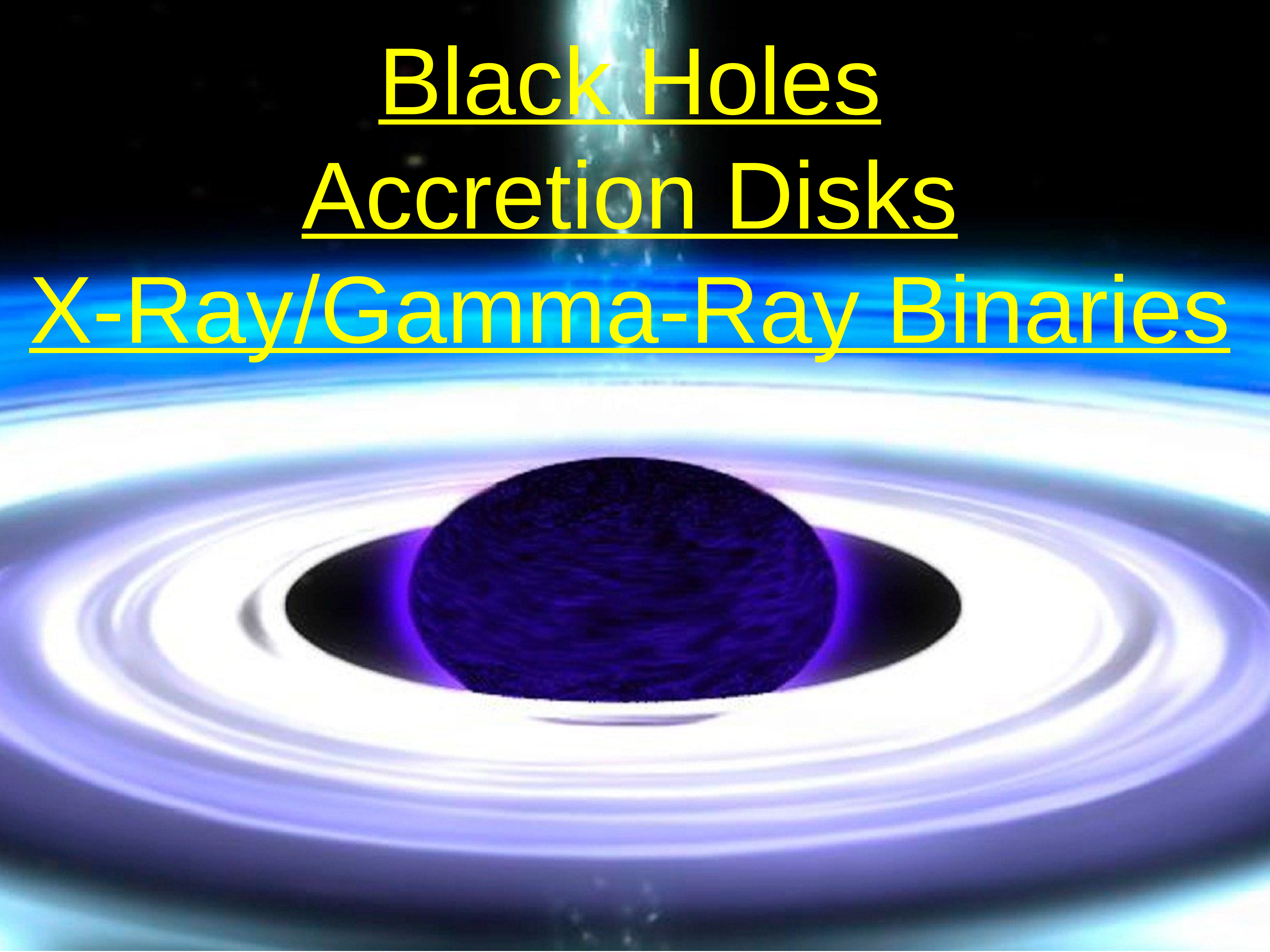
# Black Holes
# Accretion Disks
# X-Ray/Gamma-Ray Binaries



# Black Holes

Just like white dwarfs (Chandrasekhar limit: 1.4 Msun), there is a mass limit for neutron stars:

Neutron stars can not exist with masses > 3 Msun

We know of no mechanism to halt the collapse of a compact object with > 3 Msun.

It will collapse into a single point – a singularity:

## => A Black Hole!

# The Concept of Black Holes

## Schwarzschild Radius

=> limiting radius where the escape velocity reaches the speed of light:

The **Schwarzschild Radius,** Rs

**(Event Horizon)**

$$r\mathrm{S} = \frac{2GM}{c2}$$

G = Universal const. of gravity

M = Mass

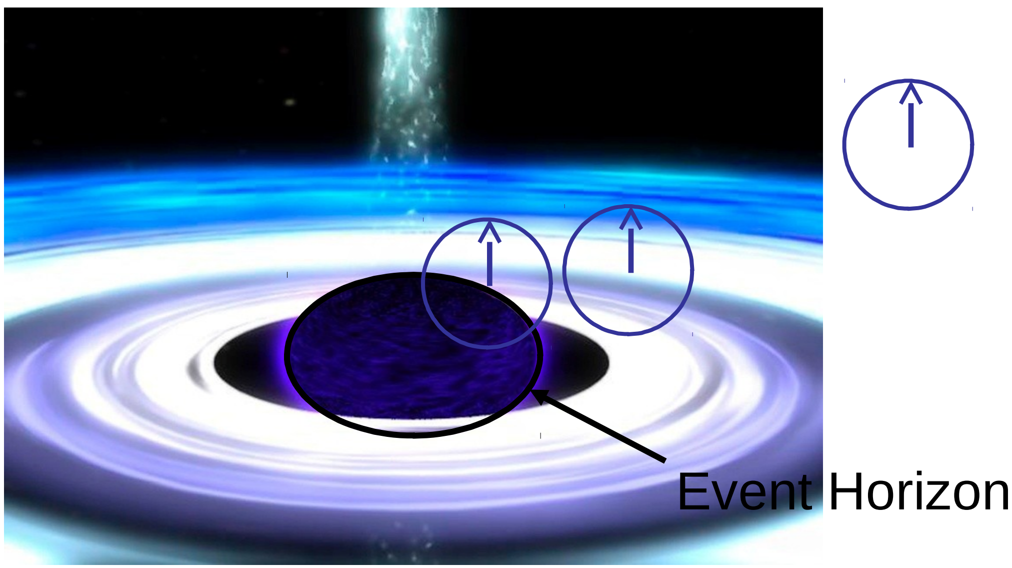
## Table 14-1 The Schwarzschild Radius

| Object | Mass ($M$ ) | Radius |
|---|---|---|
| Star | 10 | 30 km |
| Star | 3 | 9 km |
| Star | 2 | 6 km |
| Sun | 1 | 3 km |
| Earth | 0.000003 | 0.9 cm |

# General Relativity Effects Near Black Holes

## Time dilation

**Clocks closer to the BH run more slowly.**

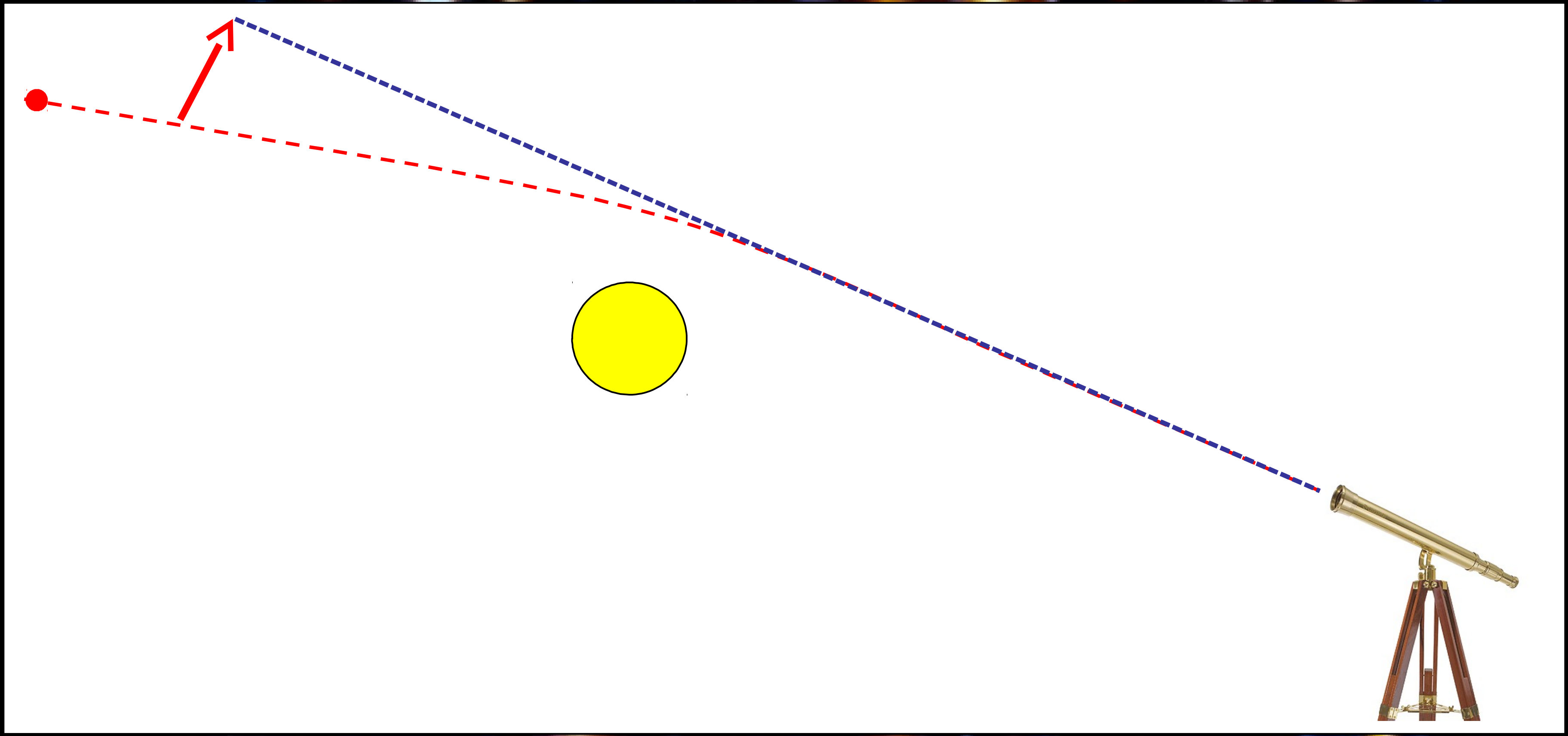



$$\Delta t' = \left(1 - \frac{r_s}{r}\right)^{1/2} \Delta t$$

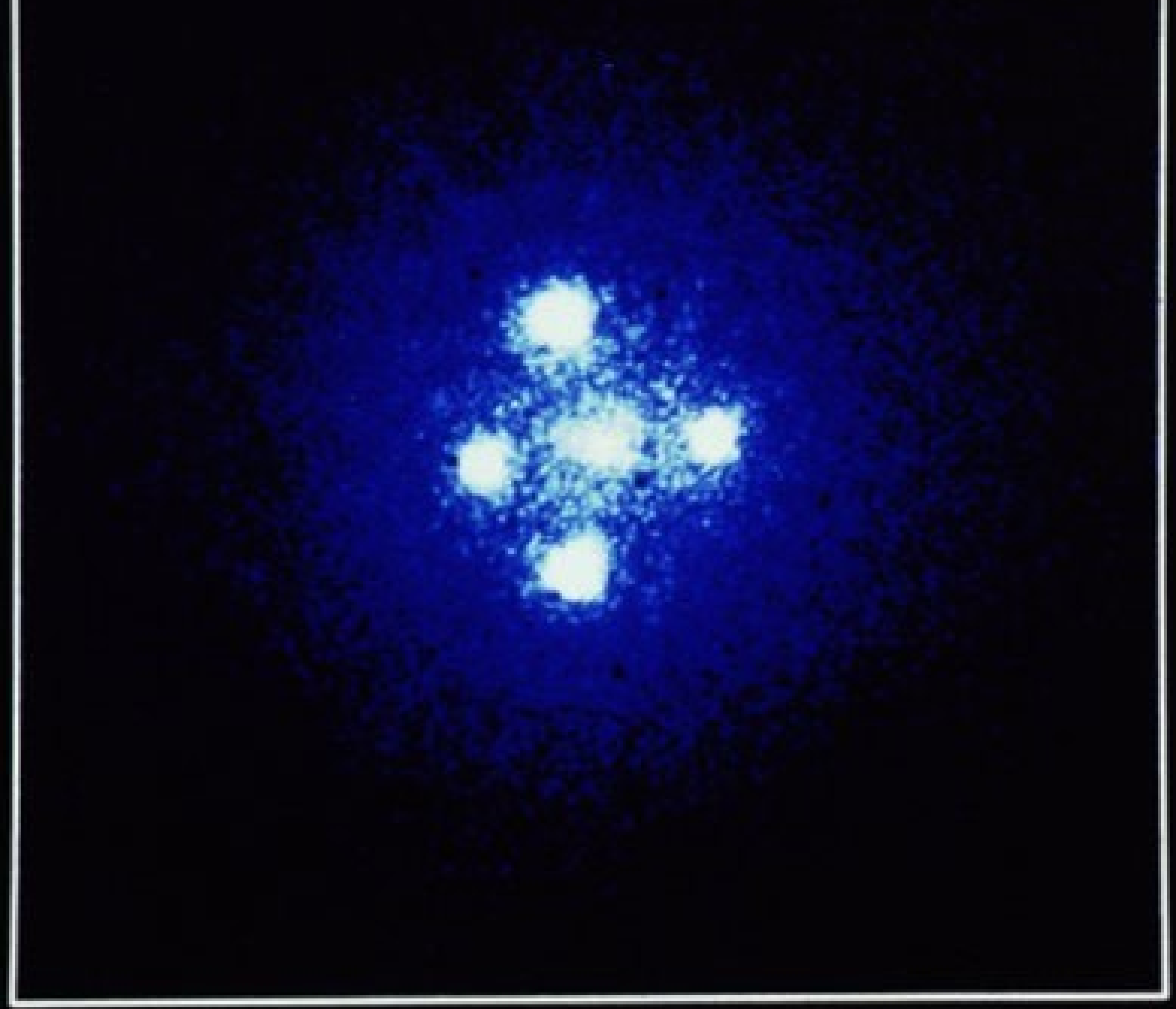
Time dilation becomes infinite at the event horizon.

# General Relativity Effects Near Black Holes

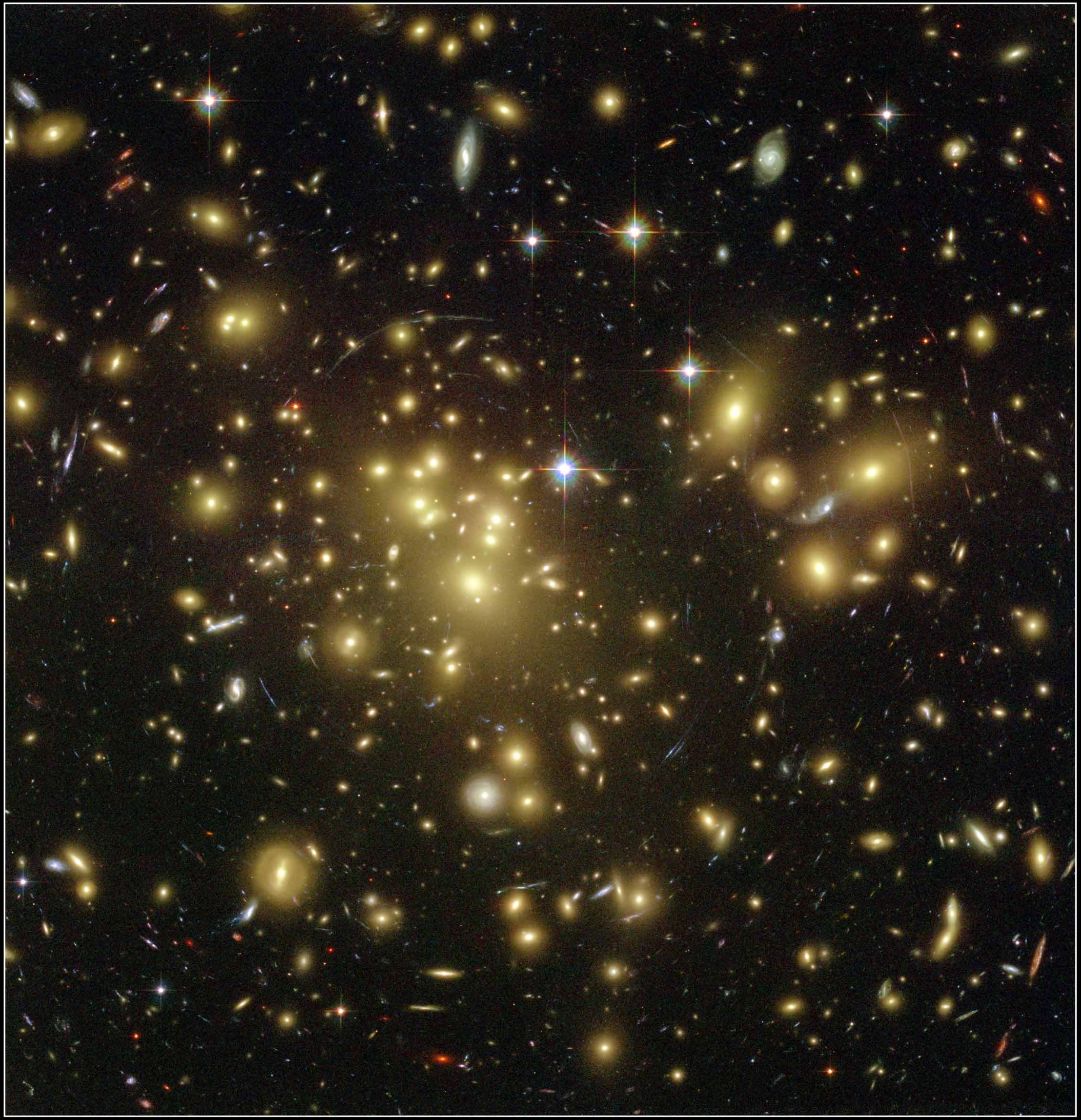
Spatial distortion of light → gravitational lensing



# Einstein Cross



Gravitational Lens G2237+0305



**Galaxy Cluster Abell 1689**

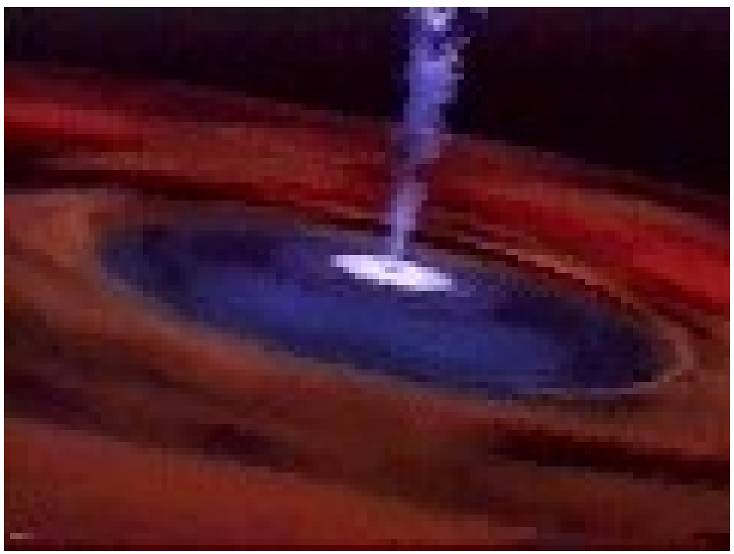
**Hubble Space Telescope** • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a

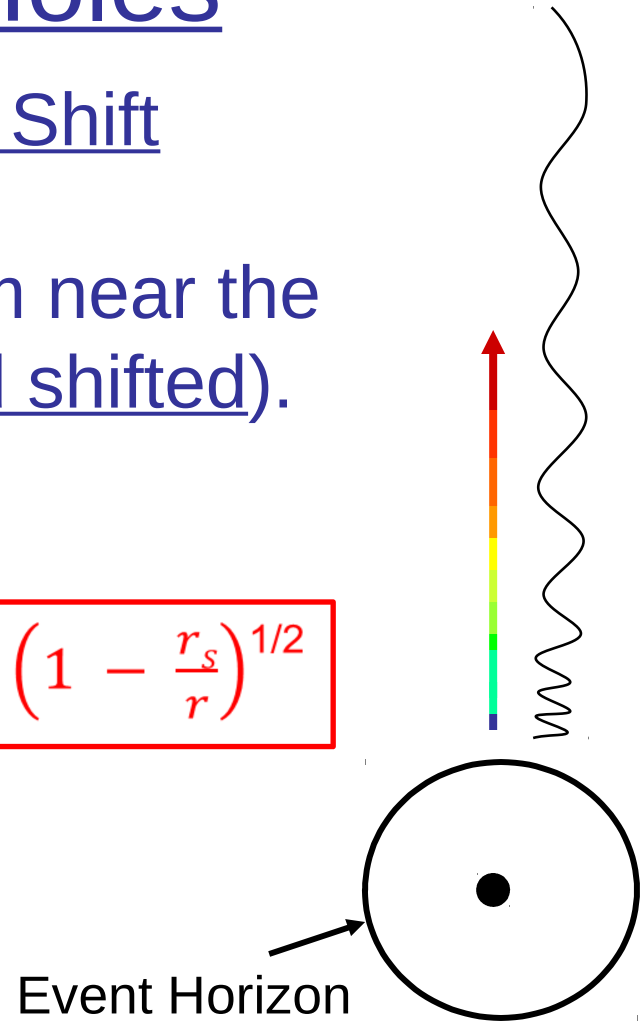
# General Relativity Effects Near Black Holes

## Gravitational Red Shift

Wavelengths of light emitted from near the event horizon are stretched (red shifted).



$$\nu_\infty = \nu_{em}(r)\left(1 - \frac{r_s}{r}\right)^{1/2}$$



# Innermost Stable Circular Orbit (ISCO)

Unlike Newtonian Gravity, in GR there is a limiting orbital radius within which there is no stable circular (or elliptical) orbit:

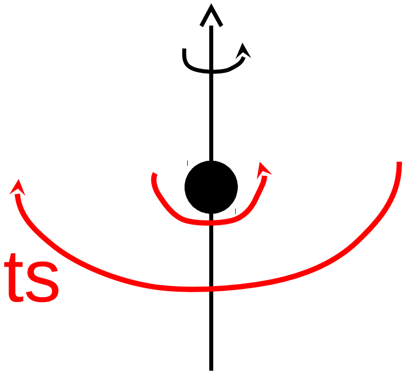
Schwarzschild Black Hole ($J = 0$):

**$r_{ISCO} = 3\ r_S$**

Maximally Rotating Kerr BH ($J \approx GM^2/c$):

$r_{ISCO} = r_S/2$ for co-rotating orbits

$r_{ISCO} = 9r_S/2$ for counter-rotating orbits



# Observing Black Holes

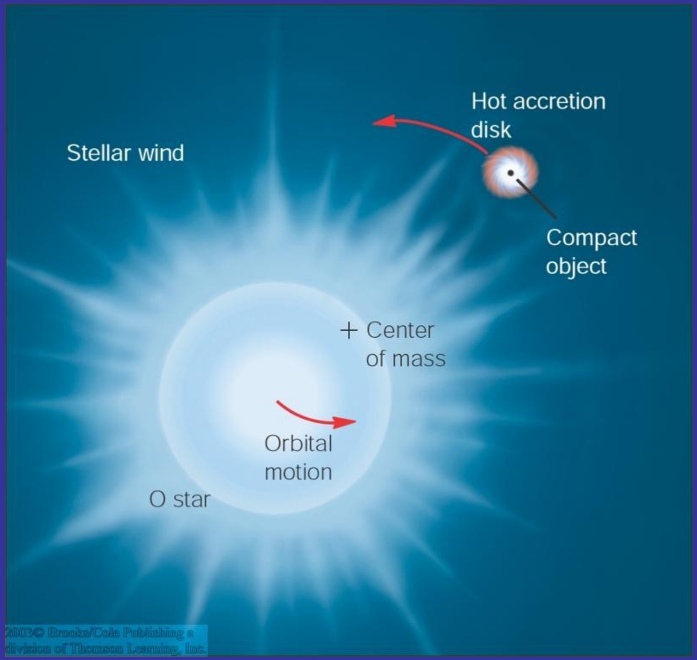
No light can escape a black hole

=> Black holes can not be observed directly.

Black hole or Neutron Star in a binary system

⇒ Wobbling motion and/or periodic blue/red shifts of stellar absorption lines

⇒ Mass estimate

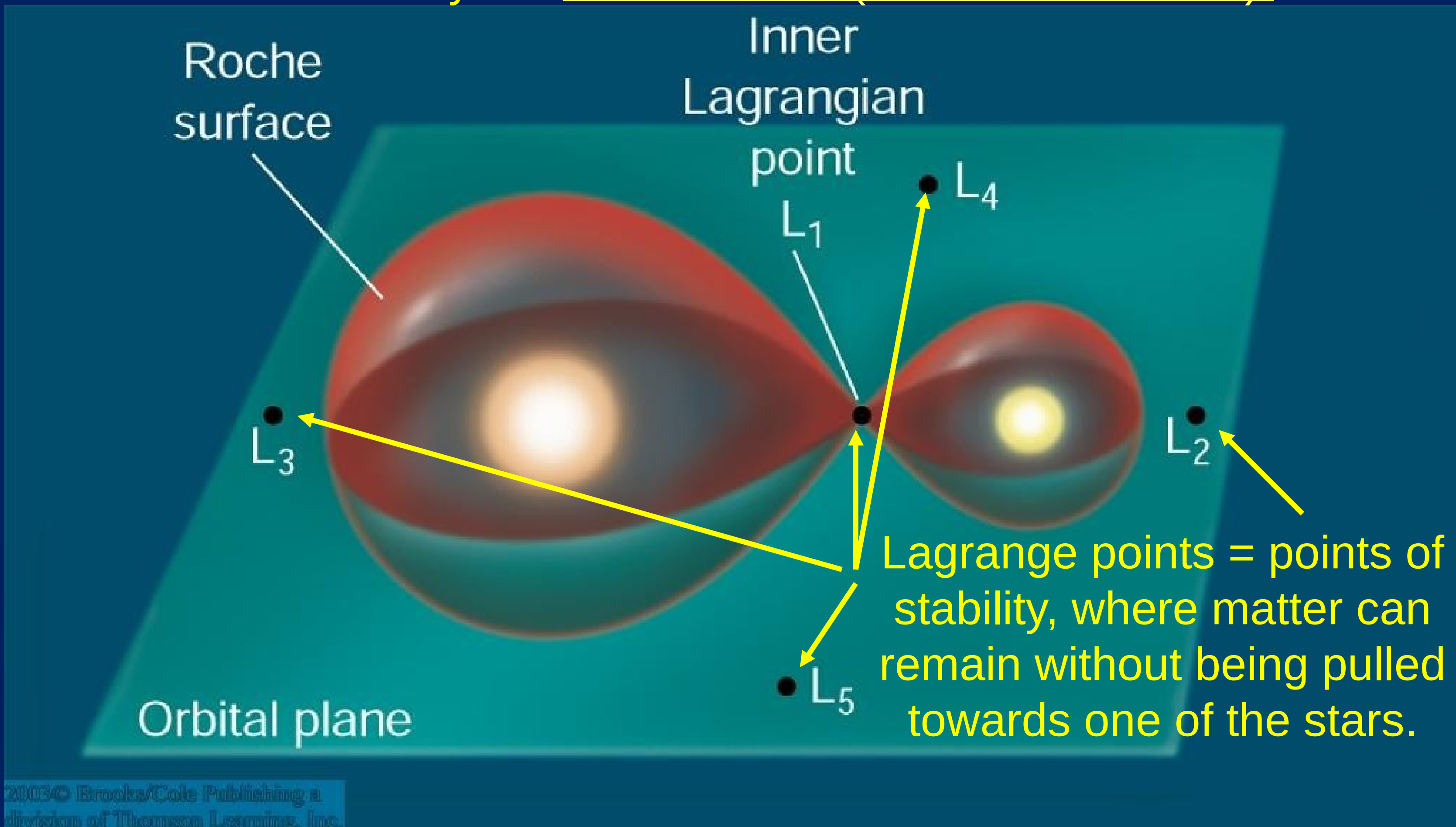



$$M_{co} > f(M) = \frac{M_{co}^3 \sin^3 i}{(M_* + M_{co})^2} = \frac{V_{*,r}^3 P}{2 \pi G}$$

Mass > 3 Msun => Black hole!

# Mass Transfer in Binary Stars

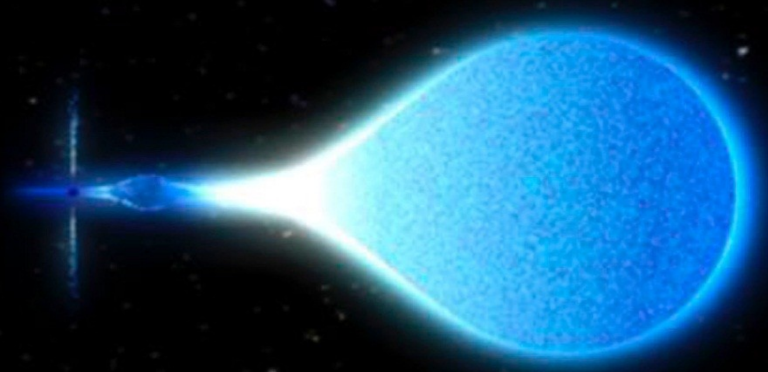
In a binary system, each star controls a finite region of space, bounded by the Roche Lobes (or Roche surfaces).




Matter can flow over from one star to another through the Inner Lagrange Point L1.

# X-Ray Binaries

Binary systems of a compact object (neutron star or black hole) and a stellar companion



Matter is flowing over from the stellar companion onto the compact object.

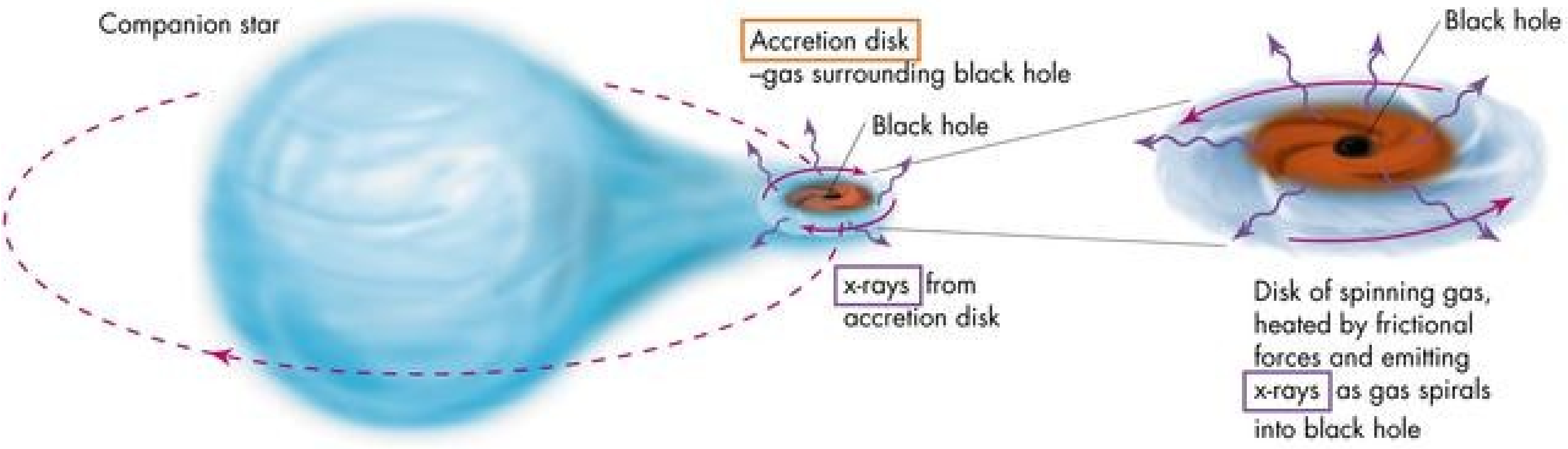
Angular momentum conservation

=> Formation of an accretion disk

Matter in the accretion disk heats up to ~ 106 - 107 K

=> X-ray emission

# Black-Hole X-Ray Binaries




## Low-Mass X-Ray Binaries

Donor star = main sequence star with M < Msun

Accretion primarily through direct Roch-Lobe overflow

## High-Mass X-Ray Binaries

Donor star = Massive (O/B) main sequence star

Accretion primarily from the stellar wind

# Accretion

- Most efficient way of converting mechanical energy to radiation:
  - Nuclear fusion: $\Delta E/(mc^2) \sim 0.007$
  - Accretion: $\Delta E/(mc^2) \sim \frac{r_g}{r}$

$\rightarrow$ White Dwarf: $\frac{r_g}{r} \sim 3*10^{-4}$

$\rightarrow$ Neutron Star: $\frac{r_g}{r} \sim 0.15$

$\rightarrow$ Black hole: $\frac{r_g}{r} \sim 0.33$

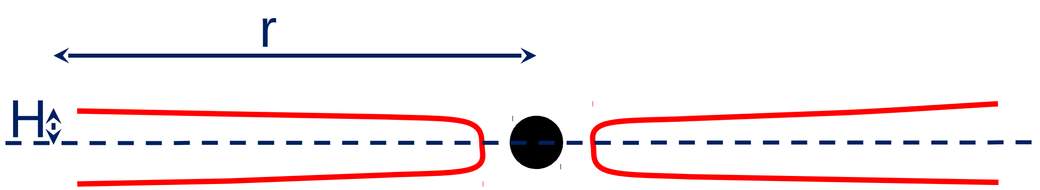
From GR: $\Delta E/(mc^2) = \begin{cases} 0.06 & \text{for non-rotating (= "Schwarzschild") BH} \\ 0.42 & \text{for maximally rotating (= "Kerr") BH} \end{cases}$

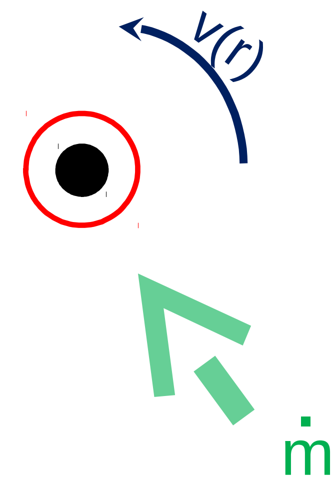
## Fundamental limit on accretion power: Eddington Luminosity:

$$L_{Edd} = \frac{4\pi G M m_p c}{\sigma_T} = 1.26*10^{38} \left(\frac{M}{M_{sun}}\right) \text{ erg/s}$$

# Accretion Disks

- Most common case: Thin accretion disks




Thin disk ⇔ H/r << 1

$$\Leftrightarrow \quad \frac{c_s}{v_\varphi} = \frac{1}{M} \ll 1$$

i.e., rotational velocity must be >> sound speed.

$$\dot{m} = 2\pi\, r\, v_r\, \Sigma = \text{const.}$$

$$\Sigma = \int_0^H \rho(h)\,dh \approx \langle\rho\rangle H$$

# Viscosity

- **Definition of viscosity η**

$$f_x(y) = \frac{dF_x}{dA_{xz}} = \eta \frac{\partial v_x}{\partial y}$$

$$f_{xy} = \eta \left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x}\right)$$

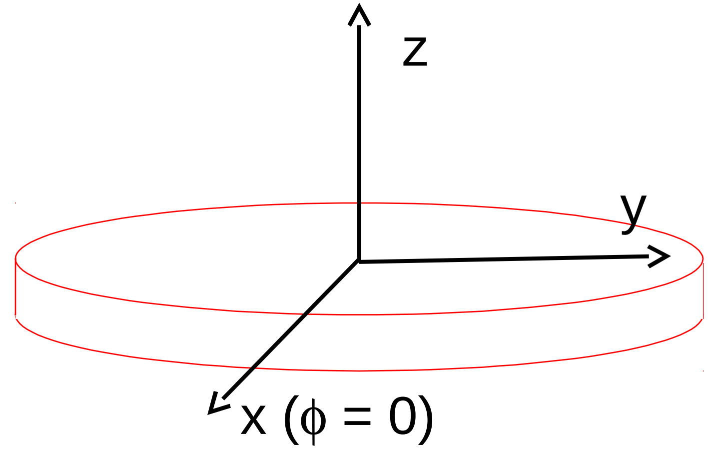
$$\Rightarrow f_{xy} = \eta\, r \frac{\partial \Omega}{\partial r}$$

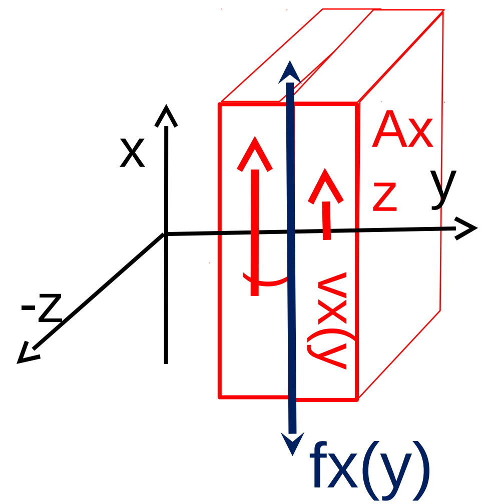
**Definition of kinematic viscosity ν**

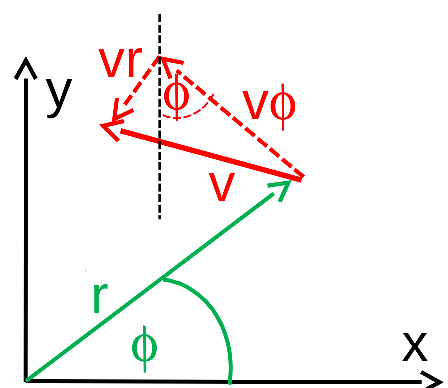
$$\nu = \eta/\rho$$

## α Prescription of (turbulent) viscosity:

$$\nu_t = \alpha\, c_s\, H$$



# Structure of Thin Accretion Disks

- ## Angular Momentum (L) Transport:

Torque: $$\tau \equiv \frac{dL}{dt} = -2\pi\, r^3\, \nu\Sigma\, \frac{\partial\Omega}{\partial r} = m\, v_\varphi\, r + const.$$

## Energy dissipation:

$$F(r) = \frac{dE}{dAdt}(r) = \frac{3}{4}\frac{GM\dot{m}}{\pi\, r^3}\left(1 - \left[\frac{r_*}{r}\right]^{½}\right)$$

## Temperature structure:

$$T(r) \approx \left(\frac{3\, GM\dot{m}}{8\,\pi\,\sigma\, r^3}\right)^{¼} \propto r^{-¾}$$

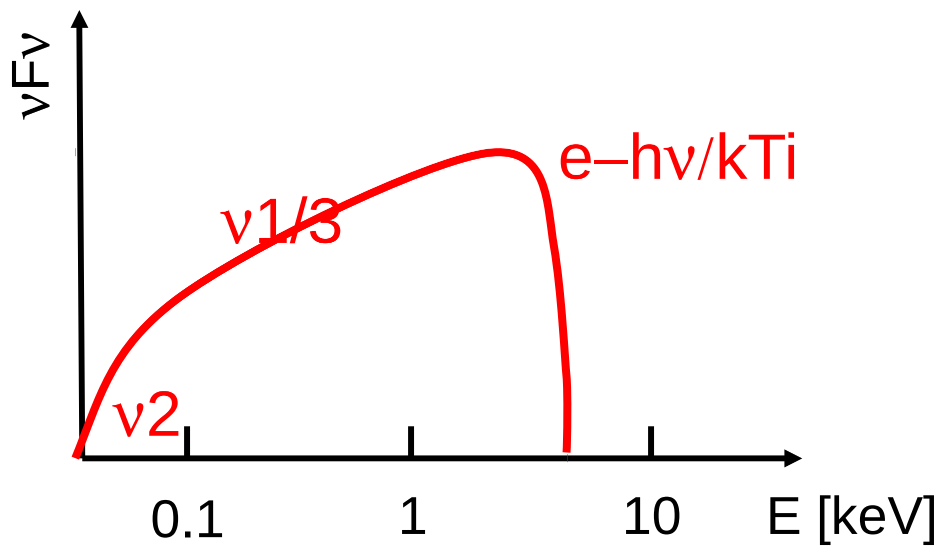
# Thin Accretion Disks

- ## Total Luminosity:

$$L_{rad} = \int_{r_*}^{\infty} F(r) 2\pi r \, dr \approx \frac{GM\dot{m}}{2\, r_*}$$

## Radiation Spectrum:

$$T(r) \approx \left(\frac{3\, GM\dot{m}}{8\, \pi\, \sigma\, r^3}\right)^{1/4} \propto r^{-3/4} \qquad I_\nu(r) = 2\pi r\, B_\nu\left(T(r)\right)$$

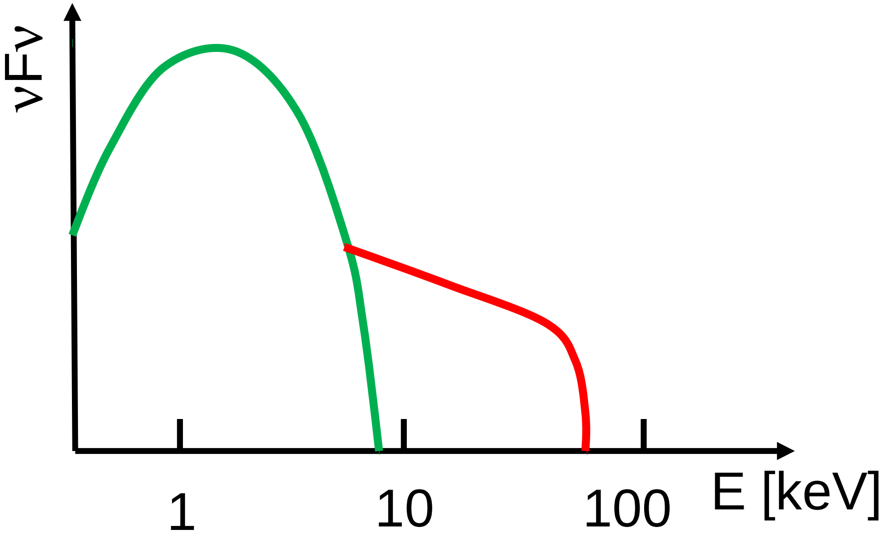



$$T_i \sim 2 \times 10^7 \left(\frac{M}{M_{sun}}\right)^{-1/4} K$$

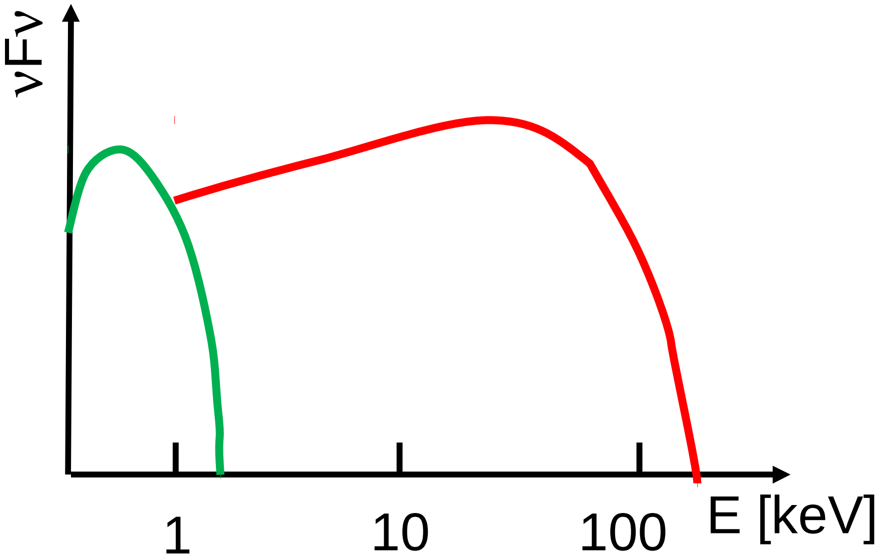
For accretion at the Eddington Limit

# Spectral States of X-Ray Binaries

- Soft / high / thermal state:
  Emission dominated by
  thermal soft X-ray emission
  from the accretion disk

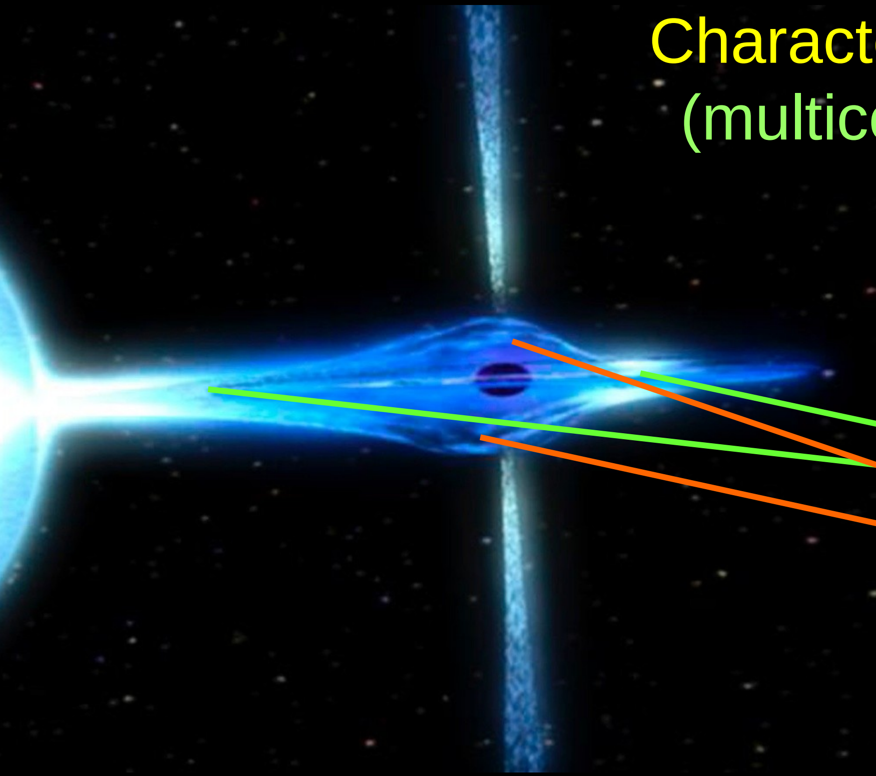


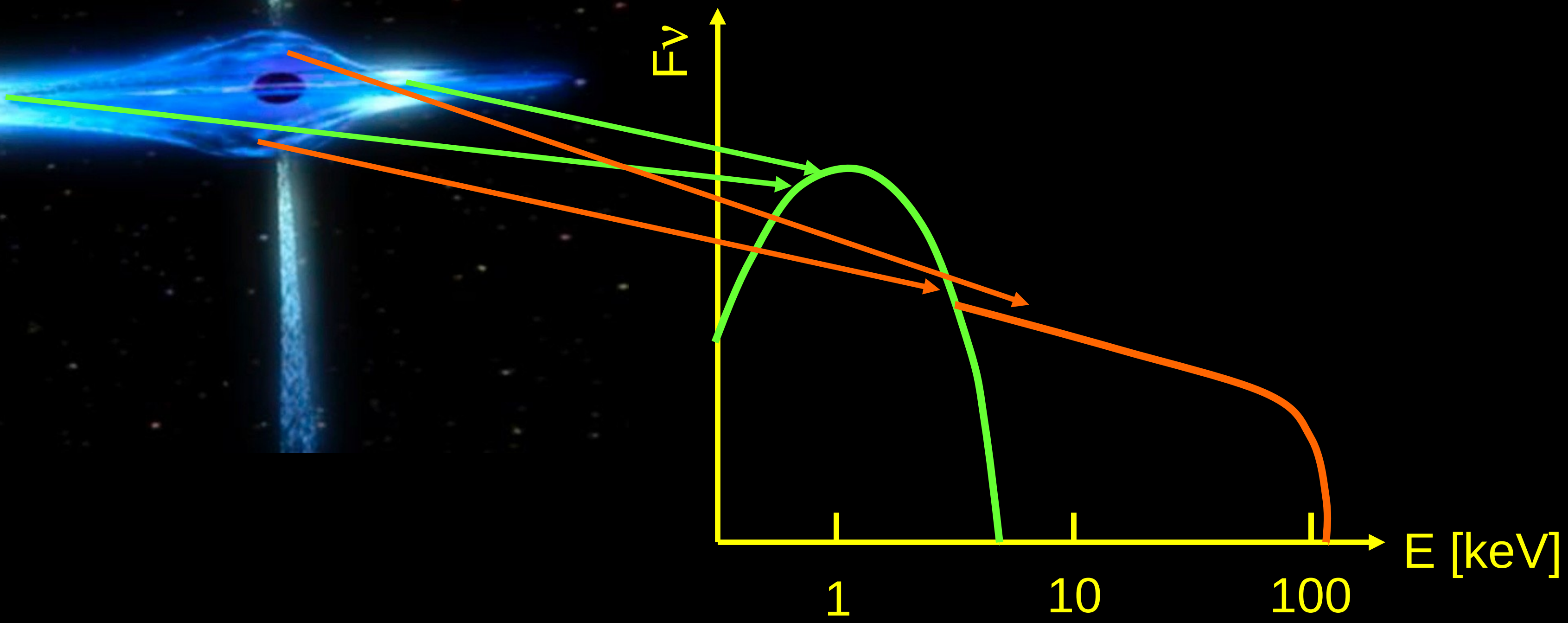

- Low / hard / non-thermal state:
  Emission dominated by
  non-thermal hard X-ray
  power-law tail



# X-Ray Binaries

Characteristic X-ray spectra: thermal (multicolor) disk + hard power-law.

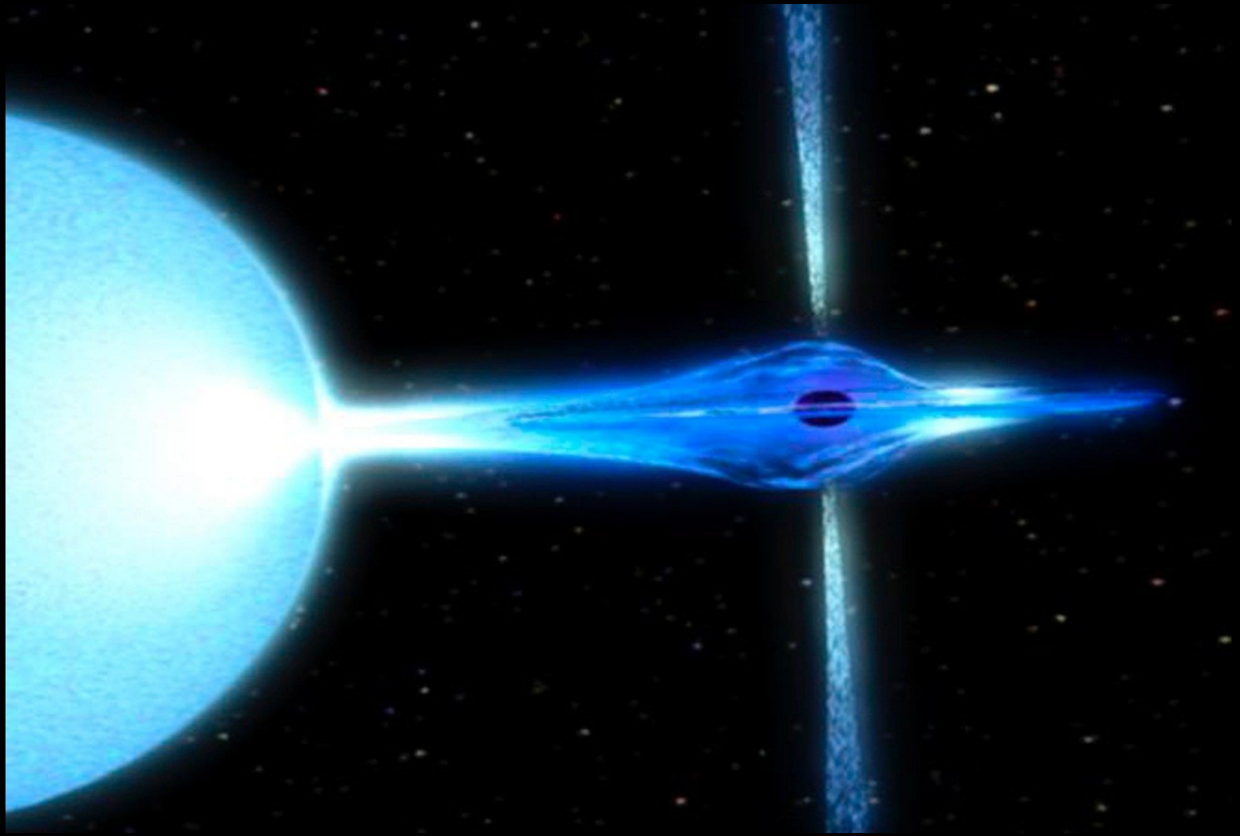





Conventional interpretation of hard X-ray power-law:
Thermal Comptonization in a hot (kT ~ 30 – 100 keV) corona

# Jets from X-Ray Binaries

As in most accretion disk systems, mass accretion is accompanied by the formation of collimated outflows:

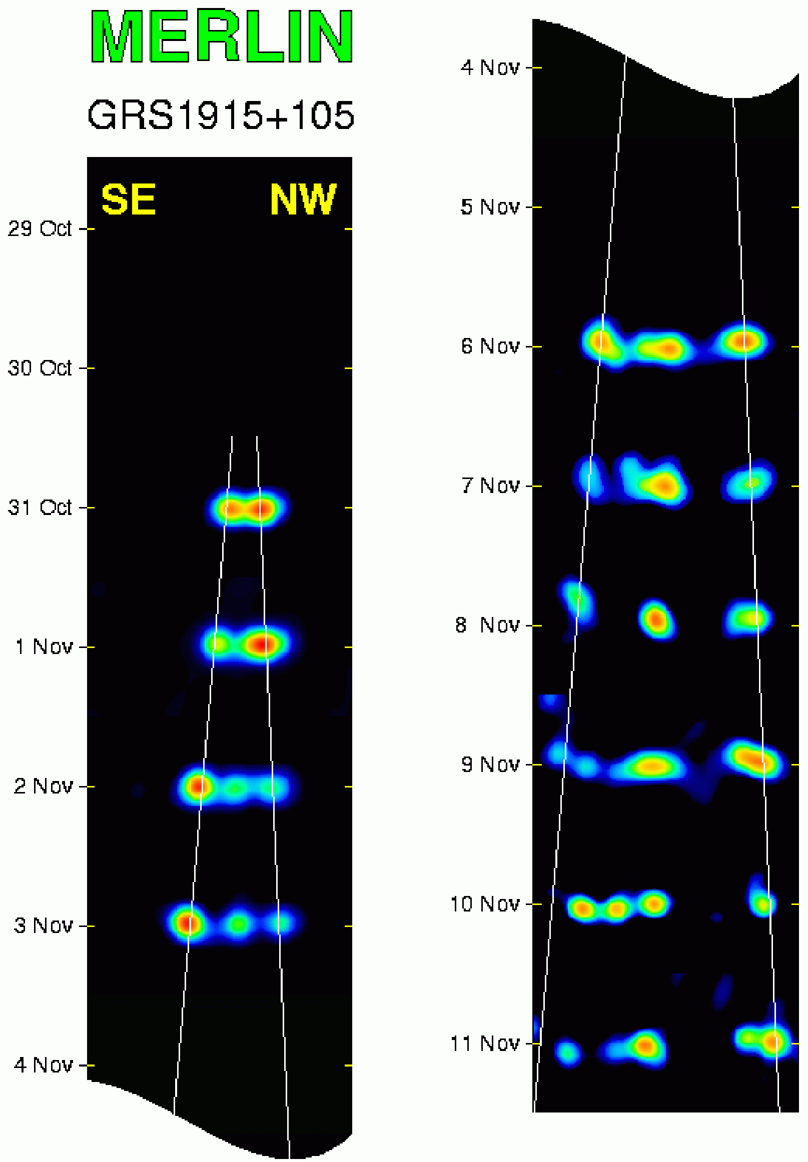


Mildly relativistic jets: $\Gamma \sim 2$

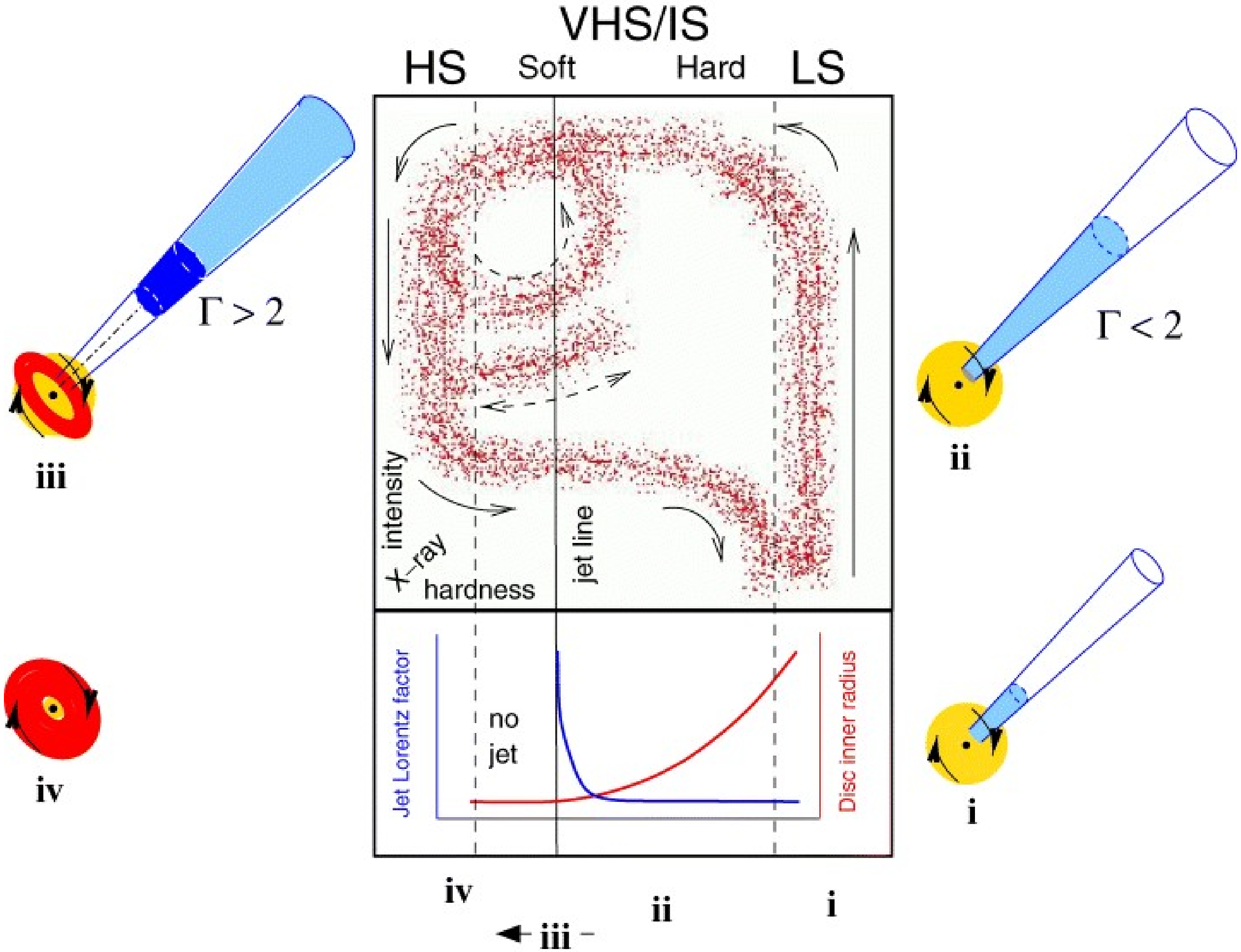
Generally identified as radio jets

# Outflows from Black Holes

Material flowing out with over 70 % of the speed of light!



# Connection between Jets and Spectral States

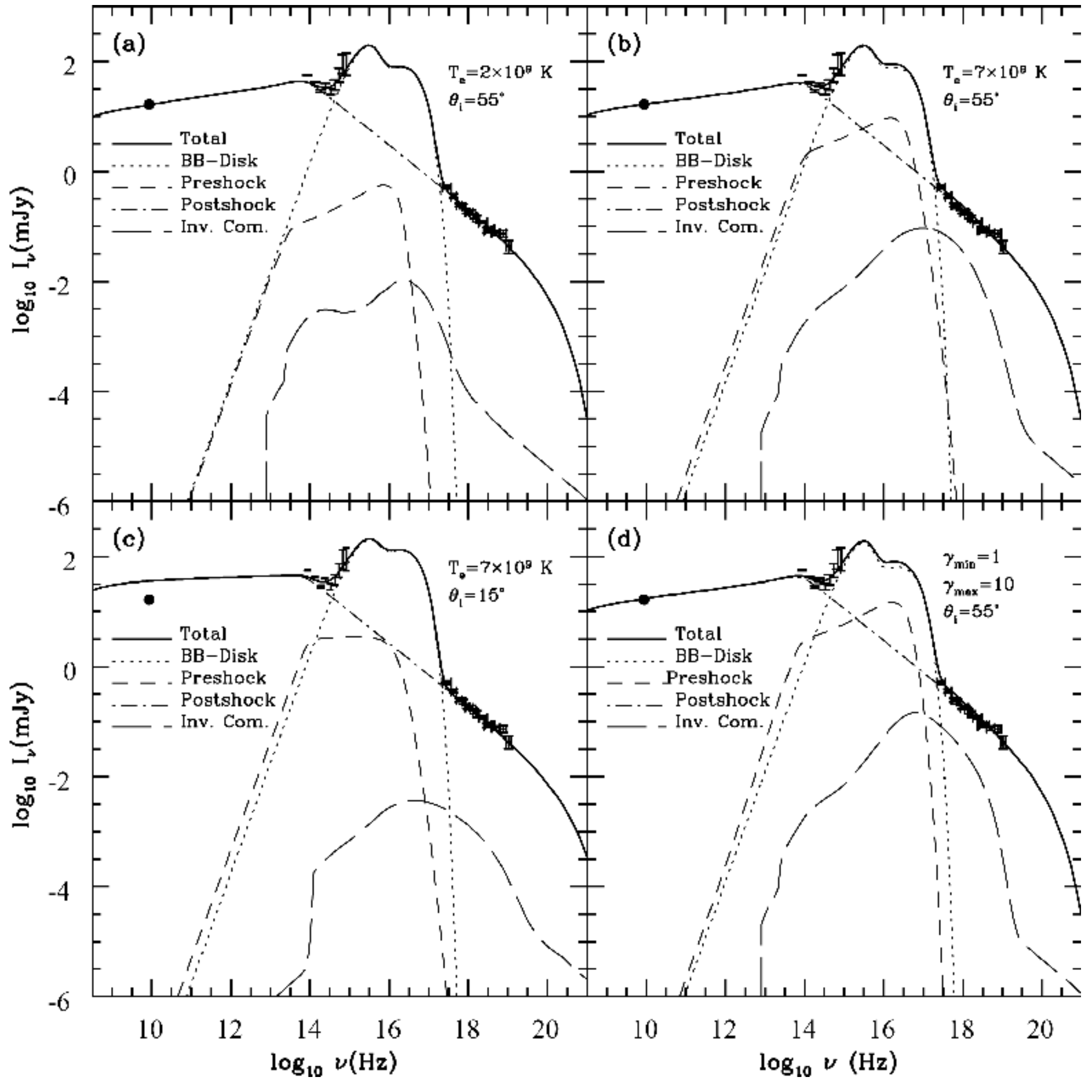



Steady jets only in the low/hard state

Intermittent jets during state transitions

(Fender, Belloni & Gallo 2004)

# X-Ray Emission from Microquasar Jets(?)

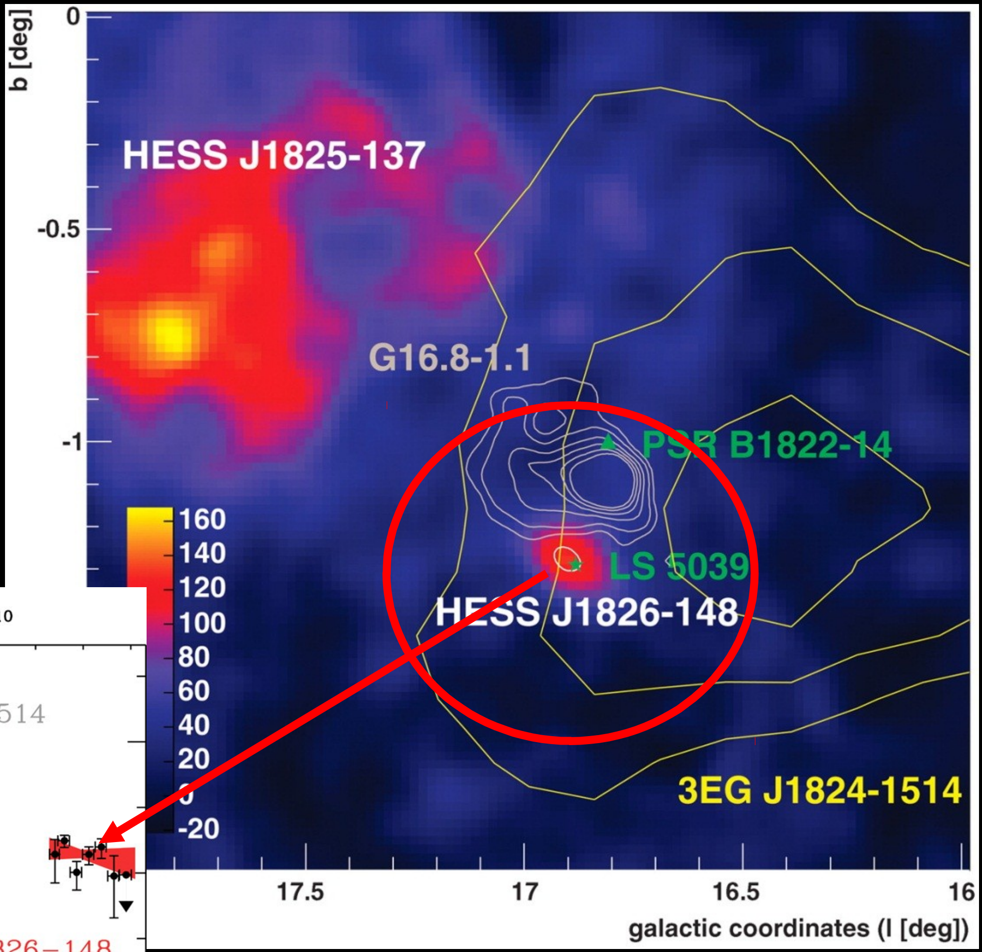


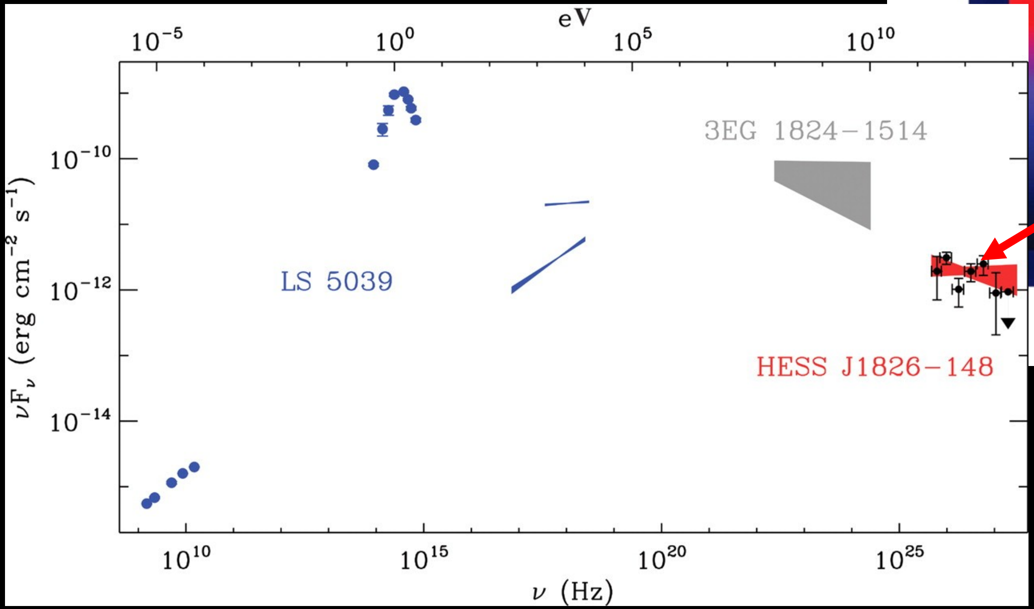

Markoff et al. (2005)

# γ–Ray Emission from X-Ray Binaries

5 X-ray binaries are known sources of VHE (> 100 GeV) gamma-rays

→ "Gamma-Ray Binaries".



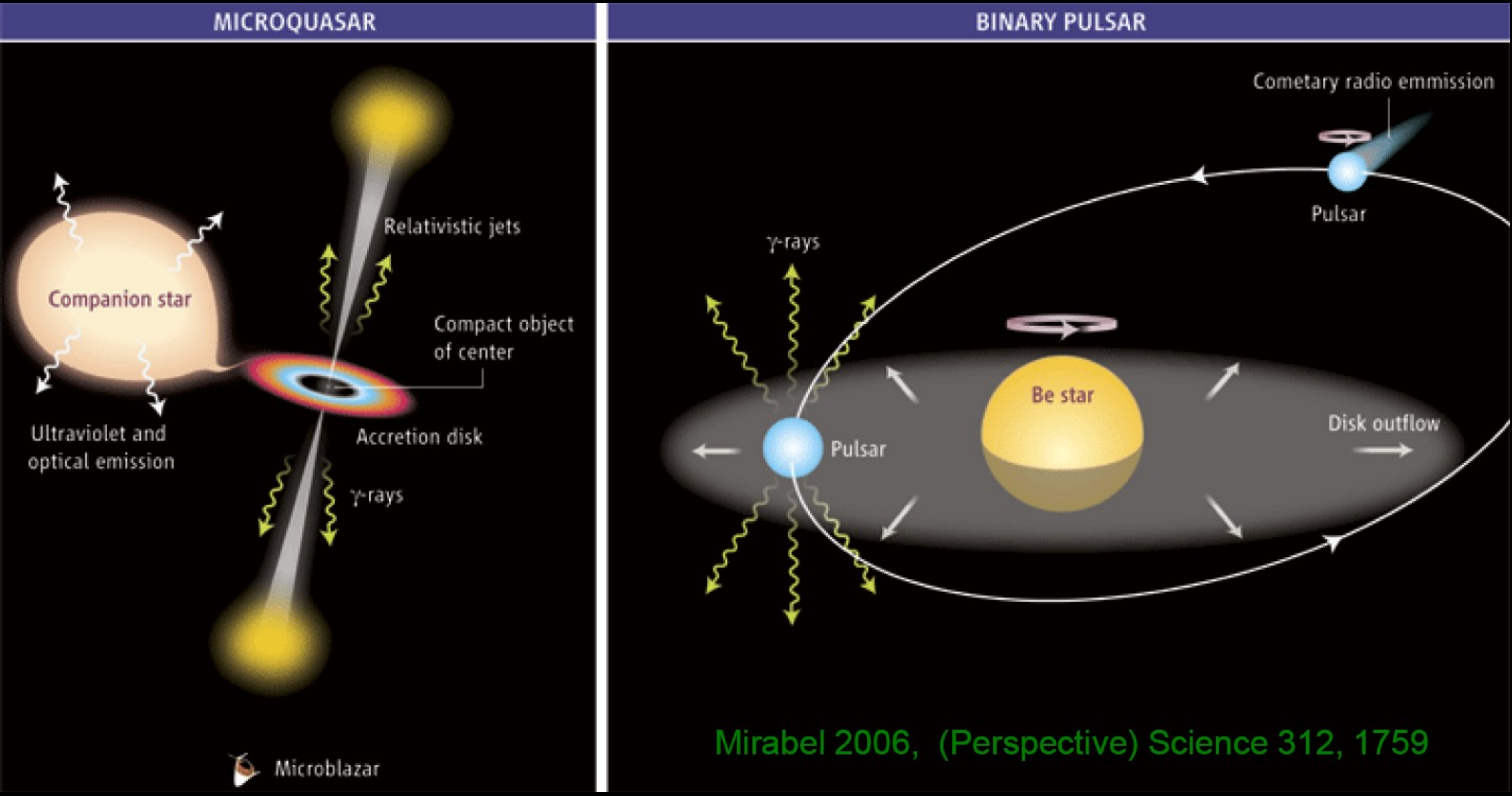




LS 5039: H.E.S.S. (Aharonian et al. 2005)

# Gamma-Ray Binaries

In most cases: Nature of the compact object (BH or NS) unknown.

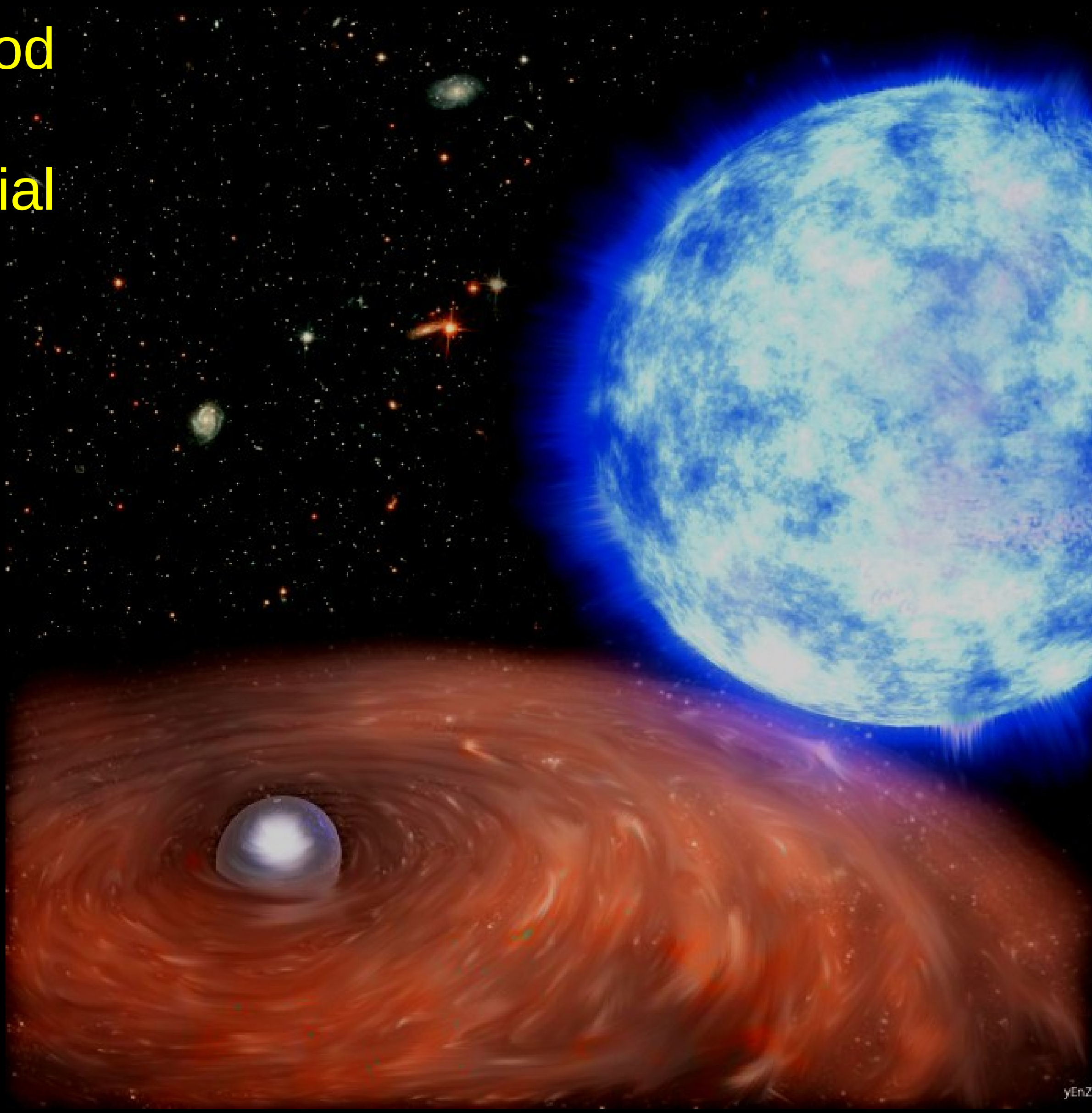
→ Microquasar (BH) or colliding-wind (NS) models




Mirabel 2006, (Perspective) Science 312, 1759

# Extraordinary Case: PSR B1259-63

Pulsar in a 3.4-year period orbit around a Be star (equatorial disk of material flowing away from the star).



Pulsar crosses the disk ~ 15 days before and after periastron.

→ Pulsed radio emission disappears; correlated X-ray and TeV gamma-ray flares

# PSR B1259-63

TeV gamma-ray and X-ray flares when the pulsar crosses the circumstellar disk

GeV (Fermi) gamma-ray flare about 30 days after periastron; not correlated with other wavelengths!

Next periastron passage is happing now!