# QRPA $E1$ and $M1$ strengths and their impact on reaction rates

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In collaboration with
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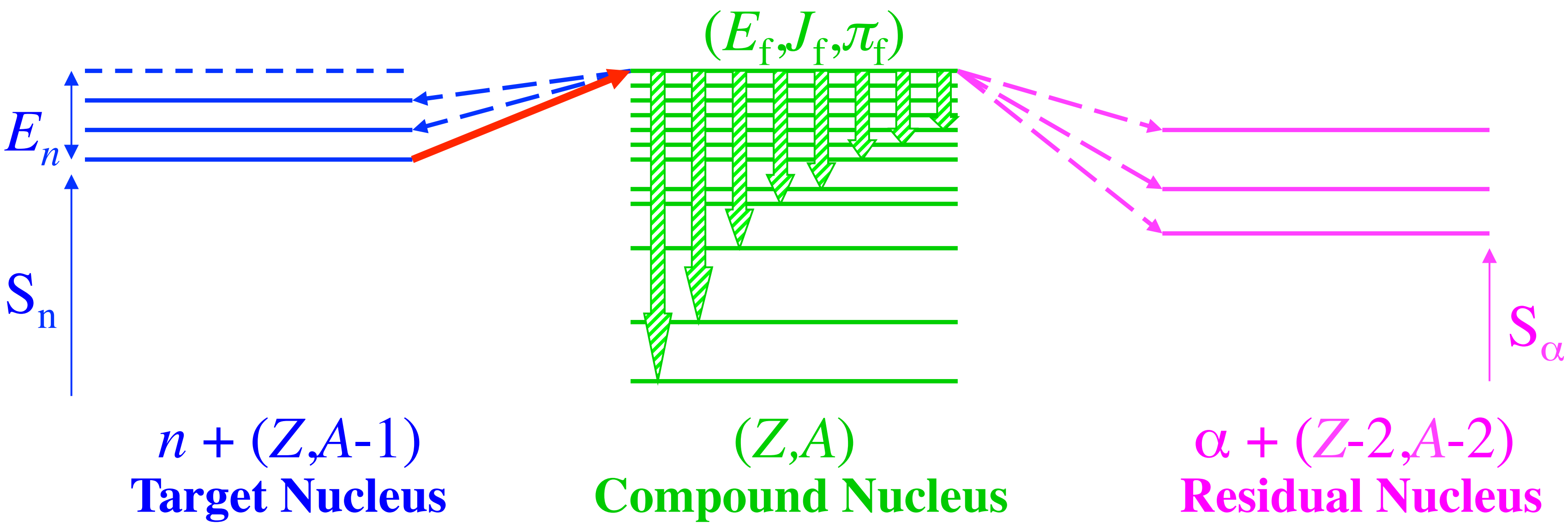
J. Kopecky (JUKO Research, The Netherlands)

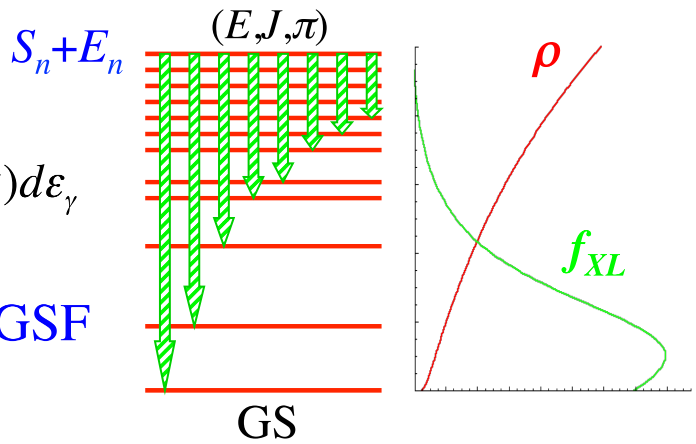
# Hauser-Feshbach model for radiative neutron capture reactions




$$\sigma_{(n,\gamma)} \propto \sum_{J,\pi} \frac{T_n(J^\pi)T_\gamma(J^\pi)}{T_n(J^\pi)+T_\gamma(J^\pi)} \approx \sum_{J,\pi} T_\gamma(J^\pi) \quad \text{since } T_n(J^\pi) >> T_\gamma(J^\pi)\text{: } E_n \text{~keV}$$

$$T_\gamma = \sum_{J^\pi XL} \int_0^{S_n+E_n} 2\pi\varepsilon_\gamma^{2L+1} f_{XL}(\varepsilon_\gamma)\rho(S_n+E_n-\varepsilon_\gamma, J, \pi)d\varepsilon_\gamma$$

*Nuclear astrophysics apps* require NLDs & GSF for ~ 8000 nuclei



# The *E*1 strength function

- Standard Lorentzian ($E_0$, $\Gamma_0$, $\sigma_0$)
- Lorentzian with *E*-dependent width (e.g McCullagh et al. 1981) $\Gamma = \Gamma_0 \left( \frac{E}{E_0} \right)^{1/2}$
- Generalized Lorentzian with *T*- and *E*-dep. width (e.g Kopecky & Uhl 1990)

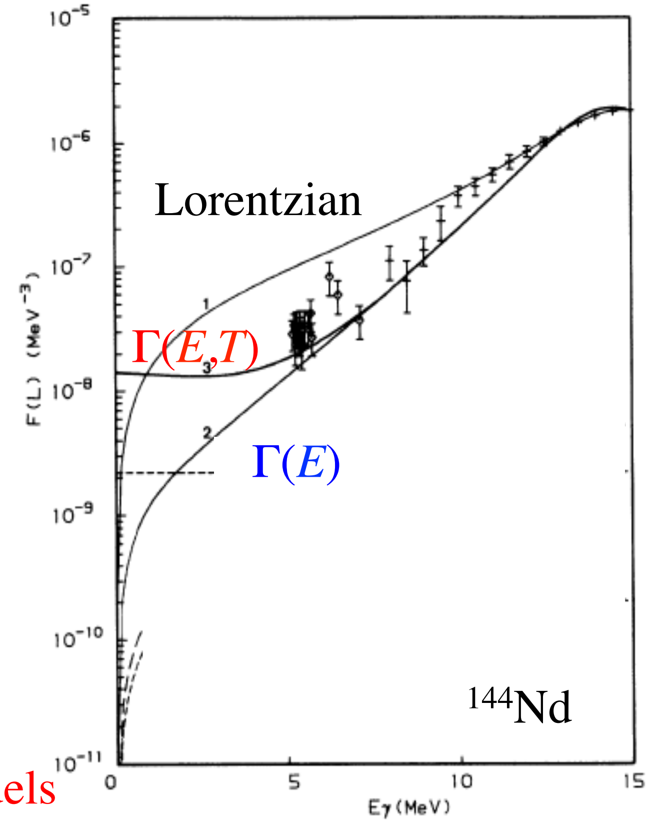
The *E*- and *T*-dependent width is essentially derived from the theory of Fermi liquids (e.g Kadmenski et al. 1983) and also suggested by experimental ARC data

$$\Gamma = \frac{\Gamma_0}{E_0^2}\left(E^2 + 4\pi^2 T^2\right)$$

decay of p-h states into more complex states ($E^2$ term)

collisions between quasi-particles ($4\pi^2 T^2$ term)

At the basis of GLO, EGLO, MLO, SMLO, Hybrid, … models




Kopecky & Uhl (1990)

# Mean Field + QRPA γ-ray strength function

Large-scale *E*1 Mean-Field + QRPA calculations

| Skyrme-HFB + QRPA | Gogny-HFB + QRPA | RMF +QRPA |
|---|---|---|

QRPA calculations can accurately reproduce experimental data, provided empirical corrections are made, *i.e.*

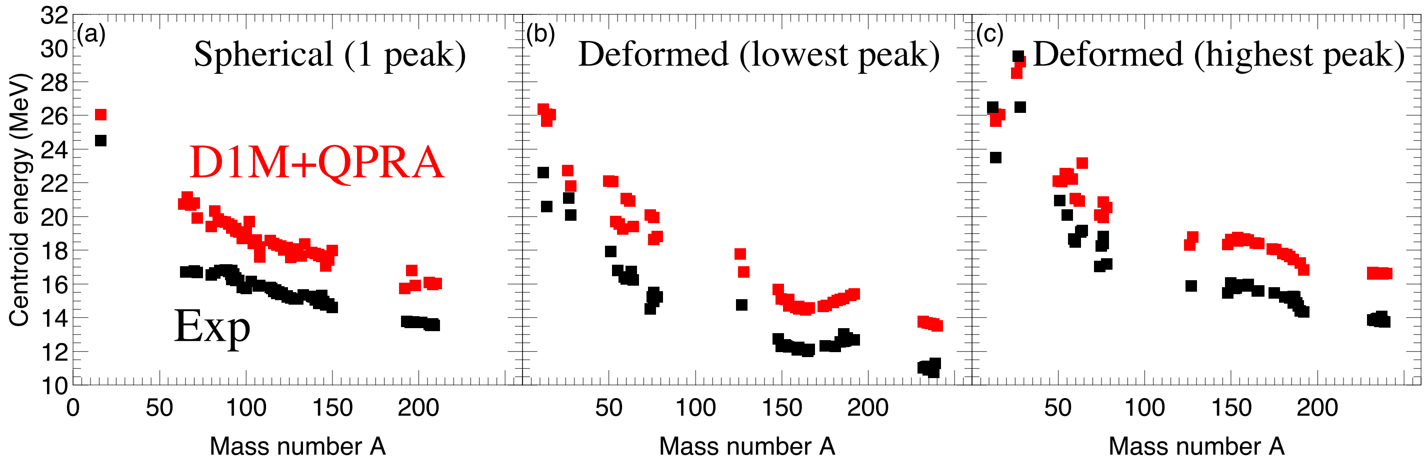
- Empirical damping of collective motions → broadening
- Empirical Energy shift (beyond 1p-1h excitations and phonon couplings)
- Empirical deformation effects for spherical calculations

Recent large-scale Gogny-HFB + QRPA calculations:
*Consistent axially deformed calculation*
for 1470 e-e nuclei with $8 \leq Z \leq 98$
(interpolation for ~ 4000 odd-A & odd-odd nuclei)

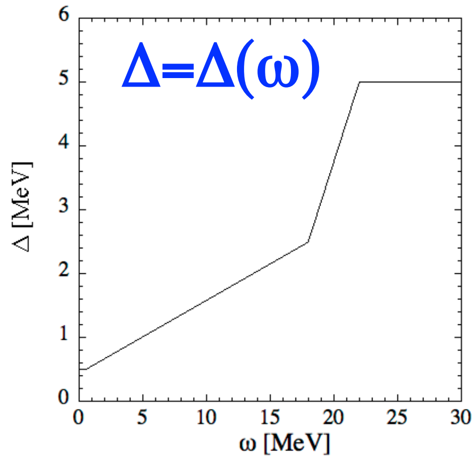
# Gogny-HFB + QRPA *E*1 strength function

Péru, Martini, Hilaire et al. (2016)

- **axially-symmetric deformed** QRPA estimate of the *E*1-strength based on the **D1M Gogny force**



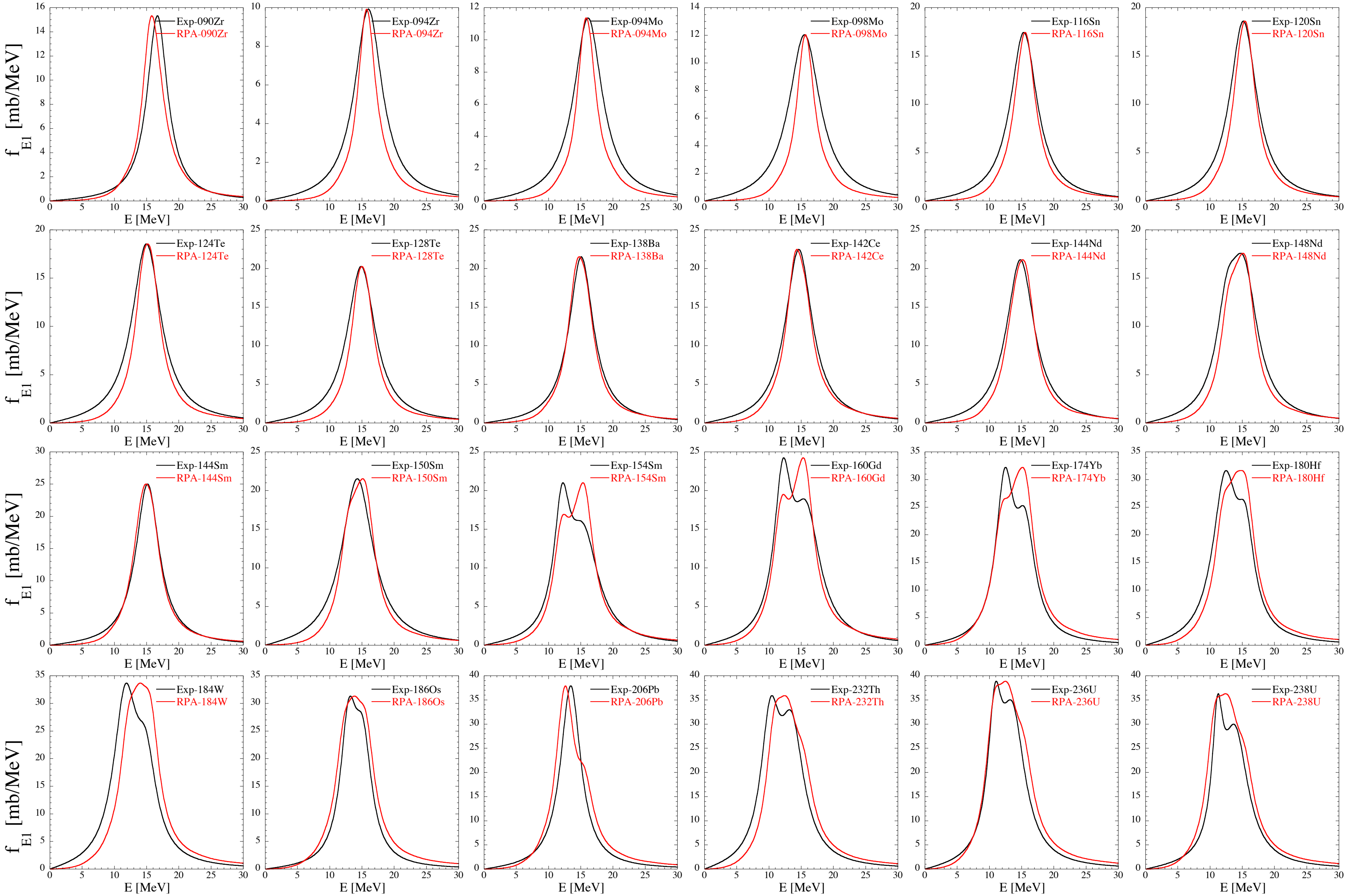

→ Energy shift at GDR centroid energy of ~ –2.5MeV with respect to experiment to take 2p-2h and phonon coupling into account




- **Empirical damping** of the collective motions : each strength is folded by a Lorentzian function (Γ~2.5 MeV)

**All details given in S. Hilaire talk (Wednesday 10am)**

# Comparison with experimental (RIPL3) photodata



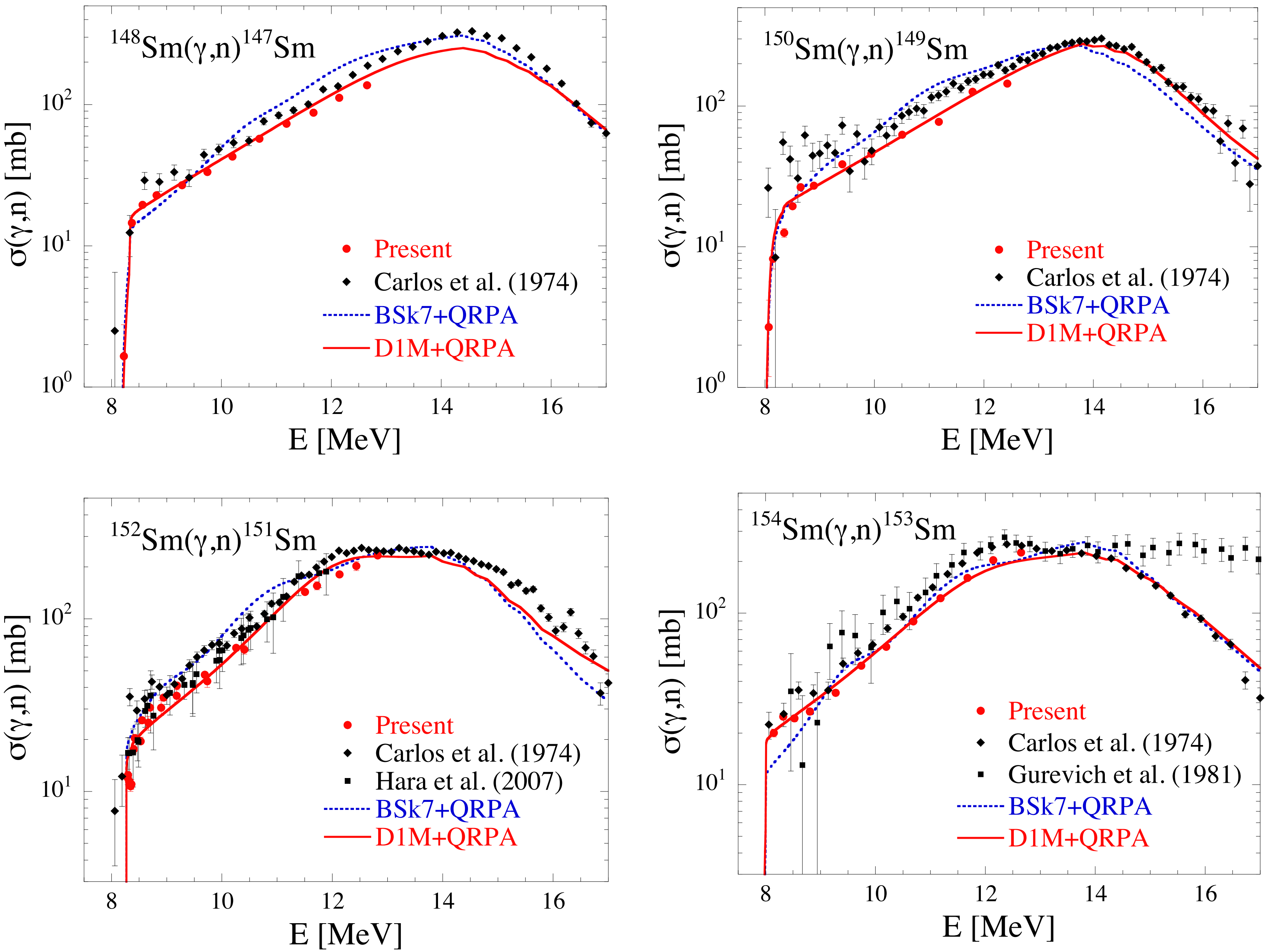
# HFB + QRPA strength

Tested on recent (γ,n) data from Utsunomiya et al.

$^{80}$Se, $^{90-96}$Zr, $^{94-100}$Mo, $^{105-108}$Pd, $^{116-124}$Sn, $^{139}$La, $^{141}$Pr, $^{143-148}$Nd, $^{144-154}$Sm, $^{181}$Ta, $^{186}$W, $^{187}$Re, $^{188}$Os, $^{206-208}$Pb

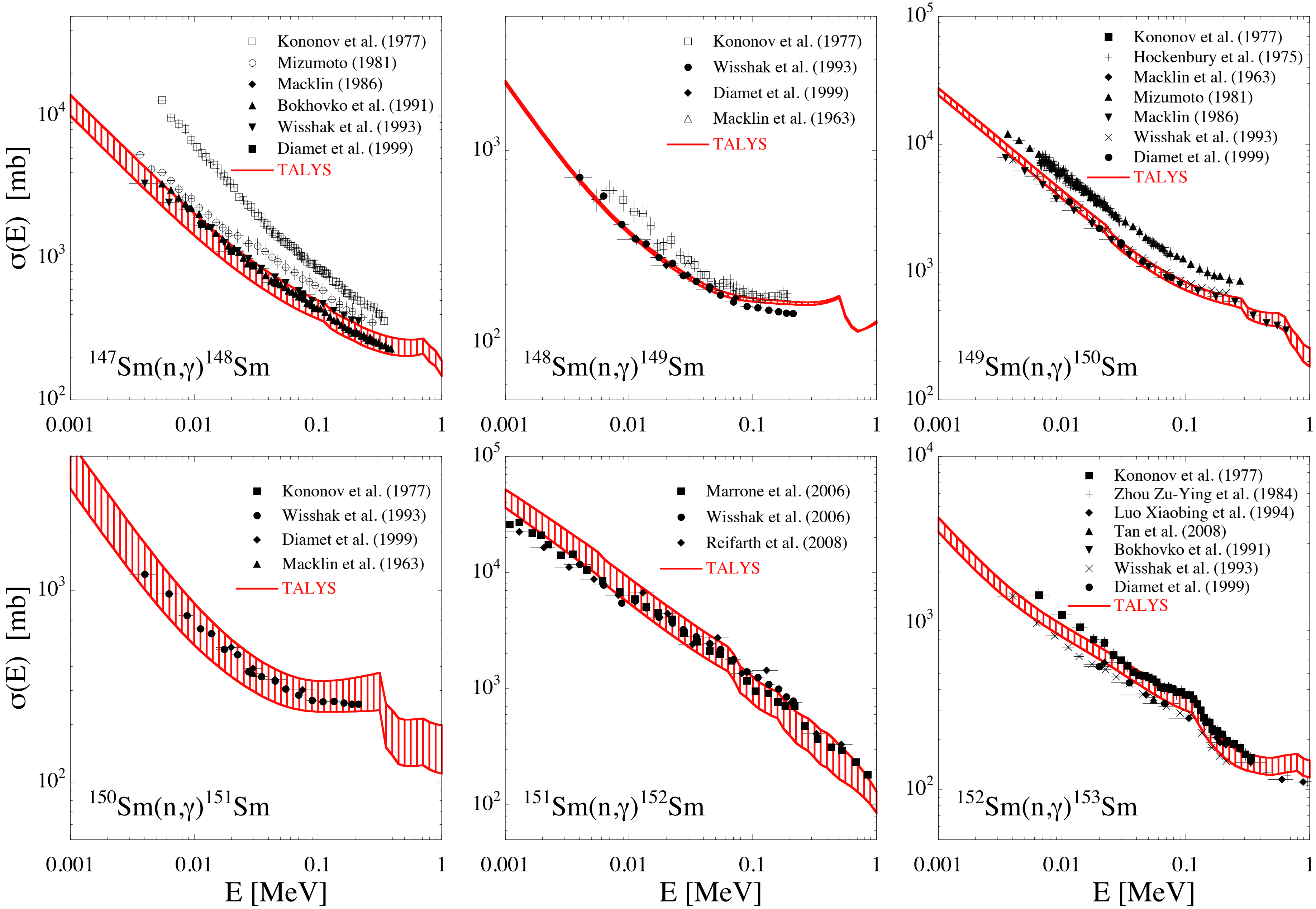
With additional constraints from the reverse experimentally known (n,γ) cross sections (though NLD-dependent)

(cf γ-ray strength method; Utsunomiya et al.)




Present = Filipescu et al. (2014)

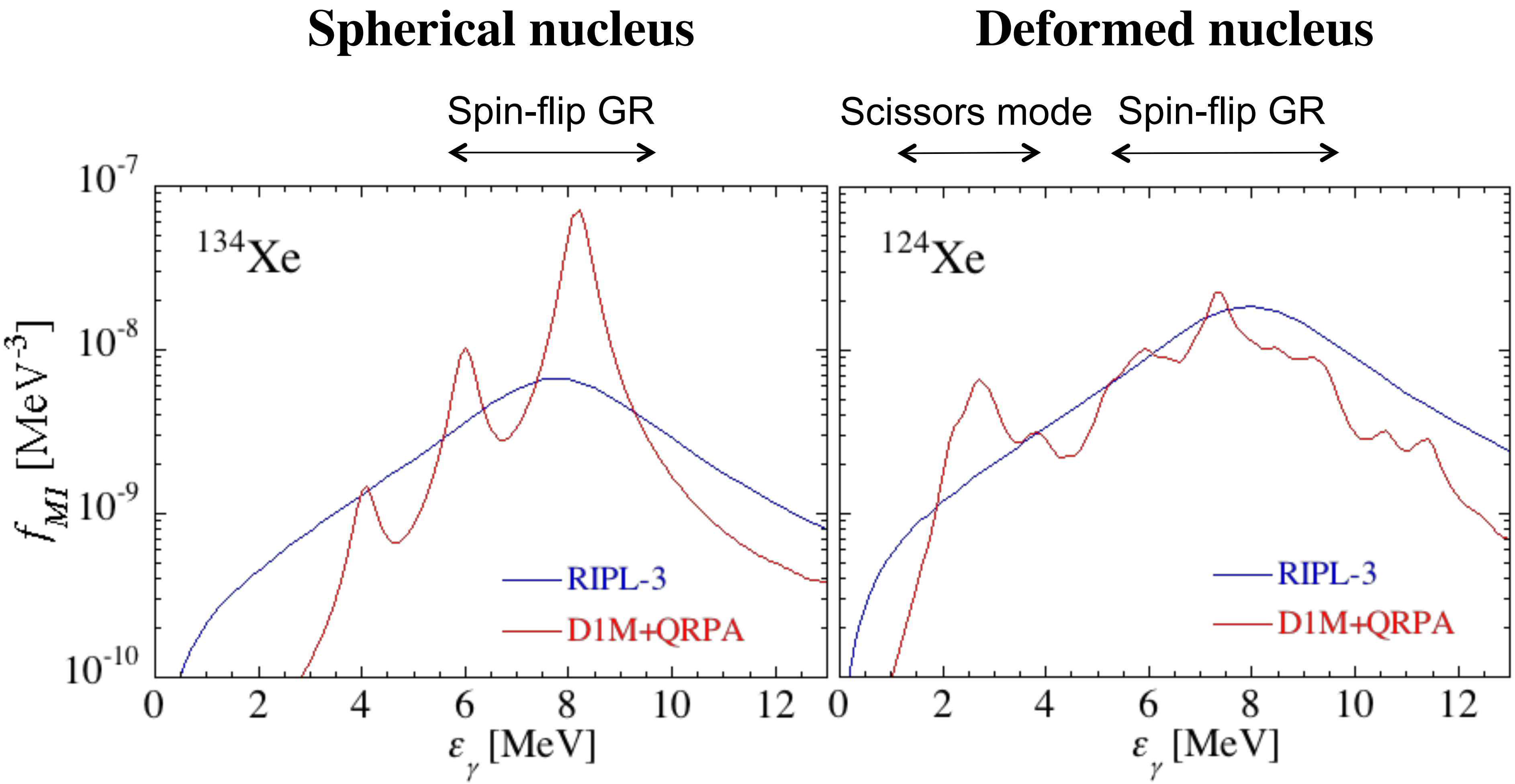
# Sm(n,γ) cross sections on the basis of the D1M + QRPA strength



# WHAT ABOUT THE $M1$ STRENGTH ?

# Gogny-HFB + QRPA *M*1 strength function

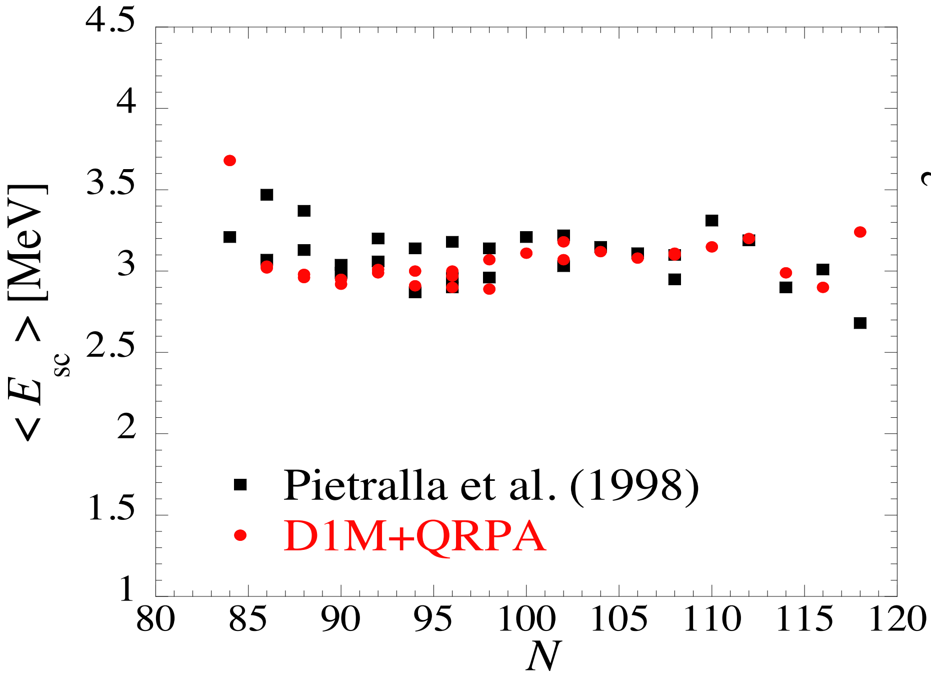
***Axially-symmetric deformed*** QRPA estimate of the *M*1-strength based on the D1M Gogny force: same normalisation as for the *E*1



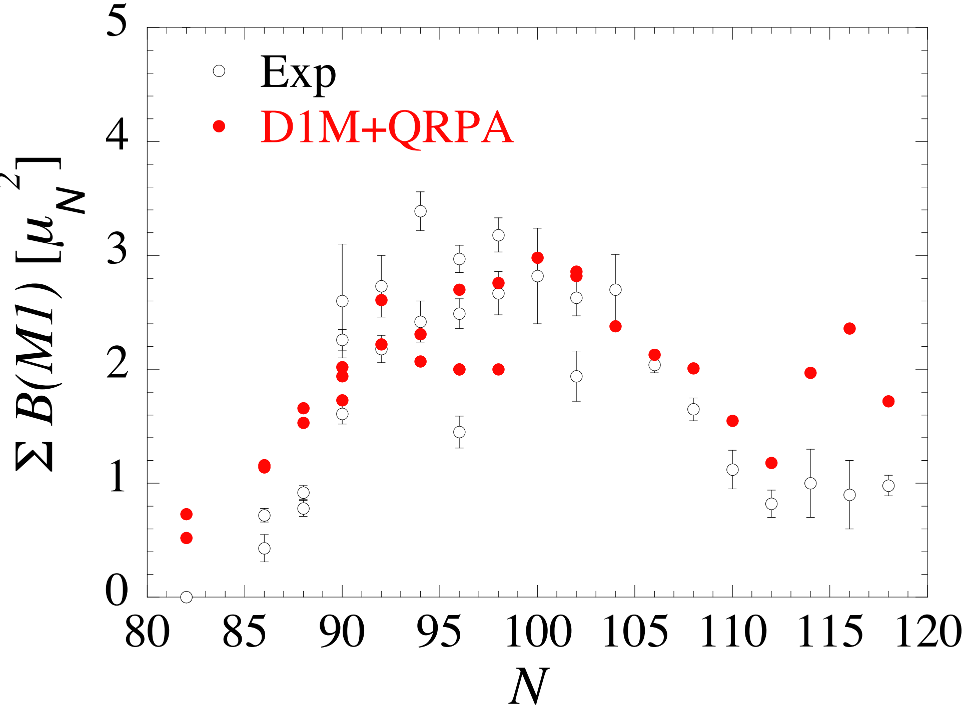
# Comparison with experimental data

## Low-energy (2.4–3.7 MeV) *M*1 strength in the rare-earth region

### Centroid energy

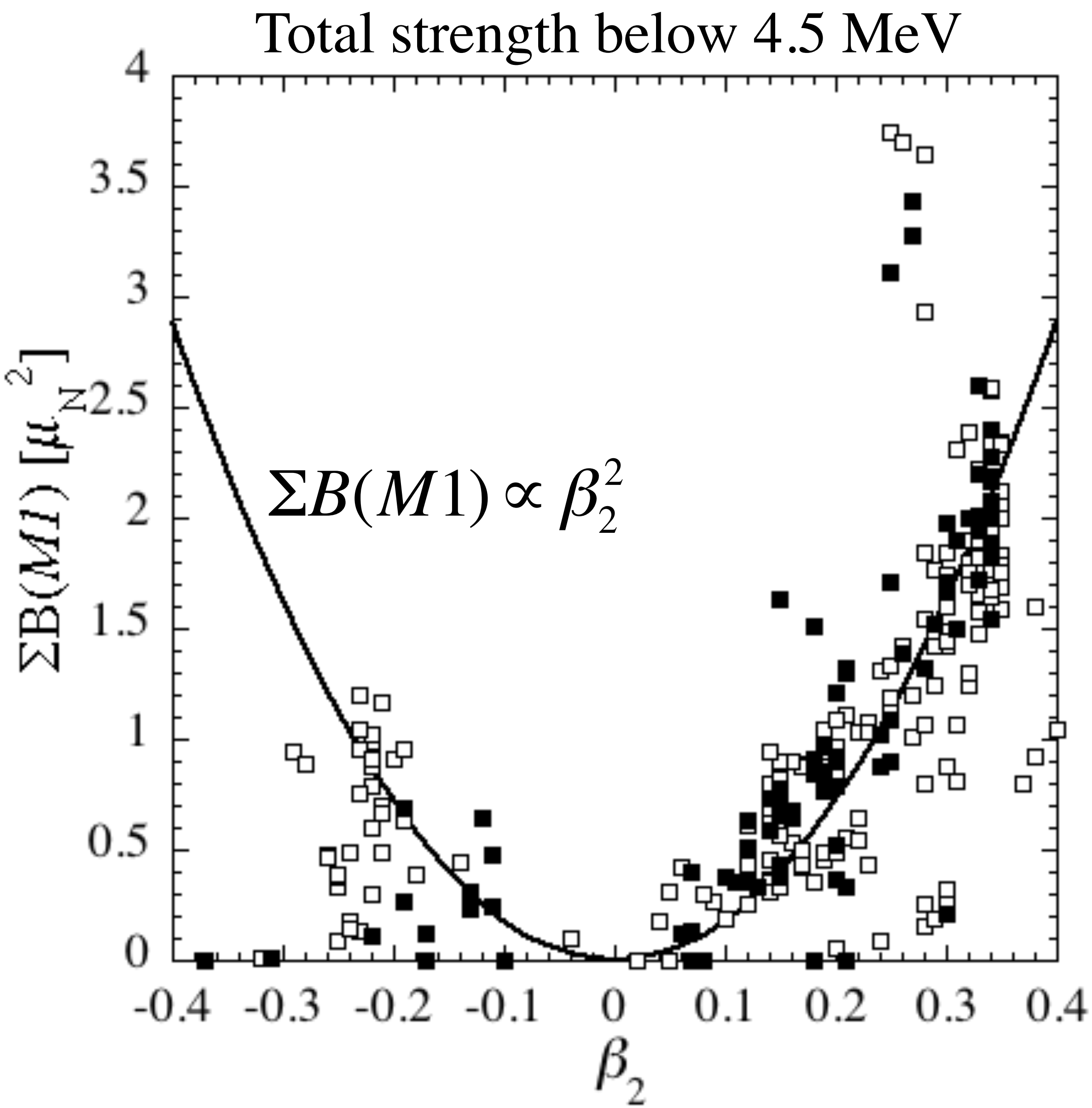



### Integrated strength



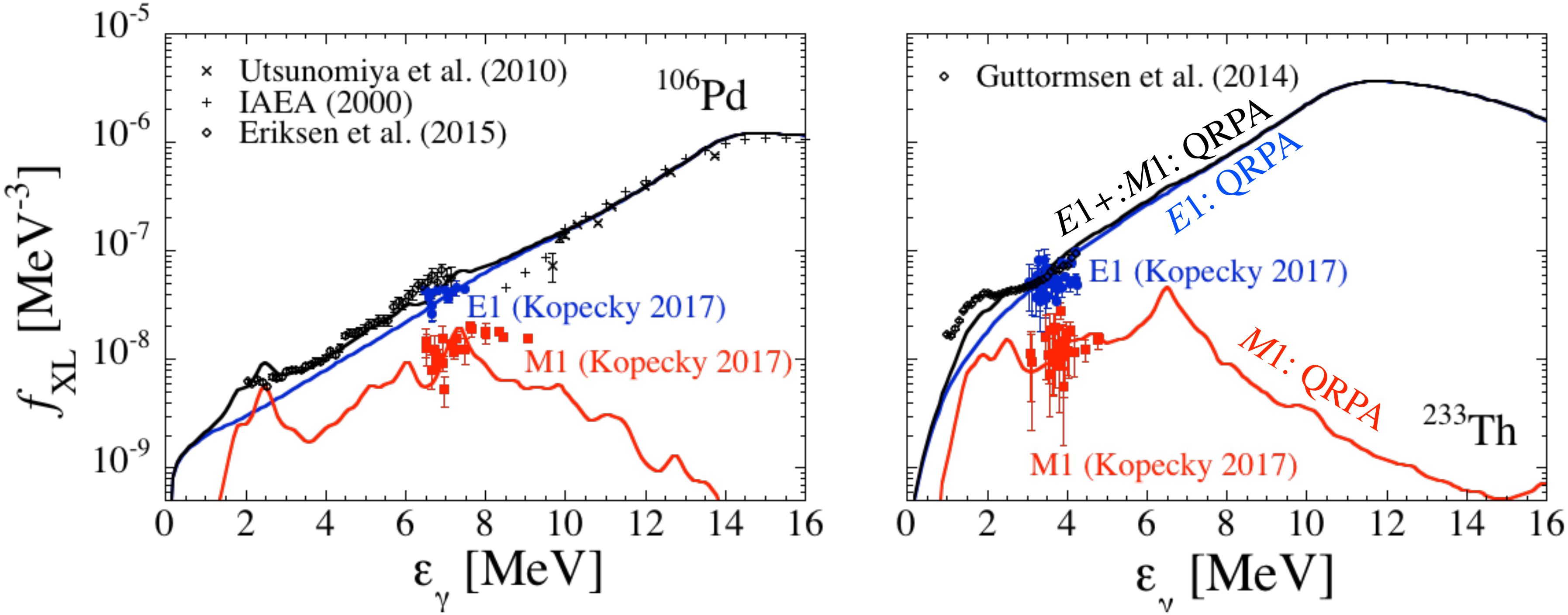

D1M + QRPA strength needs to be increased by a factor 2 !

## Deformation dependence of the scissors mode

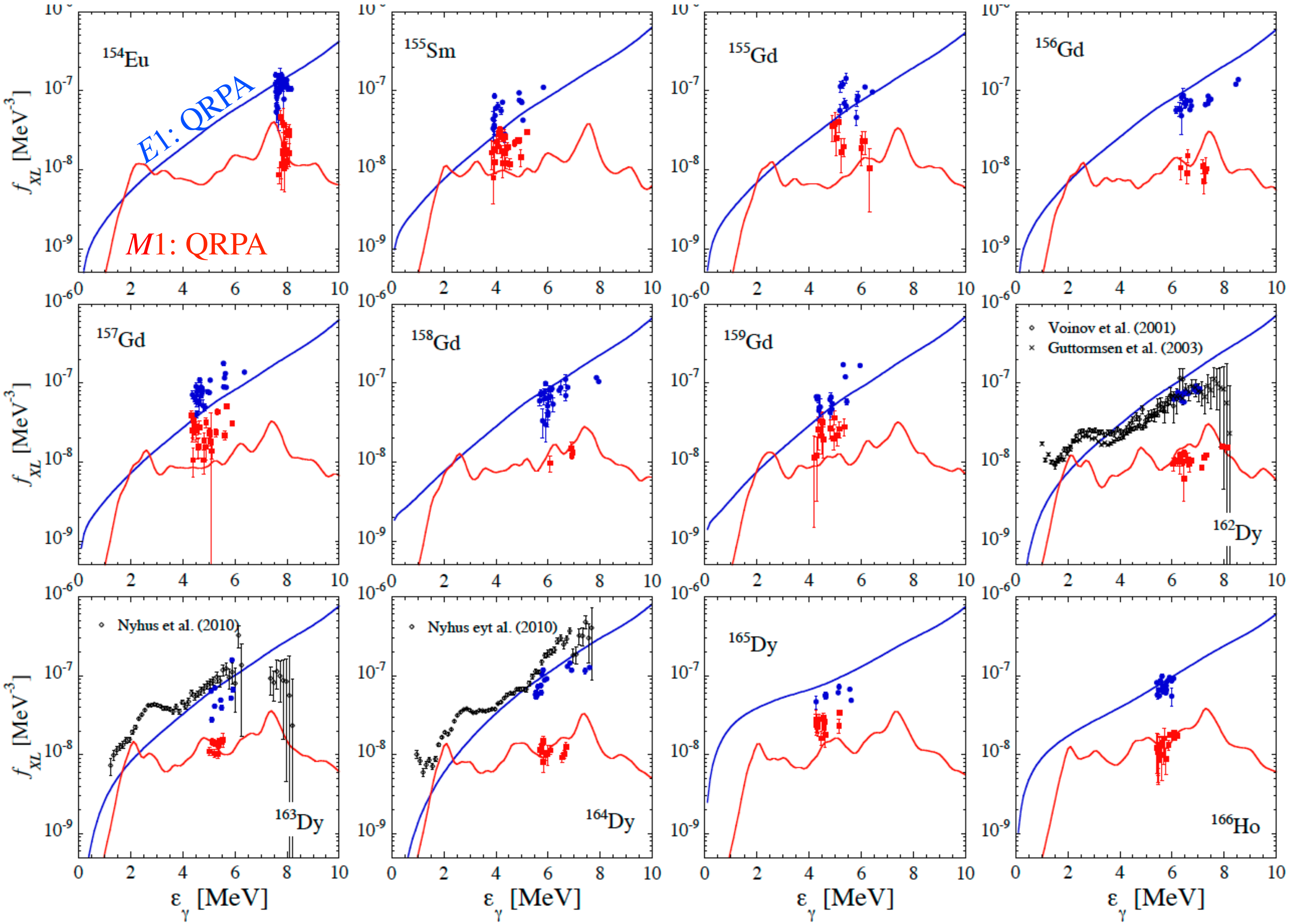


# $^{106}$Pd & $^{233}$Th strength function : $E1$ & $M1$ components

## Comparison with ARC and Oslo data

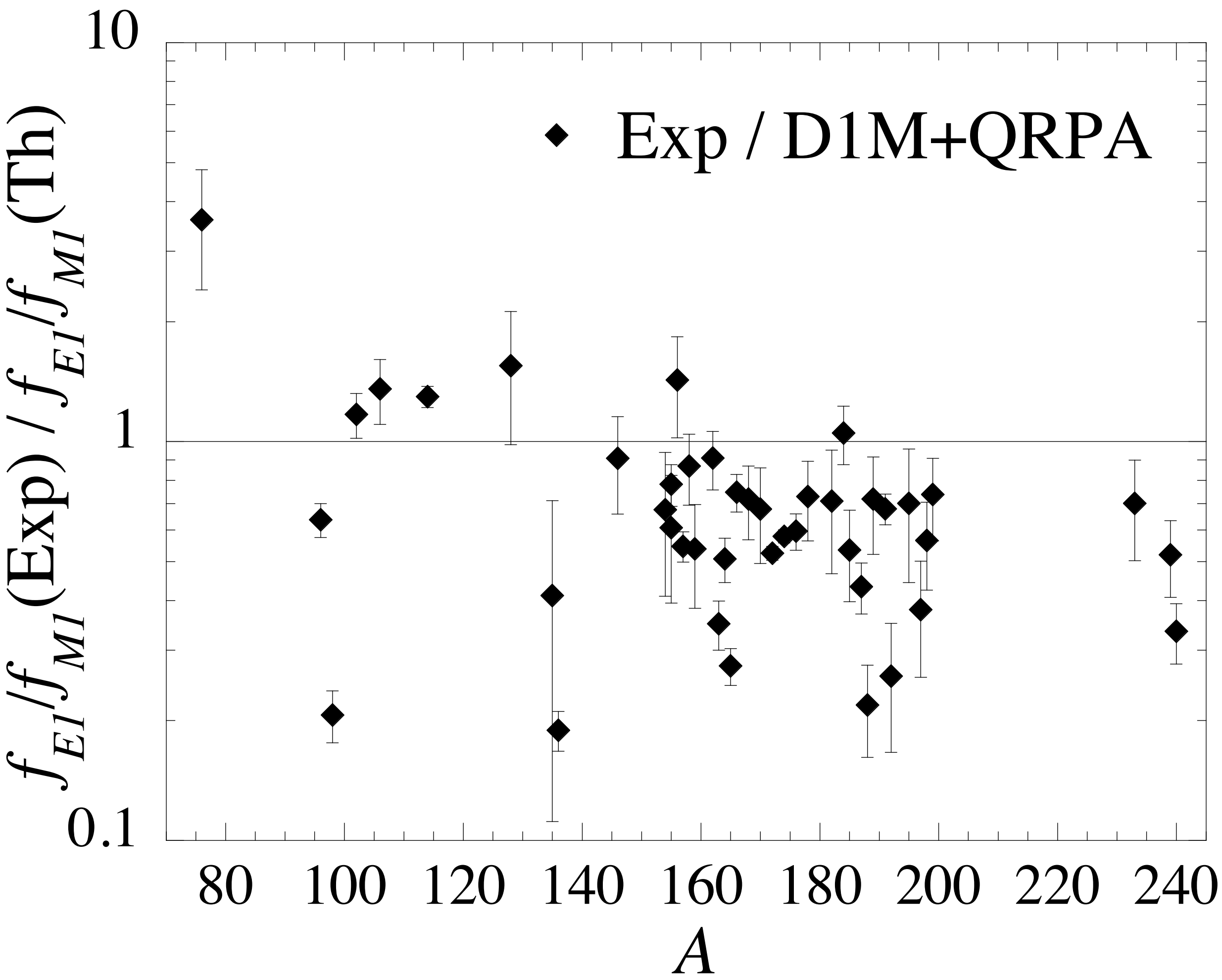


# New evaluation of ARC data for 48 nuclei (Kopecky 2017)



## New evaluation of ARC data for 48 nuclei (Kopecky 2017)

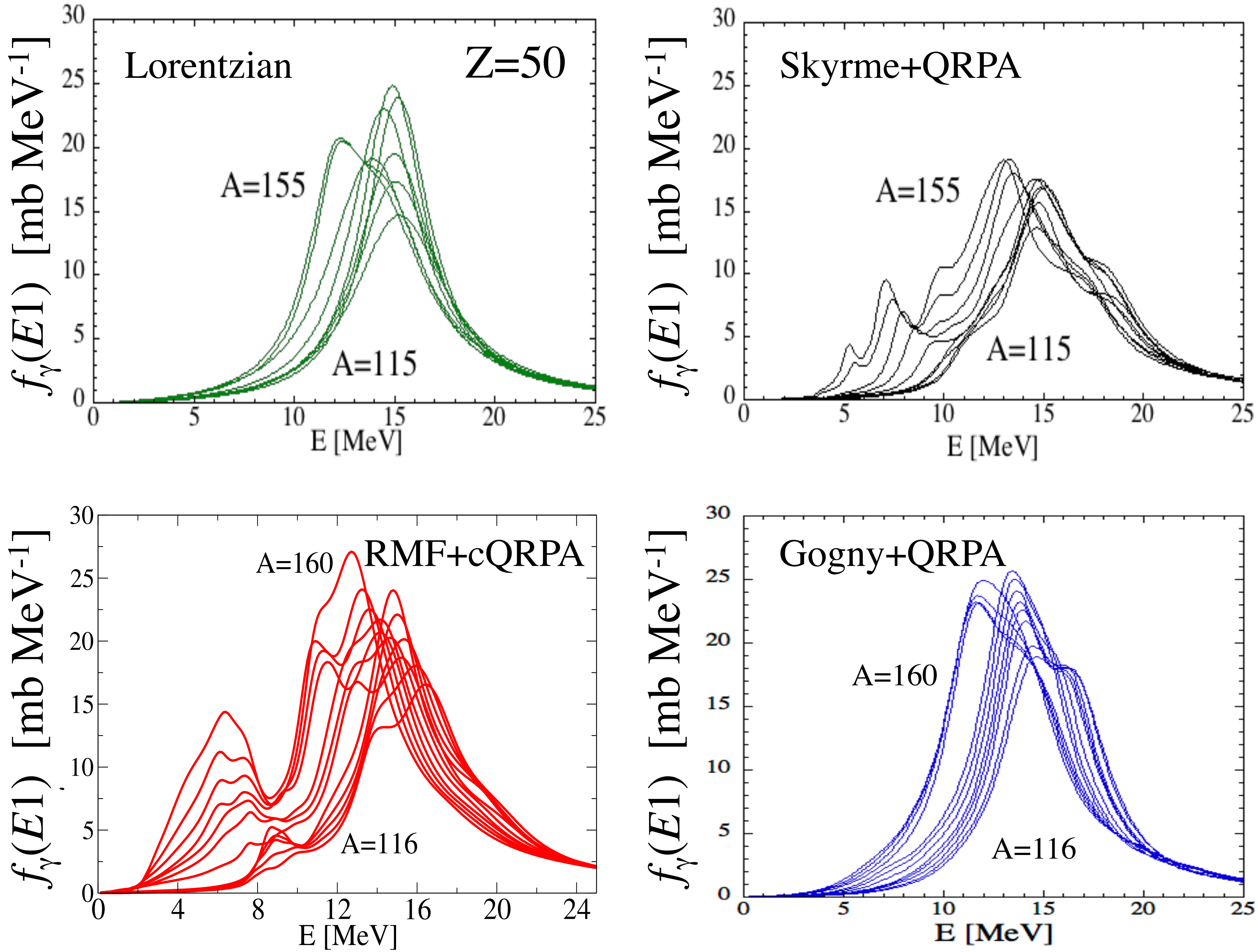
*E*1/*M*1 ratio: stringent test for γ-ray strength models



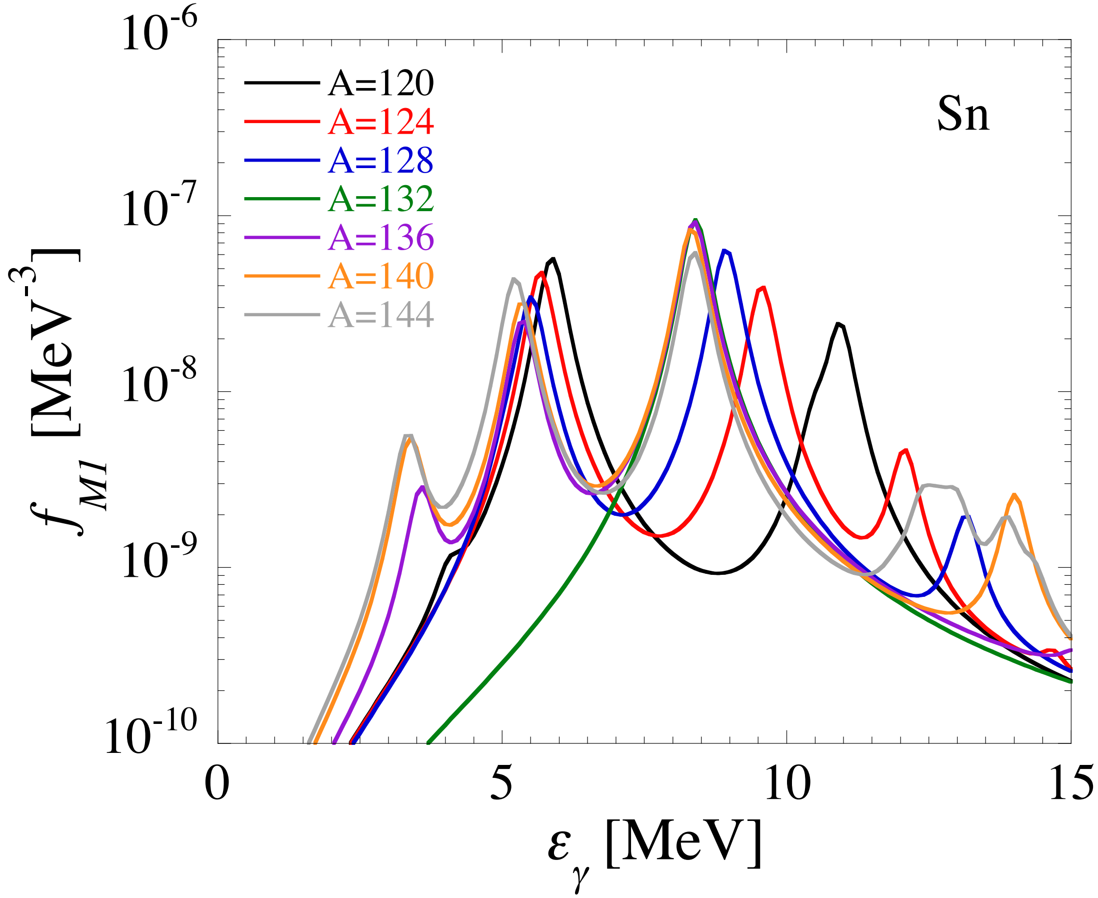

D1M+QRPA underestimate of the *M*1 strength by ~30%

What about exotic nuclei away from the valley of β-stability ?

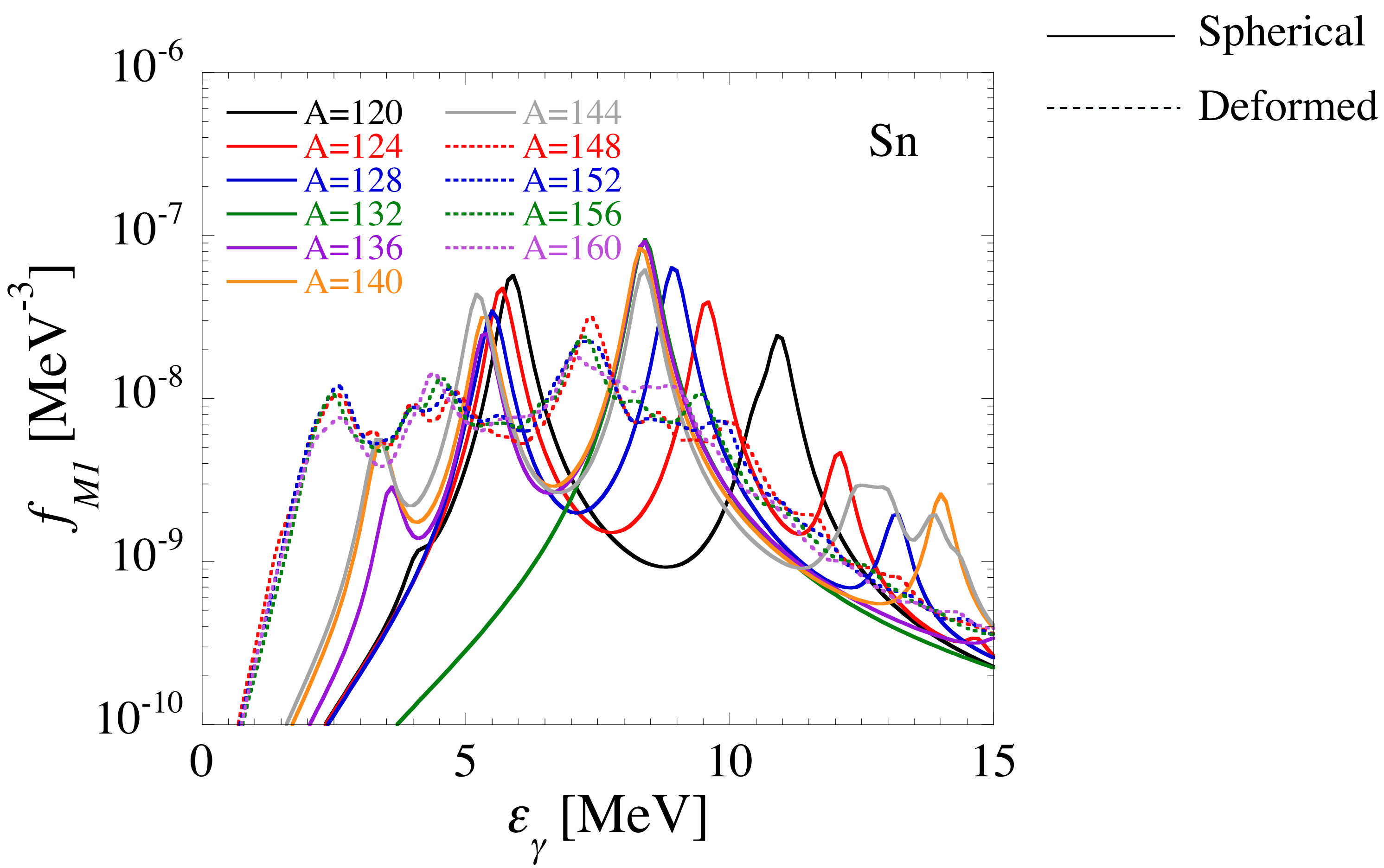
# *E*1 strength function in n-rich Sn isotopes



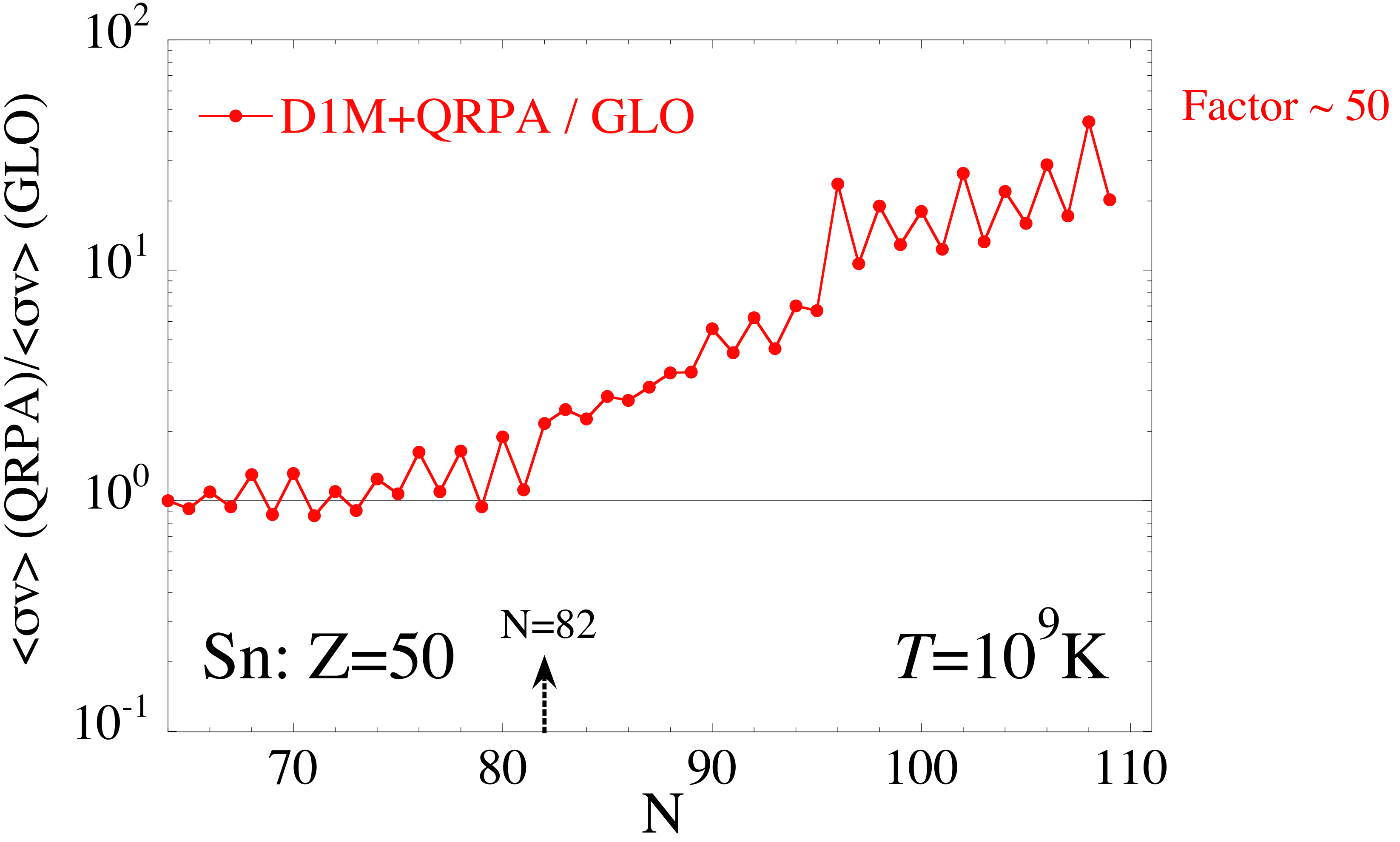
# *M*1 strength function in n-rich Sn isotopes



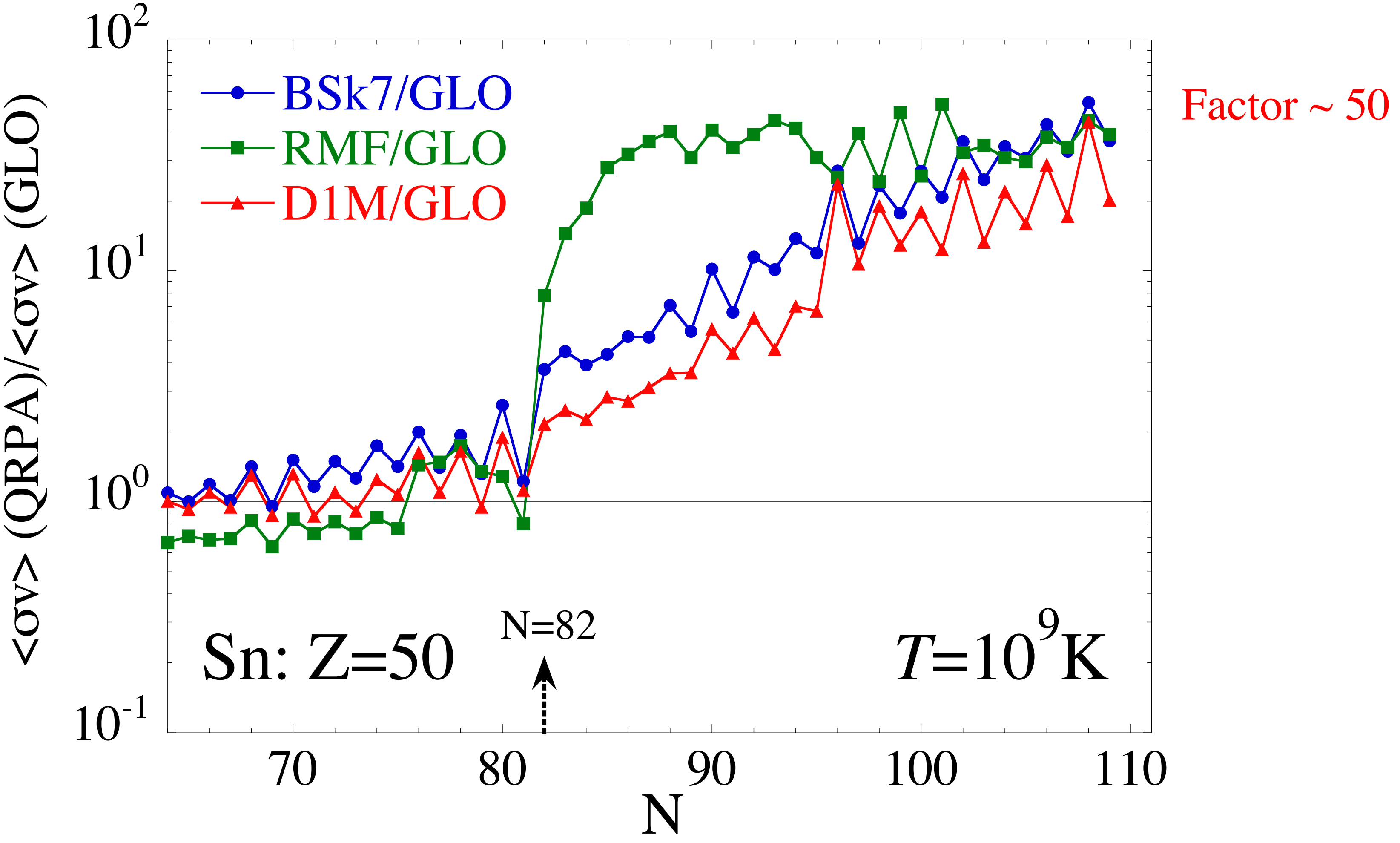
# *M*1 strength function in n-rich Sn isotopes



(n,γ) MACS with Generalized Lorentzian (GLO) *E*1 strength compared with Gogny-HFB + QRPA calculations

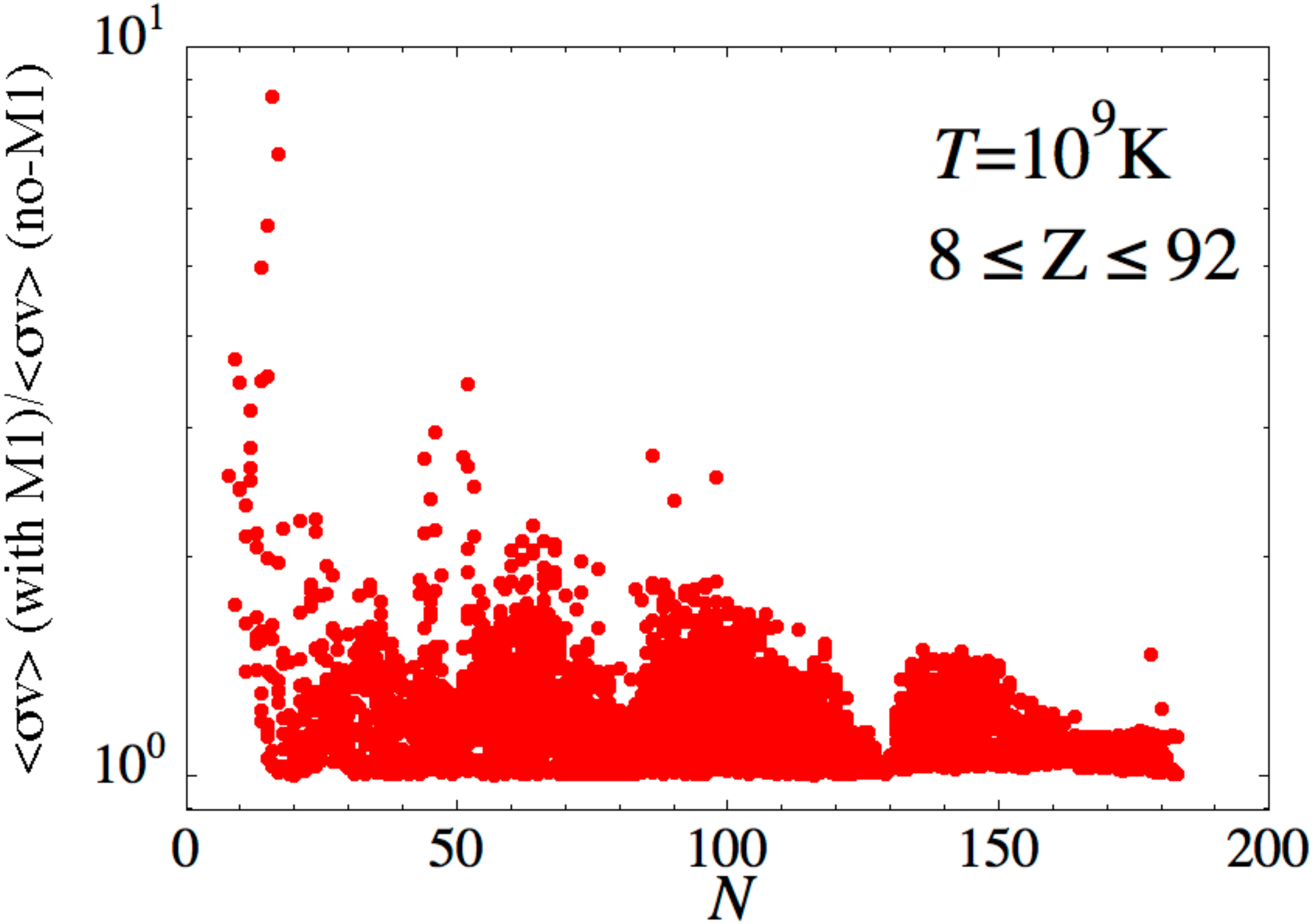


(n,γ) MACS with Generalized Lorentzian (GLO) *E1* strength
compared with
**QRPA** calculations: Skyrme-HFB, RMF and Gogny-HFB



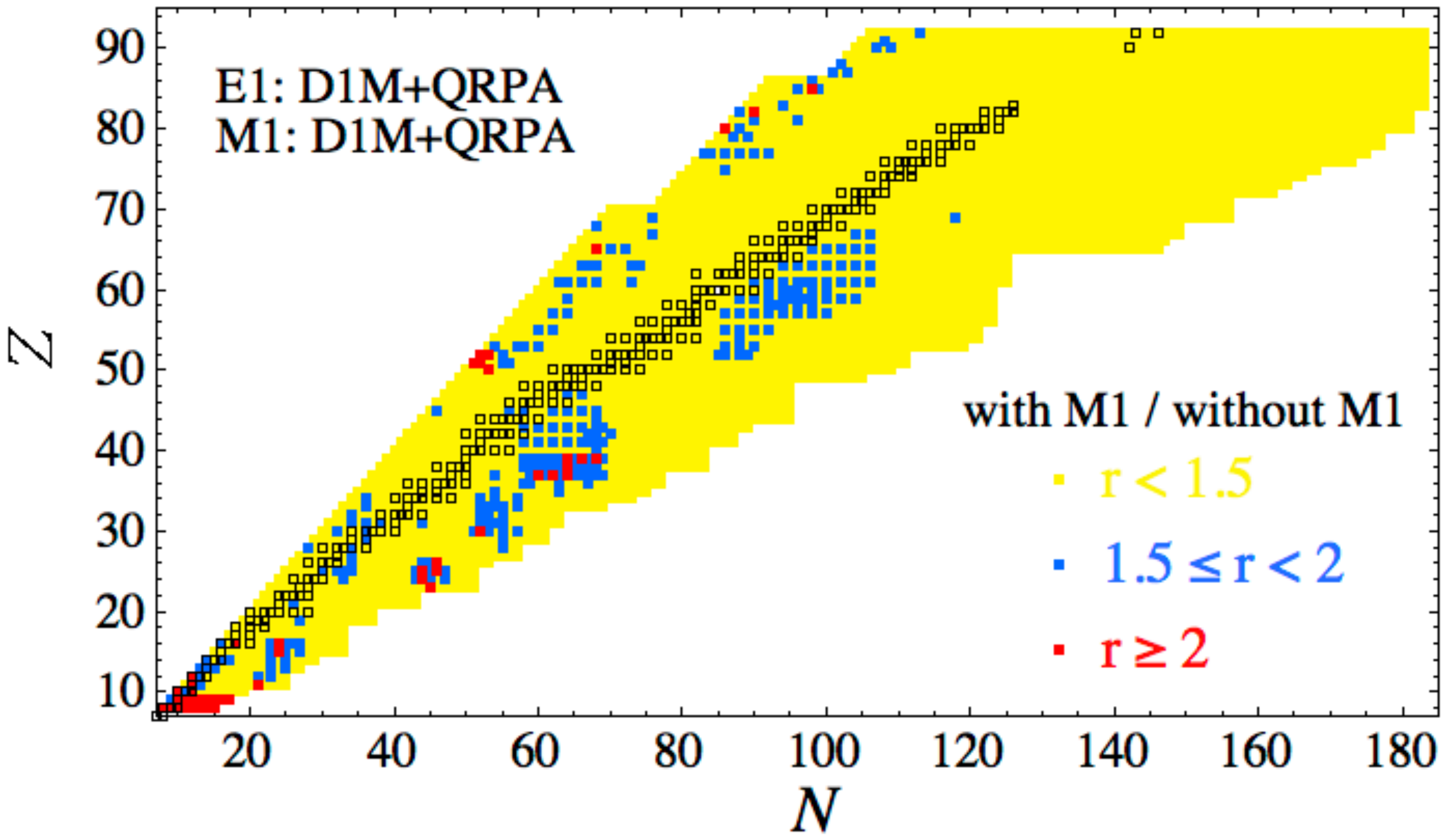
## Impact of the D1M+QRPA *M*1 strength on (n,γ) rates at $T$=10$^9$K

~ 4700 nuclei with 8 ≤ Z ≤ 92



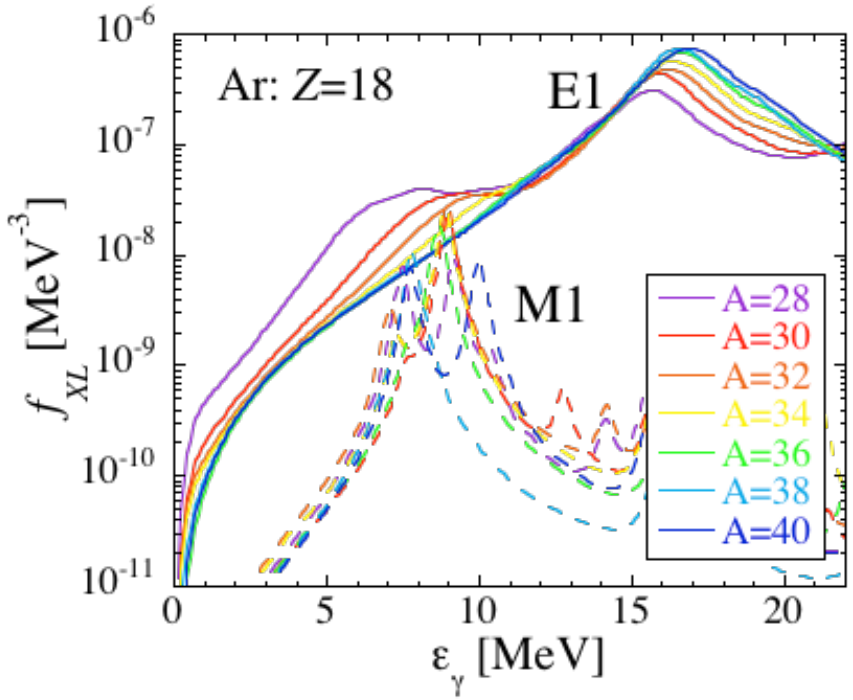

*M*1 impact stems from the appearance of the low-lying scissors mode in def. nuclei

# Impact of the D1M+QRPA $M1$ strength on (n,γ) rates at $T=10^9$K

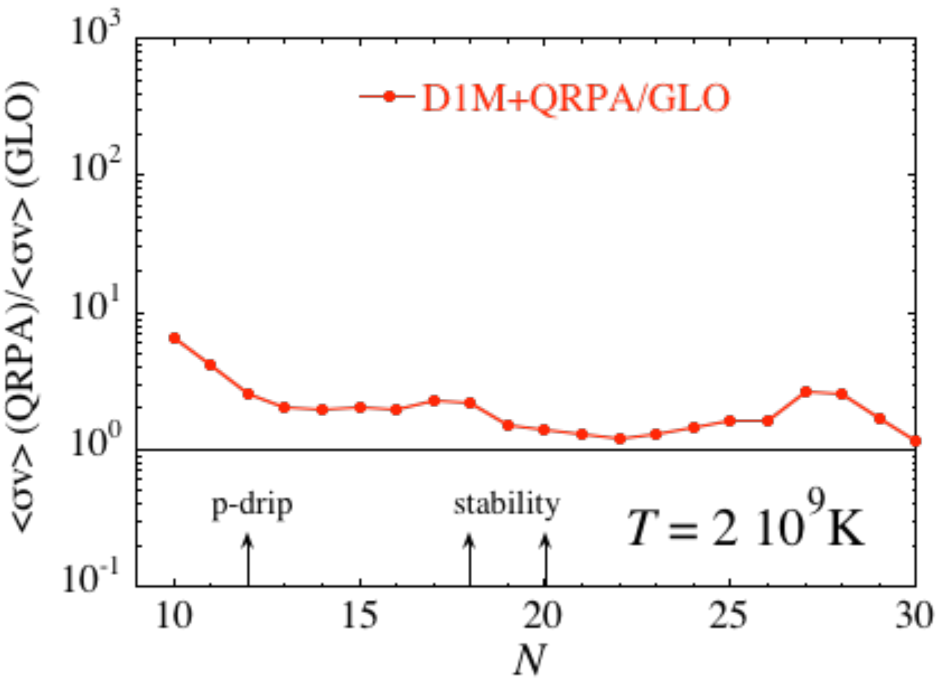


# γ-ray strength function for the *n-deficient* nuclei
# Pygmy Dipole Resonance

D1M+QRPA E1 strength in Ar isotopes



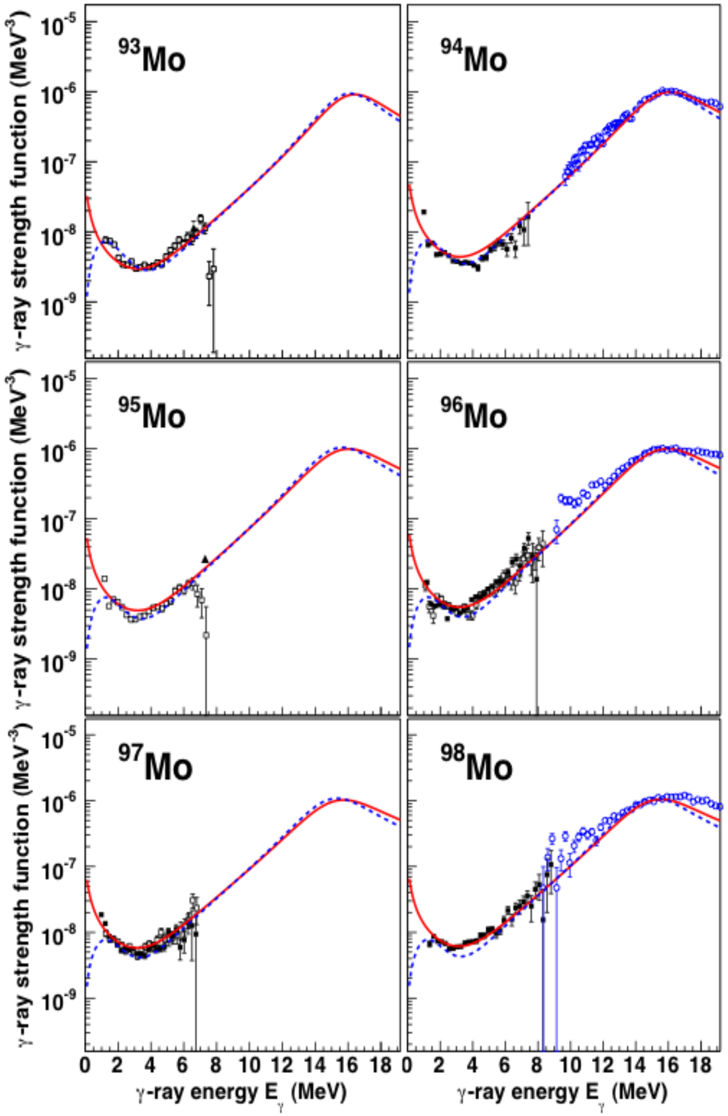

$^{A}$Cl(p,γ)$^{A+1}$Ar reaction rate



# Impact of a possible low-energy $M1$ upbend

# The low-energy upbend structure observed experimentally in Oslo

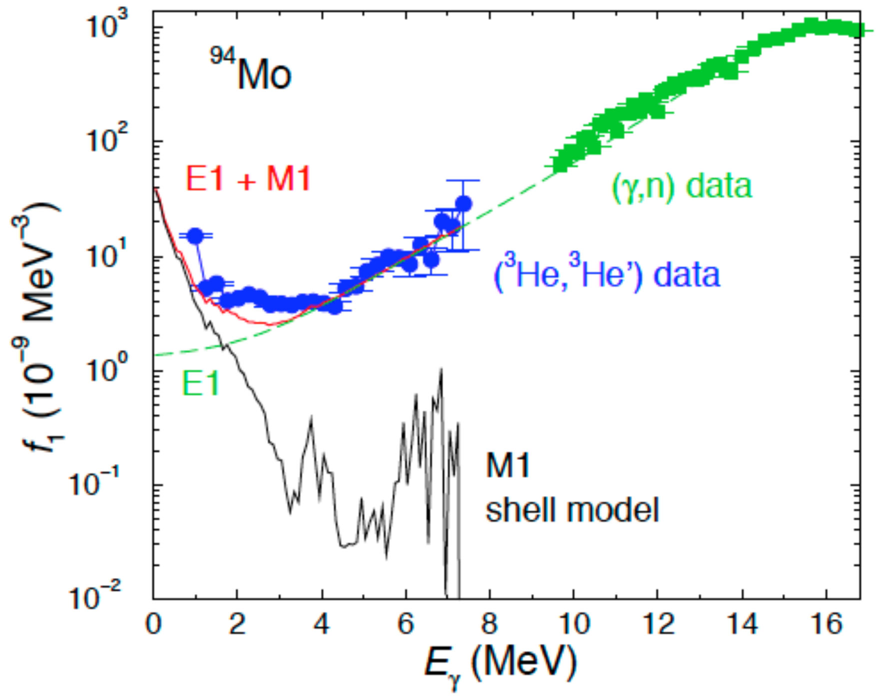
particle−γ coincidence in the ($^3$He,αγ) & ($^3$He,$^3$He' γ) reactions




A.-C. Larsen et al. (2009)

Upbend observed for $^{44,45}$Sc, $^{50,51}$V, $^{56,57}$Fe, $^{73\text{-}74}$Ge, $^{93\text{-}98}$Mo, Sm but not (yet) for Sn, Dy, Er or Yb

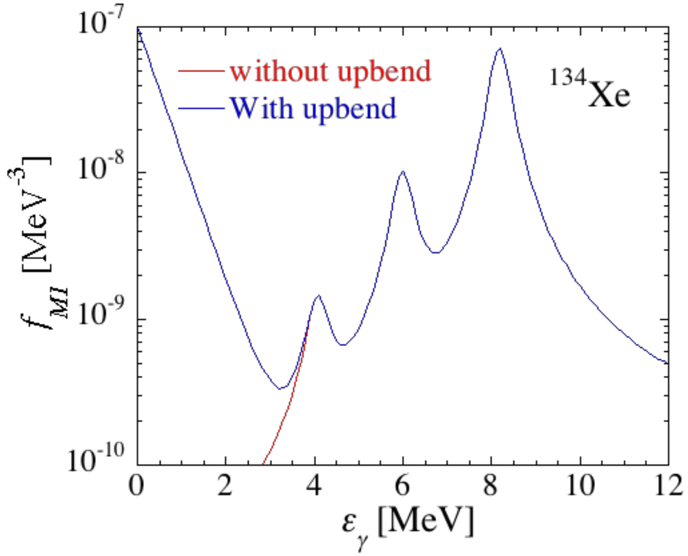
The *M*1 character of the upbend seems to be confirmed by shell model calculations (though an *E*1 character cannot be excluded yet)




R. Schwengner et al. (2013); Brown & Larsen (2014); Sieja (2016)

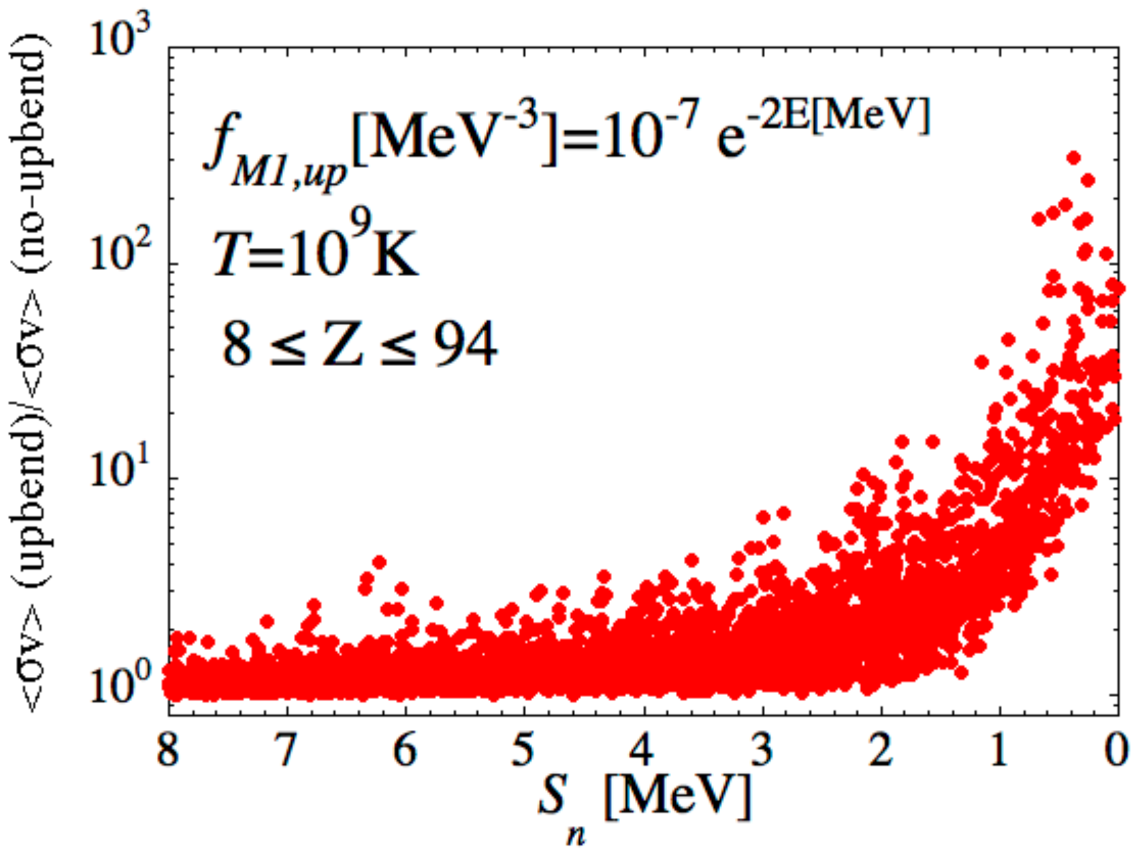
# Impact of an low-energy *M*1 upbend on the (n,γ) reaction rate

(n,γ) rate ratio : <σ>(*M*1 upbend) / <σ>(No *M*1 upbend) at $T=10^9$K




$f_{M1,up}$ [MeV$^{-3}$]=$10^{-7}$ e$^{-2E[\mathrm{MeV}]}$

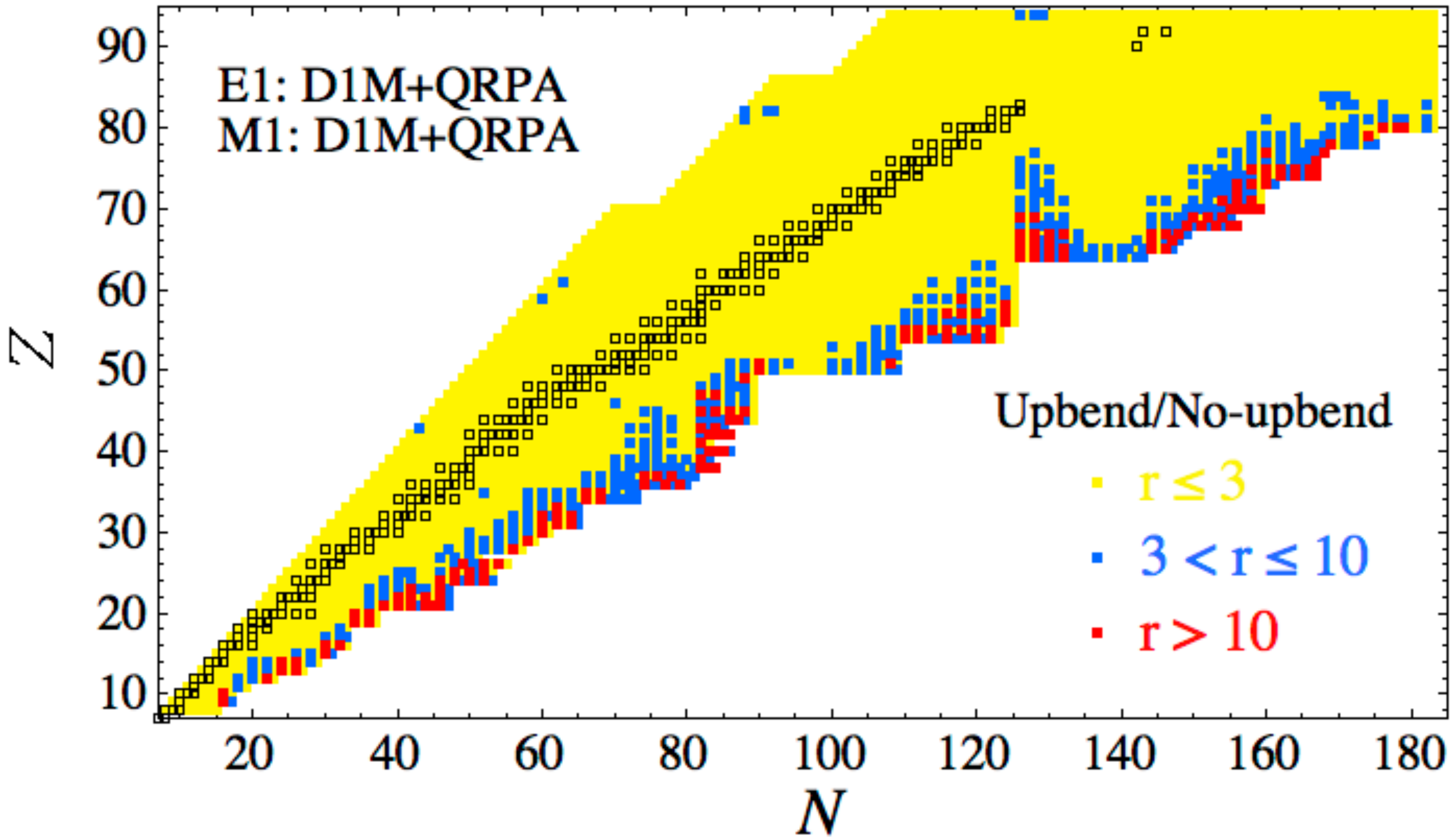
Brown & Larsen (2014)



(n,γ) rate ratio : <σ>($M$1 upbend) / <σ>(No $M$1 upbend) at $T$=$10^9$K

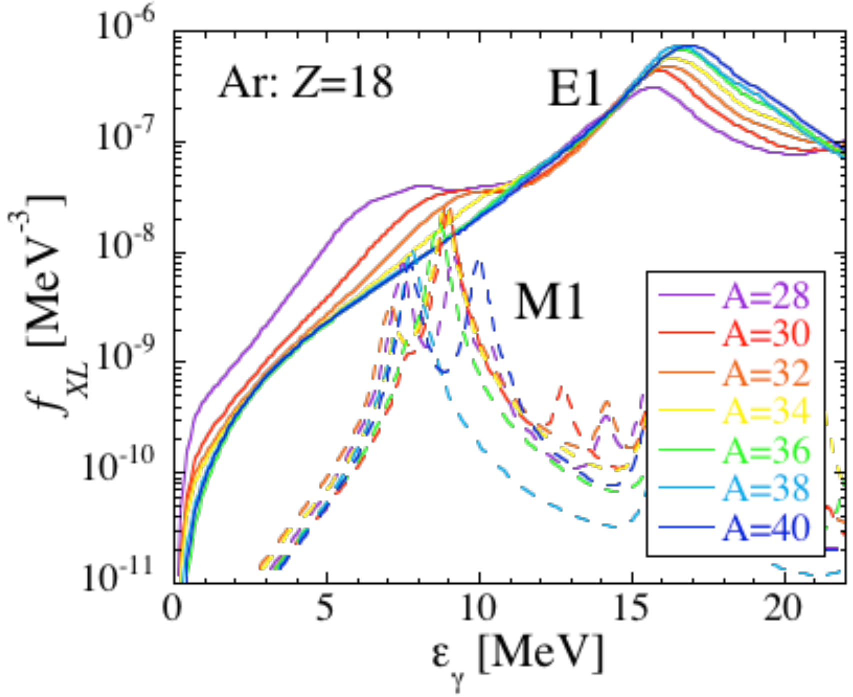
$f_{M1,up}$ [$MeV^{-3}$]=$10^{-7}$ e $^{-2E[MeV]}$

$E$1 & $M$1 from D1M+QRPA

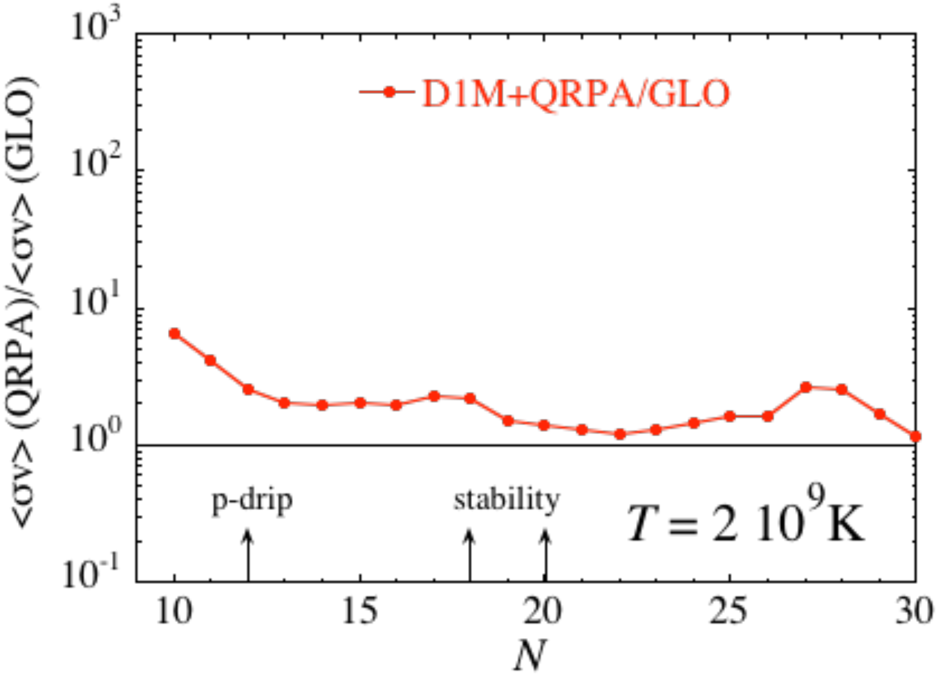


# γ-ray strength function for the *n-deficient* nuclei
# Pygmy Dipole Resonance

D1M+QRPA $E1$ strength in Ar isotopes

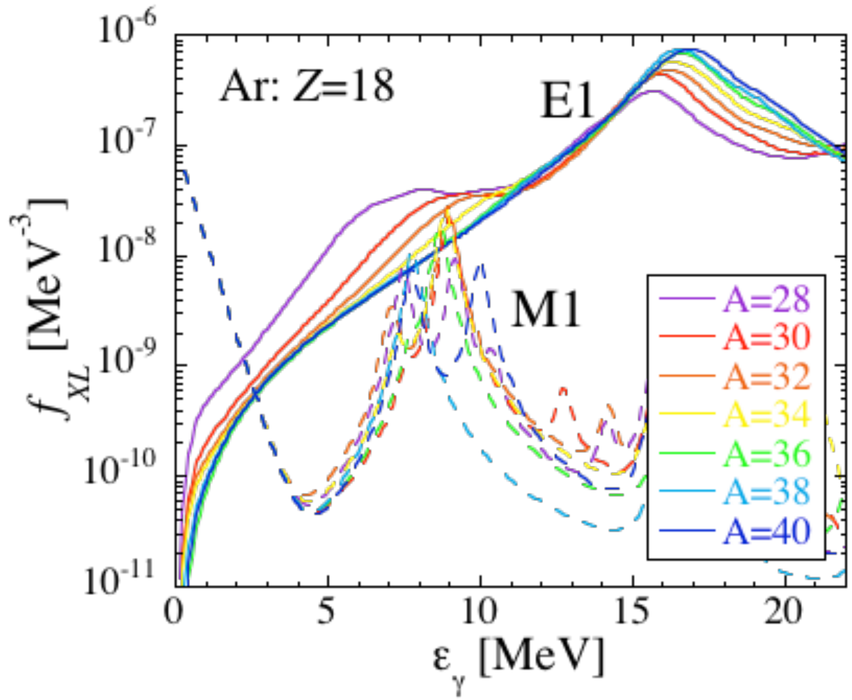



$^{A}$Cl(p,γ)$^{A+1}$Ar reaction rate

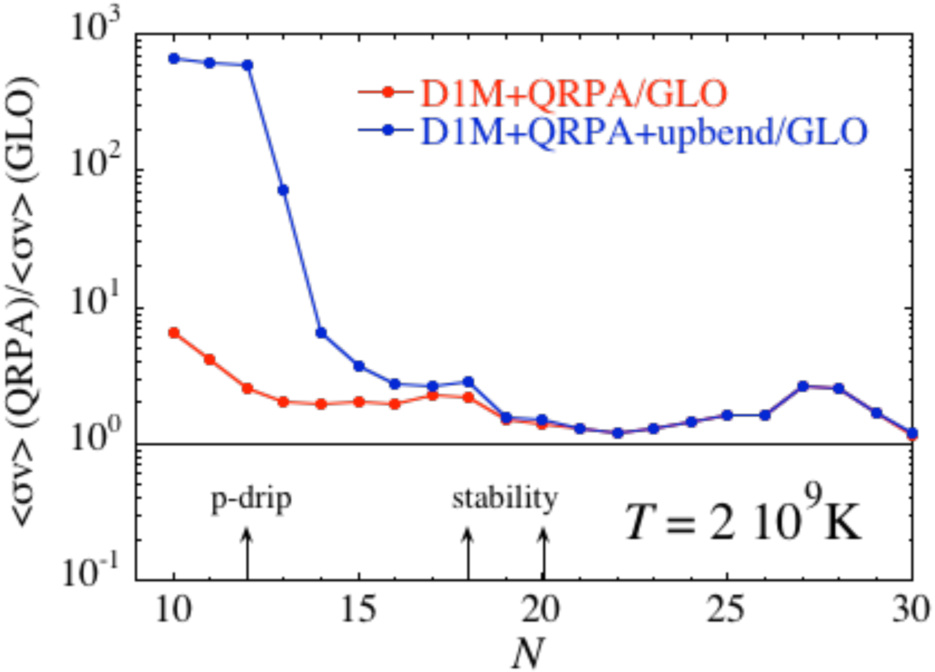


# γ-ray strength function for the n-deficient nuclei
# Pygmy dipole resonance and M1 upbend

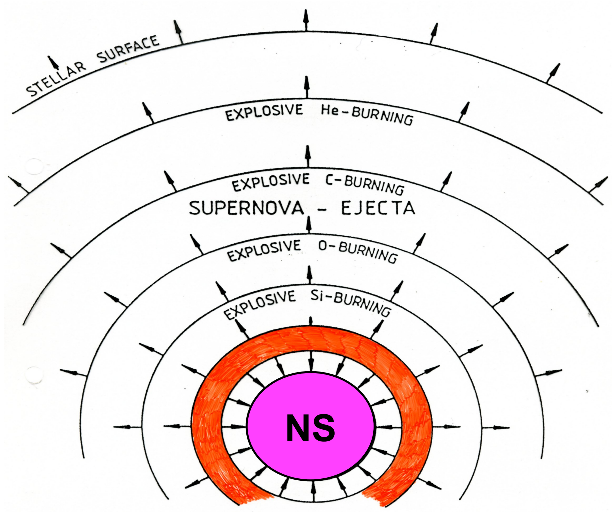
D1M+QRPA+upbend strength in Ar isotopes

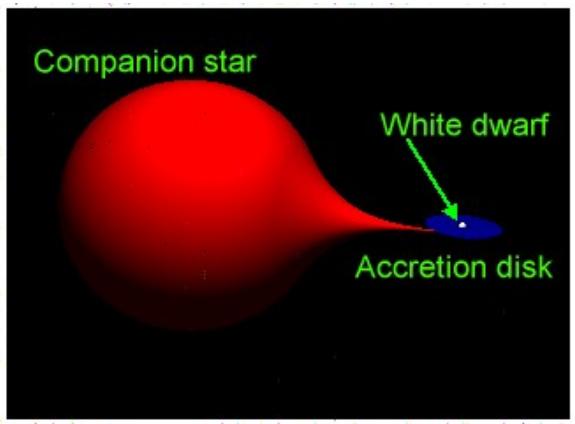



$^{A}$Cl(p,γ)$^{A+1}$Ar reaction rate

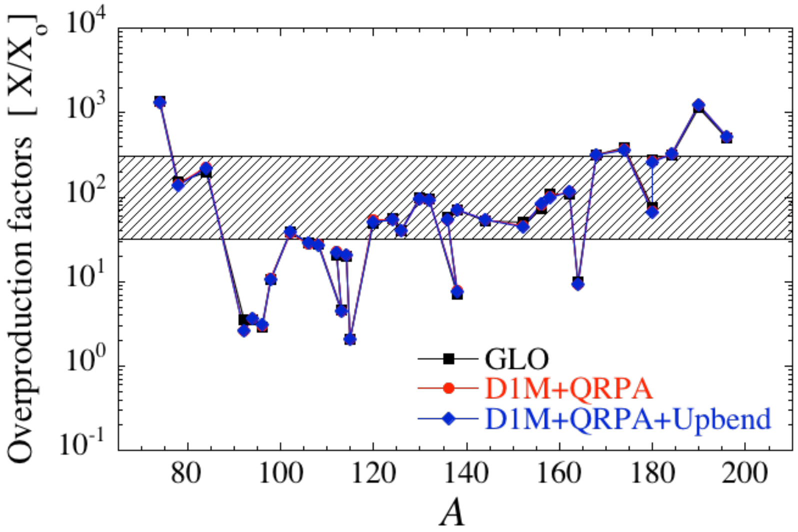


# Impact on the p-process nucleosynthesis

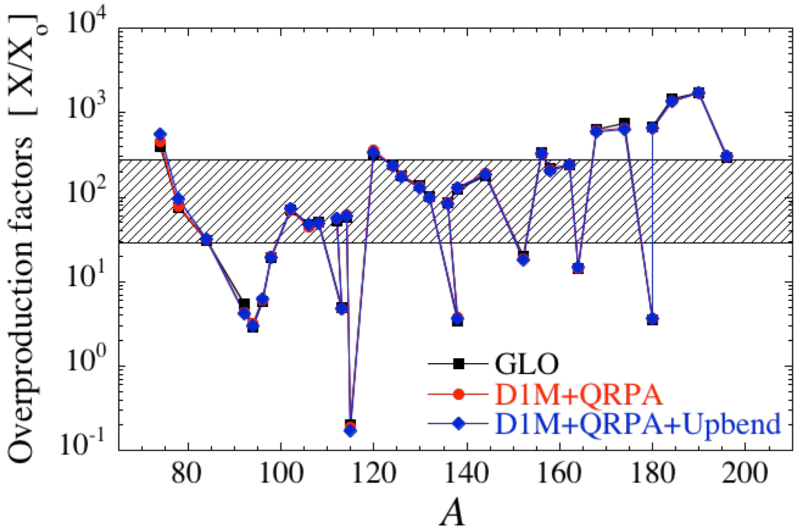


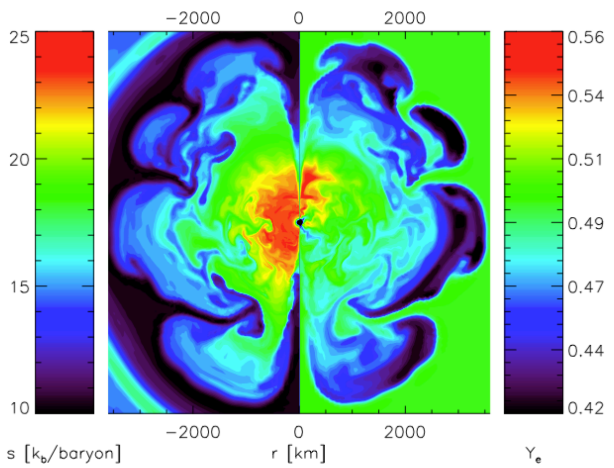

SNII – 25M$_o$

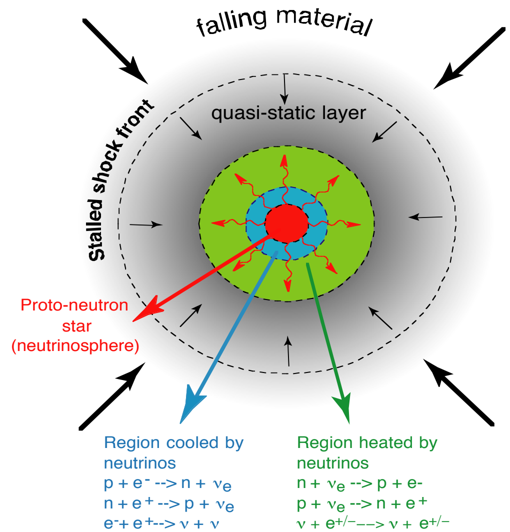



SNIa – W7



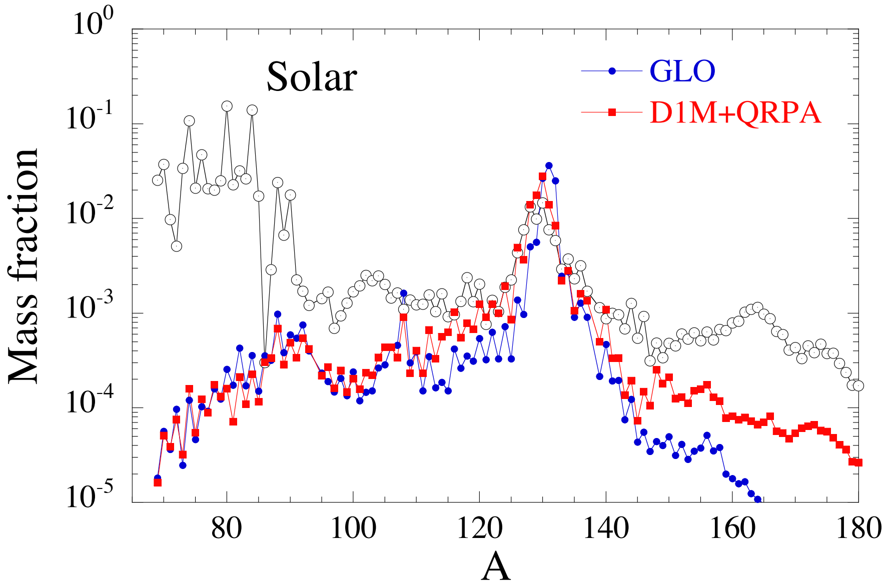
# Impact on the r-process nucleosynthesis in SNII

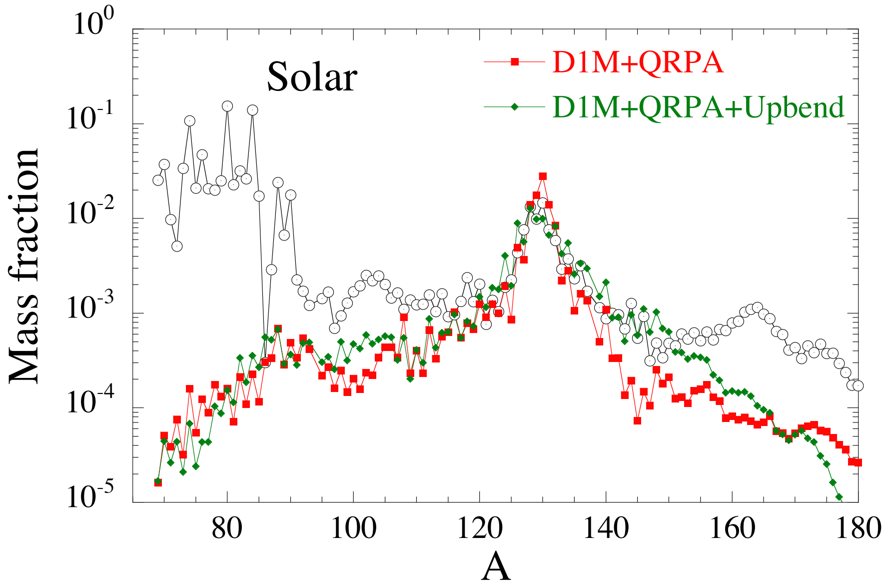



who knows…

ν-driven wind : S=195; $Y_e$=0.47; dM/dt=6 $10^{-6}M_o$/s; $f_w$=1



# Conclusions

**Skyrme- & Gogny-HFB+QRPA, as well as Relativistic HB+QRPA models are now available to describe**

- *E*1 and *M*1 components
- large number of nuclei
- spherical as well as deformed nuclei

and have shown their capacity to predict γ-ray strength

→ Can be used for nuclear applications after renormalisation !

→ Affect the cross section and astrophysical rates for exotic nuclei

→ May affect the r-process nucleosynthesis (in SNII)

**Future work will require**

- **to include *T*-effect to describe the de-excitation strength**
  - Violation of the Brink-Axel hypothesis (*E*1 strength at $\varepsilon_\gamma$ --> 0)
  - Low-energy upbend to be described microscopically
- **to go beyond QRPA**
  - Coupling between quasi-particle states and phonons
  - Configurations more complex than 1p-1h excitations