GET1024 / GEC1036 Lecture 6

Radiation in the Natural Environment

- Radiation is a Fact of Life
- Terrestrial Radiation
- Radon in the Environment
- Cosmic Rays
- Radioactivity in Food
- Overall Radiation from the Natural Environment

Radiation is a Fact of Life

Exposure to radiation from natural sources is an ***inescapable*** feature of everyday life in both working and public environments. This exposure is <u>in most cases</u> ***of little or no concern to society***, but in certain situations the introduction of <u>health protection measures</u> needs to be considered, for example when working with uranium and thorium ores and other **n**aturally **o**ccurring **r**adioactive **m**aterial (NORM).” – IAEA [1]

Today’s Lecture

Natural	mSv/yr
Radon Gas	2.00
Cosmic Rays	0.27
Terrestrial	0.28
Human body (Internal)	0.40

Let’s start with this

Artificial	mSv/yr
Medical Procedures	0.53
Consumer Products	0.10
Weapon Tests Fallout	< 0.01
Nuclear Industry	< 0.01

Elective	mSv/yr
One coast to coast Airline Flight	0.02
Watching colour TV	0.01
Heating and cooling with natural gas	0.06
Sleeping with another person	0.01

Average annual radiation exposure of a typical American[2]

[1] http://www-ns.iaea.org/tech-areas/rw-ppss/exposure-to-natural-radiation.asp?s=3

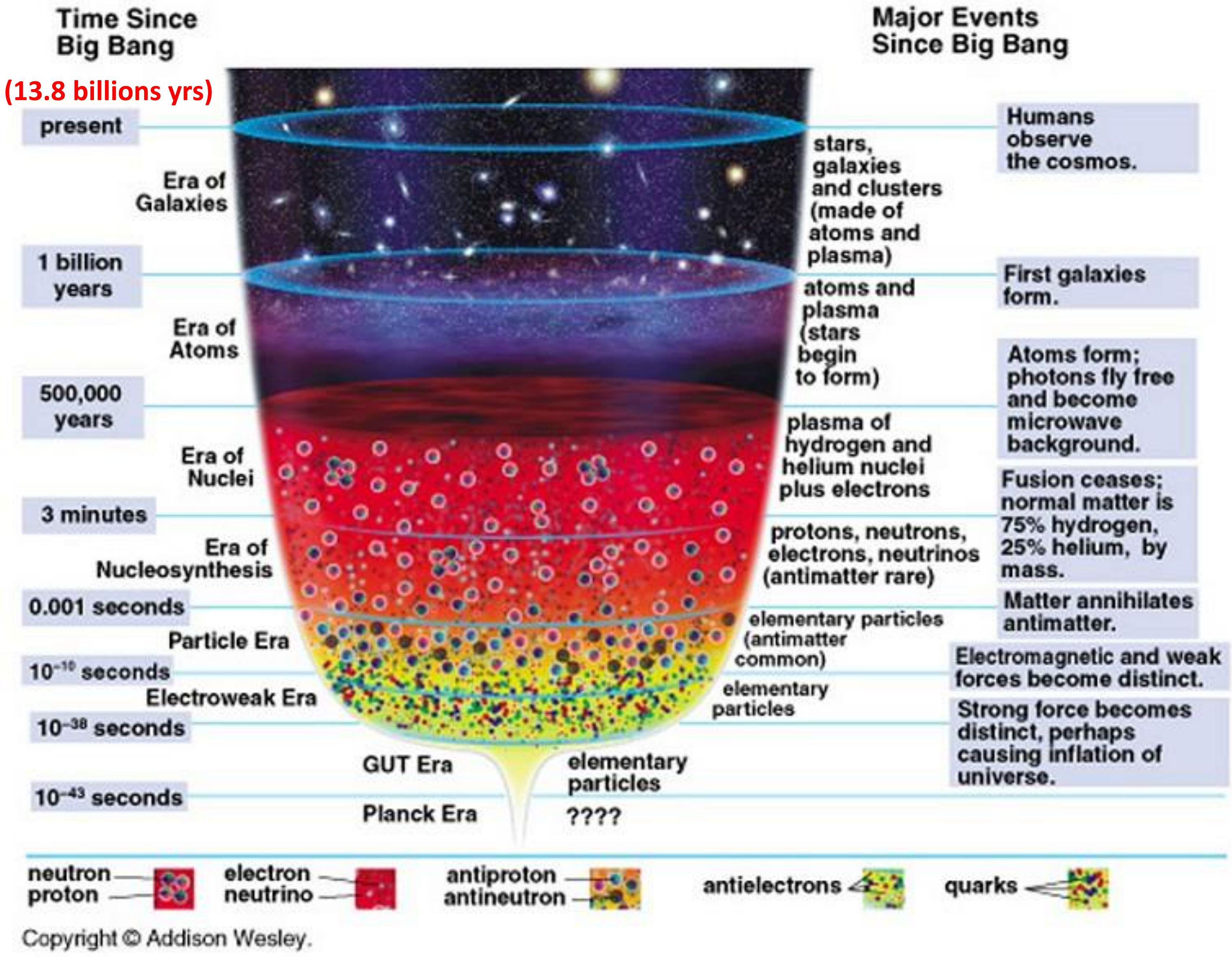
[2] Radiation and Modern Life – Alan E. Waltar

Earth – Terrestrial Radiation

- Where do the radioactive elements come from?
- How has radiation from them diminished over the eons?
- What are the main elements that contribute to the dose we get?
- How can some of these elements be still present even though their half-lives are much shorter than the age of the earth?

https://en.wikipedia.org/wiki/Earth#/media/File:The_Earth_seen_from_Apollo_17.jpg

The Very Beginning – Big Bang

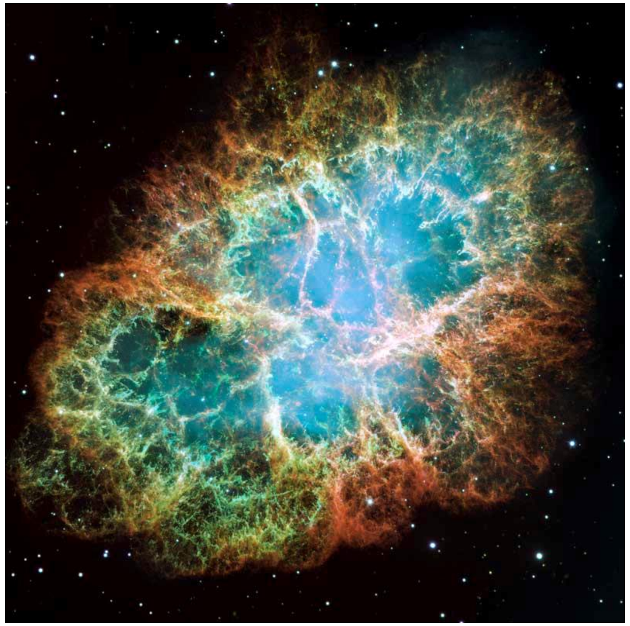


Picture taken from: http://www.physicsoftheuniverse.com/topics_bigbang_timeline.html

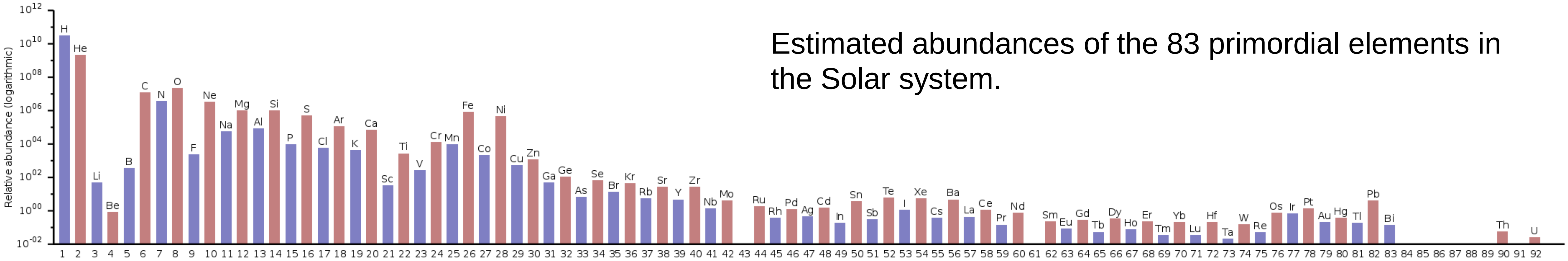
- Scientists believe that the universe came into being about 13.8 billions years ago in the event known as the Big Bang.
- **Big Bang Nucleosynthesis**: Only very light elements – mainly **hydrogen** and **helium** (with a little lithium and beryllium).
- **Stellar Nucleosynthesis**: Fusion in the core of stars and creates some heavier nuclides (up to around iron, depending on mass of stars).

Supernova and Solar System

- End stage of massive stars. <u>**Supernova nucleosynthesis**</u>: more massive elements are produced.
- Solar system was formed around 4.6 billions years ago from the gravitational collapse of a small part of a giant molecular cloud – remnants of previous supernovas.
- Contains elements from big bang nucleosynthesis, stellar nucleosynthesis, supernova nucleosynthesis and other processes, e.g., neutron star mergers and cosmic ray spallation
- Most primordial elements do not live to present time.



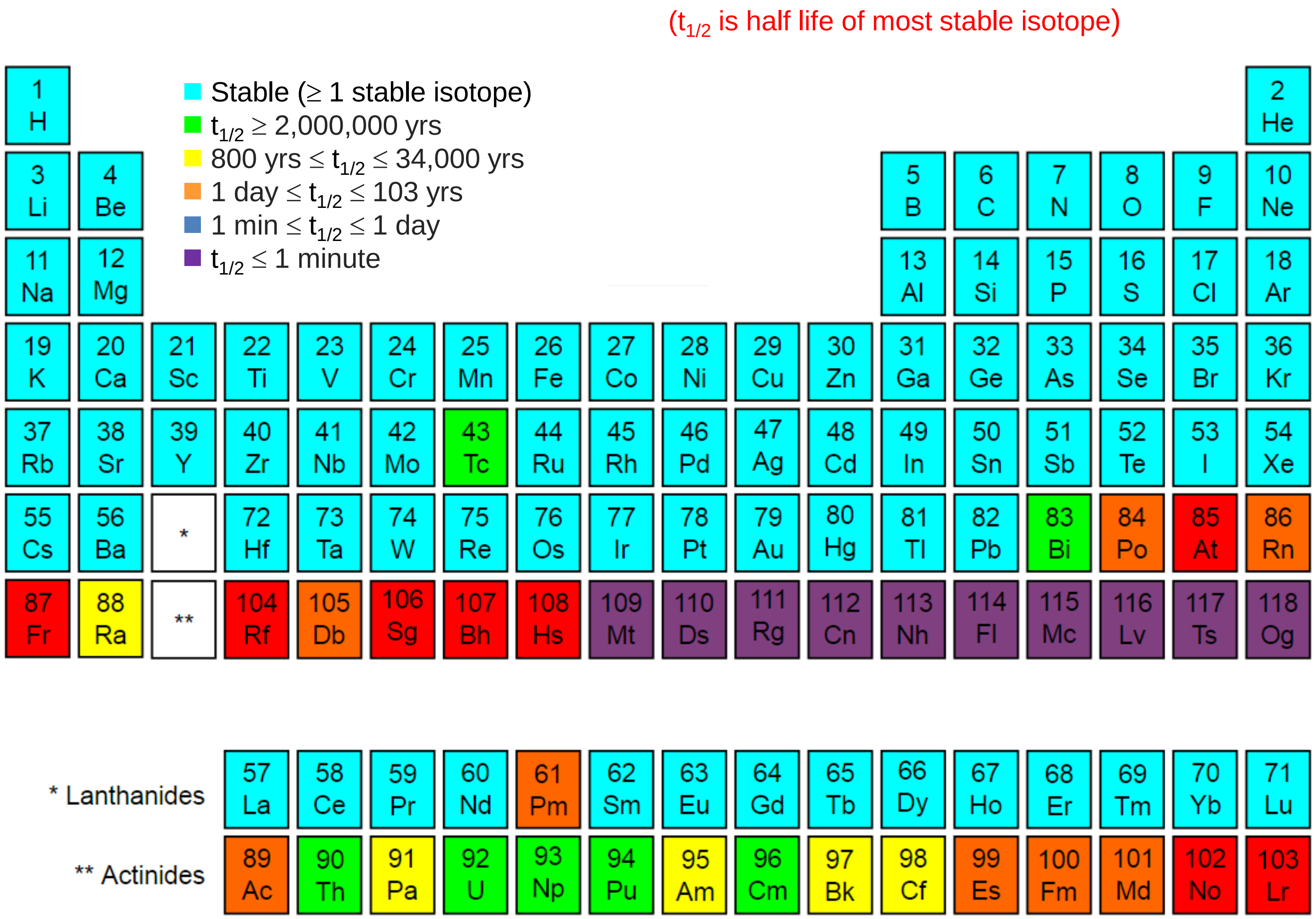
The Crab Nebula, an expanding remnant the 1054 supernova explosion recorded by the Chinese and Japanese astronomers (https://www.nasa.gov/sites/default/files/thumbnails/image/supernova-crab.jpg)



Estimated abundances of the 83 primordial elements in the Solar system.

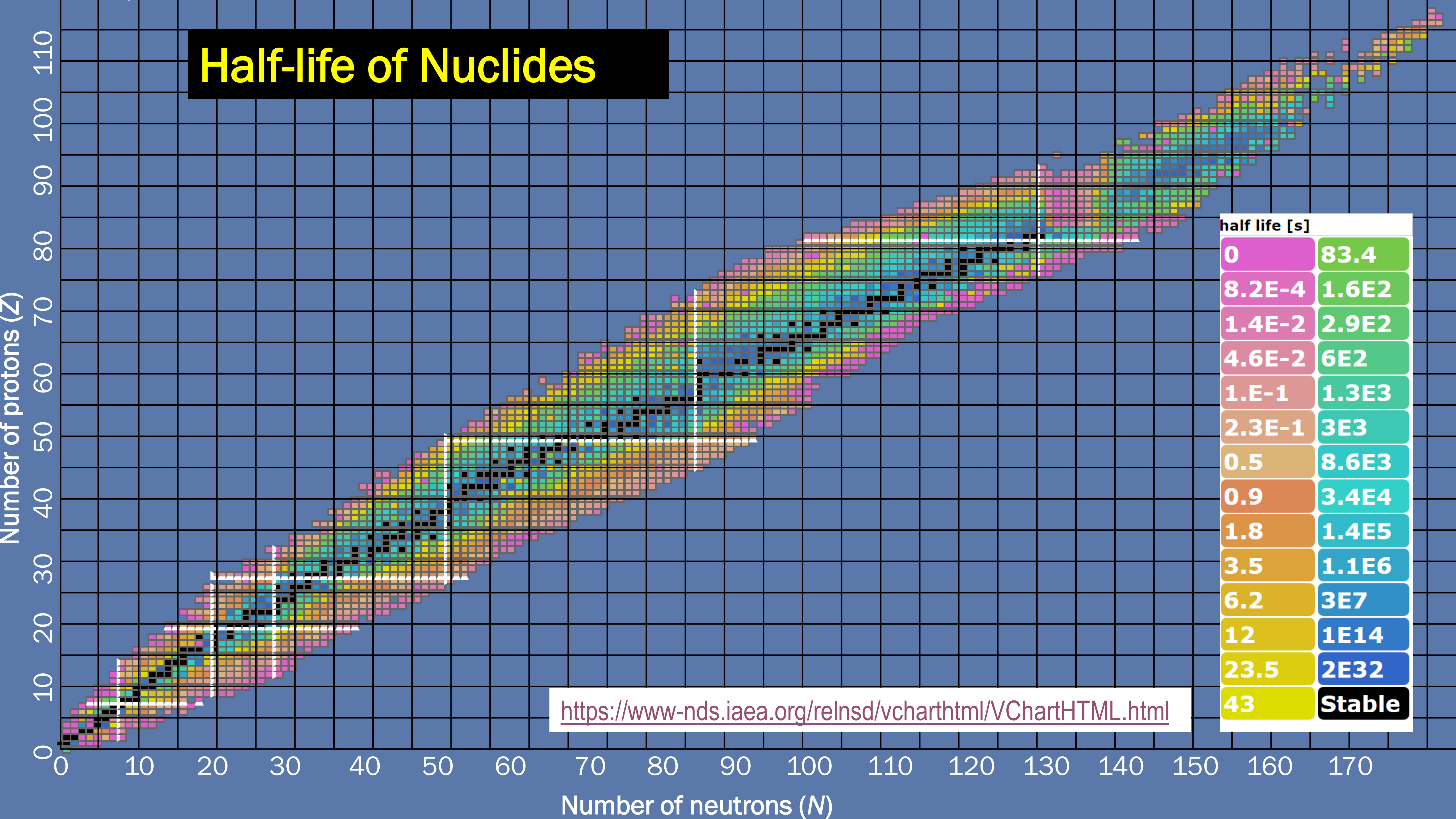
Surviving Primordial Nuclides

- Only stable primordial isotopes or those with long half-lives left. Most notable are
  - ^{40}K ($t_{1/2}$ = 1.2 x 10^9 years),
  - ^{87}Rb ($t_{1/2}$ = 4.9 x 10^{10} years),
  - ^{232}Th ($t_{1/2}$ = 1.4 x 10^{10} years),
  - ^{235}U ($t_{1/2}$ = 7.0 x 10^8 years) and
  - ^{238}U ($t_{1/2}$ = 4.5 x 10^9 years).
- All other isotopes with shorter half-lives are almost non-existent now.
- E.g., ^{244}Pu ($t_{1/2}$ = 8.08 × 10^7 years): about 57 half-lives have passed. So only 10^{-16} of the original ^{244}Pu atoms when Earth is formed are left behind.

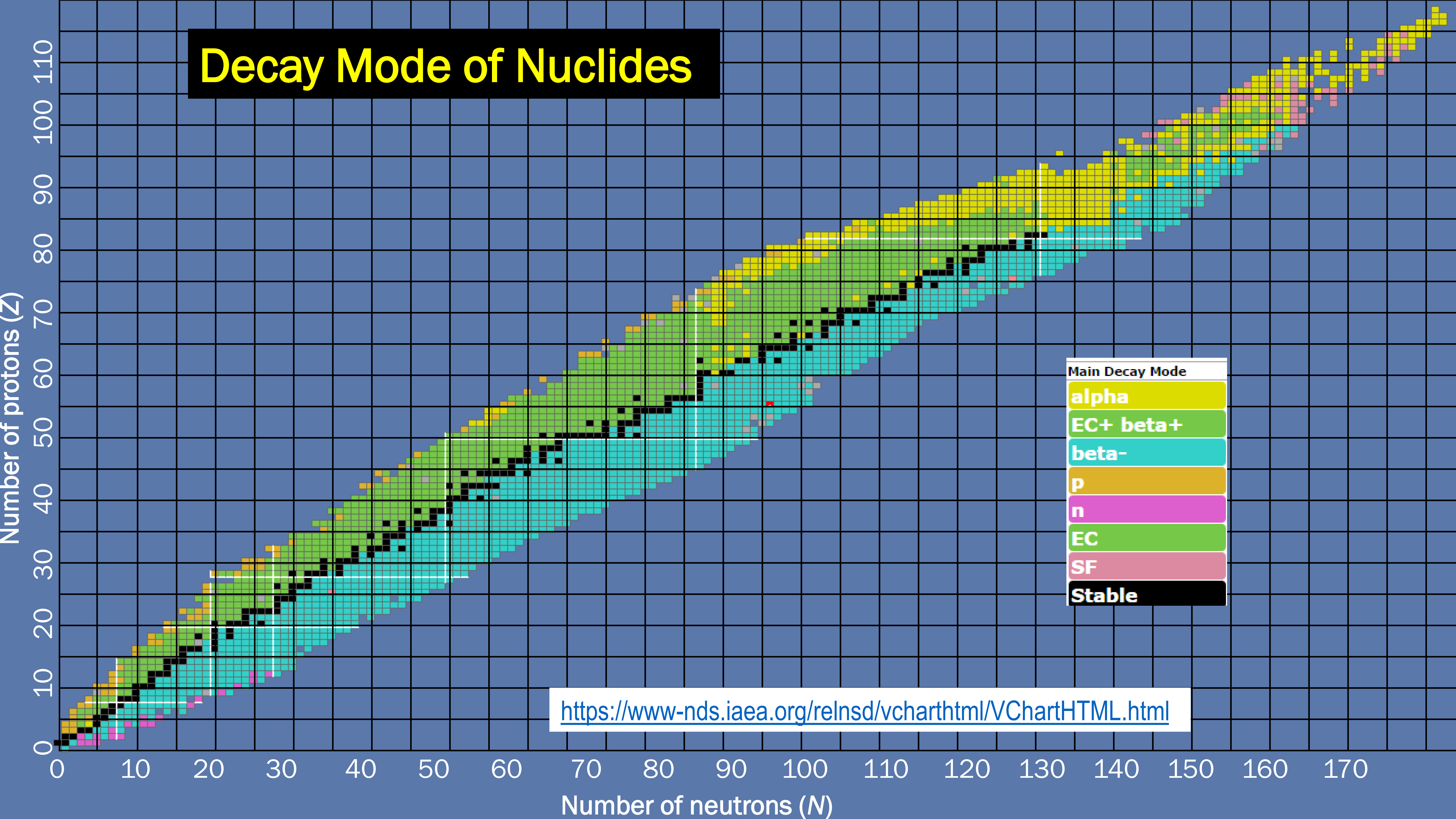


Earth was a much more radioactive planet in the distant past than it is now!

Half-life of Nuclides



https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html



Decay Mode of Nuclides
Main Decay Mode
alpha
EC+ beta+
beta-
p
n
EC
SF
Stable
https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html
Number of protons (Z)
0
10
20
30
40
50
60
70
80
90
100
110
Number of neutrons (N)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170

Radioactivity in our Environment: Primordial Nuclides

- **Primordial Radionuclides:** These nuclides have been present since the formation of earth 4.5 billion years ago – created during the earlier supernova explosion of stars. Four of the most important radionuclides have long enough half-life to be present in substantial amount on Earth today and of importance, namely:
  - **Two isotopes of uranium** (2 – 4 ppm Earth Crust)

    U-235 ($^{235}_{92}\mathrm{U}, T_{1/2} = 704$ million years) and

    U-238 ($^{238}_{92}\mathrm{U}, T_{1/2} = 4.5$ billion years)
  - **One isotope of thorium** (6 ppm in soil)

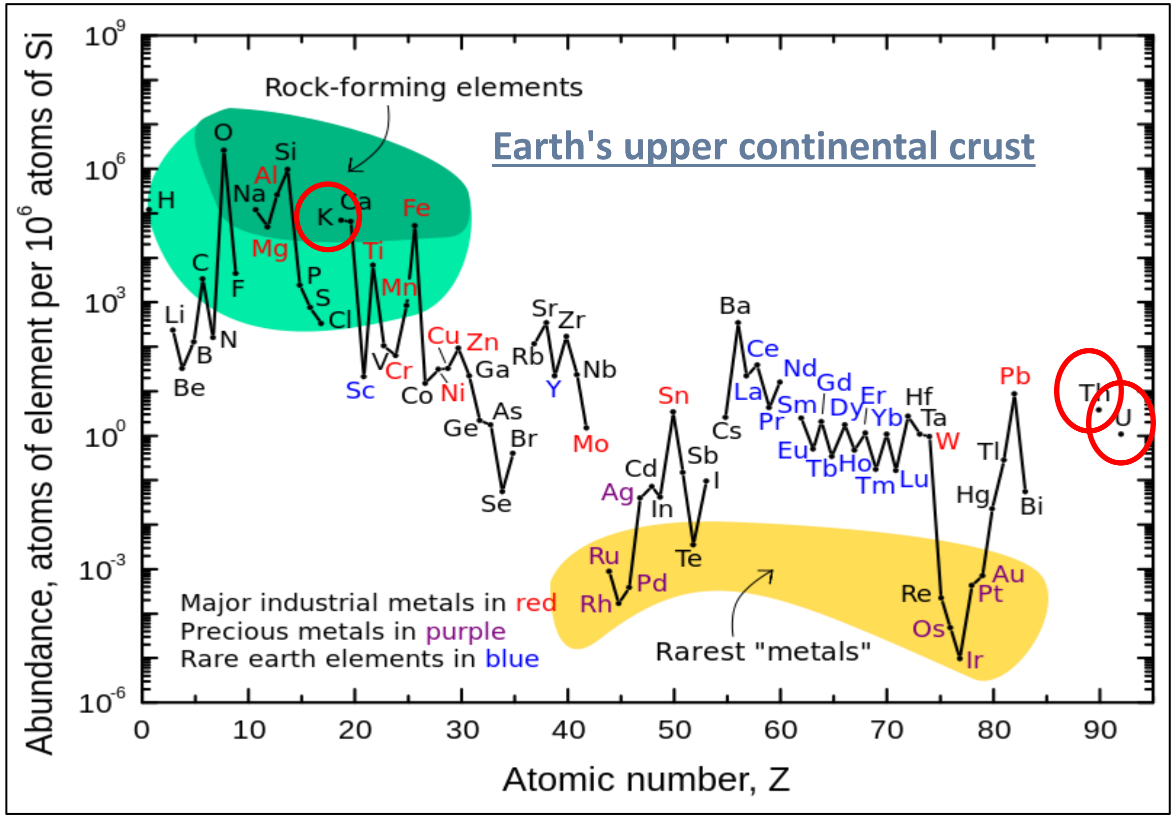
    Th-232 ($^{232}_{90}\mathrm{Th}, T_{1/2} = 14.1$ billion years)

    Other isotopes have much shorter half-life
  - **One isotope of potassium** (2% of Earth Crust)

    K-40 ($^{40}_{19}\mathrm{K}, T_{1/2} = 1.25$ billion years)

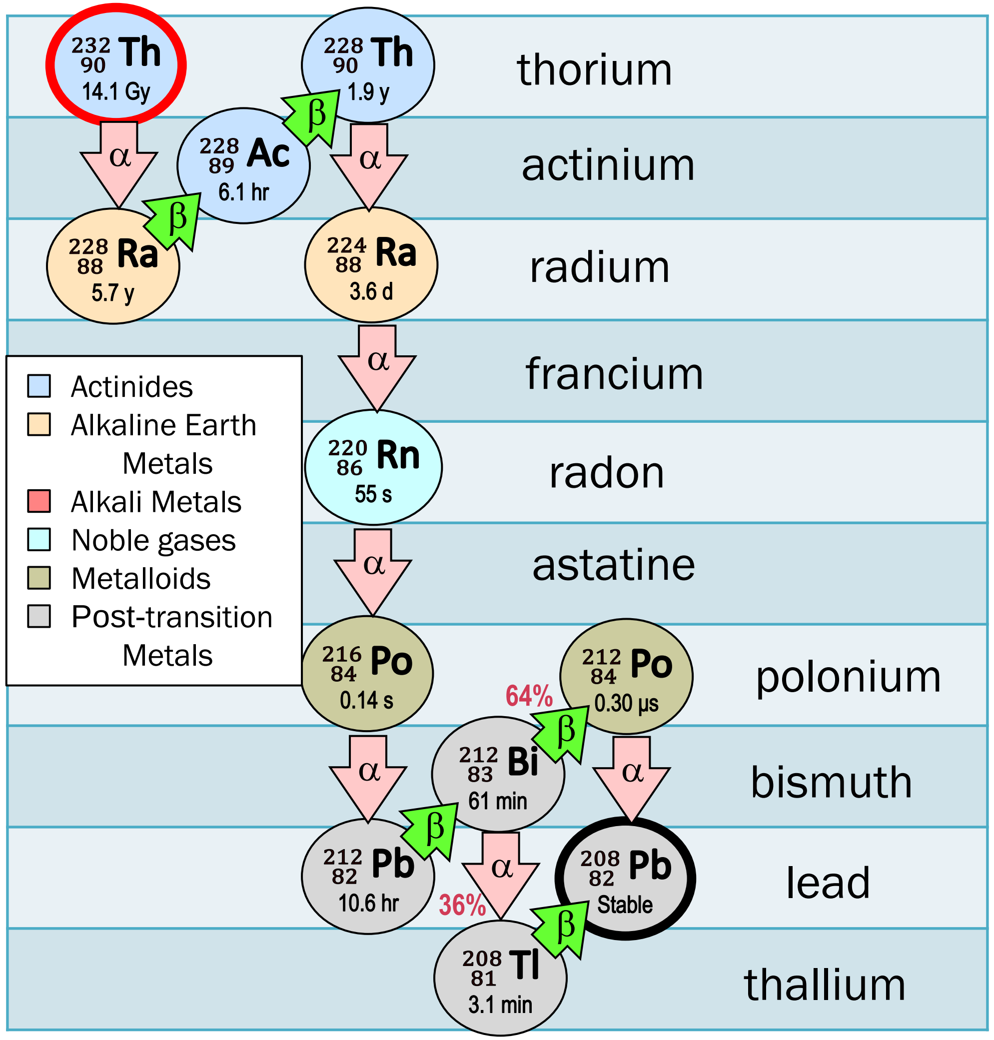
    K-40 makes up only 0.0117% of natural potassium

    Two other isotopes K-39 and K-41 are stable



Radioactivity in our Environment: Decay Series

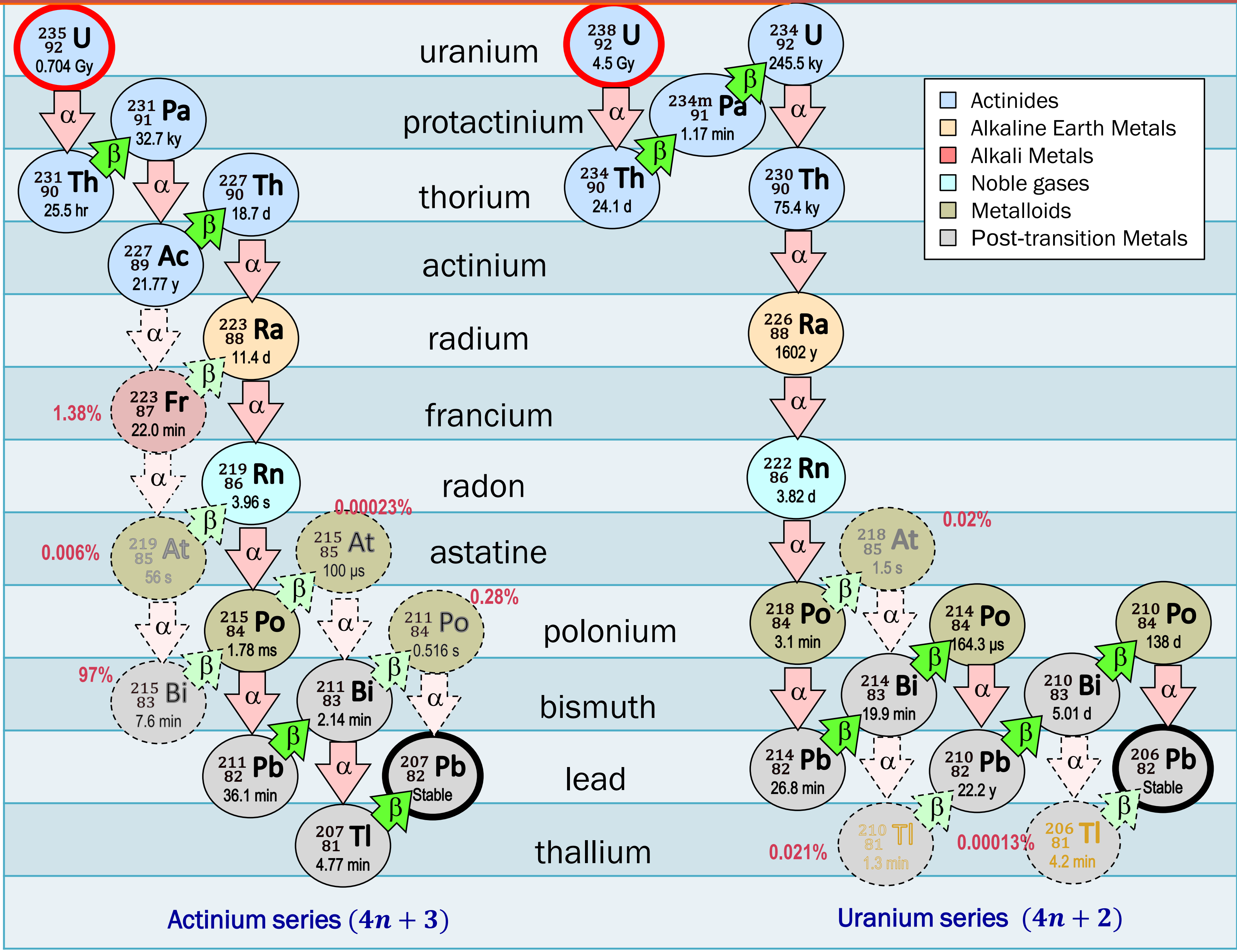
- The next most important class of radionuclides found on Earth come from the decay chains of U-235, U-238 and Th-232.
- For example, when thorium-232 decays to radium-228, via an alpha decay, the radioactivity does not stop.
- Radium-228 is not stable and has an half-life of 5.7 years to decay to actinium-228 via a beta decay.
- Again, actinium-228 is not stable and will continue to decay.
- It takes 6 alpha decays and 4 beta decays before reaching stable lead-208 and radioactive decay stops.
- Note that these intermediate radionuclides will be present so long as thorium-232 is not exhausted. Though present in small amount compared to Th-232, they can still be detected.
- Bi-212 has two modes of decay. It has a probability of 64% to β decay to Po-212, and 36% probability to α decay to Tl-208.



Thorium series $(4n)$

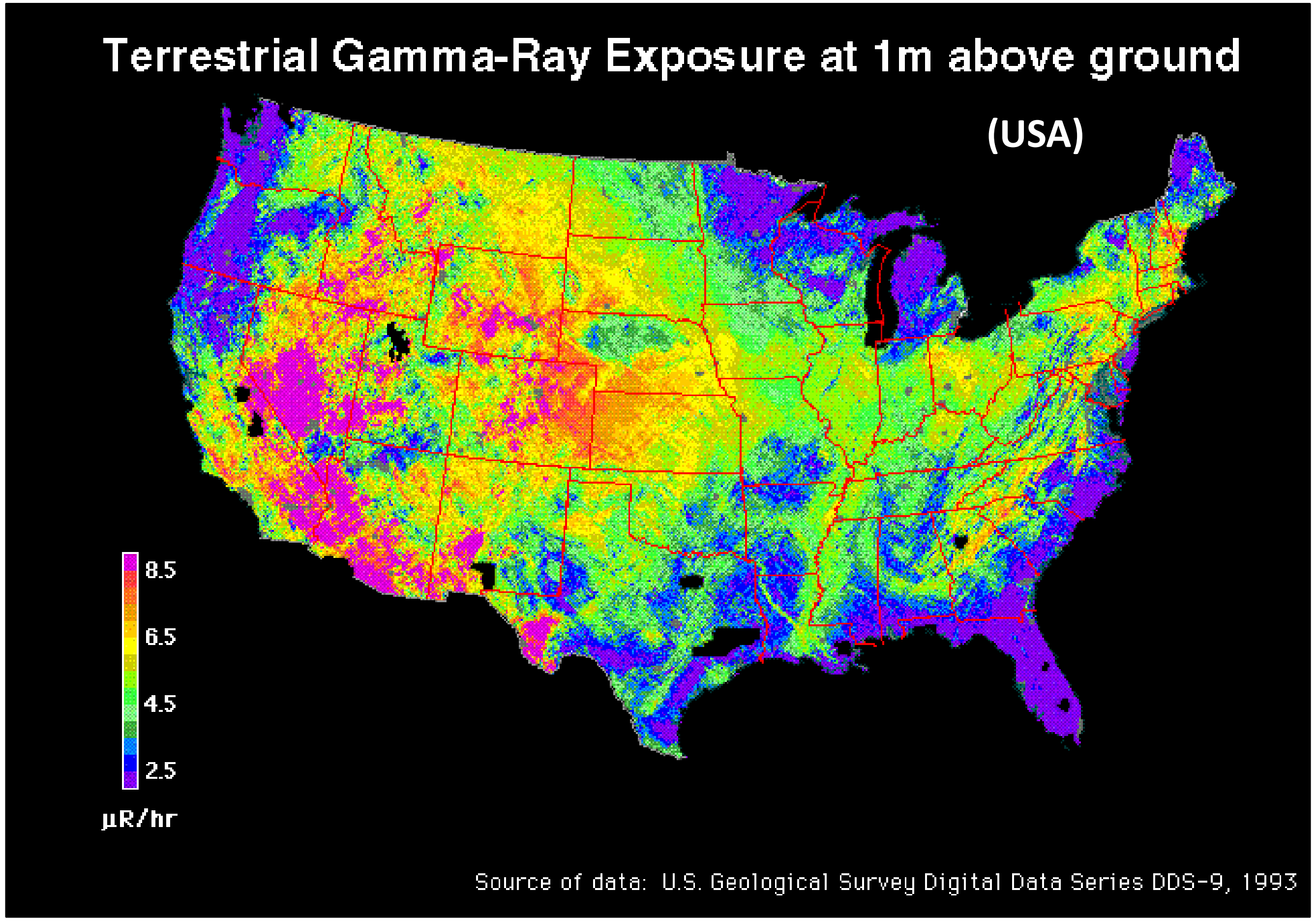
Radioactivity in our Environment: Decay Series

- Similarly U-238 and U-235 also decay through a series of α and β decays to Pb-206 and Pb-207 respectively.
- Notice that the mass number of the radionuclides in each series are a multiple of four from one another. So, the radionuclides in each series are unique.
- The series starting from Th-232, U-235 and U-238 are also known as the Thorium ($4n$), Actinium ($4n+3$) and Uranium ($4n+2$) series respectively.



Variations of Dose due to Terrestrial Radiation

- Values of exposure due to terrestrial radiation vary depending on the presence of radionuclides in the surrounding rocks, e.g., see the values in US below:



https://blogs.agu.org/wildwildscience/files/2009/09/usagamma.gif

- Note that the values on in the graph are not in SI units and are given in μR/hr (micro-röntgen per hour).
- To convert to the more familiar SI units of mSv/h (which we will use throughout this module), multiply by 0.01. [See Dr Mak's lecture.]
- If you want to convert to dose per year (mSv/yr) due to the terrestrial radiation, then you will need to $\times\ 24 \times 365\ \div$ 1000 ($= 8.76$).
- Thus, the green areas correspond to about 0.05 mSv/h or approximately 0.4 mSv/yr.

High Natural Background Radiation Areas (HBRA)

- There are a number of areas in the world which are known to have much higher natural background radiation. Examples[1] are:
  - Guarapari in Brazil – presence of monazite which contains thorium & uranium (~ 6 mSv/yr)

The background radiation level on some spots on the Guarapari beach read 175 mSv per year (20 μSv/h). Some other spots reach 55 μSv/h, while some even reach 131 μSv/hour (1148 mSv/year). The city of Guarapari has lower value of about 5.2 mSv per year. From https://en.wikipedia.org/wiki/Guarapari.

[1] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4030667/pdf/nihms573062.pdf

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  - Kerala in India – presence of thorium and its decay products (~4 mSv/yr)

A small municipality in Kerala known as Karunagappalli constantly faces high radiation, exposure can be attributed to the presence of monazite in the soil that carries traces of 8-10 percent thorium. Radiation levels in Karunagappally varied between 0.32 to 76 milligrays per year. From https://www.indiatimes.com/news/india/this-backwaters-paradise-in-kerala-is-one-of-the-most-radioactive-towns-in-the-world-258656.html

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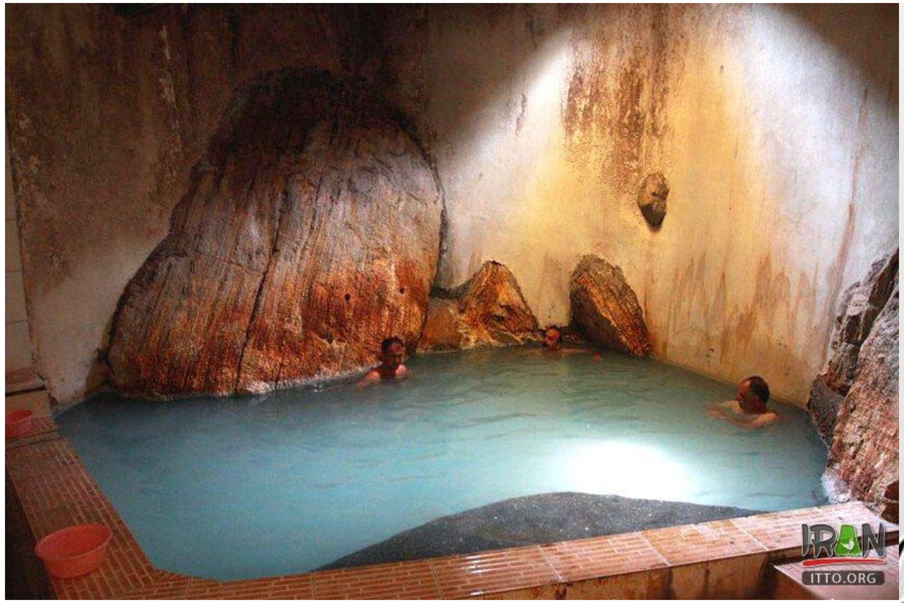

Ramsar's Talesh Mahalleh district is the most radioactive inhabited area known on Earth, due to nearby hot springs and building materials originating from them. Residents from this district and other high radiation neighborhoods receive an average radiation dose of 10 mSv per year. Record levels were found in a house where the effective radiation dose due to external radiation was 131 mSv/a, and the committed dose from radon was 72 mSv/a.
From https://en.wikipedia.org/wiki/Ramsar,_Iran.

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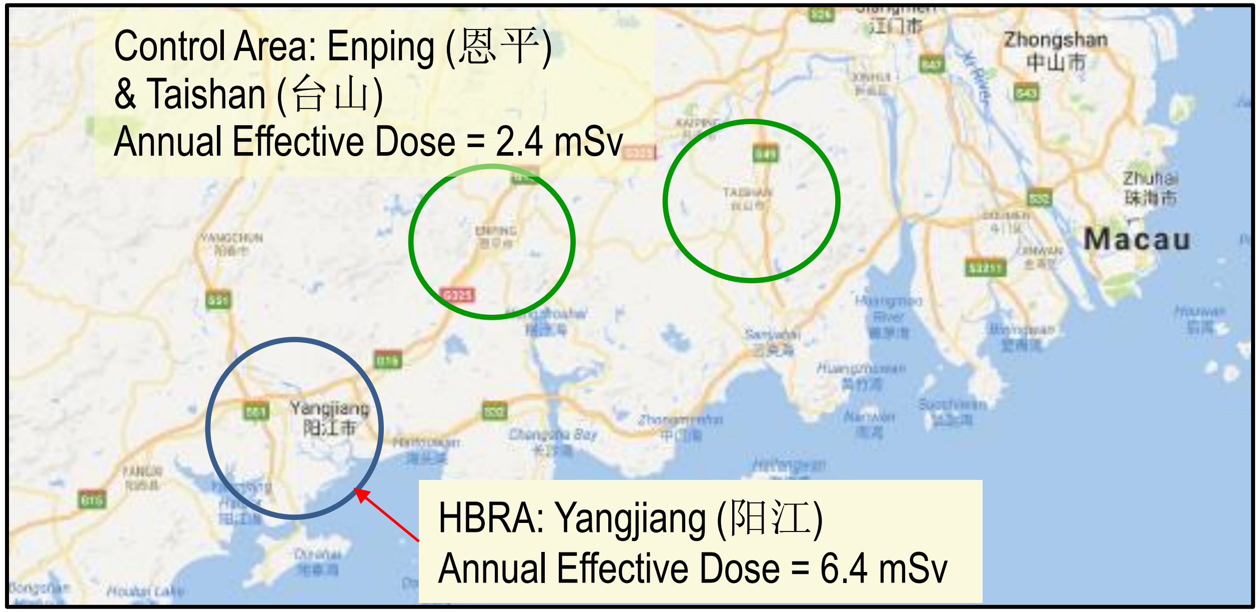
  - Yangjiang in China – presence of monazite (~4 mSv/yr)



Annual effective dose estimated for Yangjiang and surrounding villages. The higher value in Yangjiang is due to the presence of monazite washed down from the down the mountains by rain. Effective dose includes contribution from terrestrial, radon, cosmic rays, ingestion, etc.

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Now this!

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Radon in Environment

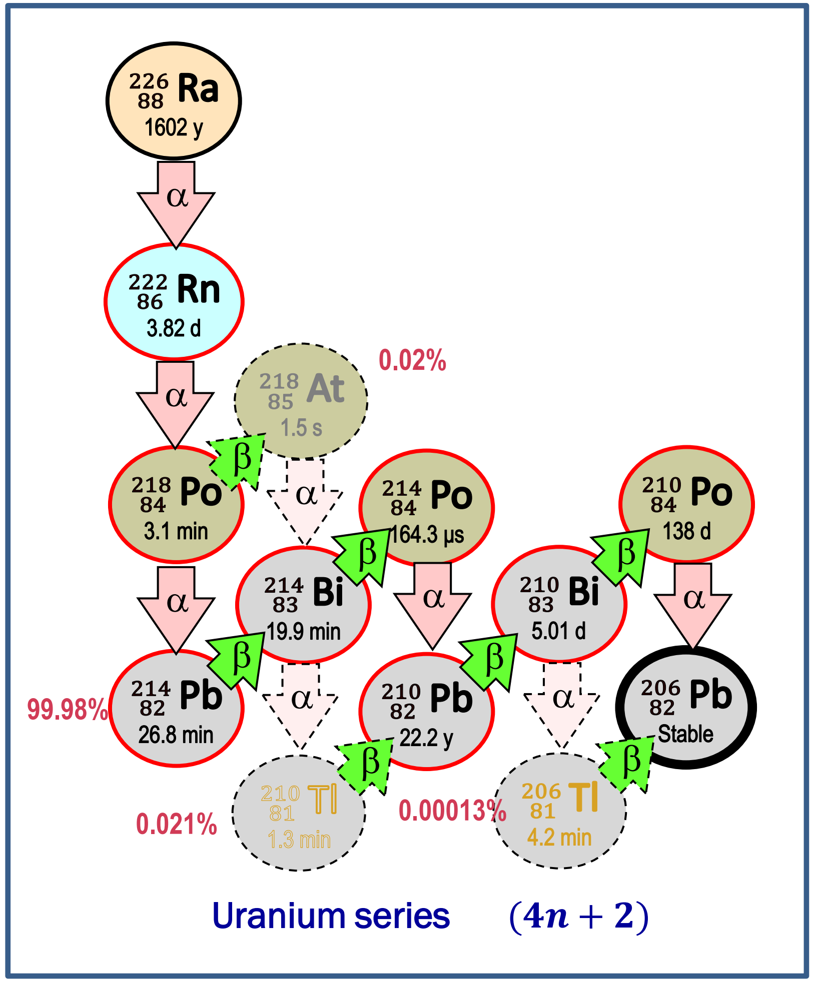
- Radon – a noble gas (inert gas – chemically). Odourless, colourless and tasteless.
- Z = 86. Densest elemental gas. No stable isotope.
  - ^{219}Rn: $t_{1/2}$ = 3.96 s (Actinium Series from ^{235}U)
  - ^{220}Rn: $t_{1/2}$ = 55.6 s (Thorium Series from ^{232}Th)
  - ^{222}Rn: $t_{1/2}$ = 3.8 days (Uranium Series from ^{238}U)

  (Question: Which is the isotope that is more likely to cause health problems?)
- Danger – radon and radon decay products (RDPs) attached to dust particles in the air are inhaled into the body. Generally radon is exhaled out but the dust particles containing RDPs can be attached to the lungs.
- Decay along the chain involved many alpha and beta processes. E.g., radon decays into polonium and polonium to lead both by alpha radiation. While alpha particles are stopped in cm of air or by the skin, when inside the body, e.g., in the lungs, they can cause a lot more damage.
- "Scientists estimate that 15,000 to 22,000 lung cancer deaths in the United States each year are related to radon."[1]

[1] https://www.cancer.gov/about-cancer/causes-prevention/risk/substances/radon/radon-fact-sheet

Radon Decay Products

- Let us look at the decay chain of ${}^{238}_{92}\mathrm{U}$ again starting from ${}^{226}_{86}\mathrm{Ra}$.
- Consider only the main sequence (solid arrows – red circles) only, which daughter nuclides do you think will contribute significantly to the dose that we would receive if these the RDPs get to our lungs?

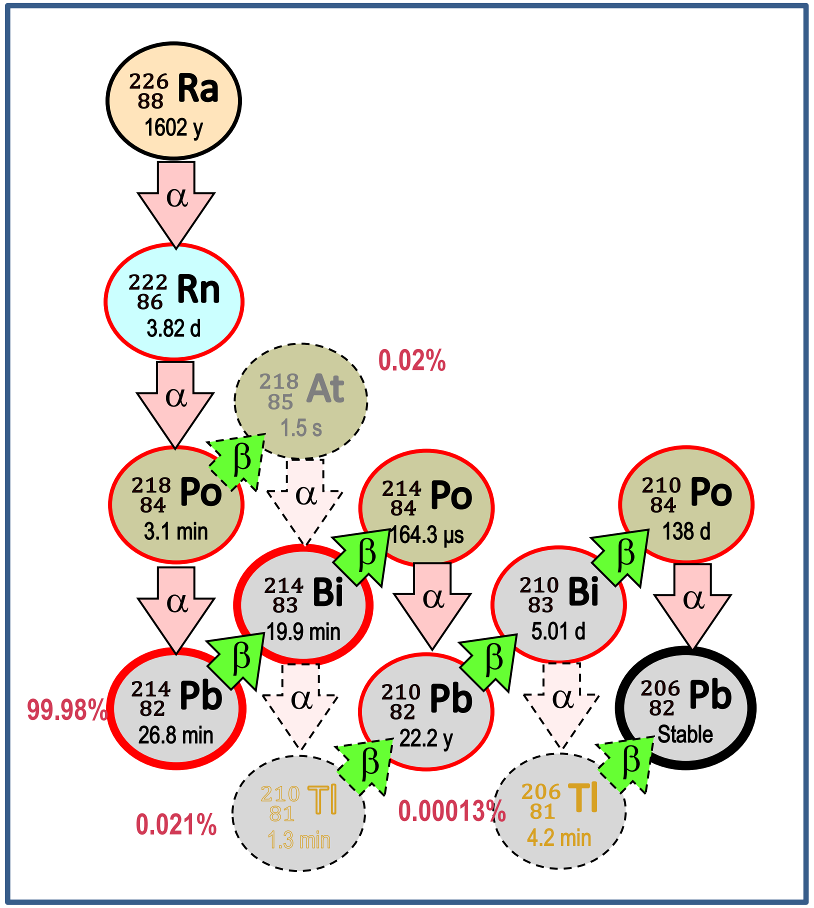


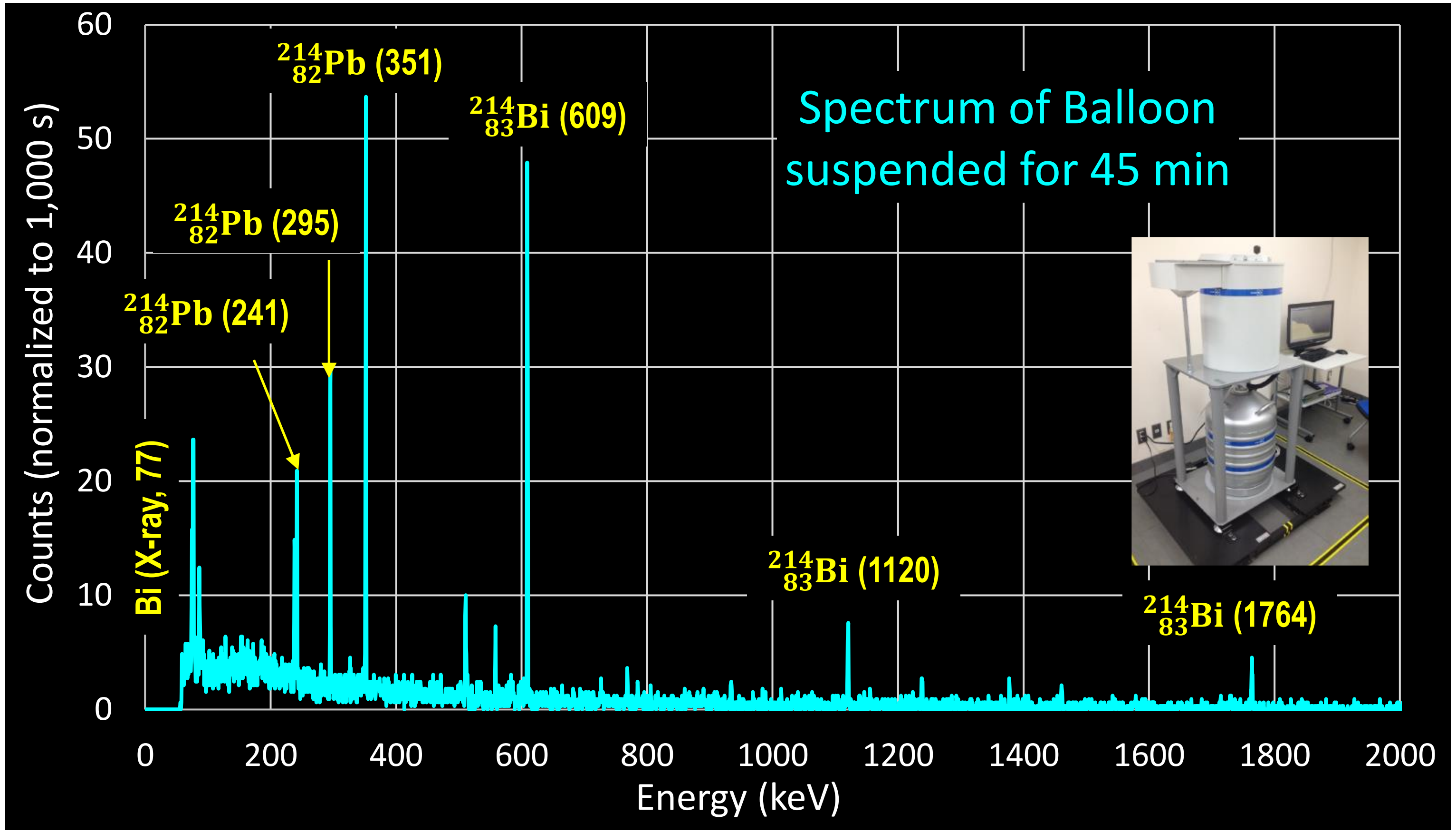
Demonstration – Trapping of RDPs

- Balloon is blown up and surface is charged by rubbing it with cloth.
- Left hanging in the air for about 45 minutes.
- Background Count:
- Balloon:

Demonstration – Trapping of RDPs

- Gamma emission from balloon was measured by HPGe (High Purity Germanium) detector.



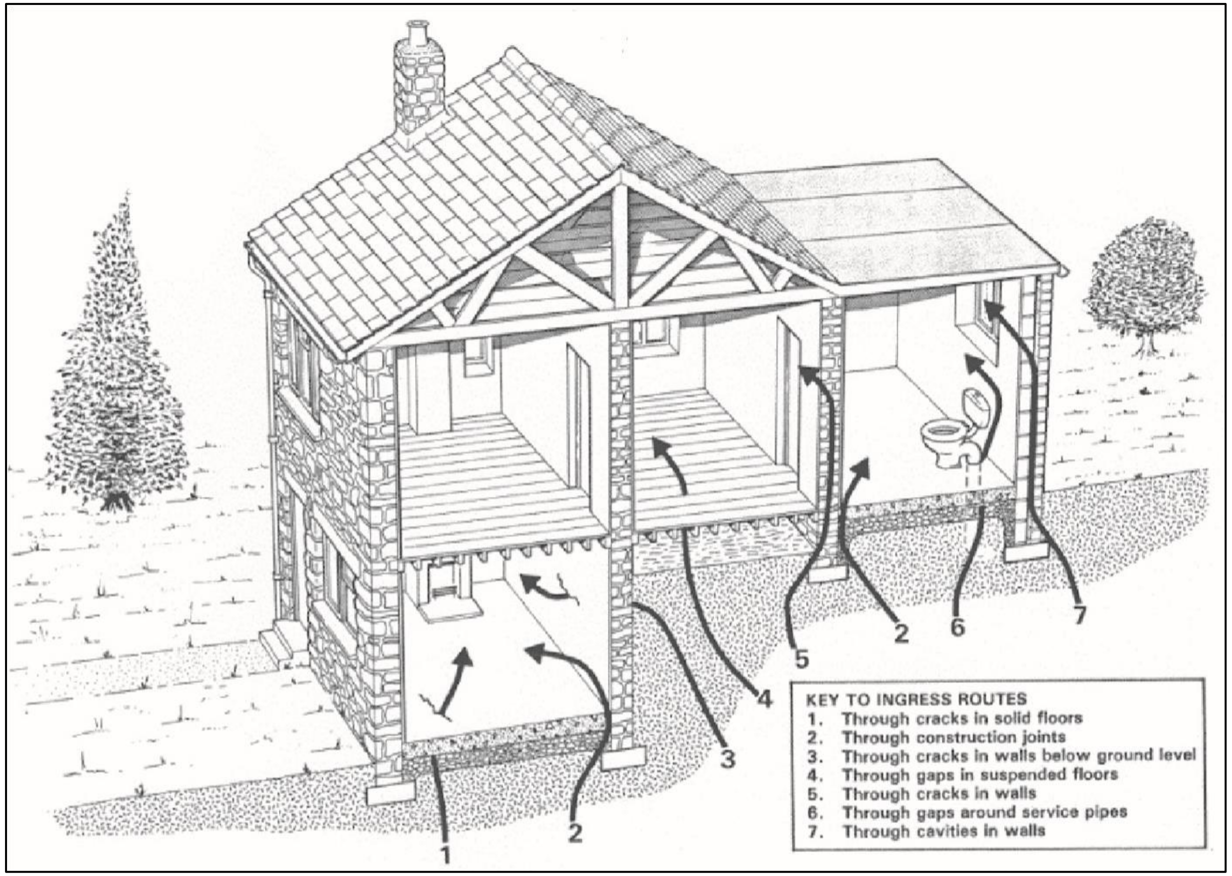


Qn: How about $^{214}_{84}\mathbf{Po}$?

Ans: $^{214}_{84}$Po emits mainly α and only 0.01% of transitions produce γ-photons of 799 keV. Similarly for $^{218}_{84}$Po.

Radon Levels (Outdoors and Indoors)

- Radon is usually emitted from the ground into the atmosphere.
- Outdoors, radon is quickly mixed and diluted. The amount of radon outdoors is generally low at about **10 Bq/m³** though it can varies from 1 to over 100 Bq/m³ in some cases.
- For houses built on ground in many countries, there are many pathways for radon to enter and trapped in the house. Values can be higher than 100 Bq/m³ and above 1000 Bq/m³ values have been reported. *Famous case of engineer Stanley Watras' basement where ~ 100,000 Bq/m³ was measured.*
- The world average indoors amount of ^{222}Rn of all dwellings is estimated to be **39 Bq/m³**.



https://www.epa.gov/radon/find-information-about-local-radon-zones-and-state-contact-information

http://www-pub.iaea.org/MTCD/publications/PDF/Pub1651Web-62473672.pdf

Radon Level Where Action is Needed

- Environmental Protection Agency (EPA) in US recommended target level of 0.4 pCi/L (picocurie per litre) for indoors which is the same as the average outdoor level. It also recommended that action should be taken to reduce radon in house if the value is above 4 pCi/L (average in US = 1.3 pCi/L)
- The WHO proposes a reference level of 100 Bq/m^3 to minimize health hazards of exposure indoors due to ^{222}Rn, adding that "if this level cannot be reached under the prevailing country specific conditions, the chosen reference level should not exceed 300 Bq/m^3".
- Which value is more stringent? What will these values correspond to in terms of annual dose? (Reminder: 1 Ci = 3.7 x 10^{10} Bq.)

1 m^3 = 1,000 litres or 1 litre = 0.001 m^3

↳ 1 pCi/L = 10^{-12} x 3.7 x 10^{10} Bq / 0.001 m^3 = 37 Bq/m^3

↳ 4 pCi/L = 148 Bq/m^3 > 100 Bq/m^3 (WHO Reference Level)

But 300 Bq/m^3 ≈ 8 pCi/L (higher than US action level)

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Dose due to Radon

- **Effective Dose** (ED) may be estimated from the **radon concentration** C_{Rn} (in Bq/m^3) by the following formula:

$$\boxed{ED \text{ (in mSv/yr)} = C_{Rn} \times D_f \times O_f \times E_f \times (365 \times 24) \times 10^{-6}}$$ where

  - D_f is the **dose conversion factor** (recommended by UNSCEAR[1] to be **9 nSv/(Bq h m^{-3})**),
  - O_f is the **indoor occupancy factor** (percentage of time spent indoors with C_{Rn}),
  - E_f is the **equilibrium factor of radon indoors**

- The equilibrium factor between the radon progeny (RDPs) and the radon gas depends on several factors, principally the aerosol concentration and air exchange rate. Measurements in several countries have shown equilibrium factors in dwellings of between 0.2 and 0.8. UNSCEAR and the International Commission on Radiological Protection (ICRP) have adopted a typical worldwide equilibrium factor of **0.4**.

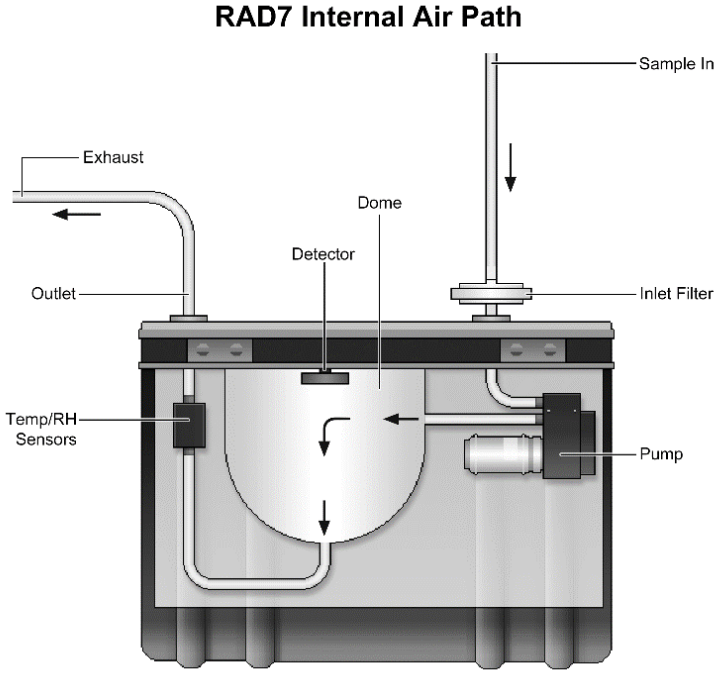
- Assuming an indoor occupancy factor of 0.8 (19 hours per day), radon concentration of 100 Bq/m^3 would correspond to 2.5 mSv/yr. [Please verify!]

[1] United Nations Scientific Committee on Effects of Atomic Radiation (UNSCEAR) 2000 Report to the General Assembly

Radon Level in Singapore

- Cannot find any radon readings in Singapore. Is radon of concern to us given our lifestyle and residential / working environment ?
- Decided to do some measurements ourselves – Physics Final Year Projects

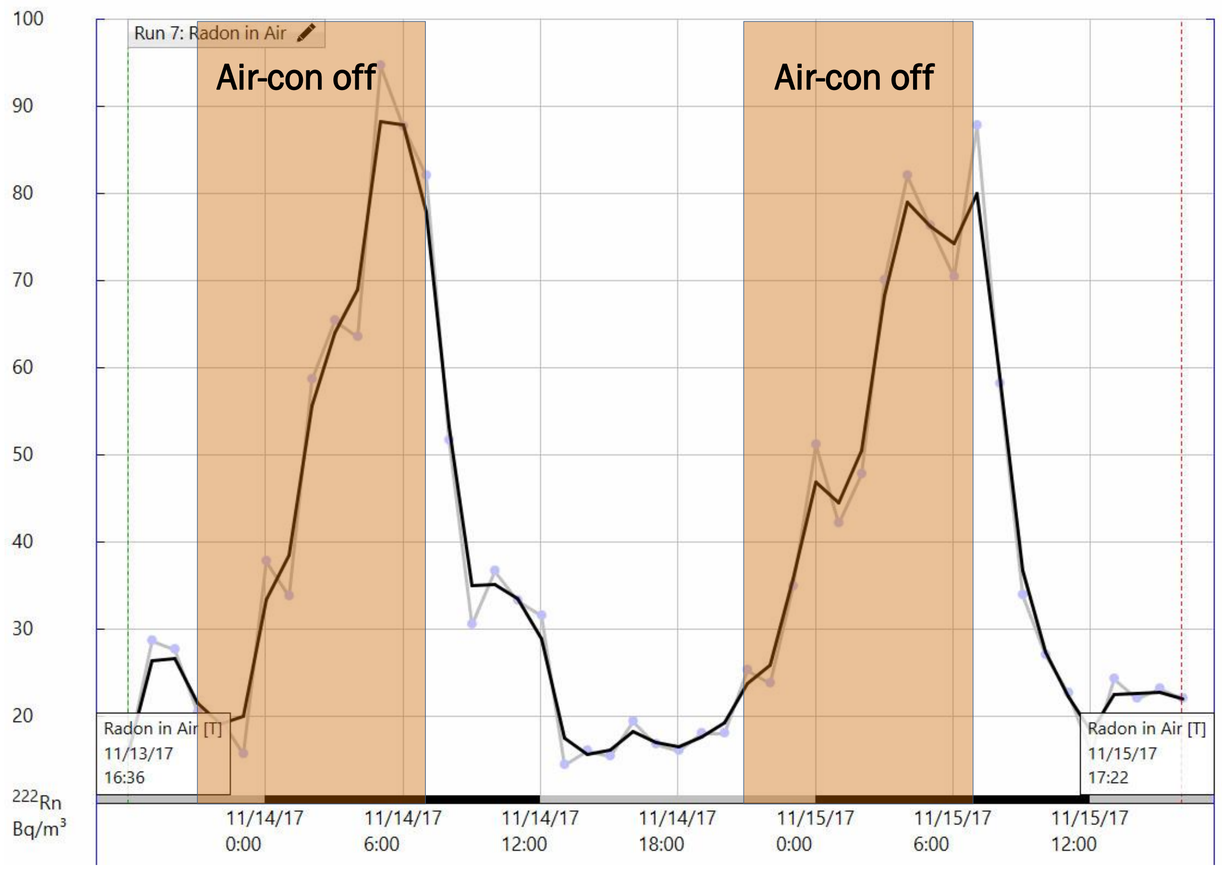
- Some results:
  - Outdoor values ~ 10 Bq/m^3
  - Indoor values – Can be as low as outdoor values (10 Bq/m^3) – with opened doors / windows or connections or slightly higher if it is partially enclosed (~ 20 – 40 Bq/m^3)
  - Can be substantially higher for some rooms if there is very little air exchange with exterior, e.g., in some air-con bedrooms over the night and in offices!



Instrument (RAD7) used to measure time variation of radon in HDB flats, offices, outdoors, etc.

Radon Level in Some Offices

- Below is the radon level taken in an office in NUS Physics Department. Most offices are closed throughout the day and not connected to the exteriors except for occasional opening of the doors.
- It shows a diurnal variation. Without reading further, can you explain why?



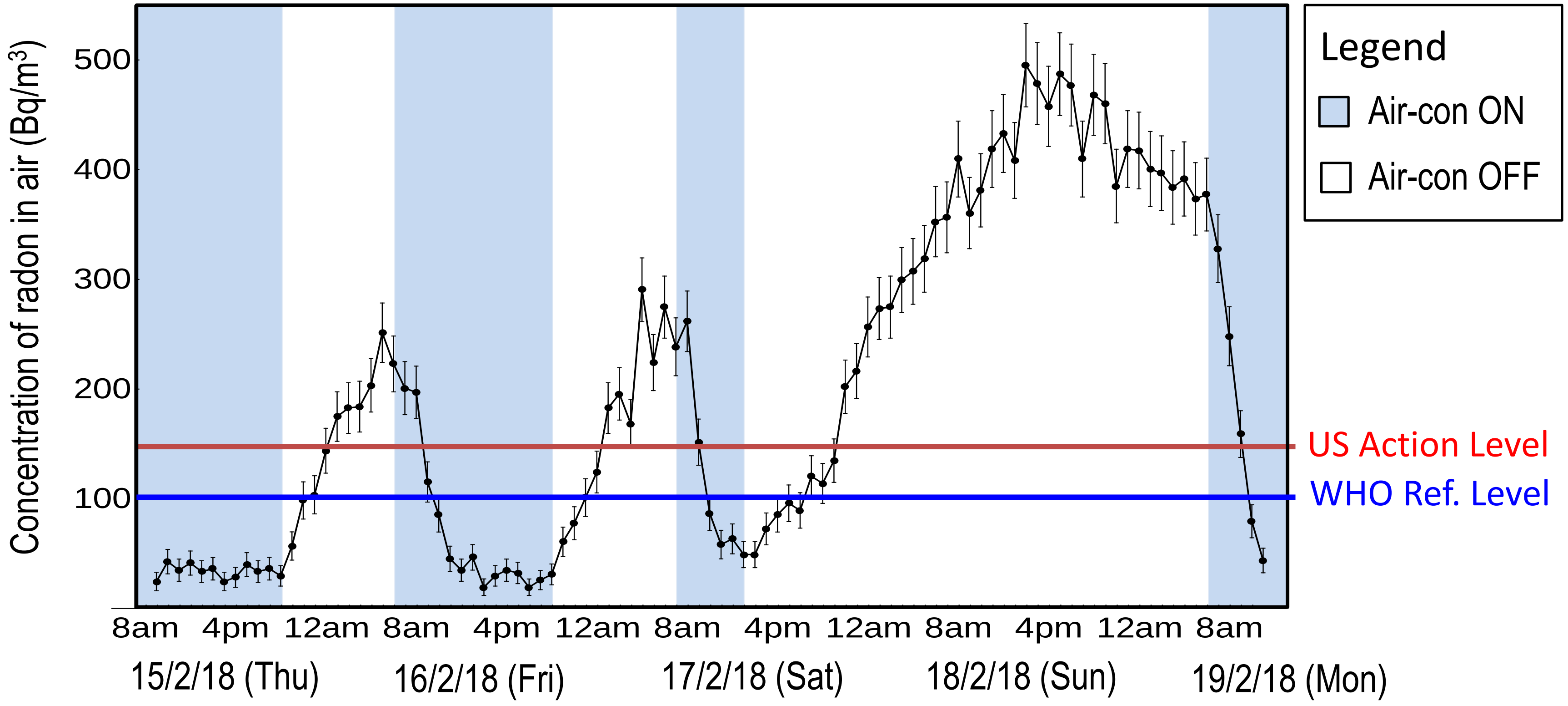
- Included in the graphs are the timing of the air-con in the office.
- This air-con works by exchanging the air in the office with air cooled by a chiller at regular intervals.
- When air-con is on, radon coming out from the concrete walls, etc. is continuously removed from office.
- At night, when air-con is off, radon accumulates and concentration increases.
- For workers' health, this is advantageous – less exposure to work during office hours!!

Radon Level in Some Offices

- Note that the radon level could be higher in some offices. For example, in another measurement done with the same instrument an another location in NUS, the following graph was obtained.

- Notice that the level reached for normal working days when ventilation is off is about twice that in the Physics Office.

- However, over extended period, it could get to a very high level (above the US Action Level and WHO Reference Level).



- More research and measurements to confirm source of radon, rate of radon production, etc. are being performed.

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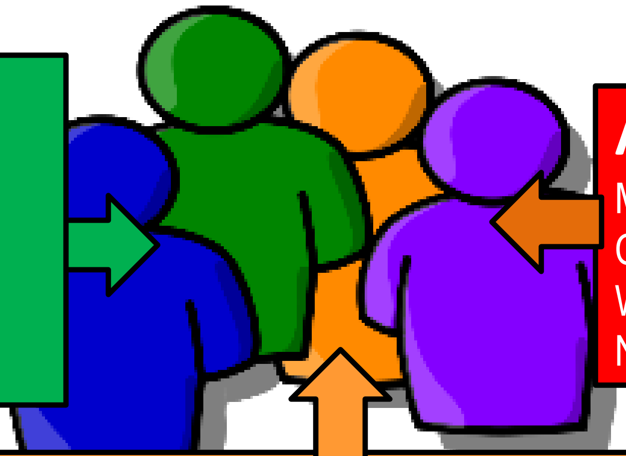

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True or False?

Global version (in Facebook)

Dev The ONE
April 26, 2015 ·

Today night 12.30 to 3.30am cosmo rays entring earth from mars.So switch off ur mobiles today night. -NASA BBC NEWS pls pass to all ur friends. DONT NEGLECT IT

5

1 share

Singapore version (in Facebook)

Parenting Made Easy
7 April 2017 ·

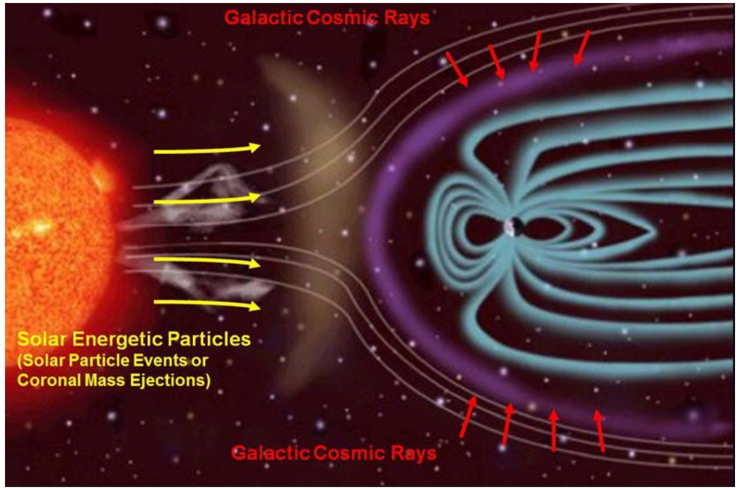
Tonight at 12:30am to 3:30am make sure to turn off the phone, cellular, tablet, ect...and put away from your body. Singapore television announced the news. Please tell your family and friends. Toinght,12:30am to 3:30am for our planet will be very high radiation. Cosmic rays will pass close to earth. So please turn off your cell phone. Do not leave your device close to your body, it can cause you terrible damage. Check Google and NASA BBC news. Send this message to all the people who matter to you.

Please share this status so that you'll be saving millions of lives

For further discussion, see for example,
https://www.snopes.com/dangerous-cosmic-gamma-rays/

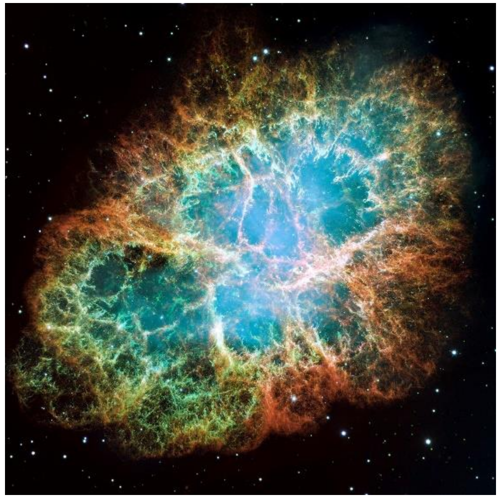
Primary Cosmic Rays

- Cosmic Rays are radiation from outer space (outside Earth).
- **<u>Primary:</u>**
  - **High speed atomic nuclei**. Elements: 90% hydrogen (protons), 9% helium (alpha particles), 1% other elements, e.g., iron (from nearby clusters of stars), a very small amount of antimatter – positrons (anti-electrons) and anti-protons.
  - **Also gamma and x-rays**!
  - Can be extremely energetic (rare but observed), e.g., a 3×10^{20} eV (= 50 J) particle was "detected" in 1991. It has the same energy as the KE of a baseball traveling at about 90 km/h!
  - Sources: Sun, supernovas, quasars (active galactic nuclei) … *(but not planets!)*



https://en.wikipedia.org/wiki/Cosmic_ray

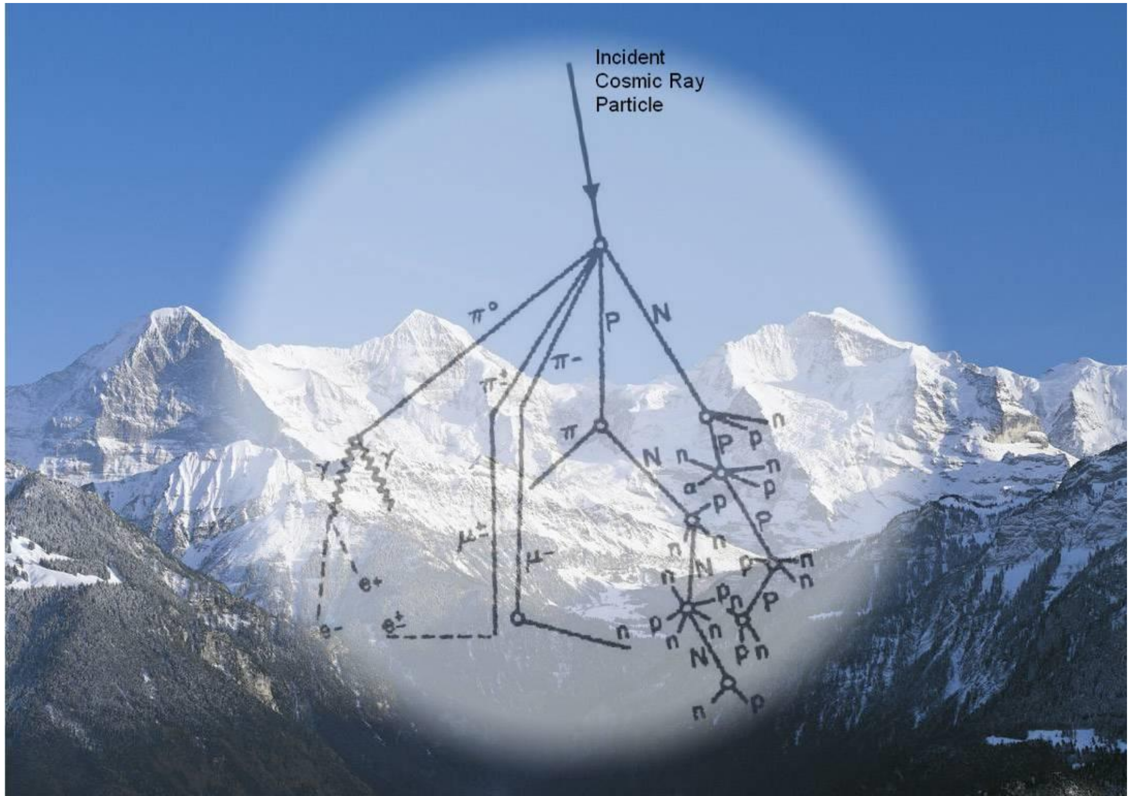
The Crab Nebula, an expanding remnant the 1054 supernova explosion recorded by the Chinese and Japanese astronomers (https://en.wikipedia.org/wiki/Supernova)



From https://en.wikipedia.org/wiki/Quasar

Secondary COSMIC Rays

- **Secondary:**
  - Interaction of energetic primary radiation with atoms in atmosphere produces a range of other particles
    - **Normal matter** – electrons, protons, neutrons, alpha particles, x-rays
    - More **exotic particles**, such as pions, muons, kaons, etc. (Note: Recall that these particles were first discovered in cosmic rays and later produced in the particle accelerators.)



N, P: Energetic neutrons and protons
n, p: lower energy neutrons and protons
$\pi^0, \pi^{\pm}$: Pions
$\mu^{\pm}$: Muons
$e^{\pm}$: Positrons and electrons
γ: Photons (gamma ray)

Image from http://www01.nmdb.eu/public_outreach/Cascade_Jungfraujoch.jpg
Source of schematic drawing: Simpson *et al.* (1953, Phys. Review 90, 934)

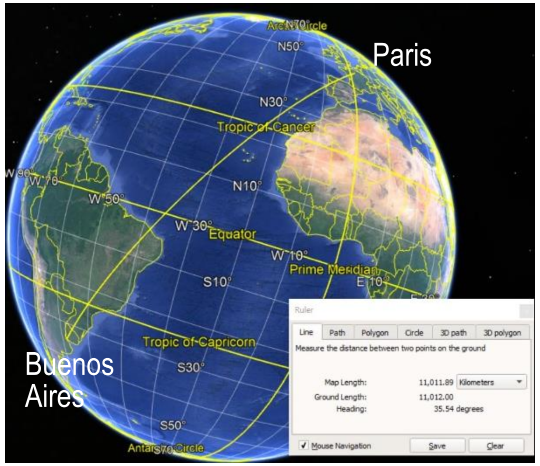
Protection From Cosmic Rays

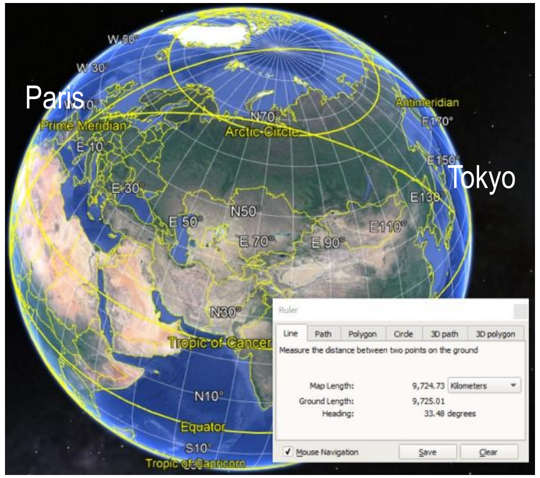
- Annual radiation exposure of human beings due to cosmic rays averages about **0.39 mSv** for the Earth's population.
- On Earth surface, we are partially protected from the cosmic rays due (1) Earth’s atmosphere and (2) Earth’s magnetic field, (3) interplanetary magnetic field
- The world's population receives an average of 0.4 mSv of cosmic radiation annually due to atmospheric shielding (0.3 for regions at sea level, and 1.0 mSv for high altitude cities).
- At 12 km altitude (above most of the atmosphere's protection) radiation as an annual rate rises to 20 mSv at the equator to 50 – 120 mSv at the poles[1] (magnetic field effects).
- At the International Space Station (~ 400 km above Earth), the dose averages 150 mSv/year. Astronauts in Apollo missions to Moon subjected to 1.2 mSv/day.
- Mission to Mars will be subjected to even higher dose due to the longer duration and away from the protection.

[1] https://en.wikipedia.org/wiki/Health_threat_from_cosmic_rays

Dose from International Flights

- Can find some of the dose rates in the literature, e.g., the lowest dose rate measured was 3 µSv/h during a Paris-Buenos Aires flight and the highest rates were 6.6 µSv/h during a Paris to Tokyo flight (11 – 12 km height) and 9.7 µSv/h on the Concorde (up to 18 km height) in 1996 –1997.[1]
  - Paris – Buenos Aires flight ~ 13.5 hours; Dose = 0.041 mSv
  - Paris – Tokyo flight ~ 11.5 hours; Dose = 0.076 mSv
  - Paris – Tokyo flight on Concorde ~ 5 hours(?); Dose ~ 0.049 mSv





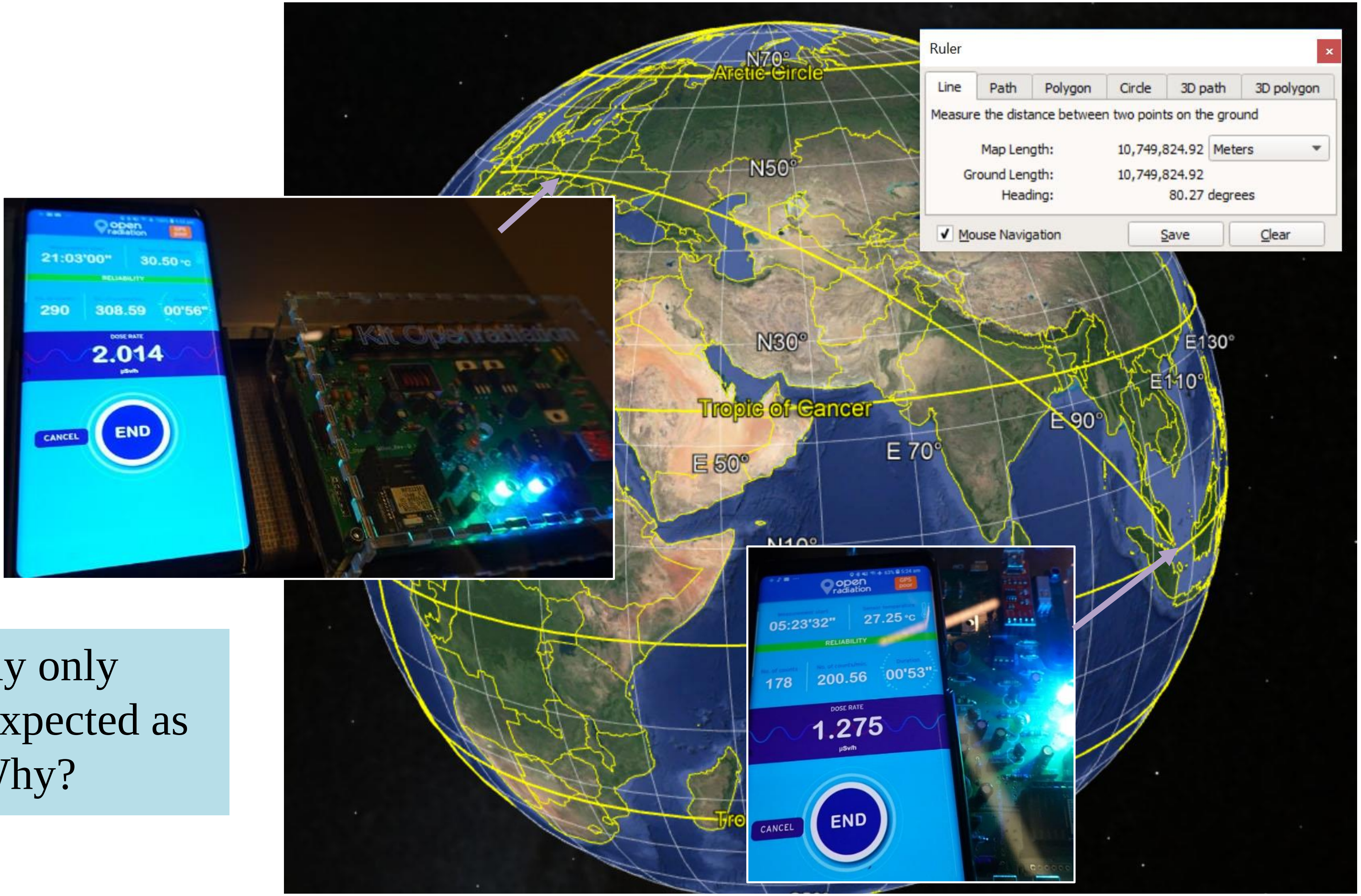
- Estimated that airline crews flying long distance high-altitude routes can be exposed to 2.2 mSv of extra radiation each year due to cosmic rays, nearly doubling their total ionizing radiation exposure. They are in fact considered to be "radiation workers" by Centers for Disease Control and Prevention (CDC) and has the highest exposure among all the radiation-exposed workers in the US.[2]

[1] https://hps.org/publicinformation/ate/faqs/commercialflights.html
[2] http://www.businessinsider.com/airplane-flight-cosmic-radiation-exposure-altitude-2015-11?IR=T&r=US&IR=T

Readings on Flight from Paris to Singapore

- Took some measurements during a recent flight from Paris to Singapore (with *OpenRadiation* [GM] detector)

- Around 2.0 µSv/h at cruising height near Paris, and 1.3 µSv/h near Singapore. This is about 10 times higher than ground measurements.



These values were actually only about half of what were expected as listed in previous slide. Why?

Radiation is a Fact of Life

Exposure to radiation from natural sources is an ***inescapable*** feature of everyday life in both working and public environments. This exposure is in most cases ***of little or no concern to society***, but in certain situations the introduction of health protection measures needs to be considered, for example when working with uranium and thorium ores and other **n**aturally **o**ccurring **r**adioactive **m**aterial (NORM)." – IAEA [1]

Have looked at these!

Now this!

Natural	mSv/yr
Radon Gas	2.00
Cosmic Rays	0.27
Terrestrial	0.28
Human body (Internal)	0.40

Artificial	mSv/yr
Medical Procedures	0.53
Consumer Products	0.10
Weapon Tests Fallout	< 0.01
Nuclear Industry	< 0.01

And this

Even this!

Elective	mSv/yr
One coast to coast Airline Flight	0.02
Watching colour TV	0.01
Heating and cooling with natural gas	0.06
Sleeping with another person	0.01

Average annual radiation exposure of a typical American [2]

[1] http://www-ns.iaea.org/tech-areas/rw-ppss/exposure-to-natural-radiation.asp?s=3

[2] Radiation and Modern Life – Alan E. Waltar

Internal Exposure – Radiation from Our Bodies!

- We take in food and water which contains a small amount of radioactive atoms, e.g., uranium in drinking water, and some of these are absorbed into our bodies.

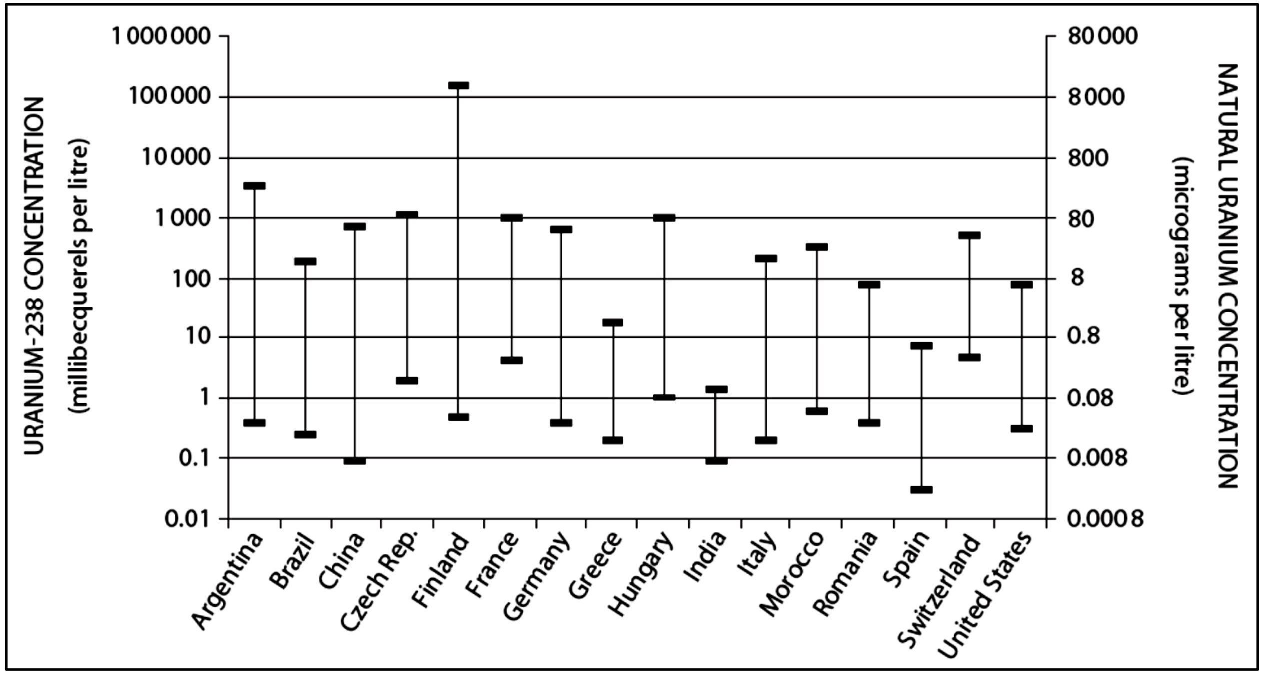


Figure from UNSCEAR 2008 Report. It shows the amount of uranium in water for various countries. Uranium is always present but in variable amount for every country.

Show that the quantities on the left & right axes are consistent with one another, e.g., 80 µg of $^{238}_{92}U$ has activity of 1 Bq.

- We also breath in air containing radioactive nuclides. So our bodies unavoidably would also contain radioactive atoms.

We are all “radioactive” and emit ionizing radiation!

Carbon-14 in Atmosphere

- Carbon-14 or $^{14}_{6}\mathbf{C}$ is formed in the atmosphere mainly through the presence of cosmic rays. (Atomic bomb testing in atmosphere and emission from nuclear power plants also add to this.)

$$^{14}_{7}\mathrm{N} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{14}_{6}\mathrm{C} + {}^{1}_{1}\mathrm{H}$$

- C-14 occurs in trace amounts, making up only about 1.3 atoms per 10^{12} atoms of the carbon in the atmosphere. [Varies slightly over location and time as we will see in a future lecture.]
- Half life of C-14 is 5730 years via beta decay:
  - $^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}e^{-} + \overline{\nu_e}$
  - Max. energy of beta = 156.5 keV, weighted average = 49 keV – relatively low energy)
- All living things (plants & animals & humans) have about the same ratio of C-14 to C-12 in their tissues. Photosynthesis utilizes the carbon dioxide in the atmosphere and plants are the ultimate source of food for animals.

https://en.wikipedia.org/wiki/Carbon-14

Carbon-14 in our Bodies

- It is estimated that carbon makes up 18.5% of our body mass. Taking again a 60-kg adult. The activity due to the carbon-14 atoms in our body is approximately:

$$A = \lambda N = \frac{\ln 2}{\underbrace{5730 \times 365 \times 24 \times 3600}_{\text{half-life in seconds}}} \left(\overbrace{\frac{18.5}{100} \times \frac{60}{0.012}}^{\text{number of moles of carbon}} \times \underbrace{6.02 \times 10^{23}}_{\text{Number of atoms in one mole.}} \right) \times \overbrace{1.3 \times 10^{-12}}^{\text{percentage of C-14}}$$

Activity ≈ 2800 Bq! $\Rightarrow$ In every second, approximately 3000 carbon nuclei in our body decay and emit an electron each.

https://en.wikipedia.org/wiki/Composition_of_the_human_body

Potassium-40 in our Body

- Potassium is present in our body in fairly large amount (about 120 g for a 60-kg adult). Important for many of the body functions.
- ${}^{40}_{19}\mathrm{K}$ (or just written as K-40) is a primordial nuclide with half-life of 1.25 billion years and is thus naturally occurring making up 0.0117% of all potassium atoms, or about 1 atom in 8540 potassium atoms is ${}^{40}_{19}\mathrm{K}$.
- ${}^{40}_{19}\mathrm{K}$ has two main modes of decay:
  - ${}^{40}_{19}\mathrm{K} \rightarrow {}^{40}_{20}\mathrm{Ca} + {}^{0}_{-1}e^{-} + \overline{\nu}_e$ (89.28%, beta decay, max. energy = 1.33 MeV)
  - ${}^{40}_{19}\mathrm{K} + {}^{0}_{-1}e^{-} \rightarrow {}^{40}_{18}\mathrm{Ar} + \nu_e$ (10.78%, electron capture, γ emission of 1.460 MeV)
- Activity due to K-40 in a 60-kg adult is approximately:

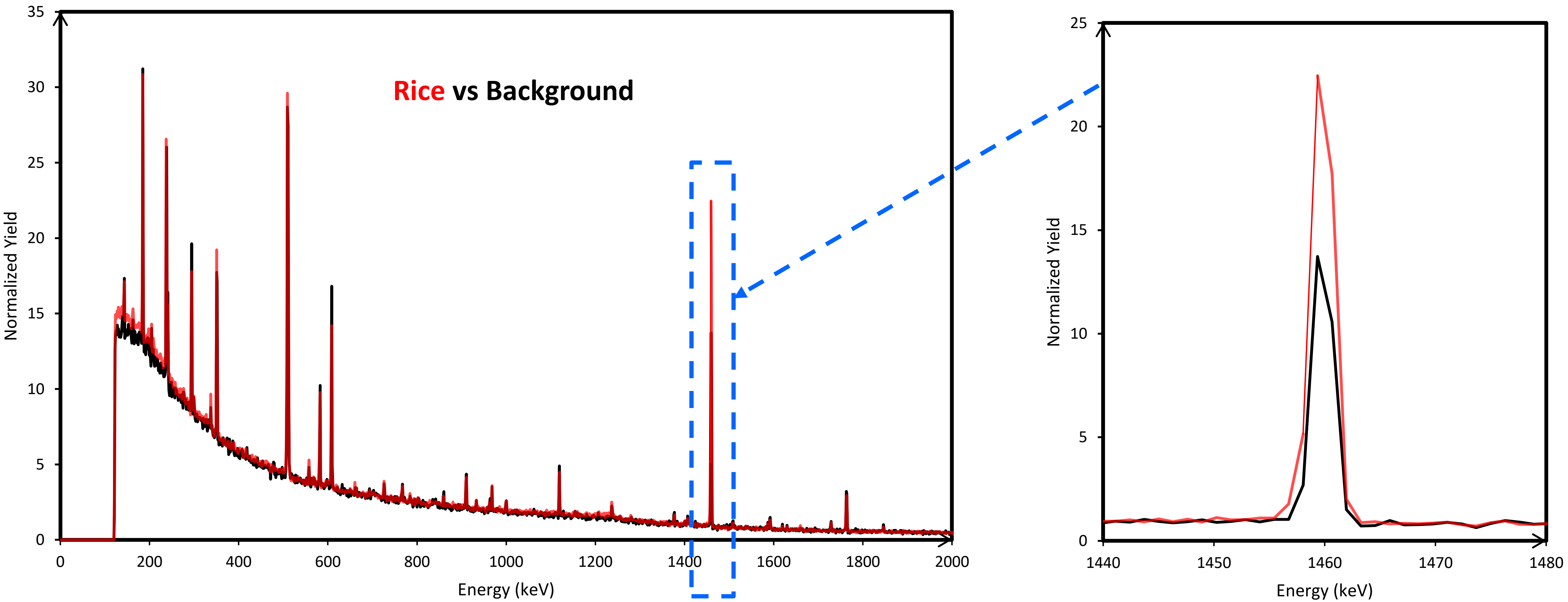
$$A = \lambda N = \frac{\ln 2}{T_{1/2}} \left(\frac{120}{40} \times 6.02 \times 10^{23} \right) \times 0.000117 \approx 3720\ \mathrm{Bq}$$

- As 10.78% of these decays are accompanied by 1.460 MeV gamma photons, which are highly penetrating, many of these photons can be detected outside each of us! And will also affect others around us.

https://en.wikipedia.org/wiki/Potassium

Potassium-40 in Food

- Potassium comes mainly from food! Recall the example of banana in Tutorial 1.
- Rice also contain potassium as can be seen in the gamma spectrum of a bag of white rice. (Note: brown rice has even higher level of potassium.)



Thanks to Chan TK for the spectra!

Dose due to Radionuclides in Human

- Under normal circumstances, the dose we got from the intake (food) comes mainly from K-40 (**average annual dose** of **0.17 mSv**) and also radionuclides from the uranium and thorium decay series (**0.12 mSv**). [1]
- During exceptional situation, e.g., when the core melts down in nuclear power plants (only two serious ones – Chernobyl and Fukushima – during the entire history of the nuclear power industry), other isotopes such as iodine-131 ($^{131}_{53}I$, half-life of 8.02 days), caesium-137 ($^{137}_{55}Cs$, half-life of 30.2 years) and strontium-90 ($^{90}_{38}Sr$, half-life of 28.8 years) are important.

[1] UNSCEAR 2008 Report: Sources and Effects of Ionizing Radiation Vol 1 – Sources. Download at http://www.unscear.org/docs/publications/2008/UNSCEAR_2008_Report_Vol.I.pdf (Read Annex B)

Summary of Annual Dose

- From UNSCEAR 2008 report[1] for annual dose worldwide due to **natural sources of exposure** (all annual dose in mSv)

Source or mode	Annual average dose (worldwide)	Typical range of individual doses	Comments
Inhalation (radon gas)	1.26	0.2 – 10	The dose is much higher in some dwellings
External terrestrial	0.48	0.3 – 1	The dose is higher in some locations
Ingestion	0.29	0.2 – 1	
Cosmic radiation	0.39	0.3 - 1	The dose increases with altitude
Total natural	**2.4**	**1 – 13**	**Sizeable population groups receive 10 – 20 mSv**

[1] UNSCEAR 2008 Report: Sources and Effects of Ionizing Radiation Vol 1 – Sources. Download at http://www.unscear.org/docs/publications/2008/UNSCEAR_2008_Report_Vol.I.pdf (Read Annex B)