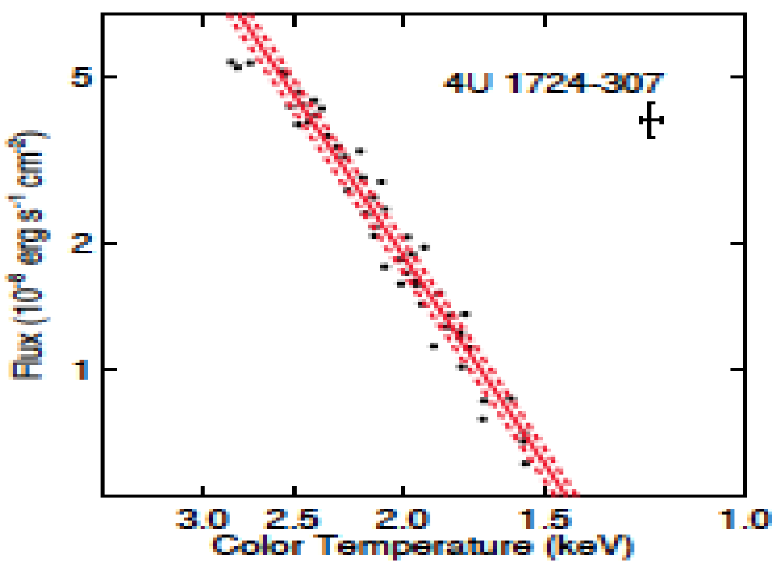
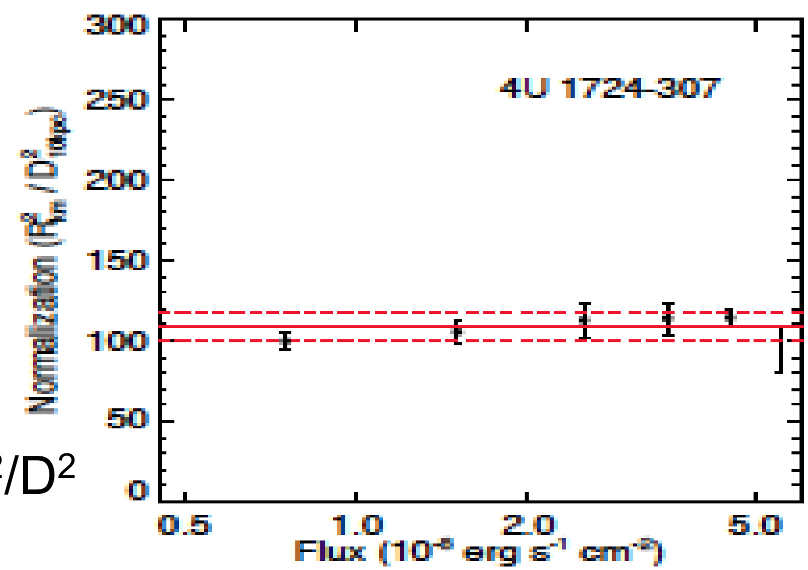
Recent Results on NS Eq of State

- Systematic Uncertainties in the Spectroscopic Measurements of Neutron-Star Masses and Radii from Thermonuclear X-ray Bursts. I. Apparent Radii T Guver, D., D. Psaltis & F Ozel 2012
- The masses and radii of low-magnetic field neutron stars can be measured by combining different observable quantities obtained from their X-ray spectra the apparent radius of each neutron star can be inferred from the X-ray flux and spectral temperature
- Need accurate absolute distances to make further progress

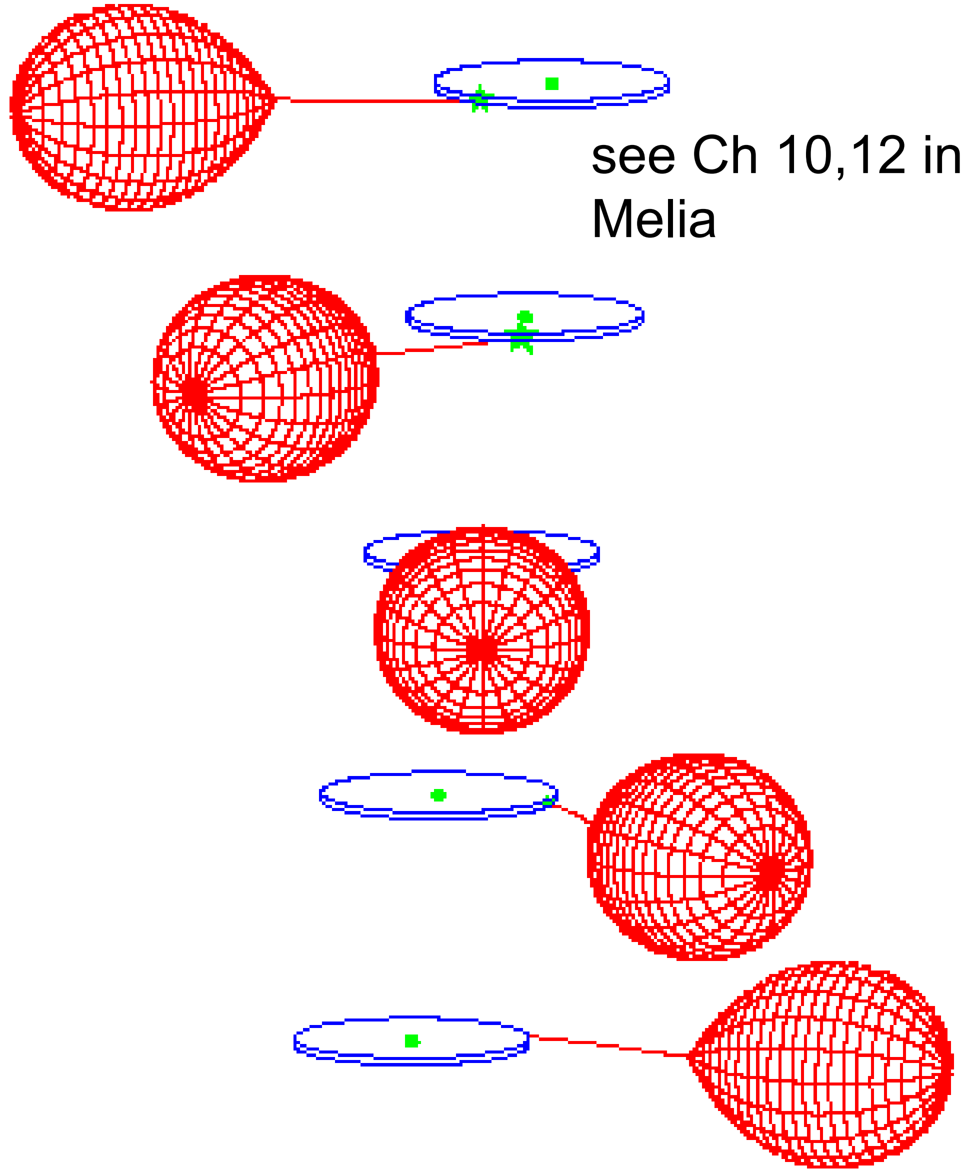


R^2/D^2



Black Holes

- What do you mean 'black holes' ?
- We know of objects whose mass (derived from observations of the lines from the companion objects and Newton's (Einstein) laws) which are larger than possible for a NS or white dwarf.
- They have other unusual properties (related to their x-ray spectrum and timing behavior)
- **Big differences- no surface, no (?) magnetic field, higher mass, stronger GR effects**.



see Ch 10,12 in Melia

How Can We Observe Black Holes

- If a black hole is a 'place' where radiation cannot escape to infinity how can they be observed ?

- Dynamical effects on 'nearby' material

- “Shining” black holes- a black hole can be a place where accretion occurs and as we have seen the process of accretion around a compact object can produce huge amounts of energy and radiation- making the black hole 'visible'

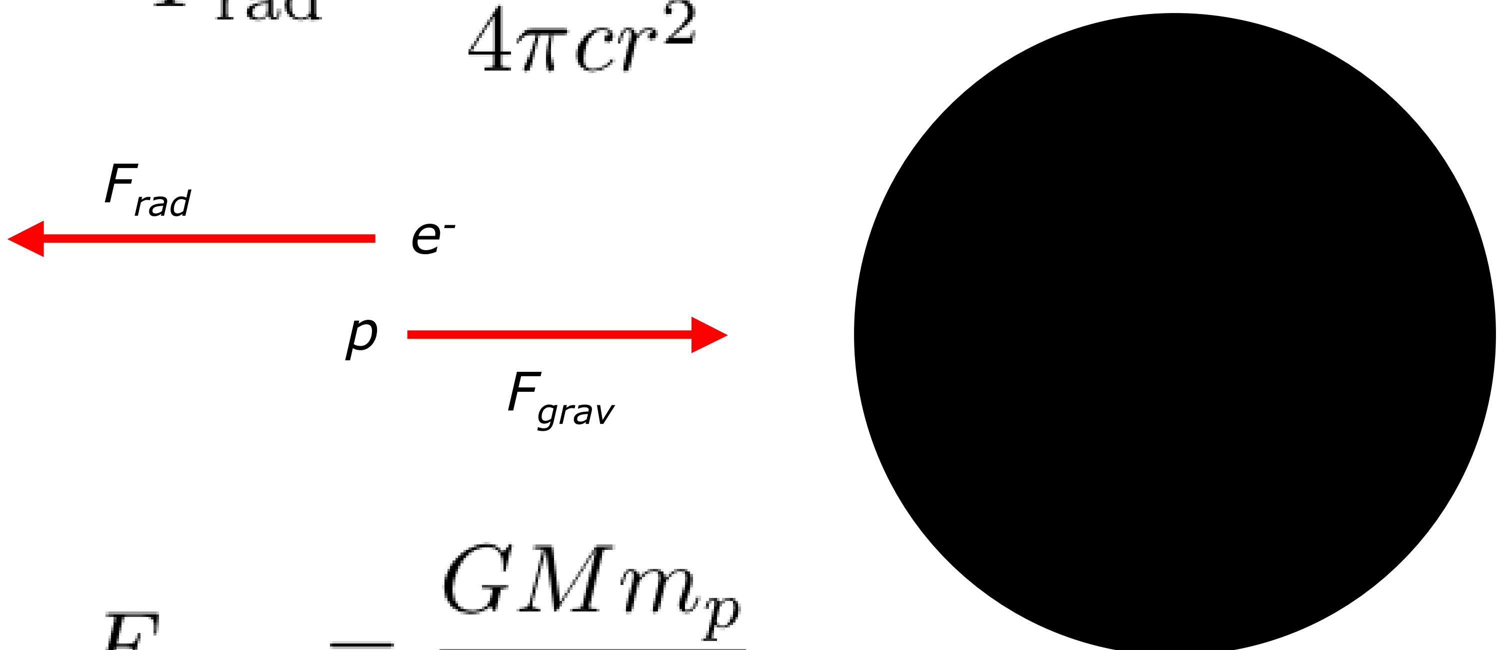
What are the possible energy sources?

- Accretion?
  - Release of gravitational potential energy as matter falls into black hole
  - YES! Thought to be primary power source of all systems just discussed

- Rotational energy of black hole
  - Tapping the rotational energy of a spinning black hole $1/2I\Omega^2$ can be very large
  - May be important in some settings… but can only be tapped if accretion occurring! (Blandford + Znajek 1977 ('Electromagnetic extraction of energy from Kerr black holes')

How luminous can an accreting black hole be?- this is the same Eddington limit as we discussed for neutron stars

$$F_{\rm rad} = \frac{L\sigma_T}{4\pi c r^2}$$



$$F_{\rm grav} = \frac{GMm_p}{r^2}$$

- The accreting matter is pushed away if

$$F_{\rm rad} > F_{\rm grav}$$

- This is the Eddington limit (L_{Edd}). Acts effective upper limit to the luminosity of accretion powered object. Numerically:

$$L > \frac{4\pi G m_p c}{\sigma_T} M$$

$$L_{\rm Edd} \approx 1.3 \times 10^{31} \left(\frac{M}{M_\odot} \right) \,\mathrm{W}$$

General properties of emission from black hole systems

- Emission usually variable on wide variety of timescales
  - Galactic black hole binaries : millisecond and up
  - AGN : minutes and up
  - Most rapid variability approaches light-crossing timescale limit of physical size of object (τ~R/c)

- Significant emission over **very** broad spectral range (radio to hard X-ray or gamma-rays)-NS and WDs tend to have 'thermal' like spectra (relatively narrow in wavelength)

- Lack of a signature of a surface - not a pulsar, no boundary layer emission (no x-ray bursts), no 'after glow' from cooling

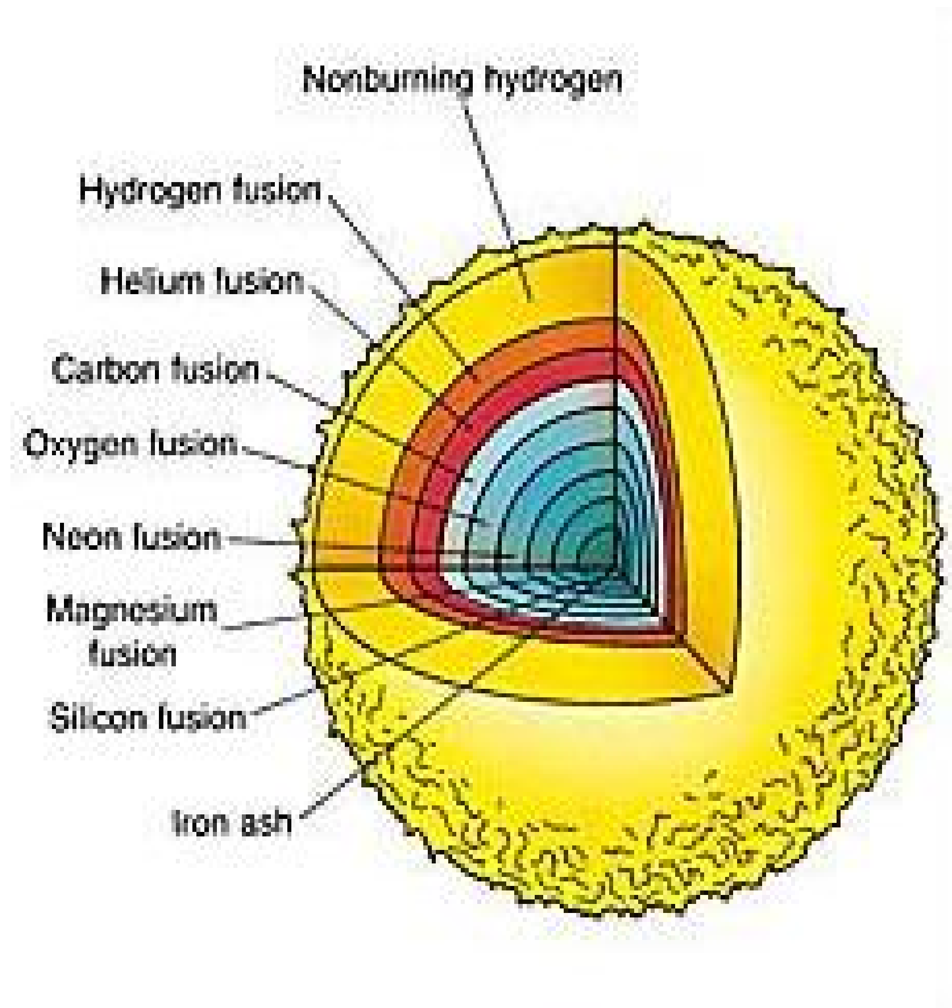
Downwards to Black Holes!

- a neutron star has a maximum mass
- If this mass is exceeded on has a complete gravitational collapse to a black hole

- Basic anatomy of a black hole
- Observational discovery of black holes

Beyond neutron stars…

- Suppose collapsing core has mass that exceeds maximum mass for a neutron star…this can happen in several ways
  - Maybe a more massive iron core forms before it cools to the point that degeneracy pressure kicks in…
  - … or initial core collapse of 1.4M core is followed by more infall from stellar envelope?



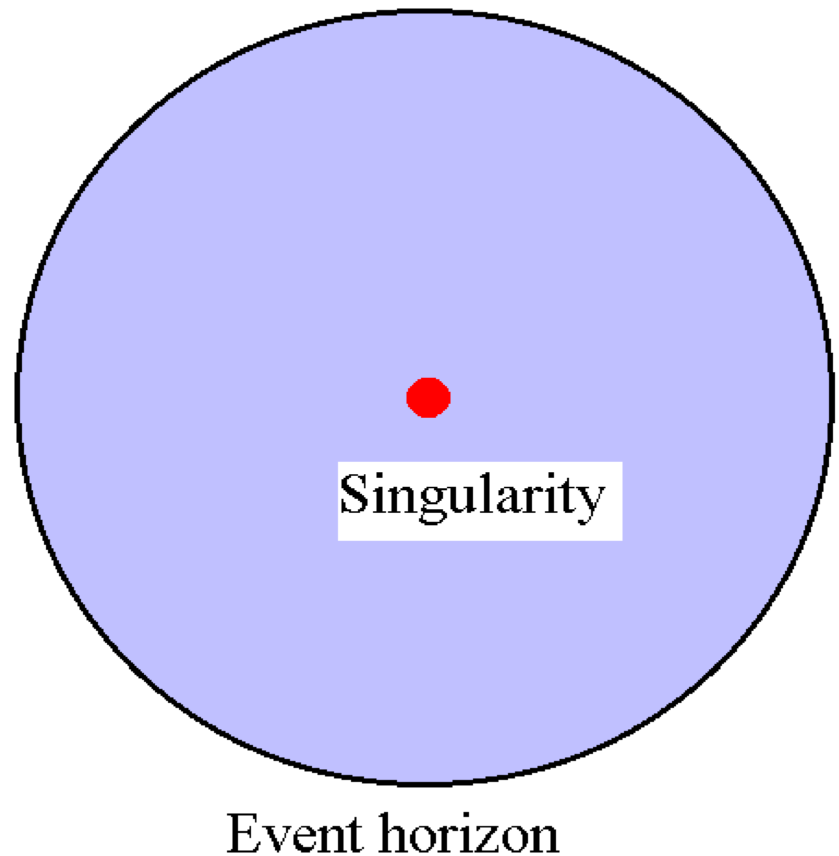
- What then occurs if the gravitational attraction exceeds the degeneracy pressure?
- We know of no physics that can prevent a <u>total</u> gravitational collapse of the core

Basic anatomy of a black hole

- Complete gravitational collapse inevitably leads to a black hole (Hawking)
- Space-time singularity
  - Where the mass-energy resides
  - *Place where GR breaks down and laws of quantum gravity must be applied*
- Event horizon
  - Point of no return for light or matter
  - Events inside horizon can have no causal effect on universe outside of the horizon
  - Analogous to the point of no return in a waterfall

*black holes have no hair

3 parameters <u>mass, angular momentum, and electric charge</u> completely characterize black holes
Everything else (quadrupole terms, magnetic moments,
weak forces, etc.) decays away*.

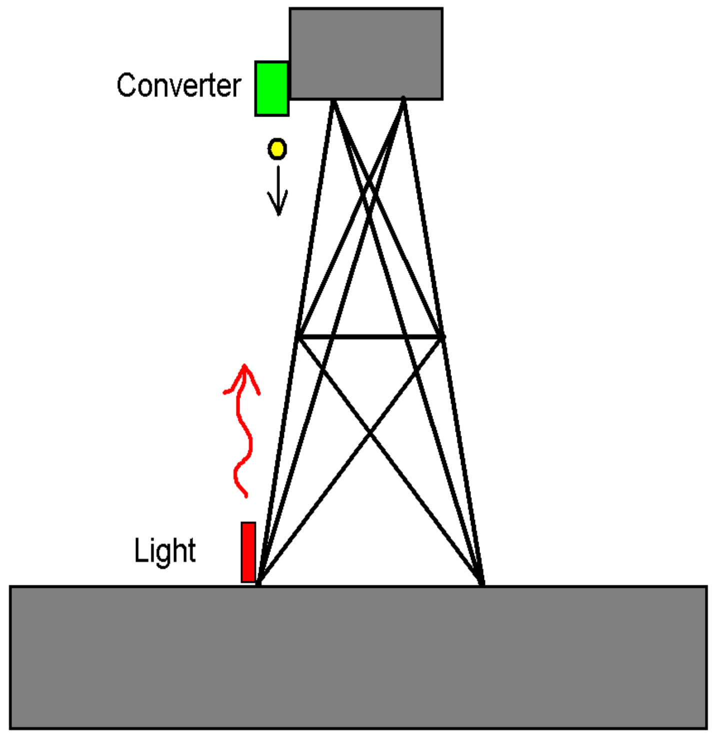


Schwarzschild Radius-AKA the Event Horizon for a Non-Spinning Black Holes

- $R_s = 2GM/c^2$
- The Schwarzschild radius is the radius of 'no return' for a non-rotating black hole- it is not the singularity.
- Events inside that horizon cannot be seen by any external observer
- inside the event horizon the radius becomes a timelike coordinate, and the time becomes a spacelike coordinate. Specifically, that means that once inside R_s, you must go to smaller radii, just as now you must go forward in time
- once you're inside the event horizon one cannot avoid the singularity at $r = 0$

Gravitational redshift

- Thought experiment:
  - Send photon upwards in a gravitational field
  - Convert that energy into mass and drop the mass
  - Convert mass back into photon
- Conservation of energy ⇒ photon must lose energy as it climbs in the gravitational field
- Another way of thinking about this - the escape speed from the object has to be less than the speed of light (assuming, incorrectly, that light could slow down and fall).
- In Newton mechnanics the escape speed is $v^2 = 2GM/r$, so $v^2 = c^2$ at $r = 2GM/c^2$
- Redshift of light $Z=(\lambda_0-\lambda_{e)}/\lambda_e$; λ_0 = wavelength as measured by the observer, λ_e as emitted



Gravitational redshifts near a black hole

- Gravitational redshift is really a form of relativistic time dilation
- As observed from infinity, time near a (non-spinning, non-charged) black hole runs slow by a factor of

$$\frac{\Delta t'}{\Delta t} = \frac{1}{\sqrt{1 - 2GM/c^2}}$$

- The event horizon is the “infinite redshift” surface where (as observed from infinity) time appears to stop!
- But… a free falling observing would fall through the event horizon without noticing anything unusual.
- The wavelength of light is redshifted ($Z=(\lambda_0-\lambda_{e)}/\lambda_e$; λ_0 = wavelength as measured by the observer, λ_e as emitted) by
- z=(1/sqrt(1-R_s/r)) -1

$$z = \frac{1}{\sqrt{1 - \left(\frac{2GM}{rc^2}\right)}} - 1$$

Question for class- what is the redshift from the surface of a NS?

- $M \sim M_{sun}$; R=10km (set by nuclear physics)

So what is the actual size ?

$R_G \sim 1.5\ (M / M_\odot)$ km

So how close are neutron stars to being black holes ?

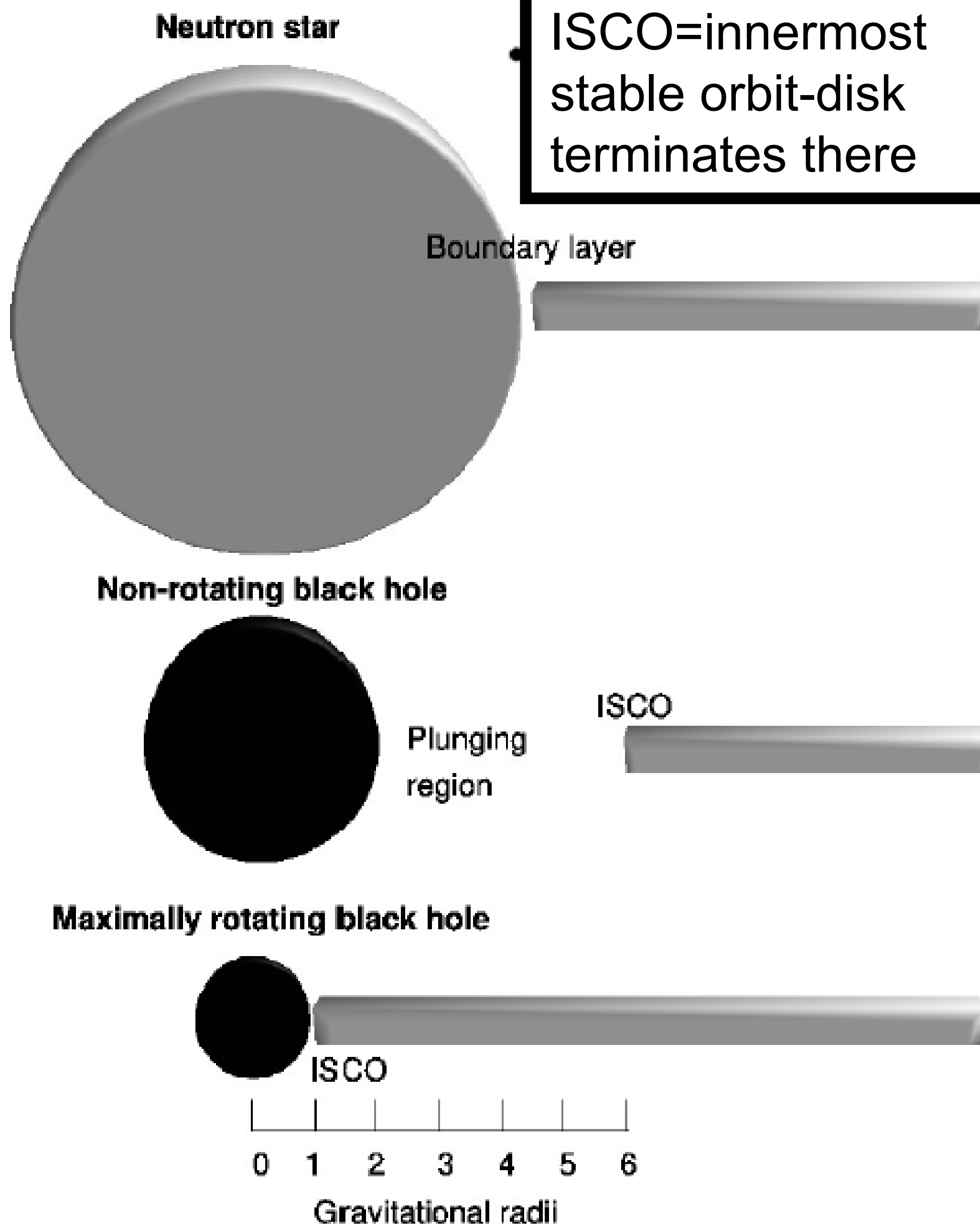
Neutron stars are only about a factor 2—3 larger than their event horizons

What about spin ?

A non-rotating ("Schwarzschild") black hole has its event horizon at 2 R_G and its ISCO at 6 R_G

A maximally rotating ("Maximal Kerr") black hole has both its event horizon and ISCO at R_G

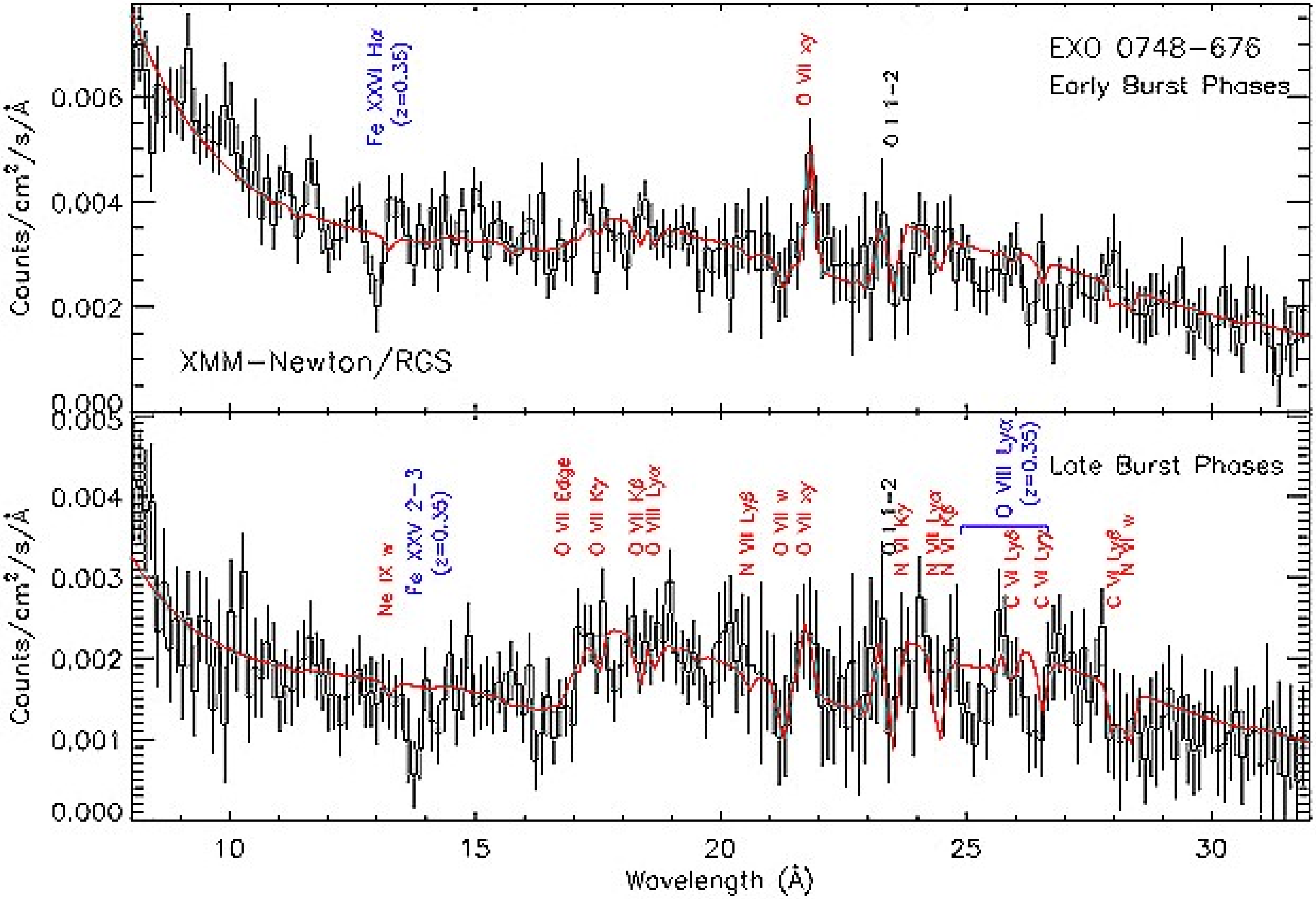
→ Spinning black holes are more compact → potentially more radiatively efficient



ISCO=innermost stable orbit-disk terminates there

R. Fender 2007

Emission of line radiation from highly ionized atoms of Fe And O from near the surface of a NS



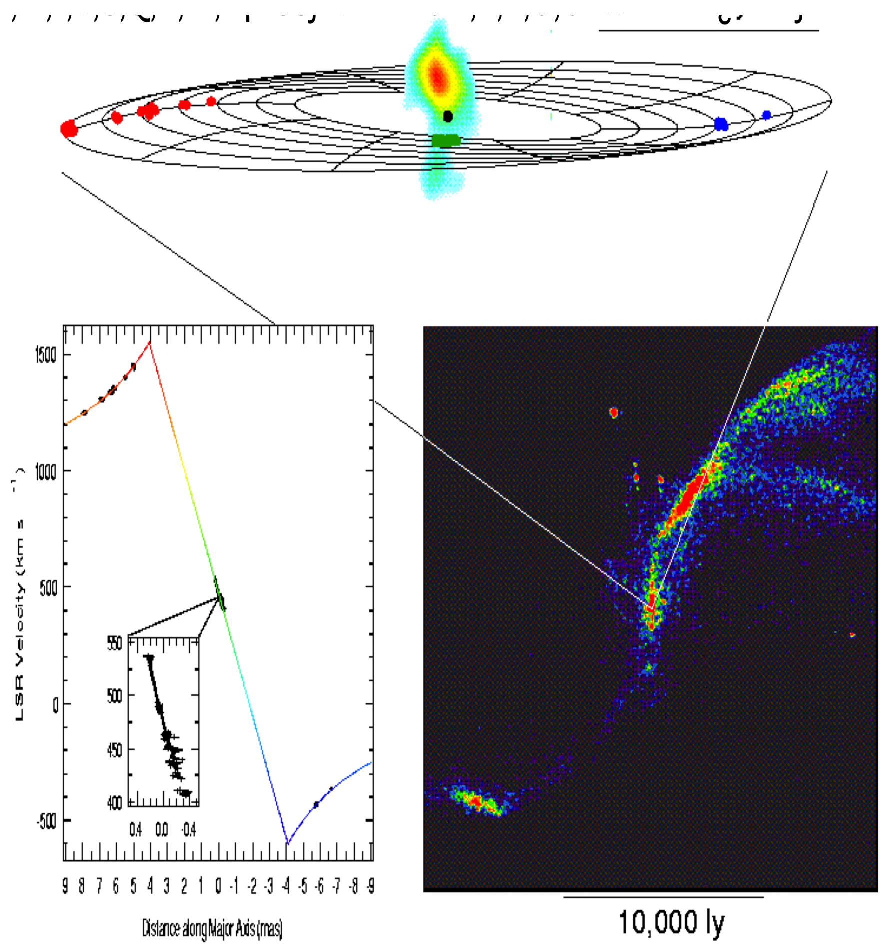
Redshifted absorption lines from a neutron star surface

Cottam, Paerels & Mendez (2002)

Examples of Astrophysical Black Holes

- We know that black holes come in 2 size scales
  - 5-20 M_{sun} ; the result of stellar evolution
  - 10^6-10^9 M_{sun} super massive black holes that reside in the centers of most massive galaxies
  - They may also come in another size scale; intermediate mass black holes with $50<M_{sun}<10^3$

- Detailed stellar evolution calculations indicate that for a star with roughly solar metallicity the maximum mass of the remnant black hole is ~20 M_{sun}



Miyoshi et al

Black Hole Metric

- The Schwarzschild solution for the metric around a point mass is
- $ds^2=-(1-2GM/c^2r)c^2dt^2 +(1-2GM/c^2r)^{-1}dr^2+r^2(d\theta^2+\sin2d\phi\theta^2)$

- Notice singularity at $r=2GM/c^2$ (can be gotten rid of in a coordinate transformation)

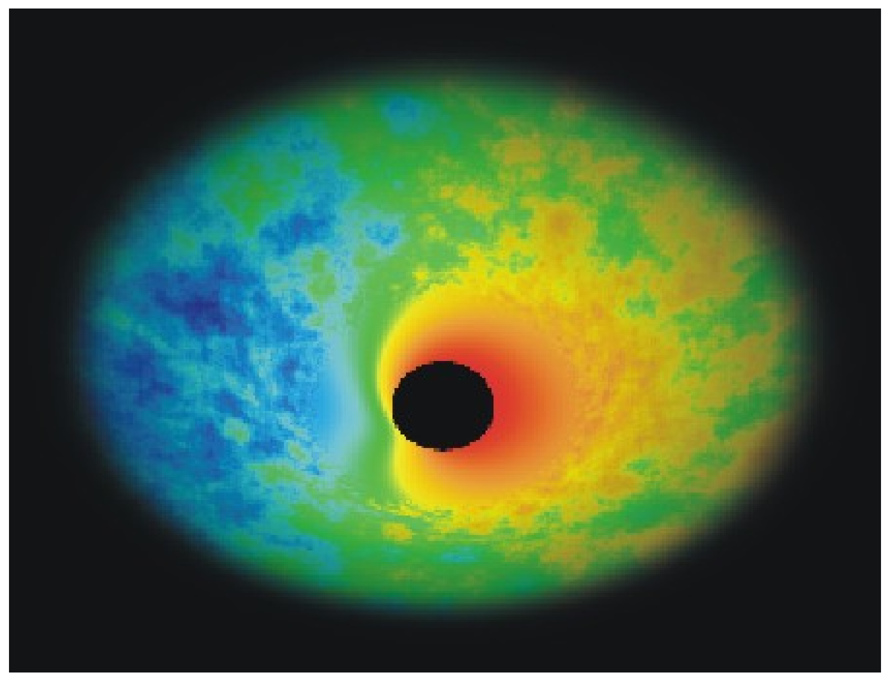
- A static observer measures proper time $c^2d\tau^2=-ds^2=-(1-2GM/c^2r)c^2dt^2$

- $d\tau/dt=\mathrm{sqrt}(1-2GM/c^2r))=1+z_{grav}$

- A spinning black hole is described

by the Kerr metric

$$R_{Sch} = \frac{2GM}{c^2} \approx 3 \left(\frac{M}{M_\odot}\right) \text{ km}$$



More features of Schwarzschild black hole

- Events inside the event horizon are causally-disconnected from events outside of the event horizon (i.e. no information can be sent from inside to outside the horizon)
- Observer who enters event horizon would only "feel" "strange" gravitational effects if the black hole mass is small, so that R_s is comparable to observer's size
- Once inside the event horizon, future light cone always points toward singularity (any motion must be inward)
- Stable, circular orbits are not possible inside $3R_s$: inside this radius, orbit must either be inward or outward but not steady
- Light ray passing BH tangentially at distance $1.5R_s$ would be bent around into a circle
- Thus black hole would produce "shadow" on sky

Evidence for black holes

- Galactic black hole candidates (dynamical measurements- last class using velocity of companion and period)

For Supermassive Black Holes

Dynamics of 'Test particles'

Orbits of gas disks around mass compact objects at the centers of other galaxies- best case is NGC4258 (water maser orbits)

Stellar orbits around a compact mass at the center of our own Galaxy (most solid case for any black hole)

Of course what these data give is the mass inside a given radius. If the mass density is higher than (?) it must be a black hole

- Emission from the region of 'strong gravity'

Extreme gravitational redshifting of emission lines in the X-ray spectrum of some accreting black holes

Rotating black holes- remember the extra special nature of accelerated frames

- Roy Kerr (1963)
  - Discovered solution to Einstein's equations corresponding to a *rotating* black hole
  - Kerr solution describes all black holes found in nature
- Features of the Kerr solution
  - Black Hole completely characterized by its mass and spin rate (no other features [except charge]; **no-hair theorem**)
  - Has space-time **singularity** and **event horizon** (like Schwarzschild solution)
  - Also has "**static surface**" inside of which nothing can remain motionless with respect to distant fixed coordinates
  - Space-time near rotating black hole is dragged around in the direction of rotation: "**frame dragging**".
  - **Ergosphere** – region where space-time dragging is so intense that its impossible to resist rotation of black hole.

Spinning BH- Longair sec 13.11.2

- A black hole with angular momentum ***J*** has a metric

$ds^2=(1-2GMr/\rho c^2)dr^2-\{(1/c^2)[4GMra \sin^2\theta/\rho c]\, dr d\phi\}+(\rho/\Delta)dr^2+$

$\rho d\theta^2+(r^2+a^2+2GMra^2\sin^2\theta/\rho c^2)\sin^2\theta\, d\phi^2]$-- Longair eq 13.63

r,θ,ϕ– usual polar coordinates

where $a=(J/Mc)$ is the angular momentum per unit mass (dimensions of distance) and

$\Delta=r^2-(2GMr/c^2)+a^2$; $\rho=r^2+a^2\cos^2\theta$

Just like Schwarschild metric it becomes singular but at a radius where

$\Delta=r^2-(2GMr/c^2)+a^2=0$; the larger root is

$r_+=GM/c^2+[(GM/c^2)^2-(J/Mc)^2]^{1/2}$

for J>0 this is smaller than the Schwarschild radius

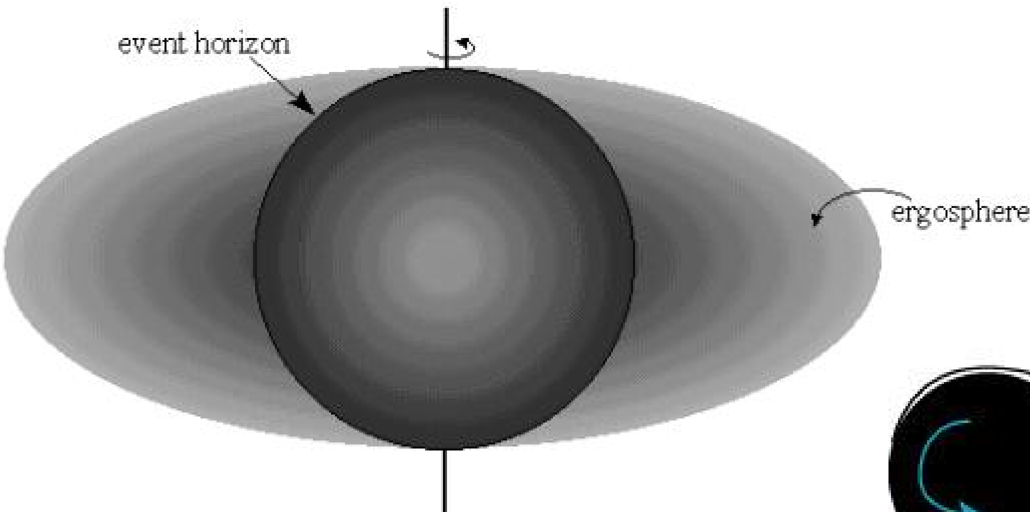
there is a maximum angular momentum ***$J=GM^2/c$; for this value of J the horizon is at $r_+=GM/c$; 1/2 of the Schwarzschild radius***

Schwarzschild and Kerr Metric

- for a Schwarzschild BH the innermost stable radius is $3r_G$=6GM/c^2 - there are no stable circular orbits at smaller radii
  - the binding energy from this orbit is 0.0572 of the rest mass energy
- For a Kerr the innermost stable radius is at r_+=GM/c^2 The spinning black hole drags the the inertial frame-
- The smaller critical radius allows more energy to be released by infalling matter
  - For a Kerr BH 0.423 of the energy can be released.

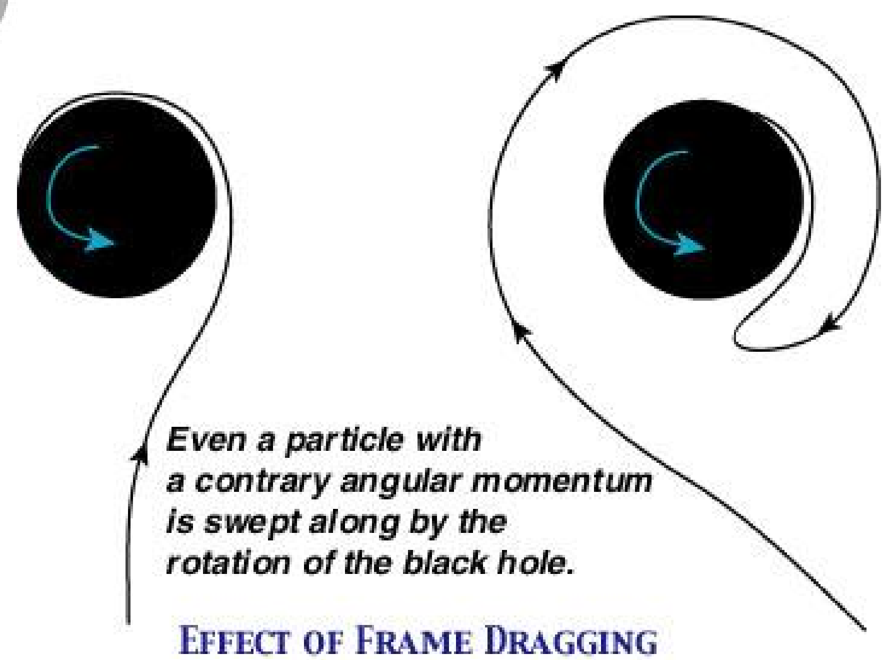
- There is another 'fiducial' radius in the Kerr solution, that radius within which all light cones point in the directon of rotation, the 'static' radius, r_{static}.
- Between r_{static} and r_+ is a region called the 'ergosphere' within which particles must rotate with the black hole and from energy might be extracted (Penrose process).

Frame dragging by rotating black hole



tested in 2004

http://www.universetoday.com/9984/frame-dragging-confirmed/



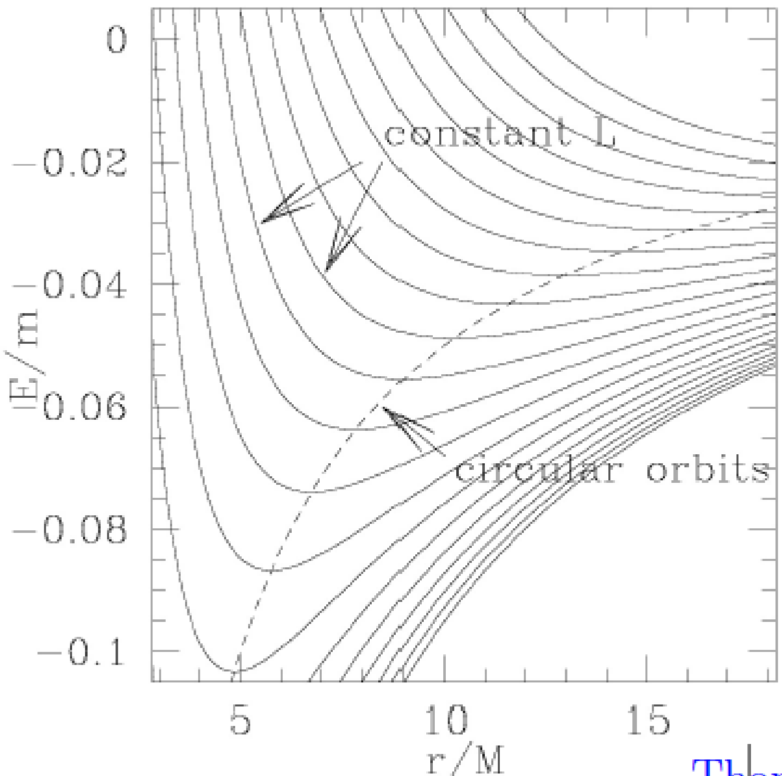
Graphics: University of Winnipeg, Physics Dept.

The innermost stable circular orbit (ISCO)

circular orbit extremizes binding energy E of test mass m at const. angular momentum L

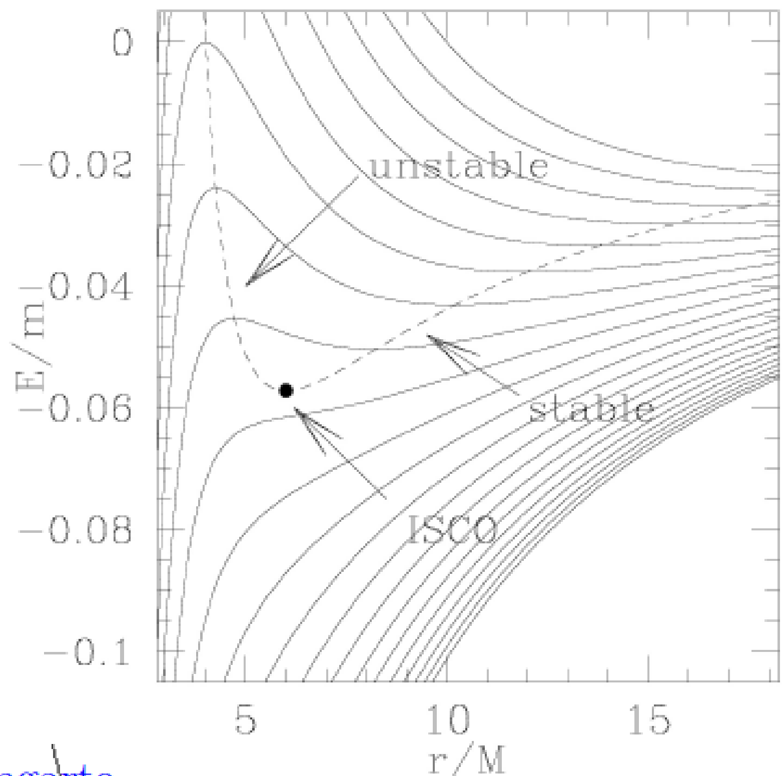
Newtonian point mass

$$\frac{E}{m} = -\frac{M}{r} + \frac{L^2}{2r^2}$$



Schwarzschild black hole

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

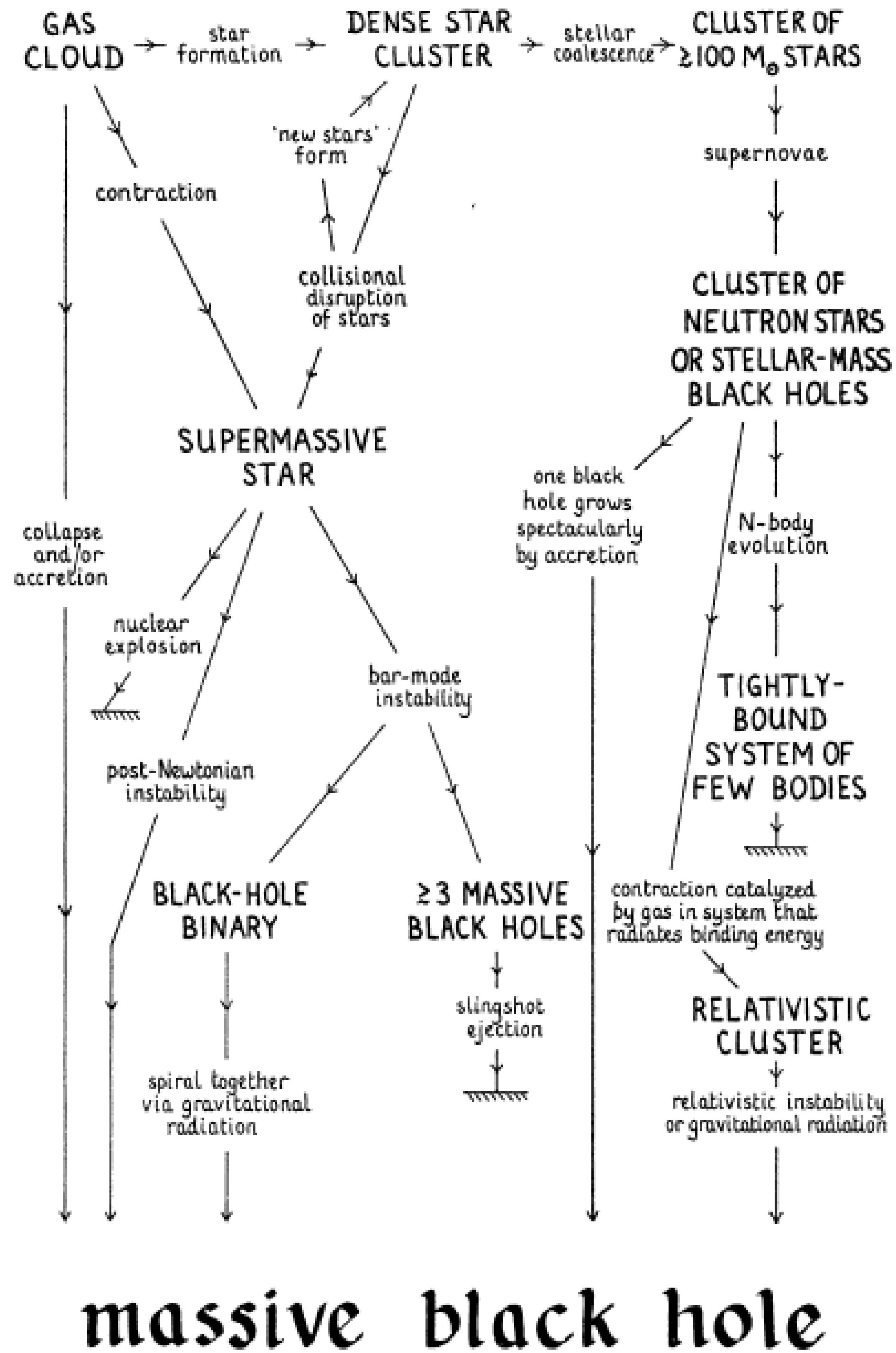


Thomas Baumgarte

Bowdoin College

Formation of SuperMassive Black Holes

In a dense region all roads lead to a black Hole (Rees 1984 ARAA)



Some Scales (Rees 1984)

A central mass M has a gravitational radius

$$r_g = \frac{GM}{c^2} = 1.5 \times 10^{13}\, M_8 \text{ cm}, \qquad 1.$$

where M_8 is the mass in units of $10^8\, M_\odot$. The characteristic minimum time scale for variability is

$$r_g/c \simeq 500\, M_8 \text{ s}. \qquad 2.$$

A characteristic luminosity is the "Eddington limit," at which radiation pressure on free electrons balances gravity:

$$L_E = \frac{4\pi G M m_p c}{\sigma_T} \simeq 1.3 \times 10^{46}\, M_8 \text{ erg s}^{-1}. \qquad 3.$$

Related to this is another time scale

$$t_E = \frac{\sigma_T c}{4\pi G m_p} \simeq 4 \times 10^8 \text{ yr}. \qquad 4.$$

The time scale to grow a black hole if it were accreting at the Eddington luminosity

The characteristic black body temperature if the Eddington luminosity is emitted at r_g

$$T_E \simeq 5 \times 10^5\, M_8^{-1/4}.$$

More massive BHs are cooler

What can come **out** of black hole?

- Magnetic fields threading ergosphere can attach to and drag surrounding matter, reducing the black hole's spin and energy
- "Hawking Radiation": black hole slowly evaporates due to quantum mechanics effects
  - Particle/antiparticle pair is created near BH
  - One particle falls into horizon; the other escapes
  - *Energy to create particles comes from gravity outside horizon*

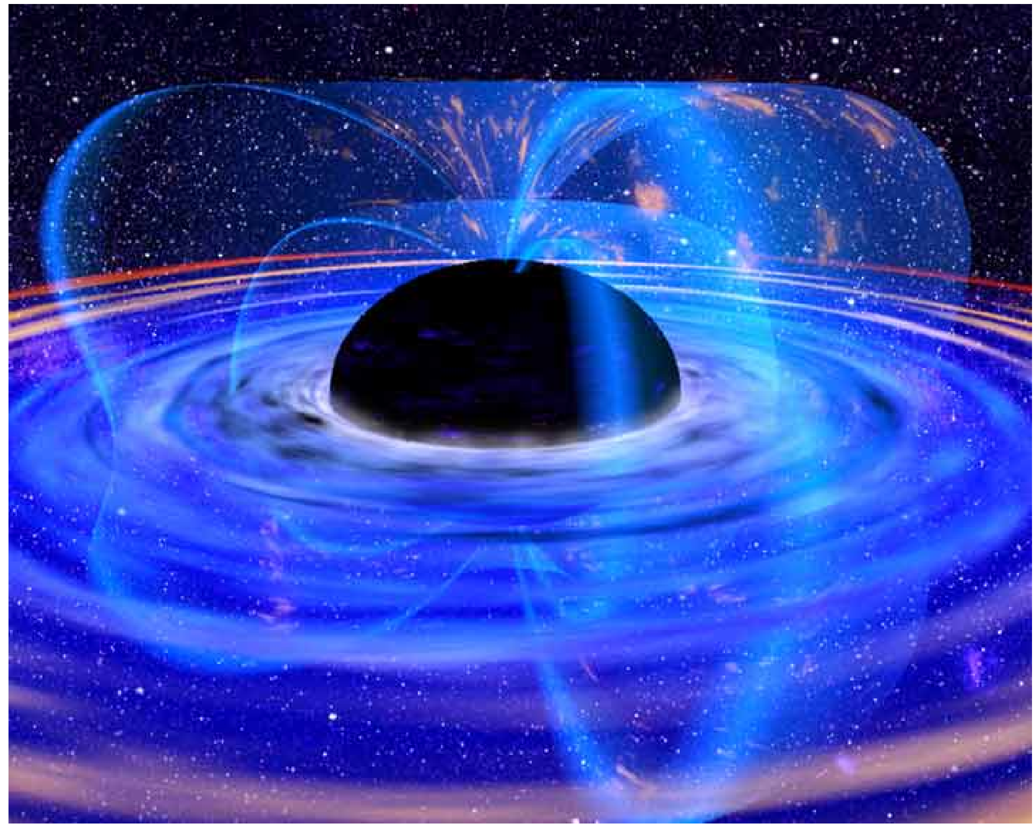
$$t_{evap} = 10^{10}\,yrs \times \left(\frac{M}{10^{12}\,kg} \right)^3$$

  - Solar-mass black hole would take 10^{65} years to evaporate!
  - Mini-black holes that could evaporate are not known to exist now, but possibly existed in early Universe

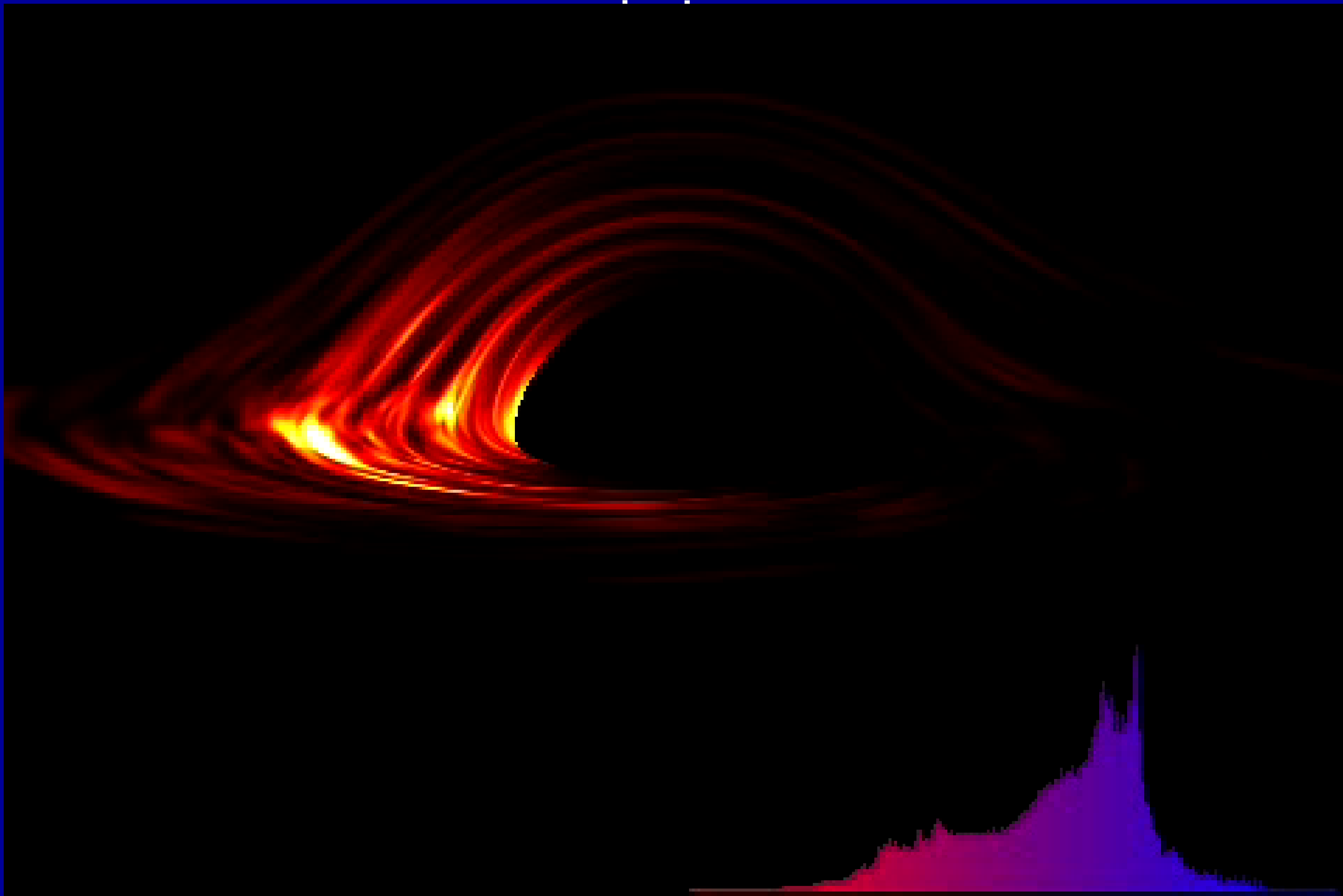
Active galaxies (e.g. radiating supermassive black holes) emit radio, IR, optical, UV, x-ray and γ-ray radiation !

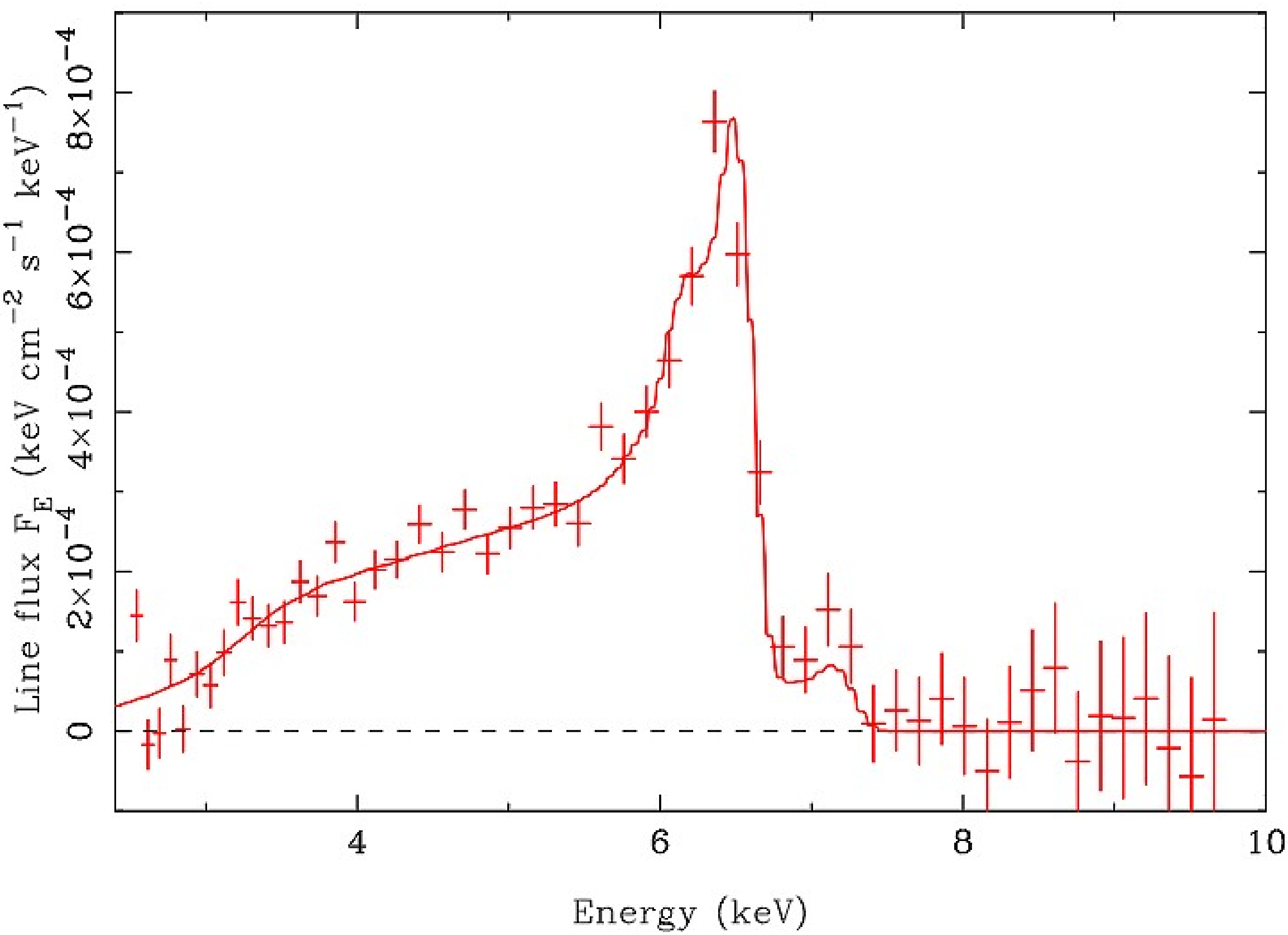
Broad band spectrum very different than stars

In the x-ray band there is a signature of the physics very close to the event horizon- Fe K emission from innermost part of disk



Numerical Simulation of Gas Accreting Onto a Black Hole





Broad iron line in MCG-6-30-15 (Fabian et al. 2002)