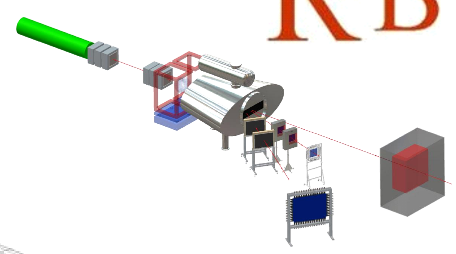
# Relativistic Radioactive Beams as a Tool for Nuclear Astrophysics



*Thomas Aumann*

December 11th 2013

***27th Texas Symposium on Relativistic Astrophysics***

***Dallas, Texas***

Bundesministerium
für Bildung
und Forschung

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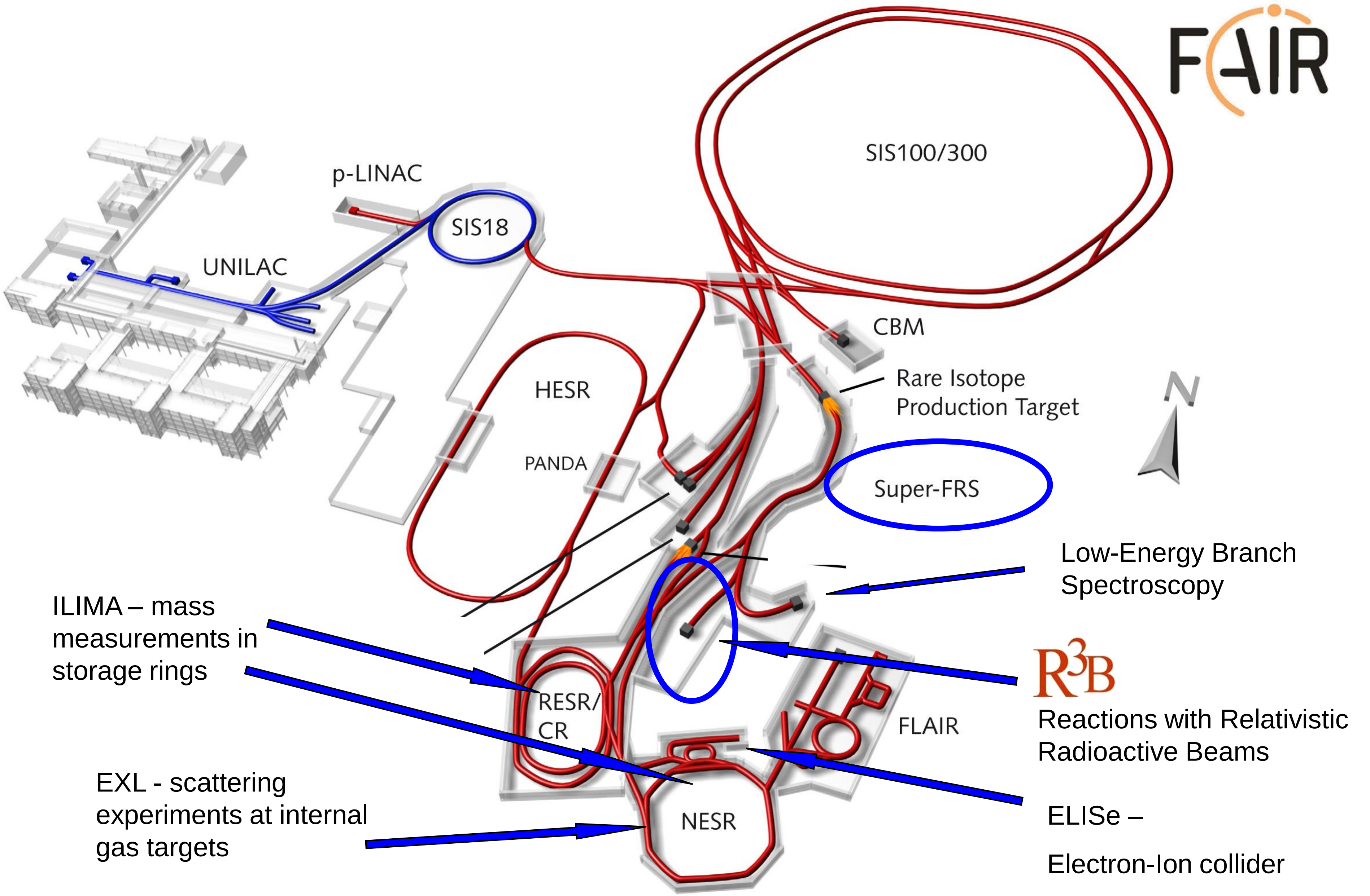
# FAIR – Facility for Antiproton and Ion Research

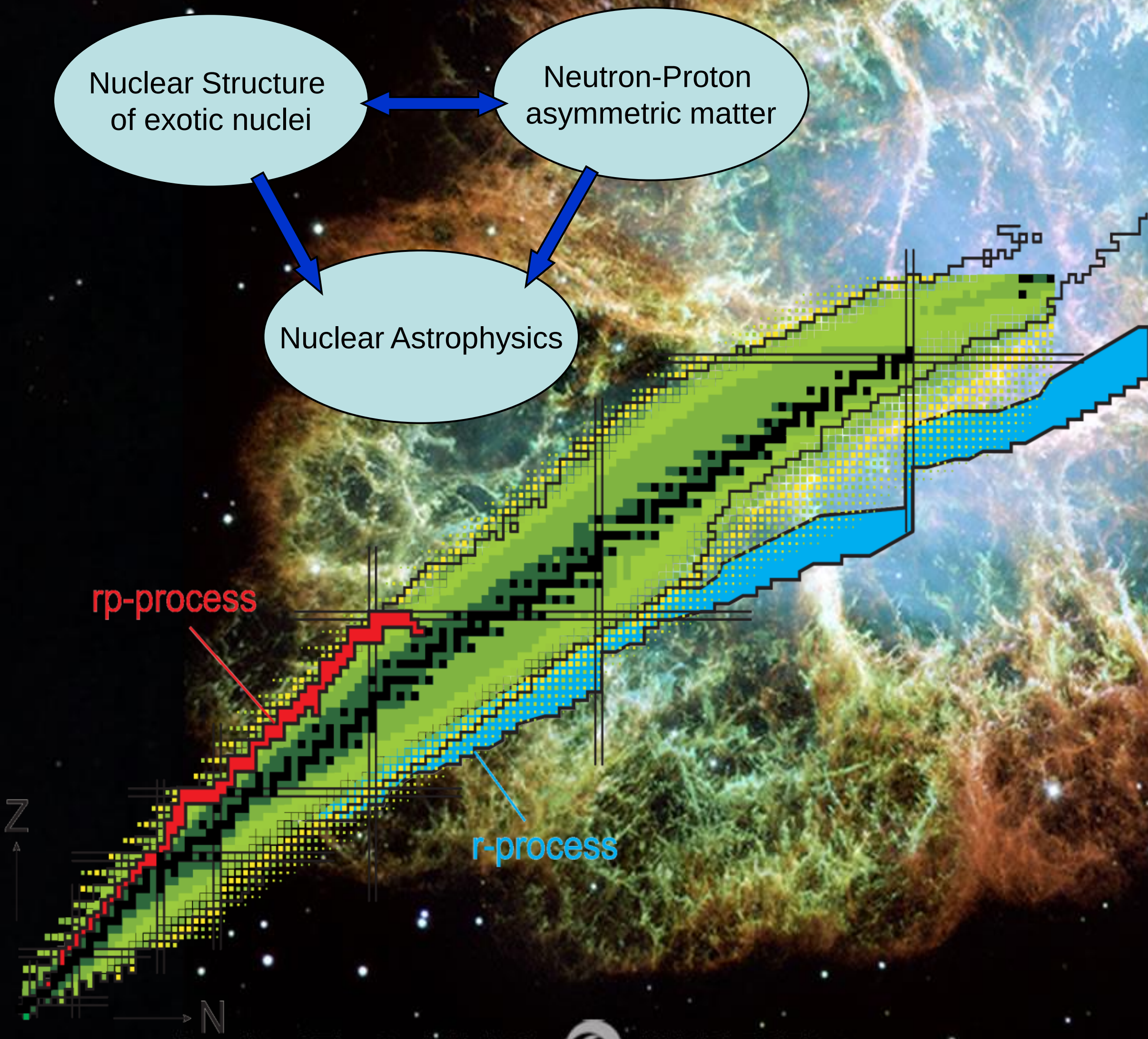
*Figure 1.1: Artists view of FAIR. The synchrotrons on the right will be located 10 to 13 m underground and will not be visible in reality. Most of the roofs will be vegetated and thus most of the facility will be hidden from view.*

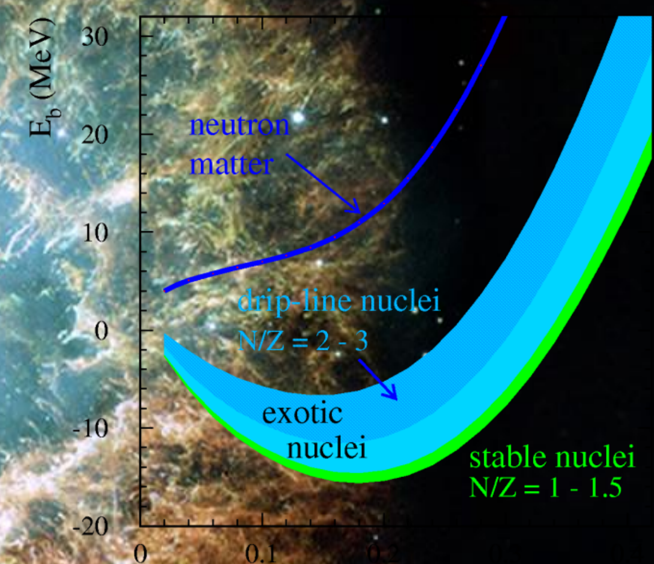
# High-energy radioactive beams at FAIR

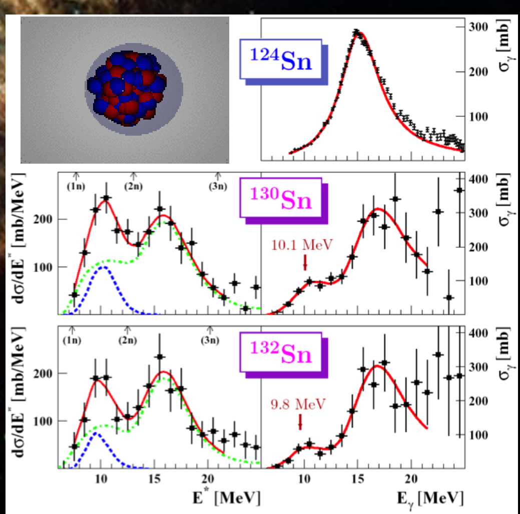


# Reactions with neutron-proton asymmetric nuclei

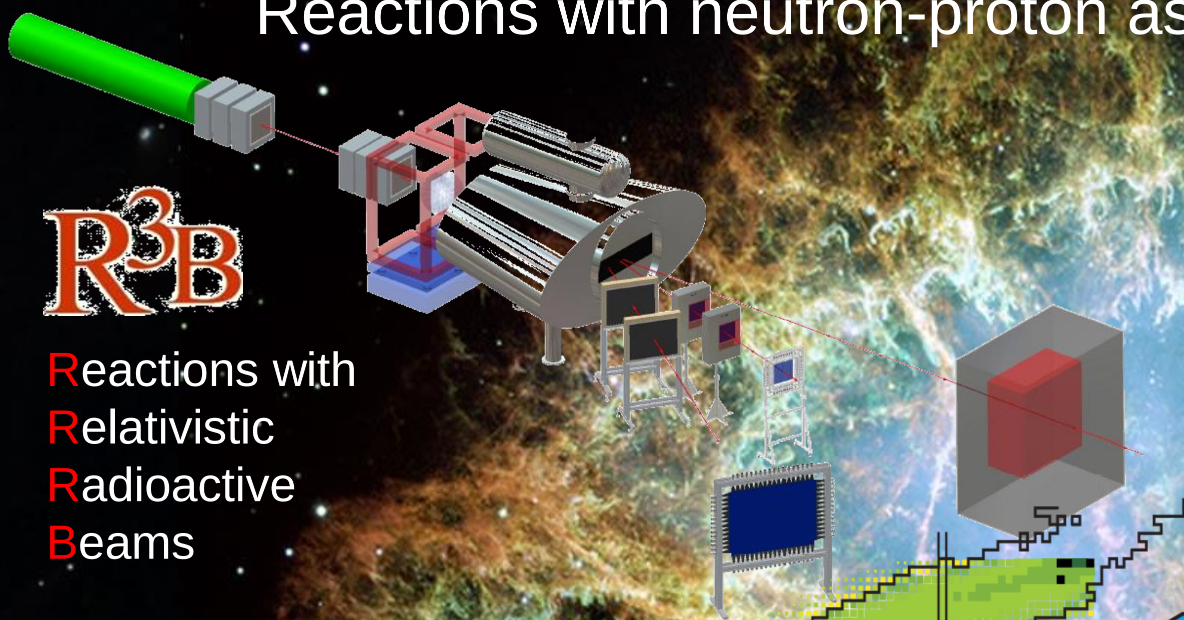
*A laboratory for studying nuclear properties as a function of isospin and density:*



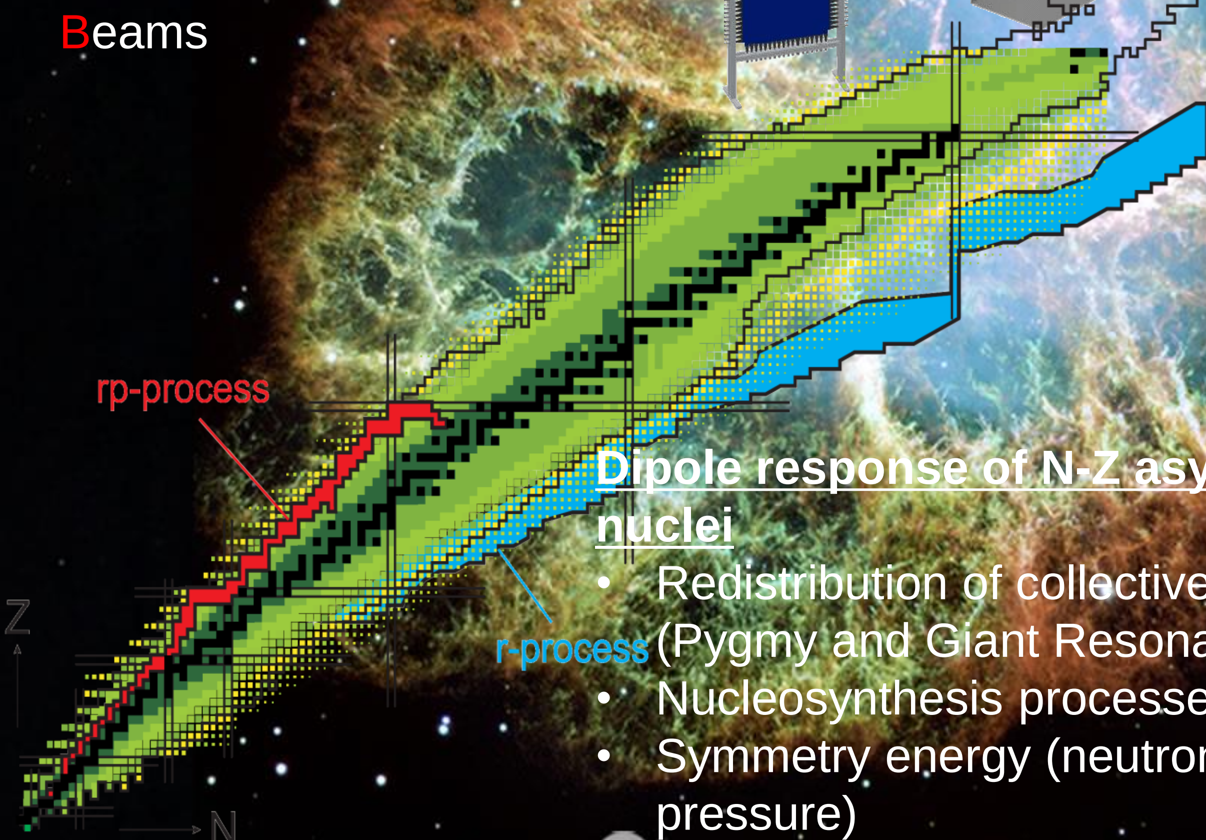



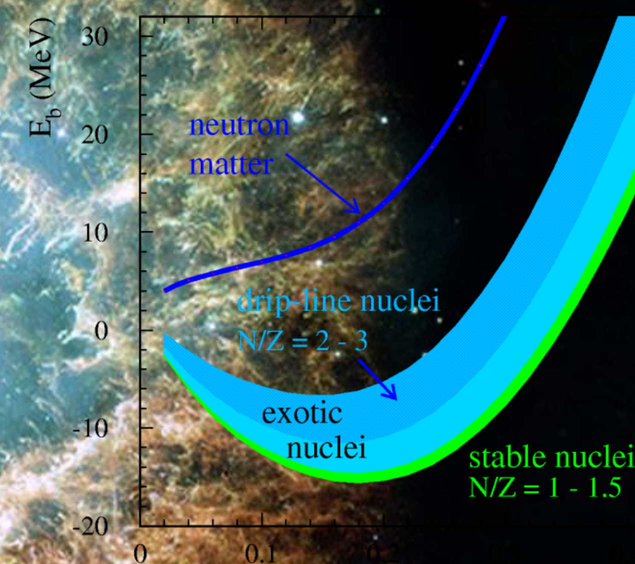



# Reactions with neutron-proton asymmetric nuclei



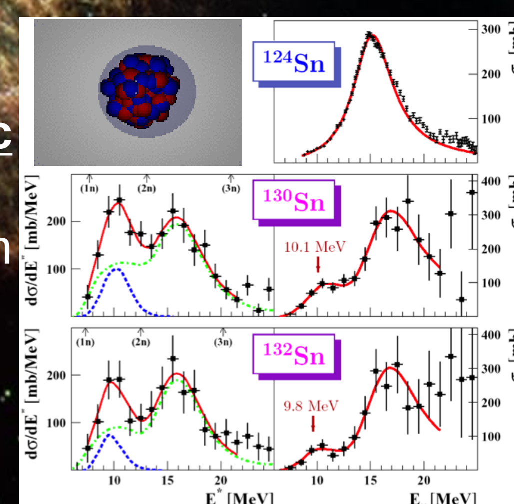
**R**eactions with
**R**elativistic
**R**adioactive
**B**eams




**Dipole response of N-Z asymmetric nuclei**

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

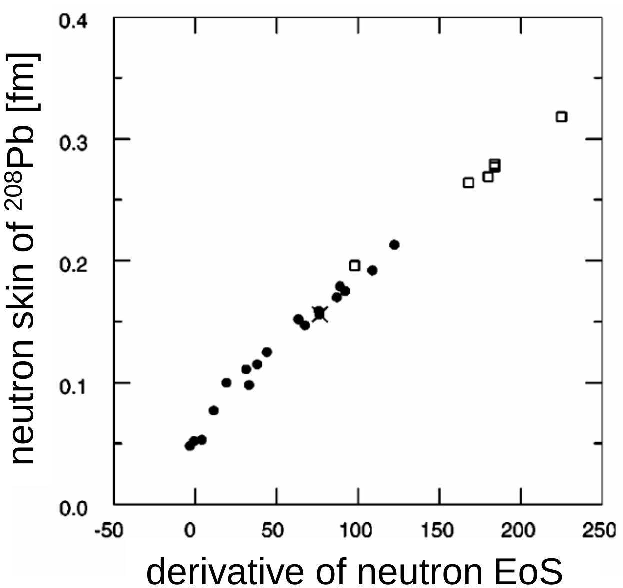


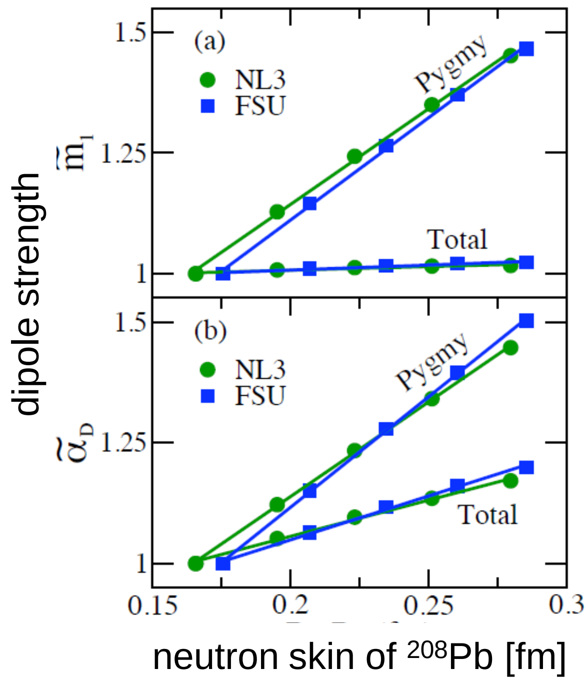
# Symmetry energy and dipole response

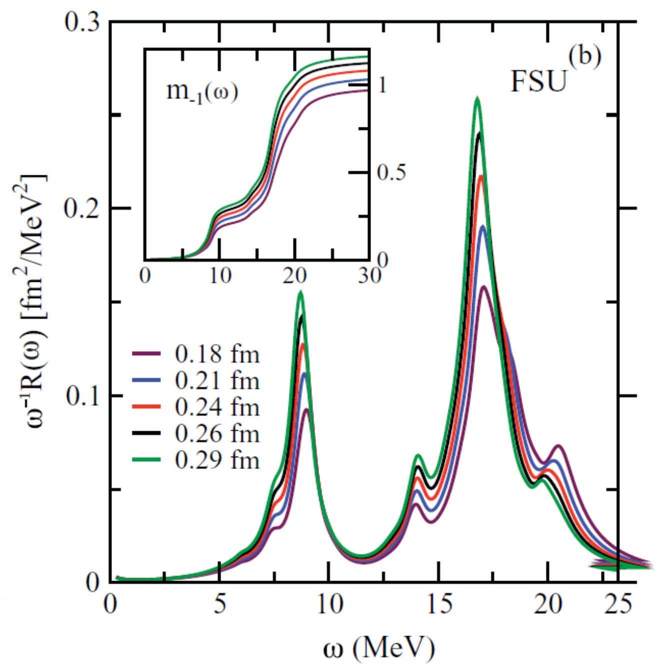
neutron-skin thickness
dipole response

⟷ density dependence of symmetry energy ⟷

properties of
neutron-rich matter




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

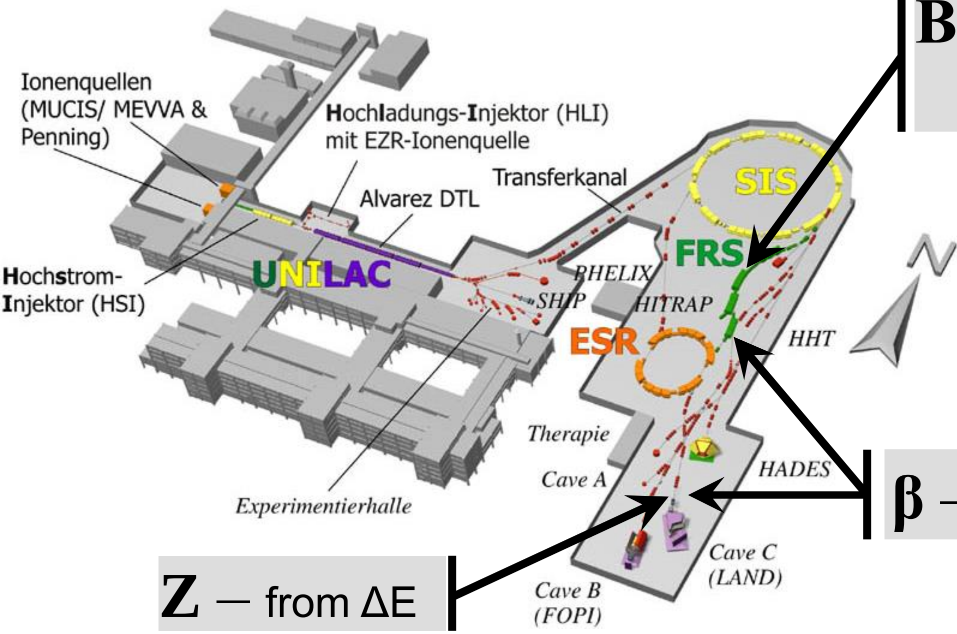
*J. Piekarewicz,PRC **83,** 034319 (2011)*

n-skin from Pygmy strength → A. Klimkiewicz et al., PRC 76 (2007) 051603(R)
A. Carbone et al., PRC 81 (2010) 041301(R)

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

# 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)

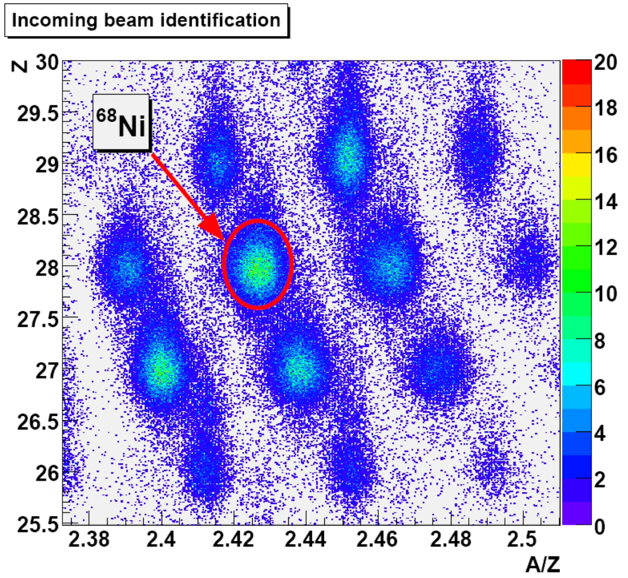



**Bρ** – from position at middle focal plane of the FRS

**β** – from TOF

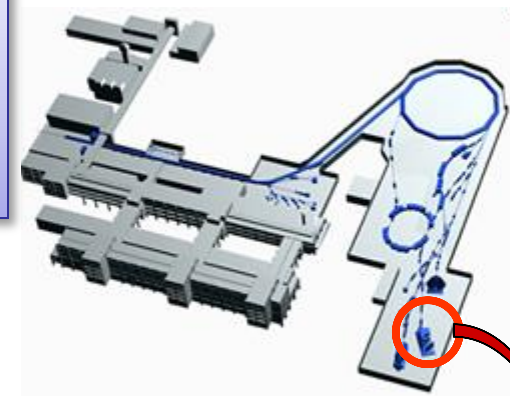
**Z** – from ΔE

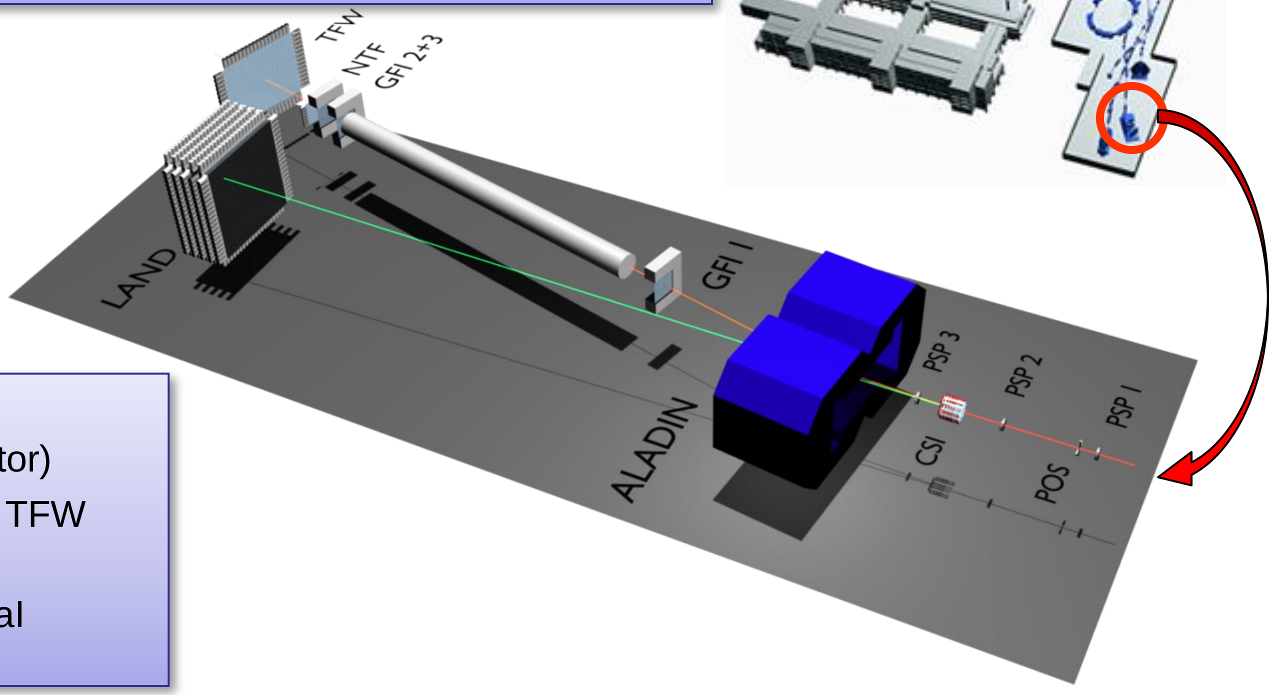
$$\frac{A}{Z} = \frac{e}{m_u c}\frac{B\rho}{\beta\gamma}$$



# Experimental Setup

- Beam tracking in Cave C: Si detectors (PSP) and scintillation detectors (POS, GFI, TFW)
- Kinematic forward-focusing (relativistic beam energies)
  → high-acceptance measurement (almost full coverage of solid angle)



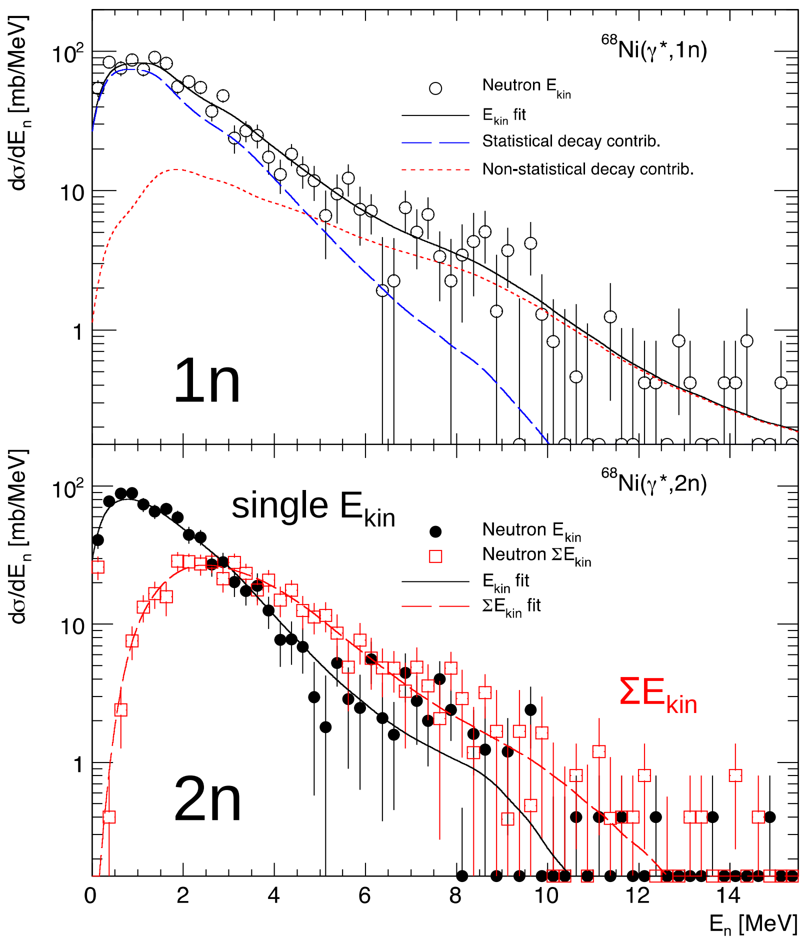



- Neutron detection with LAND
  (Fe converter + organic scintillator)
- Charged fragments detection in TFW (scintillation detector)
- Gamma detection with CsI or NaI detector

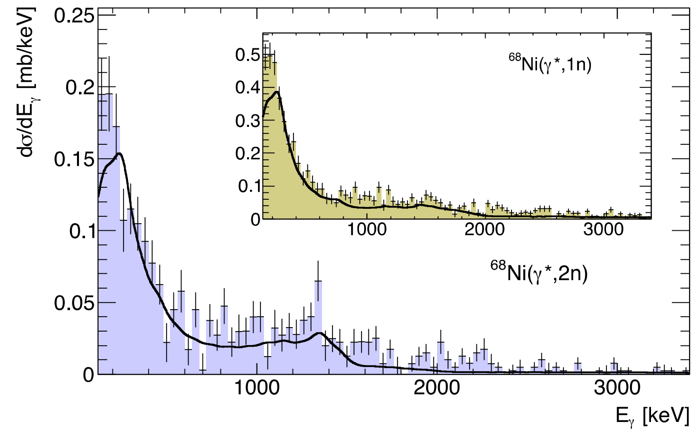
$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i \neq j} \gamma_i \gamma_j m_i m_j \left(1 - \beta_i \beta_j \cos\vartheta_{ij}\right)} + E_\gamma - m_{proj}$$

# 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>

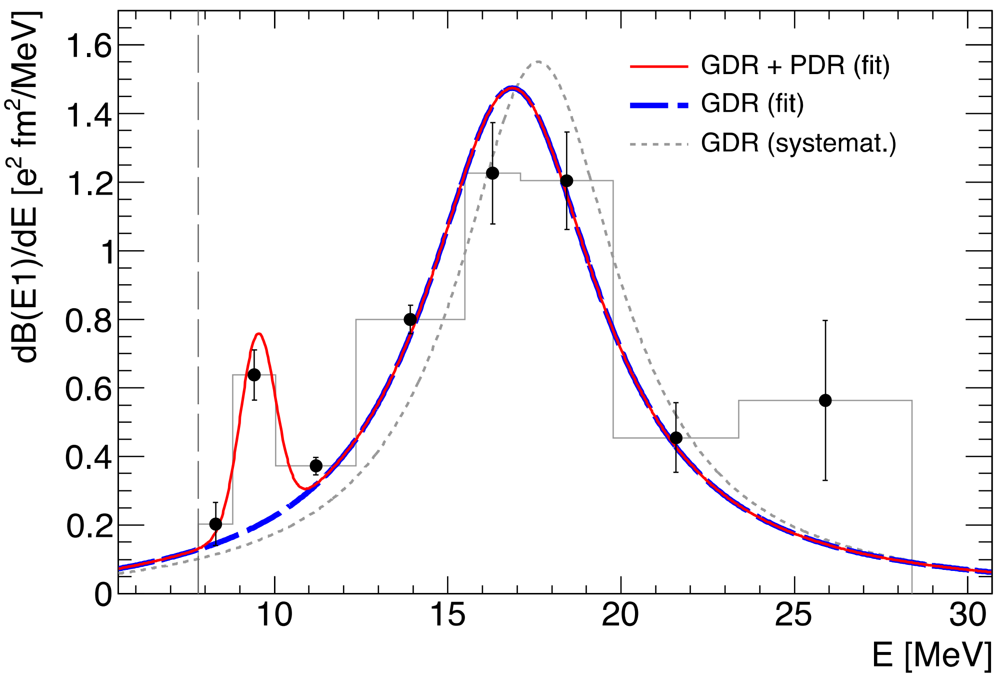
1) invariant mass, but also information of subsets like $E_{kin}$(n), $E_{\gamma sum}$ etc.

2) detailed knowledge about detector response function

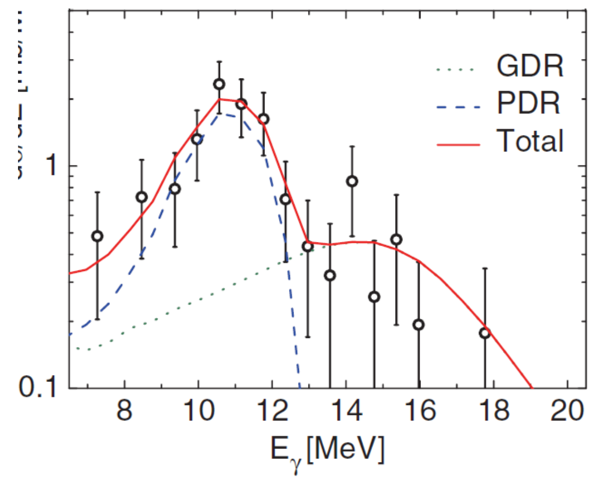
*analysis:*
*Dominic Rossi*
*PhD Thesis*
*Univ. Mainz,*
*PostDoc GSI*
*Now MSU*

# 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] |
| | $\Gamma$ | [MeV] | 6.1(5) | 5.69 | |
| | $S_{\mathrm{EWSR}}$ | [%] | 98(7) | 100 | |
| PDR | $E_m$ | [MeV] | 9.55(17) | 11 | [13, 25] |
| | $\sigma$ | [MeV] | 0.51(13) | < 1 | |
| | $S_{\mathrm{EWSR}}$ | [%] | 2.8(5) | 5.0(1.5) | |

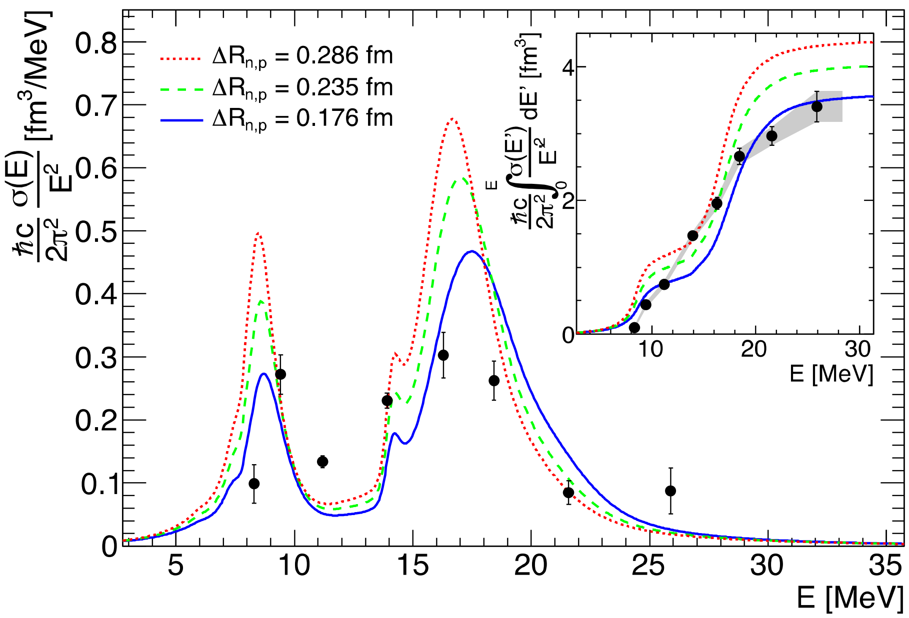


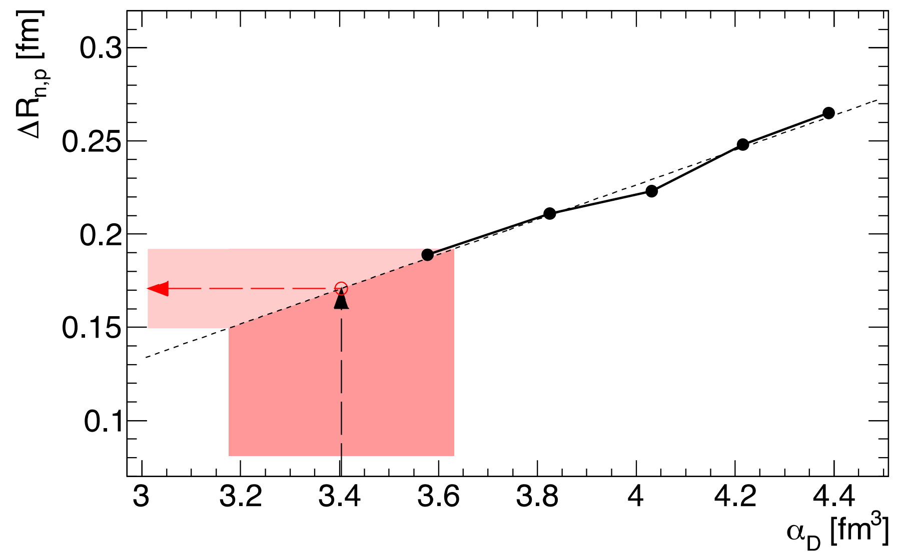

O. Wieland et al., PRL 102, 092502 (2009)

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

D. Rossi et al., to be published

# Polarizability and neutron skin



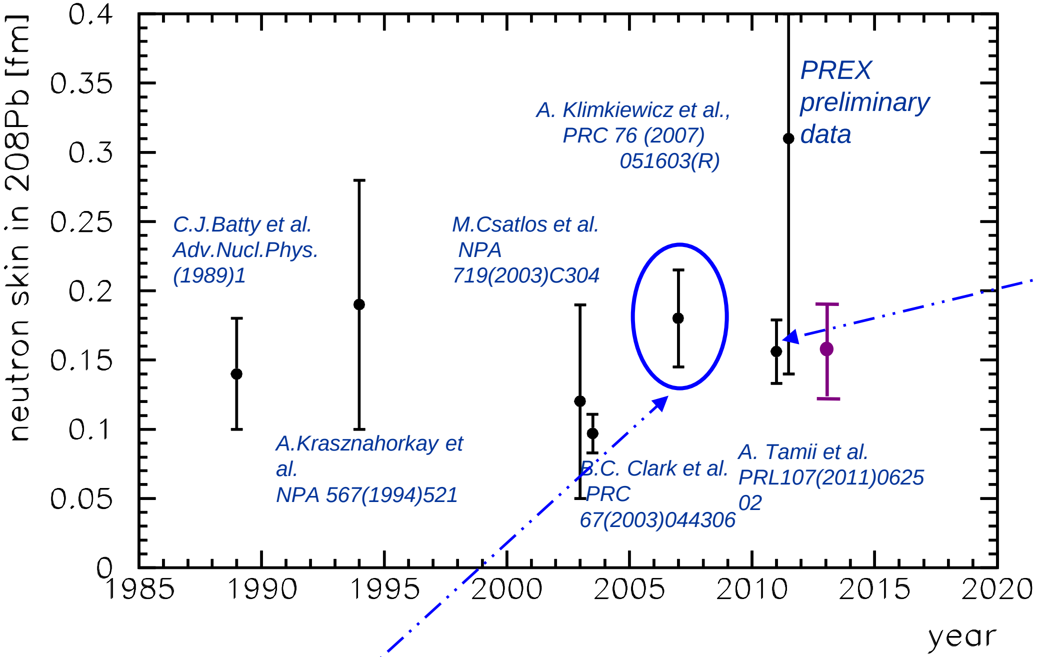



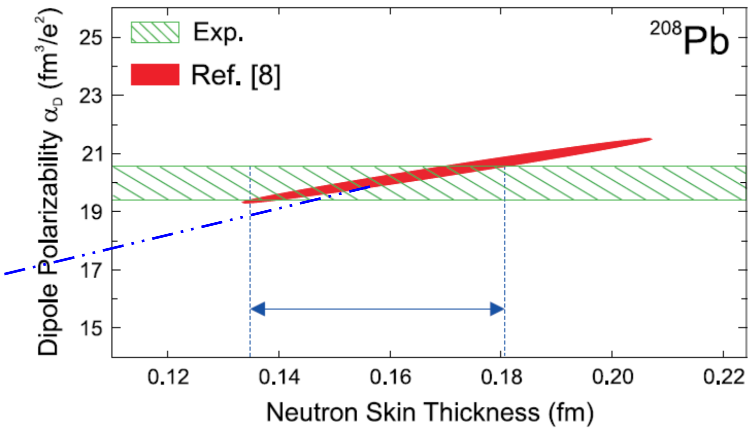

$$\alpha_D = \frac{\hbar c}{2\pi^2}\int_0^\infty \frac{\sigma(E)}{E^2} dE$$

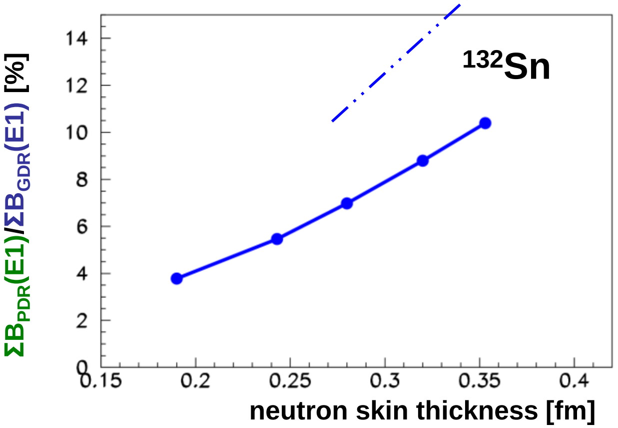
Neutron-skin thickness
$\Delta R_{n,p}$ = 0.175(21) fm

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

# Neutron skin in $^{208}$Pb from different methods

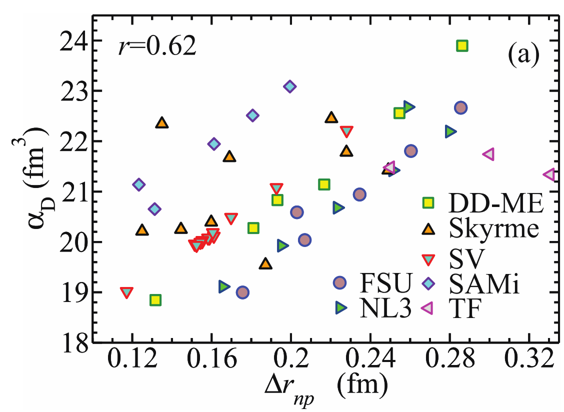


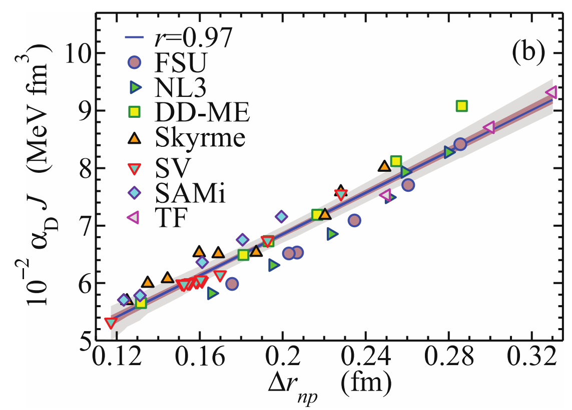




**But:**

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

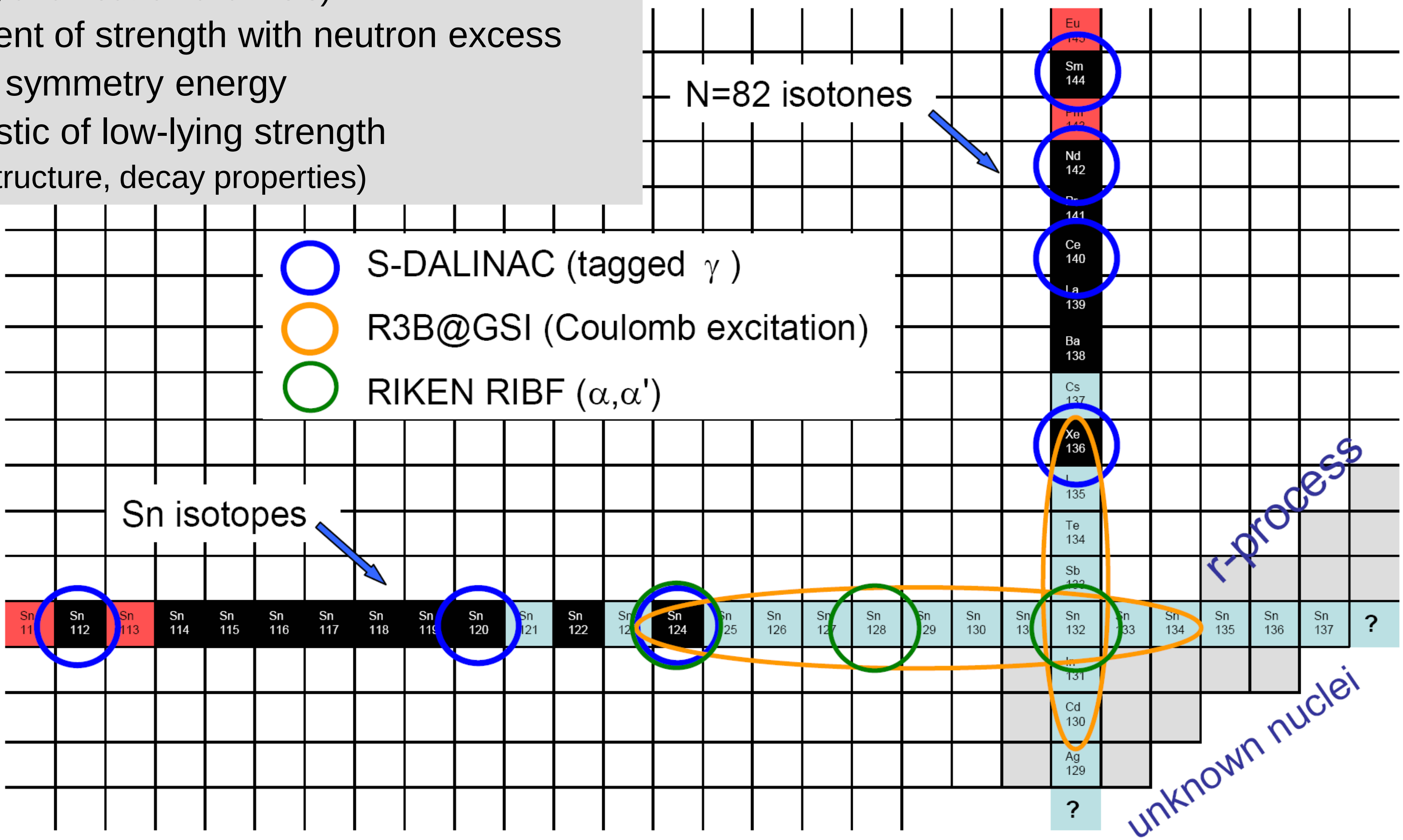


# Proposed experimental programme

**Next-generation experiments – Goals:**

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



# 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, HI$\gamma$S, 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