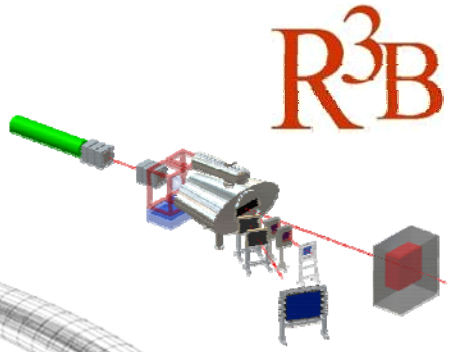
The dipole response of neutron-rich nuclei investigated at R3B



Thomas Aumann

August 12th 2014

PKU-CUSTIPEN Nuclear Reaction Conference 2014

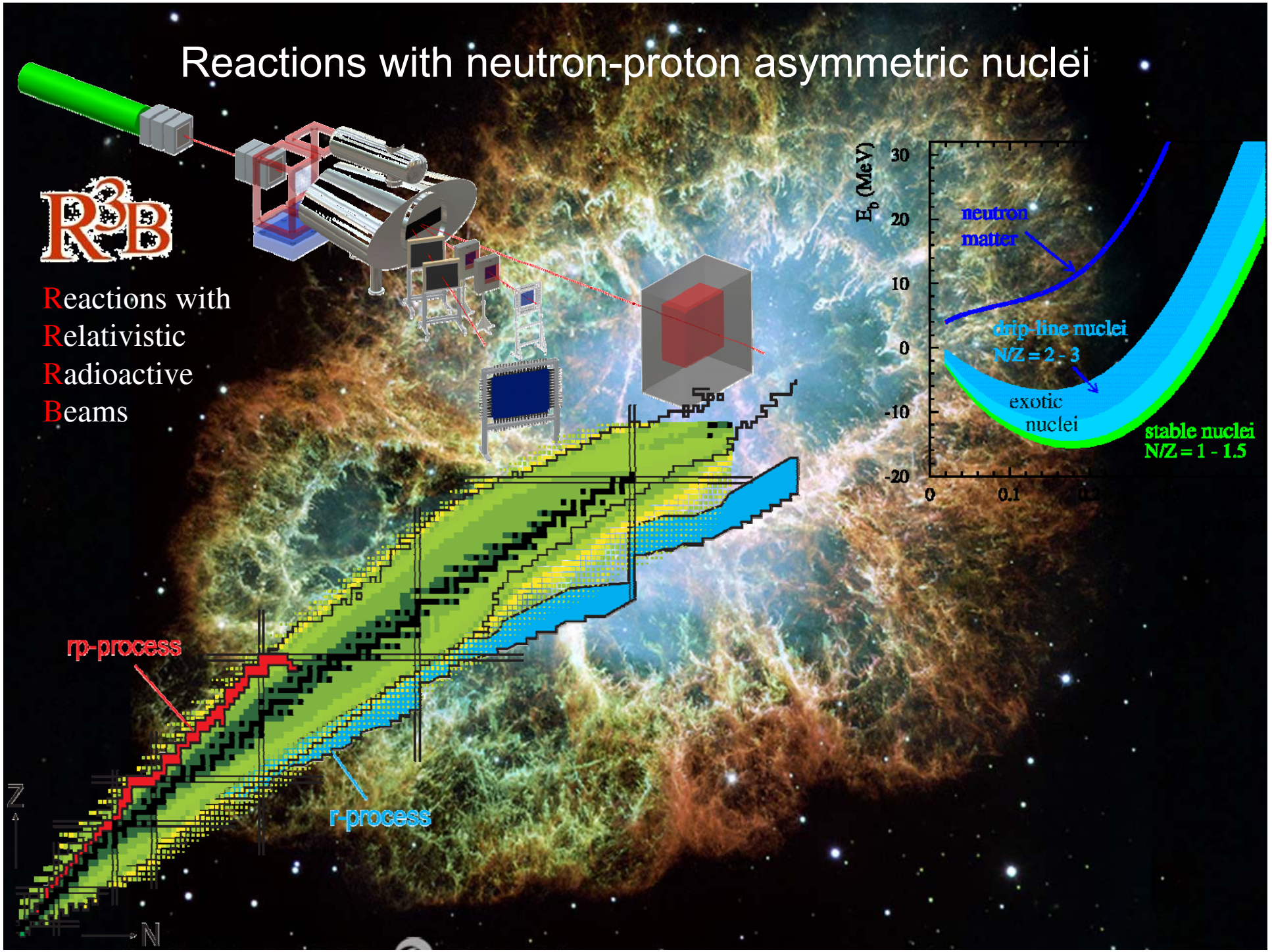
Peking University

GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

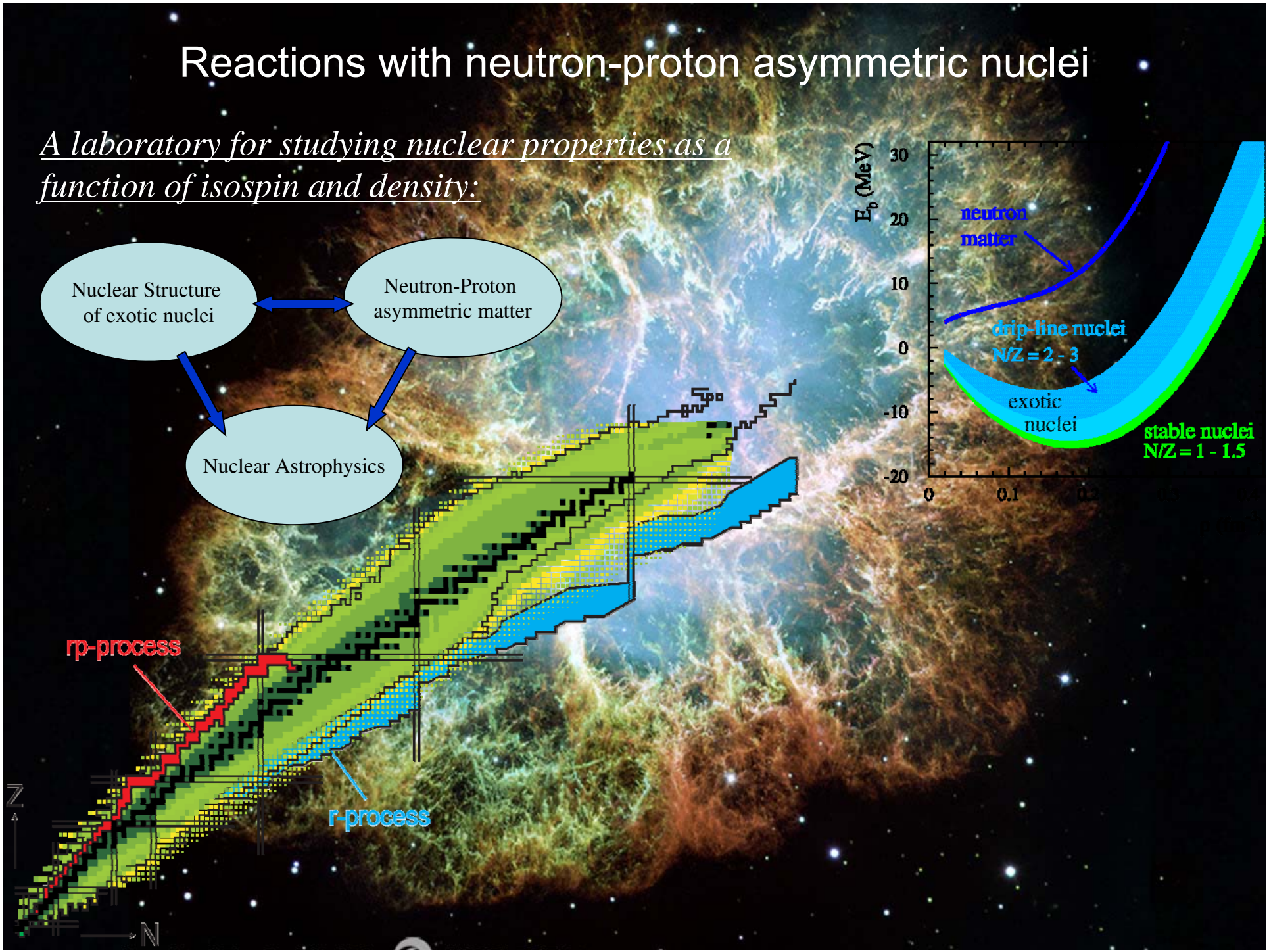
Supported by the BMBF under contract no 05P12RDFN8

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:



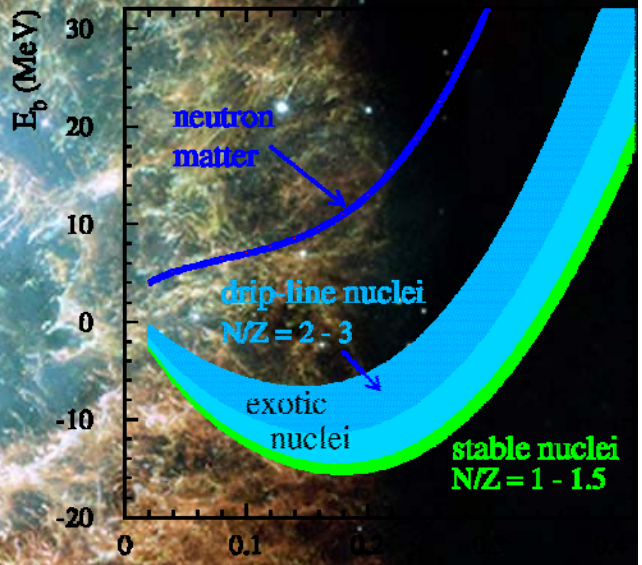
Reactions with neutron-proton asymmetric nuclei

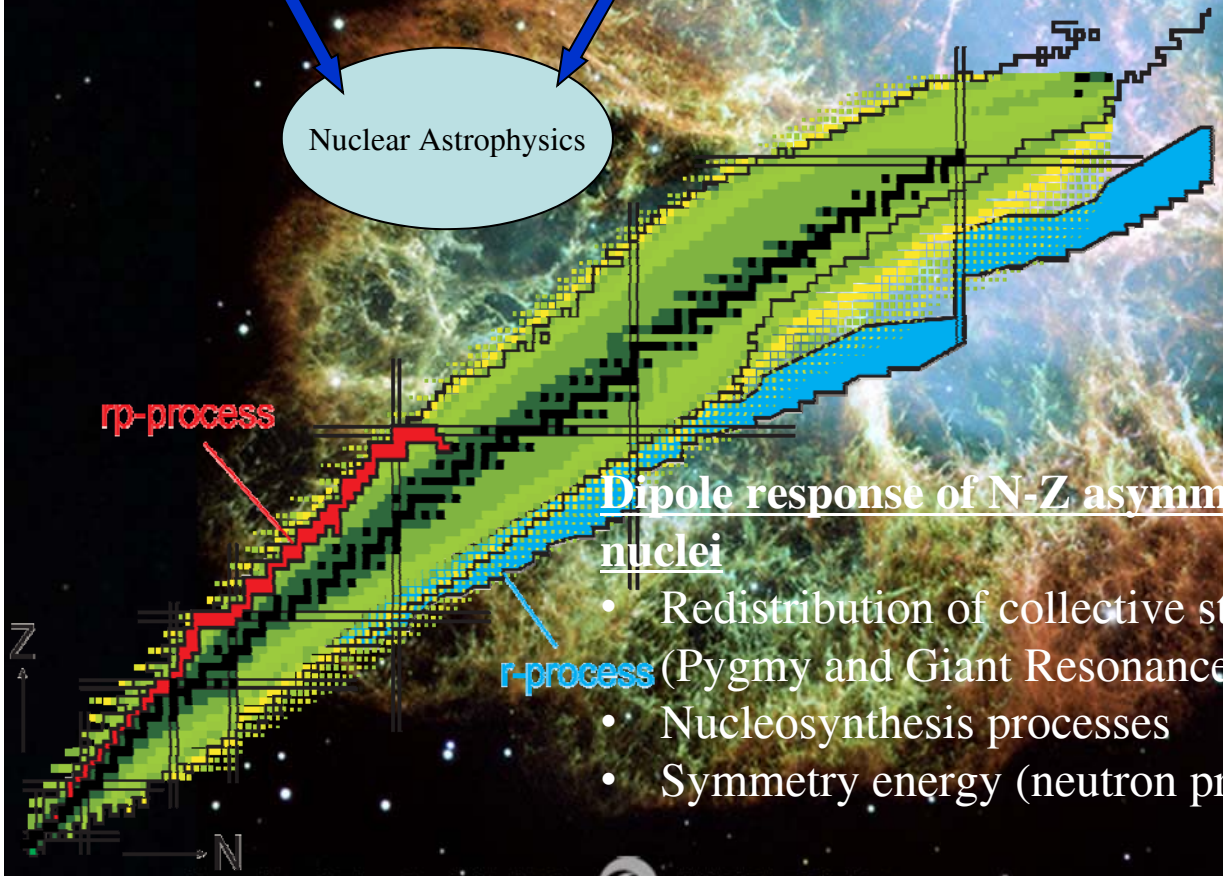
A laboratory for studying nuclear properties as a function of isospin and density:

Nuclear Structure of exotic nuclei

Neutron-Proton asymmetric matter

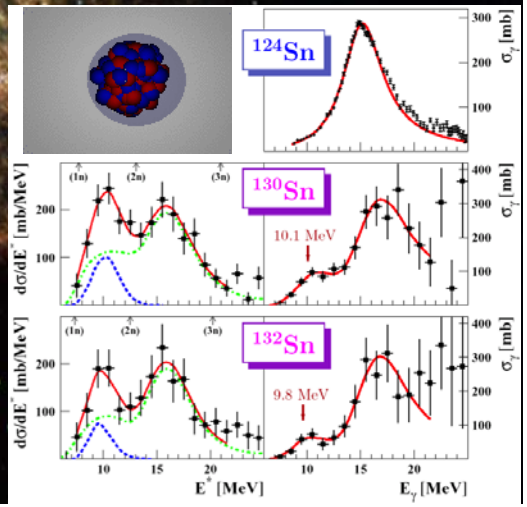
Nuclear Astrophysics





Dipole response of N-Z asymmetric nuclei

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



The collective response of the nucleus: Giant Resonances

Electric giant resonances

Isoscalar

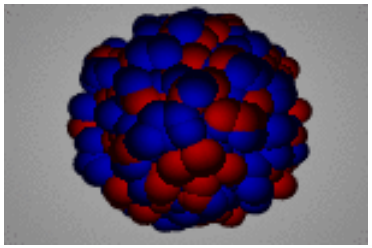
Isovector

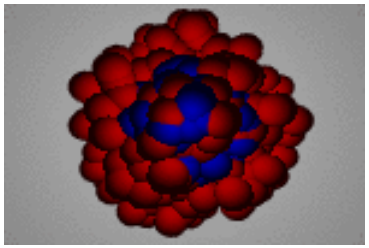
Photo-neutron cross sections

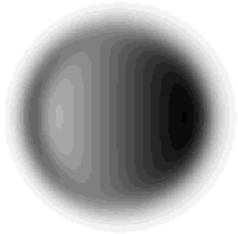
Monopole (GMR)

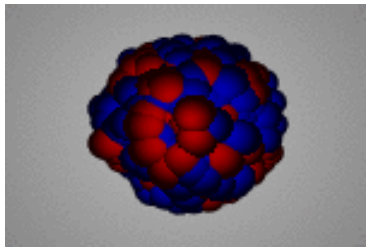
Dipole (GDR)

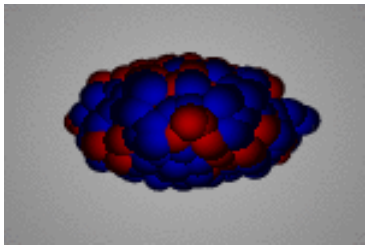
Quadrupole (GQR)

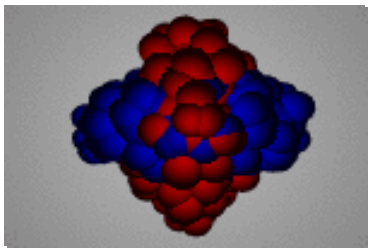


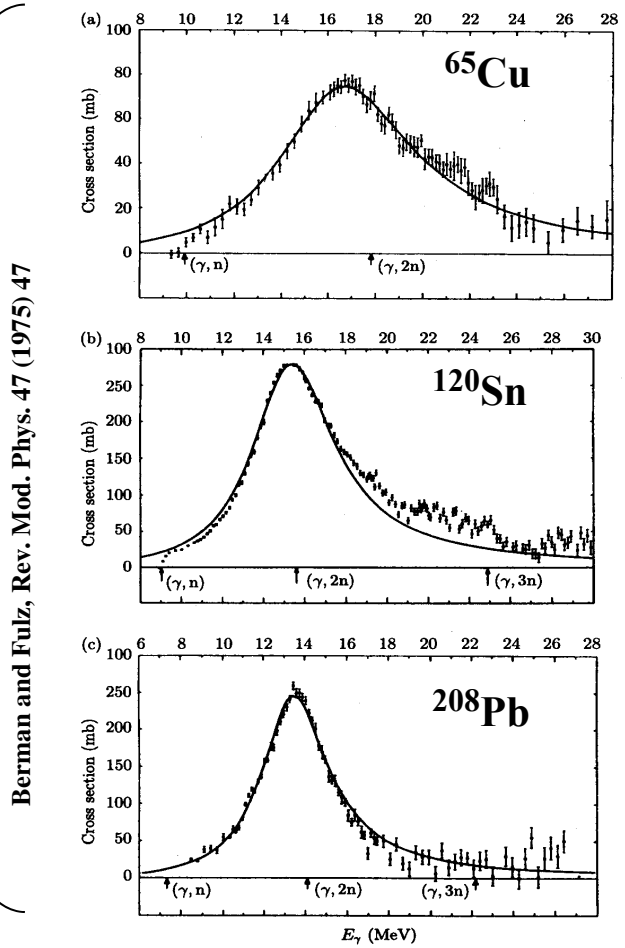






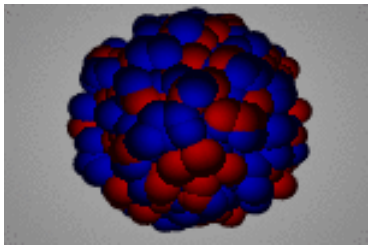
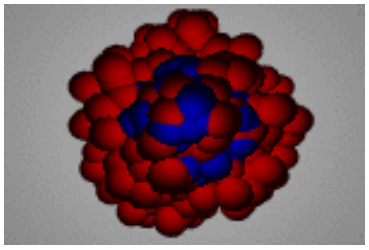
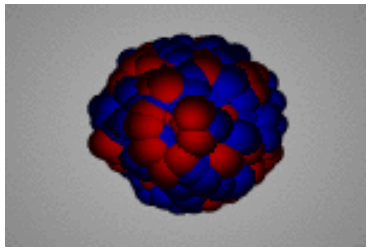
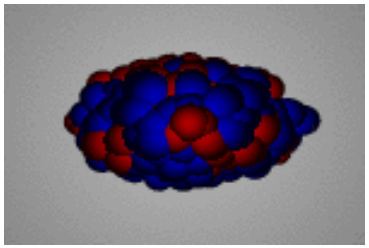
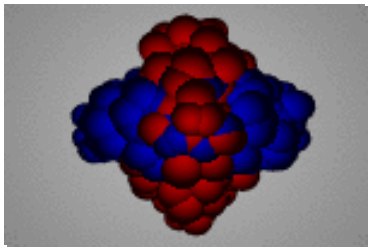






The collective response of the nucleus: Giant Resonances

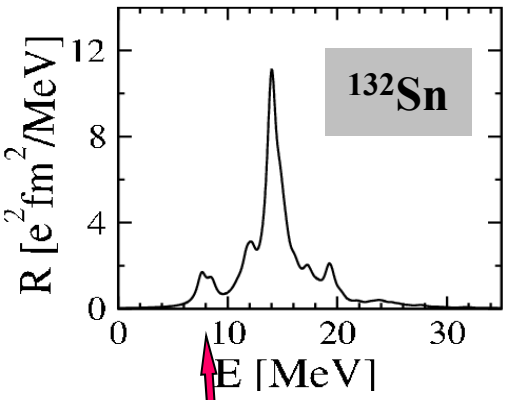
Electric giant resonances

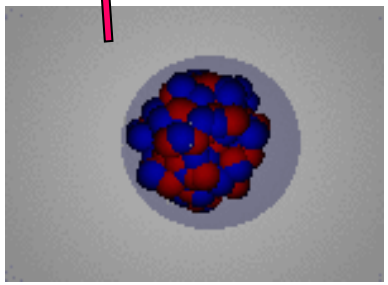
	Isoscalar	Isovector
Monopole (GMR)		
Dipole (GDR)		
Quadrupole (GQR)		

? new collective soft dipole mode

(Pygmy resonance)

Prediction: RMF
(N. Paar et al.)

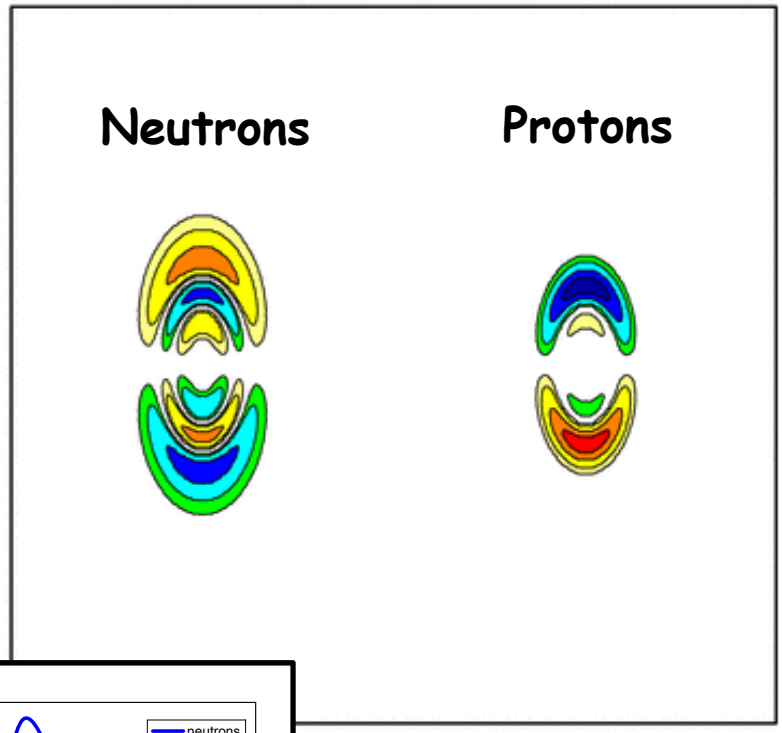


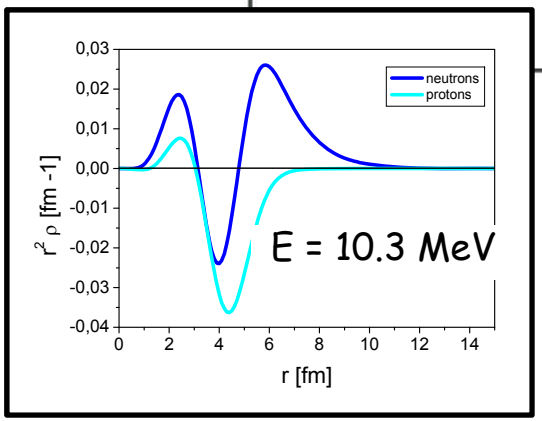


Figures by P. Adrich (GSI / Krakow)

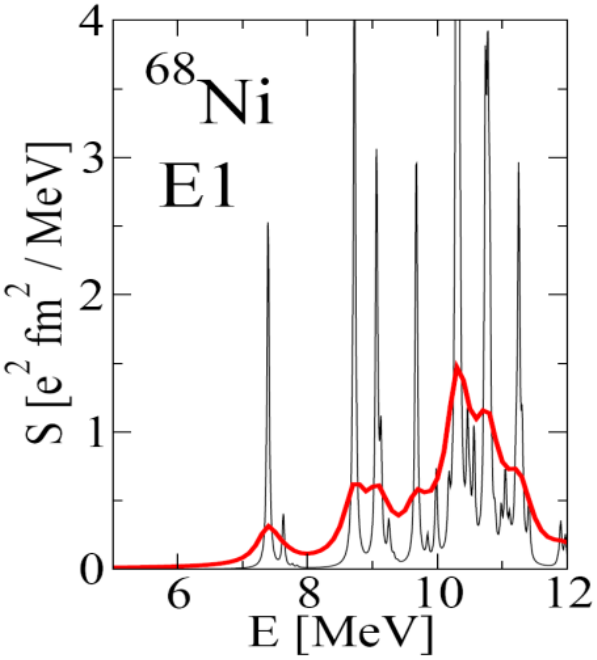
The Pygmy Dipole Resonance (PDR)
Relativistic mean-field theory

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



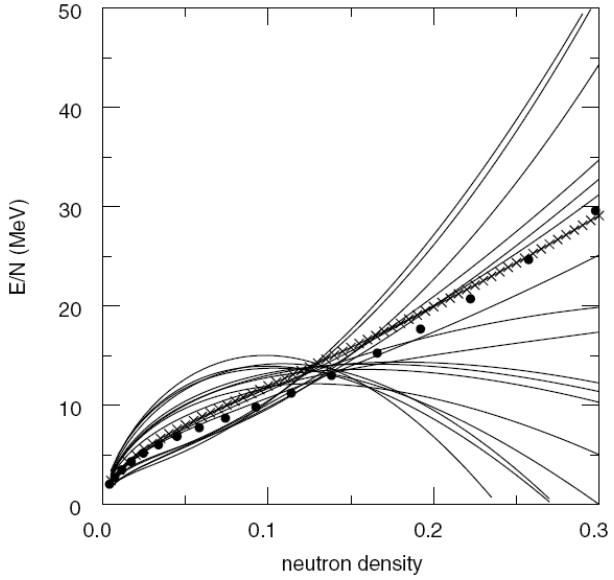


Theory: RQTBA-2



Theory:
Elena Litvinova (GSI, WMU&MSU)

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

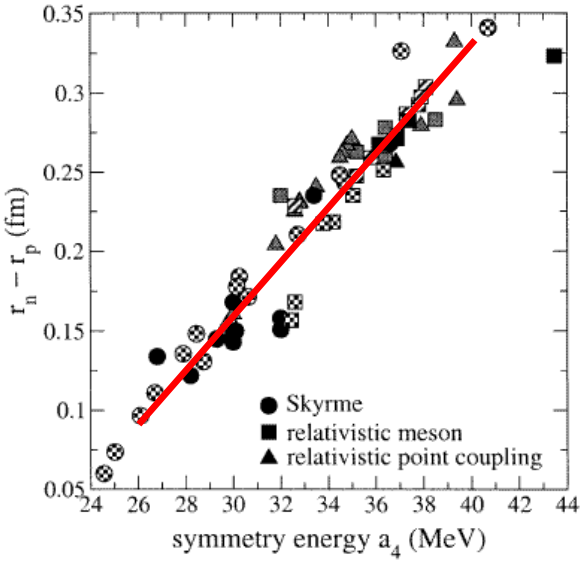


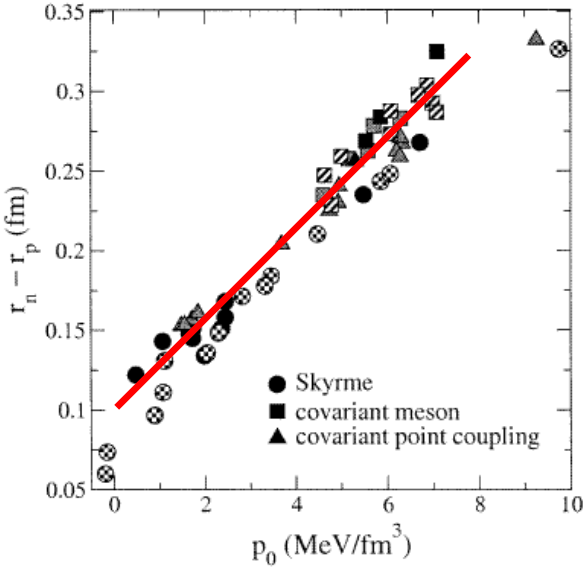
$$E(\rho,\alpha) = E(\rho,0) + S_2(\rho)\alpha^2 + O(\alpha^4),\ \alpha = \frac{N-Z}{A}$$

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

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

Alex Brown,
PRL 85 (2000) 5296





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

• strong <u>linear</u> correlation between neutron skin thickness and parameters **a_4, p_0**

Symmetry energy and dipole response

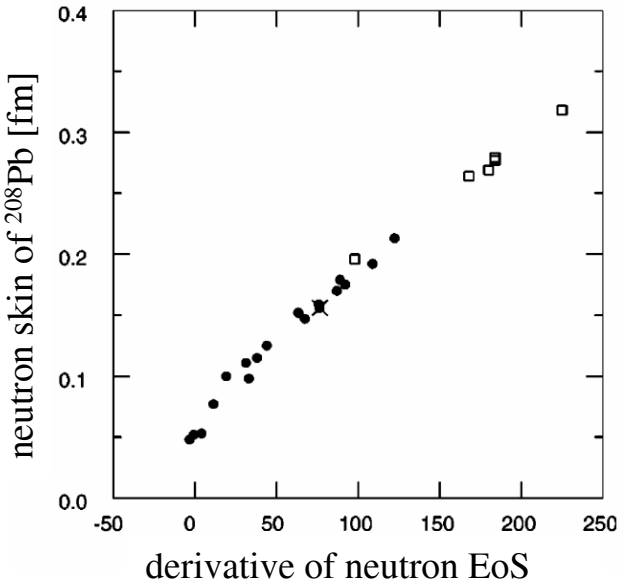
neutron-skin thickness
dipole response

⟺

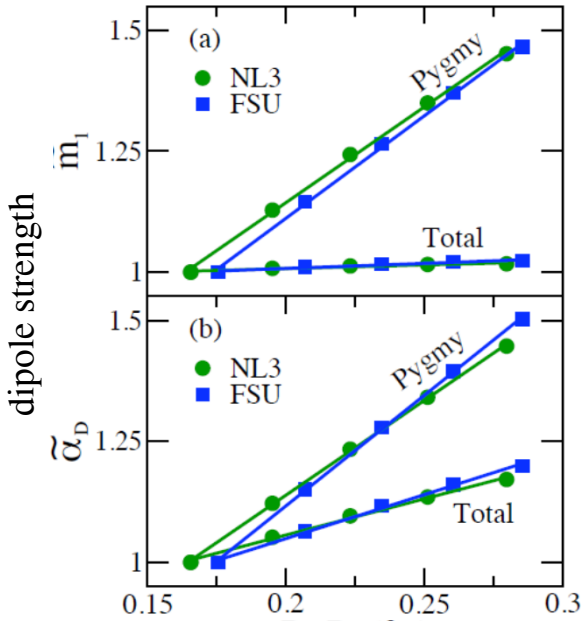
density dependence of
symmetry energy

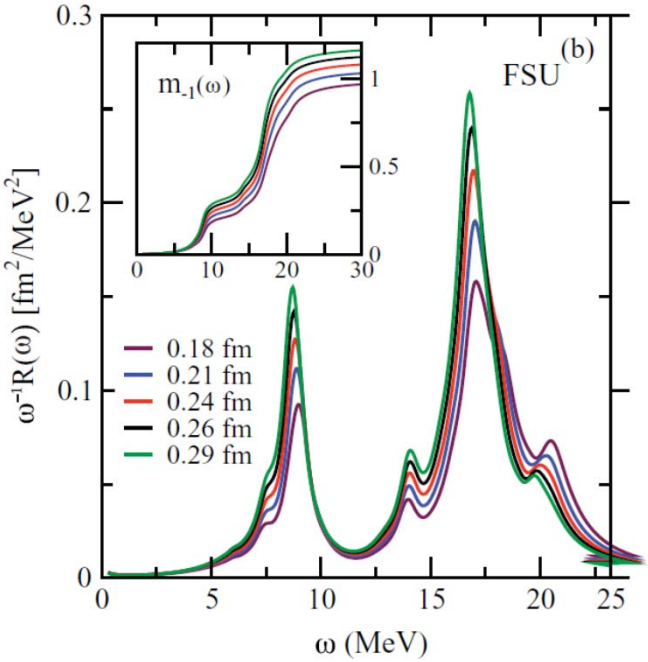
⟺

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.

How measure the dipole response of nuclei ?

Real Photons

- Photo-Absorption
  - Bremsstrahlung, tagged photons, data only for light nuclei, E>10 MeV
  - (γ,xn), (γ,xp), etc.
  - only above threshold, largest data set
- Photon-scattering
  - -> Decay Channel !

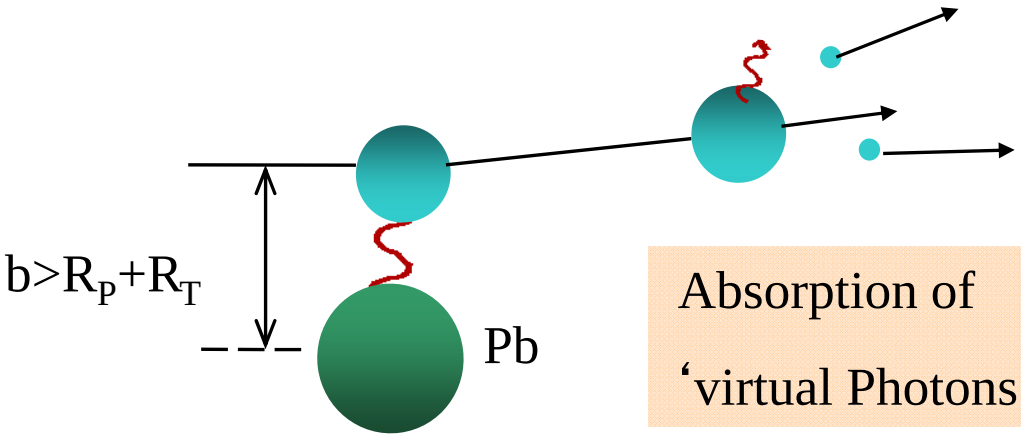
Virtual Photons: e^- - scattering

- multipole decomposition, low-momentum transfer
- difficult to apply with radioactive beams (e-A collider - > ELISe at FAIR)

Electromagnetic Excitation

- first measurement of full dipole strength in ^{208}Pb by (p,p') elm. excitation
  - Tamii et al., RCNP Osaka
- applicable to radioactive beams !

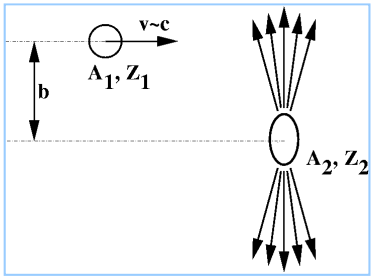
Electromagnetic excitation at high energies



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

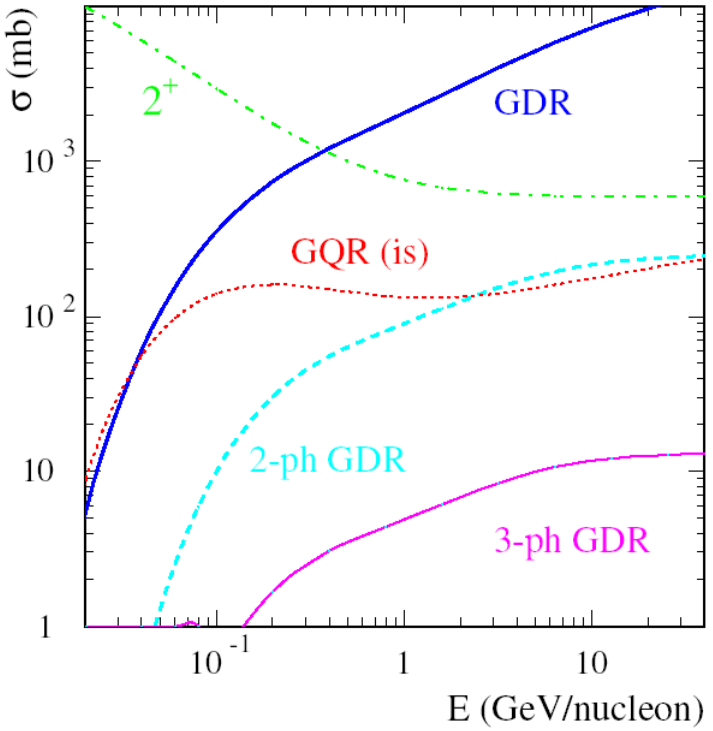
Absorption of

'virtual Photons'



Semi-classical theory:

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



High velocities v/c≈0.6-0.9

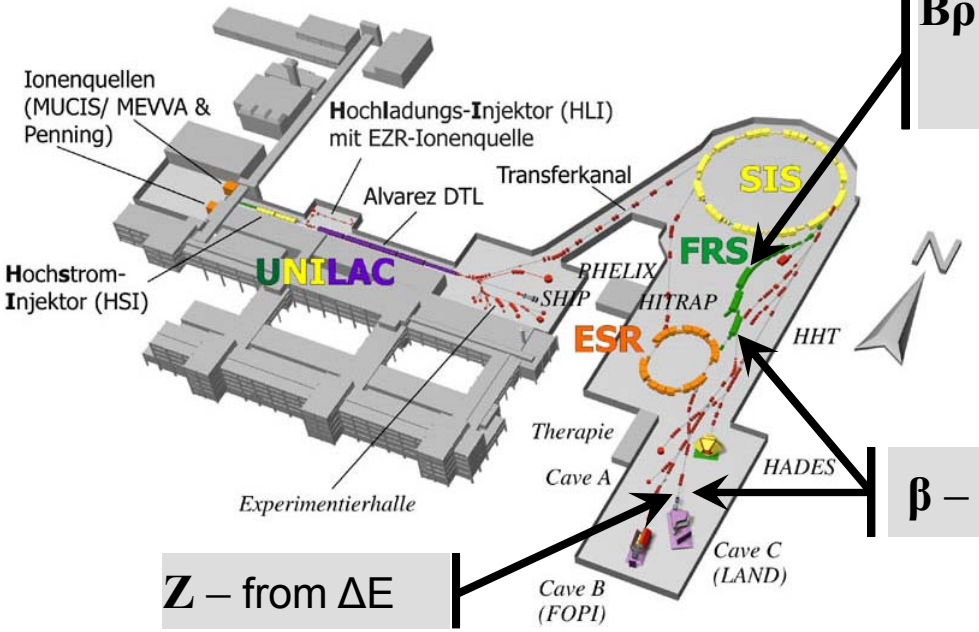
⇒ High-frequency Fourier components

$E_{\gamma,max} \approx 25$ 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

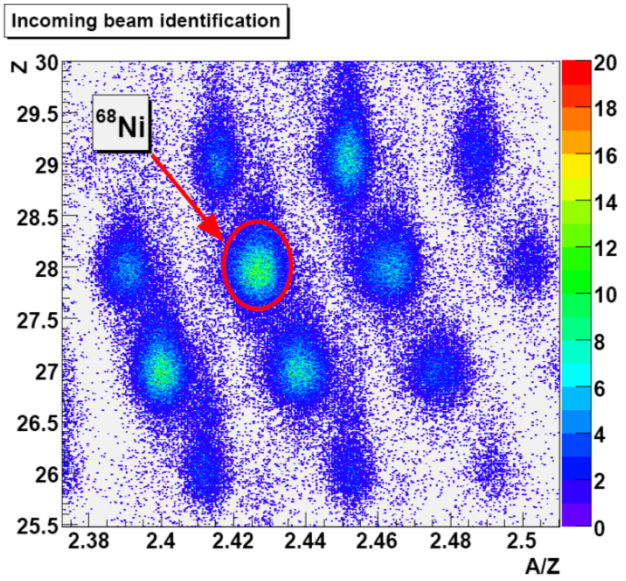
- Stable beams from SIS, fragmentation on Be target or in-flight fission
- Selection of radioactive beams in Fragment Separator (FRS)



Bρ – from position at middle focal plane of the FRS

β – from TOF

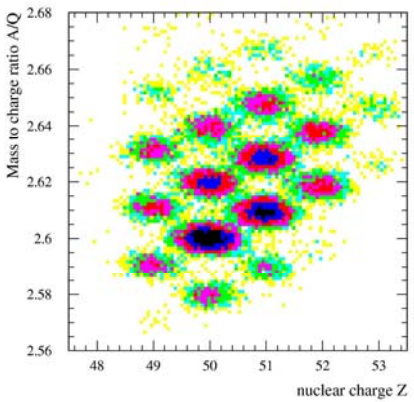
Z – from ΔE



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

The LAND reaction setup @GSI

Mixed beam



Charged fragments

ToF, ΔE

tracking → Bρ ~ A/Qβγ

LAN
D

Neutrons

ToF, x, y, z

~12 m

Photons

projectile
tracking

ALADIN
large-acceptance dipole

Beam

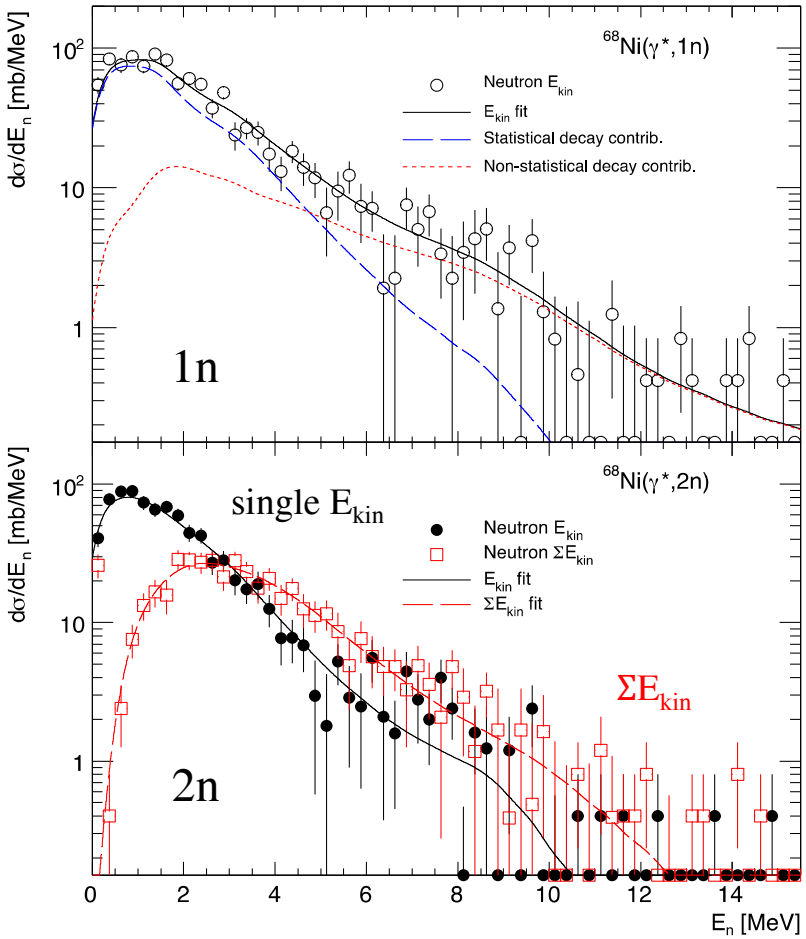
Crystal Ball
and Target

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

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

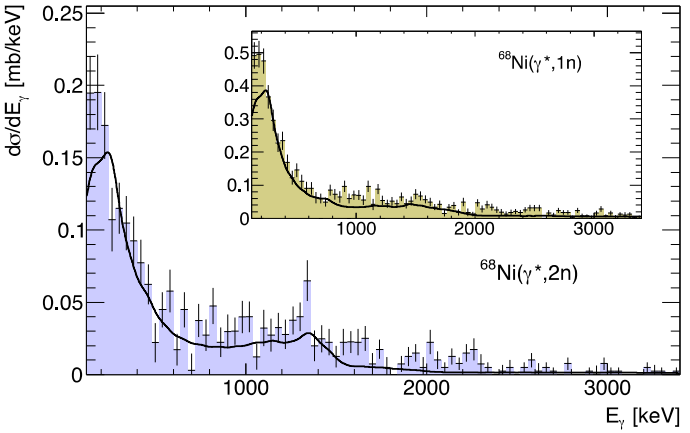
Analysis of ^{68}Ni: decay after Coulomb excitation

Neutron kinetic energy



R_{direct} = 24(4) %

gamma sum energy



consistent fit taking into account:

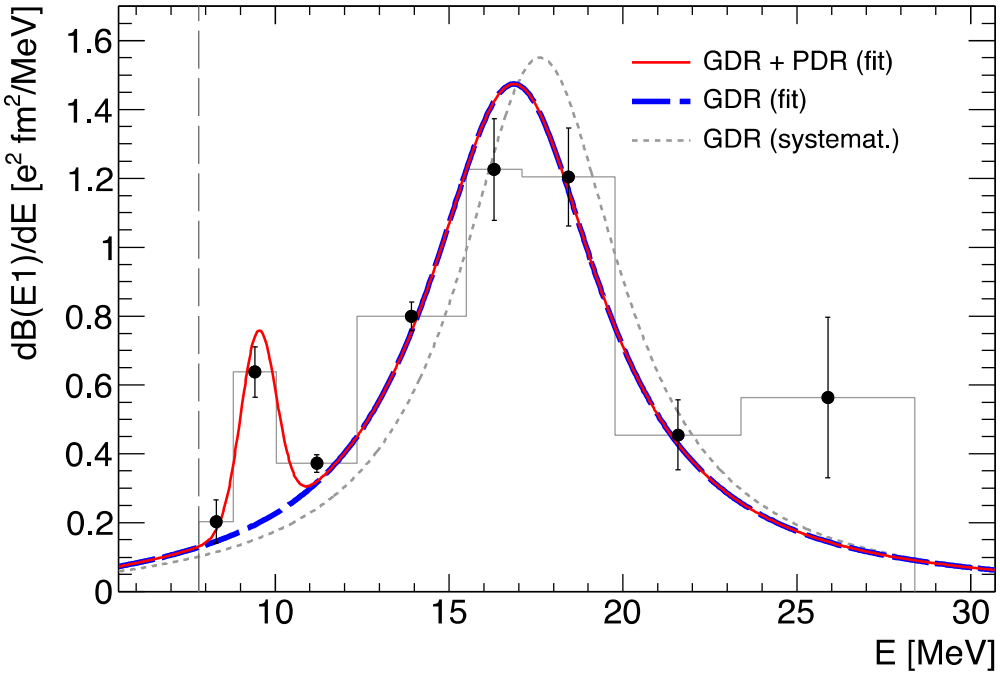
1) invariant mass, but also information of subsets like E_{kin}(n), $E_{\gamma sum}$ etc.

2) detailed knowledge about detector response function

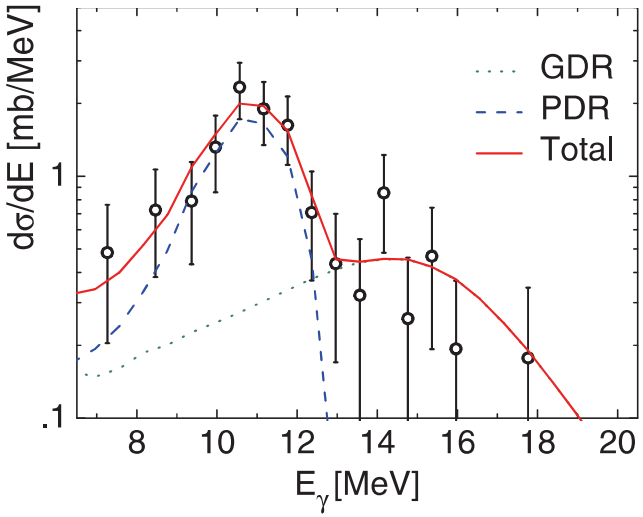
analysis:
Dominic Rossi
PhD Thesis
Univ. Mainz,
PostDoc GSI
Now MSU

Dipole strength distribution of ^{68}Ni

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



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

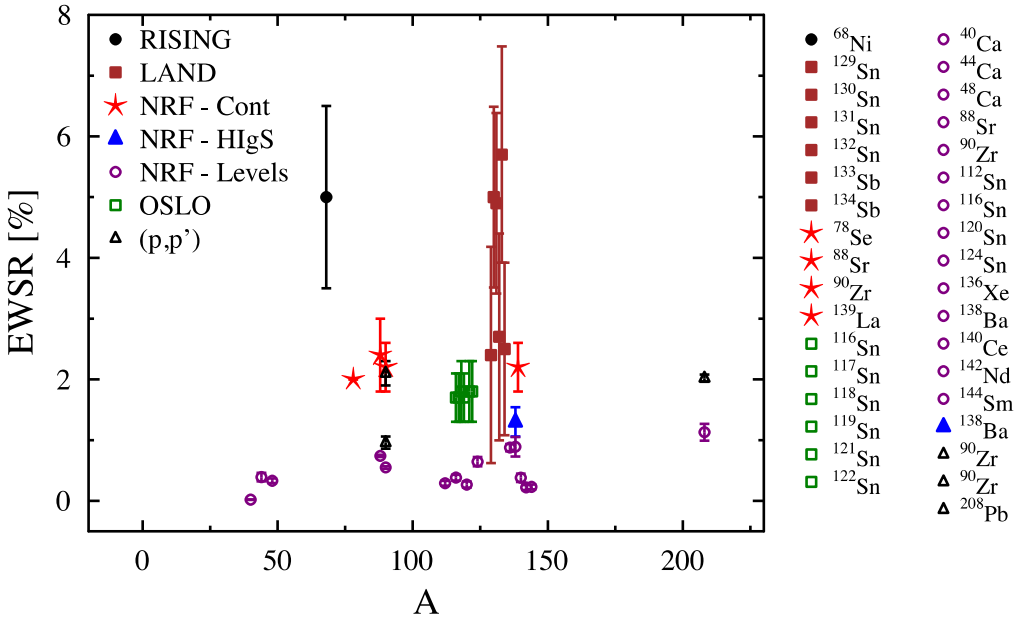


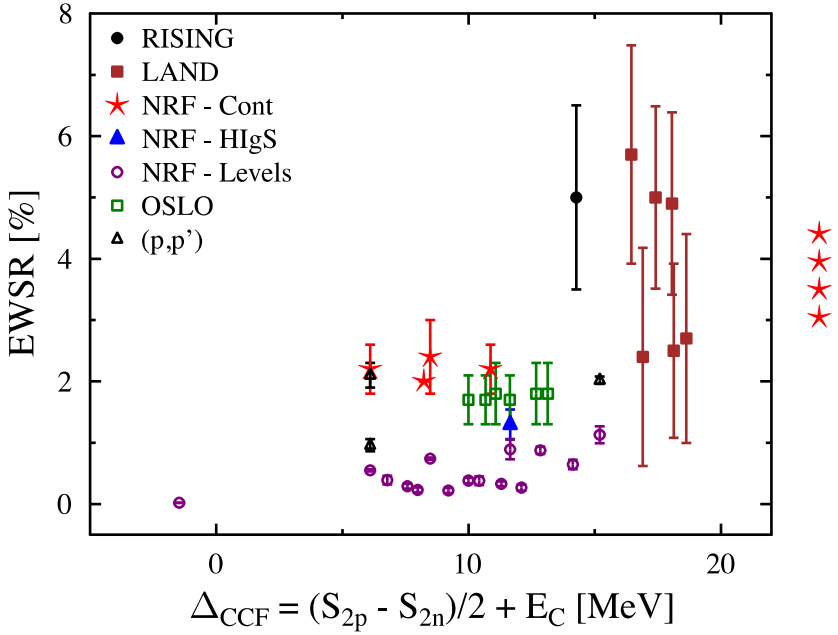
O. Wieland et al., PRL 102, 092502 (2009)

Direct gamma-decay branching ratio
Γ_0/Γ = 7(2)%

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

Systematics of Pygmy dipole strength ?



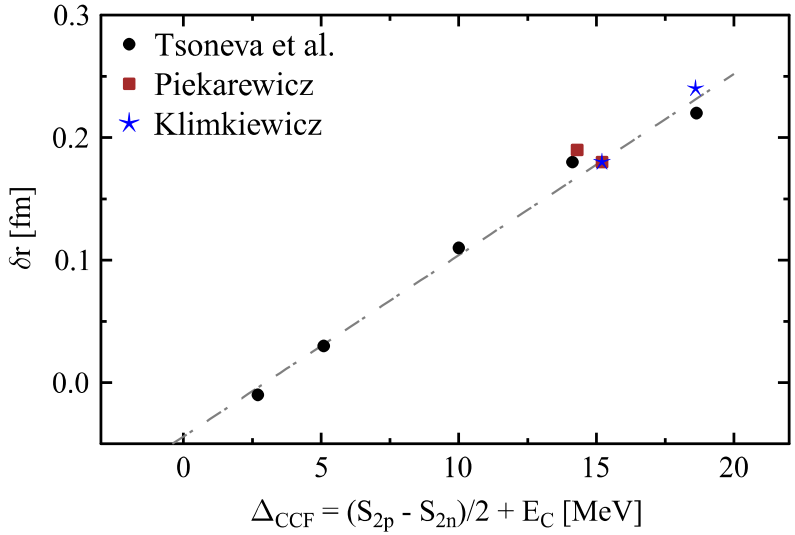


Review

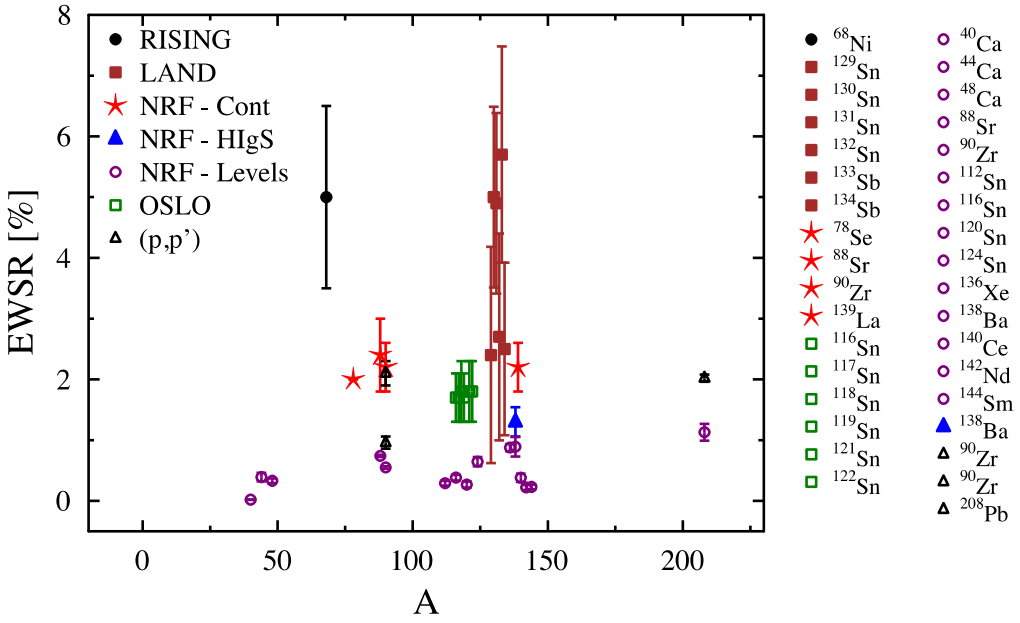
Experimental studies of the Pygmy Dipole Resonance

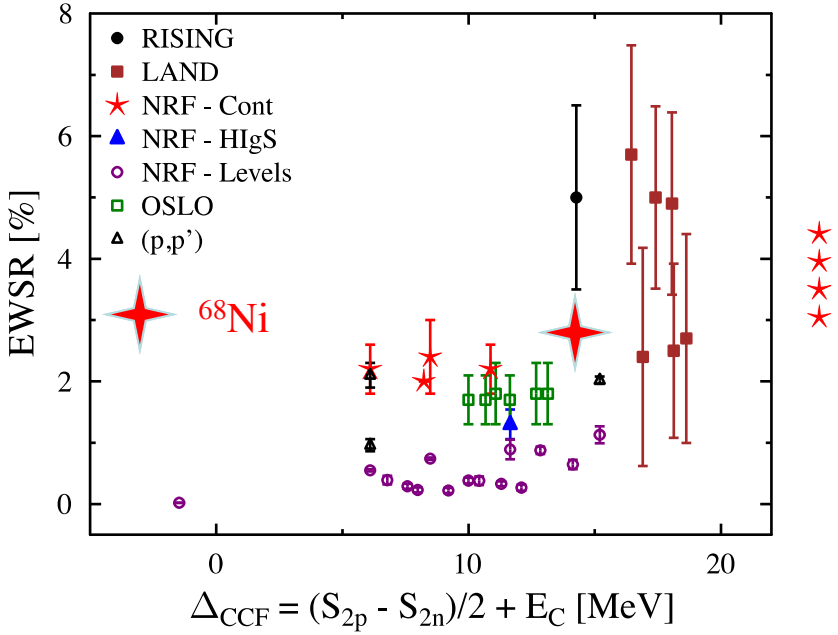
D. Savran[a,b,*], T. Aumann[c,d], A. Zilges[a]

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



Systematics of Pygmy dipole strength ?





Review

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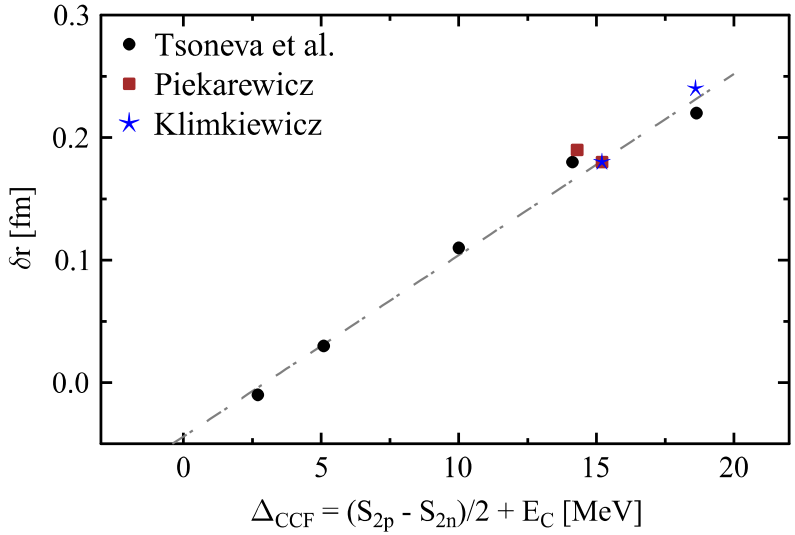
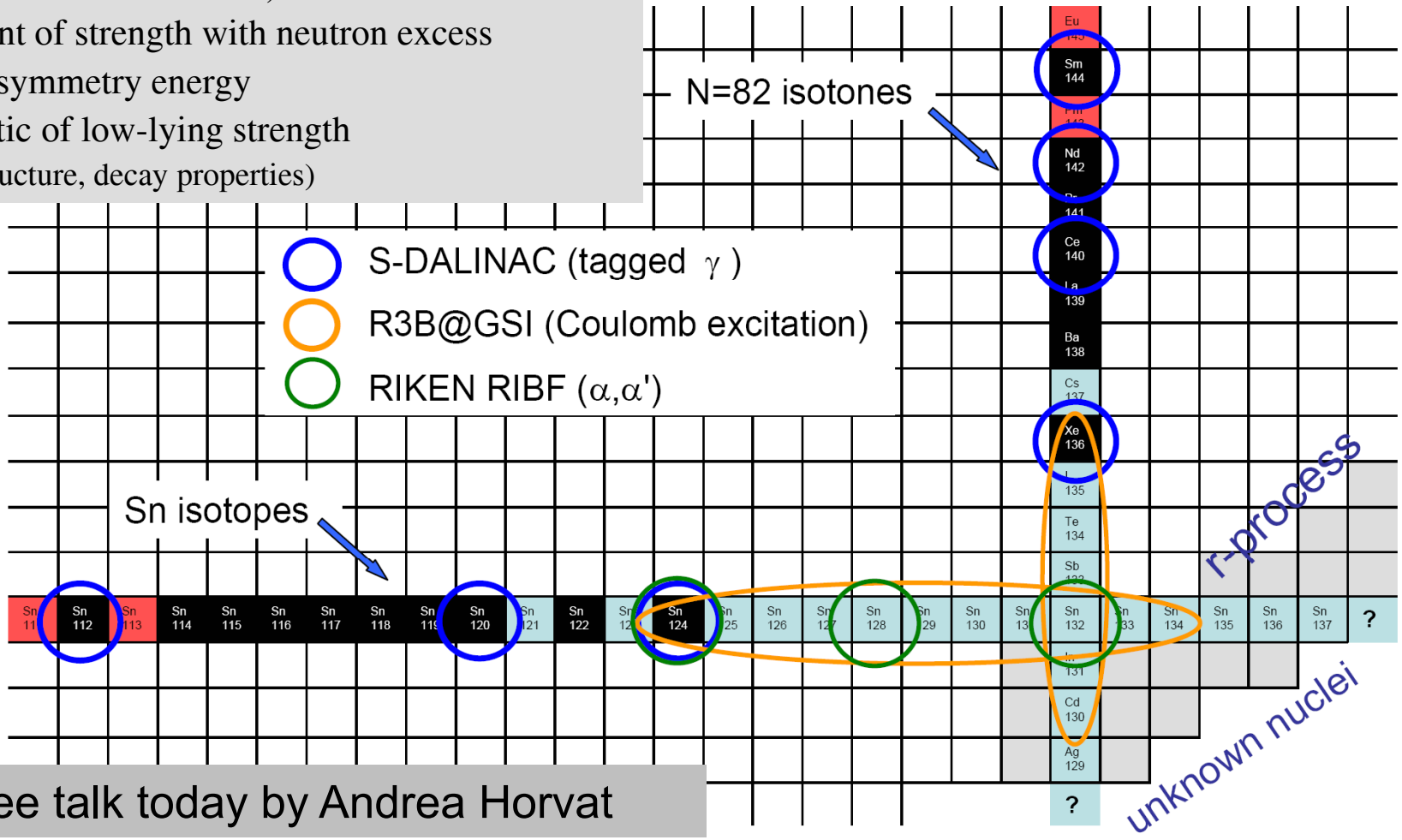


Proposed experimental programme

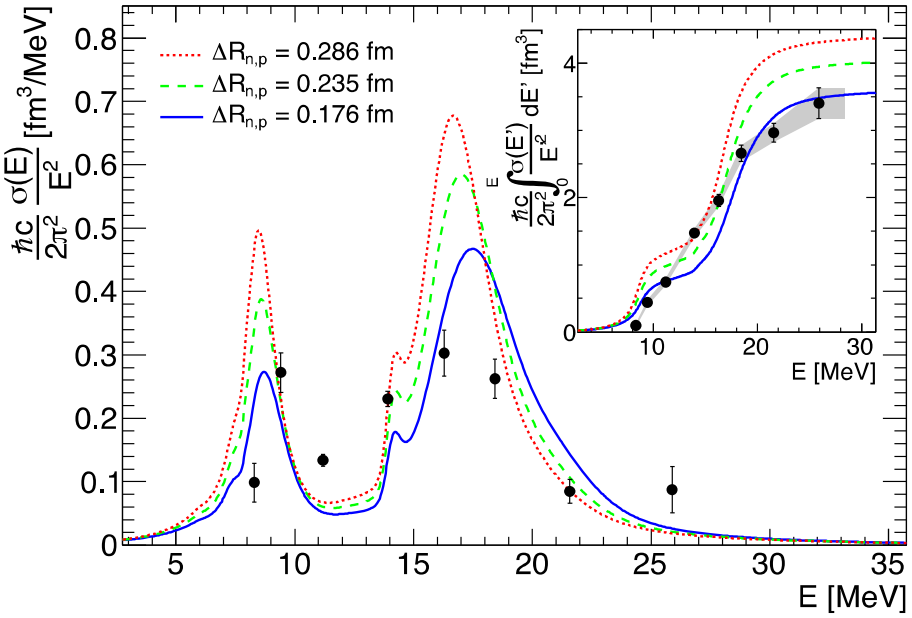
Next-generation experiments – Goals:

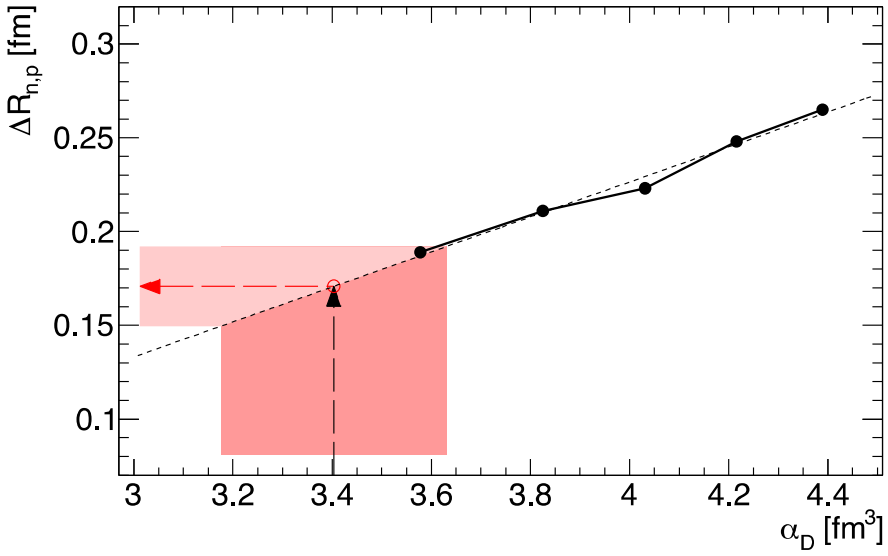
- extraction of full dipole strength function
  (below and above threshold, extracting E2 contribution, γ (-cacade) and neutron channels)
- development of strength with neutron excess
- relation to symmetry energy
- characteristic of low-lying strength
  (isospin structure, decay properties)



➔ See talk today by Andrea Horvat

Polarizability and neutron skin





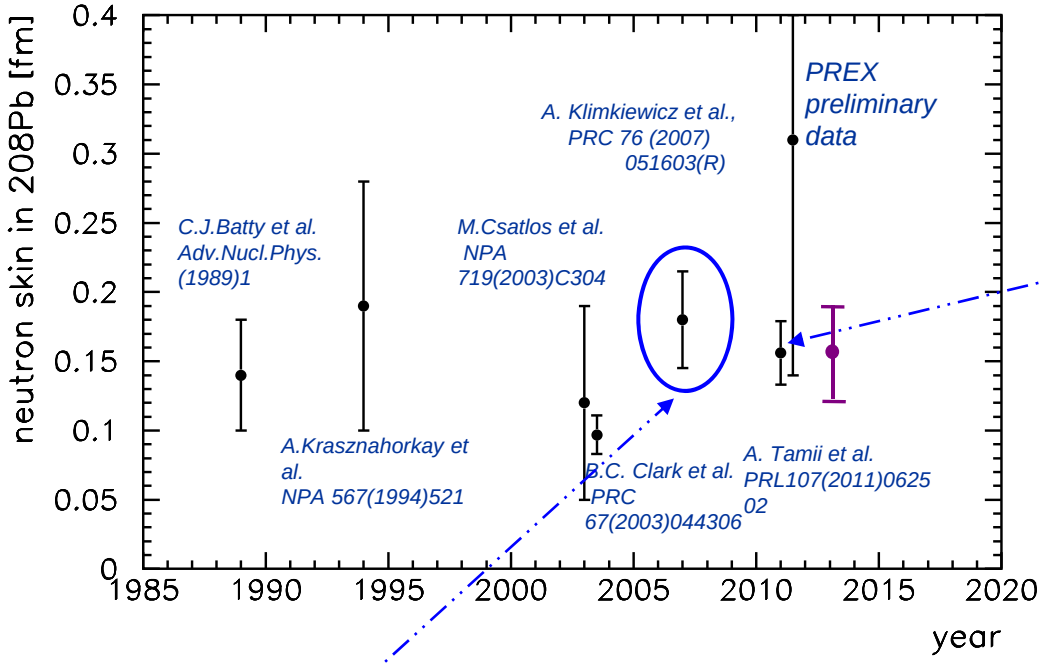
$$\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma(E)}{E^2}dE$$

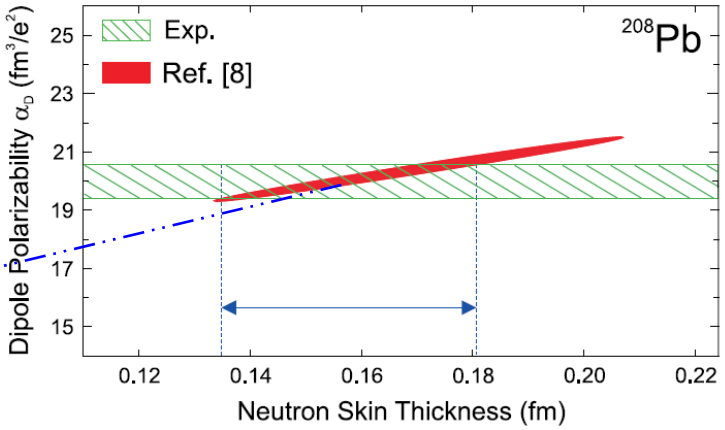
Neutron-skin thickness
$\Delta R_{n,p} = 0.175(21)$ fm

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

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

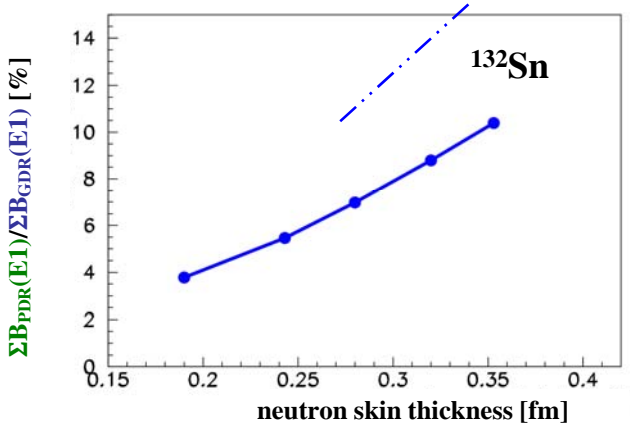
Neutron skin in ^{208}Pb from different methods

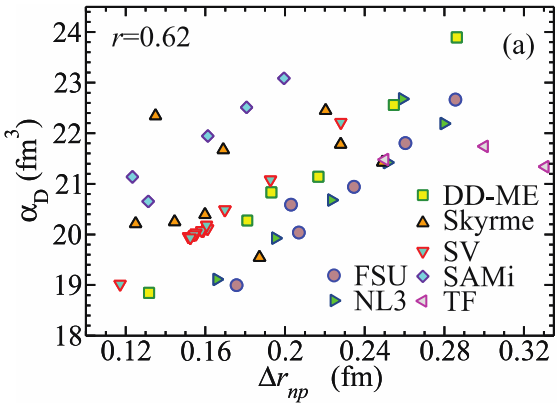


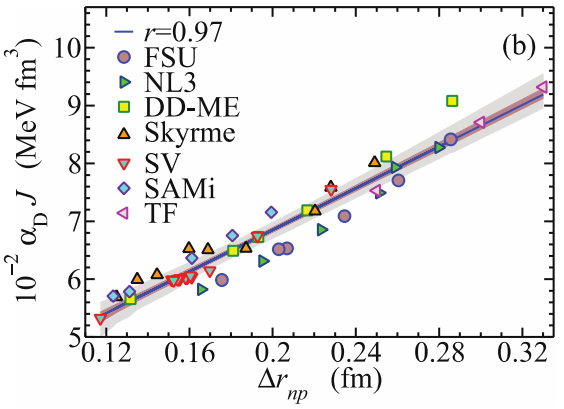


But:

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



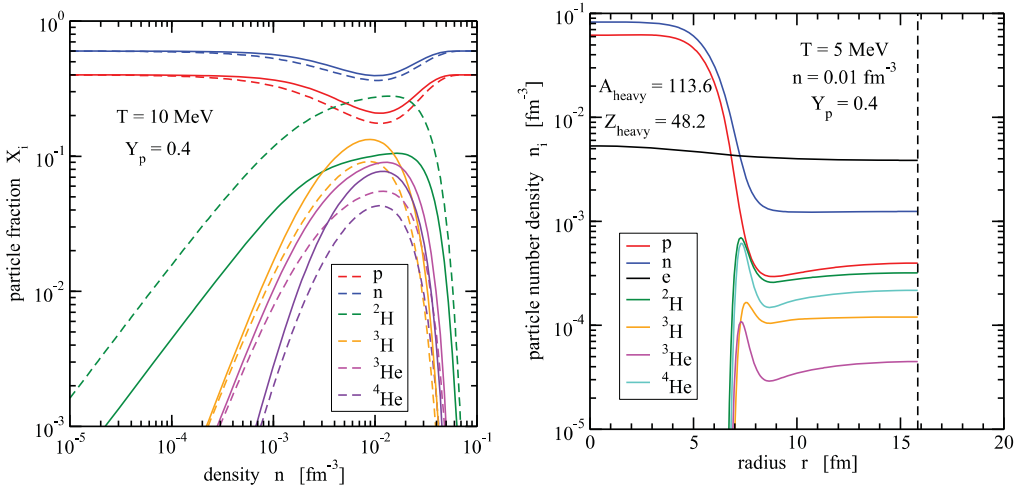


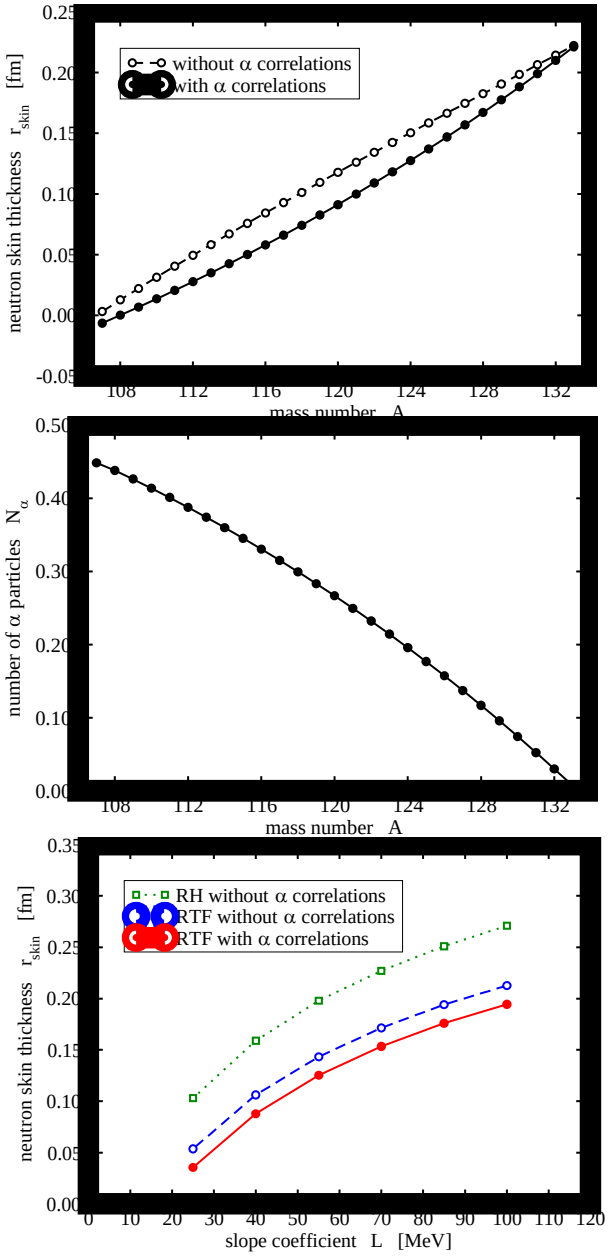


Alpha clusters in nuclear matter and heavy nuclei

Heavy Nuclei (only α relevant)

Nuclear Matter





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

S. Typel, arXiv:1403.2851v1, AIP Conf. Proc. 1520,68 (2013)

Collaboration of ^{68}Ni dipole-response experiment

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

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Summary

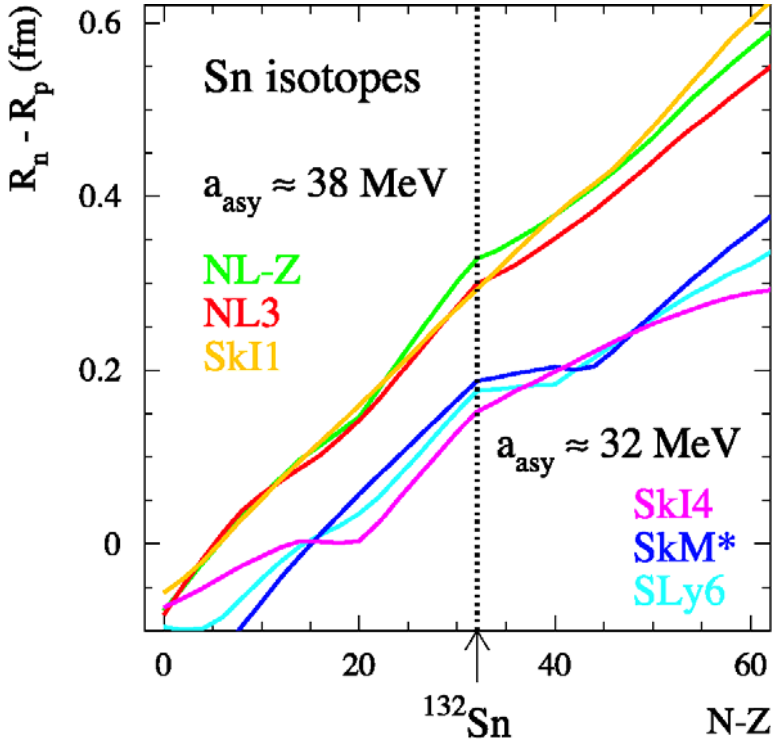
- Dipole response of n-rich nuclei – Pygmy Resonance
  - Low-lying dipole strength observed in n-rich nuclei, 'proton-Pygmy' in ^{32}Ar
  - many open questions – next-generation experimental program planned at GSI, RIKEN, SDALINAC, HIγS, Osaka, …
    systematics, strength and position as a function of 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

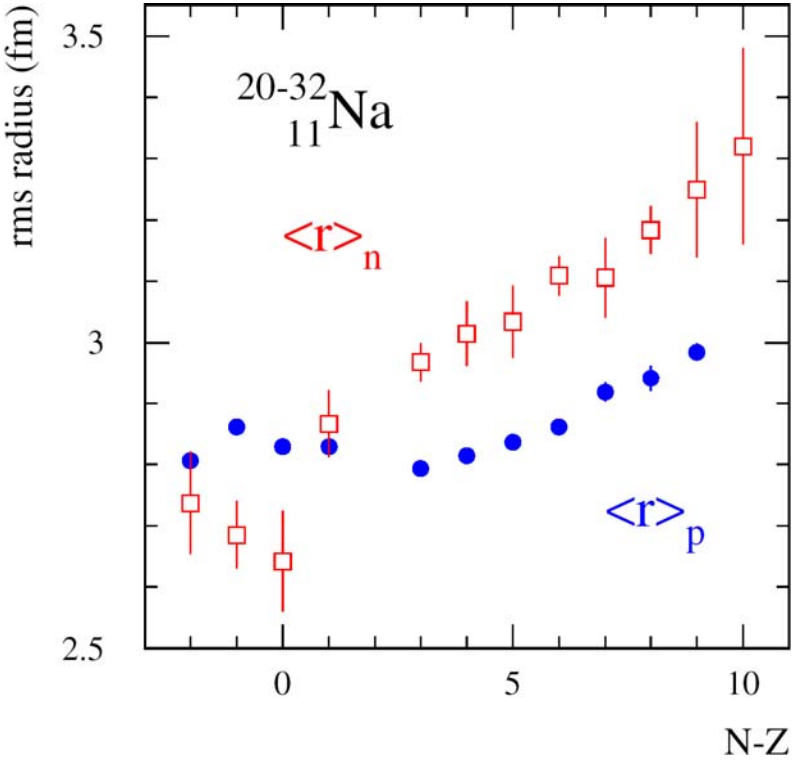
Appearance of a neutron skin in neutron-rich nuclei

Theoretical prediction



Relativistic (NL) and non-relativistic (Skyrme Sk, SL) mean-field calculations
P.G. Reinhard, priv. comm.

First experimental evidence



Interaction cross section measurement (GSI) plus
Isotope shift measurements (ISOLDE)
T. Suzuki et al., Phys. Rev. Lett. 75 (1995) 3241

Other experimental techniques: IV GDR (isoscalar probe), Spin-dipole resonance (rel. n-skin),

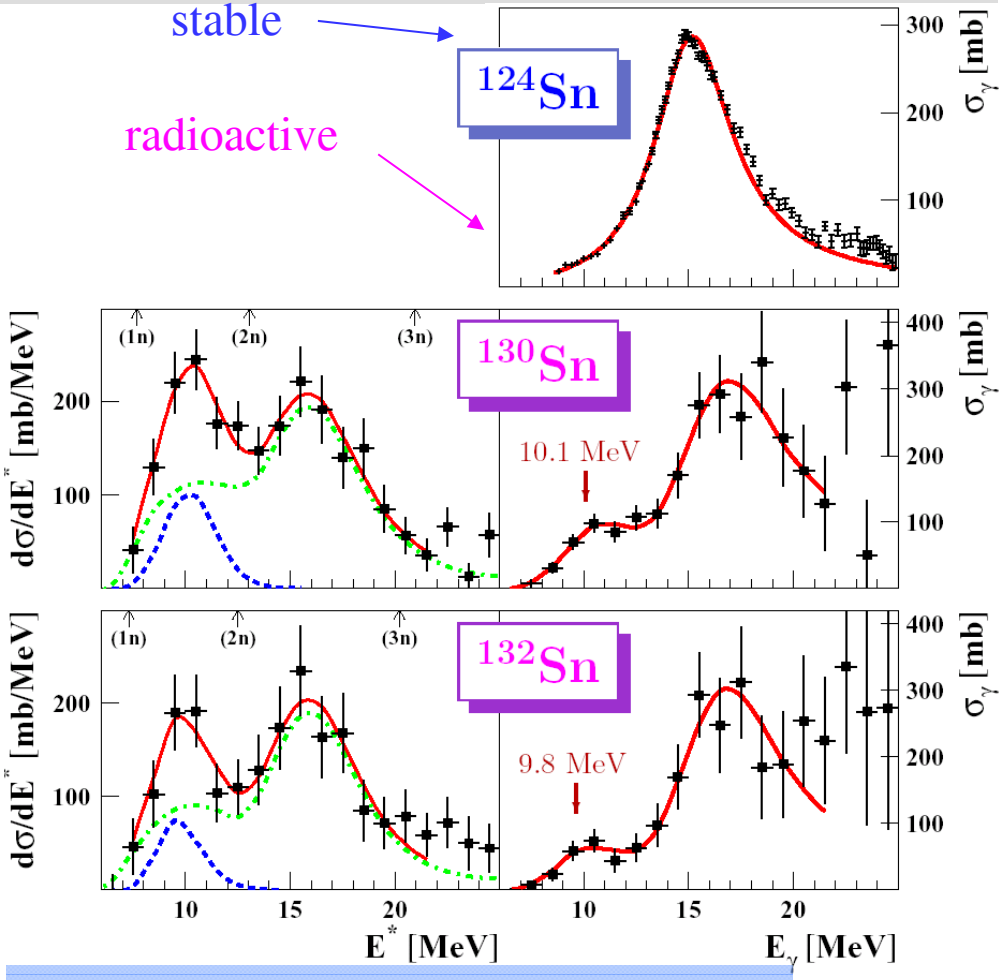
Pygmy dipole, **Polarizability**, anti-proton scattering, e- plus p elastic scattering

Previous measurements with radioactive beams

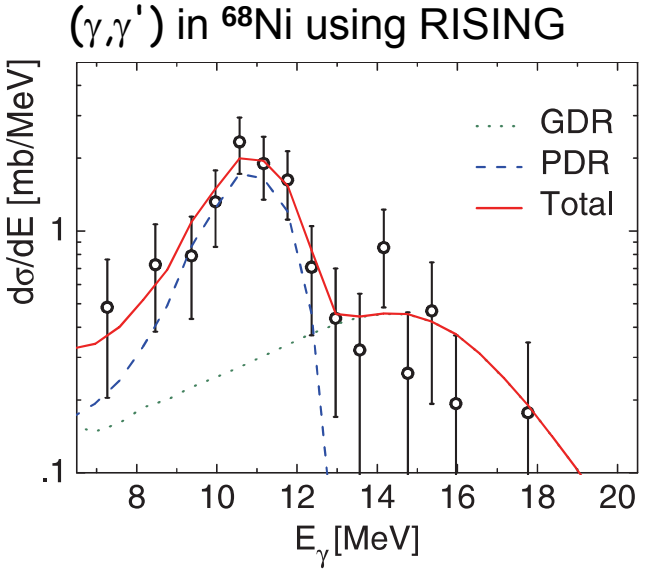
Method: Electromagnetic excitation at relativistic beam energies
(C.A. Bertulani and G. Baur, Phys. Rep. 163, 299 (1988))

Electromagnetic-excitation cross section

Photo-neutron cross section



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



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

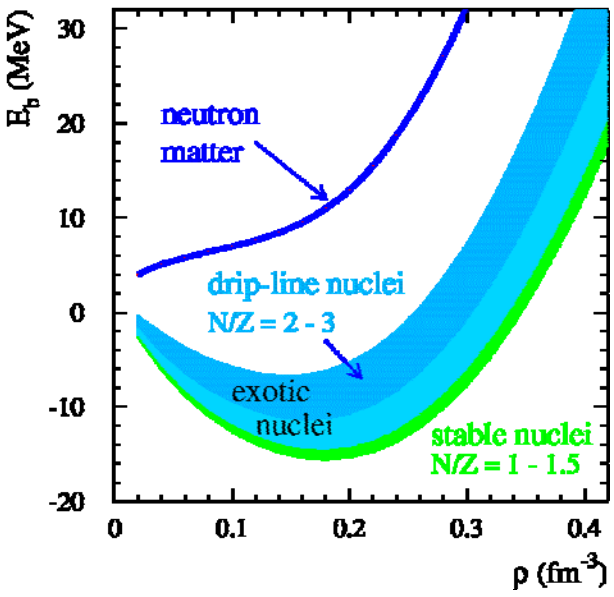
PDR

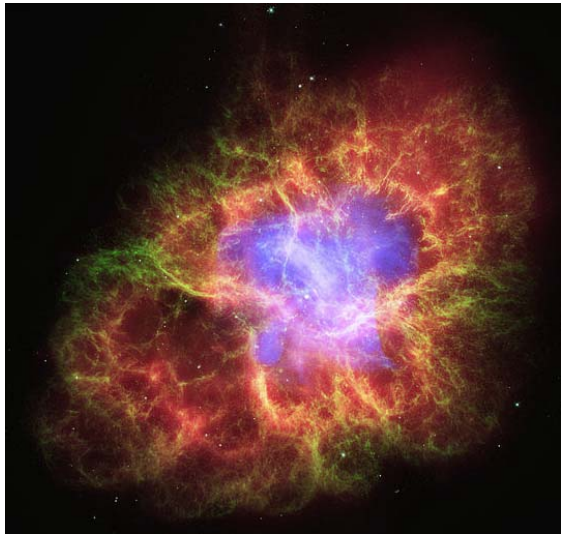
- located at 10 MeV
- exhausts a few % TRK sum rule

GDR

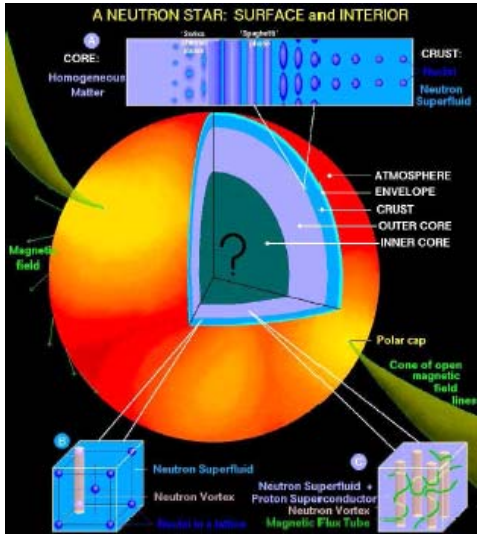
- no deviation from systematics

Can we learn something on neutron matter ?





Supernova explosion



Neutron Star

<u>The nuclear equation of state:</u>

dependence on n-p asymmetry and density

symmetry energy at higher densities

→ reactions with n-rich nuclei ?

symmetry energy and its density dependence close to saturation density

→ properties of n-rich nuclei ?

Observables related to neutron EoS

Properties and reactions of neutron-rich nuclei related to neutron matter

Symmetry energy and slope:

- Dipole response: GDR centroid, Pygmy resonance -> dipole polarizability
- Quadrupole response: centroid of isovector GQR
- GMR
- Neutron-skin thickness
- …

Correlations:

- 3N force -> nuclear structure
- 3neutron force -> structure of n-rich nuclei (at and beyond drip),
  neutron systems (e.g. 4n)
- N-N tensor and short-range correlations -> quasi-free scattering (p,pn); (p,2p)
- Clustering -> quasi-free scattering (p,pα)