QRPA for description of Collective excitations in nuclei

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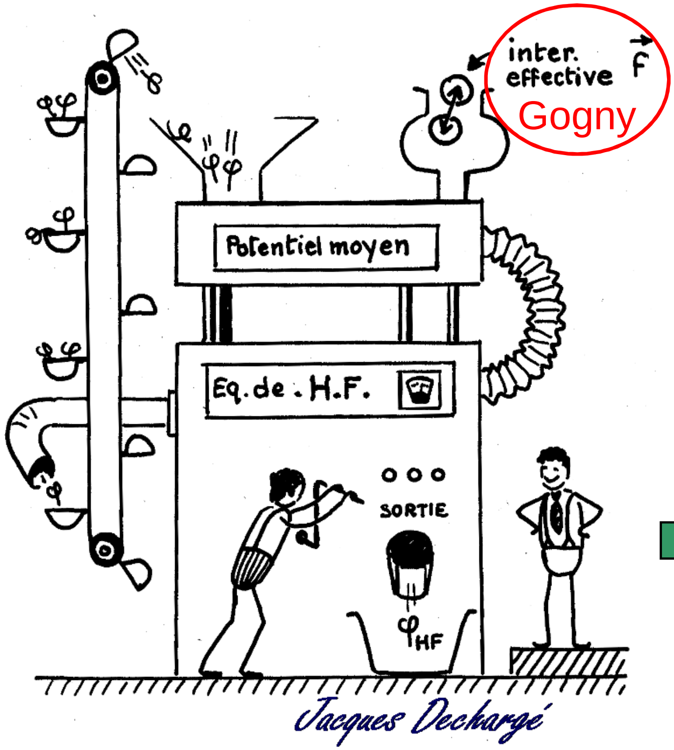
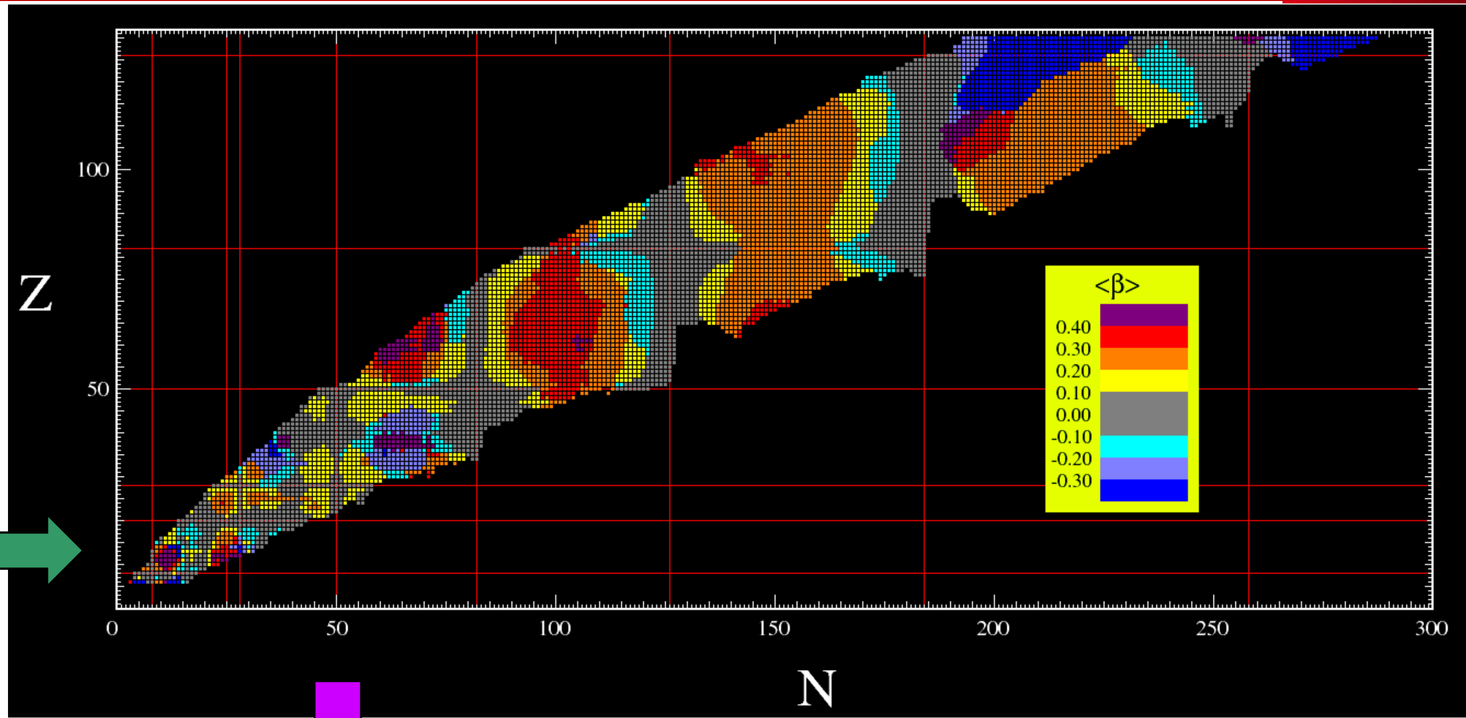
I. Deloncle (CSNSM, Orsay)

Short Reminder





Static mean field (HFB)
for Ground State Properties :
- **Masses**
- **Deformation**
- **(Single particle levels)**

Amedee database :
http://www-phynu.cea.fr/HFB-Gogny_eng.htm
S. Hilaire & M. Girod, EPJ ***A33*** *(2007) 237*

Beyond static mean field approximation (5DCH or QRPA)
for description of Excited State Properties
- **Low-energy collective levels**
- **Giant Resonances**

Nuclear Excitations

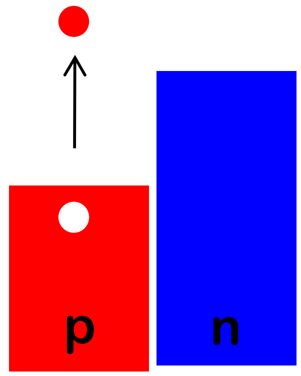
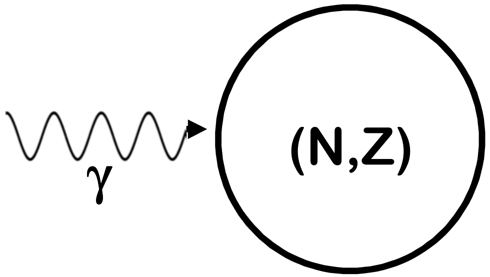
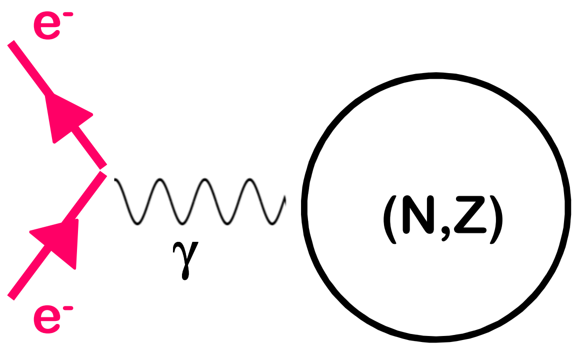


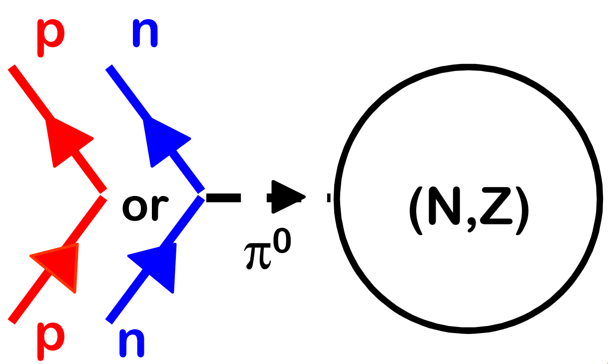
Photo-absorption



Electron scattering



(p,p) or (n,n)



QRPA Formalism

$$H|\nu\rangle = E_\nu|\nu\rangle \qquad Q^\dagger_\nu|0\rangle = |\nu\rangle \qquad Q_\nu|0\rangle = 0$$

$$\begin{pmatrix} A & B \\ B^* & A^* \end{pmatrix}\begin{pmatrix} X^\nu \\ Y^\nu \end{pmatrix} = \omega_\nu \begin{pmatrix} X^\nu \\ -Y^\nu \end{pmatrix}$$

RPA

Particle-hole excitations

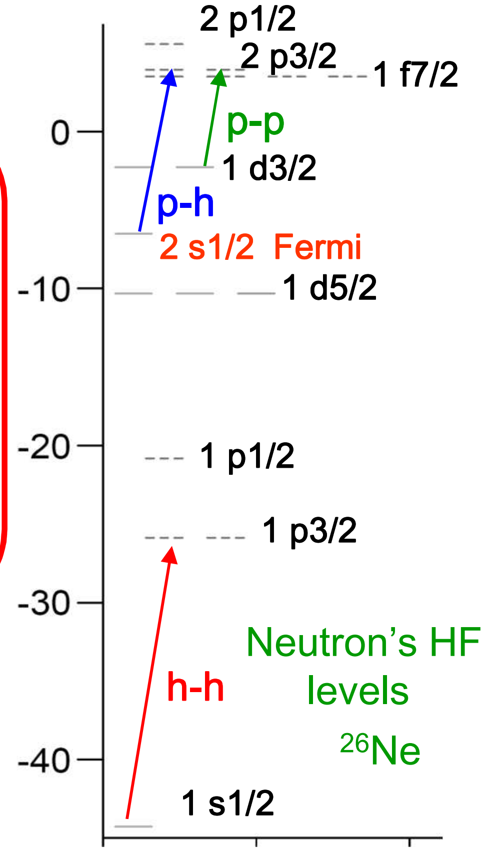
$$Q^+_\nu = \sum_{ph} X^\nu_{ph} a^+_p a_h + Y^\nu_{ph} a_h^+ a_p$$

QRPA

2 quasi-particle excitations

$$Q^+_\nu = \sum_{ij} X^\nu_{ij} \eta^+_i \eta^+_j + Y^\nu_{ij} \eta_j \eta_i$$

$$\eta^+_i = \sum_\alpha u_{i\alpha} a^+_\alpha - v_{i\alpha} a_\alpha$$



Hartree-Fock Bogoliubov: ε, **u, v** ⟶ **Ground state properties**

QRPA: ω, **X, Y** ⟶ **Excited states properties**

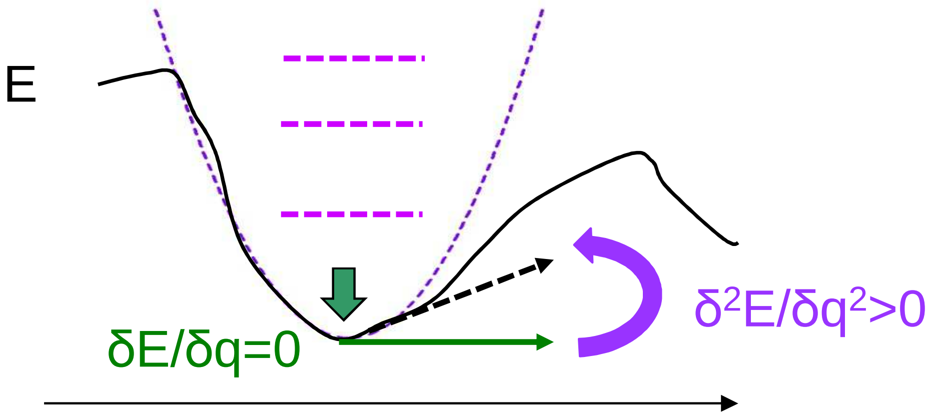
Same interaction (Gogny) in HFB and QRPA

Beyond mean field… with QRPA

RPA approaches describe

all multipolarties and all parities,
collective states and individual ones,
low energy and high energy states
with the same accuracy.

Within the small amplitude approximation, i.e. « harmonic » nuclei



<u>Spherical RPA with Gogny force</u>

J. Dechargé and L.Sips, Nucl. Phys. **A 407**,1 (1983)
J.P. Blaizot, J.F. Berger, J. Dechargé, M. Girod, Nucl. Phys. A 591, 435 (1995)
S. Péru, JF. Berger, PF. Bortignon, Eur. Phys. J. A **26**, 25-32, (2005)

<u>Axially symetric deformed QRPA with Gogny force</u>

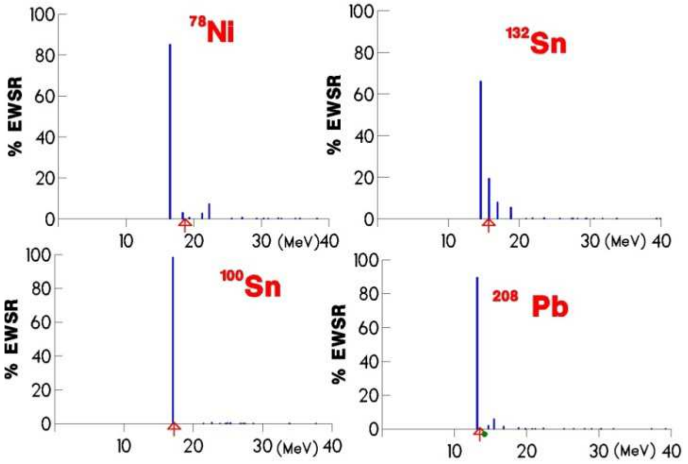
S. Péru, H. Goutte, Phys. Rev. C **77**, 044313, (2008)
M. Martini, S. Péru and M. Dupuis, Phys. Rev. C **83**, 034309 (2011)
S. Péru *et al*, Phys. Rev. C **83**, 014314 (2011)
M.Martini *et al*, submited to Phys. Rev. C (2016)

RPA in spherical symmetry

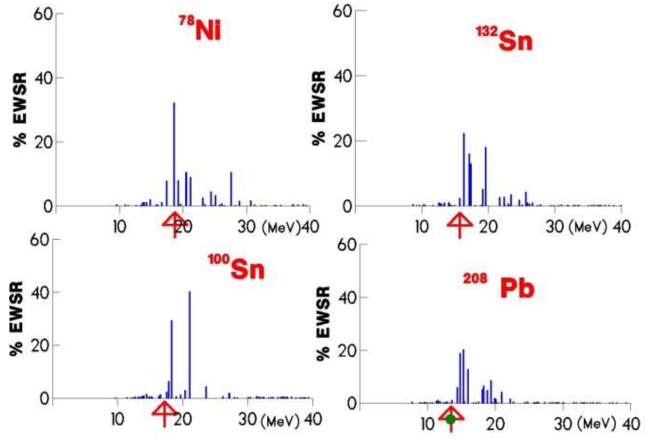
Giant resonances in exotic nuclei:

^{100}Sn, ^{132}Sn, ^{78}Ni; S. Péru, J.F. Berger, and P.F. Bortignon, Eur. Phys. Jour. A 26, 25-32 (2005)

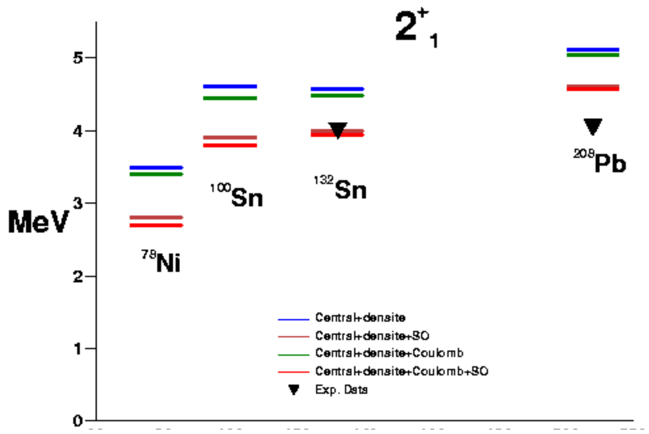
Monopole

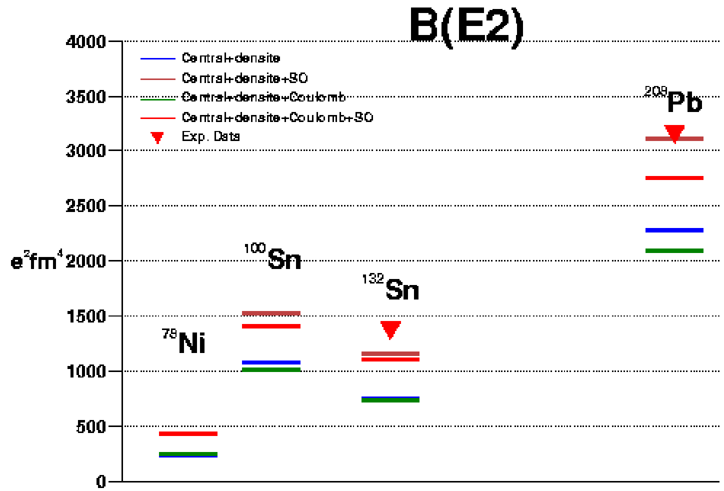


Dipole



Quadrupole



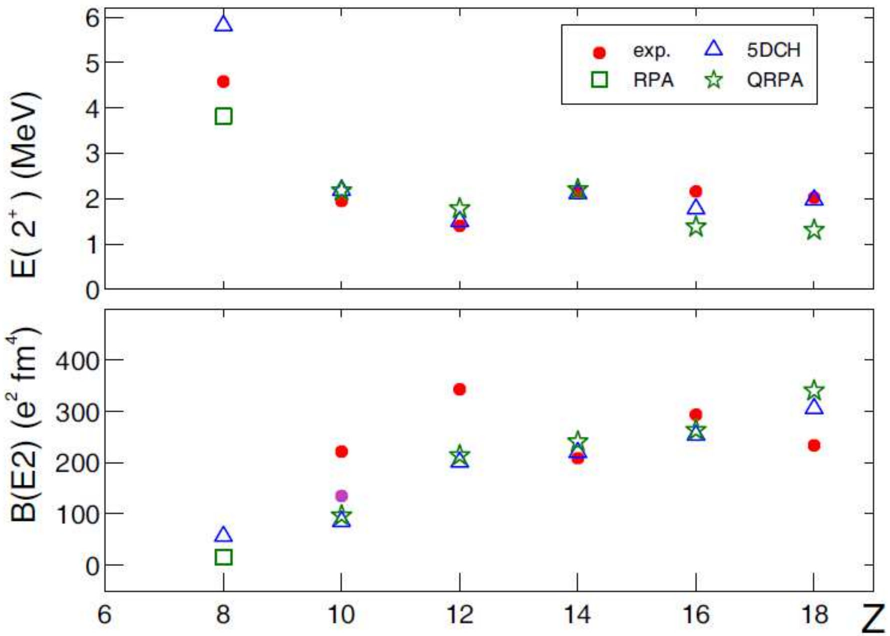


→ **Such study have shown the role of the consistence between mean field and RPA matrix.**

Approach limited to Spherical nuclei with no pairing

HFB+QRPA versus HFB+5DCH with the same interaction

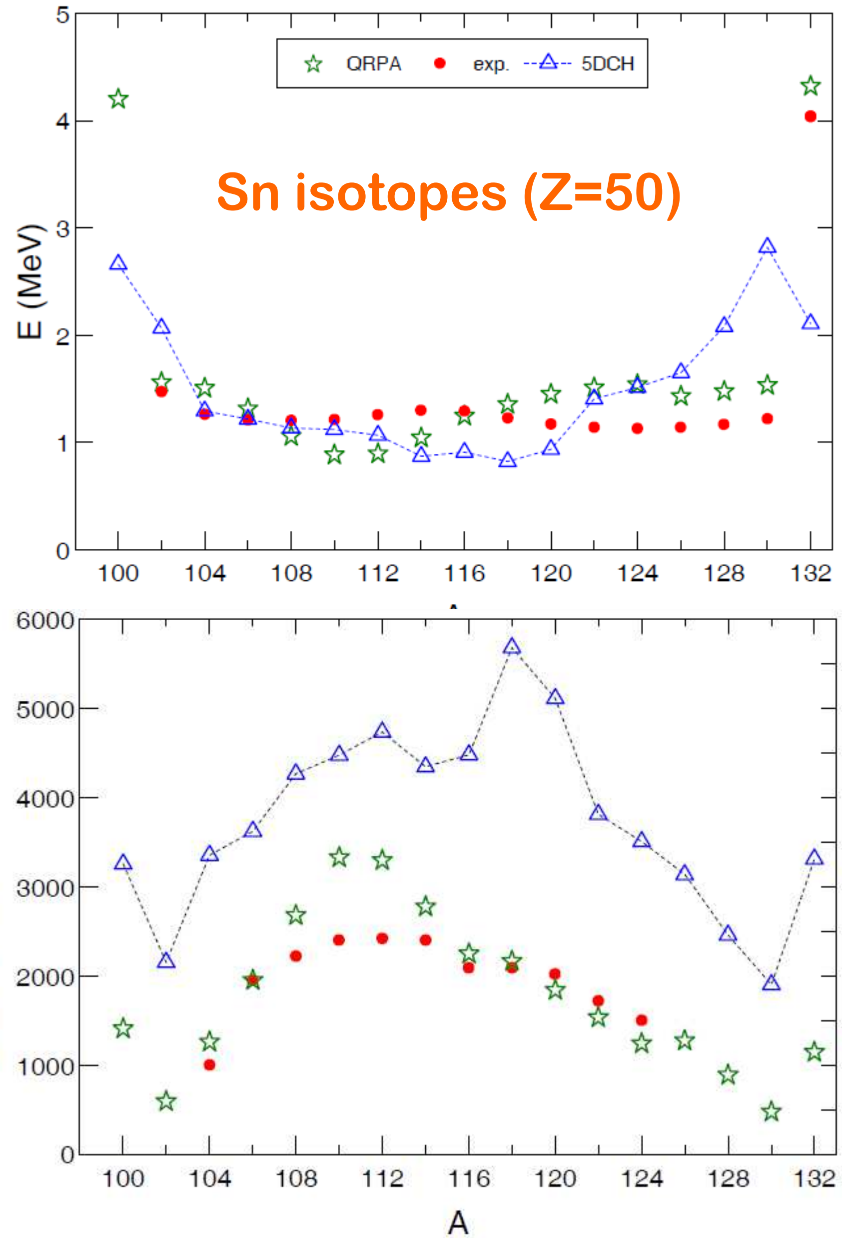
N=16 isotones



5DCH : A. Obertelli, et al, Phys. Rev. C **71**, 024304 (2005)

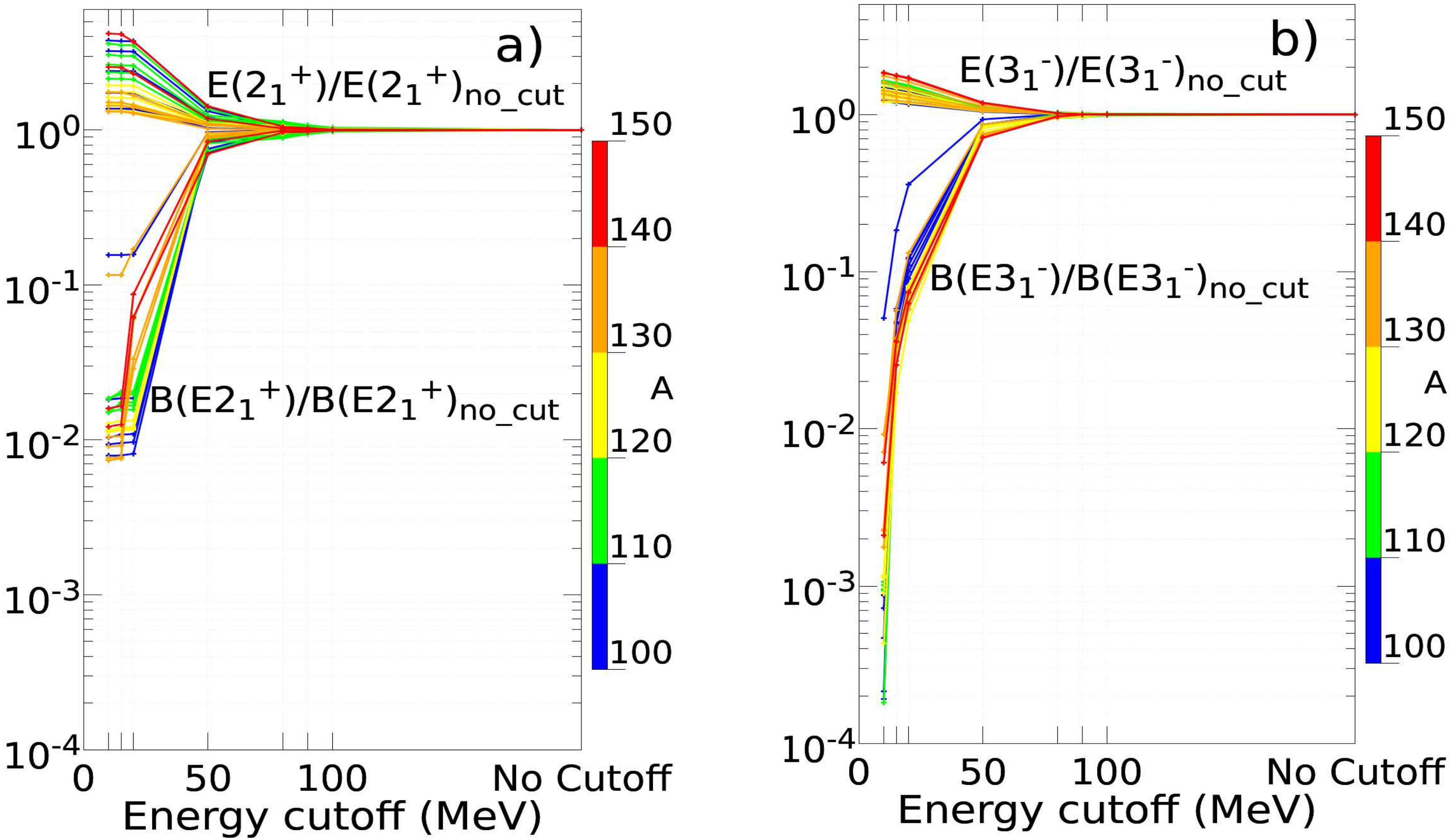
S. Péru and M. Martini, EPJA (2014) 50: 88.

Sn isotopes (Z=50)



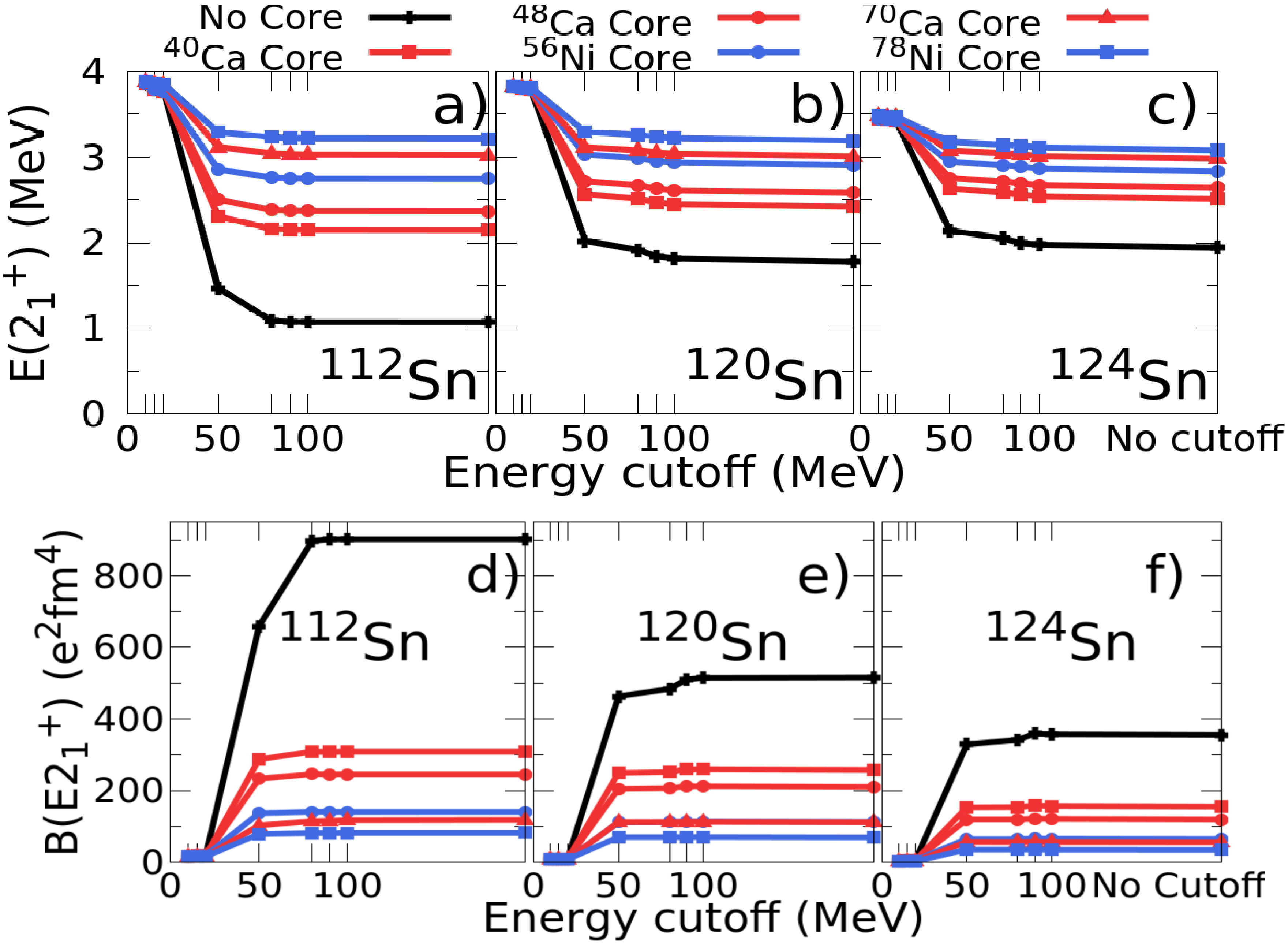
Impact of Energy Cutoff

Sn isotopes (Z=50)



*F. Lechaftois, I. Deloncle and SP, PRC **92**, 034315 (2015)*

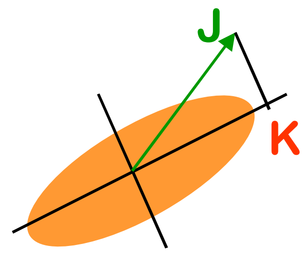
Impact of inert Core



F. Lechaftois, I. Deloncle and SP, PRC **92**, 034315 (2015)

Axially-symmetric deformed QRPA

$$|\alpha, K\rangle = \theta^{+}_{\alpha,K}|0\rangle \qquad \theta^{+}_{n,K} = \sum_{i<j} X^{ij}_{n,K}\eta^{+}_{i,k_i}\eta^{+}_{j,k_j} - (-)^K Y^{ij}_{n,K}\eta_{j,-k_j}\eta_{i,-k_i}$$



Restoration of rotational symmetry for deformed states

$$\left|JM(K)\right\rangle = \frac{\sqrt{2J+1}}{4\pi}\int d\Omega D^J_{MK}(\Omega)\mathrm{R}(\Omega)\left|\theta_K\right\rangle + (-)^{J-K} D^J_{M-K}(\Omega)\mathrm{R}(\Omega)\left|\overline{\theta}_K\right\rangle$$

to calculate: $\langle\tilde{0}|\hat{Q}_{\lambda\mu}|JM(K)\rangle$ **for all QRPA states (K ≤ J)**

$$\hat{Q}_{\lambda\mu} \propto \sum r^{\lambda}(Y_{\lambda\mu}) \qquad r^2Y_{\lambda\mu} = \sum_{\upsilon} D^{\lambda}_{\mu\upsilon} r^2 Y_{\lambda\upsilon}$$

In intrinsic frame

We use rotational approximation and relations for 3j symbols

For example: $J^{\pi} = 2^{+}$

$$\langle\tilde{0}|\hat{Q}_{20}|JM(K)\rangle = \frac{1}{\sqrt{5}}\langle 0|\hat{Q}_{20}|\theta_K\rangle\delta_{K,0} + \frac{1}{\sqrt{5}}\langle 0|\hat{Q}_{2-1}|\theta_K\rangle\delta_{K,\pm1} + \frac{1}{\sqrt{5}}\langle 0|\hat{Q}_{22}|\theta_K\rangle\delta_{K,\pm2}$$

Using time reversal symmetry, three independent calculations **($K^{\pi} = 0^{+}, 1^{+}, 2^{+}$) are needed.**

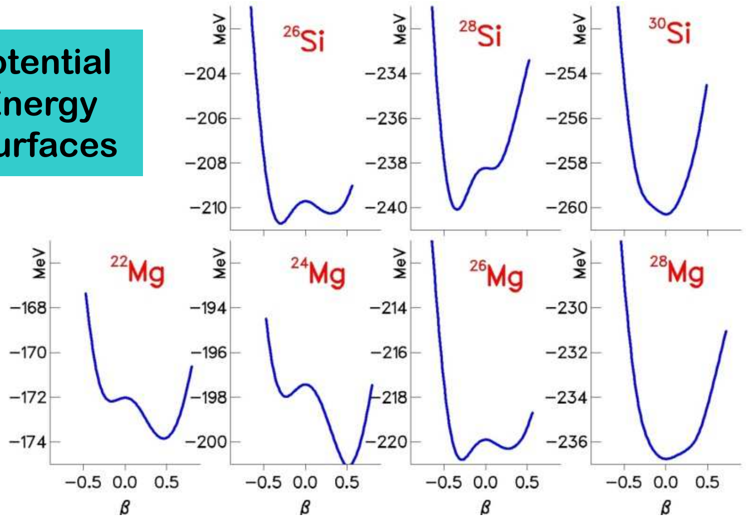
Main features:

- Possibility to treat axially-symmetric **deformed nuclei**
- **Pairing correlations** consistently included
- Use of an **unique nuclear force**: finite range Gogny force
- same interaction for all the nuclei
- same interaction for ground state and excited states (self-consistency)

essential features to treat consistently isotopic chains from drip line to drip line

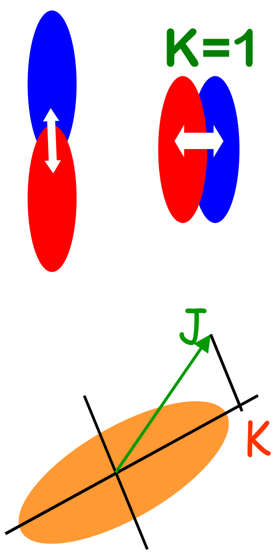
QRPA in axial symmetry

Potential Energy Surfaces



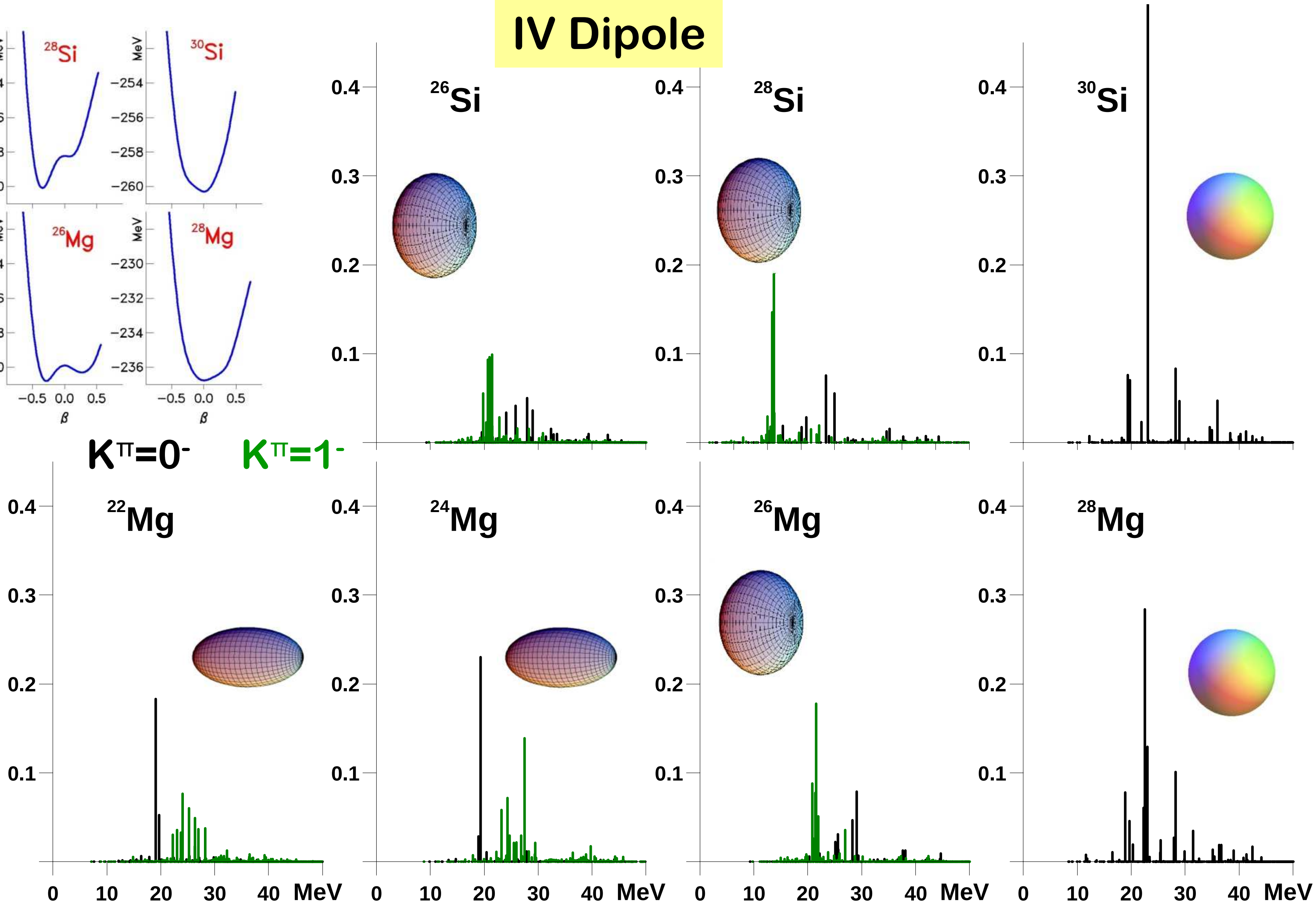
K=0

K=1



IV Dipole

$K^\pi=0^-$ $K^\pi=1^-$



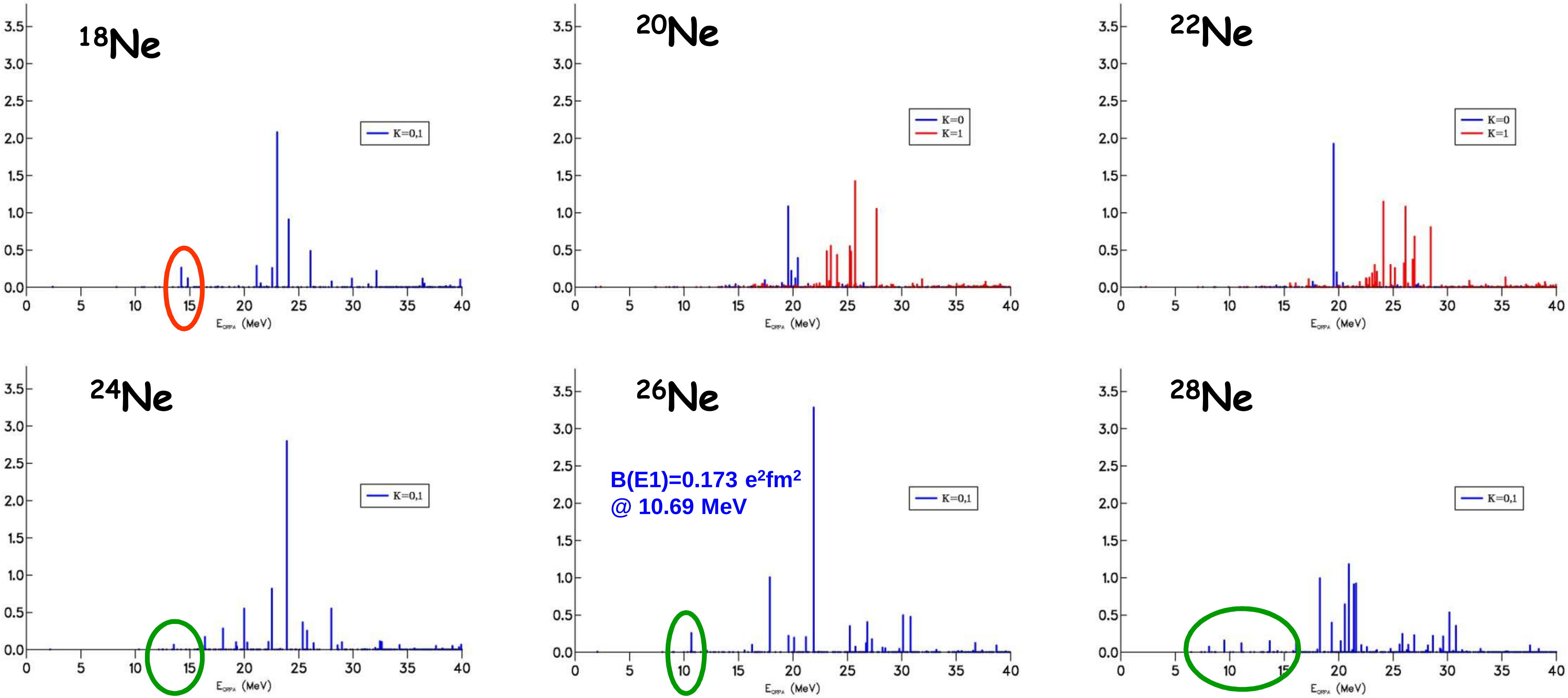
S. Péru and H. Goutte, Phys. Rev. C 77, 044313 (2008).

Dipole response for Neon isotopes

Increasing neutron number

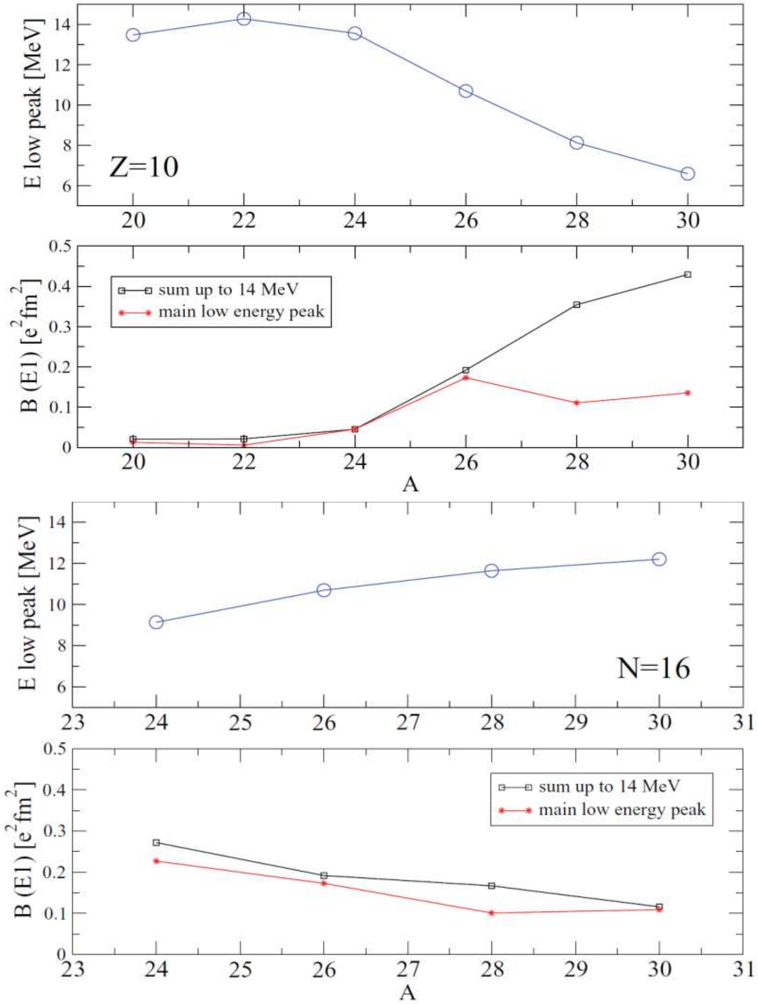
- Low energy dipole resonances and shift to low energies
- Increasing of fragmentation

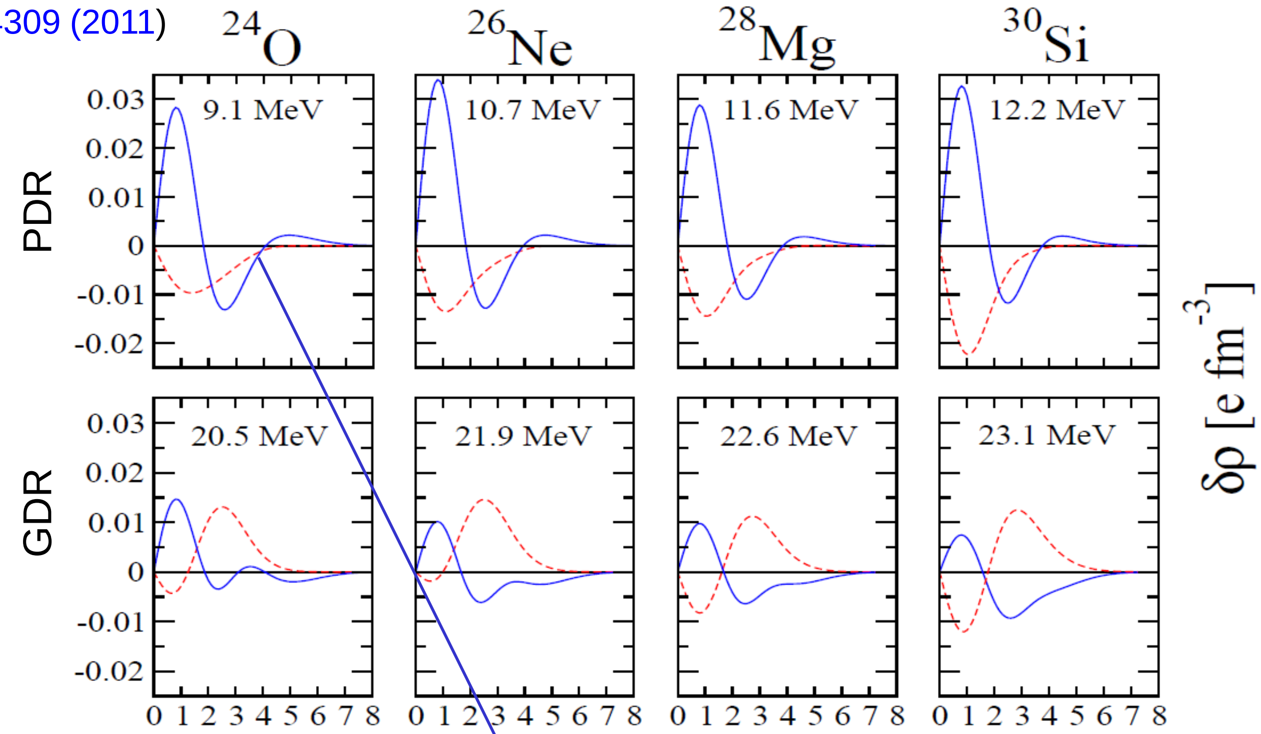
^{26}Ne : B(E1) = 0.49 ± 0.16 e^2 fm^2 %STRK = 4.9 ± 1.6 @ 9 MeV
J. Gibelin et al, PRL 101, 212503 (2008)



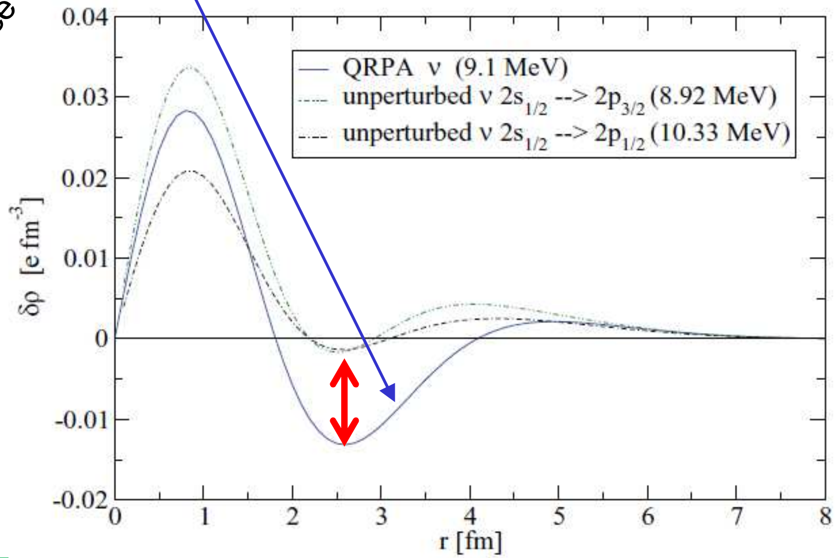
Dipole response for Neon isotopes and N=16 isotones

M. Martini, S. Péru and M. Dupuis, Phys. Rev. C **83**, 034309 (2011)





PDR : piccola dipole resonance

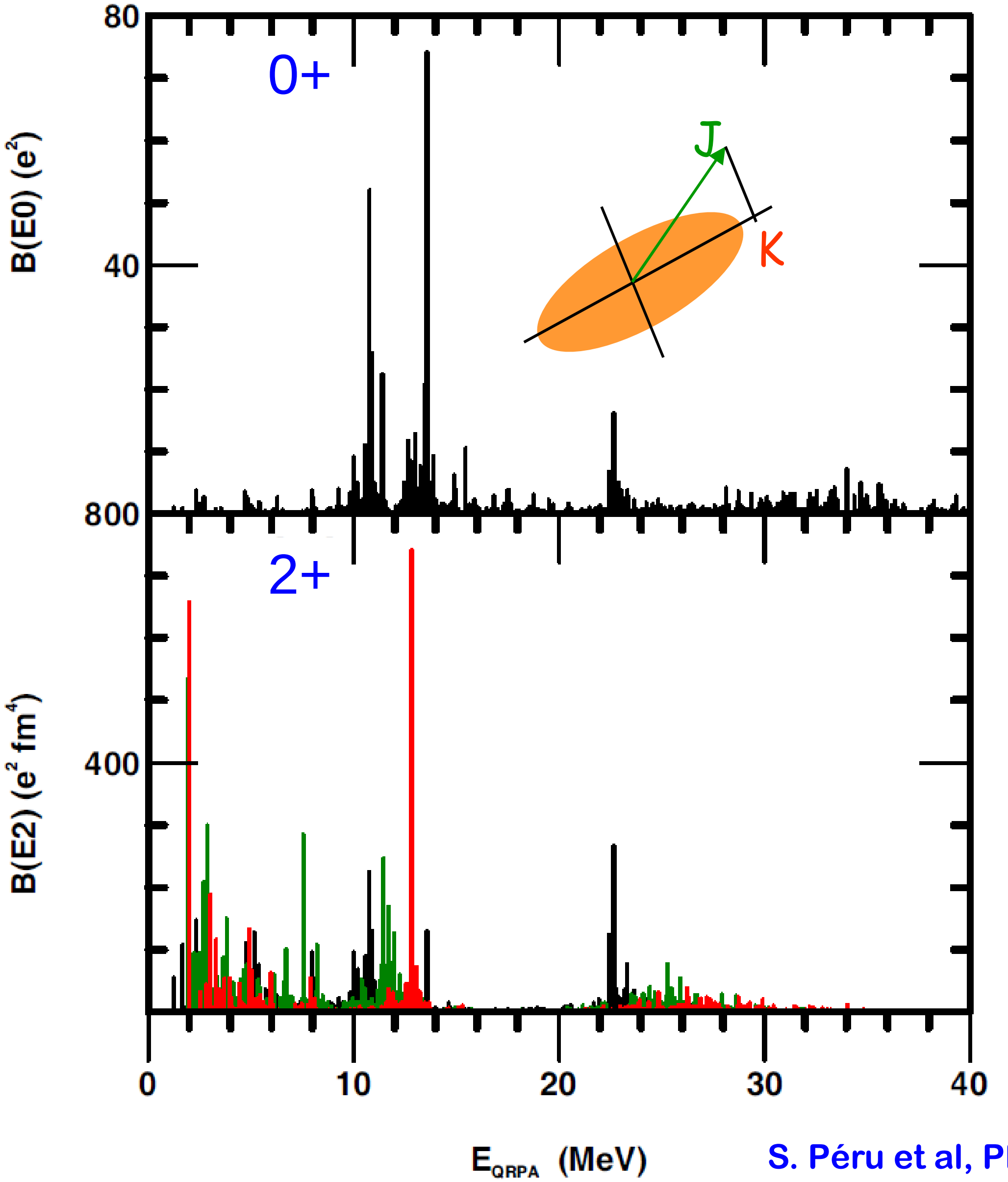


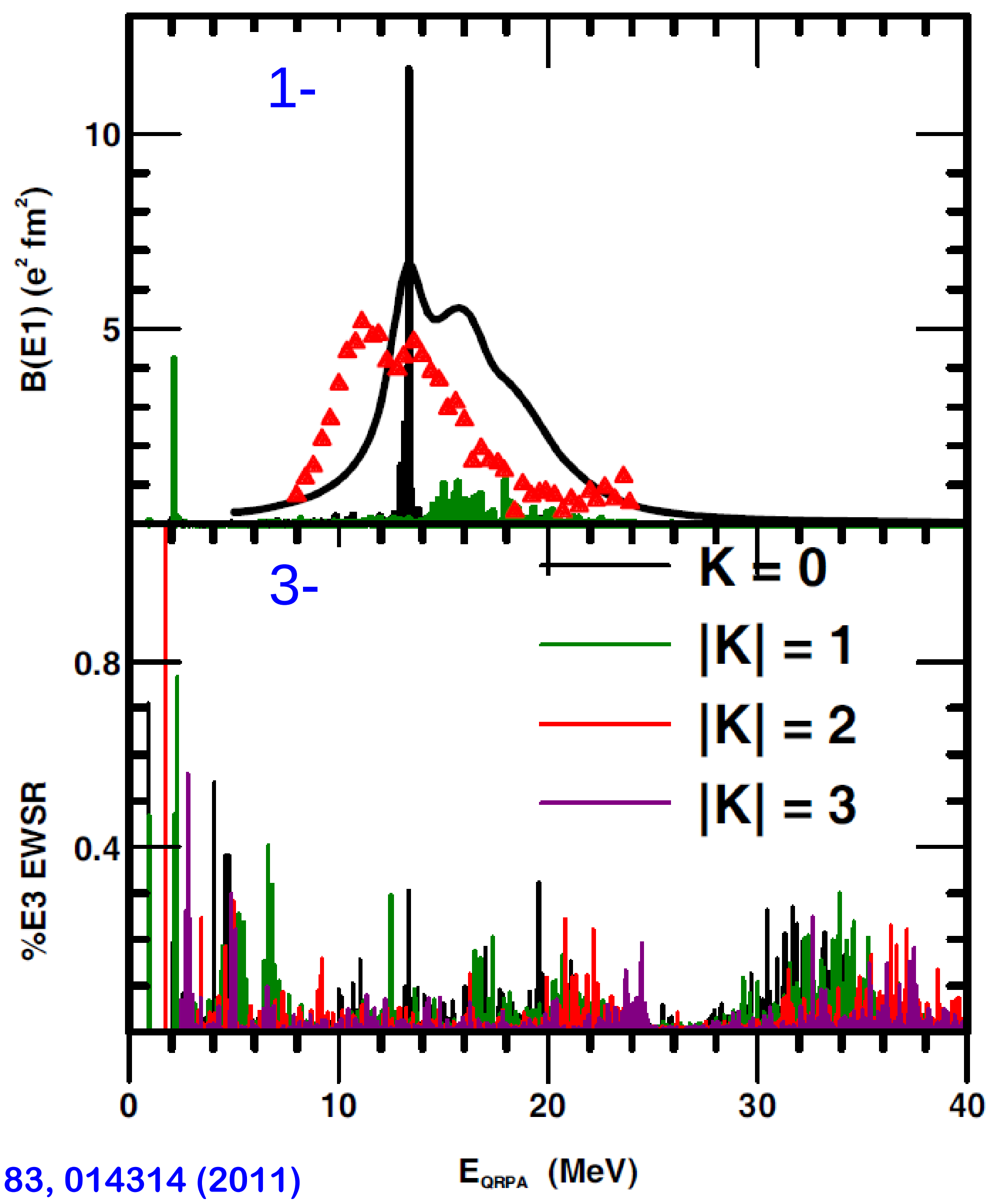
Increasing |N-Z| number :

- Low energy dipole resonances shift to low energies
- Increasing of fragmentation and collectivity

Multipolar responses for ^{238}U

Heavy deformed nucleus → massively parallel computation





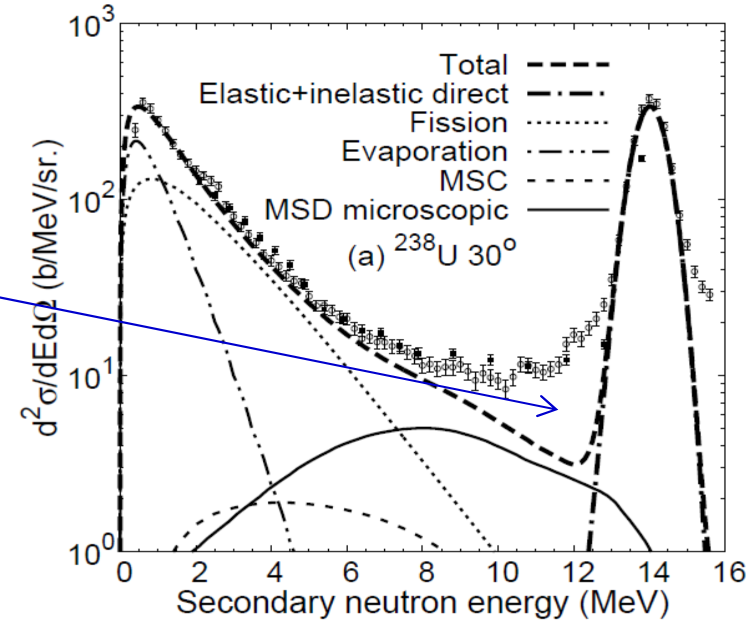
S. Péru et al, PRC 83, 014314 (2011)

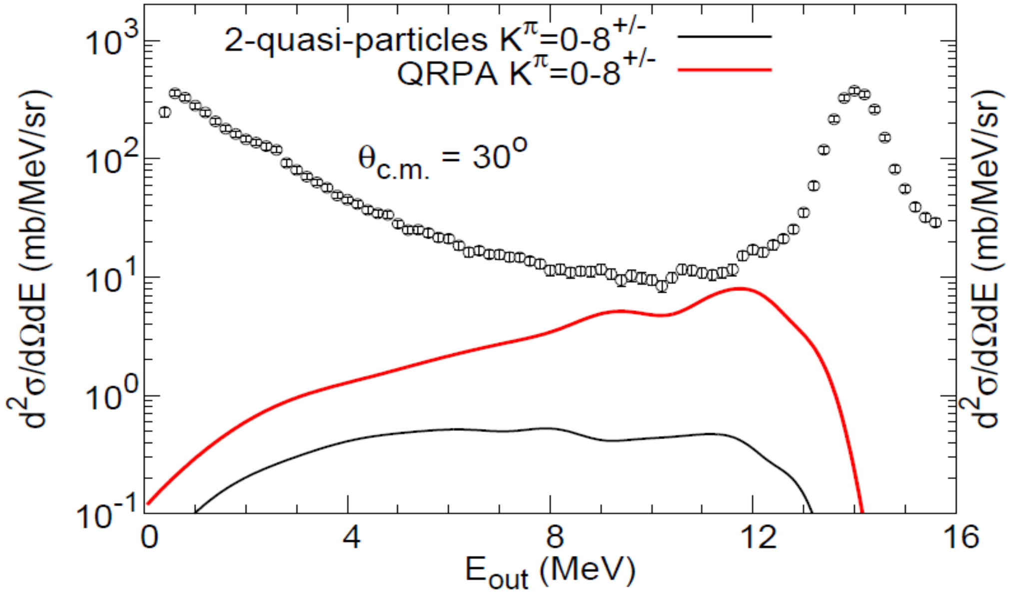
Beyond the nuclear structure

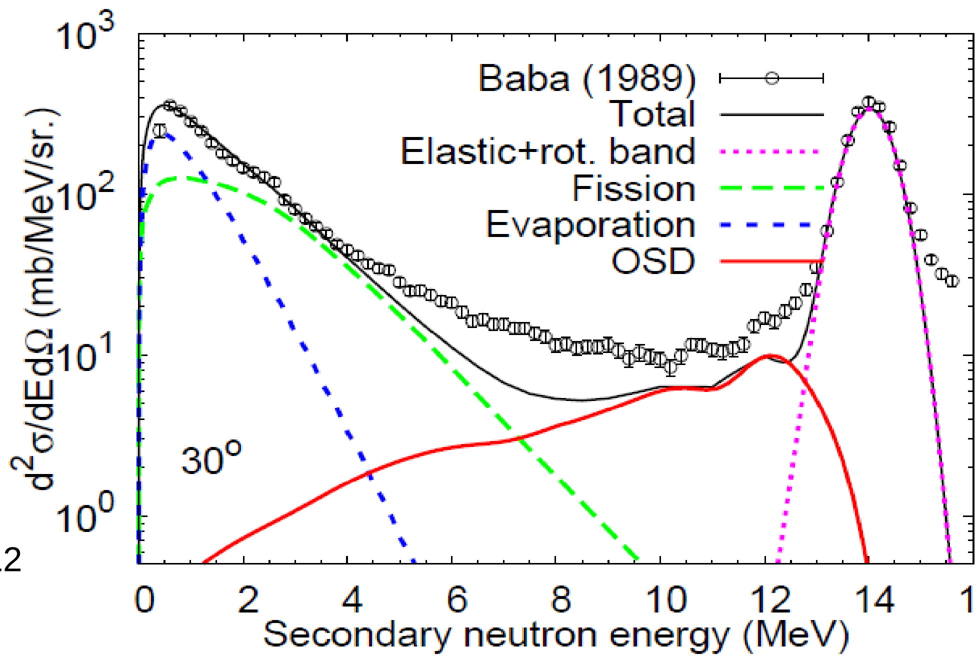
(n, *x* n) cross section on ^{238}U

Problem of underestimation of n emission cross section at high energy

QRPA provides enough collective contribution



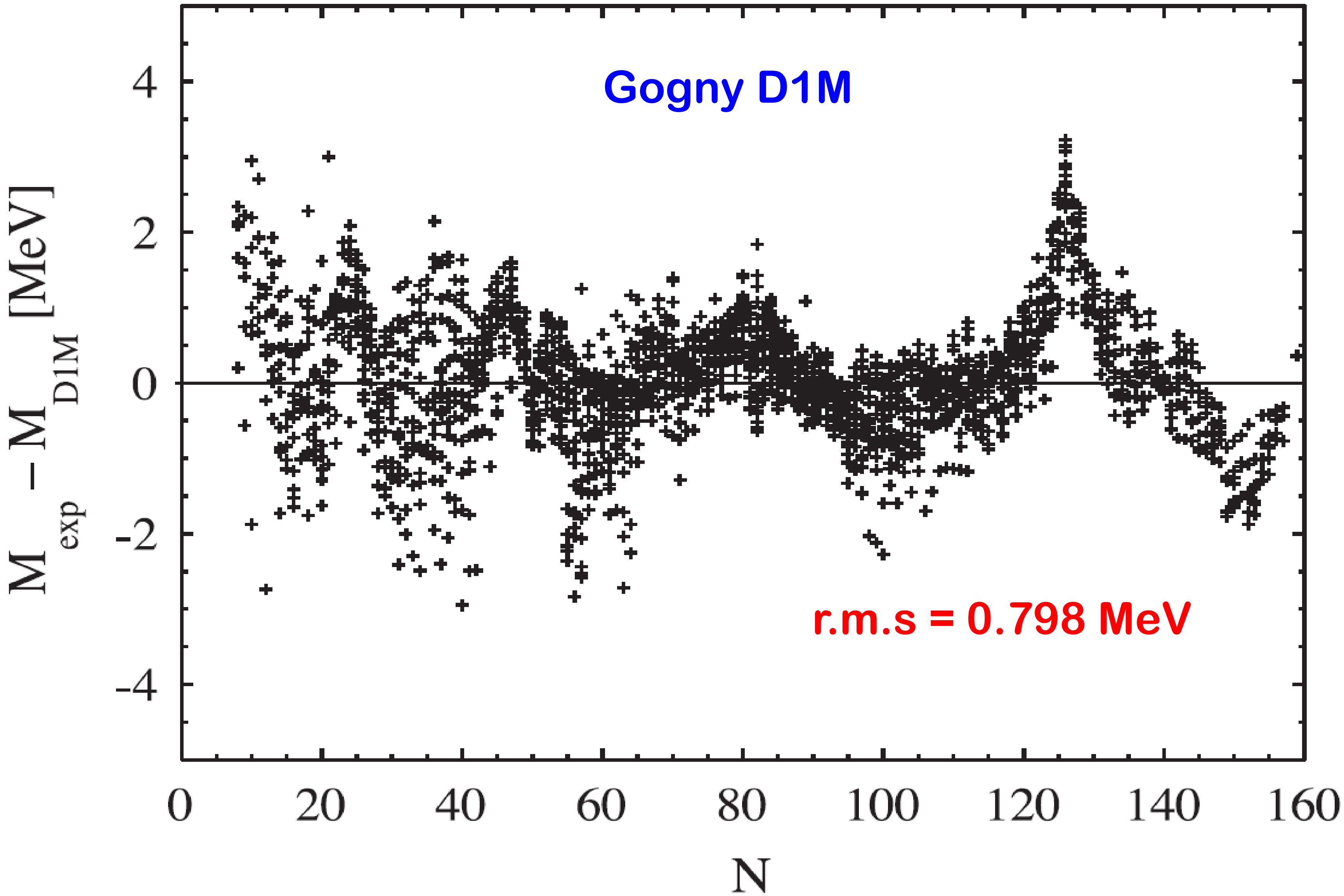




M. Dupuis, S.Péru, E. Bauge and T. Kawano,
13th International Conference on Nuclear Reaction Mechanisms, Varenna 2012
CERN-Proceedings-2012-002, p 95

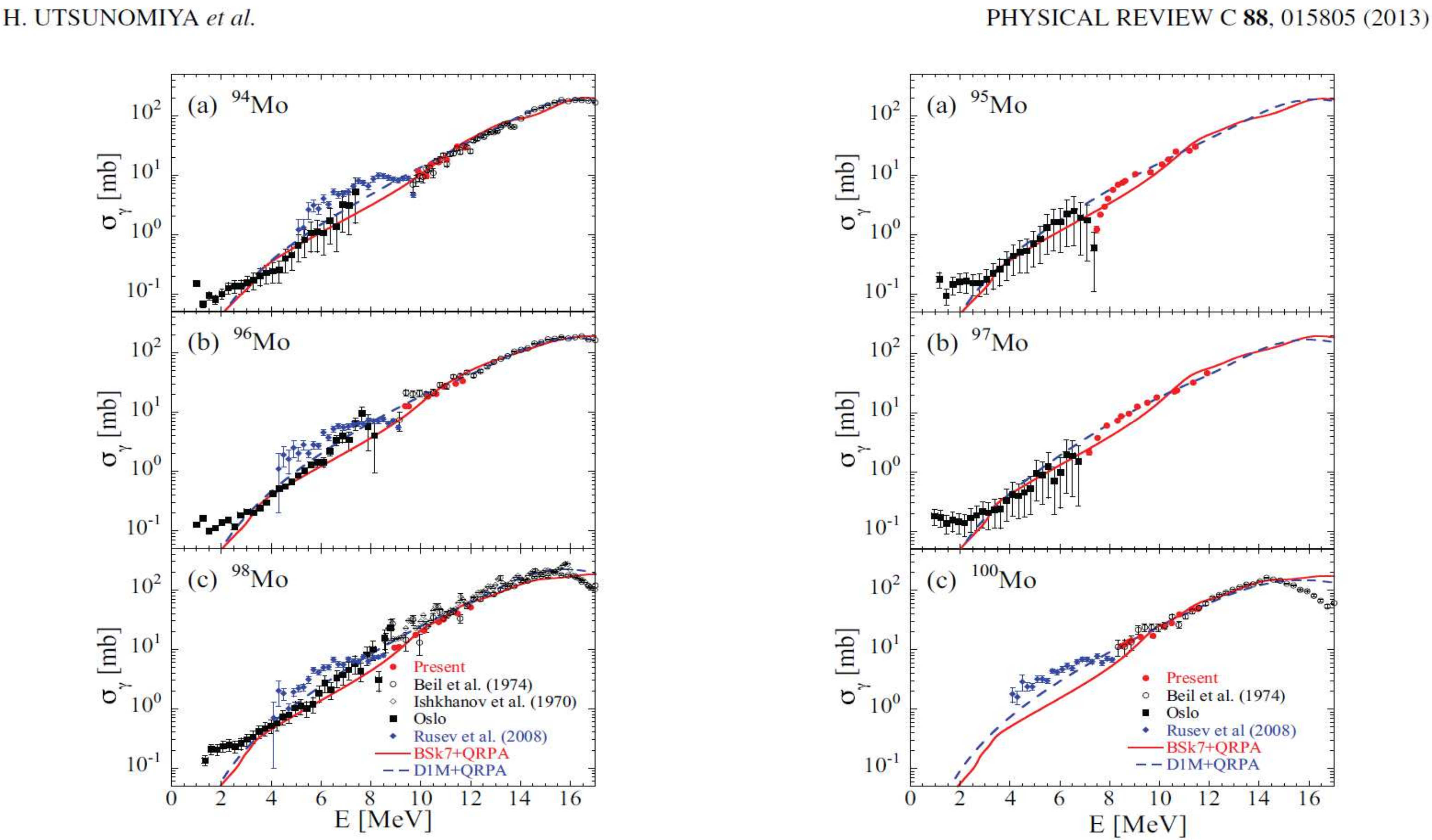
Nuclear Masses

Comparison with experimental data (2149 nuclei: Audi, Wapstra & Thibault 2003)



S. Goriely, S. Hilaire, M. Girod, S. Péru , PRL 102, 242501 (2009)

Photo-absorption cross sections for Mo isotopes



Photoneutron cross sections for Mo isotopes

PHYSICAL REVIEW C **88**, 015805 (2013)

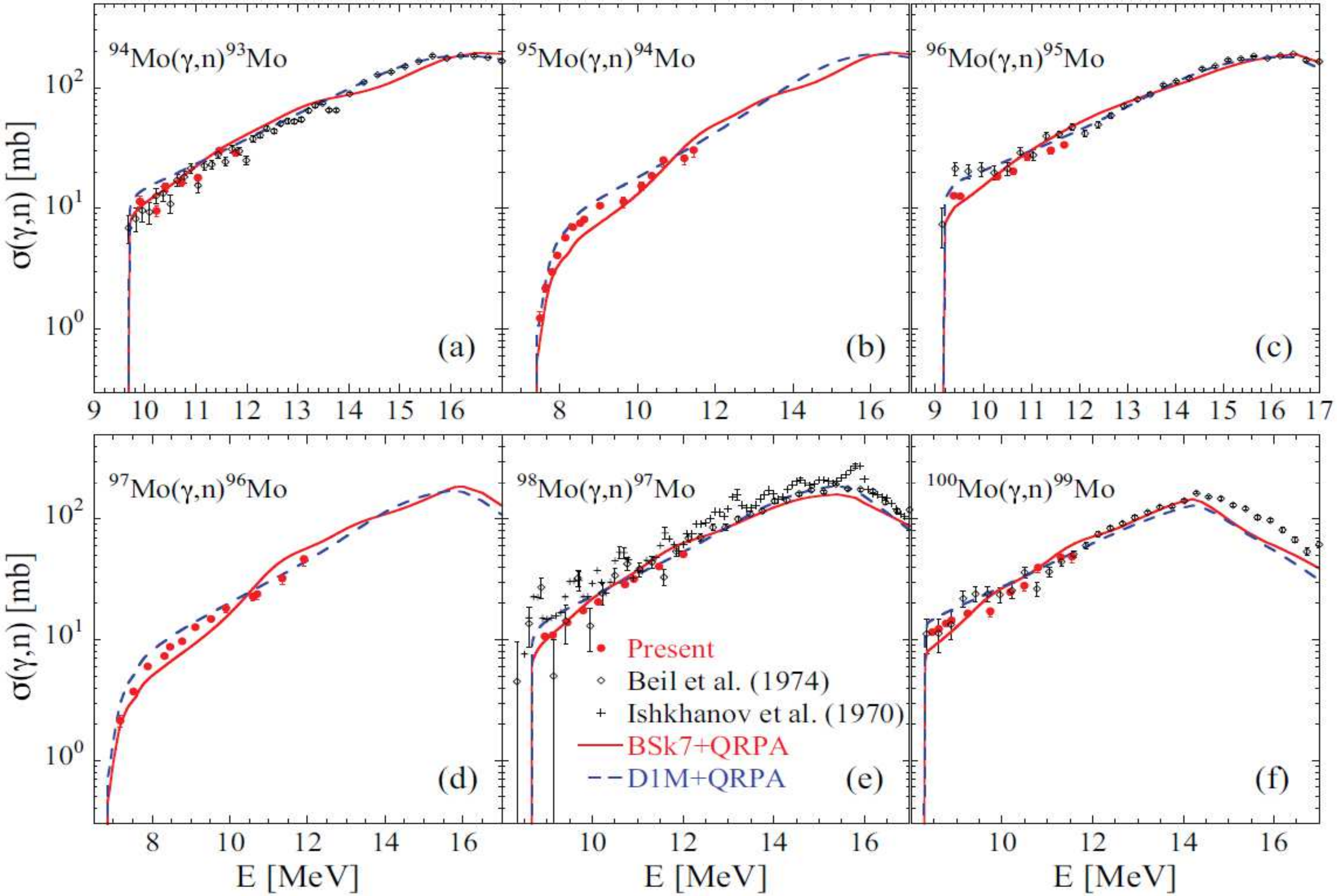
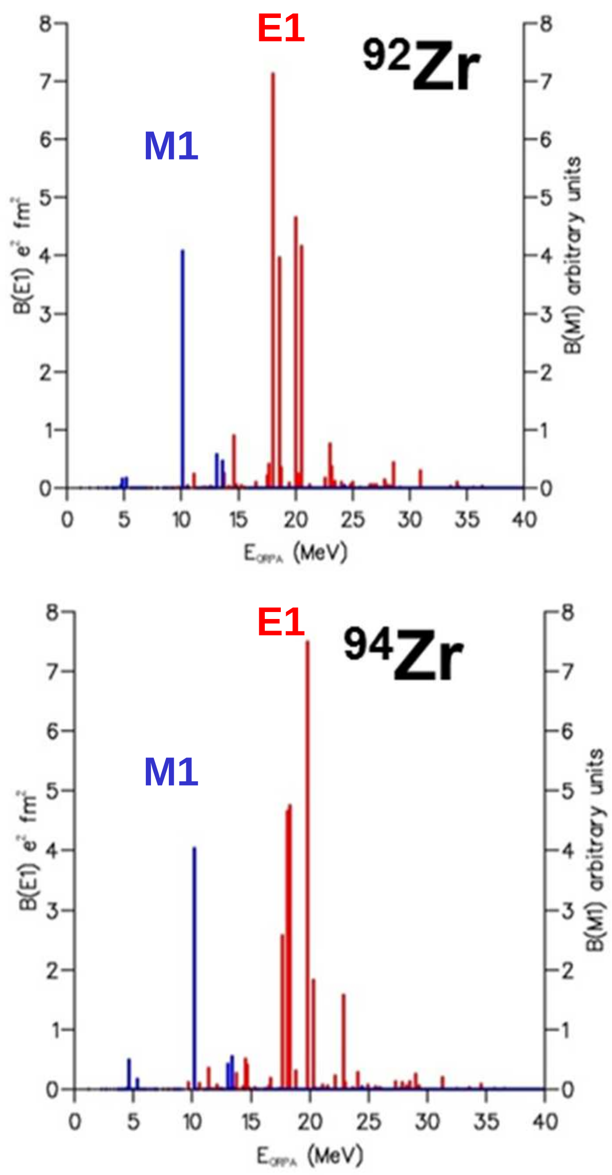
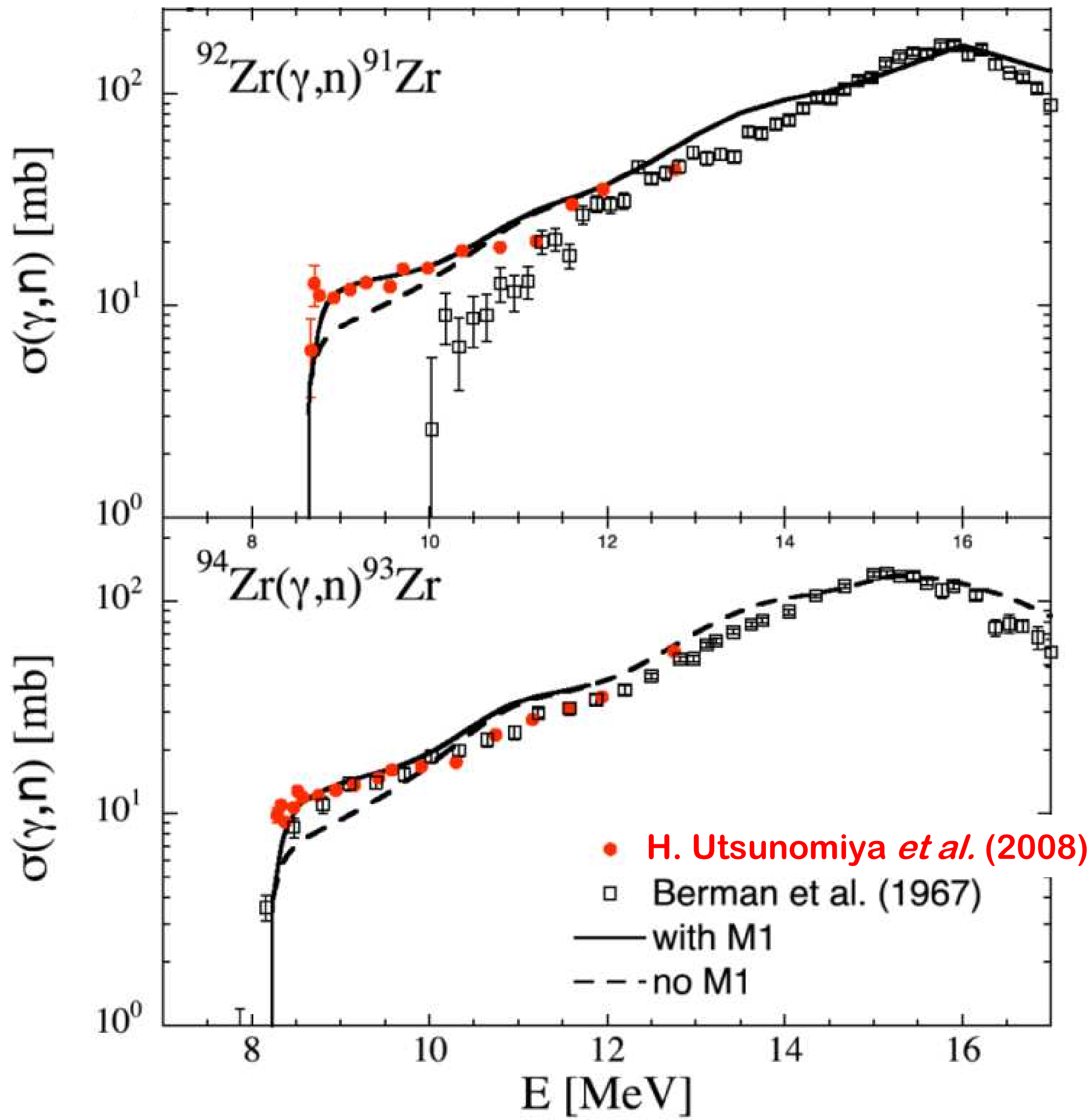


FIG. 3. (Color online) Comparison between the present photoneutron emission cross sections and previously measured ones [17,18] for six Mo isotopes, ^{94}Mo (a), ^{95}Mo (b), ^{96}Mo (c), ^{97}Mo (d), ^{98}Mo (e), and ^{100}Mo (f). Also included are the predictions from Skyrme HFB + QRPA (based on the BSk7 interaction) [20] and axially deformed Gogny HFB + QRPA models (based on the D1M interaction) [23].

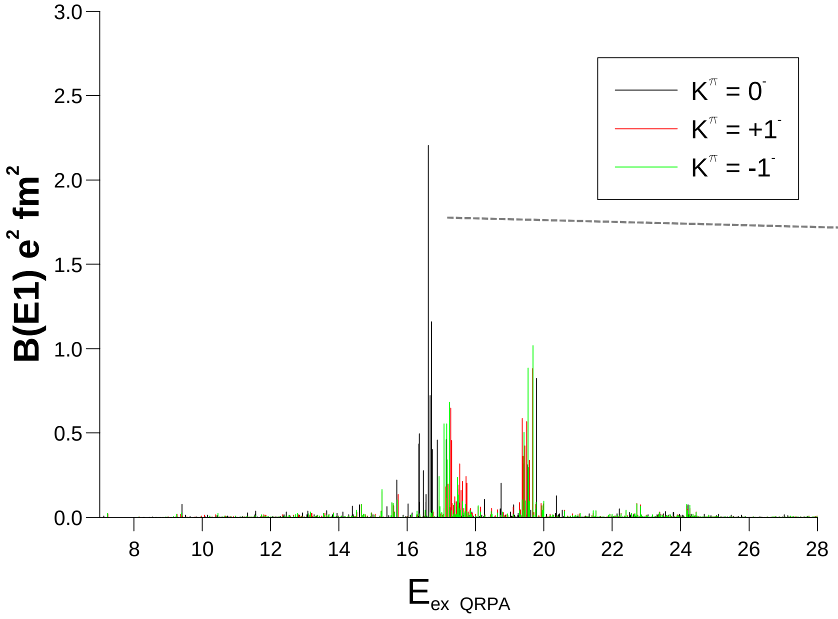
Dipole electric and magnetic excitations for Zr isotopes

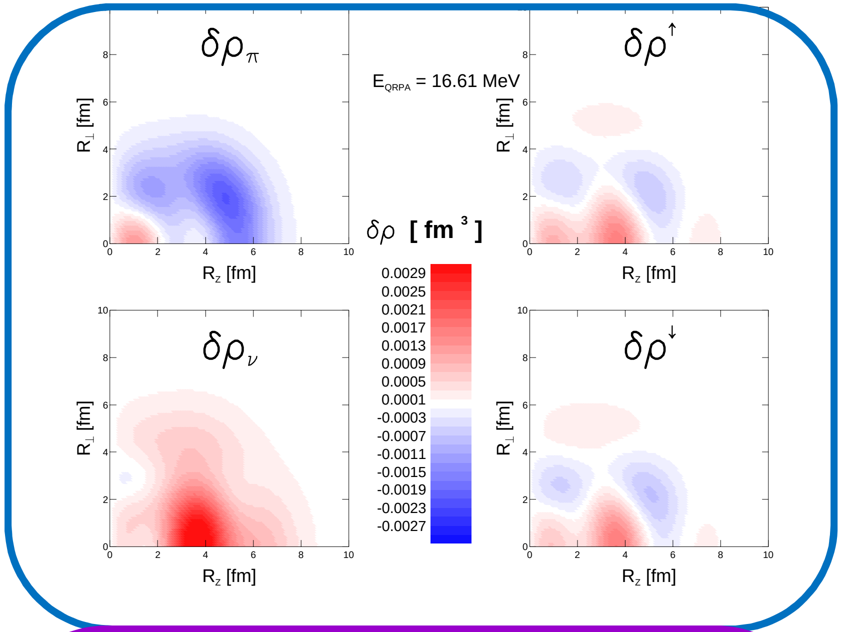


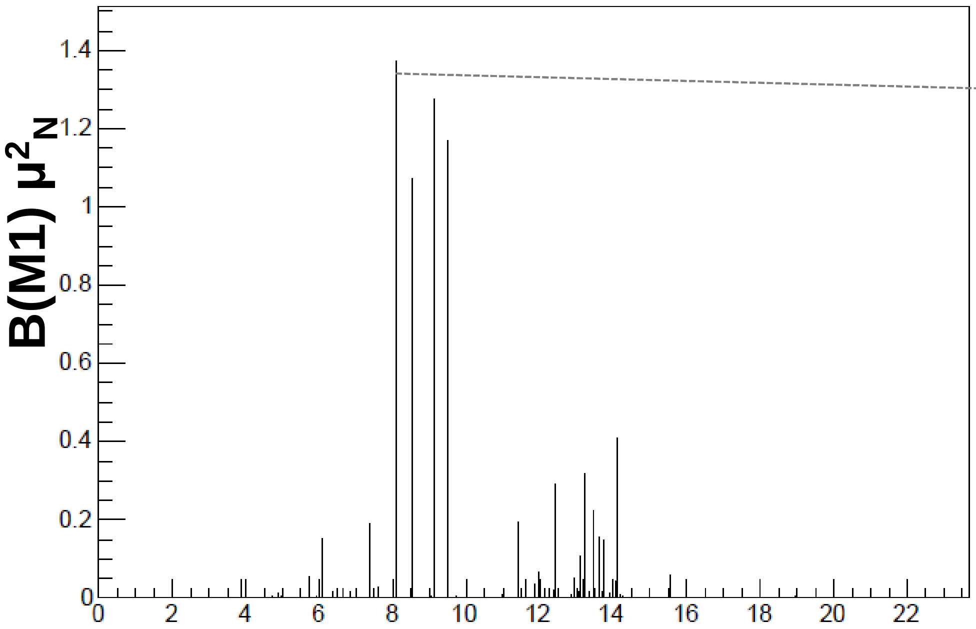


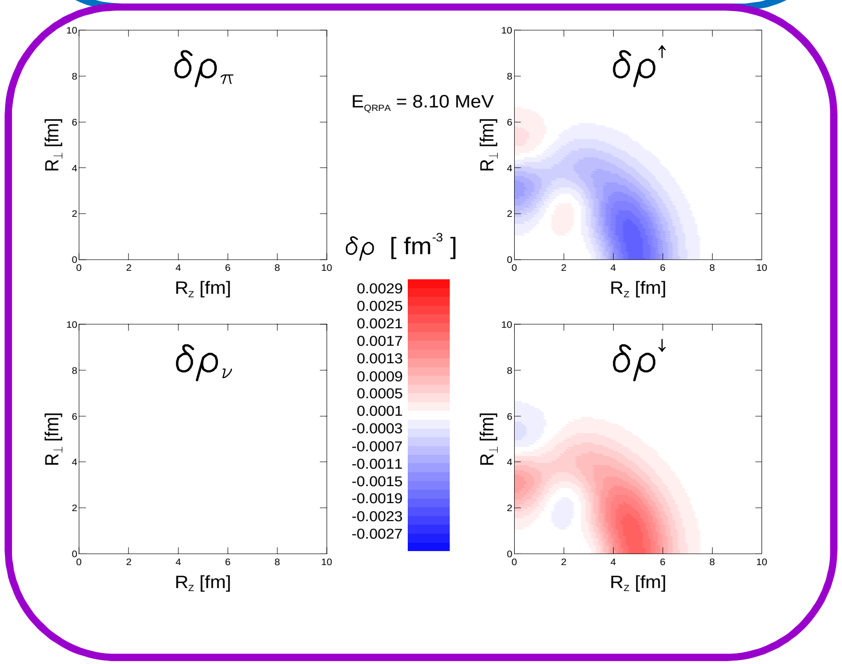
H. Utsunomiya et al, PRL 100, 162502 (2008)

Low Energy Enhancement in the γ Strength of the Odd-Even Nucleus ^{115}In

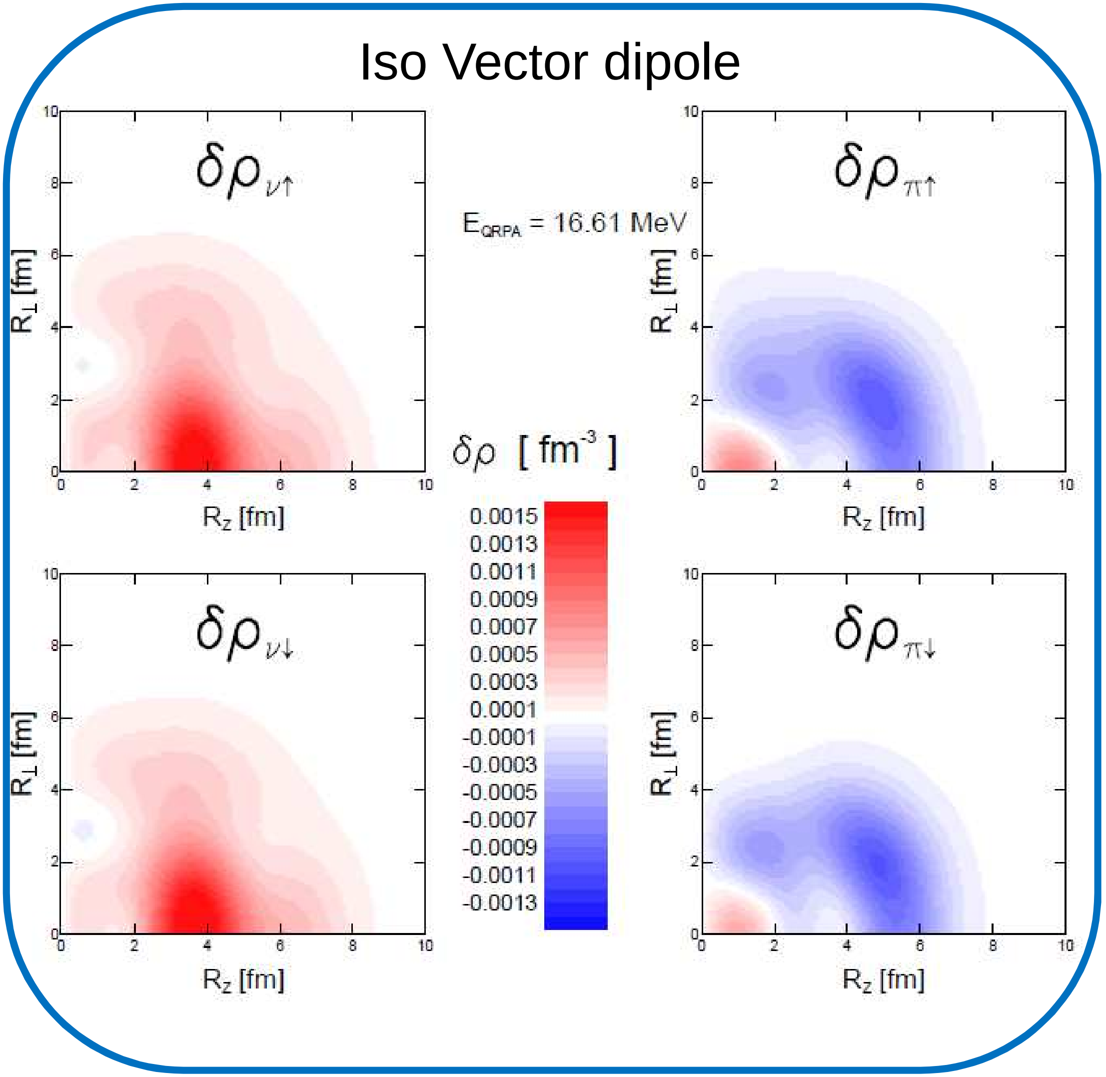


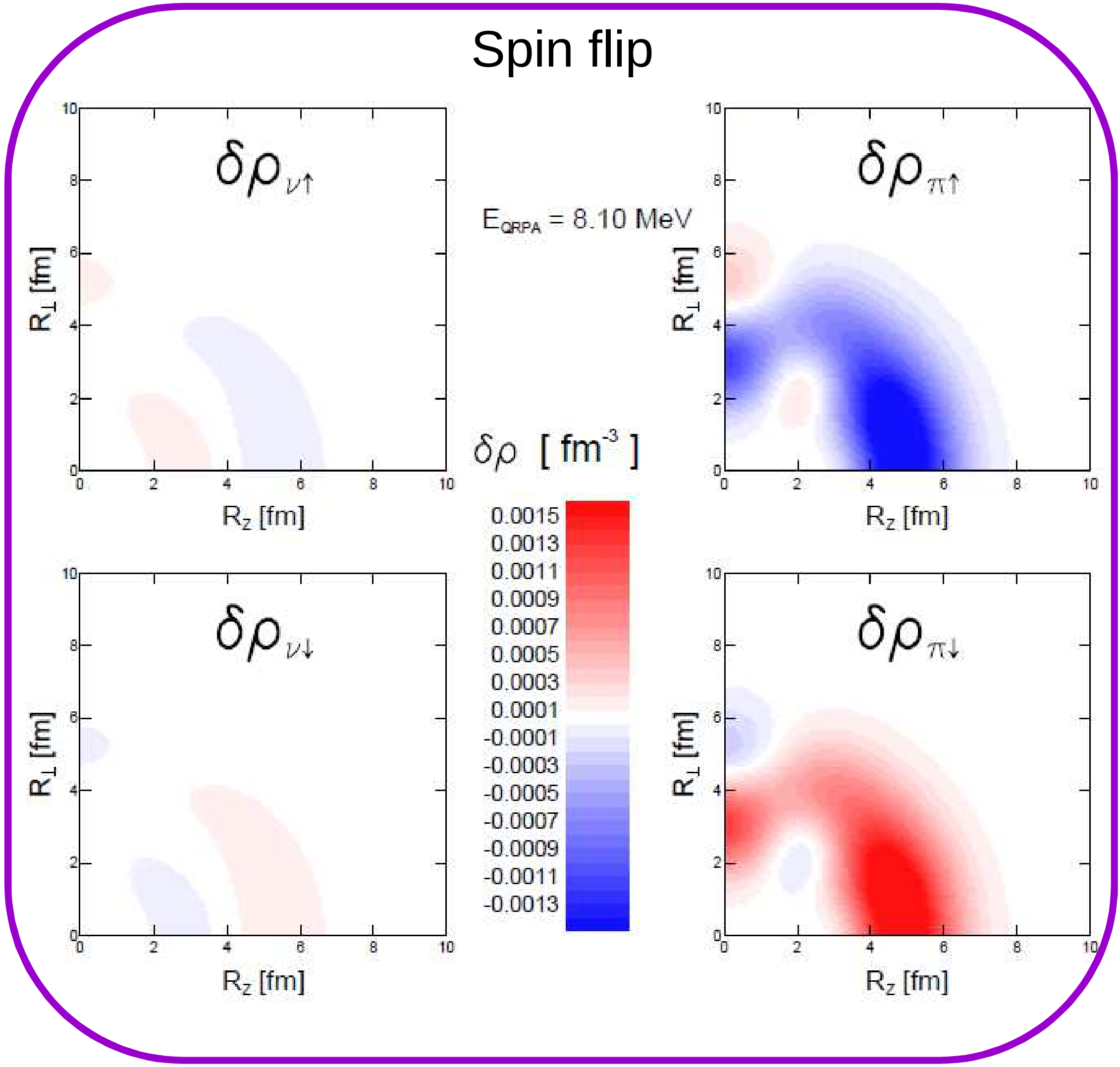






^{115}In

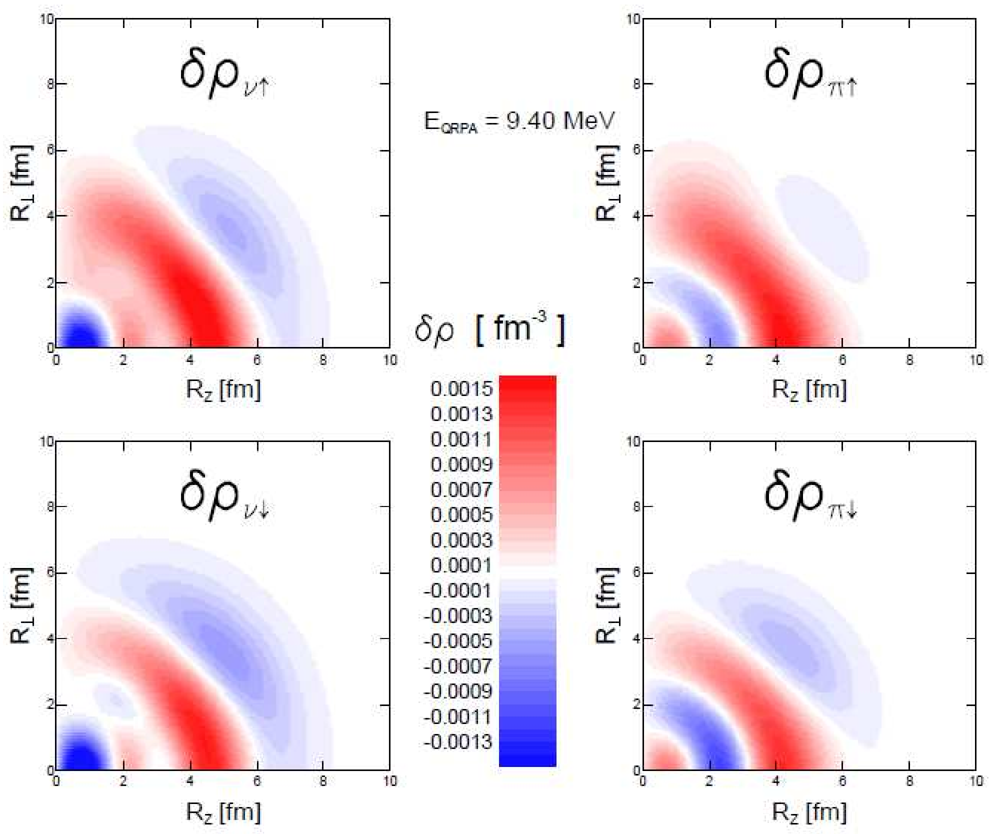




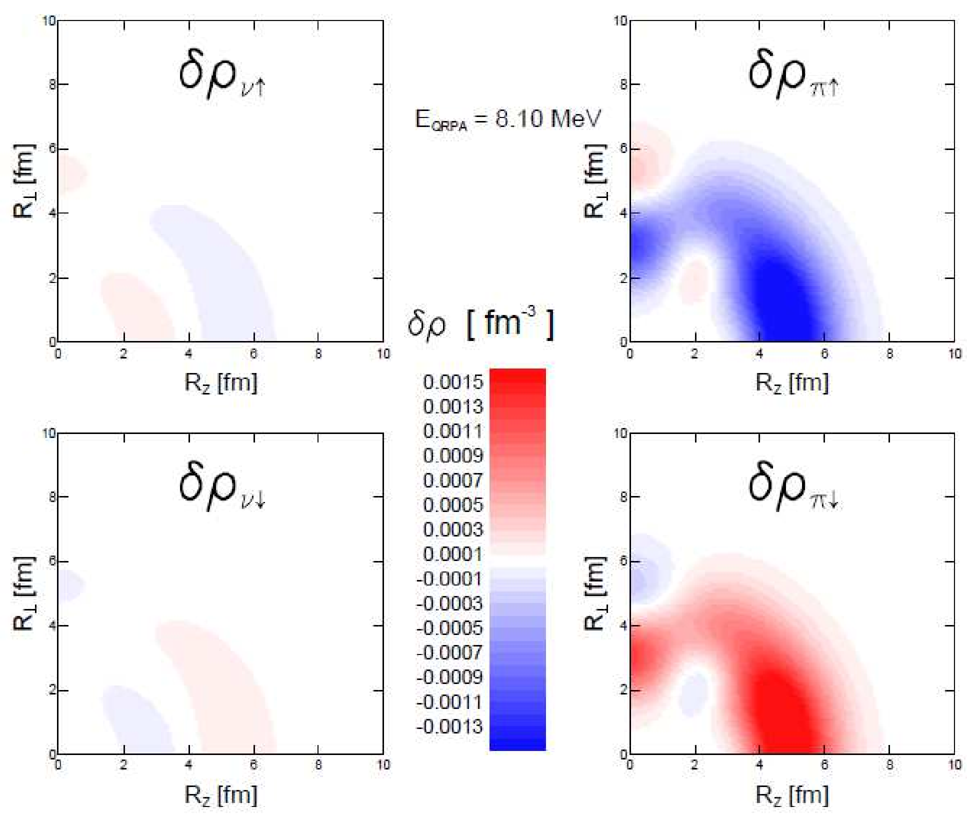
I. Deloncle, M. Martini and S. Peru, in preparation

^{115}In

Iso Saclar dipole



Spin flip



I. Deloncle, M. Martini and S. Peru, in preparation

Large scale calculation for photo-absorption

• We want to predict E1 strengths for all the nuclei.

First we want to validate our approach by calculating E1 strengths for all the nuclei for which photo-absorption data exist.

• Because large part of data is related to odd A or odd-odd nuclei,

we make the choice to calculate E1 strengths for all even-even nuclei for which data exist

and

for even-even nuclei in the neighbourhood of odd nuclei for which data exist.

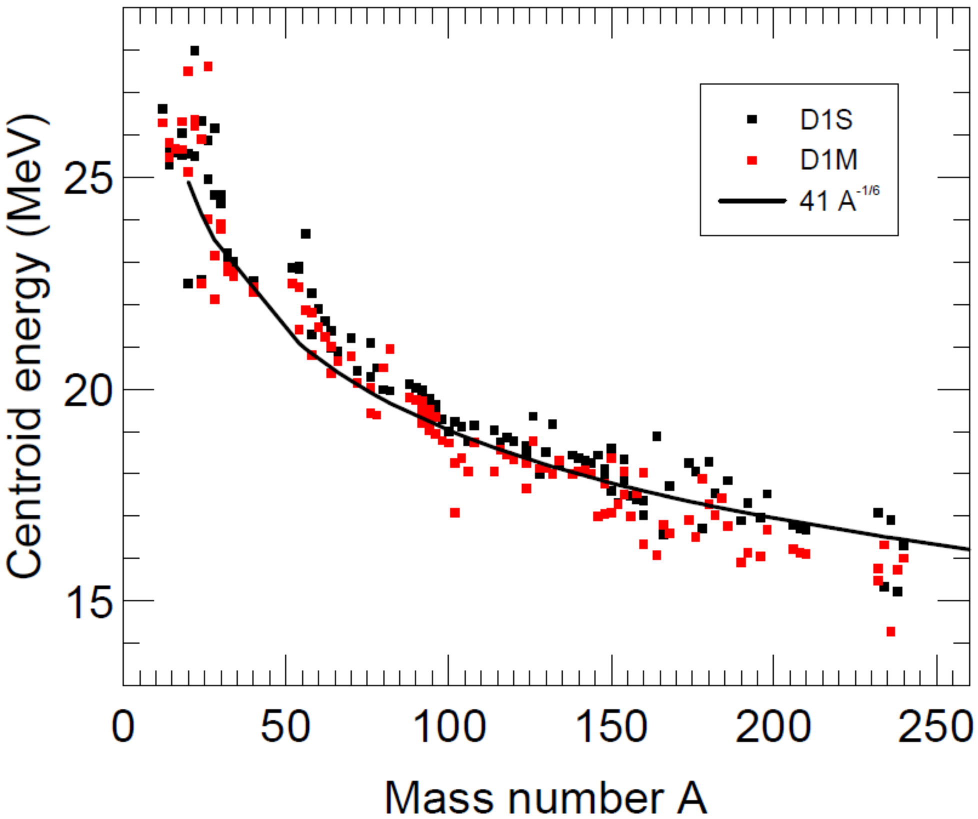
The strength of odd nuclei will be extrapolate/interpolate :

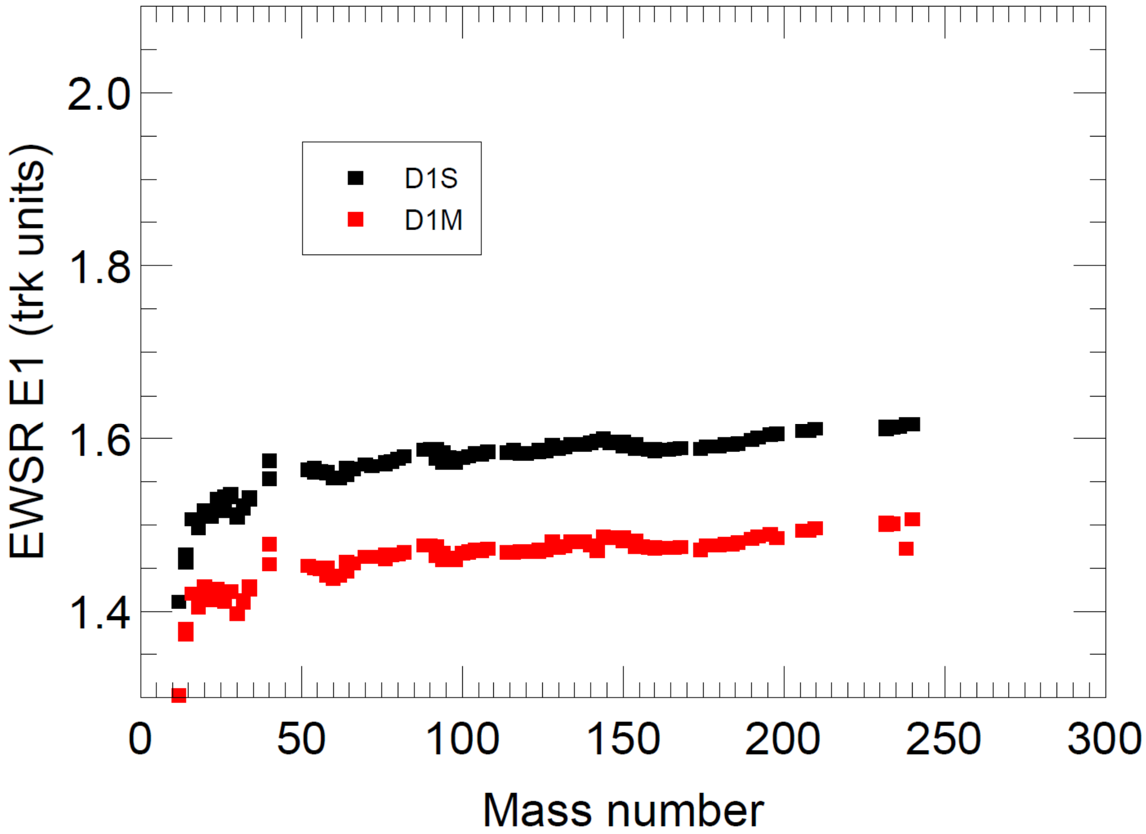
for one odd A nucleus two even nuclei are needed;

for one odd-odd nucleus four even-even nuclei are needed.

Paper under revision

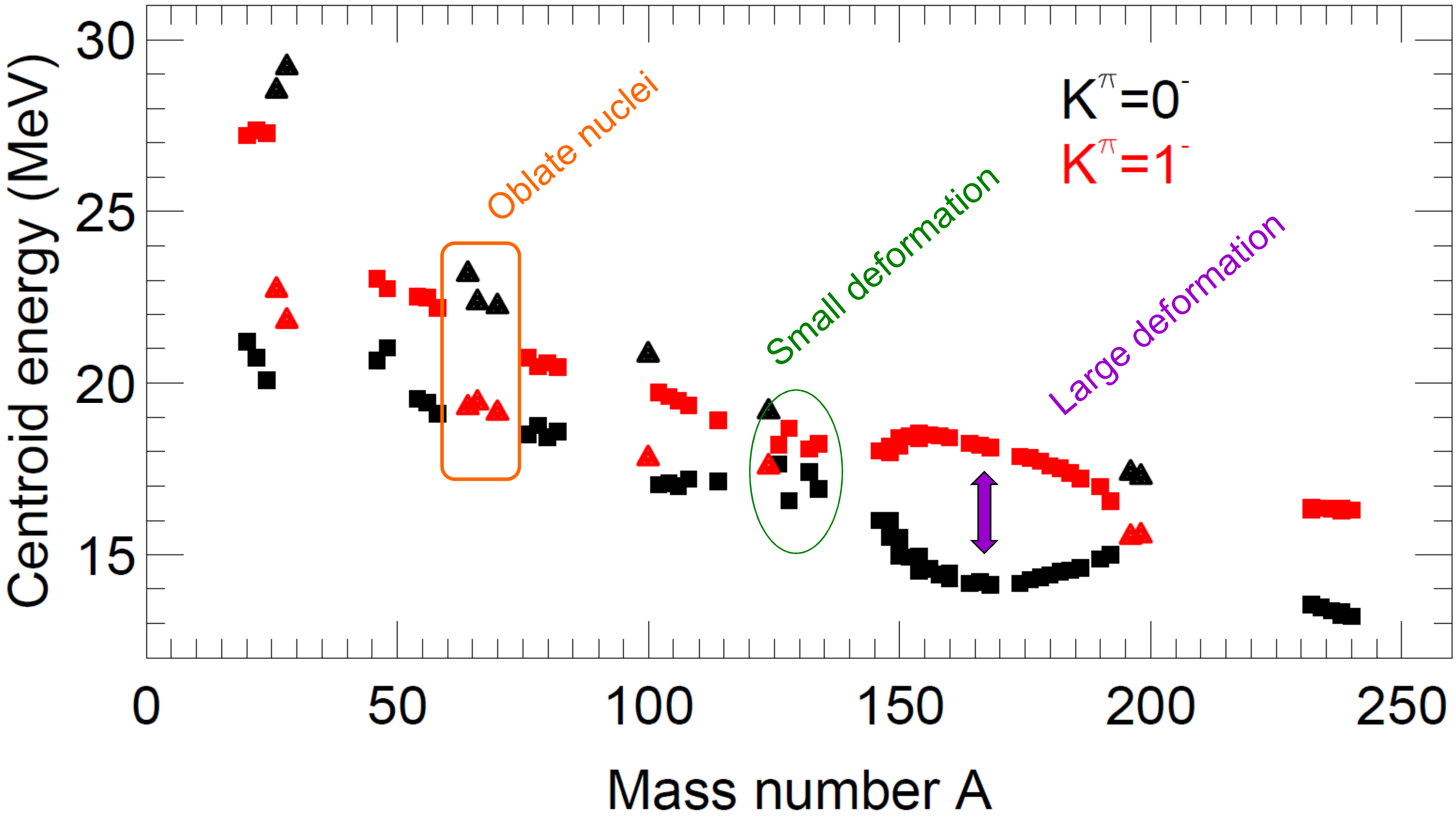
Global trend : D1S versus D1M





A few 100 keV overestimation of the D1S centroid energies with respect to D1M ones leads to a 0,2 shift of the EWSR (in TRK units).

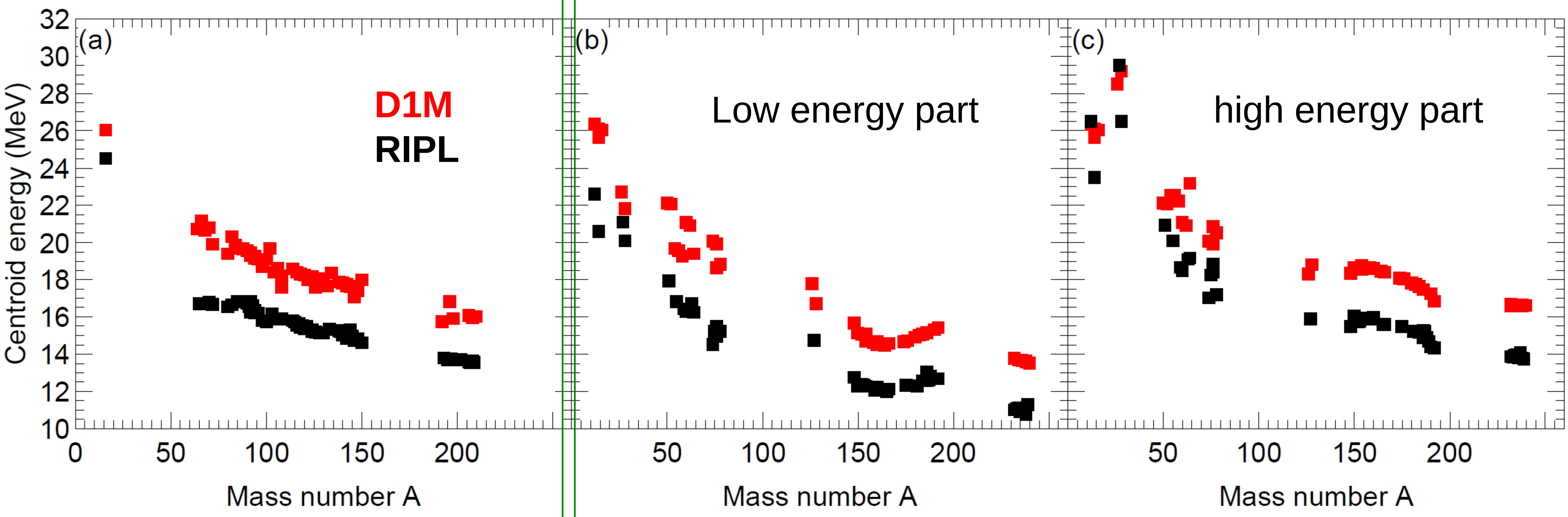
Impact of the deformation



Comparison with experimental data

One Lorentzian in RIPL

Two Lorentzians in RIPL



Systematic overestimation of the centroid energies :~ 2MeV

Semi-empirical broadening of the GDR

To take into account complex configurations as well as coupling with phonons, the deformed QRPA strength S_{E1}(w) is folded with a Lorentzian function $L(E,$w) of width Γ

$$S_{E1}(E) = \sum_n L(E,\omega_n) B(E1)(\omega_n)$$

$$L(E,\omega) = \frac{1}{\pi} \frac{\Gamma E^2}{[E^2 - (\omega - \Delta)^2]^2 + \Gamma^2 E^2}$$

Model 0:

All parameters are independent of the energy and identical for all nuclei.

Δ = 2 MeV and Γ = 2.5 MeV

Model 1:

Γ is adjusted on each photoabsortion cross section

Δ is energy dependant :$\Delta(\omega) = \Delta_0 + \Delta_{4qp}(\omega)$;

Δ_0 is constant and $\Delta_{4qp}(\omega) = \delta_{4qp} \times n_{4qp}(\omega)/n_{4qp}(30\ MeV)$

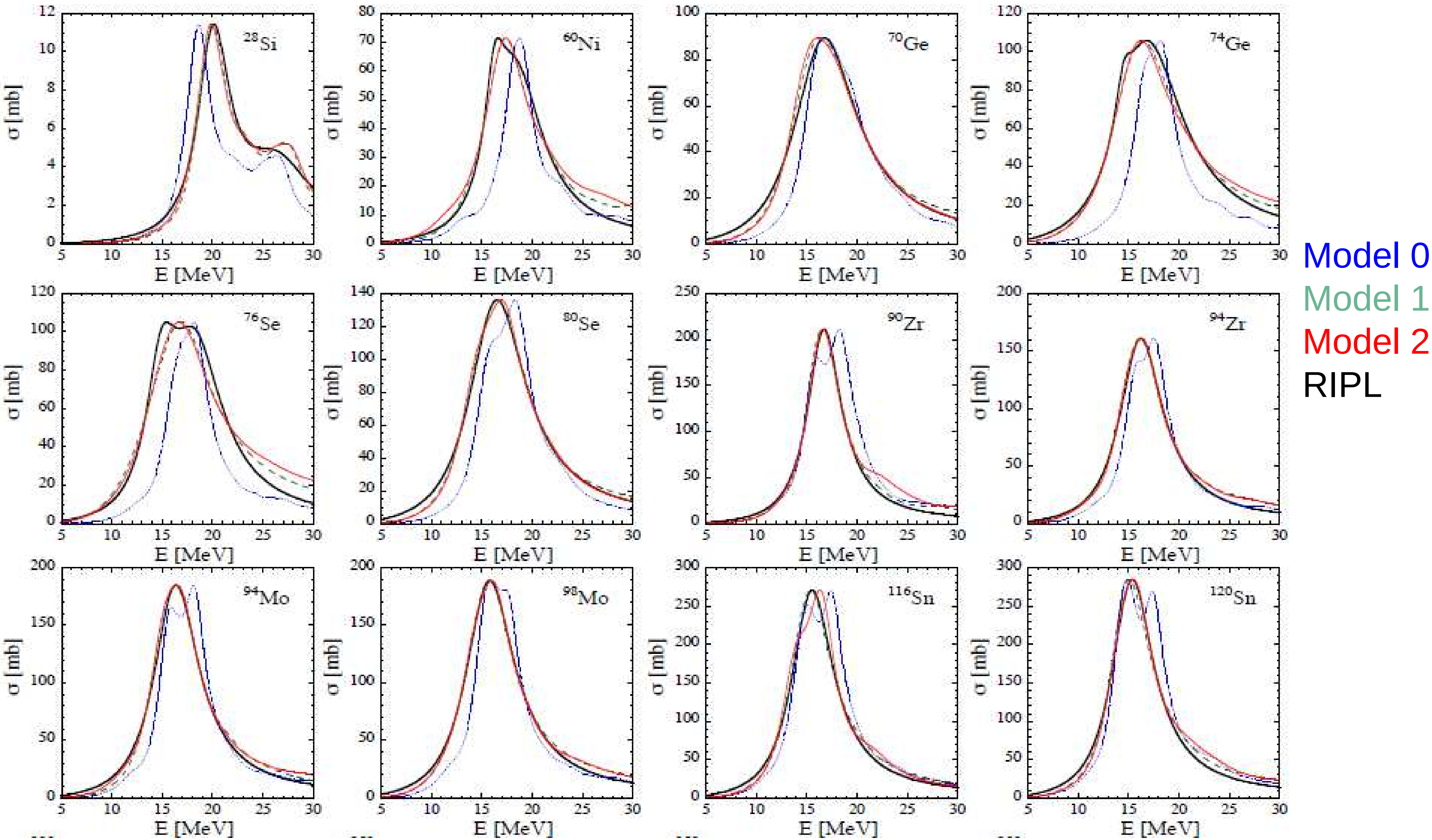
Model 2:

Γ is adjusted on each photoabsortion cross section

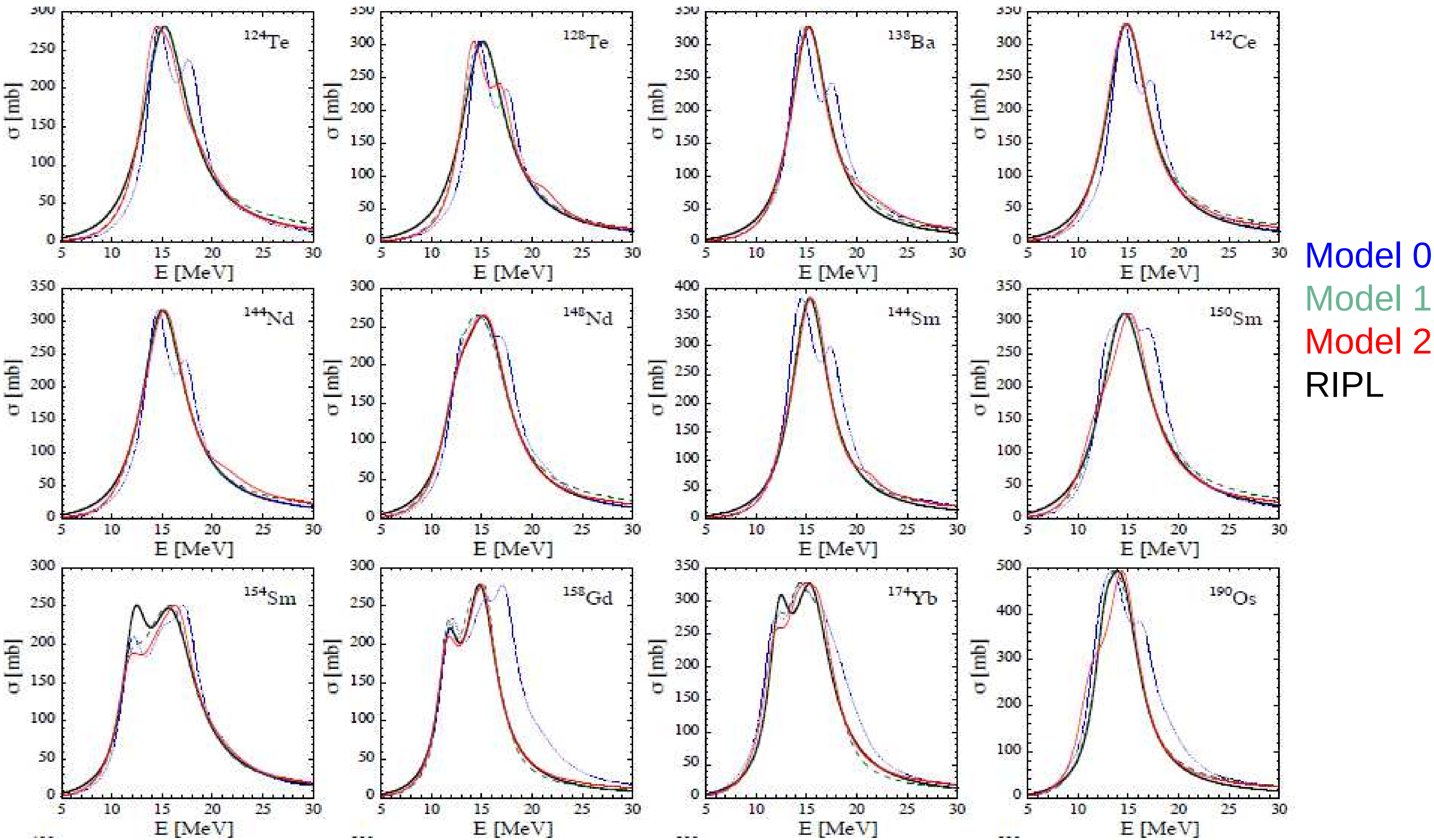
Δ is energy dependant :$\Delta(\omega) = \Delta_0 + \Delta_{4qp}(\omega)$;

Δ_0 is constant and $\Delta_{4qp}(\omega) = \delta_{4qp} \times n_{4qp}(\omega)/n_{2qp}(\omega)$

Semi-empirical broadening of the GDR

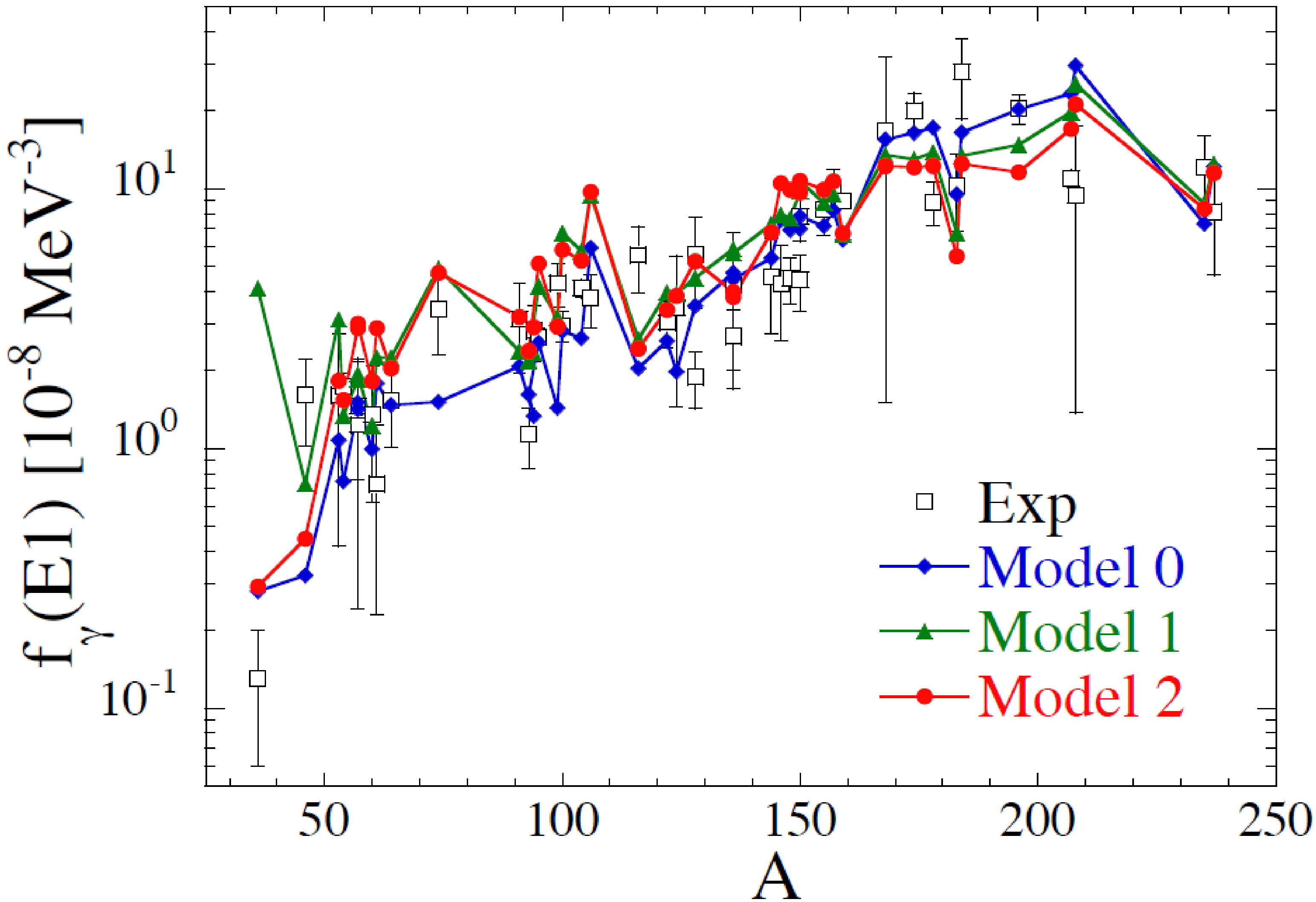


Semi-empirical broadening of the GDR



Low energy dipole excitations

Comparison of the QRPA low-energy E1 strength functions with experimental compilation for nuclei from ^{33}S up to ^{239}U at energies ranging from 4 to 8 MeV.



summary

Fully self-consistent QRPA using the finite range Gogny force can be applied to spherical and axially-symmetric-deformed nuclei.

- When 5DCH and QRPA approaches can complete each other, a full valence space and high cutoff are needed for $E(2_1^+)$ and $B(E2)$

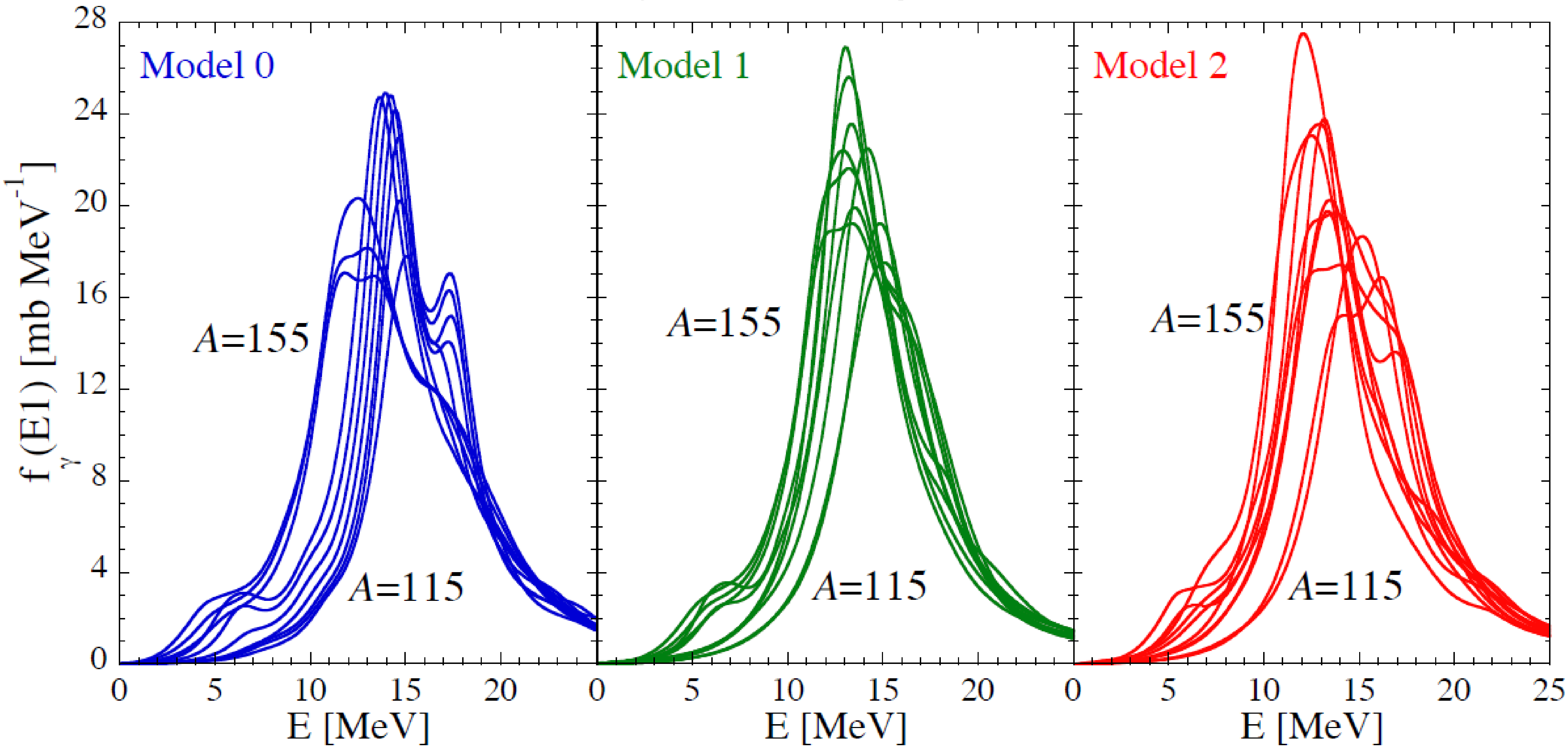
- IsoScalar-IsoVector mixing for low-lying dipole states in Ne isotopes and N=16 isotones.
- Self-consistent QRPA approach has been applied to the deformed nuclei up to ^{238}U.

- QRPA results successfully used in reaction models ;
- Systematic calculations are on the way…

- Extension to odd A or odd-odd nuclei is in progress (collaboration with I. Deloncle CSNSM)

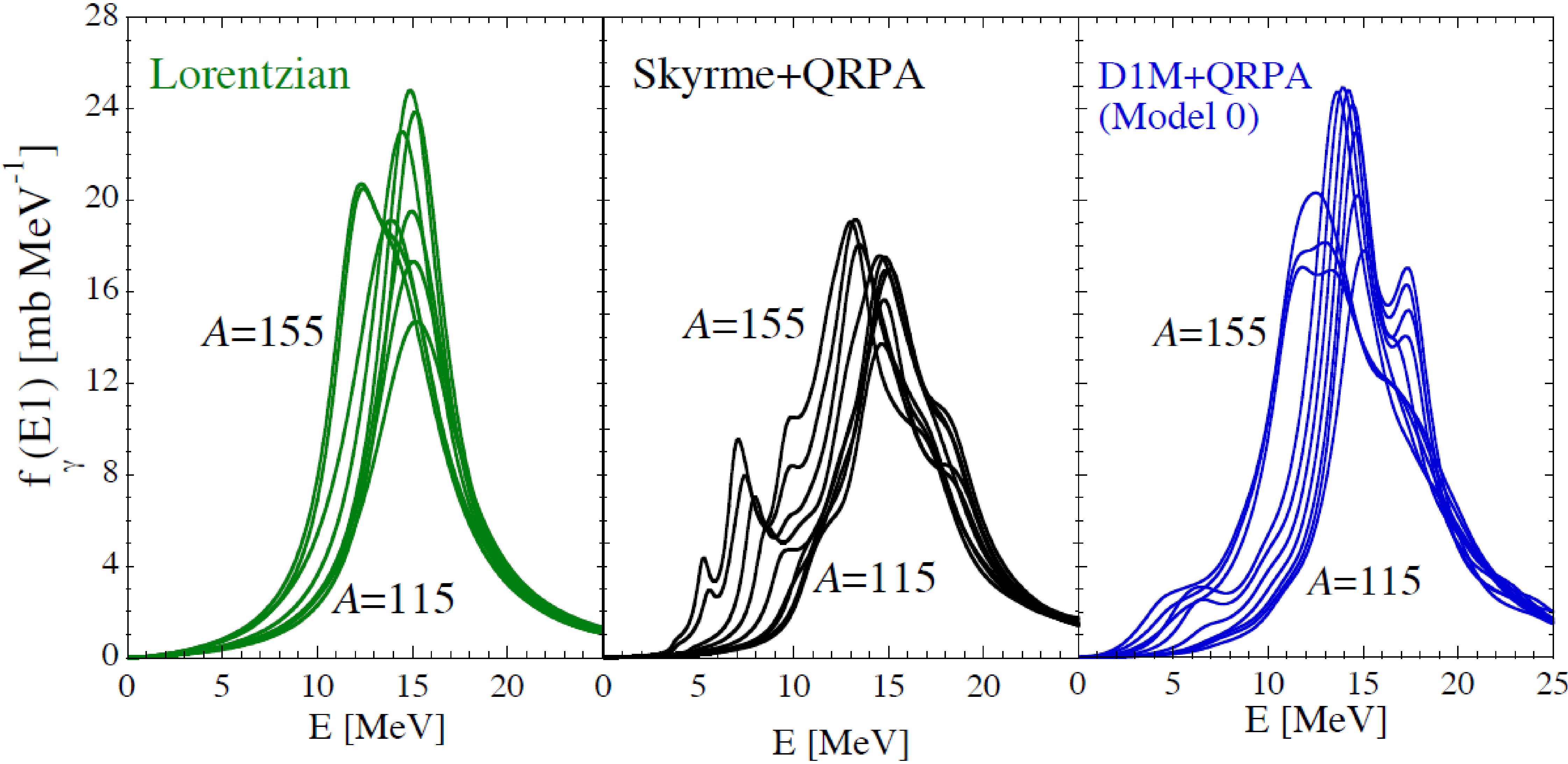
γ- ray strength functions predictions for exotic nuclei

e.g. Sn isotopes



Paper to be submitted

e.g. Sn isotopes



Paper to be submitted