EESC 2200
The Solid Earth System

Geochronology

29 Sep 08

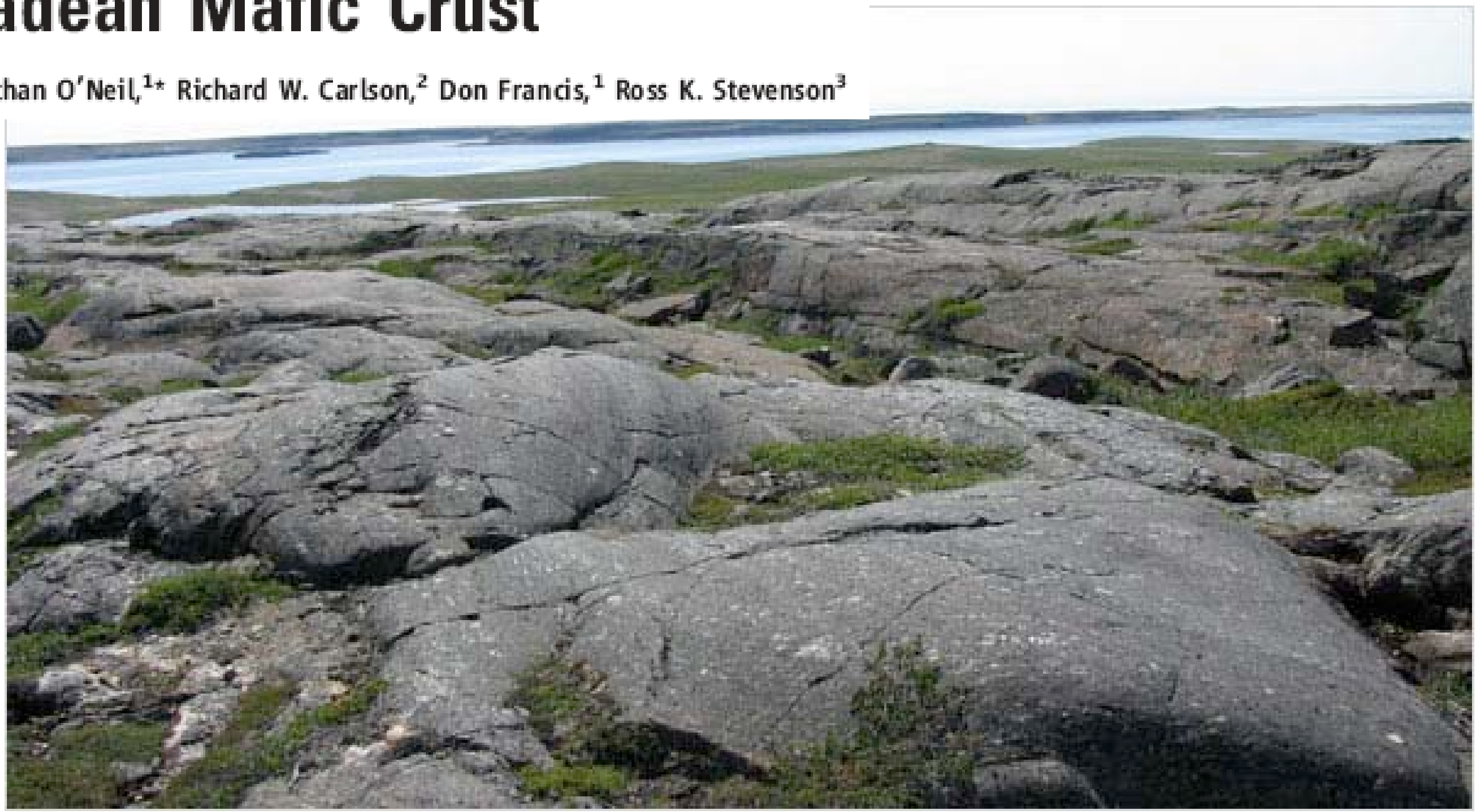
Relative Age

Absolute Age

Homework 2: Due Wednesday

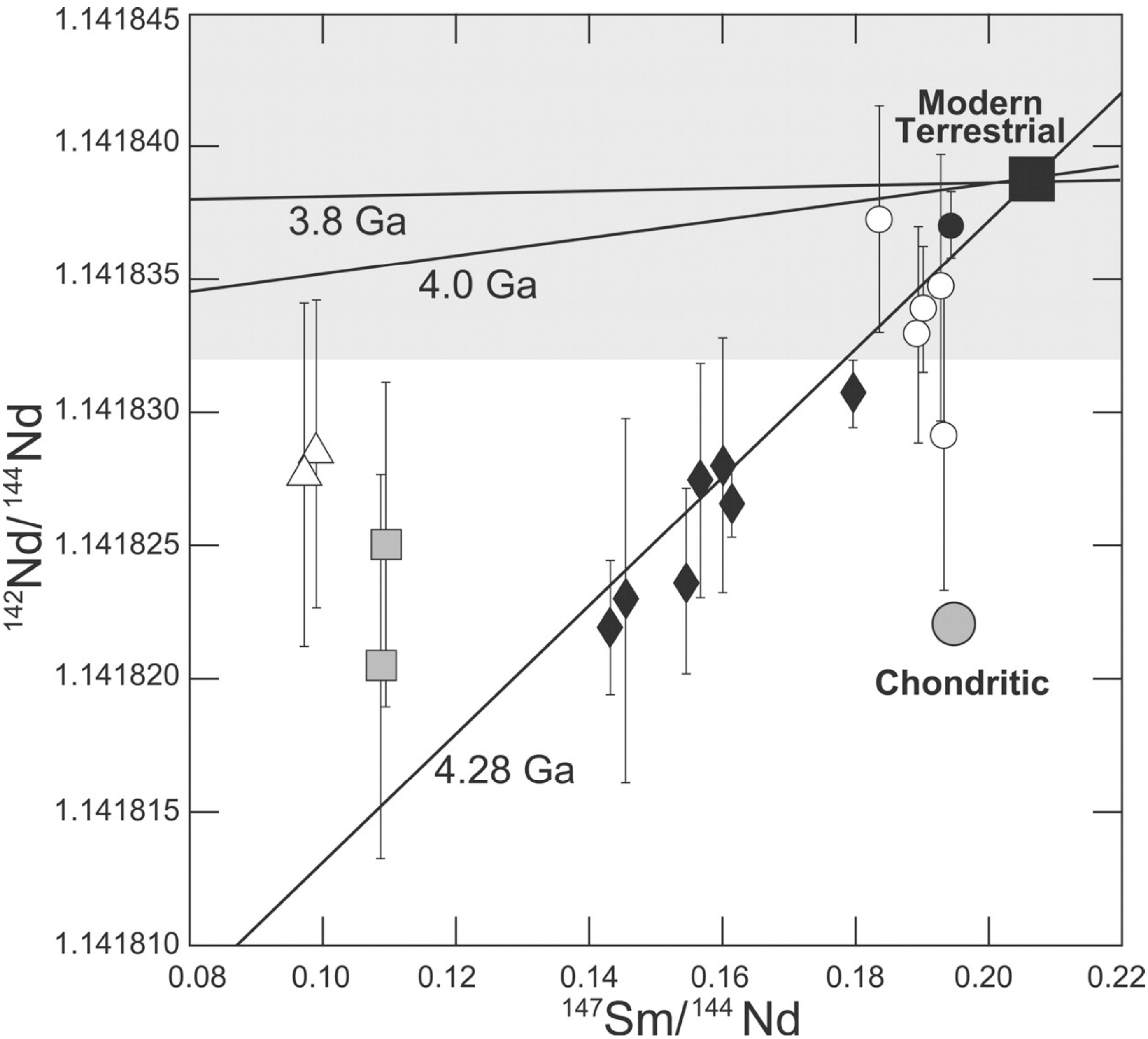
Neodymium-142 Evidence for Hadean Mafic Crust

Jonathan O'Neil,[1]* Richard W. Carlson,[2] Don Francis,[1] Ross K. Stevenson[3]



NY Times and Science, 26 September 2008, Jonathan O'Niel

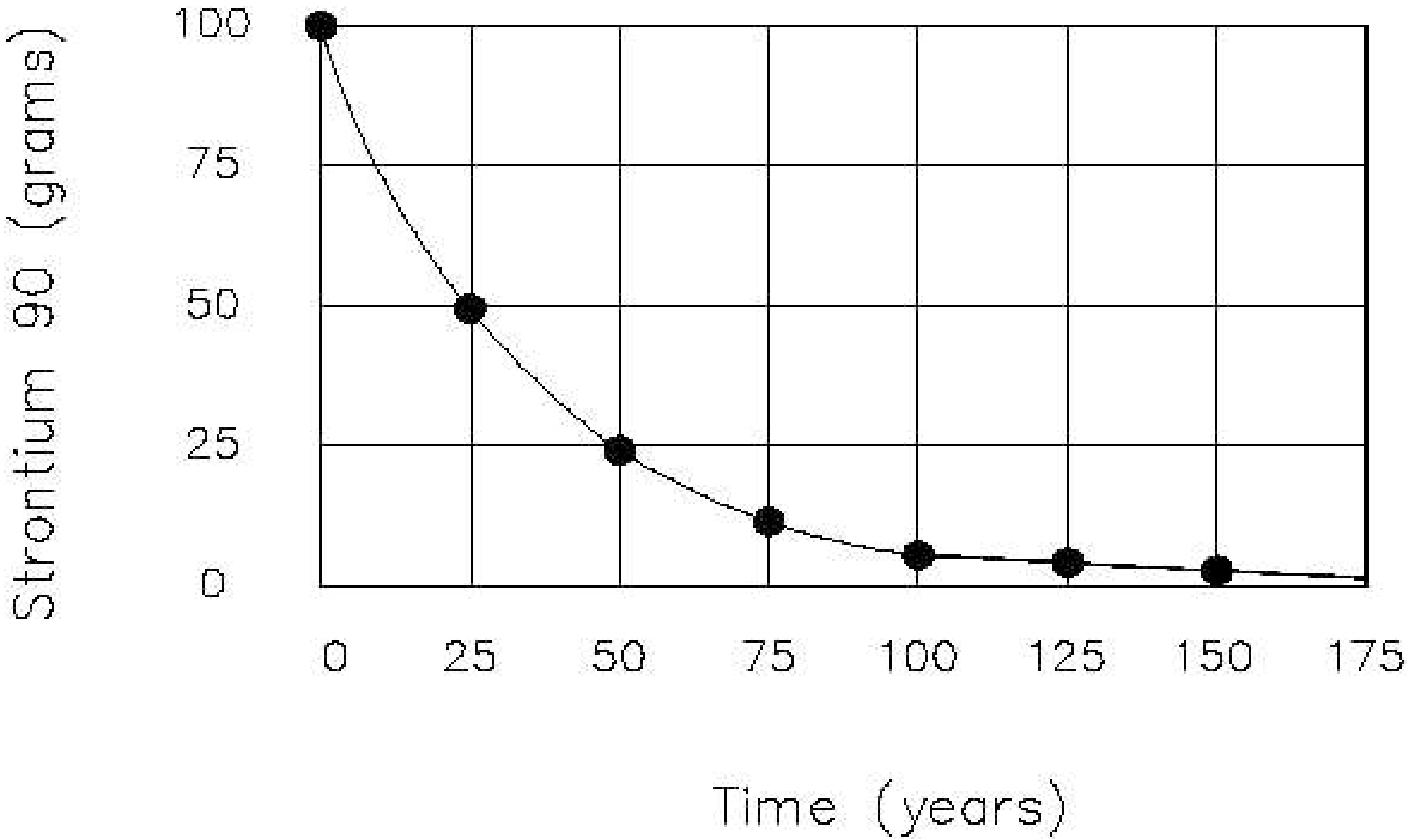
26 SEPTEMBER 2008 VOL 321 SCIENCE www.sciencemag.org


Modern Terrestrial
3.8 Ga
4.0 Ga
4.28 Ga
Chondritic
$^{142}Nd/^{144}Nd$
$^{147}Sm/^{144}Nd$
1.141845
1.141840
1.141835
1.141830
1.141825
1.141820
1.141815
1.141810
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22

Absolute vs. relative age

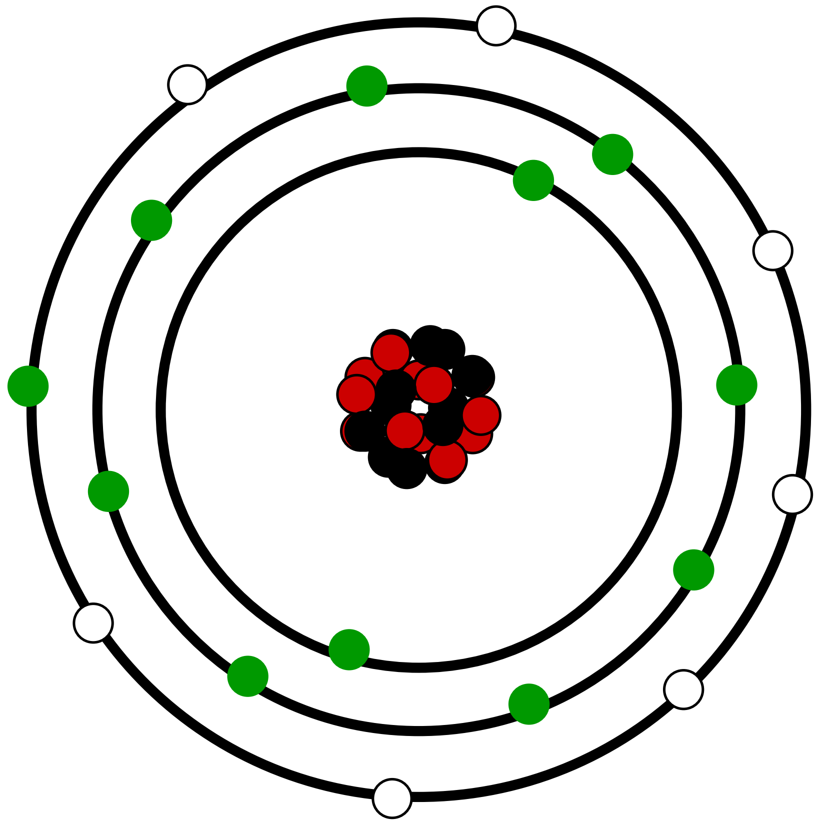
- Field and paleontological observations give us relative ages only (e.g., A is older than B)
- We want absolute ages (e.g., A is X million years old)
- Historical methods
  - Biblical chronology (Ussher, 1650)
  - Decline of the sea (De Maillet, 1748)
  - Sediment accumulation (Walcott, 1893)
  - Ocean salinity (Joly, 1899)
  - Cooling of the earth (Kelvin, 1862-97)

Dating with Radioactive Decay



Half life…..

Sodium atom



nuclide

Z = 11

N = 12

A = 23

$^{A}_{Z}\mathrm{Na}$ $\qquad$ $^{23}_{11}\mathrm{Na}$

Oxygen

	^{16}O	^{17}O	^{18}O
Z =	8	8	8
N =	8	9	10

isotopes of oxygen

$^{87}Rb \text{ --> } ^{87}Sr$

p	37	38
n	50	49

n --> p + e

$^{87}Rb \text{ --> } ^{87}Sr + e$

$^{87}_{37}Rb \text{ --> } ^{87}_{38}Sr + \beta^{-} + 0.273 \text{ Mev}$

net nuclear reaction:

$$^{87}_{37}\text{Rb} \;\text{-->}\; ^{87}_{38}\text{Sr} + \beta^{-} + 0.273\ \text{Mev}$$

net nuclear reaction:

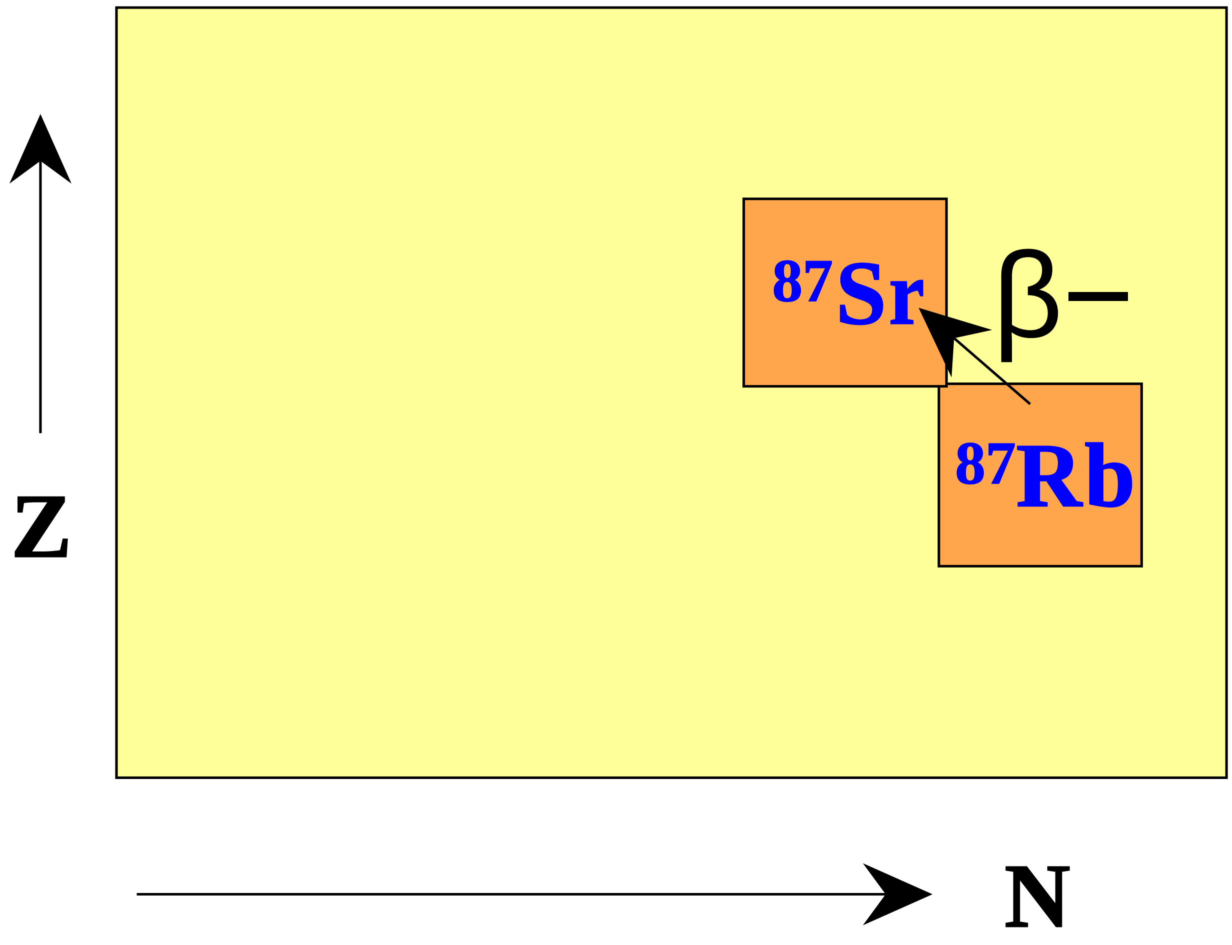
$$\mathbf{n} \;\text{-->}\; \mathbf{p} + \beta^{-} + \nu + \gamma$$

beta particle

neutrino

gamma ray

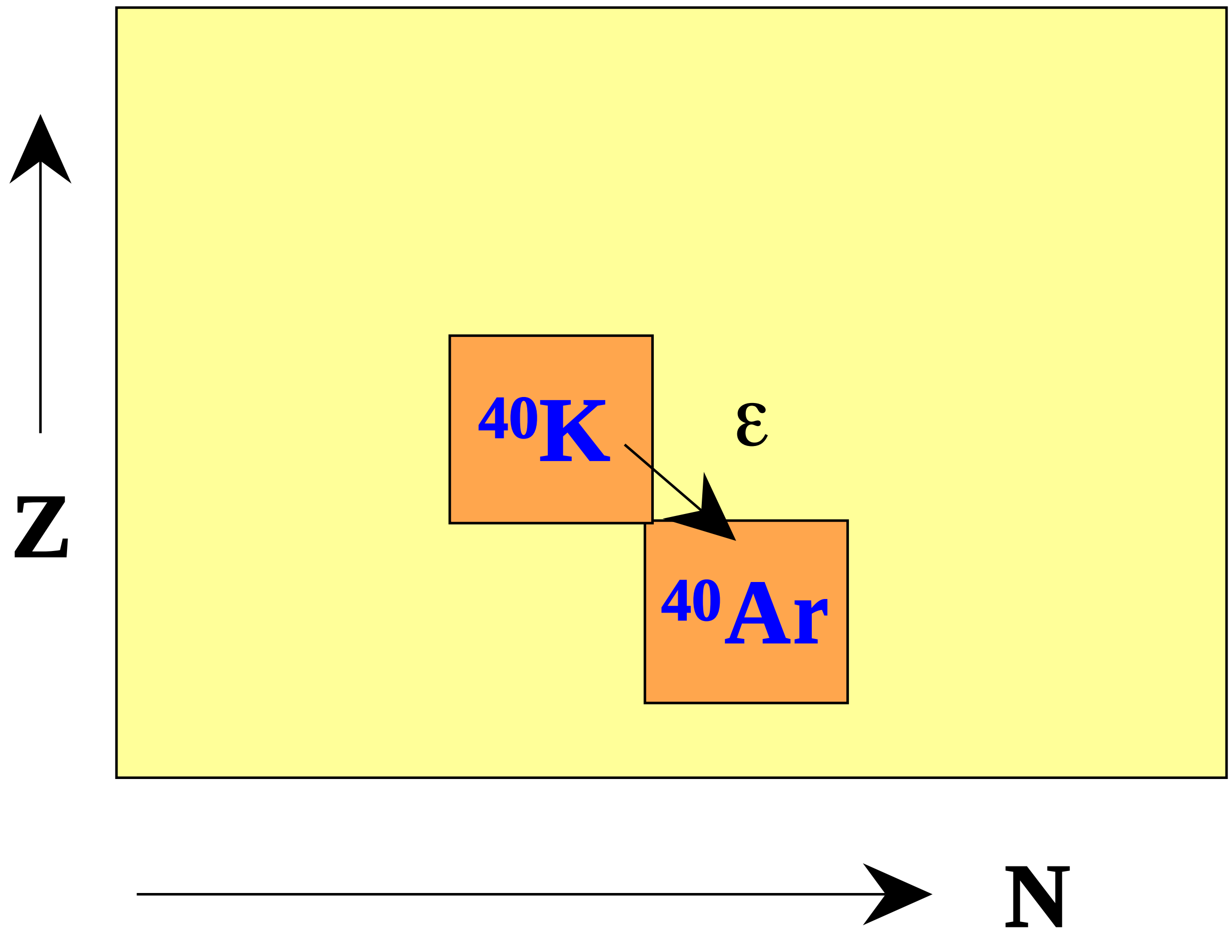
1. Beta Decay



$$\mathbf{n} \dashrightarrow \mathbf{p} + \beta^{-} + \nu + \gamma$$

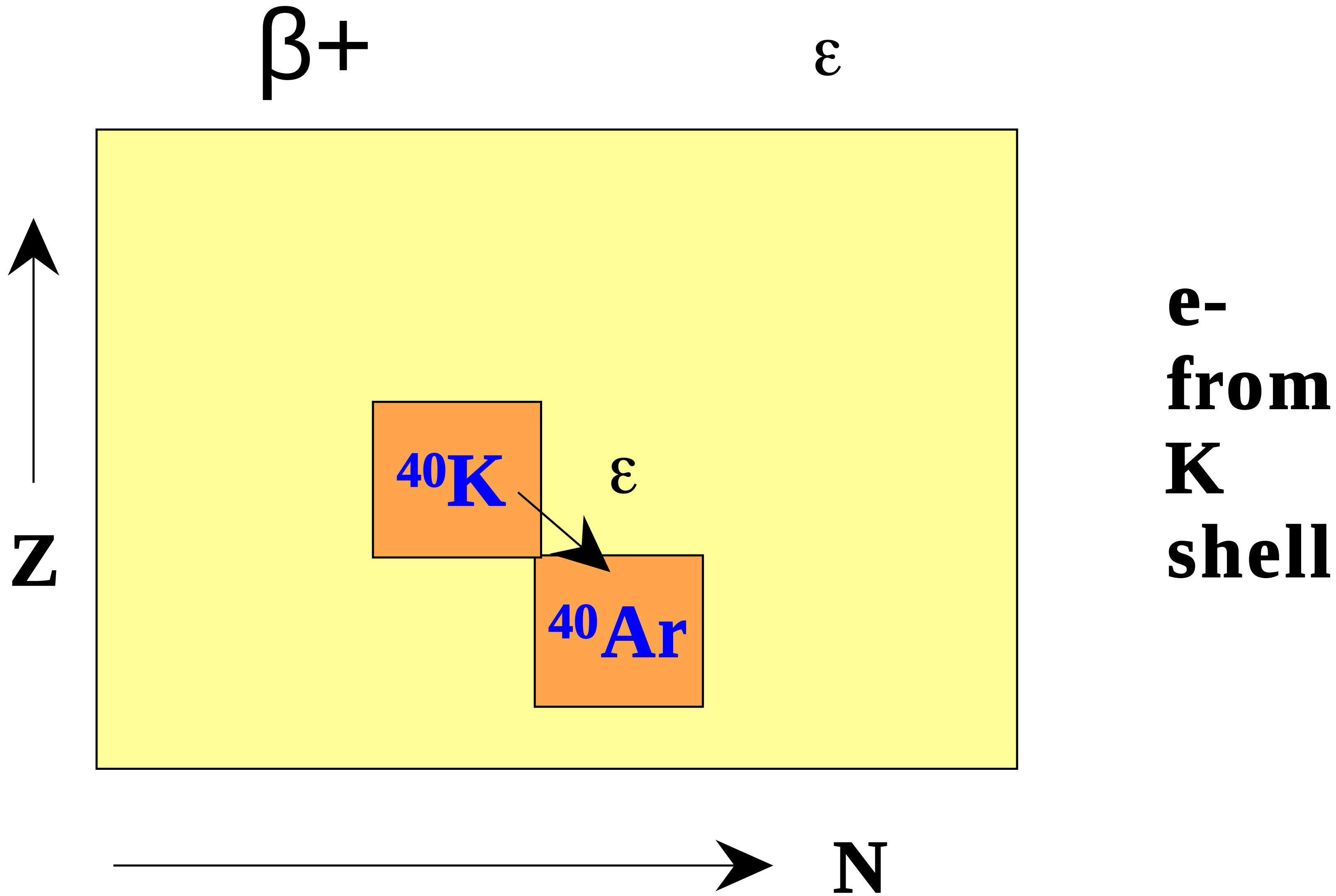
2. Positron Decay (or electron capture)

β+ ε



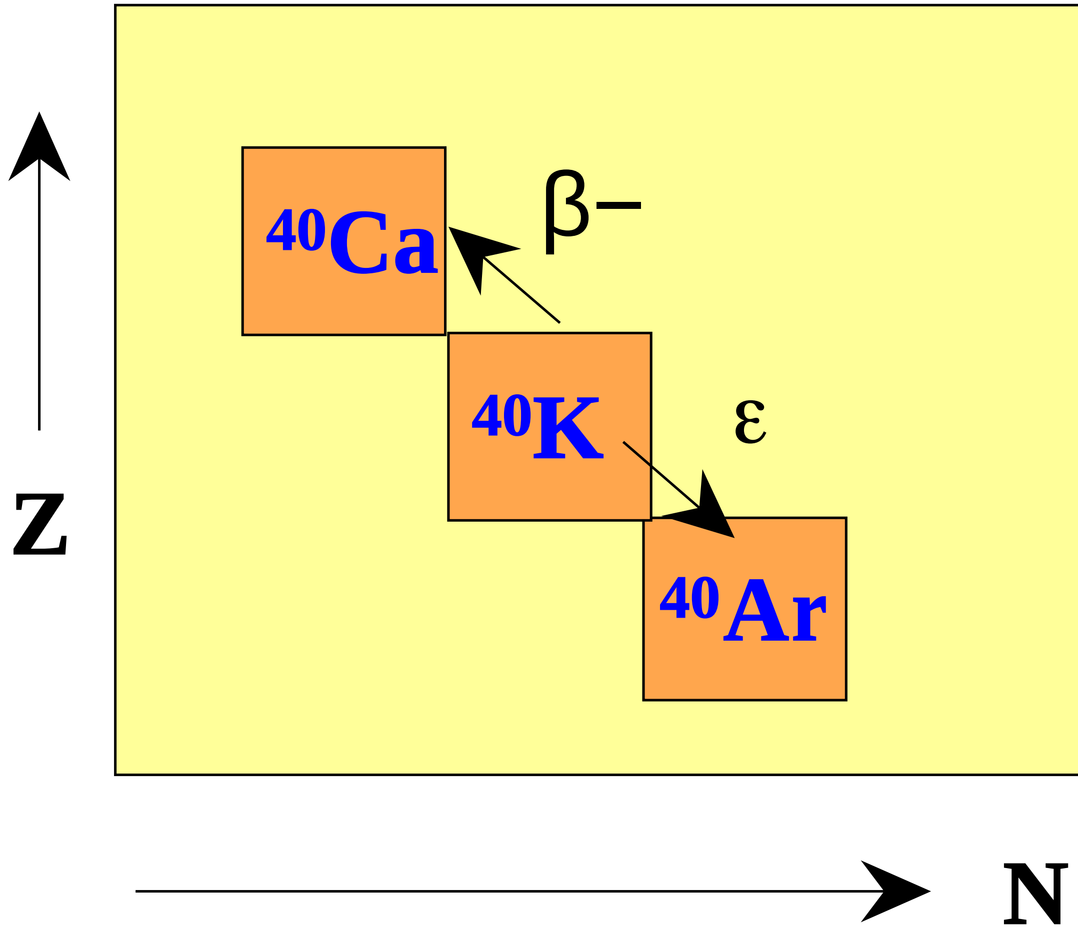
$$p \dashrightarrow n + \beta^{+} + \nu + \gamma$$

2. Positron Decay (or electron capture)

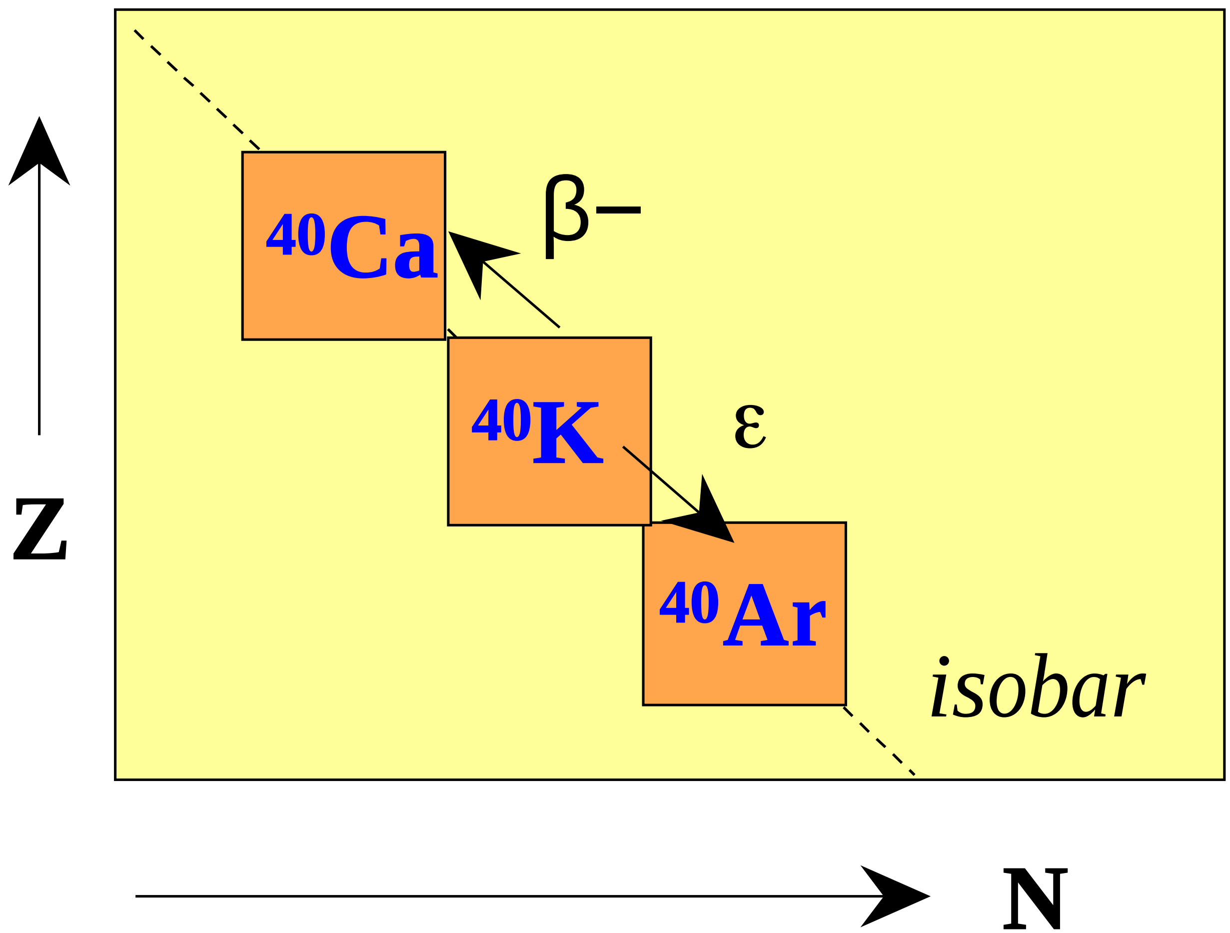


p + e$^-$ --> n + ν + γ

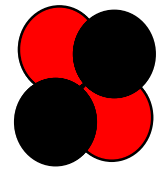
branching decay



beta decay - no change in mass

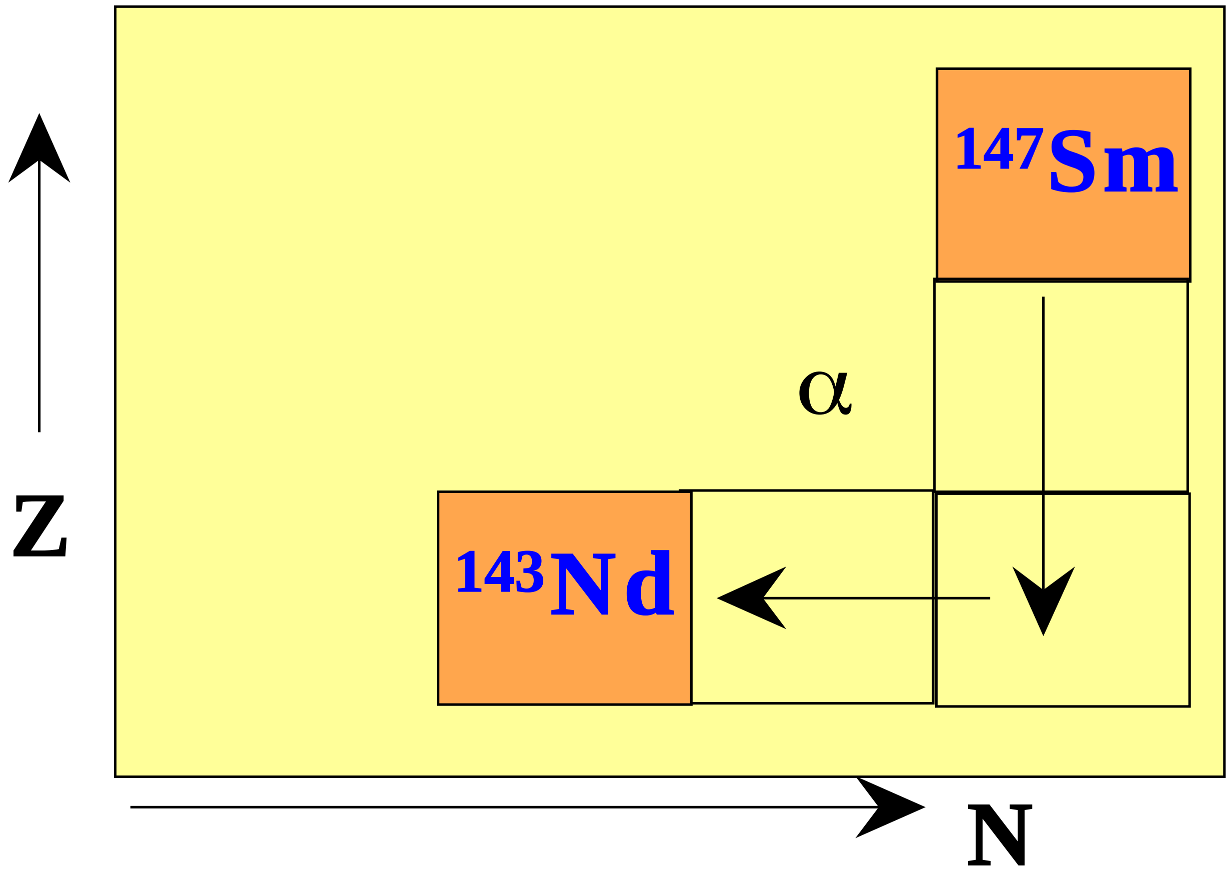


3. Alpha Decay



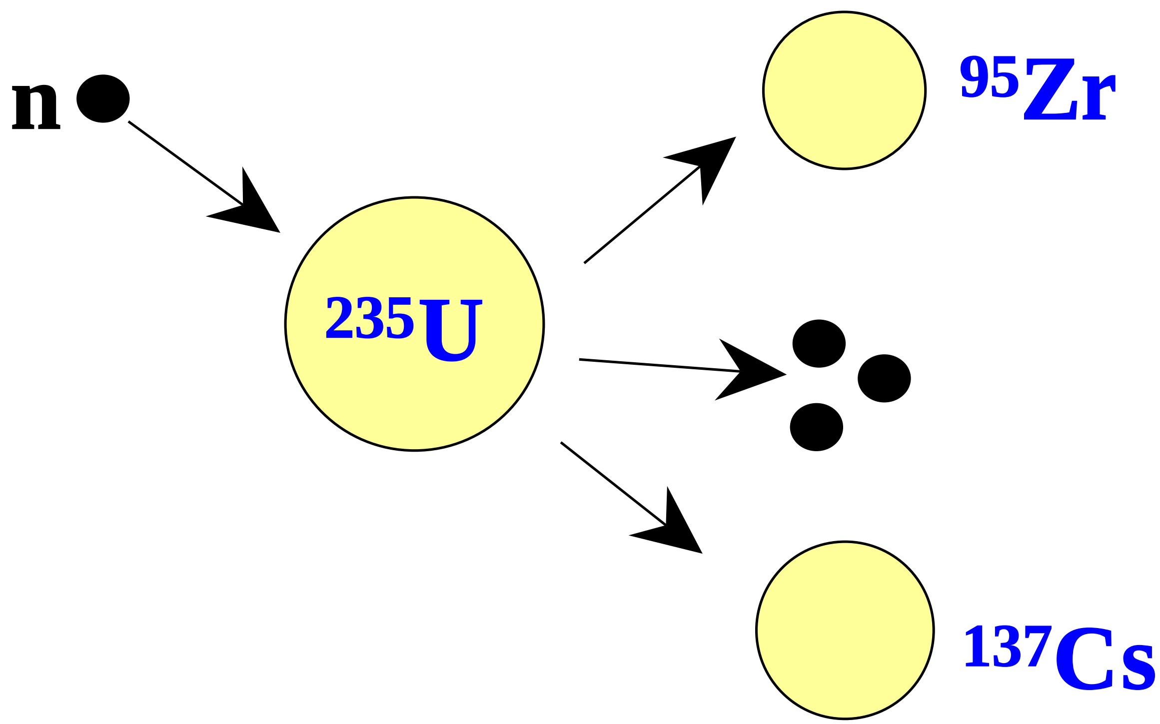
2p+
2n

$\alpha = {}^{4}_{2}He$

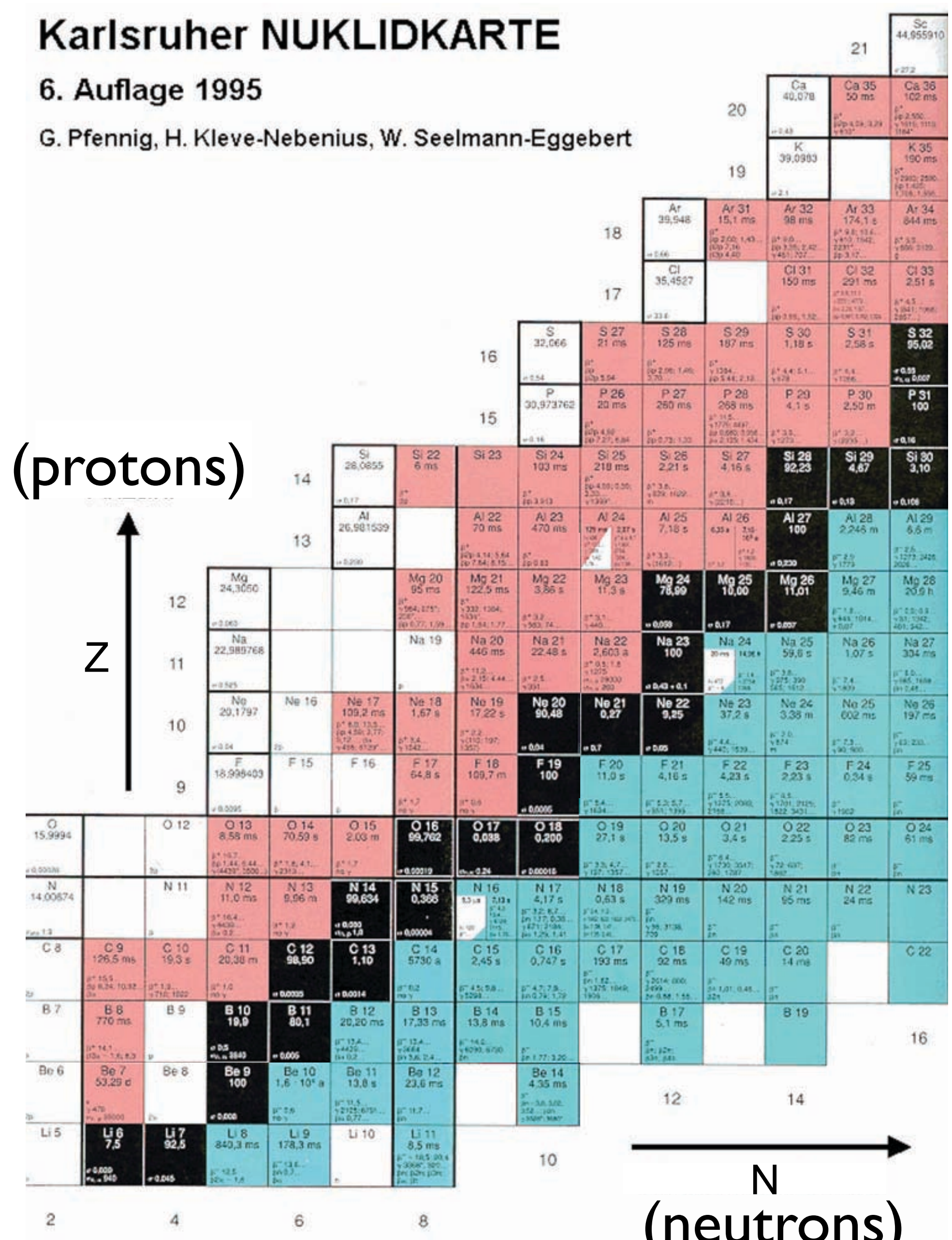


$${}^{A}_{Z}P \;\text{-->}\; {}^{A-4}_{Z-2}D + \alpha + \gamma$$

4. Fission

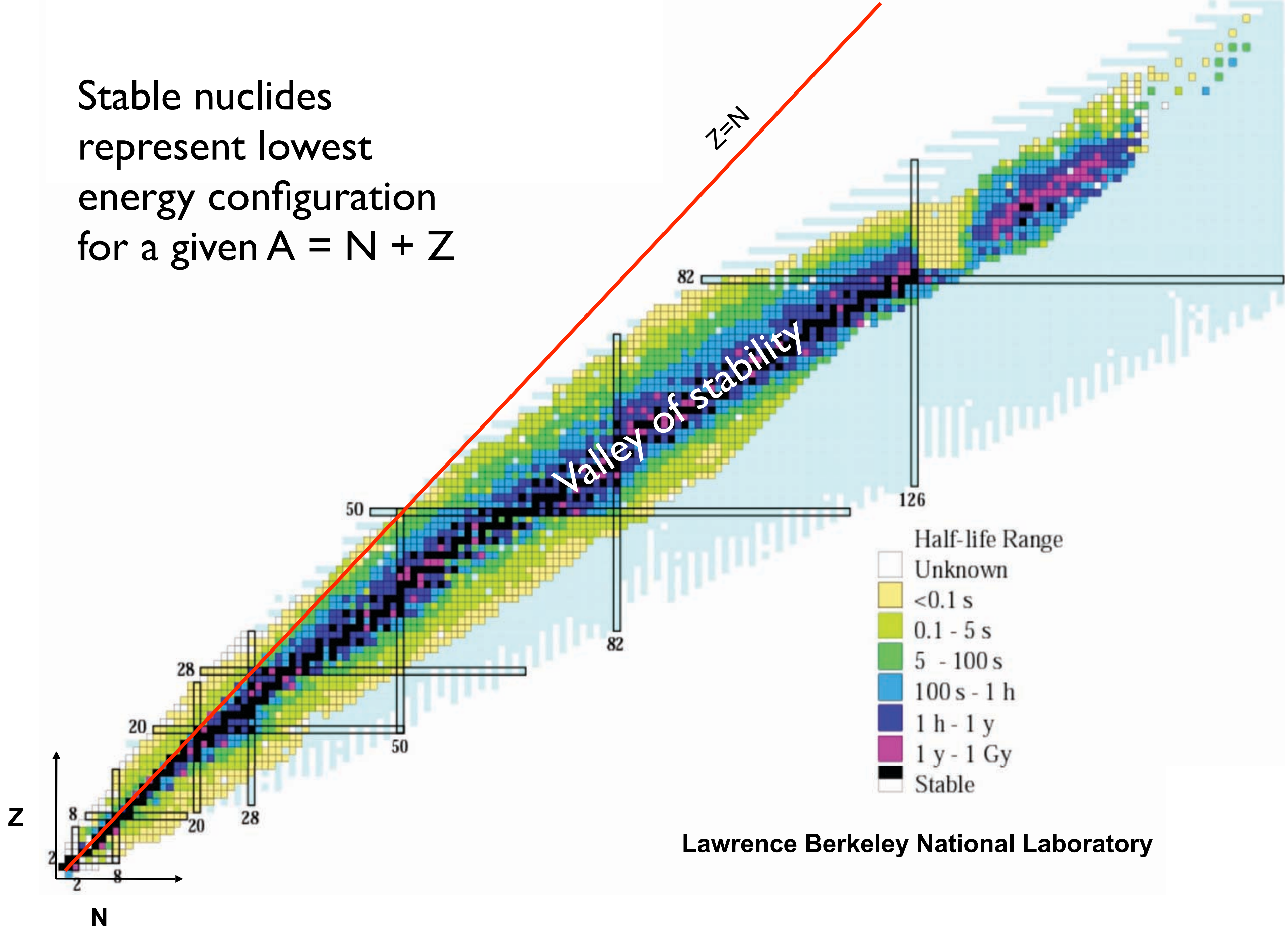


Nuclide chart and decay



- Blue: β^-
- Red: β^+ or e.c.
- Either may undergo α-decay

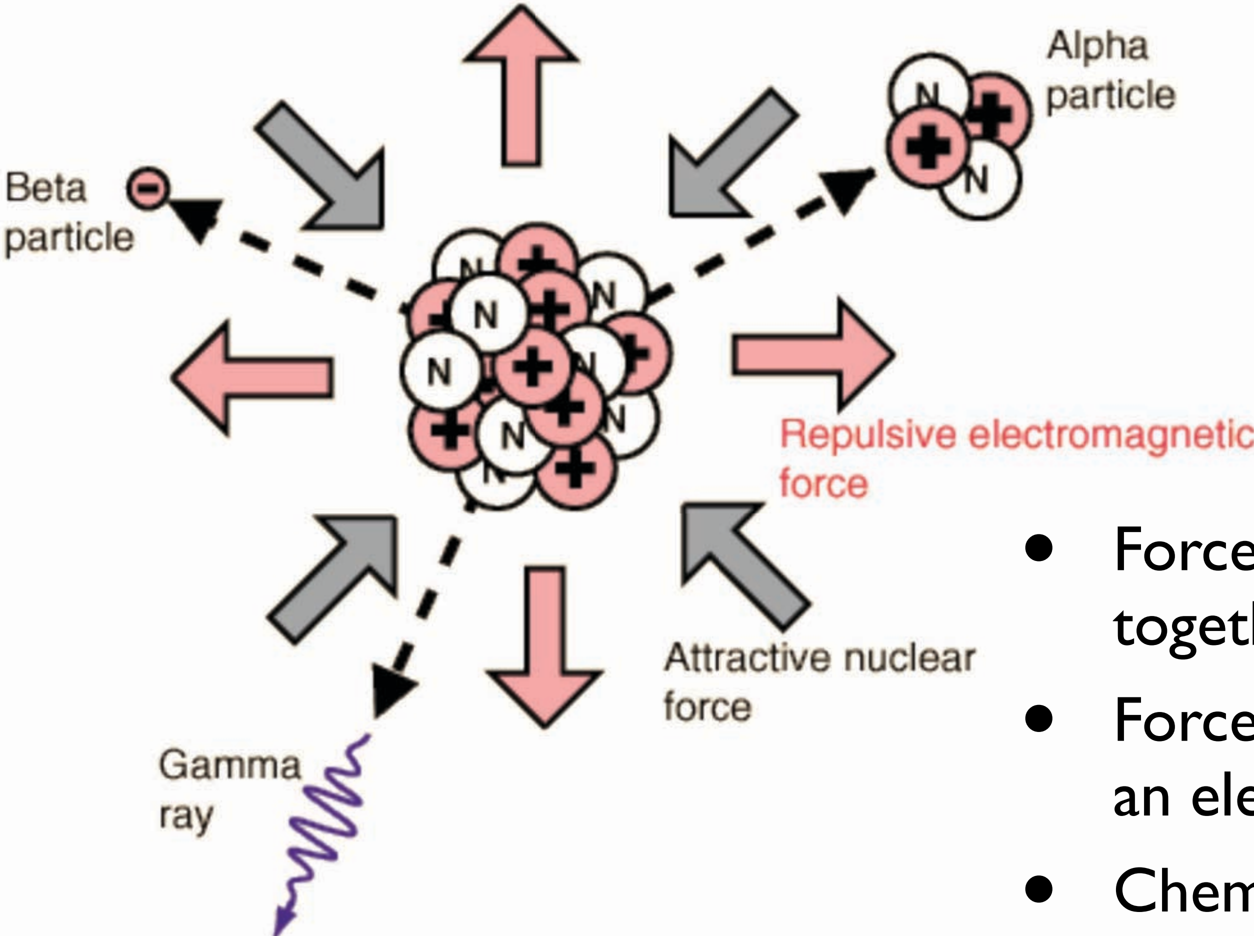
Stable nuclides represent lowest energy configuration for a given A = N + Z



Lawrence Berkeley National Laboratory

Why do some nuclei decay?

- A nucleus decays because it is unstable
- It may be energetically favorable for a nucleus to decay
- Why?
- Since energy is liberated, decay yields a lower energy state



- Forces that hold nuclei together are ~10^6 eV
- Forces required to remove an electron are ~10-100 eV
- Chemical forces that hold molecules together are ~1 eV
- Nuclear reactions liberate much more energy than chemical reactions

"Mass defects": atoms are *not* the sum of their parts

Can we calculate the mass of an atom by adding together the masses of the subatomic particles?

M_{proton} = 1.00727638 AMU (atomic mass units, ^{12}C = 12 AMU)
$M_{neutron}$ = 1.00866491 AMU
$M_{electron}$ = 0.000548579867 AMU

Let's take ^{56}Fe, which has 26 protons and electrons and 30 neutrons

26 x 1.00727638 + 26 x 0.00054857 + 30 x 1.00866491 =
56.463396 AMU
protons electrons neutrons

However, the actual mass of ^{56}Fe is 55.934942

This is **less** than the mass obtained by adding protons and neutrons. There is a "mass defect" Δm.

Δm = 0.52845 AMU -- if you add up the constituent parts, ^{56}Fe is "underweight" by about half of the mass of a proton or neutron

Mass and energy

Why is the "mass defect" important? Mass is equivalent to energy.

$E = Mc^2$, where c is the speed of light (~3.00×10^8 m/s)

1 AMU = the mass of $^{12}C/12$ = 931.5 MeV

(1 MeV = 1.602×10^{-13} joule = 3.827×10^{-23} kcal)

The mass defect of 0.52845 AMU corresponds to a release in energy in the formation of ^{56}Fe compared to the sum of the masses of the building blocks (i.e. protons, neutrons, and electrons).

This is known as the "binding energy" of a nuclide.

Lower mass means a lower energy state in the nucleus; a lower energy state is more stable.

Mass defect and radioactive decay

The product(s) of radioactive decay will show a smaller total mass than the parent.

Mass of

^{40}K: 39.96400 AMU

^{40}Ca: 39.96260 AMU

^{40}Ar: 39.96238 AMU

The energy release from the decay can be calculated by Einstein's equation:

$$E = (\Delta m)c^2$$

For ^{40}K to ^{40}Ar:
E = 0.00162 AMU x 931.5 MeV/AMU =1.51 MeV per decay

Radioactive Decay

Decay Rate N_p $dN_p / dt = -\lambda N_p$

λ = "decay constant"

$$\int_{N_{p_i}}^{N_p} \frac{dN_p}{N_p} = -\lambda \int_0^t dt$$

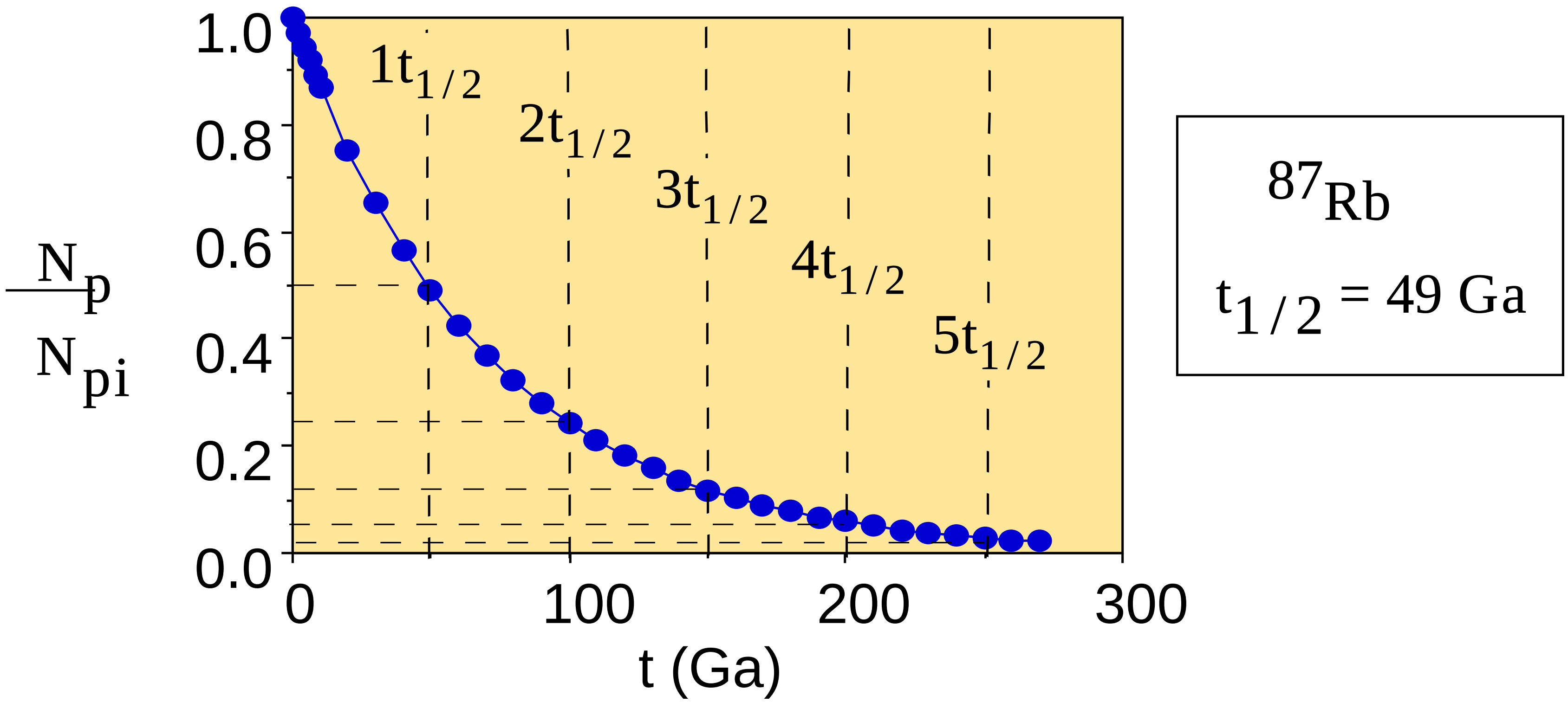
$$\ln N_p - \ln N_{pi} = -\lambda t$$

$$\ln(N_p / N_{pi}) = -\lambda t$$

$$\ln(N_p / N_{pi}) = -\lambda t$$

$$t_{1/2} = \text{half life, when } N_p / N_{pi} = 1/2$$

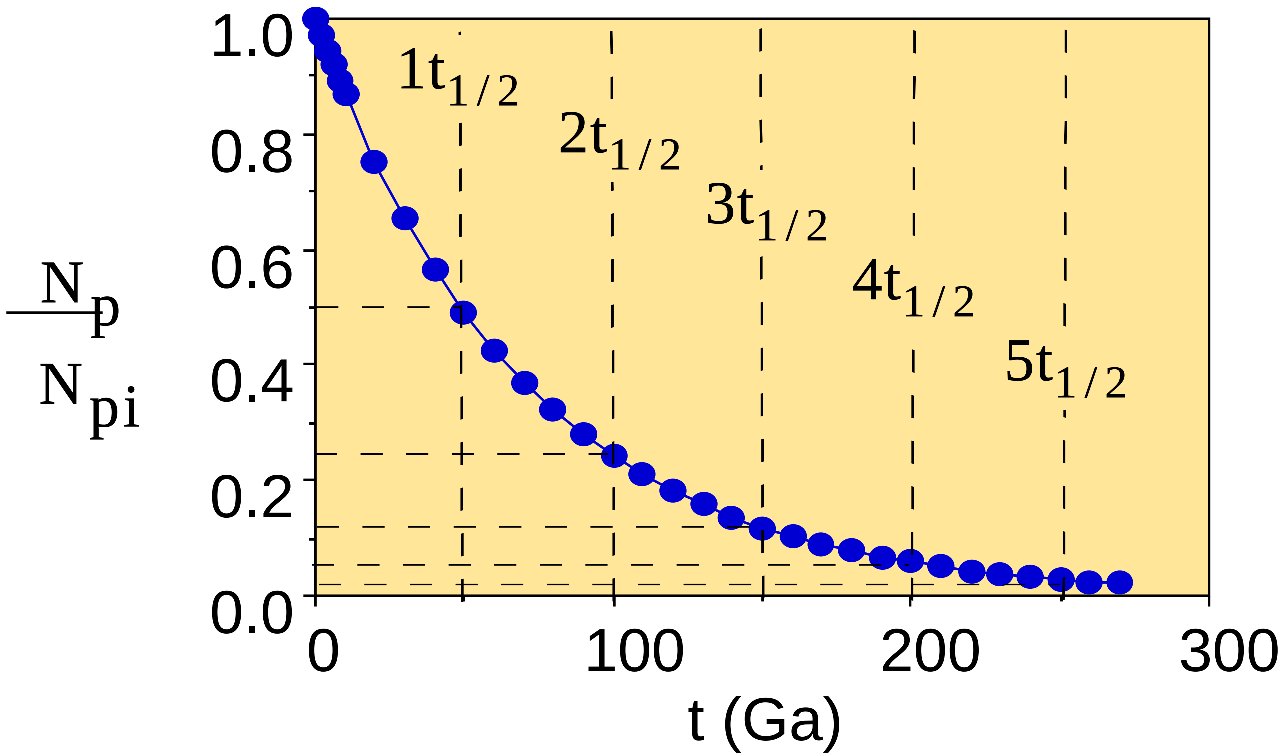
$$t_{1/2} = 0.693 / \lambda$$



coin toss

Rule of Thumb: 5 half-lives

1 50%
2 25%
3 12.5%
4 6.25%
5 3.125%



ES 371: T. Plank Lecture 5

not cats...

$$\ln(N_p / N_{pi}) = -\lambda t$$

$$N_p = N_{pi} e^{-\lambda t}$$

$$N_{pi} = N_p + N_d$$

Daughters!

$$^{87}Rb_i = {}^{87}Rb + {}^{87}Sr$$

$$\ln(N_p / N_{pi}) = -\lambda t$$

$$N_p = N_{pi} e^{-\lambda t}$$

$$N_{pi} = N_p + N_d$$

Daughters!

$$^{87}Rb_i = {}^{87}Rb + {}^{87}Sr$$

$$\ln(N_p / N_{pi}) = -\lambda t$$

$$N_p = N_{pi} e^{-\lambda t}$$

$$N_{pi} = N_p + N_d$$

$$N_d = N_{pi} - N_p$$

$$N_{pi} = N_p e^{\lambda t}$$

$$N_d = N_p e^{\lambda t} - N_p$$

$$N_d = N_p(e^{\lambda t} - 1)$$ *plus any initial daughters...*

$$\ln(N_p / N_{pi}) = -\lambda t$$

$$N_p = N_{pi}\, e^{-\lambda t}$$

$$N_{pi} = N_p + N_d$$

$$N_d = N_{pi} - N_p$$

$$N_{pi} = N_p\, e^{\lambda t}$$

$$N_d = N_p(e^{\lambda t}-1) + N_{di}$$

$$^{87}Sr = {}^{87}Sr_i + {}^{87}Rb\,(e^{\lambda t}-1)$$

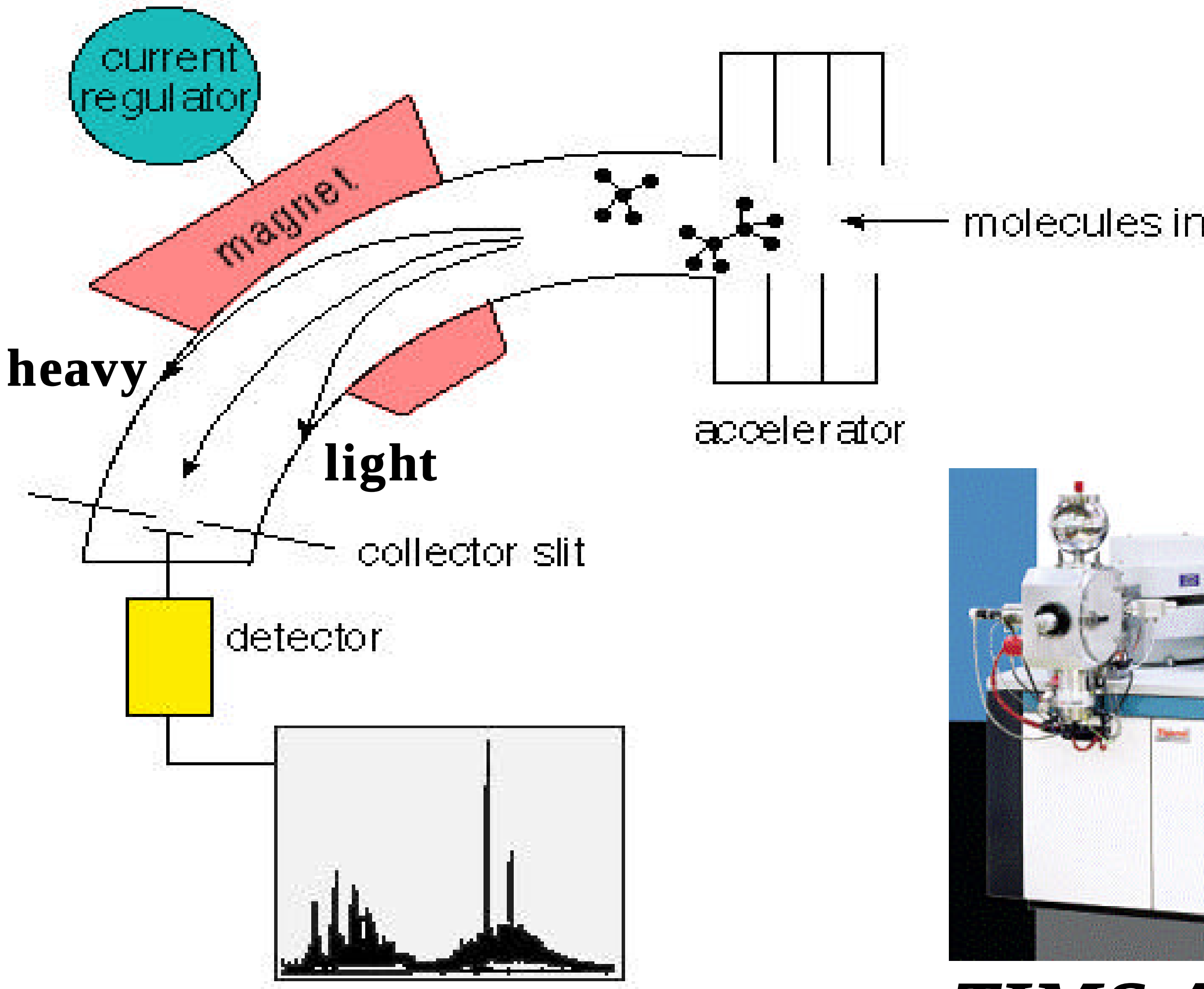
$$^{87}Sr = {}^{87}Sr_i + {}^{87}Rb\,(e^{\lambda t}-1)$$

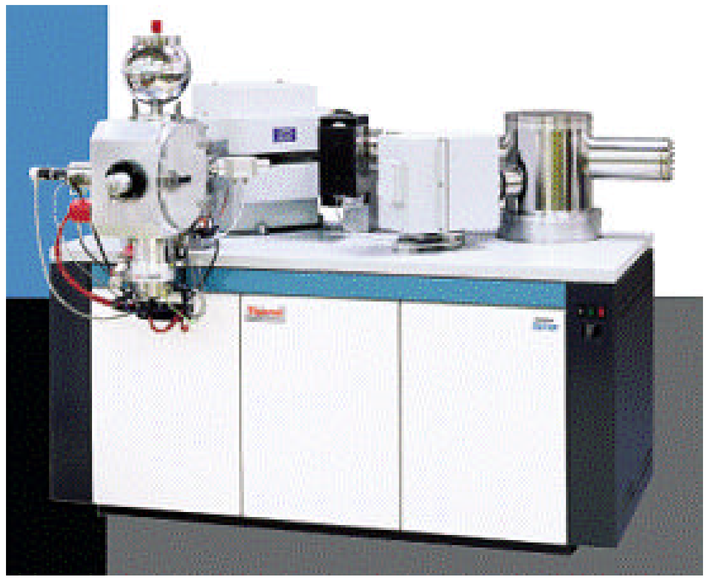
measure ratios in mass spectrometer

86Sr is non-radiogenic, non-radioactive

$$\frac{^{87}Sr}{^{86}Sr} = \frac{^{87}Sr_i}{^{86}Sr} + \frac{^{87}Rb}{^{86}Sr}(e^{\lambda t}-1)$$

mass spectrometer...





TIMS Across Hall

$$^{87}Sr = {}^{87}Sr_i + {}^{87}Rb\,(e^{\lambda t}-1)$$

measure ratios in mass spectrometer

86Sr is non-radiogenic, non-radioactive

$$\frac{^{87}Sr}{^{86}Sr} = \frac{^{87}Sr_i}{^{86}Sr} + \frac{^{87}Rb}{^{86}Sr}\,(e^{\lambda t}-1)$$

initial??

$$^{87}Sr = {}^{87}Sr_i + {}^{87}Rb\,(e^{\lambda t}-1)$$

measure ratios in mass spectrometer

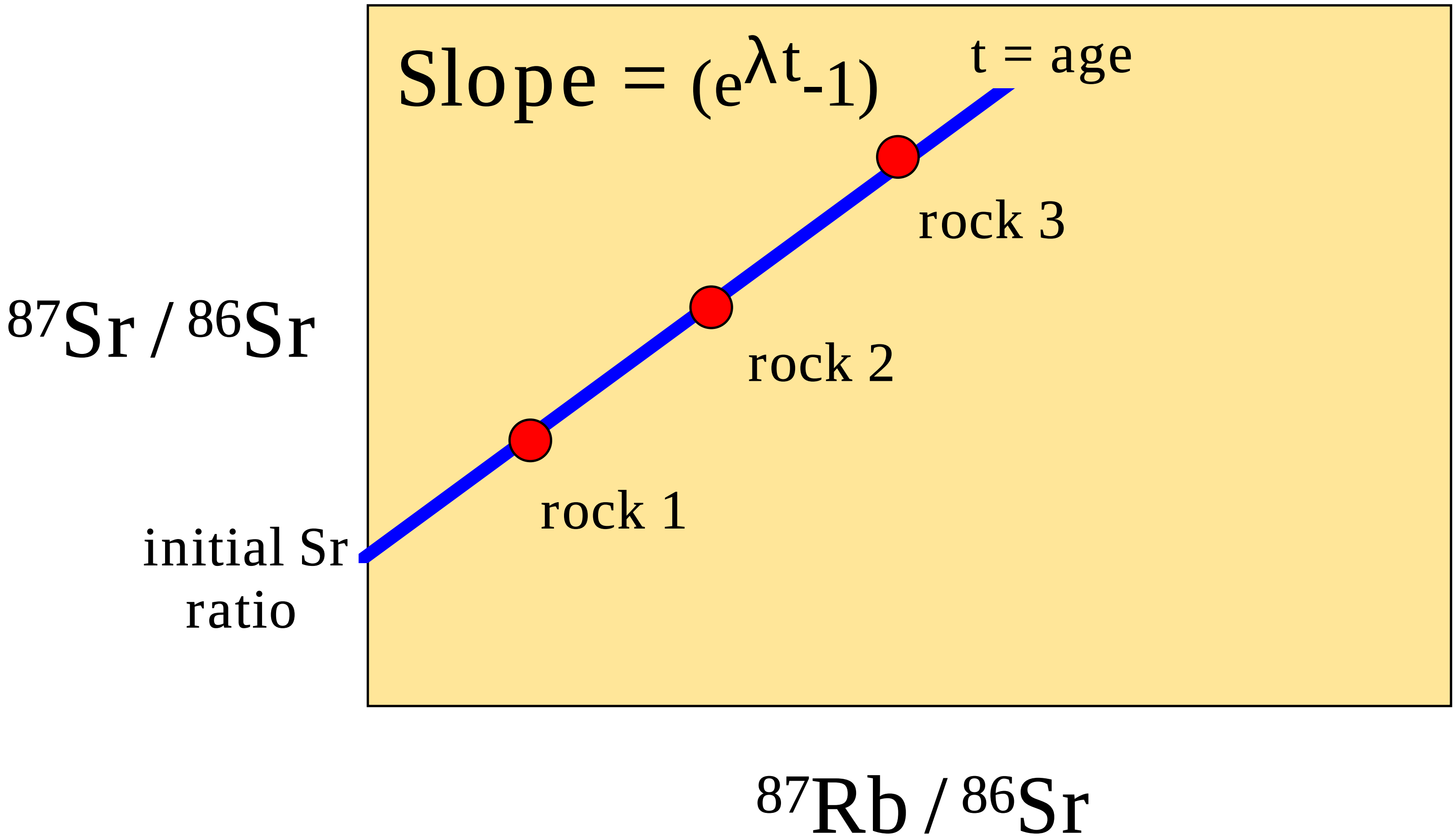
86Sr is non-radiogenic, non-radioactive

$$\frac{^{87}Sr}{^{86}Sr} = \frac{^{87}Sr_i}{^{86}Sr} + \frac{^{87}Rb}{^{86}Sr}\,(e^{\lambda t}-1)$$

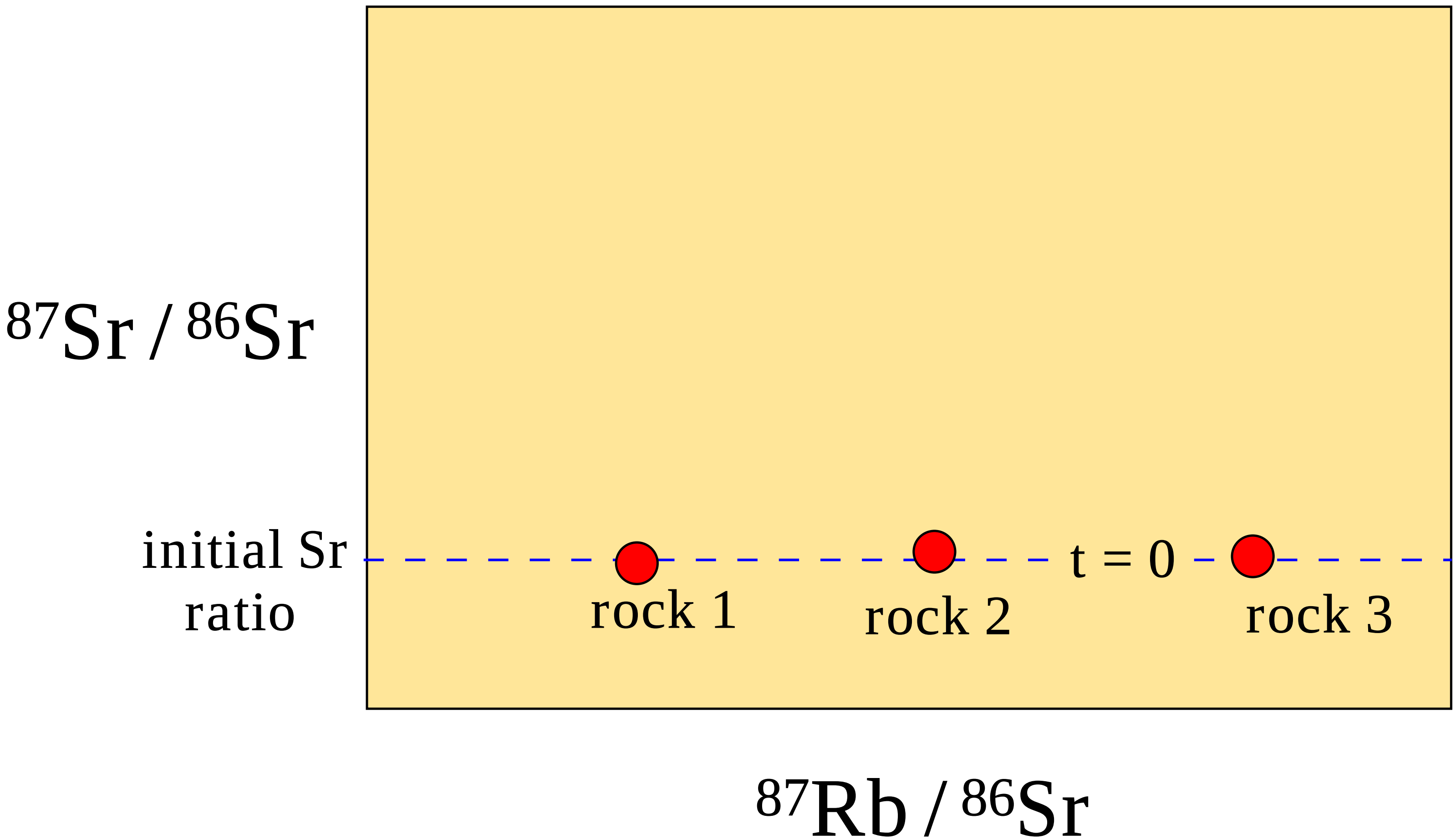
$$y \;=\; b \;+\; x \;\; m$$

Isochron Equation

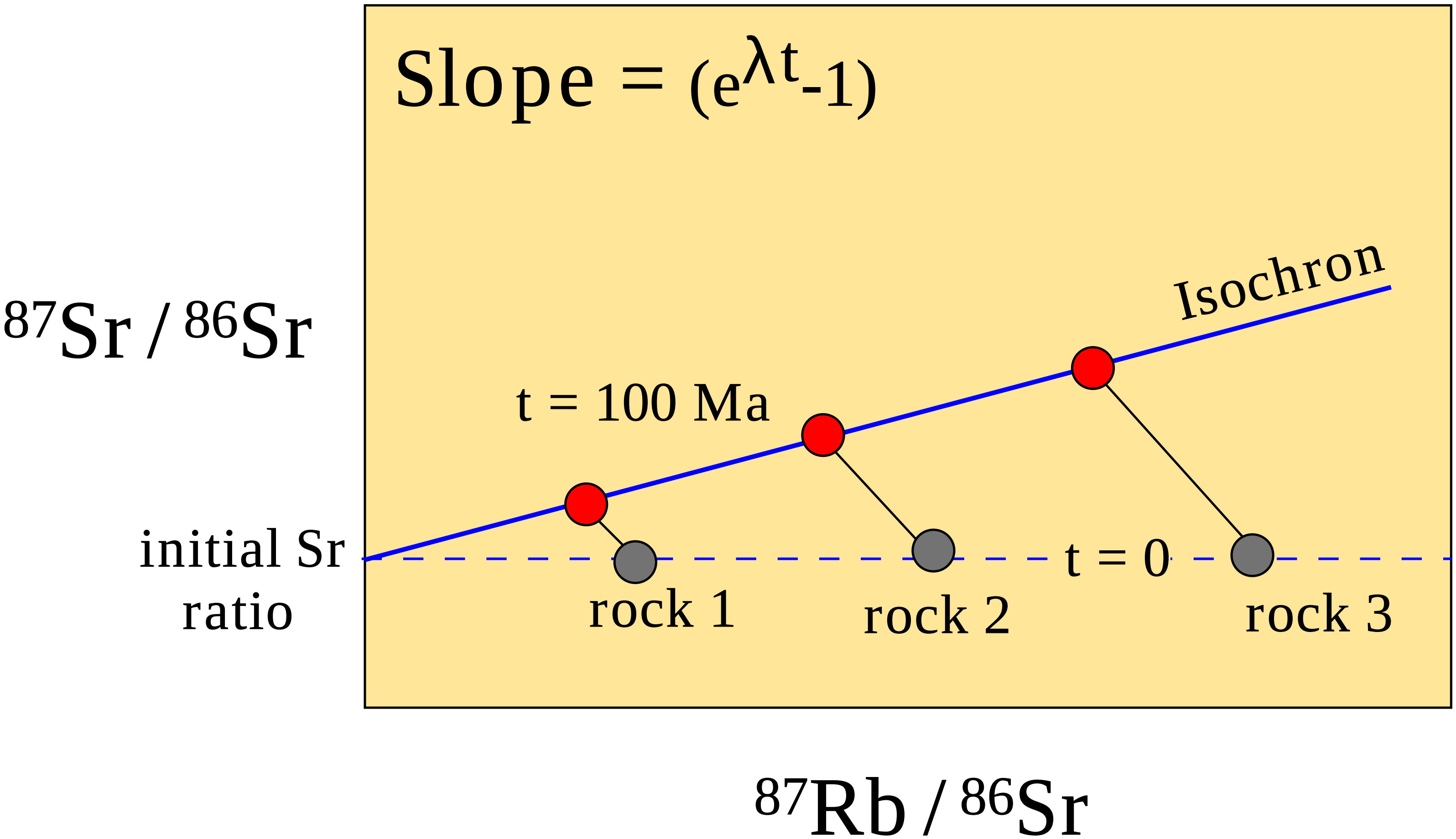
$$\frac{^{87}Sr}{^{86}Sr} = \frac{^{87}Sr_i}{^{86}Sr} + \frac{^{87}Rb}{^{86}Sr}(e^{\lambda t}-1)$$



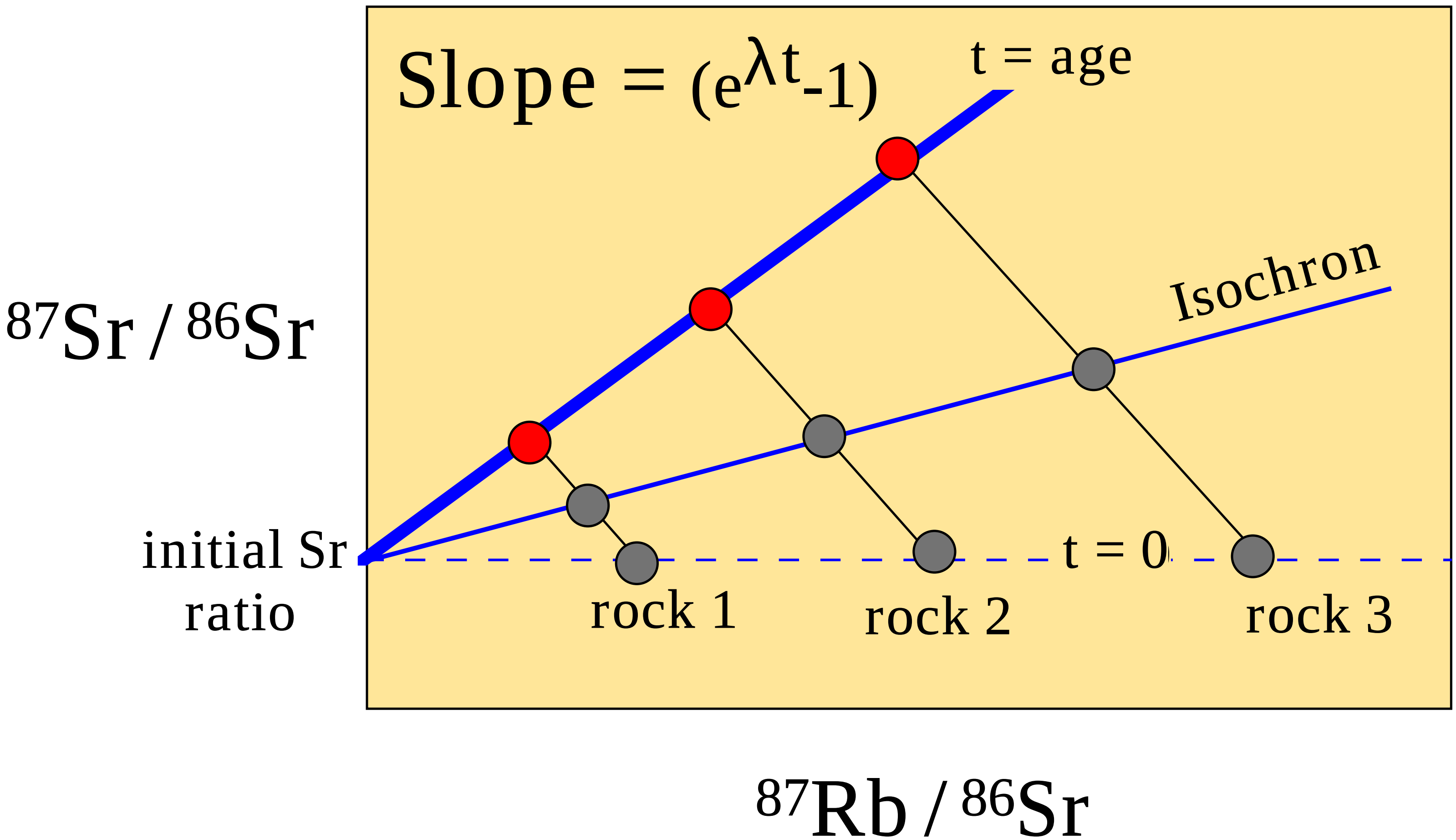
$$\frac{^{87}Sr}{^{86}Sr} = \frac{^{87}Sr_i}{^{86}Sr} + \frac{^{87}Rb}{^{86}Sr}(e^{\lambda t}-1)$$



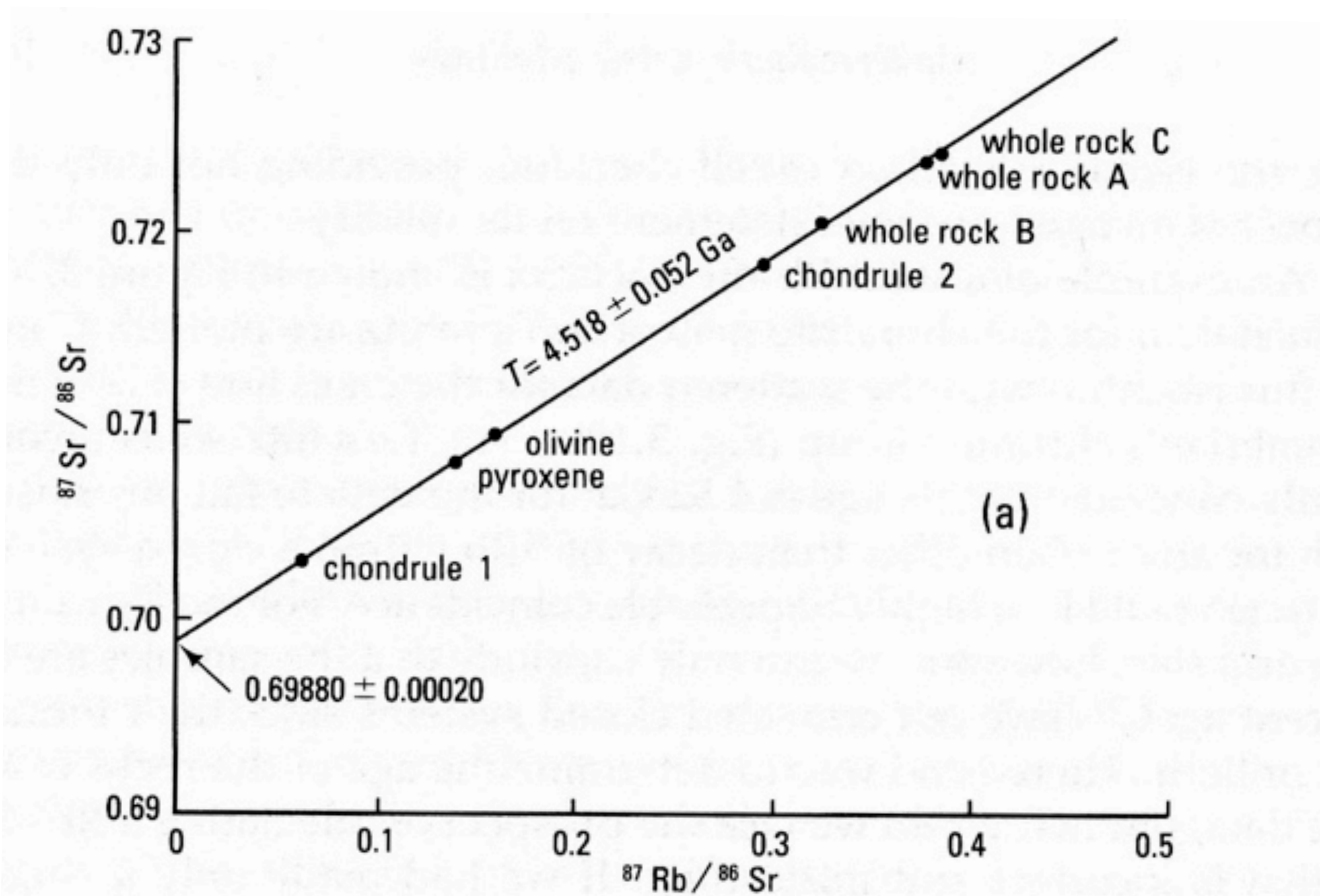
$$\frac{^{87}Sr}{^{86}Sr} = \frac{^{87}Sr_i}{^{86}Sr} + \frac{^{87}Rb}{^{86}Sr}\left(e^{\lambda t}-1\right)$$



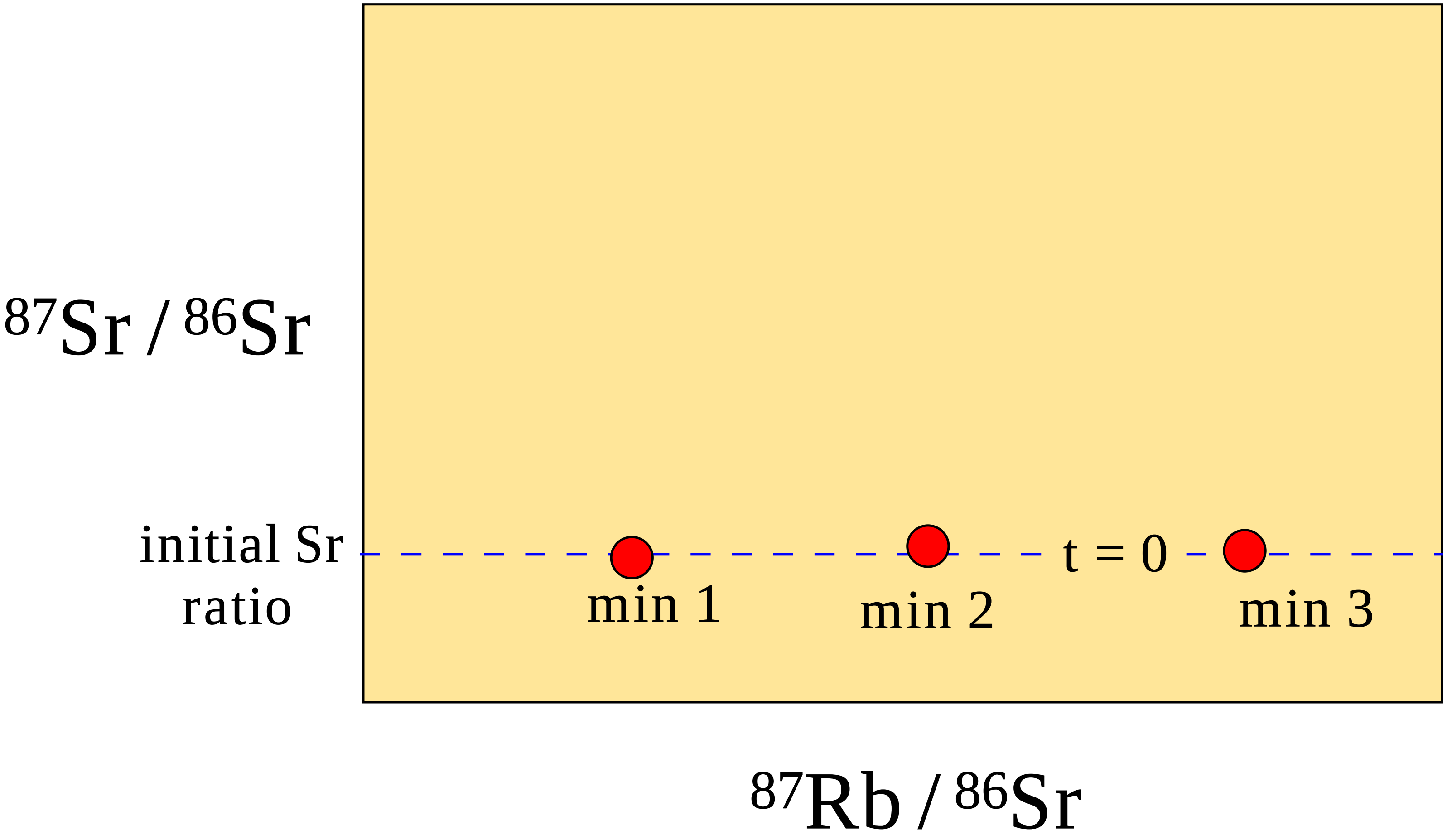
$$\frac{^{87}Sr}{^{86}Sr} = \frac{^{87}Sr_i}{^{86}Sr} + \frac{^{87}Rb}{^{86}Sr}(e^{\lambda t}-1)$$



Rb-Sr dating of a meteorite



$$\frac{^{87}Sr}{^{86}Sr} = \frac{^{87}Sr_i}{^{86}Sr} + \frac{^{87}Rb}{^{86}Sr}\,(e^{\lambda t}-1)$$



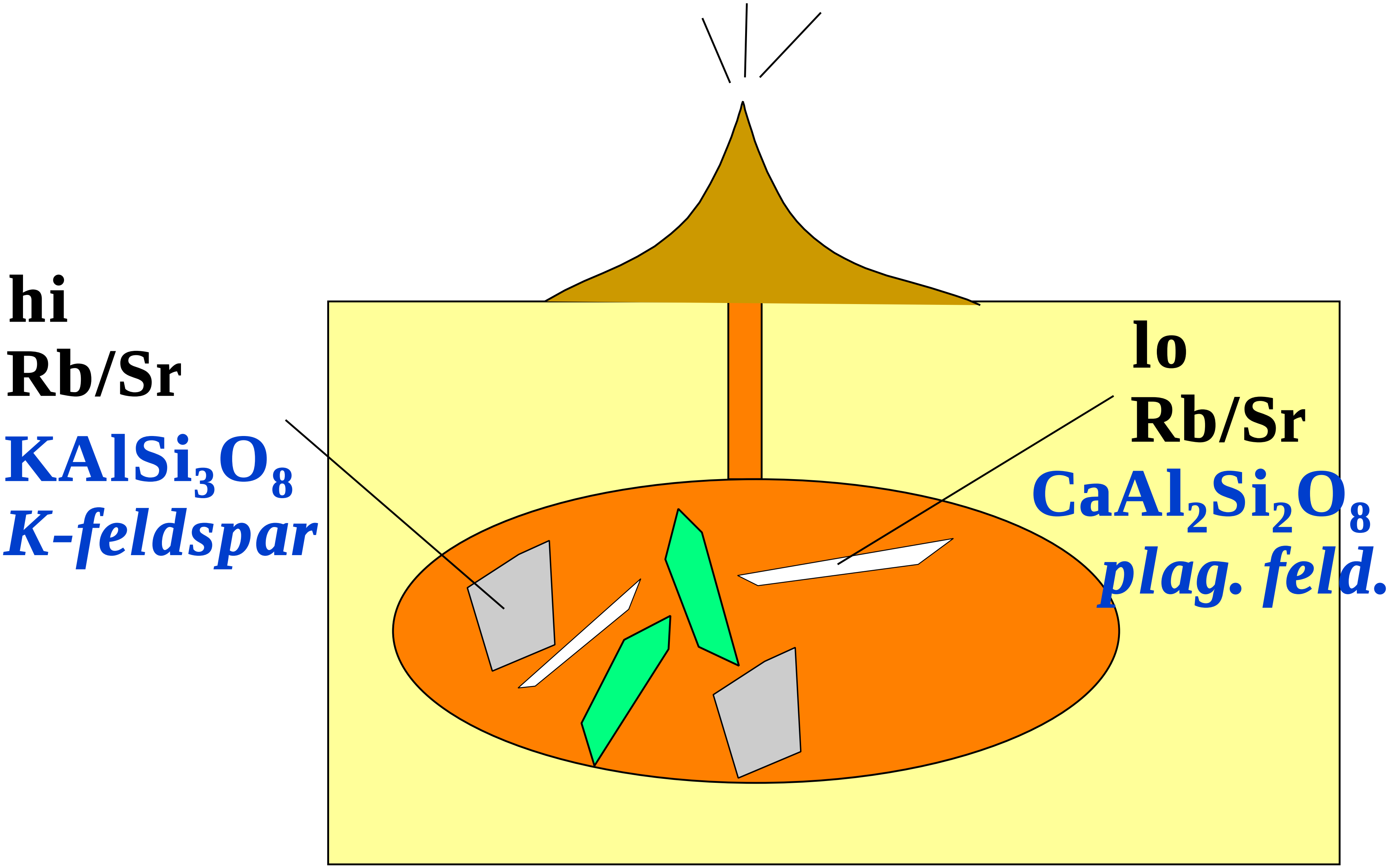

hi
Rb/Sr
$KAlSi_3O_8$
K-feldspar
lo
Rb/Sr
$CaAl_2Si_2O_8$
plag. feld.

TABLE 3.1

Principal Parent and Daughter Isotopes Used to Determine the Ages of Rocks and Minerals

Parent isotope (radioactive)	Daughter isotope (stable)	Half-life (Ma)	Decay constant (yr^{-1})
^{40}K	^{40}Ar [a]	1,250	5.81×10^{-11}
^{87}Rb	^{87}Sr	48,800	1.42×10^{-11}
^{147}Sm	^{143}Nd	106,000	6.54×10^{-12}
^{176}Lu	^{176}Hf	35,900	1.93×10^{-11}
^{187}Re	^{187}Os	43,000	1.612×10^{-11}
^{232}Th	^{208}Pb	14,000	4.948×10^{-11}
^{235}U	^{207}Pb	704	9.8485×10^{-10}
^{238}U	^{206}Pb	4,470	1.55125×10^{-10}

[a] ^{40}K also decays to ^{40}Ca, for which the decay constant is 4.962×10^{-10} yr^{-1}, but that decay is not used for dating. The half-life is for the parent isotope and so includes both decays.

U-Th-Pb

	$t_{1/2}$
$^{238}U \longrightarrow {}^{206}Pb$ + (α's +β's)	4.5 Ga
$^{235}U \longrightarrow {}^{207}Pb$ + (α's +β's)	0.7 Ga
$^{232}Th \longrightarrow {}^{208}Pb$ + (α's +β's)	14 Ga

half lives relevant?

$$N_d = N_p(e^{\lambda t} - 1)$$

	$t_{1/2}$
$^{206}Pb^* = {}^{238}U(e^{\lambda t} - 1)$	4.5 Ga
$^{207}Pb^* = {}^{235}U(e^{\lambda t} - 1)$	0.7 Ga
$^{208}Pb^* = {}^{232}Th(e^{\lambda t} - 1)$	14 Ga

*** = radiogenic**

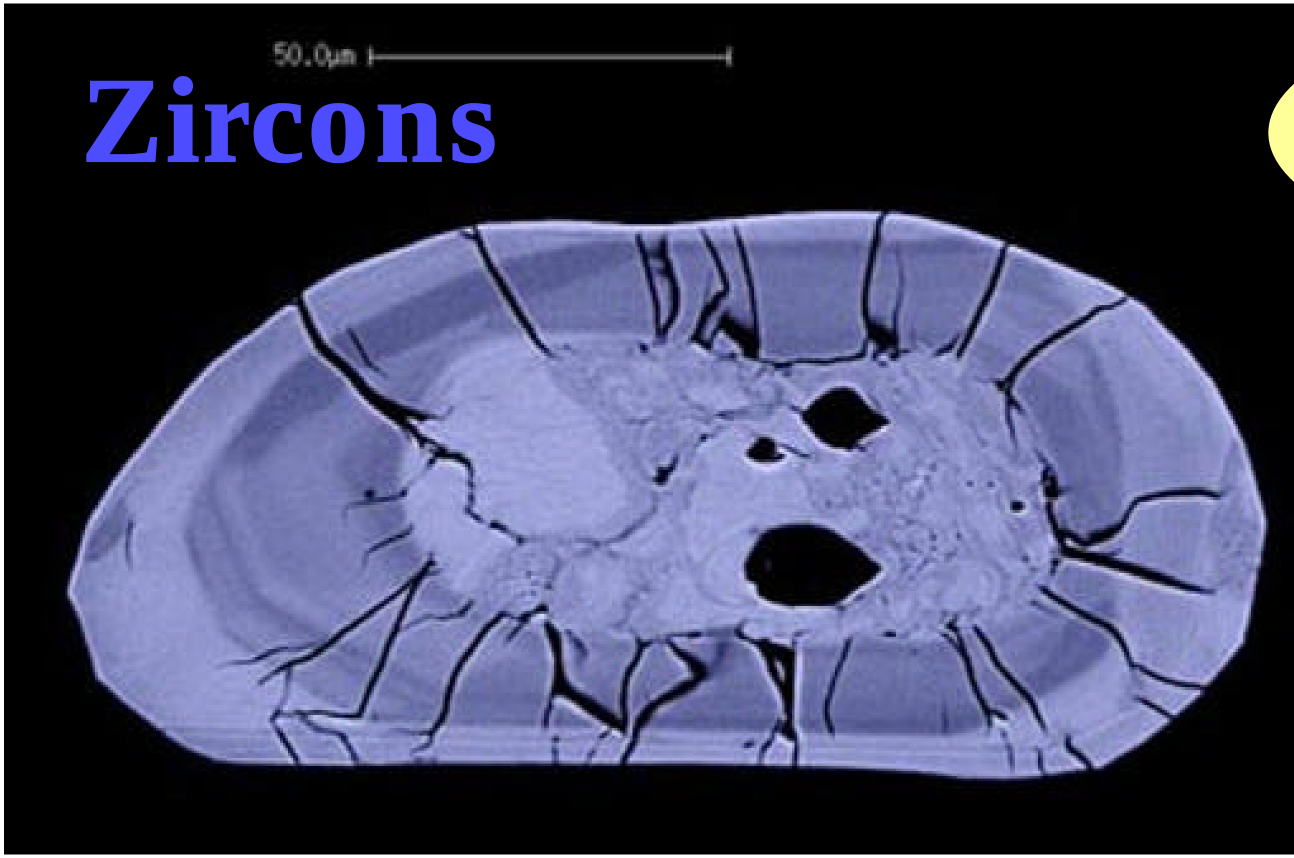
Concordia

$$^{206}Pb^* = {}^{238}U(e^{\lambda t} - 1)$$

$$^{207}Pb^* = {}^{235}U(e^{\lambda t} - 1)$$

*** = radiogenic Pb only**

which materials best?



$ZrSiO_4$

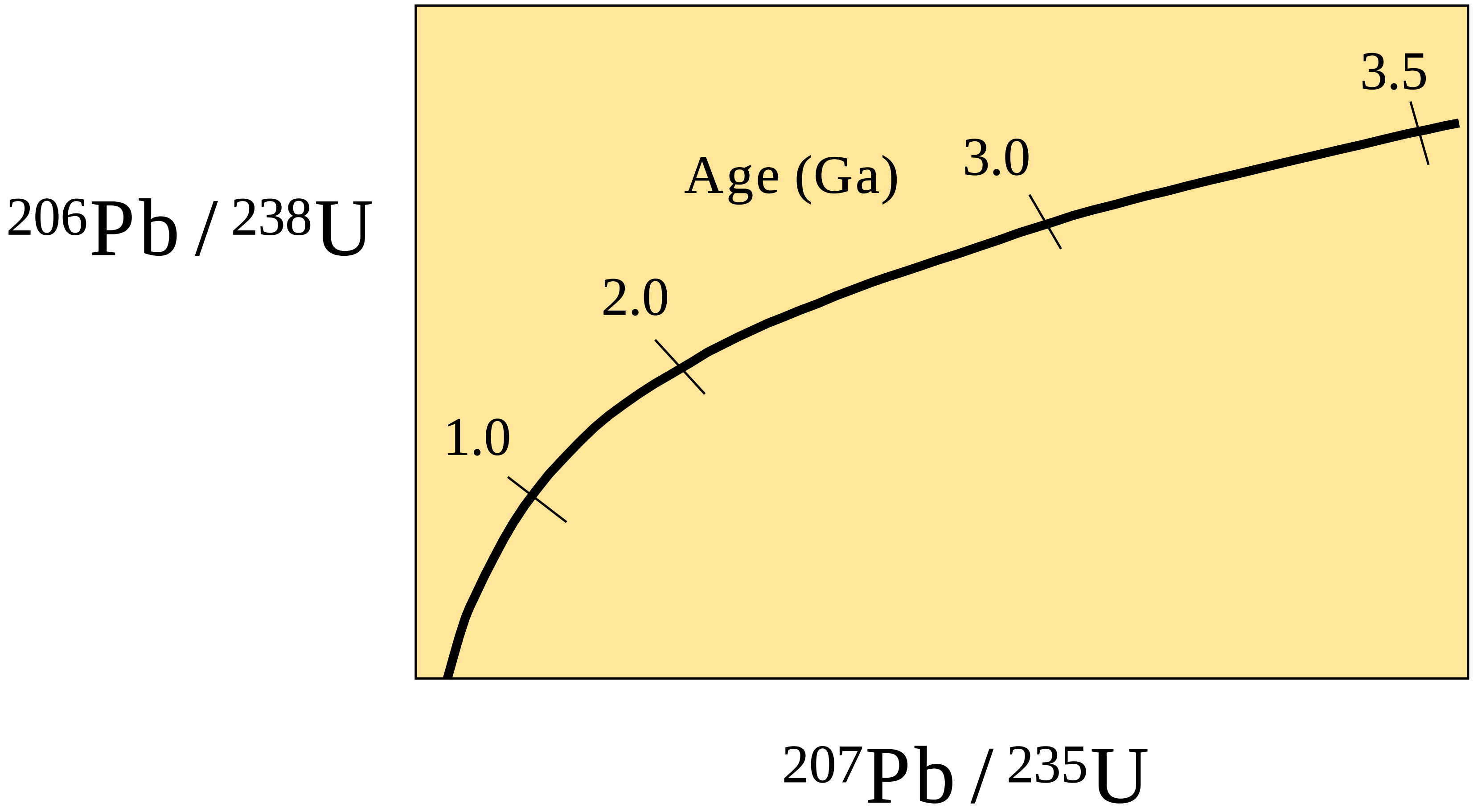
$Zr(4+)$ = 0.08 nm
$U(4+)$ = 0.093 nm
$Pb(2+)$ = 0.132 nm

$$^{206}Pb^* = {}^{238}U(e^{\lambda t} - 1)$$

$$^{207}Pb^* = {}^{235}U(e^{\lambda t} - 1)$$

- **virtually all Pb is radiogenic**

Concordia Curve

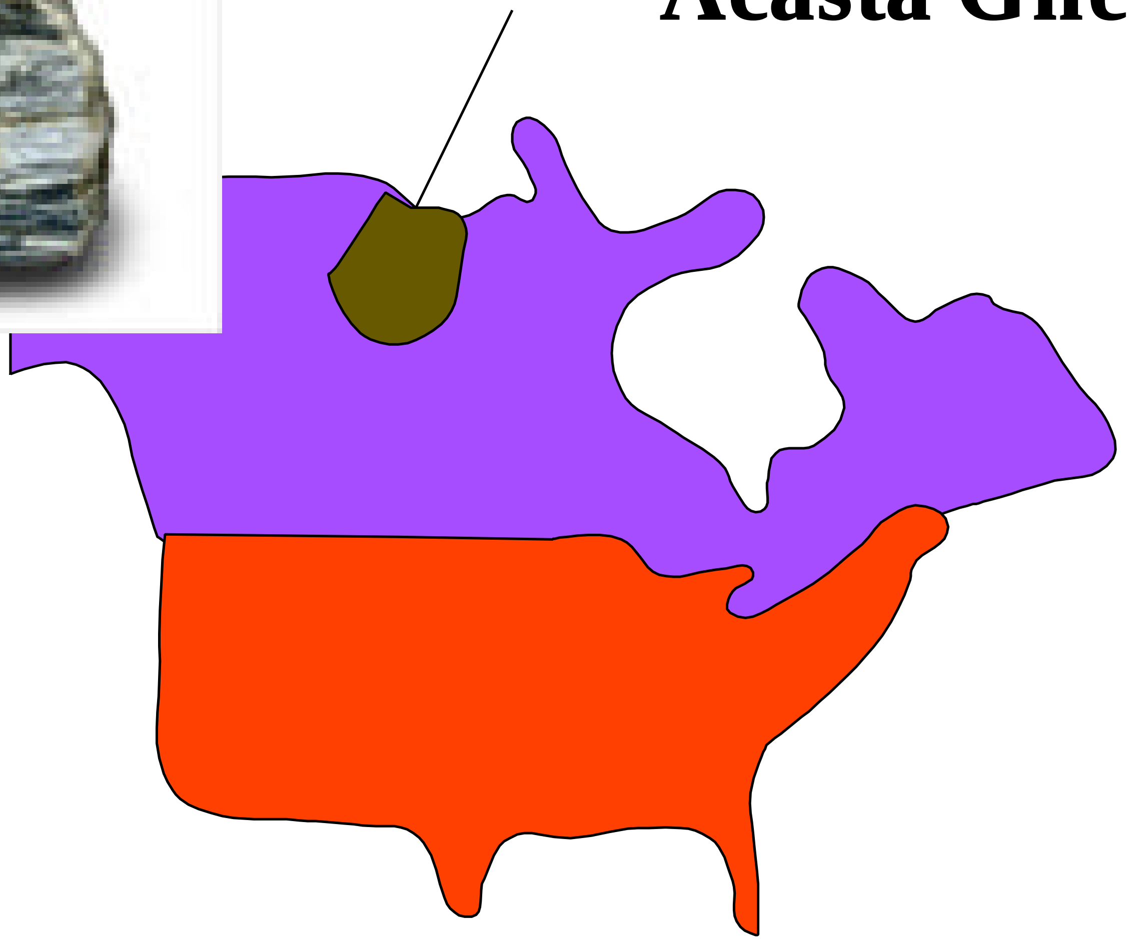


curved shape?

Oldest Rocks on Earth

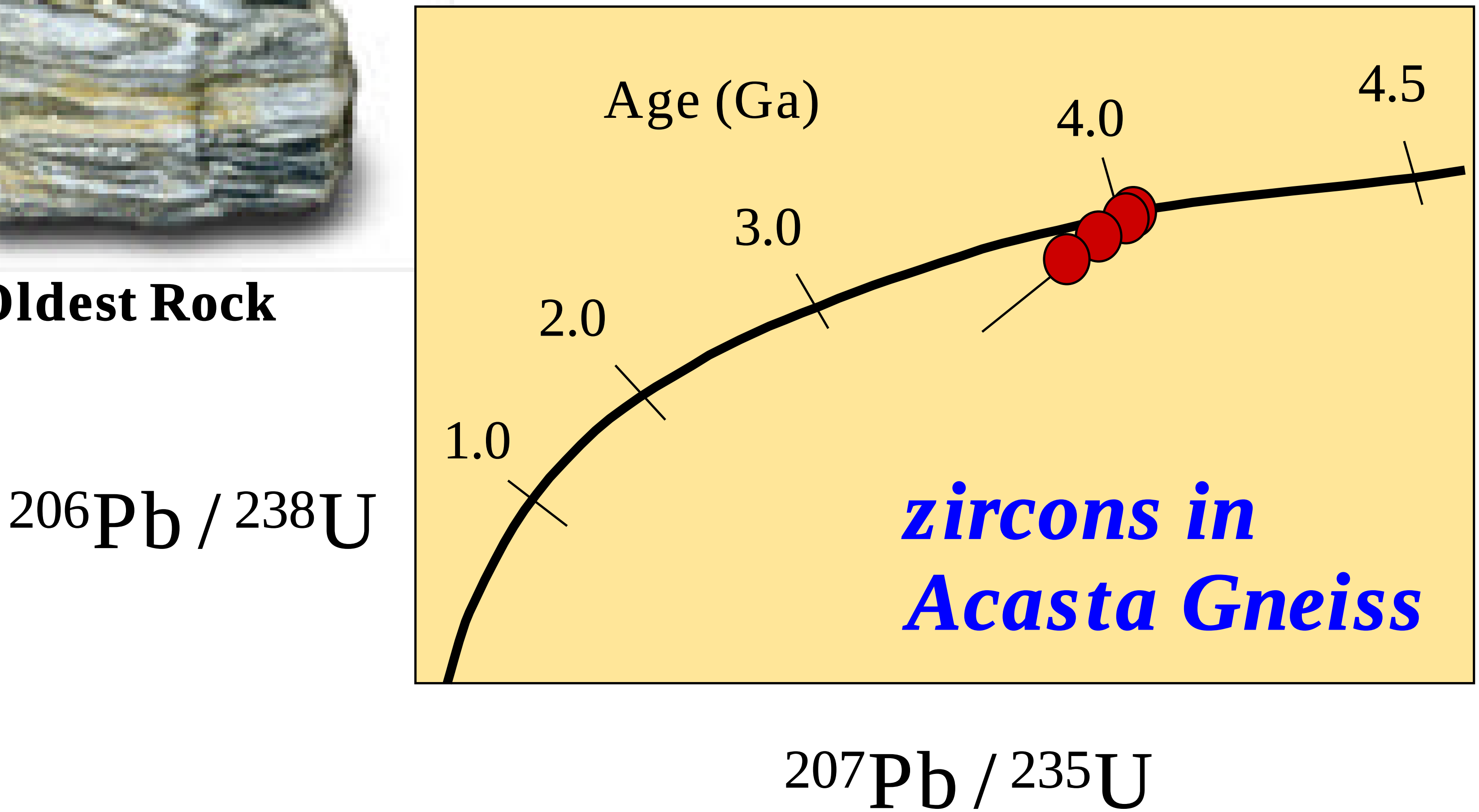
Slave Craton

Acasta Gneiss



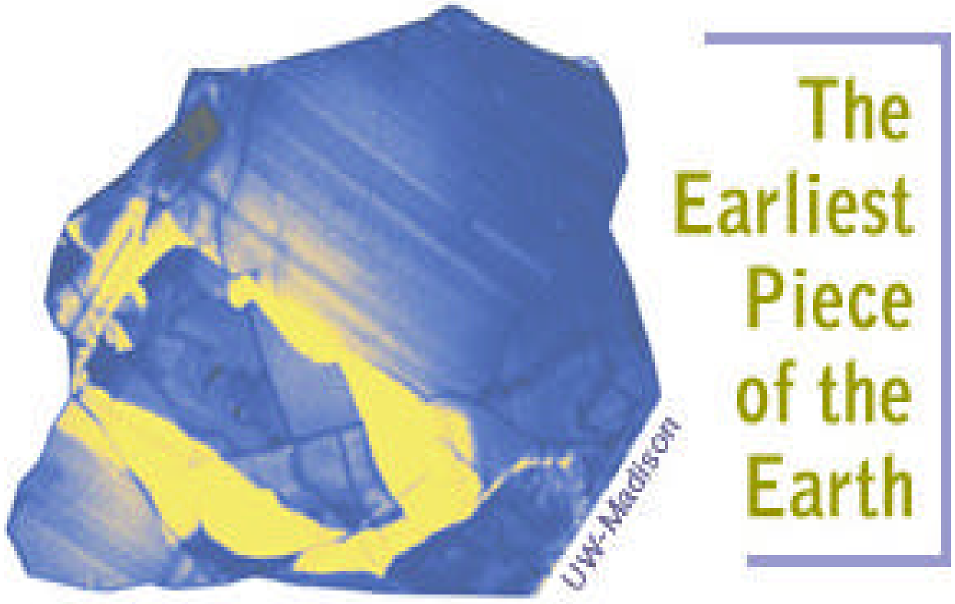
Oldest Rock

Concordia Curve



(4.00 - 4.03 Ga)

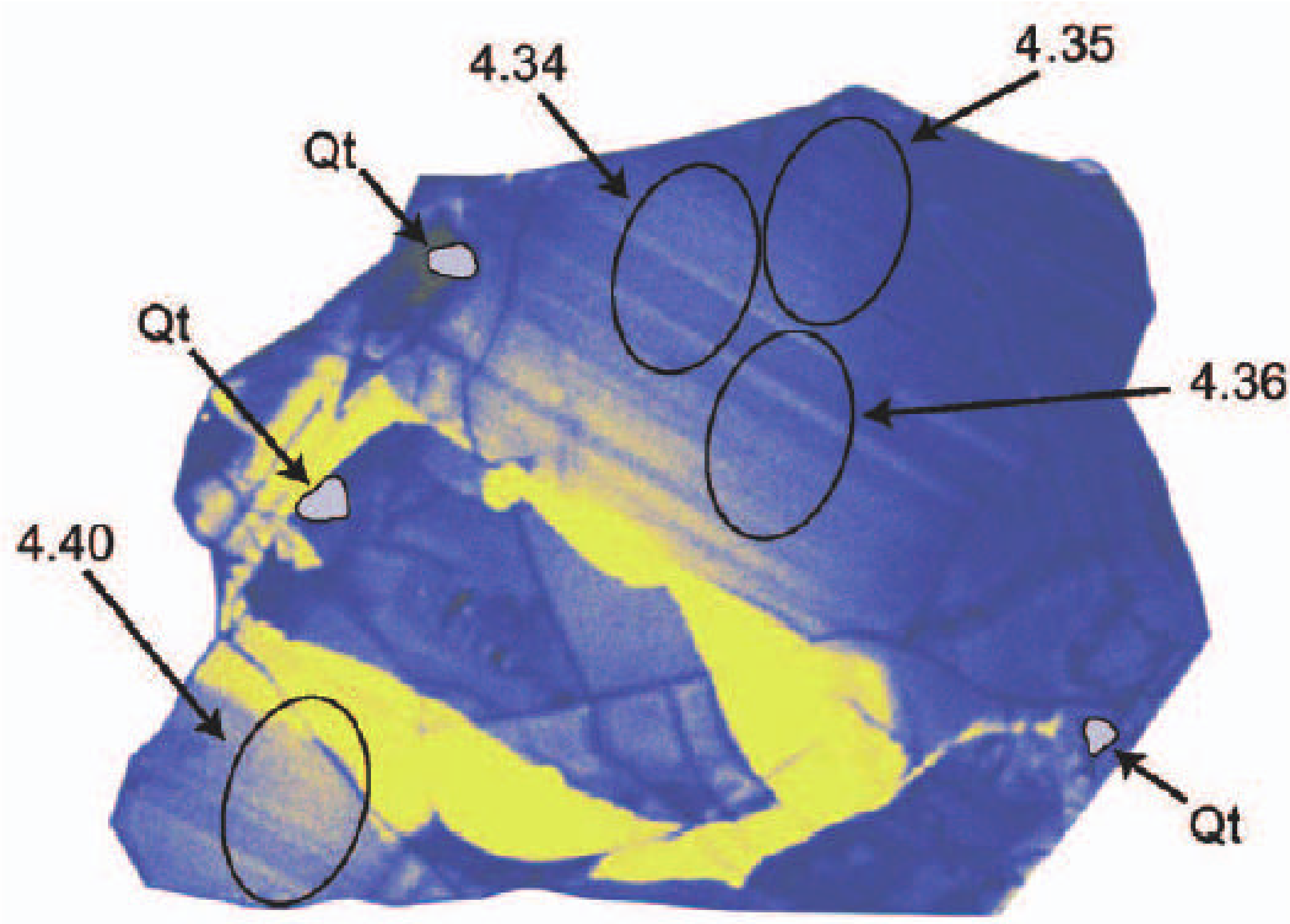
Bowring & Williams, 1999



oldest zircon!

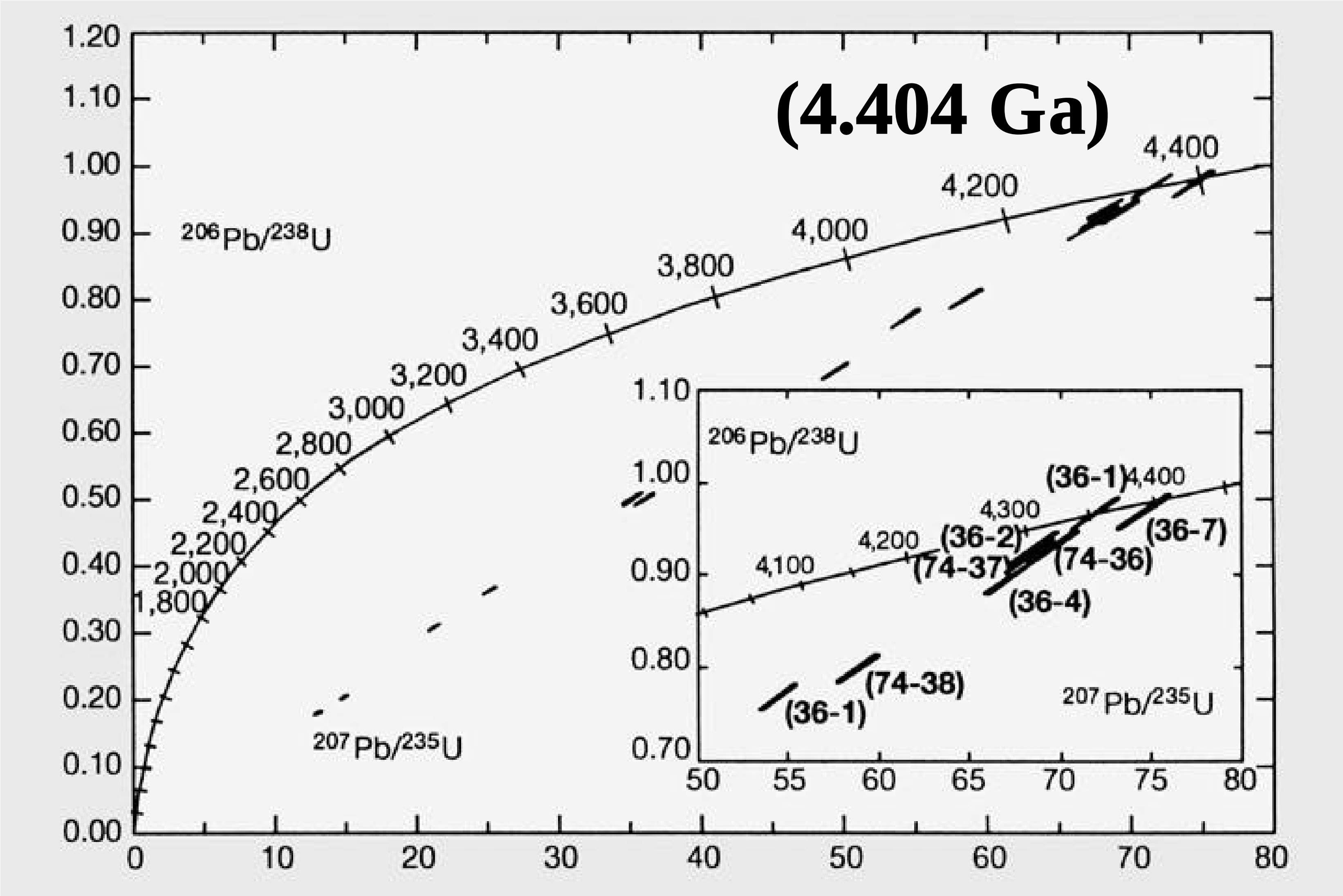
4.34 - 4.44 Ga

Yilgarn craton, Australia (Jack Hills)



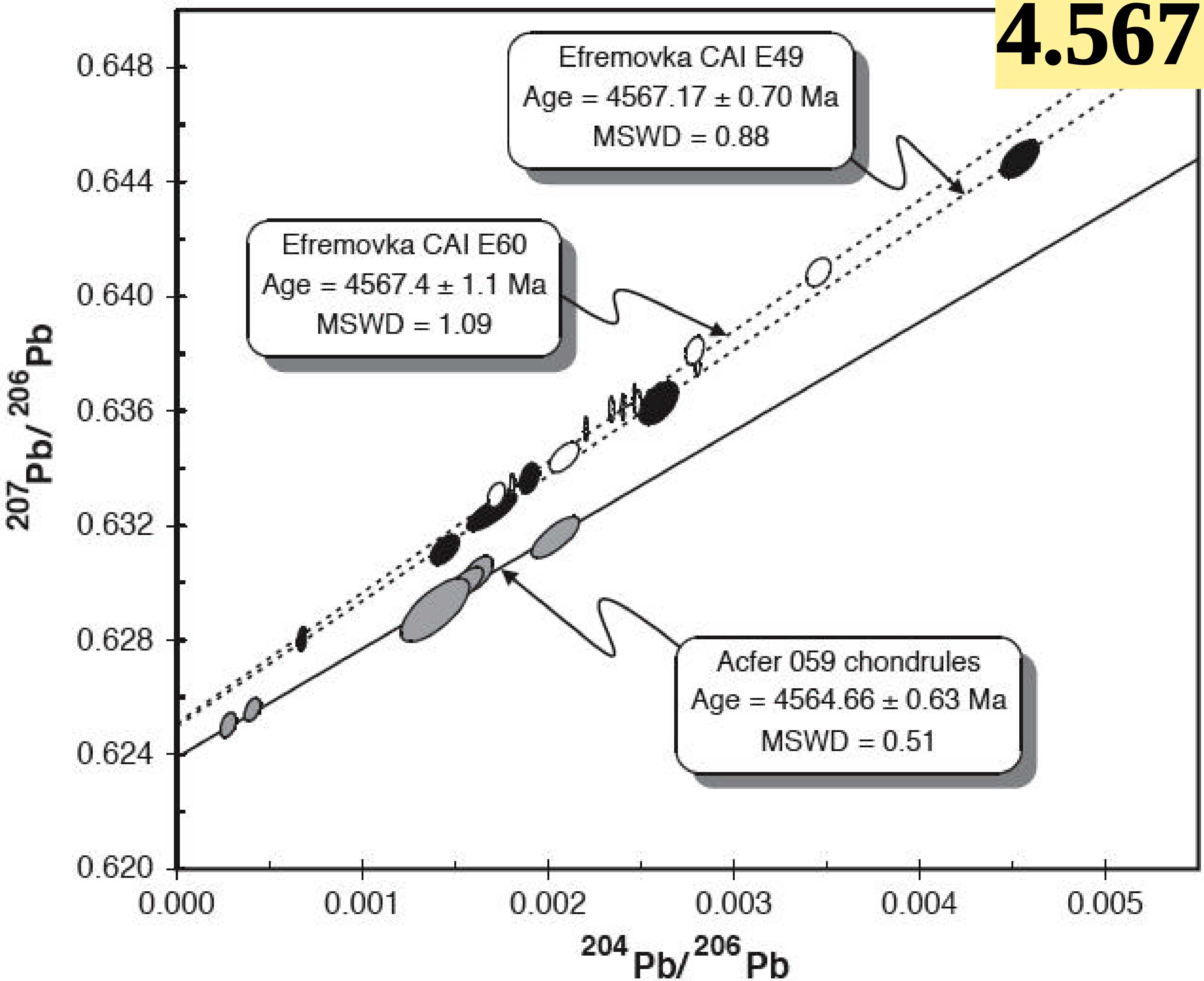
oldest bit of a zircon!

Oldest Zircon Fragment



Wilde, 2001, Nature

4.567 Ga



Amelin, 2002

re 6

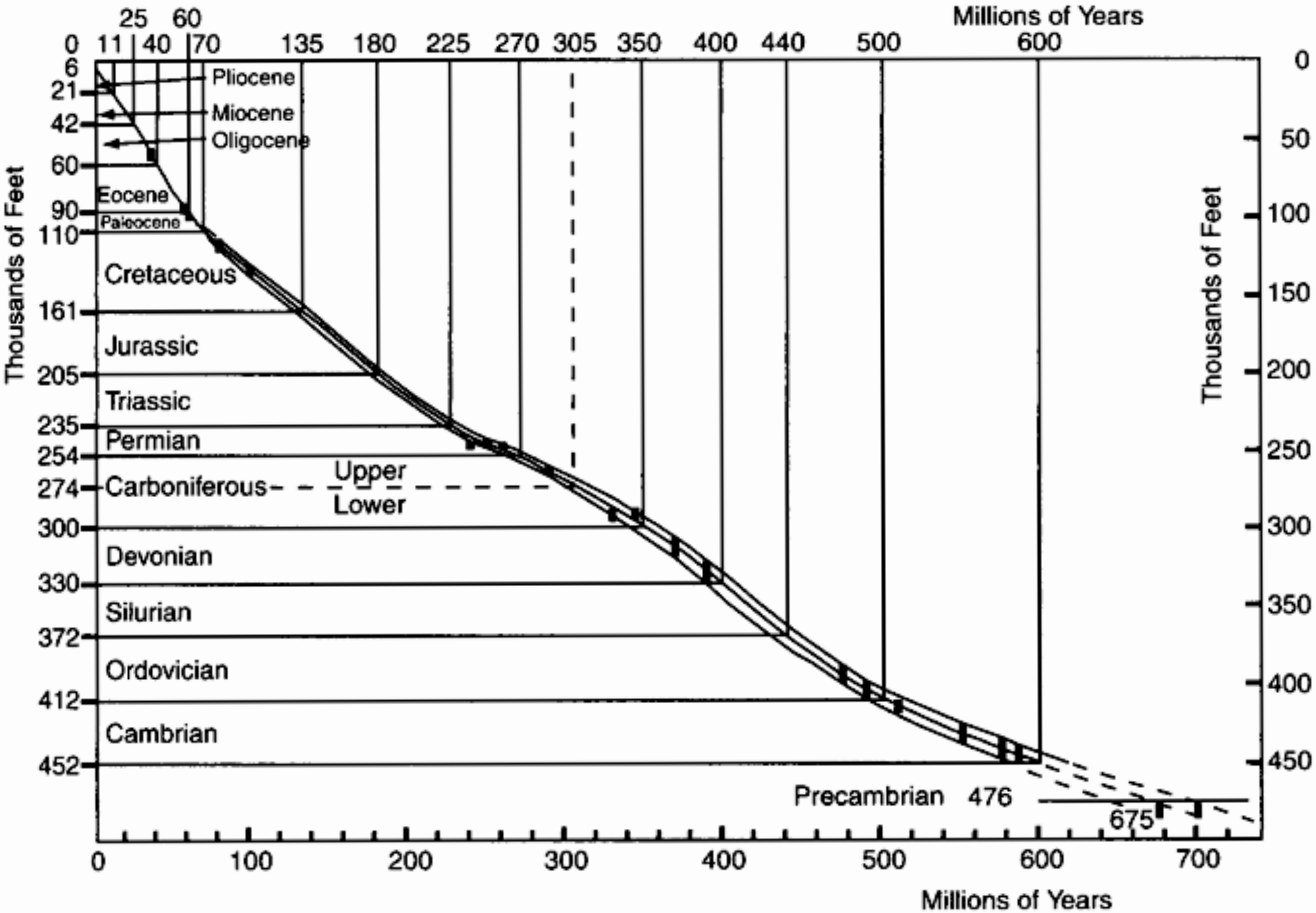


Figure 1.4 Scaling concept employed by Arthur Holmes in the first half of the previous century to construct the geologic time scale. The cumulative sum of maximum thicknesses of strata in thousands of feet per stratigraphic unit is plotted along the vertical axis and selected radiometric dates from volcanic tuffs, glauconites, and magmatic intrusives along the horizontal linear axis. This version (Holmes, 1960) incorporated an uncertainty envelope from the errors on the radiometric age constraints.

INTERNATIONAL STRATIGRAPHIC CHART

International Commission on Stratigraphy

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma
Phanerozoic	Cenozoic	Quaternary *	Holocene		0.0118
			Pleistocene	Upper	0.126
				Middle	0.781
				Lower	1.806
		Neogene	Pliocene	Gelasian	2.588
				Piacenzian	3.600
				Zanclean	5.332
			Miocene	Messinian	7.246
				Tortonian	11.608
				Serravallian	13.65
				Langhian	15.97
				Burdigalian	20.43
				Aquitanian	23.03
		Paleogene	Oligocene	Chattian	28.4 ±0.1
				Rupelian	33.9 ±0.1
			Eocene	Priabonian	37.2 ±0.1
				Bartonian	40.4 ±0.2
				Lutetian	48.6 ±0.2
				Ypresian	55.8 ±0.2
			Paleocene	Thanetian	58.7 ±0.2
				Selandian	61.7 ±0.2
				Danian	65.5 ±0.3
	Mesozoic	Cretaceous	Upper	Maastrichtian	70.6 ±0.6
				Campanian	83.5 ±0.7
				Santonian	85.8 ±0.7
				Coniacian	89.3 ±1.0
				Turonian	93.5 ±0.8
				Cenomanian	99.6 ±0.9
			Lower	Albian	112.0 ±1.0
				Aptian	125.0 ±1.0
				Barremian	130.0 ±1.5
				Hauterivian	136.4 ±2.0
				Valanginian	140.2 ±3.0
				Berriasian	145.5 ±4.0

* proposed by ICS

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma
					145.5 ±4.0
Phanerozoic	Mesozoic	Jurassic	Upper	Tithonian	150.8 ±4.0
				Kimmeridgian	155.7 ±4.0
				Oxfordian	161.2 ±4.0
			Middle	Callovian	164.7 ±4.0
				Bathonian	167.7 ±3.5
				Bajocian	171.6 ±3.0
				Aalenian	175.6 ±2.0
			Lower	Toarcian	183.0 ±1.5
				Pliensbachian	189.6 ±1.5
				Sinemurian	196.5 ±1.0
				Hettangian	199.6 ±0.6
		Triassic	Upper	Rhaetian	203.6 ±1.5
				Norian	216.5 ±2.0
				Carnian	228.0 ±2.0
			Middle	Ladinian	237.0 ±2.0
				Anisian	245.0 ±1.5
			Lower	Olenekian	249.7 ±0.7
				Induan	251.0 ±0.4
	Paleozoic	Permian	Lopingian	Changhsingian	253.8 ±0.7
				Wuchiapingian	260.4 ±0.7
			Guadalupian	Capitanian	265.8 ±0.7
				Wordian	268.0 ±0.7
				Roadian	270.6 ±0.7
			Cisuralian	Kungurian	275.6 ±0.7
				Artinskian	284.4 ±0.7
				Sakmarian	294.6 ±0.8
				Asselian	299.0 ±0.8
		Carboniferous	Pennsylvanian Upper	Gzhelian	303.9 ±0.9
				Kasimovian	306.5 ±1.0
			Pennsylvanian Middle	Moscovian	311.7 ±1.1
			Pennsylvanian Lower	Bashkirian	318.1 ±1.3
			Mississippian Upper	Serpukhovian	326.4 ±1.6
			Mississippian Middle	Visean	345.3 ±2.1
			Mississippian Lower	Tournaisian	359.2 ±2.5

Eonothem Eon	Erathem Era	System Period	Series Epoch	Stage Age	Age Ma
					359.2 ±2.5
Phanerozoic	Paleozoic	Devonian	Upper	Famennian	374.5 ±2.6
				Frasnian	385.3 ±2.6
			Middle	Givetian	391.8 ±2.7
				Eifelian	397.5 ±2.7
			Lower	Emsian	407.0 ±2.8
				Pragian	411.2 ±2.8
				Lochkovian	416.0 ±2.8
		Silurian	Pridoli		418.7 ±2.7
			Ludlow	Ludfordian	421.3 ±2.6
				Gorstian	422.9 ±2.5
			Wenlock	Homerian	426.2 ±2.4
				Sheinwoodian	428.2 ±2.3
			Llandovery	Telychian	436.0 ±1.9
				Aeronian	439.0 ±1.8
				Rhuddanian	443.7 ±1.5
		Ordovician	Upper	Hirnantian	445.6 ±1.5
				Stage 6	455.8 ±1.6
				Stage 5	460.9 ±1.6
			Middle	Darriwilian	468.1 ±1.6
				Stage 3	471.8 ±1.6
			Lower	*Stage 2*	478.6 ±1.7
				Tremadocian	488.3 ±1.7
		Cambrian	Furongian	*Stage 10*	~ 492.0 *
				Stage 9	~ 496.0 *
				Paibian	501.0 ± 2.0
			Series 3	*Stage 7*	~ 503.0 *
				Stage 6	~ 506.5 *
				Stage 5	~ 510.0 *
			Series 2	*Stage 4*	~ 517.0 *
				Stage 3	~ 521.0 *
			Series 1	*Stage 2*	~ 534.6 *
				Stage 1	542.0 ±1.0

This chart was drafted by Gabi Ogg. Intra Cambrian unit ages with * are informal, and awaiting ratified definitions.

Eonothem Eon	Erathem Era	System Period	Age Ma
			542
Precambrian Proterozoic	Neoproterozoic	Ediacaran	~630
		Cryogenian	850
		Tonian	1000
	Mesoproterozoic	Stenian	1200
		Ectasian	1400
		Calymmian	1600
	Paleoproterozoic	Statherian	1800
		Orosirian	2050
		Rhyacian	2300
		Siderian	2500
Precambrian Archean	Neoarchean		2800
	Mesoarchean		3200
	Paleoarchean		3600
	Eoarchean	Lower limit is not defined	

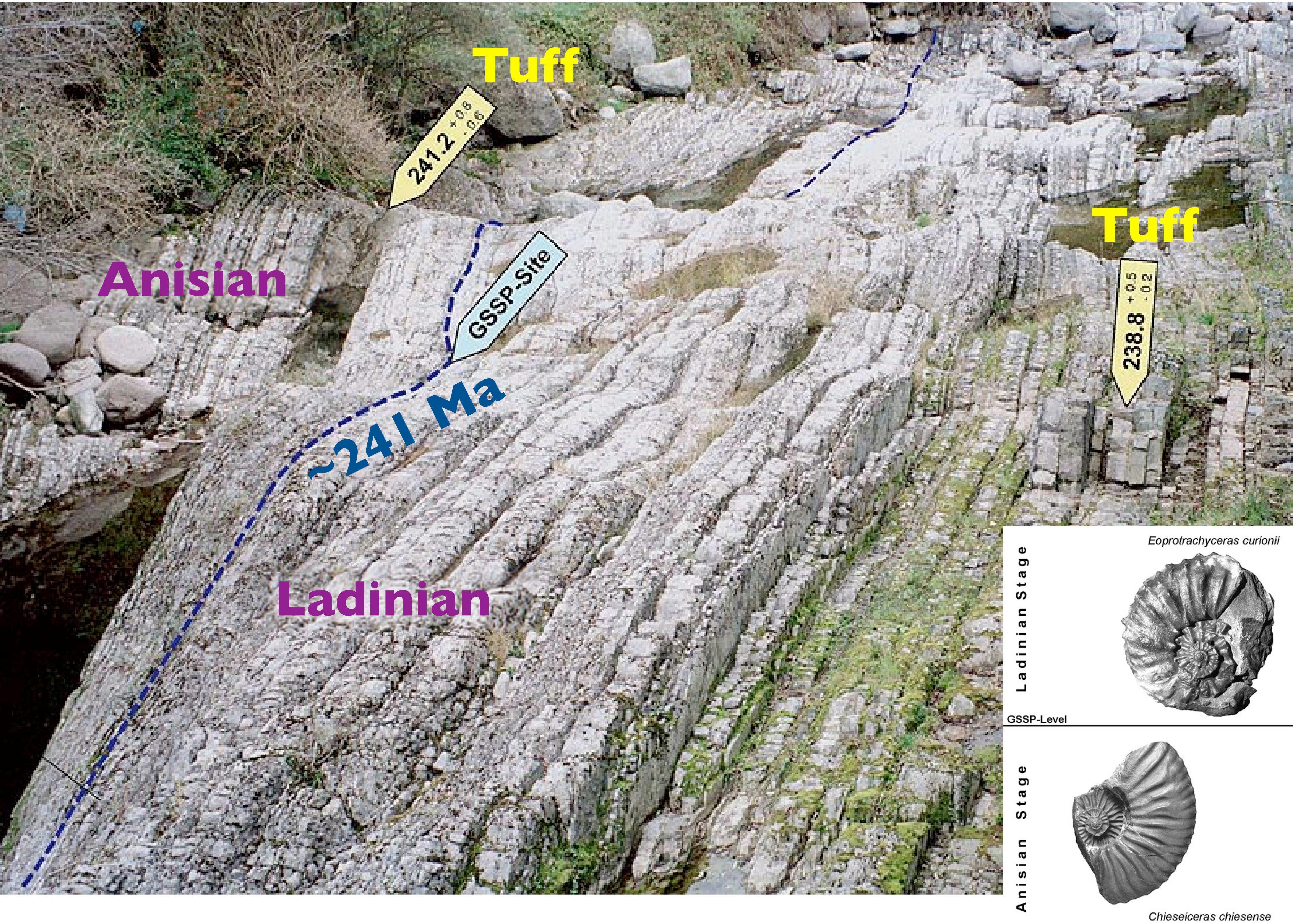
Subdivisions of the global geologic record are formally defined by their lower boundary. Each unit of the Phanerozoic (~542 Ma to Present) and the base of Ediacaran are defined by a basal Global Standard Section and Point (GSSP), whereas Precambrian units are formally subdivided by absolute age (Global Standard Stratigraphic Age, GSSA). Details of each GSSP are posted on the ICS website (*www.stratigraphy.org*).

International chronostratigraphic units, rank, names and formal status are approved by the International Commission on Stratigraphy (ICS) and ratified by the International Union of Geological Sciences (IUGS).

Numerical ages of the unit boundaries in the Phanerozoic are subject to revision. Some stages within the Ordovician and Cambrian will be formally named upon international agreement on their GSSP limits. Most sub-Series boundaries (e.g., Middle and Upper Aptian) are not formally defined.

Colors are according to the Commission for the Geological Map of the World (*www.cgmw.org*).

The listed numerical ages are from 'A Geologic Time Scale 2004', by F.M. Gradstein, J.G. Ogg, A.G. Smith, et al. (2004; Cambridge University Press).


Tuff
241.2 +.08 -.06
Anisian
GSSP-Site
~241 Ma
Ladinian
Tuff
238.8 +.5 -.2
Eoprotrachyceras curionii
Ladinian Stage
GSSP-Level
Anisian Stage
Chieseiceras chiesense