Fission rates and transactinides formation in the r-process.

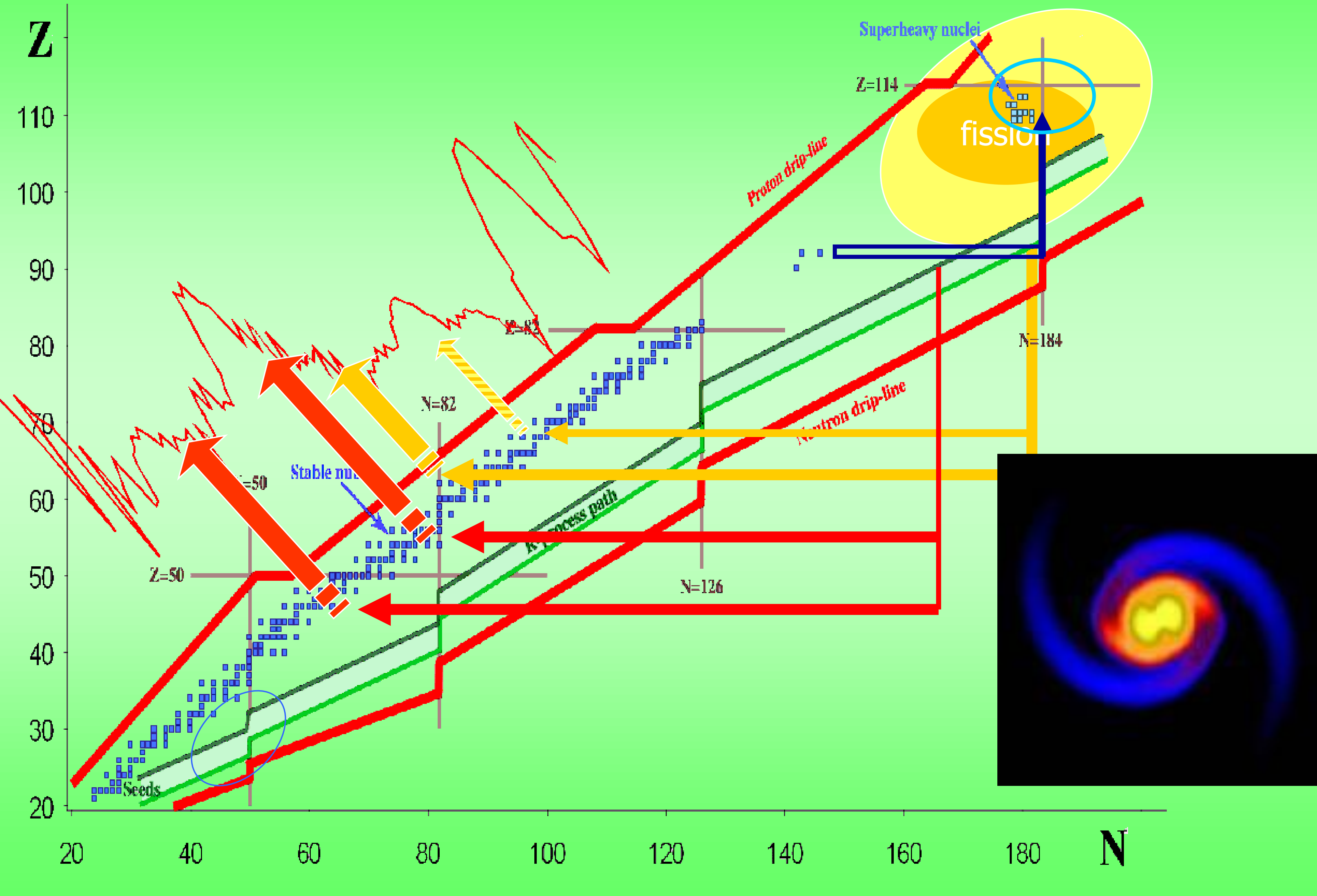
Igor Panov (ITEP)

Subject of the talk

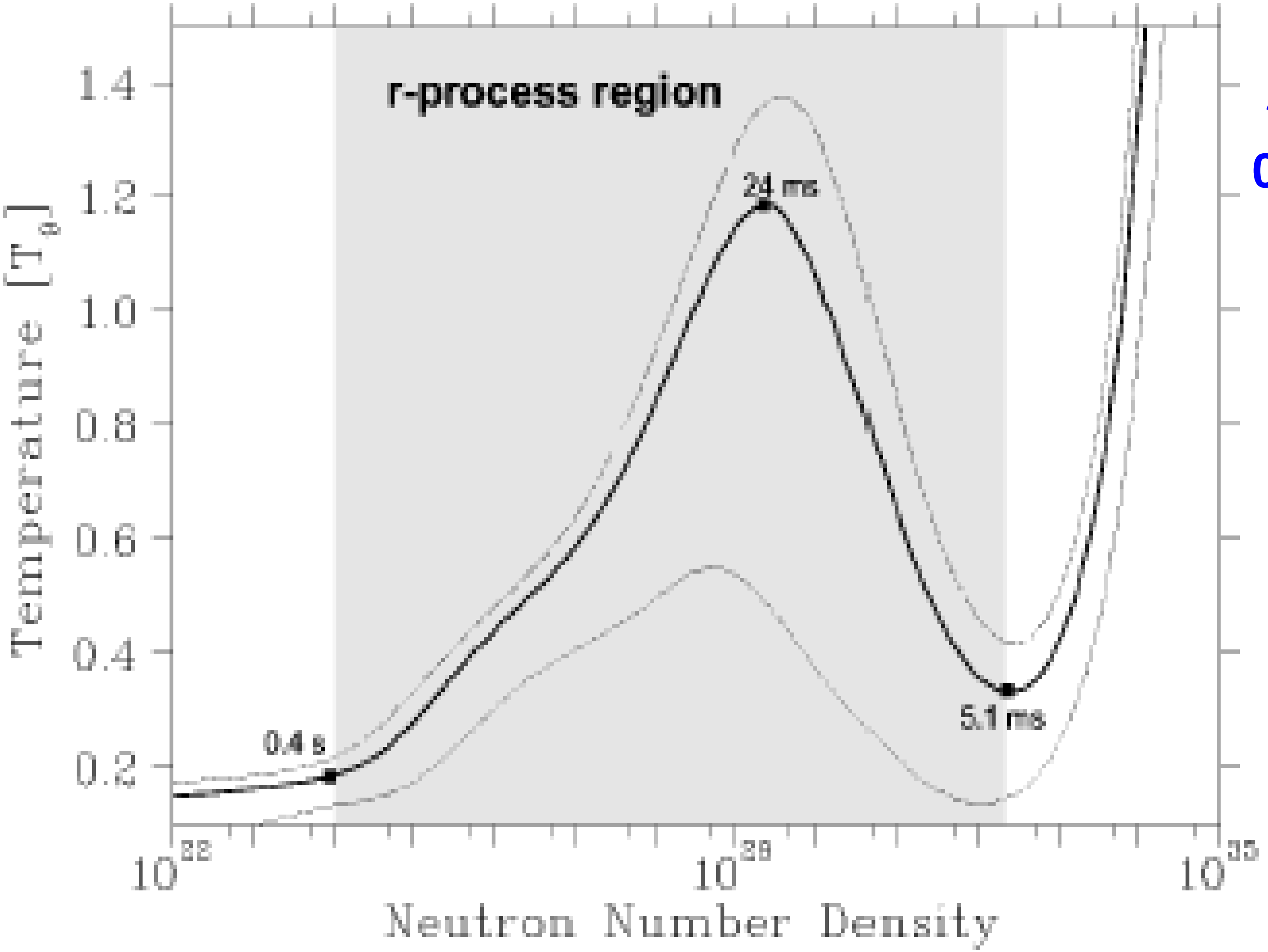
- Fission in the R-process
- Astrophysical site for the main r-process
- Actinides and transactinides
- Data: $T_{1/2}$, P_n, (n,g), (n,f), βdf, s.f.
- data for the r-process:

  Purposes and motivation
- S.f. and $P_{\beta df}$ different approaches
- S_{β} and $P_{\beta df}$ predictions
- conclusions

Main r-process: $\tau_R \geq 0.5$ s, cycling number n_{cycl} $(\log_2(Y_{fin}/Y_{init}))$ > 0, ~1

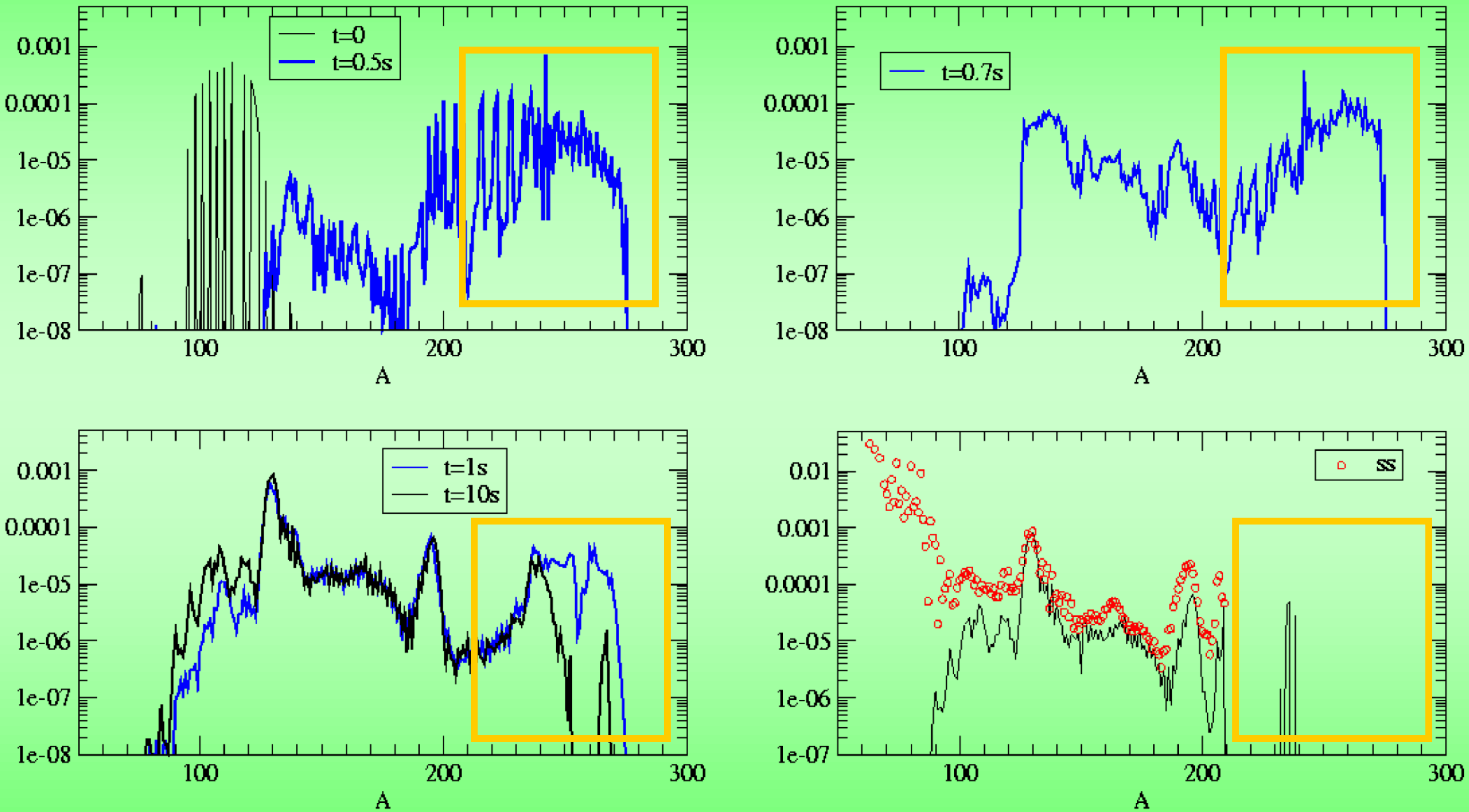


Model of NSM-simulation: Freiburghaus et al. AJ 525 (1999)



$\tau_r \sim$ **0.6-0.9s**

Y(A) during r-process with fission cycling for NSM conditions (t-duration time of the r-process; t=0 - initial composition)

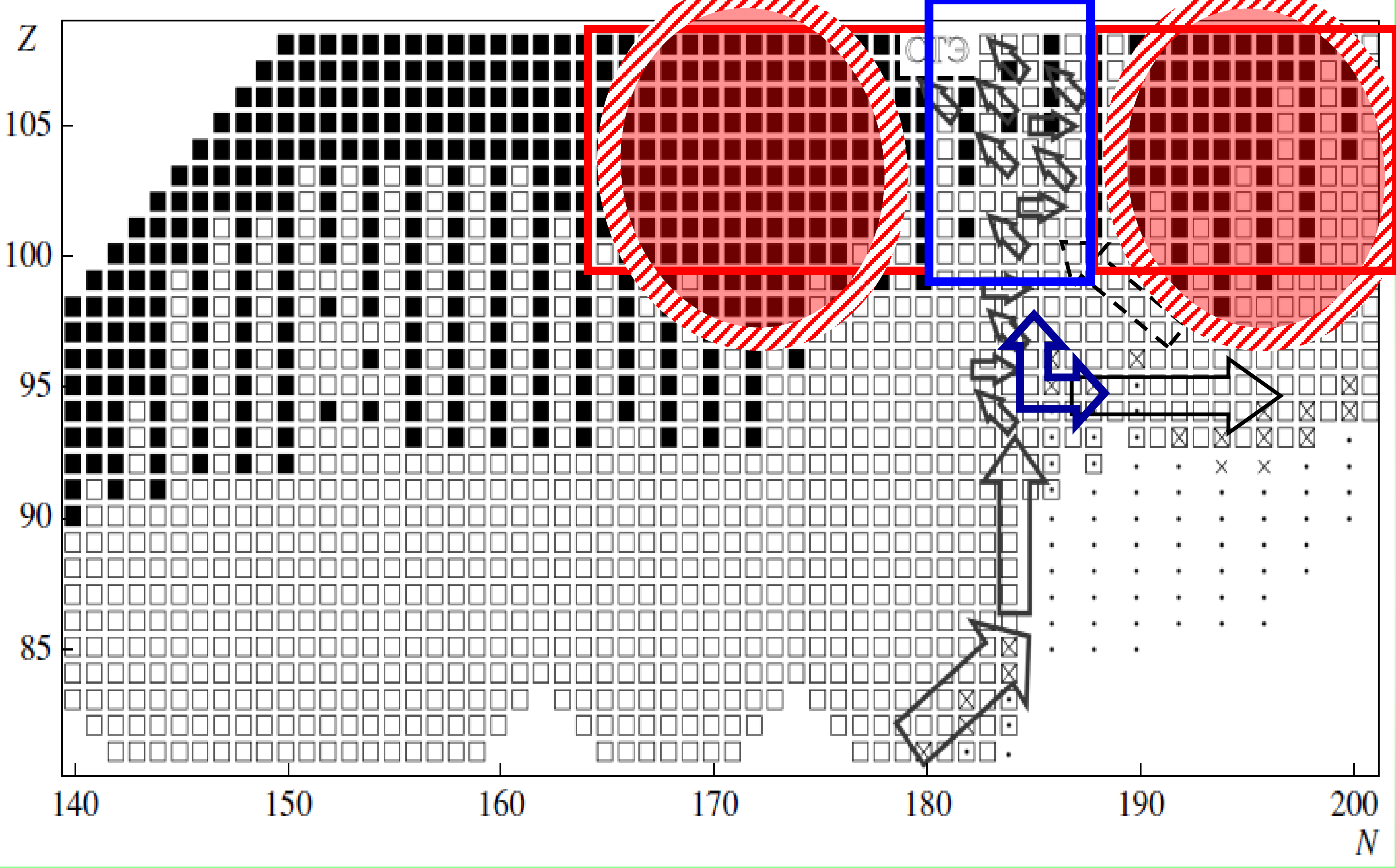


Panov I., Thielemann F.-K. Astronomy Letters, Vol. 30 (2004) 711

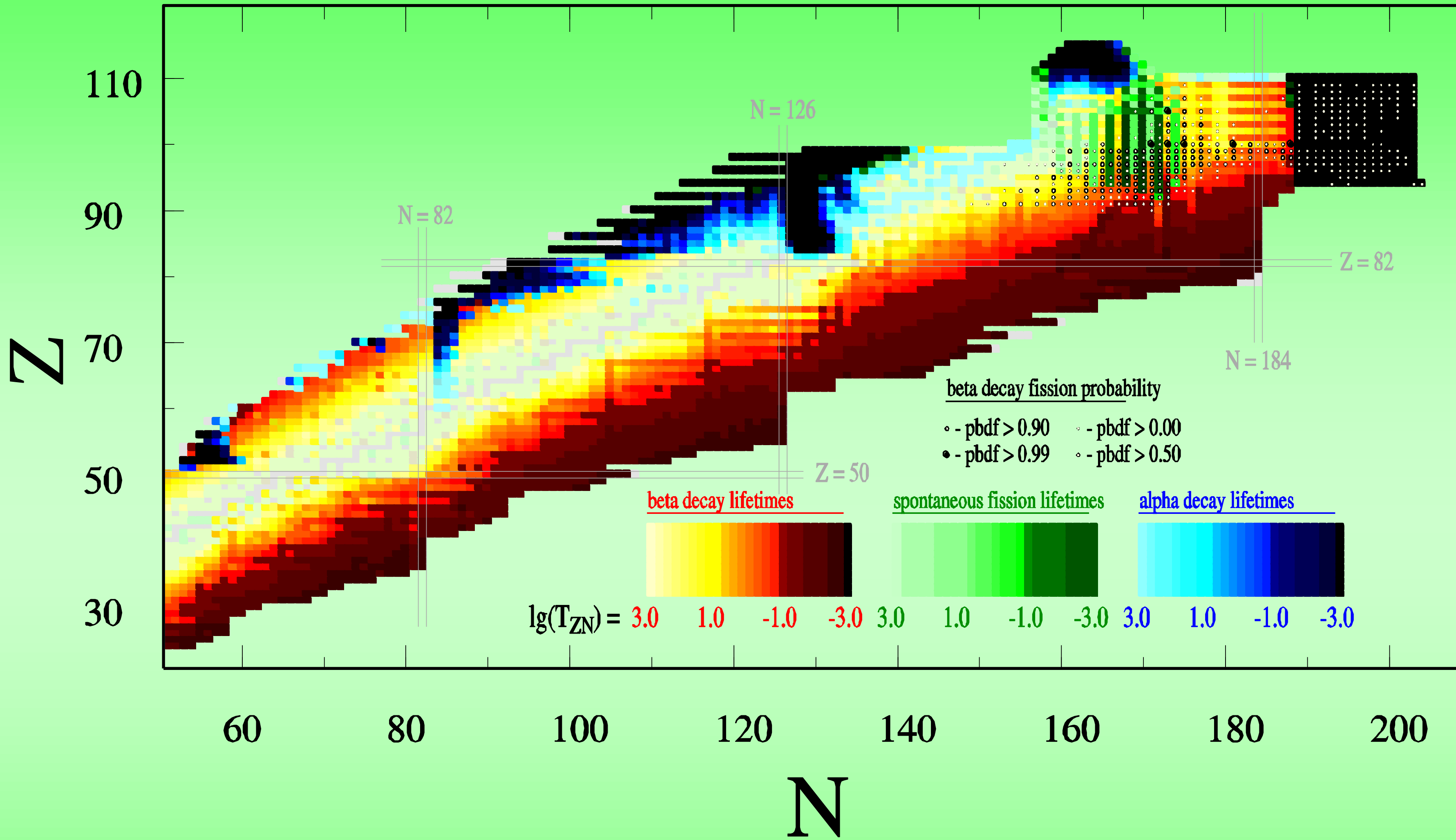
motivation:

further data predictions in the actinide and transactinide region

1. **β-delayed rates** - $P_{\beta df}$ for Z<100
2. Mass predictions and Fission barrier predictions ETFSI for Z<115 Aboussir et al. 1995; Mamdouh et al. 1998)
3. (n,γ)-rates and Neutron-induced fission rates $\lambda_{nif} \sim \langle \sigma v \rangle$ Z<115 Panov, Thielemann et al.2010
4. S. f. – **phenomenological** models (Ren&Xa 2005; Swiatezki 1957; Metropolis); macro-micro model Smolanchuk et al. 1995,1997

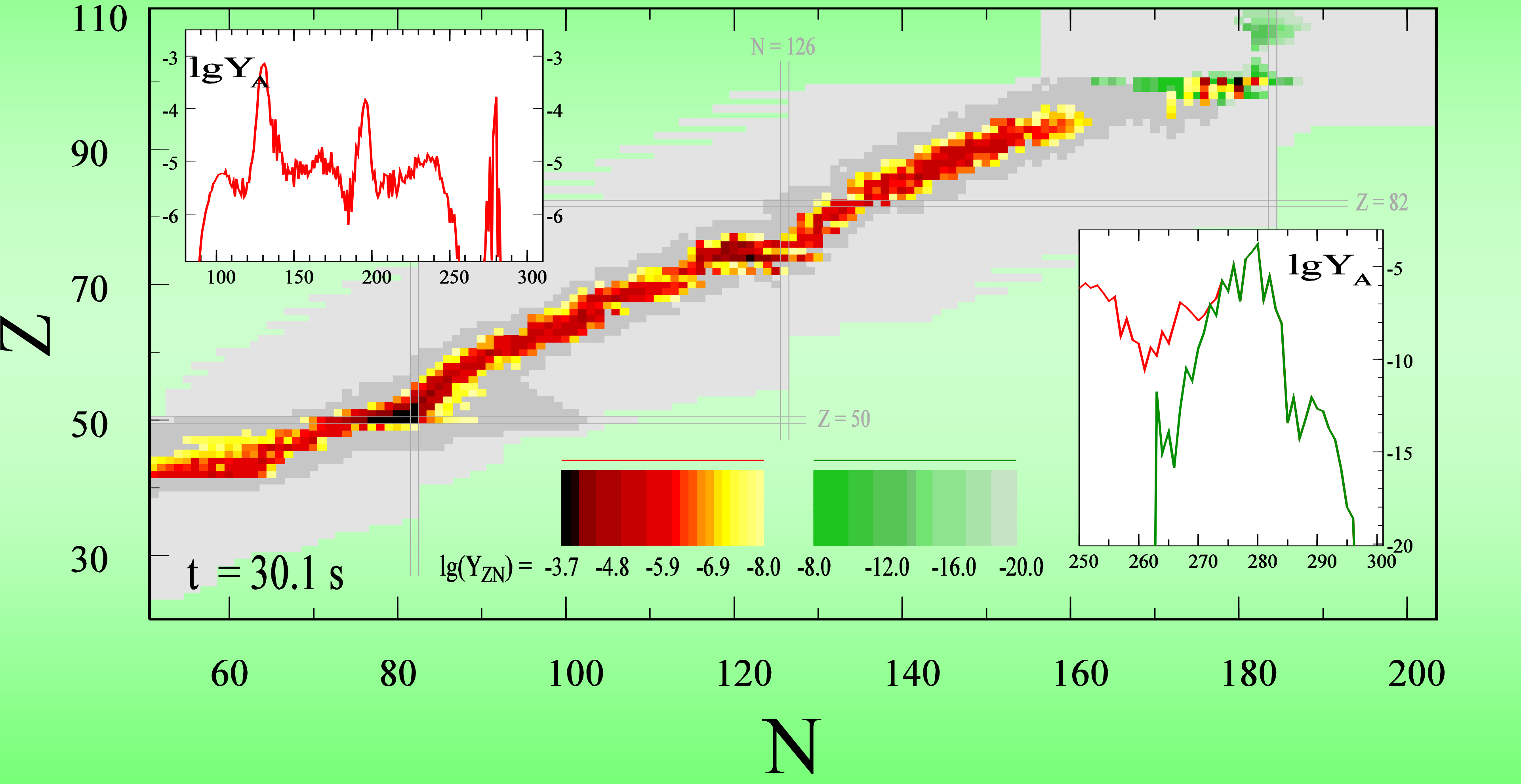


■ : $B_f < Sn$; □ : nuclei with $B_f \geq Sn$; inclined crosses: nuclei with neutron binding energy predicted by the ETFSI [5] $Sn \sim 2$ MeV; and dots: nuclei in which $2 > Sn > 0$.

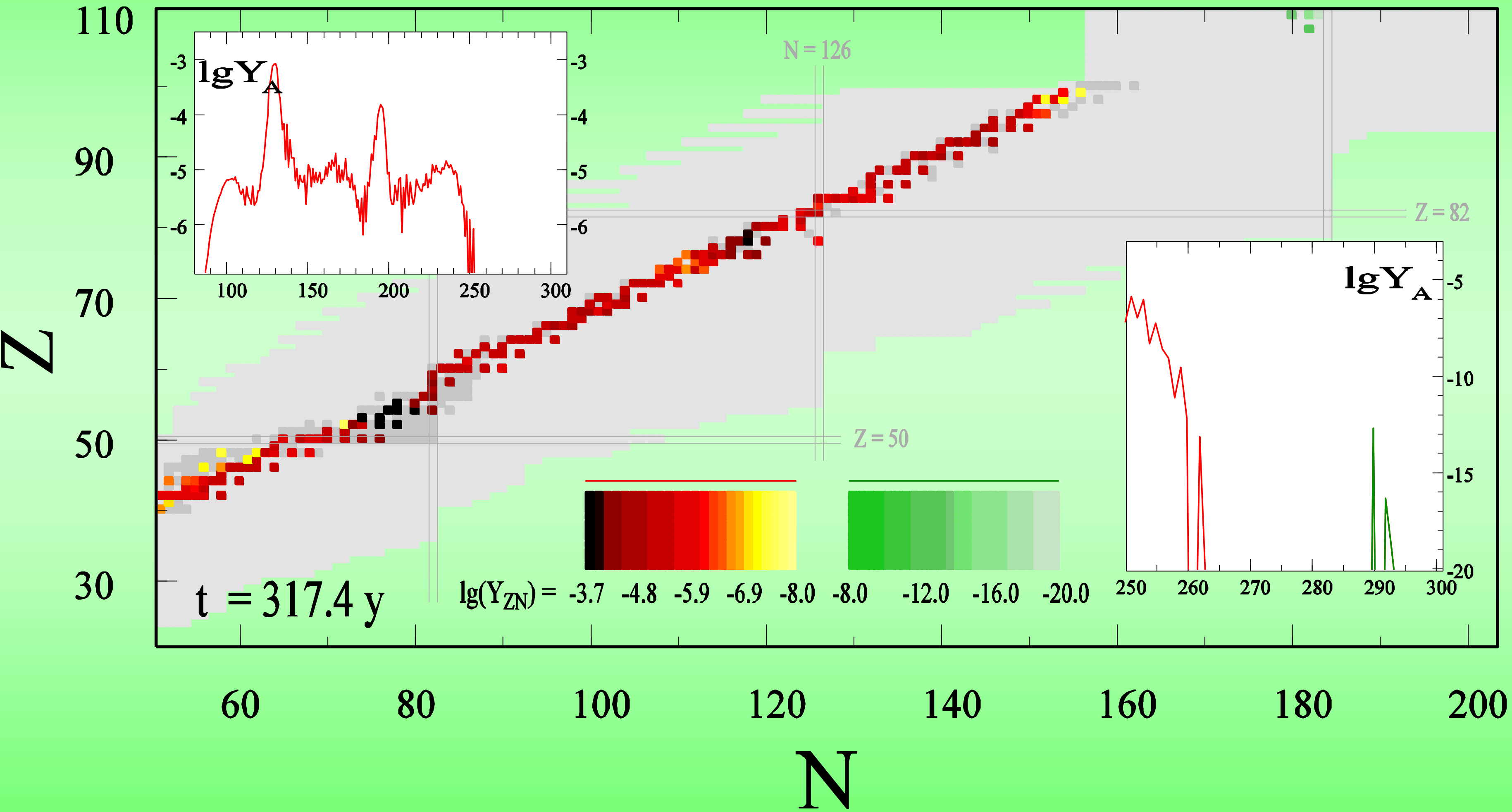


λ_{sf} - **Smolanczuk. 1997**

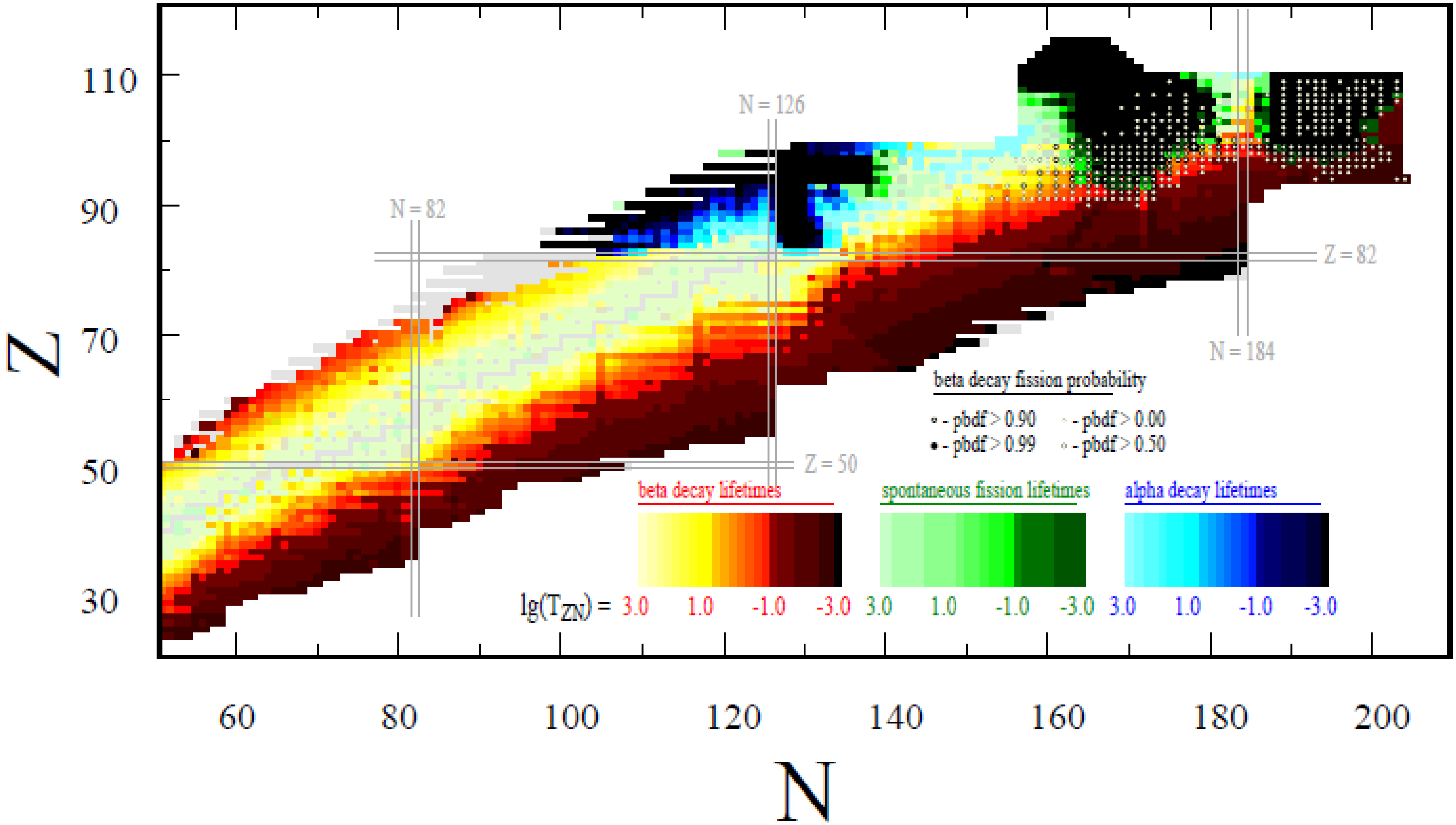
Smolańczuk, R.; Skalski, J.; Sobiczewski, A. 1995



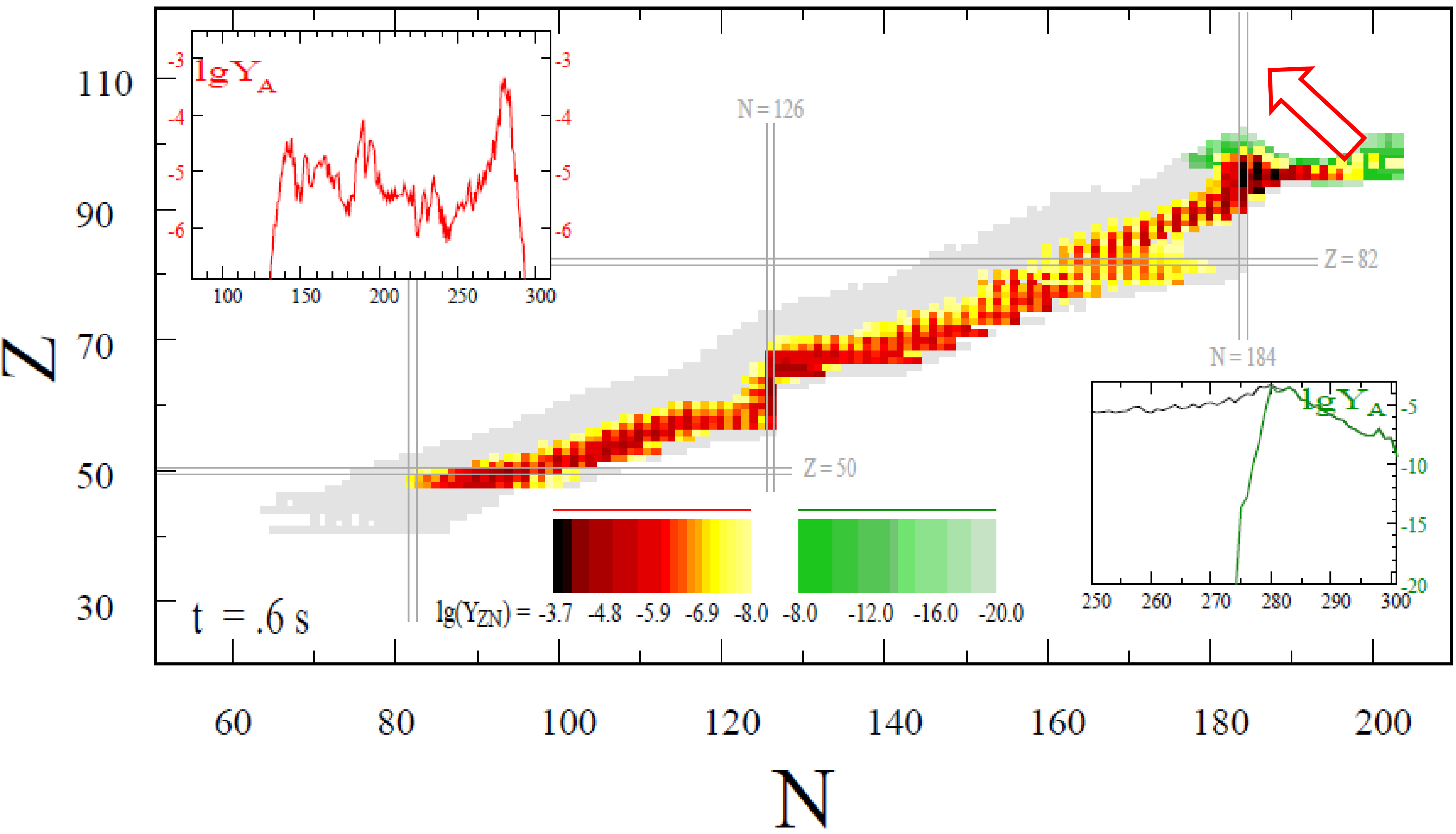
110
90
70
50
30
Z
60
80
100
120
140
160
180
200
N
N = 126
Z = 82
Z = 50
t = 30.1 s
lg(YZN) = -3.7 -4.8 -5.9 -6.9 -8.0 -8.0 -12.0 -16.0 -20.0
lgYA
-3
-4
-5
-6
100 150 200 250 300
lgYA
-5
-10
-15
-20
250 260 270 280 290 300



110
90
70
50
30
Z
60
80
100
120
140
160
180
200
N
lgY_A
-3
-4
-5
-6
100
150
200
250
300
N = 126
Z = 82
Z = 50
lgY_A
-5
-10
-15
-20
250
260
270
280
290
300
lg(Y_ZN) = -3.7 -4.8 -5.9 -6.9 -8.0 -8.0 -12.0 -16.0 -20.0
t = 317.4 y

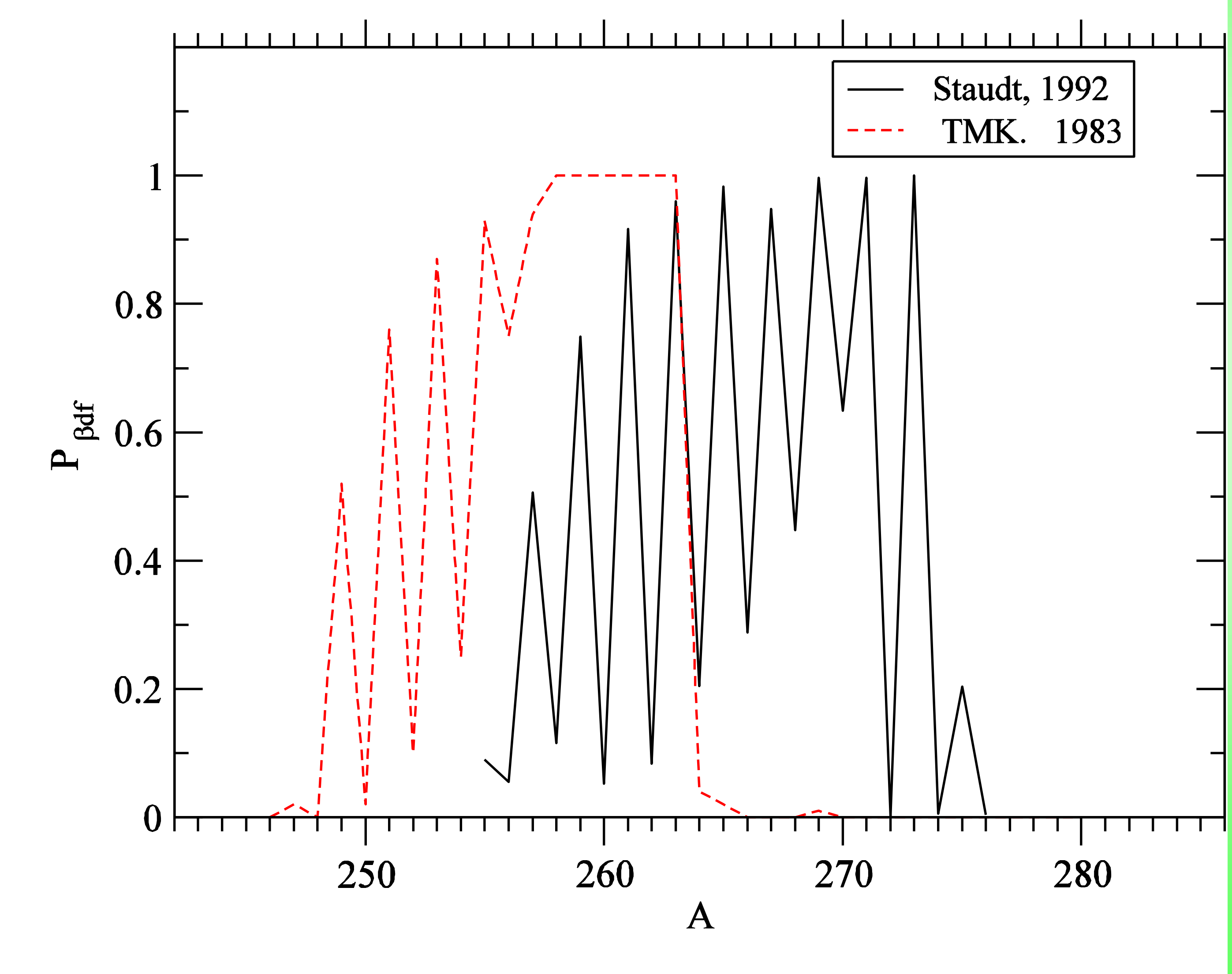


$$Lg\lambda sf = 33{,}3 \;\; - 7,\ 77 \times B_f^{exp}$$

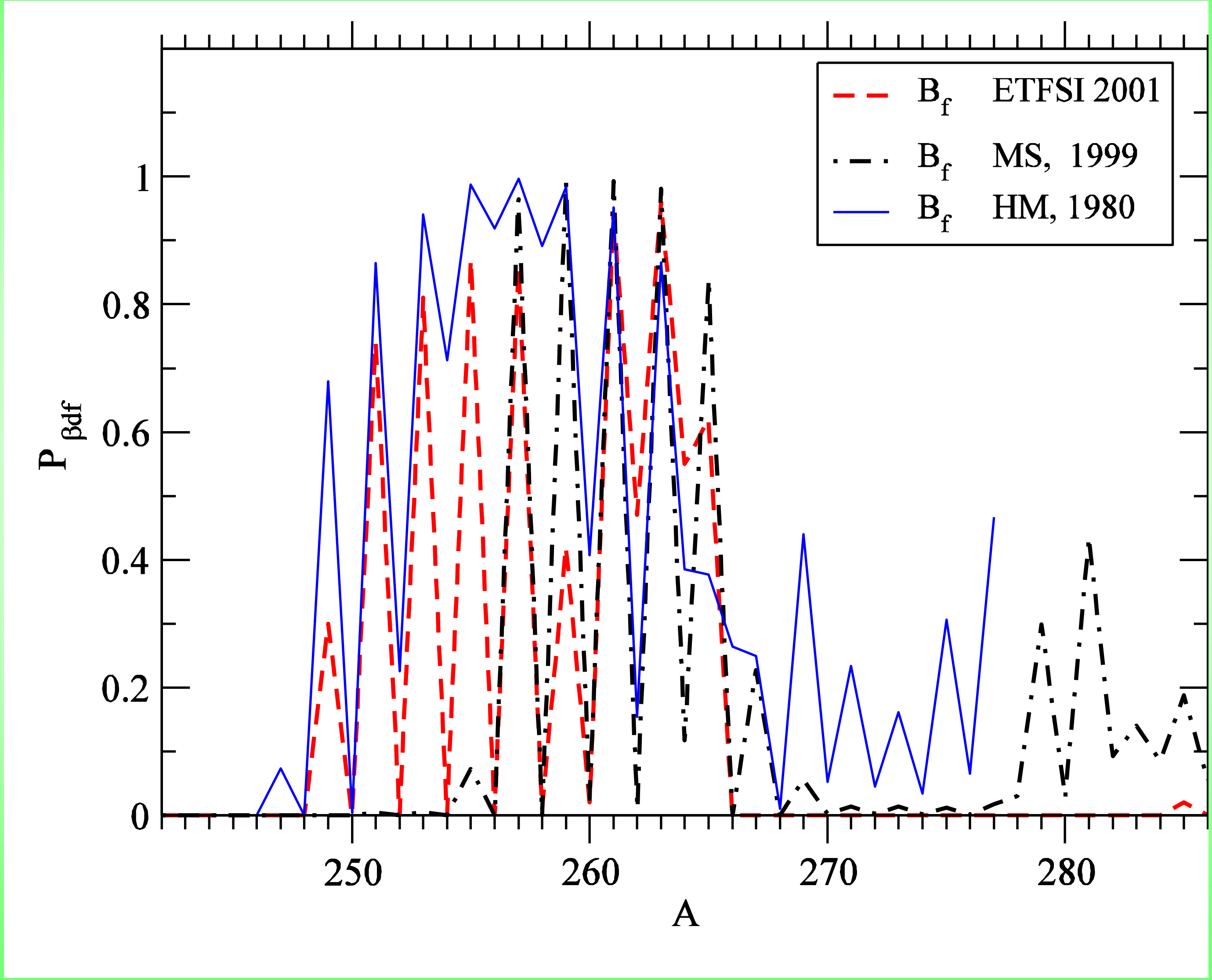


$$\mathrm{Lg}\lambda_{sf} = 33{,}3 \ - 7{,}\ 77 \times B_f^{exp}$$

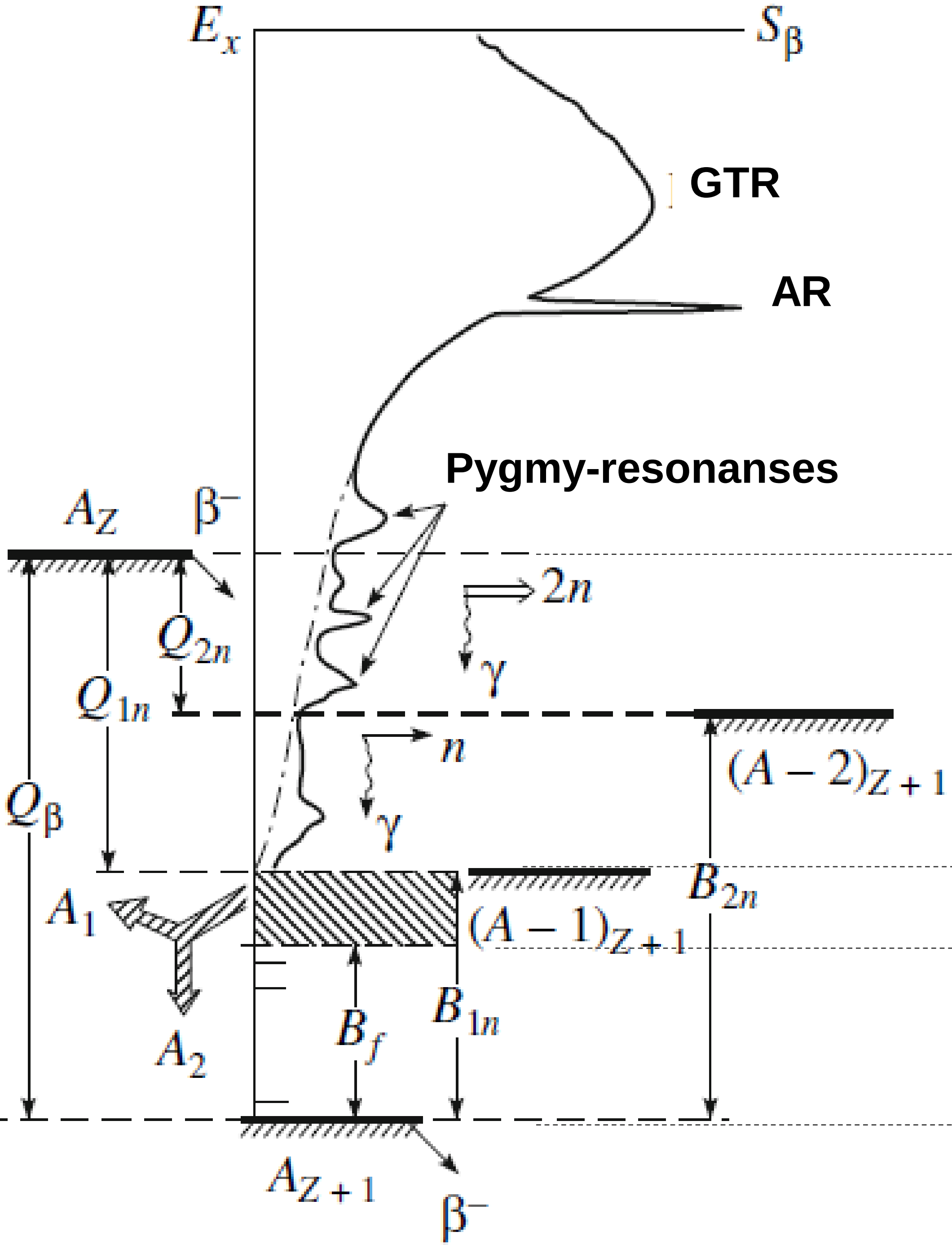
Dependence of Pβdf values on Sβ strenght function



Dependence of $P_{\beta df}$ values on different models ov mass and Bf predictions



Sβ – Krumlinde, Moller 1984



$$\Sigma \left(I_\gamma + I_{\beta df} + I_{dn} \right) = 100\%$$

$$\Sigma I_\beta, \% = I_{(dn+\beta df)}$$

$$\Sigma I_\beta, \% = I_{\beta df}$$

$$\Sigma I_\beta, \% = I_\gamma \sim 10 - 20\%$$

Calculation of Beta-Strength function in TFFS theory (Migdal)

Beta-Strength function $S_\beta(E)$ is formed by isobaric states in the Theory of Finite Fermy Systems (TFFS) calculated solving the nuclear effective field equations of Gamov – Teller type:

$$\left.\begin{array}{l} V_{\lambda\lambda'} = V^{\omega}_{\lambda\lambda'} + \sum\limits_{\lambda_1\lambda_2} \Gamma^{\omega}_{\lambda\lambda'\lambda_1\lambda_2} A_{\lambda_1\lambda_2} V_{\lambda_2\lambda_1} + \sum\limits_{\nu_1\nu_2} \Gamma^{\omega}_{\lambda\lambda'\nu_1\nu_2} A_{\nu_1\nu_2} V_{\nu_2\nu_1}; \\ V_{\nu\nu'} = \sum\limits_{\lambda_1\lambda_2} \Gamma^{\omega}_{\nu\nu'\lambda_1\lambda_2} A_{\lambda_1\lambda_2} V_{\lambda_2\lambda_1} + \sum\limits_{\nu_1\nu_2} \Gamma^{\omega}_{\nu\nu'\nu_1\nu_2} A_{\nu_1\nu_2} V_{\nu_2\nu_1}; \\ V^{\omega} = e_q \sigma\tau^{+}; \quad A^{(p\bar{n})}_{\lambda\lambda'} = \dfrac{n^n_\lambda (1 - n^p_{\lambda'})}{\varepsilon^n_\lambda - \varepsilon^p_{\lambda'} + \omega}; \quad A^{(n\bar{p})}_{\lambda\lambda'} = \dfrac{n^p_\lambda (1 - n^n_{\lambda'})}{\varepsilon^p_\lambda - \varepsilon^n_{\lambda'} - \omega}. \end{array}\right\}$$

In this equations all types of particle-hole quasiparticle excitations are included except of *l* – forbidden type. For the local single quasiparticle (στ) interaction g` constant used, included pion-exchanging mode:

$$g_0{}'_{\text{эф}} = g_0{}' - e_q^2 f_\pi^2 \frac{dn}{d\mu} \chi^{-2} \left(\frac{q^2}{1+q^2} + \frac{4\chi}{\pi m_\pi R} (1+q^2)^{-2} \right)$$

In our low energy case (ΔE_{pn}< 20 MeV) the second pion-depending term is negligible. For the isovector constants f_0 and g_0 selfconsistent procedure was used. Beta-Strength function $S_\beta(E)$ was calculated using matrix elements M_{GT} :

$$S_\beta(E) = \frac{C_N}{2\pi} \sum_i M_i^2(E_i) \frac{\Gamma(E)}{(E_i - E)^2 + \Gamma^2(E)/4}$$

Normalization = Sum-rule: $$\int_0^{E\max} S_\beta(E)\, dE = e_q^2 \cdot 3 \cdot (N - Z).$$

For E_{max} = 20 MeV and e_q = 0.8 quenching value is q = 0.64 (for $E_{max} = \infty$, e_q = 1.0, q = 1.0).

BETA - DELAYED FISSION

$$\frac{1}{g_0'} = \frac{\Delta E}{\Omega} a + \frac{\Delta E + E_{ls}}{\Omega - E_{ls}} b_+ + \frac{\Delta E - E_{ls}}{\Omega + E_{ls}} b_-$$

Gaponov, Lutostansky, 1972

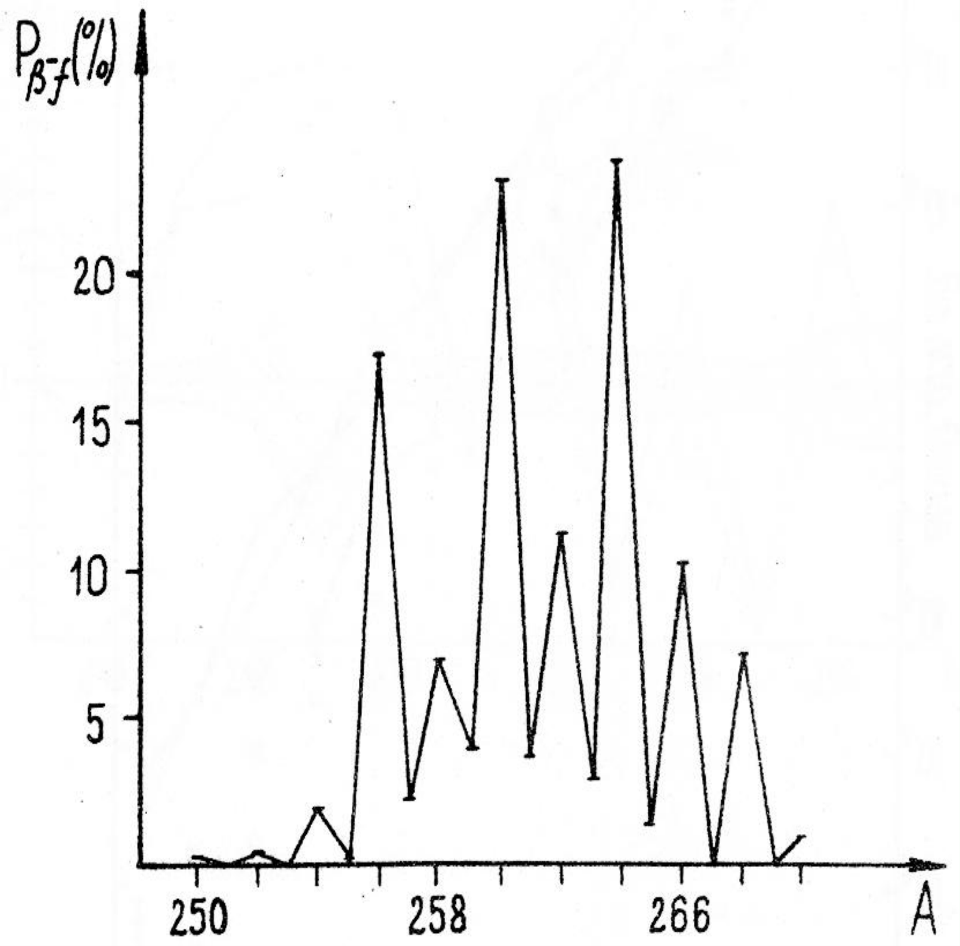
, where $\Omega = \omega - \mu$,

$$a = \sum R_\lambda^2(r)\beta_{\lambda\lambda}\delta_{l_1 l_2}$$

$$b_\pm = \sum R_{\lambda_1\lambda_2}\beta^{(\pm)}_{\lambda_1\lambda_2}\delta_{l_1 l_2}$$

For Bf<E<Sn $\Gamma_f \sim \Gamma_{tot}$.
Otherwise $\Gamma_f \ll \Gamma_{tot}$

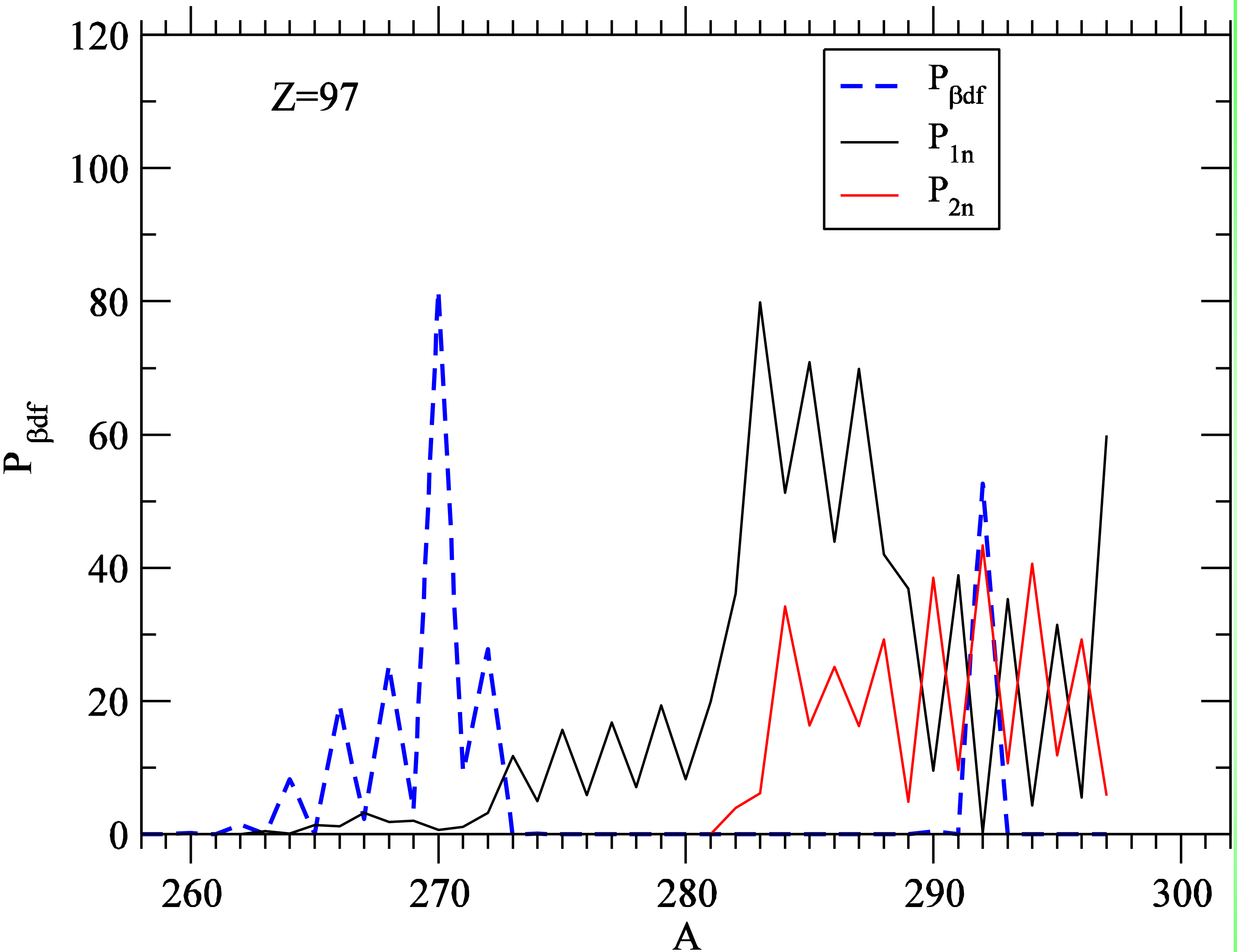
$$P_{\beta f} = \frac{\int_0^{Q_\beta} \sum_i f(Z, Q_\beta - E) S_\beta^i(E) \frac{\Gamma_f}{\Gamma_{tot}} dE}{\int_0^{Q_\beta} \sum_i f(Z, Q_\beta - E) S_\beta^i(E) dE}$$



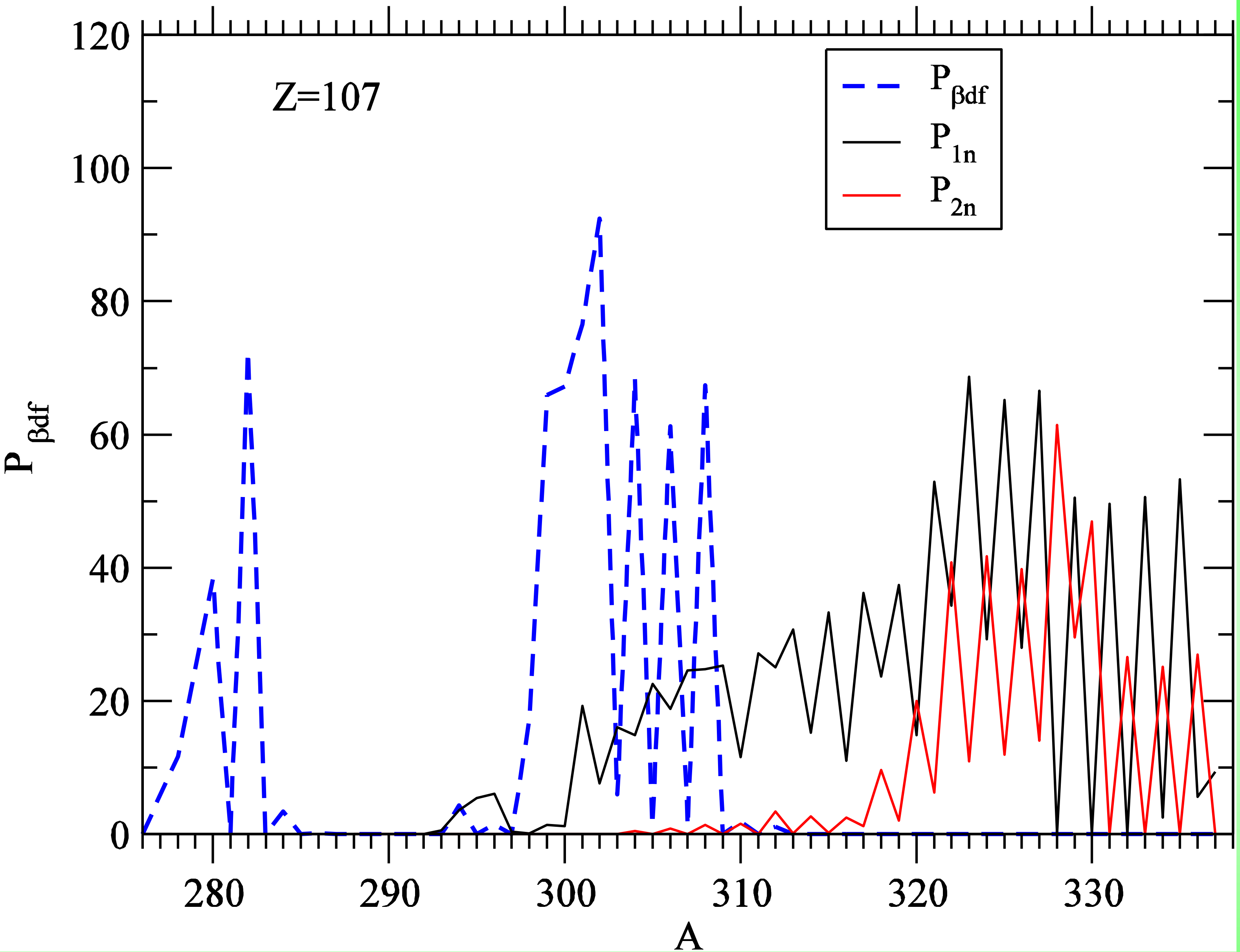
β-decay	A	Qbet	Bf	Sn	Pfis	P1n	P2n
Bk -> Cf	262	5.96	4.00	5.67	1.48	0.00	0.00
Bk -> Cf	263	4.11	4.10	3.26	0.00	0.49	0.00
Bk -> Cf	264	6.22	3.60	5.36	8.28	0.07	0.00
Bk -> Cf	265	4.53	3.60	3.25	0.00	1.39	0.00
Bk -> Cf	266	6.53	3.10	4.79	19.39	1.17	0.00
Bk -> Cf	267	5.08	2.90	3.32	2.26	3.26	0.00
Bk -> Cf	268	7.12	2.50	4.94	25.40	1.83	0.00
Bk -> Cf	269	4.83	2.70	2.99	3.60	2.06	0.00
Bk -> Cf	270	6.58	2.40	5.02	81.71	0.64	0.00
Bk -> Cf	271	5.82	2.70	3.82	9.36	1.08	0.00
Bk -> Cf	272	7.65	2.80	4.85	27.76	3.19	0.00
Bk -> Cf	273	6.46	4.20	3.22	0.00	11.72	0.00
Bk -> Cf	274	8.08	4.20	4.56	0.09	4.99	0.00
Bk -> Cf	275	7.00	5.00	3.08	0.00	15.66	0.00
Bk -> Cf	276	8.32	5.00	4.32	0.00	5.89	0.00
Bk -> Cf	277	7.23	5.30	3.16	0.00	16.83	0.00
Bk -> Cf	278	8.64	5.30	4.33	0.00	7.11	0.01
Bk -> Cf	279	7.63	6.10	3.05	0.00	19.39	0.00
Bk -> Cf	280	8.96	6.10	4.21	0.00	8.28	0.02
Bk -> Cf	281	8.11	7.00	2.94	0.00	19.95	0.00
Bk -> Cf	282	11.01	6.80	3.86	0.00	36.08	3.94
Bk -> Cf	283	9.78	6.50	1.11	0.00	79.90	6.18
Bk -> Cf	284	11.73	5.00	2.69	0.00	51.27	34.24

Bf<Sn

Bf>Sn



First evaluations: Panov,Korneev, Thielemann. *Physics of Atomic Nuclei, 2009*



If <Pbdf > ~ 50% then Ksurvive(from Z=94 to Z=114)~0.000001
If <Pbdf > ~ 25% K ~ 0.003

Conclusions:

- previously used b.d. fission Rates looks overestimated

  In part, in previous predictions ΣPin + Pβdf > 100%

  Experimentally knowen branchings of beta-deay (as well as theor. Predictions) show that average Pdn and Pdf should have less values
- s.f. Rates should be used consistently with other rates,

  based on the same mass and f.b. predictions
- Preliminary TFFS predictions give the consistent data of Pin and Pbdf - Σ Pin + Pβdf <100%
- more accurate calculations of Γ_f and Γ_n should be taken into

  account as well as fission after neutron emission
- For further investigations of the r-process nucleosynthesis Nuclear rates should be calculated for Z>115 and A>300
- The formation of SHE possible but for detailed aswer more accurate fission data are needed

Acknowledgments to
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Basel University (Thielemann group)
GSI (Martinez-Pinedo group)
RSC Kurchatov Institut (Lyutostansky et al.)

Thank you for the attention!

- **If <Pbdf > ~ 75%**

then surviving factor K (after beta-decays from Z=94 to=114)

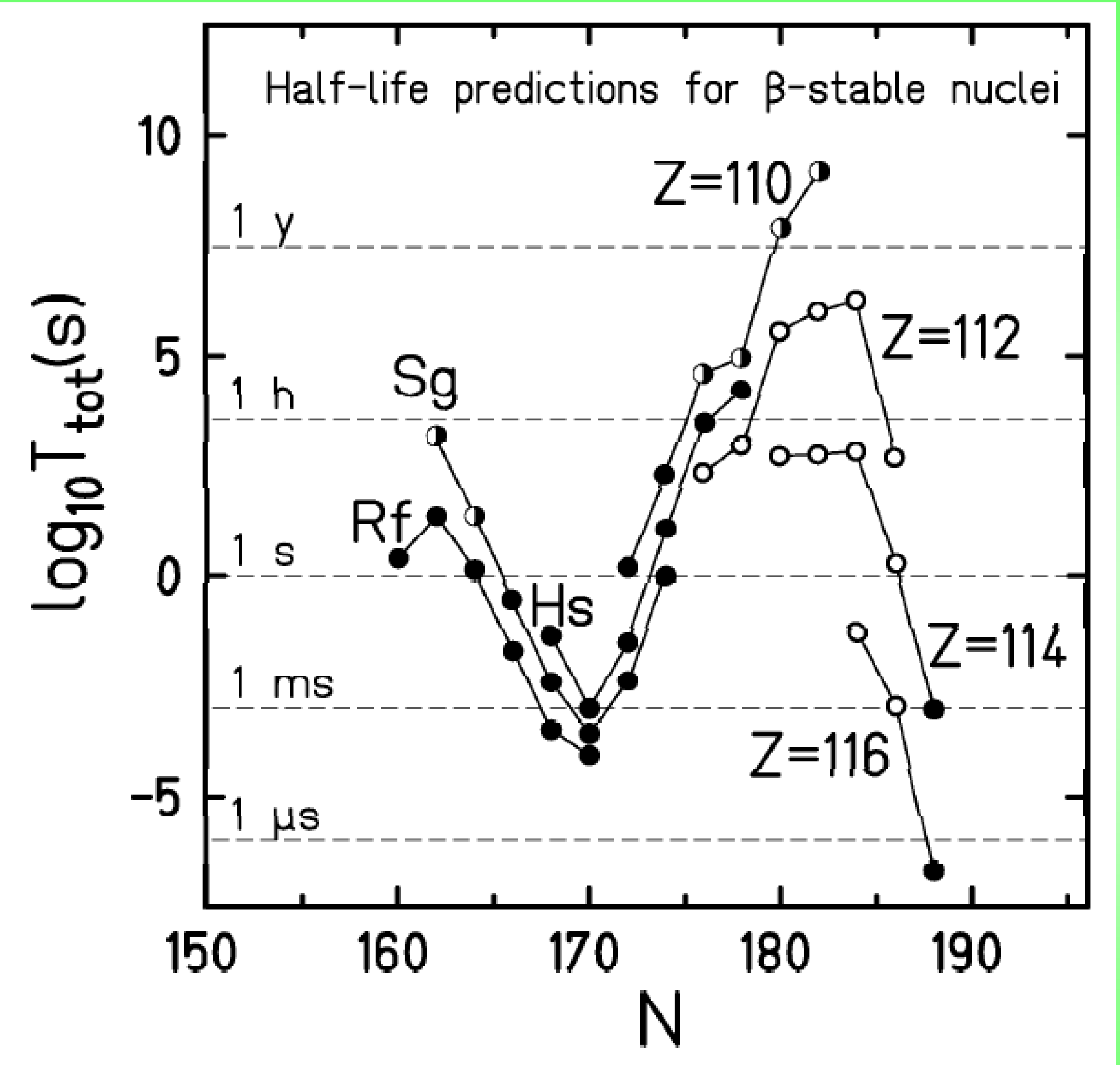
$K \sim 10^{-12}$

- **If <Pbdf > ~ 50%**

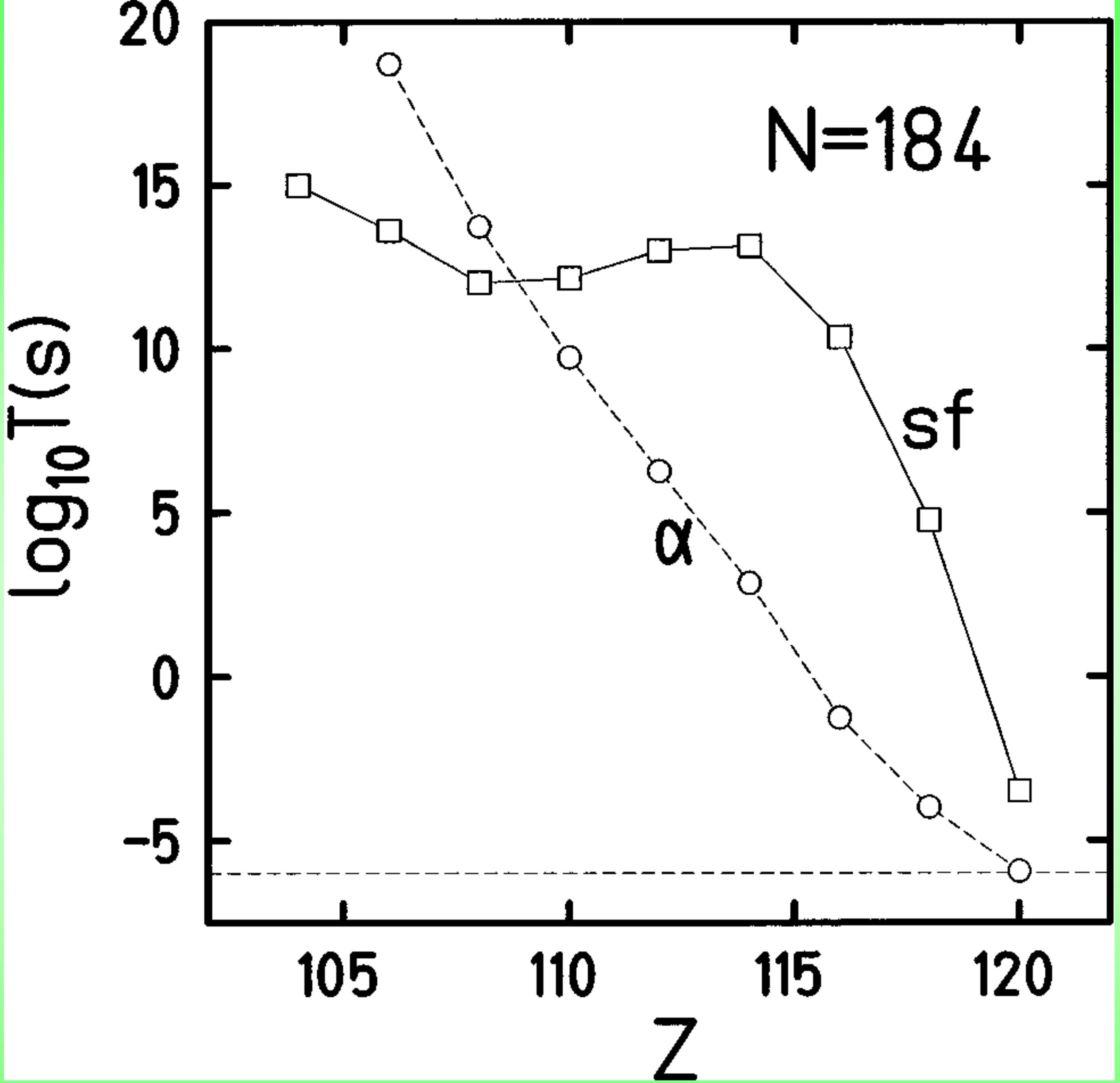
then K ~0.000001

- **If <Pbdf > ~ 25%**

K ~ 0.003



R. Smolan czuk **Acta Polonica 1999**



Smolan czuk, PHYSICAL REVIEW C VOLUME 56, 812 (1997)

model-independent evaluations of λ_{sf}

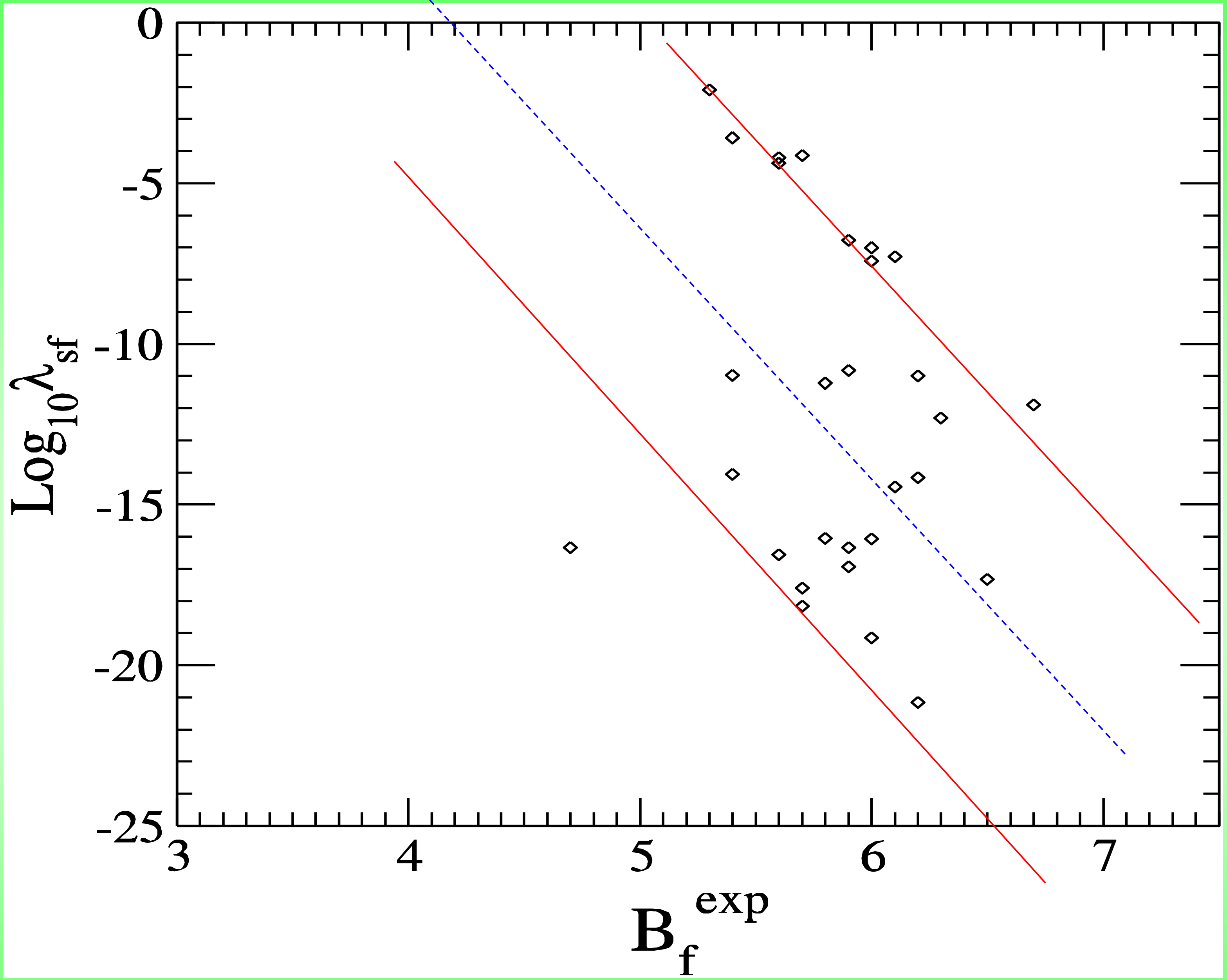
- Based on predicted Bf (G.Martinec-Pinedo):

MS: $Lg\lambda_{sf} = 23.887 - 8.0824 \times B_f$

ETFSI: $Lg\lambda_{sf} = 50.127 - 10.145 \times B_f$

- Based on experimental values of B_f

$$Lg\lambda_{sf} = 33,3 - 7,77 \times B_f^{exp}$$



$$Lg\lambda_{sf} = 33,3 - 7,77 \times B^{exp}_f$$

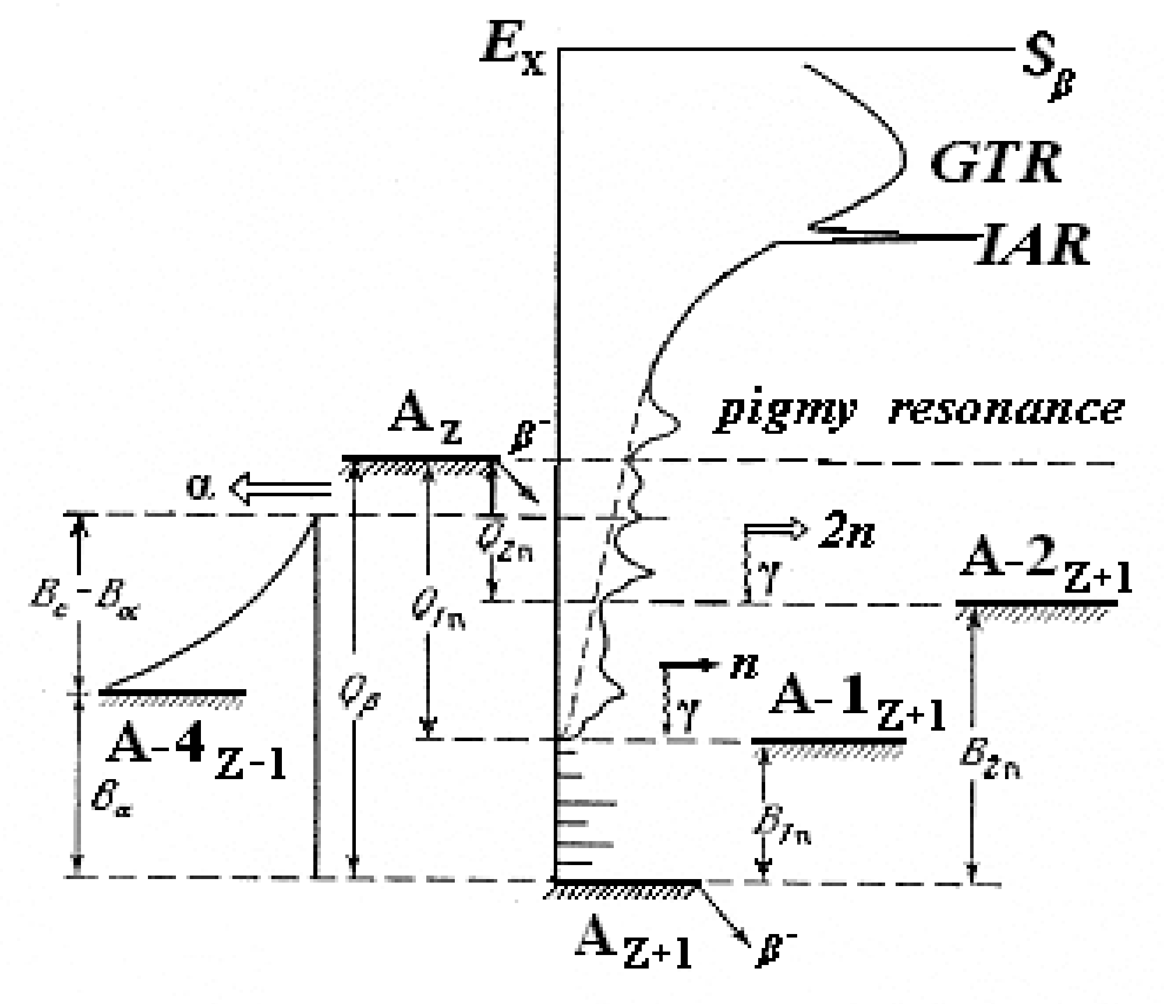
Importance of fission for the r-process

- Seeger, Fowler, Clayton, 1965 fission - long and short solutions
- Thielemann, Metzinger, Klapdor, Zt.Phys., A309 (1983) 301. $P_{\beta df}$
- Lyutostansky, Panov, Ljashuk Izv RAN, ser, fiz. 1990 $P_{\beta df}$
- **P.Moller, J.R.Nix, K.-L.Kratz.** ADNDT, 66 (1997) 131 $T_{1/2}$, P_{in}
- Goriely et al. Astron. Astrophys. 346, 798–804 (1999) s.f.
- Rauscher & Thielemann ADNDT 2000, (n,γ), (n,X) for Z<84
- Panov et al., Nucl. Phys. A, 718 (2003) 647. (n,fission) vs $P_{\beta df}$
- I.Korneev et al. NIC-2006; Astronomy Letters, 66 (2008) 131 $Y_{ff}(Z,A)$
- Kelic, et al., Phys. Lett. B. 616 (2005) 48 $Y_{ff}(Z,A)$
- I.V. Panov, E. Kolbe, F.-K. Thielemann, T. Rauscher, B. Pfeiffer, K.-L. Kratz. NP A 747 (2005) 633 (n,fission) (n,γ) $P_{\beta df}$
- G.Martinec-Pinedo et al, PPNP, 59 (2007) (n,fission) vs $P_{\beta df}$
- Y.-Z. Qian, AJ. 569 (2002); Kolbe, Langanke, Fuller. P.R. Lett. 2004 ν–induced fission
- I. Petermann et. al. NIC-2008; G.Martinec-Pinedo et al, Progr. in Particle and Nucl. Phys., 59 (2007) 199-205: (n,fission), $P_{\beta df}$, s.f., ν–induced f.
- K. Langanke, G. Martinez-Pinedo, I.Petermann, F.K. Thielemann, PPNP 2011 (n,fission) , $P_{\beta df}$, s.f., ν–induced f.
- I.V. Panov, E. Kolbe, F.-K. Thielemann et al 2010 AA (n,γ) ,(n,f) for Z>84

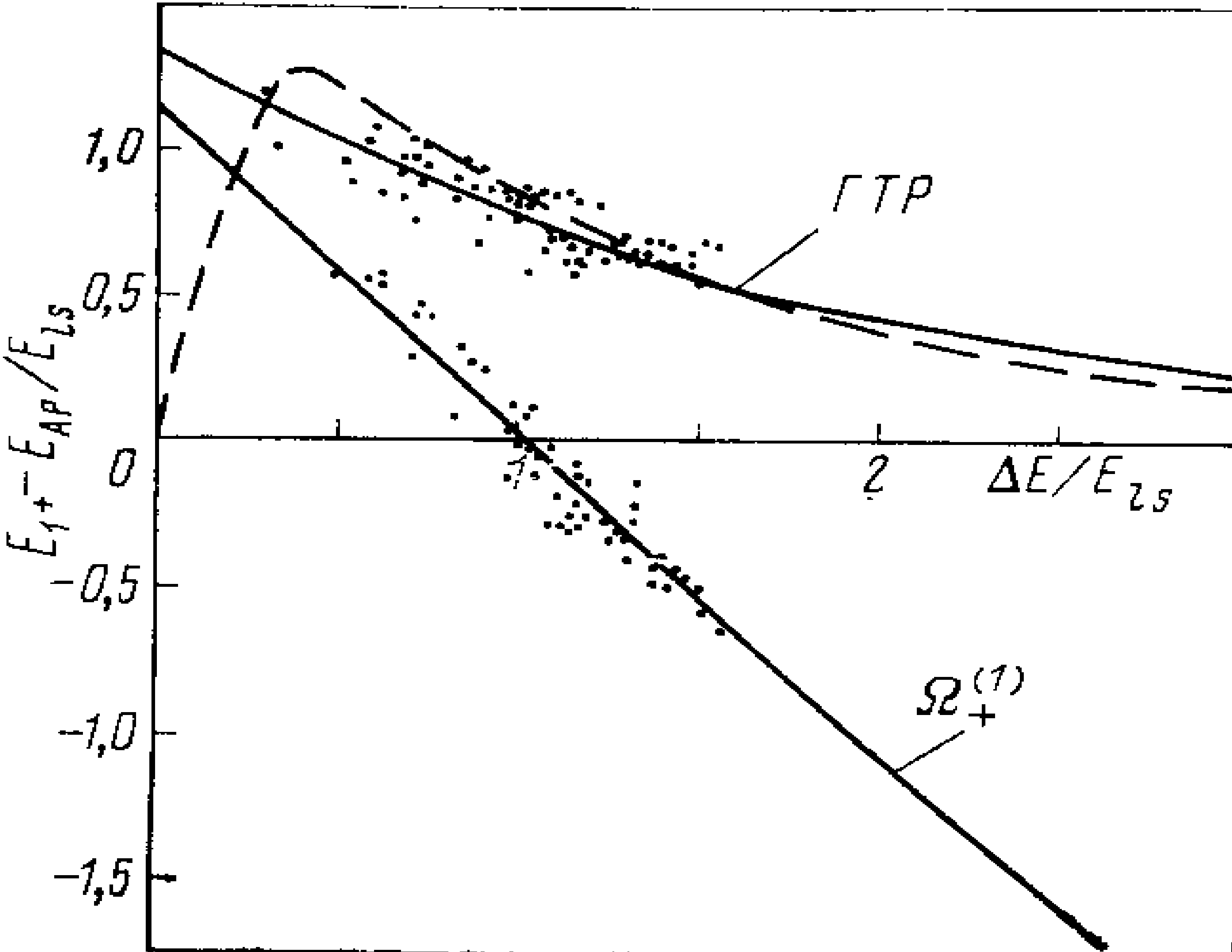
BETA - STRENGTH FUNCTION OF NEUTRON-RICH NUCLEI

In calculation of weak process connected with β-decay, ν-absorption, β-delayed processes the Beta-Strength function $S_\beta(E)$ plays the main role. $S_\beta(E)$ - function for neutron-rich nuclei presented on Fig.1.

$S_\beta(E)$– function has a resonance character with high lying Gamow-Teller (GTR) and Isobaric Analog (IAR) resonanses. Lower by energy are situated the so-called "pigmy resonanses". The GTR with low going "tail" influence strongly on the average neutrino- absorption cross-section and on the charge-exchange reactions probabilities. "Pigmy resonanses" plays the main role in the $T_{1/2}$ values, β-delayed neutron emission, β-delayed fission and in neutron emission after neutrino-absorption process.



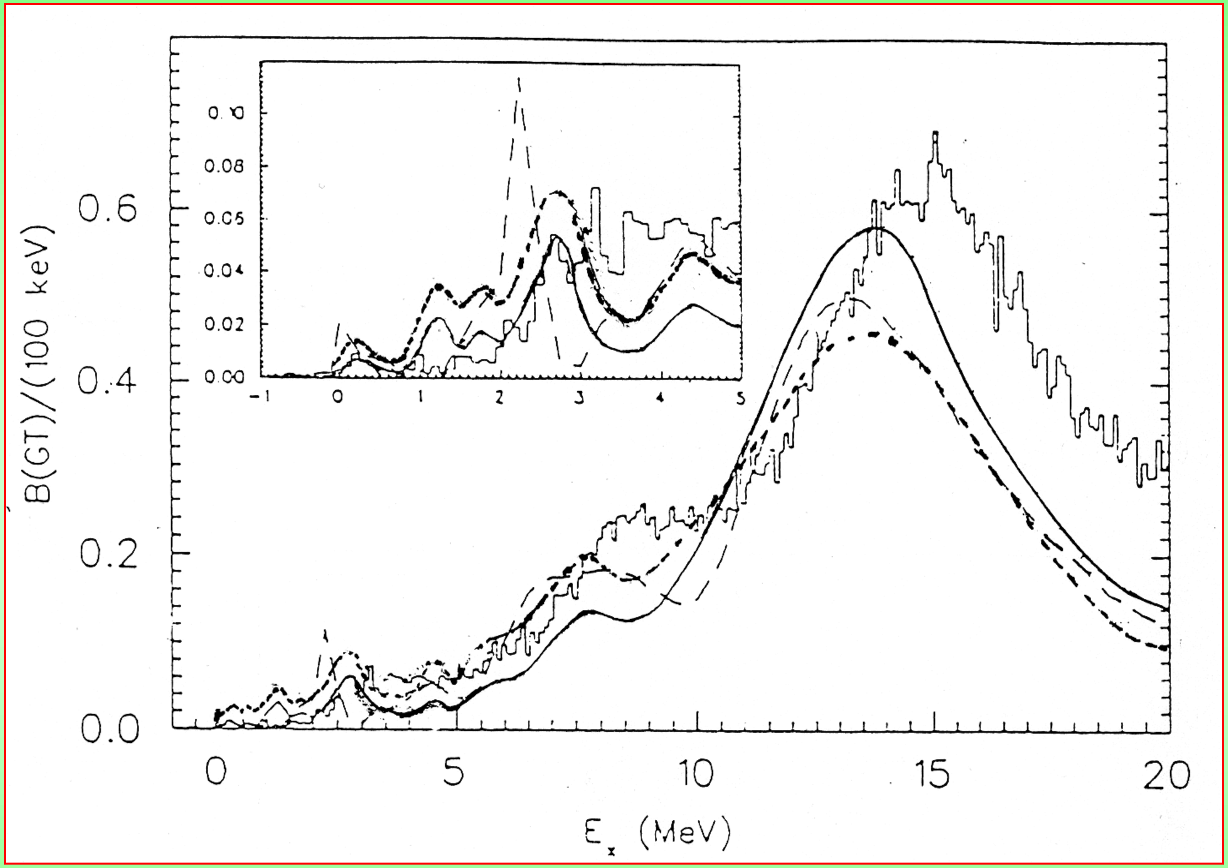
Schema of $S_\beta(E)$ – for function for neutron-rich nuclei and β-delayed processes.



1,0
0,5
0
−0,5
−1,0
−1,5
$E_{1^+} - E_{AP} / E_{ls}$
1
2
$\Delta E / E_{ls}$
ГТР
$\Omega_{+}^{(1)}$

^{127}Xe Beta-Strength function.

The comparison of measured and predicted $S_{\beta}(E)$ – function for ^{127}Xe



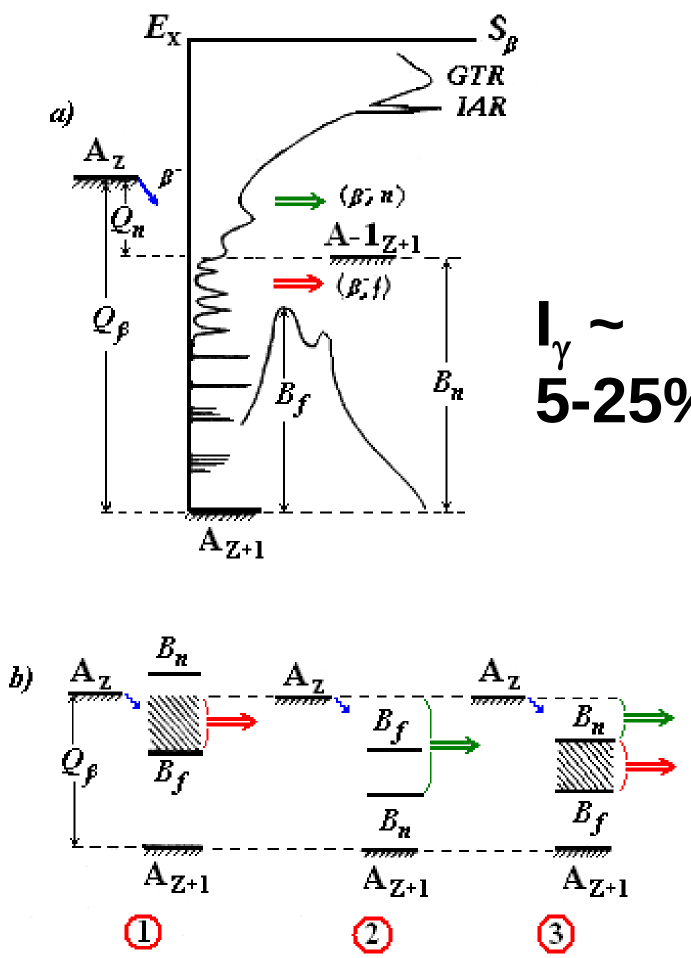
Breaking line – experimental data (1999). Solid line – TFFS calculations by Lutostansky and Shulgina (Phis. Rev. Lett. 1991). GTR and low-lying “pigmy” resonanses are well distinguished.

The experimental qwenching is *q* = 0.54, theoretical: *q* = 0.64.

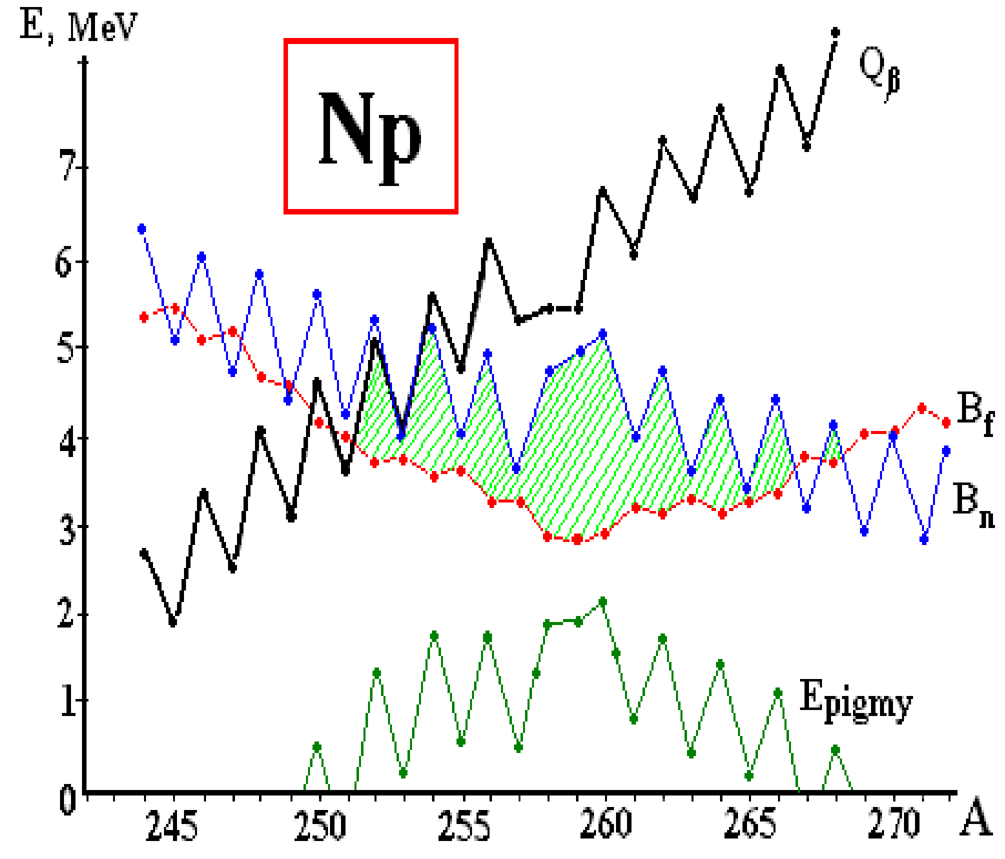
U -> Np Beta – Delayed Fission Probabilities
TFFS-calculations (beta-model)

For dashed regions, Bf<E<Sn

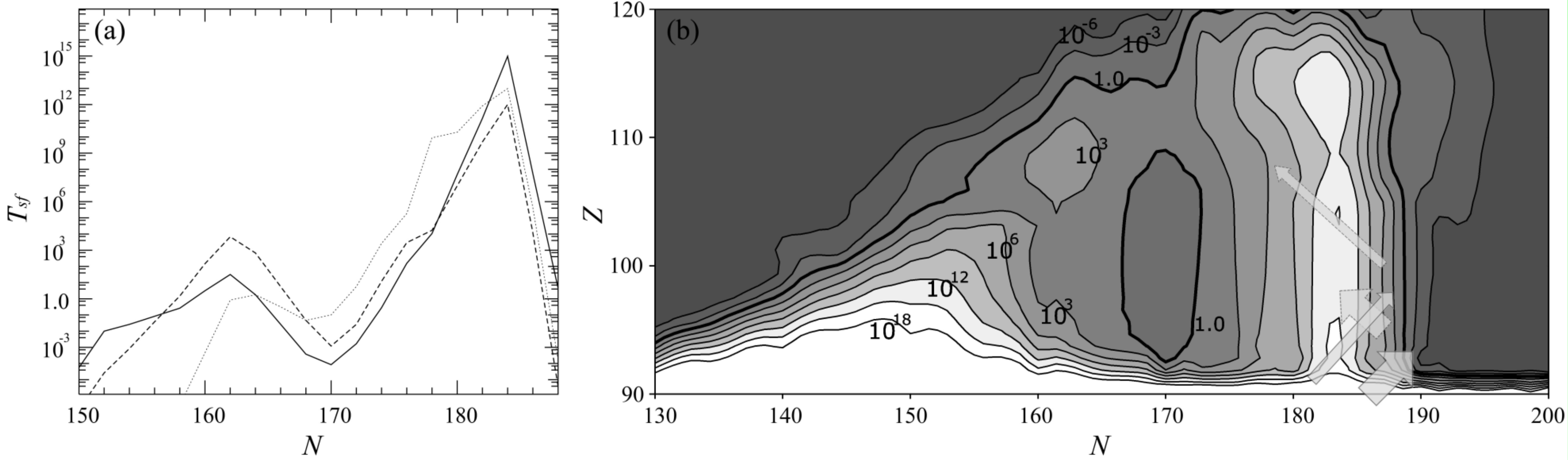
$\Gamma_f \sim \Gamma_{tot}$. **Otherwise** $\Gamma_f \ll \Gamma_{tot}$



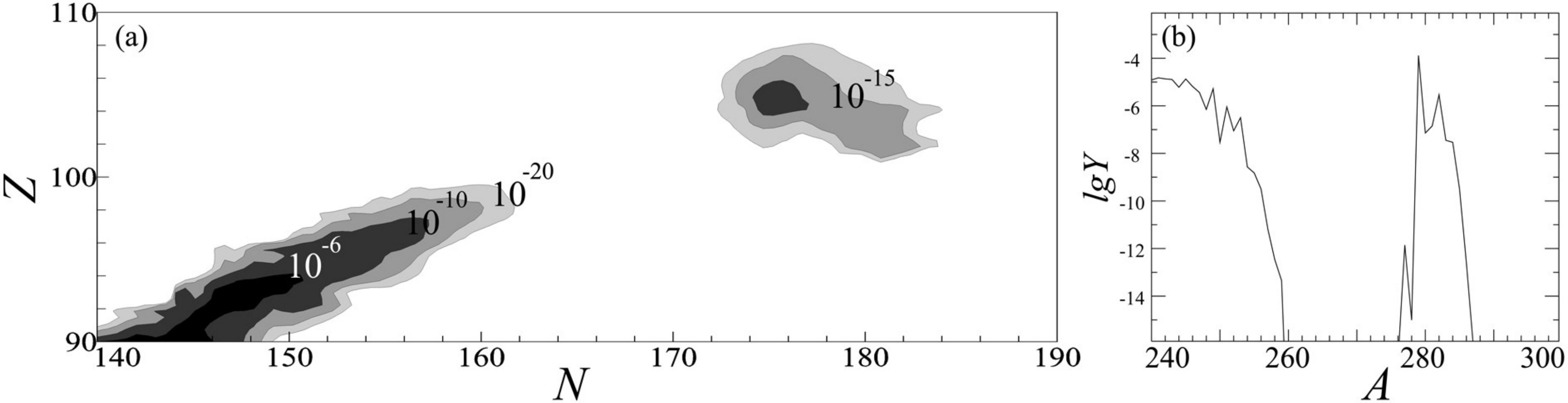
I_γ ~ 5-25%

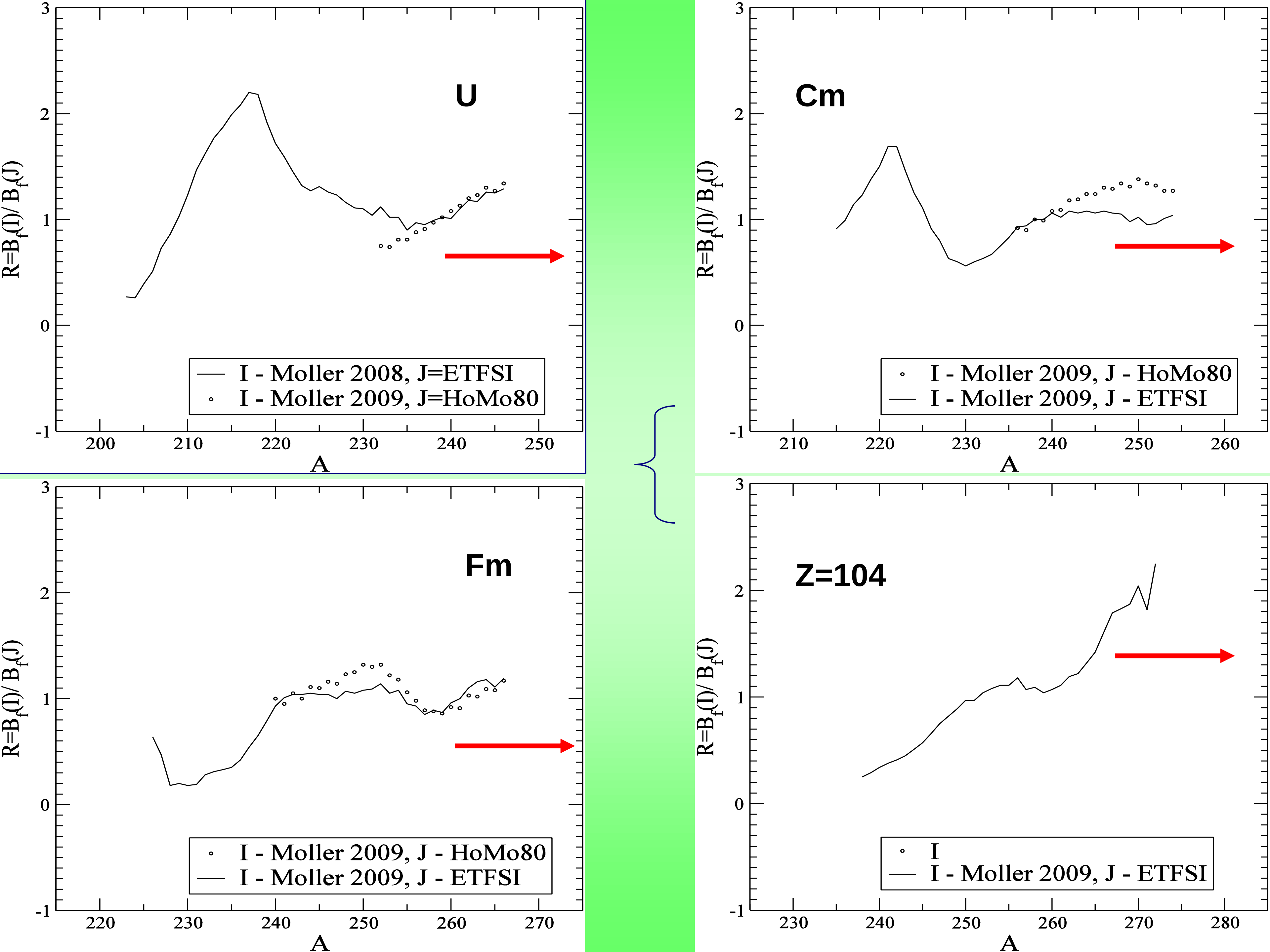


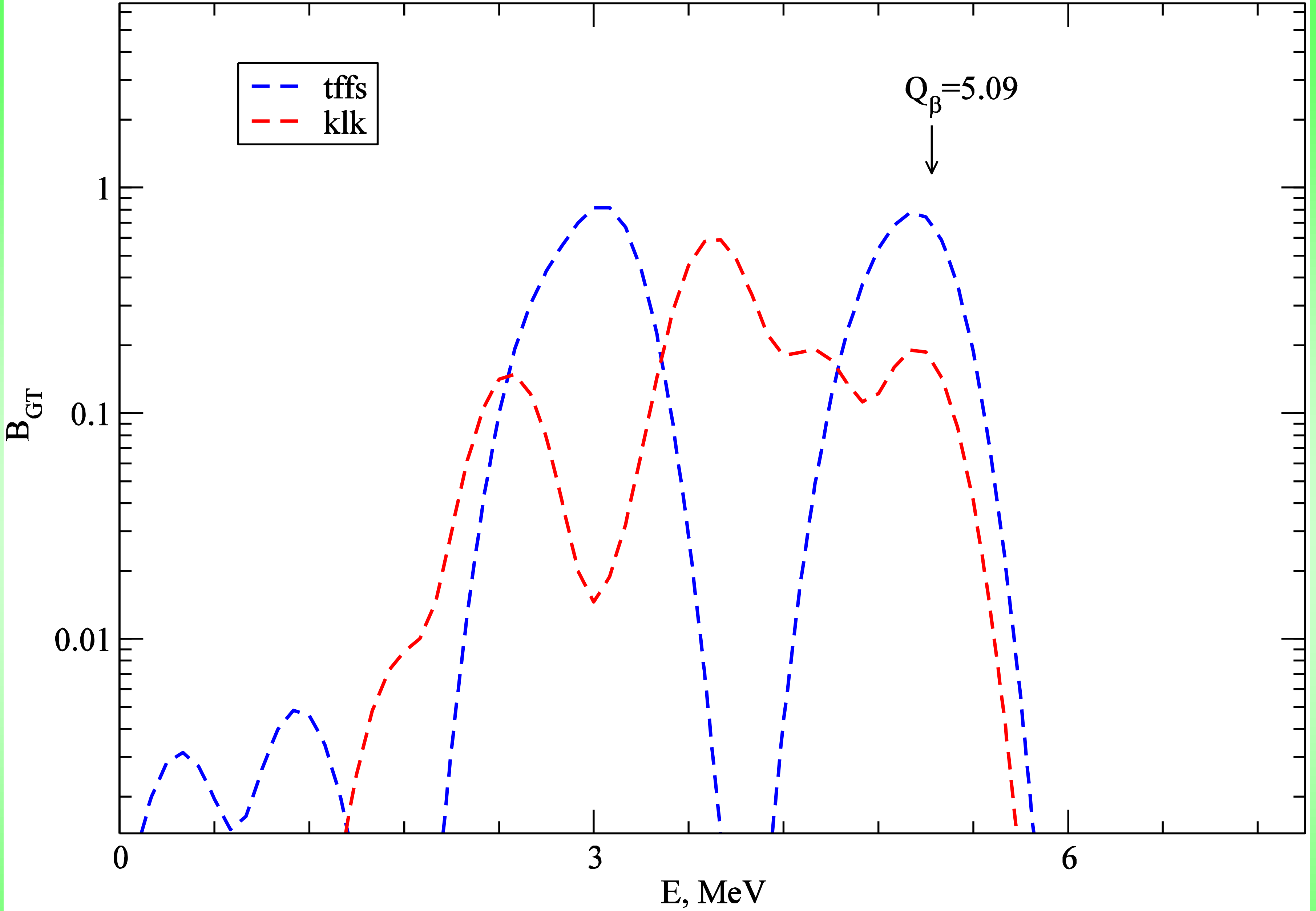
$\Sigma (I_\gamma + I_{\beta df} + I_{dn}) = 100\%$



Tsf based jn macro-micro approach by Smolan czuk, Sobiczewski et al.
Other rates were based on ETFSI

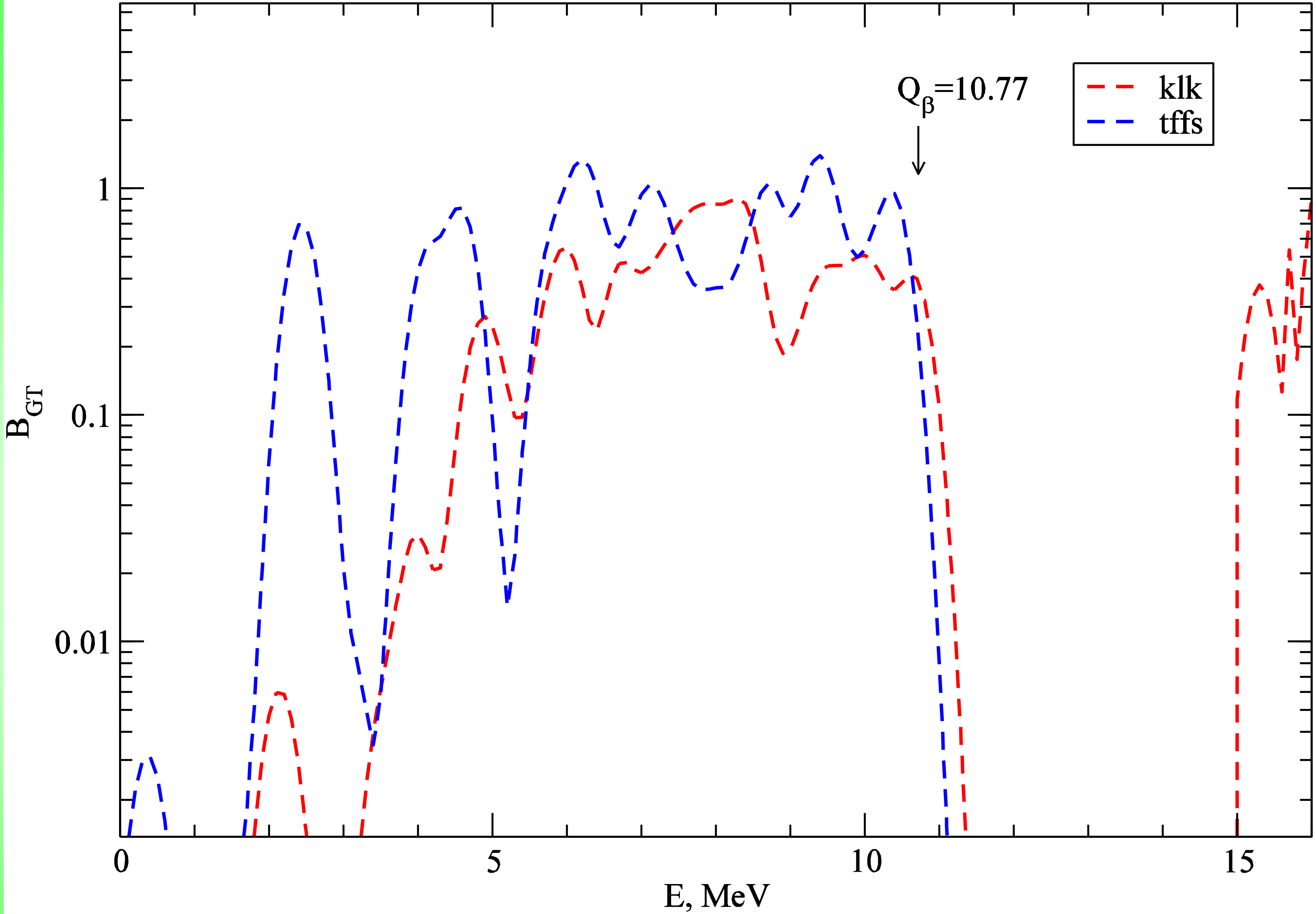



U
I - Moller 2008, J=ETFSI
I - Moller 2009, J=HoMo80
Cm
I - Moller 2009, J - HoMo80
I - Moller 2009, J - ETFSI
Fm
I - Moller 2009, J - HoMo80
I - Moller 2009, J - ETFSI
Z=104
I
I - Moller 2009, J - ETFSI
R=B_f(I)/ B_f(J)
A



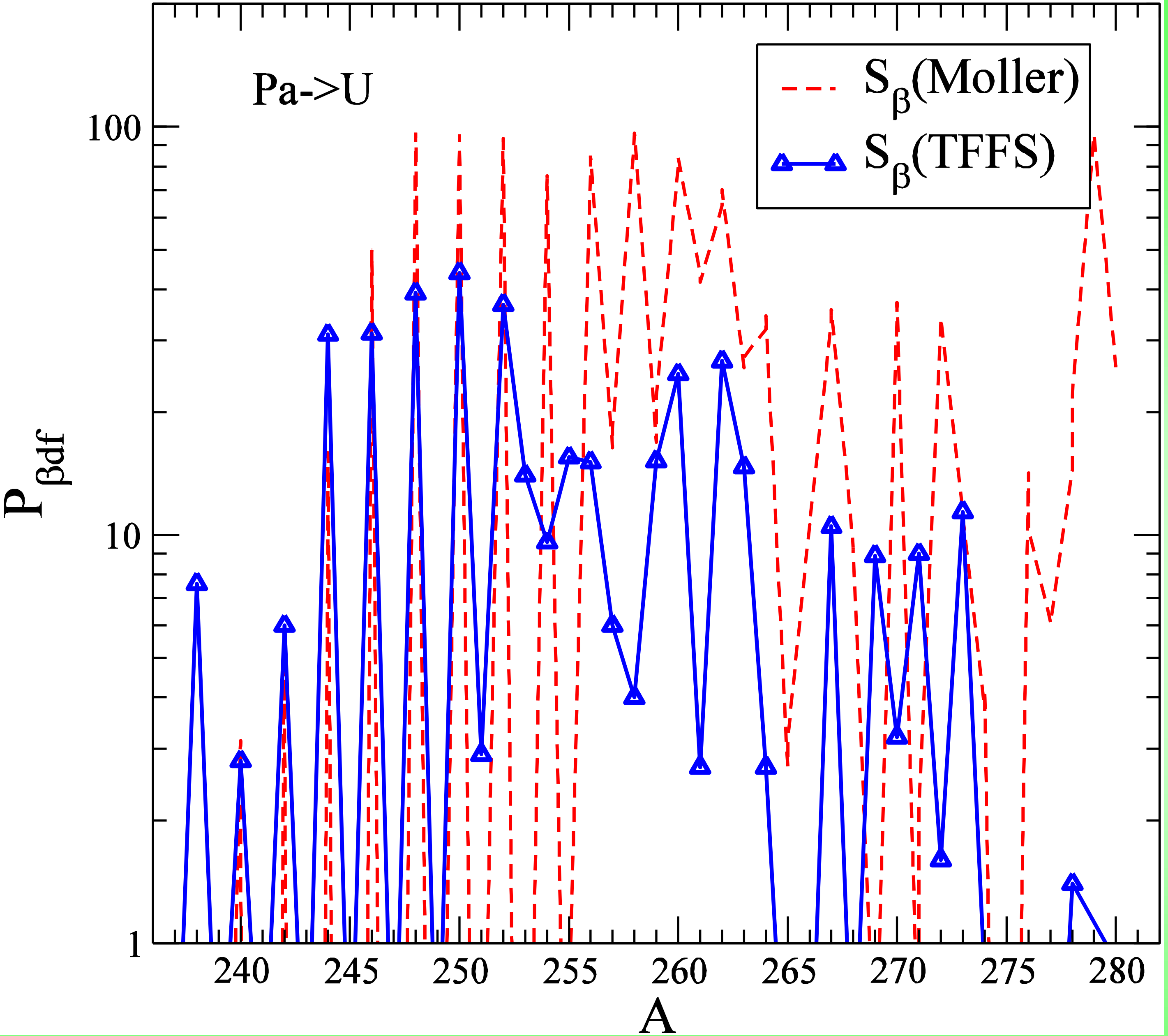
Pa240 -> U240

dB∓(GT,E) /($D(g^2_V/g^2_A)dE$) , [Mev -1, s -1]

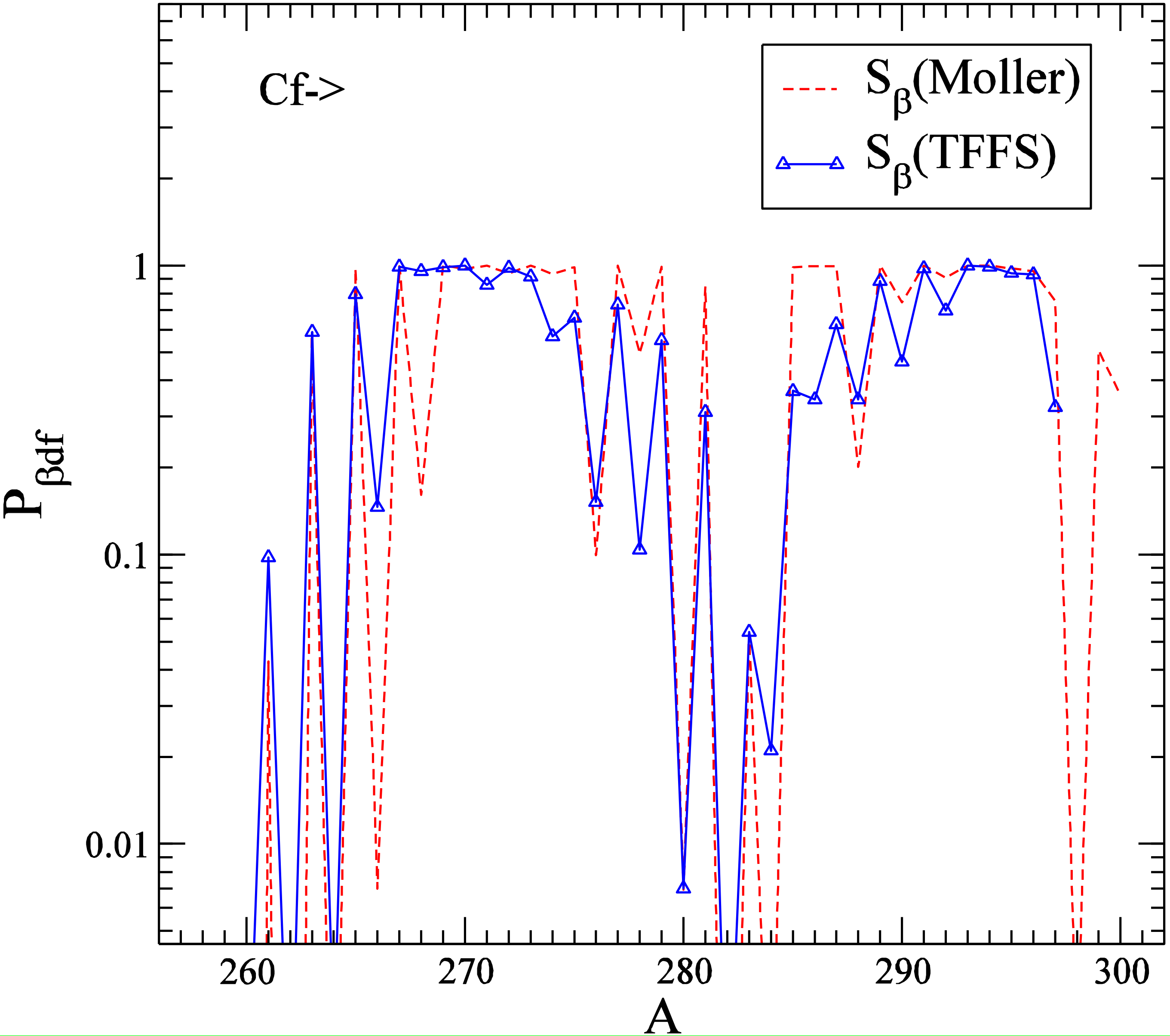


Pa260 -> U260

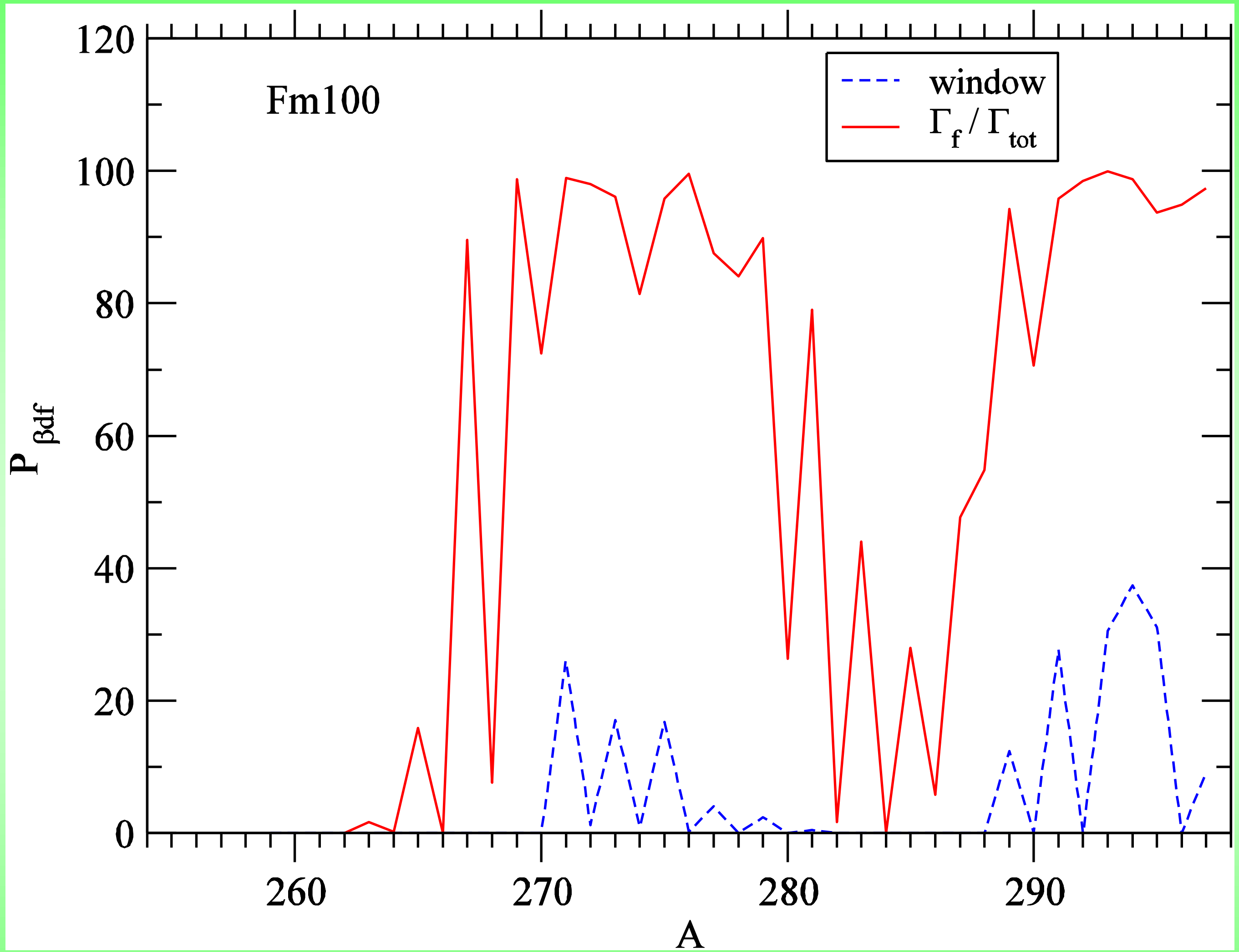
N	A	Ω_p^π	Ω_n^π	Δ_{LN_p} (MeV)	Δ_{LN_n} (MeV)	E_{bind} (MeV)	S_{1n} (MeV)	S_{2n} (MeV)	P_A (%)	P_{A-1} (%)	P_{A-2} (%)	Q_β (MeV)
$Z = 100$ (Fm)												
179	279		$1/2^+$	1.13	0.57	2006.16	2.74	7.04	48.61	51.39	0.00	5.51
180	280			1.13	0.56	2010.23	4.08	6.82	0.17	99.83	0.00	4.46
181	281		$3/2^+$	1.15	0.55	2012.94	2.70	6.78	5.71	94.29	0.00	5.84
182	282			1.12	0.53	2016.60	3.67	6.37	0.59	99.41	0.00	5.16
183	283		$3/2$	1.12	0.58	2019.02	2.42	6.09	0.92	99.08	0.00	6.41
184	284			1.11	0.62	2022.40	3.38	5.80	4.33	95.67	0.00	5.77
185	285		$1/2$	1.05	0.63	2024.10	1.69	5.08	76.30	0.05	23.66	7.51
186	286			1.15	0.67	2026.67	2.57	4.26	14.65	0.05	85.31	6.31
187	287		$3/2$	1.00	0.64	2028.93	2.26	4.83	95.67	0.08	4.25	7.94
188	288			0.85	0.70	2032.19	3.26	5.53	11.22	88.77	0.01	6.71
189	289		$5/2^+$	0.85	0.69	2034.26	2.07	5.33	5.98	70.69	23.33	7.92
190	290			0.85	0.69	2037.71	3.45	5.52	17.41	82.47	0.11	6.84
191	291		$1/2^+$	0.85	0.68	2039.62	1.91	5.36	6.72	77.60	15.68	8.41
192	292			0.85	0.67	2042.82	3.20	5.12	9.15	90.60	0.25	7.44
193	293		$7/2^+$	0.85	0.67	2044.57	1.75	4.96	1.96	56.45	41.59	8.91
194	294			0.85	0.67	2047.61	3.03	4.79	4.24	95.15	0.61	7.93
195	295		$1/2^-$	0.85	0.67	2049.19	1.58	4.61	16.95	31.00	52.03	9.40
196	296			0.84	0.66	2052.05	2.86	4.44	3.75	79.12	17.10	8.43
197	297		$5/2^-$	0.84	0.65	2053.58	1.53	4.40	7.94	24.07	67.65	9.77
198	298			0.84	0.64	2056.30	2.71	4.25	1.13	61.79	36.66	8.89
199	299		$7/2^-$	0.84	0.63	2057.75	1.45	4.17	3.50	26.02	69.91	10.23
200	300			0.84	0.62	2060.44	2.69	4.14	1.38	45.27	52.73	9.29
201	301		$9/2^+$	0.84	0.61	2061.67	1.24	3.93	1.44	13.27	84.27	10.74
202	302			0.84	0.60	2064.03	2.35	3.59	1.75	28.39	68.26	9.97
203	303		$5/2^+$	0.83	0.60	2065.16	1.14	3.49	2.36	5.58	77.07	11.23
204	304			0.83	0.60	2067.27	2.11	3.25	2.02	14.65	42.97	10.44
205	305		$11/2^+$	0.83	0.61	2067.78	0.50	2.62	2.14	0.20	26.44	12.04
206	306			0.84	0.61	2069.89	2.11	2.62	1.73	5.44	19.23	10.74

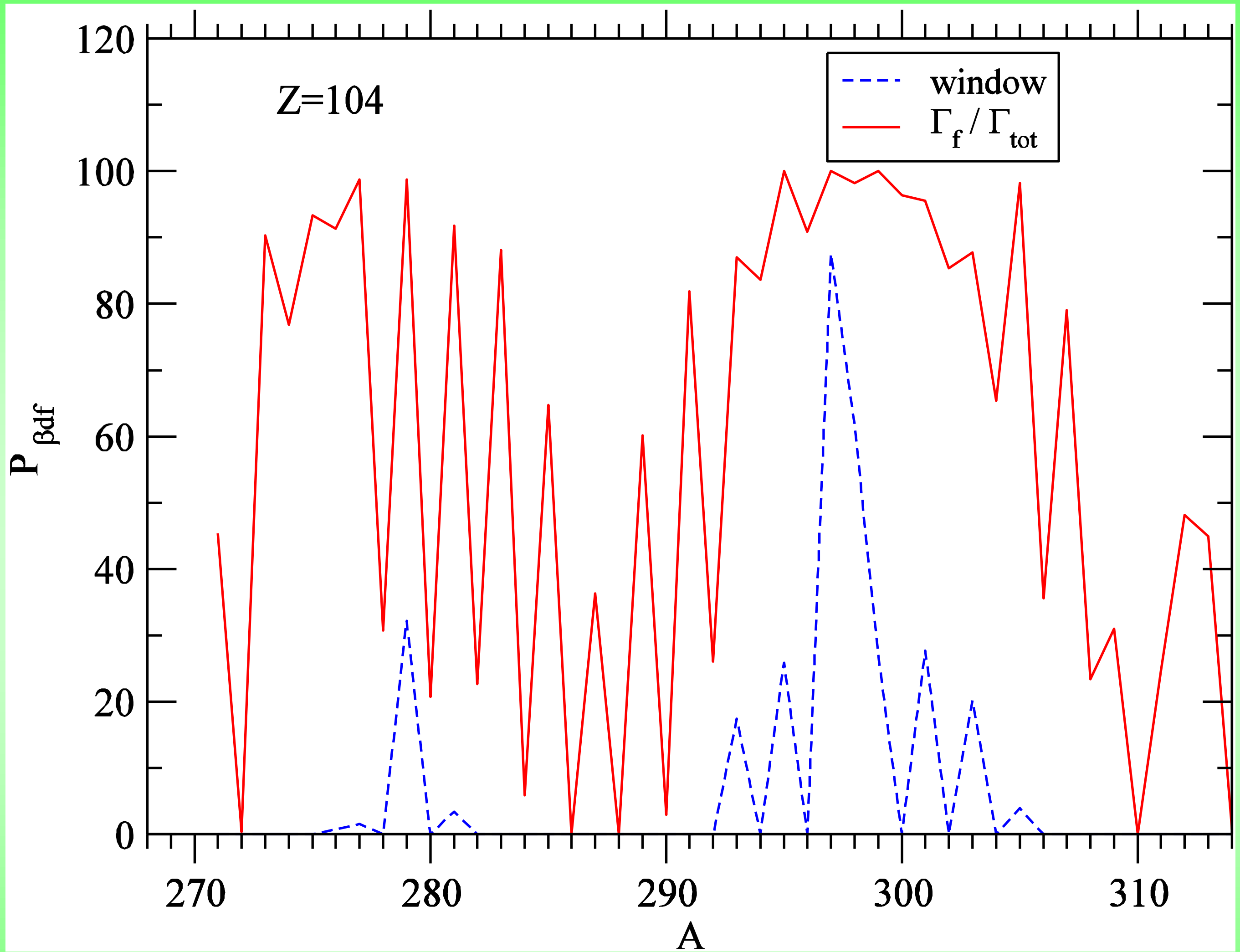


Compettition between n- emission and βd-fission – Hauser-Feshbach



Cf->
S$_\beta$(Moller)
S$_\beta$(TFFS)
1
0.1
0.01
$P_{\beta df}$
260
270
280
290
300
A


Fm100
window
Γ_f / Γ_{tot}
$P_{\beta df}$
A
0
20
40
60
80
100
120
260
270
280
290


Z=104
window
Γ_f / Γ_{tot}
$P_{\beta df}$
A
0
20
40
60
80
100
120
270
280
290
300
310