Reach for the Stars

Dr Martin Hendry

SUPA, Department of Physics and Astronomy
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New Higher Physics modules

Our Dynamic Universe

- **Equations of Motion**
- **Forces, Energy and Power**
- **Collisions and Explosions**
- **Gravitation**
- **Special Relativity**
- **The Expanding Universe**
- **The Big Bang Theory**

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links to current astrophysics research

1. Gravitation

"You may hate gravity, but gravity doesn't care"

Clayton Christensen

Fundamental to many current research topics:

- The search for extra-solar planets
- The search for gravitational waves

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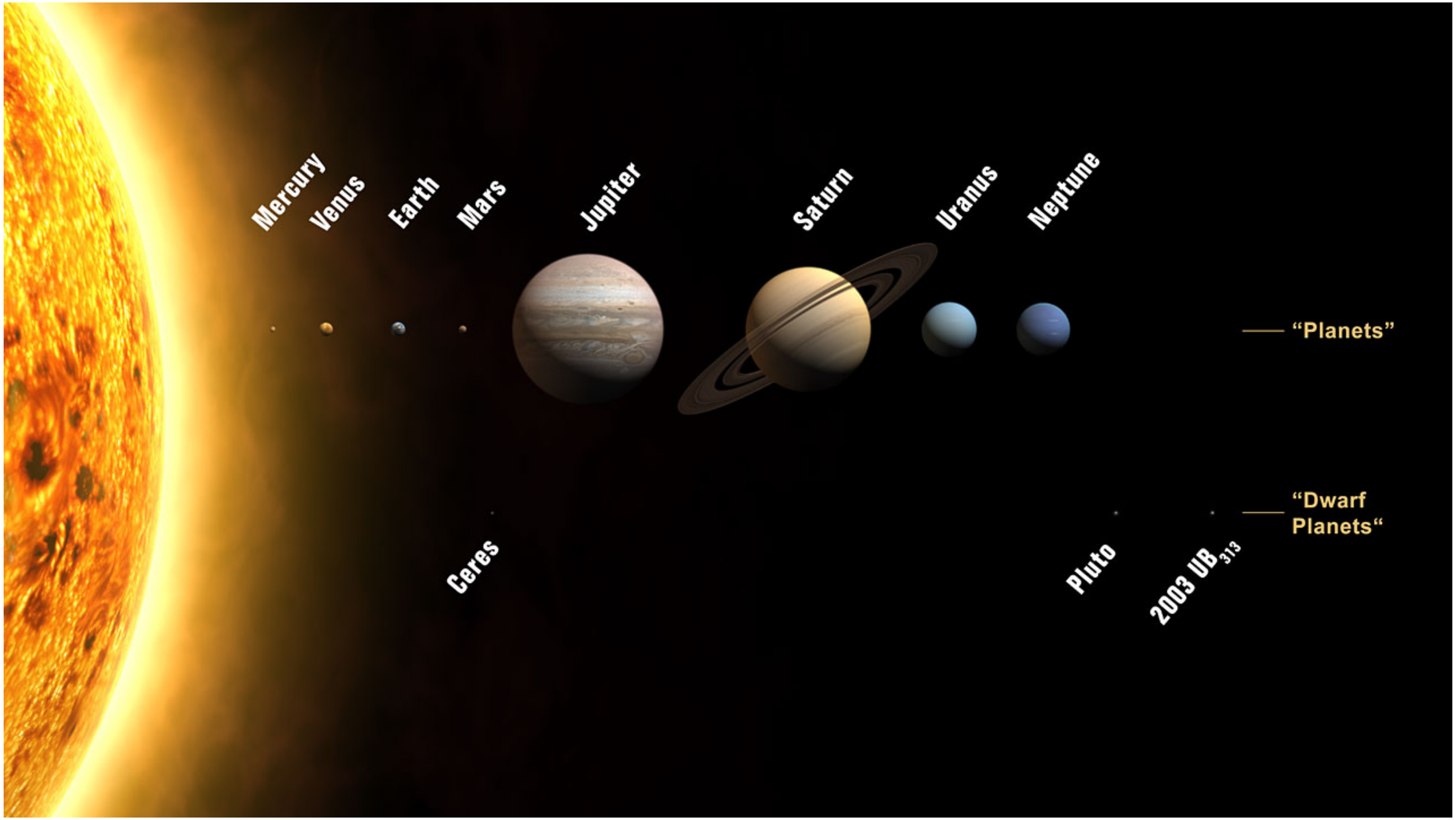
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
"Planets"
"Dwarf Planets"
Ceres
Pluto
2003 UB313

Extra-Solar Planets

- *One of the most active and exciting areas of astrophysics*
- **Over 400 exoplanets discovered since 1995, and number growing rapidly**

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Some Important Questions

- **How common are planets?**
- **How did planets form?**
- **Can we find Earth-like planets?**

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1. How can we detect extra-solar planets?

- Planets don't shine by themselves; they just reflect light from their parent star

$\Rightarrow$ Exoplanets are very ***faint***

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1. How can we detect extra-solar planets?

- Planets don't shine by themselves; they just reflect light from their parent star

$\Rightarrow$ Exoplanets are very *faint*

- We measure the intrinsic brightness of a planet or star by its **luminosity**

Luminosity, L *(watts)*

Luminosity varies with wavelength

e.g. consider Rigel *and* Betelgeuse in Orion

Luminosity varies with wavelength

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Adding up L at all wavelengths

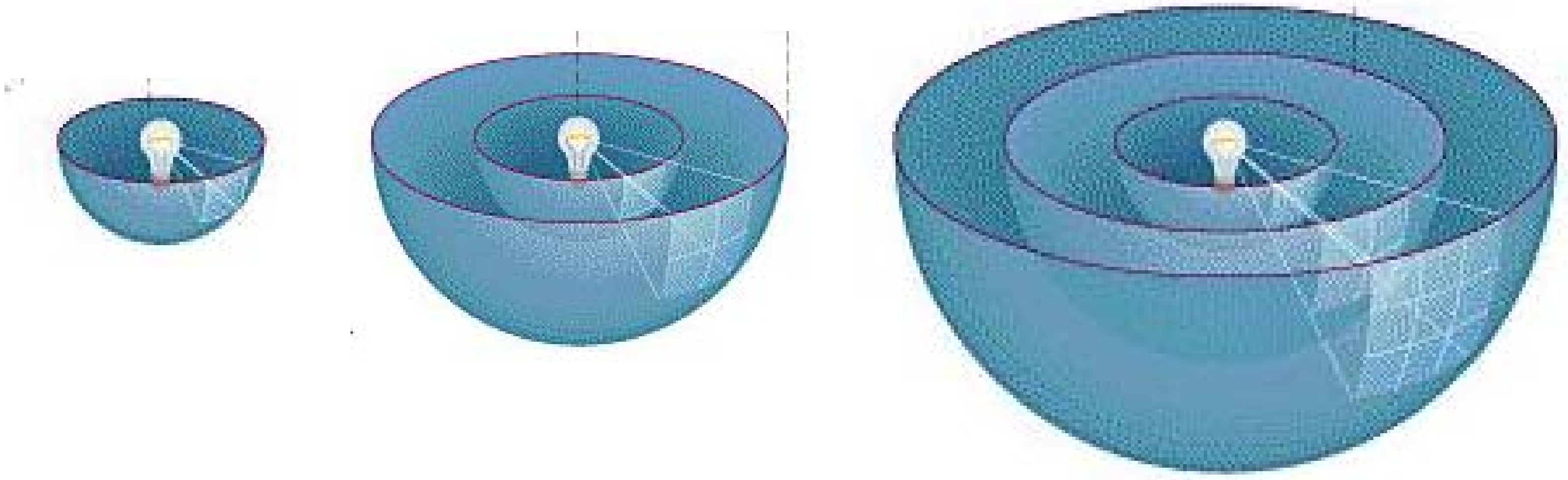
$\Rightarrow$ Bolometric luminosity

e.g. for the Sun

$$L_{\text{bol}} = 4 \times 10^{26}\ \text{W}$$

Stars radiate **isotropically**
(equally in all directions)

$\Rightarrow$ at distance r, luminosity spread over surface area $4\pi r^2$



*(this gives rise to the **Inverse-Square Law**)*

Planet, of radius R, at distance r from star

Intercepts a fraction of L_S

$$f = \frac{\pi R^2}{4\pi r^2} = \left(\frac{R}{2r} \right)^2$$

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$$f = \frac{\pi R^2}{4\pi r^2} = \left(\frac{R}{2r}\right)^2$$

Assume planet reflects *all* of this light

$$\Rightarrow \quad \frac{L_P}{L_S} = \left(\frac{R}{2r}\right)^2$$

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Examples

Sun - Earth:

$$R = 6.4\times10^{6}\ \text{m}$$

$$r = 1.5\times10^{11}\ \text{m}$$

$$\Rightarrow \quad \frac{L_{\text{P}}}{L_{\text{S}}} = 4.6\times10^{-10}$$

Examples

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Sun - Jupiter:

$$R = 7.2\times10^{7}\ \text{m} \qquad r = 7.8\times10^{11}\ \text{m} \quad \Rightarrow \quad \frac{L_\text{P}}{L_\text{S}} = 2.1\times10^{-9}$$

2nd problem:

Angular separation of star and exoplanet is **tiny**

Distance units

Astronomical Unit = mean Earth-Sun distance

$$1 \text{A.U.} = 1.496 \times 10^{11} \text{ m}$$

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For interstellar distances: **Light year**

$$1\ \text{light year} = 9.461 \times 10^{15}\ \text{m}$$

e.g. 'Jupiter' at 30 l.y.

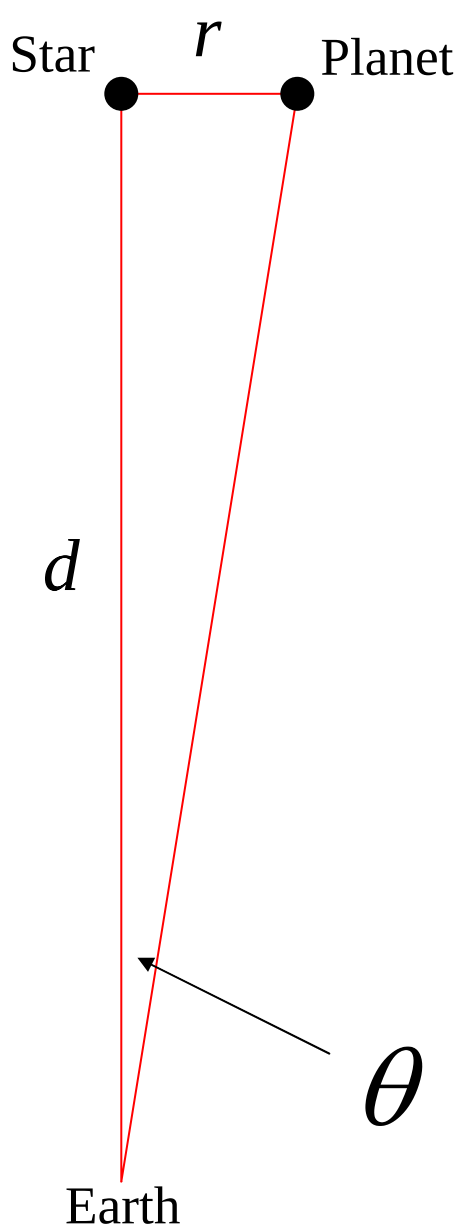
$$d = 30\,\text{l.y.} = 2.8 \times 10^{17}\ \text{m}$$

$$r = 5\,\text{A.U.} = 7.5 \times 10^{11}\ \text{m}$$

$$\tan\theta \cong \theta = \frac{r}{d}$$

$$\theta = 2.7 \times 10^{-6}\ \text{radians}$$

$$= 1.5 \times 10^{-4}\ \text{deg}$$



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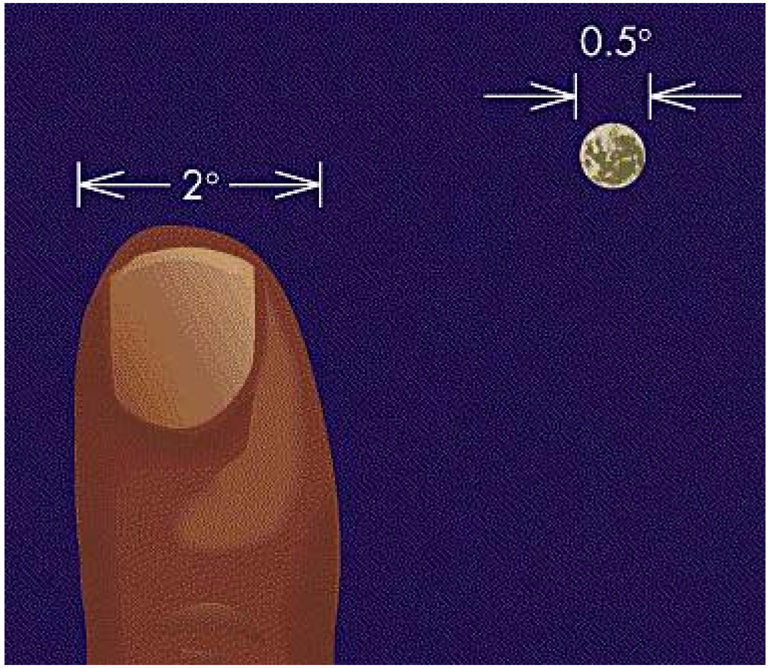

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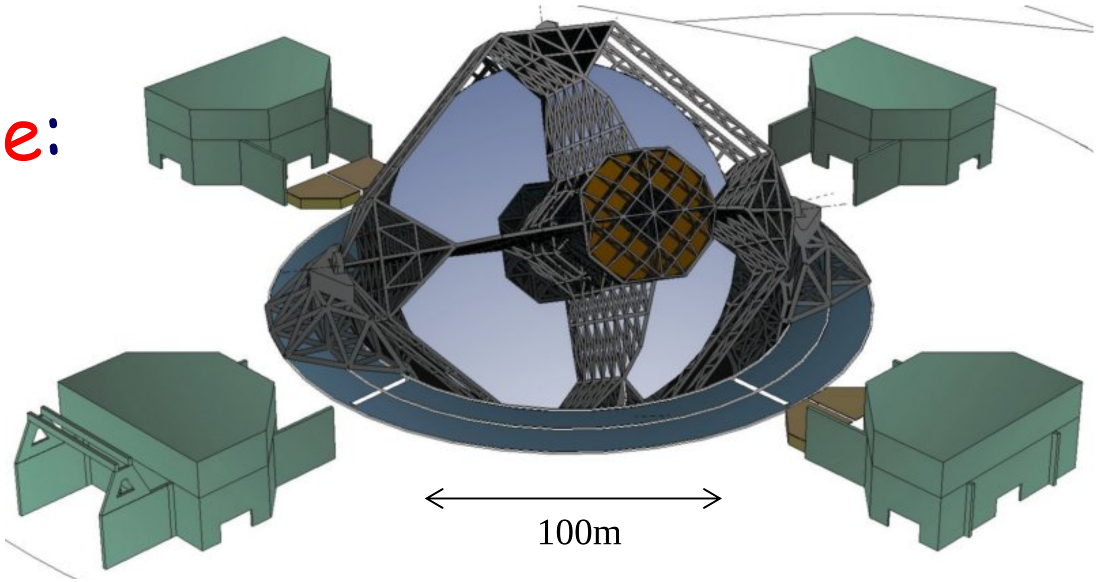
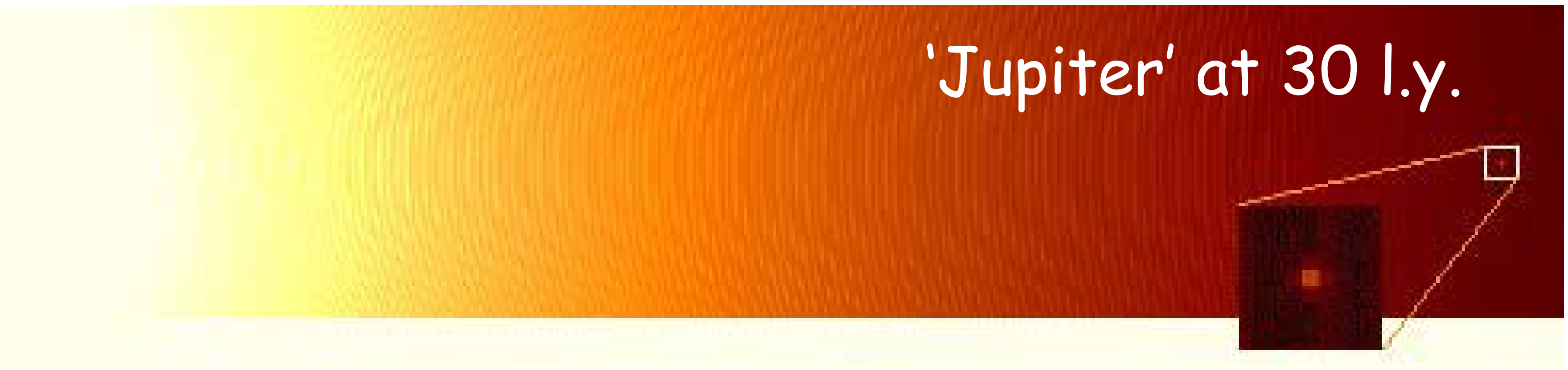
Need OWL telescope:

100m mirror, planned for next decade?





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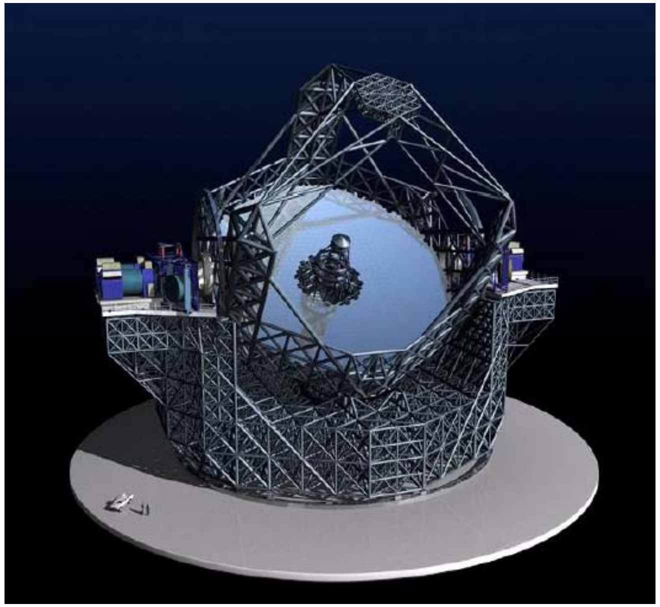

Need ELT:

30 - 50m mirror, planned for 2025

1. How can we detect extra-solar planets?

- They cause their parent star to 'wobble', as they orbit their common centre of gravity

Johannes Kepler

Isaac Newton

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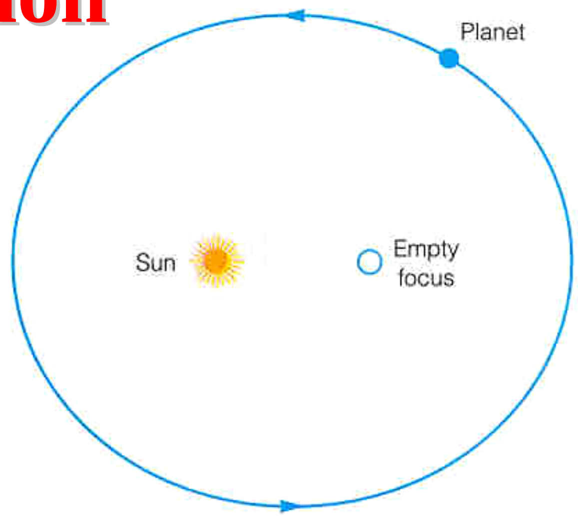
Kepler's Laws of Planetary Motion

1) **Planets orbit the Sun in an ellipse with the Sun at one focus**



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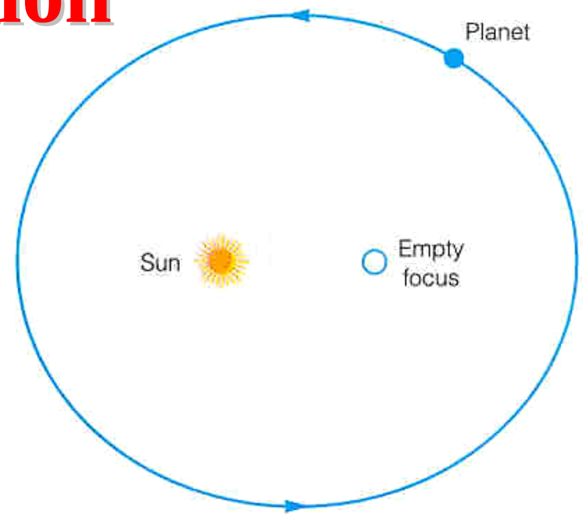
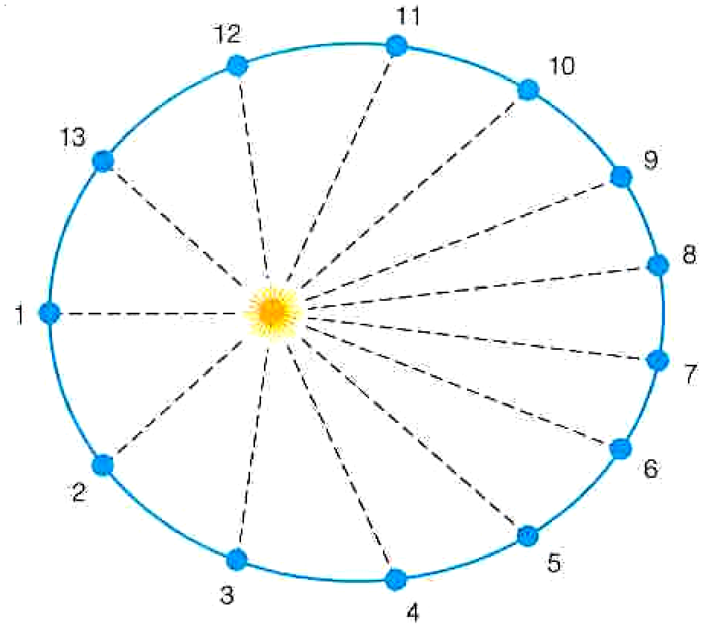


2) During a planet's orbit around the Sun, equal areas are swept out in equal times



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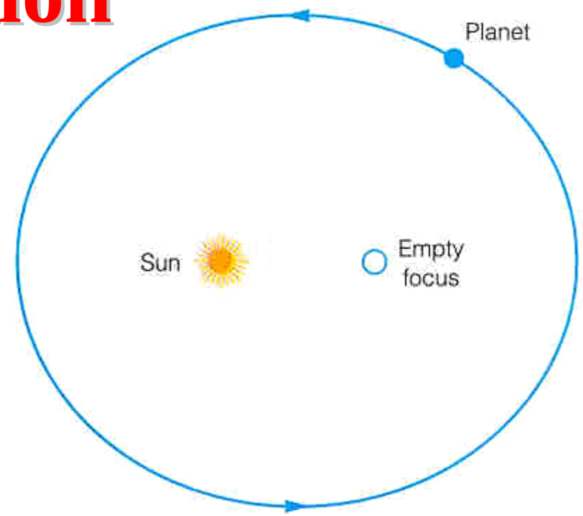

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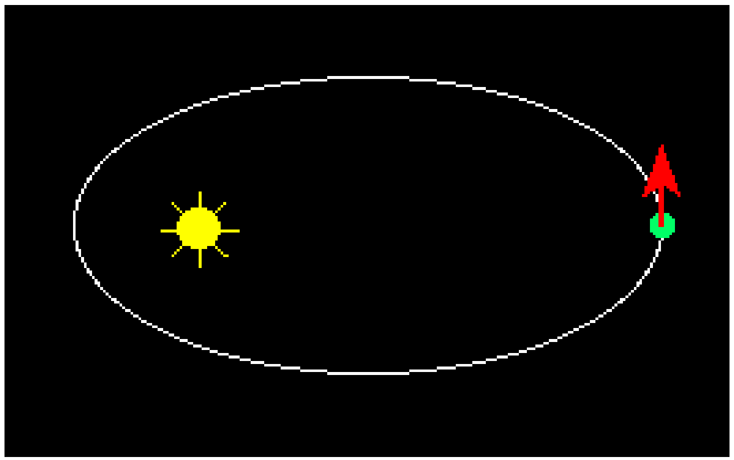
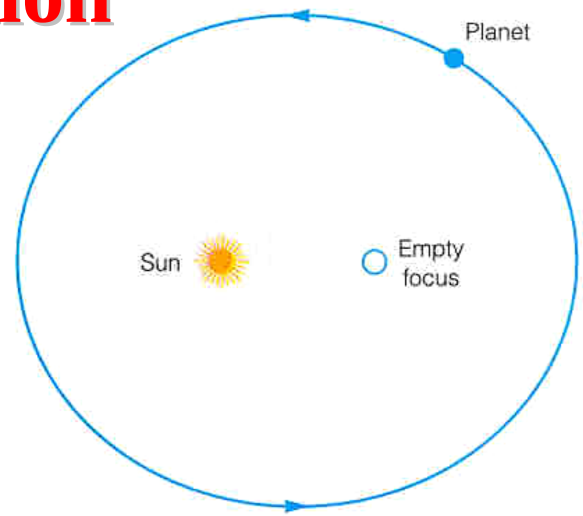


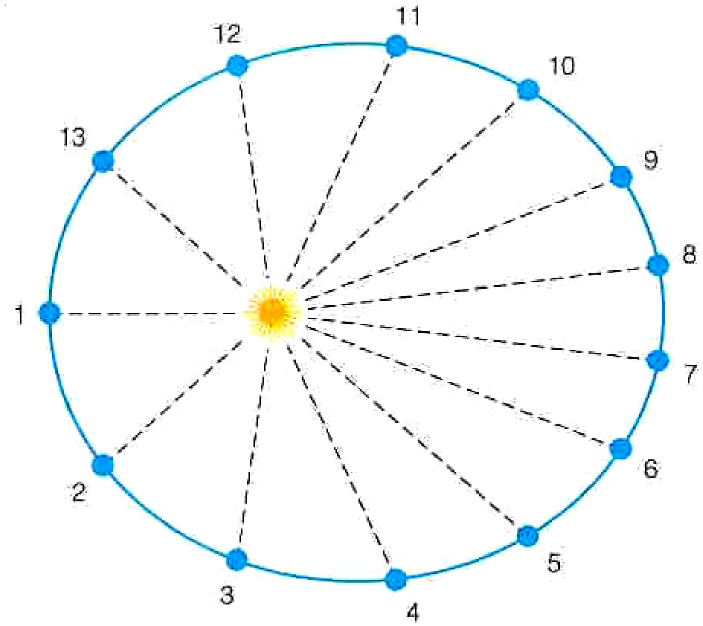
Kepler's Laws of Planetary Motion

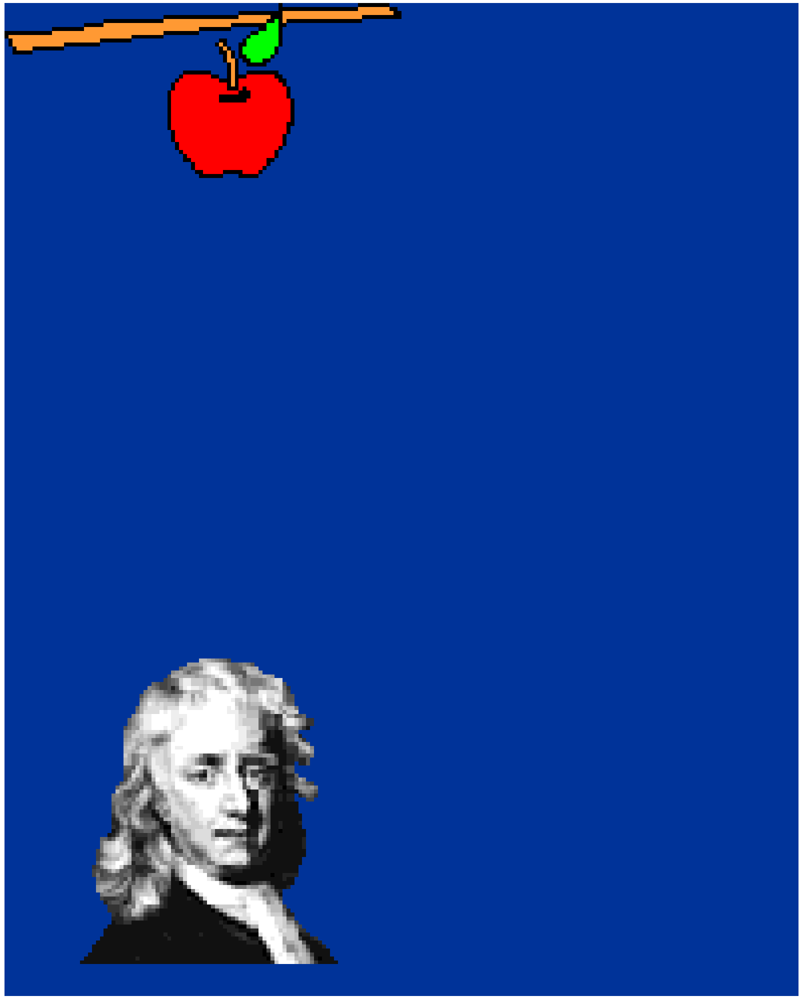
1) Planets orbit the Sun in an ellipse with the Sun at one focus

2) During a planet's orbit around the Sun, equal areas are swept out in equal times

3) The square of a planet's orbital period is proportional to the cube of its mean distance from the Sun



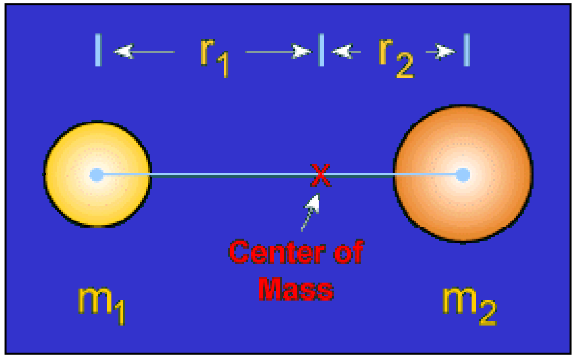




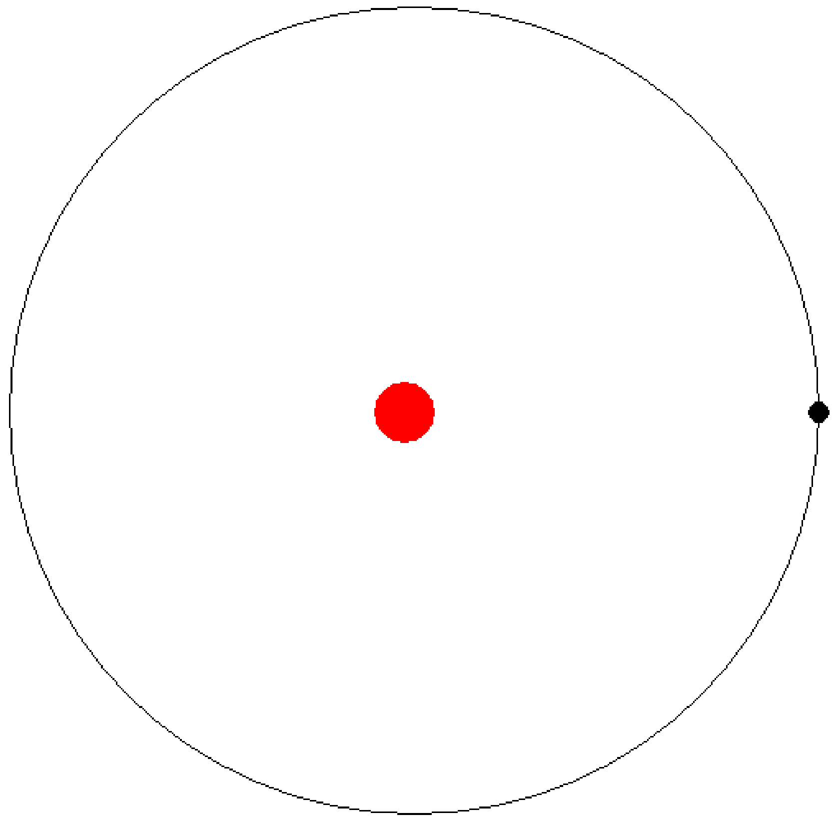
Newton's law of Universal Gravitation,
Published in the Principia: 1684 - 1686

Newton's gravitational force provided a physical explanation for Kepler's laws

$$F_G = \frac{G\, m_1\, m_2}{r^2}$$



Star + planet in circular orbit about centre of mass, ⊥ to line of sight



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Can see star 'wobble', even when planet is unseen.

But how large is the wobble?…

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Centre of mass condition

$$m_1 r_1 = m_2 r_2$$

$$r = r_S + r_P = r_S \left(1 + \frac{m_S}{m_P} \right)$$

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Can see star 'wobble', even when planet is unseen.

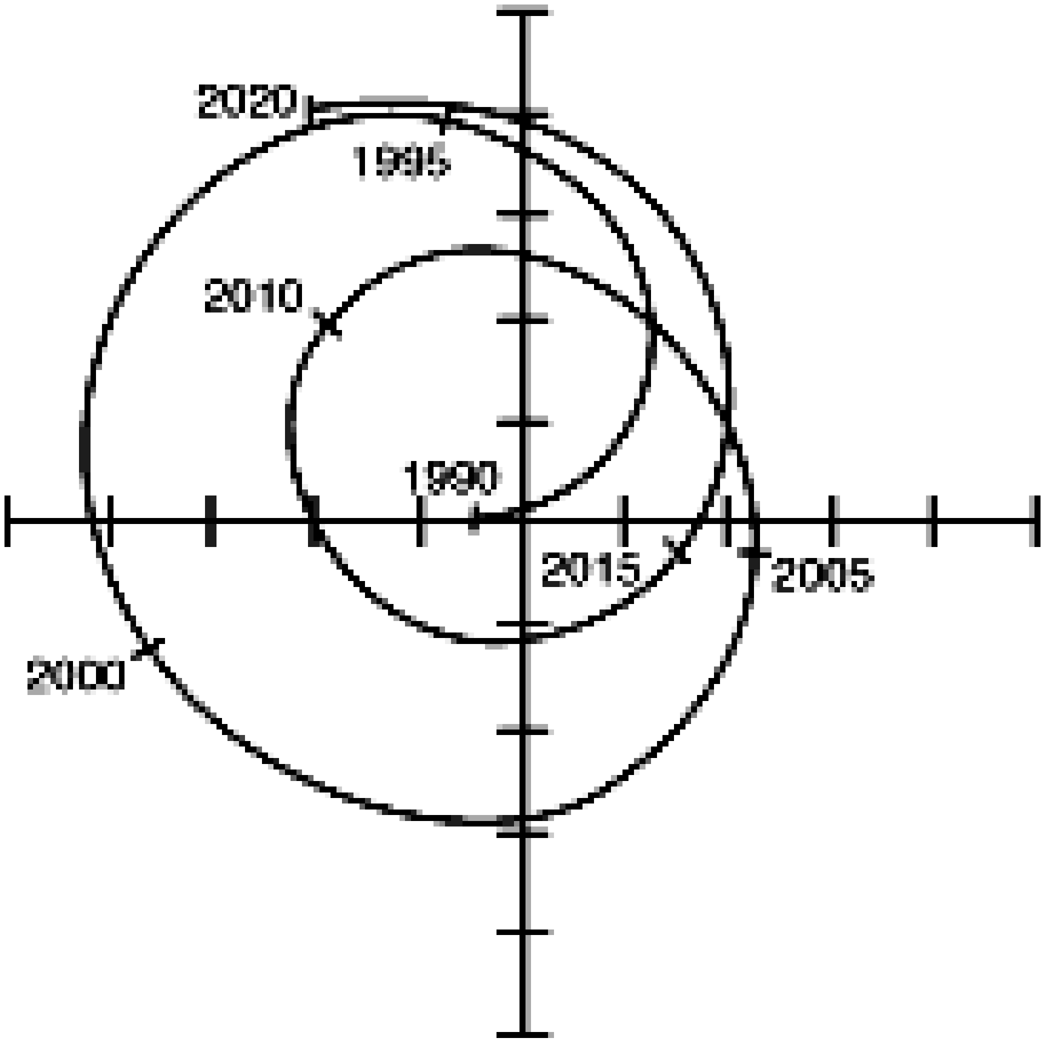
e.g. 'Jupiter' at 30 l.y.

$$m_S = 2.0 \times 10^{30} \text{ kg}$$

$$m_P = 1.9 \times 10^{27} \text{ kg}$$

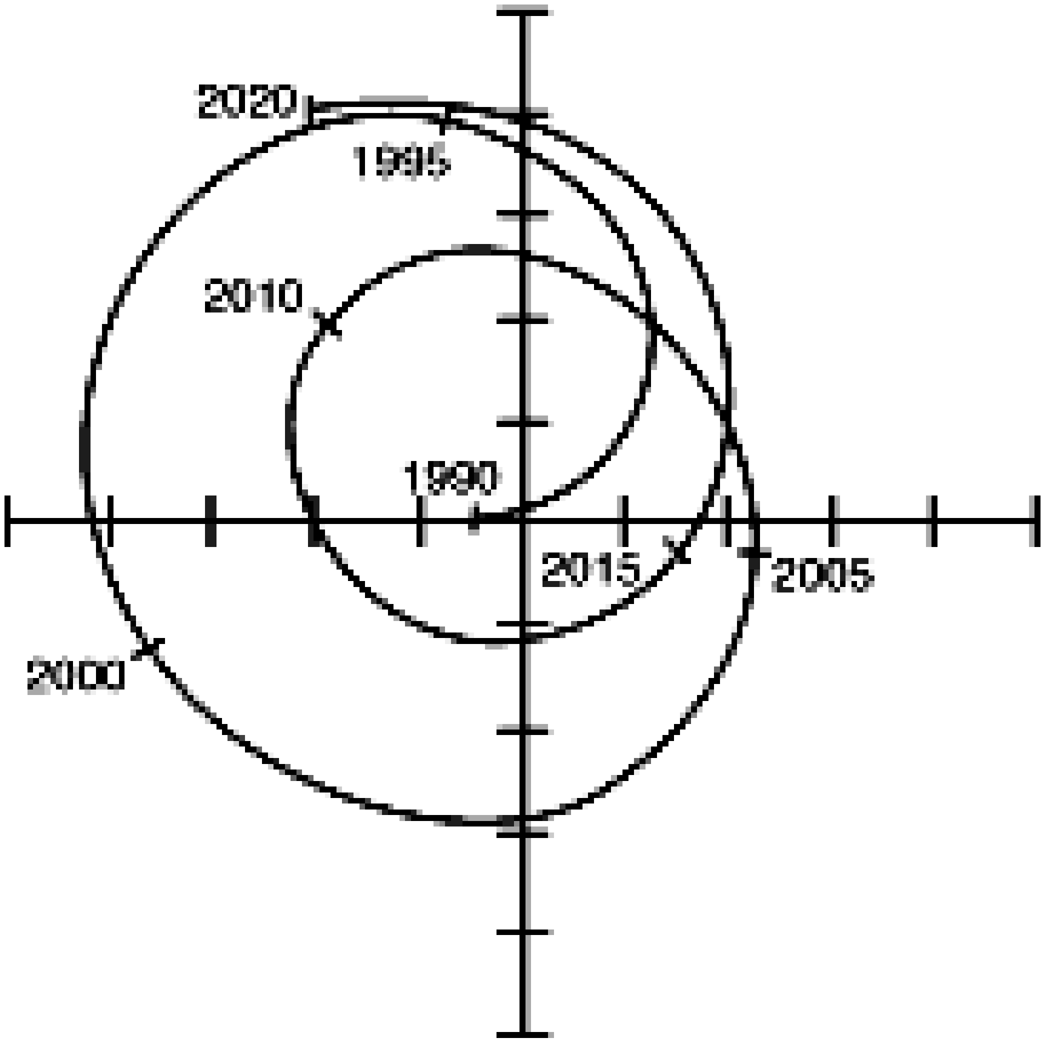
But how large is the wobble?...

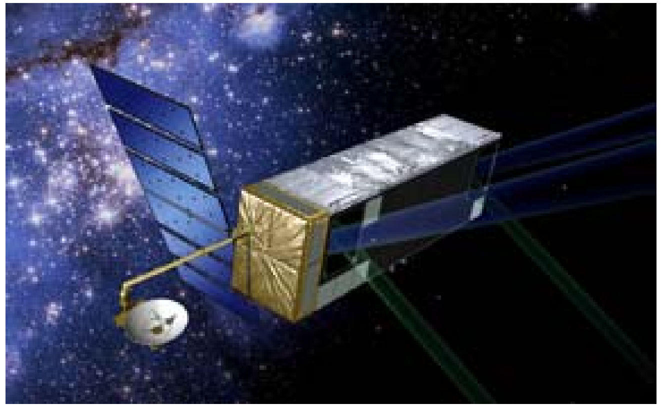
$$\theta_S \cong \frac{r_S}{d} = 1.5 \times 10^{-7} \text{ deg}$$



Width of a 5p piece, seen from a distance of nearly 7000km,

or the width of a hula hoop on the surface of the Moon…

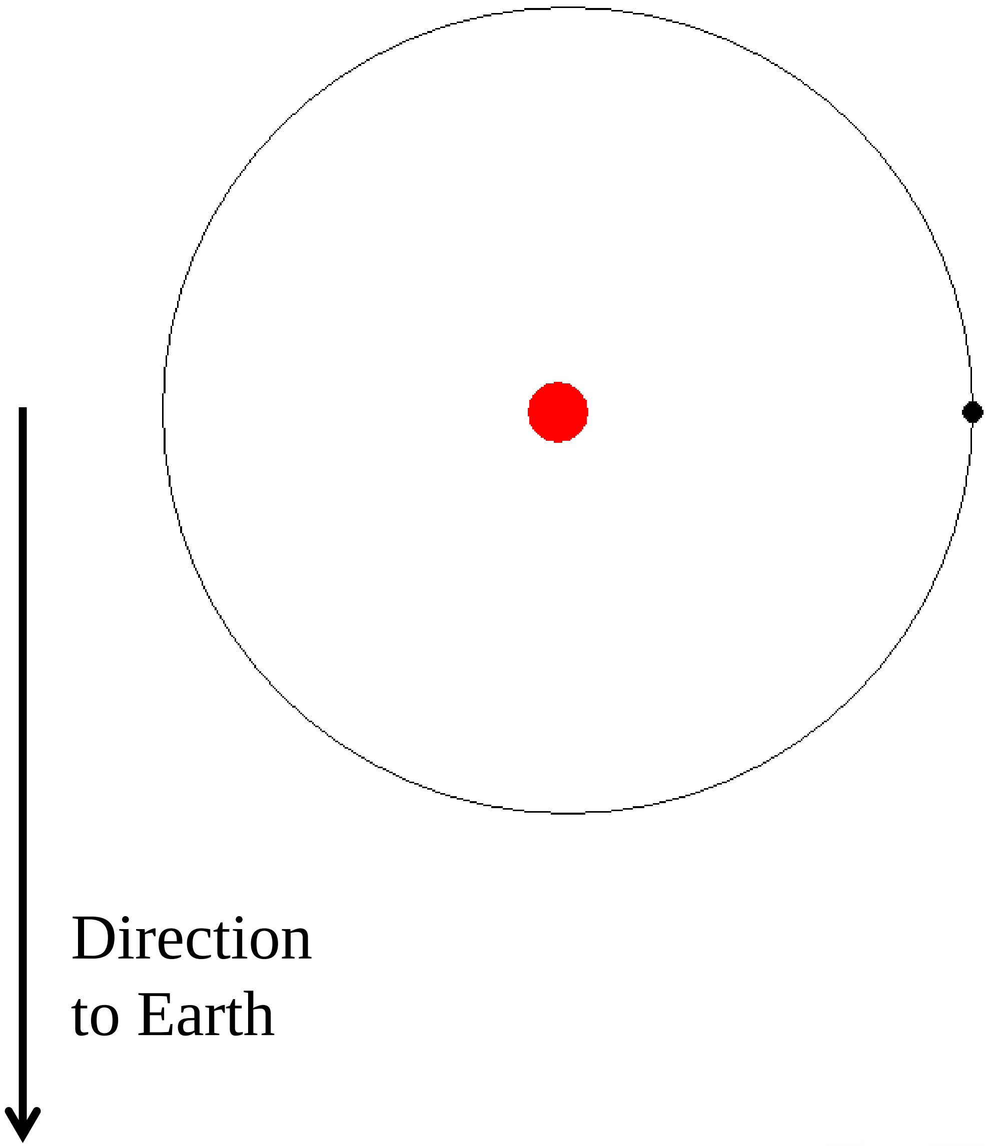




Detectable routinely with
SIM Lite
(launch date 2020?)
but ***not*** currently

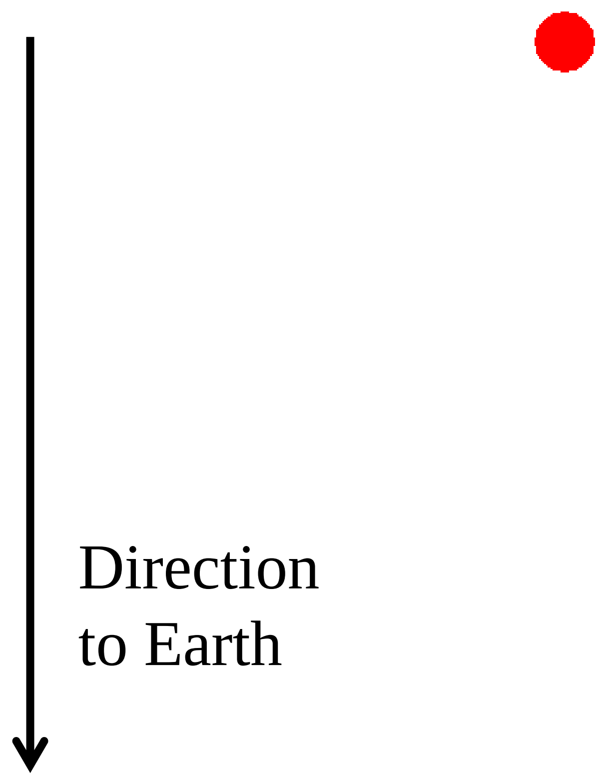
See www.planetquest.jpl.nasa.gov/SIM/

Suppose line of sight is in orbital plane



Suppose line of sight is in orbital plane

Star has a periodic motion towards and away from Earth – radial velocity varies *sinusoidally*



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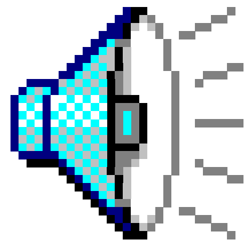
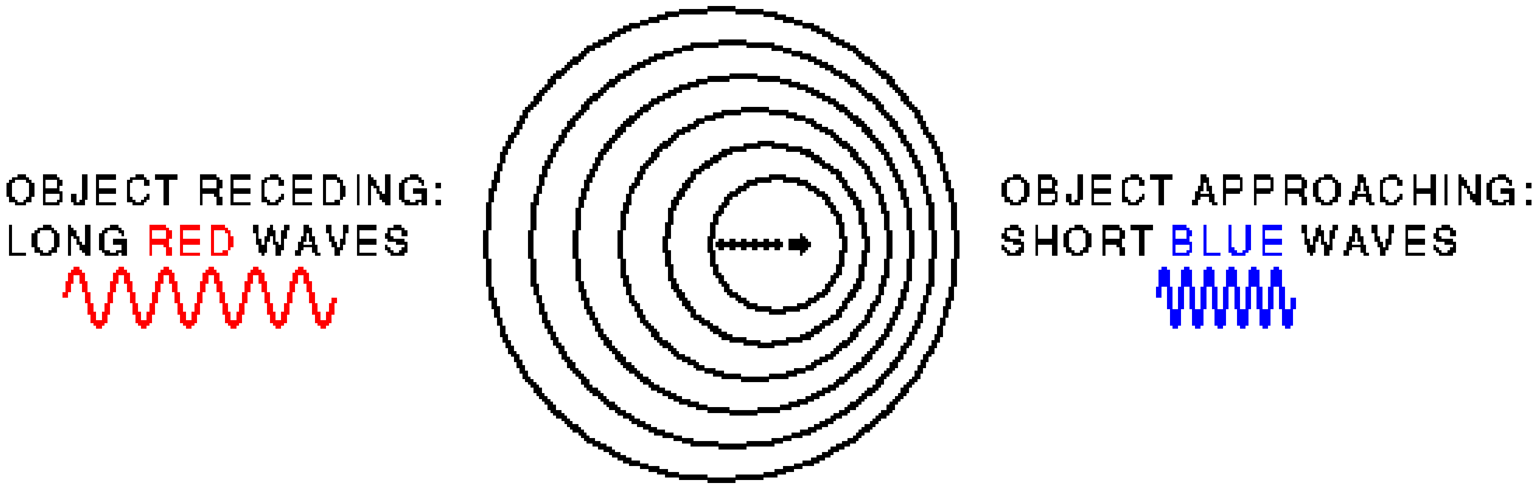
Detectable via the **Doppler Effect**





Can detect motion from shifts in ***spectral lines***

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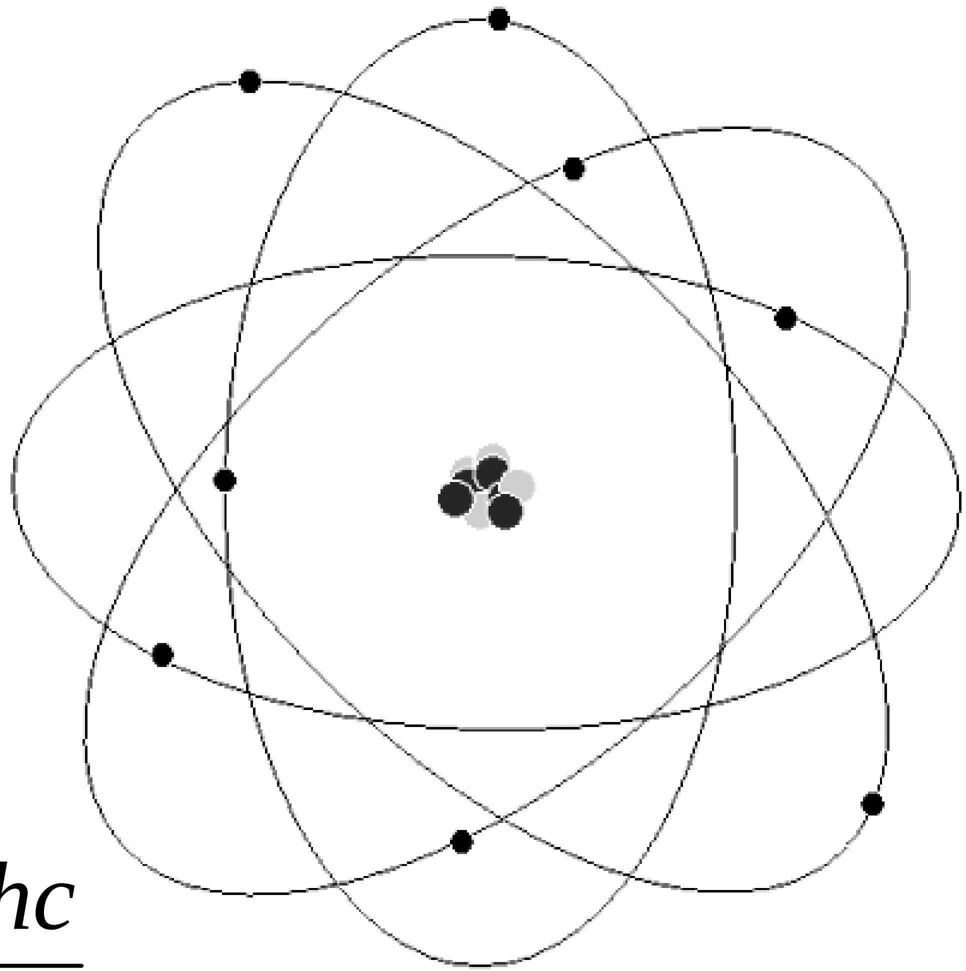
Spectral lines arise when electrons change energy level inside atoms.

This occurs when atoms absorb or emit light energy.

Since electron energies are ***quantised***, spectral lines occur at precisely defined wavelengths



$$E = h\nu = \frac{hc}{\lambda}$$

Planck's constant

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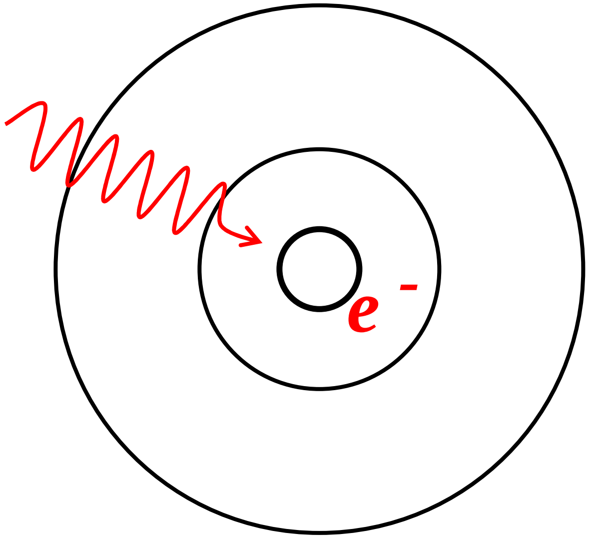
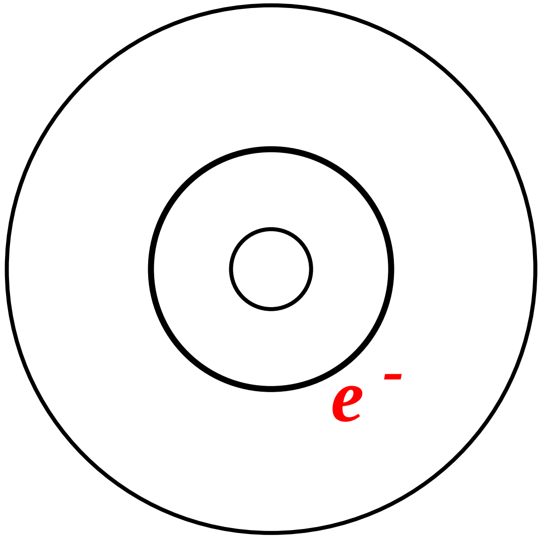
Absorption

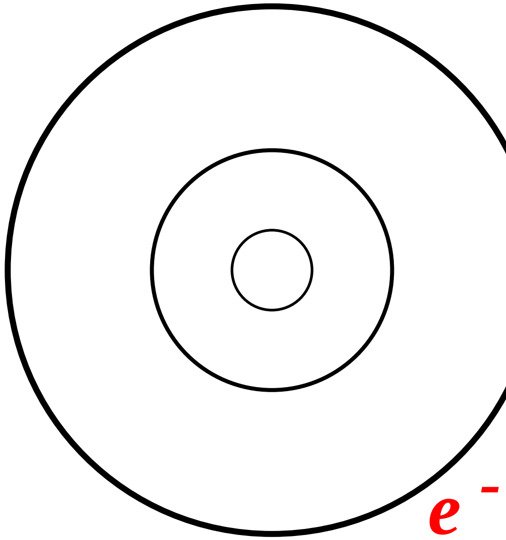


Electron absorbs photon of the precise energy required to jump to higher level.

Light of this energy (wavelength) is missing from the continuous spectrum from a cool gas

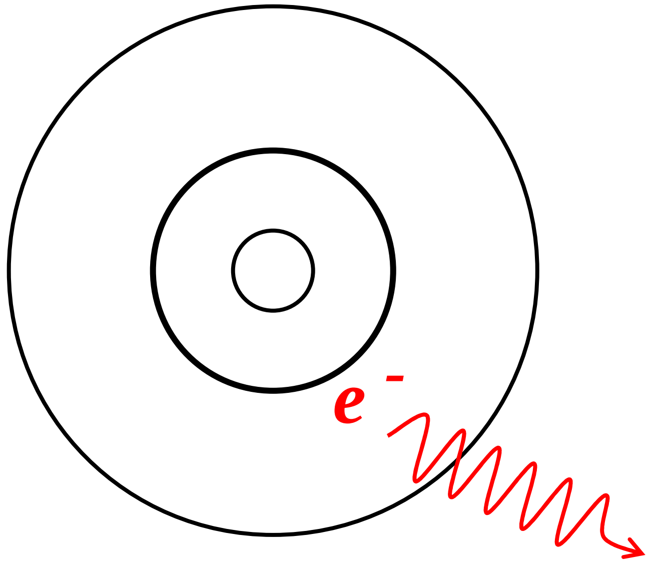


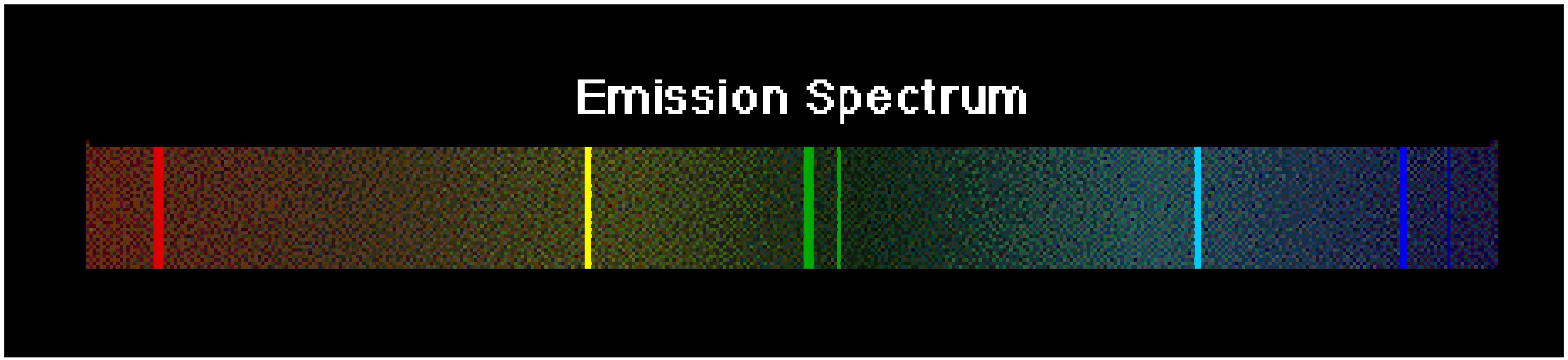
Emission

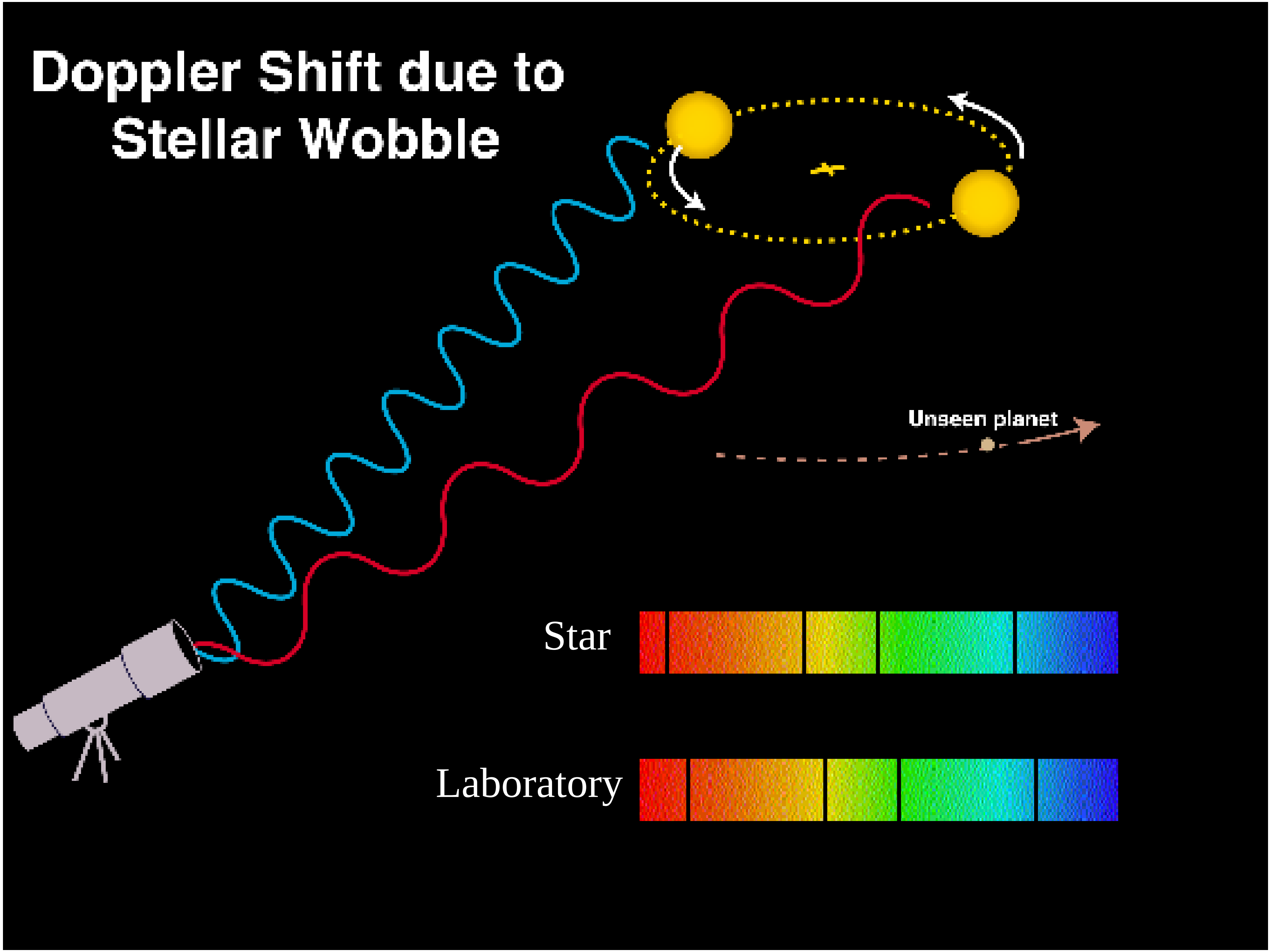


Electron jumps down to lower energy level, and emits photon of energy equal to the difference between the energy levels.

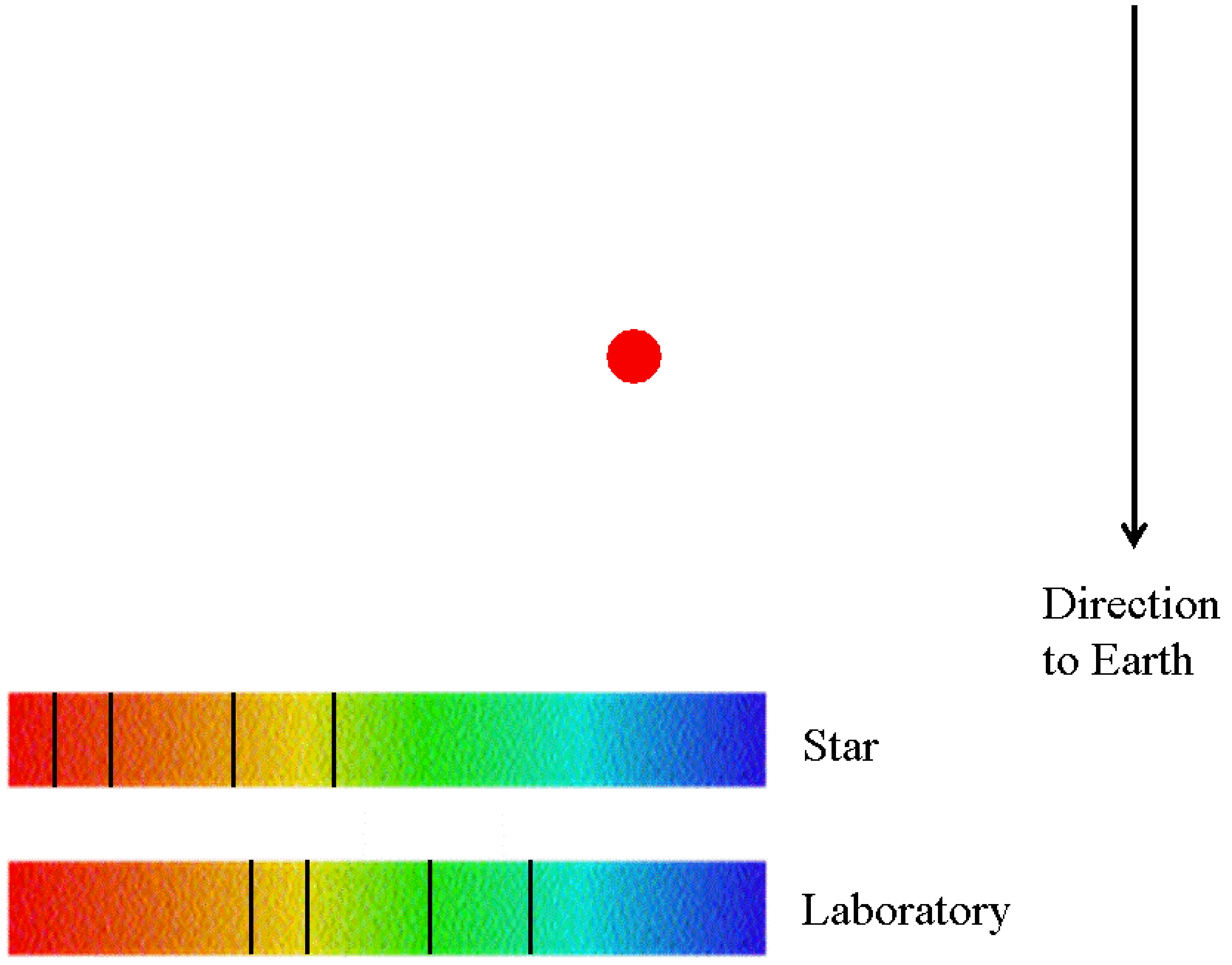
Light of this energy (wavelength) appears in the spectrum from a hot gas







Doppler Shift due to
Stellar Wobble
Unseen planet
Star
Laboratory



Direction
to Earth
Star
Laboratory

How large is the Doppler motion?

Equating gravitational and circular accleration

For the planet:-

$$F_C = m_P \omega^2 r_P = \frac{G\, m_P\, m_S}{r^2}$$

For the star:-

$$F_C = m_S \omega^2 r_S = \frac{G\, m_P\, m_S}{r^2}$$

Angular velocity

$$\omega = \frac{2\pi}{T}$$

Period of 'wobble'

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Period of 'wobble'

For the star:-

$$F_C = m_S \omega^2 r_S = \frac{G m_P m_S}{r^2}$$

Adding:-

$$\omega^2 (r_P + r_S) = \frac{G(m_S + m_P)}{r^2}$$

$$\omega^2 r^3 = \frac{4\pi^2 r^3}{T^2} = G(m_S + m_P) \cong G m_S$$

Kepler's Third Law

The square of a planet's orbital period is proportional to the cube of its mean distance from the Sun

$$\omega^2 r^3 = \frac{4\pi^2 r^3}{T^2} = G(m_S + m_P) \cong G m_S$$

Kepler's Third Law

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e.g. Earth:

$r = 1$ A.U. $\qquad T = 1$ year

Jupiter:

$r = 5.2$ A.U. $\qquad \frac{r_E^{\,3}}{T_E^{\,2}} = \frac{r_J^{\,3}}{T_J^{\,2}} \quad \Rightarrow \quad T_J = \sqrt{5.2^3} = 11.86$ years

Amplitude of star's radial velocity:-

$$v_S = \omega r_S \qquad r = \frac{(m_S + m_P)\, r_S}{m_P}$$

From centre of mass condition

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$$\Rightarrow \quad G(m_S + m_P) = \frac{\omega^2 (m_S + m_P)^3\, r_S{}^3}{m_P{}^3}$$

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$$\Rightarrow \quad G m_P{}^3 = \frac{(m_S + m_P)^2\, v_S{}^3\, T}{2\pi} \cong \frac{m_S{}^2\, v_S{}^3\, T}{2\pi}$$

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From centre of mass condition

$$\Rightarrow \quad G(m_S + m_P) = \frac{\omega^2 (m_S + m_P)^3 r_S^{\;3}}{m_P^{\;3}}$$

$$\Rightarrow \quad G m_P^{\;3} = \frac{(m_S + m_P)^2 v_S^{\;3} T}{2\pi} \cong \frac{m_S^{\;2} v_S^{\;3} T}{2\pi}$$

$$\Rightarrow \quad v_S = \left(\frac{2\pi G}{T}\right)^{1/3} m_S^{\;-2/3} m_P$$

$$v_S = \left(\frac{2\pi G}{T}\right)^{1/3} m_S^{-2/3} m_P$$

$$G = 6.673 \times 10^{-11}\ \mathrm{m^3 kg^{-1} s^{-2}}$$

$$m_{\mathrm{Sun}} = 2.0 \times 10^{30}\ \mathrm{kg}$$

Examples

Jupiter: $m_{\mathrm{Jup}} = 1.9 \times 10^{27}\ \mathrm{kg}$ $T = 11.86\ \mathrm{years}$

$$v_S = 12.4\ \mathrm{ms^{-1}}$$

$$v_S = \left(\frac{2\pi G}{T}\right)^{1/3} m_S^{-2/3} m_P$$

$$G = 6.673\times10^{-11}\ \mathrm{m^3 kg^{-1} s^{-2}}$$

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Examples

Jupiter: $m_{\mathrm{Jup}} = 1.9\times10^{27}\ \mathrm{kg}$ $\quad T = 11.86\ \mathrm{years}$

$$v_S = 12.4\ \mathrm{ms^{-1}}$$

Earth: $m_{\mathrm{Earth}} = 6.0\times10^{24}\ \mathrm{kg}$ $\quad T = 1\ \mathrm{year}$

$$v_S = 0.09\ \mathrm{ms^{-1}}$$

Are these Doppler shifts measurable?…

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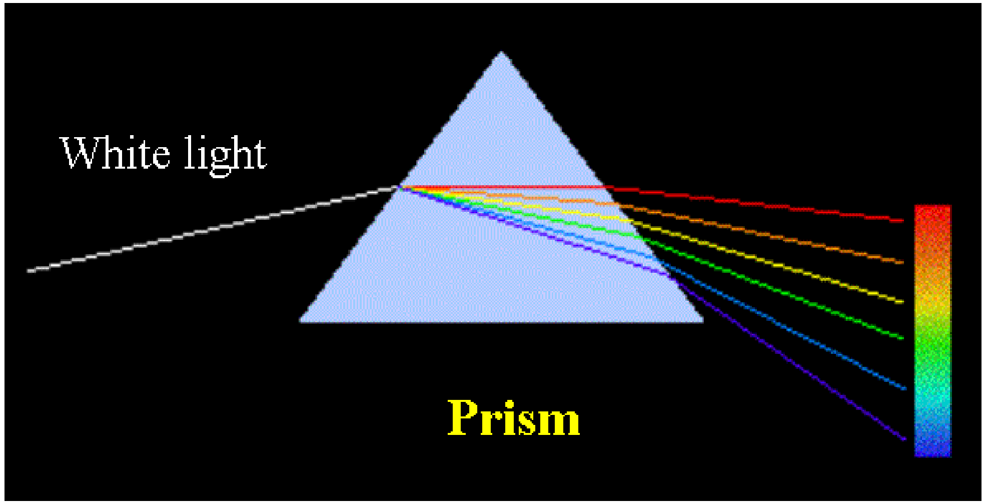
Stellar spectra are observed using prisms or diffraction gratings, which disperse starlight into its constituent colours



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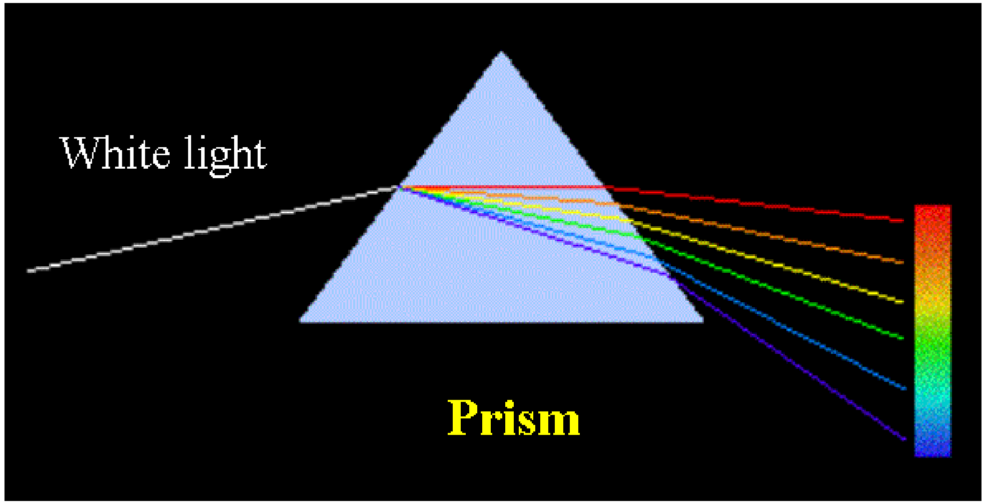

Doppler formula

Change in wavelength

Radial velocity

$$\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$$

Wavelength of light as measured in the laboratory

Speed of light

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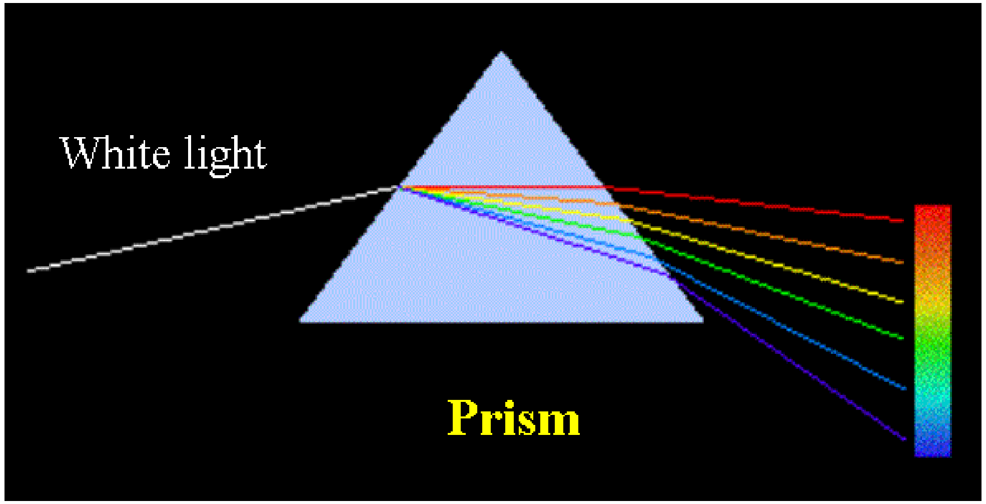


Doppler formula

$$\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c}$$

Change in wavelength ($\Delta\lambda$)

Radial velocity (v)

Wavelength of light as measured in the laboratory (λ_0)

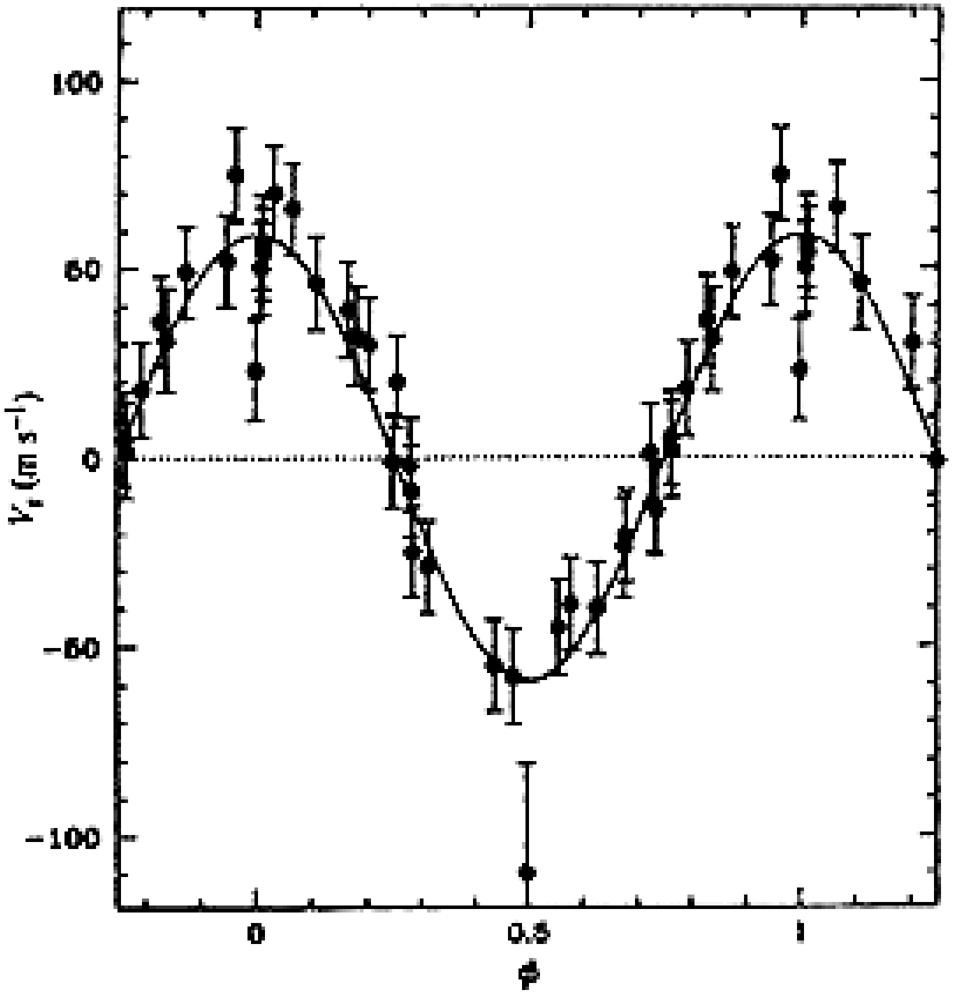
Speed of light (c)

Limits of current technology:

$$\frac{\Delta\lambda}{\lambda_0} \approx 300 \text{ millionth}$$

$$\Rightarrow \quad v \approx 1\,\mathrm{ms}^{-1}$$

51 Peg – the first new planet



Discovered in 1995

Doppler amplitude

$$v = 55\,\mathrm{ms}^{-1}$$

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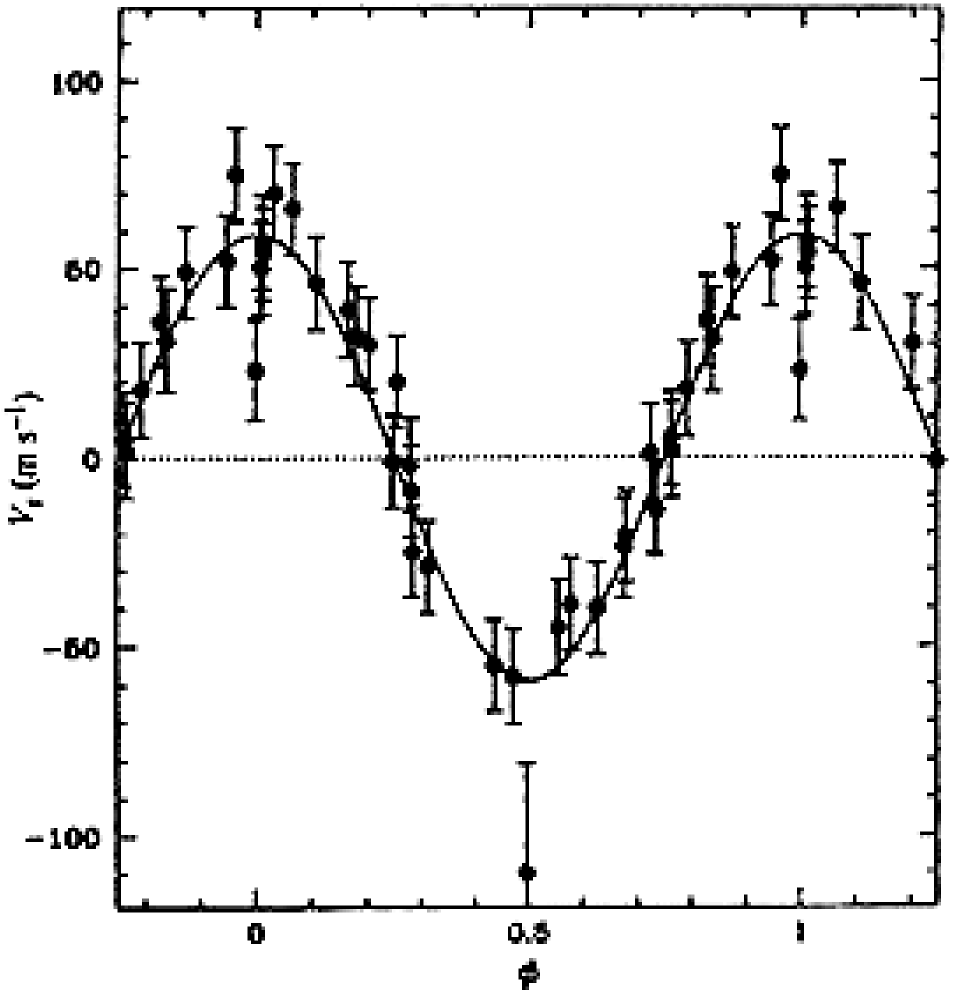
51 Peg – the first new planet



Discovered in 1995

Doppler amplitude

$$v = 55\,\mathrm{ms}^{-1}$$

How do we deduce planet's data from this curve?

$$v_S = \left(\frac{2\pi G}{T}\right)^{1/3} m_S^{-2/3} m_P$$

We can observe these directly

We can infer this from spectrum

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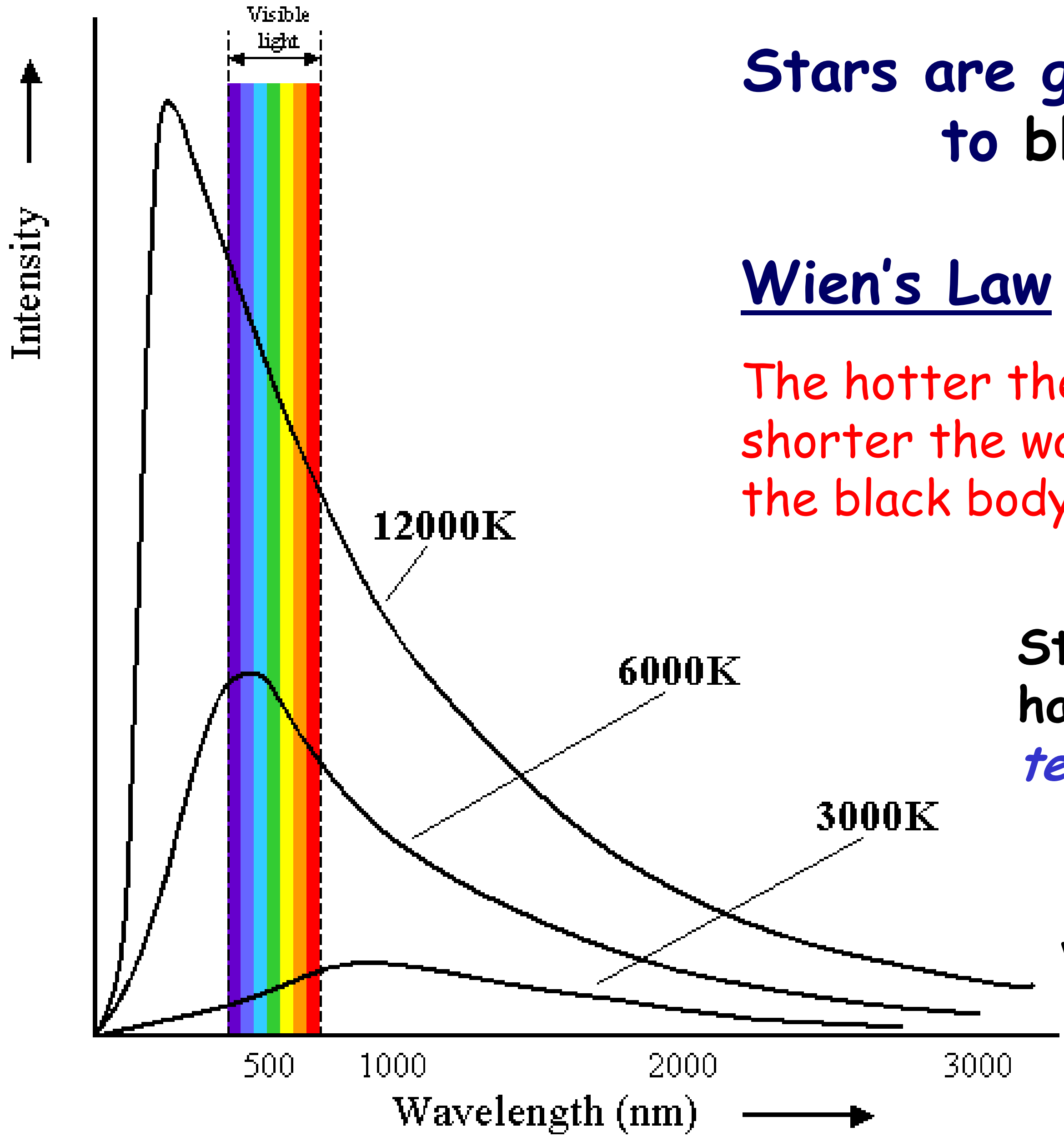


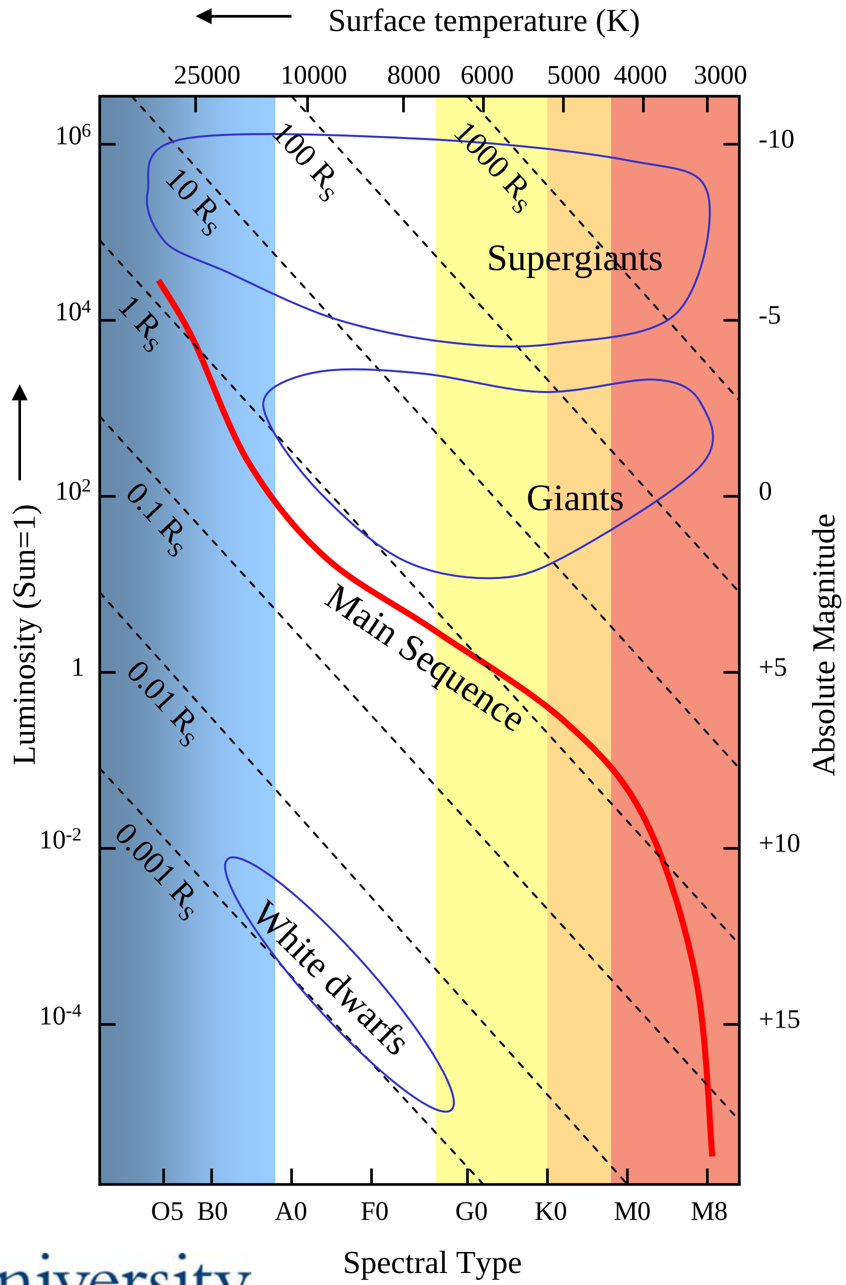
Stars are good approximations to black body radiators

Wien's Law

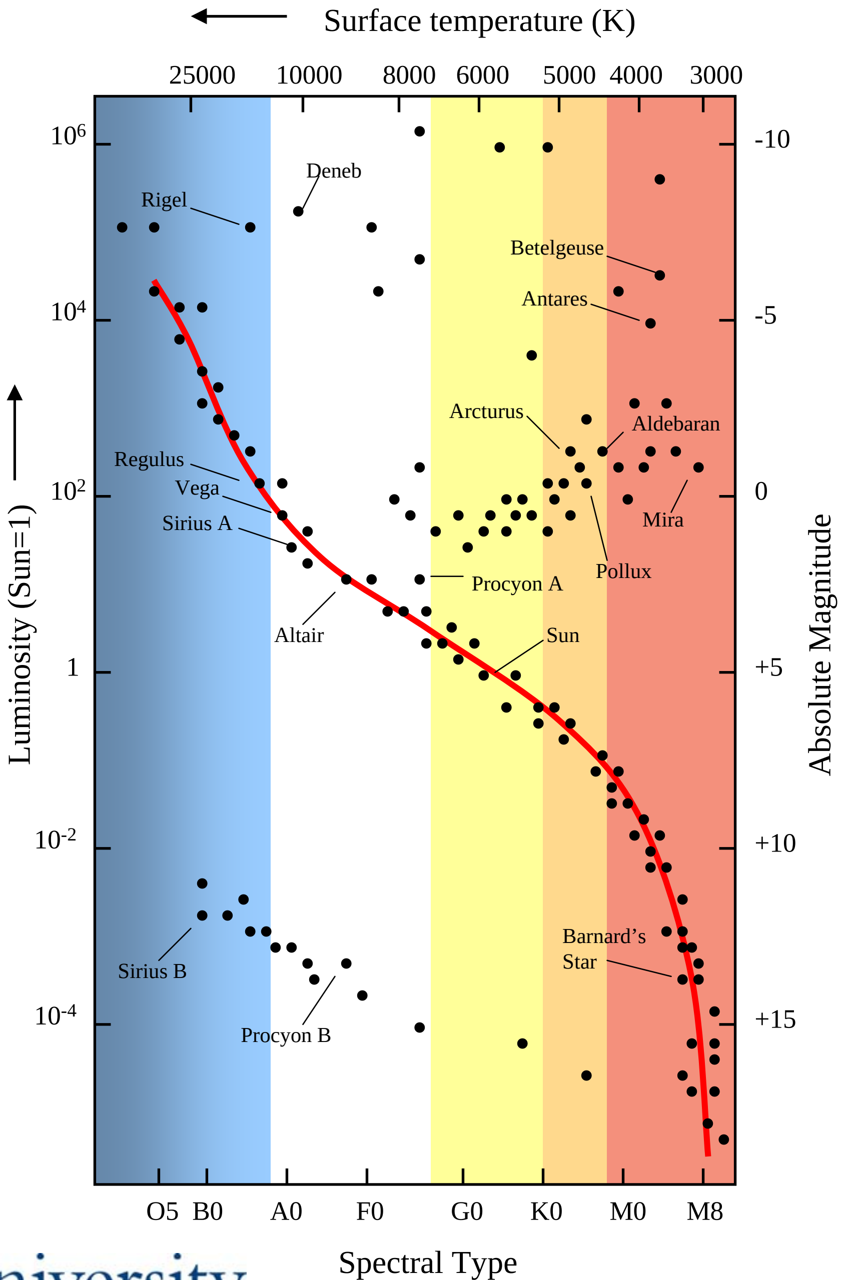
The hotter the temperature, the shorter the wavelength at which the black body curve peaks

Stars of different colours have different surface *temperatures*

We can determine a star's temperature from its **spectrum**



When we plot the temperature and luminosity of stars on a diagram most are found on the **Main Sequence**



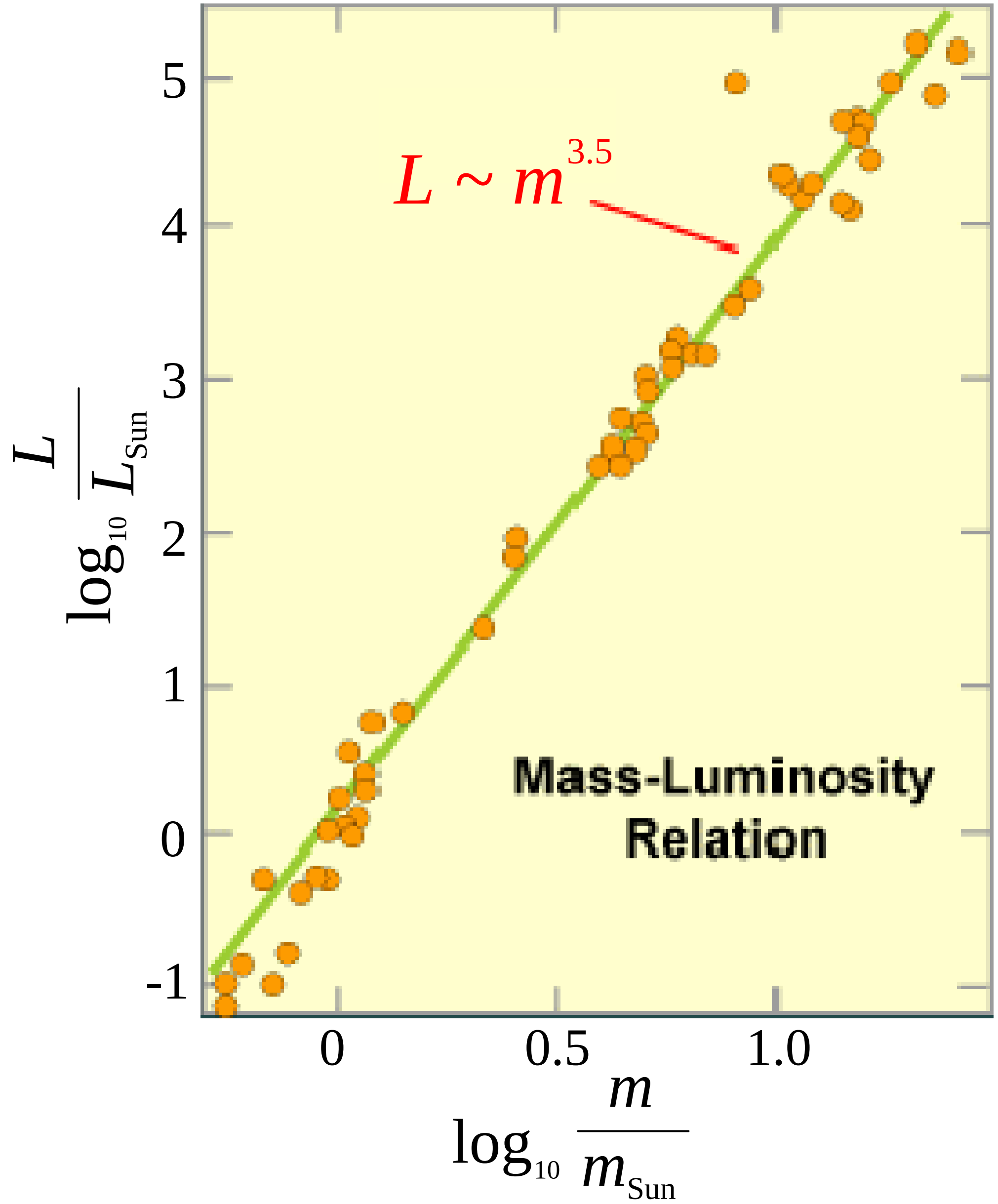
When we plot the **temperature** and **luminosity** of stars on a diagram most are found on the **Main Sequence**

Stars on the **Main Sequence** turn hydrogen into helium.

Stars like the Sun can do this for about ten billion years

Main sequence stars obey an approximate **mass-luminosity relation**

⇒ We can, in turn, estimate the mass of a star from our estimate of its luminosity



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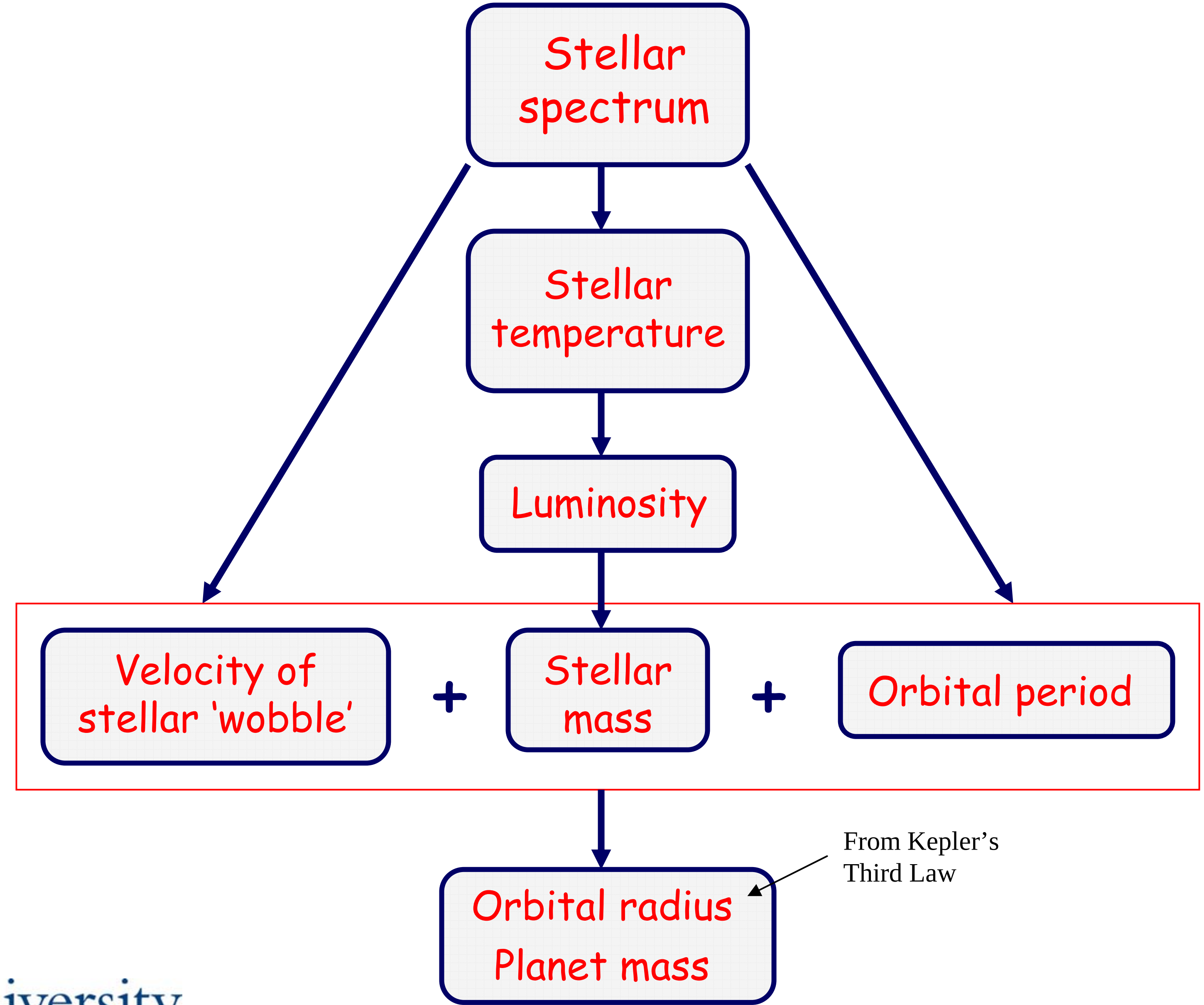
Summary: Doppler 'Wobble' method



Complications

- Elliptical orbits

  Complicates maths a bit, but otherwise straightforward
  radius ⟶ semi-major axis

- Orbital plane inclined to line of sight

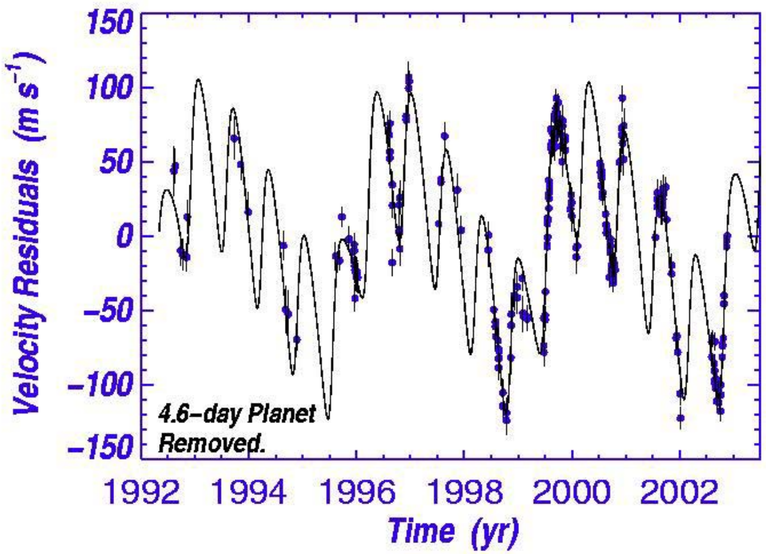
  We measure only $(v_S \sin i)_{obs}$

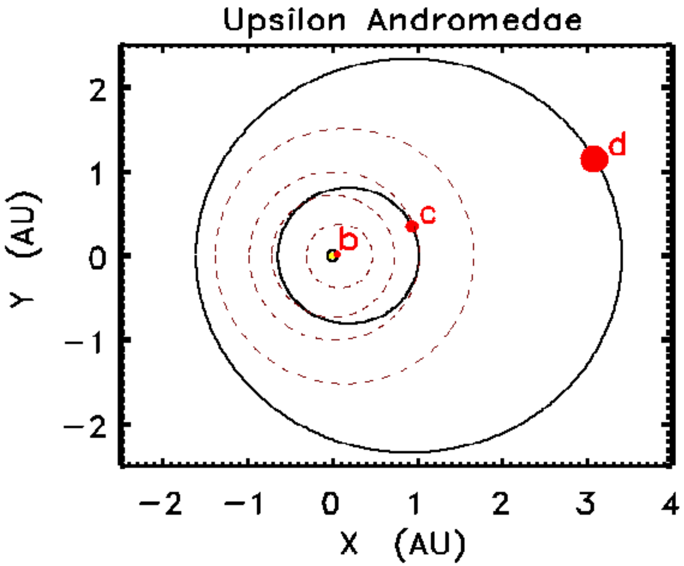
  If i is unknown, then we obtain a lower limit to m_P

  ($v_S \geq (v_S \sin i)_{obs}$ as $\sin i \leq 1$)

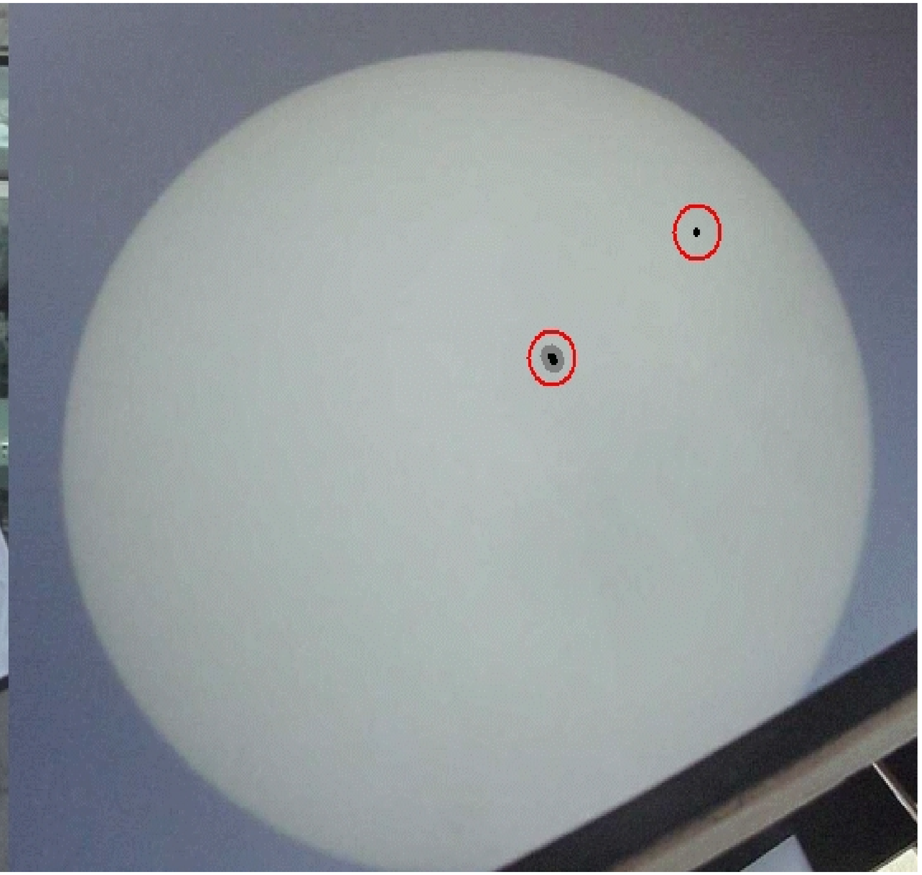
- Multiple planet systems

  Again, complicated, but exciting opportunity (e.g. Upsilon Andromedae)





In recent years a growing number of exoplanets have been detected via **transits** = temporary drop in brightness of parent star as the planet crosses the star's disk along our line of sight.



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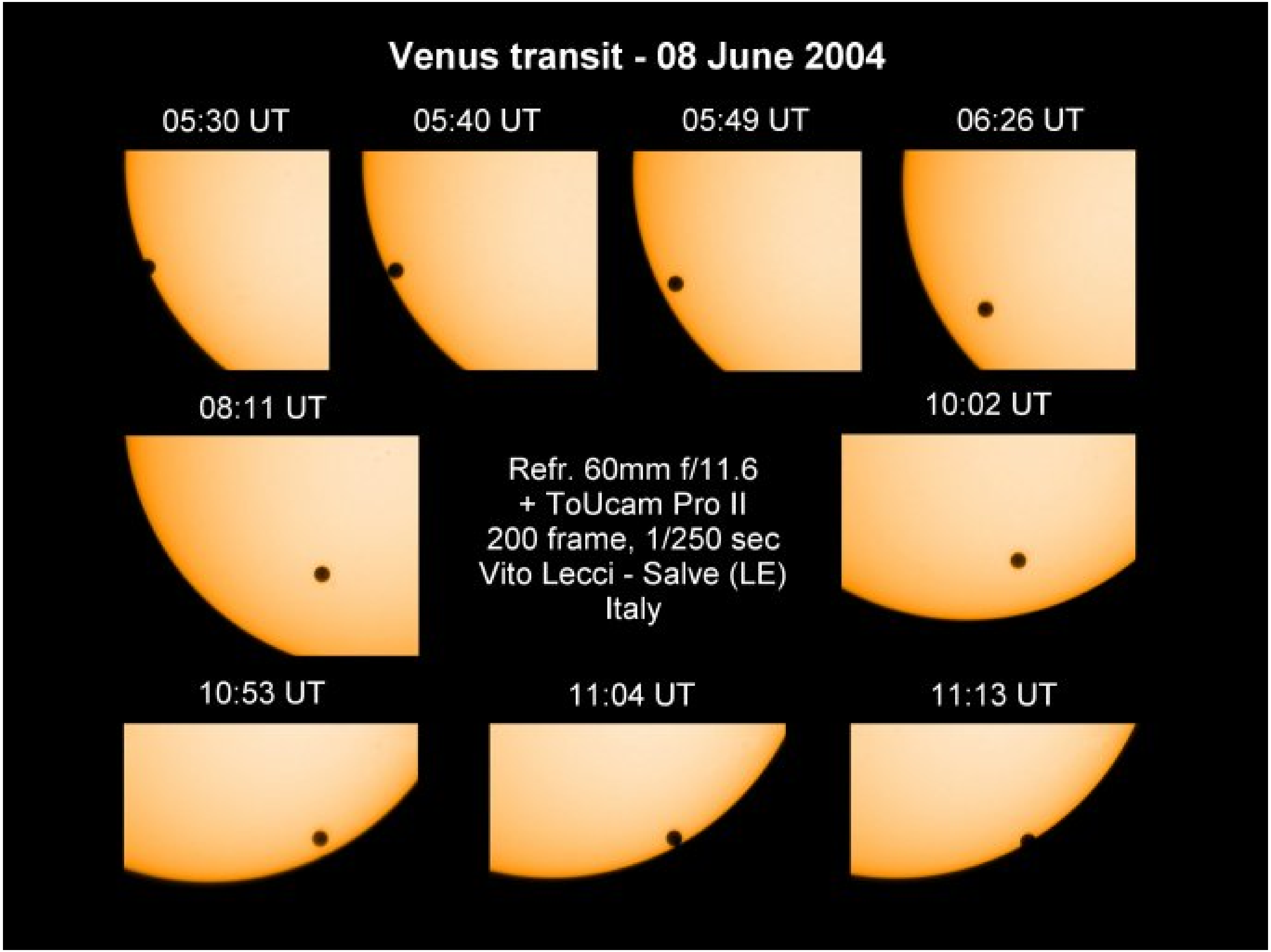
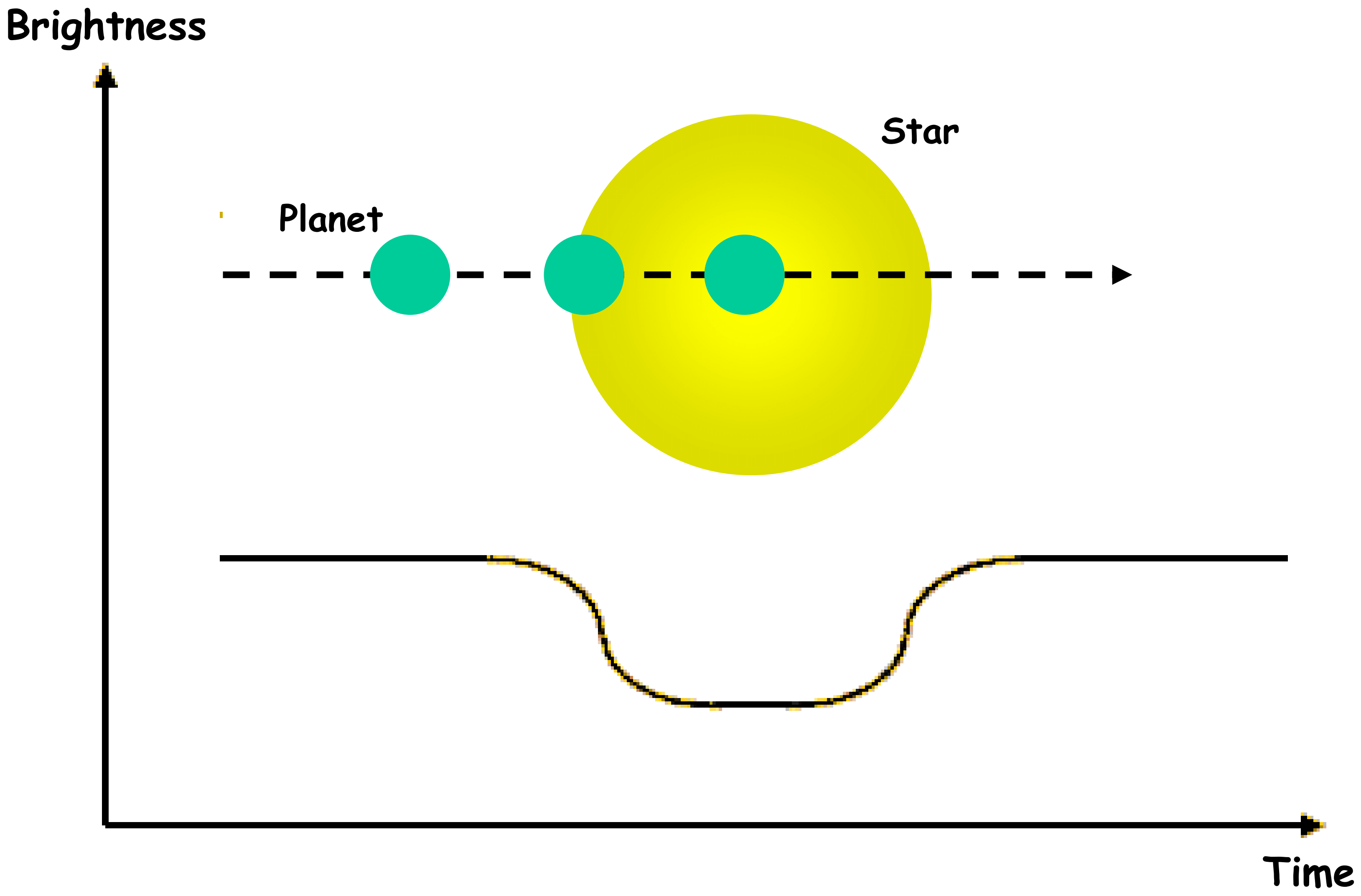

Venus transit - 08 June 2004
05:30 UT
05:40 UT
05:49 UT
06:26 UT
08:11 UT
10:02 UT
Refr. 60mm f/11.6
+ ToUcam Pro II
200 frame, 1/250 sec
Vito Lecci - Salve (LE)
Italy
10:53 UT
11:04 UT
11:13 UT

Change in brightness from a planetary transit



Ignoring light from planet, and assuming star is uniformly bright:

$$\frac{\text{Total brightness during transit}}{\text{Total brightness outside transit}} = \frac{B_* \pi \left(R_*^2 - R_P^2\right)}{B_* \pi R_*^2} = 1 - \left(\frac{R_P}{R_S}\right)^2$$

e.g. Sun: $R_{\text{Sun}} = 7.0 \times 10^8$ m

Jupiter: $R_{\text{Jup}} = 7.2 \times 10^7$ m $\Rightarrow$ Brightness change of ~1%

Earth: $R_{\text{Earth}} = 6.4 \times 10^6$ m $\Rightarrow$ Brightness change of ~0.008%

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If we know the **period** of the planet's orbit, we can use the **width** of brightness dip to relate R_P , via Kepler's laws, to the **mass** of the star.

So, if we observe *both* a transit and a Doppler wobble for the same planet, we can constrain the mass and radius of *both* the planet and its parent star.

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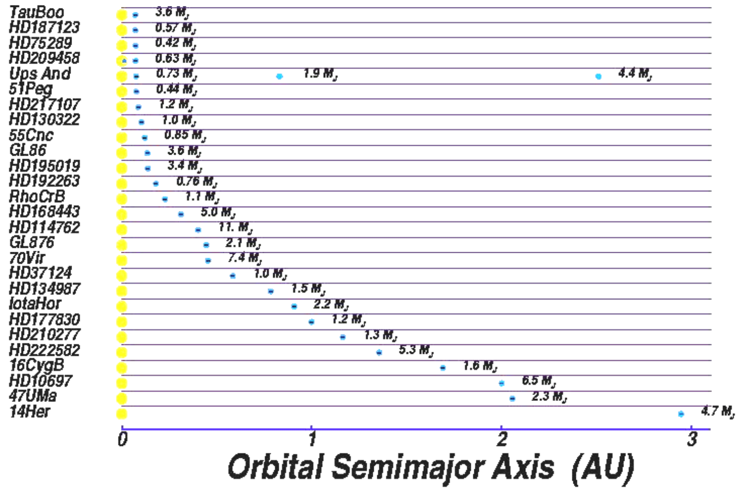
What have we learned about exoplanets?

Highly active, and rapidly changing, field



Aug 2000: 29 exoplanets

What have we learned about exoplanets?

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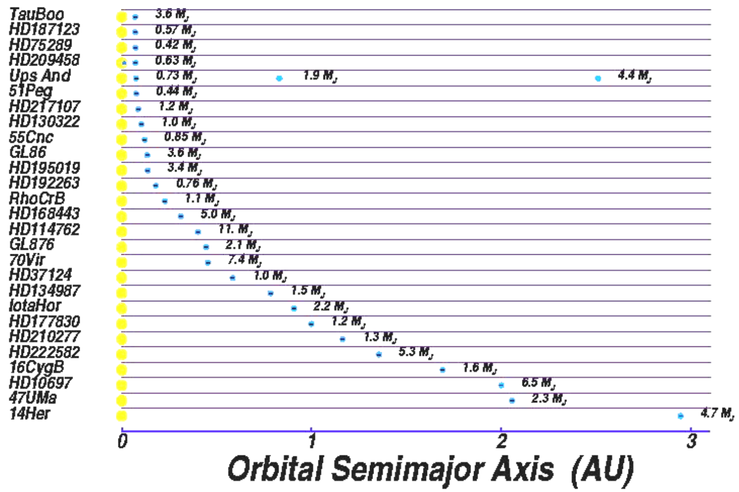

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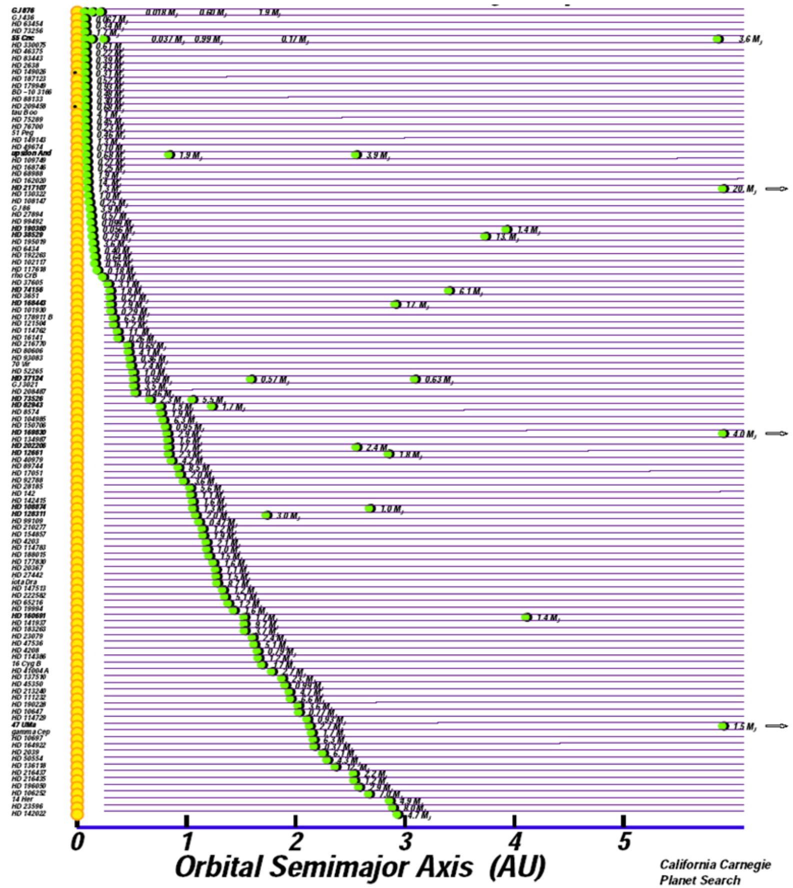

Sep 2005: 156 exoplanets

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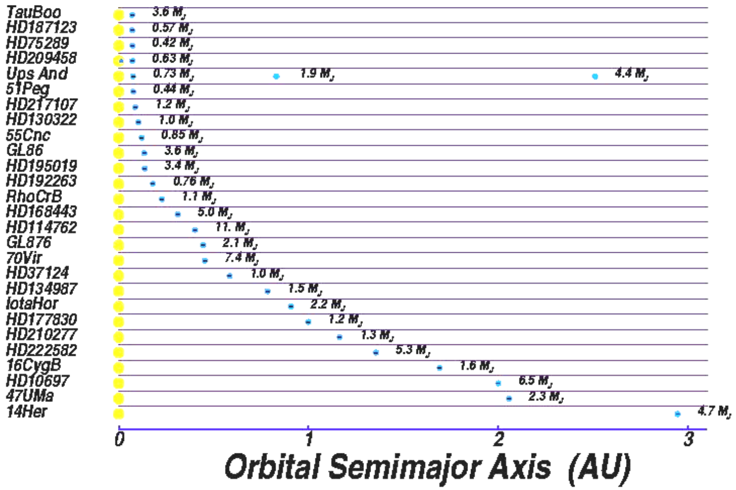
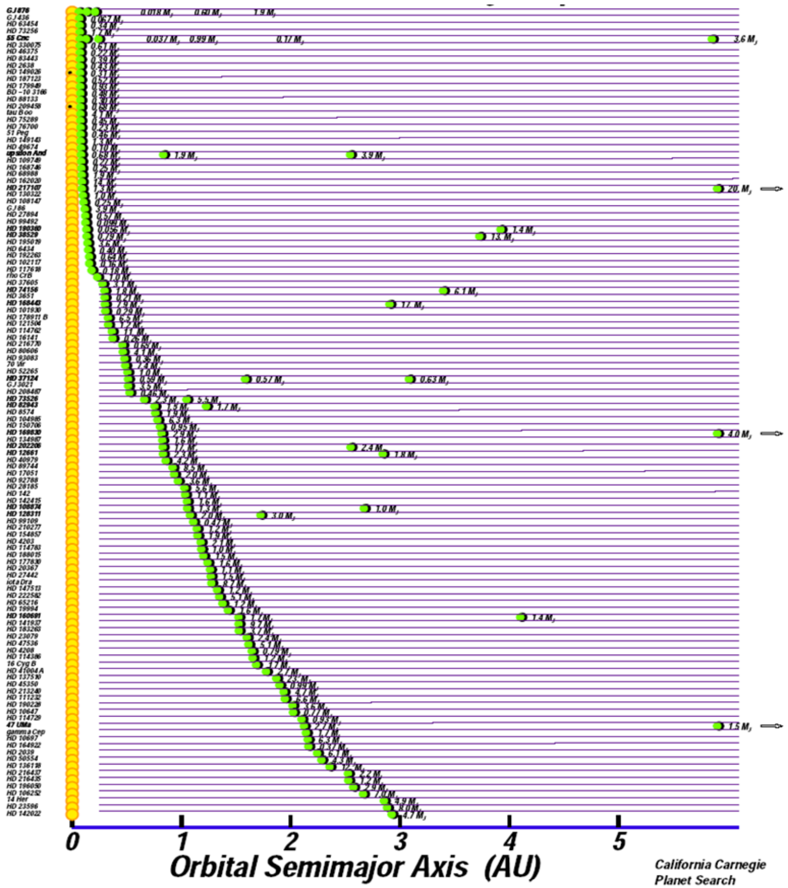


Aug 2000: 29 exoplanets

Up-to-date summary at

http://www.exoplanets.org

Now finding planets at larger orbital semimajor axis



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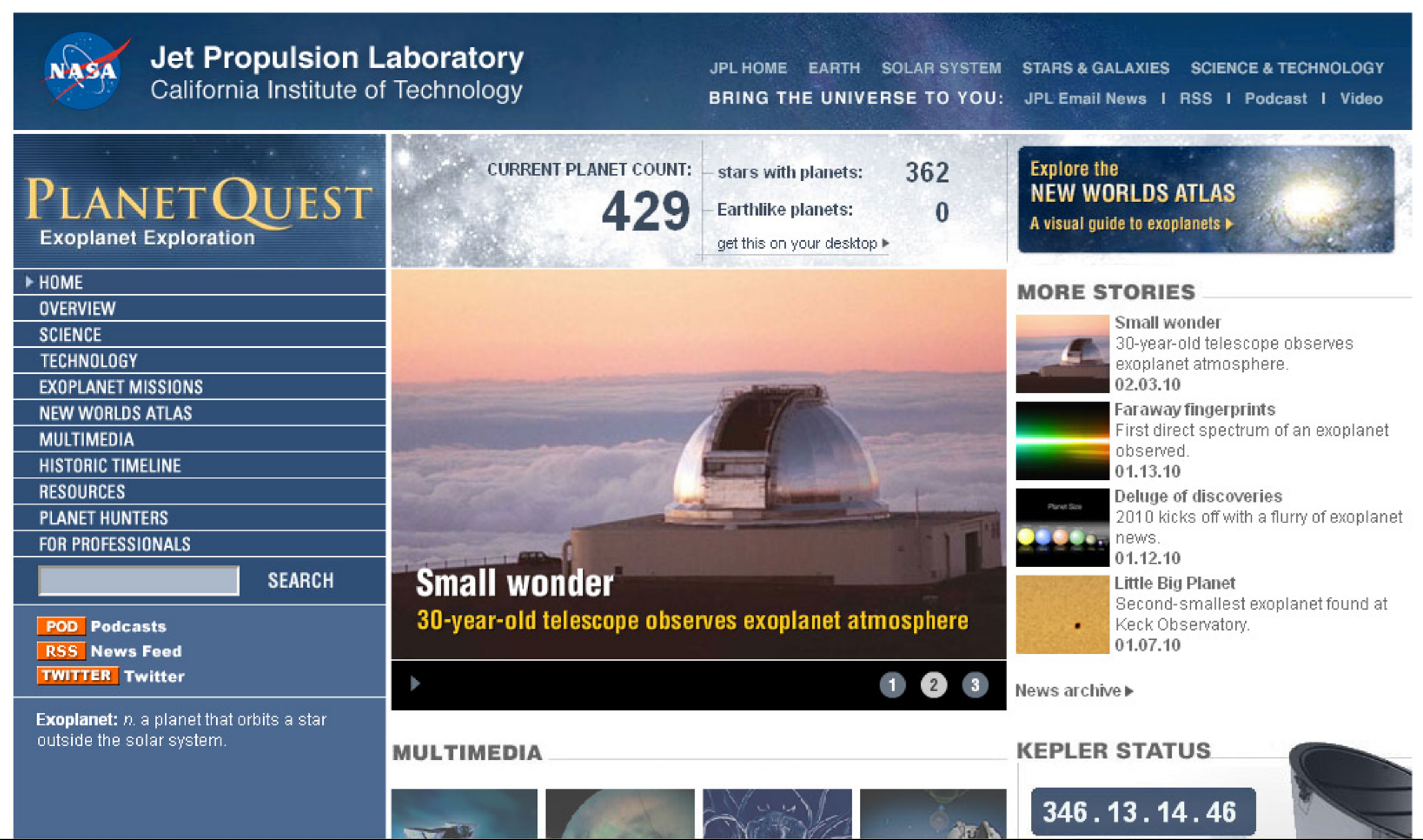

http://www.planetquest.jpl.nasa.gov/

What have we learned about exoplanets?

Why larger semi-major axes now?

- Kepler's third law implies longer period, so requires monitoring for many years to determine 'wobble' precisely

$$\mathrm{v}_S = \left(\frac{2\pi G}{T}\right)^{1/3} m_S^{-2/3} m_P$$

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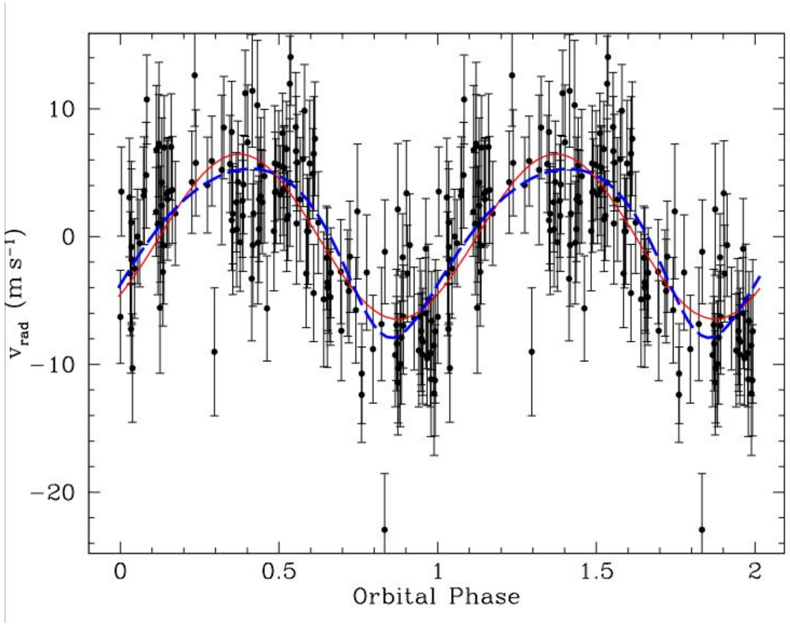


Improving precision also now finding lower mass planets (and getting quite close to Earth mass planets)

For example:
Third planet of GJ876 system

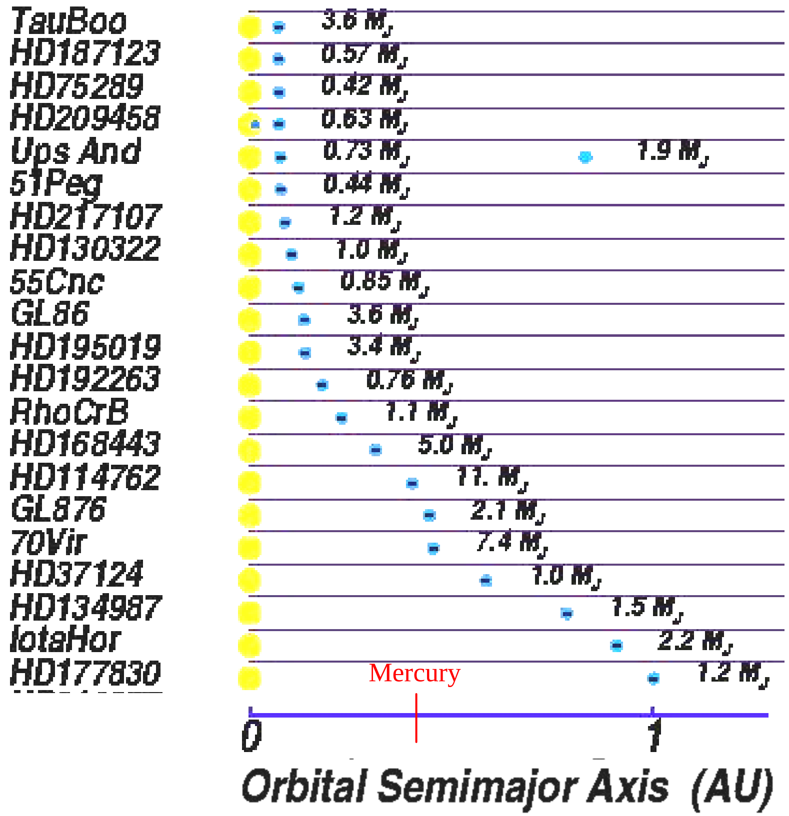
$$m_P = \frac{5.9\, m_{\mathrm{Earth}}}{\sin i}$$

What have we learned about exoplanets?

Discovery of many 'Hot Jupiters':

Massive planets with orbits closer to their star than Mercury is to the Sun

Very likely to be gas giants, but with surface temperatures of several thousand degrees.



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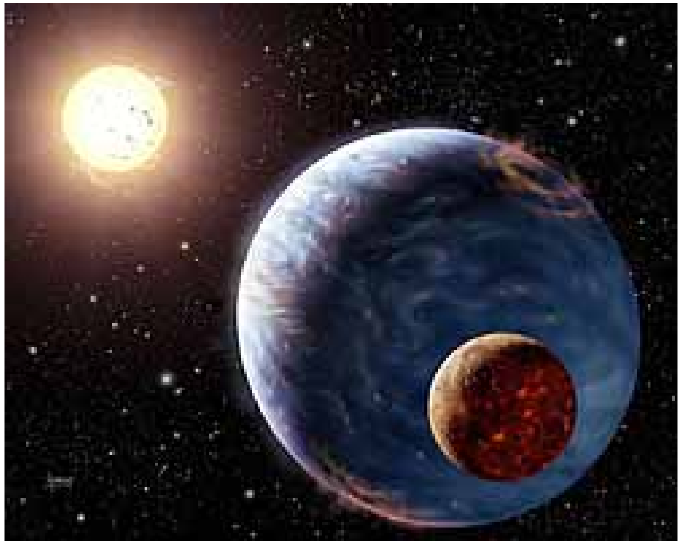
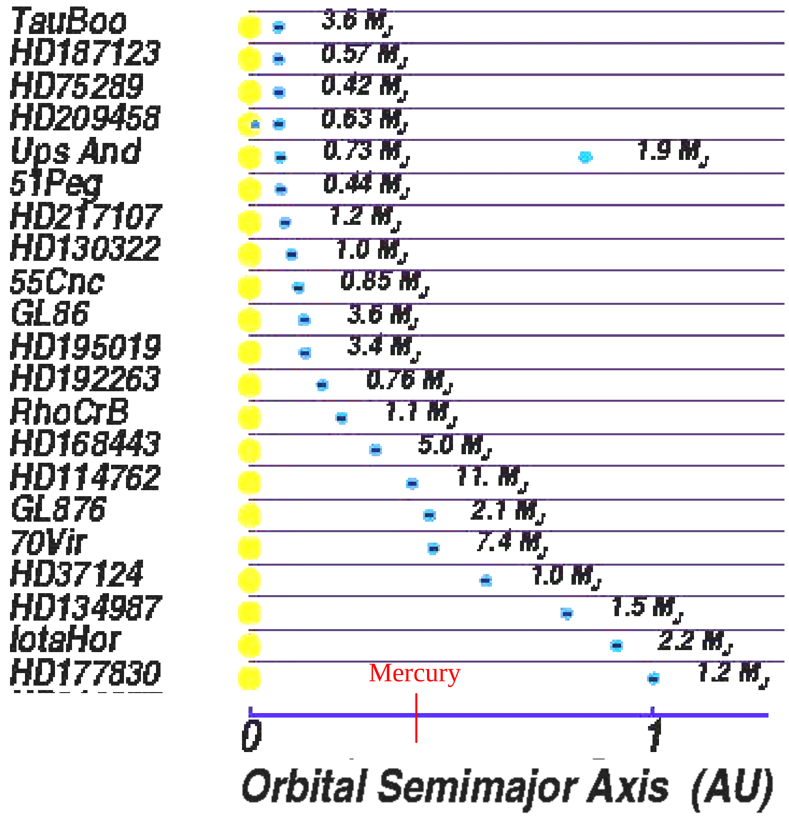


Artist's impression of 'Hot Jupiter' orbiting HD195019



'Hot Jupiters' produce Doppler wobbles of very large amplitude

e.g. Tau Boo: $v_S \sin i = 474\,\mathrm{ms}^{-1}$

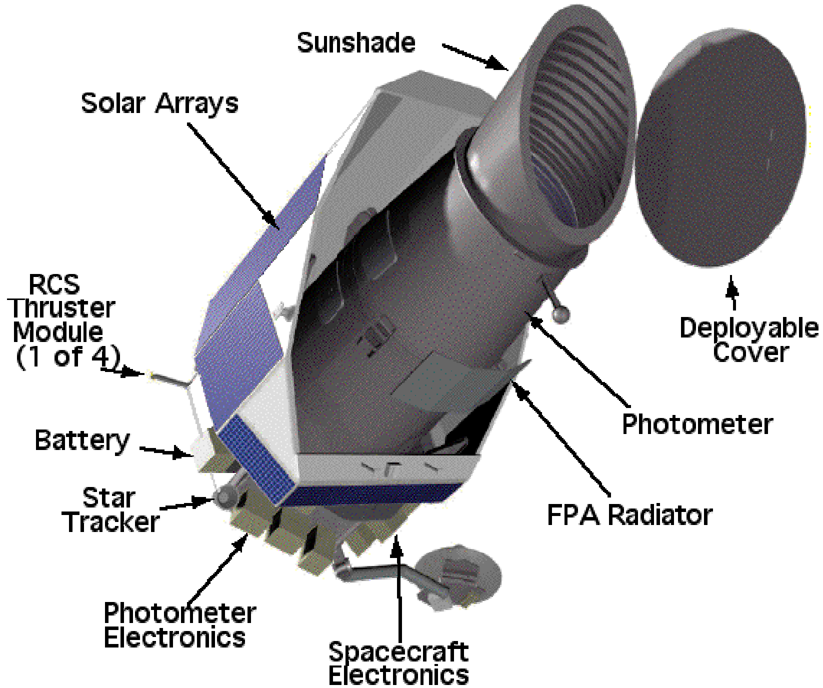
Looking to the Future

1. The Doppler wobble technique will not be sensitive enough to detect Earth-type planets (i.e. Earth mass at 1 A.U.), but will continue to detect more massive planets

2. The 'position wobble' (astrometry) technique *will* detect Earth-type planets – e.g SIM Lite after 2020

   (done with HST in Dec 2002 for a 2 x Jupiter-mass planet)

3. The Kepler mission (launched 2009) will detect transits of Earth-type planets, by observing the brightness dip of stars



The Search for Extra-Solar Planets

- The field is still in its infancy, but there are exciting times ahead
- In about 15 years more than 400 planets already discovered
- The Doppler method ultimately will *not* discover Earth-like planets, but other techniques planned for the next 5 - 10 years *will*
- Search methods are solidly based on well-understood fundamental physics:-
  - Newton's laws of motion and gravity
  - Atomic spectroscopy
  - Black body radiation

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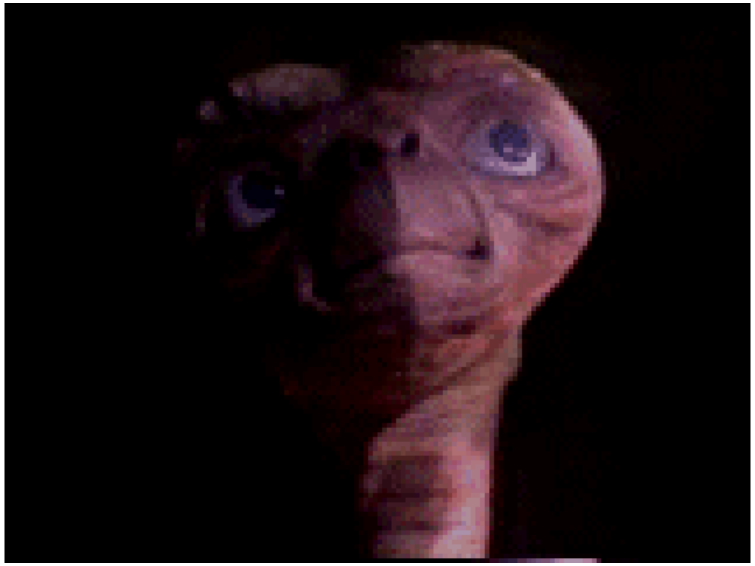

What (or who) will we find?...

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Gravity in Einstein's Universe

"The greatest feat of human thinking about nature, the most amazing combination of philosophical penetration, physical intuition and mathematical skill." *Max Born*

$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

Spacetime curvature

Matter (and energy)

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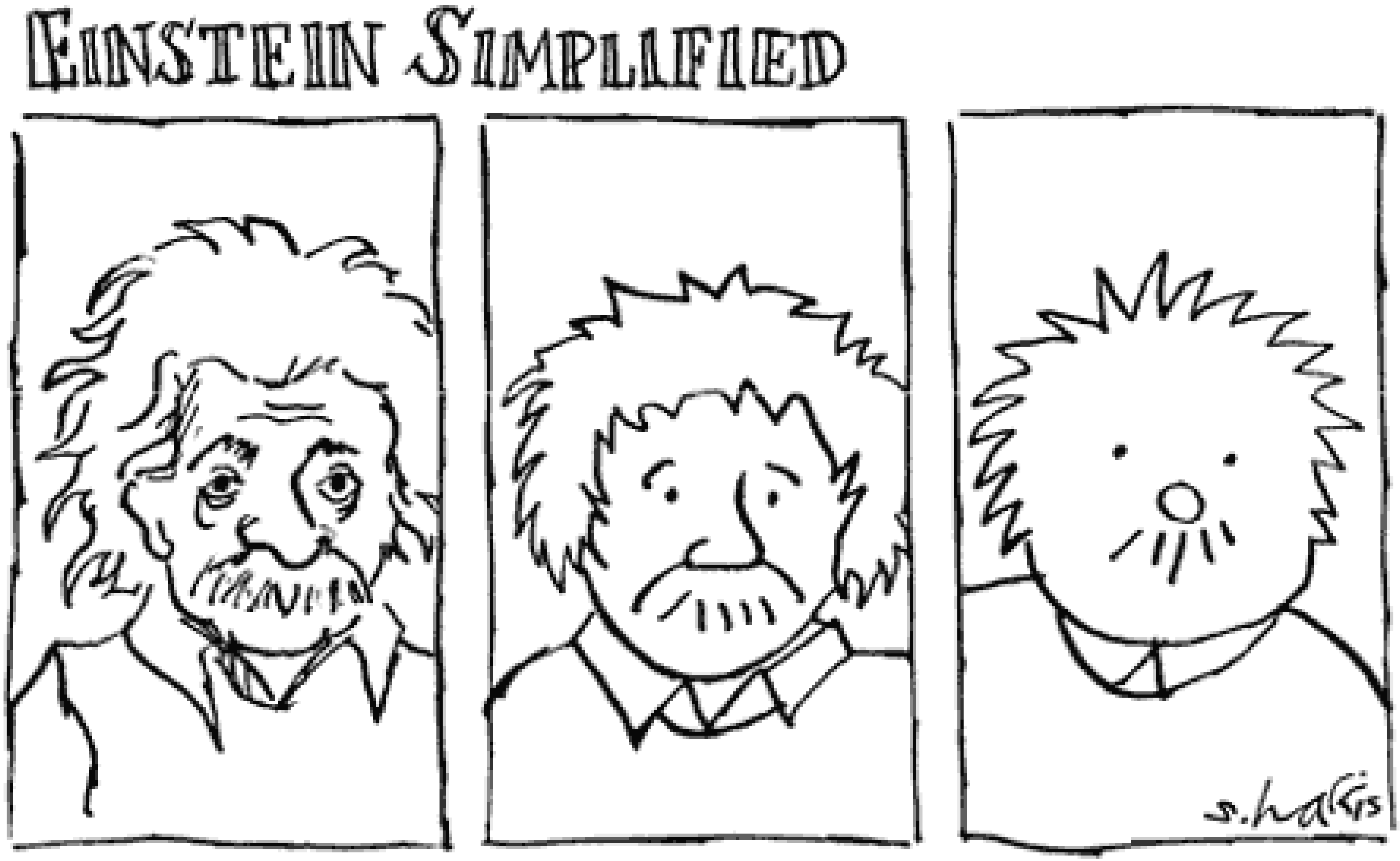
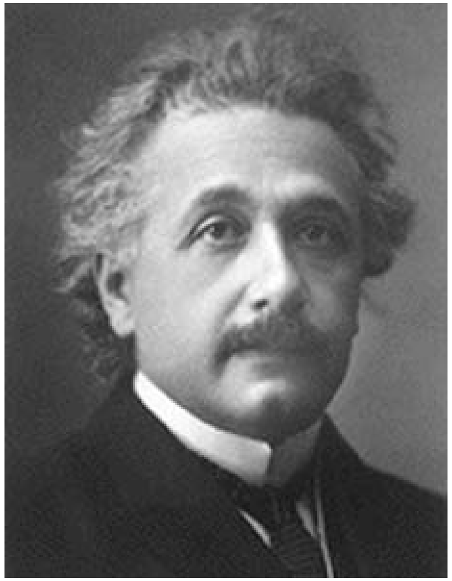
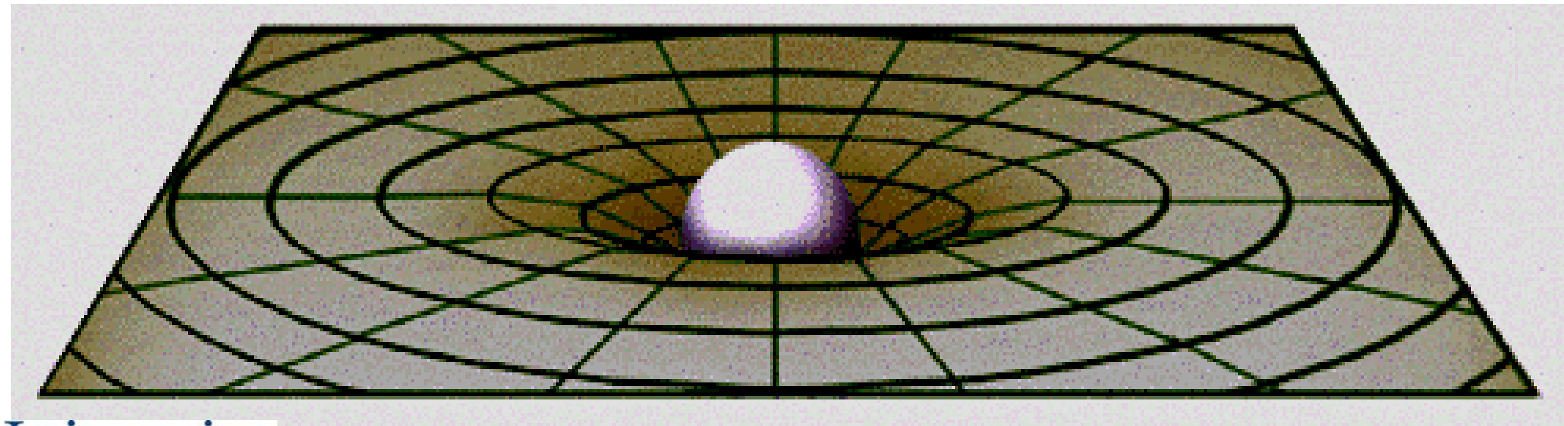

EINSTEIN SIMPLIFIED

Gravity in Einstein's Universe



Spacetime tells matter how to move, and matter tells spacetime how to curve



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Gravitational Waves

- Produced by violent acceleration of mass in:
  - neutron star binary coalescences
  - black hole formation and interactions
  - cosmic string vibrations in the early universe (?)

- and in less violent events:
  - pulsars
  - binary stars

Gravitational waves

'ripples in the curvature of spacetime'

that carry information about changing gravitational fields – or fluctuating strains in space of amplitude *h* where:

$$h = \frac{2\Delta L}{L}$$

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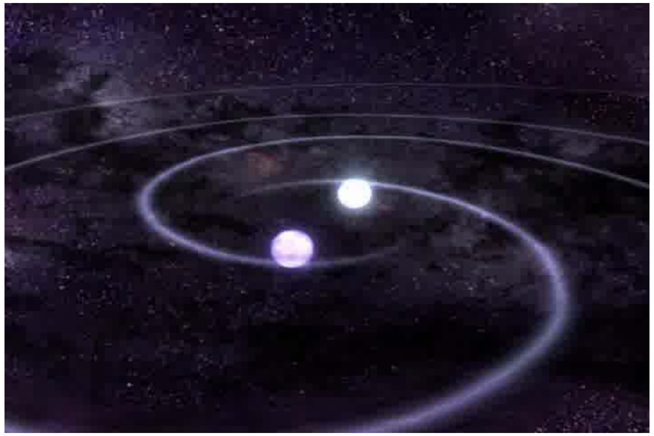
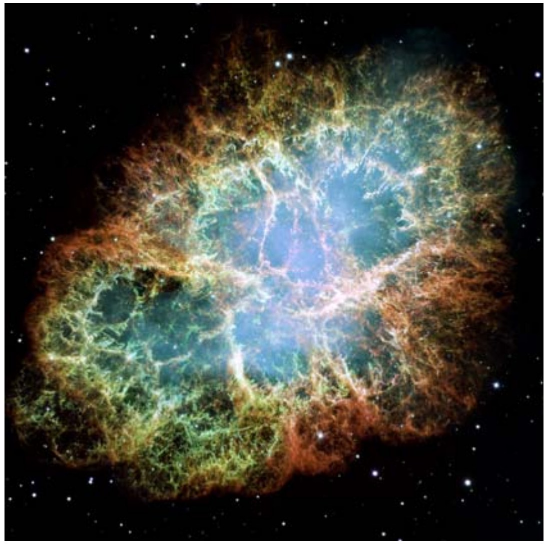
Gravitational Waves: possible sources

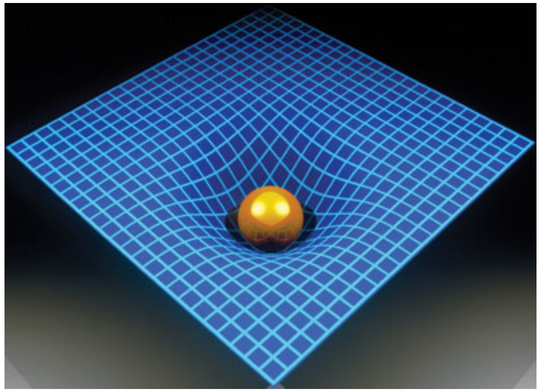
- Pulsed
  Compact Binary Coalescences:
  NS/NS; NS/BH; BH/BH
  Stellar Collapse (asymmetric) to NS or BH
- Continuous Wave
  Pulsars
  Low mass X-ray binaries (e.g. SCO X1)
  Modes and Instabilities of Neutron Stars
- Stochastic
  Inflation
  Cosmic Strings





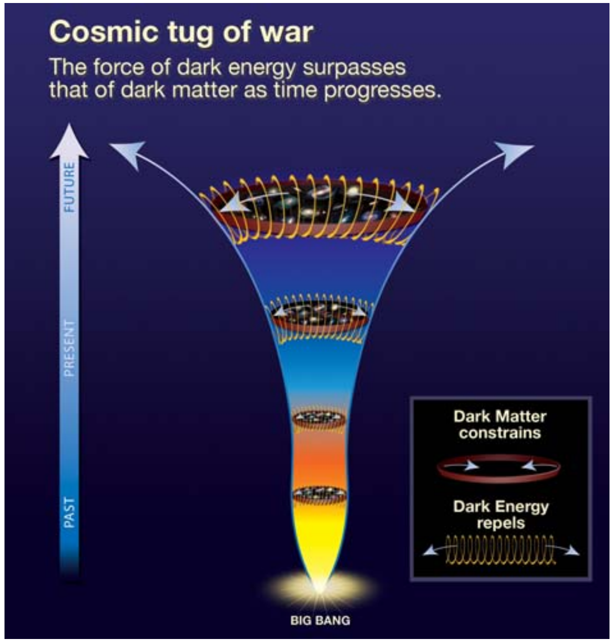
Science goals of the gravitational wave field

Fundamental physics and GR



- What are the properties of gravitational waves?
- Is general relativity the correct theory of gravity?
- Is GR still valid under strong-gravity conditions?
- Are Nature's black holes the black holes of GR?
- How does matter behave under extremes of density and pressure?

Cosmology



- What is the history of the accelerating expansion of the Universe?
- Were there phase transitions in the early Universe?

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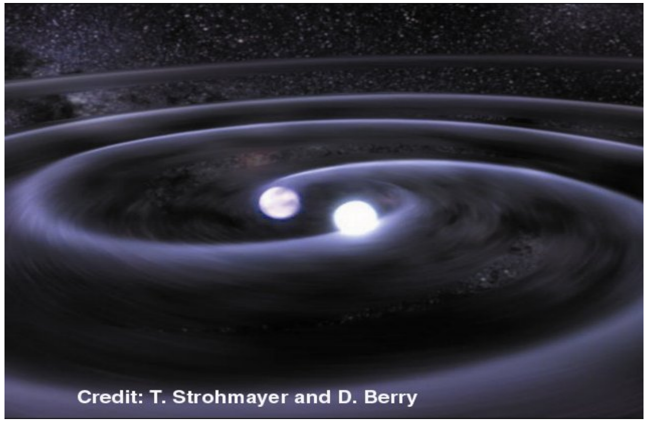
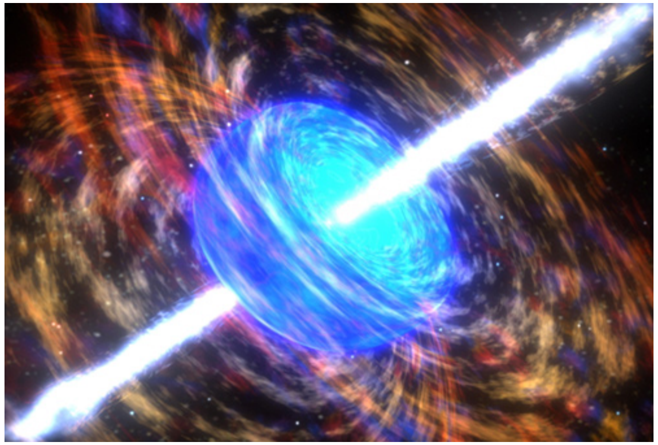
Science goals of the gravitational wave field

Astronomy and astrophysics

- How abundant are stellar-mass black holes?
- What is the central engine that powers GRBs?
- Do intermediate mass black holes exist?
- Where and when do massive black holes form and how are they connected to galaxy formation?
- What happens when a massive star collapses?
- Do spinning neutron stars emit gravitational waves?
- What is the distribution of white dwarf and neutron star binaries in the galaxy?
- How massive can a neutron star be?
- What makes a pulsar glitch?
- What causes intense flashes of X- and gamma-ray radiation in magnetars?
- What is the star formation history of the Universe?





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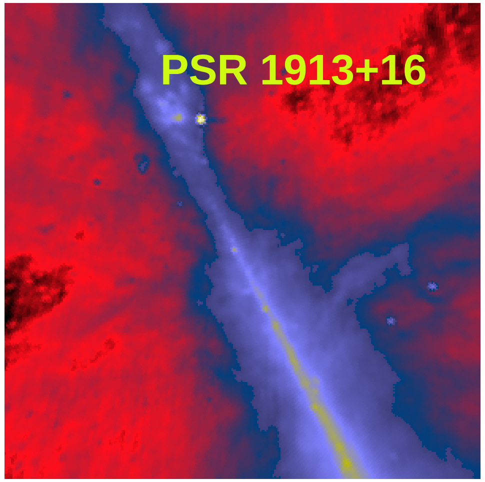
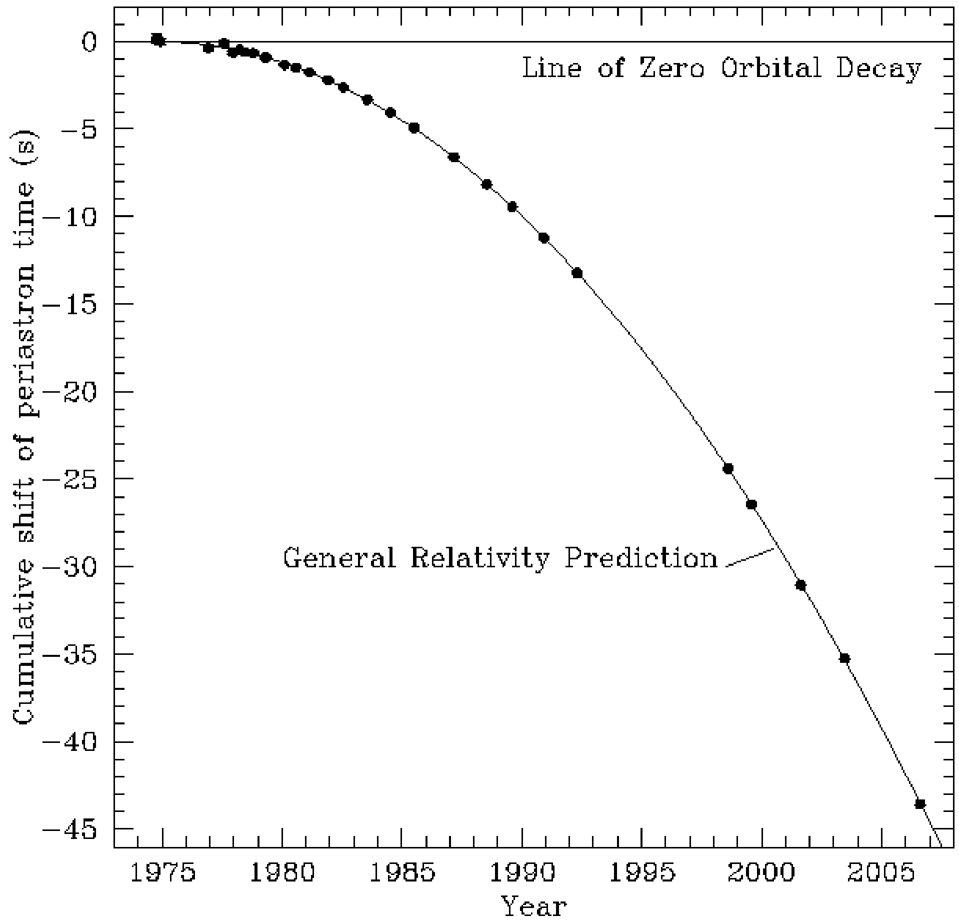
Evidence for gravitational waves

“Indirect” detection from orbital decay of binary pulsar: Hulse & Taylor





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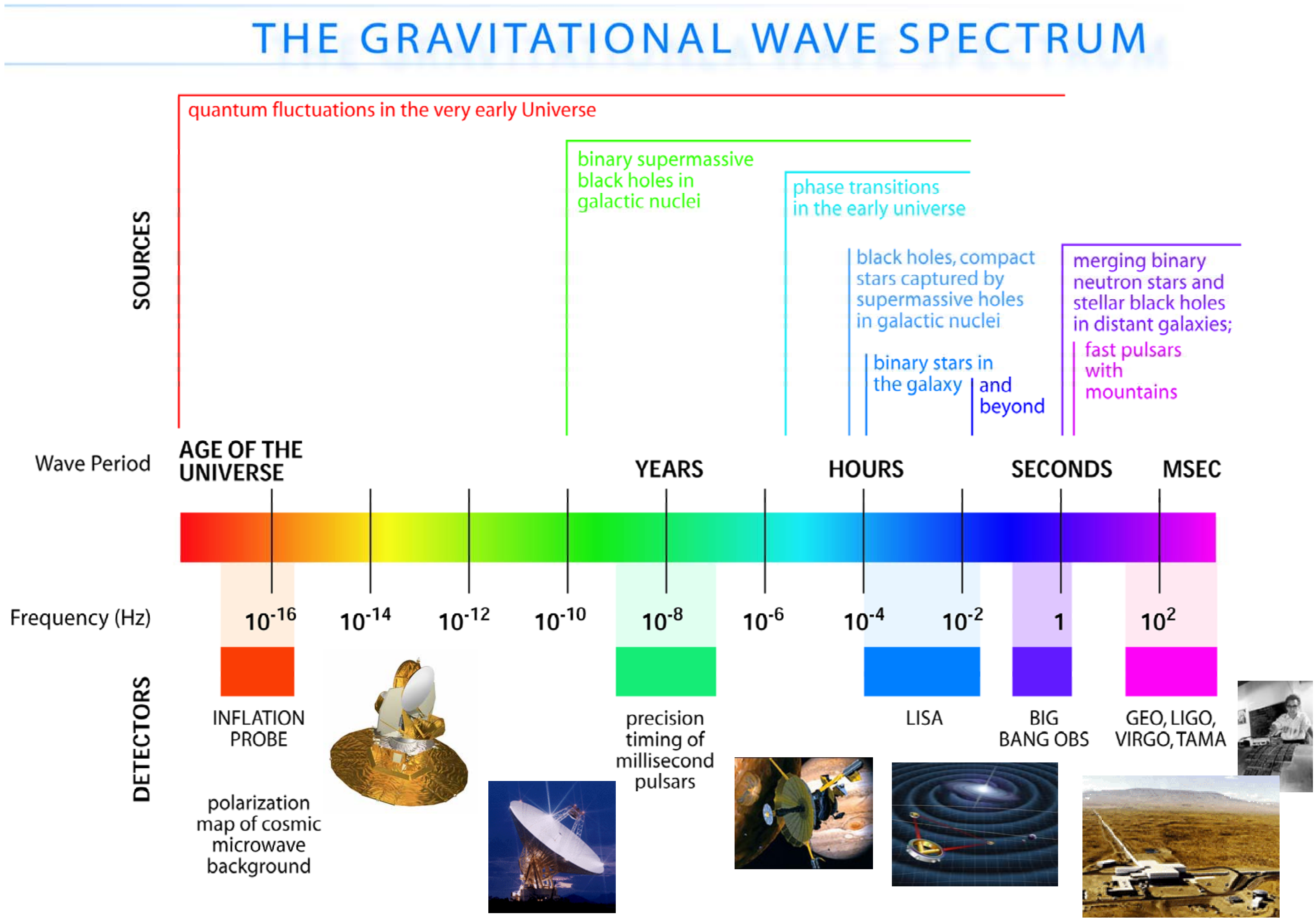
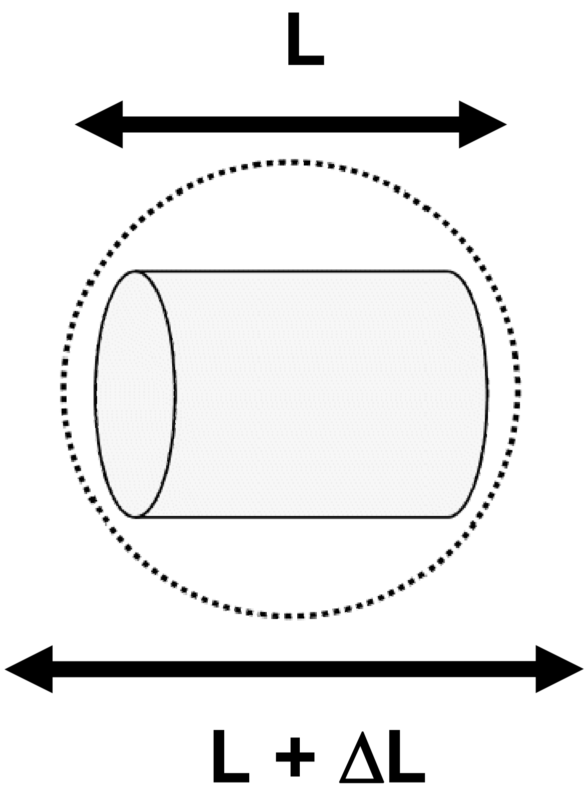
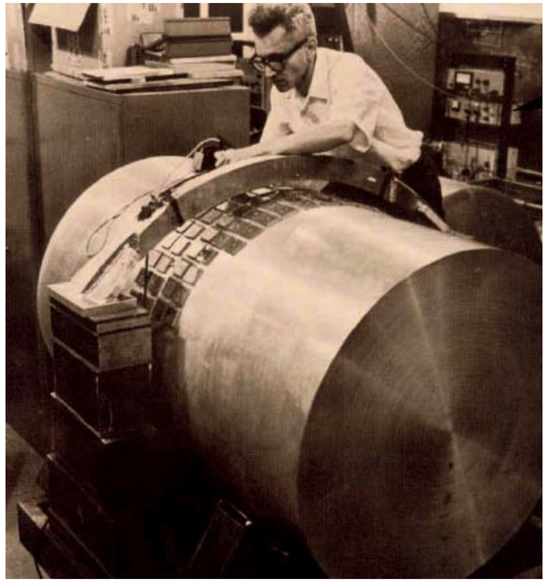

THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
10-16
10-14
10-12
10-10
10-8
10-6
10-4
10-2
1
102
DETECTORS
INFLATION PROBE
polarization map of cosmic microwave background
precision timing of millisecond pulsars
LISA
BIG BANG OBS
GEO, LIGO, VIRGO, TAMA

How can we detect them?

- Gravitational wave amplitude $h \sim \dfrac{\Delta L}{L}$



Sensing the induced excitations of a large bar is one way to measure this



VOLUME 22, NR 24 PHYSICAL REVIEW LETTERS 16 June 1969

EVIDENCE FOR DISCOVERY OF GRAVITATIONAL RADIATION

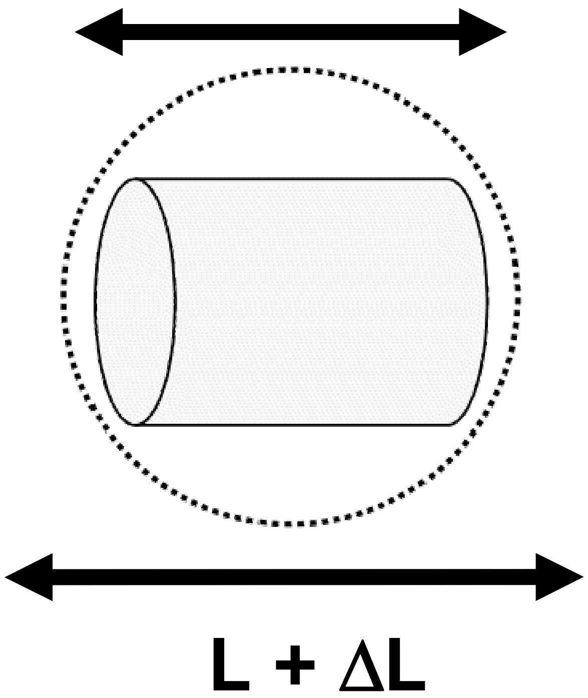
J. Weber

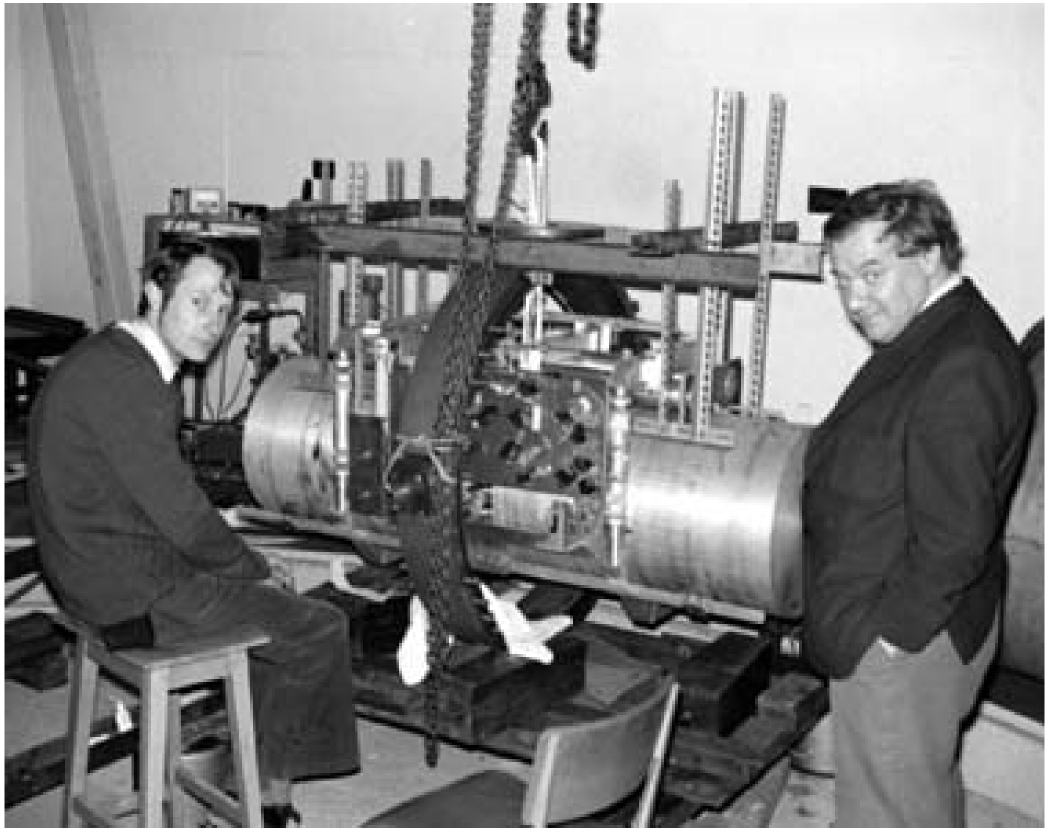
(Received 29 April 1969)

Field originated with J. Weber looking for the effect of strains in space on aluminium bars at room temperature

Claim of coincident events between detectors at Argonne Lab and Maryland – subsequently shown to be false

How can we detect them?

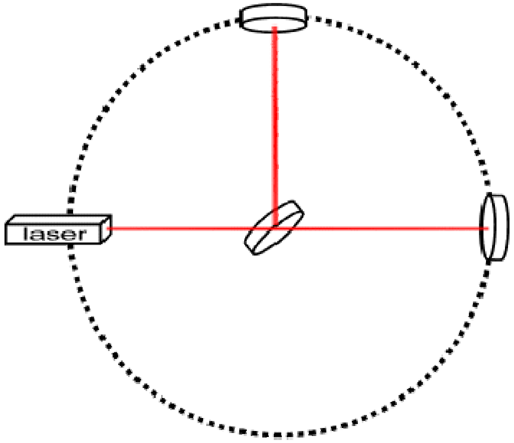




Jim Hough and
Ron Drever, March 1978

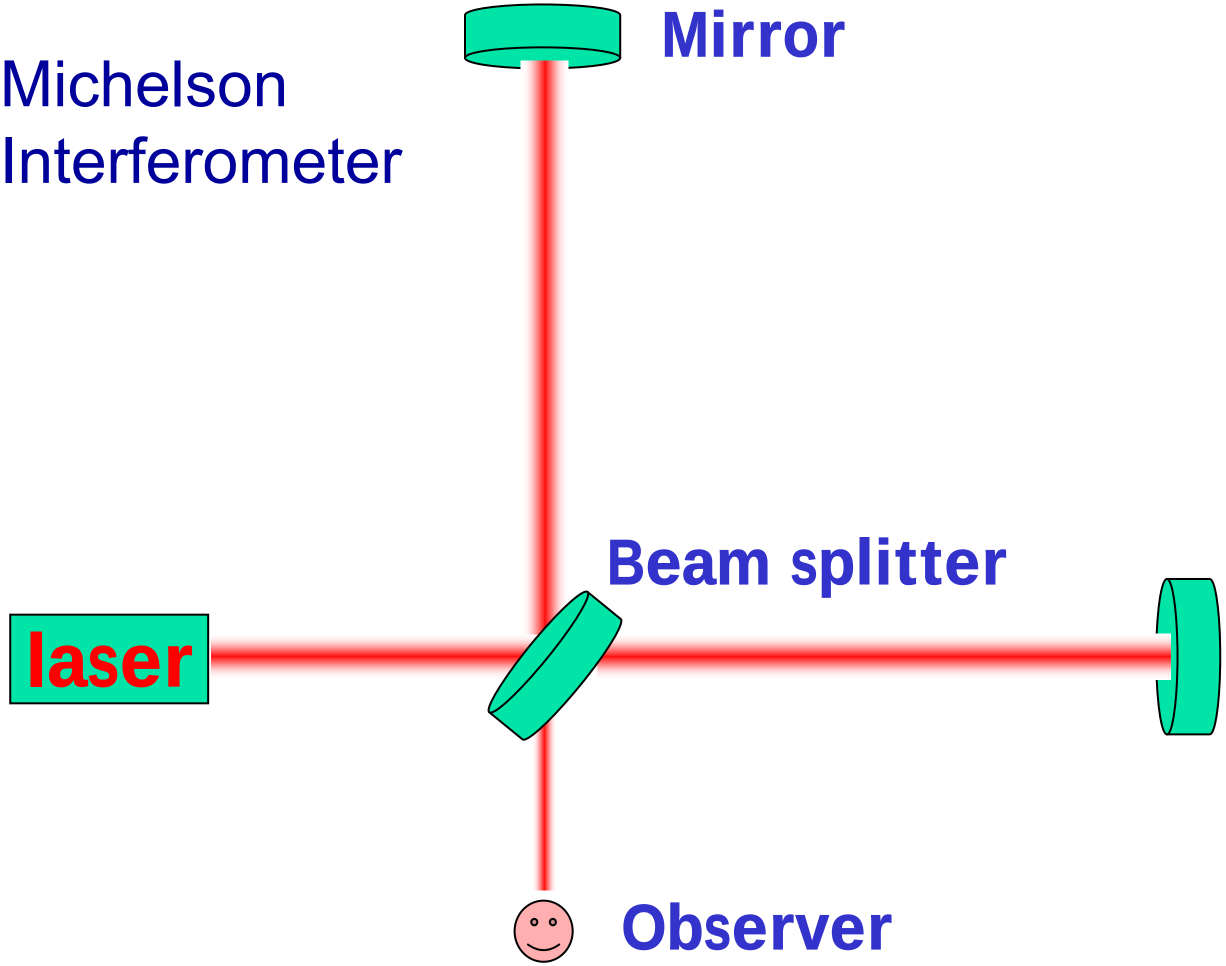
University of Glasgow

32 yrs on - Interferometric ground-based detectors



It's all done with mirrors…

Michelson
Interferometer



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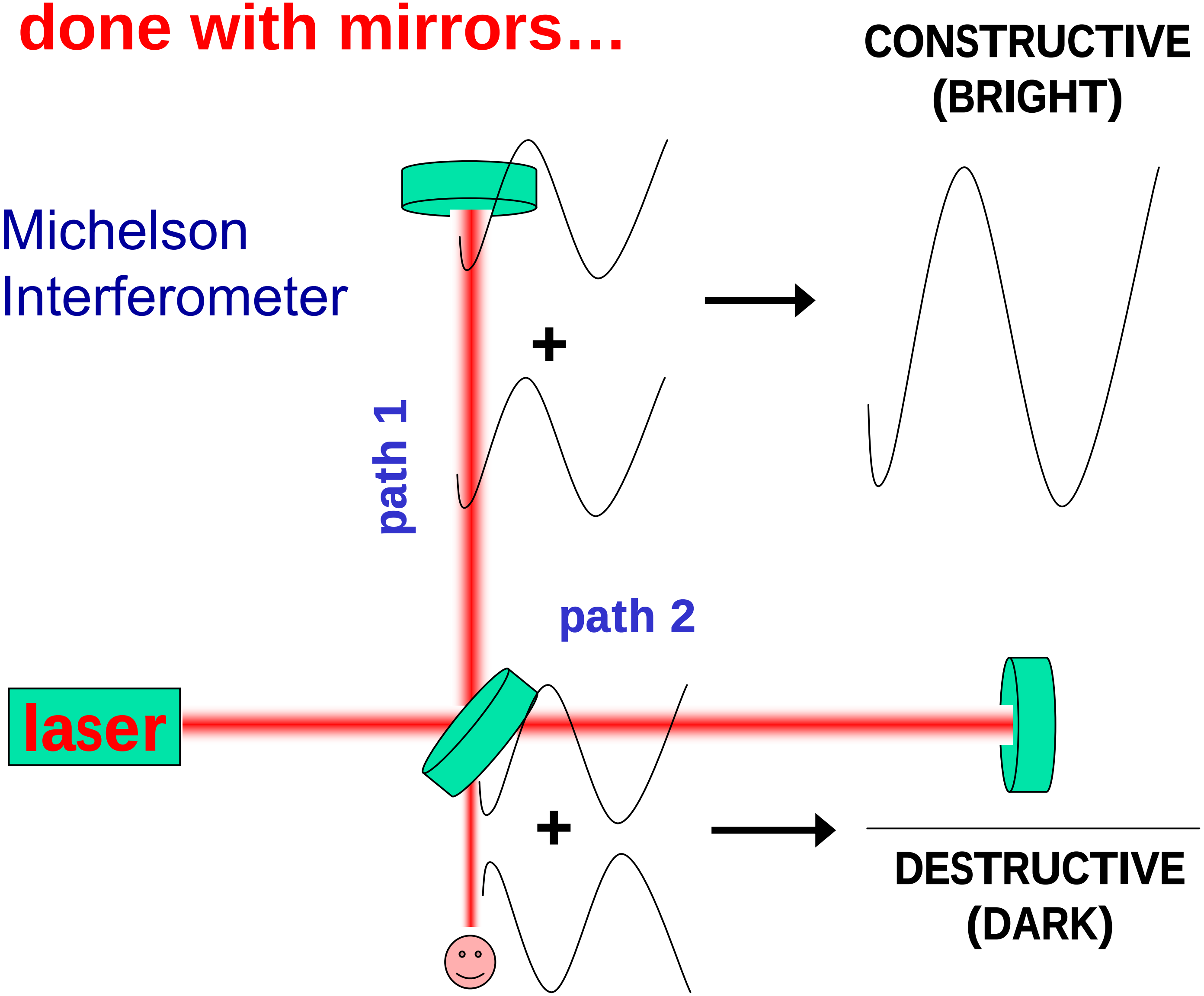

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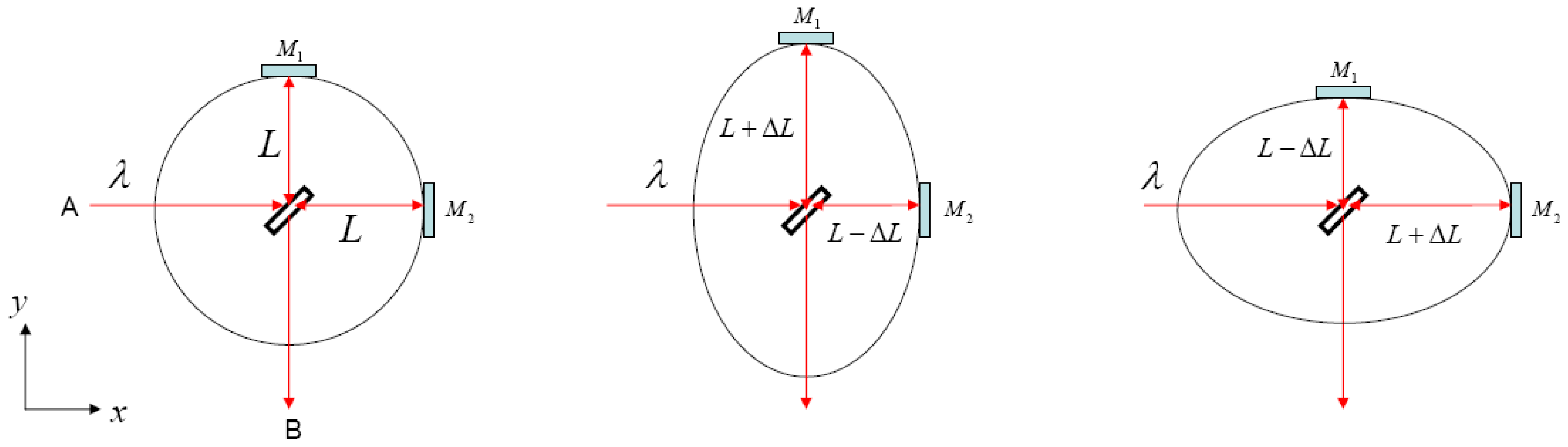
Detecting gravitational waves

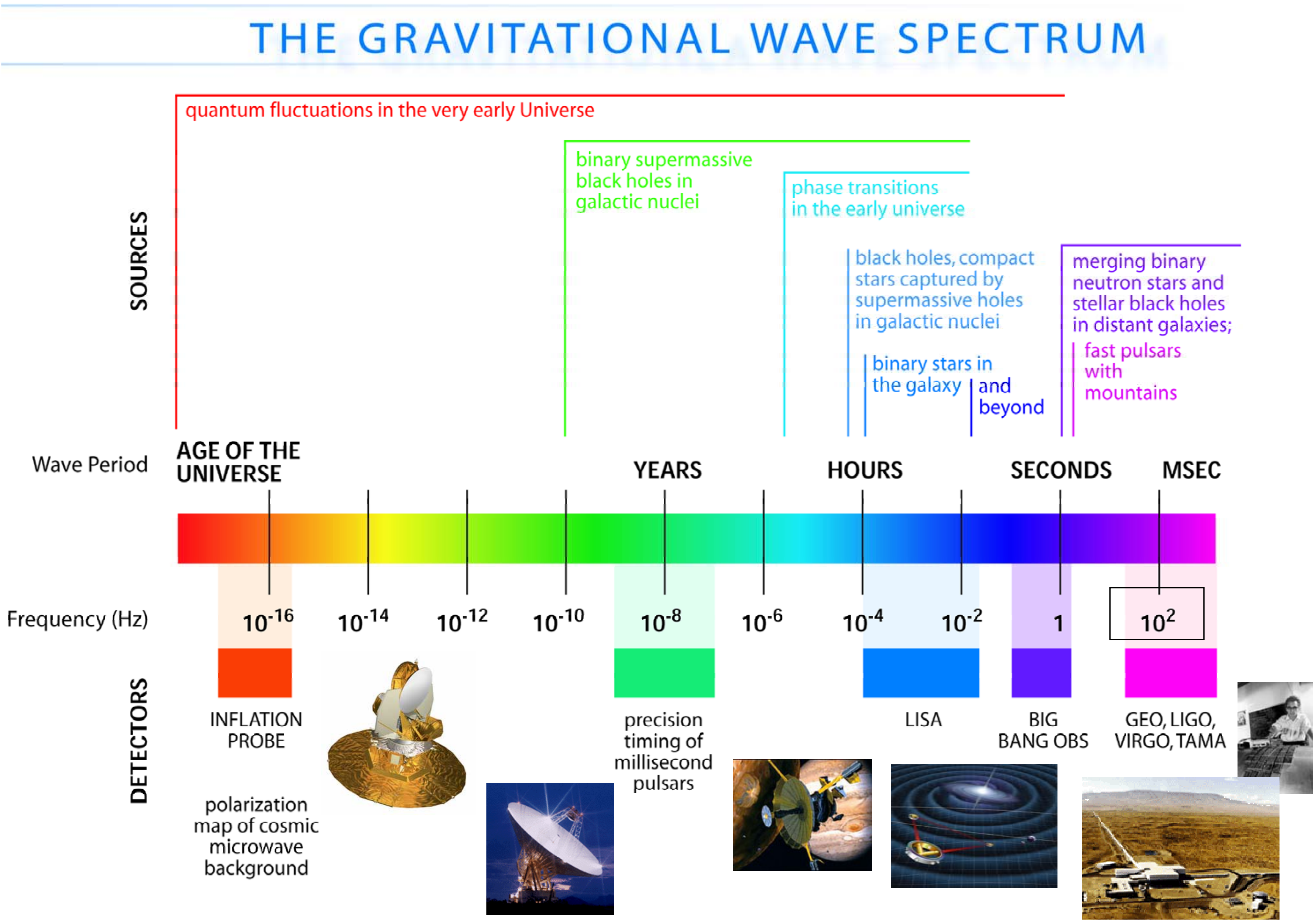
GW produces quadrupolar distortion of a ring of test particles



Dimensionless strain

$$h = \frac{2\Delta L}{L}$$

Expect movements of less than 10^{-18} m over 4km


THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
DETECTORS
INFLATION PROBE
polarization map of cosmic microwave background
precision timing of millisecond pulsars
LISA
BIG BANG OBS
GEO, LIGO, VIRGO, TAMA

Principal limitations to sensitivity – ground based detectors

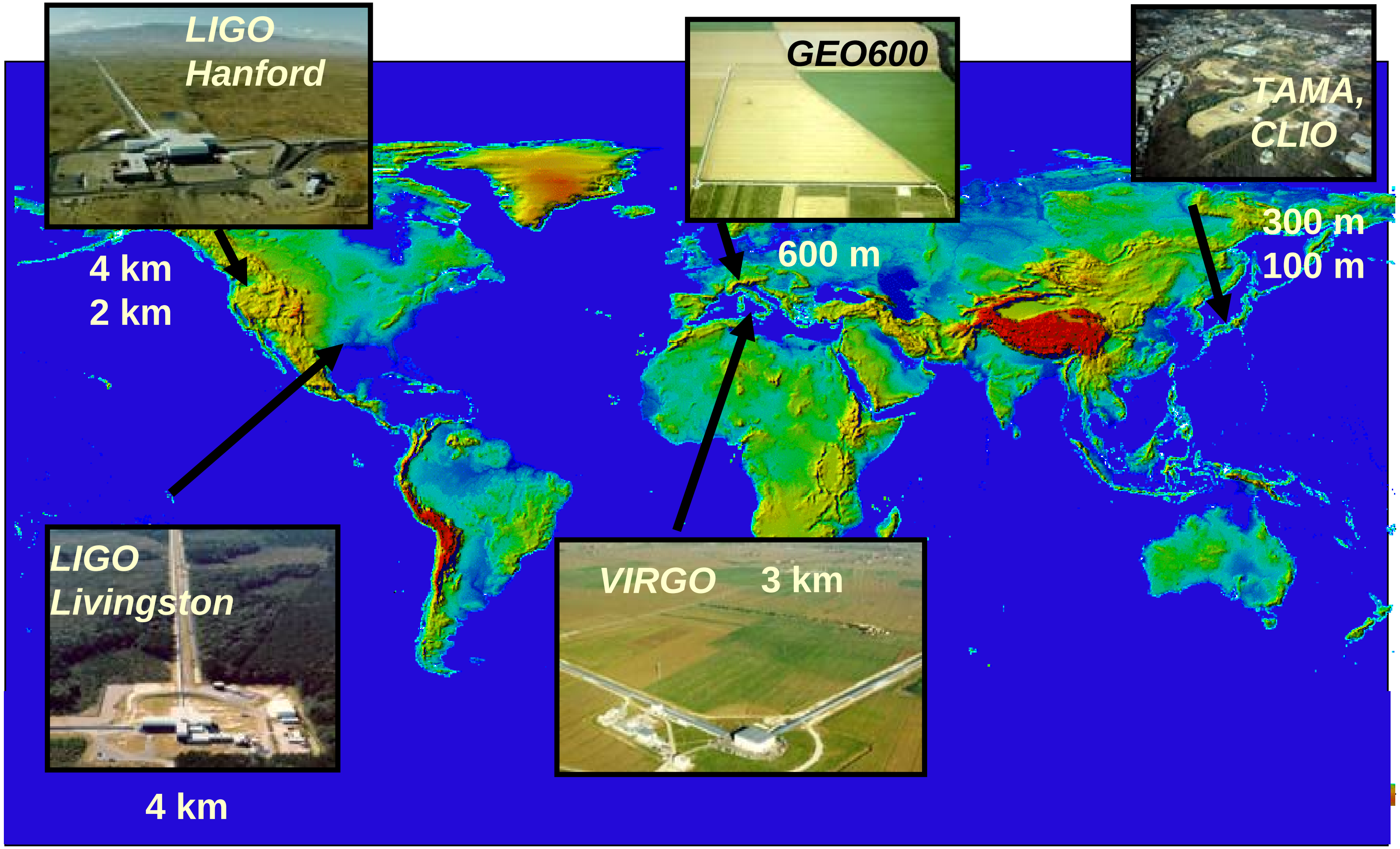
- Photon shot noise (improves with increasing laser power) and
- radiation pressure (becomes worse with increasing laser power)

There is an optimum light power which gives the same limitation expected by application of the Heisenberg Uncertainty Principle – the 'Standard Quantum limit'

- Seismic noise (relatively easy to isolate against – use suspended test masses)
- Gravitational gradient noise, - particularly important at frequencies below ~10 Hz
- Thermal noise – (Brownian motion of test masses and suspensions)

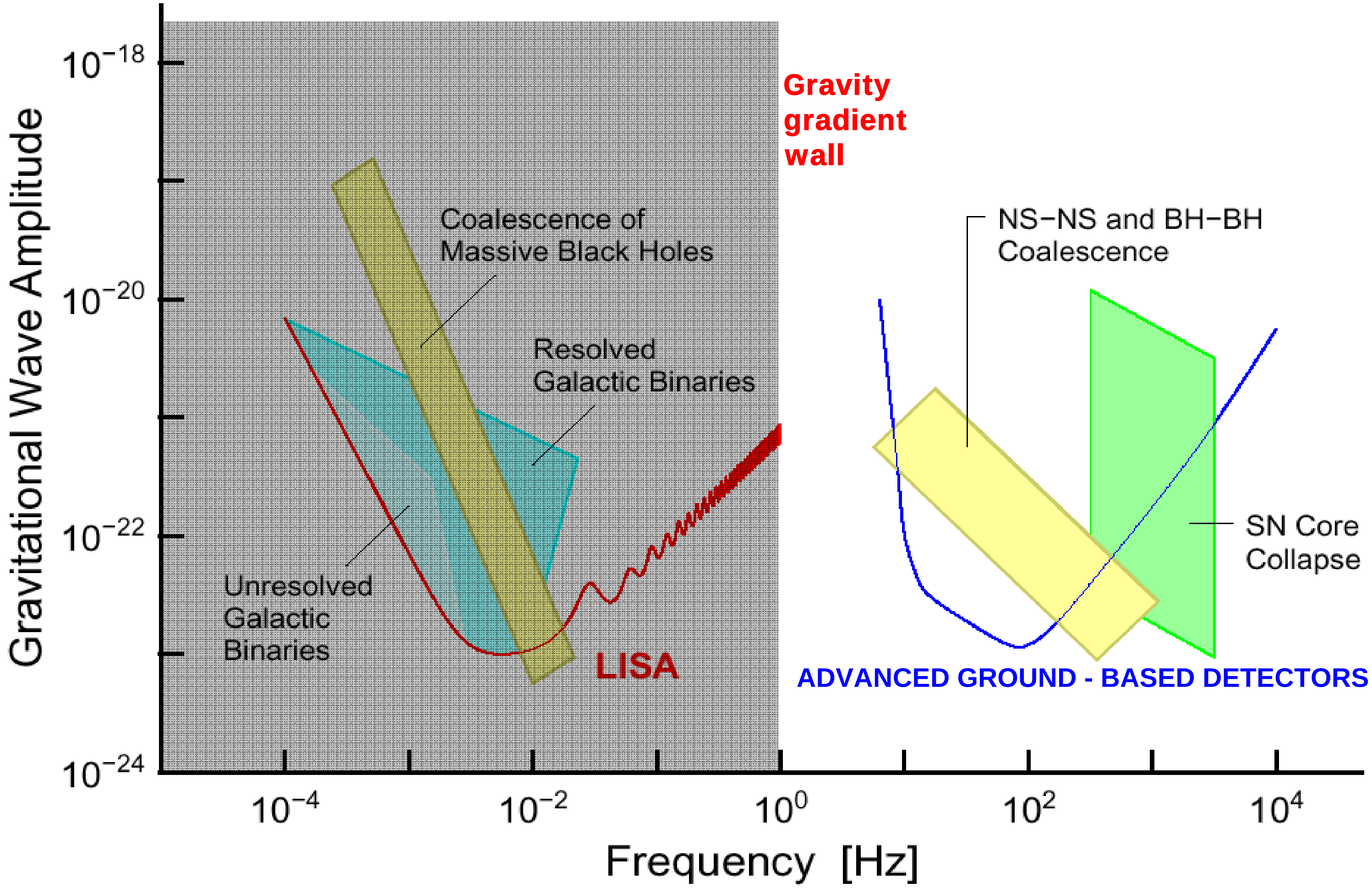
- **All point to long arm lengths being desirable**
  LIGO 4km; Virgo 3km; GEO 600m, TAMA 300m

Ground based Detector Network – audio frequency range

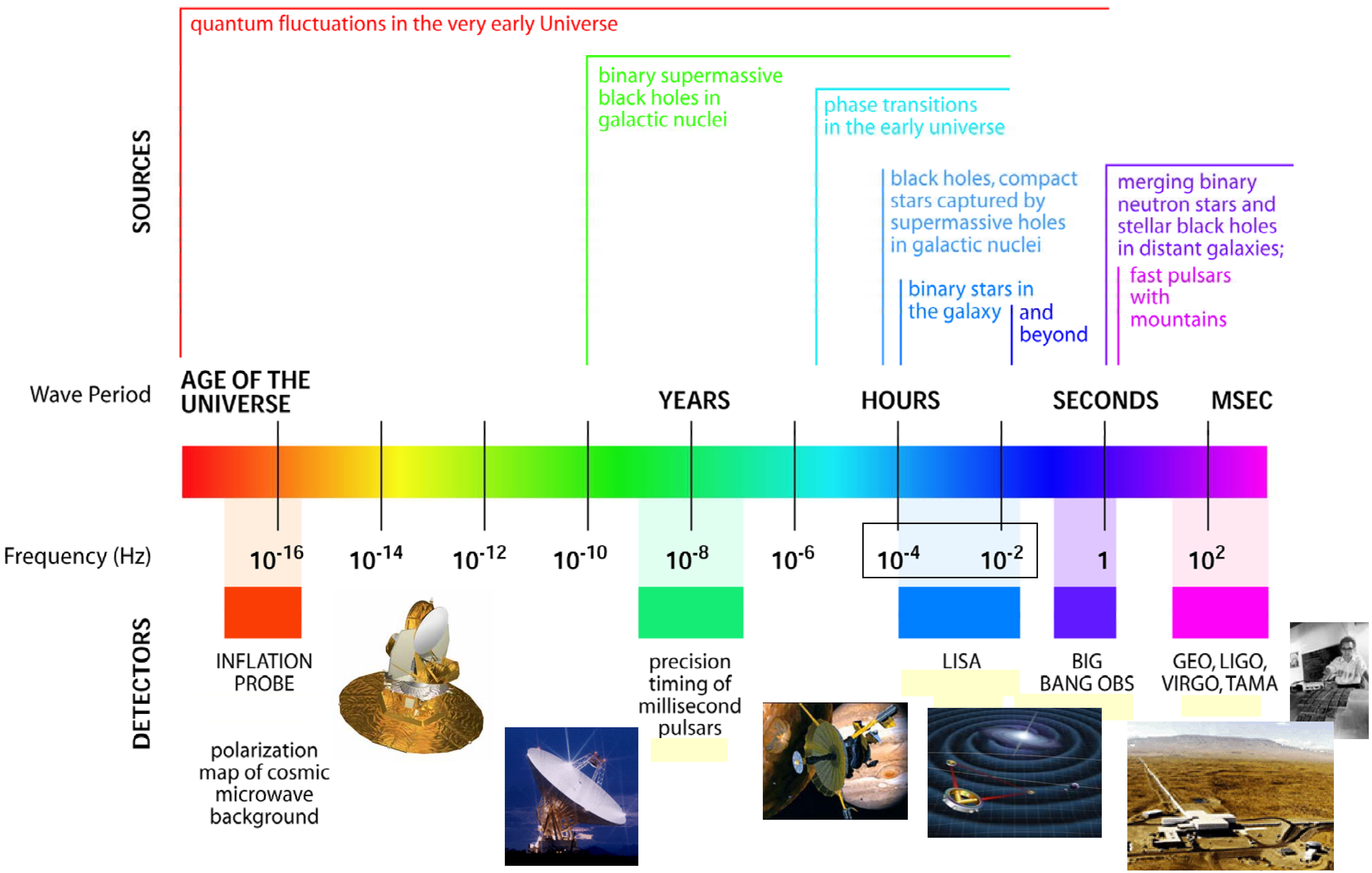


P. Shawhan, LIGO-G0900080-v1

Sources – the gravitational wave spectrum



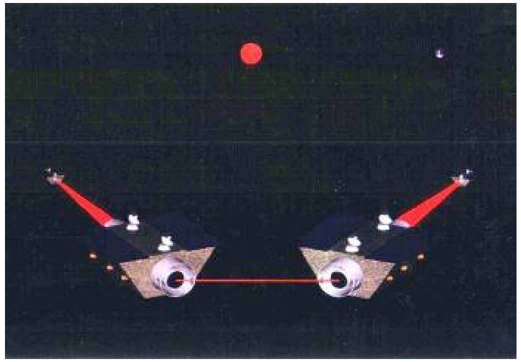
THE GRAVITATIONAL WAVE SPECTRUM

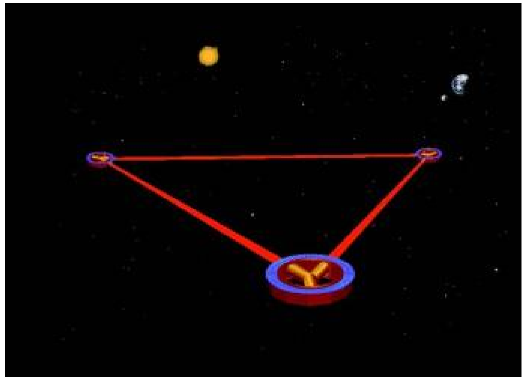


LISA: Laser Interferometric Space Antenna

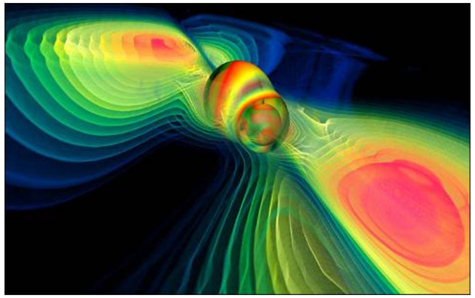
LISA – a joint ESA/NASA Mission to study Black hole physics, and much more, in the frequency range 10^{-4} Hz -10^{-1} Hz

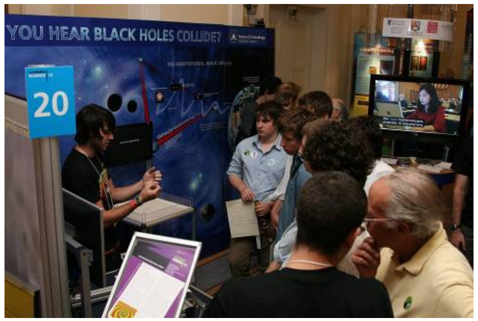
- After first studies in 1980s, M3 proposal for 4 S/C ESA/NASA collaborative mission in 1993
- LISA selected as ESA Cornerstone in 1995
- *3 S/C NASA/ESA LISA appears in 1997*
- **Baseline concept unchanged ever since!**



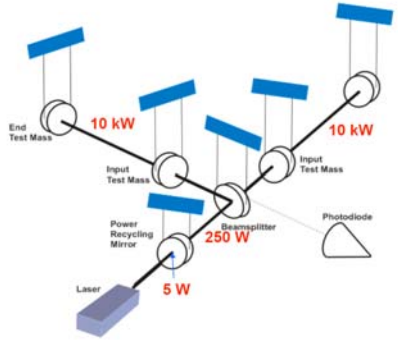


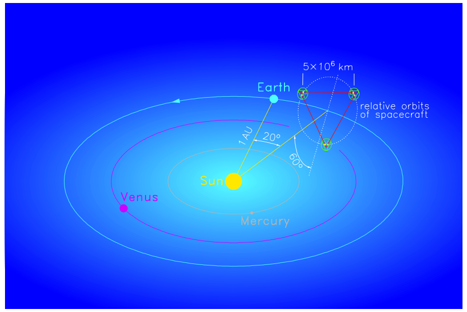
Real progress in GW astronomy over past few years





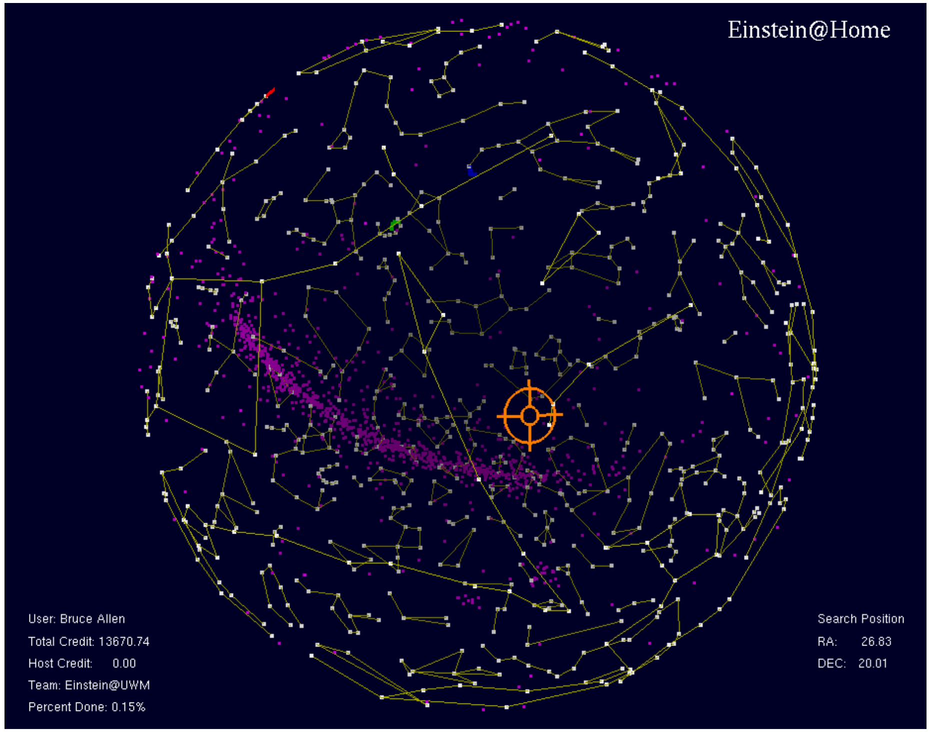
- **Operation of six ground based interferometers** (in addition to three cryogenic bar detectors)
- Advances in waveform predictions from Numerical Relativity
- Significant advances in Space Borne Detectors – **LISA** and DECIGO
- **Pulsar Timing** coming to the fore
- Importance of **Multi-messenger Astronomy**
- Using wider interest in relativity, cosmology and fundamental physics to bring science to **schools and the public**.





Einstein@Home

- Like SETI@home, but for LIGO/GEO data
- BOINC-based; ~100,000 active host machines
- ~80 Tflop of continuous processing power → CW searches
- Originally targeted as screensaver application. Now ported to German D-grid; effort to extend to US OSG.
- *Scope for extension to UK and Euro grids?*



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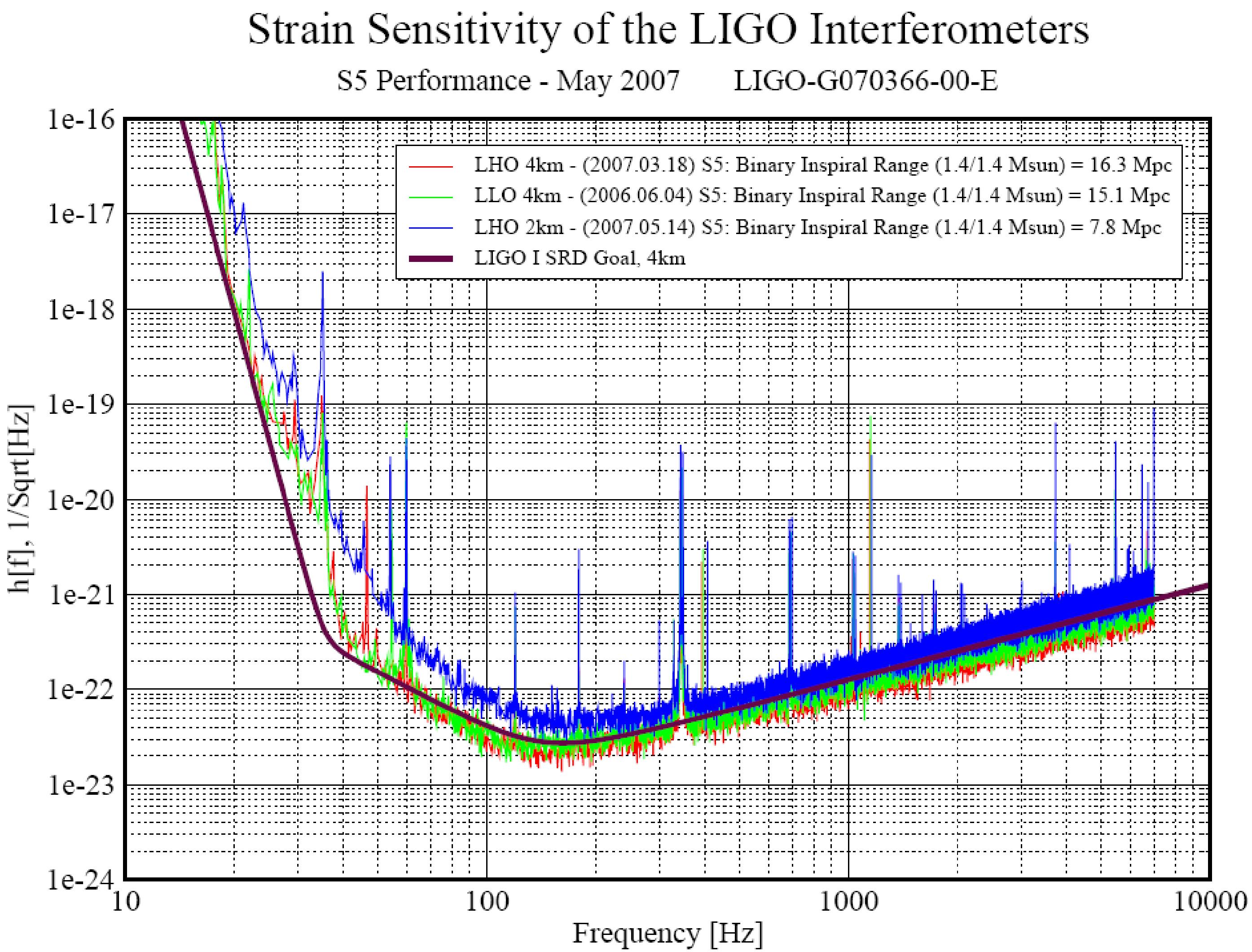
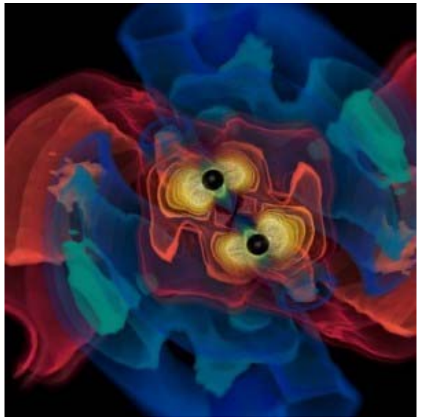
Current Status 1 -LIGO now at design sensitivity



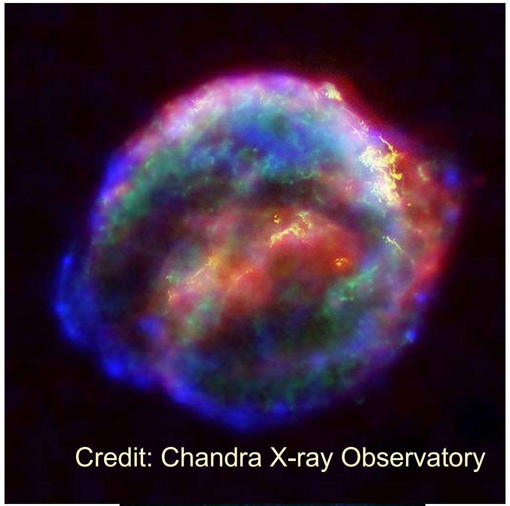
Current status 2: the advent of GW astronomy

- Initial Science Runs Complete (LIGO, Virgo, GEO 600, TAMA)
- Upper Limits set on a range of sources (no detections as yet)


Credit: AEI, CCT, LSU

Coalescing Binary Systems

• Neutron stars, low mass black holes, and NS/BS systems

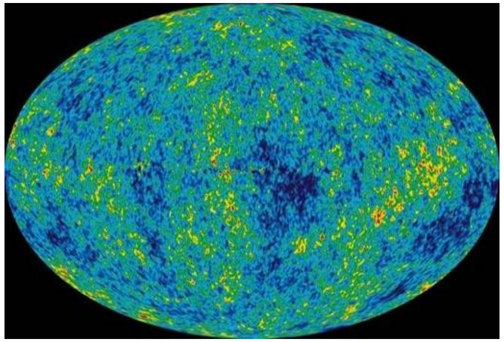

Credit: Chandra X-ray Observatory

'Bursts'

• galactic asymmetric core collapse supernovae

• cosmic strings

• ???


NASA/WMAP Science Team

Cosmic GW background

• stochastic, incoherent background

• unlikely to detect, but can bound in the 10-10000 Hz range


Casey Reed, Penn State

Continuous Sources

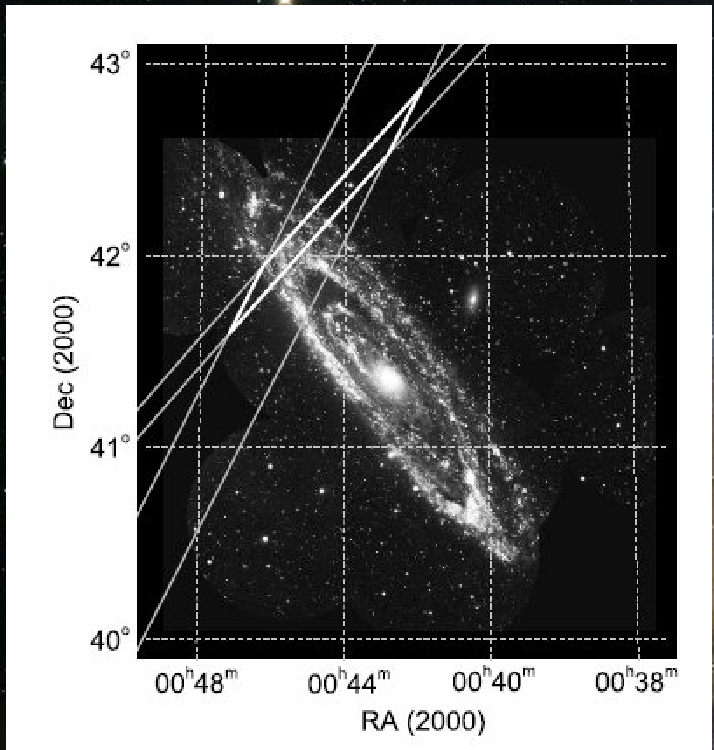
• Spinning neutron stars

• probe crustal deformations, 'quarki-ness'

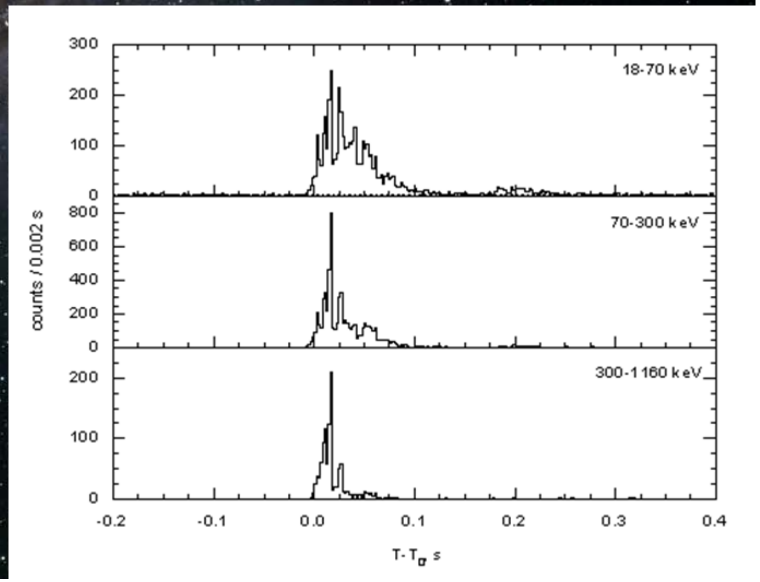
University of Glasgow

Example: GRB070201, *Not a Binary Merger in M31*

Refs:
GCN: http://gcn.gsfc.nasa.gov/gcn3/6103.gcn3



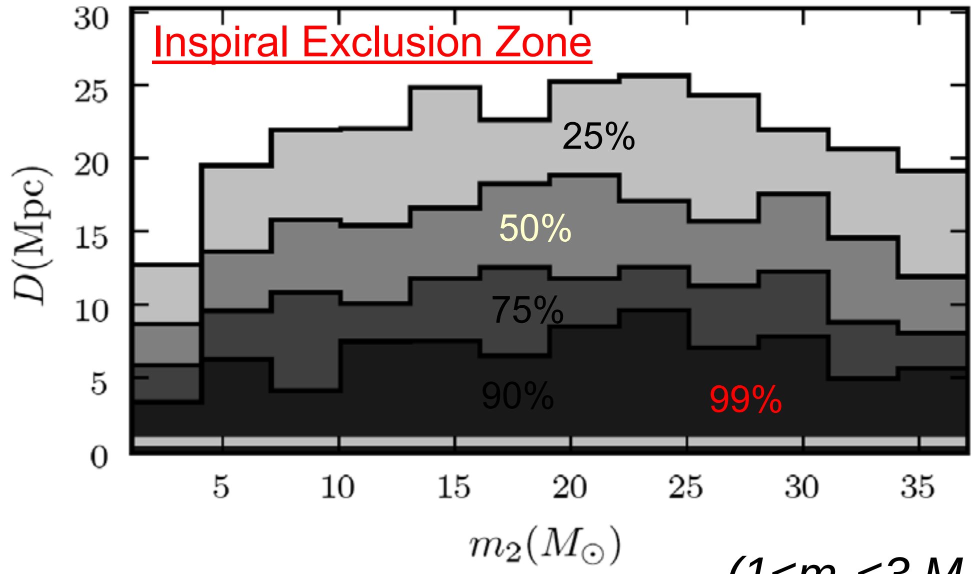
X-ray emission curves (IPN)



Example: GRB070201, *Not a Binary Merger in M31*

- **Inspiral (matched filter search:**
  - **Binary merger in M31 scenario excluded at >99% level**
  - **Exclusion of merger at larger distances**

Abbott, et al. "Implications for the Origin of GRB 070201 from LIGO Observations", Ap. J., 681:1419–1430 (2008).



($1<m_1<3\ M_{sun}$)

- **Burst search:**
  - **Cannot exclude an SGR in M31**

    SGR in M31 is the current best explanation for this emission
  - **Upper limit: 8×10^{50} ergs ($4 \times 10^{-4}\ M_\odot c^2$) (emitted within 100 ms for isotropic emission of energy in GW at M31 distance)**

Current status 3: coming attractions!

- **Enhancements to LIGO and Virgo at end of commissioning**
  - **aimed at a factor of two improvement in sensitivity**
  - **meanwhile GEO, LIGO and cryogenic bar detectors have maintained 'astrowatch'**

- **New science runs recently started (July 7th 2009)**

- **2nd generation detectors**
  - **Advanced LIGO fully funded (10 to 15 x improved sensitivity, operational ~2014)**

For Comparison:

Neutron Star Binaries:

- **Initial LIGO (S5): ~15 Mpc → rate ~1/50yr**
- **Adv LIGO: ~ 200 Mpc → rate ~ 40/year**

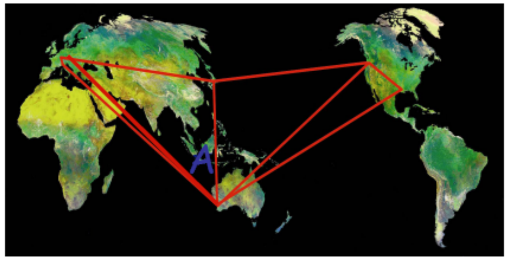
Black Hole Binaries (Less Certain):

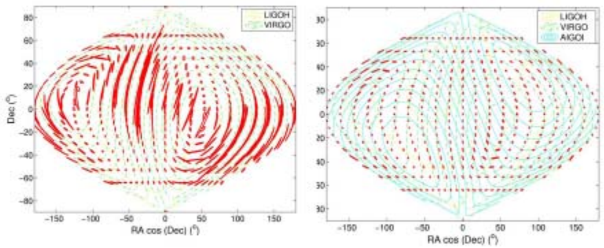
- **Initial LIGO (S5): ~100 Mpc → rate ~1/100yr**
- **Adv LIGO: ~ 1 Gpc → rate ~ 20/year**

  - **Advanced Virgo approved (Dec 4th 2009)**
  - **GEO-HF conversion starting**

Future developments – on the ground

Need a network of detectors for good source location and improve overall sensitivity





Second Generation Network

Advanced LIGO/Advanced Virgo/Geo-HF/LCGT/AIGO

- **LCGT under review (proposed cryo, underground interferometer in Kamioka mine)**
- **AIGO plans progressing (proposed interferometer in Western Australia)**

University of Glasgow

SUPA IGR

Future developments – on the ground

Third Generation Network — Incorporating Low Frequency Detectors

- Third-generation underground facilities are aimed at having excellent sensitivity from ~1 Hz to ~10^4 Hz.
- This will greatly expand the new frontier of gravitational wave astrophysics.

Recently begun:

Three year-long European design study, with EU funding, underway for a 3rd-generation gravitational wave facility, the **Einstein Telescope** (ET).

Goal: **100 times** better sensitivity than first generation instruments.

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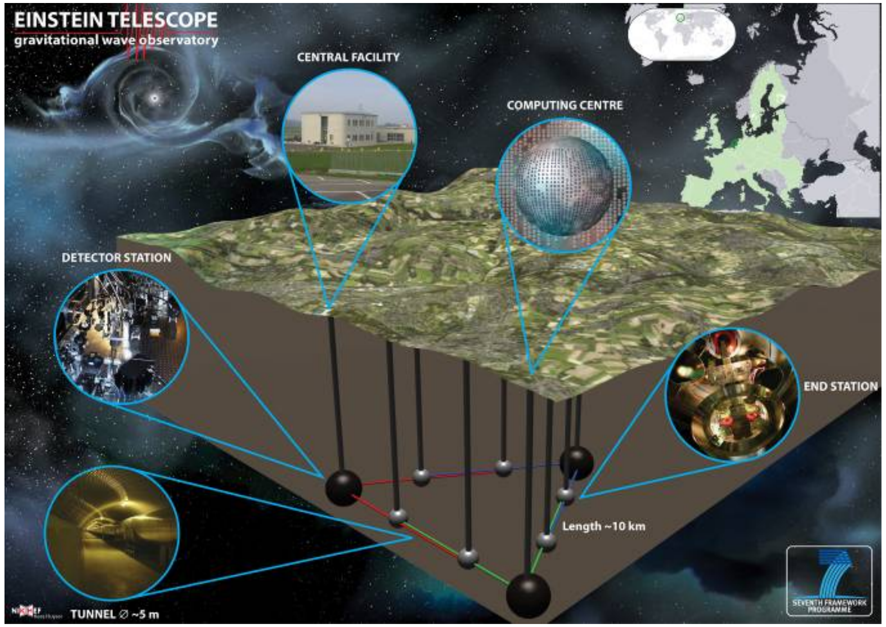

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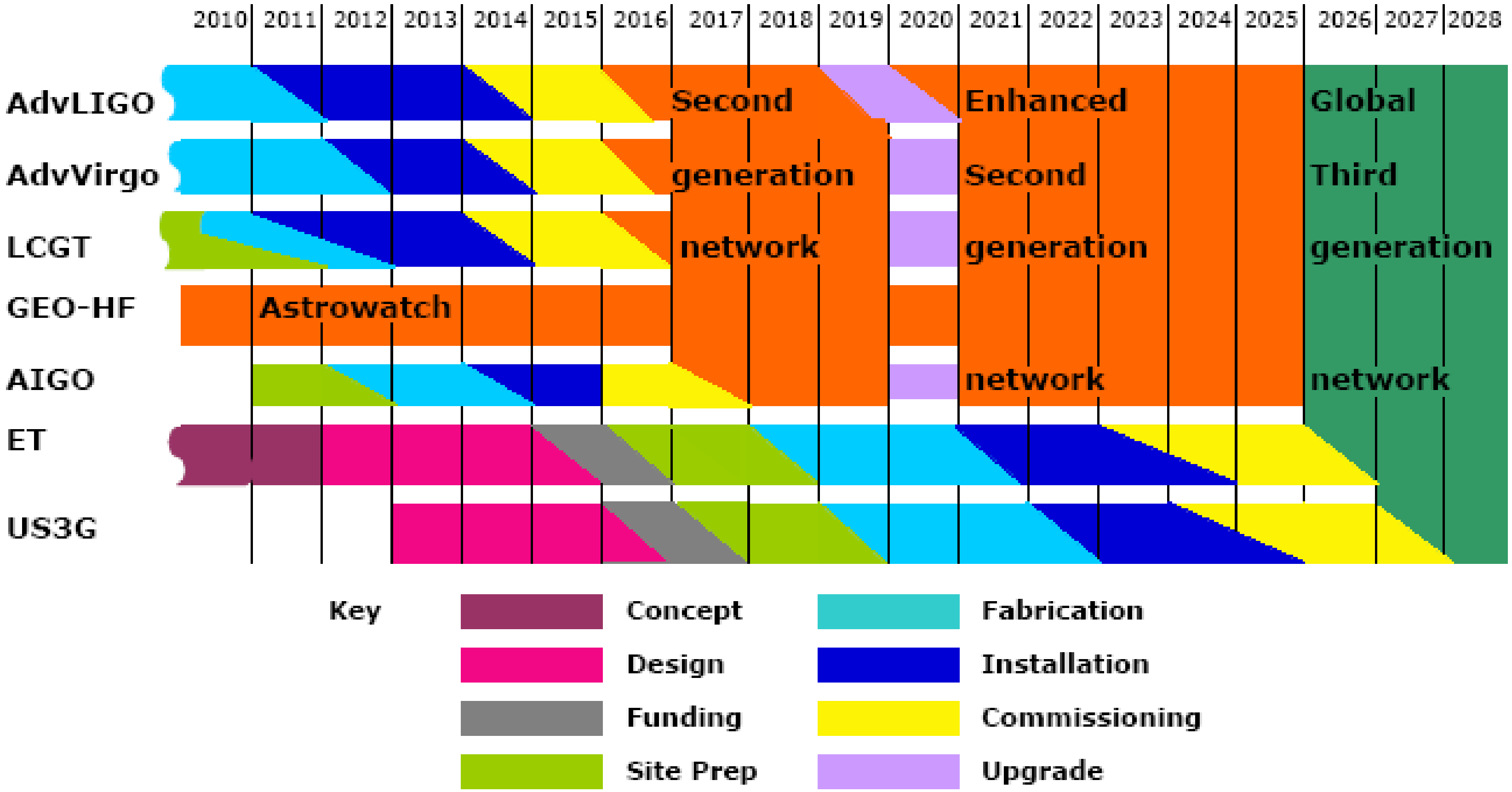
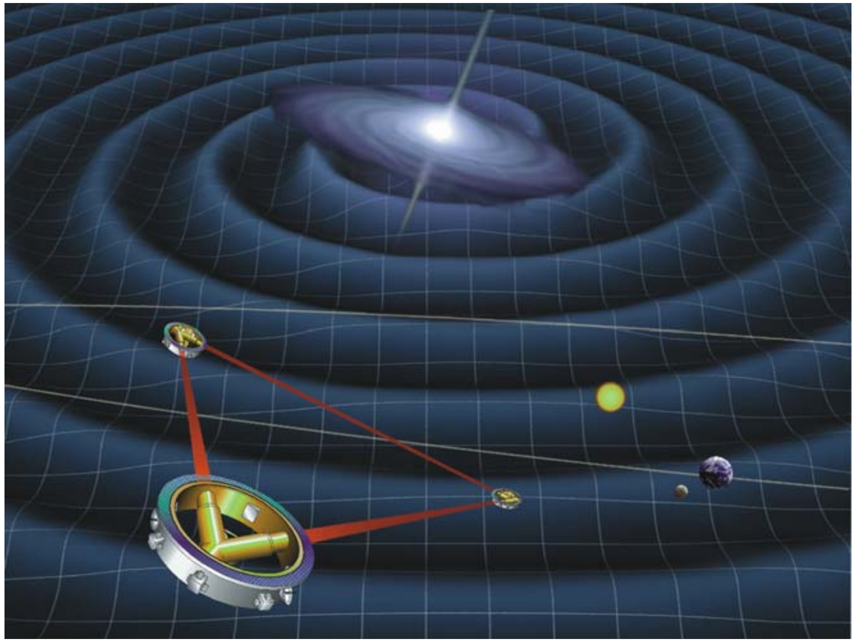


Future developments – in space

LISA (Laser Interferometer Space Antenna)

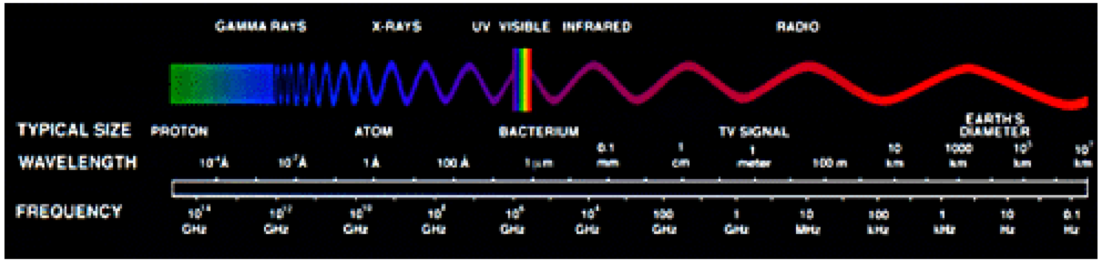
10^{-4} Hz – 10^{-1} Hz Our first priority for a space based mission

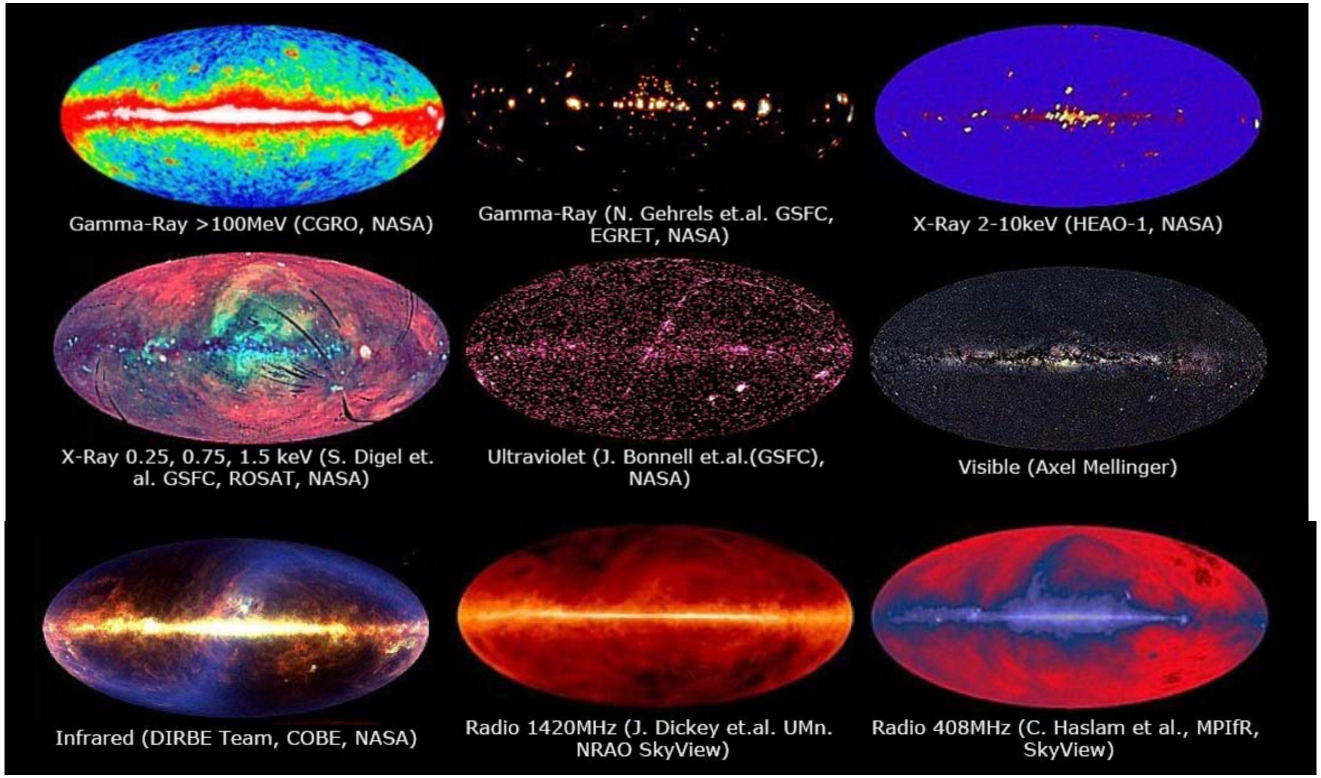


Mission Description

- 3 spacecraft in Earth-trailing solar orbit, separated by 5 x10^6 km.
- Gravitational waves are detected by measuring change in proper distance between fiducial masses in each spacecraft using laser interferometry
- Partnership between NASA and ESA
- Launch date: soon after 2020?...

Opening a new window on the Universe





Gamma-Ray >100MeV (CGRO, NASA)

Gamma-Ray (N. Gehrels et.al. GSFC, EGRET, NASA)

X-Ray 2-10keV (HEAO-1, NASA)

X-Ray 0.25, 0.75, 1.5 keV (S. Digel et. al. GSFC, ROSAT, NASA)

Ultraviolet (J. Bonnell et.al.(GSFC), NASA)

Visible (Axel Mellinger)

Infrared (DIRBE Team, COBE, NASA)

Radio 1420MHz (J. Dickey et.al. UMn. NRAO SkyView)

Radio 408MHz (C. Haslam et al., MPIfR, SkyView)

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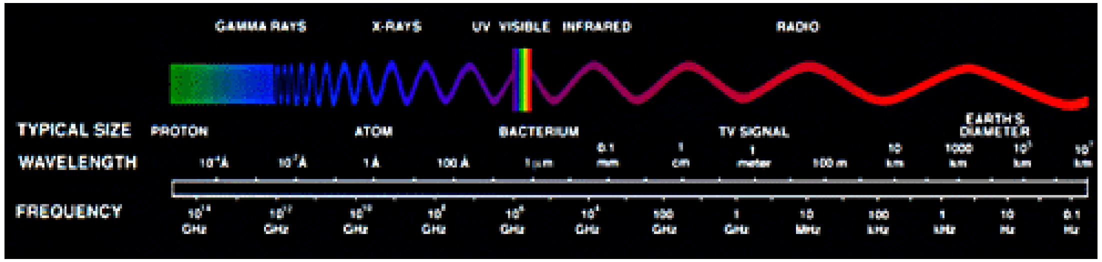
SUPA IGR

Opening a new window on the Universe



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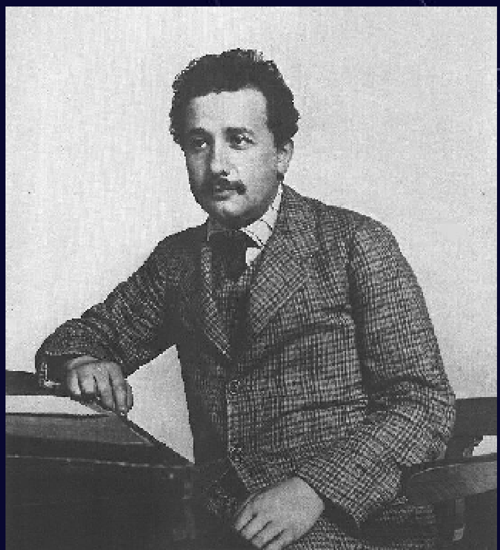
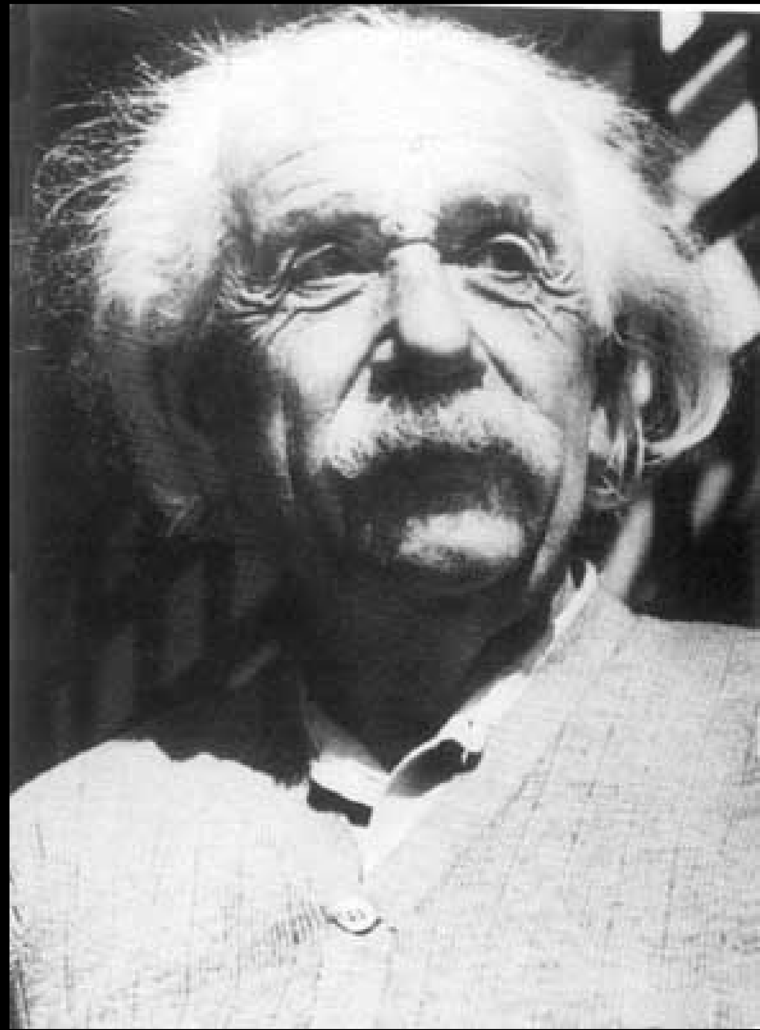
Einstein's Universe

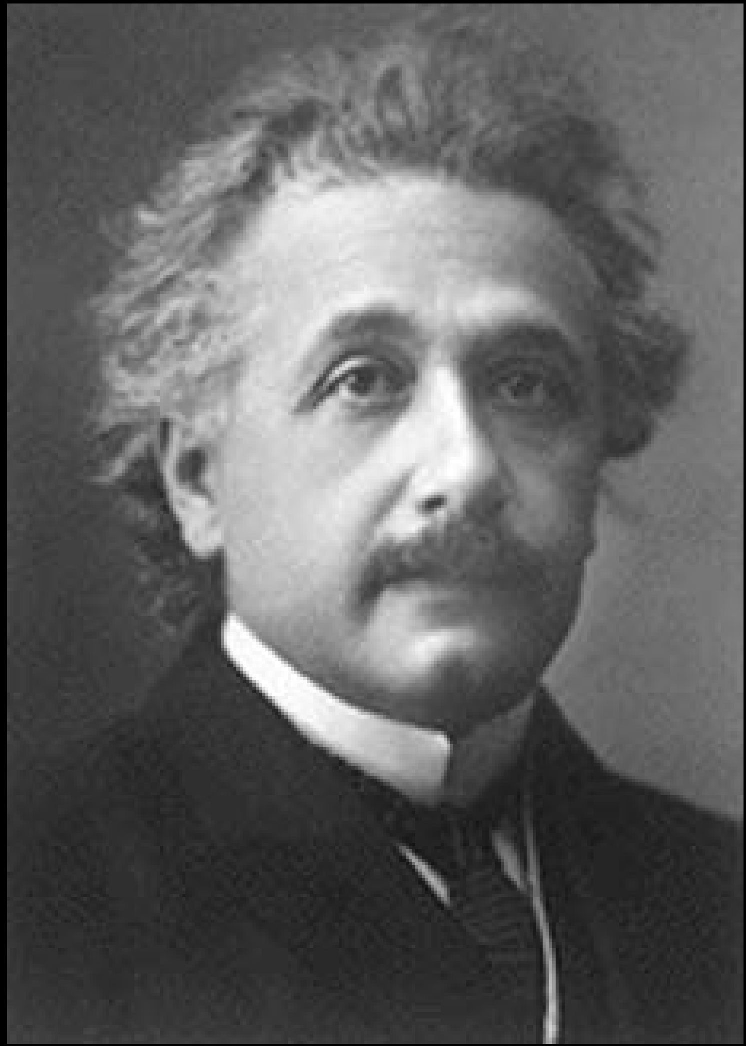


Isaac Newton



Albert Einstein

Isaac Newton



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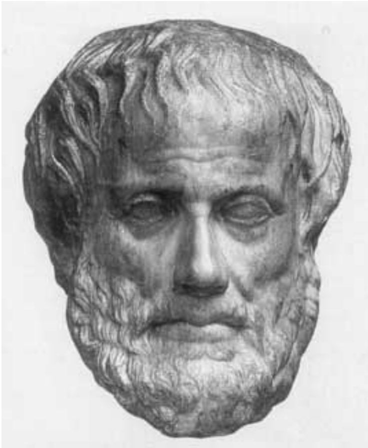
Isaac Newton

Galileo Galilei

How do things move?….



Aristotle's Theory:

1. *Objects move only as long as we apply a force to them*
2. *Falling bodies fall at a constant rate*
3. *Heavy bodies fall faster than light ones*

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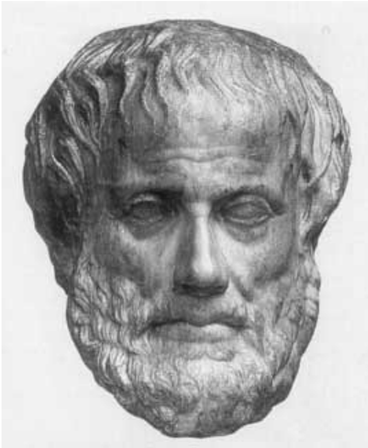

V

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Galileo's Experiment:

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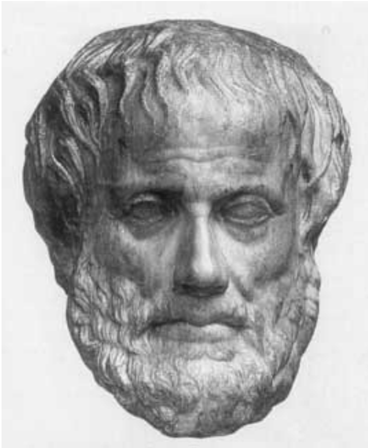

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Apollo 15 astronaut David Scott

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Newton built on Galileo's work and proposed 3 laws of motion:

1. A body moves in a straight line unless acted on by some force

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$$F = ma$$

How do things move?….

Newton built on Galileo’s work and proposed 3 laws of motion:

1. A body moves in a straight line unless acted on by some force
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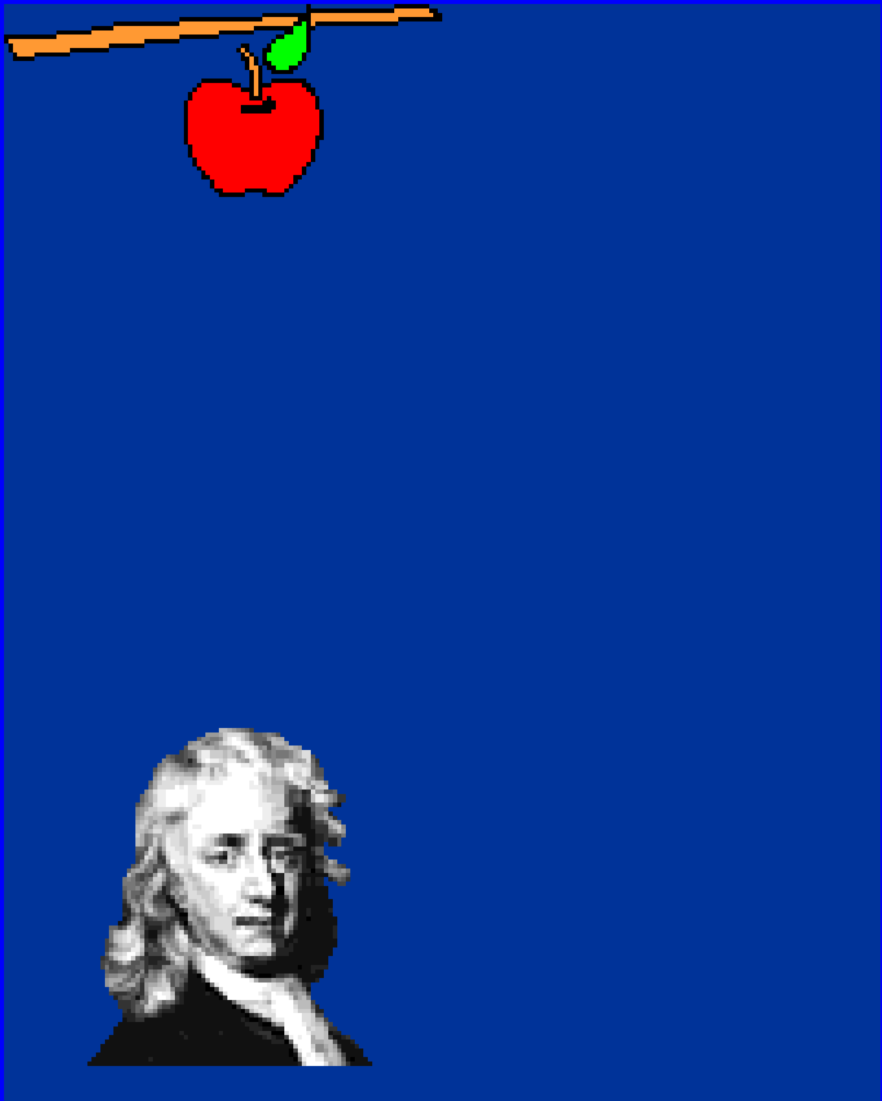
$$F = ma$$

3. To every action there is an equal and opposite reaction



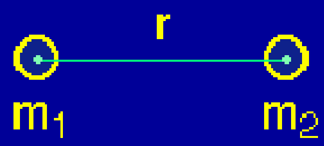
Isaac Newton:
1642 – 1727 AD

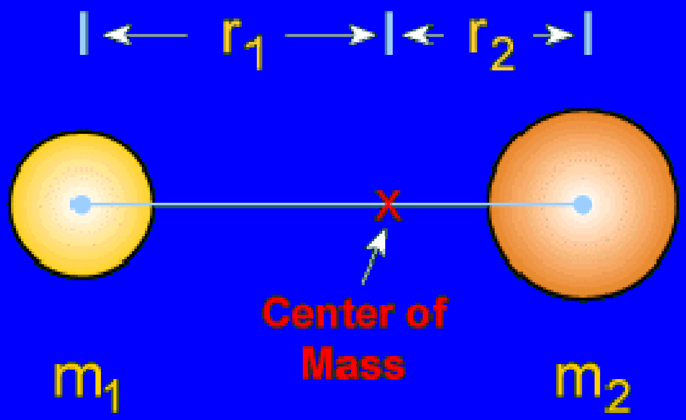
The Principia: 1684 - 1686

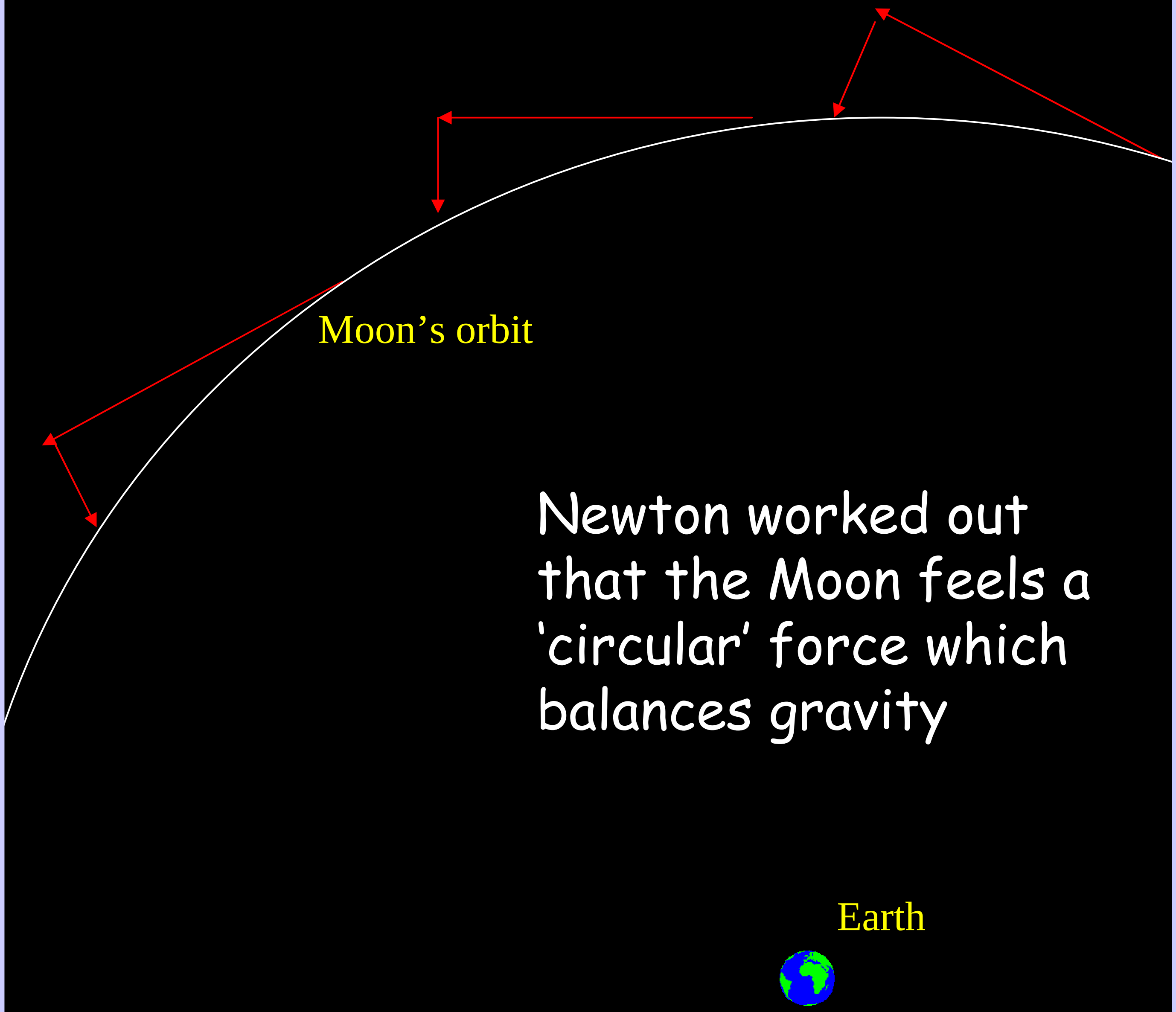
Law of Universal Gravitation

Every object in the Universe attracts every other object with a force directed along the line of centers for the two objects that is proportional to the product of their masses and inversely proportional to the square of the separation between the two objects.

$$F_g = G\frac{m_1 m_2}{r^2}$$







Newton worked out that the Moon feels a ‘circular’ force which balances gravity

Classical Physics:

"All the World's A Stage"

- Newton's physics assumes absolute space and time.
- Working out how things look to different observers follows simple rules, in different *reference frames*

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Classical Physics:

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- **Newton's physics assumes absolute space and time.**
- **Working out how things look to different observers follows simple rules, in different *reference frames***

Viewed from the blue car's rest frame

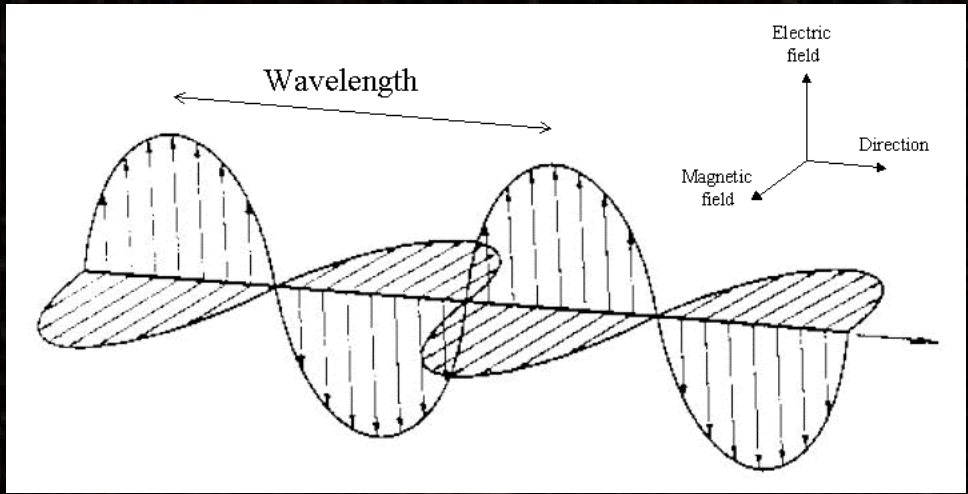
Classical Physics:

"All the World's A Stage"

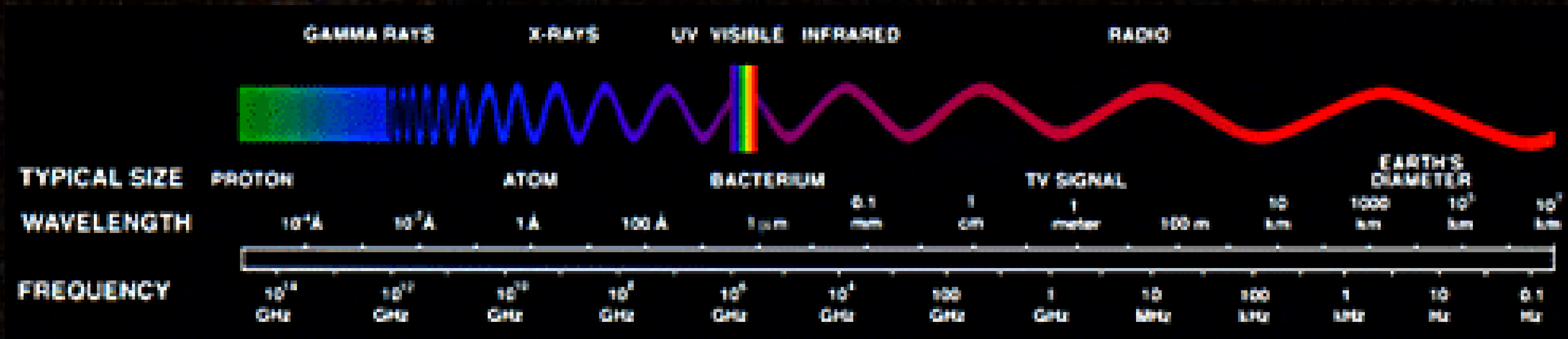
- Newton's physics assumes absolute space and time.
- Working out how things look to different observers follows simple rules, in different *reference frames*
- The laws of physics are the same for everyone, everywhere!

Classical Physics:

Maxwell's theory of light



Light is a *wave* – *electromagnetic radiation*



Classical Physics:

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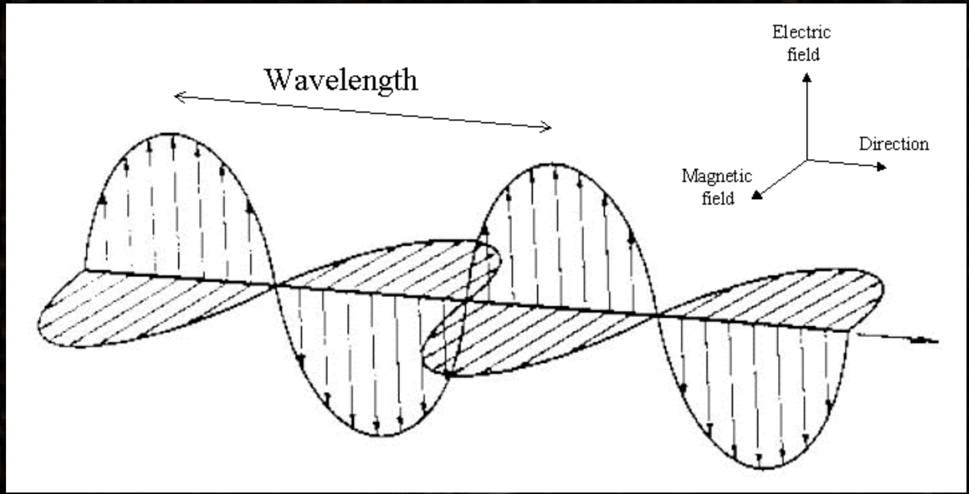

Light is a *wave* – *electromagnetic radiation*

Maxwell's Equations imply

Speed of light = 300,000 km/s

Classical Physics:

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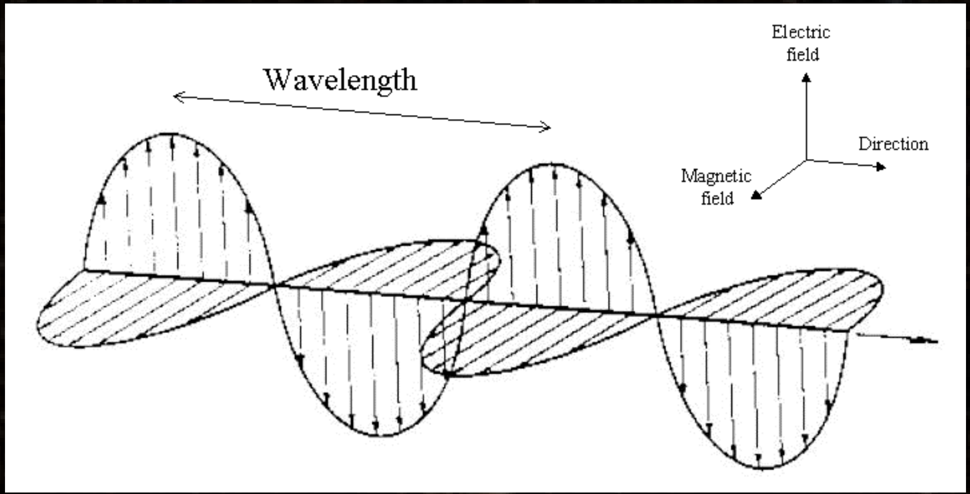


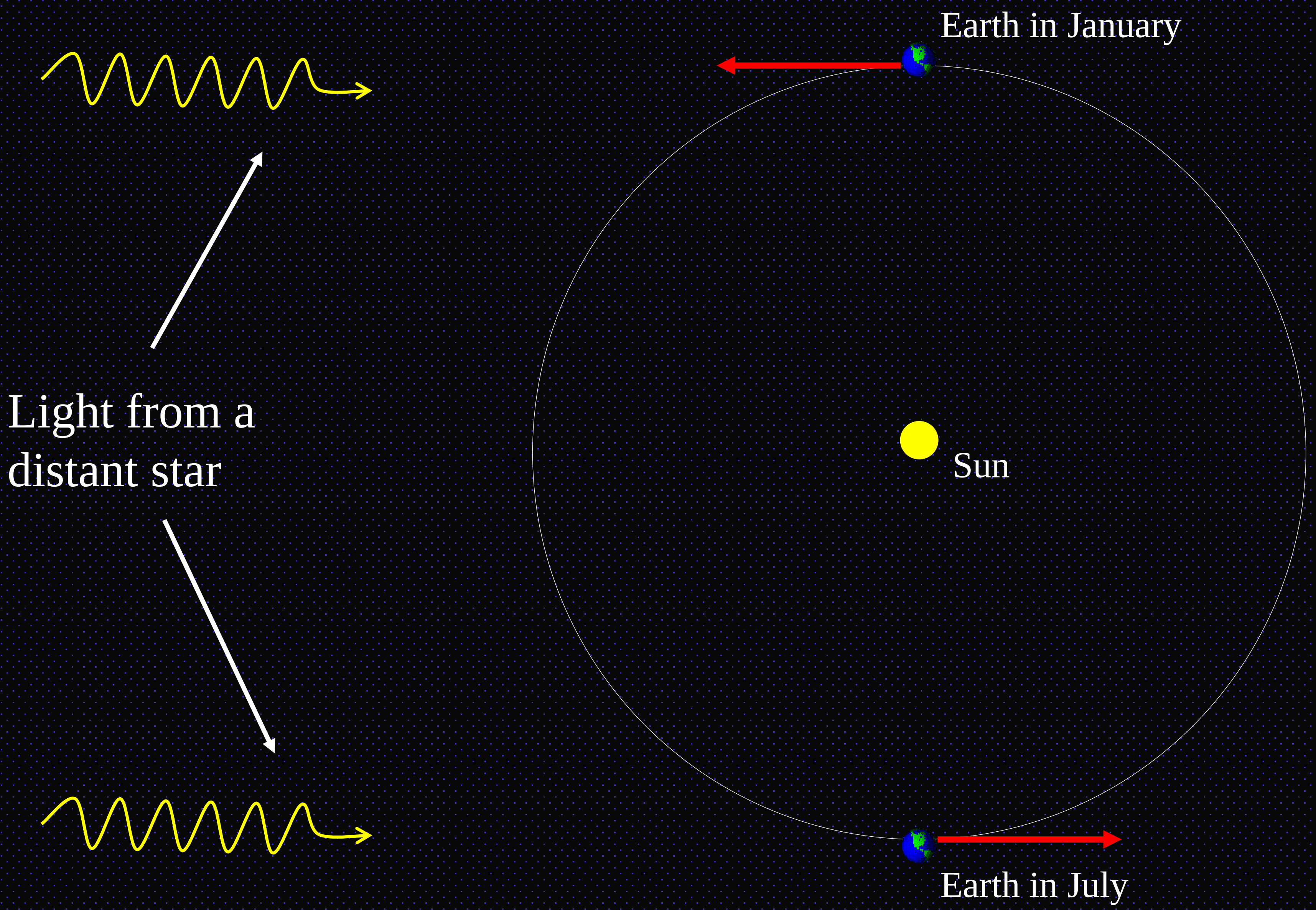
Light is a *wave* – *electromagnetic radiation*

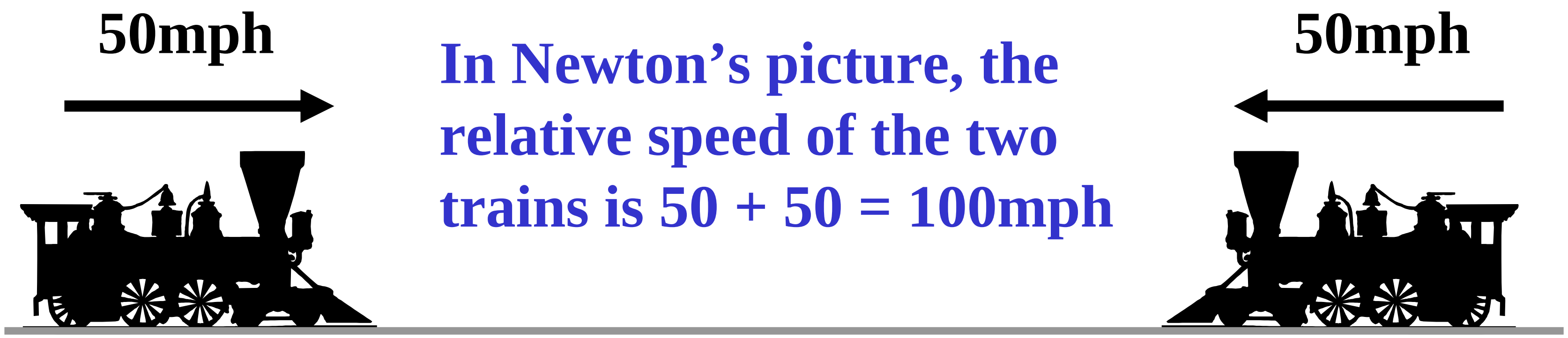
Maxwell's Equations imply

Speed of light = 300,000 km/s

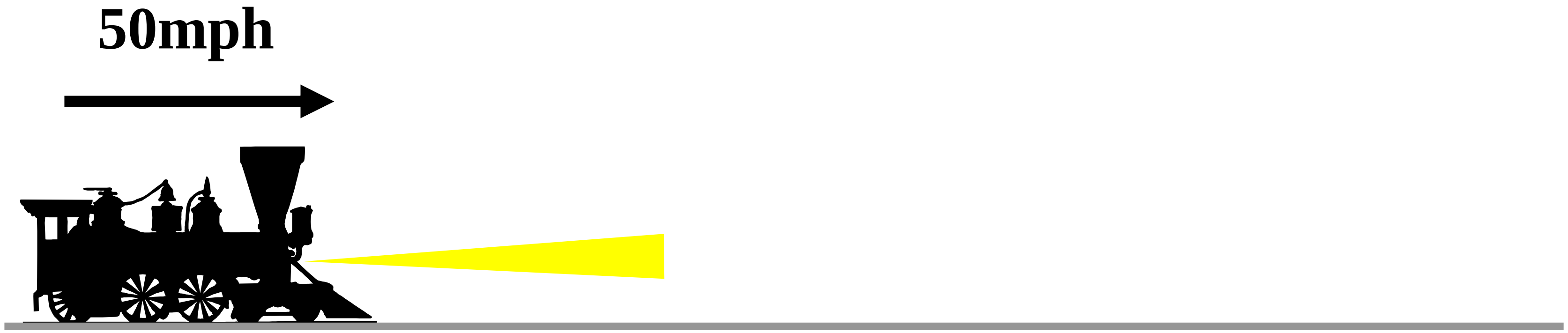
But how did light propagate?……

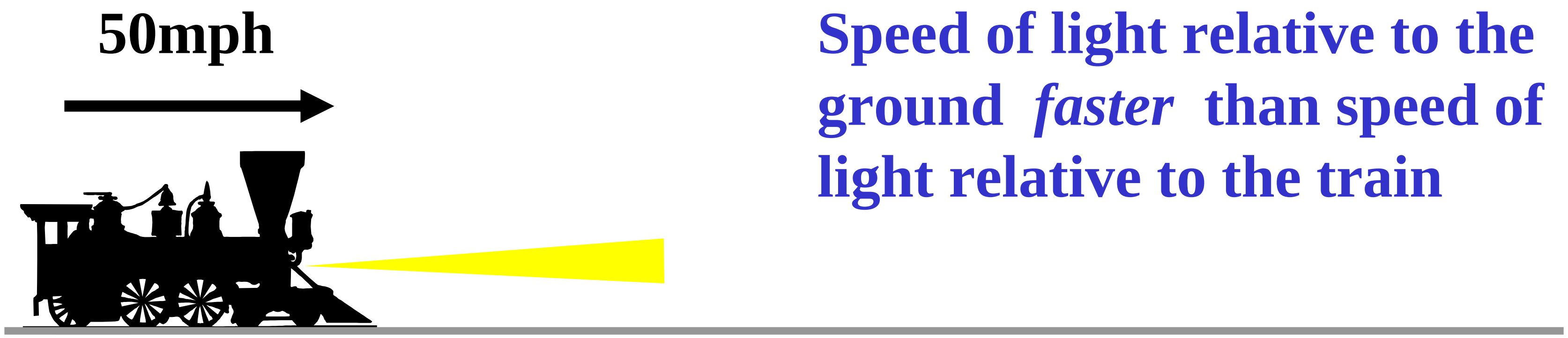
Through the Ether?...





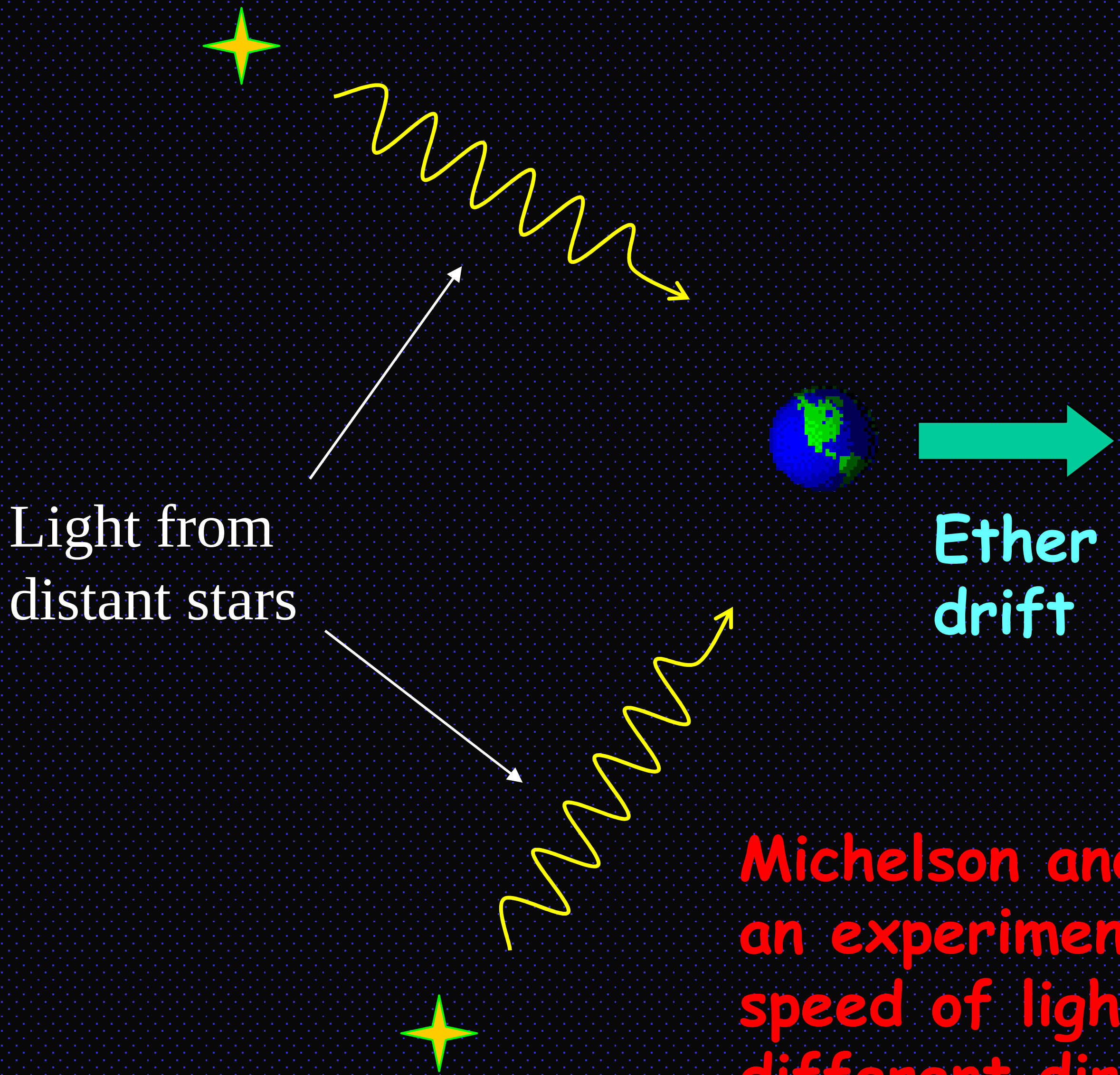
In Newton's picture, the relative speed of the two trains is 50 + 50 = 100mph


50mph



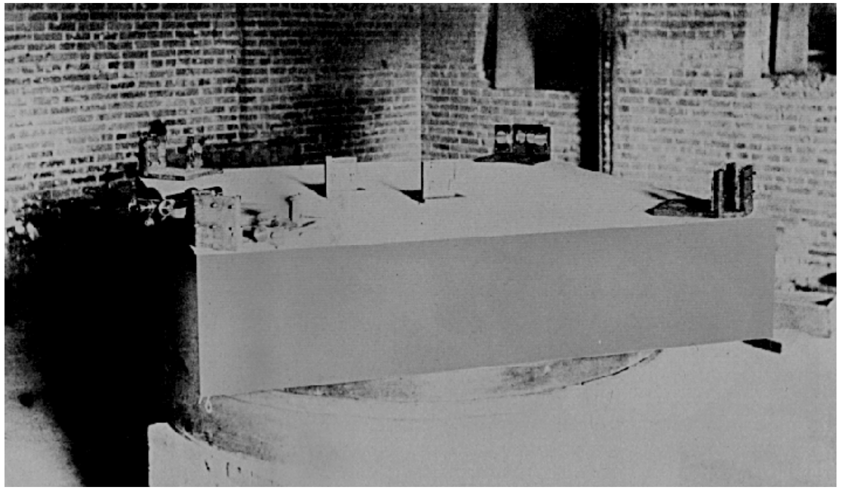
Speed of light relative to the ground *faster* than speed of light relative to the train

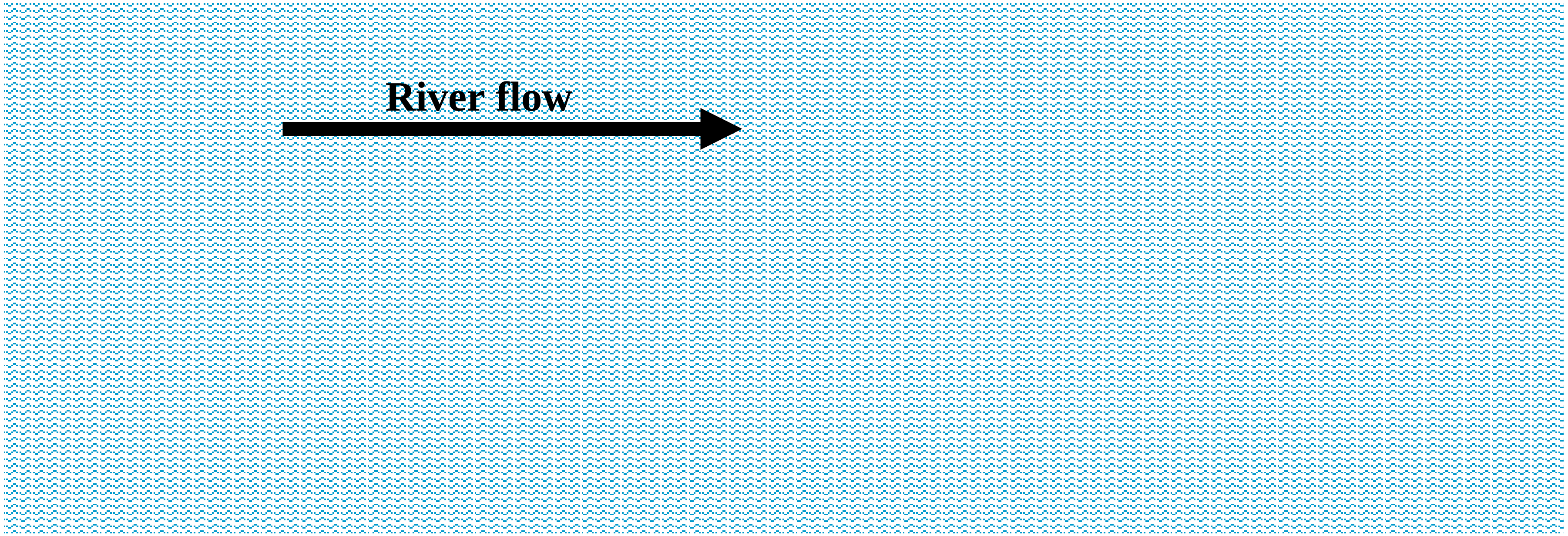
Through the Ether?...



Michelson and Morley devised an experiment to measure the speed of light coming from different directions

The Michelson and Morley Experiment would try to measure the "Ether Drift" by timing different light beams – like swimmers on a fast-flowing river





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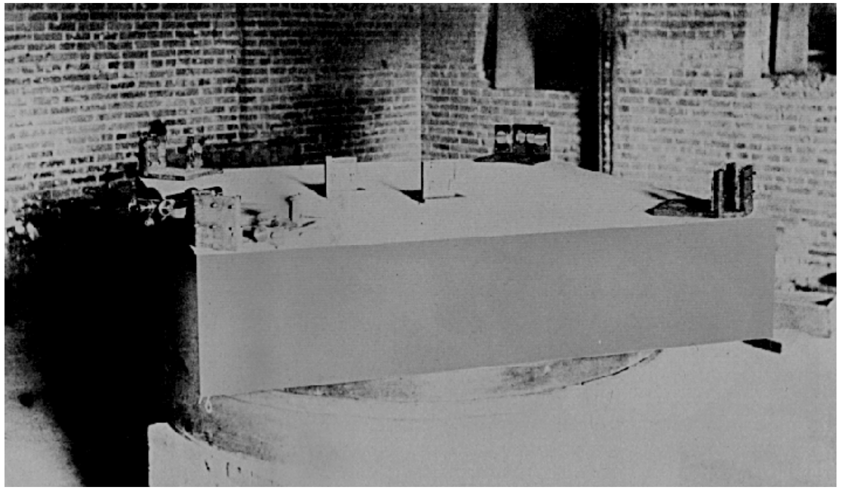
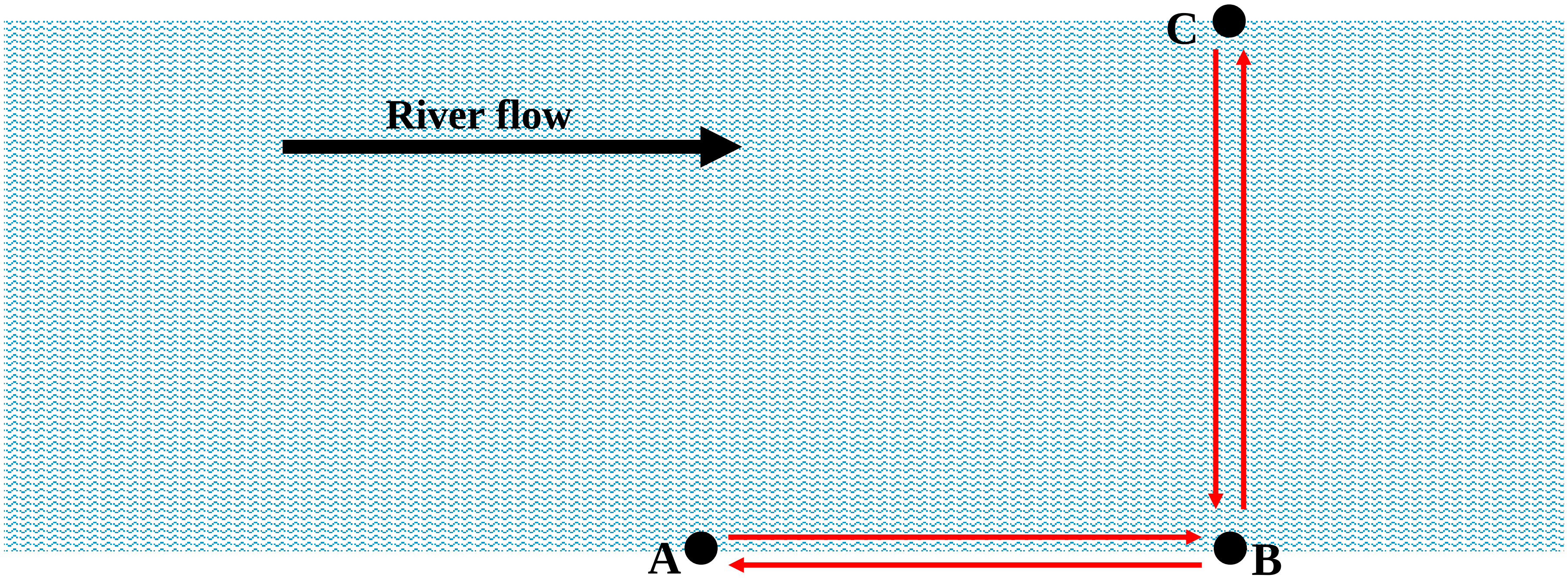
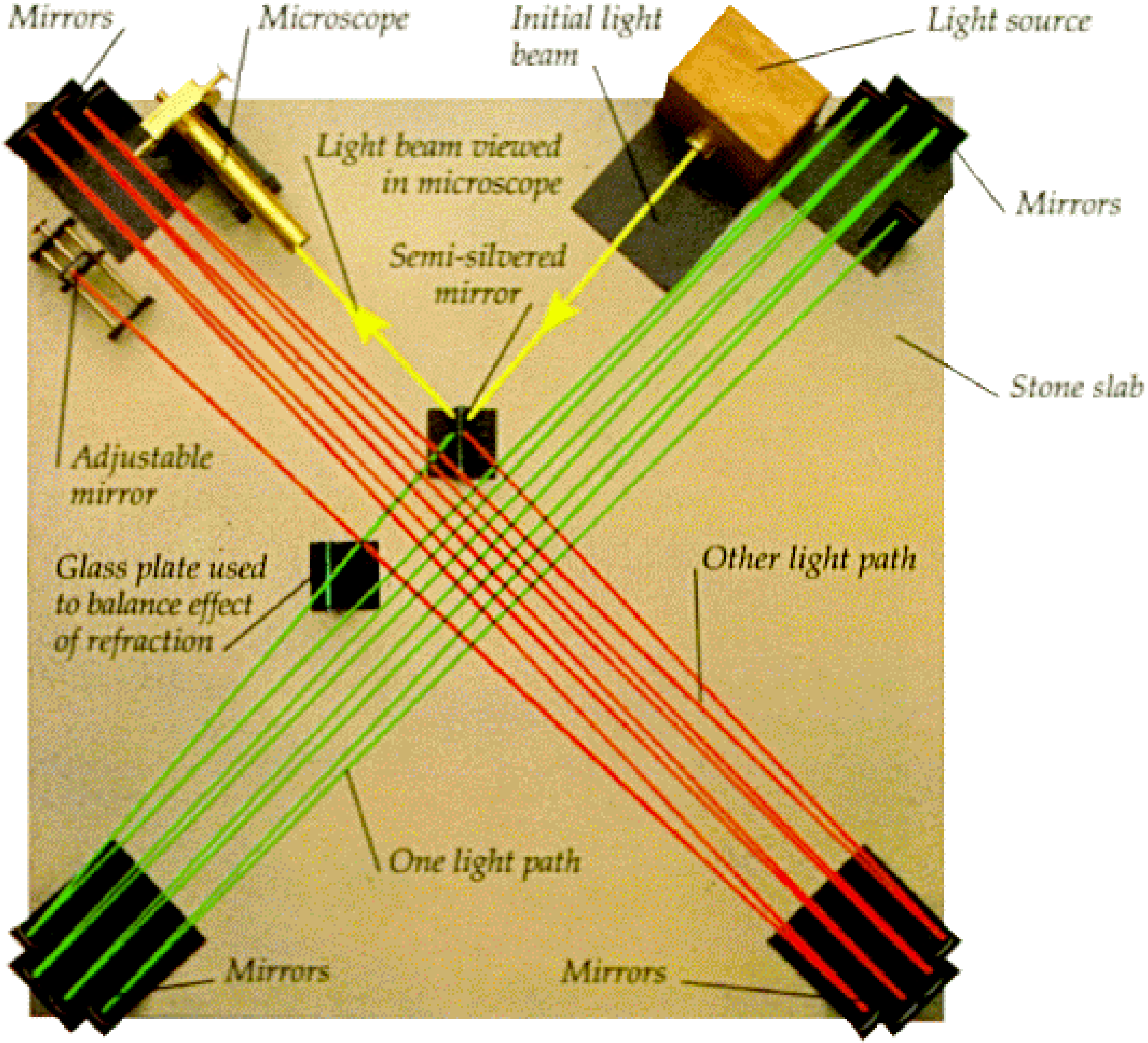
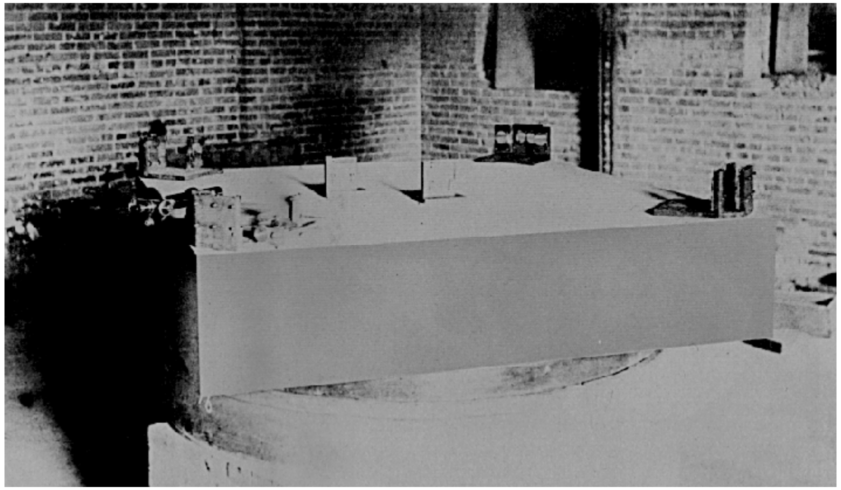
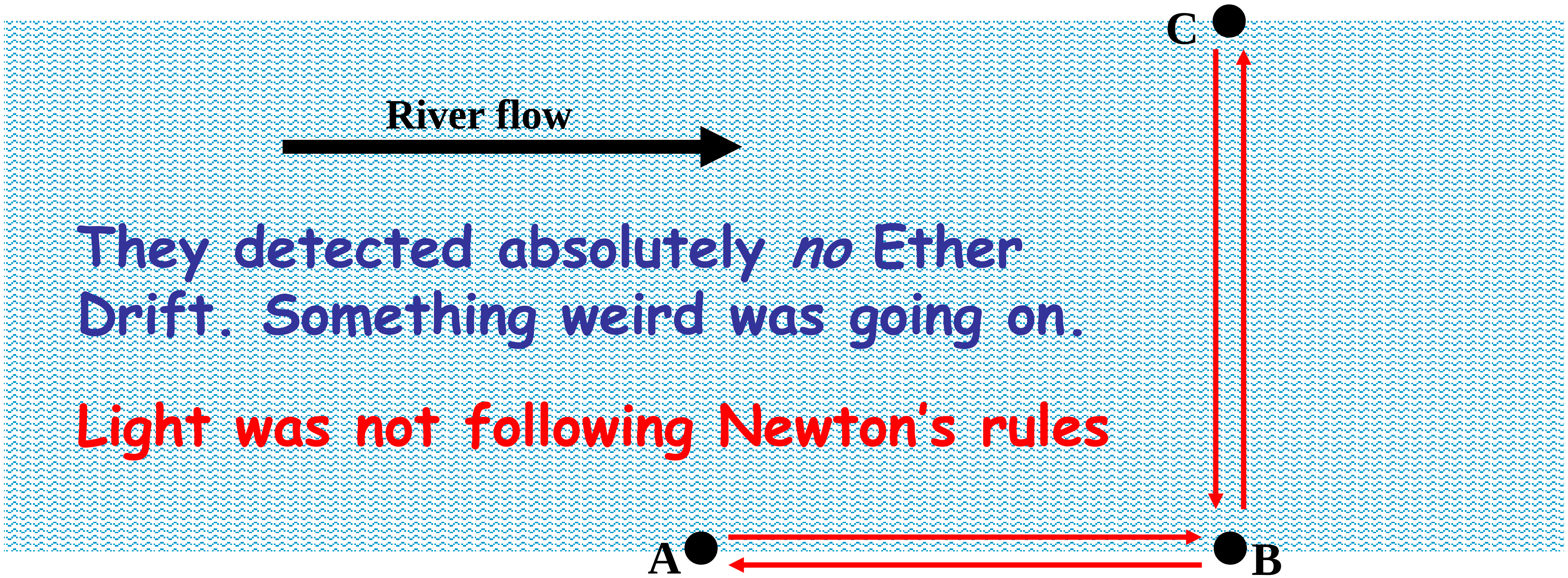





Mirrors
Microscope
Initial light beam
Light source
Light beam viewed in microscope
Mirrors
Semi-silvered mirror
Stone slab
Adjustable mirror
Glass plate used to balance effect of refraction
Other light path
One light path
Mirrors
Mirrors

The Michelson and Morley Experiment would try to measure the "Ether Drift" by timing different light beams – like swimmers on a fast-flowing river



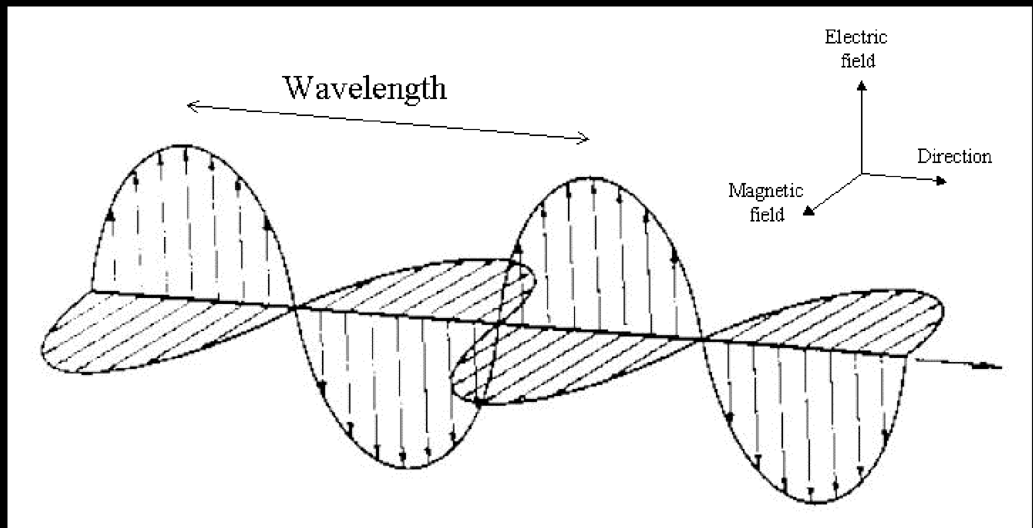


They detected absolutely *no* Ether Drift. Something weird was going on.

Light was not following Newton's rules

Special Relativity: 1905

"Maxwell's Equations of Electromagnetism take the same form for all observers, regardless of their relative motion"



Special Relativity: 1905

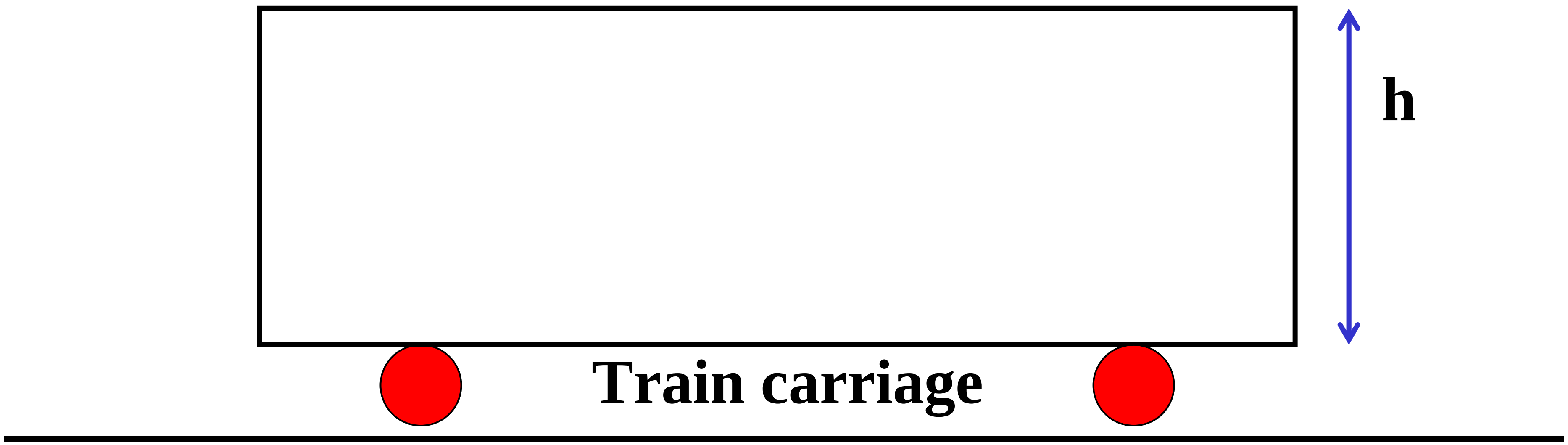
Implies the speed of light must be constant, measured to be the same by any two observers, regardless of their relative motion"

There must be *no* ether, and so no ether drift

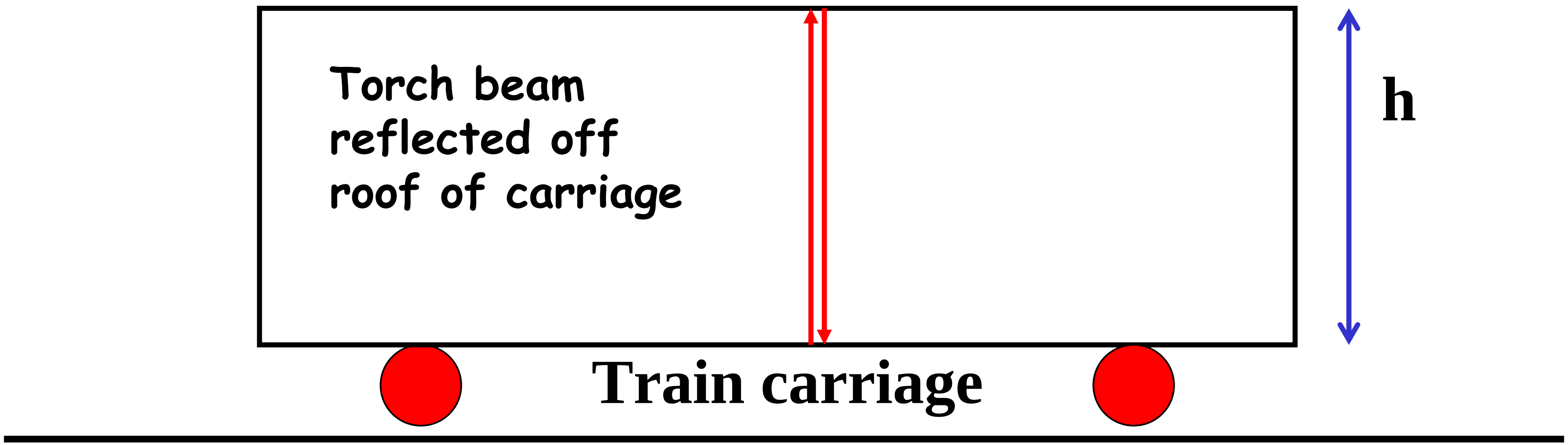
Special Relativity: 1905

Implies the speed of light must be constant, measured to be the same by any two observers, regardless of their relative motion"

This abolished completely Newton's idea that space and time were *absolute*

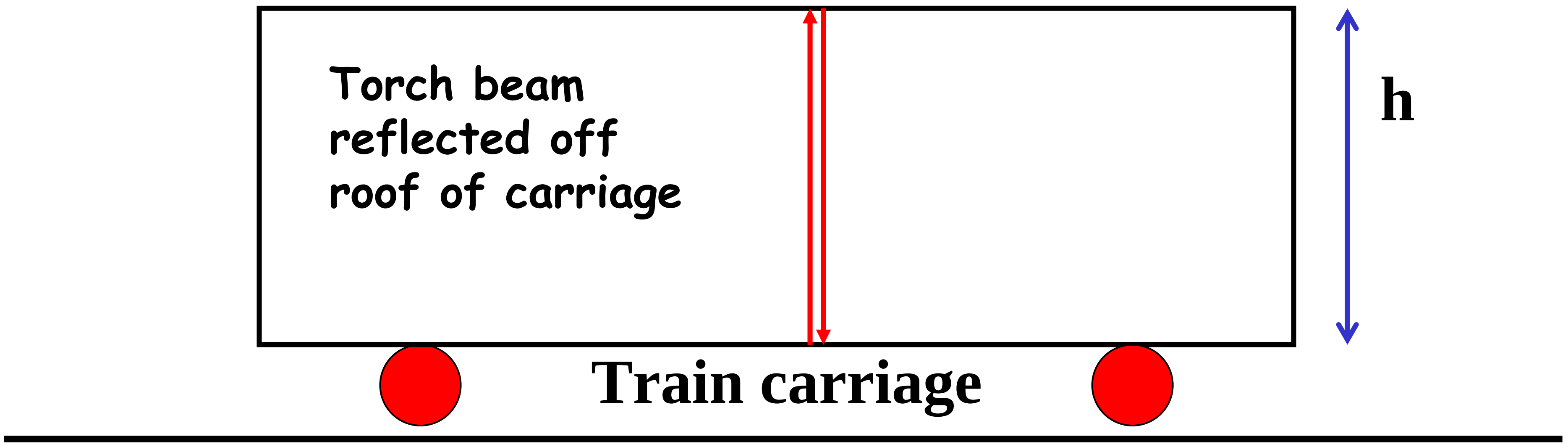


Let's try to see why!

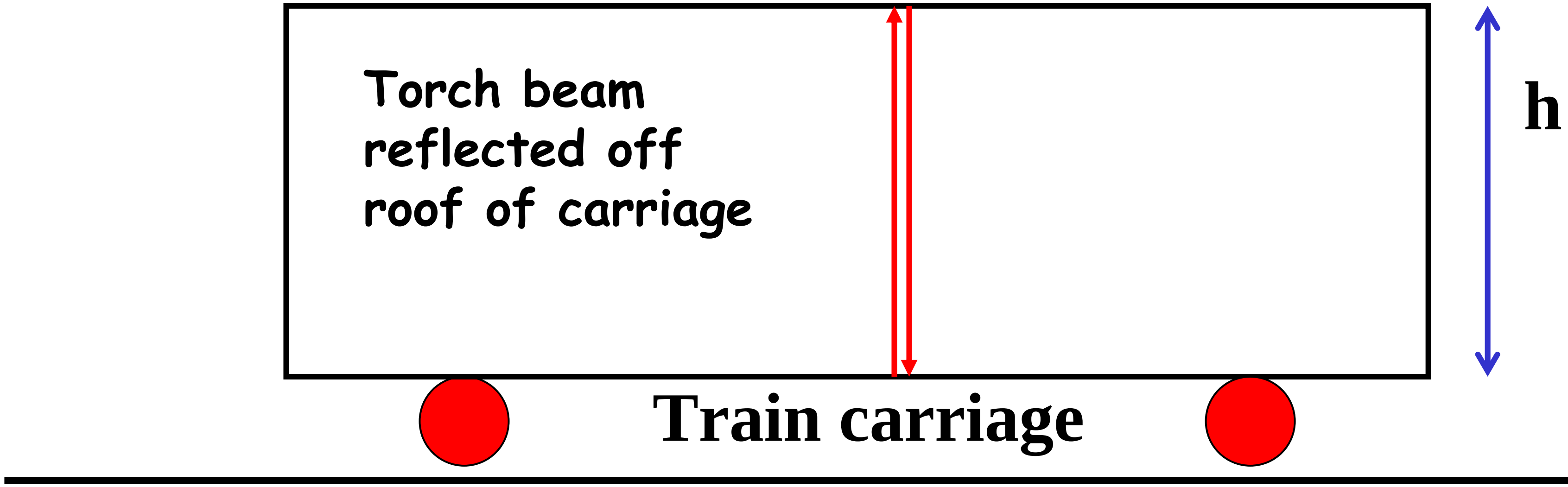


Let's try to see why!

Distance = speed x time



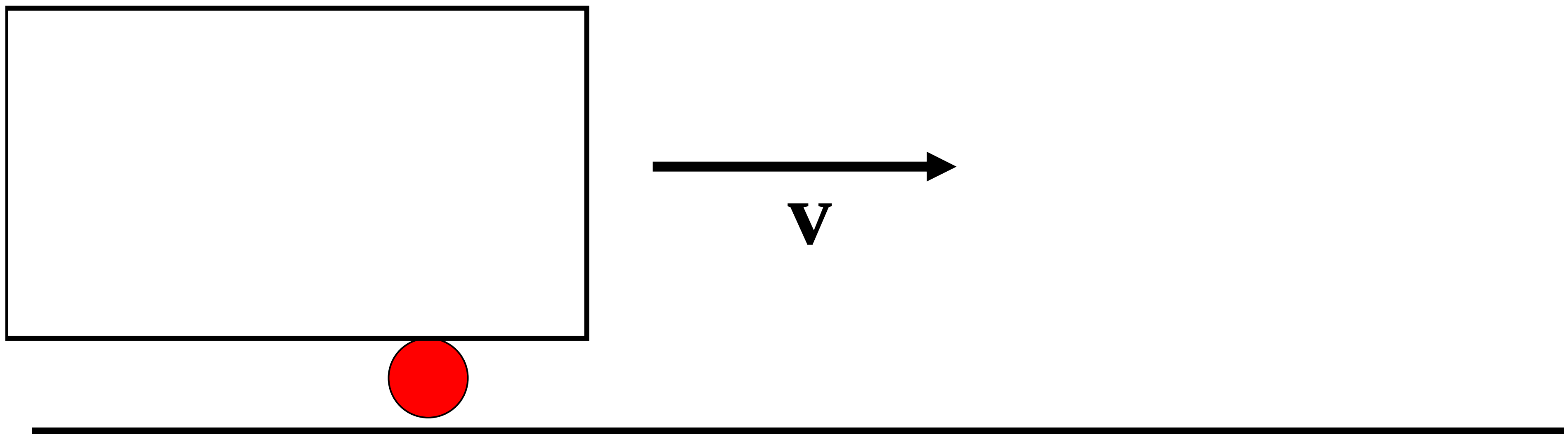
Distance = speed x time



$$2h = c \times t_c$$

Now viewed from the platform…

Now viewed from the platform…



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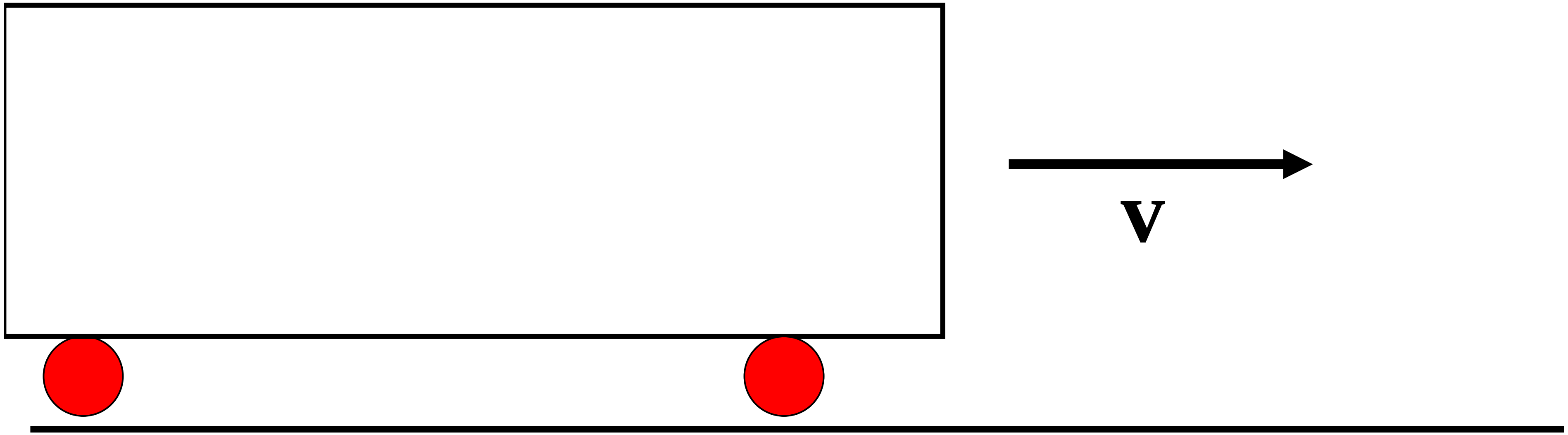

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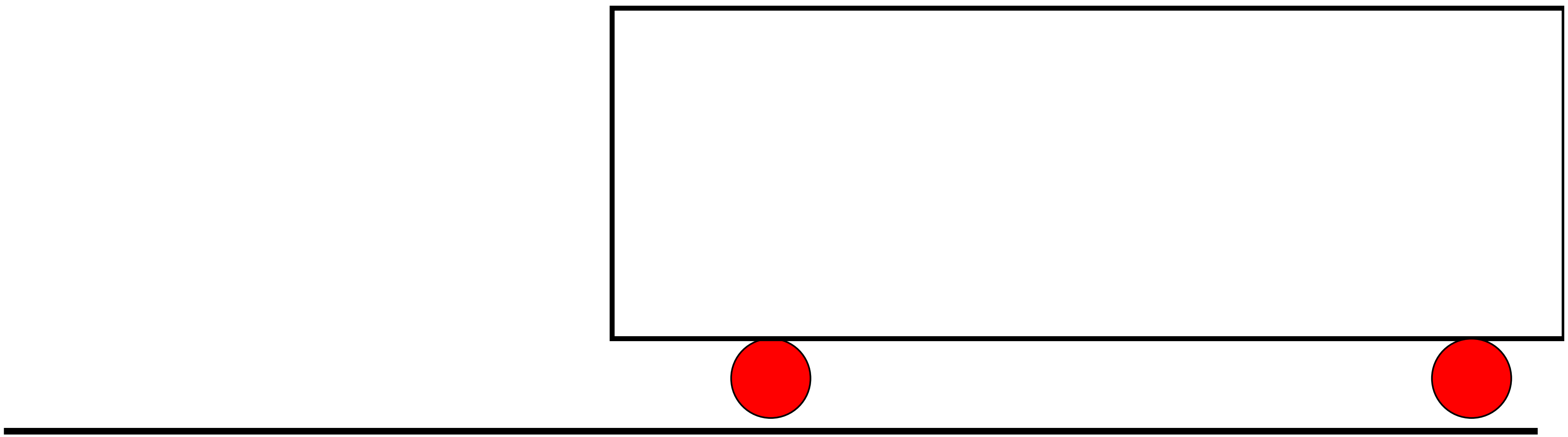

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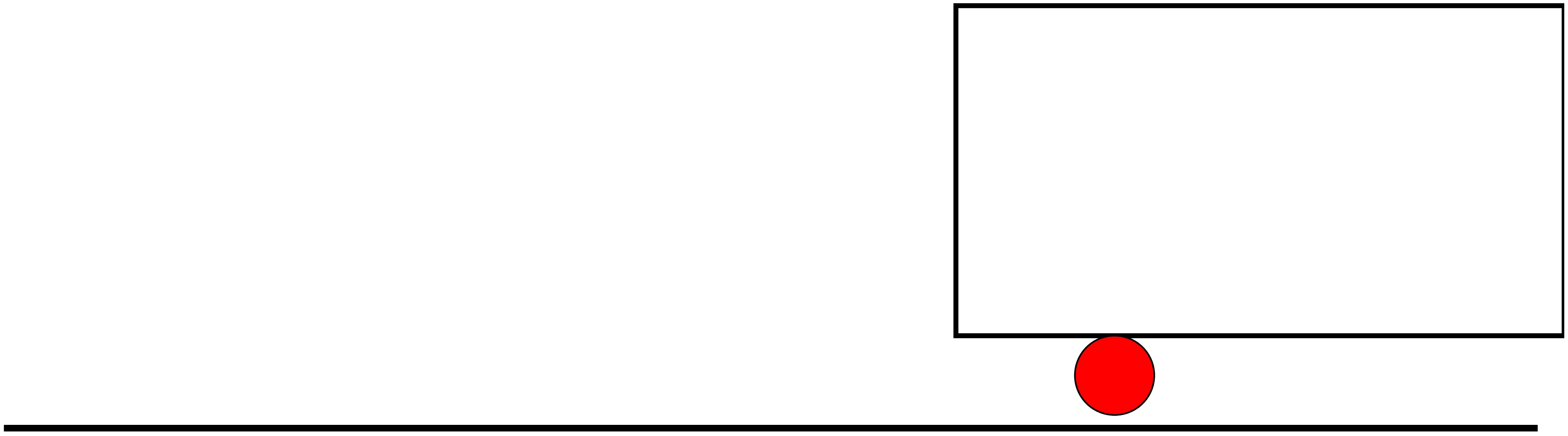

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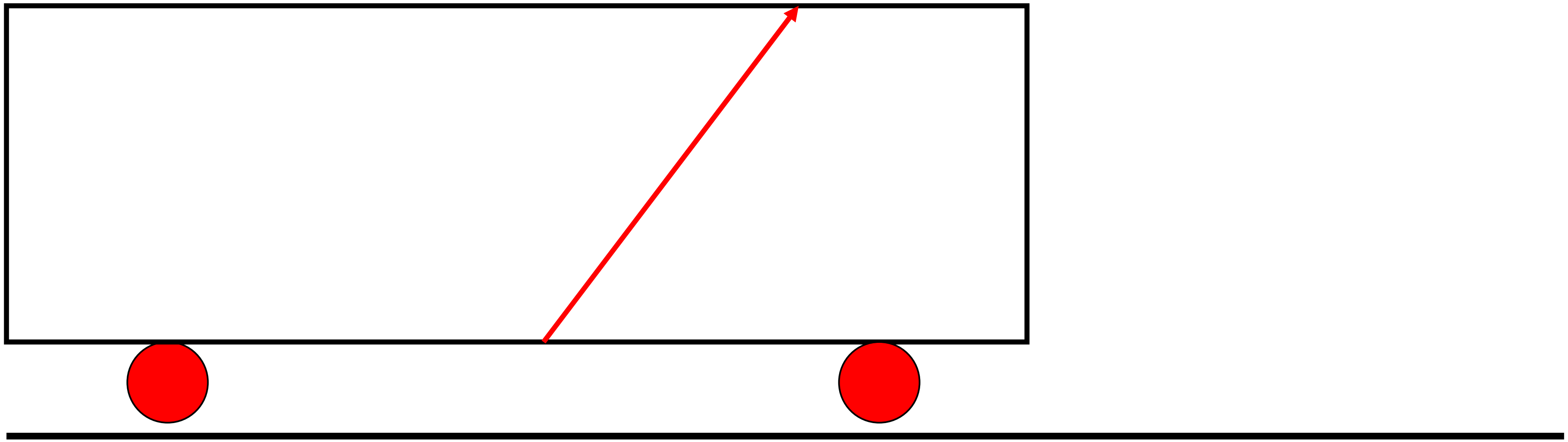

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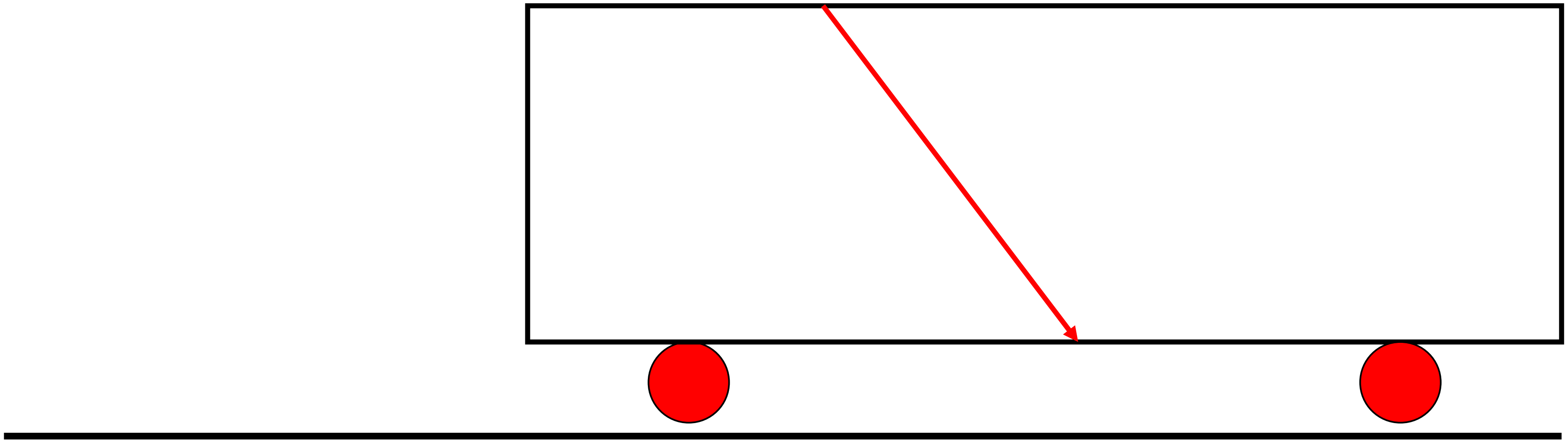
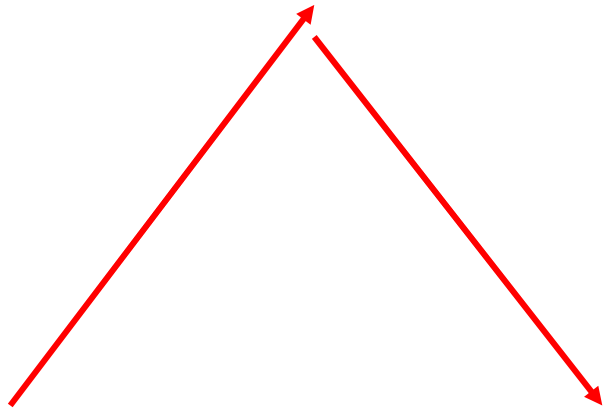


Let's call the time measured on the platform t_P

Now viewed from the platform…



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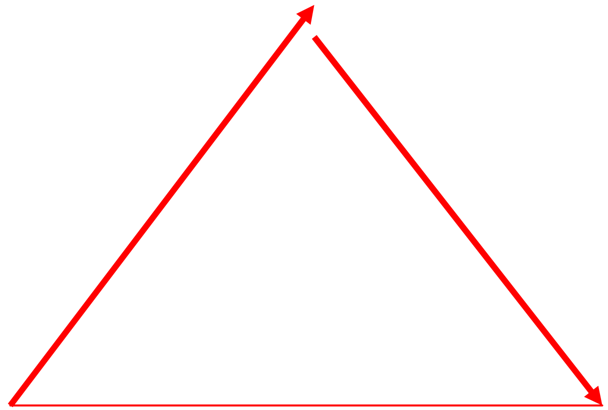

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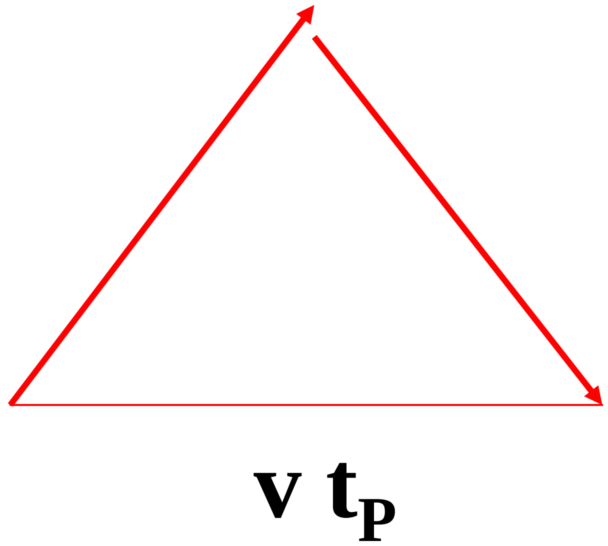
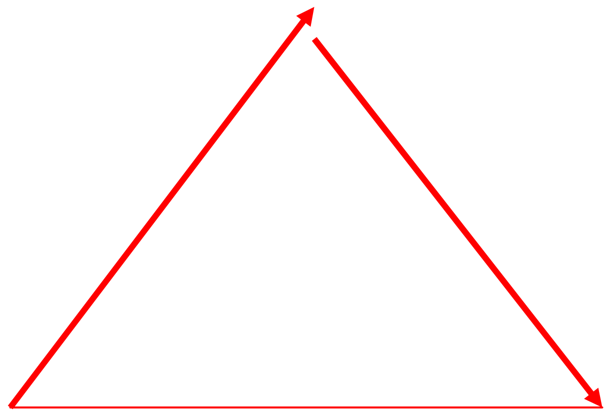


The base of this triangle is $v\ t_P$

Now viewed from the platform…



$\mathbf{v\ t_P}$

This is an isosceles triangle, so it's made up of two equal right angled triangles

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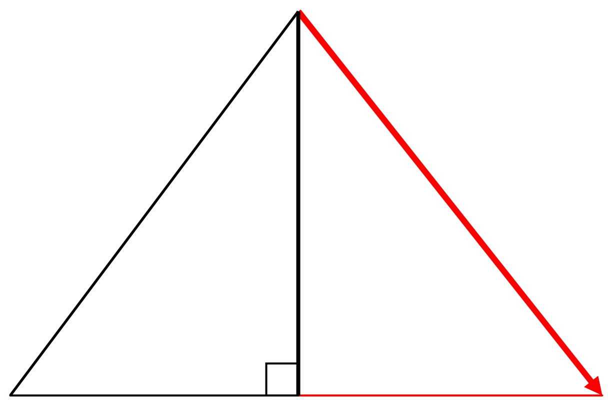

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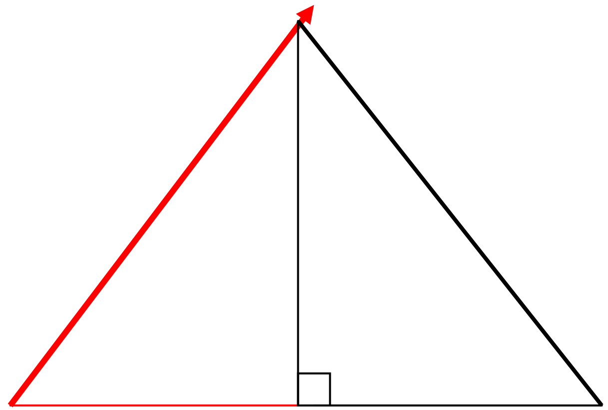

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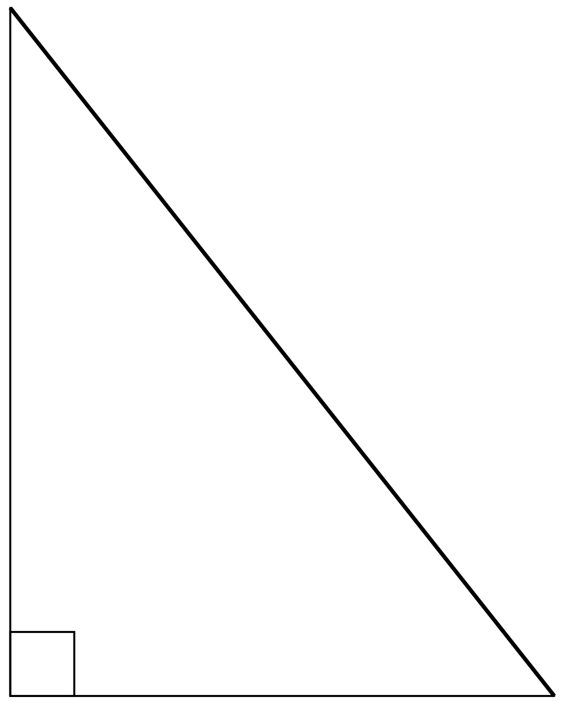
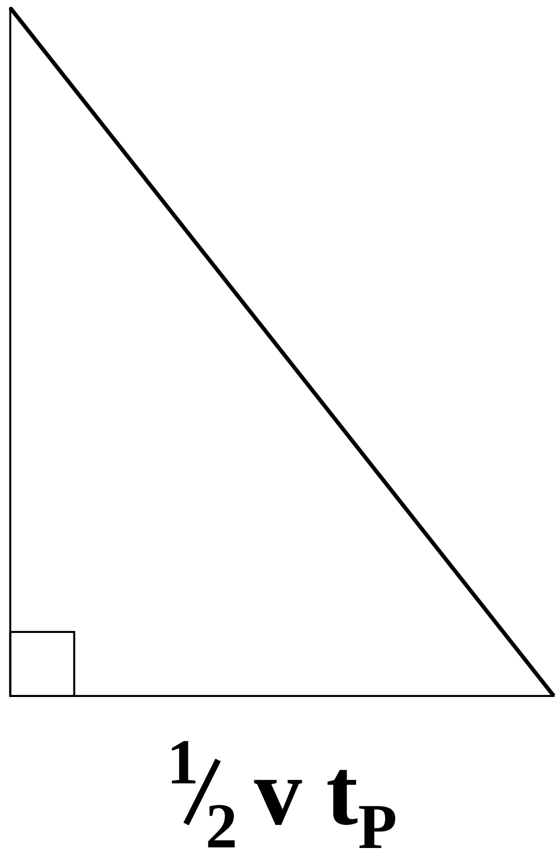


Let's look at this triangle.

What's the length of its base?



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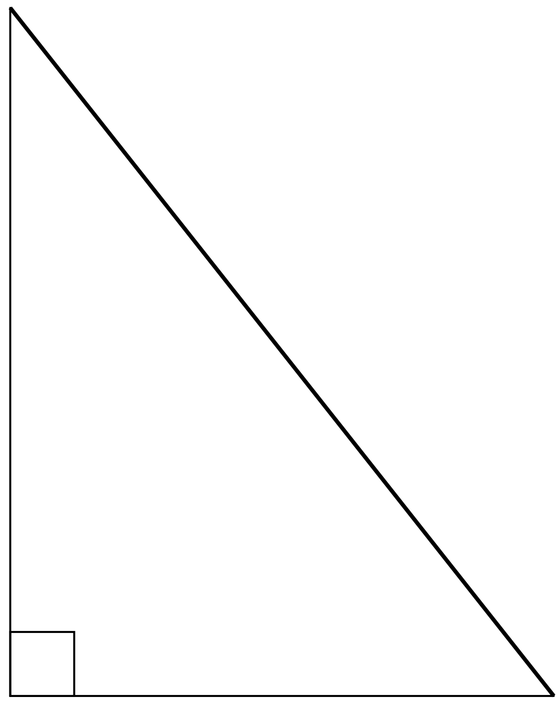
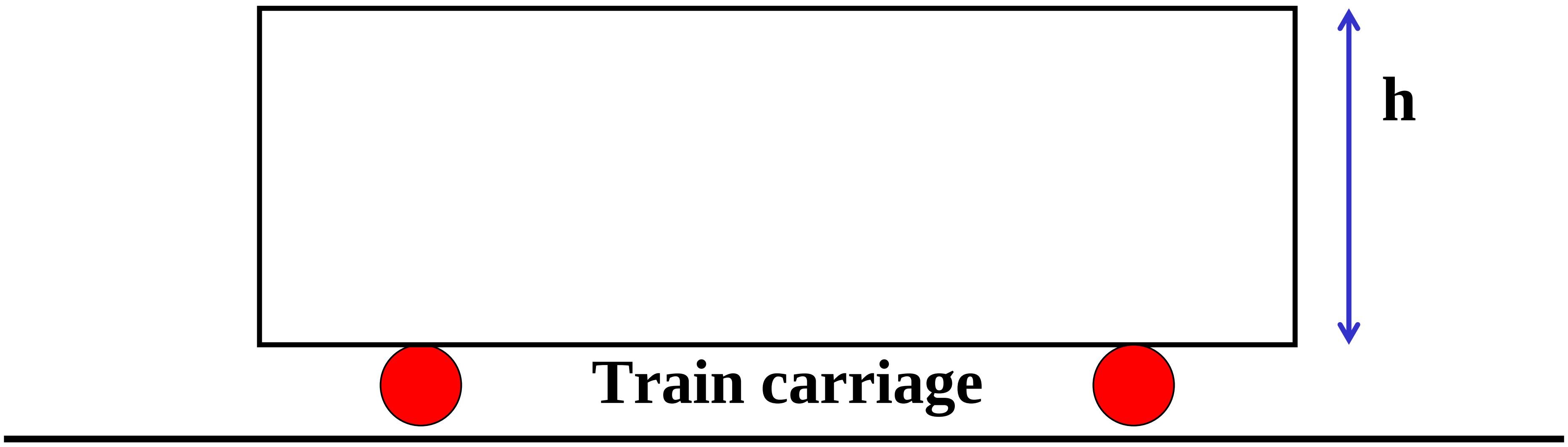
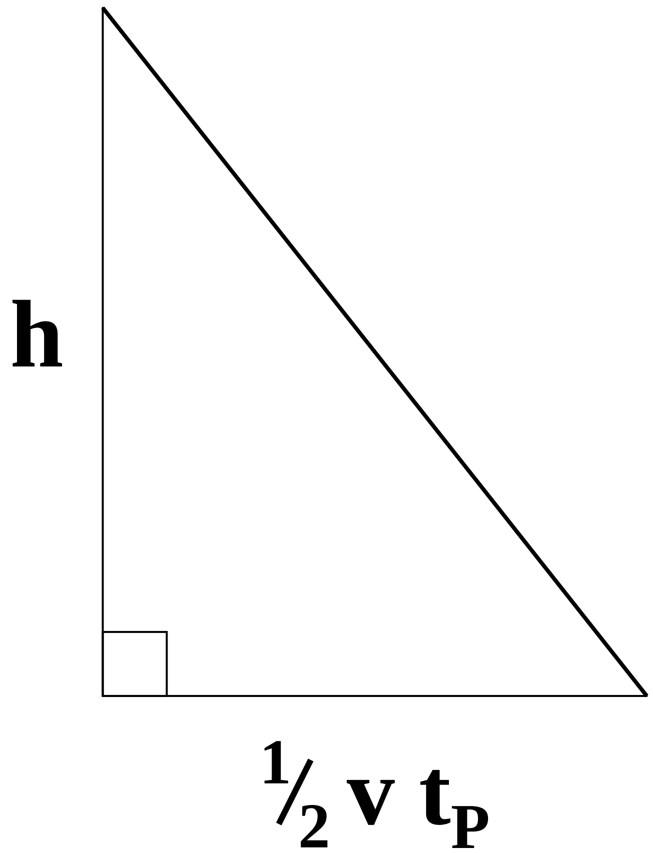


$\frac{1}{2} v\, t_P$

What about its height?


h
Train carriage



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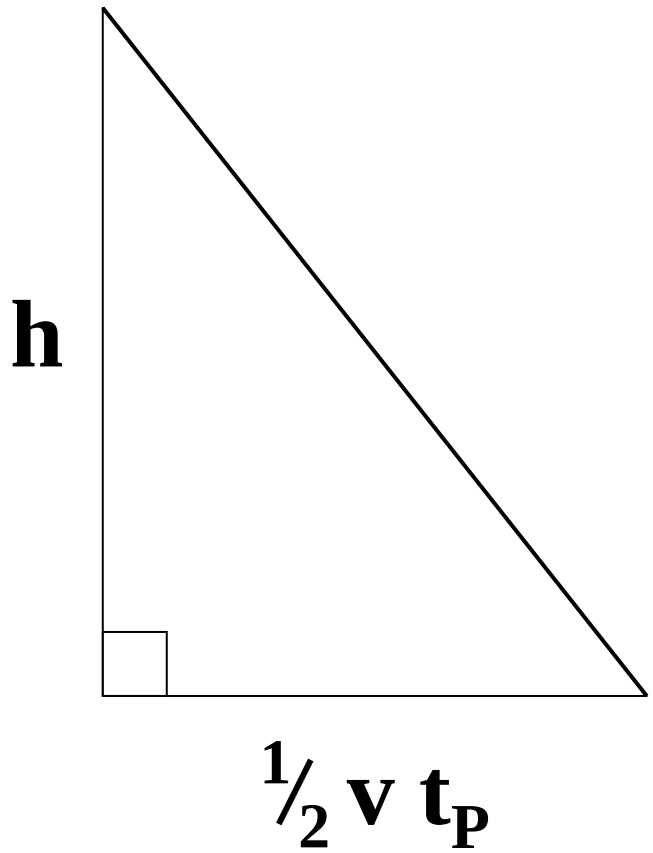
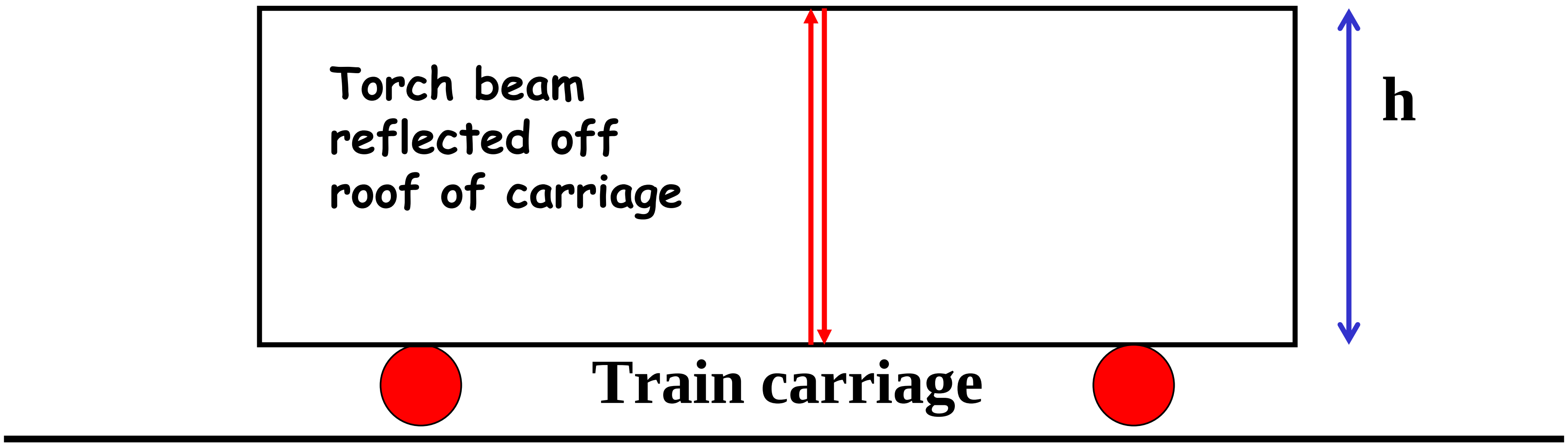


Remember: $2h = c \times t_c$

Distance = speed x time



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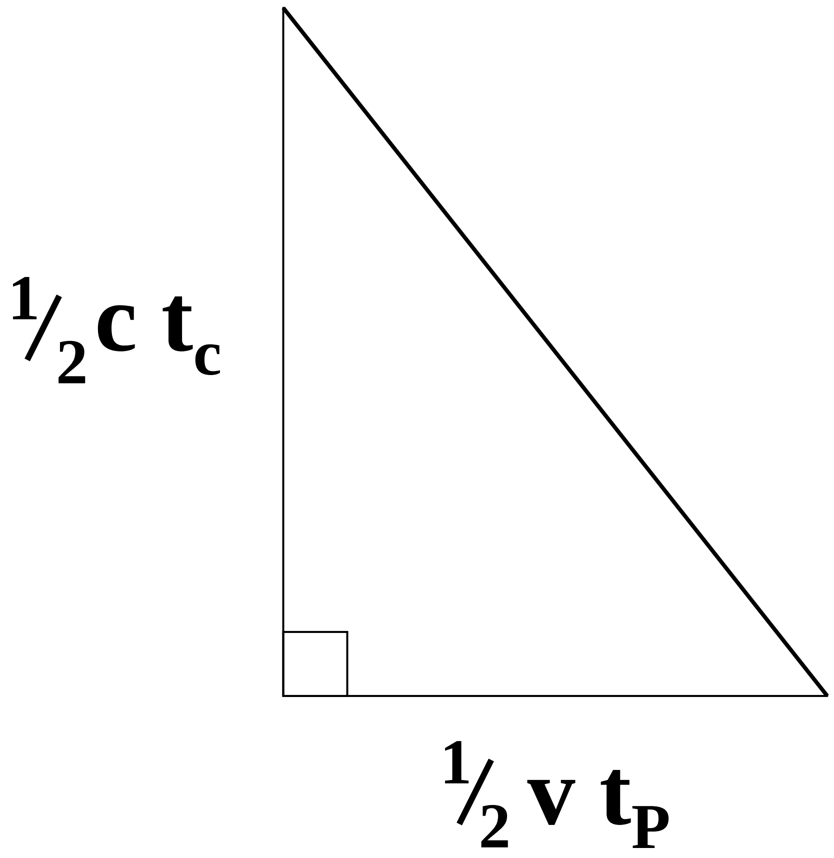

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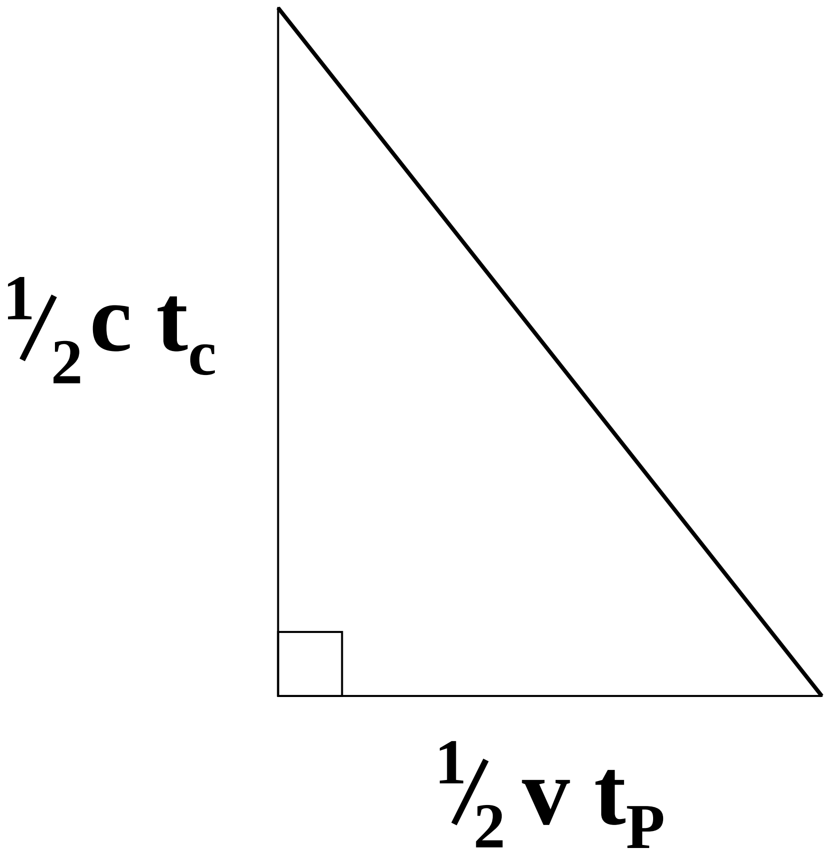
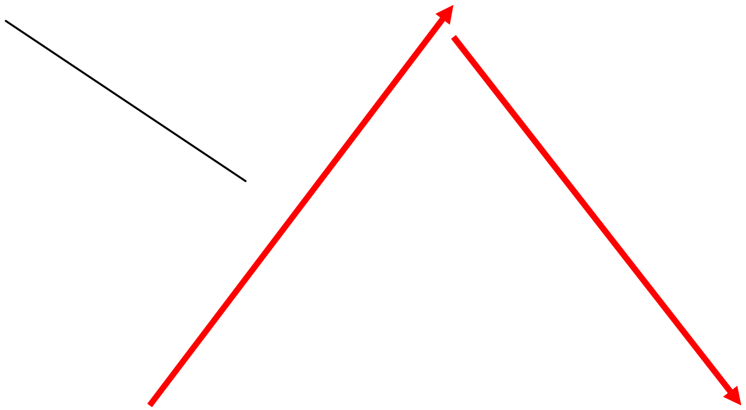


If both observers measure the same speed of light, c…

Total distance

$= c \times t_P$



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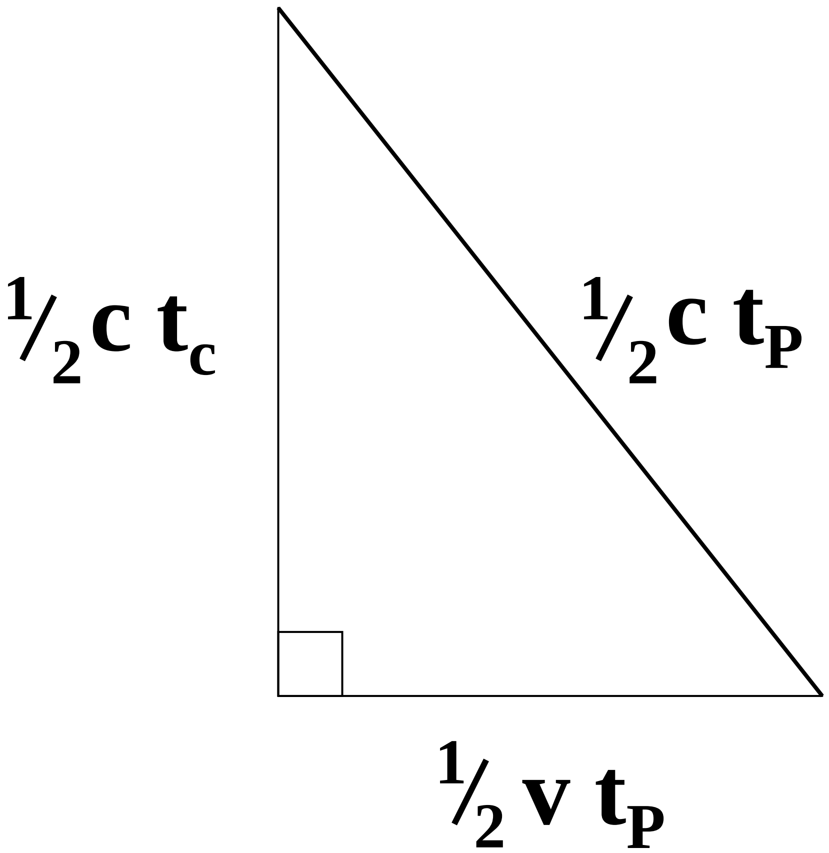

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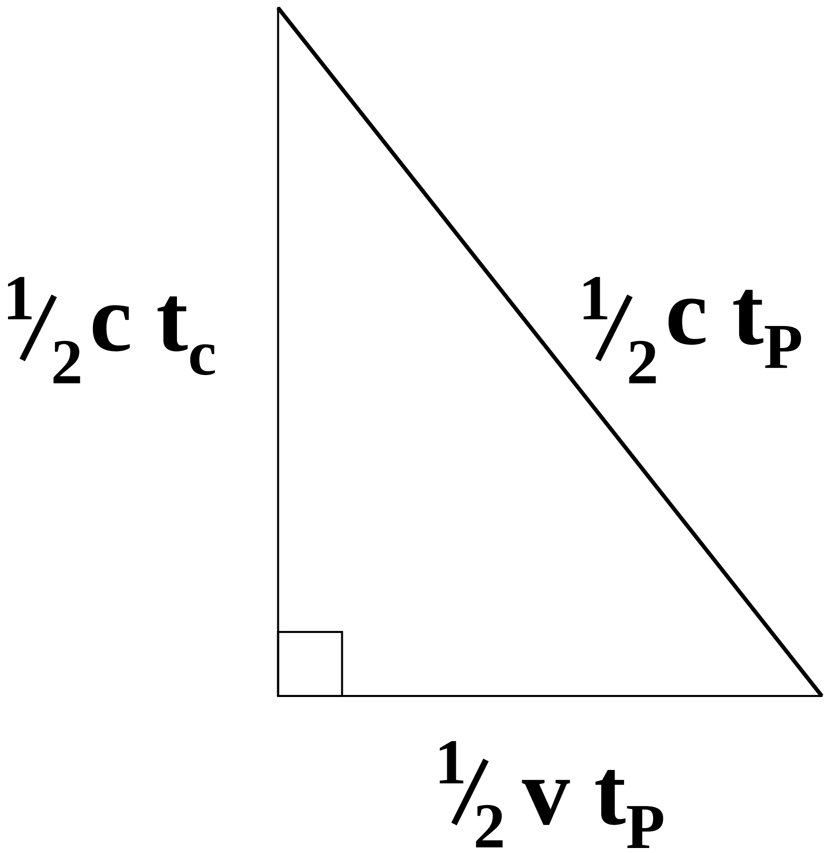
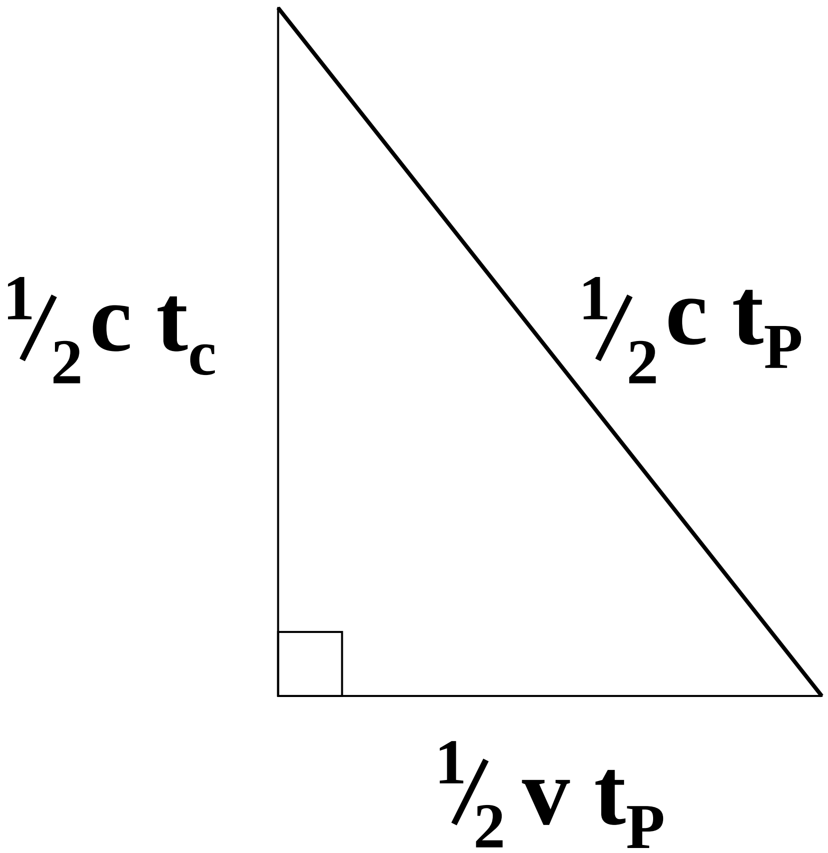


Using Pythagoras' theorem,

$$(ct_P)^2 = (vt_P)^2 + (ct_c)^2$$



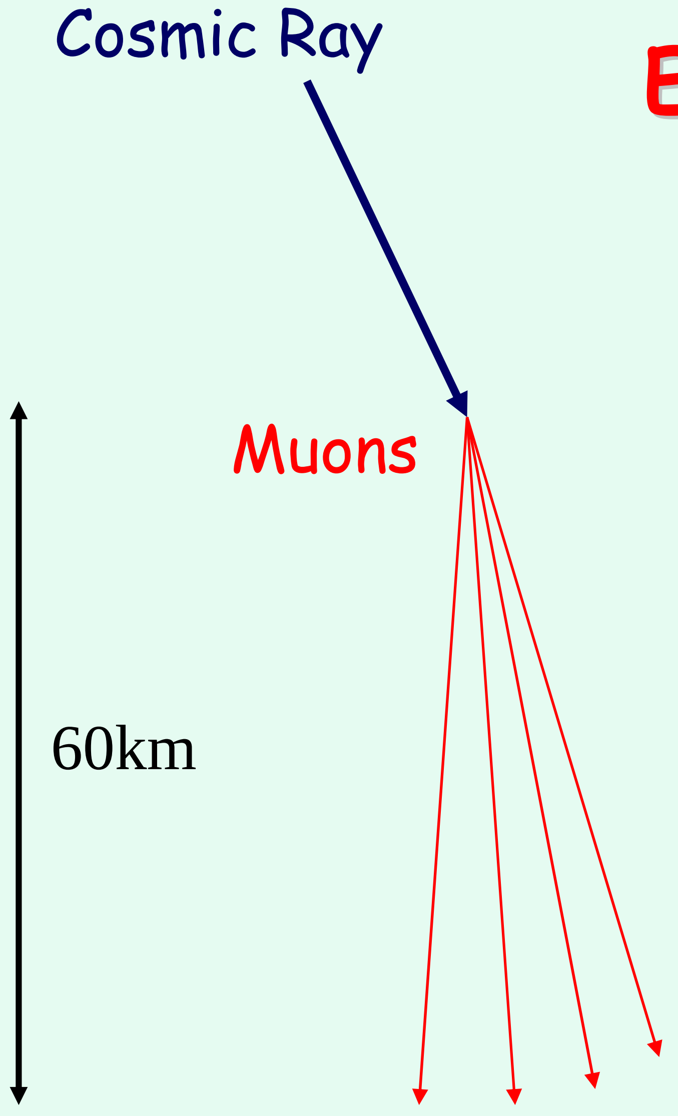
$$t_c = t_P \sqrt{(1 - v^2/c^2)}$$

It appears that time is running more slowly on the moving train!!

We need to think about a unified *spacetime*

$$t_c = t_P \sqrt{(1 - v^2/c^2)}$$

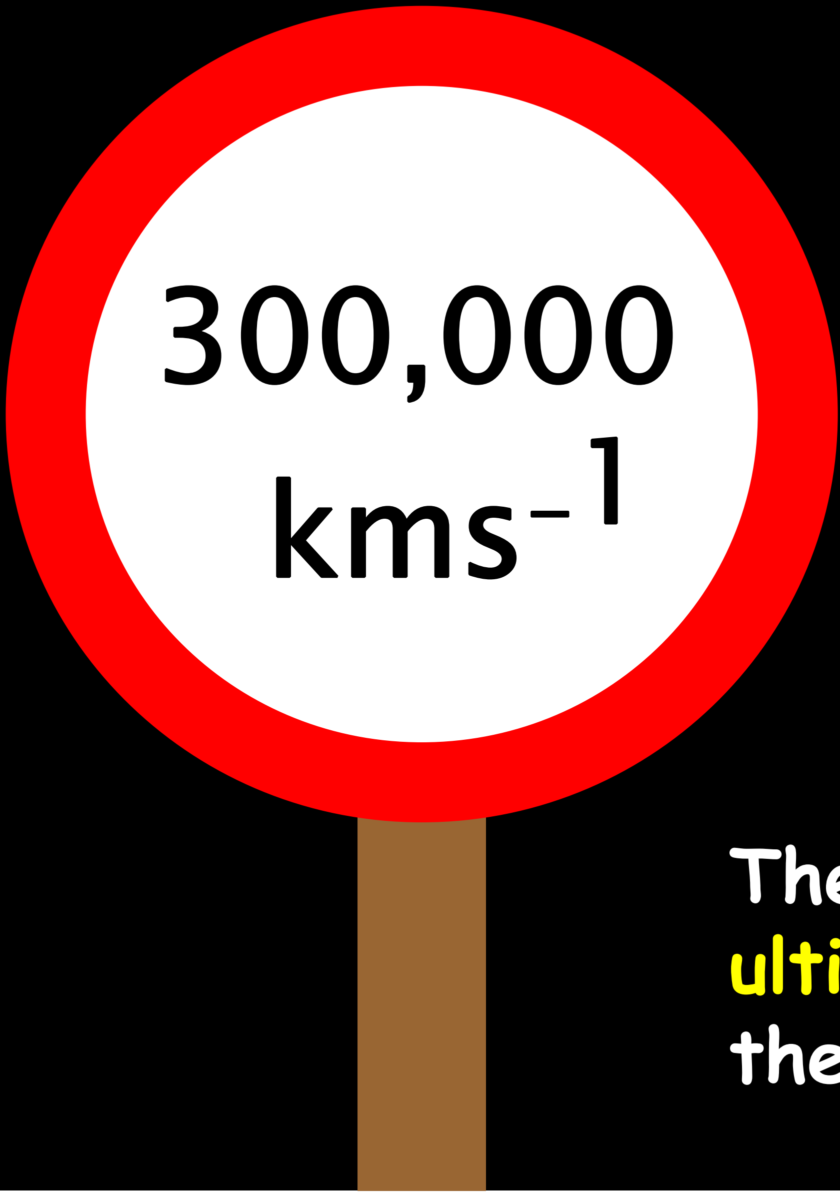
Evidence for Time Dilation



Slow moving muons, would never reach sea level…

but v = 0.999c, so muon lifetime appears to us to be greatly extended

Einstein's Relativity



The speed of light is the **ultimate speed limit** in the Universe

Just as special relativity shows that space and time are inextricably connected, so too are energy and momentum

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Particles have a particular **rest mass**, which is the mass you would measure if the particle is at rest

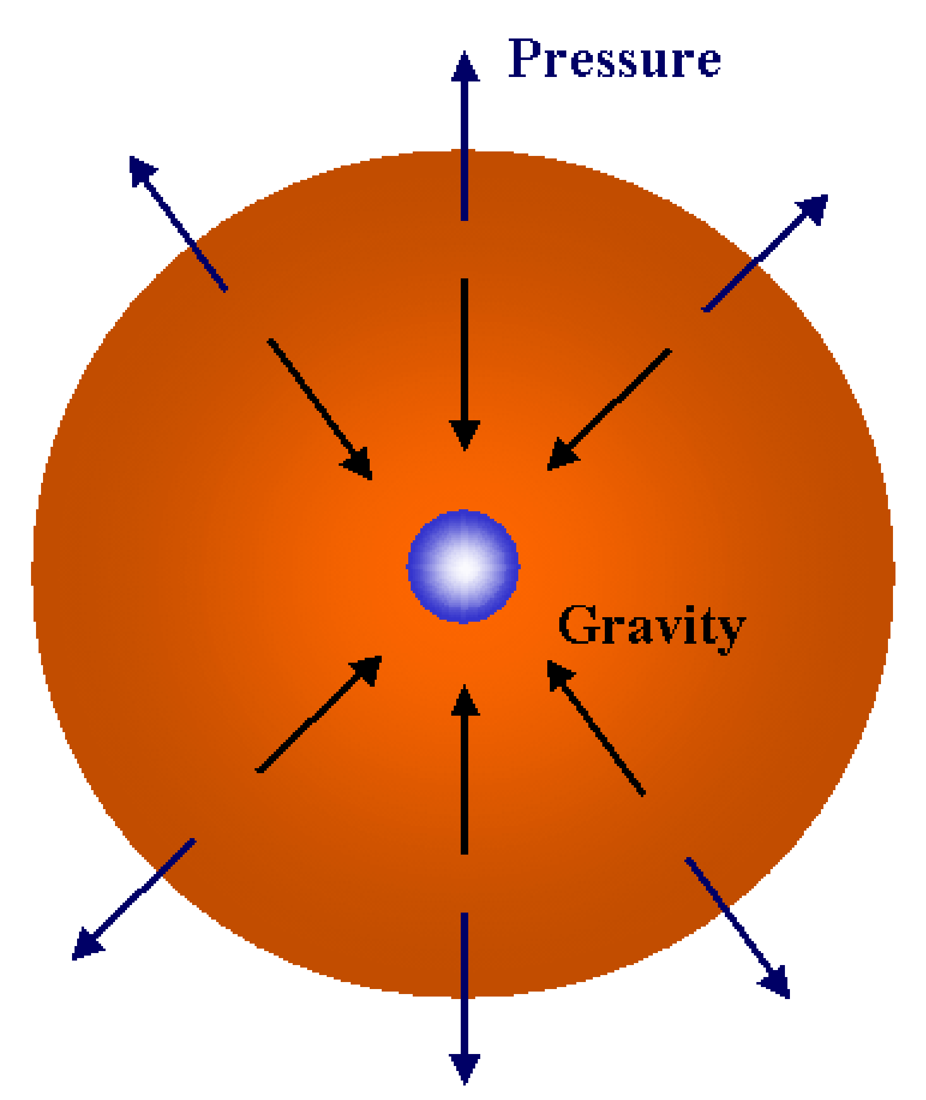
Just as special relativity shows that space and time are inextricably connected, so too are energy and momentum

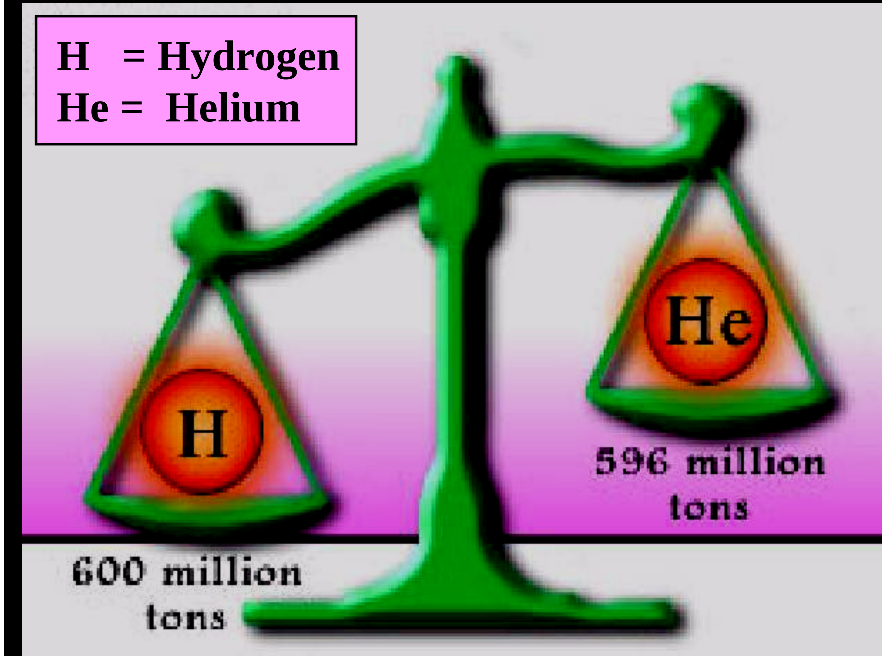
Particles have a particular **rest mass**, which is the mass you would measure if the particle is at rest

Mass and energy are equivalent

$$E = mc^2$$

Hydrogen fusion – fuelling a star's nuclear furnace



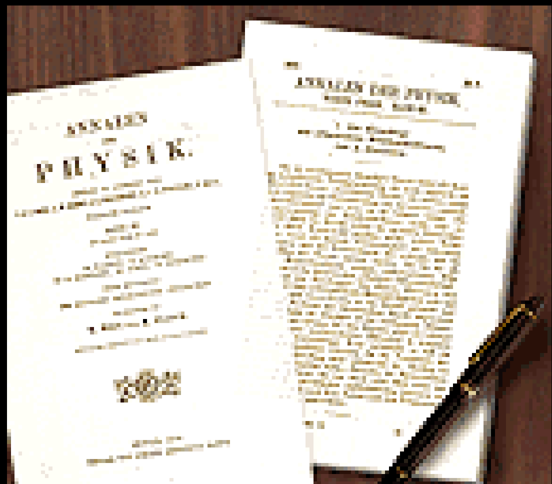


$E = mc^2$

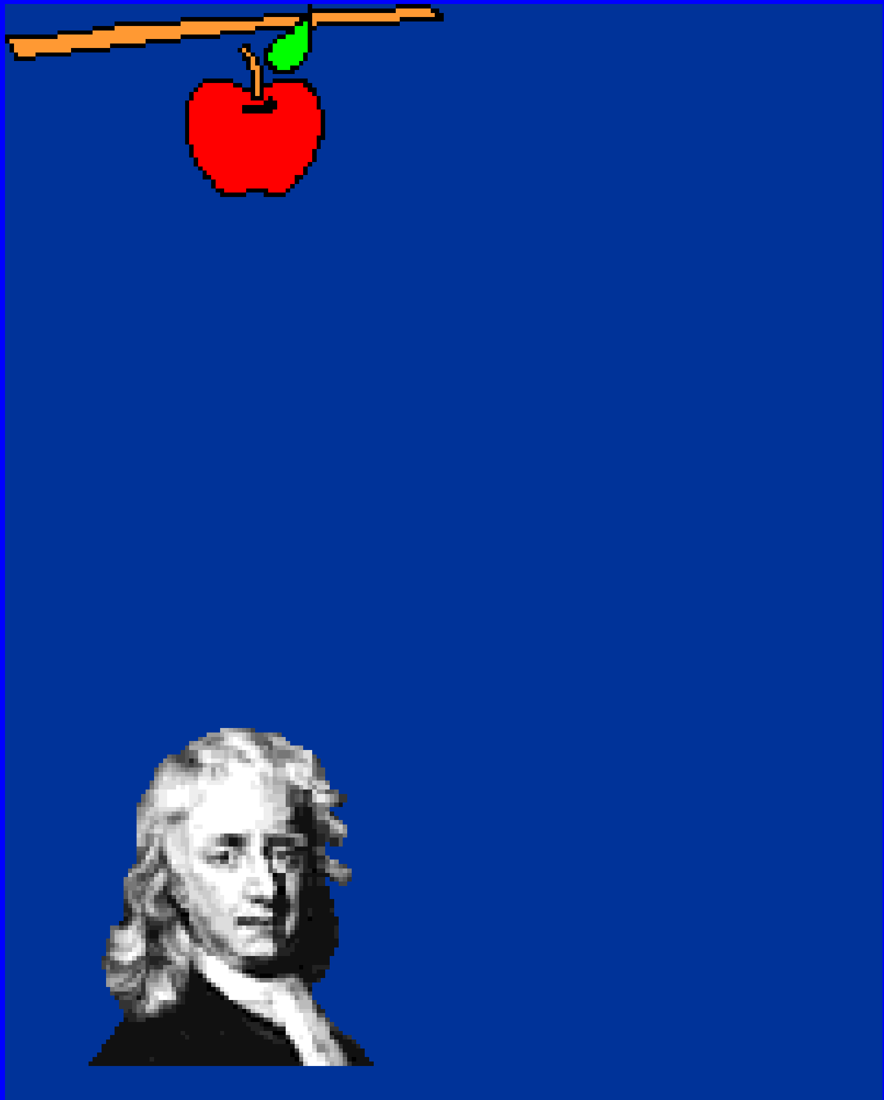
Einstein's Relativity

What about accelerated observers?

How does gravity fit into this?



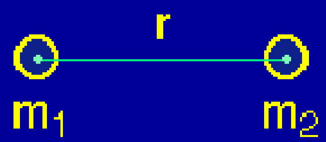
General Relativity: 1916

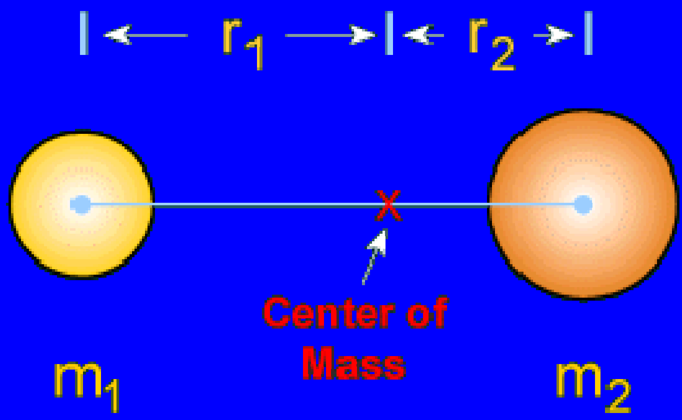


Law of Universal Gravitation

Every object in the Universe attracts every other object with a force directed along the line of centers for the two objects that is proportional to the product of their masses and inversely proportional to the square of the separation between the two objects.

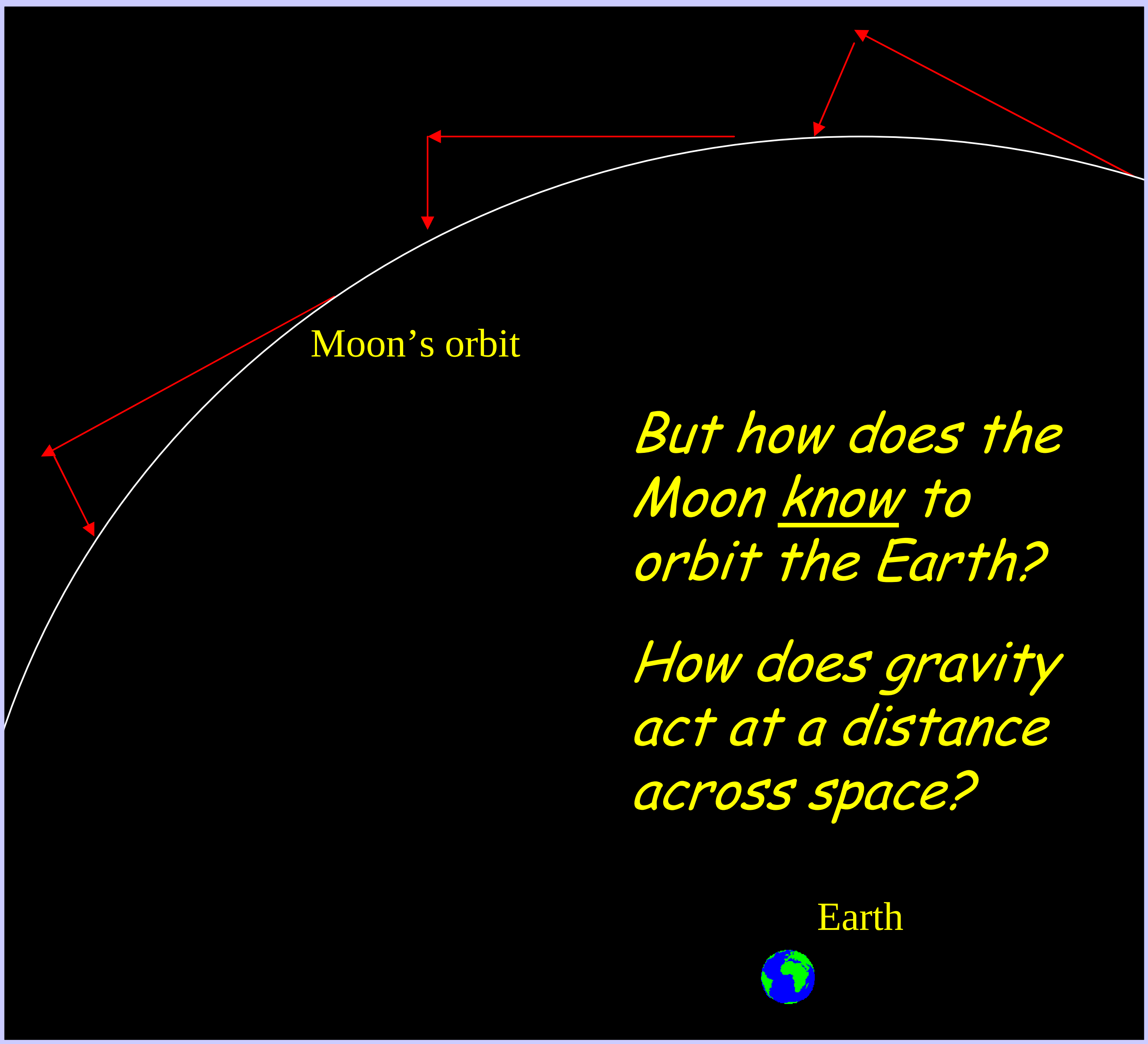
$$F_g = G\frac{m_1 m_2}{r^2}$$





Isaac Newton:
1642 – 1727 AD

The Principia: 1684 - 1686



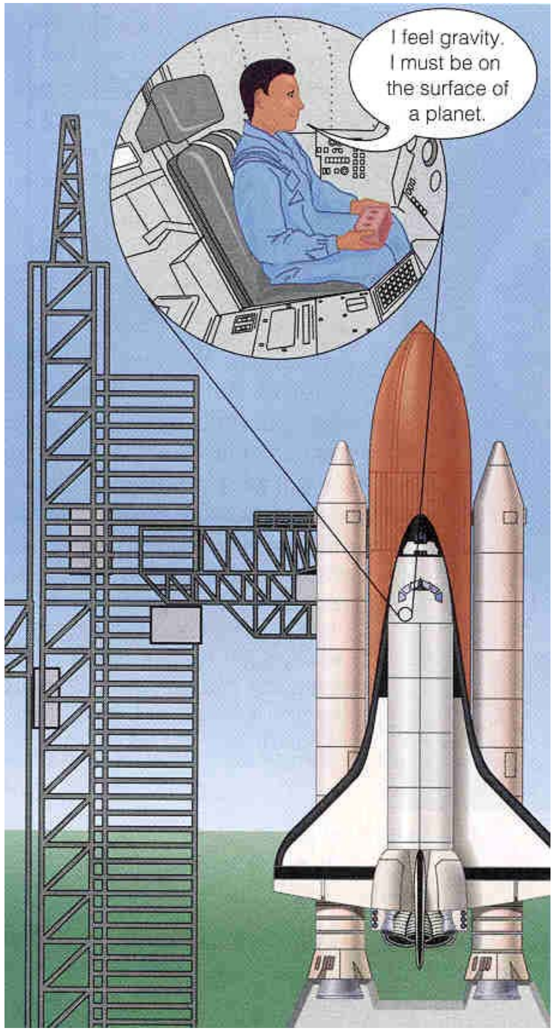
But how does the Moon know to orbit the Earth?

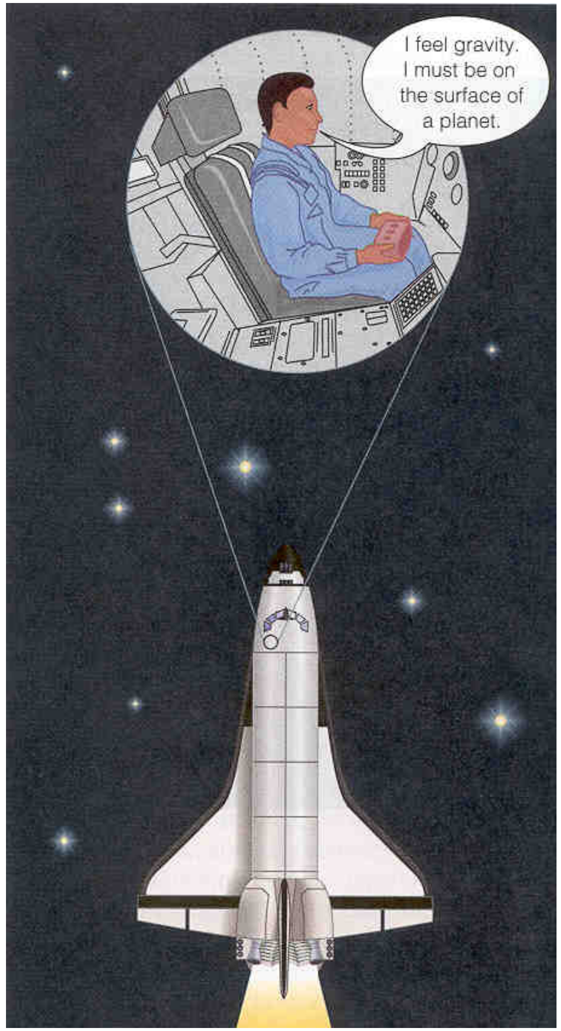
How does gravity act at a distance across space?

Gravity in Einstein's Universe

Gravity and acceleration are ***equivalent***

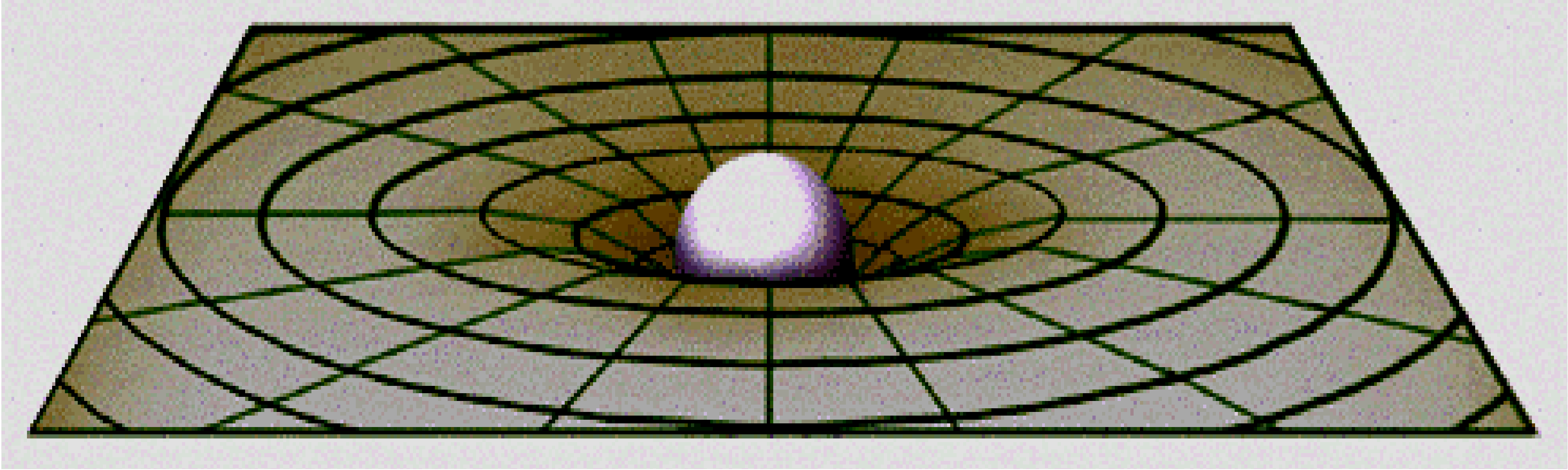
Gravity is not a force acting *through* space and time, but the result of mass (and energy) warping spacetime itself





Gravity in Einstein's Universe

"Spacetime tells matter how to move, and matter tells spacetime how to curve"



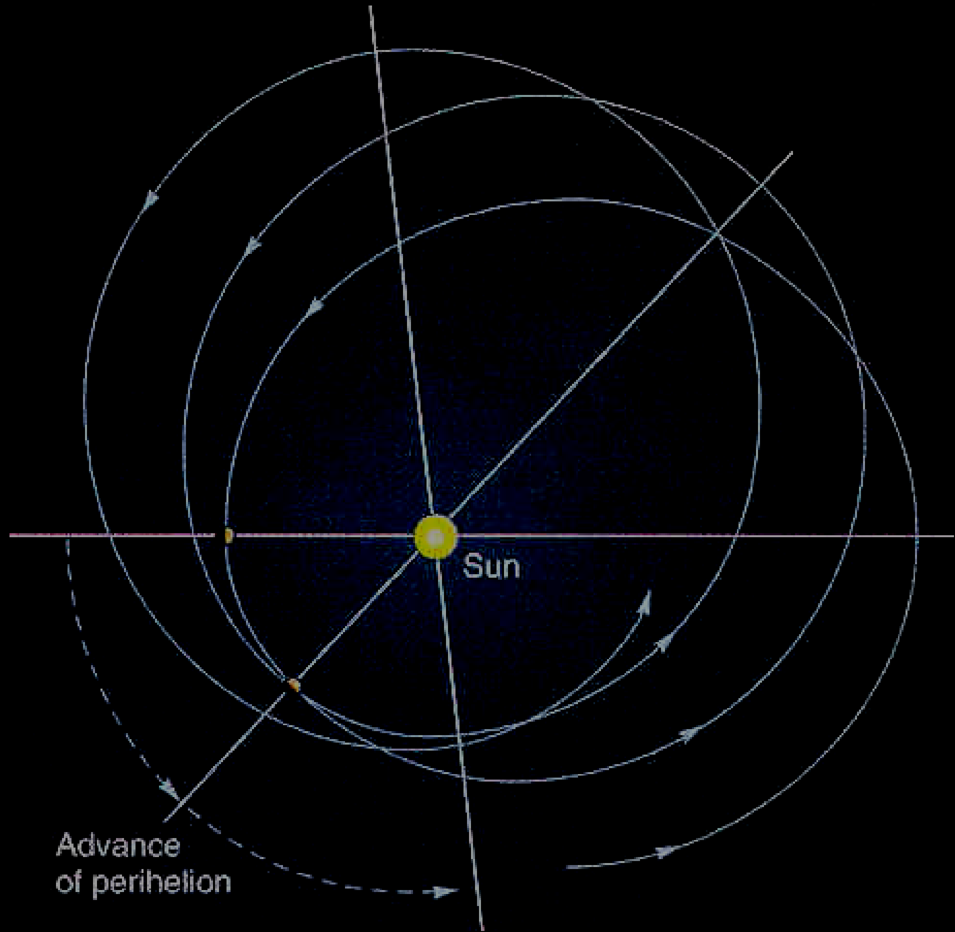
Gravity in Einstein's Universe

V

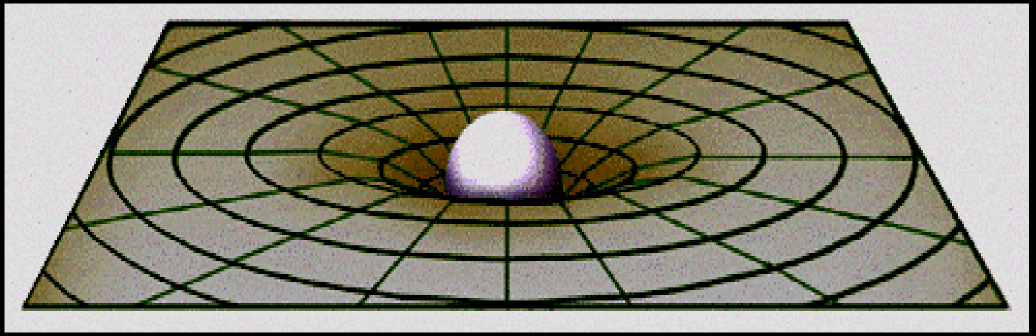
Differences between Newton's and Einstein's gravity predictions are tiny, but *can* be detected in the Solar System – and Einstein always wins!

Gravity in Einstein's Universe

1. **Precession of orbits – observed for Mercury, matching GR prediction**



Gravity in Einstein’s Universe



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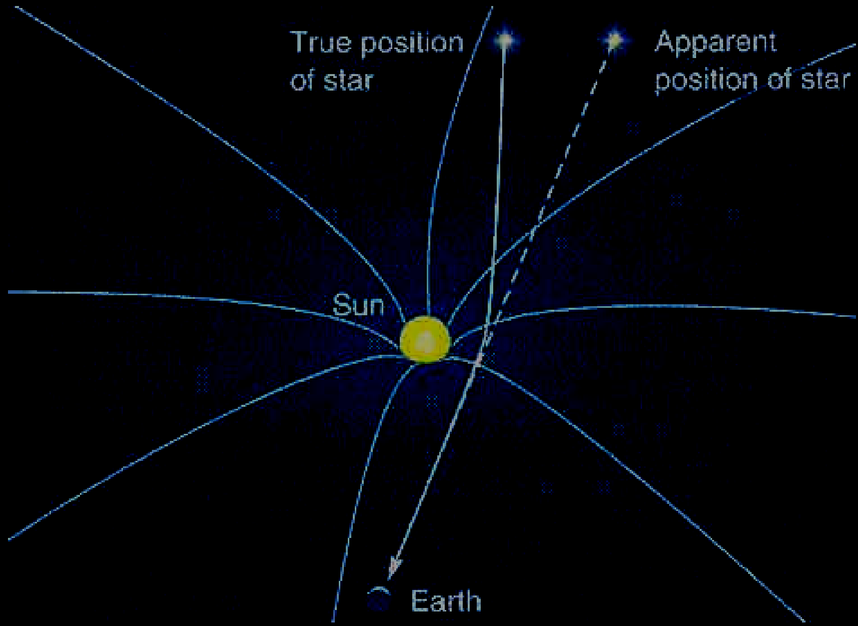
Gravity in Einstein's Universe



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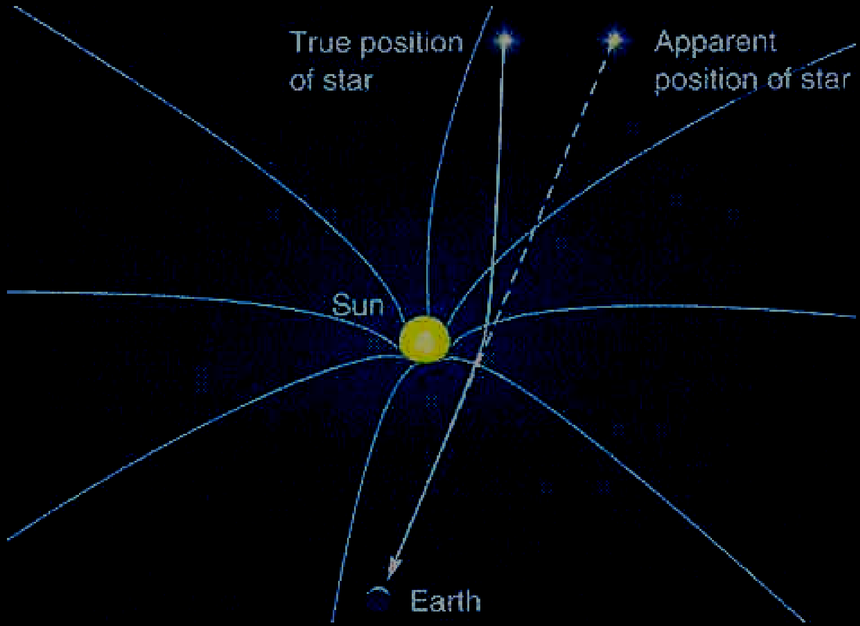
Gravity in Einstein's Universe



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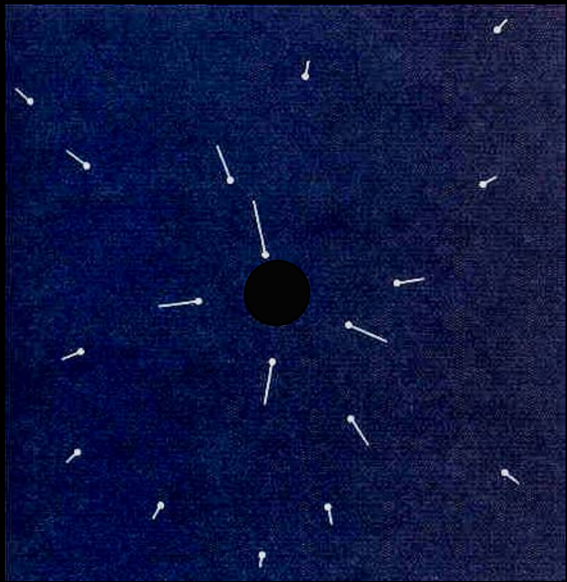
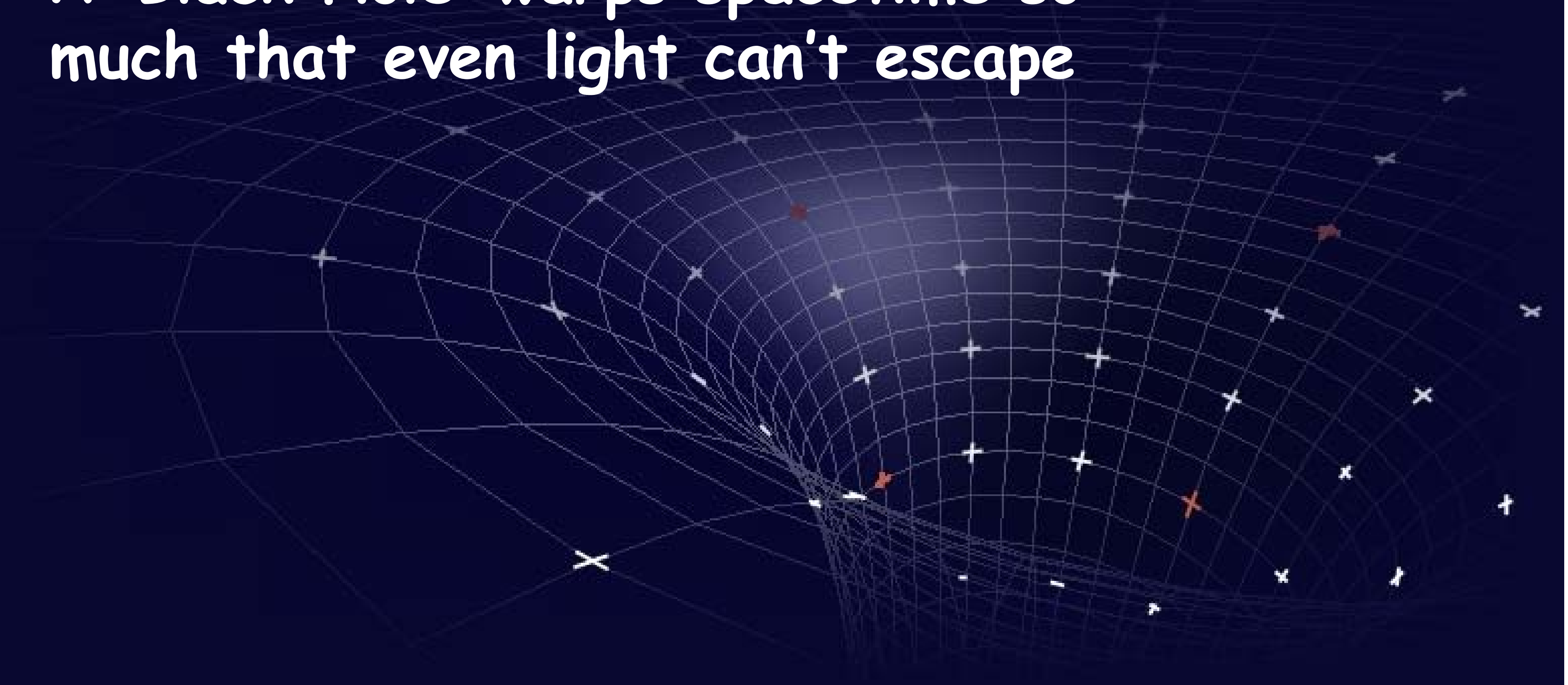
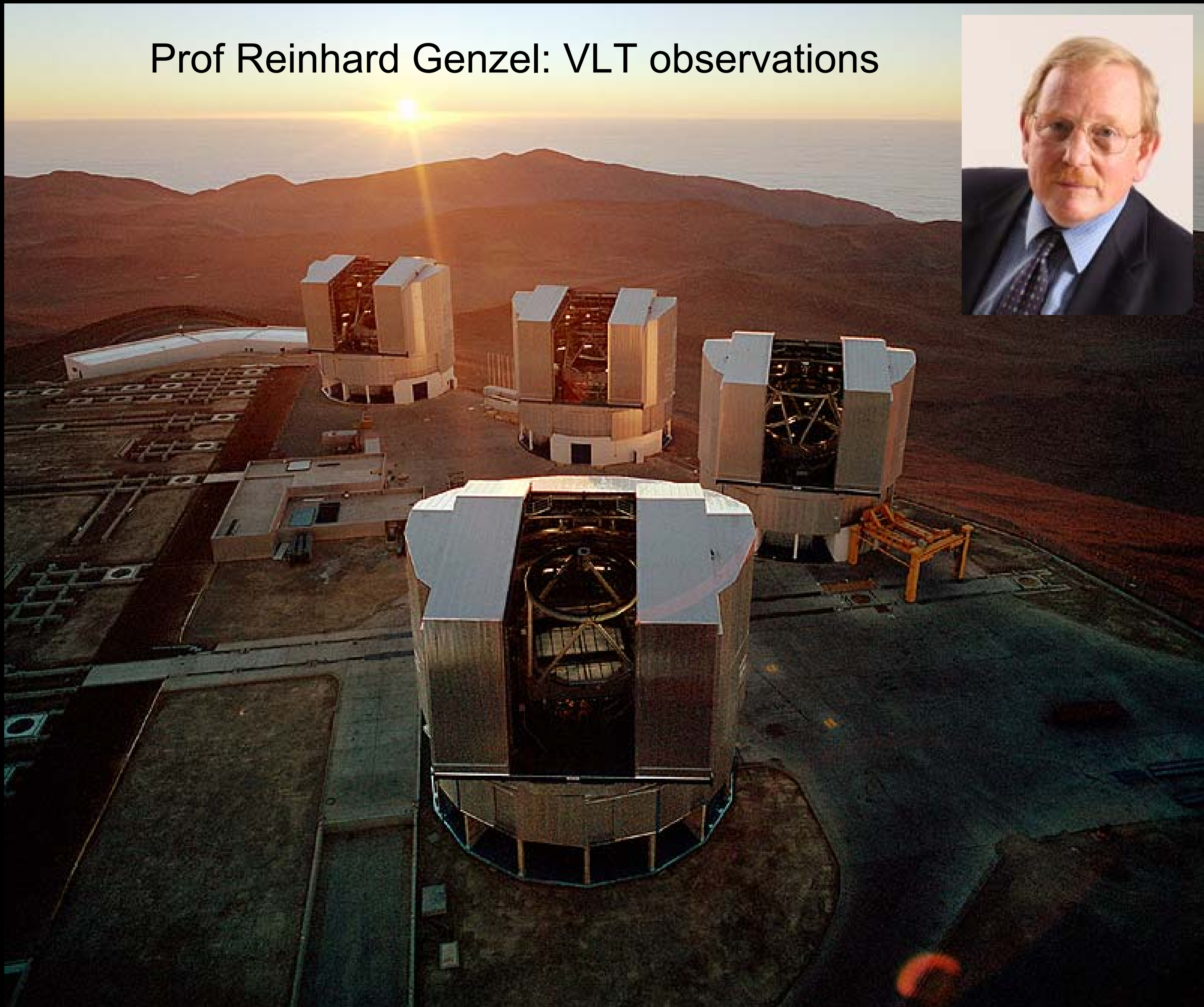


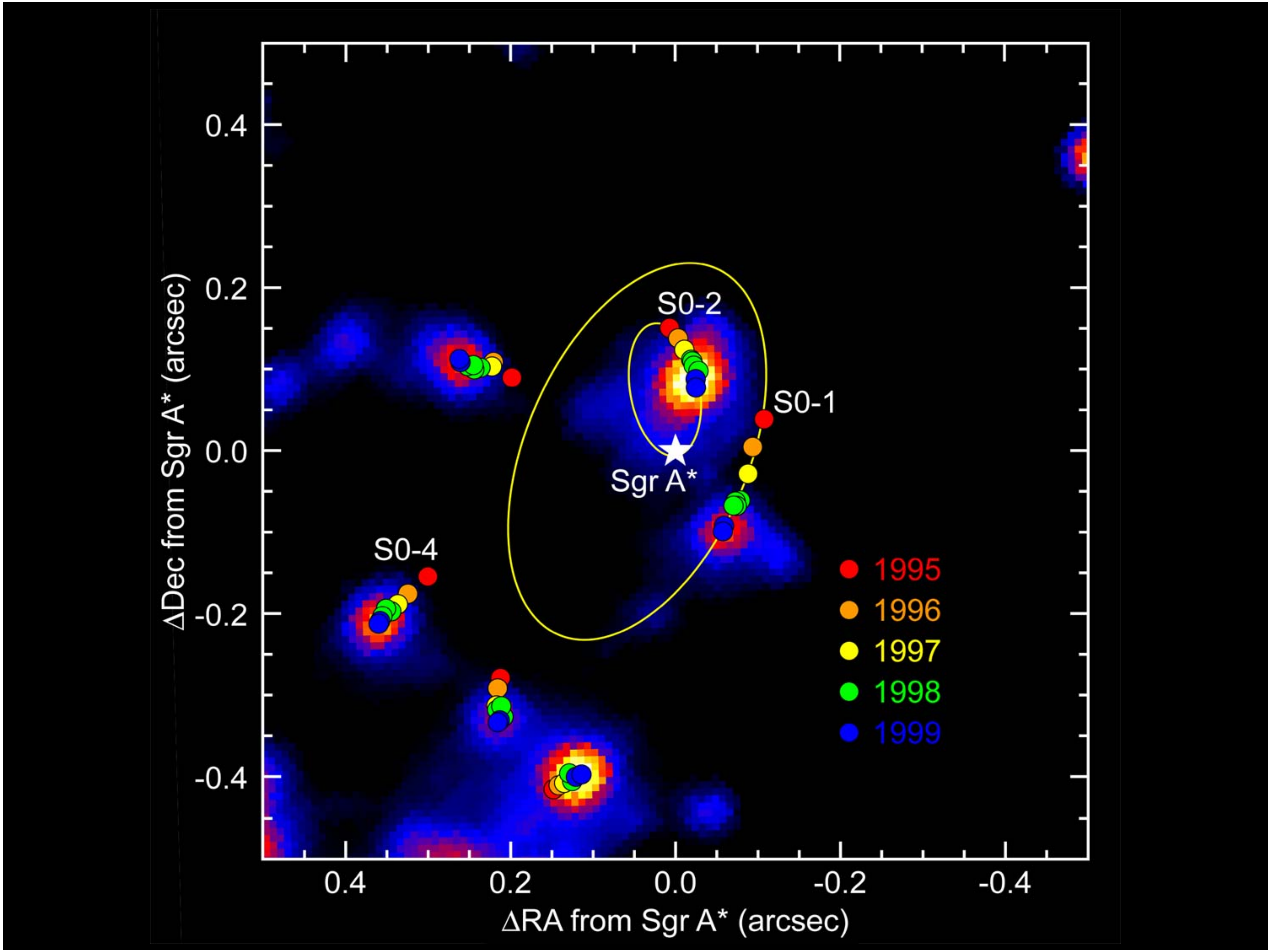
Gravity in Einstein's Universe

A 'Black Hole' warps spacetime so much that even light can't escape

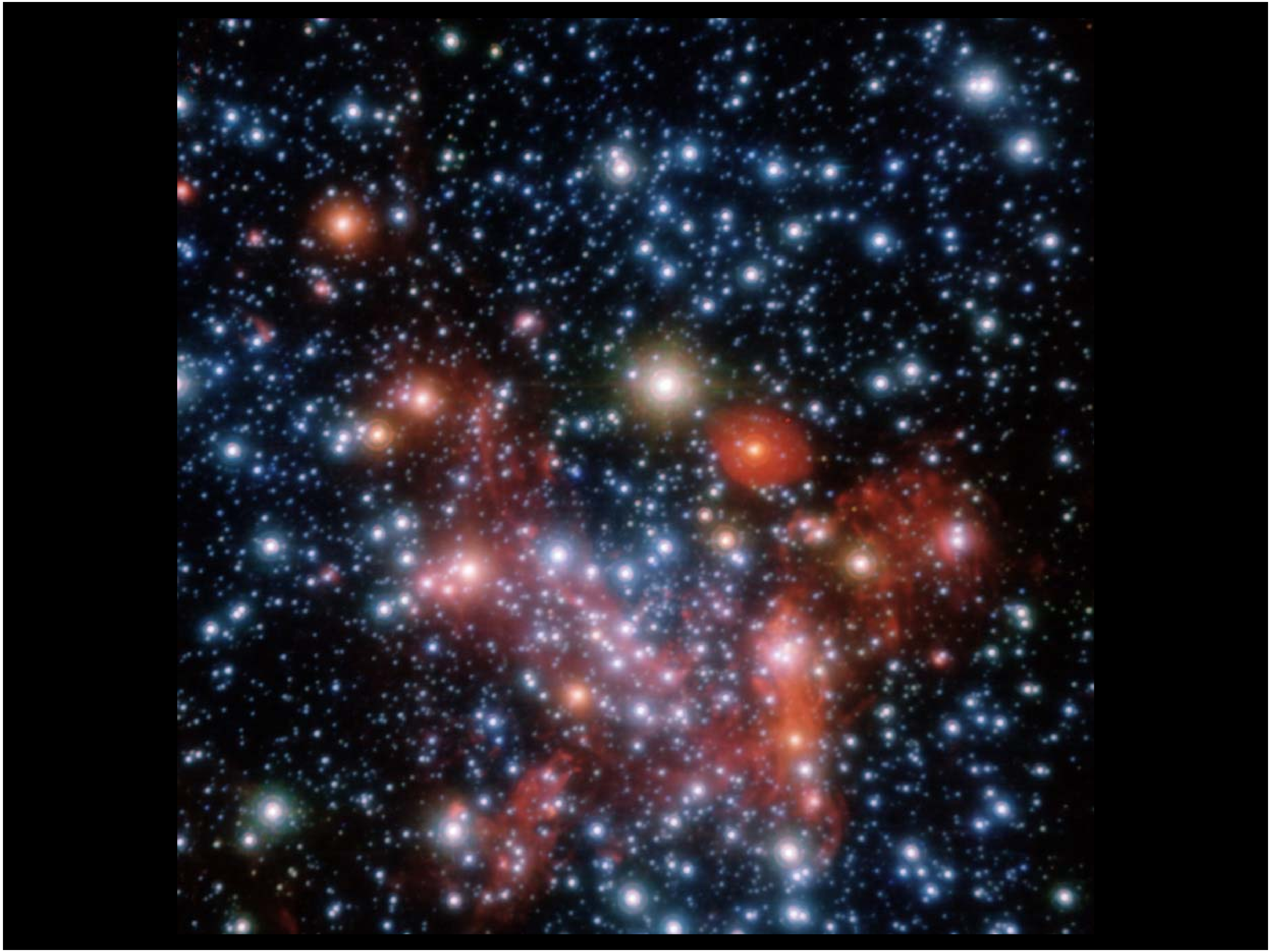


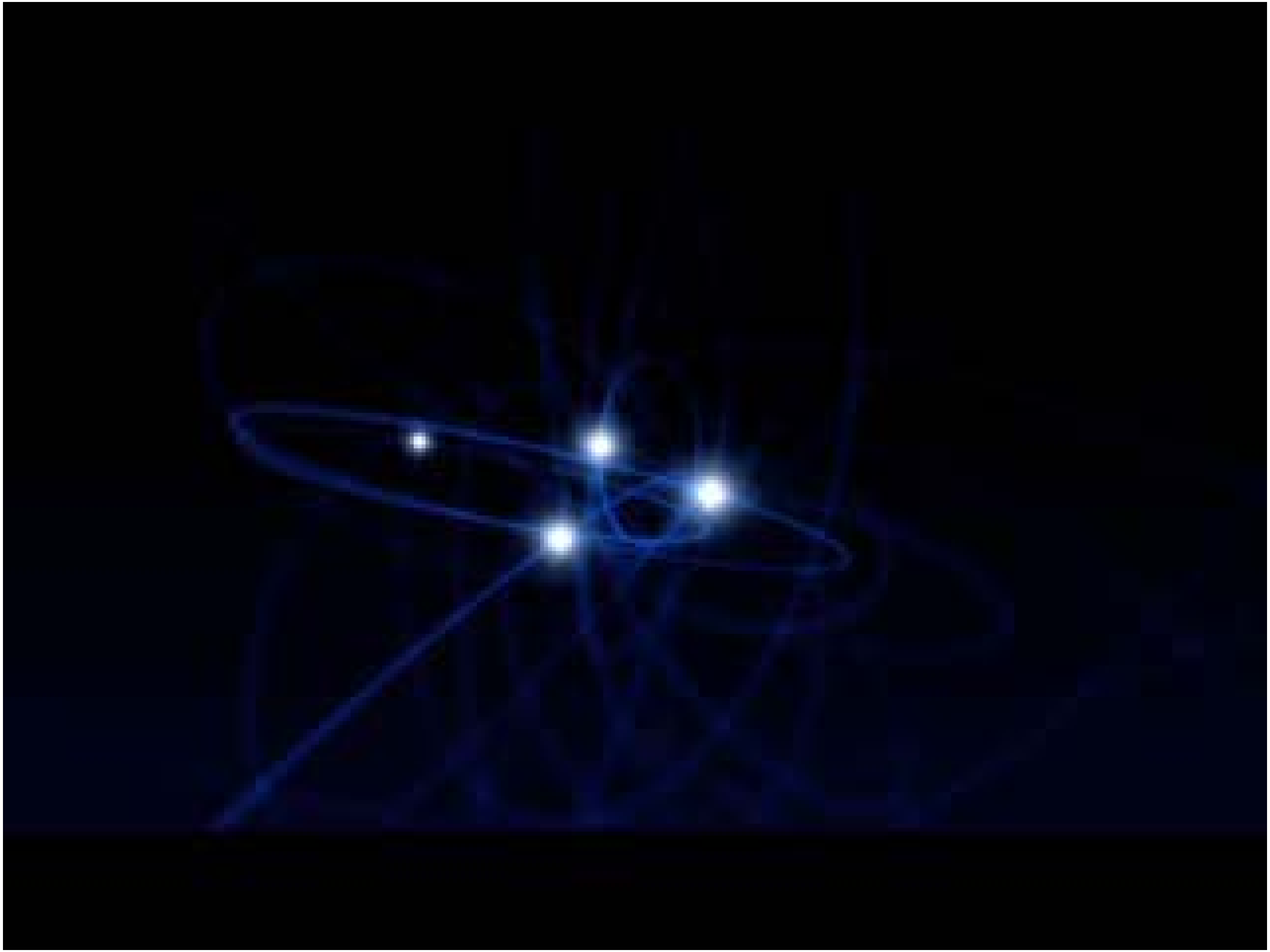
Prof Reinhard Genzel: VLT observations

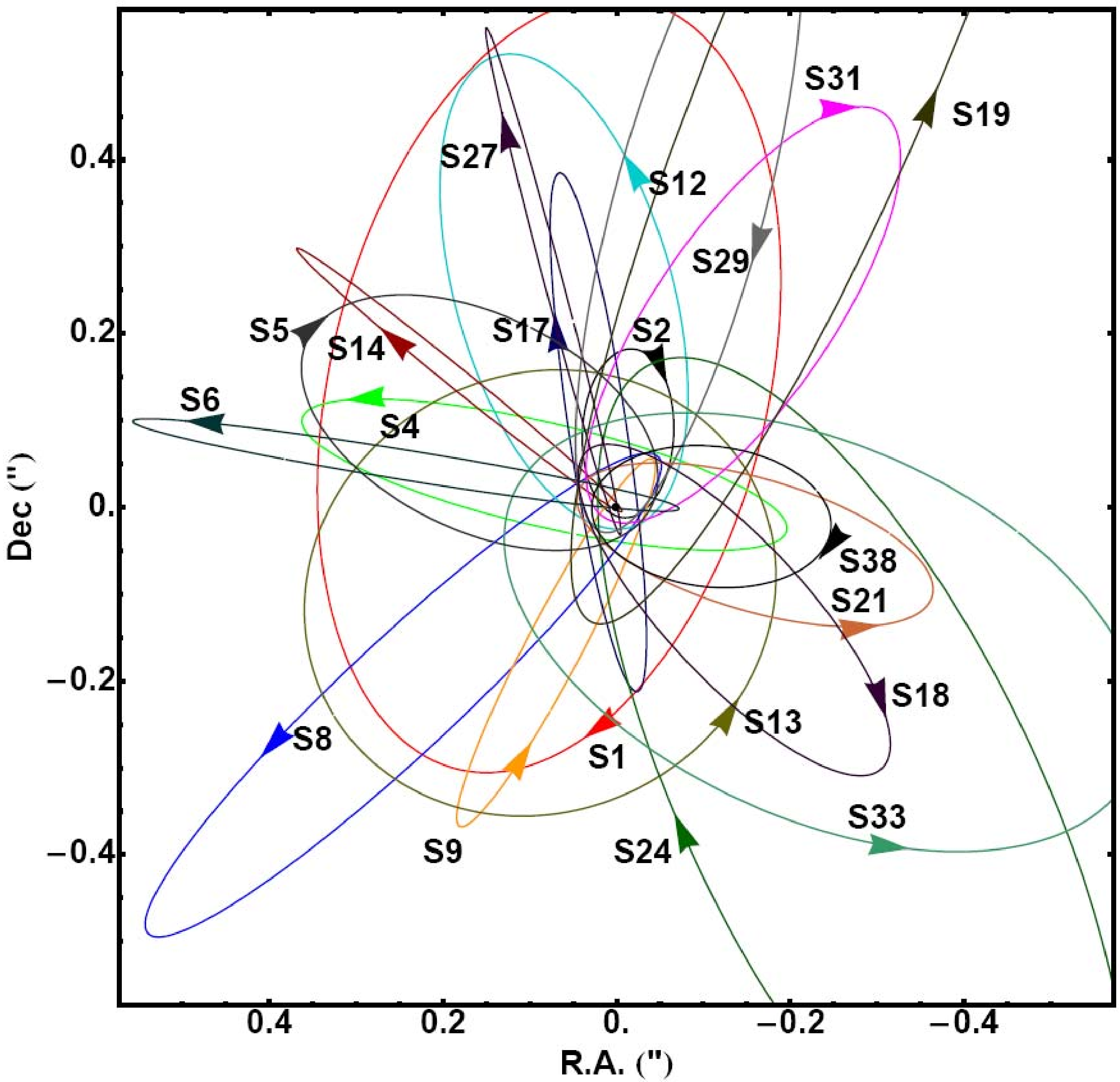




S0-2
S0-1
Sgr A*
S0-4
1995
1996
1997
1998
1999
0.4
0.2
0.0
-0.2
-0.4
ΔDec from Sgr A* (arcsec)
ΔRA from Sgr A* (arcsec)







Dec (")
R.A. (")
0.4
0.2
0.
−0.2
−0.4
S1
S2
S4
S5
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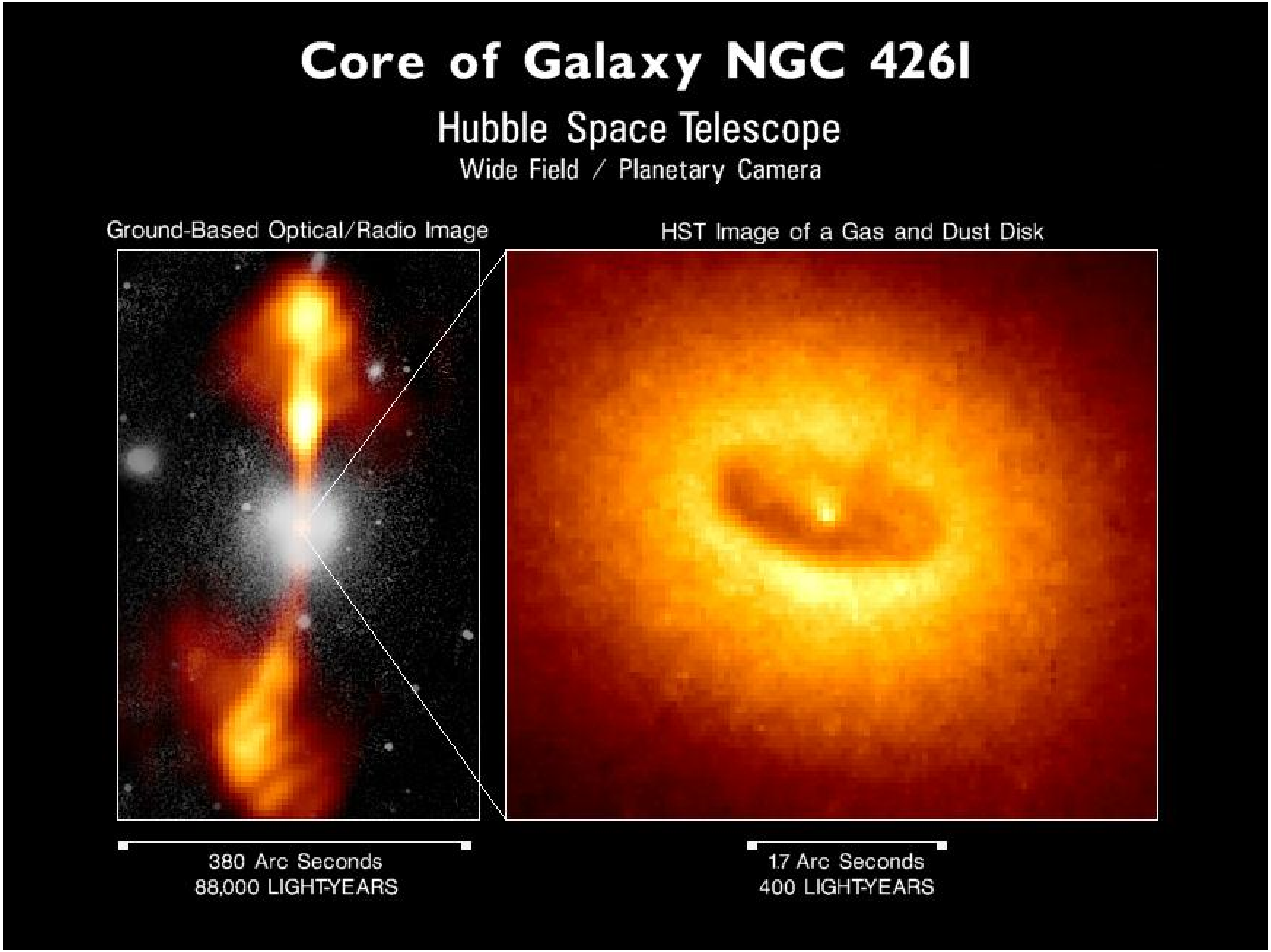
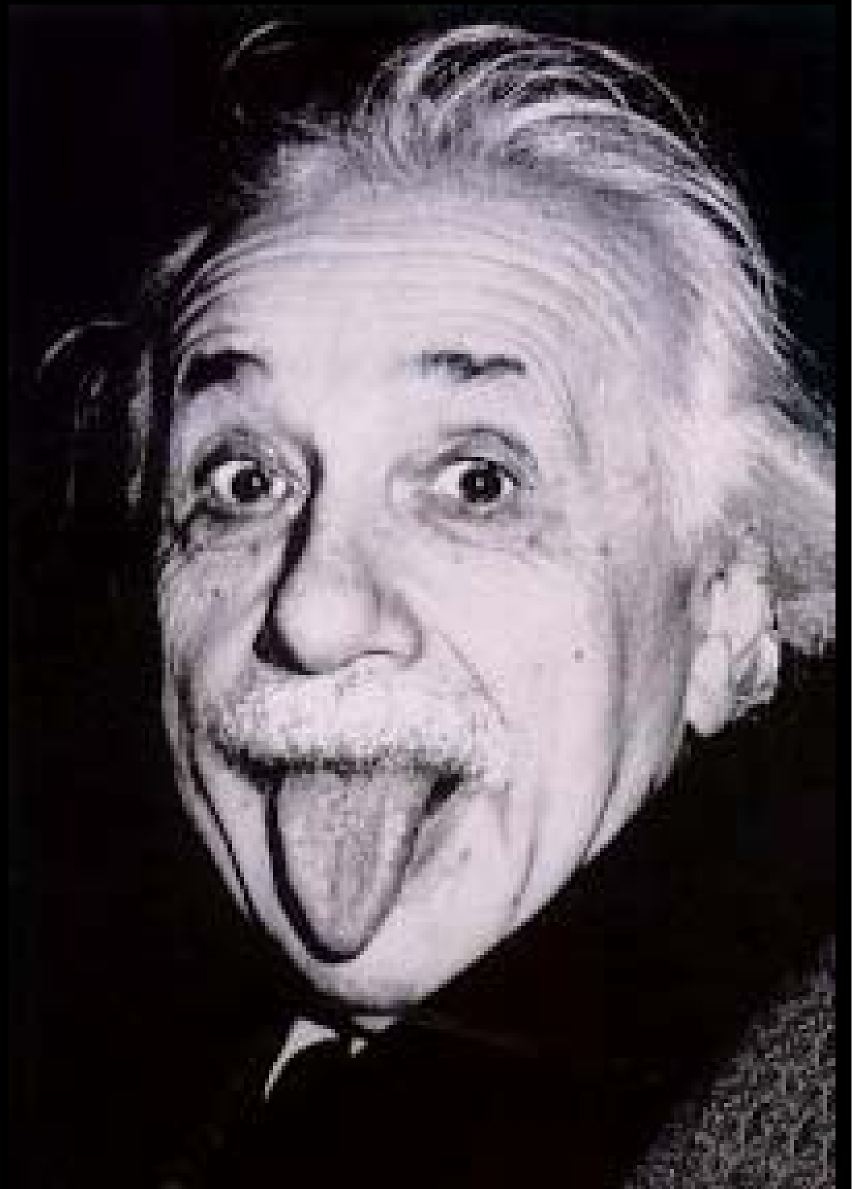
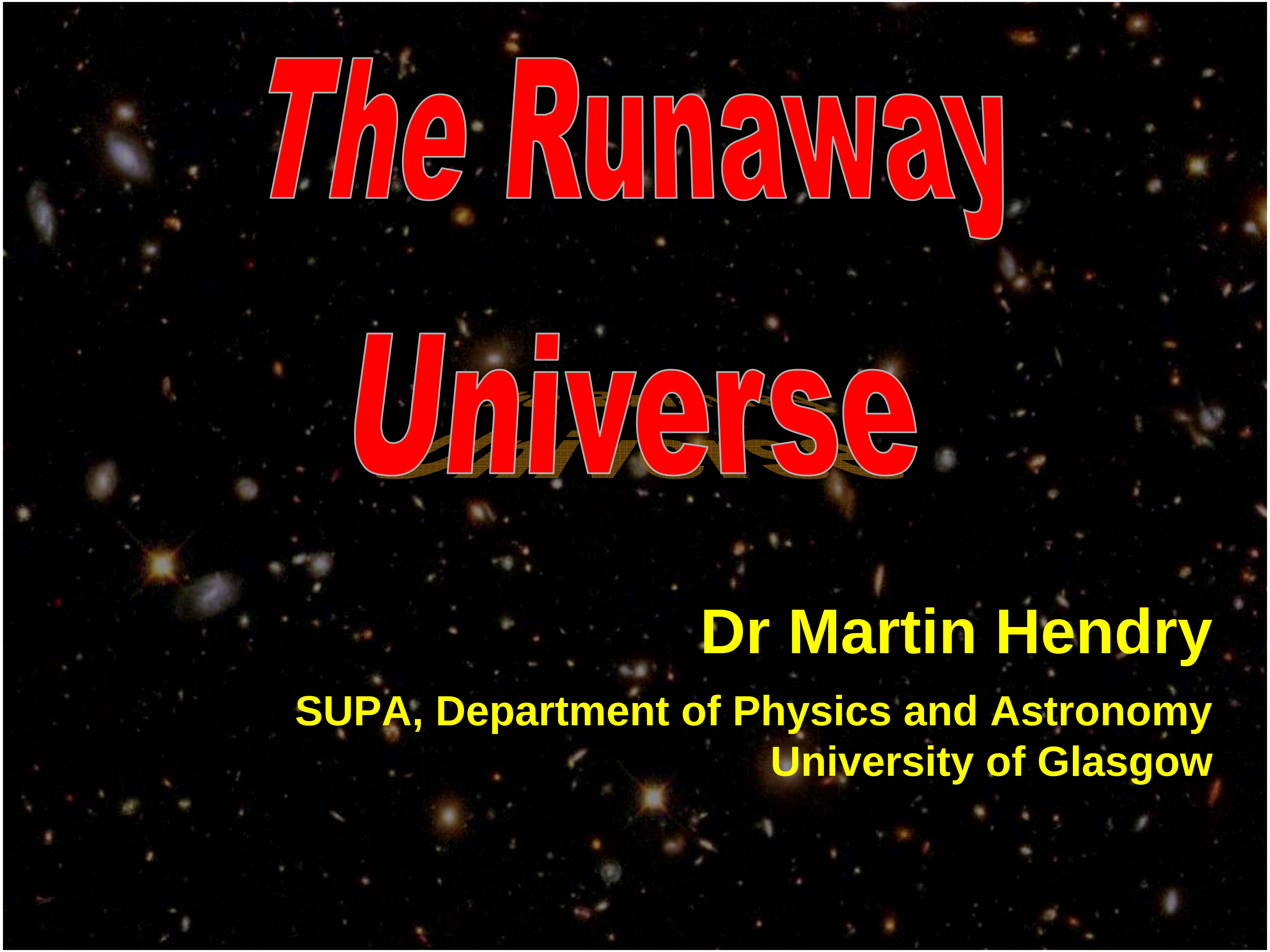

Core of Galaxy NGC 4261
Hubble Space Telescope
Wide Field / Planetary Camera
Ground-Based Optical/Radio Image
HST Image of a Gas and Dust Disk
380 Arc Seconds
88,000 LIGHT-YEARS
1.7 Arc Seconds
400 LIGHT-YEARS

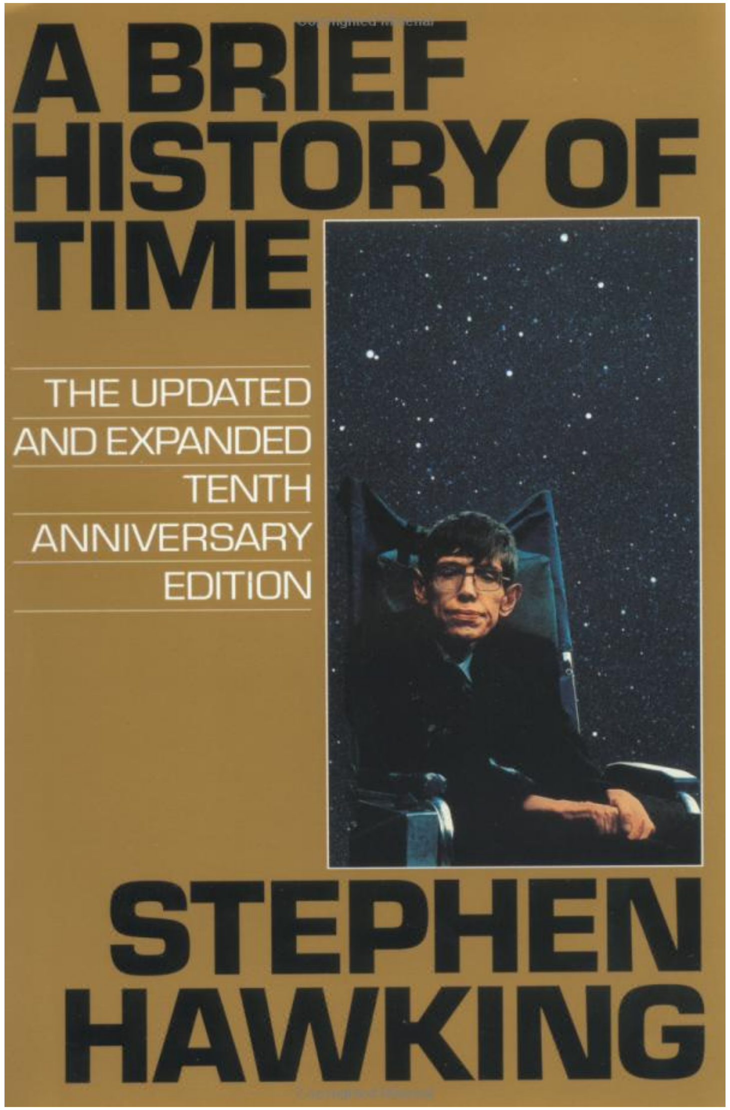
Grand Unification Theories

"The generalisation of the theory of gravitation has occupied me unceasingly since 1916"

Einstein, 1952




The Runaway Universe
Dr Martin Hendry
SUPA, Department of Physics and Astronomy
University of Glasgow



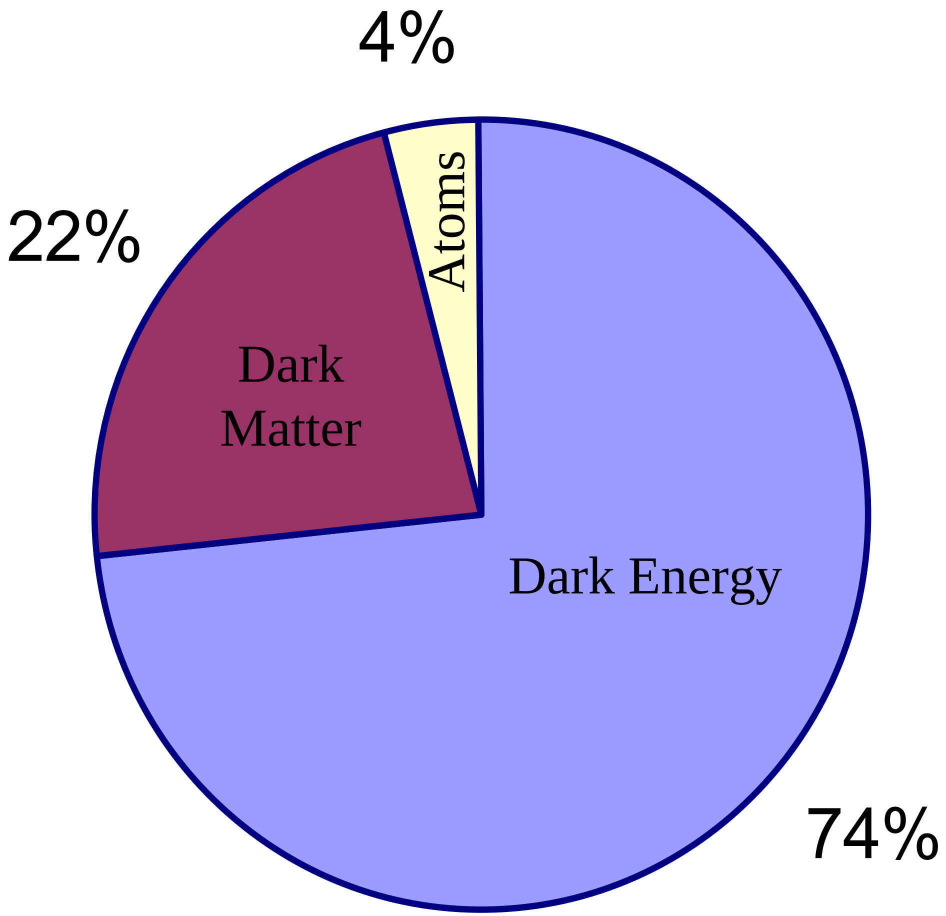
CHAPTER 1

OUR PICTURE OF THE UNIVERSE

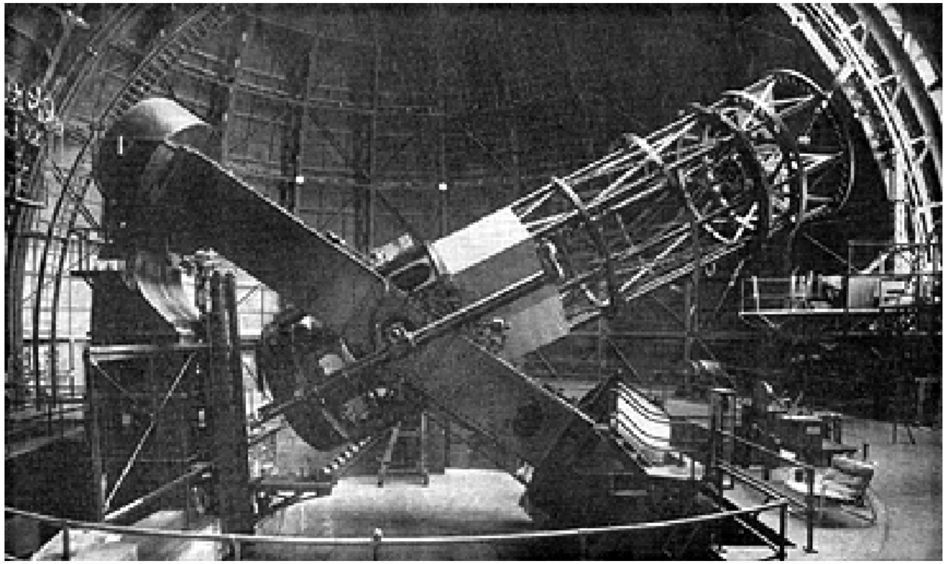
…A little old lady at the back of the room got up and said: “What you have told us is rubbish. The world is really a flat plate supported on the back of a giant tortoise.” The scientist gave a superior smile before replying “What is the tortoise standing on?”

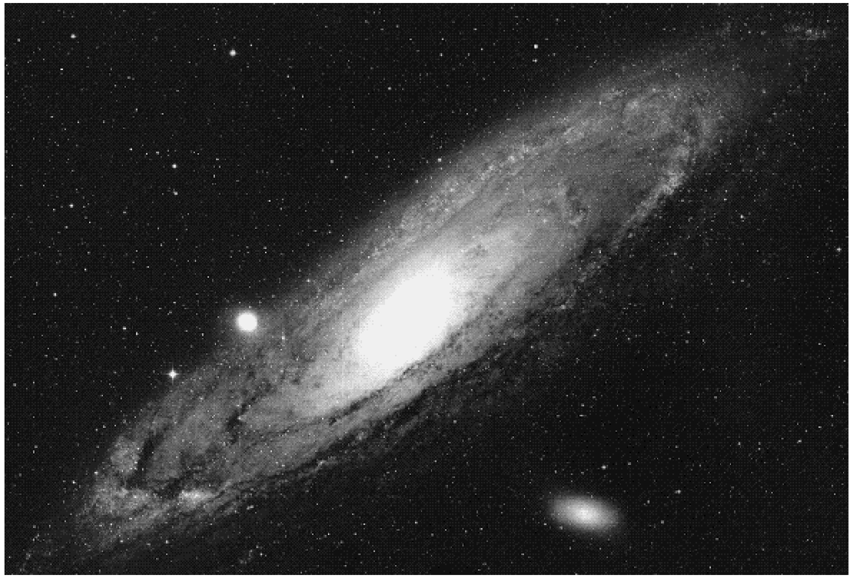
“You’re very clever young man, very clever,” said the old lady. **“But it’s turtles all the way down!”**

State of the Universe – Feb 2010



More than 95% of matter and energy in the Universe exists in a mysterious, unknown form…





Edwin Hubble

Hubble's Law

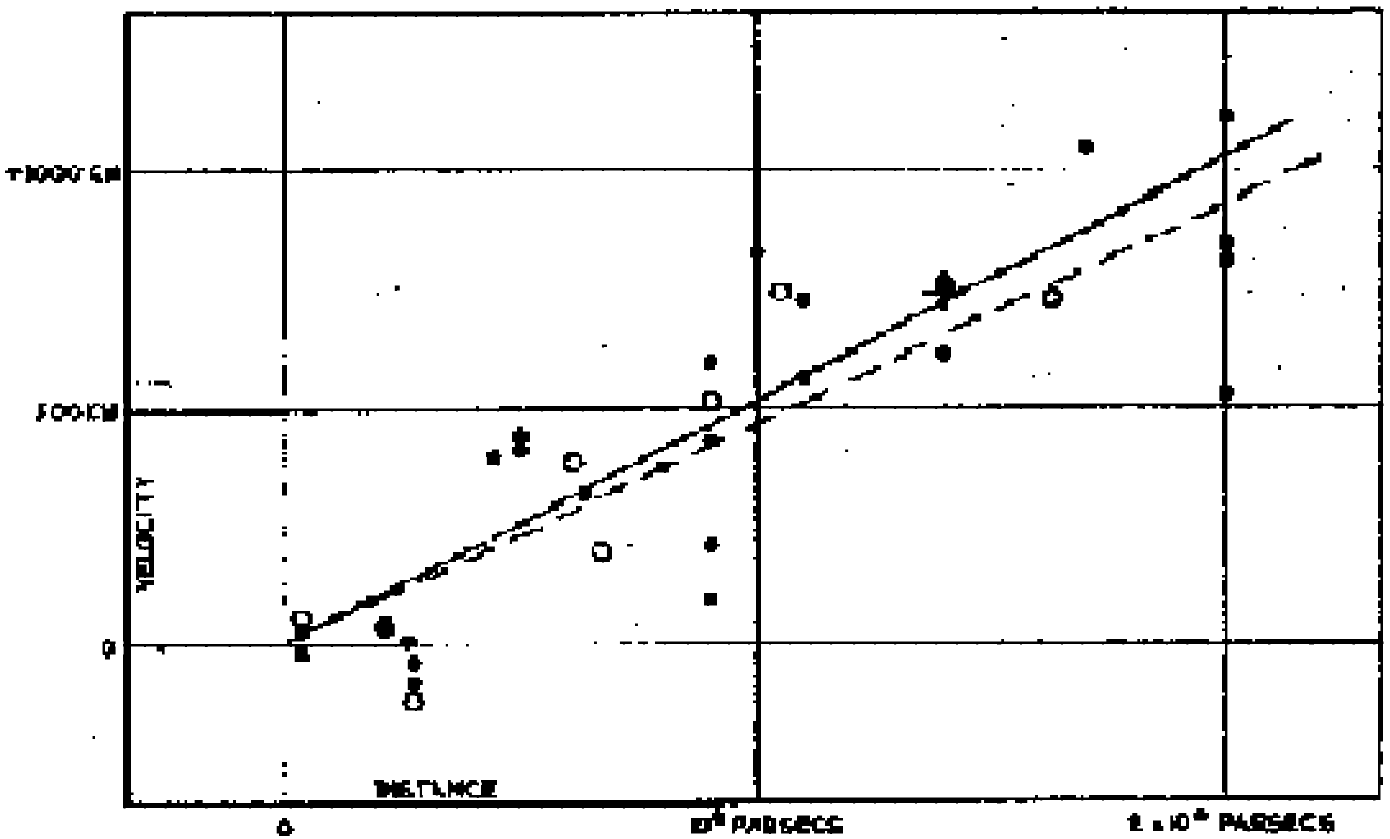
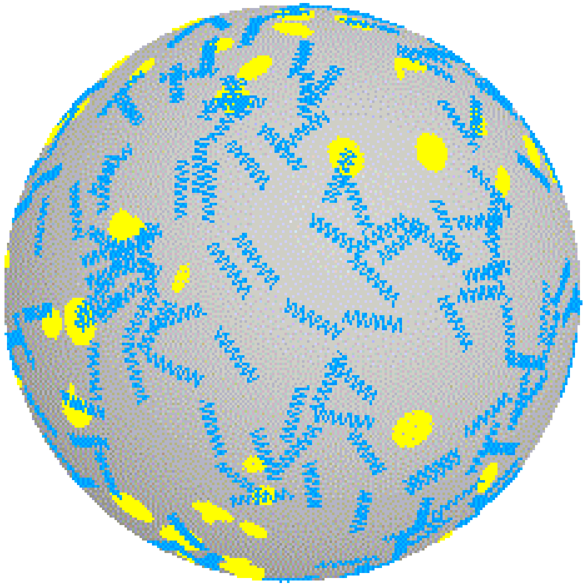


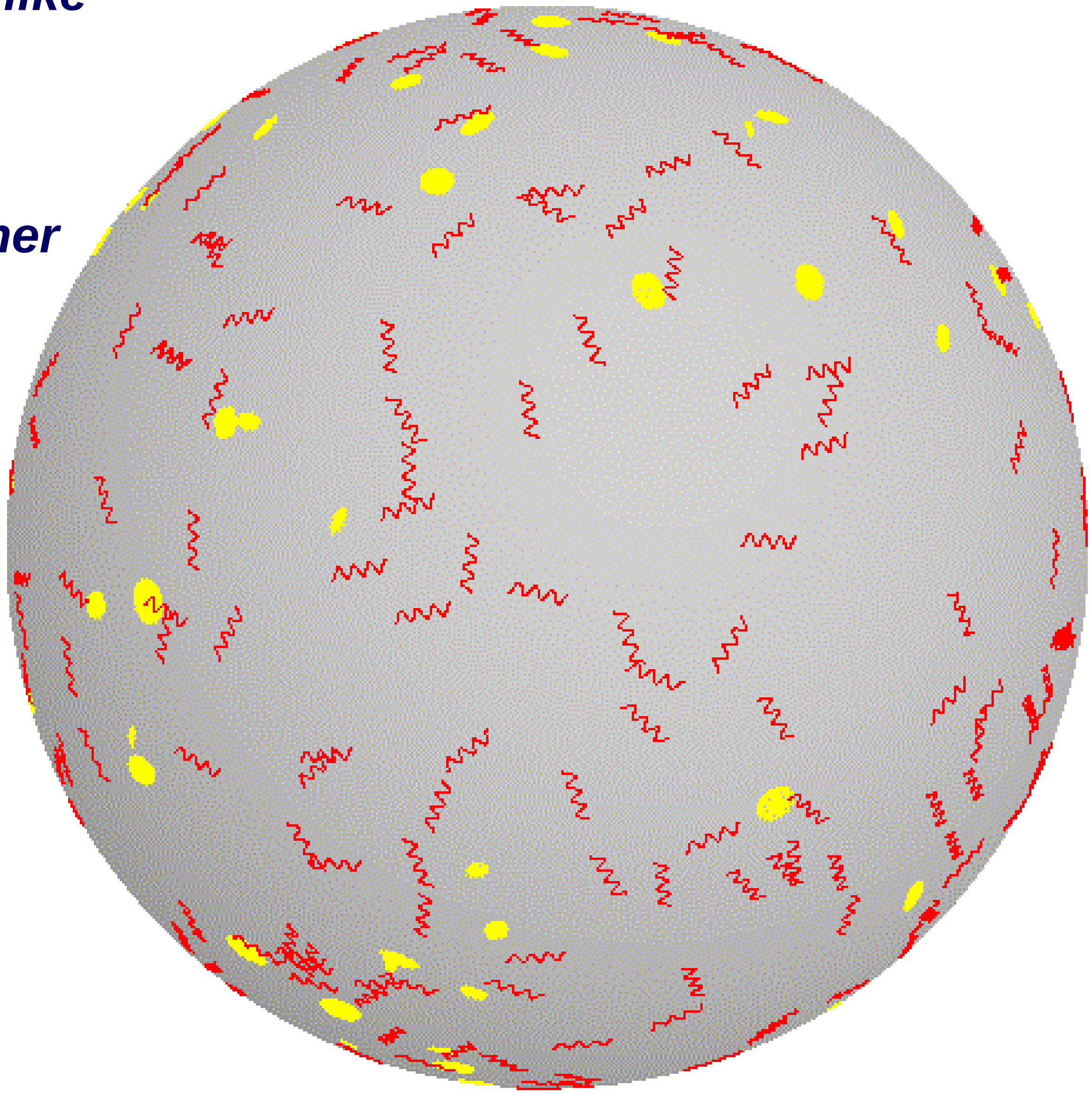
FIGURE 1

Distant galaxies are moving away from us with a speed proportional to their distance

Spacetime is expanding like the surface of a balloon.

As the balloon expands, galaxies are carried farther apart





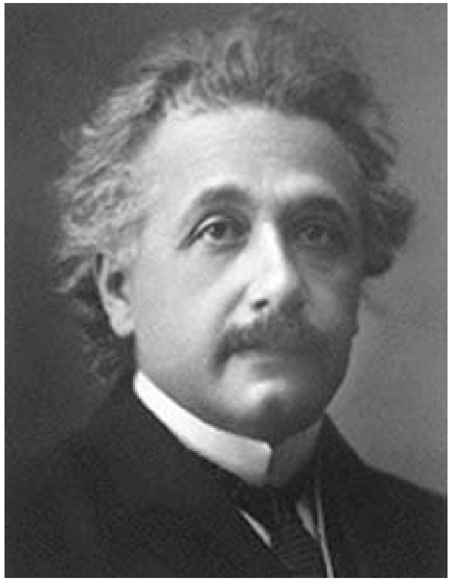
1916. № 7.

ANNALEN DER PHYSIK.
VIERTE FOLGE. BAND 49.

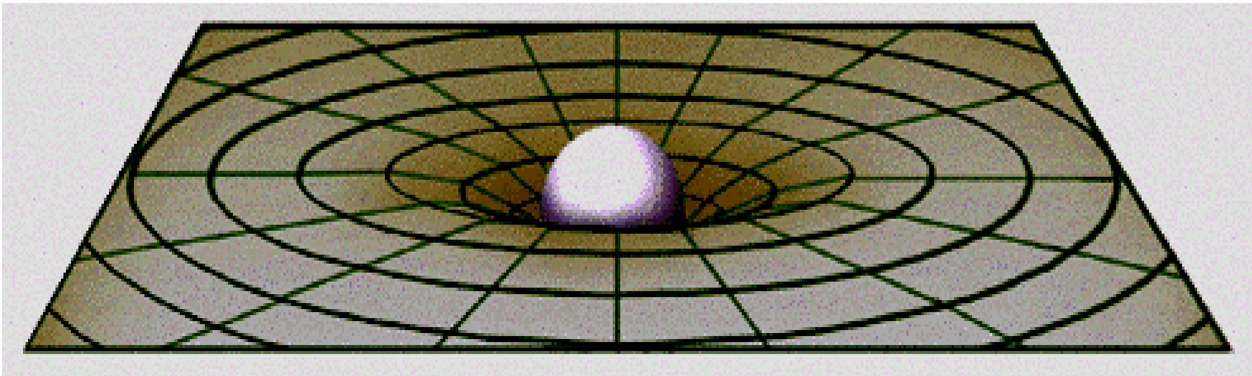
1. *Die Grundlage der allgemeinen Relativitätstheorie;*
von A. Einstein.

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül", welcher auf den Forschungen von Gauss, Riemann und Christoffel über nichteuklidische Mannigfaltigkeiten ruht und von Ricci und Levi-Civita in ein System gebracht und bereits auf Probleme der theoretischen Physik angewendet wurde. Ich habe im Abschnitt B der vorliegenden Abhandlung alle für uns nötigen, bei dem Physiker nicht als bekannt vorauszusetzenden mathematischen Hilfsmittel in möglichst einfacher und durchsichtiger Weise entwickelt, so daß ein Studium mathematischer Literatur für das Verständnis der vorliegenden Abhandlung nicht erforderlich ist. Endlich sei an dieser Stelle dankbar meines Freundes, des Mathematikers Grossmann, gedacht, der mir durch seine Hilfe nicht nur das Studium der einschlägigen mathematischen Literatur ersparte, sondern mich auch beim Suchen nach den Feldgleichungen der Gravitation unterstützte.

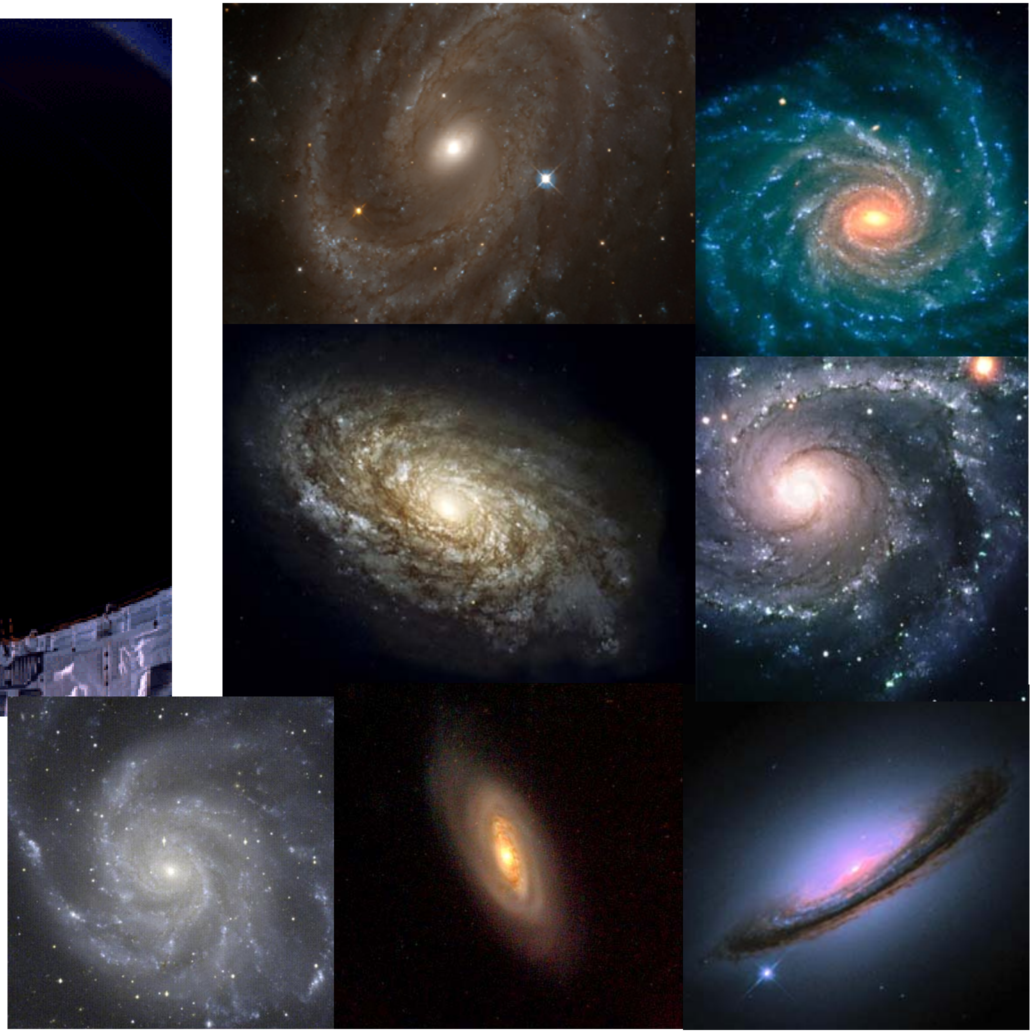
Gravity in Einstein's Universe



"Spacetime tells matter how to move, and matter tells spacetime how to curve"



How fast is the Universe expanding?

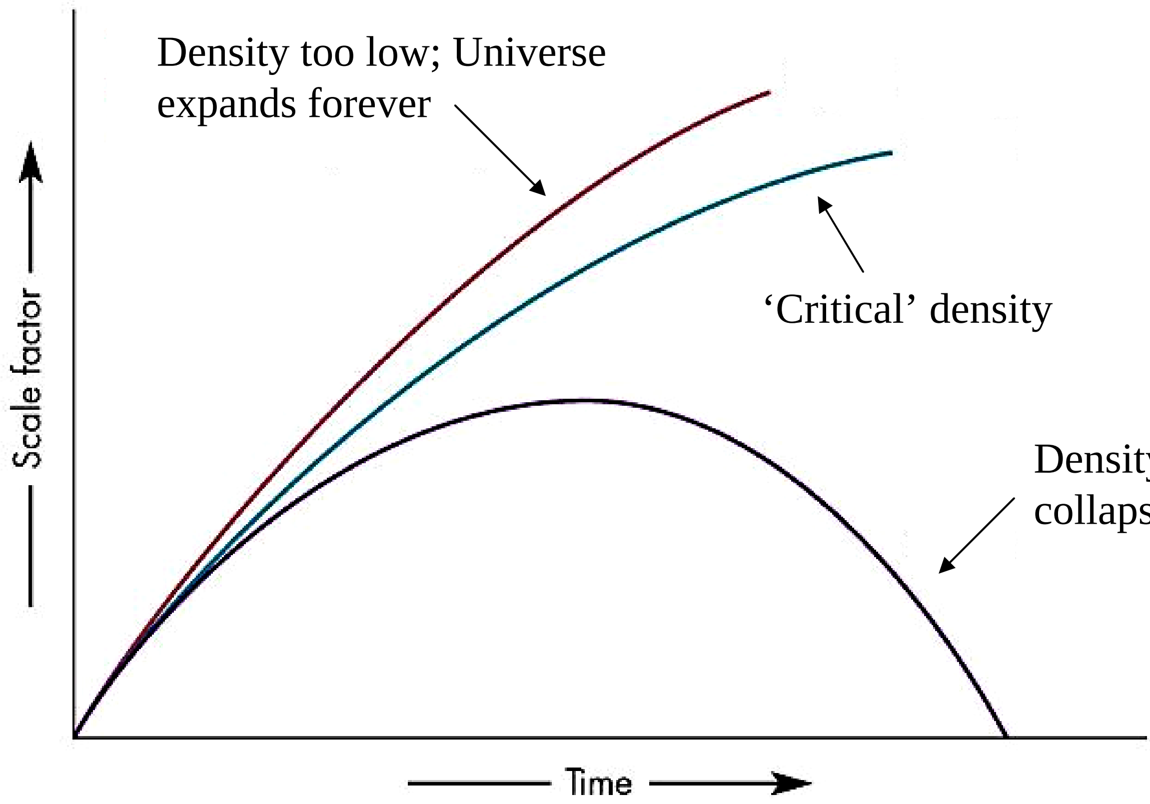


HST Key Project:

Cepheid distances to ~30 galaxies, linking to other **standard candles**

Will the Universe expand forever?

Answer depends on the density of ***matter*** in the Universe.



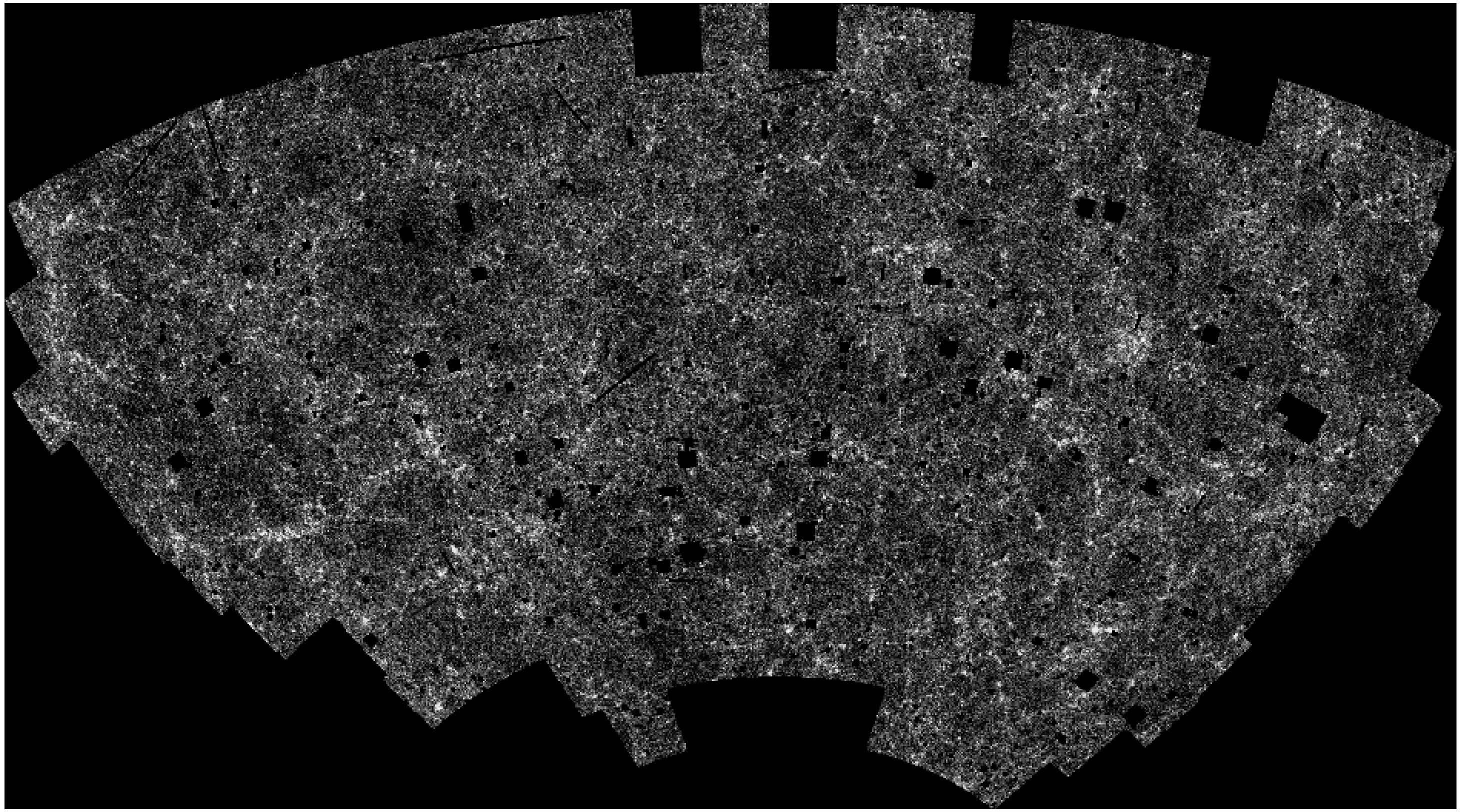
Gravity acts to ***slow down*** the expansion

University of Glasgow

SUPA IGR

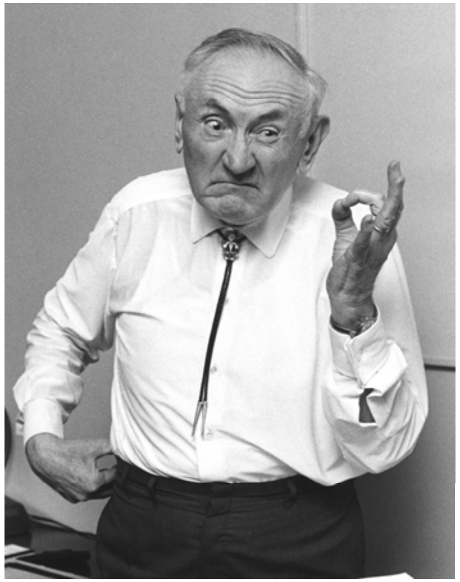
Weighing the Universe

Weighing the Universe



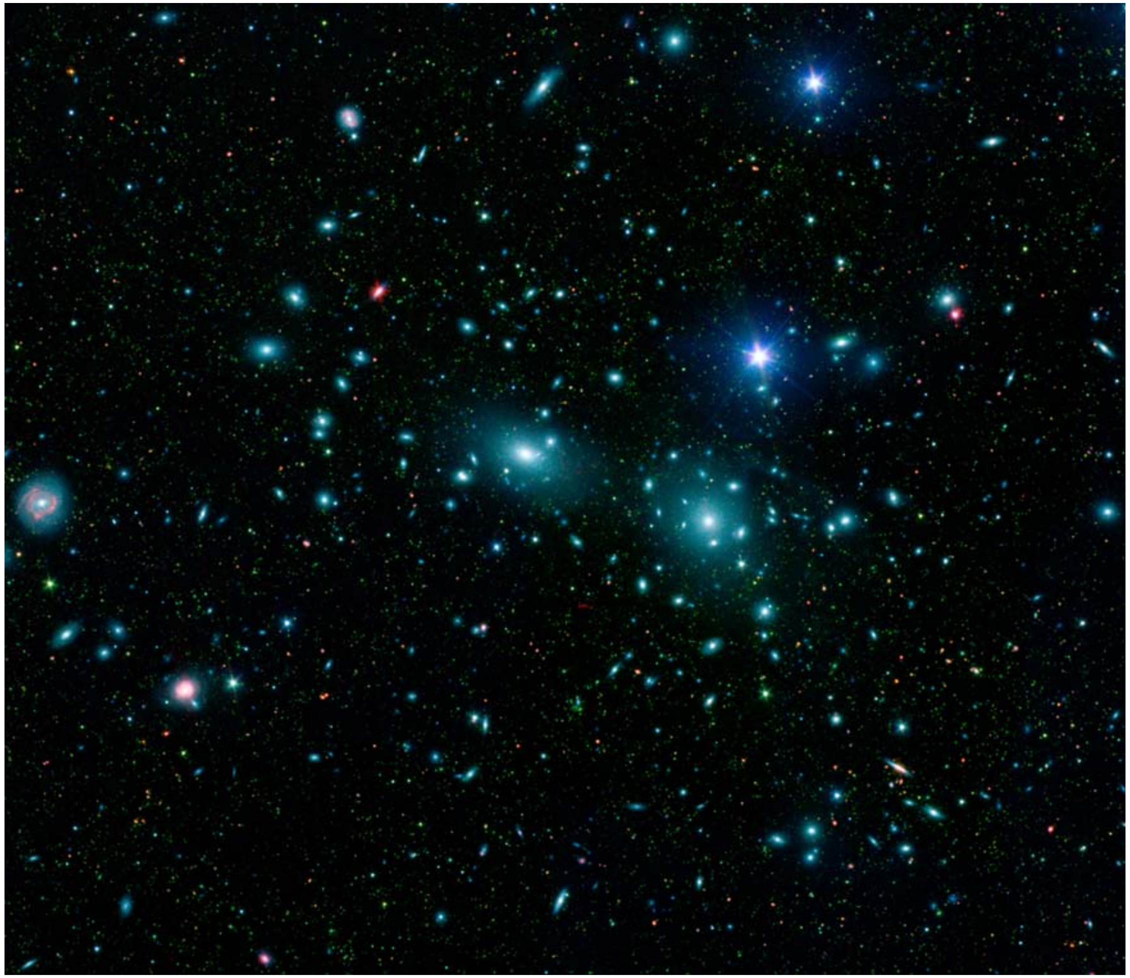
Luminous matter makes up only 0.5% of the critical density of the Universe

More than meets the eye?...



Fritz Zwicky

1933: finds evidence for **dark matter** in the Coma galaxy cluster



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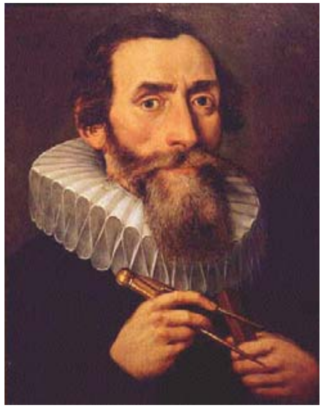
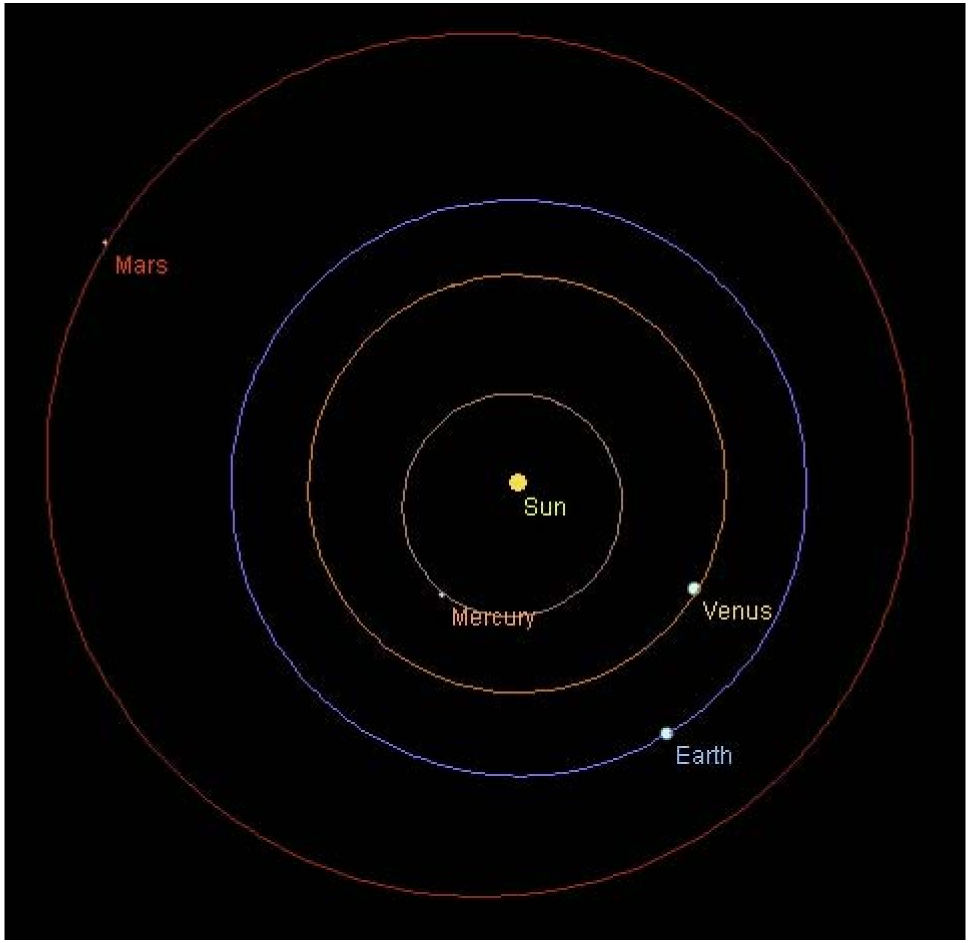
Weighing the Solar System



Johannes Kepler

Isaac Newton



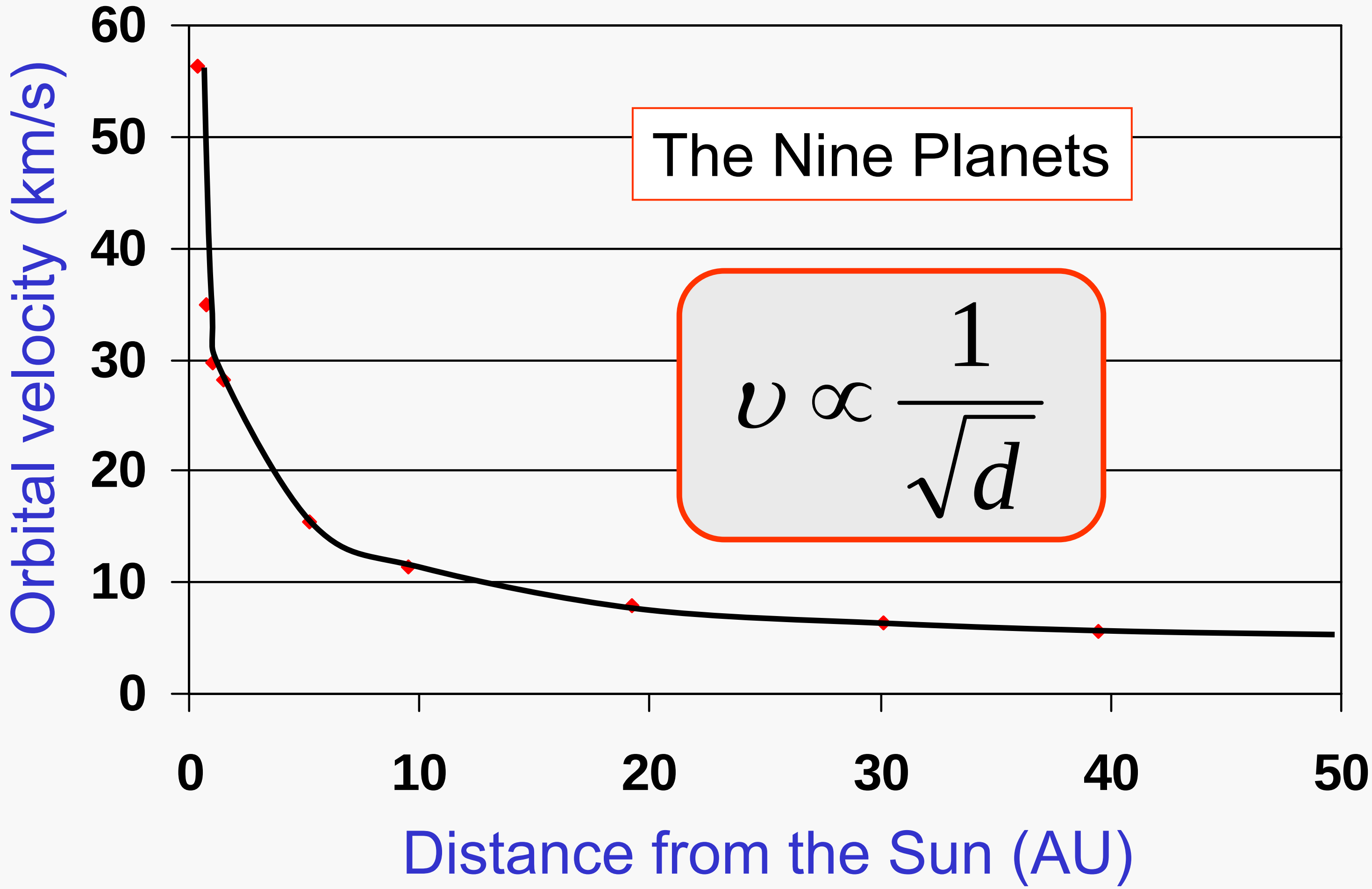
Schiehallion, from Loch Rannoch

Maskelyne's 1774 experiment to measure G

Charles Hutton

Neville Maskelyne

Weighing the Solar System

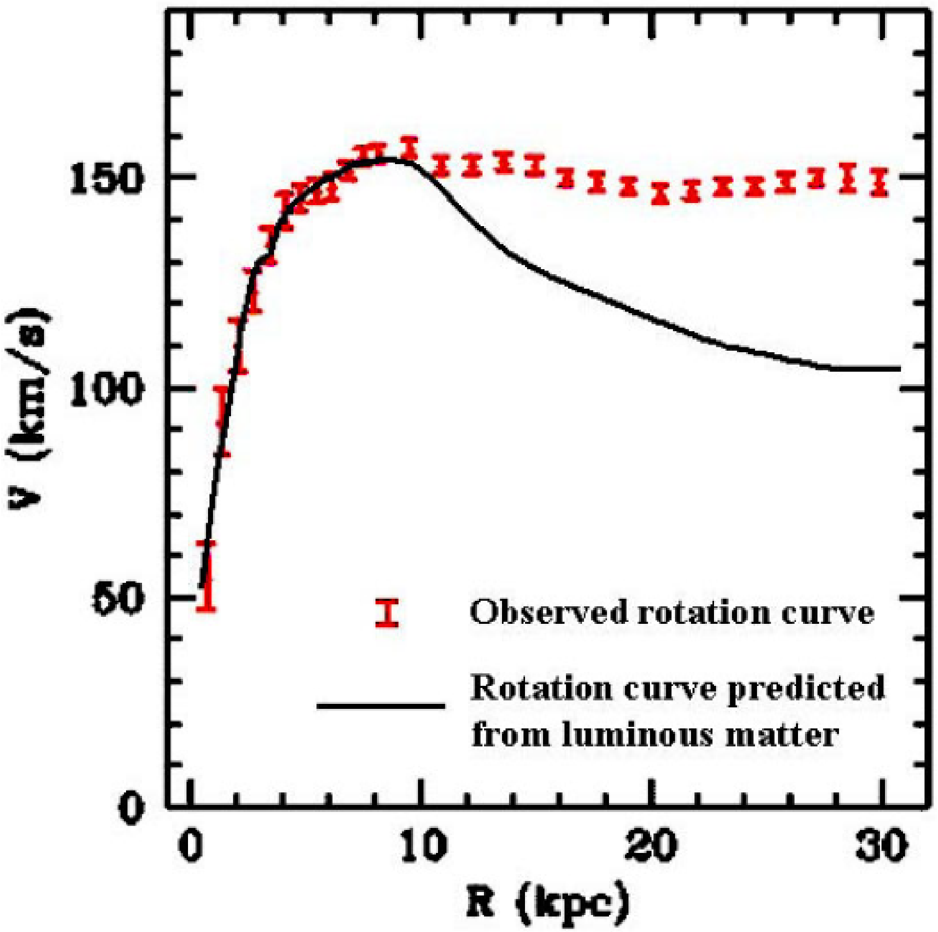


$$\upsilon \propto \frac{1}{\sqrt{d}}$$

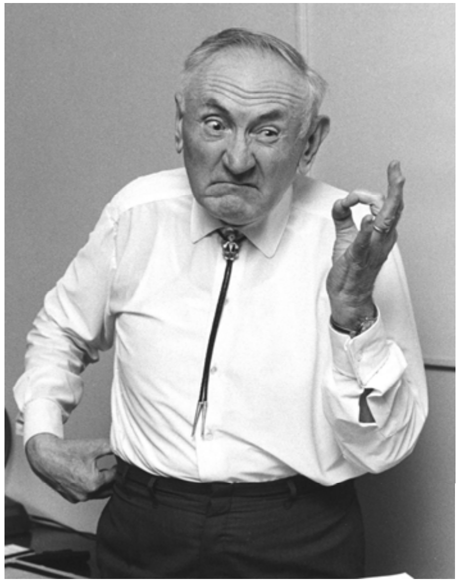
Weighing galaxies

Vera Rubin

1970s: studies the **rotation curves** of spiral galaxies, and finds that they are **flat**.

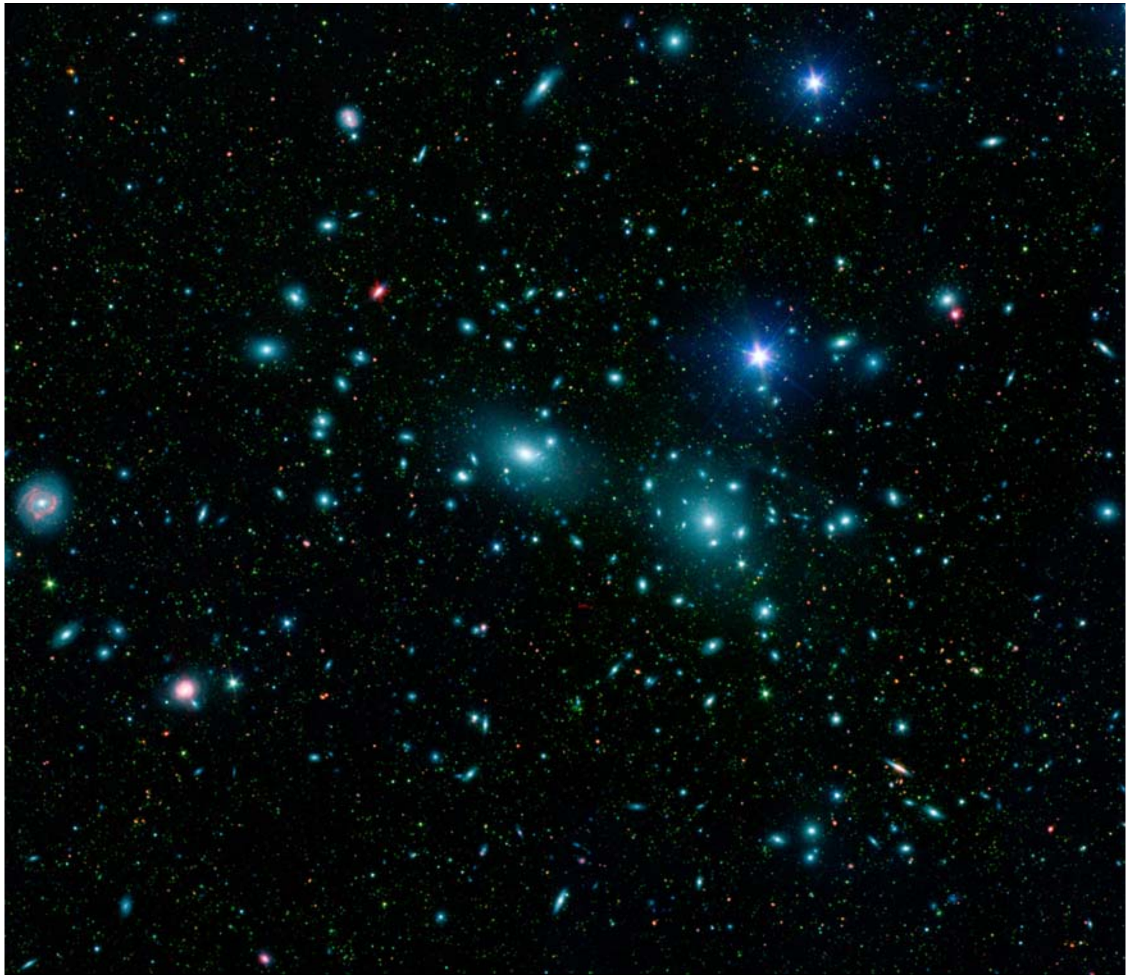


Even more dark matter in clusters…



Fritz Zwicky

1933: finds evidence for **dark matter** in the Coma galaxy cluster



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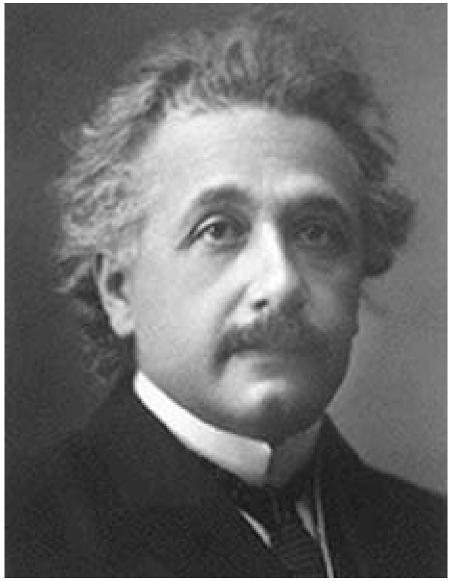
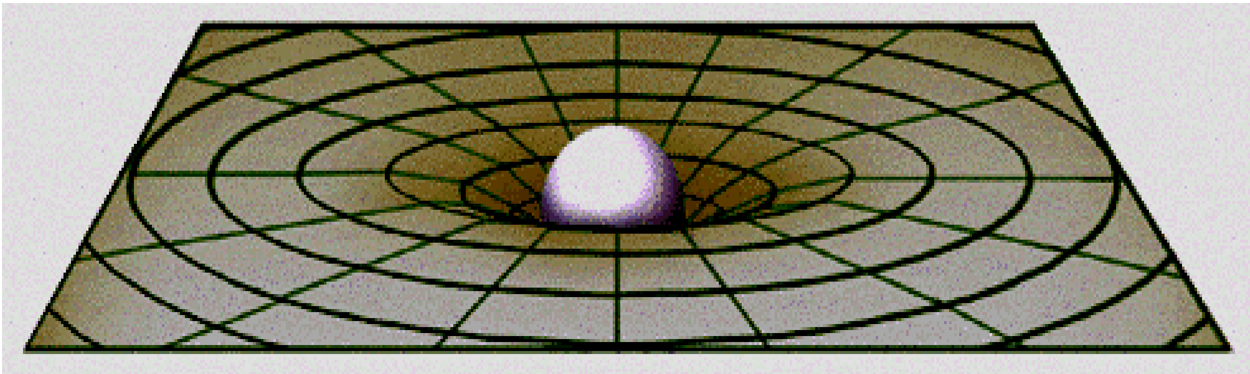
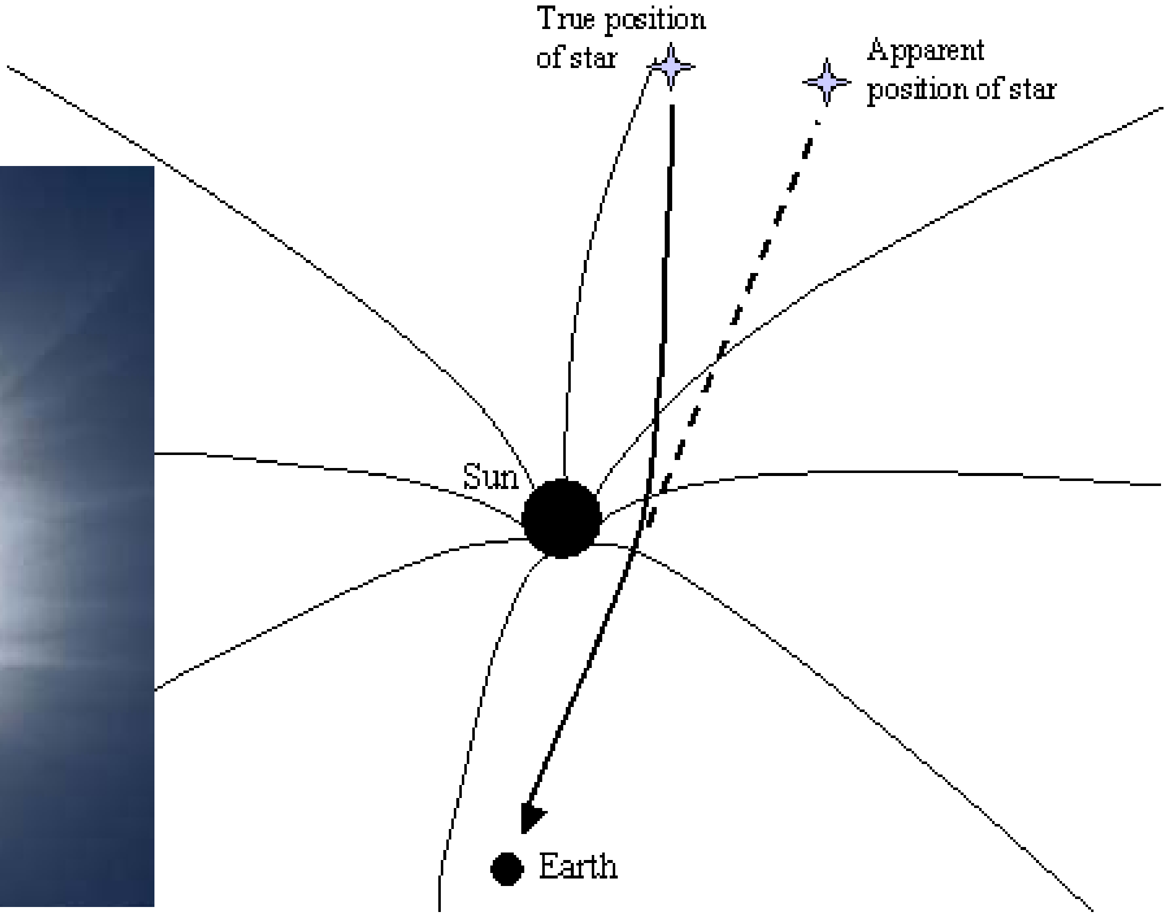
Mapping dark matter with gravitational lensing



As light passes close to a star its path is bent by the curved spacetime

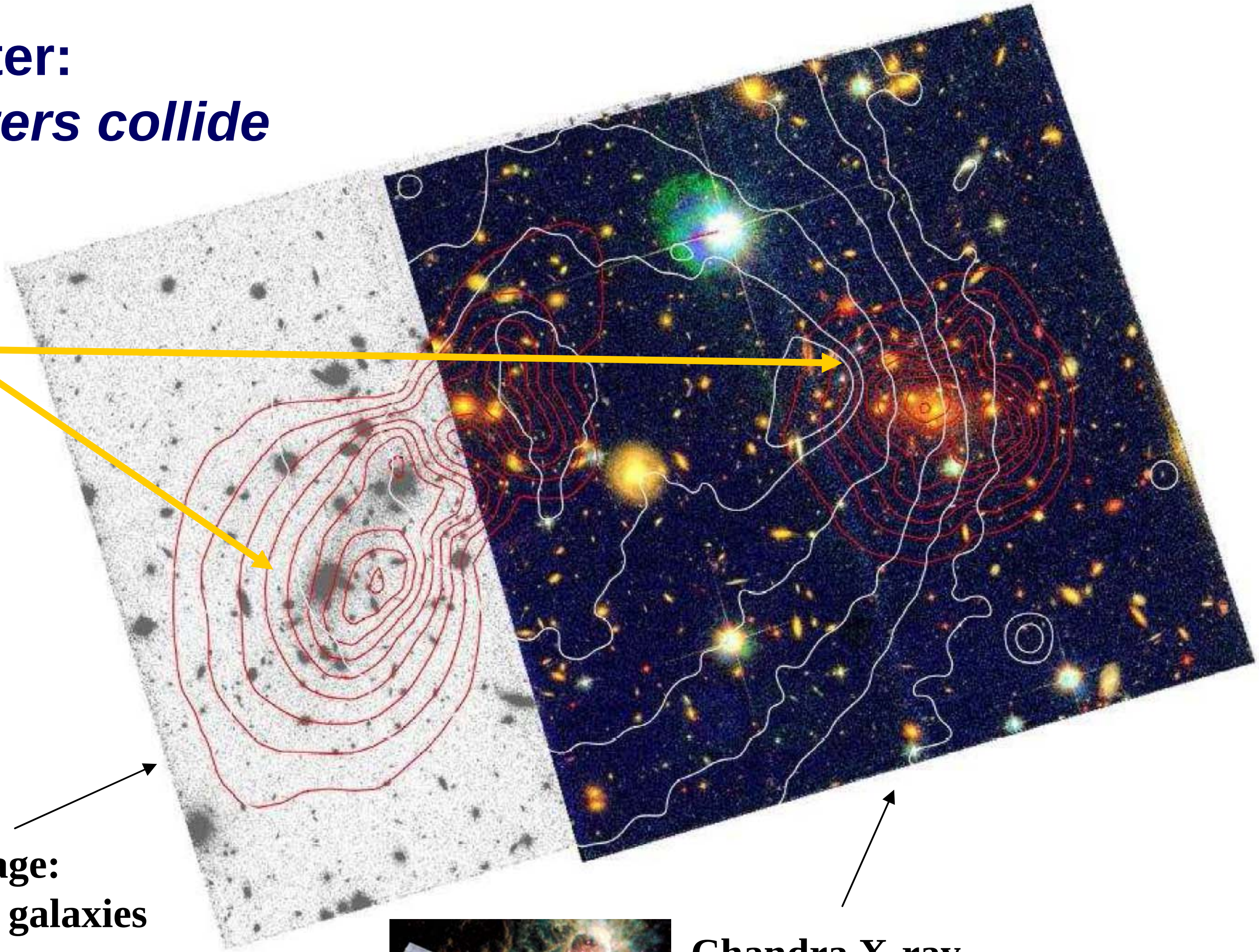


We can see gravitational lensing during a Solar Eclipse



Bullet cluster:
When clusters collide

Dark matter, reconstructed from strong and weak lensing



HST optical image: shows luminous galaxies

Chandra X-ray image: also shows ‘dark’ cluster gas

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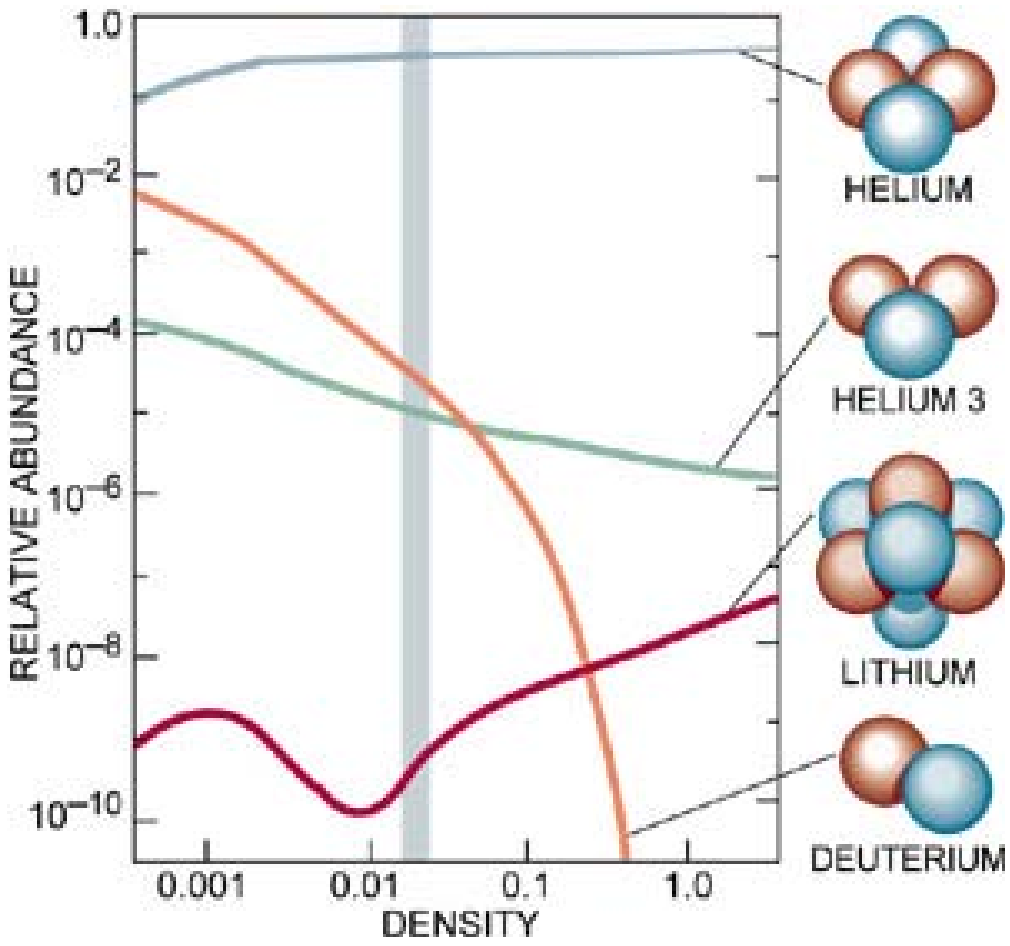
What does all of this mean?....

- There is lots of dark matter
- Less than 1/6th of it is **baryonic**
- The baryons 'clump' differently from the rest of the dark matter.
- The density of all dark matter only comes to about ¼ of critical

1980s: Cosmic Cookery

Amount of each element depends on the density of **baryons**.

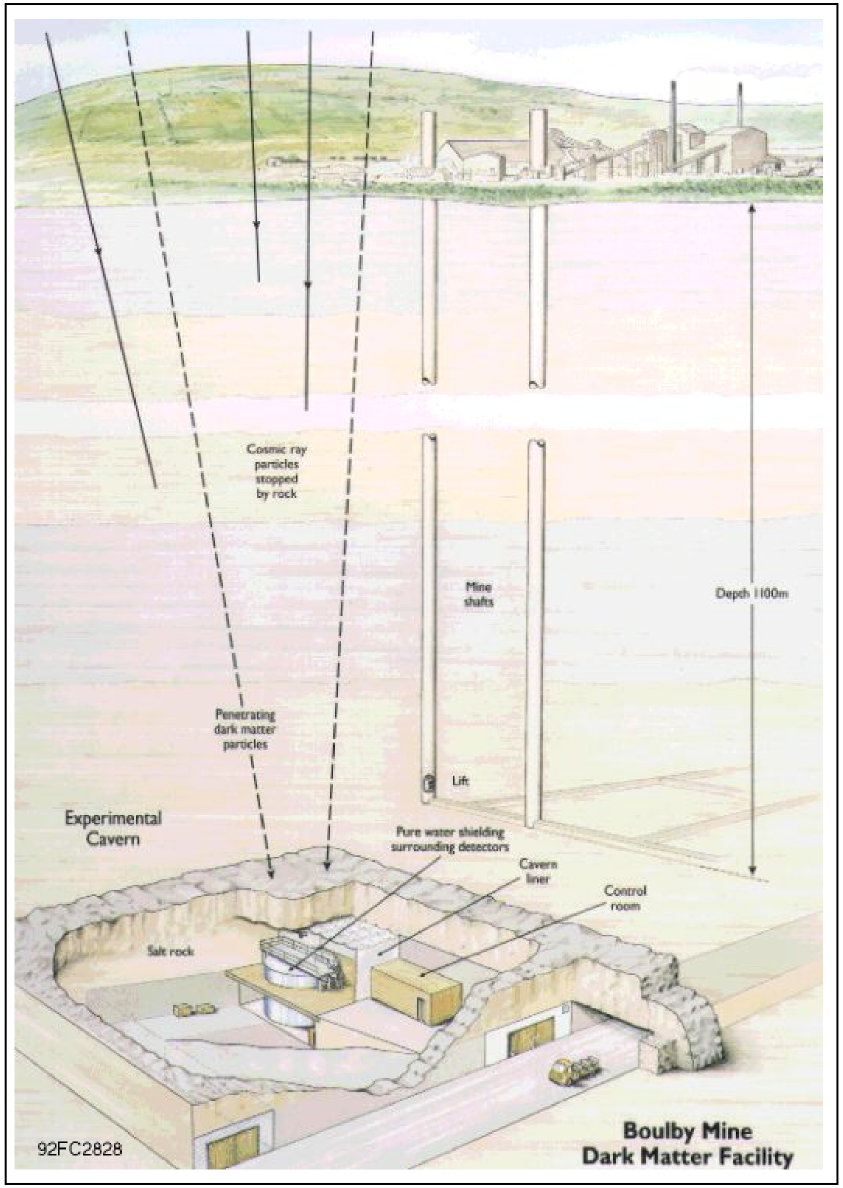
Observed amounts match predictions very well, but ***only*** if baryons make up about 15% of all the dark matter.



So what exactly *is* this dark matter?...

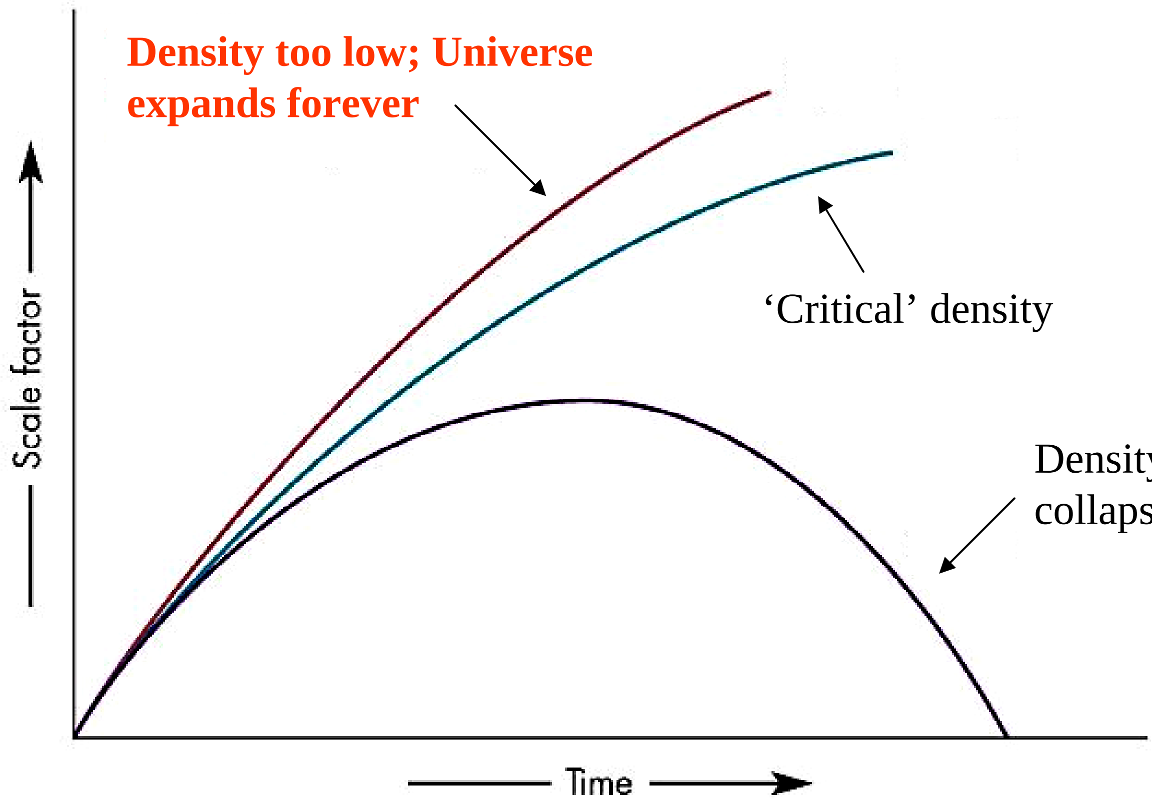
Computer models of galaxies tell us that it must be **cold** – i.e. not moving at relativistic speeds.

Cold dark matter



Will the Universe expand forever?

Answer depends on the density of ***matter*** in the Universe.



So, *is* the expansion slowing down?....

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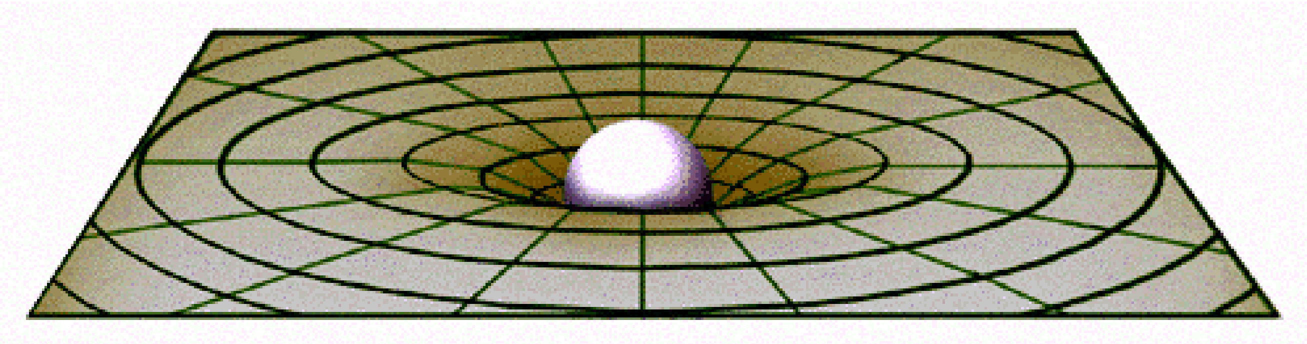
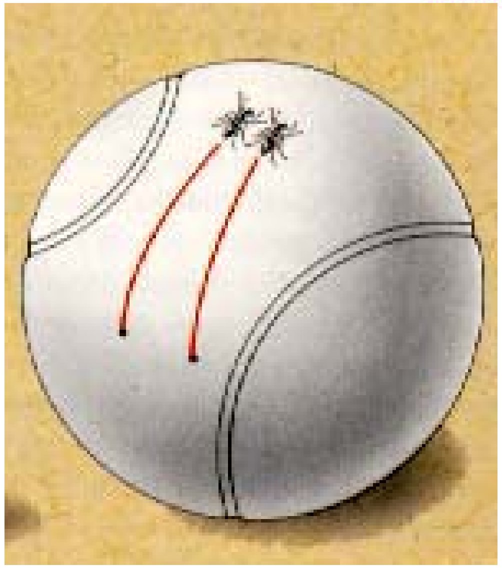
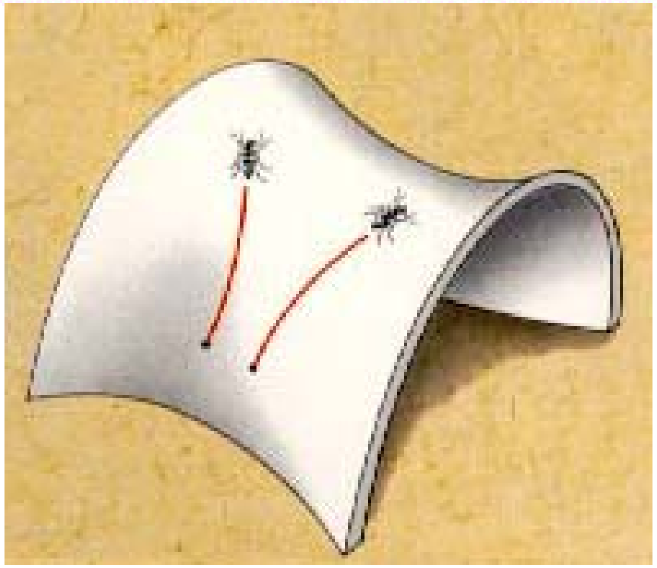
Answer depends on the **shape** of the Universe

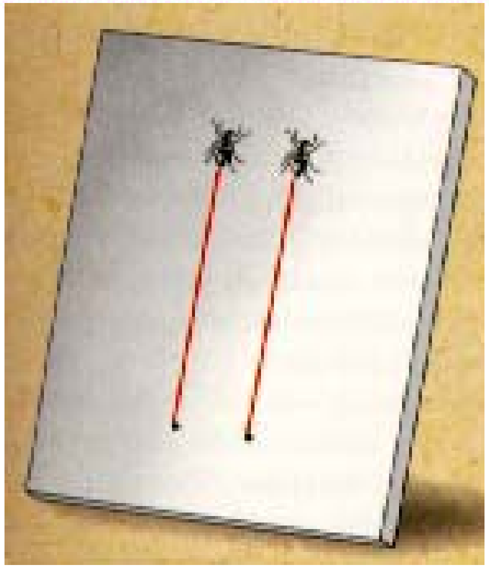




Closed

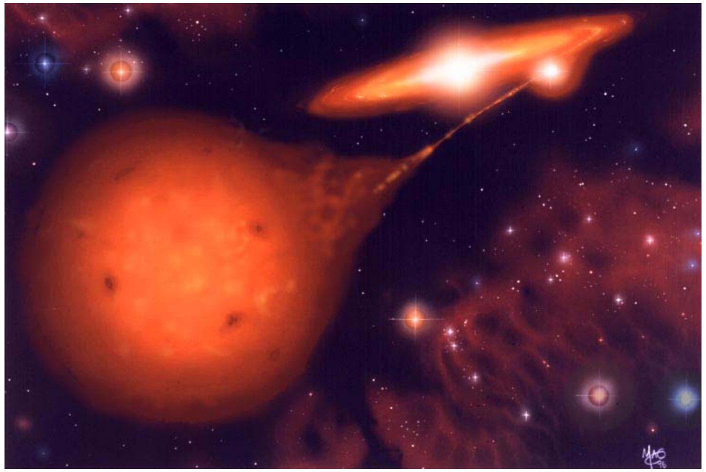


Open

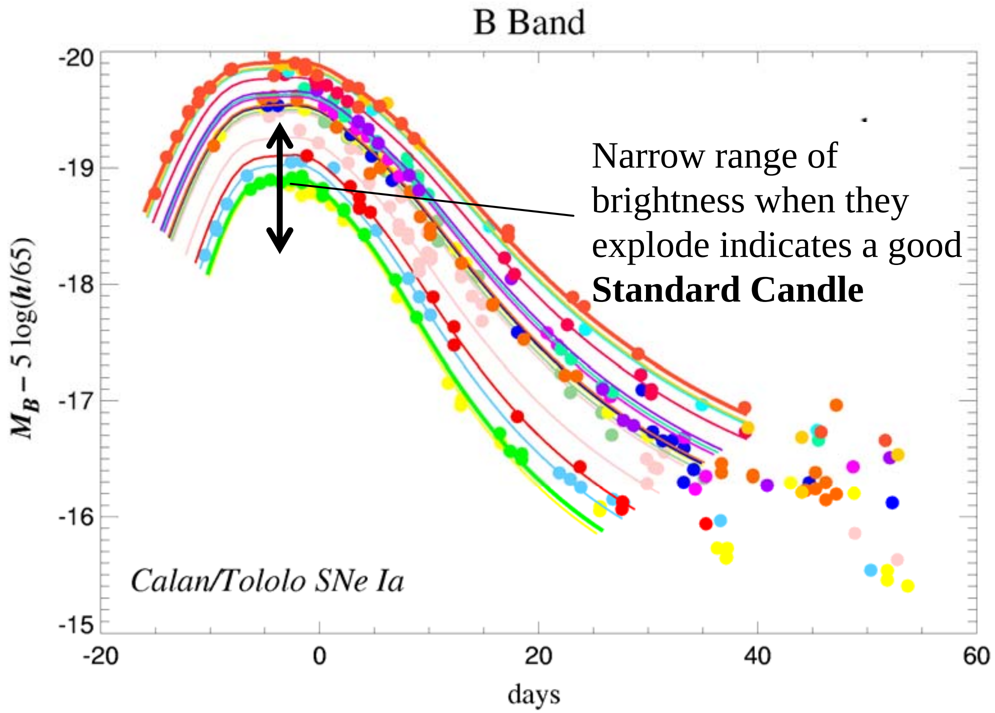


Flat

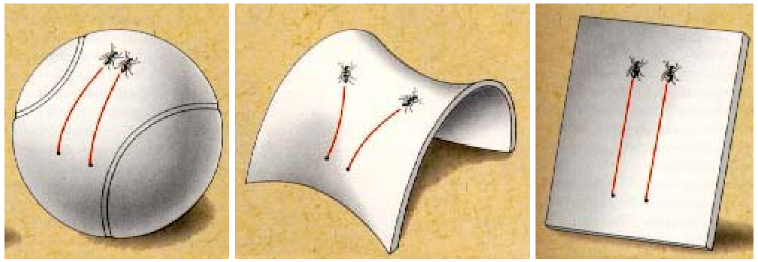
Is the Universe speeding up or slowing down?



We can answer this question using **supernovae**

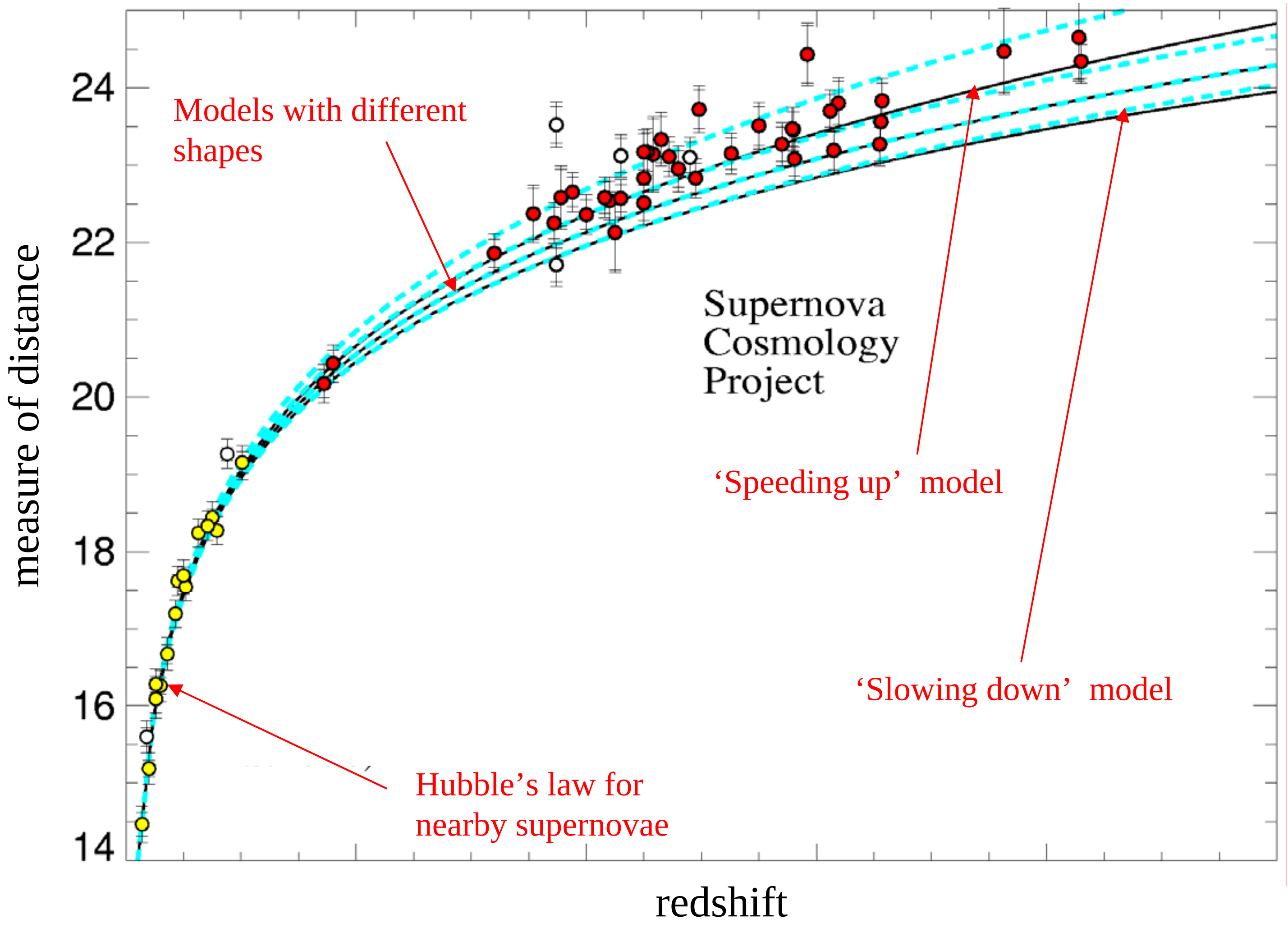


Shape of the universe affects the relationship between redshift and distance of remote supernovae



Closed **Open** **Flat**

‘Hubble diagram’ of distant supernovae



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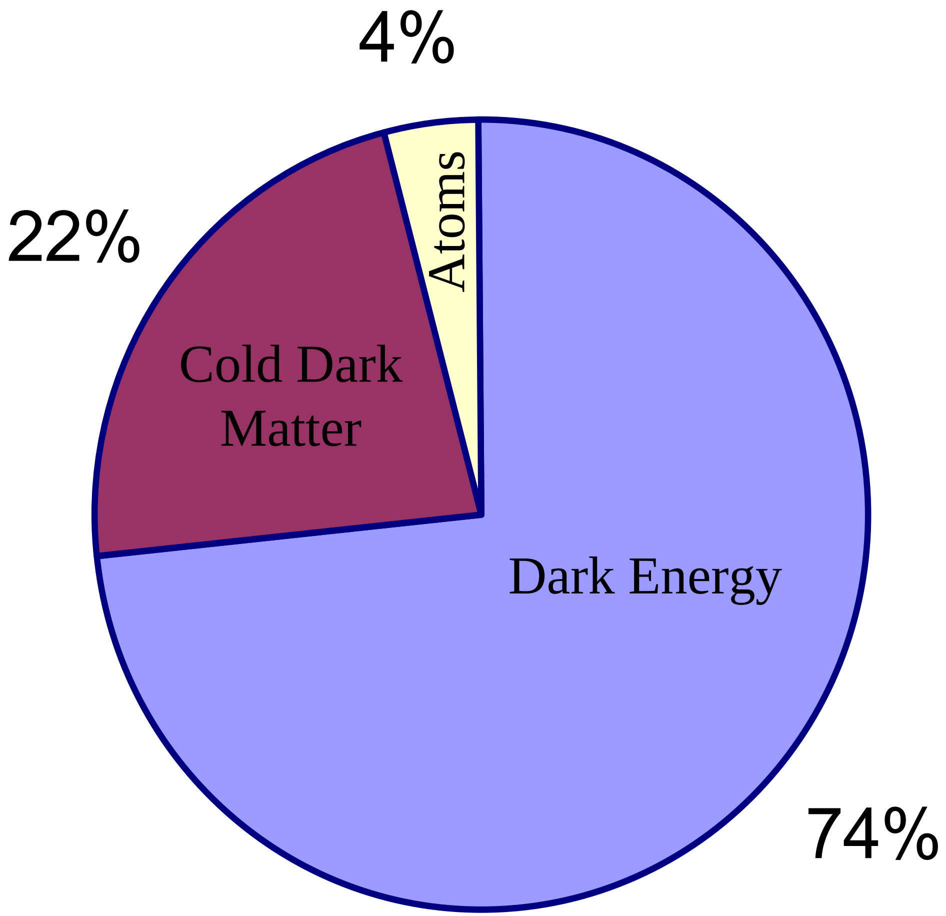
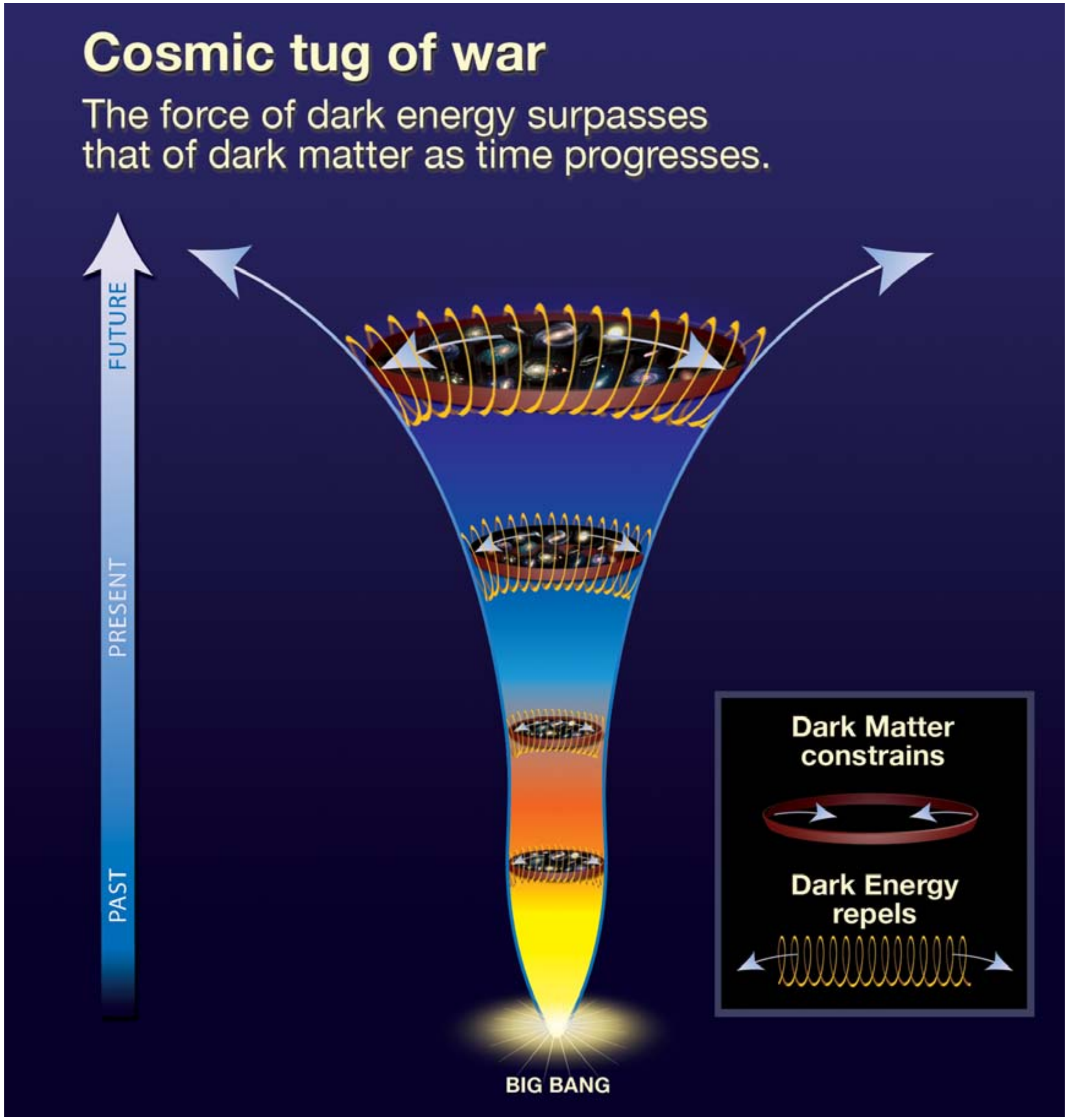
State of the Universe – Feb 2010



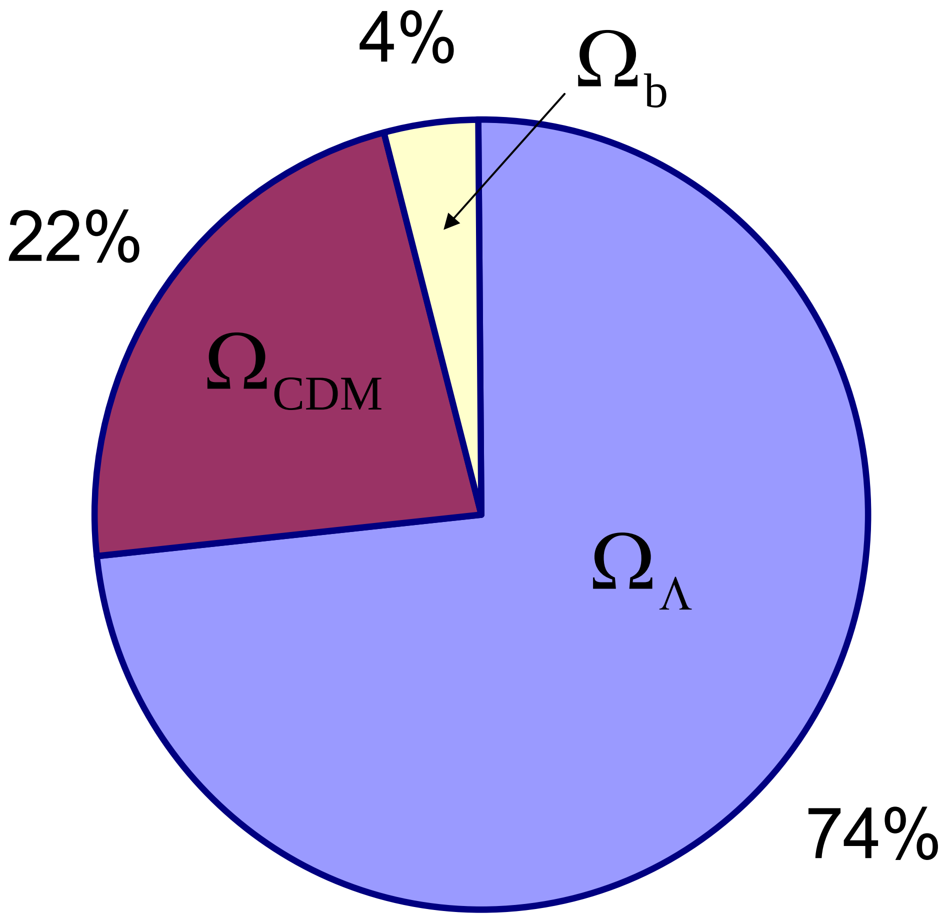
More than 95% of matter and energy in the Universe exists in a mysterious, unknown form…



So what exactly *is* this dark energy?...

Einstein's "cosmological constant"?...

Energy of the quantum vacuum?...



So what exactly *is* this dark energy?...

Einstein's "cosmological constant"?...

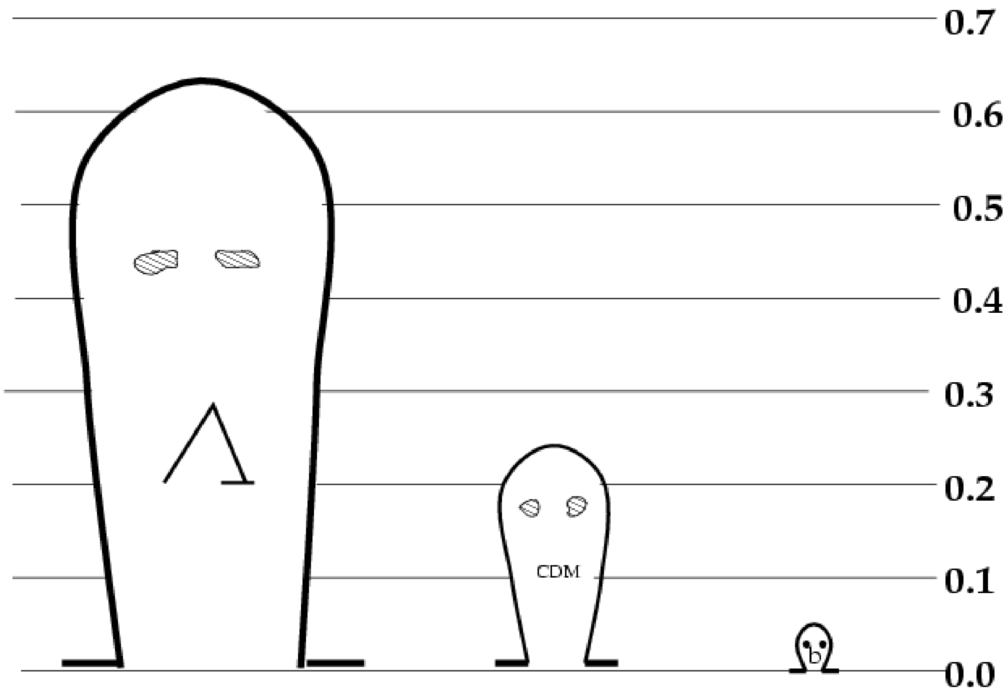
Energy of the quantum vacuum?...

Cosmology's Most Wanted

Λ CDM

Figure 3. A line up of cosmological culprits Ω_Λ is the big shot controlling the Universe. He's going to make it blow up. Ω_{CDM} would like to make the Universe collapse but can't compete with Ω_Λ. Ω_b just follows Ω_{CDM} around. Like all dangerous criminals, one can never be sure of Ω_Λ until he is behind bars. The CMB police is being beefed up. Hundreds of heroic CMB observers are now planning his capture.

From Lineweaver (1998)



Ω_Λ	Ω_{CDM}	Ω_b
cosmological constant energy of the vacuum He never clumps His evil plan is to blow up the Universe	cold dark matter He likes to clump but has never been detected directly His evil plan is to make the Universe collapse	normal baryonic matter a pawn in the cosmic game who just follows CDM around. He thinks he's a complex life form but is really just a bunch of hydrogen

The Background Radiation

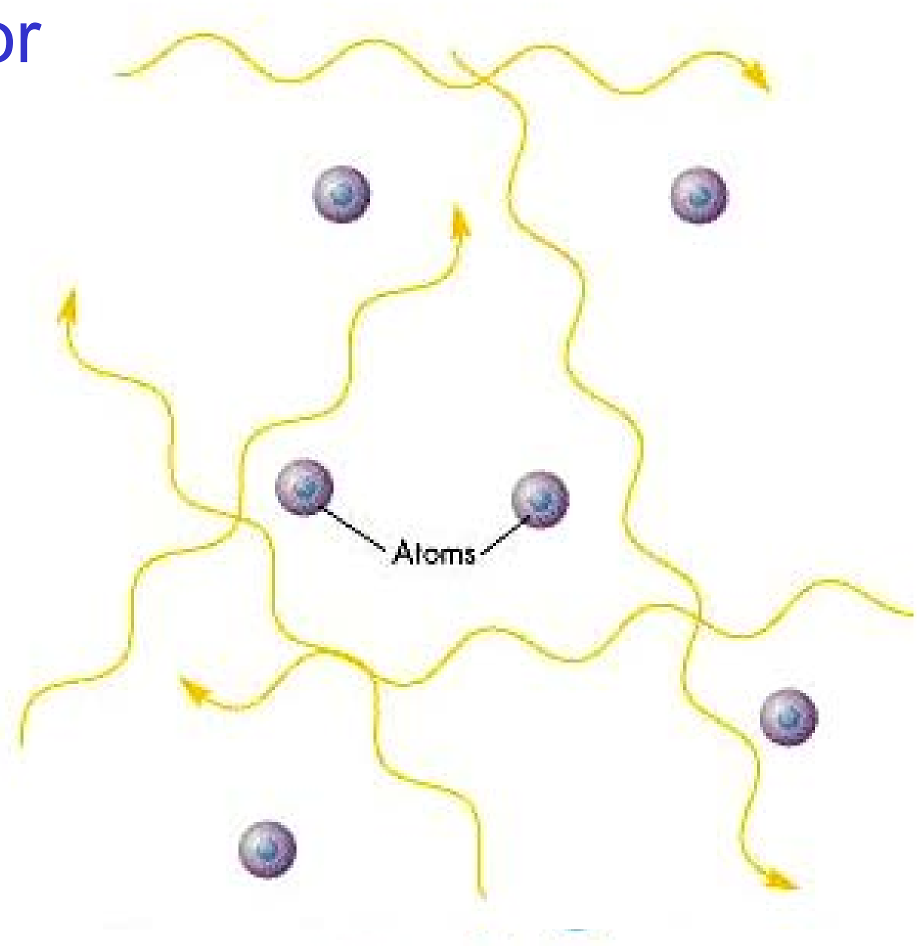
Since 2003, measurements of the **Cosmic Background Radiation** have helped to convince us that the Universe *really is* accelerating, and dominated by dark energy.

CBR = relic radiation from the Big Bang itself.

Appears to us like a 'bank of fog'

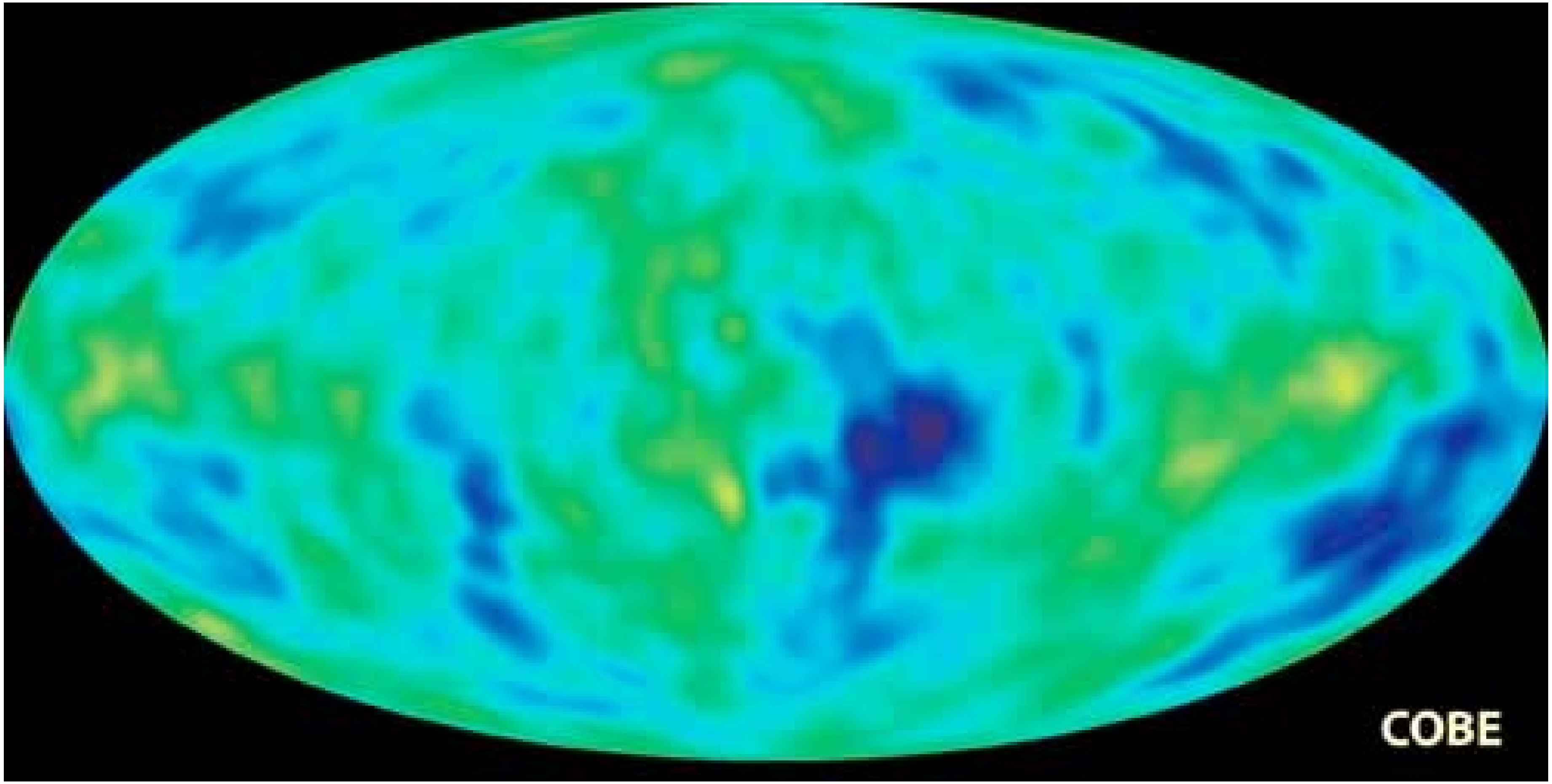
Early Universe too hot for neutral atoms to exist

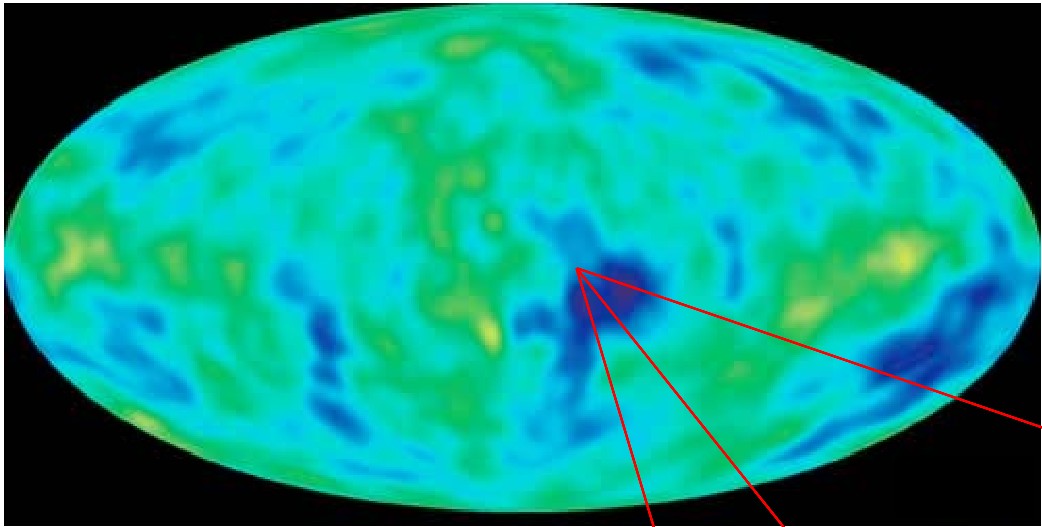
Free electrons scatter light (as in a fog)



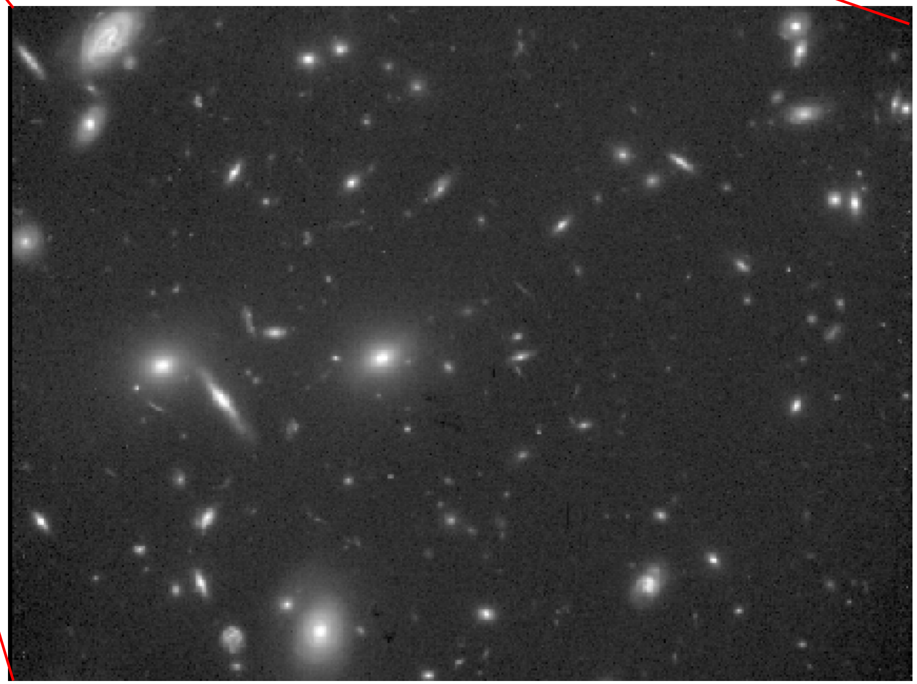
After ~380,000 years, Universe cool enough for neutral hydrogen to form: the fog clears!

COBE map of temperature across the sky



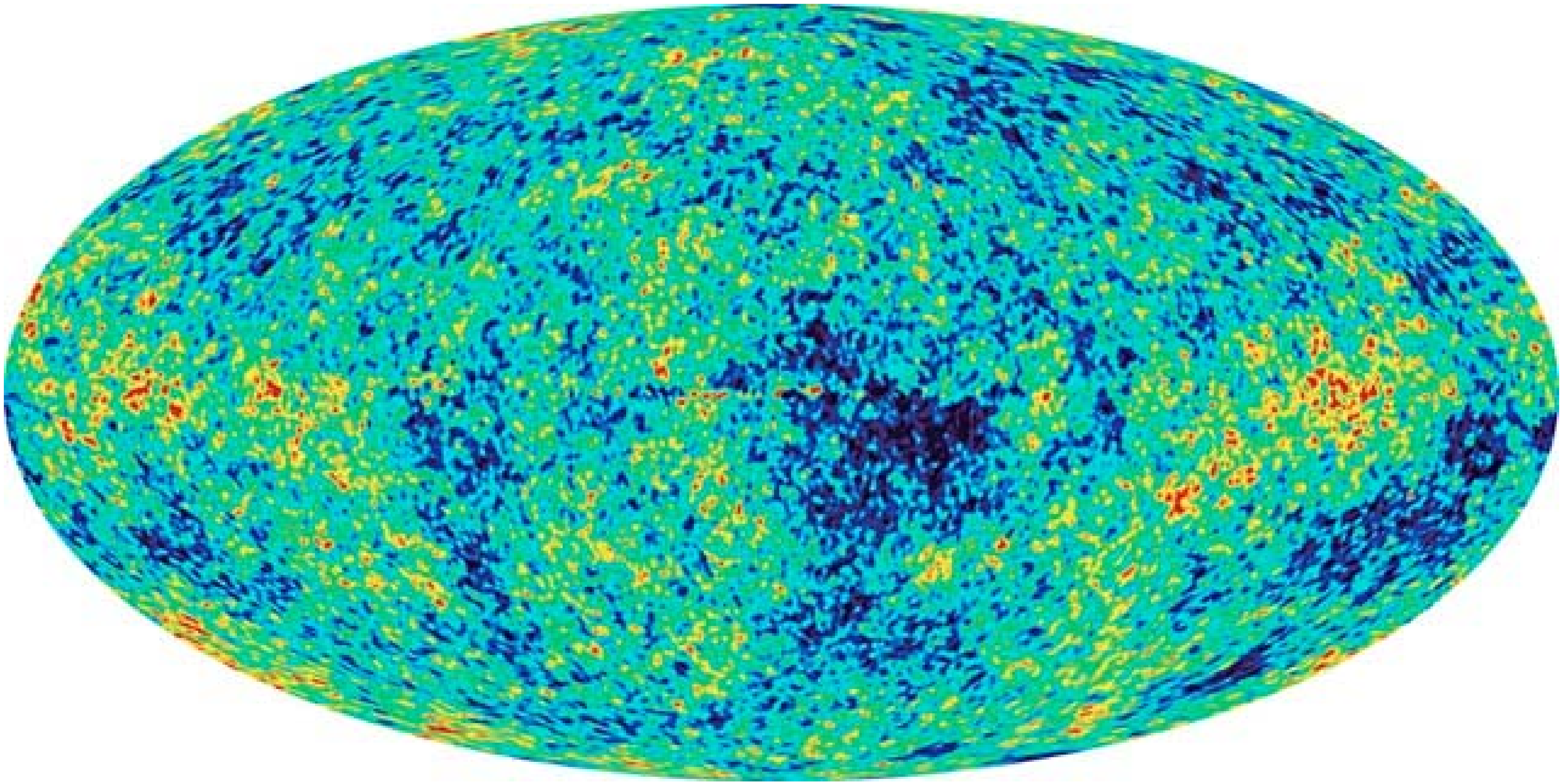


CBR 'ripples' are the seeds of today's galaxies



Galaxy formation is highly sensitive to the pattern, or power spectrum, of CBR temperature ripples

WMAP map of temperature across the sky



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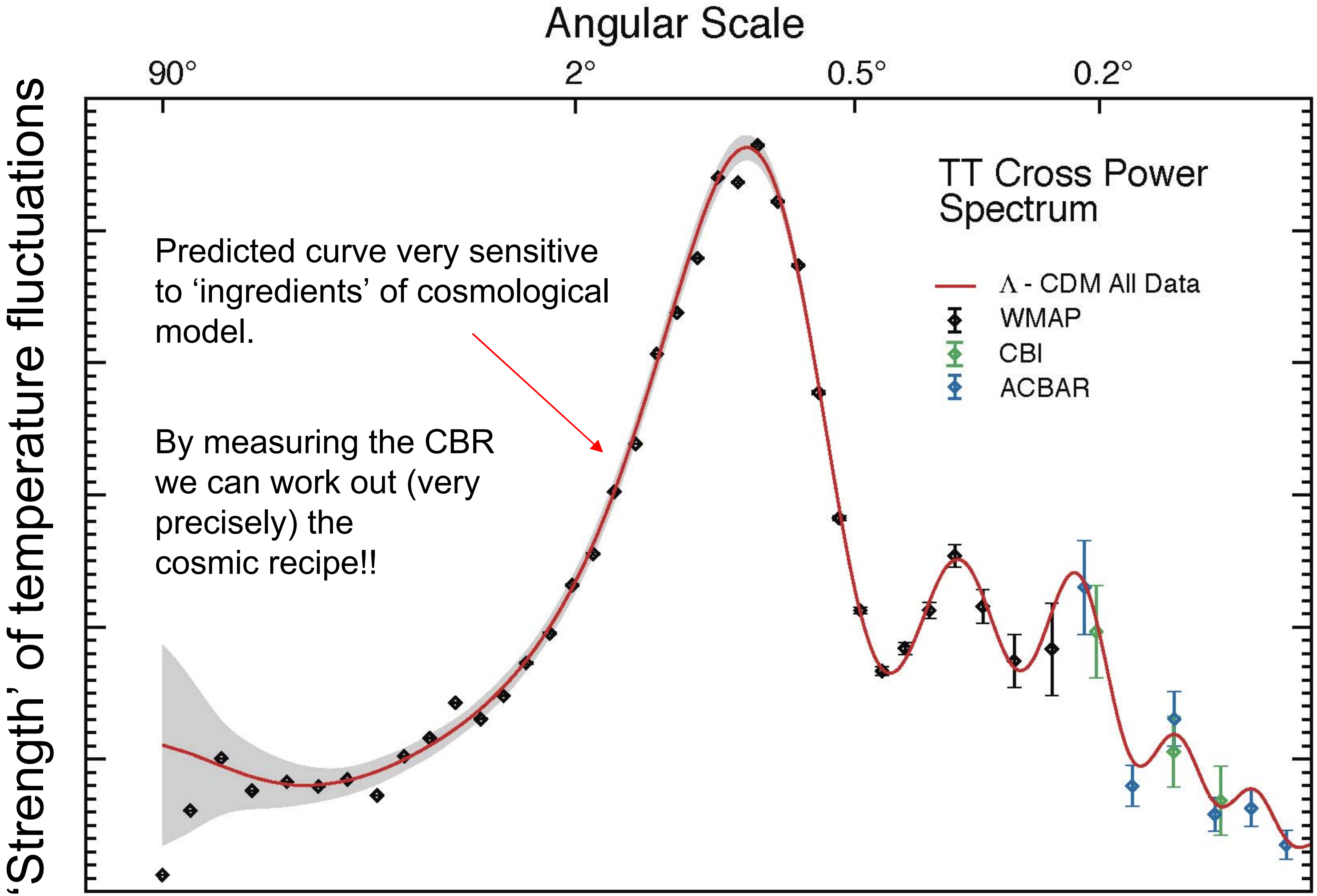
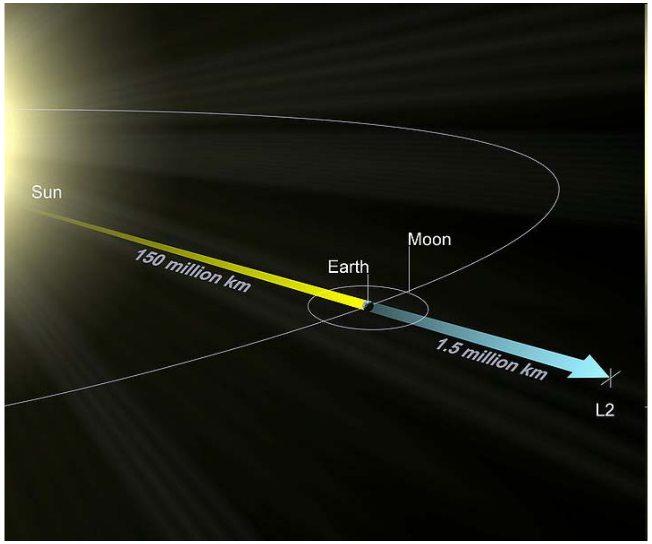
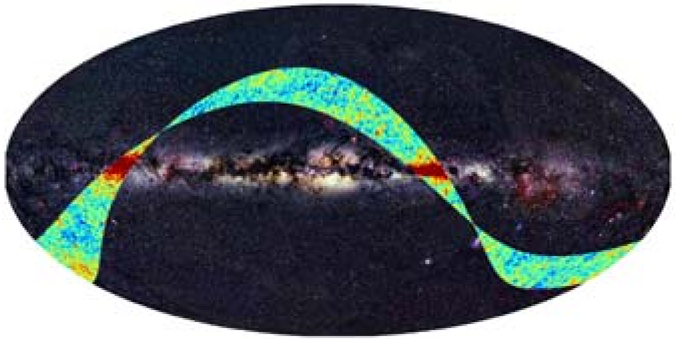
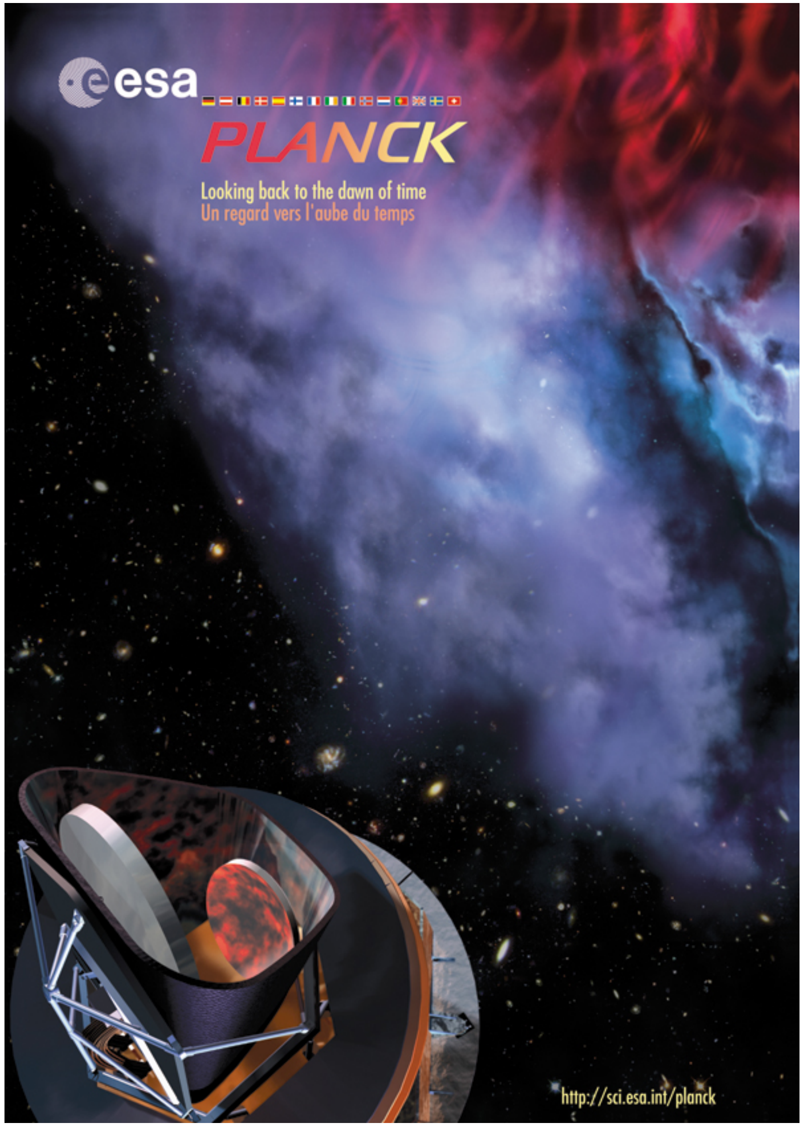


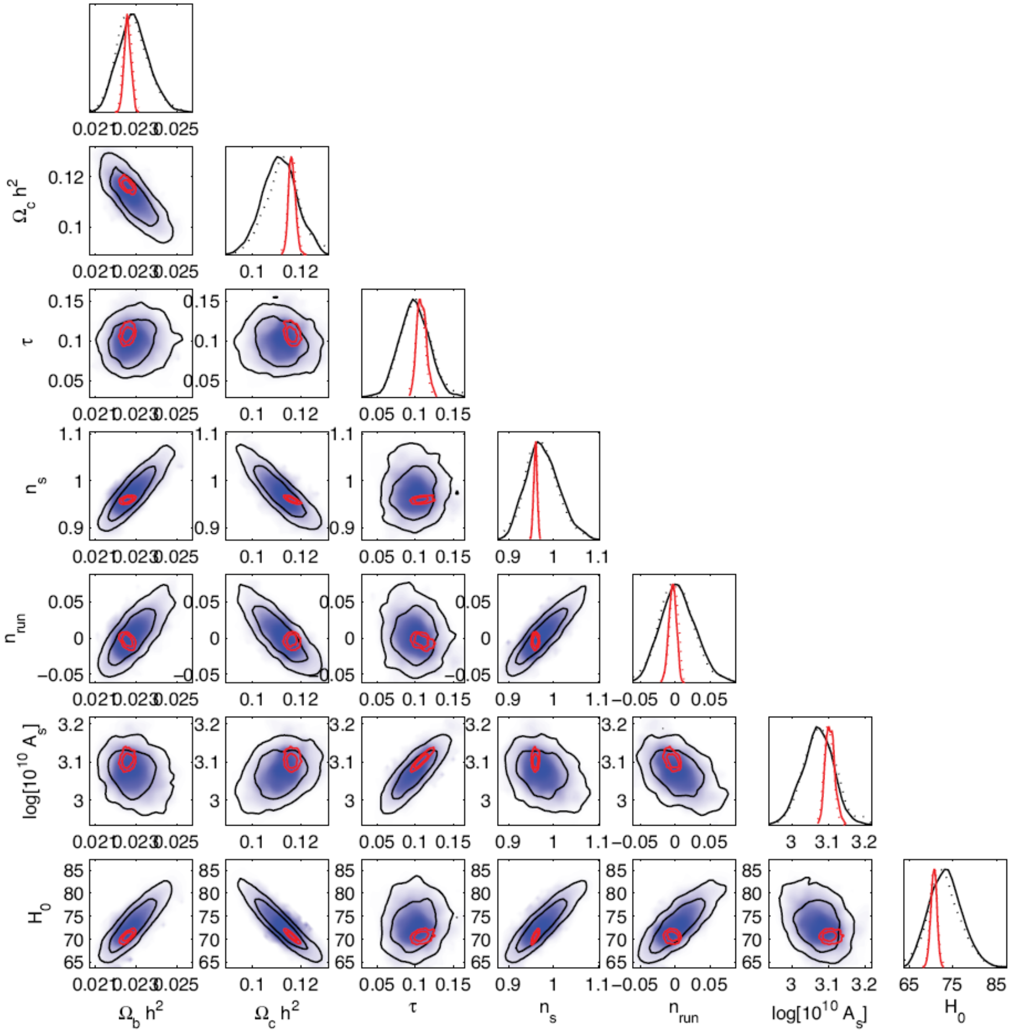
Angular Scale
90°
2°
0.5°
0.2°
'Strength' of temperature fluctuations
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
Predicted curve very sensitive to 'ingredients' of cosmological model.
By measuring the CBR we can work out (very precisely) the cosmic recipe!!


esa
ariane


Sun
150 million km
Earth
Moon
1.5 million km
L2







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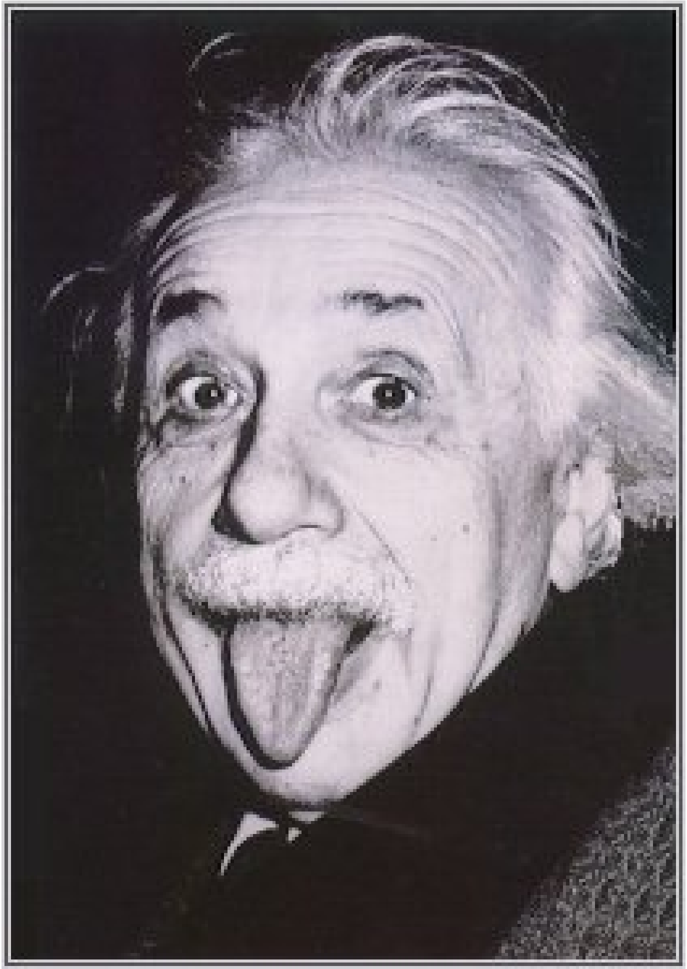
The future of the Universe?

No

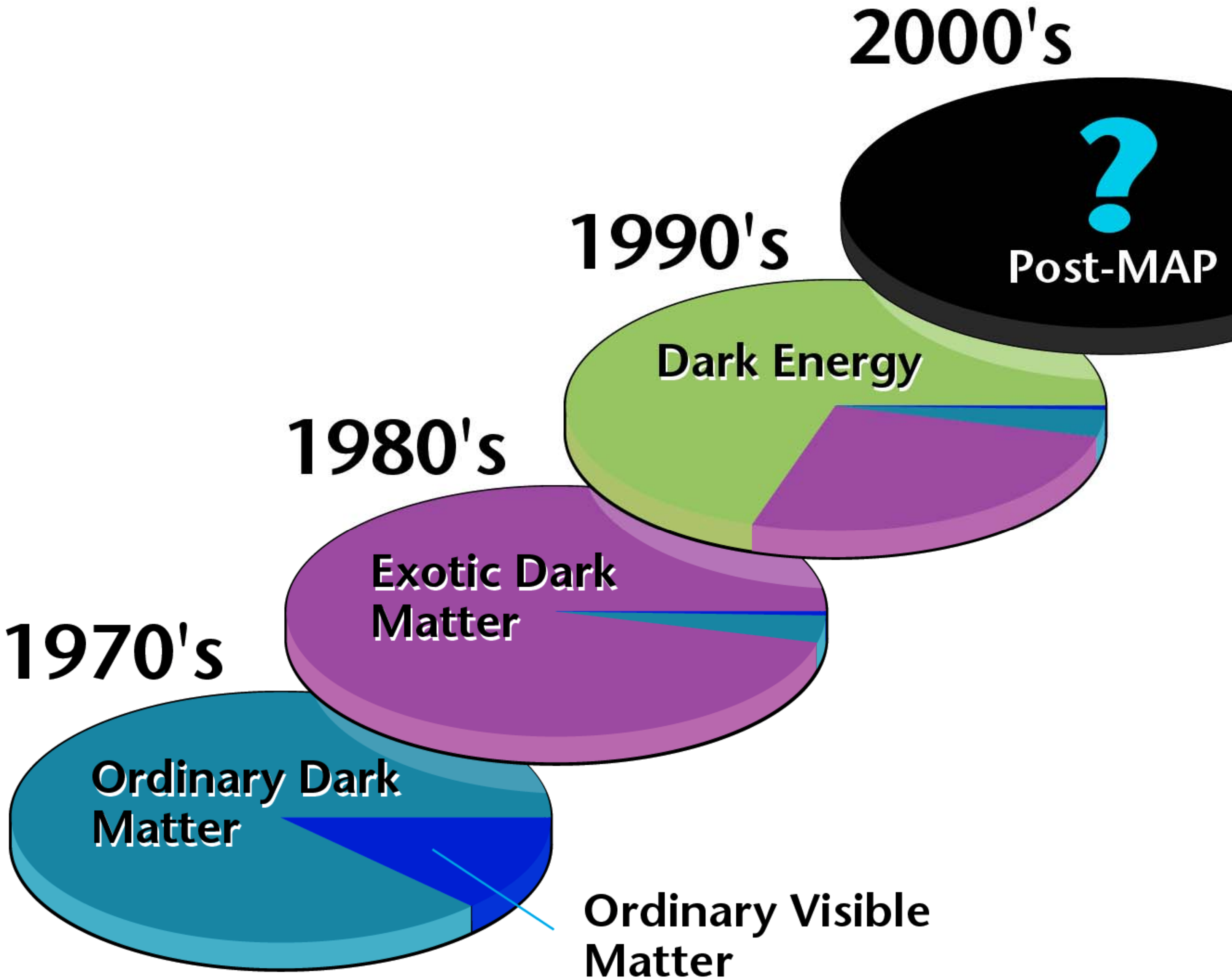
Big Crunch!!!

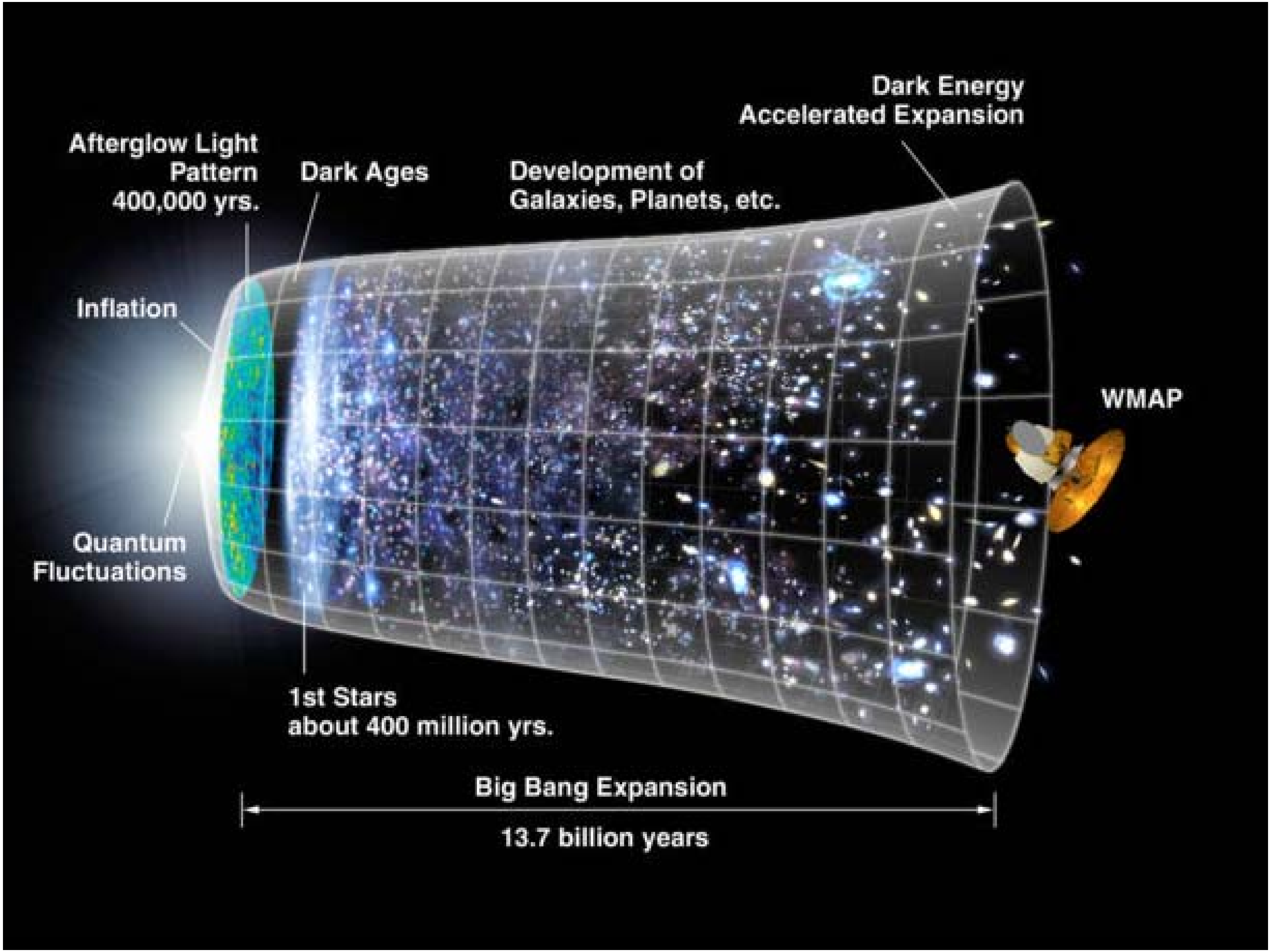
The future of cosmology?...



"What exactly *are* dark matter and dark energy?"

Was Einstein right all along?...


2000's
?
Post-MAP
1990's
Dark Energy
1980's
Exotic Dark
Matter
1970's
Ordinary Dark
Matter
Ordinary Visible
Matter


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years