The Oklo Phenomenon and Nuclear Data

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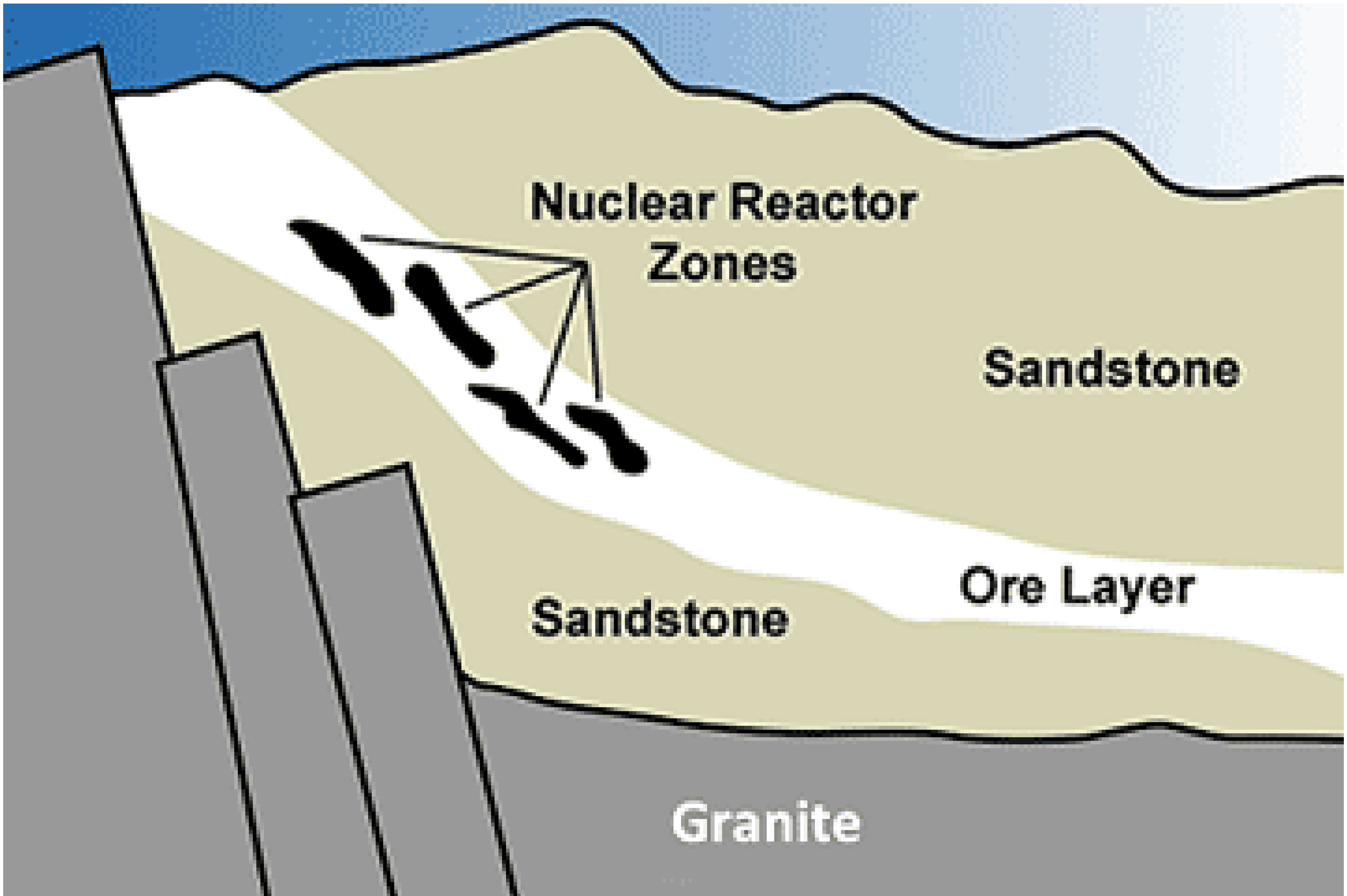
…S of the Oklo uranium
…revealed more
…es where nuclear
…taken place.

Oklo reactor zones



Characteristic Data of the Oklo Phenomenon

age	(1,75 ± 0,10) Ga
duration	200 ka – 500 ka
fluence	max. $1{,}6 \cdot 10^{21}$ cm^{-2}
flux density	10^{7} cm^{-2} s^{-1} – 10^{8} cm^{-2} s^{-1}
burn-up	10 000 MW·d/tU – 25 000 MW·d/tU
conversion factor	0,4 – 0,6
fission events	0 % - 4 % fast fission of U-238
	4 % - 10 % thermal fission of Pu-239

for comparison a modern power reactor:

burn-up	33 000 MW·d/tU
flux density	10^{13} cm^{-2} s^{-1} – 10^{14} cm^{-2} s^{-1}

Nuclear Data used for OKLO

- Neutron cross sections: S.Mughabghab, S.Suchoruchkin
- Mass distribution of fission products: JEFF-3.1.1
- Oklo mass spectroscopy isotopic ratios: Hidaka,Holliger
- Life times, beta- and γ-decay radiation data: ENSDF
- Decay heat: sublibrary of the base ENDF/B-VII.1
- Reactor Physics: IRPhE project, 2011-Handbook
- Photoexcitation cross sections: latest Astrophysics Refs

H Hidaka P Holliger, Geochimica et Cosmochimica Acta 62 1998 8
R. Naudet, Oklo: des Reacteurs Nucleaires Fossiles, Eyrolles 1991

Plan of the talk

- Nuclear data for OKLO study
- OKLO phenomenon and variation of $\alpha=e^2/\hbar c$
- Temperature problem for OKLO reactor zones
- Lutetium thermometry with 175/176 Lu-isotopes
- Analysis and suggestions on Lu-176 isomeric ratio
- Lu-176 burning through (γ,γ') channel
- Gamma ray fluxes in Oklo zone RZ10

Co-authors: C Gould, A. Sonzogni,

The work is partly published: PRC C85 (2012) 024610

OKLO and time variation of $\alpha = e^2/\hbar c$

Current Limits on $d/dt(\Delta\alpha/\alpha)$

$$\Delta\alpha = (\alpha_{past} - \alpha_{present})$$

Review: J.-P. Uzan, Liv. Rev. Relativity, v. 14 (2011), 2

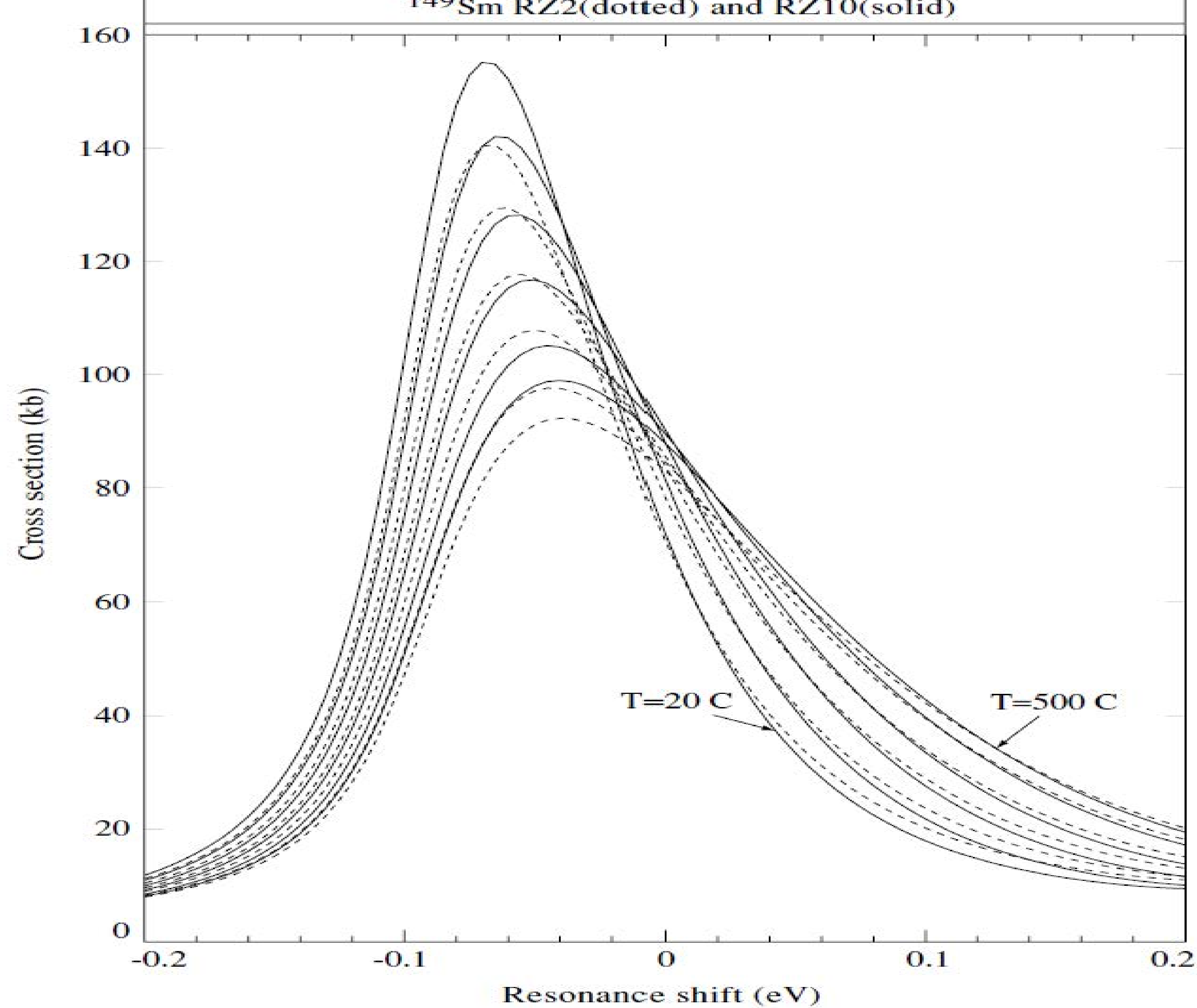
Oklo over 2 Gyr (2006) $< 4 \times 10^{-18}\ yr^{-1}$

Atomic clocks: Hg, Al (2008) $< 4 \times 10^{-17}\ yr^{-1}$

*Quasars over 10 Gyr (2011)** $\sim 2 \times 10^{-16}\ yr^{-1}$

*(smaller in the past)

C. Gould, E. Sharapov, S. Lamoreaux, PRC 83 (2006) 205618 Yu.Petrov et al.: G. Onegin, PRC 84 (2006) 205888



^{149}Sm RZ2(dotted) and RZ10(solid)
Cross section (kb)
Resonance shift (eV)
T=20 C
T=500 C
160
140
120
100
80
60
40
20
0
-0.2
-0.1
0
0.1
0.2

Oklo temperature problem

Temperatures cited for Oklo vary widely

Indirect arguments:

• *Damour and Dyson (96)*	*450 - 1000 C*
• *Fujii et al (02)*	*180 - 400*
• *Gould et al (06)*	*200- 300*
• *Petrov et al (06)*	*400- 500*

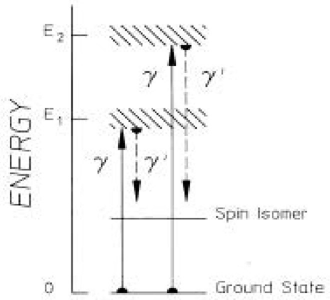
Lutetium thermometry – analyze abundances of ^{175}Lu and ^{176}Lu,
Sensitivity is due to 141 eV resonance in ^{176}Lu

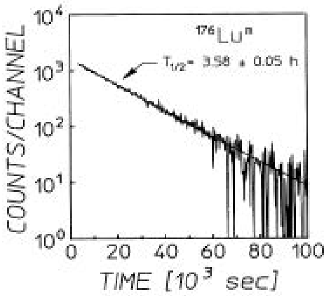
• *Holliger and Devillers (81)*	*260-280*
• *Onegin (10)*	*100-260*
• *Hidaka and Holliger (98)*	*380, or >1000 ?!*

Lutetium properties relevant for Oklo

Lu abundances and cross sections

	175	176
Natural	97.401%	2.599%
Oklo (meta sample)	99.6%	0.4%





Complications!

a)huge difference in capture

175 ~ 20b

176 ~2000b *Er=0.14 eV*

b) 175 capture is to 7⁻ g.s as well as to 4 hr 1⁻ isomer

c) 176 isomer can be photo excited in (γ , γ') reactions

Definitions specific for Oklo study

'Effective' neutron Xs: σ*_ef* $= \int \sigma(v) n(v,T) v \, dv / \int n(v,T) v_o \, dv$

'Effective' neutron Flux: Φ*_ef* $= \int n(v,T) v_o \, dv$, *vo = thermal*

Standard: $\langle \Phi \rangle = \int n(v,T) v dv$, $\langle \sigma \rangle = \int \sigma(v) n(v,T) v dv / \int n(v,T) v dv$

σ*_ef* Φ*_ef* $= \langle \sigma \rangle \langle \Phi \rangle$

Cross section branching: B_g = σ*_g/(*σ*_g +* σ*_m)*

Burning constant: λ *=* σ*_ef* Φ*_ef*

Shorthand for numbers of atoms for A=176 (Lutetium): N6(t)

Shorthand for neutron Xs of Lu-175, 176*:* σ*_ef-5,* σ*_ef-6*

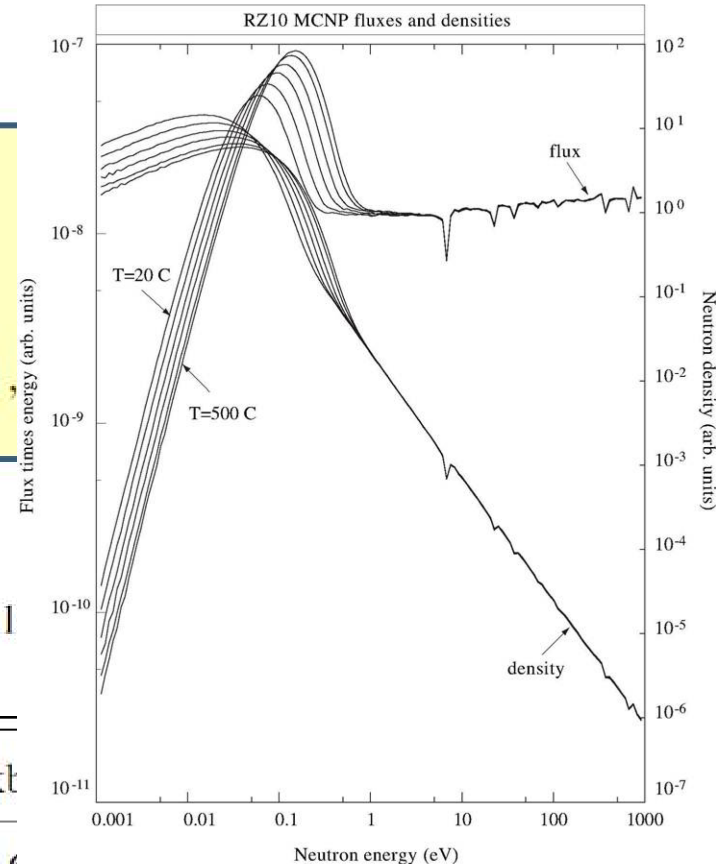
Lutetium thermometry

$$\frac{N_6}{N_5}(\text{now}) = \frac{N_6^0}{N_5^0}\exp(-(\hat{\sigma}_6 - \hat{\sigma}_5)\hat{\Phi}t_1) + B^g\frac{\hat{\sigma}_5}{\hat{\sigma}_6 - \hat{\sigma}_5} \times [1 - \exp(-(\hat{\sigma}_6 - \hat{\sigma}_5)\hat{\Phi}t_1)]\exp\left(-\frac{D\ln 2}{t_{1/2}}\right),$$

σ_ef-6 depends on T, so the isotopic ratio N6/N5(now) does!

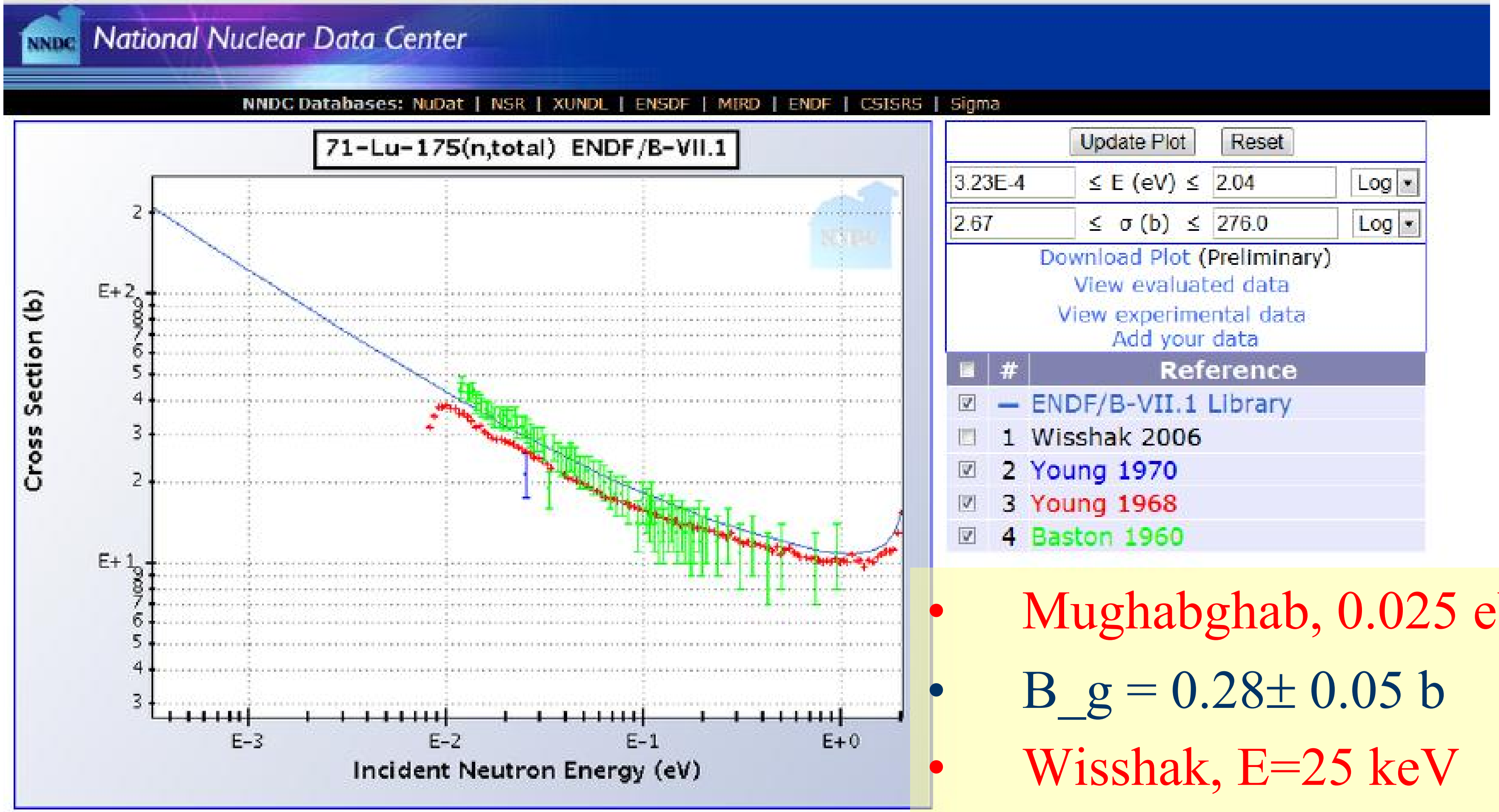
TABLE I. Lutetium cross sections $\hat{\sigma}_5$ and $\hat{\sigma}_6$ for the Oklo RZ1 reactor at temperatures T_O from 0 °C to 600 °C (see text).

T_O (°C)	$\hat{\sigma}_5$ (kb)	$\hat{\sigma}_6$ (kb)
0	0.115	4.21
20	0.115	4.487
100	0.115	5.359
200	0.115	6.310
300	0.114	7.013
400	0.114	7.544
500	0.114	7.715
600	0.114	7.750



This slide illustrates Lu-176 burning through neutron channel. There exists however problem with the B_g parameter.

Lu-175 branching ratio problem

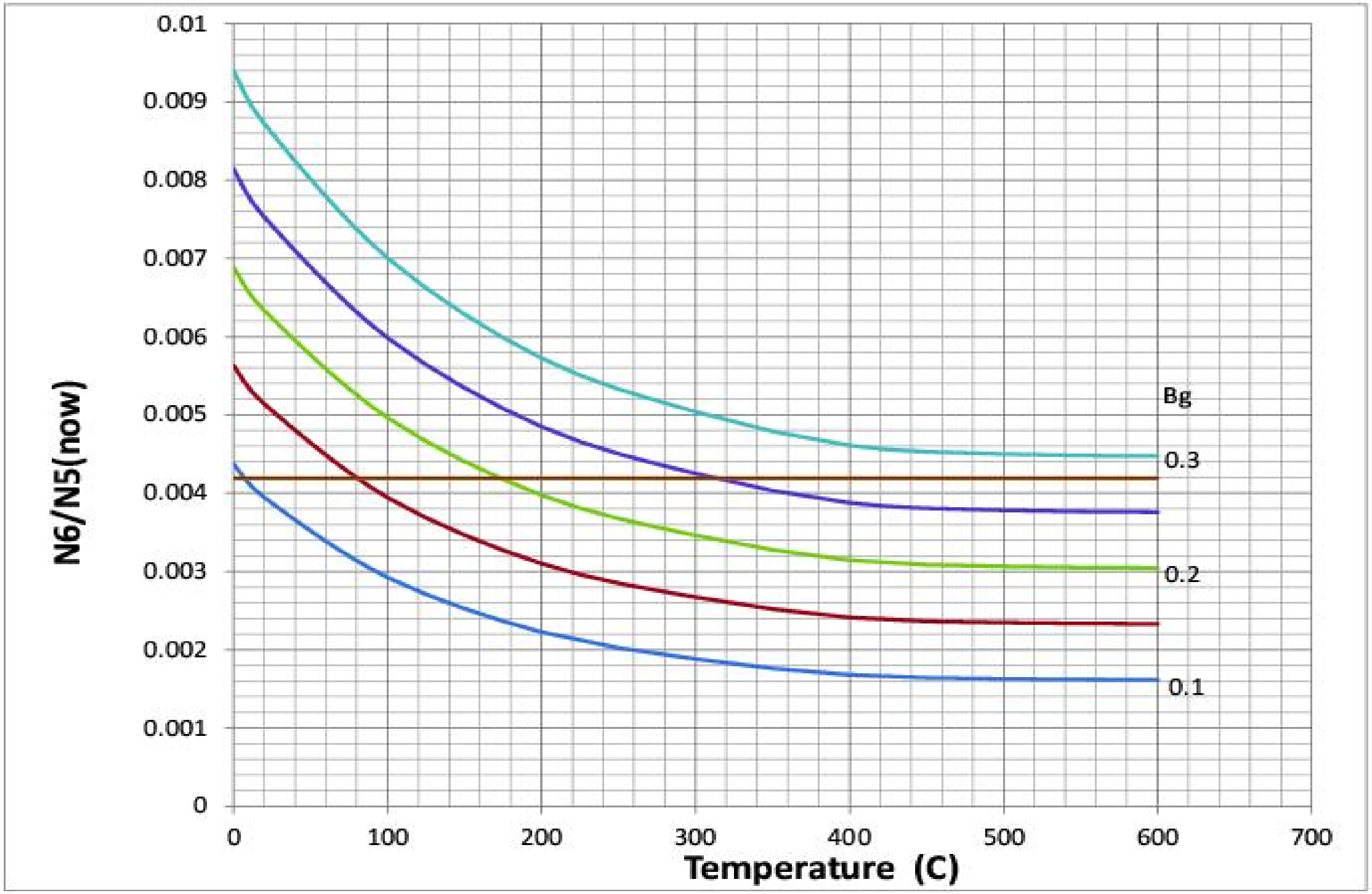


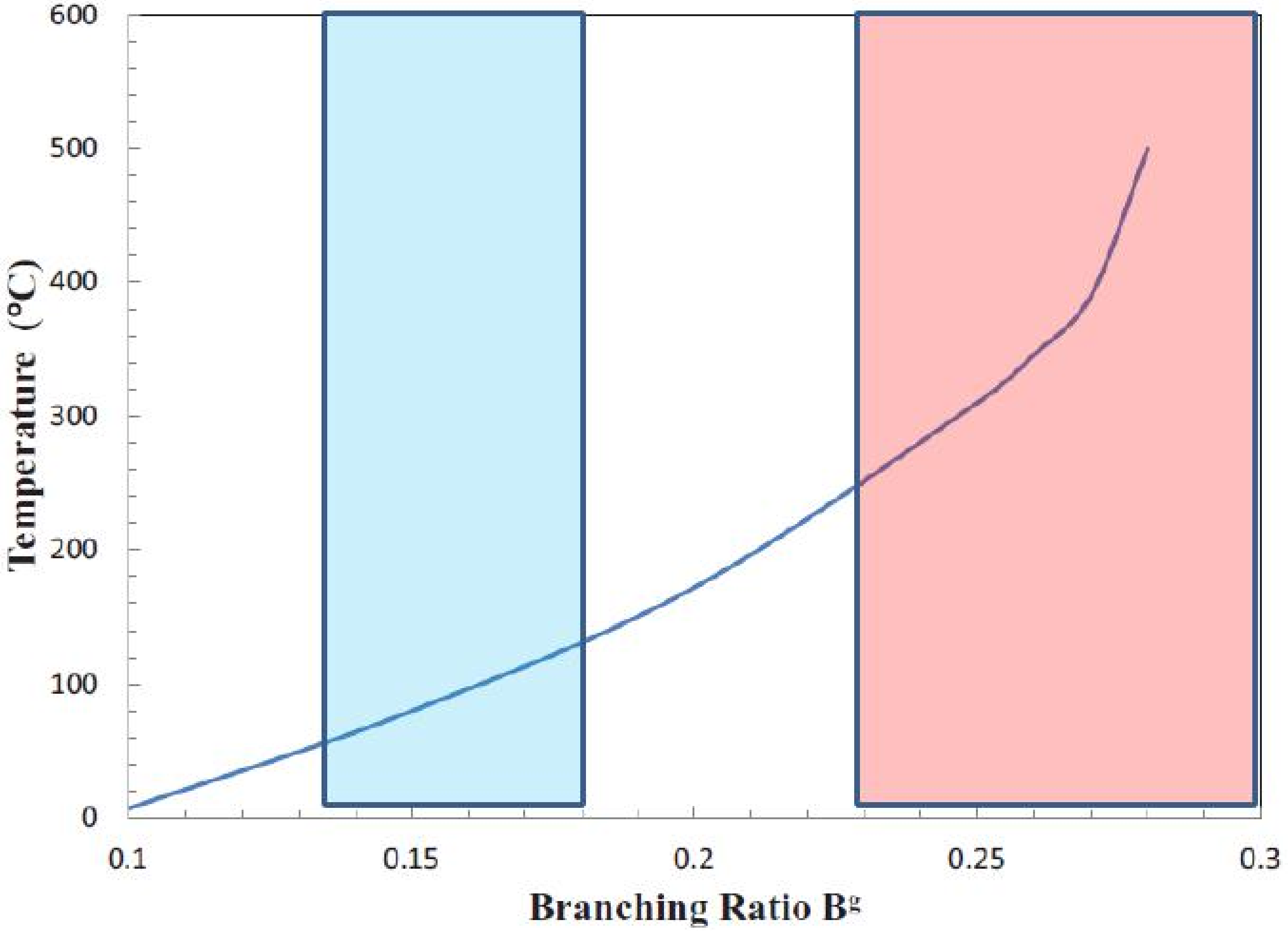
- Mughabghab, 0.025 eV
- B_g = 0.28± 0.05 b
- Wisshak, E=25 keV
- B_g = 0.14± 0.02 b
- A. Baston revisited
- B_g = 0.21± 0.11 b

Activation cross section to Lu-176m σ-m

σ_m = 17 ± 2 b; σ_m+σ_g = 23.± 2 b

Lutetium thermometry: continue

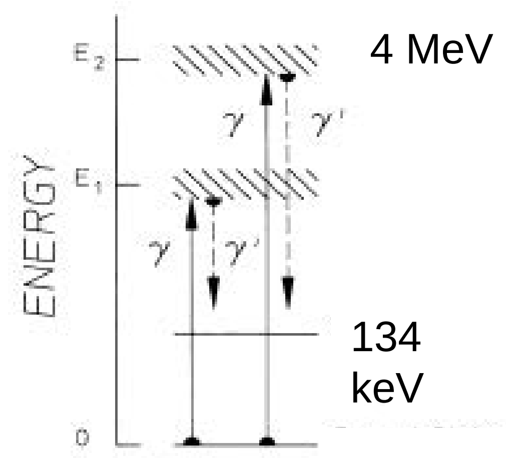




We suggest to perform new, Improved Measurements of the Lu-175 thermal capture and activation cross sections in order to obtain a precision value of the branching ratio B_g for thermal neutrons

Lu-176 burning through (γ,γ') reaction

$$\lambda_{\gamma\gamma'}(\mathbf{E_k}) = \int \Phi_\gamma(E)\,\sigma_{\gamma\gamma'}(E, \mathbf{E_k})\,dE$$
$$= \Phi_\gamma(\mathbf{E_k})\,\sigma_{\gamma\gamma'}^{int}(\mathbf{E_k})$$



Lu-176

J. Carroll, Astrophys. J. (1989) v.34

$\mathbf{E_k} = 839$ keV, $\sigma_{\gamma\gamma'}^{int} = 33.4$ mb•e

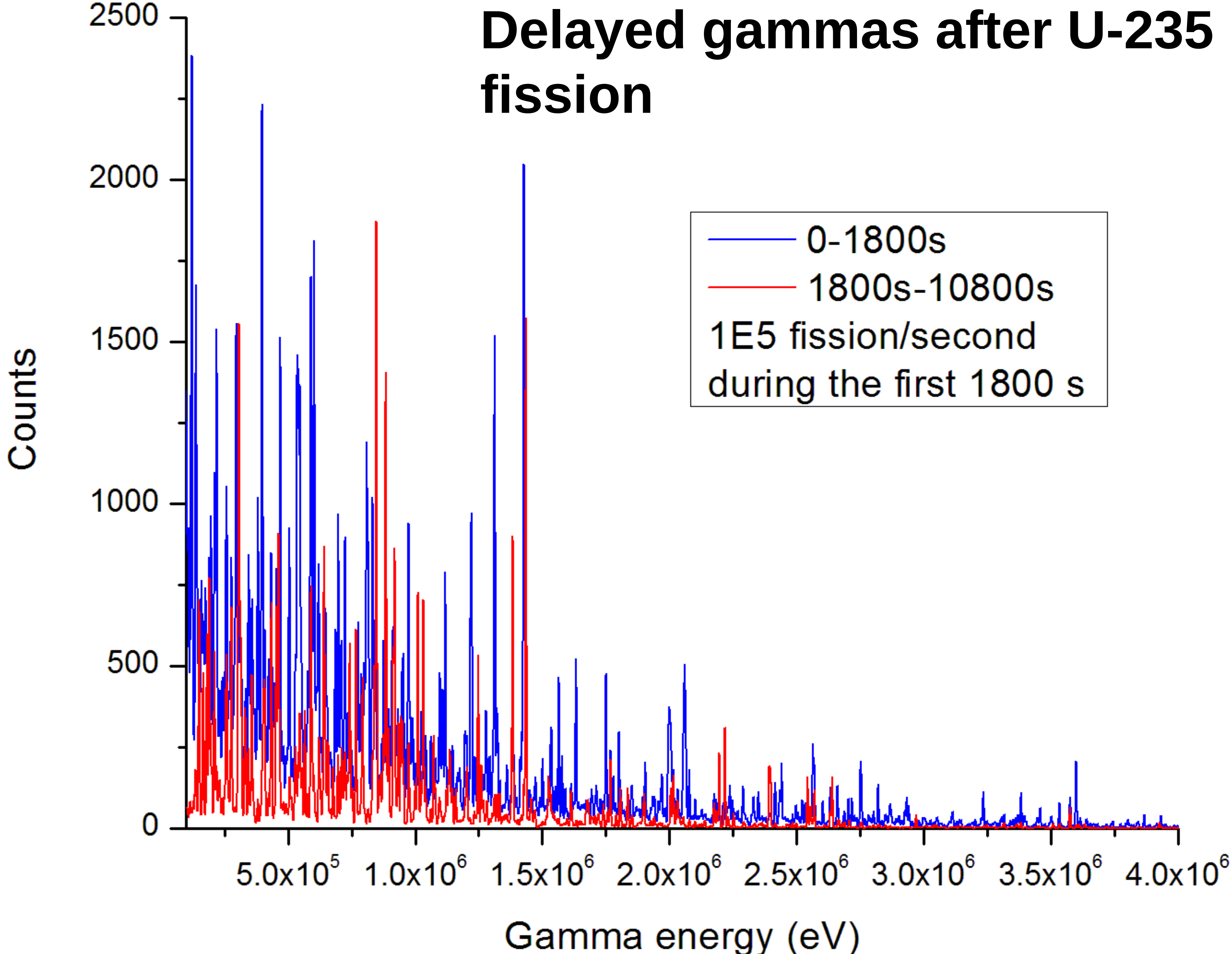
$\mathbf{E_k} = 4.0$ MeV, $\sigma_{\gamma\gamma'}^{int} = 140$ mb•keV

$\Phi_\gamma(E_k)$ = see calculations on next slides

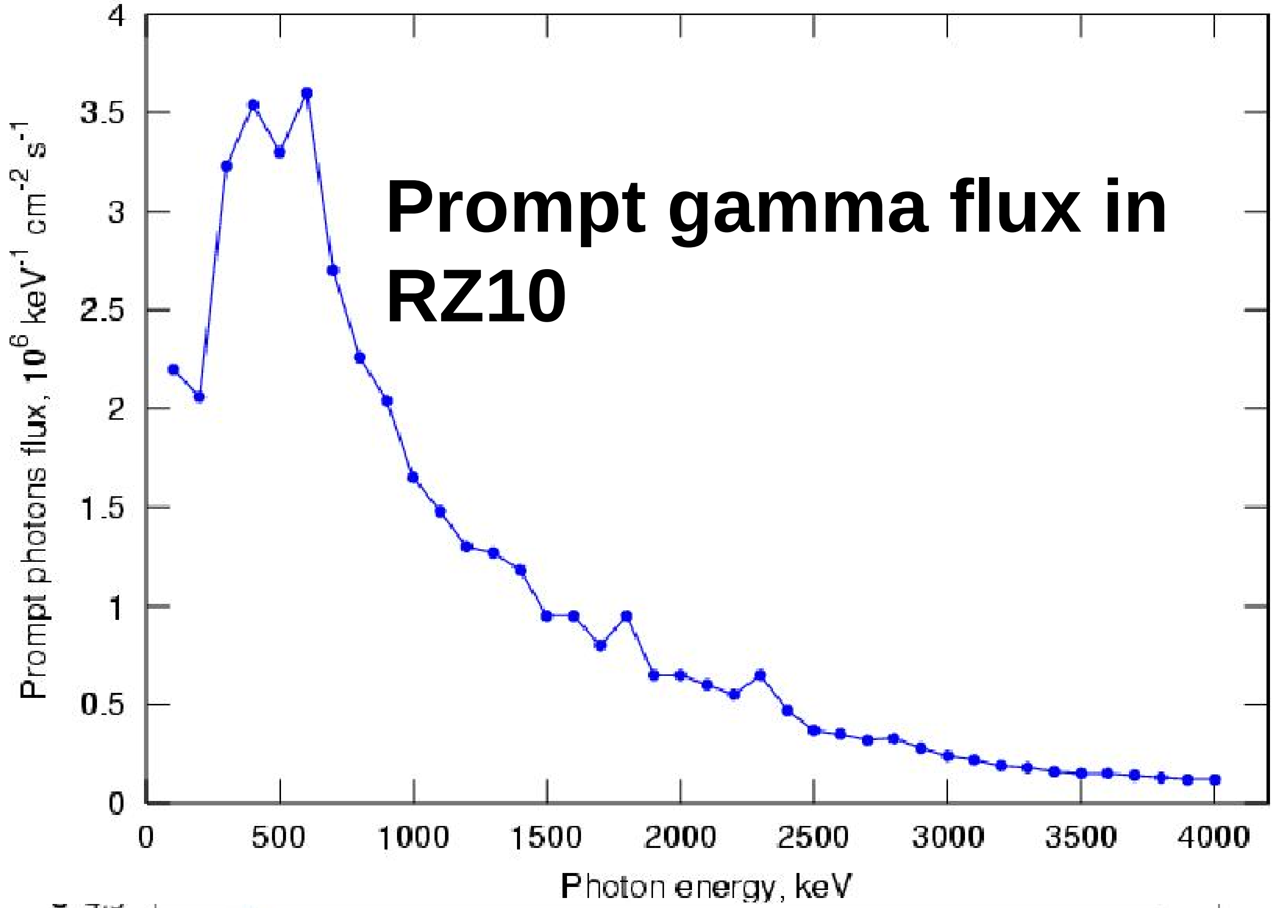
Then, for $\mathbf{E_k} = 4.0$ MeV: (T of the Universe= $1.2 \cdot 10^{10}$ yr)

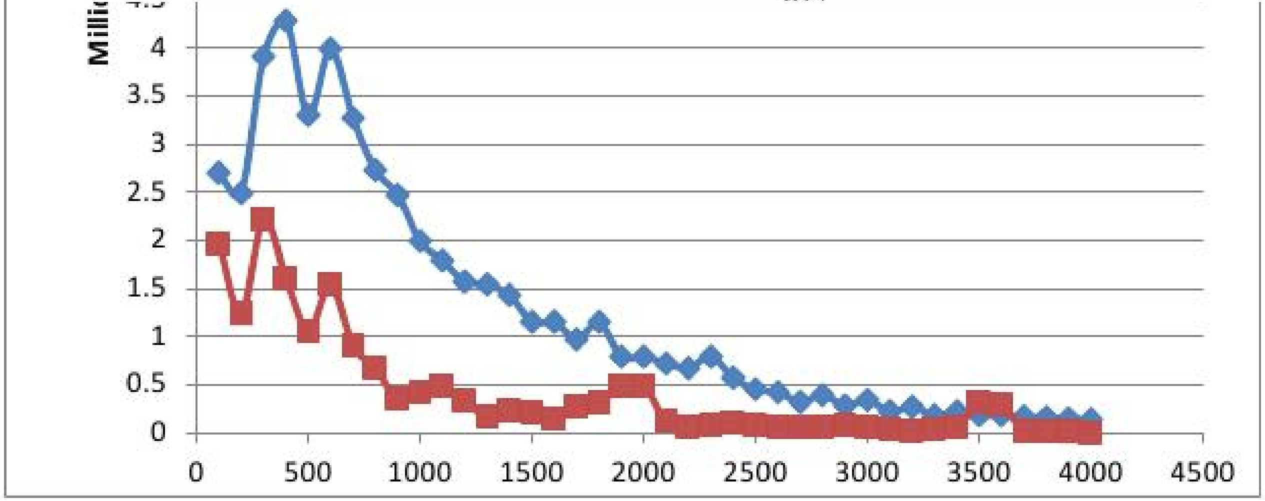
$\lambda_{\gamma\gamma'} < 1.4 \cdot 10^{-20}$ s^{-1}, $T = \ln 2/\lambda_{\gamma\gamma'} > 1.7 \cdot 10^{12}$ yr, This is huge!

Delayed gammas after U-235 fission



Prompt gamma flux in RZ10

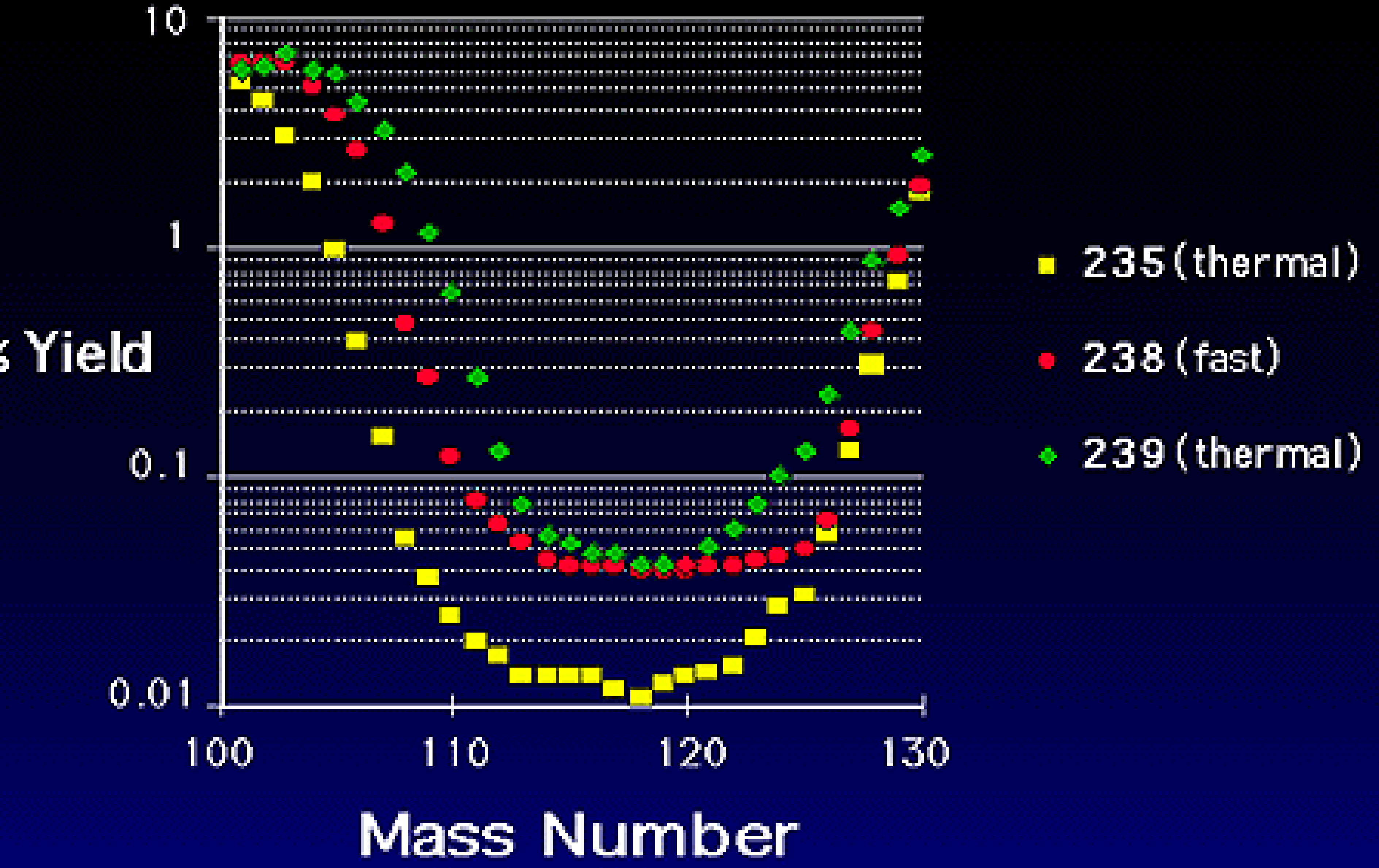


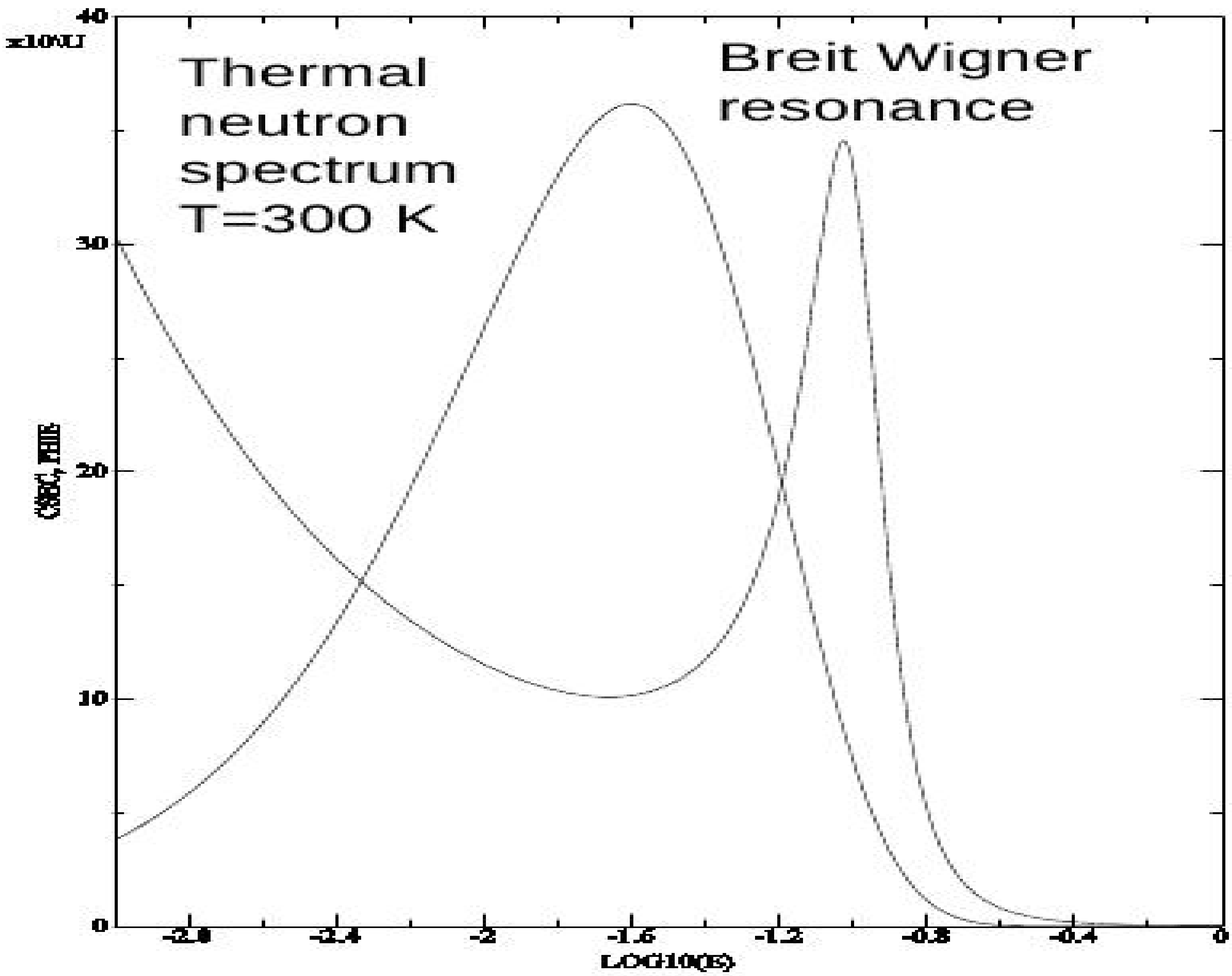


- **In view of the Lu-thermometry, the final word on limits of α variability from Oklo phenomenon might not have been said**
- **In contrast to astrophysics, the Lu-176/175 isotopic ratios in Oklo are not influenced by the (γ,γ') photoexcitation**
- **Applicability of the Lu-thermometry to Oklo reactors studies requires improved neutron cross sections measurements for Lu-175 in the thermal energy region**

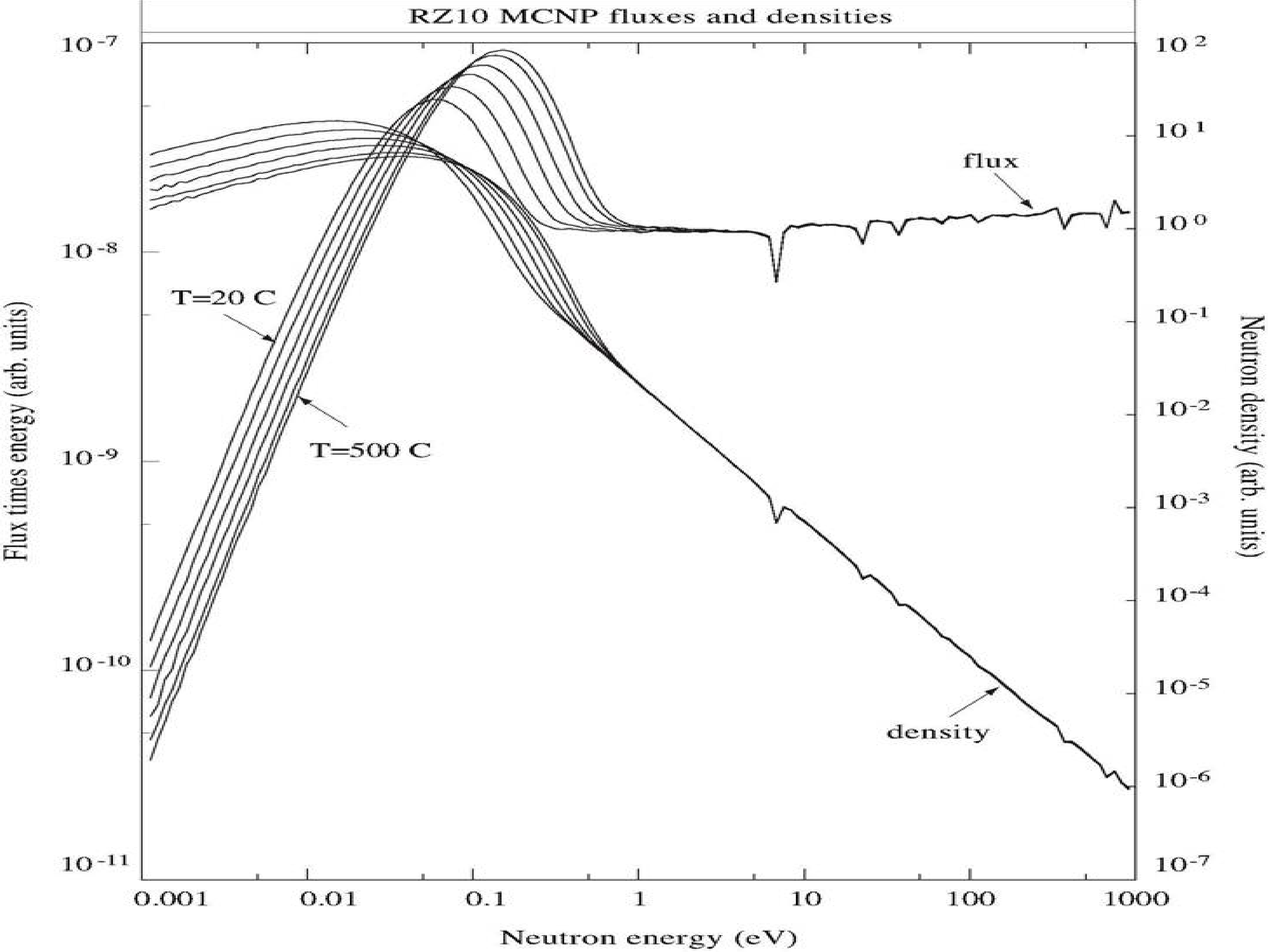
THE END
THANK YOU

Absolute Cumulative Fission Yields





Thermal
neutron
spectrum
T=300 K
Breit Wigner
resonance
40
30
20
10
0
-2.8
-2.4
-2
-1.6
-1.2
-0.8
-0.4
0
LOG10(E)



RZ10 MCNP fluxes and densities
Flux times energy (arb. units)
Neutron density (arb. units)
Neutron energy (eV)
T=20 C
T=500 C
flux
density
10-7
10-8
10-9
10-10
10-11
10 2
10 1
10 0
10-1
10-2
10-3
10-4
10-5
10-6
10-7
0.001
0.01
0.1
1
10
100
1000