energie atomique • energies alternatives

Nuclear Inputs to model codes

S. Hilaire [1]**,**
A.J. Koning [2]
&
S. Goriely [3]

www.talys.eu

1 CEA,DAM,DIF, F-91297 Arpajon, France
2 Nuclear Research and Consultancy Group, Petten, The Netherlands
3 Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Brussels, Belgium

energie atomique • energies alternatives

Nuclear cross sections : how ?

Generally evaluated with analytic models

Analytical OMP
Analytical level densities
Analytical strength function
Analytical fission barriers …

} **OK close to stability**

But for exotic nuclei ?

Extrapolations, predictive power ?

→ **Predictive & Robust Nuclear models (codes) are essential to fill the gaps**

energie atomique • energies alternatives

Contents

- **General features of TALYS**
- **From phenomenological to microscopic predictions**
- **Few results**
- **What else ?**

energie atomique • energies alternatives

What TALYS does !

- **Simulates a nuclear reaction between a projectile and a target**

  projectiles : n,p,d,t,^{3}he, ^{4}he
  target : $3 \leq Z \leq 110$ or $5 \leq A \leq 339$

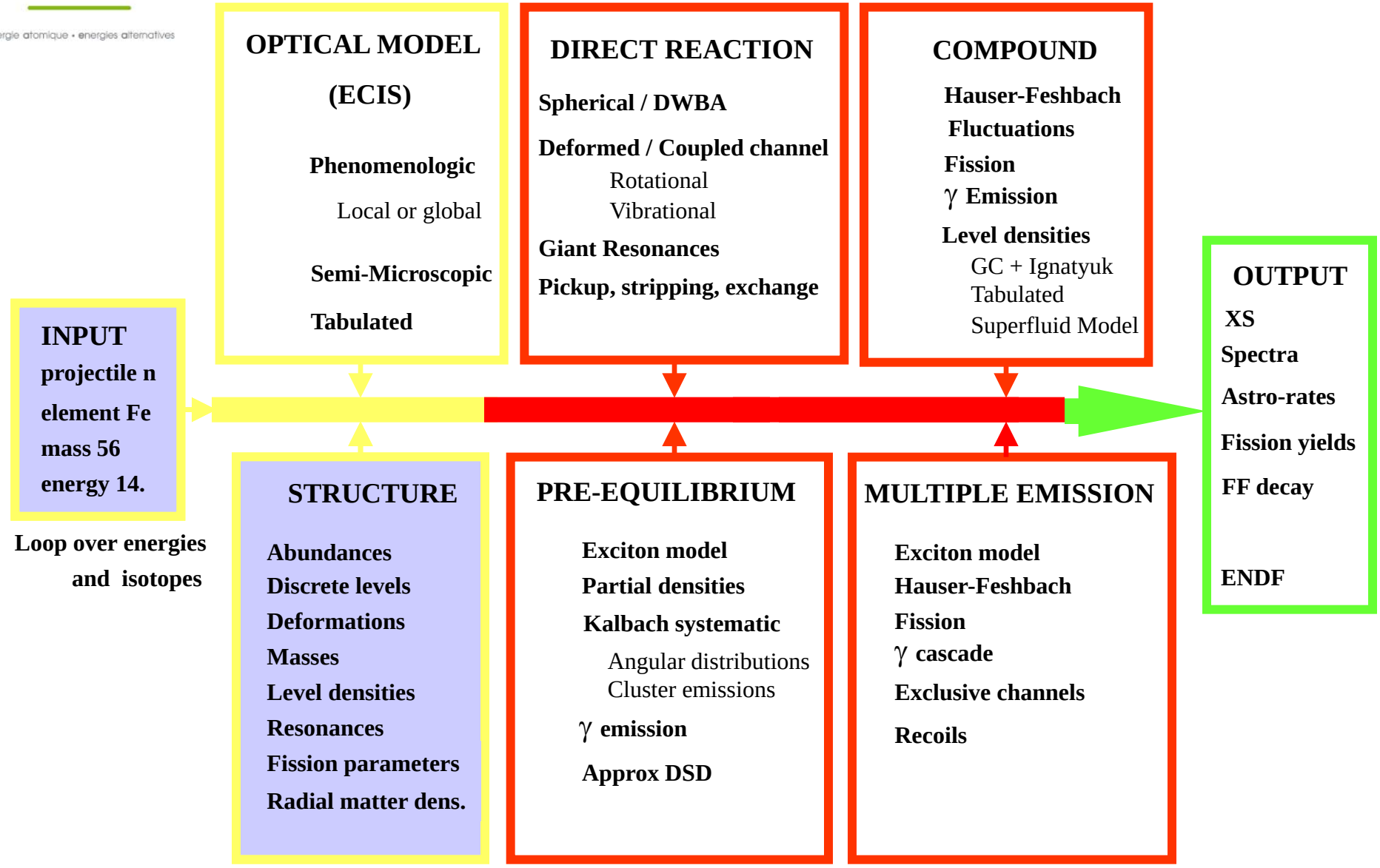
- **Projectile energy from 1keV up to 200 MeV**

- **TALYS mantra : " Completeness then quality "**

  - **Optical, pre-equilibrium and statistical model implemented with sets of default parameters**
  - **All opened channels smoothly described**
  - **Possibilities for future improvements anticipated**
    - Level densities (stored and interpolated)
    - Parity dependence
  - **Still under development (improvement)**

energie atomique • energies alternatives

How TALYS works !



energie atomique • energies alternatives

What TALYS yields !

- Cross sections : total, reaction, elastic, inelastic (per level & total) etc …
- Elastic and inelastic angular distribution
- Exclusive reaction channels : xs, spectra & ddx
- Exclusive discrete and continuum γ-ray production (cascade treated)
- Photonuclear reactions & reactions on isomeric targets
- Fission cross sections and fission yields
- Residuals production and recoils
- Total particle production : xs, spectra & ddx
- Extrapolation down to thermal energy
- Stellar reaction rates
- Fission fragment decay
- Level density tables

energie atomique • energies alternatives

Phenomenological ⇒ microscopic predictions ?

Can we calculate nuclear reaction cross sections starting from a nucleon-nucleon interaction ?

Yes we can but we need intermediate steps

Phenomenological ⇒ microscopic predictions ?

Experimentally known (deduced)		Theoretically predicted
Nuclear properties - Level properties (E, J^{π}, branching ratios) - deformations	⟹	**HFB + ν-ν interaction**
Level densities - Gilbert & Cameron - Back Shifted Fermi Gas - Generalized Superfluid Model - Williams + several corrections (p-h)	⟹	**Combinatorial method** - Total level densities - p-h level densities
Optical model - Koning & Delaroche - Soukhovistkii (actinides) - Tabulated	⟹	**Semi-microscopic JLM**
γ-strength functions - Kopecky-Uhl, Brink-Axel	⟹	**HFBCS or HFB Tables**
Fission paths - Hill-Wheeler	⟹	**HFB shapes with WKB penetrabilities**

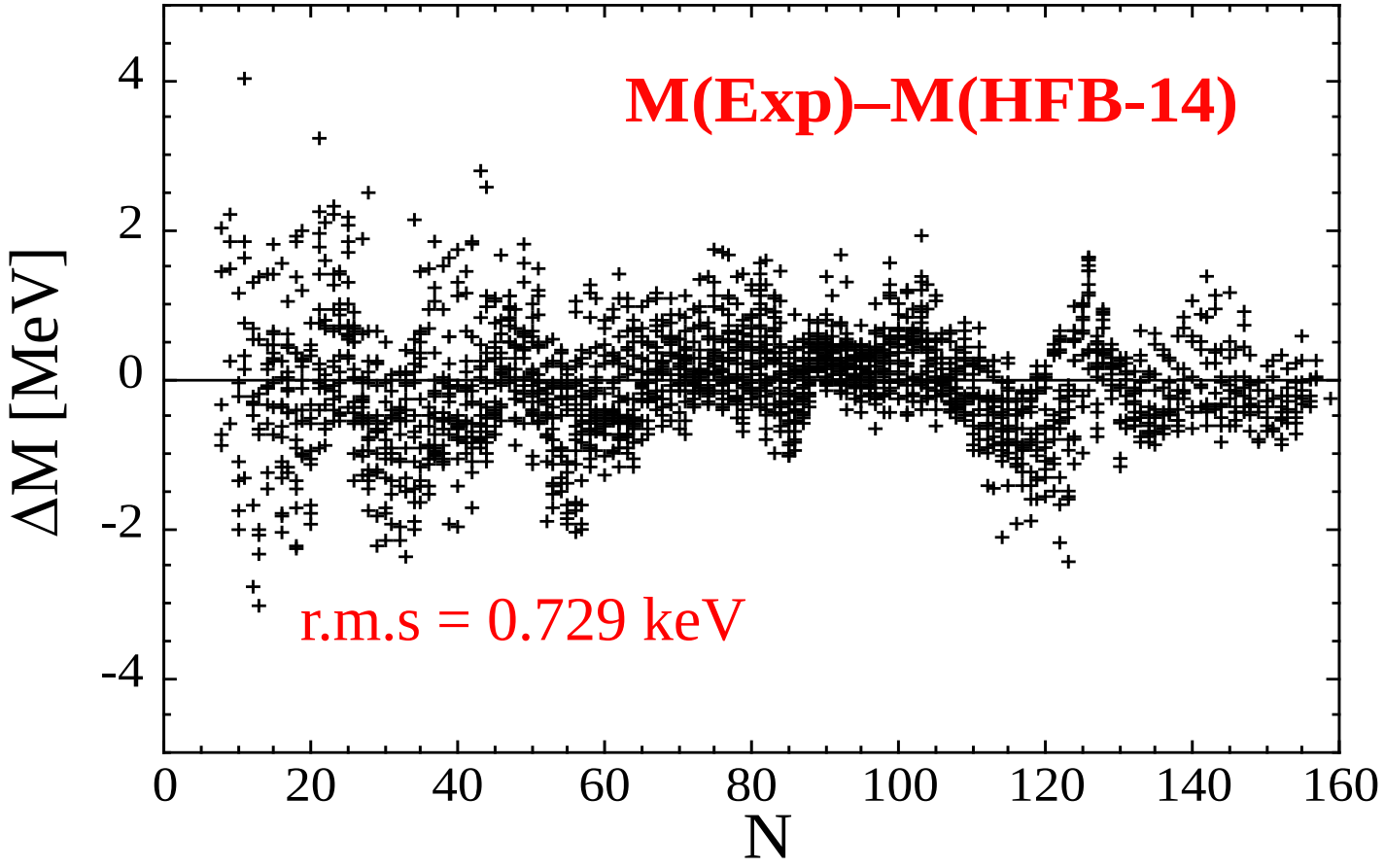
Phenomenological ⇒ microscopic predictions ?

Experimentally known (deduced)		Theoretically predicted
Nuclear properties - Level properties (E, J^{π}, branching ratios) - deformations	⟹	**HFB + ν-ν interaction**
Level densities - Gilbert & Cameron - Back Shifted Fermi Gas - Generalized Superfluid Model - Williams + several corrections (p-h)	⟹	**Combinatorial method** - Total level densities - p-h level densities
Optical model - Koning & Delaroche - Soukhovistkii (actinides) - Tabulated	⟹	**Semi-microscopic JLM**
γ-strength functions - Kopecky-Uhl, Brink-Axel	⟹	**HFBCS or HFB Tables**
Fission paths - Hill-Wheeler	⟹	**HFB shapes with WKB penetrabilities**

energie atomique • energies alternatives

HFB + ν-ν interactions !

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



energie atomique • energies alternatives

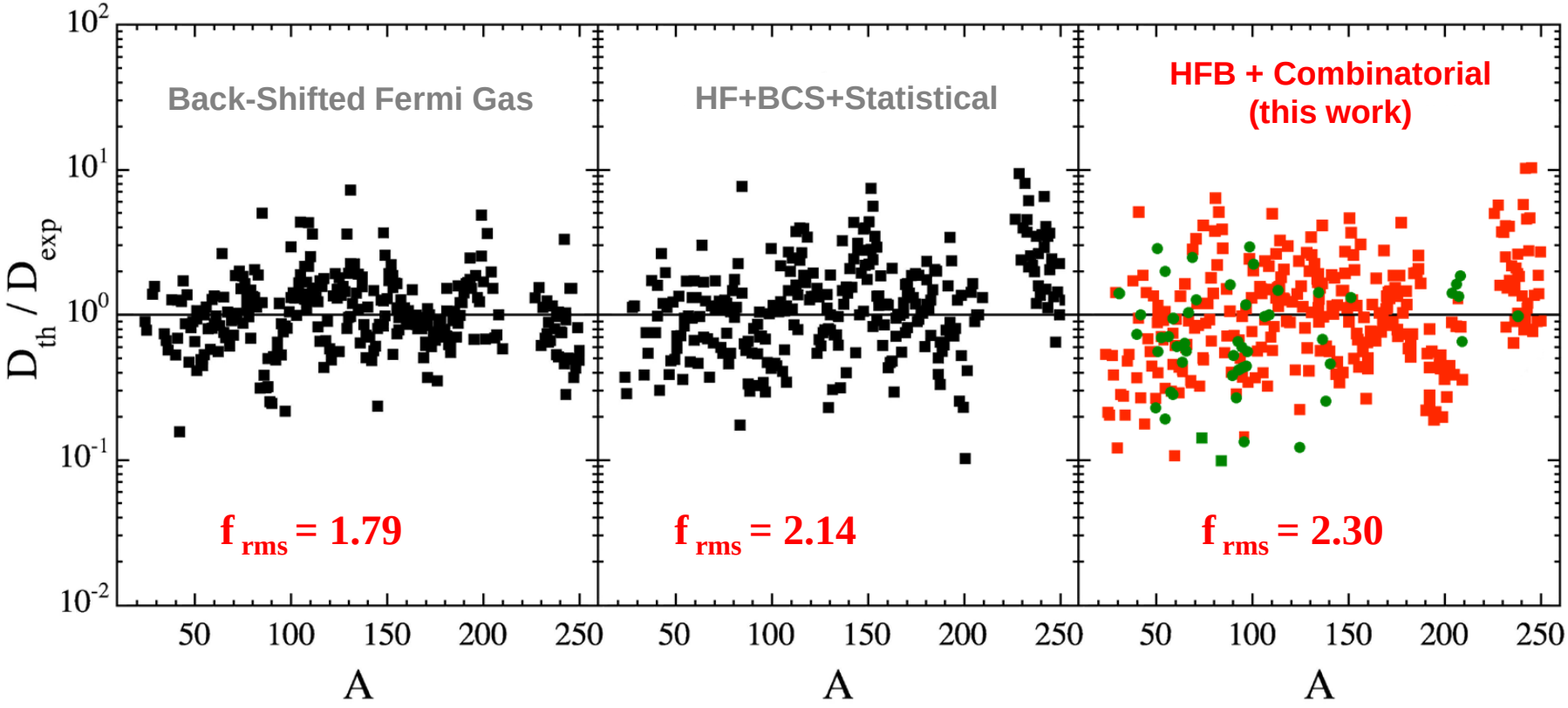
Phenomenological ⇒ microscopic predictions ?

Experimentally known (deduced)		Theoretically predicted
Nuclear properties - Level properties (E, J^{π}, branching ratios) - deformations	⟹	**HFB + ν-ν interaction**
Level densities - Gilbert & Cameron - Back Shifted Fermi Gas - Generalized Superfluid Model - Williams + several corrections (p-h)	⟹	**Combinatorial method** - Total level densities - p-h level densities
Optical model - Koning & Delaroche - Soukhovistkii (actinides) - Tabulated	⟹	**Semi-microscopic JLM**
γ-strength functions - Kopecky-Uhl, Brink-Axel	⟹	**HFBCS or HFB Tables**
Fission paths - Hill-Wheeler	⟹	**HFB shapes with WKB penetrabilities**

energie atomique • energies alternatives

Results at B_n

D values (s-waves & p-waves)



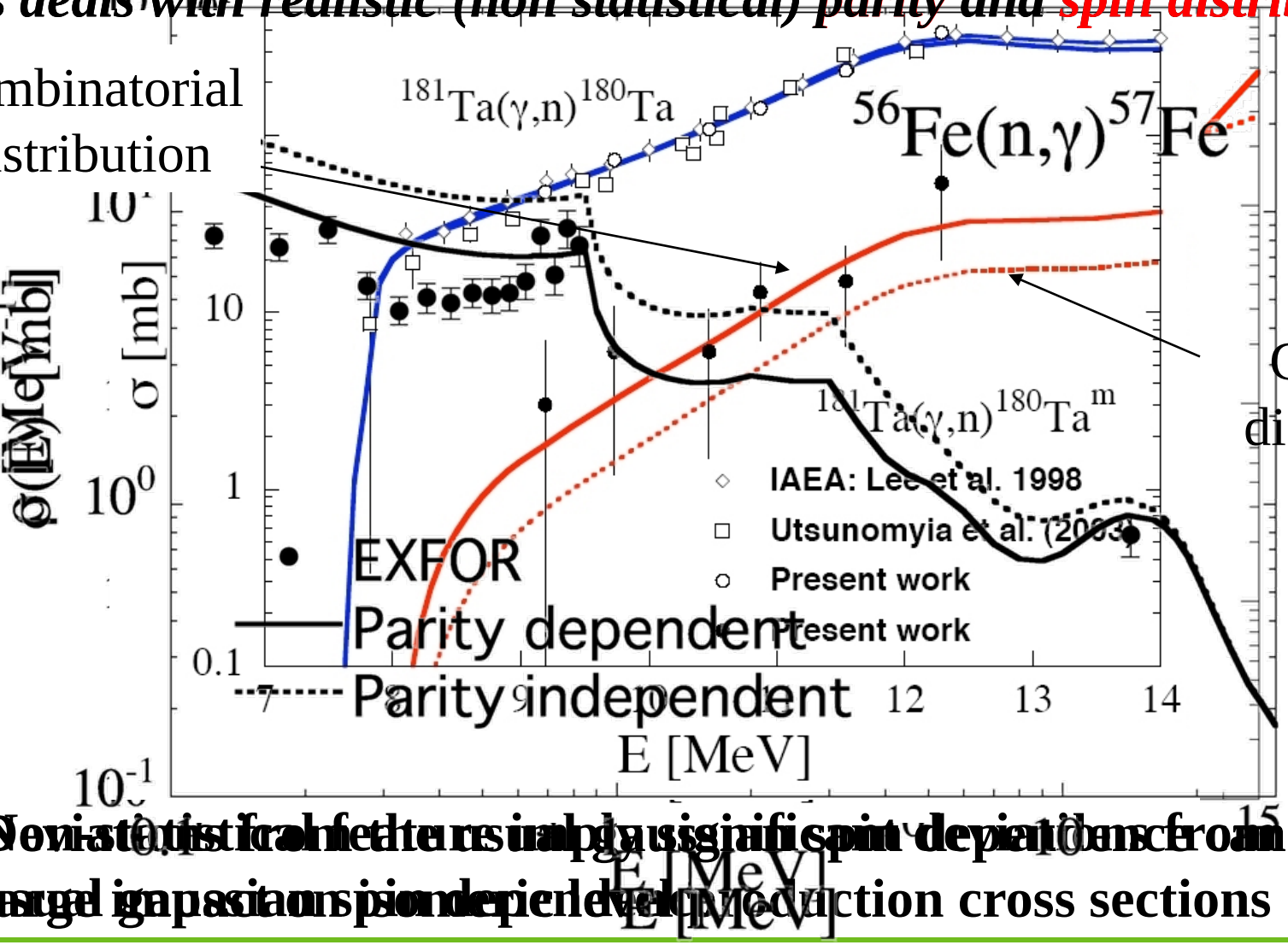
➡ **Description similar to that obtained with other global approaches**

Combinatorial level densities

See PRL 96 (2006) 192501 for details

Talys deals with realistic (non statistical) parity and spin distributions

Combinatorial distribution



Gaussian distribution

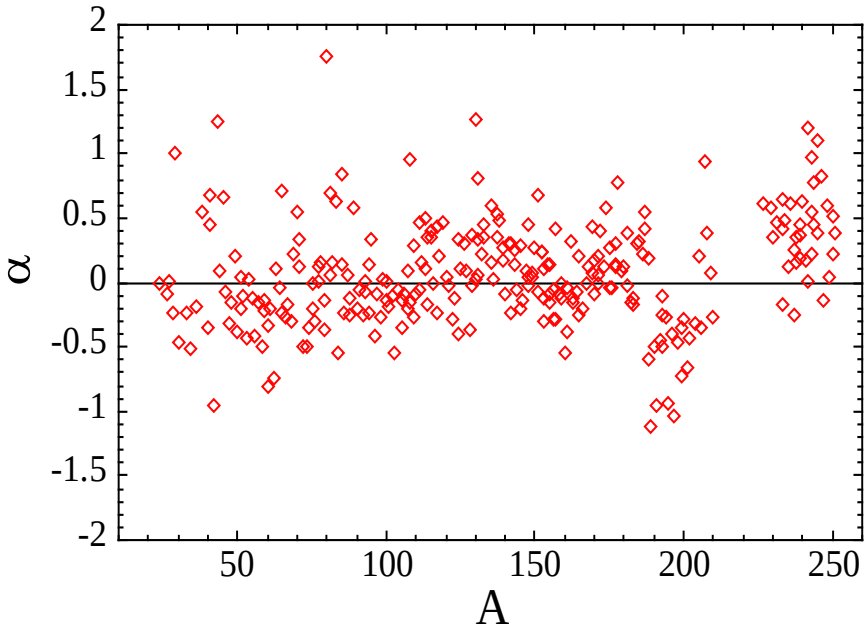
➡ **Non statistical effects usually significant and have large impact on predicted cross sections**

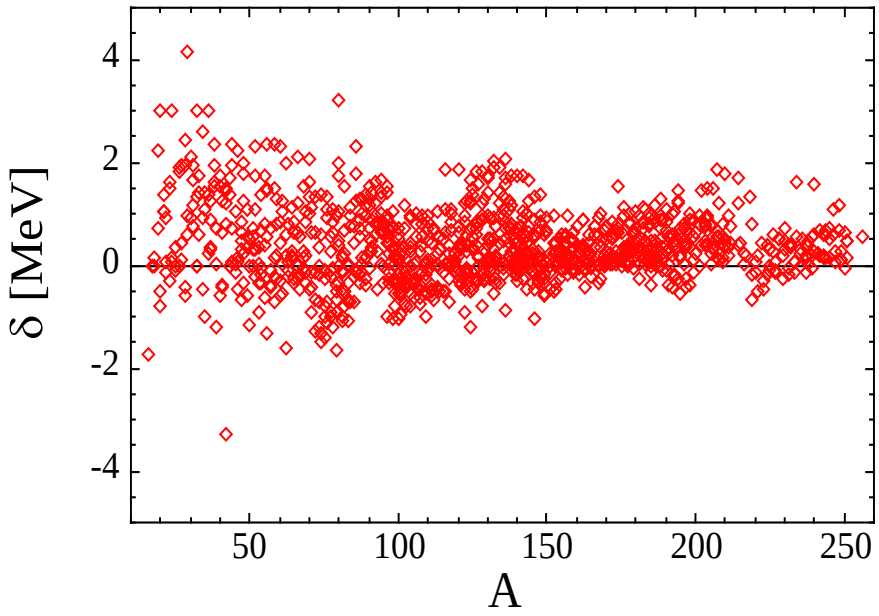
Global adjustment

See NPA 810 (2008) 13 for details

$$\rho_{renorm}(U) = e^{\alpha\sqrt{(U-\delta)}}\,\rho_{global}(U-\delta)$$

α and δ adjusted to fit discrete levels ($\approx$ 1200 nuclei) and D_0's ($\approx$ 300 nuclei) using the TALYS code





energie atomique • energies alternatives

Phenomenological ⇒ microscopic predictions ?

Experimentally known (deduced)		Theoretically predicted
Nuclear properties - Level properties (E, J^{π}, branching ratios) - deformations	⟹	**HFB + ν-ν interaction**
Level densities - Gilbert & Cameron - Back Shifted Fermi Gas - Generalized Superfluid Model - Williams + several corrections (p-h)	⟹	**Combinatorial method** - Total level densities - p-h level densities
Optical model - Koning & Delaroche - Soukhovistkii (actinides) - Tabulated	⟹	**Semi-microscopic JLM**
γ-strength functions - Kopecky-Uhl, Brink-Axel	⟹	**HFBCS or HFB Tables**
Fission paths - Hill-Wheeler	⟹	**HFB shapes with WKB penetrabilities**

energie atomique • energies alternatives

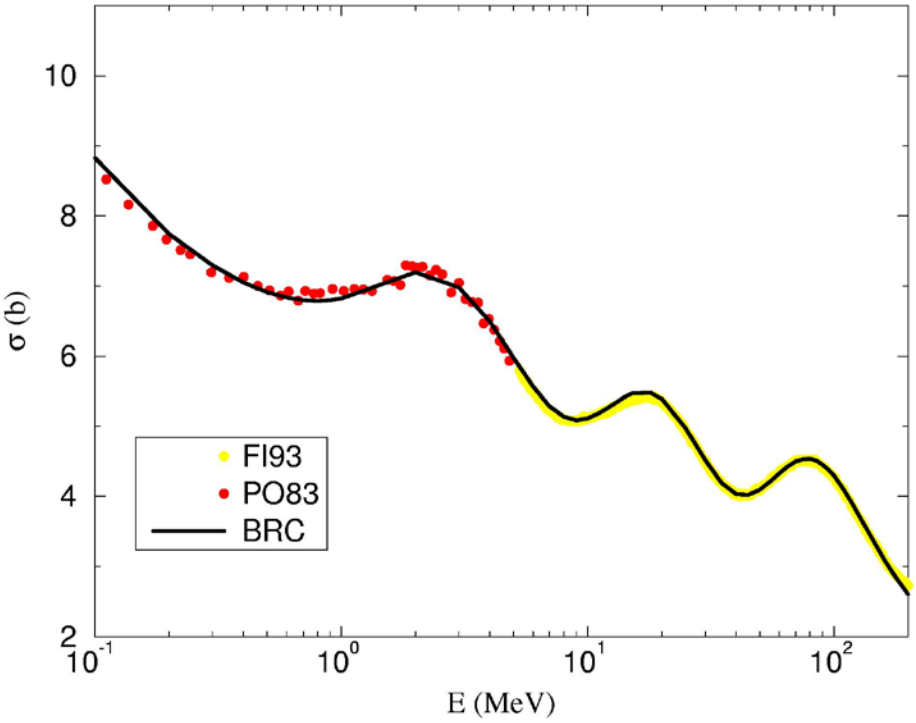
Approaches implemented in TALYS

Phenomenologic

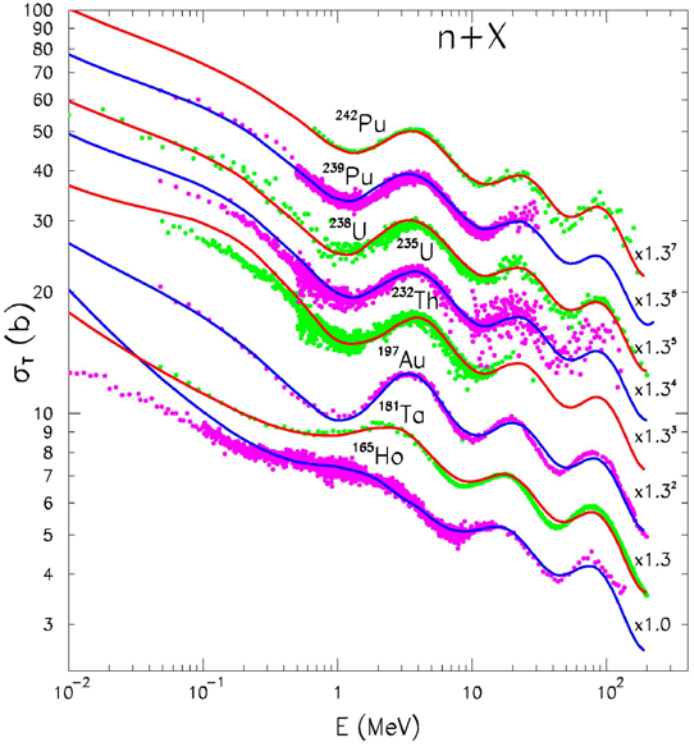
Adjusted parameters
Weak predictive power
Very precise (≈ 1%)
Important work

Semi-microscopic

No adjustable parameters
Usable without exp. data
Less precise (≈ 5-10 %)
Quasi-automated



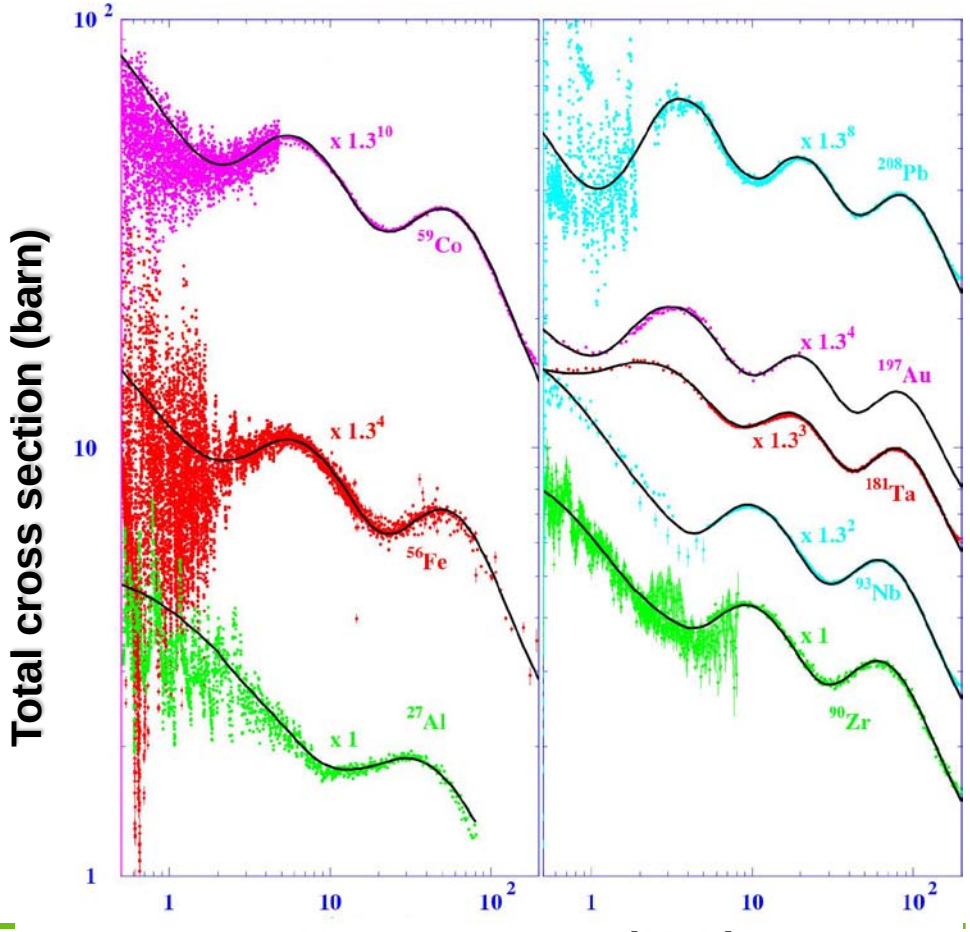
Total cross sections



energie atomique • energies alternatives

Phenomenological OMP

- ≈ 20 adjusted parameters
- Very precise (1%)
- Relatively weak predictive power far away from stability



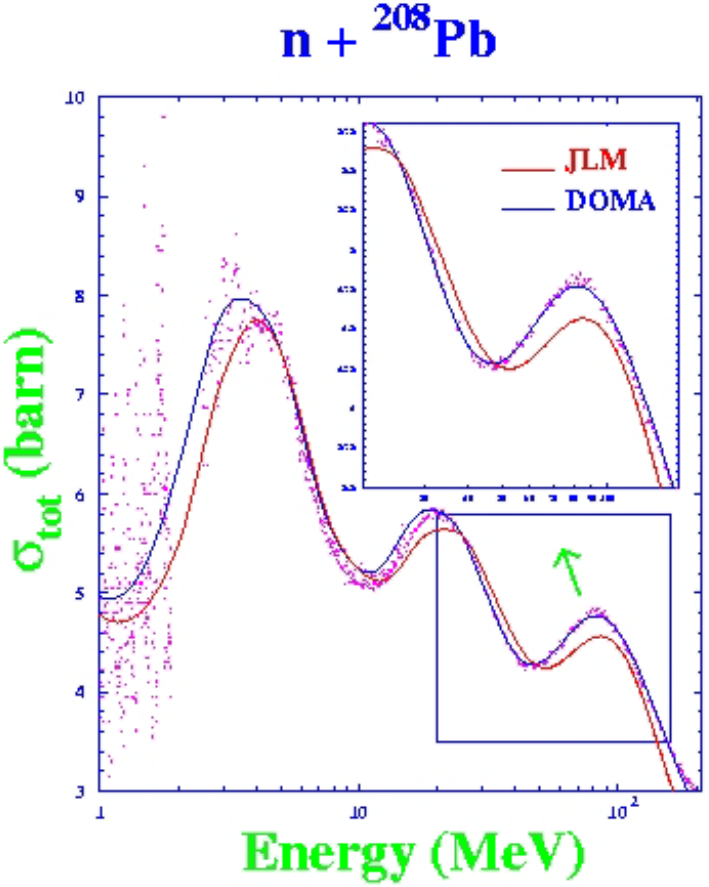
energie atomique • energies alternatives

Semi-microscopic OMP

- No adjustable parameters
- Based on nuclear structure properties

⇒ usable for any nucleus

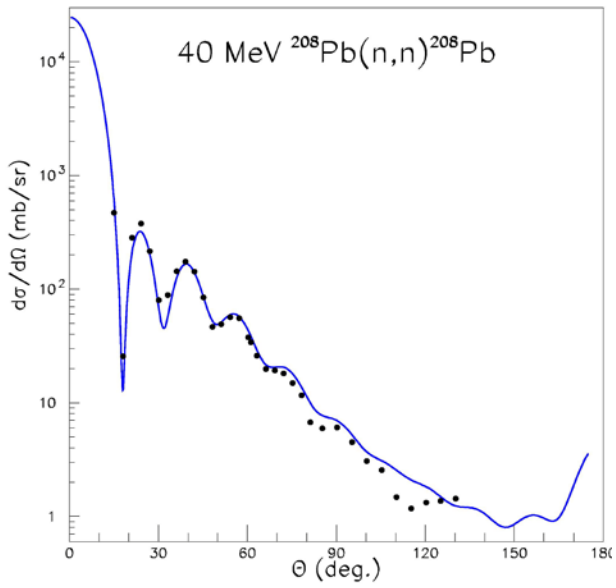
- Less precise than the phenomenological approach

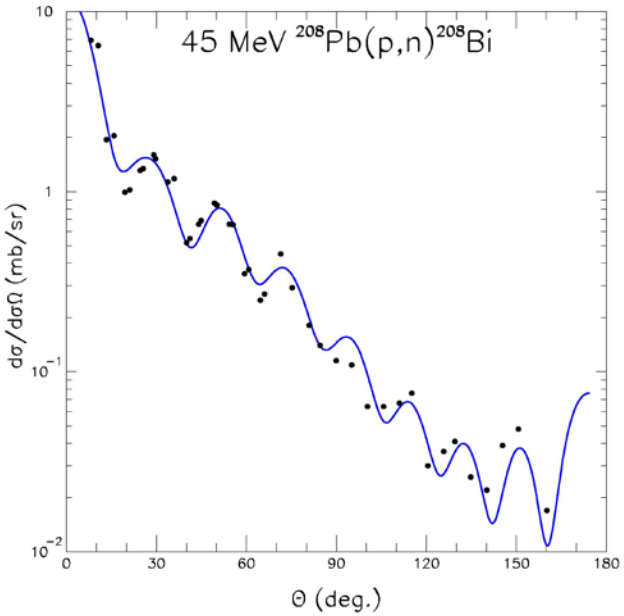


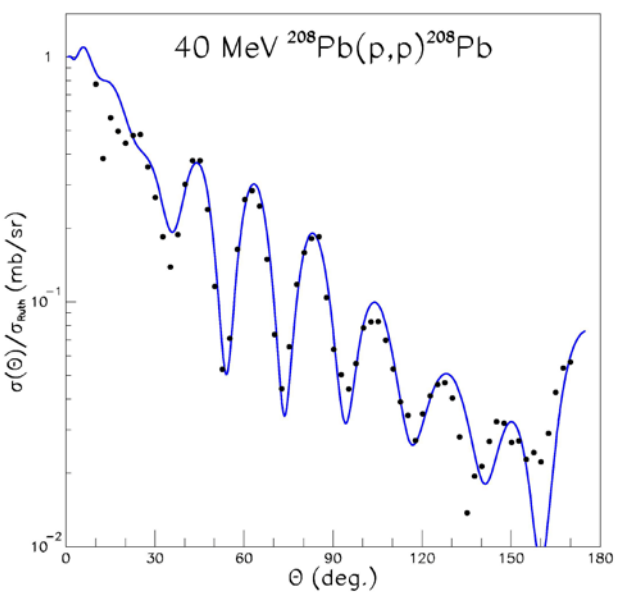
energie atomique • energies alternatives

Semi-microscopic OMP

Unique description of elastic scattering (n,n), (p,p) et (p,n)



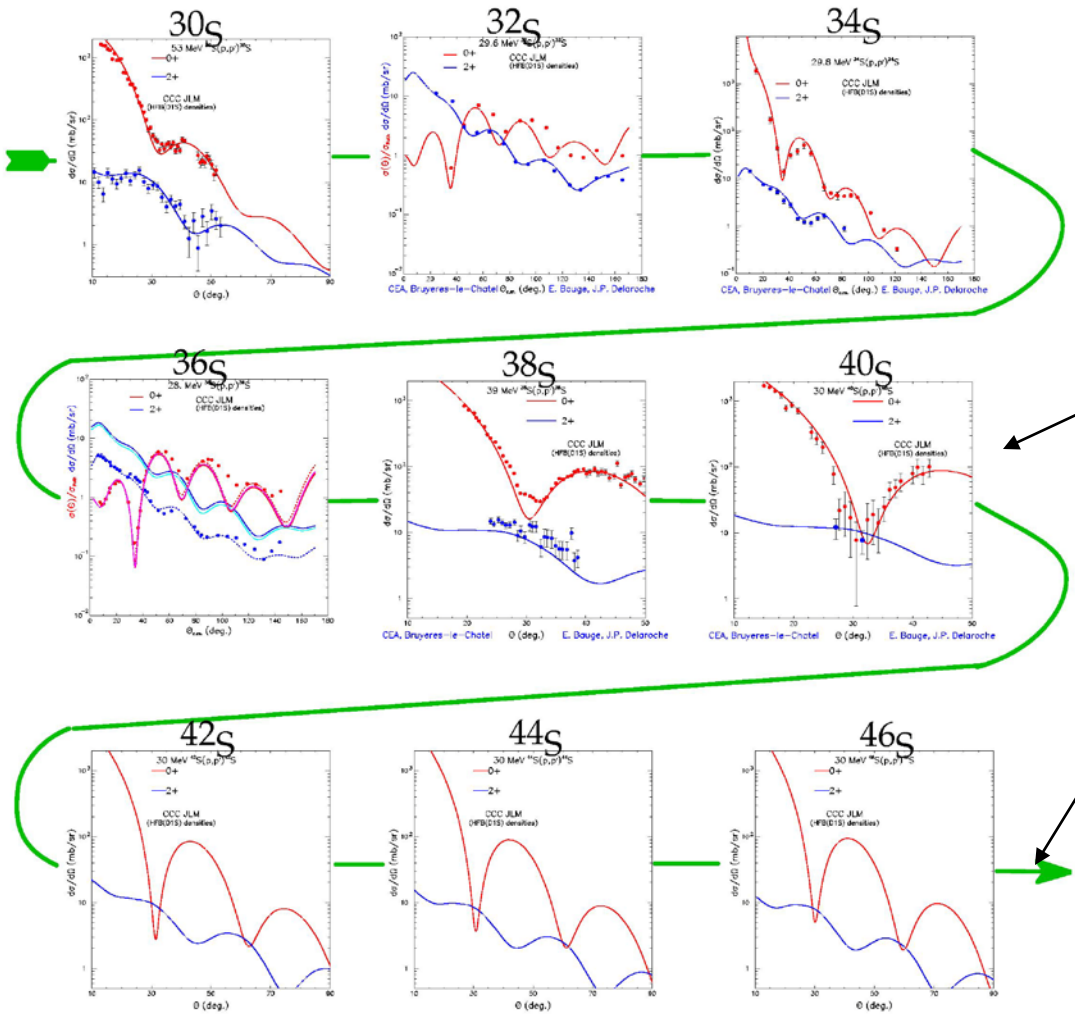




energie atomique • energies alternatives

Semi-microscopic OMP

Enables to perform predictions for exotic nuclei for which there exist no experimental data (yet)



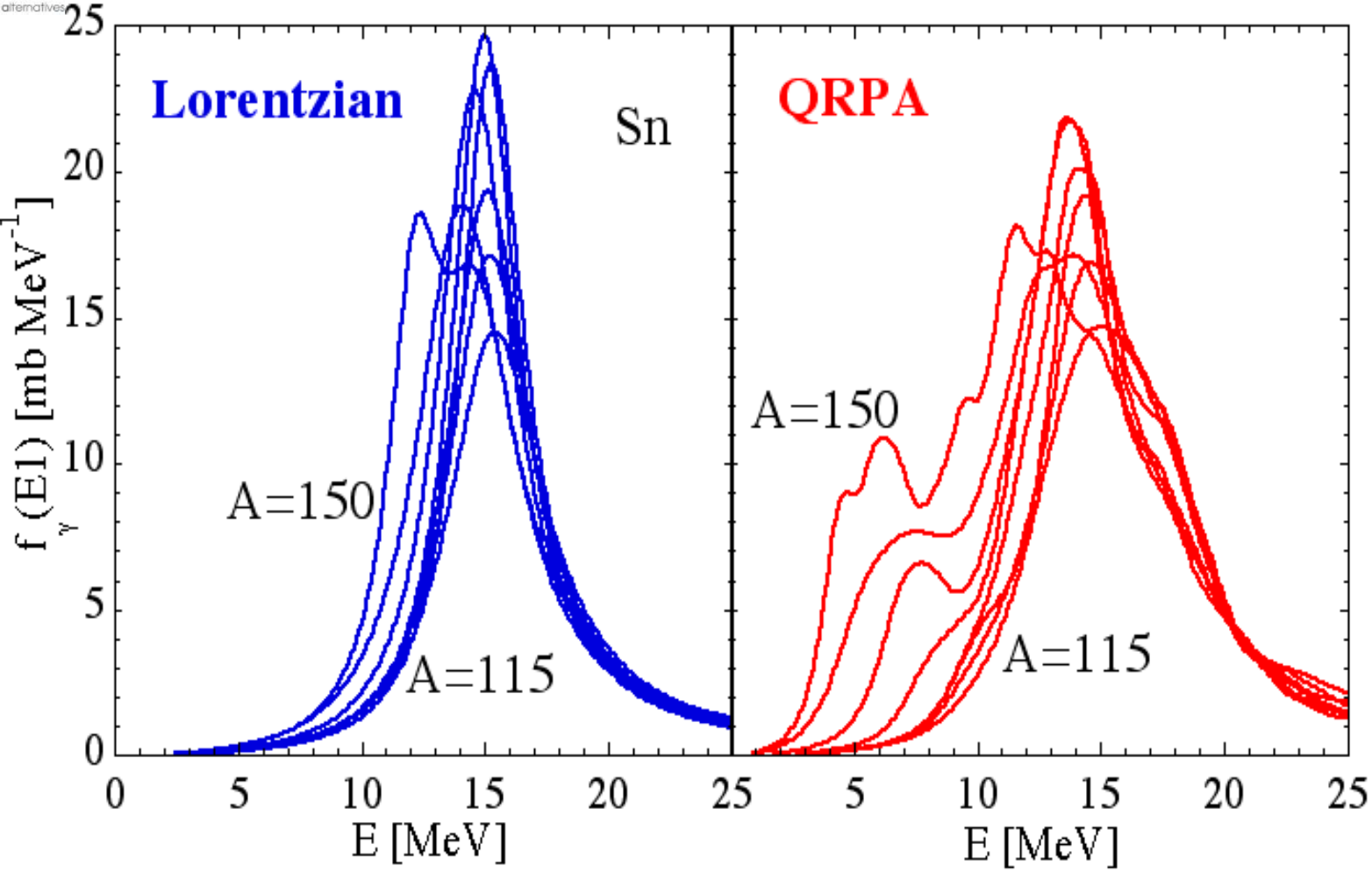
Predictions possible for unmeasured nuclei

Phenomenological ⇒ microscopic predictions ?

Experimentally known (deduced)		Theoretically predicted
Nuclear properties - Level properties (E, J^{π}, branching ratios) - deformations	⟹	**HFB + ν-ν interaction**
Level densities - Gilbert & Cameron - Back Shifted Fermi Gas - Generalized Superfluid Model - Williams + several corrections (p-h)	⟹	**Combinatorial method** - Total level densities - p-h level densities
Optical model - Koning & Delaroche - Soukhovistkii (actinides) - Tabulated	⟹	**Semi-microscopic JLM**
γ-strength functions - Kopecky-Uhl, Brink-Axel	⟹	**HFBCS or HFB Tables**
Fission paths - Hill-Wheeler	⟹	**HFB shapes with WKB penetrabilities**

energie atomique • energies alternatives

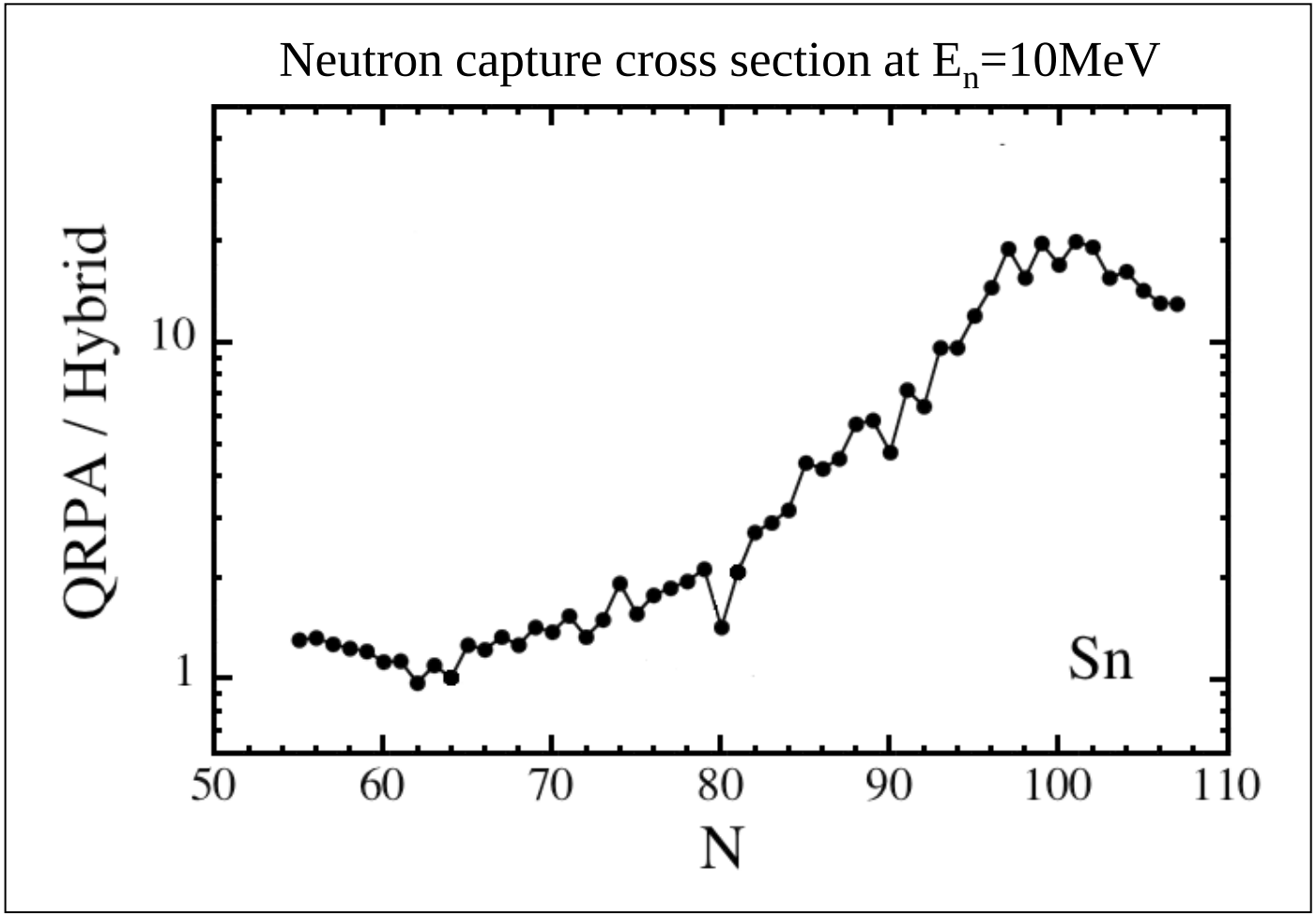
Microscopic γ-ray strength functions



⇒ Significant differences with experimental data.

energie atomique • energies alternatives

Microscopic vs Phenomenologic γ-ray strength functions and cross sections

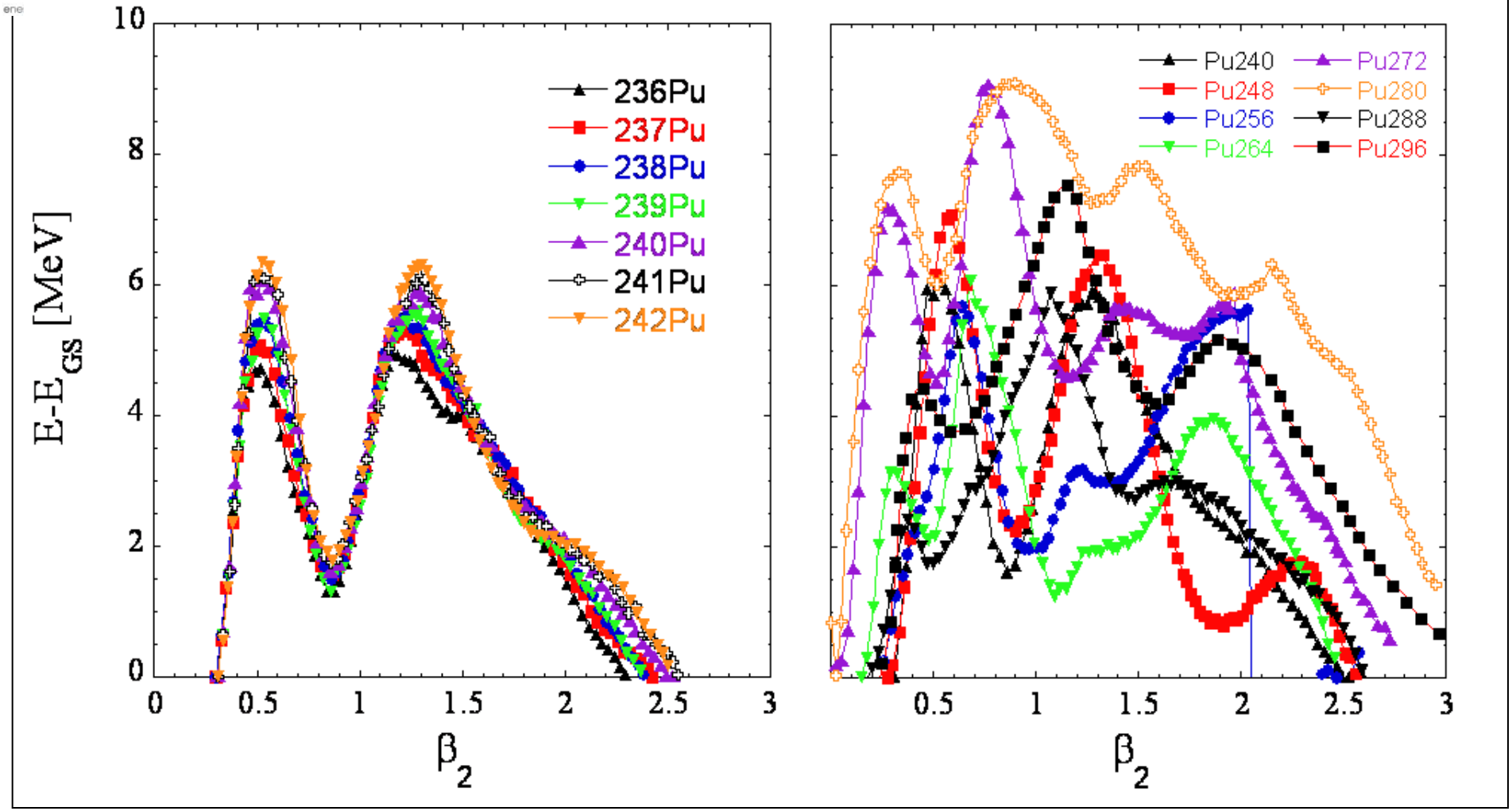


⇒ Impact not essential close to stability but crucial otherwise.

Phenomenological ⇒ microscopic predictions ?

Experimentally known (deduced)		Theoretically predicted
Nuclear properties - Level properties (E, J^{π}, branching ratios) - deformations	⟹	**HFB + ν-ν interaction**
Level densities - Gilbert & Cameron - Back Shifted Fermi Gas - Generalized Superfluid Model - Williams + several corrections (p-h)	⟹	**Combinatorial method** - Total level densities - p-h level densities
Optical model - Koning & Delaroche - Soukhovistkii (actinides) - Tabulated	⟹	**Semi-microscopic JLM**
γ-strength functions - Kopecky-Uhl, Brink-Axel	⟹	**HFBCS or HFB Tables**
Fission paths - Hill-Wheeler	⟹	**HFB shapes with WKB penetrabilities**

Microscopic fission barrier shapes

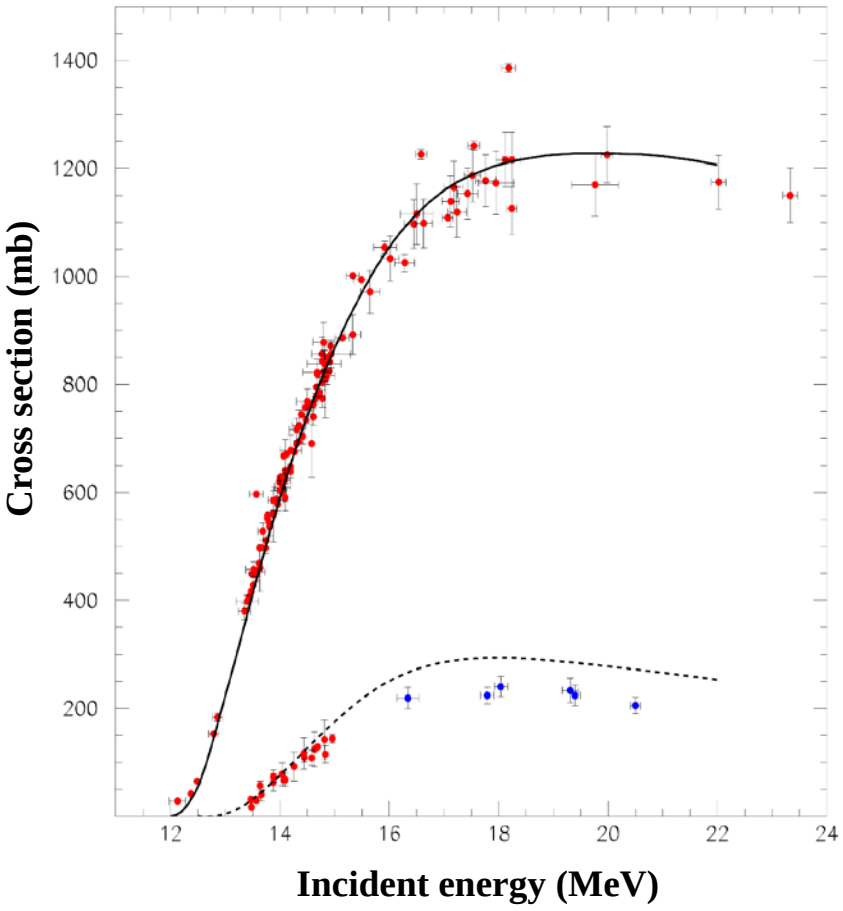


⇒ For exotic nuclei : strong deviations from Hill-Wheeler.

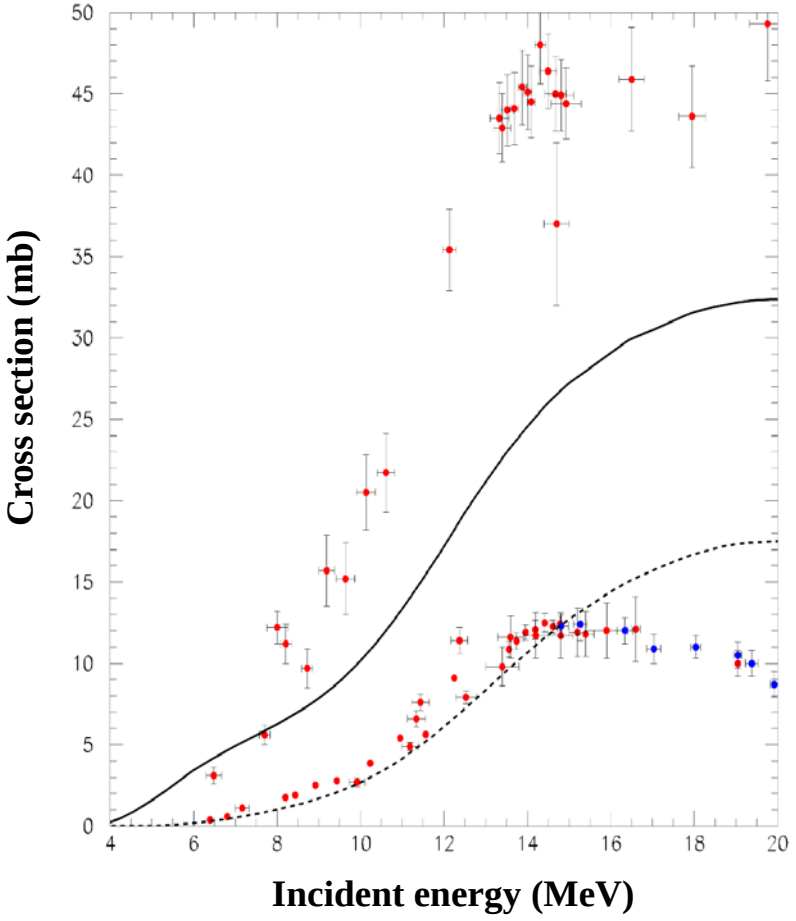
energie atomique • energies alternatives

Fully (almost) microscopic cross section

^{90}Zr (n,2n) ^{89}Zr

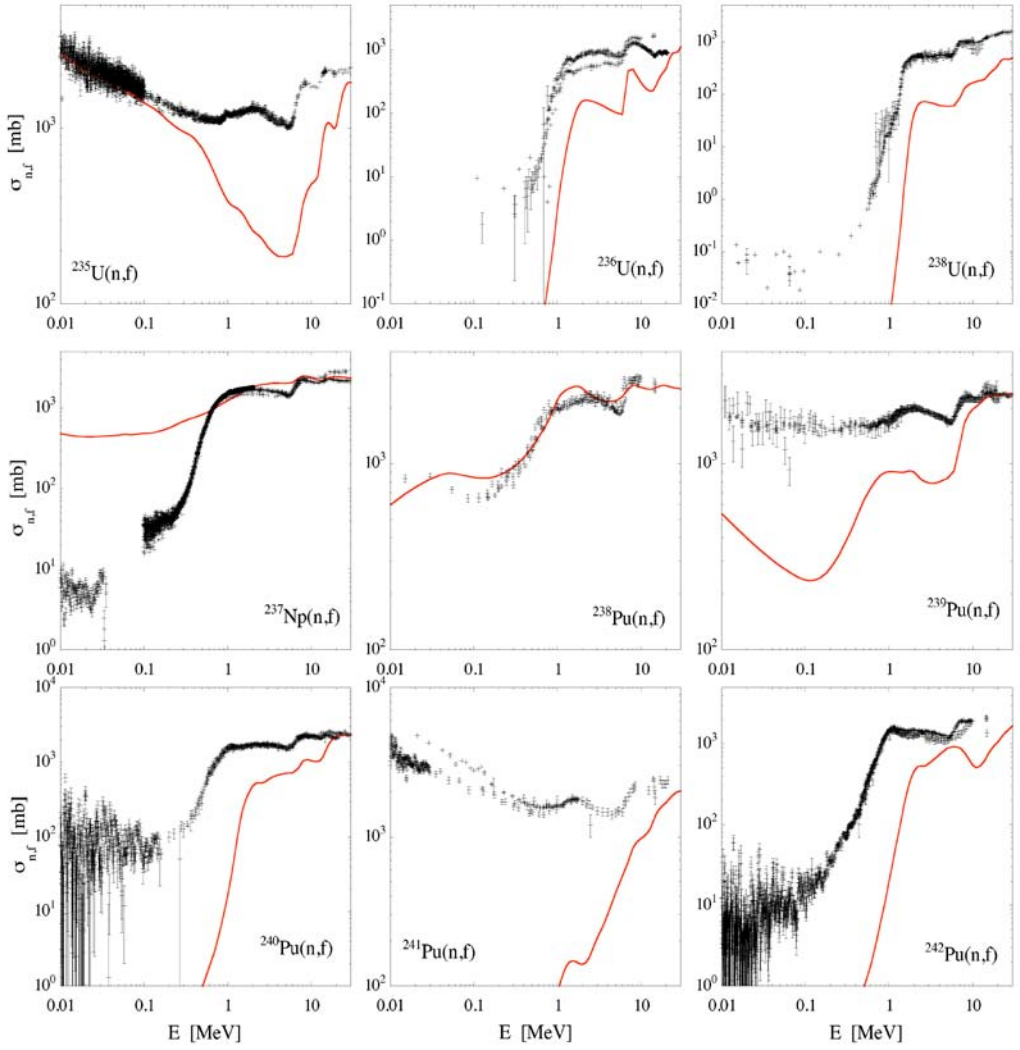


^{90}Zr (n,p) ^{90}Y



energie atomique • energies alternatives

Microscopic fission cross sections



⇒ **No artificial adjustments for applications.**

energie atomique • energies alternatives

Coherent fission cross sections with microscopic ingredients

HFB-14 predictions of fission barriers and NLD at saddle points, including renormalization (5 parameters) of

- fission path height: $B_f'(\beta_2) = B_f(\beta_2)$ x ν_{corr} $\Rightarrow$ no change of the topology !!
- NLD at 1st and 2d saddle points: $\rho'(U,J,P) = \rho(U-\delta,J,P)\,e^{\alpha\sqrt{U-\delta}}$

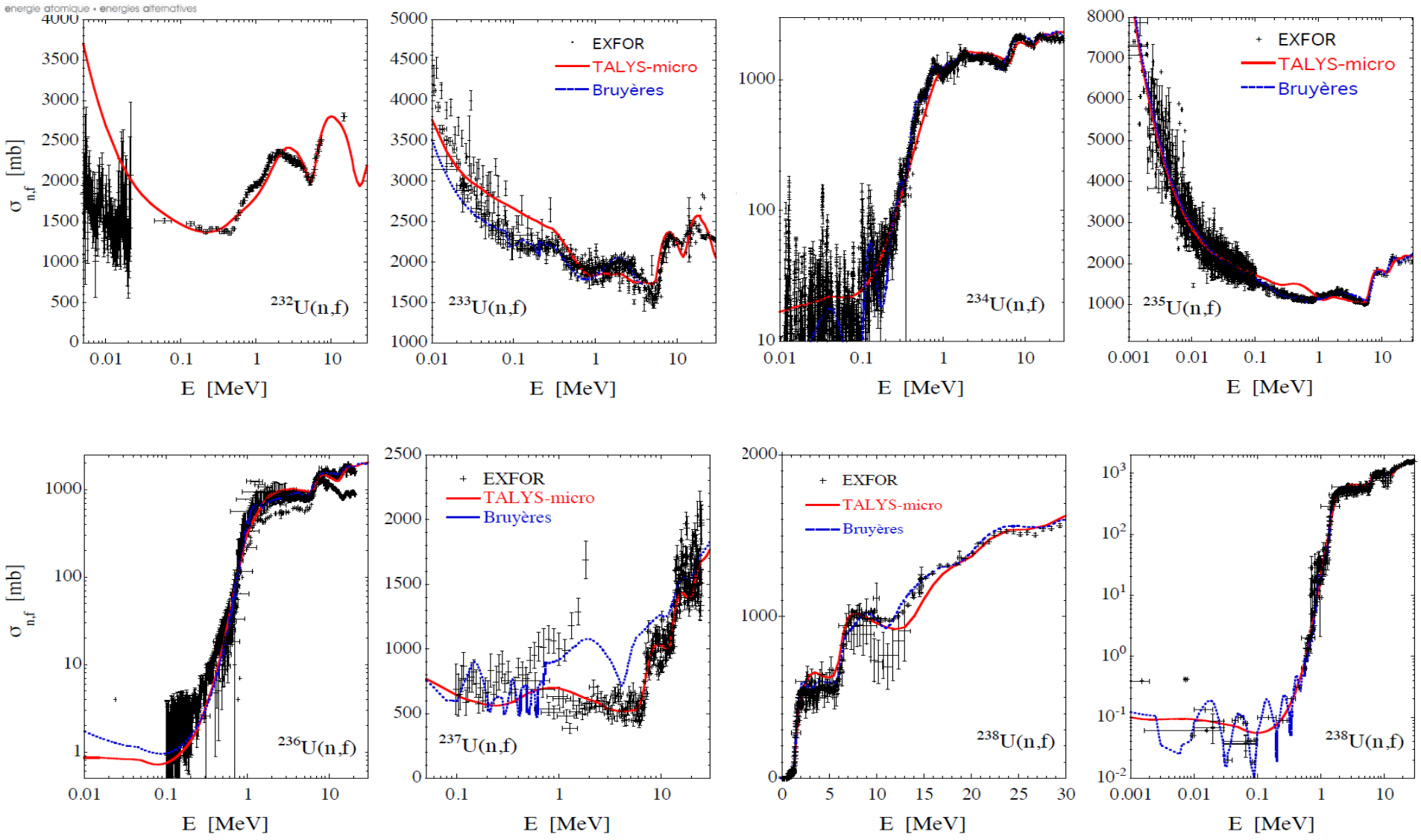
Additional nuclear inputs:

- Nuclear structure properties: HFB-14 (Goriely et al. 2007)
- Optical potential: Soukhovitskii et al. (2004)
- γ-ray strength: Hybrid model (Goriely, 1998)
- Equilibrium NLD: HFB-14 plus combinatorial model (Goriely et al., 2008) normalized on s-wave spacings and discrete levels

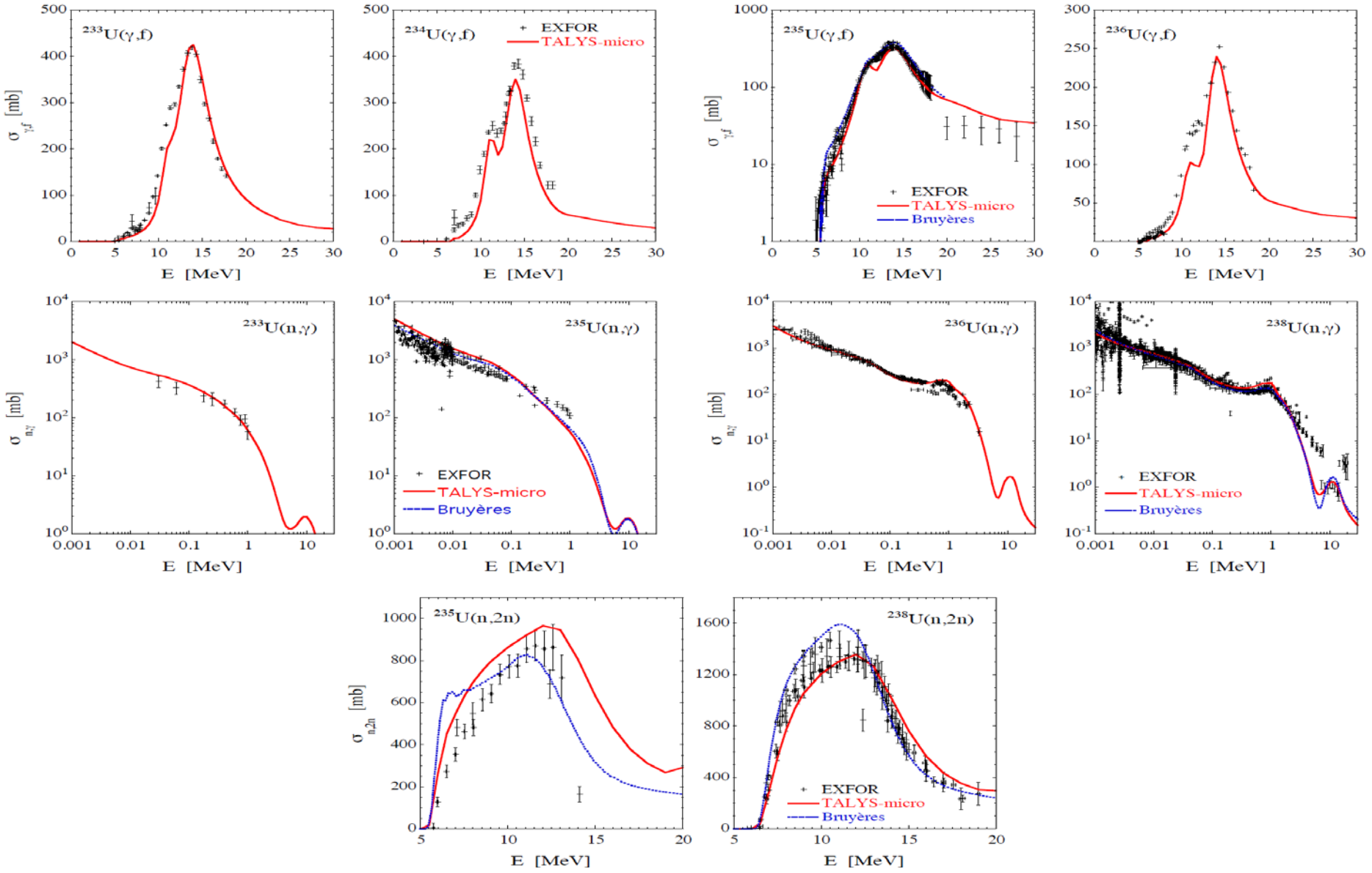
Note:

- no class 2 states included
- no discrete transition states included
- Experimental data in EXFOR only !

Coherent semi-microscopic fission



Coherent semi-microscopic fission



energie atomique • energies alternatives

What else ?

- ***Cross section modeling quite easy for non fissile nuclei***

  Microscopic or Phenomenological OMP, Γ_γ, LDs

  ⇒ full microscopic calculation for non fissile nuclei almost possible

- ***Difficult but feasible cross section modeling for fissile nuclei***

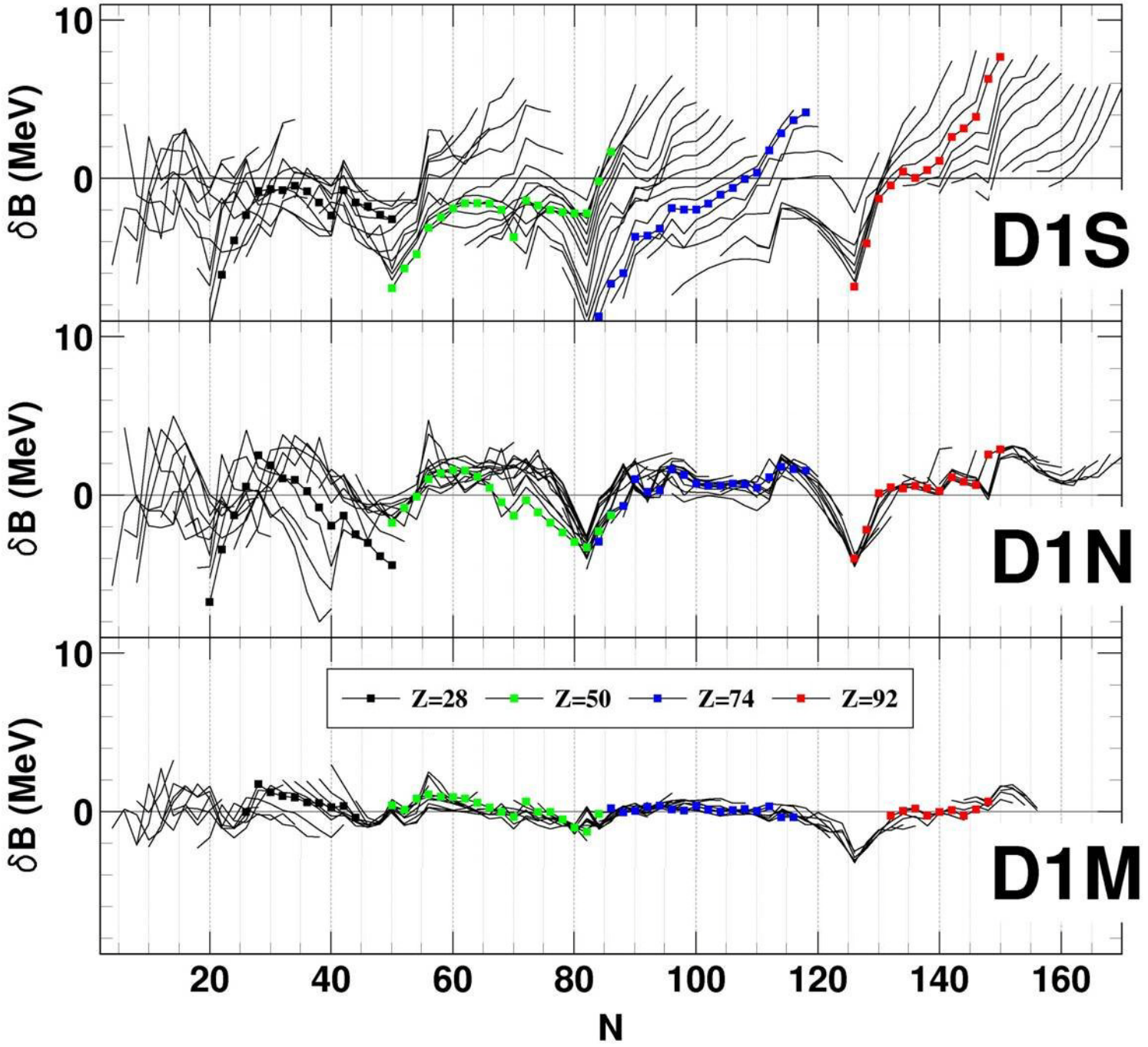
- ***Web site opened in October 2006 : www.talys.eu***

  ⇒ All microscopic ingredients mentioned included in the distribution

energie atomique • ene

- *Nev*
- *JLM*
- *Neu*
- *Mic*

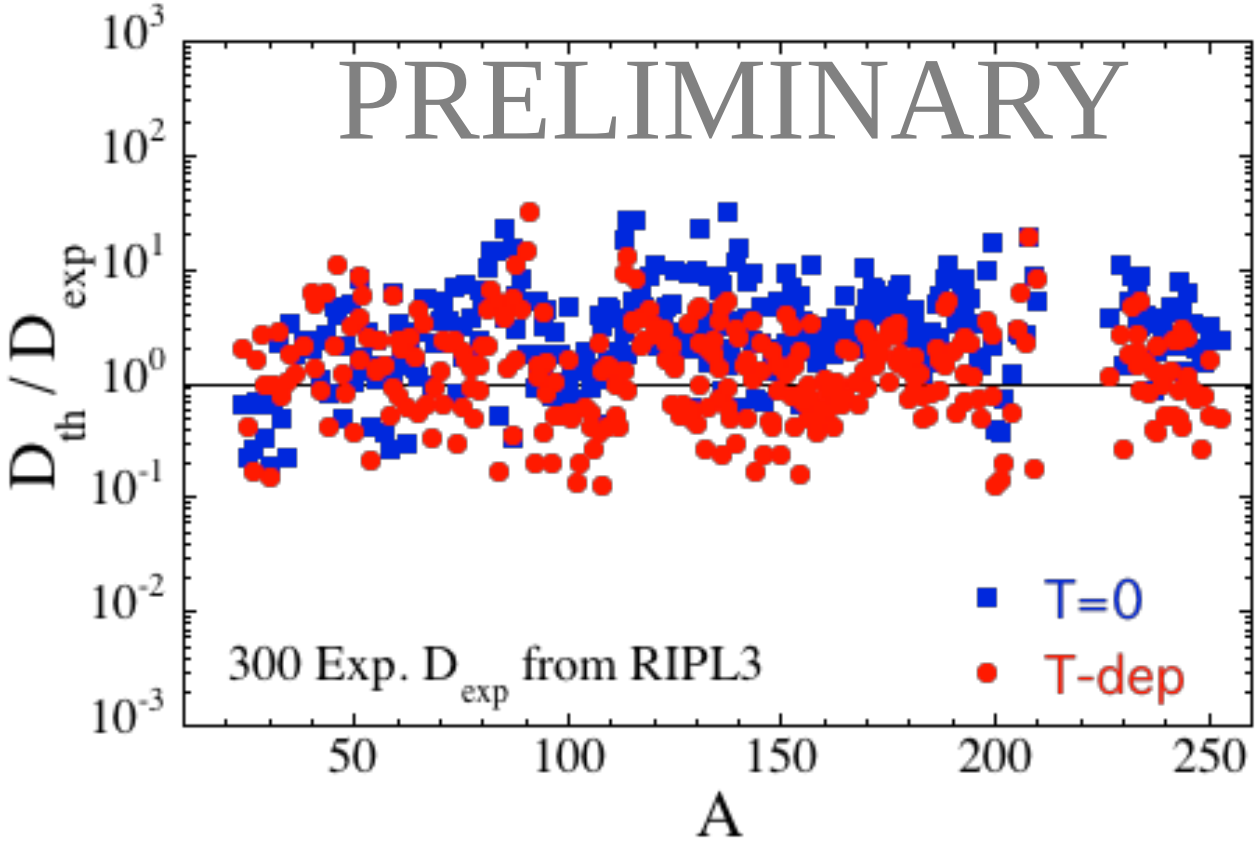
ev.)



Level densities with D1M

Method applied using the D1M Gogny force single particle levels, moments of inertia, quadrupole vibrational levels.

- **D1M (rms ≈ 798 keV) = update of D1S (rms ≈ 3 MeV)**

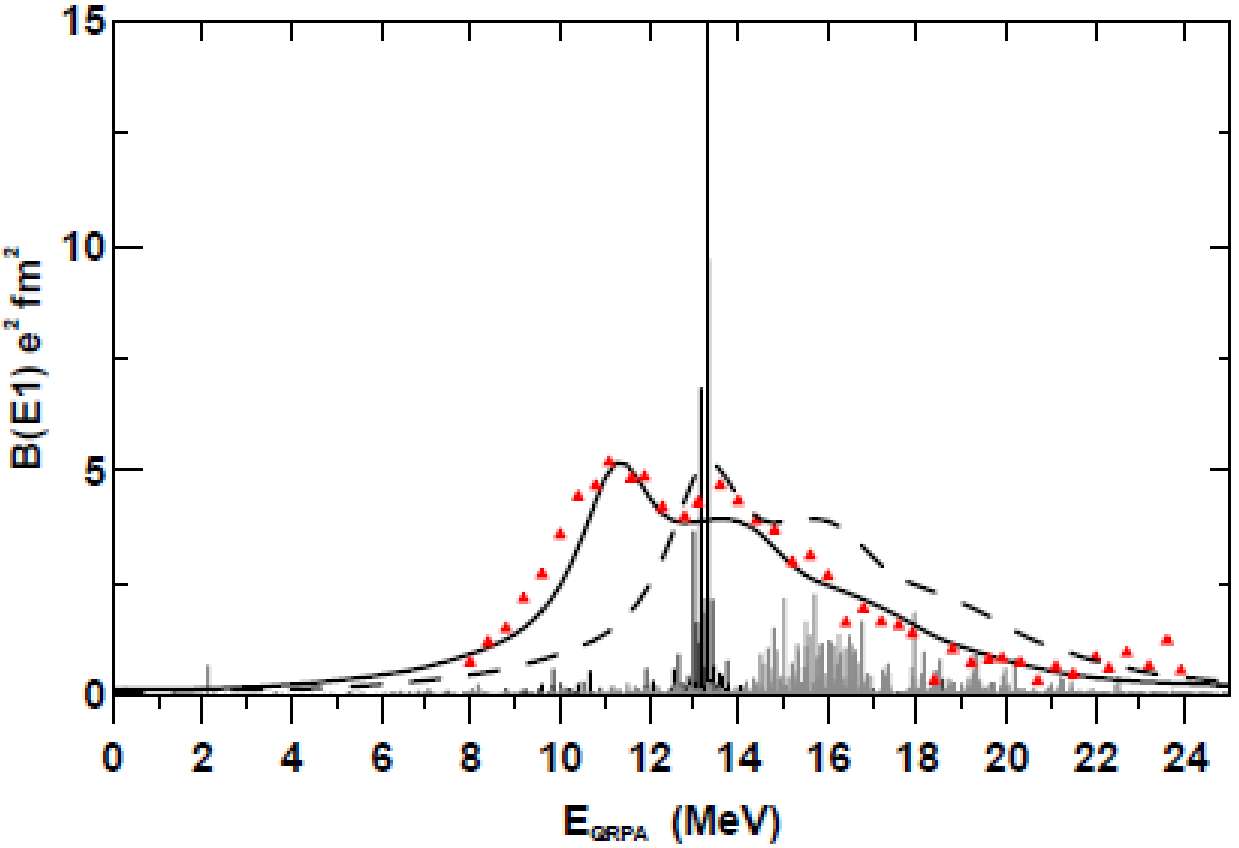


frms = 4.0

frms = 2.7

energie atomique

- *Ne*
- *JL*
- *Ne*
- *Mi*



.)

FIG. 2: (Color online) Dipole responses for ^{238}U. Transition probabilities B(E1) are given in e^2fm^2. Lorentzian distribution of 2 MeV width folding of the QRPA prediction (full line) shifted by 2 MeV with respect to the simple folding (dashed line) is plotted in order to compare with photo-absorption data. .

energie atomique • energies alternatives

What else ?

- ***New level densities for pre-equilibrium (done but not tested)***
- ***JLM OMP : spherical (OK) – deformed (soon)***
- ***Neutron multiplicities from FF decay (under dev.)***
- ***Microscopic ingredients with Gogny instead of Skyrme (under dev.)***

  - *already done for ν-ν interaction*
  - *well started for nuclear level densities*
  - *encouraging for γ-strength functions*
  - *tests still needed for fission paths (triaxiality, octupole, continuity …)*

energie atomique • energies alternatives

Remember 6th commandement

Use microscopic information as much as you can