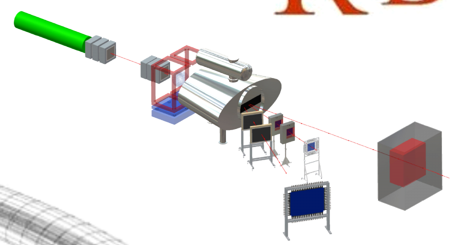
Symmetry energy from dipole polarizability



Thomas Aumann

TECHNISCHE UNIVERSITÄT DARMSTADT

HIC for FAIR Helmholtz International Center

GSI

June 14th 2016

NuSym 2016

Tsinghua University, Beijing

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

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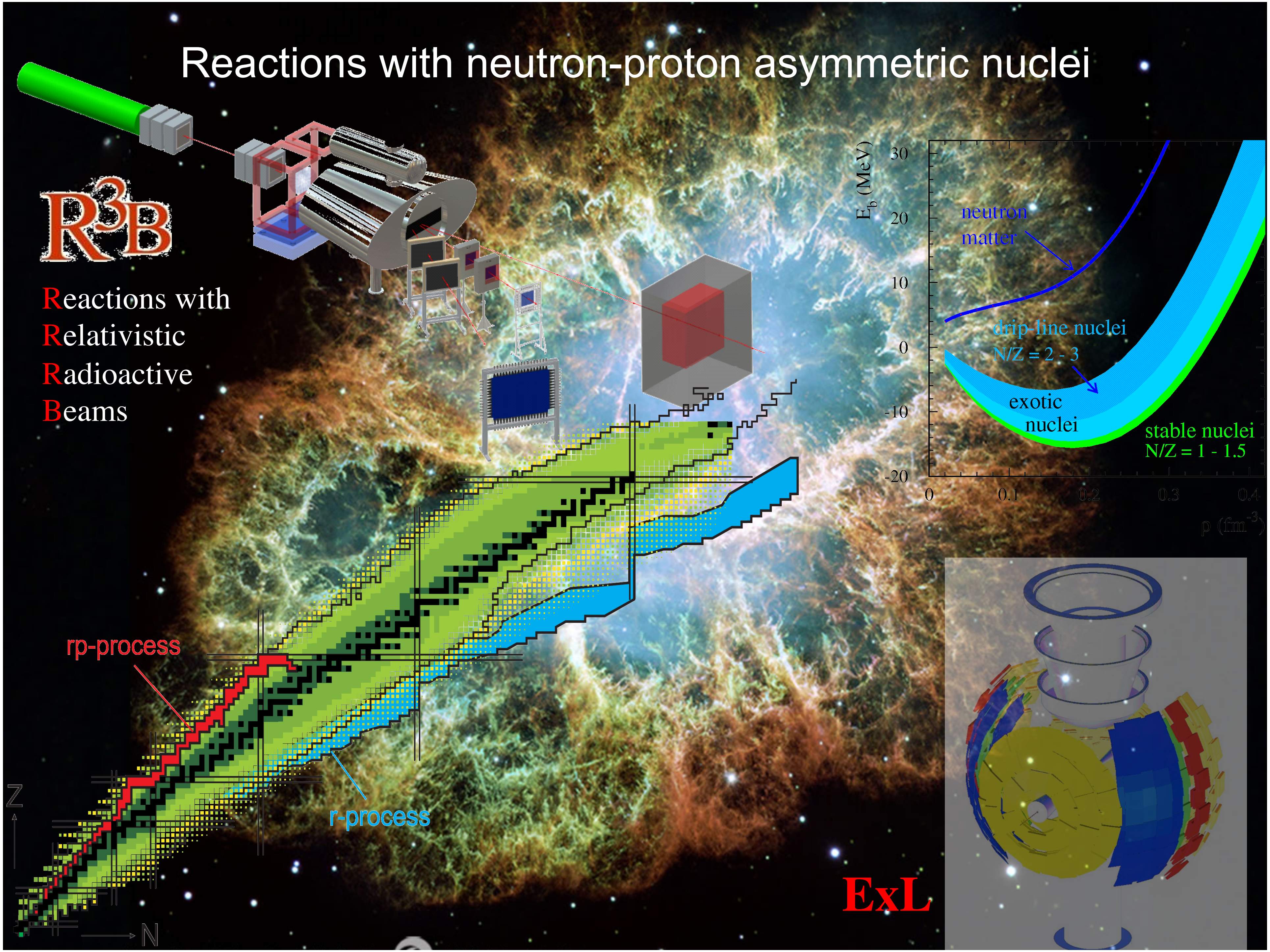
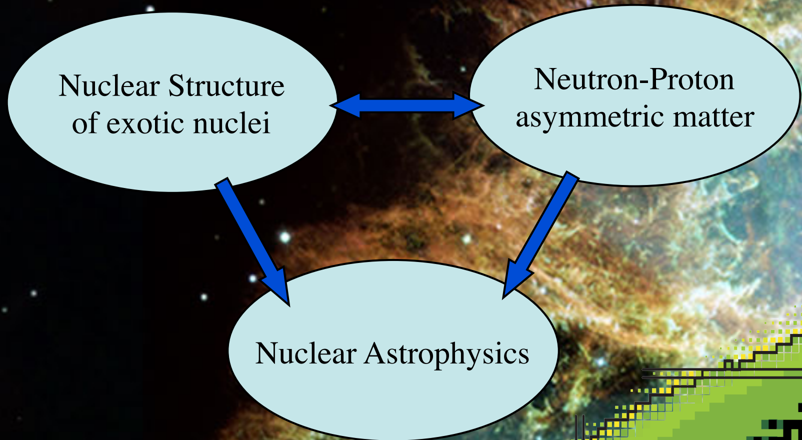
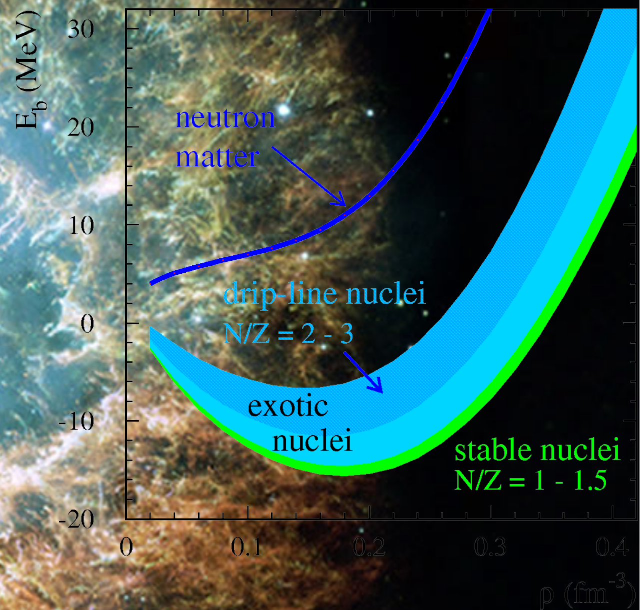
SFB 1245

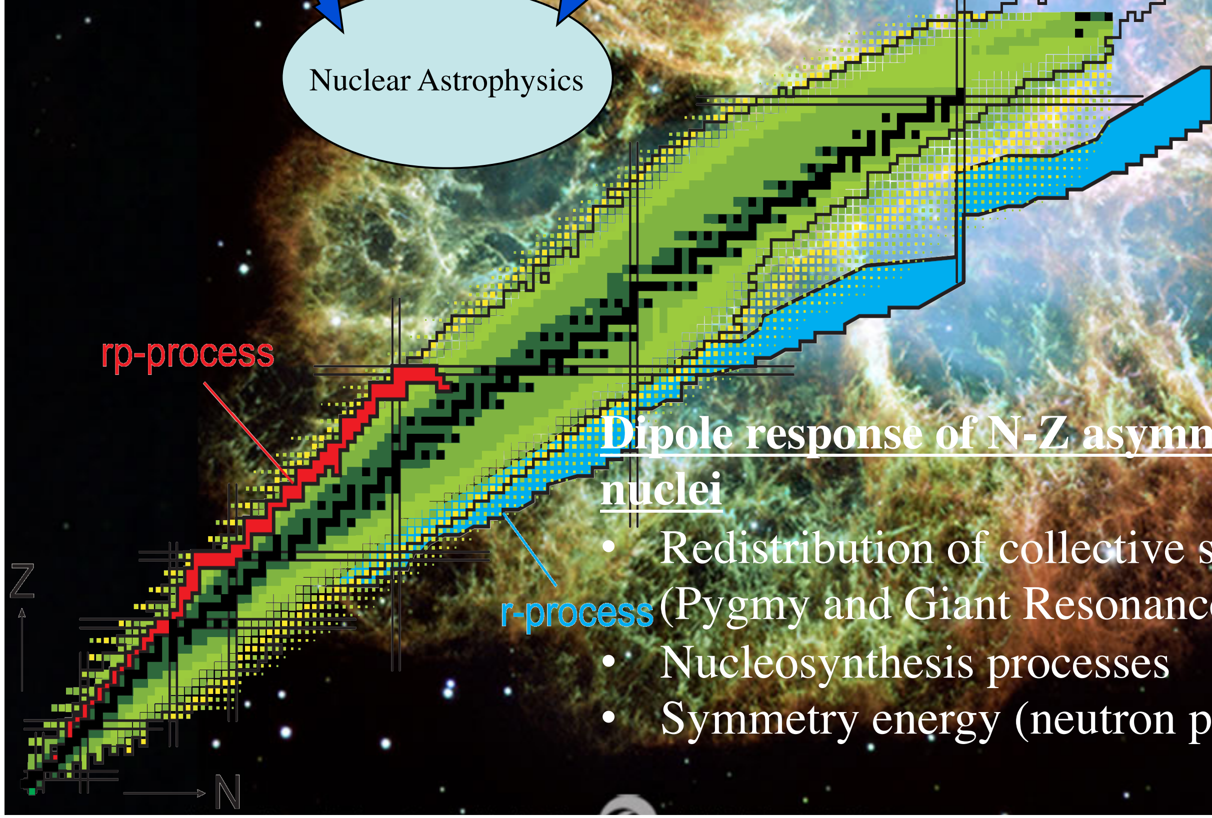

Reactions with neutron-proton asymmetric nuclei
R3B
Reactions with
Relativistic
Radioactive
Beams
E_b (MeV)
30
20
10
0
-10
-20
0
0.1
0.2
0.3
0.4
ρ (fm^-3)
neutron
matter
drip-line nuclei
N/Z = 2 - 3
exotic
nuclei
stable nuclei
N/Z = 1 - 1.5
rp-process
r-process
Z
N
ExL

Reactions with neutron-proton asymmetric nuclei

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

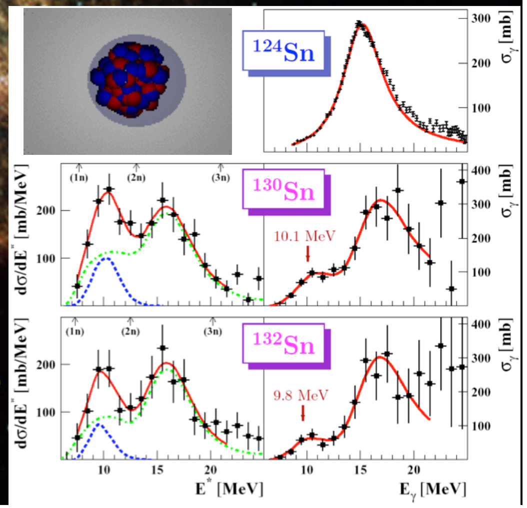






Dipole response of N-Z asymmetric nuclei

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



Constraining EoS by nuclear properties: possible experiments with radioactive beams

Relativistic Coulomb excitation and invariant-mass spectroscopy:

R3B at GSI and FAIR, EXL at HESR up to 5 GeV/nucleon

-> **Dipole polarizabilty**

Inelastic alpha scattering

EXL at ESR and/or at HESR at FAIR

-> **Giant Monopole Resonance**

Elastic proton scattering

EXL at at ESR and/or at HESR at FAIR, active target at R3B

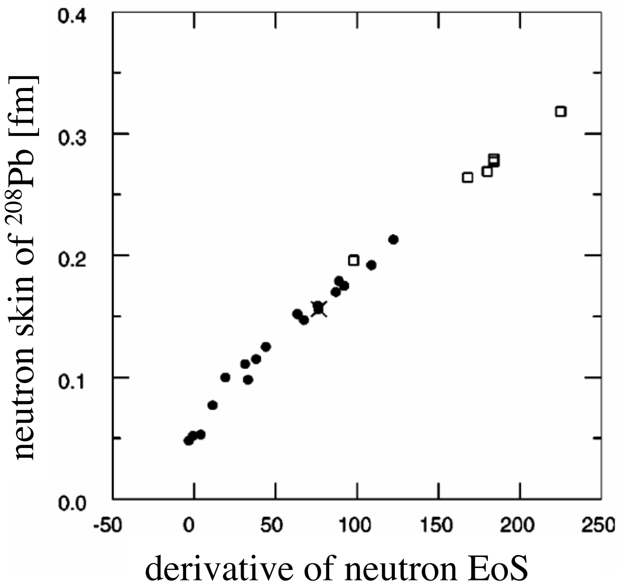
Elastic electron scattering

SCRIT at RIKEN, ELISe at ESR at FAIR

Isotope shift measurements (LASPEC at FAIR)

-> **Neutron-skin thickness**

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



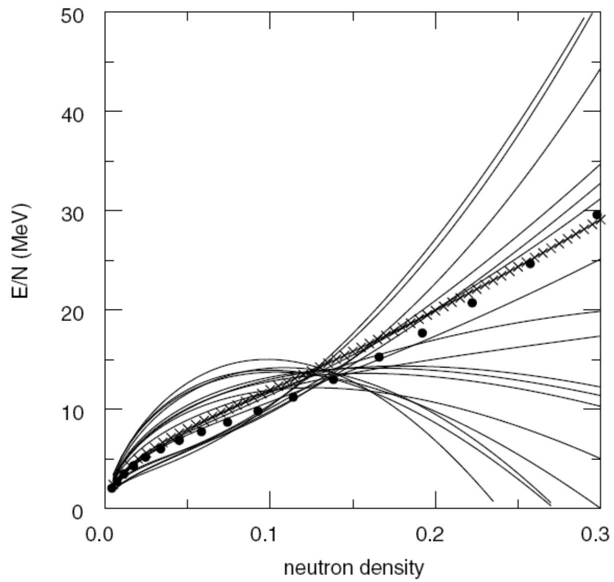
S. Typel and B.A. Brown,
*Phys. Rev. C **64** (2001) 027302*

- strong <u>linear</u> correlation between neutron skin thickness and parameters **a_4, p_0 (J, L)**

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

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

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

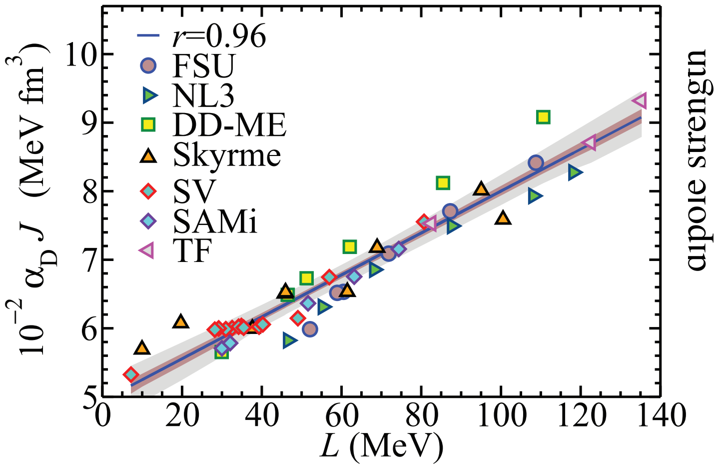


Alex Brown,
PRL 85 (2000) 5296

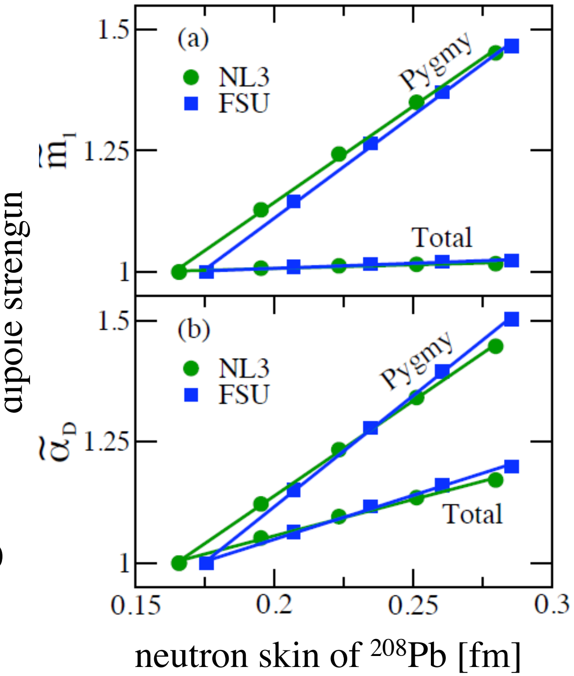
Symmetry energy and dipole response

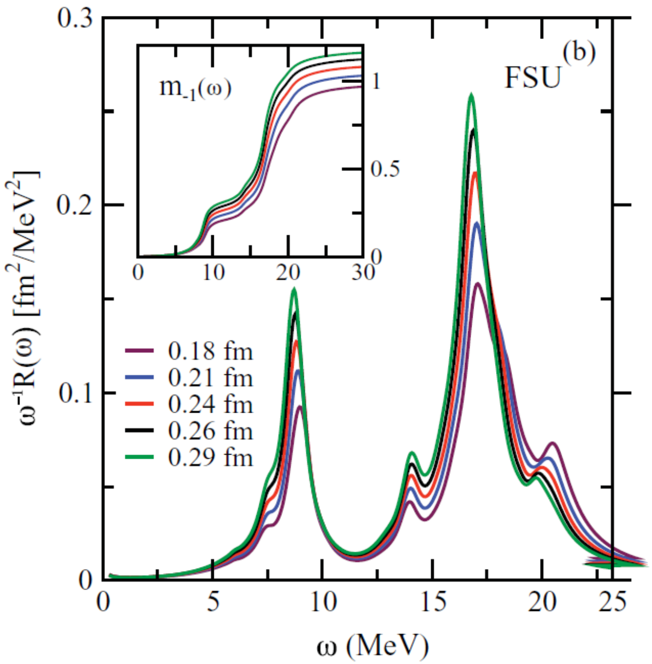
polarizability
dipole response ⟺ density dependence of symmetry energy ⟺ properties of neutron-rich matter

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



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





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

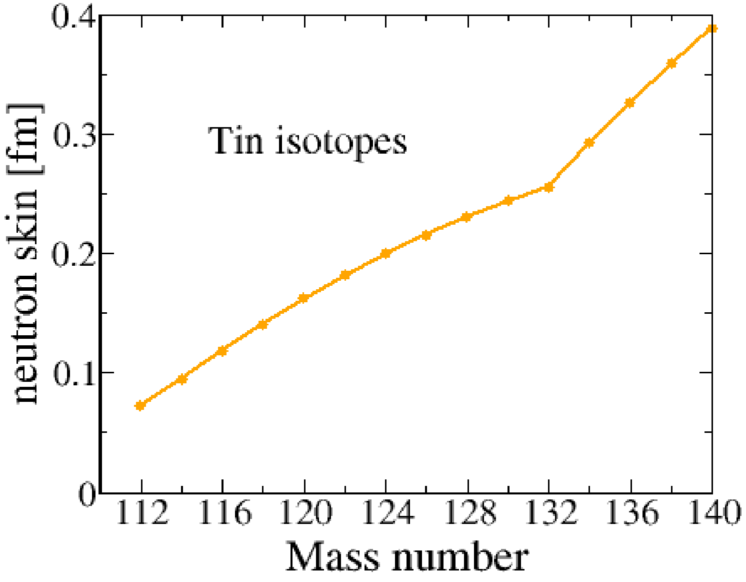
n-skin / (L, J) from Pygmy strength →
J. Piekarewicz,PRC 73, 044325 (2006)
A. Klimkiewicz et al., PRC 76 (2007) 051603(R)
A. Carbone et al., PRC 81 (2010) 041301(R)

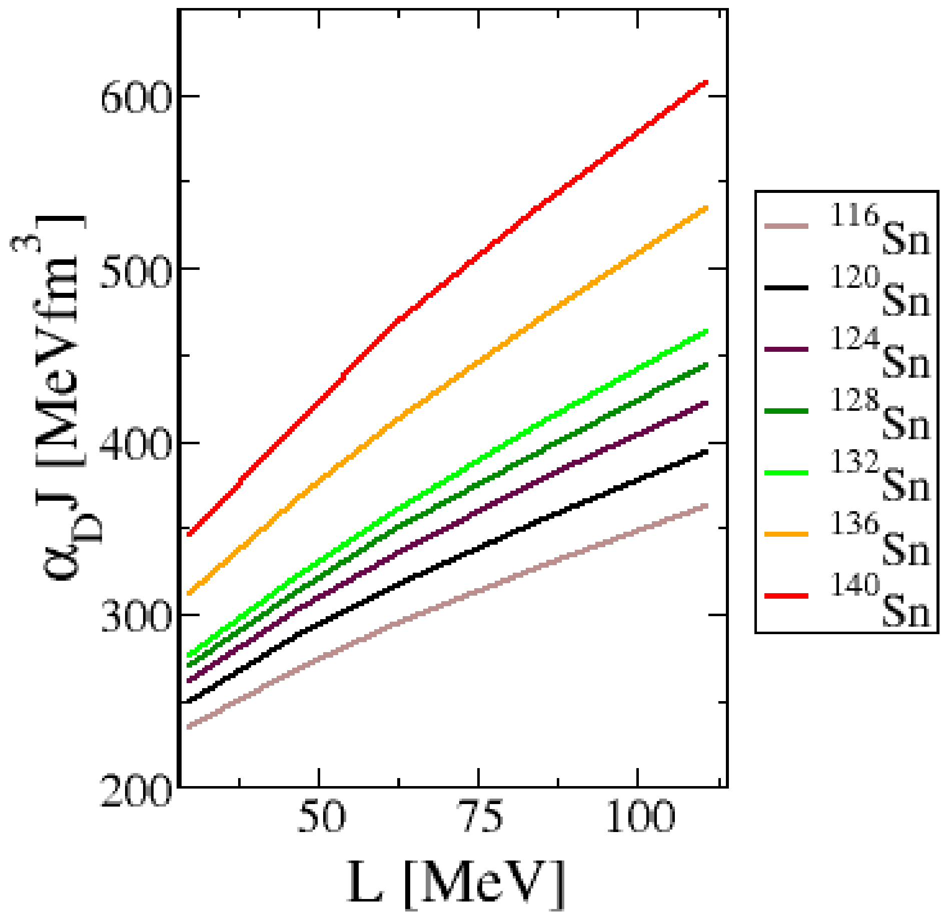
n-skin / (L, J) from polarizability →
P.-G. Reinhard, W. Nazarewicz, PRC 81 (2010) 051303(R)
A. Tamii et al., Phys. Rev. Lett. 107 (2011) 062502.

Dipole polarizability and neutron skin: neutron-rich nuclei

Relativistic Mean Field Calculation
by Andrea Horvat

Higher sensitivity for n-rich nuclei

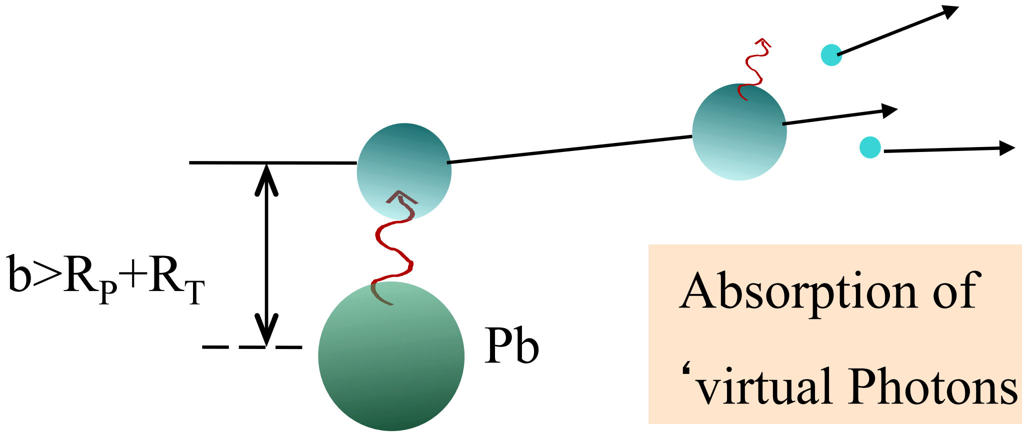




Calculation using RHB+RQRPA framewoork with DD-ME2* effective interaction

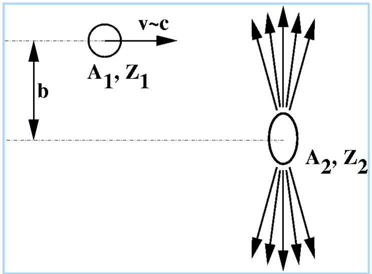
*G. A. Lalazissis, T. Nikšić, D. Vretenar, P. Ring, Phys. Rev. C 71 024312 (2005)

Electromagnetic excitation at high energies



Absorption of 'virtual Photons'

$\sigma_{elm} \sim Z^2$



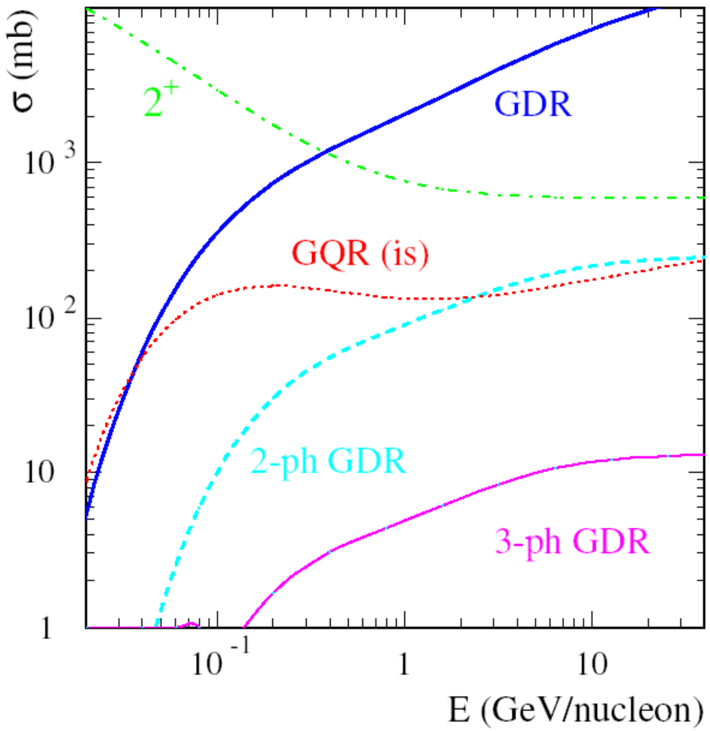
High velocities v/c≈0.6-0.9

⇒ High-frequency Fourier components

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

Semi-classical theory:

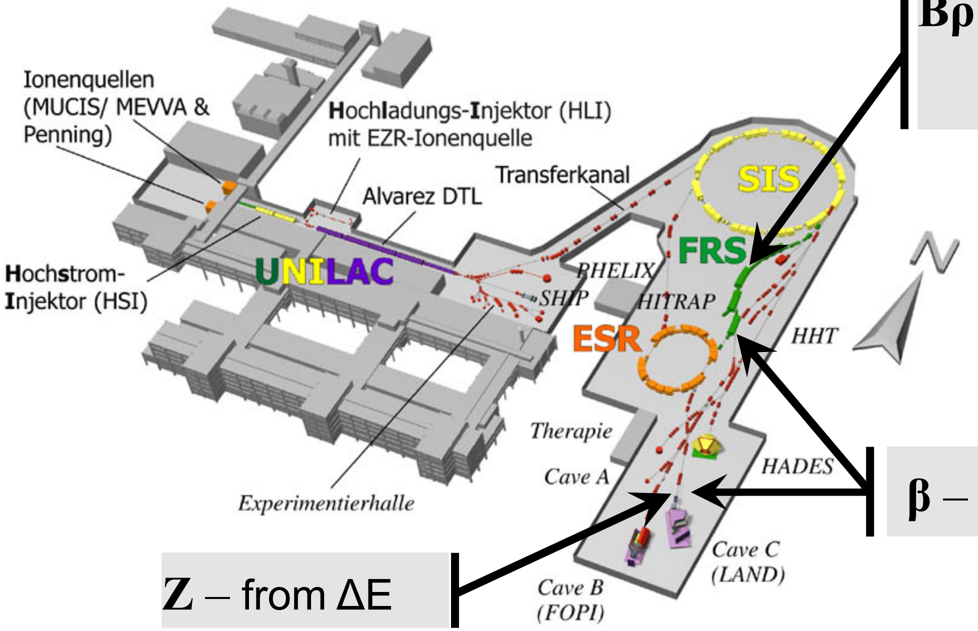
$$d\sigma_{elm} / dE = N_\gamma(E)\, \sigma_\gamma(E)$$



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

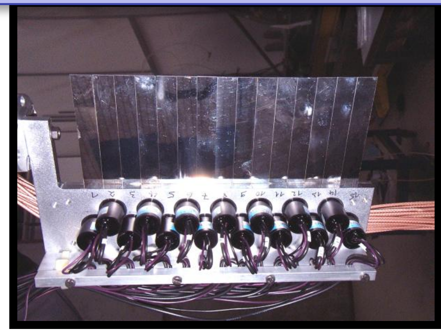
- Stable beams from SIS, fragmentation on Be target or in-flight fission
- Selection of radioactive beams in Fragment Separator (FRS)

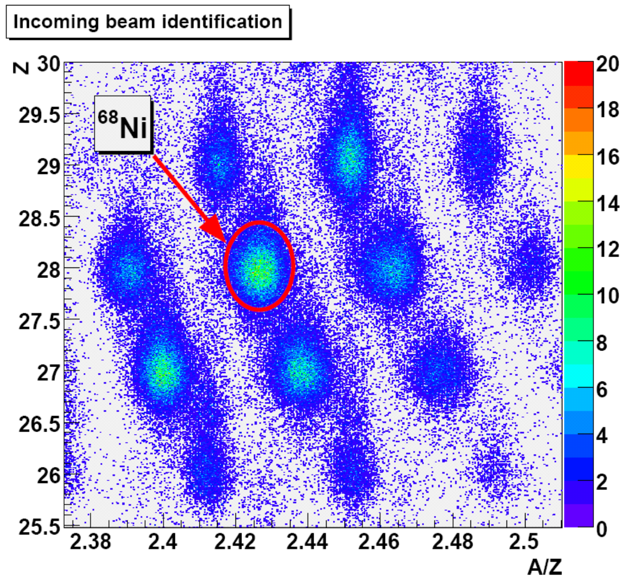


Bρ – from position at middle focal plane of the FRS

β – from TOF

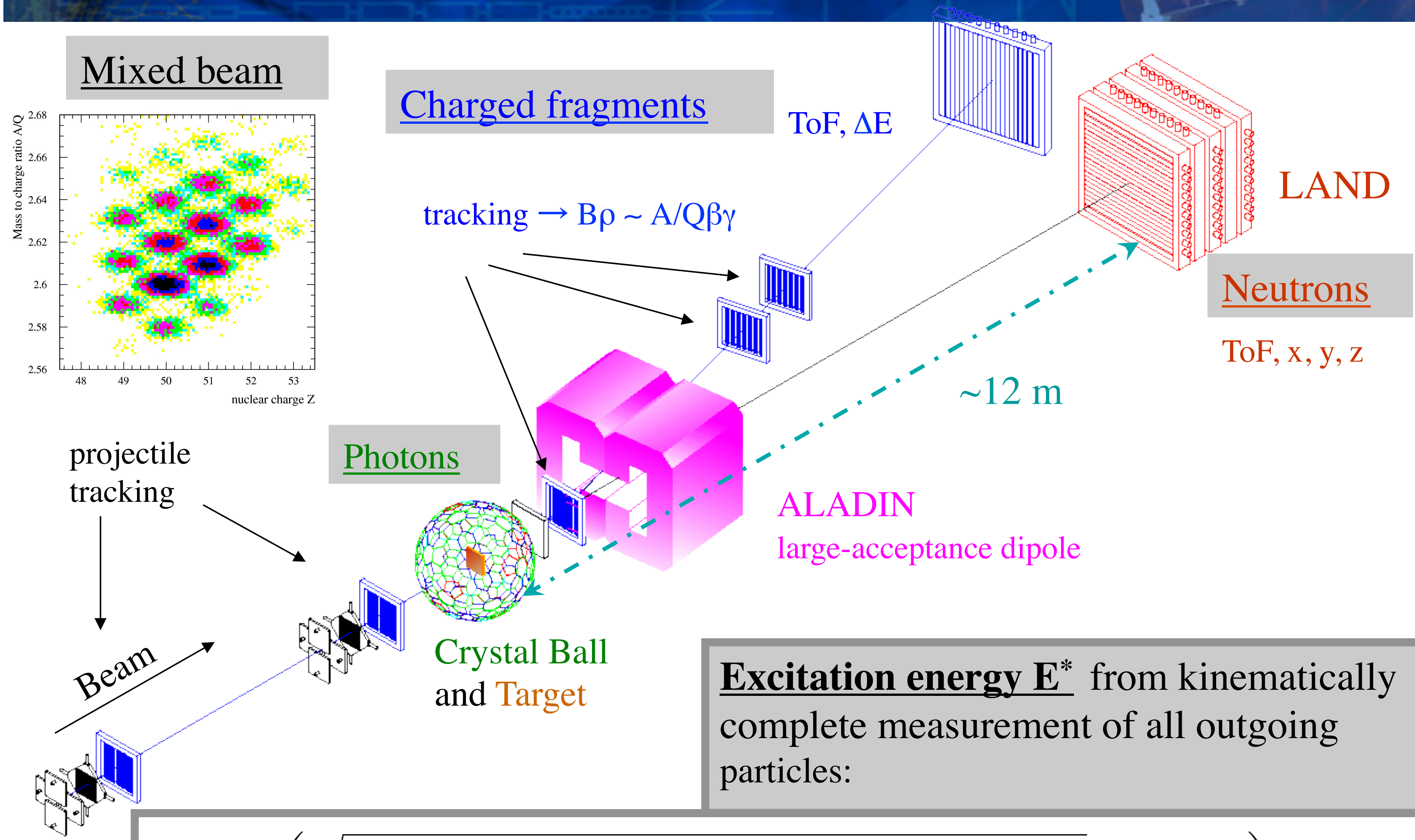
Z – from ΔE





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

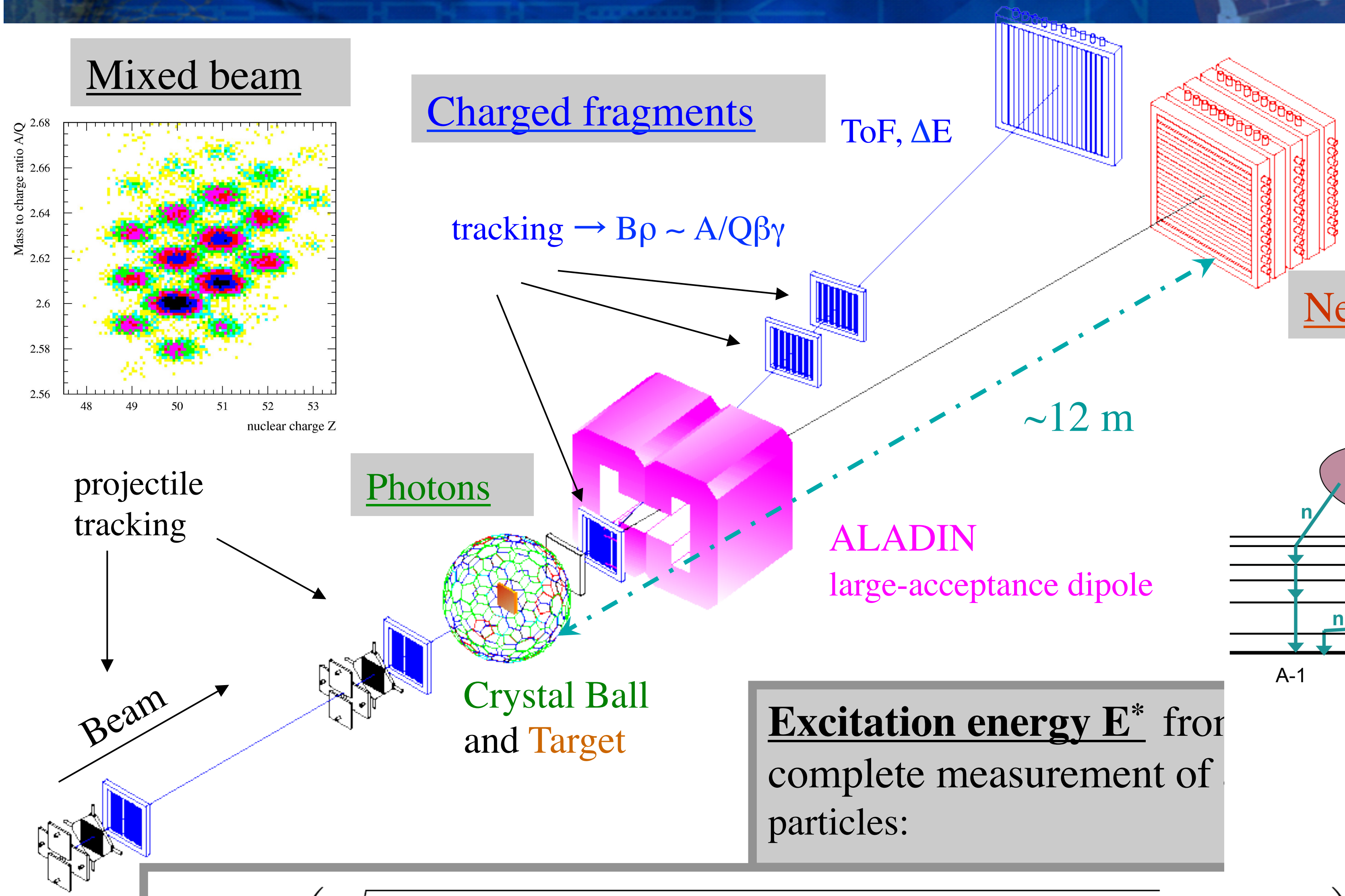
The LAND reaction setup @GSI

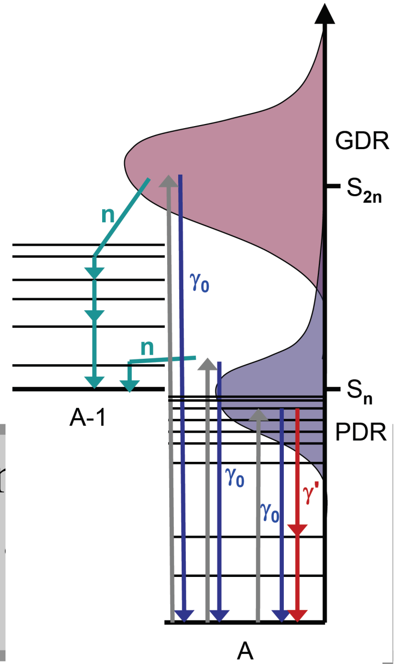


Excitation energy E* from kinematically complete measurement of all outgoing particles:

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

The LAND reaction setup @GSI



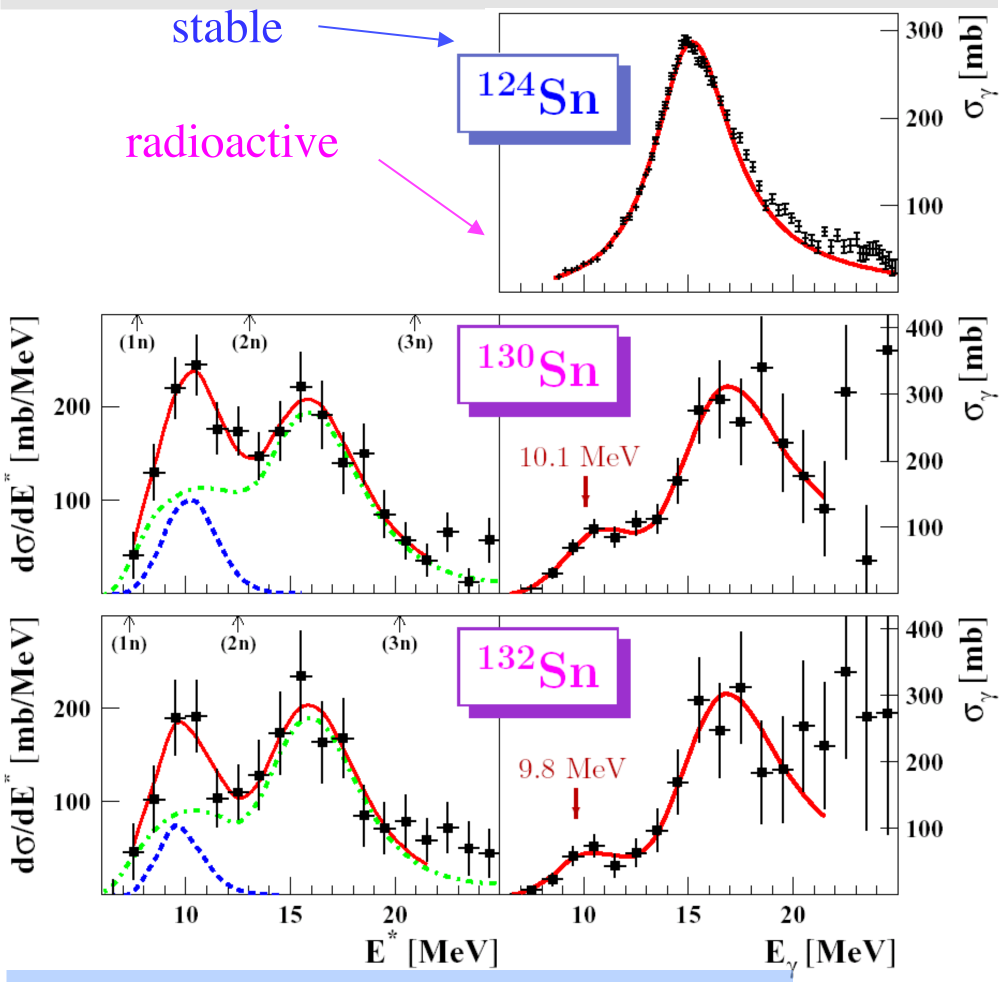


Excitation energy E* from complete measurement of particles:

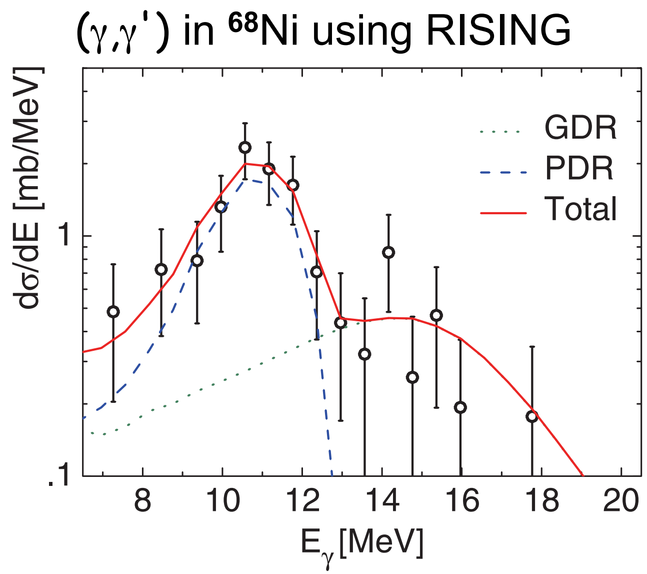
$$E^* = \left(\sqrt{\sum_i m_i^2 + \sum_{i \neq j} m_i m_j \gamma_i \gamma_j (1 - \beta_i \beta_j \cos\theta_{ij})} - m_{proj}\right)c^2 + E_\gamma$$

Previous measurements with radioactive beams

Method: Electromagnetic excitation at relativistic beam energies
(C.A. Bertulani and G. Baur, Phys. Rep. 163, 299 (1988))



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



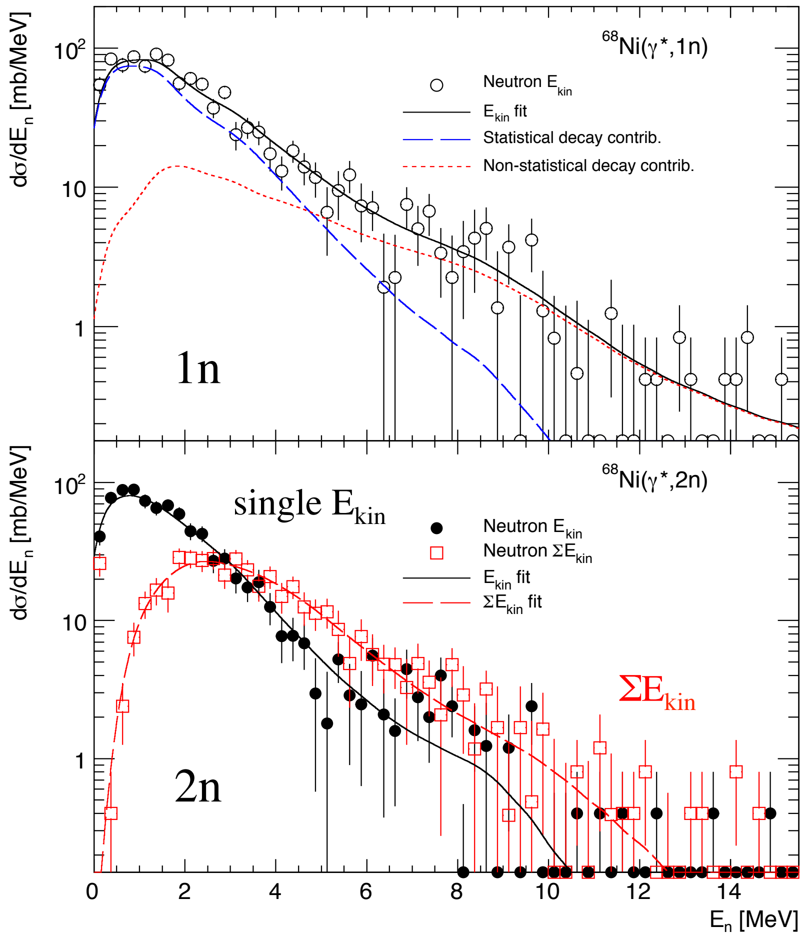
Oliver Wieland et al., PRL 102, 092502 (2009)

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

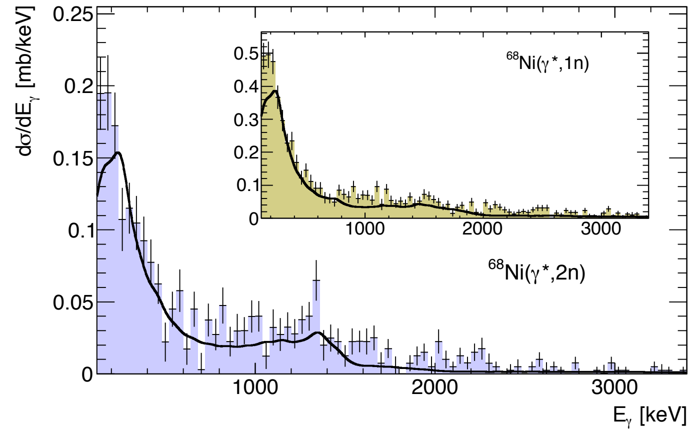
GDR
- no deviation from systematics

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

Neutron kinetic energy



Gamma sum energy



R_{direct} = 24(4) %

<u>consistent fit taking into account:</u>

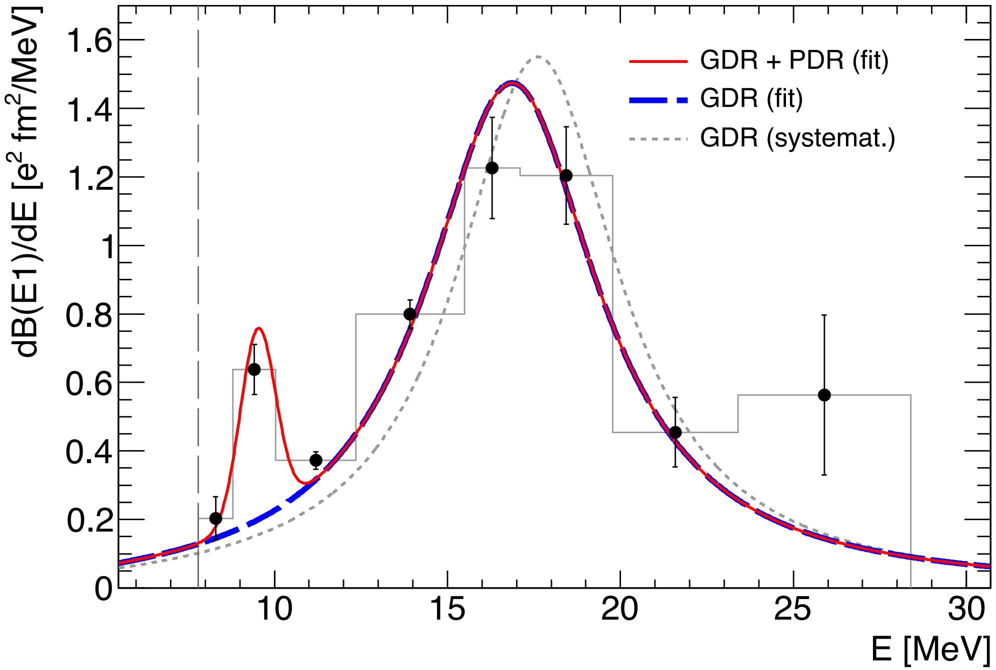
1) invariant mass, but also information of subsets like E_{kin}(n), E_{gsum} etc.

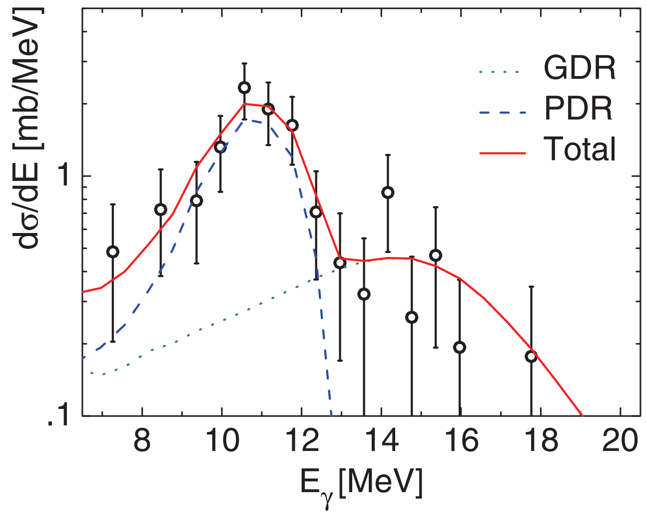
2) detailed knowledge about detector response function

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

Dipole strength distribution of ^{68}Ni

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





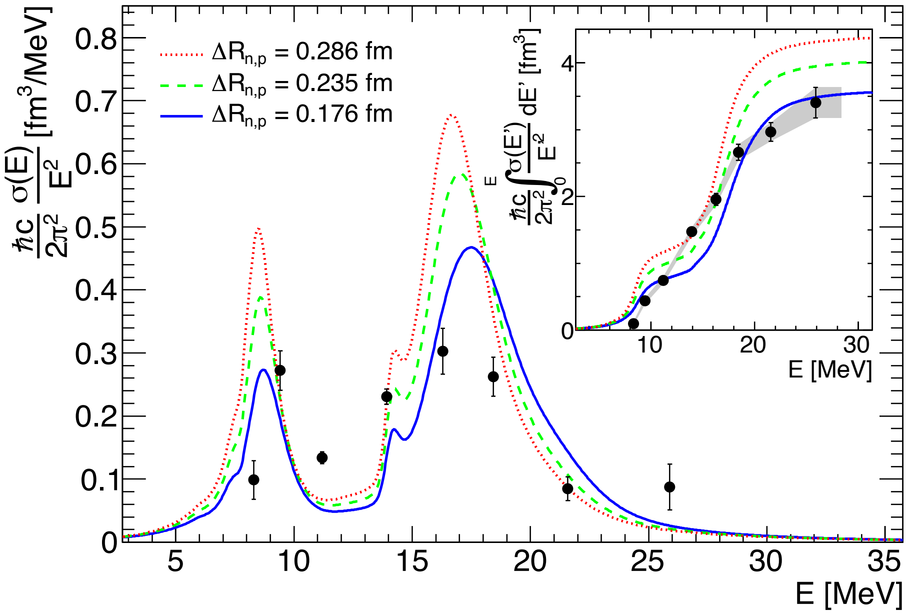
O. Wieland et al., PRL 102, 092502 (2009)

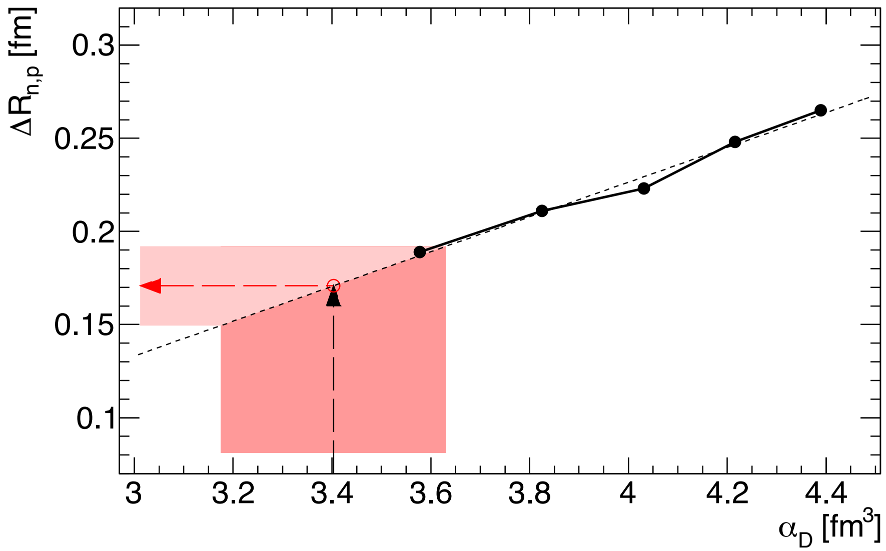
			This work	Lit.	Ref.
	E_m	[MeV]	17.1(2)	17.84	
GDR	Γ	[MeV]	6.1(5)	5.69	[30]
	S_{EWSR}	[%]	98(7)	100	
	E_m	[MeV]	9.55(17)	11	
PDR	σ	[MeV]	0.51(13)	< 1	[13, 25]
	S_{EWSR}	[%]	2.8(5)	5.0(1.5)	

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

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

Polarizability and neutron skin





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

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

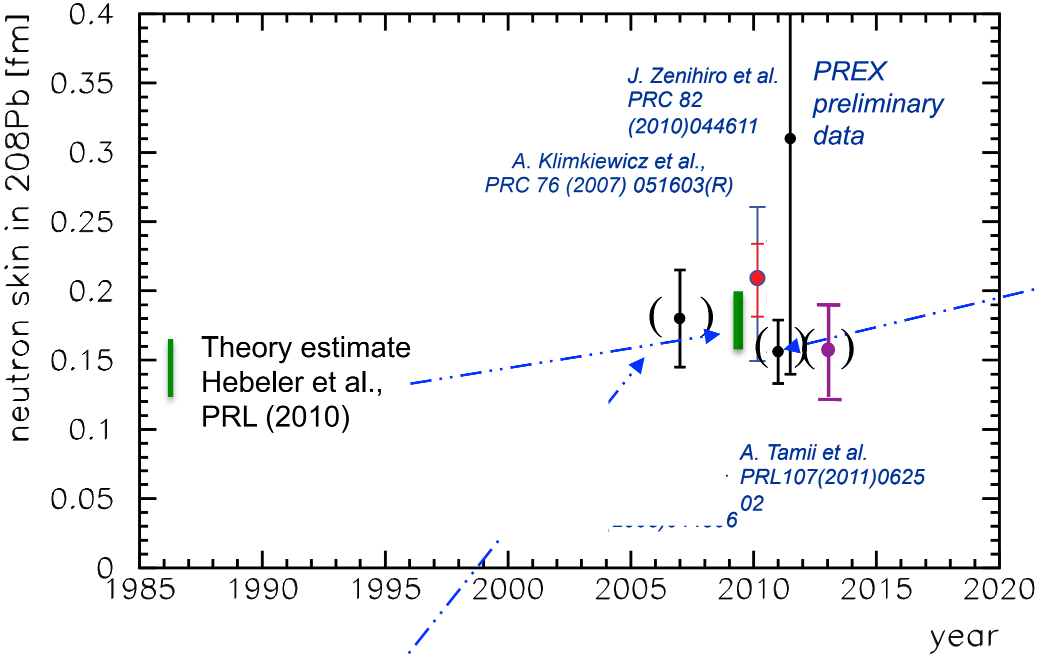
Neutron-skin thickness
Using one particular RMF interaction (Piekarewicz)

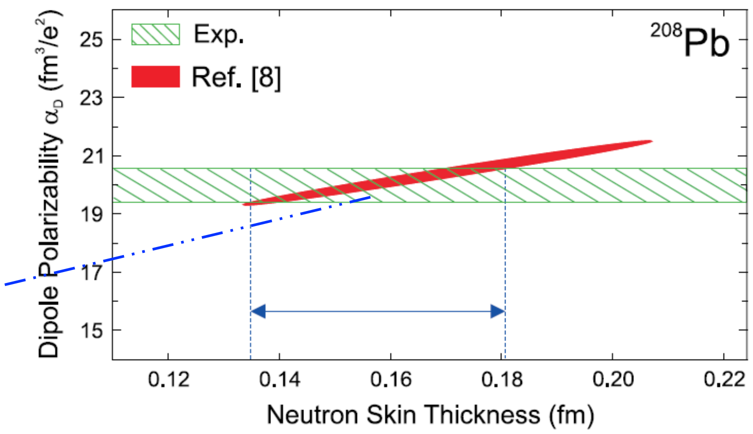
$\Delta R_{n,p} = 0.175(21)$ fm

Extracted value depends on functional used !

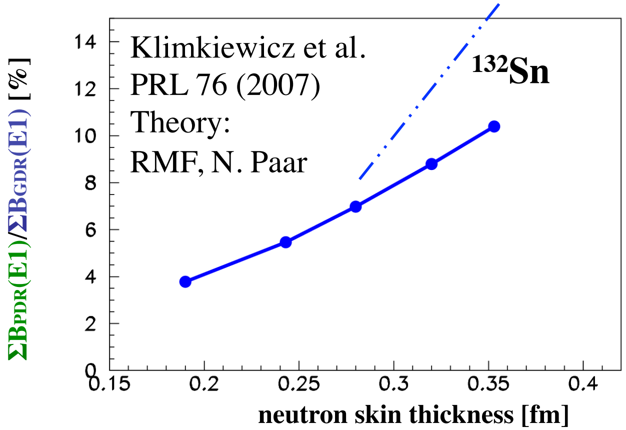
D. Rossi et al., PRL 111 (2013) 242503

Neutron skin in ^{208}Pb from different methods

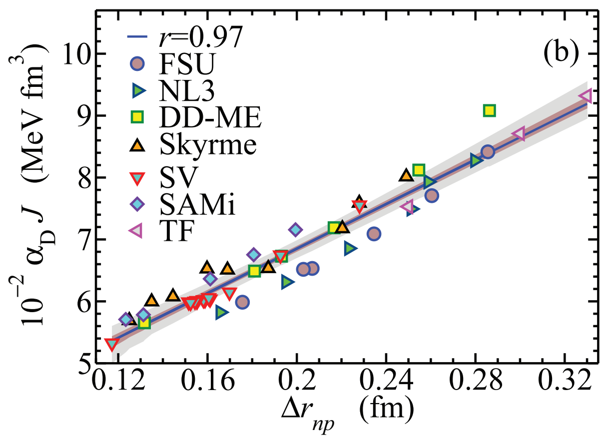


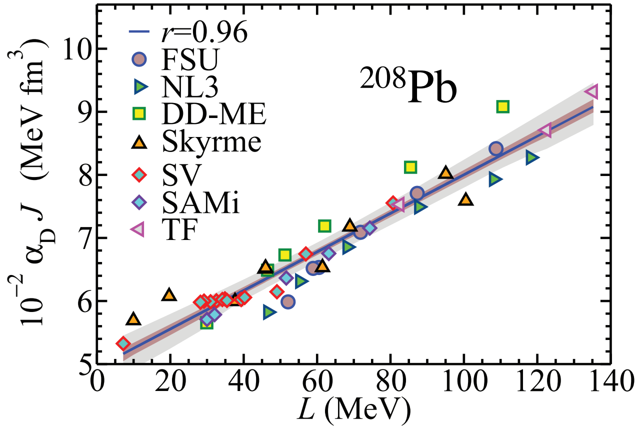


Experiment: Tamii et al., PRL 107 (2011)
Theory: P.-G. Reinhard and W. Nazarewicz,
PRC 81 (2010) 051303(R)

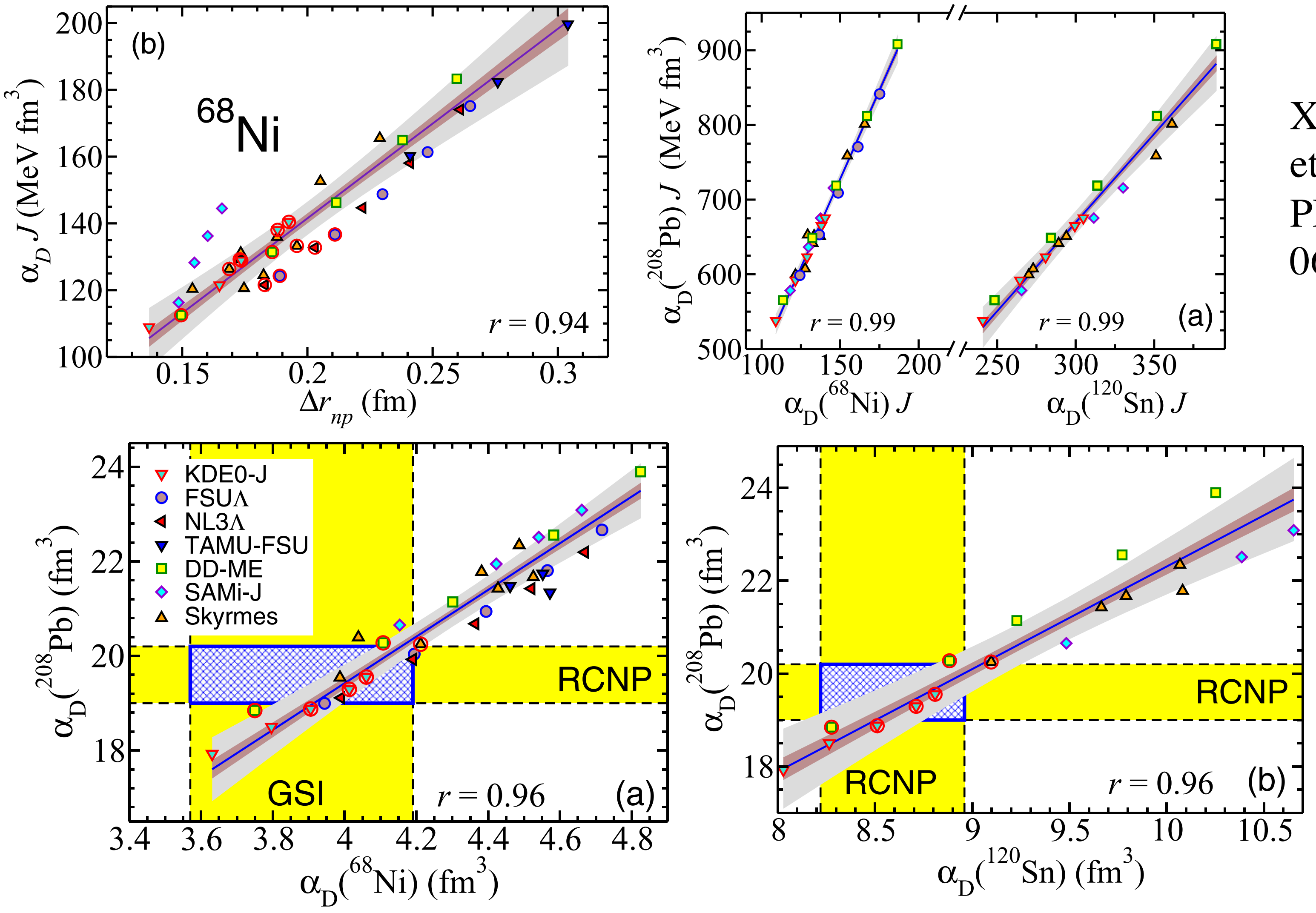


X. Roca-Maza et al., PRC 88 (2013) 024316





Combined analysis of polarizabilities



X. Roca-Maza et al., PRC 92 (2015) 064304

Data:

^{208}Pb: Tamii et al, PRL 107 (2011) 062502

^{68}Ni: D. Rossi et al., PRL 111 (2013) 242503

^{120}Sn: T. Hashimoto et al, PRC 92 (2015) 031305

Constraining symmetry-energy parameters L and J with measurements of the dipole polarizability

Combined analysis of polarizabilities for ^{208}Pb, ^{120}Sn (RCNP), and ^{68}Ni (GSI)

Xavi Roca-Maza et al.,
Phys. Rev. C 92 (2015) 064304

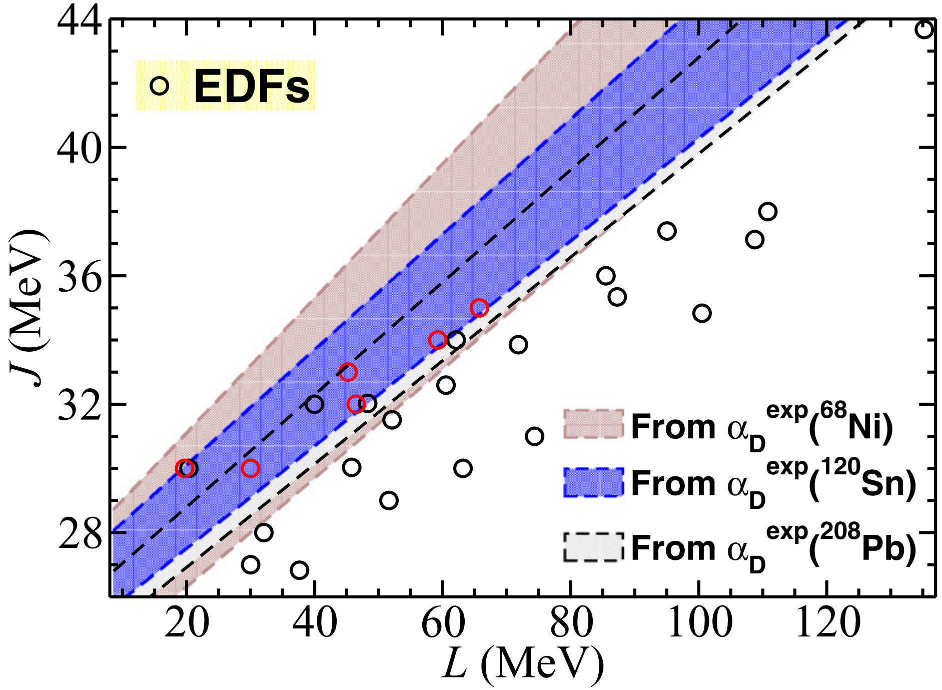


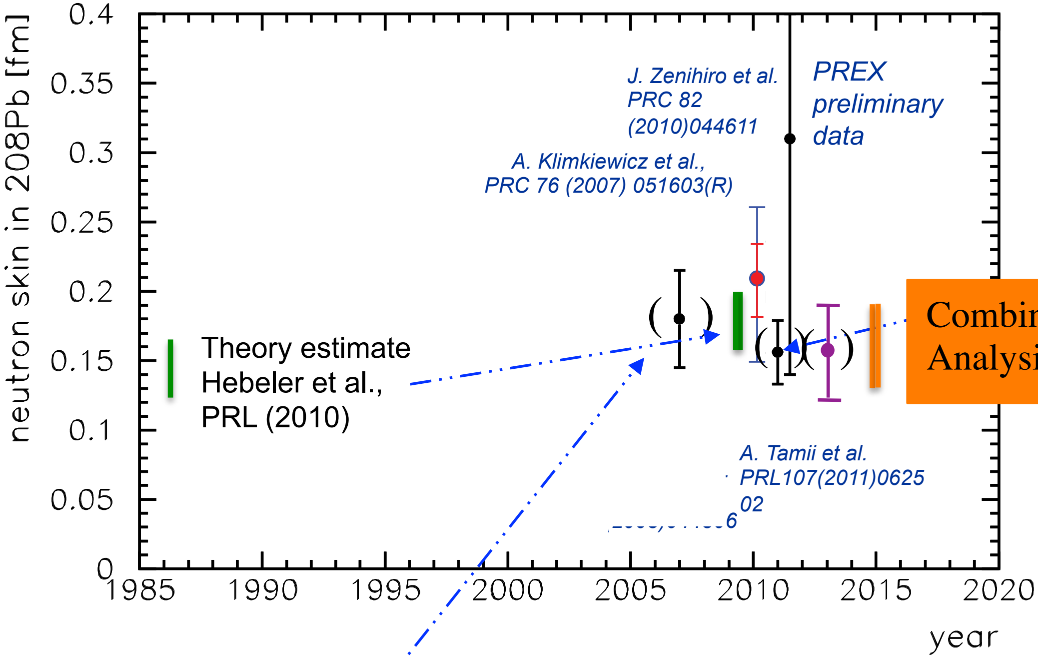
TABLE I. Various estimates of the neutron skin thickness (in fm) of ^{68}Ni, ^{120}Sn, and ^{208}Pb. (a) Lower and upper values of Δr_{np} as predicted by those models that reproduce the experimental values of the electric dipole polarizability of ^{68}Ni, ^{120}Sn, and ^{208}Pb. (b) Mean value and standard deviation of Δr_{np} as predicted by the same subset of models in column (a). (c) Predictions extracted from the correlation $\alpha_D J$-Δr_{np} using a suitable range for the symmetry energy coefficient J (see text for details).

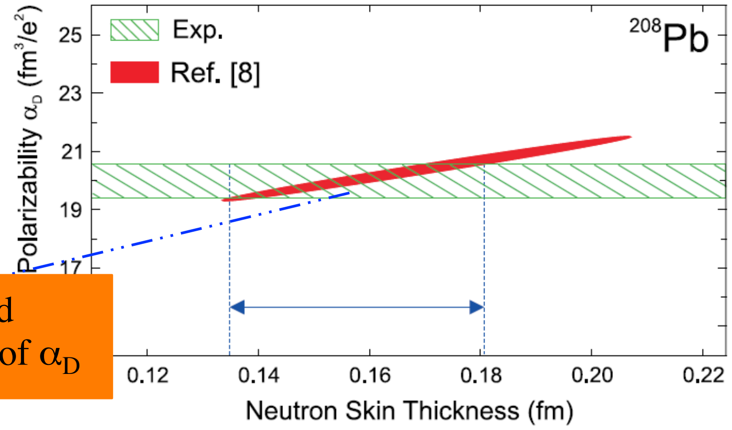
Nucleus	Δr_{np} (a)	Δr_{np} (b)	Δr_{np} (c)
^{68}Ni	0.15–0.19	0.18 ± 0.01	0.16 ± 0.04
^{120}Sn	0.12–0.16	0.14 ± 0.02	0.12 ± 0.04
^{208}Pb	0.13–0.19	0.16 ± 0.02	0.16 ± 0.03

$$30 \leqslant J \leqslant 35\,\text{MeV}$$

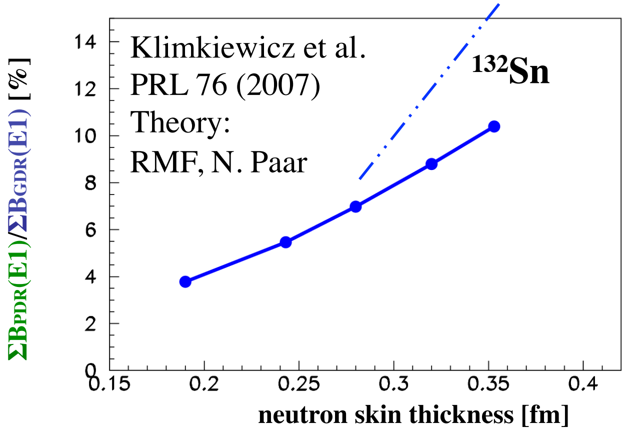
$$20 \leqslant L \leqslant 66\,\text{MeV}$$

Neutron skin in ^{208}Pb from different methods

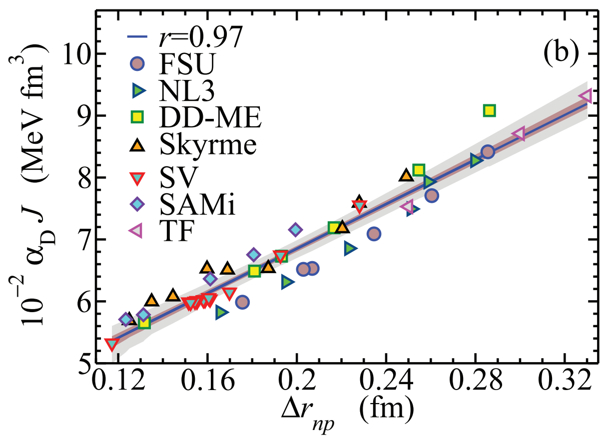


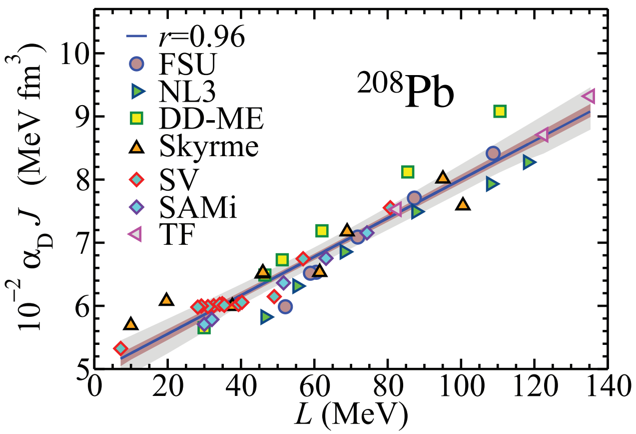


Experiment: Tamii et al., PRL 107 (2011)
Theory: P.-G. Reinhard and W. Nazarewicz, PRC 81 (2010) 051303(R)



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





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. Winkler[1]

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[18] *ExtreMe Matter Institute EMMI and Research Division, GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany*
[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, RCNP, …
    - 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