JRJC - 2024

Shell Model Photo-Strength Functions and Pygmy Dipole Resonance

E1 response of sd-shell nuclei using the configuration interaction shell model

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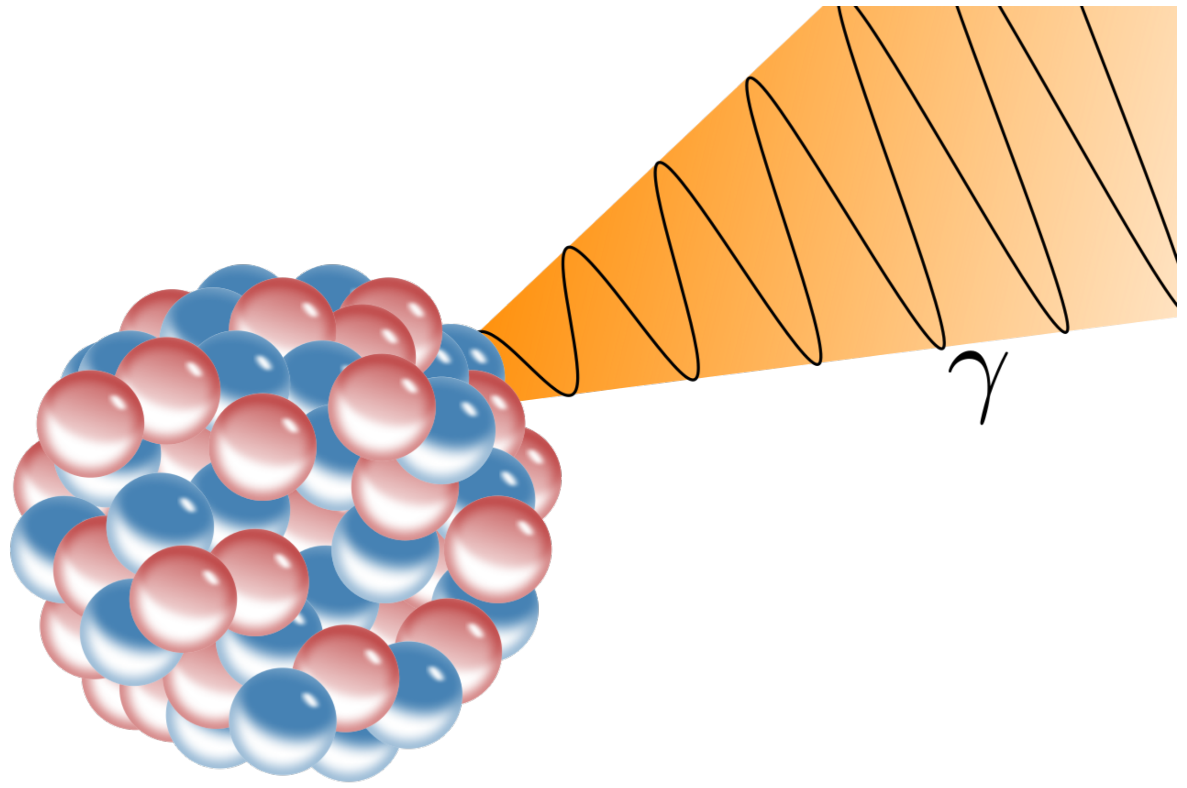
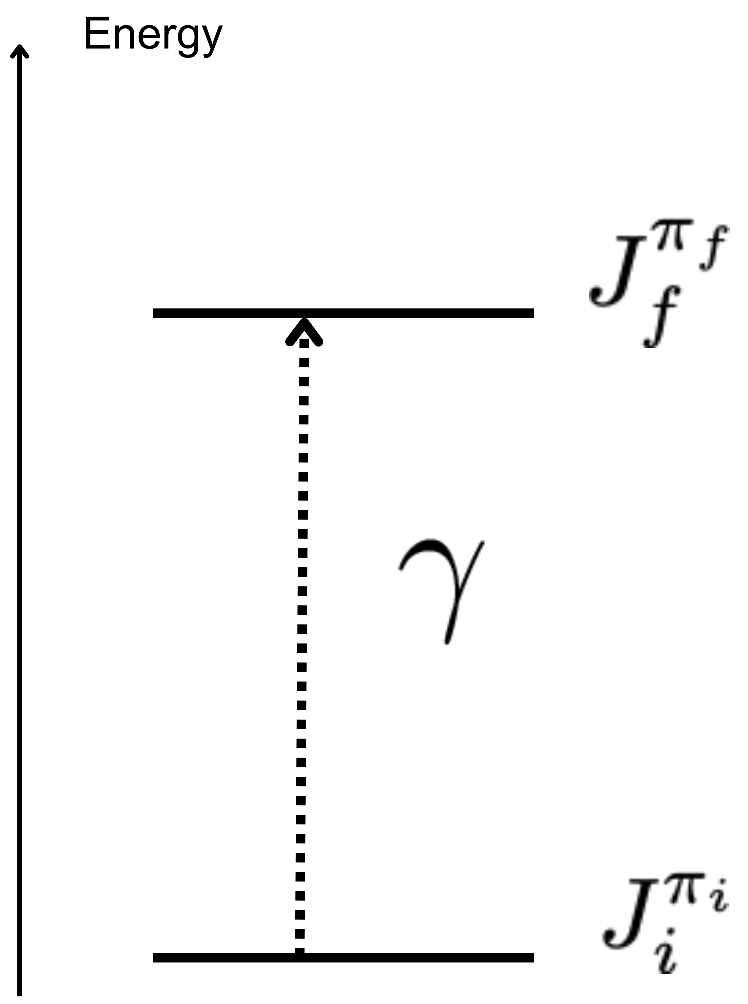
Under the supervision of Kamila Sieja

Photo-strength function (PSF) definition

Nuclear electromagnetic transitions





Transition probability rate

$$\Gamma_{fi} \propto B_{fi}(X\lambda)$$

$$B_{fi}(X\lambda) = \frac{1}{2J_i + 1} \left| \langle \psi_f || \mathcal{O}_\lambda || \psi_i \rangle \right|^2$$

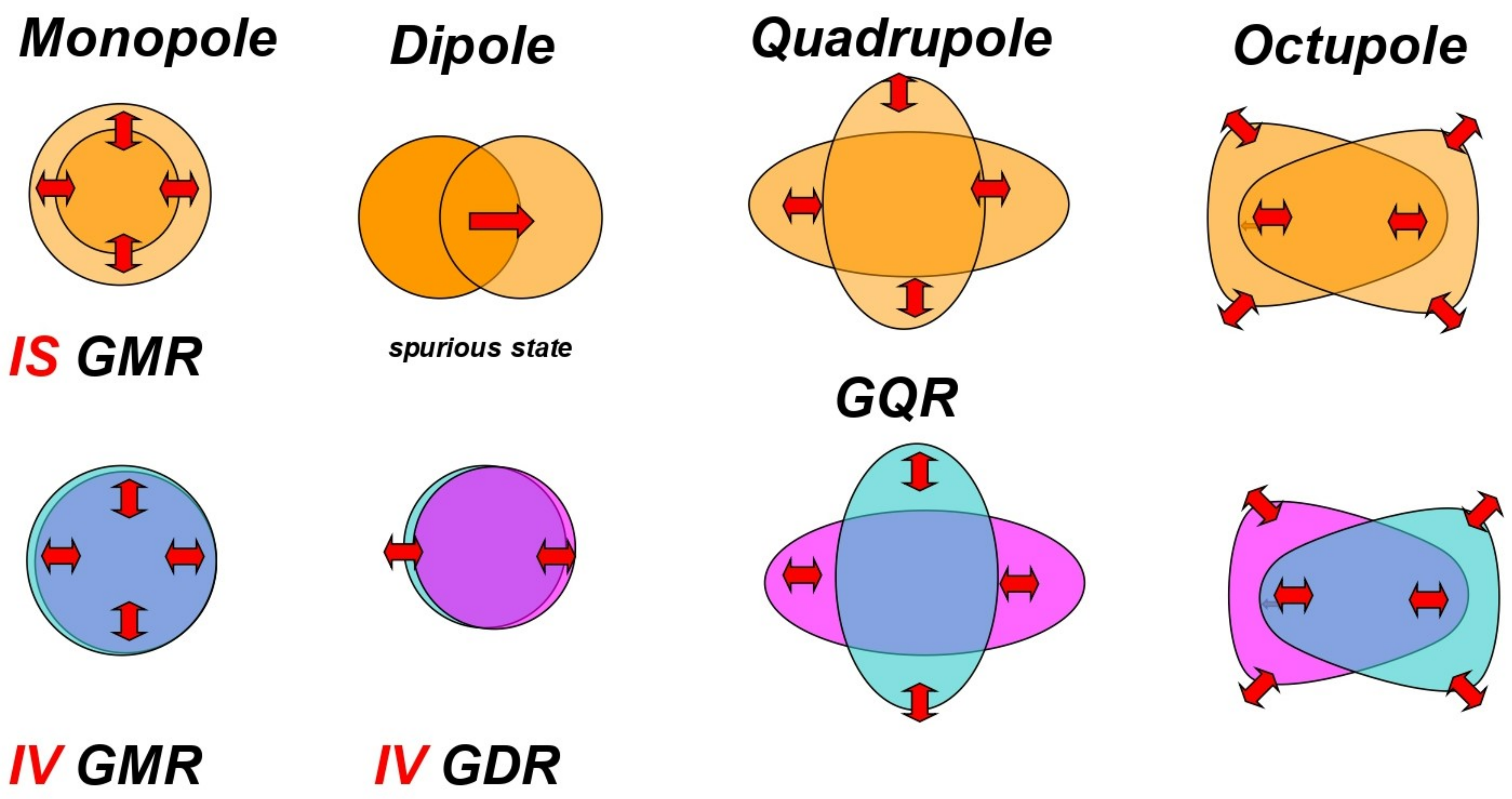
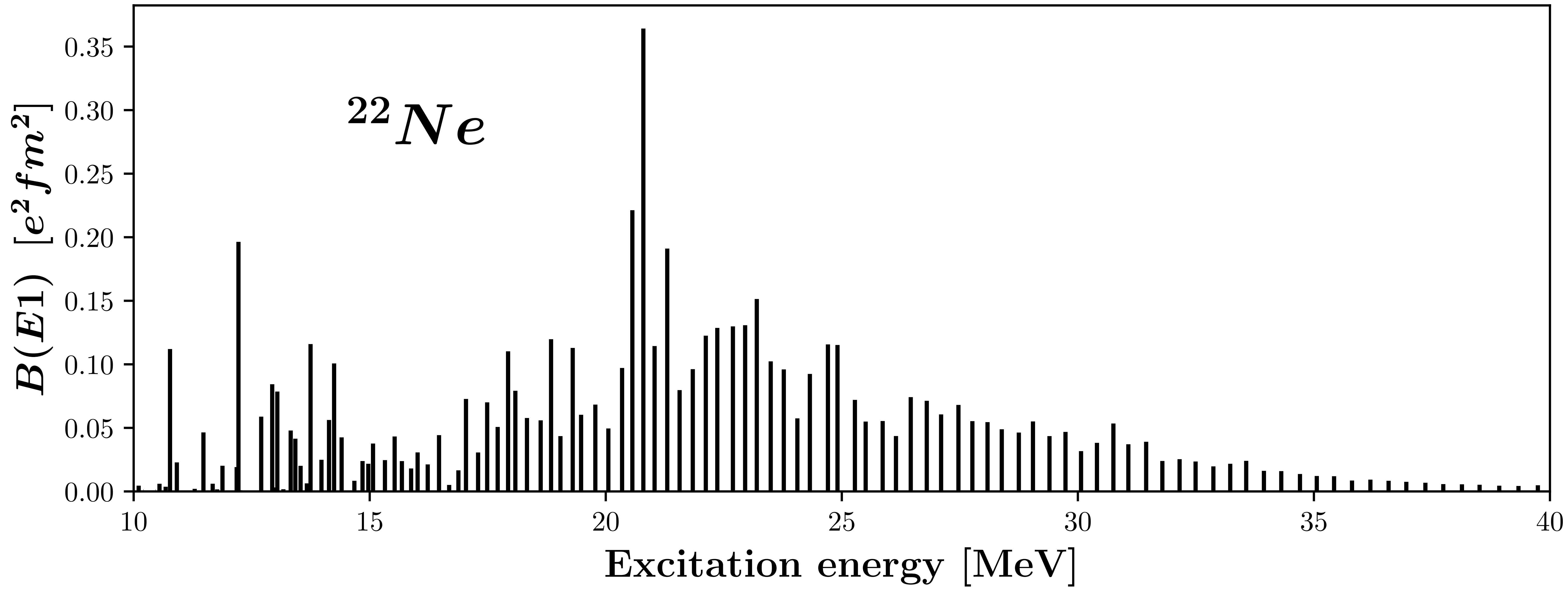


Photo-strength function (PSF) definition

Photo-stength function (PSF)

$$S(\varepsilon) = \sum_f B_{fi}\delta(\varepsilon - \varepsilon_f)$$

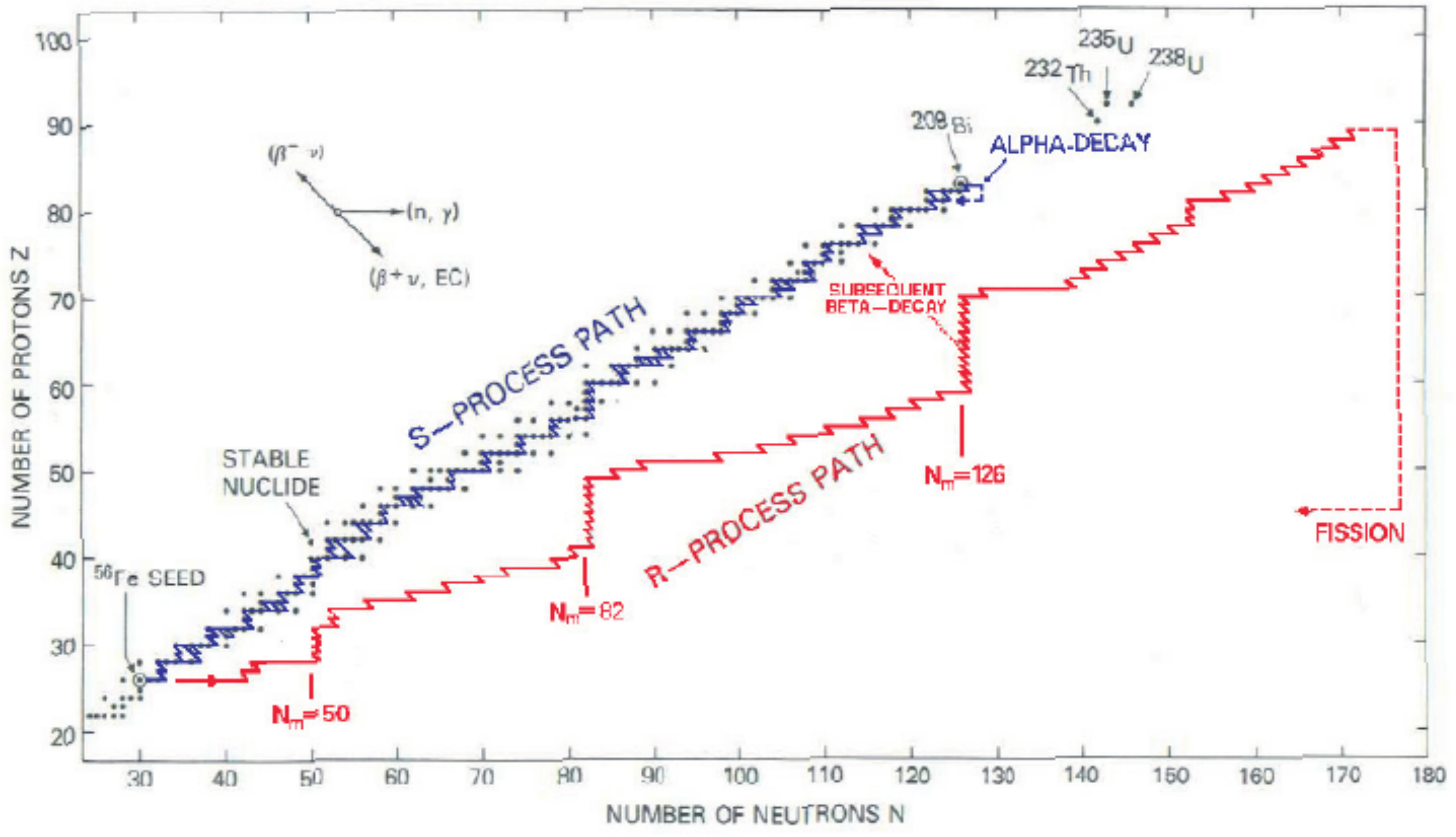


This work

Global response to an EM perturbation of a given type and multipolarity e.g. E1

Why is it interesting ?

R-process nucleosynthesis

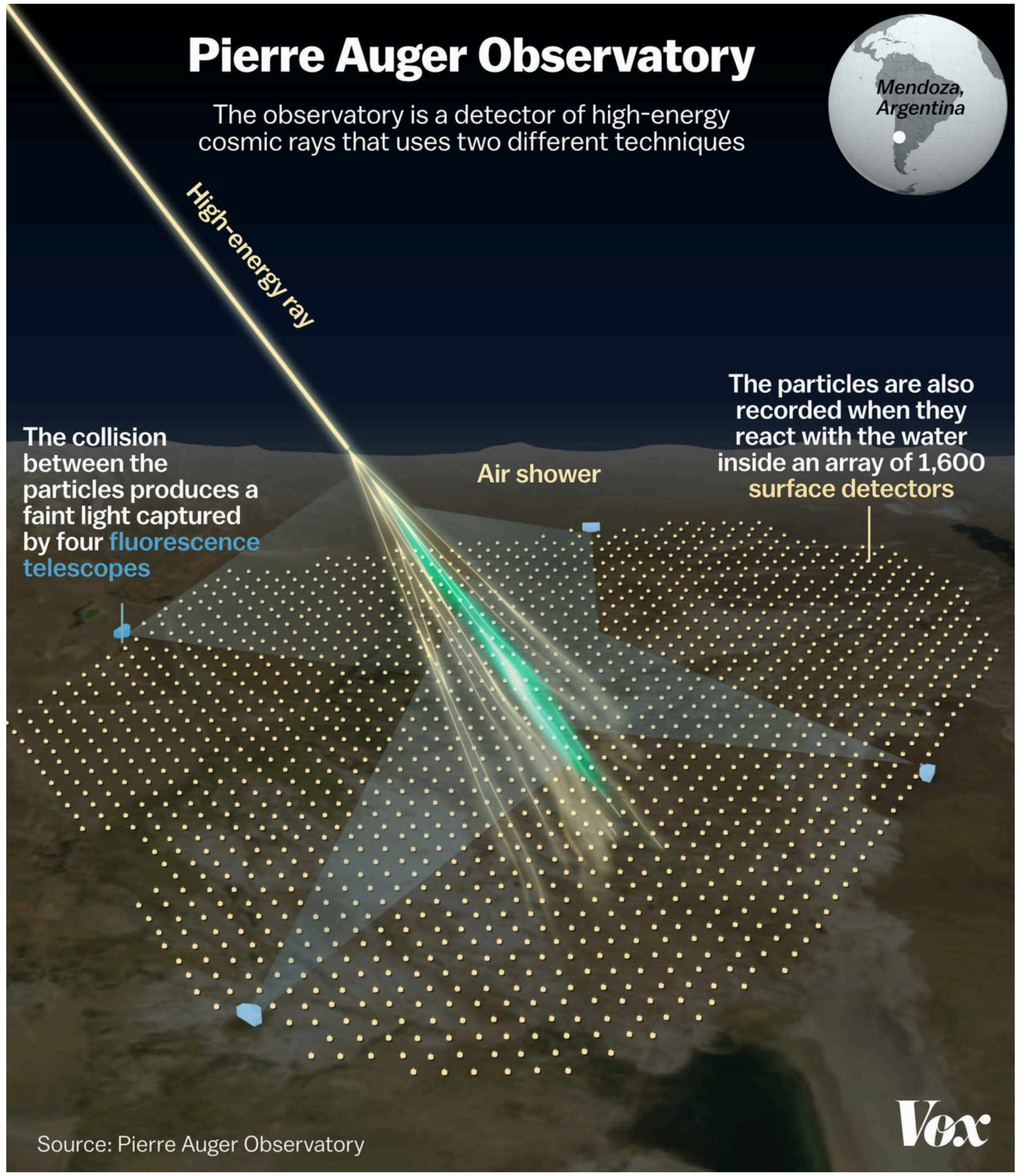


M.L Pumo. The s-process nucleosynthesis in massive stars: current status and uncertainties due to convective overshooting. (2012) ISBN 978-953-51-0473-5

Hauser-Feshbach model for (n,γ) cross sections

$$\sigma_{(n,\gamma)} \sim T_\gamma(\varepsilon, X\lambda) \propto S(\varepsilon, X\lambda)$$

Ultra High Energetic Cosmic Rays (UHECR)



Why is it interesting ?

Neutron matter equation of state (EOS)

$$\mathcal{E}(\rho,\alpha) = \mathcal{E}_{\mathrm{SNM}}(\rho) + \alpha^2 \mathcal{S}(\rho) + \mathcal{O}(\alpha^4)$$

$\rho = (\rho_n + \rho_p)$ $\quad$ $\alpha = (\rho_n - \rho_p)/\rho$

where the **density-dependent symmetry energy** is:

$$\mathcal{S}(\rho) = J + L\frac{(\rho-\rho_0)}{3\rho_0} + \ldots .$$

symmetry energy at saturation density

slope parameter, related to **pressure of pure neutron matter** at saturation density

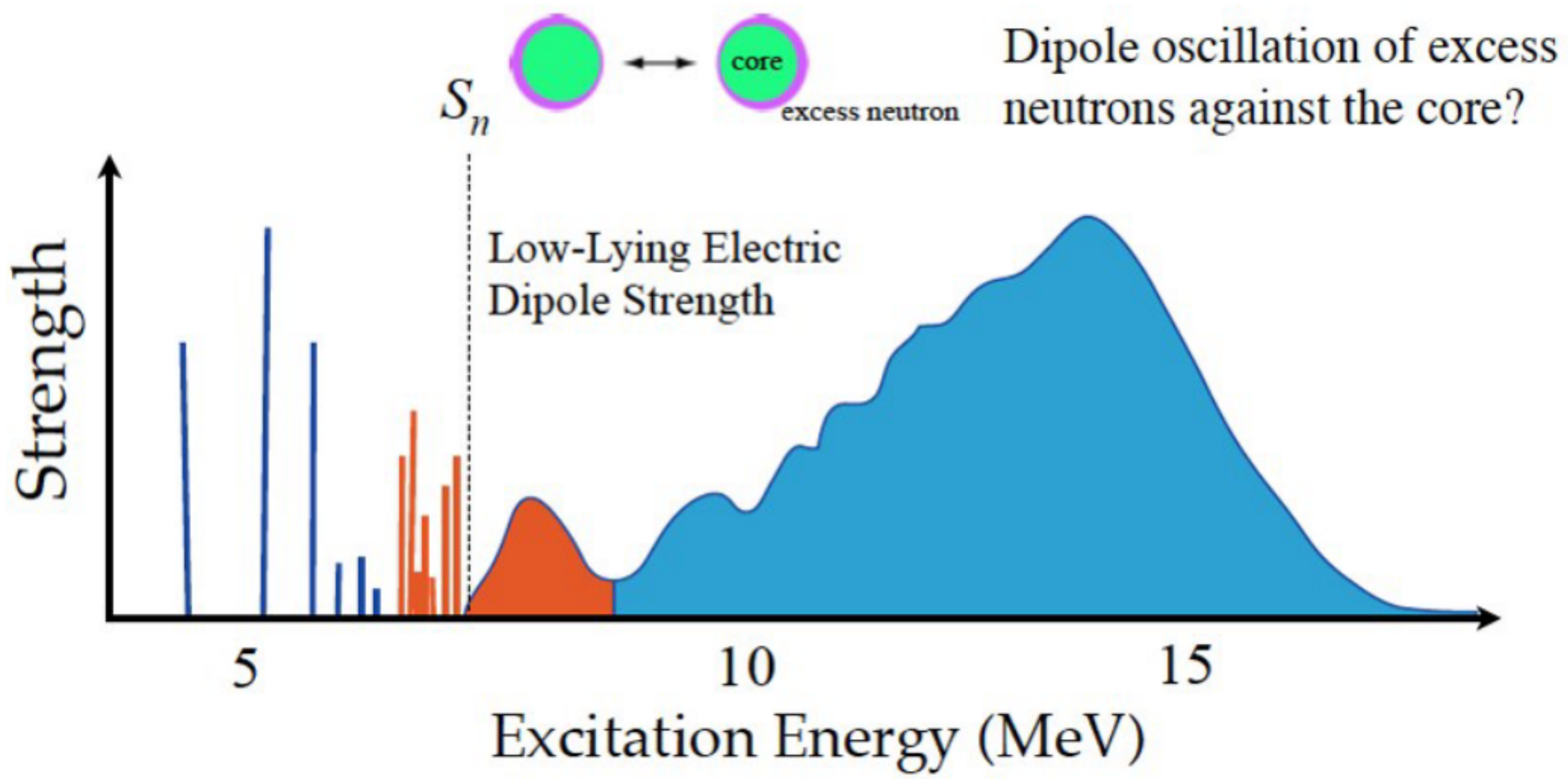
FRANCESCA BONAITI, JGU MAINZ RISING RESEARCHERS SEMINAR SERIES (2023)

- Neutron skin thickness
- Electric dipole polarizability

$$\alpha = \frac{8\pi}{9}\int d\varepsilon \frac{S(\varepsilon)}{\varepsilon}$$

Nuclear structure

Pigmy Dipole Resonance (PDR)



Tamii (2016). Adelaide International Conference

Model and Method

- QRPA approaches
- Generator coordinates method
- Time-dependent Hartree-Fock

Configuration Interaction Shell Model

$$S(\varepsilon) = \sum_f B_{fi}\delta(\varepsilon - \varepsilon_f)$$

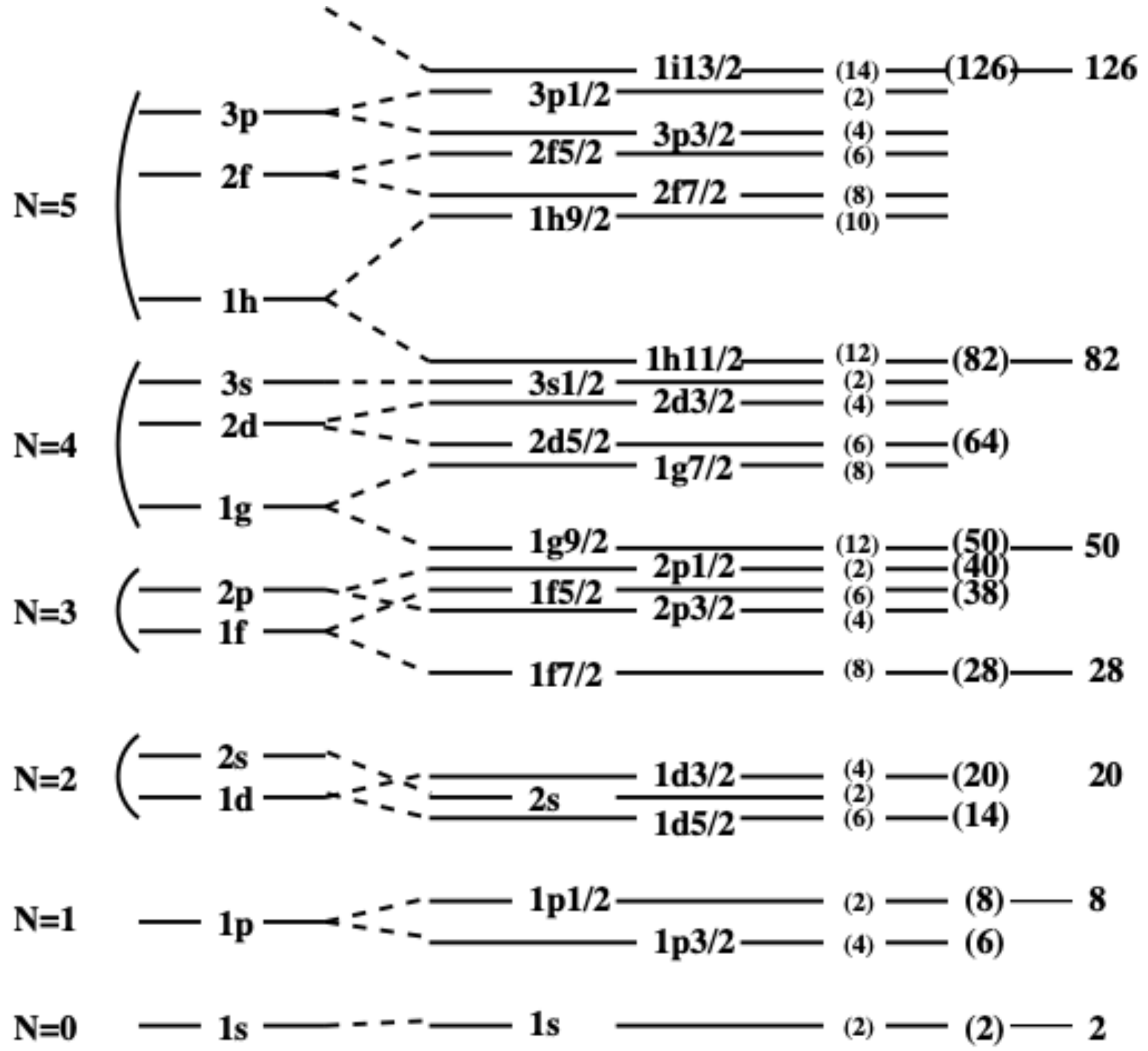
$$B_{fi}(X\lambda) = \frac{1}{2J_i + 1} | \langle \psi_f || \mathcal{O}_\lambda || \psi_i \rangle |^2$$

A-Body Quantum Problem

$$i\hbar \frac{\partial}{\partial t} |\psi\rangle = \mathcal{H} |\psi\rangle$$

Hilbert space basis : product of one body harmonic oscillator states

$$|n, l, j, m_j, \tau_3\rangle$$

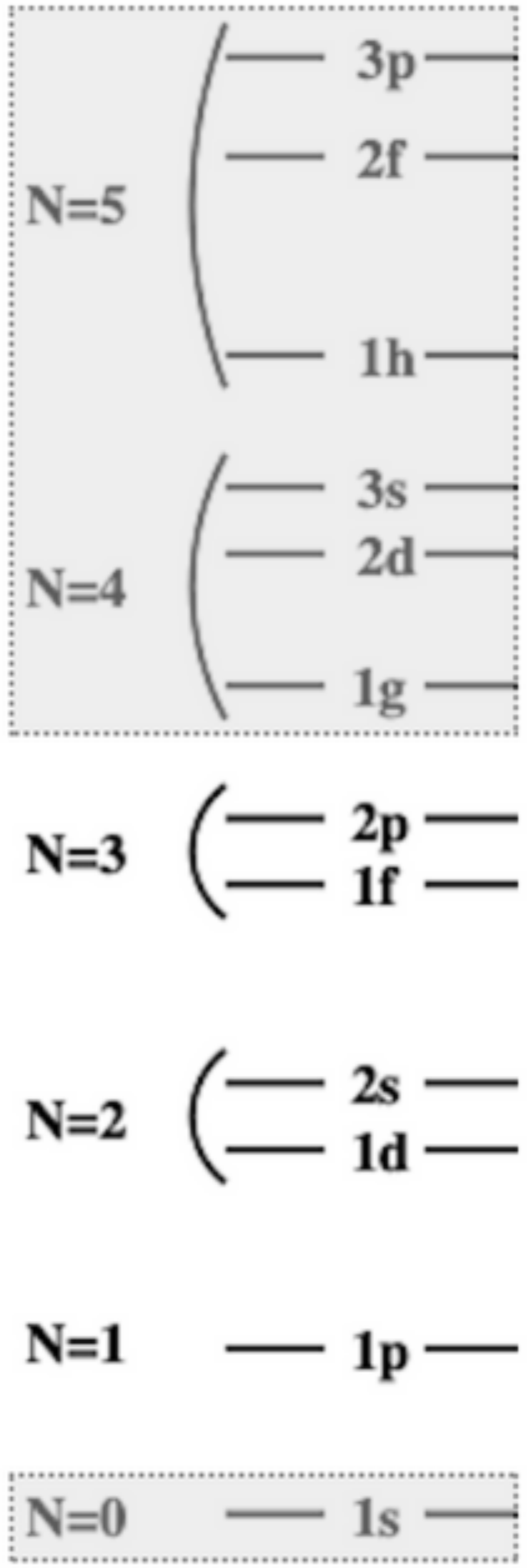


Model and Method

Configuration Interaction Shell Model

Restriction to a sub space : the valence space

sd shell nuclei : psdpf model space :



$\mathcal{H}|\psi\rangle = E|\psi\rangle$ Mapped to $\mathcal{H}_{eff}|\tilde{\psi}\rangle = E|\tilde{\psi}\rangle$

- Lee-Suzuki
- Similarity renormalization group
- + phenomenological fit

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Nuclear Physics A 864 (2011) 113–127

NUCLEAR PHYSICS A

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A PSDPF interaction to describe the 1 $\hbar\omega$ intruder states in sd shell nuclei

M. Bouhelal [a,*], F. Haas [b], E. Caurier [b], F. Nowacki [b], A. Bouldjedri [c]

Model and Method

Configuration Interaction Shell Model

Iterative diagonalization procedure : Lanczos Algorithm

$$H|\psi\rangle = E|\psi\rangle \qquad H = \sum_i \epsilon_i c_i^\dagger c_i + \sum_{ijkl} V_{ijkl} c_i^\dagger c_j^\dagger c_l c_k + \beta H_{COM} \qquad H = UDU^\dagger$$

Bare electric dipole operator $\hat{O}_{1\mu} = -e\frac{Z}{A}\sum_{i=1}^{N} r_i Y_{1\mu}(\hat{r}_i) + e\frac{N}{A}\sum_{i=1}^{Z} r_i Y_{1\mu}(\hat{r}_i)$

Initial pivot as $\frac{\hat{O}_{10}|GS\rangle}{\sqrt{S_0}}$ $\quad S(\varepsilon) = \sum_f U_{1f}^2 S_0 \delta(\varepsilon - \varepsilon_f) = \sum_f B_{fi}\delta(\varepsilon - \varepsilon_f)$

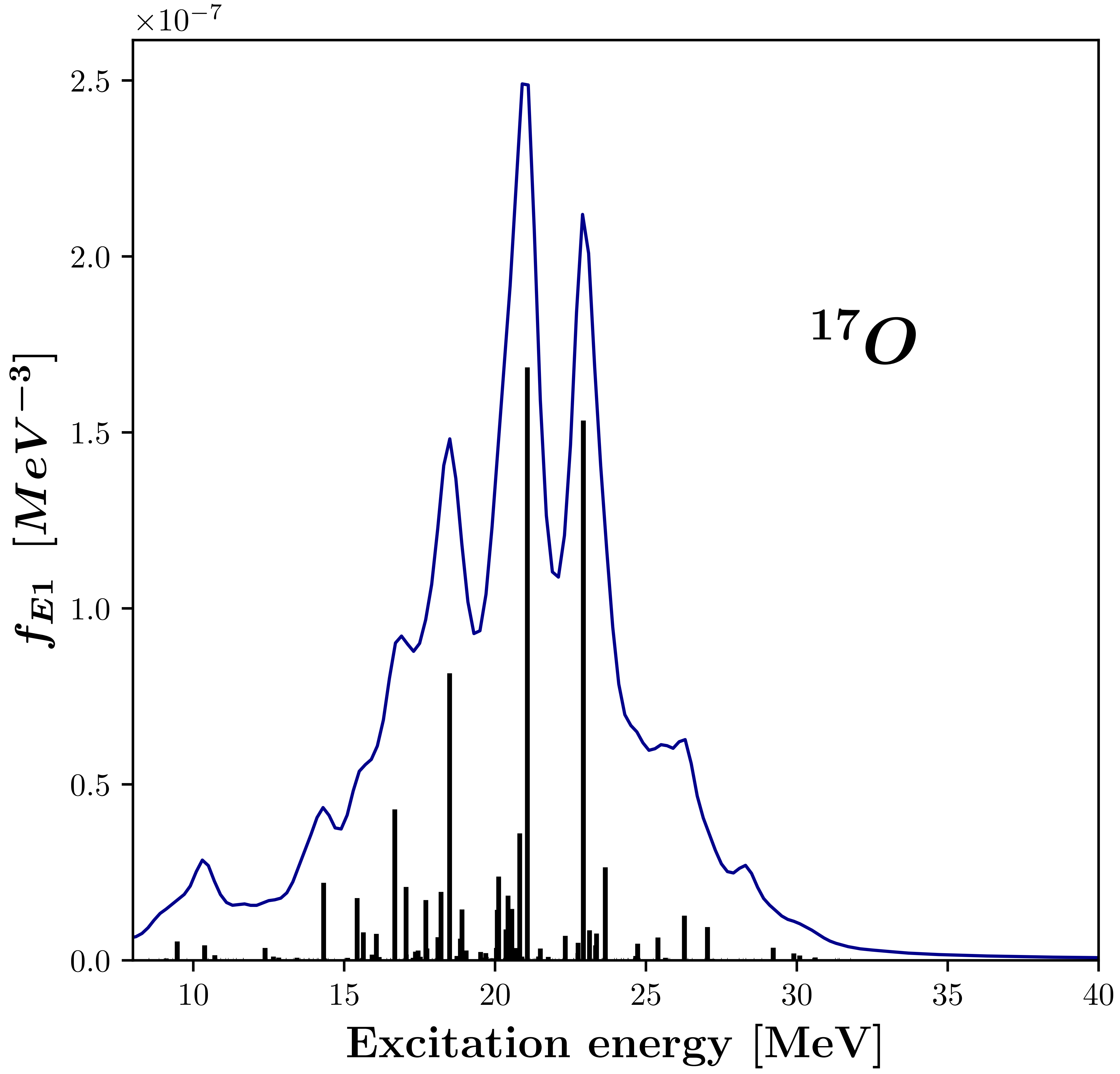
Reduced transition probability $B_{fi}(X\lambda) = \frac{1}{2J_i+1}|\langle\psi_f||\mathcal{O}_\lambda||\psi_i\rangle|^2$

Model and Method

To compare to experiments and to account for the quasi continuum : Lorentzian folding

$$f(\varepsilon) = \sum_f \frac{1}{2\pi} \frac{\Gamma}{(\varepsilon - \varepsilon_f)^2 + \frac{\Gamma^2}{4}} B_{fi}$$

$$\Gamma = 1 \quad \text{MeV}$$



This work

Model and Method

E1 Quenching Factor

Systematic strength overestimation

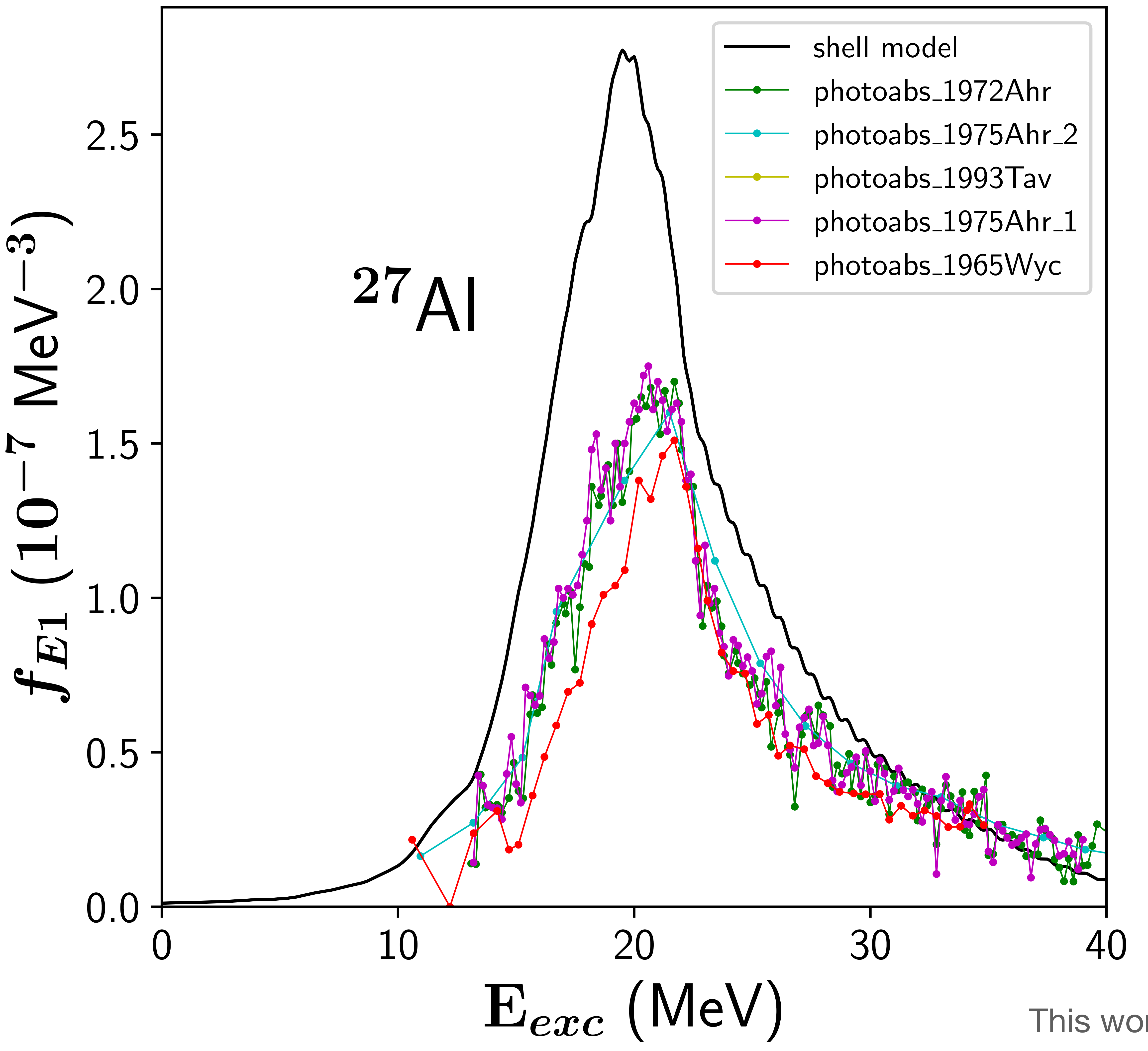
Non-renormalization of E1 operator : bare $\hat{O}_1$

Known issue e.g. Gamow-Teller, M1 cases

Caurier et al.
The Shell Model as Unified View of Nuclear Structure (2005)

To account for the core and external spaces correlations :

- Many body perturbation theory on E1 operator (e.g. Lee-Suzuki approach)
- Phenomenological Quenching : scaling to experimental data
- Scaling to TRK-values (E1)



This work

One experimental data set discarded !

Model and Method

E1 Quenching Factor

Energy Weighted Sum Rule (EWSR)

$$S_1 = \sum_{\nu} \varepsilon_{\nu} |\langle \nu | \hat{O} | 0 \rangle|^2$$

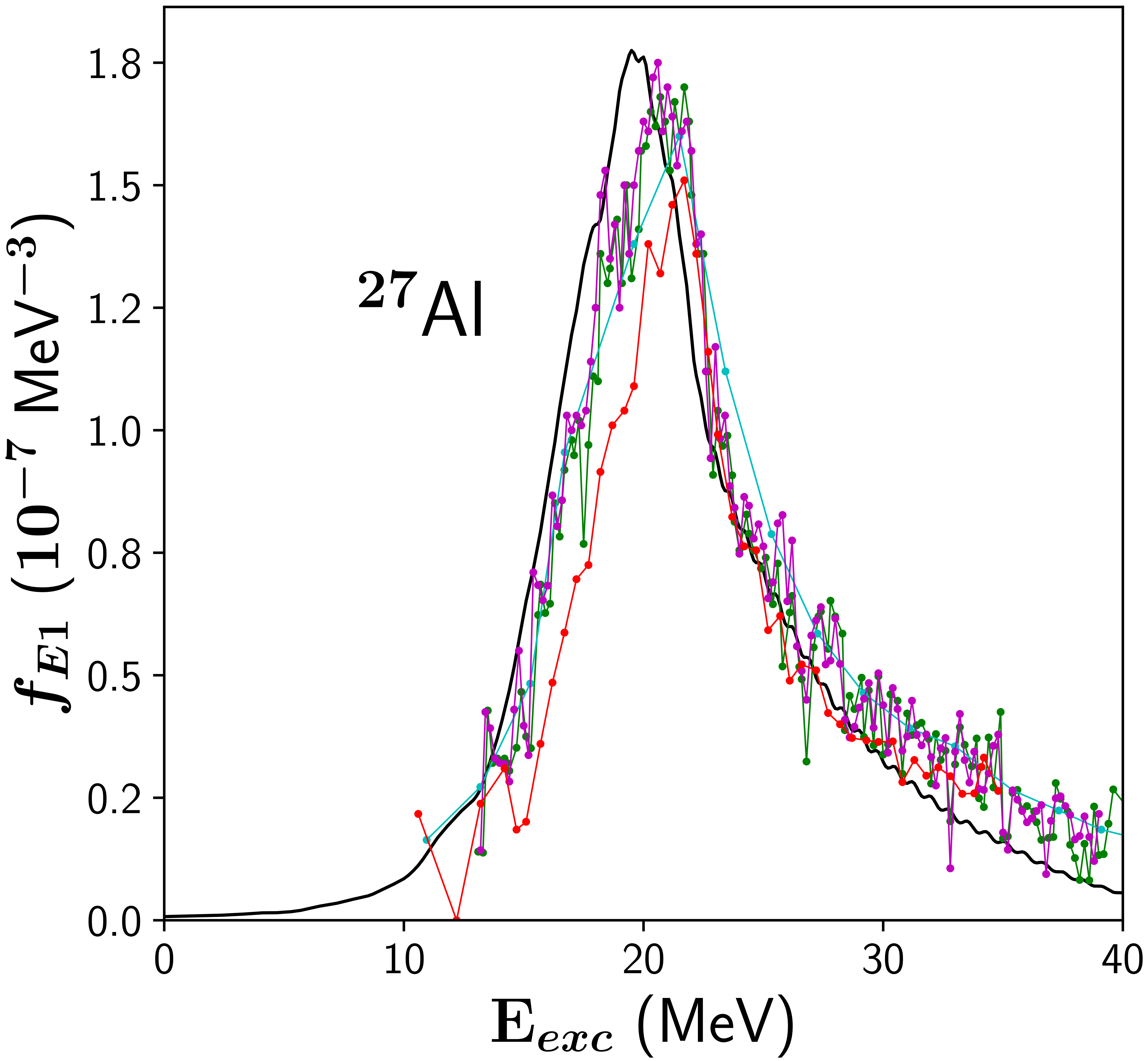
TRK Sum Rule (lower bound)

$$S_1^{TRK} = \frac{9\hbar^2 e^2}{8\pi m} \frac{NZ}{A}$$

$$Q^2 = 0.64$$

Quenching Factor

$$Q^2_{TRK} = \frac{S_1^{TRK}}{S_1^{SM}} \qquad Q^2_{EXP} = \frac{S_1^{EXP}}{S_1^{SM}}$$



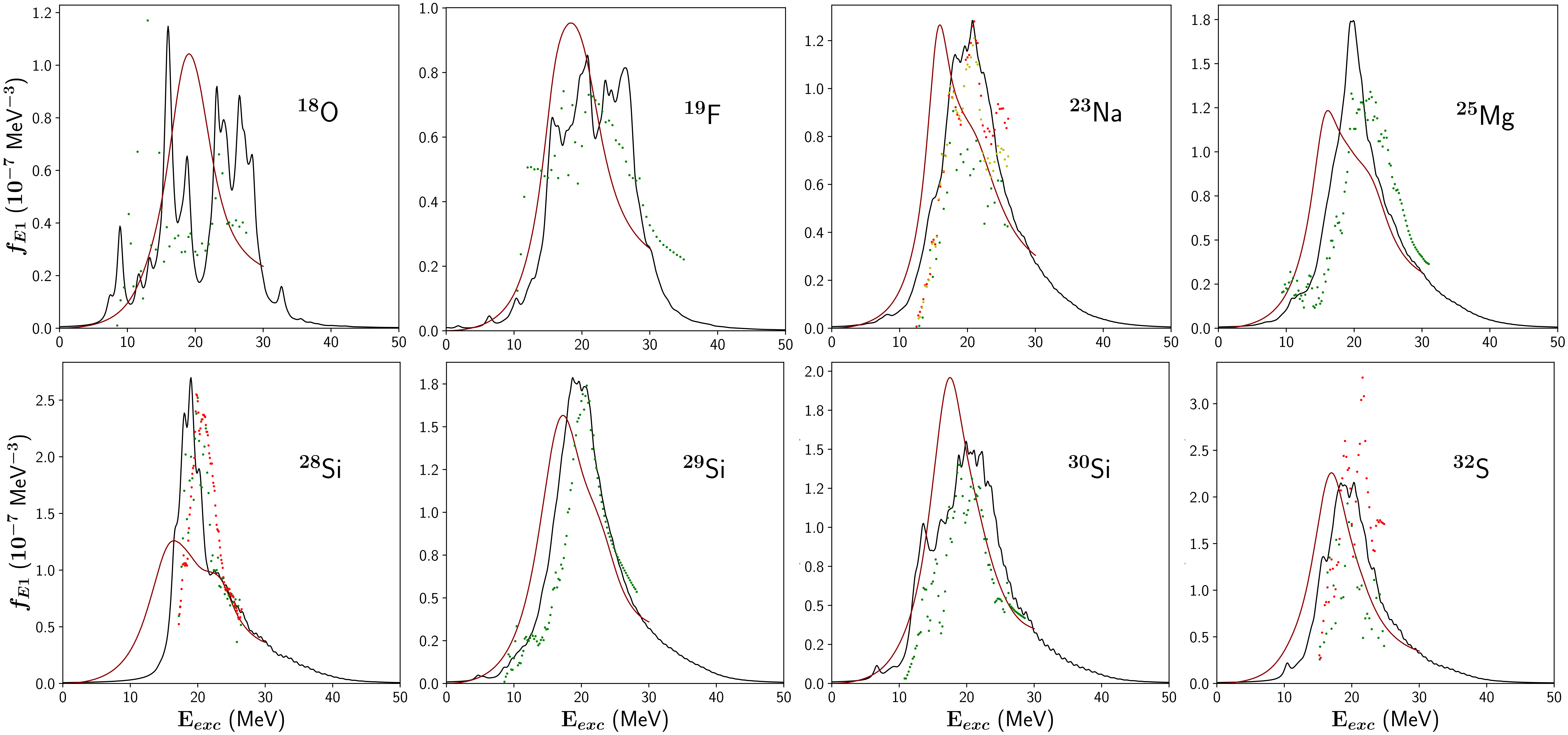
Results : PSF for all long lived sd nuclei

Gogny-HFB+QRPA

S. Goriely, S. Hilaire, S. Péru, K. Sieja, Phys. Rev. C 98, 014327 (2018).

- V.V.**Varlamov**, M.E. Stepanov, V.V. Chesnokov; Izv. Ros. Akad. Nauk, Ser.Fiz. 67, 656(2003); (Bull.Rus.Acad.Sci.Phys. 67, 724 (2003))
- J.**Ahrens**, H.Borchert, H.B.Eppler, H.Gimm, H.Gundrum; Conf.Nucl.Structure Studies, Sendai, Japan, 213, (1972)
- B.S.**Ishkhanov**, I.M.Kapitonov, E.I.Lileeva, et al.,; Moscow State Univ. Inst. of Nucl. Phys. Reports, No.2002, 27/711(2002)

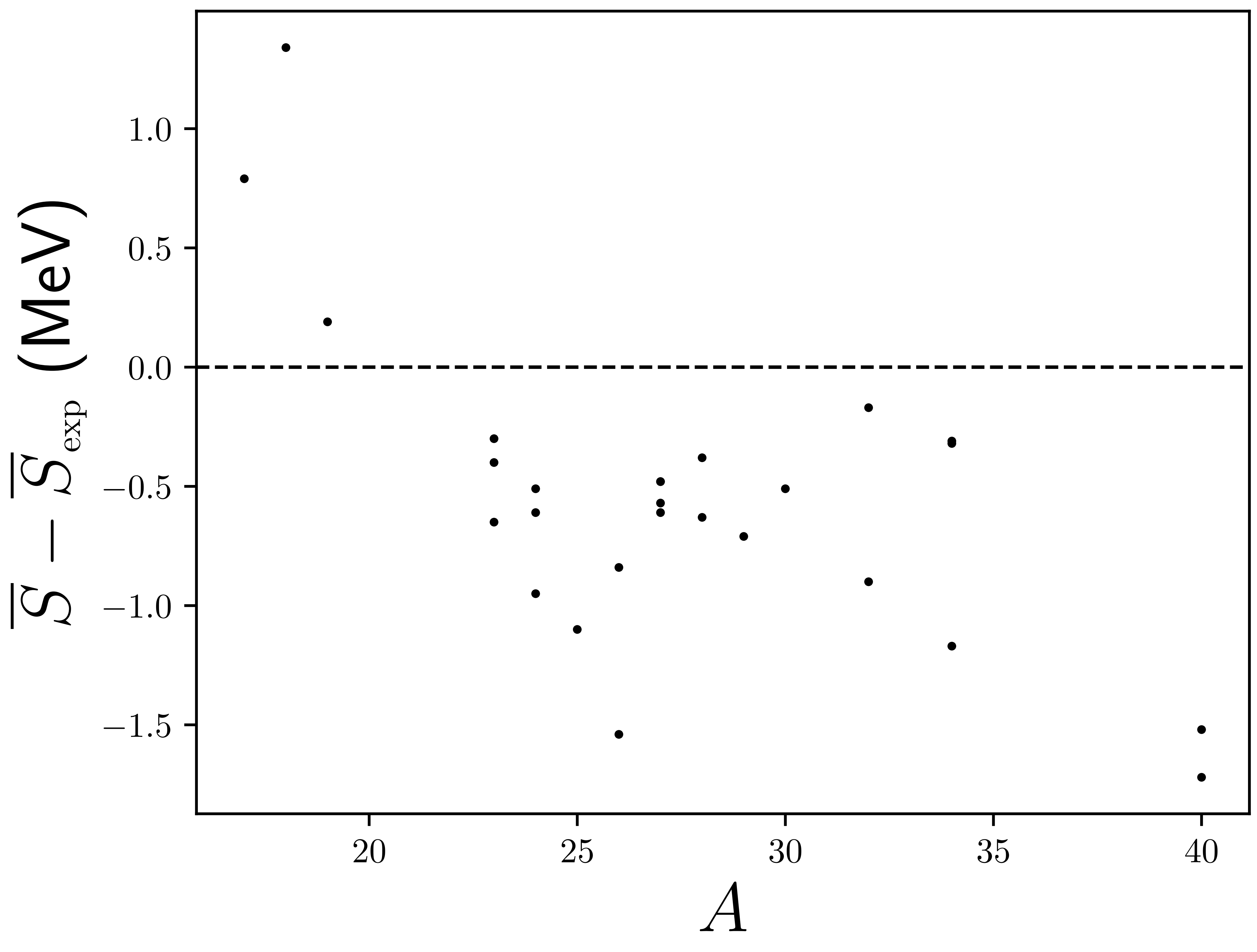
Results : PSF for all long lived sd nuclei

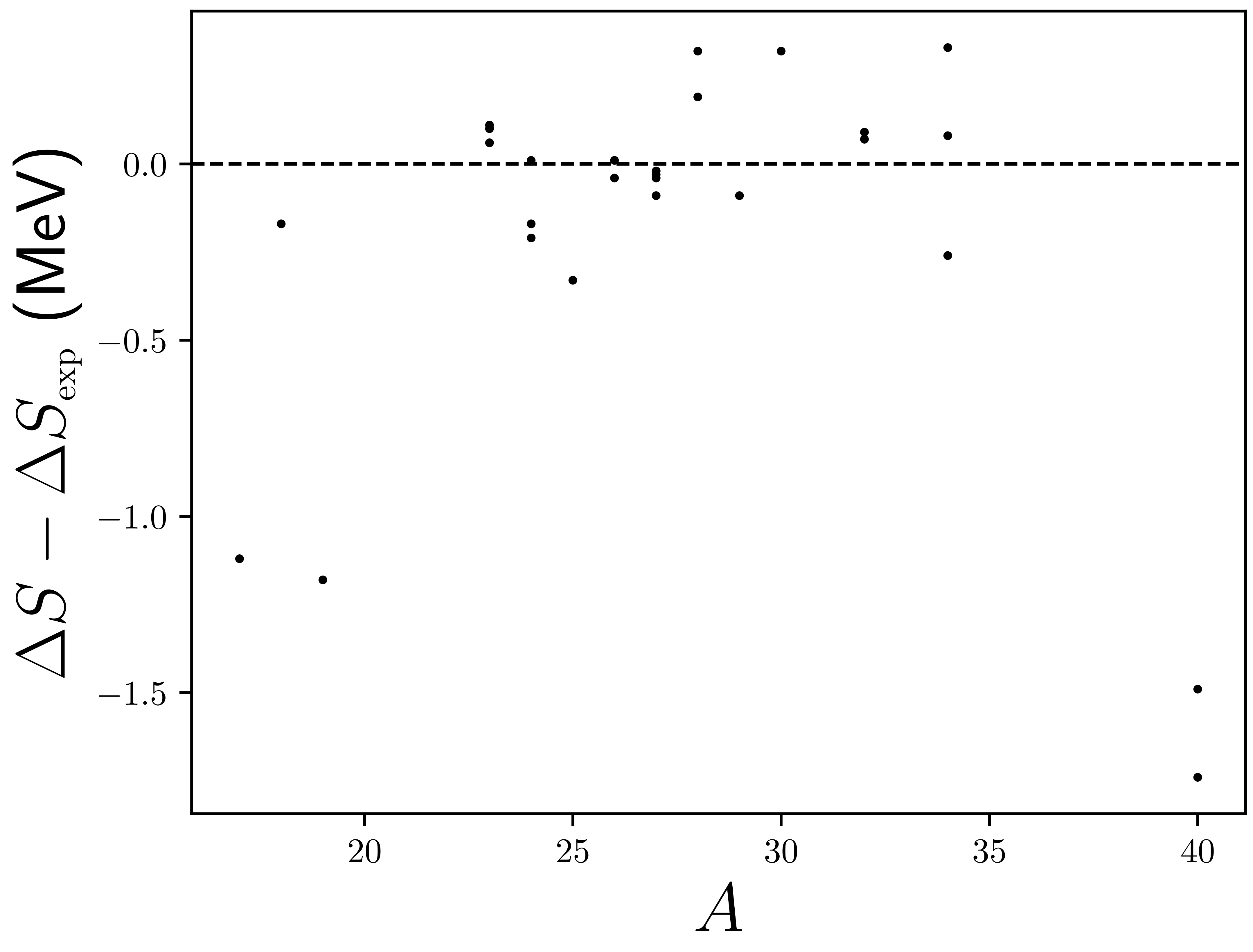


Results : PSF for all long lived sd nuclei

Centroids $\bar{S} = \frac{S_1}{S_0}$

Width $\Delta S = \sqrt{\frac{S_2}{S_0} - \bar{S}^2}$

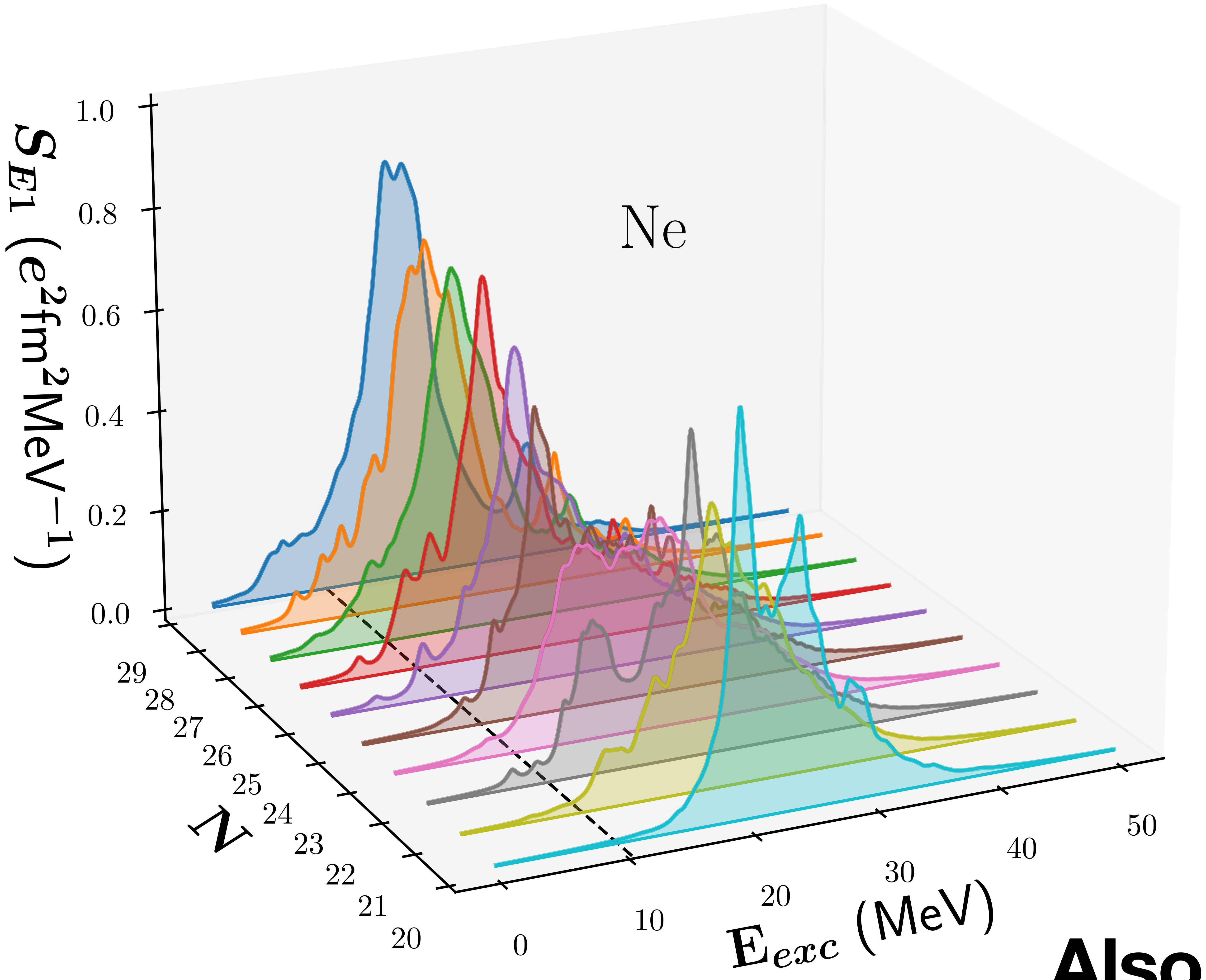




RMS $0.84 \quad \mathrm{MeV}$

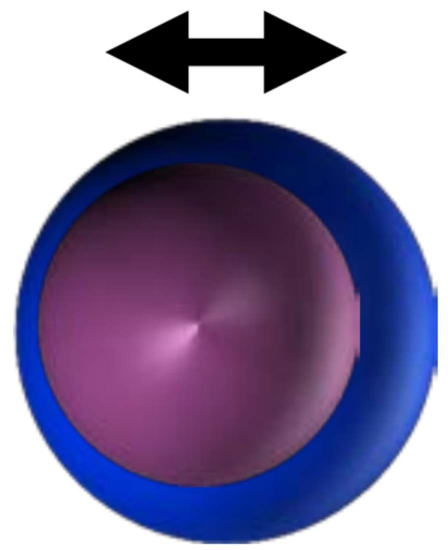
RMS $0.56 \quad \mathrm{MeV}$

Results II : Pygmy Dipole resonance in $^{26}\mathrm{Ne}$



Can the PDR be said to be collective ?

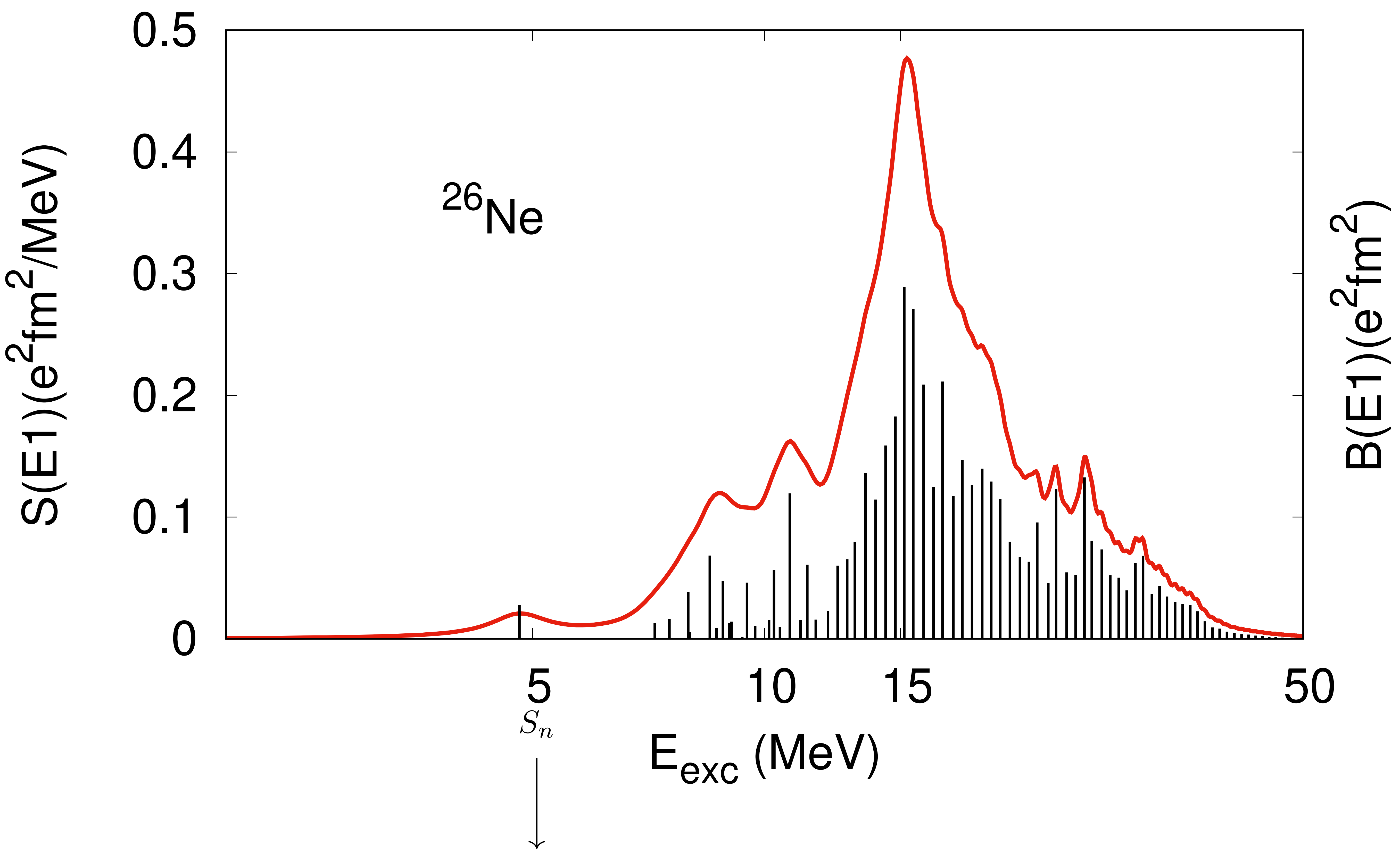
Can we give a classical interpretation to this resonance ?



Also called kramplouz resonance

Results II : Pygmy Dipole resonance in $^{26}\mathrm{Ne}$

Focus on $^{26}\mathrm{Ne}$

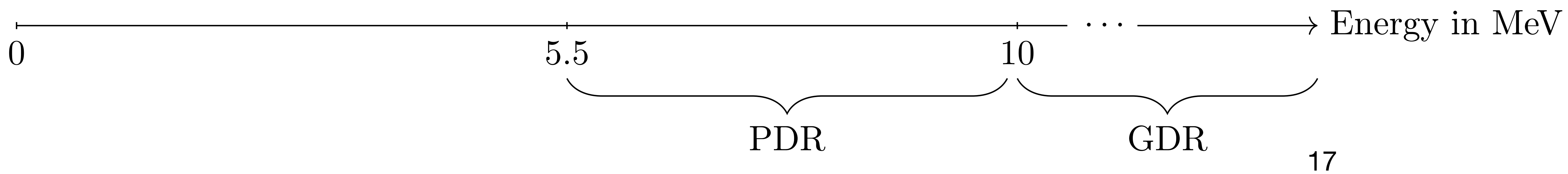


Consistent with :

- Suzuki et al, Phys. Atom. Nuclei 2004 (SM, WBP10)
- Kimura, Phys. Rev. C 2017 (AMD)
- Cao et al, Phys. Rev C 2005 (RQRPA)
- Yoshida, Phys. Rev. C 2008 (QRPA)

Gibelin et al

Phys. Rev. Lett. 2008



Results II : Pygmy Dipole resonance in $^{26}\mathrm{Ne}$

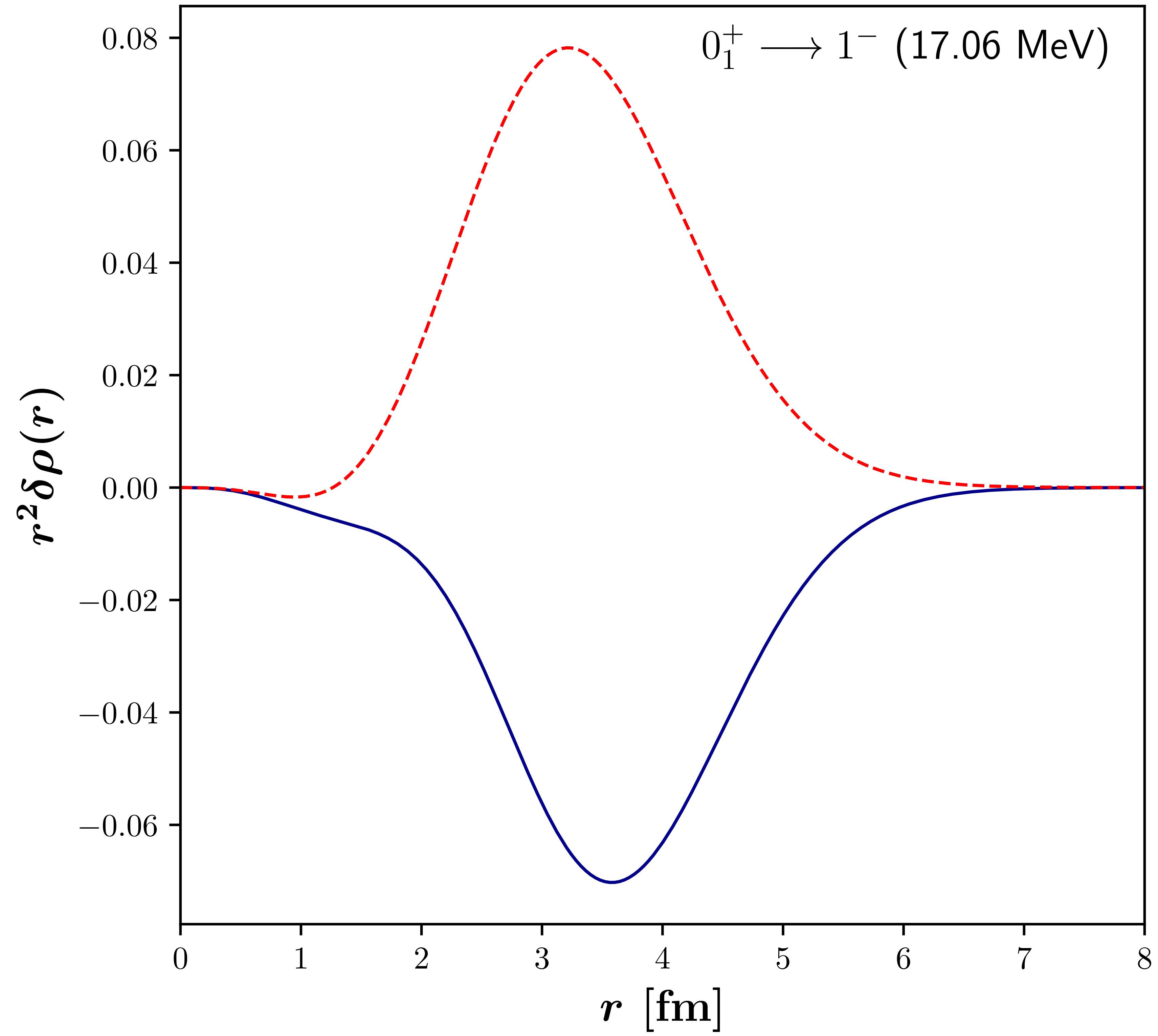
Collectivity indicators :

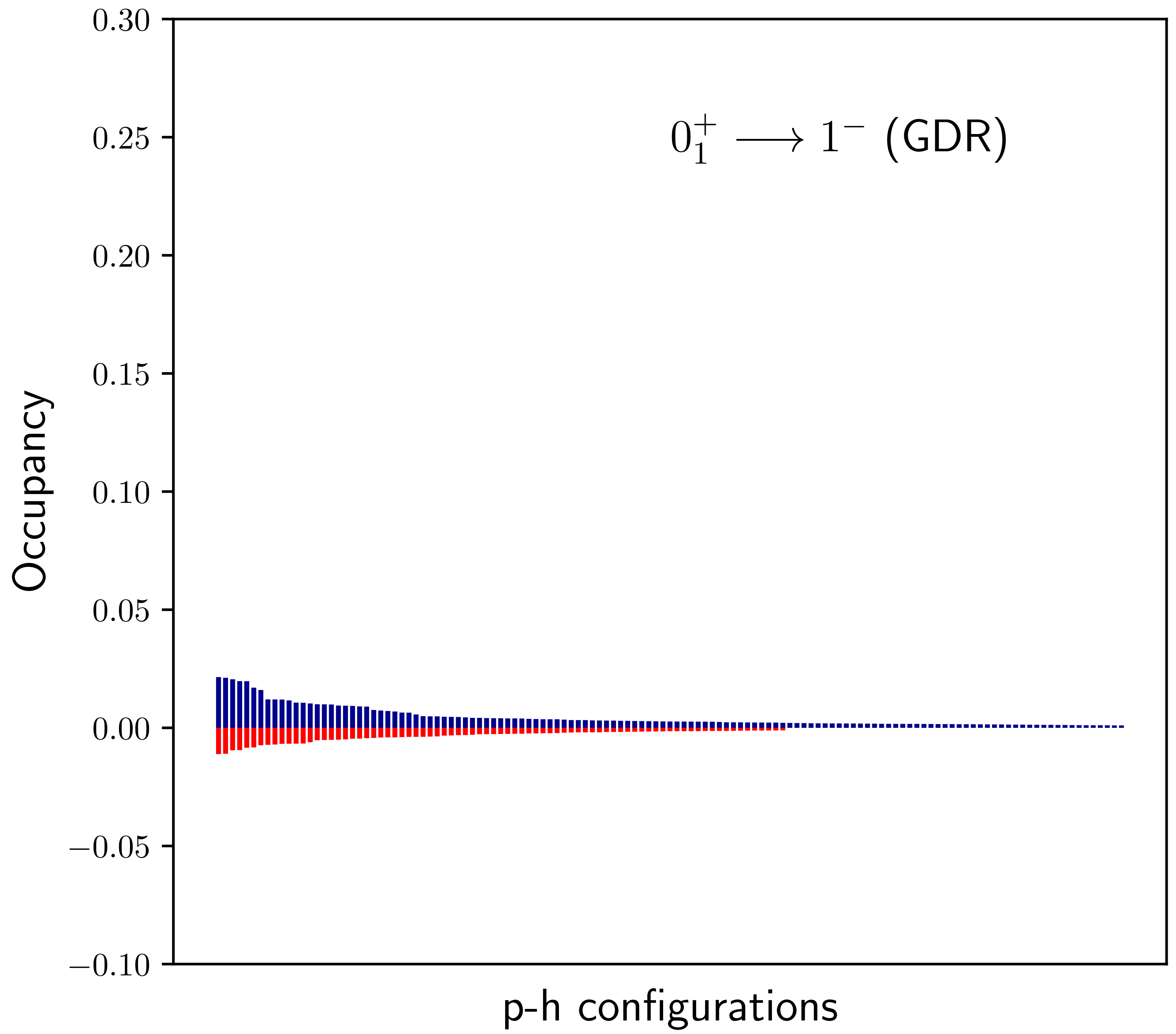
- Great regularity over large area of the nuclear chart
- Display rather classical properties, smooth dependence on (N,Z)
- Similar structures (transition densities, ν and π ratio)
- Imply 'many' p-h contributions (occupancy spread)
- Coherence => collective strength (% of TRK)

Method : We investigate GDR states to have a reference point in terms of collectivity and then compare to PDR states

Results II : Pygmy Dipole resonance in $^{26}\mathrm{Ne}$

GDR





Transition densities = Fourier modes of the shape dynamics

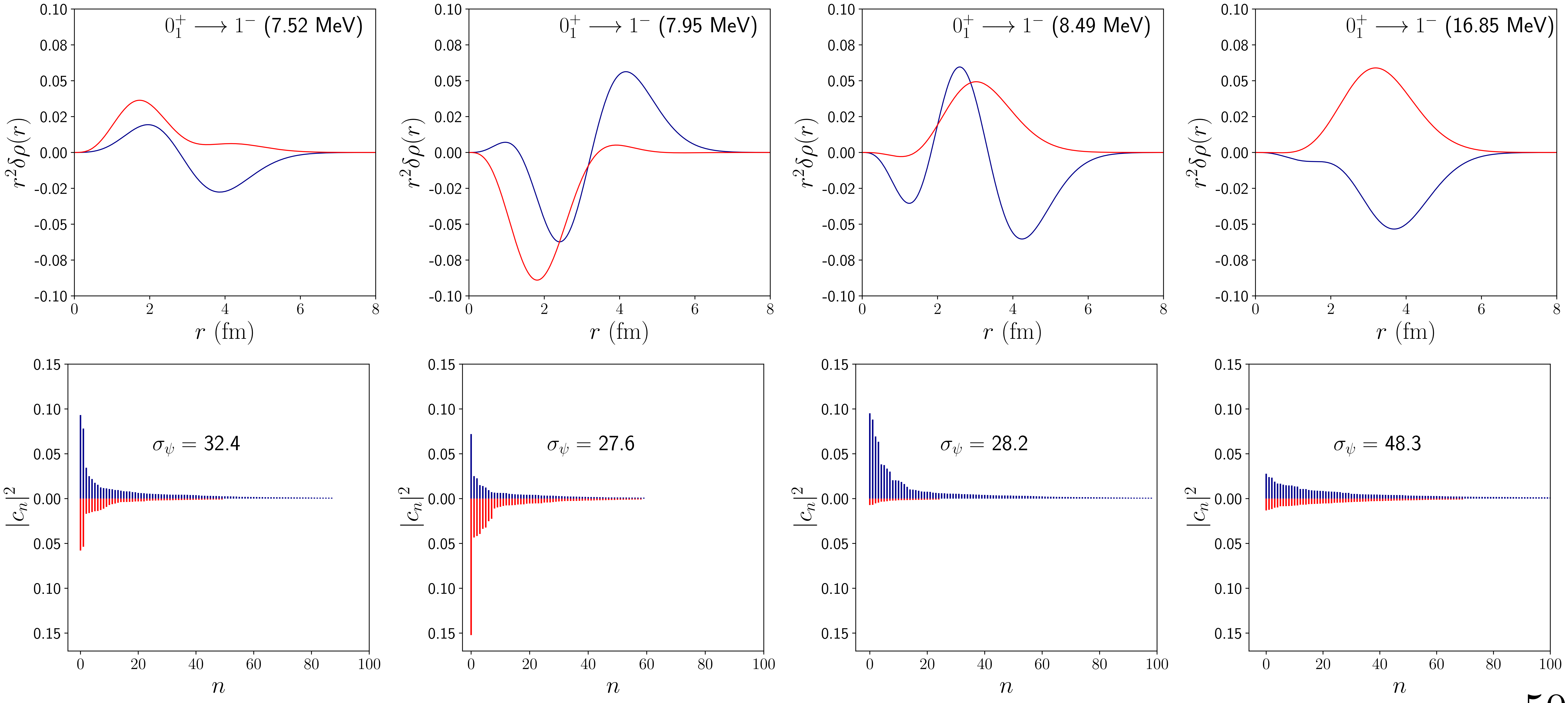
$$\delta\rho_\psi(\mathbf{r},t) = \rho_\psi(\mathbf{r},t) - \rho_0(\mathbf{r}) = \sum_{\nu\neq 0} b_\nu \langle 0|\,\hat{\rho}(\mathbf{r})\,|\nu\rangle\, e^{-\frac{i}{\hbar}\varepsilon_\nu t}$$

$$\delta\rho_{0\nu}(\mathbf{r}) = \langle 0|\,\hat{\rho}(\mathbf{r})\,|\nu\rangle$$

$$\sigma_{GDR} \sim 50$$

Results II : Pygmy Dipole resonance in $^{26}\mathrm{Ne}$

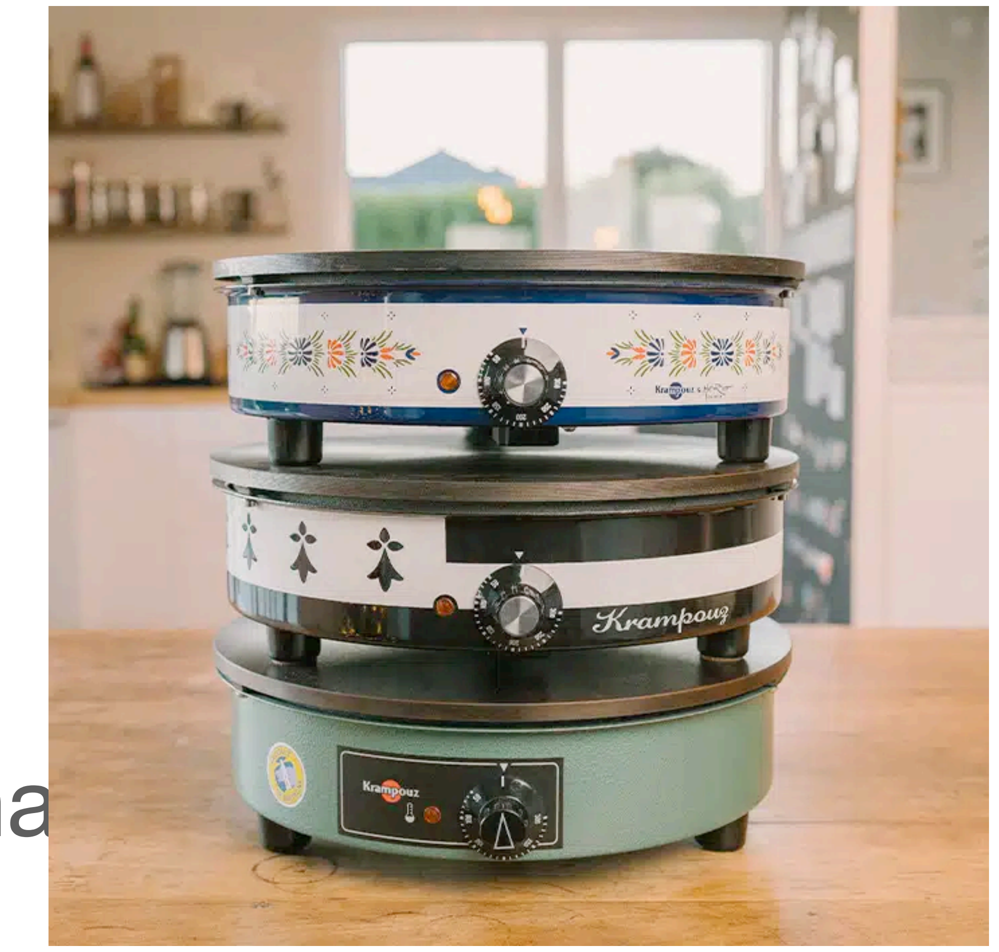
PDR Region : 6-10 MeV



$\sigma_{PDR} \sim 30$ $\sigma_{GDR} \sim 50$

Conclusion

E1 PSF predicted for 36 sd-shell long-lived isotopes : will be added to PSF database



Will be tested in TALYS reaction code (S. Goriely's team, ULB)

Pigmy Dipole Resona

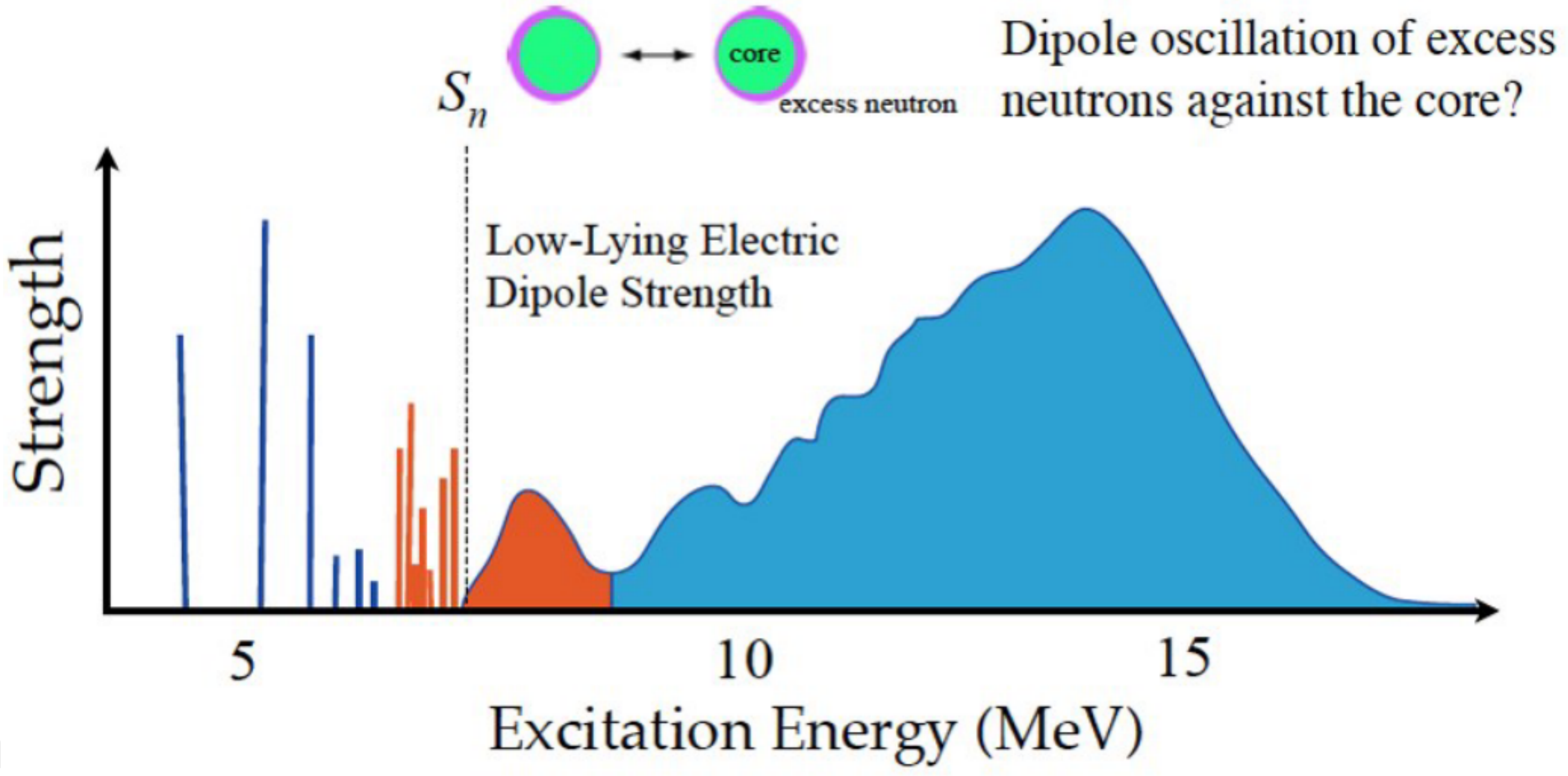
Pygmy Dipole Resonance

PDR differs from single-particle-like excitations

Not tail GDR

Some collectivity

Classical interpretation of a neutron skin oscillation seems to h



Tamii (2016). Adelaide International Conference

Opening : E1 Strength Function from PGCM

Why PGCM ?

Shell Model Dimensionality Curse : factorial increase

Caurier et al.
The Shell Model as Unified View of Nuclear Structure (2005)

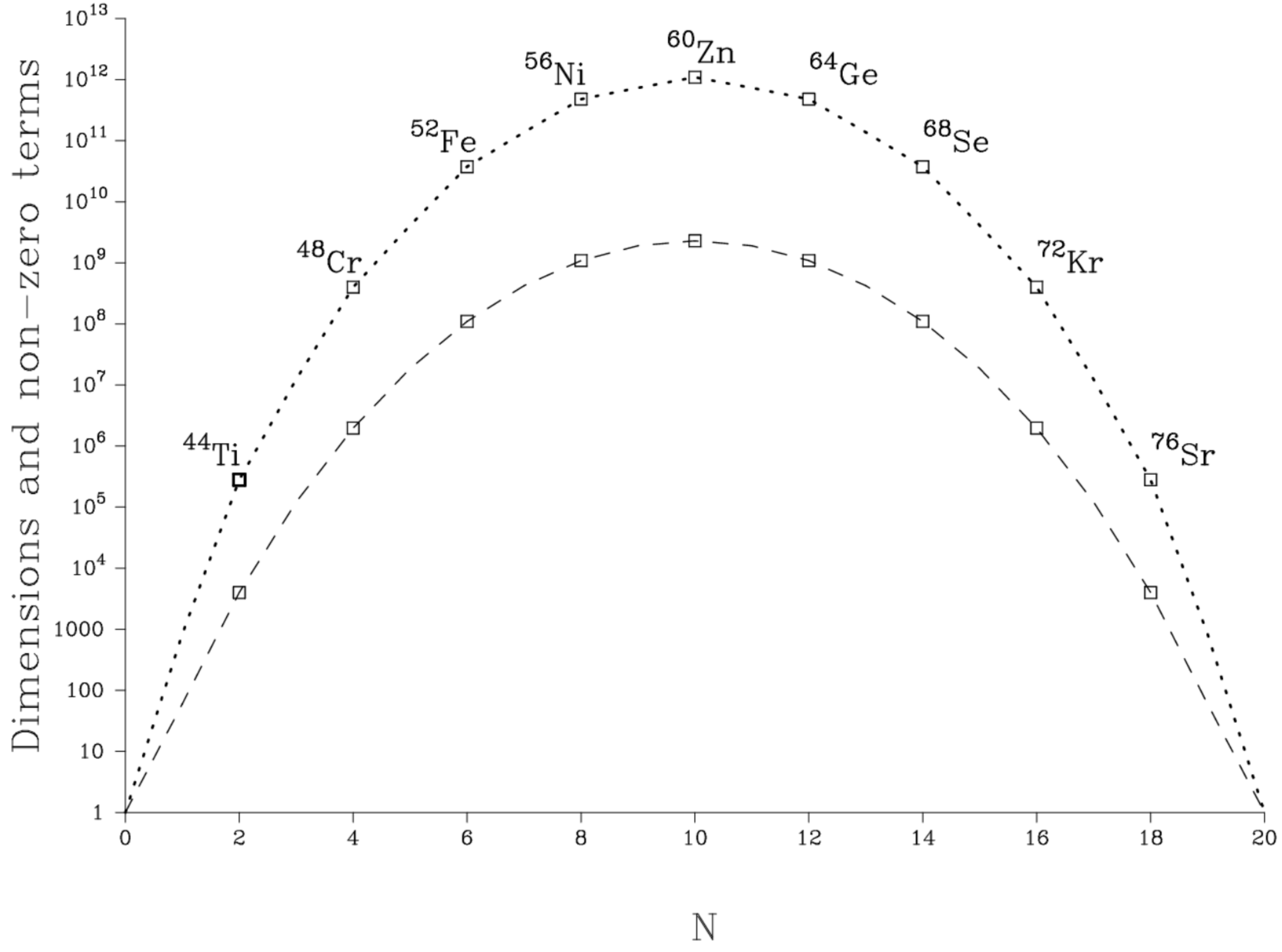


FIG. 8 m-scheme dimensions and total number of non-zero matrix elements in the pf-shell for nuclei with $M = T_z = 0$

E1 Strength Function from PGCM

Projected Generator Coordonate Method (PGCM)

Reference states : Set of HFB states
with constrains $a = \{a_1, ..., a_n\}$

$$\{|\Phi_a\rangle, a\}$$

PGCM Variational Ansatz

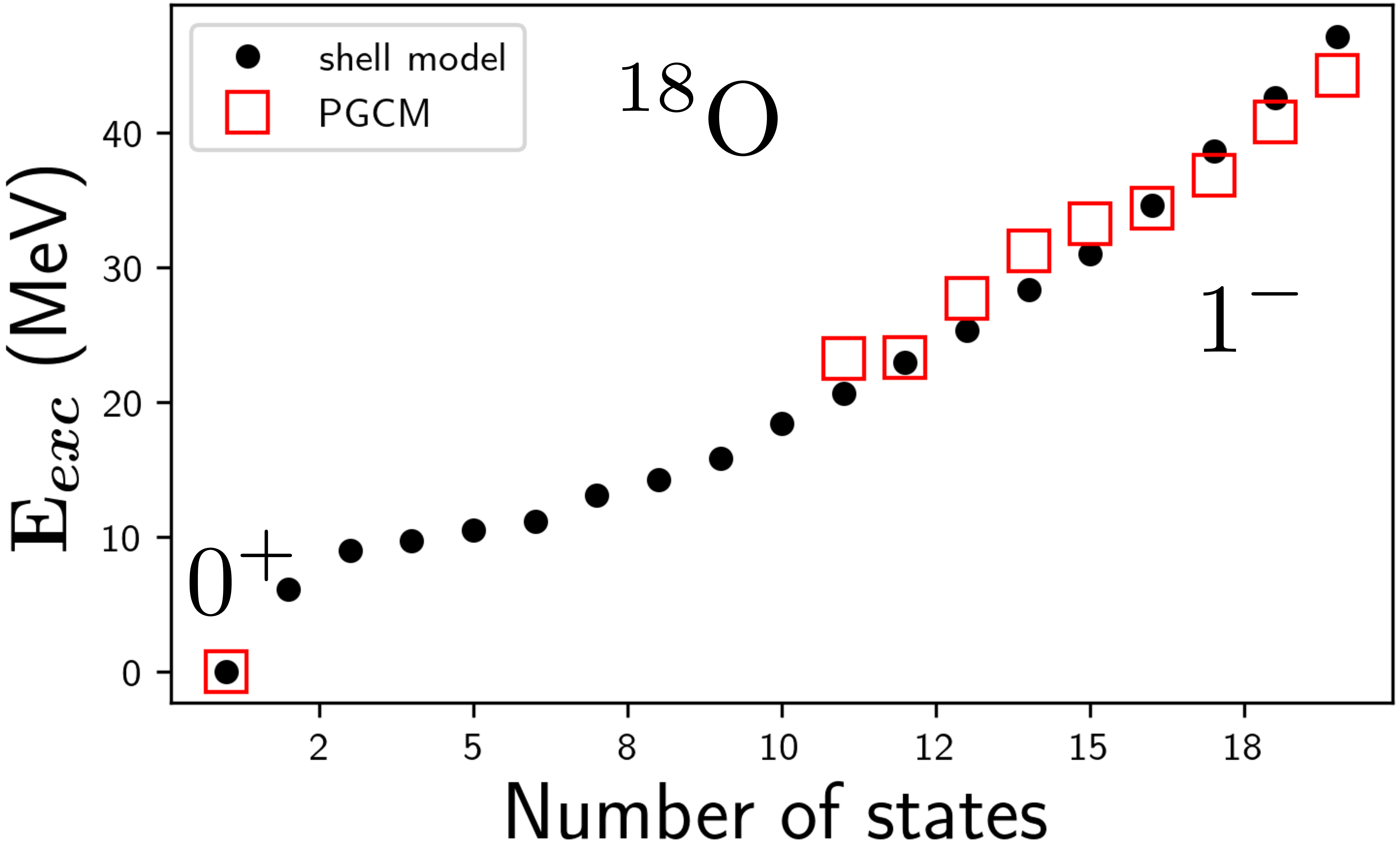
$$|\Psi^{\lambda i}_{\Sigma\varepsilon}\rangle = \sum_a^{\Sigma} \sum_j^{d_\lambda} f^{\lambda j}_{\Sigma a \varepsilon} P^{\lambda}_{ij} |\Phi_a\rangle$$

Generaliezed eigenvalue problem

$$H^{\lambda\Sigma}\mathbf{f} = EN^{\lambda\Sigma}\mathbf{f}$$

E1 Strength Function from PGCM

Choice of the collective coordinates



9 reference HFB states

Collective variables :

Q_{10} Q_{11}