c is constant.

Suppose you fly away from the Earth at 1/2 the speed of light.

Someone sitting on Earth fires a light beam past you, as you travel away.

The light wave passes you at the speed of light.

Relativity

Astronomy 1101

Key Ideas:

Central Postulates:

- *same* for all uniformly moving observers.
- The speed of light is the *same* for all observers.

Consequences:

- Different observers measure *different* times, lengths, and masses.
- Only *spacetime* is observer-independent.

General Relativity:

- Matter tells spacetime how to curve, spacetime tells matter how to move.

Newton's Universe

In Newton s view:

- The universe keeps absolute time.
- Objects move through absolute space.
- Universe looks the same to all observers, regardless of how they move through it.

Result:

A set of laws formulated from the perspective of an absolute God's Eye View of the Universe.

Einstein's Relativity

1905: Einstein challenged Newton:

- We cannot have an absolute view of the Universe.
- We can only *compare* our view with that of other observers.
- All information we have is carried by light.
- But, light moves at a *finite speed*.

Result:

Introduces an irreducible relativity to our physical perspective of the World.

Your world is non-relativistic.

Information about the Universe carried by light.

Speed of Light: $c = 3 \times 10^5$ km/sec

Compared to everyday scales:

- 65 mph = 0.028 km/sec = 9.3×10^{-8} c
- light travels across this room in ~30 nanosec
- Human Reflexes: ~0.1 sec (~10^8 nanosec)

You rarely (never) encounter things moving relativistically.

1st Postulate of Relativity

The laws of physics are the same for all uniformly moving observers.

(Uniformly = with a *constant velocity*”; no acceleration: “inertial reference frame”)

Implications:

- No such thing as **true** “absolute rest”.
- Any uniformly moving observer can consider themselves to be “at rest”. Not accelerating.

2nd Postulate of Relativity

The speed of light in a vacuum is the same for all observers, regardless of their motion.

Implications:

- The speed of light is a *Universal Constant*.
- We cannot send or receive information faster than the speed of light.

Experimentally verified in *all* cases.

Essential Relativity

Two observers moving relative to each other experience the world *differently*:

- Both measure the *same* speed of light
- Both find the *same* physical laws relating distance, time, mass, etc.

But, both measure *different* distances, times, masses, etc. when applying those laws.

The key is the role of *light*.

The Relativity of Time

A Thought Experiment

Consider a simple photon clock:

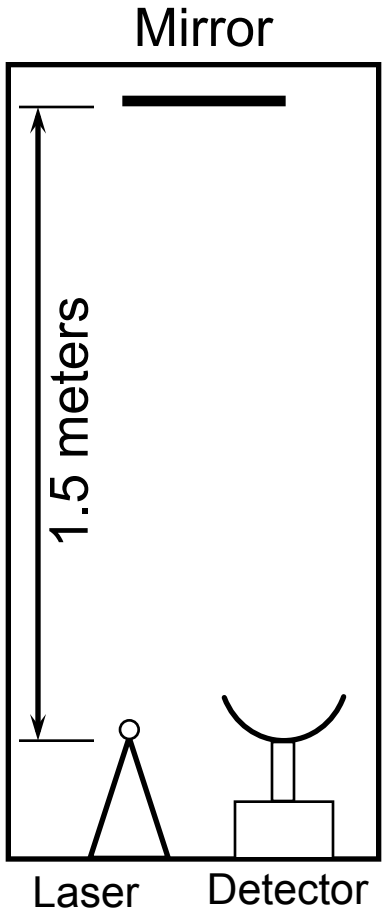
-
-

Photon Path Length = 3 meters

One “Tick” = Time of Flight

= 3 meters / c

= 10^{-8} seconds

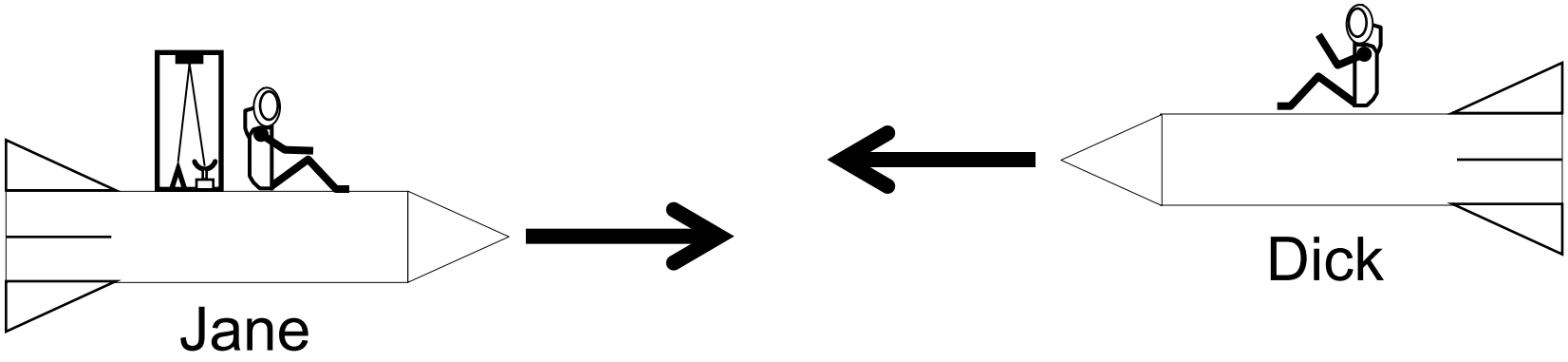


Tick!

Relativity with Dick & Jane

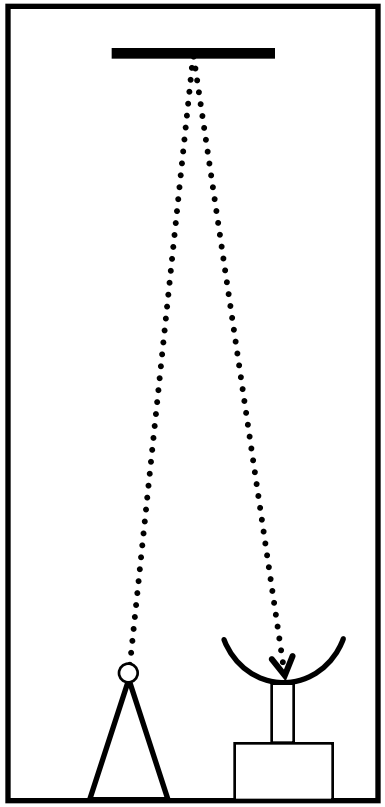
Dick & Jane fly past each other in rockets:

- Constant Relative Speed = 0.8 c
- Jane is carrying a photon clock
- Each measures how long it takes between "ticks" of Jane's photon clock.



What do they see?

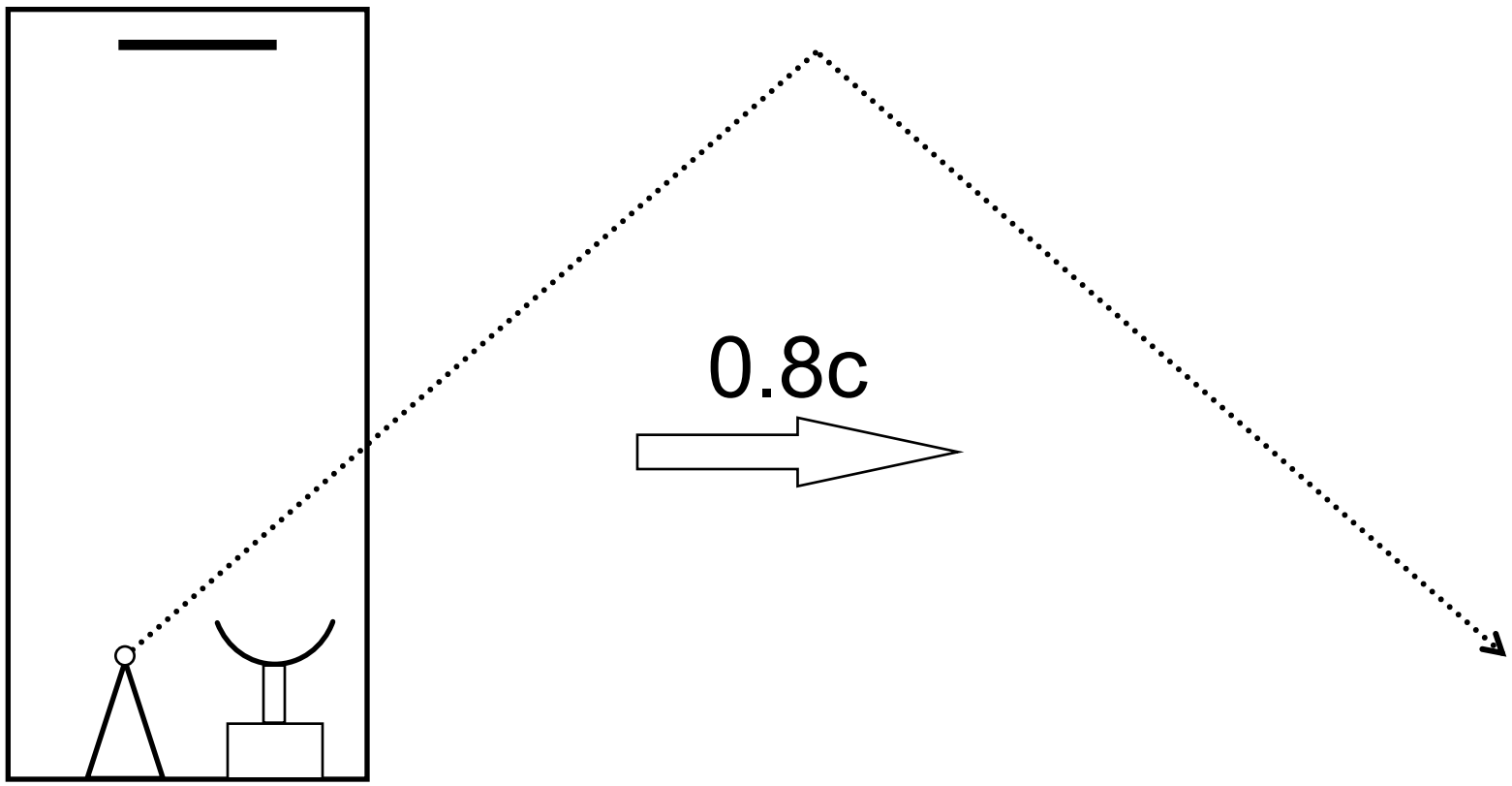
Jane's clock as seen by Jane:



Tick!!

Photon Path = 3 meters

Jane's clock as seen by Dick:



Photon Path = 5 meters

A Comparison

Jane's Observations:	Dick's Observations:
• Jane's Speed = 0	• Jane's Speed = 0.8c
• Dick's Speed = 0.8c	• Dick's Speed = 0
• Photon Speed = c	• Photon Speed = c
• Path Length = 3 m	• Path Length = 5 m
• Tick = 3/c = 10^{-8} s	• Tick =5/c=1.67x10^{-8} s
"My Clock Runs OK"	"Your Clock runs *slow*"

The "twin paradox".

Relative Time

This result is true for *all* kinds of clocks.

Conclusion: There is no *absolute time*.

- Times passes at different rates for observers moving relative to each other.
- At speeds small compared to c, the difference is very small.
- At speeds comparable to c, the difference is dramatic.

Verified experimentally using atomic clocks on airplanes and satellites. They literally slow down their atomic transitions relative to us.

Consequences of Relativity

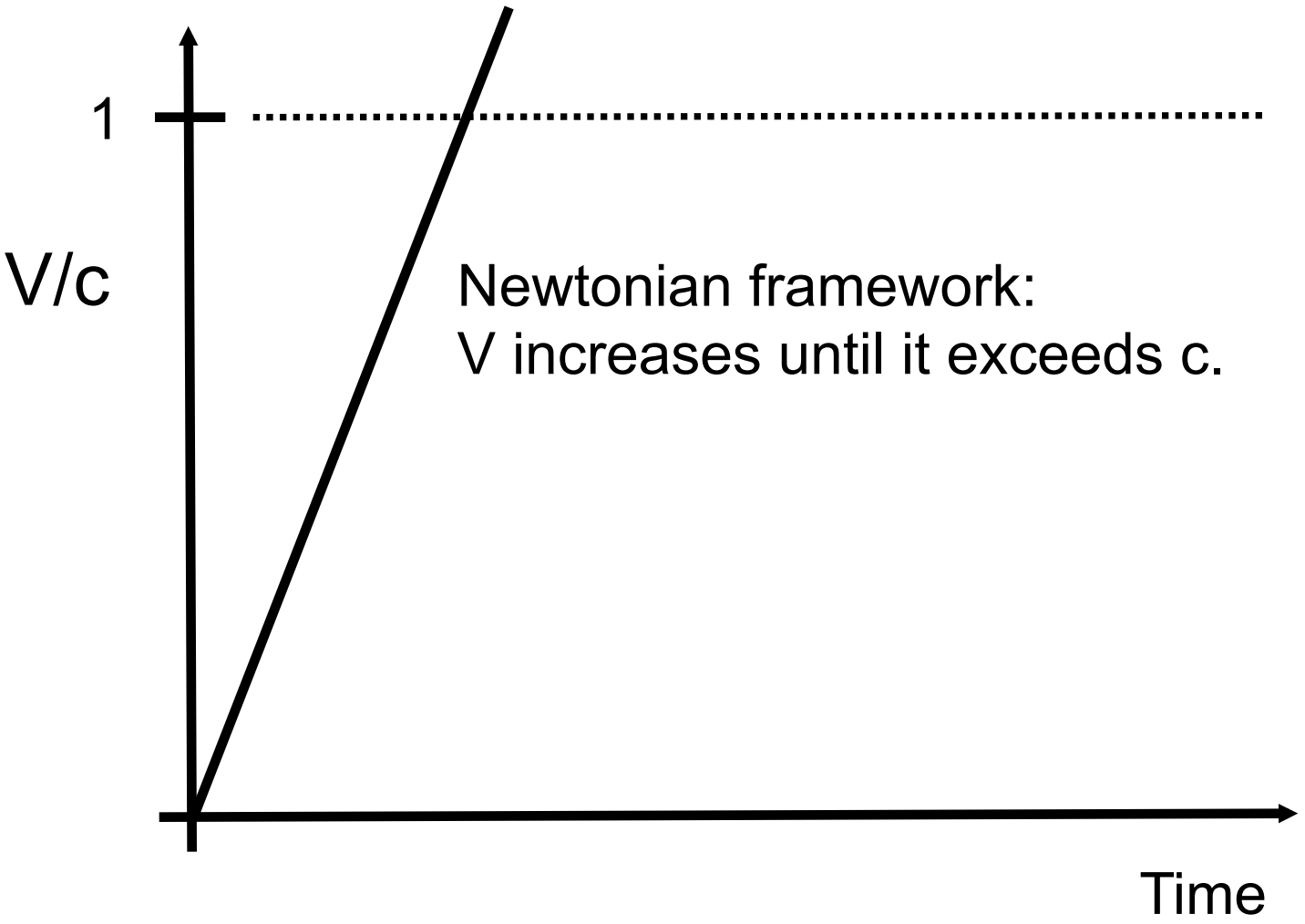
Observers moving relative to each other:

- Do not measure the same times.
- Disagree on what events occur simultaneously.
- Do not measure the same lengths.
- Do not measure the same masses.

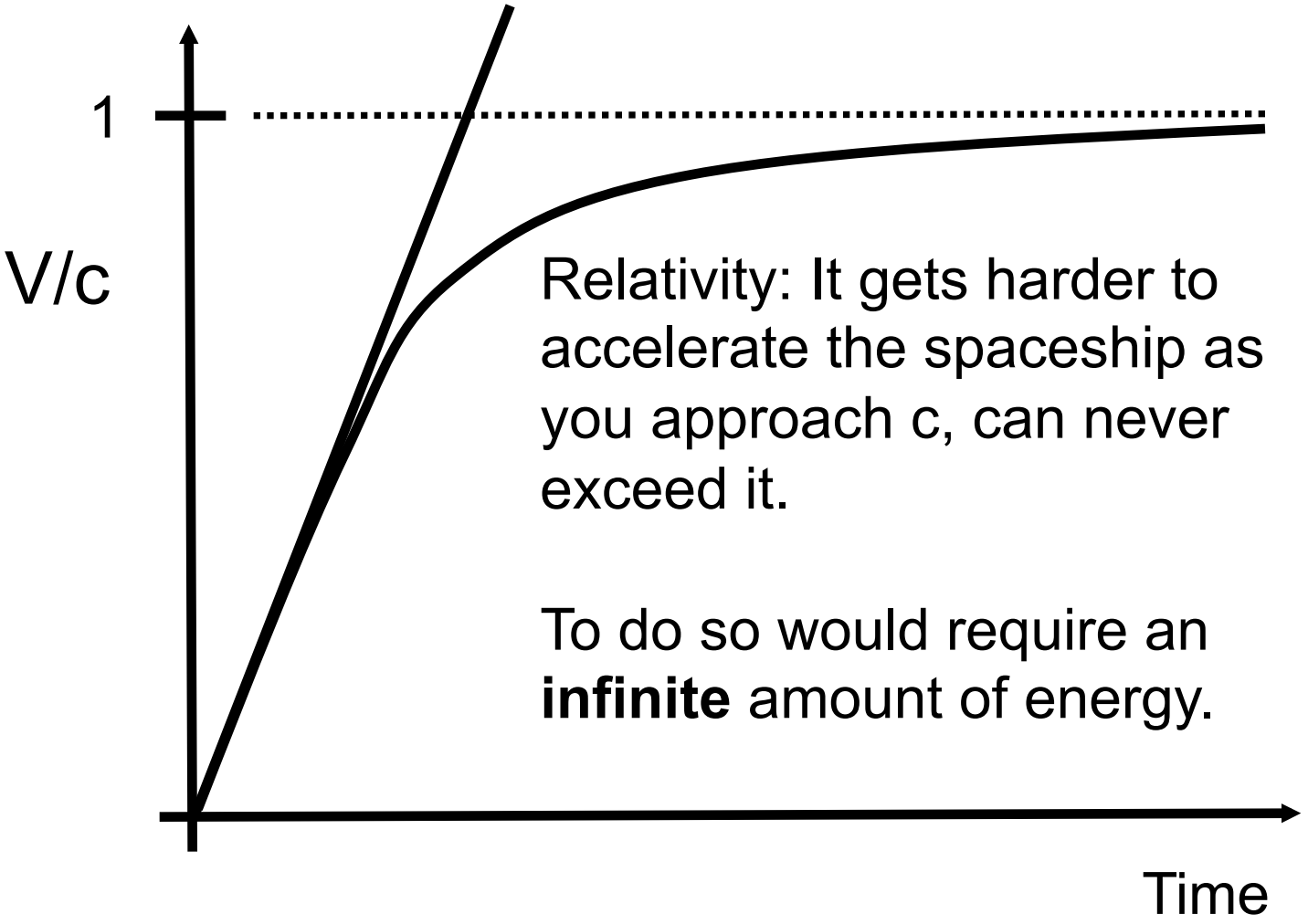
Other Consequences:

- Mass and Energy are *equivalent*: $E=mc^2$
- Massless particles *must* move at speed of light
- Massive particles can never reach *c*.

Spaceship undergoing constant acceleration



Spaceship undergoing constant acceleration



Spacetime

Newton's View:

- Space & Time are *separate* and *absolute*.
- Universe looks the same to all observers.

Einstein's View:

- Space & Time are *relative*.
- United by light into *Spacetime*.

Only spacetime has an absolute reality independent of the observer.

Light & Physical Laws

Because all information is carried by light at a finite speed:

- All observers see the same physical laws.
- All observers measure the same speed of light.

We must unify otherwise disparate ideas:

- Space & Time are unified into Spacetime.

Matter & Energy are equivalent ($E=mc^2$)

What about Gravity?

Special Relativity is restricted to uniformly moving (*unaccelerated*) observers.

But, objects are *accelerated* by gravity. (Newton: “They feel a *gravitational force*.”)

It took Einstein another 8 years to generalize relativity.

Led to a completely new theory of gravity.

Curved Spacetime

Matter *curves* the spacetime around it:

- The shortest paths are *curved* lines.
- More mass = Greater spacetime curvature.
- Closer = Greater spacetime curvature.

A freely falling object follows a *curved* path in spacetime.

Newton would have said:

> *"It feels a force deflecting it from a straight line path."*

A New Theory of Gravity

General Relativity may be summarized as:

- *Matter tells spacetime how to curve.*
- *Curved spacetime tells matter how to move.*

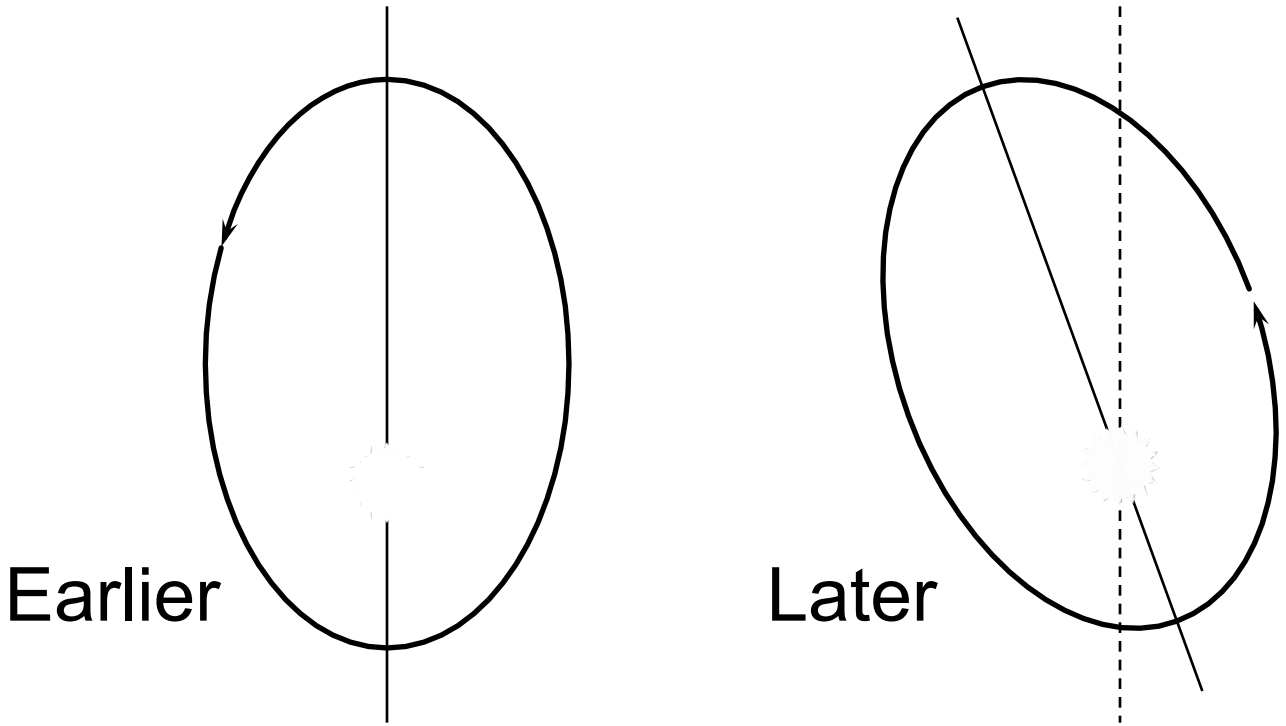
Replaces the Newtonian idea of a “force” with the curvature of spacetime as the agent of Gravity.

But, how do the “ripples” move? Time dependence.

GR has withstood all experimental tests.

The Precessing Orbit of Mercury

The major axis of Mercury's orbit precesses slowly by 574 arcseconds/century:



Einstein 1, Newton 0

Newtonian Gravity:

- predicts precession of 531 arcsec/century
- ~43 arcsec/century **smaller** than observed.

General Relativity:

- Spacetime curvature changes as Mercury gets closer to the sun on its orbit (eccentricity). The shape of spacetime changes.
- Gives the orbit a little twist.
- This adds an extra 43 arcsec/century!!

Bending of Starlight

Light travels on the *shortest* path through spacetime.

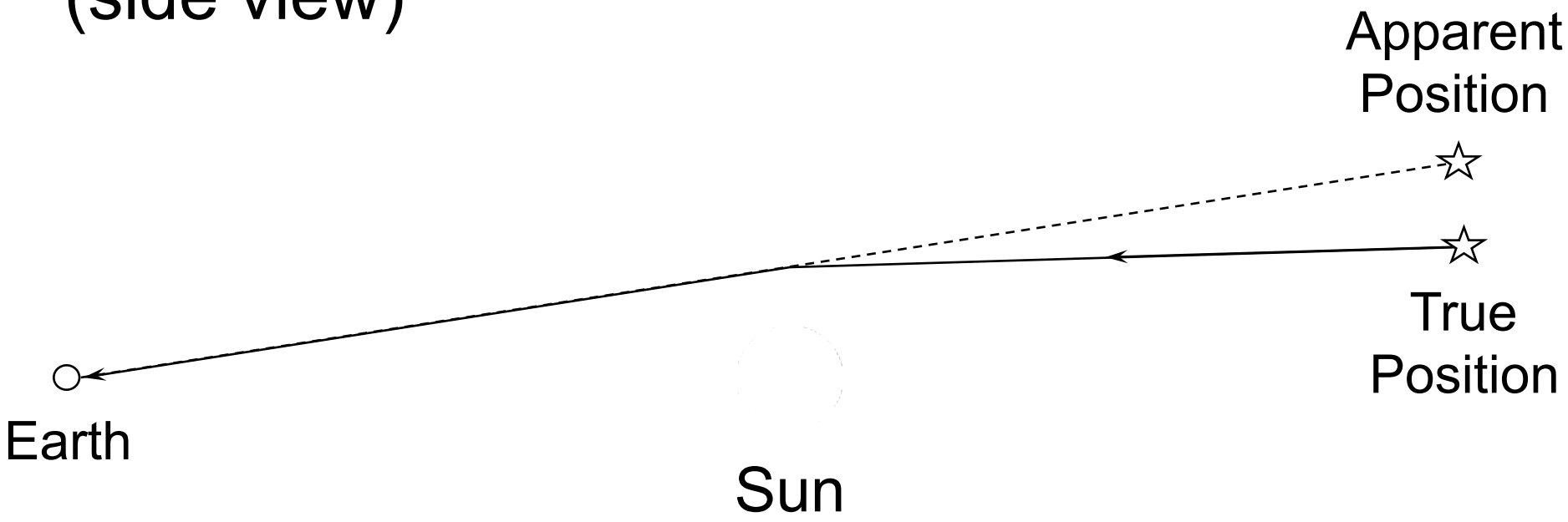
Prediction:

- Gravity bends light passing a massive object

Confirmed:

- 1919 Solar Eclipse
- Gravitational Lenses (1980s)

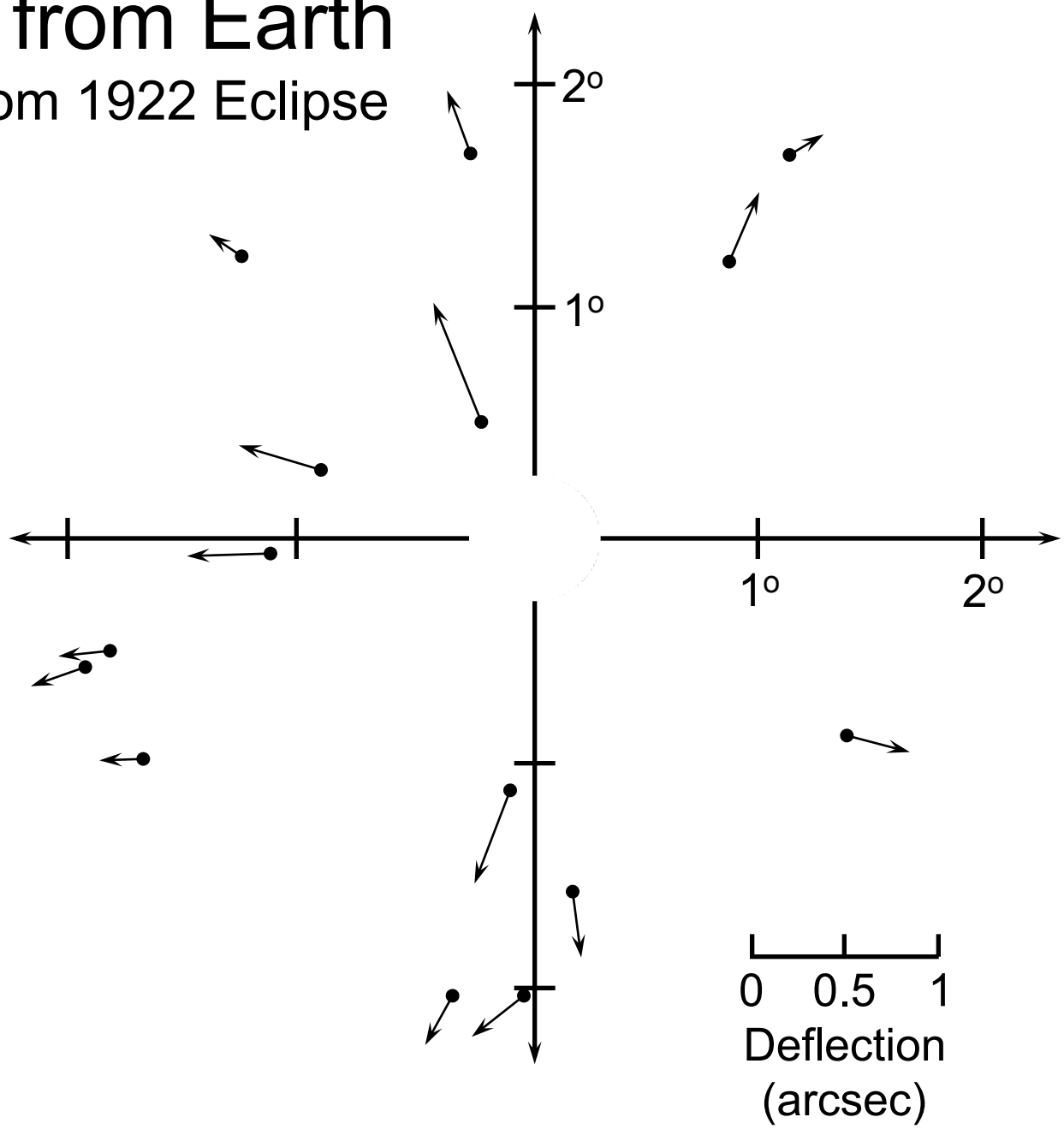
Bending of Starlight
(side view)

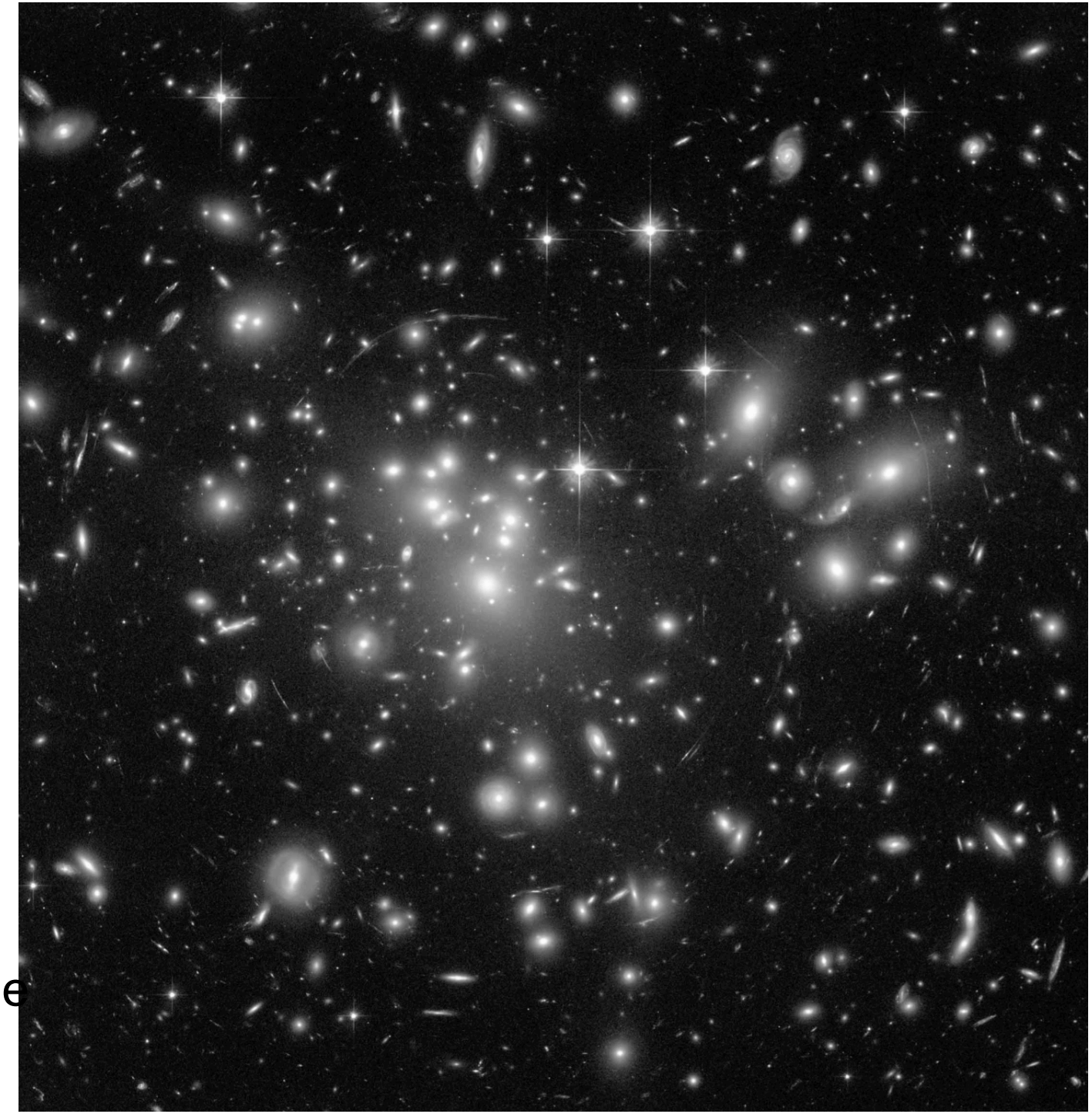


Scale is exaggerated

View from Earth

Data from 1922 Eclipse





Hubble

Binary Neutron Stars

•

binary) should radiate their orbital energy in gravitational waves, leading to eventual merger.

• The effect is usually (way) too small to see, unless you have two very massive, compact bodies.

• Hulse-Taylor pulsar: two neutron stars in a binary.

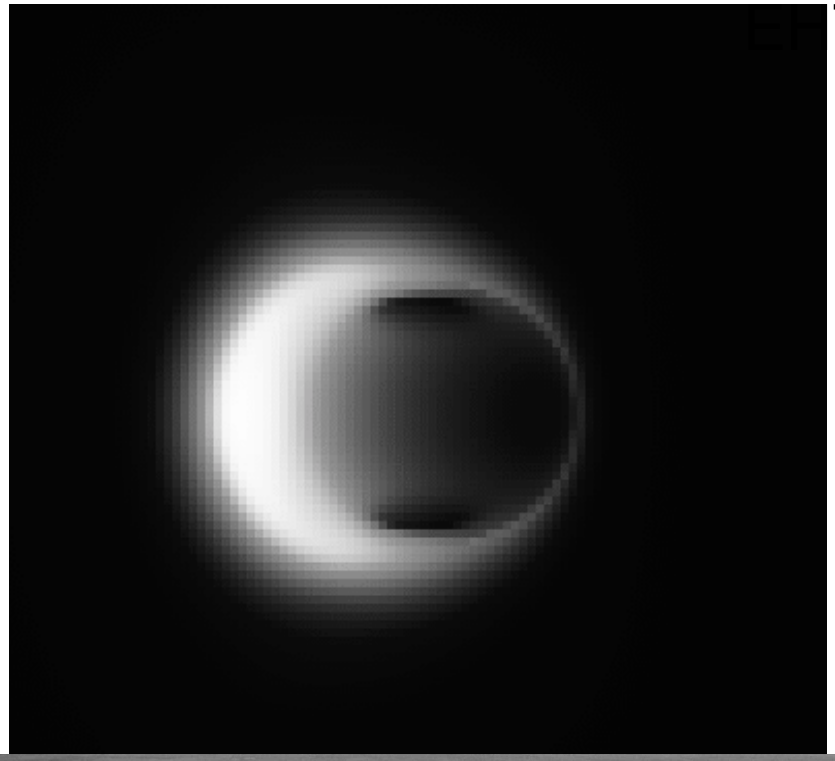
- was decaying exactly the way predicted by GR.
- Nobel Prize 1993.

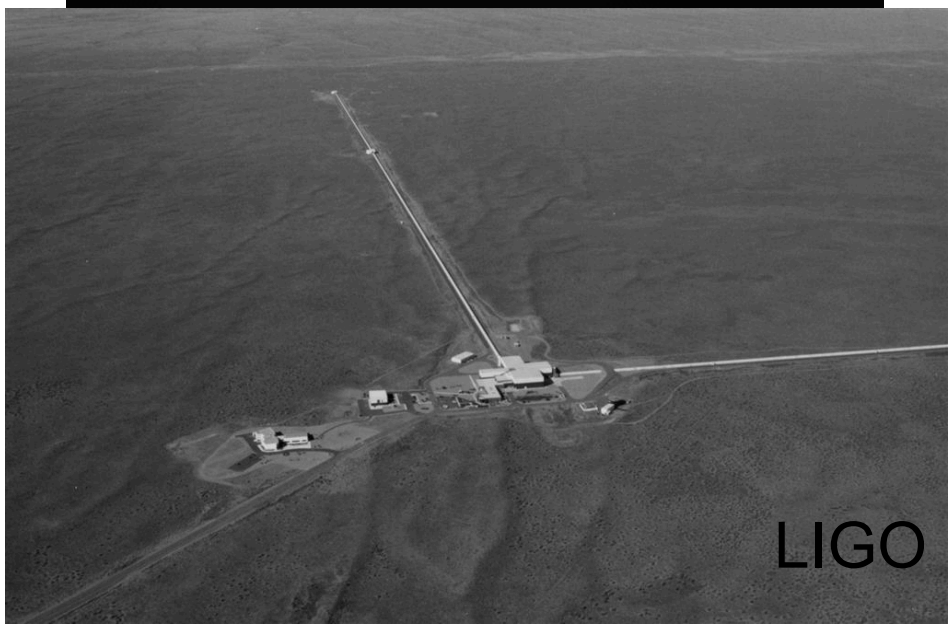
Future Tests

- Event Horizon Telescope: first test of GR in the strong field regime.

- LIGO: observation of gravitational waves from merging neutron stars and black holes.

- Both soon: 5-10 years.





Practical Relativity

Global Positioning System (GPS)

- 24 satellites in high Earth orbit
- 20,000km altitude, 12^h period (14,000 km/h)
- Carry on-board atomic clocks

Relativistic effects on these clocks:

- Special Relativity: 7 sec/day *slower*
- General Relativity: 45 sec/day *faster*

Combined correction: 45–7 = 38 sec/day

There is no absolute time or space.

Common Sense & Relativity

"Common Sense is the collection of prejudices acquired by the age of 18."

Albert Einstein