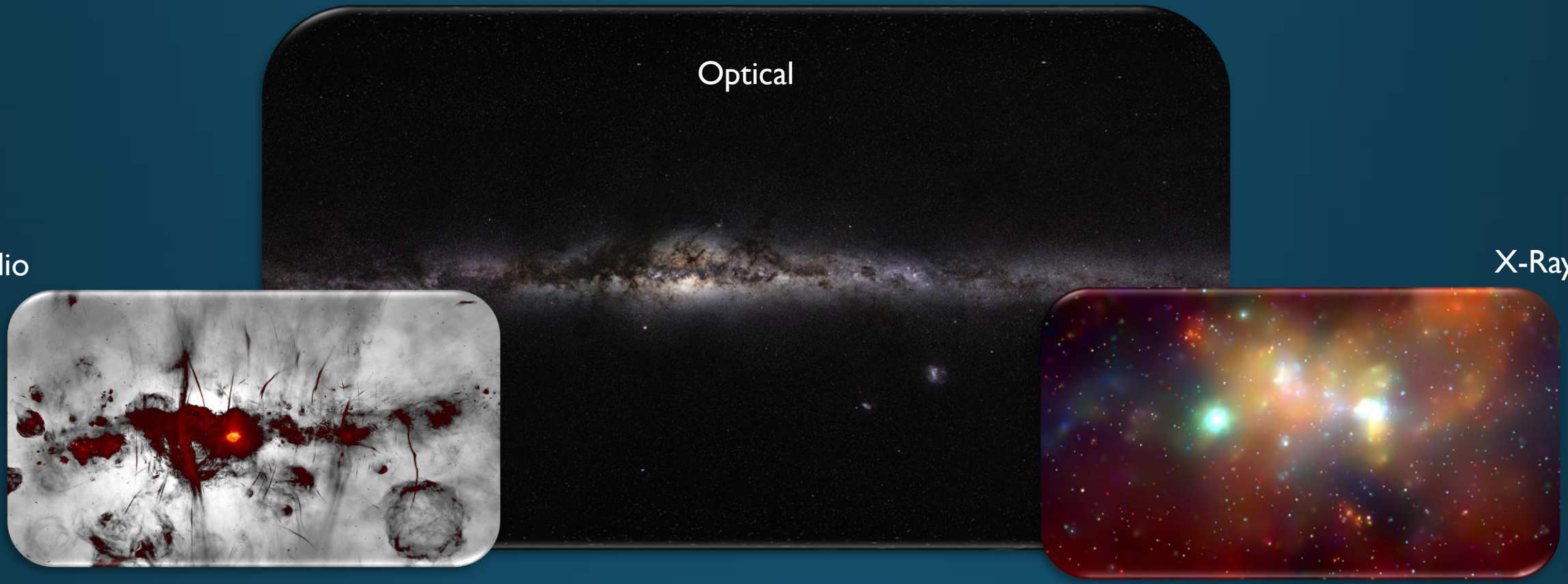
The Astroparticles Lens:
Using Particles From Space To Understand Our World

Cosmic Rays Impacting the Origin and Survival of Life

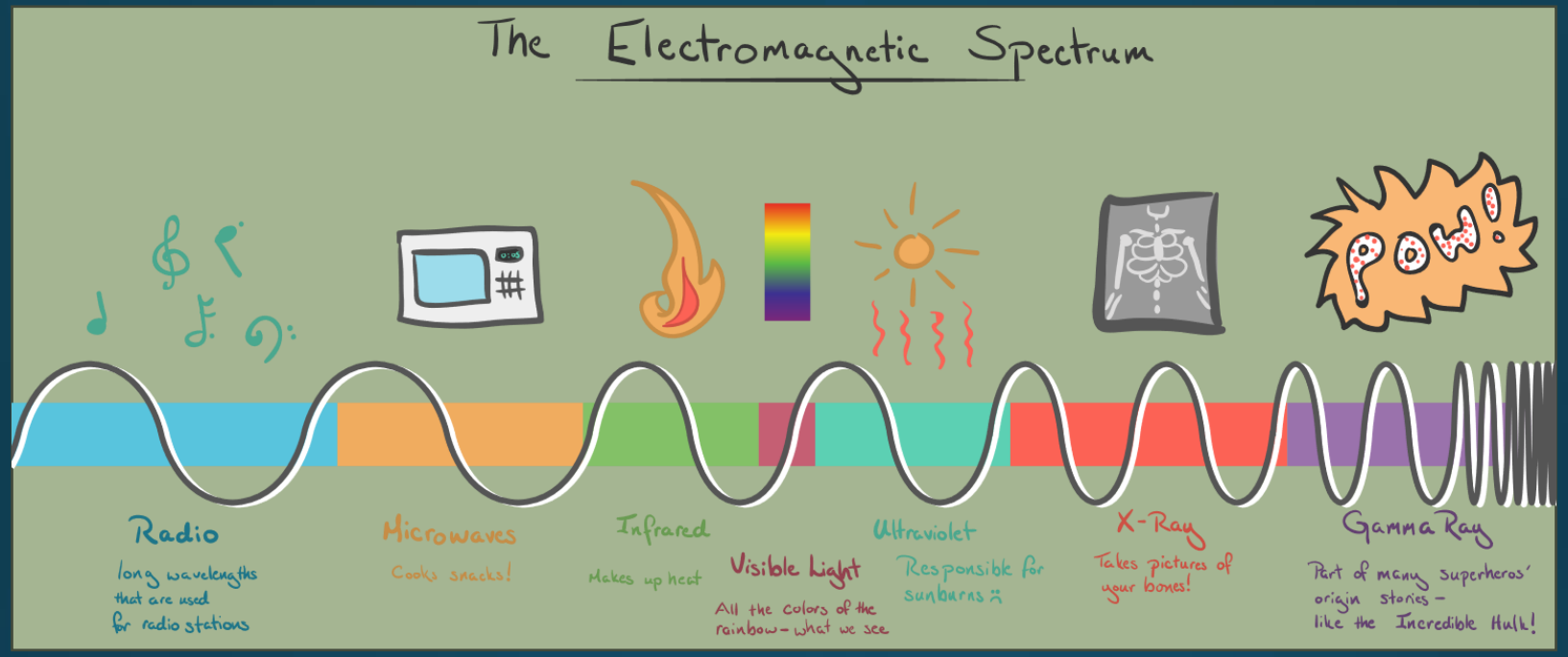
Keith McBride-Compton Lecture 5

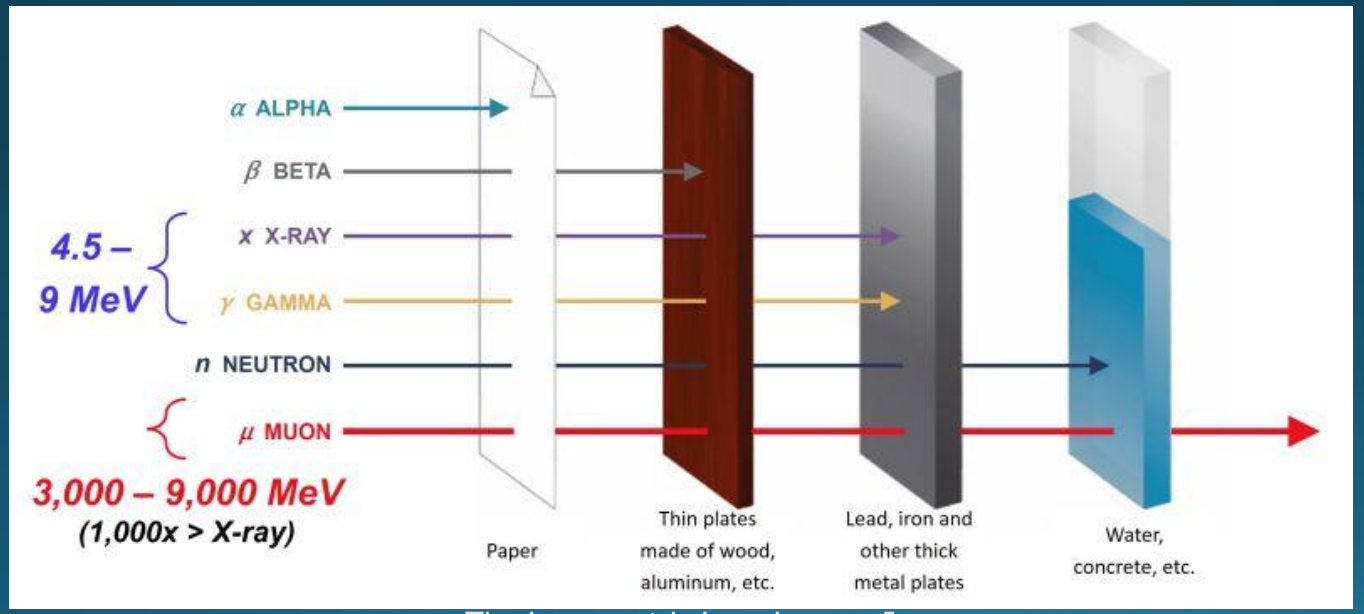


With a different type of lens, you can:

1. See through opaque objects
2. Observe different processes
3. Reveal previously hidden structure

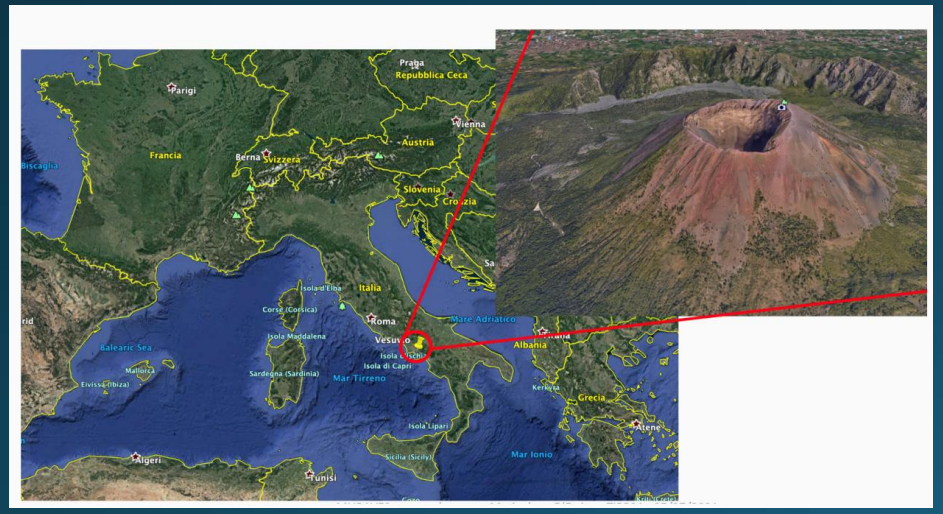
Radiation

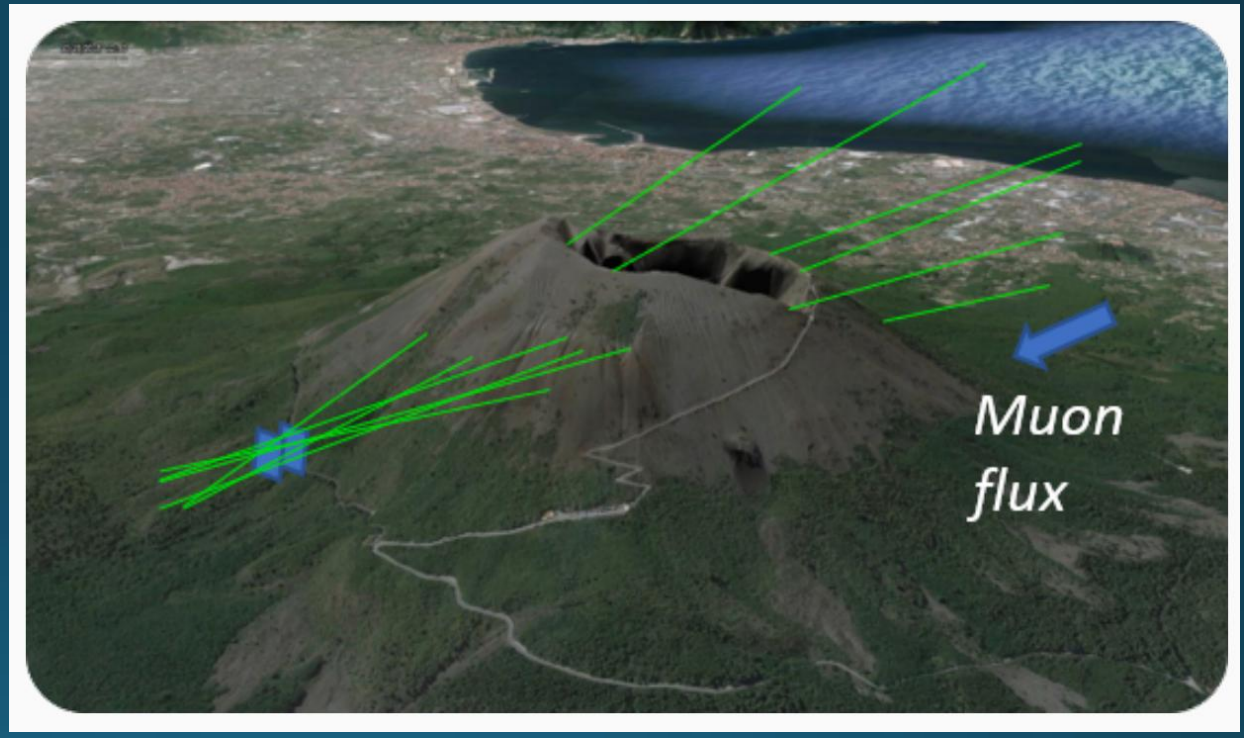

The Electromagnetic Spectrum
POW!
Radio
long wavelengths that are used for radio stations
Microwaves
Cooks snacks!
Infrared
Makes up heat
Visible Light
All the colors of the rainbow - what we see
Ultraviolet
Responsible for sunburns
X-Ray
Takes pictures of your bones!
Gamma Ray
Part of many superheros' origin stories - like the Incredible Hulk!


α ALPHA
β BETA
x X-RAY
γ GAMMA
n NEUTRON
μ MUON
4.5 – 9 MeV
3,000 – 9,000 MeV
(1,000x > X-ray)
Paper
Thin plates made of wood, aluminum, etc.
Lead, iron and other thick metal plates
Water, concrete, etc.

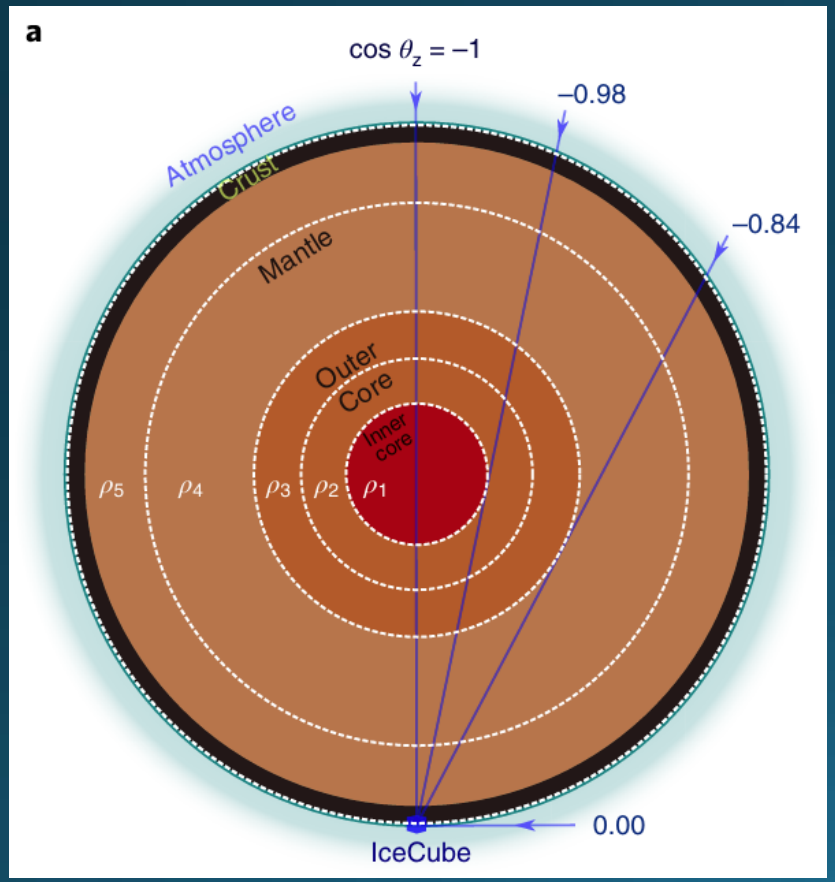
We can use cosmic rays muons to see through volcanoes

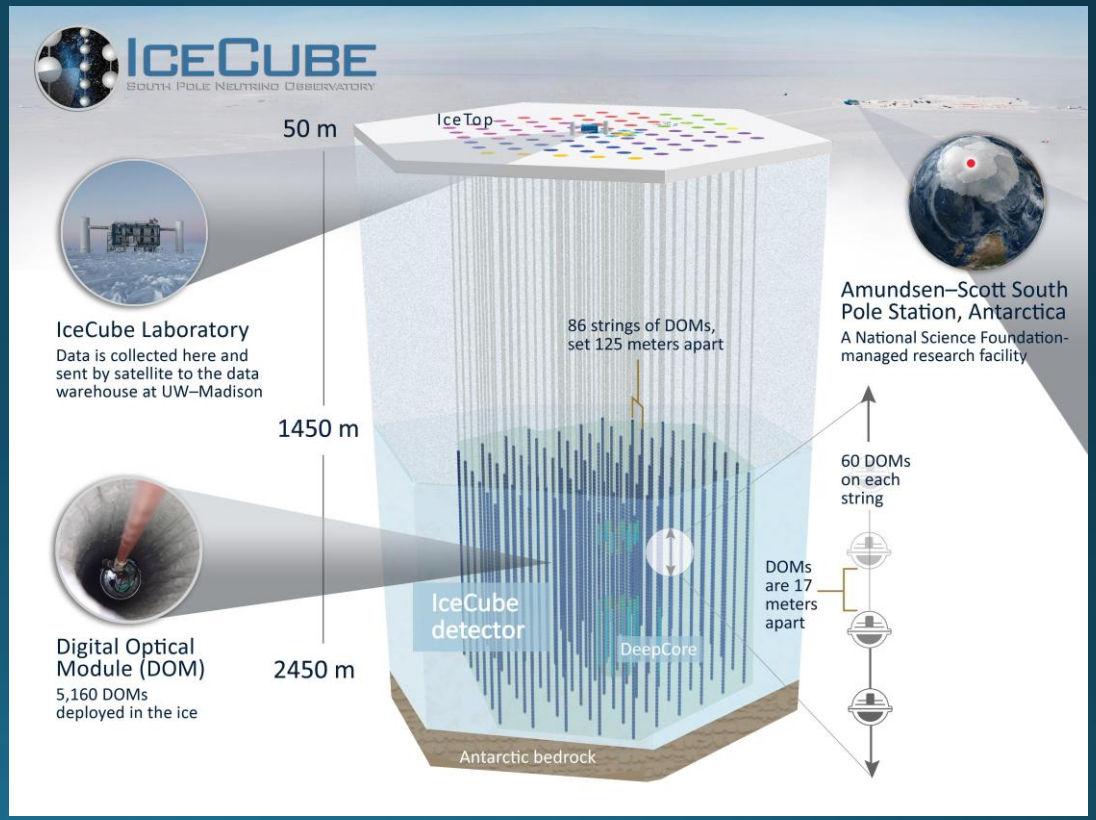
Mu-Ray project



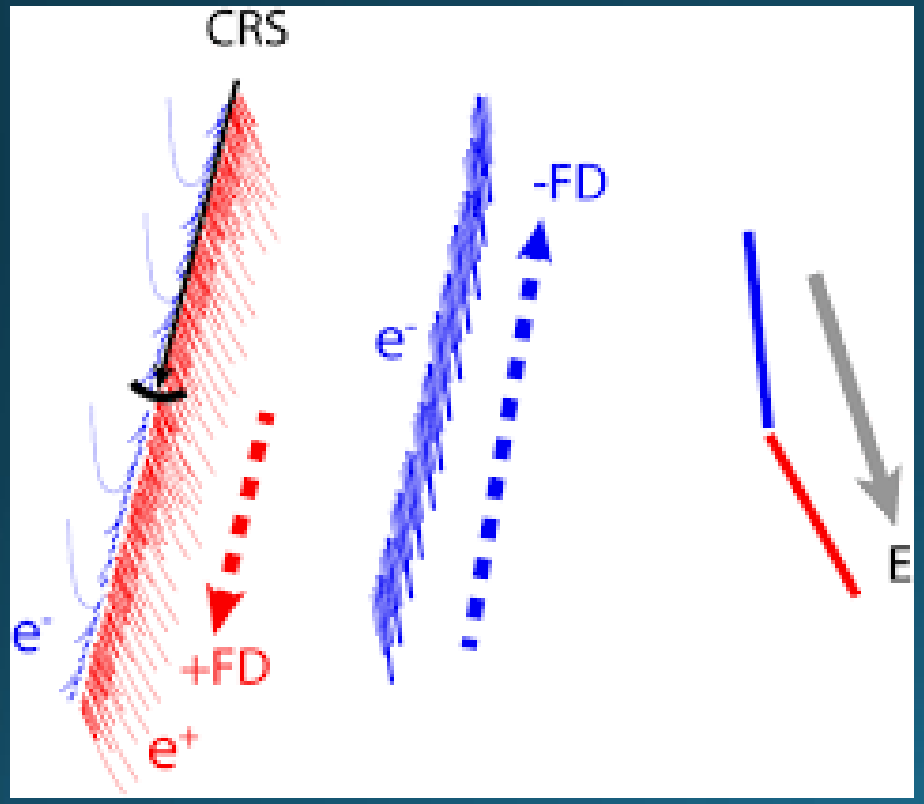


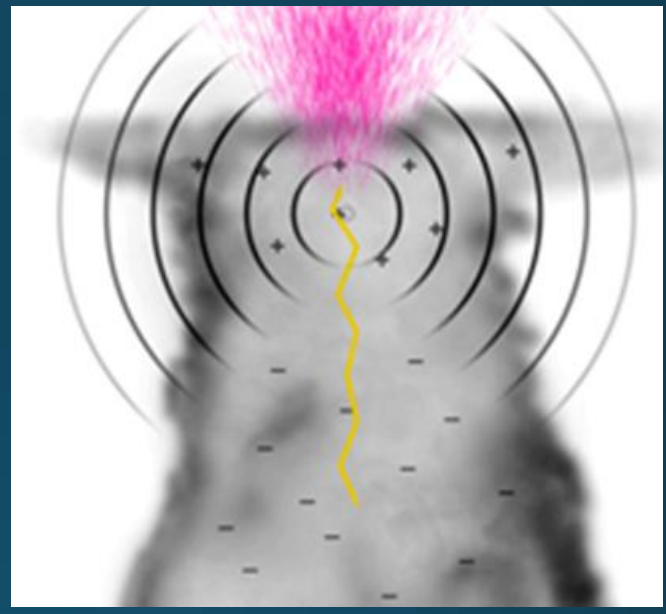
We can use cosmic ray neutrinos to see through the Earth

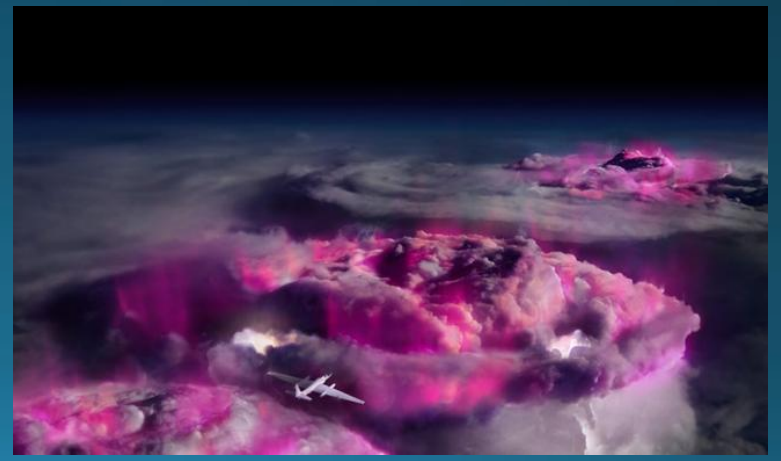




Cosmic ray showers may be triggering lightning





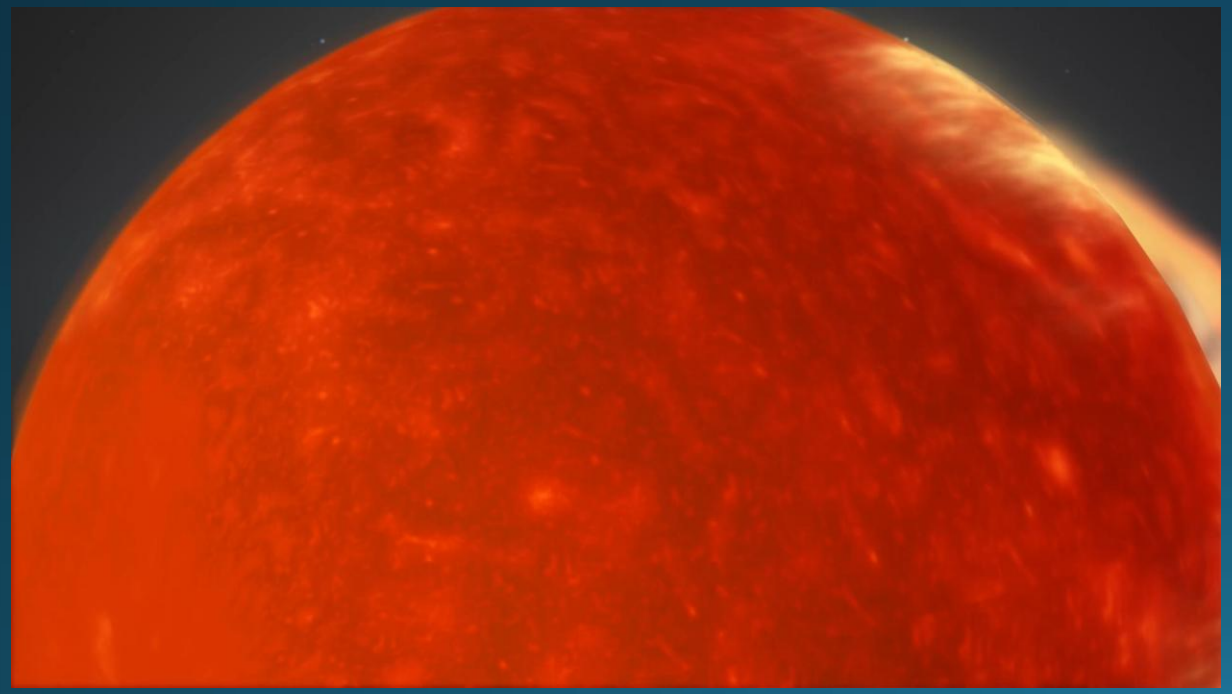


What accelerates/produces cosmic rays?

Supernovae Remnants do

- The powerful expansion of material around a star that exploded

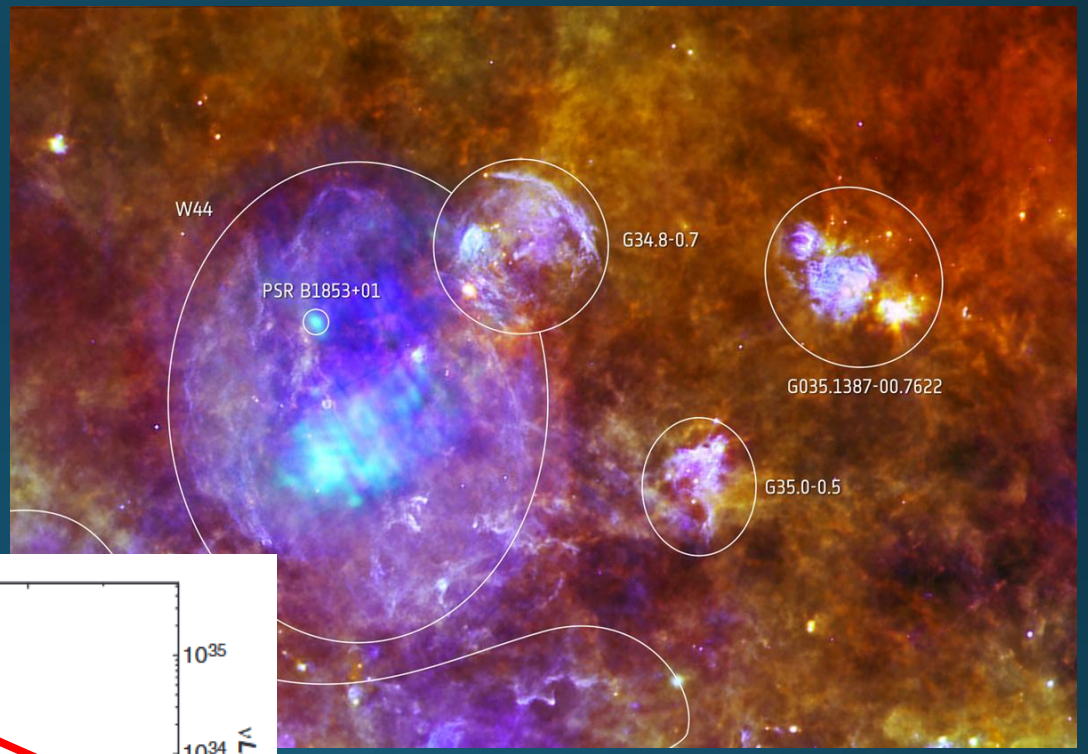
1. Supernova

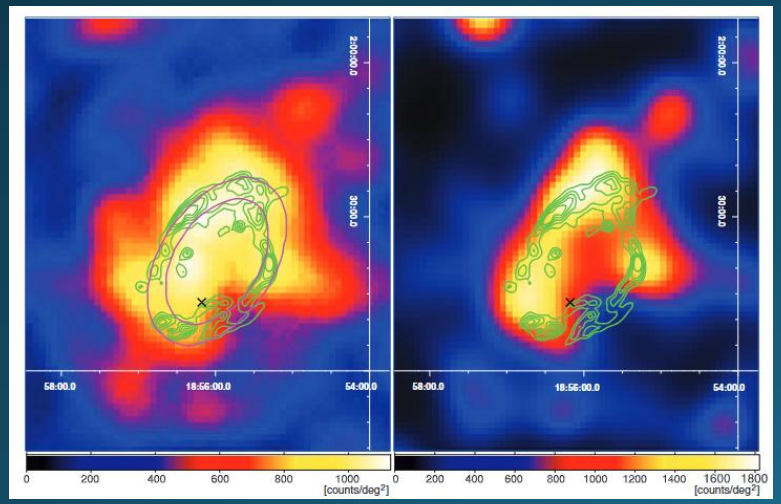


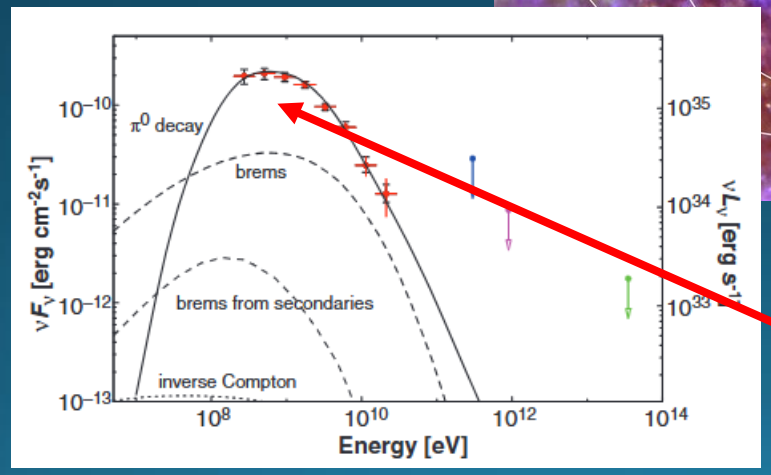
2. Supernova Remnant

What produces cosmic rays?

- Supernovae Remnants:
  - Within the Milky Way – accelerates cosmic rays to high energy
    - Active field of research
  - Example W44
  - Fermi telescope observations
    - Gamma ray signatures show strong evidence



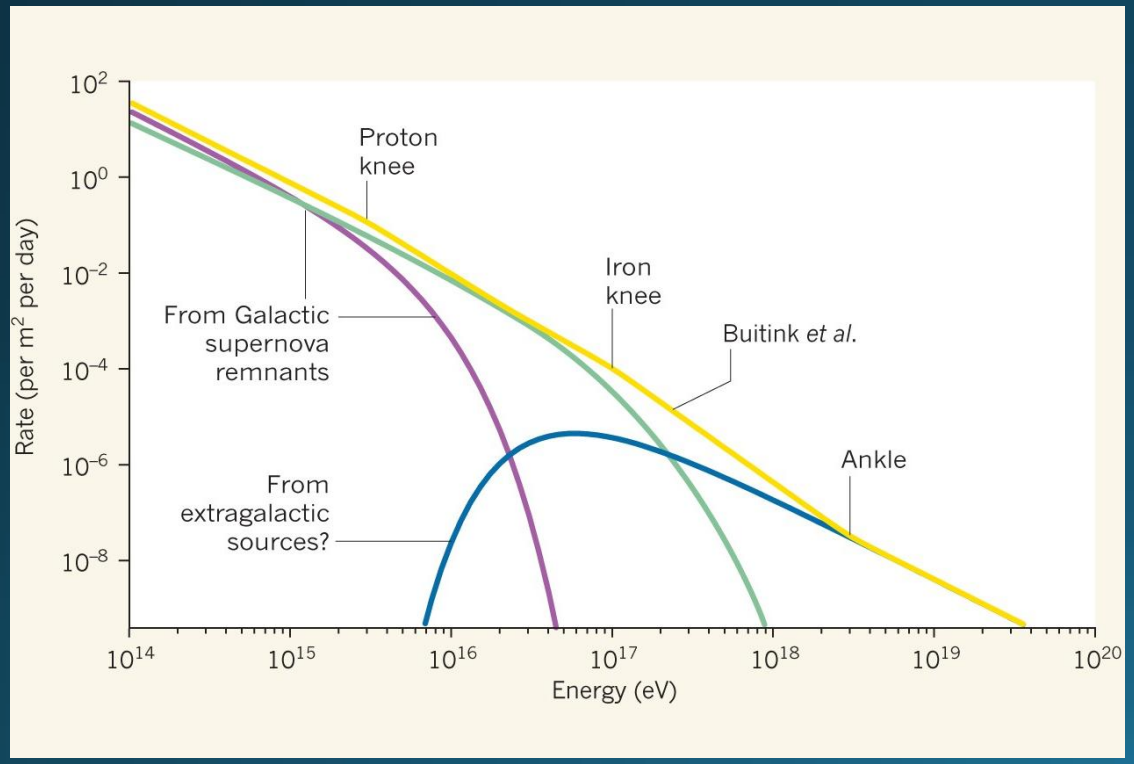


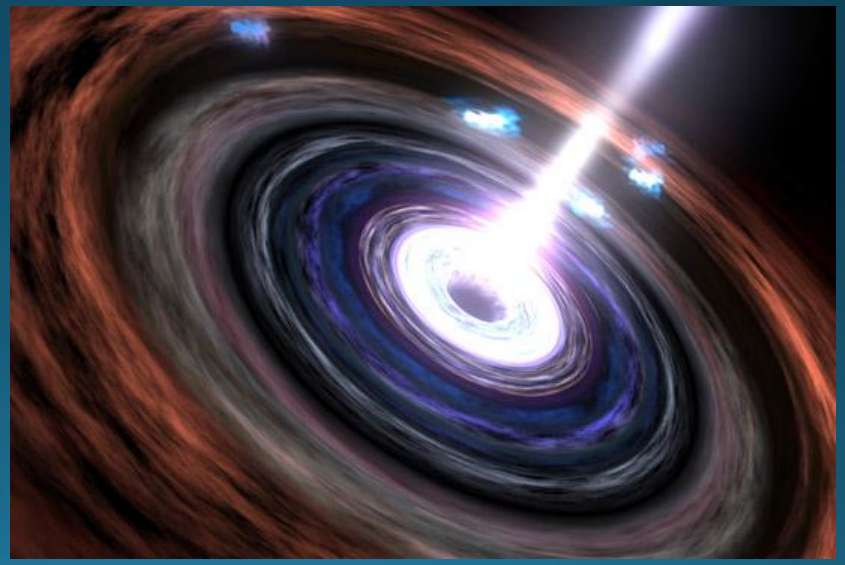


*Pions are evidence of cosmic ray interactions

Galactic

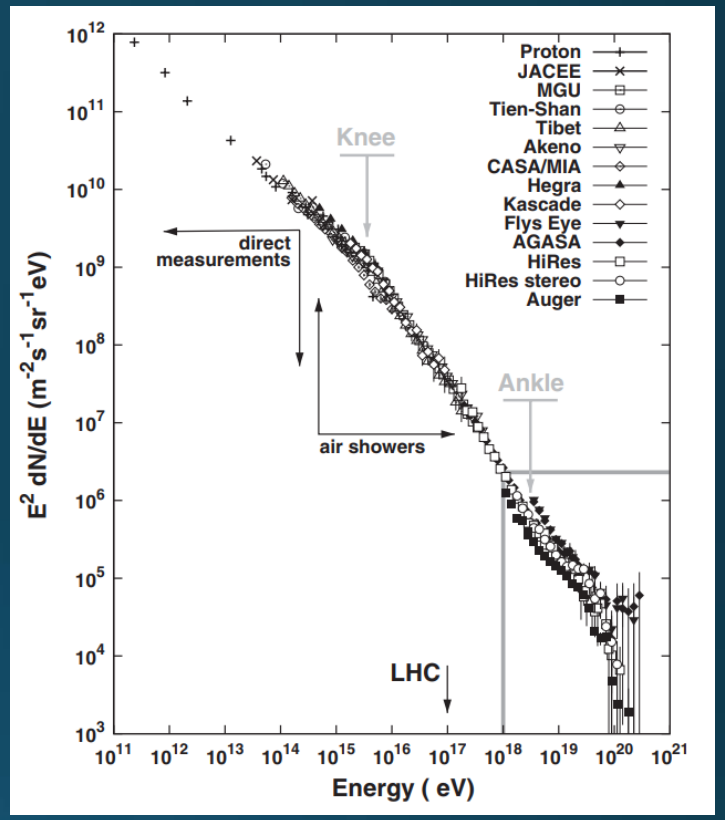
Vs Extragalactic

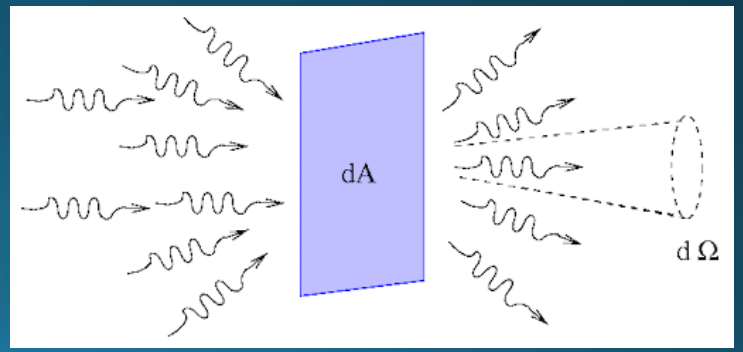




The flux of primary cosmic rays

- Cosmic rays at higher energies are rarer (i.e. less frequent)
- Measured a spectrum of cosmic rays
  - Higher energies, flux falls off (i.e. power law)
  - Hold out your hand (while in space) for 6 billion years to catch the 100 EeV cosmic ray
    - If you want 99% chance – then closer to 30 billion years
- Particles are accelerated somewhere in the universe to these extreme energies
  - Will revisit in the last lecture





Cosmic rays are accelerated in the Milky Way

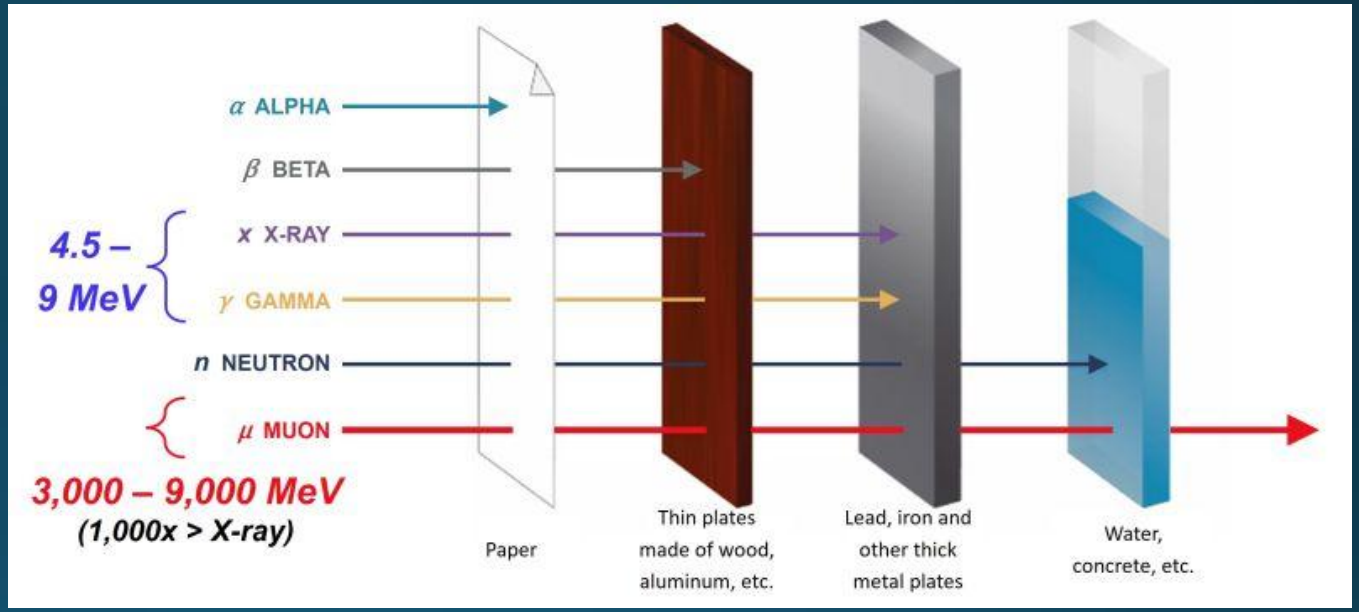
- Accelerated/ produced at SNR sites across the Milky Way
- In bursts over the age of the Milky Way

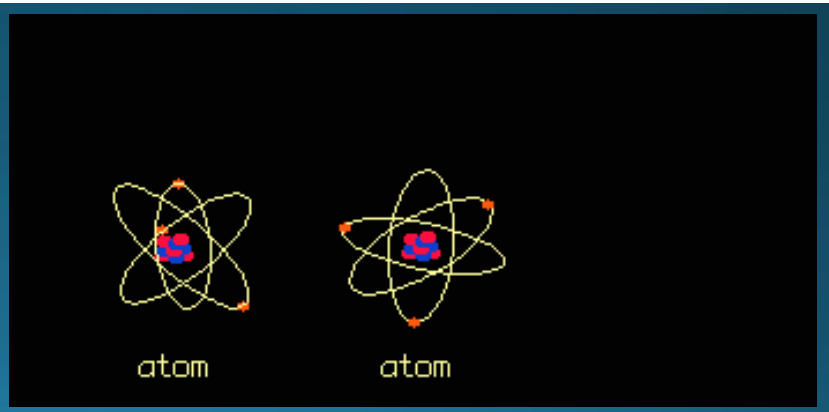
- Cosmic rays fill the Milky Way like a sea
- The Solar System is immersed in a sea of cosmic rays

We will revisit cosmic rays in the Milky Way next week

These cosmic rays are radiation

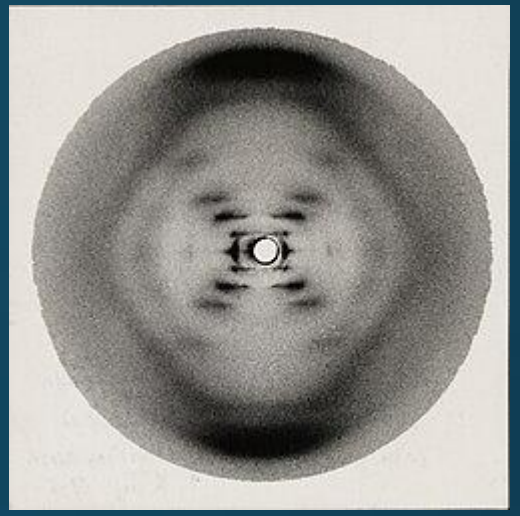
- Higher energy radiation penetrates more material than low energy
  - Each types of radiation interacts through different processes
    - Ionization
    - Bremsstrahlung
- The hazard comes from too much radiation
  - Some types of radiation are more harmful than others
  - Deposits more energy into the material



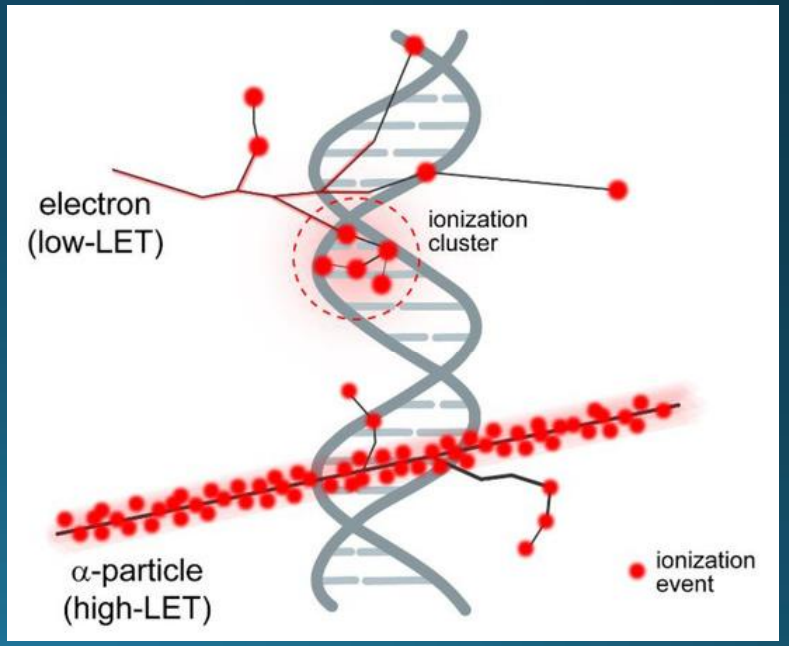


Radiation impact on DNA

- Biology:
  - It's all about damage to DNA
  - But DNA-repair is common
    - Otherwise, we wouldn't be here
- DNA - double helix structure (2 strands)
  - One side is damaged → repair is easy and common
- Linear Energy Transfer
  - Deposited energy by the radiation
  - Low-LET (next slide)
  - High-LET
    - More likely for both sides to be damaged
    - Higher risk of mutation and cell death

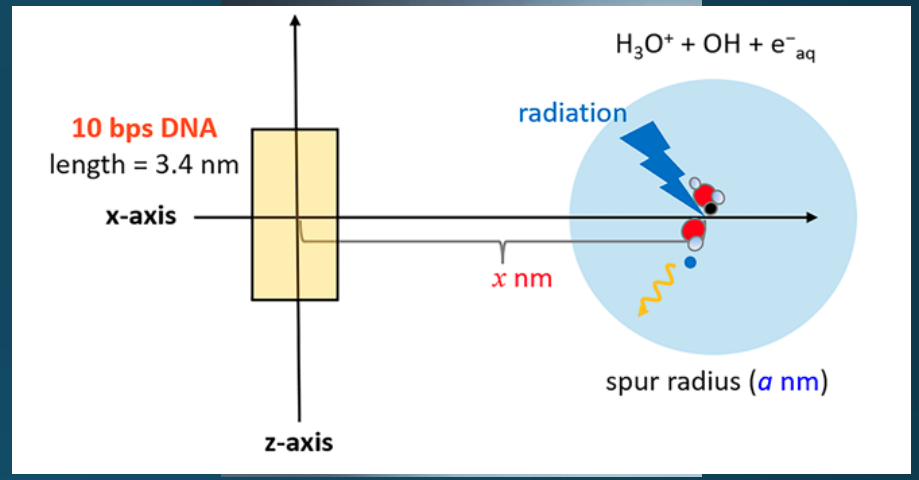


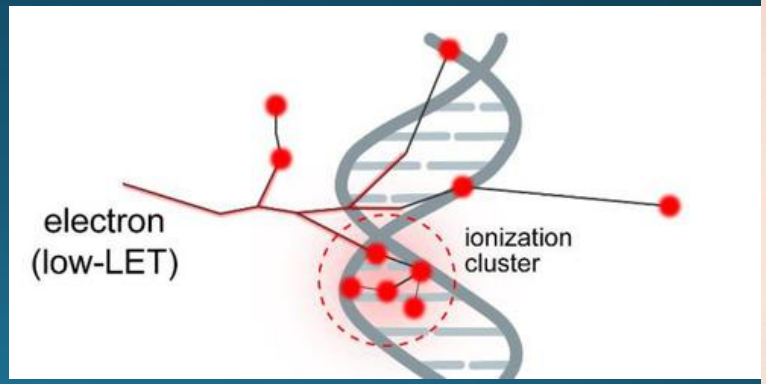
Discovery of double helix structure in DNA
Photo 51

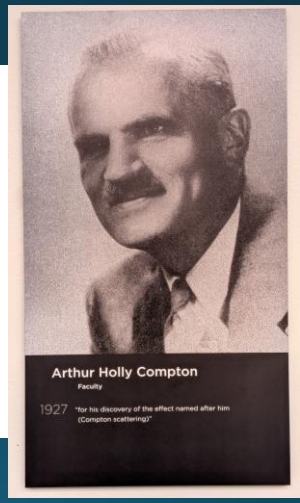


Low-LET example of DNA damage

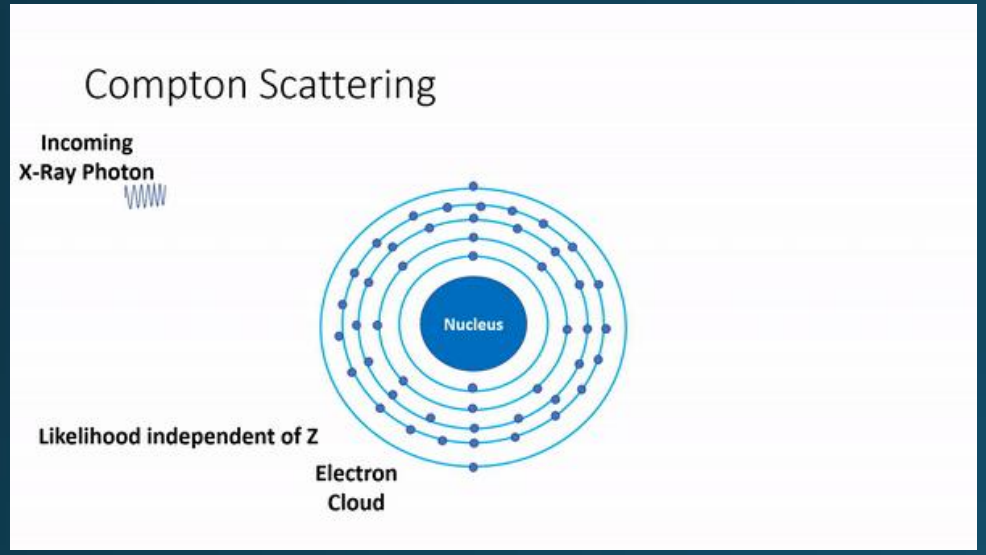
- 60% of humans are water
  - DNA suspended in water in humans
- Radiation results in ionization
  - Inside of the water, ionization seeds the reactions
  - Products can damage DNA
  - Entire research field summarized here
- X-Rays, Gamma rays, low energy electrons
  - Spread energy out
    - Processes like Compton scattering

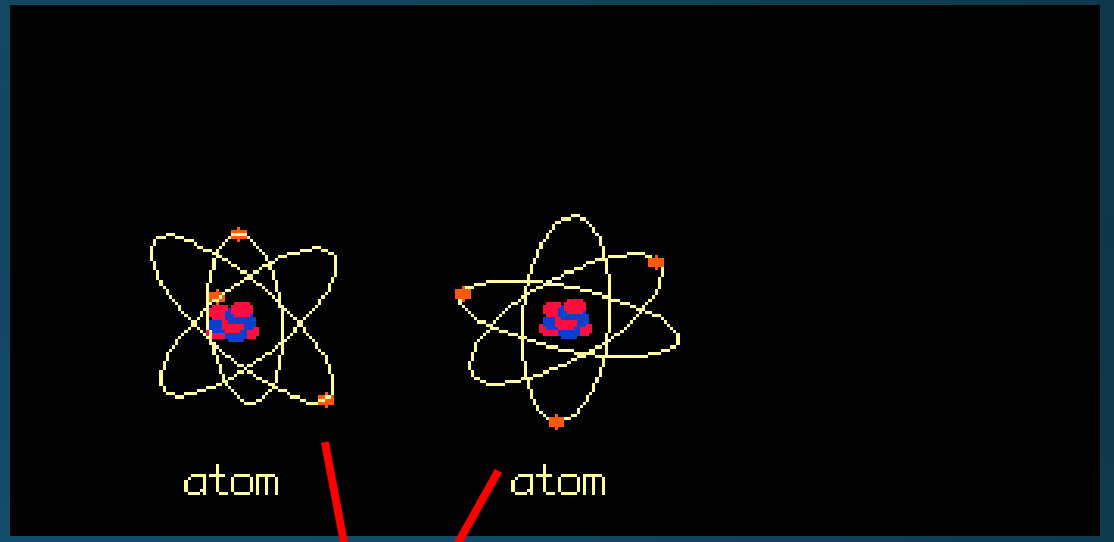


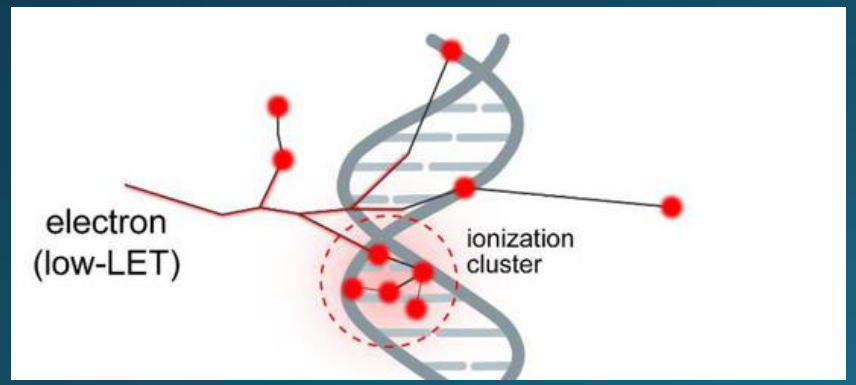


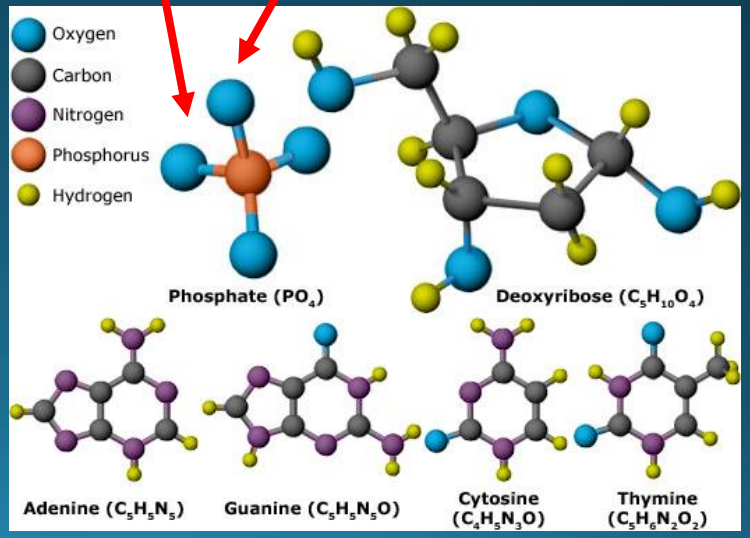


Ionization from Low-LET

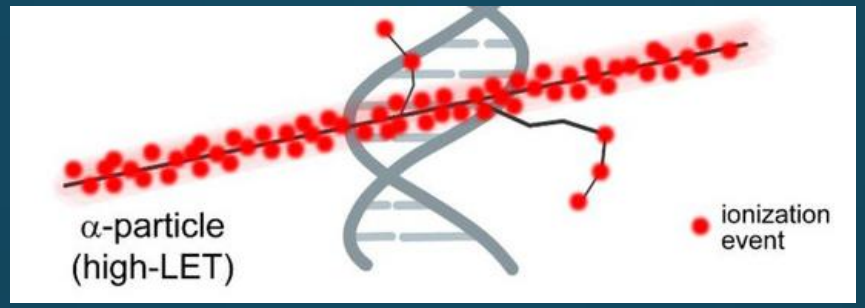






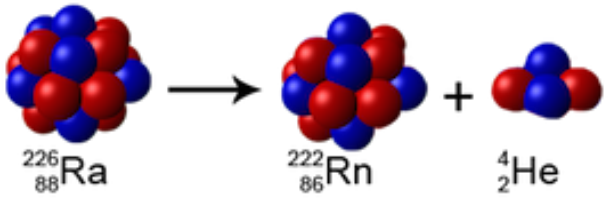


High-LET



- Energy deposition in a narrow track
  - Doesn't spread out compared to low-LET
  - Lower chance that repair is possible
- Protons, neutrons, and nuclei
- Alpha (Helium nuclei) particles are useful in medicine
  - Deposits more energy per length
  - Penetration of ~100 um (like 10 cell diameters)
  - From radium and other isotopes

Radiation type	Linear Energy Transfer, keV/μm
Cobalt-60 γ-rays	0.2
250-kV x-rays	2.0
10-MeV protons	4.7
150-MeV protons	0.5
14-MeV neutrons	12 (track average) 100 (energy average)
2.5-MeV α-particles	166
2-GeV Fe ions	1,000



The nucleus of an atom of radium-226 contains 88 protons and 138 neutrons. A radium-226 nucleus undergoes alpha decay to form a different element, radon-222, and an alpha particle.

LET for different types of radiation

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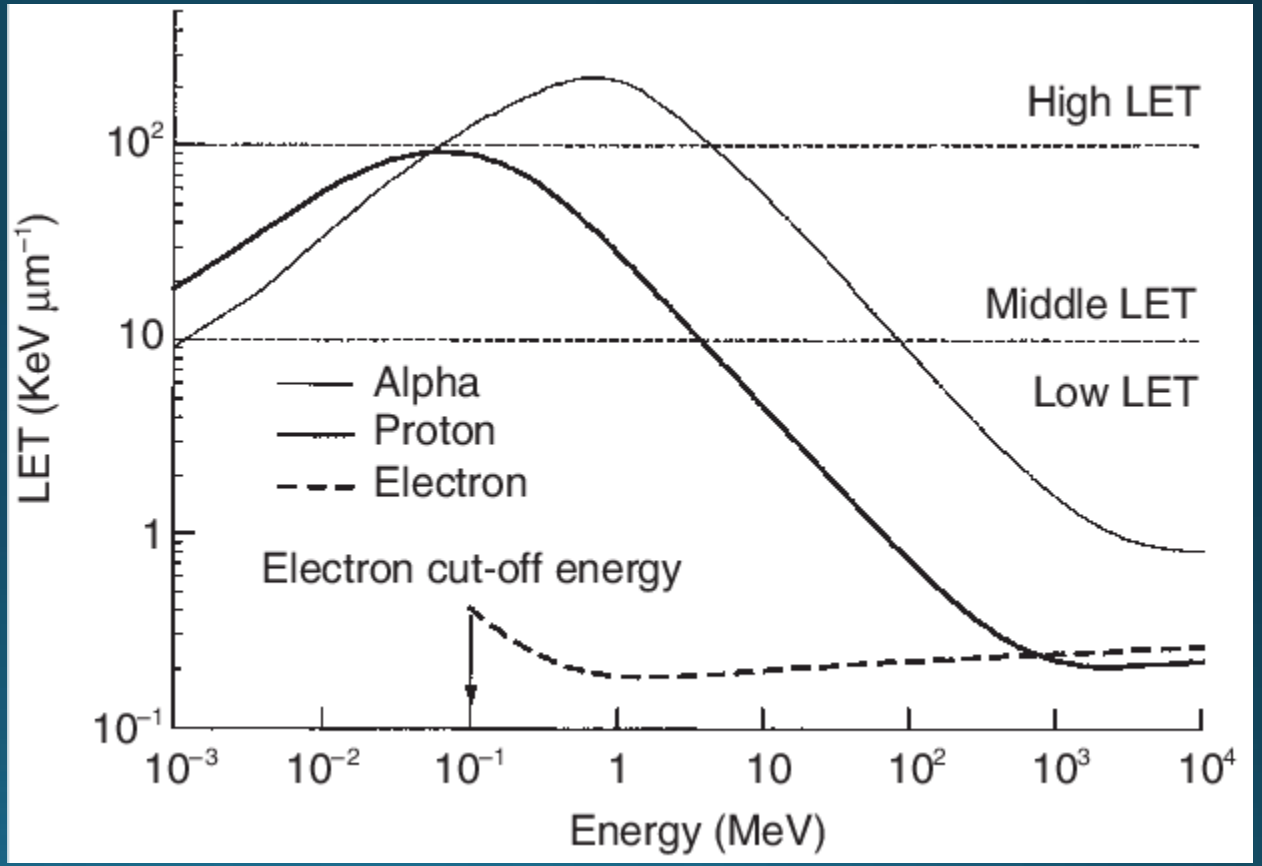
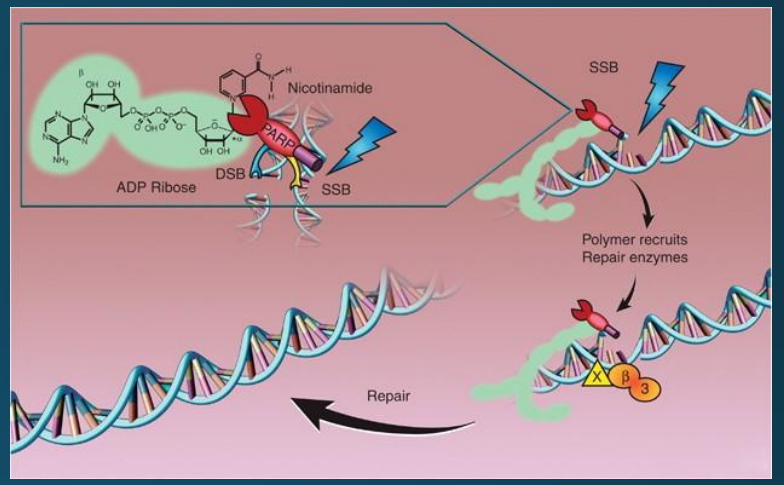
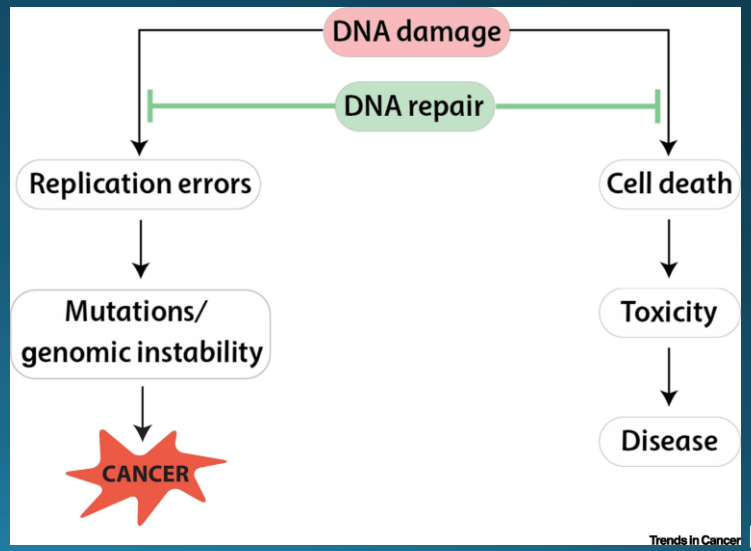


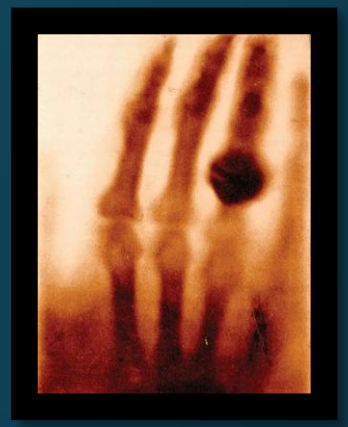
Radiation can create damage

- Our DNA (and cells) are repaired
- Common amounts of radiation determine impact
  - 3 options: repair, mutate, or die
  - Deterministic
    - Radiation burns, cataracts, radiation sickness
  - Stochastic
    - Cancer, genetic mutations, passed to offsprings
- Personal aspect
  - Need for more thorough understanding of the impact of radiation





History of radiation dosage

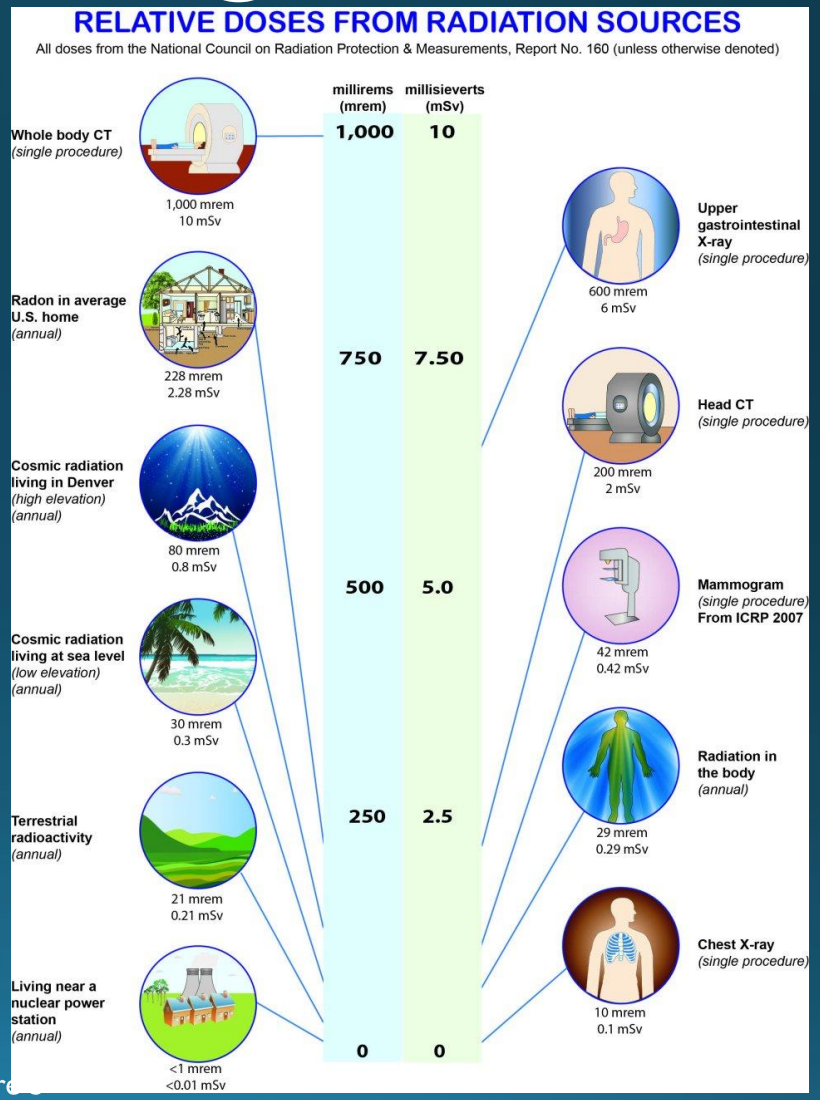


- Skin Erythema Dose (SEDs) was a subjective "first" unit
  - UV & (originally) X-Rays
  - "what is the minimum amount of radiation to cause the skin to turn red"?
    - Like sunburn
- Radiation can be lethal
  - Slotin Accident 1946
- X-Rays (and other radiation) can cause mutations
  - Hermann Muller won Nobel prize in medicine in 1946 for this discovery

Radium girls ~1917

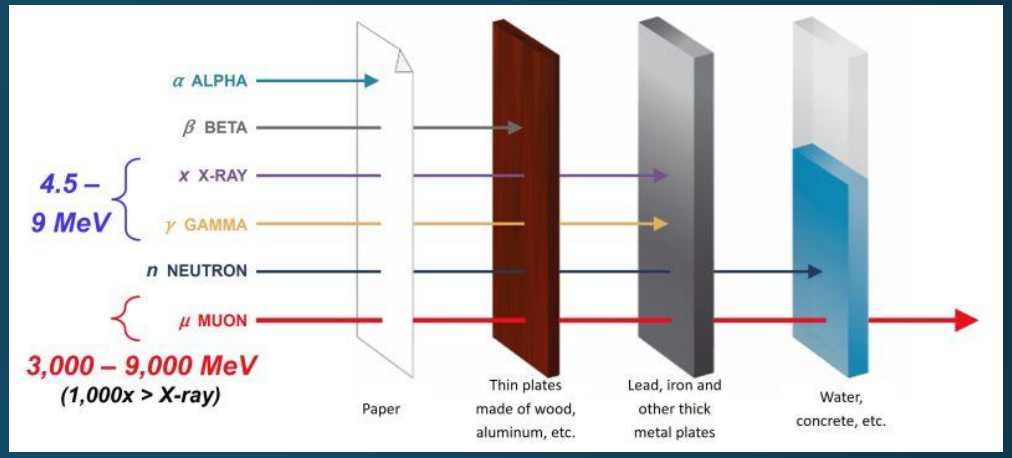
History of radiation dosage

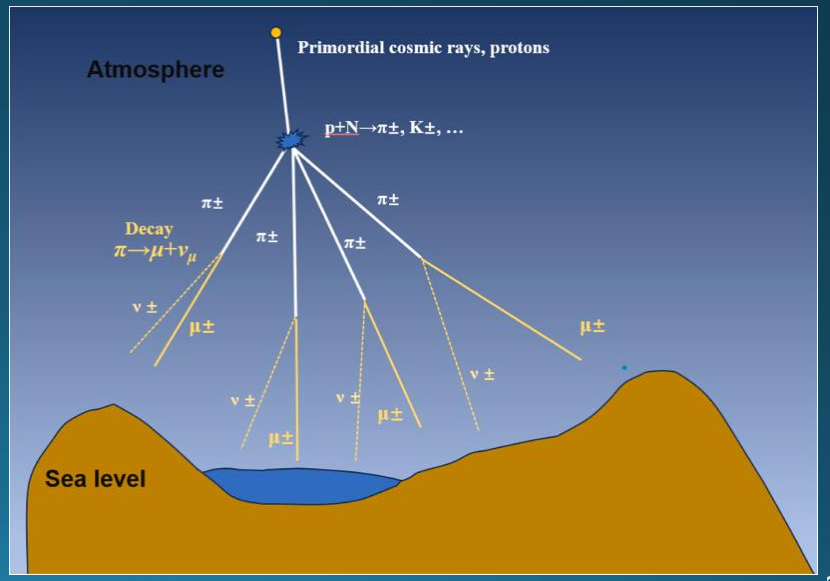
- More objective units:
  - Rad (Radiation absorbed dose)
    - Energy deposited in matter (ergs/gram)
    - 1 Rad of alphas results in more damage than 1 Rad of X-Rays
    - Because of clustering
  - Rem (Roentgen Equivalent Man) – Manhattan project era
    - Quality factor * Rads
- Sievert introduced in 1979



Muons as background radiation

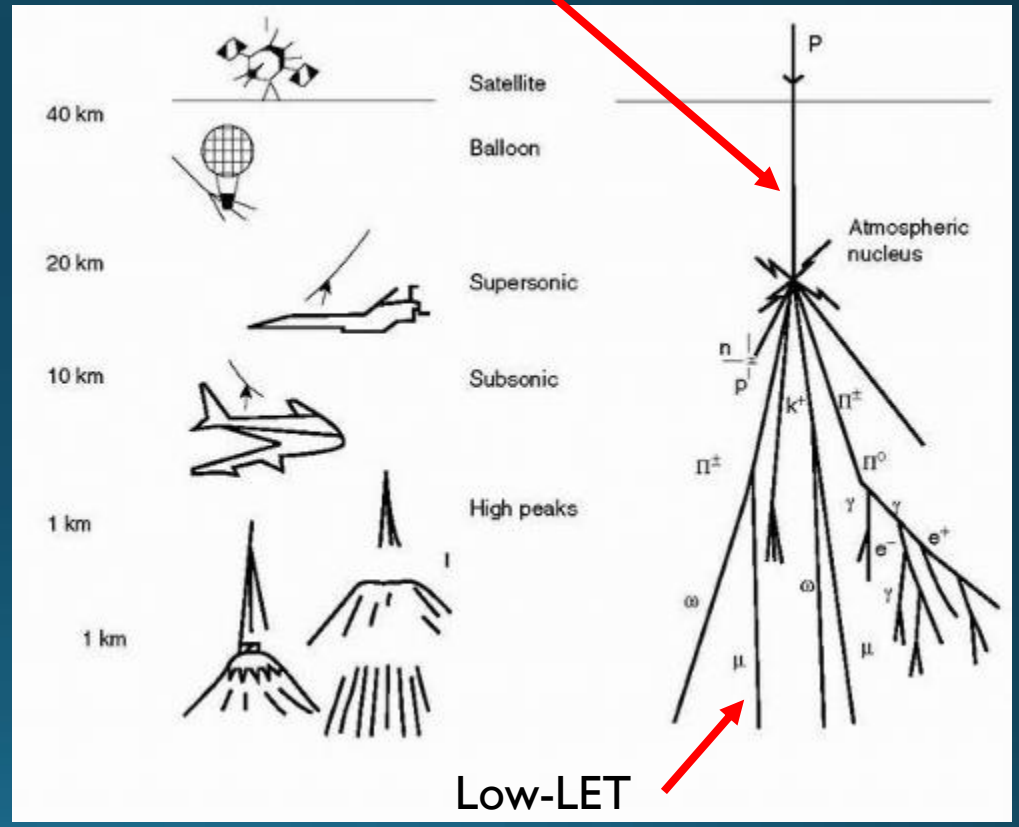
- Muons are low-LET
  - They are highly penetrating
  - Deposit energy over larger distances
- Dose rate from cosmic ray muons to human body:
  - ~0.4 mSv/year
  - mSv is milli Sieverts or 1/1000 of a Sievert
  - Potassium-40 in bananas is about the same annually
- Total human natural radiation dose is 2.5mSv/yr
  - So only ~20% comes from cosmic radiation





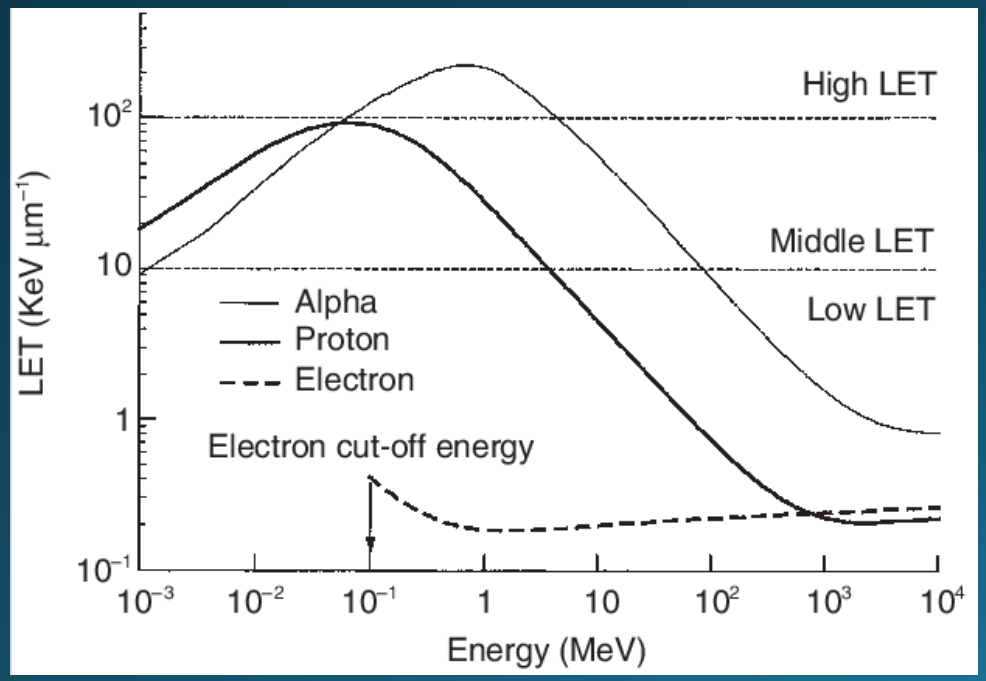
High-LET at higher altitudes

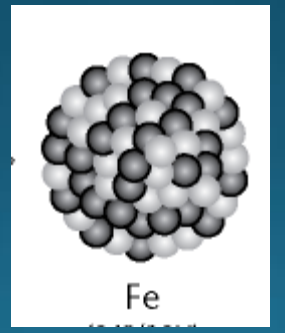
- Recall that the atmosphere is in the way of measuring these cosmic rays
- Ascend on balloons
  - As altitude increases, so does the risk of damage from the radiation

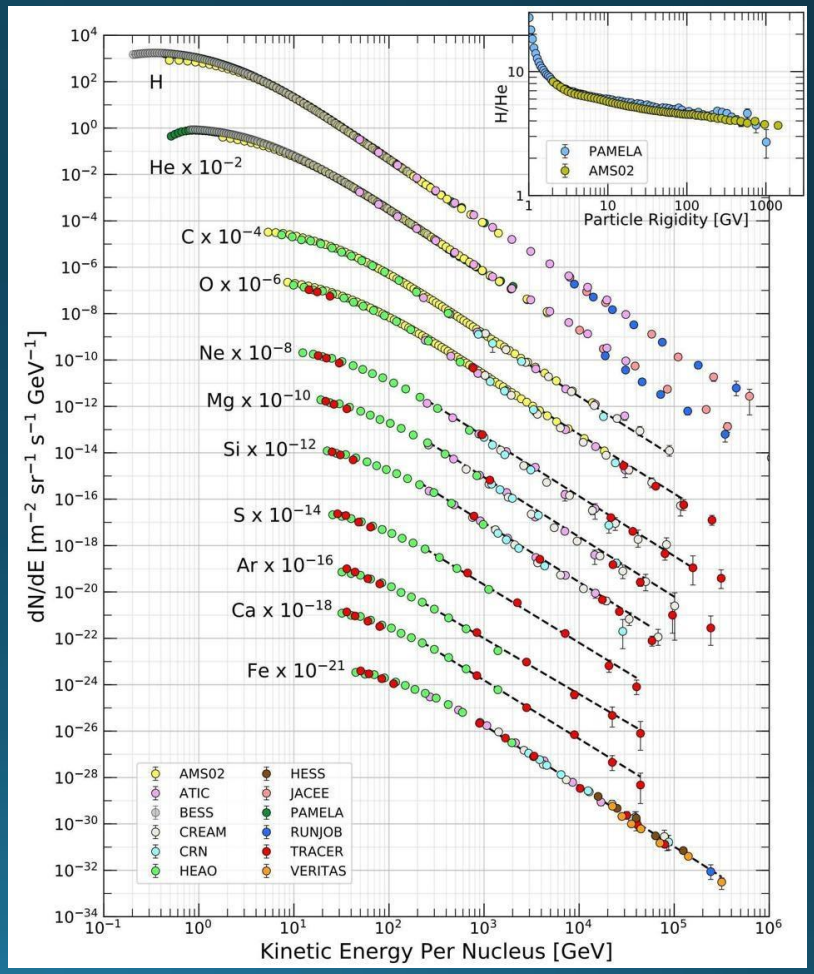


High-LET for higher charged particles

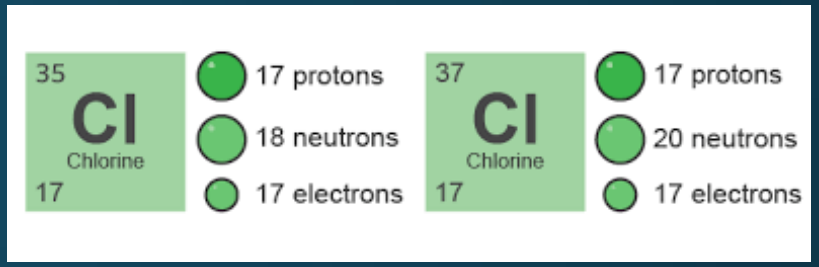
- Cosmic rays are not just protons
  - ~90% are protons
  - But high-charge nuclei also, the other 10%



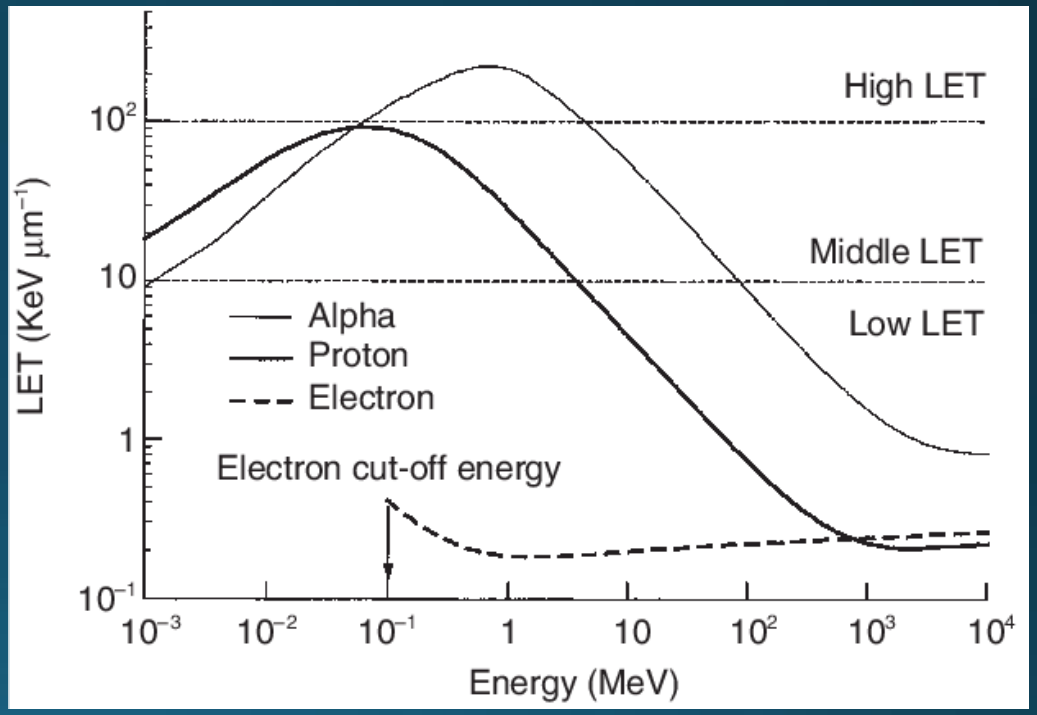




Danger in space – Hi-Z



- Hi-Z means high charge
  - Z= number of protons
- Cosmic rays are nuclei with many protons
  - Higher charge → more damage to human health
- At higher energies, the LET falls
  - Still radiation loses energy, but it loses less if it is higher energy/traveling faster



$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

Summary – the danger of cosmic radiation

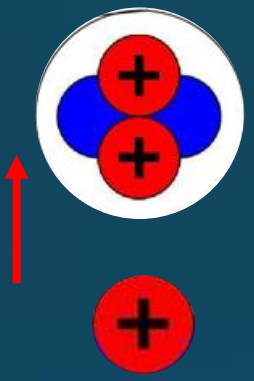
- Higher charge of nuclei → Higher risk from radiation

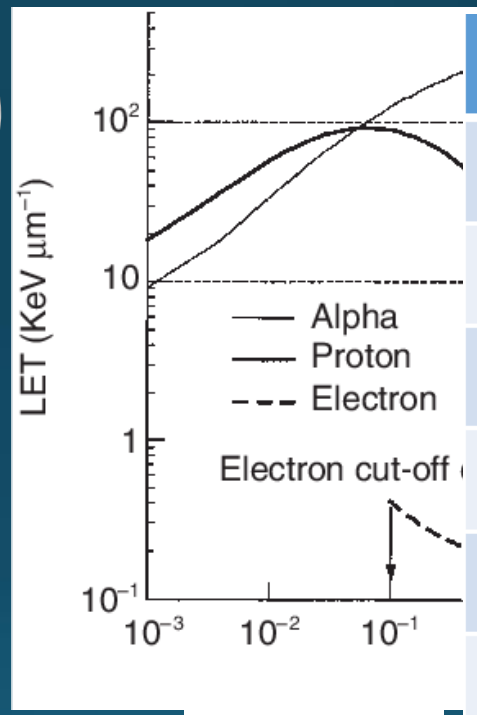
- Higher energy, less energy loss (in energy range of discussion for this lecture)

We actually use the ideas of the energy loss in proton therapy

1. Fast/high-energy protons penetrate skin

2. Protons slow down and deposit their energy mostly in tumor at depths





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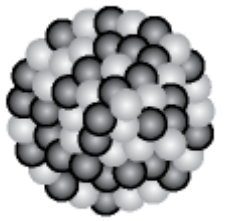
250-kV x-rays	2.0
10-MeV protons	4.7
150-MeV protons	0.5
14-MeV neutrons	12 (track average) 100 (energy average)
2.5-MeV α-particles	166
2-GeV Fe ions	1,000

$$-\left\langle \frac{dE}{dx} \right\rangle$$

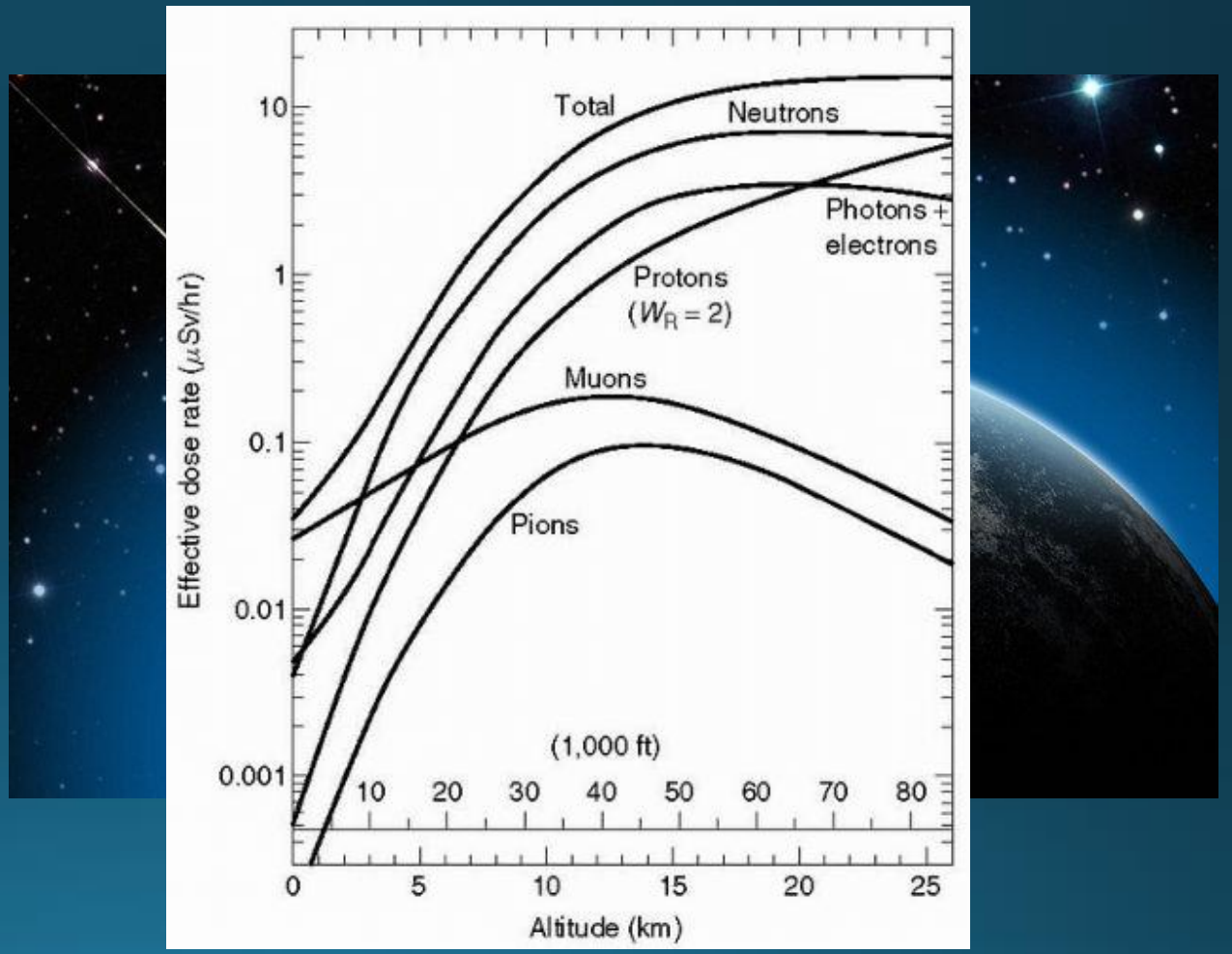


$$\left(4\pi\varepsilon_0\right) \quad \left[\left(I\cdot(1-\beta^2)\right)\right.$$

The atmosphere as a shield

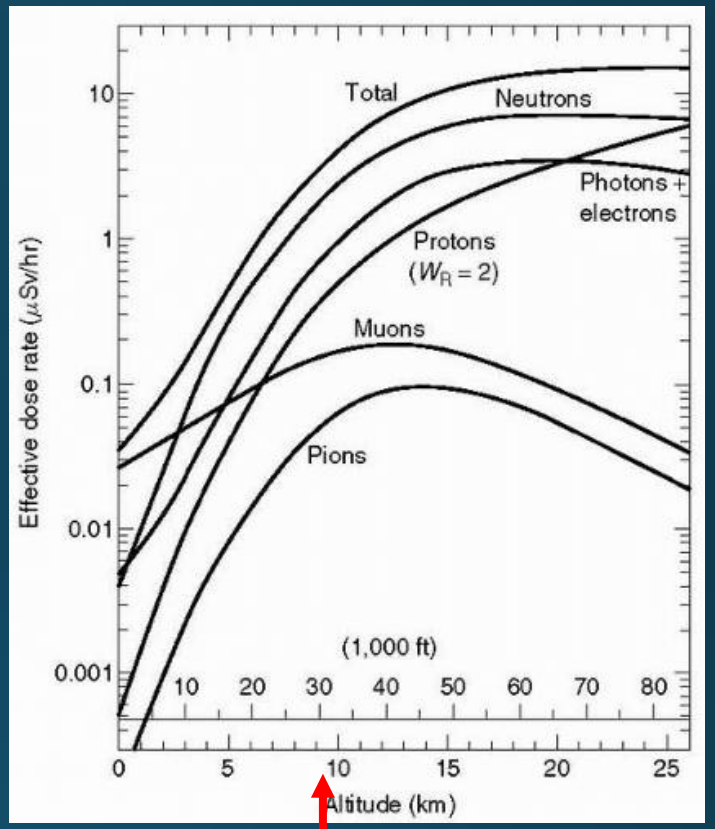
- These high-energy particles don't make it to the surface
  - Just their by-products
- The interactions in the atmosphere distribute the focused energy to a diffuse flux of particles
- Muons = not *as* harmful
  - Hence the 0.4mSv/yr

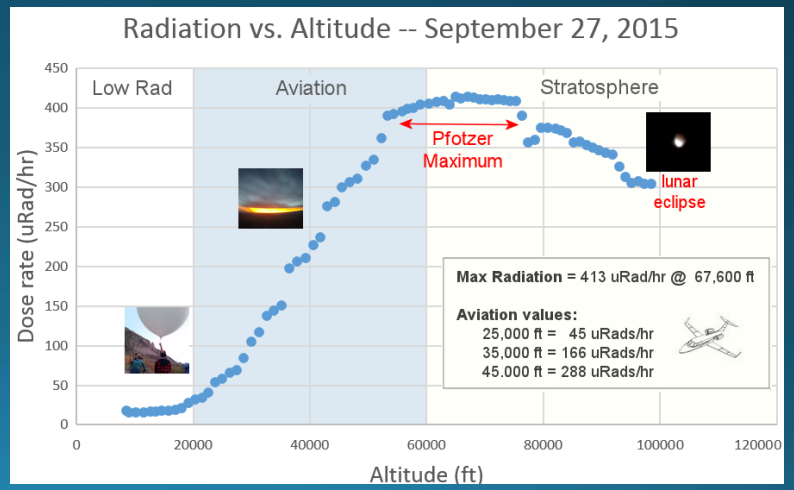
Remember: 2.5mSv/yr



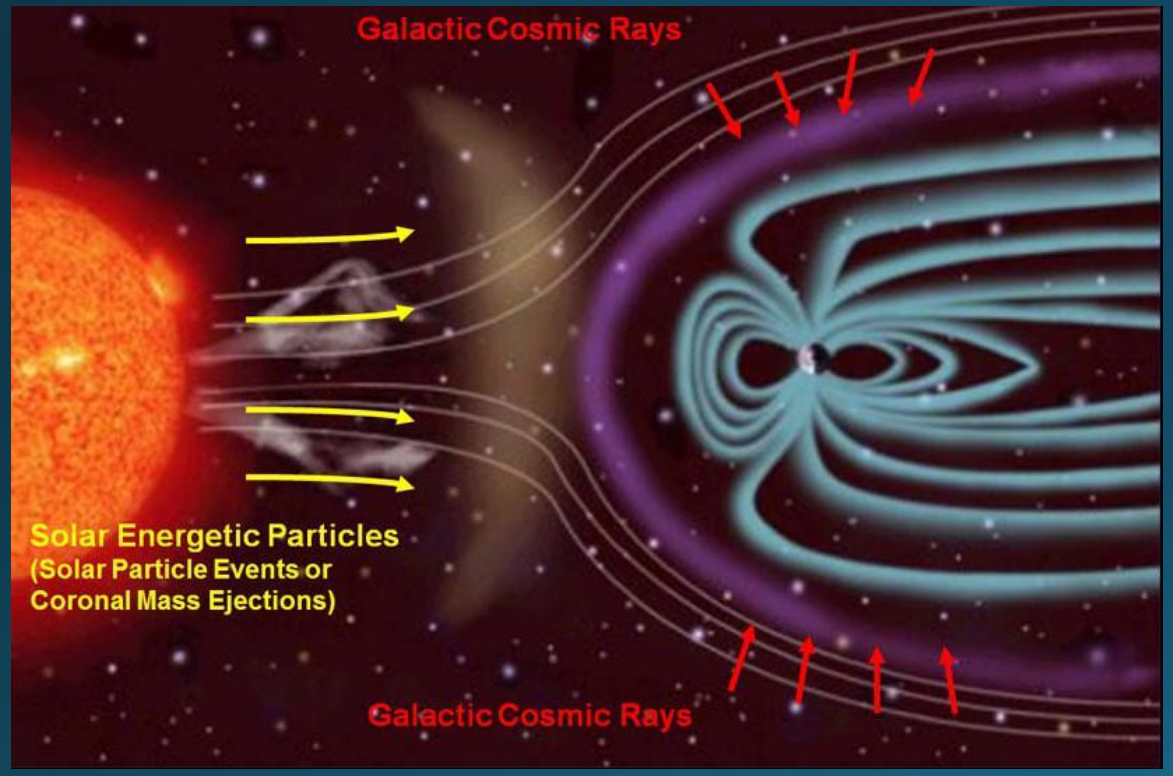
Pilot vs avg human

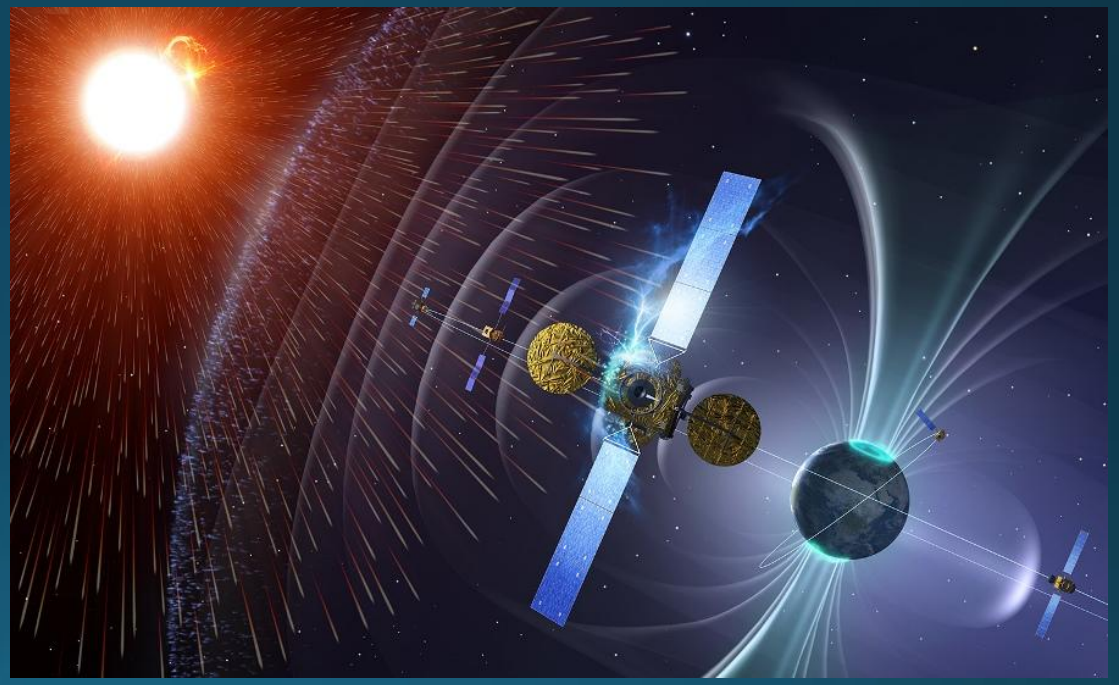
- Closer to 7mSv/yr
  - Compared to 2.5mSv/yr
- But where is the extra radiation dose coming from?
  - The cosmic radiation
  - Mostly neutrons
    - Neutrons do more damage so even though they are not so frequent, they have higher Sieverts (impact)
- Astronauts are exposed to even more radiation
  - Less atmosphere

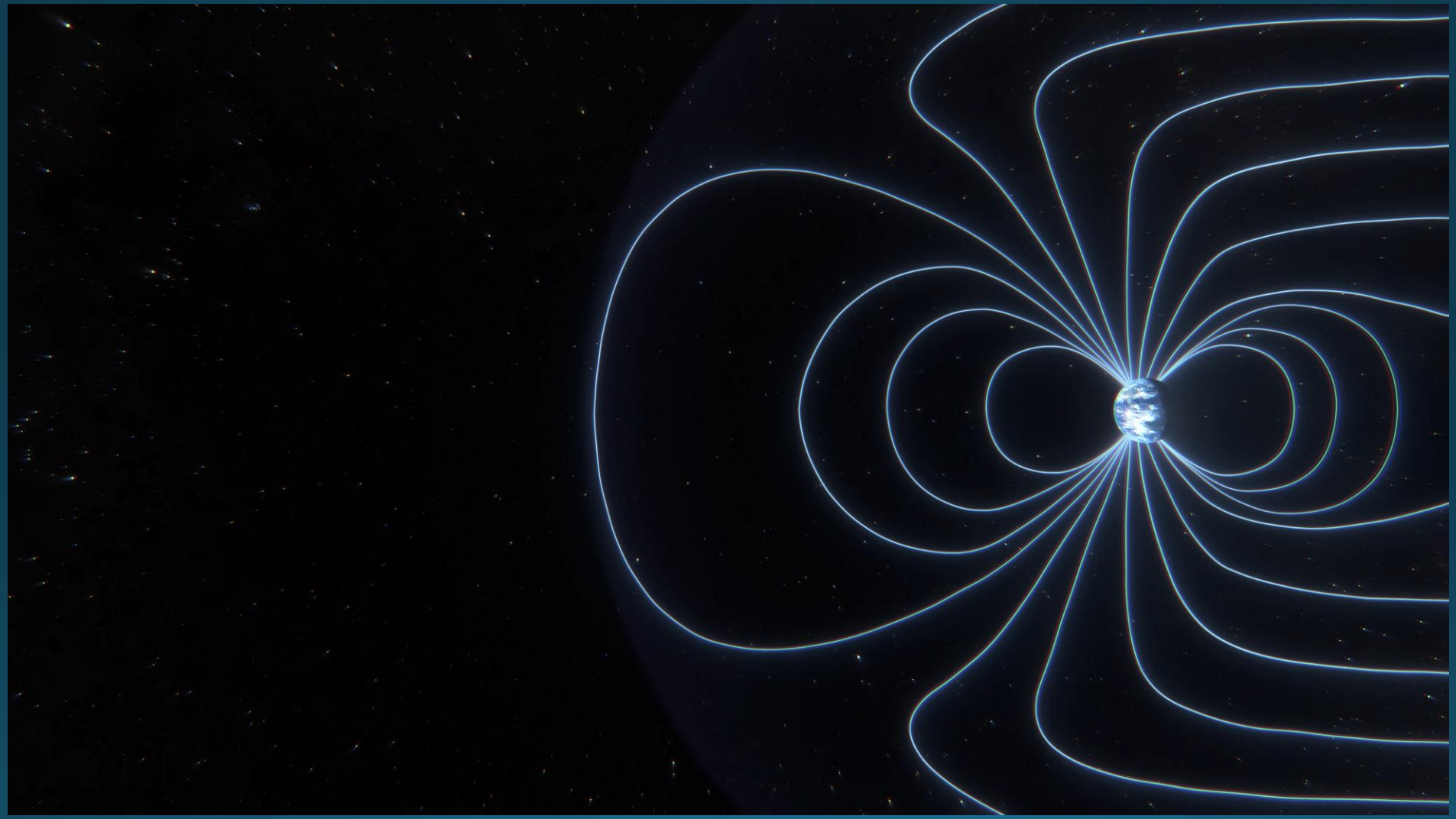




The magnetic field as a shield

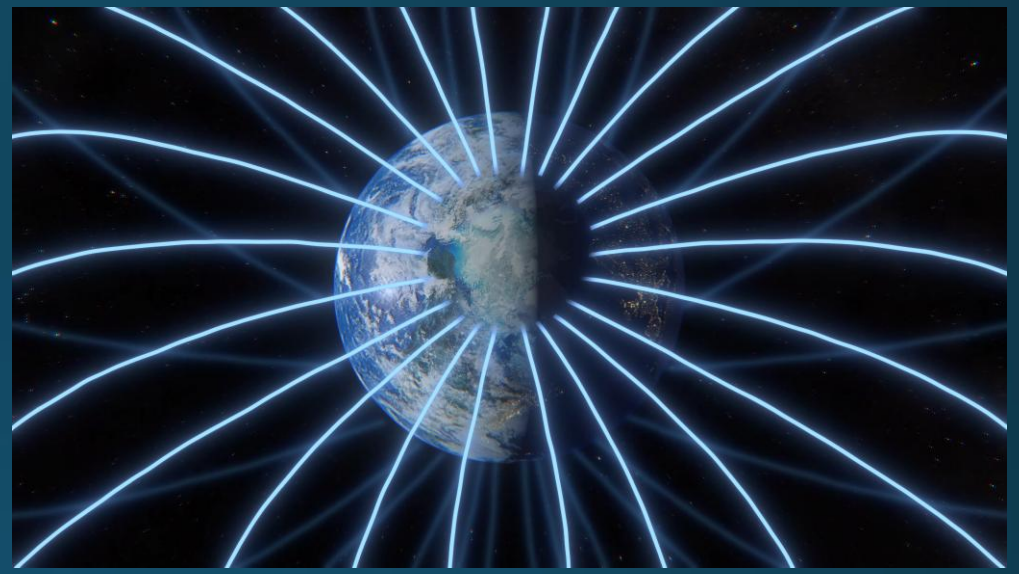


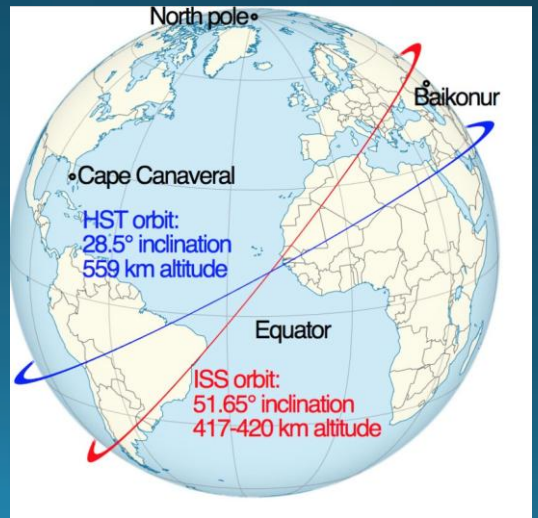




Funneling particles to the poles

- Higher latitudes, more cosmic rays
- Towards equator, less cosmic rays
  - ISS astronauts receive higher doses than Space Shuttle astronauts
  - 0.5 mSv/day (180 mSv/yr)
- Energy/rigidity cutoff
  - If the cosmic rays are fast enough, they punch through the magnetic field
- Earths' field is a few milliGauss
  - If there were a stronger magnetic field, less energetic cosmic rays would make it to the Atmosphere





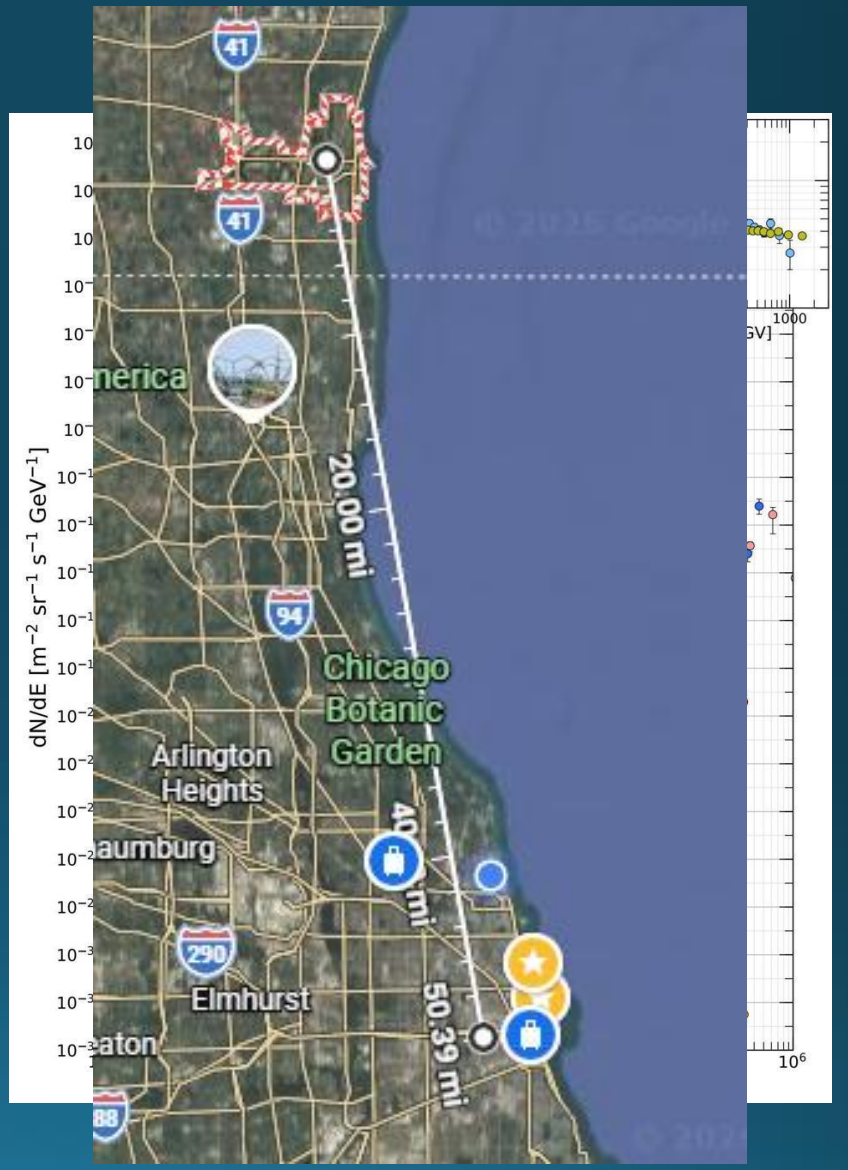
Going from LEO to lunar missions

- Remove the atmosphere
- Still some protection with magnetic fields
- Exposure to much higher radiation
- Radiation from the sun and cosmic rays
- Lunar orbiter (and ~surface)
- Measurements from LRO
  - 1.3mSv/day
  - 2.5 times the ISS astronauts' dosage rate
  - 200 times higher than Earth surface!

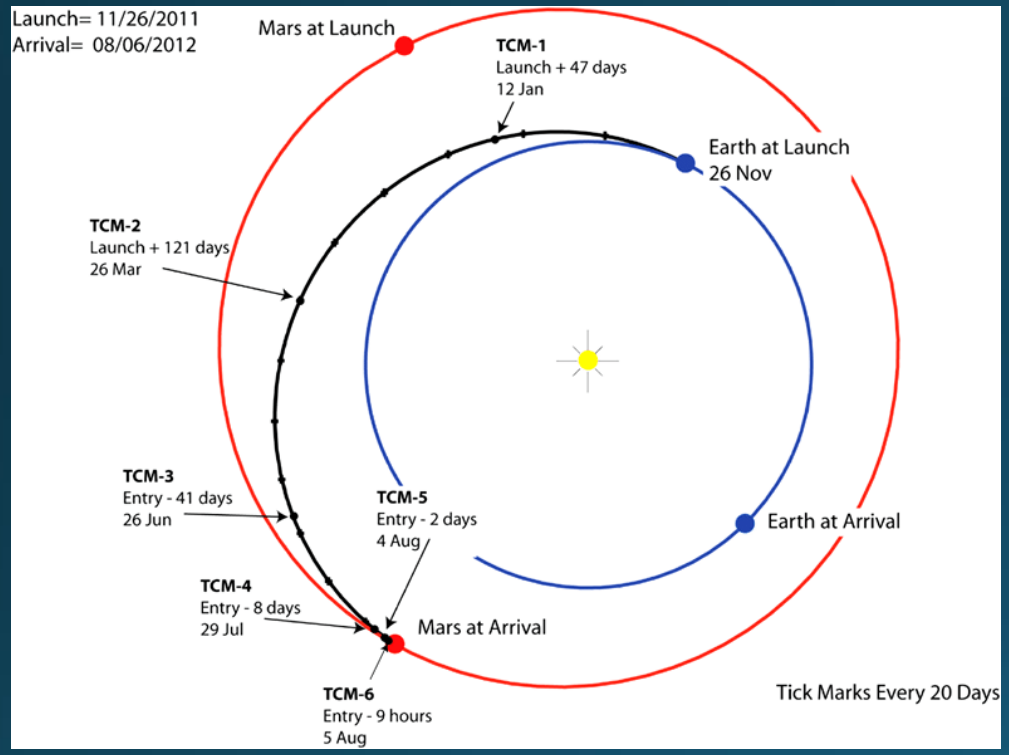

Scale: 1 Pixel = 10 Km / 6.2 mi
2000 Km / 1243.7 mi
Orbital Altitudes of many significant satellites of earth
0 km / mi - Sea Level.
37.6 km / 23.4 mi - Self Propelled Jet Aircraft Flight Ceiling (Record Set in 1977).
215 km / 133.6 mi - Sputnik-1 The first artificial satellite of earth.
340 km / 211.3 mi - International Space Station.
390 km / 242.3 mi - Former Russian Space Station MIR.
595 km / 369.7 mi - Hubble Space Telescope.
[700 - 1700 km] - Polar Orbiting Satellites.
[435 - 1056 mi]
Earth Radius 6378 Km / 3963 mi
LEO Zone (Low Earth Orbit)
MEO Zone (Medium Earth Orbit)
2000 Km / 1243.7 mi
600 - 800 km / 372.8 - 497.1 mi - Sun-synchronous Satellites
These satellites orbit the Earth in near exact polar orbits north to south.
They cross the equator multiple times per day and each time they are at the same angle
with respect to the sun. Satellites on these types of orbits are particularly useful
for capturing images of the Earth's surface or images of the sun.
20,350 km
GPS (Global Positioning System) Satellites
These Satellites are on a Semi-synchronous Orbit (SSO)
meaning that they orbit the earth in exactly 12 hours (twice per day).
35,786 km
Geosynchronous (GEO) and Geostationary (GSO) Satellites
Geosynchronous satellites orbit the Earth at the same rate that the
Earth rotates. Thus they remain stationary over a single line of longitude.
A geostationary satellite will remain in a fixed location as observed
from the earths surface, allowing a satellite dish to be alligned to them.
This particular altitude marks the border between the MEO and
HEO Zones.
HEO Zone (High Earth Orbit)
Scale: 1 Pixel = 100 Km / 62.1 mi
20000 Km / 12437.4 mi
MEO Zone (Medium Earth Orbit)
HEO Zone (High Earth Orbit)
LEO Zone (Low Earth Orbit)
384,000 km
The Moon

Distance scaling

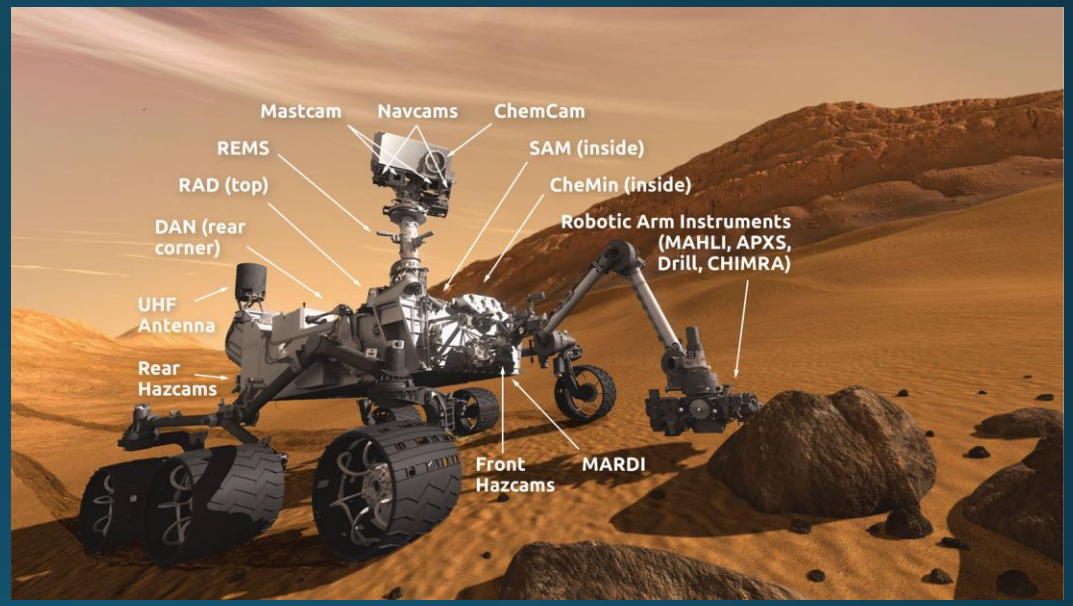
- ISS at 400km
- Lunar orbit at 385,000km
  - or ~0.385 Giga meters
- If the ISS was the building across the street, the Moon would be somewhere in Kenosha
- Daily radiation dose is 2-3 times the ISS astronauts
  - Integrate or sum up all the cosmic rays
  - Somewhat still protected by Earth's magnetic field
  - As measured with lunar landers
    - Ask Payton about them in 2 weeks



Mars - traveling even farther



- Deep space measurements (en route to Mars)
- ~2mSv/day (750 mSv/yr)



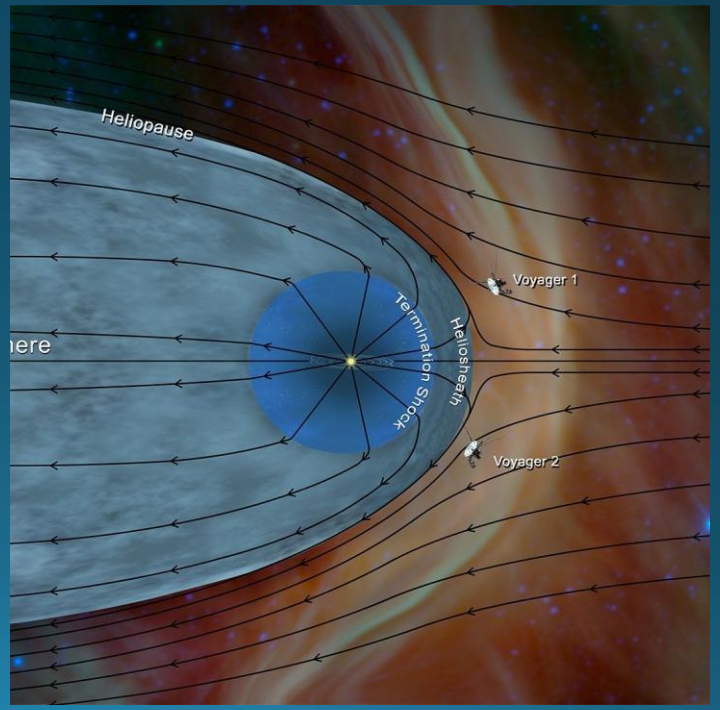
- Mars has thin atmosphere
- Measurements by Mars Science Lab on Curiosity ~0.6 mSv/day (220 mSv/yr)

The total radiation dose astronauts would receive is close to ~1Sv/yr level
Types of shielding needed!

What about leaving the Solar system?

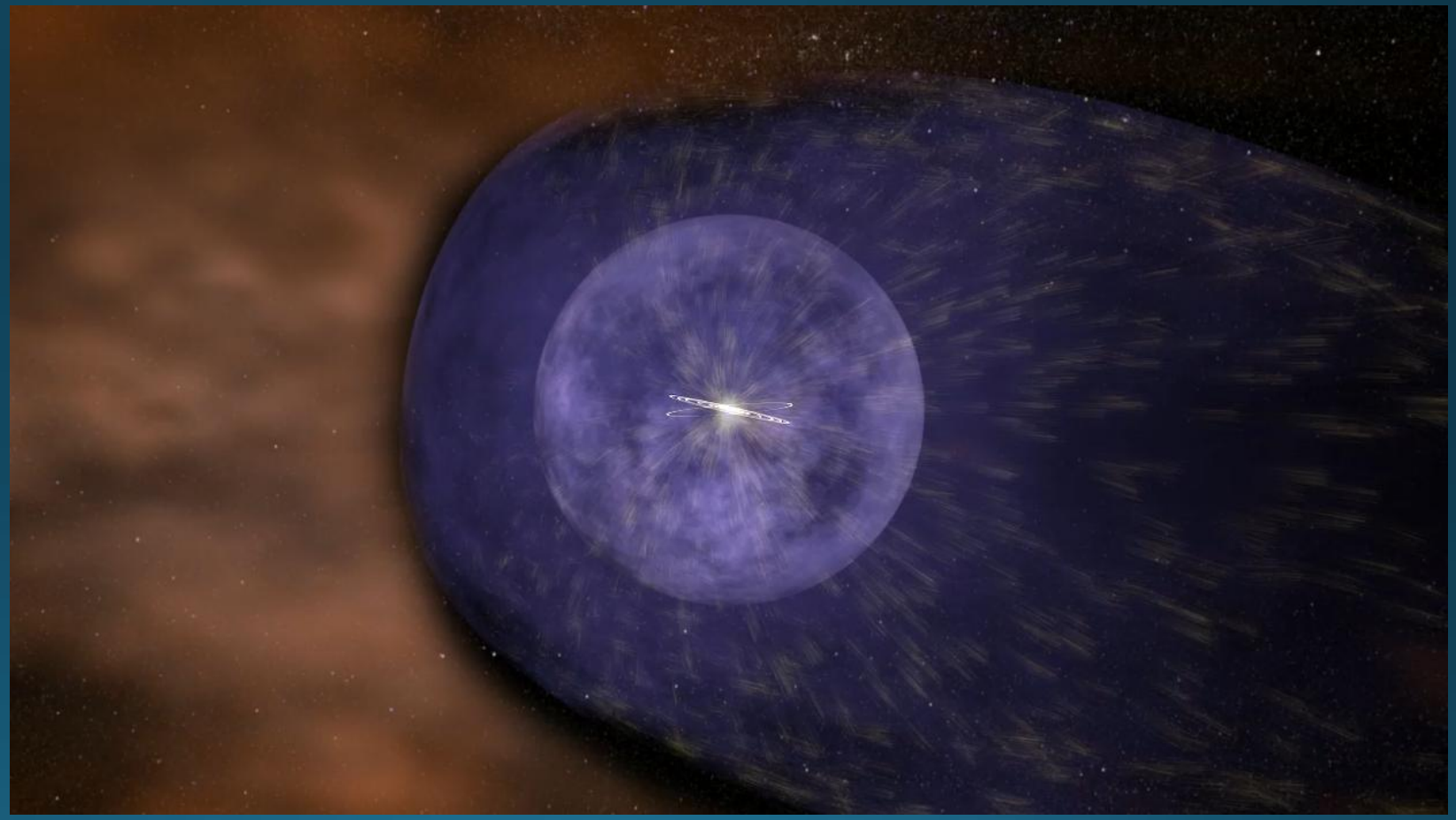
Well, something has…and it had detectors on-board

- Voyager 1 (2012) and 2 (2018)
- Cosmic ray measurements
  - Outside the heliosphere for the first time
  - Charged particles from the sun make a solar wind, the heliosphere
- "Low energy" cosmic ray flux (<100 MeV) increases by 4 times outside the solar system
  - Crossing the heliosphere →more radiation
  - This is interstellar space



The heliosphere as a shield

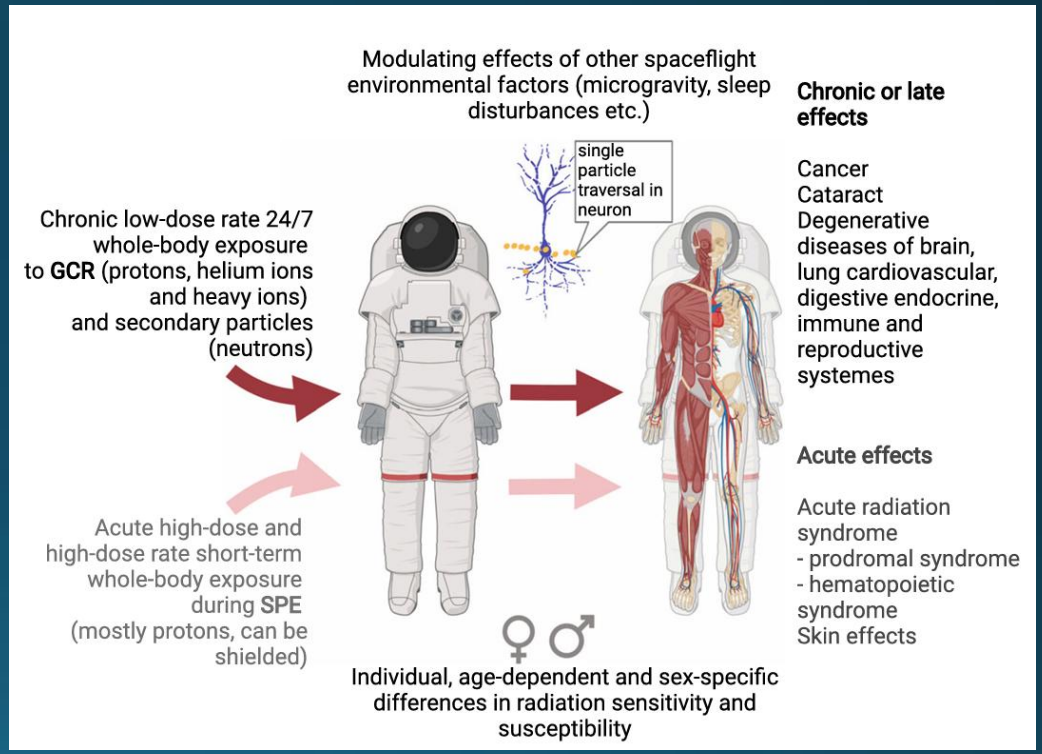
- Solar system in the heliosphere
- As the sun's activity changes, so does its extent to shield solar system from GCRs



Types of shielding possible

- Passive
  - More material
    - Like the Atmosphere
  - ISS astronauts do this already during SPE
    - Solar particle events and geomagnetic storms
- Active
  - Like the Earth's and the Sun's magnetic field
- Challenges
  - Heavy material (passive) and requires more energy (active)

Ongoing work – human ingenuity at its best!



Dosage rate with aluminum shielding

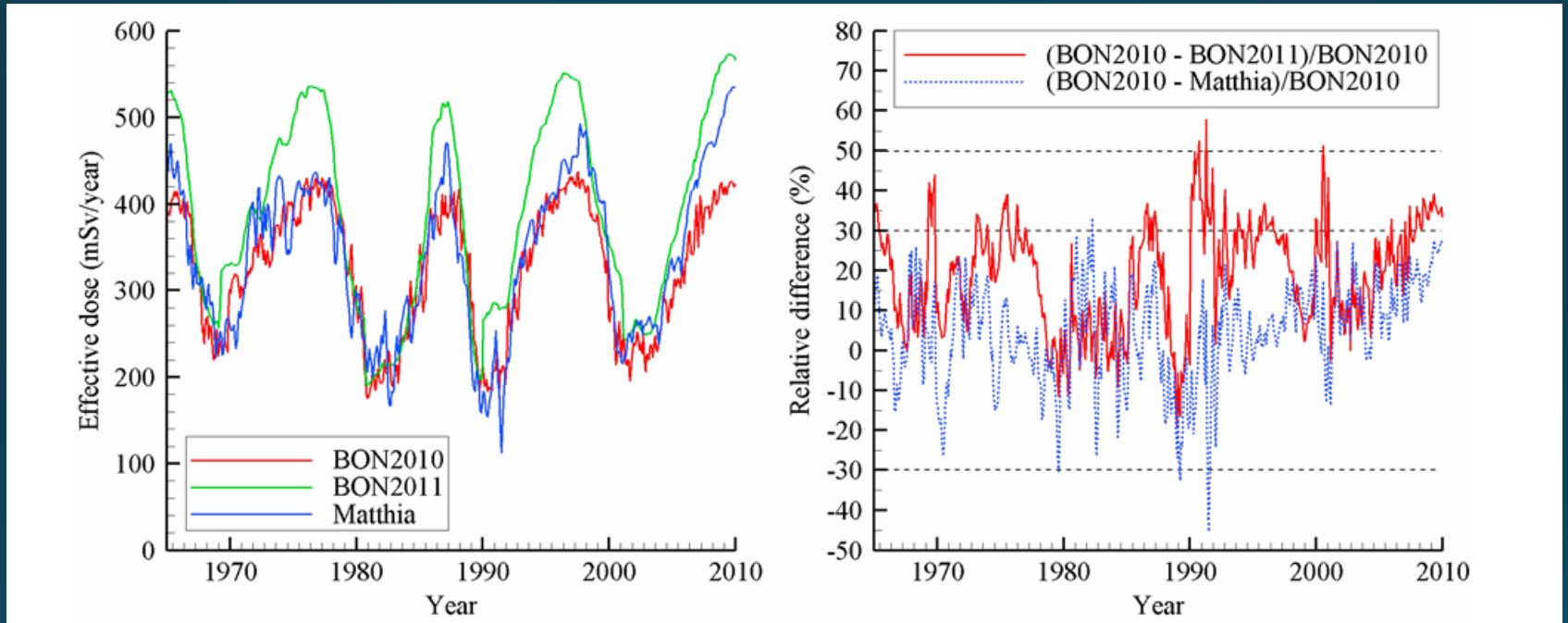


Figure 1. Effective dose versus time behind 2 g/cm^2 of aluminum shielding using three different GCR models. Effective dose was computed using the ICRP 60 quality factor [*ICRP*, 1990] and ICRP 103 tissue weights [*ICRP*, 2007] with the FAX (Female Adult Voxel) human phantom [*Kramer et al.*, 2004] as described by *Slaba et al.* [2010a]. Transport was performed with HZETRN-π/EM [*Wilson et al.*, 1991; *Slaba et al.*, 2010b, 2010c; *Norman et al.*, 2013].

Active field of research

The safe dose evolution

- NASA originally for Apollo missions had very little (no) guidance on radiation dose
  - It wasn't nearly the biggest risk to the astronaut
- ~1970 the doubling rule
  - Career exposure was 4 Sv
  - Doubles the lifetime risk of leukemia
- Individualized exposure risk assements
  - The Age & Gender Shift (NCRP Report 98)

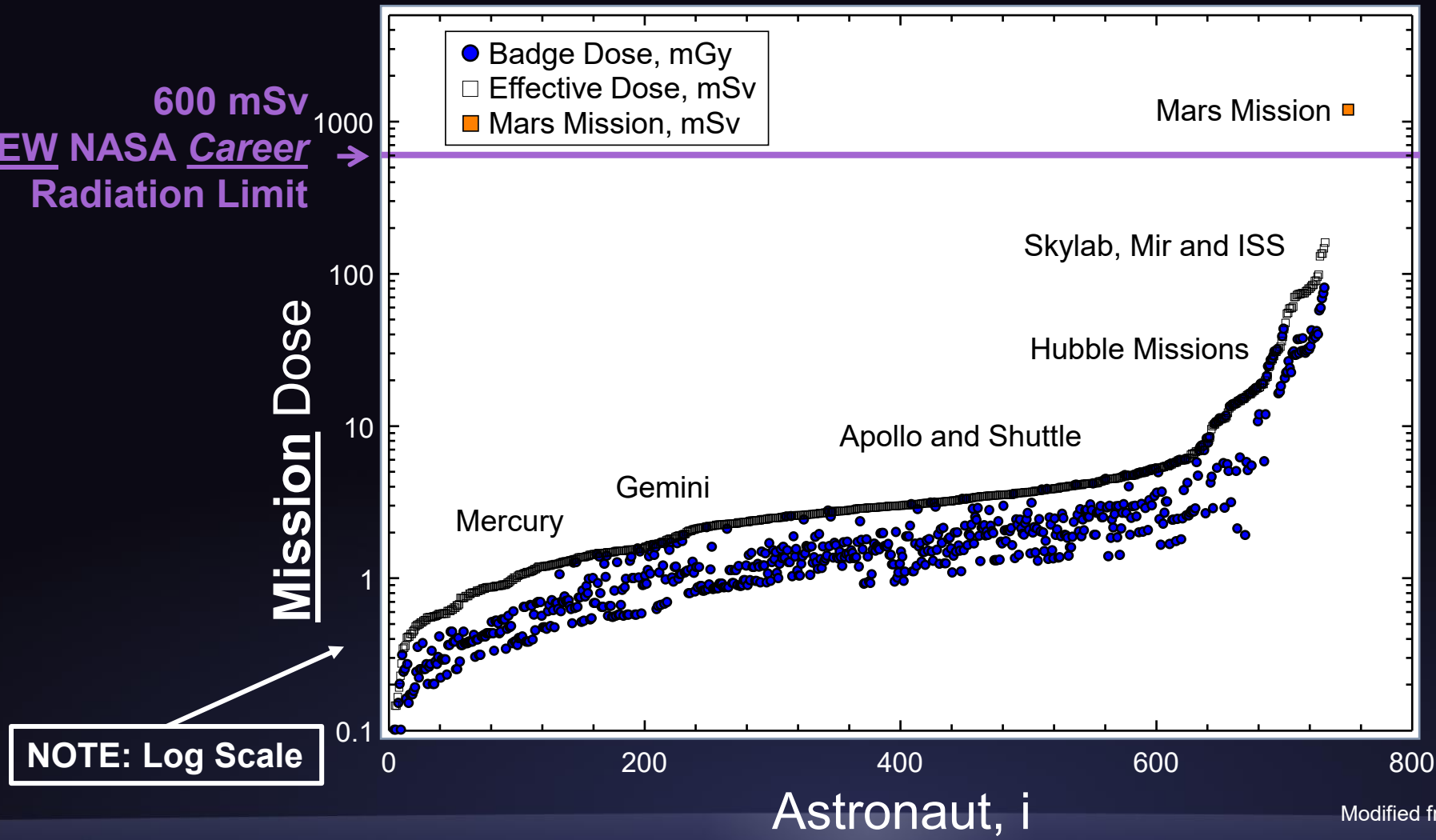
NASA has followed several distinct recommendations on radiation limits since the Apollo era today due to the evolving understanding of space radiation environments inside spacecraft and tissue, new epidemiology data, and the age and gender makeup of astronauts. Recommendations by the National Academy of Sciences (NAS) in 1967 (NAS 1967) noted that radiation protection in manned space flight is philosophically distinct from protection practices of terrestrial workers because of the high-risk nature of space missions. The 1967 NAS report did not recommend "permissible doses" for space operations, noting the possibility that such limits may place the mission in jeopardy and instead made estimates of what the likely effects would be for a given dose of radiation (Schimmerling, 2009).

TABLE 6.7—*Career whole-body dose equivalent limit (Sv) for a lifetime excess risk of fatal cancer of three percent as a function of age at exposure.* [a, b]

Age	25	35	45	55
Male	1.5	2.5	3.25	4.0
Female	1.0	1.75	2.5	3.0

[a] 1 Sv = 100 rem.
[b] Based on a 10 year exposure duration.

Historical NASA Crew MISSION Doses



600 mSv
NEW NASA *Career* Radiation Limit

NOTE: Log Scale

650 mSv
NCRP Guidance for Radiation Worker *Lifetime* Limit for 65yo

50 mSv/yr
Radiation Worker *Annual* Limit

3.6 mSv
Average US *Annual* Background Dose

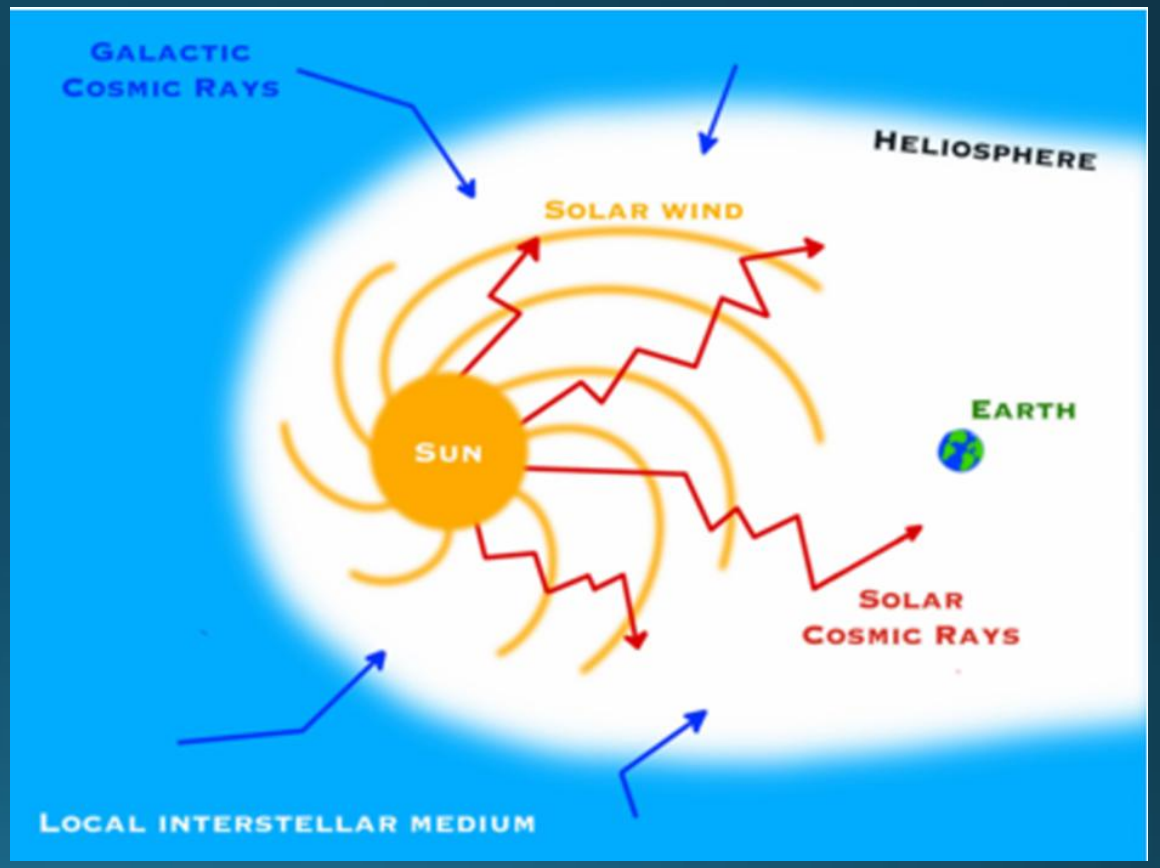
Modified from Cucinotta et al. Radiat Res (2008)

What about finding life?

- A related field of research
  - Radiation is a hazard
- Other worlds
  - Exoplanets (or extrasolar planets)
- First 3 exoplanets discovered are near a pulsar
  - Unknown if they have atmospheres
  - The amount of radiation at the surface is probably extremely high (but depends on the atmosphere)
- Over 6,000 exoplanets discovered

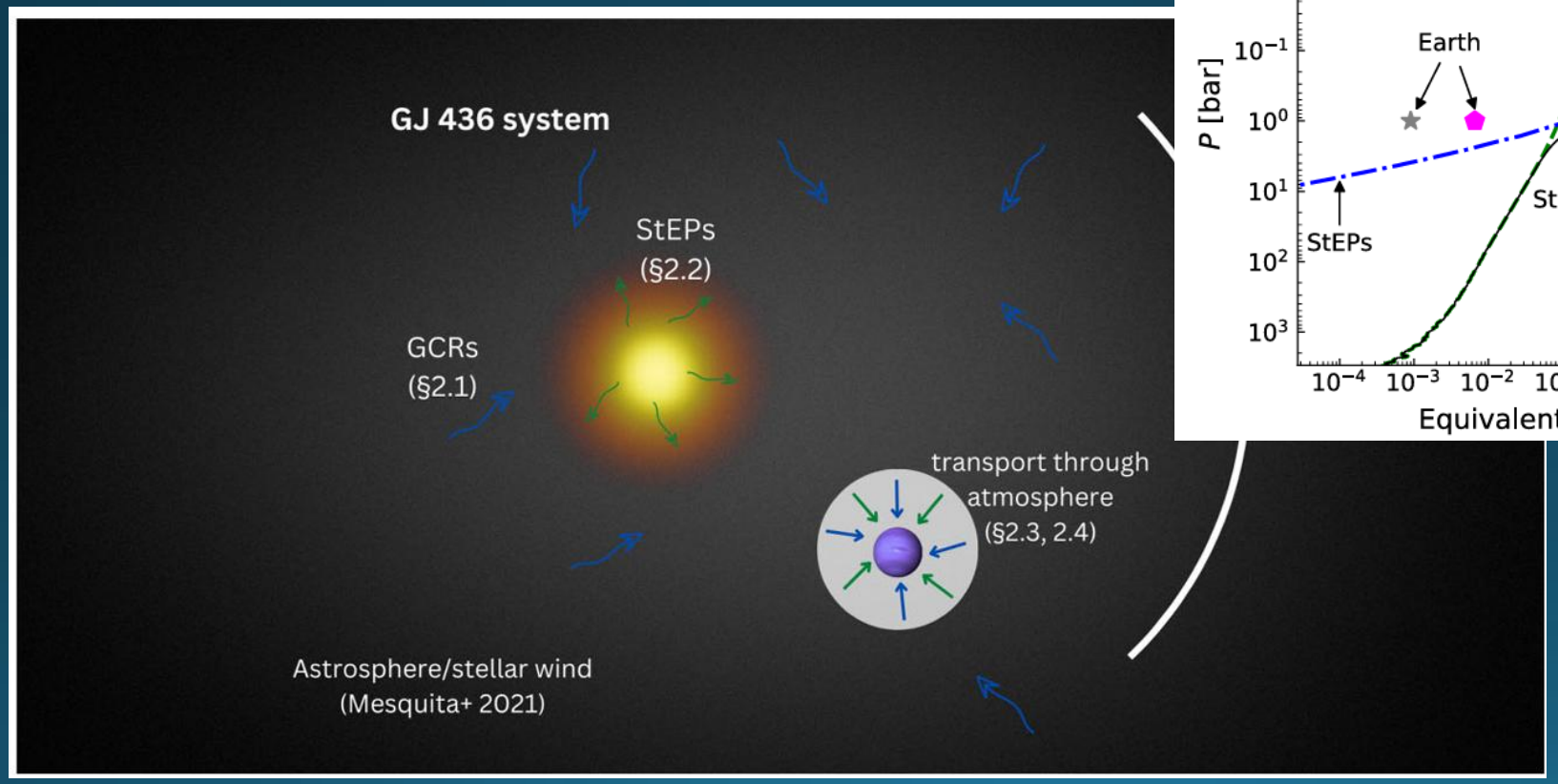
Habitable zones

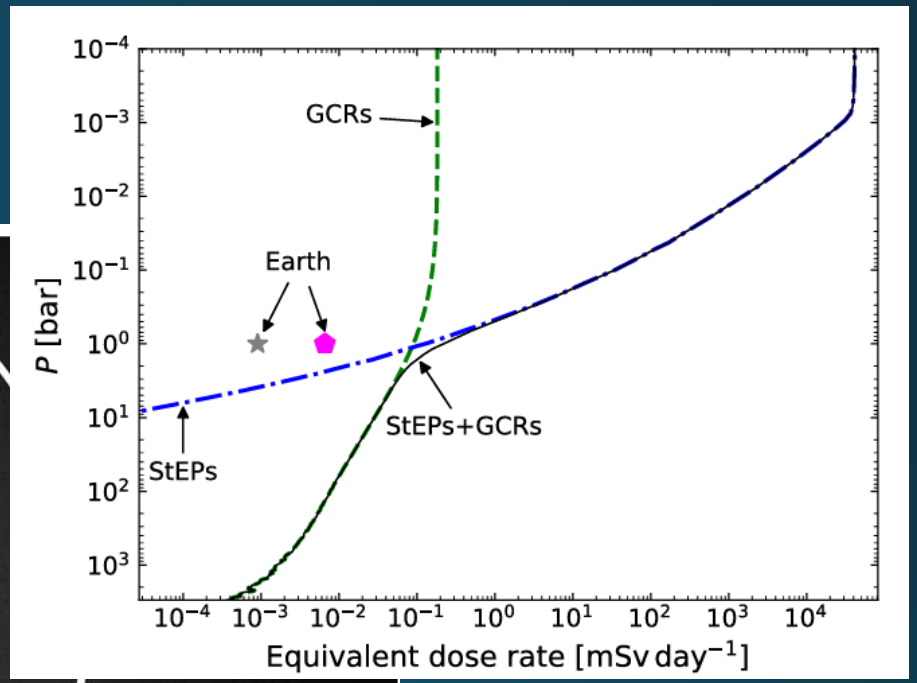
- The sun's activity impacts the cosmic rays that make it to Earth
  - And, therefore, the radiation environment here on Earth
- Other planets around other stars can have a similar coupling
- Active research in determining if an exoplanet is in the habitable zone
  - energetic particle environments



Energetic particle environments of exoplanets

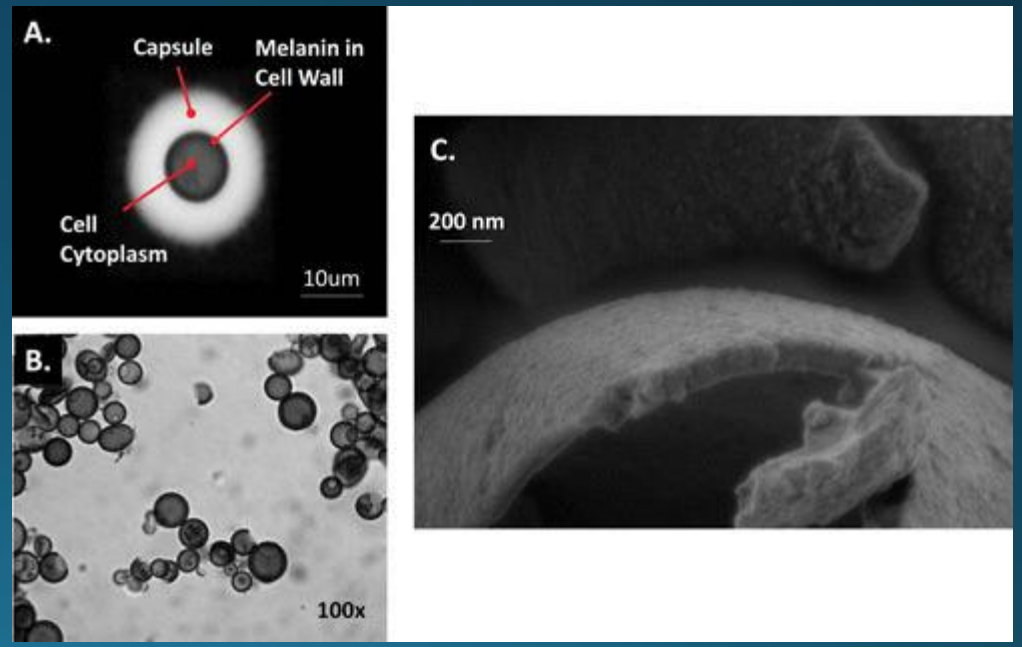
Dr. Rodgers-Lee's research





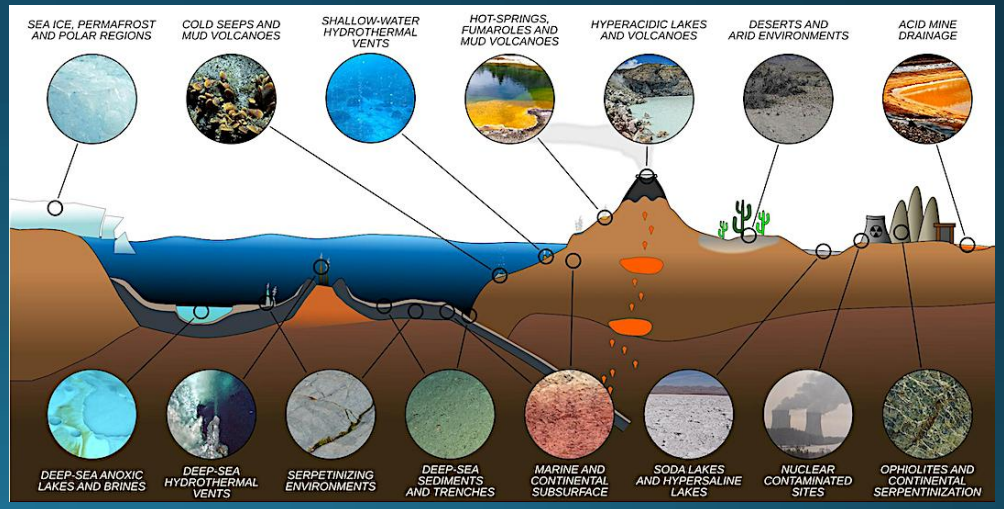
Some lifeforms use radiation

- Black mold found in Chernobyl walls
  - Early 1990s
  - Melanin in the fungus allows it to "eat" radiation - radiosynthesis
- Transform ionizing radiation into biological energy
  - Ongoing research
  - Even research on using fungi like this in space



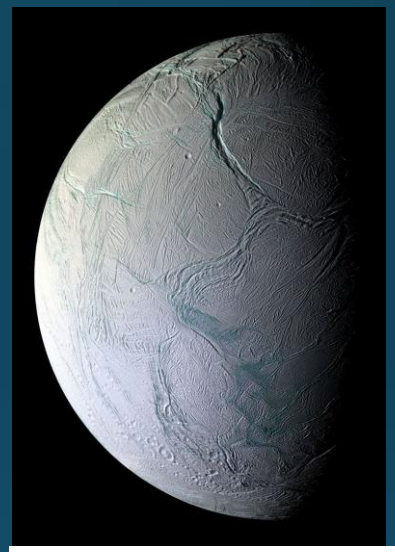
Extremophiles

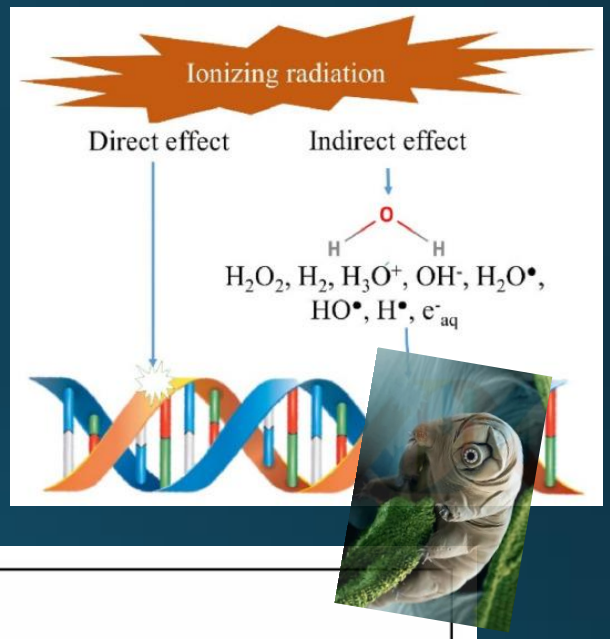
- Life can withstand ridiculous environments
- Too many interesting things to mention
- The most resistant organism found so far is:
  Deinococcus radiodurans
  - Survives more than 1000 times the radiation dose needed to kill a person
  - Even more than tardigrades



Searching for life on other planetary bodies

- Life on other worlds might utilize the radiation
  - Might not be life as we know it
- Radiolysis on planetary bodies with lack of atmosphere
  - Beneath ice of Enceledus
  - Cosmic rays make it through some of the rock/ice
  - Source of radiation/energy for those extraterrestrial extremophiles





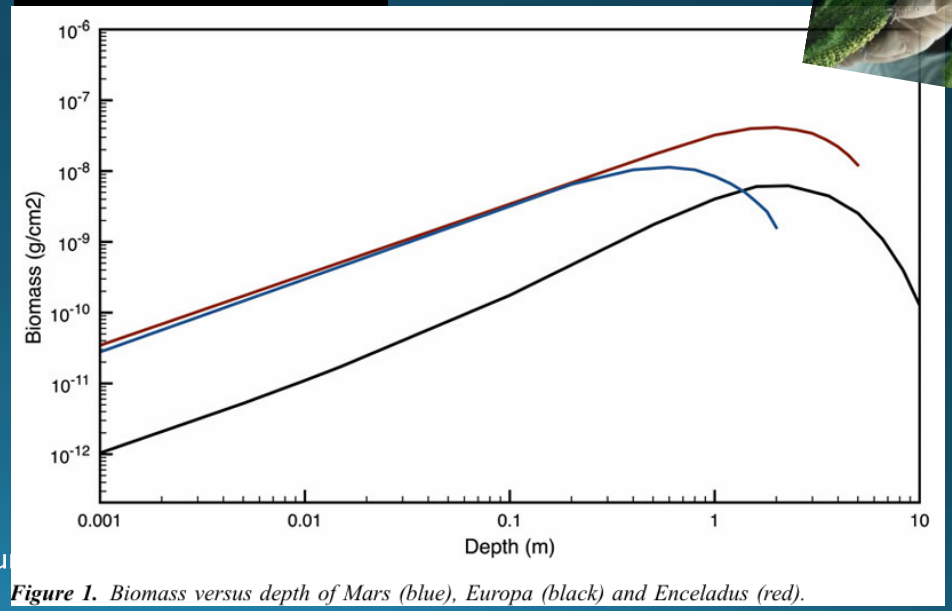
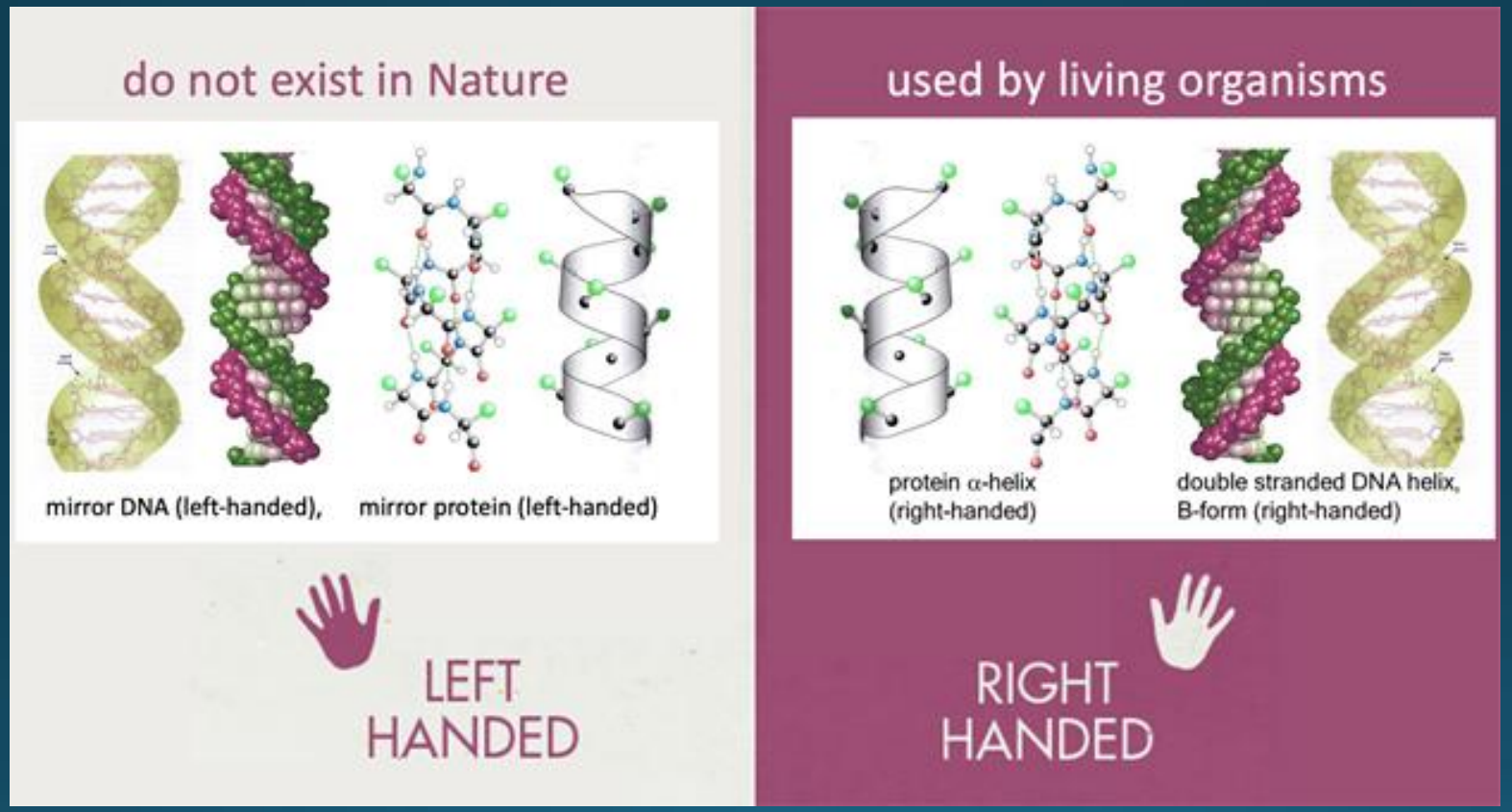


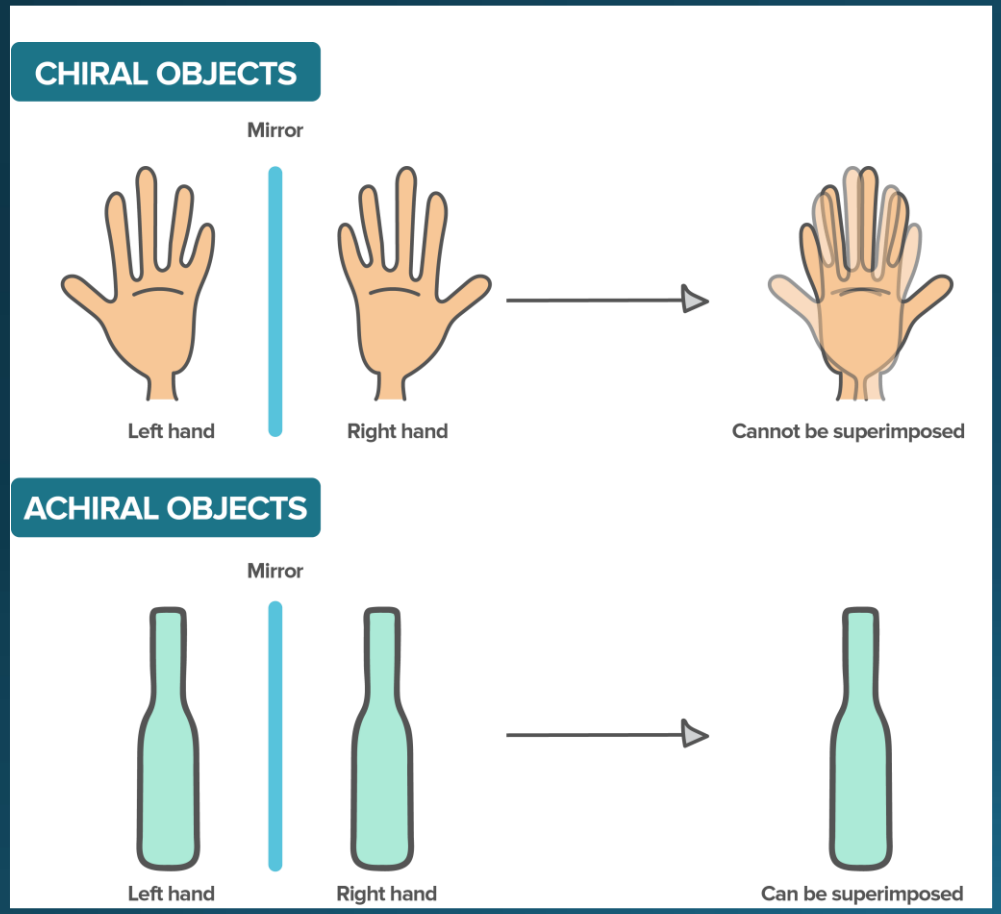
Figure 1. *Biomass versus depth of Mars (blue), Europa (black) and Enceladus (red).*

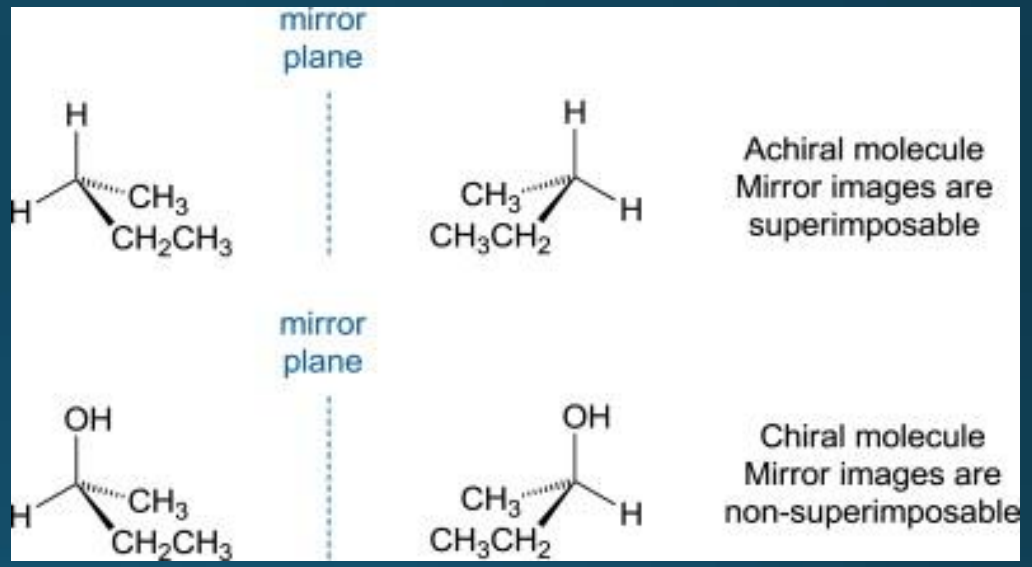
The chirality of life

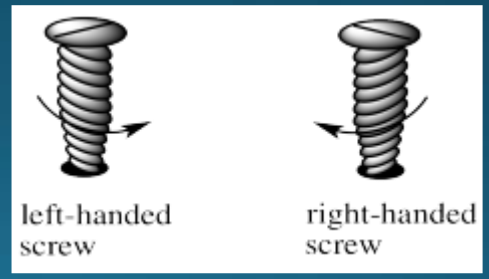


Perplexing puzzle in the origin of life on Earth.
Why does life exhibit homochirality?

What is chirality

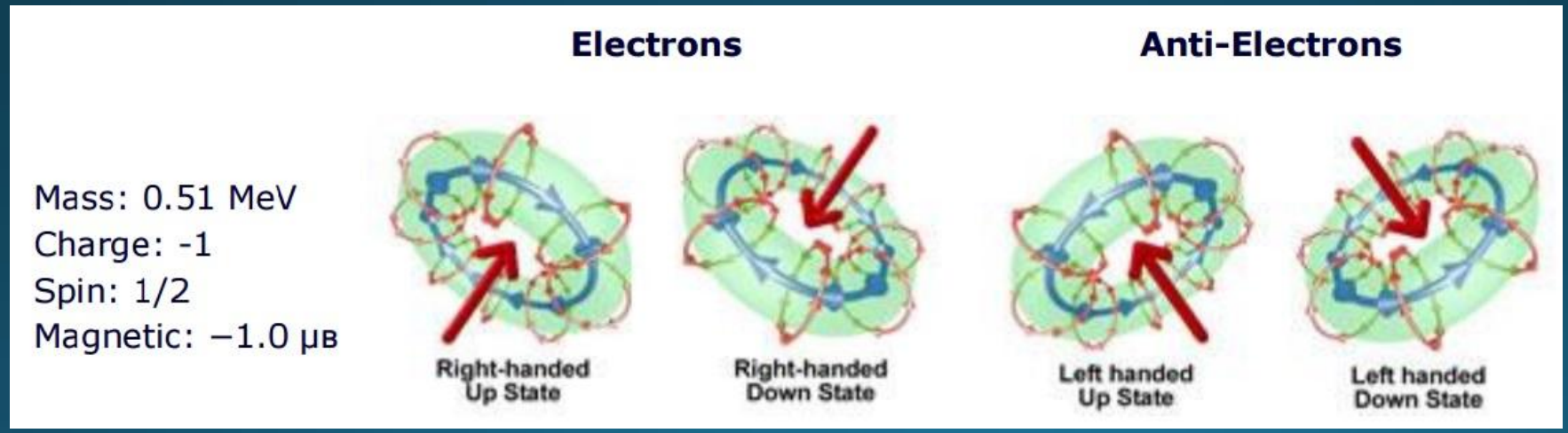






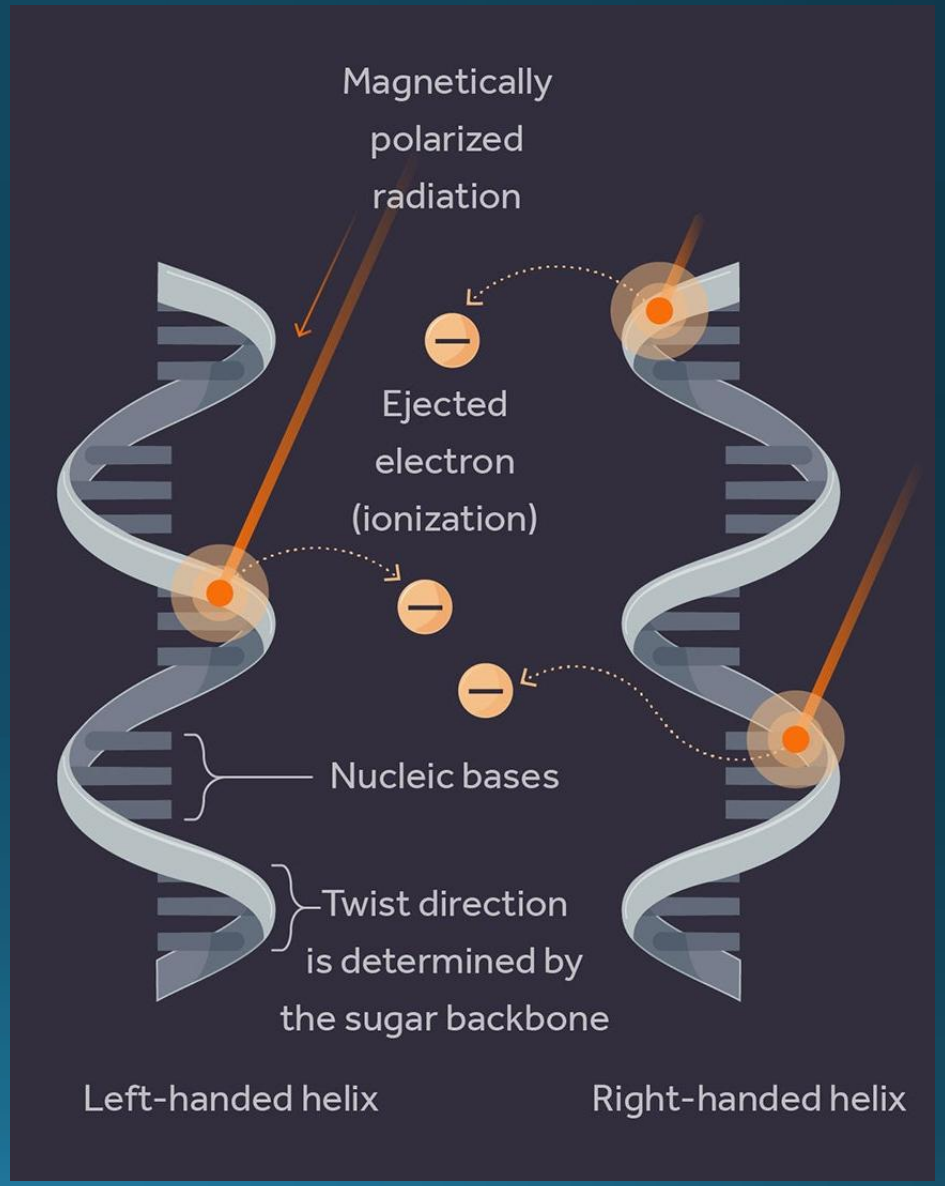
Spin state of electrons

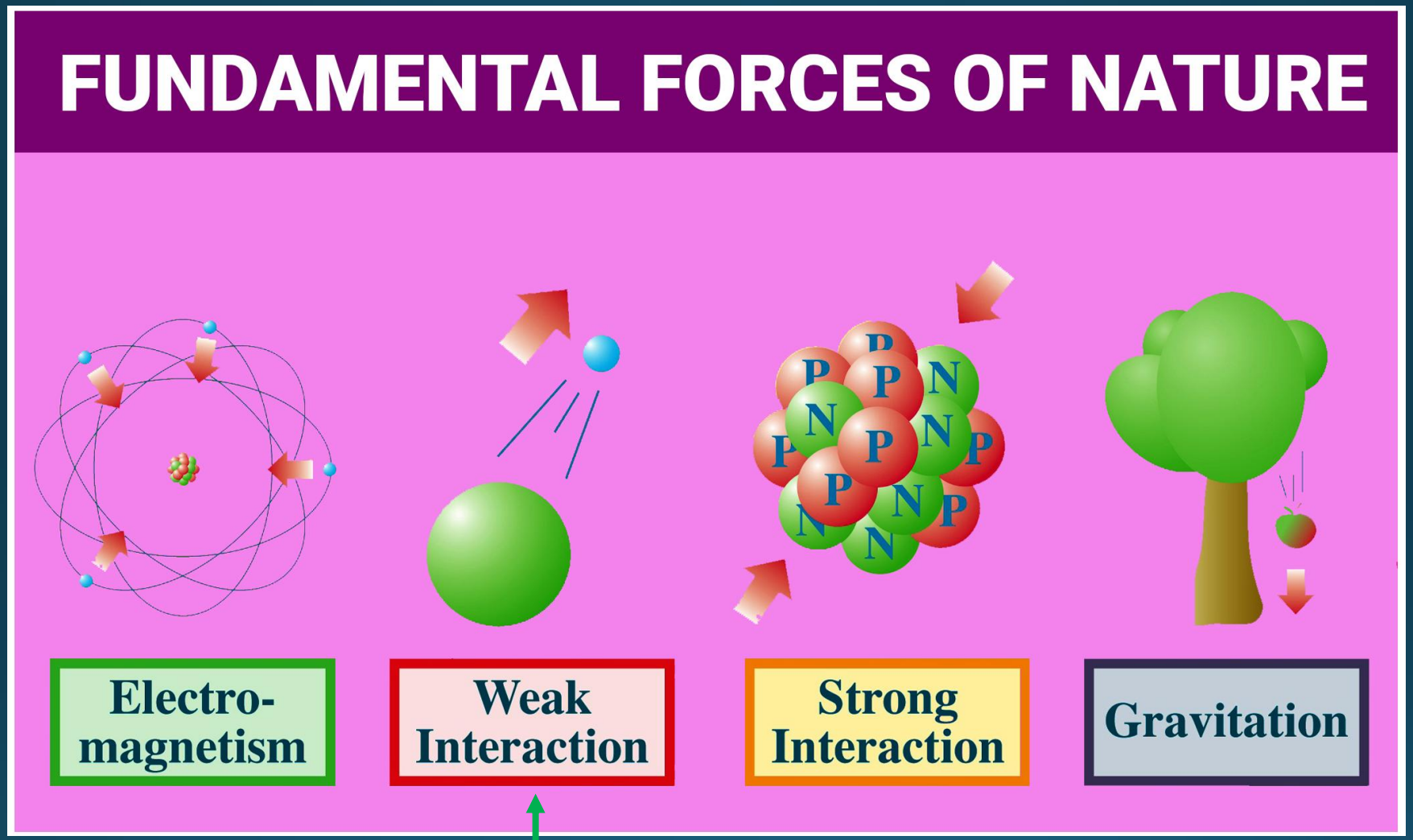
- The Vester-Ulbricht hypothesis
  - ~50 years ago
  - lefty electrons can selectively damage/destroy molecules of one handedness
  - So the origin of life may have been "handed" an asymmetry



Polarized radiation

- Spin of particles as a collection in the same direction
  - Polarization
- Polarized radiation
  - Higher chance of interaction with one type of prebiotic molecule over the other
- Research on creating prebiotic molecules of both handedness in labs

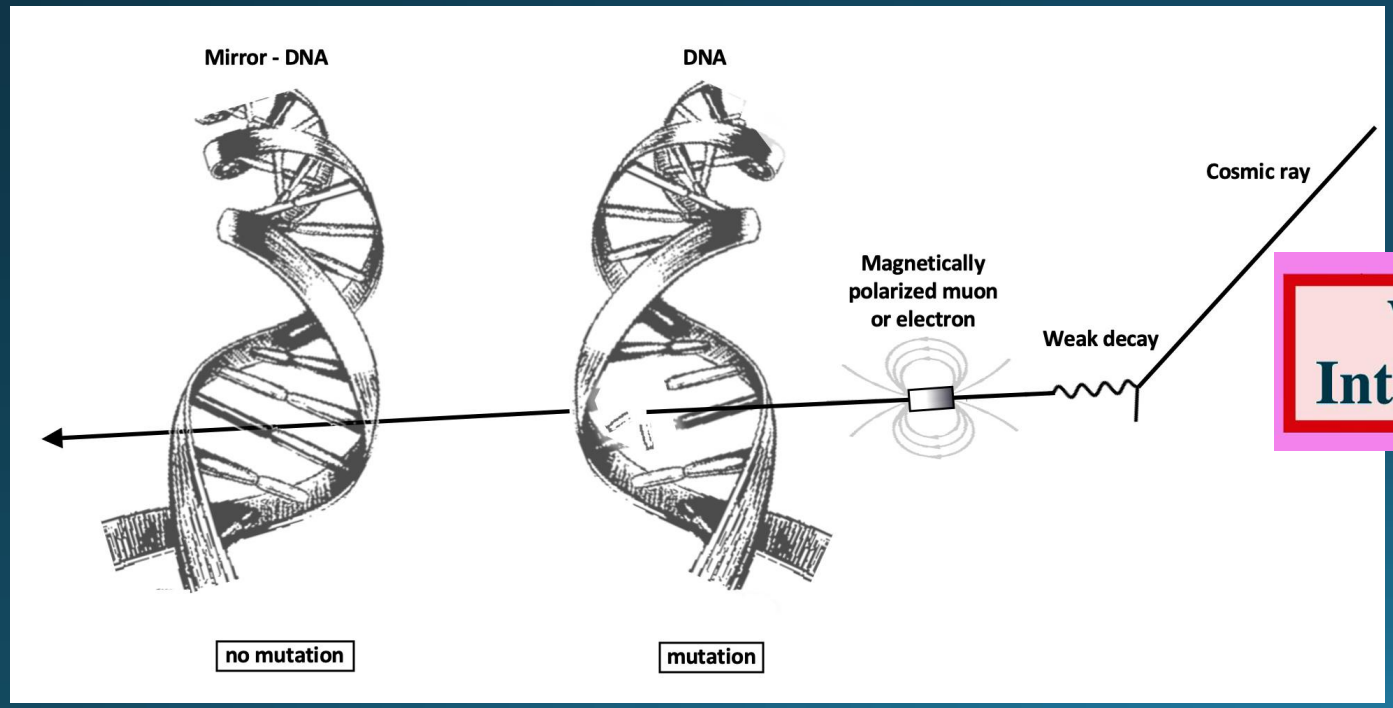




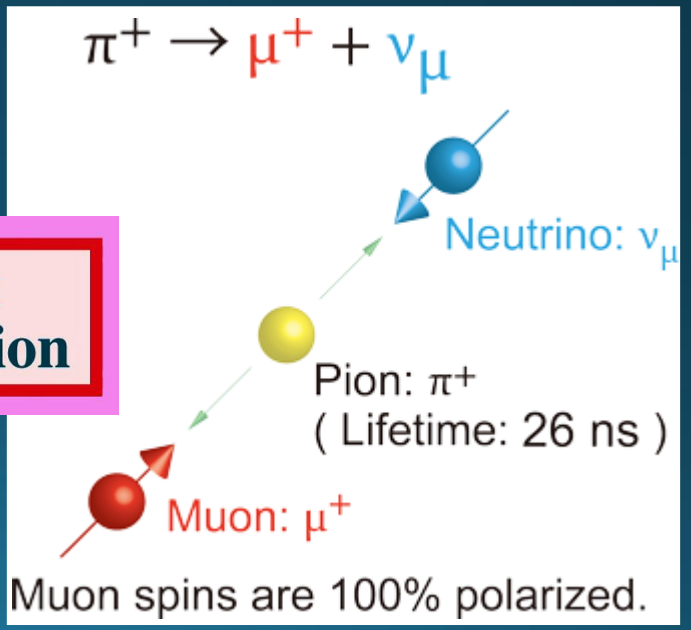
The only Parity-violating Force – distinguishes between left and right

Life's chiral puzzle and cosmic rays

- Noémie Globus' ongoing research on cosmic ray muons impacting the evolution of life on Earth
- (anti)Muons are polarized-weak force decay from pions

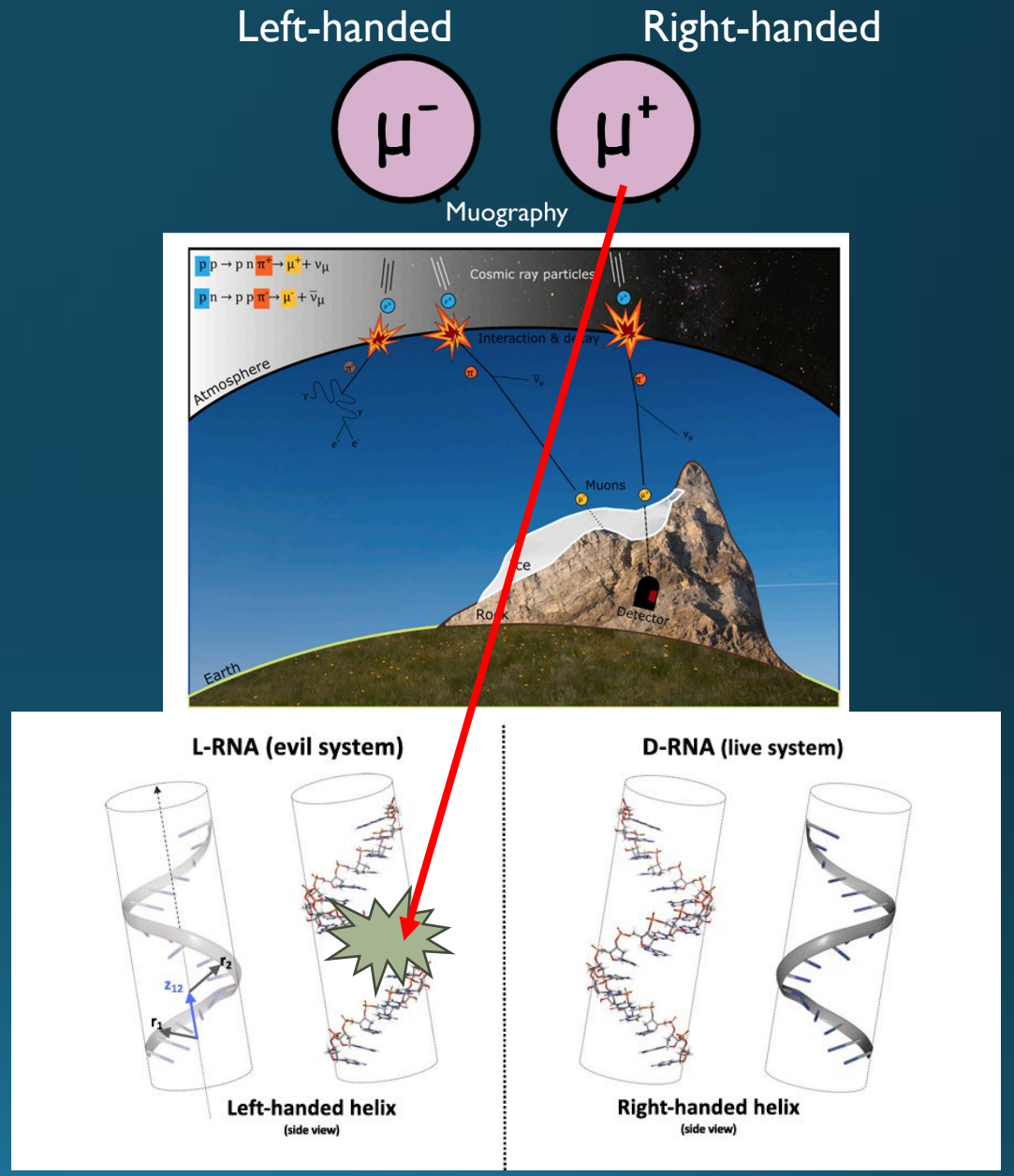


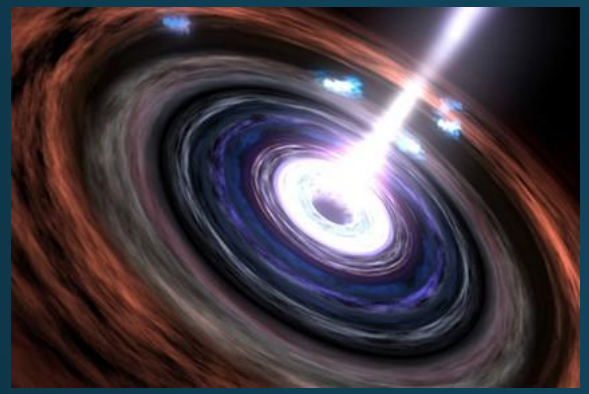
Weak Interaction

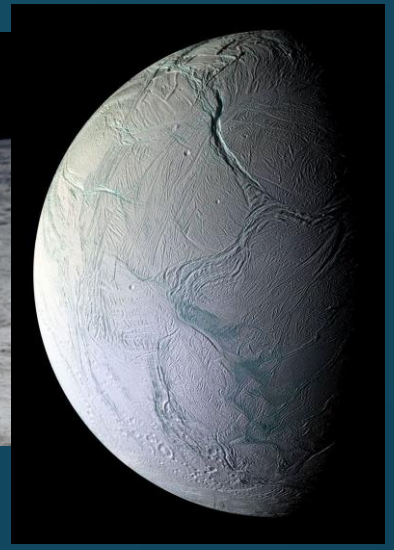


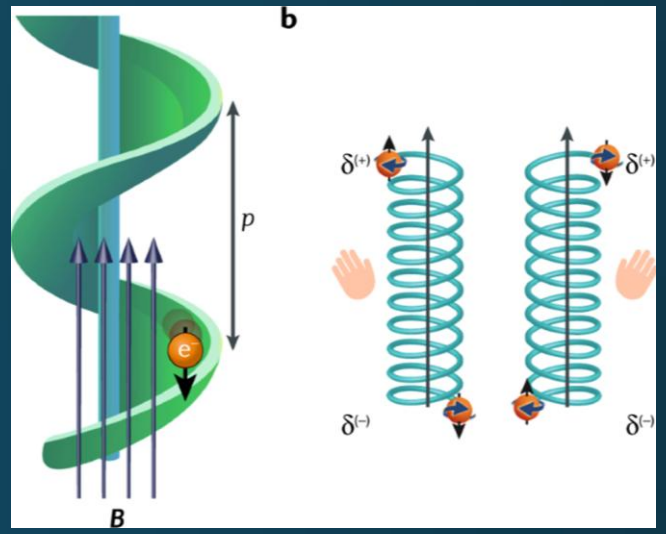
Positive cosmic rays

- Results in a ratio of about ~1.25 antimuons (+) over muons (-)
- Which provides a cosmic ray muon rain of right-handed antimuons (slightly) over left-handed muons
- Which is *hypothesized to have* a higher interaction with right-handed prebiotic amino acids
  - Preferentially destroys the left-handed/mirrored molecules

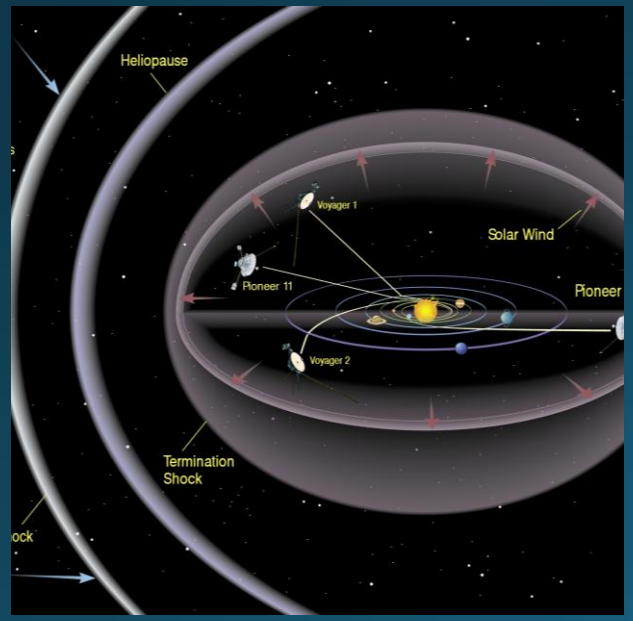


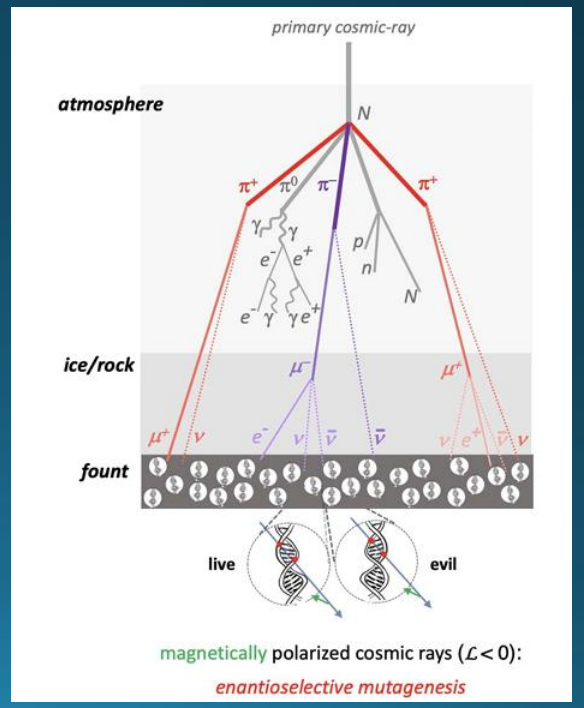






With the astroparticle lens, we can survive and find out how we got here.





Next week: Cosmic ray isotopes that help us understand the Milky Way

Thank you!