MEASURING DISTANCES IN ASTRONOMY

Basic Principles:

- **Geometric methods**
- **Standard candles**
- **Standard rulers**

[the last two methods relate quantities that are independent of distance to quantities that depend on distance]

Parallax and Proper Motion

- Angular size: degree [º], arcminute ['], arcsecond ["]

- θ [in arcseconds] = 206265 (L/D)

  where: θ = angular size; L = linear (or "true") size; D = distance

- Definitions: parallax (p), Astronomical Unit [AU], parsec [pc]

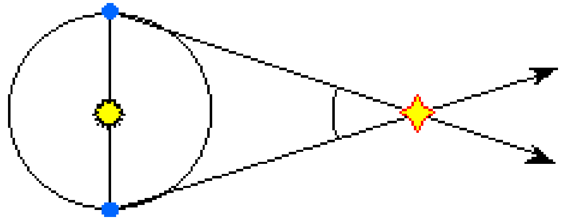
  D [in parsec] = 1/p [in arcseconds]

  where: 1 pc = 206265 AU = 3.26 light yr

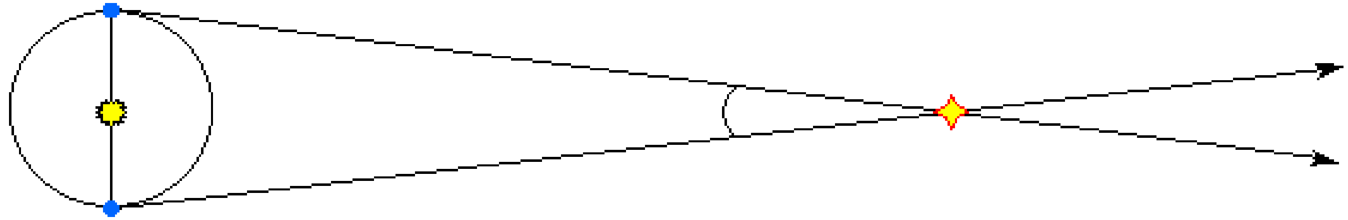
- Parallax can only be used on nearby stars (D < 100 pc)

  [Atmospheric blurring (seeing); Hipparcos satellite; Hubble Space Telescope]

Closer stars have *larger* parallaxes:



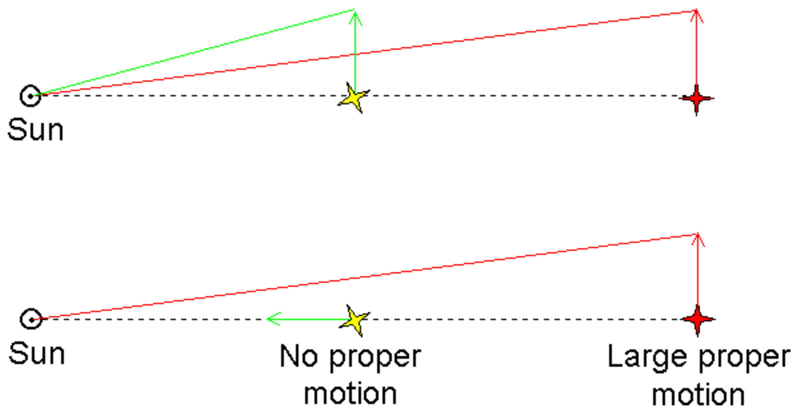
Distant stars have *smaller* parallaxes:



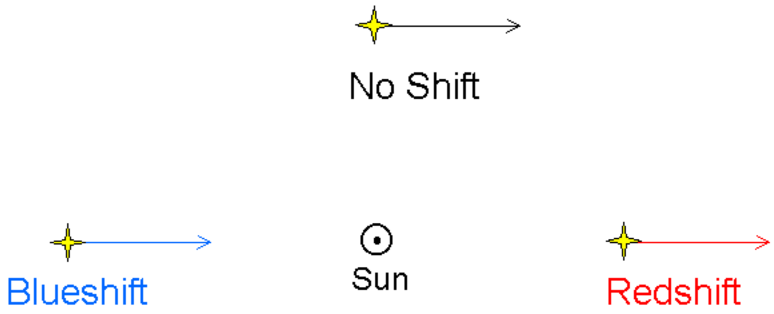
Motion of stars within a cluster

- Proper motion [arcsec/s] = change of angular position
- Line-of-sight motion [km/s] - measured via Doppler shift
- Comparison of average stellar proper motion in cluster with average line-of-sight speed yields distance to cluster

Proper Motions



Radial Velocities



Luminosity and Flux

- Inverse square law: $f = L / (4\pi D^2)$

  where: f = flux [erg/s/cm^2]; L = luminosity [erg/s]; D = distance [cm]

- Magnitude scale: brightnesses of astronomical sources

Standard Candles and Rulers

- Variable stars: Cepheids and RR Lyrae stars
  Period-luminosity relation; measure P & infer L; measure f & infer D

- Other standard candles: brightest red giants, HII regions, planetary nebulae, supernovae, globular cluster luminosity

- Galaxies: Luminosity is seen to be correlated with the typical speed of internal motion of stars and gas
  - [Tully-Fisher relation: rotation of disks of spiral galaxies]
  - [Faber-Jackson relation: random stellar motion in elliptical galaxies]

- Galaxies: Size correlated with typical speed of (random) stellar motion
  - [D_n-σ relation for elliptical galaxies]

Redshift as Distance Indicator

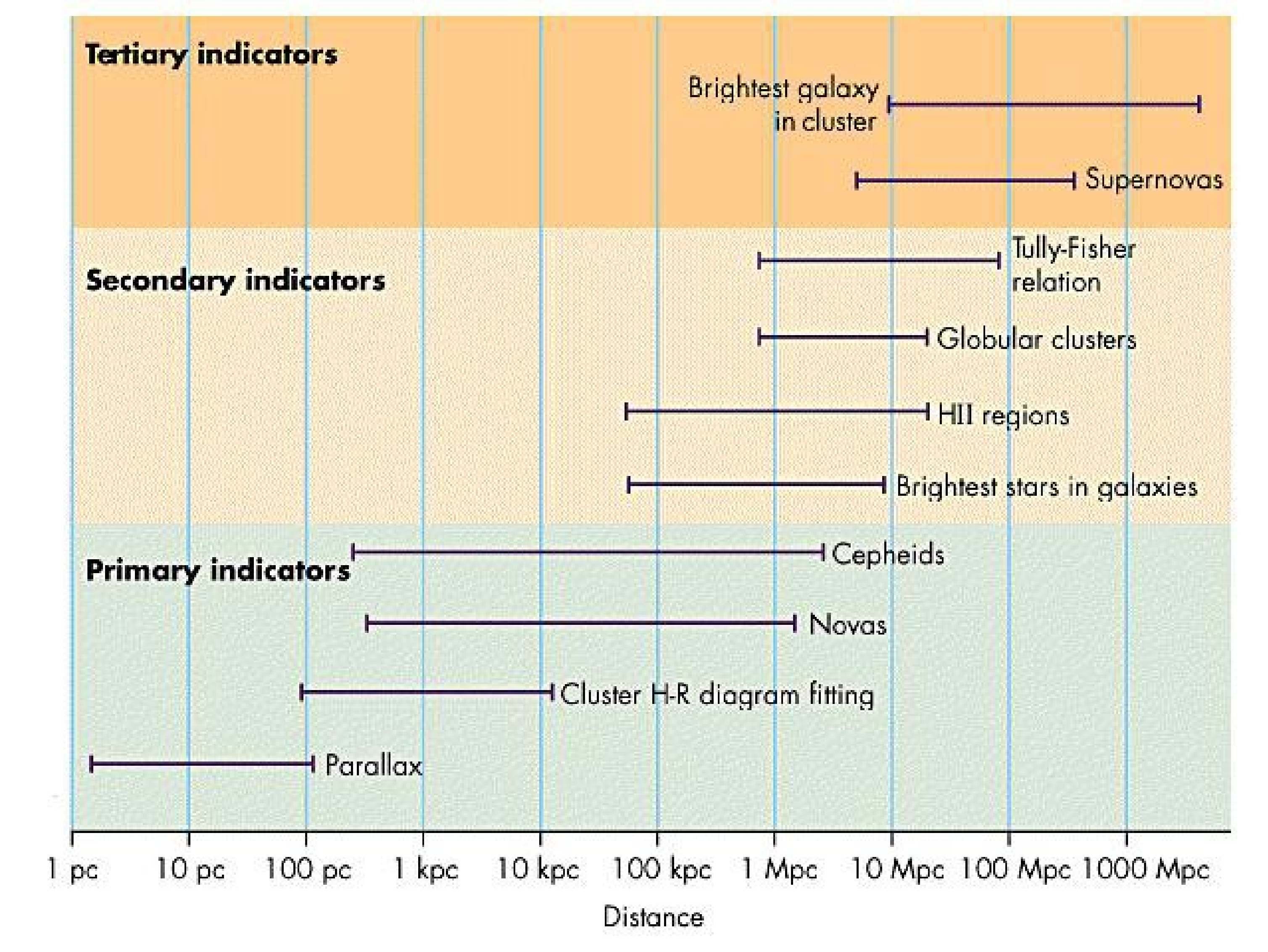
- Expansion of the Universe
- Hubble's law: $v = H_0 D$

  where: H_0 = Hubble constant [km/s/Mpc]
- Doppler shift used to measure recession velocity:

  $$v \approx c\,(\Delta\lambda / \lambda)$$

  where: $\Delta\lambda/\lambda$ = fractional change in wavelength

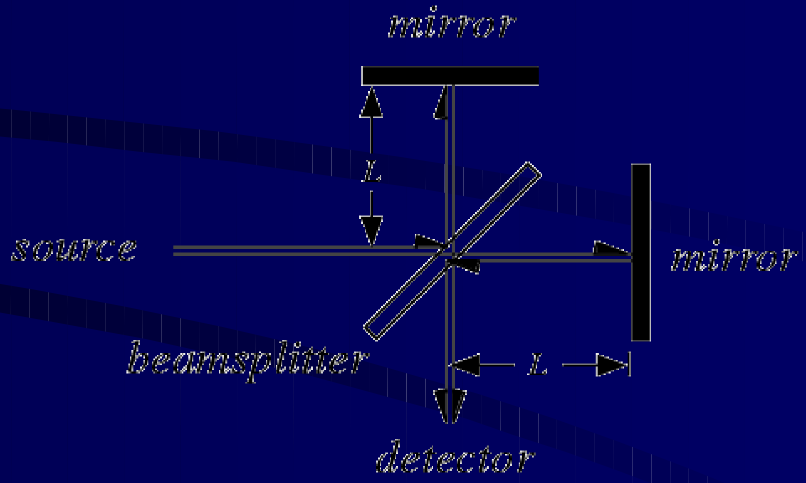
Astronomical Distance Ladder



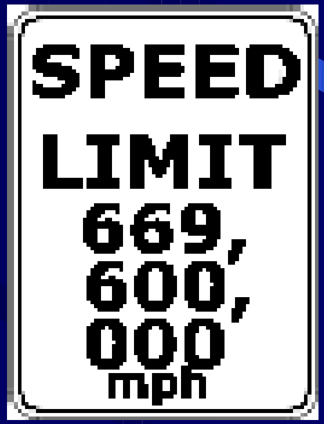
Special Theory of Relativity (STR)

- Speed of light (in vacuum): c = 300,000 km/s

- Constancy of the speed of light: Michelson & Morley experiment



- No signal or object can travel faster than c [The ultimate speed limit!]



Special Theory of Relativity (STR)

Basic Principles

- The speed of light is the same to all observers
- The laws of physics are the same to all observers

Observable Consequences

- Simultaneity is a relative concept
- Length contraction: moving rulers appear to be short
- Time dilation: moving clocks appear to run slow
- The apparent mass (inertia) of an object increases as its speed increases (impossible to accelerate it up to c)
- Equivalence of mass and energy: $E = mc^2$

Special relativistic effects are important when the SPEED of an object is CLOSE TO THE SPEED OF LIGHT: $v \approx c$

Simultaneity and time are relative, not absolute

A

B

Marion Jones sees A and B flash simultaneously

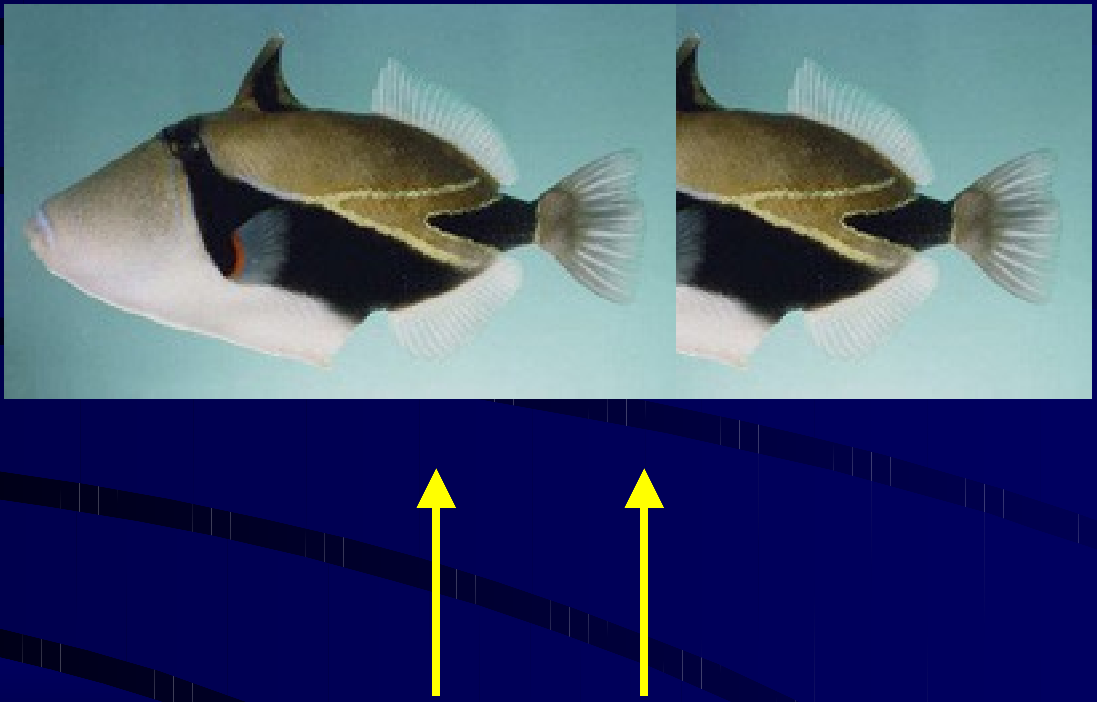
A

B

Marion Jones sees A flash before B

Measuring the length of a moving object:

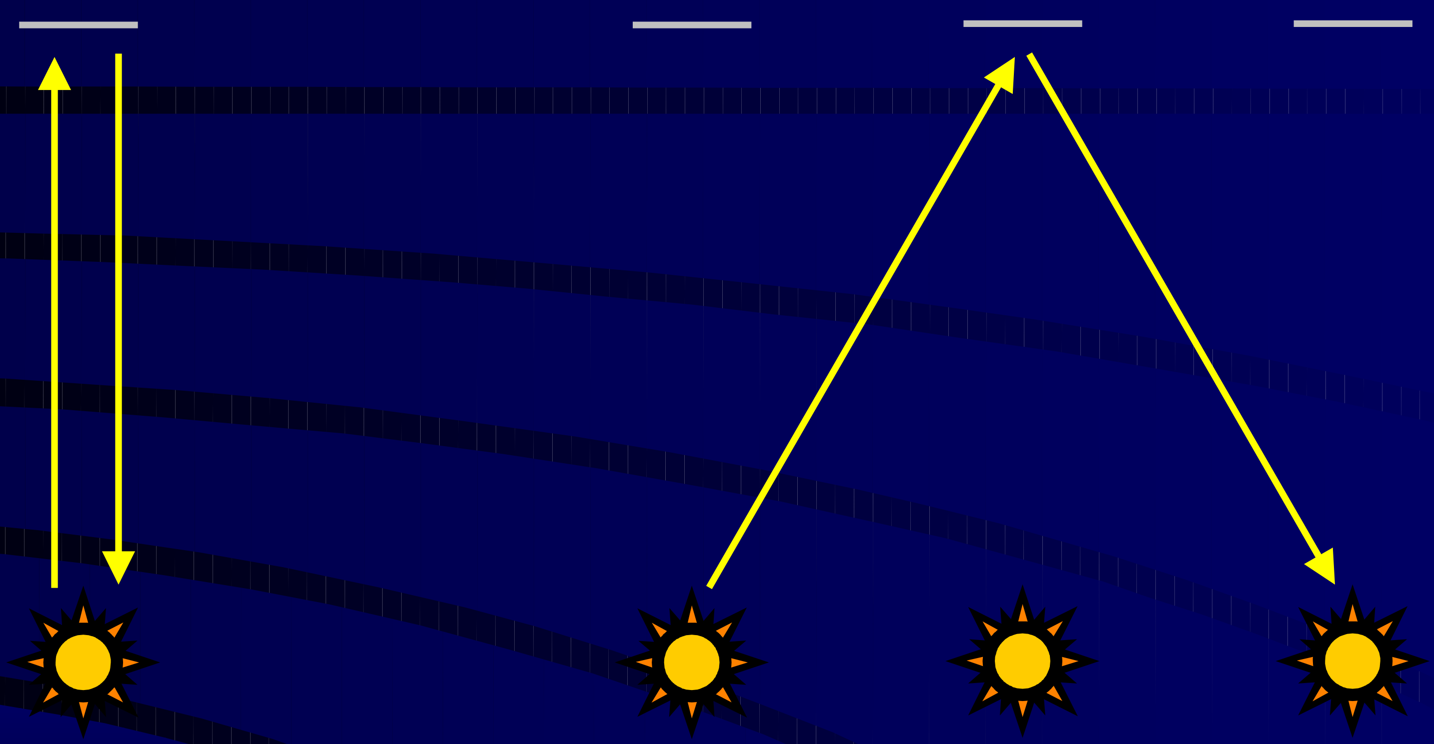
Length Contraction



The apparent (i.e., measured) length of a moving object is shorter than the “true” length (measured when the object is at rest)

Measuring time on a moving clock:

Time Dilation



Stationary Clock

Moving Clock

A moving clock runs slower than its counterpart at rest

A Thought Experiment:

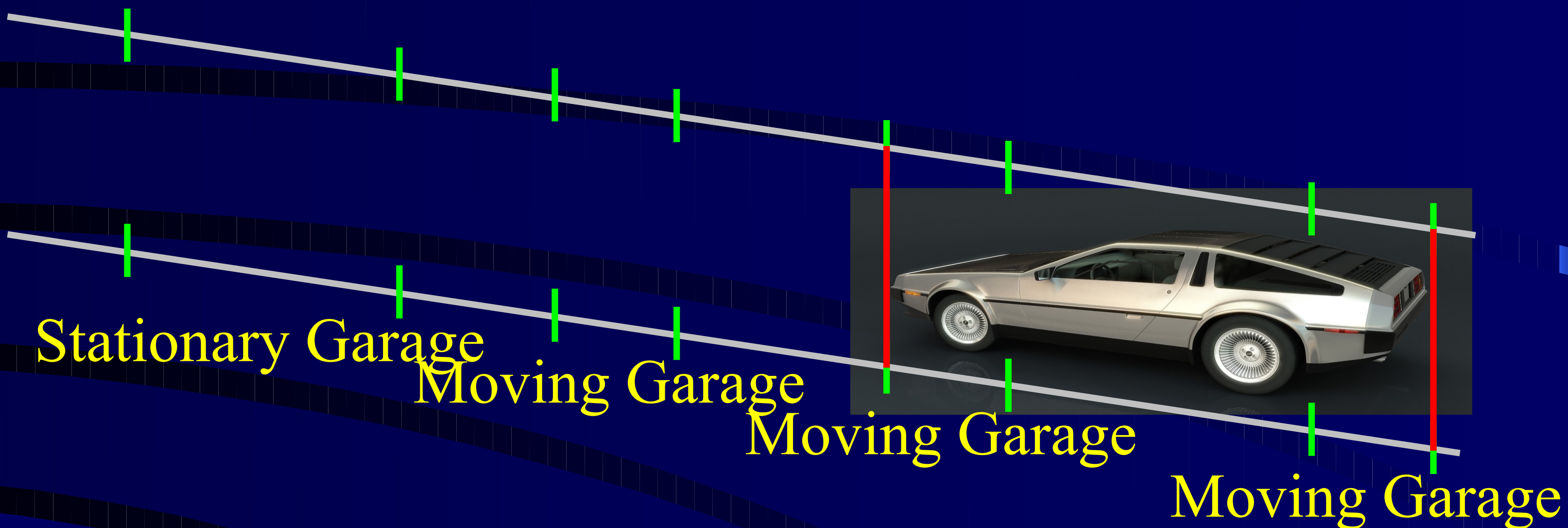
Length Contraction and an Apparent Paradox

The Garage Attendant's Perspective

A Thought Experiment:

Length Contraction and an Apparent Paradox

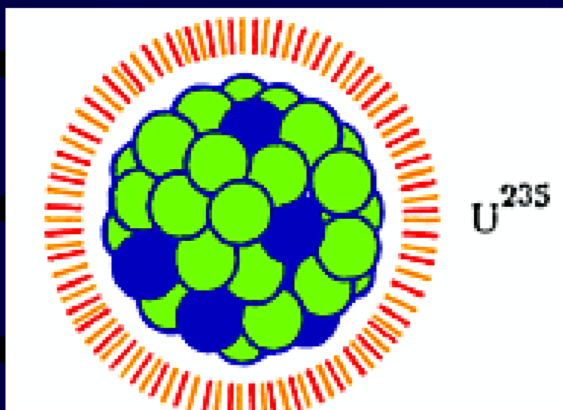
The Driver's Perspective



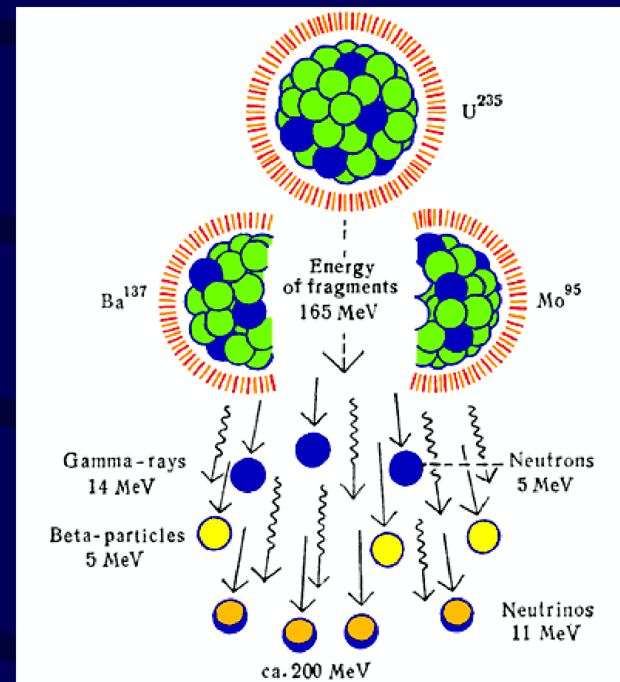
Solution: The driver and garage attendant do <u>not</u> agree on the question of whether the two doors were closed simultaneously

A Real Laboratory Experiment:

Direct Verification of Time Dilation and Length Contraction as Predicted by the Special Theory of Relativity



Beam of fast-moving Uranium atoms



Nuclear fission of Uranium atoms

Suitably placed Geiger counter

The scientist in the laboratory witnesses time dilation, while the Uranium atoms "witness" length contraction

General Theory of Relativity (GTR)

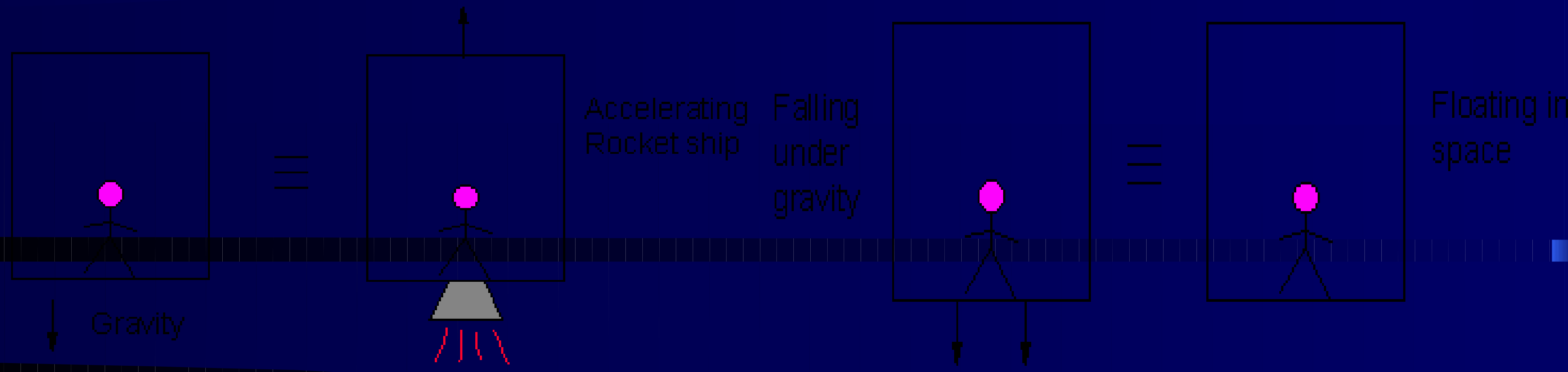
Principle of Equivalence

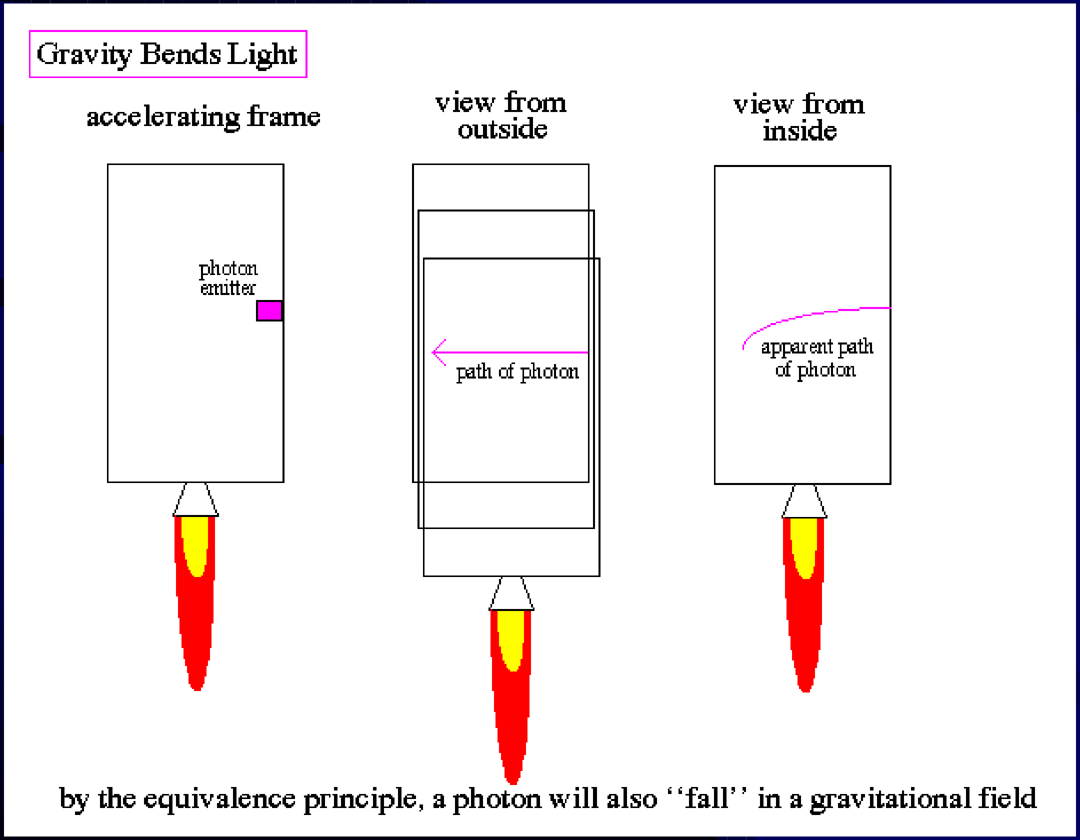
- All objects experience the same motion in a given gravitational field, irrespective of their mass

  [Galileo's experiment at the leaning tower of Pisa]

- Gravitational field <===> Accelerated reference frame

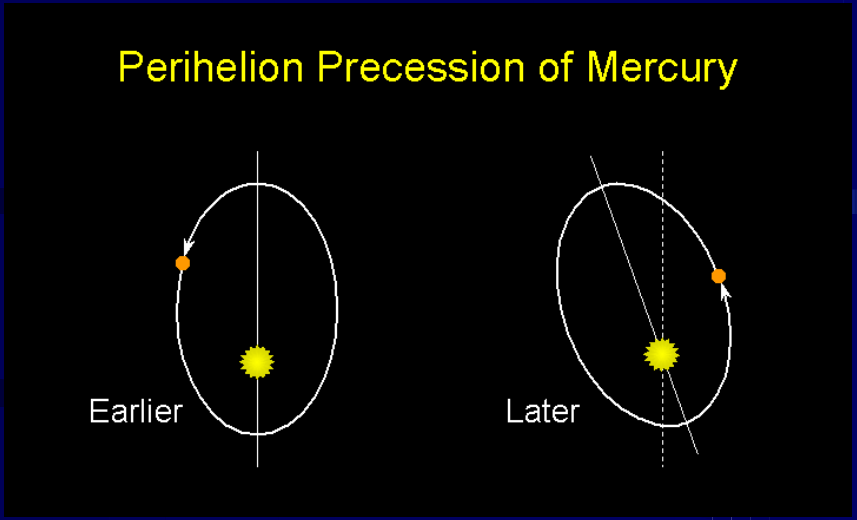
- Gravity can be thought of as a distortion of space-time


Gravity
≡
Accelerating Rocket ship
Falling under gravity
≡
Floating in space

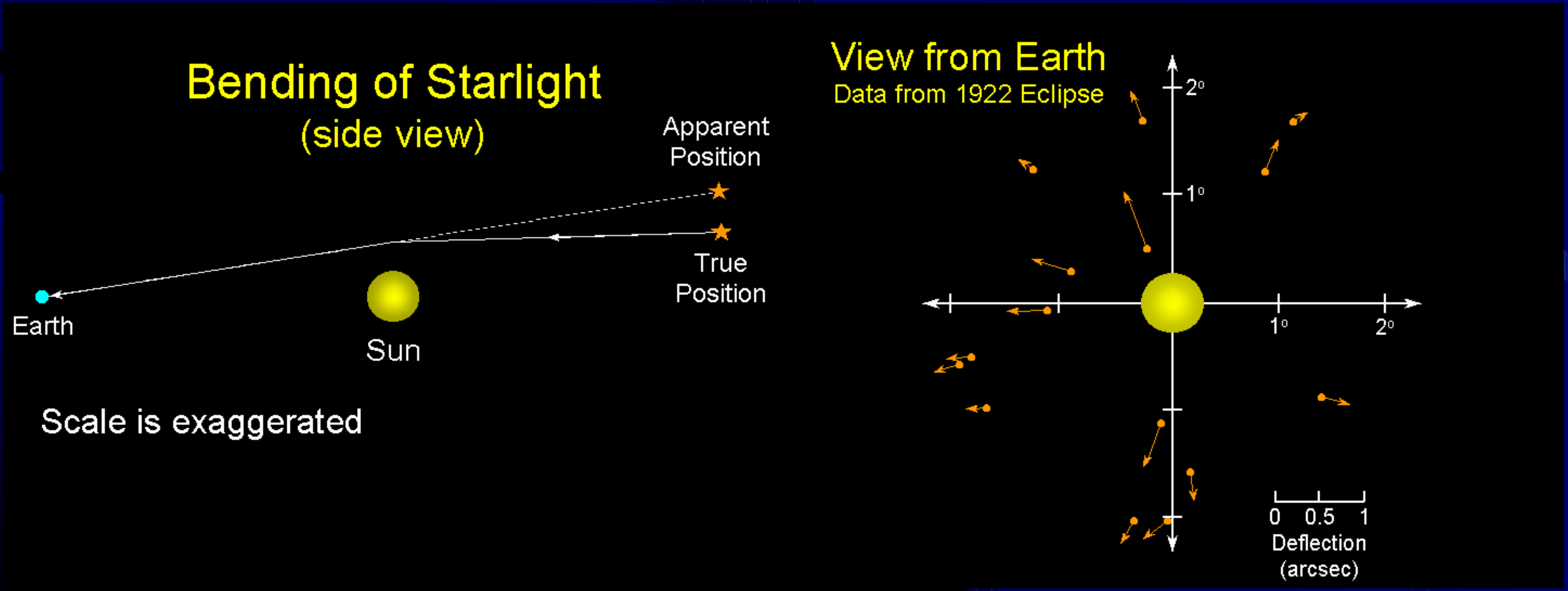

Gravity Bends Light
accelerating frame
photon emitter
view from outside
path of photon
view from inside
apparent path of photon
by the equivalence principle, a photon will also ''fall'' in a gravitational field

Observable Consequences of GTR

- Perihelion precession of Mercury



- Light bending:
  Solar eclipse experiment

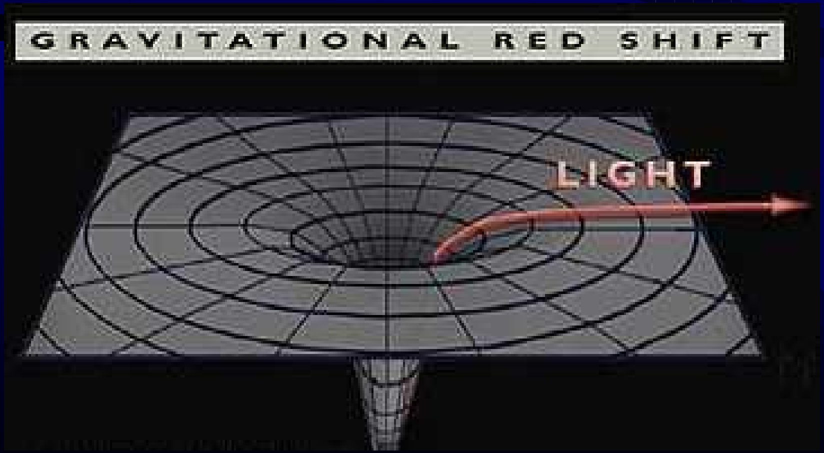


- Gravitational lensing:

  Multiple images,
  image distortion

- Gravitational Redshift

  [Extreme case: light is "trapped" in a black hole]



General relativistic effects are important in a STRONG GRAVITATIONAL FIELD