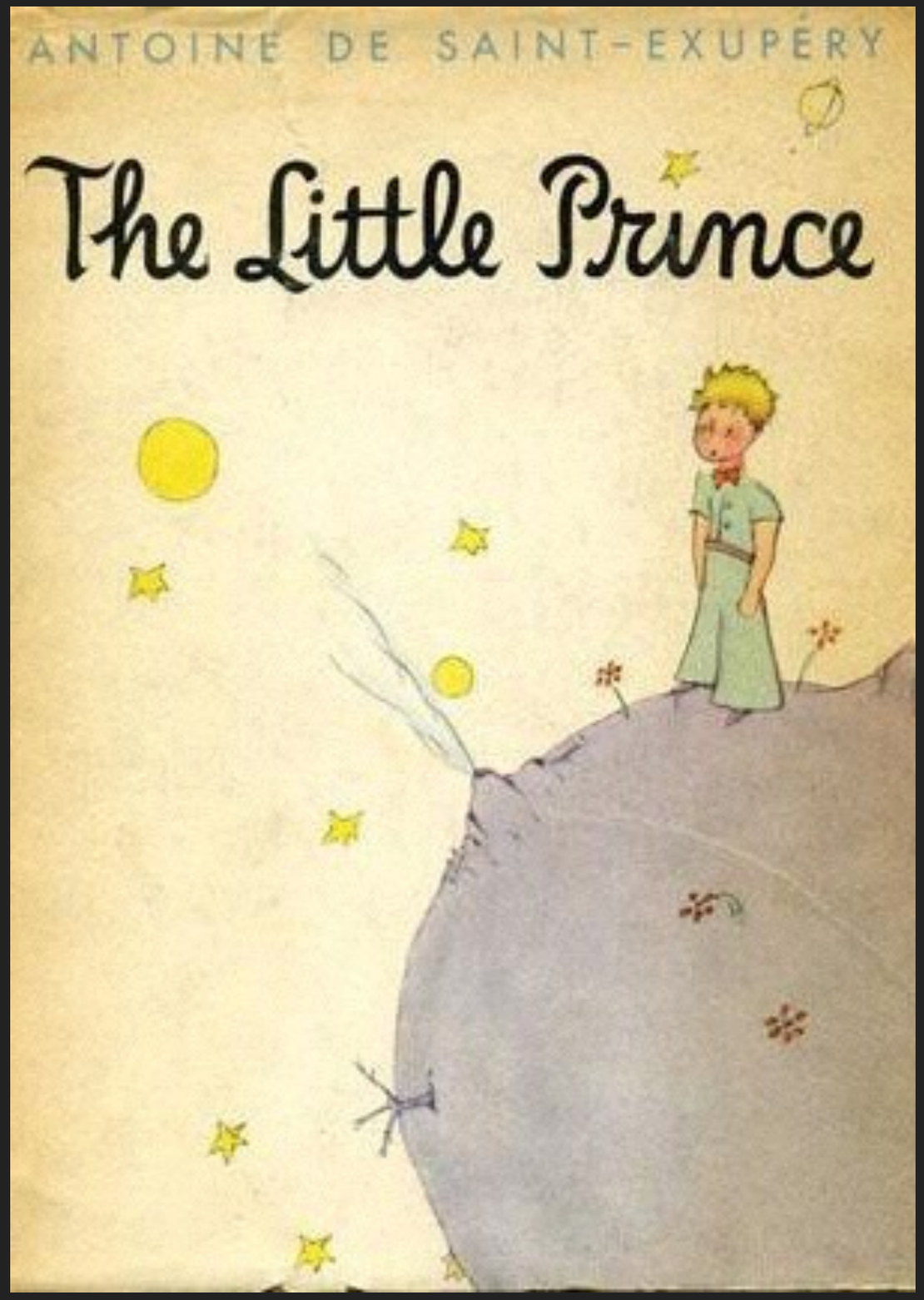
"You can't blame gravity for falling in love." – Albert Einstein

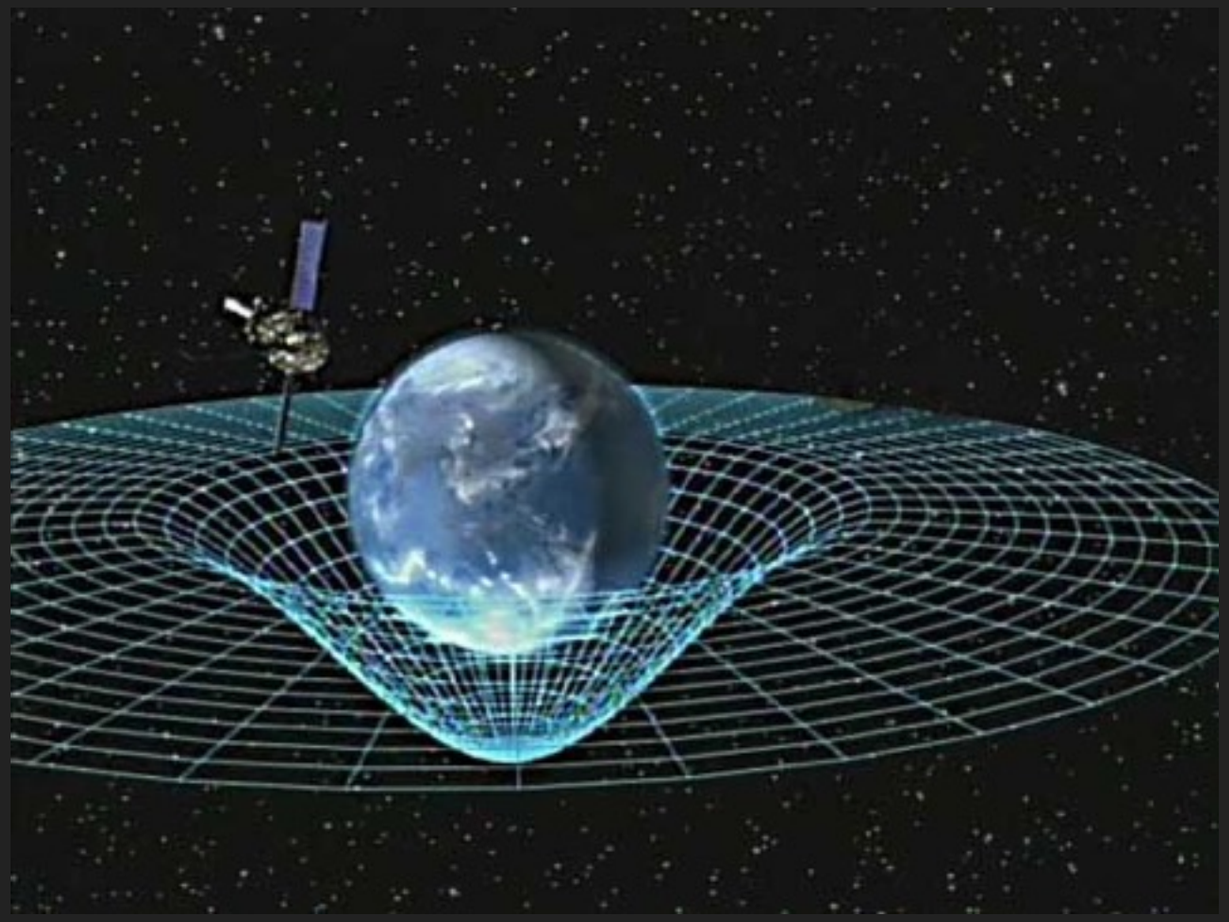
LITTLE PLANET

- If an asteroid was very small but supermassive, could you really live on it like the Little Prince?



WHAT IS GRAVITY?

- Gravity is geometry
  - Distortions in spacetime due to the presence of mass
- Spacetime is the four dimensional fabric of the Universe
  - It’s a mathematical model that combines the three spatial dimensions (up/down, left/right, forward/backward) and time into a single, interwoven continuum



WHAT IS GRAVITY?

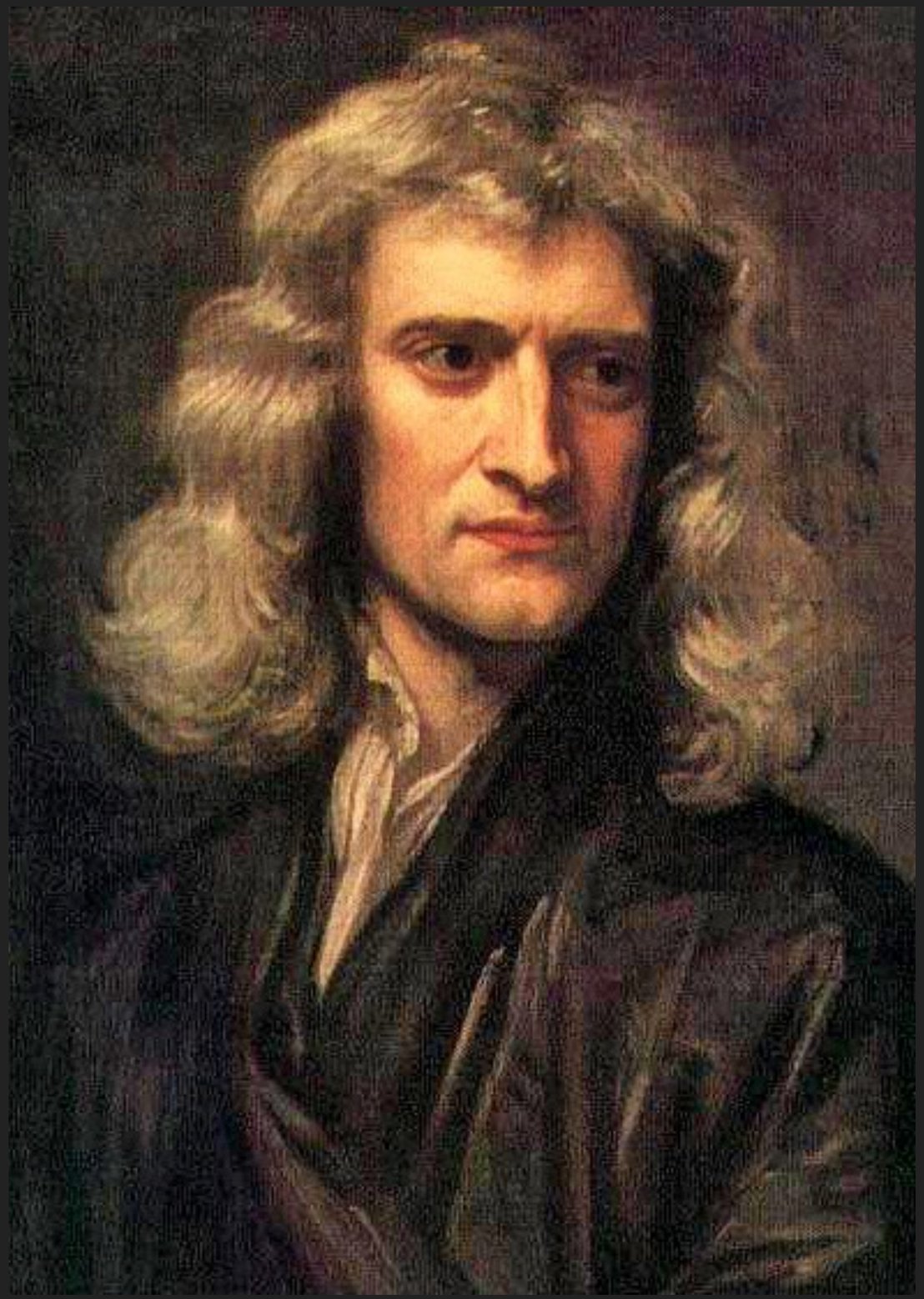
- Means by which masses communicate with each other
  - Masses attract each other
  - Equal and opposite

Four Fundamental Forces of Fysics

Force	Particles Experiencing	Force Carrier Particle	Range	Relative Strength*
Gravity acts between objects with mass	all particles with mass	graviton (not yet observed)	infinity	much weaker ⋮
Weak Force governs particle decay	quarks and leptons	W^+, W^-, Z^0 (W and Z)	short range	
Electromagnetism acts between electrically charged particles	electrically charged	γ (photon)	infinity	
Strong Force** binds quarks together	quarks and gluons	g (gluon)	short range	much stronger

SIR ISAAC NEWTON AND THE 1ST LAW OF MOTION

- ca 1680s
- Galileo introduced us to inertia in 16th Century
- Newton's 1st Law of Motion:
  - Object at rest tends to stay at rest unless acted on by an outside force
- What about falling objects?

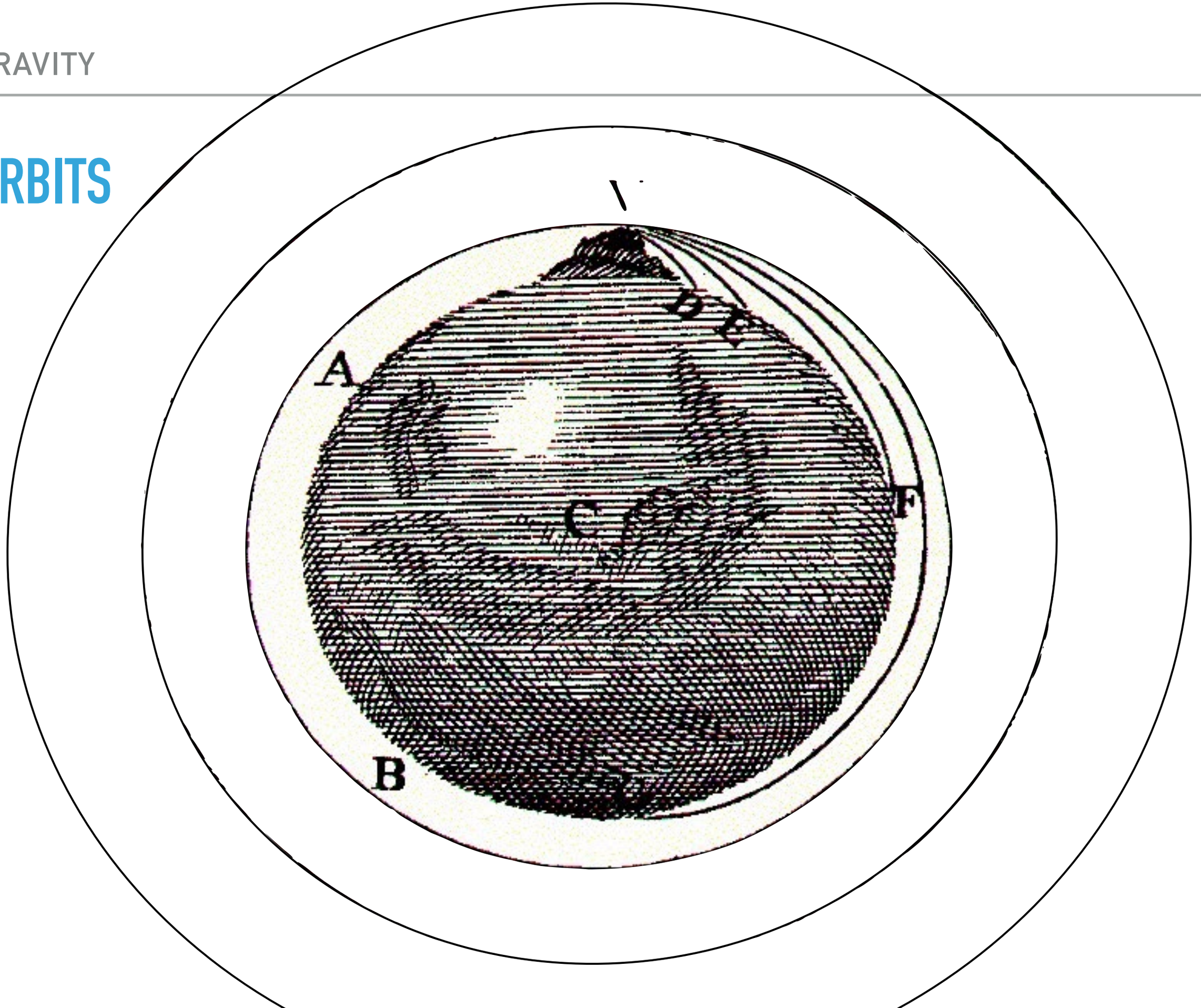


ISAAC NEWTON

FALLING MOON

- Why doesn’t the Moon crash into Earth?
  - The Moon has tangential velocity
- What if the force of gravity disappeared?
  - The Moon would fly away in a straight, tangential path

ORBITS



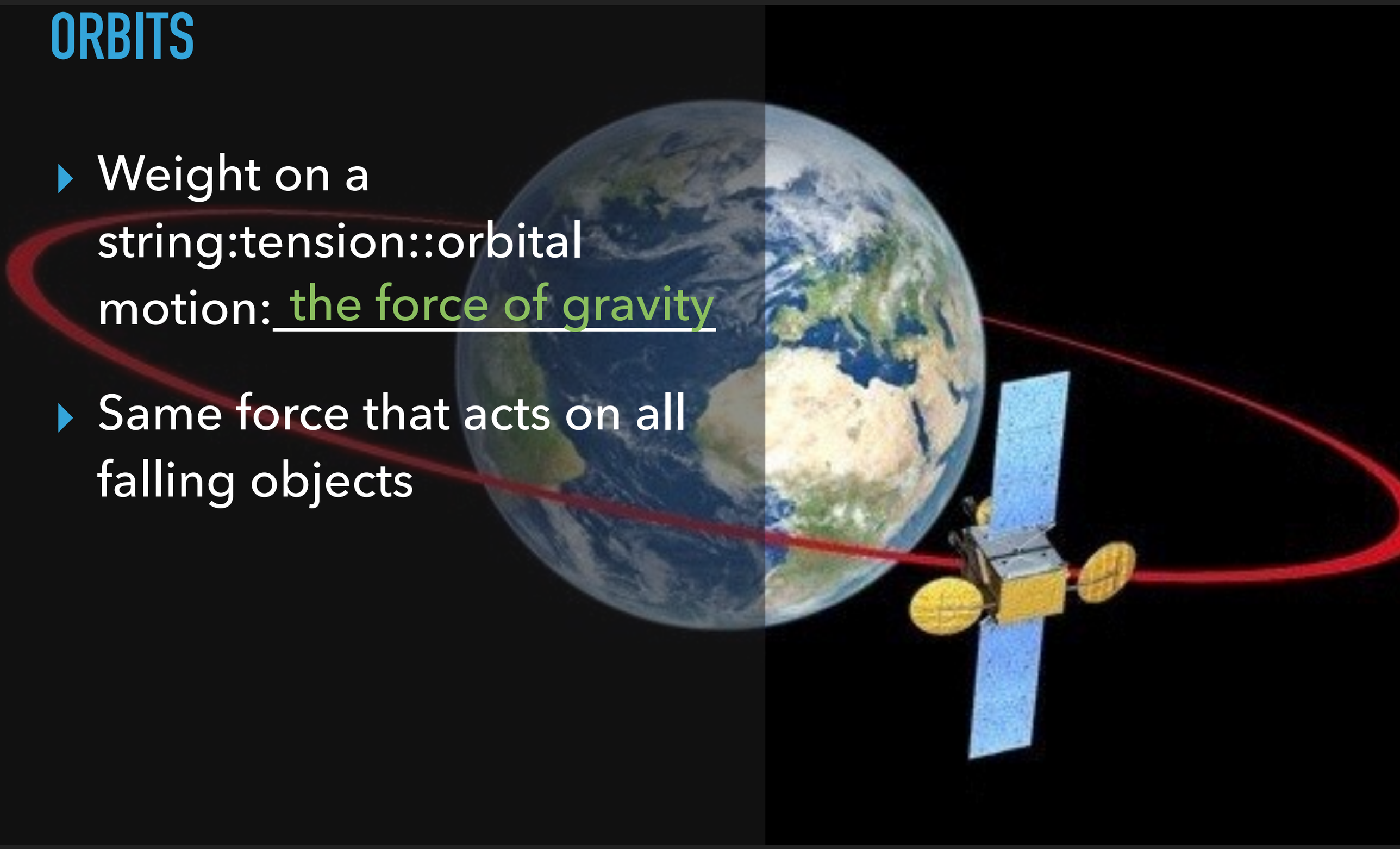
ORBITS

FLYING IS JUST FALLING AND MISSING THE GROUND

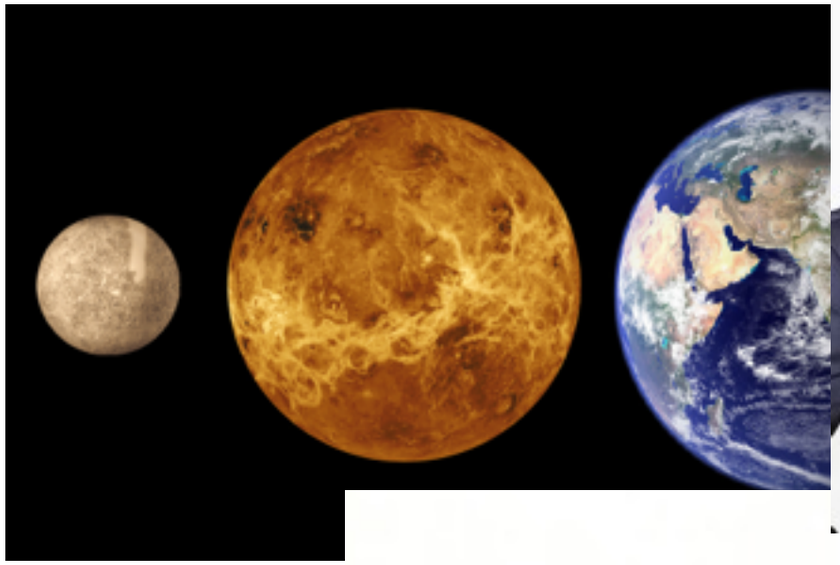
Douglas Adams

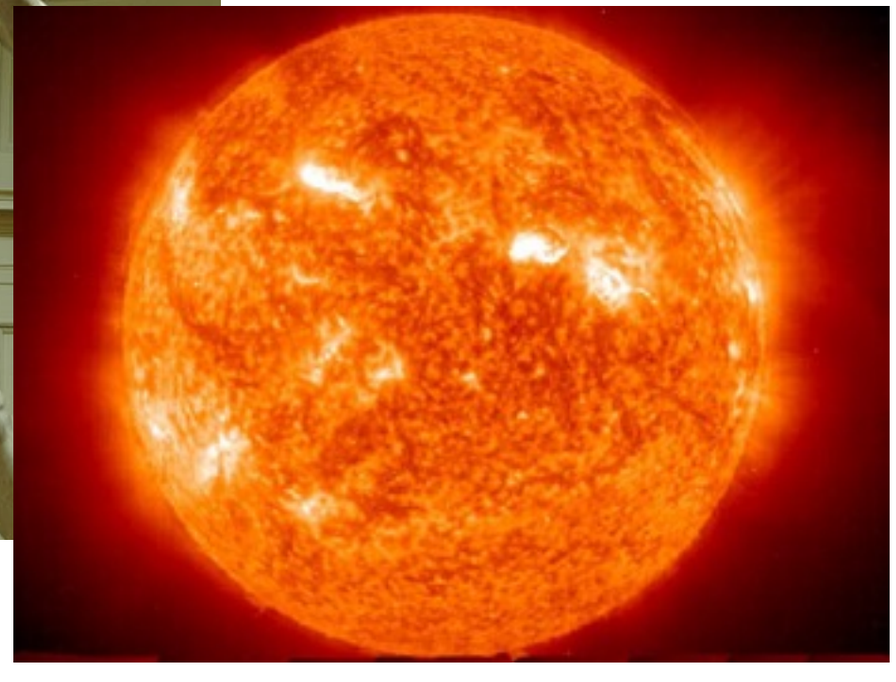
ORBITS

- Weight on a string:tension::orbital motion: the force of gravity
- Same force that acts on all falling objects



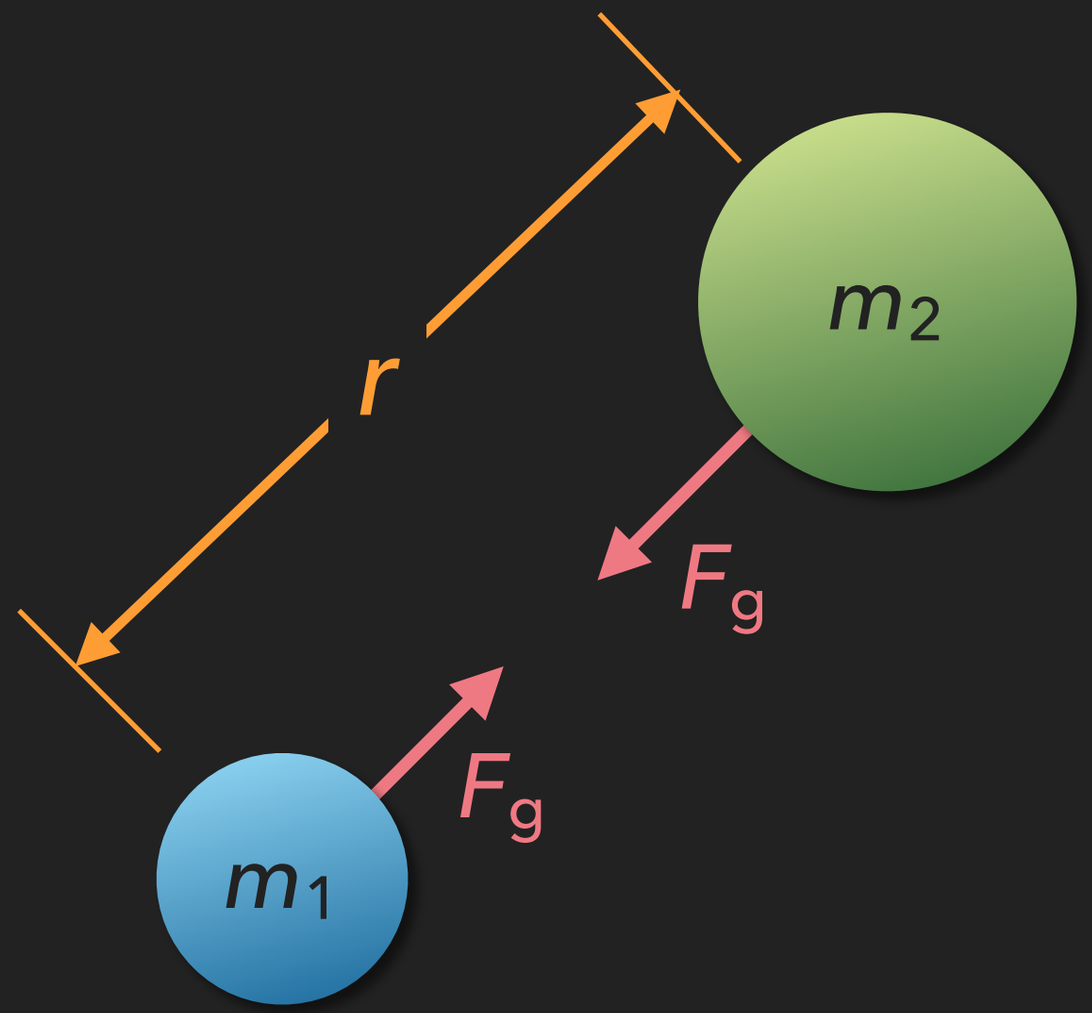
UNIVERSAL GRAVITY



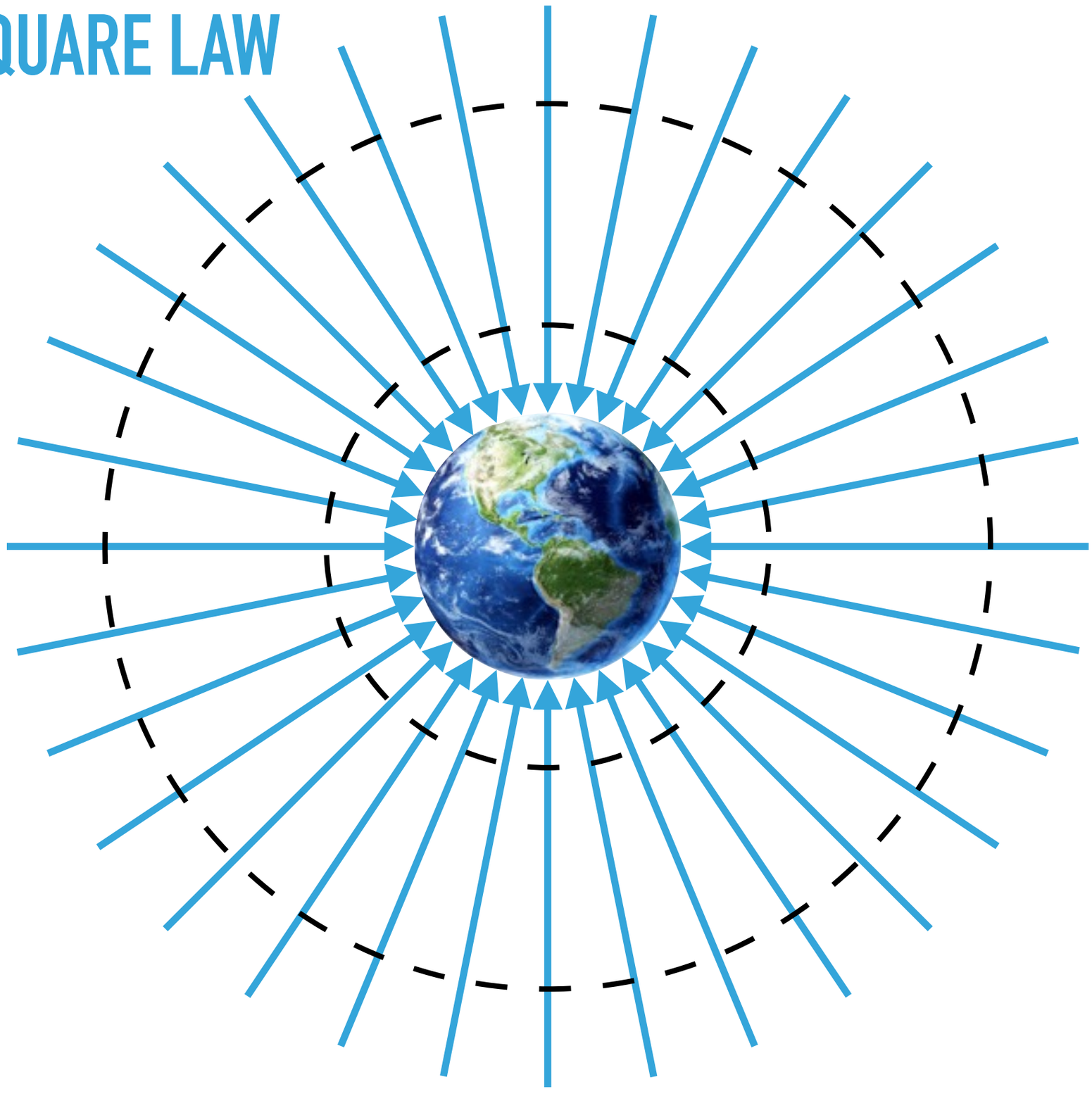


FORMALIZING GRAVITY

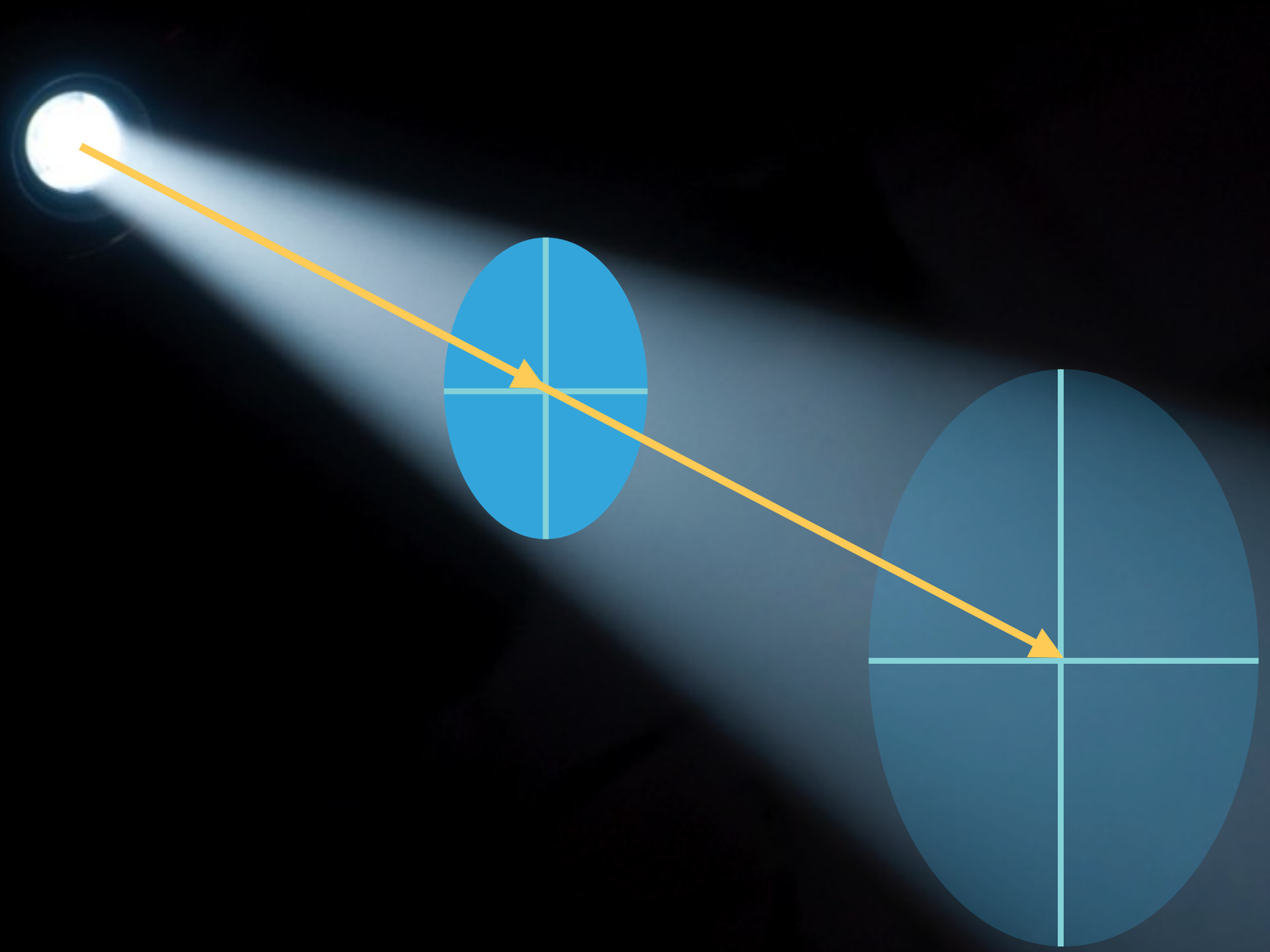
- The force of gravity between two objects depends on 3 quantities
  - How big is the first object: m_1
  - How big is the second object: m_2
  - How far apart are they: r



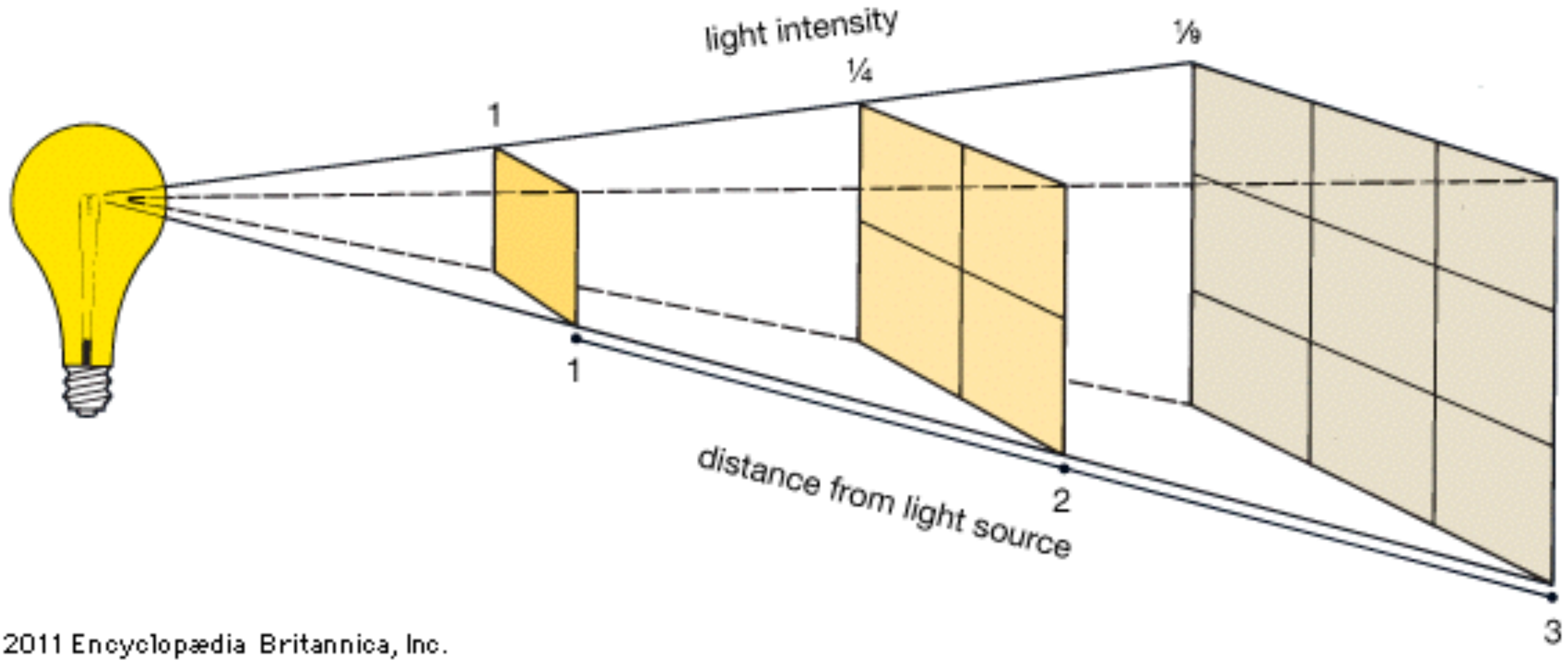
INVERSE SQUARE LAW



INVERSE SQUARE LAW



INVERSE SQUARE LAW



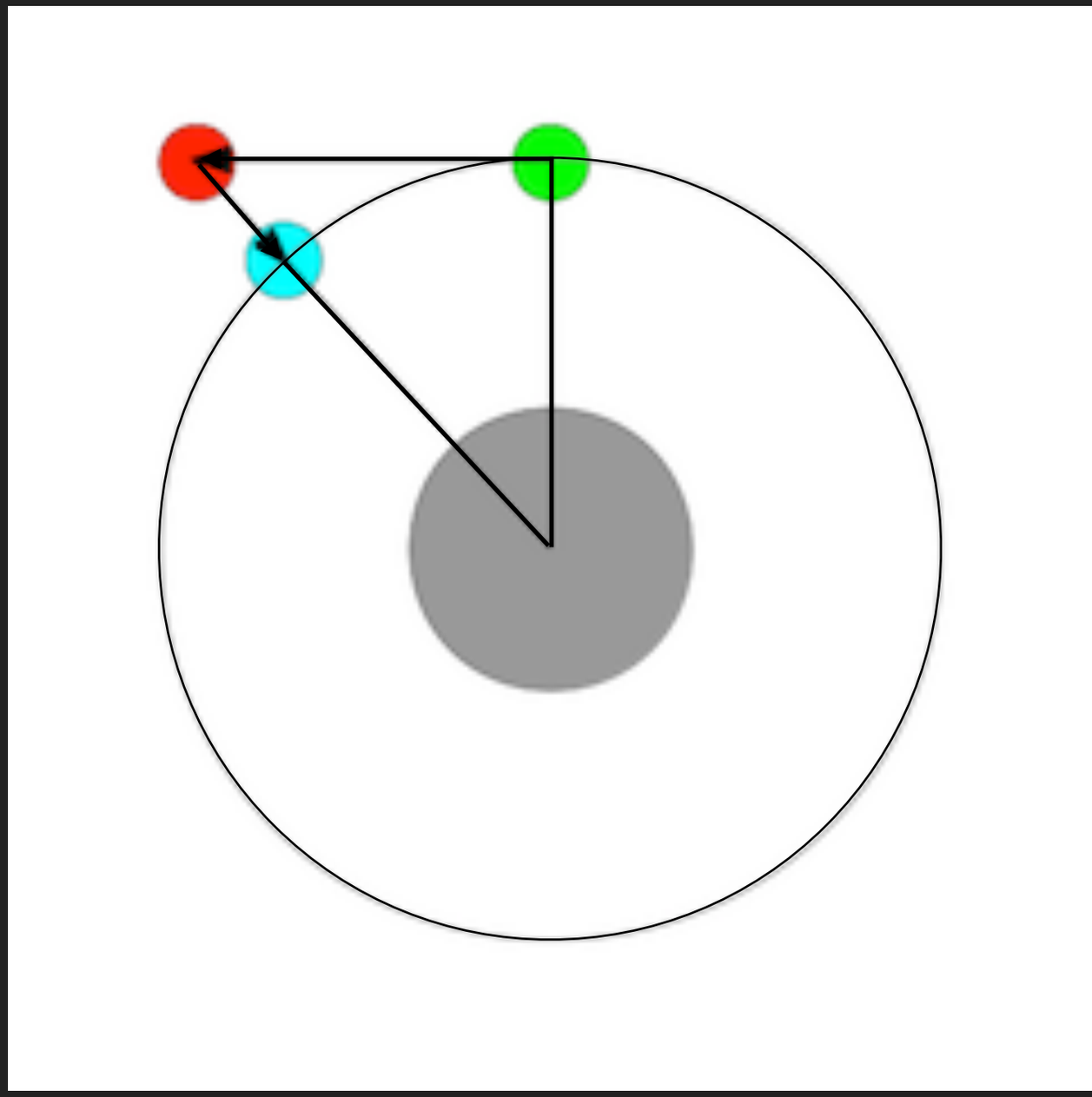
INVERSE SQUARE LAW

FORCE OF GRAVITY

- $F_g = \frac{Gm_1m_2}{r^2}$
- $G = 6.67 \times 10^{-11}\ Nm^2/kg^2$
  - Gravitational constant
  - Always the same, no matter where you are in the Universe

FALLING MOON TEST

- Mass doesn't matter. Only distance
- Compare fall of an apple to fall of the Moon
  - Apple falls 4.9m in 1s
  - The Moon is 60x further from Earth
  - F_g is diluted by $1/r^2$
  - Moon falls 1.4mm – QED



EXAMPLE 1

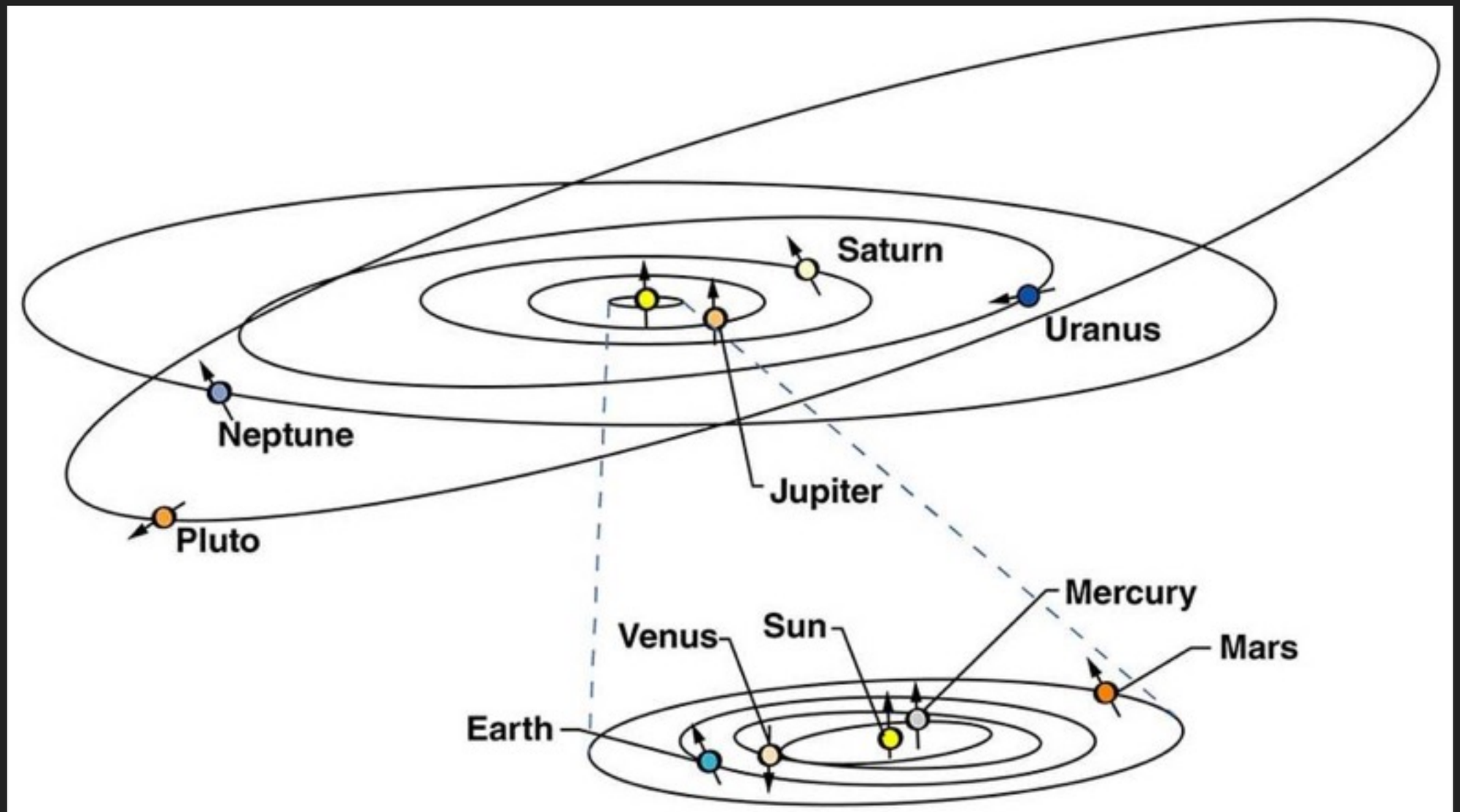
- What's the force of gravity between two students?
- m_1 = _____
- m_2 = _____
- r = _____
- *Ans*: F_g = _____

THE MASS OF EARTH

- $F = ma = GmM/R^2$
- $\cancel{m}g = G\cancel{m}M/R^2$
- $M = gR^2/G$
  - $R = 6.37 \times 10^6 m$
- $M = (9.81 m/s^2)(6.37 \times 10^6 m)^2/(6.67 \times 10^{-11} Nm^2/kg^2)$
- $M = 5.97 \times 10^{24} kg$

GRAVITATIONAL POTENTIAL ENERGY

- $PE_g = -\frac{Gm_1m_2}{r}$
- Why negative?



EXAMPLE 2

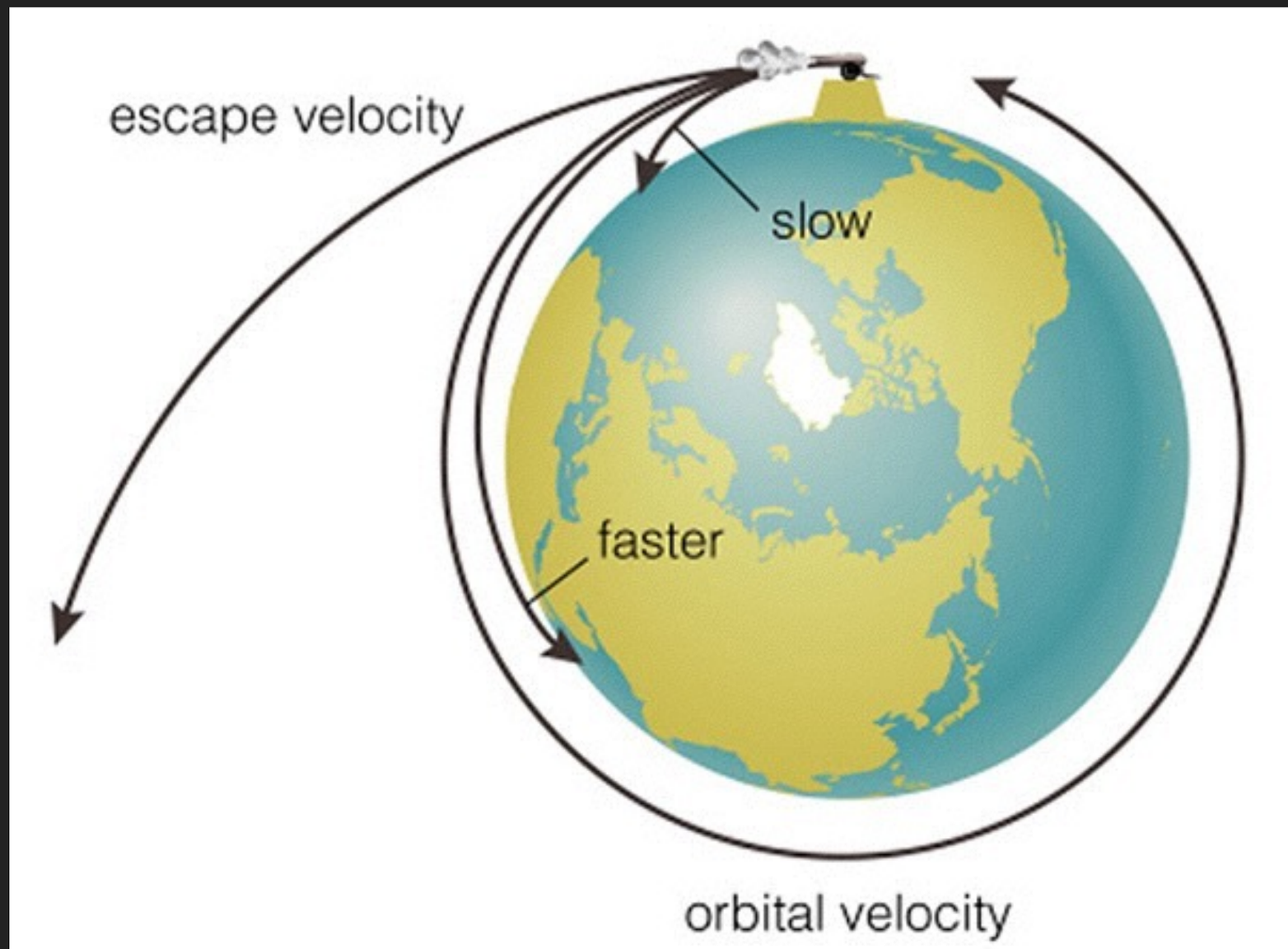
- How fast would you need to throw a ball of mass *m* for it to escape Earth's gravity?
- E = KE + PE
- $E = \frac{1}{2}mv^2 - GMm/R = 0$
- *Ans.* $v_{esc} = \sqrt{2GM/R}$
  - Escape speed
  - Independent of the mass of the object in question!

OUR SOLAR SYSTEM

	Mass	Radius
Sun	1.99×10^{30} kg	6.96×10^{8} m
Mercury	3.20×10^{23} kg	2.44×10^{6} m
Venus	4.88×10^{24} kg	6.05×10^{6} m
Earth	**5.97×10^{24} kg**	**6.37×10^{6} m**
Mars	6.42×10^{23} kg	3.40×10^{6} m
Jupiter	1.90×10^{27} kg	7.15×10^{7} m
Saturn	5.68×10^{26} kg	6.03×10^{7} m
Uranus	8.68×10^{25} kg	2.56×10^{7} m
Neptune	1.02×10^{26} kg	2.48×10^{7} m

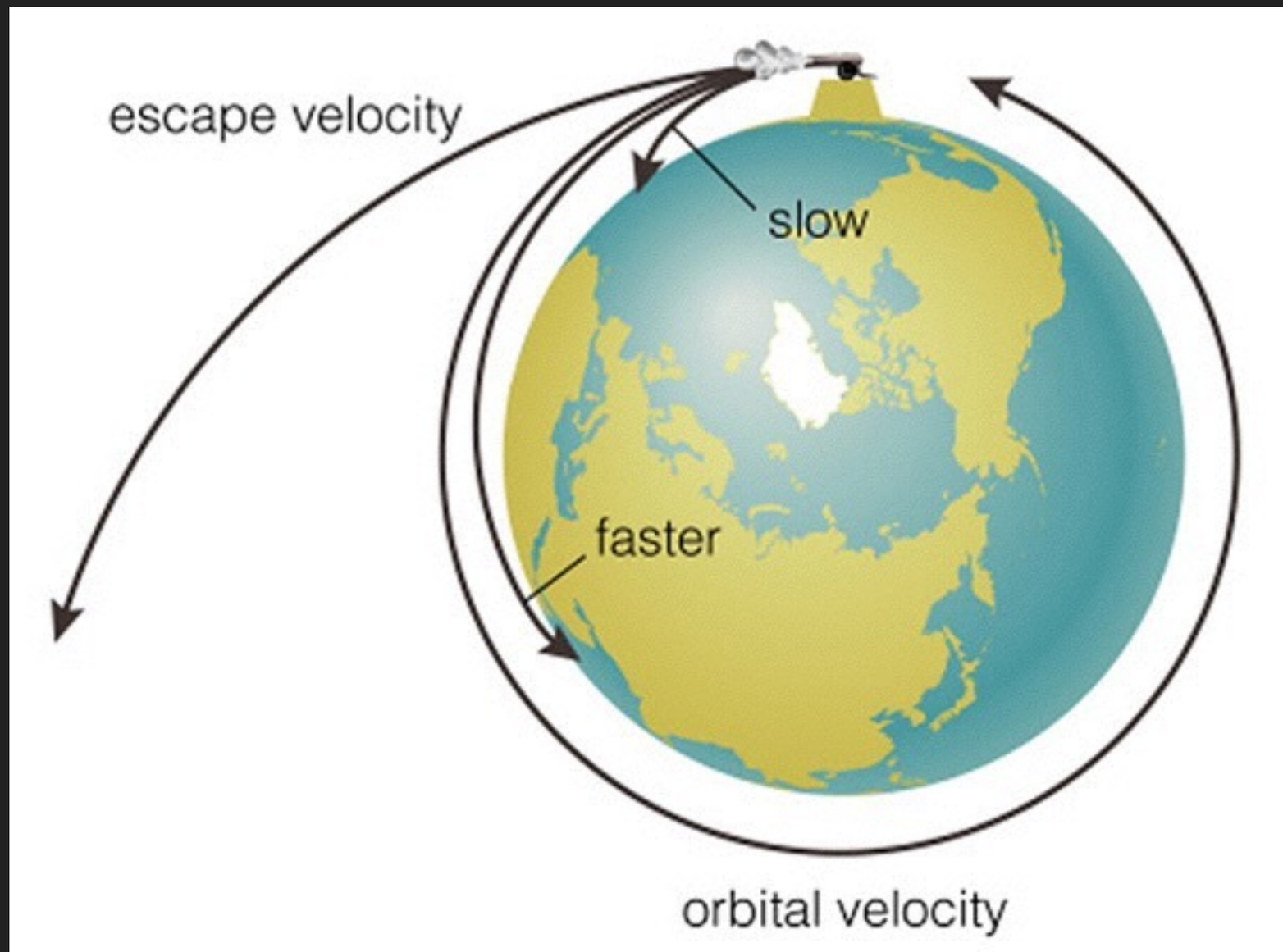
EXAMPLE 3

- What's escape speed from the surface of Earth?
  - *Ans.* v_{esc} *= 11.2 km/s*



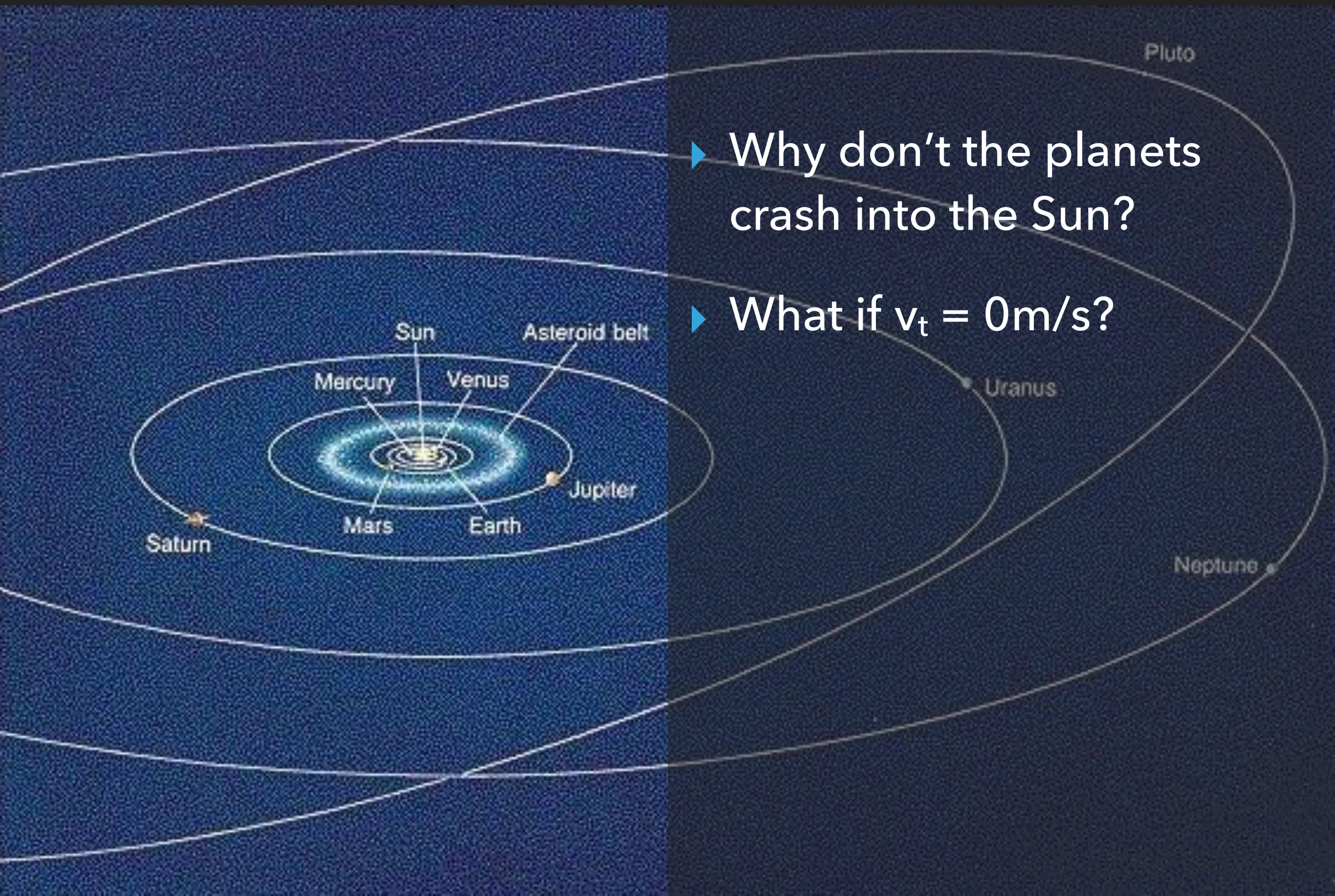
EXAMPLE 4

- What's the orbital velocity at a distance *r* away from the center of Earth?
  - $F_g = F_c$
  - *Ans.* $v_{orb} = \sqrt{GM/R}$



DID YOU GET ALL THAT?

- Why don't the planets crash into the Sun?
- What if v_t = 0m/s?



PULLING UP ON THE EARTH

- What is the force of gravity between the Earth and a 70.0kg student?
- $m = 70.0\ kg$ $M = 5.97 \times 10^{24}\ kg$
- $R = 6.37 \times 10^{6}\ m$ $G = 6.67 \times 10^{-11}\ Nm^2/kg^2$
- $F_g = GmM/R^2$
- $F_g = \dfrac{(6.67 \times 10^{-11} Nm^2/kg^2)(70.0kg)(5.97 \times 10^{24} kg)}{(6.37 \times 10^{6} m)^2}$
- $F_g = 687\ N$

PULLING UP ON THE EARTH

- F_g = 687 N
- What is the acceleration of the Earth due to this student?
- F = Ma
- 687N = (5.97×10^{24} kg) a
- a = 1.15×10^{-22} m/s^2

HERE'S A QUESTION

- An apple on a tree feels 1N of force due to gravity
- If the tree were twice as tall, the force of gravity on the apple would then be:

A. twice as strong

B. half as strong

C. a fourth as strong

D. none of the above

HERE'S A QUESTION

- An apple on a tree feels 1N of force due to gravity
- If the tree were twice as tall, the force of gravity on the apple would then be:

A. twice as strong

B. half as strong

C. a fourth as strong

D. none of the above

ALTITUDE

- What is the force of gravity at 2.53×10^5m above the surface of the Earth on a 50.0kg object?
  - $M = 5.97 \times 10^{24}$kg
  - $R = 6.37 \times 10^6$m

ALTITUDE

- $F_g = GmM/r^2$
  - $r = R + h$
  - $r = 6.37x10^6m + 2.53x10^5m$
  - $r = 6.623x10^6m$
- $F_g = \frac{(6.67x10^{-11}Nm^2/kg^2)(50.0kg)(5.97x10^{24}kg)}{(6.623x10^6m)^2}$
- $F_g = 454N$

ALTITUDE

- $F_g = 454N$
- What is the normal weight on the surface of Earth?
  - $W = mg$
  - $W = (50.0kg)(9.81m/s^2)$
  - $W = 491N$

"WEIGHTLESSNESS"

- Astronauts in orbit are said to be "weightless"
- Gravity is still acting on them!
- Astronauts are in perpetual free fall!

DOUBLE CHECK

- Since the Moon is pulled to the Earth by gravitational attraction, why doesn’t it crash into the Earth?

DOUBLE CHECK

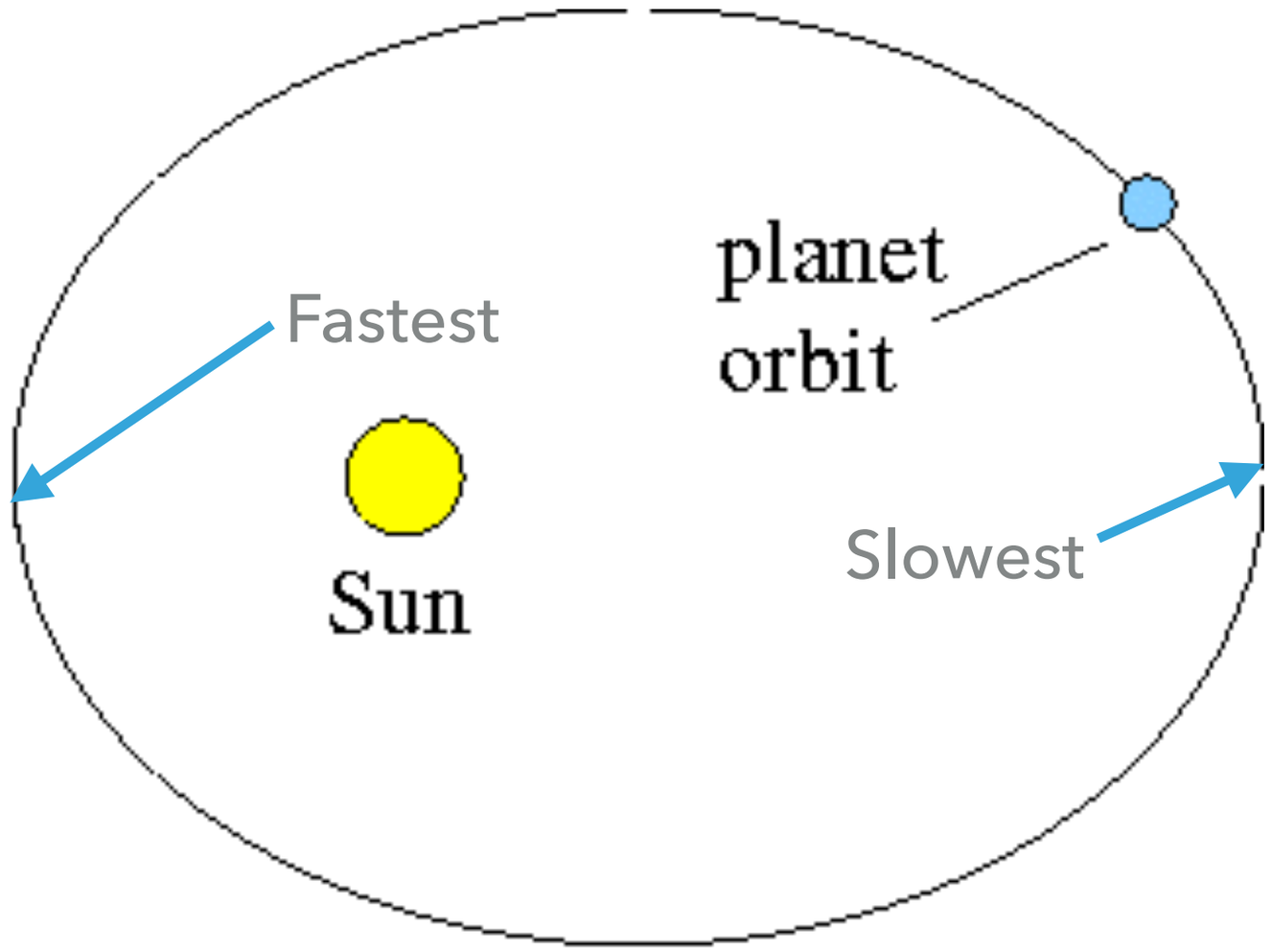
- If there is an attractive force between all objects, why do we not feel ourselves gravitating toward massive buildings in our vicinity?

DOUBLE CHECK

- Which requires more fuel – a rocket going from from Earth to the Moon or a rocket coming from the Moon to Earth? Why?

SATELLITE MOTION

- Shape of orbit?
  - Ellipse
- What's conservation of angular momentum tell us about the planet's orbit?
  - The closer it gets, the faster it orbits
- $L = mr_1^2\omega_1 = mr_2^2\omega_2$

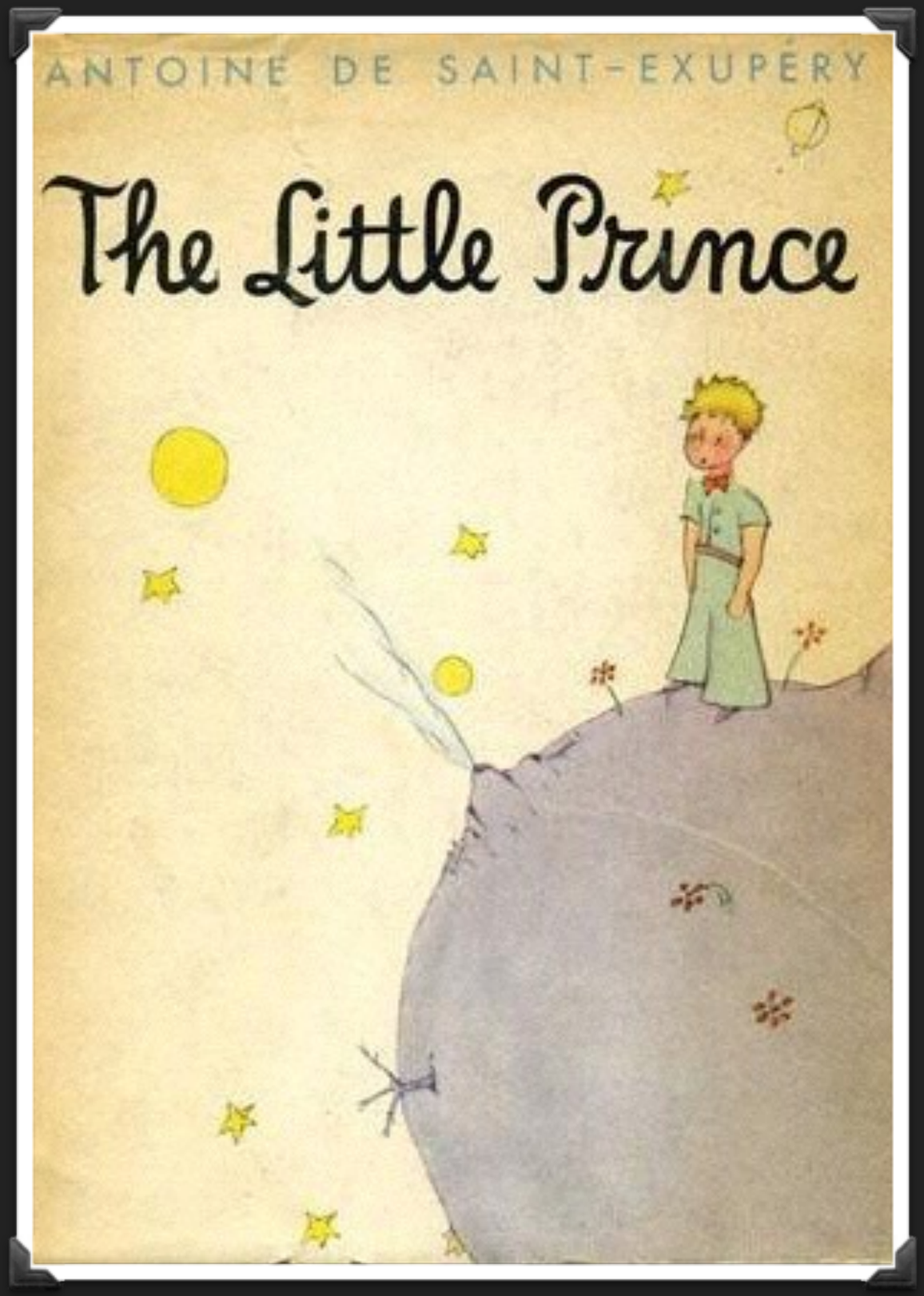


EARTH'S ORBIT

- At its furthest, Earth is 1.52×10^{11} m from the Sun. At that distance, our planet orbits at 1.93×10^{-7} rad/s. At its nearest, Earth is 1.47×10^{11} m from the Sun. What's its orbital velocity at that distance (in rad/s)?
  - *Ans. $\omega = 2.06\times10^{-7}$ rad/s*
- What's that orbital velocity in m/s?
  - *Ans. $v = 30{,}300$ m/s*
  - That's 88 times the speed of sound! (or 73 times a speeding bullet!)

LITTLE PLANET

- If an asteroid was very small but supermassive, could you really live on it like the Little Prince?

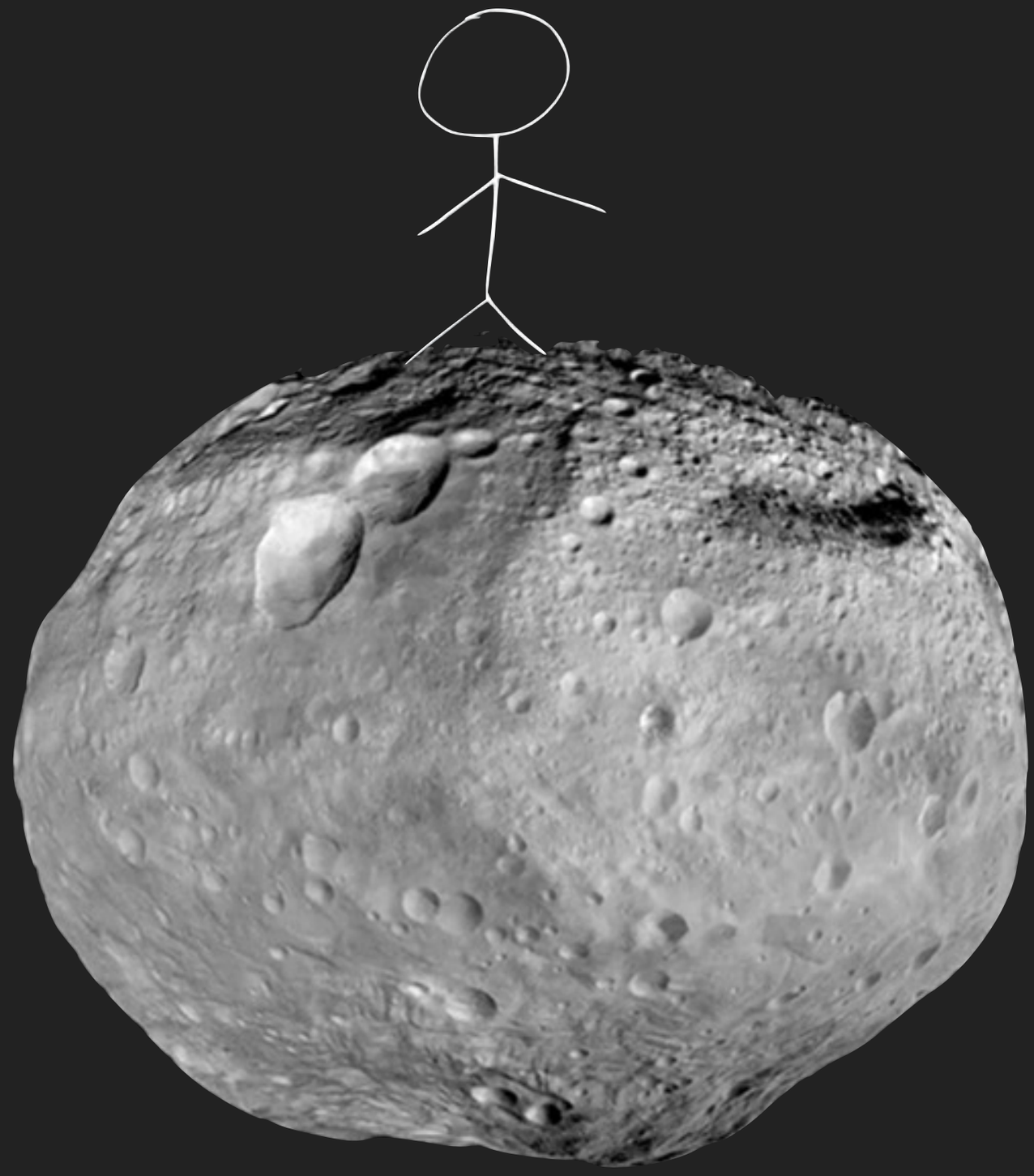


LITTLE PLANET

- If the astroid has a radius of 1.75 m, what mass would it need to in order to have Earthlike gravity at the surface?

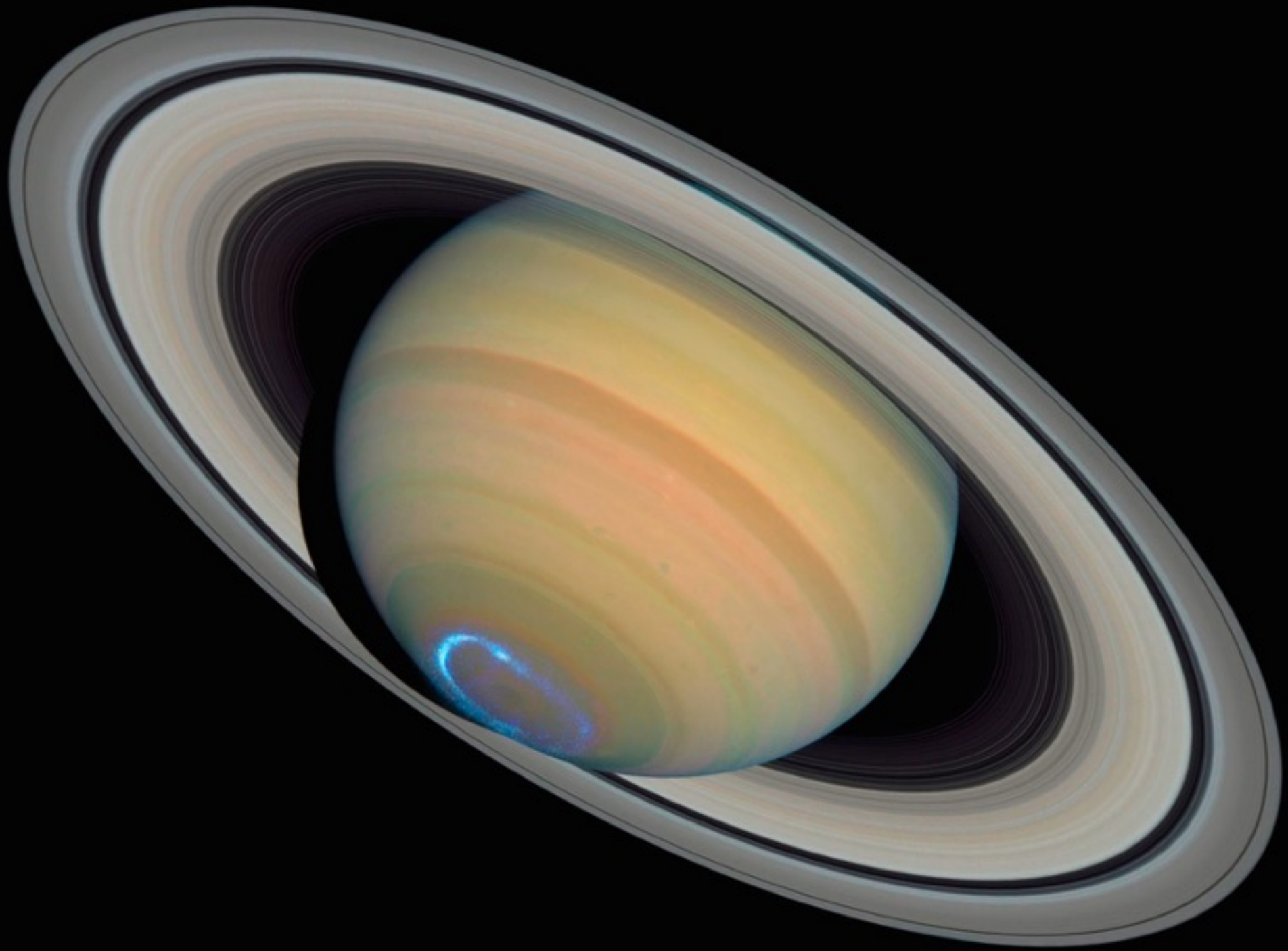
- $M = 4.5 \times 10^{11}$ kg (just under 500 million tons)

- That's roughly equal to the combined mass of every human on Earth



LITTLE PLANET

- What would be the difference between the force of gravity at your head vs. your feet?
- Compare the force of gravity on 60 kg at the surface vs. 1.6 m (~5′ 3″) above the surface?
  - $F_g\,(h = 0) = 588$ N
  - $F_g\,(h = 1.6\text{ m}) = 160$ N
- Called tidal forces – where there's a substantial difference in the force of gravity between different ends of a body
- It would feel like lying on a merry-go-round with your head near the center



LITTLE PLANET

- What would be the escape speed on the surface?
  - v_{esc} = 5.9 m/s
- That's slower than a sprint (but still pretty fast)
- If you can't dunk a basketball, you wouldn't be able to escape the asteroid by jumping
  - However, you might be able to escape by running horizontally and jumping off a ramp

LITTLE PLANET

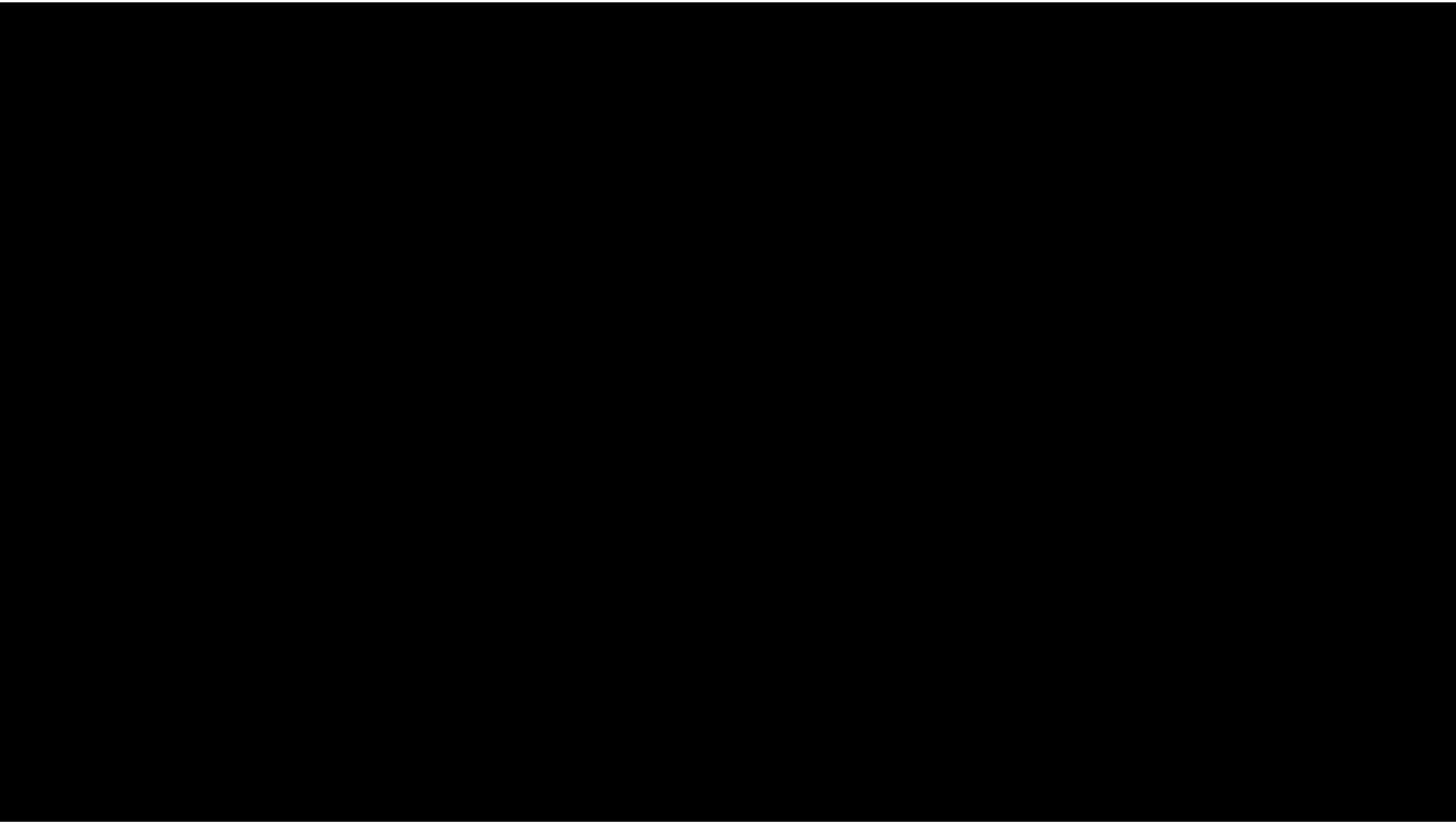
- Say you center of mass is 1.4 m above your feet. How fast would you need to run to start orbiting the asteroid?
  - v_{orb} = 3.1 m/s
- That's typical jogging speed
- This would be a *weird* orbit

"If I have seen further than others, it is by standing on the shoulders of giants" – Isaac Newton

HISTORY OF GRAVITATIONAL THEORY

https://www.youtube.com/watch?v=GyN2RhbhiEU

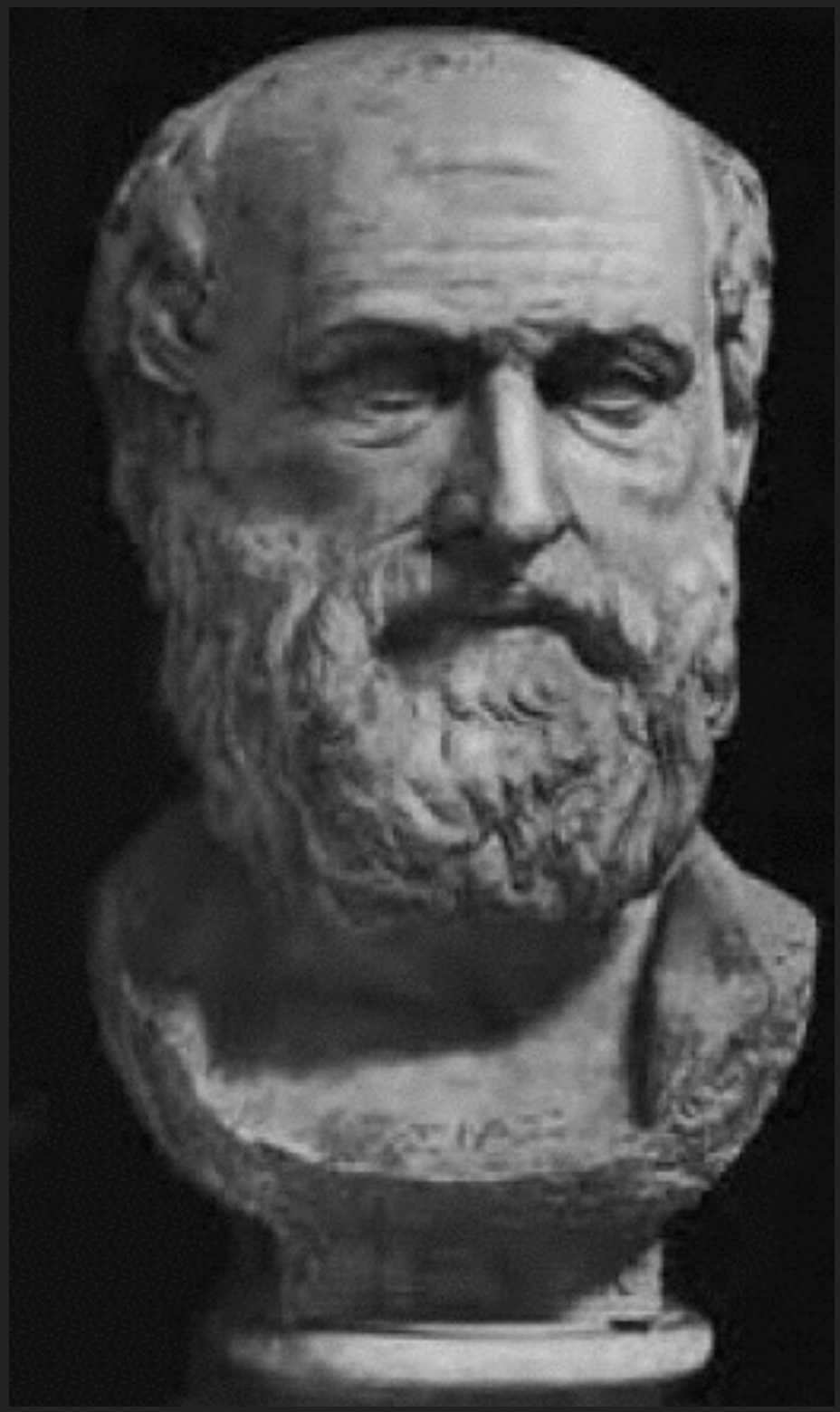
SCIENTIFIC LAW VS. THEORY



ERATOSTHENES

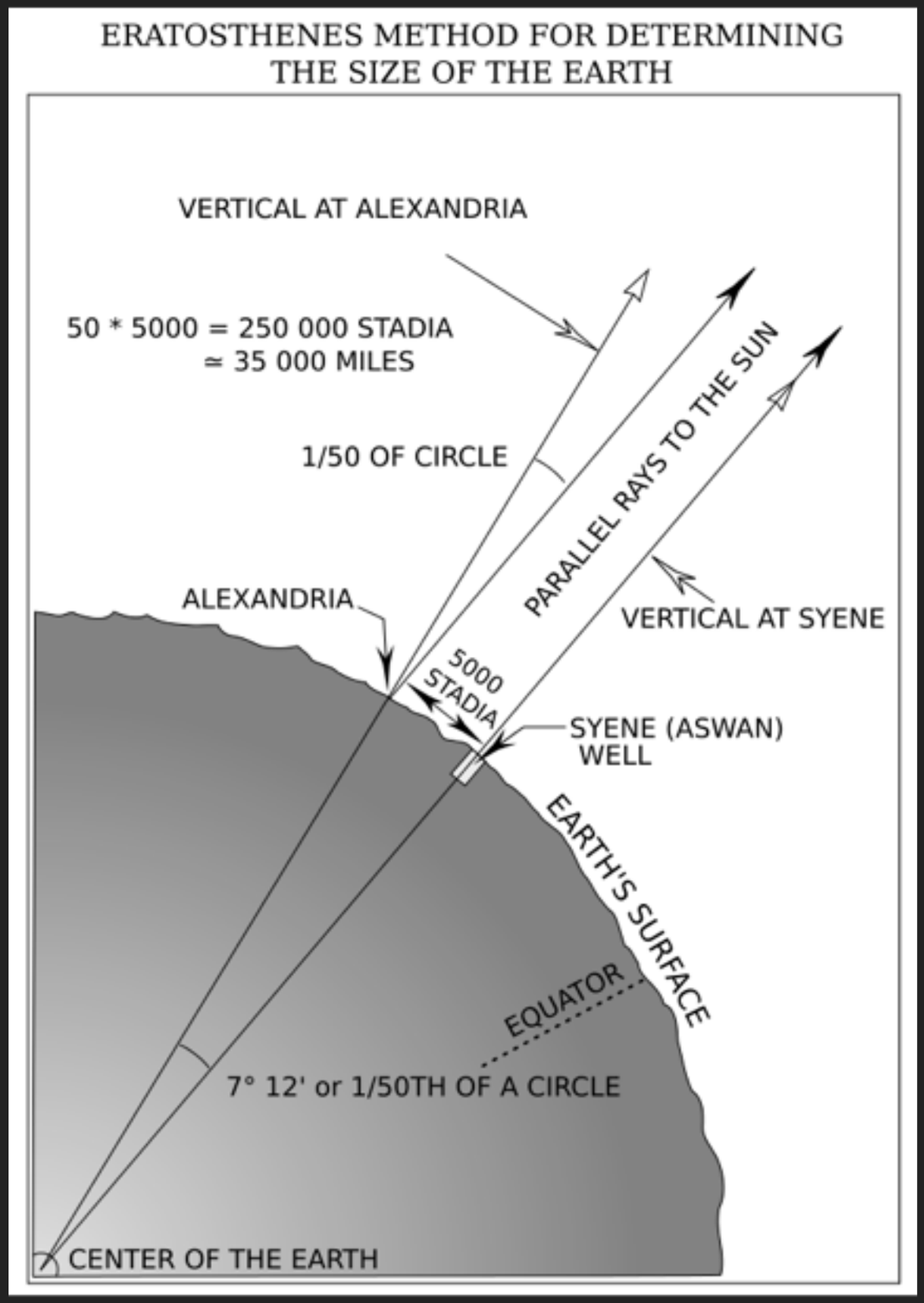
CA. 276 BC– 194 BC

- Greek mathematician, geographer, poet, astronomer, and music theorist
- First to measure the circumference of the Earth



THE CIRCUMFERENCE OF THE EARTH

- Syene lies on the Tropic of Cancer
  - Noon on the Summer Solstice, the Sun is directly overhead
- At the that same time, measured the Sun's angle of elevation in Alexandria
  - 7° 12′ (or 1/50th of a circle)
- Calculated circumference: 46,620km (err. 16.3%)



REASONS FOR ERROR

- Alexandria and Syene do not lie on the same meridian
- In accurate distance between Alexandria and Syene
- Earth is not a perfect sphere
- **Accepted circumference of Earth: 40,075km**

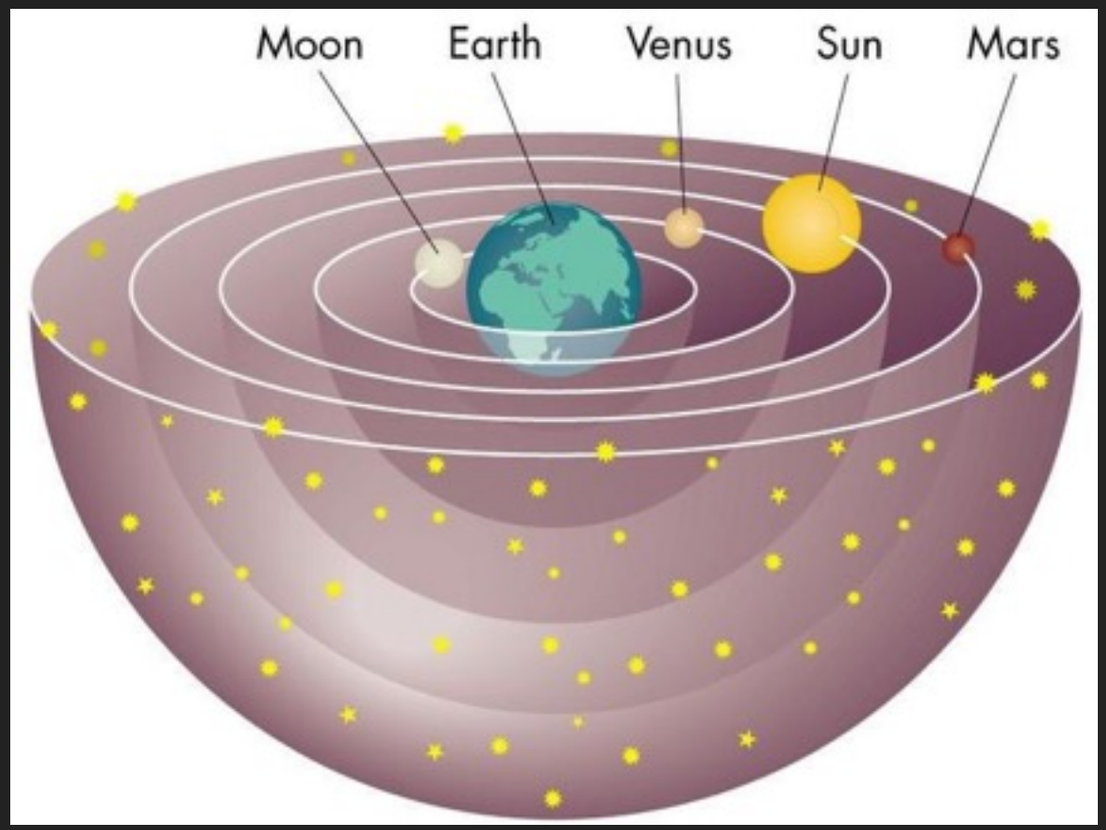
PTOLEMY

CA. 100 – 170 AD

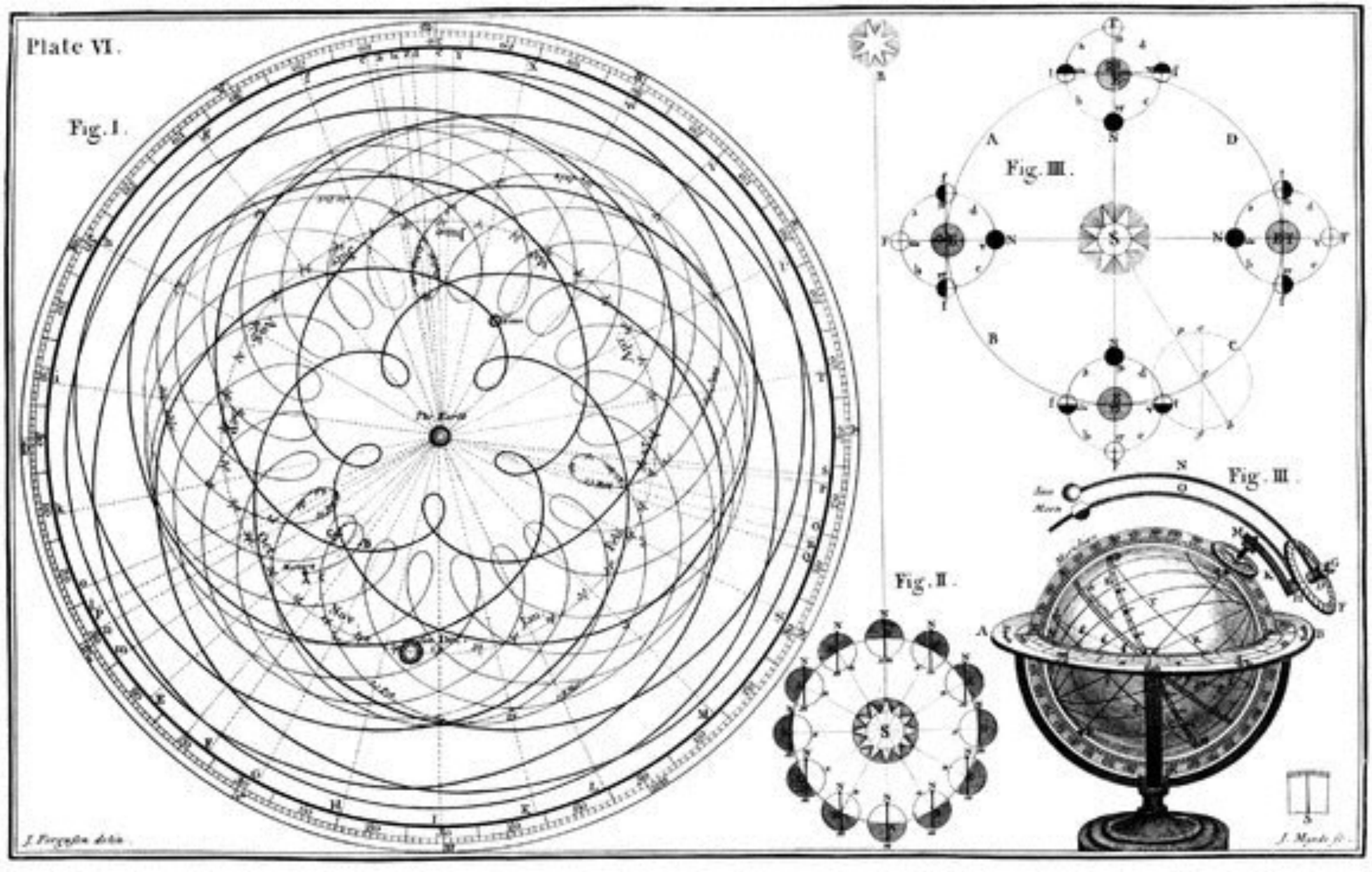
- Greco-Egyptian mathematician, astronomer, geographer, astrologer, and poet
- Developed his *Planetary Hypotheses* which provided the conventional model of the Universe for the next millennium and a half

THE PTOLEMAIC MODEL OF THE UNIVERSE

- Consisted of concentric shells, called *celestial spheres*, with the Earth at the center
  - Geocentric Theory
- The Sun and other planets orbit the Earth
- The stars are fixed to the outmost shell



ORBITS UNDER GEOCENTRIC THEORY



NICOLAUS COPERNICUS

CA. 1473 – 1543

- Prussian mathematician and astronomer
- Father of the Heliocentric Theory
  - Earth goes around the Sun, not vise versa
- Often cited as the beginning of the Scientific Revolution

TYCHO BRAHE

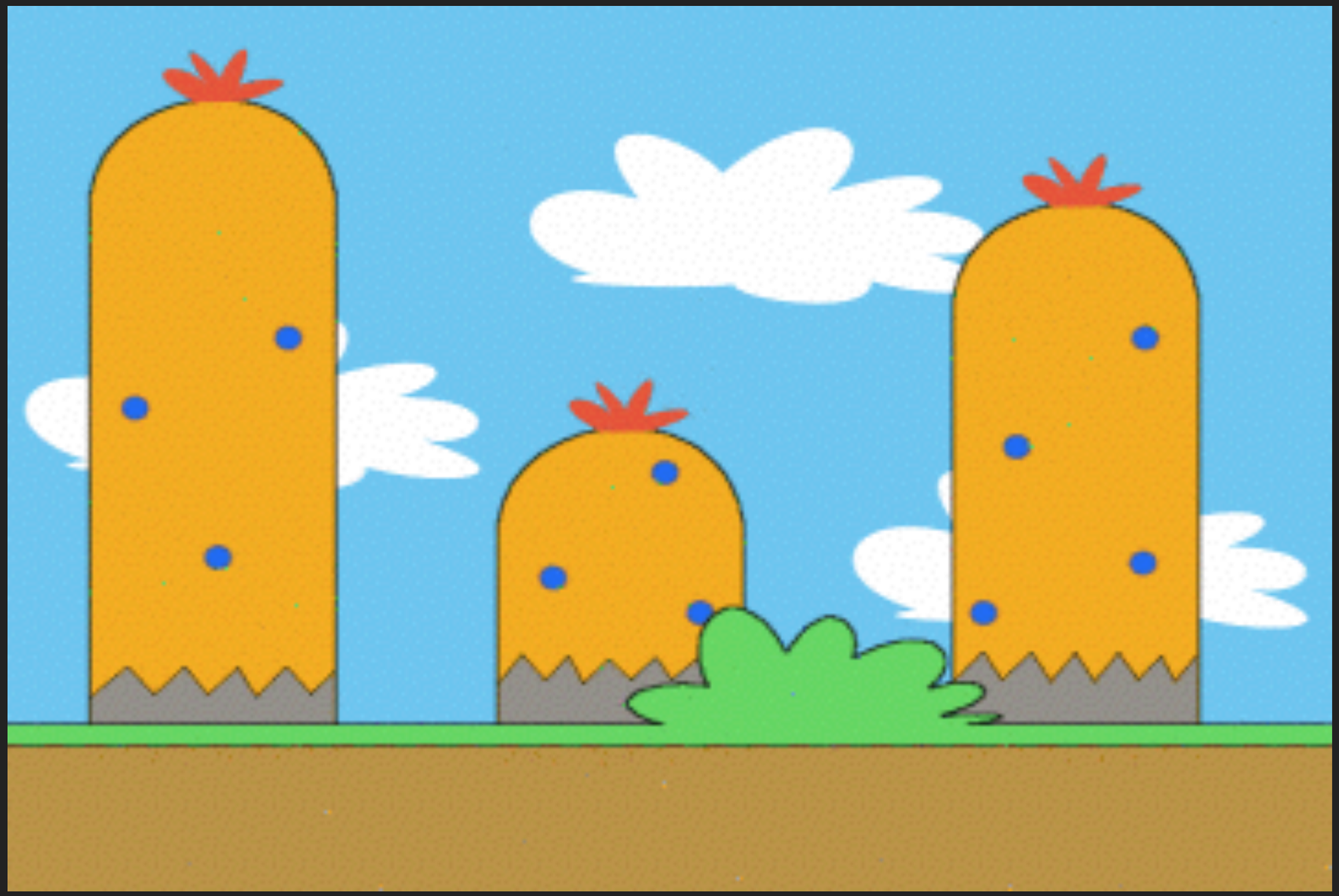
CA. 1546 – 1601

- Danish astronomer, astrologer, and alchemist
- Published *De Nova Stella* in 1573
- Discovered that our Universe is dynamic and ever changing

A DYNAMIC UNIVERSE

- In 1572, observed a bright new star in the constellation Cassiopeia
  - Lacked a daily parallax against the background of stars, suggesting it was much further away
- Parallax - difference in apparent position of an object viewed along two different lines of sight

PARALLAX



Viewpoint A

Object

Viewpoint B

Distant background

Viewpoint A

Viewpoint B

A DYNAMIC UNIVERSE

- In 1572, observed a bright new star in the constellation Cassiopeia
  - Lacked a daily parallax against the background of stars, suggesting it was much further away
- Parallax - difference in apparent position of an object viewed along two different lines of sight
- Refuted the Aristotelian belief in an unchanging celestial realm

JOHANNES KEPLER

CA. 1571 – 1630

- German mathematician, astronomer, and astrologer
- Assistant to Tycho Brahe
- Laws of Planetary Motion

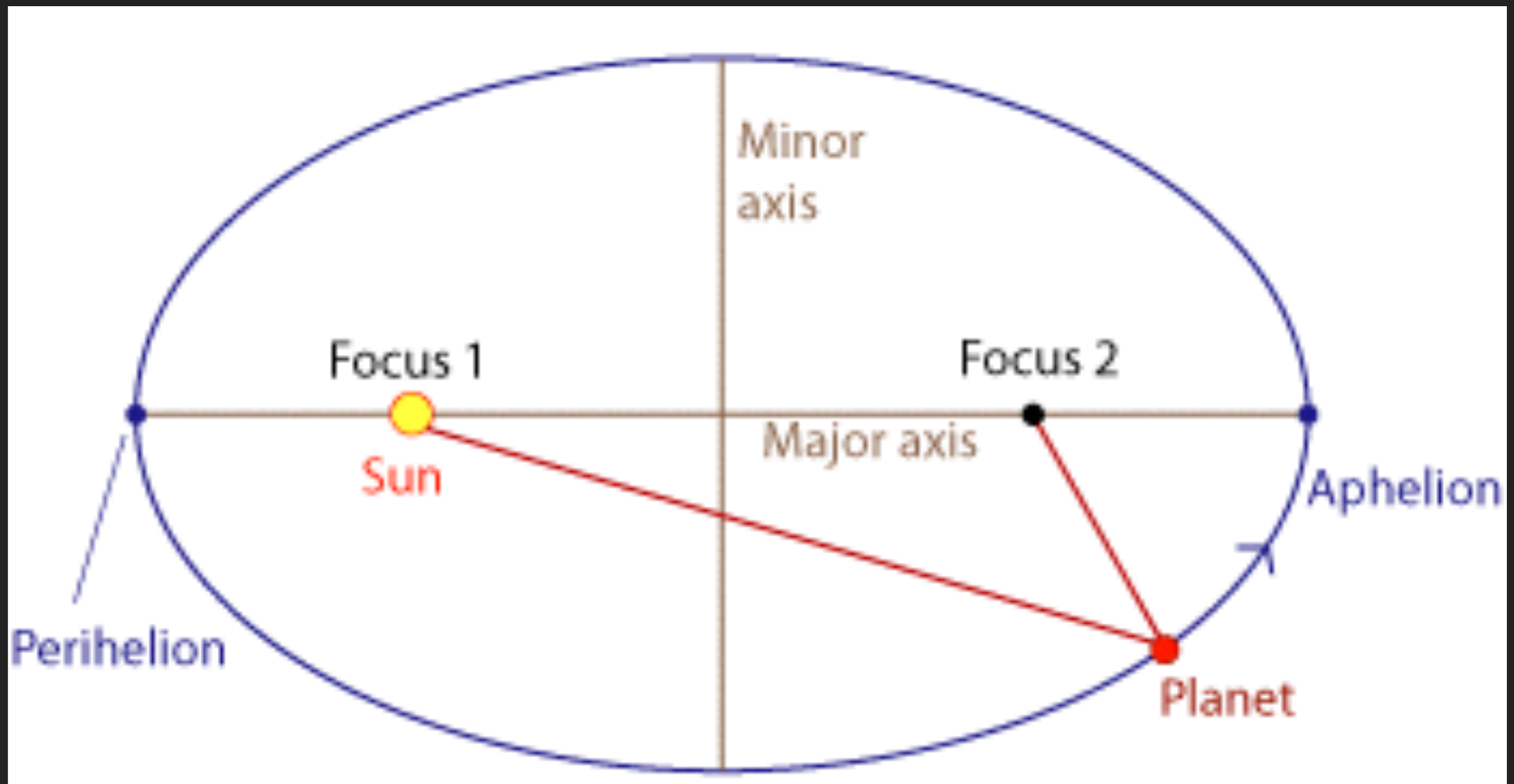
KEPLER'S THREE LAWS OF PLANETARY MOTION

1) The orbit of a planet is an **ellipse** with the Sun at one of the two **focus** points

2) A line segment joining a planet and the Sun sweeps out **equal areas** during **equal intervals of time**

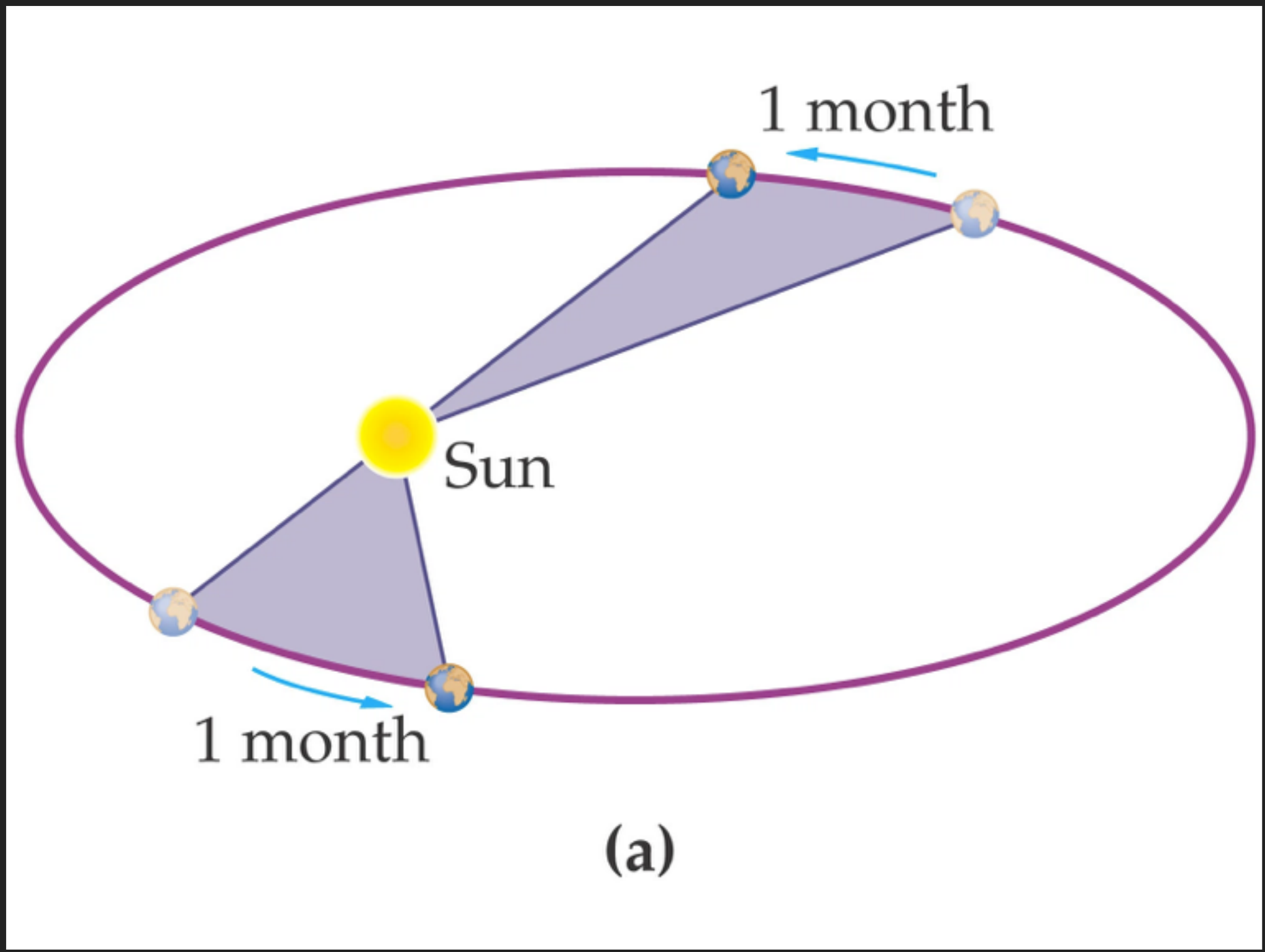
3) The **square of the orbital period** of a planet is proportional to the **cube of its average distance** from the Sun

KEPLER'S 1ST LAW

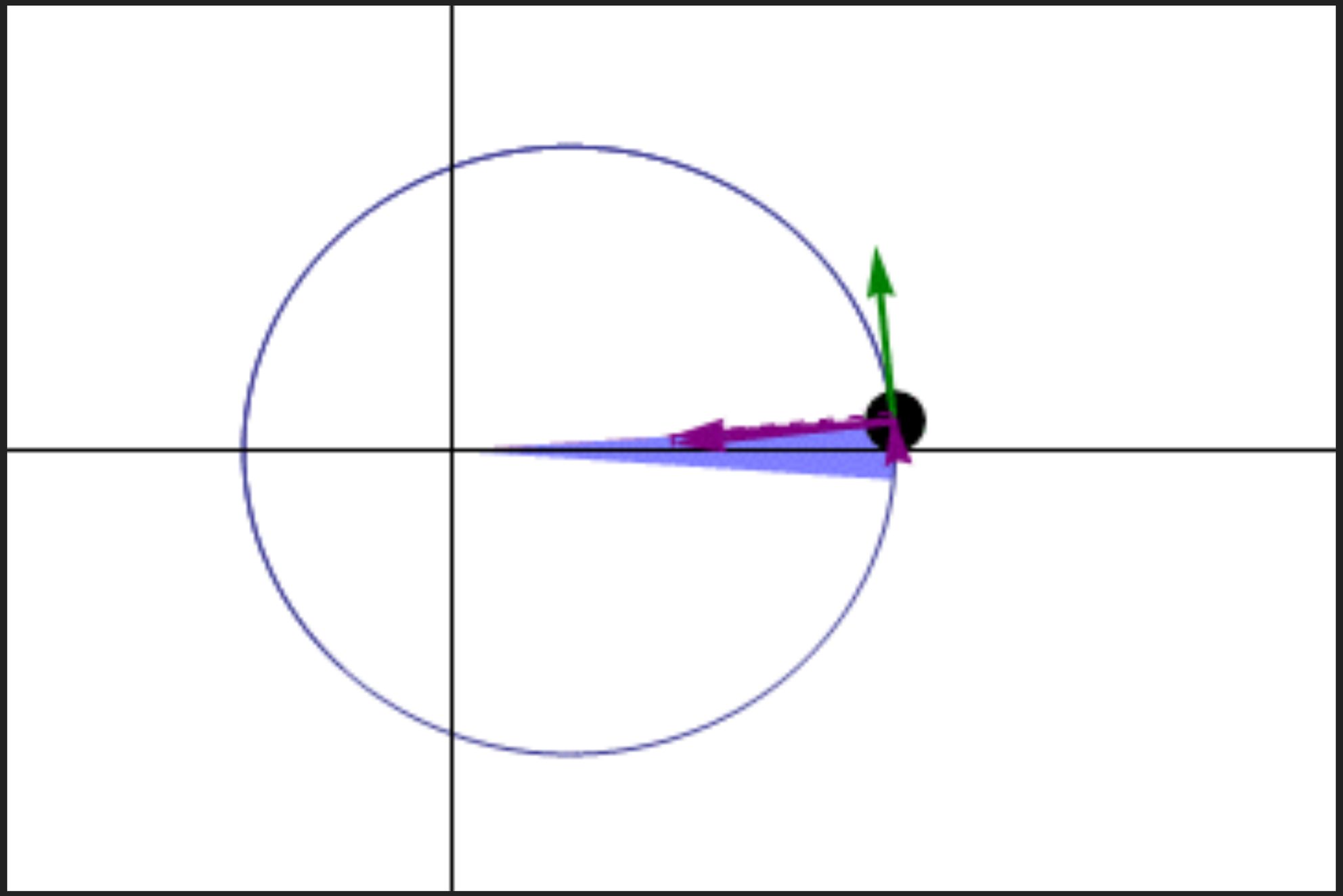


An elliptical orbit of a planet
(greatly exaggerated)

KEPLER'S 2ND LAW



KEPLER'S 2ND LAW



KEPLER'S 3RD LAW

- $T^2 = \frac{4\pi^2 r^3}{GM_S}$
  - r = the average distance from the sun

EXAMPLE 8

- Determine the mass of the Sun given the Earth is an average distance of 1.5×10^{11} m from the Sun.

- *Ans.* $M_S = 2.0\times10^{30}$ *kg*

LAWS OF PLANETARY MOTION, REDUCED

1) Planets orbit in an ellipse

2) The change in area swept out by a planet per time is always constant

3) $T^2 = \frac{4\pi^2 r^3}{GM_S}$

KEPLER'S KONTRIBUTIONS

- Improved heliocentric theory
  - Planets move in ellipses, not circles
  - The Sun is at a focal point, not the center
  - Neither linear speed nor angular speed are constant. Area speed in constant

GALILEO GALILEI

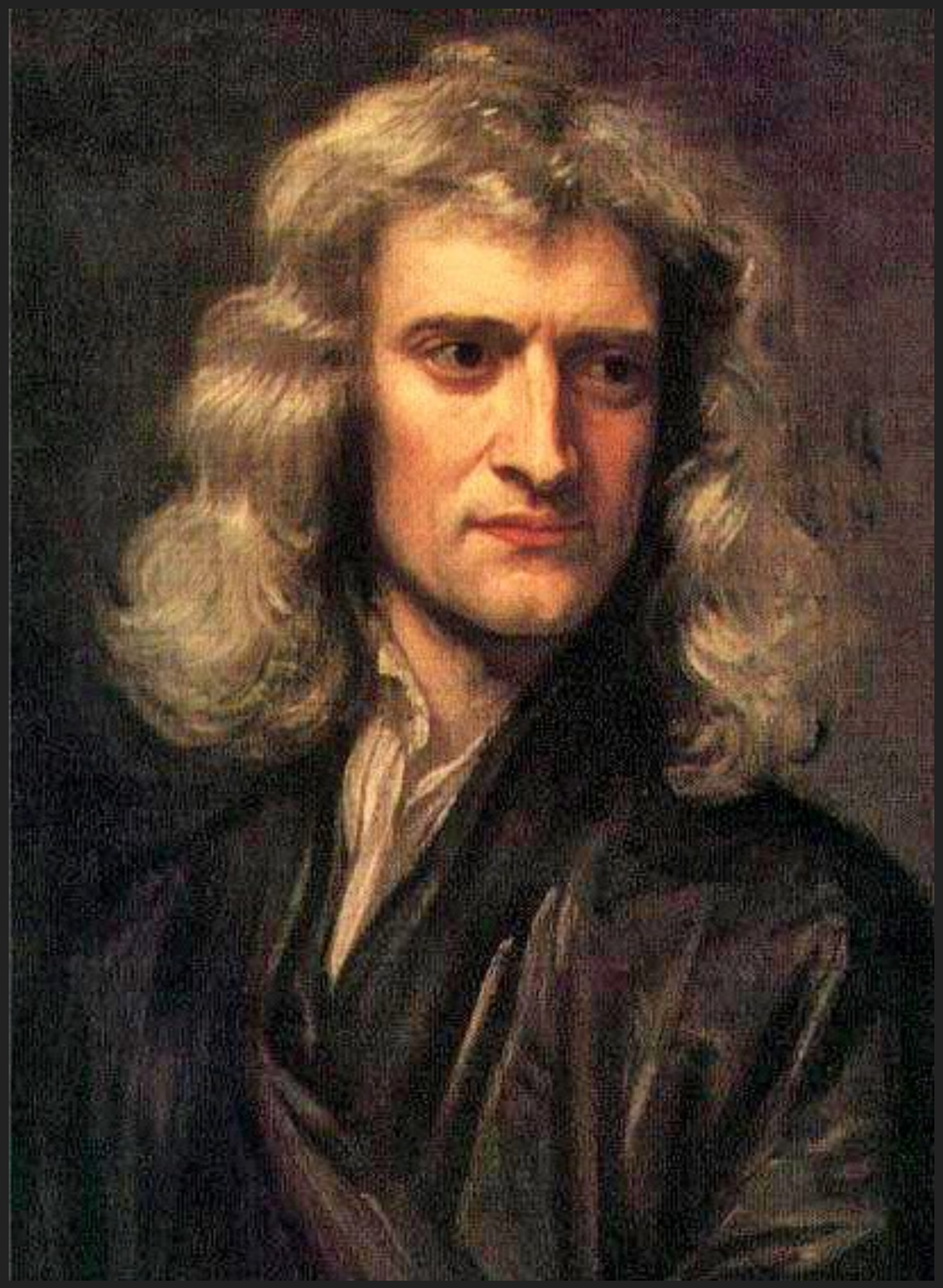
CA. 1564 – 1642

- Italian physicist, mathematician, engineer, astronomer, and philosopher
- In the absence of air resistance, all objects accelerate toward the Earth at the same rate, regardless of mass

ISAAC NEWTON

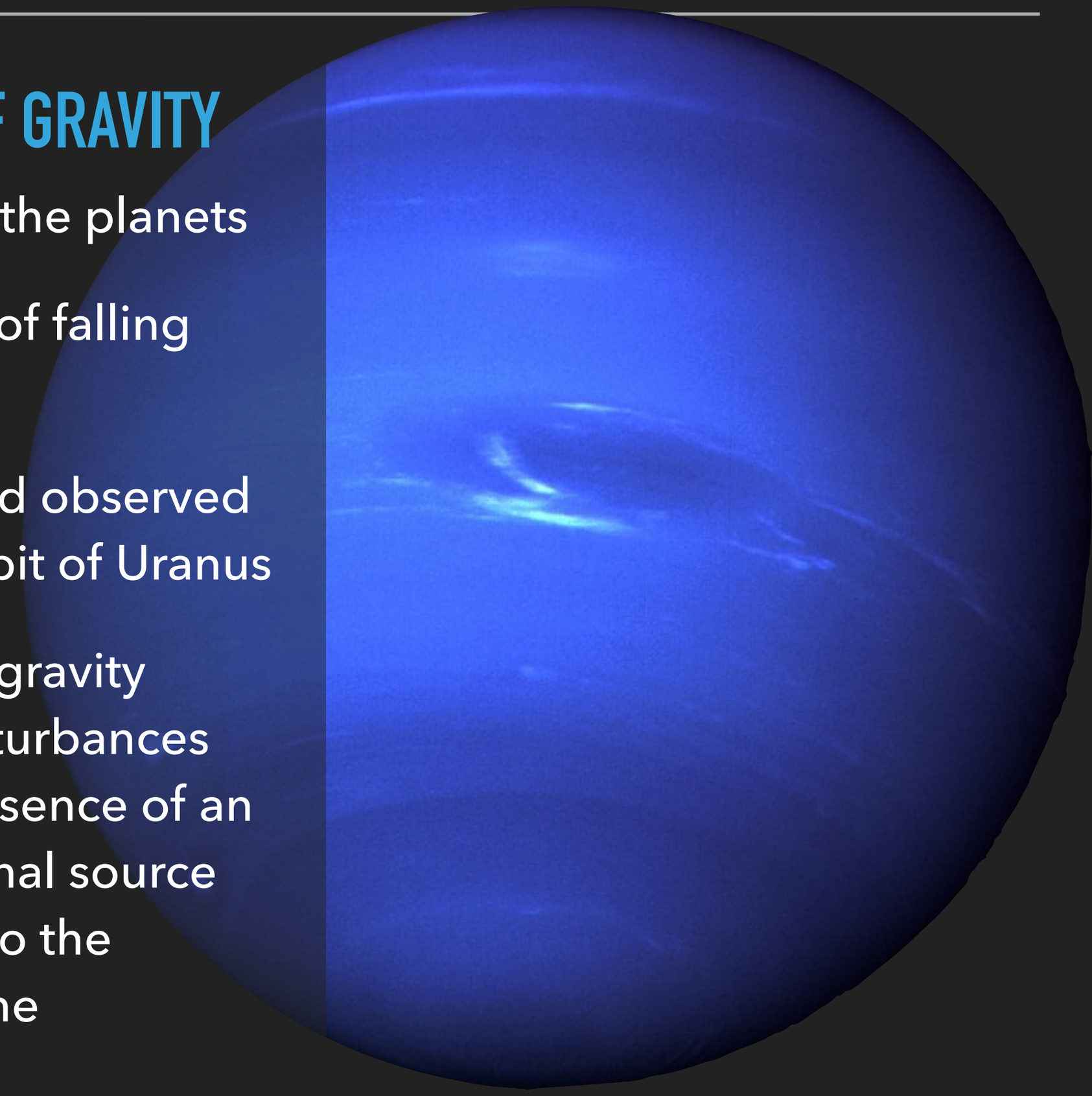
CA. 1642 – 1726

- English physicist and mathematician
- Published *Principia* in 1687
- Laws of Motion
- Foundation of classical mechanics
- Law of Universal Gravitation
- Derivation of Kepler's Laws of Planetary Motion



NEWTON'S THEORY OF GRAVITY

- Explained the orbit of the planets
- Explained the motion of falling objects
- In 1821, Alexis Bouvard observed disturbances in the orbit of Uranus
- Newton's theory of gravity predicted these disturbances were due to the presence of an unknown gravitational source and eventually led to the discovery of Neptune



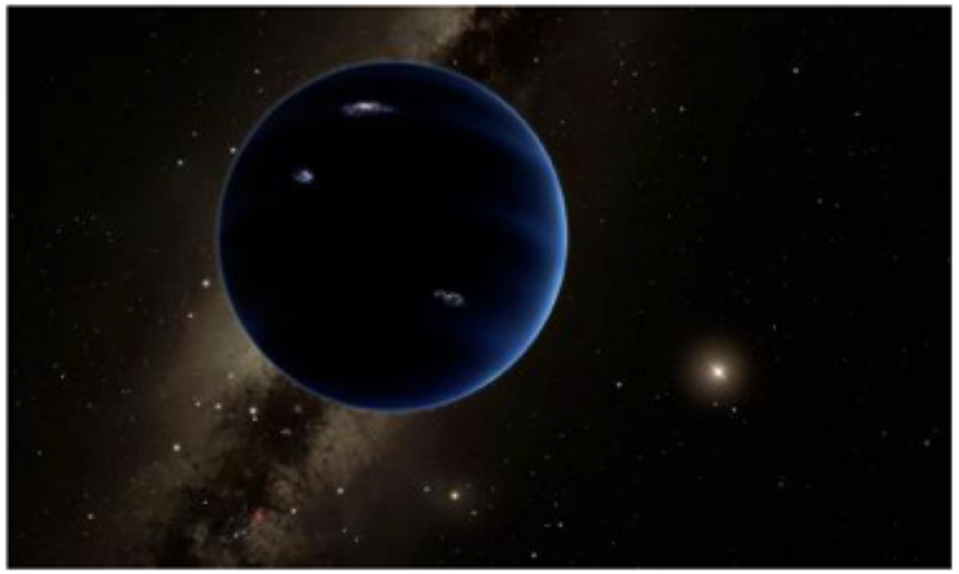
NINTH PLANET?

01/20/2016

Caltech Researchers Find Evidence of a Real Ninth Planet

Caltech researchers have found evidence of a giant planet tracing a bizarre, highly elongated orbit in the outer solar system. The object, which the researchers have nicknamed Planet Nine, has a mass about 10 times that of Earth and orbits about 20 times farther from the sun on average than does Neptune (which orbits the sun at an average distance of 2.8 billion miles). In fact, it would take this new planet between 10,000 and 20,000 years to make just one full orbit around the sun.

The researchers, Konstantin Batygin and Mike Brown, discovered the planet's existence through mathematical modeling and computer simulations but have not yet observed the object directly.



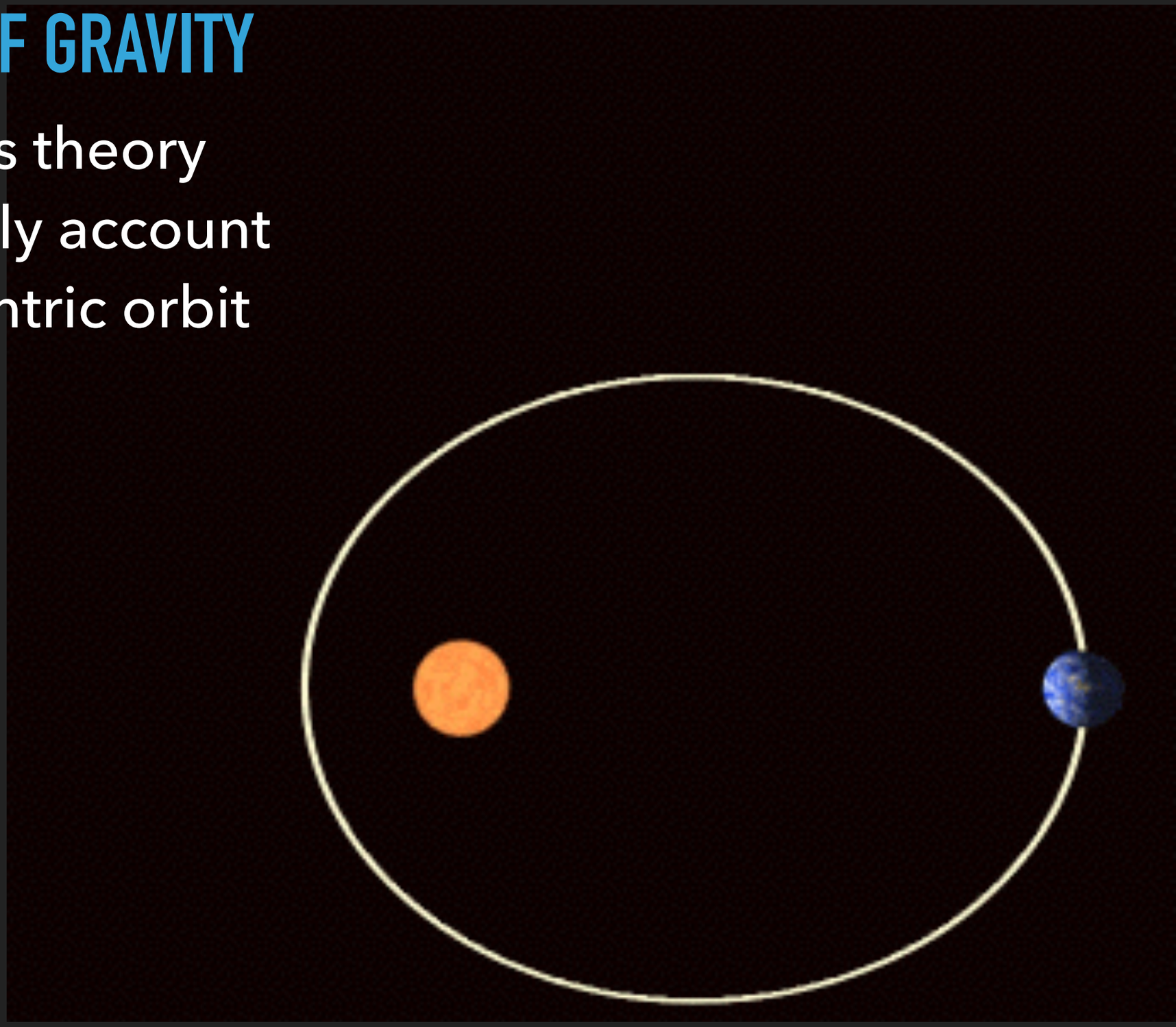
This artistic rendering shows the distant view from Planet Nine back towards the sun. The planet is thought to be gaseous, similar to Uranus and Neptune. Hypothetical lightning lights up the night side.

Credit: Caltech/R. Hurt (IPAC)

https://www.caltech.edu/news/caltech-researchers-find-evidence-real-ninth-planet-49523

NEWTON'S THEORY OF GRAVITY

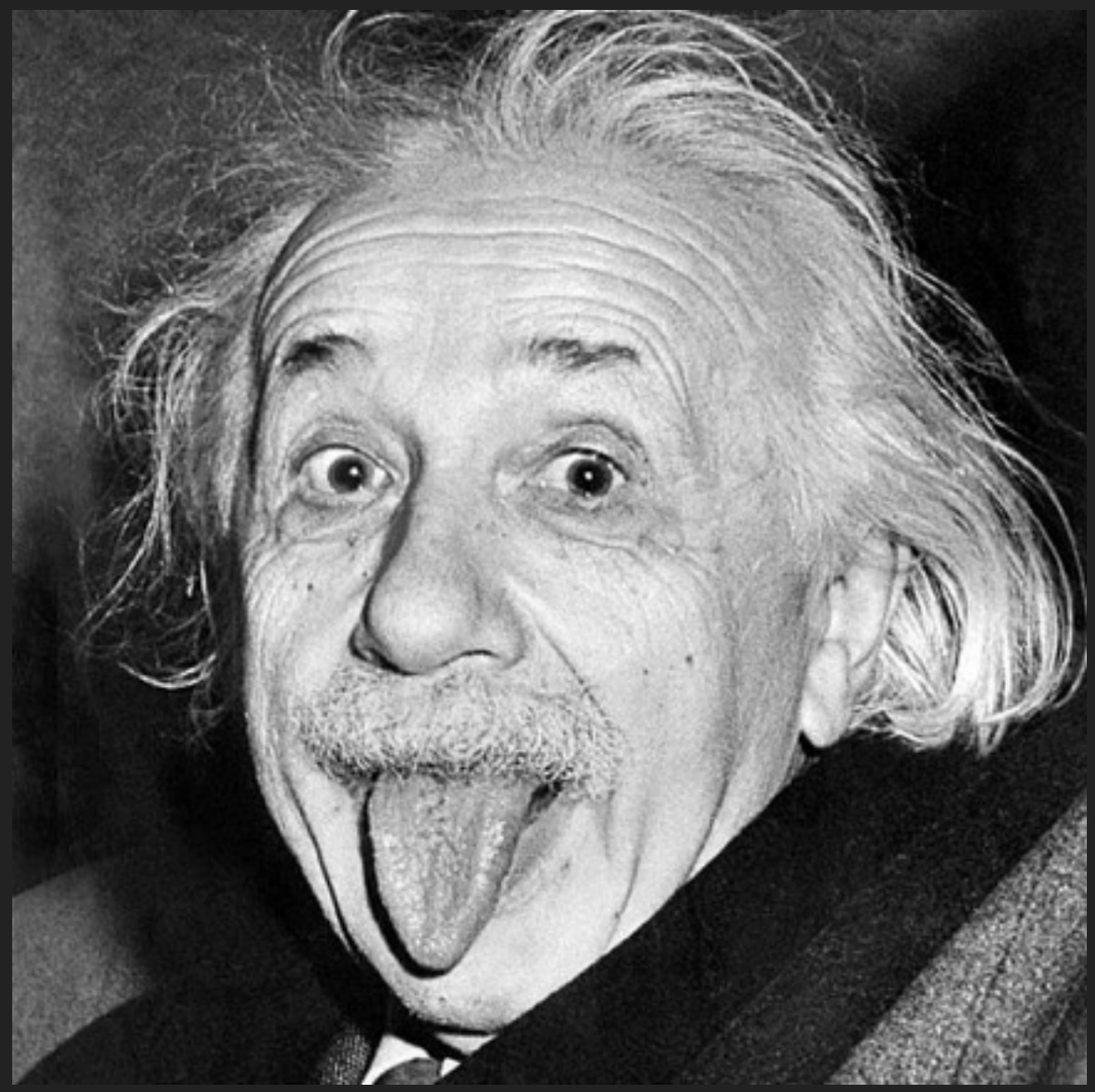
- However, Newton's theory could not accurately account for Mercury's eccentric orbit



ALBERT EINSTEIN

CA. 1879 – 1955

- German theoretical physicist and philosopher of science
- Gravity as curvature of spacetime
- Einstein’s theory of general relativity explained the precession of Mercury’s orbit is due to the severely curved spacetime near the Sun



EINSTEIN'S SPECIAL THEORY OF RELATIVITY

1. The speed of light is the same in all inertial reference frames

$c = 3.00 \times 10^8$ m/s

Albert Einstein

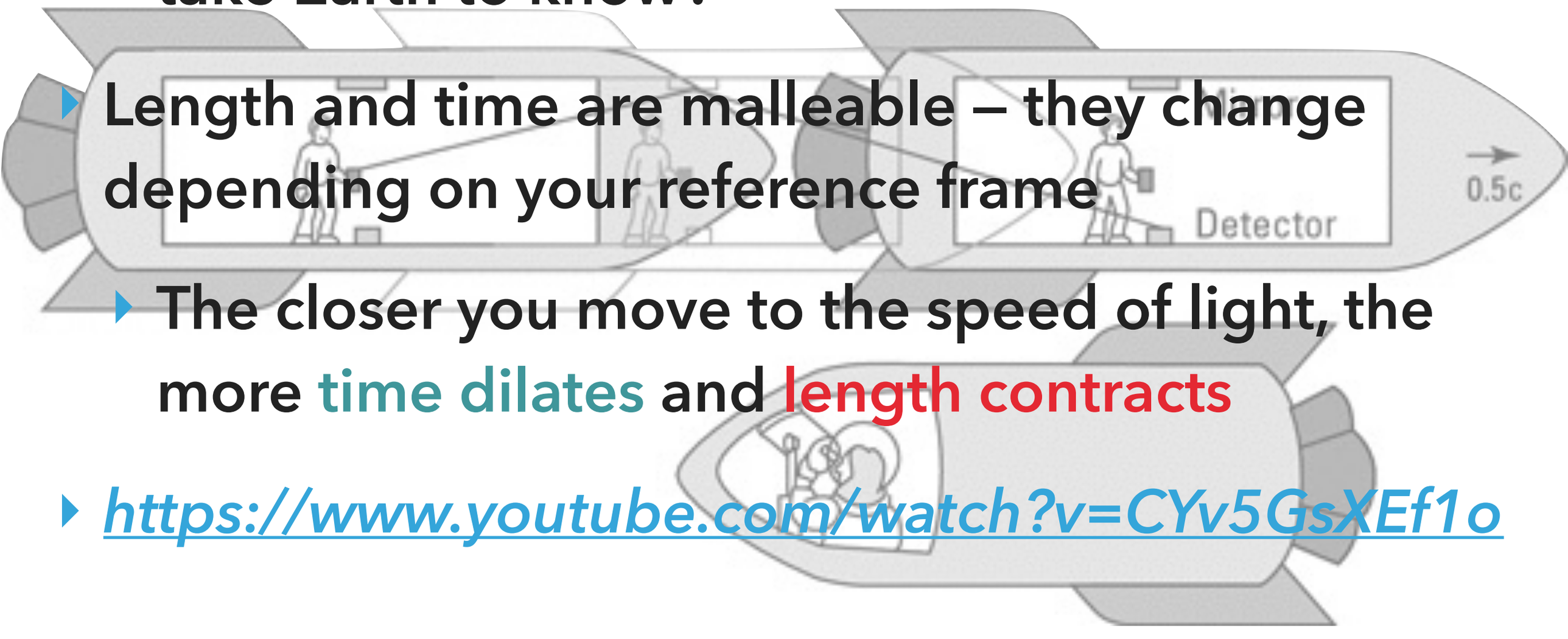
EINSTEIN'S SPECIAL THEORY OF RELATIVITY

2. The laws of physics are the same in all inertial reference frames

Albert Einstein

IMPLICATIONS

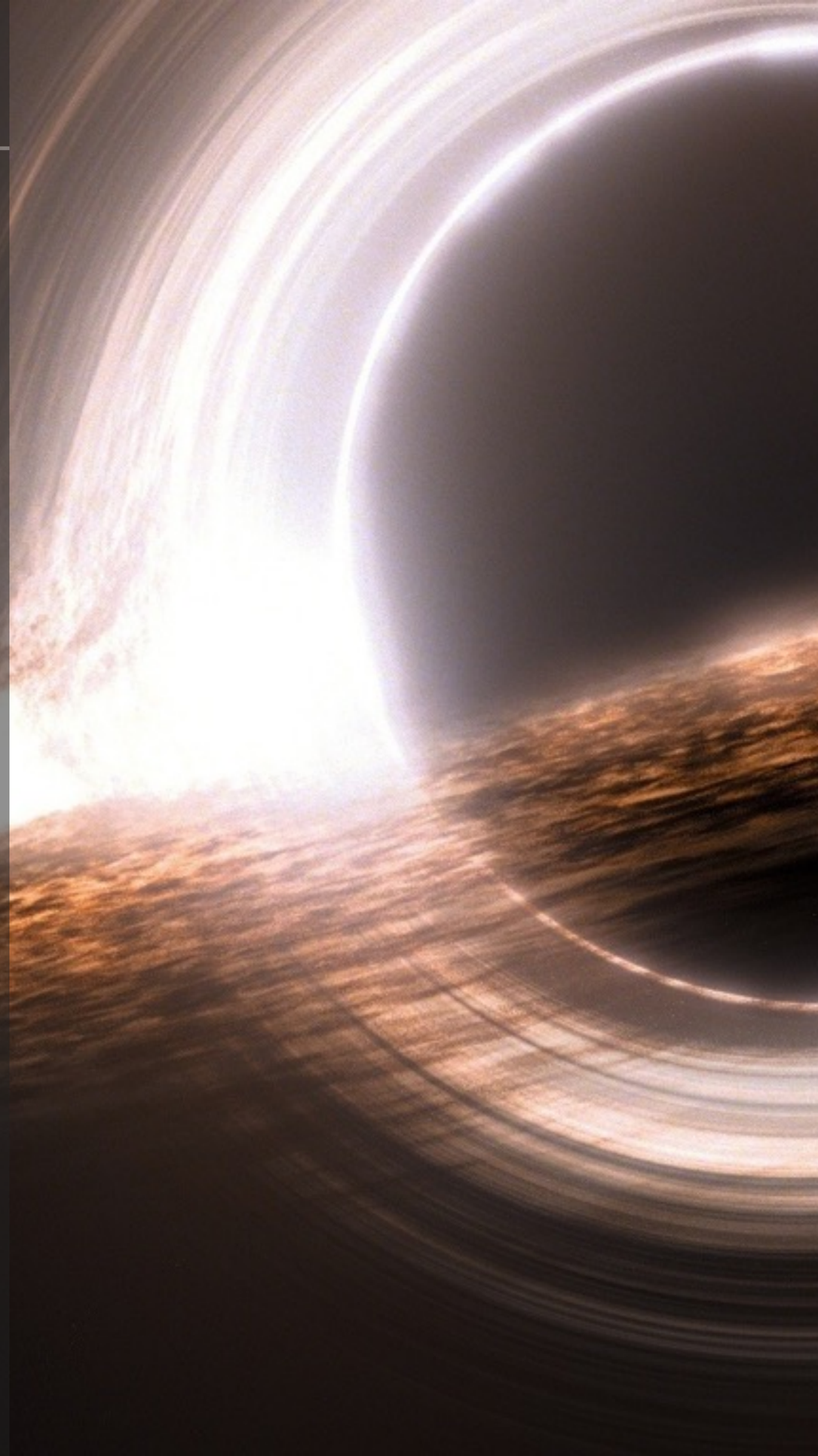
- *Nothing* can go faster than light
  - If the Sun magically vanished, how long would it take Earth to know?



- Length and time are malleable – they change depending on your reference frame
  - The closer you move to the speed of light, the more time dilates and length contracts
- *https://www.youtube.com/watch?v=CYv5GsXEf1o*

EINSTEIN'S GENERAL THEORY RELATIVITY

- Gravity is the universal attraction between all mass, and, since $E = mc^2$, all forms of energy
- Gravity is the curvature of spacetime – the four dimensional fabric of the universe



https://www.youtube.com/watch?v=MTY1Kje0yLg

BENDING SPACETIME

SCHWARZSCHILD METRIC

- $ds^2 = -\left(1 - \frac{2GM}{c^2 r}\right)(c\,dt)^2 + \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2 + r^2\,(d\theta^2 + \sin^2\theta\, d\varphi^2)$
- Describes the geometry of spacetime around a star
- Super important in GPS navigation

EDWIN HUBBLE

CA. 1889 – 1953

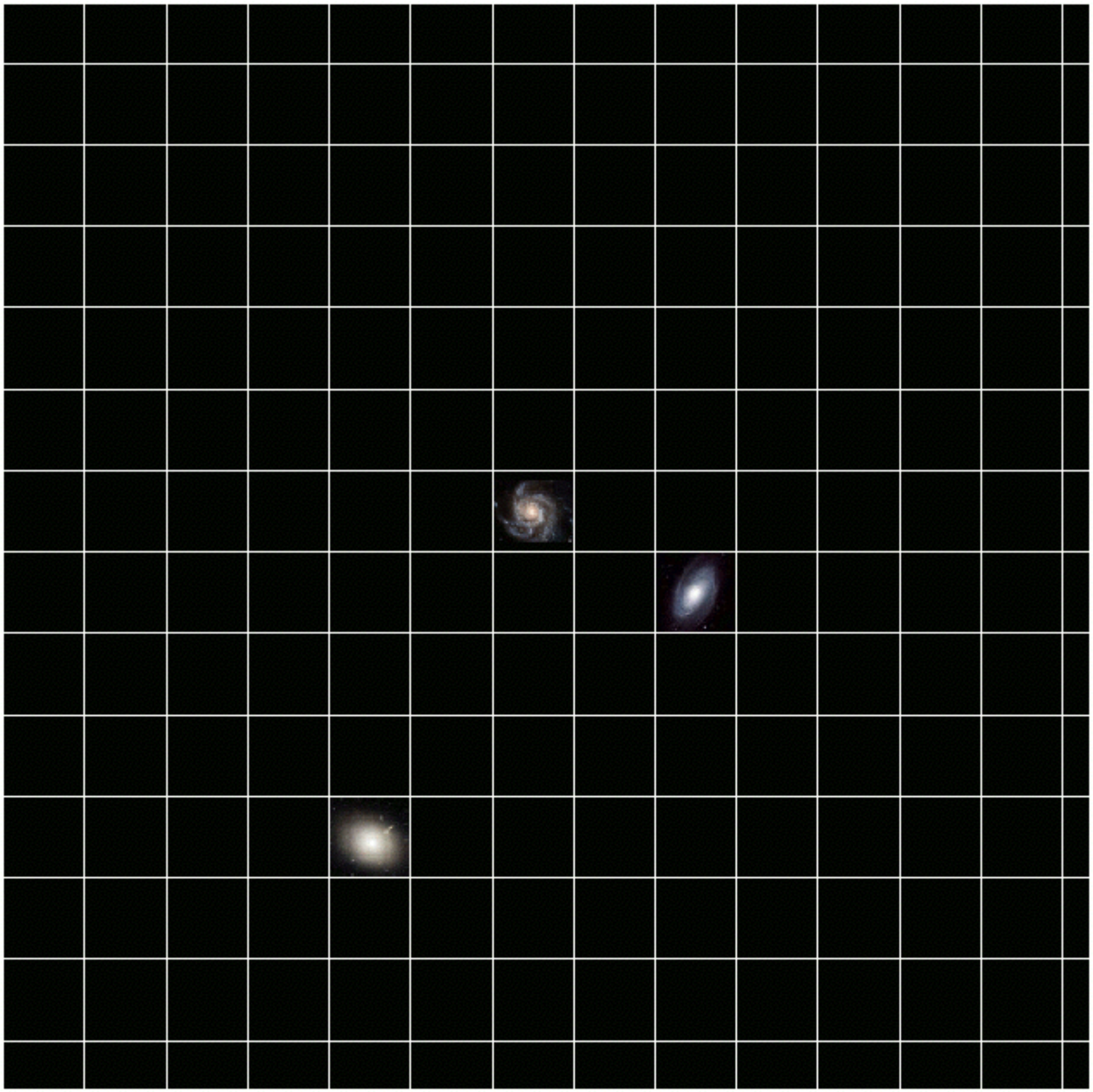
- American astronomer and cosmologist
- Universe goes beyond the Milky Way galaxy
- Expanding Universe

GRAVITY

ANDROMEDA GALAXY

ANDROMEDA GALAXY

EXPANDING UNIVERSE



EXPANDING UNIVERSE; RED SHIFT


HUBBLE