Terrestrial Planets

Week 1

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Earth and Planetary Sciences
FD Adams 131C

Creation of the universe, solar system, planets and satellites

Pluritas non est ponenda sine necessitate.

... William Ockham (c 1285?-1349)

Paraphrasing ***Ockham's Razor***: KISS (Keep it simple stupid!)
… I shall try!

Creation mythologies

- Prehistory… every human tribe holds to a creation myth that sufficiently explains their existence.
- Middle eastern and western religions commonly hold to one that involves their creating “god”.
  - Sumerians: The Epic of Gilgamesh describes the adventures of the King of Uruk leading to the edge of creation. (circa 2700BCE)
  - Judaic-Christian: Genesis 1:1 “ In the beginning God created the heaven and the Earth....” (when? 5777 years ago)
  - Islam: Sura 57:4 (Q’aran) “He is the One who created the heavens and the earth”
- The indigenous people of North America, Europe and northern Asia all describe agents of creation.
- The great civilizations of the Indian subcontinent, south east Asia, China and Japan all hold to stories of their creation.

Creation mythologies II

Philosophies and contemporary pseudo-religious cults:

- ***Raëlism*** – a UFO religion: Humans are a creation or genetic engineering experiment by more advanced beings.
- ***Scientology:*** Xenu, the dictator of the "Galactic Confederacy" brought billions of his people to Earth 75 million years ago
- ***Intelligent Design:*** A "God" must have directly created humans and other living things because nothing so complex could have arisen without explicit design… a contemporary take on ***Creationism***
- … and there are many, many others that we tend to discount as fanciful. But then, who decides what is fancy?

Creation mythologies III

- **The scientific model; this is the narrative that we shall follow it in this course:**

  What should distinguish the scientific model of creation and evolution is that it is “testable” and ***any*** model that fails a test must be discarded or modified.

Creation mythologies III

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  Scientists of all stripes, physicists, astrophysicists, geologists, biologists, even psychologists continually test models for failures. We are left with our contemporary narrative.

Creation mythologies III

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We shall see that in arriving at our currently-favoured ***Λ-CDM Concordance Model*** of the Universe, we have discarded many prior models and modified those that once satisfied all their tests except for the one they failed.

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Creation mythologies III

- **The scientific model; this is the narrative that we shall follow it in this course:**

The ***Λ-CDM Concordance Model*** continues to be under relentless challenge.

Scientific narrative

Our cosmologies properly describe models of the evolution of the Universe; they do not explain the moment of creation of the Universe!

"Why?". We retreat to the metaphysical edge of physics – ***"a quantum fluctuation of the nothing"*** – as an admittedly lame explanation of its ***"creation".***

- The ***Big Bang*** hypothesis ***(Georges LeMaître, 1894-1966)*** – the beginning. ***"When?"*** Our best estimate: ***13.798*** billion years ago
- ***de Sitter (1872-1934)***modelled the evolution of the Universe as a solution of Einstein's General Relativistic field equations. His simple model was of an ***"empty" Universe.***
- The ***Inflationary Big Bang*** (***Alan Guth , 1947-*** - MIT), modified the Big Bang to explain homogeneity and distribution of observed matter
- Discovery of the acceleration of the expansion (***Saul Perlmutter***, ***Brian Schmidt*** and ***Adam Riess, Nobel Prize 2011***) leads to the current ***Λ-CDM Concordance Model*** and the invocation of ***Cold Dark Matter*** and ***Dark Energy***.

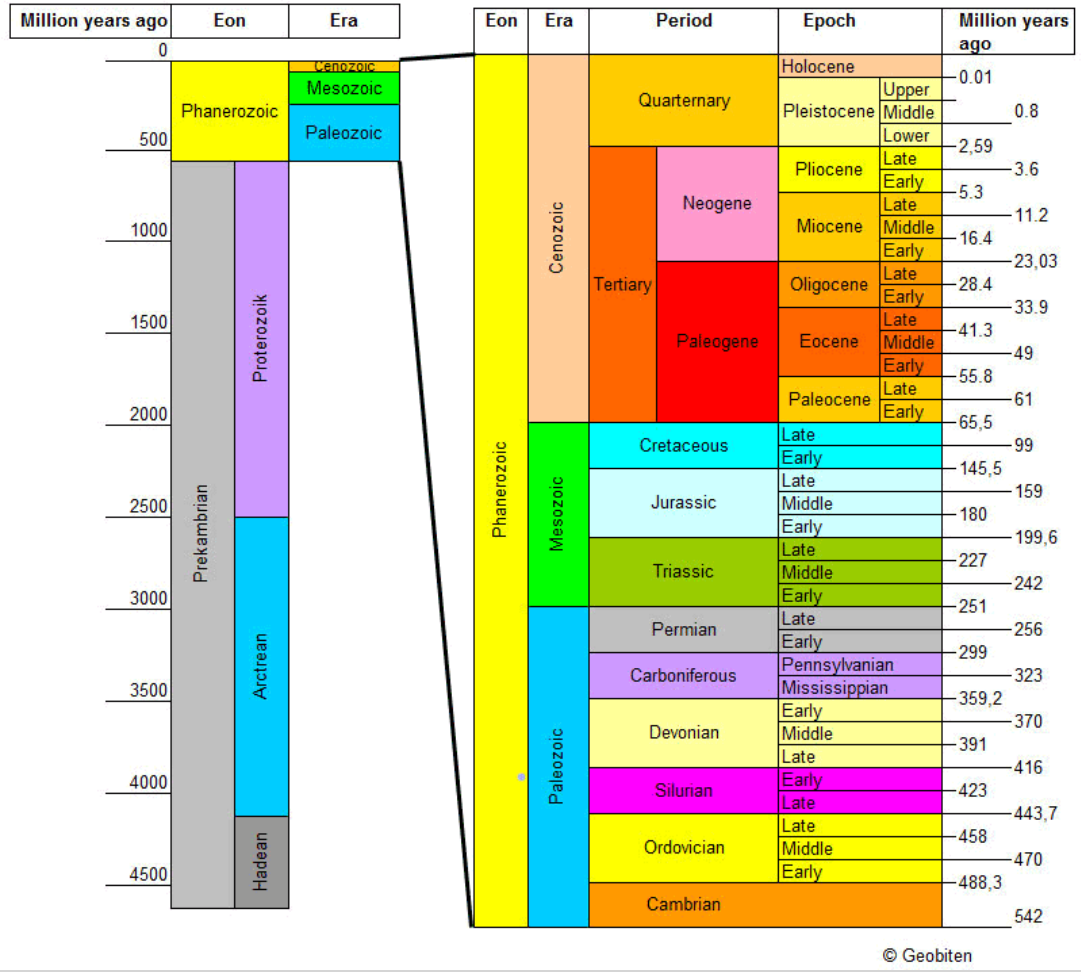
Quantifying the moment of creation

Let us try to answer the question: ***"When?"*** **did the Big Bang occur?** I suggest that we can already answer this question: ***"Where"*** **did it occur?: "Right here!" But let's first ask the question:** ***"How old is the Earth?"***

- ***Nicolas Steno*** ***(1669)*** ... recognized that the layering of Tuscan sediments ordered the history of Earth... but how old?
- ***Immanuel Kant*** ***(chemistry)***... How long has the Sun been burning?
- ***James Hutton*** ***(1785, father of geology)*** – Why has Hadrian's wall not shown more erosion?
- ***von Helmholtz*** ***(introducing physics)*** – The gravitational energy accumulated in the Sun's formation could account for 20 Ma!
- ***Lord Kelvin*** ***(1897, geophysics cooling of Earth and in 1900, solar physics)*** – less than 100 million years
- ***John Joly*** ***(evaporation of river waters into salt water oceans)*** at least 90-100 million years
- ***Charles Walcott*** ***(paleontology - fossils and the geological clock)*** at least 1.6 billion years

The Geological Clock

The Geological clock orders events in the geological record…



Source: https://stoneshop.se/userfiles/image/geological_timescale.png

Modern physics gives us a clock

The discovery of radioactivity by ***Becquerel*** **(1896)** provided science a "clock" with which the actual "age" of rocks could be measured .... numbers in years could be assigned to events in the geological record.

- ***John William Strutt*** **(Lord Rayleigh, 1905)** measured the radium content of uranite containing rocks to find an age of 1.65 billion years,
- ***Bertram B. Boltwood*** **(also 1905)**, working with the more stable uranium-lead system, calculated the numerical ages of 43 minerals to be in the range of 400 million to 2.2 billion years
- by the 1950s, the oldest materials found on Earth were geochronologically dated using a radioactive clock, based upon the U-Pb (uranium-lead) decay sequence, to more than 4.5 billion years...
- Now we could assign dates to the events in the Geological Clock originally based on the work of Steno and Walcott.

Radioactivity and clocks

Given a sufficiently large number, $\boldsymbol{N(t)}$, of radioactive atoms... their nuclei would decay according to a simple statistical law, here described as a differential equation:

$$\frac{\boldsymbol{dN(t)}}{\boldsymbol{dt}} = -\frac{\boldsymbol{N(t)}}{\boldsymbol{\tau}}$$

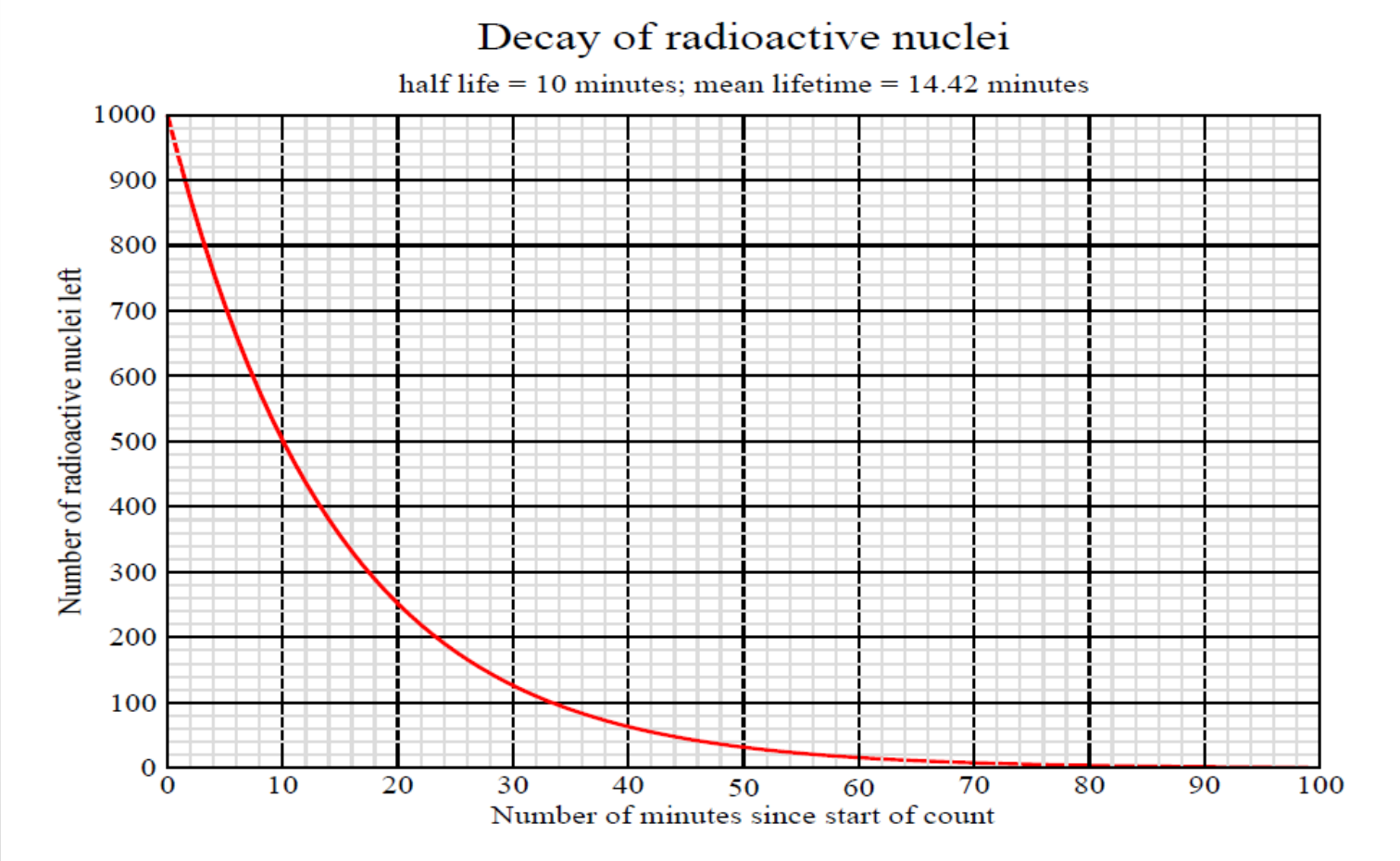
where $\boldsymbol{\tau}$ is a time constant related to the half-life $\mathbf{t_{1/2}}$ as $\boldsymbol{\tau = t_{1/2}/\ln 2}$ and $\boldsymbol{\ln 2}$ **= 0.69314718...** .

If we start at time $\mathbf{t = 0}$ with $\boldsymbol{N_0}$ radioactive atoms, at any later time $\boldsymbol{t}$, we would have:

$$\boldsymbol{N(t) = N_0 e^{-t/\tau}}$$

Let us look at a graphical example.

Radioactivity and clocks



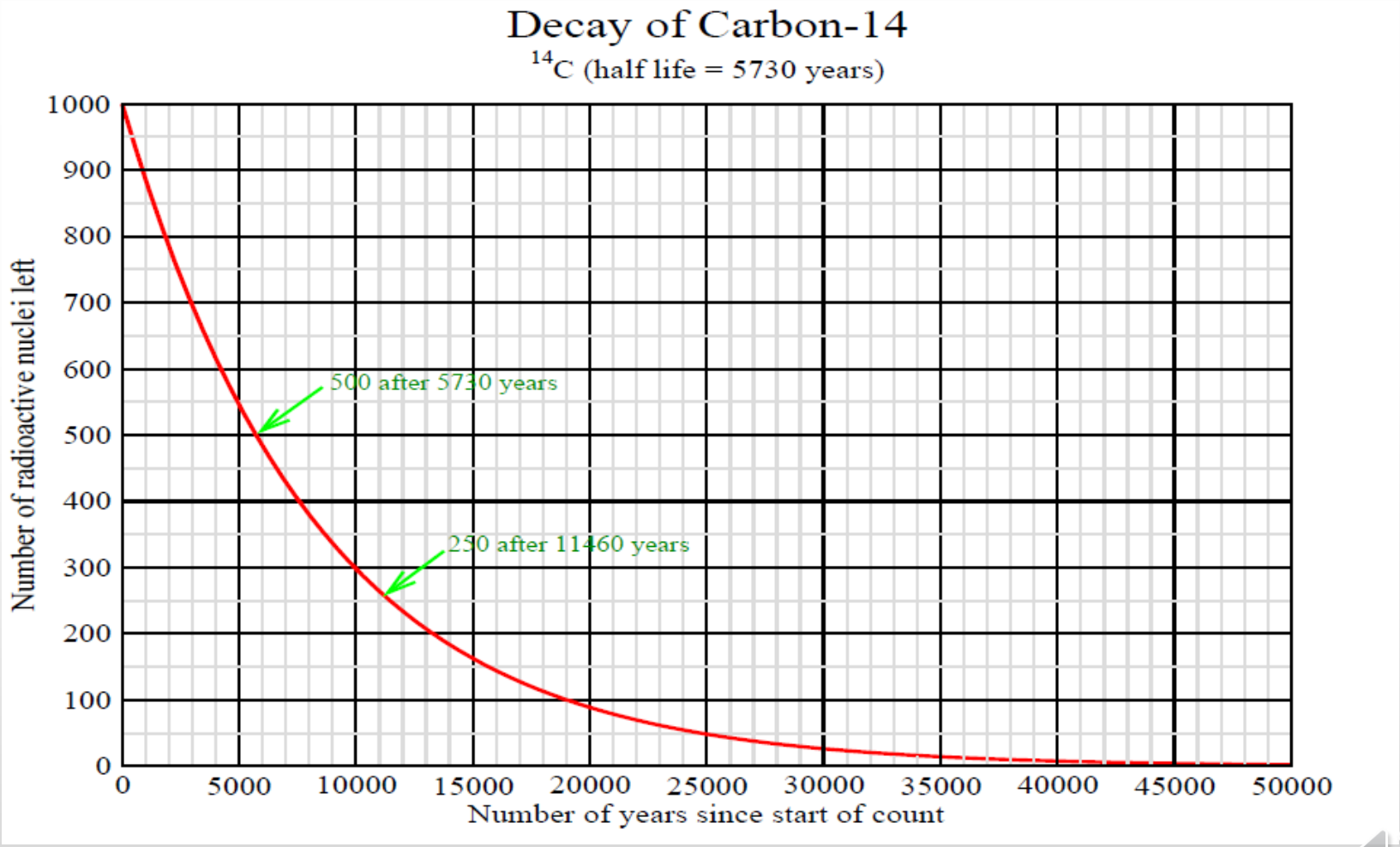
^{14}C dating method

The half life of a particular isotope of carbon, **^{14}C**, is 5730 years. **^{14}C** is created in the upper atmosphere through bombardment of **^{14}N** by cosmic rays from the depths of the Universe. This is the radio-isotope used in the method of radio-carbon dating. **^{14}C** (6 p^+ and 8 n^0) decays via β-decay back to stable **^{14}N** (7 p^+ and 7 n^0) according to a rule determined by its 5730-year half life. β-decay is not pressure or temperature dependent.

^{14}C dating method

Common **^{12}C** is not radioactive. The ratio of **$^{14}C/^{12}C$** in the atmosphere is maintained at a nearly constant level through the continuing bombardment of cosmic rays. Plants and animals take in carbon from the atmosphere with the constant **$^{14}C/^{12}C$** ratio. While living, they maintain the atmospheric ratio but when they die they cease taking in atmospheric carbon. Within their bodies, then, **^{14}C** decays and the **$^{14}C/^{12}C$** ratio decreases with a 5730 half life.

^{14}C dating method



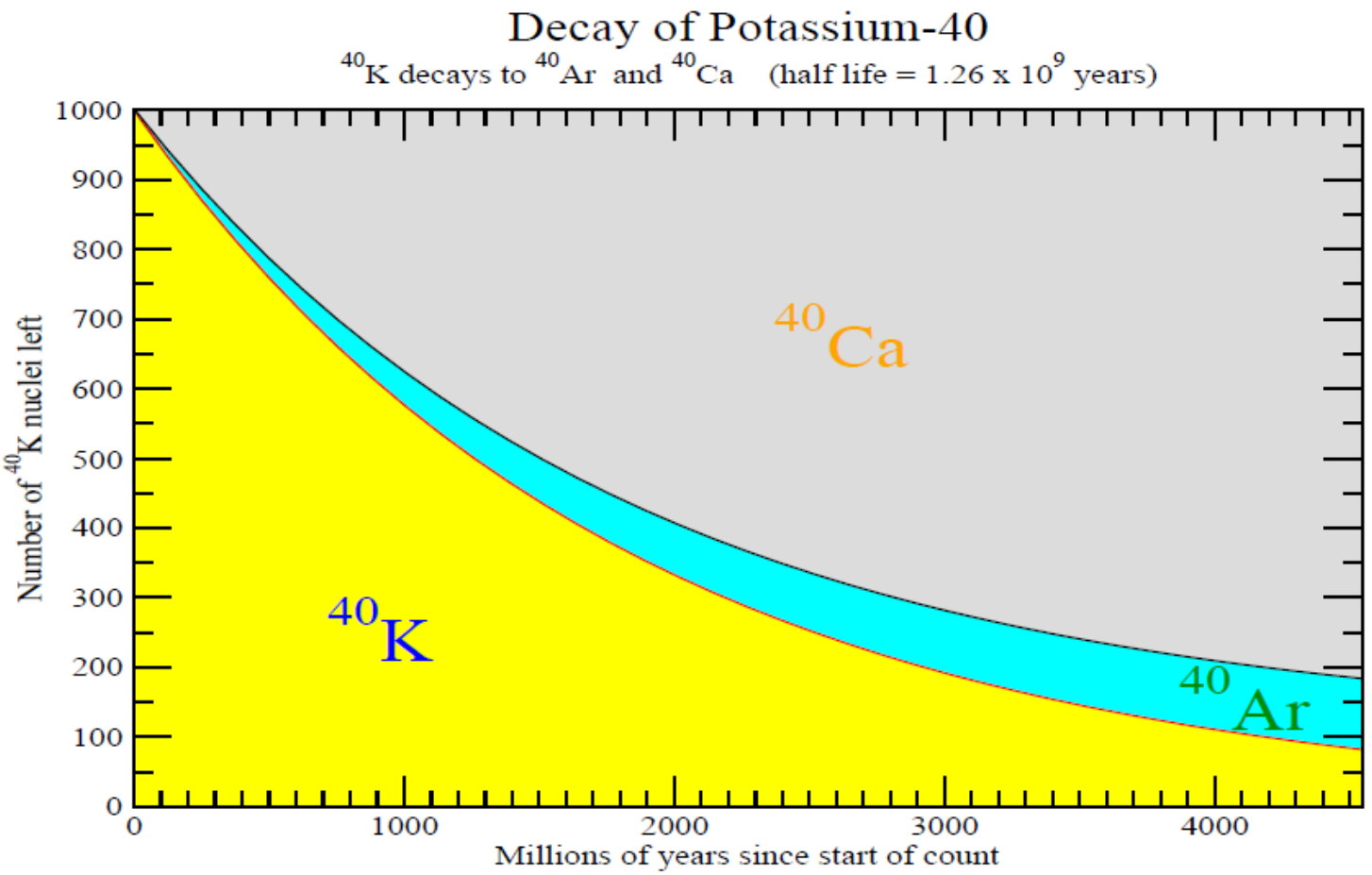
Dating on geological time scales

^{14}C dating methods are only useful for dating during short past intervals… to perhaps 40000 years past. The geological record is more than 10000 times longer than that. Luckily there are many other clocks.

Potassium-Argon dating: There are many, many radioactive decay clocks available to us that may be used in determining the "age" of minerals within rocks. **^{40}K** decays to **^{40}Ar** (10.9% of decays via β-capture) and to **^{40}Ca** (89.1% of decays via β-emission) with a half-life of about 1.3 Ga (1.3×10^9 years). This long half life makes it a useful tool in aging the oldest materials on Earth.

It does, however, introduce a complication in that **^{40}K** decays by two modes into different daughters and β-capture is pressure dependent.

^{40}Ar geochronology



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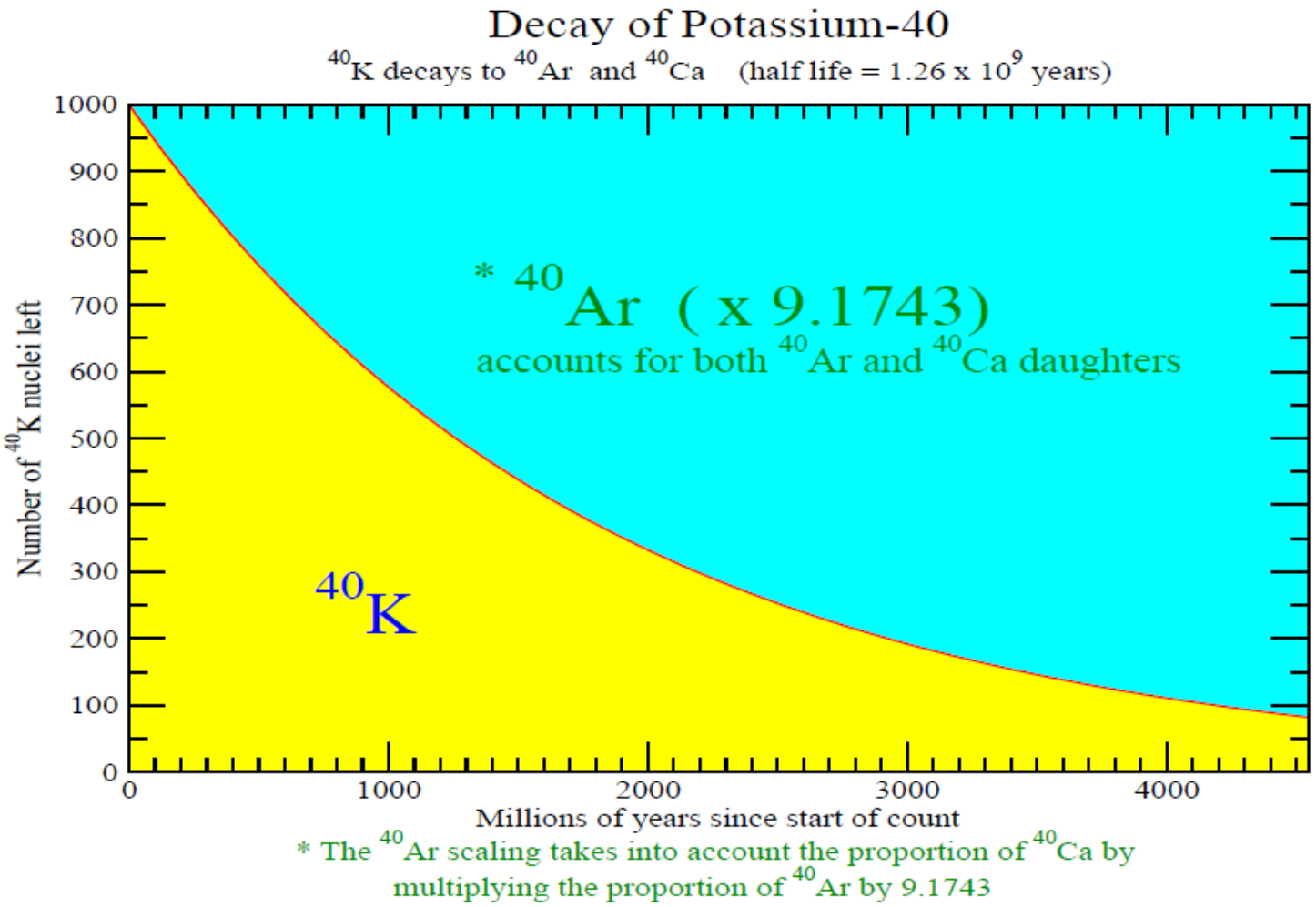


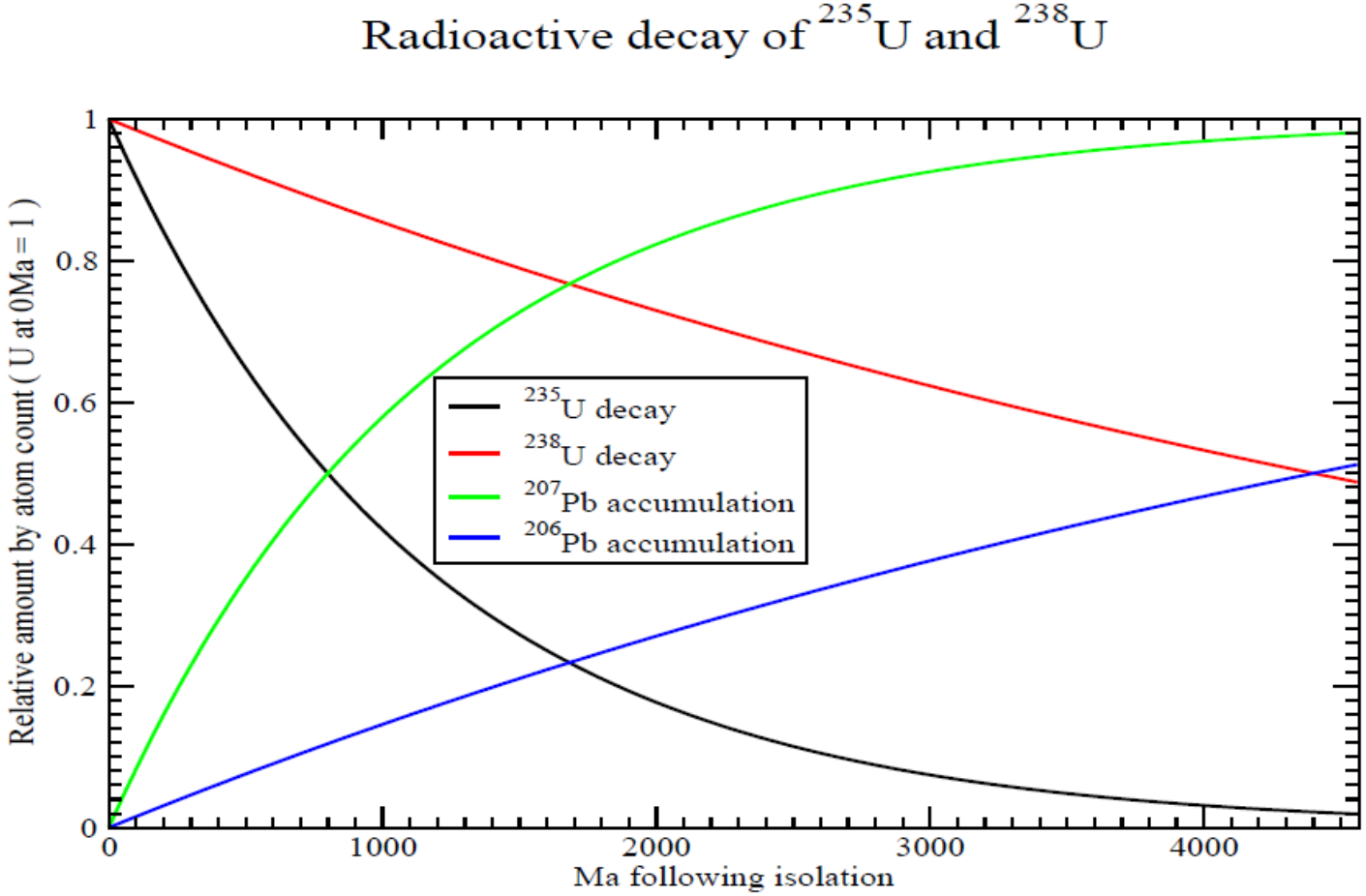
Dating on geological time scales

Rubidium-Strontium dating: ^{87}**Rb** decays to ^{87}**Sr** via β-decay (emission of an electron) with a half-life of about 47 Ga. (A very slow ticking clock!)

Uranium-Lead dating (a double, self-checking clock): ^{238}**U** decays in a complicated cascade of processes involving α-decay, β-decay and β-capture to ^{206}**Pb** with a half-life of 4.47Ga. ^{235}**U** decays similarly to ^{207}**Pb** with a half-life of 704 Ma. Uranium lead dating on zircon crystals is regarded by most geologists as the most secure method of dating old geological materials.

Zircon crystals take up small amounts of environmental uranium when they form or "close". They are very reliable closed "vaults" to contain the uranium and its lead decay products through billions of years. Chemically, both isotopes of **U** behave identically during their containment and both isotopes of **Pb** do as well. Their ratios only change through the physical decay processes.

Uranium-Lead dating: Concordia Plots



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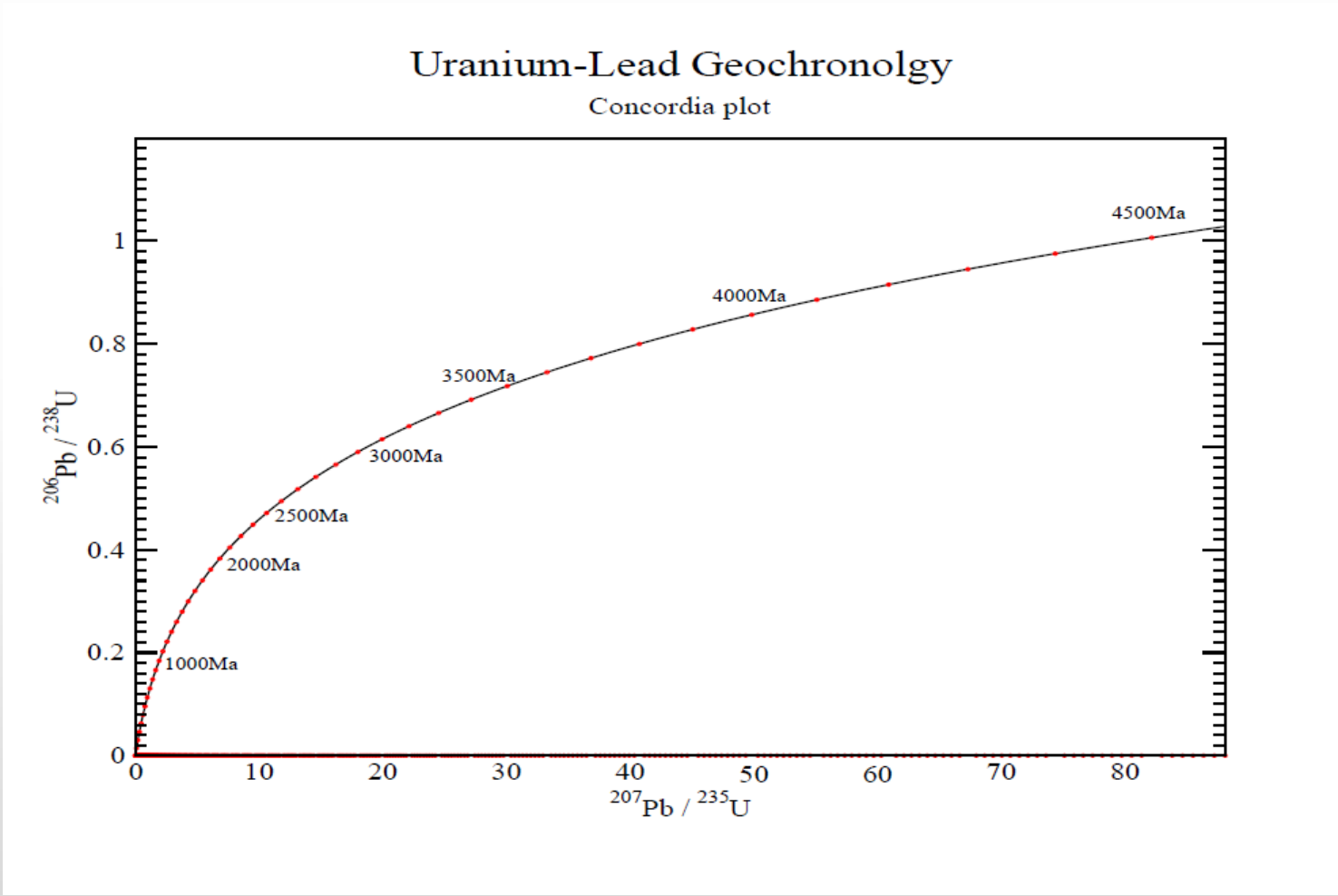


What do we learn?

The setting of the clock and the "Oldest Materials"

"Age" in the context of rocks and minerals is the time since the radio-decay clock was last set: the **"closure"**

- **Oldest mineral**... **zircons** found in Australia have been dated by the uranium-lead decay sequence to approximately 4.4×10^9 years.
- **Oldest rocks**... zircons within a large assembly of rocks in Northern Canada and Greenland date to between 3.96×10^9 and 4.03×10^9 years - the **Acasta Gneiss** complex. The Acasta Gneiss is a metamorphic rock, one which has undergone some important physical and even mineralogical-chemical transformations but zircons within the rock secure the age date.

Older rocks?

The Nuvvuagittuq faux amphibolites

- A mantle-derived igneous rock that has maintained its physical integrity since its solidification has been found near Porpoise Cove in northwestern Quebec with zircon **U–Pb** ages of about 3.86×10^9 years.
- More recent isotopic analysis (using **Sm–Nd** dating) on bulk samples of the now-famous faux-amphibolites in this Nuvvuagittuq greenstone belt show a deficiency of ^{142}**Nd** in comparison to all other known rock masses on Earth. The ^{142}**Nd** deficiency is argued to result from the crystallization of the rock minerals from a magmatic mass that was originally deficient in ^{146}**Sm** and therefore a magma that was not well mixed with the mantle and crust during the formation of the early Earth.
- The deficiency argues for an age of 4.28×10^9 years. This source mass has retained its negative isotopic anomaly in ^{142}**Nd** since its original accretion. Some areas of the continental surfaces are very, very old.

Meteorites are older!

- The **Allende meteorite** is the largest carbonaceous chondrite ever found on Earth. The fireball was witnessed at 01:05 on February 8, 1969, falling over the Mexican state of Chihuahua. The CAI (calcium-aluminum silicate inclusions) date to **4.567×10^9 years**. This is taken to be the **"age" of the terrestrial planets including the Earth**: 4,567,000,000 years!
- Interestingly, the CAI also comprise a small amount of **^{26}Mg**. It should not have condensed with the CAI-silicates. **^{26}Al** could/would! But **^{26}Al** decays with a very short half-life to common **^{26}Mg**. This is the source of the **^{26}Mg.**
- That there is magnesium in these CAI tells us that the minerals that condensed into the Allende meteorite had been formed very shortly before condensation in a prior supernoval explosion.

Meteorites are older!

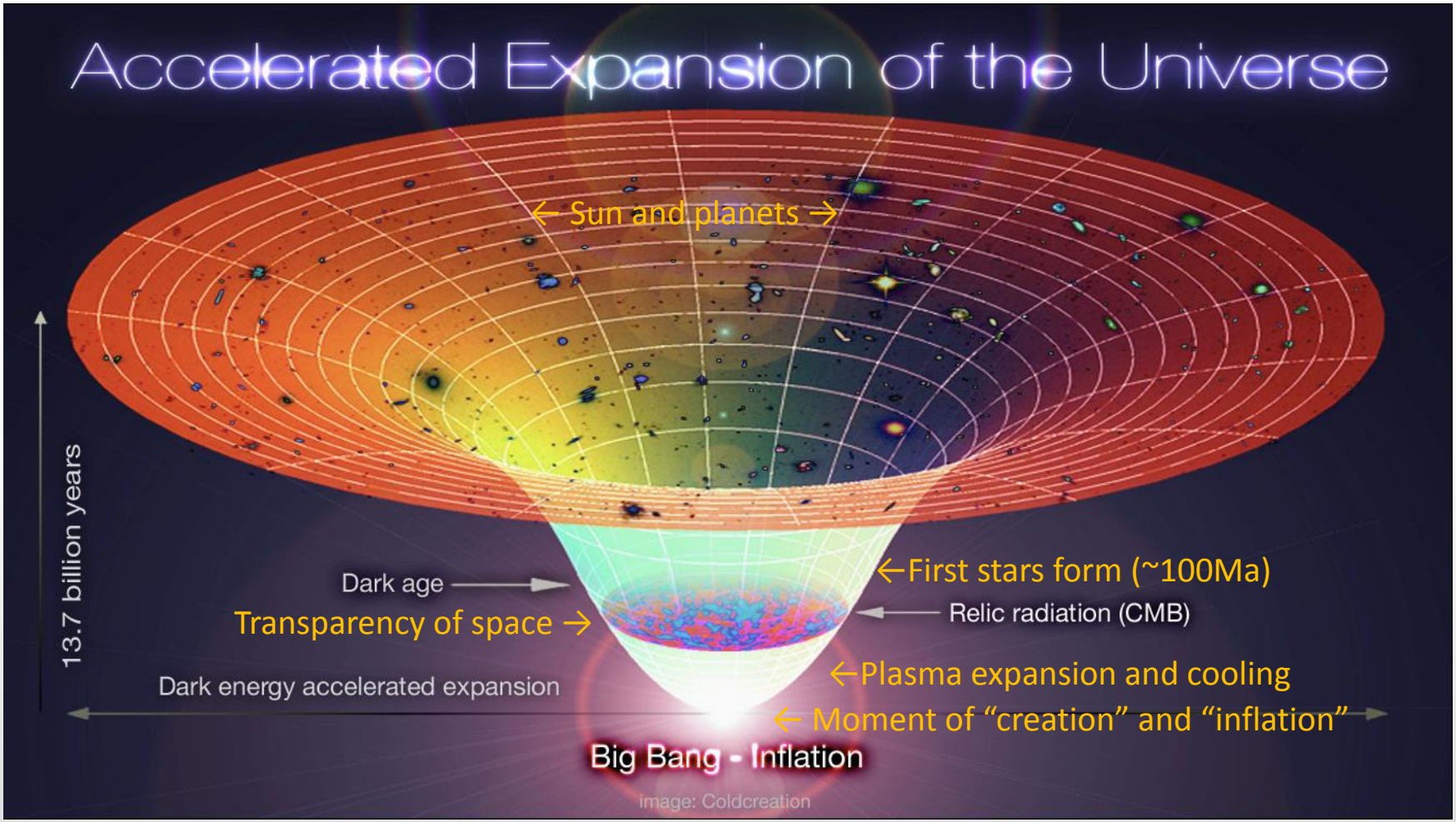
Calcium-Aluminum-Silicate inclusion containing ^{26}Mg.

This CAI has been dated to 4.567 billion years of age.

Meteorites are older!

- **Meteorites** which fall upon the Earth – almost all seem to have set their clocks before 4.55×10^9 years ago (4.55 Ga). The oldest cluster has been dated to **4.567×10^9 years**. This latter date is now attributed to be the age of condensation of minerals in the inner part of the solar nebula from which the Sun and planets formed.
- This is taken to be the **"age" of the Earth**: 4,567,000,000 years!
- ***What characterizes these minerals and materials?*** The unique **Tagish Lake meteorite** that fell on the lake in northern British Columbia in 2000 is believed to represent the most primitive materials from the condensing solar nebula.

The Λ-CDM Concordance Model



By Design Alex Mittelmann, Coldcreation