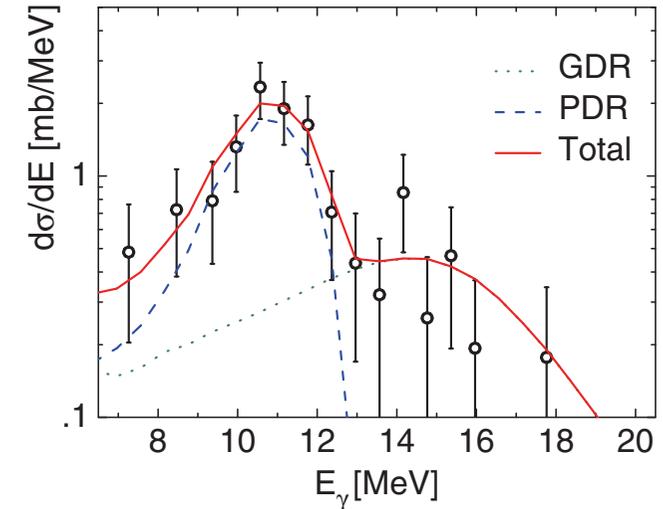
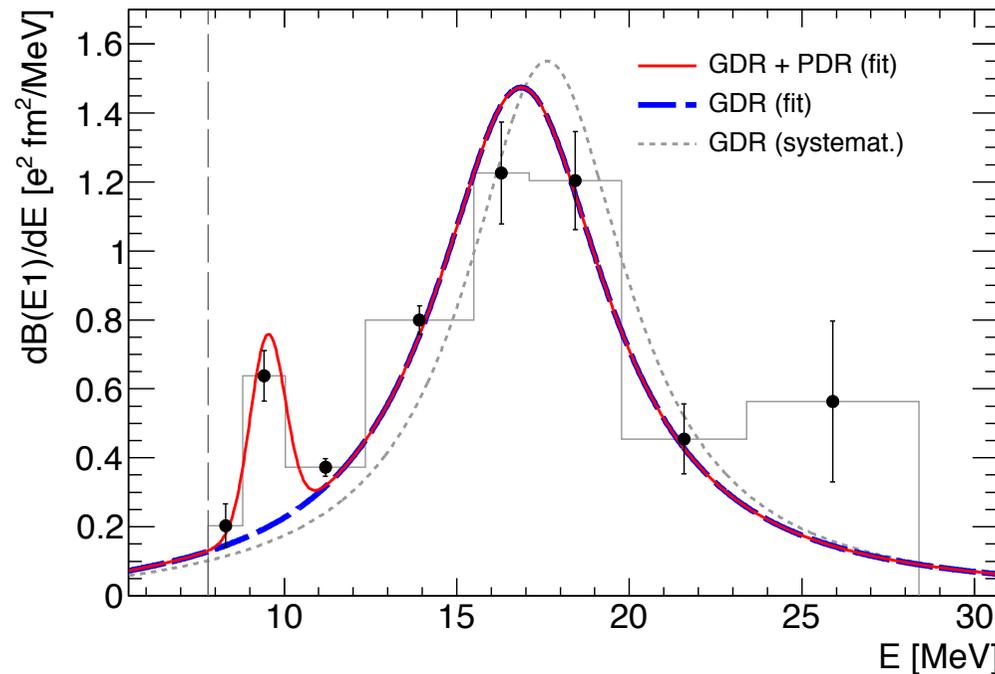
- 1) invariant mass, but also information of subsets like $E_{\text{kin}}(n)$, $E_{\gamma\text{sum}}$ etc.
- 2) detailed knowledge about detector response function



analysis:
 Dominic Rossi
 PhD Thesis
 Univ. Mainz,
 PostDoc GSI
 Now MSU

Dipole strength distribution of ^{68}Ni

Simultaneous fit of spectra with 8 individual energy bins as free fit parameters:
 „deconvolution“



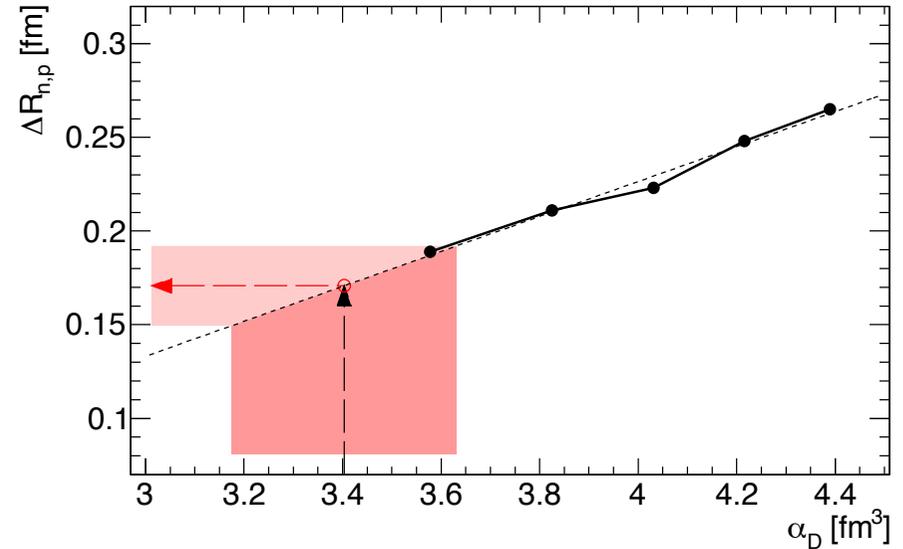
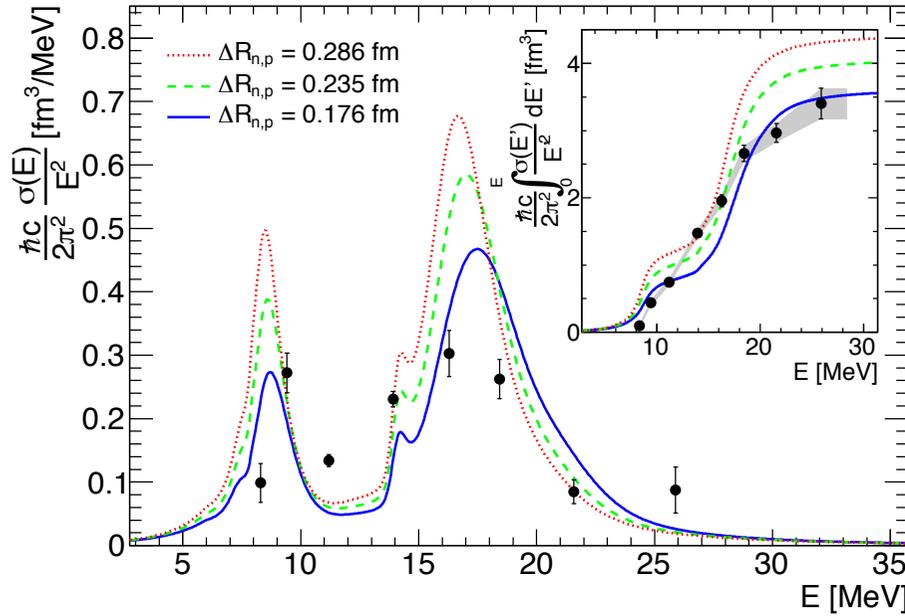
O. Wieland et al., PRL 102, 092502 (2009)

		This work	Lit.	Ref.
GDR	E_m [MeV]	17.1(2)	17.84	
	Γ [MeV]	6.1(5)	5.69	[30]
	S_{EWSR} [%]	98(7)	100	
PDR	E_m [MeV]	9.55(17)	11	
	σ [MeV]	0.51(13)	< 1	[13, 25]
	S_{EWSR} [%]	2.8(5)	5.0(1.5)	

Direct gamma-decay
 branching ratio
 $\Gamma_0/\Gamma = 7(2)\%$

D. Rossi et al., PRL 111 (2013) 242503

Polarizability and neutron skin



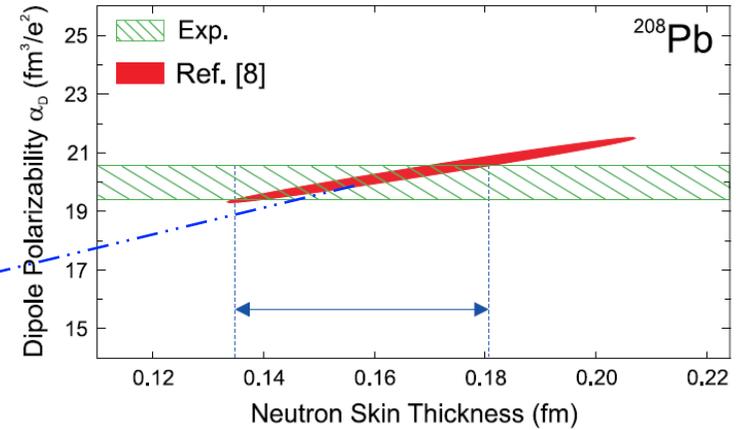
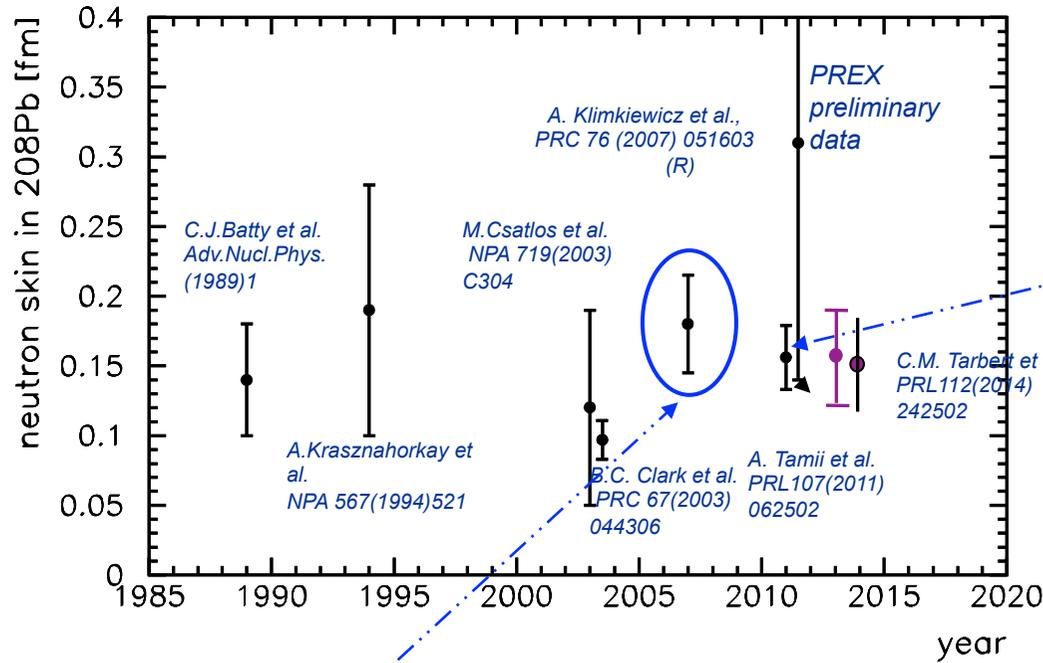
$$\alpha_D = \frac{\hbar c}{2\pi^2} \int_0^\infty \frac{\sigma(E)}{E^2} dE$$

Neutron-skin thickness
 $\Delta R_{n,p} = 0.175(21)$ fm

Theoretical calculations from
 J. Piekarewicz, PRC **83**, 034319 (2011)

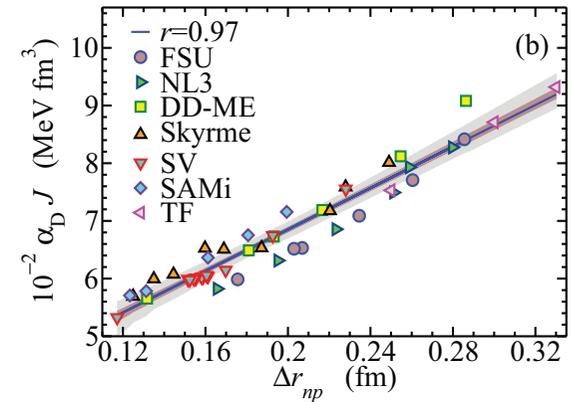
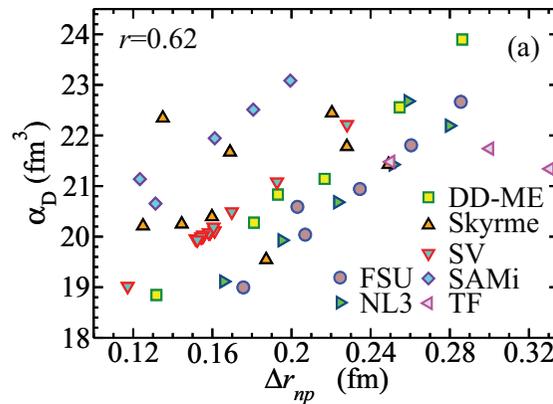
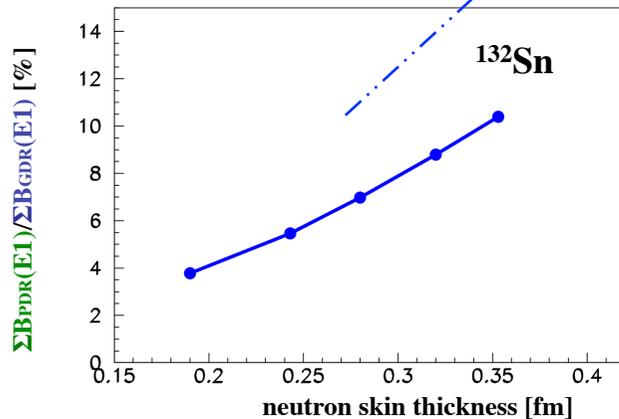
D. Rossi et al., PRL 111 (2013) 242503

Neutron skin in ^{208}Pb from different methods

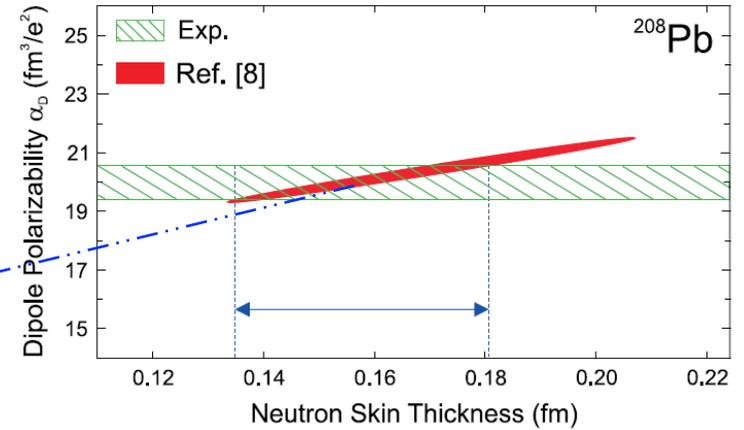
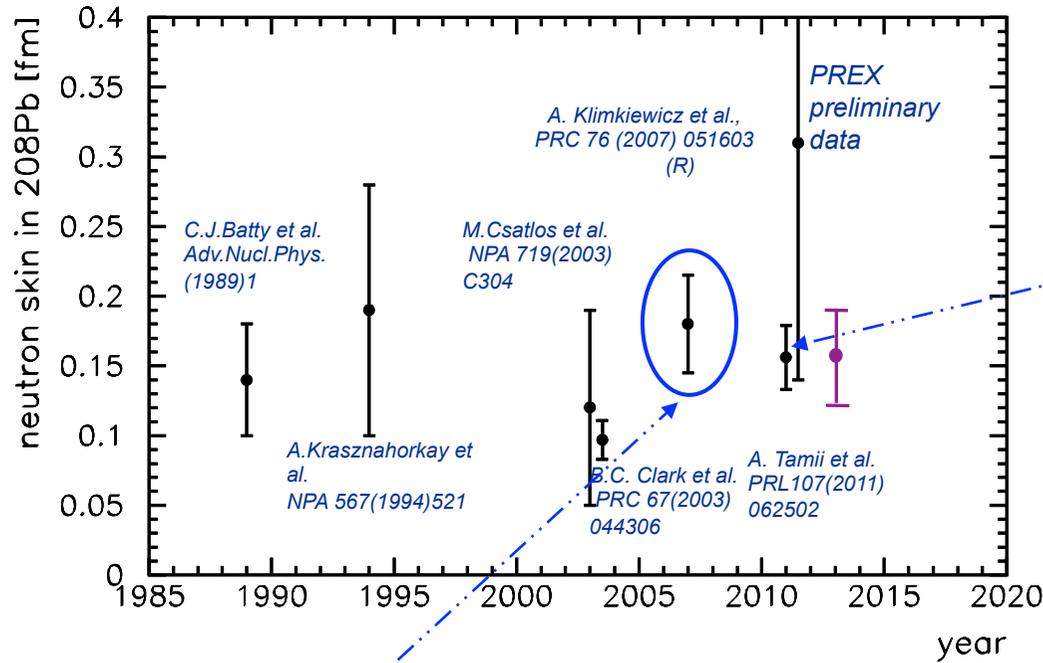


But:

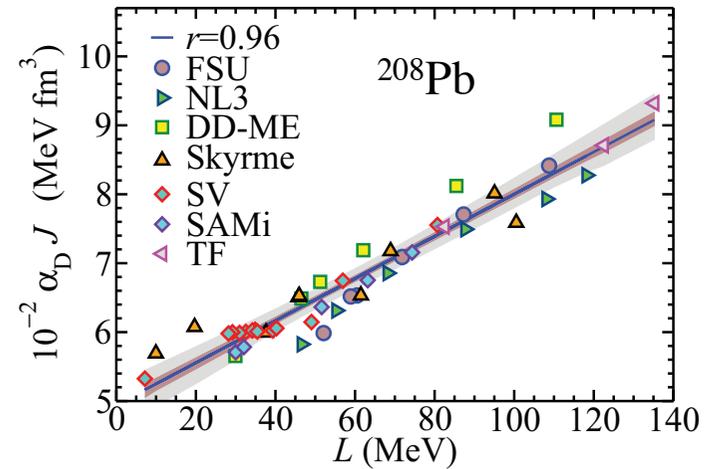
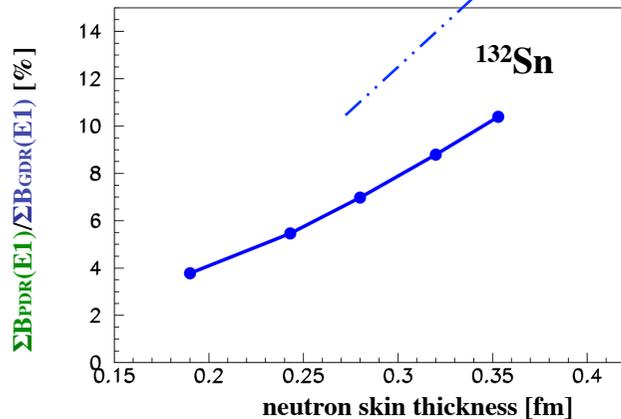
X. Roca-Maza et al., *PRC* 88 (2013) 024316



Neutron skin in ^{208}Pb from different methods



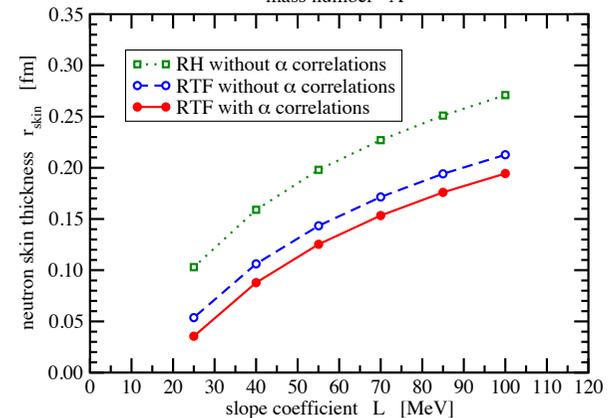
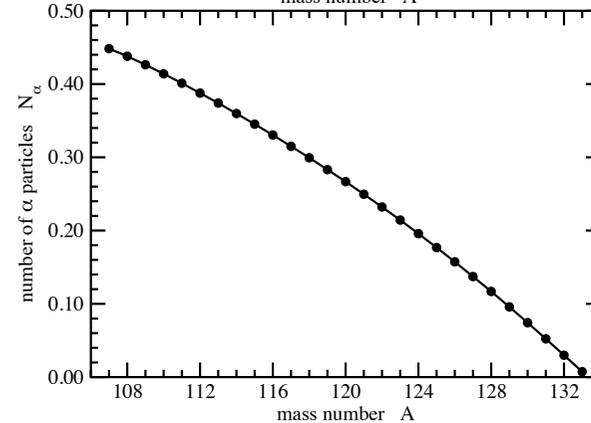
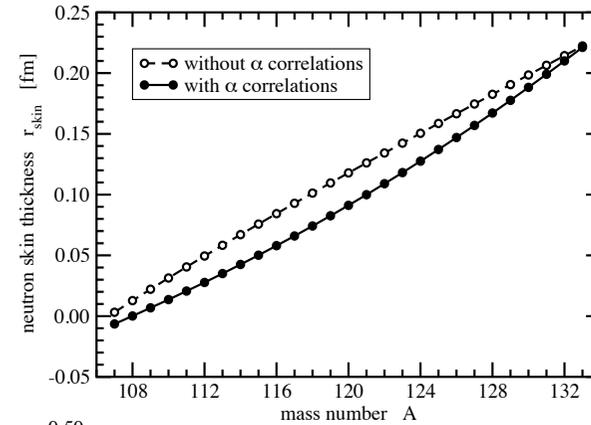
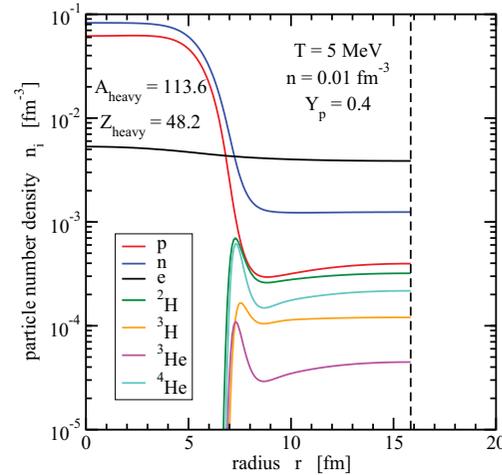
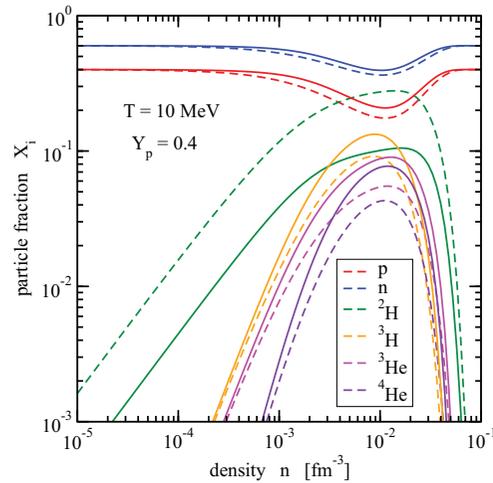
X. Roca-Maza et al., *PRC* 88 (2013) 024316



Alpha clusters in nuclear matter and heavy nuclei

Nuclear Matter

Heavy Nuclei (only α relevant)



- Clustering at surface changes neutron-skin thickness
- > relation slope symmetry energy – n-skin
- > experiment to test a preformation in heavy nuclei (p,p α) at RCNP (Aumann, Uesaka, Typel et al.) with RIB: SAMURAI, R3B

Collaboration of ^{68}Ni dipole-response experiment

Measurement of the dipole polarizability of the unstable neutron-rich nucleus ^{68}Ni

D. M. Rossi,^{1,2,*} P. Adrich,¹ F. Aksouh,^{1,†} H. Alvarez-Pol,³ T. Aumann,^{4,1,‡} J. Benlliure,³ M. Böhmer,⁵ K. Boretzky,¹
E. Casarejos,⁶ M. Chartier,⁷ A. Chatillon,¹ D. Cortina-Gil,³ U. Datta Pramanik,⁸ H. Emling,¹ O. Ershova,⁹
B. Fernandez-Dominguez,^{3,7} H. Geissel,¹ M. Gorska,¹ M. Heil,¹ H. T. Johansson,^{10,1} A. Junghans,¹¹ A. Kelic-Heil,¹
O. Kiselev,^{1,2} A. Klimkiewicz,^{1,12} J. V. Kratz,² R. Krücken,⁵ N. Kurz,¹ M. Labiche,^{13,14} T. Le Bleis,^{1,9,15} R. Lemmon,¹⁴
Yu. A. Litvinov,¹ K. Mahata,^{1,16} P. Maierbeck,⁵ A. Movsesyan,⁴ T. Nilsson,¹⁰ C. Nociforo,¹ R. Palit,¹⁷ S. Paschalis,^{4,7}
R. Plag,^{9,1} R. Reifarth,^{9,1} D. Savran,^{18,19} H. Scheit,⁴ H. Simon,¹ K. Sümmerer,¹ A. Wagner,¹¹ W. Waluś,¹²
H. Weick,¹ and M. Winkler¹

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²*Institut für Kernchemie, Johannes Gutenberg-Universität, D-55128 Mainz, Germany*

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¹⁰*Chalmers University of Technology, SE-41296 Göteborg, Sweden*

¹¹*Helmholtz-Zentrum Dresden-Rossendorf e.V., D-01328 Dresden, Germany*

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¹⁹*Frankfurt Institute for Advanced Studies, D-60438 Frankfurt am Main, Germany*

Summary

- Dipole response of n-rich nuclei – Pygmy Resonance

- Low-lying dipole strength observed in n-rich nuclei, ‘proton-Pygmy’ in ^{32}Ar
- many open questions – next-generation experimental program planned at GSI, RIKEN, SDALINAC, HIγS, Osaka, ...

systematics, strength and position as a function of N-Z (and mass)

isospin character (isoscalar dipole)

decay properties

relation to nuclear-matter properties

relation to observed low-lying strength for stable nuclei

extraction of quadrupole strength

- Dipole response of ^{68}Ni

- 25(2)% non-statistical decay
- PDR: 2.8(5)% EWSR, 7(2)% direct gamma decay
- Dipole polarizability extracted for the first time for a radioactive nucleus

This opens the possibility for systematic studies as a function of N-Z which will enable to provide tight constraints on neutron skins and the density dependence of the symmetry energy