Centers of Galaxies

= Black Holes and Quasars

Models of Nature:

Kepler

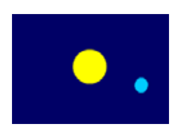
Newton

Einstein (Special Relativity)

Einstein (General Relativity)

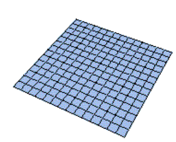
Motions under influence of gravity [23]

- Kepler
  - The planets move in ellipses with $P^2 = a^3$, etc.
  - Didn't know why.



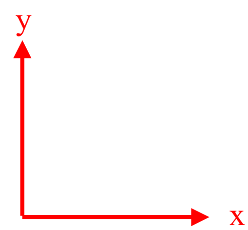
- Newton
  - 3 laws of motion affect everything.
    - $F = ma$, etc.
  - Gravity = force = Gm_1m_2/r^2

- General Relativity
  - Everything tries to take shortest distance through space & time.
  - Gravity = distortion of space & time.



How many dimensions do we live in?

- What is simplest description of coordinate system?
  - "Orthogonal" axes
    - no projection on each other.
    - Each axis is at right angles to all other axes.
  - Flat surface = 2 orthogonal dimensions

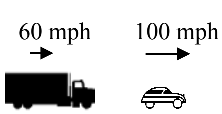


  - We live in three orthogonal dimensions.

Special Relativity ➔ time dilation

- **The Principal of Relativity.** The laws of physics are the same in all inertial reference frames.
- **The constancy of the speed of light.** Light travels through a vacuum at a speed *c* which is independent of the light source.

➔ distance, time, velocity add up in funny ways



Classical: **v' = v−u**

Special relativity: $v' = \frac{v-u}{1-\frac{uv}{c^2}}$

➔ Rate at which time passes depends on relative velocity.

- Only noticeable at velocities approaching c (speed of light).

$$dt_{moving} = \frac{dt_{rest}}{\sqrt{1-\frac{v^2}{c^2}}}$$

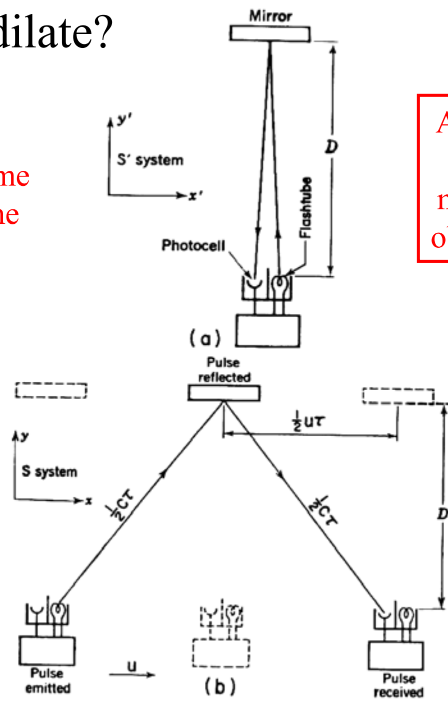
- ➔Twin paradox.

Time dilation:
We see time pass more slowly in an object moving relative to us.

Why does time dilate?

"Light Clock"

velocity = distance / time
speed of light = D / time



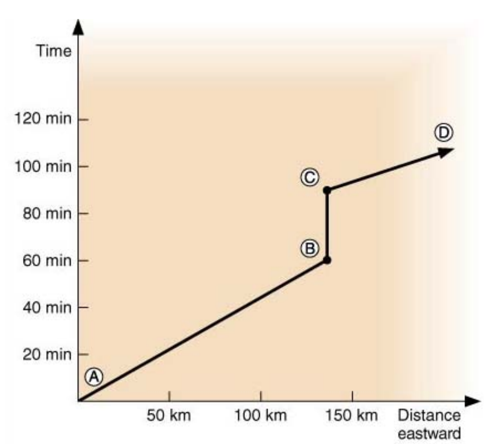
As seen by moving observer

As seen by stationary observer

Direction of motion

Spacetime

- Cross-talk between space & time.
  ➔ convenient to think of time as 4th dimension.
- But time is still different from space.
  - "space-like", "time-like" dimensions.
- Special Relativity:
  - 1 time-like, 3 space-like dimensions.



[Fig 23.5]

General relativity

- Worked out in 1907 - 1915
- Consistent with (incorporates) special relativity
- Describes motions of objects in presence of gravity
- Gravity = distortion into extra space-like dimensions.

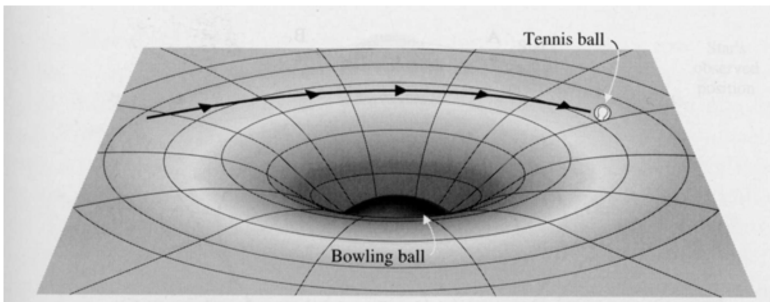


Figure 16.2 Rubber sheet analogy for curved space around the Sun.

[see Fig 23.6]

Curved Space

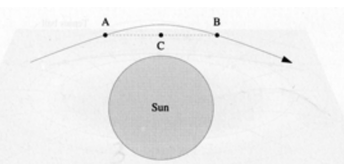


Figure 16.3 A photon's path around the Sun is shown by the solid line. The bend in the photon's trajectory is greatly exaggerated.

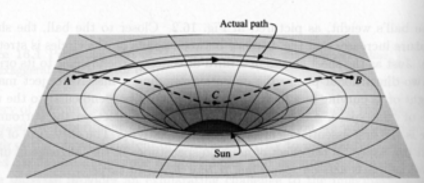


Figure 16.4 Comparison of two photon paths through curved space between points *A* and *B*.

- Everything finds shortest path in spacetime.
- Photons (light) find shortest path of all, because they move the fastest.

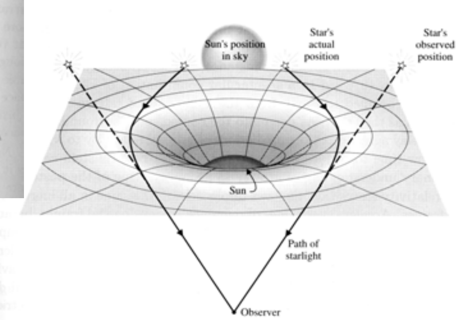


Figure 16.5 Bending of starlight measured during a solar eclipse.

The mathematical solution:

$$R_{\eta\eta} = -\frac{2a^2\frac{\partial\psi}{\partial\theta}\cot\theta}{\delta\psi} + \frac{2ac\frac{\partial\psi}{\partial\eta}\cot\theta}{\delta\psi} + \frac{a\frac{\partial c}{\partial\eta}\cot\theta}{\delta} - \frac{\frac{\partial a}{\partial\eta}c\cot\theta}{2\delta} - \frac{a\frac{\partial a}{\partial\theta}\cot\theta}{2\delta} - \frac{2a^2\frac{\partial^2\psi}{\partial\theta^2}}{\delta\psi}$$

$$-\frac{2a^2(\frac{\partial\psi}{\partial\theta})^2}{\delta\psi^2} + \frac{4ac\frac{\partial\psi}{\partial\eta}\frac{\partial\psi}{\partial\theta}}{\delta\psi^2} - \frac{a^2\frac{\partial d}{\partial\theta}\frac{\partial\psi}{\partial\theta}}{\delta d\psi} + \frac{ac\frac{\partial d}{\partial\eta}\frac{\partial\psi}{\partial\theta}}{\delta d\psi} + \frac{2a\frac{\partial c}{\partial\eta}\frac{\partial\psi}{\partial\theta}}{\delta\psi} - \frac{\frac{\partial a}{\partial\eta}c\frac{\partial\psi}{\partial\theta}}{\delta\psi}$$

$$-\frac{3a\frac{\partial a}{\partial\theta}\frac{\partial\psi}{\partial\theta}}{\delta\psi} - \frac{2a^2c\frac{\partial c}{\partial\theta}\frac{\partial\psi}{\partial\theta}}{\delta^2\psi} + \frac{2a^2b\frac{\partial c}{\partial\eta}\frac{\partial\psi}{\partial\theta}}{\delta^2\psi} - \frac{a^2\frac{\partial b}{\partial\eta}c\frac{\partial\psi}{\partial\theta}}{\delta^2\psi} - \frac{a\frac{\partial a}{\partial\eta}bc\frac{\partial\psi}{\partial\theta}}{\delta^2\psi} + \frac{a^3\frac{\partial b}{\partial\theta}\frac{\partial\psi}{\partial\theta}}{\delta^2\psi}$$

$$+\frac{a^2\frac{\partial a}{\partial\theta}b\frac{\partial\psi}{\partial\theta}}{\delta^2\psi} - \frac{2ab\frac{\partial^2\psi}{\partial\eta^2}}{\delta\psi} - \frac{2\frac{\partial^2\psi}{\partial\eta^2}}{\psi} + \frac{4ac\frac{\partial^2\psi}{\partial\eta\partial\theta}}{\delta\psi} - \frac{2ab(\frac{\partial\psi}{\partial\eta})^2}{\delta\psi^2} + \frac{6(\frac{\partial\psi}{\partial\eta})^2}{\psi^2}$$

$$+\frac{ac\frac{\partial d}{\partial\theta}\frac{\partial\psi}{\partial\eta}}{\delta d\psi} - \frac{ab\frac{\partial d}{\partial\eta}\frac{\partial\psi}{\partial\eta}}{\delta d\psi} - \frac{2c\frac{\partial c}{\partial\eta}\frac{\partial\psi}{\partial\eta}}{\delta\psi} + \frac{\frac{\partial a}{\partial\theta}c\frac{\partial\psi}{\partial\eta}}{\delta\psi} - \frac{2a\frac{\partial b}{\partial\eta}\frac{\partial\psi}{\partial\eta}}{\delta\psi} + \frac{\frac{\partial a}{\partial\eta}b\frac{\partial\psi}{\partial\eta}}{\delta\psi}$$

$$+\frac{2a^2b\frac{\partial c}{\partial\theta}\frac{\partial\psi}{\partial\eta}}{\delta^2\psi} - \frac{2abc\frac{\partial c}{\partial\eta}\frac{\partial\psi}{\partial\eta}}{\delta^2\psi} - \frac{a^2\frac{\partial b}{\partial\theta}c\frac{\partial\psi}{\partial\eta}}{\delta^2\psi} - \frac{a\frac{\partial a}{\partial\theta}bc\frac{\partial\psi}{\partial\eta}}{\delta^2\psi} + \frac{a^2b\frac{\partial b}{\partial\eta}\frac{\partial\psi}{\partial\eta}}{\delta^2\psi} + \frac{a\frac{\partial a}{\partial\eta}b^2\frac{\partial\psi}{\partial\eta}}{\delta^2\psi}$$

$$+\frac{a\frac{\partial c}{\partial\eta}\frac{\partial d}{\partial\theta}}{2\delta d} - \frac{\frac{\partial a}{\partial\eta}c\frac{\partial d}{\partial\theta}}{4\delta d} - \frac{a\frac{\partial a}{\partial\theta}\frac{\partial d}{\partial\theta}}{4\delta d} - \frac{\frac{\partial^2 d}{\partial\eta^2}}{2d} + \frac{(\frac{\partial d}{\partial\eta})^2}{4d^2} - \frac{c\frac{\partial c}{\partial\eta}\frac{\partial d}{\partial\eta}}{2\delta d}$$

$$+\frac{\frac{\partial a}{\partial\theta}c\frac{\partial d}{\partial\eta}}{4\delta d} + \frac{\frac{\partial a}{\partial\eta}b\frac{\partial d}{\partial\eta}}{4\delta d} + \frac{a\frac{\partial^2 c}{\partial\eta\partial\theta}}{\delta} - \frac{a\frac{\partial^2 b}{\partial\eta^2}}{2\delta} - \frac{a\frac{\partial^2 a}{\partial\theta^2}}{2\delta} + \frac{ac\frac{\partial c}{\partial\eta}\frac{\partial c}{\partial\theta}}{\delta^2}$$

But there's more…

(hairy math II)

$$-\frac{a\frac{\partial a}{\partial\theta}c\frac{\partial c}{\partial\theta}}{2\delta^2} - \frac{a\frac{\partial a}{\partial\eta}b\frac{\partial c}{\partial\theta}}{2\delta^2} - \frac{a\frac{\partial b}{\partial\eta}c\frac{\partial c}{\partial\eta}}{2\delta^2} - \frac{a^2\frac{\partial b}{\partial\theta}\frac{\partial c}{\partial\eta}}{2\delta^2} + \frac{a\frac{\partial a}{\partial\eta}\frac{\partial b}{\partial\theta}c}{4\delta^2} - \frac{a\frac{\partial a}{\partial\theta}\frac{\partial b}{\partial\eta}c}{4\delta^2}$$

$$+\frac{a^2\frac{\partial a}{\partial\theta}\frac{\partial b}{\partial\theta}}{4\delta^2} + \frac{a^2(\frac{\partial b}{\partial\eta})^2}{4\delta^2} + \frac{a\frac{\partial a}{\partial\eta}b\frac{\partial b}{\partial\eta}}{4\delta^2} + \frac{a(\frac{\partial a}{\partial\theta})^2 b}{4\delta^2}$$

$$R_{\eta\theta} = -\frac{2ac\frac{\partial\psi}{\partial\theta}\cot\theta}{\delta\psi} + \frac{2ab\frac{\partial\psi}{\partial\eta}\cot\theta}{\delta\psi} - \frac{2\frac{\partial\psi}{\partial\eta}\cot\theta}{\psi} - \frac{\frac{\partial d}{\partial\eta}\cot\theta}{2d} - \frac{\frac{\partial a}{\partial\theta}c\cot\theta}{2\delta} + \frac{a\frac{\partial b}{\partial\eta}\cot\theta}{2\delta}$$

$$-\frac{2ac\frac{\partial^2\psi}{\partial\theta^2}}{\delta\psi} - \frac{2ac(\frac{\partial\psi}{\partial\theta})^2}{\delta\psi^2} + \frac{4ab\frac{\partial\psi}{\partial\eta}\frac{\partial\psi}{\partial\theta}}{\delta\psi^2} + \frac{2\frac{\partial\psi}{\partial\eta}\frac{\partial\psi}{\partial\theta}}{\psi^2} - \frac{ac\frac{\partial d}{\partial\theta}\frac{\partial\psi}{\partial\theta}}{\delta d\psi} + \frac{ab\frac{\partial d}{\partial\eta}\frac{\partial\psi}{\partial\theta}}{\delta d\psi}$$

$$-\frac{\frac{\partial d}{\partial\eta}\frac{\partial\psi}{\partial\theta}}{d\psi} + \frac{2a\frac{\partial c}{\partial\theta}\frac{\partial\psi}{\partial\theta}}{\delta\psi} - \frac{3\frac{\partial a}{\partial\theta}c\frac{\partial\psi}{\partial\theta}}{\delta\psi} + \frac{2a\frac{\partial b}{\partial\eta}\frac{\partial\psi}{\partial\theta}}{\delta\psi} + \frac{\frac{\partial a}{\partial\eta}b\frac{\partial\psi}{\partial\theta}}{\delta\psi} - \frac{2a^2b\frac{\partial c}{\partial\theta}\frac{\partial\psi}{\partial\theta}}{\delta^2\psi}$$

$$+\frac{2abc\frac{\partial c}{\partial\eta}\frac{\partial\psi}{\partial\theta}}{\delta^2\psi} + \frac{a^2\frac{\partial b}{\partial\theta}c\frac{\partial\psi}{\partial\theta}}{\delta^2\psi} + \frac{a\frac{\partial a}{\partial\theta}bc\frac{\partial\psi}{\partial\theta}}{\delta^2\psi} - \frac{a^2b\frac{\partial b}{\partial\eta}\frac{\partial\psi}{\partial\theta}}{\delta^2\psi} - \frac{a\frac{\partial a}{\partial\eta}b^2\frac{\partial\psi}{\partial\theta}}{\delta^2\psi} - \frac{2bc\frac{\partial^2\psi}{\partial\eta^2}}{\delta\psi}$$

$$+\frac{4ab\frac{\partial^2\psi}{\partial\eta\partial\theta}}{\delta\psi} - \frac{6\frac{\partial^2\psi}{\partial\eta\partial\theta}}{\psi} - \frac{2bc(\frac{\partial\psi}{\partial\eta})^2}{\delta\psi^2} + \frac{ab\frac{\partial d}{\partial\theta}\frac{\partial\psi}{\partial\eta}}{\delta d\psi} - \frac{\frac{\partial d}{\partial\theta}\frac{\partial\psi}{\partial\eta}}{d\psi} - \frac{bc\frac{\partial d}{\partial\eta}\frac{\partial\psi}{\partial\eta}}{\delta d\psi}$$

$$+\frac{2b\frac{\partial c}{\partial\eta}\frac{\partial\psi}{\partial\eta}}{\delta\psi} - \frac{3\frac{\partial b}{\partial\eta}c\frac{\partial\psi}{\partial\eta}}{\delta\psi} + \frac{a\frac{\partial b}{\partial\theta}\frac{\partial\psi}{\partial\eta}}{\delta\psi} + \frac{2\frac{\partial a}{\partial\theta}b\frac{\partial\psi}{\partial\eta}}{\delta\psi} + \frac{2abc\frac{\partial c}{\partial\theta}\frac{\partial\psi}{\partial\eta}}{\delta^2\psi} - \frac{2ab^2\frac{\partial c}{\partial\eta}\frac{\partial\psi}{\partial\eta}}{\delta^2\psi}$$

and still more…

(hairy math III)

$$+\frac{a\,b\,\frac{\partial b}{\partial \eta}\,c\,\frac{\partial \psi}{\partial \eta}}{\delta^2\,\psi}+\frac{\frac{\partial a}{\partial \eta}\,b^2\,c\,\frac{\partial \psi}{\partial \eta}}{\delta^2\,\psi}-\frac{a^2\,b\,\frac{\partial b}{\partial \theta}\,\frac{\partial \psi}{\partial \eta}}{\delta^2\,\psi}-\frac{a\,\frac{\partial a}{\partial \theta}\,b^2\,\frac{\partial \psi}{\partial \eta}}{\delta^2\,\psi}+\frac{\frac{\partial d}{\partial \eta}\,\frac{\partial d}{\partial \theta}}{4\,d^2}-\frac{\frac{\partial a}{\partial \theta}\,c\,\frac{\partial d}{\partial \theta}}{4\,\delta\,d}$$

$$+\frac{a\,\frac{\partial b}{\partial \eta}\,\frac{\partial d}{\partial \theta}}{4\,\delta\,d}-\frac{\frac{\partial^2 d}{\partial \eta\,\partial \theta}}{2\,d}-\frac{\frac{\partial b}{\partial \eta}\,c\,\frac{\partial d}{\partial \eta}}{4\,\delta\,d}+\frac{\frac{\partial a}{\partial \theta}\,b\,\frac{\partial d}{\partial \eta}}{4\,\delta\,d}-\frac{\frac{\partial c}{\partial \eta}\,\frac{\partial c}{\partial \theta}}{\delta}+\frac{\frac{\partial a}{\partial \theta}\,\frac{\partial c}{\partial \theta}}{2\,\delta}$$

$$+\frac{c\,\frac{\partial^2 c}{\partial \eta\,\partial \theta}}{\delta}+\frac{\frac{\partial b}{\partial \eta}\,\frac{\partial c}{\partial \eta}}{2\,\delta}-\frac{\frac{\partial^2 b}{\partial \eta^2}\,c}{2\,\delta}-\frac{\frac{\partial^2 a}{\partial \theta^2}\,c}{2\,\delta}-\frac{\frac{\partial a}{\partial \eta}\,\frac{\partial b}{\partial \theta}}{4\,\delta}+\frac{\frac{\partial a}{\partial \theta}\,\frac{\partial b}{\partial \eta}}{4\,\delta}$$

$$+\frac{a\,b\,\frac{\partial c}{\partial \eta}\,\frac{\partial c}{\partial \theta}}{\delta^2}-\frac{\frac{\partial a}{\partial \eta}\,b\,c\,\frac{\partial c}{\partial \theta}}{2\,\delta^2}-\frac{a\,\frac{\partial a}{\partial \theta}\,b\,\frac{\partial c}{\partial \theta}}{2\,\delta^2}-\frac{a\,\frac{\partial b}{\partial \theta}\,c\,\frac{\partial c}{\partial \eta}}{2\,\delta^2}-\frac{a\,b\,\frac{\partial b}{\partial \eta}\,\frac{\partial c}{\partial \eta}}{2\,\delta^2}+\frac{a\,\frac{\partial a}{\partial \theta}\,\frac{\partial b}{\partial \theta}\,c}{4\,\delta^2}$$

$$+\frac{a\left(\frac{\partial b}{\partial \eta}\right)^2 c}{4\,\delta^2}+\frac{\frac{\partial a}{\partial \eta}\,b\,\frac{\partial b}{\partial \eta}\,c}{4\,\delta^2}+\frac{\left(\frac{\partial a}{\partial \theta}\right)^2 b\,c}{4\,\delta^2}+\frac{a\,\frac{\partial a}{\partial \eta}\,b\,\frac{\partial b}{\partial \theta}}{4\,\delta^2}-\frac{a\,\frac{\partial a}{\partial \theta}\,b\,\frac{\partial b}{\partial \eta}}{4\,\delta^2}$$

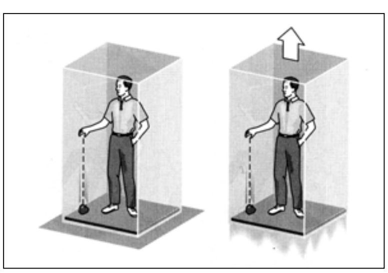
$$R_{\theta\theta}=-\frac{2\,a\,b\,\frac{\partial \psi}{\partial \theta}\cot\theta}{\delta\,\psi}+\frac{2\,b\,c\,\frac{\partial \psi}{\partial \eta}\cot\theta}{\delta\,\psi}-\frac{\frac{\partial d}{\partial \theta}\cot\theta}{d}-\frac{c\,\frac{\partial c}{\partial \theta}\cot\theta}{\delta}+\frac{\frac{\partial b}{\partial \eta}\,c\cot\theta}{2\,\delta}+\frac{a\,\frac{\partial b}{\partial \theta}\cot\theta}{2\,\delta}$$

$$-\frac{2\,a\,b\,\frac{\partial^2 \psi}{\partial \theta^2}}{\delta\,\psi}-\frac{2\,\frac{\partial^2 \psi}{\partial \theta^2}}{\psi}-\frac{2\,a\,b\left(\frac{\partial \psi}{\partial \theta}\right)^2}{\delta\,\psi^2}+\frac{6\left(\frac{\partial \psi}{\partial \theta}\right)^2}{\psi^2}+\frac{4\,b\,c\,\frac{\partial \psi}{\partial \eta}\,\frac{\partial \psi}{\partial \theta}}{\delta\,\psi^2}-\frac{a\,b\,\frac{\partial d}{\partial \theta}\,\frac{\partial \psi}{\partial \theta}}{\delta\,d\,\psi}$$

Oops! This only is for a 2-dimensional axisymmetric case. More complicated situations are much worse!

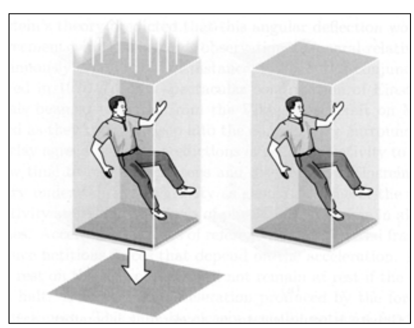
The Principle of Equivalence

- A thought experiment: falling elevators.



Gravity

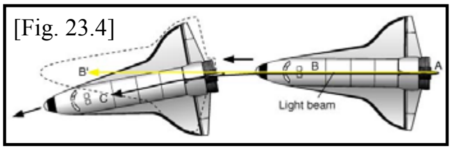
Upwards acceleration, no gravity.



Falling due to gravity

No gravity

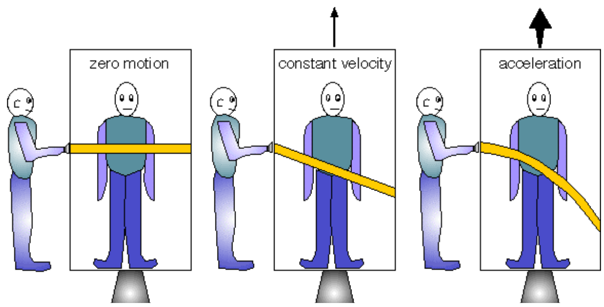
- Can't tell difference between gravity & acceleration
- …or between freefall & no gravity.
- So *any* experiment should give same answer in either case.



[Fig. 23.4]

Light in space shuttle follows curved path, due to Earth's gravity.

Light & Gravity



The Principle of Equivalence

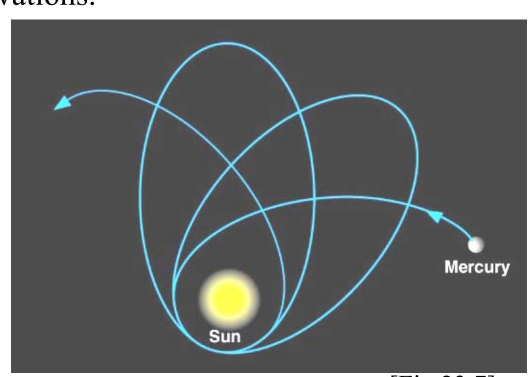
Can't tell difference between gravity and acceleration.

Tests (Proofs) of General Relativity

- Precession of Mercury
  - 43 arcsec/century observed (1/90 degree) in excess of amount expected from Newton's laws.
    - Small effect, but easy to observe because of long time span of observations.
  - GR predicts this.
  - Need extra planet to explain with Newton's laws.

Orbits in strongly curved spacetime

GR vs Newtonian orbits



[Fig 23.7]

Tests (Proofs) of General Relativity

- Bending of starlight in Sun's gravitational field.
  - Seen during 1919 eclipse.

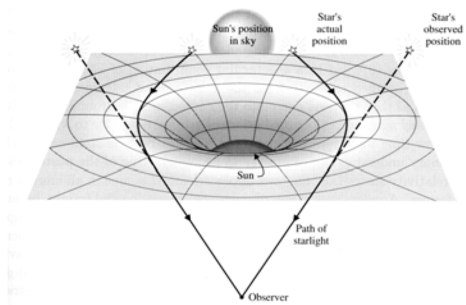
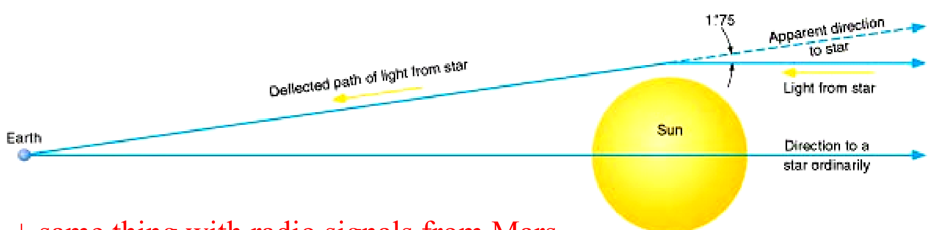


Figure 16.5 Bending of starlight measured during a solar eclipse.



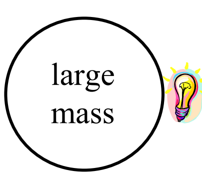
+ same thing with radio signals from Mars.

[Fig 23.8]

Tests (Proofs) of General Relativity

- Time runs slower in stronger gravitational field [23.4]
  - Time dilation (again).

- ➔ gravitational redshift: light waves emitted at different frequency than we receive them.
  - Observed from surface of white dwarfs.

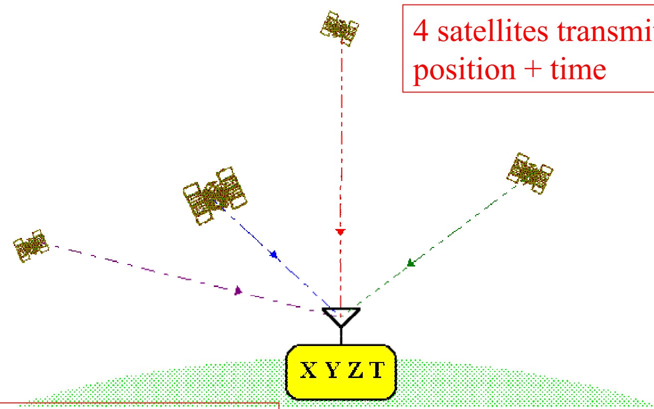


Flashes once per 1.00000 second in its frame.

We see one flash per 1.00001 second due to time dilation.

GPS Navigation

4 satellites transmit position + time



Receiver calculates its position + time

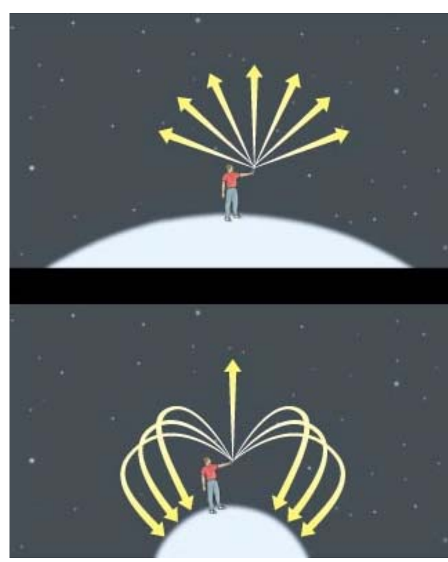
- General Relativity ➔ time runs slower in the satellites.
- If no correction applied, 6 mile position error after only 1 day!

Black holes

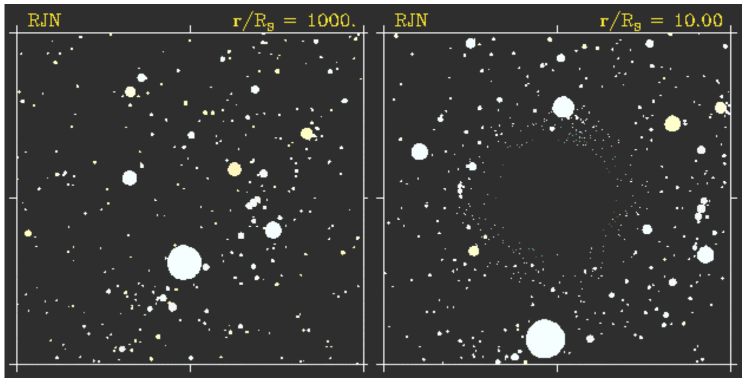
- Extremely strong gravitational field
- Schwarzschild radius.
  - $R_S = 2GM/c^2$
  - Same as result from setting

    c = escape velocity,

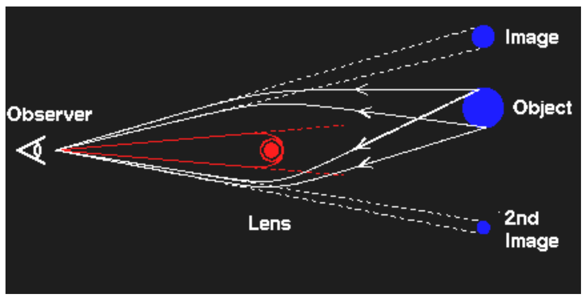
    in $v = \sqrt{2GM/R}$



[Fig 23.12]

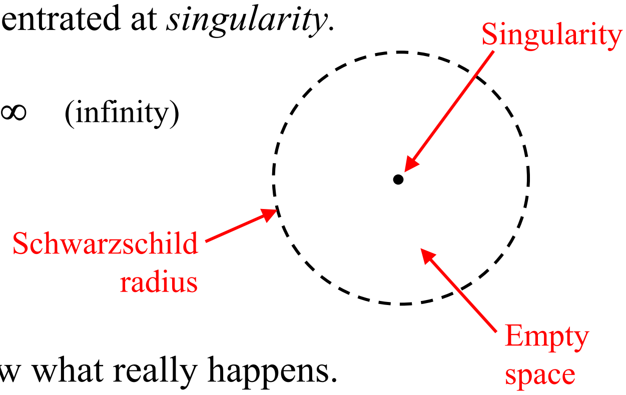


movie



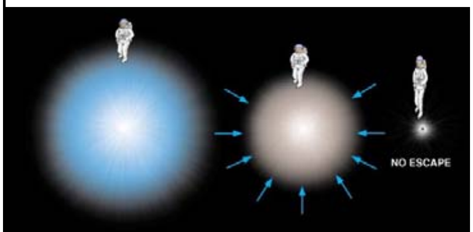
What's Inside?

- Only known mathematical solutions are for free space.
- All mass concentrated at *singularity*.
  - Radius = 0
  - ➔ density = ∞ (infinity)

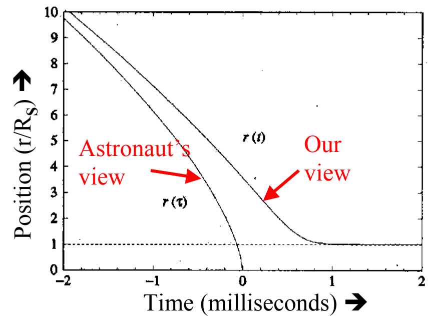


- We don't know what really happens.

Falling into a Black Hole



[Fig 23.10]



Astronaut's view:

- Time runs normally.
- Tidal forces become stronger & stronger.
- Nothing special happens at Schwarzschild radius.
- But singularity is real. Splat!

Our view:

- Time runs slower & slower.
- Tidal forces become stronger & stronger.
- Never quite reaches Schwarzschild radius.
- No knowledge about interior.

Black Holes in binary star systems

[Fig 23.14]

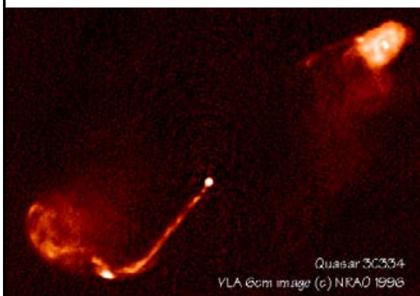
- Formed in some supernovae
  - Neutron star can support only up to 3 $M_\odot$
- Detected by orbital motion of the normal star.

$$P^2 (M_1 + M_2) = a^3$$

- 3 reasonably good cases known.

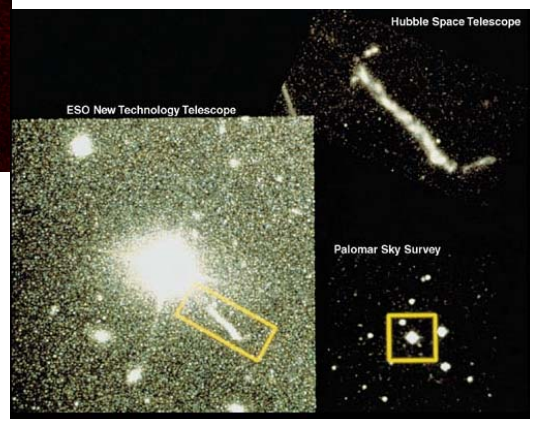
Quasars: Quasi-Stellar Radio Sources [26]

- But most are *not* radio sources
  - Quasi-Stellar Objects (QSOs)



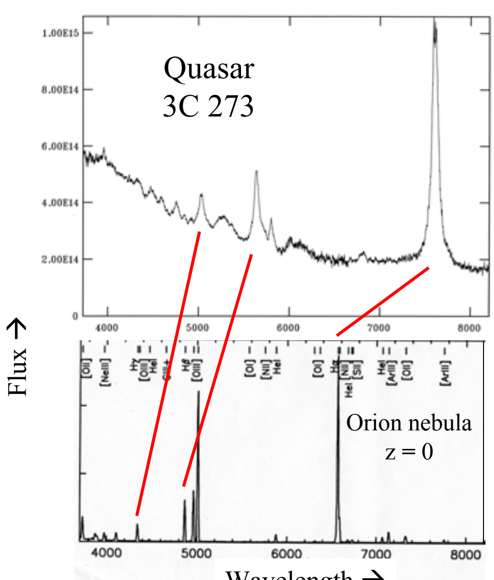
Radio image

Optical image



[Fig 26.3]

Large redshifts

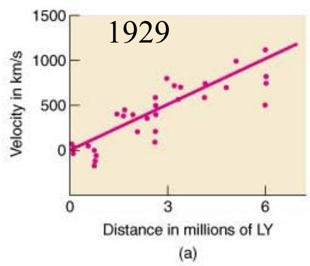


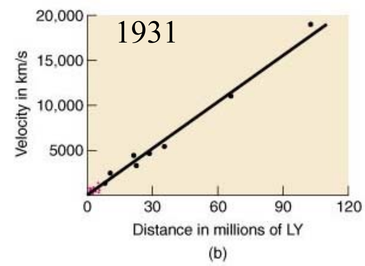
- Measure Doppler shift from emission or absorption lines:

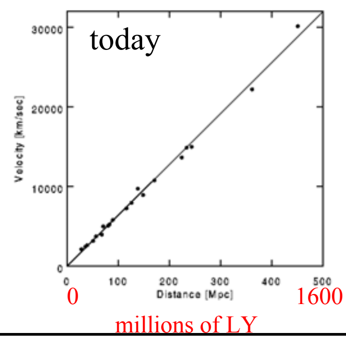
Redshift $z = \Delta\lambda/\lambda = v/c$

Hubble's Law (1929)

[Fig 25.18]







- Measure radial velocity v from Doppler shift.
- Hubble's Law:

  $v = H_o\, d$

- Proportionality constant H_o is called "Hubble constant"
- Note huge change in measured value of H_o between 1931 and today
  - Constant refinement of distance scale

Measuring Distances using Redshifts

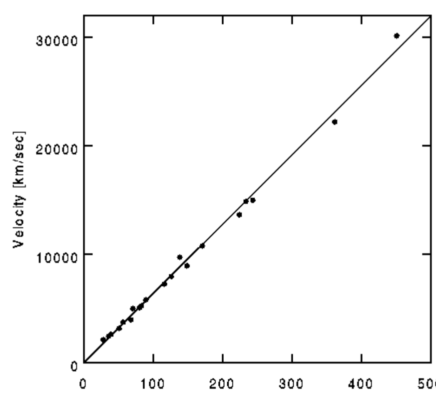
- Measure Doppler shift from emission or absorption lines:

  Redshift $z = \Delta\lambda/\lambda = v/c$

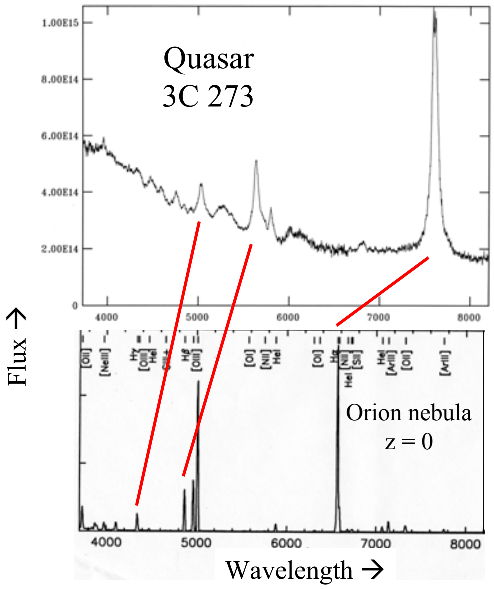
- Plug v into Hubble's Law:

  $v = H_o\, d$

  $d = v/H_o$



Back to QSOs:
Large redshifts ➔ Large distances



- Measure Doppler shift from emission or absorption lines:

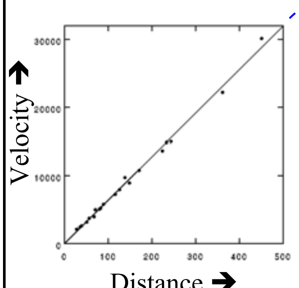
  Redshift $z = \Delta\lambda/\lambda = v/c$

- Plug v into Hubble's Law:

  $v = H_o d$

  $d = v/H_o$

Largest known QSO redshift:
z = 6



Redshift $z = \Delta\lambda/\lambda = v/c$ ➔ $v = 6\,c$

Special relativity:

$$z = \frac{\Delta\lambda}{\lambda} = \sqrt{\frac{1 + v_{radial}/c}{1 - v_{radial}/c}} - 1$$ ➔ $v = 0.96\,c$

➔ Distance = 13 billion light years.
Light travel time = 13 billion years.

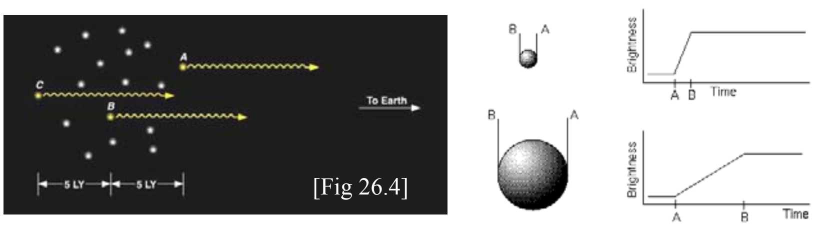
Quasars & Active Galaxies

- Large redshift ➔ large distance

$$F = L/4\pi d^2$$
$$4\pi d^2\, F = L$$

- Measured flux + distance ➔ huge luminosity
  - Up to 1000 x luminosity of an entire galaxy of stars.

- Rapid flux variability ➔ small volume.

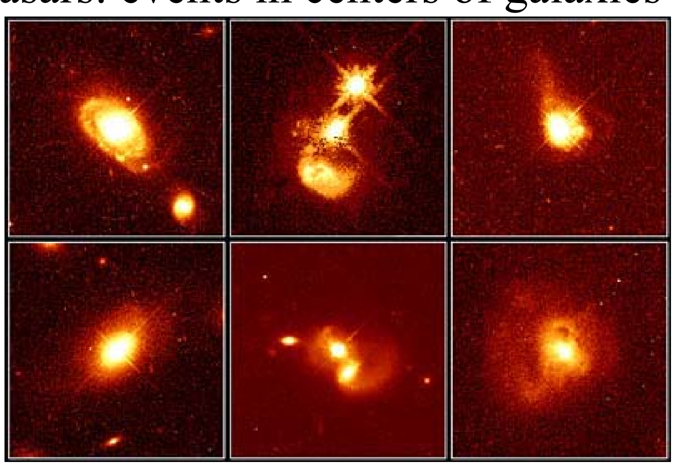


[Fig 26.4]

Some luminous quasars vary in *few days* ➔ same size as solar system.

Quasars: events in centers of galaxies

[Fig. 26.6]



- Hubble Space Telescope images.
  - bright star-like objects at centers of faint galaxies.

Black Holes in binary star systems

[Fig 23.14]

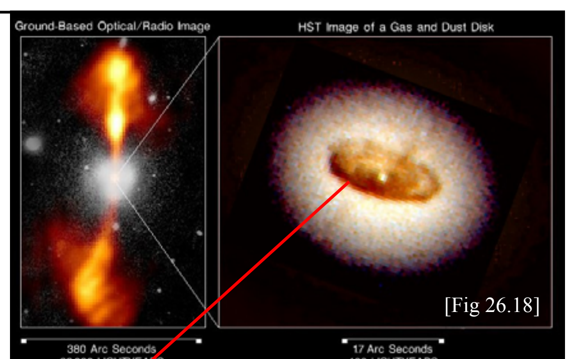
- Formed in some supernovae
  - Neutron star can support only up to 3 $M_\odot$
- Detected by orbital motion of the normal star.

$$P^2 (M_1 + M_2) = a^3$$

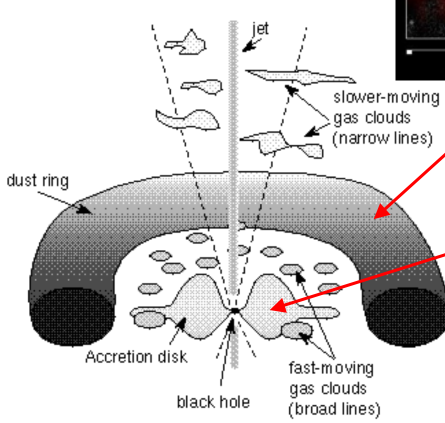
- 3 reasonably good cases known.

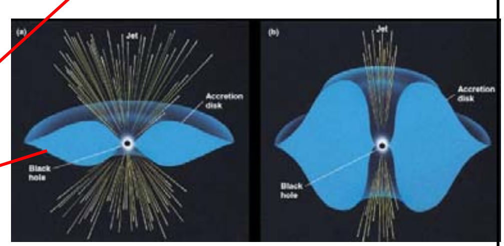
Energy Source:

- Gas, stars fall into 10^8 $M_\odot$ black hole.
- Gravitational potential energy ➔ thermal energy ➔ light



[Fig 26.18]





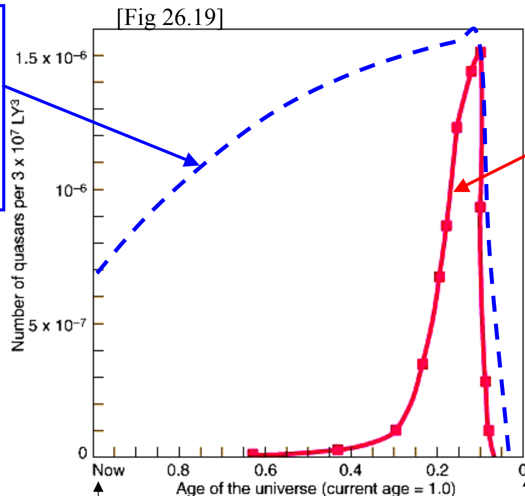
[Fig 26.17]

Accretion disk +
Black Hole + Jets

Most Quasars Lived and Died Long Ago

Rate at which stars are formed in galaxies.

[Fig 26.19]



Number of Quasars per unit volume

Conclusion:
Quasars are events in young galaxies.

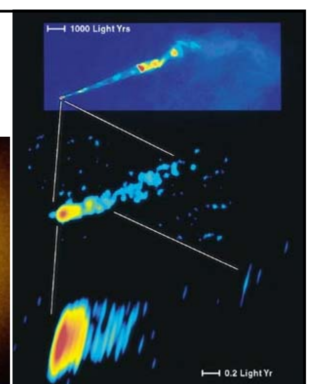
Strobel's QSO in spiral galaxy

Now = 14 billion yrs

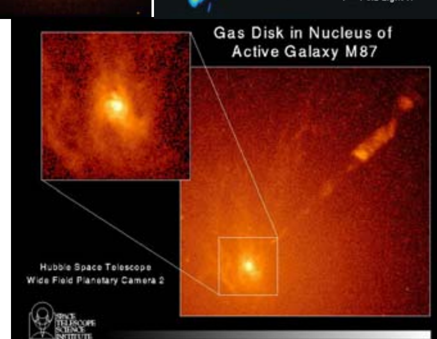
← time

Formation of universe

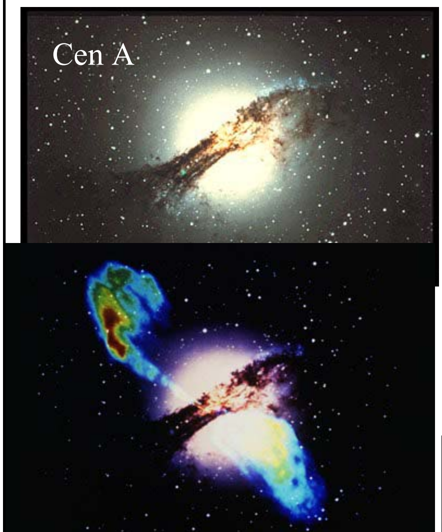
The Leftovers:
The Active Galaxy M87

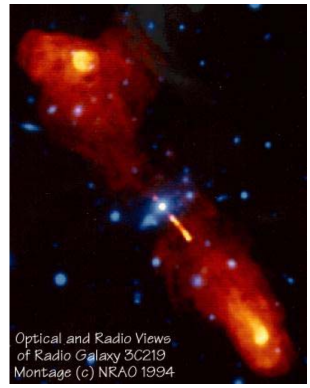


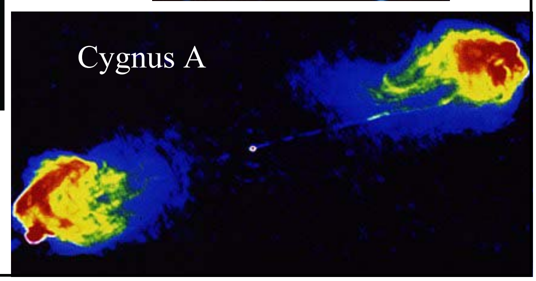
[see 26.2]



Some other Active Galaxies







These Radio Galaxies are E galaxies.

Also… Seyfert Galaxies = spirals with very low-luminosity QSO at center.

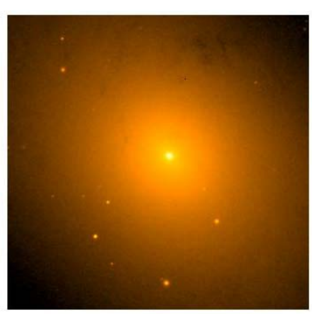
The Nucleus of M31 in Visible Light

M 31

The Andromeda Galaxy

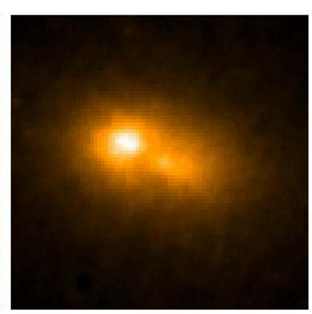
40,000 LY

Ground View of Galaxy



2,000 LY

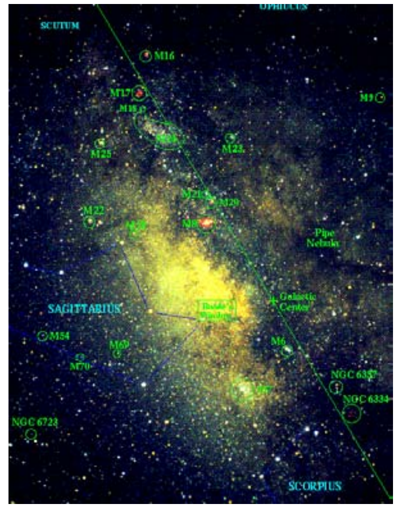
Ground View of Galaxy Core



40 LIGHT–YEARS

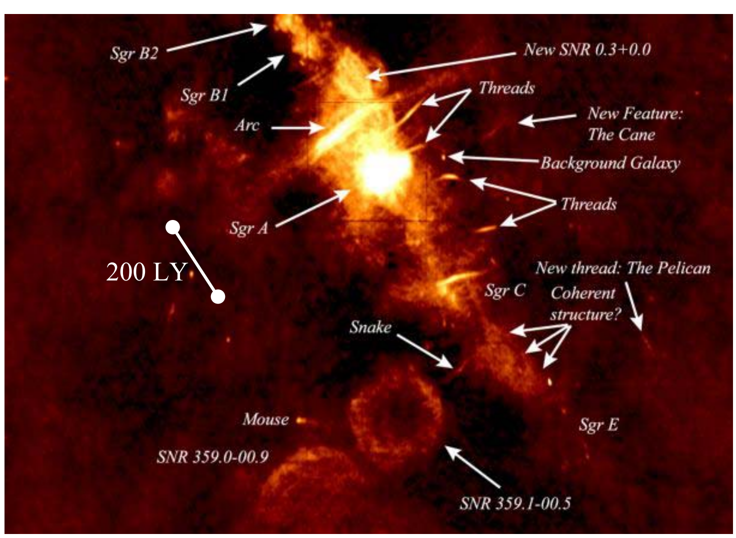
HST View of Galaxy Nucleus

The Galactic Center
(visible wavelengths)

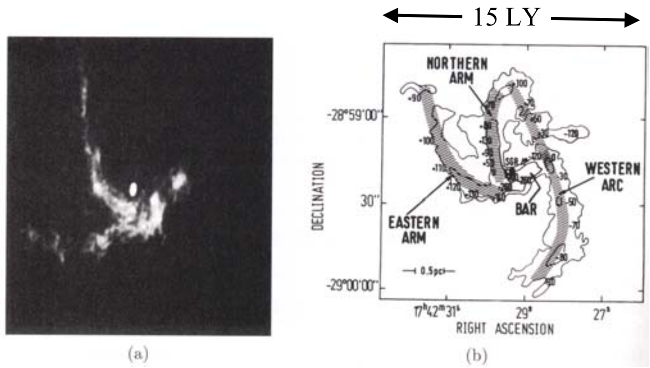


From Bill Keel, UA Astronomical Image Galleries

Radio Image of the Center of our Galaxy

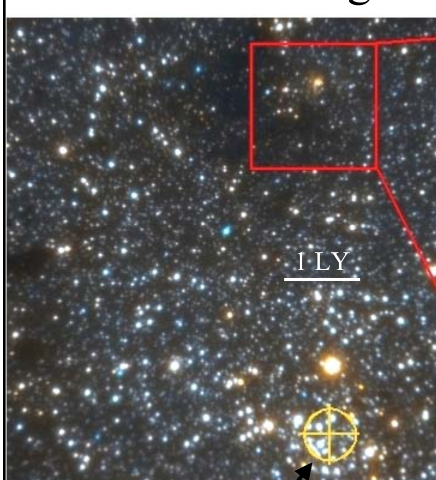


Sagittarius A*



- Radio observations with higher angular resolution.
- Western arc is segment of rotating ring of molecular gas.
  - 6 LY radius.
- Eastern Arm and Bar are disconnected filaments.
- Small oval is the point source Sagittarius A*

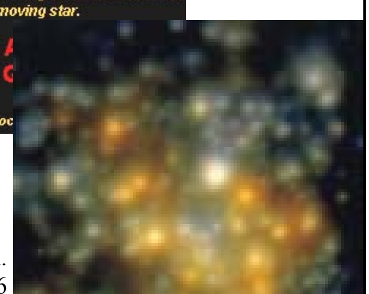
Infra-red Images of the Galactic Center



Using "adaptive optics" technique on new Gemini 8m telescope.

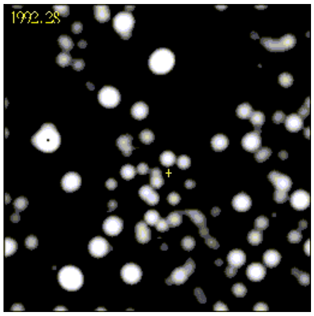
Galactic Center

300,000 x more stars per unit volume than in vicinity of Sun



Fraknoi et al. Fig 24.16

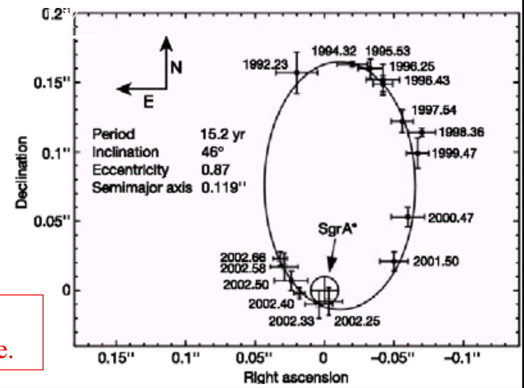
The Black Hole at the the Galactic Center



$$P^2 (M_1 + M_2) = a^3$$

Velocities of stars in very center
➔ black hole at position of Sagittarius A*

$10^6 M_\odot$

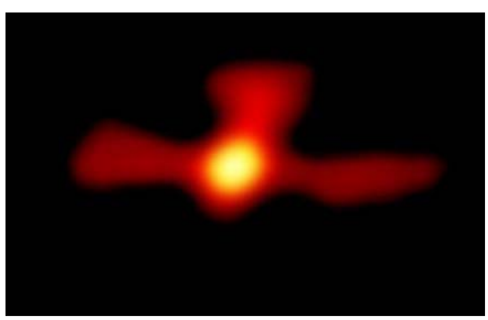


Infrared observations over 6 years show proper motion.

Galactic Center Research at MPE

Latest data (2002): follows complete orbits to within 60AU from black hole.

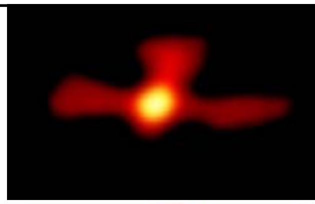
Matter-Antimatter Annihilation at the Galactic Center

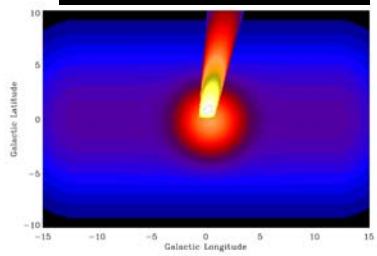


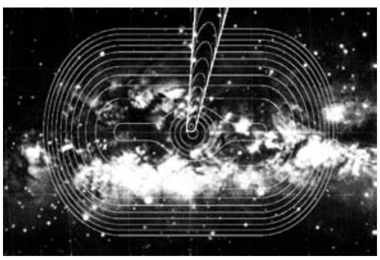
- For every sub-atomic particle, there is an anti-particle.
- Collision between particle, anti-particle ➔ self-annihilation.
- $e^- + e^+$ ➔ γ-ray (very high energy photon)
- Characteristic photon energy ($E = mc^2$) is predicted,

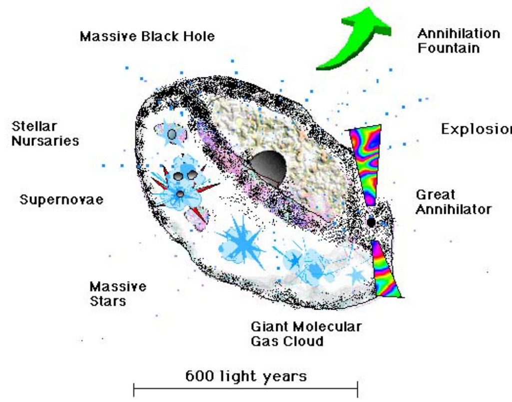
  … and observed at Galactic Center.

Antimatter Fountains?









The Galactic Center Region