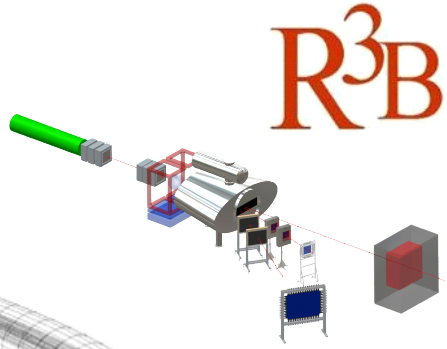
Collective excitations of exotic neutron-rich nuclei



Thomas Aumann

TECHNISCHE UNIVERSITÄT DARMSTADT

HIC for FAIR Helmholtz International Center

GSI

EMMI

NAVI Nuclear Astrophysics Virtual Institute

ENSAR

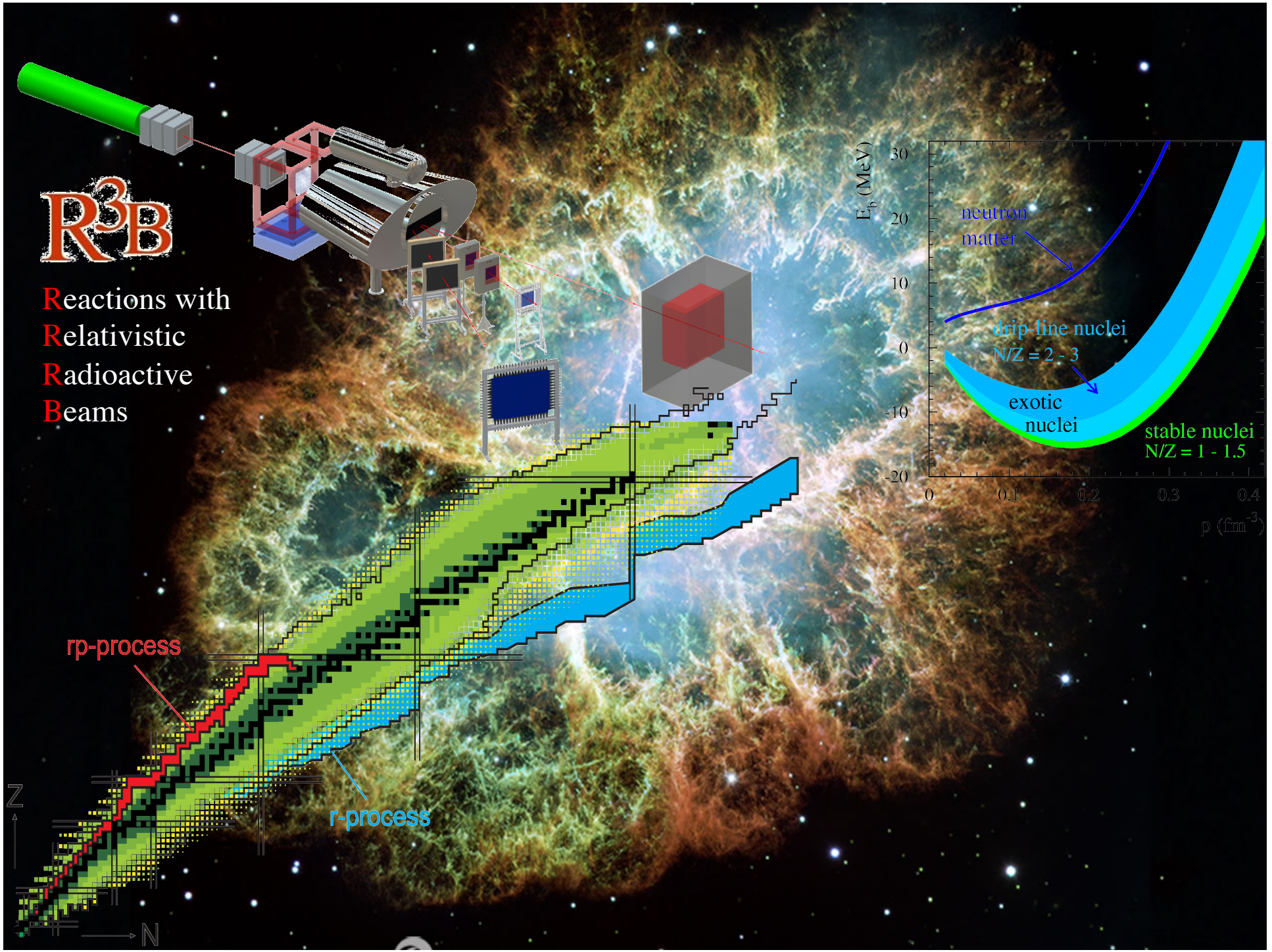
February 25th 2014

Physics Colloquium

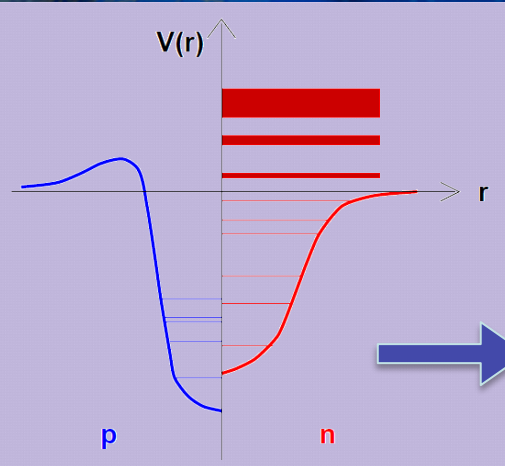
Università degli studi di Milano

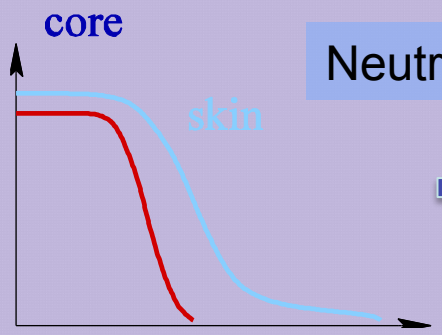
Bundesministerium für Bildung und Forschung

Supported by the BMBF under contract no 05P12RDFN8

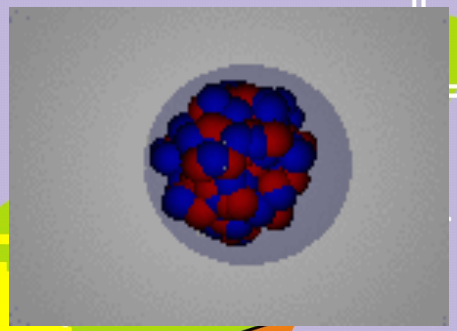

R3B
Reactions with
Relativistic
Radioactive
Beams
rp-process
r-process
Z
N
E/A (MeV)
30
20
10
0
-10
-20
neutron
matter
drip-line nuclei
N/Z = 2 - 3
exotic
nuclei
stable nuclei
N/Z = 1 - 1.5
0
0.1
0.2
0.3
0.4
ρ (fm-3)

Neutron-proton asymmetric nuclei





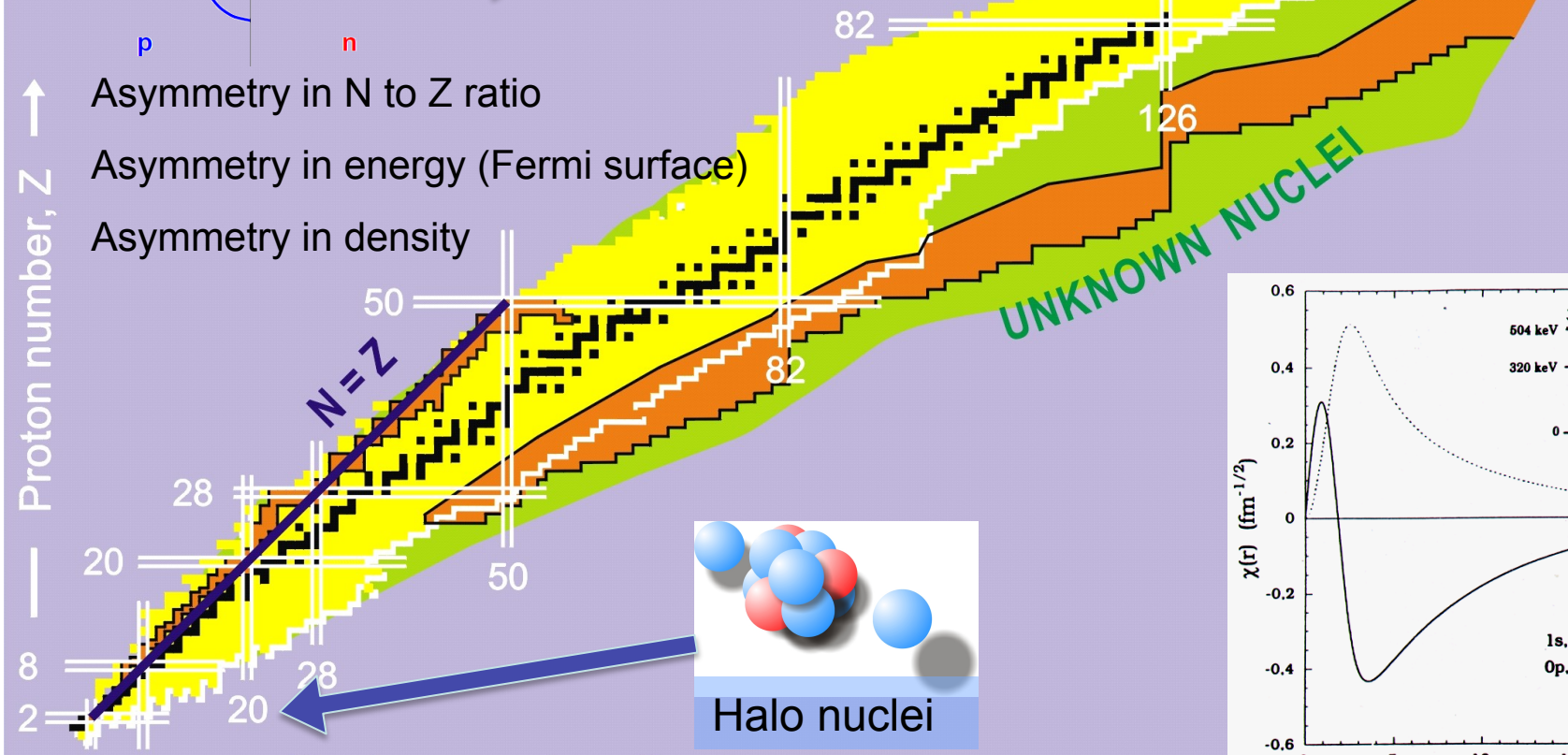
Neutron skin



Asymmetry in N to Z ratio

Asymmetry in energy (Fermi surface)

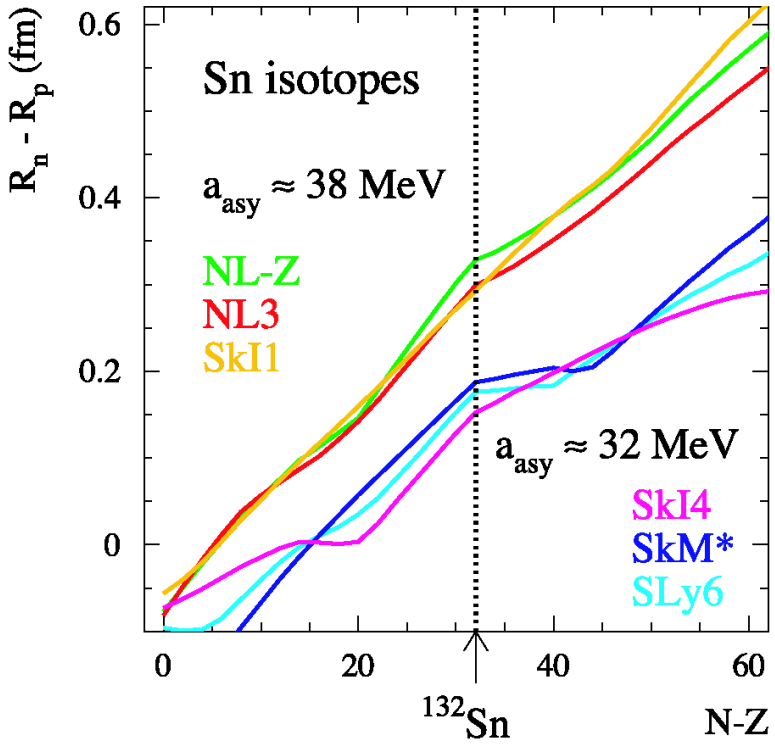
Asymmetry in density



Halo nuclei

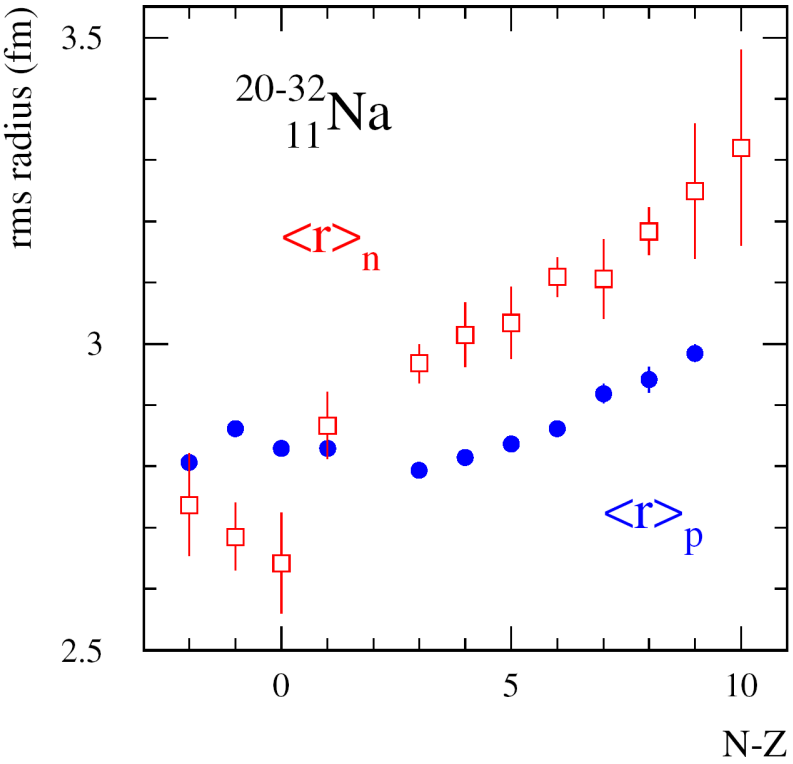
Appearance of a neutron skin in neutron-rich nuclei

Theoretical prediction



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

First experimental evidence

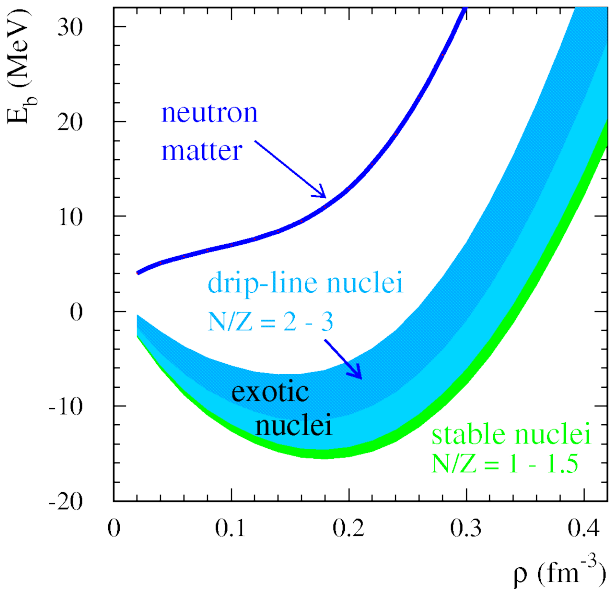


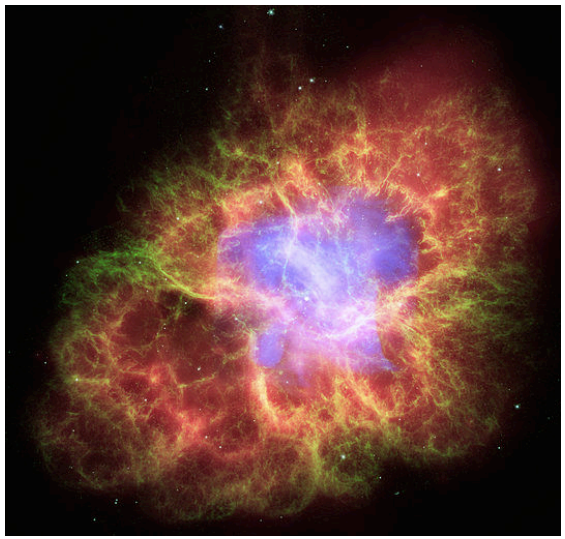
Interaction cross section measurement (GSI) plus
Isotope shift measurements (ISOLDE)
T. Suzuki et al., Phys. Rev. Lett. 75 (1995) 3241

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

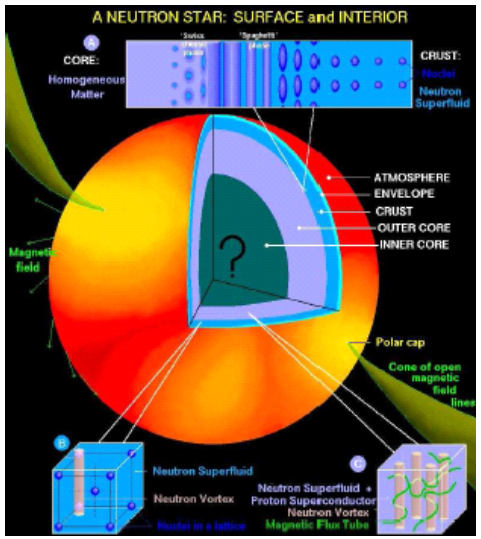
Pygmy dipole, **Polarizability**, anti-proton scattering, e- plus p elastic scattering

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

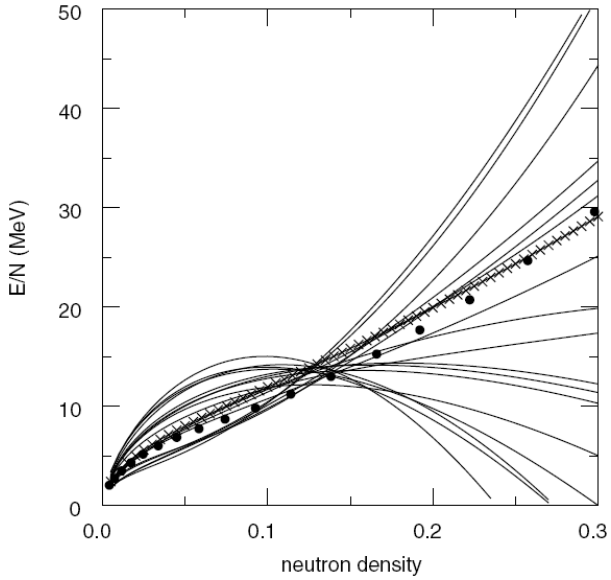
symmetry energy and its density dependence close to saturation density

→ properties of n-rich nuclei ?

symmetry energy at higher densities

→ reactions with n-rich nuclei ?

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

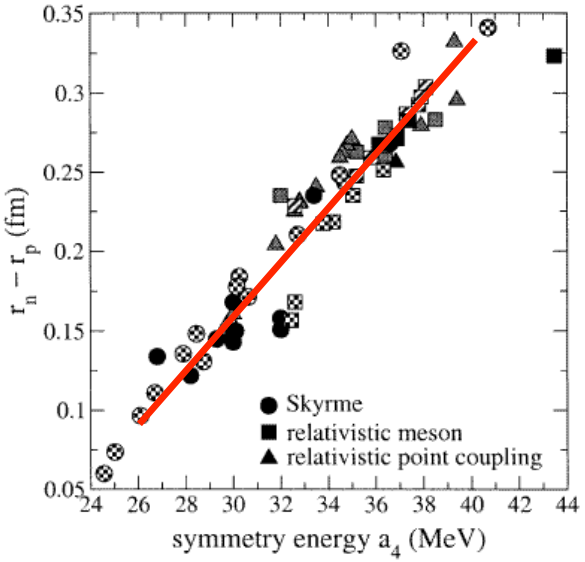


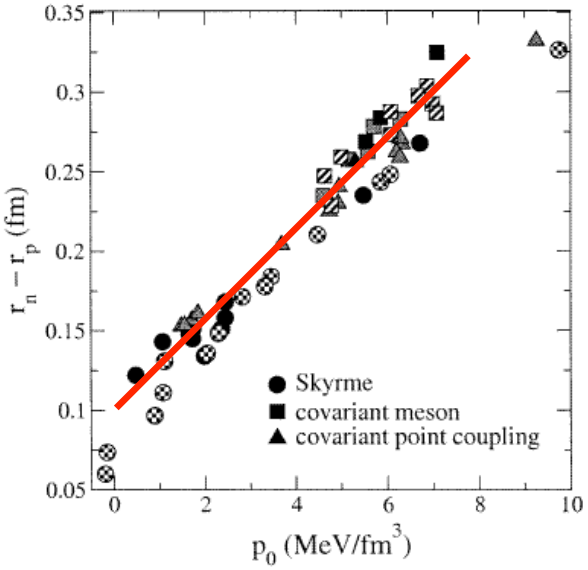
$$E(\rho,\alpha) = E(\rho,0) + S_2(\rho)\alpha^2 + O(\alpha^4),\ \alpha = \frac{N-Z}{A}$$

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

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

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**

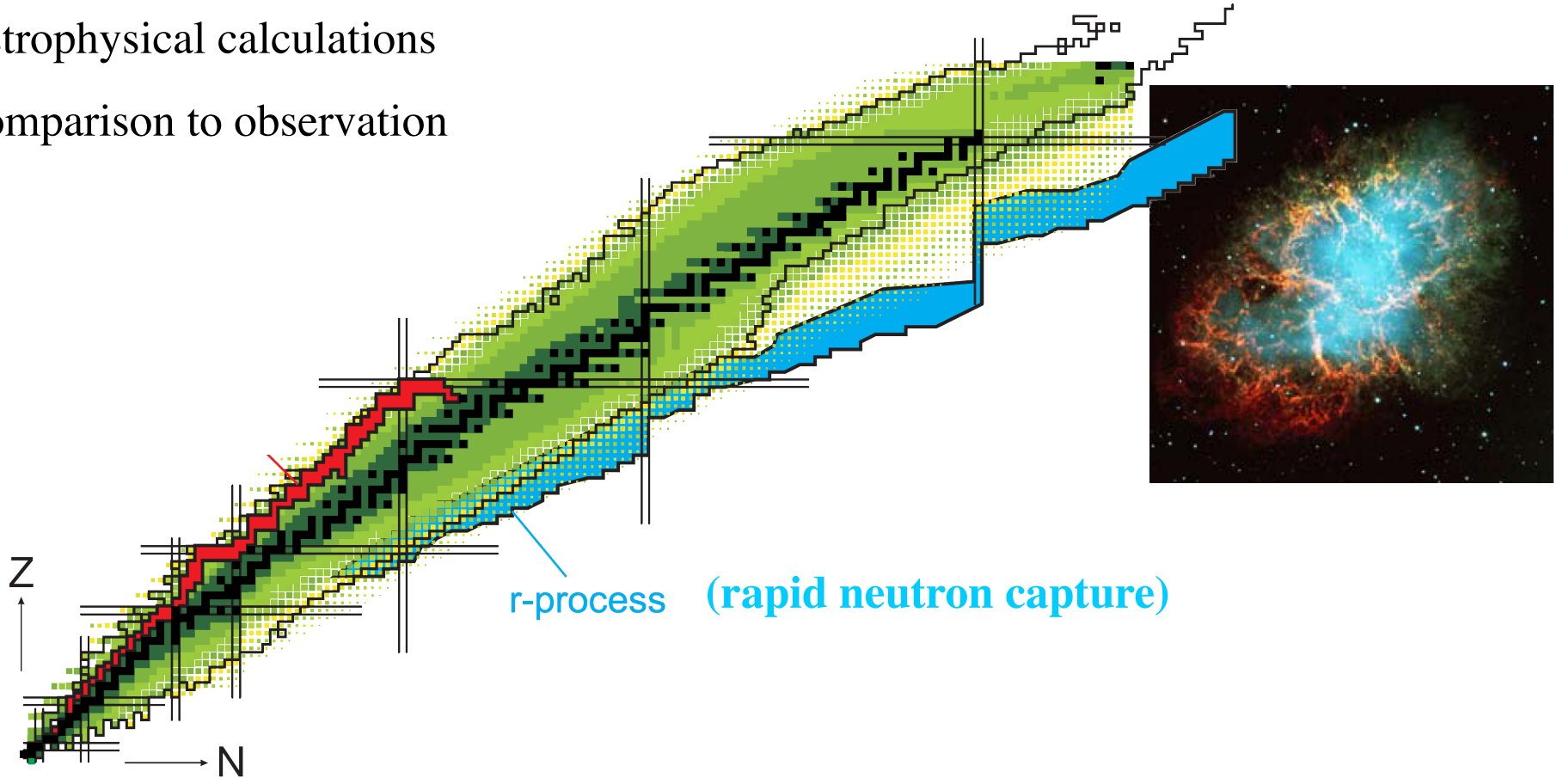
Astrophysical implications: r-process

The challenge: For the understanding of nucleosynthesis and stellar dynamics we need to know properties of many **exotic** nuclei.

Nuclear input: half lives, masses, reaction rates

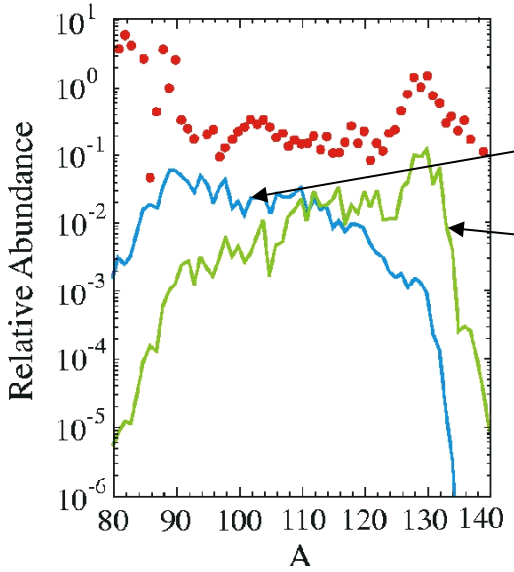
Astrophysical calculations

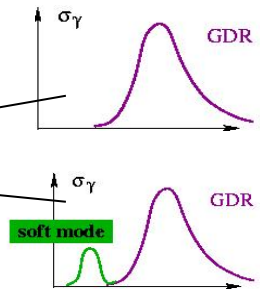
Comparison to observation



Astrophysical implications: r-process

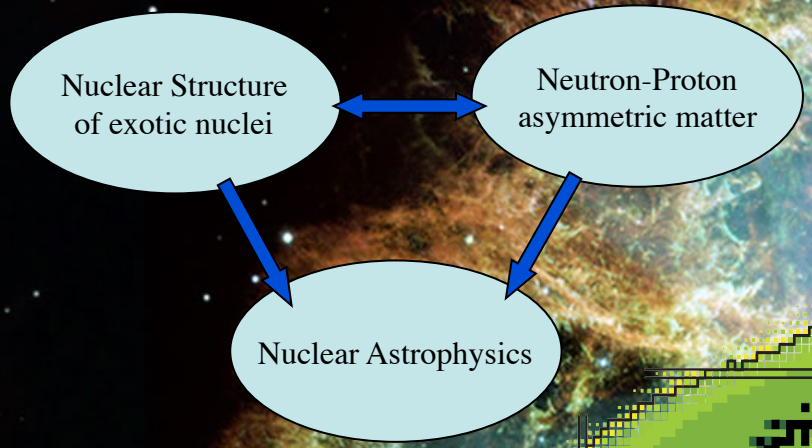
r-process abundance

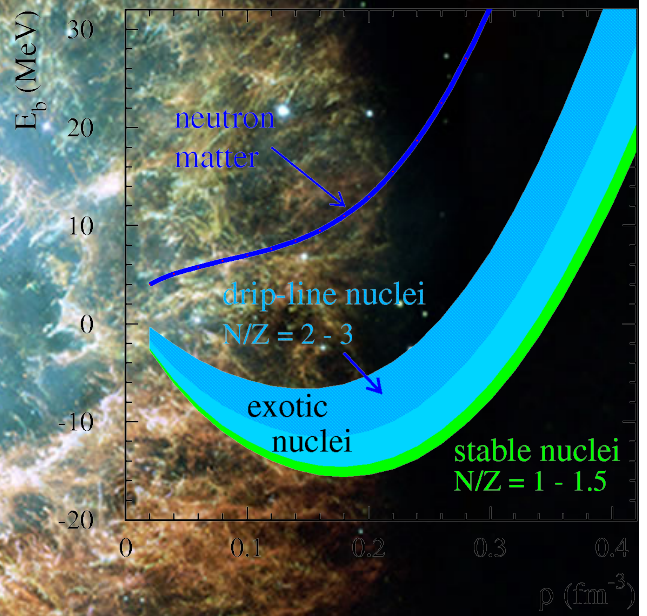




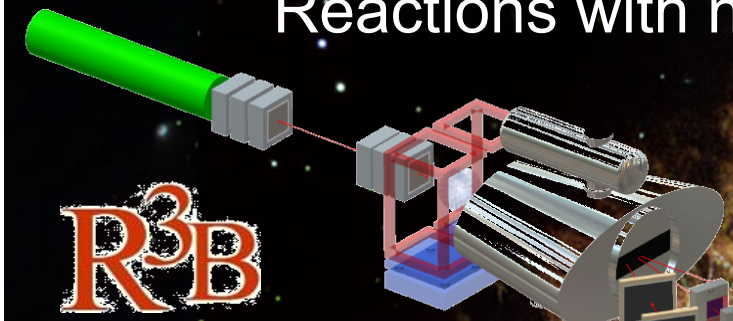
Reactions with neutron-proton asymmetric nuclei

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



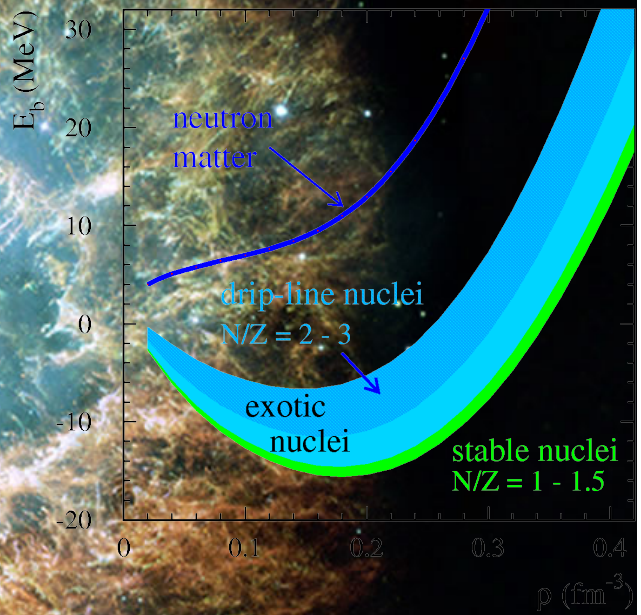


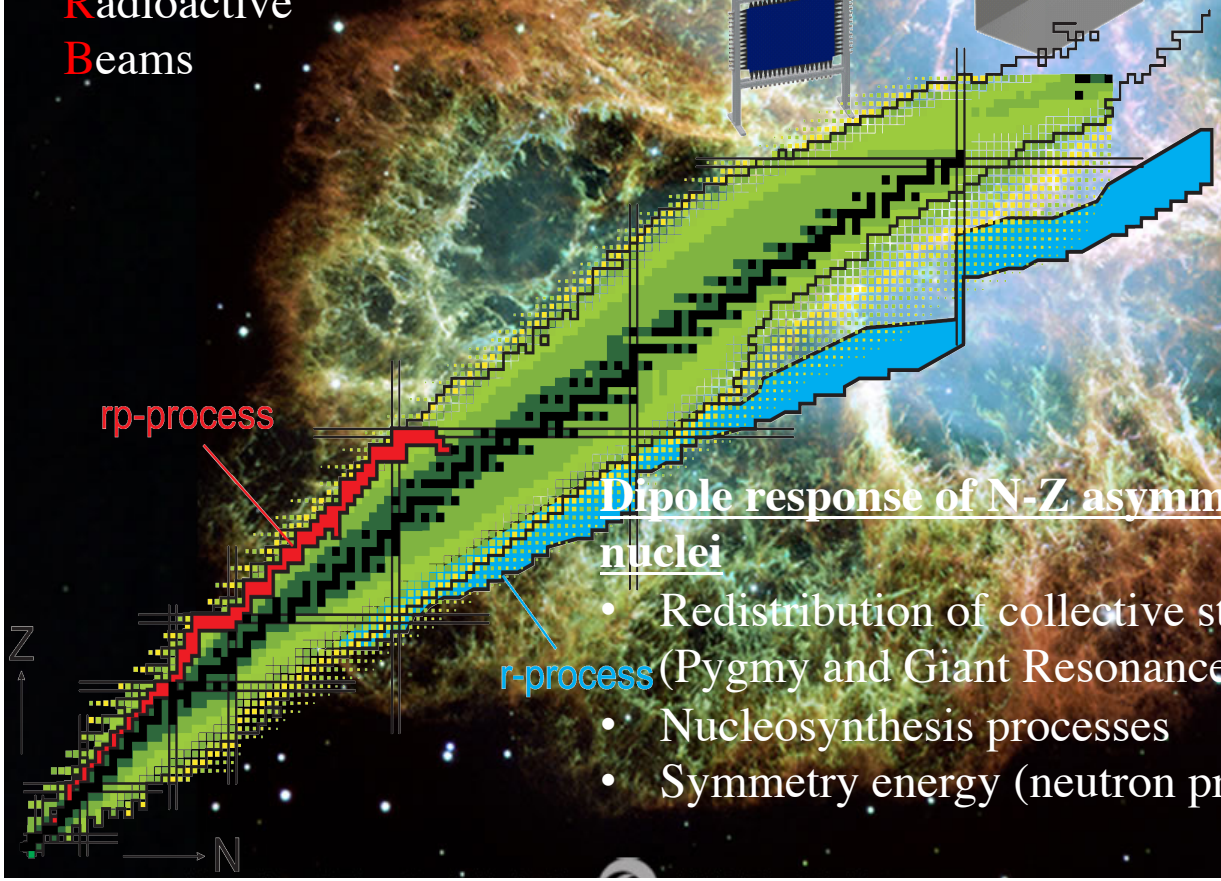
Reactions with neutron-proton asymmetric nuclei



R³B

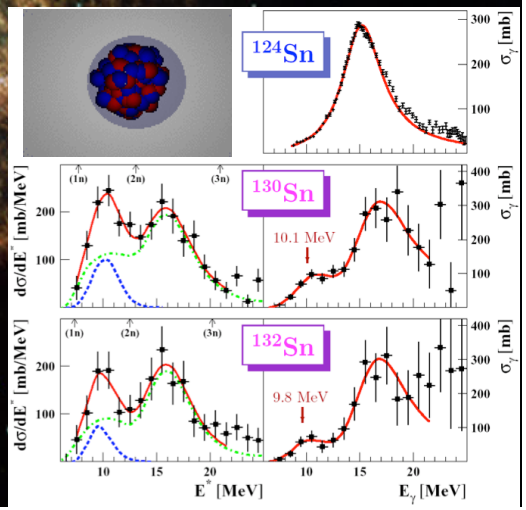
Reactions with
Relativistic
Radioactive
Beams





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

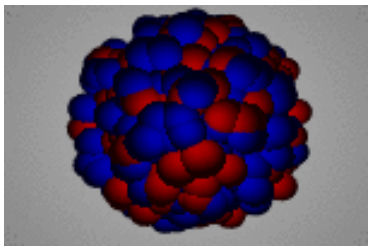
Isovector

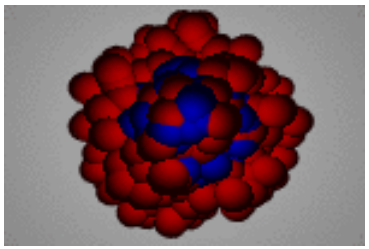
Photo-neutron cross sections

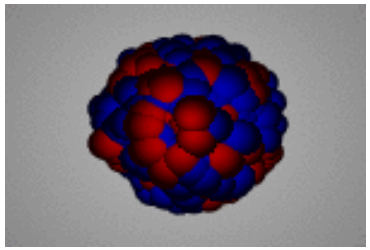
Monopole (GMR)

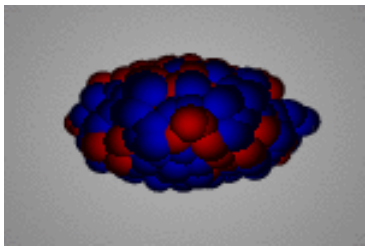
Dipole (GDR)

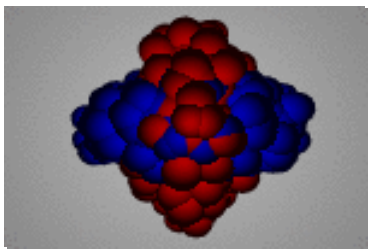
Quadrupole (GQR)

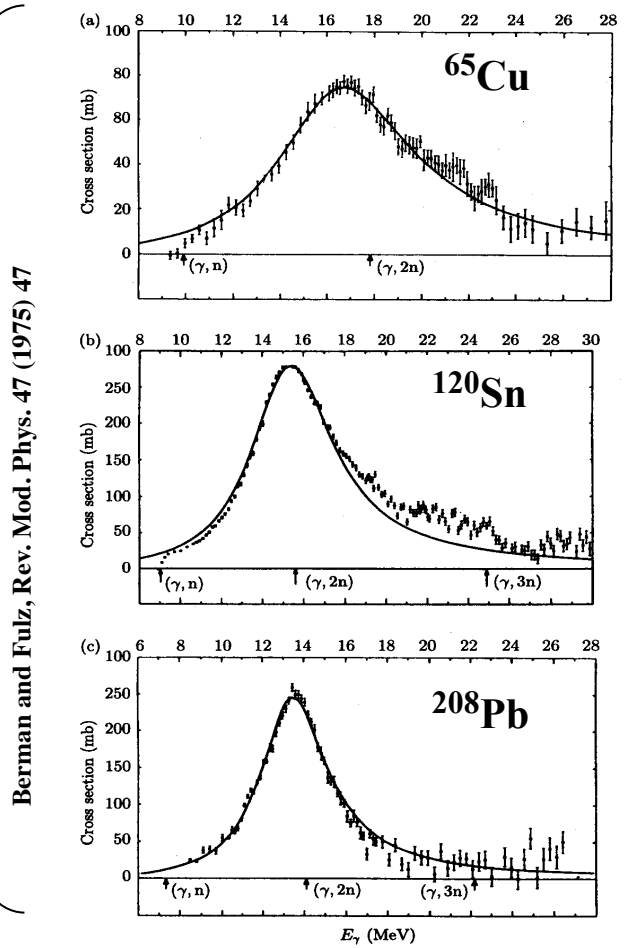






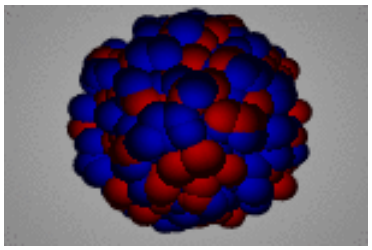
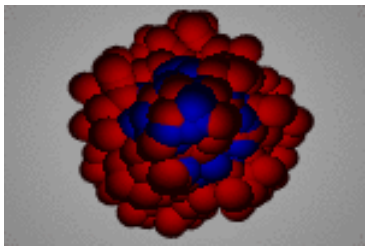
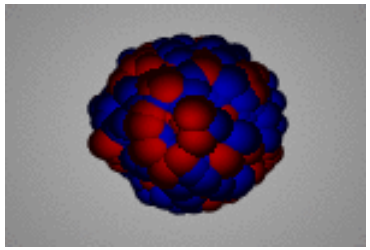
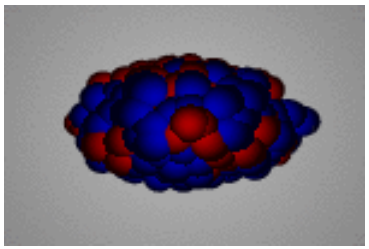
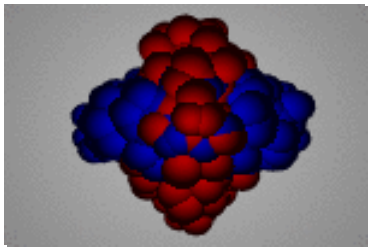






The collective response of the nucleus: Giant Resonances

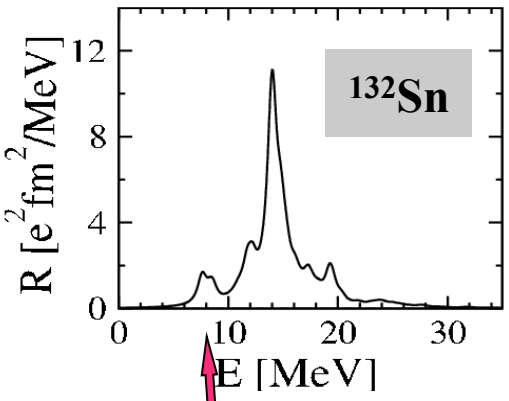
Electric giant resonances

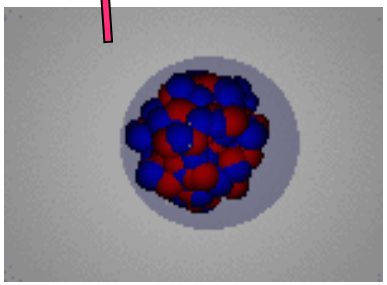
	Isoscalar	Isovector
Monopole (GMR)		
Dipole (GDR)		
Quadrupole (GQR)		

? new collective soft dipole mode

(Pygmy resonance)

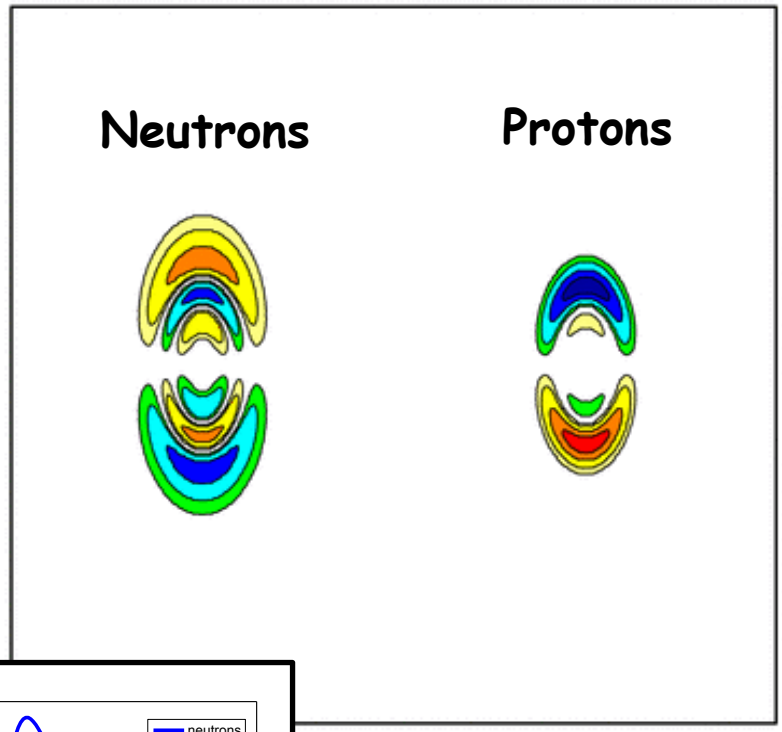
Prediction: RMF
(N. Paar et al.)

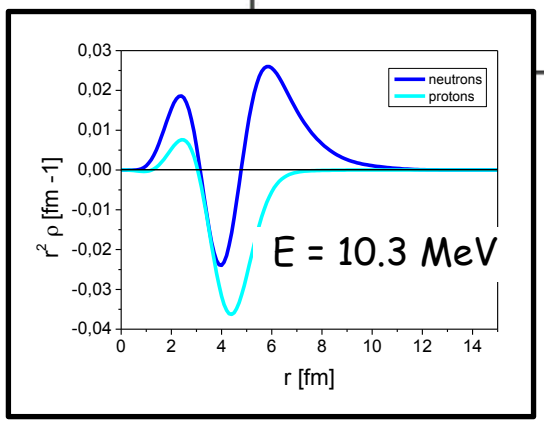




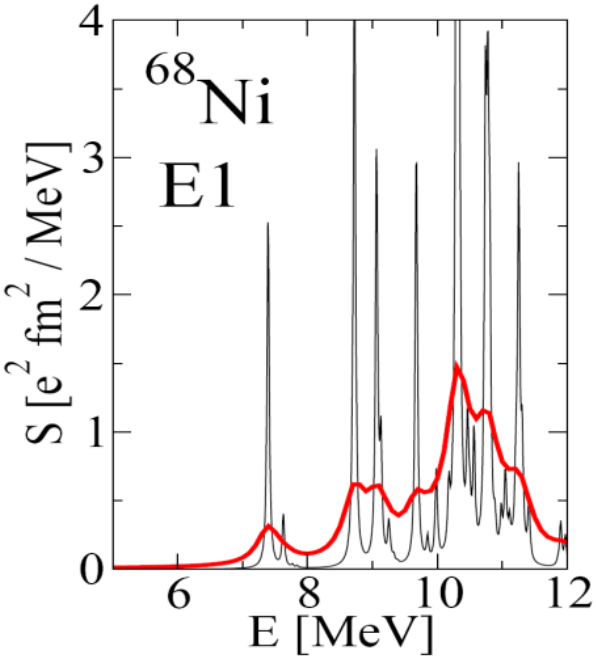
The Pygmy Dipole Resonance (PDR)
Relativistic mean-field theory

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





Theory: RQTBA-2



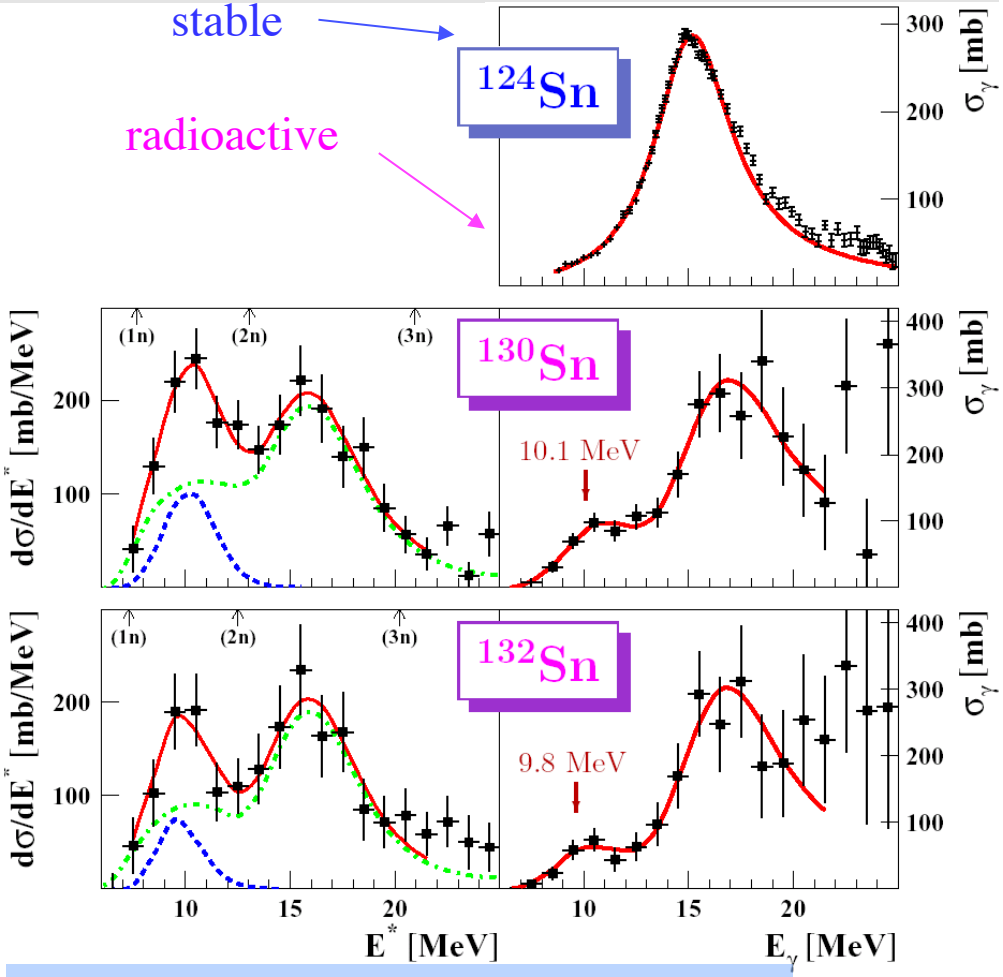
Theory:
Elena Litvinova (GSI)

Previous measurements with radioactive beams

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

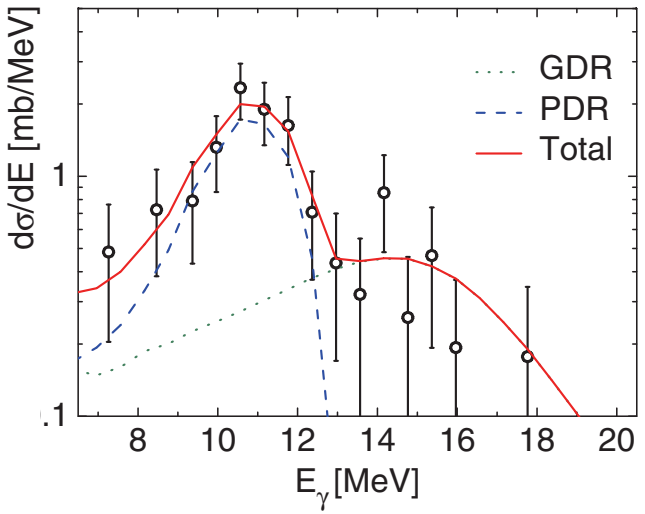
Electromagnetic-excitation cross section

Photo-neutron cross section



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

(γ,γ') in ^{68}Ni using RISING



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

PDR

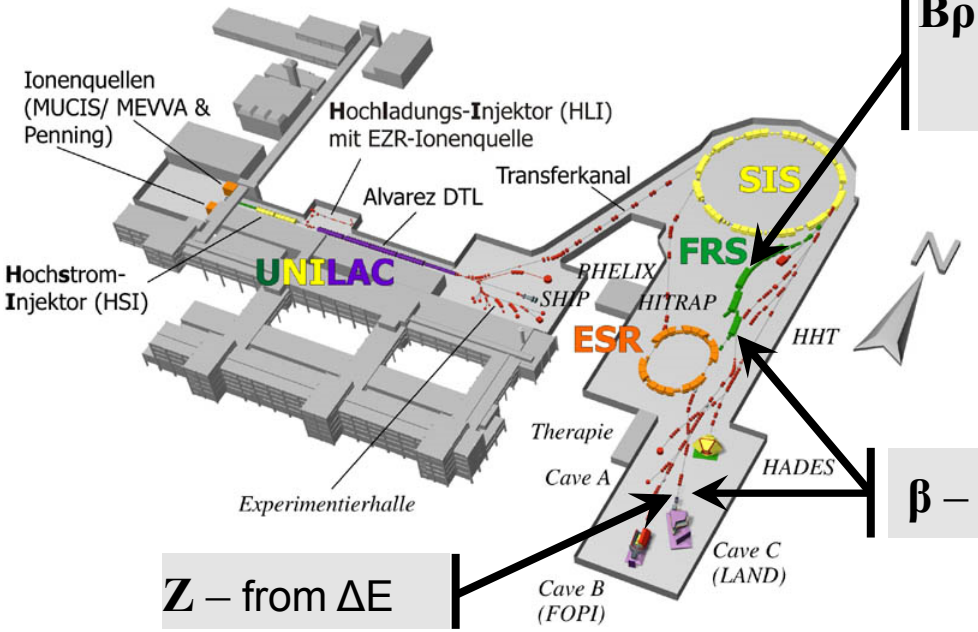
- located at 10 MeV
- exhausts a few % TRK sum rule

GDR

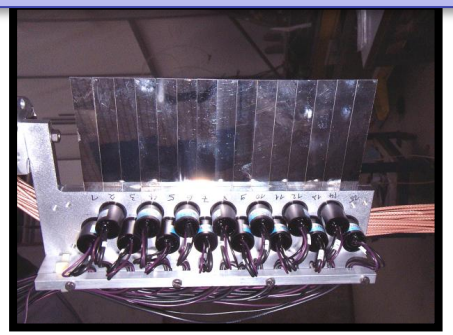
- no deviation from systematics

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)

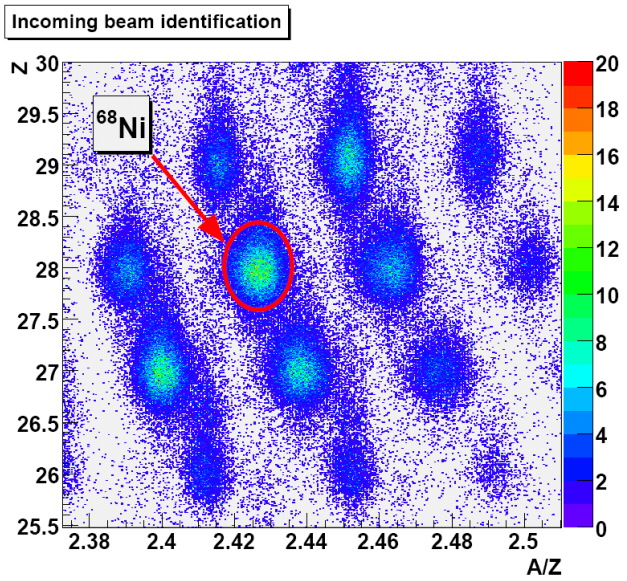


Bρ – from position at middle focal plane of the FRS



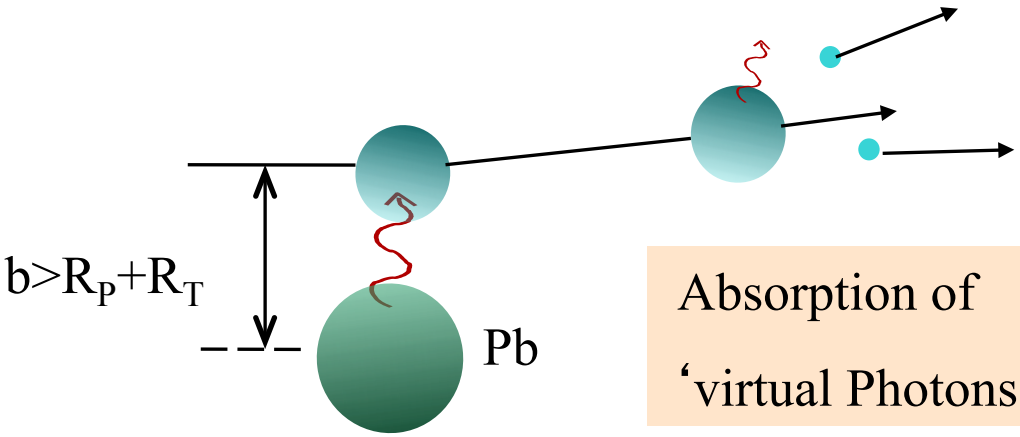
β – from TOF

Z – from ΔE



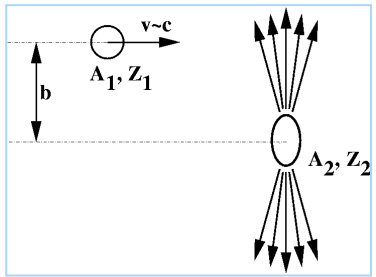
$$\frac{A}{Z} = \frac{e}{m_u c}\frac{B\rho}{\beta\gamma}$$

Electromagnetic excitation at high energies



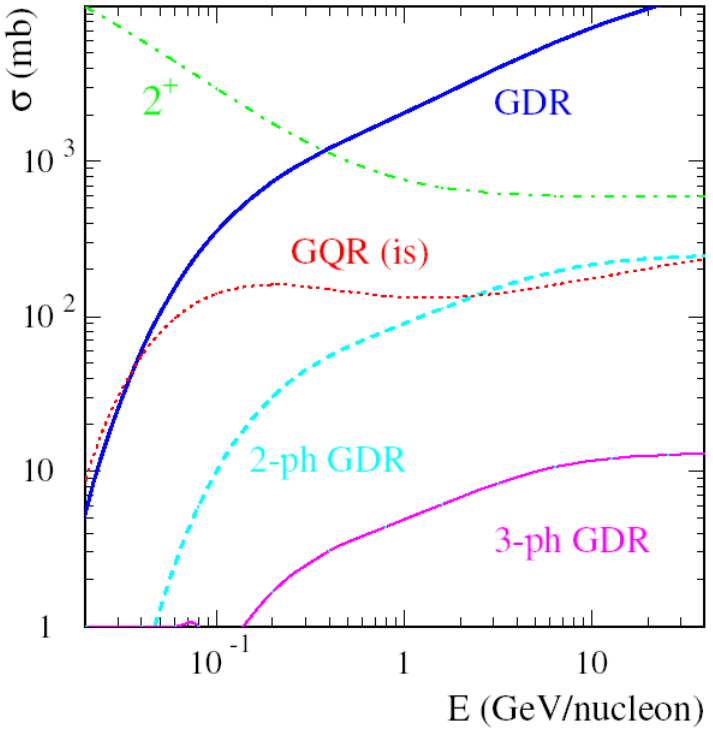
$\sigma_{elm} \sim Z^2$

Absorption of
'virtual Photons'



Semi-classical theory:

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

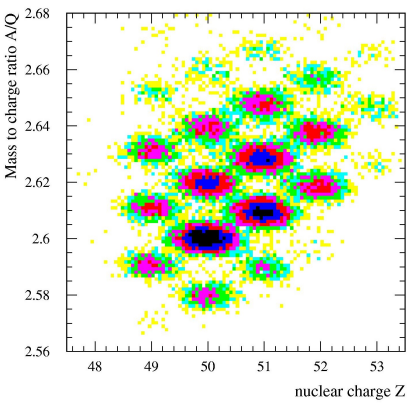


High velocities v/c≈0.6-0.9
⇒ High-frequency Fourier components
$E_{\gamma,max} \approx 25$ MeV (@ 1 GeV/u)

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

The LAND reaction setup @GSI

Mixed beam



Charged fragments

ToF, ΔE

tracking → Bρ ~ A/Qβγ

LAN
D

Neutrons

ToF, x, y, z

~12 m

projectile
tracking

Photons

ALADIN
large-acceptance dipole

Beam

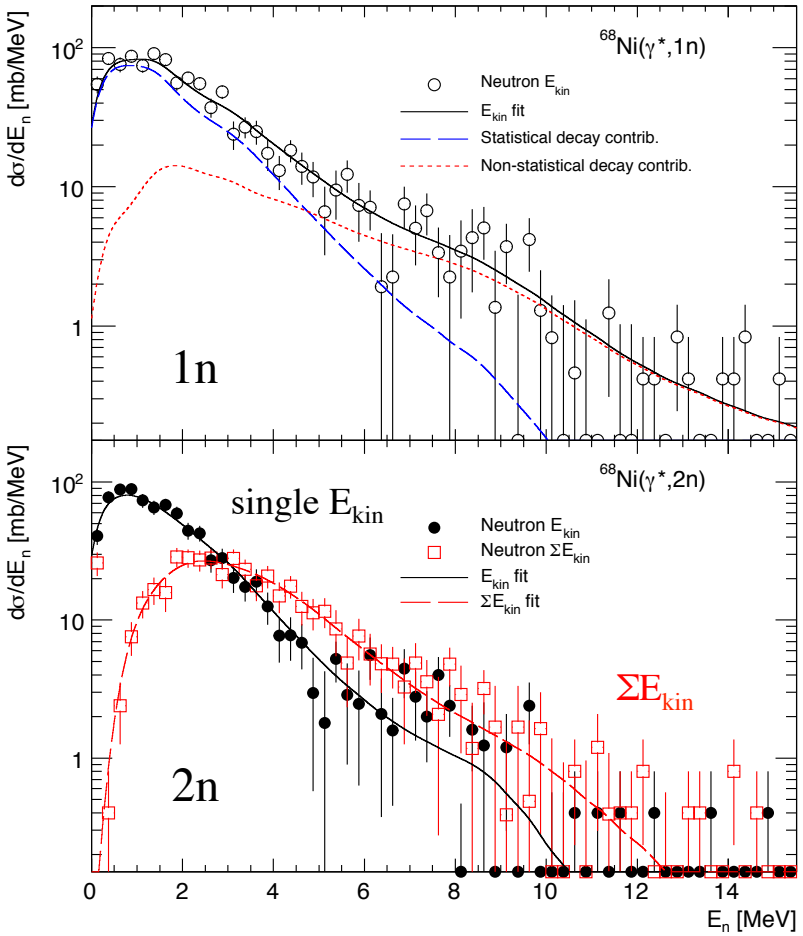
Crystal Ball
and Target

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

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

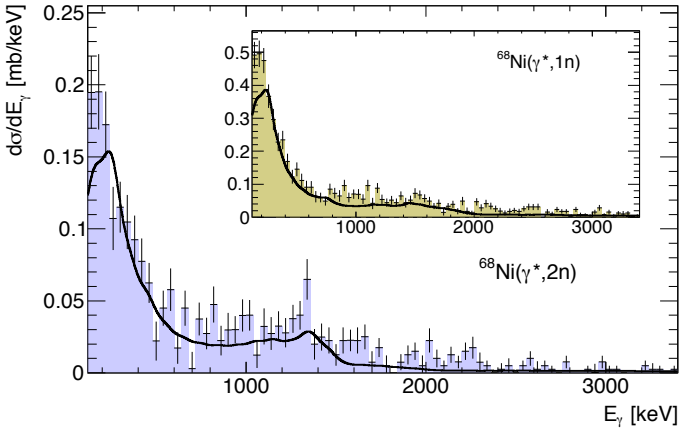
Analysis of ^{68}Ni: decay after Coulomb excitation

Neutron kinetic energy



R_{direct} = 24(4) %

gamma sum energy



consistent fit taking into account:

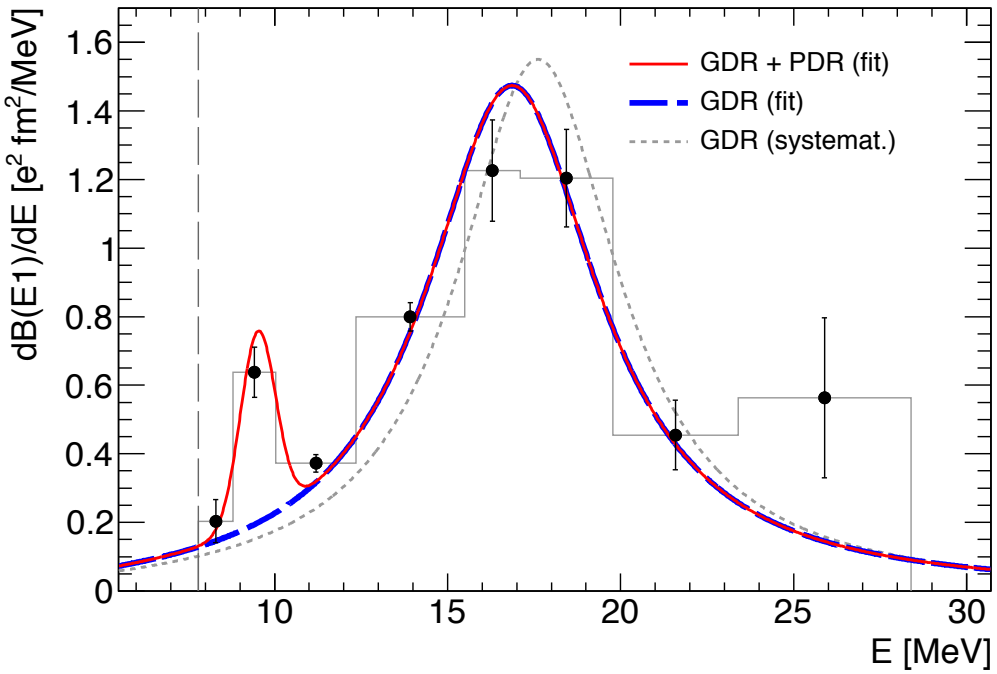
1) invariant mass, but also information of subsets like E_{kin}(n), $E_{\gamma sum}$ etc.

2) detailed knowledge about detector response function

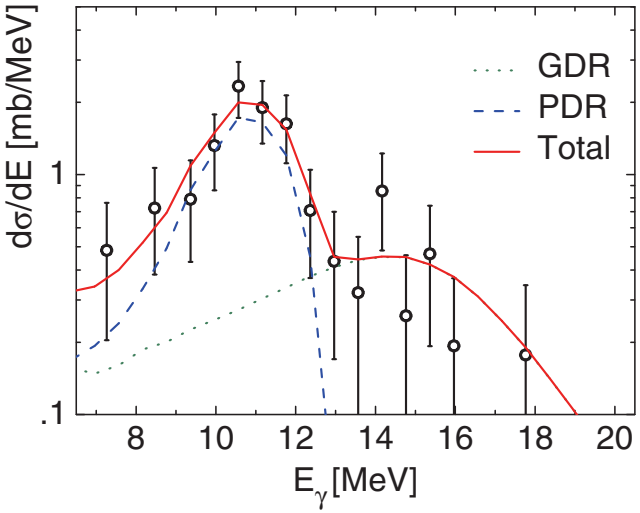
analysis:
Dominic Rossi
PhD Thesis
Univ. Mainz,
PostDoc GSI
Now MSU

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)	

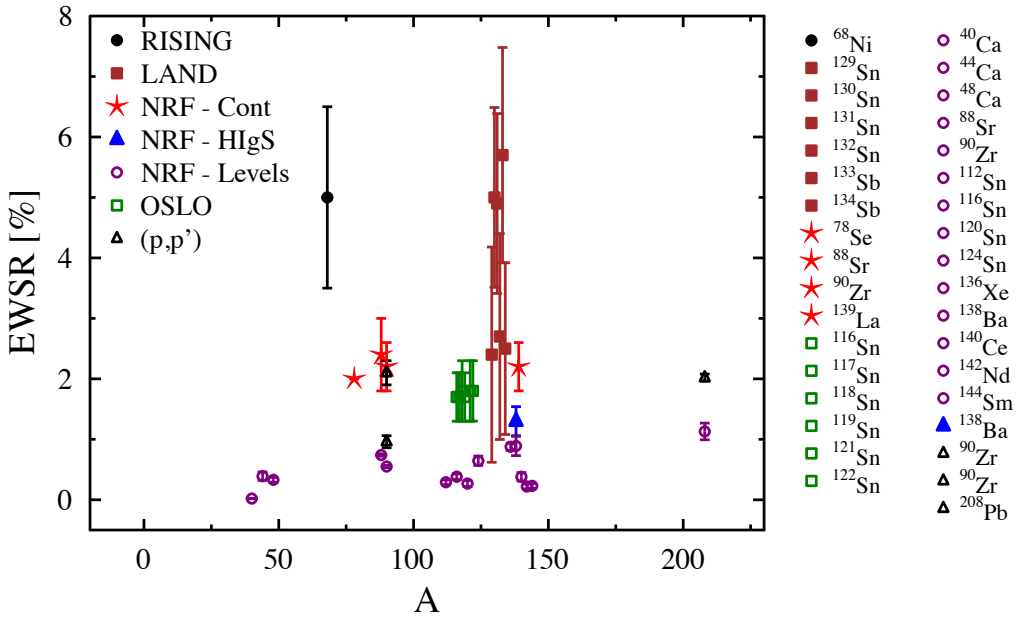


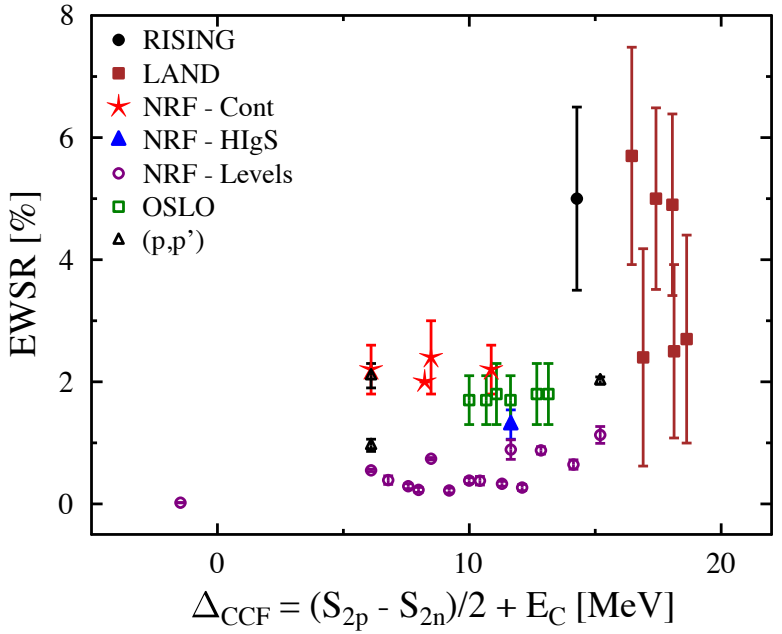
O. Wieland et al., PRL 102, 092502 (2009)

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

D. Rossi et al., to be published

Systematics of Pygmy dipole strength ?



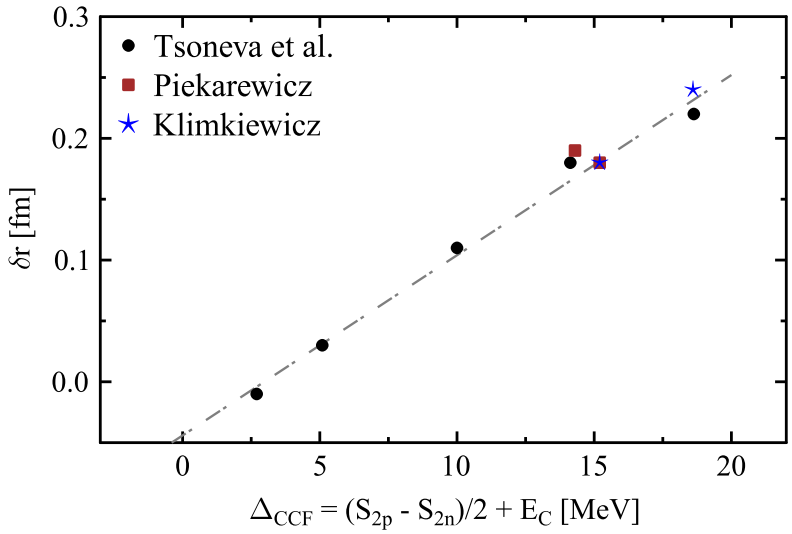


Review

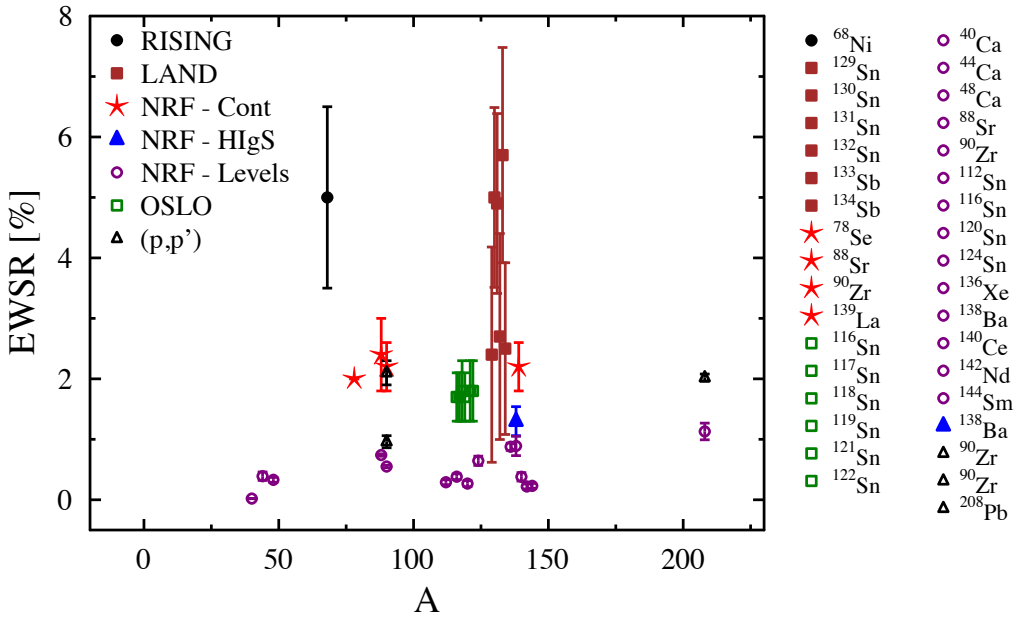
Experimental studies of the Pygmy Dipole Resonance

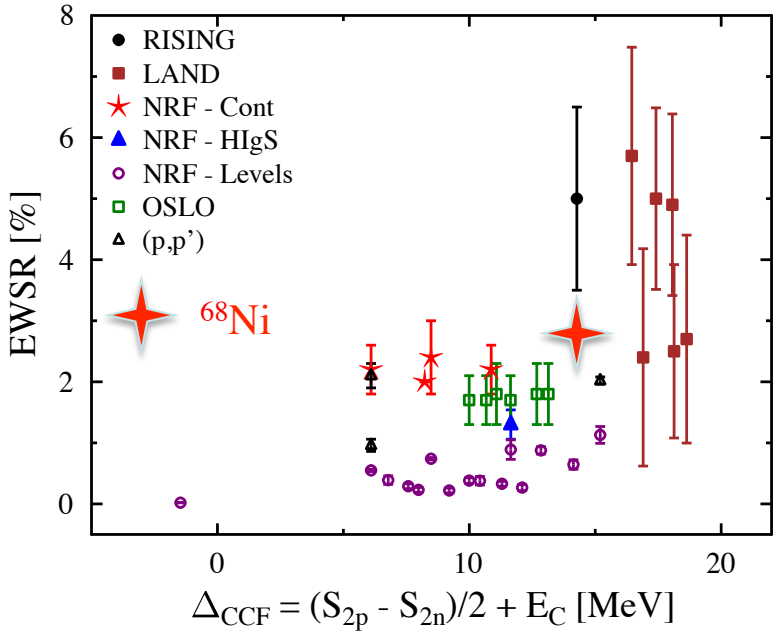
D. Savran [a,b,*], T. Aumann [c,d], A. Zilges [e]

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



Systematics of Pygmy dipole strength ?





Review

Experimental studies of the Pygmy Dipole Resonance

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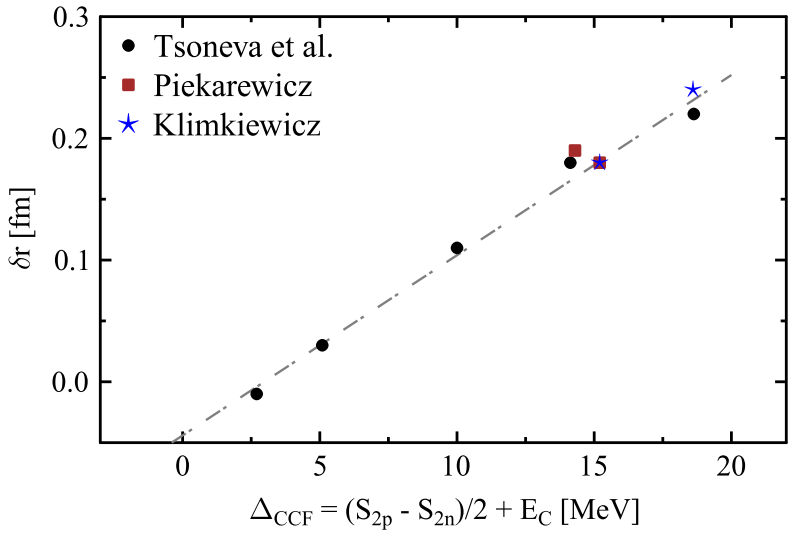
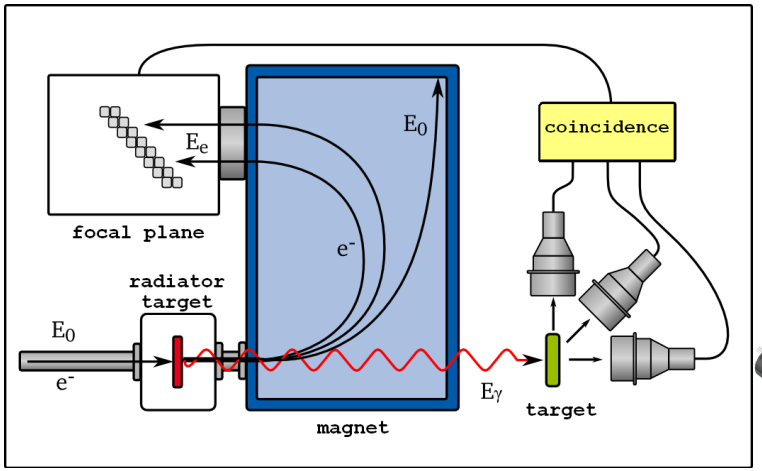
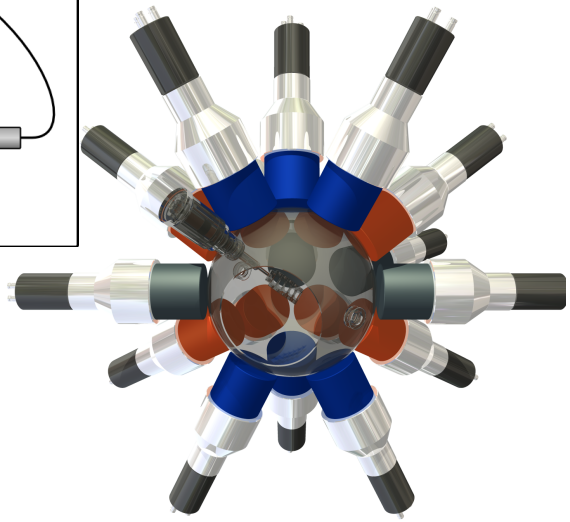
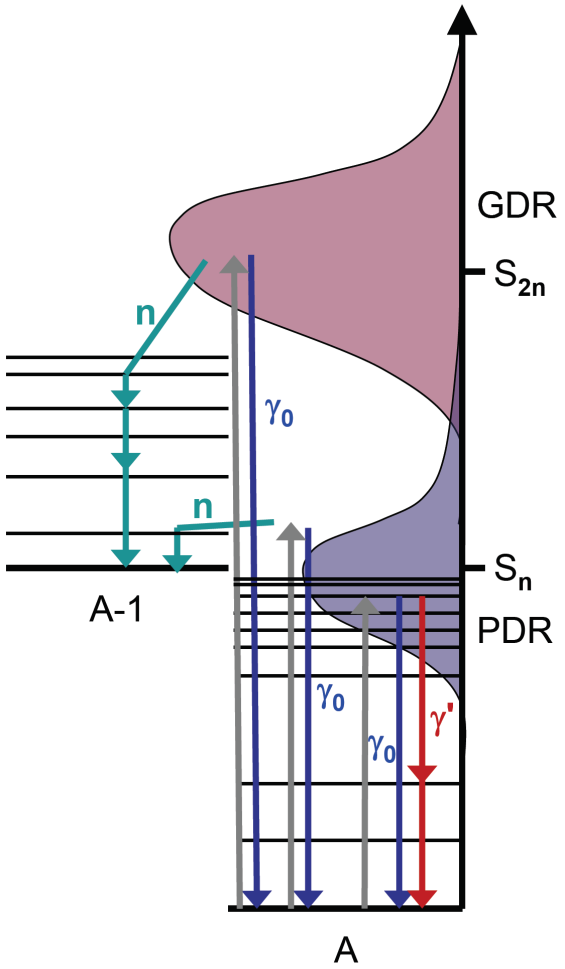


New measurements with stable nuclei: Experimental approach

- **Real-photon scattering** at NEPTUN (quasi-monoenergetic photons)
- Measure (γ,n), (γ,γ_0), $(\gamma,\gamma_i\gamma_k)$ cross sections in one experiment for E_γ **above** and **below** S_n







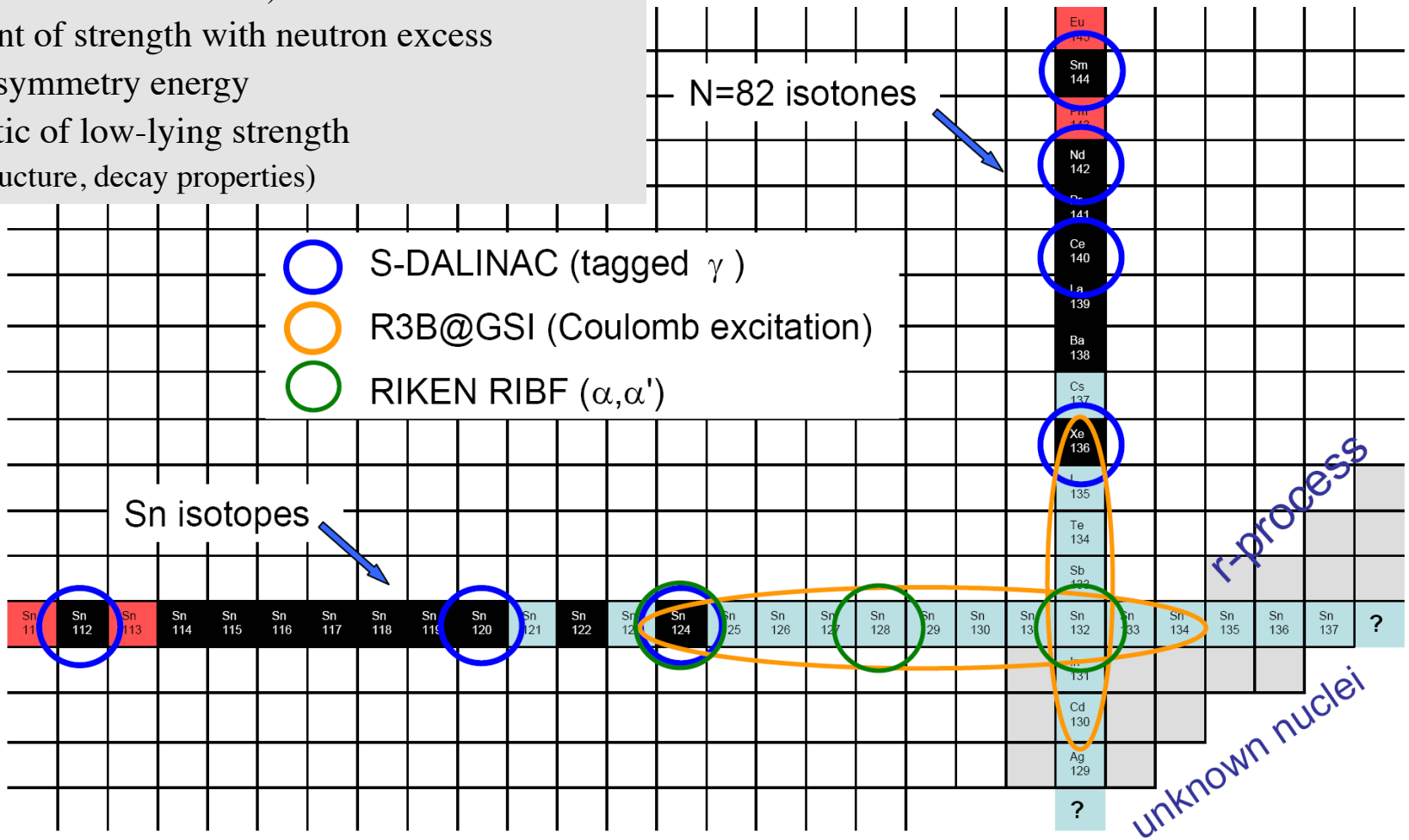
TECHNISCHE UNIVERSITÄT DARMSTADT

SFB 634

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)



Symmetry energy and dipole response

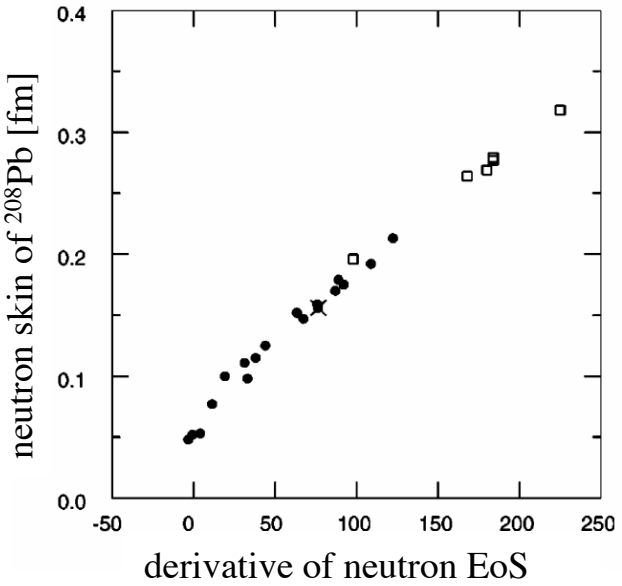
neutron-skin thickness
dipole response

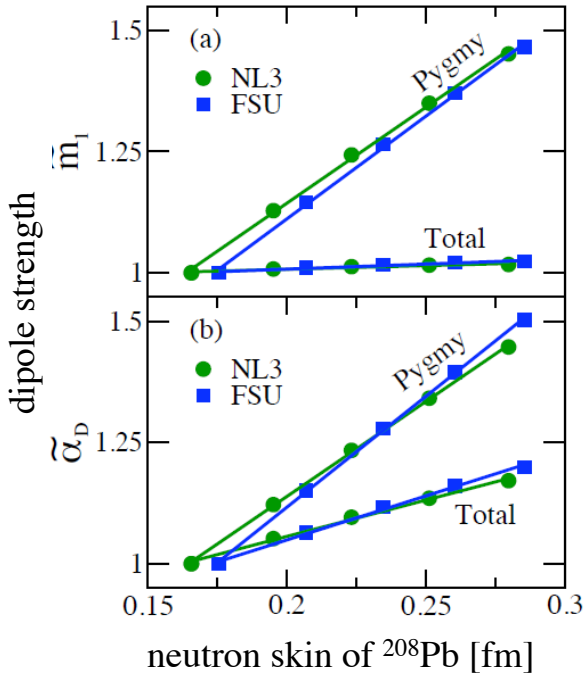
⟺

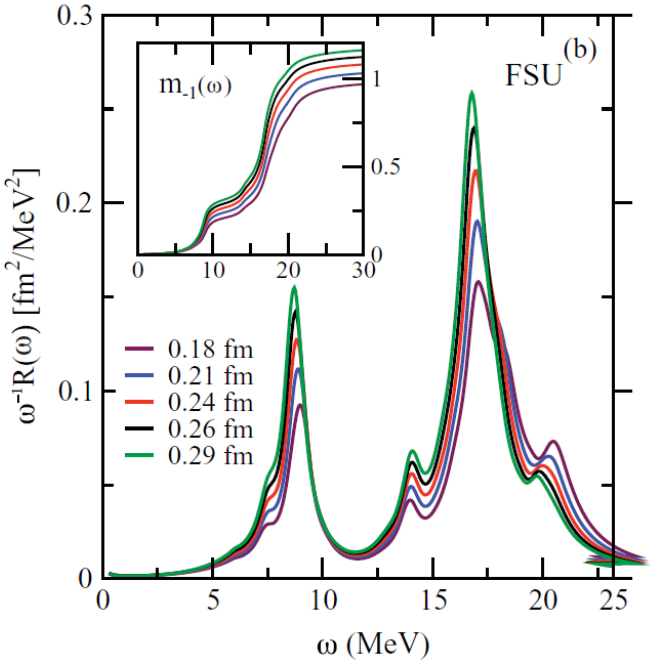
density dependence of
symmetry energy

⟺

properties of
neutron-rich matter







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

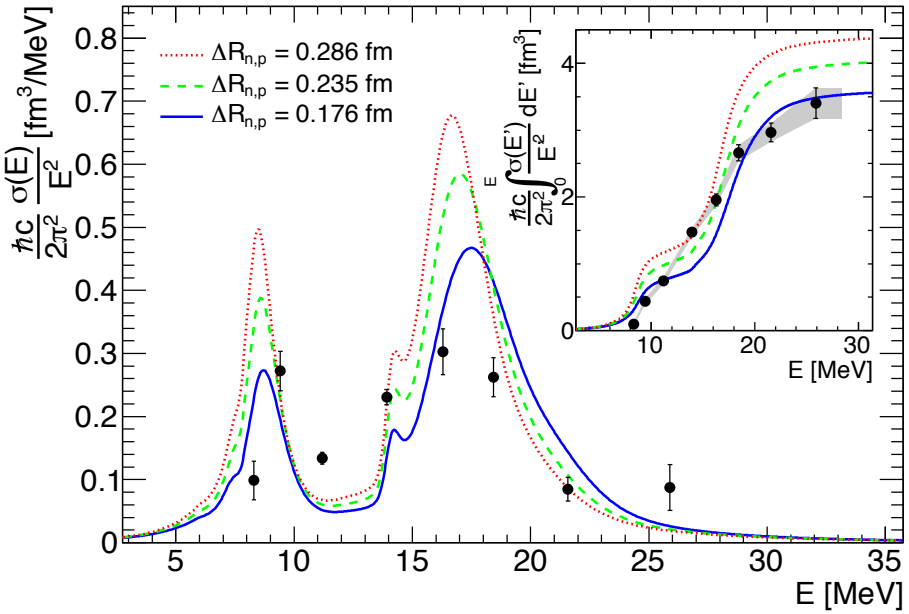
J. Piekarewicz,PRC ***83,*** *034319 (2011)*

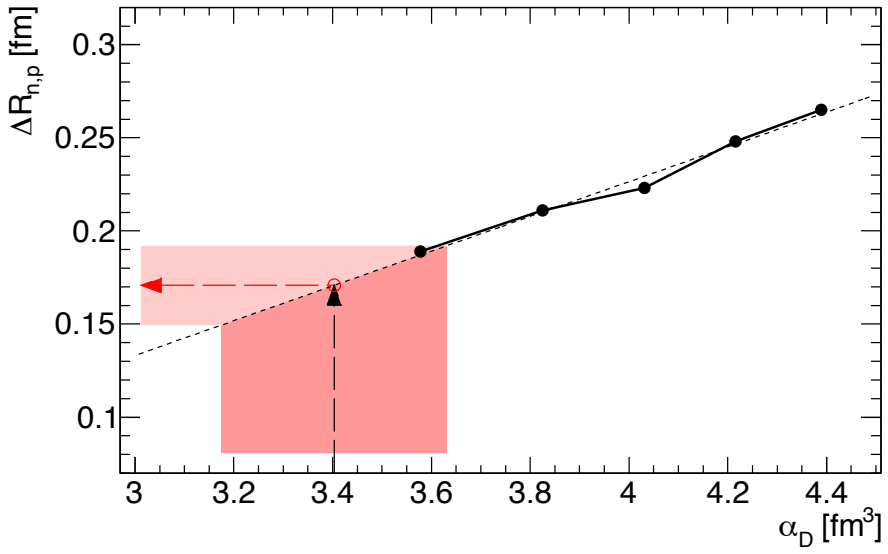
n-skin from Pygmy strength

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.

Polarizability and neutron skin



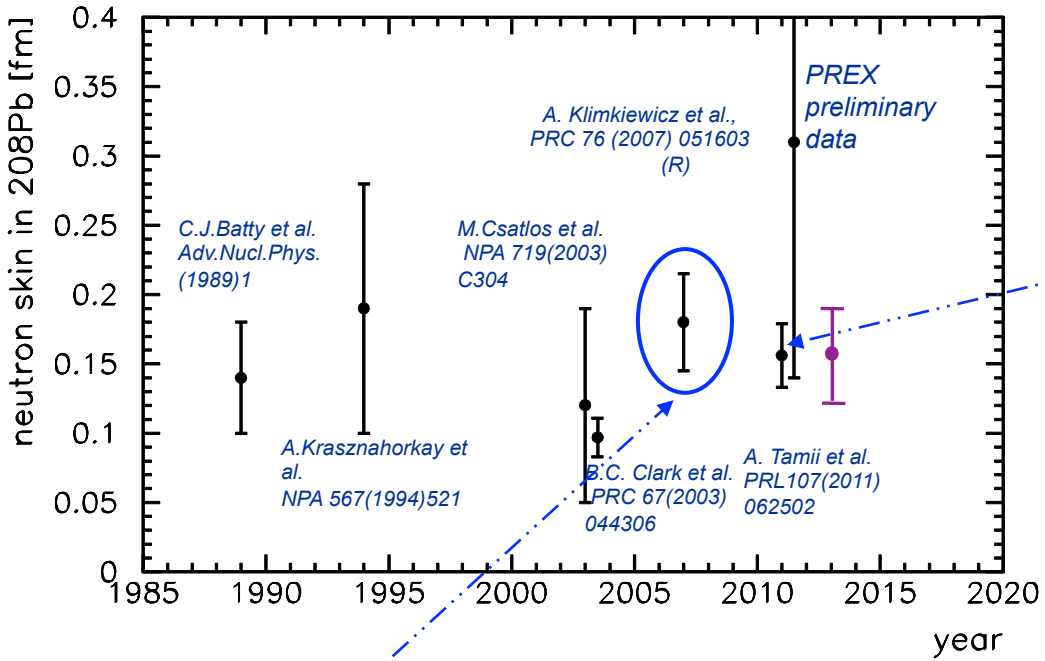


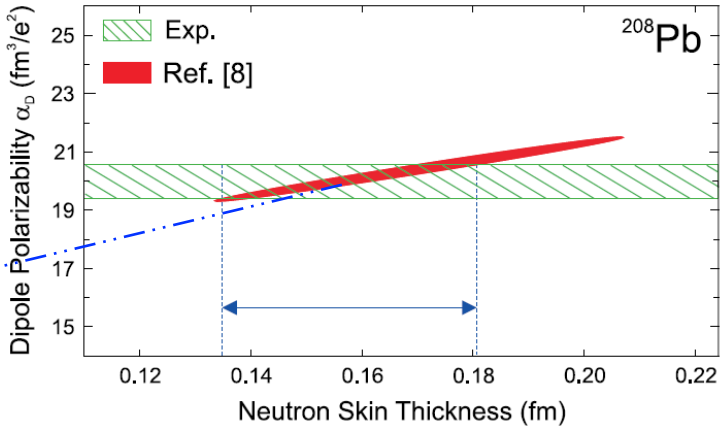
$$\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma\,(E)}{E^2}dE$$

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

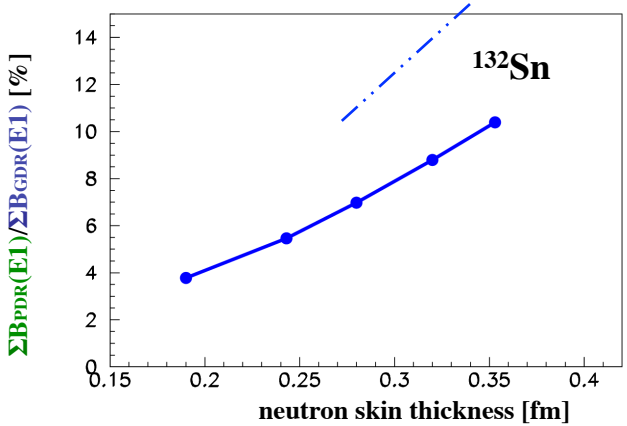
Theoretical calculations from J. Piekarewicz,PRC **83,** 034319 (2011)

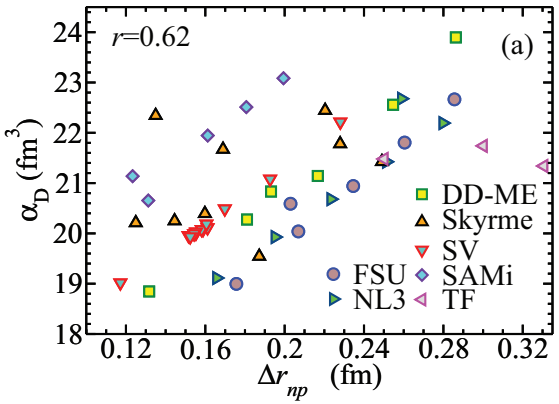
Neutron skin in ^{208}Pb from different methods

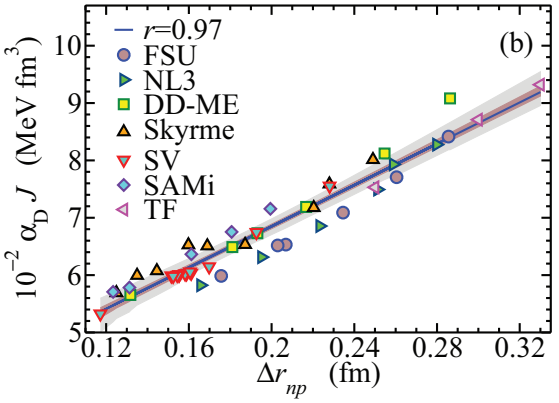




But:
X. Roca-Maza et al., PRC 88 (2013) 024316







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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[2] *Institut für Kernchemie, Johannes Gutenberg-Universität, D-55128 Mainz, Germany*
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[5] *Physik-Department E12, Technische Universität München, D-85748 Garching, Germany*
[6] *University of Vigo, E-36310 Vigo, Spain*
[7] *University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[8] *Saha Institute of Nuclear Physics, Kolkata 700-064, India*
[9] *Institut für Angewandte Physik, Goethe Universität, D-60438 Frankfurt am Main, Germany*
[10] *Chalmers University of Technology, SE-41296 Göteborg, Sweden*
[11] *Helmholtz-Zentrum Dresden-Rossendorf e.V., D-01328 Dresden, Germany*
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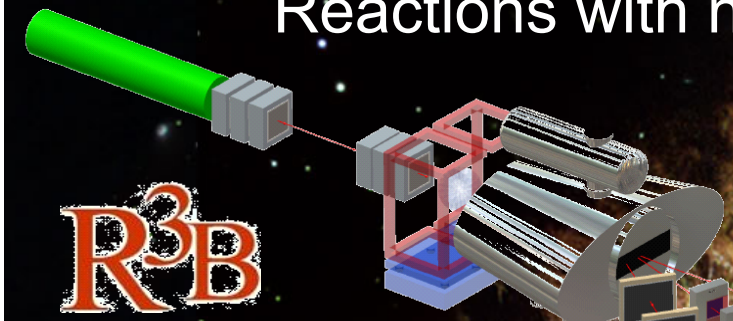
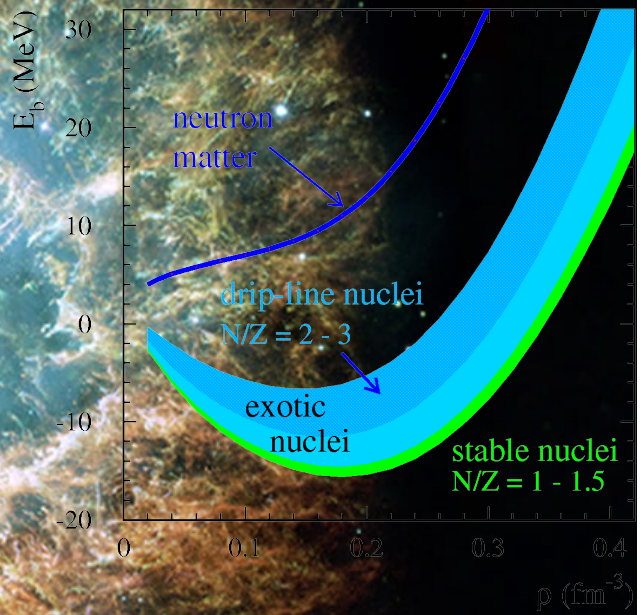
[14] *STFC Daresbury Laboratory, Warrington WA4 4AD, United Kingdom*
[15] *Institut Pluridisciplinaire Hubert Curien, F-67037 Strasbourg, France*
[16] *Bhabha Atomic Research Centre, Mumbai 400-085, India*
[17] *Tata Institute of Fundamental Research, Mumbai 400-005, India*
[18] *ExtreMe Matter Institute 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*

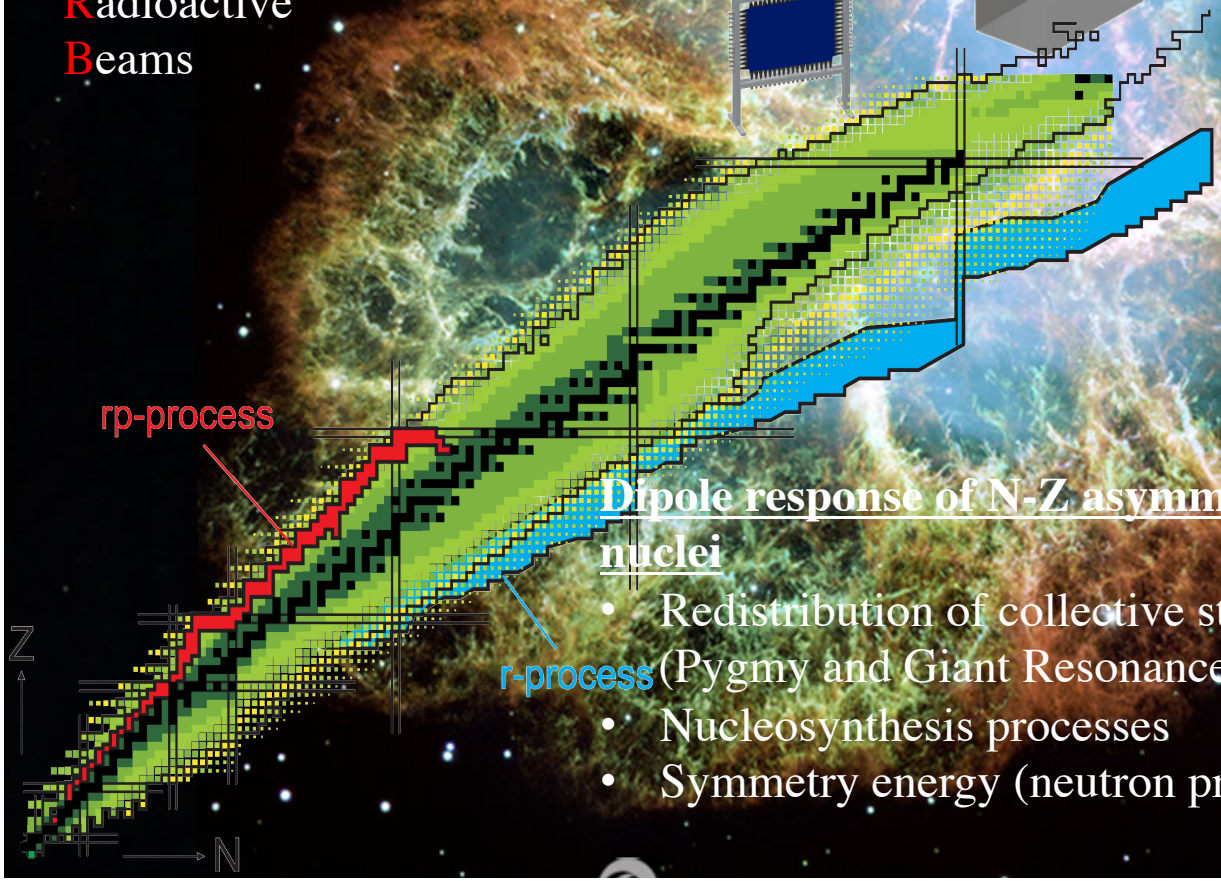
Reactions with neutron-proton asymmetric nuclei



R³B

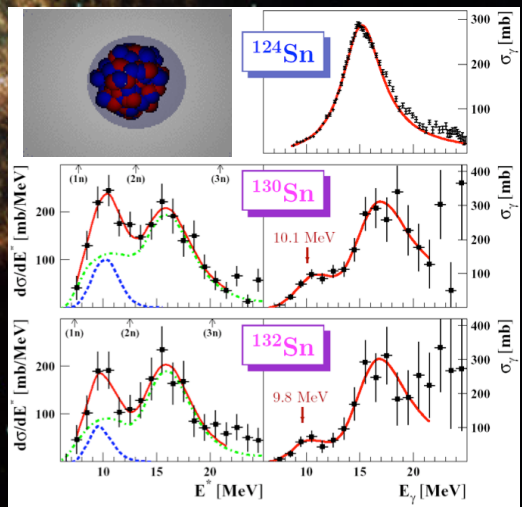
Reactions with
Relativistic
Radioactive
Beams





Dipole response of N-Z asymmetric nuclei

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



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

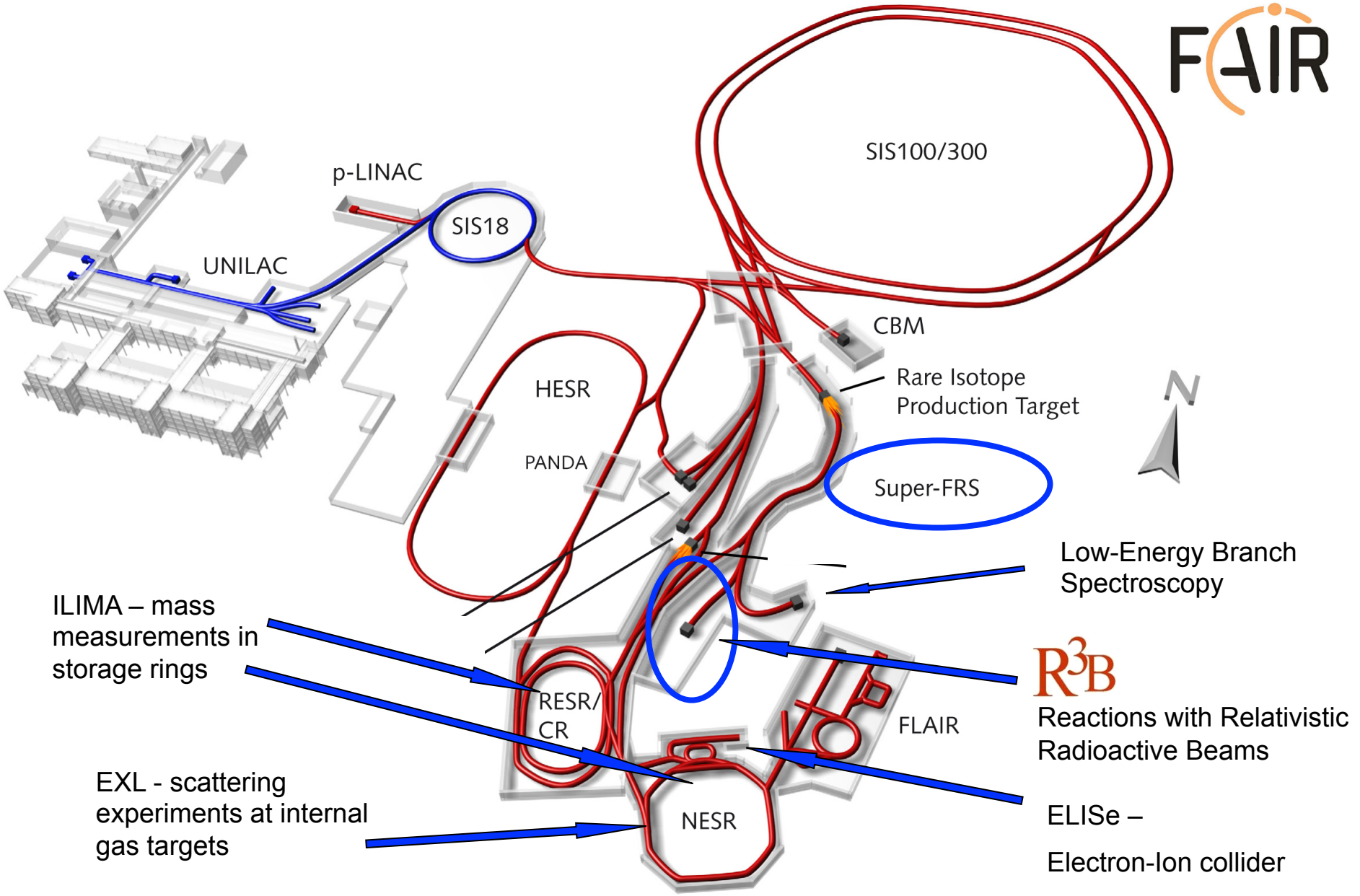
- Dipole response of ^{68}Ni
  - 25(2)% non-statistical decay
  - PDR: 2.8(5)% EWSR, 7(2)% direct gamma decay
  - Dipole polarizability extracted for the first time for a radioactive nucleus

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

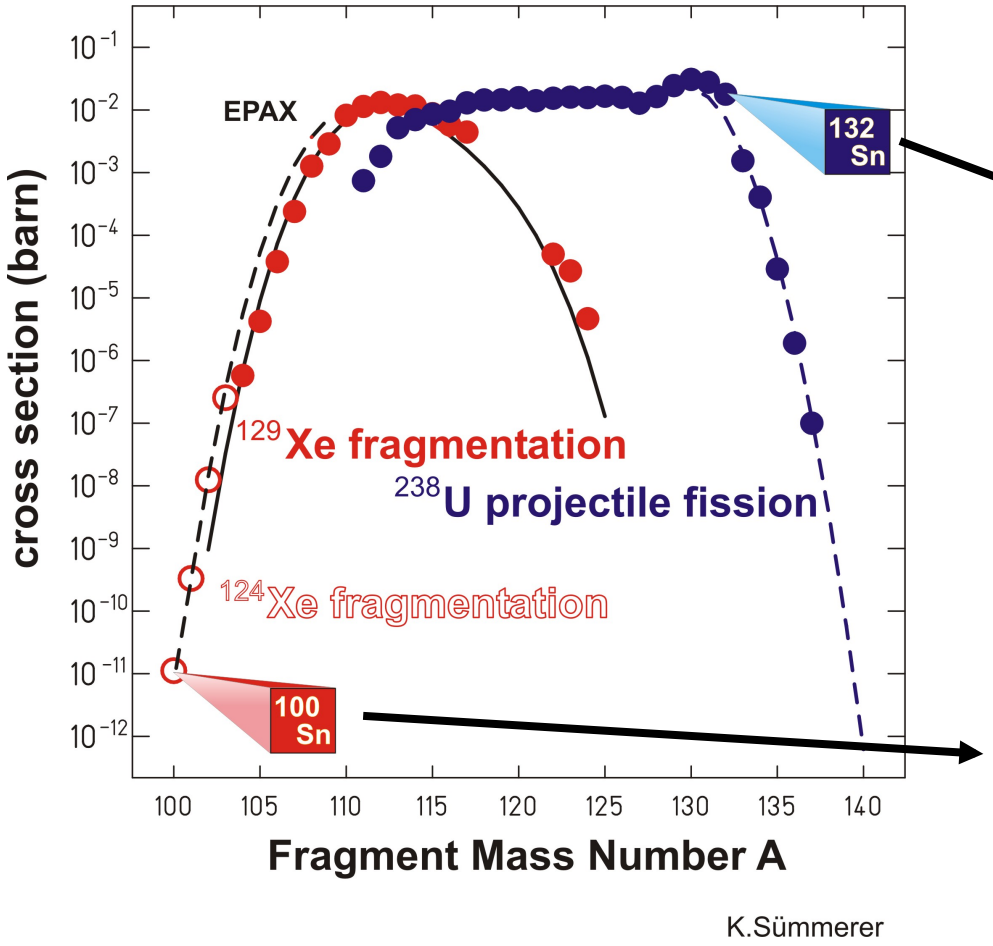
Facility for Anti-Proton and Ion Research FAIR

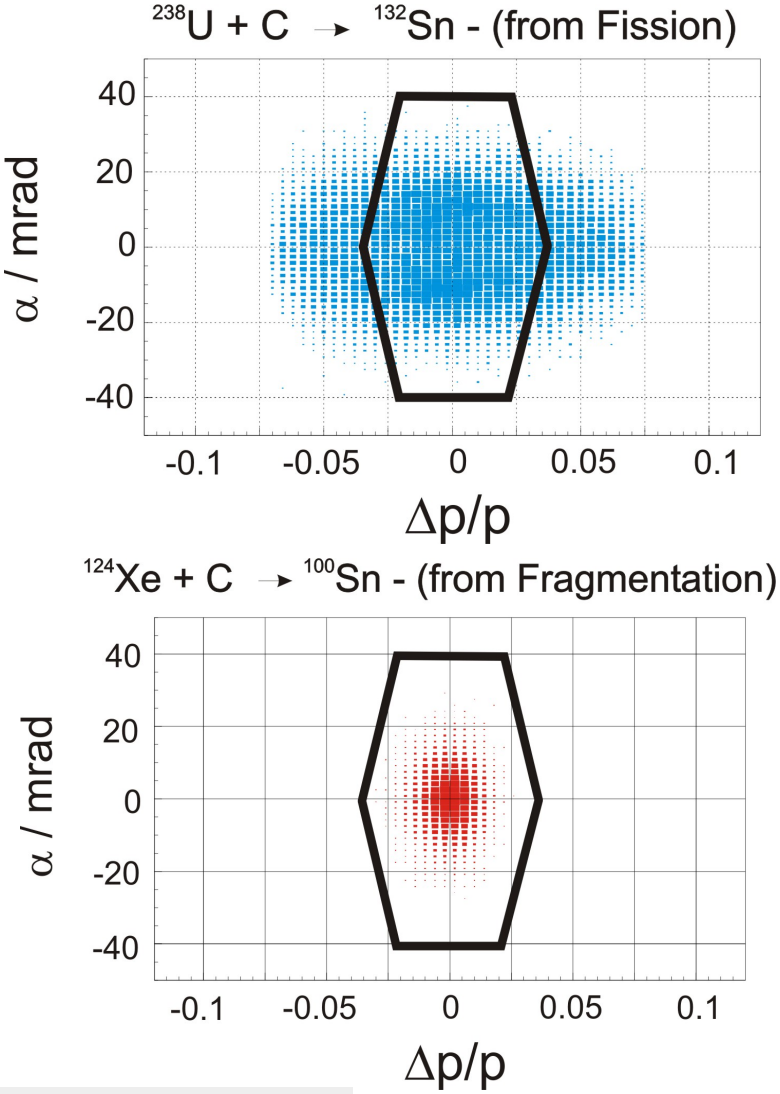
Facility for Anti-Proton and Ion Research FAIR

High-energy radioactive beams at FAIR



Production of radioactive beams by fragmentation and fission





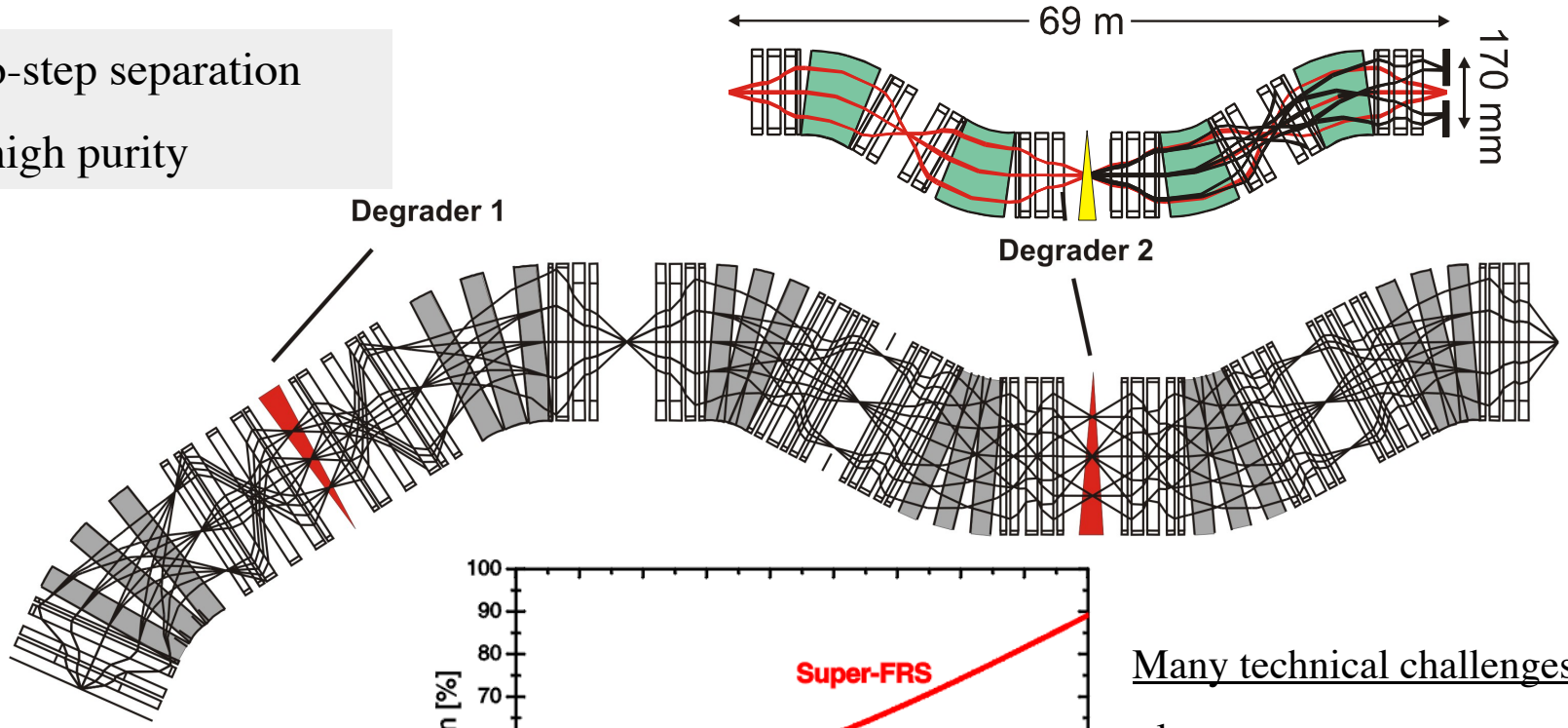
Large acceptance required for separation of fission fragments

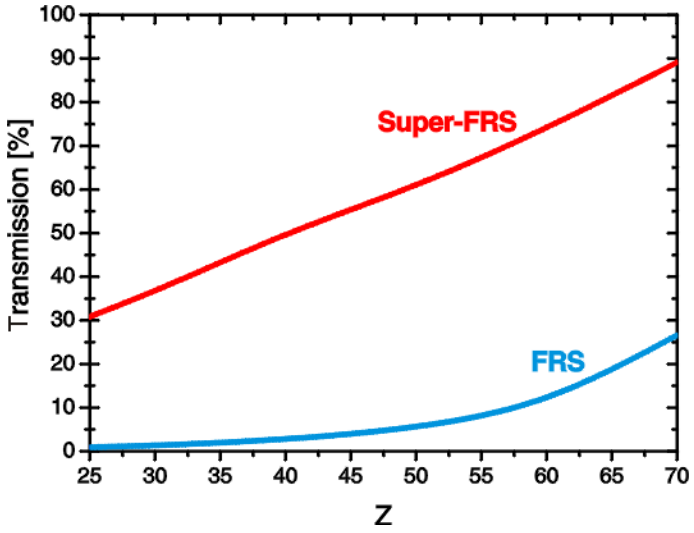
Martin Winkler

Superconducting Fragment Separator Super-FRS

Two-step separation

→ high purity





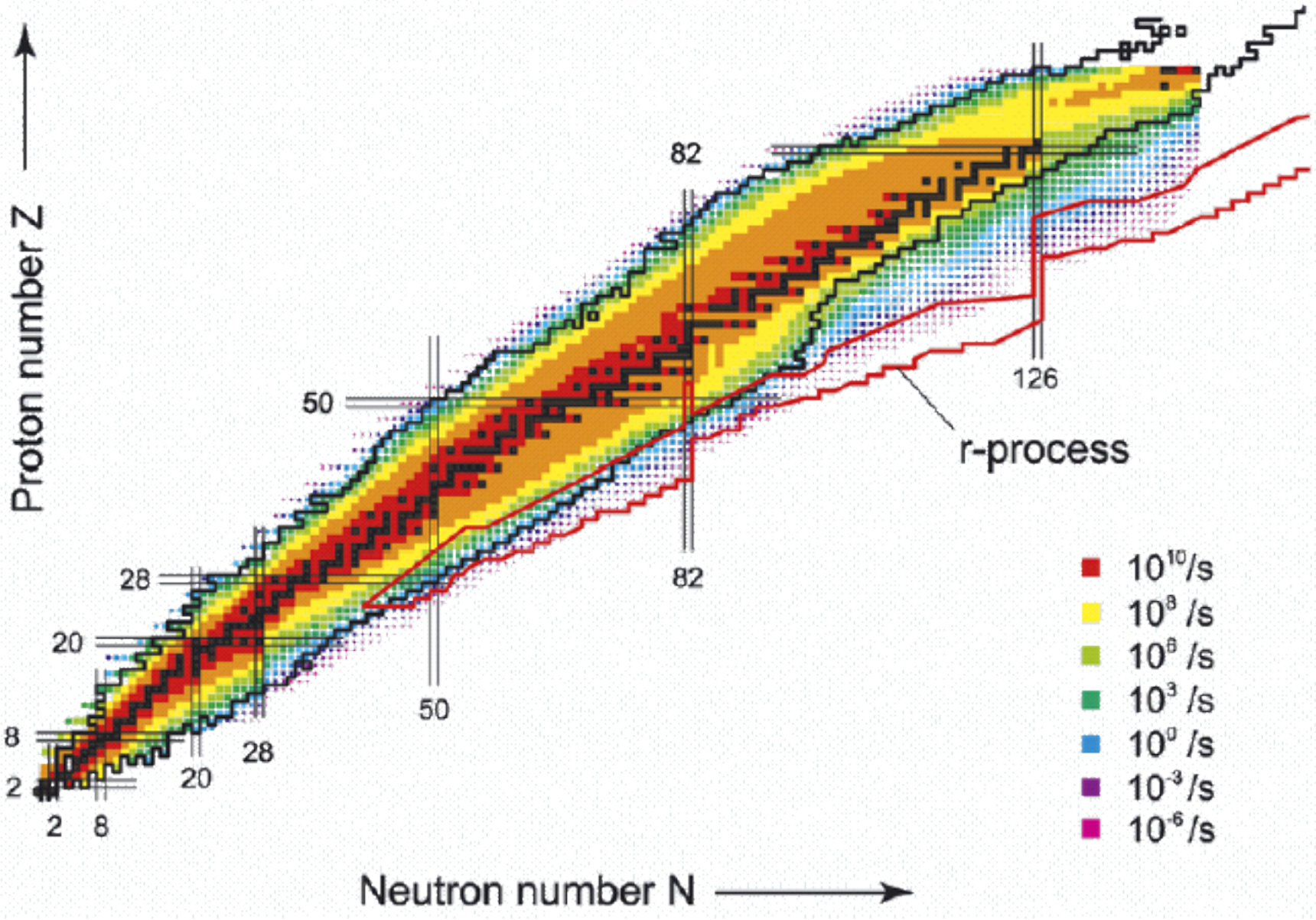
- up to 20 Tm beams
- Large acceptance:
  - $\Delta p/p = \pm 2.5\%$
  - $\Delta\Phi_x = \pm 40$ mrad
  - $\Delta\Phi_y = \pm 20$ mrad

Many technical challenges:

- large-aperture s.c. magnets
- radiation-hard magnets
- high-power target
- beam dumps
- radiation issues
- .....

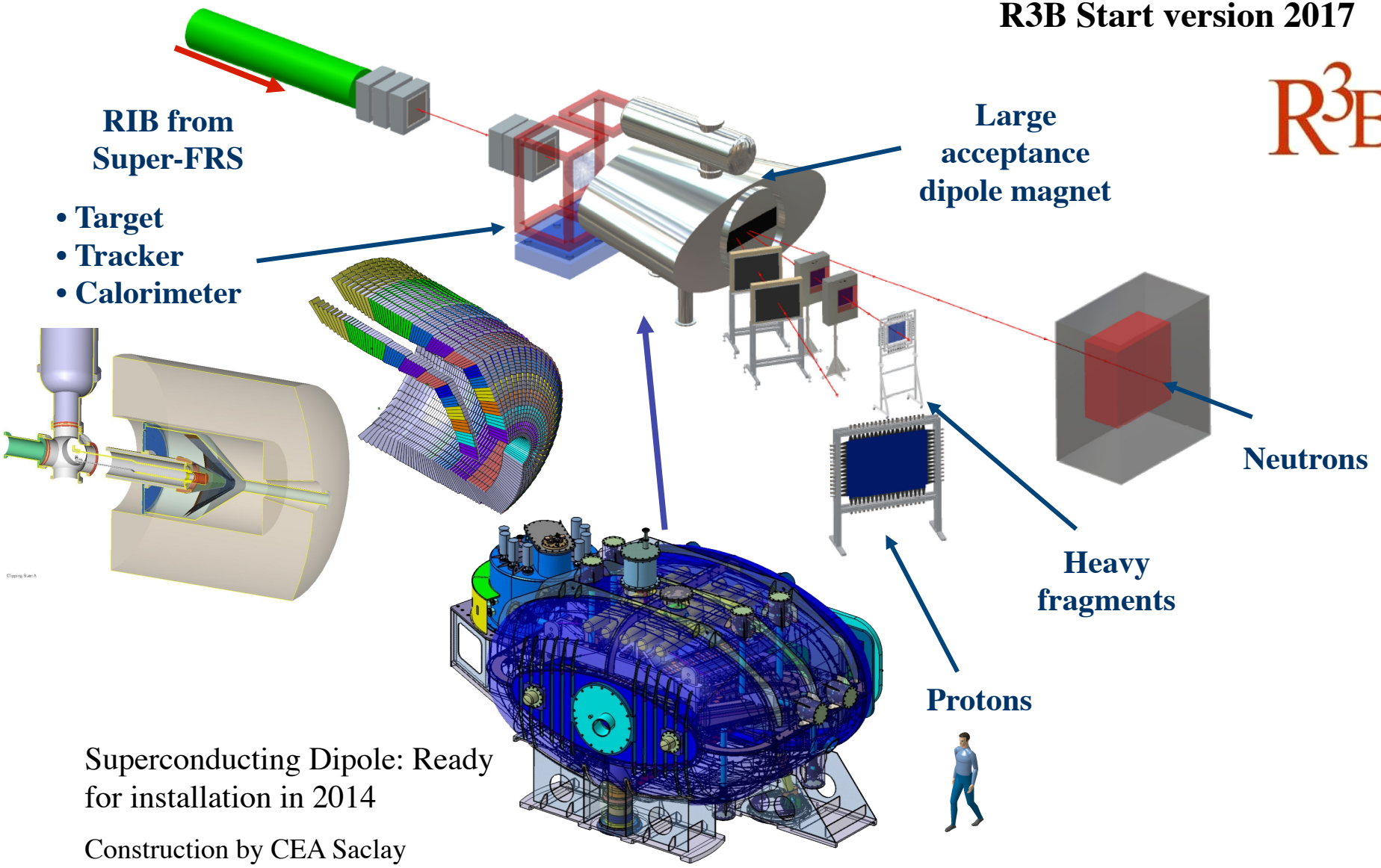
→ High transmission for fission fragment (intensity gain by a factor of ~10)

RIB intensities after Super-FRS



Reactions with Relativistic Radioactive Beams

R3B Start version 2017



Superconducting Dipole: Ready for installation in 2014

Construction by CEA Saclay