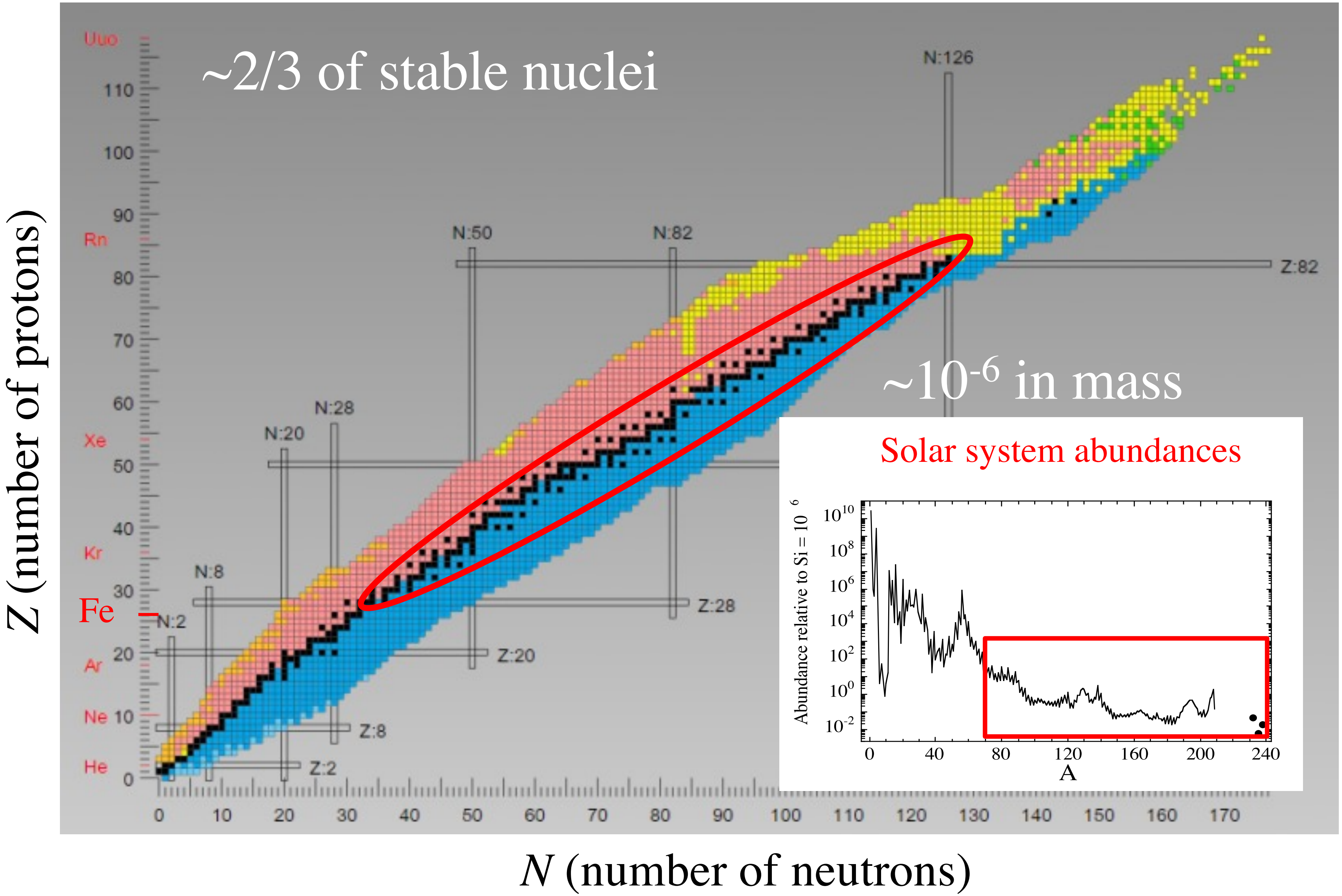
The Photon Strength Function & Its Impact on Stellar Nucleosynthesis

S. Goriely
IAA-ULB, Belgium

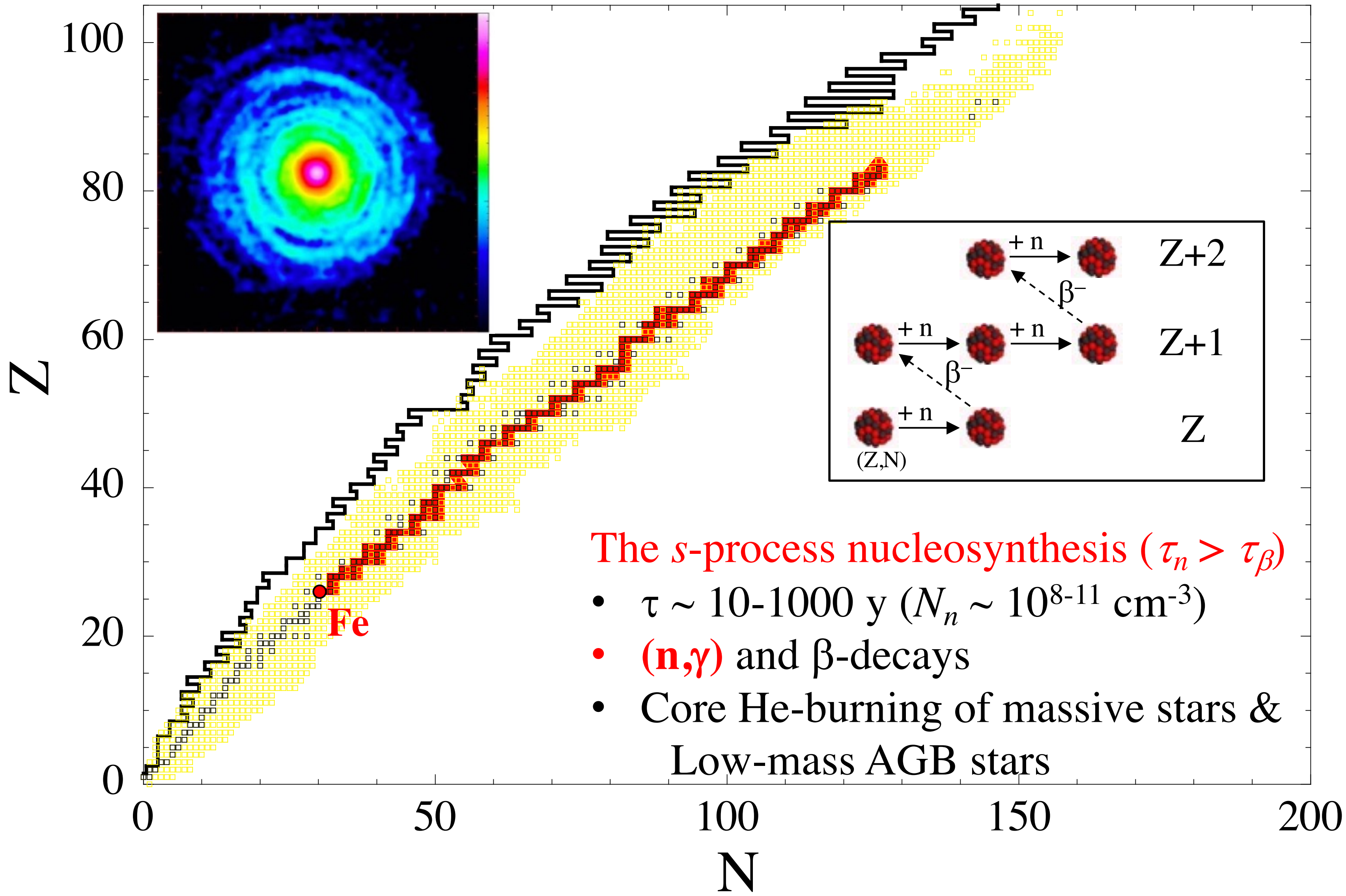
- Introduction to Nucleosynthesis of the elements heavier than Fe
- Photon strength functions
  - Existing PSF models for applications
  - Experimental constraints
  - Impact on astrophysical rates
- Impact on Nucleosynthesis

In collaboration with S. Hilaire and S. Péru (CEA/DAM)

Nucleosynthesis of the elements heavier than iron

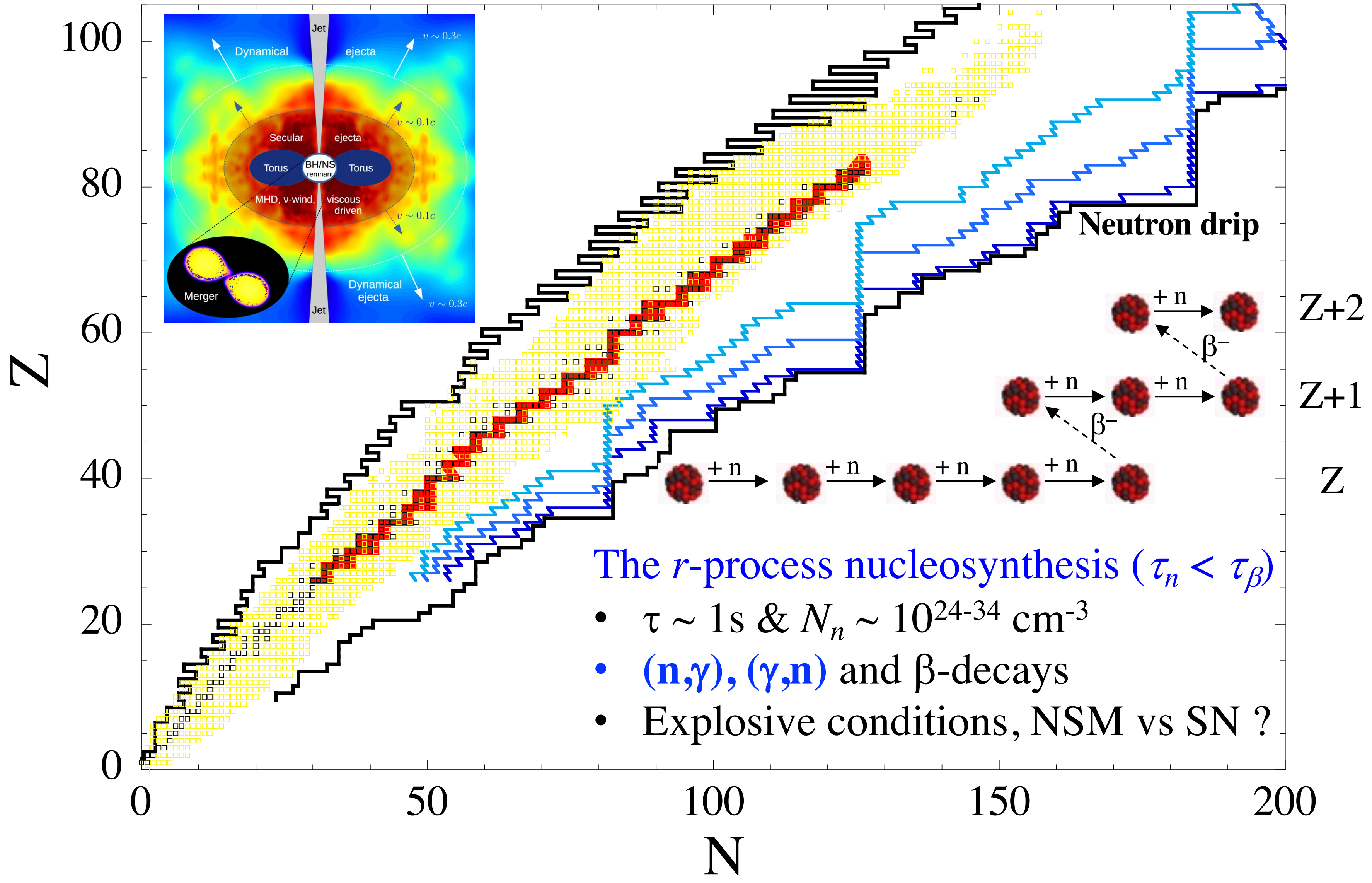


The slow neutron-capture process (or s-process)



- The s-process is responsible for about half of the elements heavier than iron in the Universe
- Most of the nuclear inputs are based on experimental data, including measured (n,γ) rates

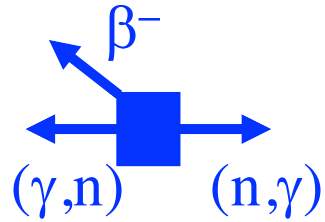
The rapid neutron-capture process (or r-process)



- The r-process is responsible for about half of the elements heavier than iron in the Universe

Nuclear physics input to the r-process nucleosynthesis

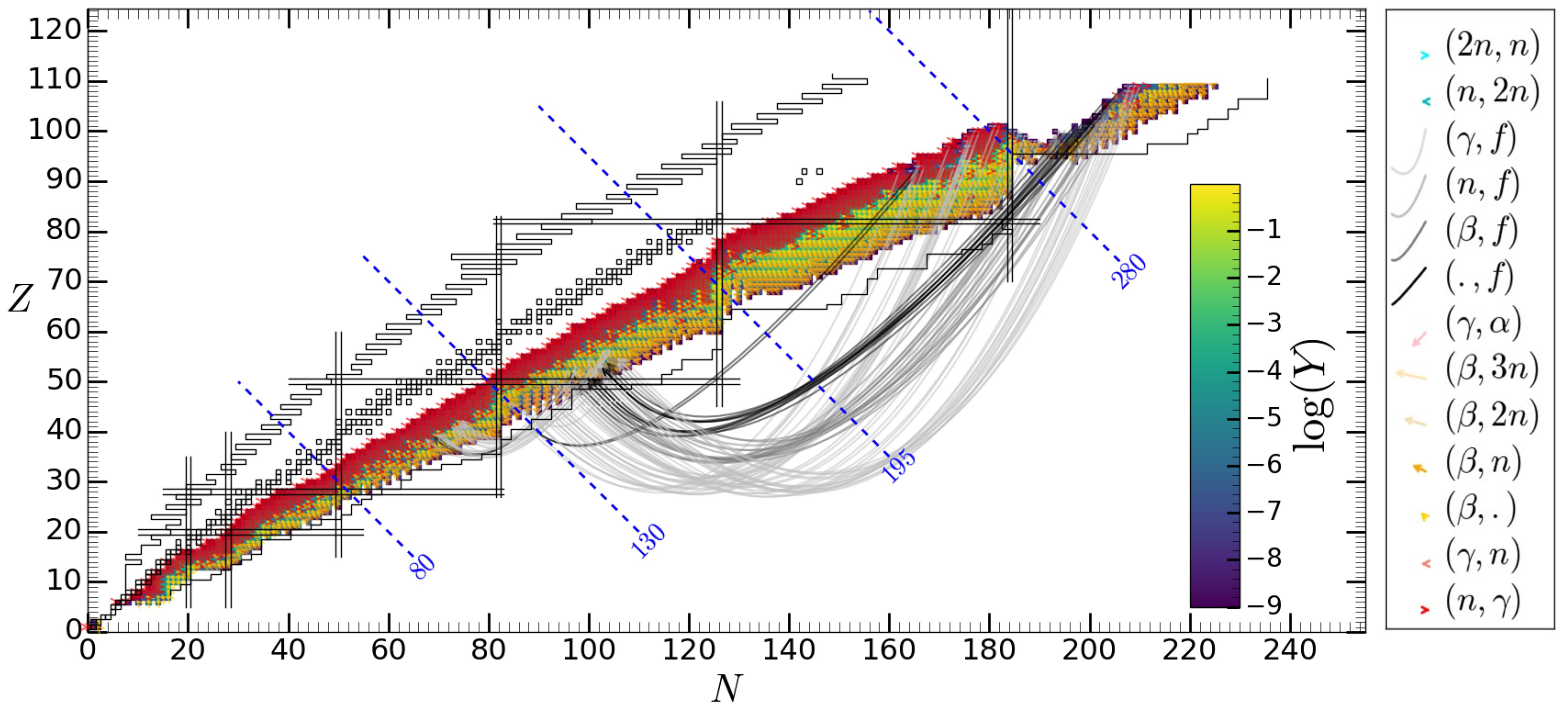
(n,γ) – (γ,n) – β competition & Fission



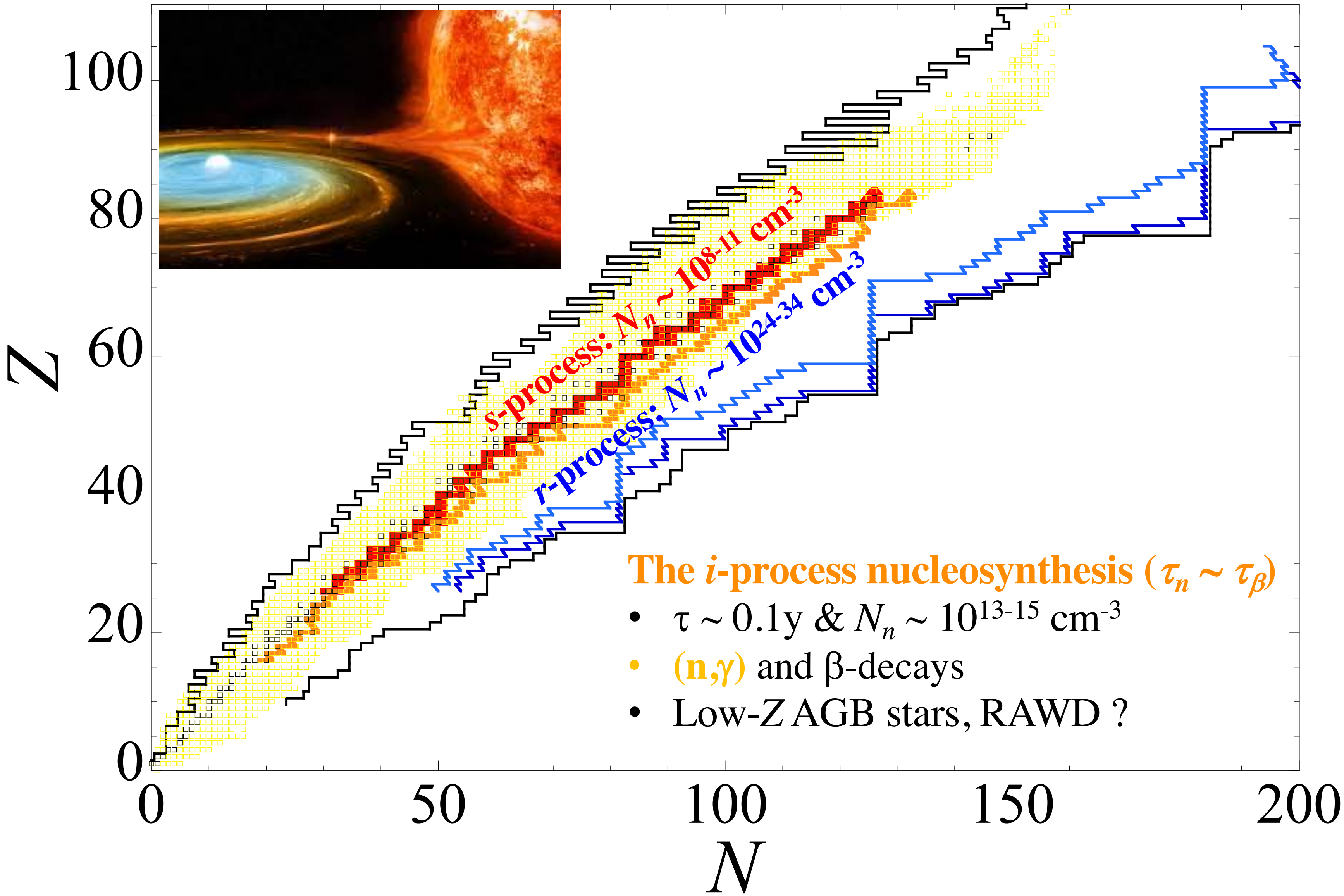
- β-decay **rates**
- (n,γ) and (γ,n) **rates**
- Fission (nif, sf, βdf) **rates**
- Fission Fragments Distributions

Simulations rely almost entirely on theory

~ 5000 nuclei involved – almost no exp. data – still many open questions

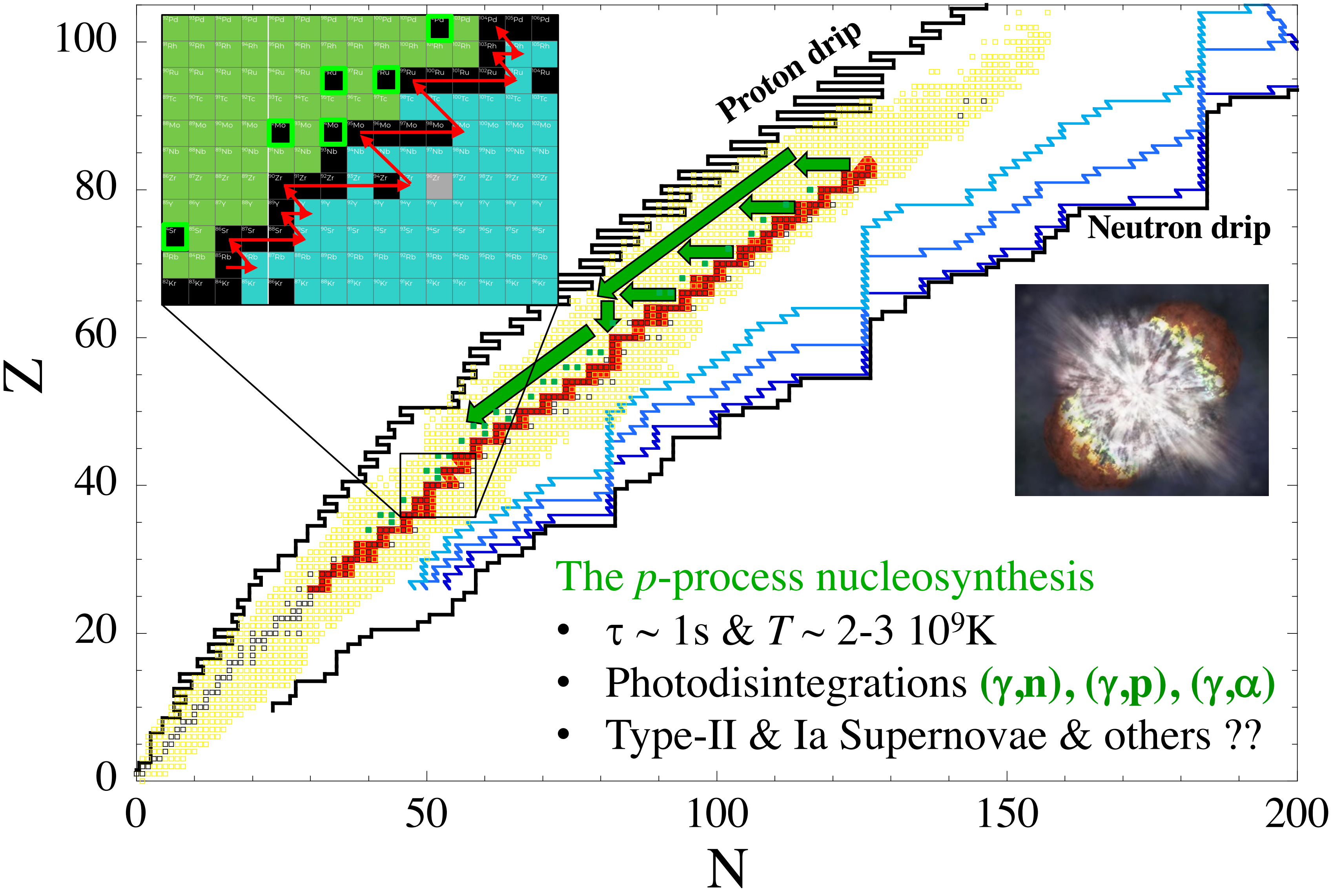


The intermediate neutron-capture process (or *i*-process)



- The *i*-process may, or may not, contribute to the SoS but is needed to explain CEMP-rs stars
- Important part of the nuclear inputs are based on predictions, in particular (n,γ) rates

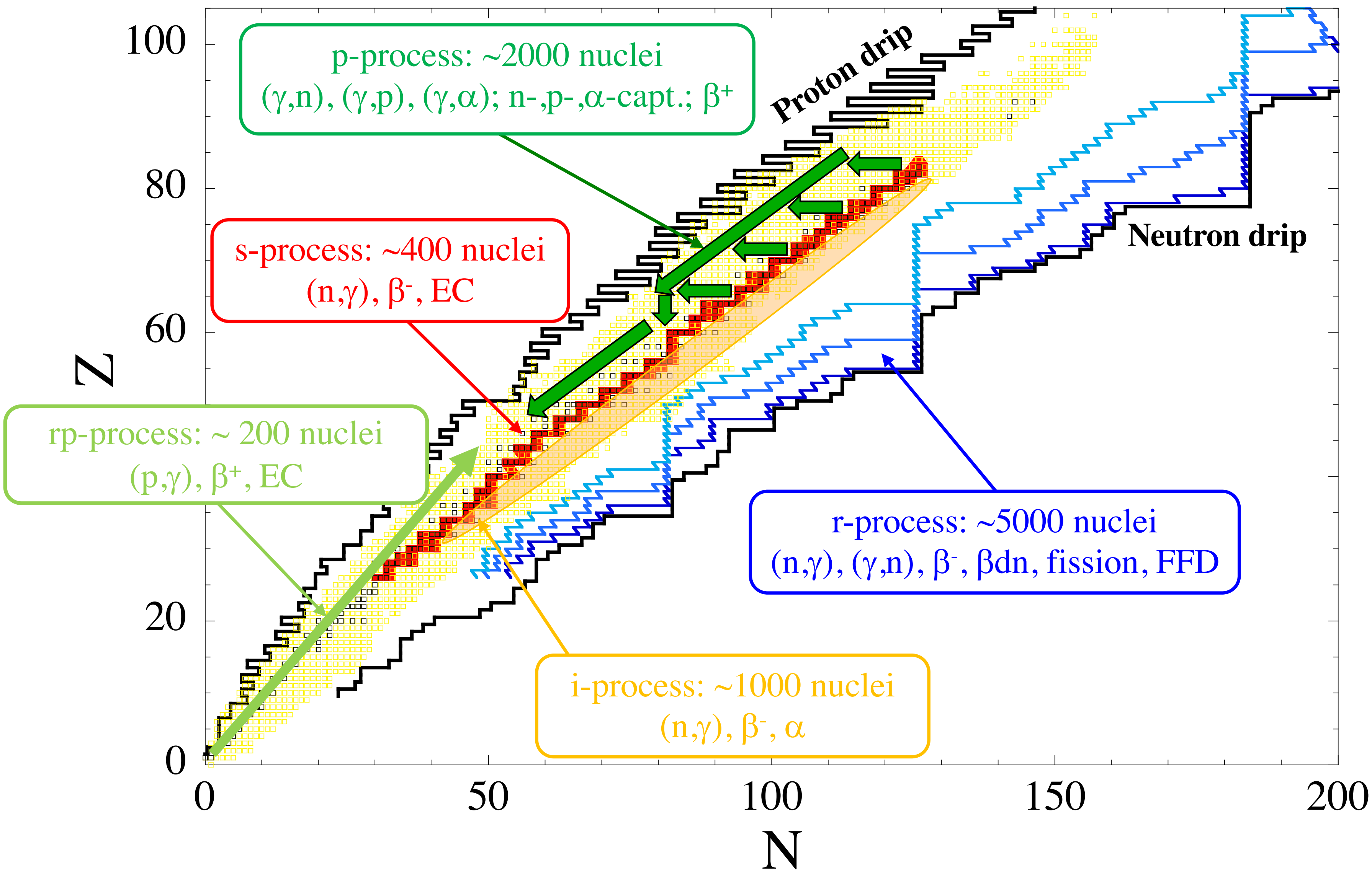
The p-process nucleosynthesis



The *p*-process nucleosynthesis

- $\tau \sim 1$s & $T \sim$ 2-3 10^9K
- Photodisintegrations **(γ,n), (γ,p), (γ,α)**
- Type-II & Ia Supernovae & others ??

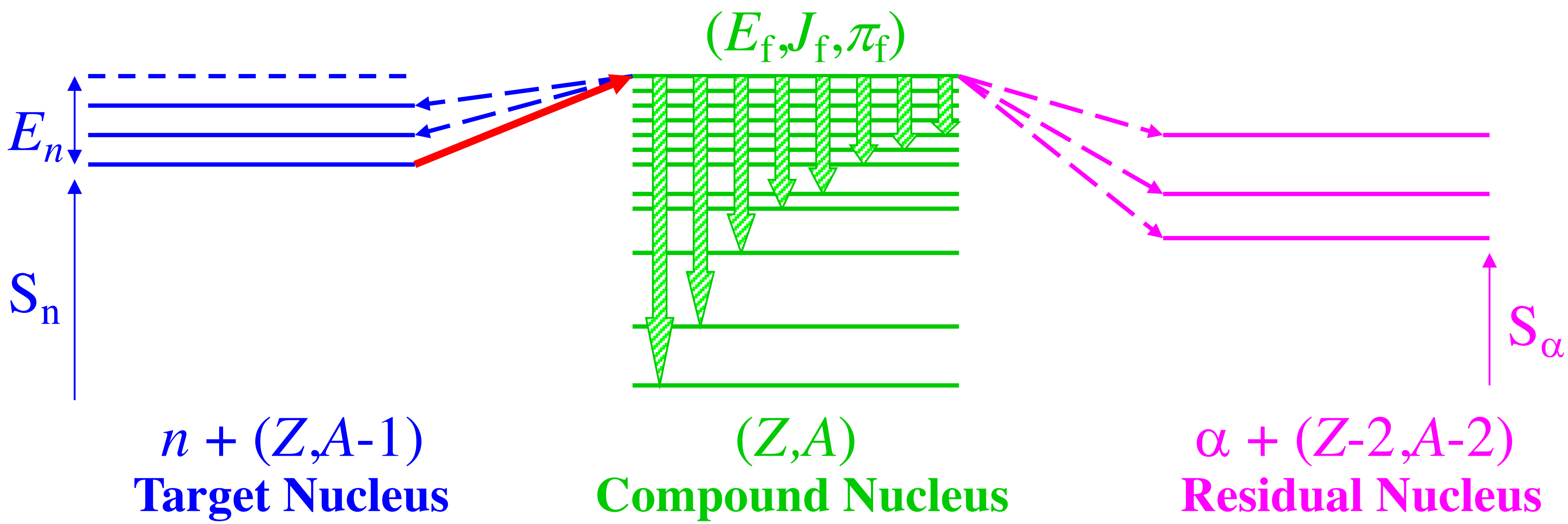
Many different nuclear needs for the various nucleosynthesis processes



Processes based essentially on - Radiative captures

- Photon-induced reactions

Hauser-Feshbach model for radiative neutron capture reactions

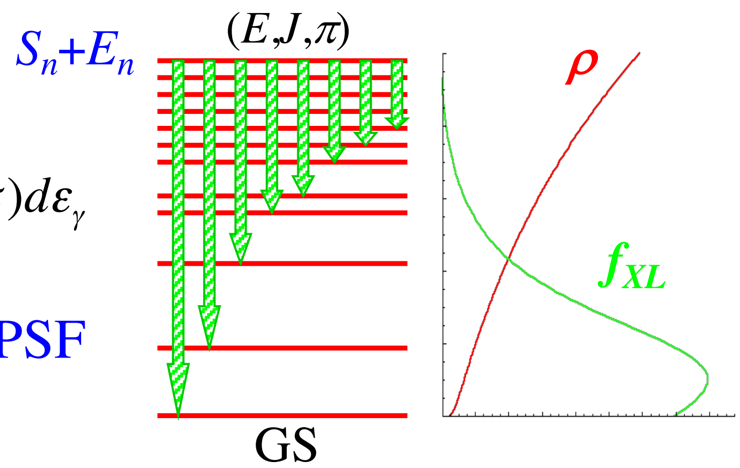


$$\sigma_{(n,\gamma)} \propto \sum_{J,\pi} \frac{T_n(J^\pi)T_\gamma(J^\pi)}{T_n(J^\pi)+T_\gamma(J^\pi)} \approx \sum_{J,\pi} T_\gamma(J^\pi)$$

since $T_n(J^\pi) >> T_\gamma(J^\pi)$ for E_n~keV

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

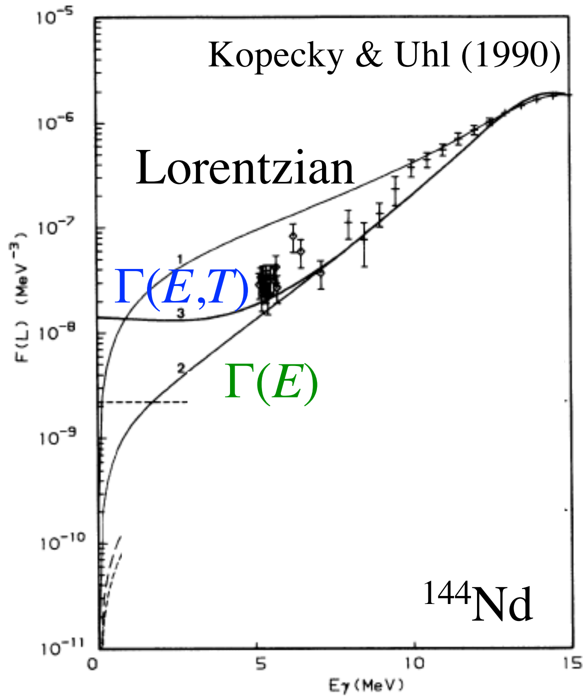
Nuclear astrophysics apps require NLDs & PSF for ~ 8000 nuclei



The Lorentzian model of the dipole strength function

- *E1 strength function*
  - Standard Lorentzian (E_0, Γ_0, σ_0)
  - Lorentzian with E-dependent width
  - Generalized Lorentzian with T- and E-dep. width

    → at the basis of GLO, EGLO, MLO, SMLO, Hybrid, … models



- *M1 strength function*

SLO (Kopecky & Uhl 1990) - SMLO (SG & Plujko 2019)

$$\overrightarrow{f_{M1}}(\varepsilon_\gamma) = \frac{1}{3\pi^2\hbar^2c^2}\sigma_{sc}\frac{\varepsilon_\gamma\,\Gamma_{sc}^2}{(\varepsilon_\gamma^2 - E_{sc}^2)^2 + \varepsilon_\gamma^2\Gamma_{sc}^2}$$

Scissors mode for deformed nuclei

$$+\frac{1}{3\pi^2\hbar^2c^2}\sigma_{sf}\frac{\varepsilon_\gamma\,\Gamma_{sf}^2}{(\varepsilon_\gamma^2 - E_{sf}^2)^2 + \varepsilon_\gamma^2\Gamma_{sf}^2}$$

Spin-Flip mode

Two variants considered here for both E1 & M1
- **GLO** (Kopecky & Uhl 1990) - Still extensively used
- **SMLO** (SG & Plujko 2019) - Updated version

The Mean Field + QRPA model of the dipole strength function

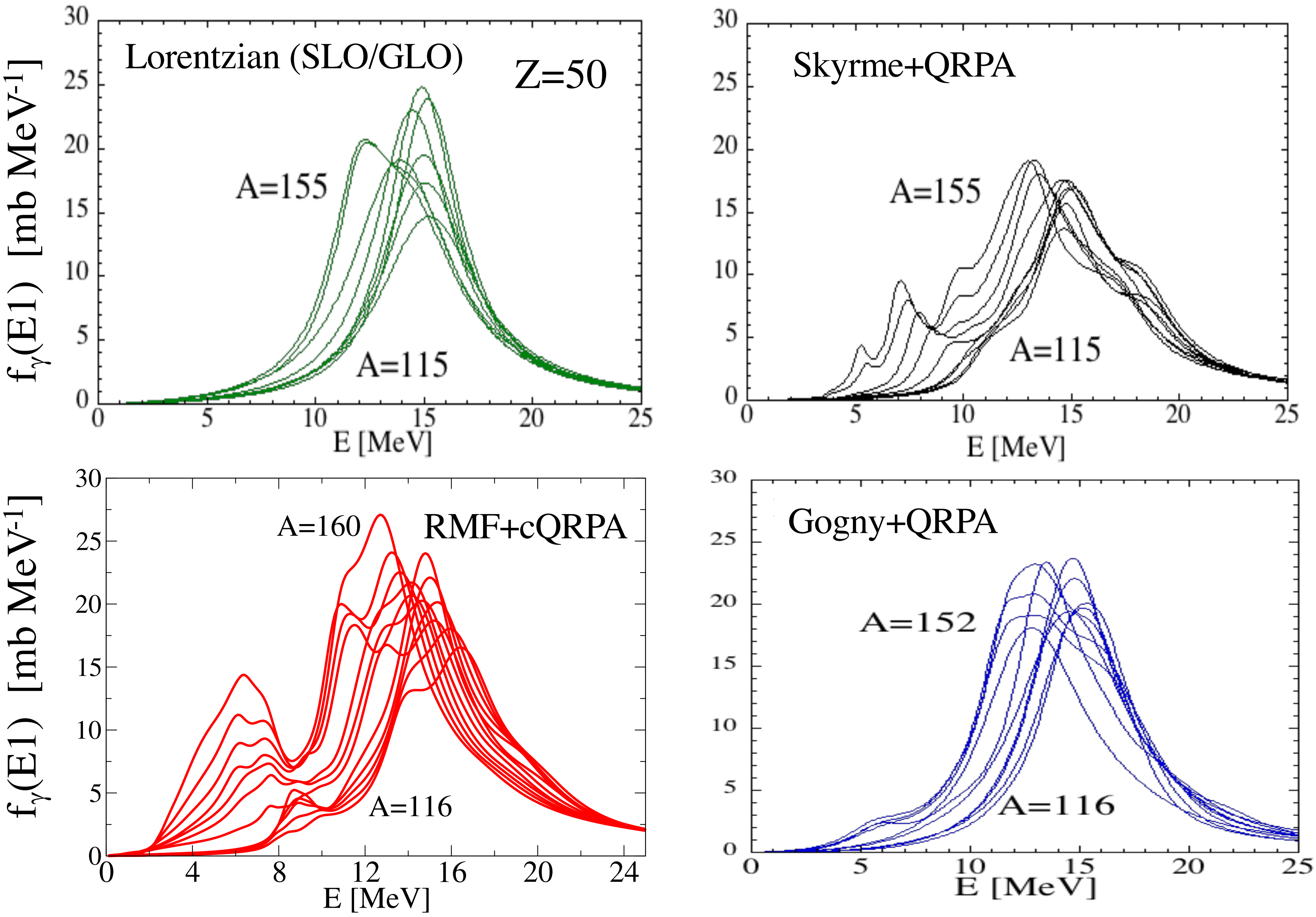
Large-scale $E1/M1$ Mean-Field + QRPA calculations

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

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

- Empirical *energy shift* (beyond QRPA excitations and phonon couplings)
- Empirical damping of collective motions → *broadening*
- Empirical deformation effects for *spherical calculations*
- Approximation / Interpolation for *odd systems*

Large-scale Gogny-HFB + QRPA calculations:
Consistent axially deformed calculation
for e-e nuclei with $8 \leq Z \leq 110$
on the basis of the D1M Gogny force: **D1M+QRPA**



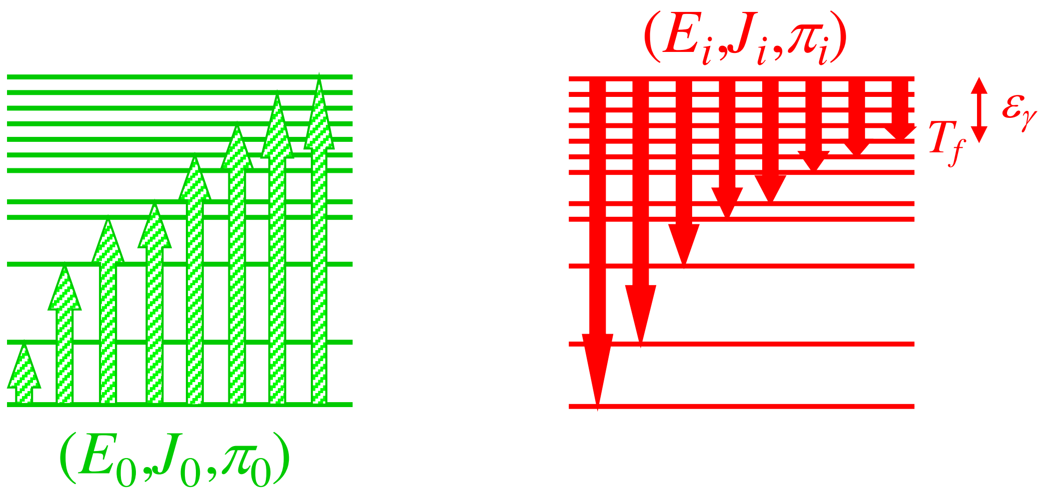
Lorentzian (SLO/GLO)
Z=50
A=155
A=115
f$_\gamma$(E1) [mb MeV^{-1}]
E [MeV]
Skyrme+QRPA
A=155
A=115
E [MeV]
A=160
RMF+cQRPA
A=116
f$_\gamma$(E1) [mb MeV^{-1}]
E [MeV]
Gogny+QRPA
A=152
A=116
E [MeV]

Possible additional low-energy contribution to the **dipole de-excitation strength function**

Violation of the Brink hypothesis (e.g. Isaak et al., 2019)

$$\overleftarrow{f}_{E1}(\varepsilon_\gamma) \neq \overrightarrow{f}_{E1}(\varepsilon_\gamma)$$

$$\overleftarrow{f}_{E1} = \overleftarrow{f}_{E1}(\varepsilon_\gamma, T_f)$$

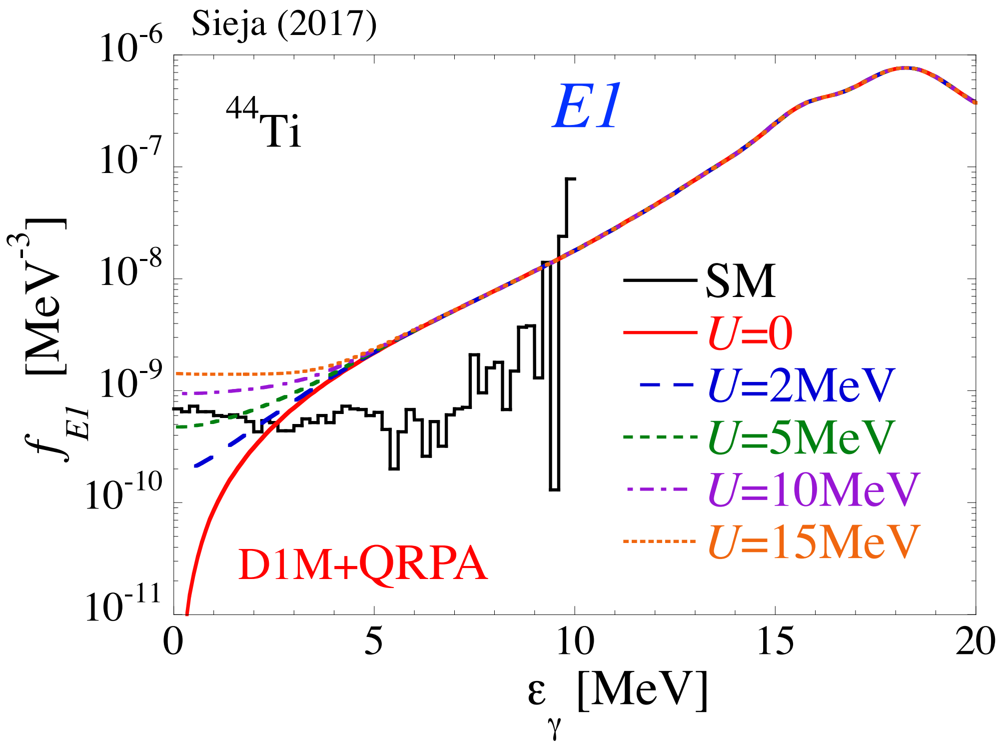


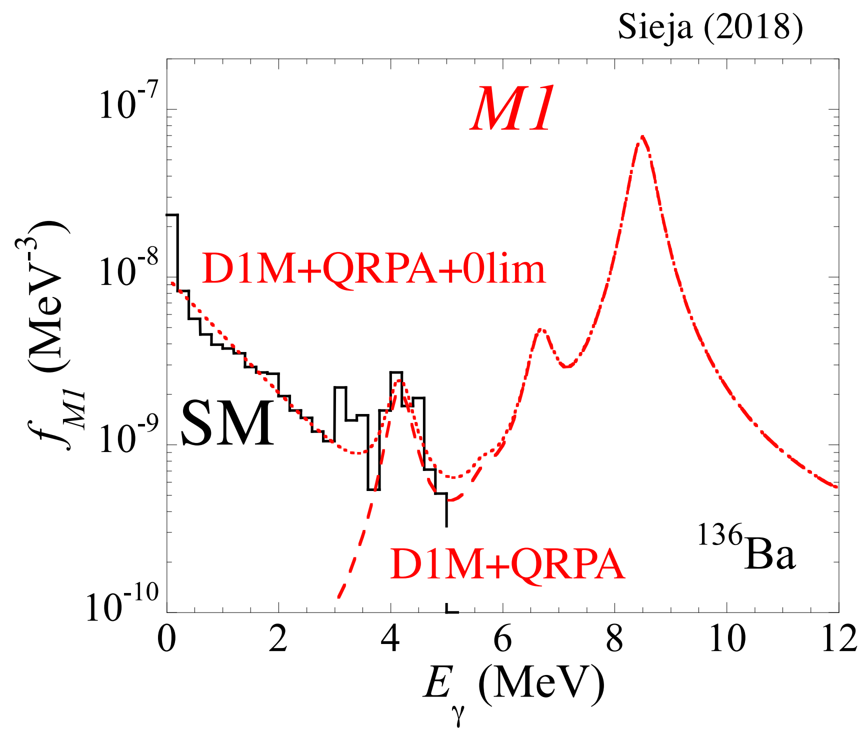
SM-inspired low-energy correction of the de-excitation strength

$$f_{E1} = f_{E1}^{QRPA} + f_{E1}(\varepsilon_\gamma \to 0)$$ Non-zero limit of the *E1* strength at $\varepsilon_\gamma \to 0$

$$f_{M1} = f_{M1}^{QRPA} + f_{M1}(\varepsilon_\gamma \to 0)$$ Upbend of the *M1* strength at $\varepsilon_\gamma \to 0$

D1M+QRPA+0lim model





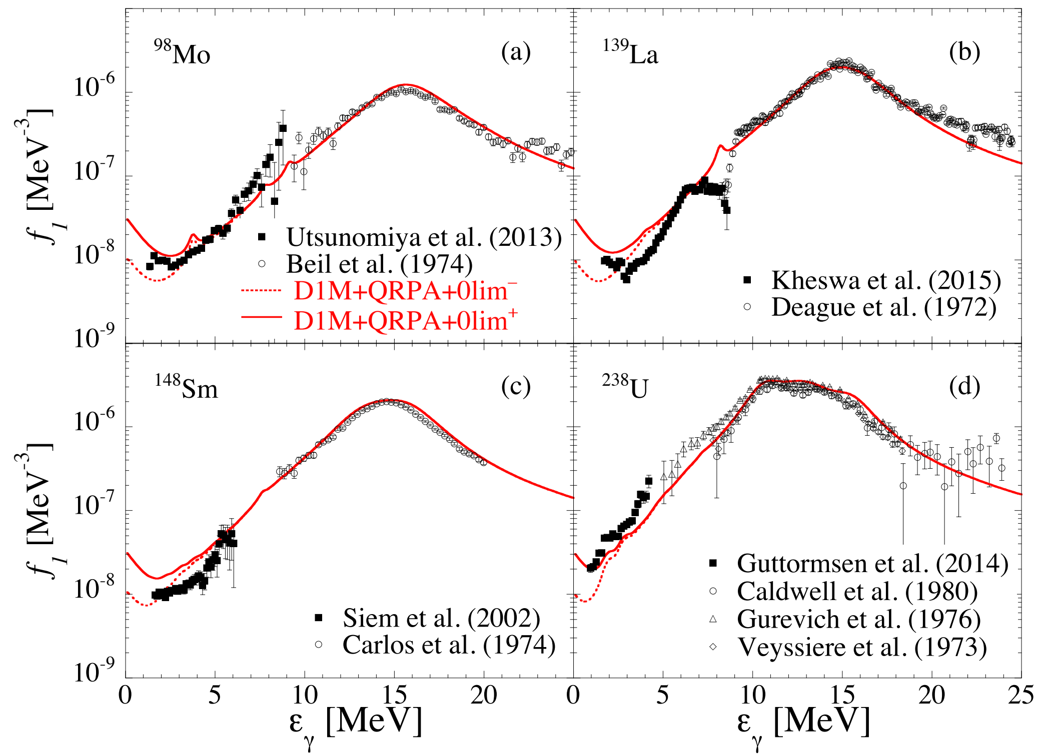
Schwengner et al. (2013, 2017), Brown et al. (2014), Sieja (2017, 2018), Karampagia et al. (2017), Midtbø et al. (2018)

SM-inspired low-energy correction of the de-excitation strength

$$f_{E1} = f_{E1}^{QRPA} + f_{E1}(\varepsilon_\gamma \rightarrow 0)$$ Non-zero limit of the *E1* strength at $\varepsilon_\gamma \rightarrow 0$

$$f_{M1} = f_{M1}^{QRPA} + f_{M1}(\varepsilon_\gamma \rightarrow 0)$$ Upbend of the *M1* strength at $\varepsilon_\gamma \rightarrow 0$

D1M+QRPA+0lim model

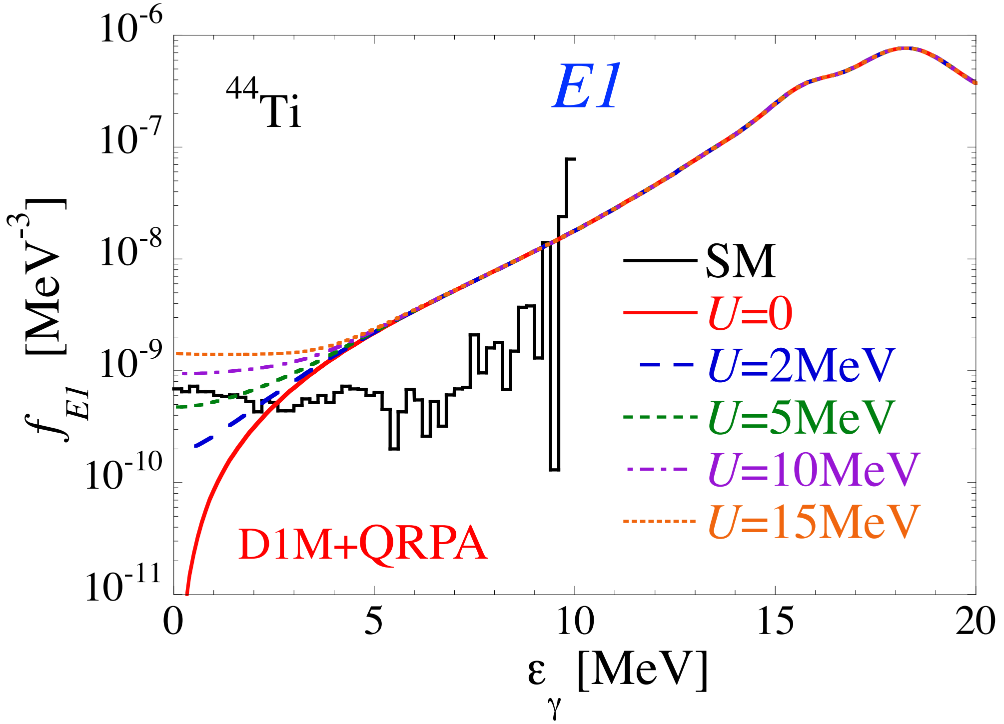


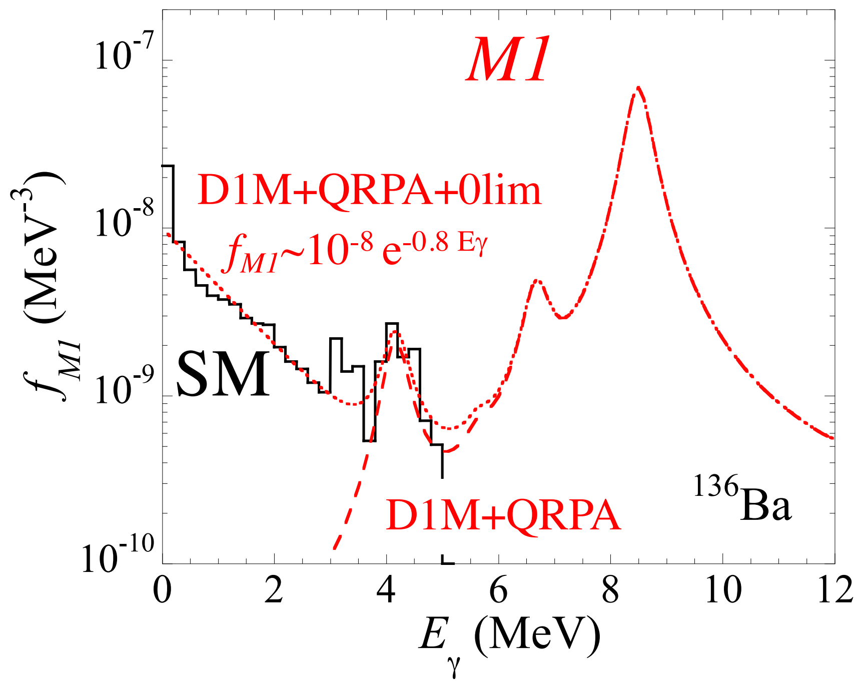
Oslo data

SM-inspired low-energy correction of the de-excitation strength

$f_{E1} = f_{E1}^{QRPA} + f_{E1}(\varepsilon_\gamma \to 0)$ Non-zero limit of the *E1* strength at $\varepsilon_\gamma \to 0$

$f_{M1} = f_{M1}^{QRPA} + f_{M1}(\varepsilon_\gamma \to 0)$ Upbend of the *M1* strength at $\varepsilon_\gamma \to 0$





Non-negligible impact of the low-*E* enhancement of the PSF for low-S_n targets essentially if it compensates the ε_γ^3 factor in T_γ, i.e if there is an "upbend"

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

Major questions related to the dipole PSF for astrophysics applications (~8000 nuclei)

E1 strength

- → Centroid energy and width of the GDR for experimentally unknown nuclei ?
- → Presence of a *E1* pygmy resonance or more generally low-*E* tail of the GDR ?
- → Non-zero limit of the *E1* strength (*T*-effect ?)

M1 strength

- → Properties of the *M1* Spin-flip strength ?
- → Properties of *M1* Scissors mode ?
- → Non-zero limit of the *M1* strength: upbend ?

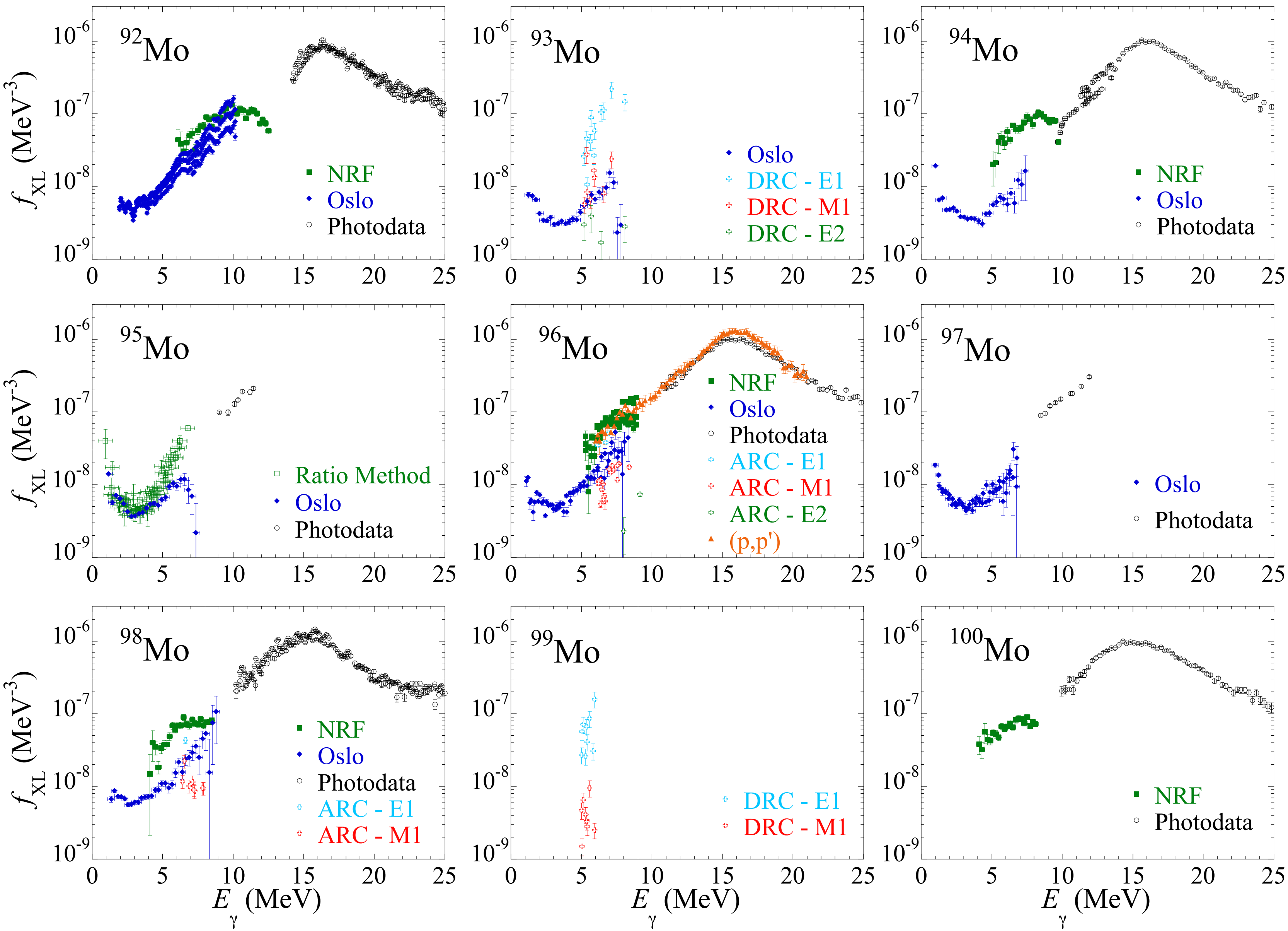
“Validation” of the theoretical dipole Photon Strength Function on

IAEA Reference Database developed within the 2016-2019 CRP

...to be updated (2022)

1. Photodata in the GDR region (10-20MeV): *E1* for ~159 nuclei
2. ARC/DRC data: $\varepsilon_\gamma \sim$ 5-8MeV; *E1* & *M1* for 88 nuclei
3. Oslo data: $\varepsilon_\gamma < S_n$; *E1*+*M1* for 72 nuclei
4. NRF data: $\varepsilon_\gamma < S_n$; *E1*+*M1* for 23 nuclei
5. $\Sigma B(M1)$ scattering data: $\varepsilon_\gamma \sim$ 2-4MeV for ~47 nuclei
6. (p,γ) data: *E1*+*M1* at $\varepsilon_\gamma \sim$ 5-10MeV for 22 nuclei ($A = 46 - 90$)
7. (p,p’) data for ^{96}Mo, ^{120}Sn, ^{208}Pb: *E1* & *M1* at $\varepsilon_\gamma \sim$ 5-20MeV
8. MSC & MD spectra: *E1*+*M1* for ~15 nuclei with ~4 J^π/nuc (NLD)
9. Neutron capture spectra: *E1*+*M1* for 5 nuclei & diff J^π (NLD)
10. Average radiative width $<\Gamma_\gamma>$: $0 \le \varepsilon_\gamma \le S_n$ *E1*+*M1* for ~230 nuc (NLD)
11. 30keV (n,γ) MACS $0 \le \varepsilon_\gamma \le S_n$ *E1*+*M1* for ~240 nuc (NLD)

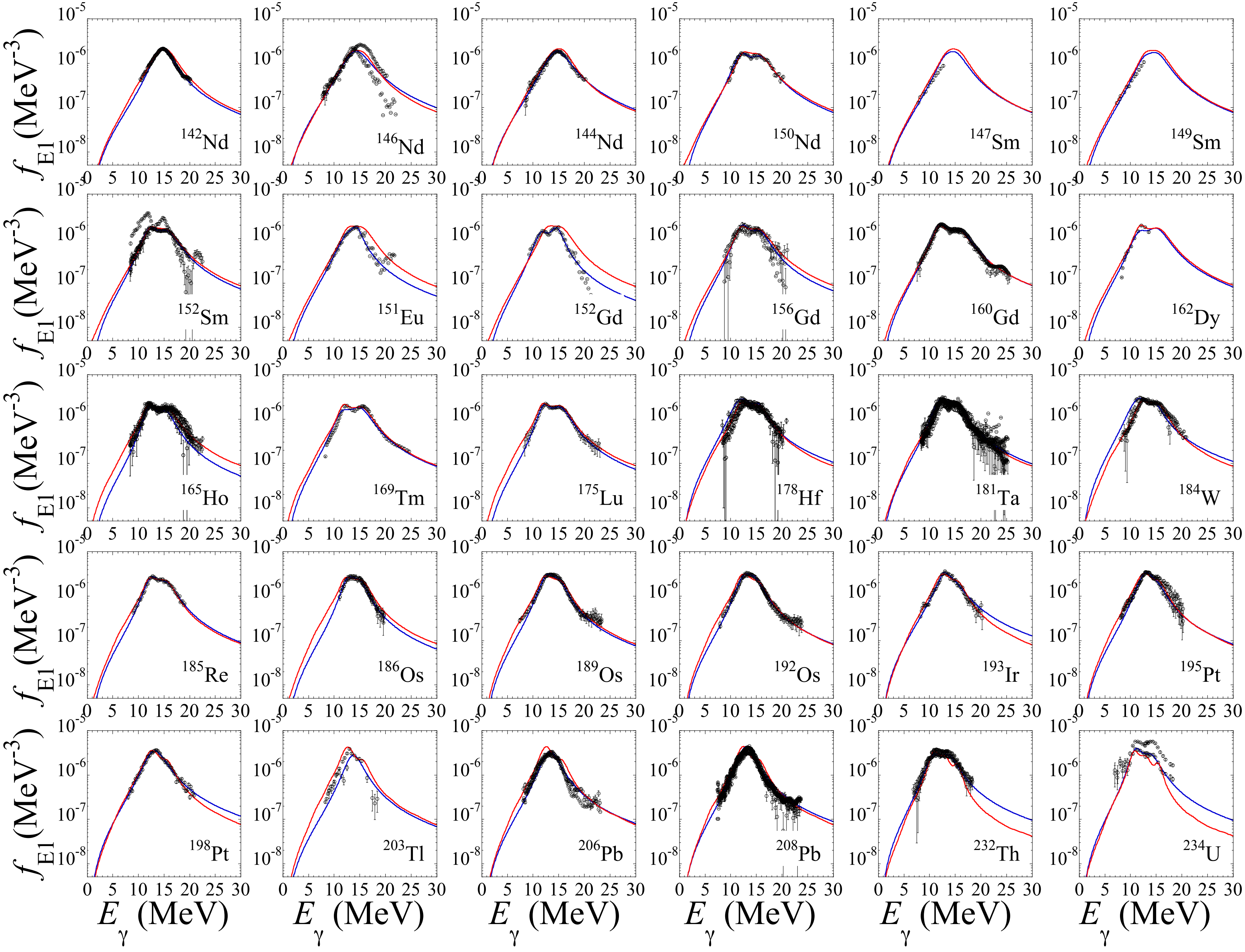
IAEA Reference Database for Photon Strength Functions



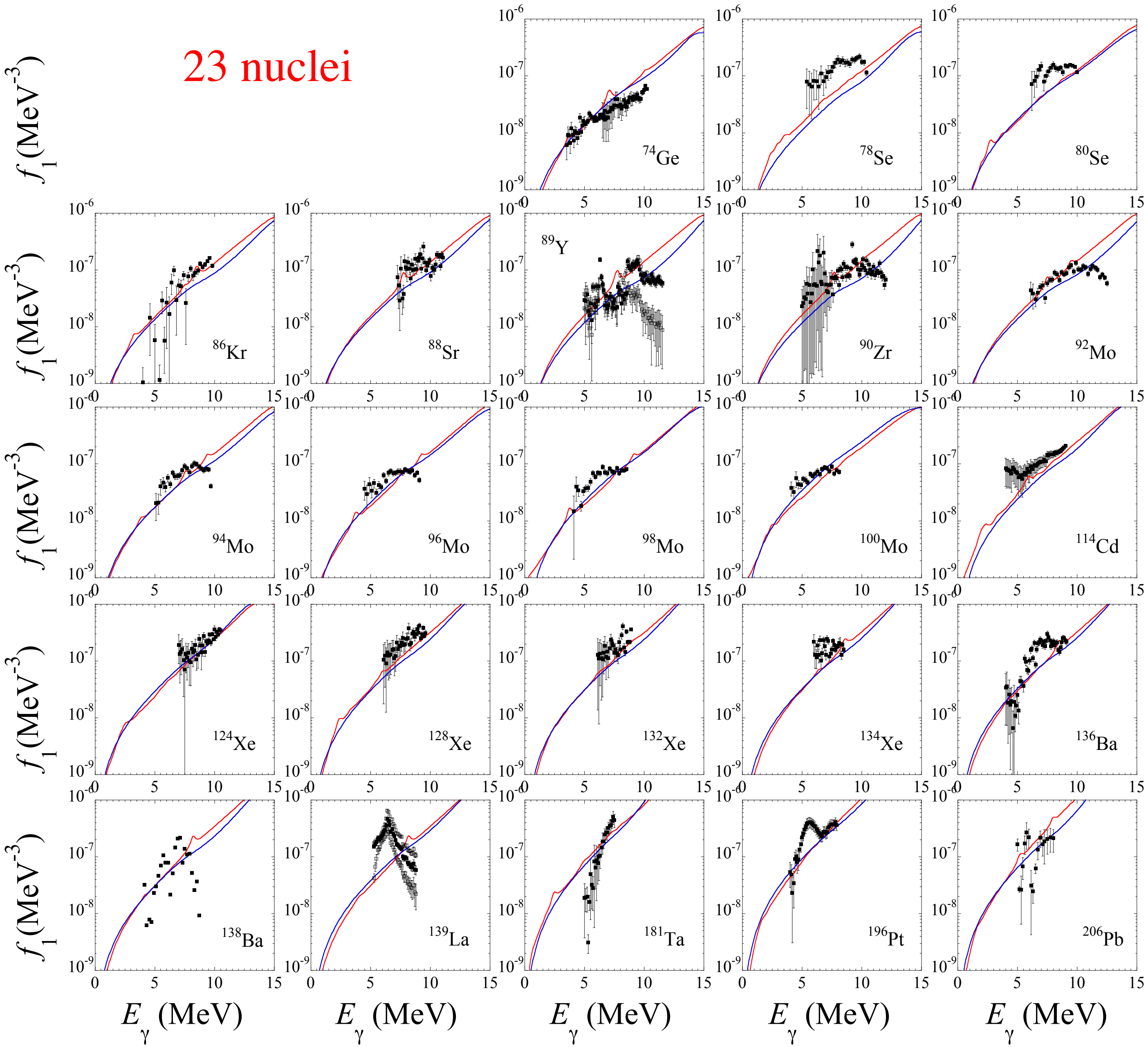
Requires further "evaluation" and detailed uncertainty analysis

Comparison of D1M+QRPA and SMLO with Photodata

30 nuclei out of 159



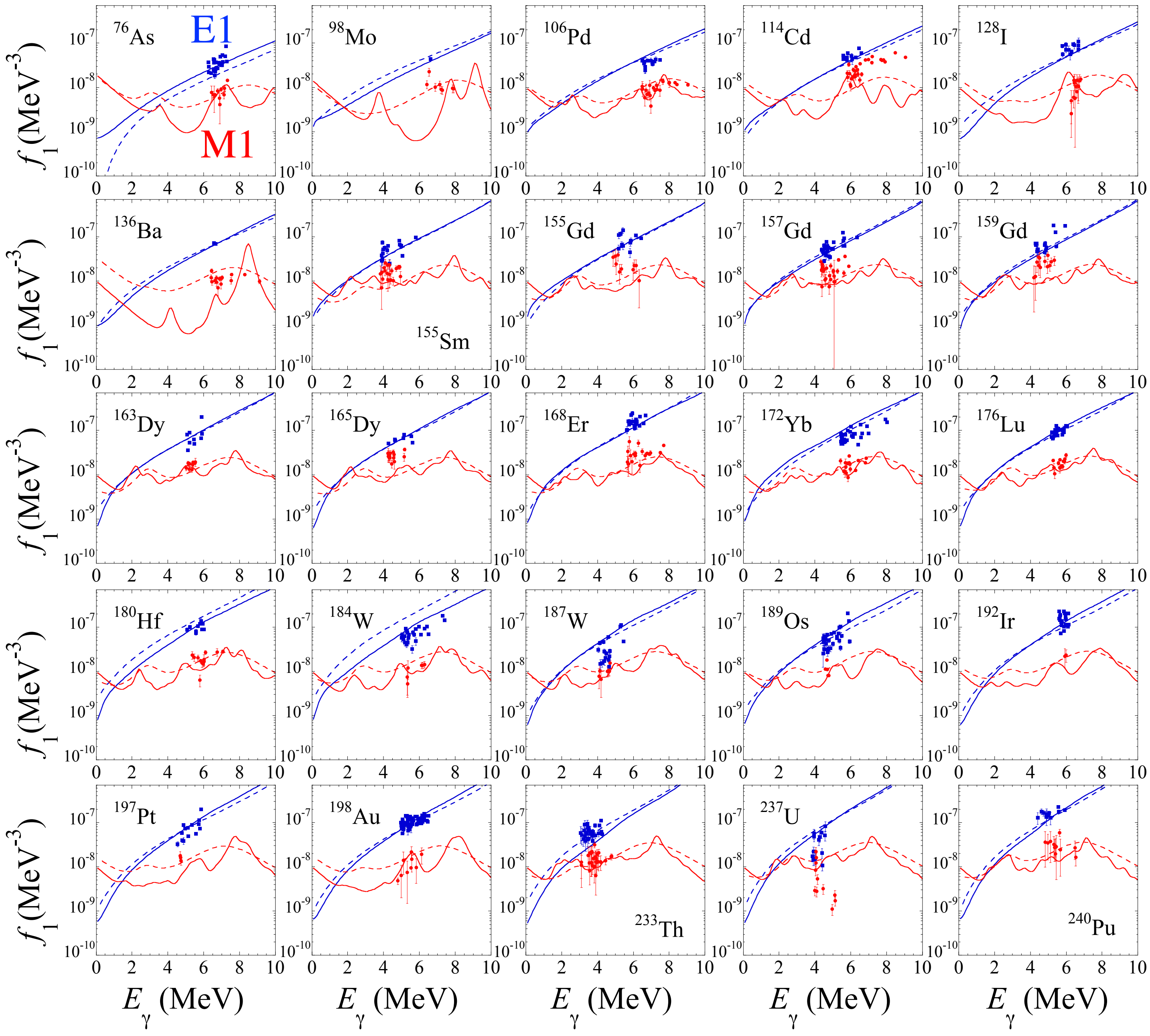
Comparison of D1M+QRPA and SMLO with NRF data



Comparison with E1 and M1 ARC data (Kopecky 2019)

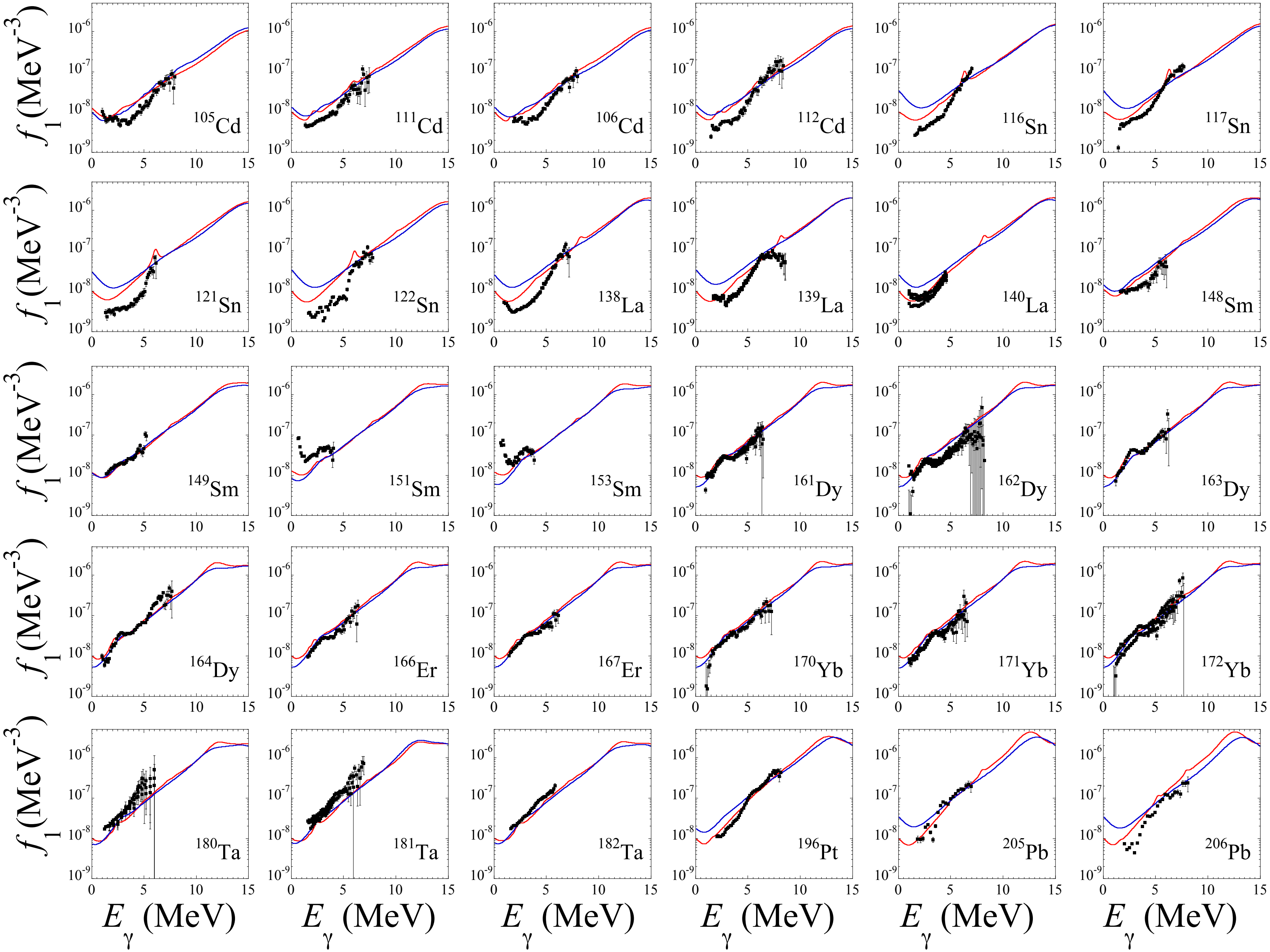
25 nuclei out of 88

D1M+QRPA+0lim ——— SMLO - - - - - - -



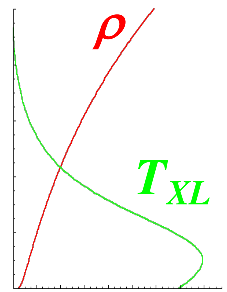
Comparison of D1M+QRPA+0lim and SMLO with Oslo data

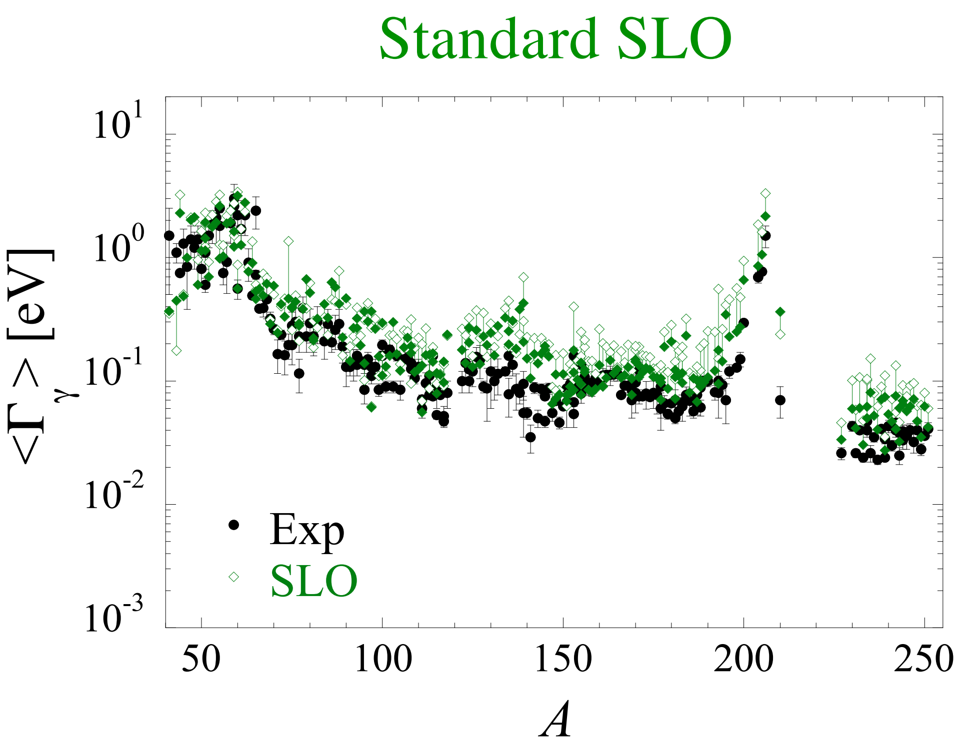
30 nuclei out of 72

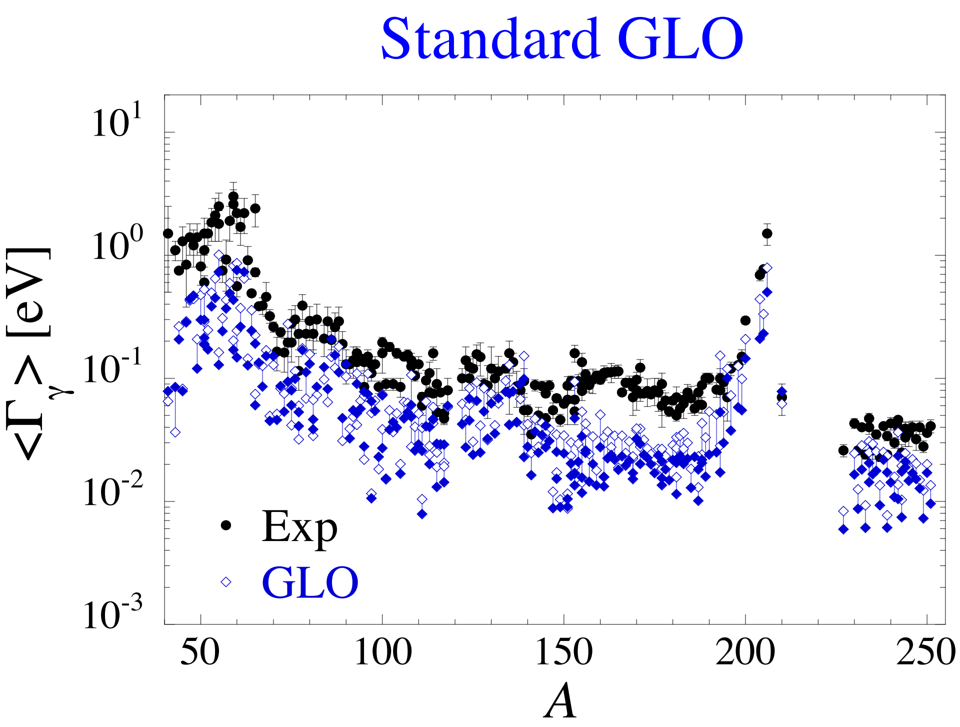


The long-standing problem of the average radiative width <Γ$_\gamma$>

$$\langle \Gamma_\gamma \rangle = \frac{D_0}{2\pi} \sum_{X,L,J,\pi} \int_0^{S_n+E_n} T_{XL}(\varepsilon_\gamma) \times \rho(S_n + E_n - \varepsilon_\gamma, J, \pi) d\varepsilon_\gamma$$





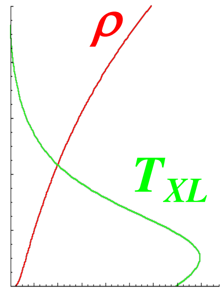


230 nuclei

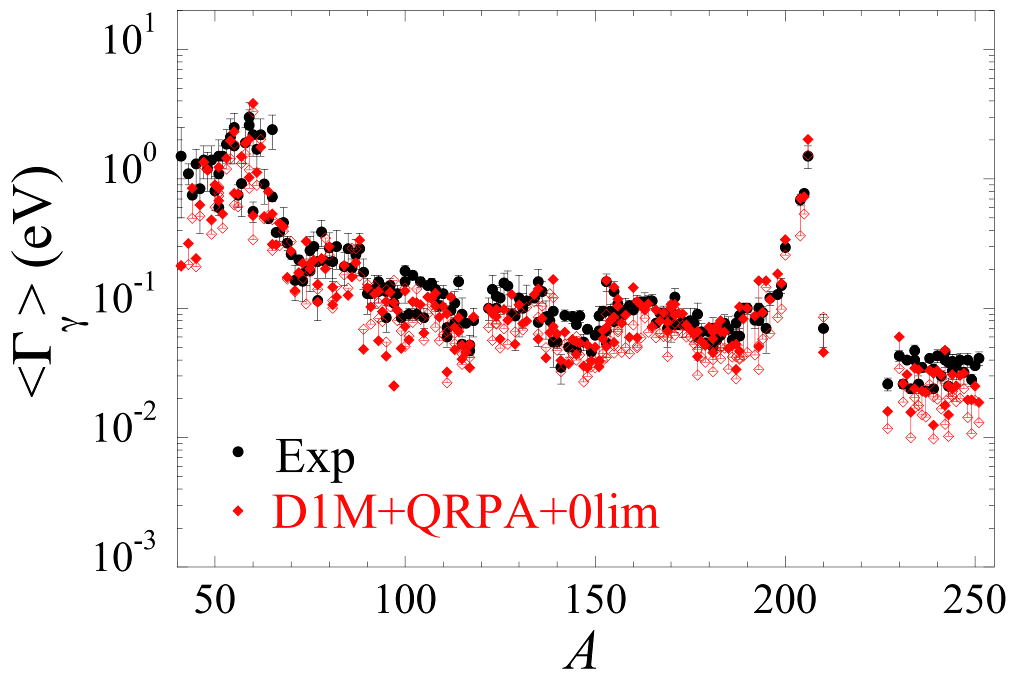
Full diamonds = CT + BSFG
Open diamonds = HFB + Combinatorial

Comparison of D1M+QRPA+0lim and SMLO with <Γ$_\gamma$> data

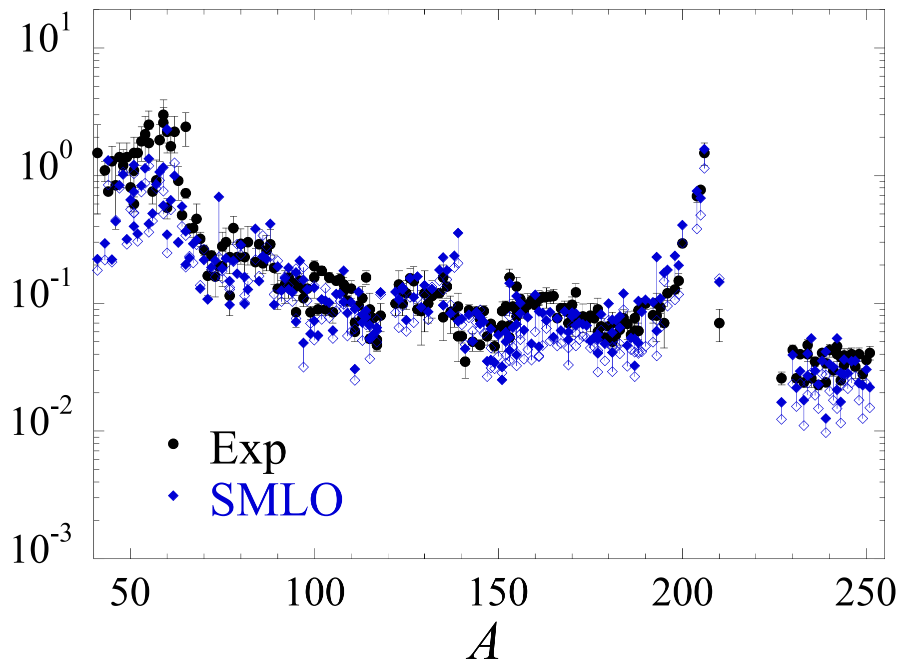
$$\langle \Gamma_\gamma \rangle = \frac{D_0}{2\pi} \sum_{X,L,J,\pi} \int_0^{S_n+E_n} T_{XL}(\varepsilon_\gamma) \times \rho(S_n + E_n - \varepsilon_\gamma, J, \pi) d\varepsilon_\gamma$$



D1M+QRPA+0lim



SMLO

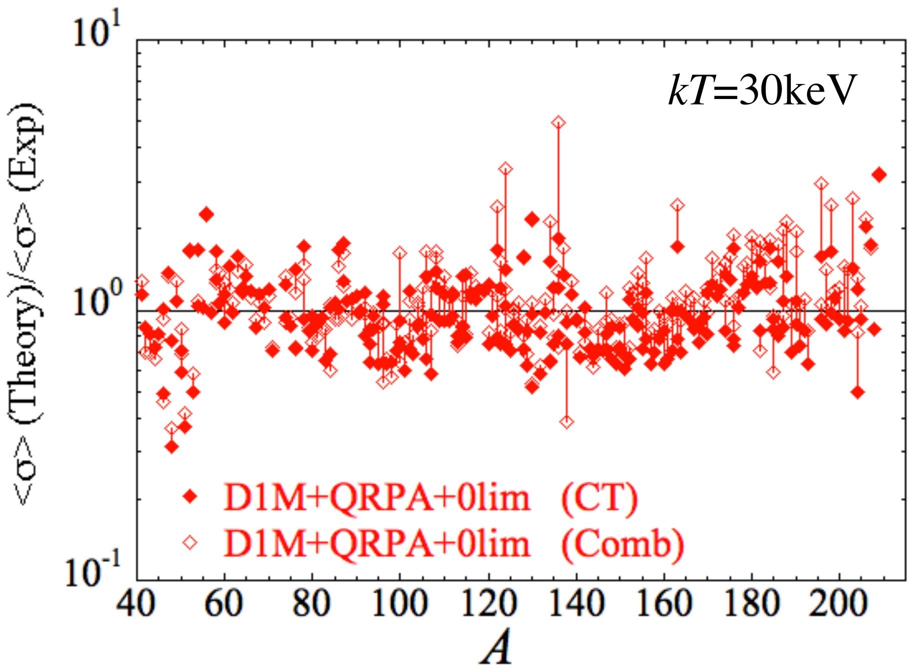


Open diamonds = CT + BSFG
Full diamonds = HFB + Combinatorial

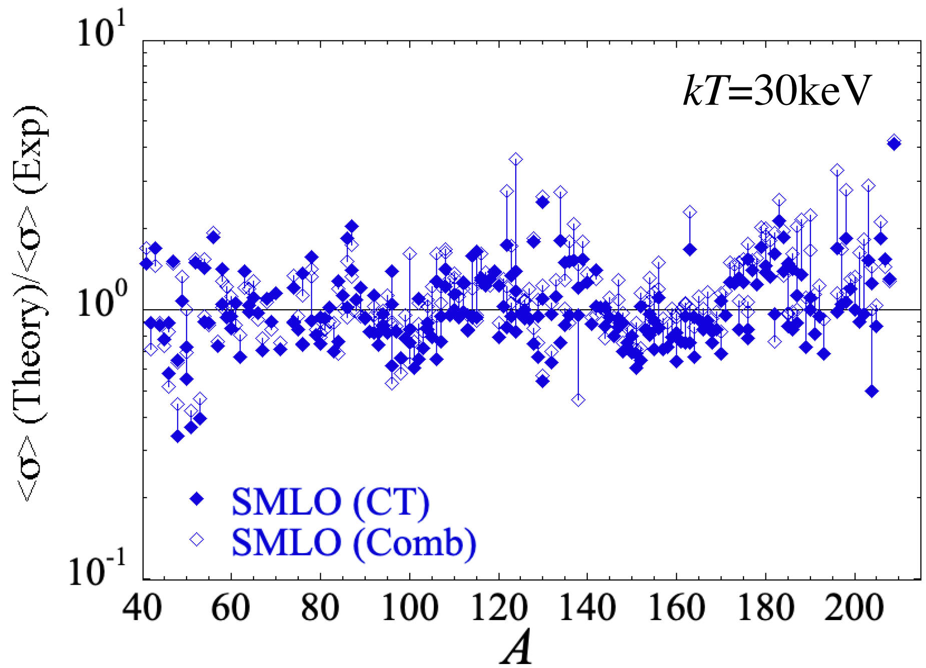
Both PSF models reproduce ~230 <Γ$_\gamma$> within ~ 30-50%

Comparison of D1M+QRPA+0lim and SMLO with MACS

D1M+QRPA+0lim



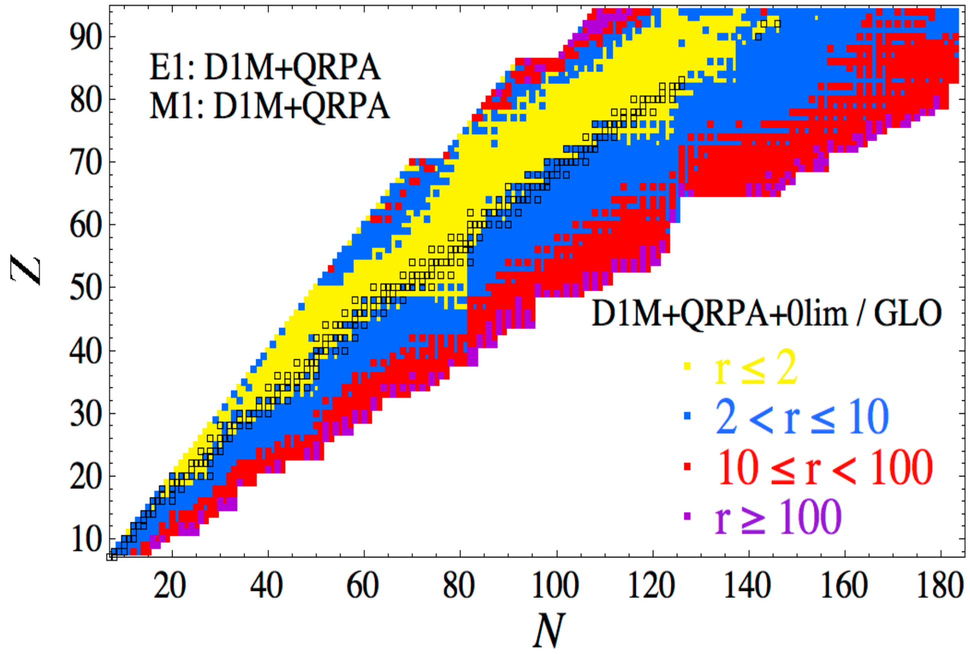
SMLO



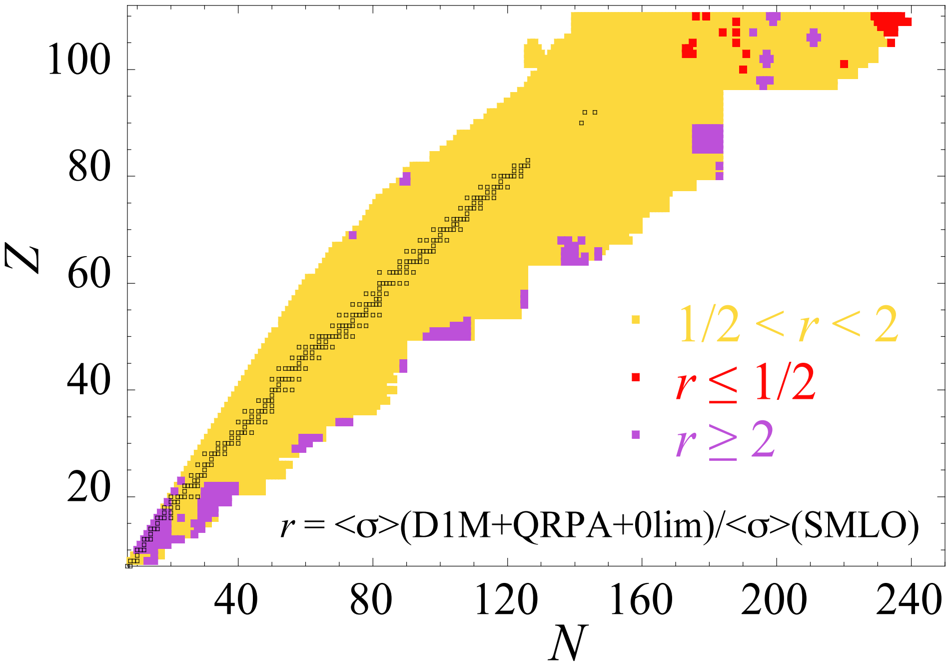
Both PSF models reproduce ~240 MACS within ~ 40-50%

Comparison of radiative n-capture MACS <σ> between D1M+QRPA+0lim and SMLO / GLO

D1M+QRPA+0limit *versus* GLO



D1M+QRPA+0limit *versus* SMLO



Increase of <σ>

- Extra *E*1 strength at low-*E*
- *M*1 upbend & scissors mode not included in GLO

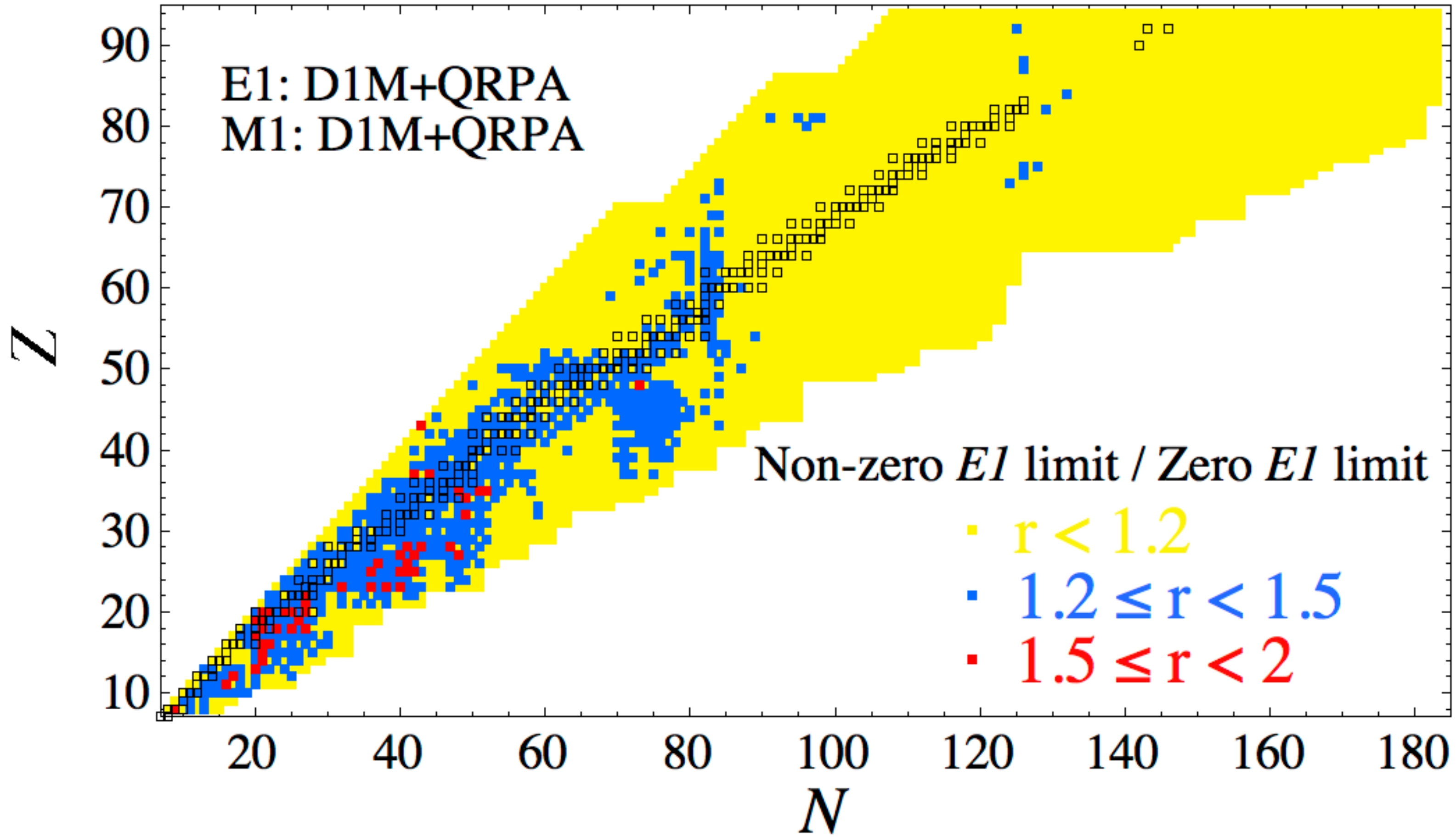
Very similar <σ>

- Similar *M*1 scissors mode
- Similar *M*1 upbend
- Similar description of GDR

Impact of the $\varepsilon_\gamma \to 0$ *E1* strength limit on the radiative neutron capture

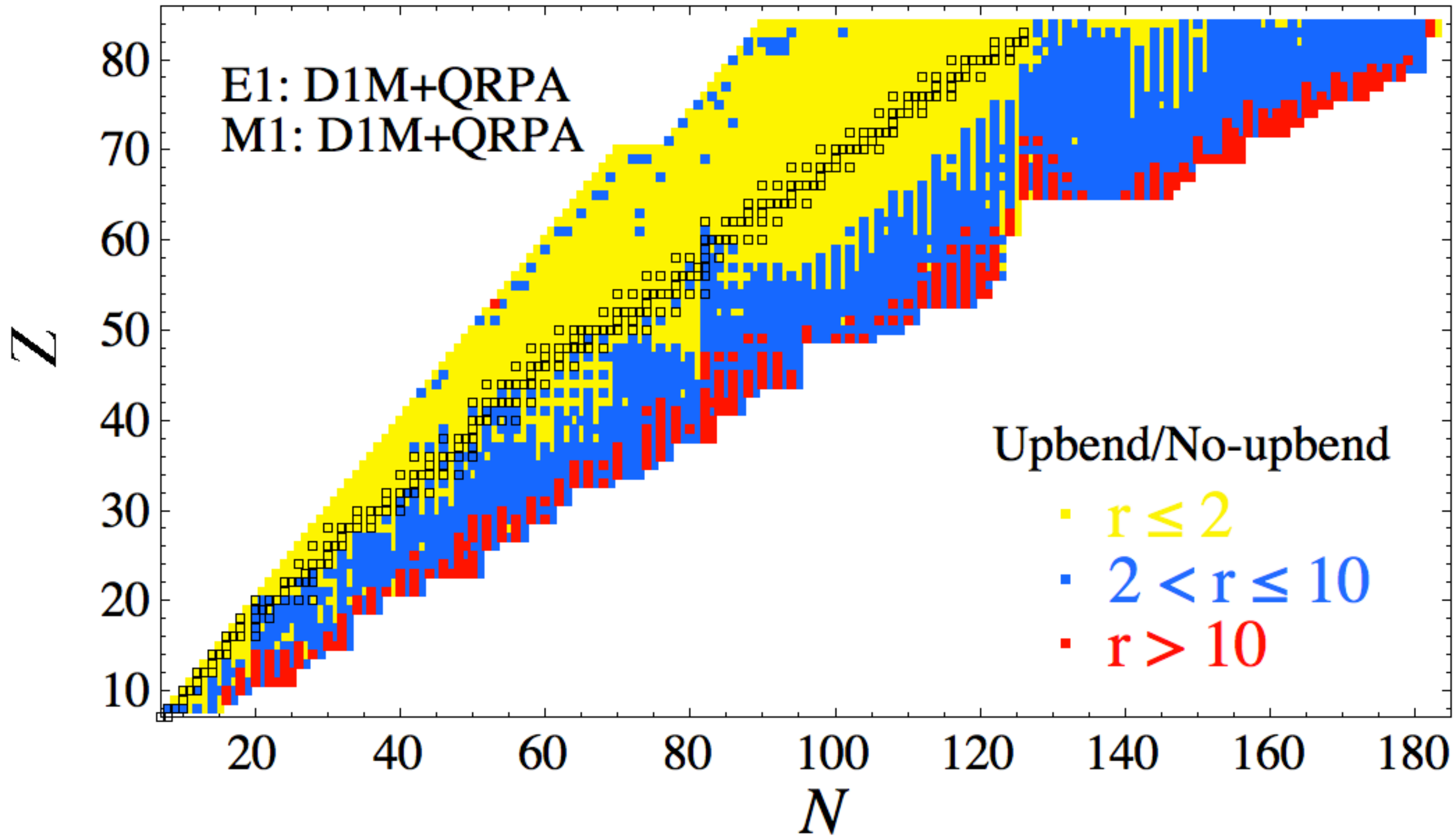
For exotic n-rich nuclei : $S_n \sim$ 0-3 MeV & $k_B T \sim$ 0.1 MeV $\to$ U small

MACS ratio at T=10^9K



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

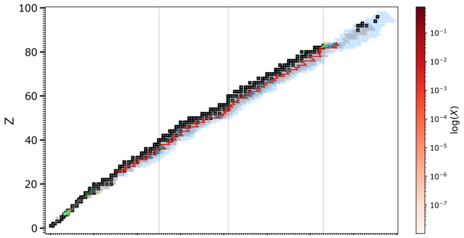
Impact of the *M1* upbend (and *E1* zero-limit) on the (n,γ) MACS at T=10^9K

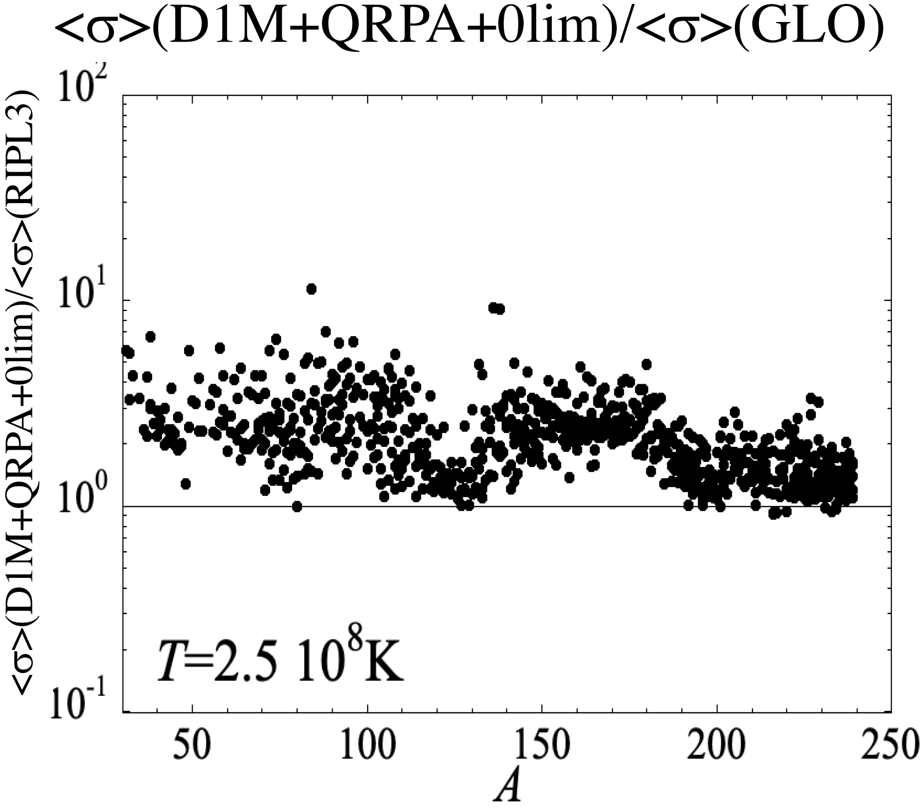


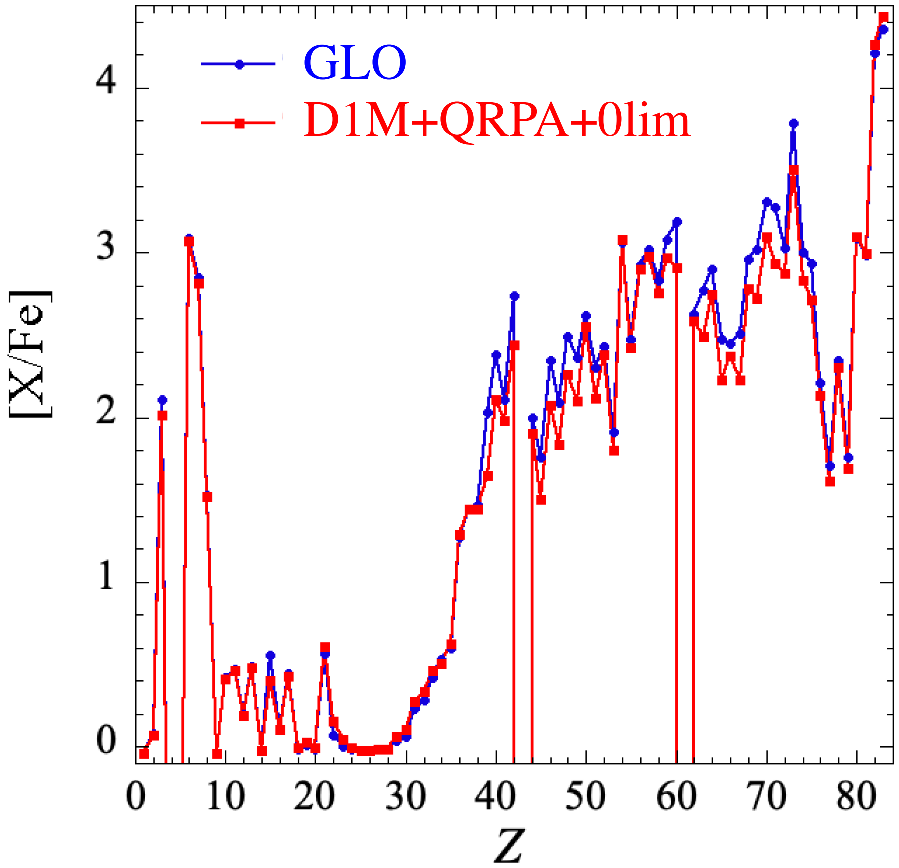
Significant impact of the *M*1 upbend on <σ> for n-rich nuclei

Impact of PSF on the *i*-process in low-*Z* low-*M* AGB stars

For all the 793 non-experimental (n,γ) reaction rates
on $14 \leq Z \leq 93$



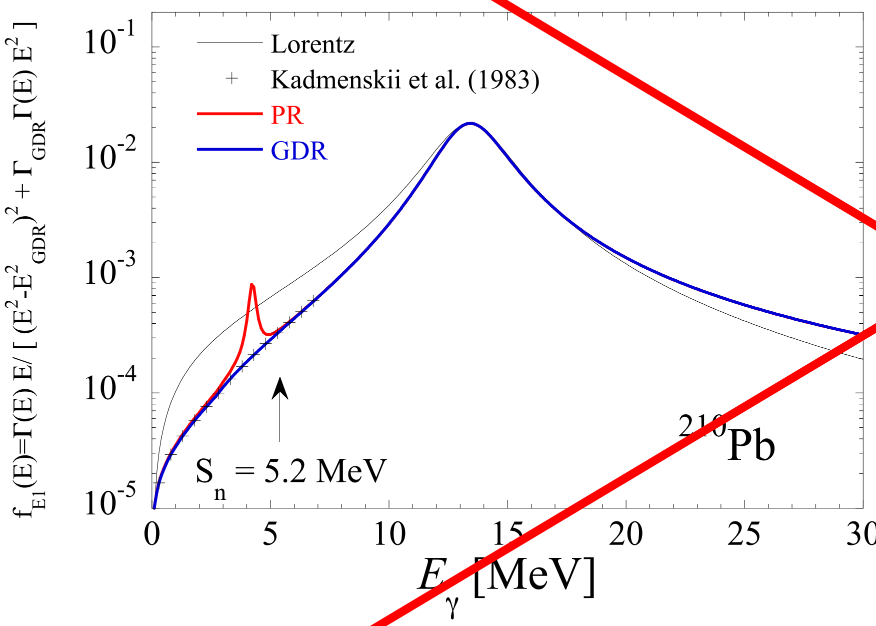


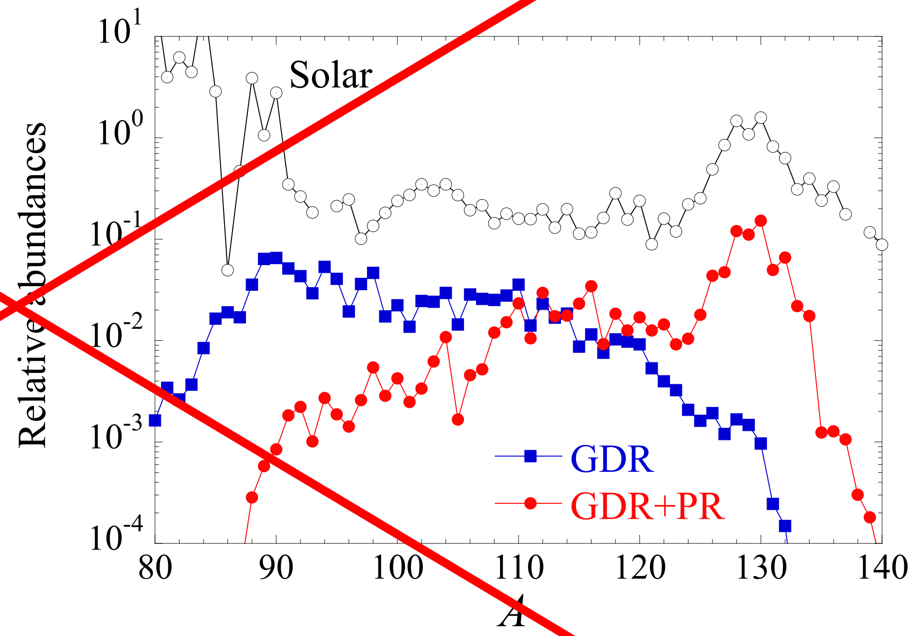


Non-negligible impact of the largest E1 and M1 strength at low energies with D1M+QRPA+0lim

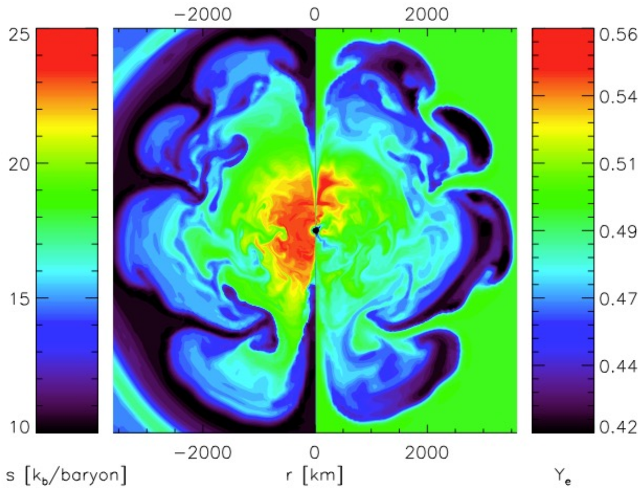
Impact on the r-process nucleosynthesis

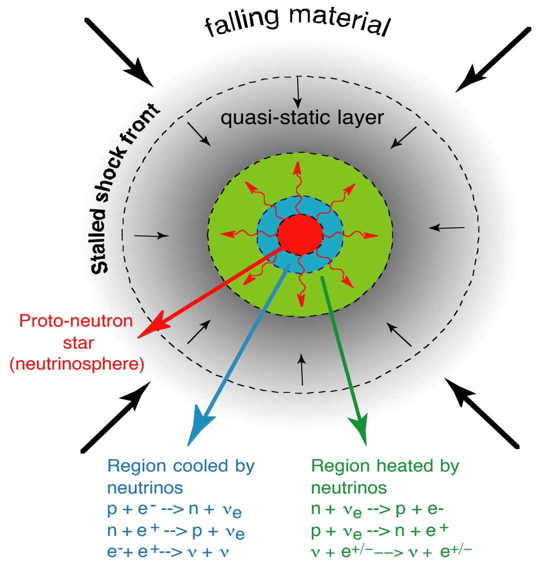
Simple site-independent "canonical r-process model" (1998): T=10^{9}K; N_n=10^{20}cm^{-3} t_{irr}=2.4s





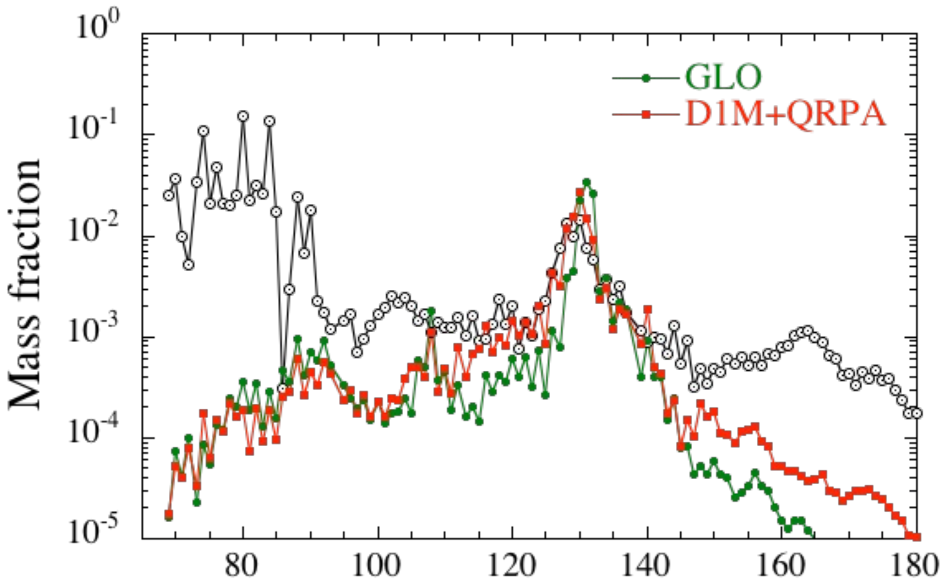
Impact on the r-process nucleosynthesis in type-II SN

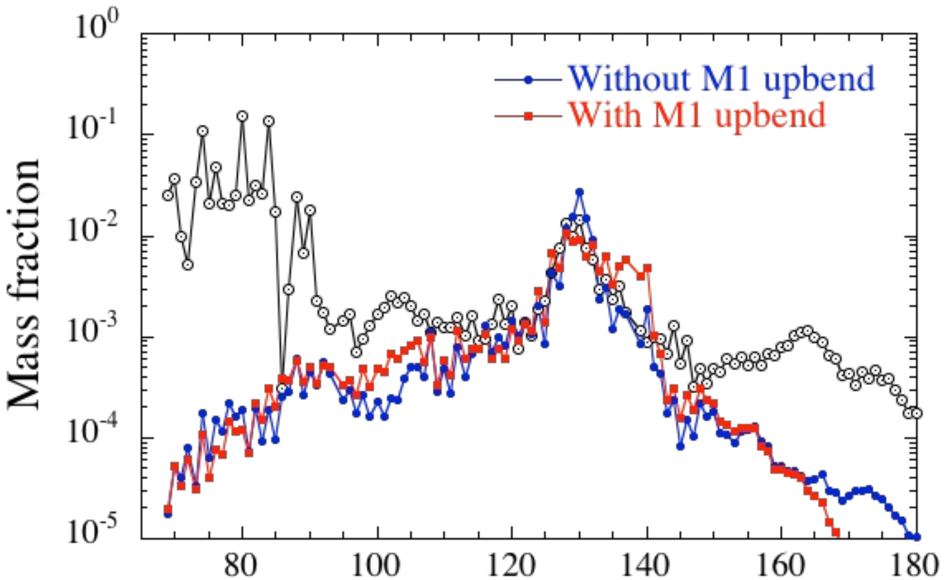




who knows…

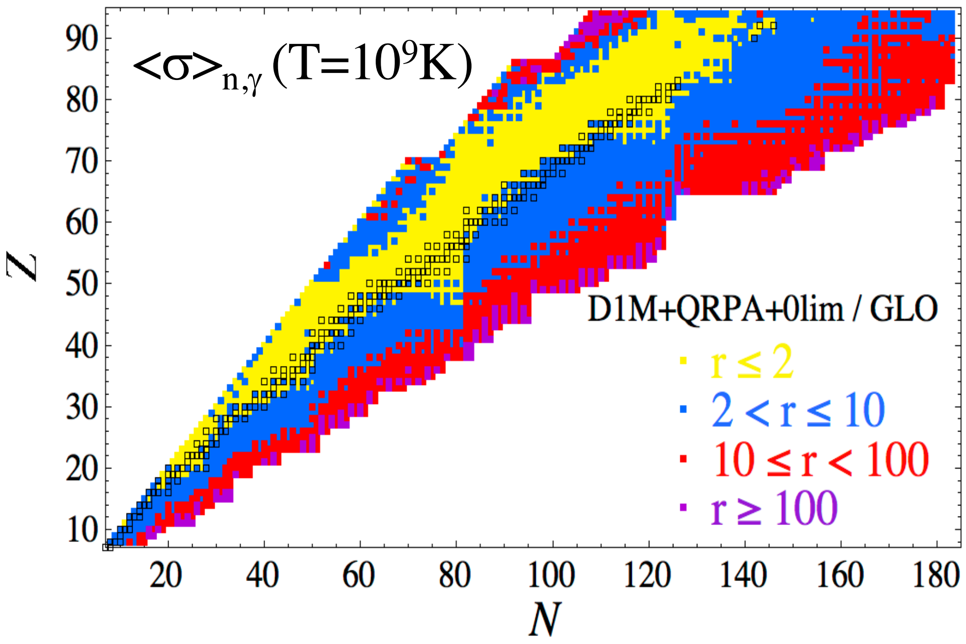
1 trajectory: S=195; Y_e=0.47; dM/dt=6 10^{-6}M$_o$/s; f_w=1



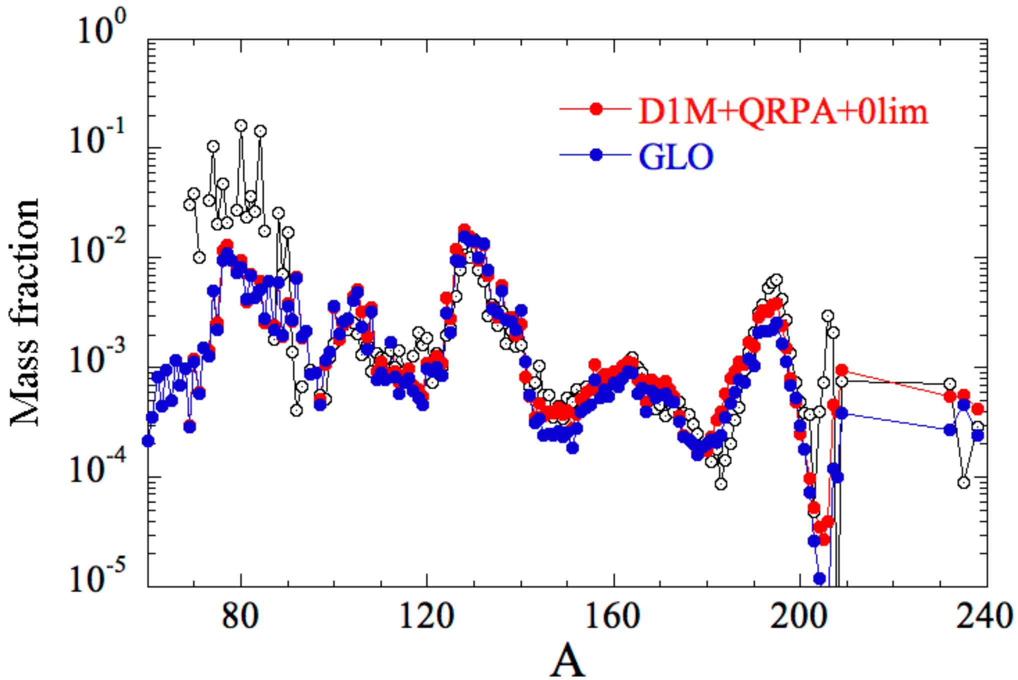


Impact of PSF on the *r*-process in Neutron Star Mergers

Impact of the PSF on the radiative n-capture rate



Impact of the PSF on the r-process in NSM *disk ejecta* (thousands of traj)



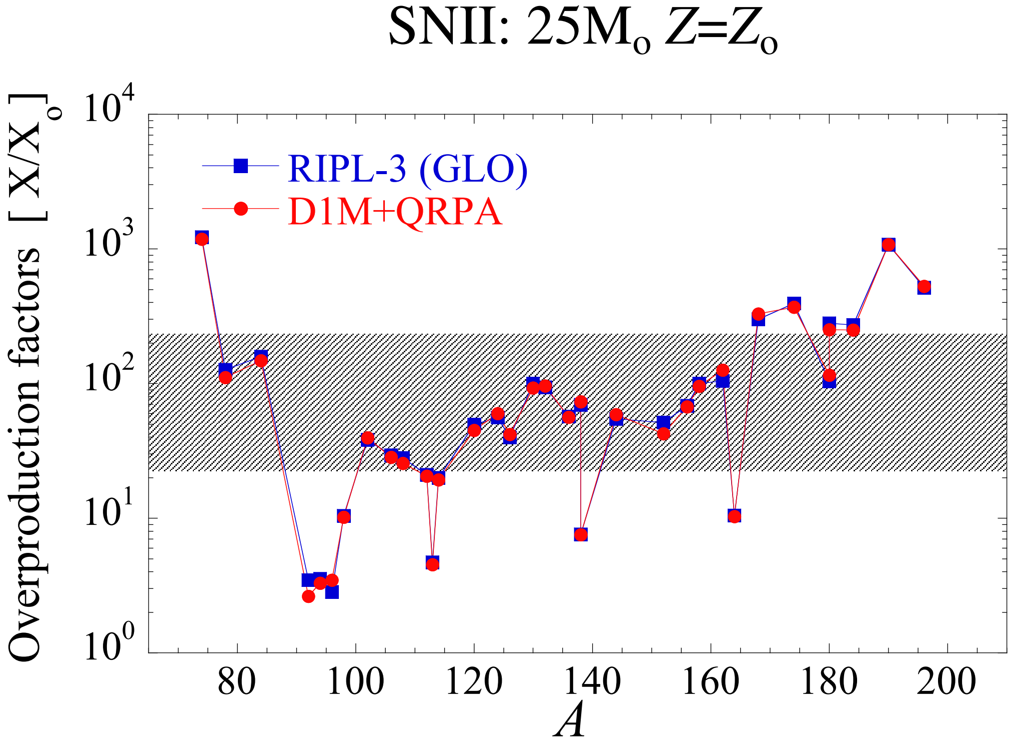
Increase of <σ> due to

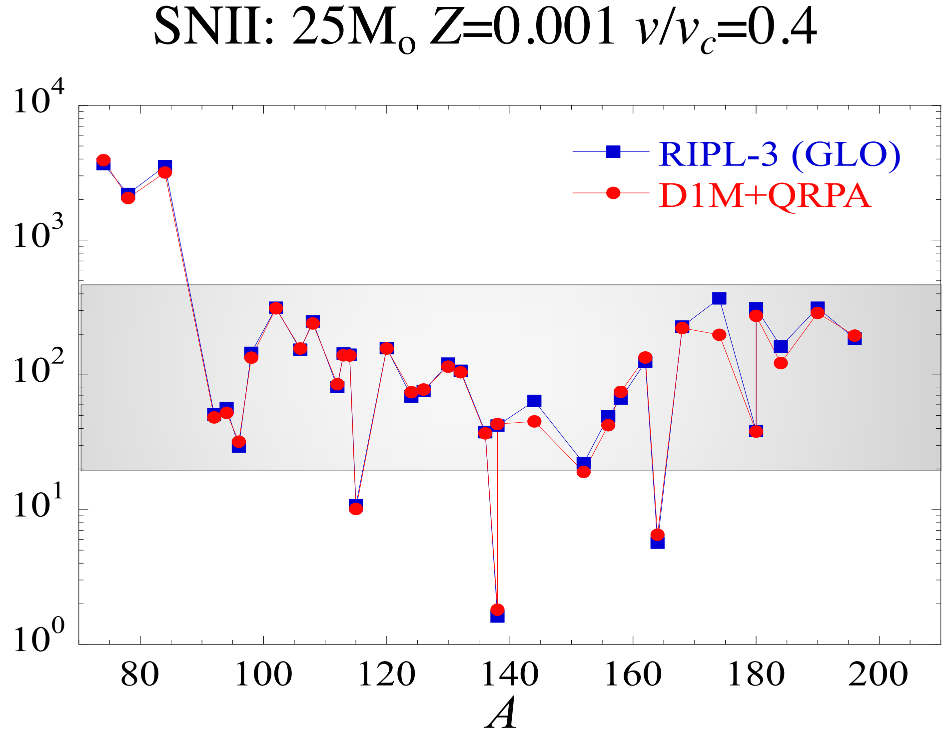
- *E*1 QRPA at low-*E*
- *M*1 scissors & upbend

Increase production of

- Lanthanides & 3rd peak
- Actinides & chronometers

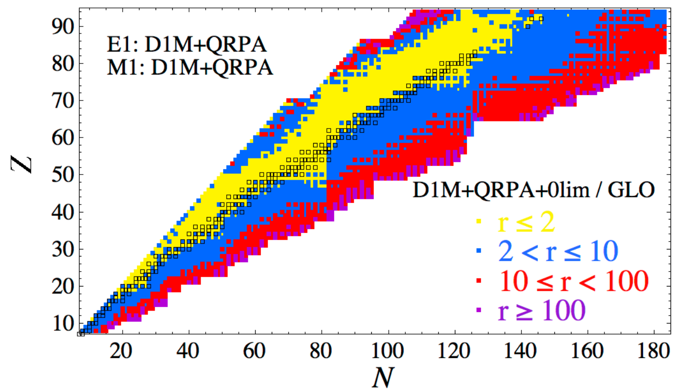
Impact of PSF on the *p*-process in Type-II Supernovae



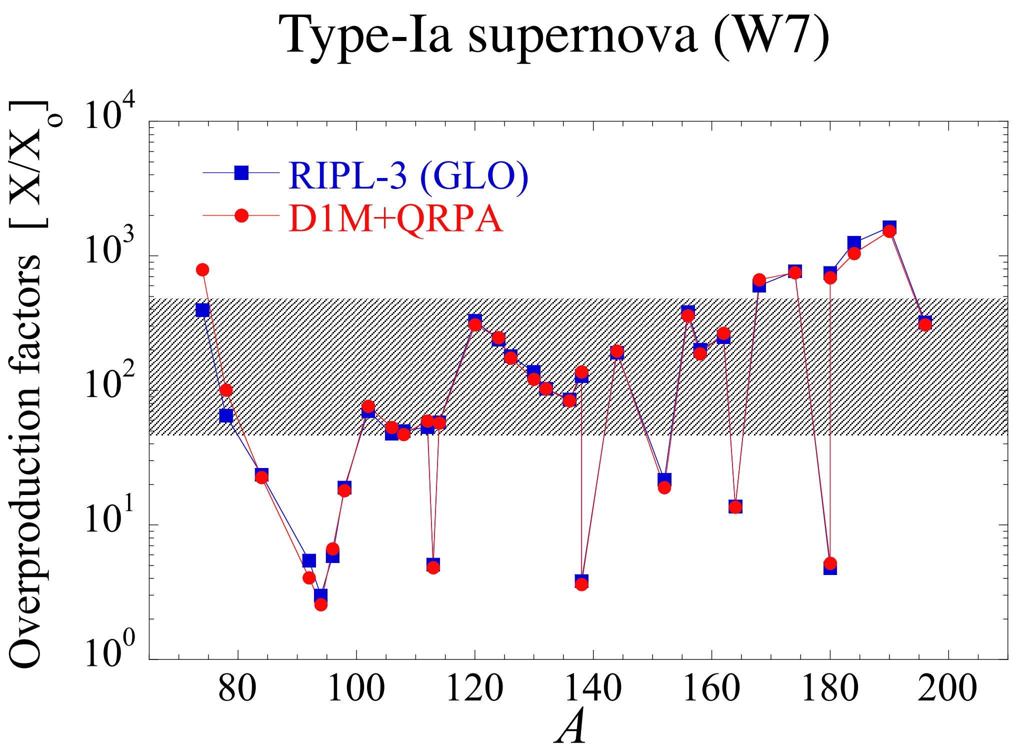


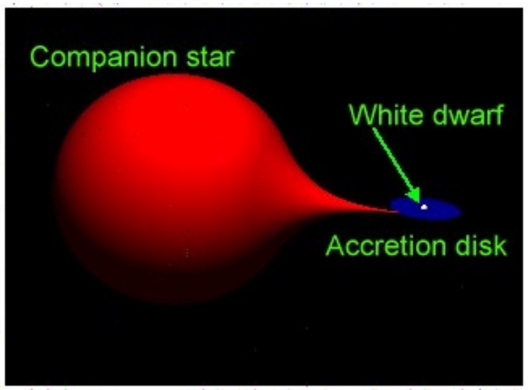
Relatively small impact:

- Similar (γ,n) predictions for n-deficient nuclei (r≤2)
- No zero-limit for photo-excitations



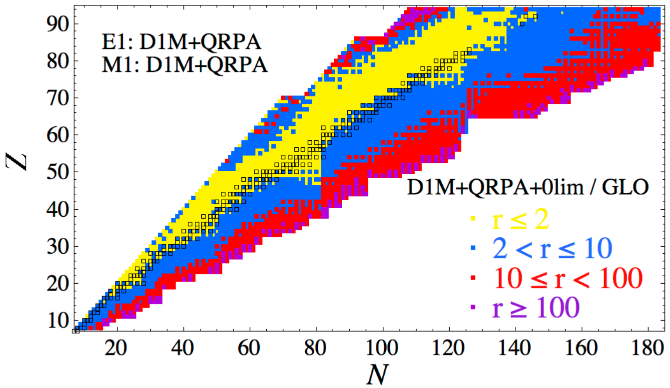
Impact of PSF on the *p*-process in Type-Ia Supernovae





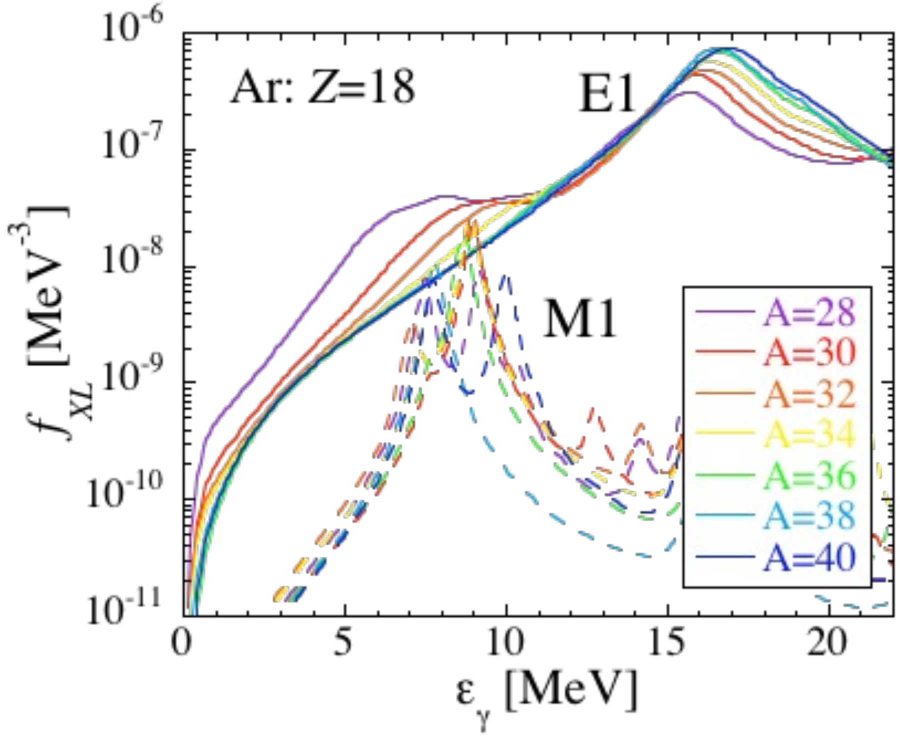
Relatively small impact:

- Similar (γ,n) predictions for n-deficient nuclei ($r \leq 2$)
- No zero-limit for photo-excitations

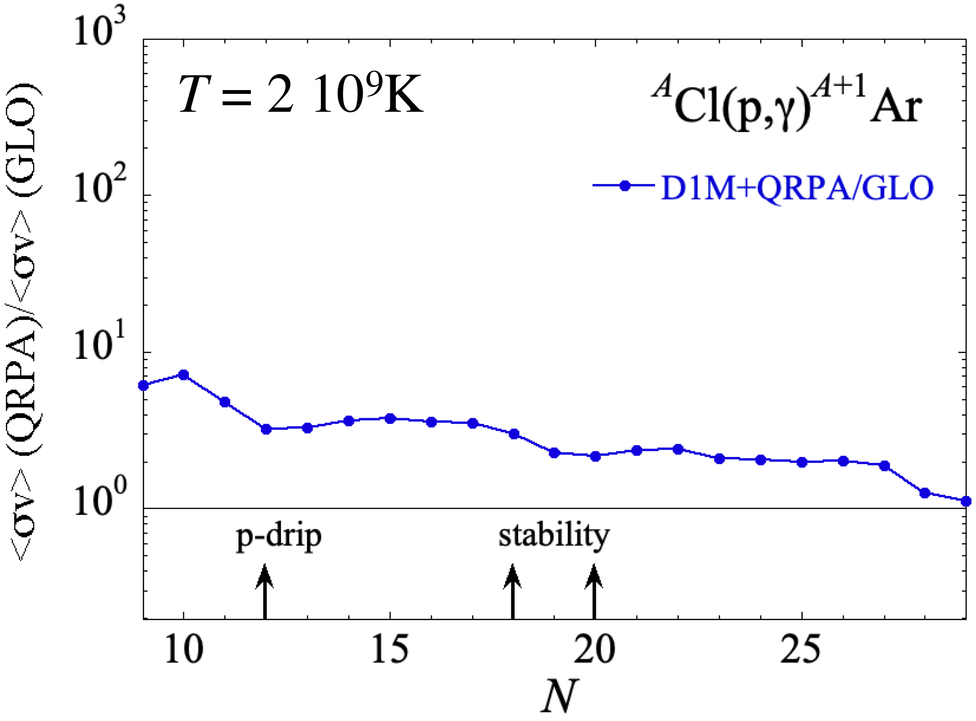


γ-ray strength function for the *n-deficient* nuclei
Pygmy Dipole Resonance

D1M+QRPA *E*1& *M*1 strength in Ar

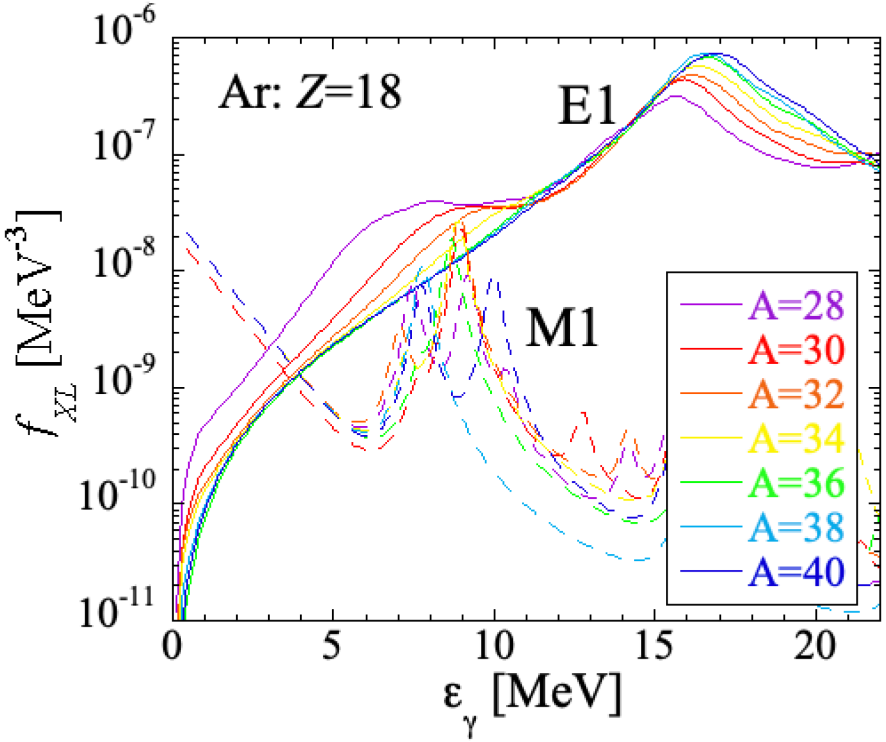


^{A}Cl(p,γ)$^{A+1}$Ar reaction rates

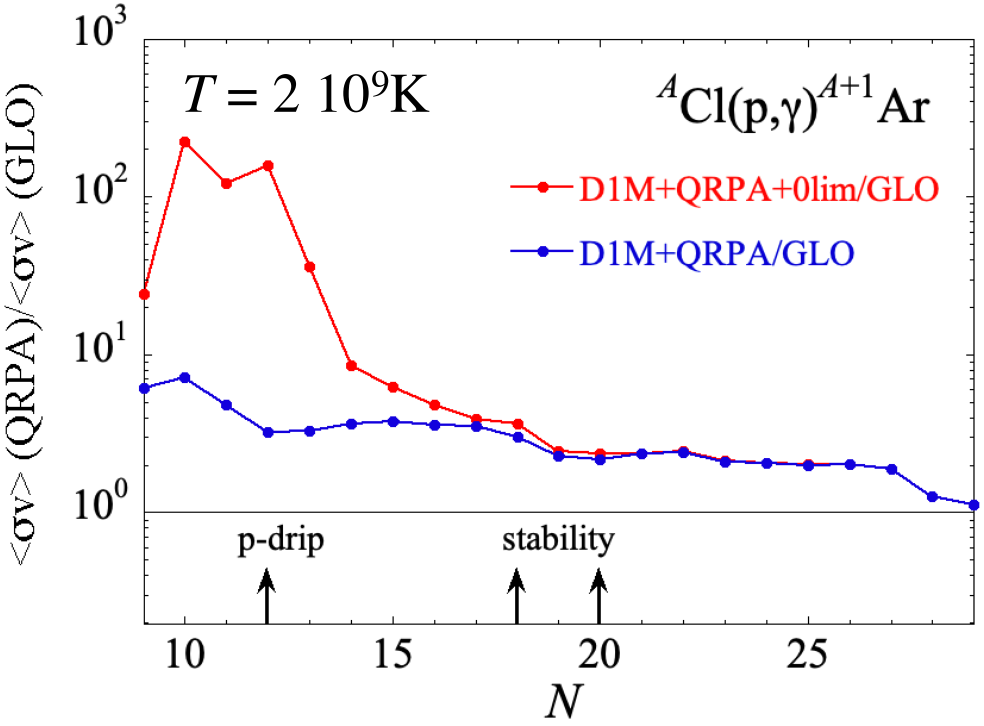


γ-ray strength function for the n-deficient nuclei
Pygmy dipole resonance and E1 limit and M1 upbend

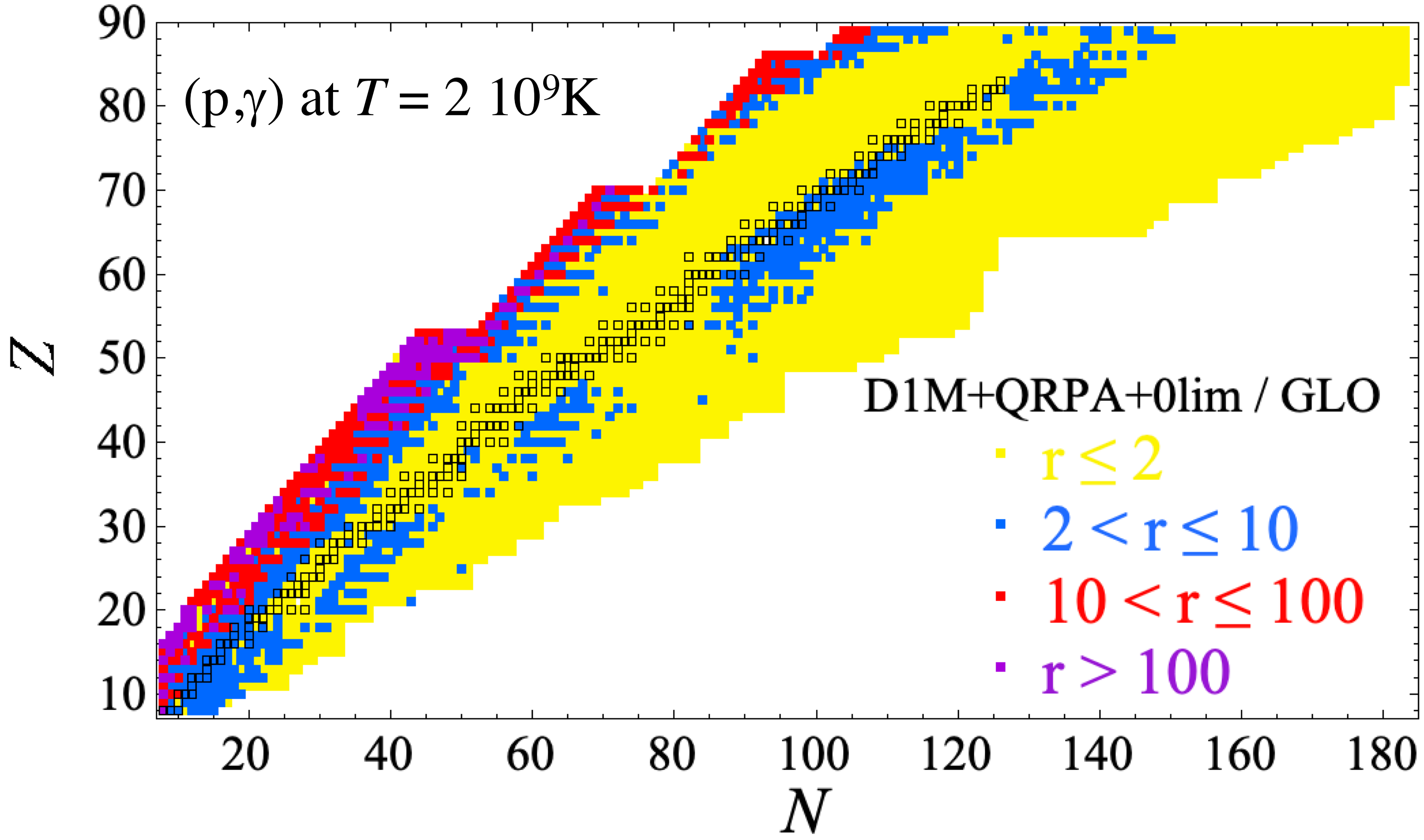
D1M+QRPA+upbend strength in Ar



^{A}Cl(p,γ)$^{A+1}$Ar reaction rates



Impact of the *PSF* on the (p,γ) MACS at $T = 2\ 10^9$K



Significant impact for light n-deficient nuclei ($Z \leq 50$):

- *M*1 upbend
- Pygmy resonance or low-*E* tail of the GDR

Possible implication for the rp-process in X-ray bursts ... to be followed

Conclusions

PSF models have been developed and shown to globally describe experimental data and to affect radiative n-capure cross sections:

- → Low-energy *E1* QRPA strength for exotic n-rich nuclei: up to x 50
- → Non-zero limit of the *E1* strength from SM has small impact : ~20-50%
- → Spin-flip *M1* strength has small impact on (n,γ) cross section : ~10%
- → *M1* Scissors mode can impact (n,γ) cross section : up to x 2
- → *M1* upbend can affect cross sections of exotic n-rich nuclei: up to x 100

Future work will require

- Understanding the discrepancies between some experimental techniques, in particular Oslo vs NRF
- Experimental constraints on the low-*E* PSF and, in particular, the zero limit *E1* & *M1* (upbend ?)
- Improved microscopic description of the de-excitation strength
- Large-scale calculations beyond 1p-1h QRPA (2RPA, QPM, ...)