*Time Variation of the Fine Structure Constant from Realistic Models of Oklo Natural Nuclear Reactors**

Chris Gould
North Carolina State University and TUNL
Eduard Sharapov
JINR, Dubna
Steve Lamoreaux
Yale University

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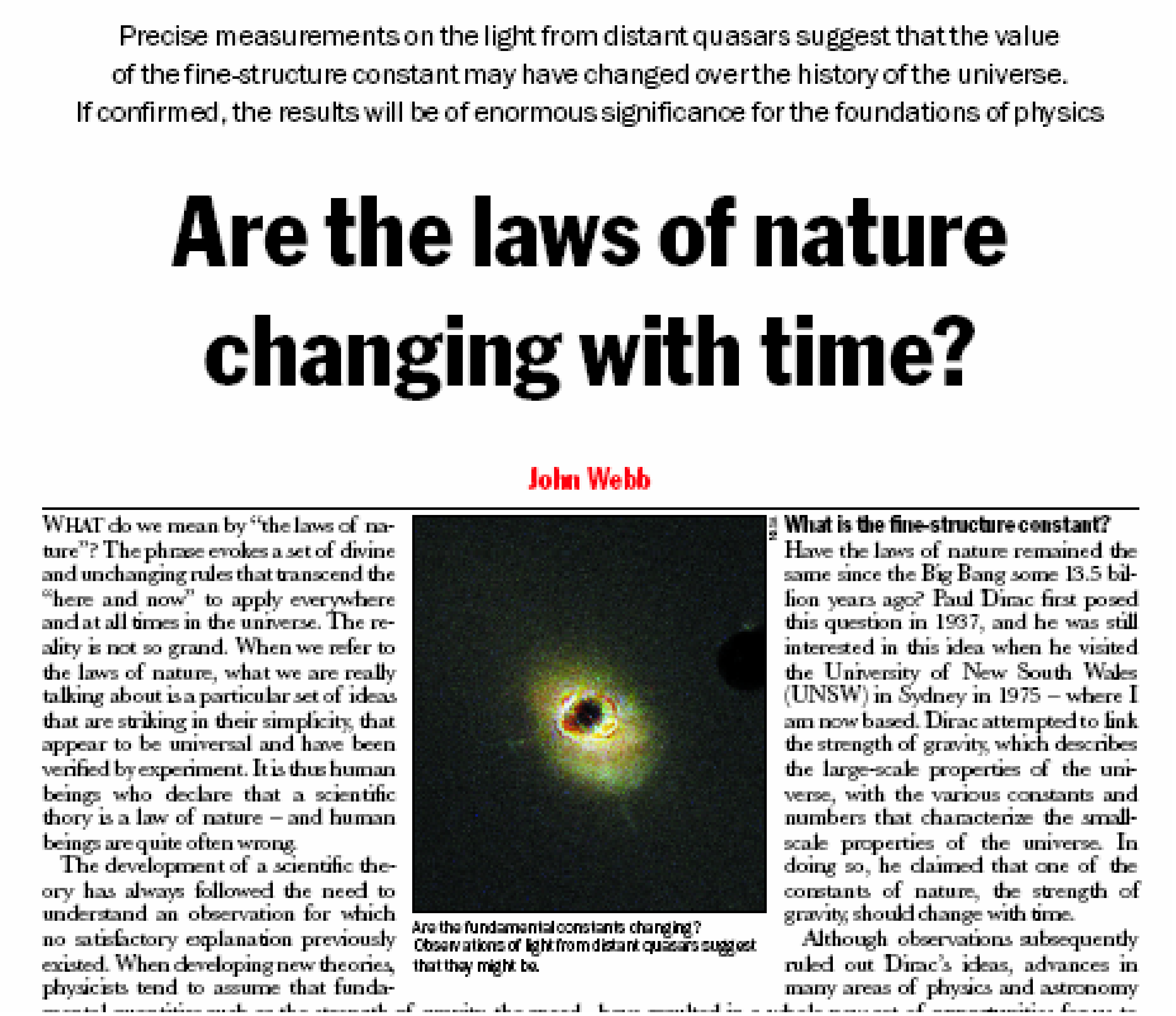


Precise measurements on the light from distant quasars suggest that the value of the fine-structure constant may have changed over the history of the universe. If confirmed, the results will be of enormous significance for the foundations of physics

Are the laws of nature changing with time?

John Webb

WHAT do we mean by "the laws of nature"? The phrase evokes a set of divine and unchanging rules that transcend the "here and now" to apply everywhere and at all times in the universe. The reality is not so grand. When we refer to the laws of nature, what we are really talking about is a particular set of ideas that are striking in their simplicity, that appear to be universal and have been verified by experiment. It is thus human beings who declare that a scientific theory is a law of nature – and human beings are quite often wrong.

The development of a scientific theory has always followed the need to understand an observation for which no satisfactory explanation previously existed. When developing new theories, physicists tend to assume that funda-

Are the fundamental constants changing? Observations of light from distant quasars suggest that they might be.

What is the fine-structure constant?

Have the laws of nature remained the same since the Big Bang some 13.5 billion years ago? Paul Dirac first posed this question in 1937, and he was still interested in this idea when he visited the University of New South Wales (UNSW) in Sydney in 1975 – where I am now based. Dirac attempted to link the strength of gravity, which describes the large-scale properties of the universe, with the various constants and numbers that characterize the small-scale properties of the universe. In doing so, he claimed that one of the constants of nature, the strength of gravity, should change with time.

Although observations subsequently ruled out Dirac's ideas, advances in many areas of physics and astronomy

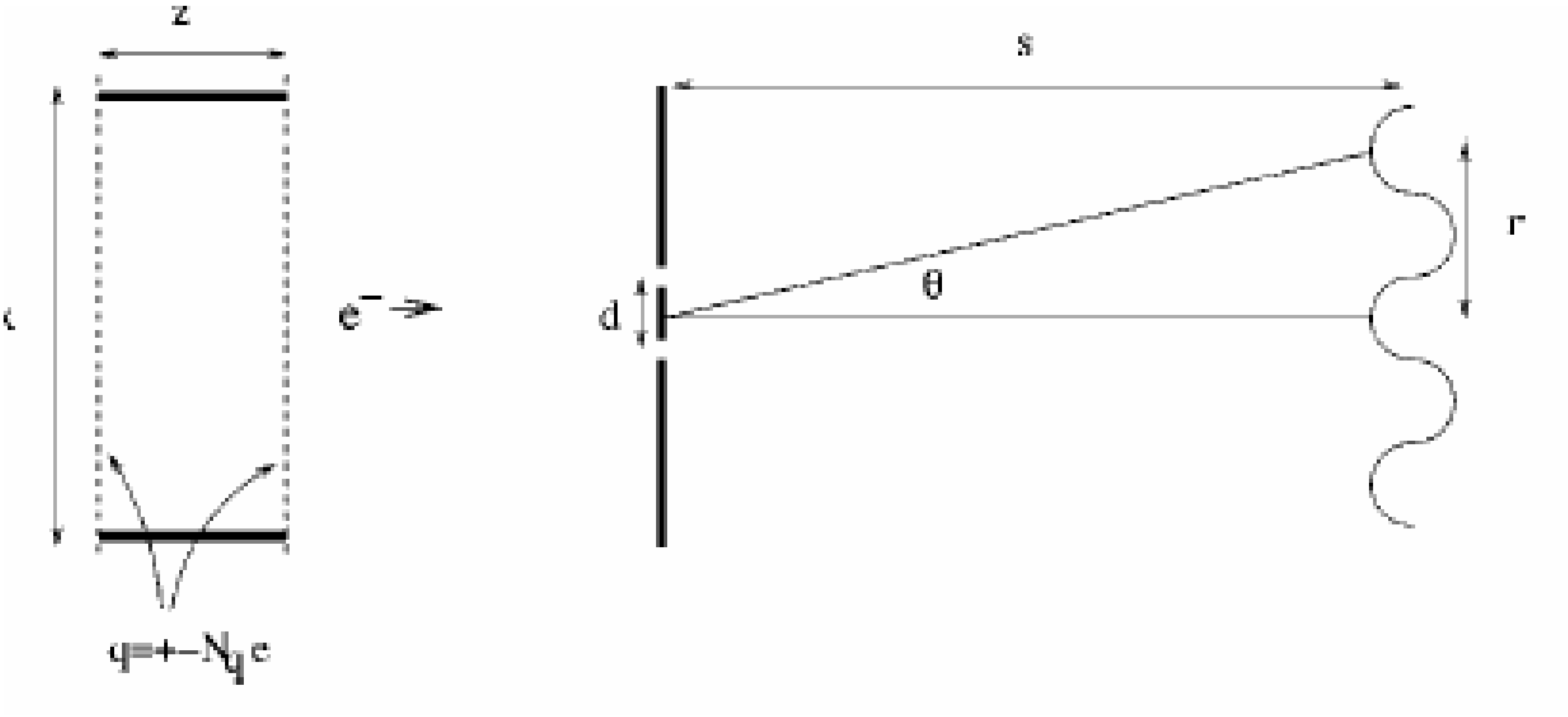
Outline

- *Introduction – time varying constants*
- *History of Oklo natural nuclear reactors*
- *Realistic modeling of Oklo reactor zones*
- *Calculations of ^{149}Sm effective cross section*
- *Bounds on $\Delta\alpha/\alpha$ from RZ2 and RZ10*
- *Conclusions*

Time variation of fundamental constants

- *Long history (Dirac: $G_N \sim 1 / t$)*
- *Feature of extra dimensional theories (Uzan, RMP 03)*
- *Only dimensionless ratios have meaning ($\alpha_G \sim G_N m_p^2/ \hbar c$, $W \sim m_s/\Lambda_{QCD}$, m_e/m_p)*
- *Among the most studied is the fine structure constant $\alpha_{EM} \sim e^2/\hbar c \sim 1/137$*
- *If α_{EM} does vary, it's a matter of taste whether to ascribe it to e, ħ or c*

Detect a change in ħ from two slit interference with electrons?



Rich, AJP (2005)

Look for a change in the diffraction pattern as a function of time

From $p = h/\lambda$ *and* $\Theta = \lambda/d$*, so* $\Theta = h/(pd)$

Expect: $\Theta \sim h$

But wait, d depends on h too:

Bohr radius $a_0 \sim h^2$*, so with* $d = N a_0$

Expect $\Theta \sim 1/h$

But wait again, p depends on h also

Energy $\sim p^2 \sim e\ (Q/\text{area})\ z$*, so* $p \sim 1/h$

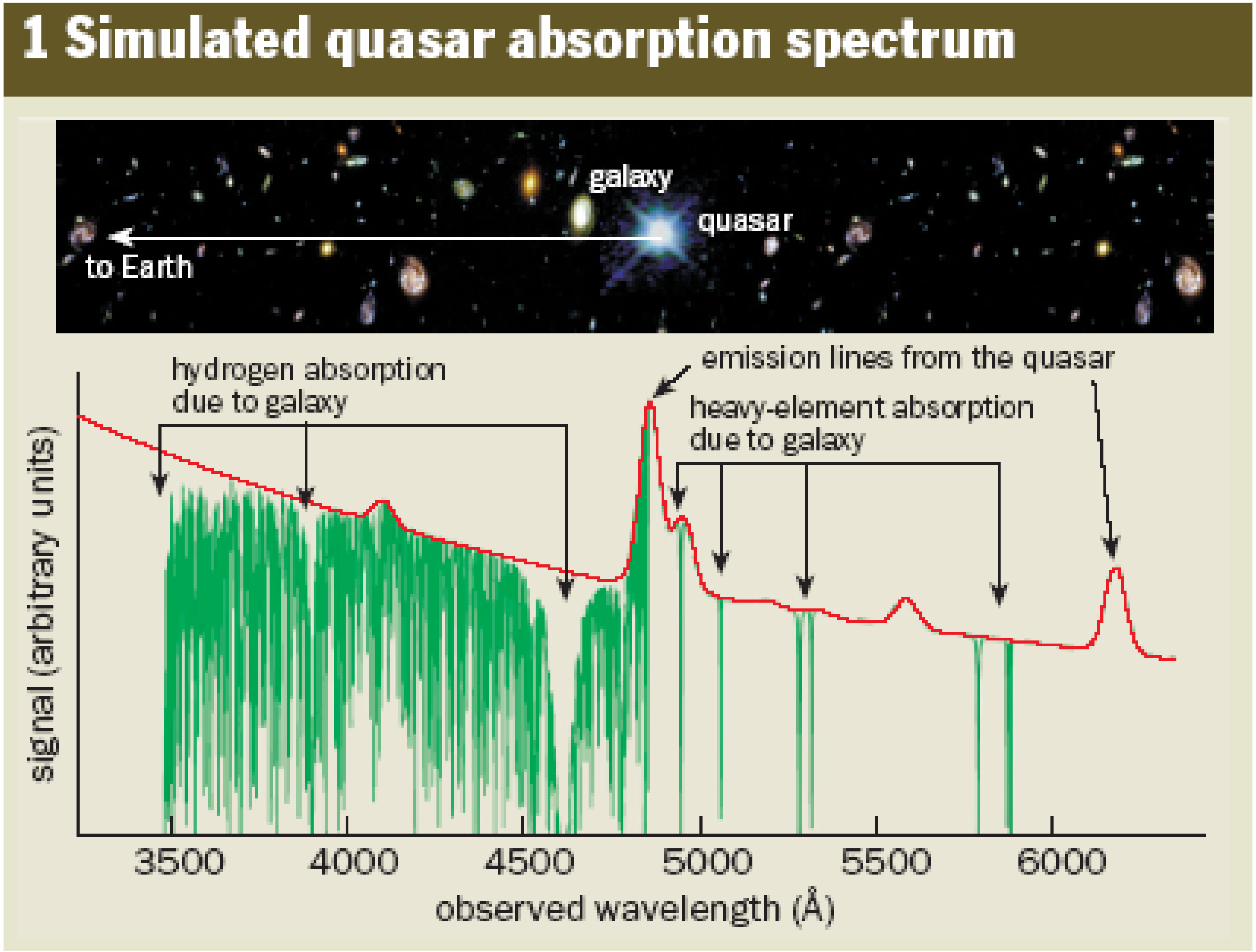
Result: Θ *doesn't depend on h at all (OK, it shouldn't, it's dimensionless)*

Does α vary with time - Quasars

- *Observations of absorption lines in the spectra of distant quasars ($z > 0.5$)- model independent probe of times ~ 10 BY.*

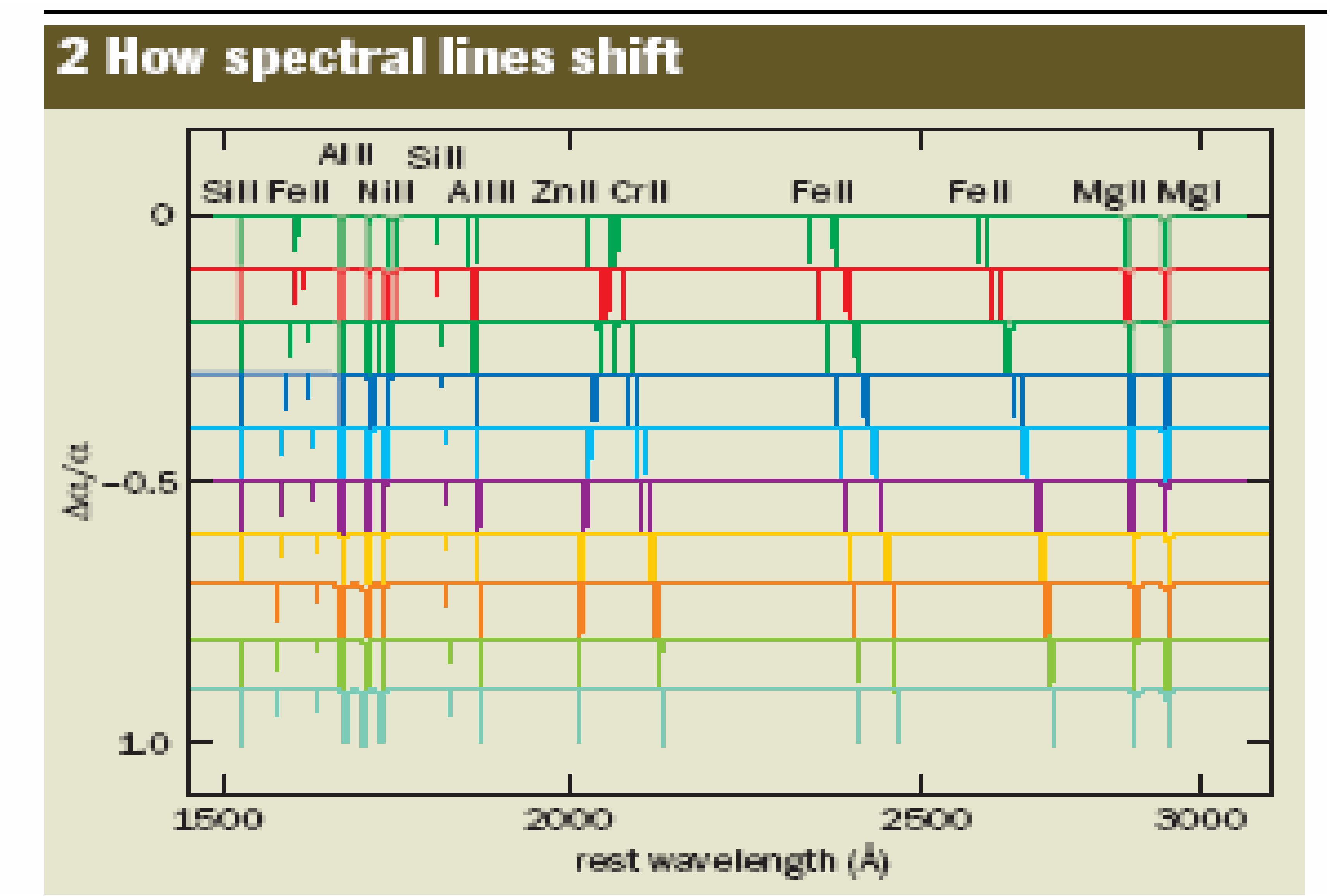
- *Webb et al (01): α increased by ~ $1x10^{-5}$ (5σ effect)*
- *Srianand et al (04): no change, or (Murphy et al (06) reanalysis), 3σ effect increase*
- *Mathews et al (05): change due to Mg isotope abundance differences?*

Quasar absorption lines (Webb et al)



1 Simulated quasar absorption spectrum

Many multiplet method (Webb et al)

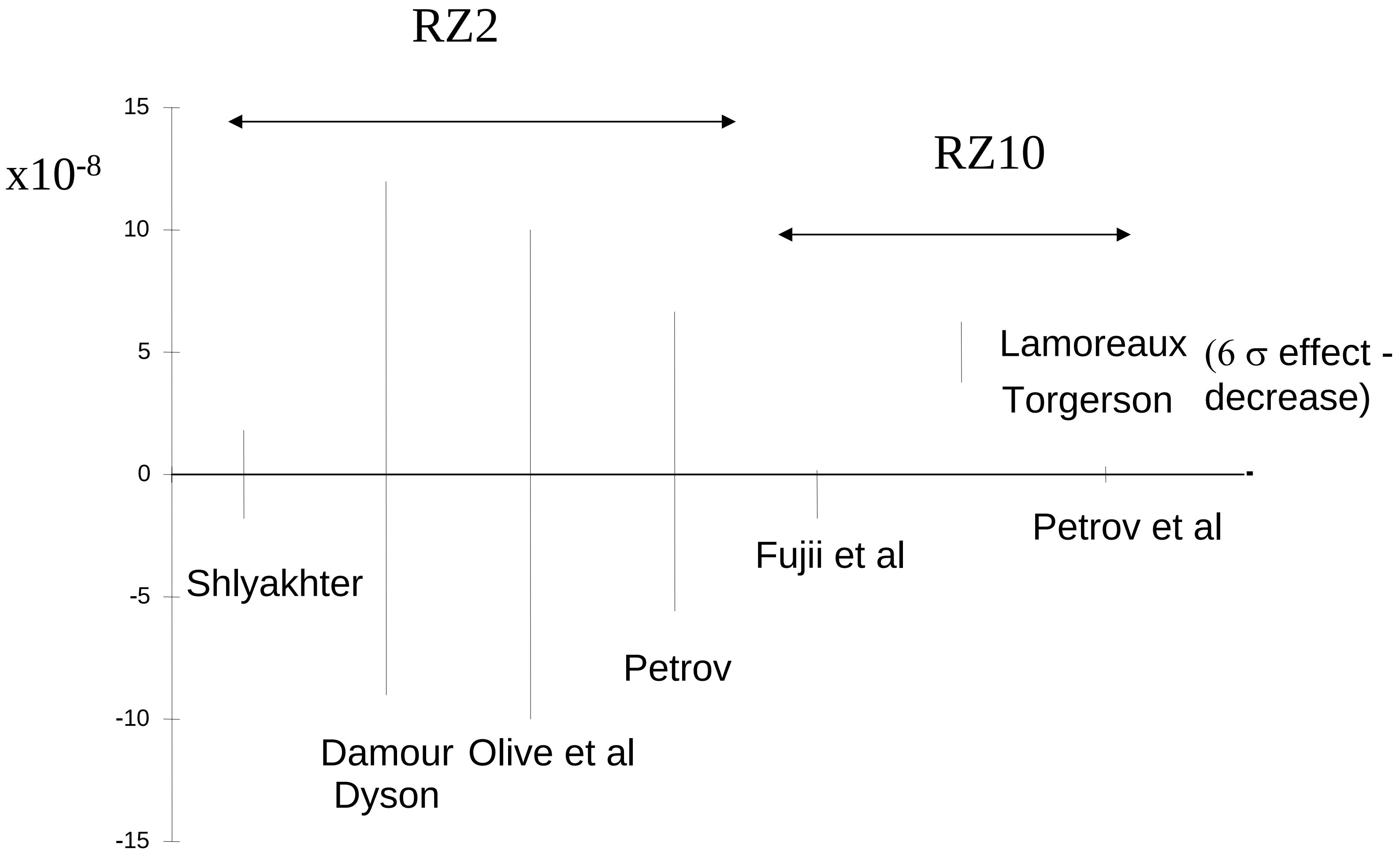


2 How spectral lines shift

Does α vary with time - Oklo

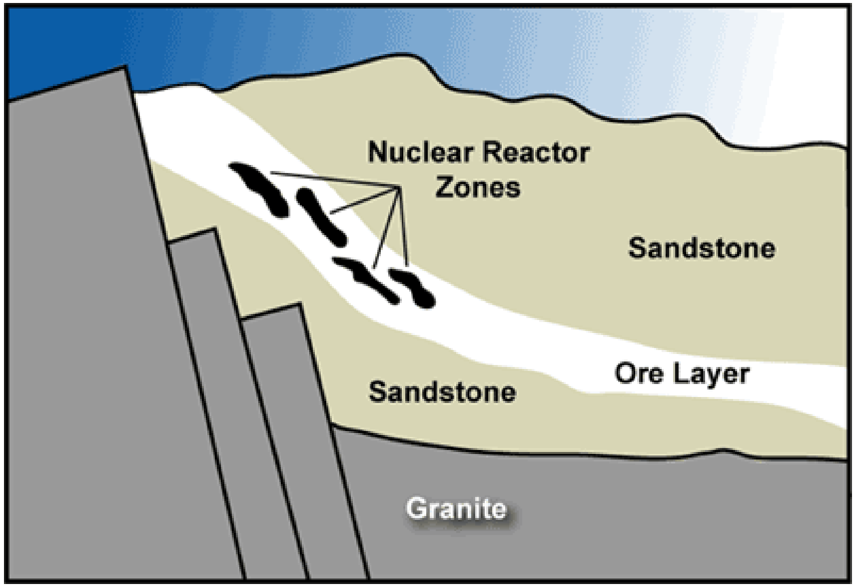
- *^{149}Sm resonance at 97.3 meV- has its energy changed over 2 BY?*
- *No, from early analyses of Sm abundance data for RZ2- Shlyakhter (76), Petrov (77), Damour and Dyson (96)*
- *But recent data for RZ10 are contradictory - Fuji et al (00), Lamoreaux and Torgerson (04), Petrov et al (05)*

$\Delta\alpha/\alpha$ over 2 BY from Oklo RZ2 and RZ10 analyses



Oklo Natural Nuclear Reactors

The uranium isotopes found at Oklo strongly resemble those in the spent nuclear fuel generated by today's nuclear power plants.



http://www.ocrwm.doe.gov/factsheets/doeymp0010.shtml

Discovery of Oklo phenomon

- *1972 French technician analyzes UF_6 samples and gets ^{235}U fraction of 0.7171% instead of expected 0.7202%*
- *Alarm bells – 700 tons of U processed (~100 kg ^{235}U missing: diversion of ore? secret nuclear explosion?)*
- *Traced to Oklo ores – find ^{235}U depleted to as low as 0.64%, plus anomalous amounts of other isotopes (Nd, Sm, Gd)*

Sm(Z=62) % isotope abundances for ‘144’ : ‘147’ :’ 148’ : ‘149’

Natural abundance	3.1 : 15.1 : 11.3 : 13.9
^{235}U fission products	0.0 : 61.3 : 0.0 : 29.4
Oklo ore (RZ10)	0.1 : 55.3 : 2.8 : 0.5

Unique time window for a natural reactor two billion years ago

Need ^{235}U, oxygen, and water

- *2 BY ago 235/238 = 3.7%, OK for light water moderation.*
- *Later than 2 BY ago, not enough ^{235}U*
- *Earlier than 2 BY, not enough oxygen to create soluble U oxides (need life).*

Reactor zone 2 (open mine site)

Photo courtesy of Andreas Mittler

One of the Oklo Fossil Reactors exposed by mining operations

Reactor Zone 15 accessed thru a tunnel from the main site

Uranium oxide remains visible as yellowish rock. Robert D. Loss

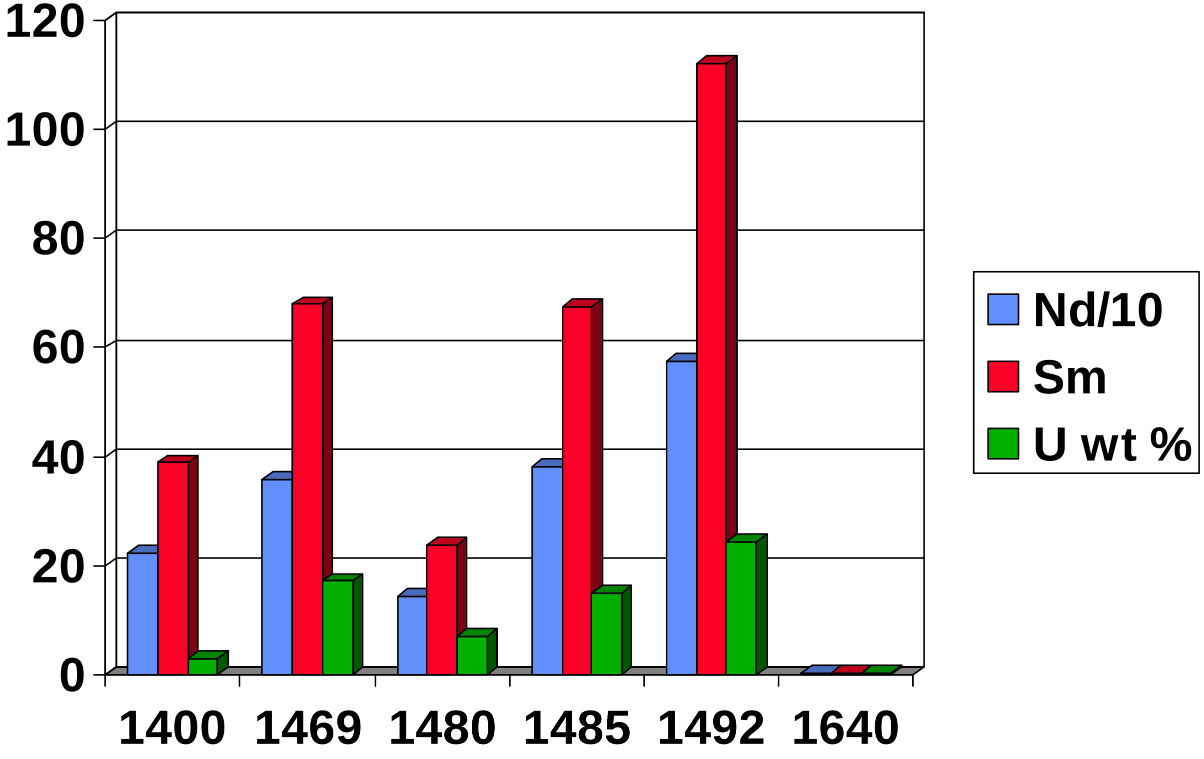
Reactor zones 2 and 10

- *Natural nuclear reactors operated 2 BY ago at a depth of a few km when ^{235}U fraction was 3.7% - similar conditions to today's PWR's (T= 300 deg C, pressure ~ 20 atm)*

- *RZ2 burned 1800 kg ^{235}U over 0.85 MY*
- *RZ10 burned 650 kg ^{235}U over 0.16 MY*

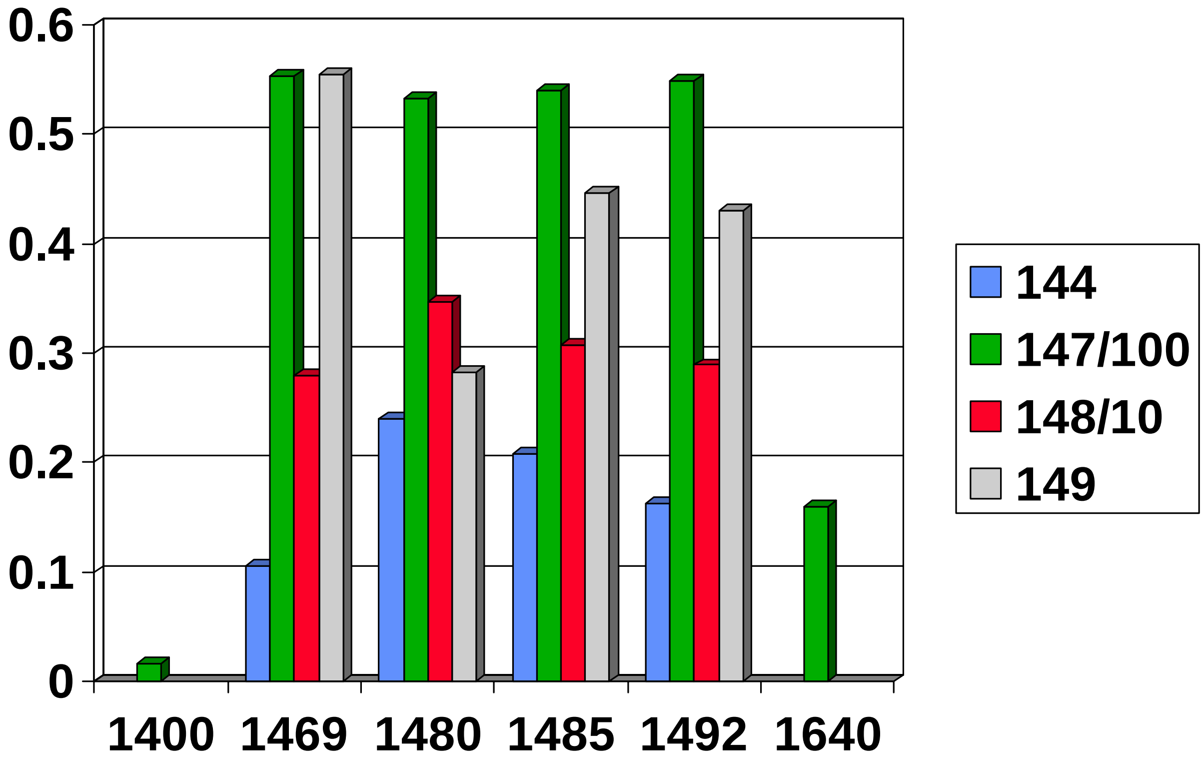
- *Reactor power - 10-15 kW*
- *Operation cycled ½ hr on, few hrs off*

Nd and Sm abundances (ppm), and % U for RZ10 (Hidaka and Holliger) define reactor zone



Reactor zone

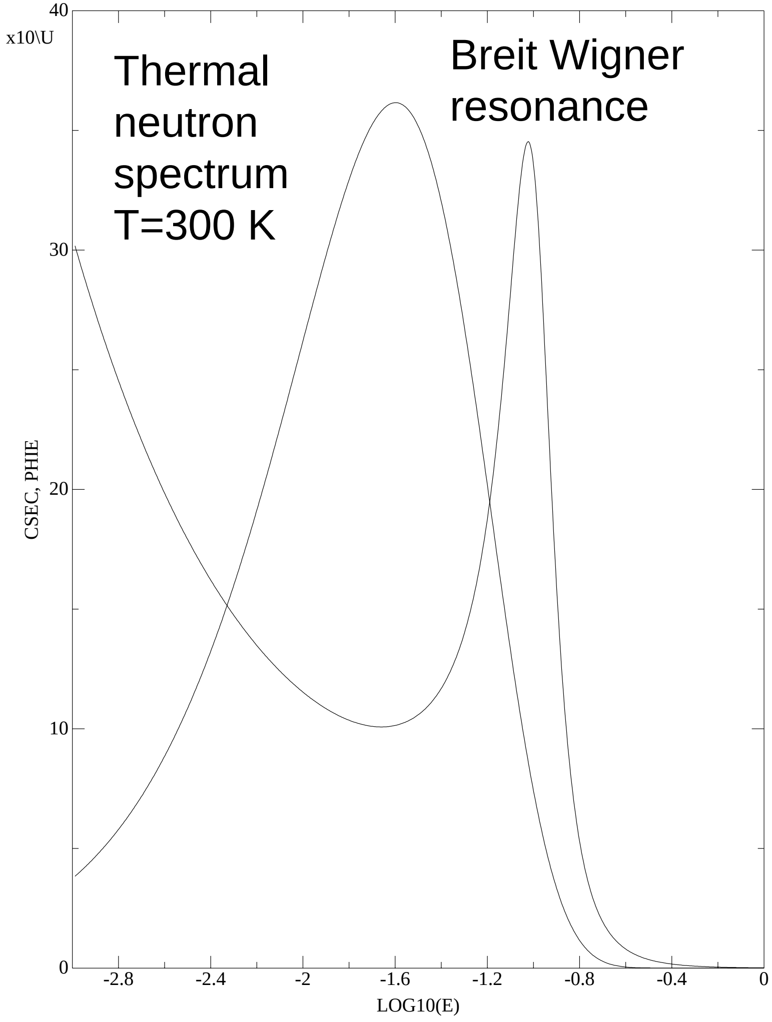
Sm % isotopic abundance data for RZ10 samples – reactor zone 14.69m to 14.92m



Define a "meta" sample as the average of the RZ samples

Burn up of ^{149}Sm due to n capture

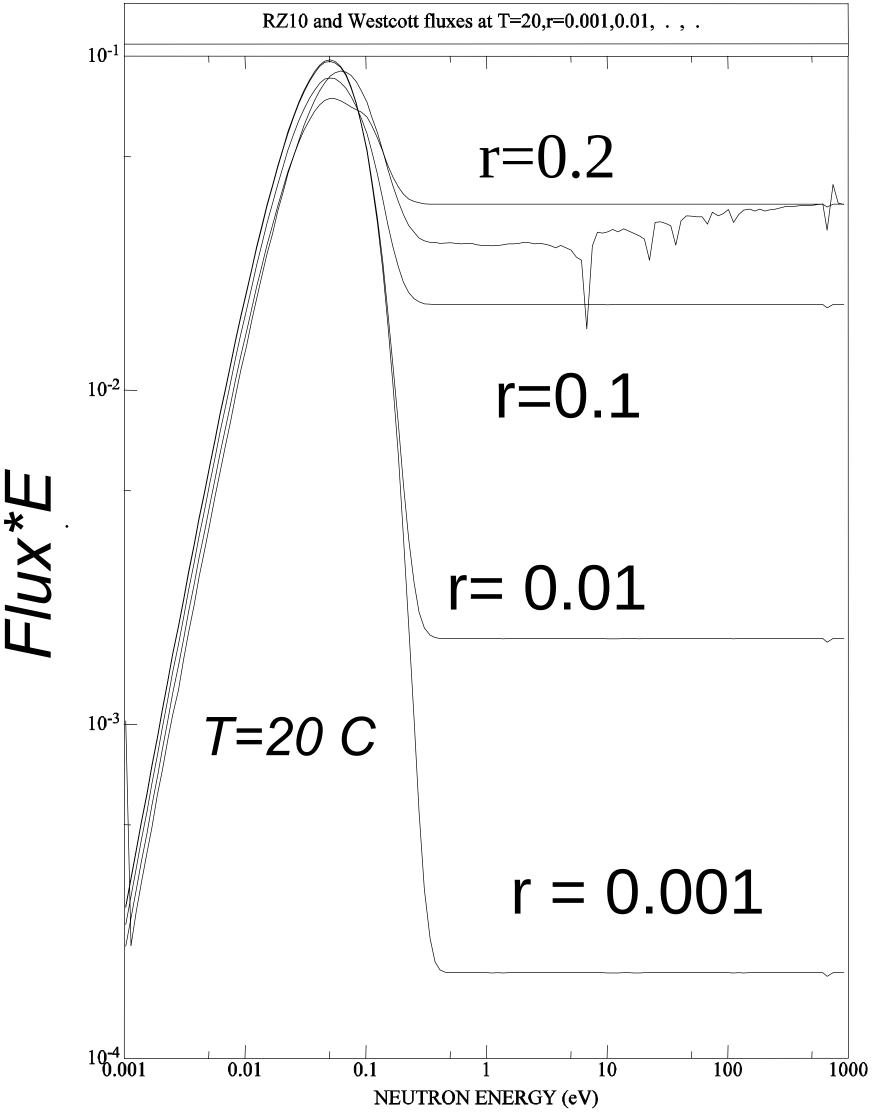
- *Overlap Oklo neutron flux with ^{149}Sm 97.3 meV resonance capture cross section $\sigma(n,\gamma)$.*
- *If resonance shifts up, capture yield goes down, and vice versa.*
- *Use relative yields of Sm and U nuclides in ores to bound shift in resonance ΔE_{r}.*
- *Reaction rate $R=\Phi\sigma$, but how well known is the neutron flux Φ?*



Characterizing the neutron flux

Neutron flux Φ= “Maxwell-Boltzmann at unknown T” + “Unknown fraction of epithermals (1/E) characterized by r ”

Q: how to choose r and temperature?
A: match r to measured spectral indices, and analyze a range of T 20 - 500 C.



Analysis of Oklo isotopic abundances show r is not zero

Isotopic abundances depend on reaction rate: $R = \Phi_{eff}\,\sigma_{eff}$

- *Effective flux* $\Phi_{eff} = n\,v_0$
- *Effective cross section* $\sigma_{eff} = (1/nv_0)\int \sigma(v)\,n(v)\,v\,dv$
- *Rewrite as a function of thermal cross section* σ_0 *and r:*
  Example: $\sigma_{eff}(^{143}\mathrm{Nd}) = 335 - 100\,r$

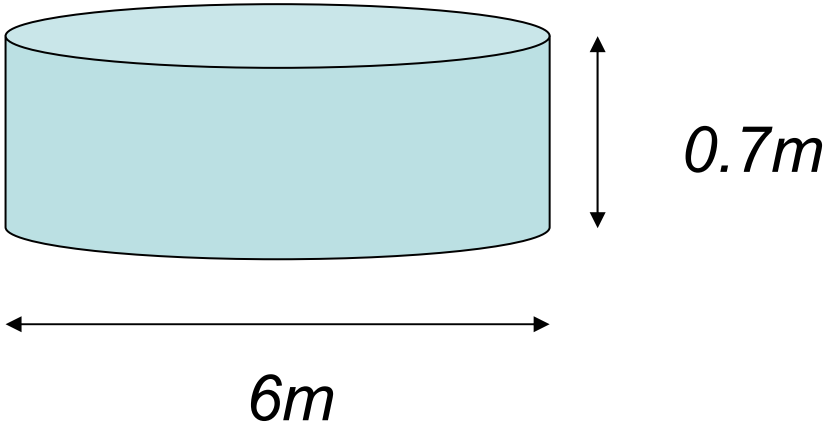
From ^{143}*Nd,* ^{147}*Sm,* ^{235}*U geochemical data (Naudet, HH)*

RZ2: $r = 0.20 - 0.25$
RZ10: $r = 0.15 \pm 0.02$

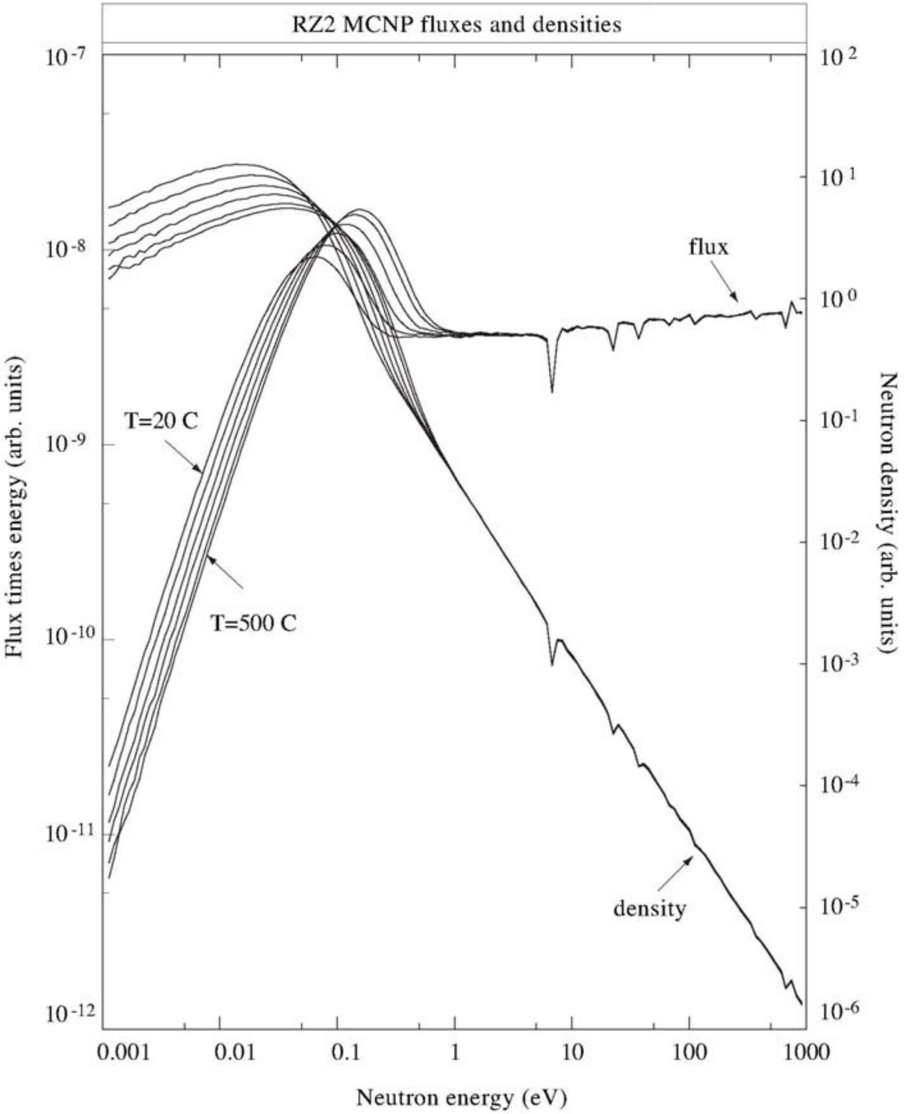
Use r values to select realistic models of the reactor zones, and then calculate the implications for ^{149}*Sm burn up.*

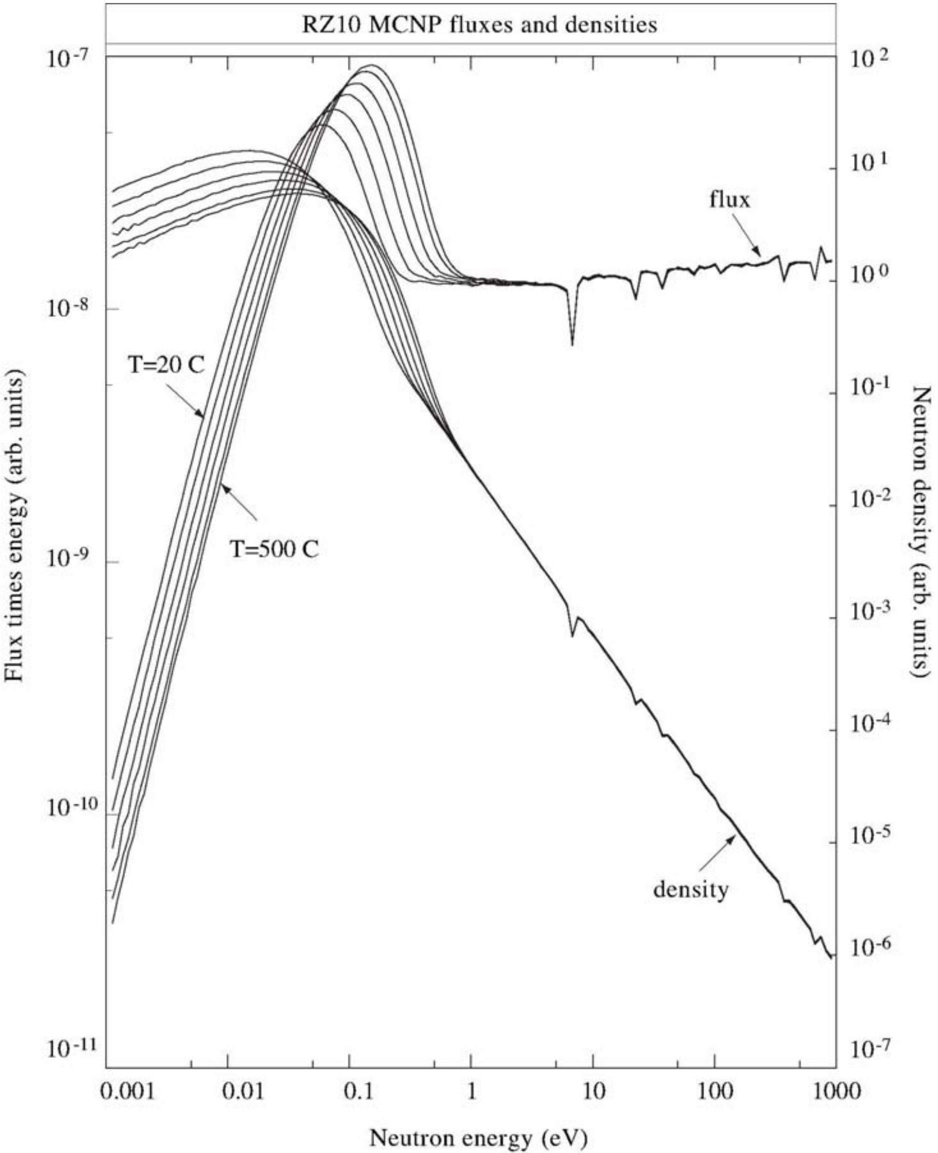
Reactor zone modeled by a flat cylinder surrounded by water saturated sandstone

- *Most uncertain parameter in Oklo modeling is the water to uranium ratio.*
- *Find RZ10: H/U = 13.0 (very little $U0_2$) and RZ2: H/U = 7.6*
- *Metal oxides (Fe, Al, Mg, Mn, K) contribute to both thermalization and absorption - important to making RZ10 critical*
- *Finite size reactor cannot be made critical with only water and uranium*



RZ2 and RZ10 fluxes and densities for T=20:500 C





Confirming epithermal indices are correct

Confirm r values four ways

1) *Integrate MCNP densities up to and above 5kT*
2) *Compare MCNP flux per unit lethargy at ~100 eV to integrated thermal flux (Naudet)*
3) *Reactor theory:* $r \sim \Sigma_{a,eff} / \xi\Sigma_s$, *(Westcott)*
4) *From* $\Delta \equiv 2A\Sigma_{a0} / \Sigma_s \sim (4/\sqrt{\pi})\, r$ *(Weinberg-Wigner)*

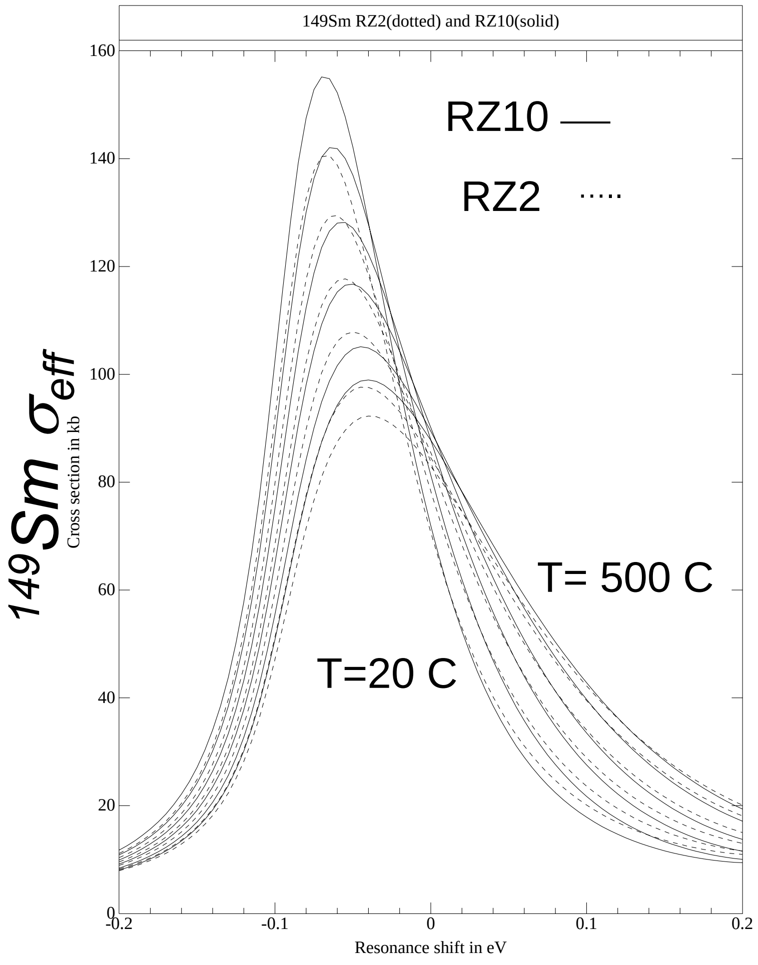
All methods agree OK, and match well to expt'l values

RZ2: 0.22

RZ10: 0.15

Calculate ^{149}Sm σ_{eff} as a function of resonance shift using MCNP fluxes

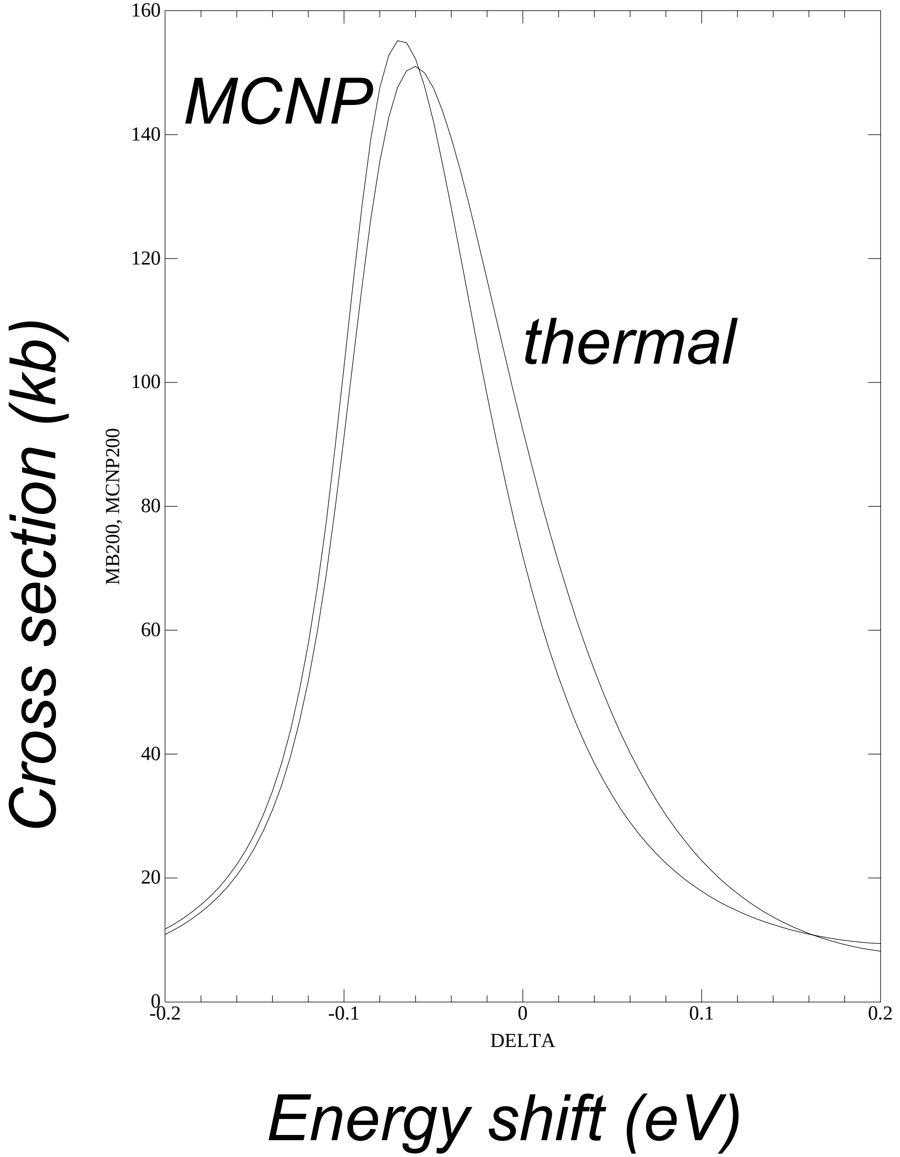
- *Include resonances up to 50 eV, and sub-threshold resonance at -285 meV*
- *Shift all resonances:* $-0.2\ eV < \Delta E_r < +0.2\ eV$
- *Numerically evaluate using SPEAKEASY*
- *Incorporate Doppler broadening (negligible)*
- *97.3 meV resonance contributes 98%*



Resonance shift

Maxwell Boltzmann predictions compared to MCNP RZ10 predictions at 200 C

- *Thermal only calculations agree with previous work (Fujii, Damour)*
- *“Thermal” and “realistic” $\sigma_{eff}(^{149}Sm)$ are different (Petrov, (Lamoreaux): 1/E spectrum moves curve to left*
- *Need ancient σ_{eff} to derive a possible energy shift over time*



New calculation of ancient σ_{eff} (^{149}Sm), explicitly including Pu decay, and Pu restitution thru "p"

$$
\begin{aligned}
\frac{dN_5}{\hat{\phi}dt} &= -\hat{\sigma}_{5,tot}N_5 + \frac{\lambda_9}{\hat{\phi}}N_9 \\
\frac{dN_8}{\hat{\phi}dt} &= -\hat{\sigma}_8^0 N_8 - \Gamma \\
\frac{dN_9}{\hat{\phi}dt} &= \hat{\sigma}_8^0 N_8 - \frac{\lambda_9}{\hat{\phi}}N_9 - \hat{\sigma}_{9,tot}N_9 + \Gamma \\
\Gamma &= (1-p)(\nu_9\hat{\sigma}_{f,9}N_9 + \nu_5\hat{\sigma}_{f,5}N_5) \\
\frac{dN_{147}}{\hat{\phi}dt} &= -\hat{\sigma}_{147}N_{147} + \hat{\sigma}_{5,f}Y_{5,147}N_5 + \hat{\sigma}_{9,f}Y_{9,147}N_9 \\
\frac{dN_{148}}{\hat{\phi}dt} &= -\hat{\sigma}_{148}N_{148} + \hat{\sigma}_{147}N_{147} \\
\frac{dN_{149}}{\hat{\phi}dt} &= -\hat{\sigma}_{149}N_{149} + \hat{\sigma}_{148}N_{148} + \hat{\sigma}_{5,f}Y_{5,149}N_5 + \hat{\sigma}_{9,f}Y_{9,149}N_9.
\end{aligned}
$$

Solve equations to match geochemical data

- *Step 1: with p, duration, and start time fixed, solve U and Pu equations for flux, given starting and ending ^{235}U fractions*

- *Step 2: with fluence fixed, solve for starting Sm:U ratio given ending ^{147}Sm fraction (check agreement with ^{144}Sm)*

- *Step 3: with Sm:U ratio fixed , solve for σ_{149} given ending ^{149}Sm fraction.*

Results for RZ2 and RZ10 agree with previous work

- *Using meta sample values and sample standard deviations:*

RZ2:

σ_{149} = 71.5 ± 10.0 kb

(Damour: 57 < $\sigma <$ 93 kb)

RZ10:

σ_{149} = 85.0 ± 6.8 kb

(Fuji: 91.2 ± 7.6 kb)

RZ2	σ (kb)	RZ10	σ (kb)
1408	69	1469	94
1410	78	1480	86
1413	65	1485	81.5
1416	91	1492	96
1418	75		
Meta	71.5	Meta	85

Results for ^{149}Sm energy shift

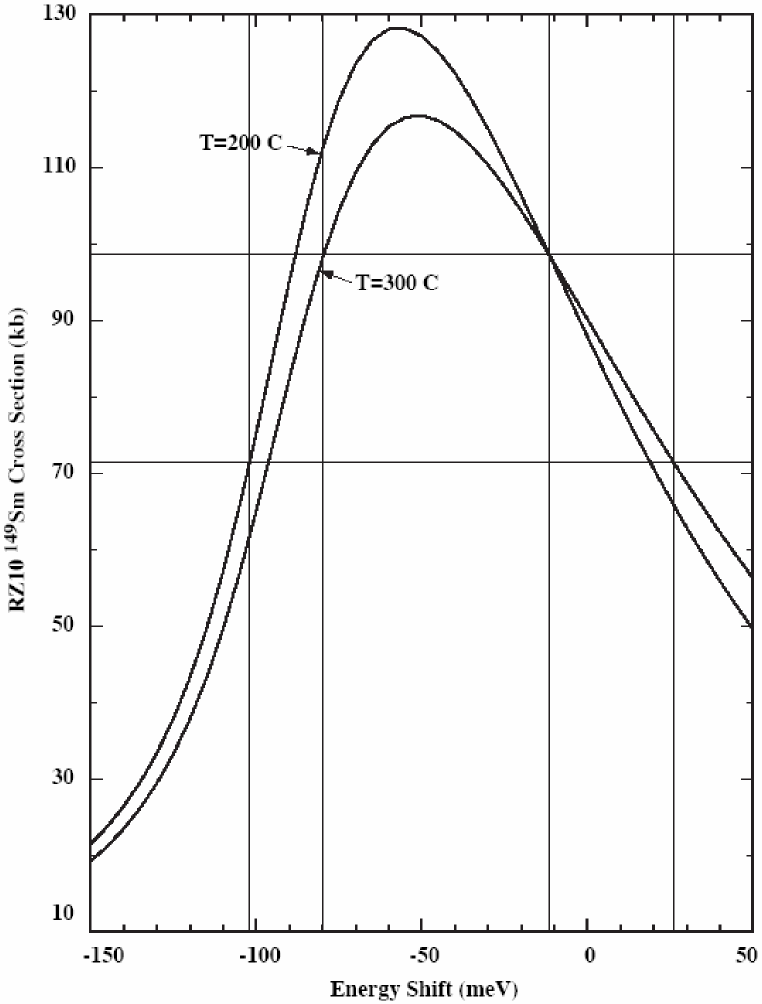
- *Use 200<T<300 for temperature range (Meshick)*
- *Use more precise RZ10 data with 2σ bounds on energy shift*

Left branch

$-101.9 \leq \Delta E_r \leq -79.6$ meV

Right branch

$-11.6 \leq \Delta E_r \leq +26.0$ meV



Coulomb energy difference sets scale for sensitivity to change in α

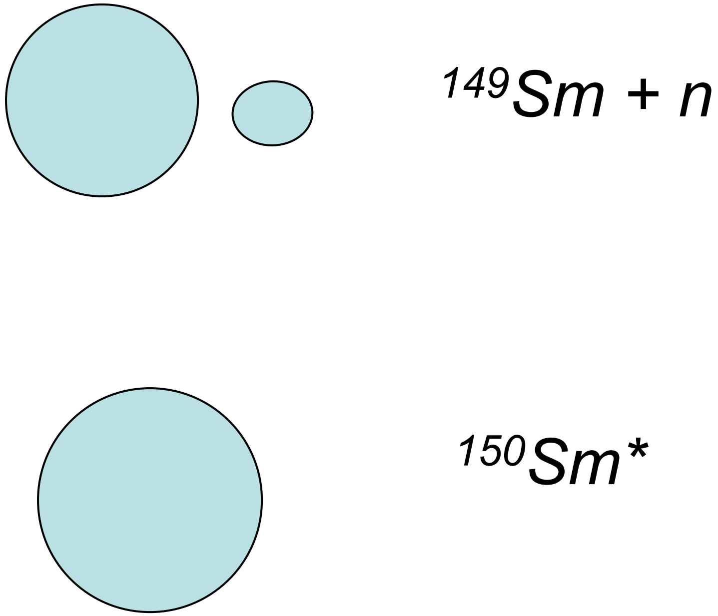
$E_c = 0.4 \times Z^2/A^{1/3}$ MeV

$\Delta E_c = E_c(149) - E_c(150) \sim 1.1$ MeV

$d\alpha/\alpha \sim -\Delta E_r/\Delta E_c$

ΔE_r is of order meV's, therefore 10^9 magnification in sensitivity

If α decreases, the resonance shifts up

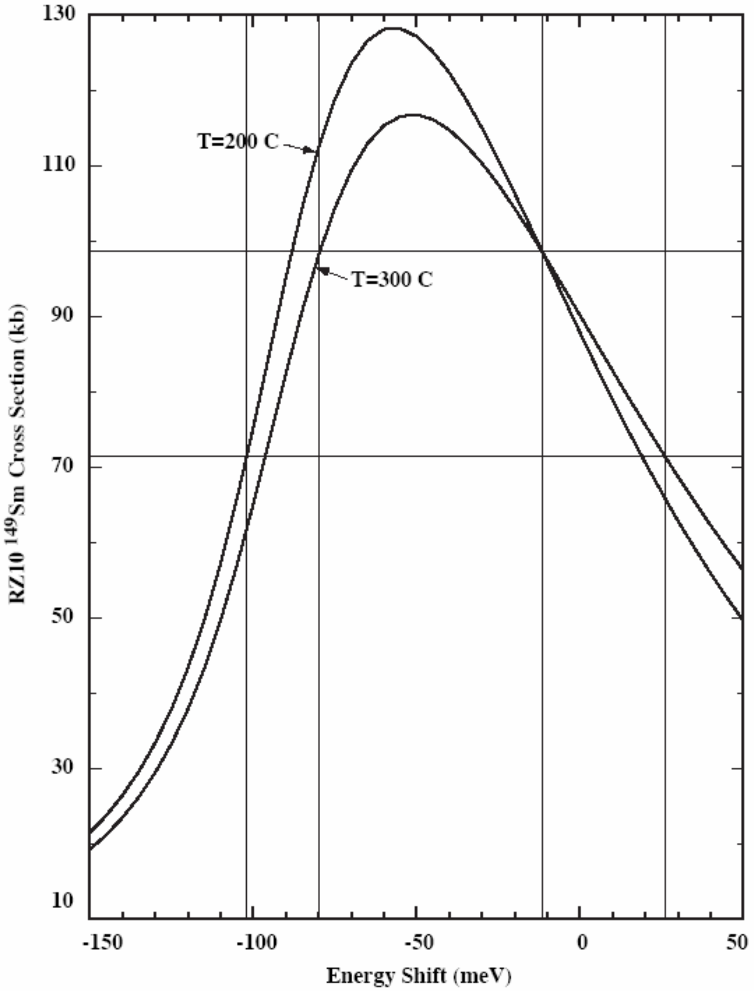


^{149}Sm + n

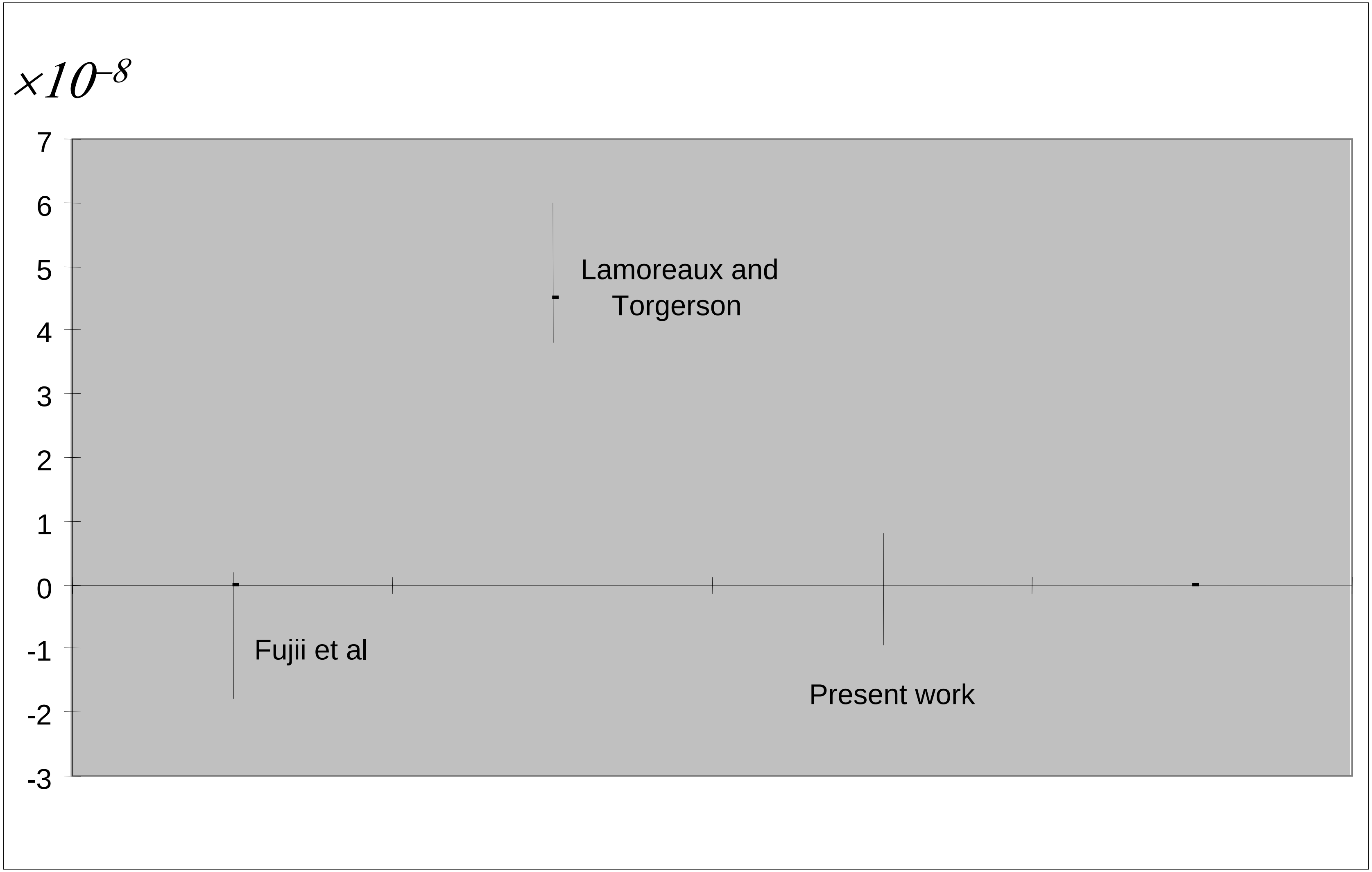
^{150}Sm*

Results for $\Delta\alpha/\alpha$

- *Right branch solution consistent with zero, gives $-0.24\times10^{-7} < \Delta\alpha/\alpha < 0.11\times10^{-7}$*
- *Left branch non-zero – unfavored by Fuji Gd analysis, but not yet definitively ruled out*



Comparison of $\Delta\alpha/\alpha$ from RZ10 analyses



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

- *Oklo over 2 BY < 1.2 x 10^{-17} per year*

- *Quasars over 10 BY ~ 6 x 10^{-16} per year*

- *Atomic clocks (Hg, Cs, Yb) over ~1Y*
  < 1 x 10^{-15} per year

Maybe Oklo bound is meaningless (or too model dependent)?

- *Marciano, Flambaum… argue sensitivity of hadronic properties to strong interaction is much more important – therefore Oklo data aren't useful in bounding* α_{EM}

Defining $W \sim m_{strange}/\Lambda_{QCD},$ *(Flambaum and Shuryak)*

$\Delta E_{res} = 100\ \mathrm{MeV}\ (\Delta W/W) + 1\ \mathrm{MeV}\ (\Delta\alpha/\alpha)$

In this case, Oklo limit $d/dt(\Delta W/W) < 1.2 \times 10^{-19}$ *per year*

Conclusions

- *Oklo data lead to very tight (albeit model dependent) constraints on the time variation of α over 2 billion years – factors of 10 or more precise than quasar data analysis or laboratory experiments.*
- *Discrepancies between recent RZ10 results are due to different assumptions about the epithermal neutron fraction present; matching to known spectral indices leads to realistic models of the reactor zones.*
- *New results are consistent with no change in α, but also a non-zero shift cannot yet be ruled out.*
- *Would be useful to get additional constraints on the possible reactor zone temperatures (Lu resonance data?)*