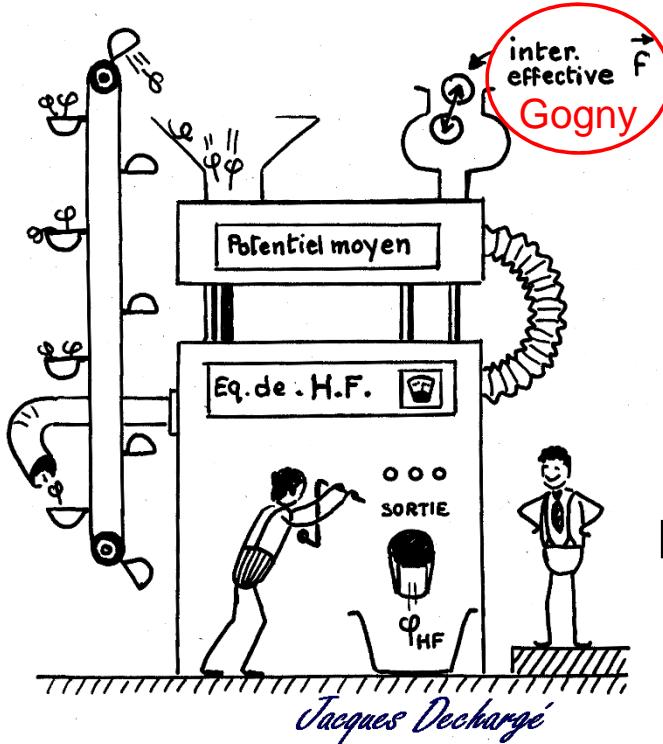


# 5DCH and QRPA models for collective modes in neutron rich nuclei

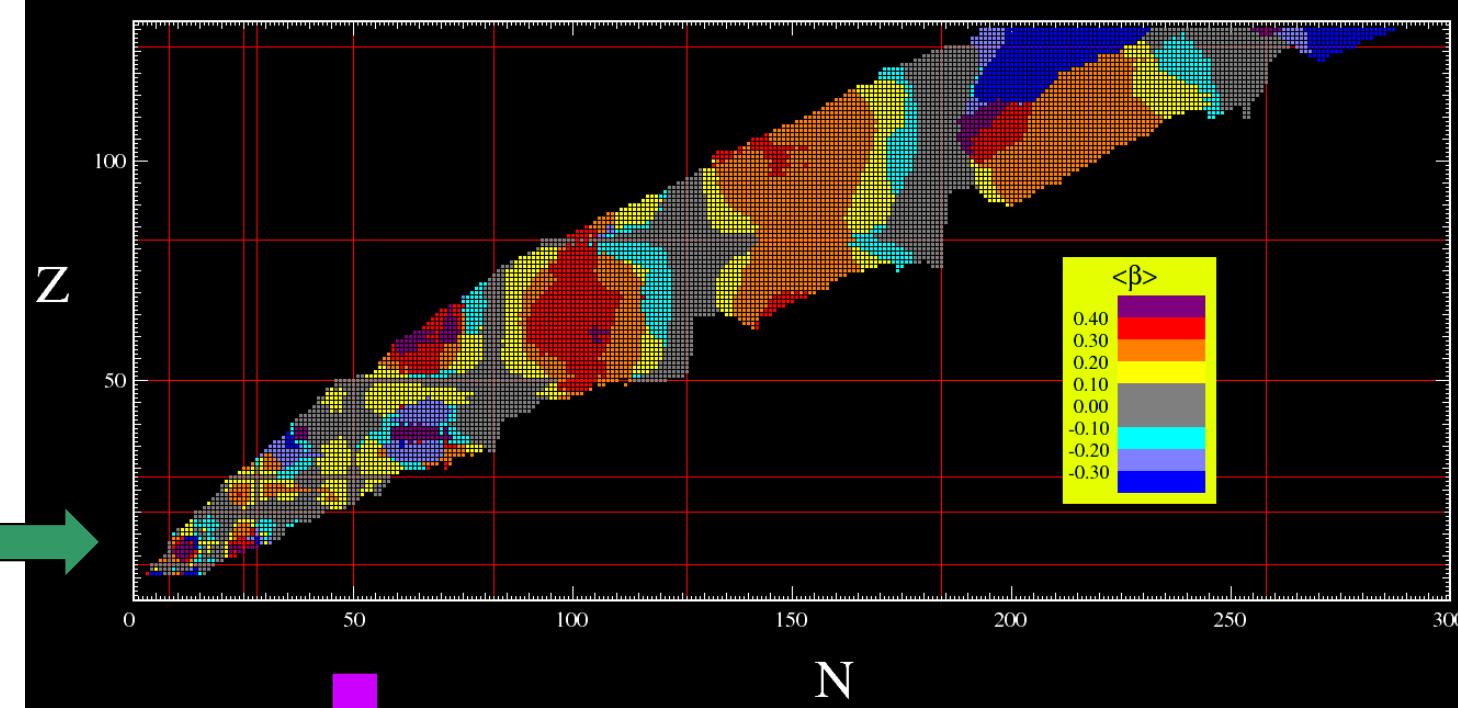
M. Dupuis, S. Goriely , S. Hilaire, F. Lechaftois, M. Martini  
and  
Sophie Péru

# Reminder



**Static mean field (HFB)**  
for Ground State Properties :

- Masses
- Deformation
- (Single particle levels)

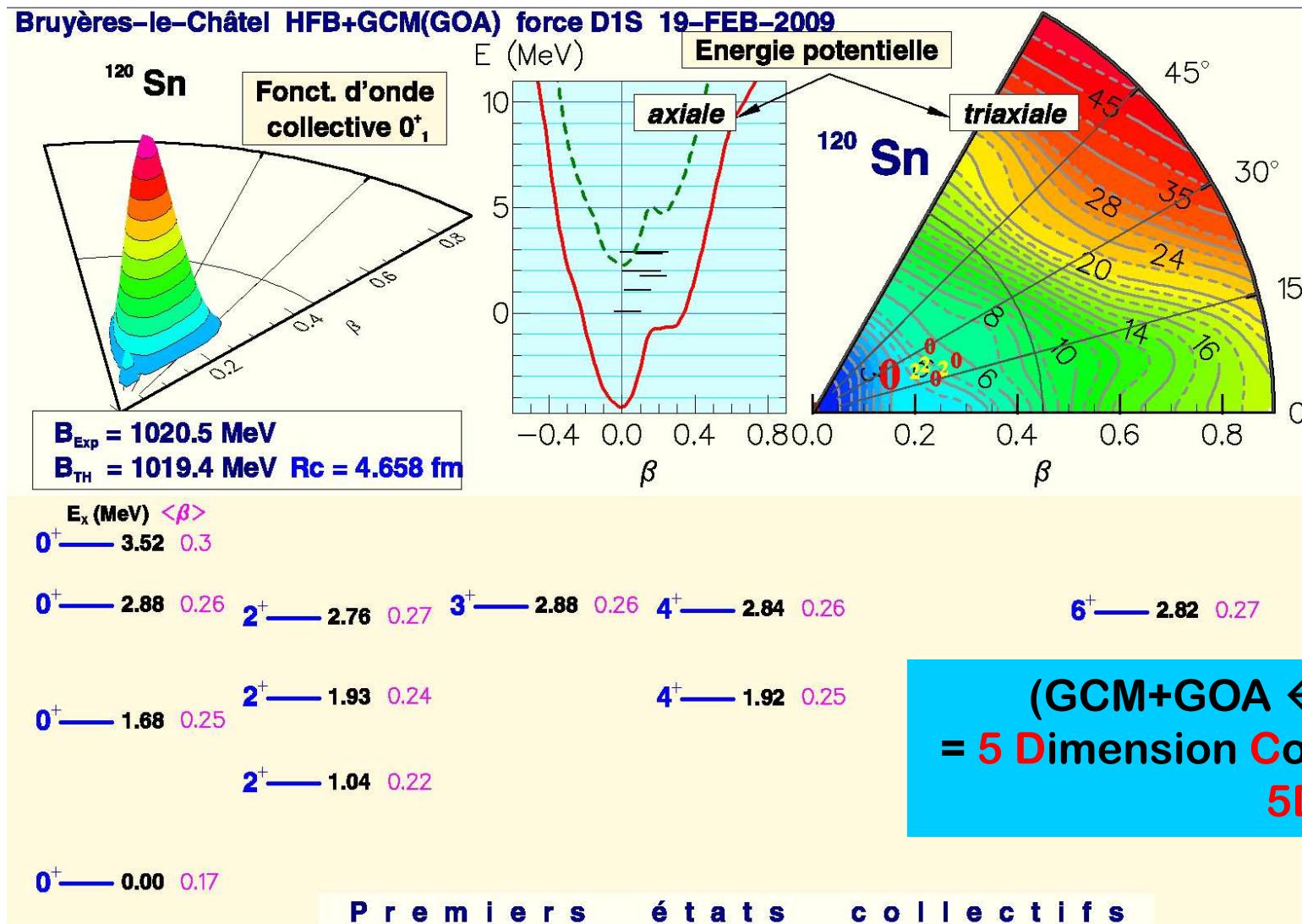


Amedee database :  
[http://www-phynu.cea.fr/HFB-Gogny\\_eng.htm](http://www-phynu.cea.fr/HFB-Gogny_eng.htm)  
 S. Hilaire & M. Girod, EPJ A33 (2007) 237

**Beyond static mean field approximation (5DCH or QRPA)**  
for description of Excited State Properties

- Low-energy collective levels
- Giant Resonances

# Beyond mean field... with 5DCH



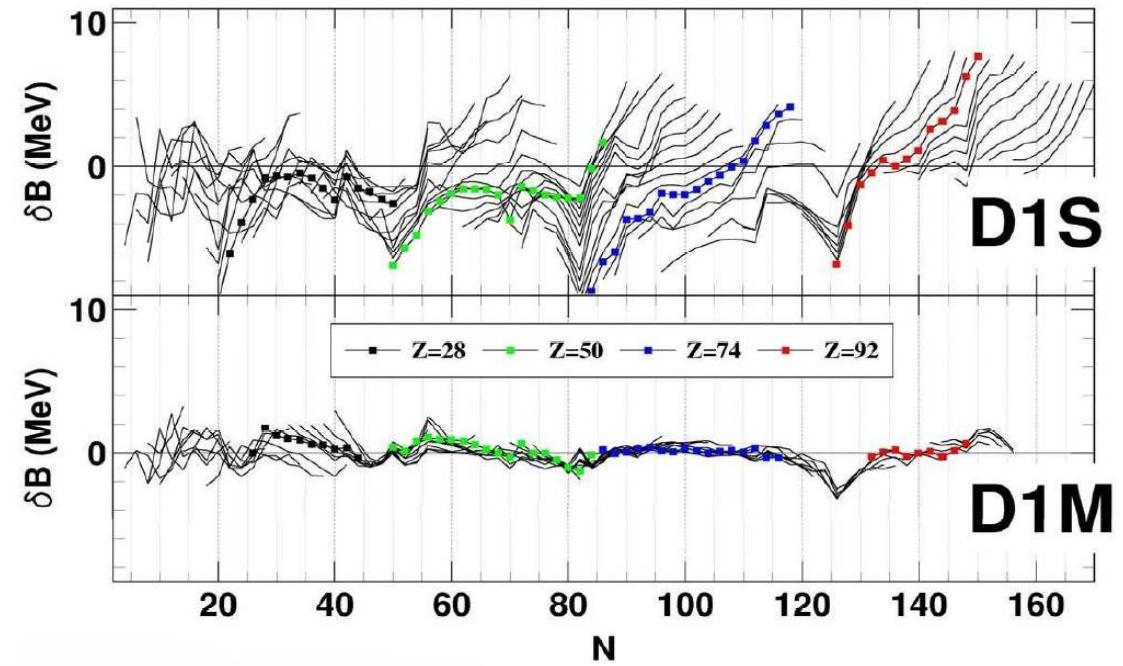
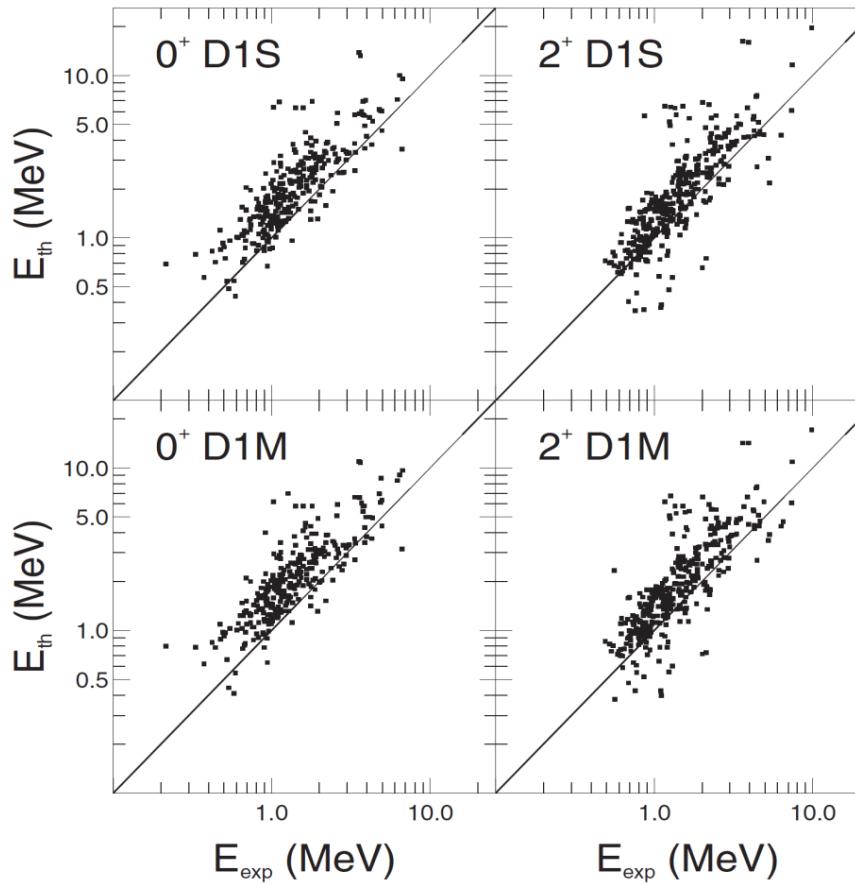
Some exploitation of 5DCH with Gogny forces for shell closures studies

S. Péru, M. Girod, JF. Berger , Eur. Phys. J. A 9,35-47, (2000)  
 A. Obertelli *et al*, Phys. Rev. C 71, 024304, (2005)  
 L. Gaudefroy *et al*, Phys.Rev. C 80, 064313, (2009)

# Some exploitation of 5DCH with Gogny forces

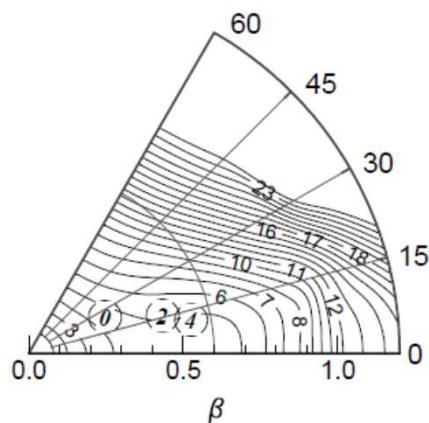
## Systematics studies

D1S: J. P. Delaroche et al. PRC 81, 014303 (2010)  
 D1M: S. Hilaire et al. PRC 86, 064317 (2012)



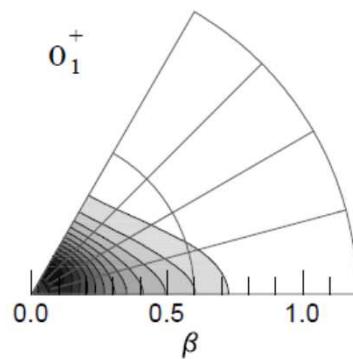
S. Goriely, S. Hilaire, M. Girod, S. Péru , PRL 102, 242501 (2009)

# Shell closures studies with 5DCH

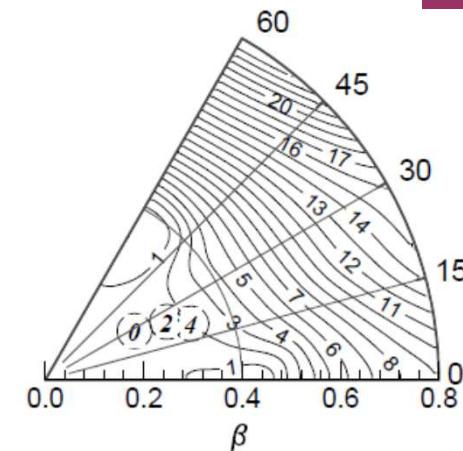
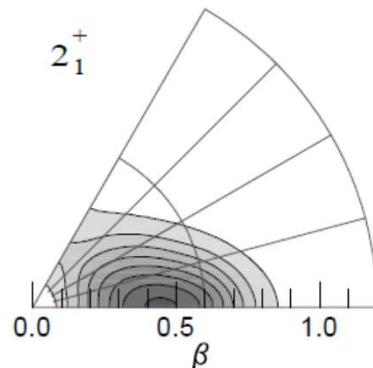


$E(2^+_1)_{\text{Theo.}} = 1.32 \text{ MeV}$

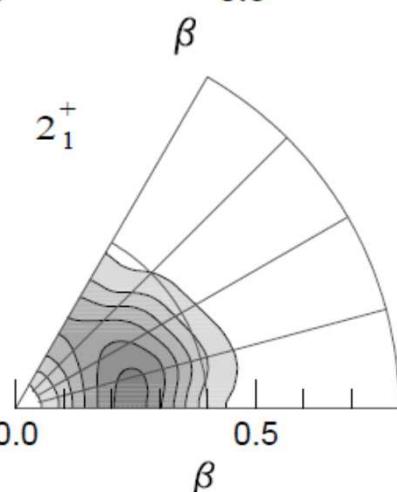
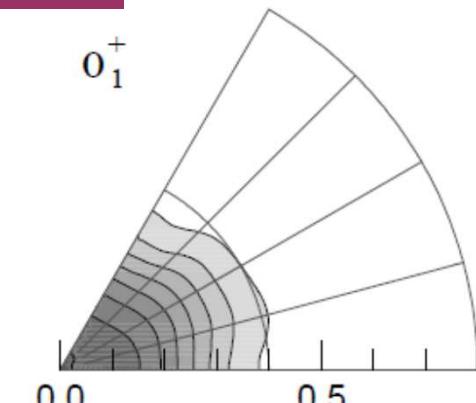
$E(2^+_1)_{\text{Exp.}} = 885 \text{ keV}$



$N=20, {}^{32}\text{Mg}$



$N=28, {}^{44}\text{S}$

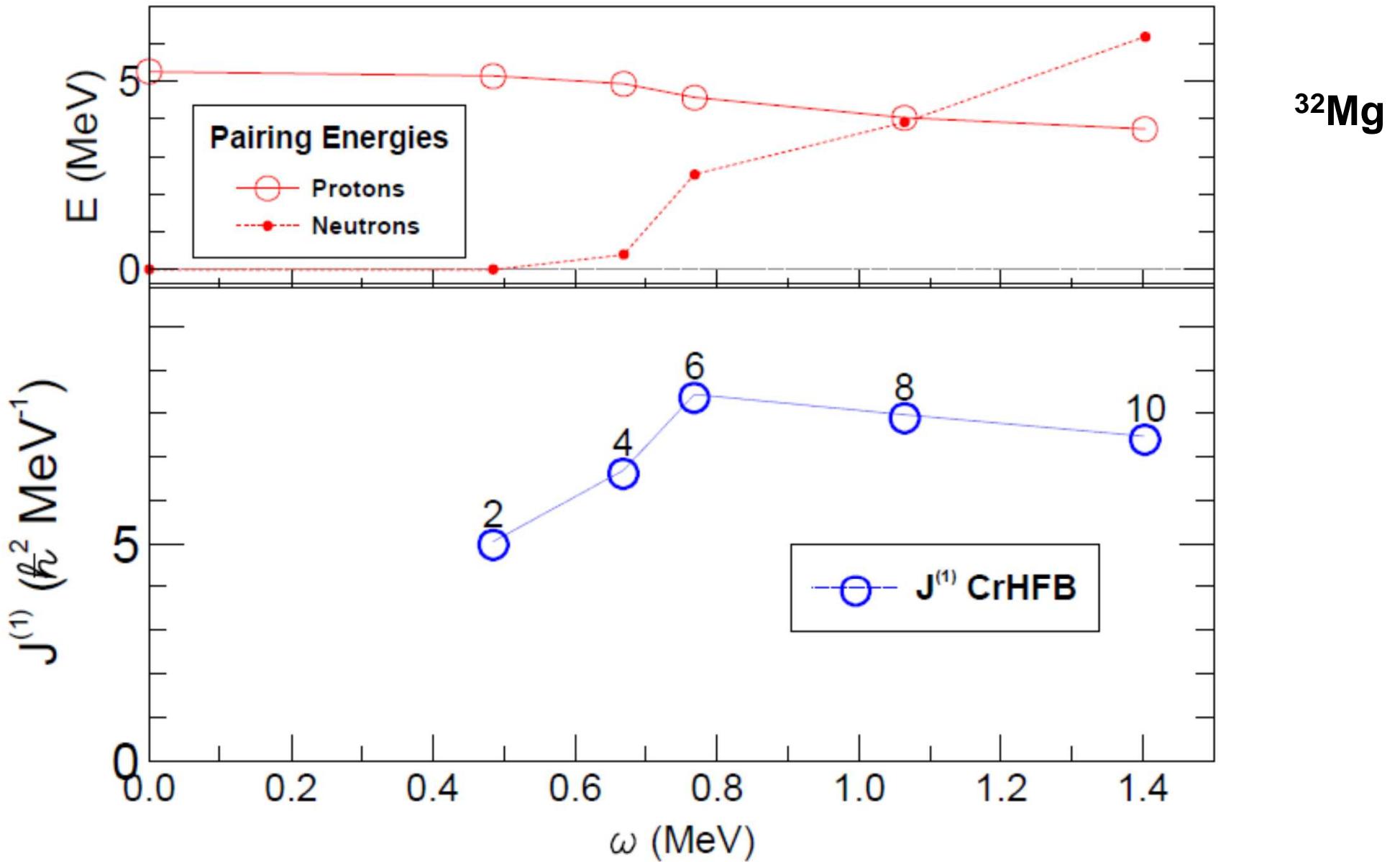


$E(2^+_1)_{\text{Theo.}} = 1.46 \text{ MeV},$   
 $E(2^+_1)_{\text{Exp.}} = 1.297 (0.018) \text{ MeV},$

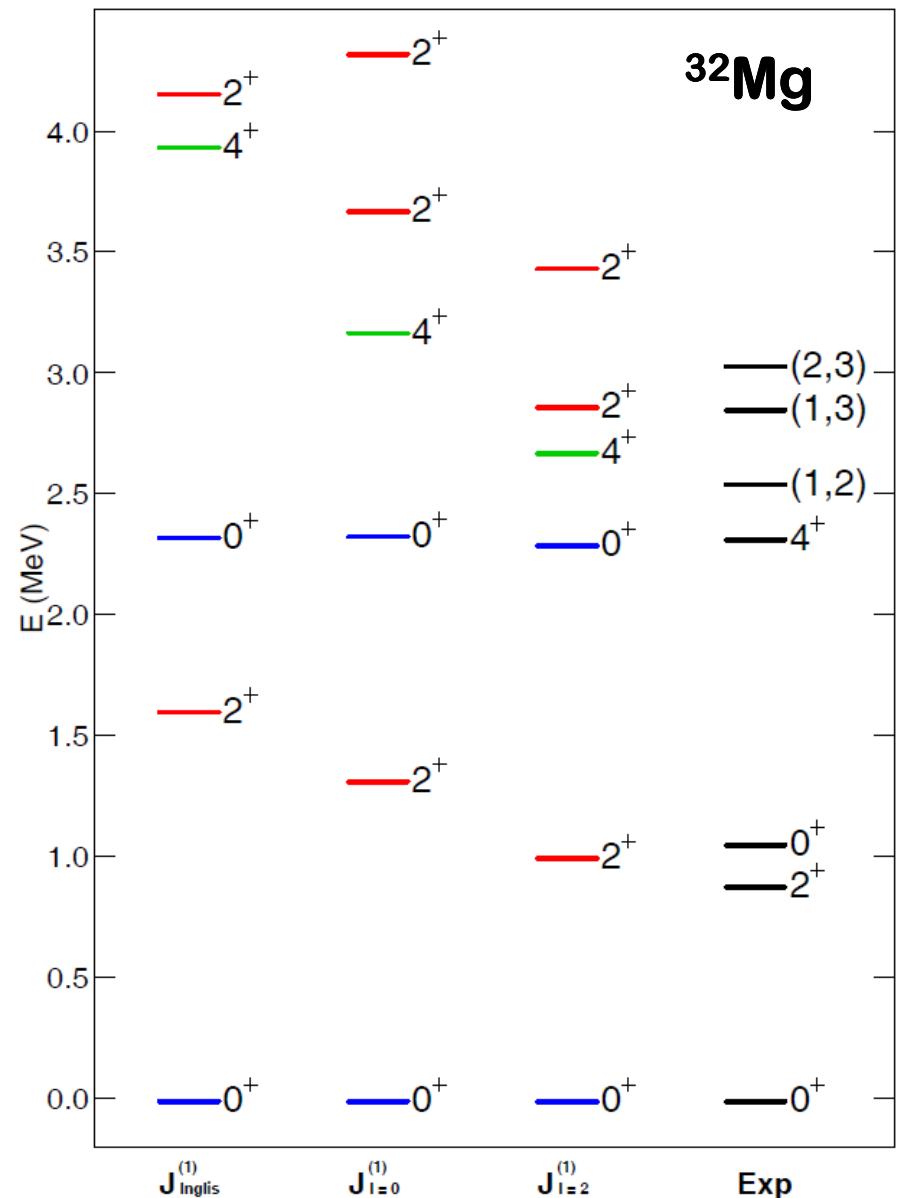
$B(E2, 0^+_{\text{gs}} \rightarrow 2^+_1) = 420 \text{ e}^2 \text{fm}^4$

$B(E2, 0^+_{\text{gs}} \rightarrow 2^+_1) = 314 (88) \text{ e}^2 \text{fm}^4$

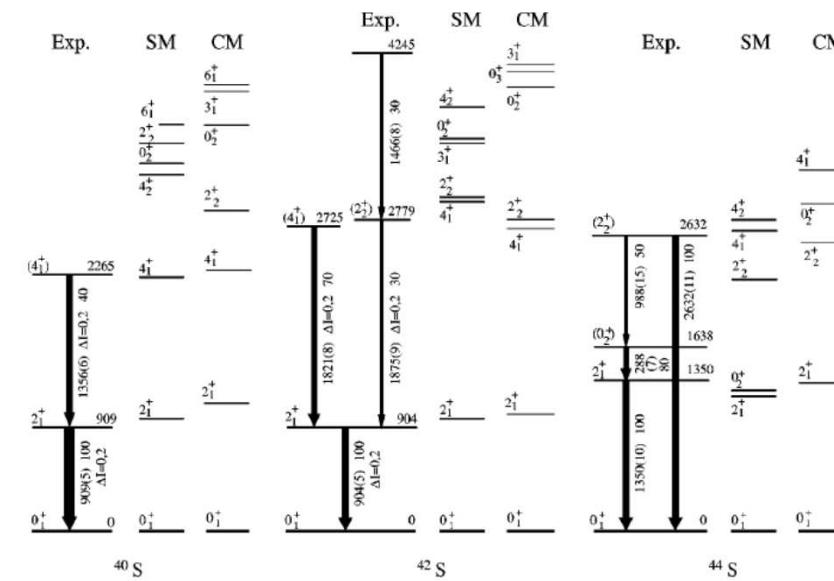
# Further analysis : moments of inertia



# Further analysis : moments of inertia



## Sulfur isotopes

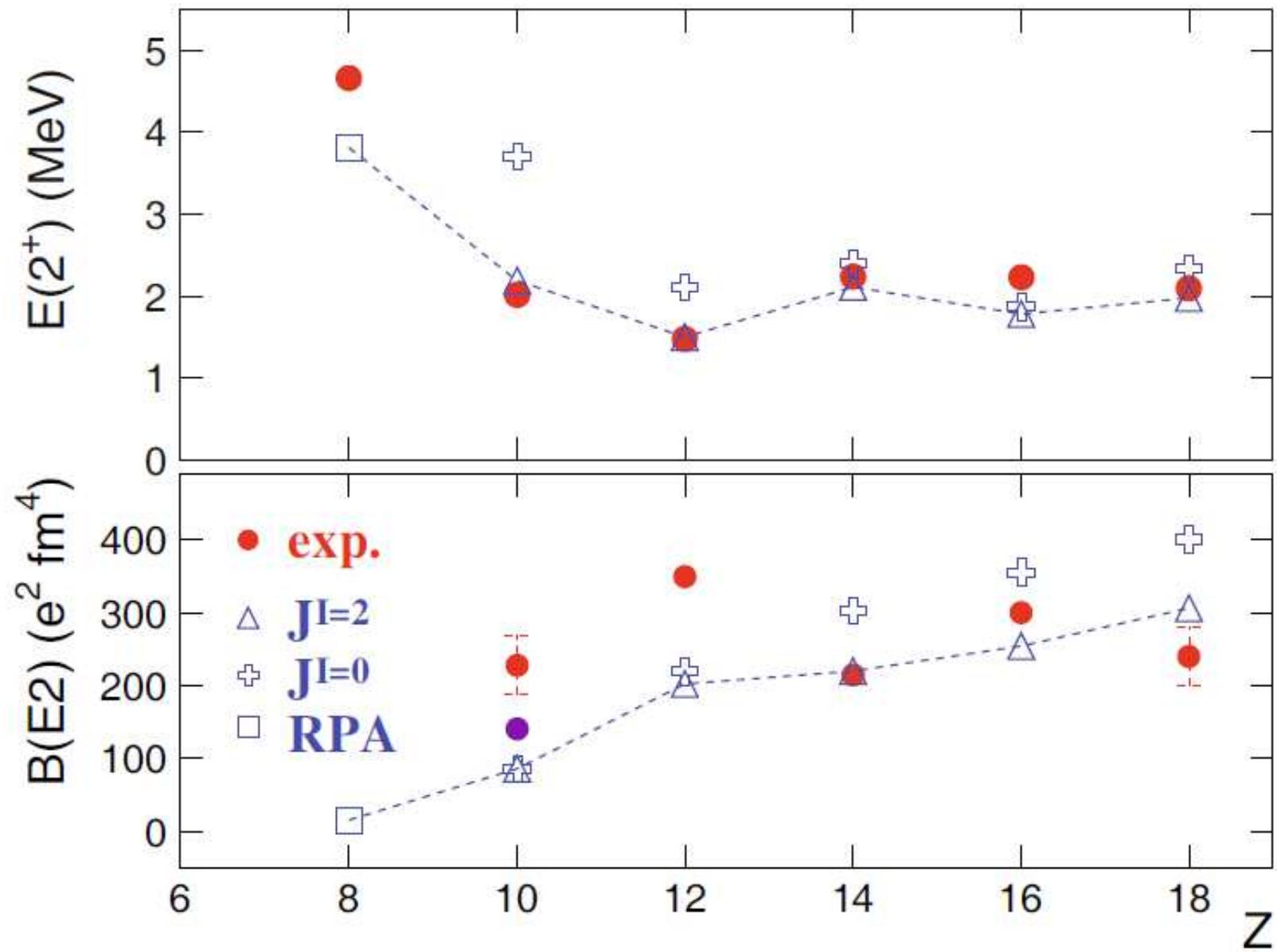
D. SOHLER *et al.*

PHYSICAL REVIEW C 66, 054302 (2002)

FIG. 3. Proposed level schemes of  $^{40,42,44}\text{S}$  from the present experiment in comparison with the results of shell-model (SM) and microscopic collective-model (CM) calculations.  $\gamma$ -ray energies (with uncertainties), multipolarities, and relative intensities are given.

# Shell closures studies with 5DCH

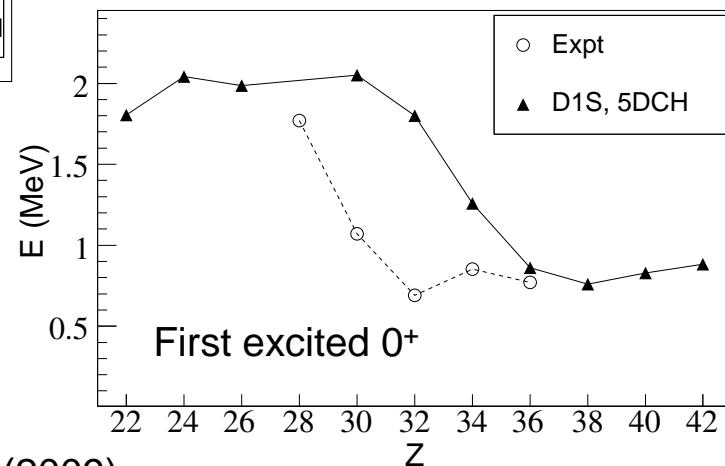
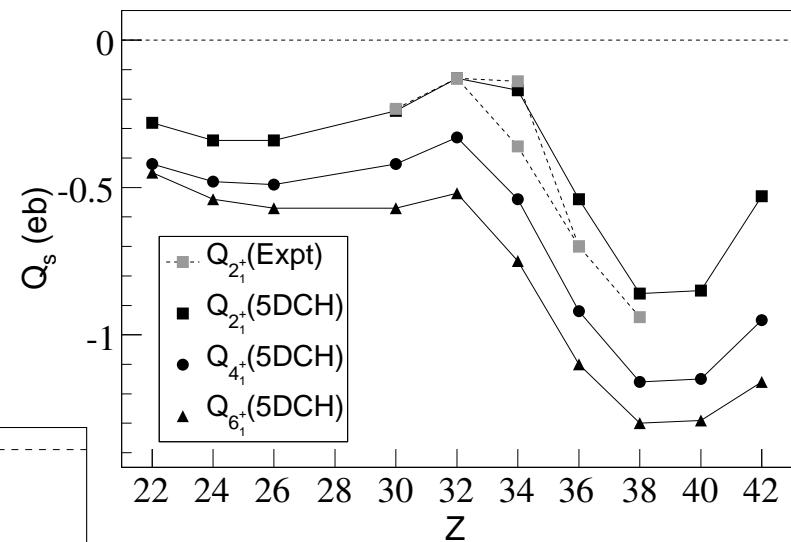
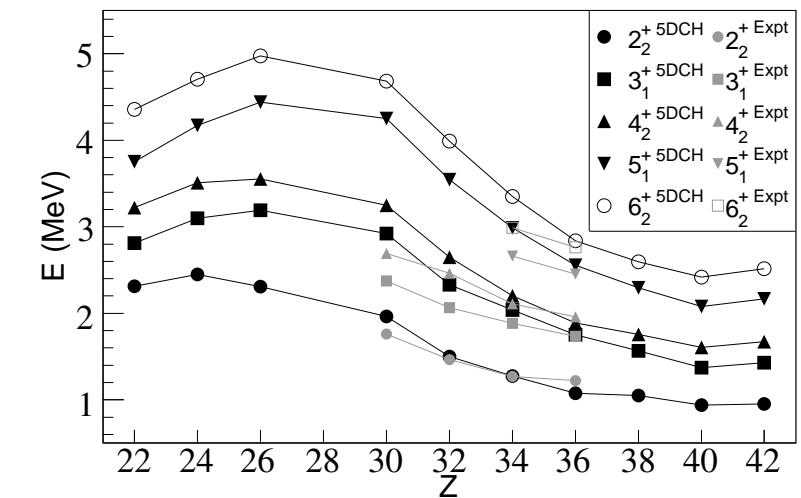
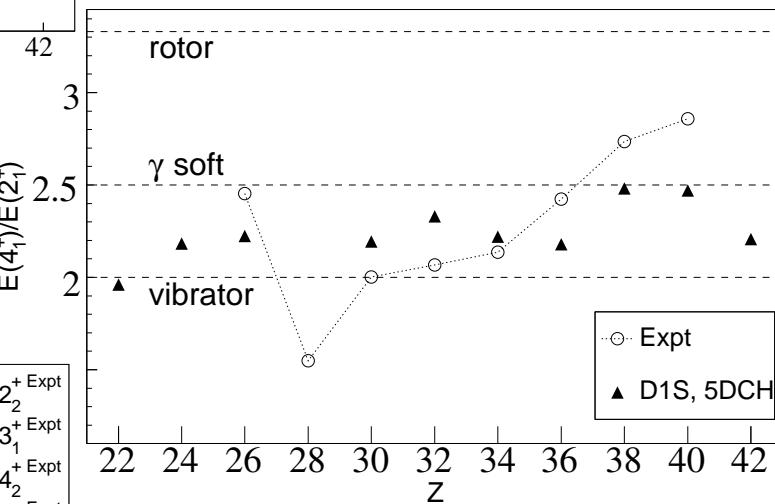
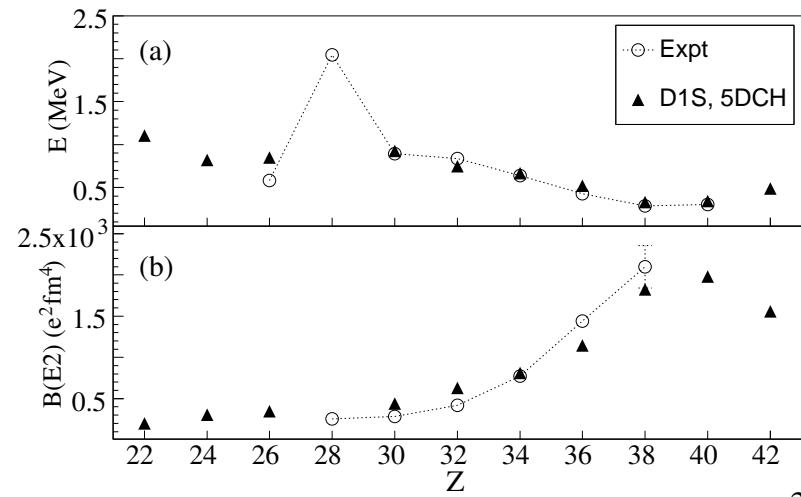
N=16



A. Obertelli, S. Péru, J.-P. Delaroche, A. Gillibert, M. Girod et H. Goutte, Phys. Rev. C **71**, 024304 (2005)

N=40

# Shell closures studies with 5DCH

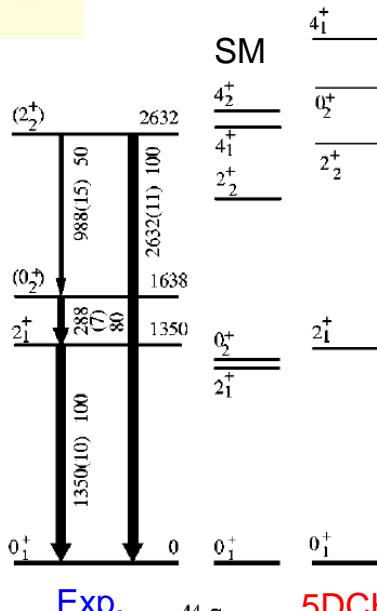
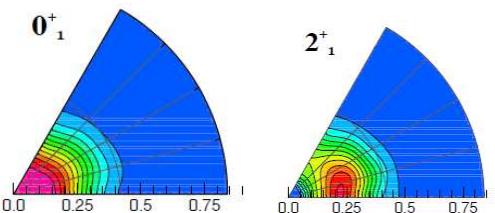
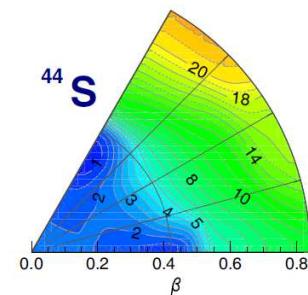
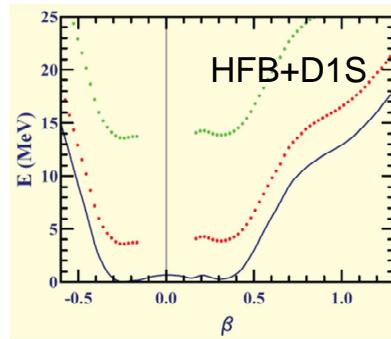


L.Gaudefroy, A. Obertelli, S. Péru,  
N. Pillet, S. Hilaire, J.-P. Delaroche,  
M.Girod and J. Libert, PRC 80,064313 (2009).

# Beyond static mean field ... with 5DCH or QRPA

## 5 Dimension Collective Hamiltonian

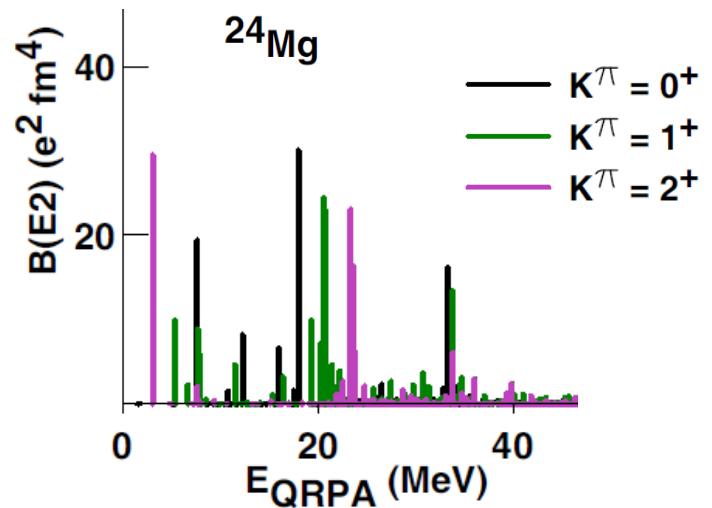
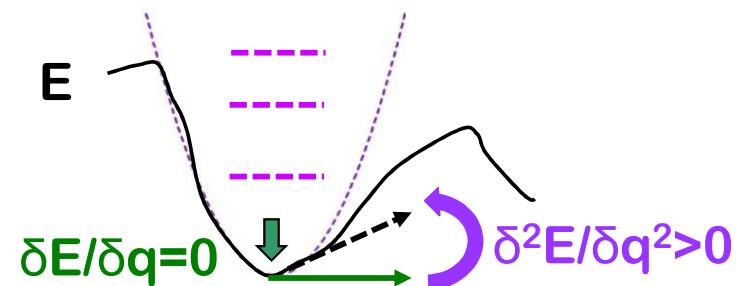
describes ground state and excited states  
within configuration mixing :  
quadrupole vibration  
and rotational degrees of freedom.



S.Péru and M. Martini, EPJA (2014) 50: 88.  
D. Sohler et al, PRC 66, 054302 (2002)

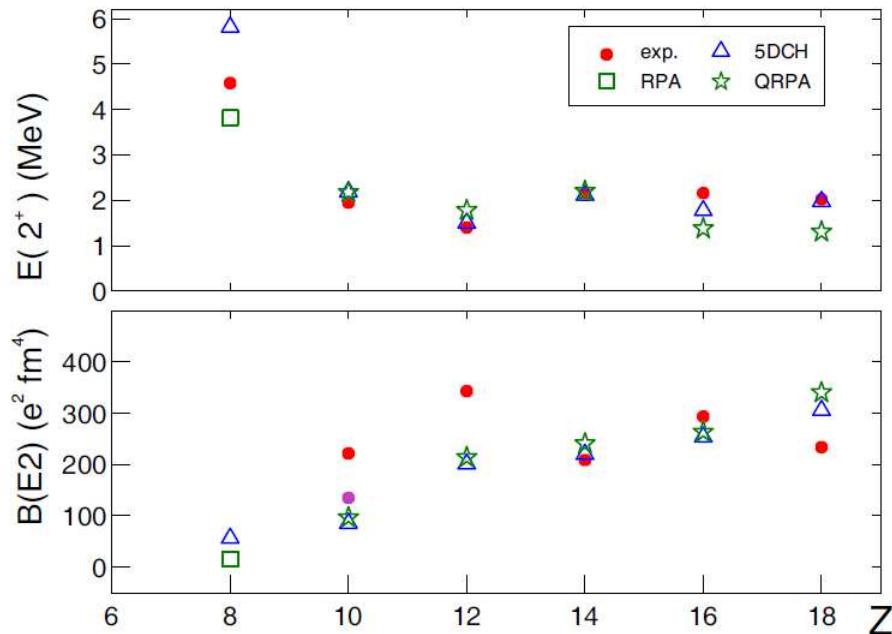
(Q)RPA approaches describe all multipolarities and all parities, collective states and individual ones, low energy and high energy states with the same accuracy.

But small amplitude approximation  
i.e. « harmonic » nuclei



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

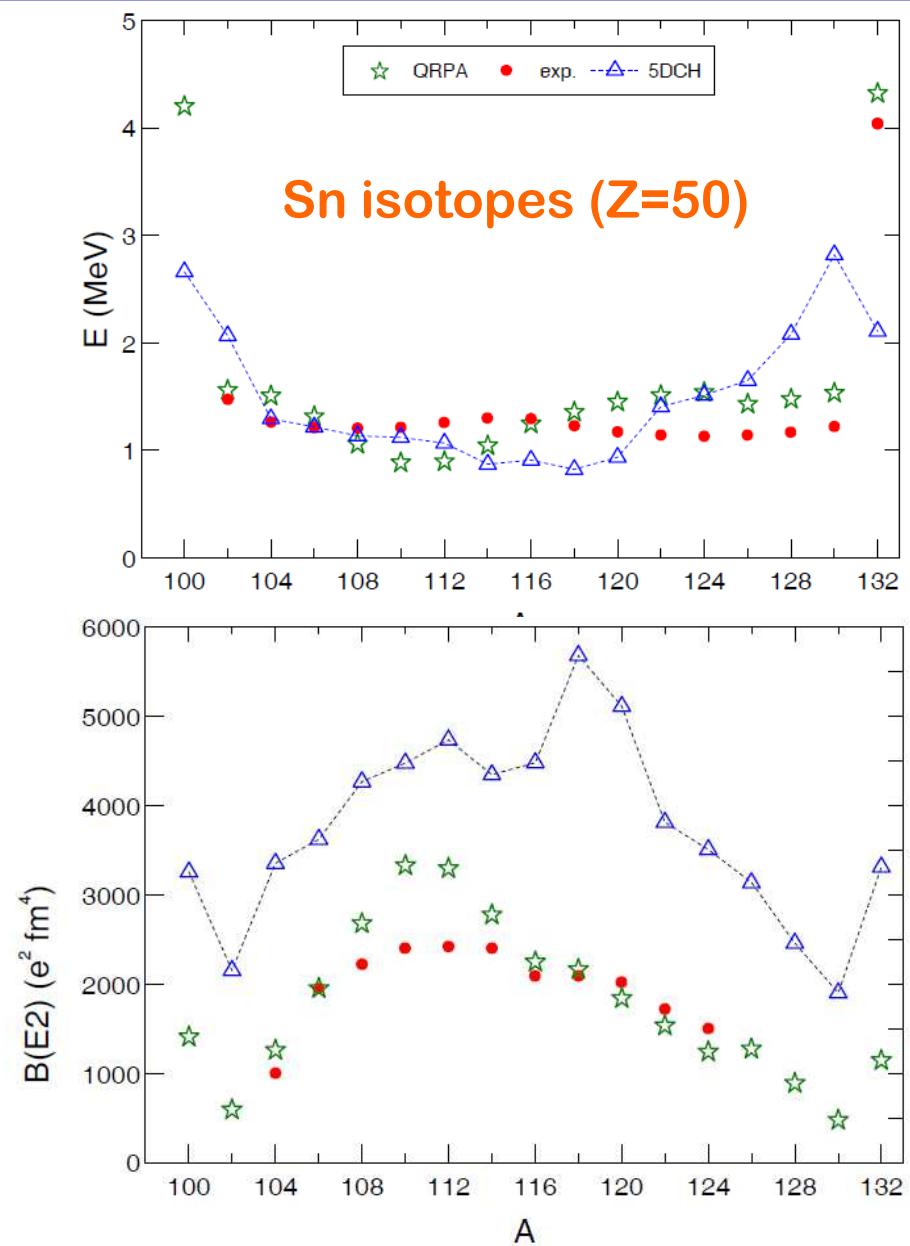
## N=16 isotones



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

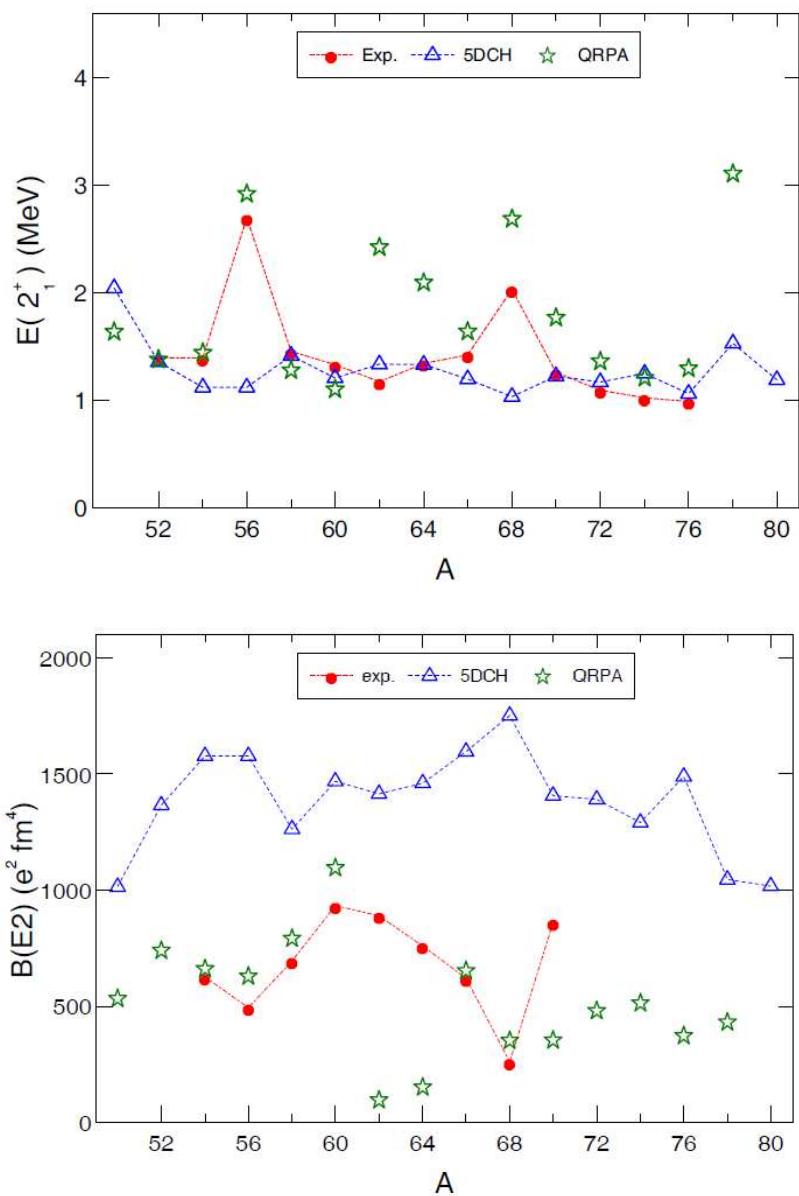
S.Péru and M. Martini, EPJA (2014) 50: 88.

## Sn isotopes ( $Z=50$ )



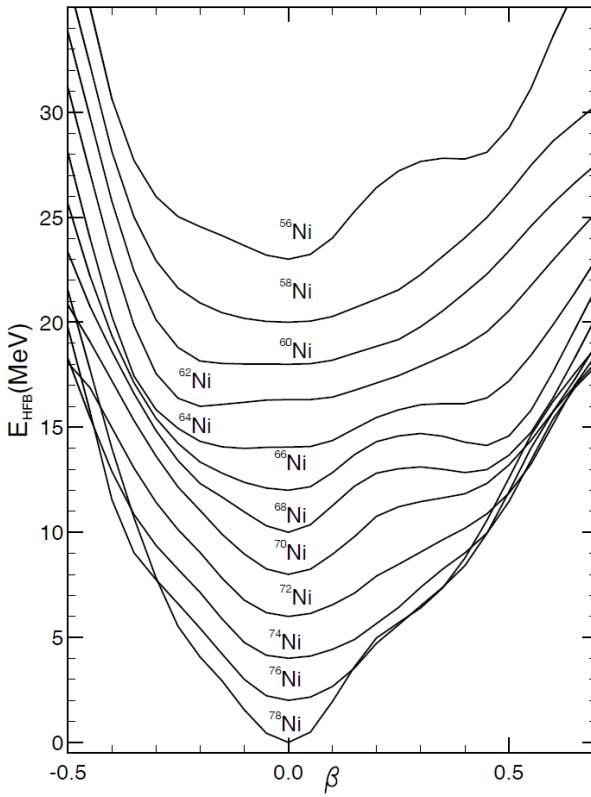
# HFB+QRPA versus HFB+5DCH with the same interaction

DE LA RECHERCHE À L'INDUSTRIE

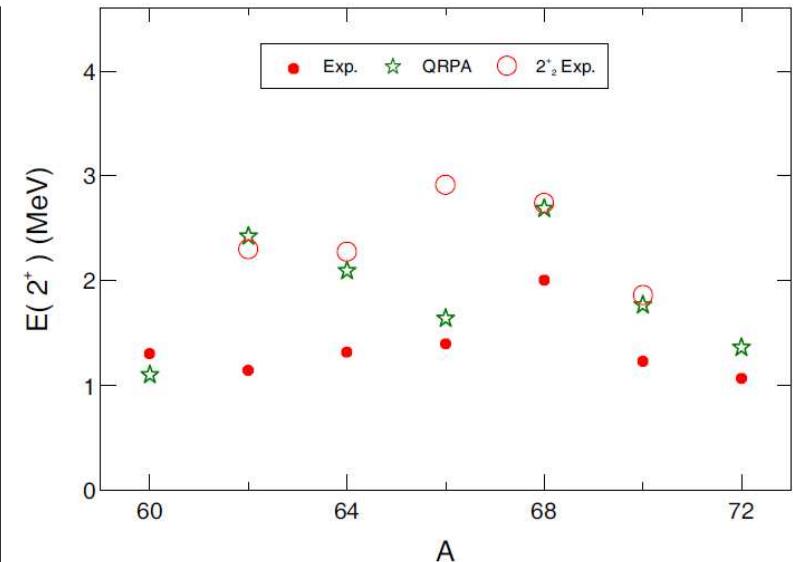


## Ni isotopes ( $Z=28$ )

Two shell ( $N= 28, 50$ ) and one sub-shell ( $N=40$ ) closures



$^{78}\text{Ni}$  is predicted doubly magic



! For deformed nuclei  
the first  $2^+$  state is rotational

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

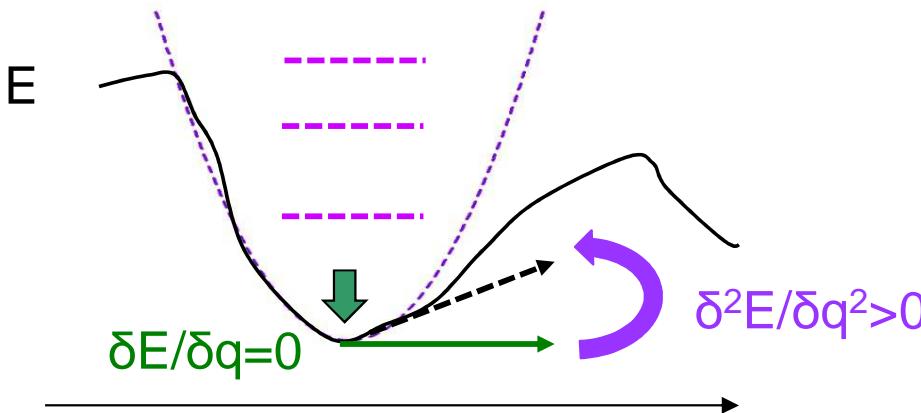
# Beyond mean field... with QRPA

RPA approaches describe

**all multipolarities 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



## Spherical RPA with Gogny force

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, J.F. Berger, PF. Bortignon, Eur. Phys. J. **A 26**, 25-32, (2005)

## Axially symmetric deformed QRPA with Gogny force

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)

RPA approaches are well adapted for describing giant resonances

# QRPA Formalism

$$H|\nu\rangle = E_\nu |\nu\rangle \quad Q_\nu^\dagger |0\rangle = |\nu\rangle \quad Q_\nu |0\rangle = 0$$

Particle-hole excitations: RPA

$$Q_\nu^\dagger = \sum_{ph} X_{ph}^\nu a_p^\dagger a_h - Y_{ph}^\nu a_h^\dagger a_p$$

2 quasi-particles excitations: QRPA

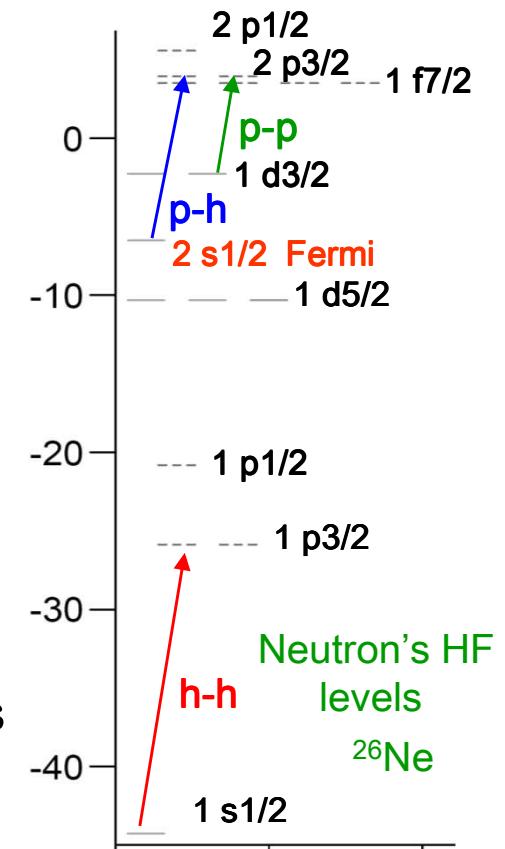
$$Q_\nu^+ = \sum_{ij} X_{ij}^\nu \eta_i^+ \eta_j^+ + Y_{ij}^\nu \eta_j^- \eta_i^- \quad \eta_i^+ = \sum_\alpha u_{i\alpha} a_\alpha^+ - v_{i\alpha} a_\alpha^-$$

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

Hartree-Fock Bogoliubov:  $\varepsilon, u, v \longrightarrow$  Ground state properties

QRPA:  $\omega, X, Y \longrightarrow$  Excited states properties

Same interaction (Gogny) in HFB and QRPA

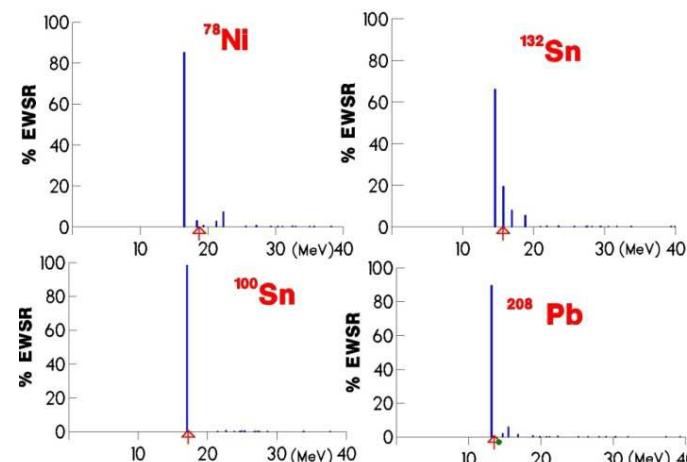


# RPA in spherical symmetry

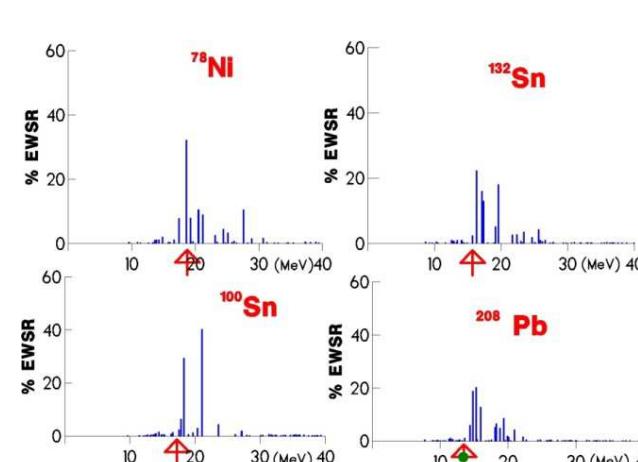
## Giant resonances in exotic nuclei:

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

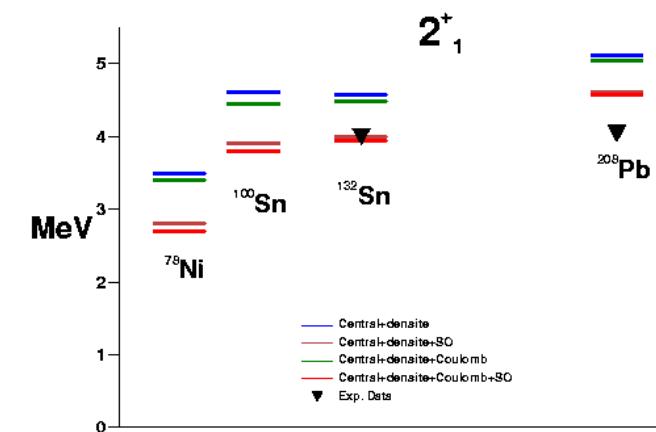
Monopole



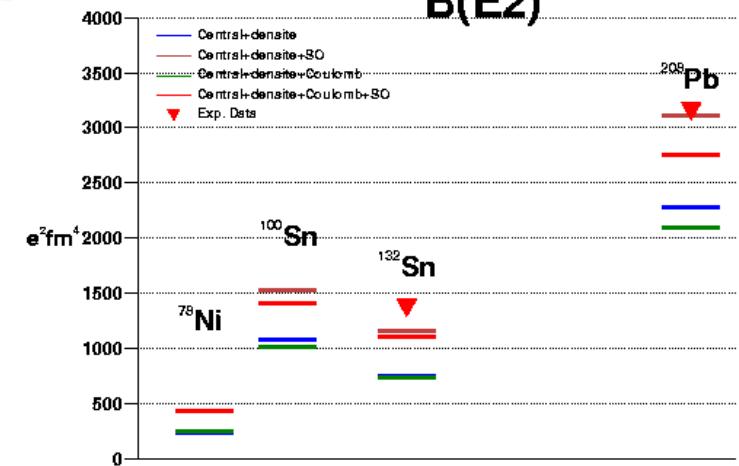
Dipole



Quadrupole



B(E2)



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

Approach limited to Spherical nuclei with no pairing

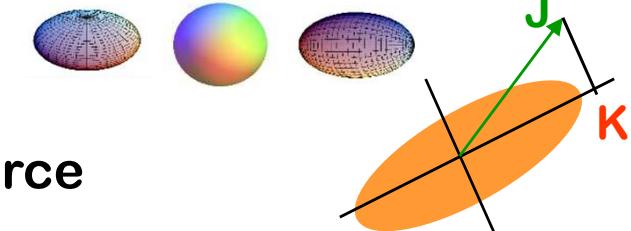
# Axially-symmetric deformed QRPA

$$|\alpha, K\rangle = \theta_{\alpha, K}^+ |0\rangle \quad \theta_{n, K}^+ = \sum_{i < j} X_{n, K}^{ij} \eta_{i, k_i}^+ \eta_{j, k_j}^+ - (-)^K Y_{n, K}^{ij} \eta_{j, -k_j} \eta_{i, -k_i}$$

$$\begin{pmatrix} A & B \\ B & A \end{pmatrix} \begin{pmatrix} X_{\alpha, K} \\ Y_{\alpha, K} \end{pmatrix} = \omega_{\alpha, K} \begin{pmatrix} X_{\alpha, K} \\ -Y_{\alpha, K} \end{pmatrix}$$

## 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**

## Gogny force (D1M, D1S)

$$\begin{aligned}
 V(1, 2) = & \sum_{j=1,2} e^{-\frac{(\vec{r}_1 - \vec{r}_2)^2}{\mu_j^2}} (W_j + B_j P_\sigma - H_j P_\tau - M_j P_\sigma P_\tau) \\
 & + t_0 (1 + x_0 P_\sigma) \delta(\vec{r}_1 - \vec{r}_2) \left[ \rho \left( \frac{\vec{r}_1 + \vec{r}_2}{2} \right) \right]^\alpha \\
 & + i W_{ls} \overleftrightarrow{\nabla}_{12} \delta(\vec{r}_1 - \vec{r}_2) \times \overrightarrow{\nabla}_{12} \cdot (\vec{\sigma}_1 + \vec{\sigma}_2)
 \end{aligned}$$

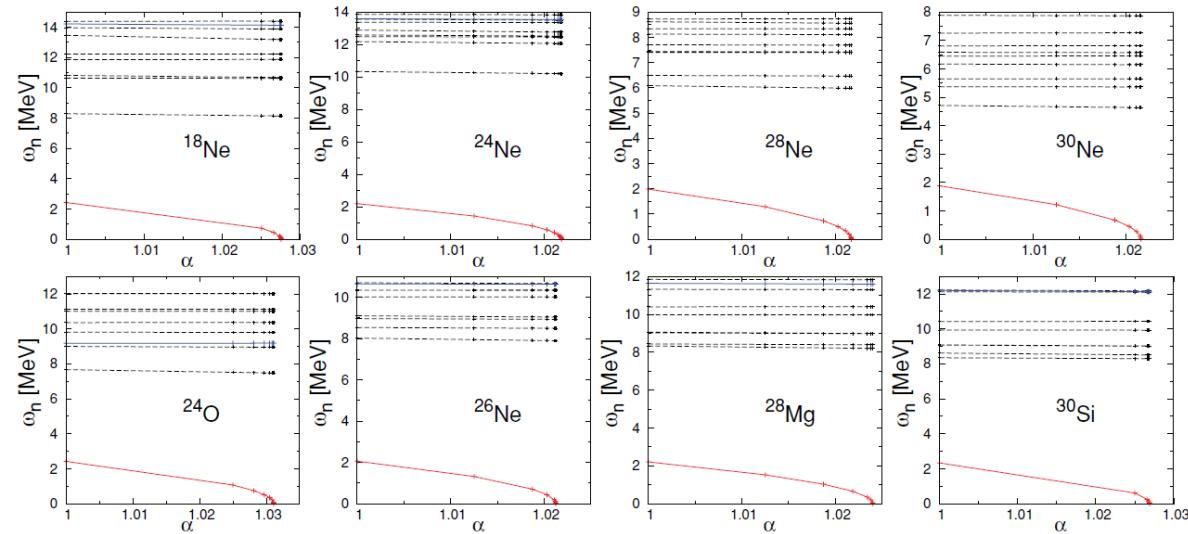
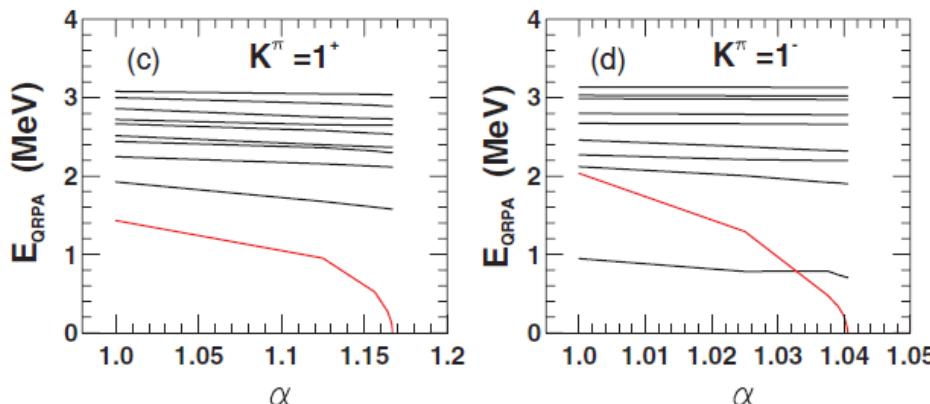
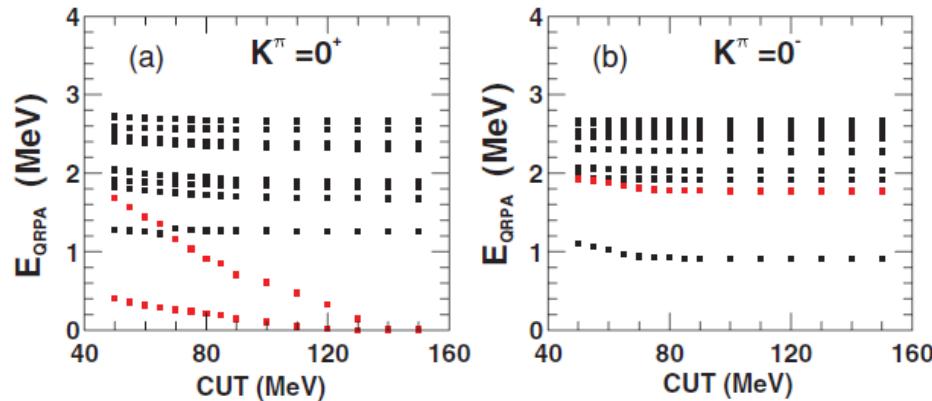
central      finite range  
density dependent  
spin-orbit

# Spurious states « treatment »

PHYSICAL REVIEW C 83, 014314 (2011)

## Giant resonances in $^{238}\text{U}$ within the quasiparticle random-phase approximation with the Gogny force

S. Péru,<sup>1,\*</sup> G. Gosselin,<sup>1</sup> M. Martini,<sup>1</sup> M. Dupuis,<sup>1</sup> S. Hilaire,<sup>1</sup> and J.-C. Devaux<sup>2</sup>



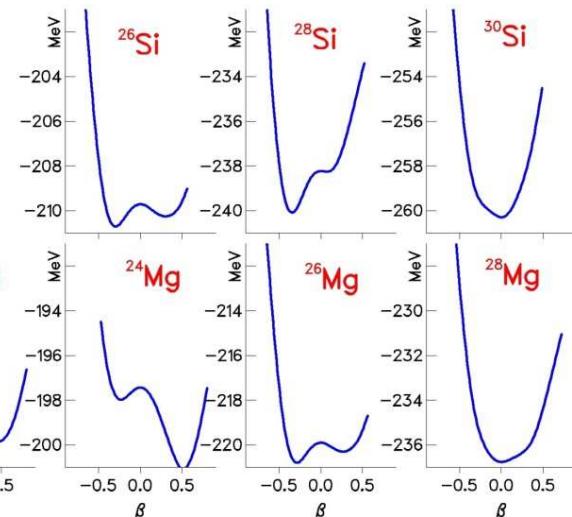
PHYSICAL REVIEW C 83, 034309 (2011)

## Low-energy dipole excitations in neon isotopes and $N = 16$ isotones within the quasiparticle random-phase approximation and the Gogny force

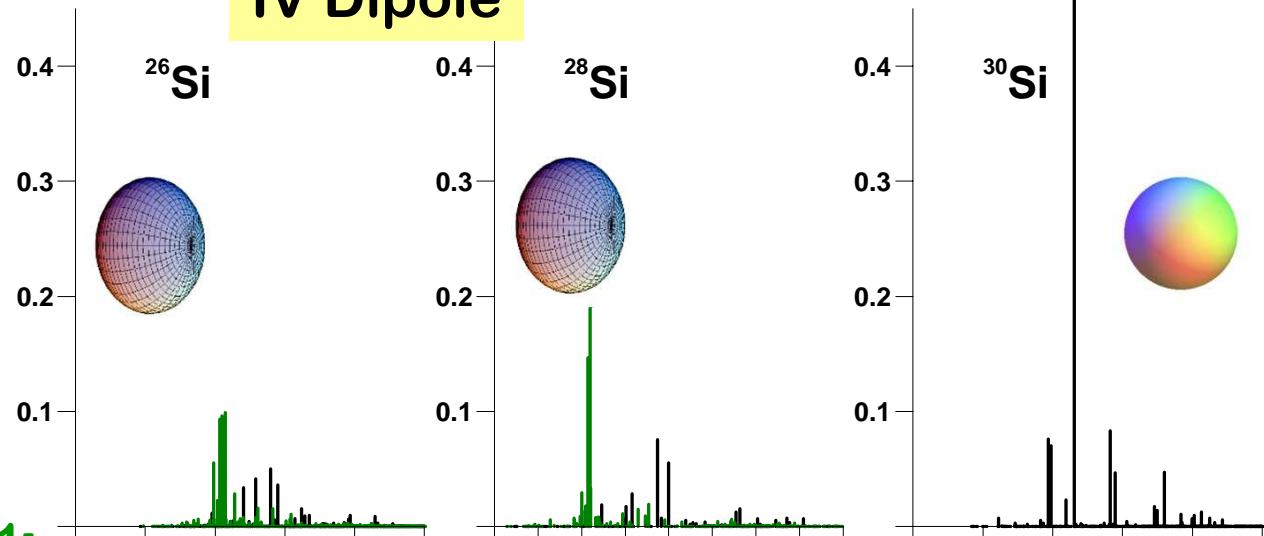
M. Martini, S. Péru, and M. Dupuis

# First study with QRPA in axial symmetry

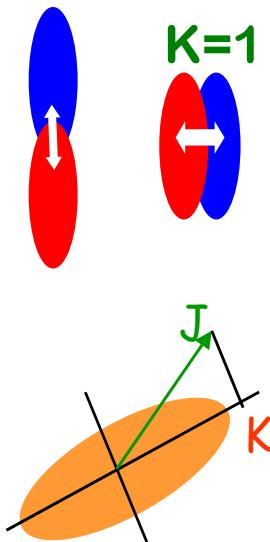
## Potential Energy Surfaces



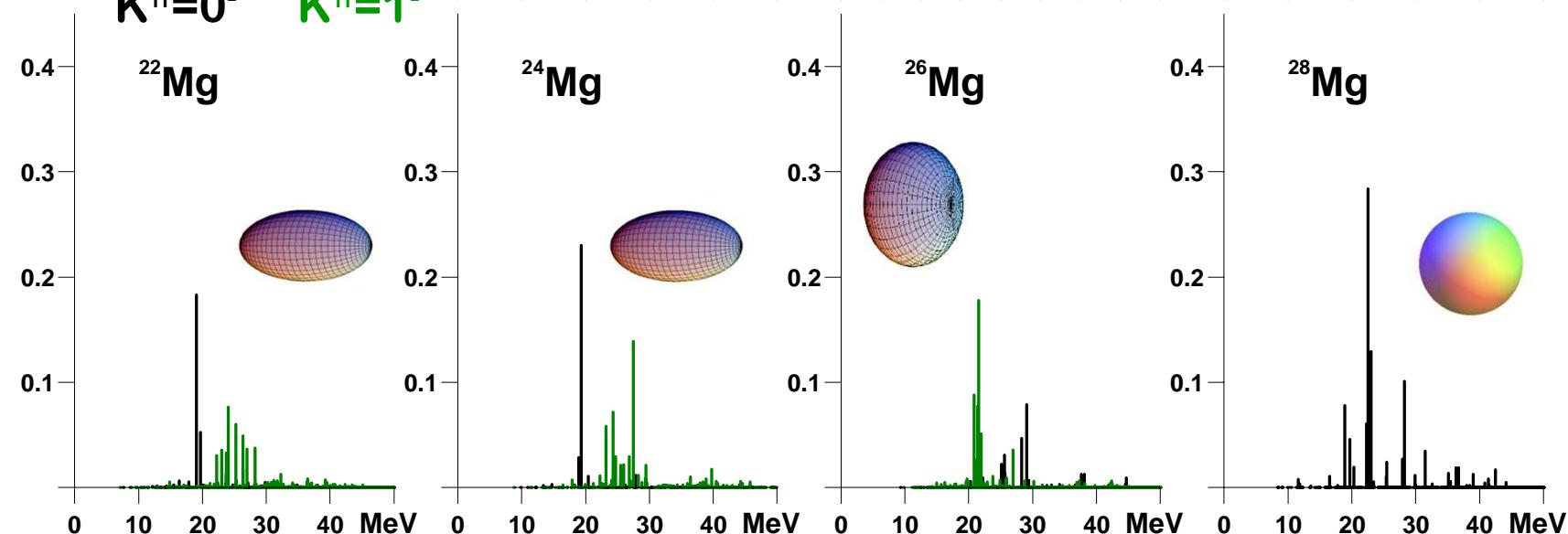
## IV Dipole



$K=0$



$K^{\pi}=0^-$     $K^{\pi}=1^-$



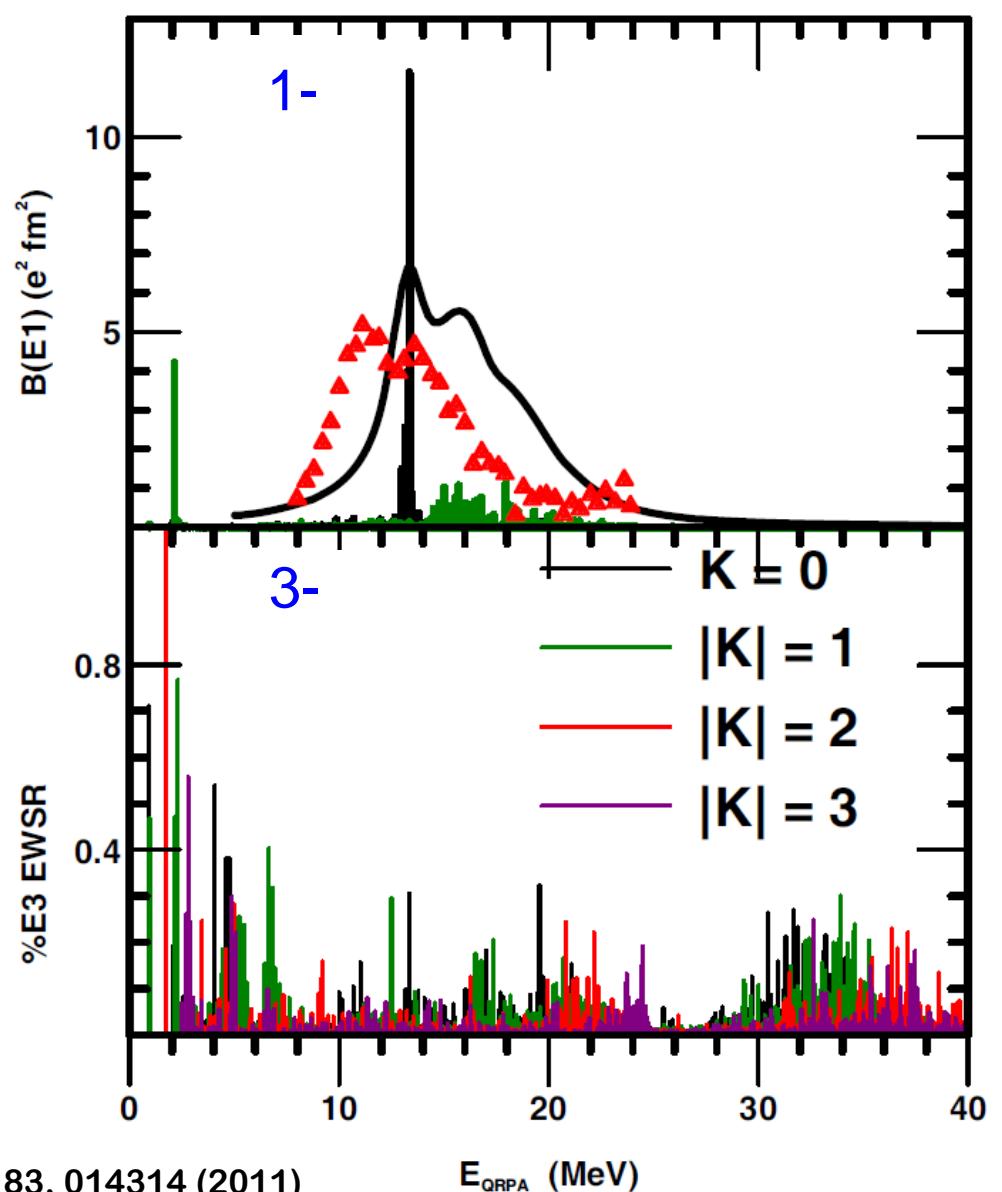
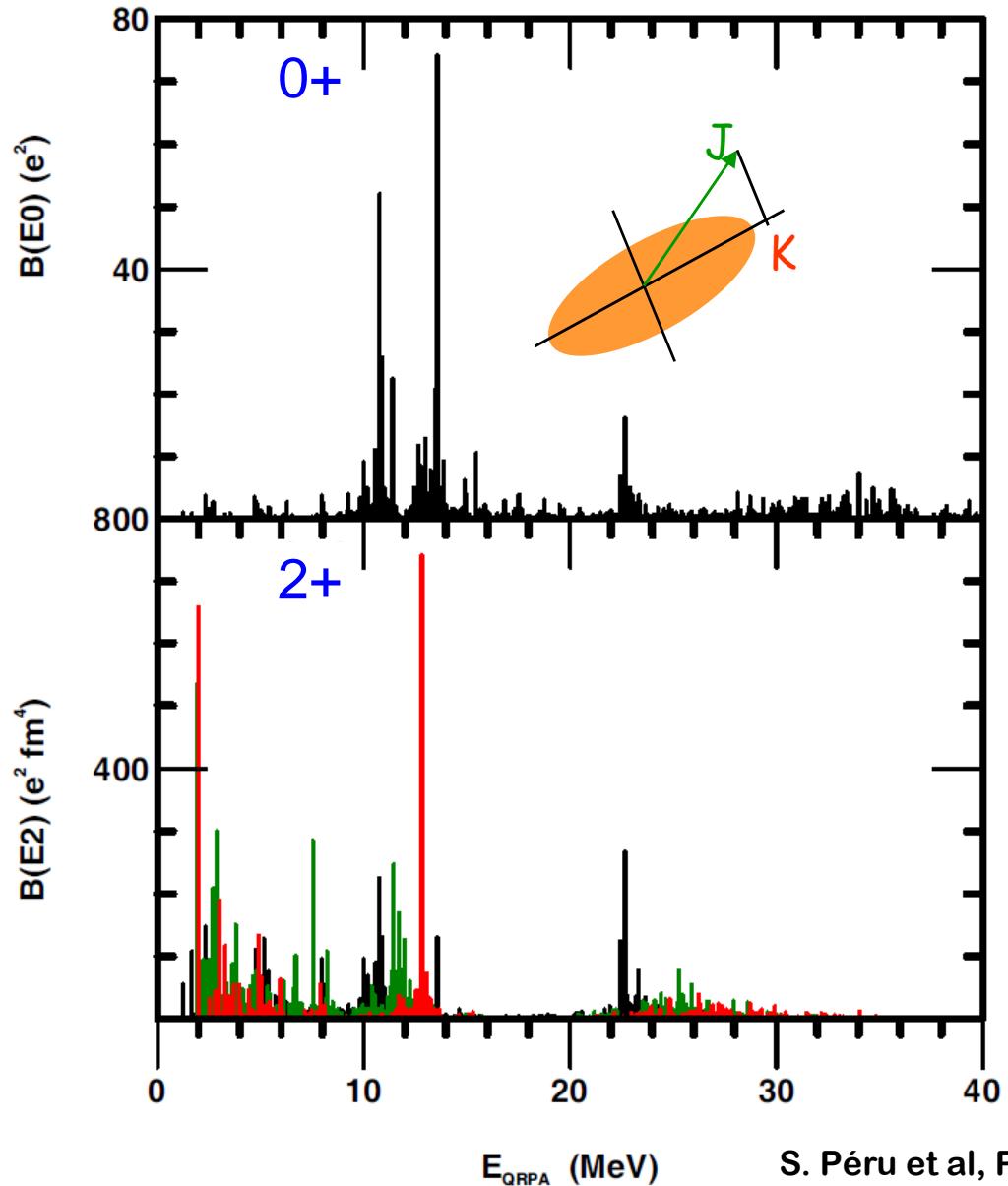
S. Péru and H. Goutte, Phys. Rev. C 77, 044313 (2008).

# Multipolar responses for $^{238}\text{U}$

Heavy deformed nucleus



massively parallel computation

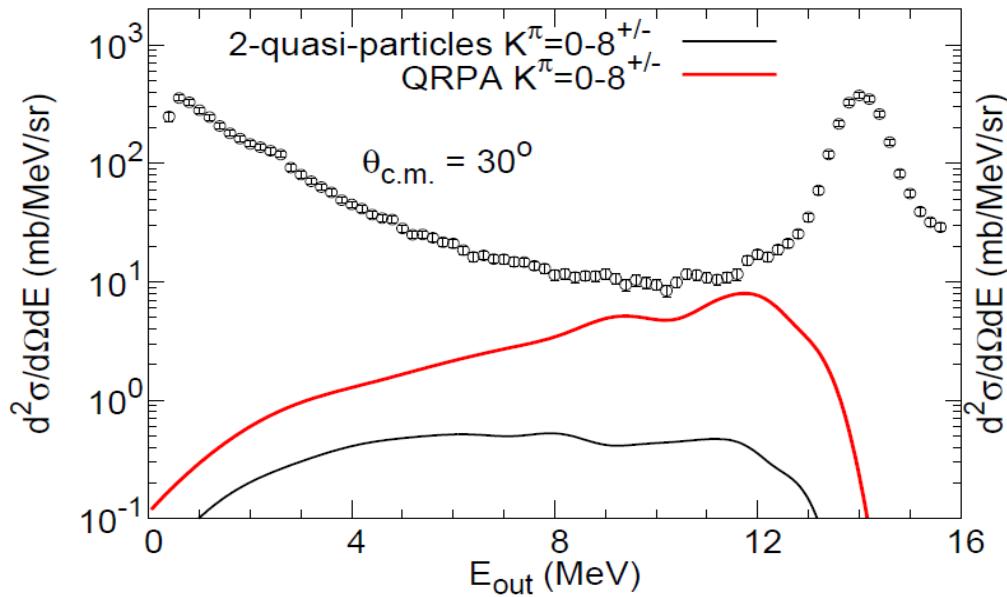


# Beyond the nuclear structure

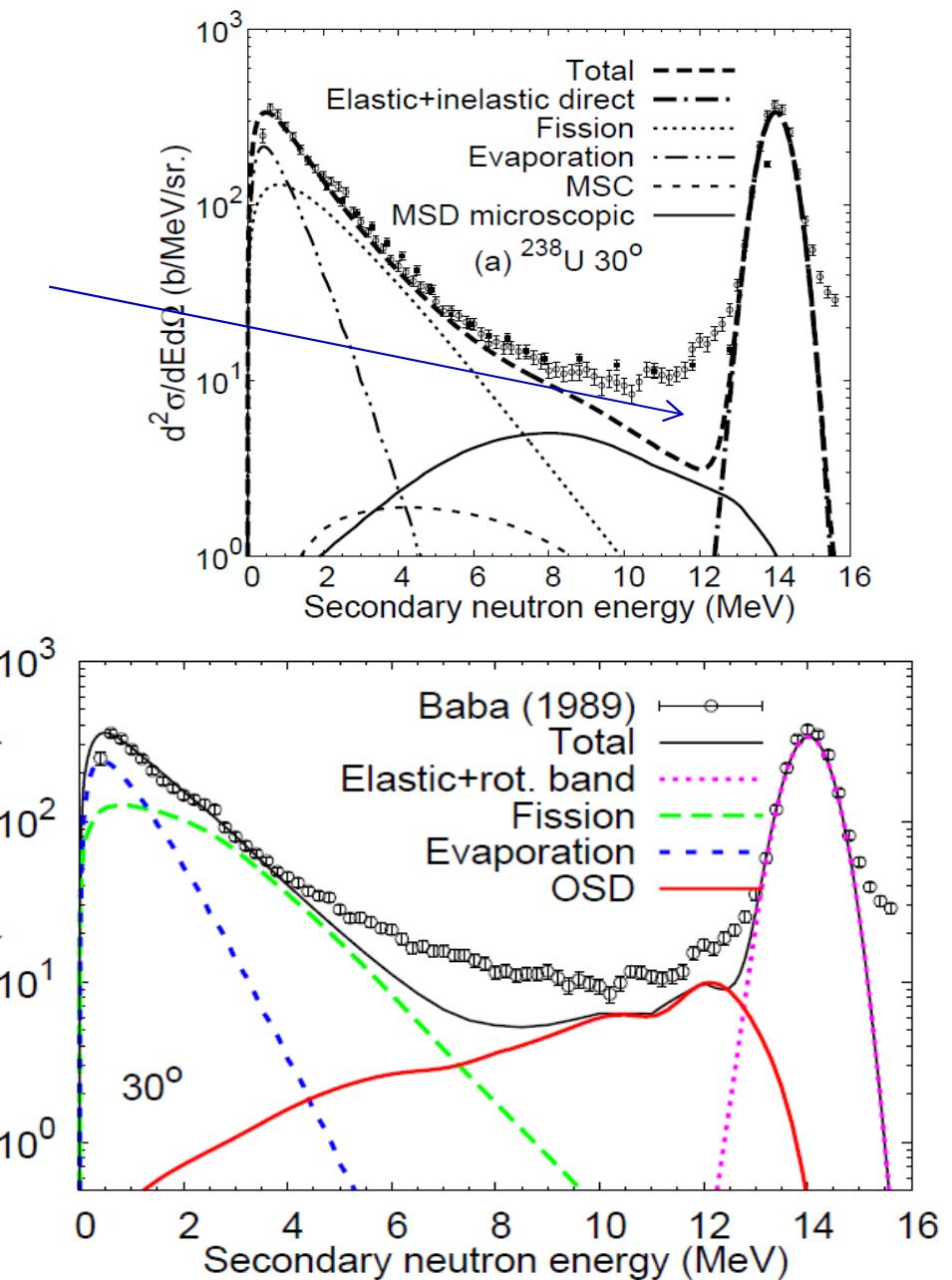
(n, x n) cross section on  $^{238}\text{U}$

Problem of underestimation of  
n emission cross section at high energy

**QRPA provides  
enough collective contribution**

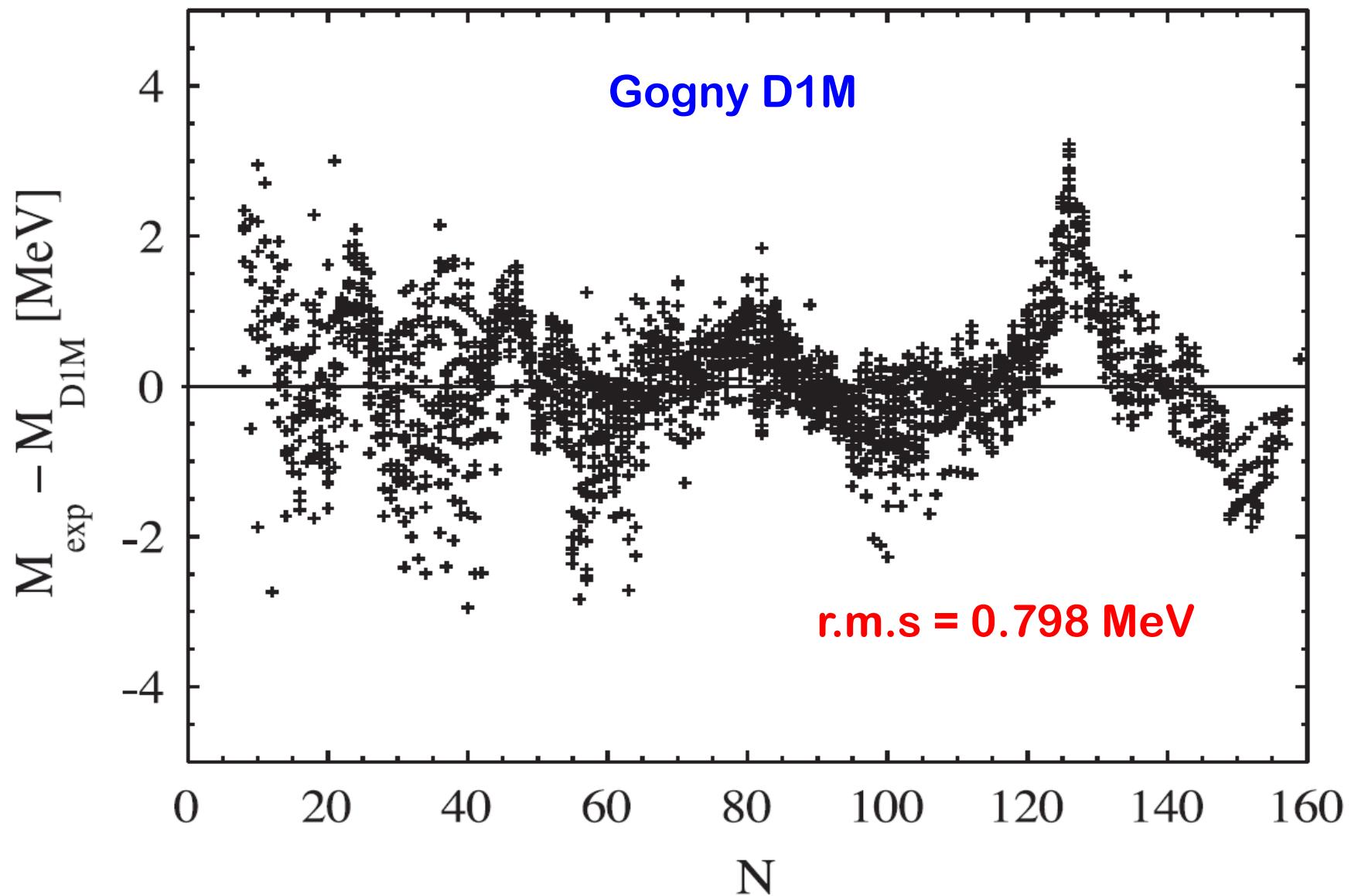


M. Dupuis, S. Péru, E. Bauge and T. Kawano,  
13th International Conference on Nuclear Reaction Mechanisms, Varenna 2012  
CERN-Proceedings-2012-002, p 95



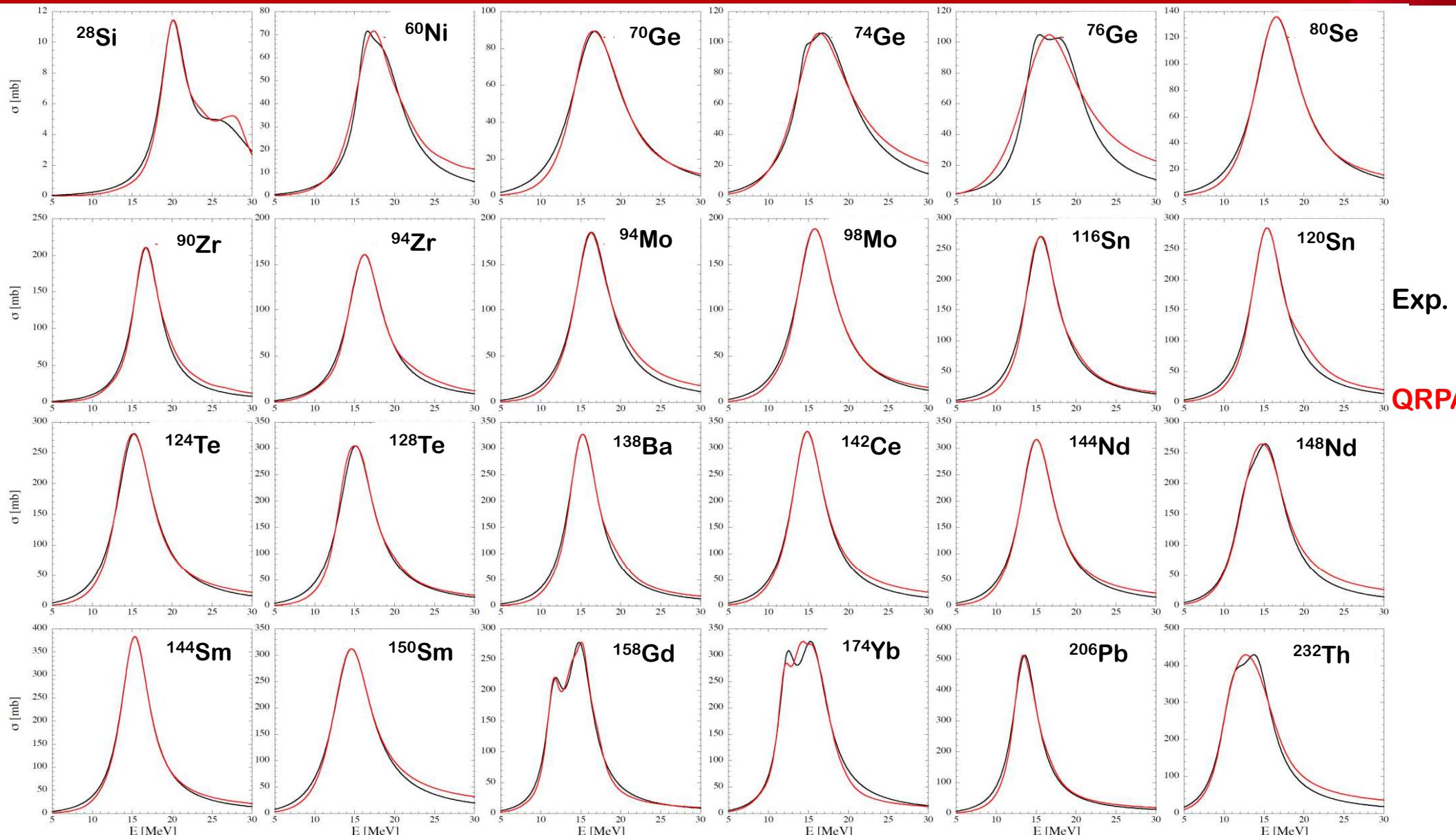
# Nuclear Masses

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



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

# Dipole excitations and photoabsorption results



We calculate E1 strength for all the nuclei for which photoabsorption data exist.

QRPA strength  $S_{E1}(w)$  is folded with a Lorentzian function with an energy shift deduced from GDR centroid.

# 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  $\Gamma$

$$f_{E1}(E) = \int_{-\infty}^{+\infty} L(E, \omega) S_{E1}(\omega) d\omega \quad L(E, \omega) = \frac{1}{\pi} \frac{\Gamma^2 E^2}{(E^2 - (\omega - \Delta)^2)^2 + \Gamma^2 E^2}$$

## Model 0:

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

$$\Delta = 2 \text{ MeV} \text{ and } \Gamma = 2.5 \text{ MeV}$$

## Model 1:

$\Gamma$  is adjusted on each photoabsortion cross section

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

$$\Delta_0 \text{ is constant and } \Delta_{4qp}(\omega) = \delta_{4qp} \times n_{4qp}(\omega) / n_{4qp}(30 \text{ MeV})$$

## Model 2:

$\Gamma$  is adjusted on each photoabsortion cross section

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

$$\Delta_0 \text{ is constant and } \Delta_{4qp}(\omega) = \delta_{4qp} \times n_{4qp}(\omega) / n_{2qp}(\omega)$$

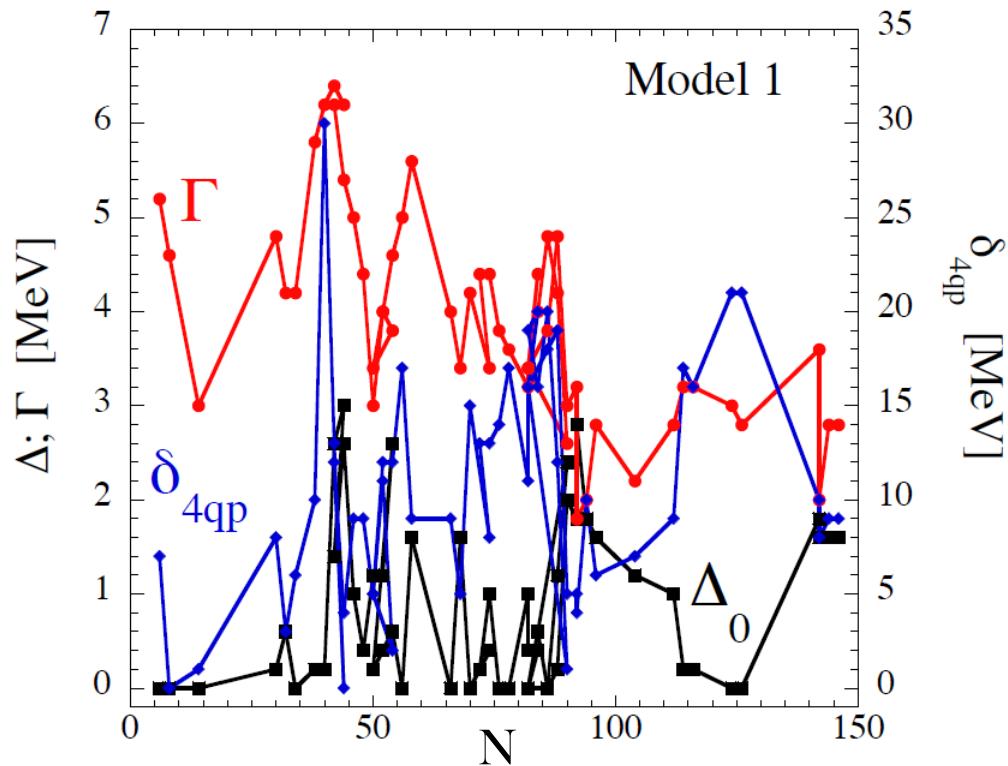


# Semi-empirical broadening of the GDR

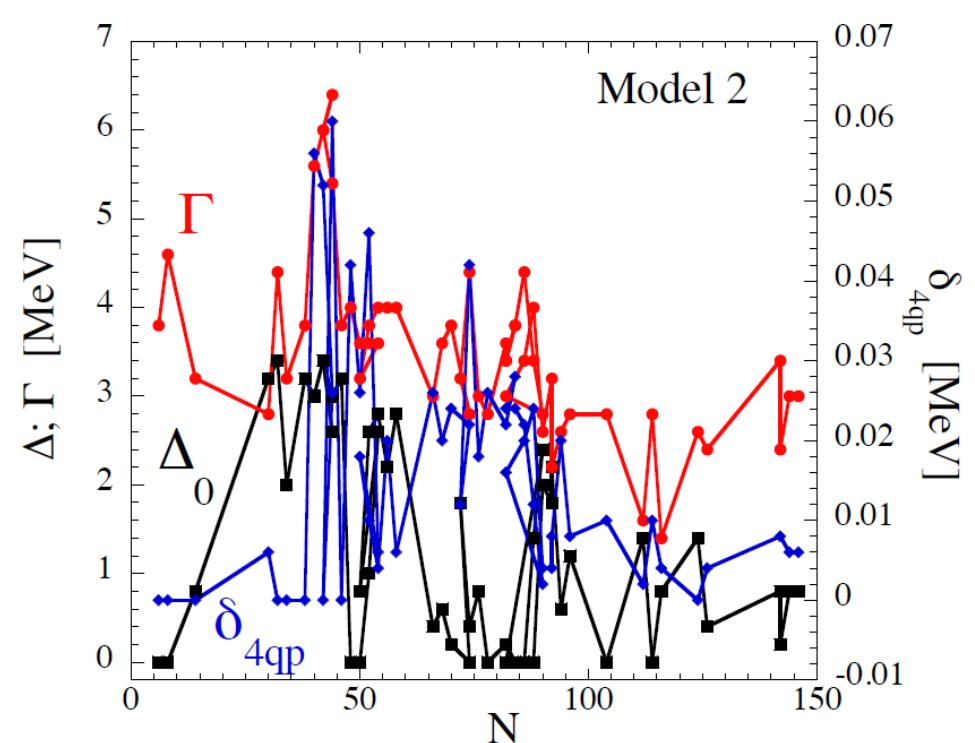
$$L(E, \omega) = \frac{1}{\pi} \frac{\Gamma^2 E^2}{(E^2 - (\omega - \Delta)^2)^2 + \Gamma^2 E^2}$$

$$\Delta(\omega) = \Delta_0 + \Delta_{4qp}(\omega)$$

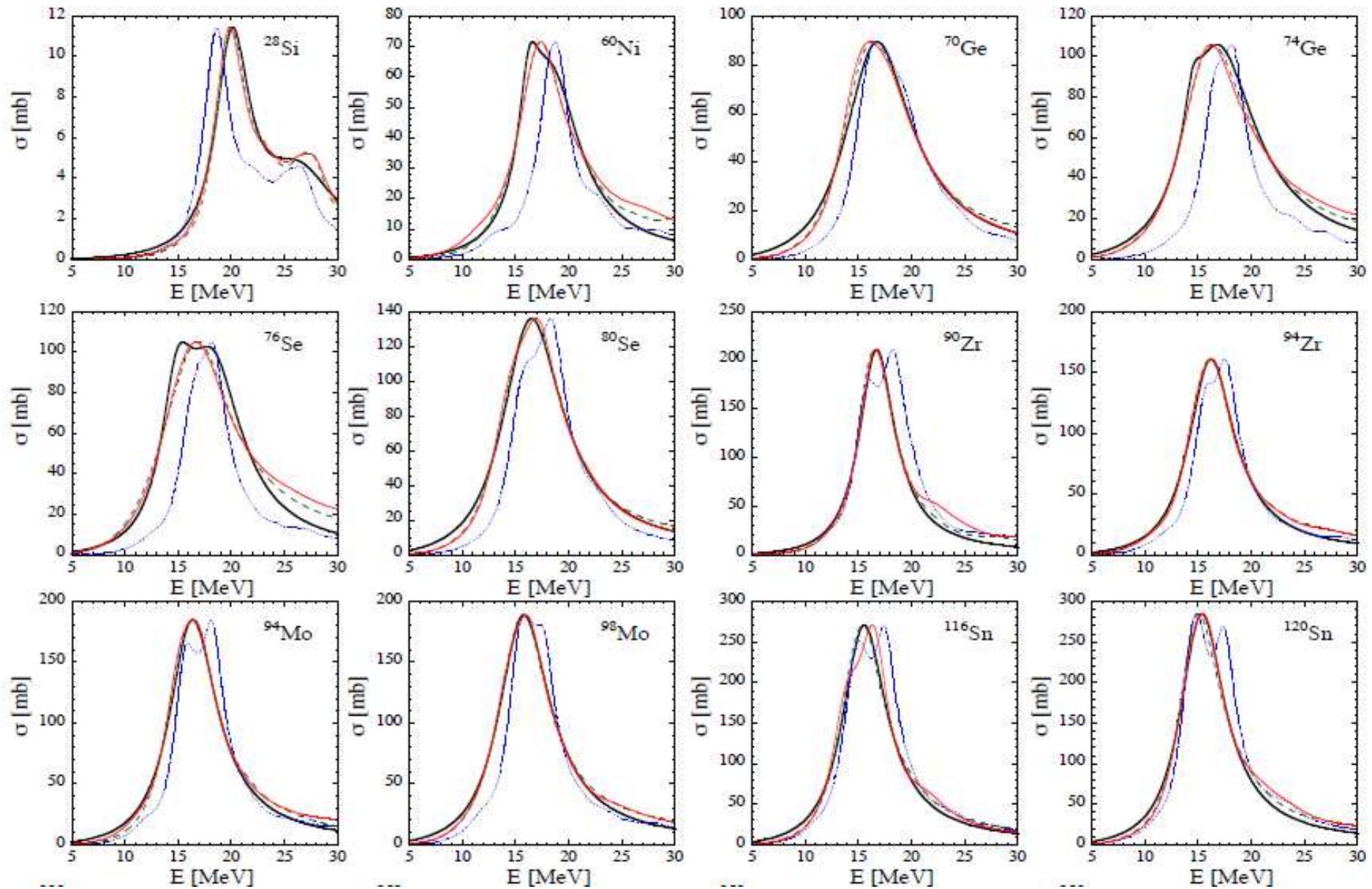
$$\Delta_{4qp}(\omega) = \delta_{4qp} \times n_{4qp}(\omega)/n_{4qp}(30 \text{ MeV})$$



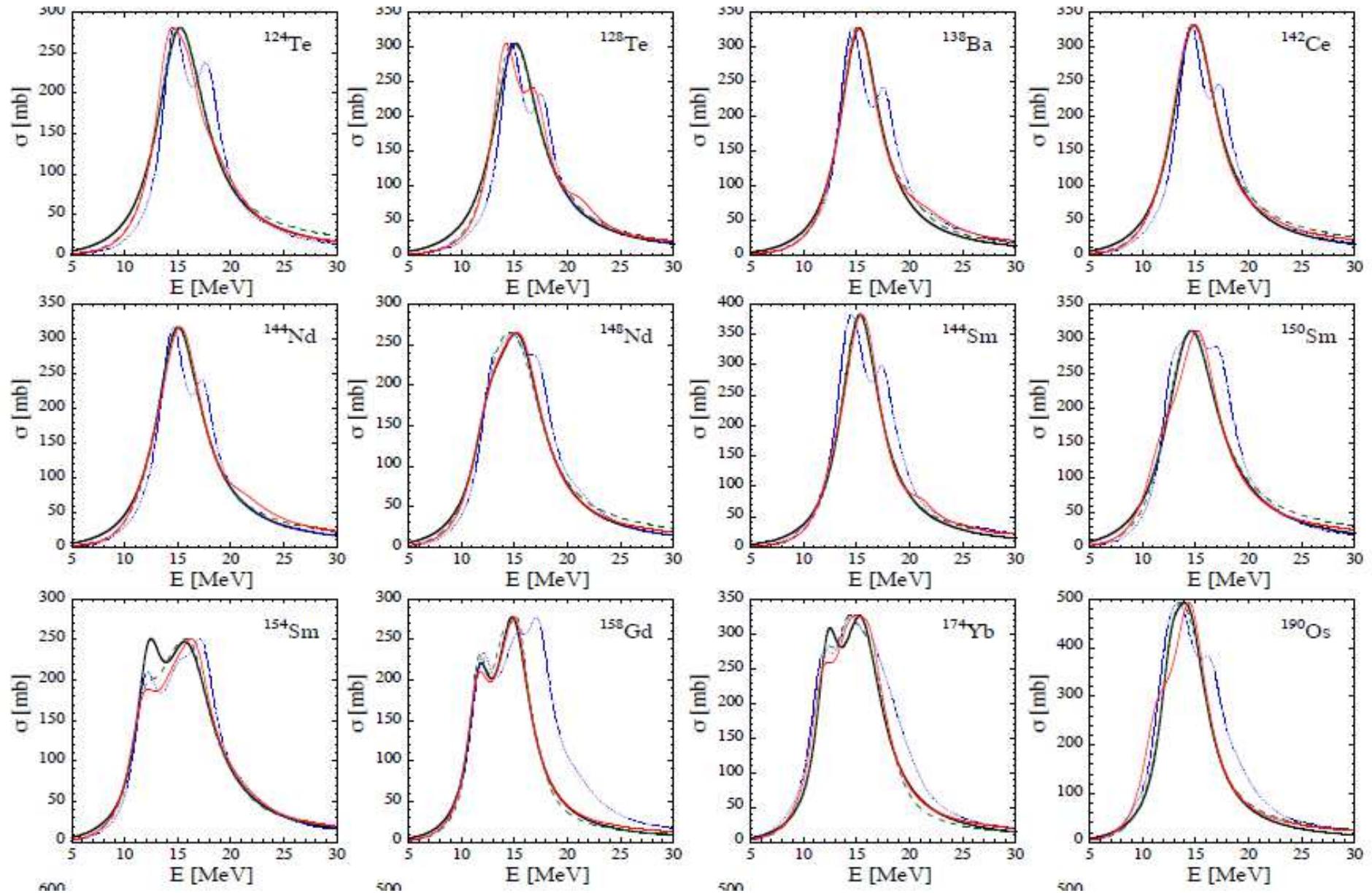
$$\Delta_{4qp}(\omega) = \delta_{4qp} \times n_{4qp}(\omega)/n_{2qp}(\omega)$$



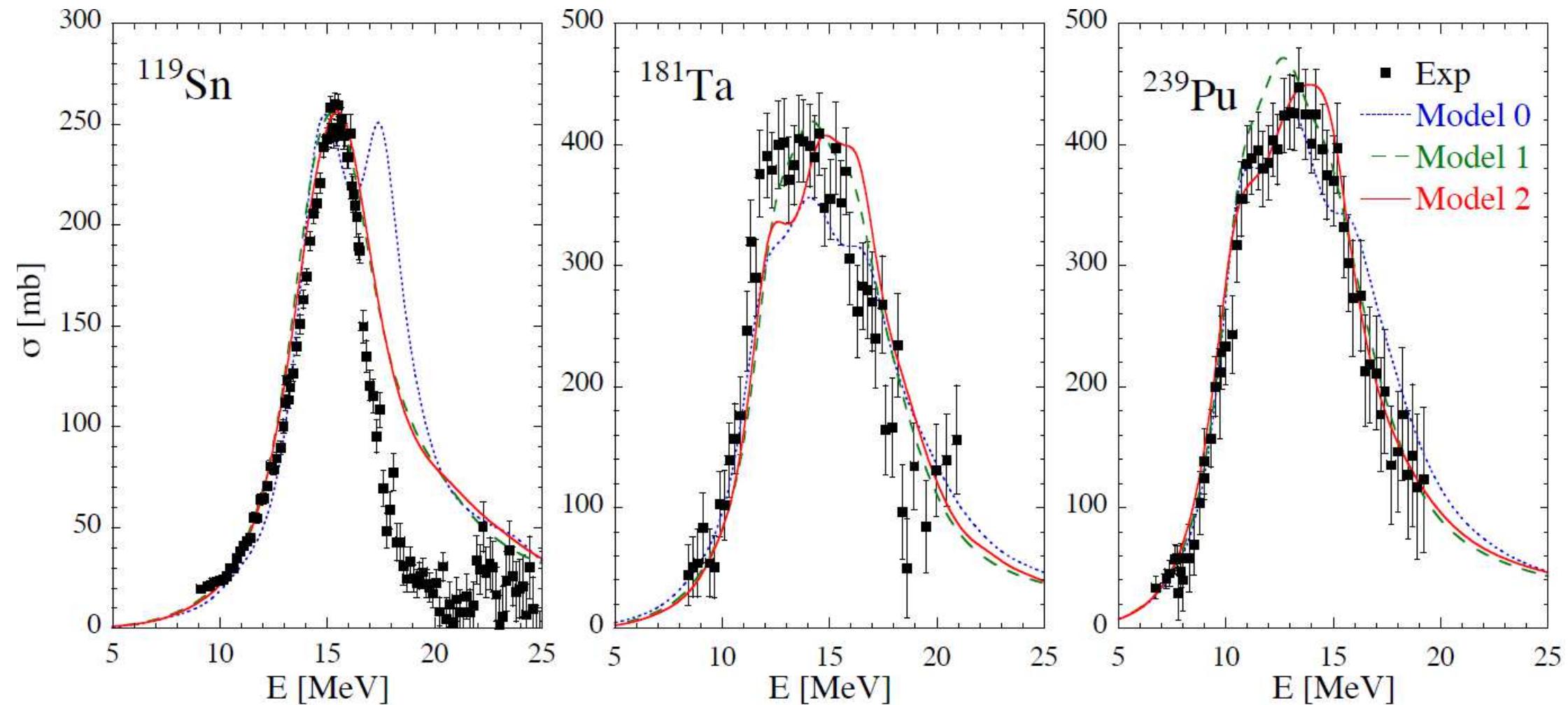
# Semi-empirical broadening of the GDR



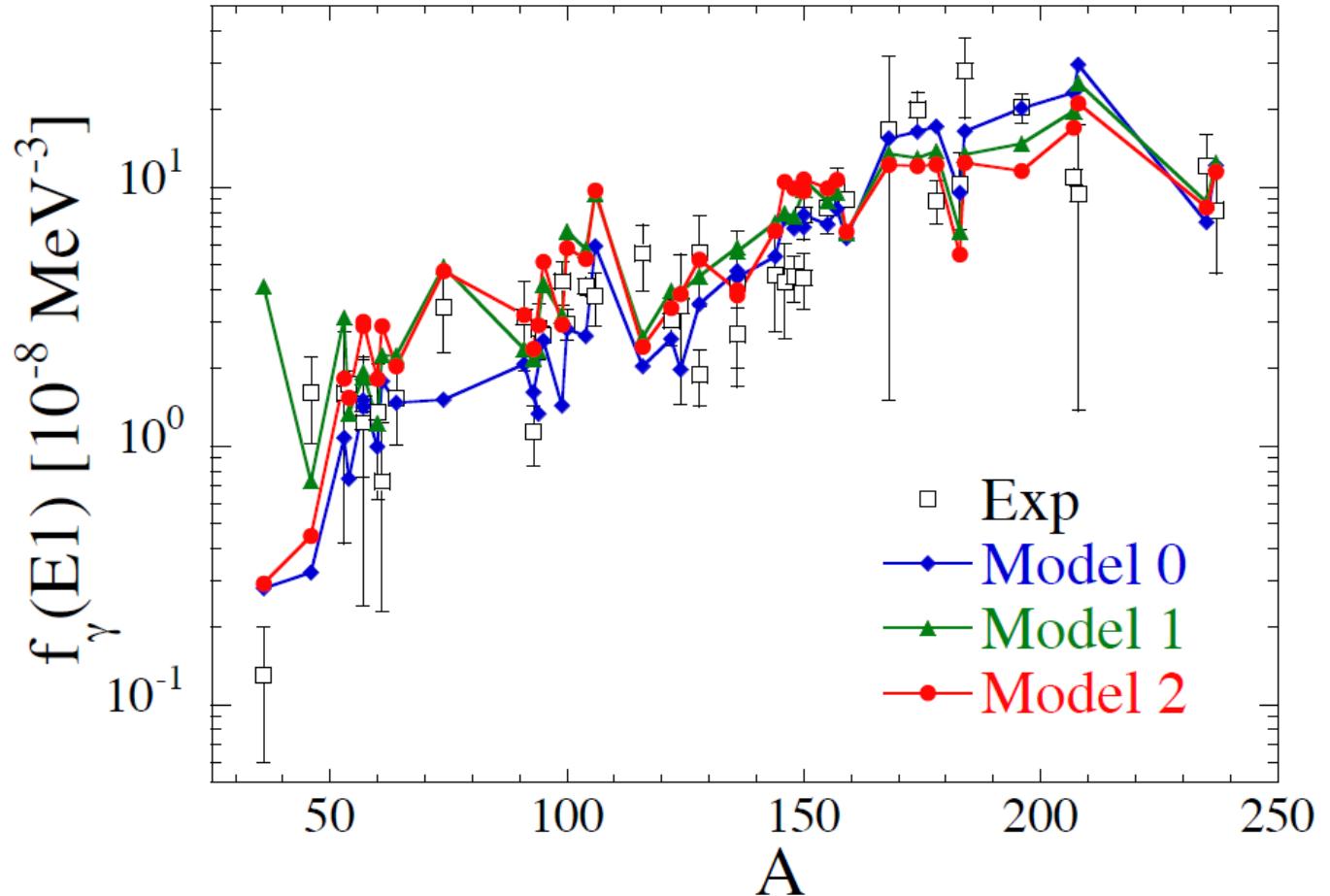
# Semi-empirical broadening of the GDR



# Dipole excitations and photoabsorption results



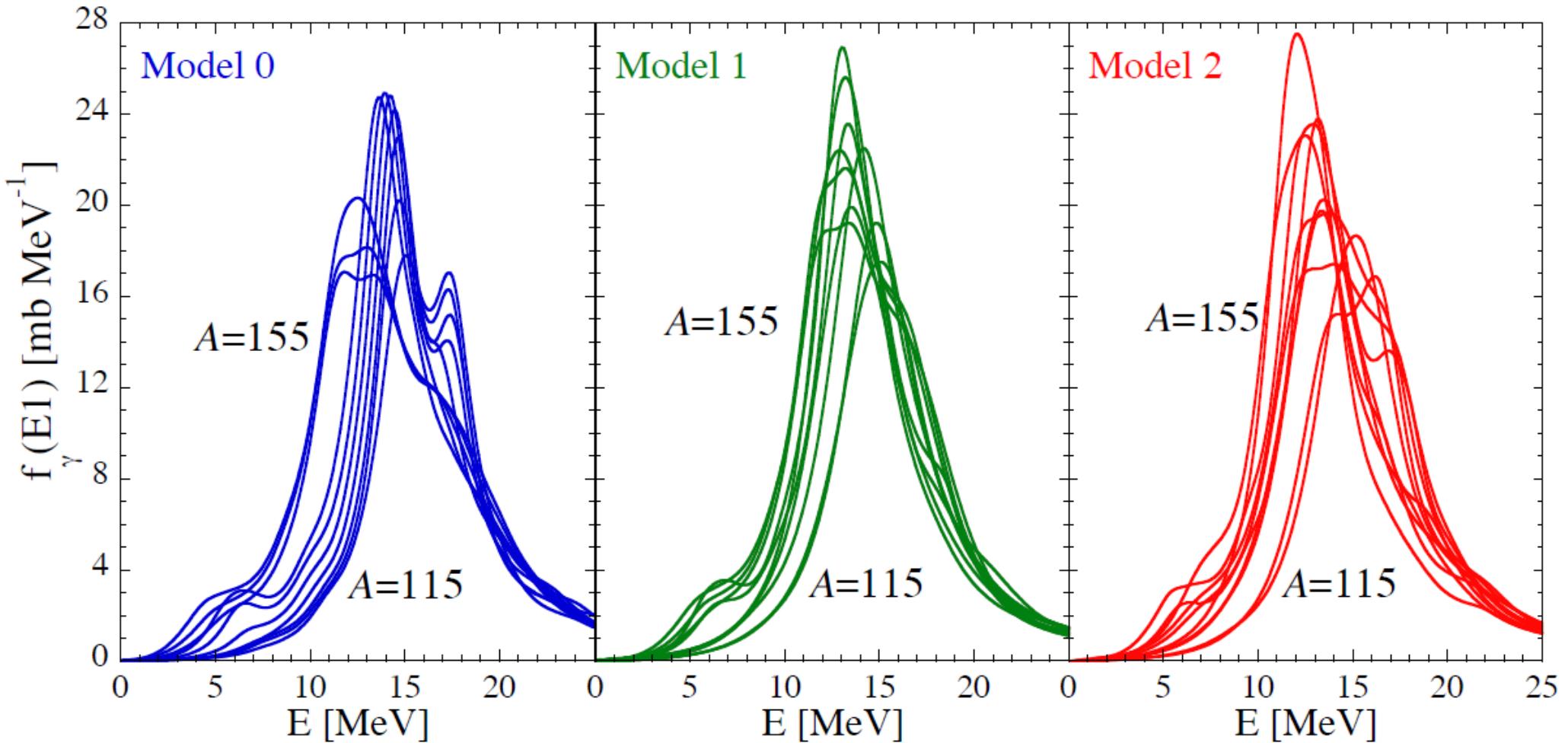
# Low energy dipole excitations



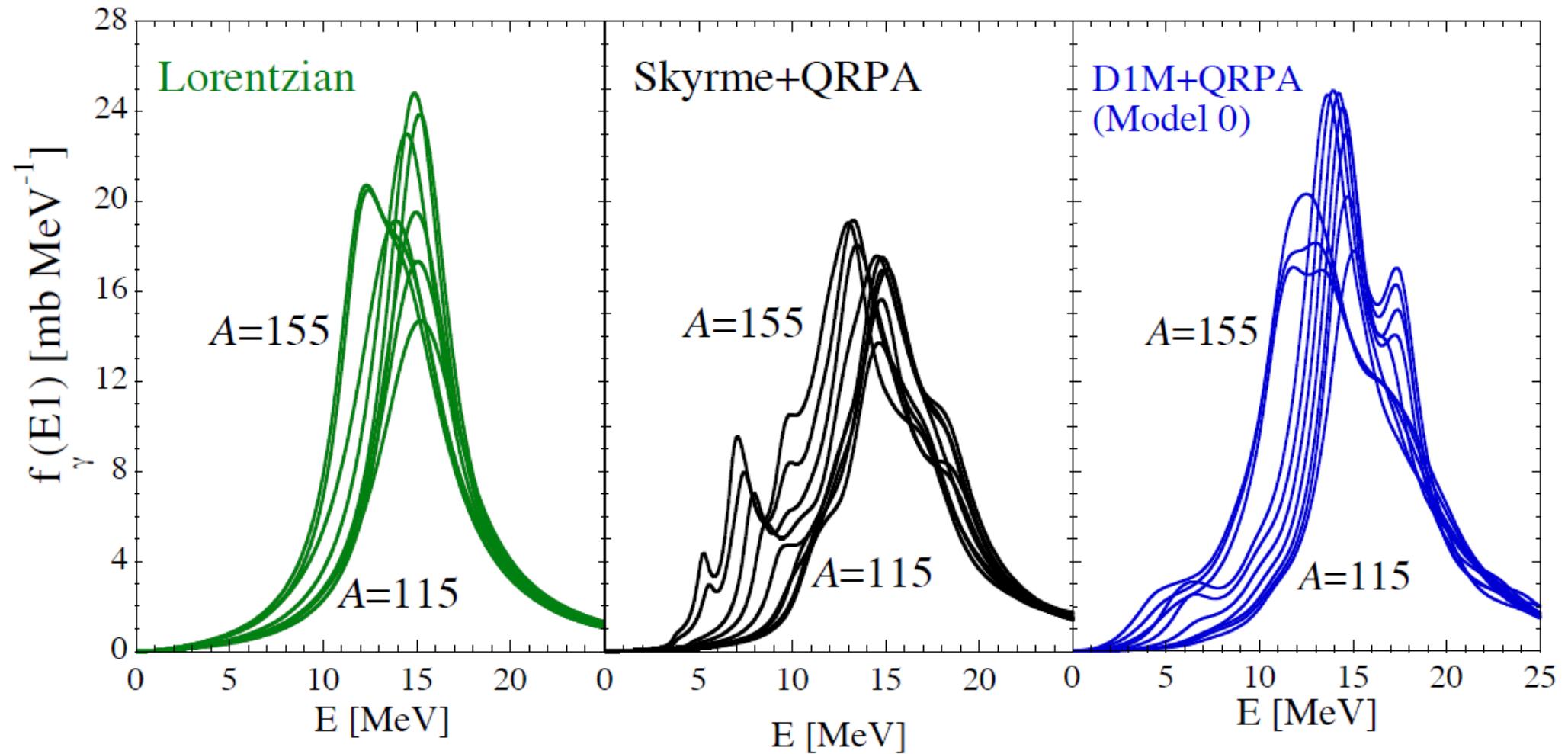
Comparison of the QRPA low-energy E1 strength functions with experimental compilation for nuclei from  $^{33}\text{S}$  up to  $^{239}\text{U}$  at energies ranging from 4 to 8 MeV.

Calculations performed also for isotopic chains of astrophysical interest (e.g. Sn).

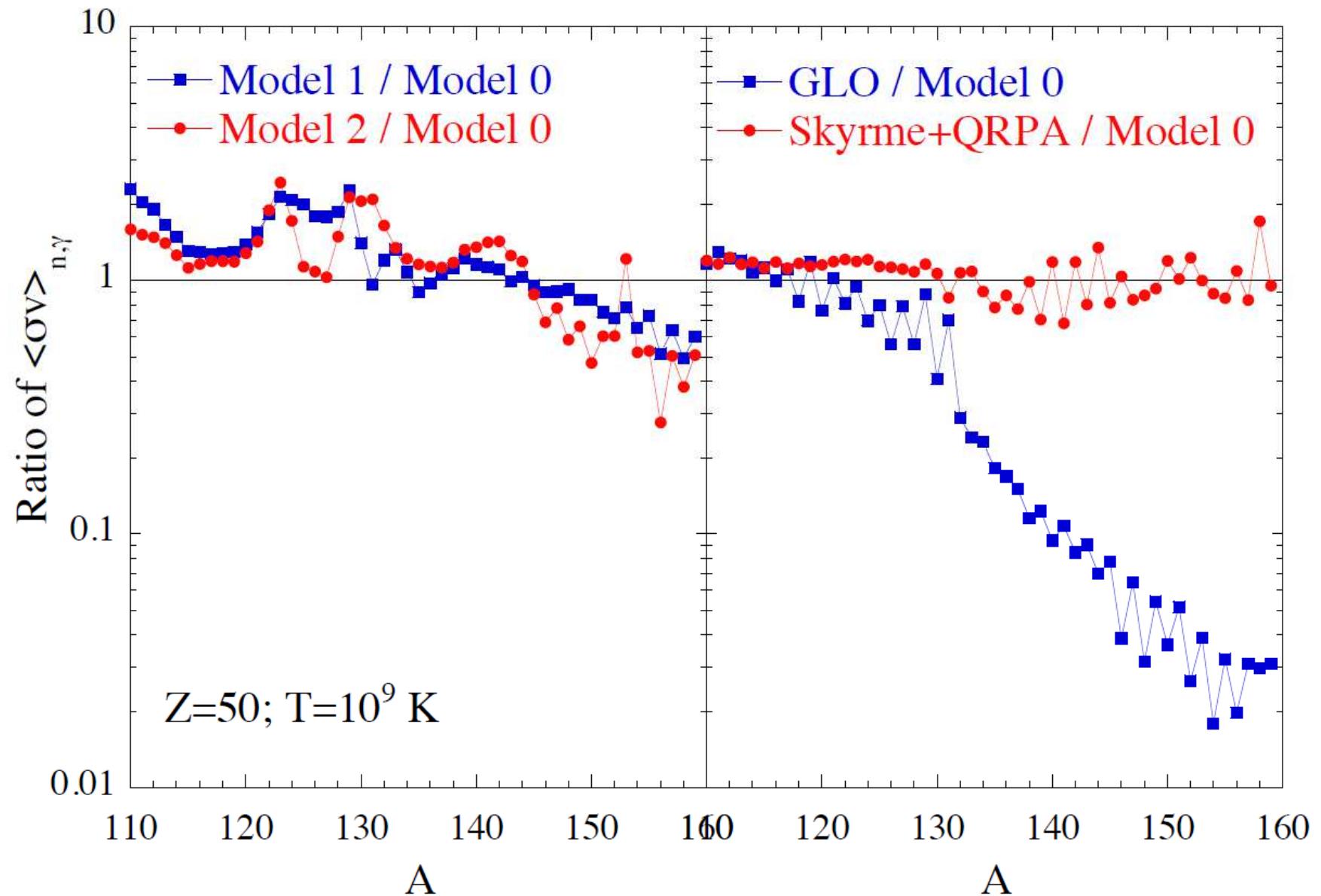
e.g. Sn isotopes



e.g. Sn isotopes



# Impact on the predicted neutron-capture cross section of astrophysical interest



# Photoneutron cross sections for Mo isotopes

PHOTONEUTRON CROSS SECTIONS FOR Mo ISOTOPES: ...

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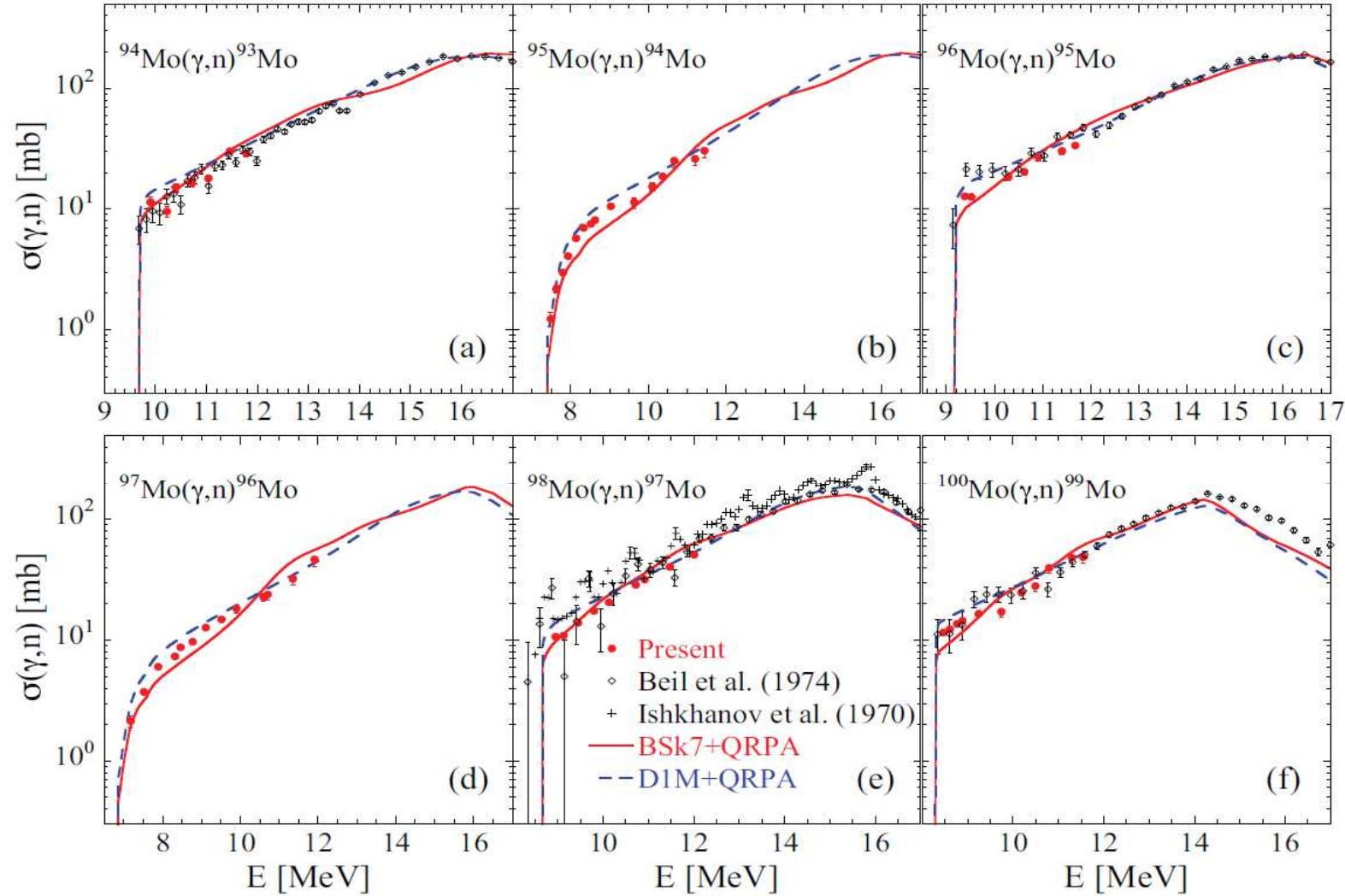
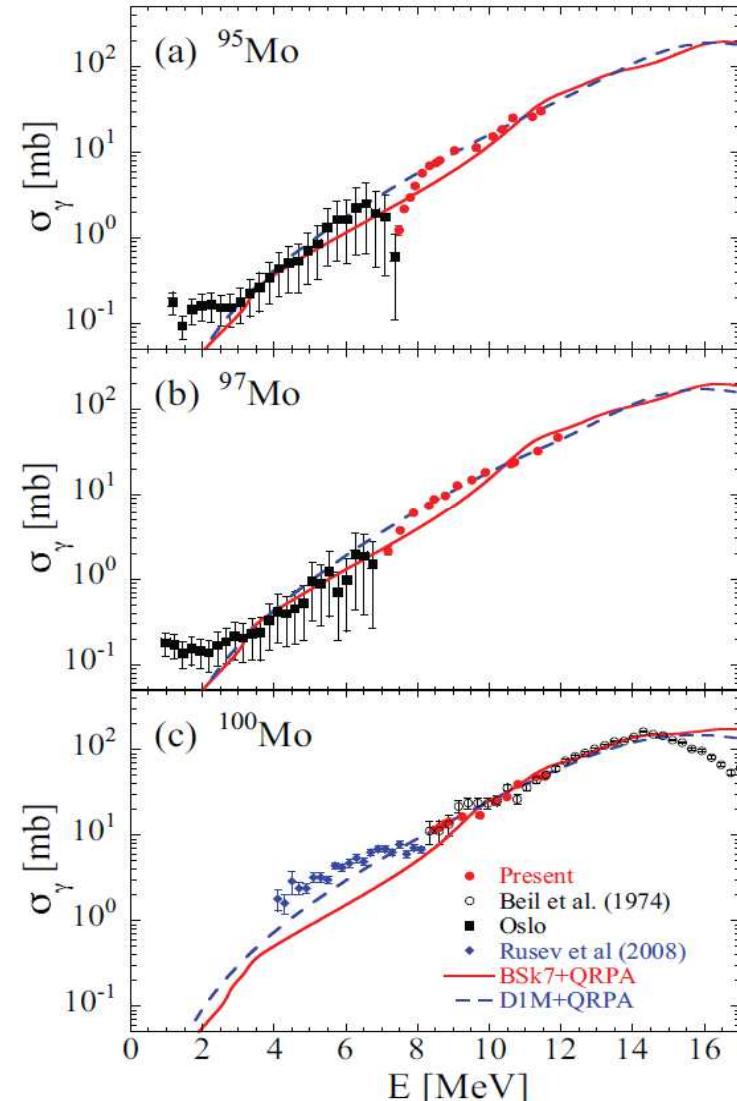
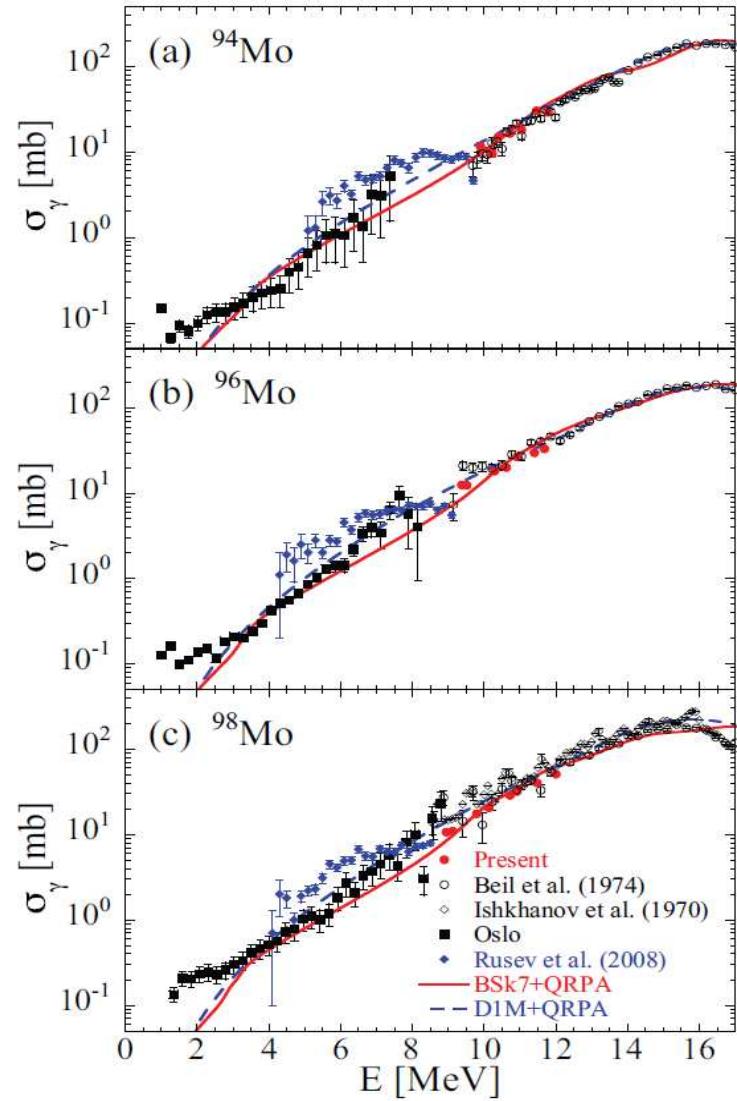


FIG. 3. (Color online) Comparison between the present photoneutron emission cross sections and previously measured ones [17,18] for six Mo isotopes,  $^{94}\text{Mo}$  (a),  $^{95}\text{Mo}$  (b),  $^{96}\text{Mo}$  (c),  $^{97}\text{Mo}$  (d),  $^{98}\text{Mo}$  (e), and  $^{100}\text{Mo}$  (f). Also 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].

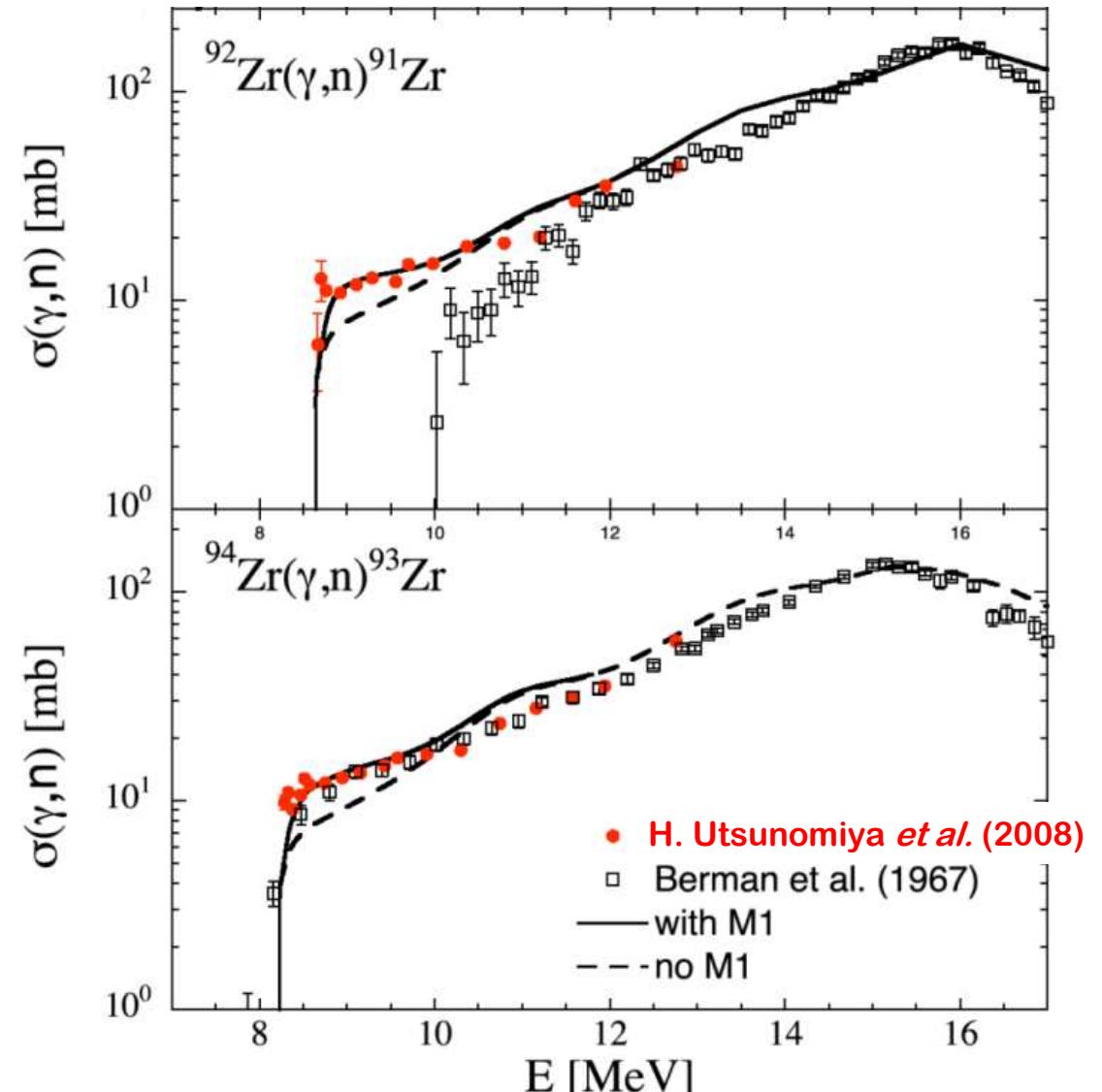
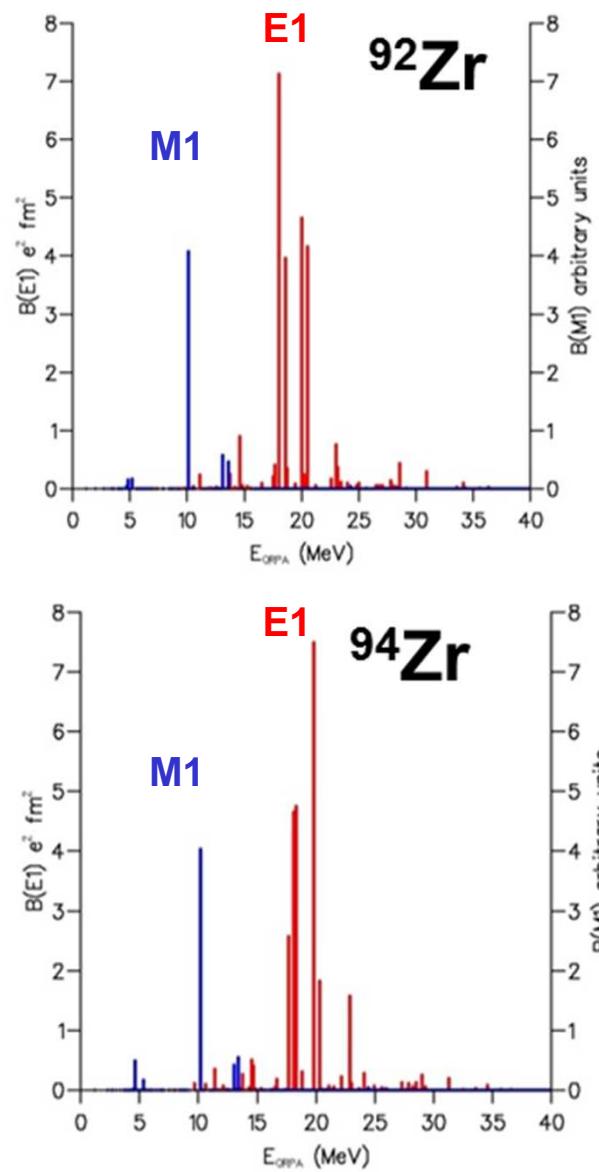
# Photoabsorption cross sections for Mo isotopes

H. UTSUNOMIYA *et al.*

PHYSICAL REVIEW C 88, 015805 (2013)



# Dipole electric and magnetic excitations for Zr isotopes



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

# To summarize

Fully self-consistent QRPA using the finite range Gogny force has been applied to axially-symmetric-deformed nuclei.

- \* 5DCH and QRPA approaches can complete each other.
- \* Self-consistent QRPA approach has been applied to the deformed nuclei up to  $^{238}\text{U}$ .
- \* IsoScalar-IsoVector mixing for low-lying dipole states in Ne isotopes and N=16 isotones.
- QRPA results successfully used in reaction models : ( $\text{n}, \chi\text{n}$ ) , photoabsorption
- ...