ASTR20A:
Introduction to Astrophysics I

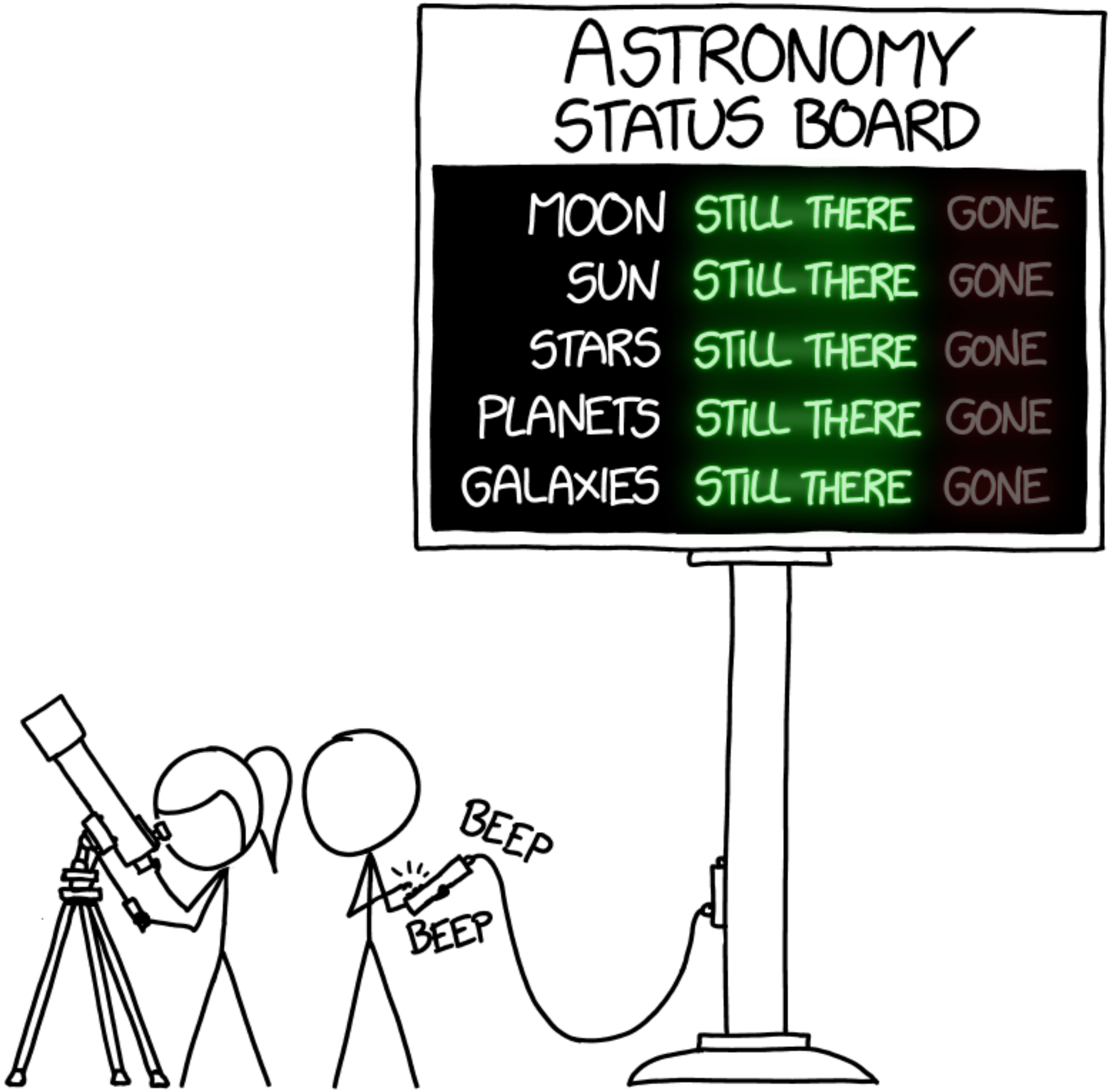
Dr. Devontae Baxter

Lecture 11 | The Earth & Moon

Tuesday, November 04, 2025

Announcements

- Thank you all for completing **the Anonymous Student Feedback Survey!**
  - **If you haven't done so already, please provide your feedback before tonight at 11:59pm.**
- HW **#5 due Tuesday, 11/04 by 11:59 pm.**
- **The last day to drop the course with a "W" is Friday, November 7th.**
- Midterm Exam II will take place on **Thursday, 11/13 from 2:00-3:10pm**
- **Coding assignment #4 due Sunday, 11/16 by 11:59 pm via Gradescope.**
- **No HW next week!**
  - **HW #6 will be due Tuesday, 11/18 by 11:59 pm.**




Questions?

Coding Project

Coding Project (15% of your grade)

- The project will require:
  1. Reading in a datafile.
  2. Plotting the data and saving the figure.
  3. Writing a 2-page *narrative* report (including at least one figure) that explains the data.

- Rubric for grading provided in course syllabus

Formatting of the Coding Project Write-up

- You will be given a random CSV data file with the spectrum of an astronomical object.
- You must write code to read in the data file and plot of the spectrum with errorbars.
- Include all of your code as a separate document attached to your write-up (merged PDF or separate PDFs).

Project Write Up:
What are the minimum requirements

- Your write-up must include one plot *at a minimum.*
  - Additional plots are allowed *if they help your narrative.*
  - **Plots should be numbered** — same goes for tables and equations.
  - **Plots must be referred to in the text** — same goes for tables and equations.
- Must include at least **1-page of written text**
  - Figures and tables should be provided on subsequent pages.
- Must include name, date, and UCSD ID in the header.
- All **pages must be numbered.**
- Reports must be **submitted on Canvas in PDF format**

Project Write Up:
How should the report be formatted?

- **12-point** font in either **Arial** or **Times New Roman**
- **1-inch margins on all sides**
- **1.5 line spacing**
- All axes must be **labeled and given units.**
- Title can be included, but must be 12-point font.
  - **Must not take up more than 2 lines.**
  - **Must include a space between the title and main text.**

Project Write-up:
What should go in the text?

- Your goal is to **use the features in the spectrum to develop a hypothesis regarding the nature of the astronomical object.**
  - Does the spectrum exhibit absorption/emission lines?
    - What wavelengths do they correspond to?
    - Do the lines correspond to a hydrogen spectral series?
    - Are the emission/absorption lines *narrow* or *broad*?
    - What are the potential sources of the emission/absorption?
  - What wavelength corresponds to the peak flux?
  - Is the spectrum *high* or *low* resolution?

Project Write-up: What should go in the text? (continued)

- In *your own words*, explain how you arrived at your hypothesis.
- Where possible, use **numbers** instead of **descriptors.**
- Include a few interesting facts about the type of astronomical object you are analyzing.
  - Could also include an artist's impression (give credit).
- Include equations if useful.

Project Write-up: Equations

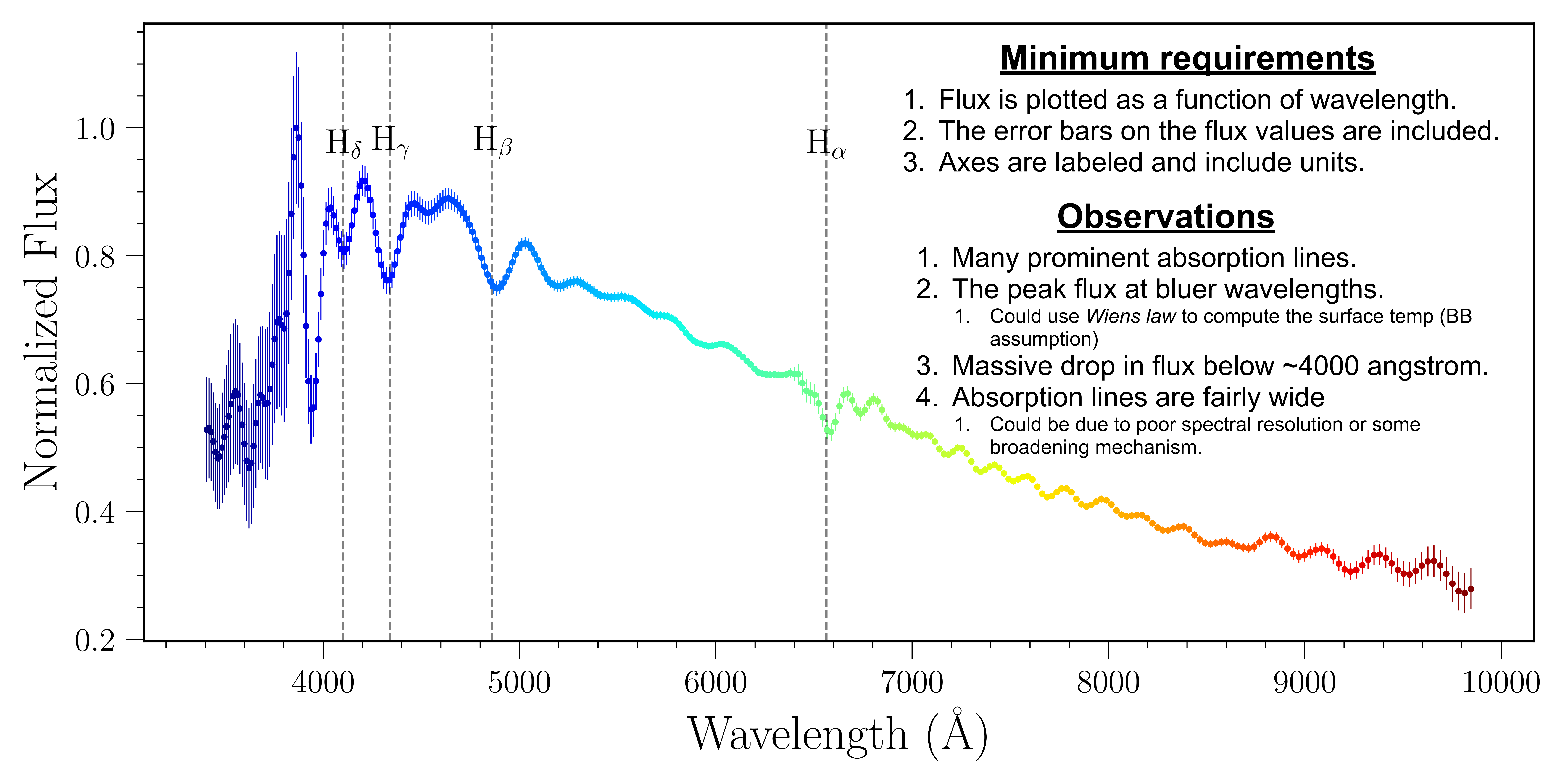
- Equations should be labeled with equation numbers so that you can refer to them in the text.
- When you include an equation, the text preceding and following it will explain in words what the equation means.
- Equations are delineated by punctuation because they are part of sentences

Example: The sum of two numbers is typically given as,

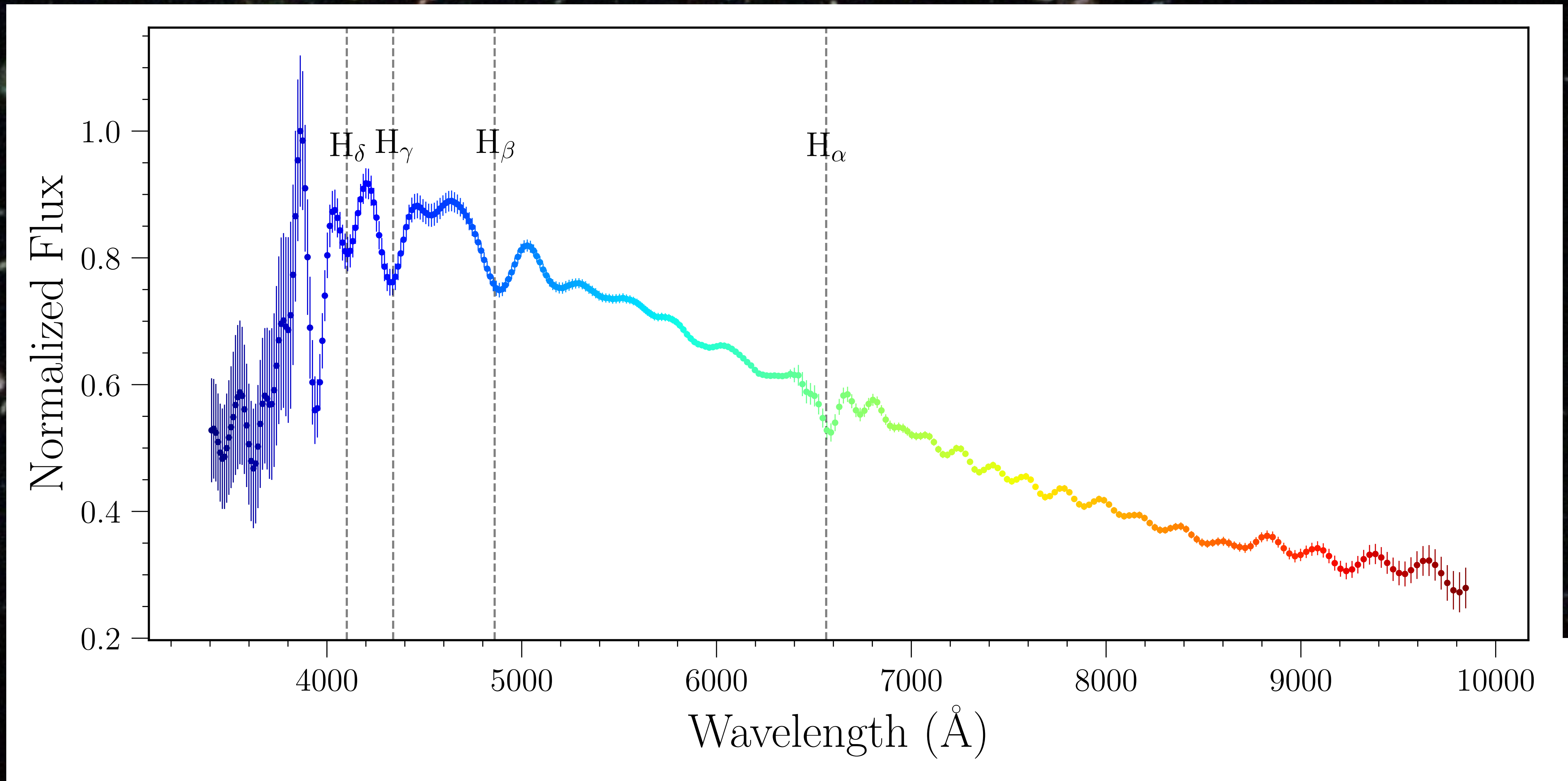
$$x_1 + x_2 = x_3,$$

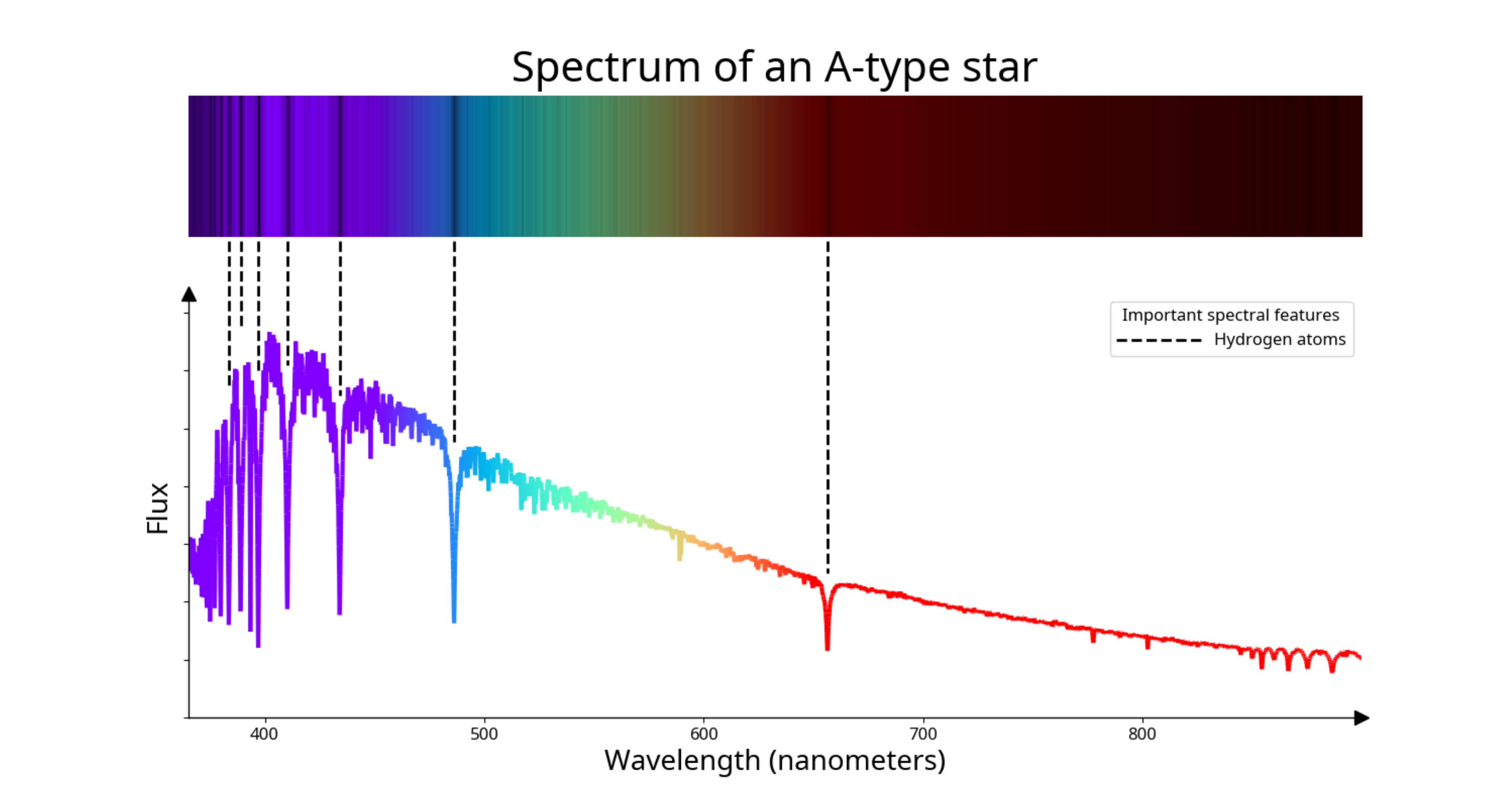
where x_1 and x_2 are the numbers being added, and x_3 is the sum of those two numbers.

Project Write-up: Example Plot



Project Write-up: Example Plot






Questions?

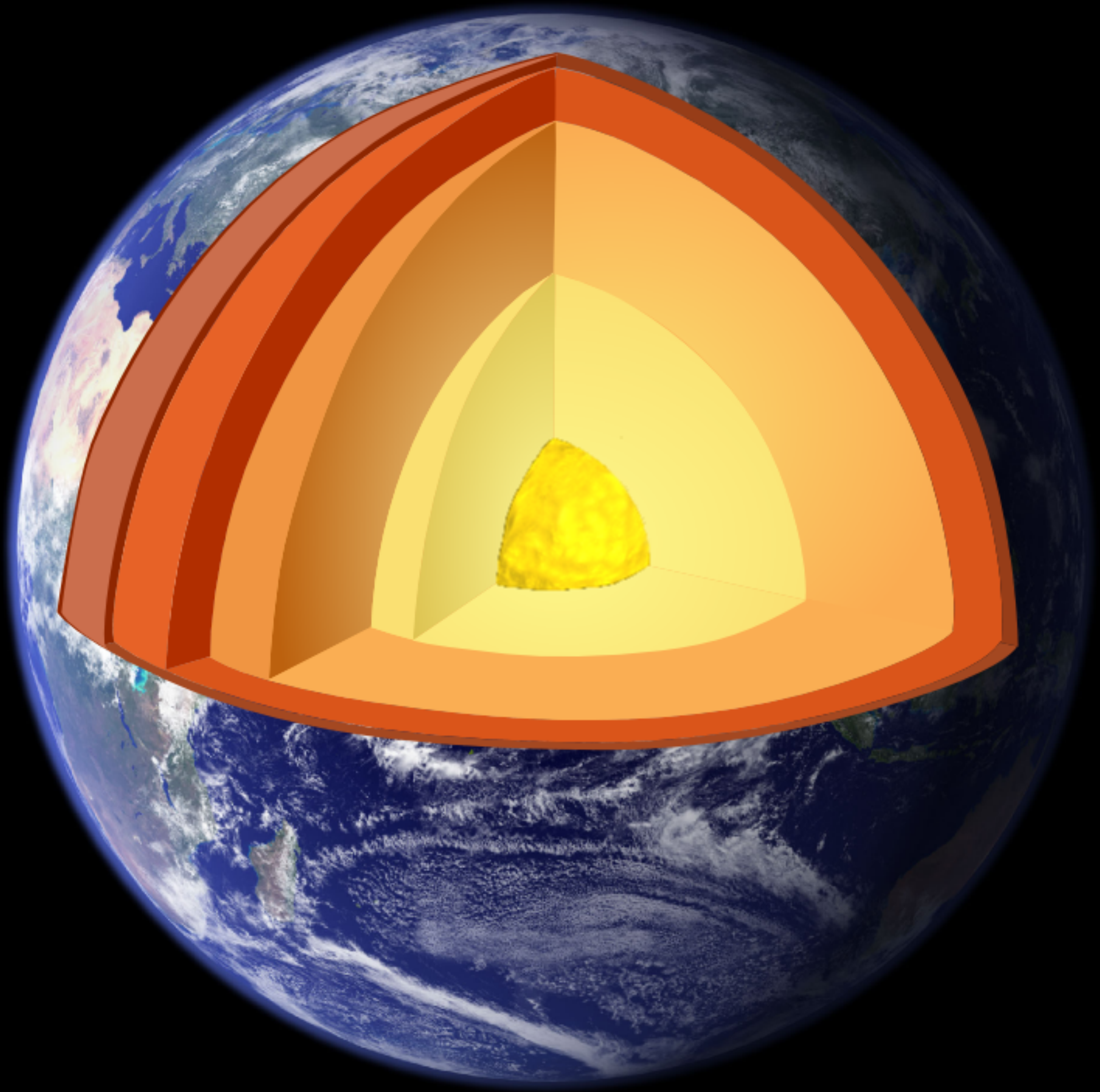
Learning Objectives

By the end of today's lecture you will be able to:

- Describe the **three main layers** of the interior of the Earth.
- Explain how we probe the interior of the Earth.
- Explain the differences between *P- and S-waves.*
- Explain how *hydrostatic equilibrium* keeps the atmosphere intact.
- Describe the **four main layers** of Earth's atmosphere.
- Identify the characteristics of the lunar exterior and interior.
- Describe the "giant impact" theory.

The Interior of the Earth

Like an onion, Earth has many layers



The Interior of the Earth

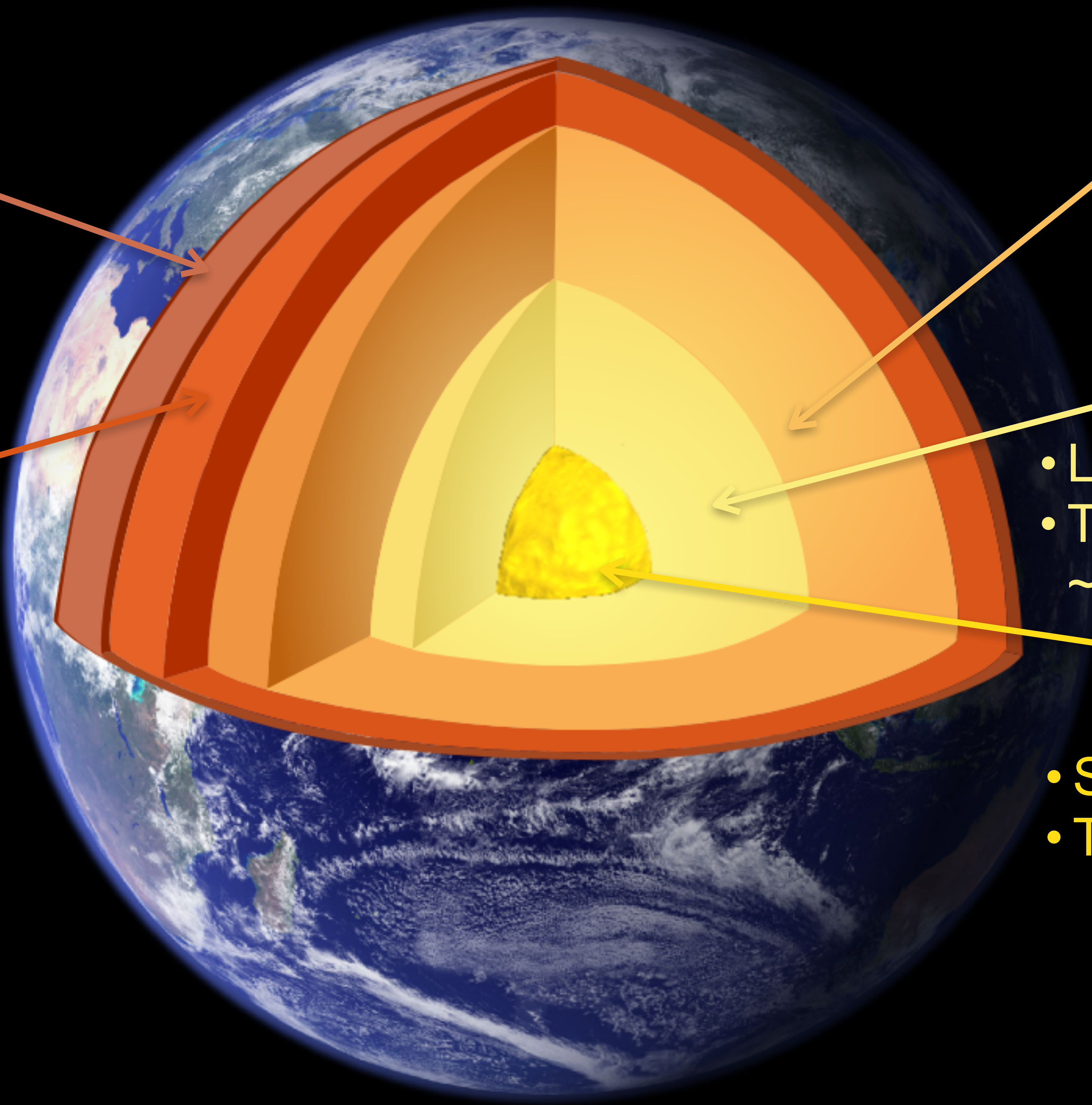
Like an onion, Earth has many layers

Crust

- Sits atop the mantle.
- Poor in heavy elements.
- Rich in light elements.
- ~30 km thick.

Lower mantle

- Composed mostly of silicates.
- 56% of Earth's volume.



Outer core

- Liquid, made up of mostly iron and nickel
- Take us ~15% of Earth's volume and ~31% of mass.

Upper mantle

- Also composed mostly of silicates.
- Fairly ductile, behaving like a very thick, viscous liquid.
- The total mantel takes up 84% of the Earth's volume!

Inner core

- Solid, made up of mostly iron and nickel.
- Takes up less than 1% of Earth's volume.

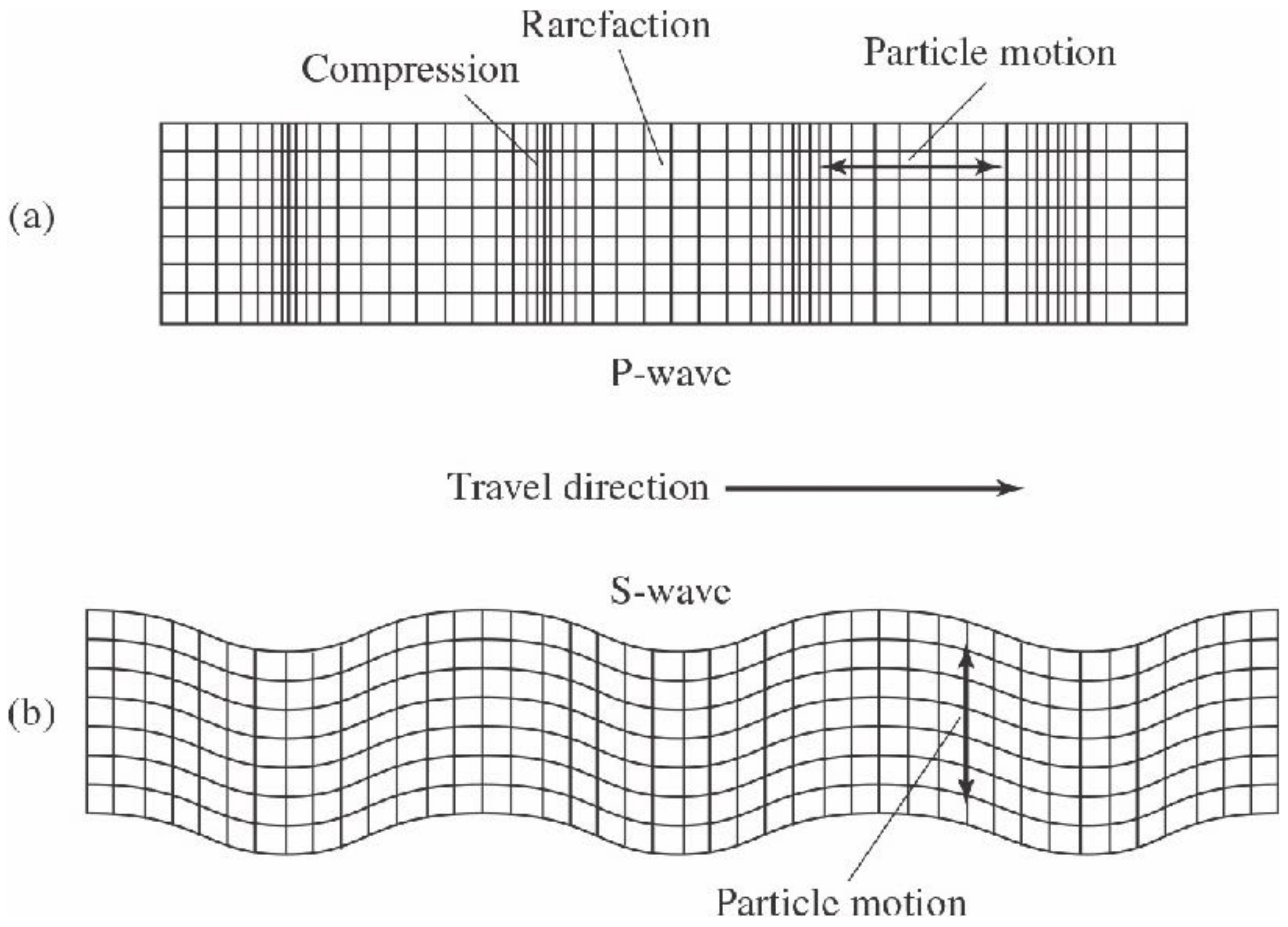
THE DEEPEST HOLE IN THE WORLD

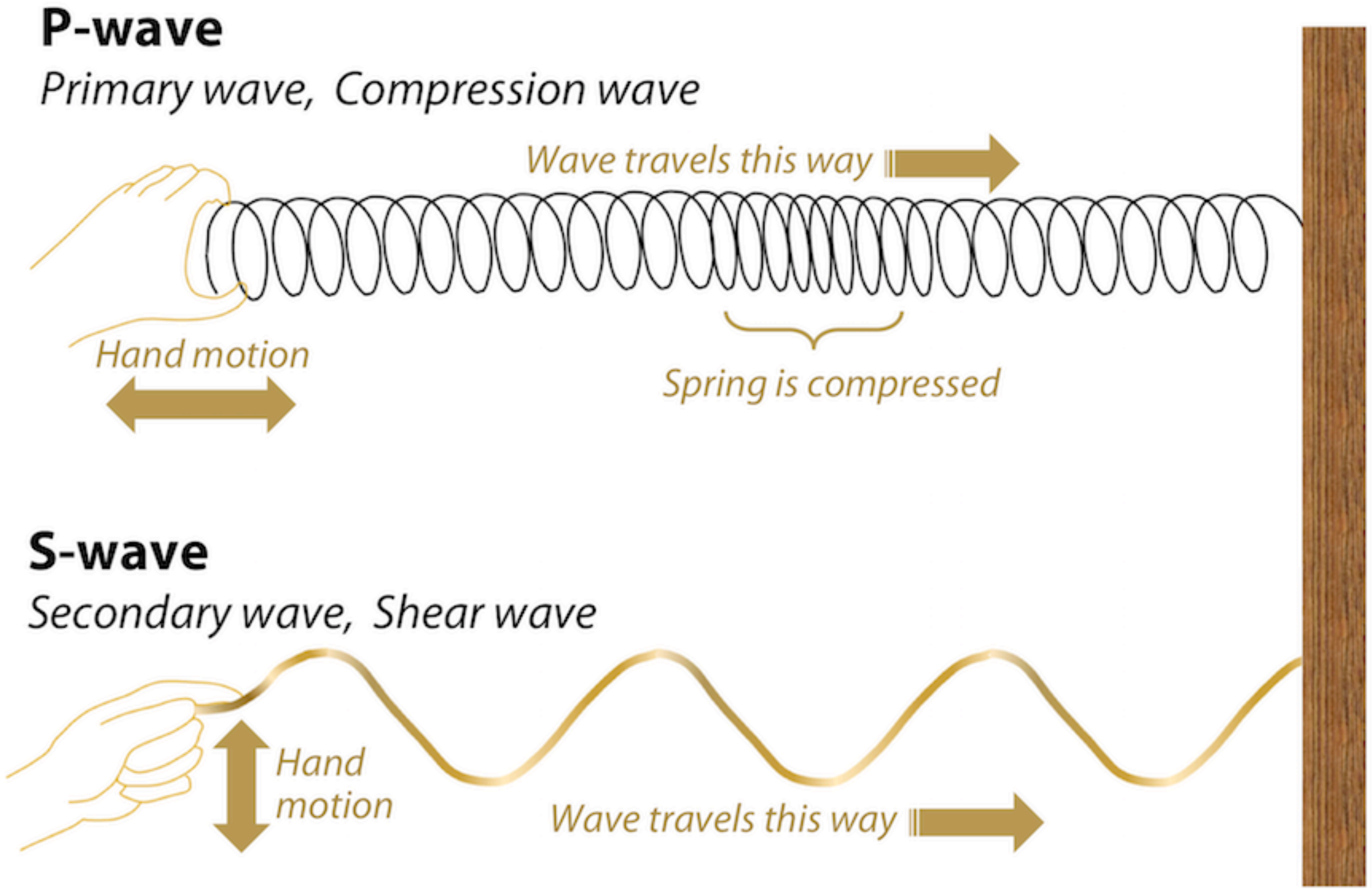
The Kola Borehole is the deepest hole on Earth and plummets 7.5 miles. It was made as part of a Soviet experiment, which only stopped digging because the temperatures down there got too hot.

How do we probe the layers?

Seismic waves travel through Earth's interior

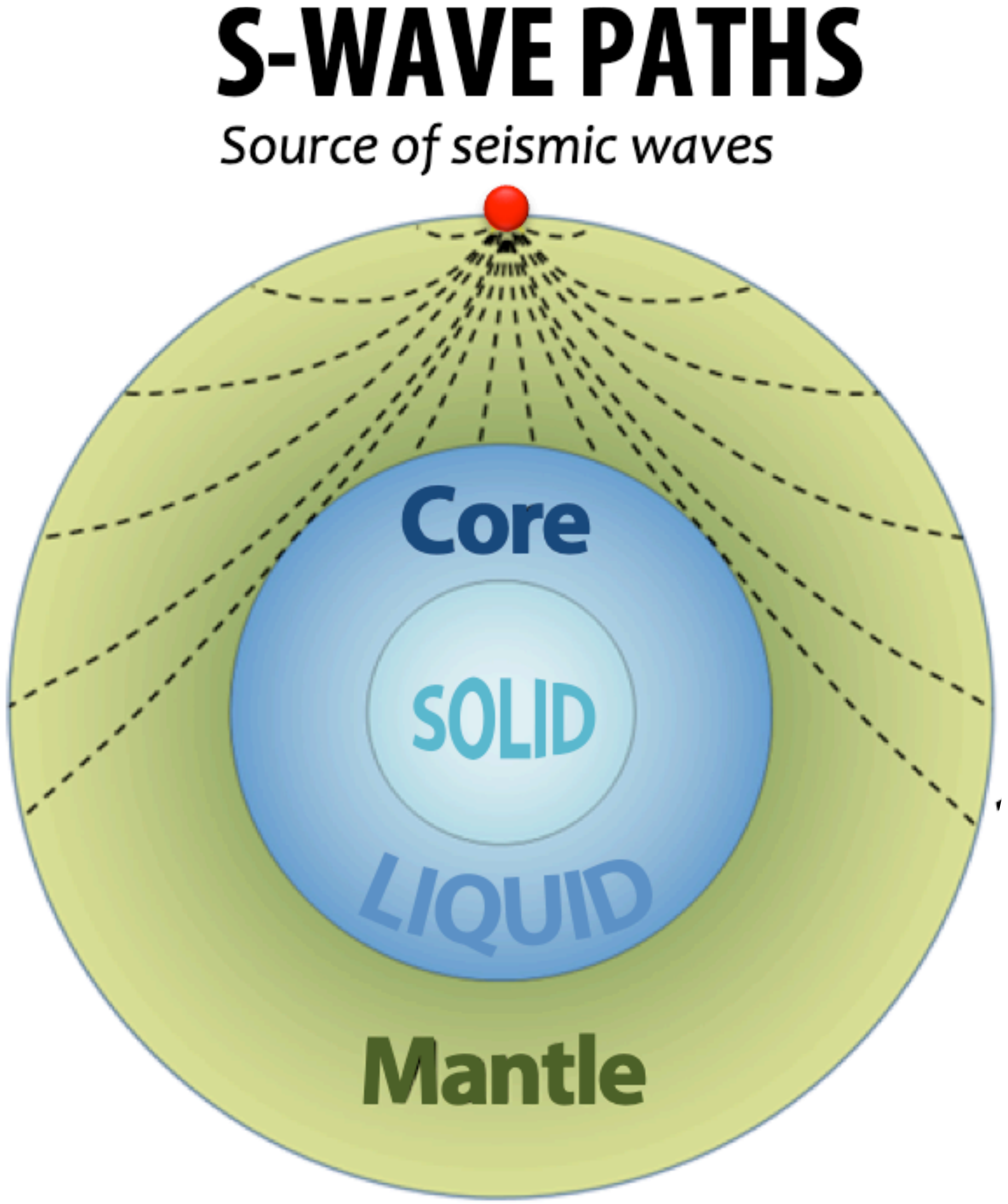
P-waves: Pressure/ compressional waves, like *sound waves.*
S-waves: Shear/ transverse waves, like waves along a string.

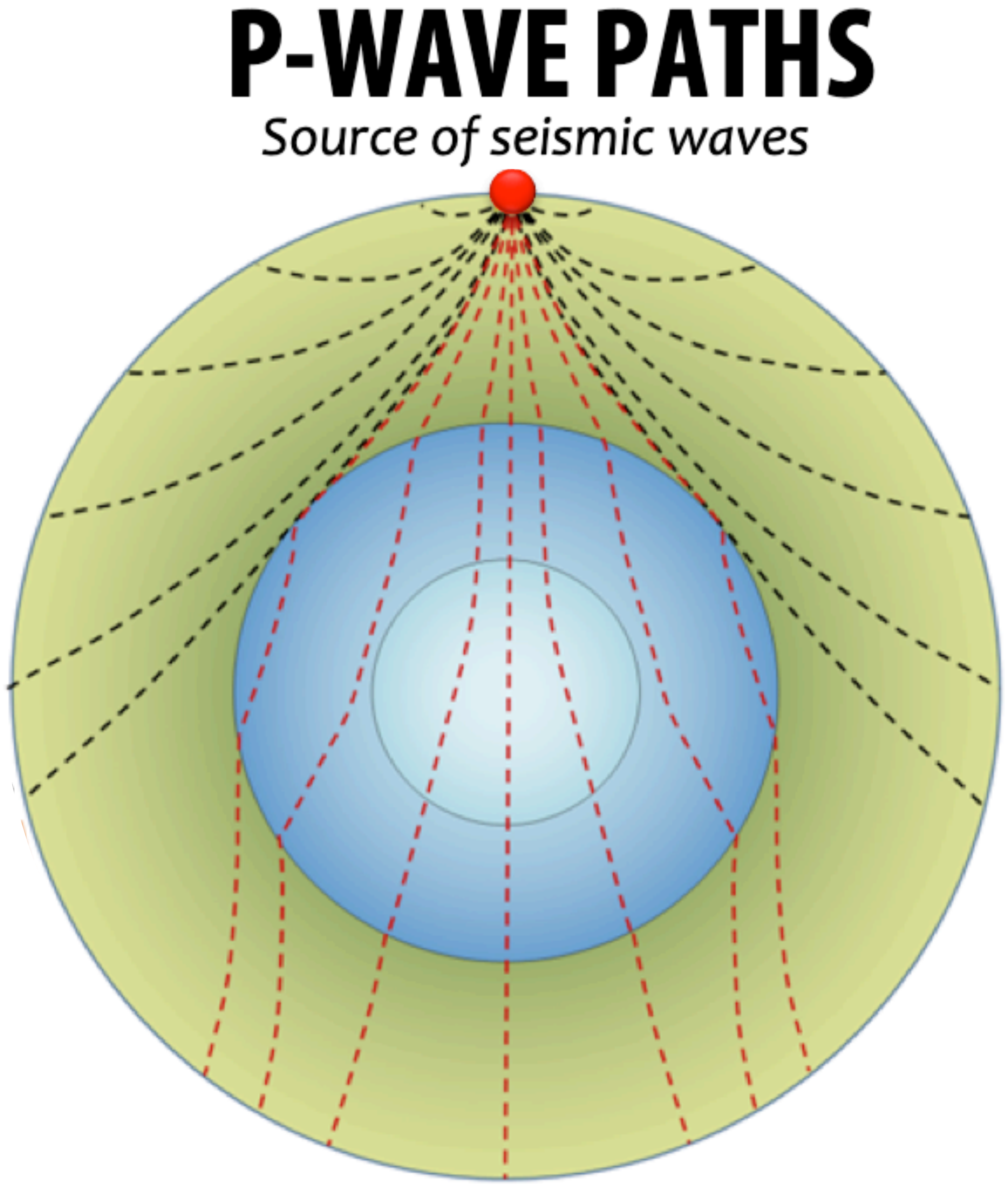




Differences between P-waves and S-waves

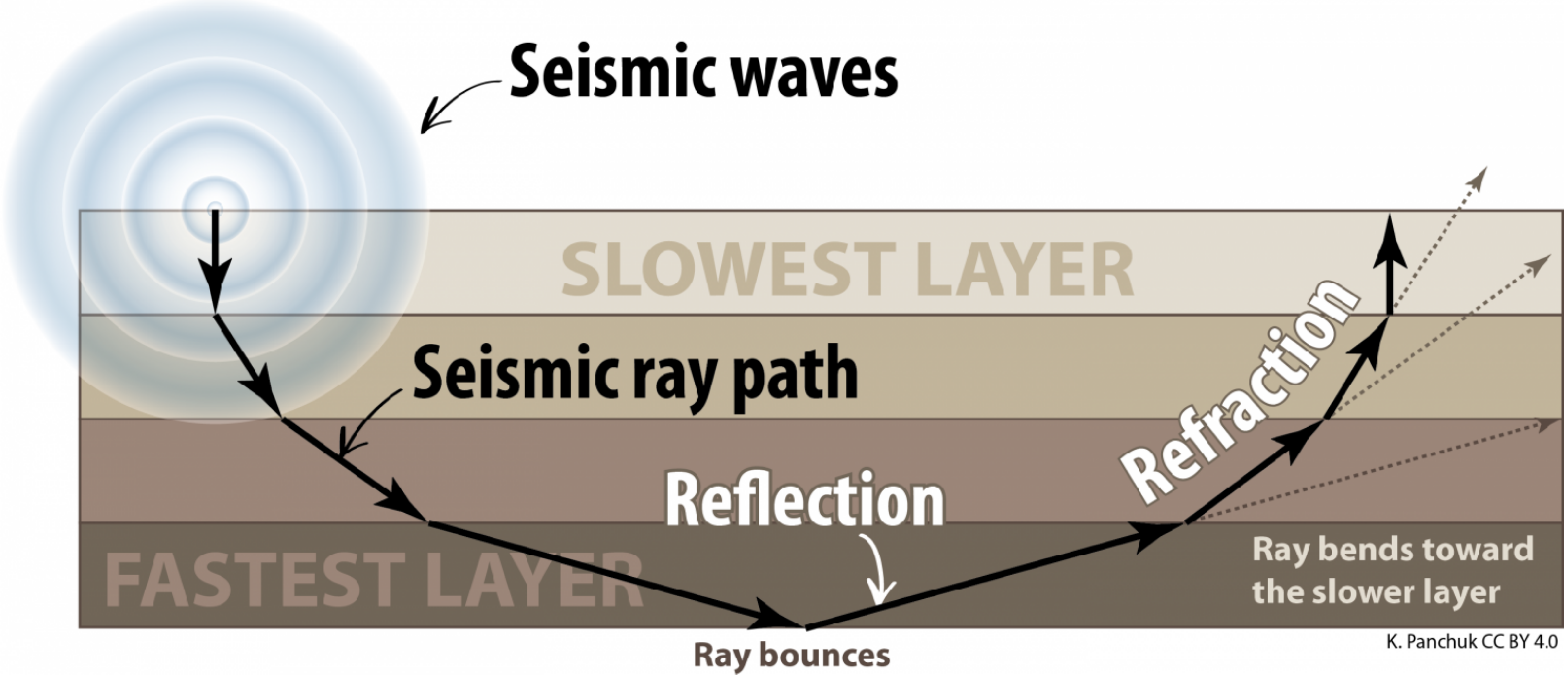
1. P-waves (*primary*) and S-waves (*secondary*) and can **both travel through the mantle.**
2. However, **S-waves *cannot travel* through the liquid or solid core.**
   - This is because they are **absorbed/reflected by the outer liquid core.**
3. S-waves or P-waves travel along bent paths.



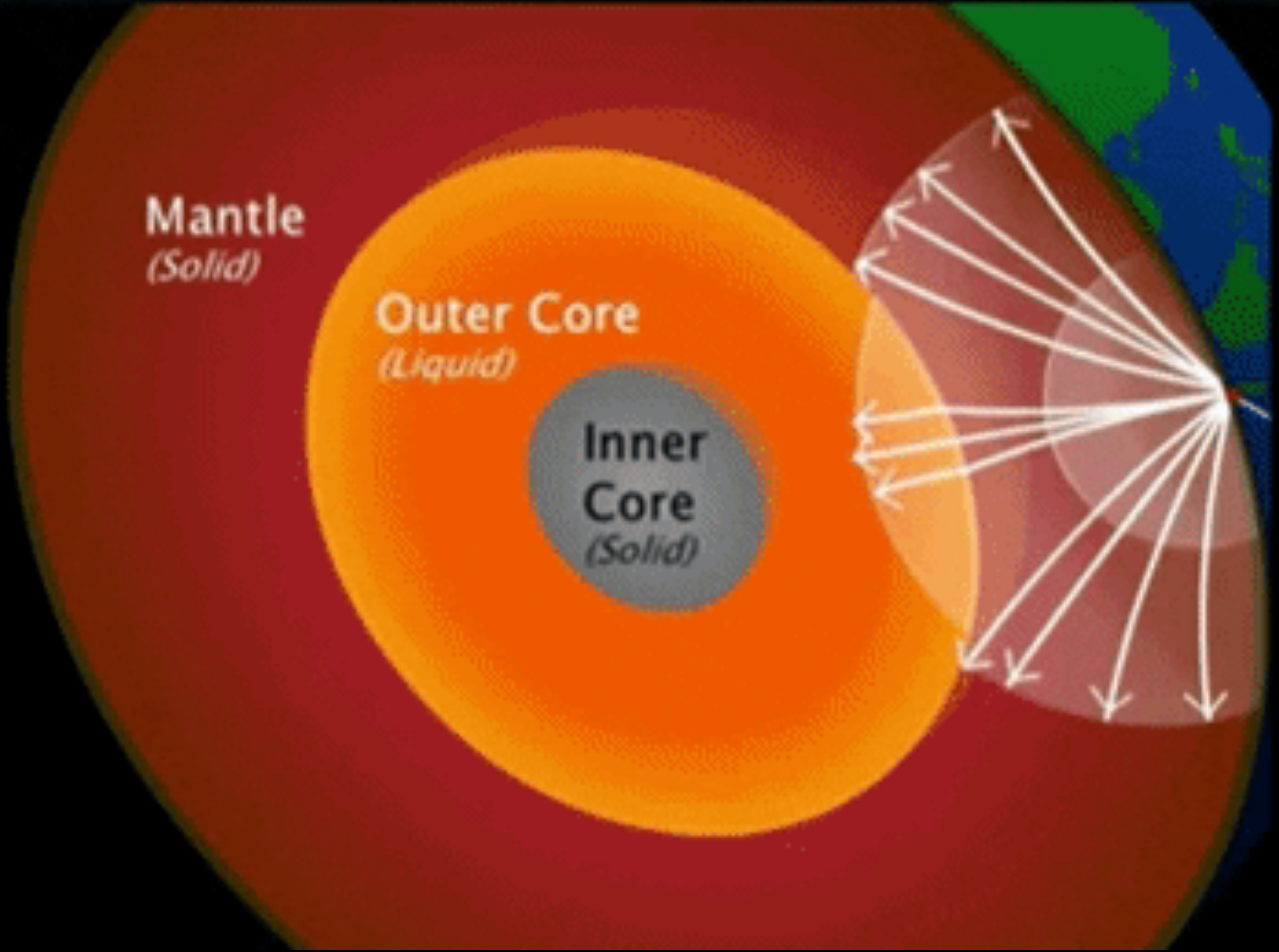


Why do seismic waves travel on bent paths?

As you go deeper into the Earth's interior, the **pressure increases**, and the **rock and metal is squeezed** until it is **very stiff.**



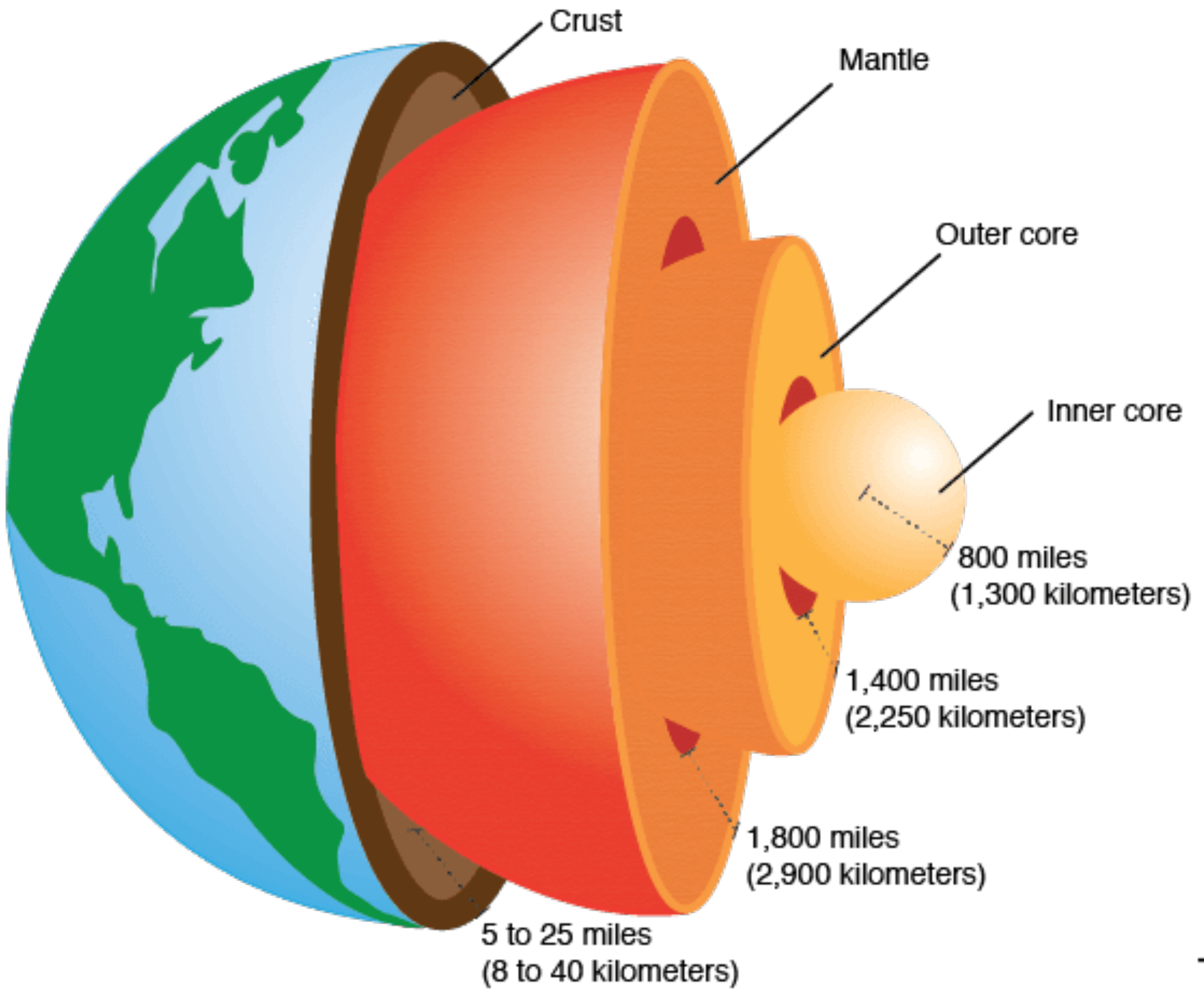
Seismic waves travel more rapidly through a stiffer material; the **increasing wave speed** with **increasing depth** causes <u>seismic waves to be refracted upward</u>.



P-waves traveling through the center of the Earth arrive faster than those that do not because they receive a speed-boost by traveling through the solid core.

Takeaway: Earth is Like an Onion

1. ~~It stinks (no, well some places)~~
2. ~~It makes you cry (possibly…)~~
3. It has layers (yes!!!)



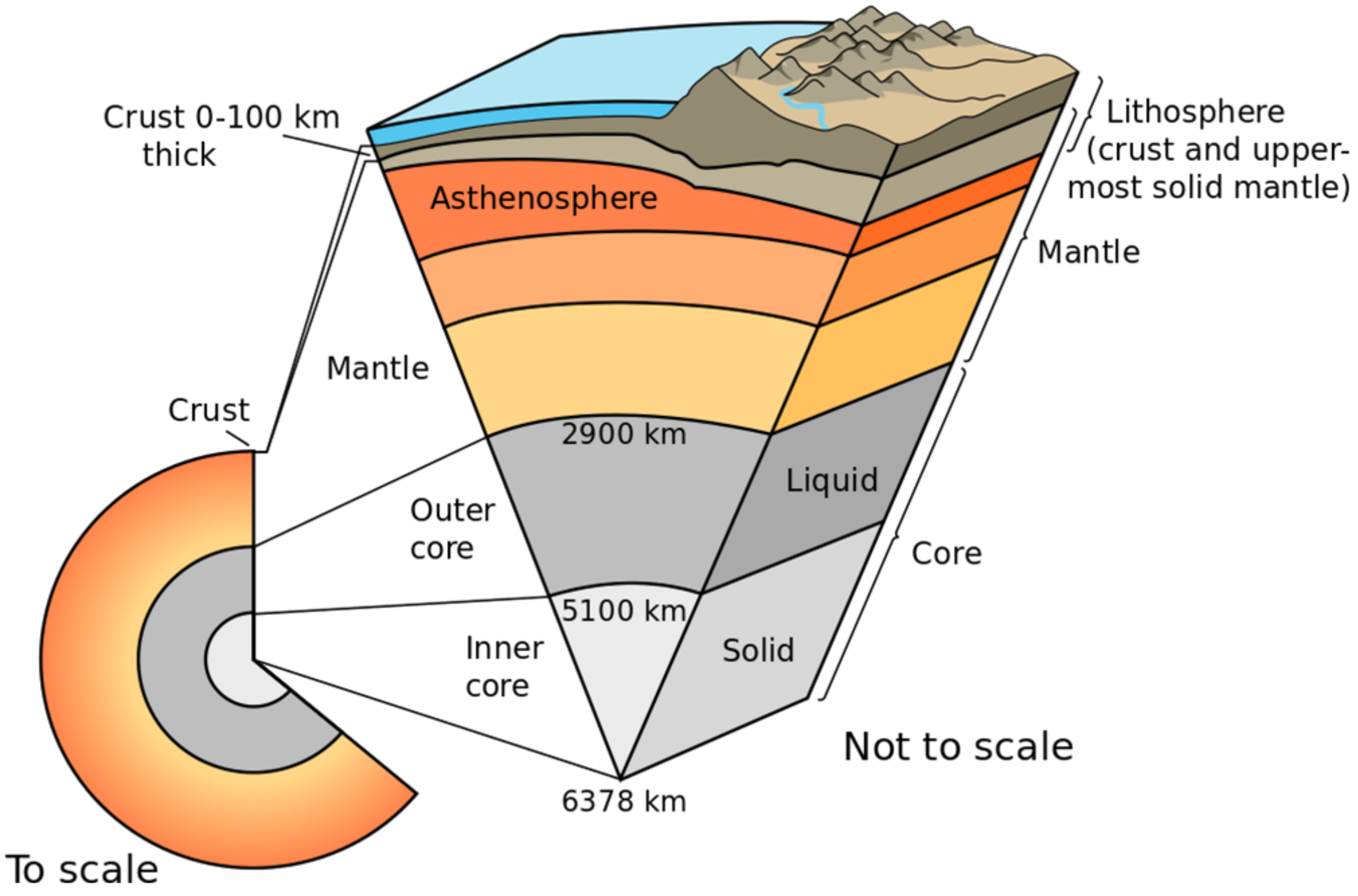
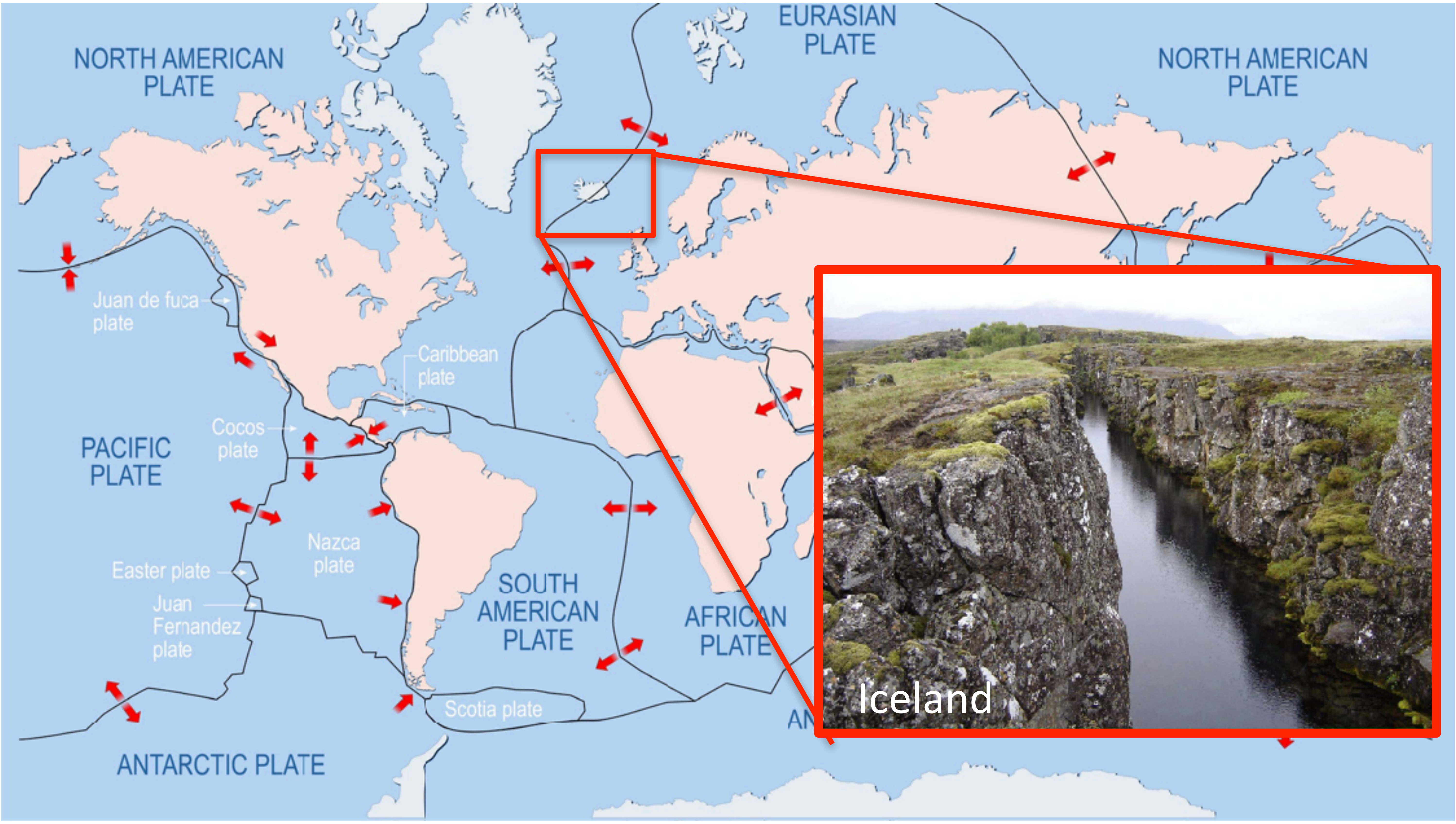
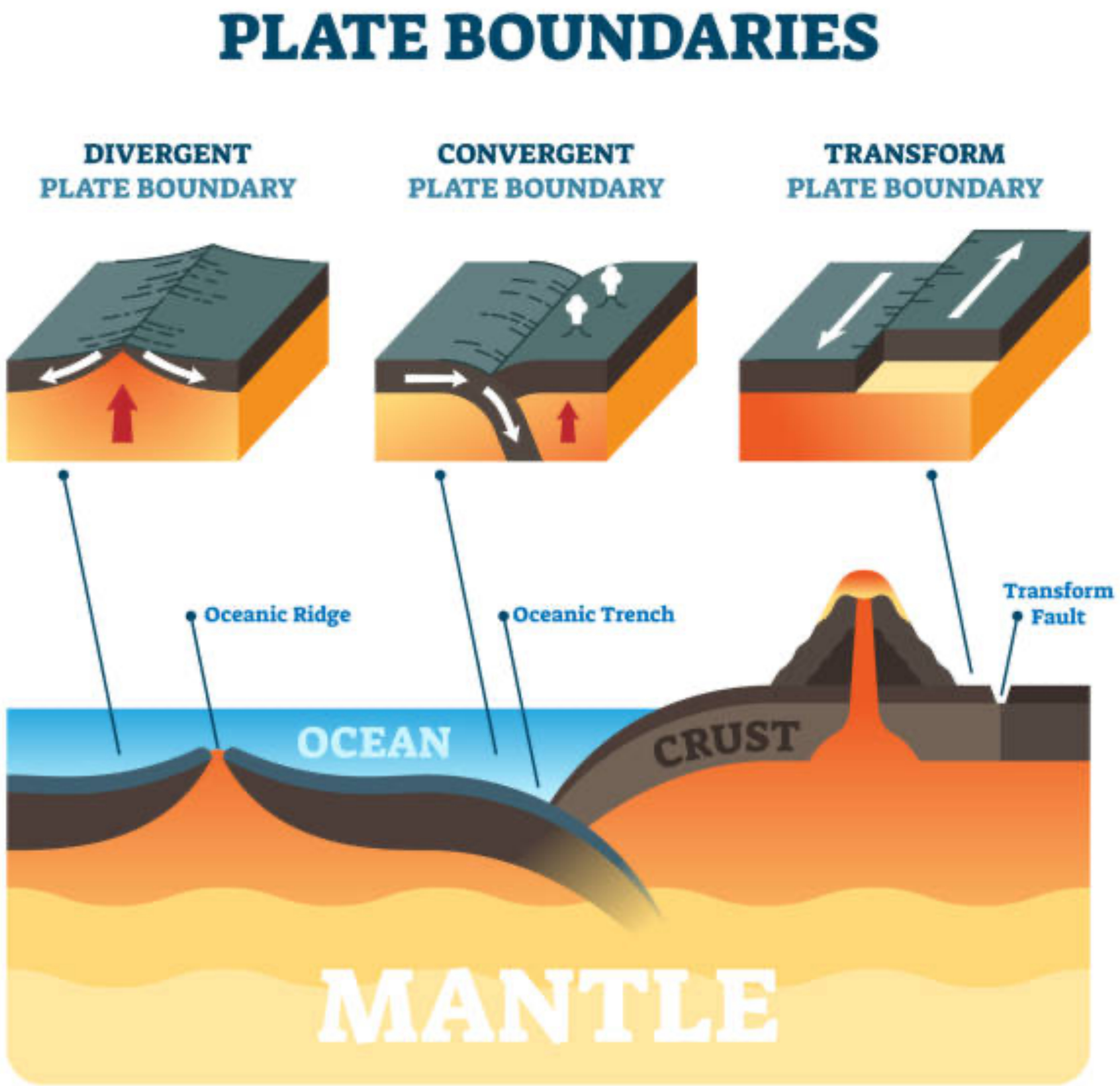


Plate Tectonics

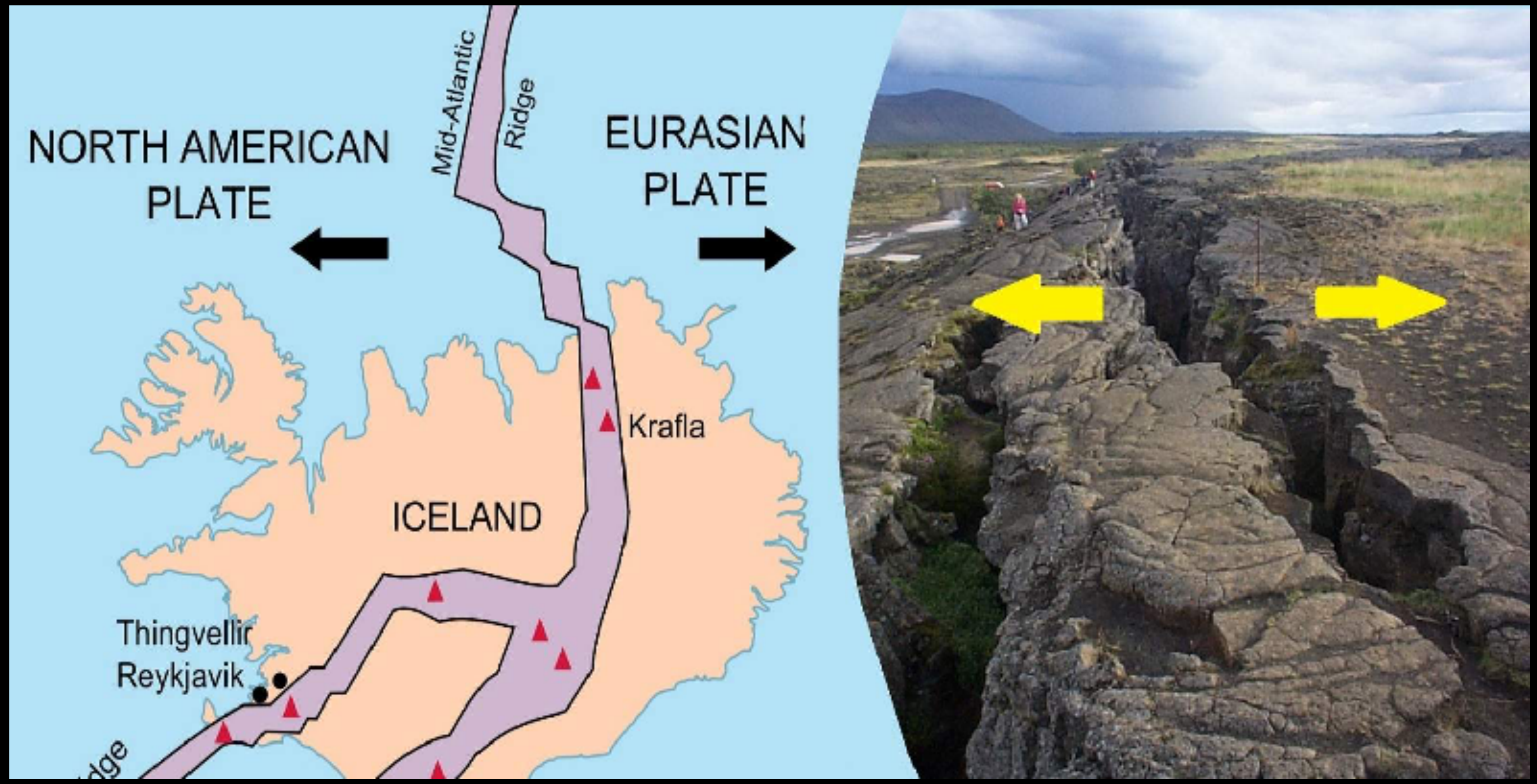




Rift Zones are regions where plates are moving away from each other

How long will it take the Earth to cool down?

The measured geothermal heat flux through the surface of the Earth is $F_{\rm geo} \approx 5 \times 10^{-2}\ \mathrm{W\ m^{-2}}$, on average — much higher in Iceland due to active rift zone.



Therefore, **the rate at which the Earth is radiating away its internal energy is**

$$\frac{dE}{dt} = 4\pi R_\oplus^2 F_{\rm geo}$$

How long will it take the Earth to cool down?

The stored energy in the Earth can be roughly estimated from the **energy per atom** ($E = 3kT$ for solids), divided by the **mass per atom** (about $m \approx 40m_p$ for the mix of elements in the Earth), multiplied by the mass of the Earth ($M_\oplus = 5.972 \times 10^{24}$ kg).

$$E_{\text{therm}} \approx \frac{3kT}{40m_p} M_\oplus \approx 1.1 \times 10^{31}\ \text{J}$$

Note: This assumes that the Earth's interior temperature is $T \approx 3000\ \text{K}$

Brain Break – Think-pair-share

The ***current average power consumption of humanity*** is $P_0 = 14 \times 10^{12}$ W.

The ***total thermal energy of the Earth*** is $E_{\text{therm}} = 1.1 \times 10^{31}$ J.

The **total solar power that reaches Earth** is $P_{\text{solar}} = 1.75 \times 10^{17}$ W.

Assuming that humanity's energy usage will **double every 100 years,** answer the following:

1. When will humanity's **instantaneous power usage equal the solar power hitting Earth?**
2. How long until the cumulative **human energy usage equals Earth's total thermal energy?**
3. Should we prioritize limiting energy use, slowing population growth, or investing in space-based solar harvesting technology?

Brain Break – Hints

The instantaneous power as function of time is given by,

$$P(t) = P_0 \cdot 2^{t/T_\mathrm{d}}$$

where P_0 is the initial power and T_d is the time it takes the initial power to double.

Likewise, the cumulative power is,

$$E(t) = \int_0^{t'} P(t)dt$$

No data 0 kWh 1,000 kWh 3,000 kWh 10,000 kWh 30,000 kWh 100,000 kWh

Earth’s Atmosphere

In the beginning, Earth’s atmosphere was primarily composed of hydrogen, helium, methane, and ammonia.

We lost hydrogen and helium since they were too light to stay bound

Ammonia and methane were *dissociated* by solar UV light. (No ozone created yet to absorb UV light)

Secondary atmosphere created by outgassing, volcanic activity that released CO_2 and H_2O. These reacted to form heavier molecules.

Earth’s Atmosphere

Present day, the Earth’s atmosphere is primarily composed of the following.

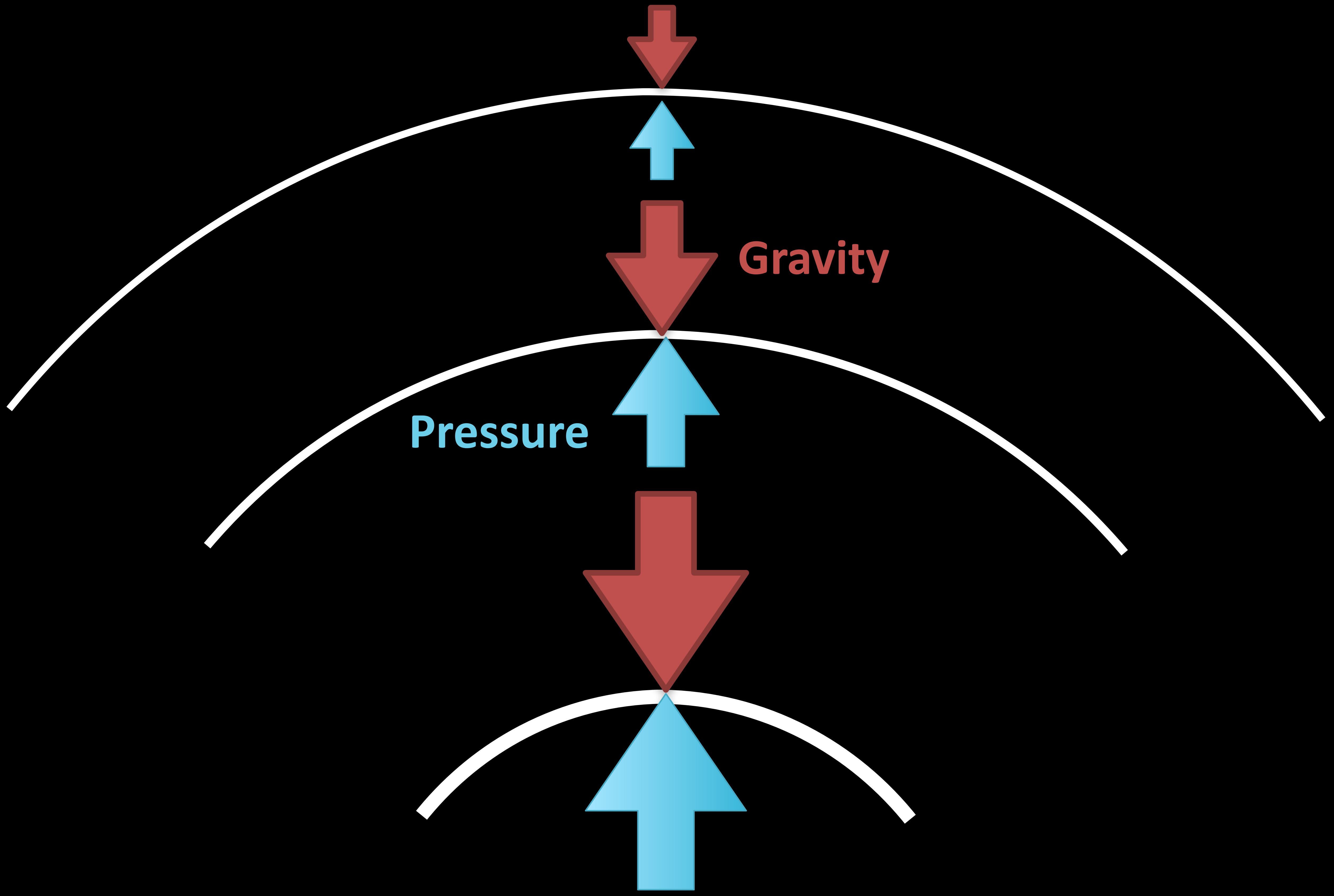
Fraction (by mass)	Fraction (by no. of molecules)	Species
75.5%	78.1%	N_2 (molecular nitrogen)
23.1%	20.9%	O_2 (molecular oxygen)
1.3%	0.93%	Ar (argon)
0.05%	0.04%	CO_2 (carbon dioxide)
trace	trace	Ne, He, CH_4, Kr (neon, helium, methane, krypton)


Questions?

Hydrostatic Equilibrium

The Earth exerts a gravitational force on the gas that makes up our atmosphere.

The atmosphere is stabilized against gravitational collapse by a **balance between the gravitational force and the differential gas pressure.**



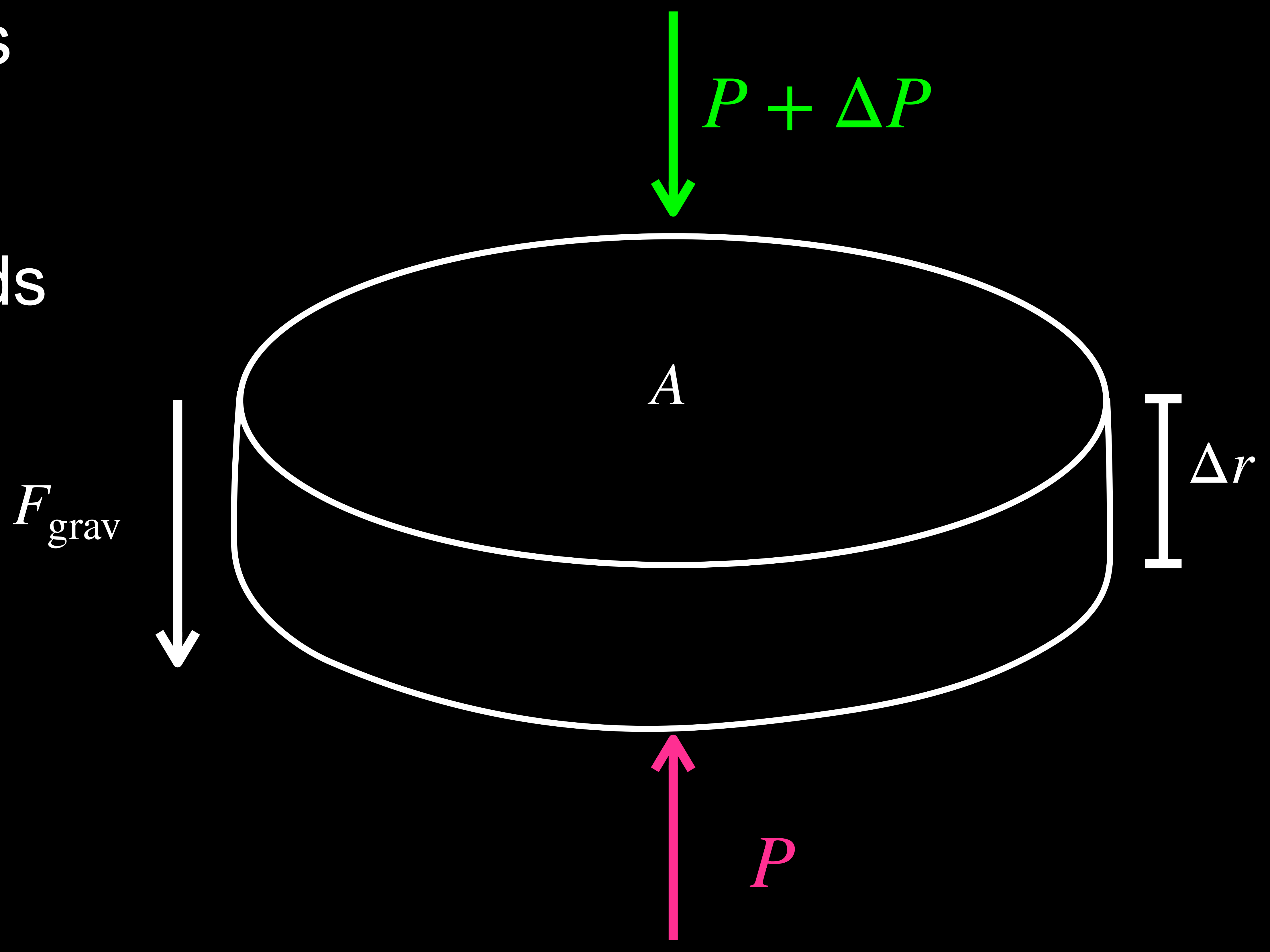
Hydrostatic Equilibrium

Hydrostatic Equilibrium

Consider the forces acting on an infinitesimally thick cylindrical volume of gas.

Gas pressure pushes on the bottom and top faces of the cylinder:

- P is the pressure pushing the bottom face upwards
- $P + \Delta P$ is the pressure pushing the top face downwards.



The net force on the volume element in the vertical direction is:

$$F_{\mathrm{pres}} = A[P - (P + \Delta P)]$$

Note: The sign convention is chosen such that a **positive force is acting upwards.**

Hydrostatic Equilibrium

The gravitational force acing on the volume element is:

$$F_{\rm grav} = -\frac{GM_r\rho A\Delta r}{r^2}$$

M_r is the mass enclosed within a sphere of radius r centered on the center of the Earth.

In equilibrium, the atmosphere is neither expanding or contracting downward, meaning the sum of differential pressure and gravitational force is zero.

$$F_{\rm pres} + F_{\rm grav} = A[P - (P + \Delta P)] - \frac{GM_r\rho A\Delta r}{r^2} = 0$$

Solving for the differential pressure:

$$\Rightarrow \qquad \Delta P = -\frac{GM_r\rho}{r^2}\Delta r$$

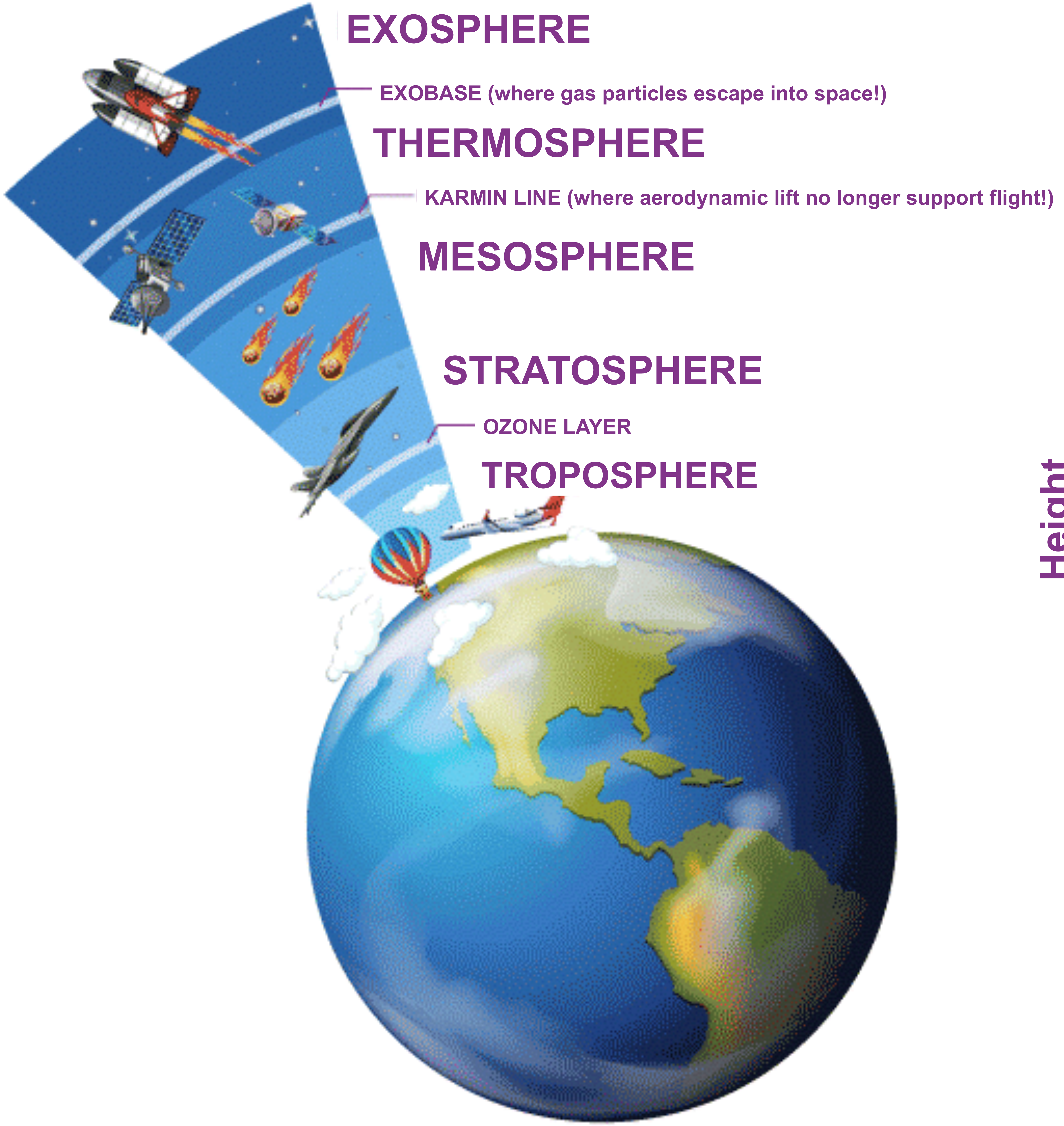
Hydrostatic Equilibrium

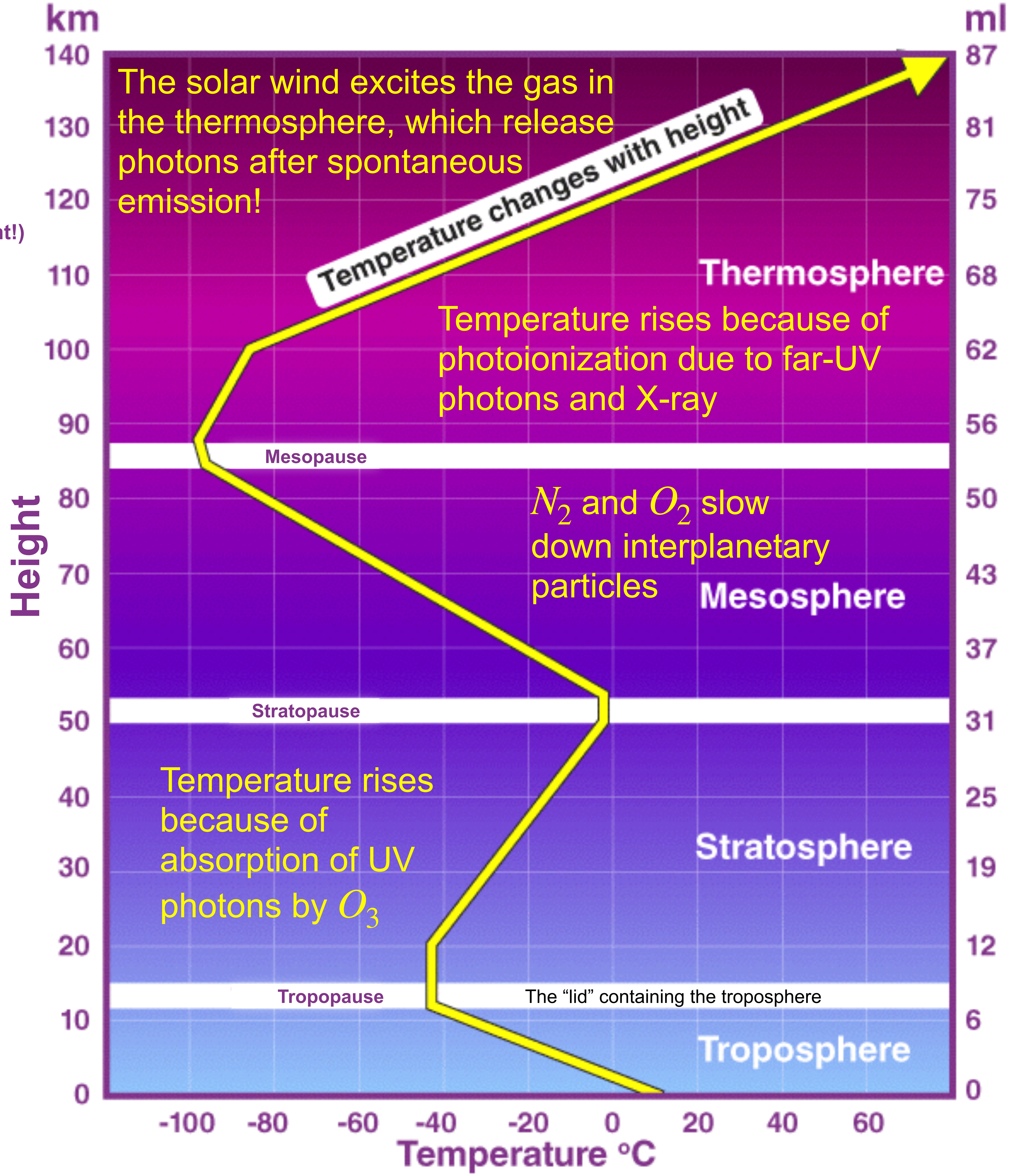
In the limit that the cylinder becomes infinitesimally thin ($\Delta r \to 0$), this becomes the differential equation:

$$\frac{dP}{dr} = -\frac{GM_r \rho}{r^2}$$ (equation of hydrostatic equilibrium)

This equation **holds true for any spherical object** ***supported by its internal pressure,*** ***including stars!***

(more on this in lecture 15)


EXOSPHERE
EXOBASE (where gas particles escape into space!)
THERMOSPHERE
KARMIN LINE (where aerodynamic lift no longer support flight!)
MESOSPHERE
STRATOSPHERE
OZONE LAYER
TROPOSPHERE


km
ml
140 130 120 110 100 90 80 70 60 50 40 30 20 10 0
87 81 75 68 62 56 50 43 37 31 25 19 12 6 0
Height
The solar wind excites the gas in the thermosphere, which release photons after spontaneous emission!
Temperature changes with height
Thermosphere
Temperature rises because of photoionization due to far-UV photons and X-ray
Mesopause
N_2 and O_2 slow down interplanetary particles
Mesosphere
Stratopause
Temperature rises because of absorption of UV photons by O_3
Stratosphere
Tropopause
The "lid" containing the troposphere
Troposphere
-100 -80 -60 -40 -20 0 20 40 60
Temperature °C

Scattering of Light

The scattering cross-section σ depends on the ratio L/λ, where L is particle size and λ is the wavelength of light

- **Rayleigh Scattering ($L \ll \lambda$):** When particles are much smaller than the wavelength the scattering cross-section scales as $\sigma \propto \lambda^{-4}$, meaning smaller wavelengths of light are preferentially scattered. This is the reason why the day sky is blue and sunsets are red.

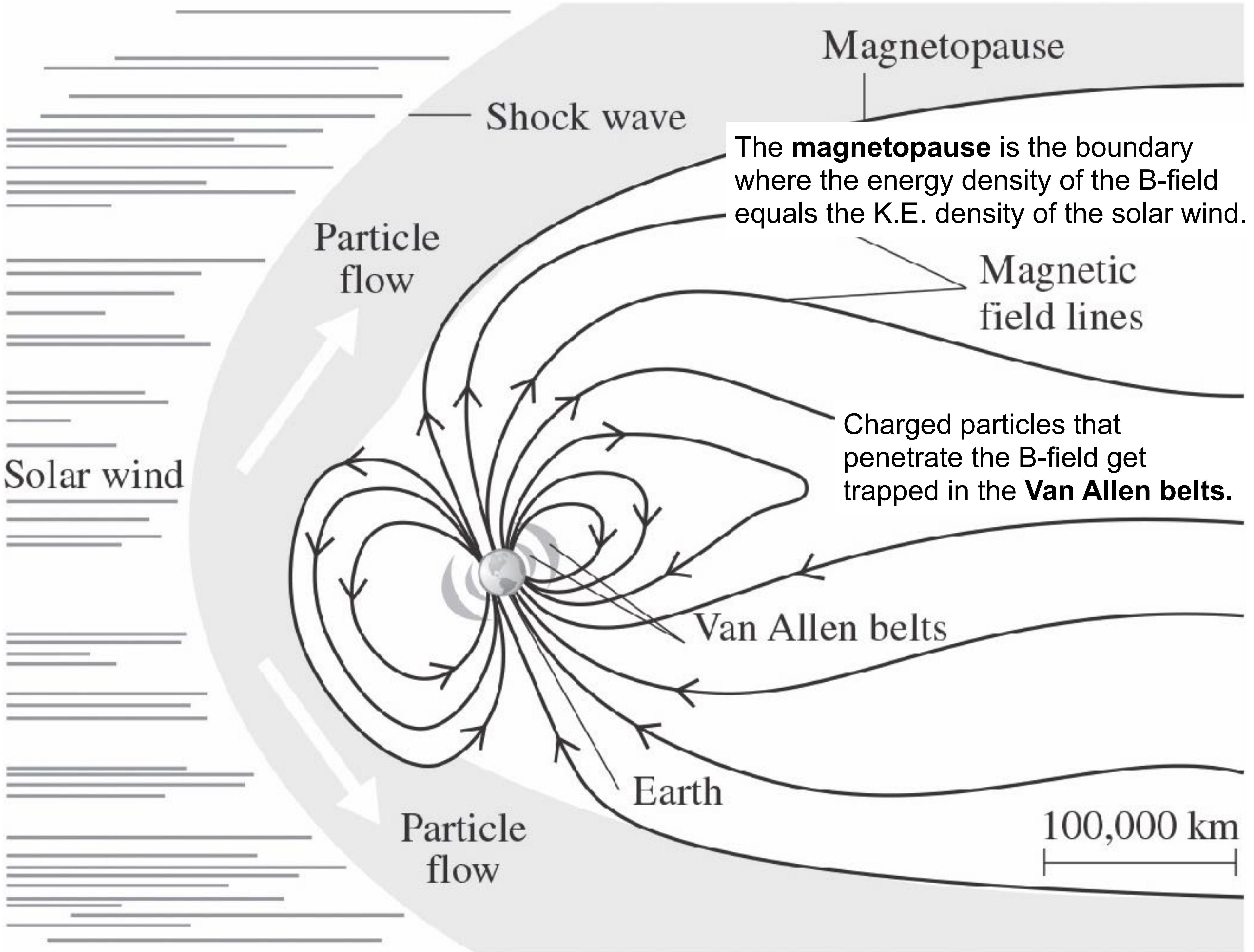
- ***Mie Scattering*** **($L \sim \lambda$):** When particles are similar size to the wavelength, the scattering cross-section scales as $\sigma \propto \lambda^{-1}$. Common for dust with $L \sim 1\ \mu m$ and has the effect of scattering red and near-IR light. This is the reason why dusty galaxies look red.

- ***Geometric scattering ($L \gg \lambda$):*** When particles are much larger than the wavelength, the scattering cross-section becomes wavelength independent. Common for large particles such as water droplets $L \sim 10\ \mu m$. Since all light is evenly scattered, the objects appear white — reason why clouds are white.

Earth's Magnetic Field

Magnetic dipole generated by *convective motions* within the outer core.

- Shields us from solar winds!
- Magnetic axis **tilted by ~12 degrees from the rotation axis.**
- Flips on average **once every ~100,000 years.**
- **Channels charged particles** into the Earth's atmosphere at high latitude, **where the B-field converge at the magnetic poles.**
  - These particles **excite and ionize atoms** in the *thermosphere*, giving rise to **aurorae — or northern/southern lights.**



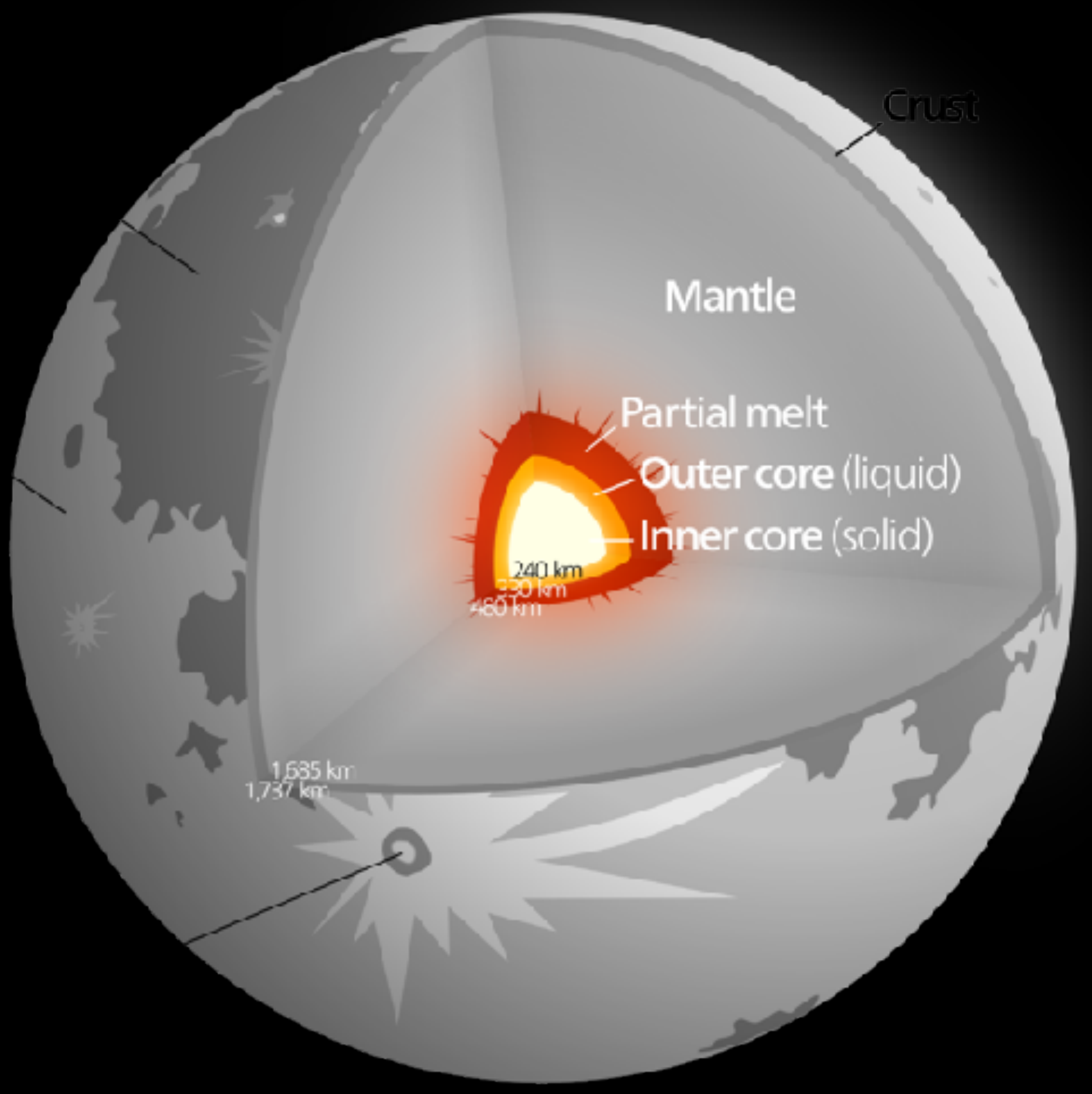
Credit: NASA/Goddard Space Flight Center/Scientific Visualization Studio/Mary P. Hrybyk-Keith


esa
Colors vary with altitude:
- Oxygen atoms glow red highest up via a forbidden transition.
- Oxygen atoms also glow green (most prominent color)
- Nitrogen glows both blue and pink.

Moon’s Interior and Exterior

The Moon’s average density is approximately the same as the Earth’s crust ($\rho = 3370\ \mathrm{kg\ m^{-3}}$)

- Geologically dead, with very rare, weak “moonquakes”
- Solid core (but not an iron core like terrestrial planets)
  - Still not well understood, maybe iron alloy
- Extremely weak magnetic field (stronger in the past)



The surface of the moon is characterized by:

- Dark regions known as “**lunar maria**”
- Lighter regions known as “**lunar highlands**”

Impact Craters

Craters were created primarily early in the Moon's lifetime

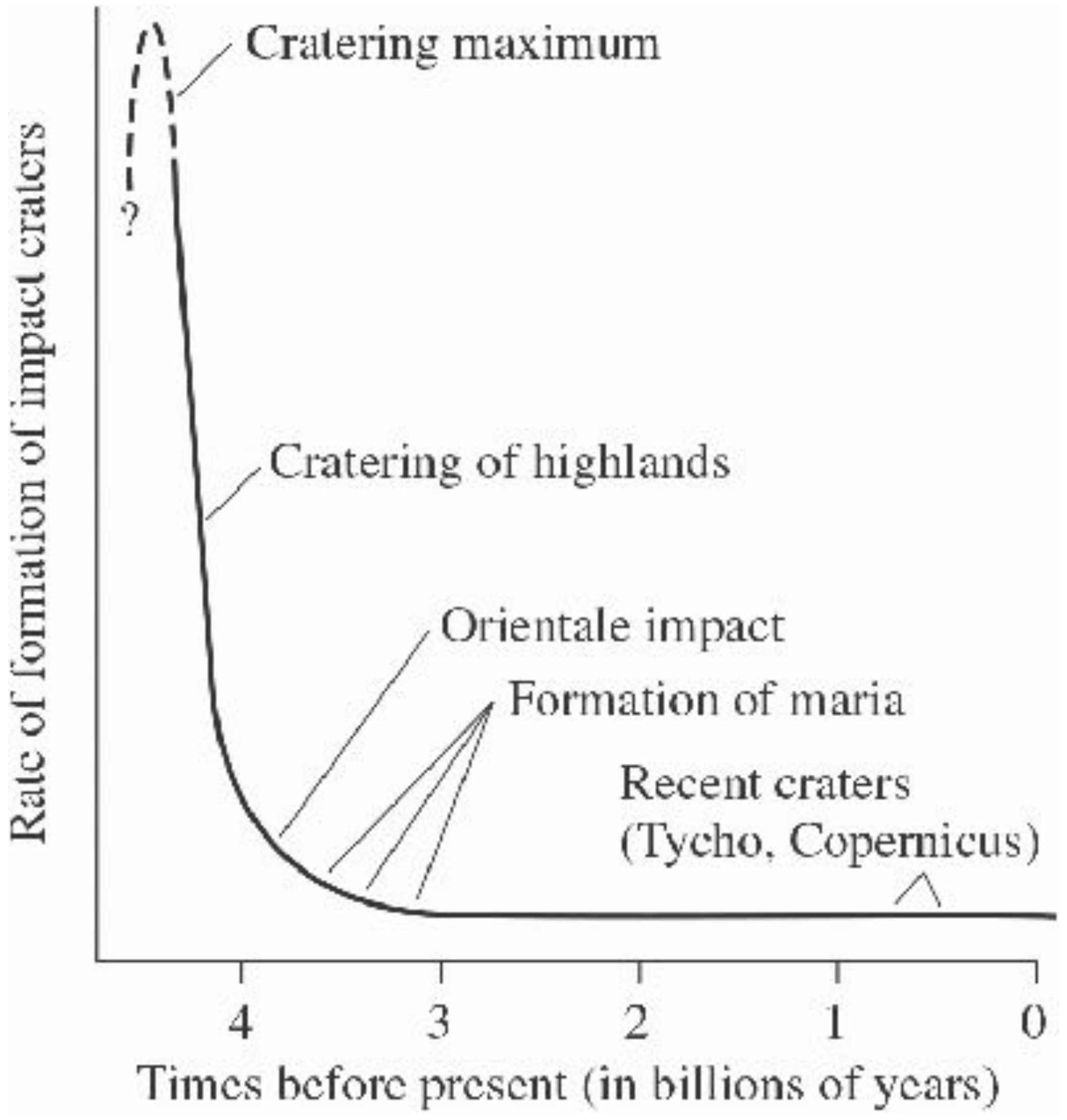
Formation of Craters:

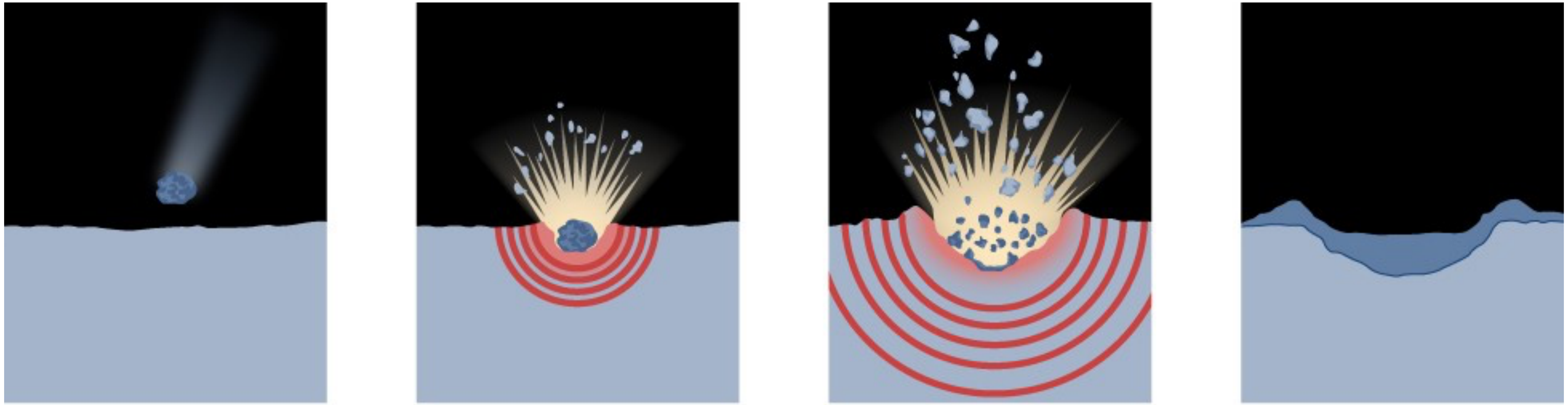
(a) **Impact** – The impactor's velocity equals its own speed plus the target body's orbital velocity.

(b) **Deep penetration and vaporization** – If the impact speed exceeds the sound speed in rock, the object penetrates and vaporizes, releasing its full kinetic energy.

(c) **Crater & Ejecta Formation** – Expanding hot gas from vaporized material explodes outward, excavating a circular crater and ejecting debris.

(d) **Crater Walls & Central Peak**– The lunar crust rebounds, creating raised walls and a central peak.



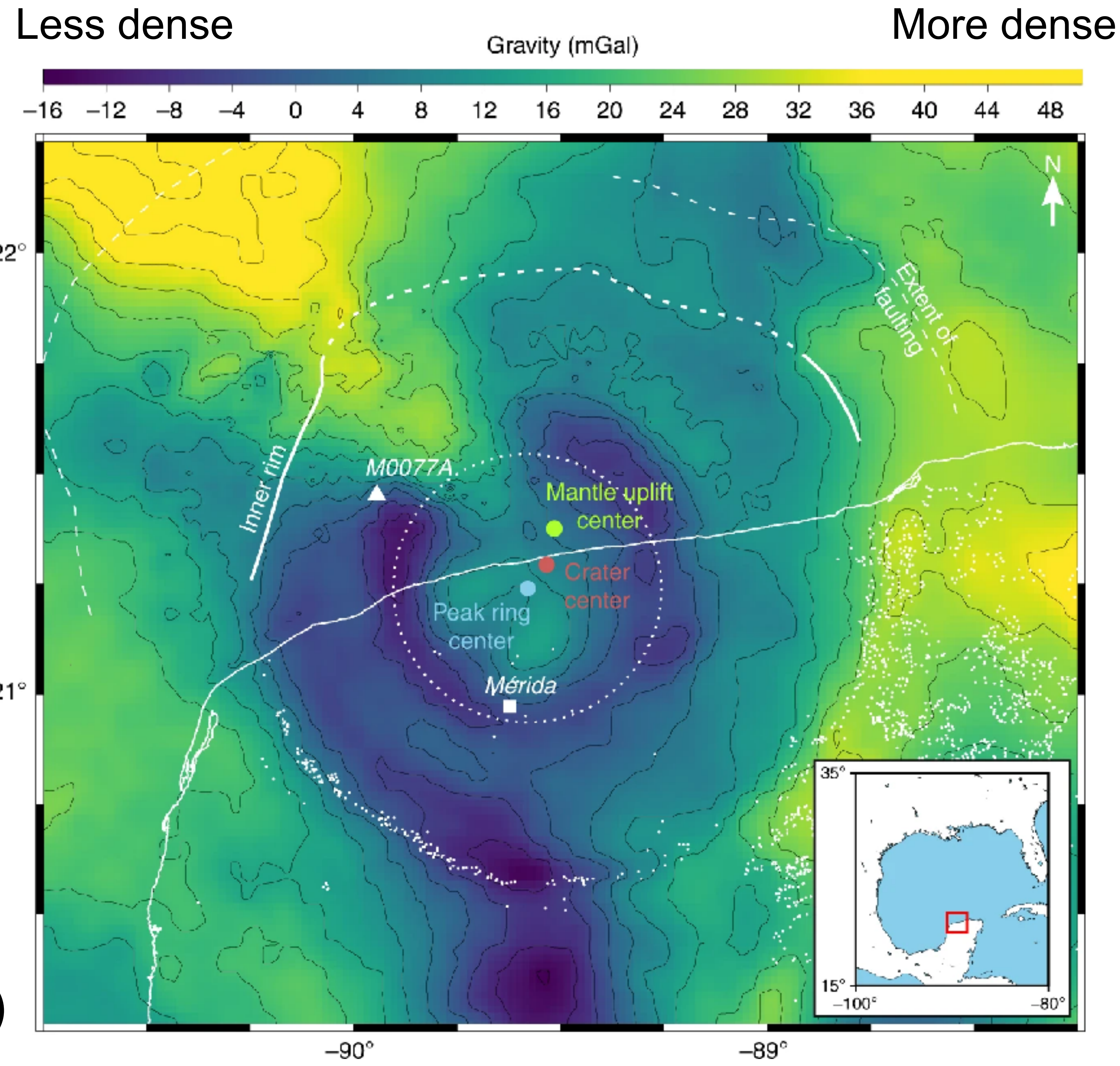


(a) (b) (c) (d)


The central peak of a crater forms for the same reason why a geyser is created after a cannonball.
CANNONBALL!

Craters close to home

We still see some of the large impact craters on Earth



Left: Meteor Crater in Arizona
Right: Chicxulub crater (adiós dinosaurios 🦕🦖)


How was the Moon created?
The leading theory is a giant impact.


SCIENCE BULLETINS
AstroViz
Our Moon
An object the size of Mars
occupied an orbit close to Earth's...

Assessment of Learning Objectives

Q1: Only S-waves can travel through the core of the Earth.

False = ✊

True = ☝️

Assessment of Learning Objectives

Q2: The Troposphere is the hottest layer of Earth’s Atmosphere

False = ✊

True = ☝


Questions?

Reminders

- **Homework #5 due tonight, 11/04 by 11:59 pm via Gradescope.**
- Coding assignment #4 is due Sunday, 11/16 by 11:59 pm.
- Log into canvas and submit your answer to the discussion question <u>by the end of the day</u> to receive participation credit.
- **If you haven’t done so already, please provide complete the anonymous feedback from by 11:59pm tonight.**