This is a vast field - here are some references for further reading

- Dippers: Smale et al. 1988 MNRAS 232 647
- Black hole transient lmxbs: Remillard and McClintock, 2006 ARAA 44, 49
- Color-color diagrams for atoll/Z sources : Hasinger and VanderKlis 1989
- Microquasar GRS 1915+105: Mirabel and Rodriguez 1995 PNAS 92 11390
- ADC sources: White and Holt 1982 Ap. J. 257 318
- Iron line from Cyg X-1: Miller et al. 2003 Ap. J. 578, 348
- Cyg X-3 Chandra HETG: Paerels et al. 2000 Ap. J. 533, 135
- Accretion disk corona modeling: Jimenez-Garate et al. 2002 Ap. J. 558, 458
- 4U1822-37 spectrum :Cottam et al., 2001 Ap. J. 557, 101
- ‘Accretion power in Astrophysics’ Frank, King and Raine
- Catalog of X-ray Binaries, Liu Van Paradijs and Lewin 2007 A&A 469, 807
- GRO J1655 chandra spectrum: Miller et al., 2006 Nature 441, 953
- Hydrodynamics of HMXB winds: Blonding 1994 Ap. J.

Maximum Mass of a Compact object (Kalogera and Baym 1996)

- The set of fundamental constraints, independent of the detailed physical properties of neutron matter, imposed on the equation of state of the inner core are
- (i) the mass density, ρ, is non-negative, i.e., gravity is attractive;
- (ii) the pressure,P, at zero temperature is a function of ρ only, i.e., neutron matter is a fluid
- (iii) $dP/d\rho \geq 0$, -sound speed of neutron matter $(dP/d\rho)^{1/2}$ is real and matter is stable against collapse;
- (iv) the sound speed does not exceed the speed of light, i.e., $dP/d\rho \leq c^2$, hence signals cannot be superluminal and causality is satisfied.

Under these conditions mass of NS
Is maximum for 'stiffest' equation of state
-the sound speed is the speed of light
$c^2_s = dP/d\rho = c^2$.

A huge amount of messy nuclear physics define the equation of state and it is not well understood.

Using the equation of hydrostatic equilibrium in general relativity

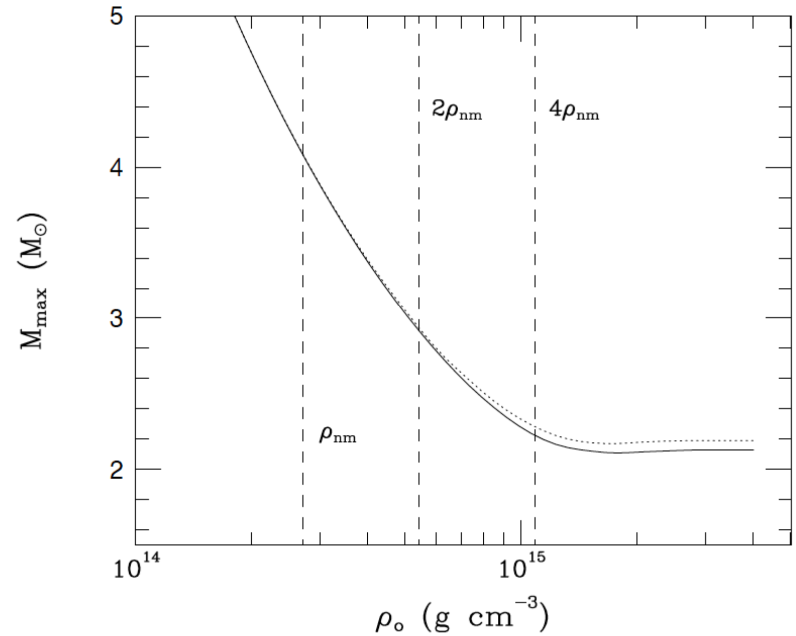
$$\frac{dP}{dr} = -\frac{G}{r^2}\left[\rho(r) + \frac{P(r)}{c^2}\right]\left[m(r) + 4\pi r^3\frac{P(r)}{c^2}\right]\left[1 - 2G\frac{m(r)}{rc^2}\right]^{-1},$$

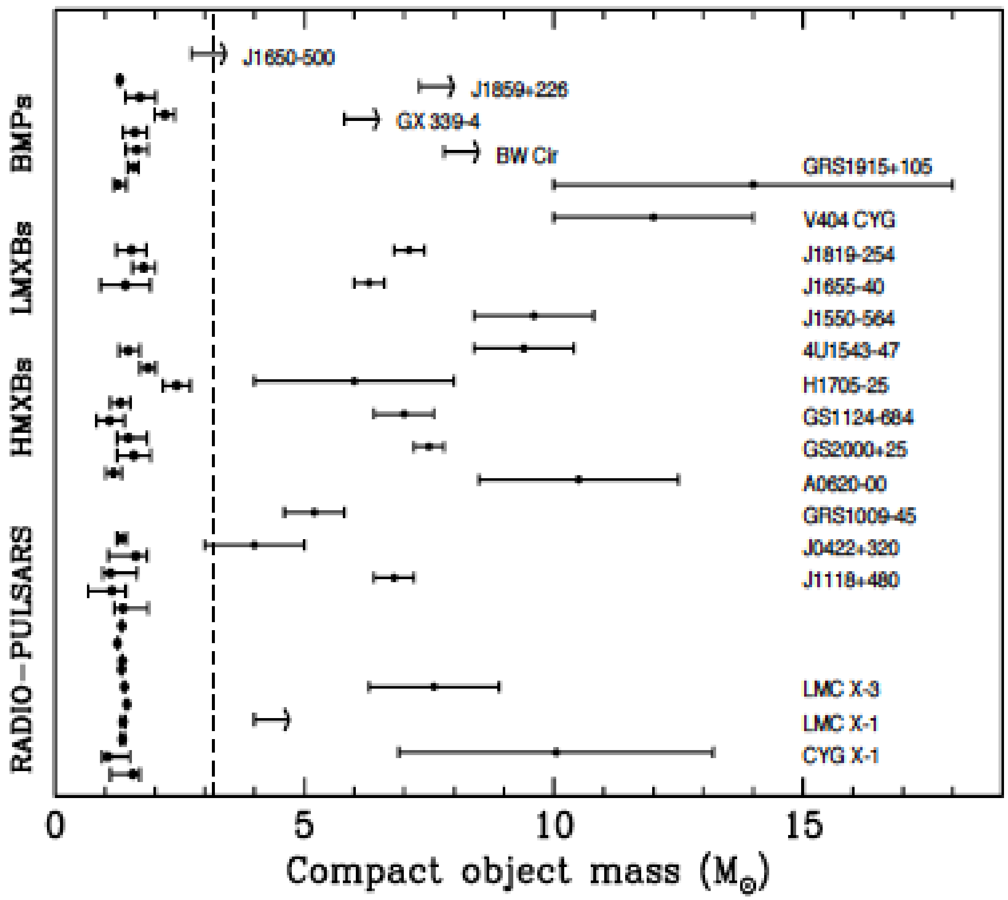
$$M_{max} = 6.7\, M_\odot \left(\frac{\rho_0}{10^{14}\mathrm{g\,cm^3}}\right)^{-1/2}.$$

Maximum Mass (Cont)

- None of the objects thought to be NS have a mass >$2.4M_{sun}$ but objects exist in the Milkyway way with a mass up to $19M_{sun}$

nuclear matter density $\rho_{nm} = 2.7 \times 10^{14}\,\mathrm{g\,cm^{-3}}$.

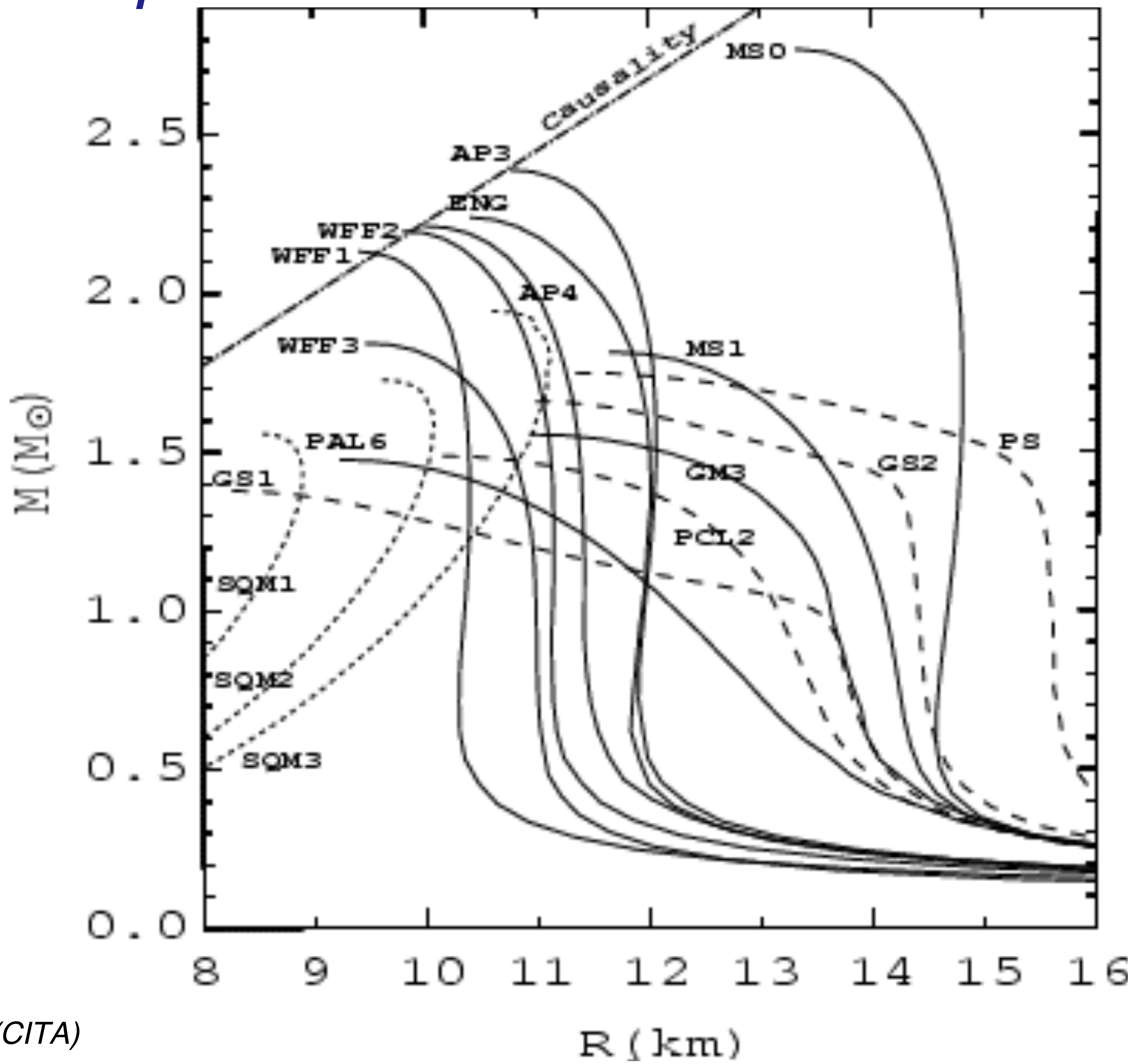




Possible Equations of State of a NS

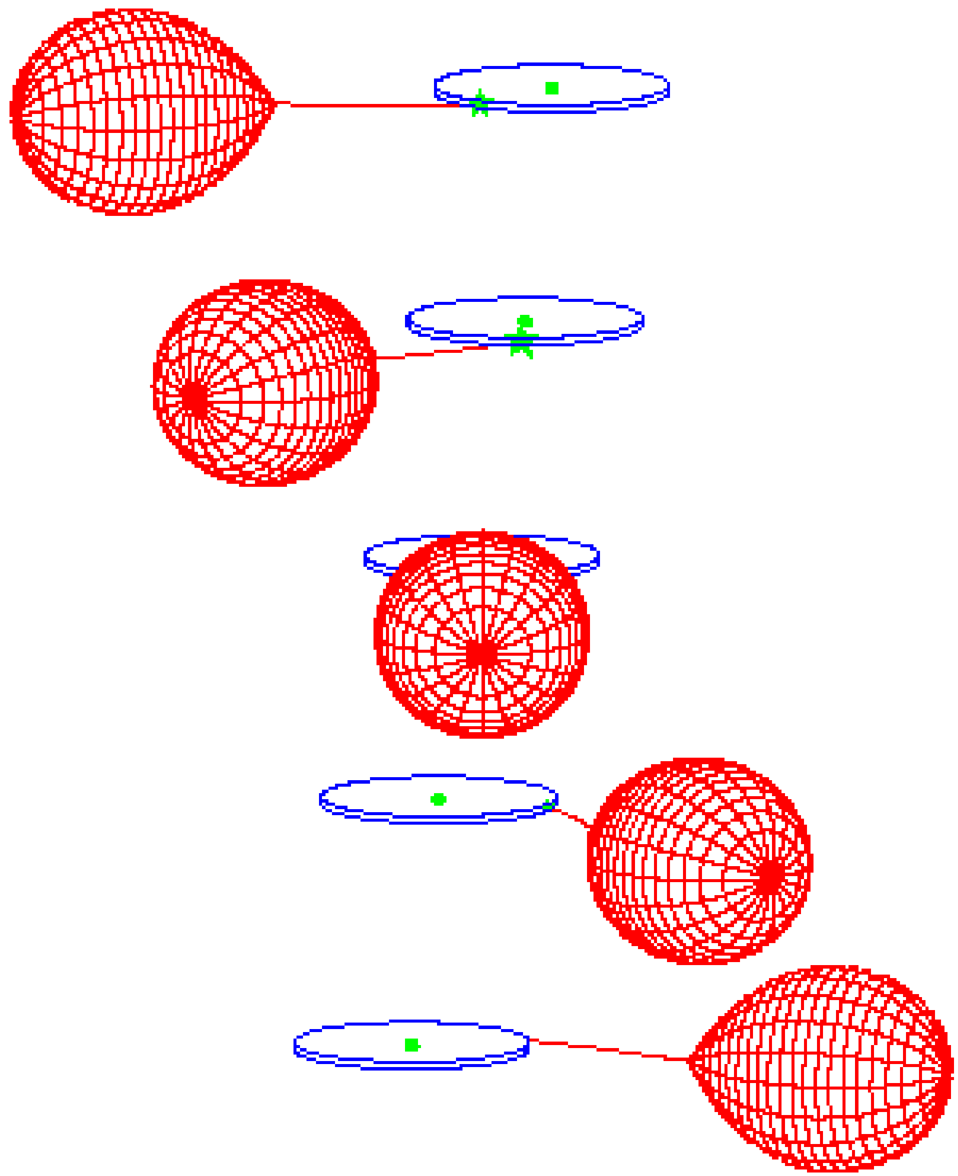
Each line represents a different possible equation of state- the relationship between Pressure and density

Maximum mass is ~3 M_{sun}



From website of Kaya Mori (CITA)

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 strong GR effects**.

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'

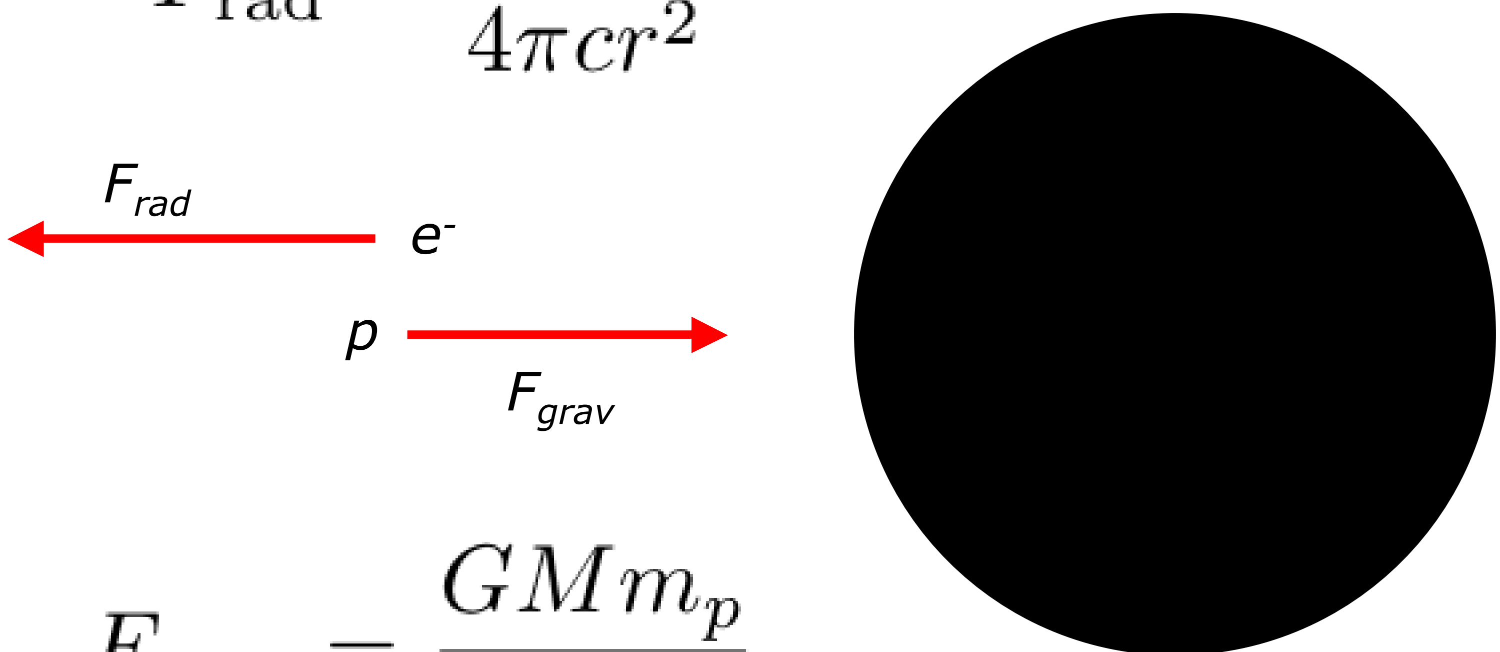
What are the possible energy sources?

- 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!

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:

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

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

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

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

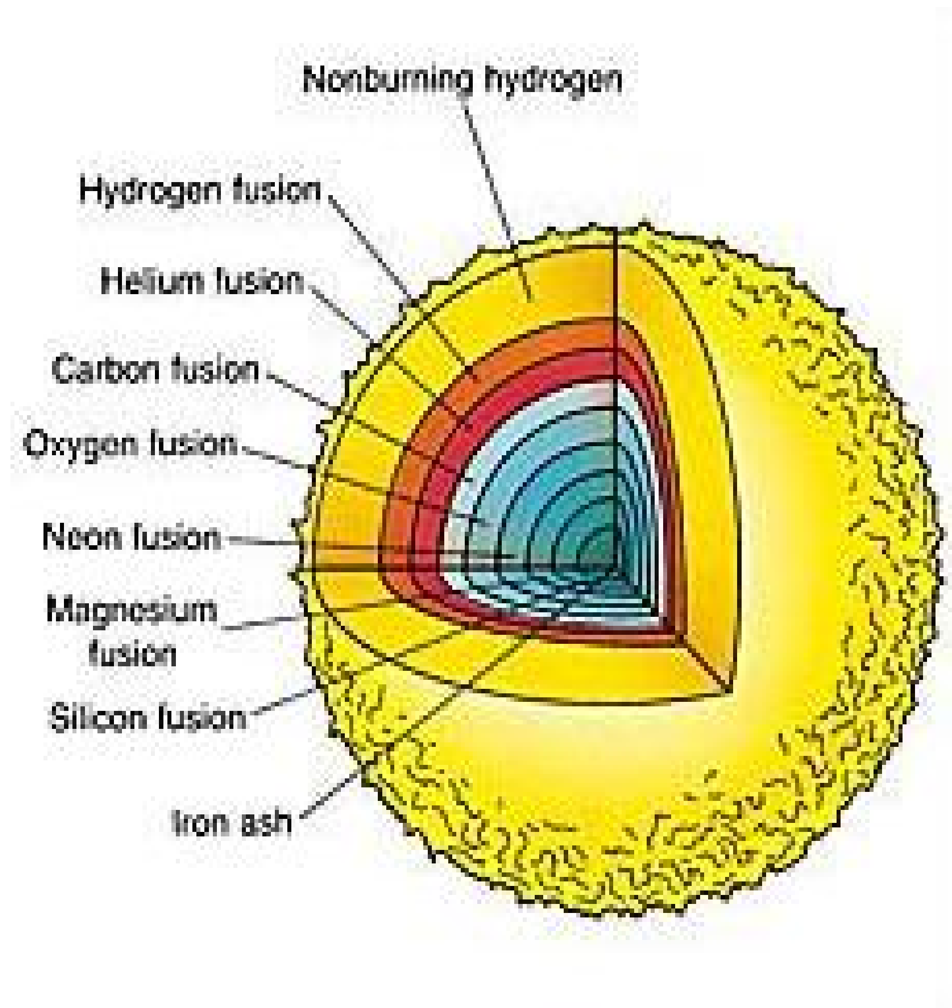
Downwards to Black Holes!

- 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?



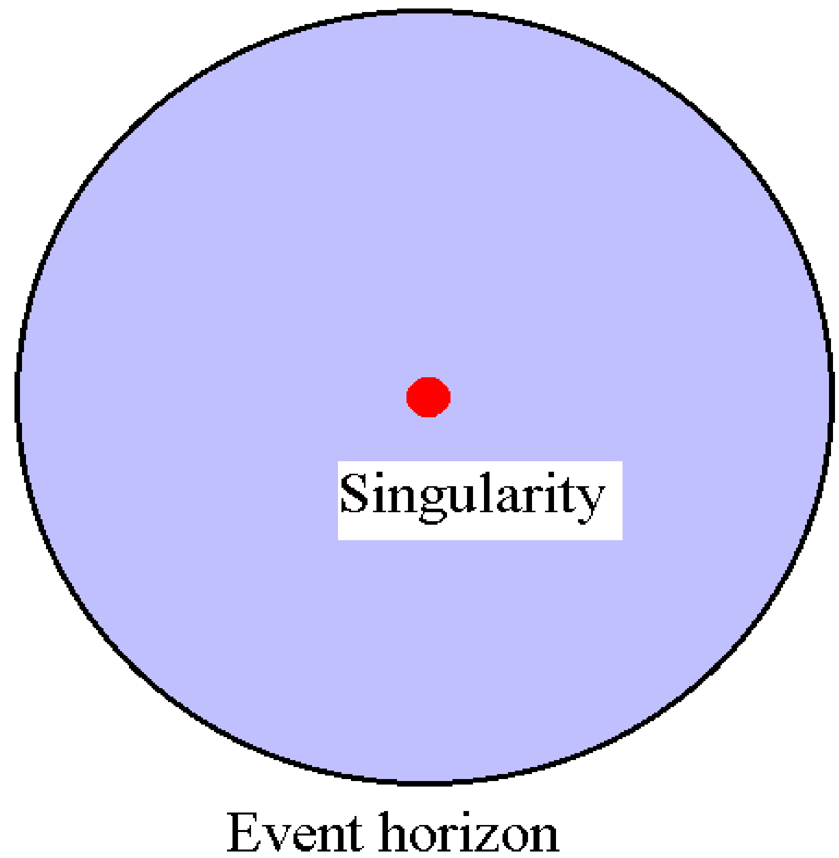
- What then when the gravitational attraction exceeds the degeneracy pressure?
- We know of no physics that can prevent a total gravitational collapse of the core

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

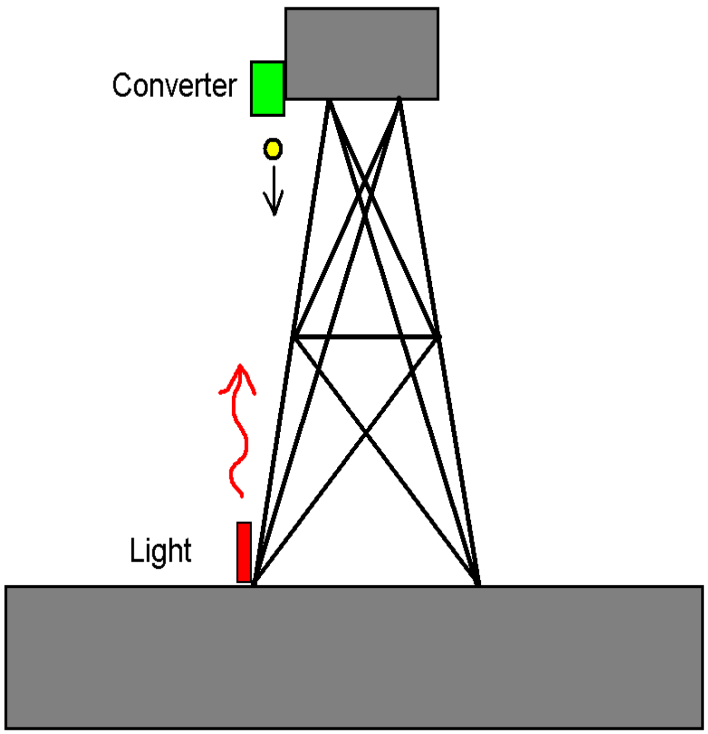
- $R_s = 2GM/c^2$

- 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, incorrectluy, 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

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

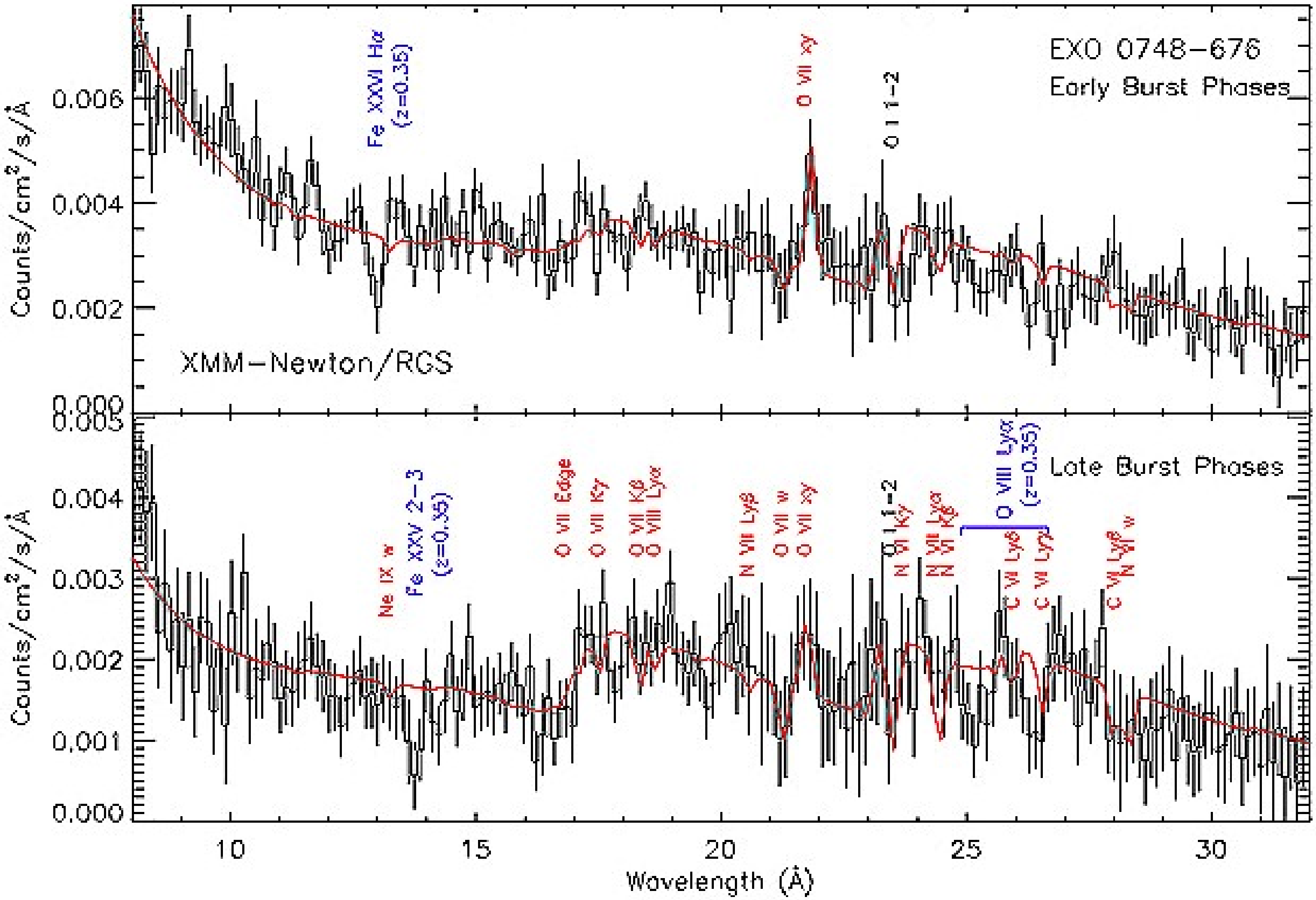
- The event horizon is the "infinite redshift" surface where (as observed from infinity) time appears to stop!
- But… a free falling observing would fall through the event horizon without noticing anything unusual.
- The wavelength of light is redshifted ($Z=(\lambda_0-\lambda_{e)}/\lambda_e$; λ_0 = 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 ~M_{sun} ; R=10km (set by nuclear physics)

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



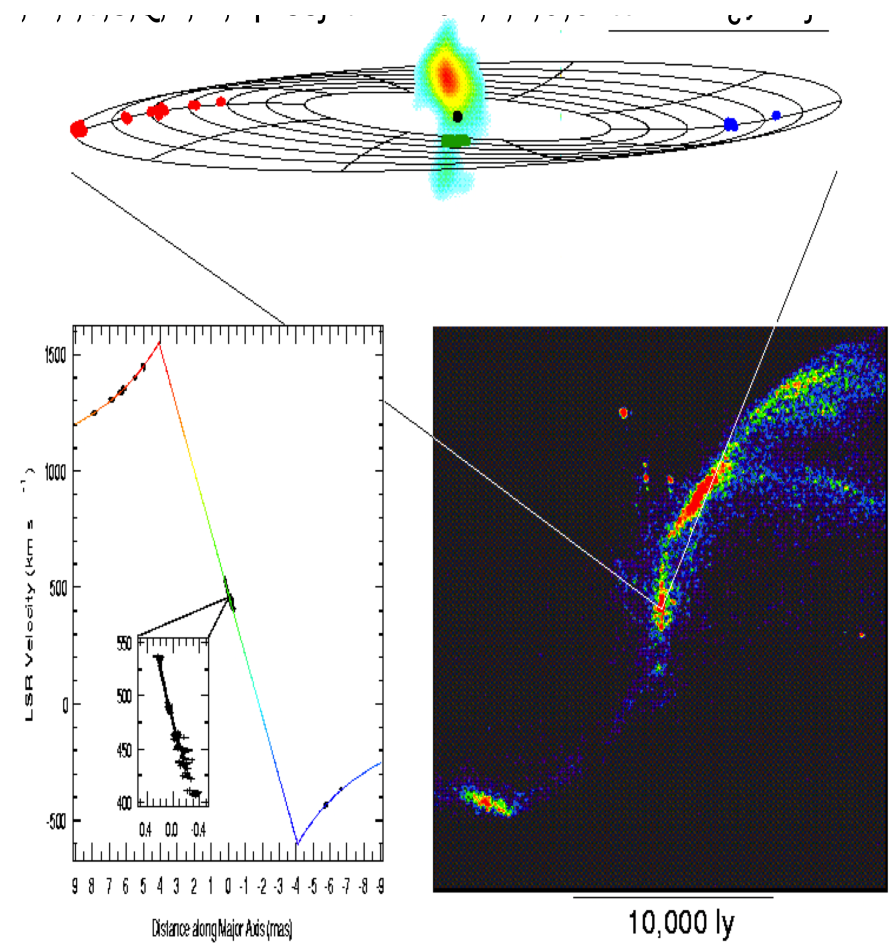
Redshifted absorption lines from a neutron star surface

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

Evidence for black holes

- Galactic black hole candidates (just discussed)

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)

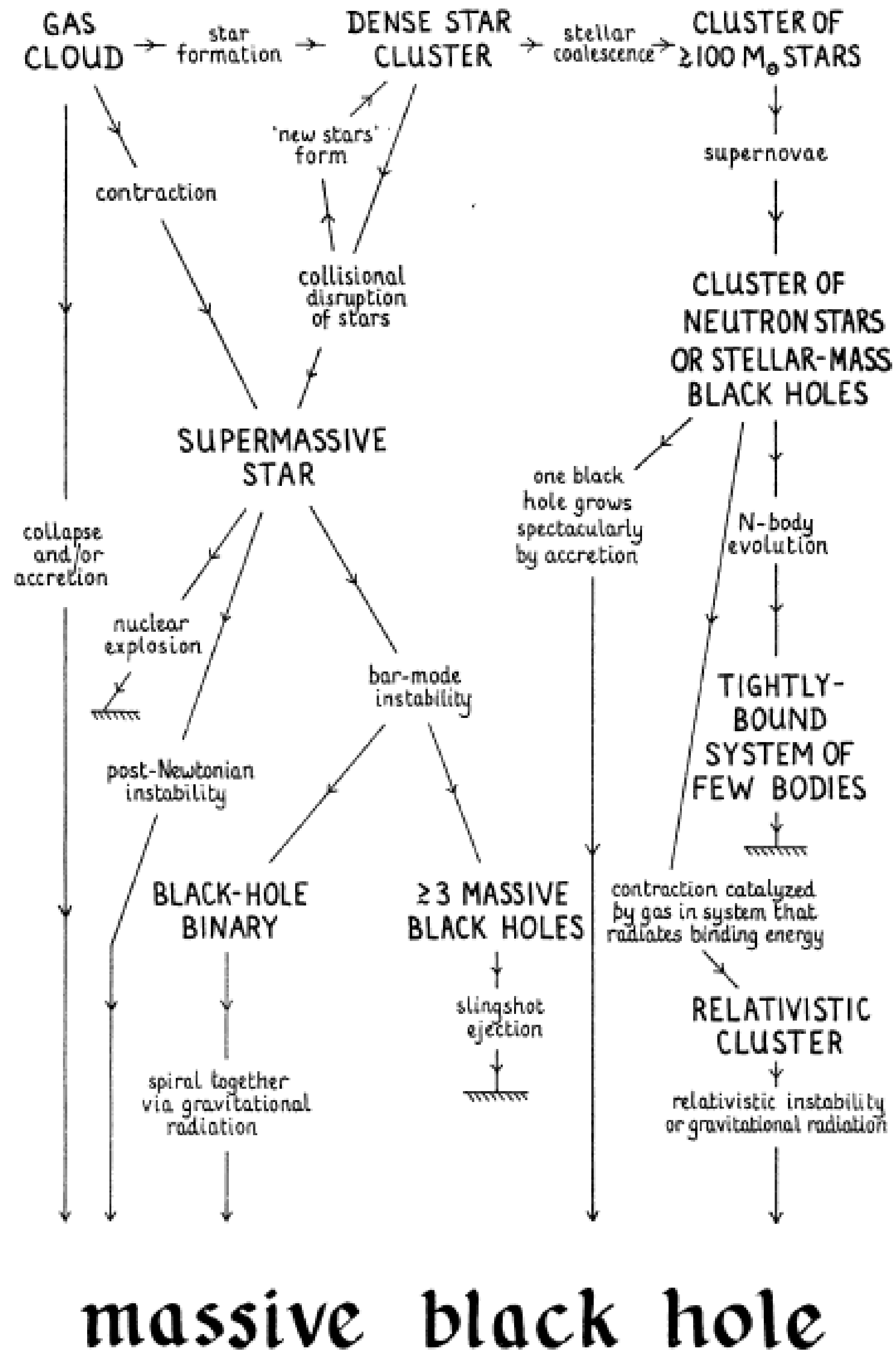
Stellar orbits around a compact mass at the center of our own Galaxy (most solid case for any black hole)

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

In a dense region all roads lead to a black Hole (Ress 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:

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

Related to this is another time scale

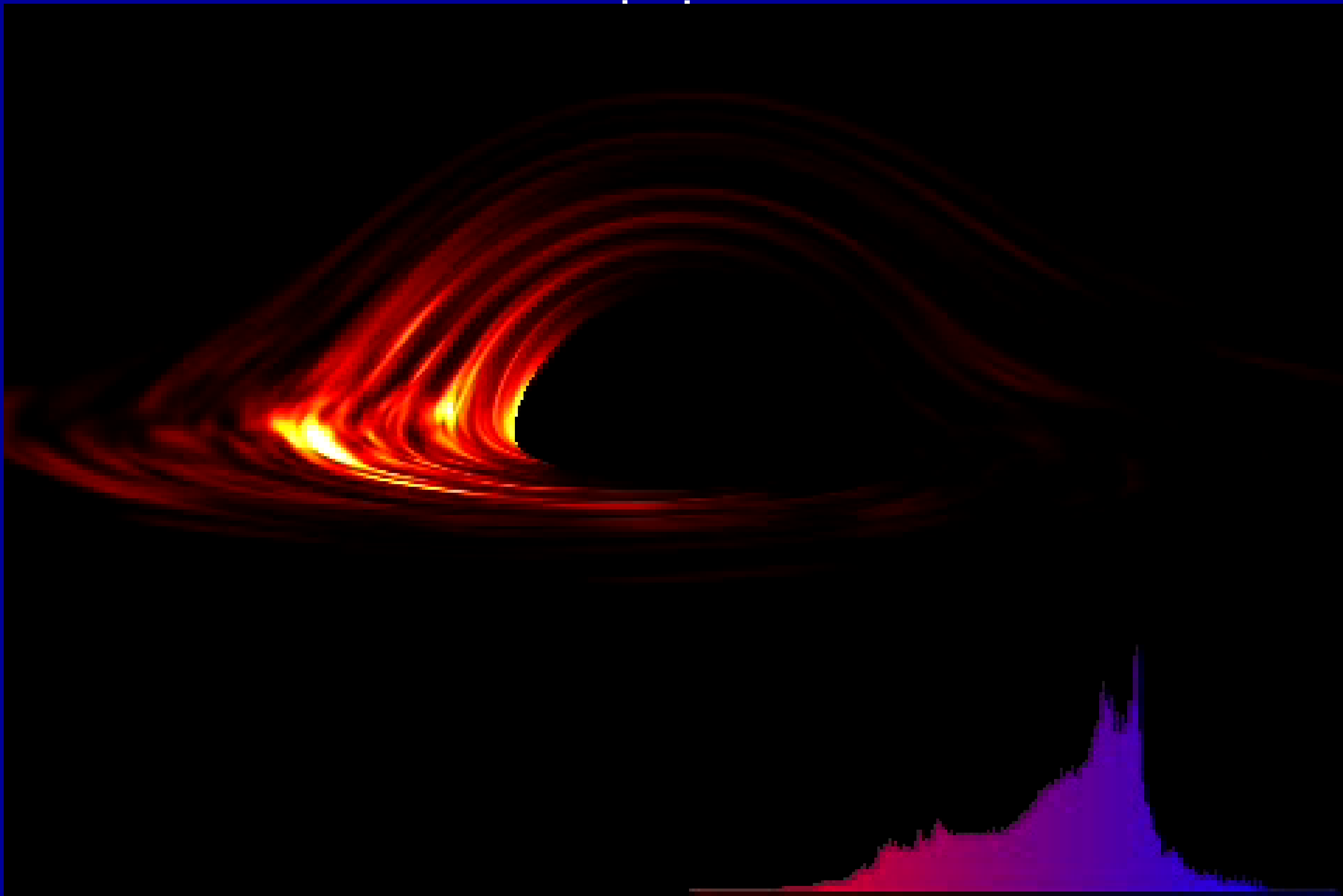
$$t_E = \frac{\sigma_T c}{4\pi G m_p} \simeq 4 \times 10^8\ \text{yr}. \qquad 4.$$

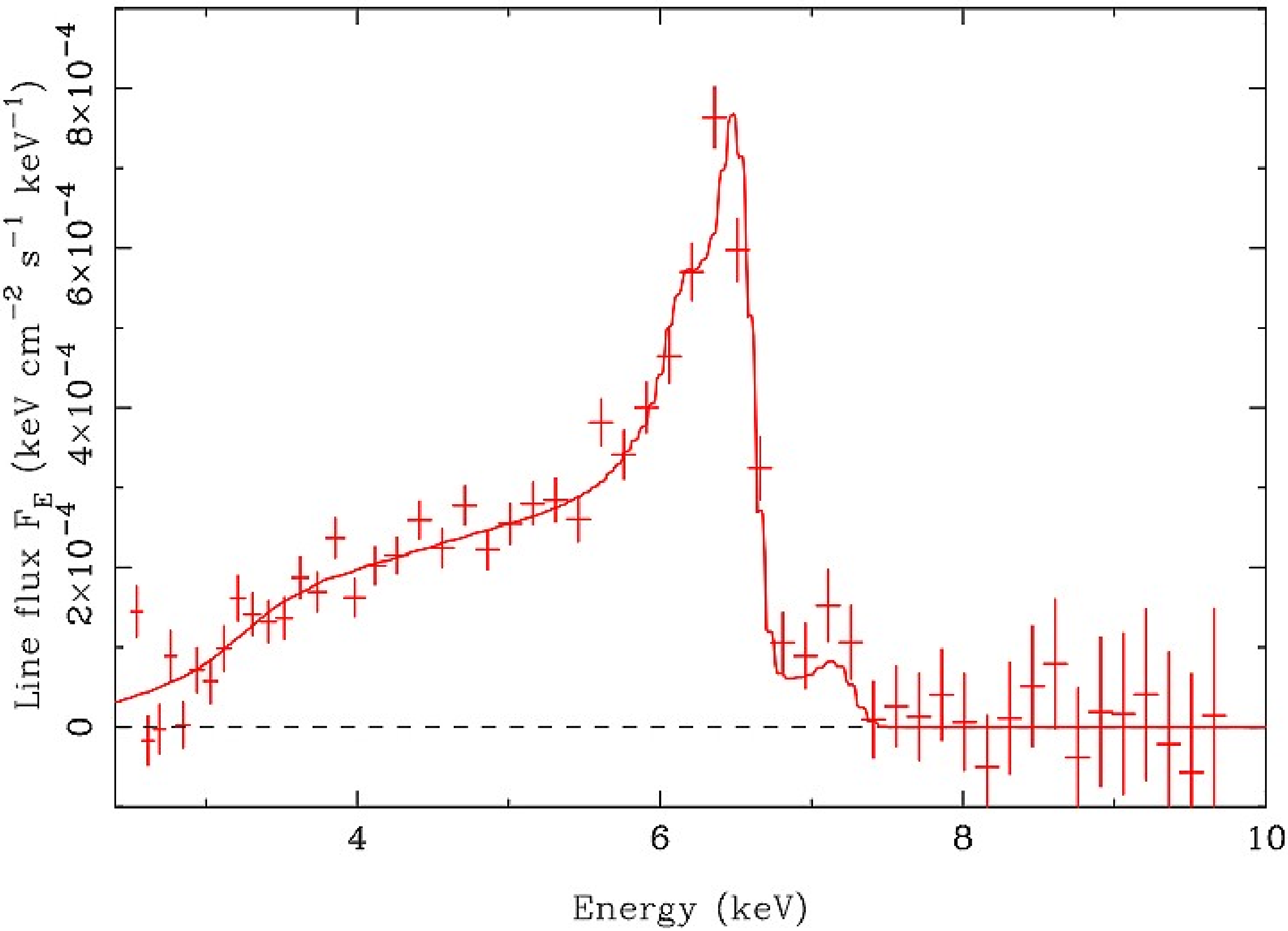
The time scale to grow a black hole if it
Were accreting at the Eddington luminosity

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

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

Numerical Simulation of Gas Accreting Onto a Black





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