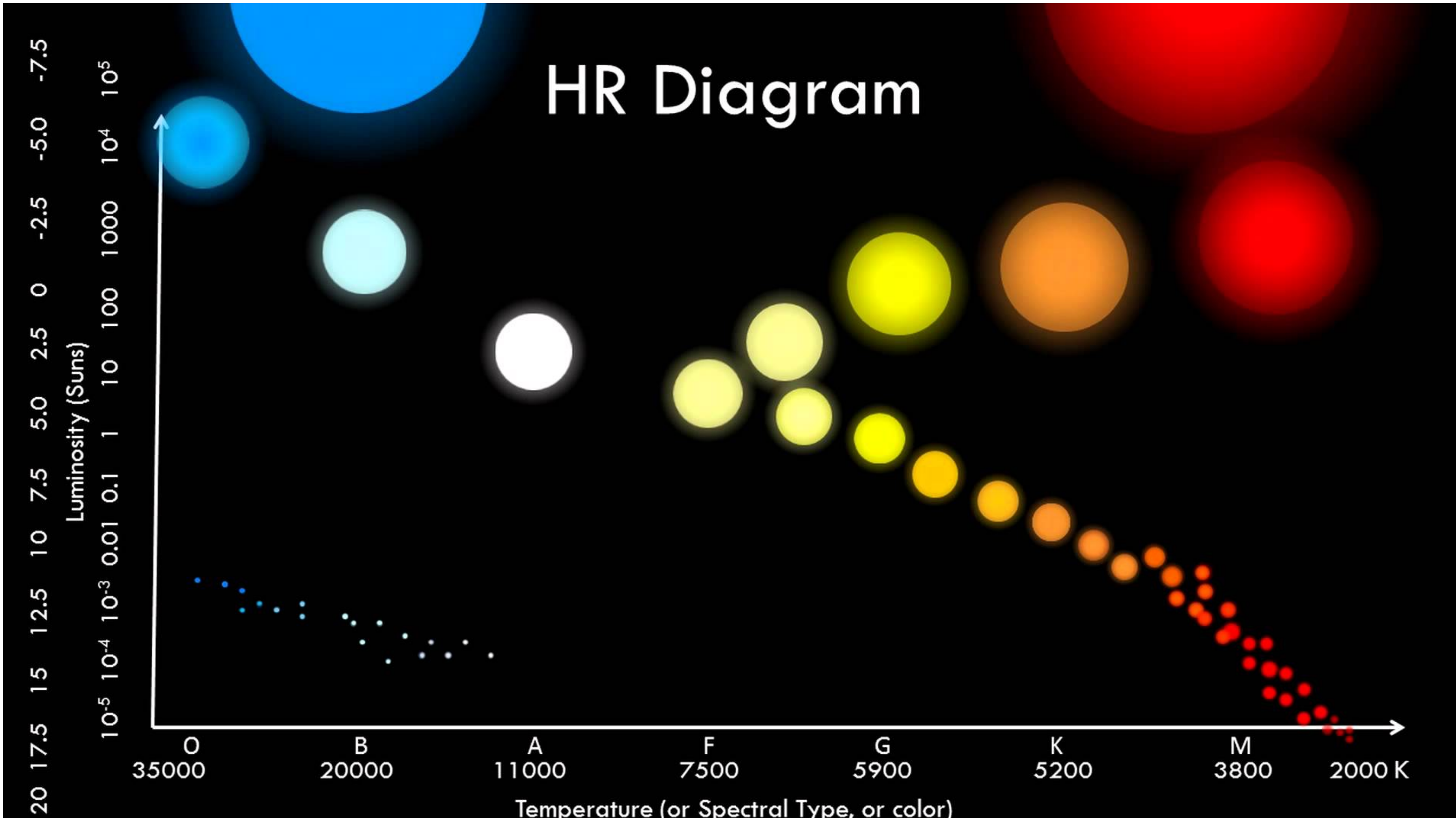
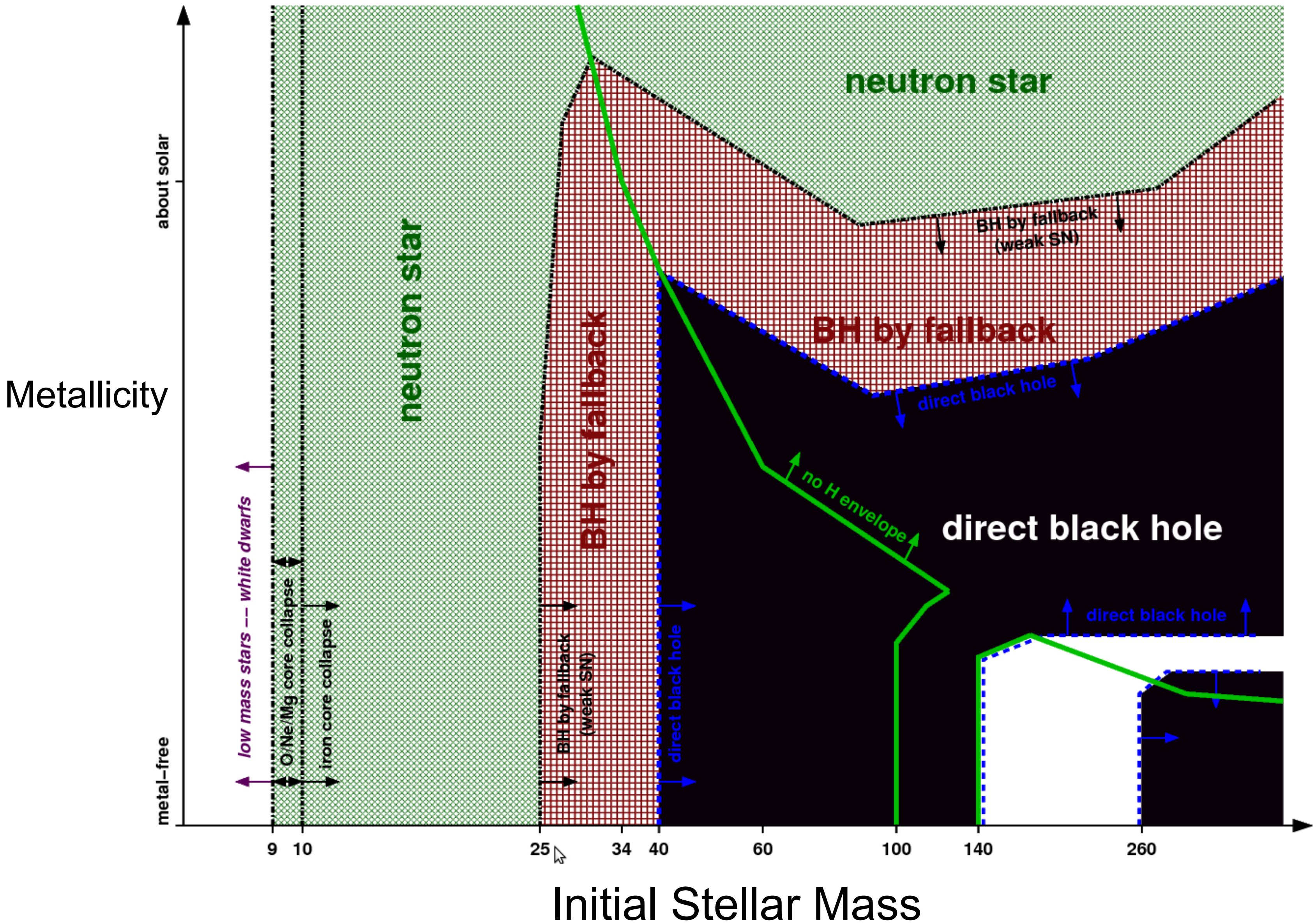
Accretion and X-Ray Binaries

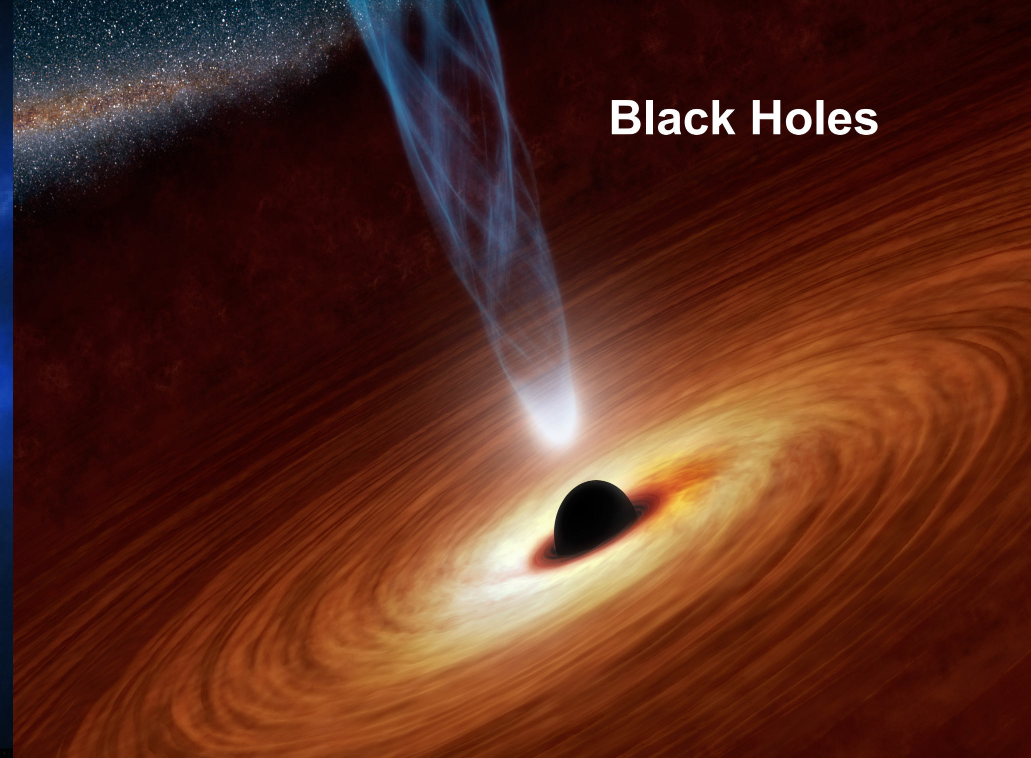
How Compact Objects are Formed



How Massive *Single* Stars End their Lives

Heger et al. (2003), The Astrophysical Journal, Volume 591, Issue 1, pp. 288-300



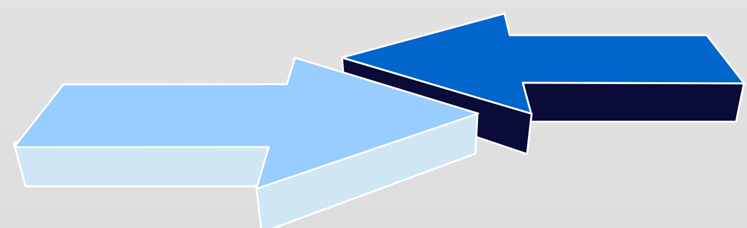


Astrophysics

- Accretion Flows
- Compact objects
- Binary evolution

Fundamental Phys.

- Ultra-Dense Matter
- Grav. Waves.
- Strong GR tests



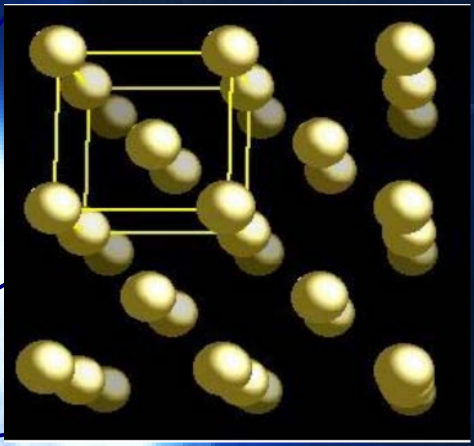
White Dwarfs

Degenerate exhaust cores of low mass stars

Supported by electron degeneracy pressure

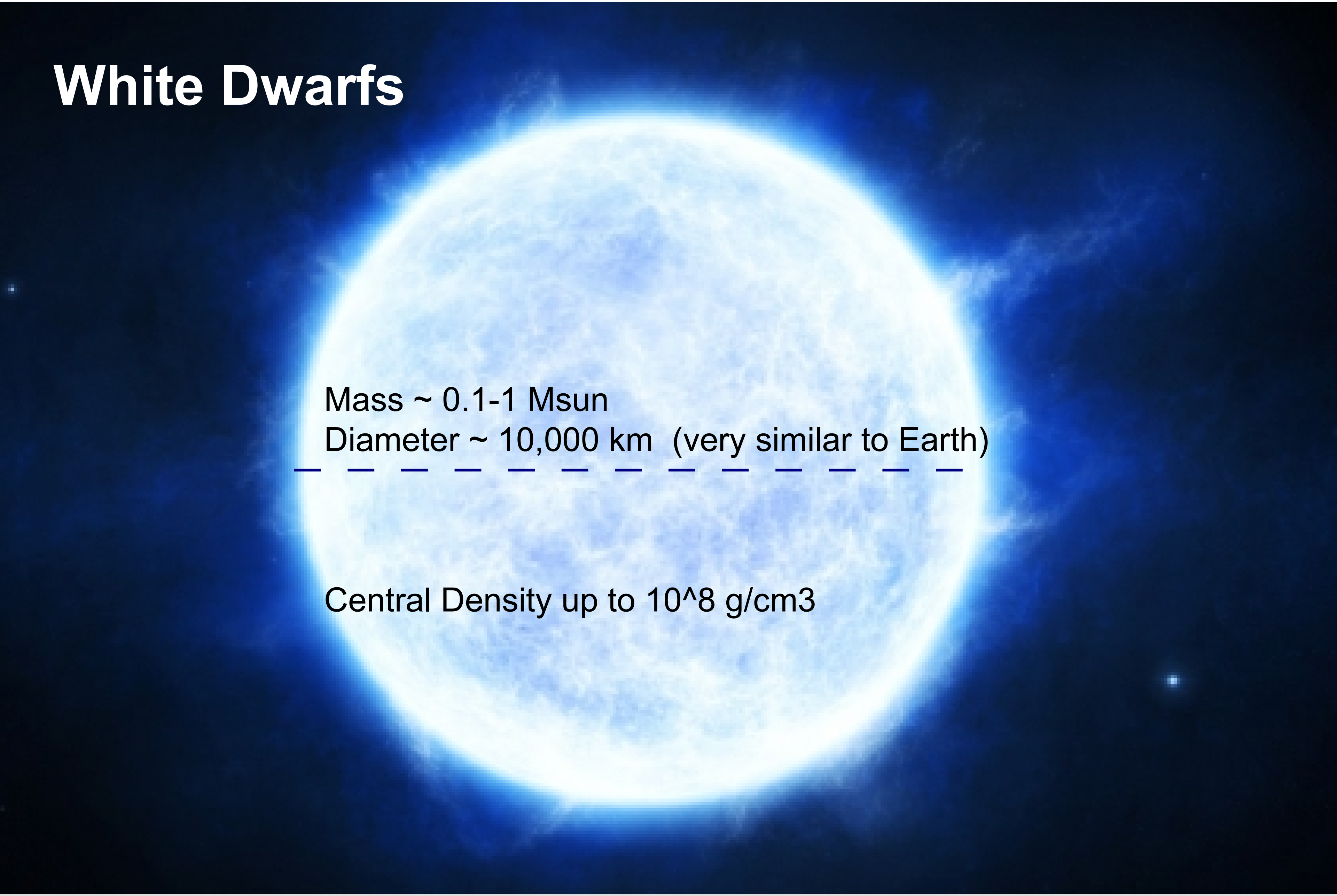
About 10% of stars in the galaxy are WDs

White Dwarfs



The microscopic structure of WDs is relatively well understood: crystal lattice of He or C/O with free degenerate electrons

White Dwarfs

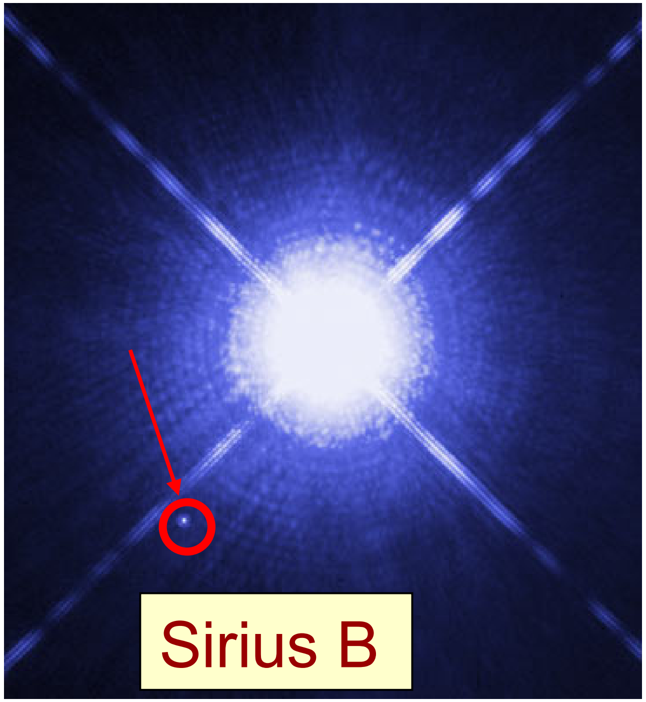


Mass ~ 0.1-1 Msun
Diameter ~ 10,000 km (very similar to Earth)

Central Density up to 10^8 g/cm3

White Dwarf Discovery

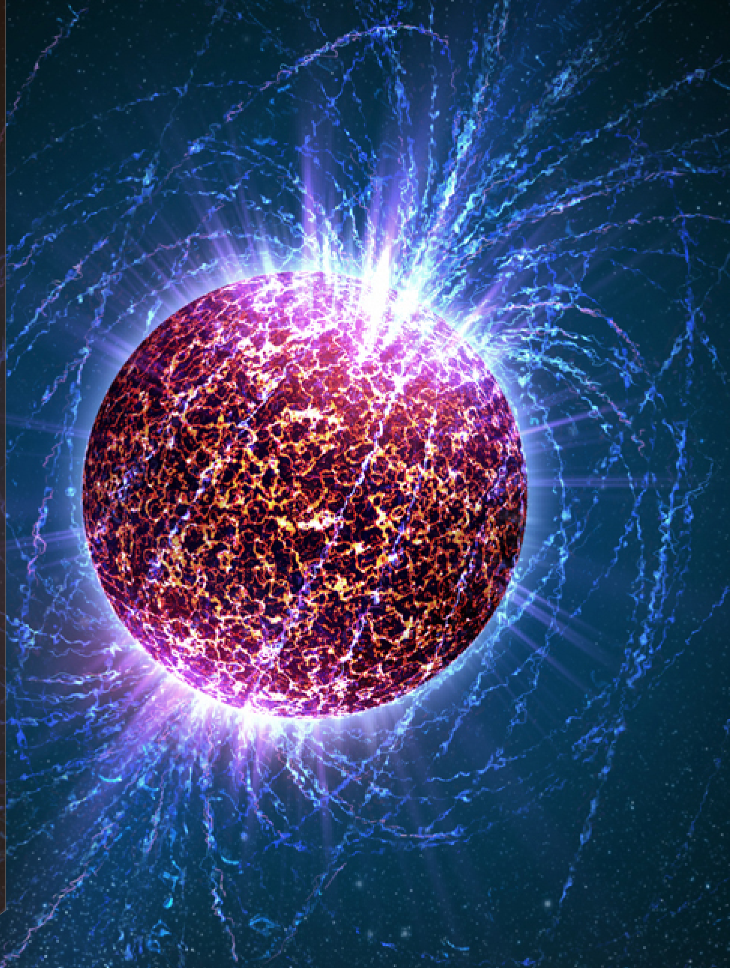
- 1834: Indirect evidence of a WD in Sirius B (F.W. Bessel)
- 1862: Direct detection of the WD Sirius B (A.G. Clark)
- 1917: Discovery of Isolated White Dwarf “Van Maanen Star” (van Maanen)
- 1925: Measure of WD optical spectrum (M and R) in Sirius B (W.S. Adams)
- 1926: Fermi and Dirac publish their study on the so-called Fermi-Diract distirbutio



“I adhere to the conviction that the star Sirius is a binary system consisting of a visible and an invisible star. There's no reason to suppose that luminosity is an essential quality of cosmic bodies. Visibility of countless stars is no argument against the invisibility of countless others.”

From a letter of F. Bessel to A. von Humboldt in 1836

Neutron Stars



Mass: 1.2-2.0 Msun

Tiny Size: 10-15 km

Huge Density: 2-10 nuclear density

Strong Gravity: surface radius at just 2-3 Rs

Strong Magnetic Field: 10**8 – 10**15 Gauss

Fast rotations: 0.001 – 10 s

Neutron Stars

Mass: 1.2-2.0 Msun

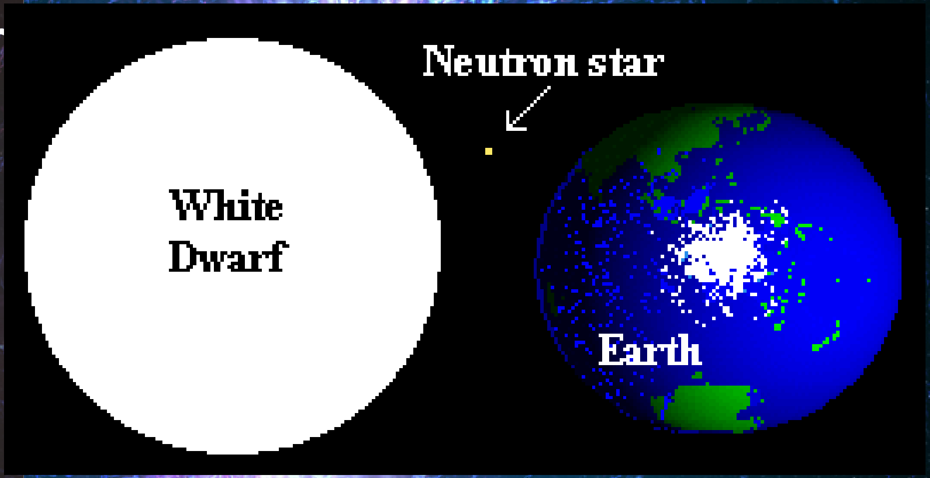
Tiny Size: 10-15 km

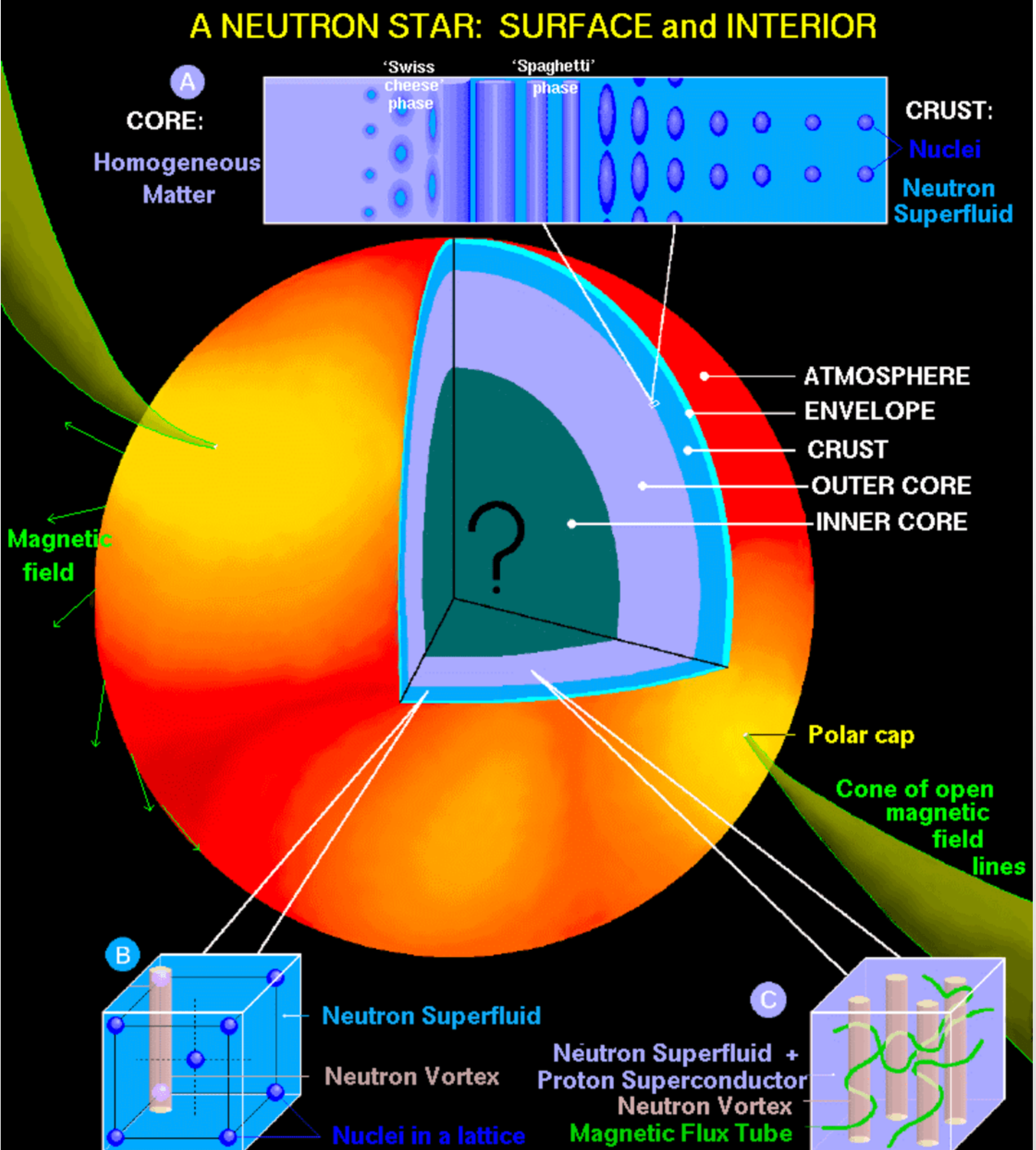
Huge Density: 2-10 nuclear density

Strong Gravity: surface radius at just 2-3 Rs

Strong Magnetic Field: 10**8 – 10**15 Gauss

Fast rotations: 0.001 – 10 s

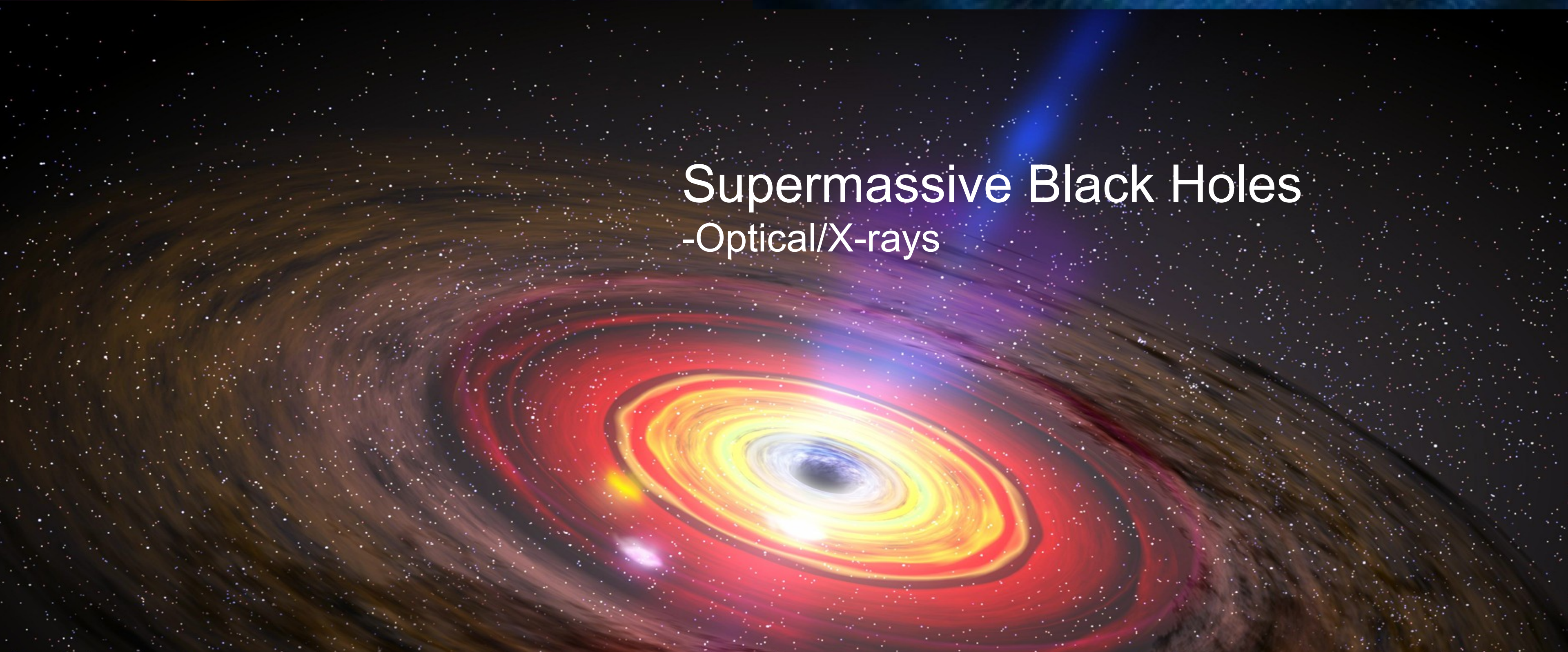




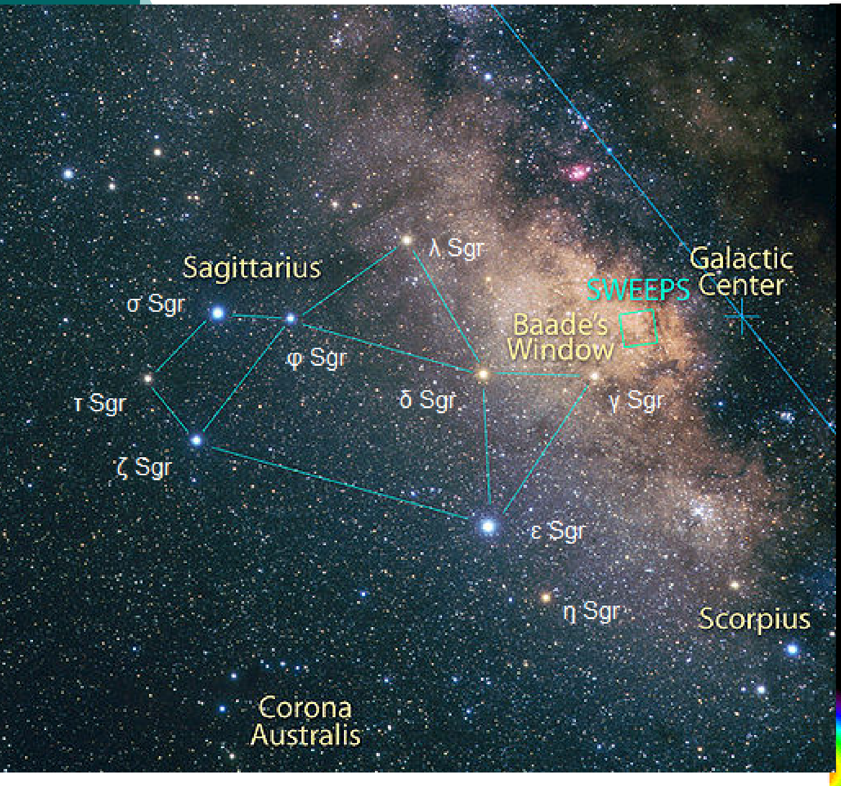
Neutron Stars

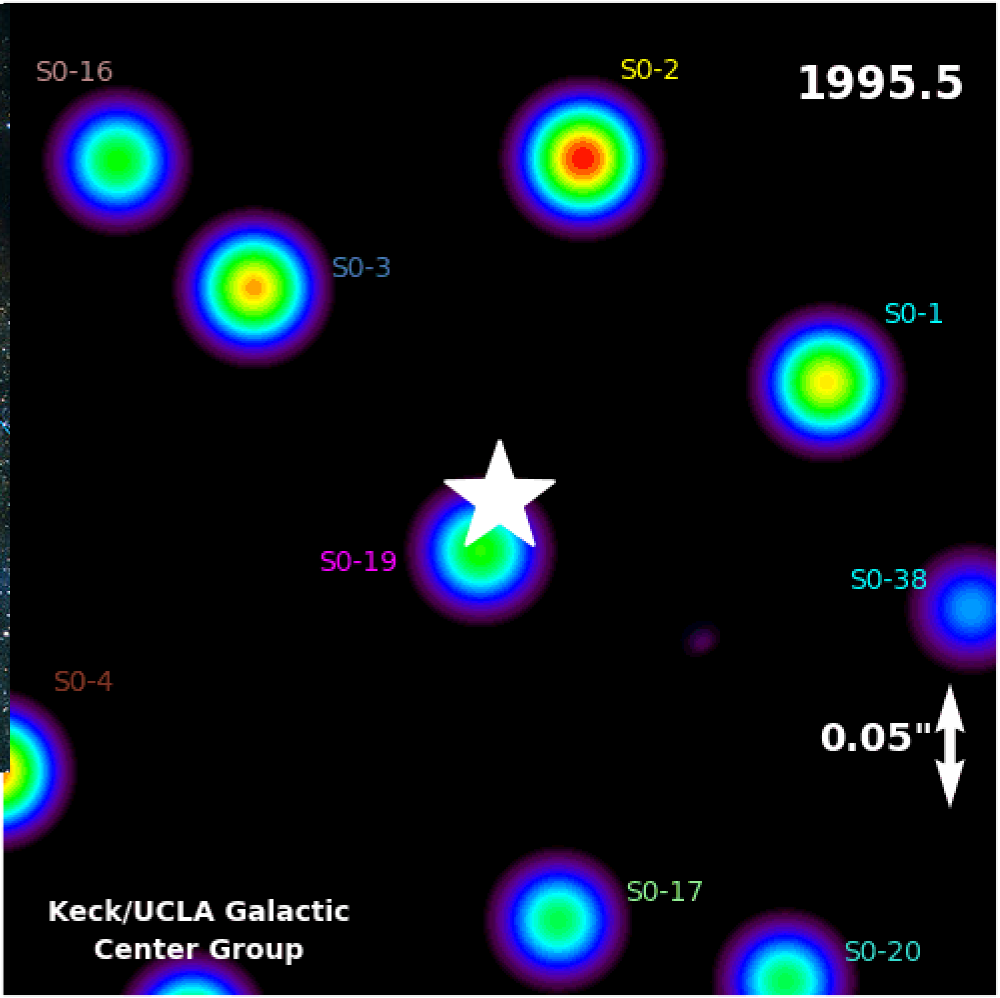
Neutron Star Structure


Accreting Black Holes
- X-rays (spectra, timing)

Binary Black Holes
-Gravitational Waves

Supermassive Black Holes
-Optical/X-rays

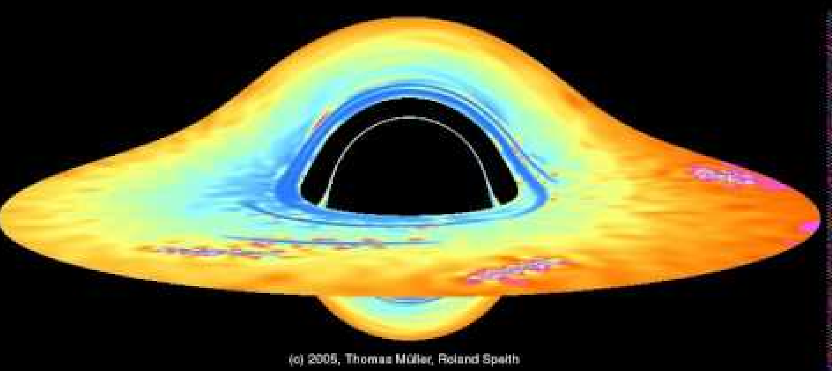
Supermassive BH in the Galactic Center

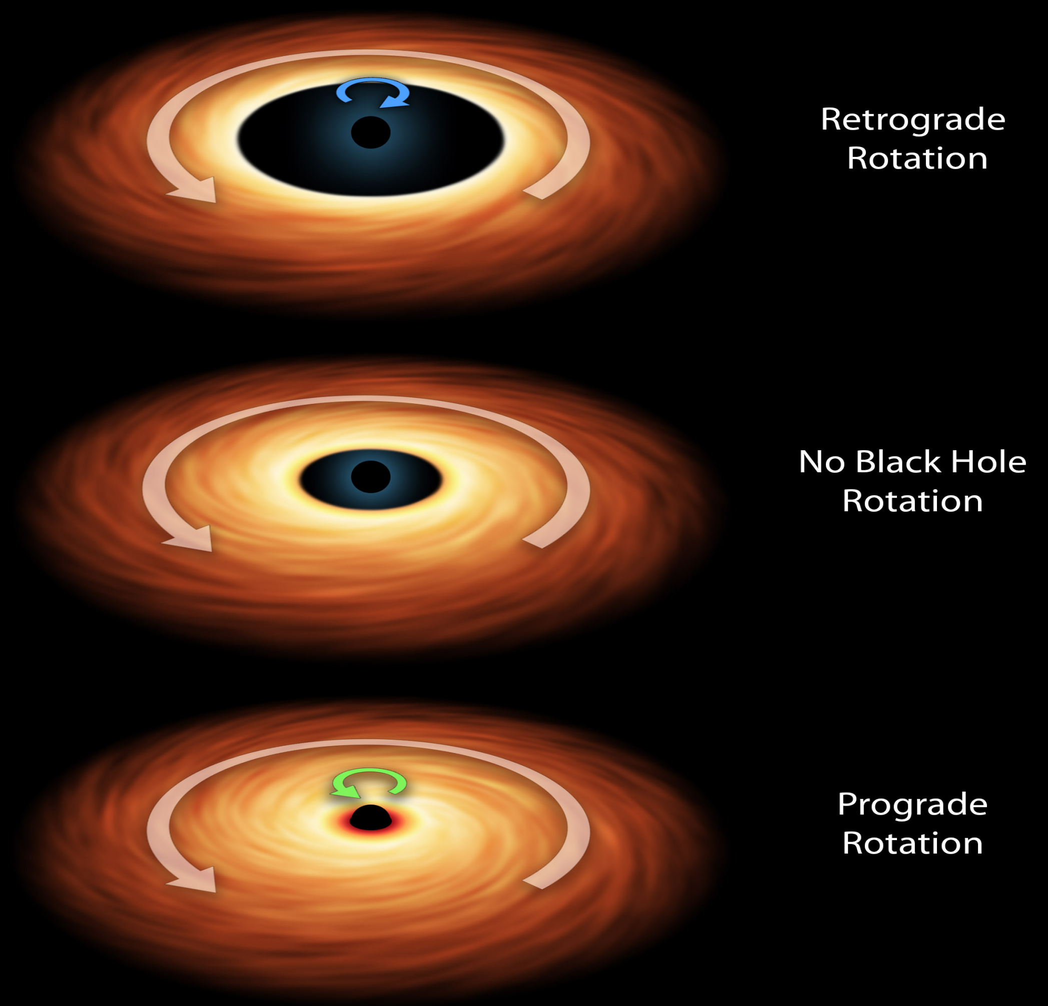




Central Mass of ~4 Million Msun

Innermost Stable Circular Orbit

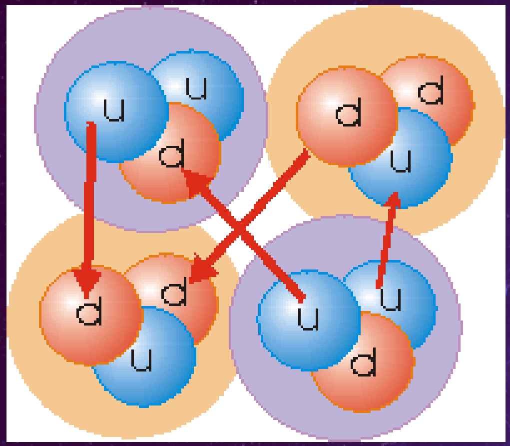




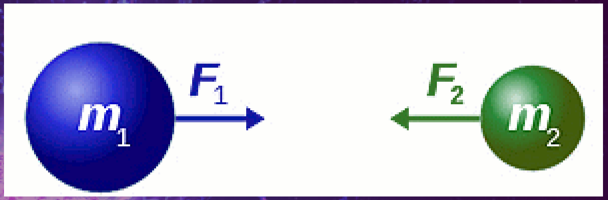
Innermost stable circular orbit (ISCO): *smallest orbit in which a test particle can stably orbit a massive object in general relativity*.

Fundamental Forces

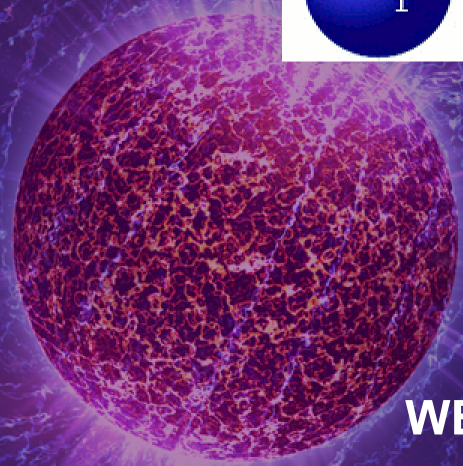
STRONG INTERACTION



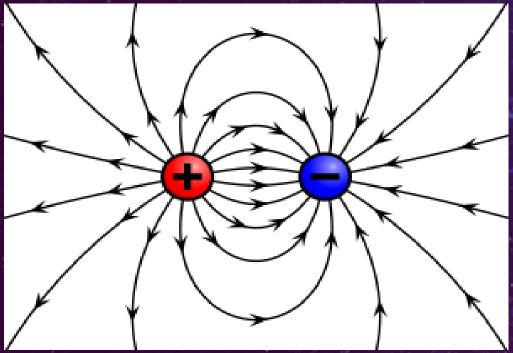
GRAVITY



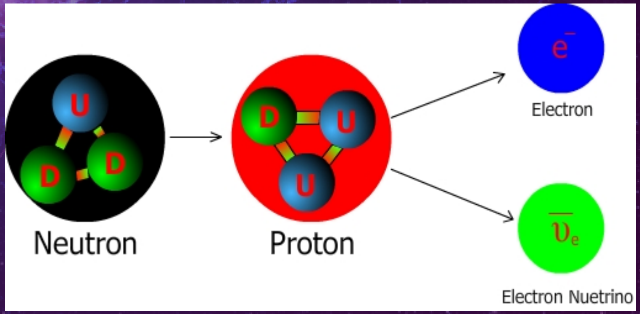
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$



ELECTROMAGNETISM



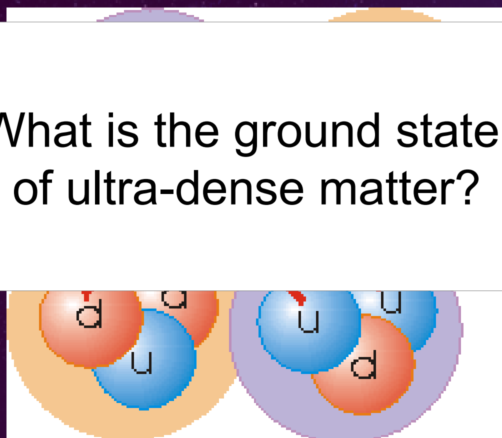
WEAK INTERACTION



Fundamental Forces: Key Questions

STRONG INTERACTION

What is the ground state of ultra-dense matter?

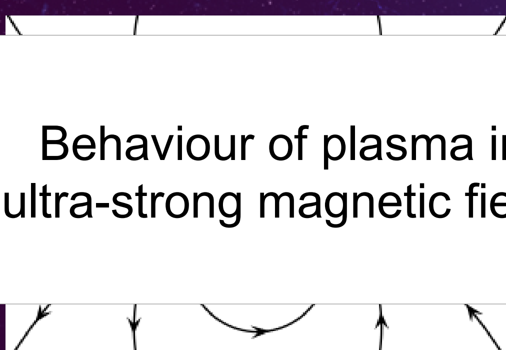


GRAVITY

Test GR in strong gravity regime

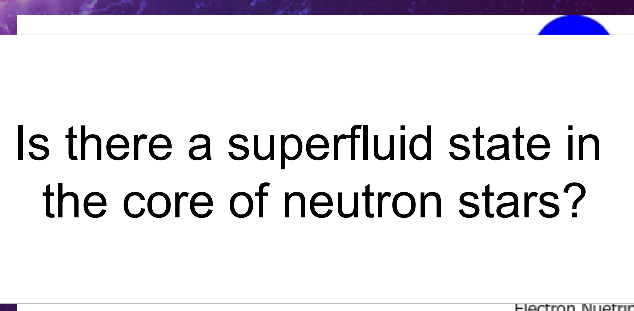
ELECTROMAGNETISM

Behaviour of plasma in ultra-strong magnetic fields



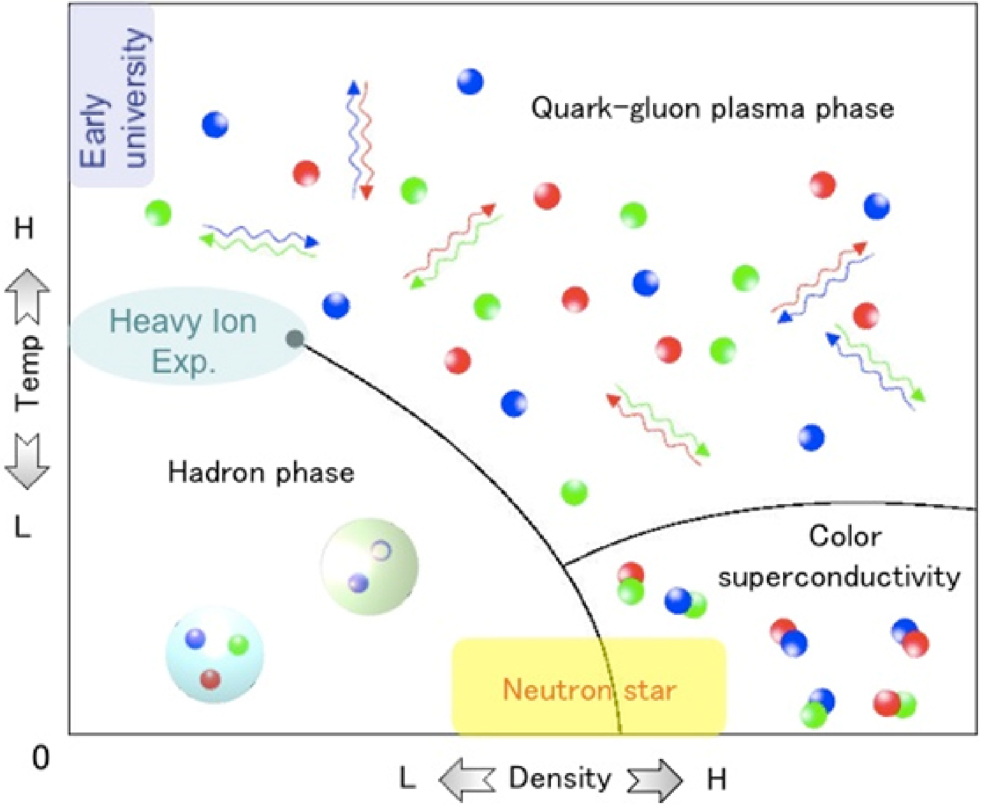
WEAK INTERACTION

Is there a superfluid state in the core of neutron stars?



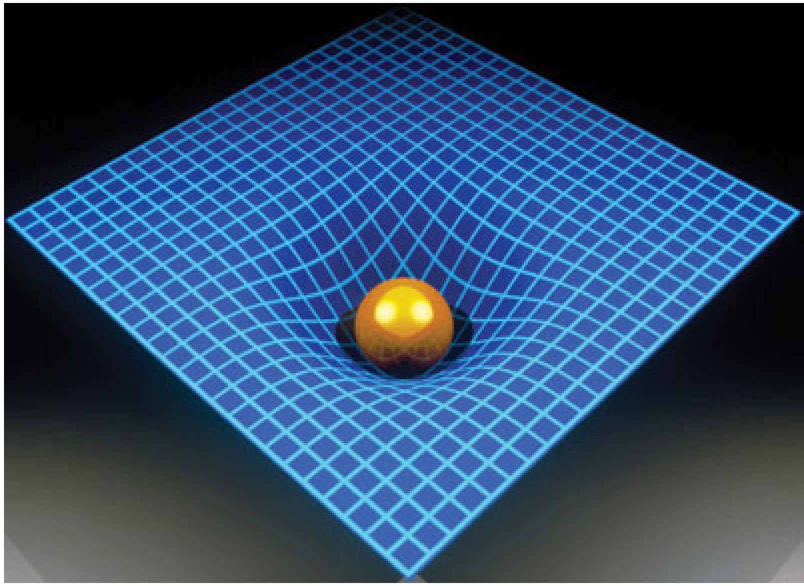
Extreme Regimes

STRONG INTERACTION



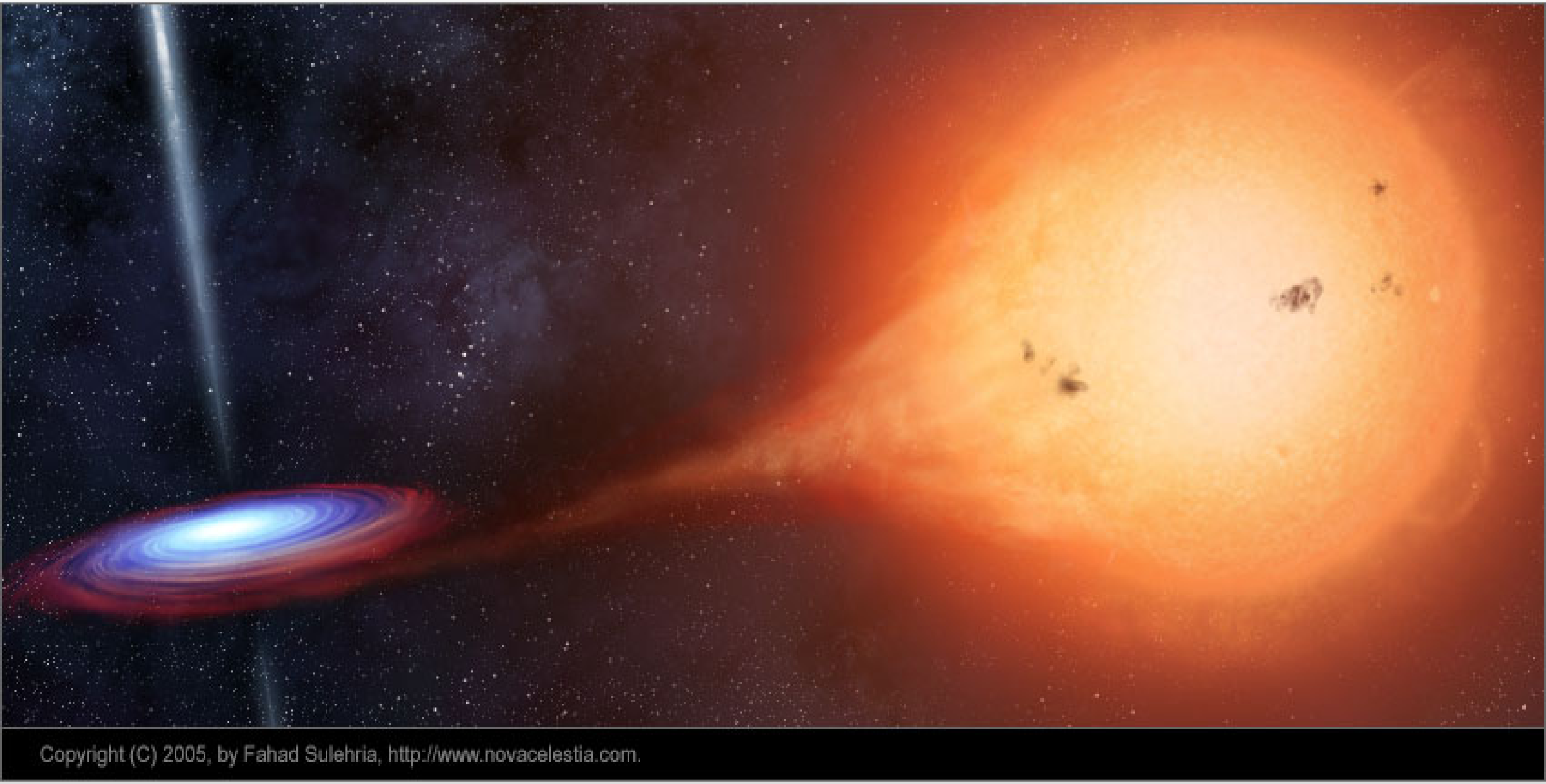
Which properties does Ultra-Dense Matter have ?

GRAVITY



Is General Relativity the correct theory of gravity ?

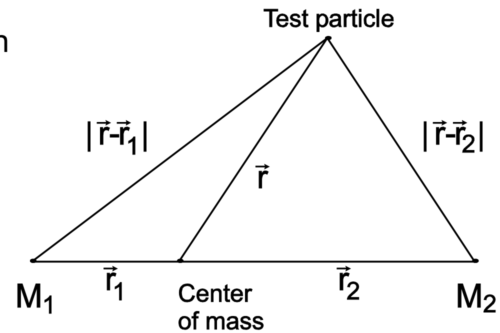
Cataclysmic Variables & Low Mass X-Ray Binaries

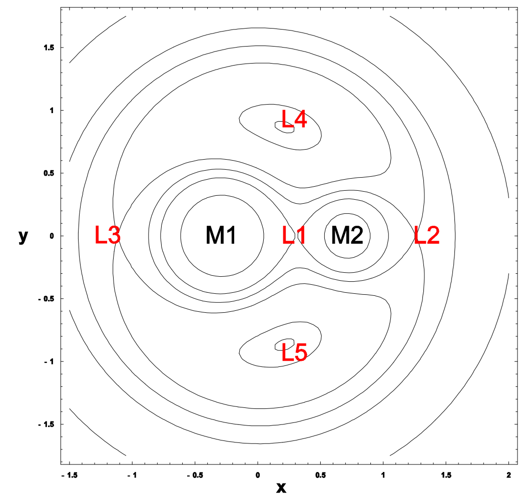


The Roche potential

Any gas flow between two stars is governed by the Euler equation (conservation of momentum for each gas element):

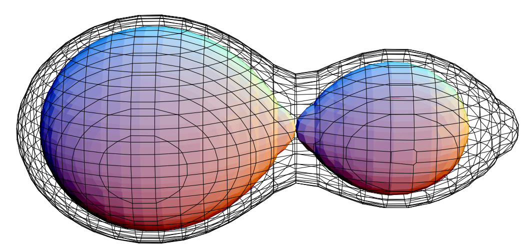
$$\rho \frac{\partial \vec{v}}{\partial t} + \rho \vec{v} \cdot \nabla \vec{v} = -\nabla P + \vec{f}$$





In the co-rotating reference frame of a binary it becomes:

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho \left(\vec{v} \cdot \nabla \right) \vec{v} = -\nabla P - 2\omega \times \vec{v} - \rho \nabla \varphi_R$$



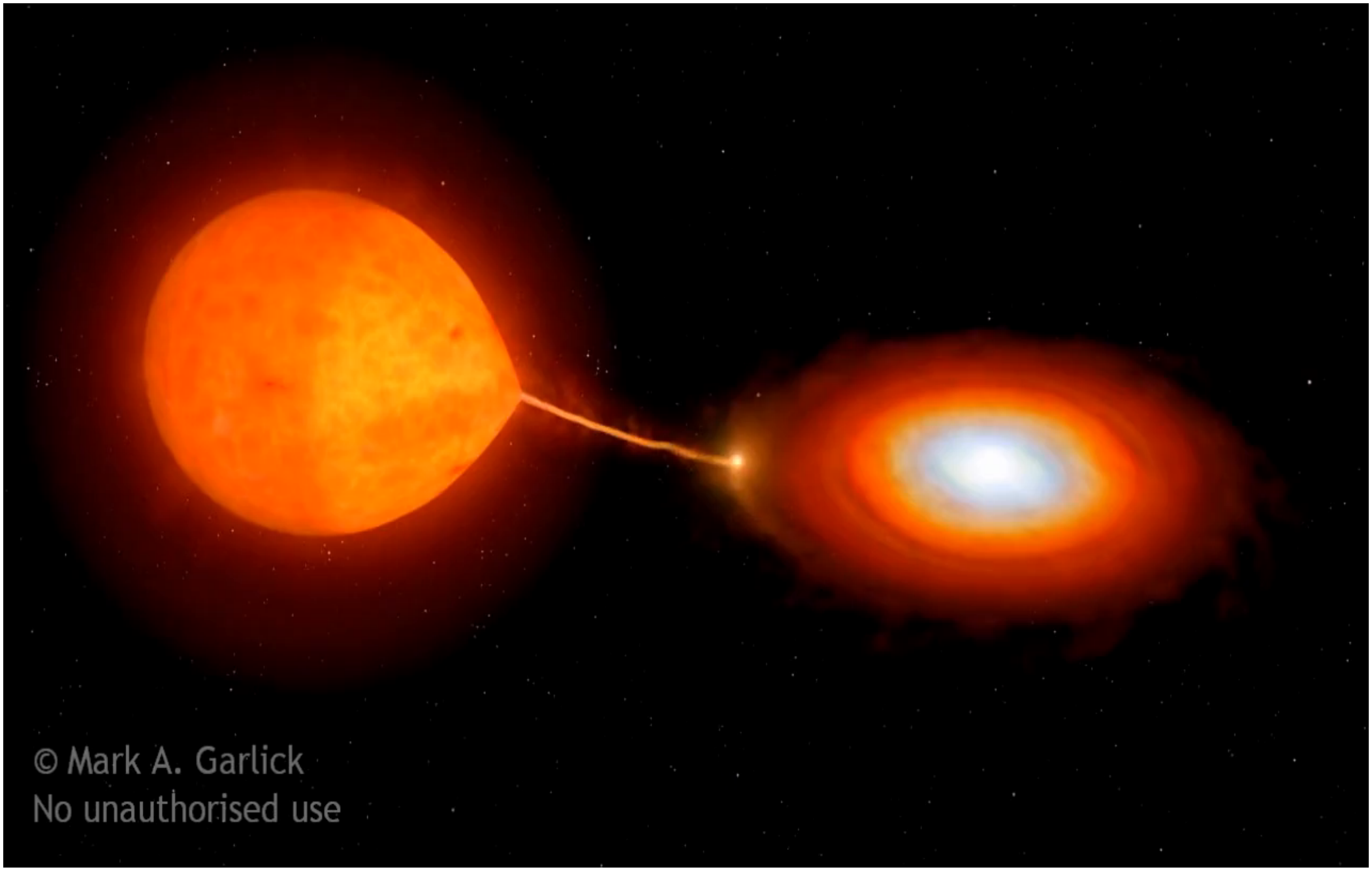
Convection of momentum through the fluid by velocity gradients

Coriolis force

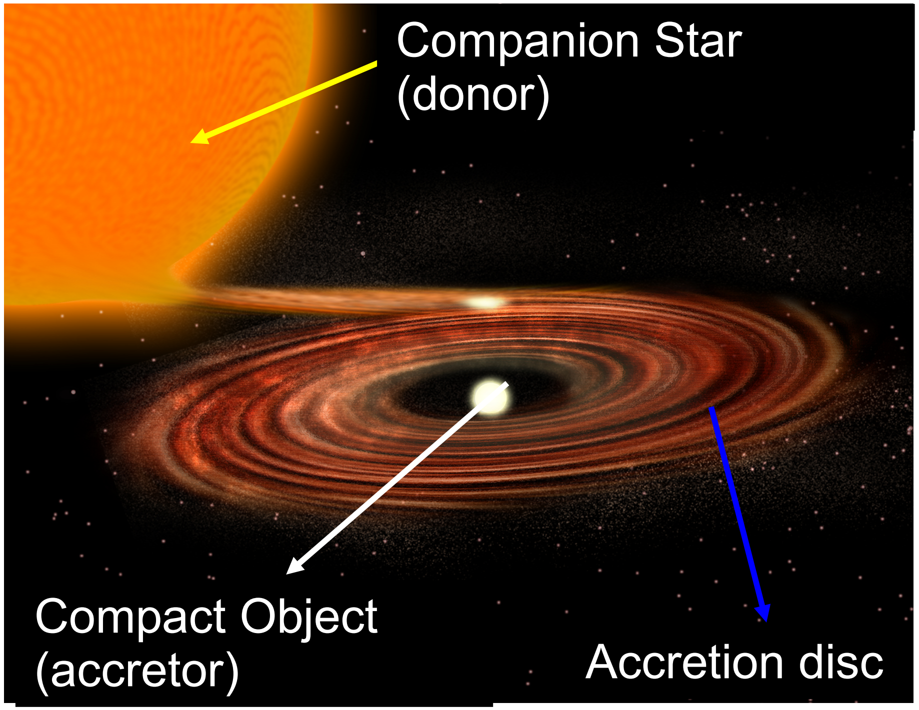
Gravitational +centrifugal potential

$$\varphi_R = -\frac{GM_1}{|\vec{r} - \vec{r}_1|} - \frac{GM_2}{|\vec{r} - \vec{r}_2|} - \frac{1}{2}\left(\vec{\Omega}_B \times \vec{r}\right)^2$$

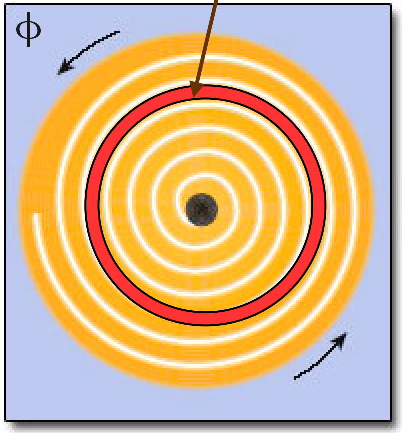
X-ray binaries: the Roche potential



Accretion discs



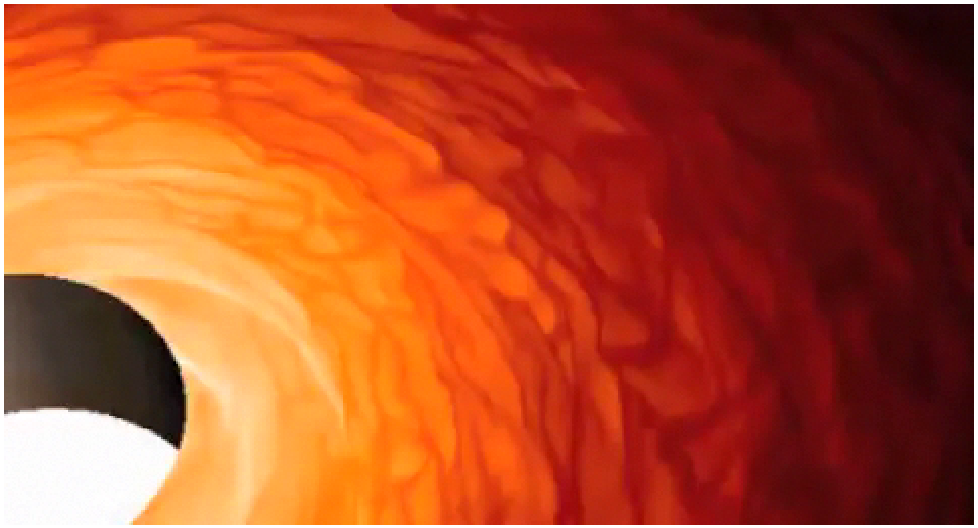
Circularization radius $R_{circ.} = \frac{GM}{v_\phi}$



Accretion discs are the “medium” through which the gravitational potential energy is first transformed into kinetic energy and then transformed into thermal energy (mainly radiation) through viscosity

Accretion discs are important because they “lit up” the compact object

Viscosity



Accretion dics are usually plasma of mostly hydrogen (from the stellar composition)

They form because of a source of viscosity which is not understood yet. (It's not molecular viscosity which is the one operating for water or air for example).

$$\Re = \frac{inertial\ forces}{viscous\ forces} = \frac{R\, v_\phi}{\nu}$$

Best candidate today is the Magneto-Rotational Instability (MRI) aka Balbus-Hawley instability

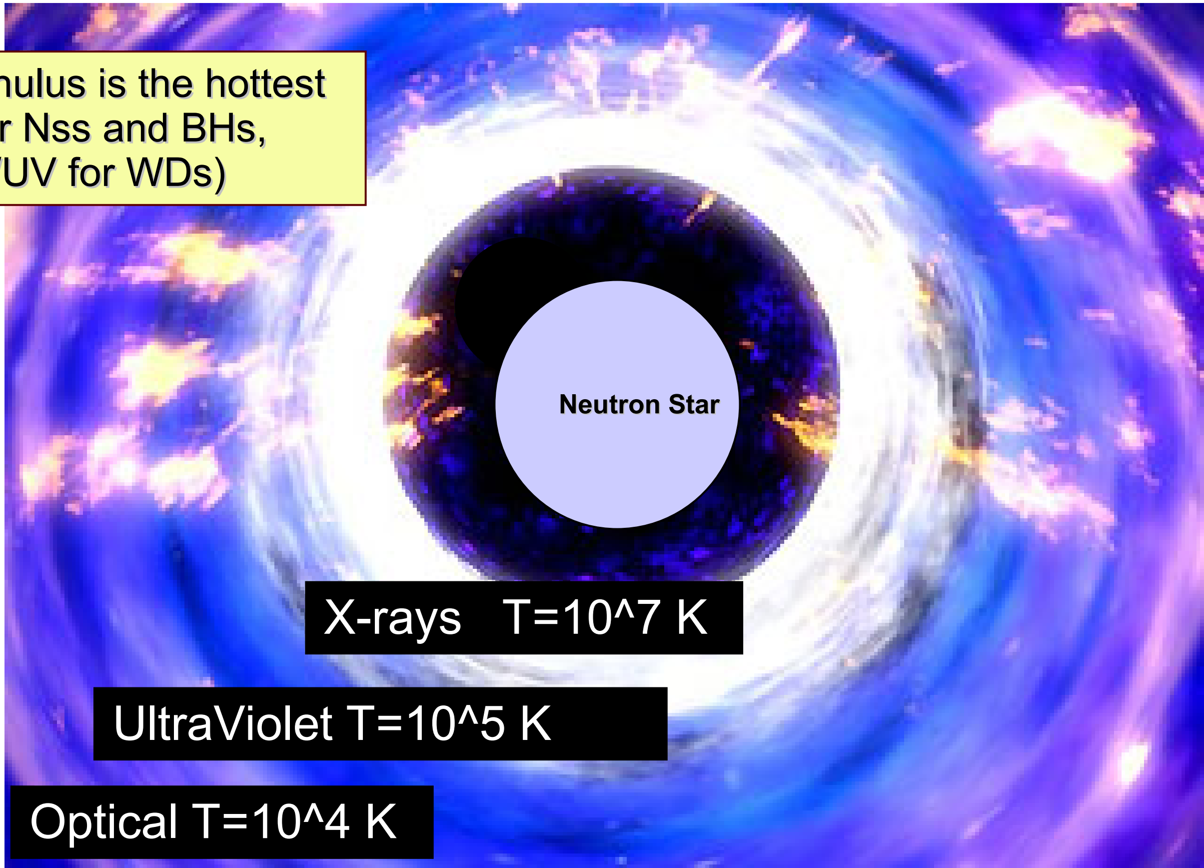
e.g., Balbus 2003

Accretion disc structure

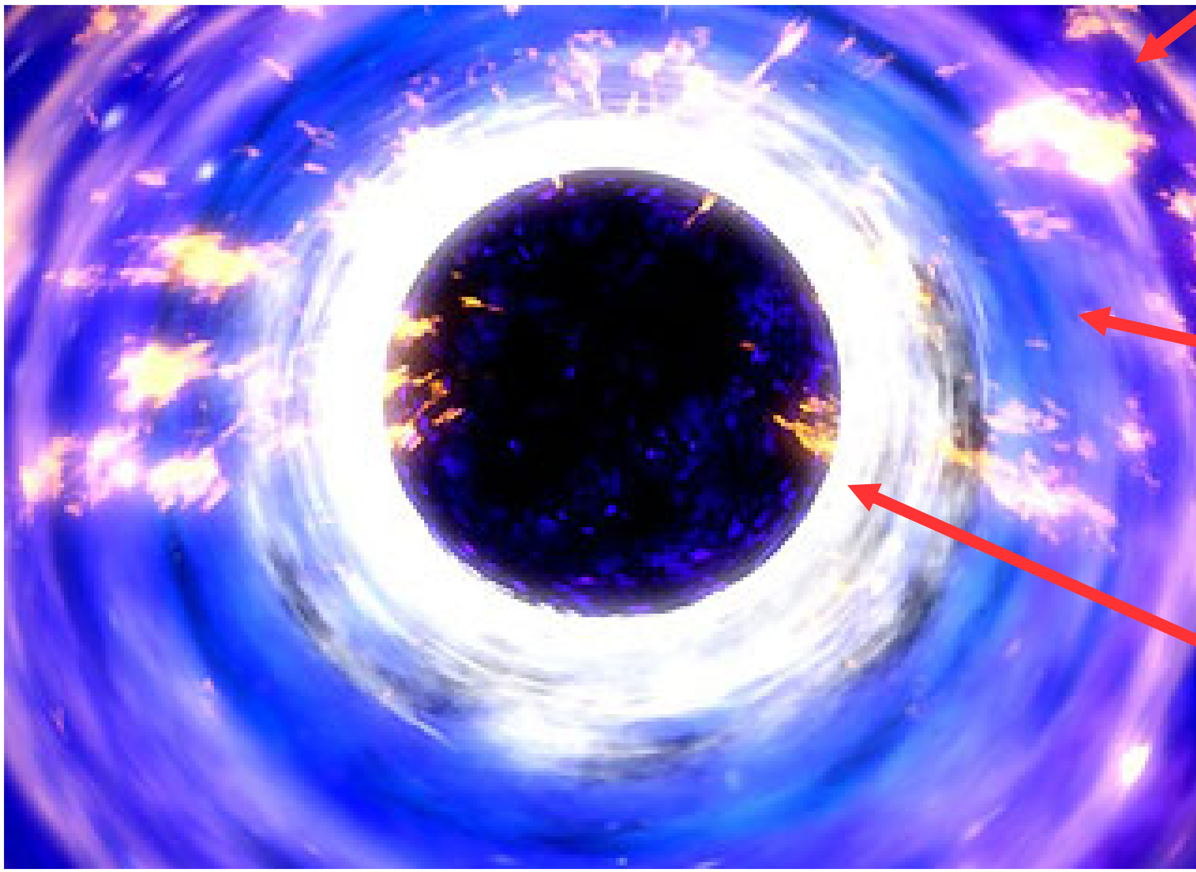
Gas rotates in the disc with “Keplerian frequency”, i.e., the inner annulus rotates faster than the outer one. → $\Omega_K = \sqrt{\frac{GM}{r^3}}$

The inner annulus is the hottest (X-rays for Nss and BHs, Optical/UV for WDs)

The disc is usually composed mainly by ionized Hydrogen (i.e., a plasma of electrons + protons)



Accretion disc regions



Outer Region: gas pressure dominates. Opacity: free-free absorption (i.e., inverse Bremsstrahlung)

Middle Region: gas pressure dominates Opacity: electron scattering

Inner Region: radiation pressure dominates. Opacity: electron scattering

Eddington Luminosity

If you have an e-/p+ plasma (ionized hydrogen), then radiation interacts with the electrons via electron scattering (or Compton, but let's assume we are in the Thomson limit).

If the radiation has a preferential radial direction, it can compete with radial forces like gravity. The radiation force each e- experiences is equal to the rate at which it absorbs momentum:

$$F_{rad} = \frac{\sigma_T f}{c}$$

where here "F" (g * cm /s2) means force and "f" flux (erg/s/cm2).
(units: cm2 * (erg/s/cm2) * (s/cm) = erg/cm = (g cm2/s2) / cm = g * cm /s2 → it is a force)

Gravity operates mainly on the p+, which then "drag" the electrons via Coulomb force:

$$F_G = \frac{-G\,M\,m_p}{r^2}$$

Eddington Luminosity

Since flux “f” is a luminosity over a distance, we can write, for a spherical symmetric source:

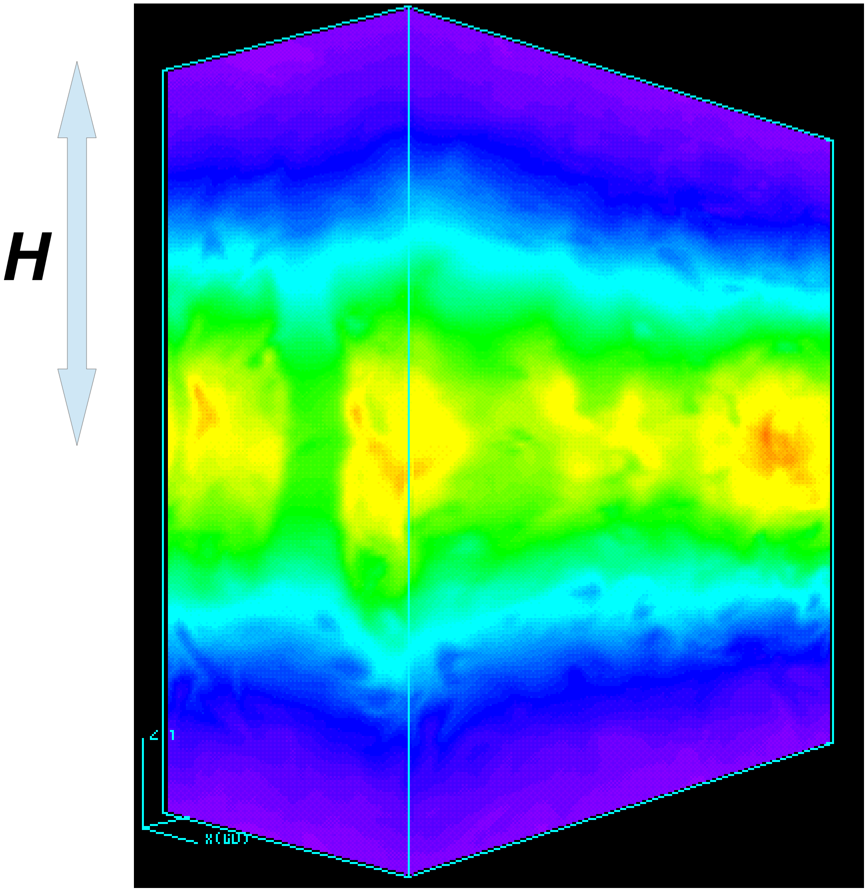
$$f = \frac{L}{4\pi r^2}$$

Putting this in the radiation force expression and equating with the gravitational force we obtain a limiting luminosity, called Eddington luminosity:

$$L_{Edd} = 4\pi G M m_p c / \sigma_T \approx 1.3 \times 10^{38} \left(\frac{M}{M_{sun}} \right) erg/s$$

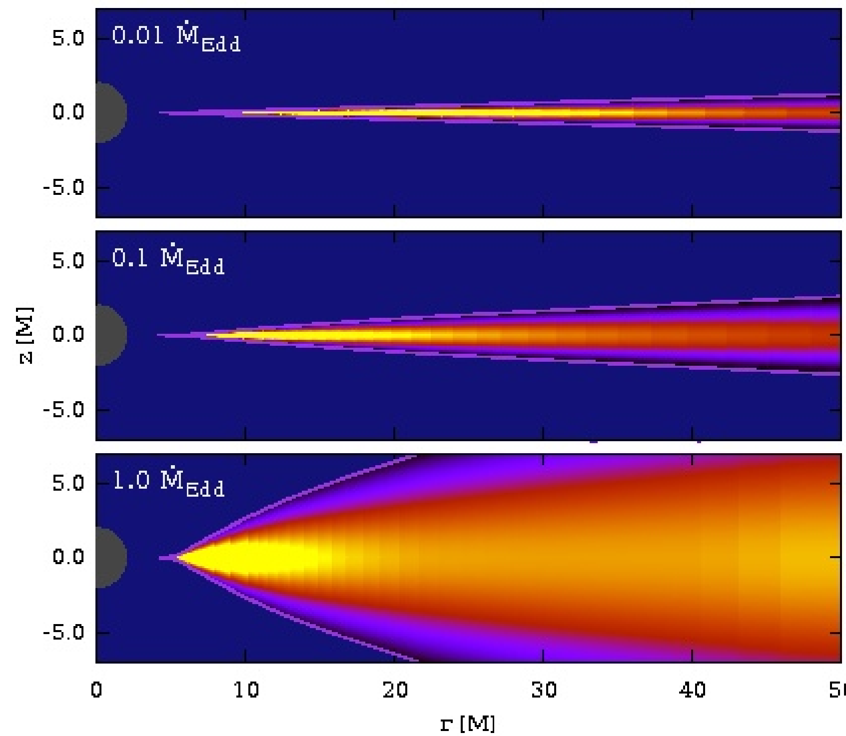
At greater luminosities the outward pressure of radiation would exceed the inward gravitational attraction and accretion would be halted. If all the luminosity of the source were derived from accretion this would switch off the source; if some, or all, of it were produced by other means, for example nuclear burning, then the outer layers of material would begin to be blown off and the source would not be steady. For stars with a given mass-luminosity relation this argument yields a maximum stable mass.

Accretion disc Vertical Structure



$$\frac{1}{\rho}\frac{dP}{dz} = -\frac{GM}{r^2}\frac{z}{r}$$

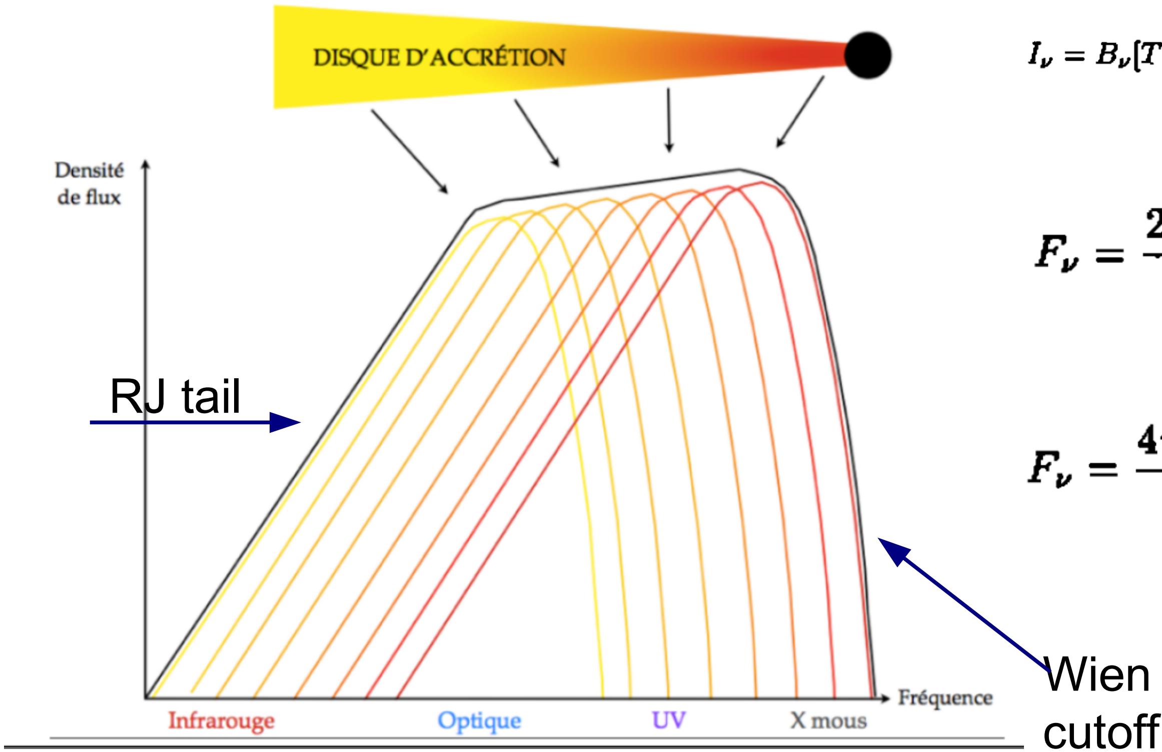
$$H = \left(\frac{P}{\rho}\right)^{1/2}\left(\frac{r^3}{GM}\right)^{1/2} \approx \frac{c_s}{\Omega}$$



- Vertical disc is in hydrostatic equilibrium
- Disk thickness changes with radial distance

e.g., Frank, King & Rane 2002

Spectrum of Accretion Disks



$$I_\nu = B_\nu[T(R)] = \frac{2h\nu^3}{c^2(e^{h\nu/kT(R)} - 1)} (\text{erg s}^{-1}\ \text{cm}^{-2}\,\text{Hz}^{-1}\ \text{sr}^{-1})$$

$$F_\nu = \frac{2\pi \cos i}{D^2} \int_{R_*}^{R_{\text{out}}} I_\nu\, R\, \mathrm{d}R$$

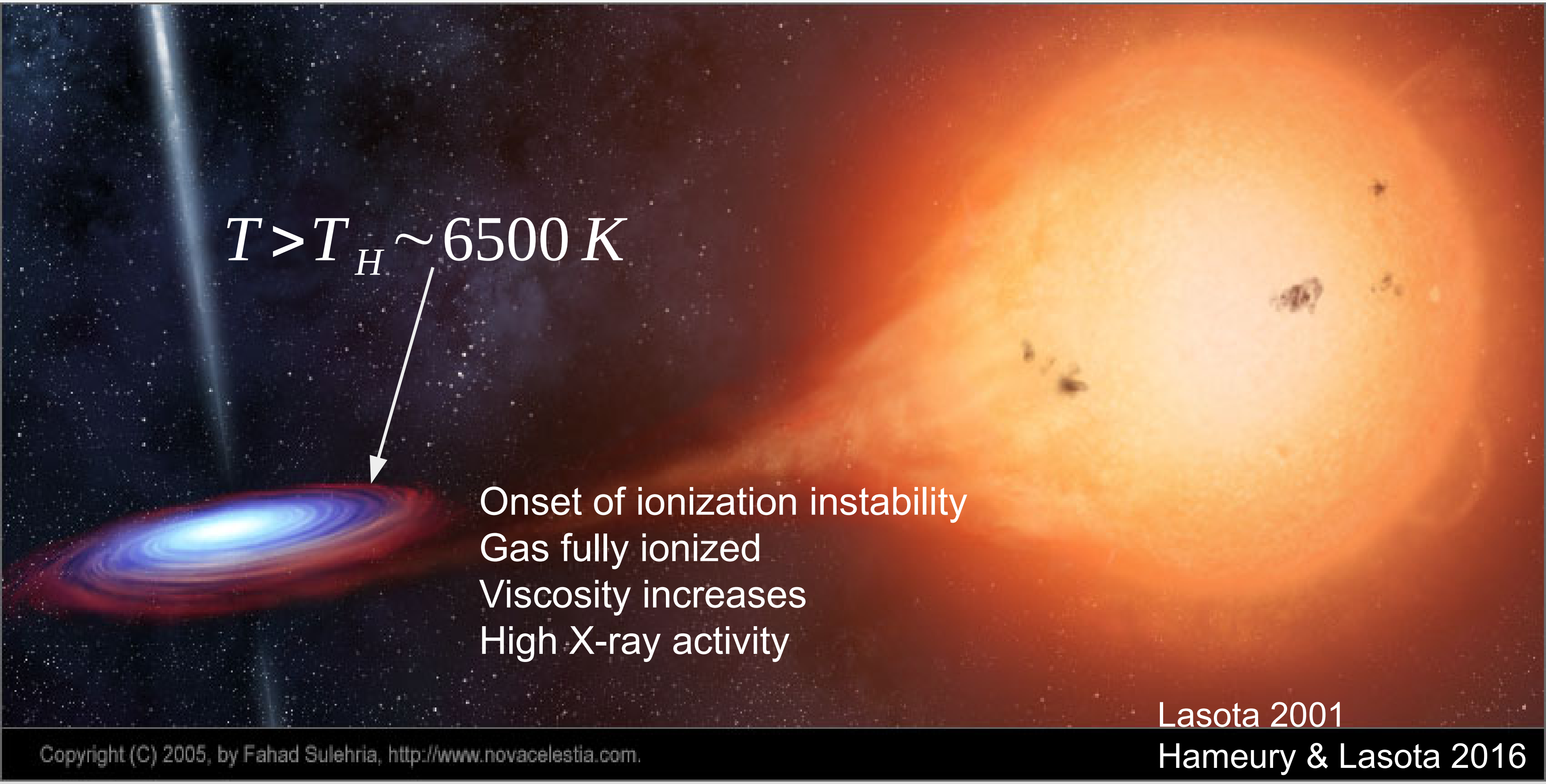
$$F_\nu = \frac{4\pi h \cos i\, \nu^3}{c^2 D^2} \int_{R_*}^{R_{\text{out}}} \frac{R\,\mathrm{d}R}{e^{h\nu/kT(R)} - 1}$$

See Compact Objects course

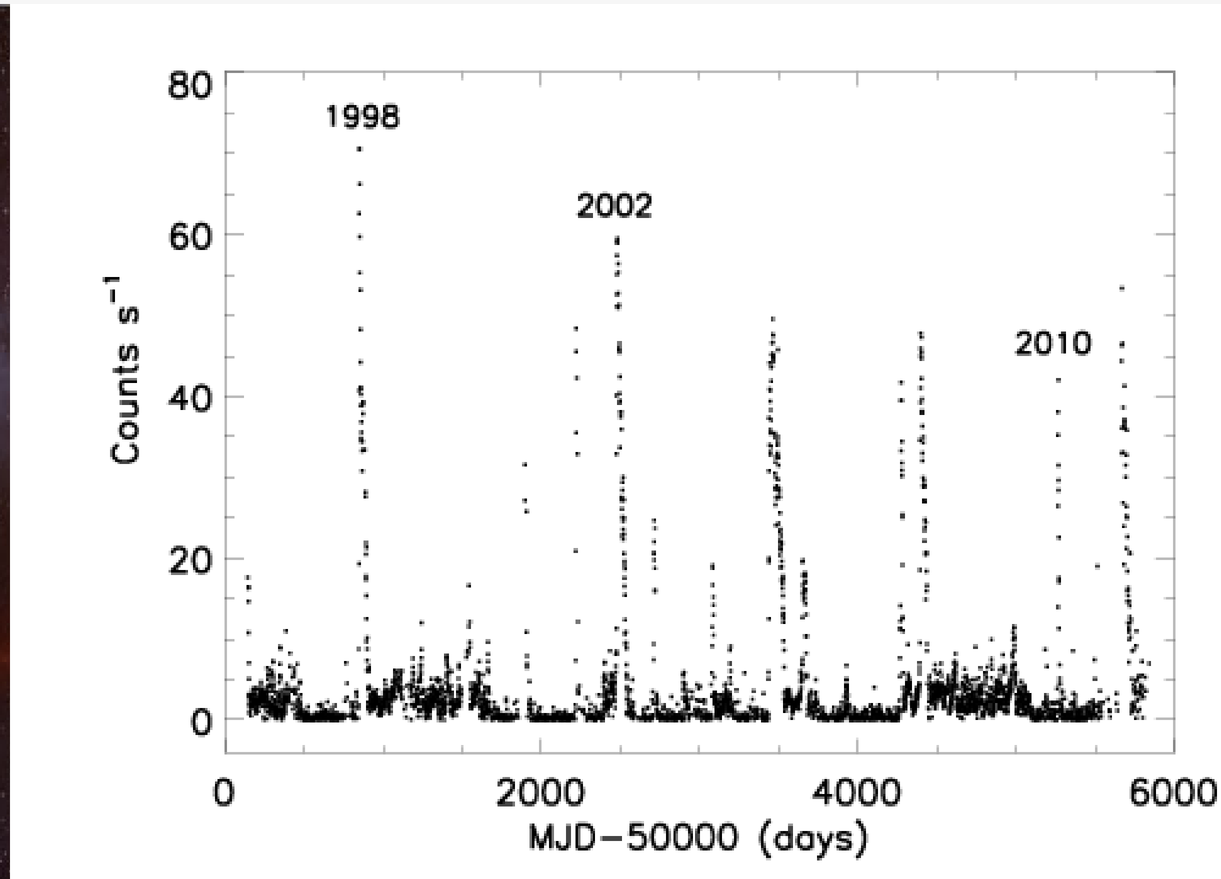
Intermediate part:

$$F_\nu \propto \nu^{1/3} \int_0^\infty \frac{x^{5/3}}{e^x - 1} \mathrm{d}x \propto \nu^{1/3}$$

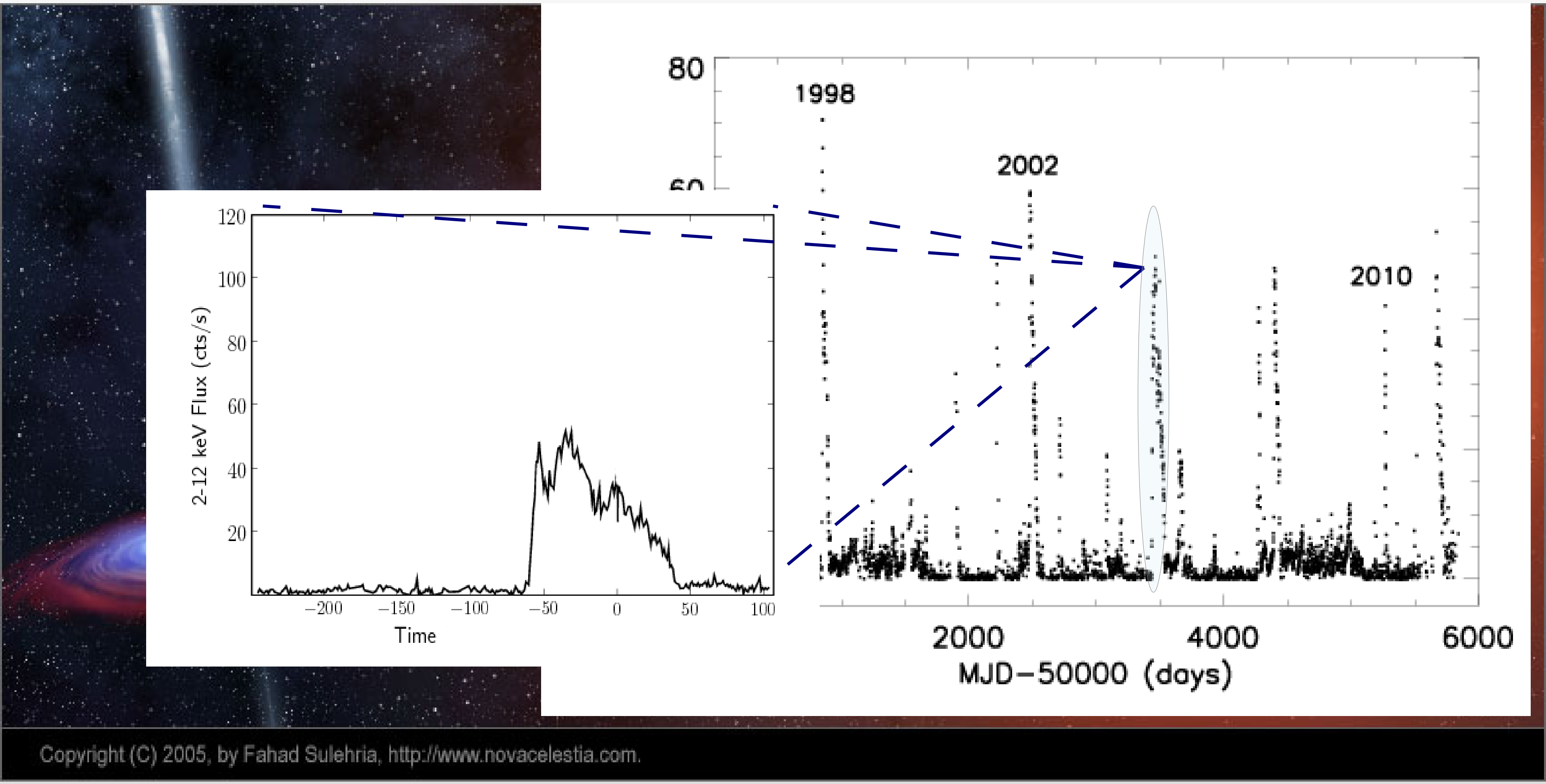
Low Mass X-Ray Binaries

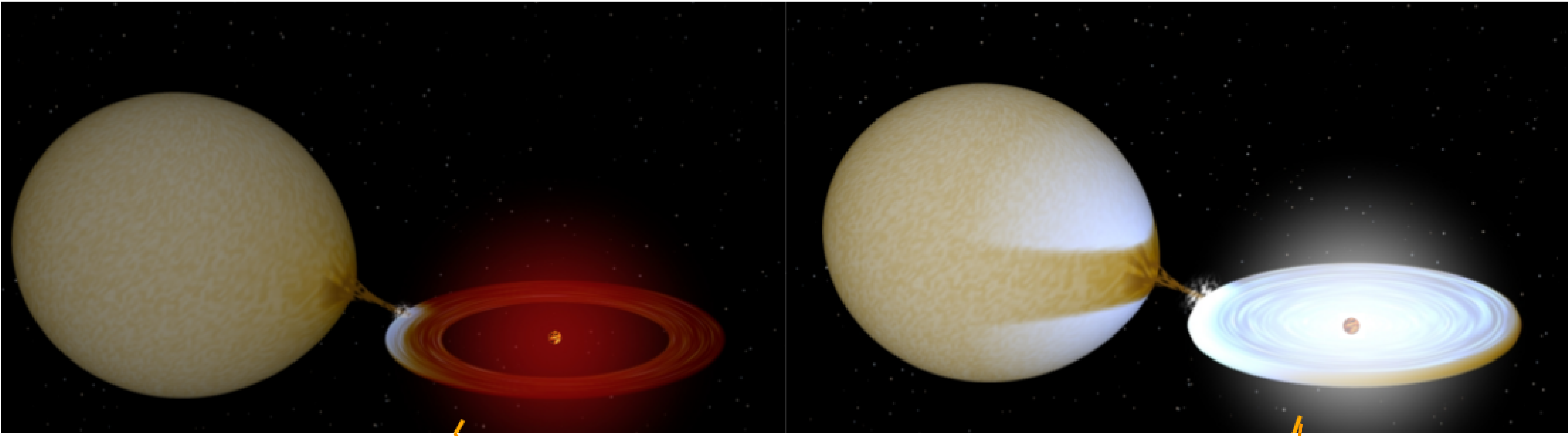


Low Mass X-Ray Binary Transients

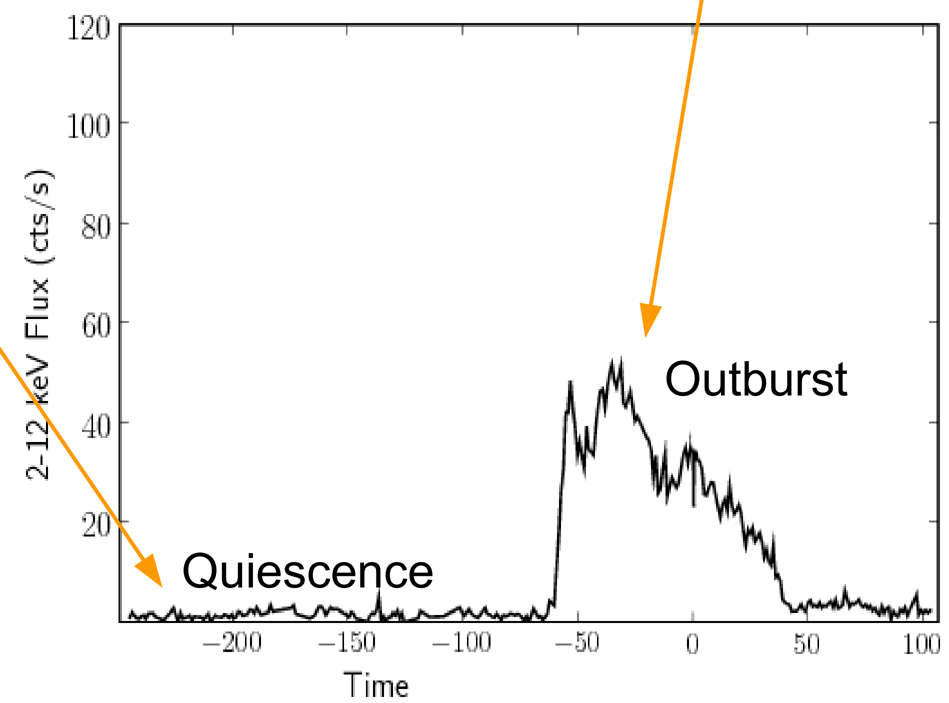


Low Mass X-Ray Binaries

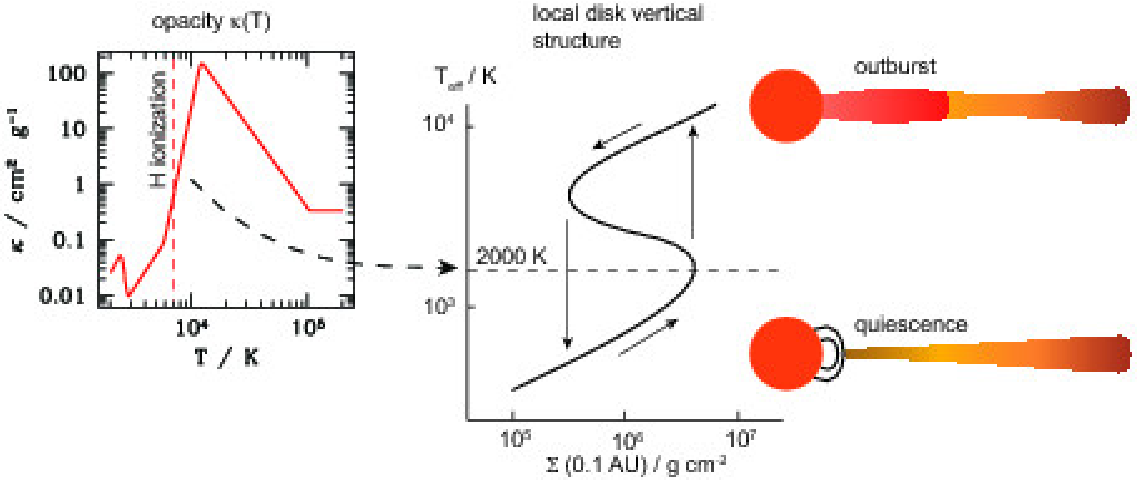


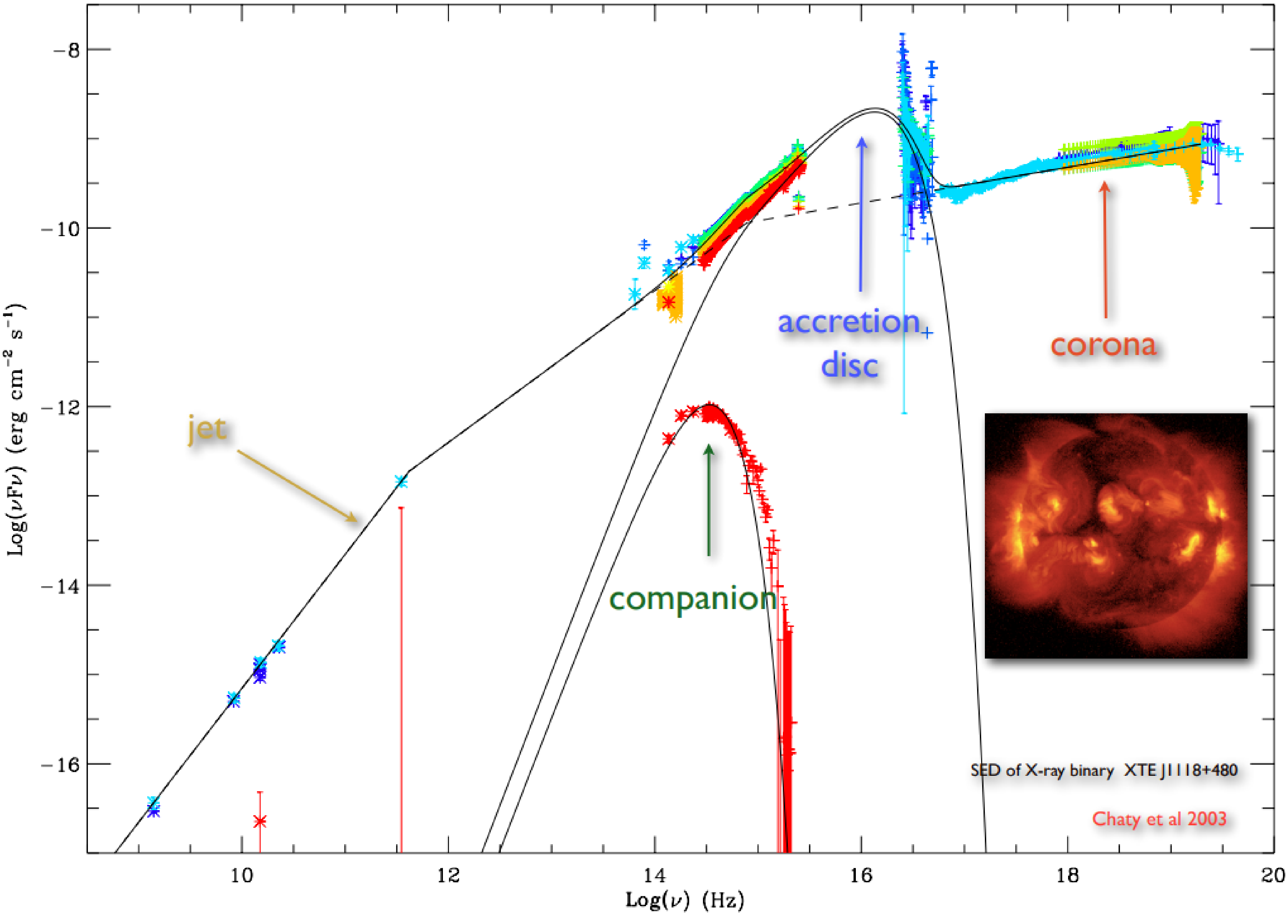


Transient behavior is common, but X-ray binary systems can also be persistent (disk always ionized).



Disk Instability and Production of X-rays

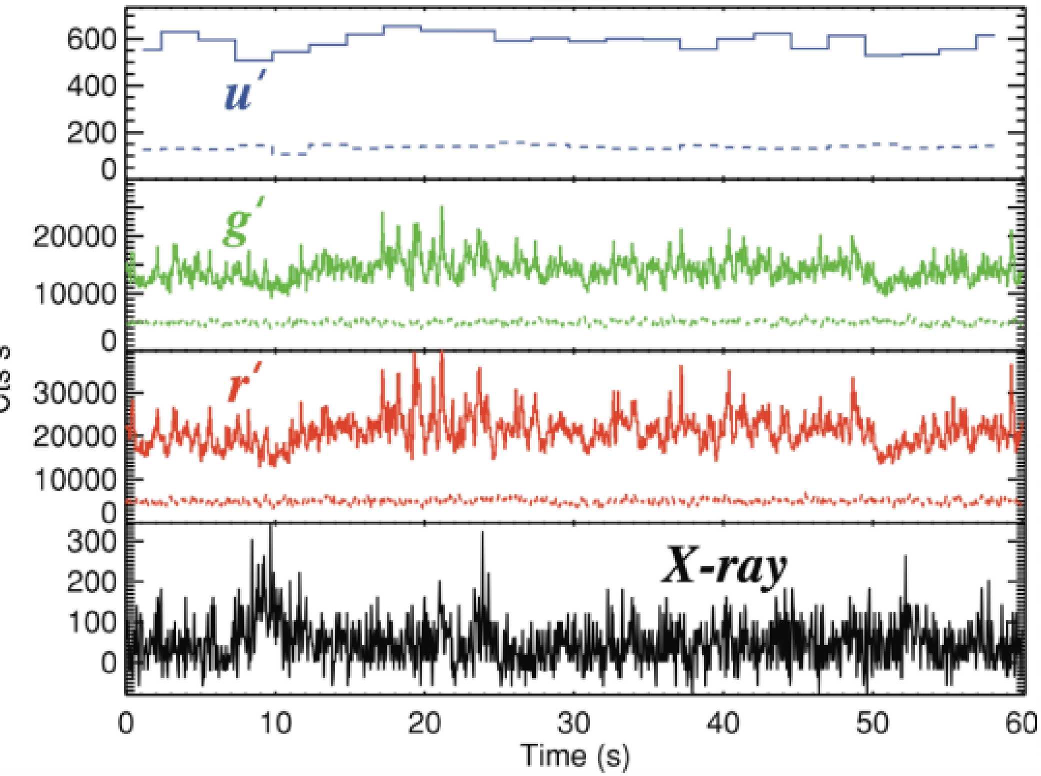




−8
−10
−12
−14
−16
10
12
14
16
18
20
Log(νFν) (erg cm⁻² s⁻¹)
Log(ν) (Hz)
jet
accretion
disc
corona
companion
SED of X-ray binary XTE J1118+480
Chaty et al 2003

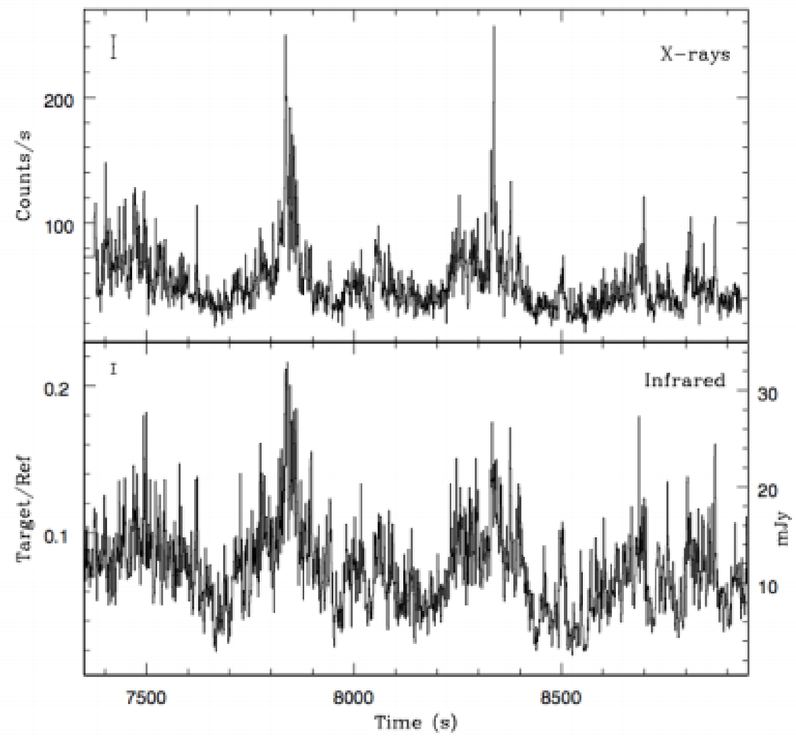
IR, Optical and X-ray Flickering

Optical



Gandhi et al. 2010

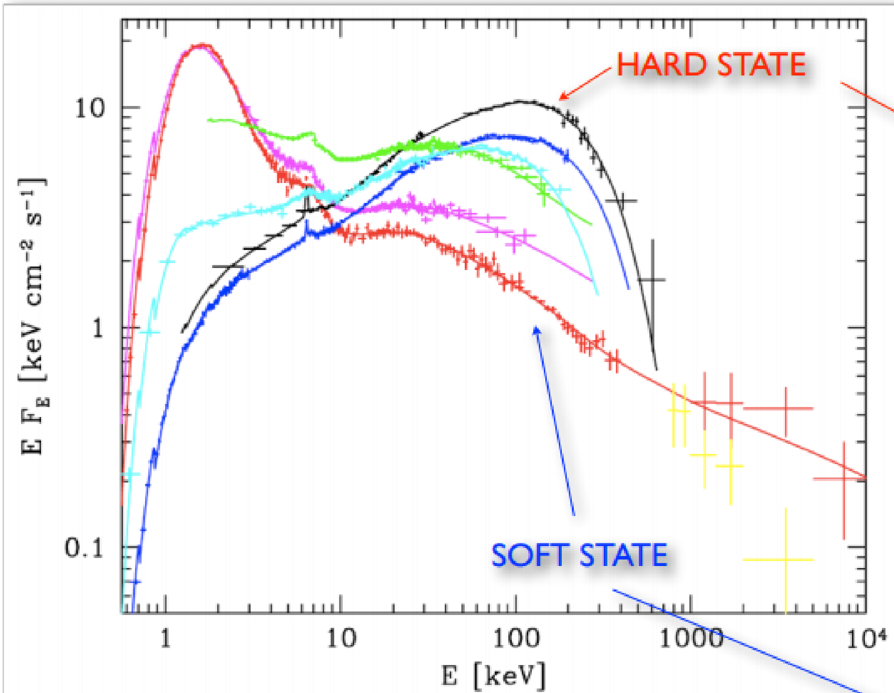
Infrared



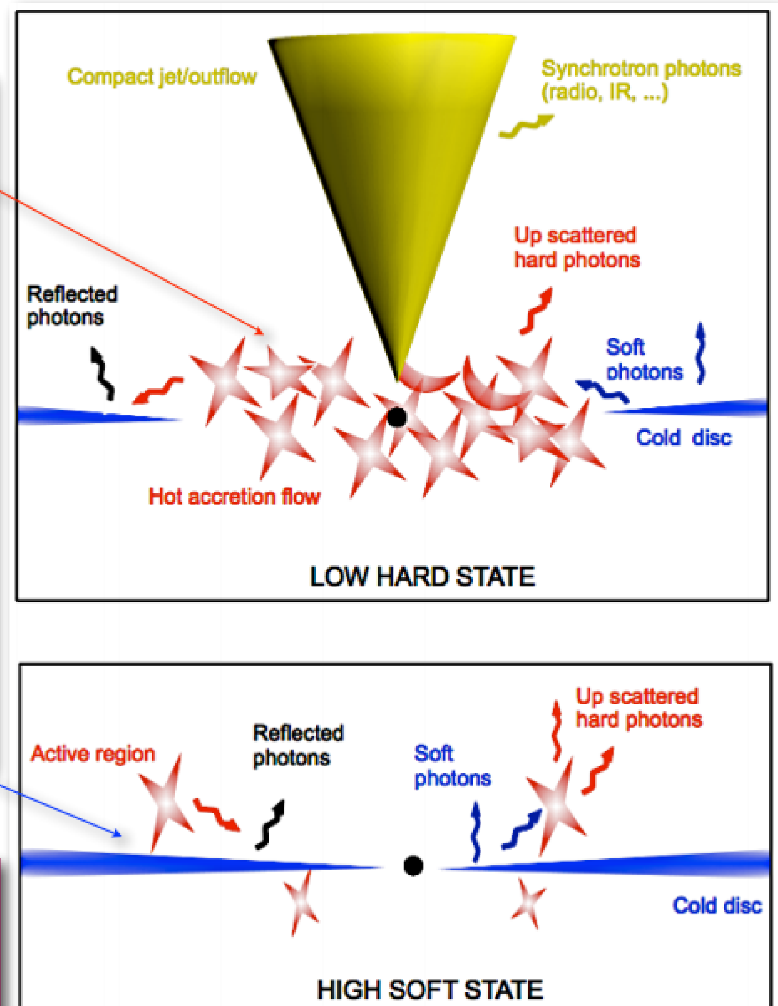
Casella et al. 2010

Observations of GX 339-4

Corona and Thermal/Non-thermal electrons



Zdziarski et al 2003



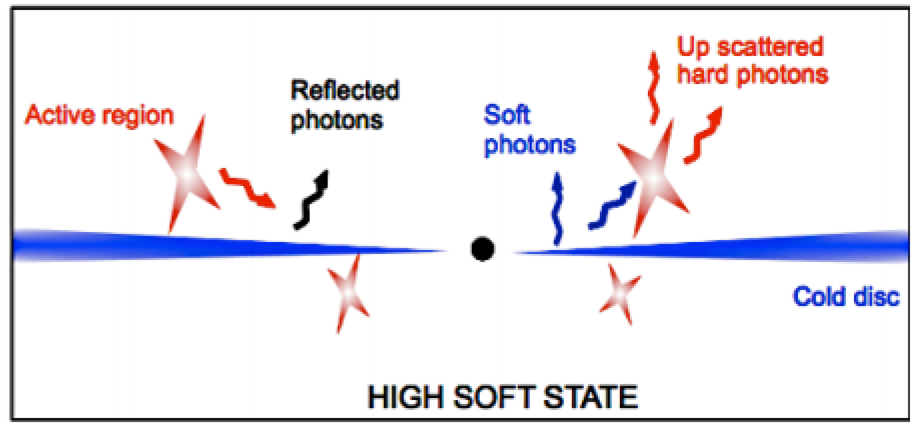
HARD STATE: (compact radio jet)
disc blackbody: weak / Corona: mostly THERMAL electrons

SOFT STATE:
disc blackbody: strong / Corona: mostly NON-THERMAL electrons

Soft State: disk + corona with non-thermal particle distribution

Observed in a narrow range of luminosities (~0.01 -0.1 L_{Edd})

X-ray spectrum dominated by soft thermal emission: perfect for tests of accretion disc models and measurements of parameter of the inner accretion disc



The high/soft state is seen with both black hole and neutron star accretors. In the latter case the nomenclature is different, but the basic physics is similar.

Note: X-ray variability in the accretion disk is *low.*

Hard State: faint disk + thermal Compton

Observed only at $L<0.1\ L_{Edd}$

Thermal emission from accretion disc barely detected (T_{in}~0.1 KeV)

X-ray emission dominated by power-law Γ = 1.4 – 1.9

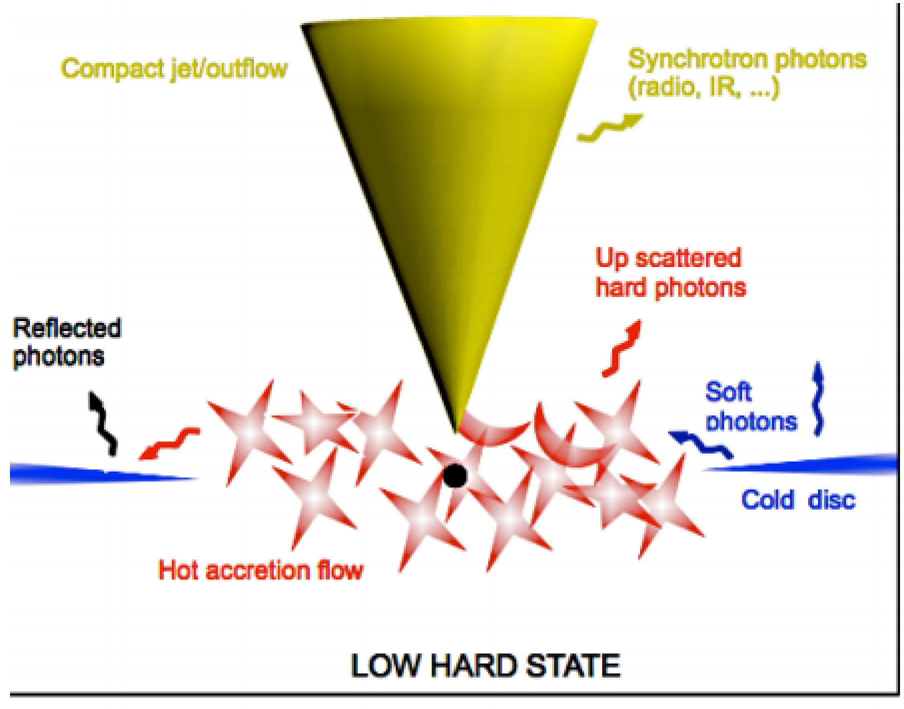
High energy cut-off at ~100 keV

Fits with Thermal comptonisation models:

$$\tau = 0.5 - 3.5,\ kT_e = 30 - 200\,\mathrm{keV}$$

Reflection amplitude is small R~0.3

Associated with the presence of a compact radio jet

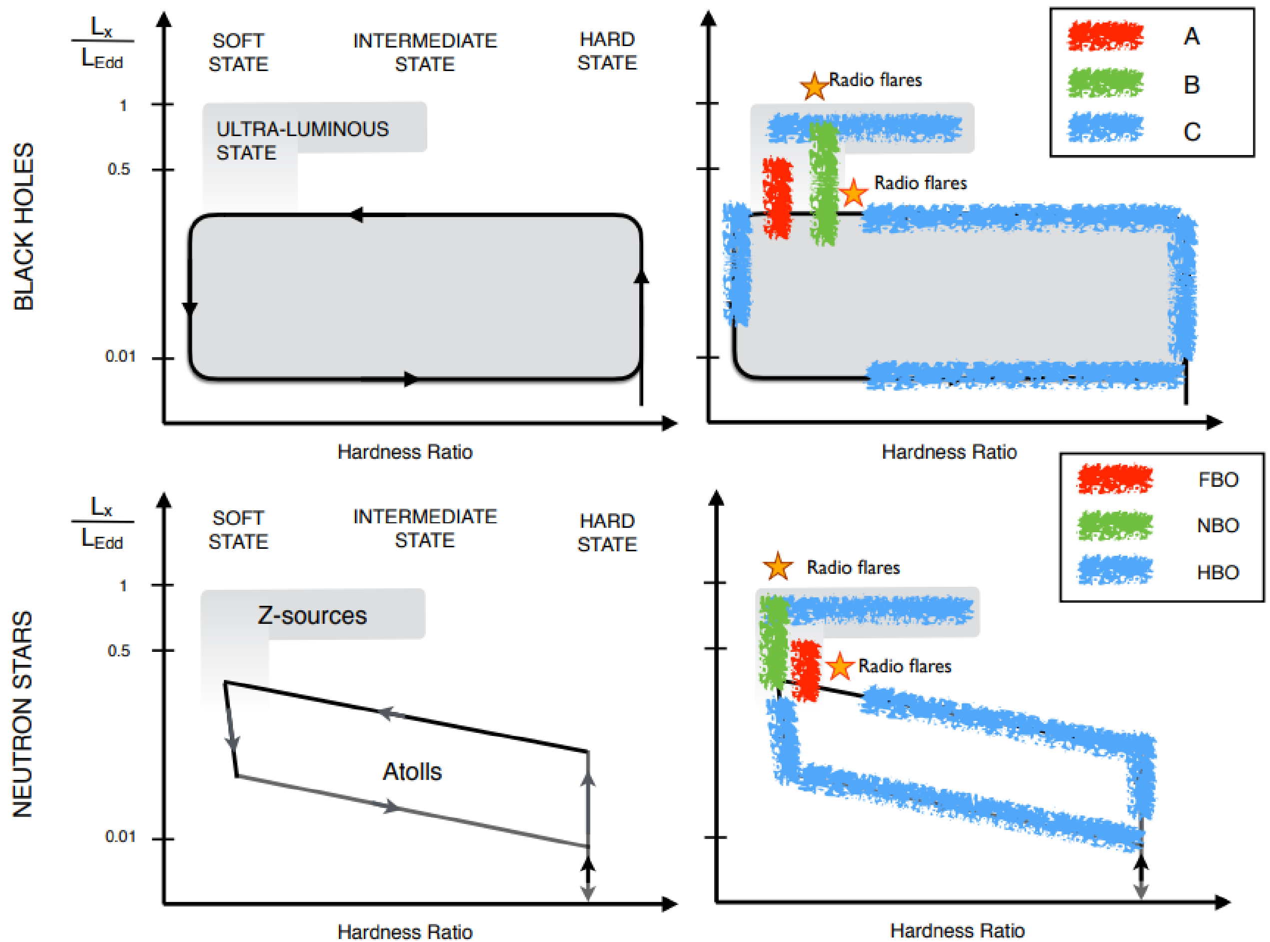


Reflection component is usually small ("reflection" in the sense that it is the result of radiation that is returned from the accretion disk by fluorescence or electron scattering)

The low/hard state is seen with both black hole and neutron star accretors. Again, the nomenclature is different, but the basic physics is similar.

The X-ray variability in the low/hard state is *high.*

Hardness-Intensity Diagram



X-Ray Variability

X-ray emitting region is small $R < 100 R_G \simeq 1500 \left(\frac{M}{10 M_\odot} \right) \quad \mathrm{km}$

Time scales in X-ray emitting region:

Orbital time-scale: $t_K = 0.3 \left(\frac{M}{10 M_\odot} \right) \left(\frac{R}{50 R_g} \right)^{-3/2} \quad s$

Vicous time-scale: $t_{vis} = (H/R)^{-2} \frac{t_K}{2\pi\alpha}$

- Thin disc, gas pressure dominated: $H/R \sim 10^{-2} \quad t_{vis} \simeq 10^4 t_K \sim 10^3 \mathrm{s}$

- Hot flow: $H/R \sim 0.3 \quad t_{vis} \simeq 10\, t_K \sim 1 - 10\, \mathrm{s}$

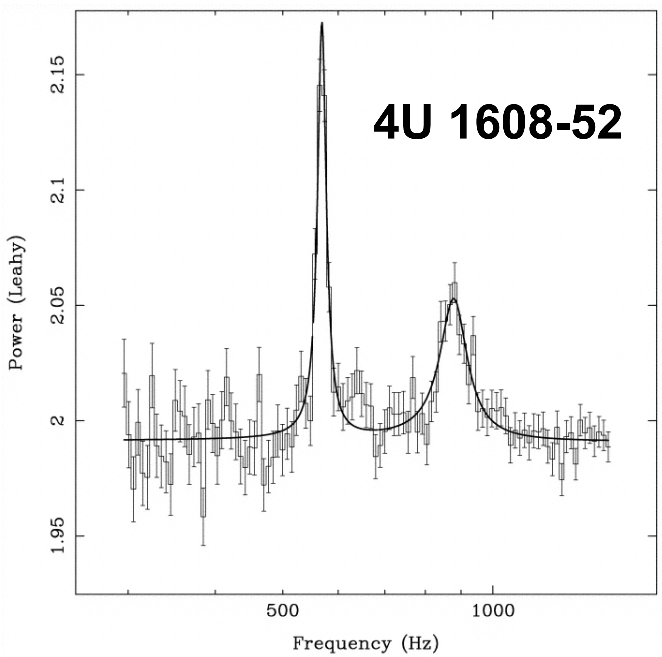
High Fourier frequencies can be produced in this region

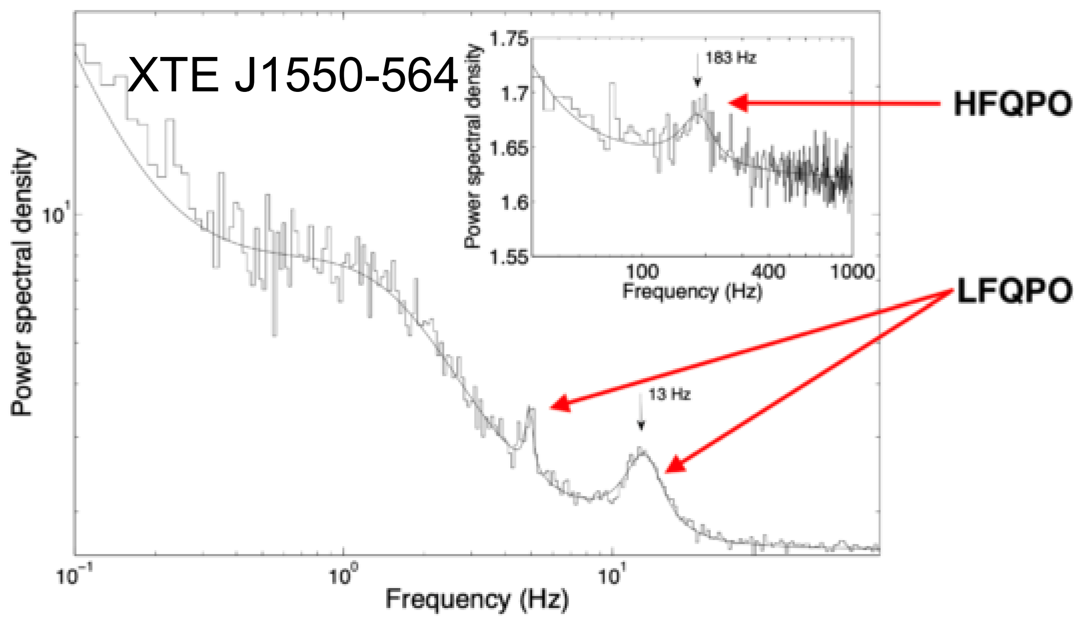
But the longest observed times scales are too long to be produced in the region of main energy release. Must be generated in the outer parts of the accretion flow

Quasi Periodic Oscillations: High Frequencies

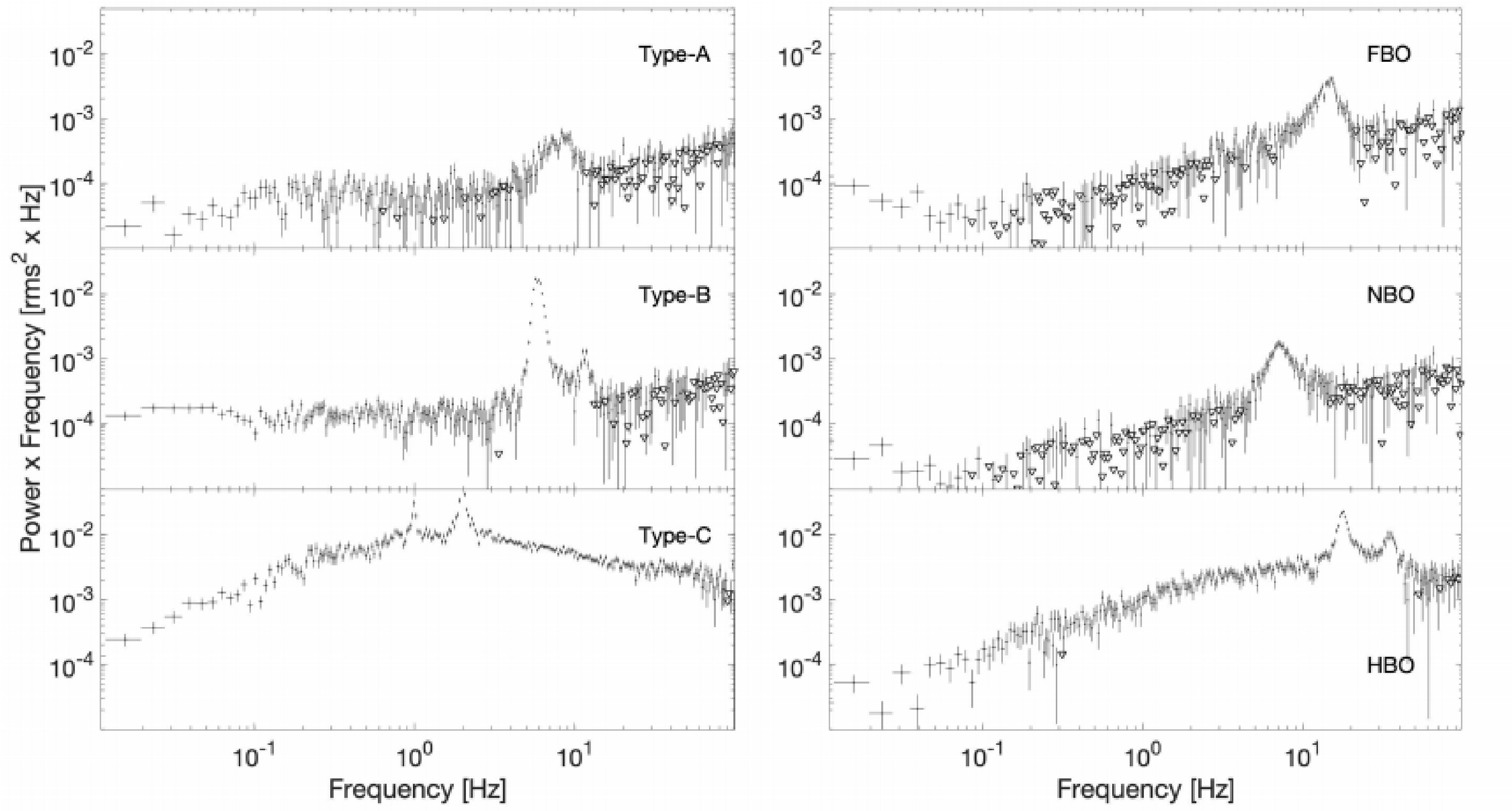
QPOs are interesting because they track variability in the disk.
The highest frequency QPOs track the closes regions to the black hole or neutron stars.

They are called kHz QPOs (neutron star accretors) or High-Frequency QPOs (black hole accretors)





Quasi Periodic Oscillations: Low Frequency Complex



Neutron Star Accreting Binaries have horizontal branch oscillations (HBOs), normal branch oscillations (NBOs) and flaring branch oscillations (FBOs)

Ingram & Motta 2020

What is a QPO?

As a starting point, take two harmonics to represent a signal:

$$f(t) = 1 + a_1(t)\sin[\varphi(t)] + a_2(t)\sin[2(\varphi(t) - \psi(t))].$$

with:

$$\varphi(t) = \varphi_0 + 2\pi \int_0^t \nu_{\rm qpo}(t')dt',$$

where ϕ0 is the QPO phase at t = 0, ν_{qpo} is the centroid frequency of the fundamental and ψ is the phase difference between the harmonics.

What happens if phi, psi, a1(t) and a2(t) are held constant all the time?

What is a QPO?

In this case we would have a purely periodic function, whose power spectrum would be a sum of delta-functions (i.e. a pulsation). What if we modulate the signal amplitude and frequency?