r-process Nucleosynthesis including fission

-Importance of realistic nuclear data-

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Numazu Workshop 2009

クォークカ学･原子核構造に基づく爆発的天体現象と元素合成

科研費･新学術領域「素核宇宙融合」A03宇宙班

Plan

- r過程元素合成の計算には、いかに多様な（雑多な？）核データが必要か
  - EOSを除く
- で、それを全部そろえるのがいかに大変か
- 可能な限り多くのデータを国産にしたい
- 核反応率を知るためには、核構造が重要なのは確か（なのでこの科研費のタイトルは正しい）
- 現実的に、時間のかかる微視的原子核計算を利用するにはどうしたらいいかを考えたい

Collaborators

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T. Wada (Kansai University)

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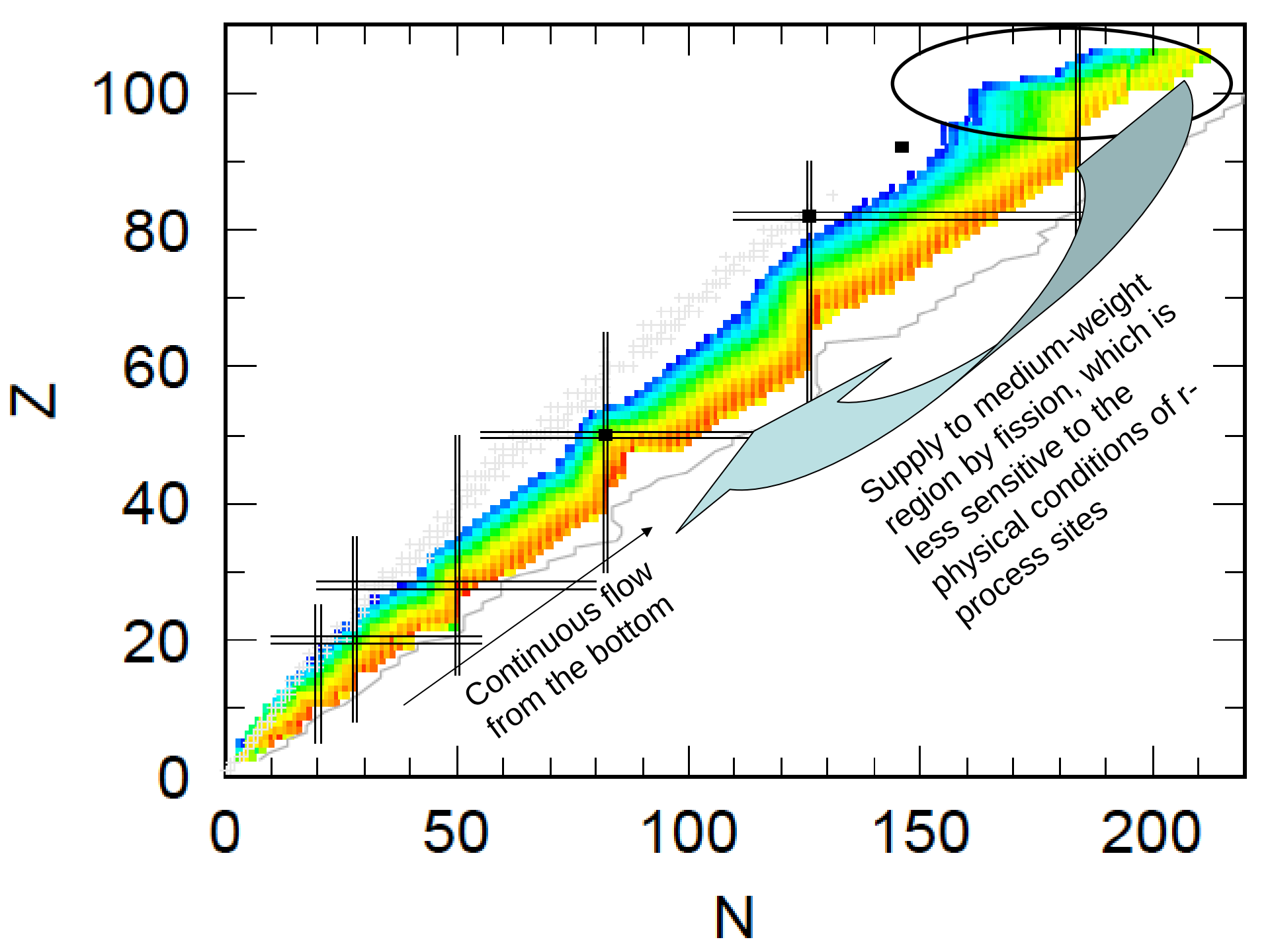
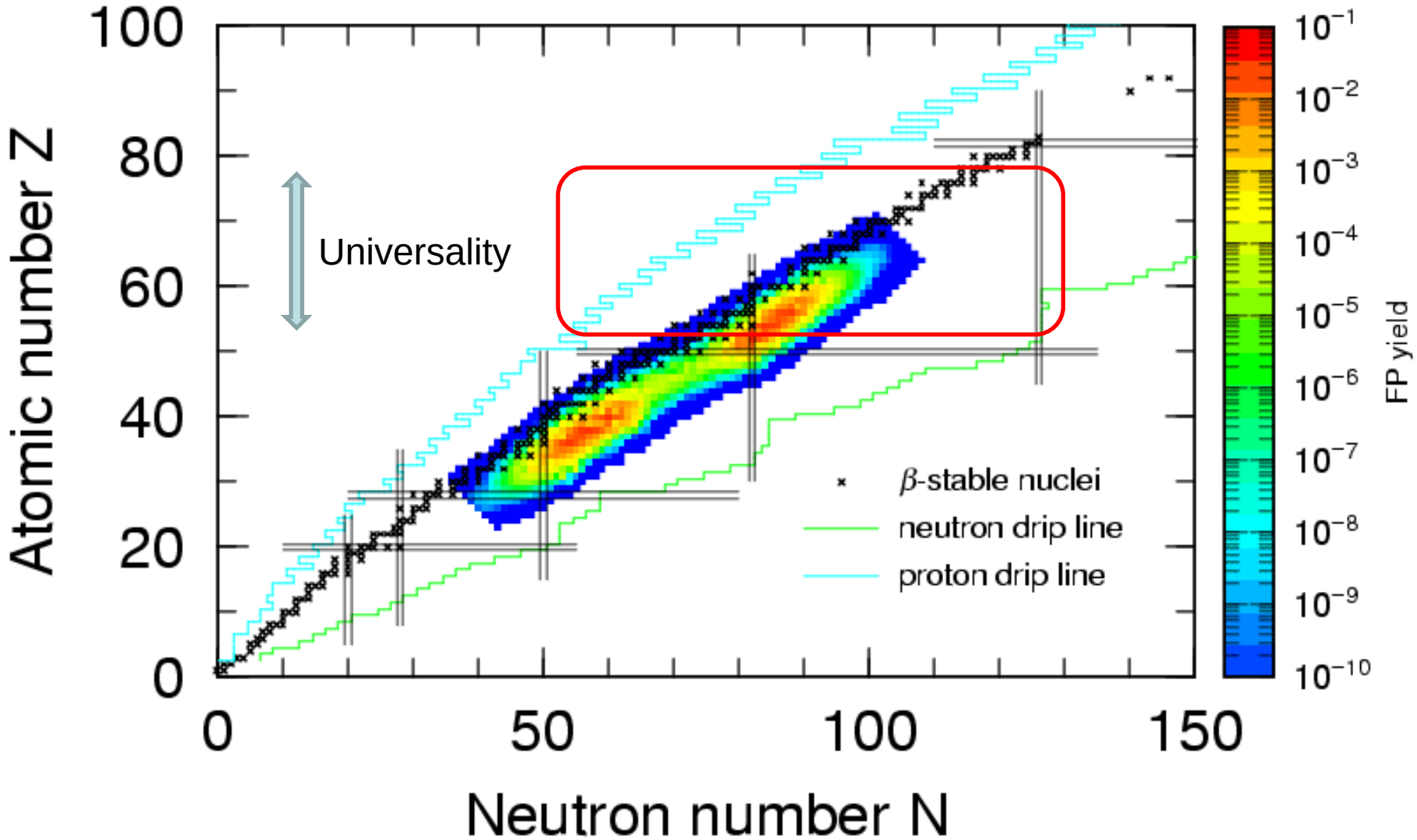
T. Yoshida, T. Kajino (NAO)

Fission (cycling) in r-process nucleosynthesis

- Discovery of Th and U in metal poor stars
- Realistic calculation of r-process nucleosynthesis
  - Is there a termination point? Where is that?
  - Possibility of SHE generation and discovery of its relics in meteorites
  - Impacts on universality ($56 \leqq Z \leqq 75$)
    - enhanced abundance of Mo, Ru, Rh...
    - abundance ratio between different Z regions
  - Impacts on nucleo-cosmochronometers
    - Th/Eu, U/Th, Th/Os,....

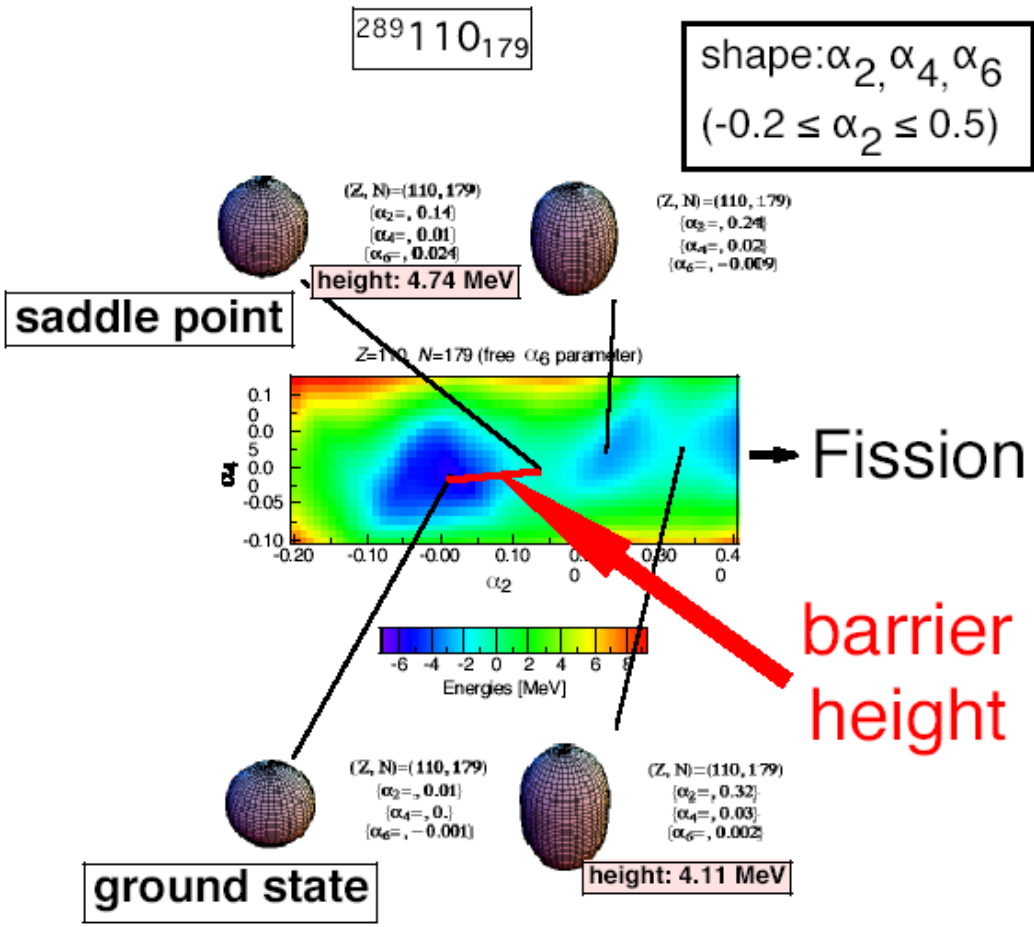

Supply to medium-weight region by fission, which is less sensitive to the physical conditions of r-process sites
Continuous flow from the bottom
Z
N
0
20
40
60
80
100
0
50
100
150
200

FFMD of n_{th} + ^{235}U

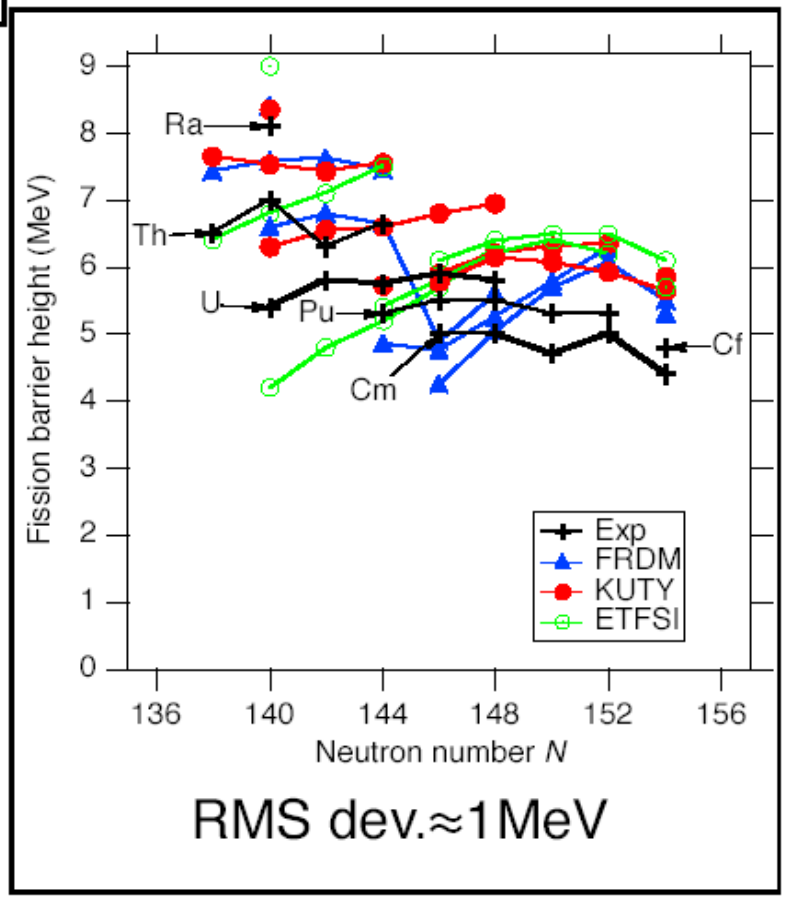


Estimation of Spontaneous Fission

(1)Fission barrier height

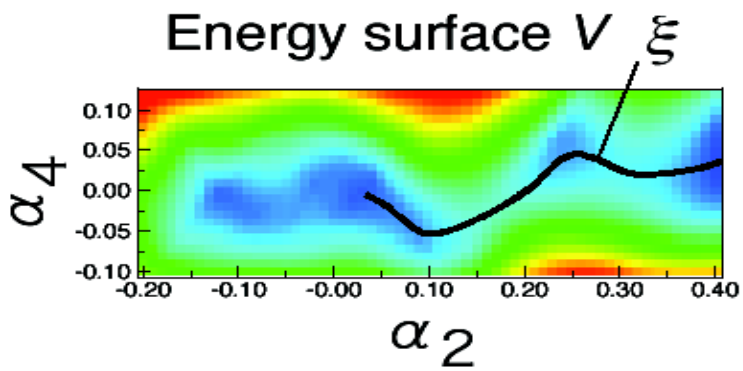


Energy surface KTUY05



RMS dev.≈1MeV

Estimation of half-lives of spontaneous fission



$$\mathrm{Log}_{10}(T_{\mathrm{SF}}) = \mathrm{Log}_{10}\left(1 + \exp\left[\frac{2}{\hbar}K\right]\right)$$
$$+\mathrm{Log}_{10}(N_{\mathrm{Coll}}) - 0.159$$
$$+ h\delta_{\mathrm{odd}\,Z} + h\delta_{\mathrm{odd}\,N} - \Delta_{oo}\delta_{\mathrm{odd}\,Z}\delta_{\mathrm{odd}\,N}$$

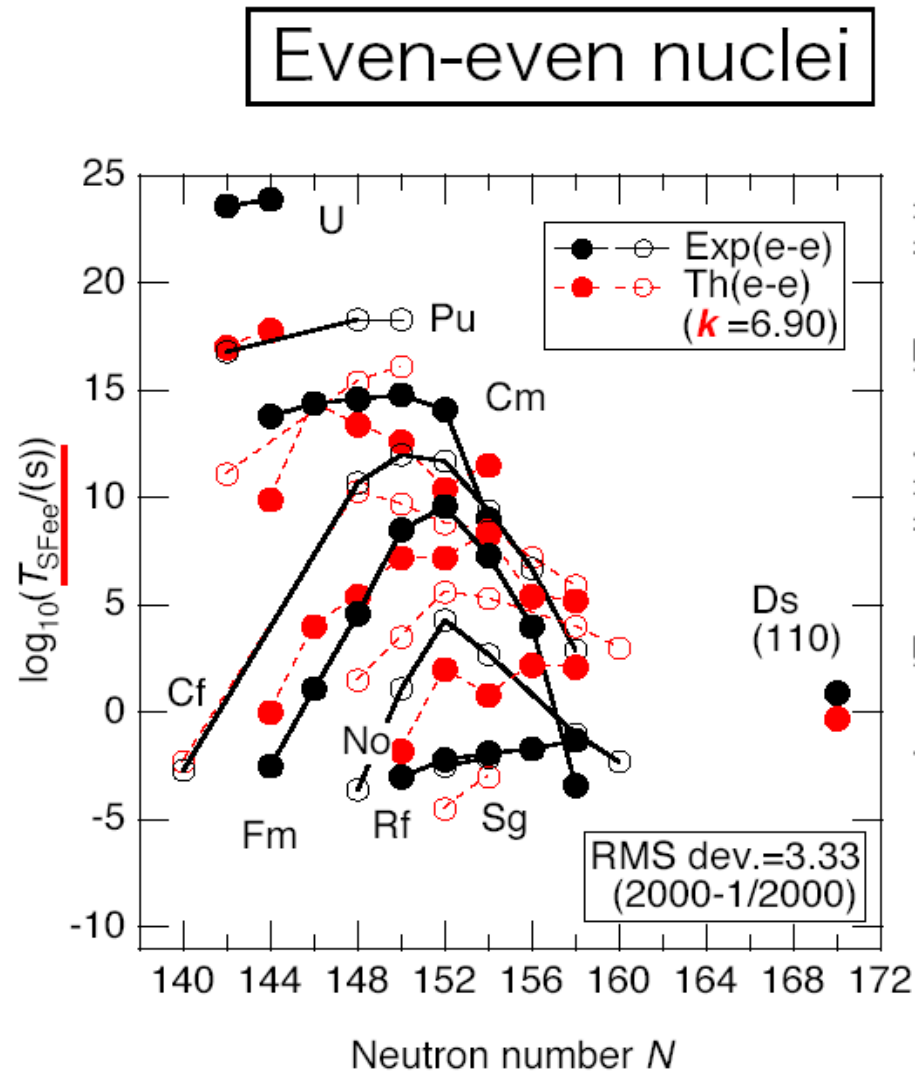
$$K = \int \sqrt{2M(V(\xi) - E_{\mathrm{gs}})}\, d\xi$$

$M = k\mu$, μ:reduced mass

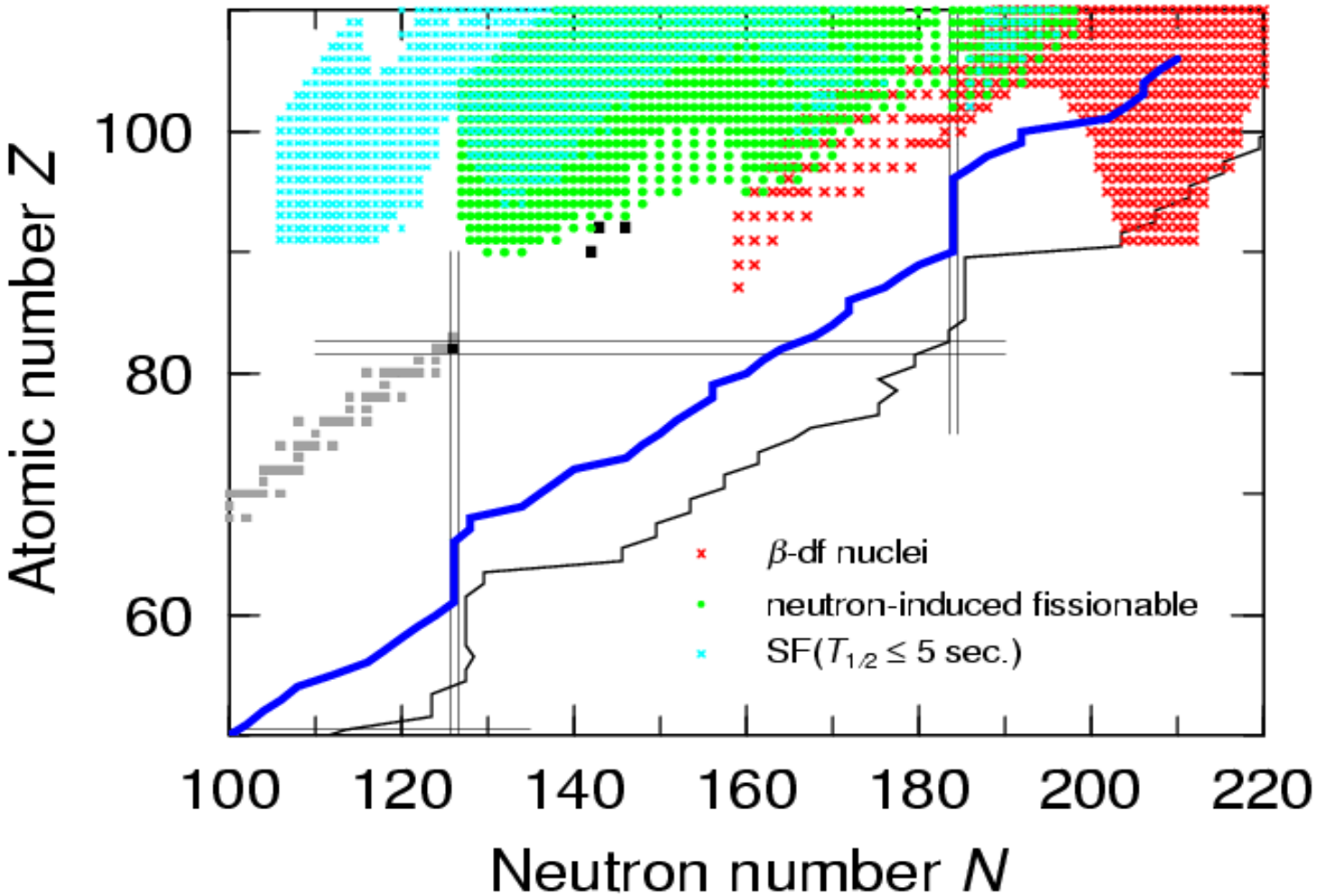
$d\xi = r_0 A^{1/3} d\alpha$

$r_0 = 1.2\mathrm{fm}$, $\mathrm{Log}_{10}(N_{\mathrm{Coll}}) = 20.38$

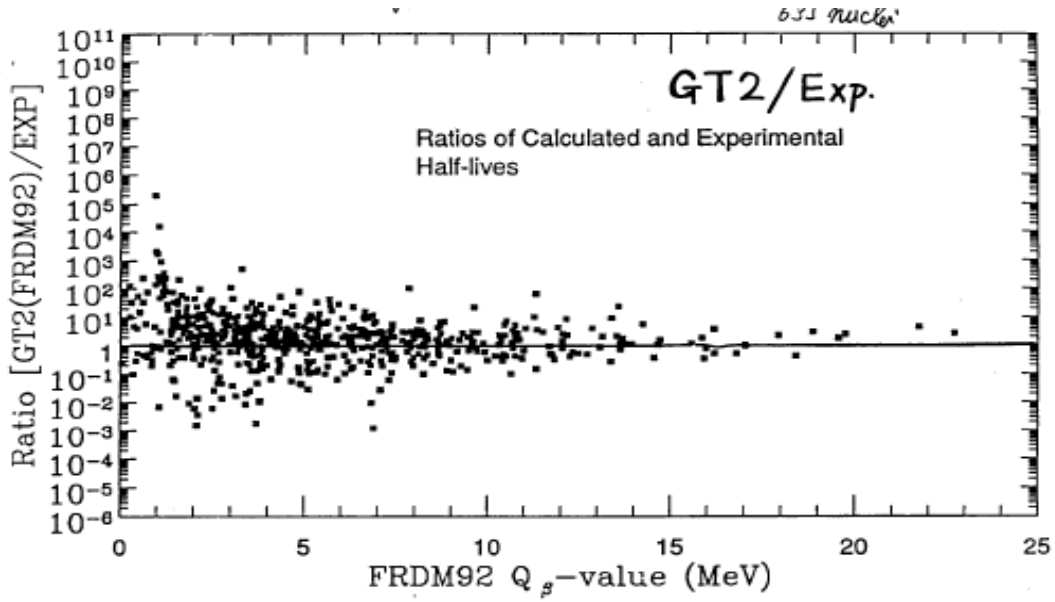
$$\delta_{\mathrm{odd}\,Z} = \begin{cases} 0 \text{ for even}-Z \\ 1 \text{ for odd}-Z, \end{cases} \quad \delta_{\mathrm{odd}\,N} = \begin{cases} 0 \text{ for even}-N \\ 1 \text{ for odd}-N, \end{cases}$$

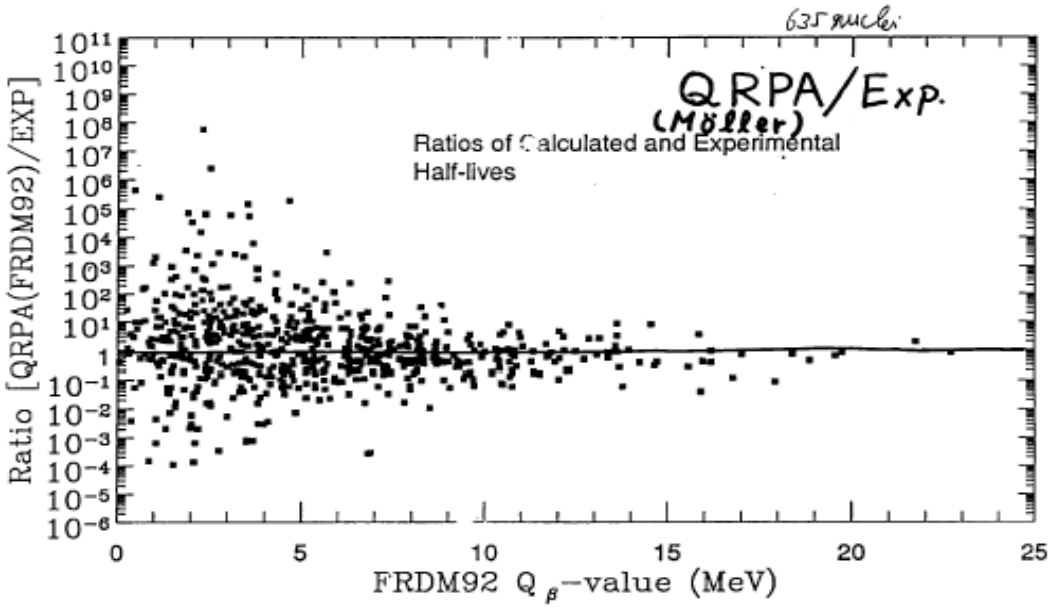


Regions where fissions take place in terms of KTUY05



Gross theory 2 for $\beta^{\mp}$−decay rates





T. Tachibana
(Waseda)

β -decay branching rates by Gross Theory

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{\ln 2}{C\int_{-Q}^{0} S_\beta(E) f(-E) dE}$$

$$P_\gamma = \frac{C}{\lambda}\int_{-Q}^{0} S_\beta(E) f(-E) \frac{\Gamma_\gamma}{\Gamma_n + \Gamma_\gamma + \Gamma_f} dE$$

$$P_n = \frac{C}{\lambda}\int_{-Q}^{0} S_\beta(E) f(-E) \frac{\Gamma_n}{\Gamma_n + \Gamma_\gamma + \Gamma_f} dE$$

$$P_f = \frac{C}{\lambda}\int_{-Q}^{0} S_\beta(E) f(-E) \frac{\Gamma_f}{\Gamma_n + \Gamma_\gamma + \Gamma_f} dE$$

Calculation of FFMD (Fission Fragment Mass Distribution)

- Presented by M. Ohta in ND07 and INPC07, S. Tatsuda P-30 (this symposium)
- Static effect: PES by 2-center shell model
  - collective coordinates : mass asymmetry, distance between fragments, deformation of fragments
  - yields asymmetry α
- Dynamic effects : based on multi-dimensional Langevin calculation for U, Sg and Fm
  - ratio of symmetric and asymmetric fission : determined by considering calculated and experimental results for Fm isotopes, especially for ^{264}Fm
  - width of FFMD : determined by considering Langevin calculation
- FFMD is expressed by 3 Gaussians

Calculation of PES

Liquid drop model + 2-center shell model

3-dimensional parameter space

- distance between fragments

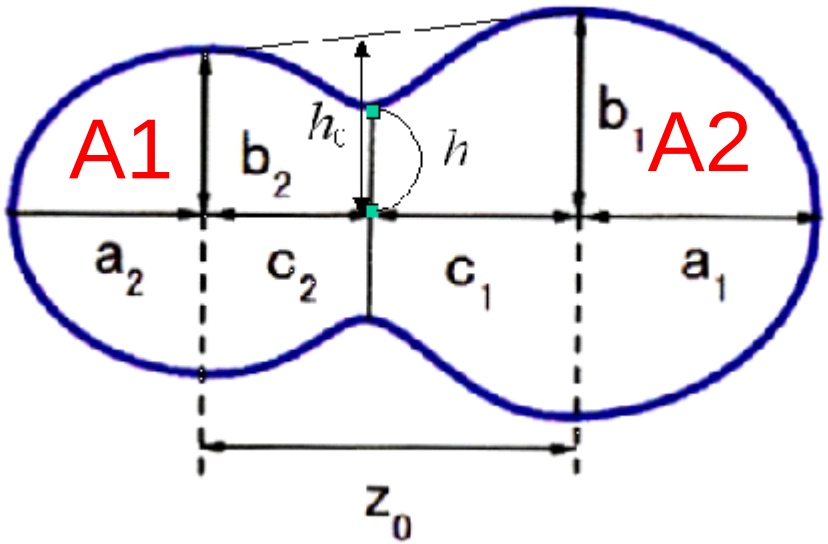
$$Z = \frac{Z_0}{BR}$$

- deformation of fragments

$$\delta = \frac{3(a-b)}{2a+b}$$

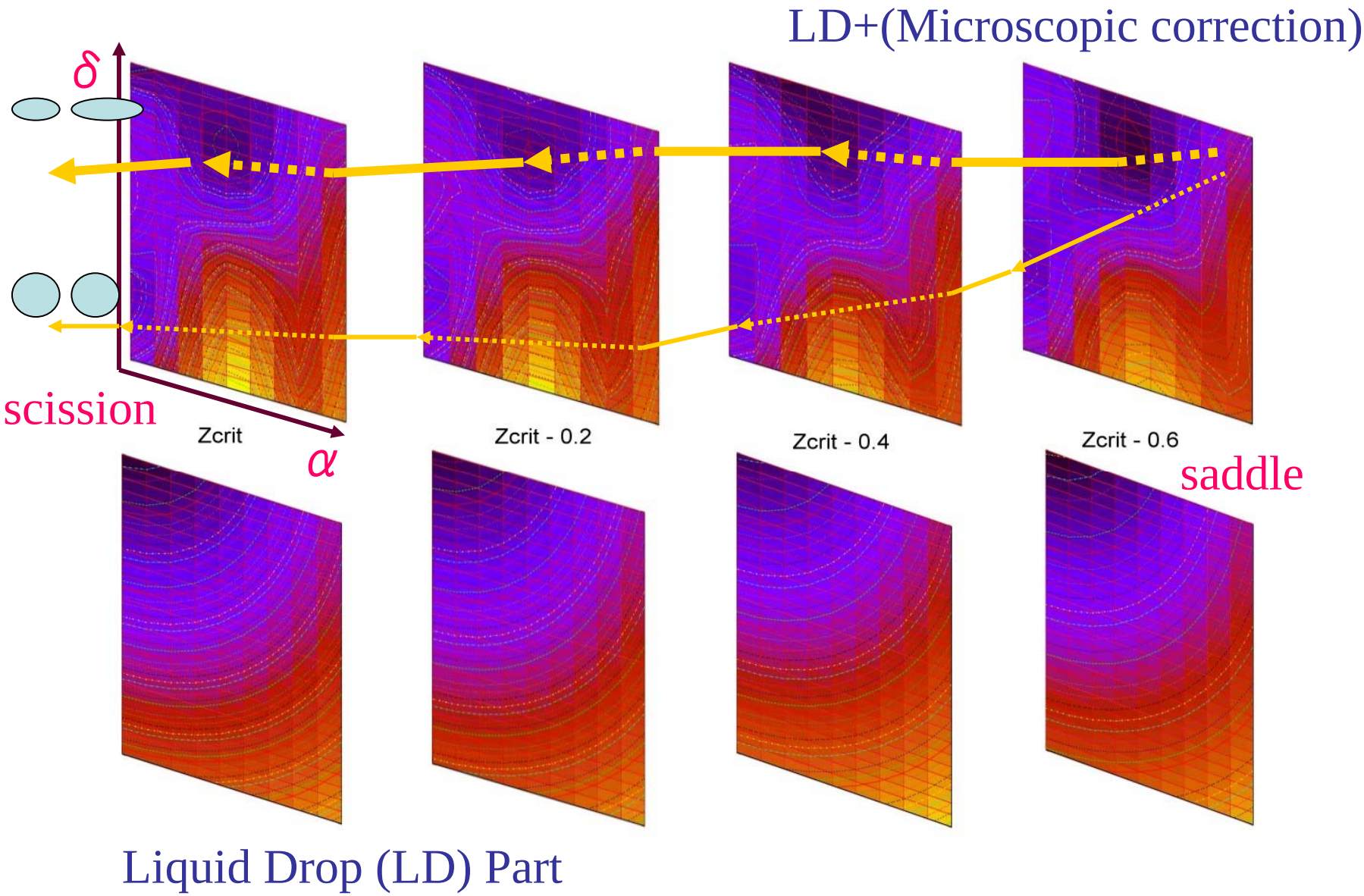
- mass asymmetry

$$\alpha = \frac{A_1 - A_2}{A_1 + A_2}$$

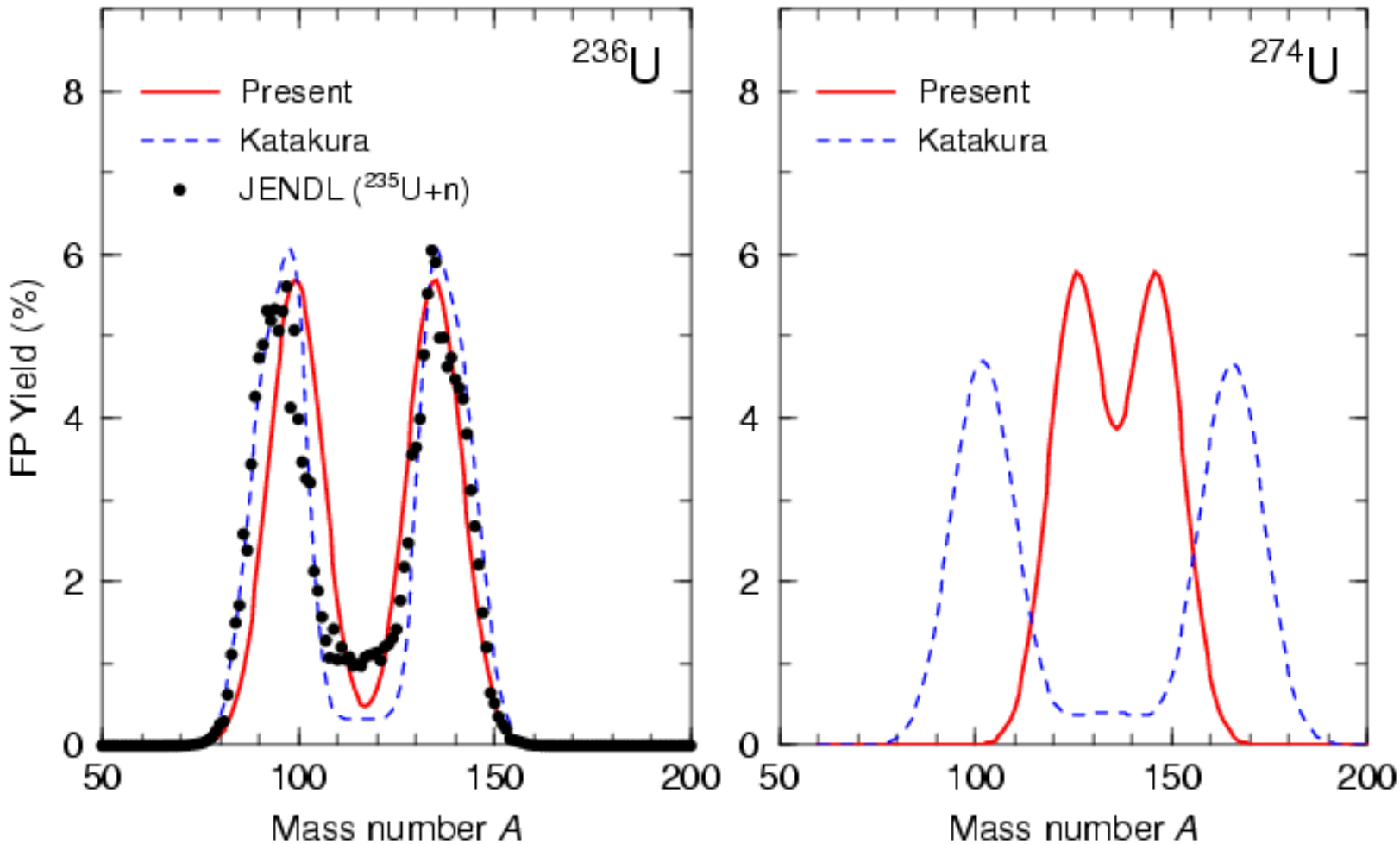


$$\left(B = \frac{3+\delta}{3-2\delta} \quad , \quad \text{R : Radius of the spherical compound nucleus} \right)$$

3次元変形空間における分裂経路



FFMD ^{236}U, ^{274}U

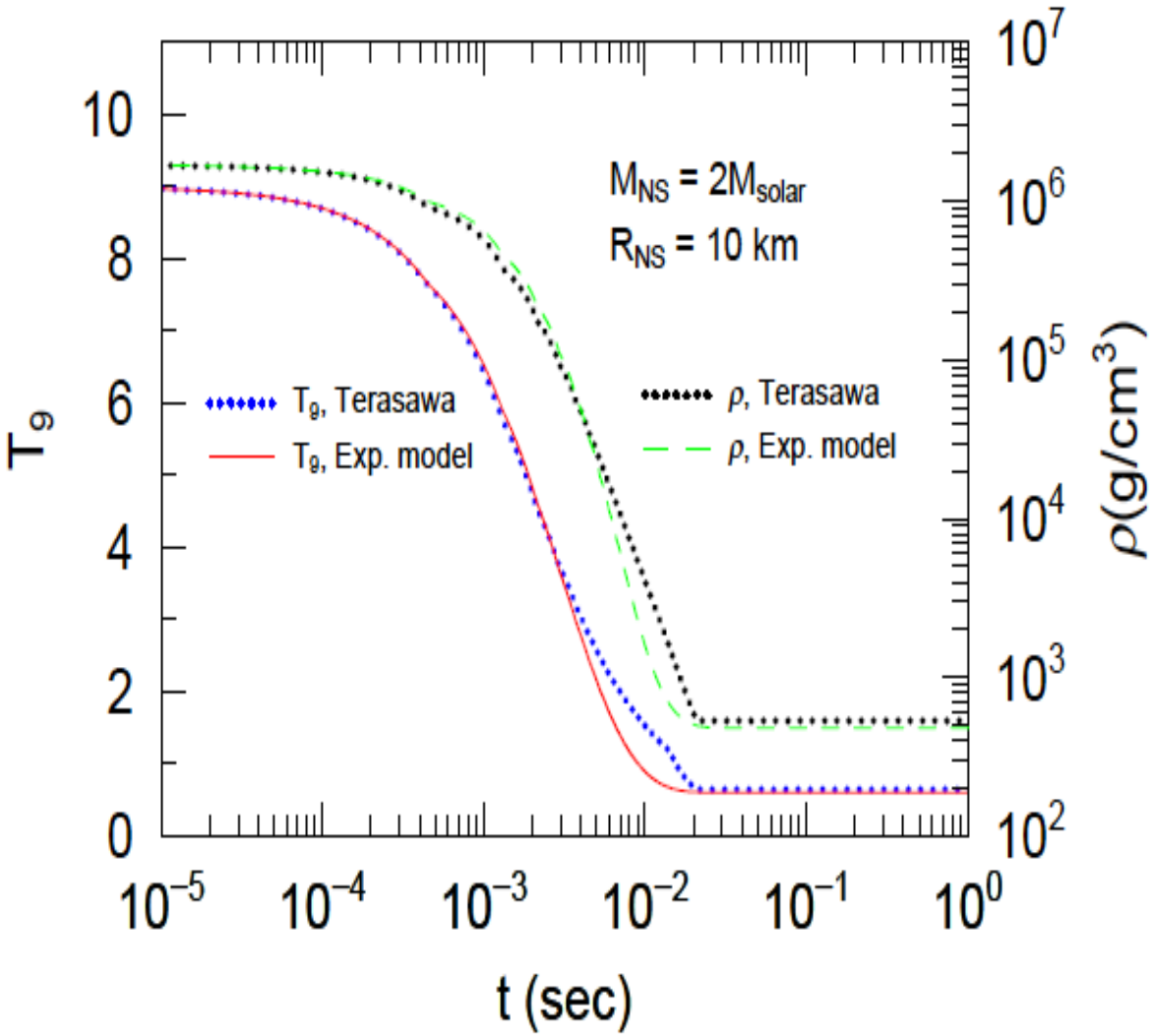


Dynamical network calculation

Terasawa et al., ApJ 562, 470(2001)

- Reaction rates
  - Thielamann , Caughlan-Fowler, Maleney-Fowler, Fowler-Hoyle, Rauscher, Mohr, Wagoner, Kajino-Boyd, Orito-Kajino-Mathews, Kajino-Fukugita,Ohsaki, NACRE96
- Nuclear Mass
  - Hilf-Groote-Takahashi (modified) →KTUY05
- β -decay rates
  - Klapdor →GT-2(2007)
- ν -induced spallation rate (A(ν ,e^- xn)A') (x=0, 8)
  - Langanke (5 ≦ Z ≦100) with dumping
- Trajectory : numerically read ⇒ exponential model
- no fission mode ⇒ β -delayed fission, spontaneous fission(KTUY05)
- α -decay (KTUY05)

Exponential model for expanding nuclear matter



c.f. General-relativistic hydro-dynamical simulation by Terasawa (ApJ 562, 470(2001))
（dots）:prompt explosion

lower 2 lines : T_9

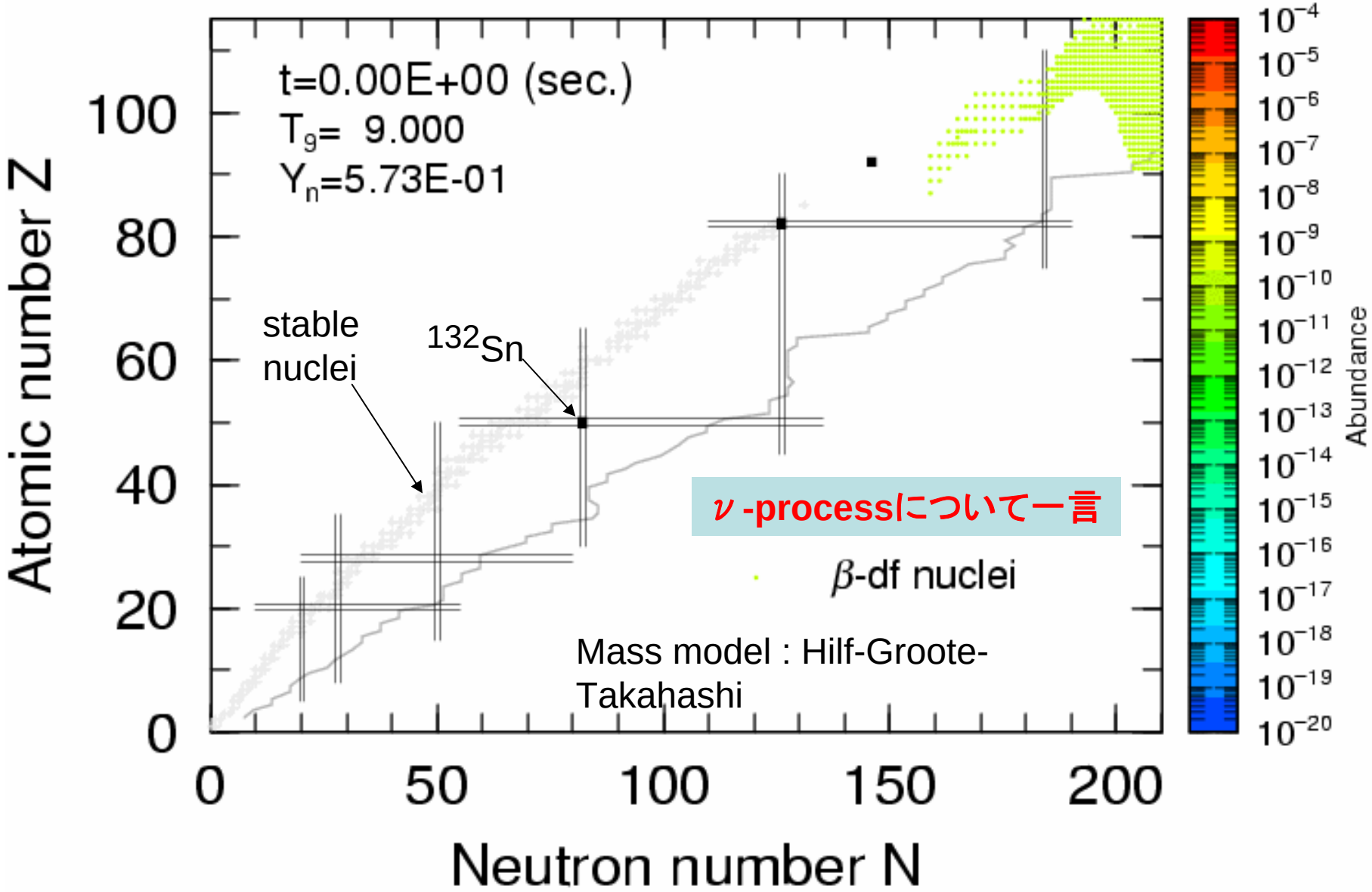
upper 2 lines : density

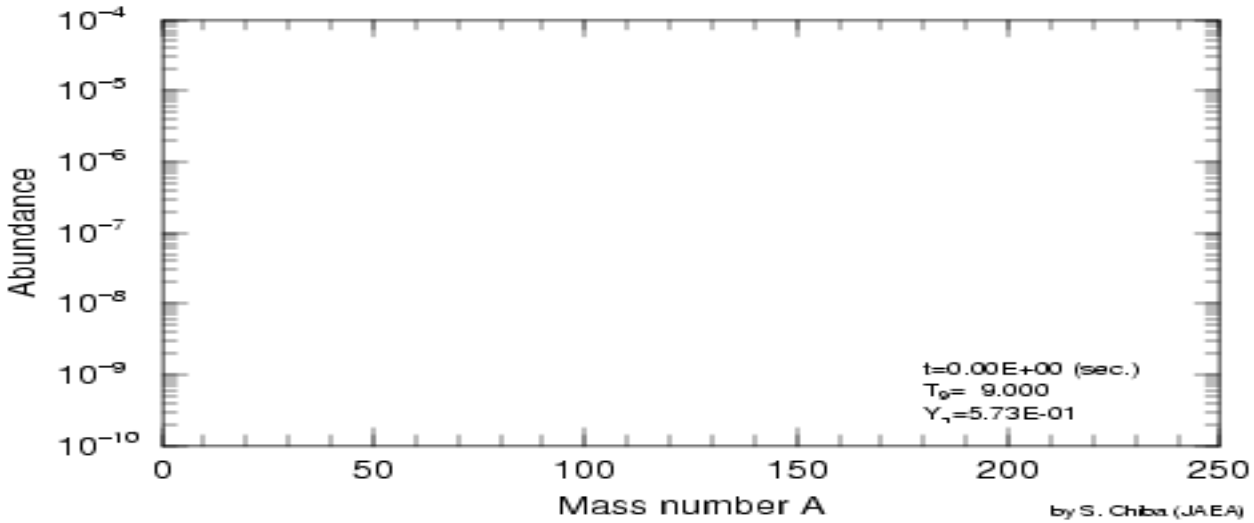
Exponential model

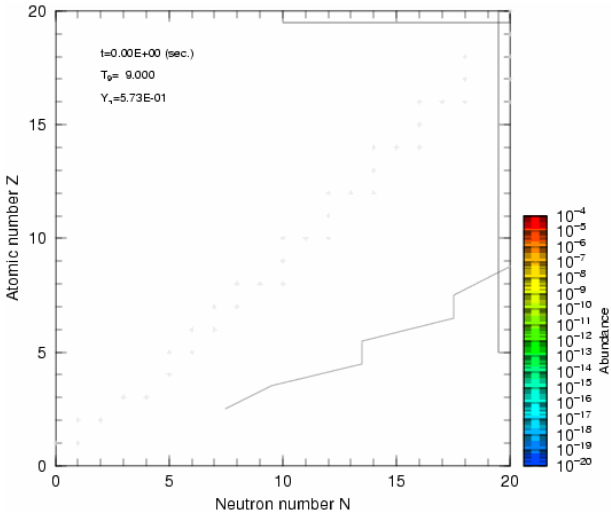
$$T_9(t) = 8.4\exp(-t/7ms) + 0.7$$

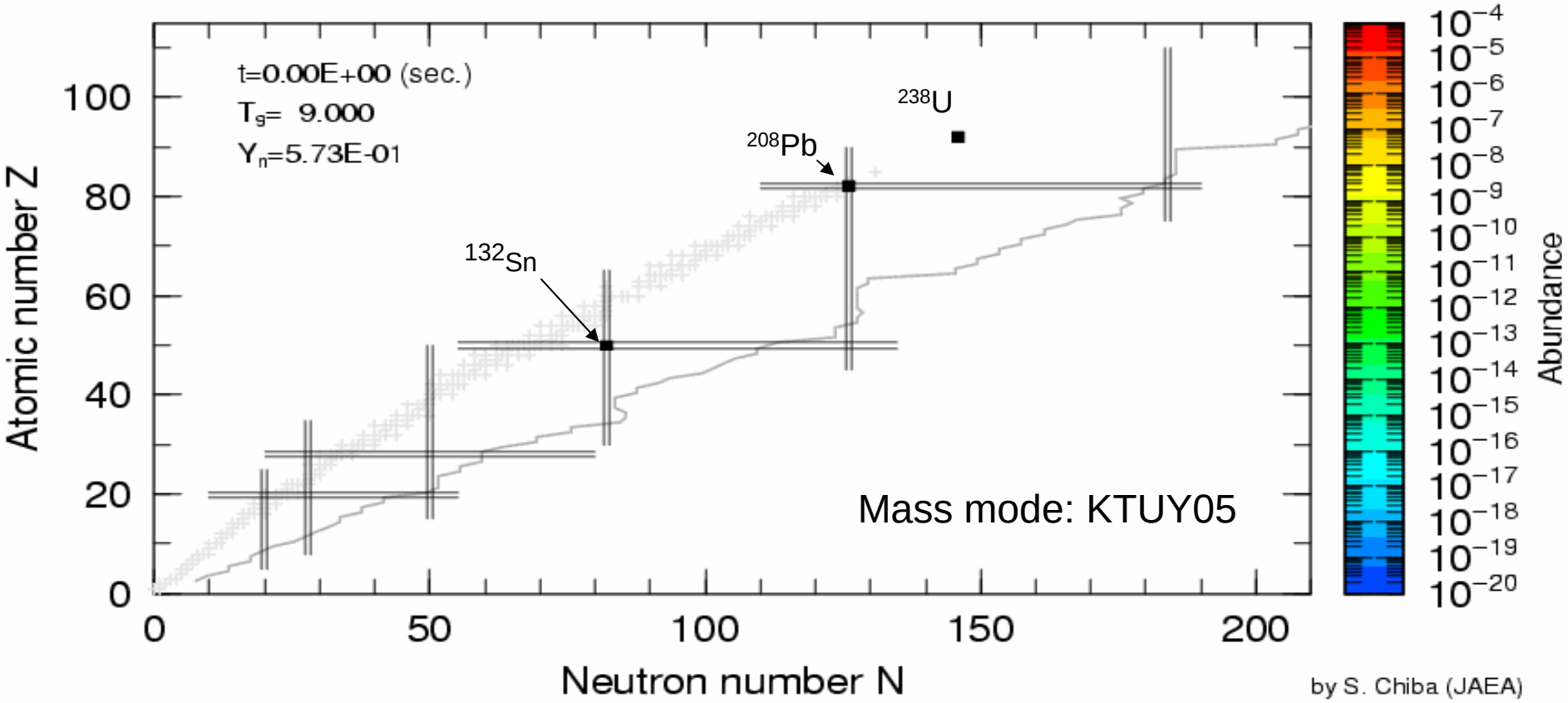
$$\rho(t) = \frac{3.33\times10^5 T_9(t)^3}{S}$$

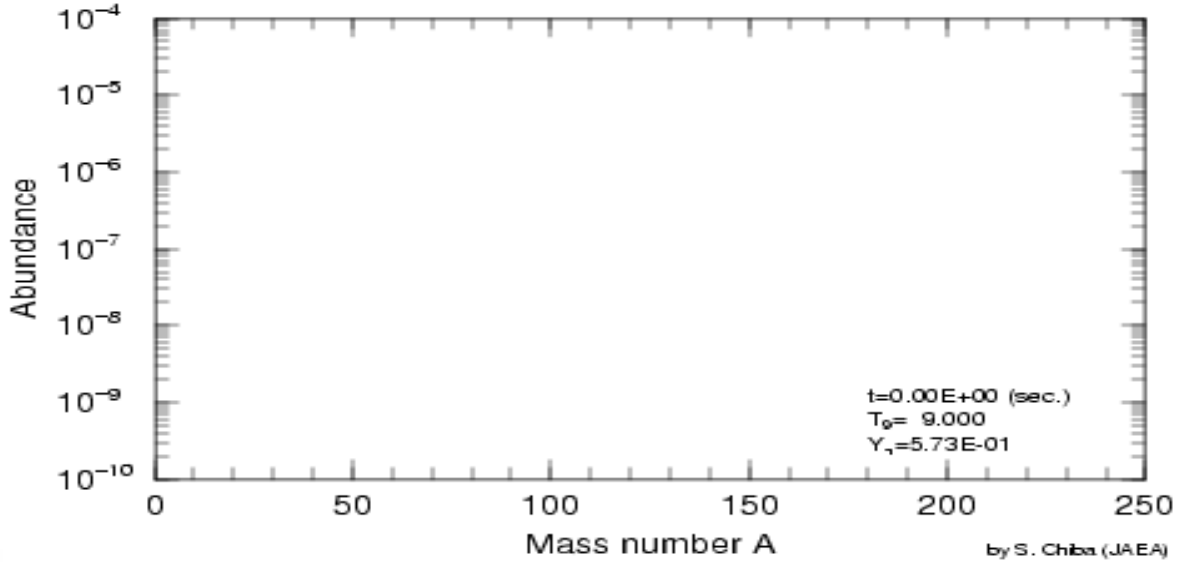
$Y_e = Y_p = 0.427$
$L_\nu \sim T_9$

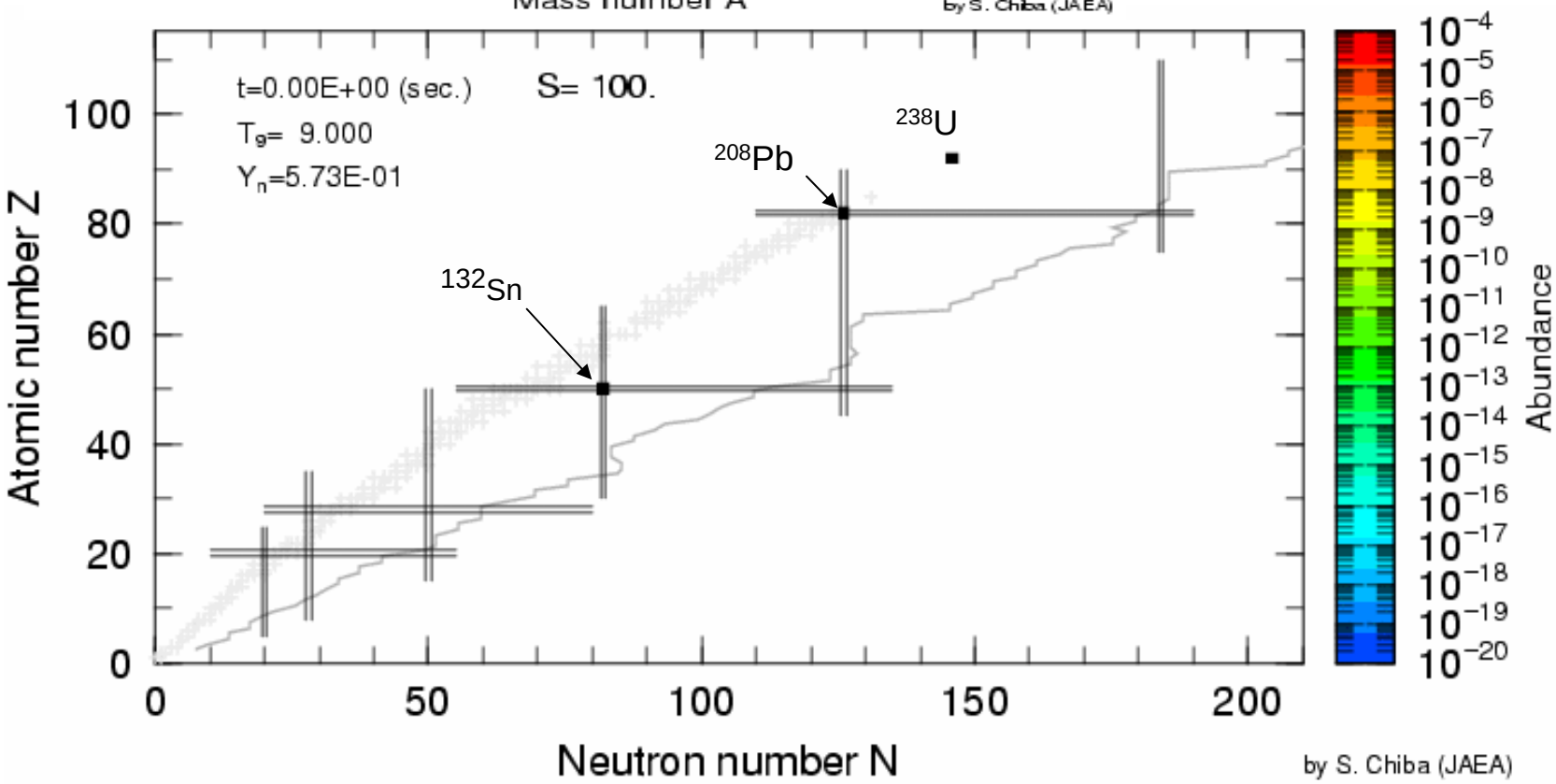

t=0.00E+00 (sec.)
T_9= 9.000
Y_n=5.73E-01
stable nuclei
^{132}Sn
ν-processについて一言
β-df nuclei
Mass model : Hilf-Groote-Takahashi
Atomic number Z
Neutron number N
Abundance
0
20
40
60
80
100
0
50
100
150
200
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}


Abundance
Mass number A
t=0.00E+00 (sec.)
Tg= 9.000
Yn=5.73E-01
by S. Chiba (JAEA)

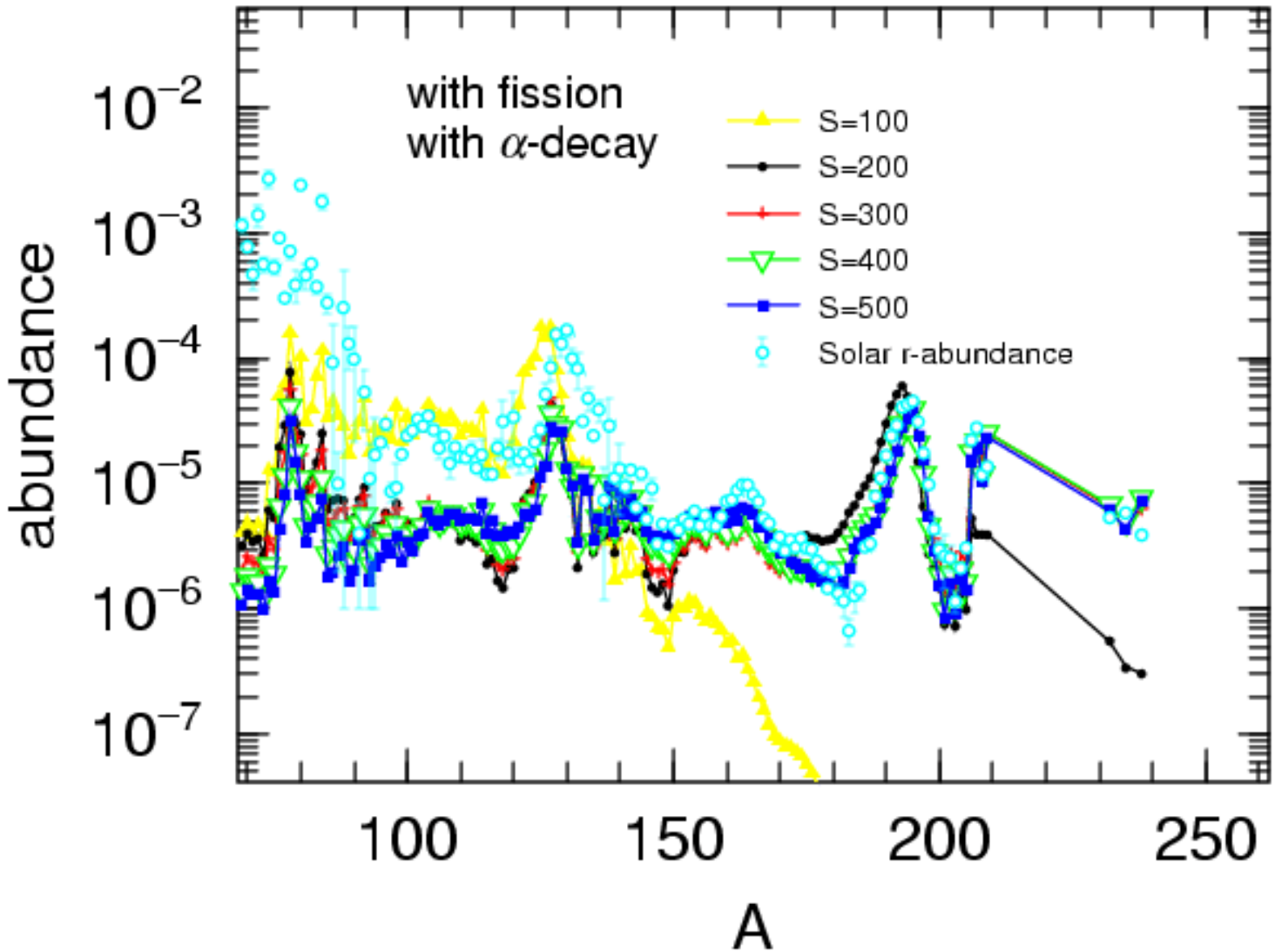

Atomic number Z
Neutron number N
Abundance

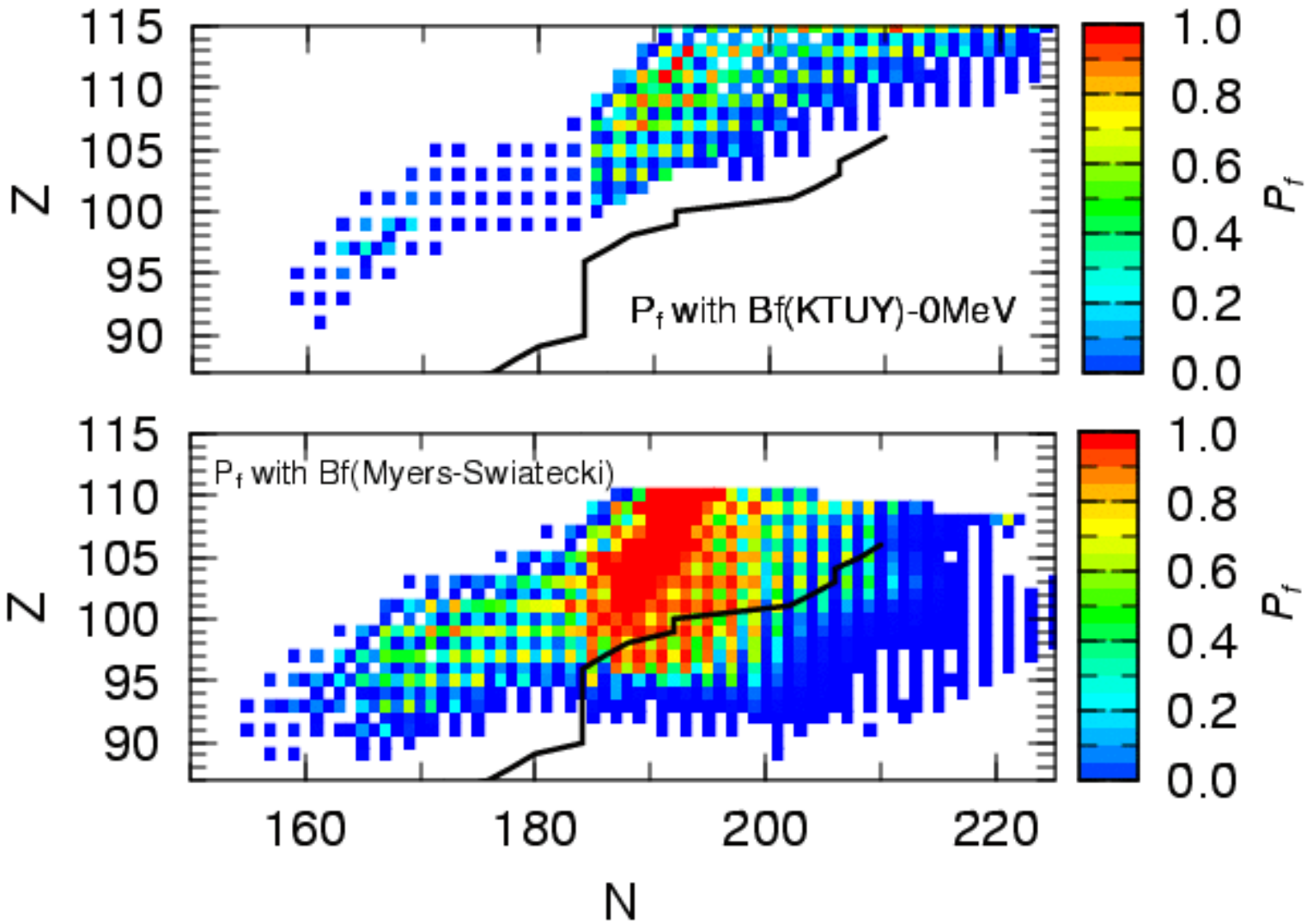

t=0.00E+00 (sec.)
Tg= 9.000
Yn=5.73E-01
238U
208Pb
132Sn
Mass mode: KTUY05
Atomic number Z
Neutron number N
Abundance
by S. Chiba (JAEA)

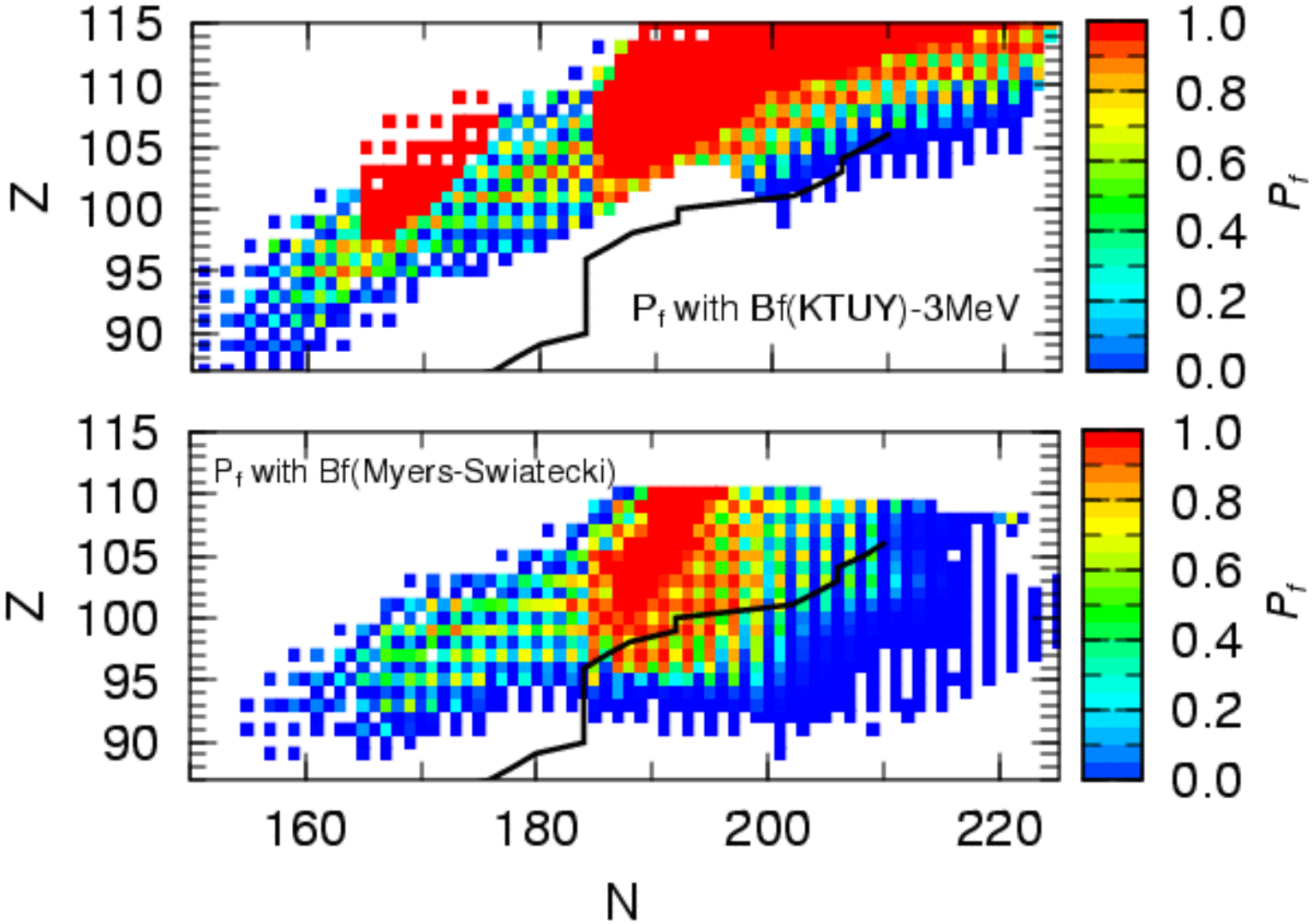

Abundance
Mass number A
t=0.00E+00 (sec.)
Tg= 9.000
Yn=5.73E-01
by S. Chiba (JAEA)


t=0.00E+00 (sec.)
S= 100.
Tg= 9.000
Yn=5.73E-01
238U
208Pb
132Sn
Atomic number Z
Neutron number N
Abundance
by S. Chiba (JAEA)

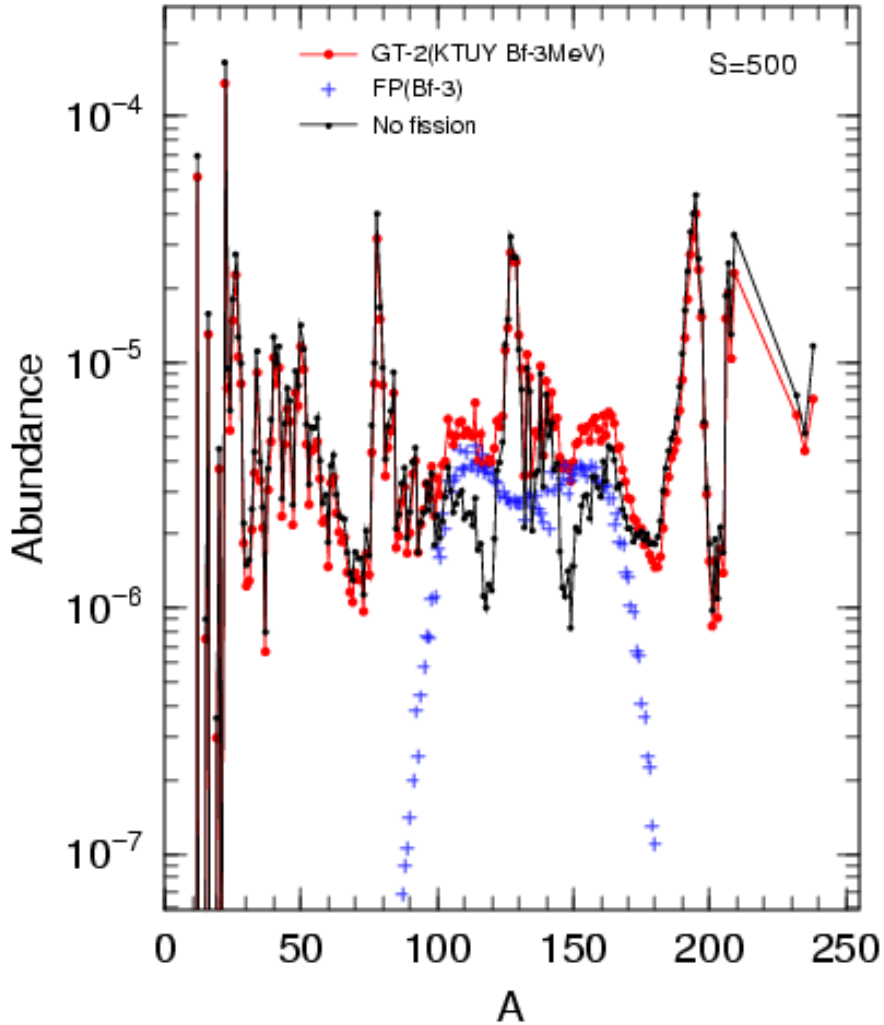
Entropy-dependence of r-process abundance

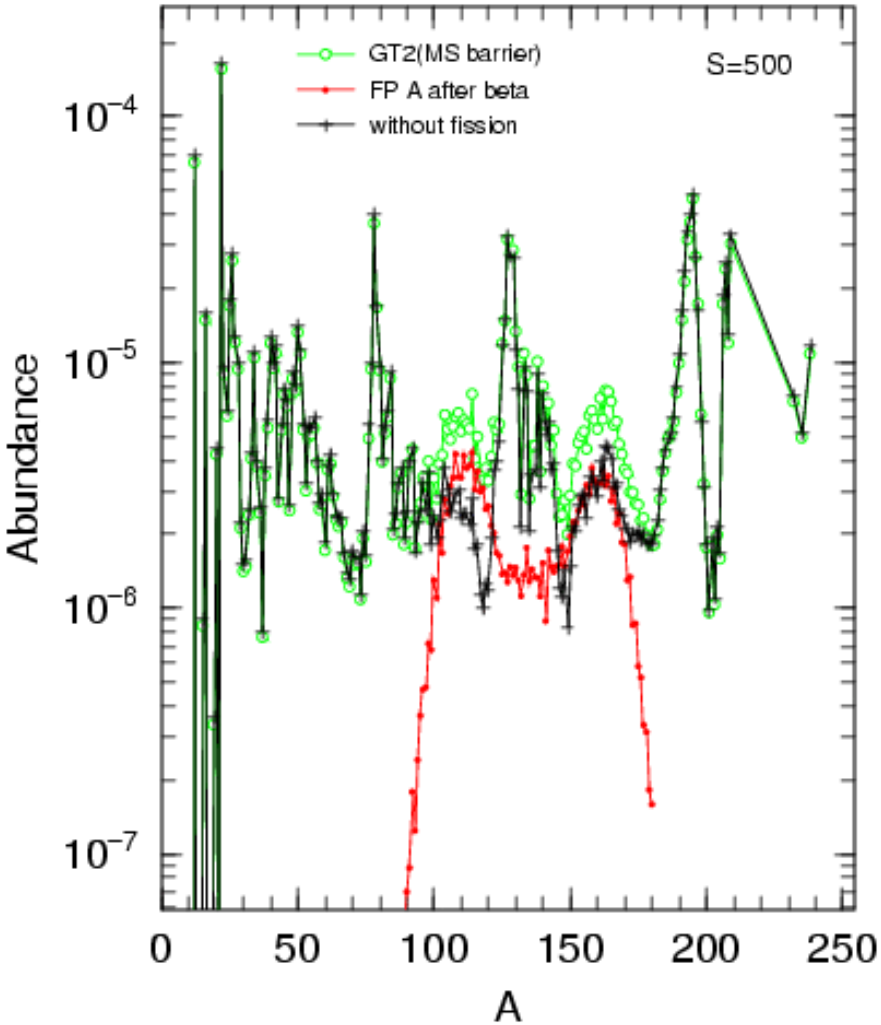



115
110
105
100
95
90
Z
P_f with Bf(KTUY)-0MeV
1.0
0.8
0.6
0.4
0.2
0.0
P_f
P_f with Bf(Myers-Swiatecki)
160
180
200
220
N

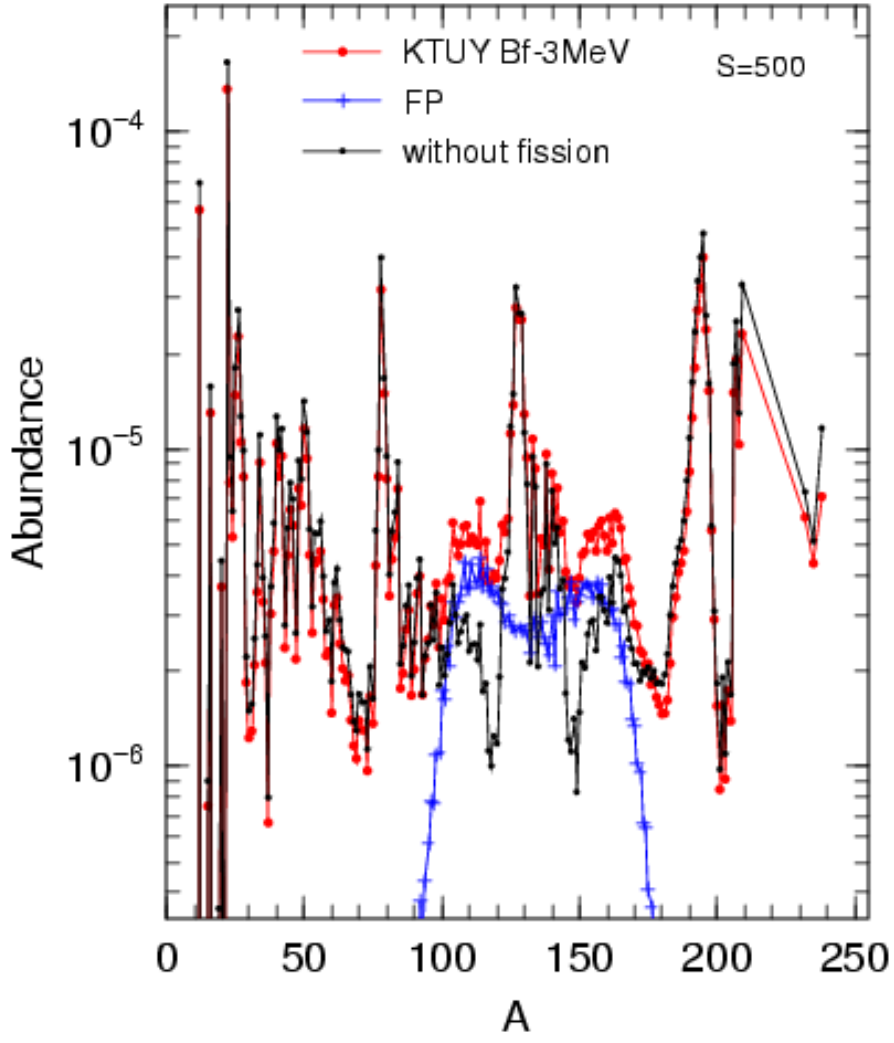

115
110
105
100
95
90
Z
P_f with Bf(KTUY)-3MeV
1.0
0.8
0.6
0.4
0.2
0.0
P_f
P_f with Bf(Myers-Swiatecki)
160
180
200
220
N

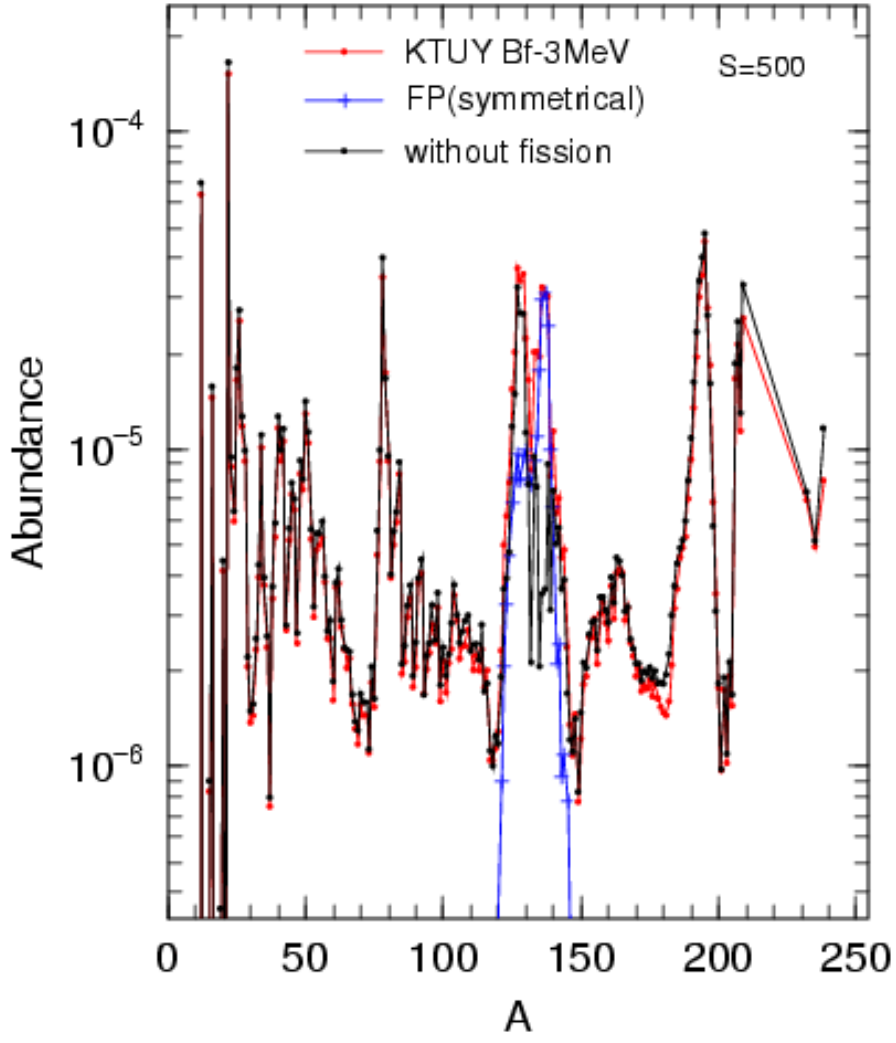
(KTUY-3MeV（left）、MS96（right））

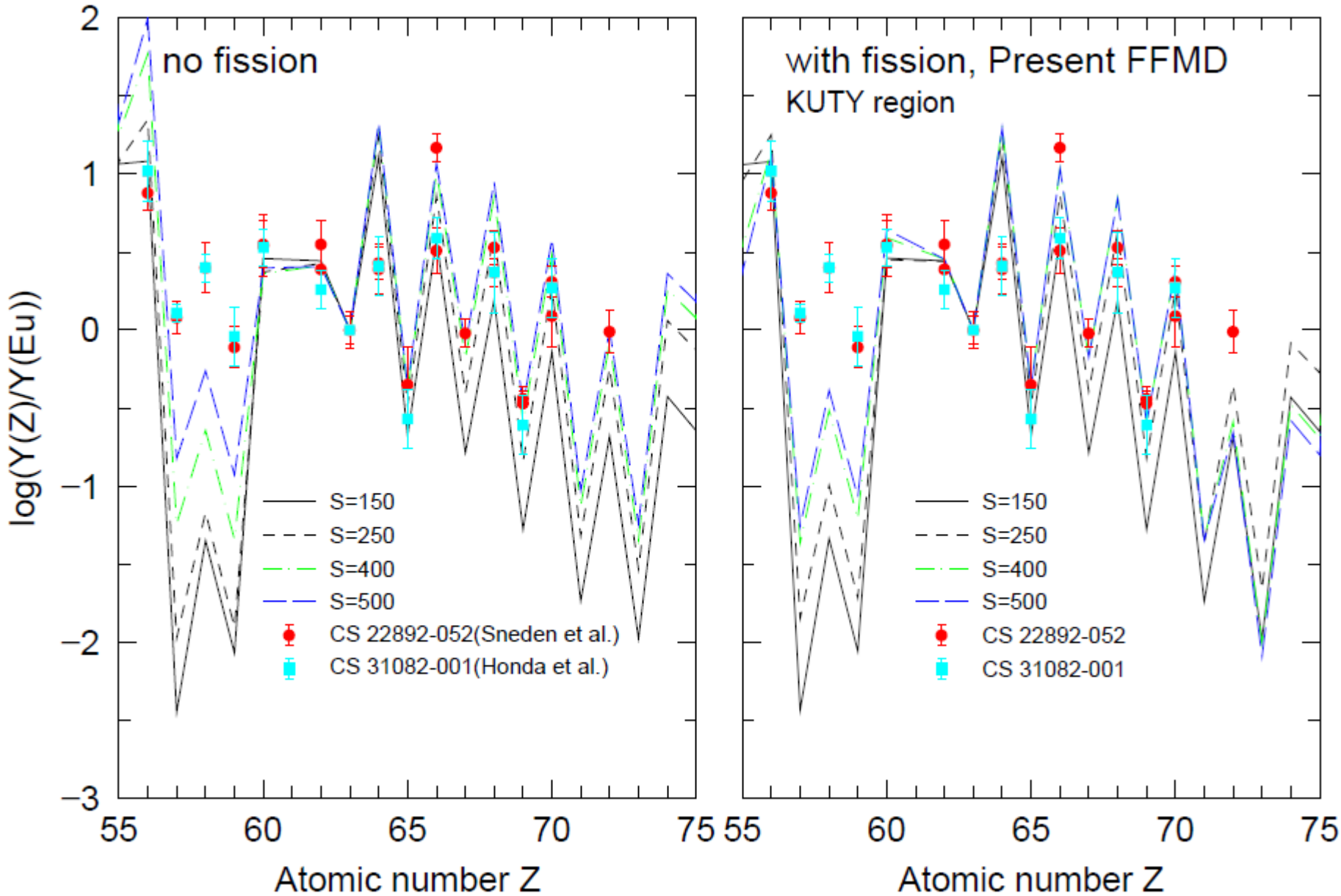




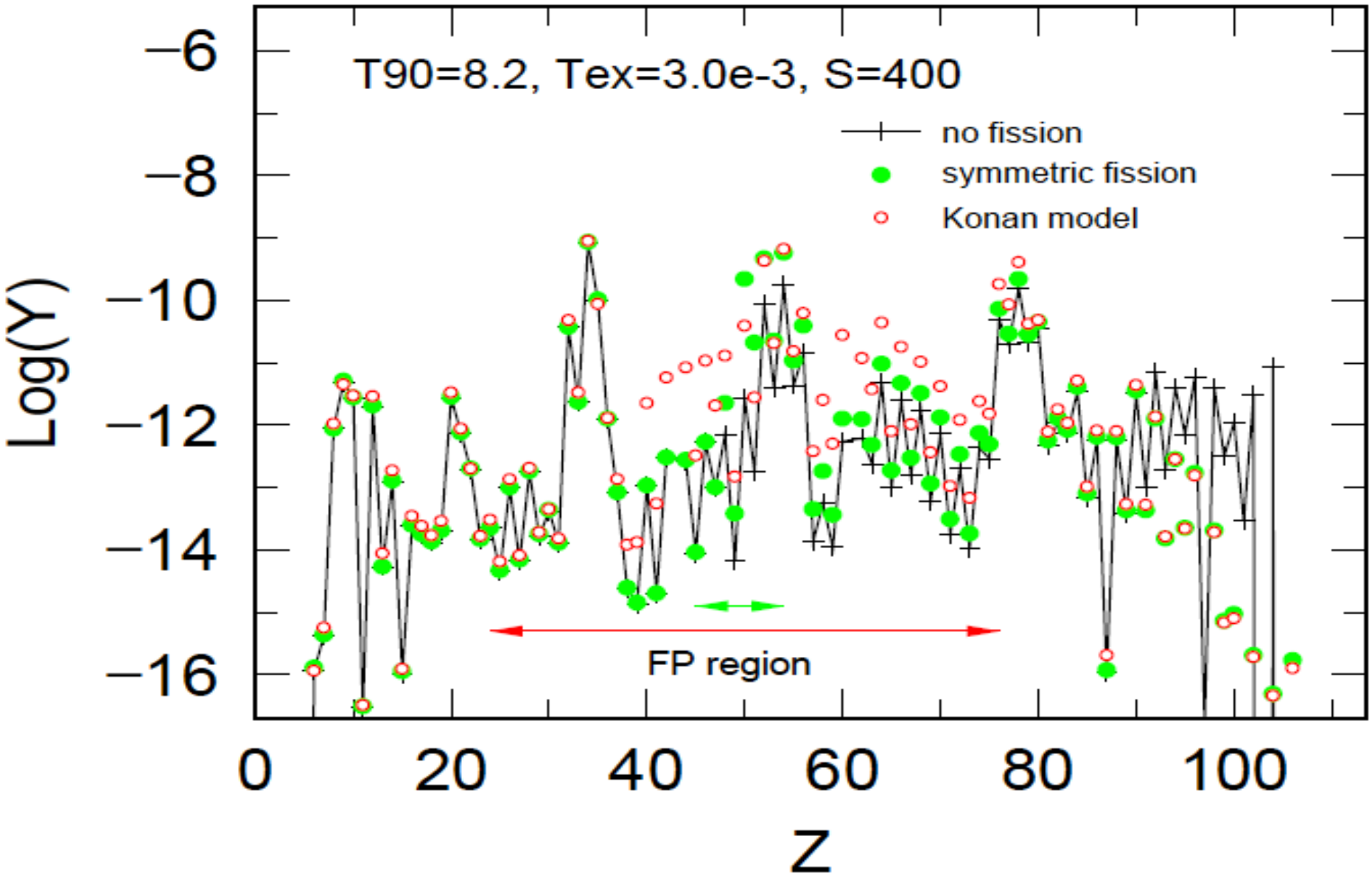
Impact of FFMD on abundance : realistic (left) vs. symmetric(right)



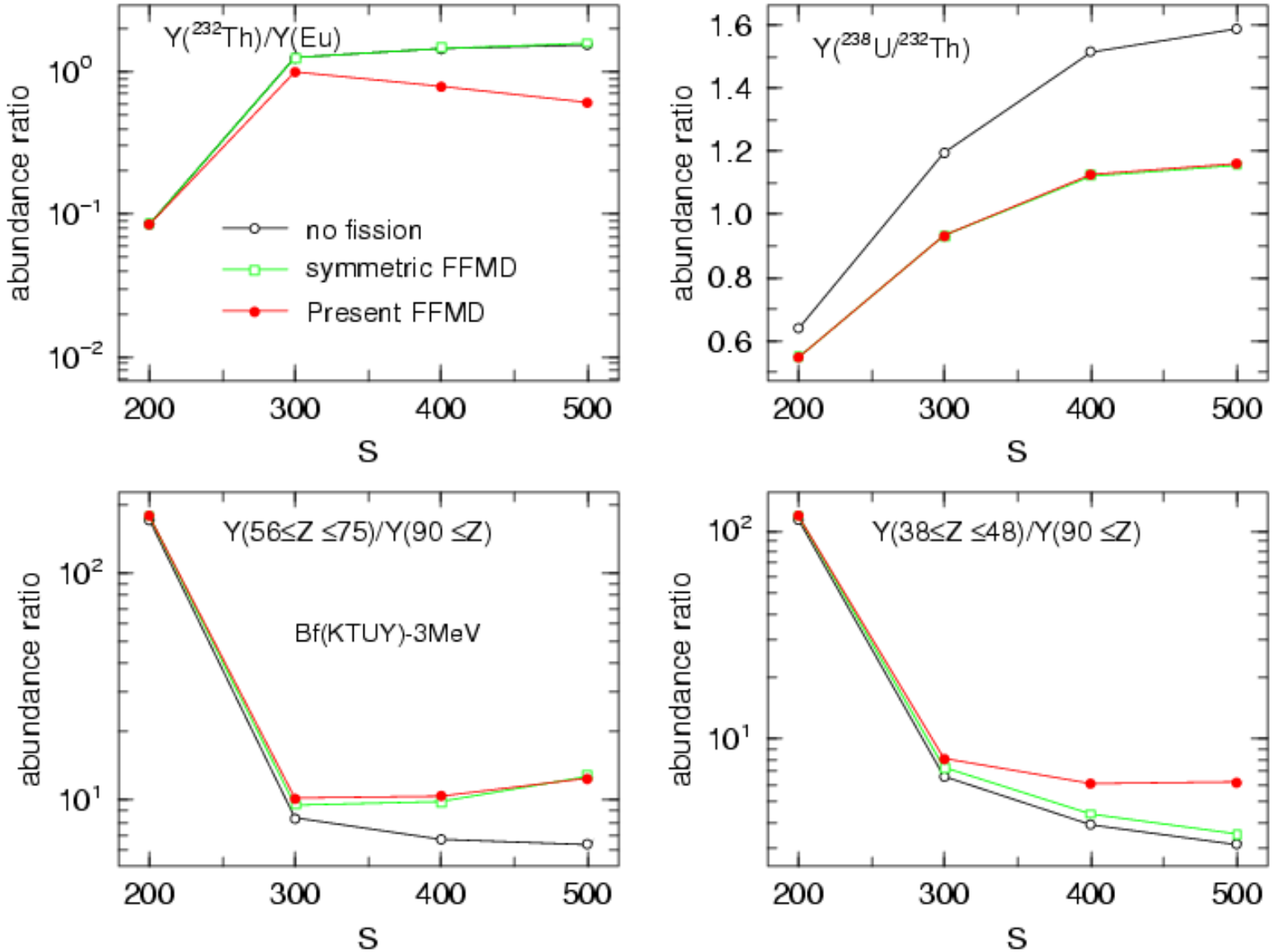



no fission
with fission, Present FFMD
KUTY region
log(Y(Z)/Y(Eu))
Atomic number Z
S=150
S=250
S=400
S=500
CS 22892-052(Sneden et al.)
CS 31082-001(Honda et al.)
CS 22892-052
CS 31082-001
2
1
0
−1
−2
−3
55
60
65
70
75

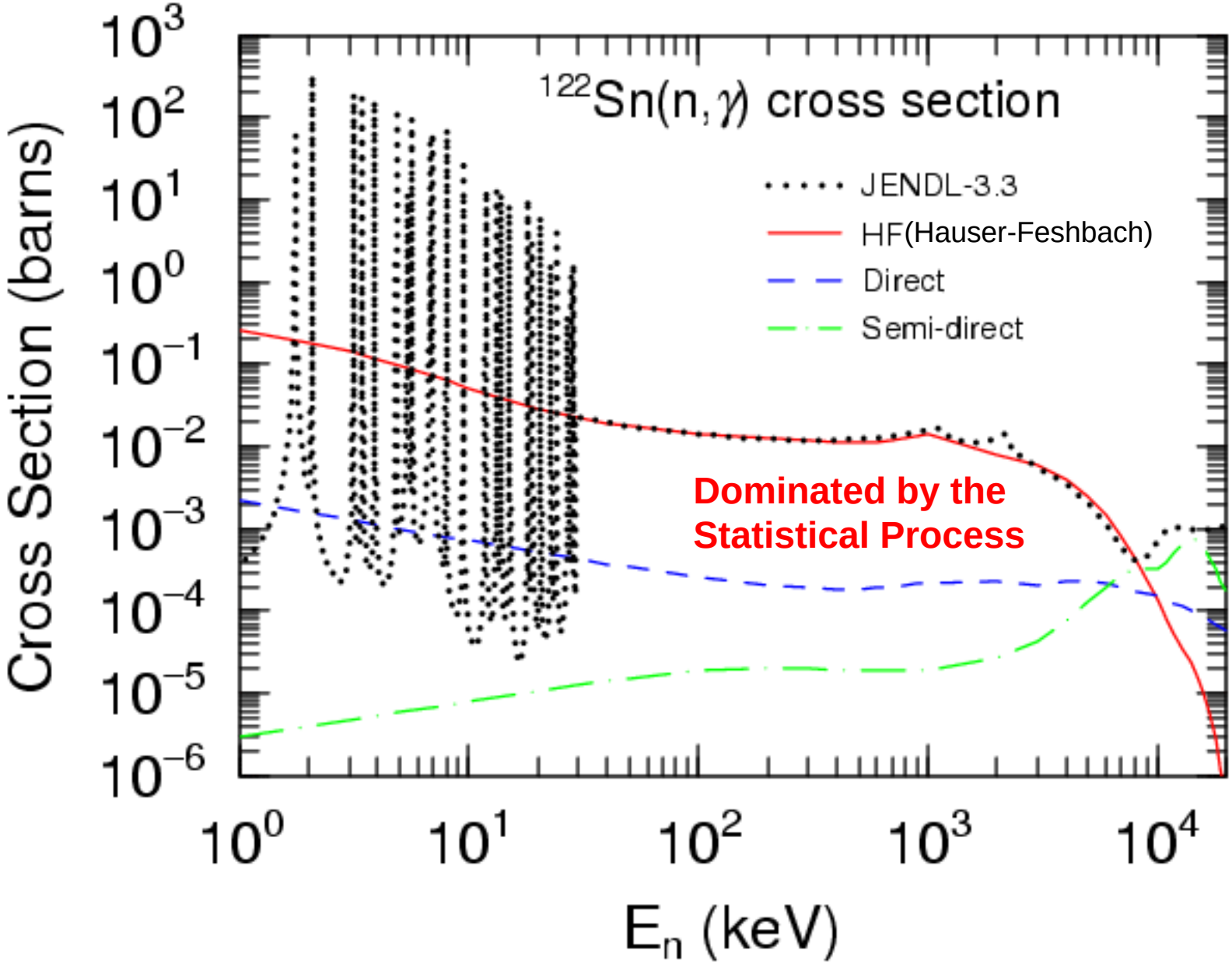
Z分布(S=400)

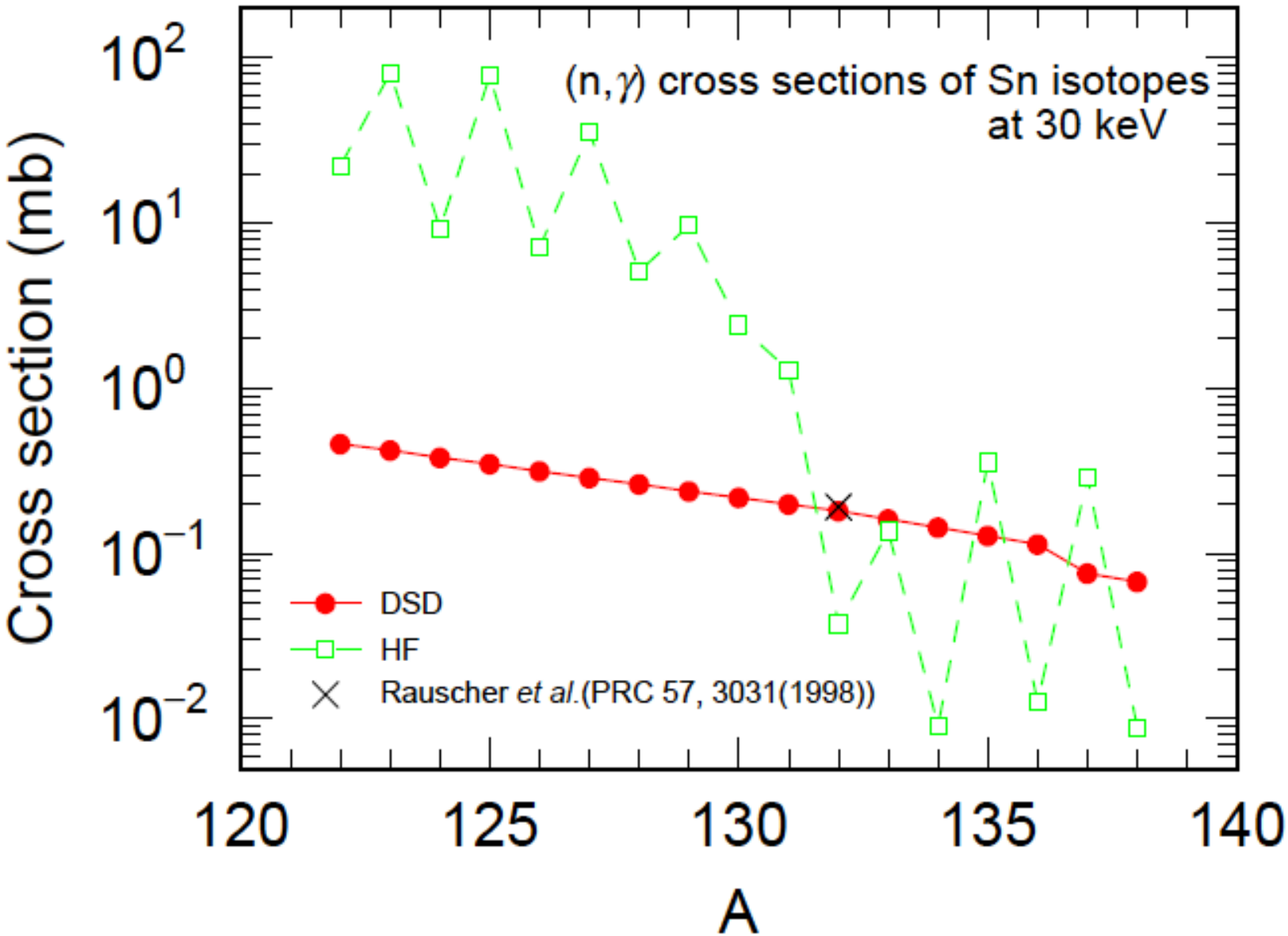

T90=8.2, Tex=3.0e-3, S=400
no fission
symmetric fission
Konan model
FP region
Log(Y)
Z
−6
−8
−10
−12
−14
−16
0
20
40
60
80
100

Isotope (or element) production rates

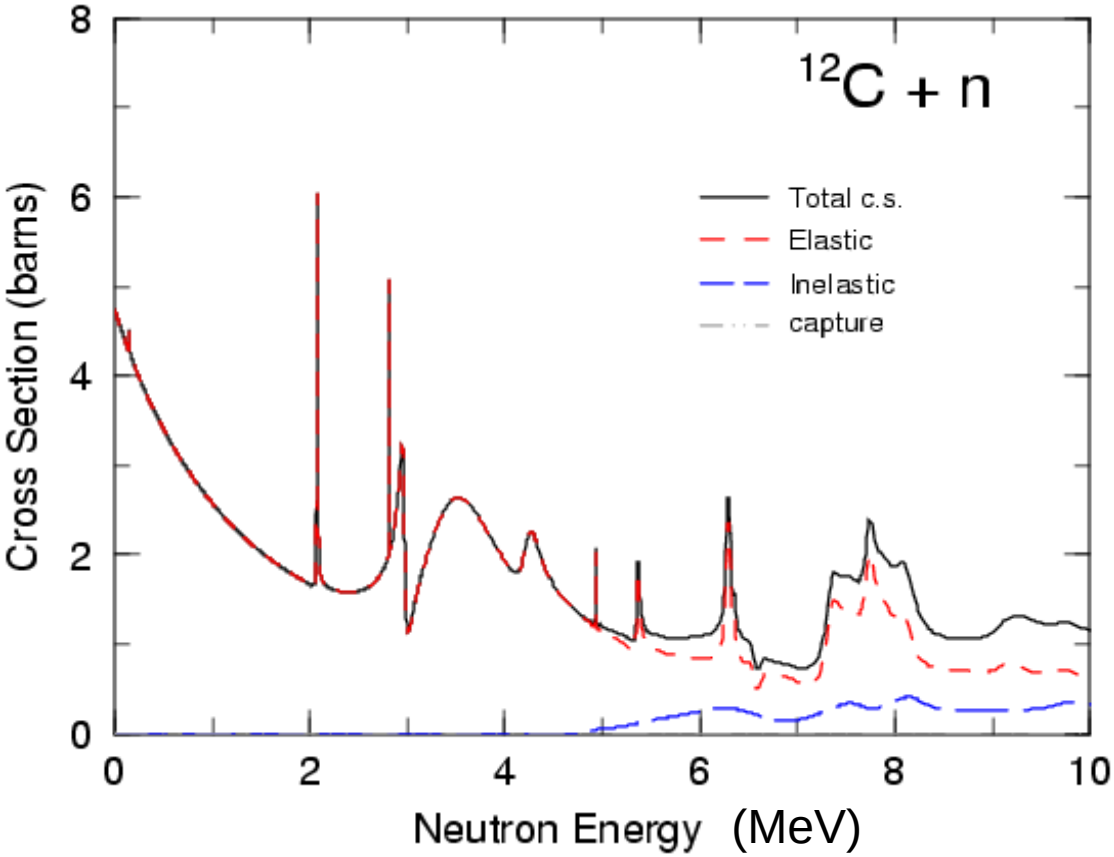


Neutron capture C.S.



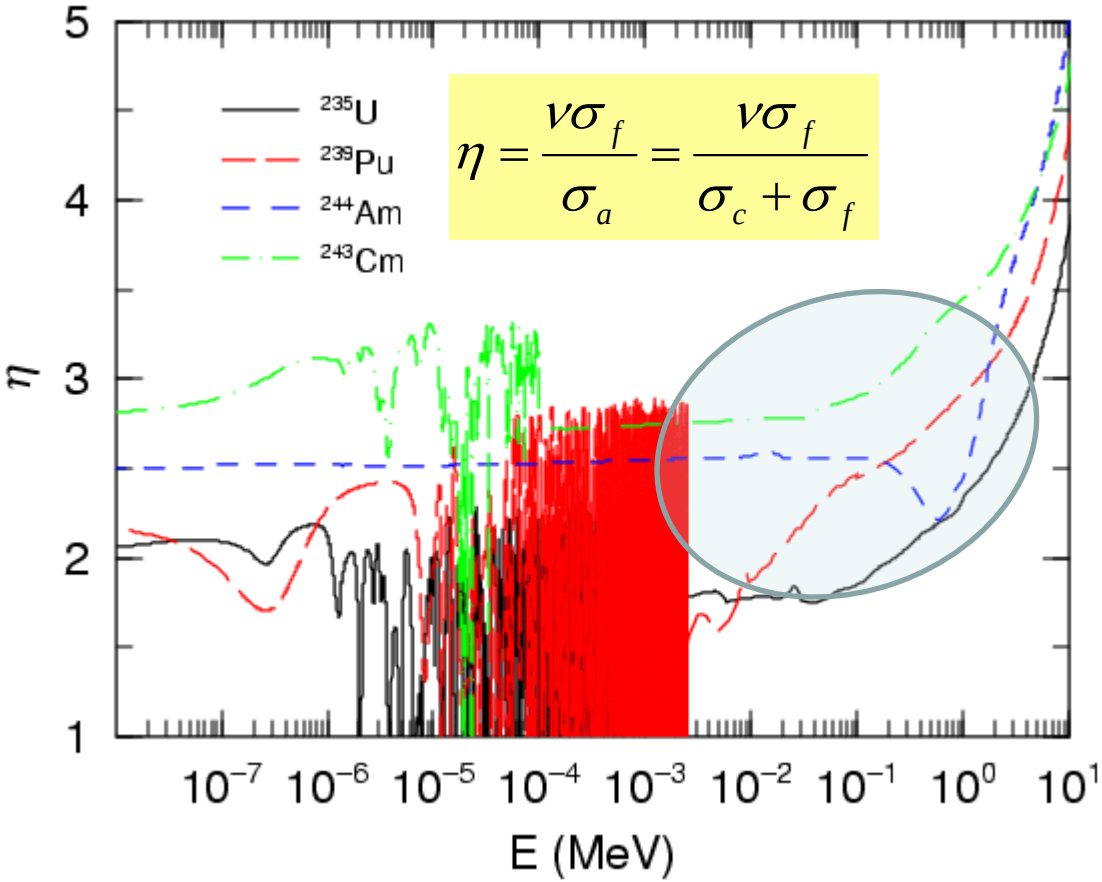

(n,γ) cross sections of Sn isotopes
at 30 keV
DSD
HF
Rauscher et al.(PRC 57, 3031(1998))
Cross section (mb)
A
10^2
10^1
10^0
10^−1
10^−2
120
125
130
135
140

Some nuclear data issues （light nuclei）



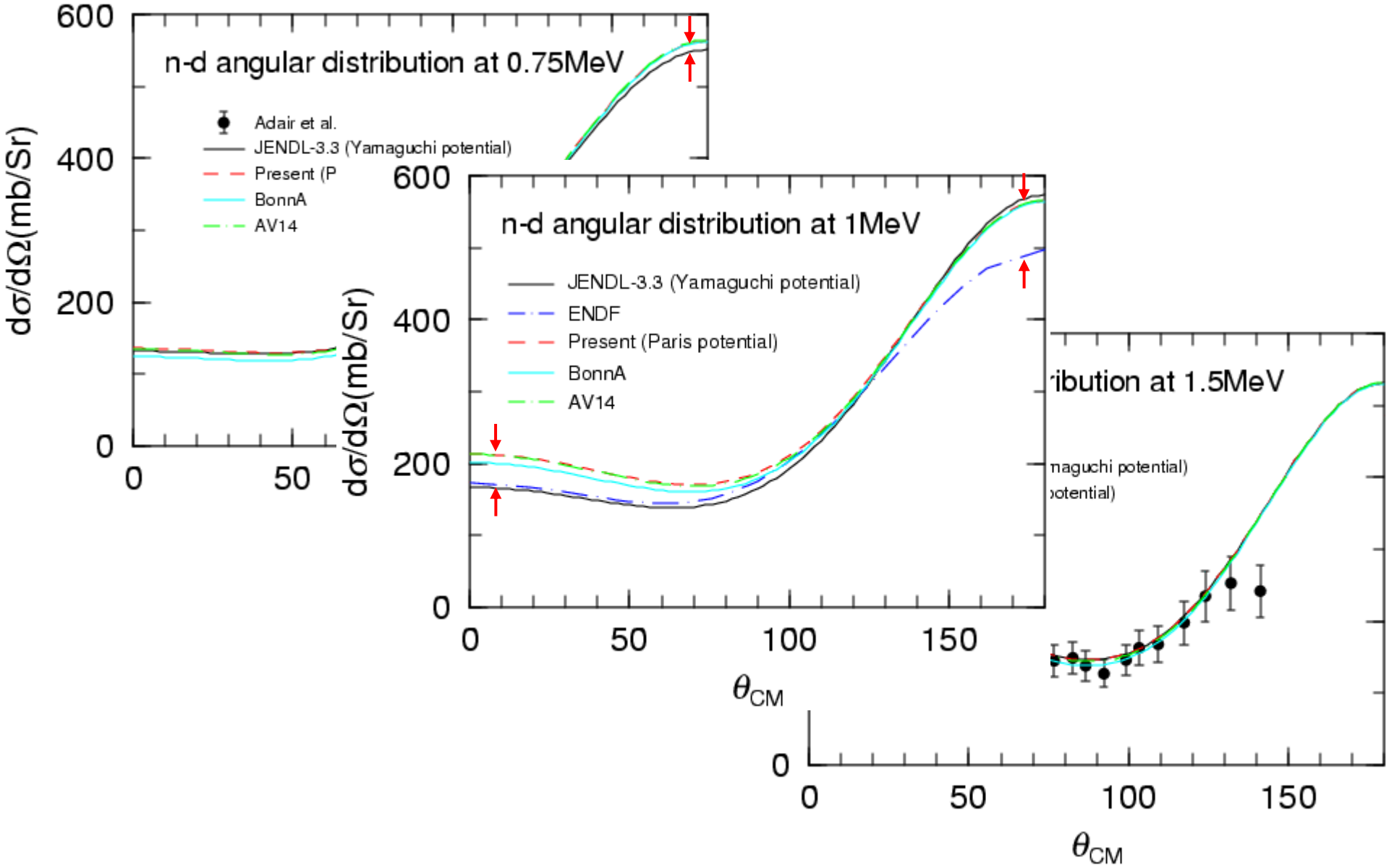
- resonance structure is prominent (measurement at single energy point may not be enough)
- rearrangement reactions such as $^{6}Li(n, \alpha)$ has positive Q-value, so it is dominant than (n, γ) at astrophysical energies.
- It may even affect the explosion (ORNL, Mathews).
- If so, the energy distribution may deviate from the thermal one, and we need "energy dependent" cross sections.

Some nuclear data issues （heavy nuclei）

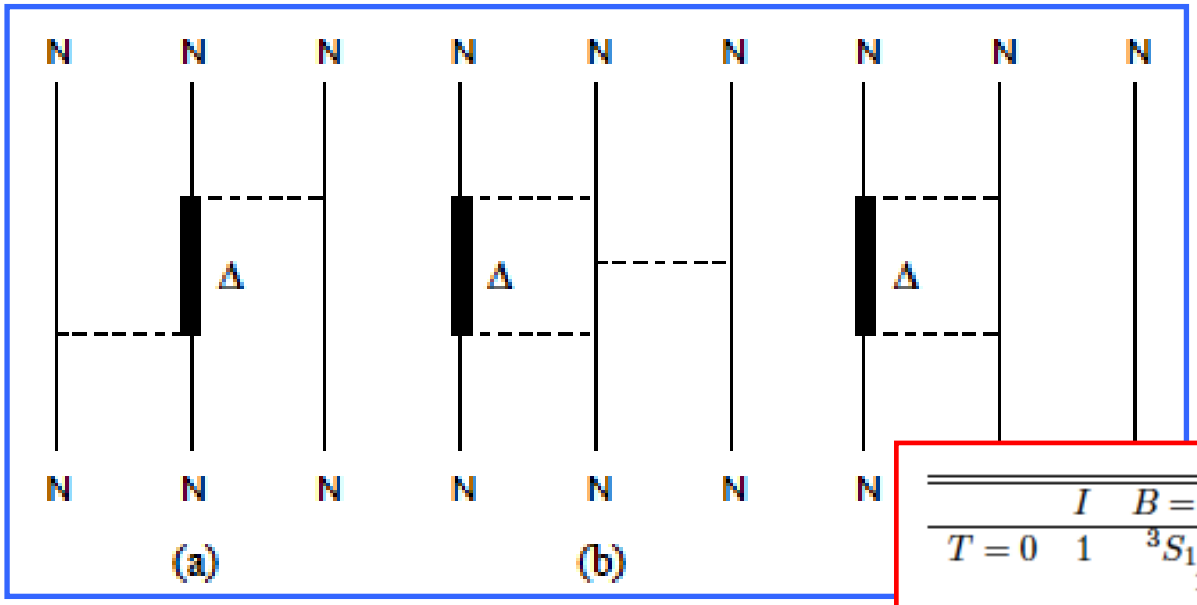


- compound v.s. direct capture
- fission-related quantities are difficult to calculate : e.g., fission barrier parameters, level density at the saddle
- ν （average number of neutrons emitted per fission）may be very large for neutron-rich region (β -delayed fission-neutron driven r-process after cease of normal r-process?)

n-d弾性散乱（低エネルギー）



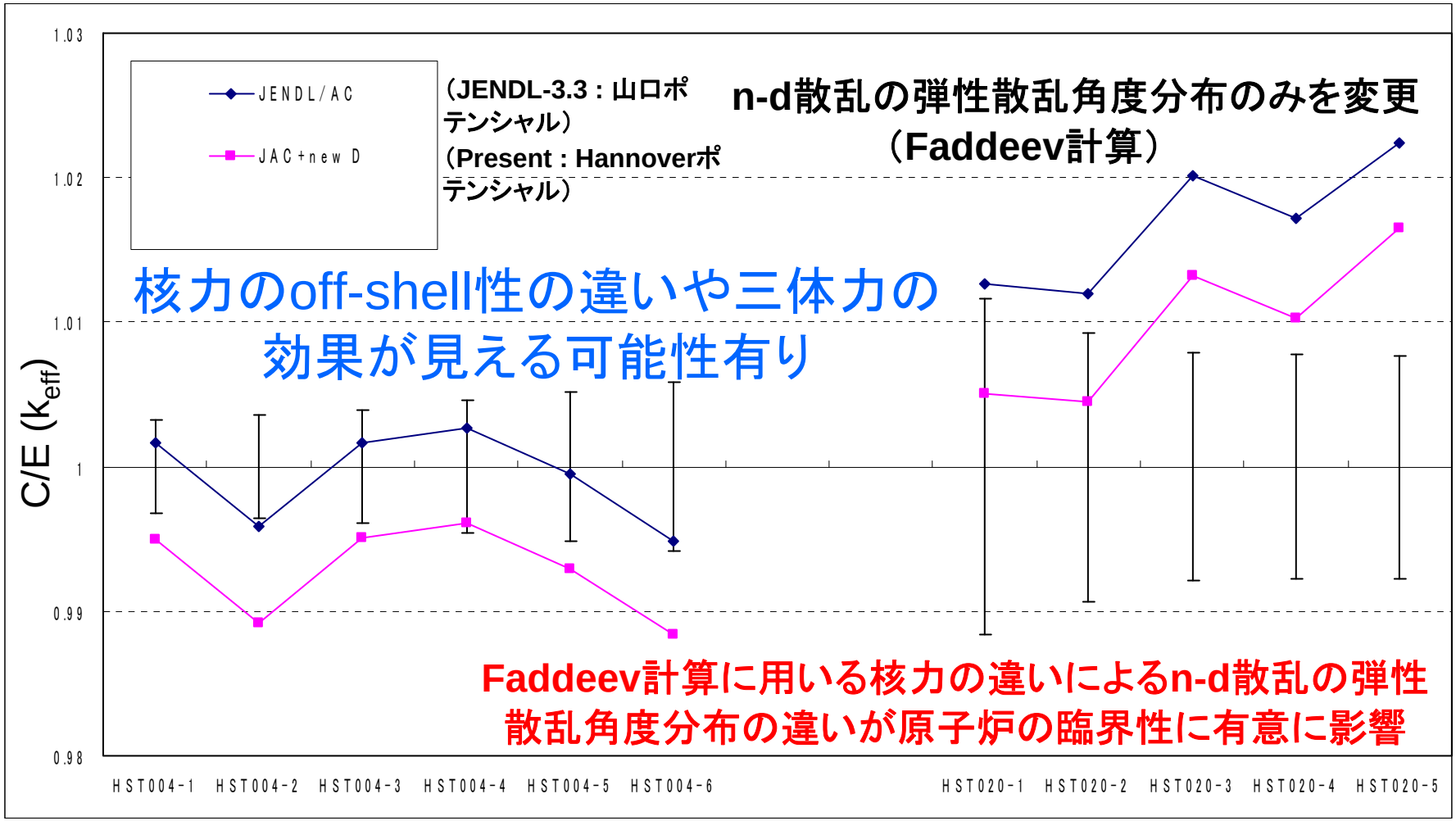
Faddeev理論計算



- N-N : PEST（Paris ポテン
- Δ粒子チャンネルを介す
- p-d散乱に対するクーロン
- 部分波

	I	$B=1(NN)$	$B=0(N\Delta)$
$T=0$	1	${}^3S_1$ - ${}^3D_1$	
		${}^1P_1$	
	2	${}^3D_2$	
	3	${}^3D_3$ - ${}^3G_3$	
		${}^1F_3$	
	4	${}^3G_4$	
$T=1$	0	${}^1S_0$	${}^5D_0$
		${}^3P_0$	${}^3P_0$
	1	${}^3P_1$	${}^3P_1$ - ${}^5P_1$ - ${}^5F_1^*$
	2	${}^3P_2$ - ${}^3F_2$	${}^3P_2$ - ${}^5P_2$ - ${}^3F_2^*$ - ${}^5F_2^*$
		${}^1D_2$	${}^3D_2$ - ${}^5S_2$ - ${}^5D_2$ - ${}^5G_2^*$
	3	${}^3F_3$	
	4	${}^1G_4$	
		${}^3F_4$ - ${}^3H_4$	

重水溶液原子炉の臨界性（実効増倍係数）

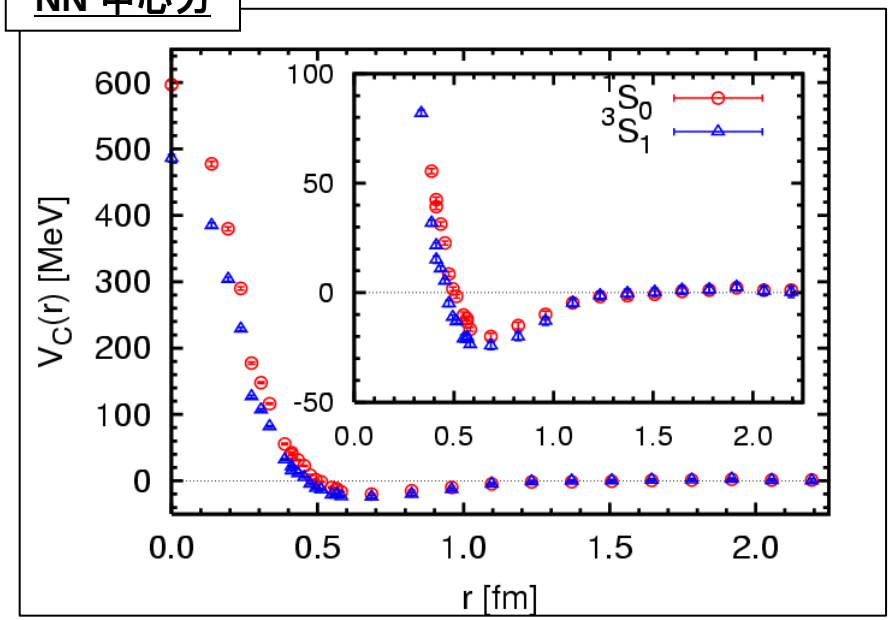


小型重水溶液燃料、重水反射対付き原子炉　　中型で裸の重水溶液燃料原子炉

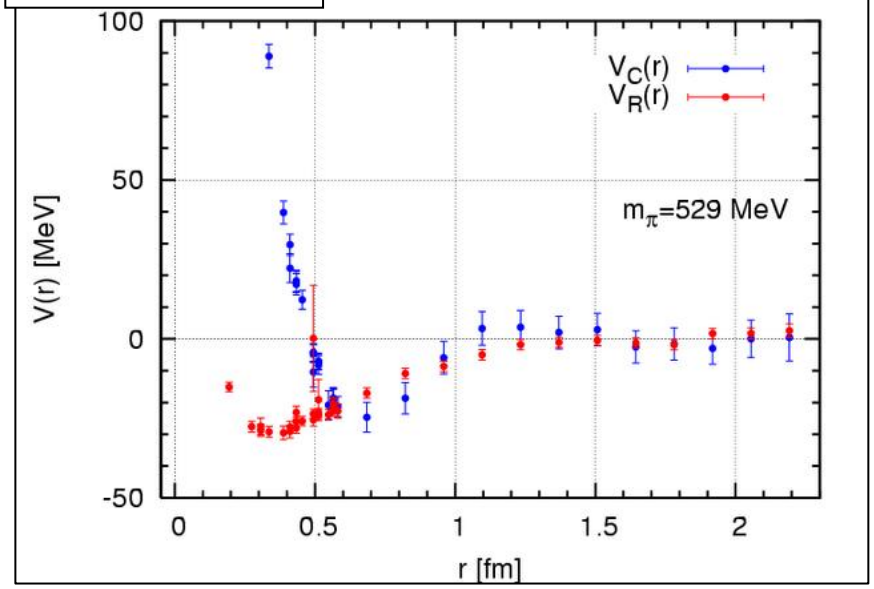
ICSBEP : International Criticality Safety Benchmark Evaluation Project

石井　理修氏（つくば大）のPPTより

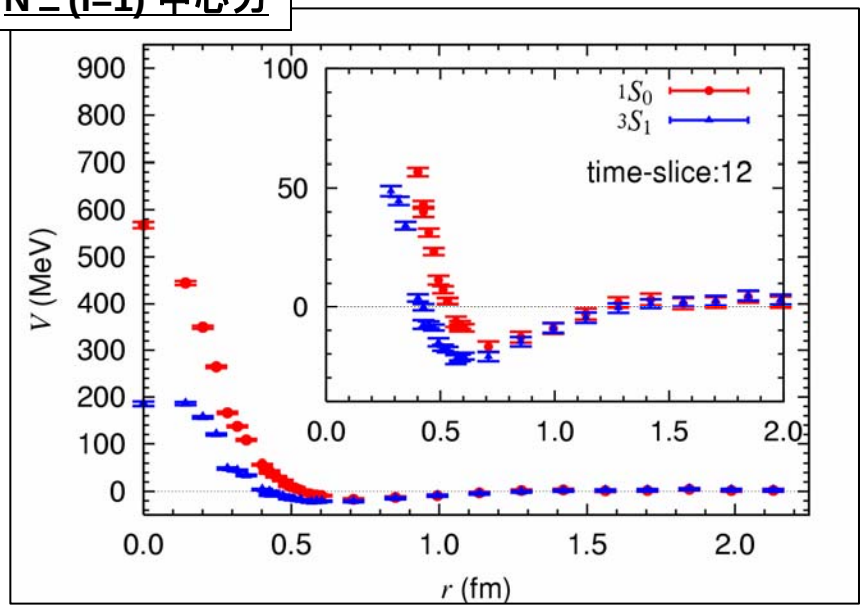
NN 中心力



NN テンソル力



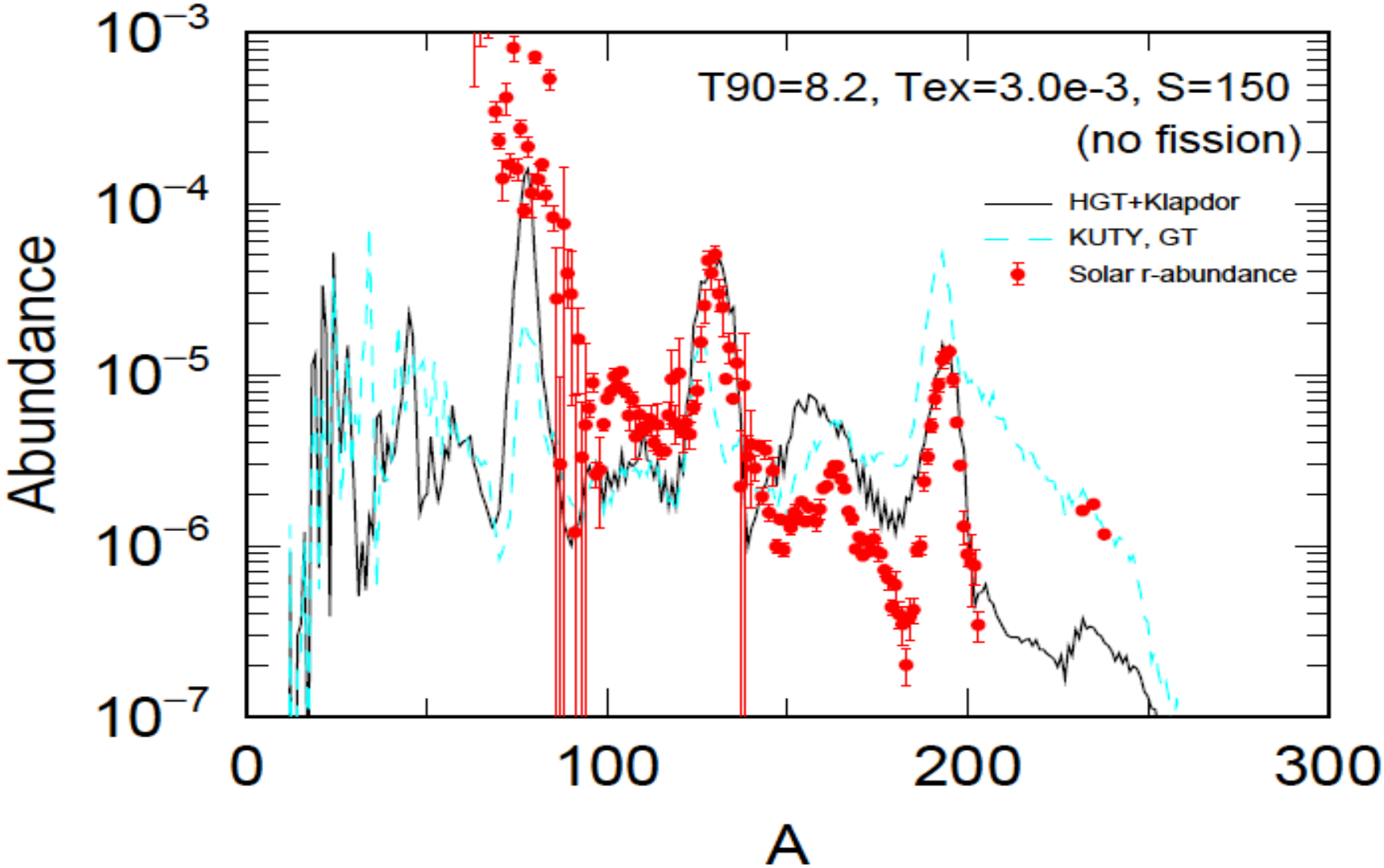
N Ξ (I=1) 中心力



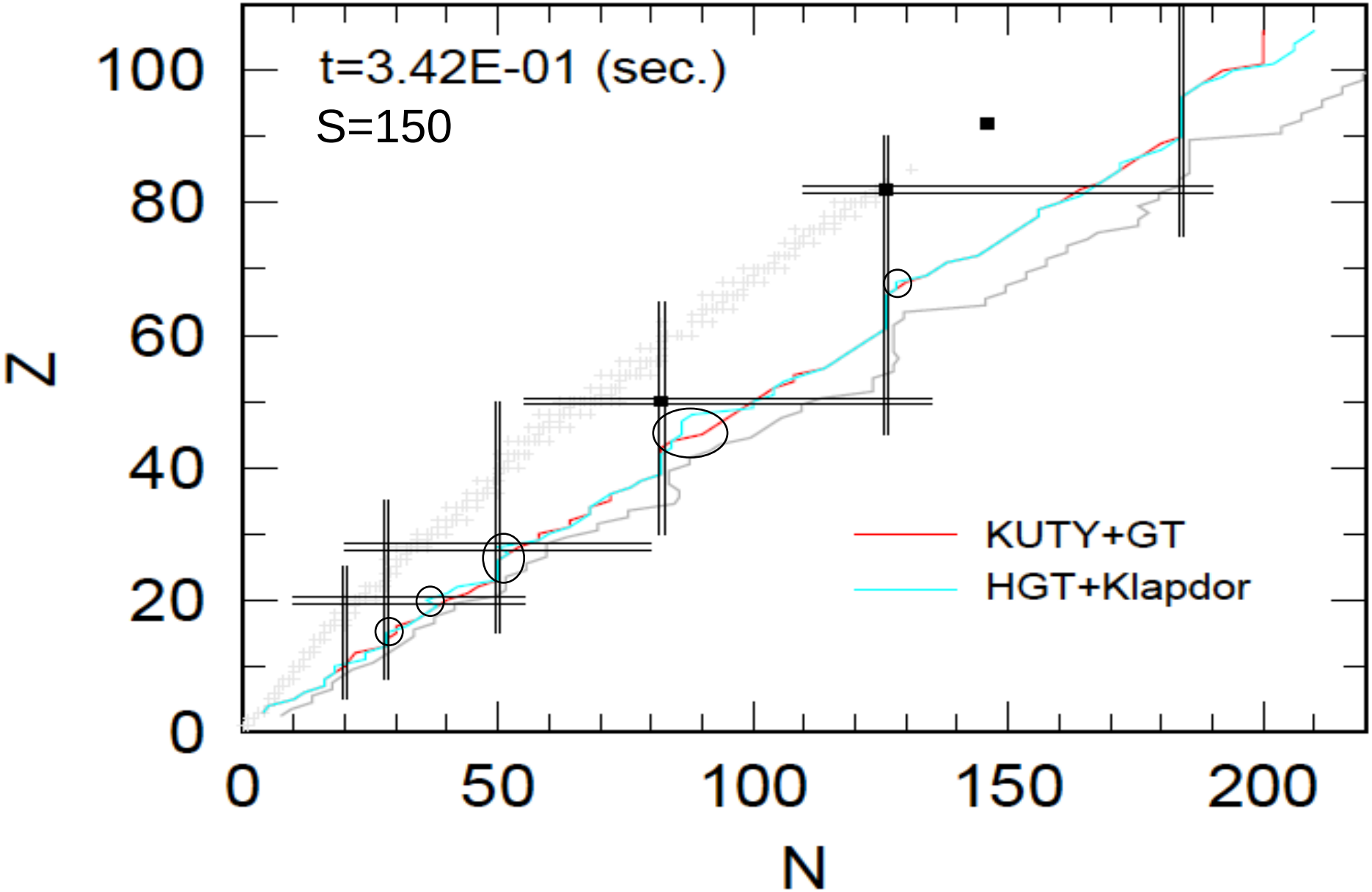
- 中心力だけでなく、テンソル力も。
- ハイペロン力も容易に求まる。
  （現在、NΛポテンシャルが進行中）
- full QCDも進行中。

•原子力工学者には、非局所ポテンシャルや運動量表示のポテンシャルは使いにくい
•これを使えば文句を言われない、という核力を使い安い形で出して欲しい
•ストレンジネスの有効利用のアイデア

HGT+Klapdor → KUTY+GTへの変更結果(質量分布)



最も中性子過剰側に寄った時間でのパス



Concluding remarks

- Realistic nuclear data are important for r-process network calculation : many problems still remain unresolved
- So far, we have prepared
  - FFMD (Fission Fragment Mass Distribution) based on 2CSM
  - Nuclear mass : KTUY05
  - β -decay rates : Gross Theory
    - β -delayed fission rates
    - β -delayed neutron emission rates
  - some ν -induced reactions

Concluding remarks

- We have carried out r-process dynamical network calculations with β-delayed fission and found
  - Strong model dependence on β-df rates due to difference in B_f
  - If β-df is significant, FFMD has a strong impact on abundance
  - If β-df is significant, universality is influenced
- The model uncertainty in the fission barrier height is still large (around 3 MeV) to make quantitative conclusions on the effect of fission in the r-process abundance
- Ultimately, we need (n,f) reaction rates : we need to refine B_f