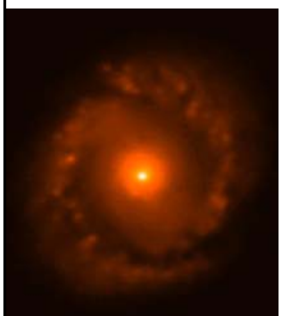
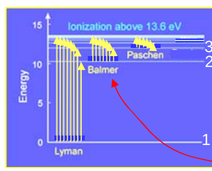
Quasars and Active Galactic Nuclei

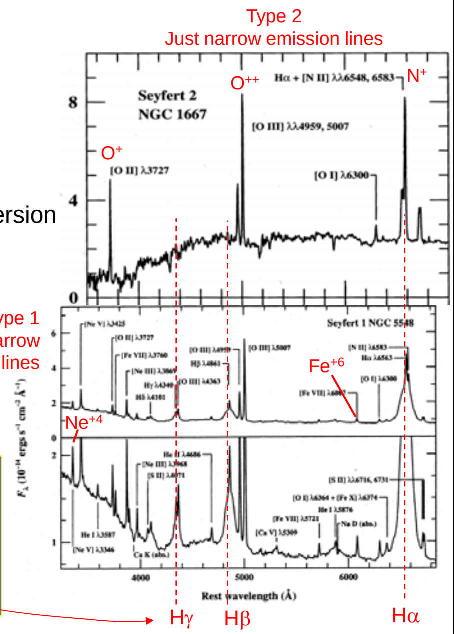
Seyfert Galaxies
- Carl Seyfert, 1940's
- Spirals
- Very bright unresolved nucleus
- Strong emission lines
    - High ionization states
    - Broad lines = large internal velocity dispersion
        - 10,000 km/s



NGC 1097
Gemini J-band image
+ diffraction ring??

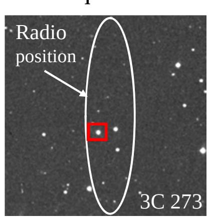


H energy levels

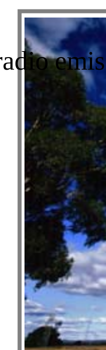


Quasars

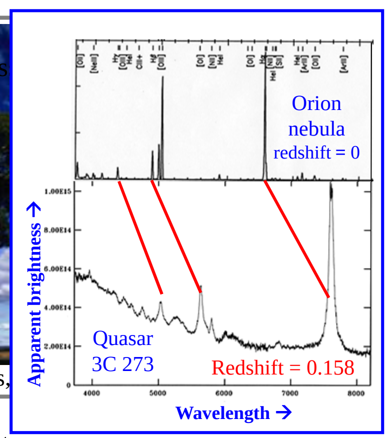
- Luminosity = (apparent brightness) x distance^2
- Apparent brightness:
    - Discovered quasars from their radio emis
    - But… *which object???*



Lunar occultation



Parkes,



- Distance: Now measure optical spectrum
    - *Doppler shift* of wavelength of light
        ➔ velocity of recession (redshift) due to expansion of Universe.
        ➔ huge distance ➔ **huge luminosity!**

Quasars and Active Galactic Nuclei

- Homework 7 due Tuesday.
- Study guide now on web.
- Evaluation: https://sirsonline.msu.edu

Seyfert Galaxies

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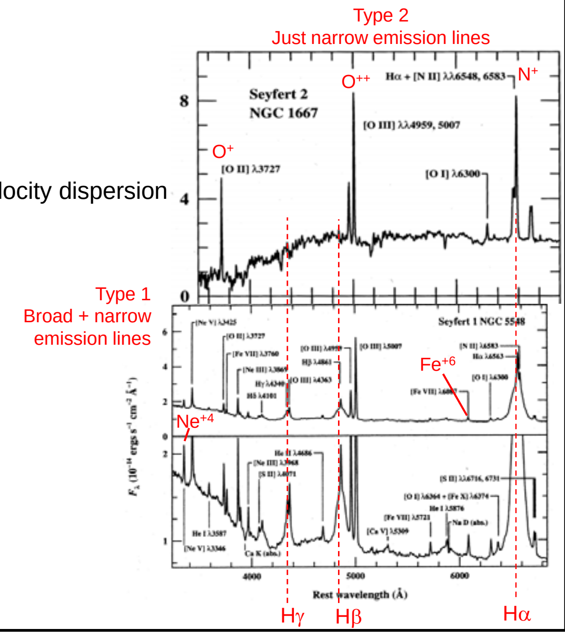


Quasars

- 1960's example: 3C 273
- Bright (m ~ 13 mag)
- Stellar appearance on images
- Seyfert-like spectrum
- Redshift ➔ HUGE luminosity
  - 1000x Milky Way luminosity.

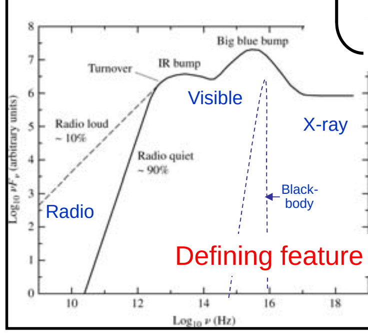
Classification

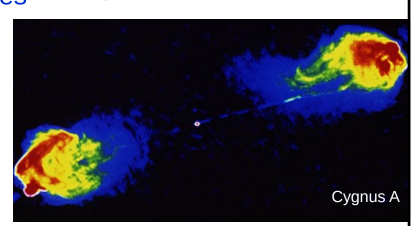
Active Galactic Nuclei (AGN)

- Quasar = Quasi Stellar Radio Source
- QSO = Quasi Stellar Object
  - radio-quiet
  - 1000's of times more numerous than Quasars
- Blazars (or BL Lac objects)
  - bright continuum source, but no emission lines
- Seyfert Galaxies
  - Types 1 and 2
- Radio galaxies
- etc

High Luminosity

Lower Luminosity



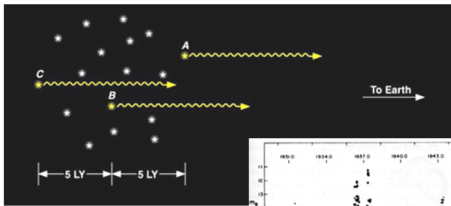


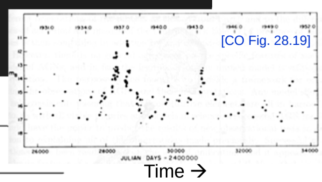
Defining feature = non-thermal continuum

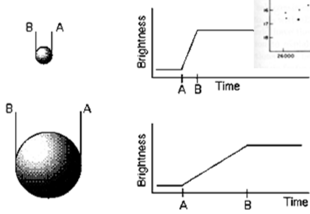
- Strong in Quasars, QSOs
- Weaker in Seyferts, radio galaxies

Measured Properties

Rapid brightness changes (weeks, days. hours).

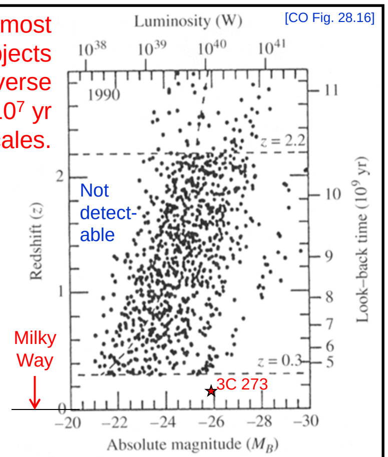






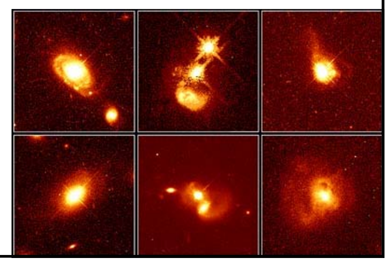
➔ Size = light-weeks, light-days, light-hours.

QSOs are most luminous objects in universe on 10^7 yr timescales.



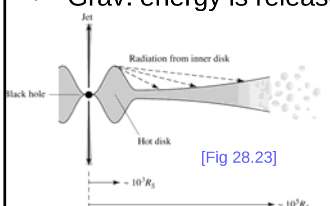
In centers of galaxies

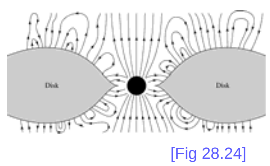
HST images

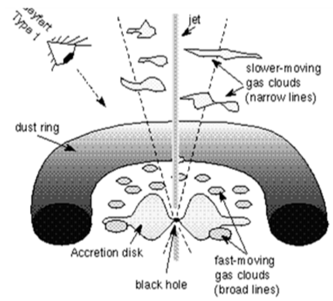


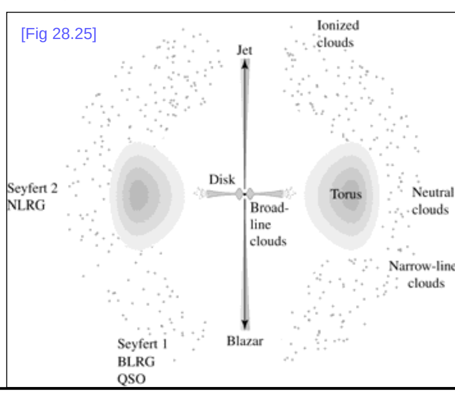
What are they?

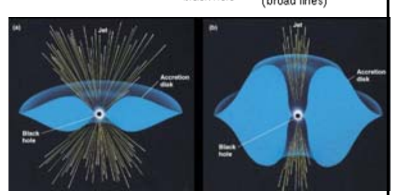
- Gas, stars fall into 10^6-10^8 M_{sun} black hole.
- Grav. energy is released







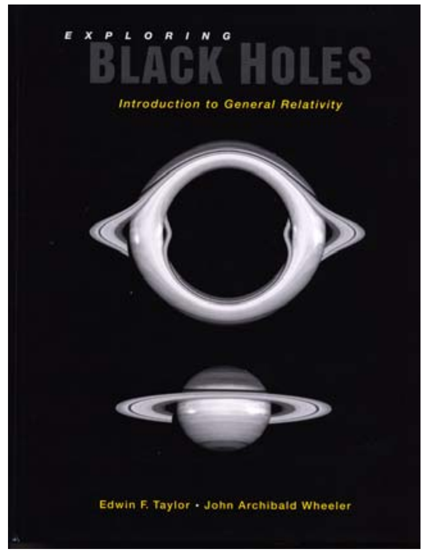




- Black hole
- Accretion disk
- Broad emission-line region
- Obscuring torus
- Narrow emission-line region

Black Holes

- [CO 17.3]
- "Exploring Black Holes – An Introduction to General Relativity"
  by Taylor & Wheeler (TW2)
  - Excellent treatment using simple calculus.
- AST 860 "Gravitational Astrophysics"
  - Prof. Loh
  - TuTh 2:40-4:00
  - Textbook is Hartle *"Gravity, An Introduction to Einstein's General Relativity"*

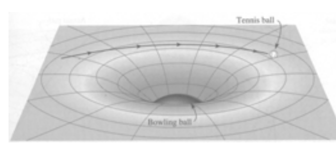


What happened to Saturn?

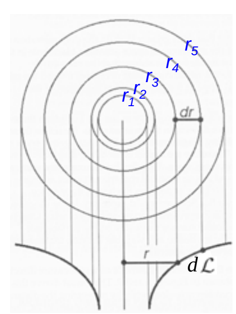
Black Holes & the Schwarzschild Metric

Simplified metric, from Taylor & Wheeler2 (no c^2, no G, no θ):

$$ds^2 = \left(1 - \frac{2M}{r}\right)dt^2 - \frac{dr^2}{\left(1 - \frac{2M}{r}\right)} - r^2 d\phi^2$$



- Schwarzschild radius: $R_S = 2M$
- *Schwarzschild coordinates*
  - reconstructed as if seen from a point where space is flat.
  - imagine concentric shells of radius r_1, r_2, r_3 …
  - shell "radius" defined to give correct surface area $4\pi r^2$



- But for an observer in free-fall:
  - Metric = flat space-time in local region (*i.e.* special relativity).
    $ds^2 = dt^2 - dr^2 - r^2 d\phi^2$
  - In observer's free-falling frame, $dr = d\phi = 0$.
  - So time on observer's wristwatch = $\tau = s$.

Energy as a Constant of Motion

(leaving out constants c, G, and dimension θ)

- Newtonian: Total energy per unit mass = $\frac{E}{m}$ = constant

  Example: $\frac{E}{m} = \frac{1}{2}v^2 - \frac{M}{r}$

- Special Relativity

  $ds^2 = dt^2 - dr^2 - r^2 d\phi^2$ + objects follow *geodesics*: $\int ds$ = extremum ⇒ $\frac{E}{m} = \frac{dt}{ds}$

- Schwarzschild Geometry

  $$ds^2 = \left(1 - \frac{2M}{r}\right)dt^2 - \frac{dr^2}{\left(1 - \frac{2M}{r}\right)} - r^2 d\phi^2$$ + objects follow *geodesics*: $\int ds$ = extremum ⇒ $\frac{E}{m} = \left(1 - \frac{2M}{r}\right)\frac{dt}{ds}$

Astronaut Falling into a Black Hole

- Schw. conservation of energy: $\frac{E}{m} = \left(1 - \frac{2M}{r}\right)\frac{dt}{ds}$
- Schw. metric

$$ds^2 = \left(1 - \frac{2M}{r}\right)dt^2 - \frac{dr^2}{\left(1 - \frac{2M}{r}\right)} - r^2 d\phi^2$$

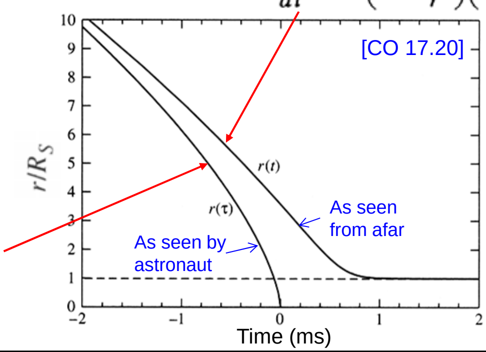
Eq. of motion for freefall in Schw. Coords:

Homework Q. 1: Show this → $$\frac{dr}{dt} = -\left(1 - \frac{2M}{r}\right)\left(\frac{2M}{r}\right)^{1/2}$$

Homework Q. 2: Show this

For free-falling astronaut, time steps on wristwatch = *ds*, so velocity is:

$$\frac{dr}{ds} = -\left(\frac{2M}{r}\right)^{1/2}$$

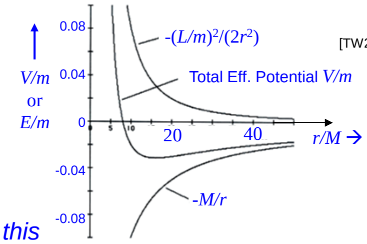


Orbits around black holes
(from TW2)

- Schw. metric $ds^2 = \left(1-\frac{2M}{r}\right)dt^2 - \frac{dr^2}{\left(1-\frac{2M}{r}\right)} - r^2 d\phi^2$
- Schw. conservation of energy: $\frac{E}{m} = \left(1-\frac{2M}{r}\right)\frac{dt}{ds}$
- Schw. conservation of angular mom: $r^2\frac{d\phi}{ds} = \text{constant}$ $\quad \frac{L}{m} = r^2\frac{d\phi}{ds}$
- Effective potential
  - Newtonian

$$\frac{1}{2}\left(\frac{dr}{dt}\right)^2 = \frac{E}{m} - \left[-\frac{M}{r} + \frac{(L/m)^2}{2r^2}\right]$$

$$\frac{1}{2}\left(\frac{dr}{dt}\right)^2 = \frac{E}{m} - \frac{V(r)}{m}$$



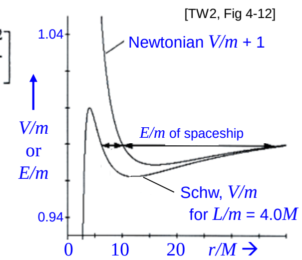
Remember [CO 25.3] discussion of epicycles.

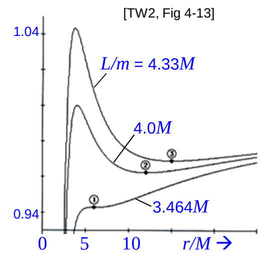
Homework Q. 3: Show this

  - Schwarzschild

$$\left(\frac{dr}{ds}\right)^2 = \left(\frac{E}{m}\right)^2 - \left(1-\frac{2M}{r}\right)\left[1+\frac{(L/m)^2}{r^2}\right]$$

$$\left(\frac{dr}{ds}\right)^2 = \left(\frac{E}{m}\right)^2 - \left(\frac{V}{m}\right)^2$$





- Precession of perihelion
- Innermost stable orbit

Notation:
No G, no c

Spinning Black Holes

A fond memory: $ds^2 = \left(1-\frac{2M}{r}\right)dt^2 - \frac{dr^2}{\left(1-\frac{2M}{r}\right)} - r^2 d\phi^2$

Kerr metric (1963)

$d\phi d\tau$ cross term → "frame dragging"

$$ds^2 = -\left(1-\frac{2Mr}{\rho^2}\right)dt^2 - \frac{4M\,ar\,\sin^2\theta}{\rho^2}d\phi dt + \frac{\rho^2}{\Delta}dr^2 + \rho^2 d\theta^2 + \left(r^2+a^2+\frac{2M\,ra^2\sin^2\theta}{\rho^2}\right)\sin^2\theta\, d\phi^2$$

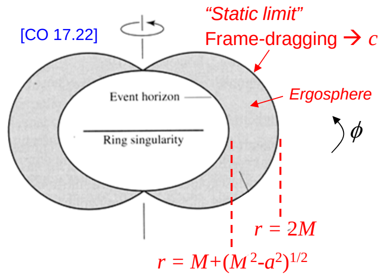
where $a \equiv J/M, \quad \rho^2 \equiv r^2 + a^2\cos^2\theta, \quad \Delta \equiv r^2 - 2M\,r + a^2$

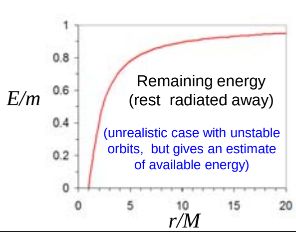
J = Angular Momentum

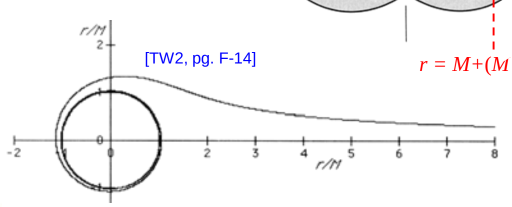
Maximal spin: $J_{max} = M^2$ (or = GM^2/c^2 in CO units)

- Usually ~ the case.
- Then Event Horizon in equatorial plane is at $r=M$

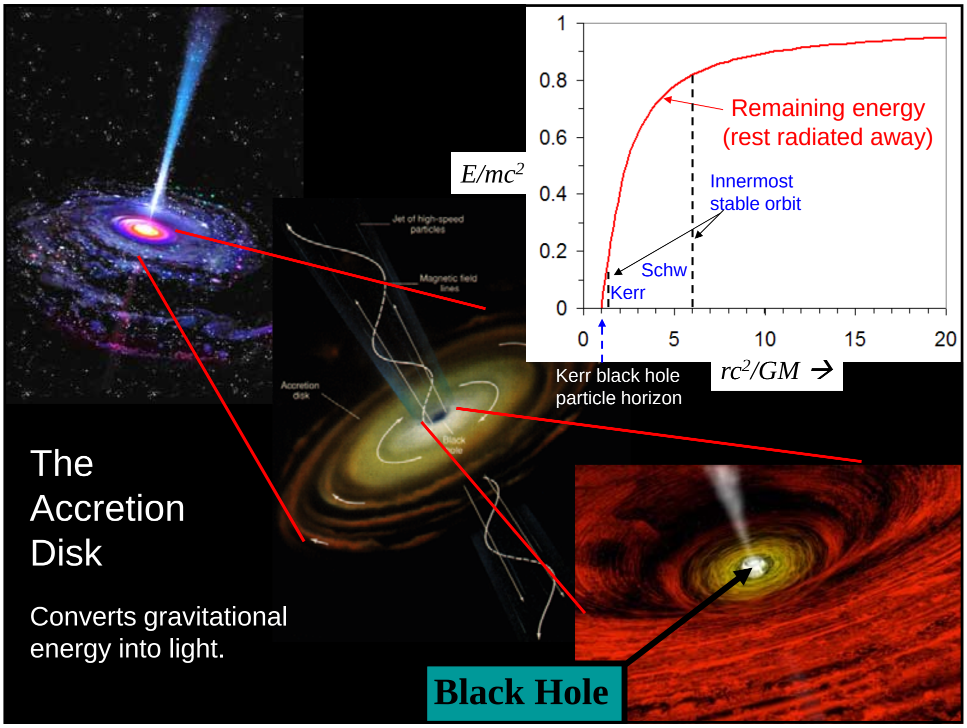
Infalling particle with no angular momentum:



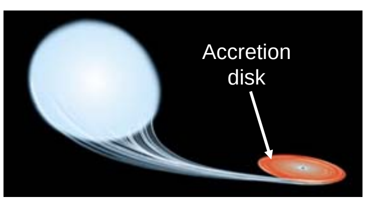




Both plots for equatorial plane only



Accretion Disks



- Well-studied phenomena in local binary star systems
  - "cataclysmic variables"
- Angular momentum ➔ material cannot fall directly onto central mass.
- Binary stars ➔ "thin" accretion disks
  - Material works its way in toward center due to viscosity
- For QSO: Material eventually falls into Black Hole
  - From innermost stable orbit

Disk material loses energy by black body radiation

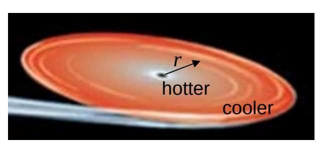
$$L(r) \propto T(r)^4 \times (2\pi r\, dr)$$

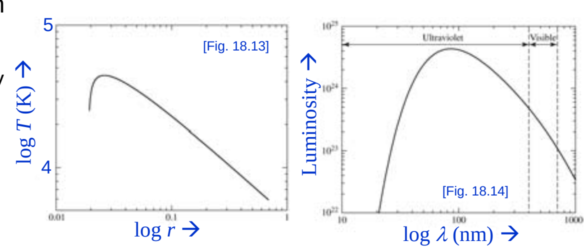
$$\Downarrow$$

[CO pgs. 661-665]

$$T(r) \propto r^{-3/4}$$

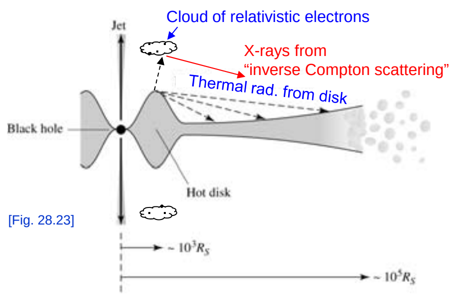
➔ total radiation = sum of black bodies.

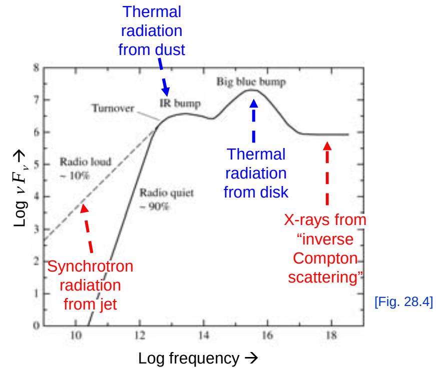




Binary star results, but QSOs are similar.

Continuum Source





Energetics

- Accretion rate & luminosity.
  - mass falls into black hole: $L_{disk} = \eta \frac{dM}{dt} c^2 = \eta \dot{M} c^2$

$\eta \approx 0.1$

$\dot{M} \approx 1 - 10\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$

- Eddington limit.
  - Radiation pressure = gravity: $\frac{L_{Edd}}{4\pi r^2} m\sigma = \frac{GmM_{BH}}{4\pi r^2}$

absorption cross-section

Luminous QSOs: $L \sim L_{Edd}$

Seyferts, Radio Galaxies: $L << L_{Edd}$