ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

Lecture 5 • Principles of space and time I

09/14/2021

COVID protocol

Please scan the **QR codes** today and for every lecture!

Participation: Recap

Respond to the poll on TurningPoint

Session ID: diemer

 30 seconds

Recap

- Newton's 1st law: **v = constant if F = 0**
- Newton's 2nd law: **F = ma**
- Newton's 3rd law: every action has an **equal and opposite reaction**
- Newton's law of gravity: **$F = GMm/r^2$**
- Galilean Relativity: **laws of nature are the same** in reference frames that move with constant velocity

Newton in perspective

Theory of motion and gravity **removed Aristotle's distinction** between the Earth and the Heavens

- The same phenomena happen **there and here** (Galileo)
- They obey the **same set of physical laws** (Newton)
- The Universe is **knowable**

Newton in perspective

- With Newton's laws, it was possible to make **predictions** about orbits of solar system bodies
  - Halley argued that several comet appearances separated by 76 years were actually the same comet, and predicted its recurrence in 1758
- Planet orbits are **not perfectly elliptical** orbits due to gravity of other planets
  - Herschel, in 1781, discovered Uranus; its orbit showed enough variations to predict there must be another as-yet-unknown planet, leading to discovery of Neptune in 1846
- Huge **cultural impact**
  - A Universe describable by precise mathematical laws supports the idea of "rationality" in other arenas (e.g., architecture, government, history, etc.)

Today

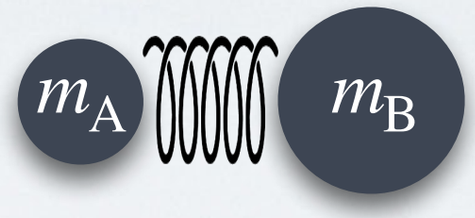
- Galilean relativity & transformations
- Inertial frames & fictitious forces
- Weak equivalence principle
- Symmetry, isotropy, homogeneity

Part 1: Galilean relativity & transformations

Galilean relativity

$$m_A = 2g,\ m_B = 4g$$

$$v_A = v_B = 0$$



$v_A = ?\frac{cm}{s}$

$v_B = 5\frac{cm}{s}$

Participation: What is v_A?

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Galilean relativity

$$m_A = 2g,\ m_B = 4g$$

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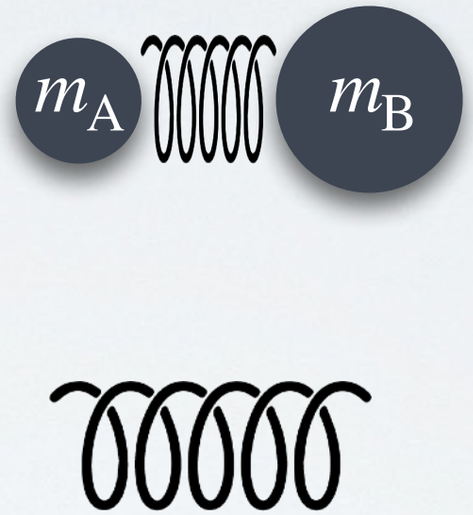
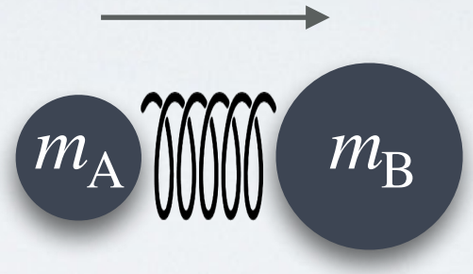


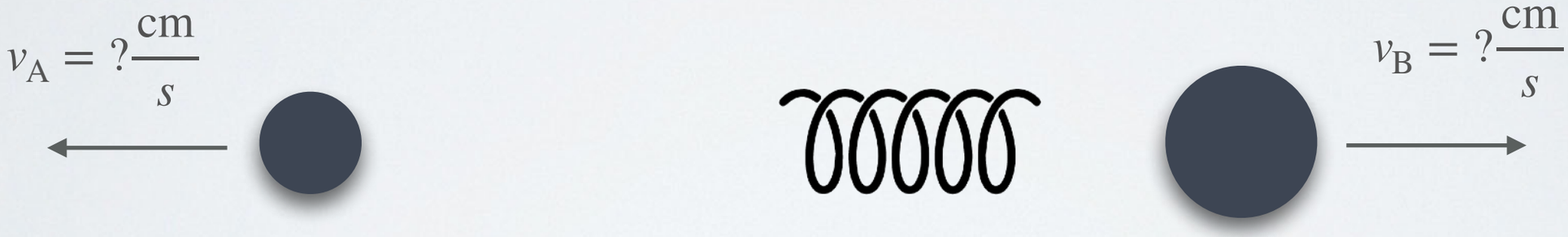
$$m_A v_A + m_B v_B = 0$$

Galilean relativity

$$m_A = 2g,\ m_B = 4g$$

$$v_A = v_B = 3\frac{\text{cm}}{s}$$





Participation: What is v_A?

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Galilean relativity

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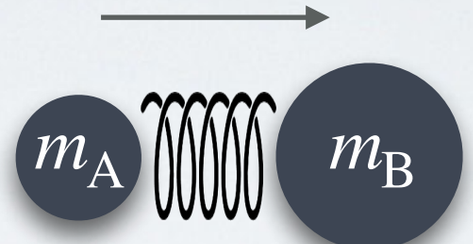
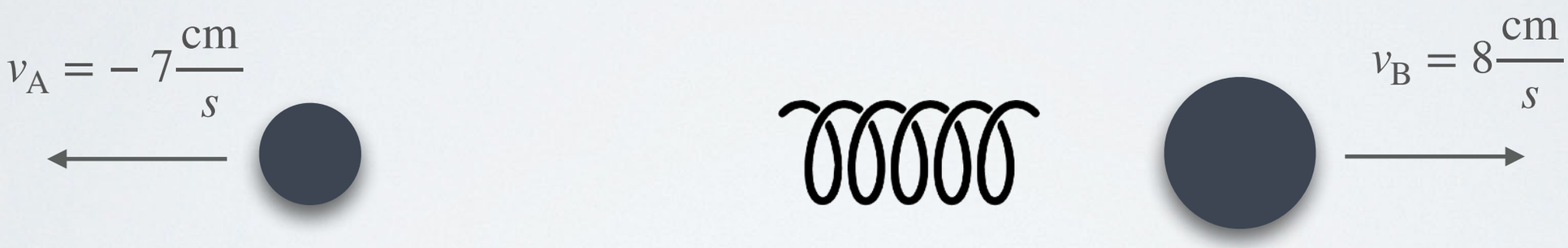




$$m_A v_A + m_B v_B = (m_A + m_B) \times 3\frac{\text{cm}}{s}$$

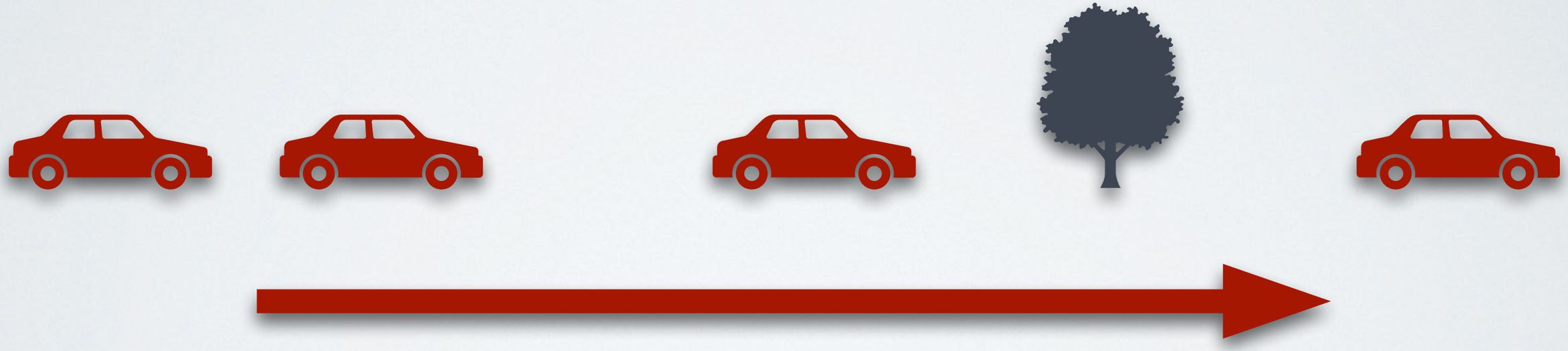
Galilean relativity

- Second problem solved by **changing your frame of reference**
- The "velocity addition" rule when the reference frame changes is called a **Galilean transformation**
- **Galilean relativity** means that laws of physics are the same in frame moving with some **constant velocity**
- In either case, **total momentum before = total momentum after**
- There is **no absolute standard of rest** in the Universe; the appearance of rest is always relative

Part 2: Inertial frames and inertial forces

Inertial frames

Imagine looking out the window of an accelerating car: velocity of objects you see is not constant — Newton's 1st law does not hold!



Inertial frames

- **Inertial frame:** an unaccelerated reference frame that moves with constant velocity, a=0
- **Non-inertial frame:** an accelerated reference frame

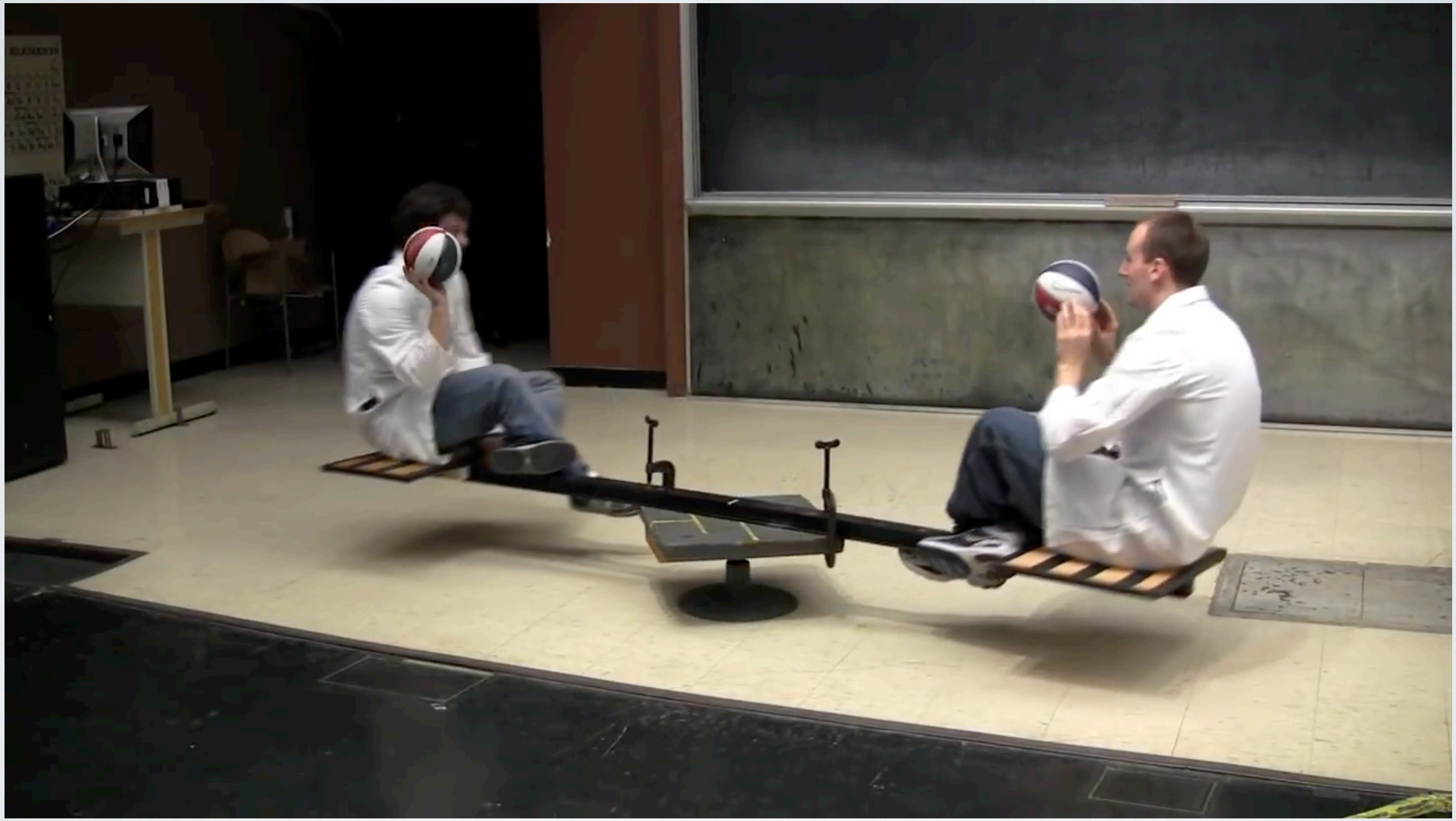
Newton's laws hold only in inertial frames

- In an inertial frame, a free particle (no forces acting) has constant velocity
- In a non-inertial frame, a free particle's velocity varies
- Humans can sense accelerations physiologically

Inertial forces

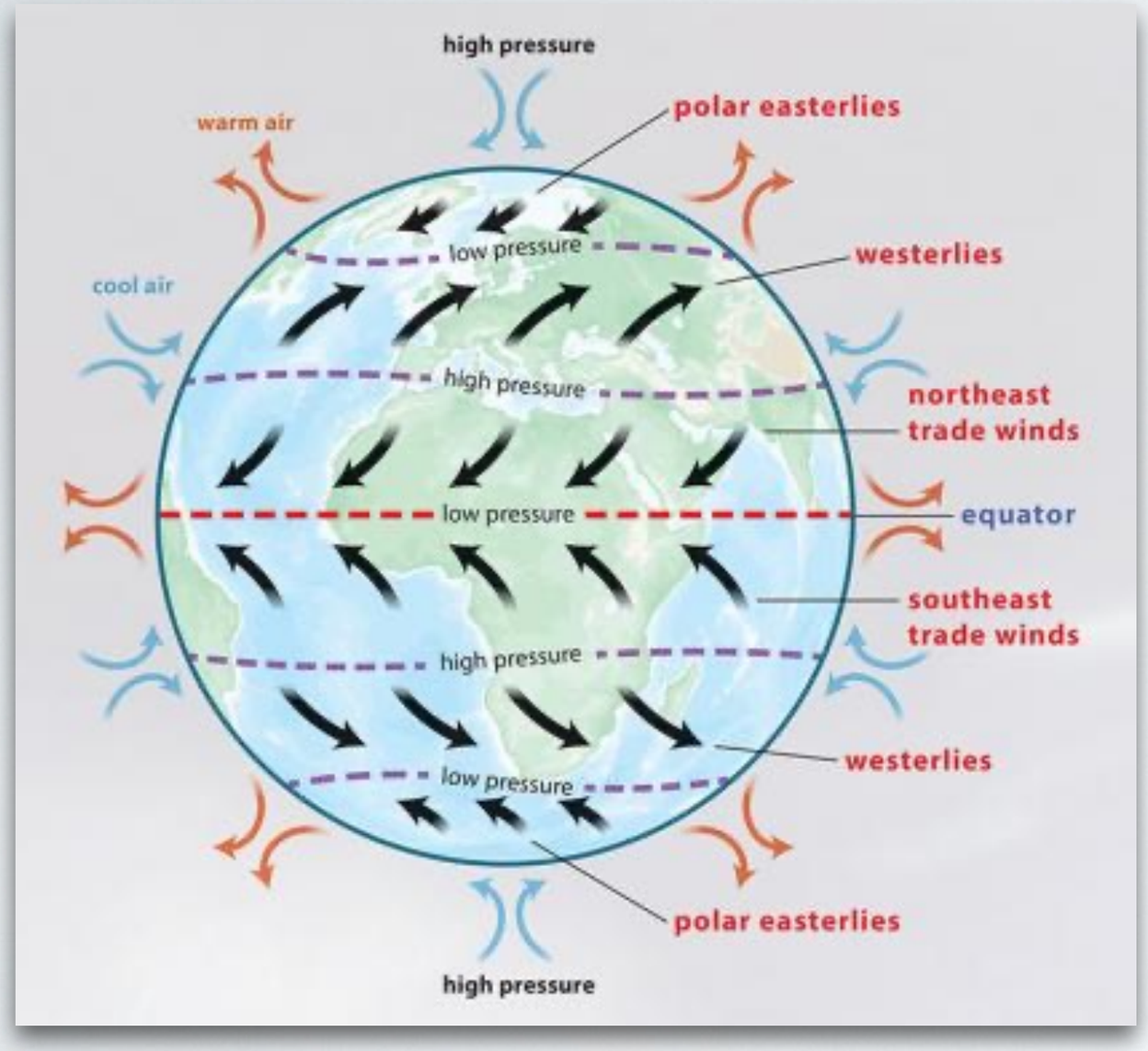
- In **non-inertial frames**, we might be fooled into thinking that there are forces acting on free bodies
- Such forces are call **fictitious forces** or **inertial forces**
  - G-forces in an accelerating vehicle
  - Centrifugal forces in amusement park rides
  - The Coriolis force on the Earth
- Inertial forces point **opposite to the direction of acceleration**
- Inertial forces are always **proportional to the mass** of the body

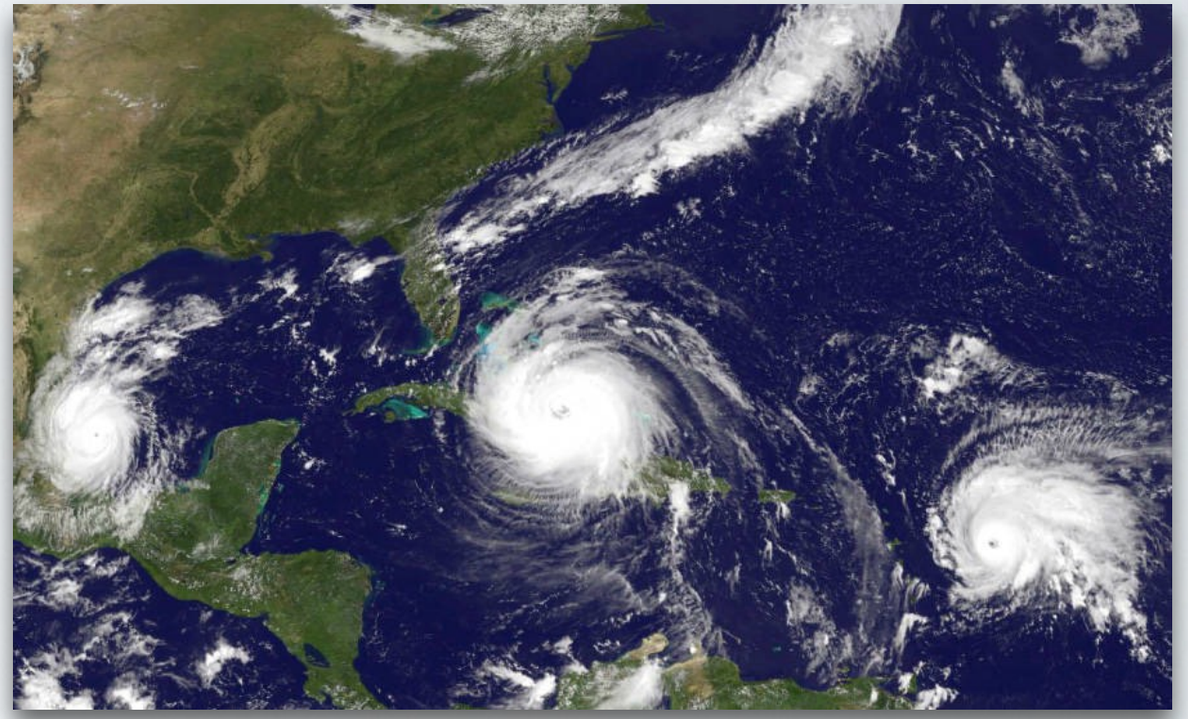
Coriolis effect



MIT Physics Department

Coriolis effect





Images: NASA

Part 3: The weak equivalence principle

Weak equivalence principle

Newton's 2nd law: $F = m_i a$ m_i = inertial mass

Newton's gravity: $F = \dfrac{GMm_g}{r^2}$ m_g = gravitating mass

$$\Longrightarrow \; a_g = \left(\frac{m_g}{m_i}\right)\frac{GM}{r^2}$$

Participation: Equivalence principle

Respond to the poll on TurningPoint

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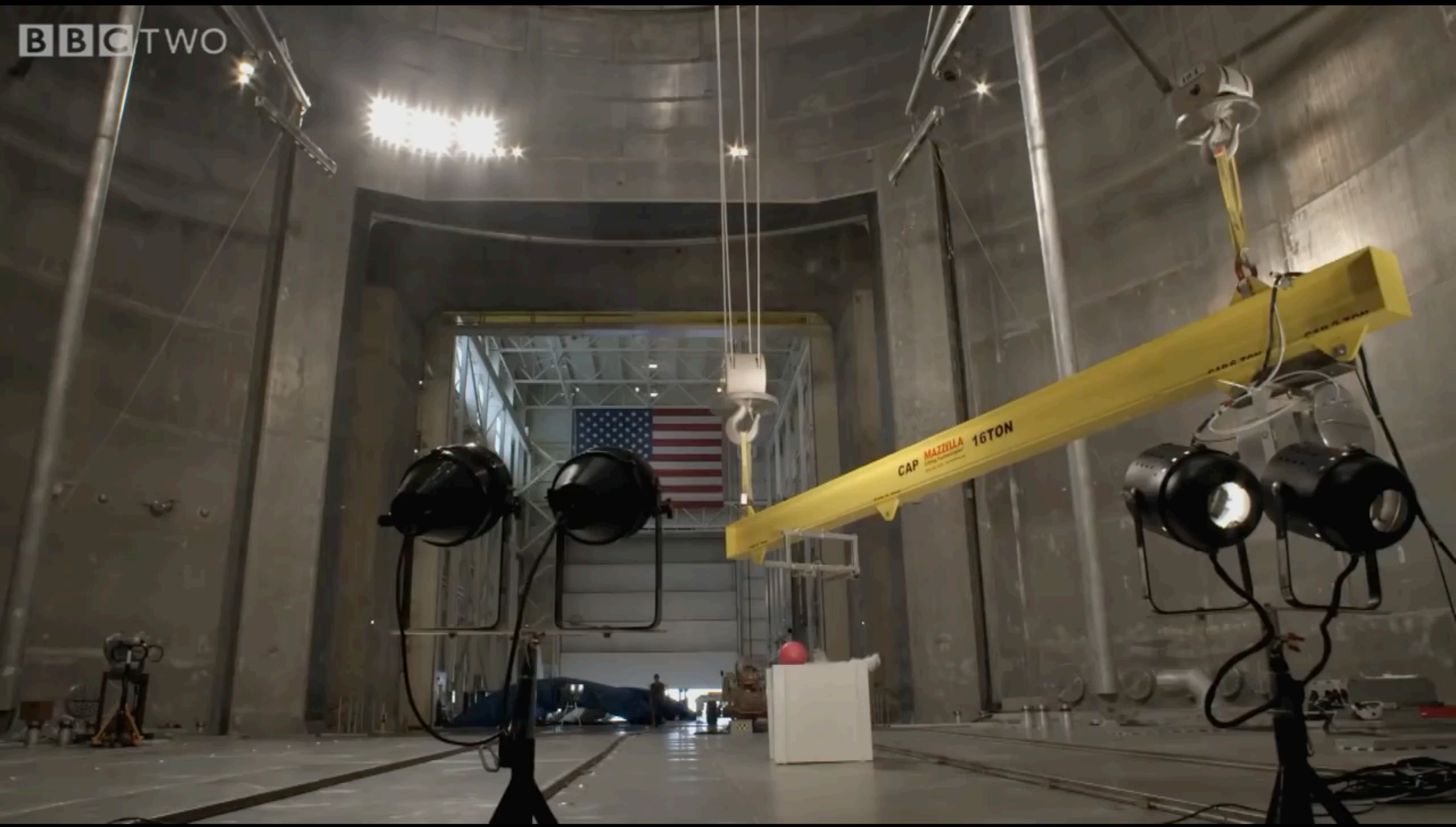
30 seconds

David Scott • Apollo 15 • 1971



Brian Cox • 2014

Participation: Equivalence principle again

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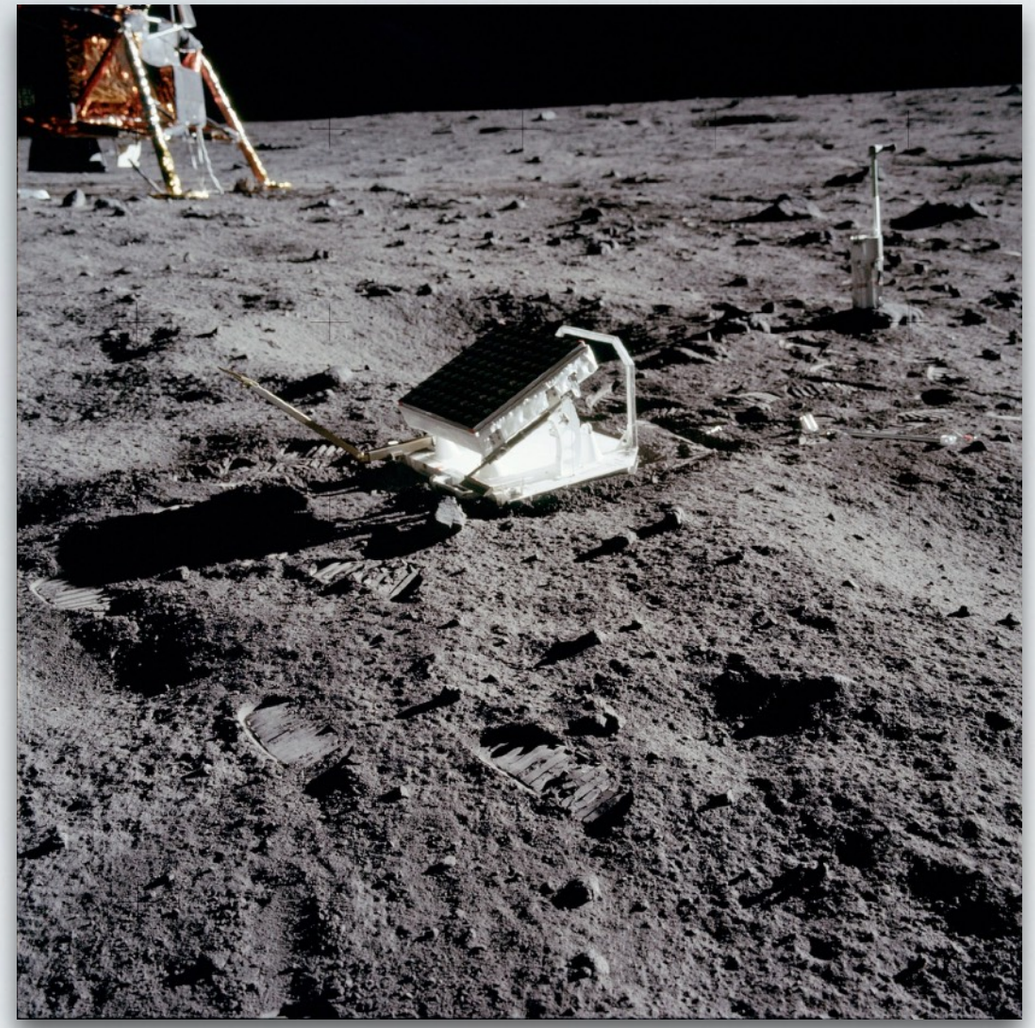
Lunar laser ranging to the rescue!



Earth and Moon “fall” towards the Sun with the same acceleration

$$\Longrightarrow \quad |m_i/m_g - 1| < 10^{-13}$$

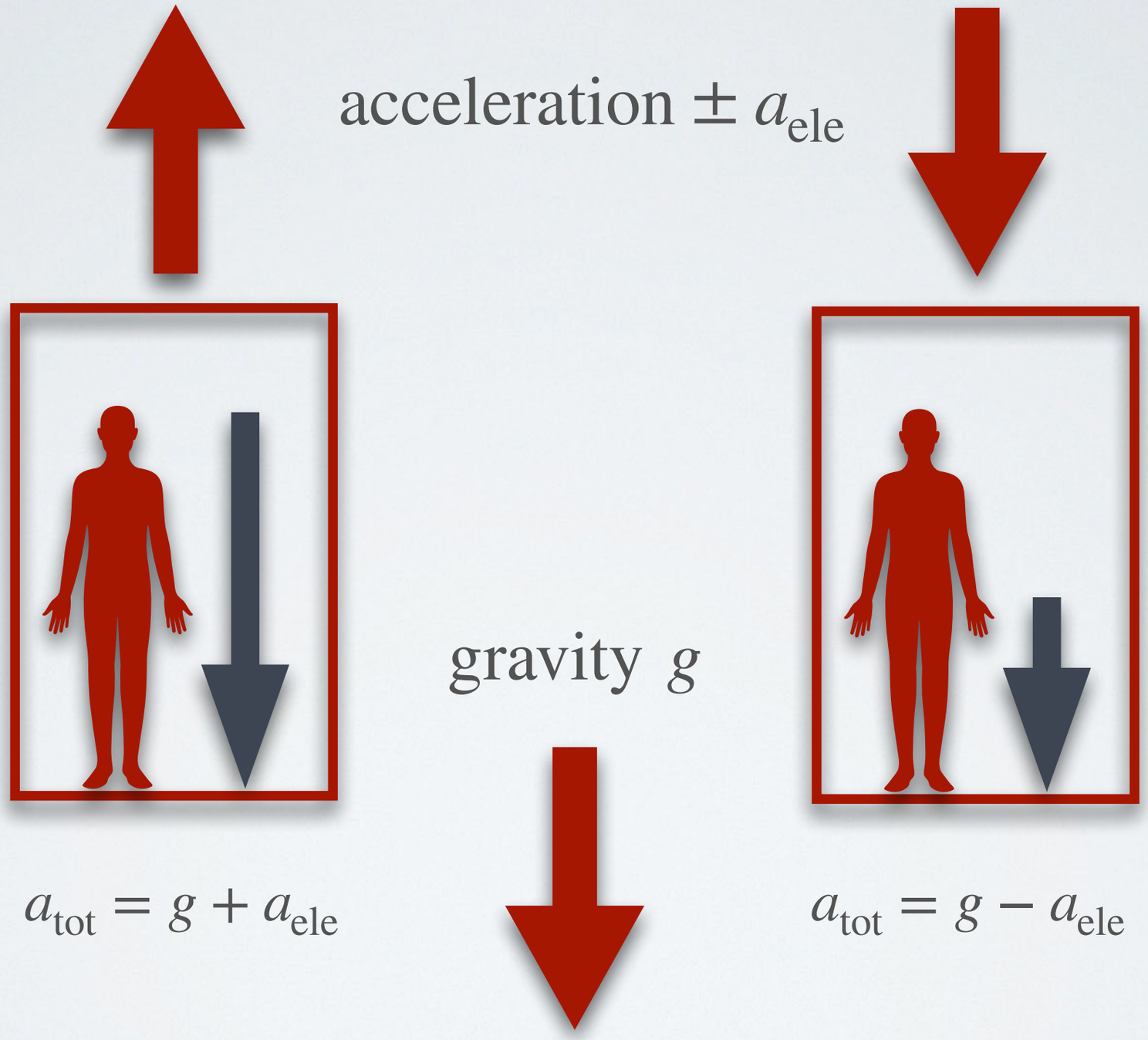
Images: NASA • Williams et al. 2009

Weak equivalence principle

Gravity is indistinguishable from any other acceleration.

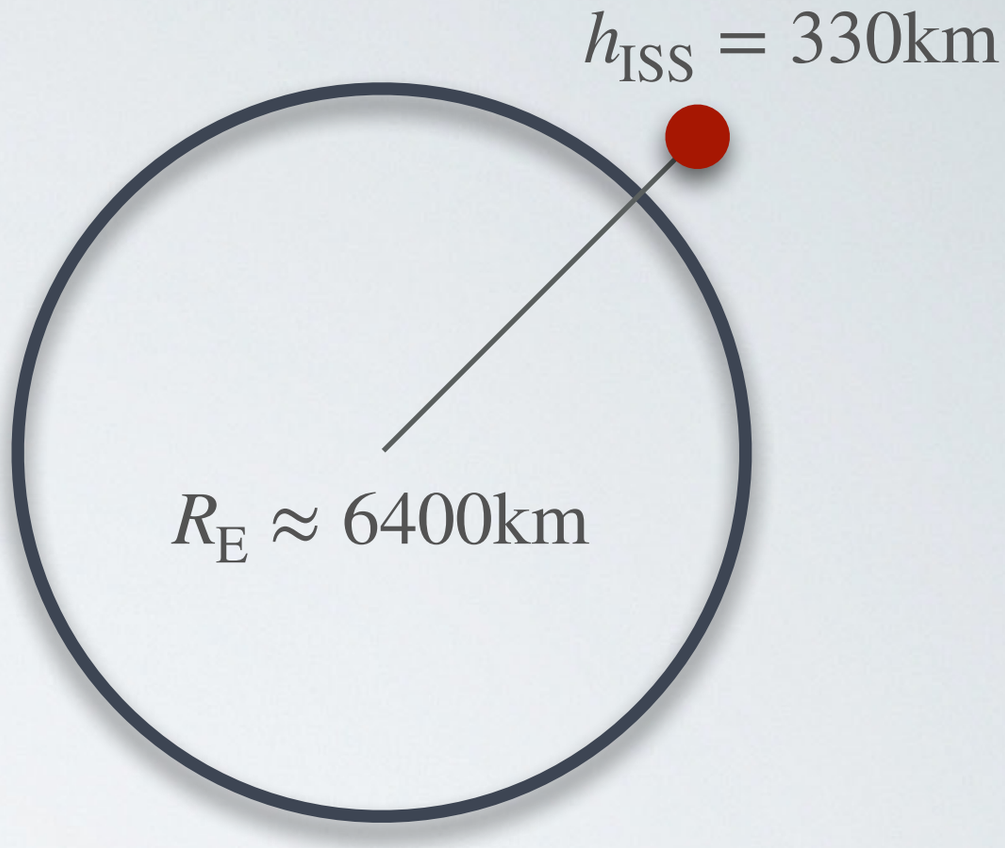
Note: we have made a choice to set G such that $m_i = m_g$.

Is gravity an inertial force?

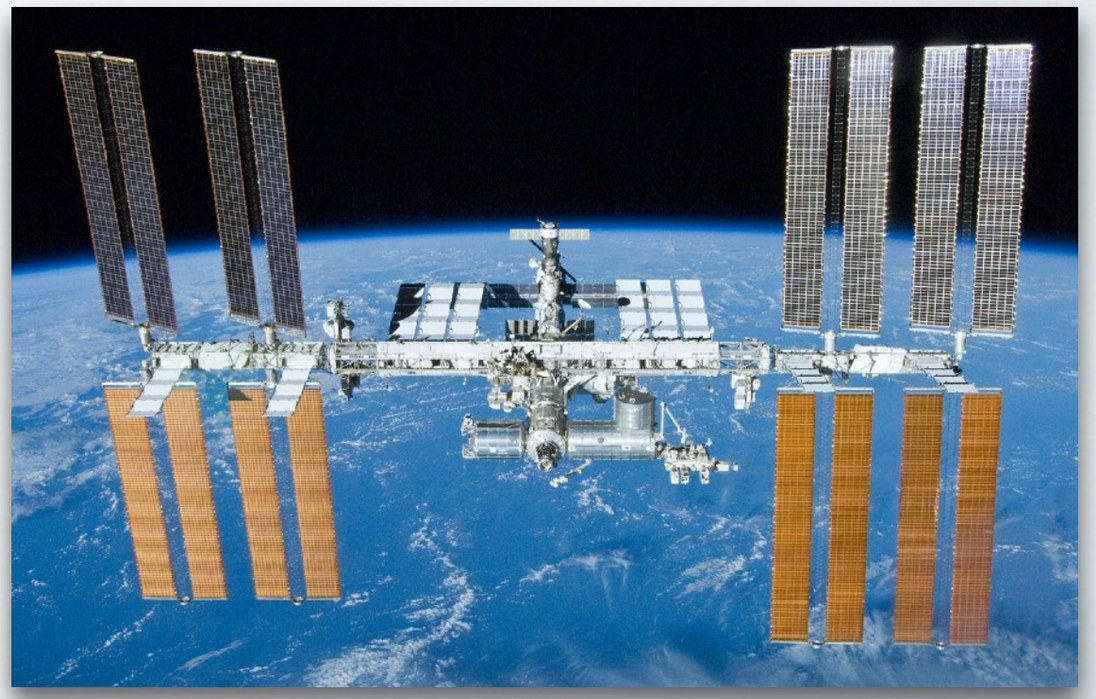


Weight or acceleration?

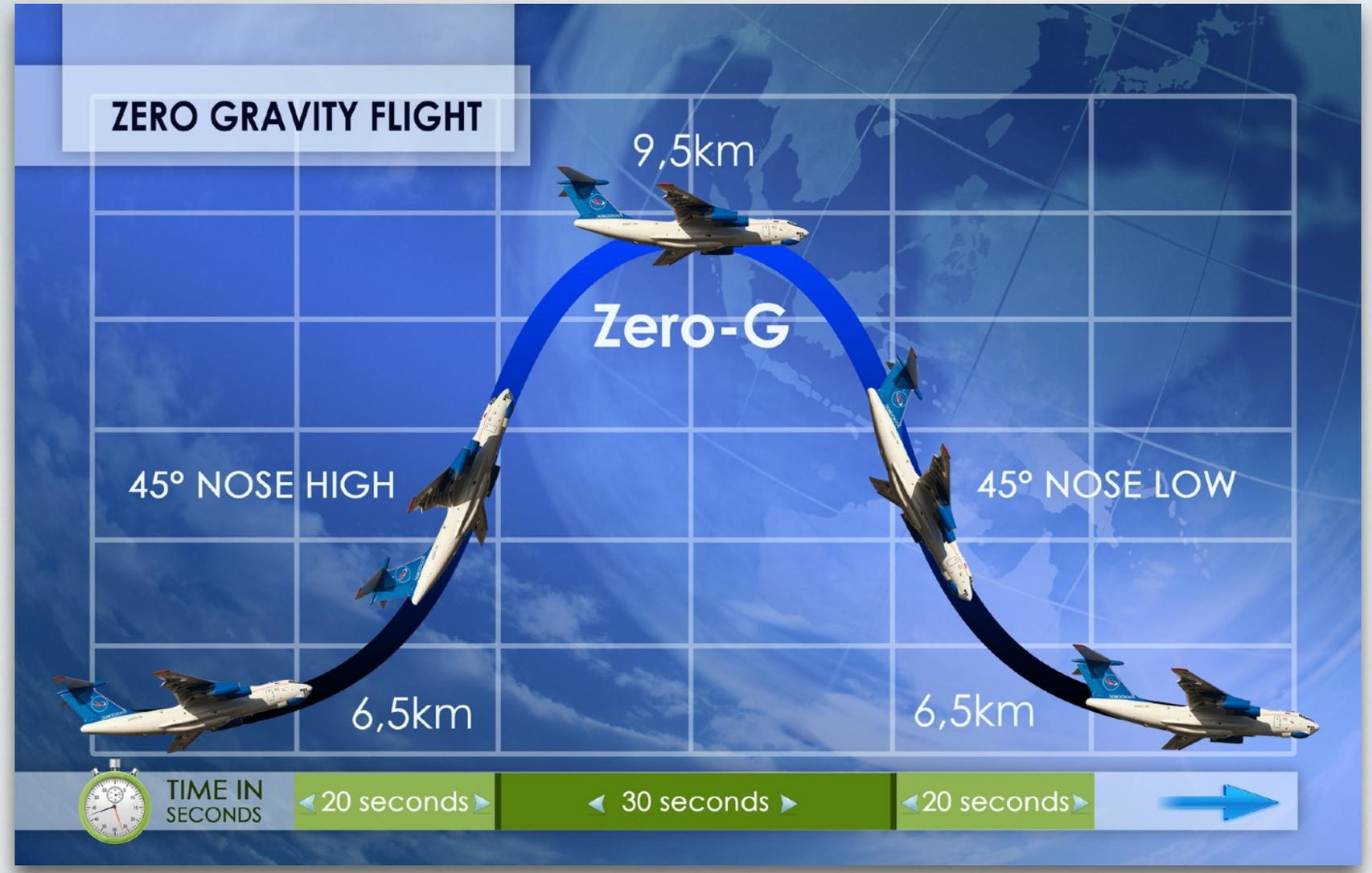
$$\frac{g_{\mathrm{ISS}}}{g_{\mathrm{E}}} = \frac{R_{\mathrm{E}}^2}{(R_{\mathrm{E}} + h_{\mathrm{ISS}})^2} \approx 0.9$$



- The astronauts “fall” toward Earth at the same rate as the space station
- Another example of the equivalence principle!



Zero-G flights



Water Balloon Rupture In Low Gravity

Experiments Aboard DC-9 Aircraft

NASA Lewis Research Center

Participation: Discussion #5

Wrong answers only!

What have you heard about relativity? What is special relativity? General relativity? What is relative here — space, time, something else?

5 minutes

Part 4: Symmetry, isotropy, homogoneity

Newton from symmetry

Aristotle: body at rest remains at rest

Galilean relativity

Newton’s 1st law

Momentum conservation

Newton’s 2nd/3rd law

Noether's theorem

If a system has a continuous symmetry property, then there are corresponding conserved quantities.

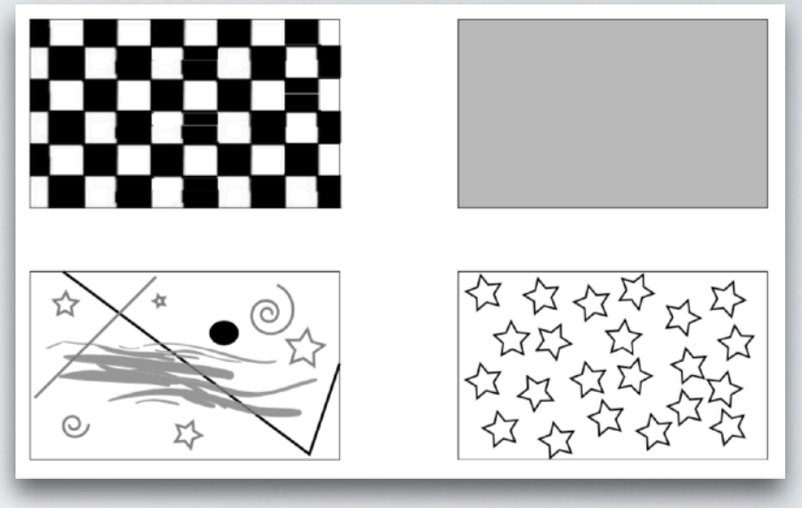
Translational symmetry → Momentum conservation

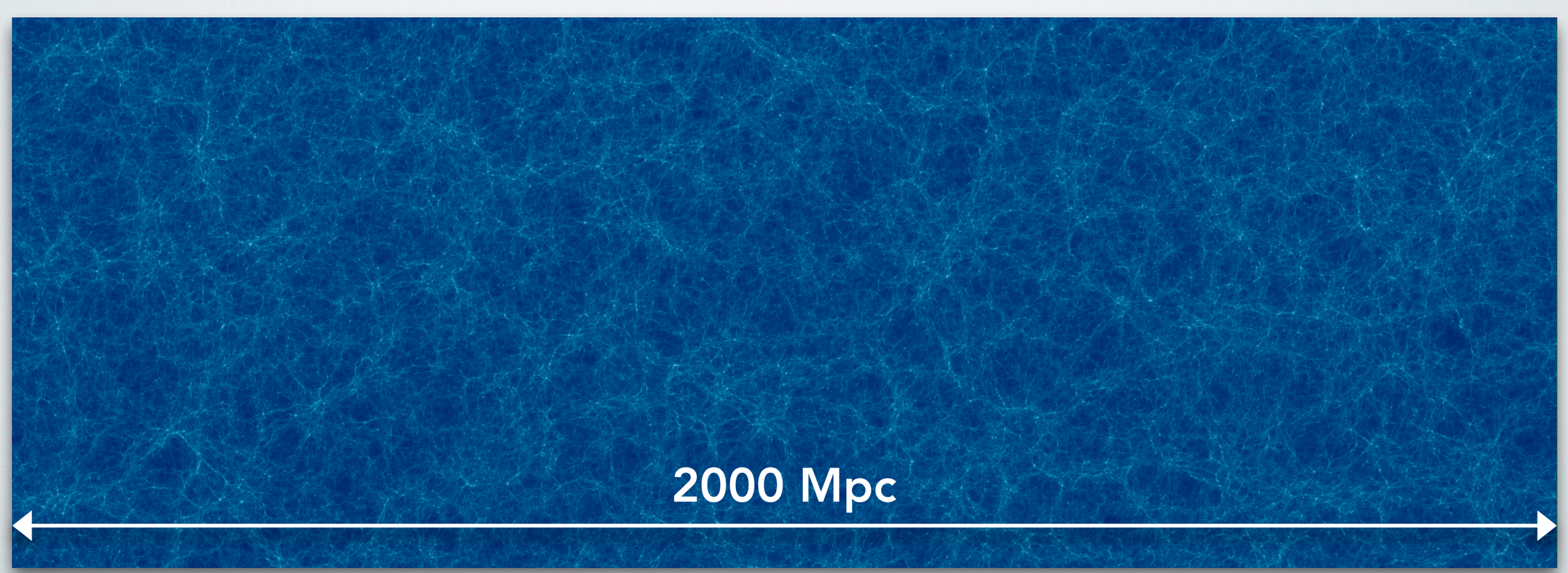
Rotational symmetry → Angular momentum cons.

Temporal symmetry → Energy conservation

Symmetry in the cosmos

- **Cosmological principle**:
  - the Universe **has no center** and is thus….
  - **isotropic**: roughly the same in all directions
  - **homogeneous**: roughly the same in all locations
- Isotropy implies homogeneity, but not vice versa
- Observations support this hypothesis





Take-aways

- Newton's laws of mechanis and gravity respect **Galilean relativity**

- The **weak equivalence principle** says that gravity is equivalent to acceleration

- **Symmetries** are intimately connected with conservation laws and Newton's laws

Next time…

We'll talk about:

- More spacetime, ether, and light

Assignments

- Post-lecture quiz (by tomorrow night)

Reading:

- H&H Chapter 6 (full chapter)