Title: Time variation of fundamental constants and the Oklo phenomenon

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Abstract:

Time variation of fundamental constants and the Oklo phenomenon

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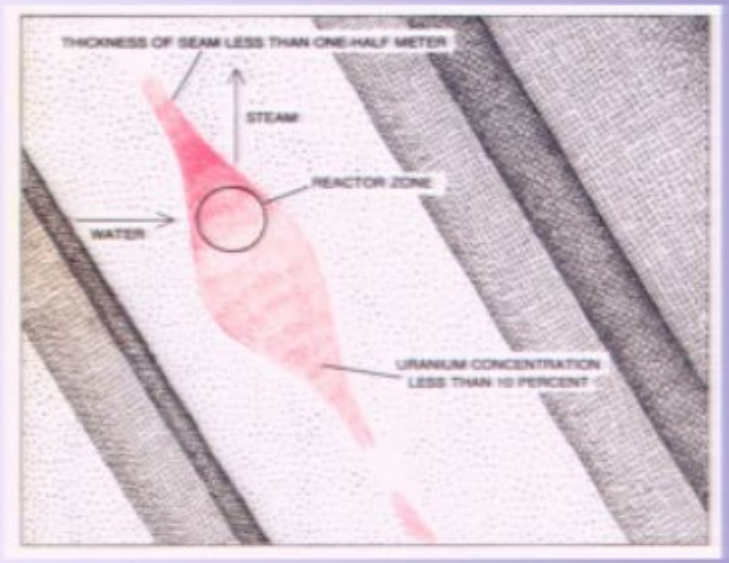
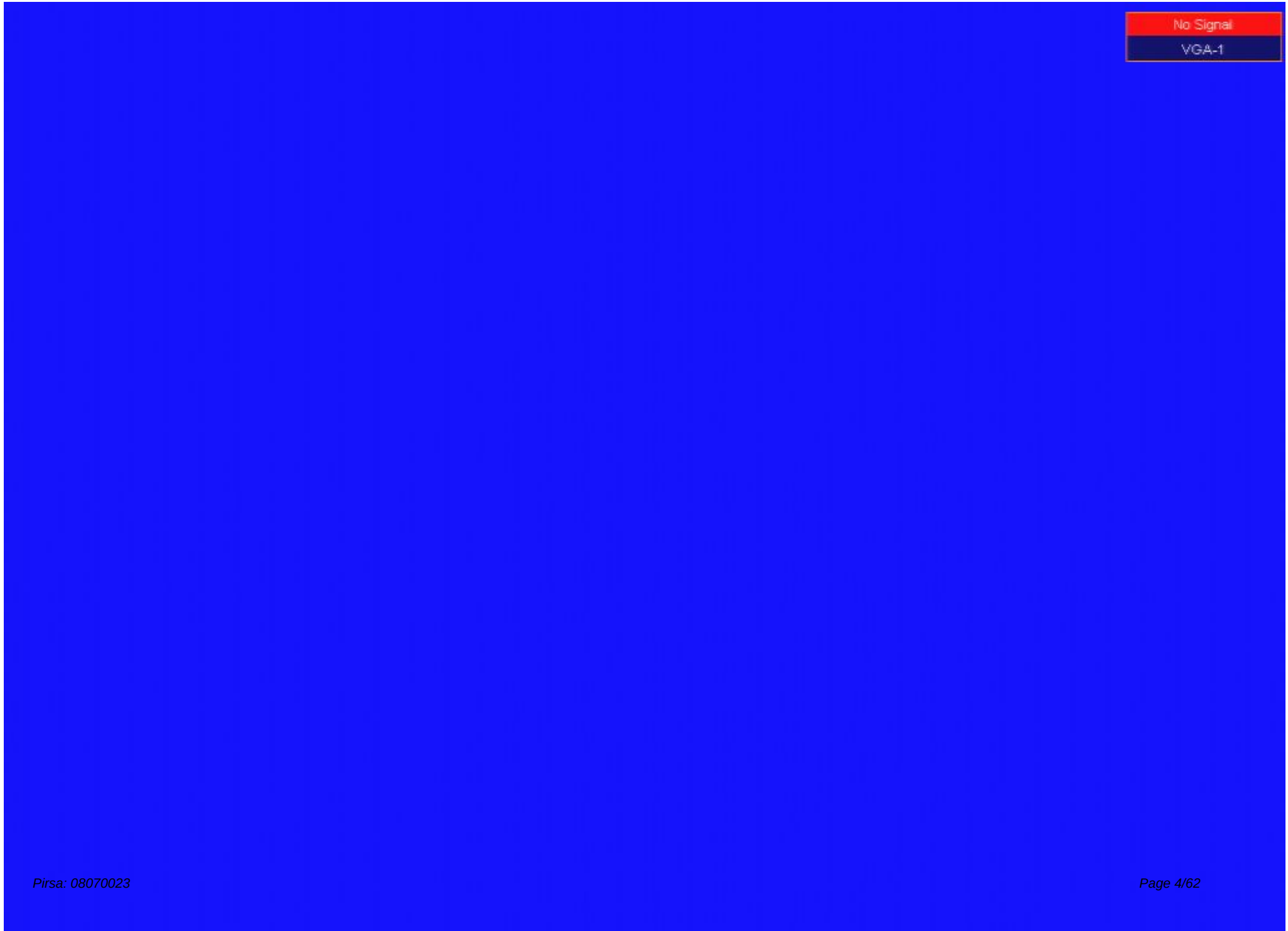


- Site of several naturally occurring uranium fission reactors
- Effects of natural reactors discovered in 1972

Discovery of Oklo Phenomenon

- H. Bouzigues, on the staff of the Pierrelatte fuel processing plant in France, finds during routine analysis a sample that is anomalously low in U-235, 0.7171% compared to the usual 0.7202% in natural uranium ore. (May 1972)
- With rare exceptions (Pb, Os, He) the natural isotopic ratios of elements are remarkably constant.
- UF_6 gas used in mass spectroscopy might have been contaminated with spent fuel; that possibility was ruled out.
- Other explanations included, but not limited to:
  - Crash of nuclear powered spacecraft
  - Prehistoric civilization
  - U-235 somehow stolen
- The anomalous samples were traced to ore from a very concentrated uranium deposit in Gabon, Africa. (Oklo Deposit)
- Some samples showed depletion of U-235 to a level of 0.35%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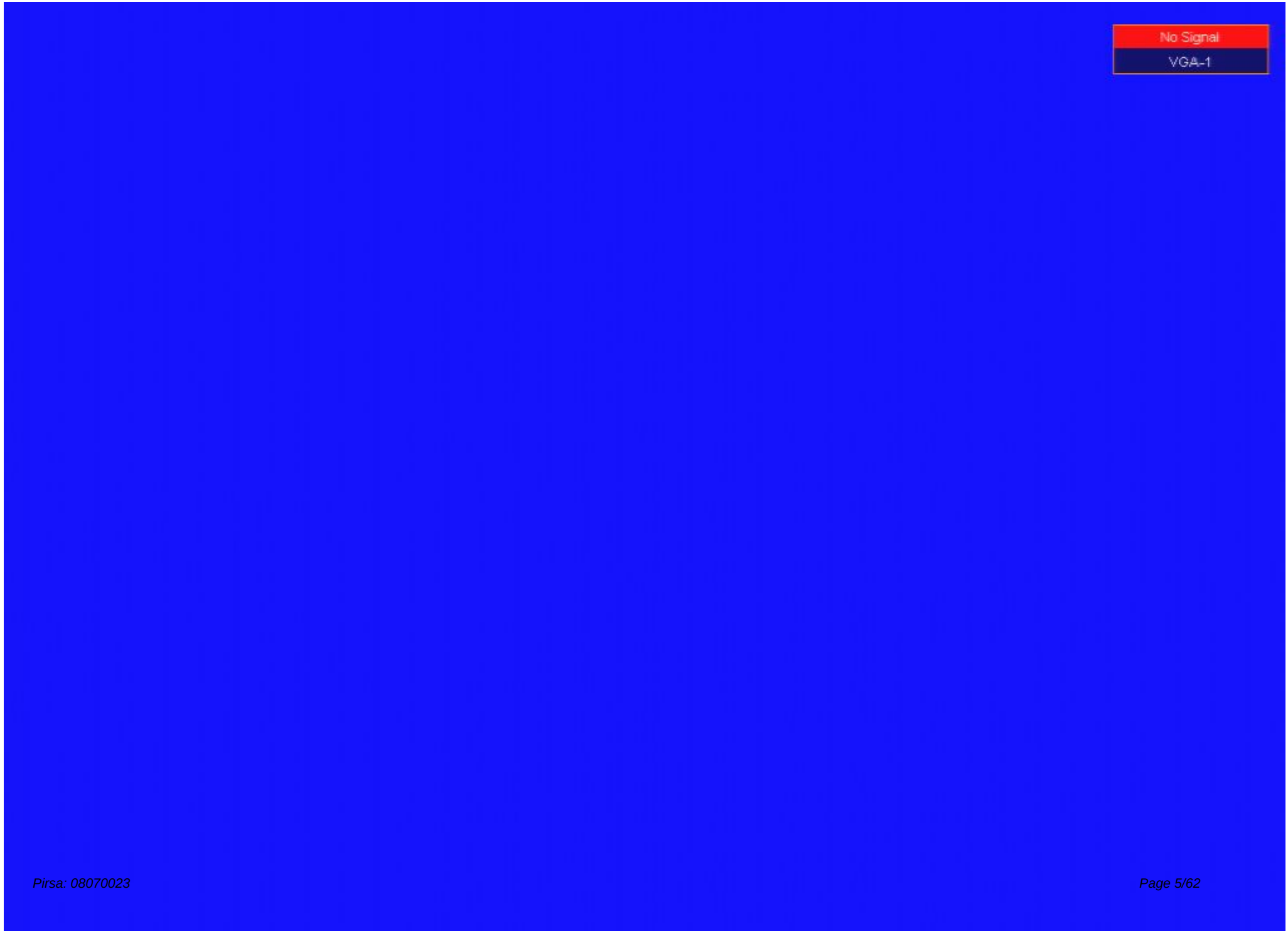
VGA-1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Explanation of low ^{235}U abundance

Paul Kazuo Kuroda (1956, Univ. of Arkansas), in two scholarly papers, discussed the stability of uranium ore deposits. With the proper conditions, in the distant past, a uranium ore deposit could become "critical' and operate as a nuclear reactor.

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Requirements for a natural reactor

- Relatively high U-235 isotopic concentration

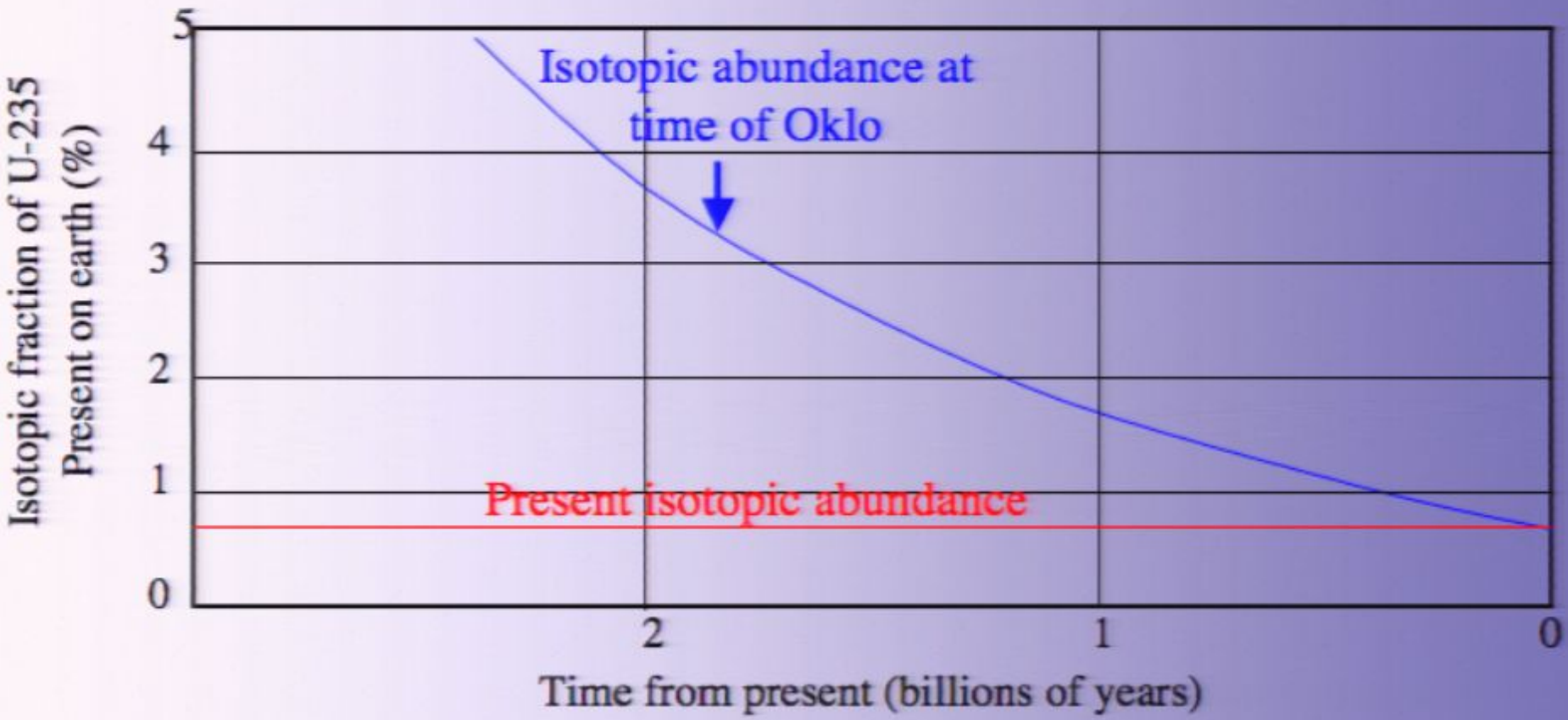
The reason why the natural reactor was possible 2 billion years ago is given by the following data. The essential fact is that the half life of ^{235}U is smaller than that of ^{238}U.

	^{235}U	^{238}U
Nat. Abund. (Present)	0.720%	99.27%
Half Life	7×10^{8}years	4.5×10^{9}years
Nat. Abund. (2×10^{9} years ago)	3.7%	96.3%

Based on these facts, K. Kuroda first predicted [7] that with the presence of some amount of water, the vein of uranium could undergo a chin reaction spontaneously. In 1972, the uranium slightly depleted in ^{235}U was detected at French uranium-enrichment plant. It was traced and found out that at Oklo in Gabon Republic, uranium with ^{235}U abundance of 0.4% - 0.5% was mined. It is well proved now that in 2 billion years ago, the reactors were operating in Oklo area (Oklo, Oklobondo, Bagombe). In spite of serious efforts to find the natural reactors in other area, no evidence was found up to now.

- Low concentration of neutron absorbers
- Presence of water to provide moderation
- Sufficiently large deposit

Isotopic fraction of U-235 through time



- U-235 decays about 6x faster than U-238
- Isotopic abundance of U-235 was 3.2% 1.8 billion years ago (25% when the earth formed 4.6 billion years ago)
- Isotopic abundance should be the same everywhere in the solar system

Some conditions for a homogeneous reactor

TABLE 18.1

VALUES OF p, f, AND k AND RATIO OF URANIUM TO MODERATOR AT MAXIMUM k FOR VARIOUS UNIFORM MIXTURES OF MODERATOR AND NATURAL URANIUM

Moderator	Molecules of Moderator / Atoms of Uranium	f	p	k
H_2O	2.43	0.828	0.755	0.838
D_2O (+0.2% H_2O)	167	.955	.910	1.145
Be	193	.816	.728	0.796
C	452	0.837	0.757	0.849

$k = 1.38$ for 3.7% U-235 and 2.4 H_20/U

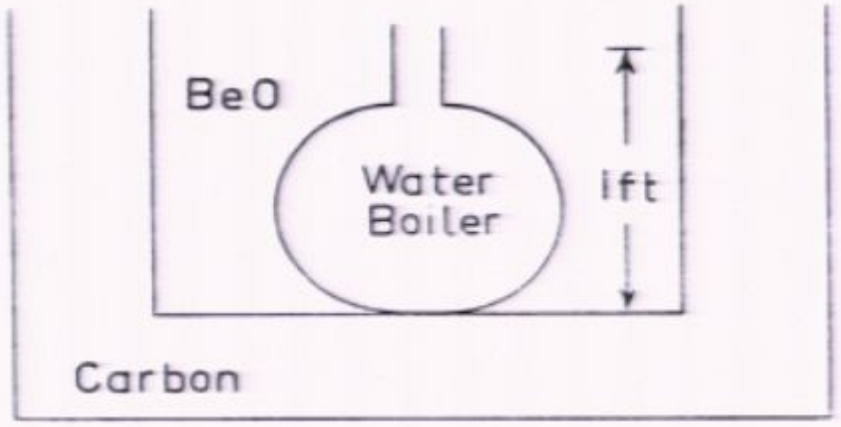
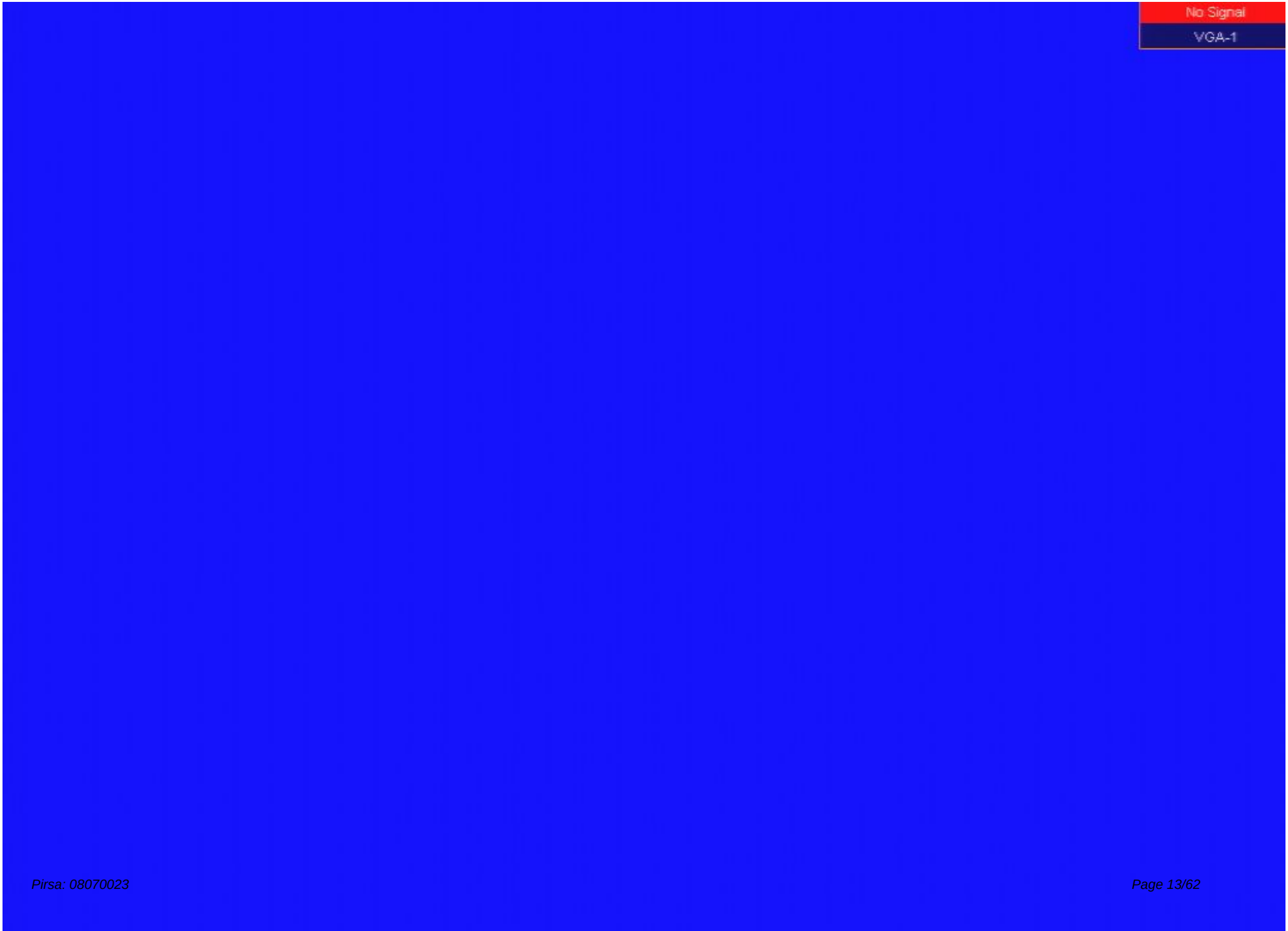


Fig. 83. – Los Alamos water boiler.

Possibility for a test of time variation of fundamental constants using Oklo

- Isotope with low-energy neutron absorption resonance (eg. ^{149}Sm, ^{155}Gd, ^{157}Gd)
- Accurate data for initial and final isotope abundance
  - Isolated, preserved samples
  - Natural abundance
  - Reactor-produced abundance (fission products, neutron captures, *etc.*)
  - Effect of neutron captures
- Energy-dependence of neutron resonance
  - Energy-dependence of other parameters such as decay rates (usually assumed to be independent of energy to first order)
- Model for Oklo reactor dynamics
- Model for relating change in resonance energy to change in fundamental constant(s)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History of searches for time variation of α with Oklo

- Basic idea due to A.I. Shlyakhter, Nature **264**, 340 (1976)

$$\left|\frac{\dot{\alpha}}{\alpha}\right| < 1\times10^{-17}/yr$$

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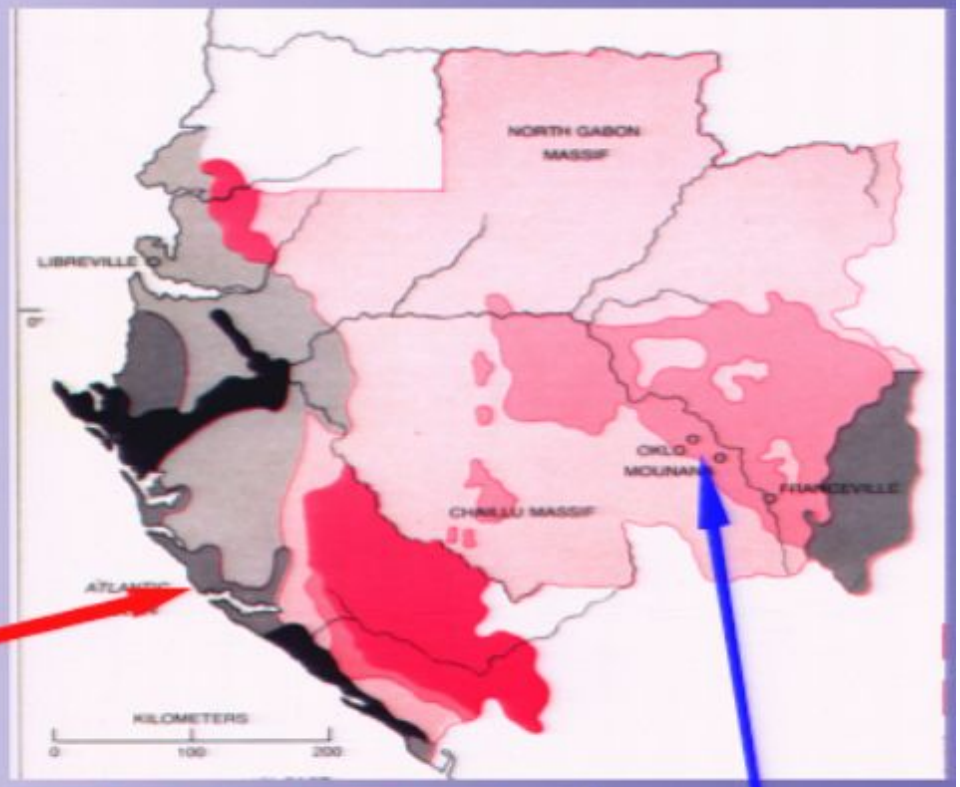
$$\frac{\dot{\alpha}}{\alpha} = +\left(2^{+6}_{-5}\right)\times10^{-18}/yr$$

$$\frac{d\ln(E_r)}{dt} = c_\alpha \frac{d\ln(\alpha)}{dt} + c_\Lambda \frac{d\ln(m_q/\Lambda_{QCD})}{dt}$$

Where is Oklo?



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- Mine in sedimentary rock bordered by older igneous rock

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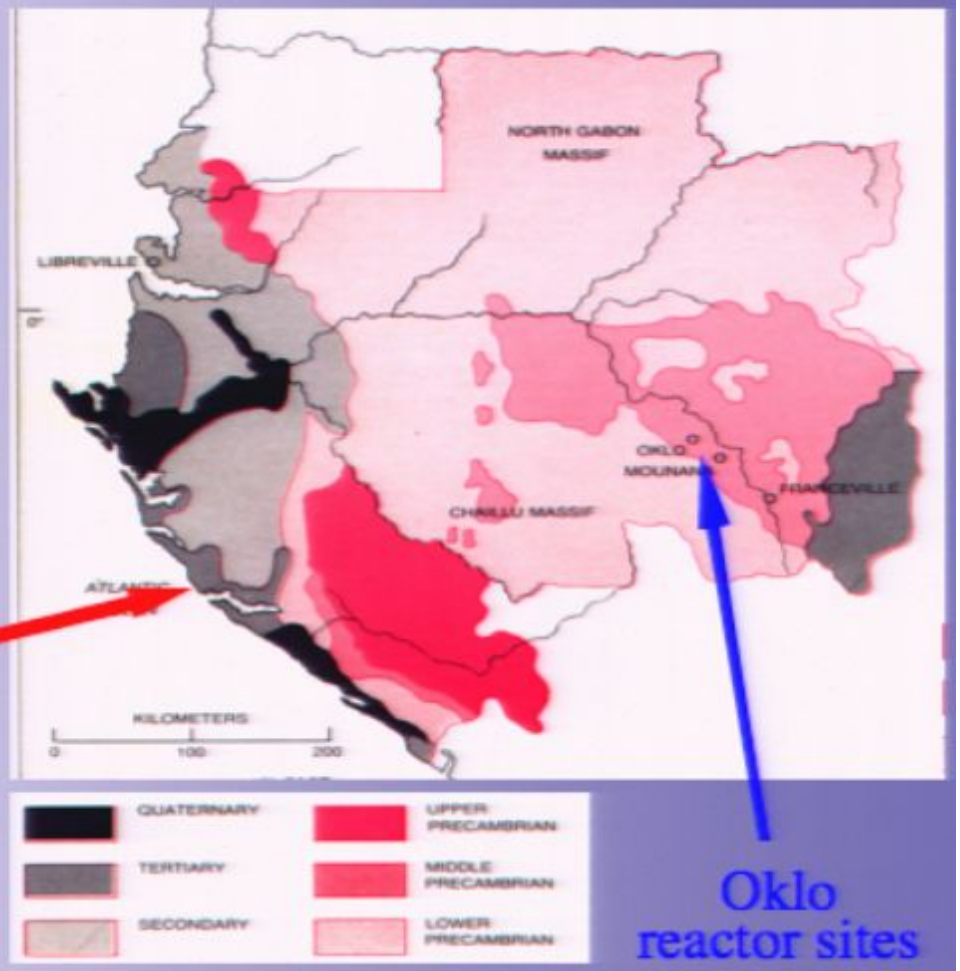

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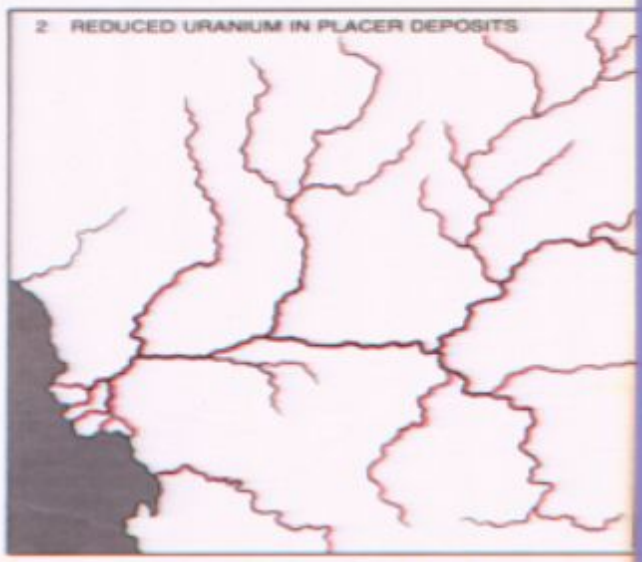
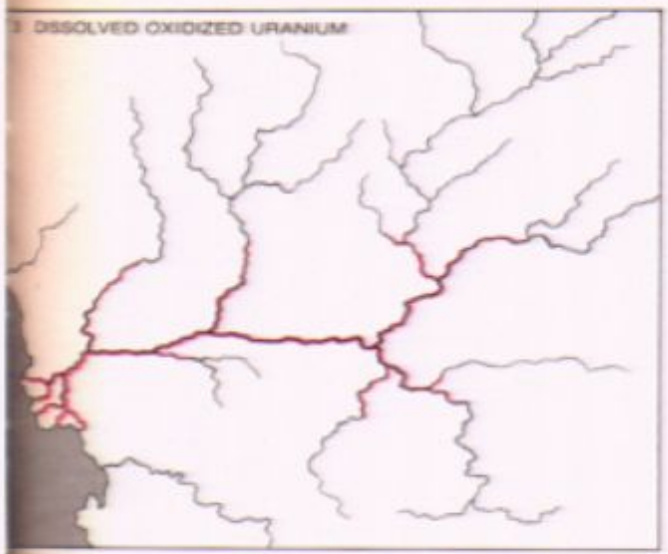
Oklo mine site

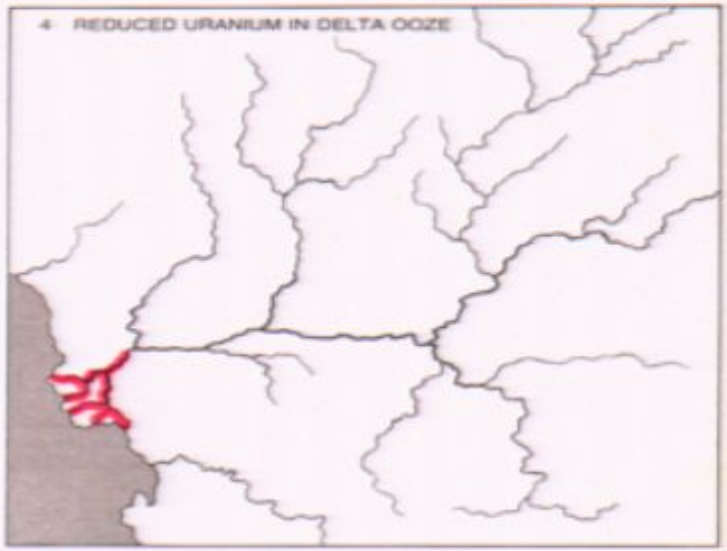
Zone 15 Mine

Formation of ancient uranium deposits



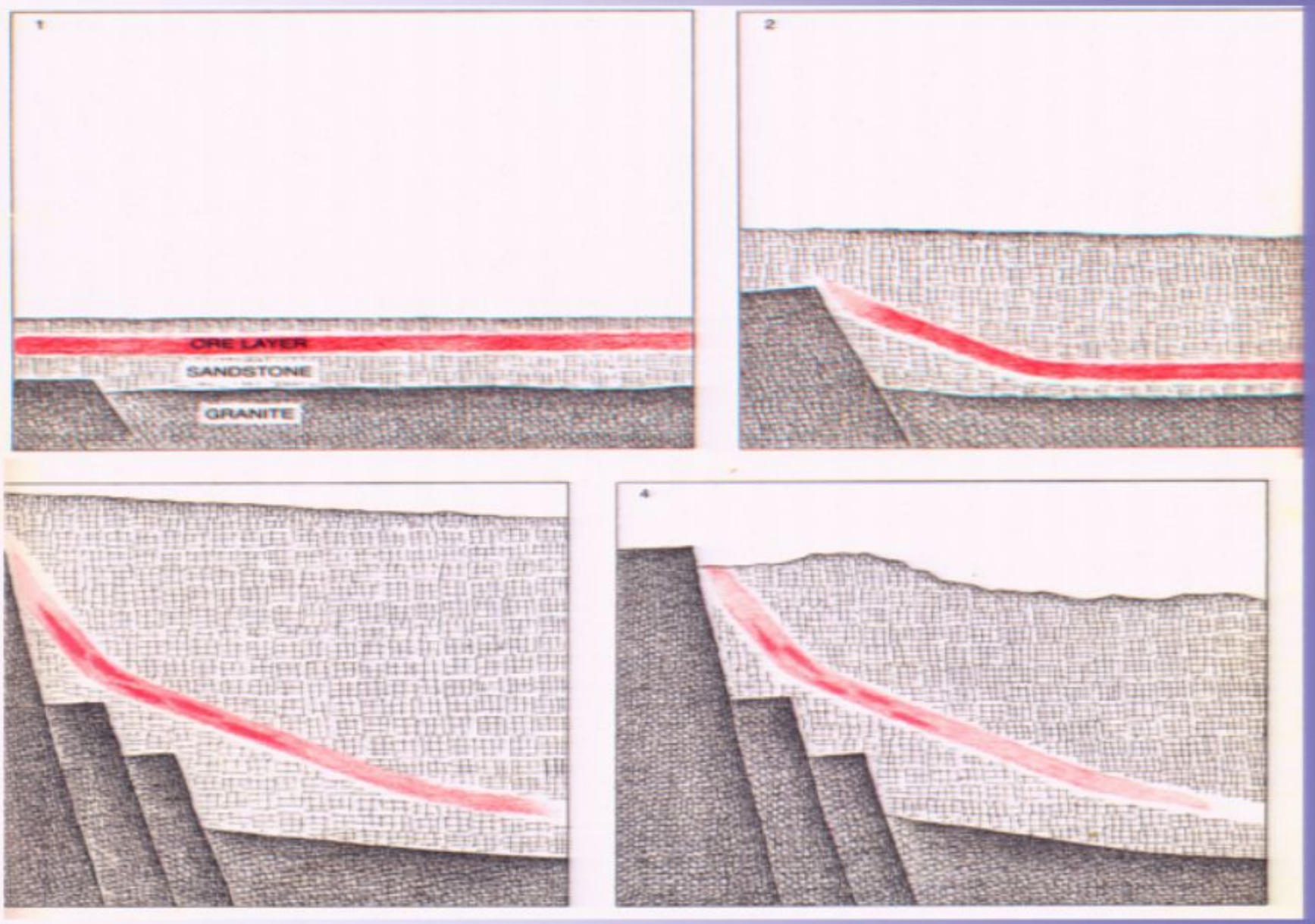
ACCRETION OF THE ORE DEPOSIT at Oklo involved the concentration of uranium derived from an entire watershed. The uranium (*color*) was originally dispersed in igneous rocks over a large area (*1*). As the rocks were eroded by weathering, the uranium accumulated in streambeds in a relatively reduced state (*2*). It may have formed placer deposits like those in which gold and low-grade, Precambrian uranium ores are found today. Some two billion years ago a biological development profoundly altered the disposition of the uranium:



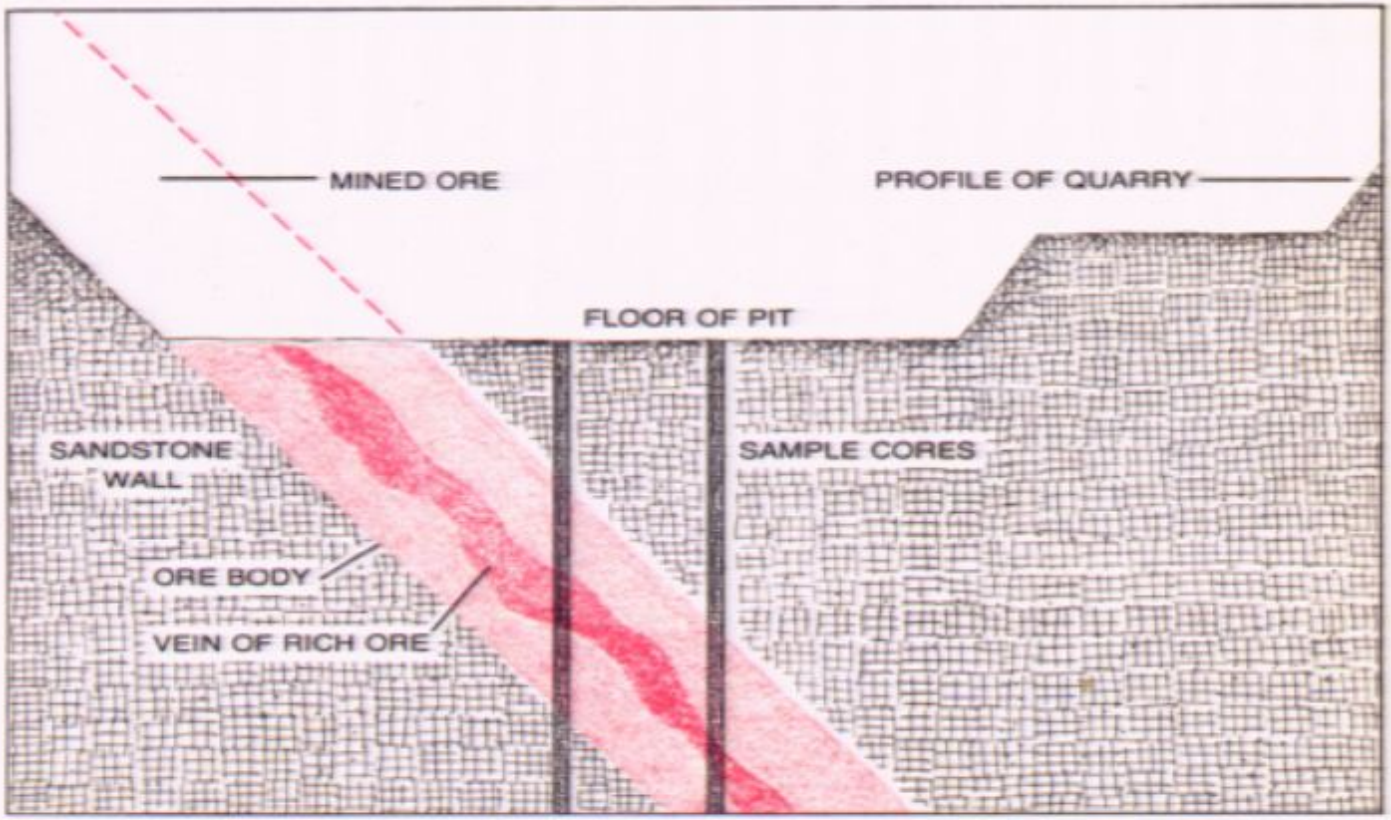


the proliferation of photosynthetic algae increased the concentration of oxygen in the water. Highly oxidized uranium is more soluble than the reduced form, and the uranium was therefore dissolved and carried downstream (*3*). It remained in solution until it reached the delta of the river system, where sediments rich in organic ooze again created a condition of oxygen deficiency. In these sediments the uranium was returned to the reduced form and was precipitated out of the solution (*4*). In the delta the ore was covered by later sediments.

Evolution of the ore deposit

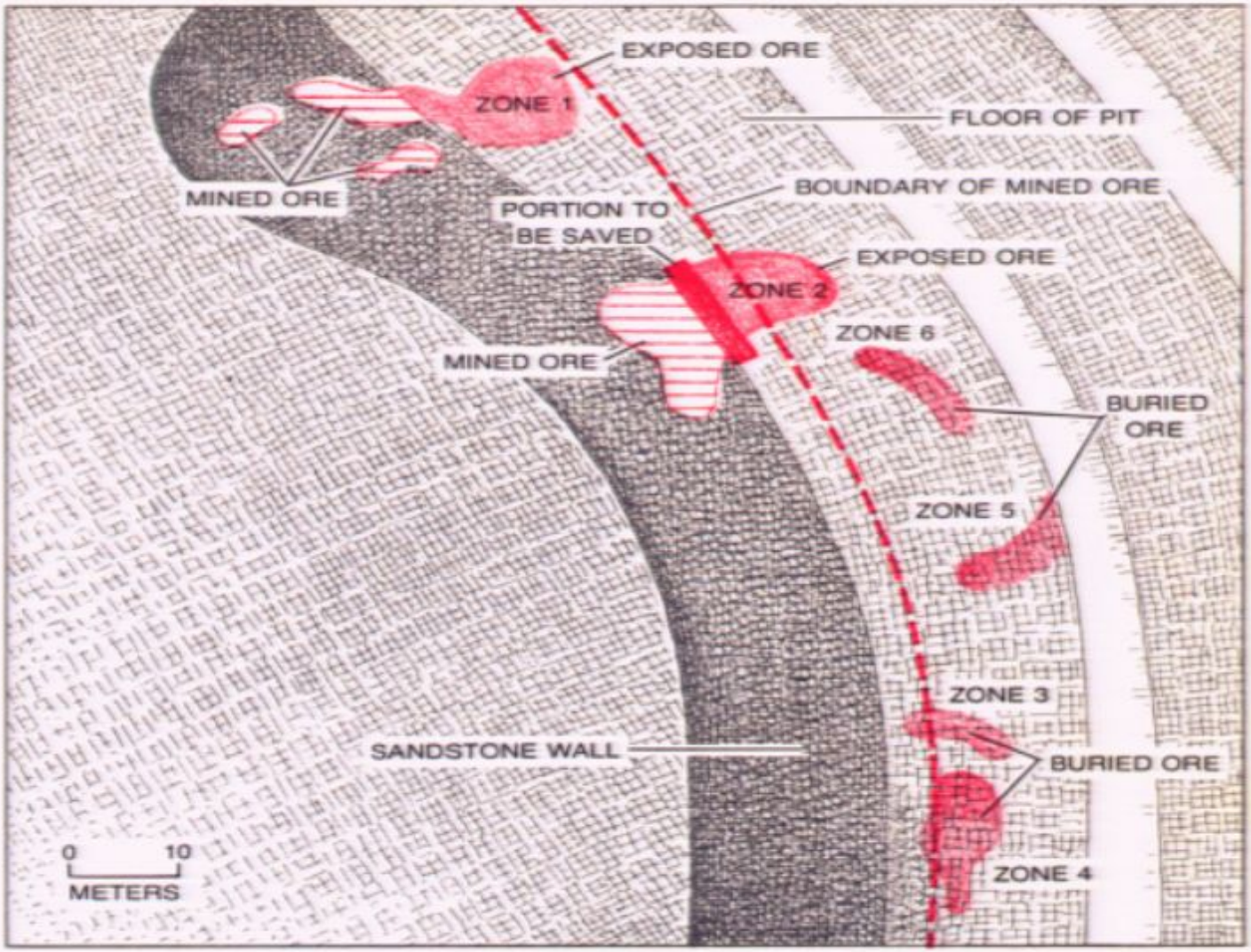


Recovery of ore samples



ORE BODY AT OKLO, shown in a schematic profile of the mine, lies above a sandstone wall with an average slope of about 45 degrees. The reactor zones are within the rich vein of ore, which is roughly a meter thick. The zones generally have a lenticular cross section. The extent of the ore body and the location of the reactor zones were revealed by removing core samples.

Distribution of several reactor sites



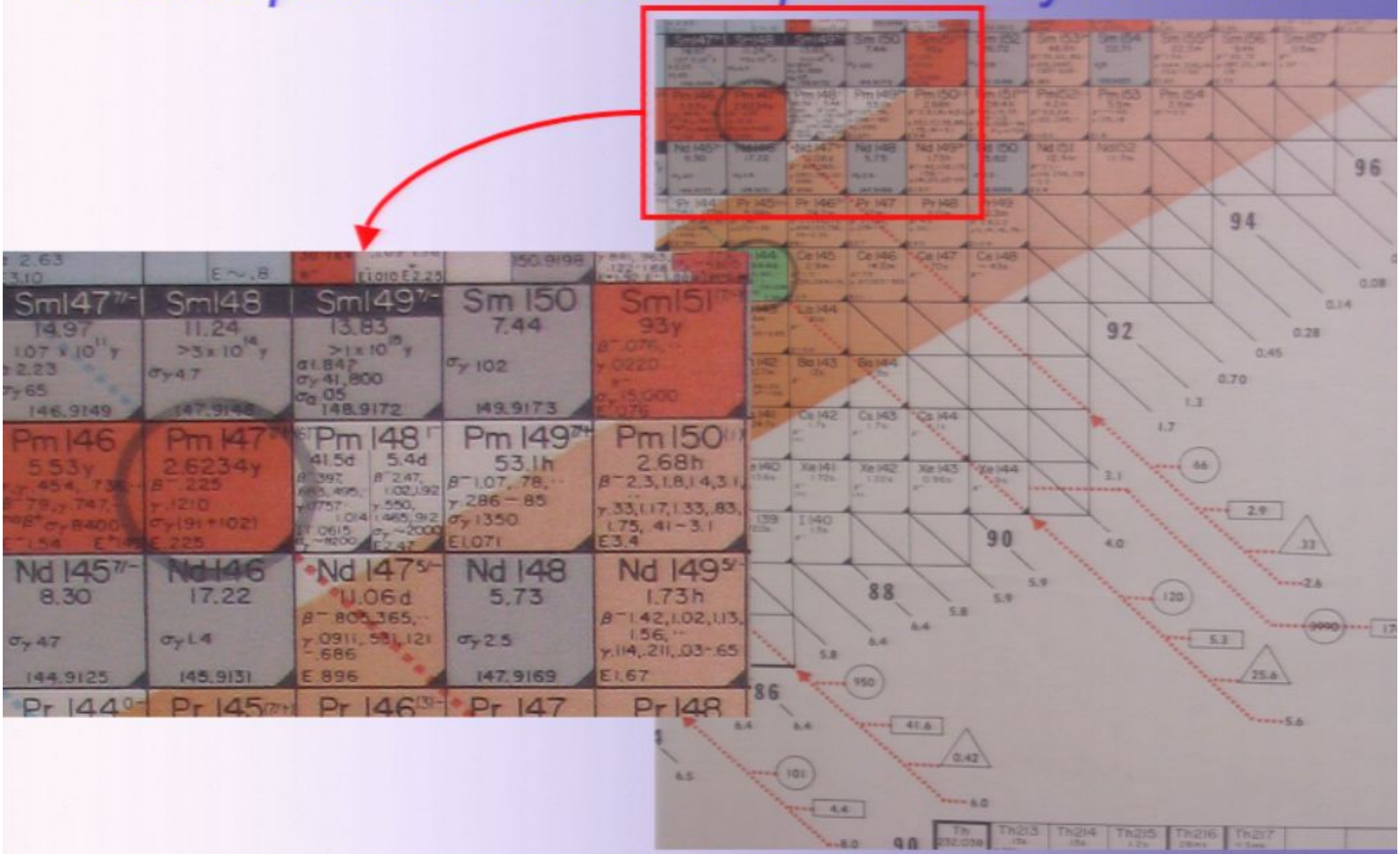
SIX REACTOR ZONES at Oklo were found in lenses of exceptionally rich ore. Parts of zones 1 and 2 had already been mined when the reactor was discovered, and their boundaries are therefore conjectural. Zones 3, 4, 5 and 6 have not yet been exposed; they lie below the present floor of the pit and were found by drilling cores. A portion of Zone 2 has been pinned to the rock face so that it will not be destroyed when the pit is deepened. In ore from the reactor zones the average concentration of uranium is from 20 to 30 percent, more than 50 times the concentration elsewhere. On the other hand, the uranium in the reactor zones is strongly depleted in U-235.

Operating characteristics of Oklo reactors

- Operating lifetime estimated as about 100,000 years: of sufficient duration for ^{239}Pu, bred by ^{238}U neutron absorption, to decay to ^{235}U and contribute to the reaction
- Some samples actually show enhanced ^{235}U isotopic abundance
- Average age of reactors: 1.8×10^9 years
- Integrated neutron flux: $\Phi \sim 10^{21}/cm^2$
- Recent work indicates the reactor operated at low temperature (Meshick, Wash. U.)
  - Operation not continuous: chain reaction supported for only a few minutes
  - Long cycle of cooling between successive chain reactions


Old Faithful
Yellowstone National Park

Fission products and subsequent decay channels

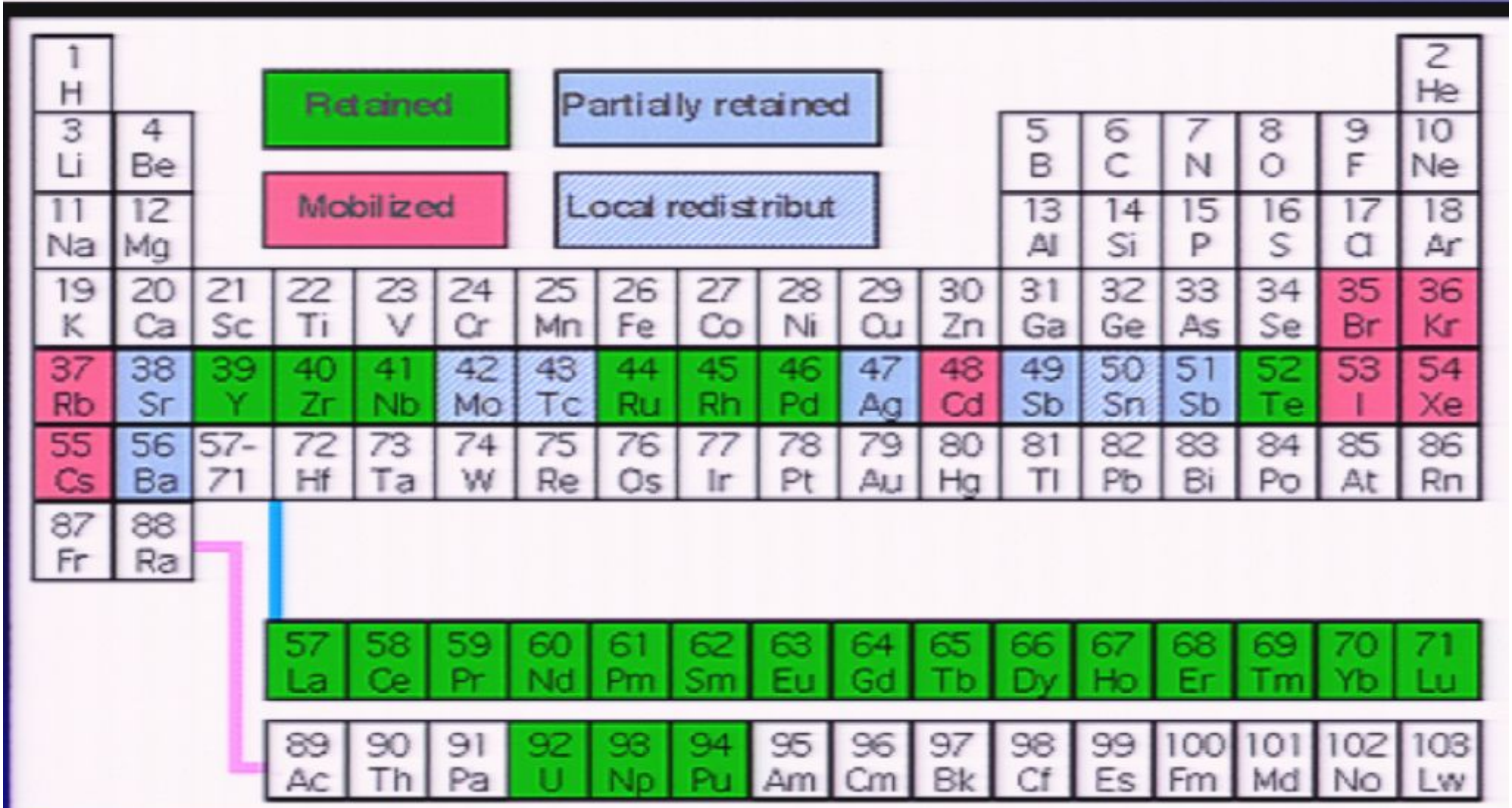


✓ Reactor-produced abundance

Los Alamos

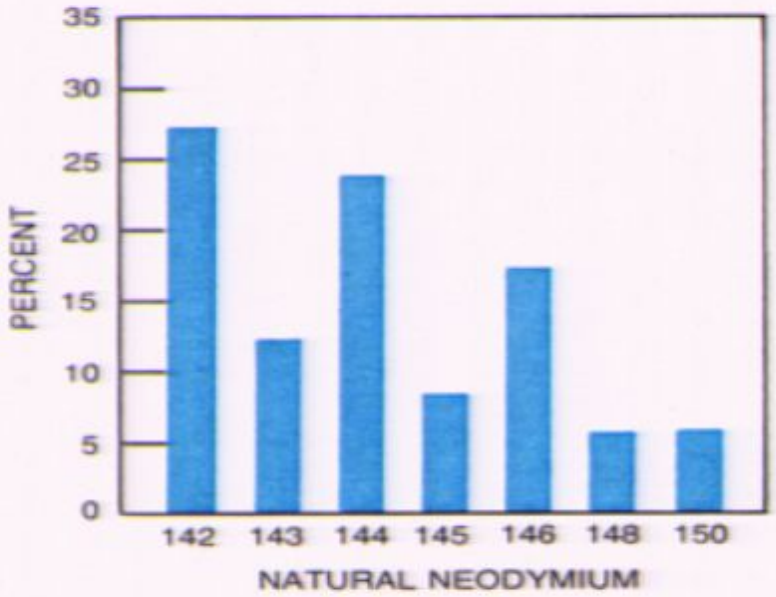
Physics

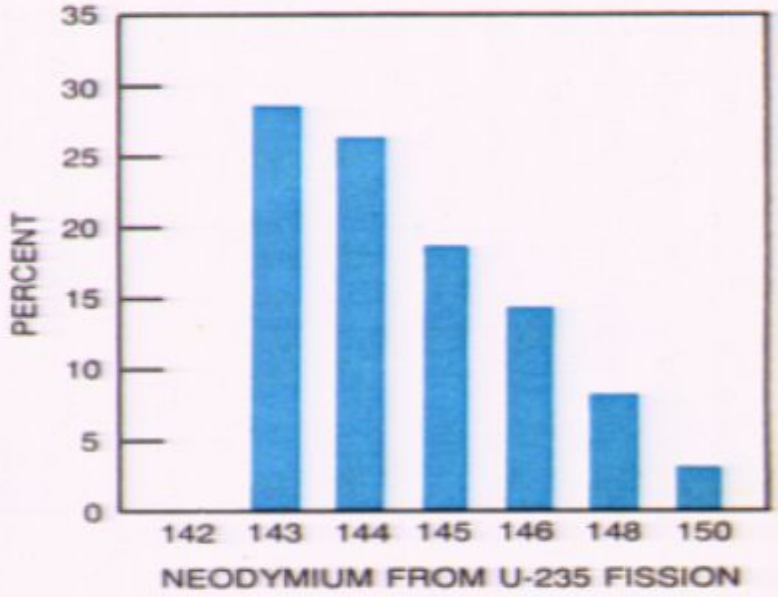
Retention of fission products at Oklo

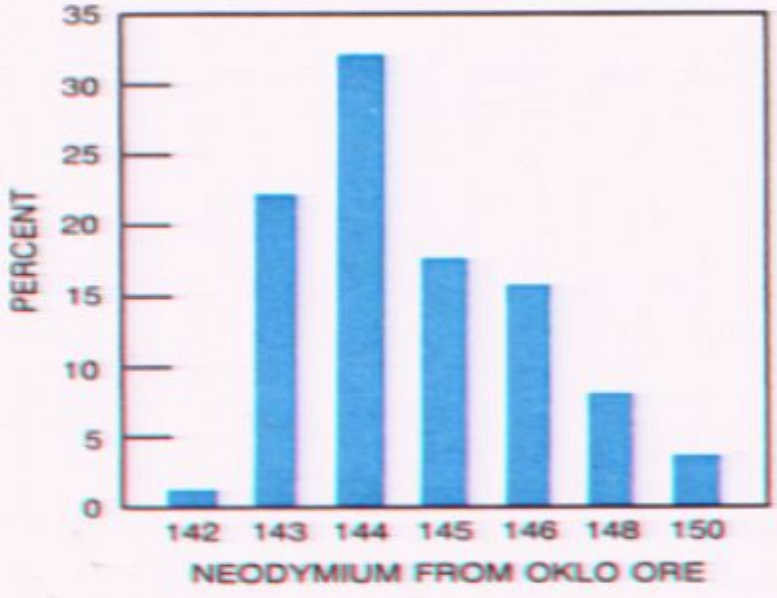


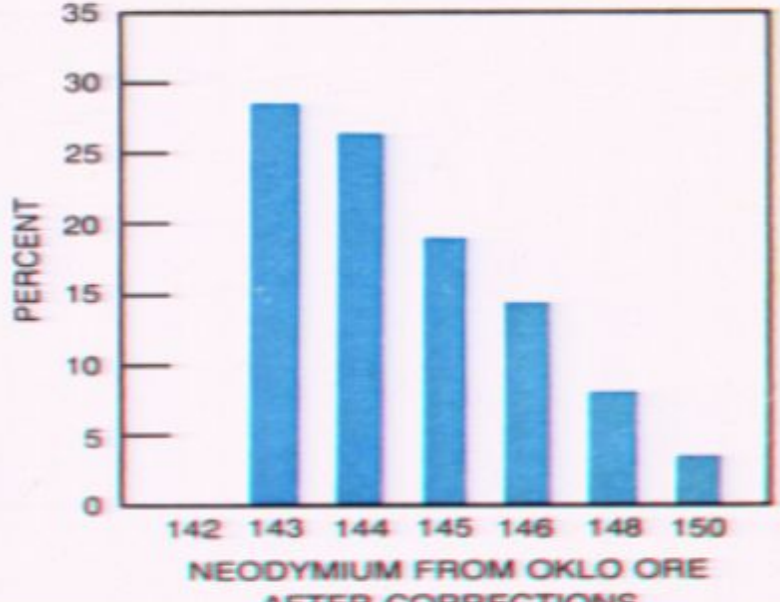
✓ Isolated, preserved samples

Detection of fission products from ore

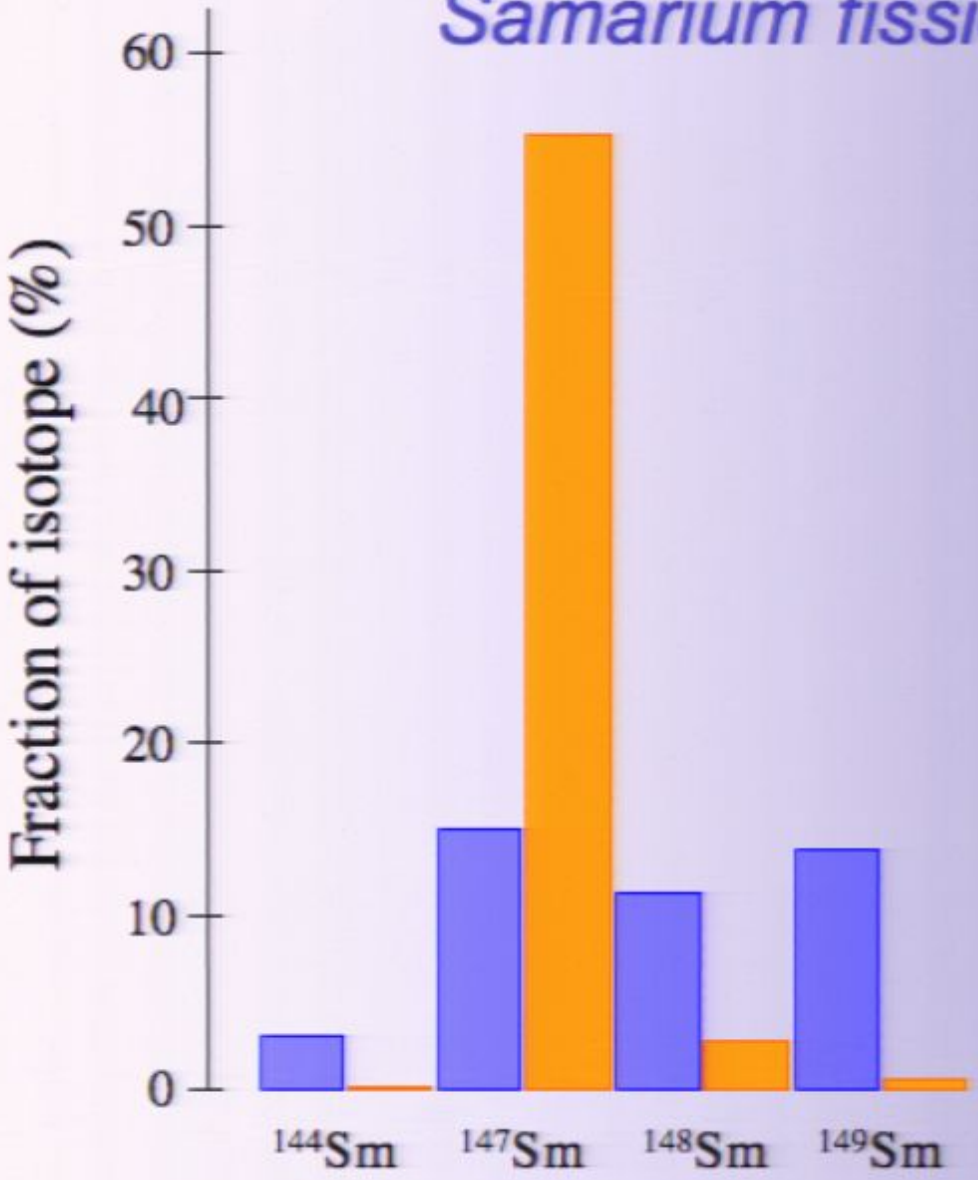








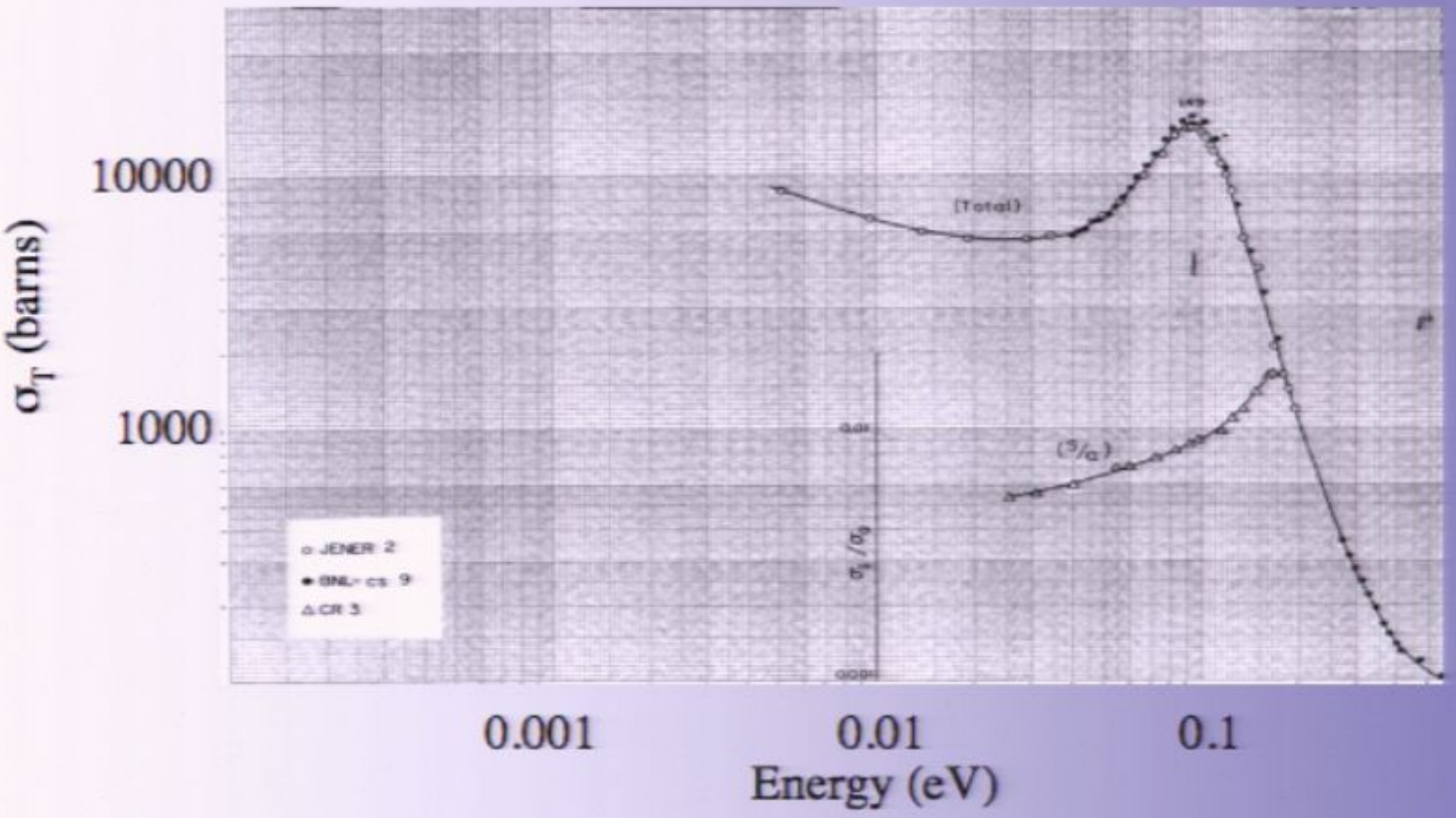
Samarium fission products



- Clear indication of natural reactor operation
- ^{144}Sm - indicator of reactor contamination
- Only ^{149}Sm possesses low-energy neutron absorption (all others are 1/v absorbers)

✓ Natural abundances
✓ Reactor-produced abundances

Experimental ^{149}Sm resonance



- E_r = 97.3 meV
- Reproduced by several groups

- ✓ Low-energy neutron resonance
- ✓ Effect of neutron captures

Calculation of cross-sections from neutron spectra

- Breit-Wigner approximation:

$$\sigma(E) = \frac{g\hbar^2\pi}{2mE}\frac{\Gamma_n\Gamma_\gamma}{(E-E_r)^2+\Gamma_{tot}^2/4}$$

$$\Gamma_{tot} = \Gamma_n(E) + \Gamma_\gamma$$

$$\Gamma_n(E) = \sqrt{E}\Gamma_{n,0}$$

- g, $\Gamma_{n,0}$, Γ_γ all available in tabularized form
- E_r known from experimental data

$$\langle\sigma\rangle = \int \sigma(E)\Phi_n(E,T)dE \quad \Rightarrow \quad \langle\sigma\rangle = \frac{\int \sigma(E)\Phi_n(E,T)dE}{v_0\int \rho_n(E,T)dE}$$

- For 1/v absorber (*eg.* ^{235}U):

$$\langle\sigma\rangle = \sigma(E_0) \qquad \Phi_n(E,T) = v_0\int \rho_n(E,T)dE$$

✓ Energy dependence of neutron resonance

Calculation of cross-sections from Oklo samples

$$\frac{dN_{147}}{dt}\frac{1}{\Phi_n} = -\langle\sigma_{147}\rangle N_{147} + \langle\sigma_{5,f}\rangle Y_5^{147} N_5^0 e^{-\langle\sigma_a\rangle\Phi_n t}$$

$$\frac{dN_{148}}{dt}\frac{1}{\Phi_n} = \langle\sigma_{147}\rangle N_{147}$$

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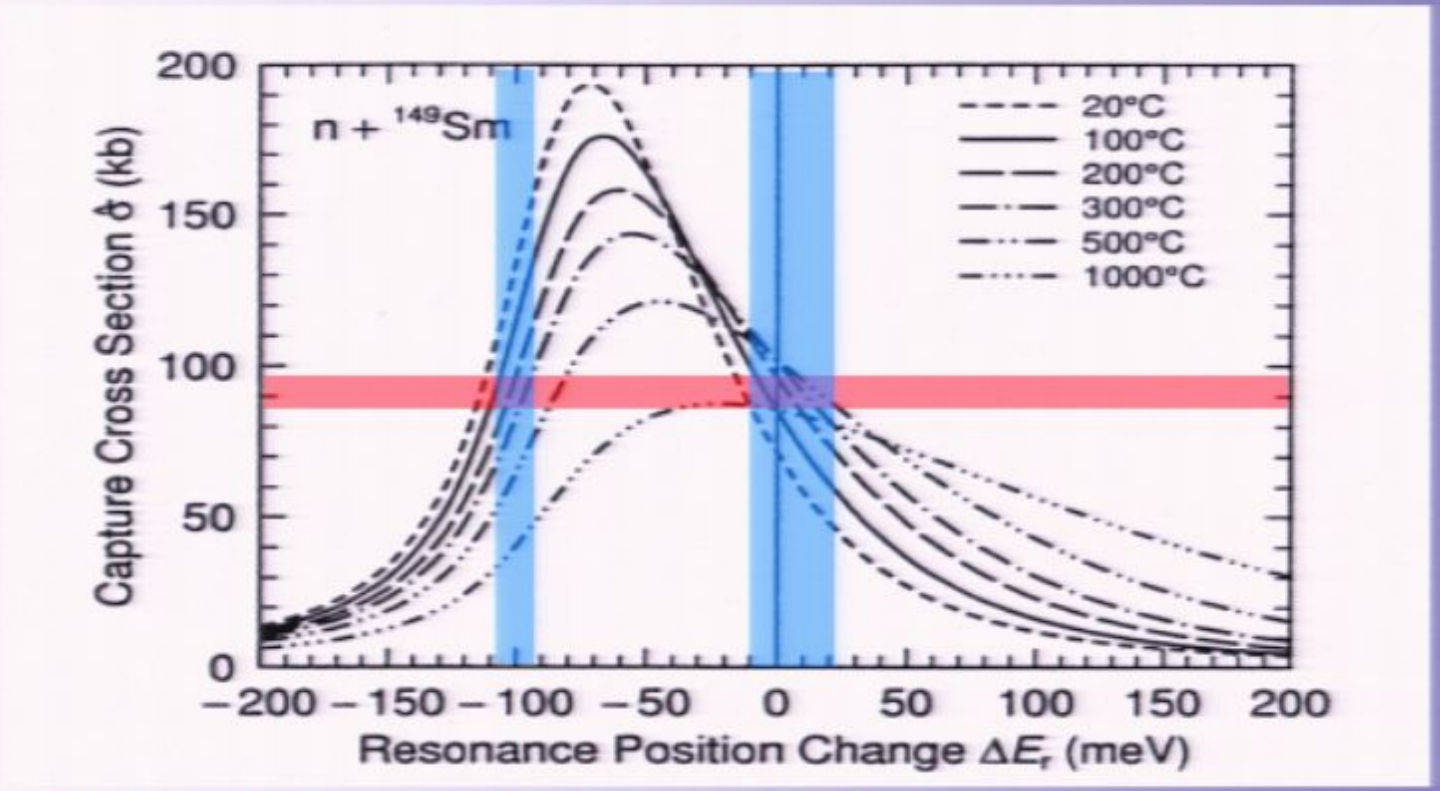
	Sample				
	SF84-1469	SF84-1480	SF84-1485	SF84-1492	SD.37
$\hat{\phi}t_1$ (1/kb)	0.525	0.798	0.622	0.564	0.780
$N_{144}(t_1)$ (%)	0.1052	0.2401	0.2073	0.1619	0.06909
$N_{147}(t_1)$ (%)	55.34	53.23	54.03	54.81	52.74
$N_{148}(t_1)$ (%)	2.796	3.468	3.079	2.890	4.694
$N_{149}(t_1)$ (%)	0.5544	0.2821	0.4466	0.4296	0.3088
$N_{235}(t_1)/N_{238}(t_1)$	0.03181	0.02665	0.02971	0.03047	0.02435
$\hat{\sigma}_{149}$ (kb)	85.6	96.5	83.8	99.0	89.5

✓ Partial model for reactor dynamics

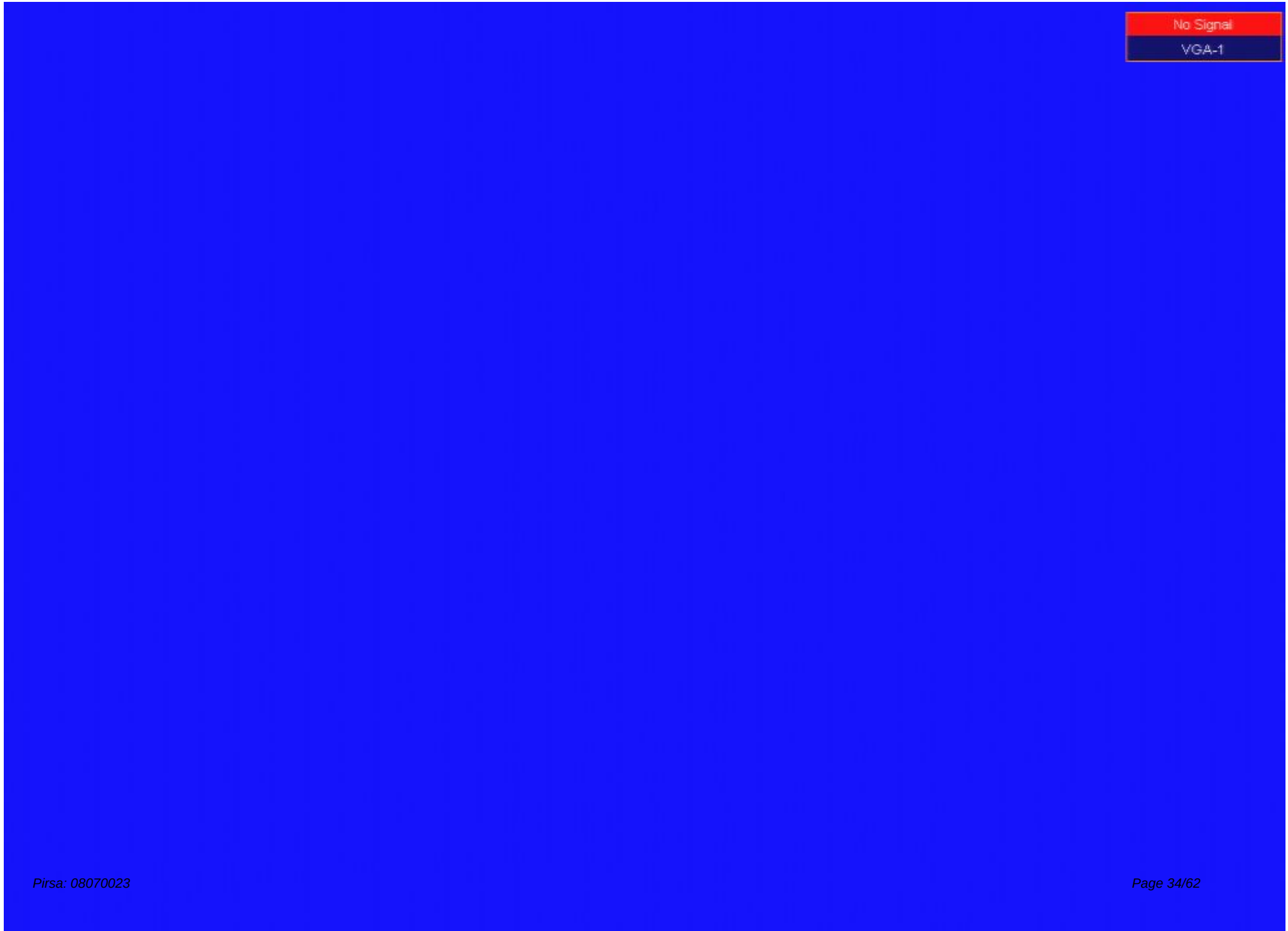
Results of Fujii, et al.



- Uses Maxwell-Boltzman distribution for $\Rightarrow \rho_n(E,T)$ (assumes thermal equilibrium)
- Experimentally determined $\Rightarrow \langle \sigma_{149} \rangle$ (from these data)
- Two solutions:

$$\Delta E = -(97 \pm 8) \times 10^{-3}\, eV \qquad \Delta E = +(4 \pm 16) \times 10^{-3}\, eV$$

Y. Fujii et al. Nuclear Physics B 573 (2000) p 377-401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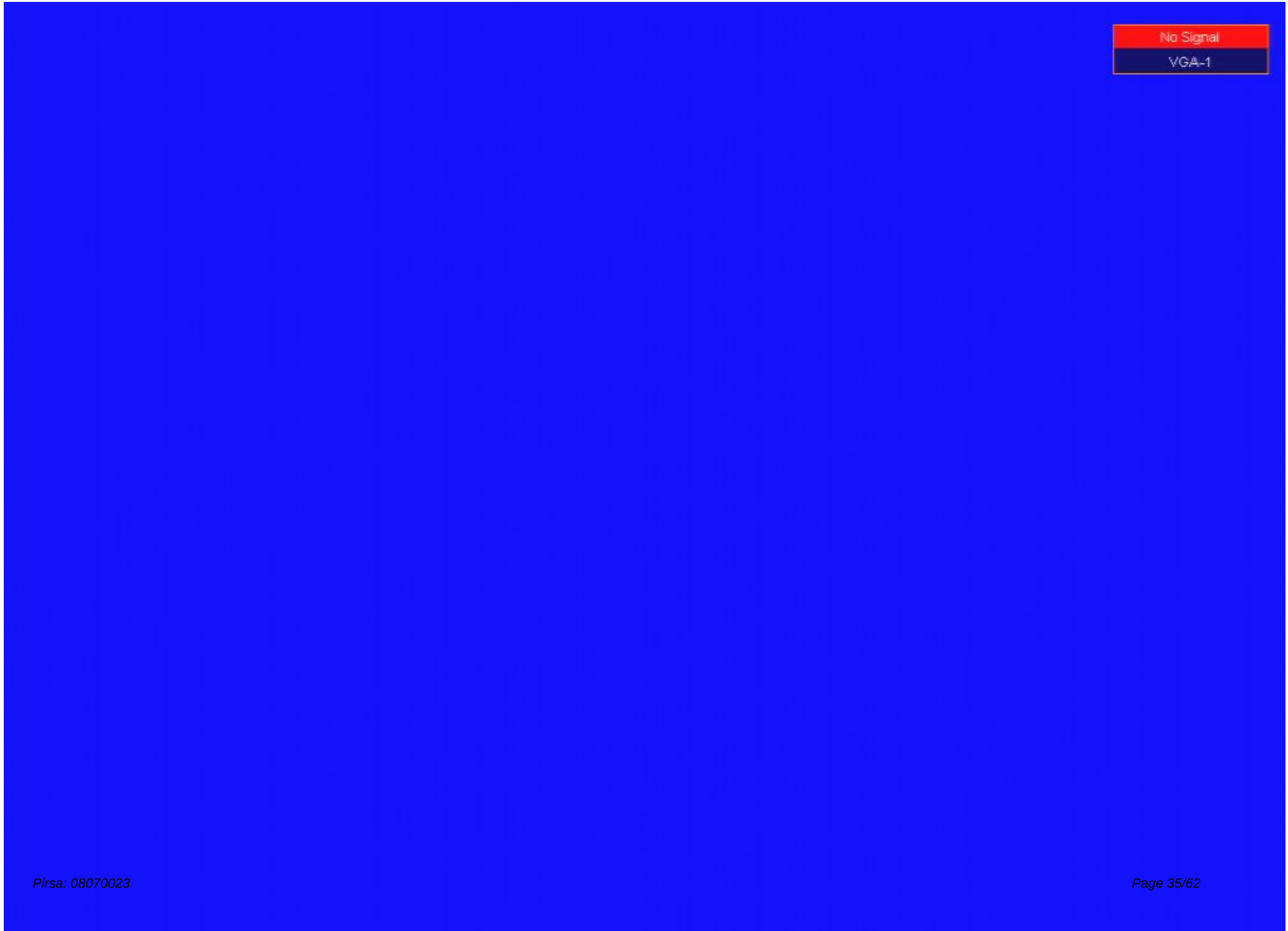
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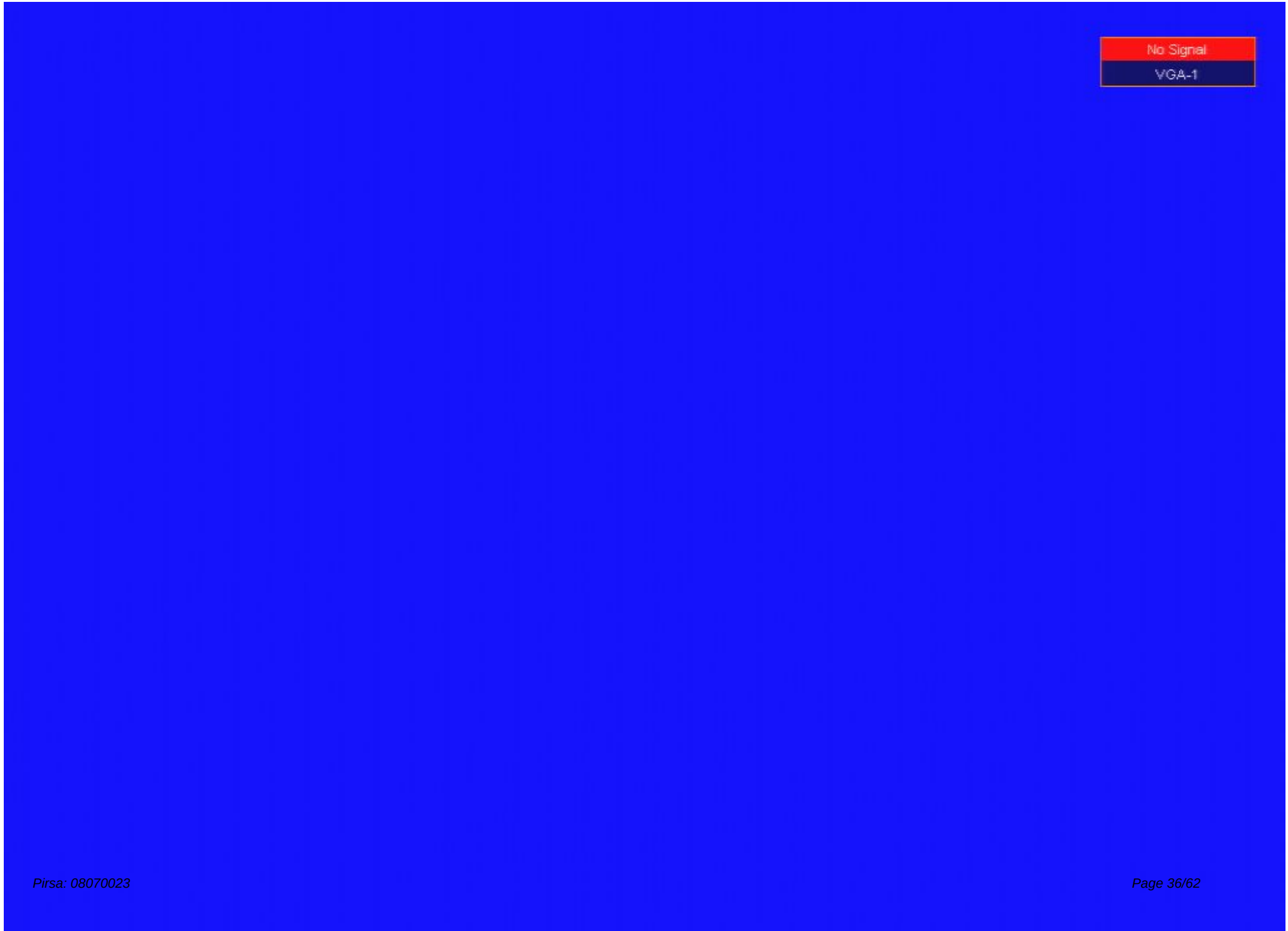
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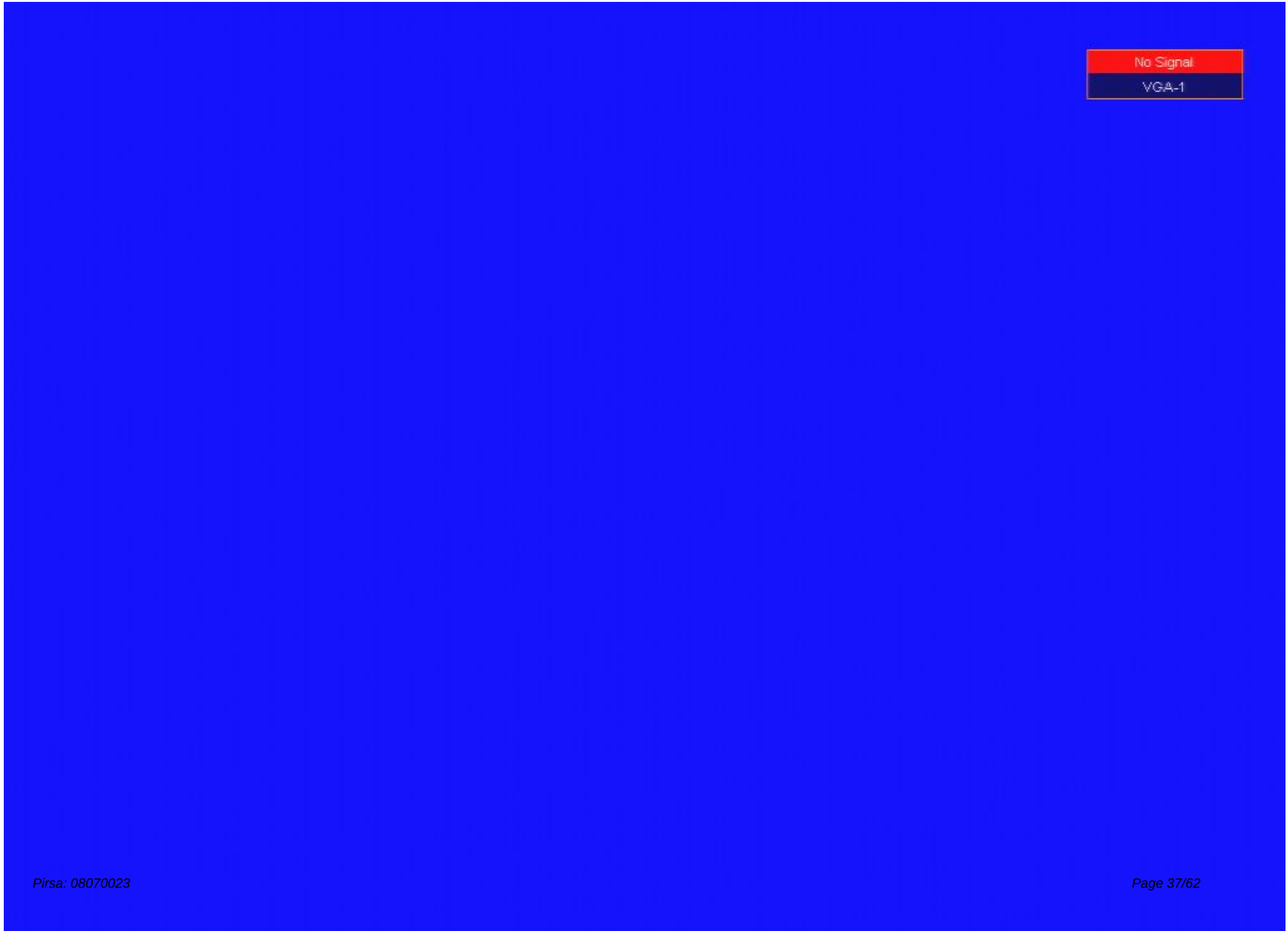
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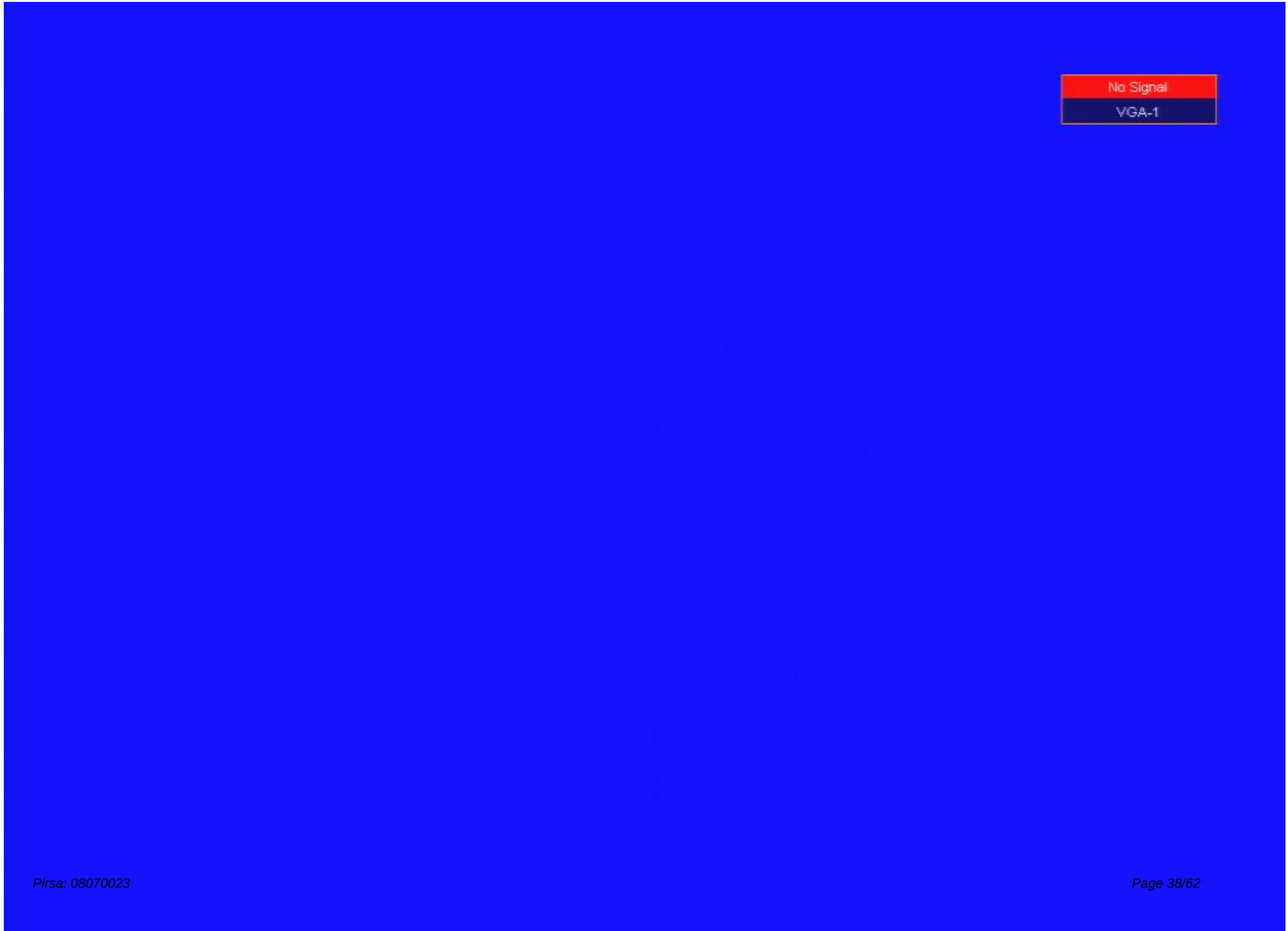
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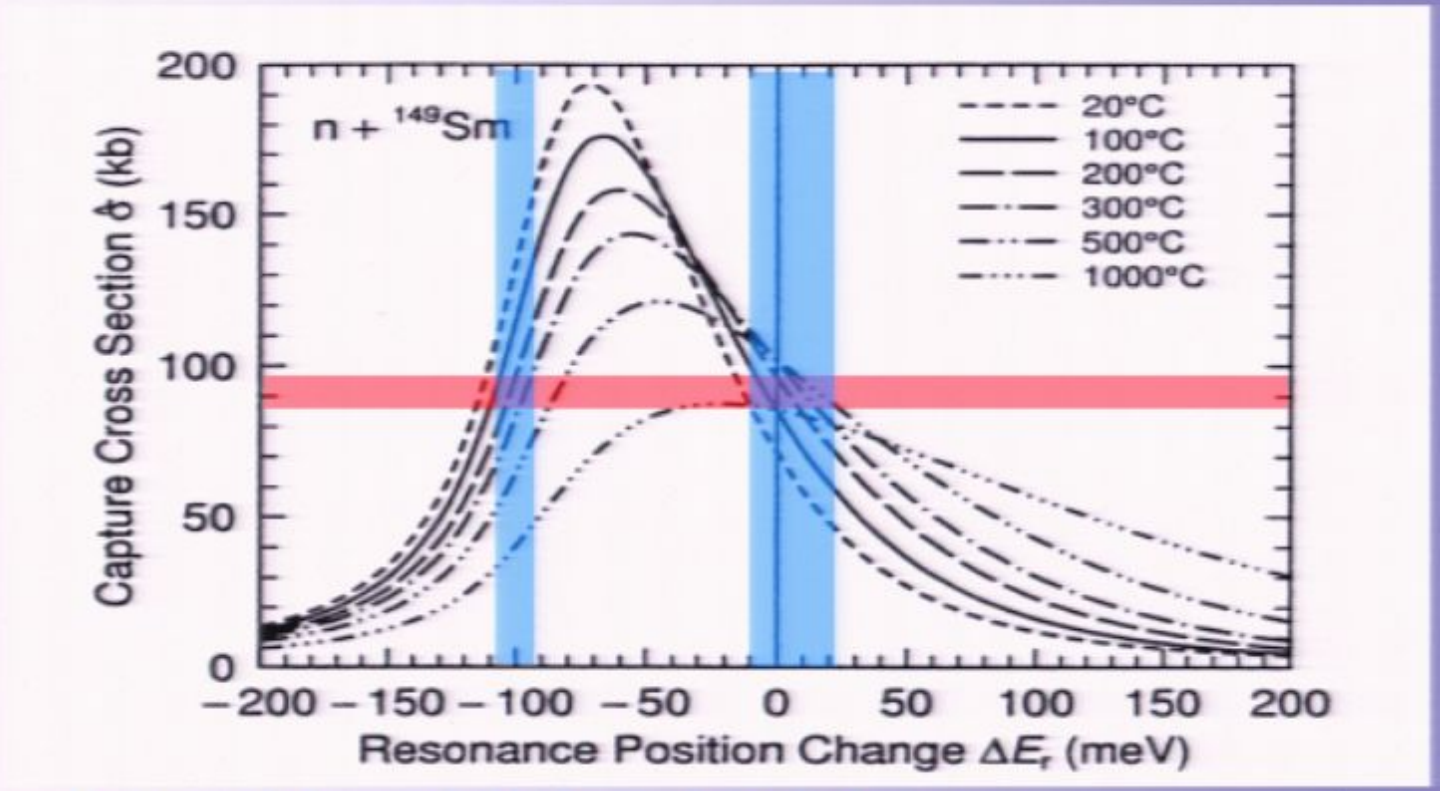
Results of Fujii, et al.



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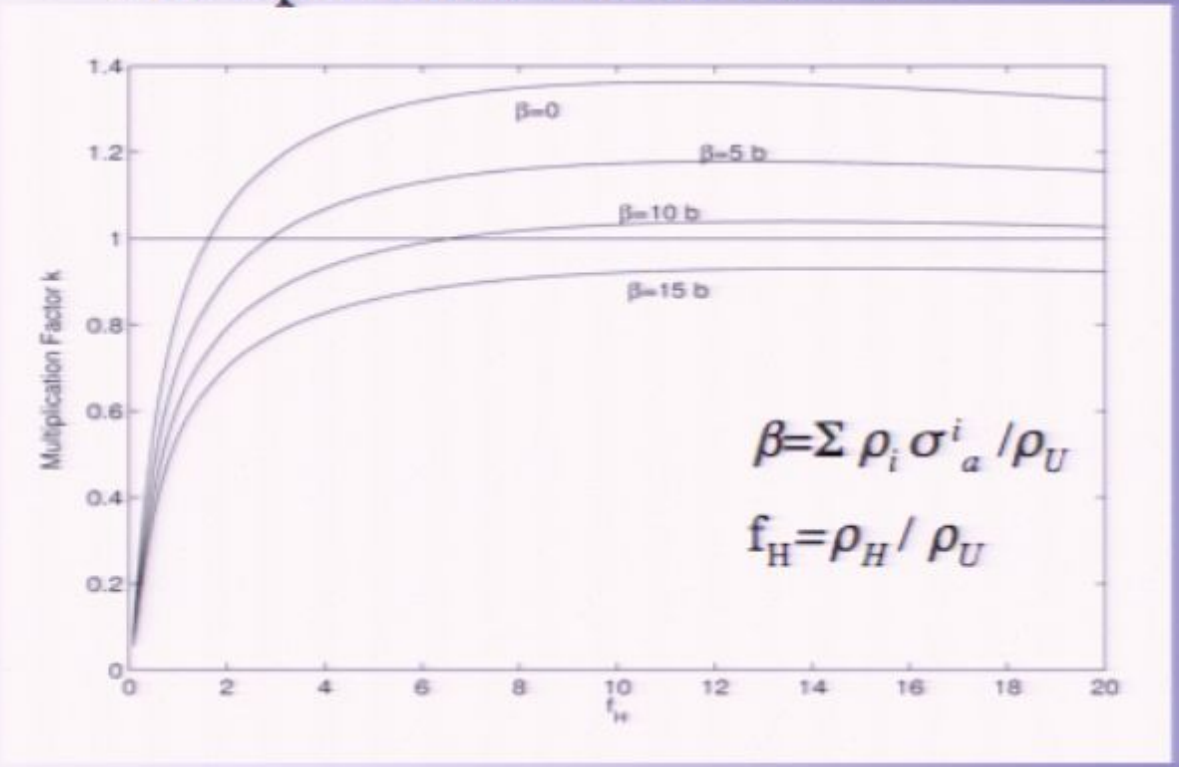
- Experimentally determined $\Rightarrow \langle \sigma_{149} \rangle$ (from these data)
- Two solutions:

$$\Delta E = -(97 \pm 8) \times 10^{-3}\, eV \qquad \Delta E = +(4 \pm 16) \times 10^{-3}\, eV$$

Y. Fujii et al. Nuclear Physics B 573 (2000) p 377-401

Homogeneous reactor with H_2O moderator

Multiplication factor for 3.7% ^{235}U



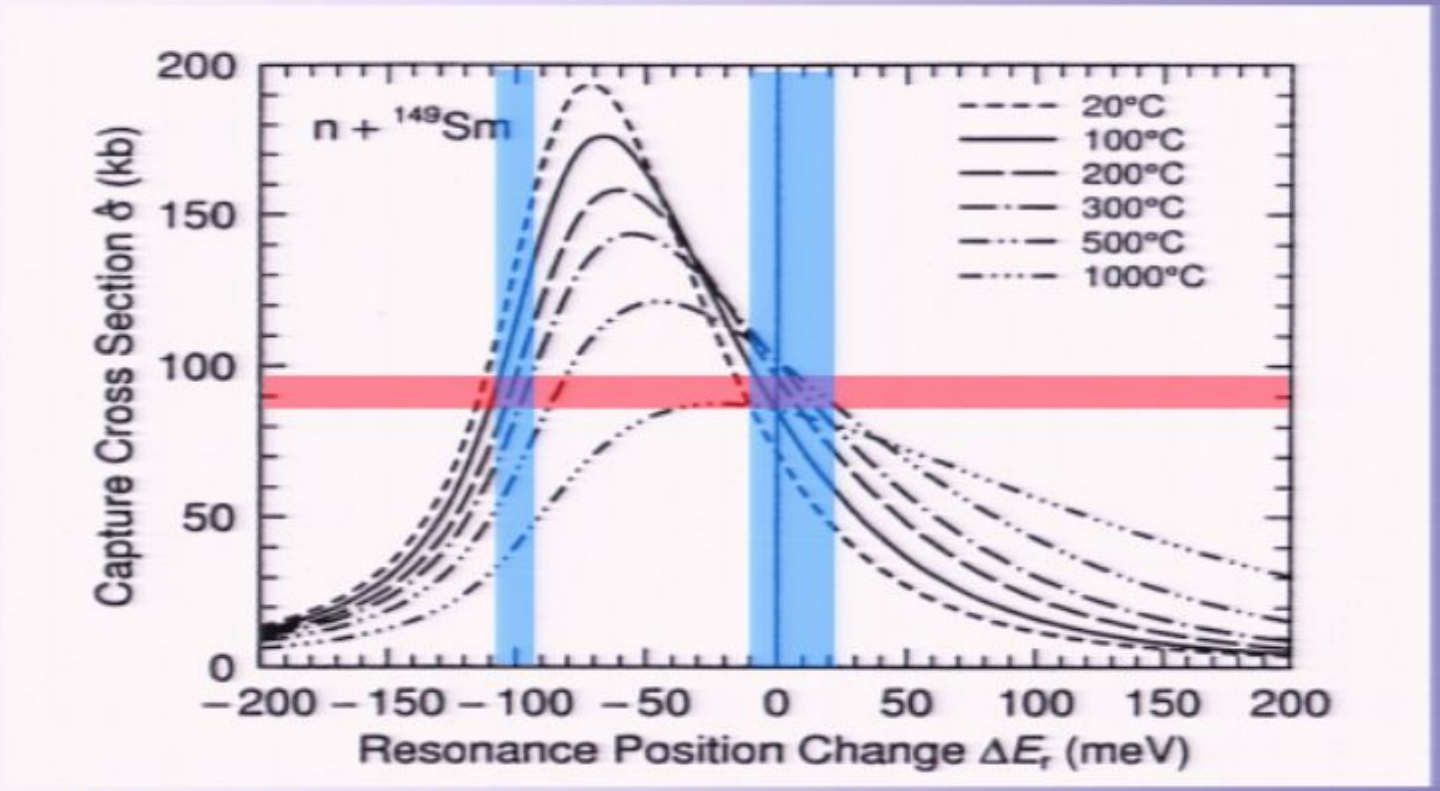
$$k = \nu p \frac{x\rho_U \sigma_f^{235}}{x\rho_U \sigma_a^{235} + (1-x)\rho_U \sigma_a^{238} + \rho_H \sigma_a^H + \sum \rho_i \sigma_a^i}$$

$\nu = 2.47$ Neutrons per fission

$p = e^{-0.7(\rho_U / \rho_H)^{0.58}}$ Resonance escape probability

✓ An important part of a better model for reactor dynamics

Results of Fujii, et al.



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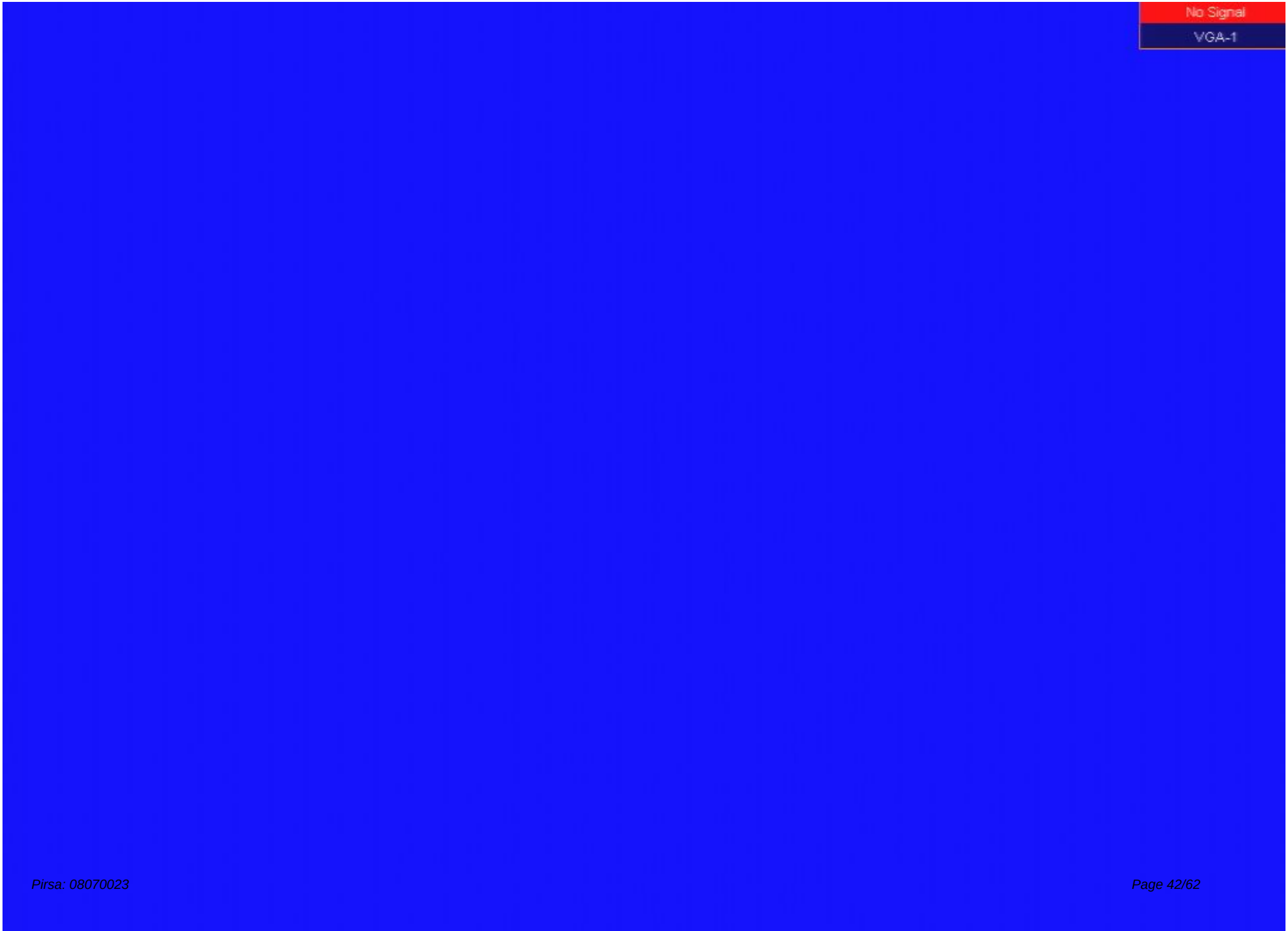
No Signal
VGA-1

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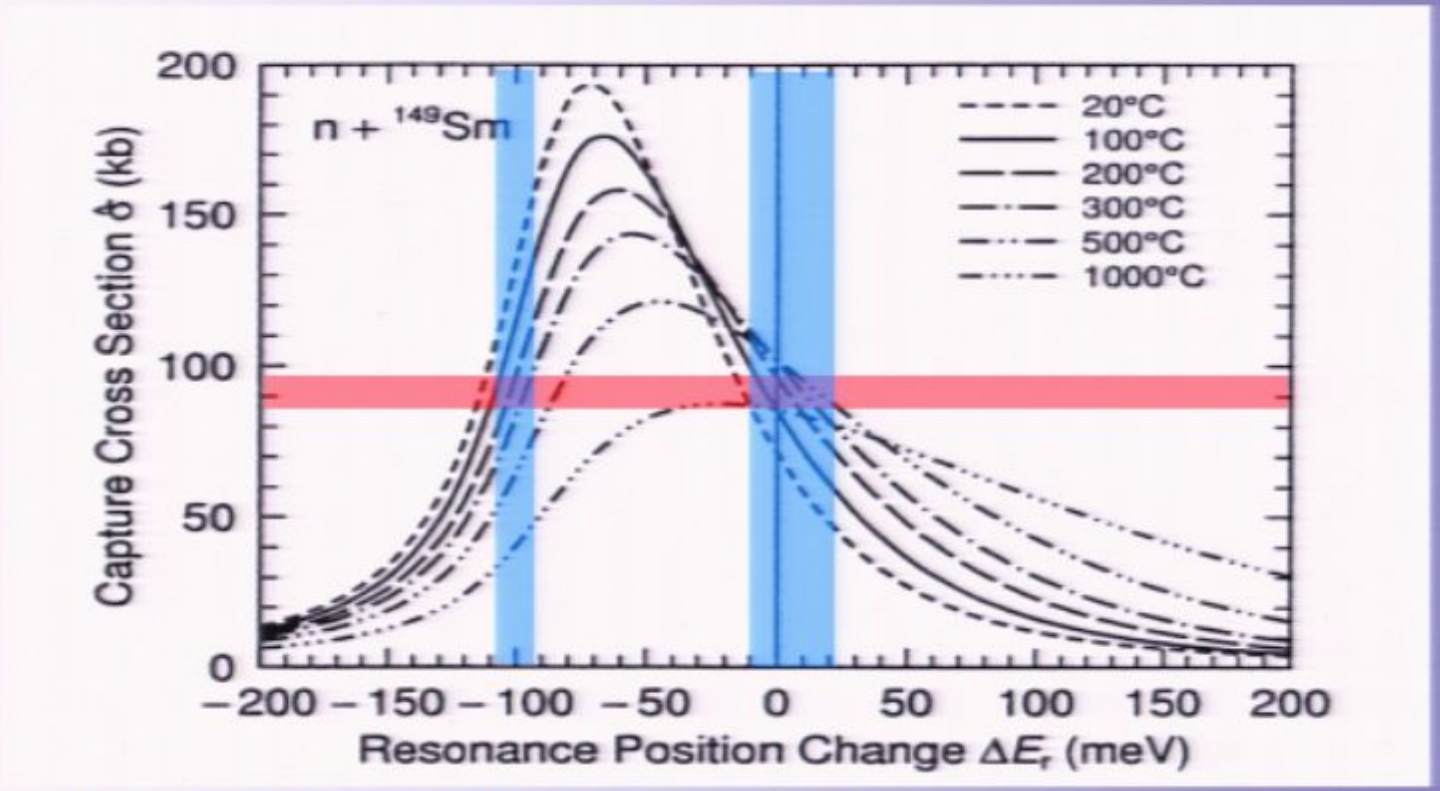

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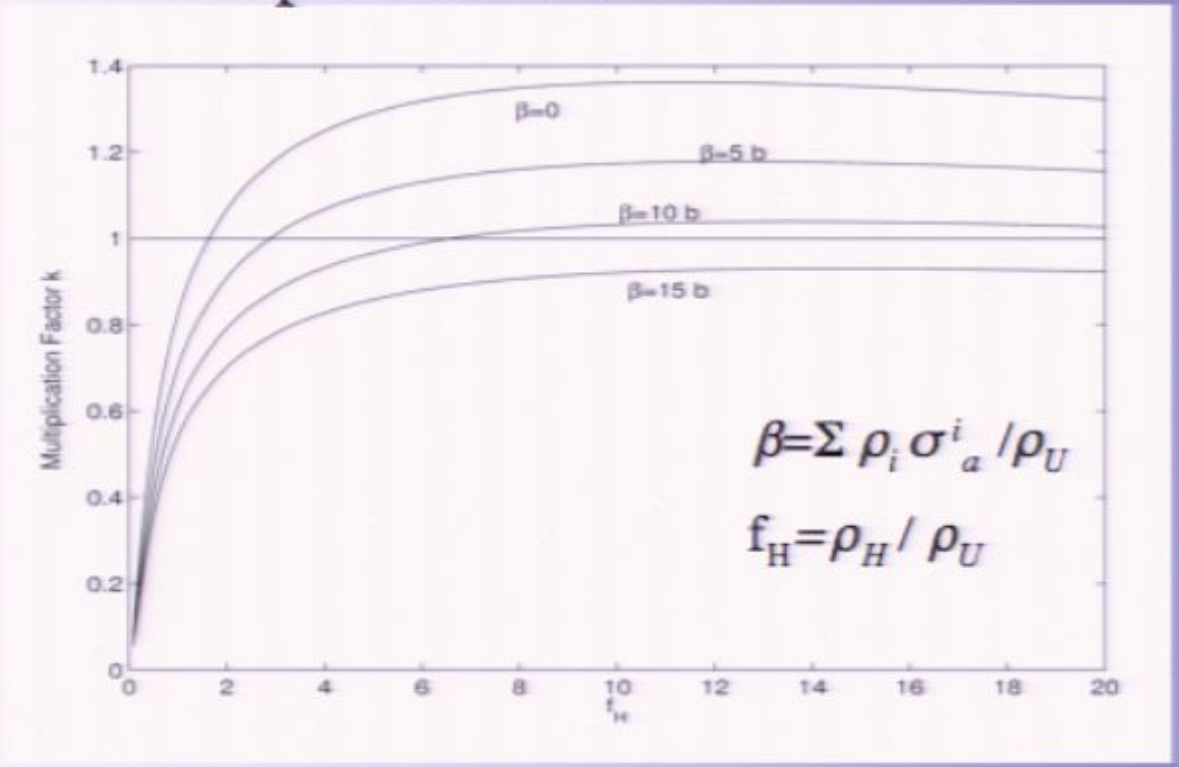

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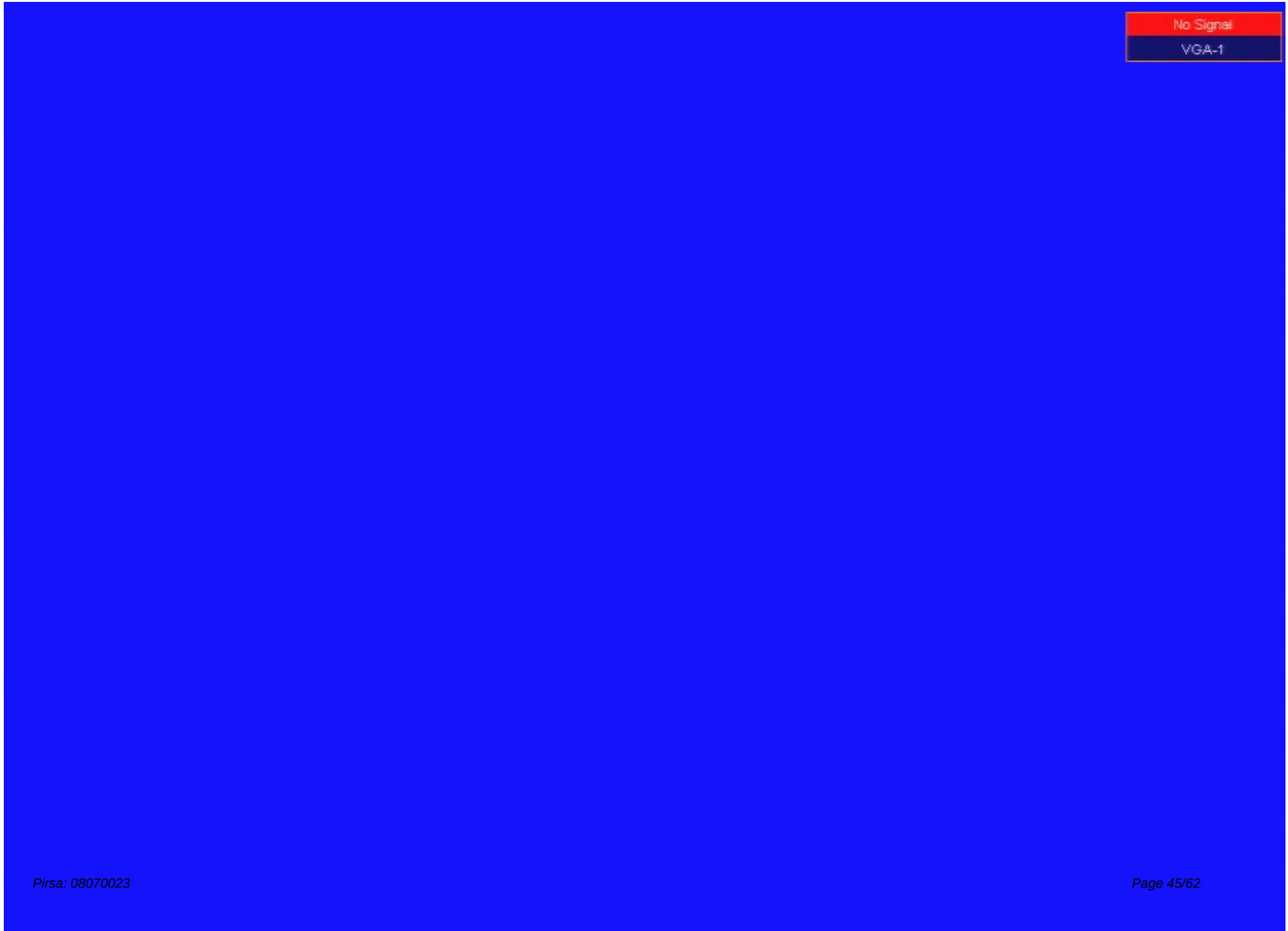
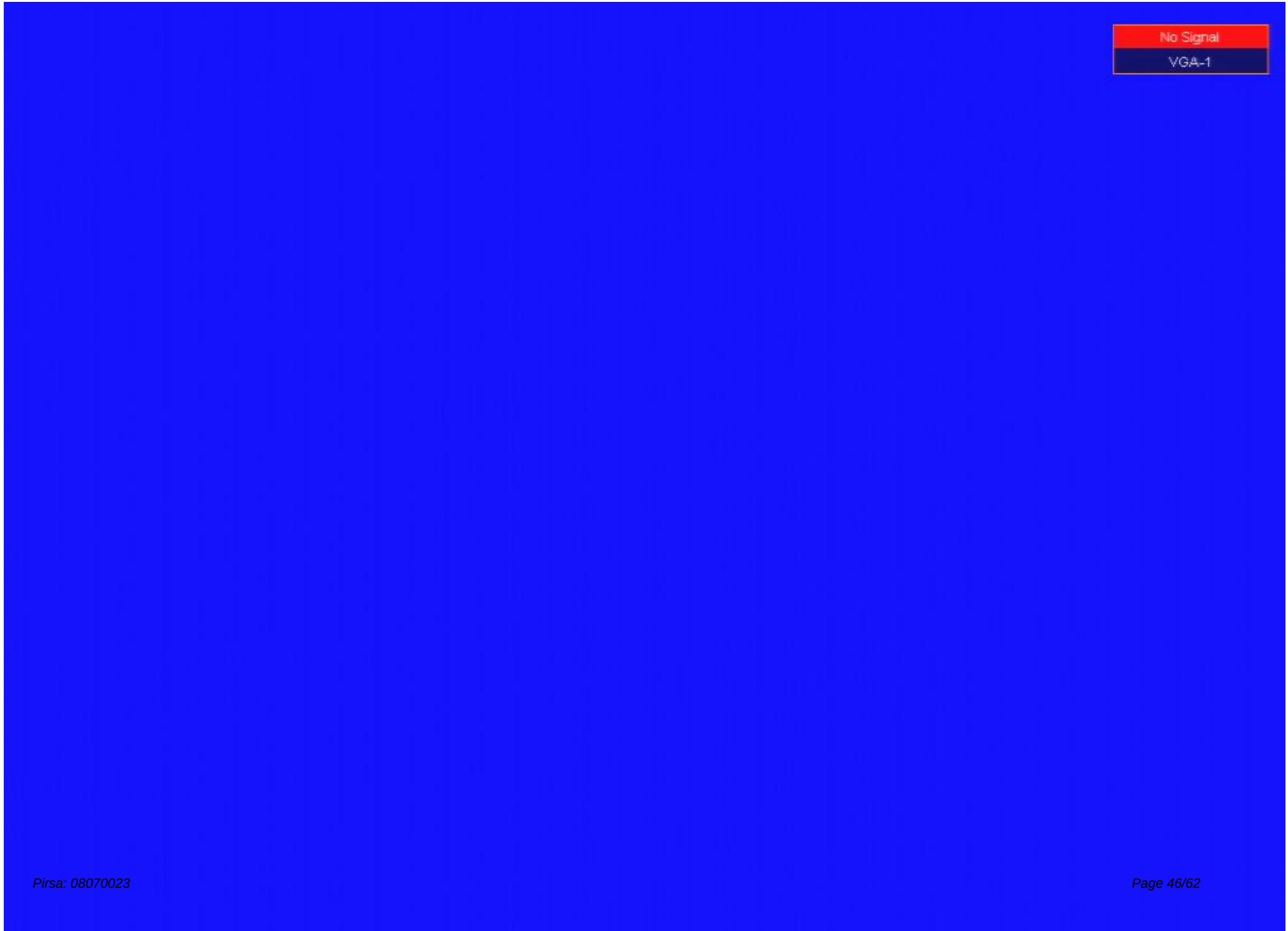

No Signal
VGA-1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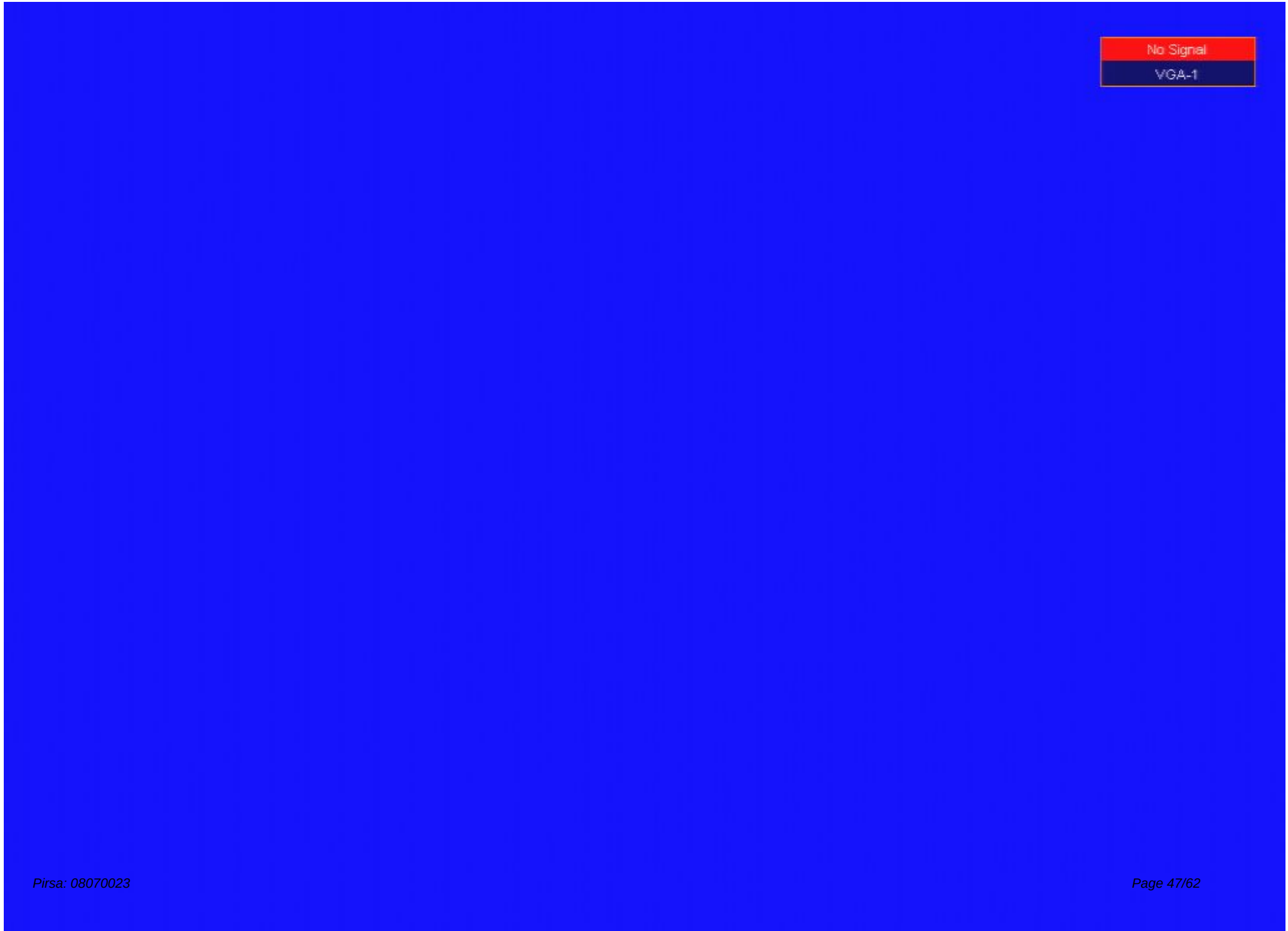
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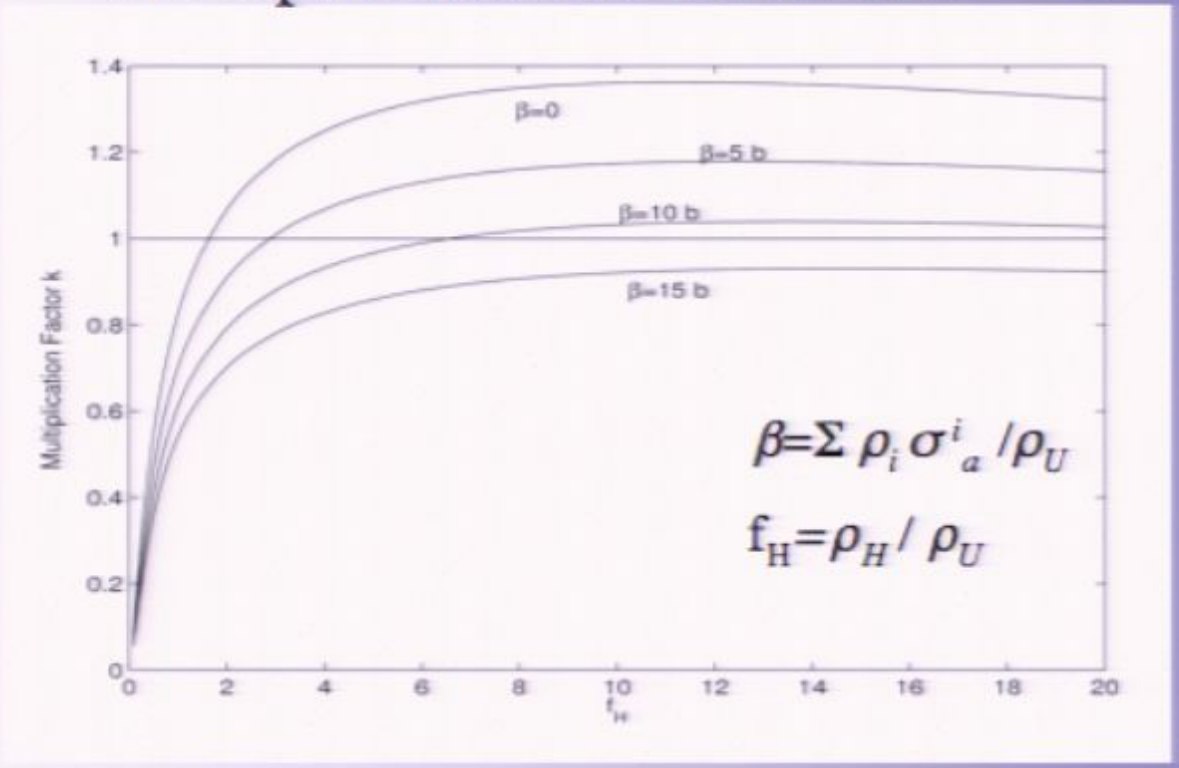

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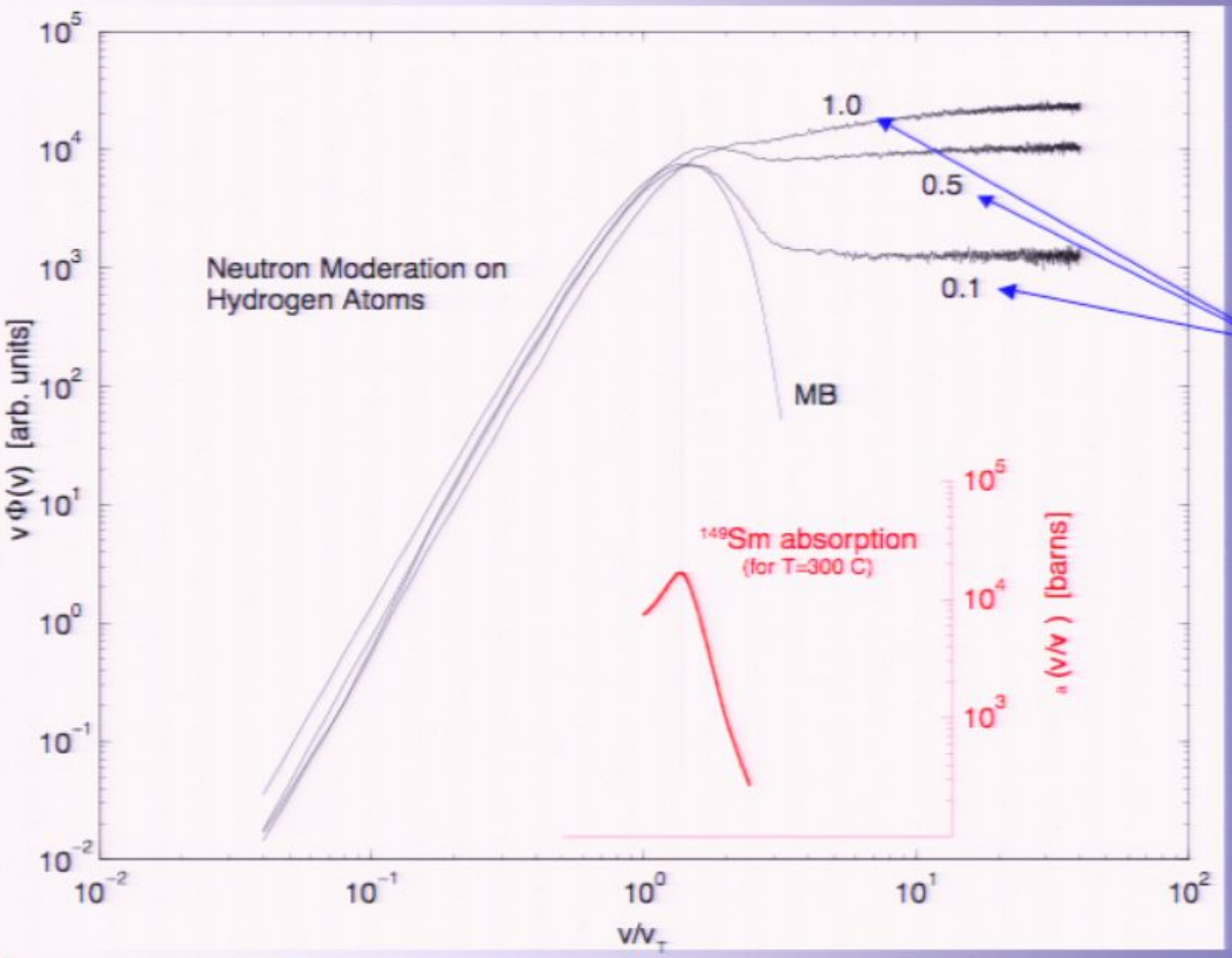
✓ An important part of a better model for reactor dynamics

Realistic neutron spectra with absorbers

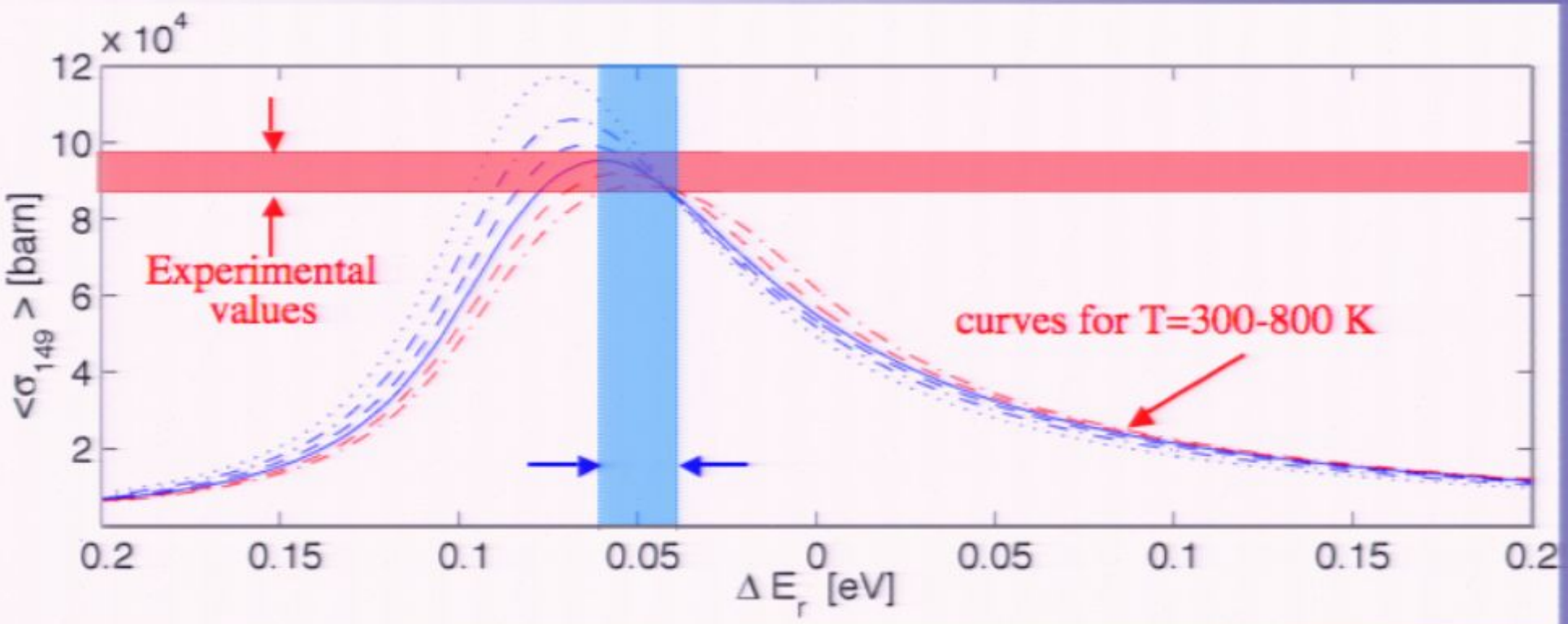


$$\frac{\Sigma_a(v_T)}{\Sigma_s}\left(\frac{absorption}{scatter}\right)$$

✓ A better model for reactor dynamics (still infinite)

Our first results

Calculated $\langle \sigma_{149} \rangle$ as a function of resonance energy



$$\Delta E = -\left(45\ ^{+7}_{-15}\right) \times 10^{-3}\, eV$$

~~$\frac{\Delta E}{-1.1 MeV} = \frac{\Delta\alpha}{\alpha}$~~ ~~$\frac{\Delta\alpha}{\alpha} = +\left(45\ ^{+17}_{-7}\right) \times 10^{-9}$~~

Los Alamos

S. K. Lamoreaux and J. R. Torgerson, Phys. Rev. D 69, 121701(R) (2004)

Physics

More complete calculation of total cross section

- Including effects from ^{239}Pu

$$\frac{dN_{147}}{dt}\frac{1}{\Phi_n} = -\langle\sigma_{147}\rangle N_{147} + \langle\sigma_{5,f}\rangle Y_5^{147} N_5 + \langle\sigma_{9,f}\rangle Y_9^{147} N_9$$

$$\frac{dN_{148}}{dt}\frac{1}{\Phi_n} = -\langle\sigma_{148}\rangle N_{148} + \langle\sigma_{147}\rangle N_{147}$$

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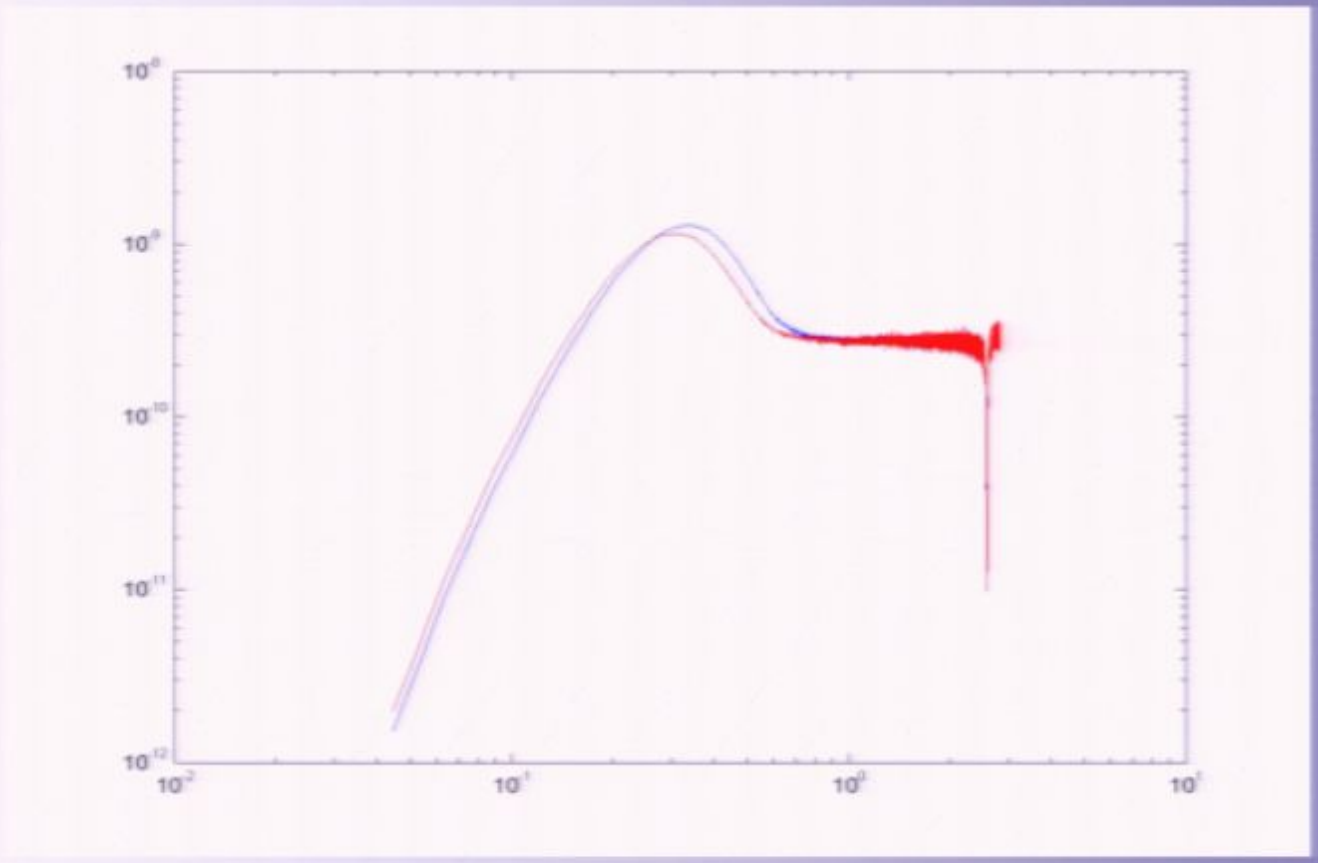
- More complete approach to uranium burning:

$$\frac{dN_8}{dt}\frac{1}{\Phi_n} = -\langle\sigma_8\rangle N_8 - \Gamma \qquad \Gamma = (1-p)\left(\nu_9\langle\sigma_{f,9}\rangle N_9 + \nu_5\langle\sigma_{f,5}\rangle N_5\right)$$

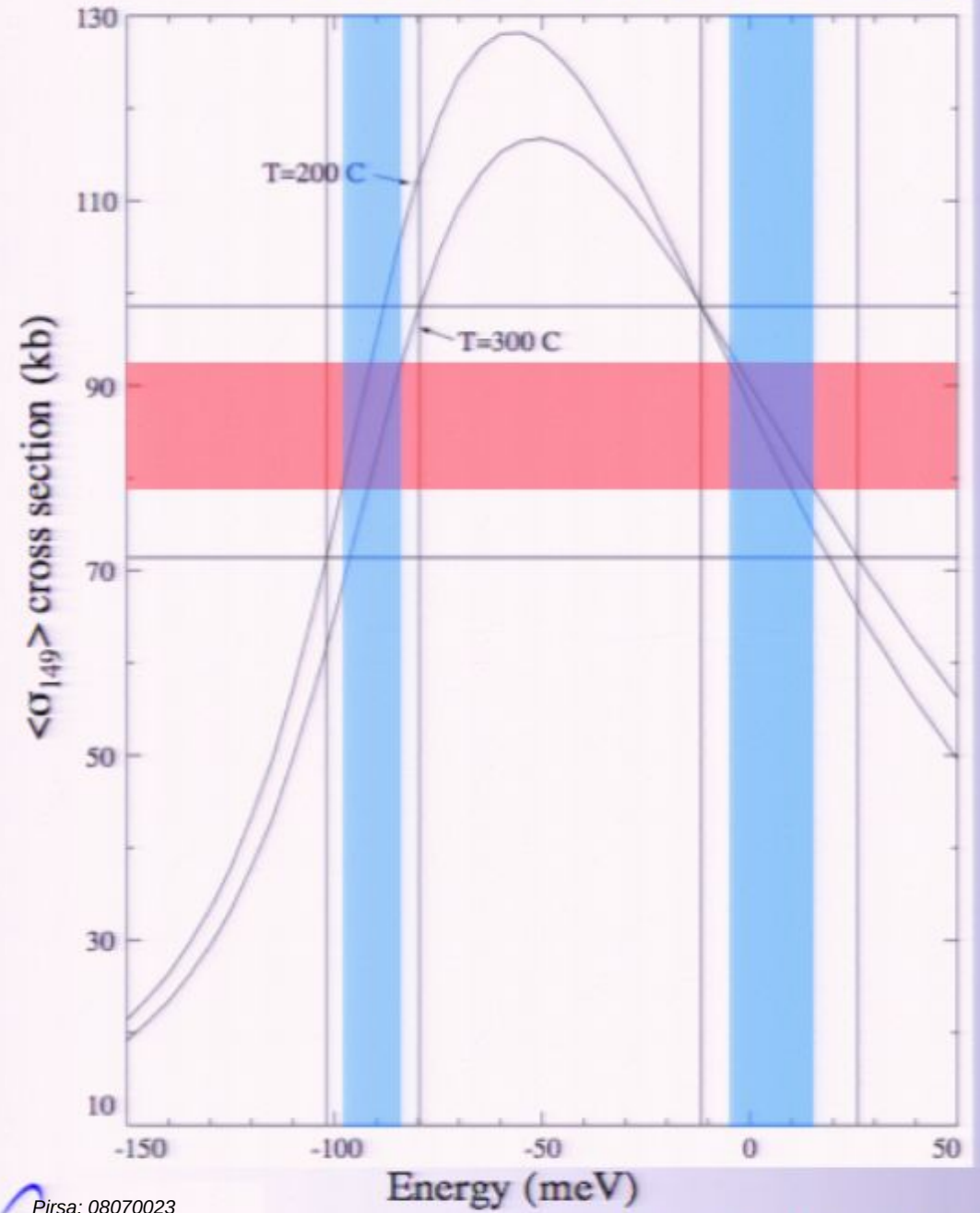
$$\frac{dN_5}{dt}\frac{1}{\Phi_n} = -\langle\sigma_5\rangle N_5 + \frac{\lambda_9}{\Phi_n} N_9 \qquad \frac{dN_9}{dt}\frac{1}{\Phi_n} = \langle\sigma_8\rangle N_8 - \langle\sigma_9\rangle N_9 - \frac{\lambda_9}{\Phi_n} N_9$$

MCNP calculation of neutron spectra



- Fewer “slow” neutrons
- More pronounced structure around 100 meV

MCNP calculation of neutron spectra -



- Still two solutions:

$$\Delta E = +\left(4\,^{+12}_{-9}\right)\times 10^{-3}\,eV$$

$$\Delta E = -\left(91\,^{+8}_{-6}\right)\times 10^{-3}\,eV$$

- Some issues:
  - Finite temperature of absobers
  - Chemical potentials (ie. Protons in H_20 are treated as free)
  - Inhomogeneous reactor
  - Isotope-dependent chemistry (aging of samples over 2 billion years)

Gould, et al., Phys. Rev. C 74, 024607 (2006)

Conclusion

- Ideally, Oklo Phenomenon can be a sensitive test for time variation of fundamental constants
- Result is model-dependent
- Finite-size restriction produced a significant change to the values for ΔE_r
  - For example: chain reactions were found to be limited to a few 10cm within the ~1m x 3m reactor sites
- Estimates of un-included effects suggest that the result will not change by more than 10%
- Data from ^{155}Gd is poor due to contamination with natural Gd, but favor the lower energy bound near $\Delta E_r \sim 0$ (some bias in this determination)
- Need a better model to set bounds on fundamental parameters:

$$\frac{d\ln(E_r)}{dt} = c_\alpha \frac{d\ln(\alpha)}{dt} + c_\Lambda \frac{d\ln(m_q/\Lambda_{QCD})}{dt}$$

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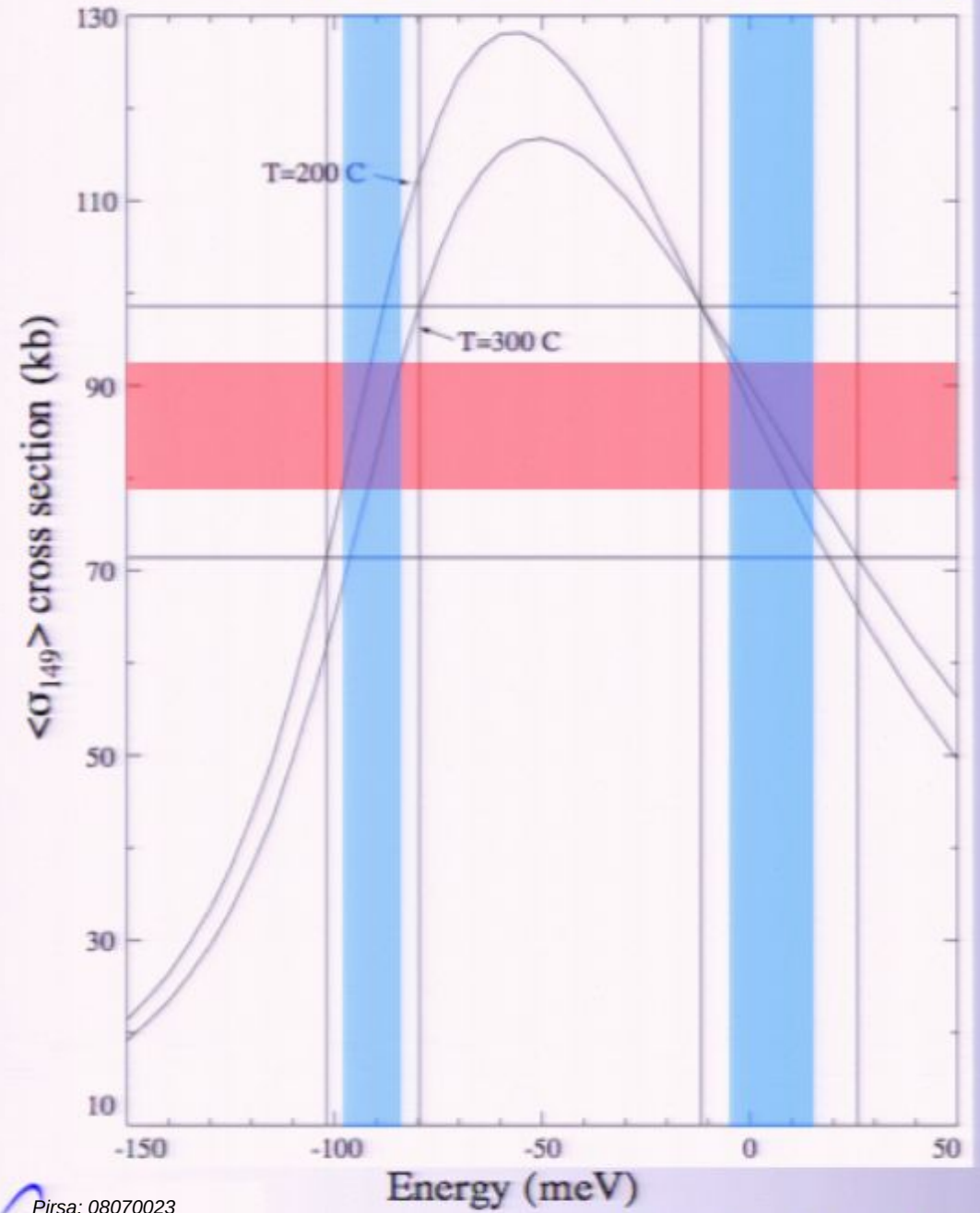

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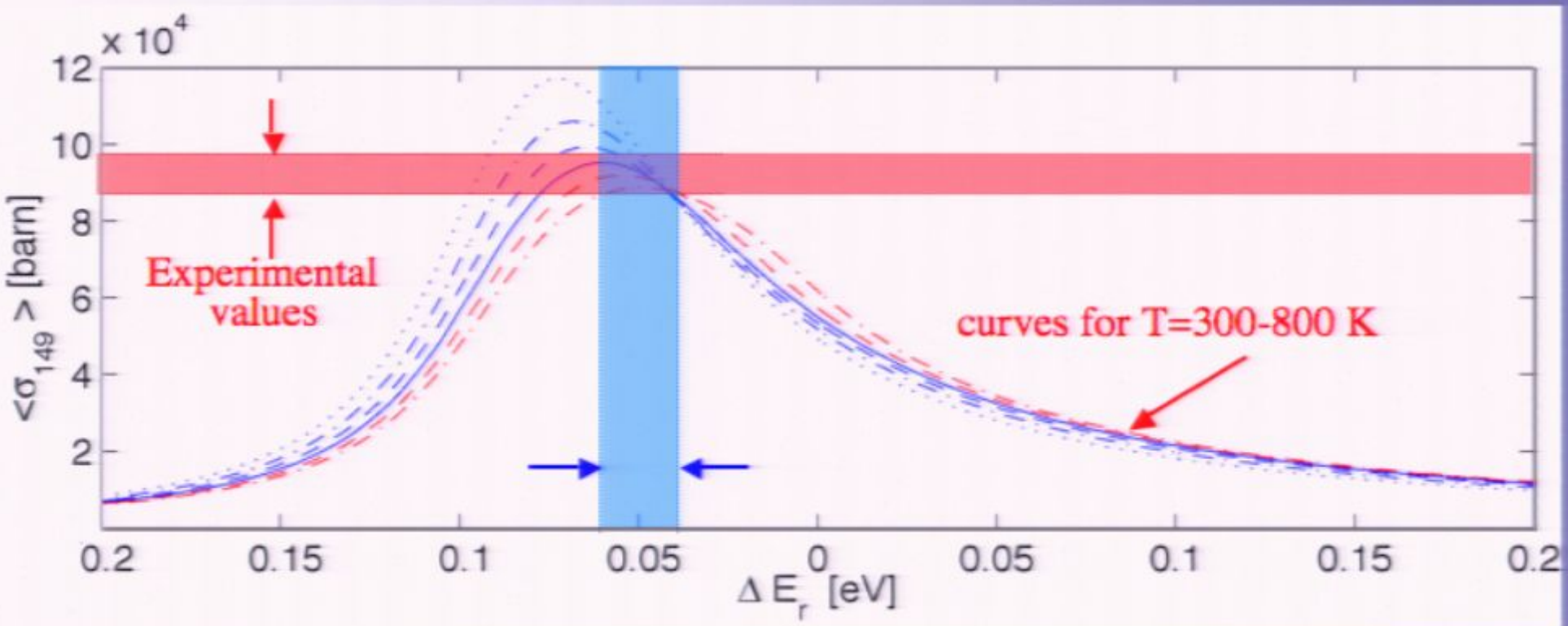

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History of searches for time variation of α with Oklo

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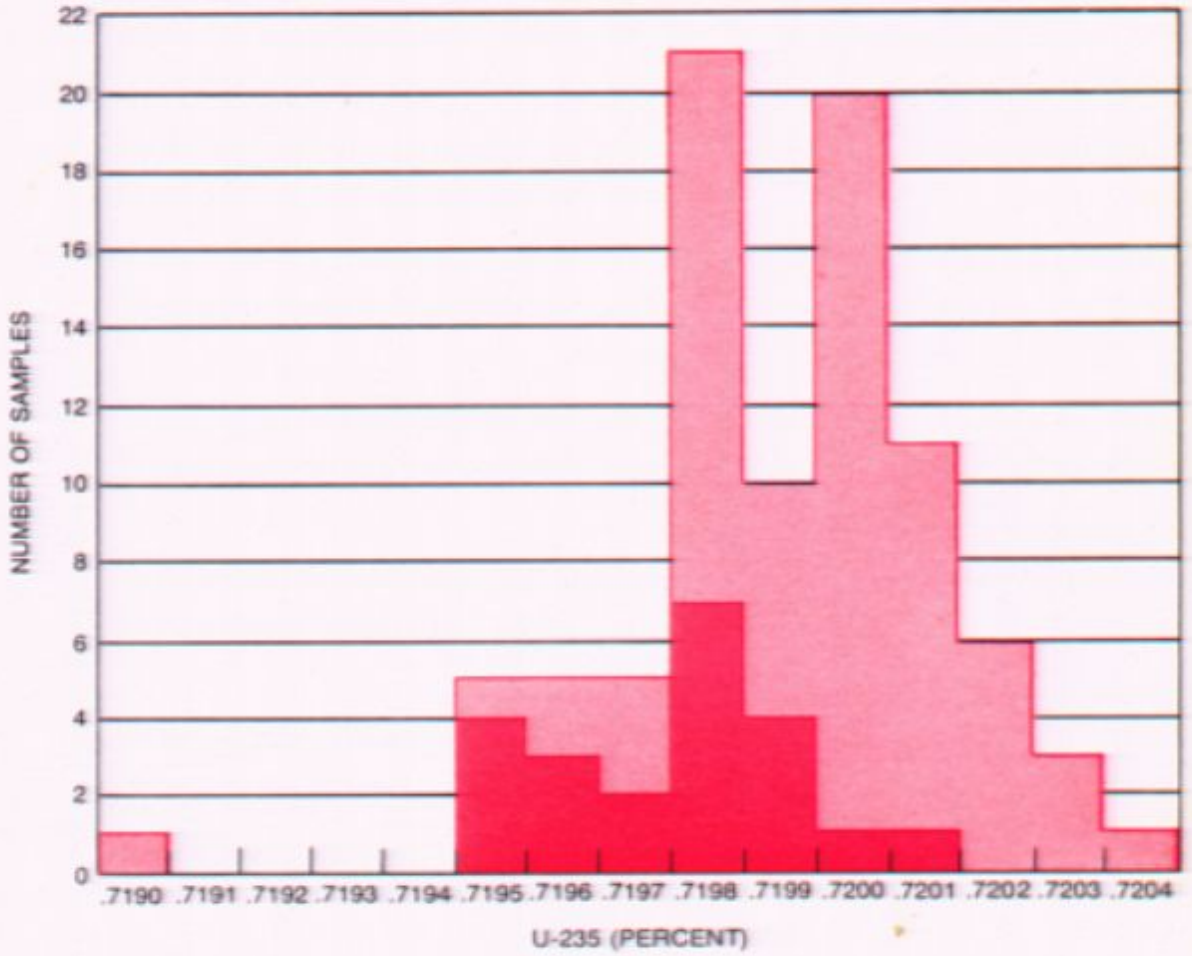
Worldwide ^{235}U fraction



ABUNDANCE OF U-235 in 88 samples of uranium ore shows a clearly bimodal distribution. The peak at .7200 percent represents ores mined mainly in Canada, Europe and Australia. The peak at .7198 percent is produced by ores taken from the Colorado Plateau region of the U.S. One group of these ores, mined in New Mexico, is shown separately (*dark color*); it plainly suggests that uranium from the Colorado Plateau has a U-235 content smaller than the world average. One possible explanation of this small discrepancy is that the isotopes were separated by some chemical process in the ore-bearing rocks. Another explanation is that a natural reactor once operated in the region and that its depleted ore has been dispersed throughout the plateau.

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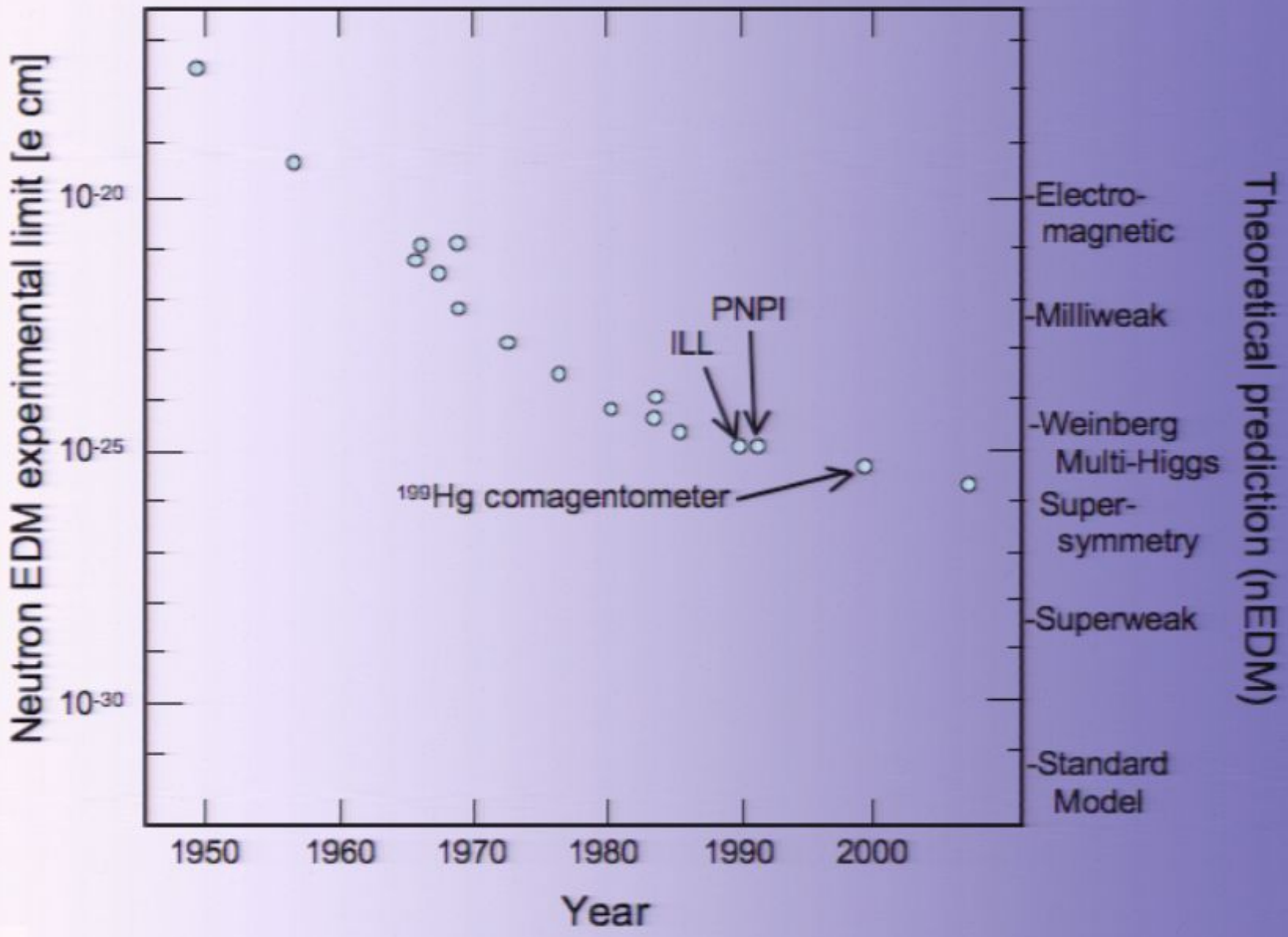
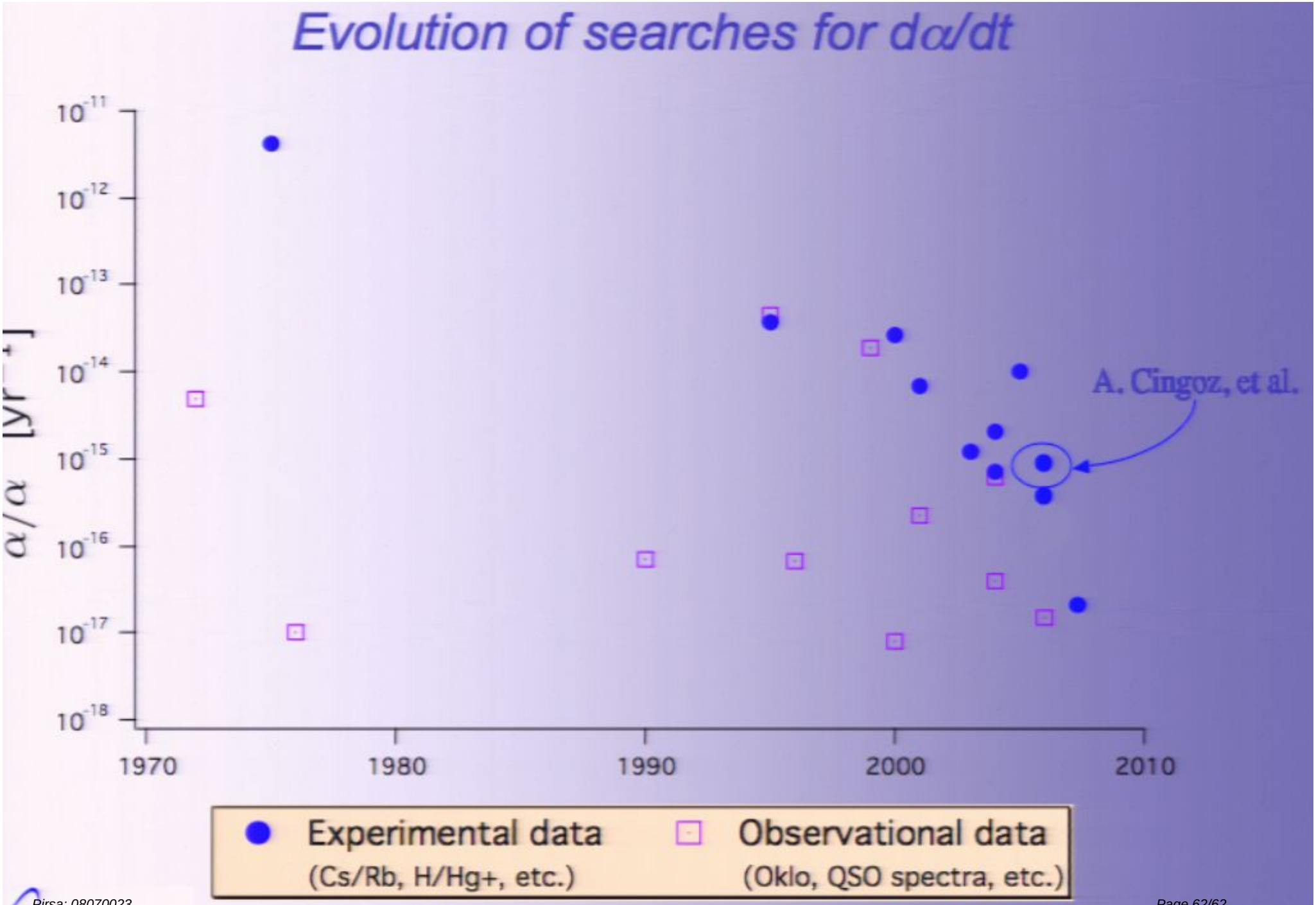
Evolution of searches for EDMs




Evolution of searches for dα/dt
10^-11
10^-12
10^-13
10^-14
10^-15
10^-16
10^-17
10^-18
α/α [yr^-1]
1970
1980
1990
2000
2010
A. Cingoz, et al.
Experimental data
(Cs/Rb, H/Hg+, etc.)
Observational data
(Oklo, QSO spectra, etc.)