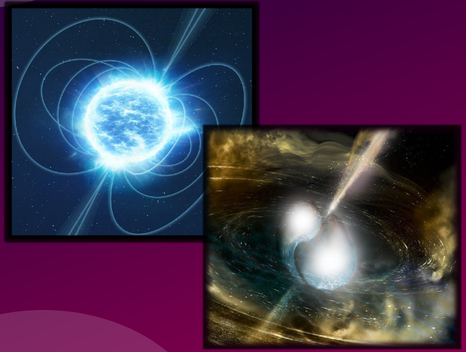
Study of Pygmy Dipole Resonances and their <u>potential</u> role in nuclear astrophysics

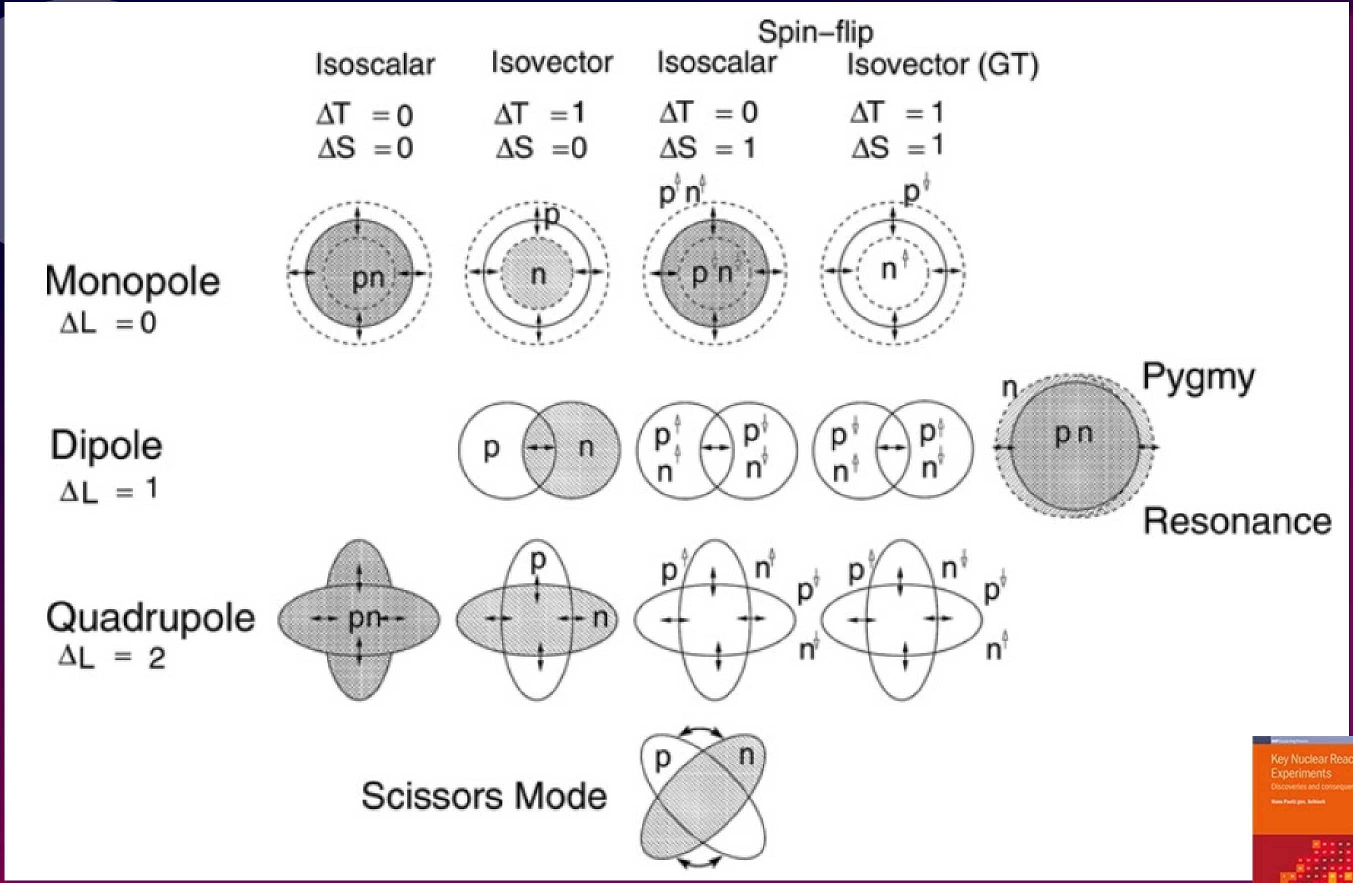
Iolanda Matea Macovei (IJCLab)



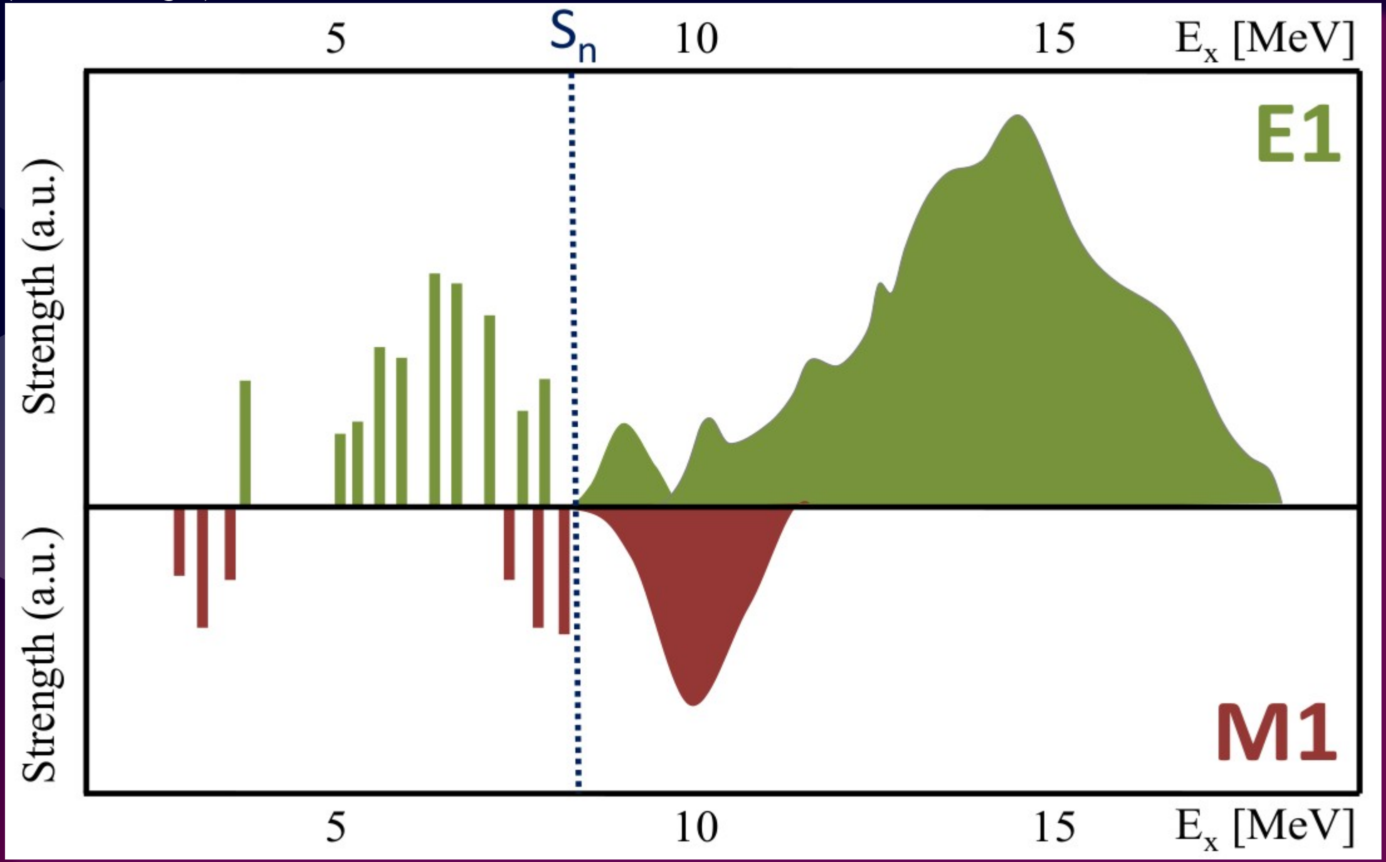
Collective vibrational excitations in nuclei

ΔT, ΔS, ΔL

ΔL = 1 →

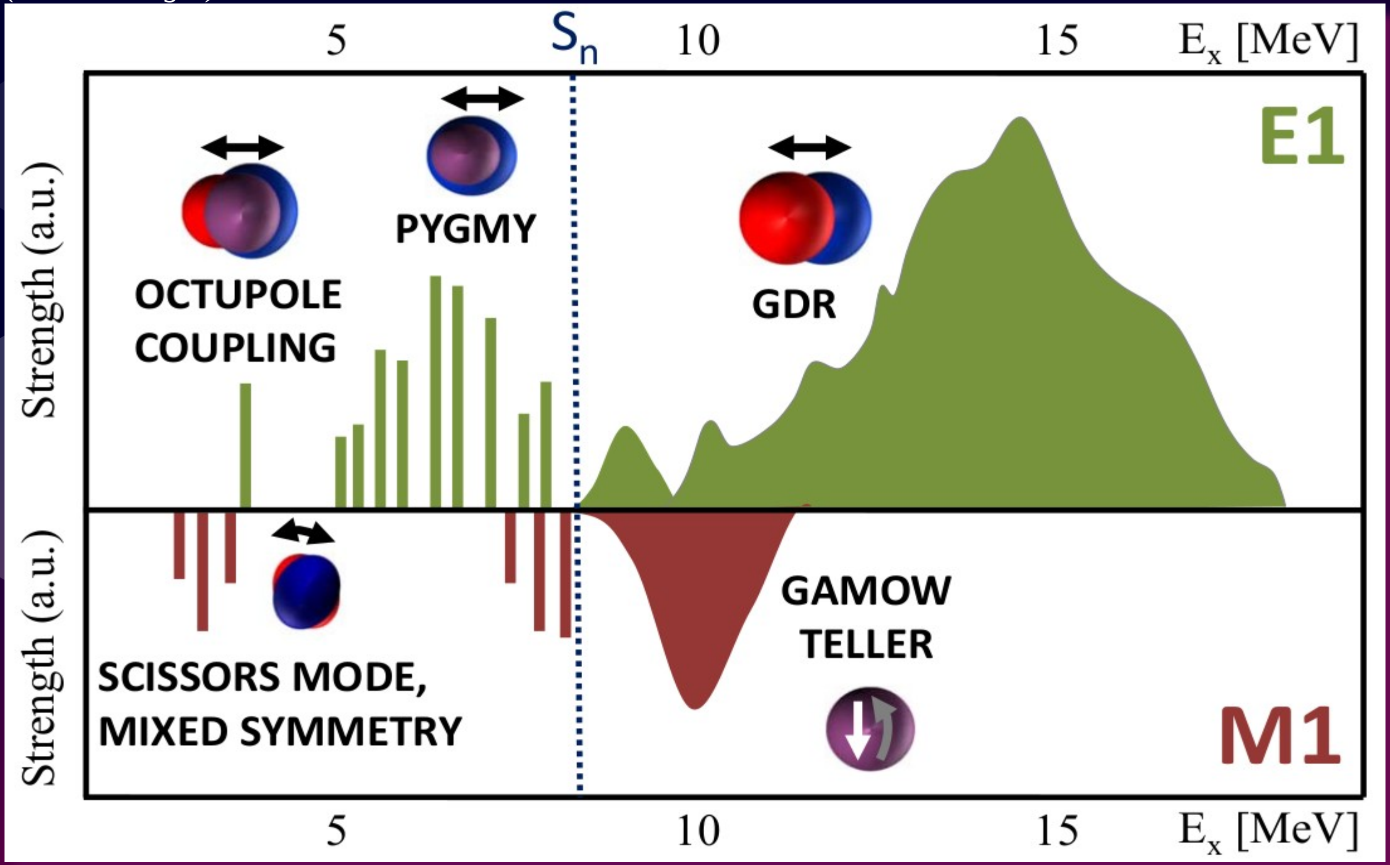


(Andreas Zilges)



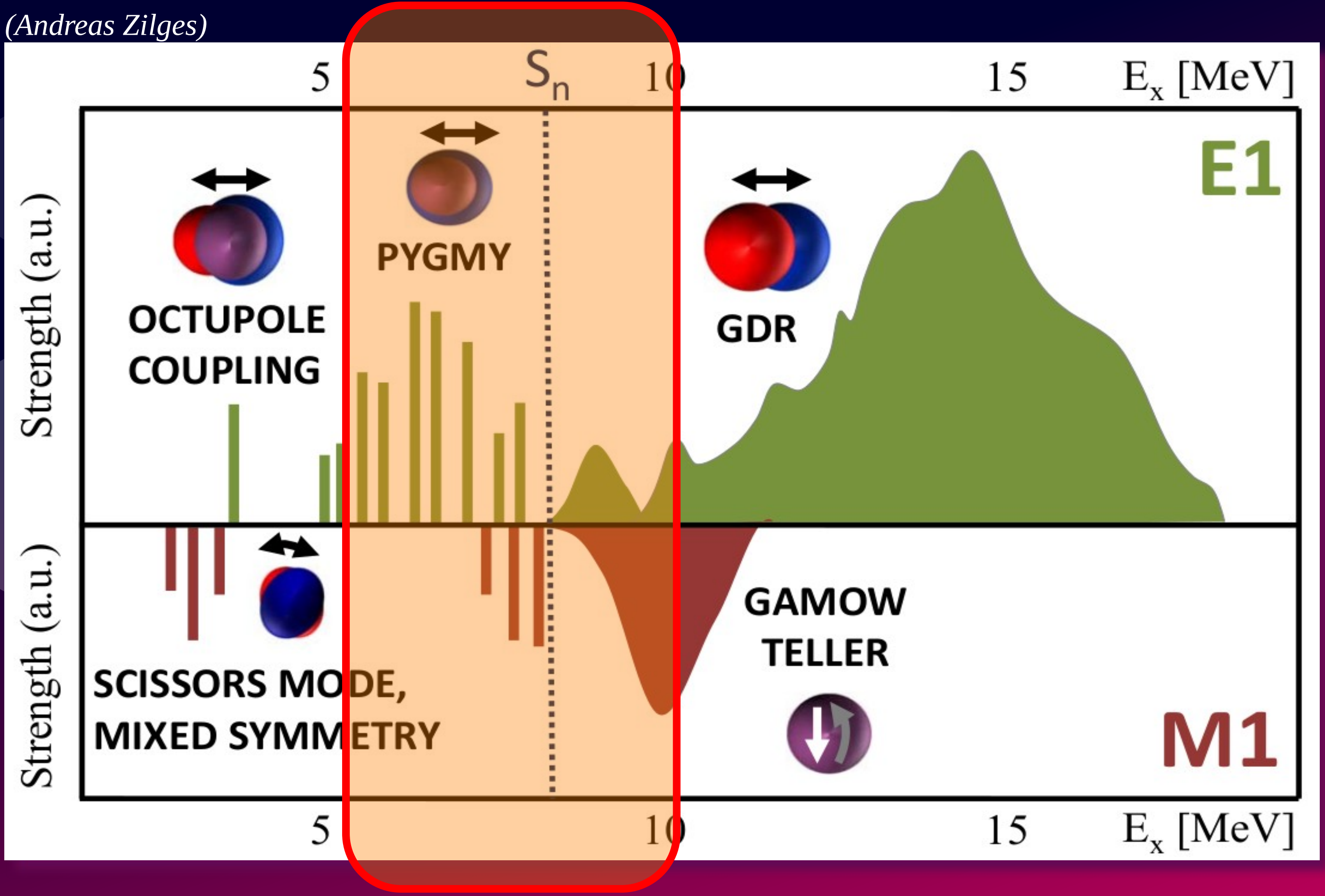
This strength distribution is related to the average probability of **γ-ray <u>absorption</u> or <u>emission</u>** as a function of γ-ray energy : **<u>γSF</u>**

(Andreas Zilges)



Dipole Strength in Nucleus

(Andreas Zilges)



Only neutron-rich nuclei will be considered throughout the lecture

Why studying PDR ?

PDR

- E* and evolution with N/Z ratio
- Collective vs. single particle structure
- Excitation x-sections with different probes
- Temperature dependence
- γ-decay branching above S_n
- Isospin character
- Dipole Polarizability
- B(E1) distribution (EWSR)
- (n,γ) capture

A.Bracco et al, PPNP106 (2019)
E.G. Lanza et al, PPNP129 (2023)
D. Savran et al, PPNP70 (2013)
N. Paar et al, Rep.Prog.Phys70 (2007)

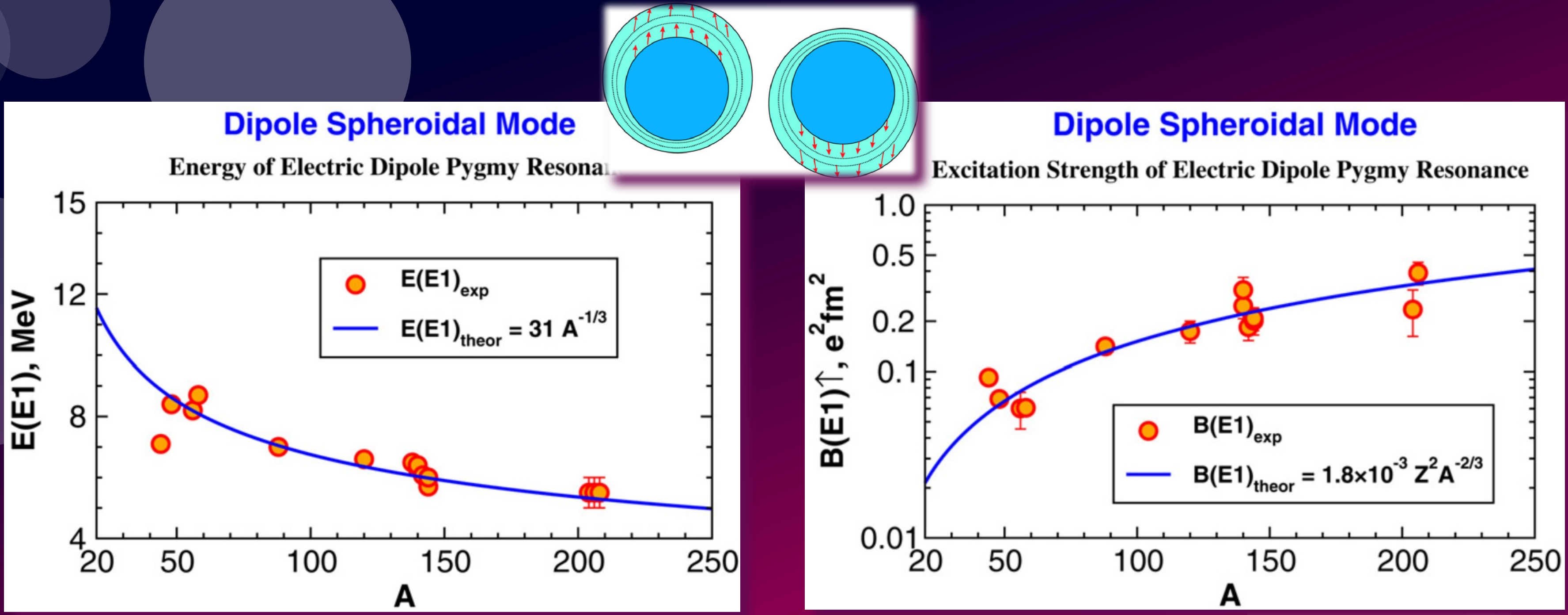
→ linear displacement of core/neutron excess density distributions
→ density distributions : Wood-Saxon
→ restoring force : np interaction

$$B(E1)_{PDR} = \frac{(N-N_c)Z \cdot E_{GDR}}{(Z+N_c)N \; E_{PDR}} \cdot B(E1)_{GDR}$$

$$E^{*}_{PDR} = \left[\frac{Z}{3(Z+N_c)}\right]^{1/2} \cdot f(a_n, a_p, R_n, R_p) \cdot E^{*}_{GDR}$$

P. van Isacker et al, PRC45 (1992)

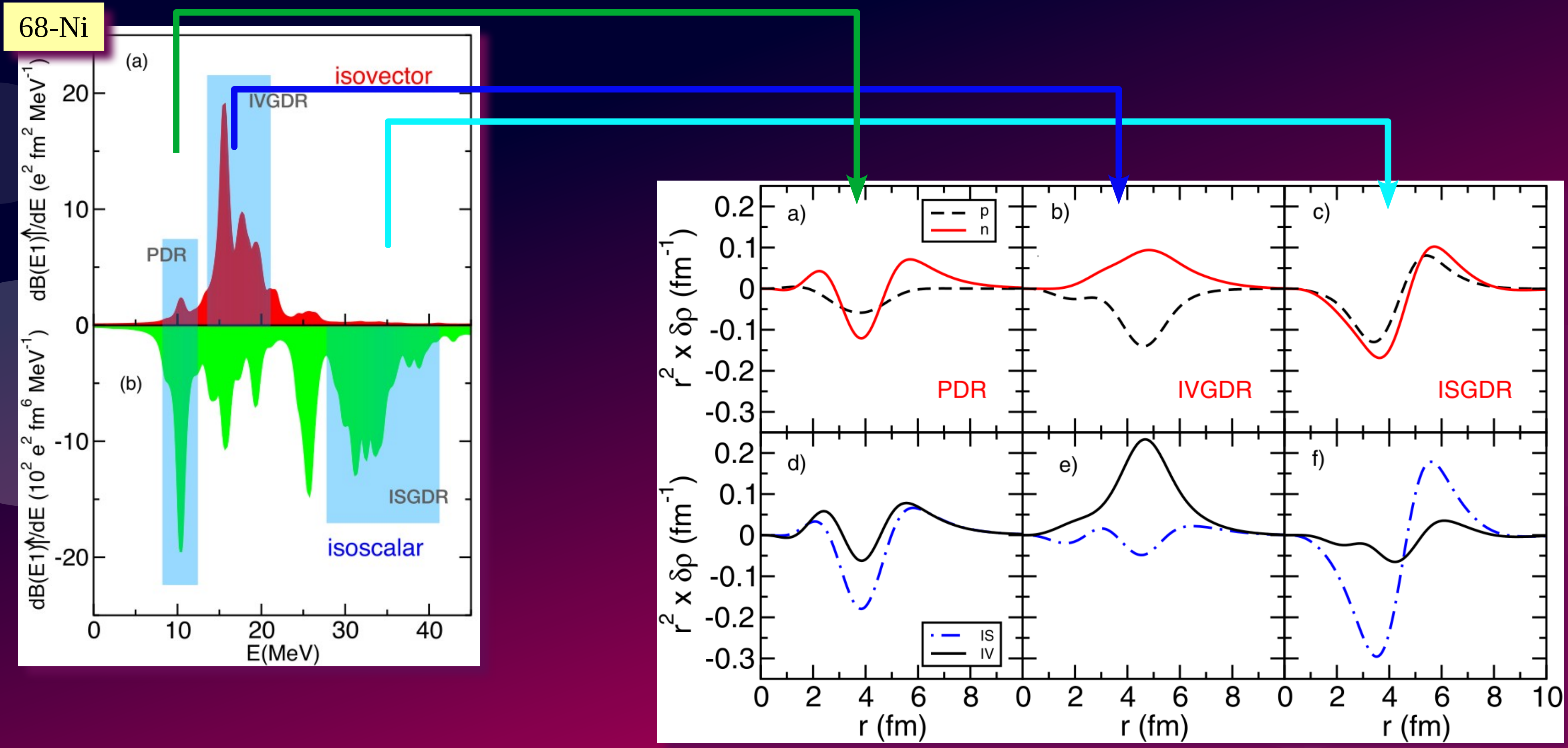
→ elasto-dynamic excitation of the electric PDR
→ elastic layer oscillation against elastic continuous core



S.I. Bastrokov et al, PLB664 (2008)

PDR : microscopic picture

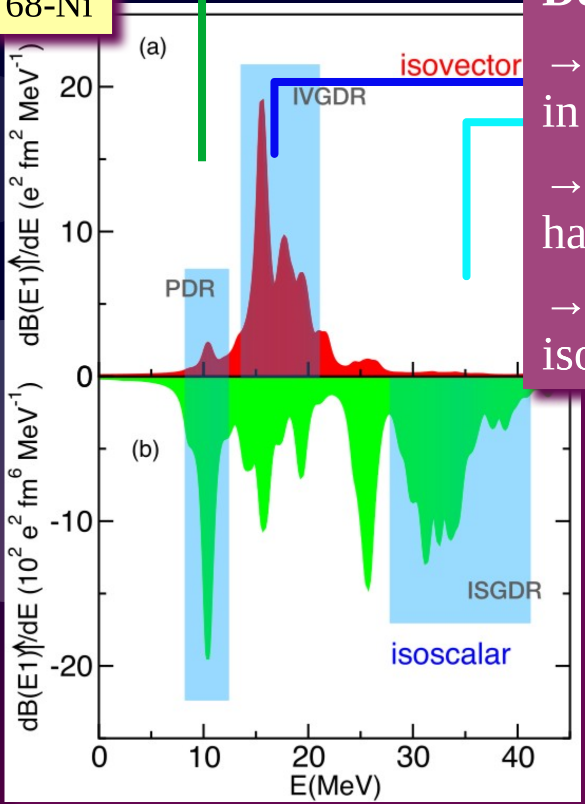
E. Lanza et al, PPNP129 (2023)



PDR : microscopic picture

E. Lanza et al, PPNP129 (2023)

68-Ni

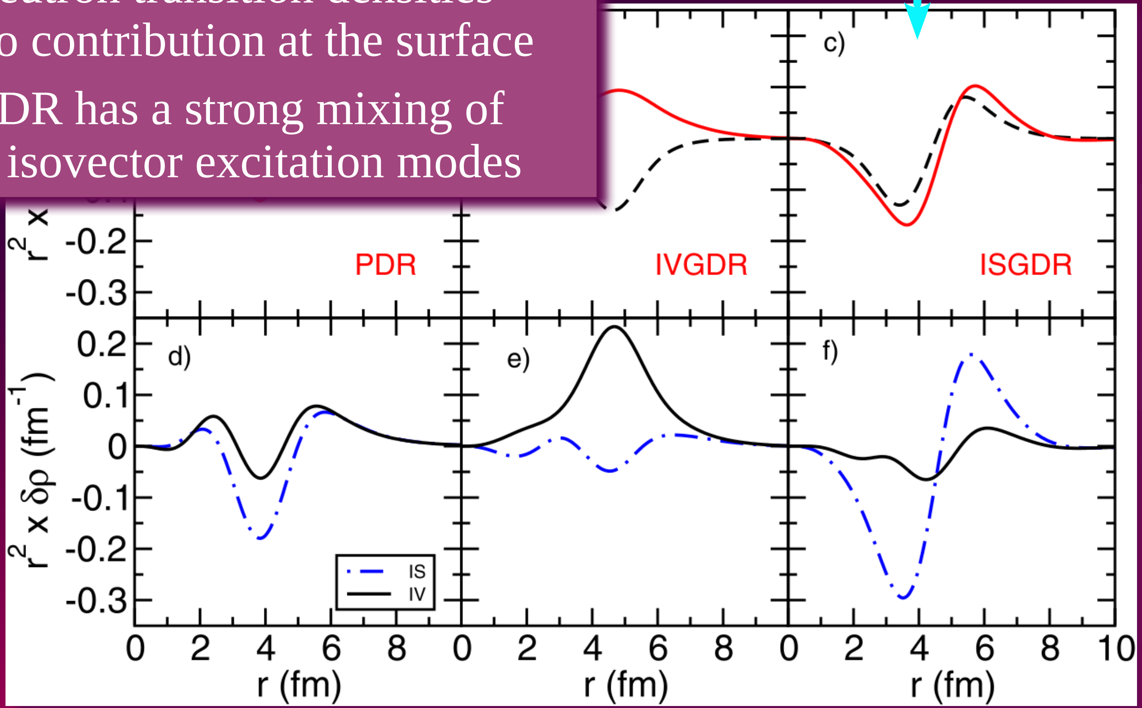


Definition of PDR:

→ proton/neutron transition densities are in phase inside the nucleus

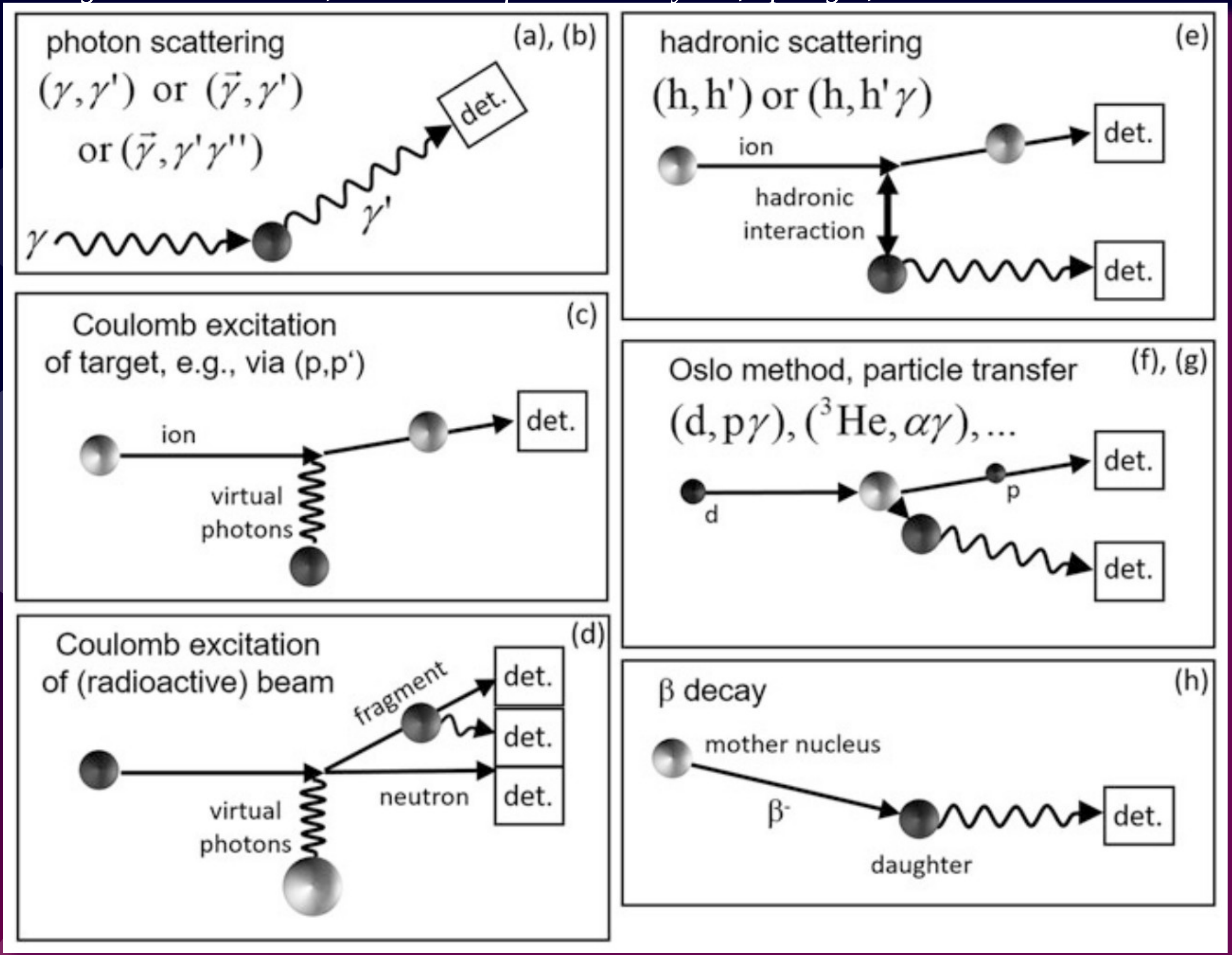
→ only the neutron transition densities have non-zero contribution at the surface

→ as such, PDR has a strong mixing of isoscalar and isovector excitation modes



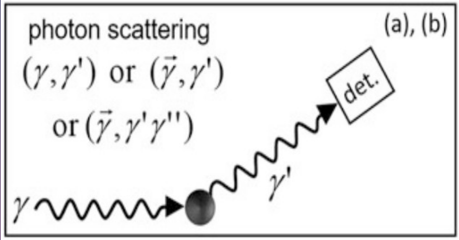
Measuring PDR

A. Zilges and D. Savran, Handbook of Nuclear Physics, Springer, 2022



Selected remarks and examples follow …

Real photon scattering



– L=1 excitations dominant

– photon : EM interaction, under control

 – NRF (nuclear resonance fluorescence) with bremsstrahlung γ
 – tagged photon NRF : lower bandwidth
 – laser Compton back-scattered γ beam (LCB)
  – small bandwidth + polarized

– in-volume interaction

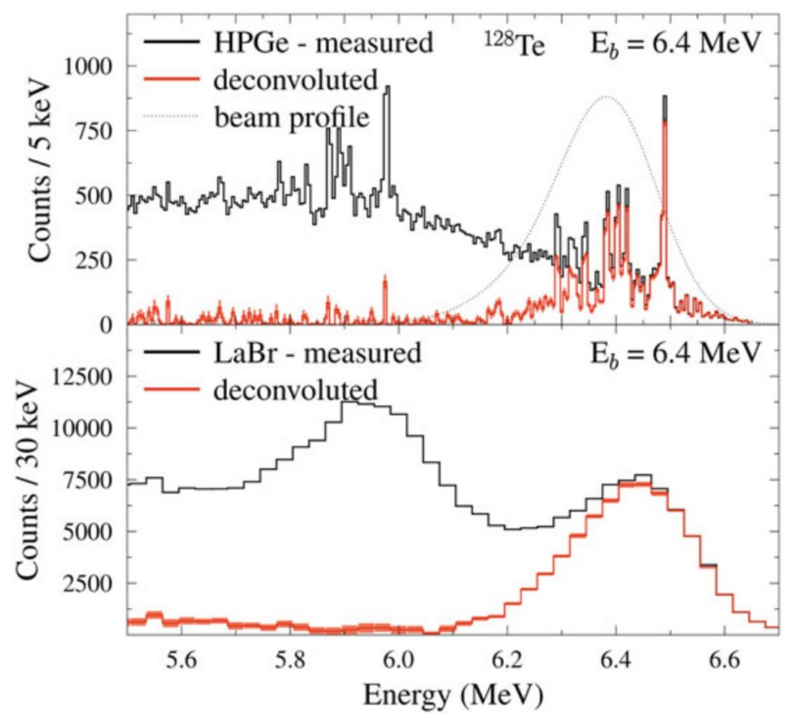
– iso-vector probe

– measure the strength up to S_n

– limited to stable nuclei

– detection usually HPGe with W(θ,φ) measure =>

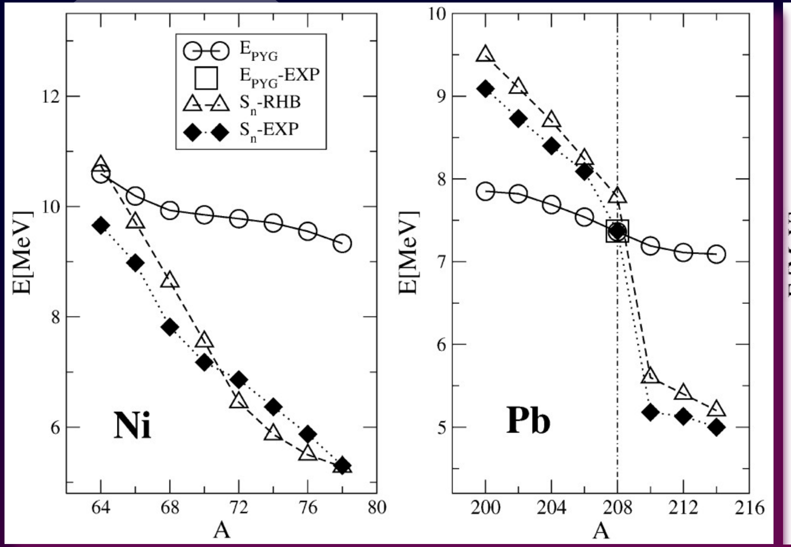
 clear measurement L and π (polarized) of γ-radiation

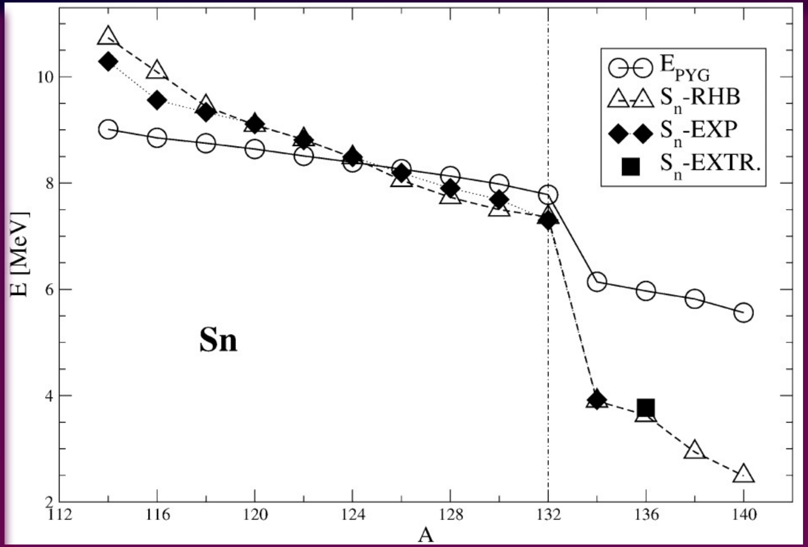


J. Isaak et al, PRC103 (2021)

One remark about (γ,γ') experiments :

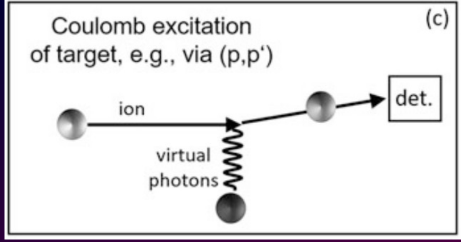
N. Paar et al., PLB606 (2005)





PDR is well above S_n in exotic n-rich nuclei => γ-decay is to slow …

Virtual photon scattering



– mixed L=1,2,3… excitations

– (polarized) proton at ~300-400MeV scattered at extreme forward angles

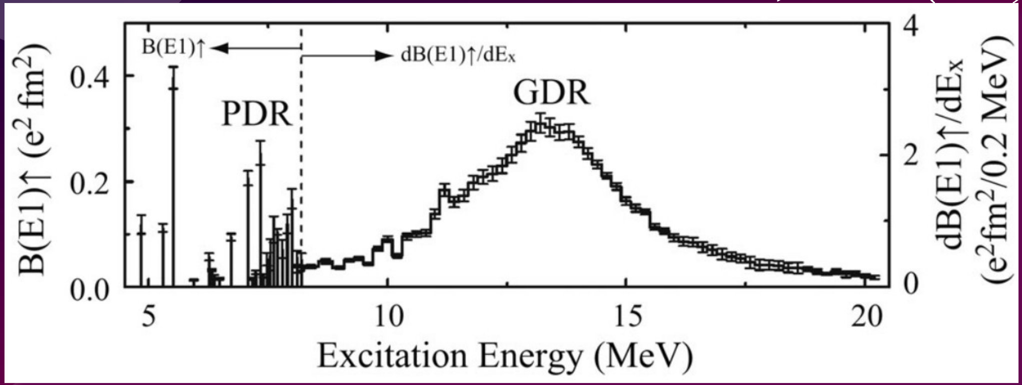
- – detection of the scattered proton => <u>measure the strength below and above</u> S_n
- – L=1 excitations favored, but not only … MDA needed.
- – π measurements (polarized proton beam)

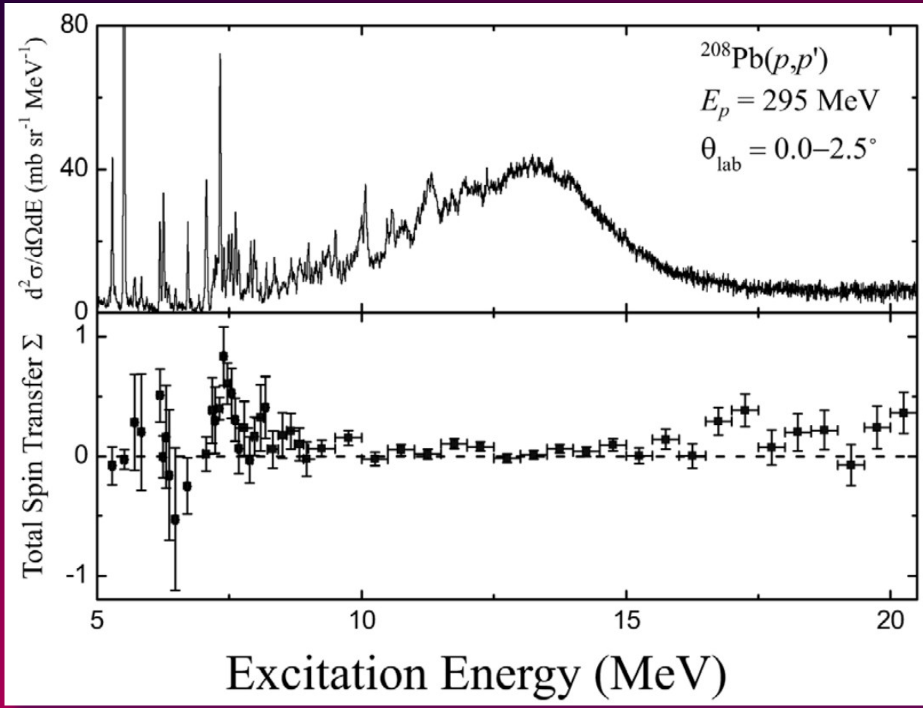
– in-volume interaction

– iso-vector probe

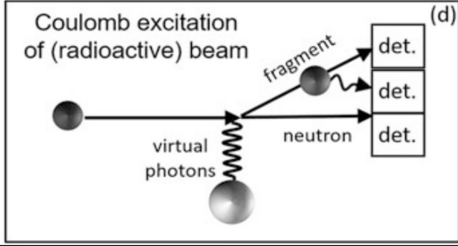
– limited to stable nuclei

A. Tamii et al, EPJA50 (2014)

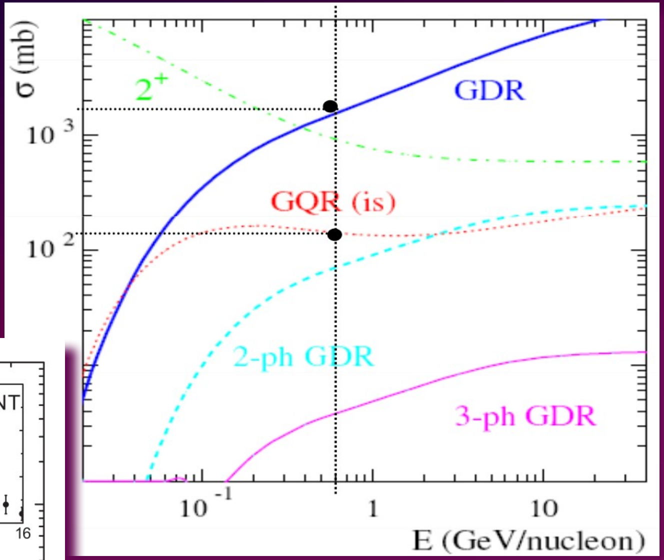




Virtual photon scattering



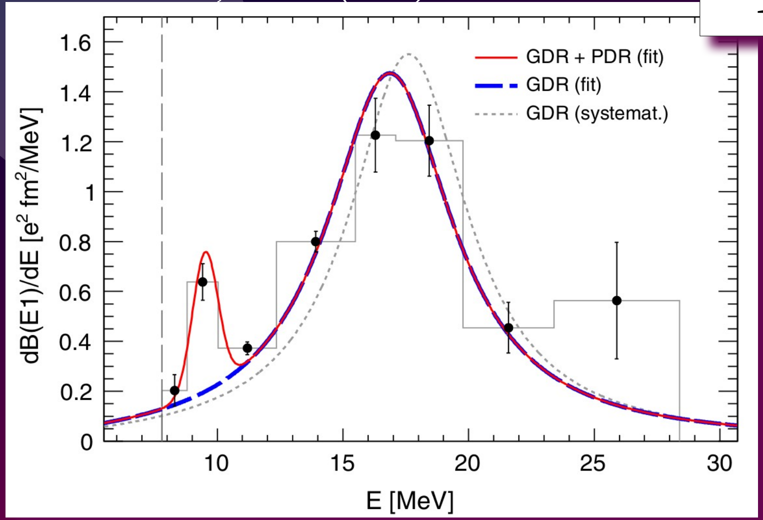
- radioactive nuclei
- inverse kinematics => less resolved γ spectra
- lower statistics
- relativistic beam energies => L=1 dominates
  - can measure also above S_n (if neutrons are detected)



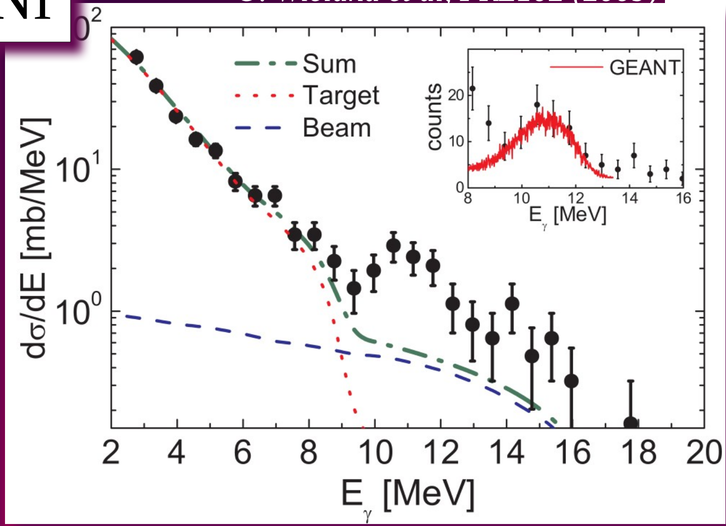
(Angela Bracco)

D.M. Rossi et al, PRL111 (2013)

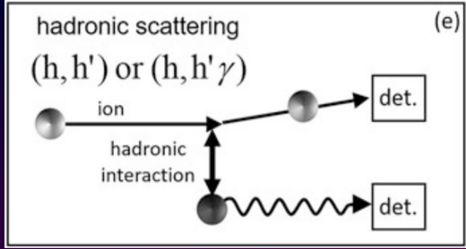
^{68}Ni



O. Wieland et al, PRL102 (2009)



Different isospin response



– e.g., α or 12-C → iso-scalar response

– non selective population of states; to pin down the E1 character → (h,h'γ)

– function of the energy of the probe:

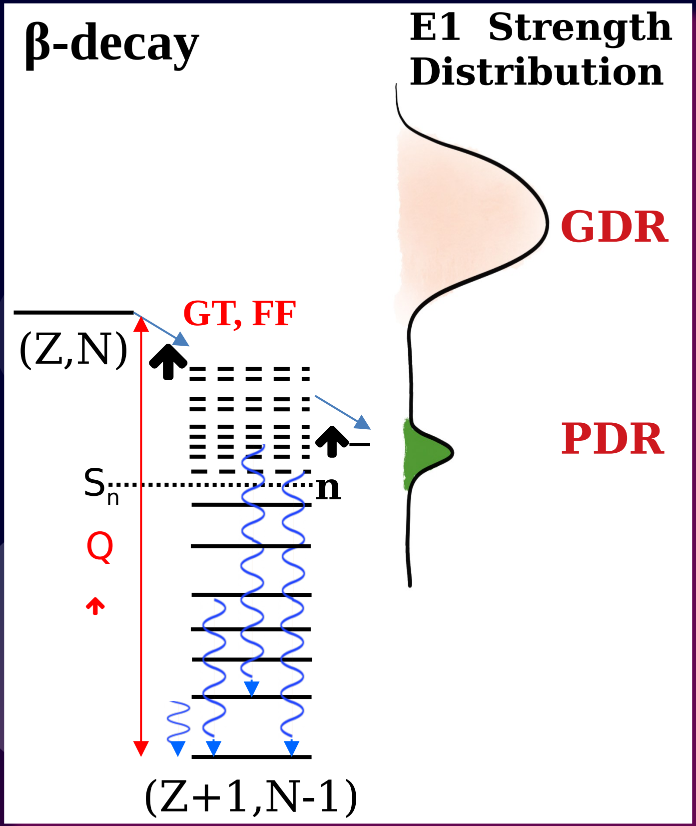
- 30MeV neutrons : iso-vector
- ~1GeV neutrons : iso-scalar

– surface interaction (ignoring the charge)

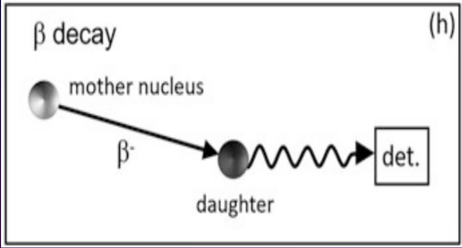
– most relevant studies were done below S_n

– direct or inverse kinematics => stable and radioactive nuclei

Mainly for the PDR structure studies
(see Perine's poster)

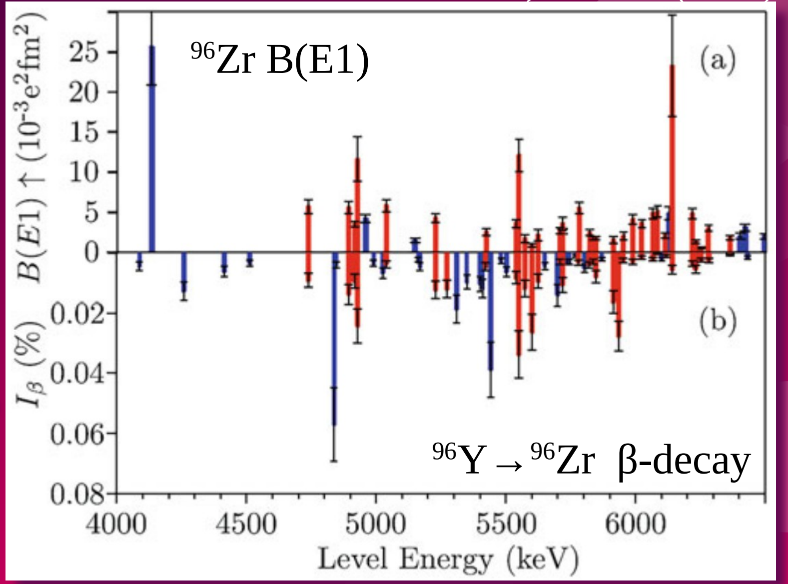


– weak interaction selection rules (GT, FF)
 - selective population of states around S_n
– very clean γ and (γ,γ)-coincidence spectra
 - but (very) low statistics
– access to very exotic nuclei, but a very partial picture
 - beta decay of ^{82}Ga (L. Al Ayoubi, PhD Univ. Paris Saclay, 2023)
 - beta decay of ^{80}Ga (R. Li, PhD Univ. Paris Saclay, 2022)

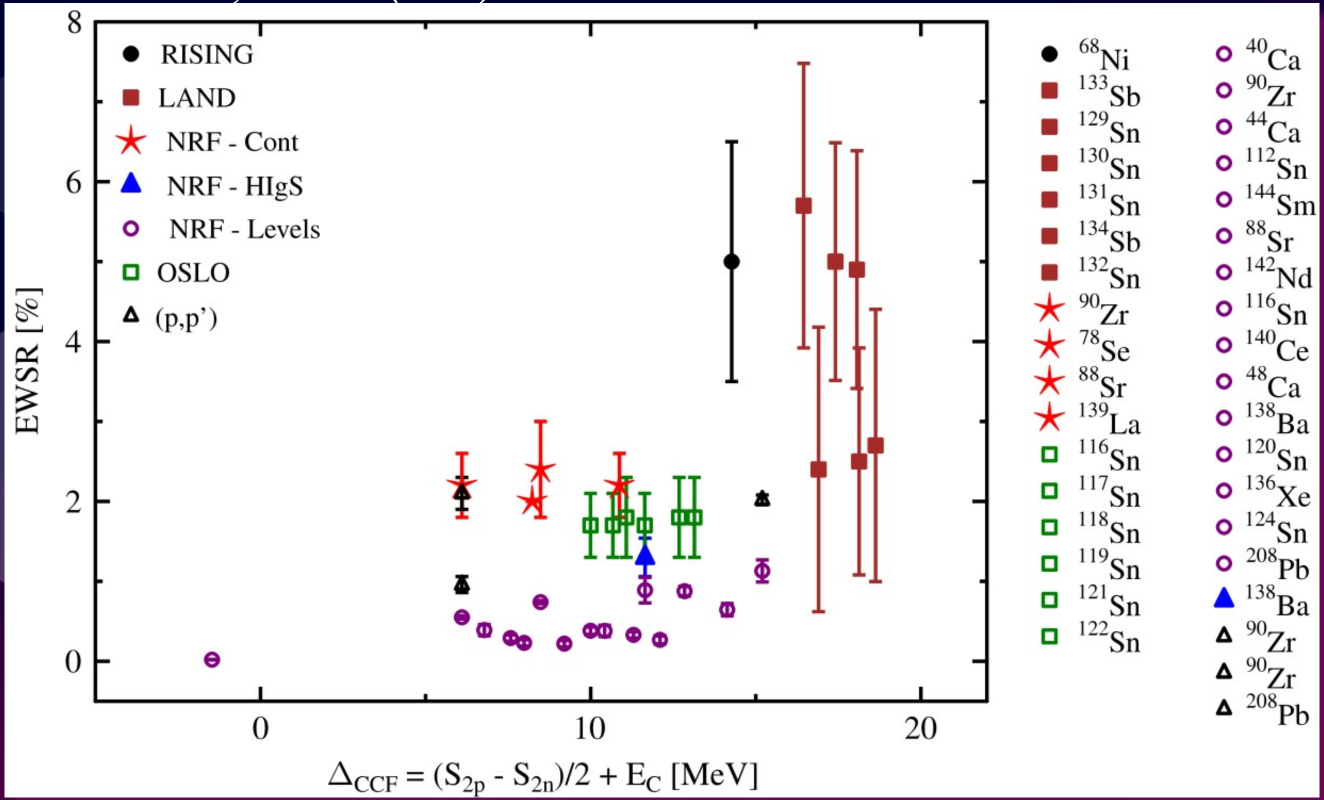


K.R. Mashtakov et al, PLB820 (2021)

Exemple of NRF vs β-decay measurements : controlled interpretation available only on few stable nuclei



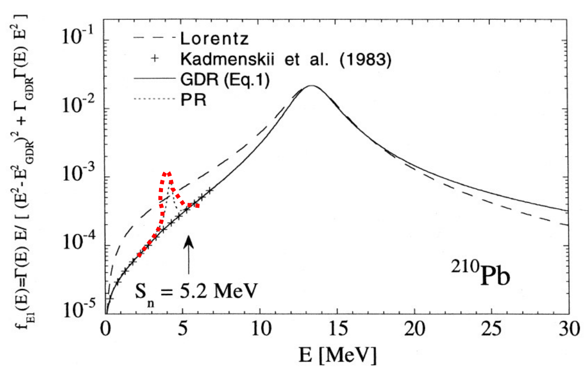
D. Savran et al, PPNP70 (2013)



E* ~ 5-10 MeV

EWSR (% of TRK SR) ~ 1-5%

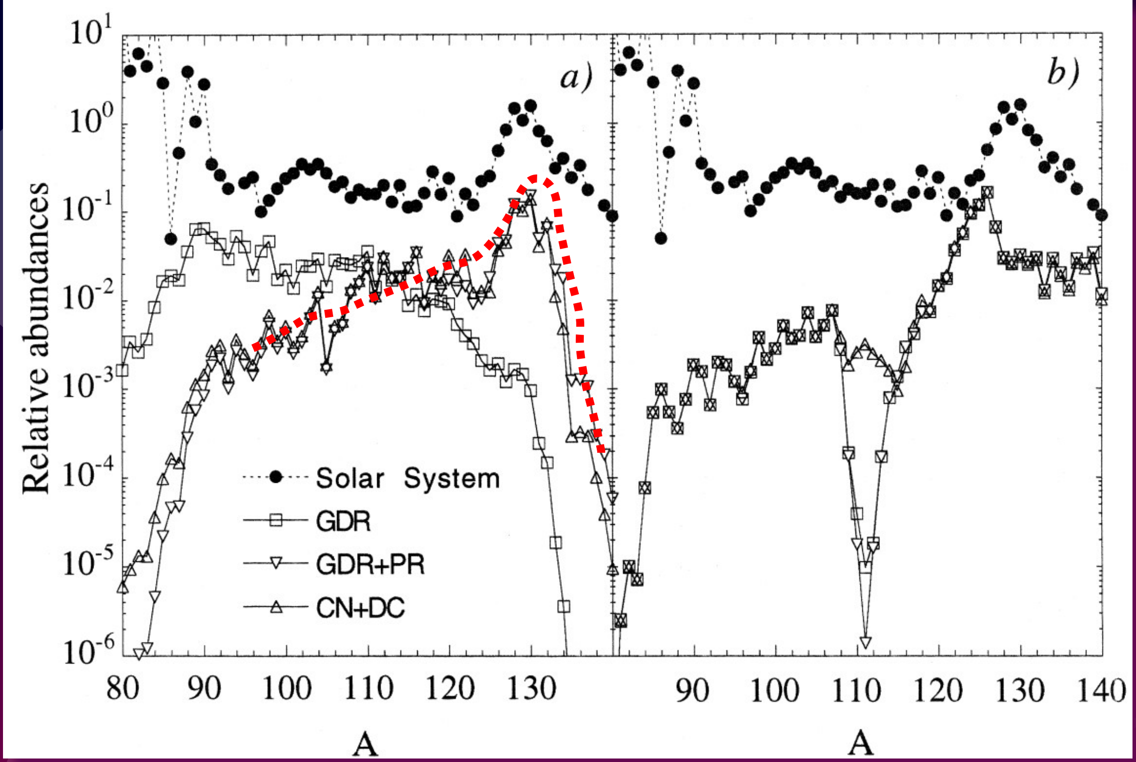
(TRK SR = 14.8·(NZ)/A (e^2fm^2MeV))



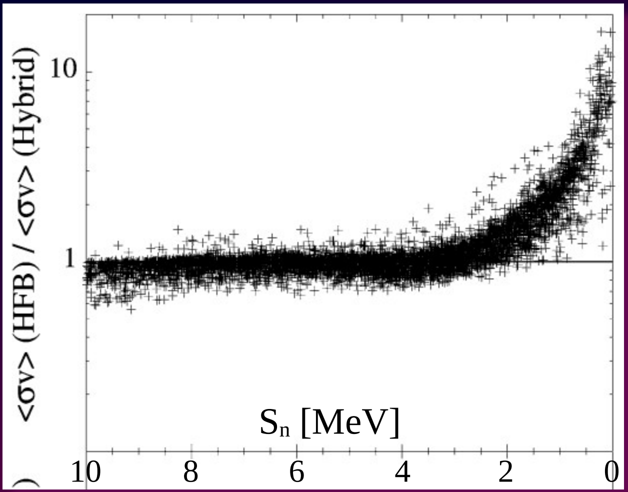
(n,γ) capture

S. Goriely, PLB436 (1998)

T=10^9 K; Nn = 10^{20} cm^{-3}; tirr = 2.4 sec   T=1.5x10^9 K; Nn = 10^{28} cm^{-3}; tirr = 0.3 sec



S. Goriely et al, NPA739 (2004)

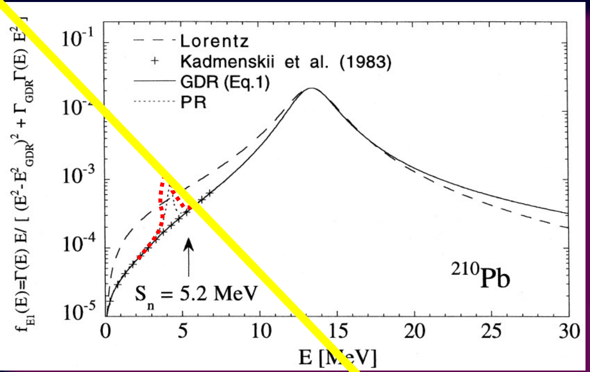


- under certain conditions (T, N_n, time), PDR (few % of TRK) is able to produce the A~130 peak in relative abundances where Lorentz-shaped GDR can't

- microscopic models (HFB+QRPA) for E1 distribution in nuclei predict an even more pronounced modification in the (n,γ) x-sections for very exotic nuclei

- closer to stability, low energy E1 strength can also influence locally the abundance of i-process nuclei (M. Markova et al, PRC109 2024)

(n,γ) capture



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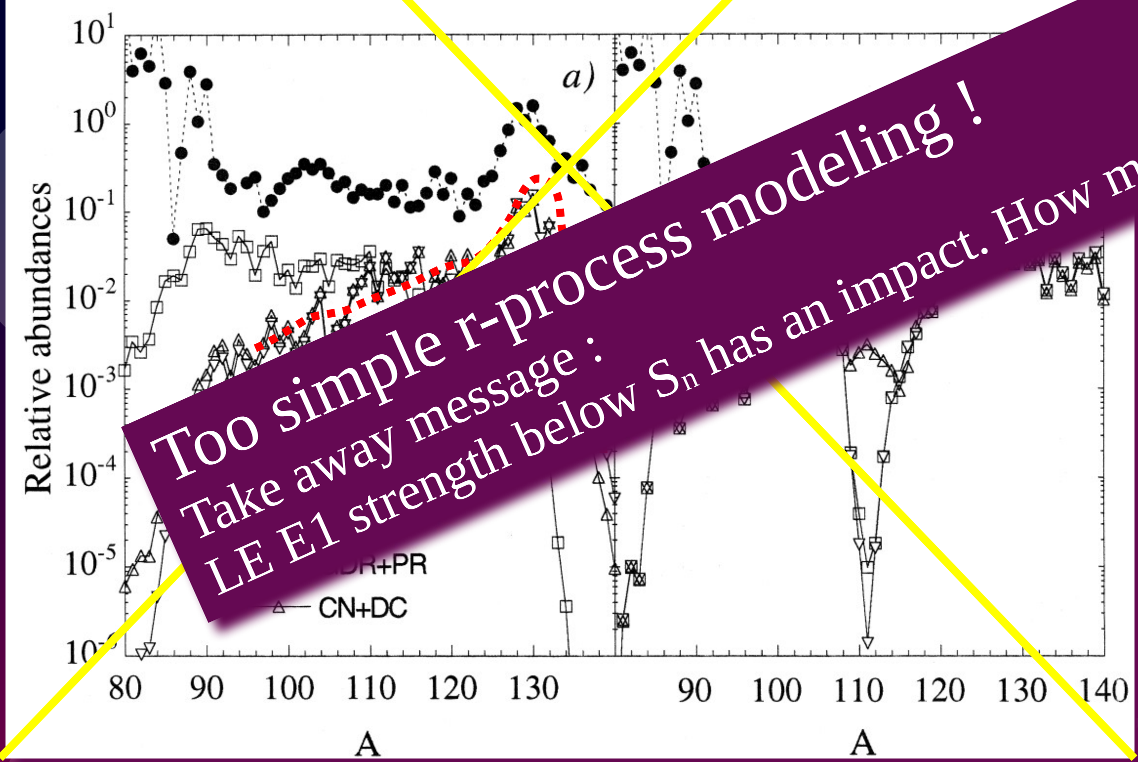
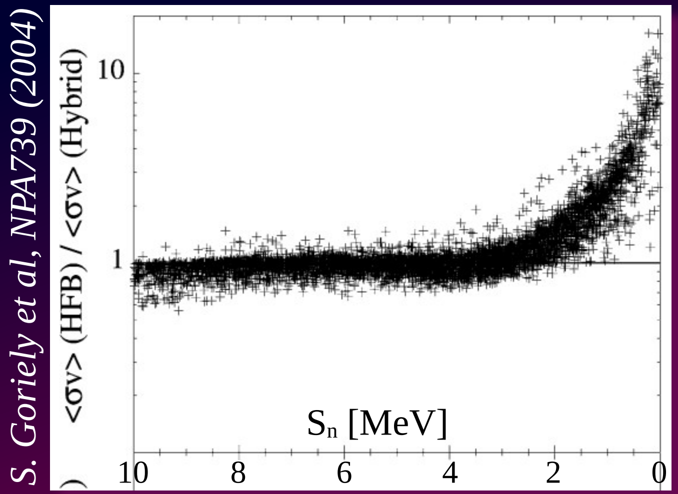


Too simple r-process modeling !

Take away message :

LE E1 strength below S_n has an impact. How much ?...



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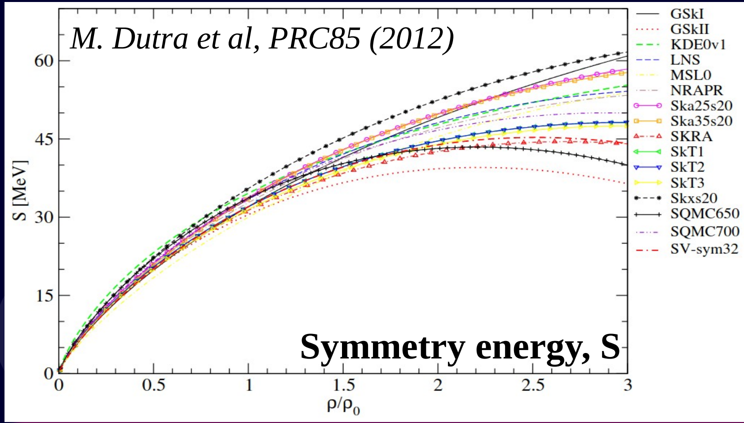
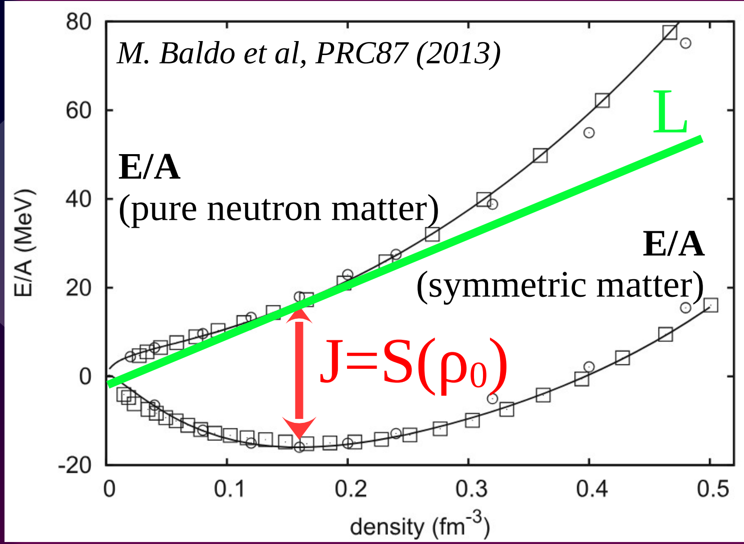
Connection to EoS and NS





$$\frac{E}{A}(\rho,\delta) = \underbrace{\frac{E}{A}(\rho,0)}_{\text{energy per nucleon of symmetric NM}} + \overbrace{S(\rho)}^{\text{symmetry energy}}\cdot\delta^2 + \mathcal{O}(\delta^4) \quad \text{with} \quad \delta = \frac{\rho_n-\rho_p}{\rho}$$

$$\frac{E}{A}(\rho,0) = \frac{E}{A}(\rho_0,0) + \frac{1}{2}K\cdot\varepsilon^2 + \mathcal{O}(\varepsilon^3) \quad \text{with} \quad \varepsilon = \frac{\rho_0-\rho}{3\rho_0}$$

$$S(\rho) = S(\rho_0) - L\cdot\varepsilon + \frac{1}{2}K_{sym}\cdot\varepsilon^2 + \mathcal{O}(\varepsilon^3)$$

Astrophysical systems (like NS) require the knowledge of EoS of asymmetric matter, related to the isovector parameters of the symmetry energy : J and L

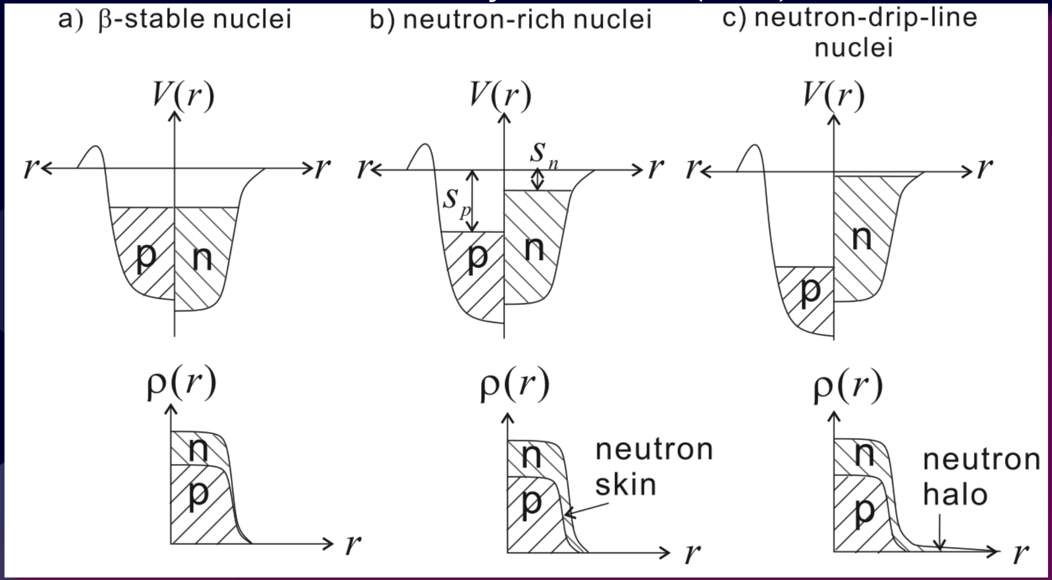
The natural choice for finding physical quantities that could be sensitive to the symmetry energy is to look at the iso-vector elementary nuclear excitations

GDR and iso-vector part of the PDR

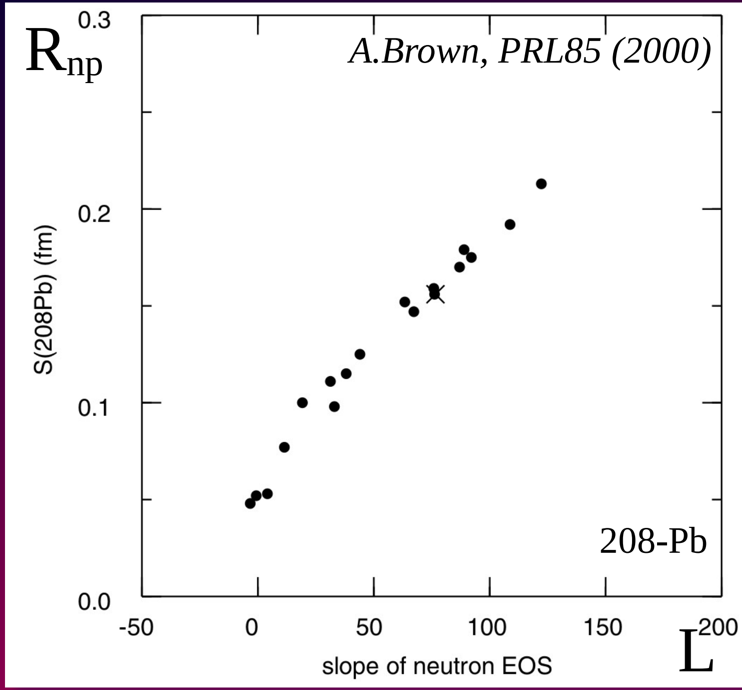
Connection to EoS and NS

Neutron skin (R_{np}) and L

T. Aumann and T. Nakamura, Phys. Scr. T152 (2013)



~8 MeV **S_n (neutron separation energy)** **~0 MeV**

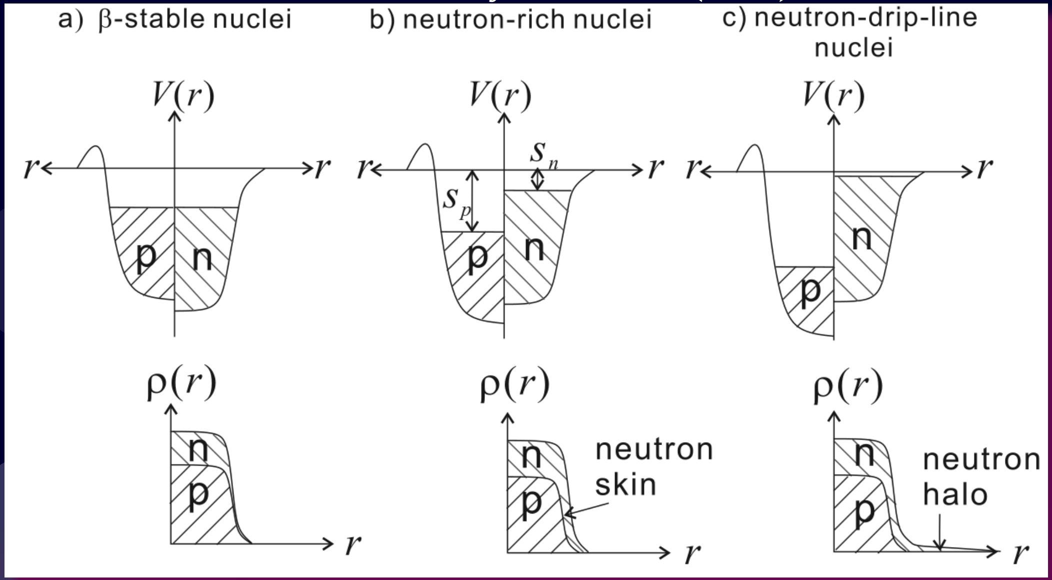


PDR is related with neutron skin !

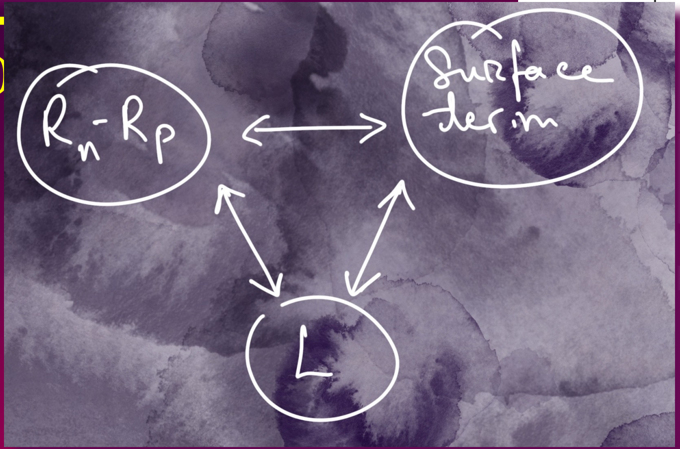
Connection to EoS and NS

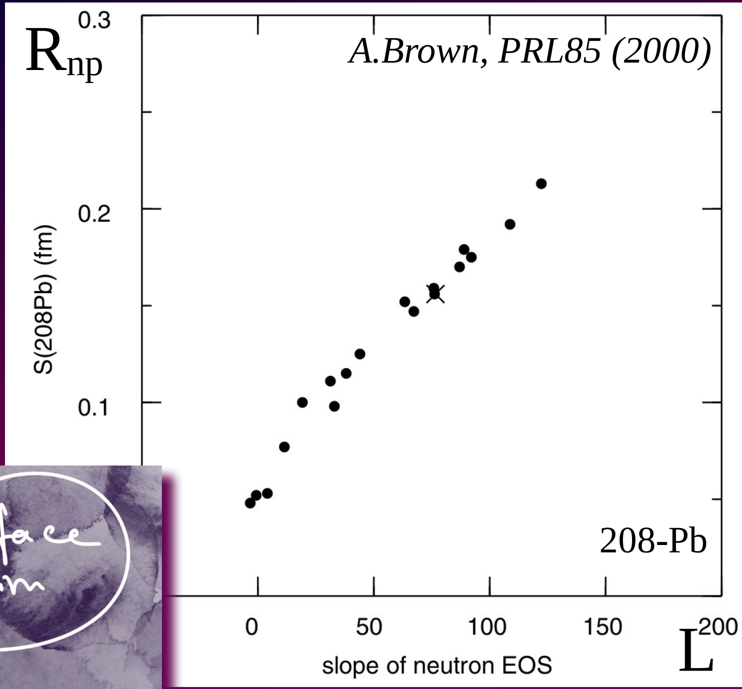
Neutron skin (R_{np}) and L

T. Aumann and T. Nakamura, Phys. Scr. T152 (2013)



~8 MeV S_n (neutron separation energy)



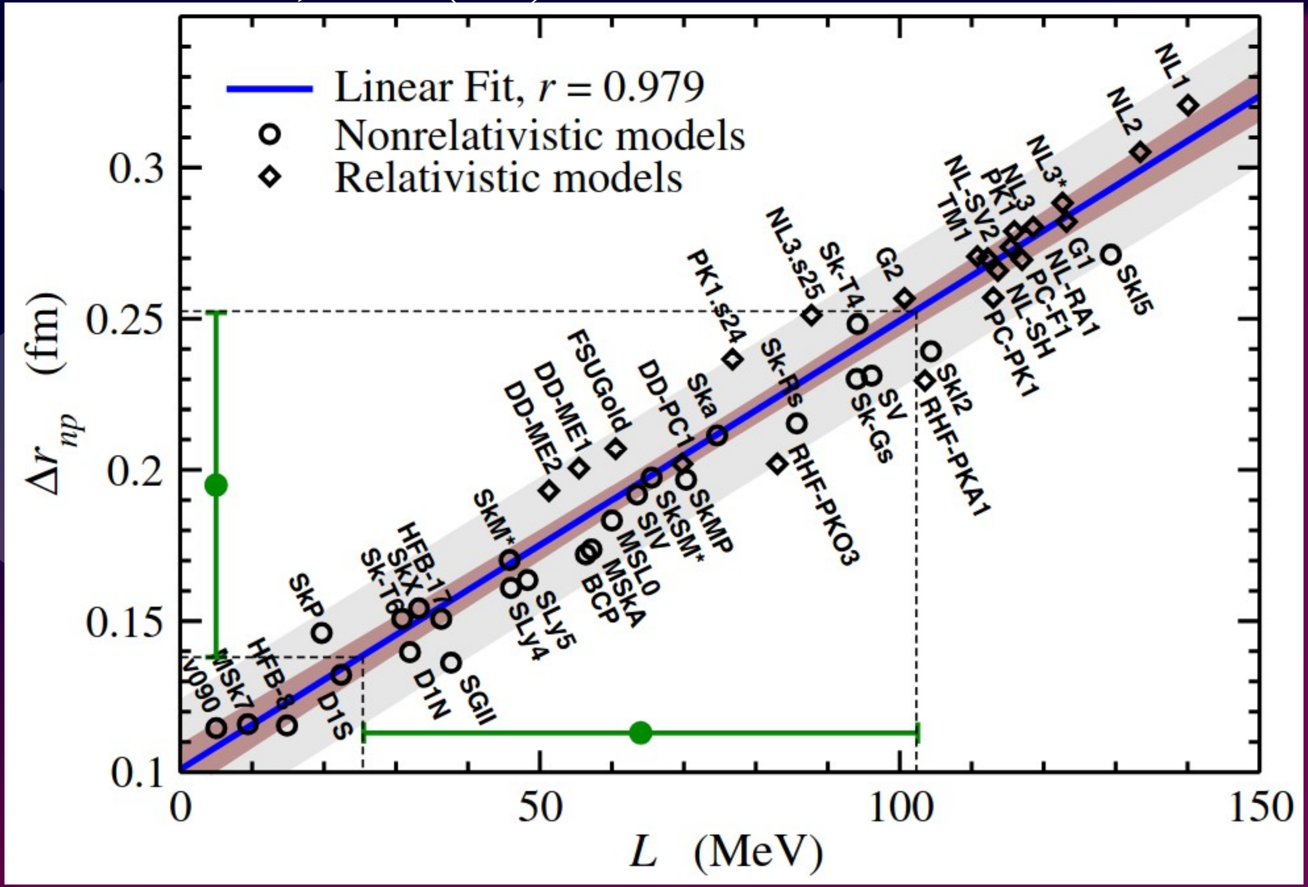


related with neutron skin !

Connection to EoS and NS

Neutron skin (R_{np}) and L

X. Roca-Maza et al, PRL106 (2011)



PREX experiment

– electroweak parity-violating e scattering

– asymmetry measurement

– Δr_{np} (^{208}Pb) = 0.283(71) fm – PREX II

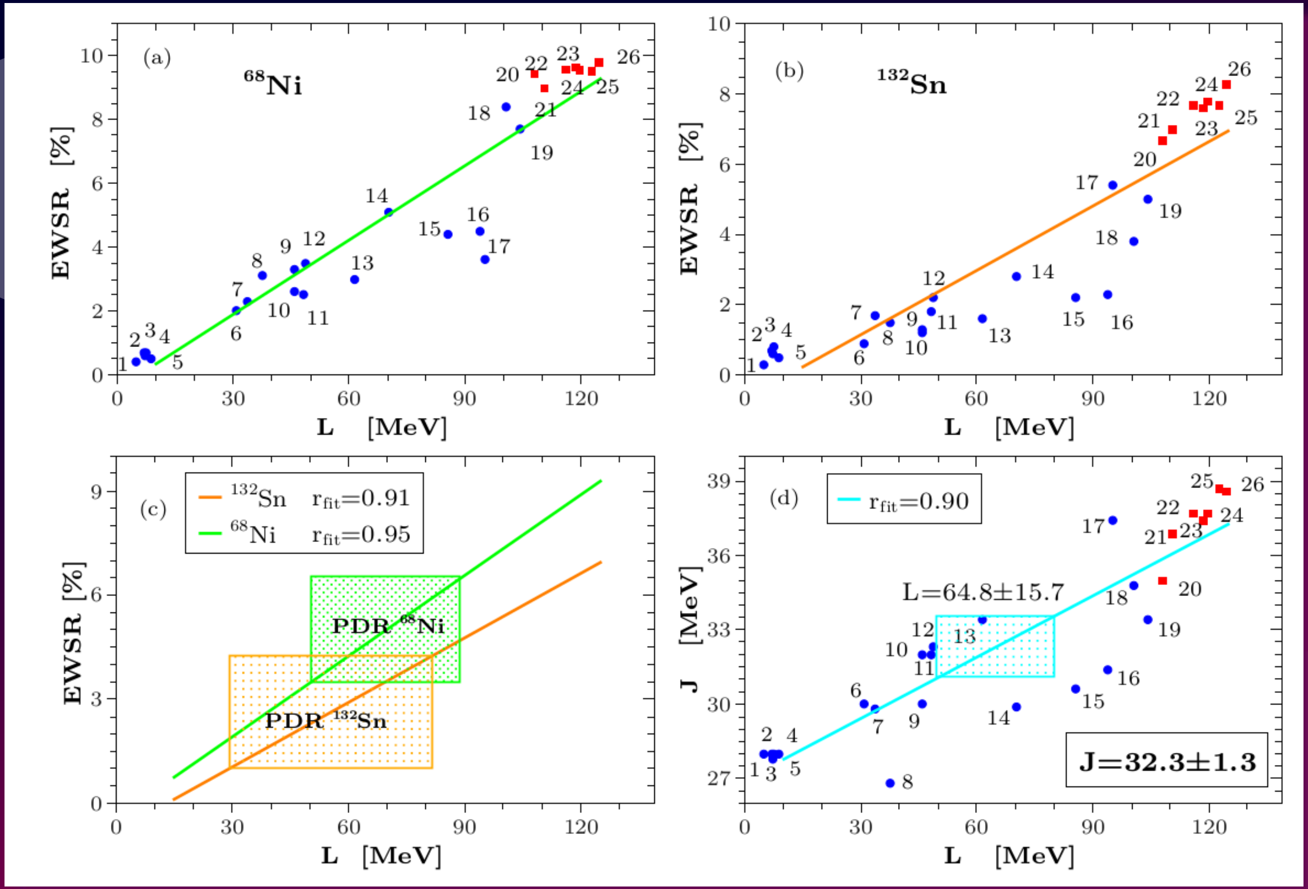
BUT :

tension with polarizability measurements and with the CREX measurement

(not the end of the story ...)

Connection to EoS and NS

PDR EWSR and L

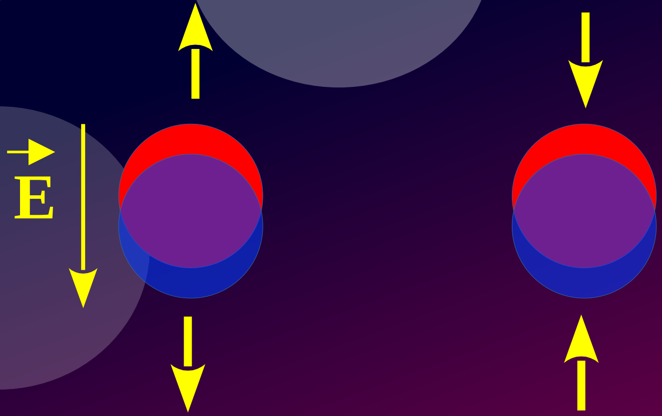


A. Carbone et al, PRC81 (2010)

Connection to EoS and NS

Dipole Polarizability and (L,J)

$$\alpha_D = \frac{\hbar c}{2\pi^2}\int \frac{\sigma_{abs}^{E1}}{\omega^2}\,d\omega = \frac{8\pi e^2}{9}\int \frac{dB(E1)}{\omega}$$

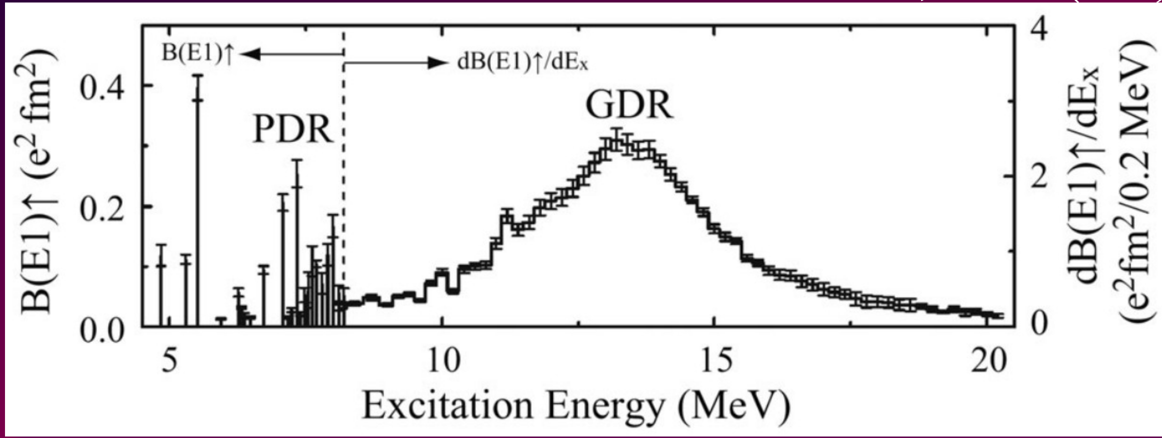


Electric force separate p/n

Symmetry energy restoring force

(figure inspired by A. Tamii)

A. Tamii et al, EPJA50 (2014)

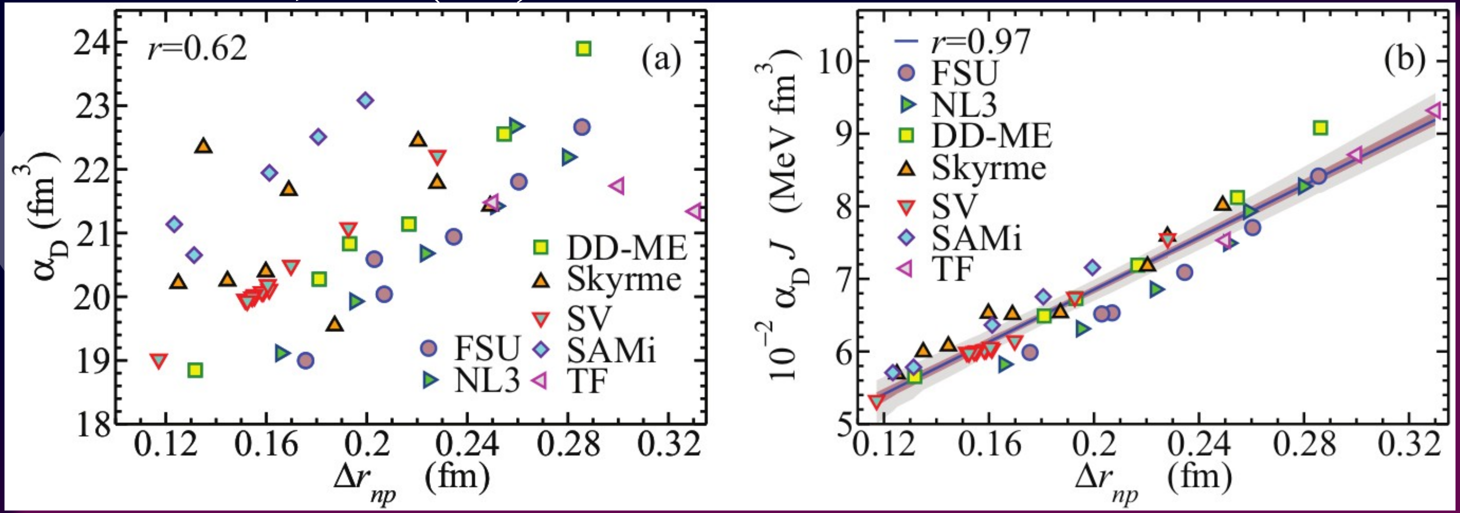


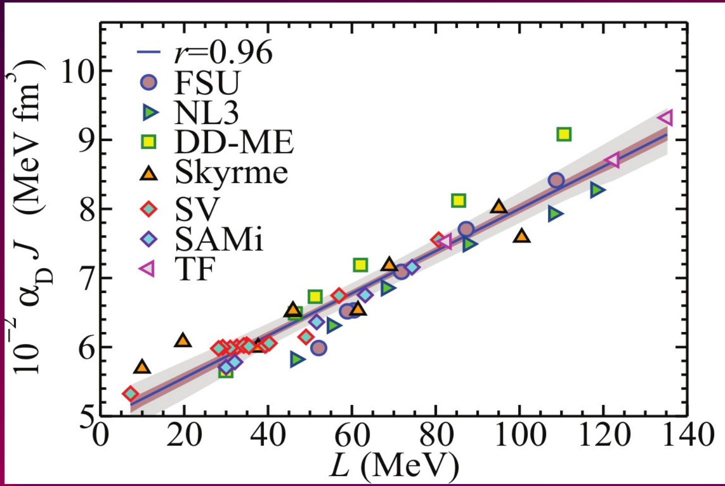
α_D (fm^3) = 2.7 | 16.2 | 1.2

Connection to EoS and NS

Dipole Polarizability and (L,J)

X. Roca-Maza et al, PRC88 (2013)



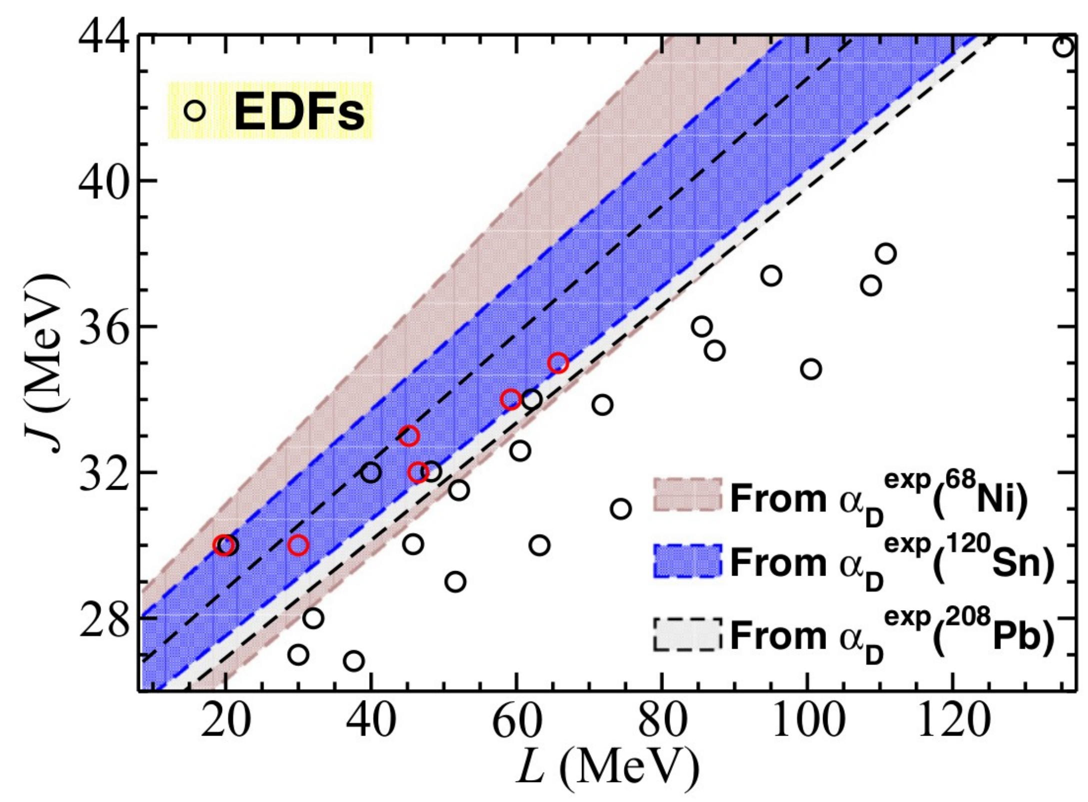


^{208}Pb

Connection to EoS and NS

Dipole Polarizability and (L,J)

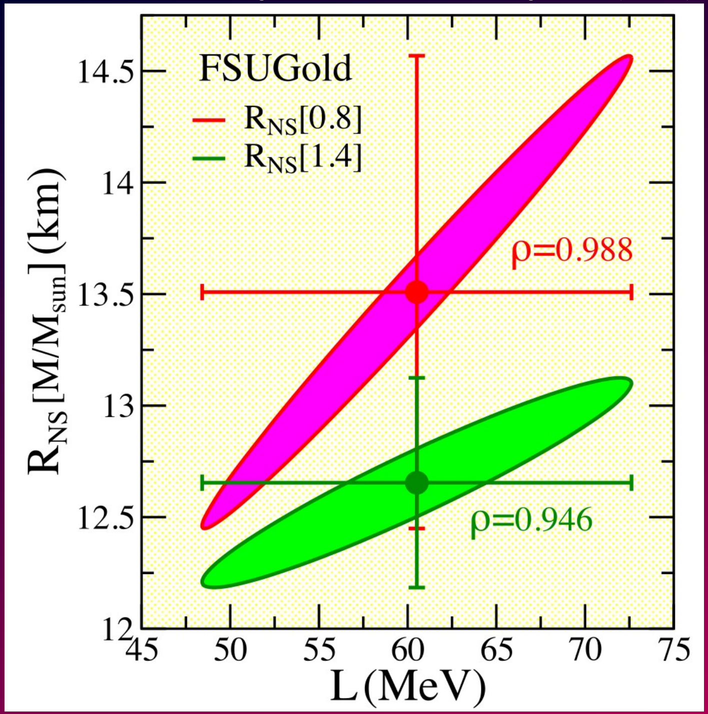
X. Roca-Maza et al, PRC92 (2015)



Connection to EoS and NS

(one exemple among many ...)

M. Thiel et al, J. Phys. G: Nucl. Part. Phys. 46 (2019)



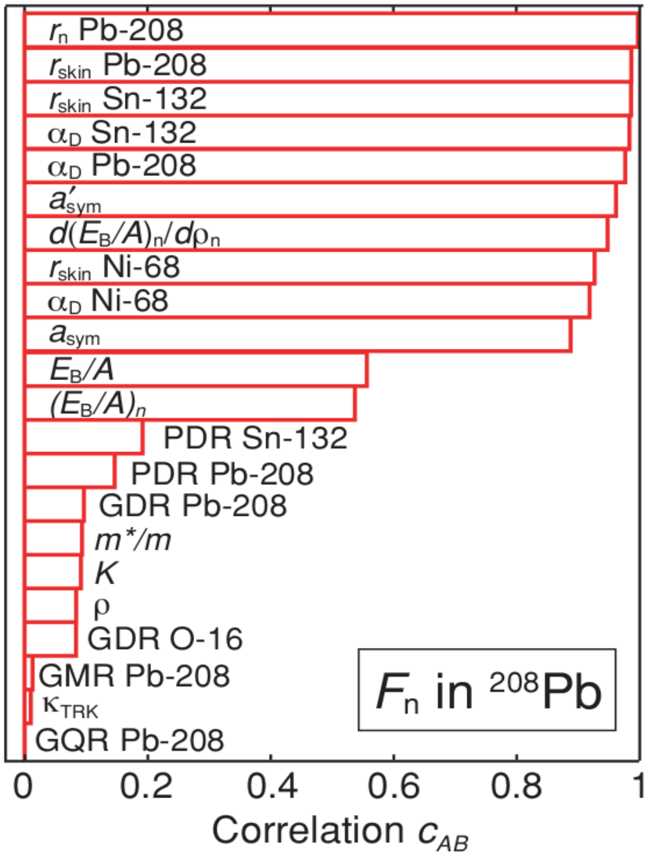
Connection to EoS and NS

Maybe not that clear …

PHYSICAL REVIEW C **81**, 051303(R) (2010)

Information content of a new observable: The case of the nuclear neutron skin

P.-G. Reinhard[1] and W. Nazarewicz[2,3,4,5]



^{208}Pb study case :

EWSR of PDR → not strongly correlated with Δr_{np} !
Polarizability → strong correlation with Δr_{np}
(even better, α_D*J)

But there are indications that these correlations are model dependent (cf X. Roca-Maza studies)

Not the end of the story …