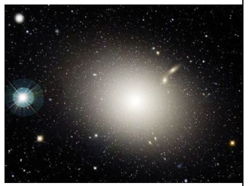
FORMATION AND EVOLUTION OF GALAXIES

Lecture 13

- Supermassive black holes
  - Evidence for their existence
- The Milky Way
  - The monster in the middle



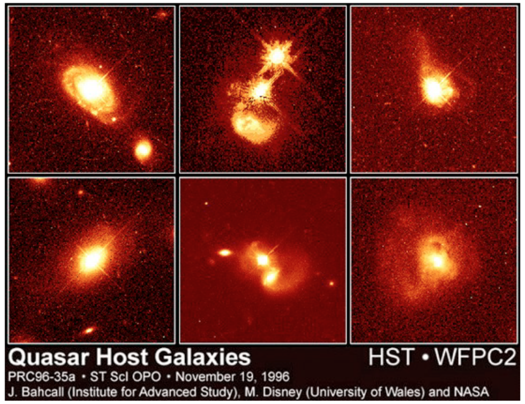
Somak Raychaudhury

Two or Three Types of Black Holes?

- Stellar Mass Black Holes: 3-100 times the mass of our Sun
- Intermediate mass Black Holes: 1,000 to 100,000 times the mass of our Sun

  Controversial
- Supermassive black holes: Millions to billions of times the mass of our Sun; found at the cores of galaxies

Supermassive Black holes live in galaxy centres

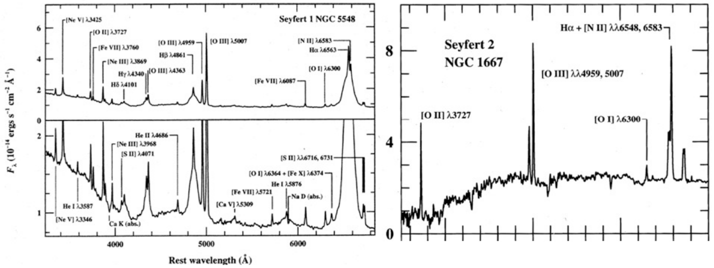


To establish the existence of SMBHs

- Stellar kinematics in the core of the galaxy
- Optical spectra: the width of the spectral line from broad emission lines
- X-ray spectra: The iron Kα line is seen is clearly seen in some AGN spectra
- The bolometric luminosities of the central regions of some galaxies is much larger than the Eddington luminosity
- Variability in X-rays: Causality demands that the scale of variability corresponds to an upper limit to the light-travel time

Doppler width of optical spectral lines

- Broad lines $\Delta\lambda/\lambda = \Delta v/c \Rightarrow \Delta v = 8000\ \mathrm{km s^{-1}}$.



Also GR effects- gravitational broadening

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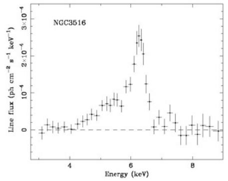
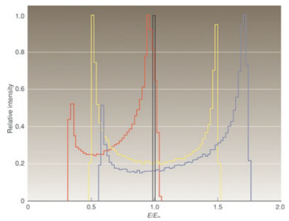
Central Engine: Why a Black Hole? Energetic Considerations

- very large extents of jets, up to >1 Mpc, so lifetime is at at least 10^7 yr (assuming expansion speed c)
- $L_{bol} = 10^{47}$ erg/s. Multiply this by 10^7 yr gives 3 10^{61} erg
- can vary luminosity dramatically, by 50% in one day, so central source must be smaller than one light-day (<<3 10^{15} cm)
- burning hydrogen into Fe (nucleus w/ highest binding energy) releases 8MeV/nucleon, or 0.008 $m_p c^2$ per nucleon (i.e., efficiency 0.8%)
- to create 3 10^{61} erg one this needs $m = E/c^2/0.008 \sim 2\ 10^9\ M_{sun}$

X-ray spectra: the Fe K line

- Iron line at 6.35 keV (Fe K-line, transition in tightly bound electrons) is distorted: combination of Doppler effect in the accretion disk and strong gravitational field of the black hole.
- Very broad (50.000km/s) line-profiles, offset to the red + gravitational redshift





black: intrinsic energy of Fe line (6.35 KeV)

yellow: double horned profile due to rotation

blue: shift due to relativistic Doppler effect and relativistic aberration

red: gravitational redshift effect (photons climb out of gravitational well)

the red line is what's observed

Does every galaxy have a supermassive black hole?

CMO=Central Massive Object

$>10^6$ Msun- most probably BH. Milky way at the lowest end

Others could be dense star clusters

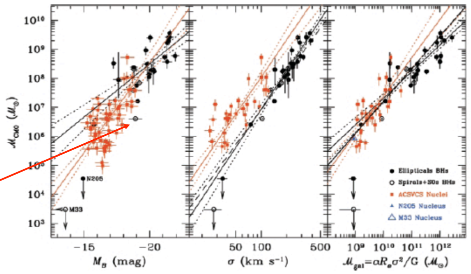
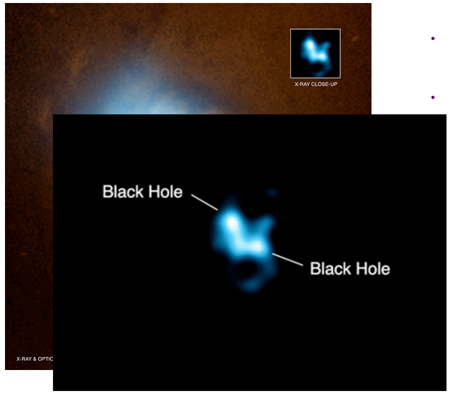


FIG. 2.—*Left panel:* Mass of the CMO plotted against absolute blue magnitude of the host galaxy (or bulge for spiral galaxies). Nuclei from the ACSVCS are shown as red squares. The SBHs in early-type and spiral galaxies are shown as filled and open circles, respectively. *Middle panel:* CMO mass as a function of the velocity dispersion of the host galaxy, measured within R_e. *Right panel:* CMO mass plotted against galaxy mass, defined as $\mathcal{M}_{gal} \equiv \alpha R_e \sigma^2/G$ with $\alpha = 5$. In

Ferrarese et al 2006

Two black holes in one galaxy?



- NGC 3393- 50 Mpc away
- Spiral galaxy with two SMBHs at its core

Separated by 150 pc=490 ly

Found by the Chandra X-ray observatory

Believed to be the result of a merger

Fabbiano et al 2011

The Schwarzschild solution

The spherically symmetric solution of Einstein's equations of general relativity, for a non-rotating system, is

$$(ds)^2 = \left(c\,dt\sqrt{1-2GM/rc^2}\right)^2 - \left(\frac{dr}{\sqrt{1-2GM/rc^2}}\right)^2 - (r\,d\theta)^2 - (r\sin\theta\,d\phi)^2.$$

So the radial distance between two nearby points on the same radial line (dθ=0, dφ=0) measured simultaneously (dt=0) is the proper distance

$$d\mathcal{L} = \sqrt{-(ds)^2} = \frac{dr}{\sqrt{1-2GM/rc^2}}.$$

The proper time $d\tau$ recorded by clock at radial distance r is related to the time t recorded at infinity

$$d\tau = \frac{ds}{c} = dt\sqrt{1-\frac{2GM}{rc^2}},$$

Time dilation!

$$d\tau < dt$$

Schwarzschild radius

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$$d\tau = \frac{ds}{c} = dt\sqrt{1-\frac{2GM}{rc^2}},$$

When the radial coordinate of the star's surface has collapsed to

$$\boxed{R_S = 2GM/c^2,} \quad (17.27)$$

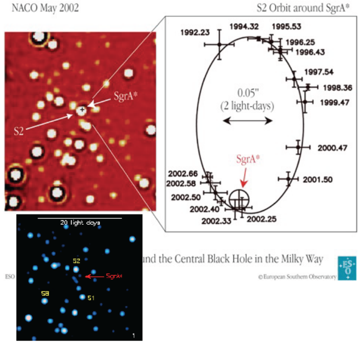
called the **Schwarzschild radius**, the square roots in the metric go to zero. The resulting behavior of space and time at $r = R_S$ is remarkable. For example, according to Eq. (17.17), the proper time measured by a clock at the Schwarzschild radius is $d\tau = 0$. Time has slowed to a complete stop, as measured from a vantage point that is at rest a great distance away.[14] From this viewpoint, *nothing ever happens at the Schwarzschild radius*!

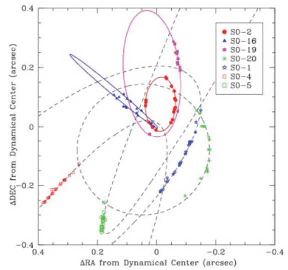
Size of a black hole

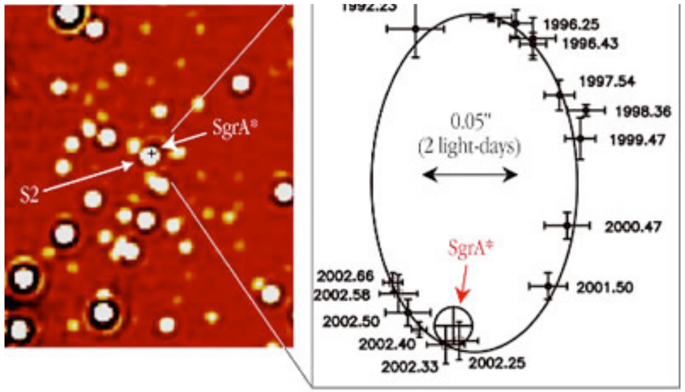
Schwarzschild radius

Mass	$R_S=3\left(\frac{M}{M_\oplus}\right)$ km
1 Earth mass	2 cm
1 Solar mass	3 km
10 Solar masses	30 km
1 million Solar masses	3 million km ~ 4 x Solar radius!

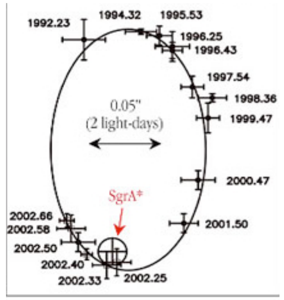
Centre of the Milky Way







S2: star with orbital period 15.2 yr



- For S2, Eccentricity =0.87
- Perigalacticon distance = 120 AU
  r_p = 120 x 1.5 x 10^8 km

$$a = \frac{r_p}{1-e} = 1.4 \times 10^{14} \text{ m}$$

- From Kepler 3,

$$\frac{4\pi^2 a^3}{GP^2} \simeq 7 \times 10^{36} \text{ kg} = 3.5 \times 10^6 M_\odot.$$

- Schwarzschild radius=

$$R_S = \frac{2GM_{BH}}{c^2} = 4.2 \times 10^{-7} \text{ pc} = 0.08 \text{ AU} = 15 R_\odot.$$