Feedback on Course

Course topics: planetary vs stellar

→ add/drop topics

Course content

→ More/less quantitative
→ More/less non-science content

Interlude topics: change vs keep

→ suggestions

Course work: too much vs too little

→ Problem sets
→ Midterms
→ Interludes: papers & talks

Lecture format

→ More visual vs less visual
→ More/less worked examples
→ More/less interactive
→ More/less PollEv
→ More/less in-class demonstrations

Interlude 2 Talks
Space Art

Wednesday, December 4

Team 9: Clay Littel, Luciano Saporito, Jack Slater, Colby Sorsdal

Team 10: Rachel Williamson, Stella Brockwell, Carter Helmandollar, Guy Rahat

Team 11: Emily MacKenzie, Abby Maher, Margaret McLaughlin, William Rhodes

Team 12: Kira Quintin, Jeannine Brokaw, Alex MacNamara, Jireh Jin Lee

Note 1: Talks will be 10 minutes long.

Note 2: Do not use paragraphs and long sentences.

Send me your PowerPoint or PDF talk by 8am Monday morning.

Papers are due in class on Friday, December 6 (last day of classes).

Today's Topics

Monday, December 2, 2019 (Week 14, lecture 32) – Chapter 24.

1. Special Relativity review.
2. General Relativity.
3. Gravitational Waves.

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   What happens when you travel close to the speed of light “c”

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1. Special Relativity review.

   What happens when you travel close to the speed of light “c”

2. General Relativity.

   What happens when you have very strong gravity

3. Gravitational Waves.

Special Relativity (REVIEW)

Principle of Relativity

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

Corollary #1

You cannot tell if you are moving (based on local measurements) in an inertial frame.

Corollary #2: Universal speed of light

The speed of light in vacuum is the same in all inertial frames, regardless of the motion of the source.

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➡ Length contraction & time dilation

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→ Length contraction & time dilation

General Relativity

Equivalence Principle

A coordinate system that is falling freely in a gravitational field is (equivalent to) an inertial frame.

Corollary

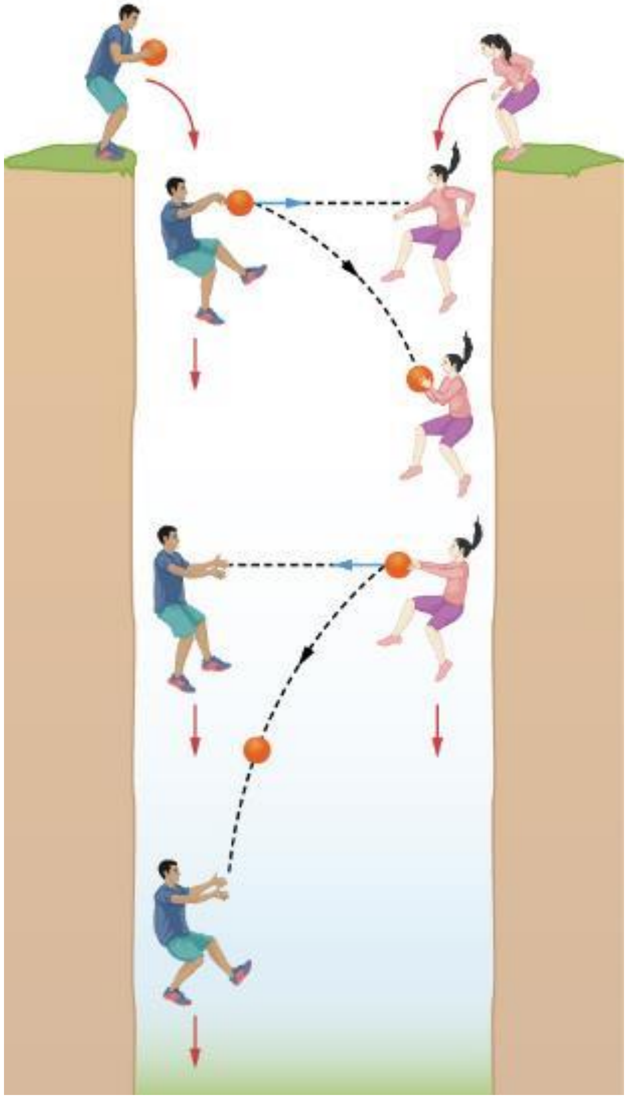
You cannot tell if you are at rest in a non-gravitational field (i.e. in a standard inertial frame) or freely falling under gravity based in based on local measurements.

Equivalence Principle

You cannot tell if you are at rest in free space (i.e. in a standard inertial frame) or freely falling under gravity based in based on local measurements.

Example

- Two people play catch as they descend into a bottomless abyss.
- Since the people and ball all fall at the same speed, it appears to them that they can play catch by throwing the ball in a straight line between them.
- Within their frame of reference, there appears to be no gravity.

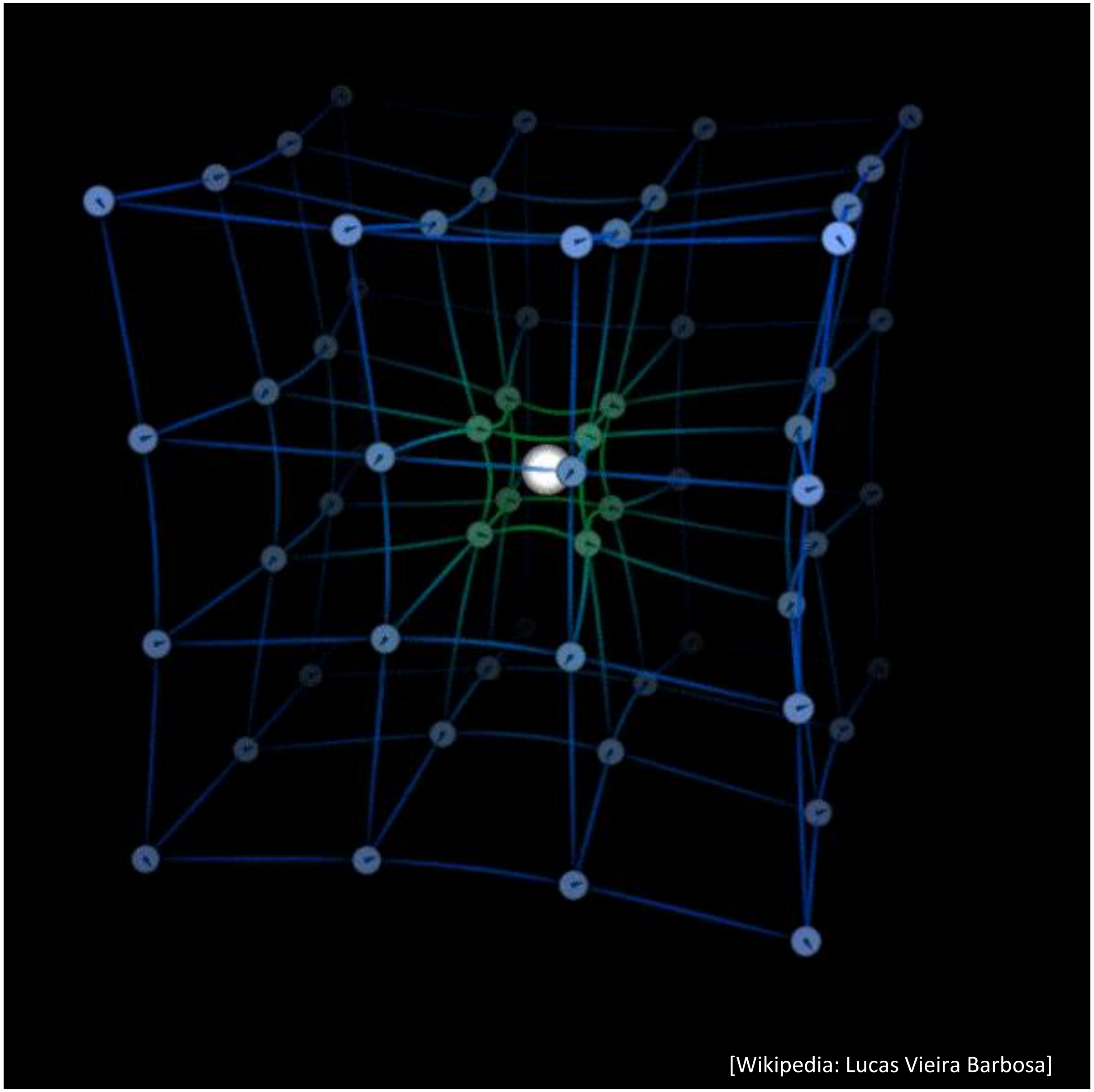


[OpenStax: Astronomy]

Equivalence Principle on ISS

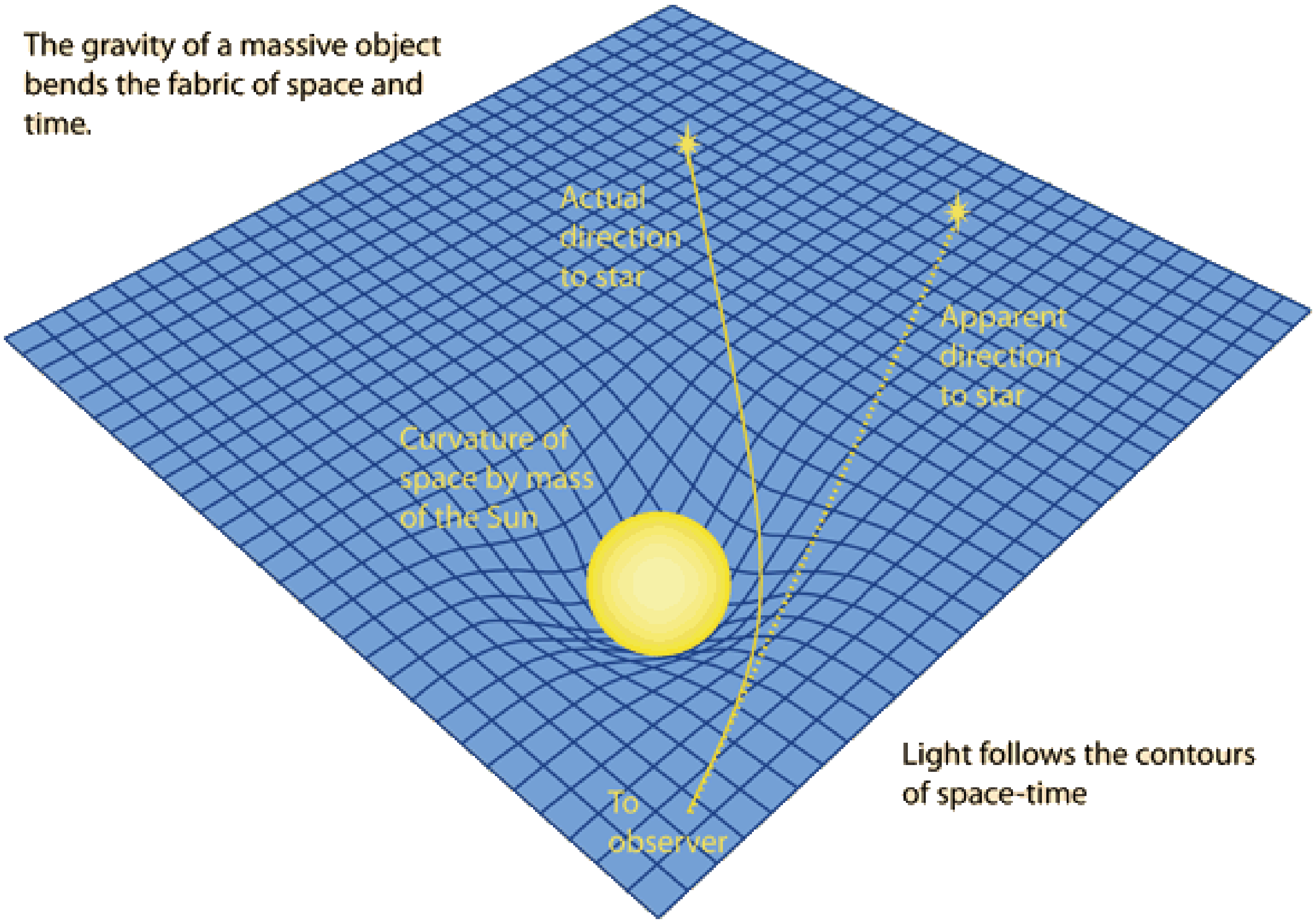
[NASA]

Curved Space-Time



[Wikipedia: Lucas Vieira Barbosa]

Curved Space-Time: light rays in 2D



The gravity of a massive object bends the fabric of space and time.

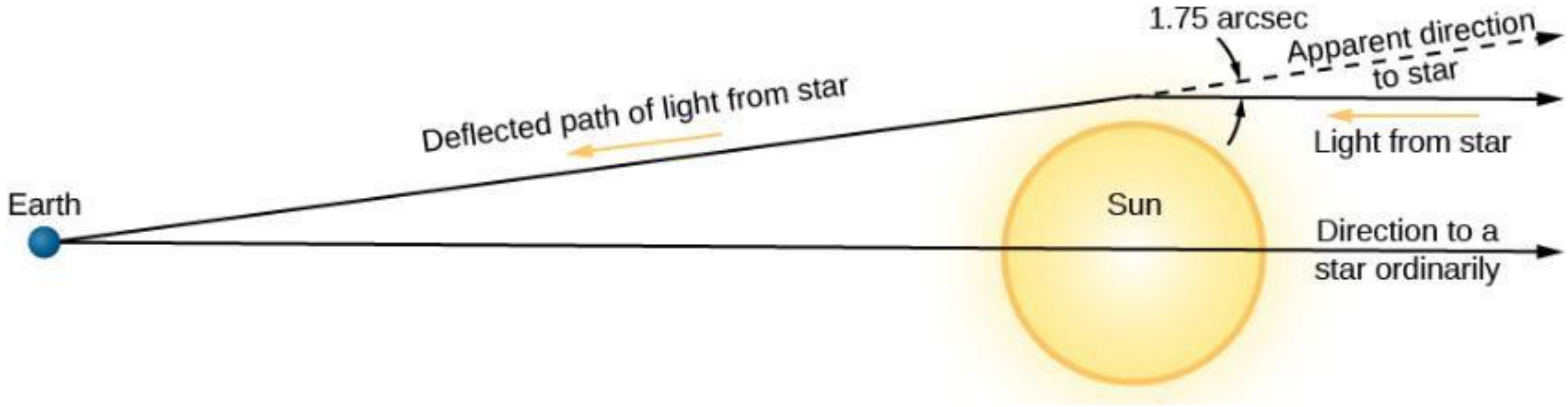
Light follows the contours of space-time

[http://hyperphysics.phy-astr.gsu.edu/hbase/Relativ/grel.html]

Curved Space-Time

Eddington's measurement of deflection of light

- Arthur Eddington measures the deflection of starlight by the Sun.
- 1919 solar eclipse: West Africa & Brazil.
- The star appears shifted: Measurements show deflection that agrees with General Relativity.



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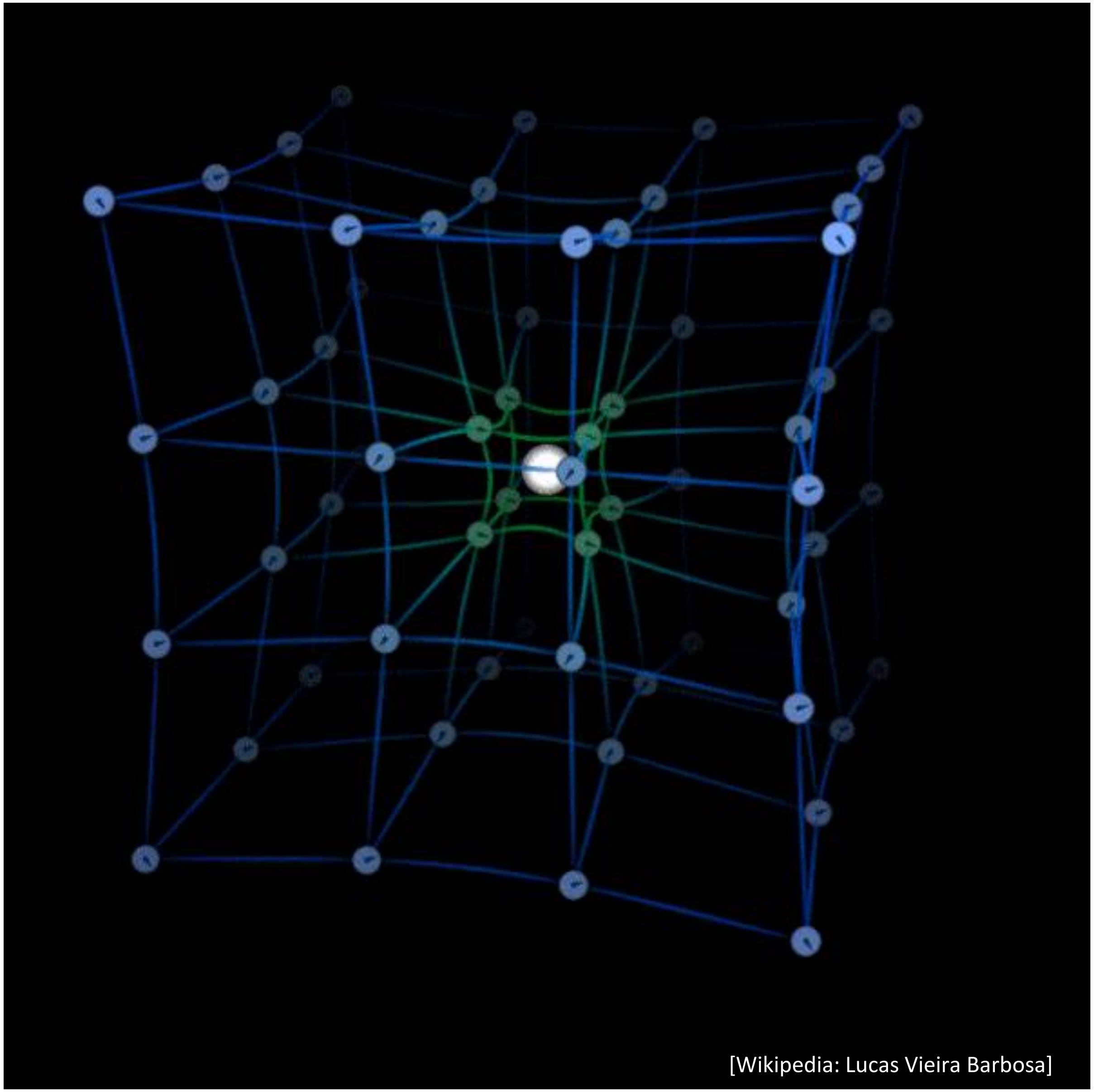

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Gravitational Time Dilation: small heights

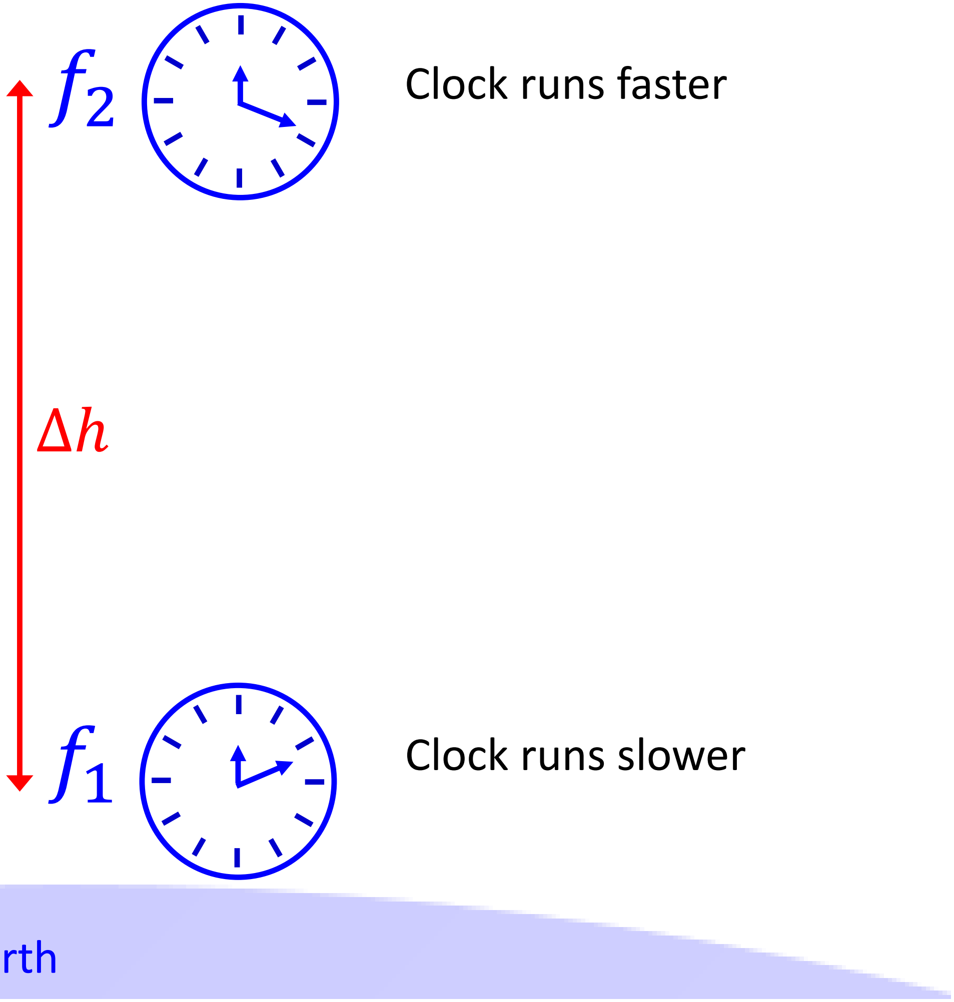
Clocks in a gravitational field run slower than clocks in free space.

For small changes in height Δh:

$$\boxed{\frac{\Delta f}{f} = \frac{g\Delta h}{c^2}}$$

f = frequency of clock

g = acceleration of gravity
= 9.8 m/s^2 at Earth’s surface



Clock runs faster

Clock runs slower

Gravitational Time Dilation: large distances

Clocks in a gravitational field run slower than clocks in free space.

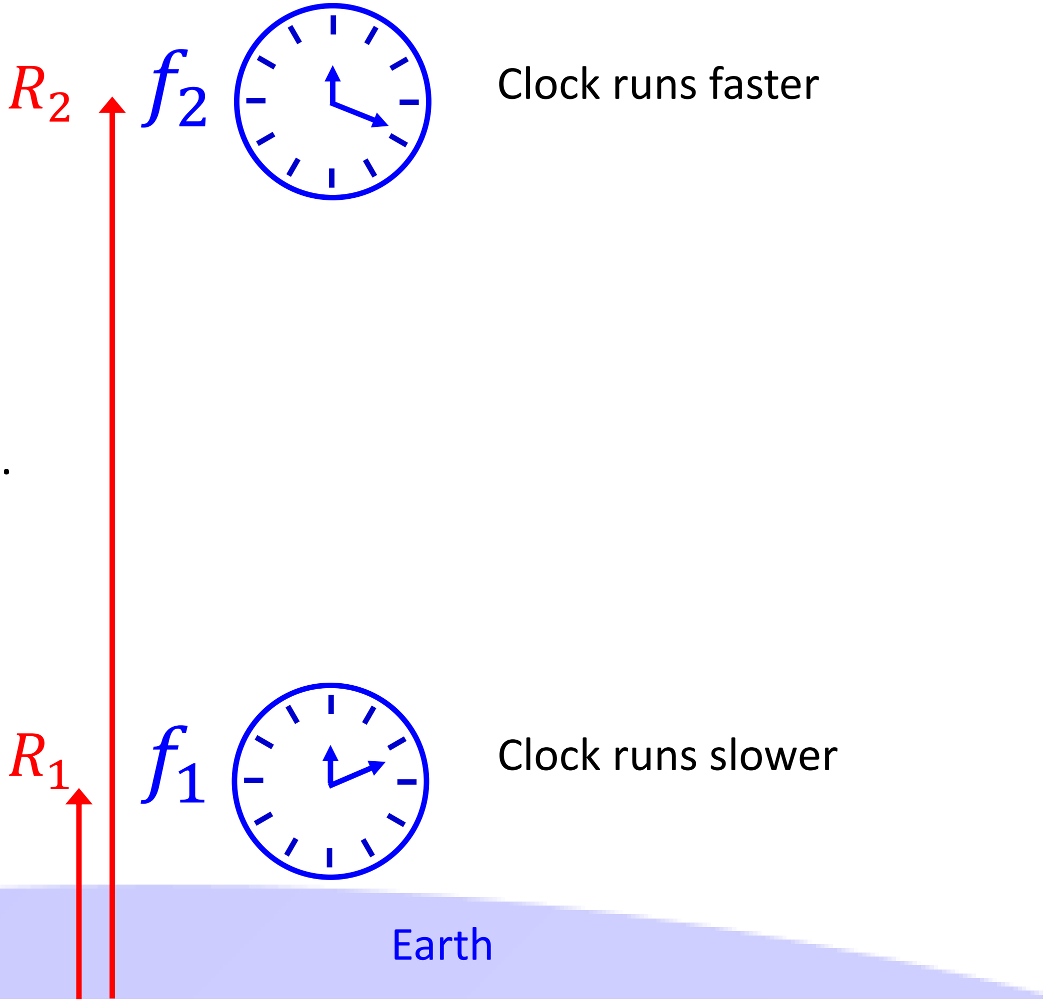
$$\boxed{\frac{f_2}{f_1} = \sqrt{\frac{1 - \frac{R_s}{R_2}}{1 - \frac{R_s}{R_1}}}}$$

$f_{1,2}$ = frequencies at R_1 and R_2.

R_S = Schwarzchild radius

$= \frac{2GM}{c^2}$

M = mass of Earth, star, etc.



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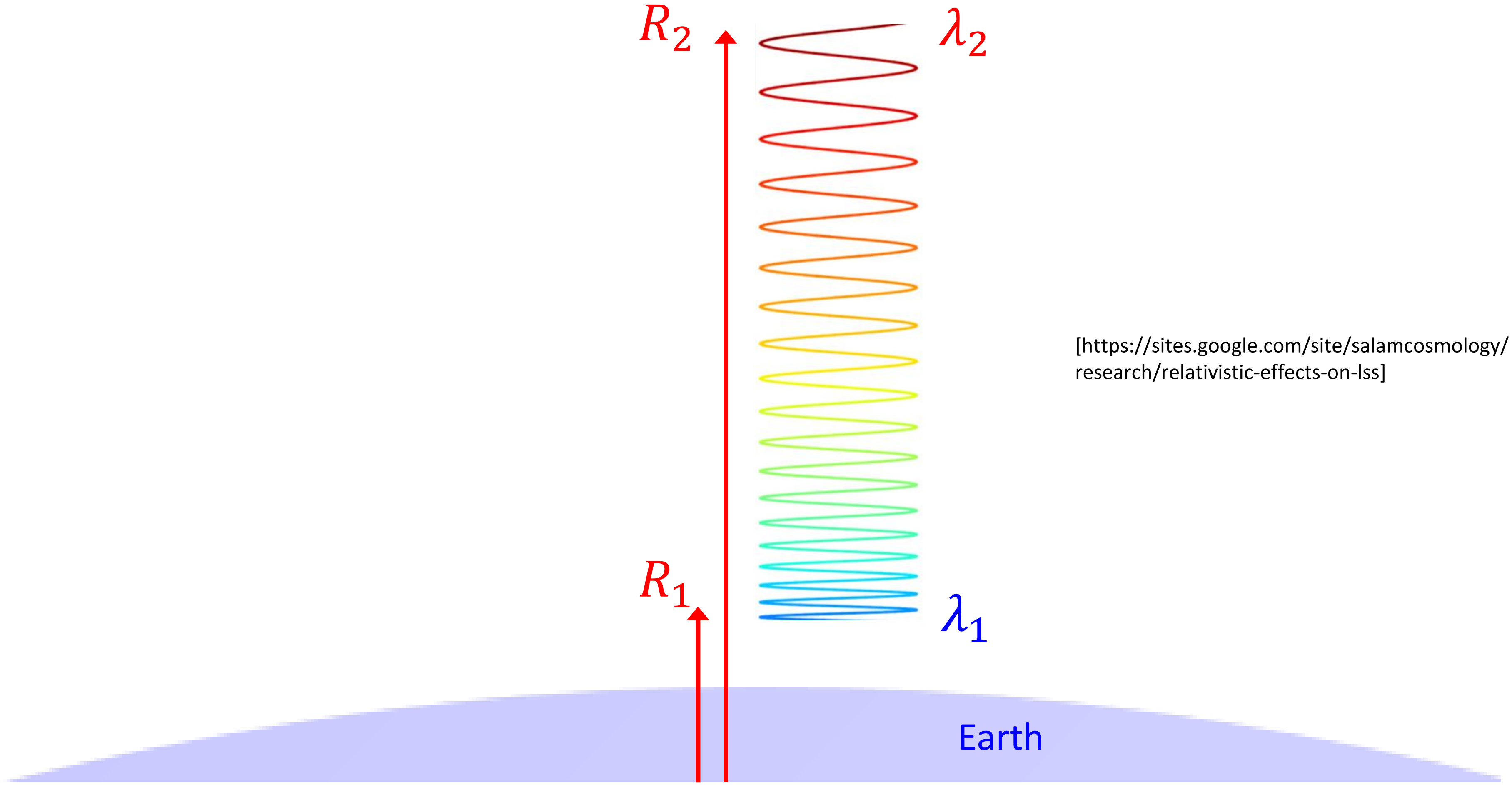
Gravitational Redshift:

Light shifts to the **red** when it escapes gravity

As light leaves the gravitational pull of Earth/star/blackhole, it loses “kinetic energy” and shifts to the red ($E_{photon} = hf$).



[https://sites.google.com/site/salamcosmology/research/relativistic-effects-on-lss]

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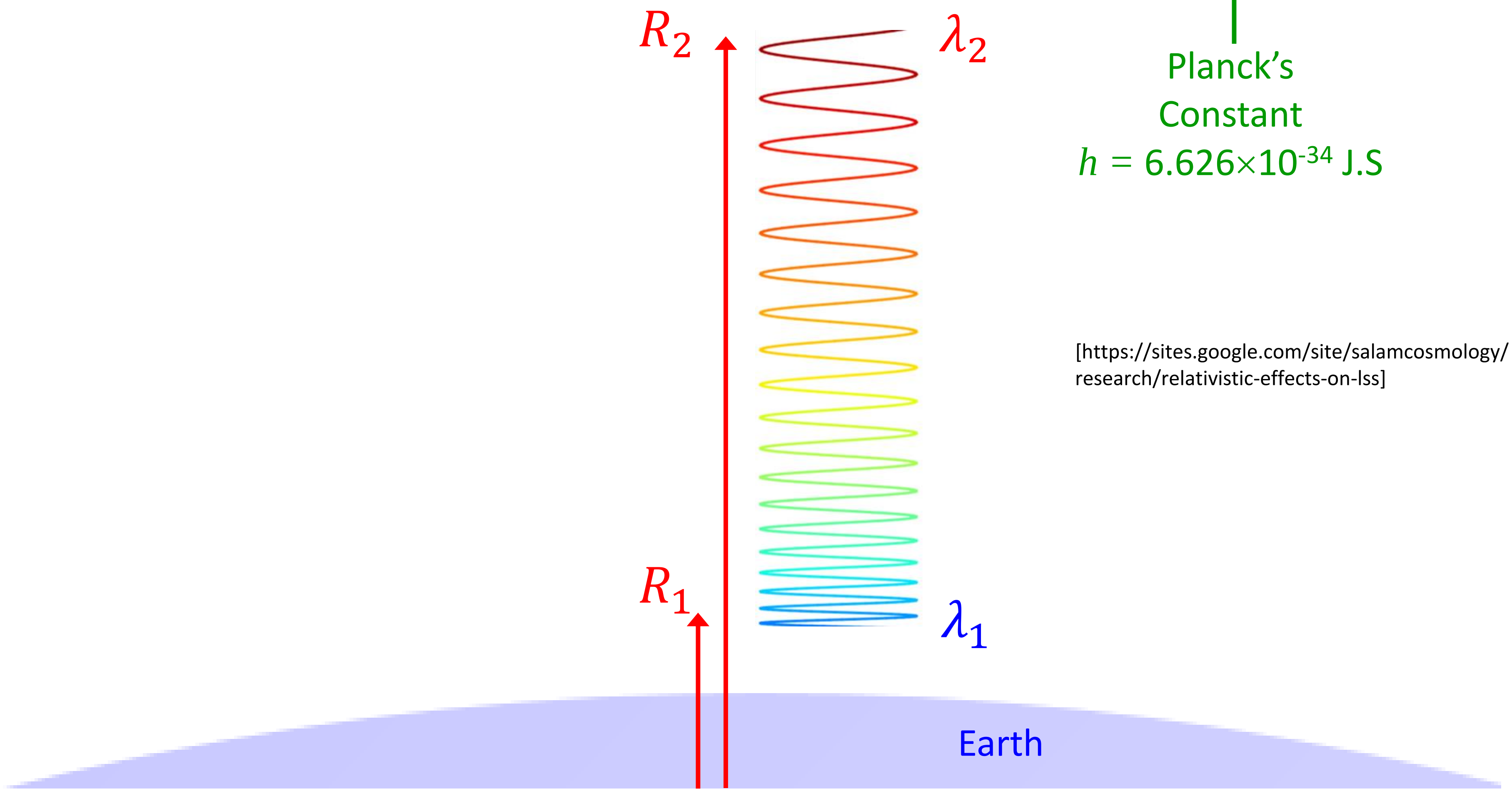

Planck's Constant

h = 6.626×10^{-34} J.S

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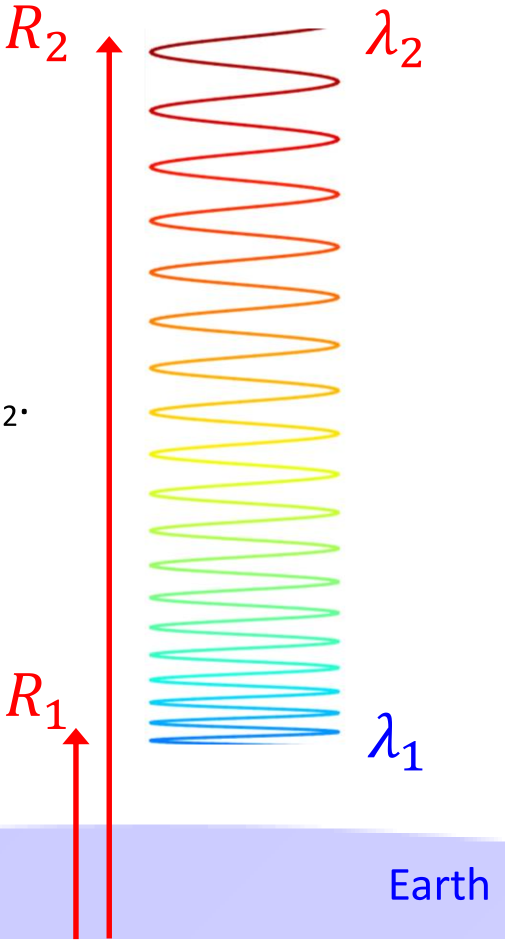

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Gravitational Waves

- Accelerating and ***orbiting*** masses will emit gravitational waves.

- Gravitational waves are a consequence of the **finite speed of gravity** *(speed of light)*.
  - → a change in gravity's strength propagates at the speed of light.
  (i.e. it's not instantaneous.)

- Only large masses emit significant gravitational waves.
  - → Orbiting **black holes** and **neutron stars.**
  - → Masses must be close together (i.e. fast moving) for significant emission.

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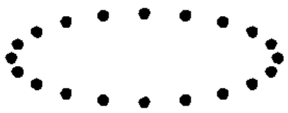
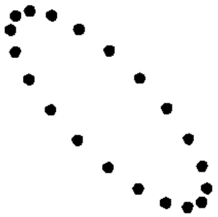


"+" polarization

or



"×" polarization

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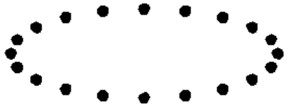
- A passing gravitational wave applies weak pulling & stretching of **space** along two perpendicular axes (and time).



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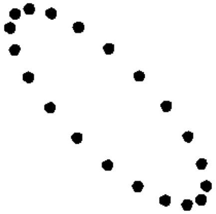


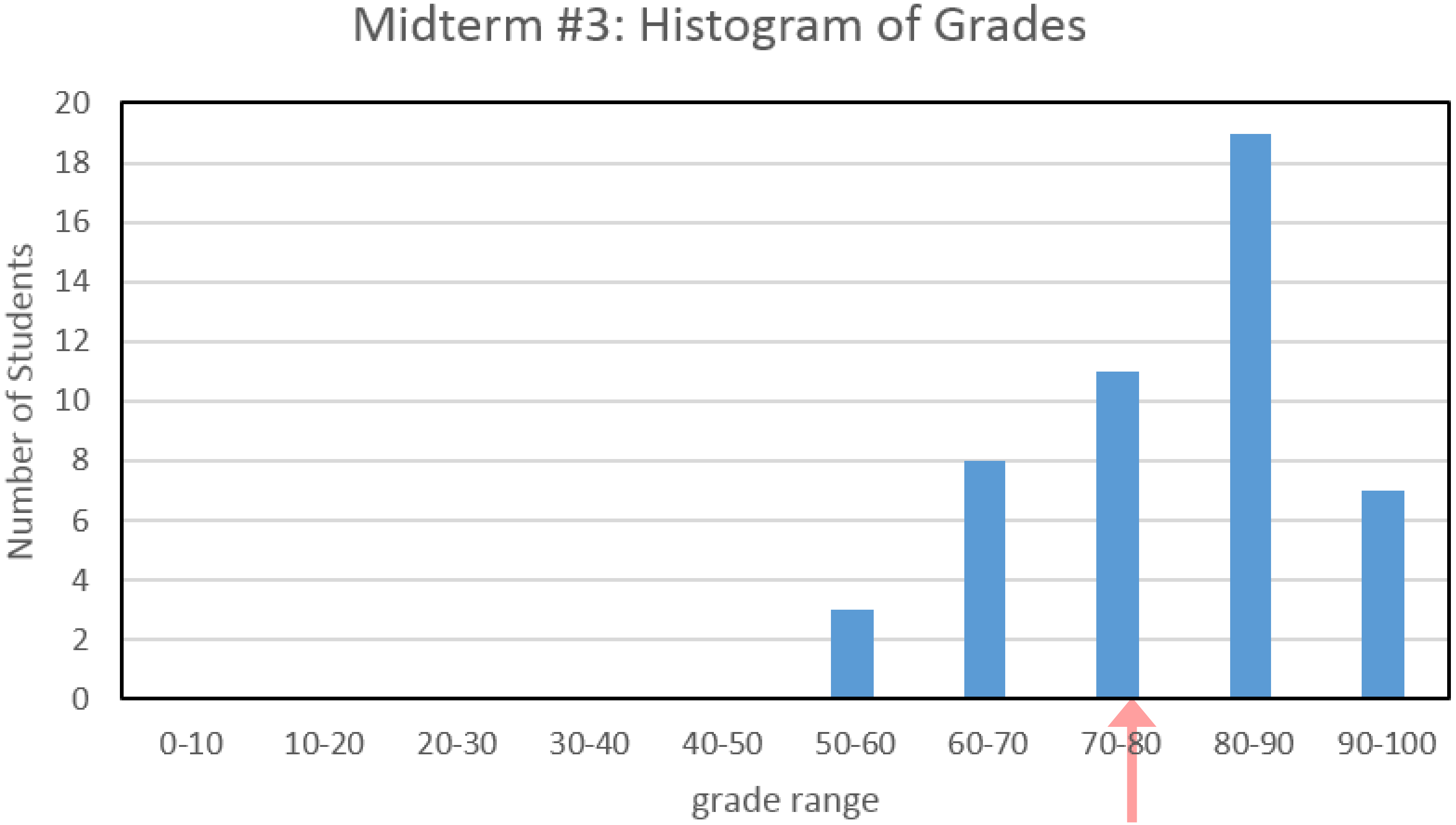
"×" polarization

Gravitational Wave “Telescope”

LIGO: Laser Interferometer Gravitational-Wave Observatory

[http://ligo.caltech.edu: LIGO Livingston, LA]

Midterm Test #3



Average = 79

Median = 81

High Score = 96.5