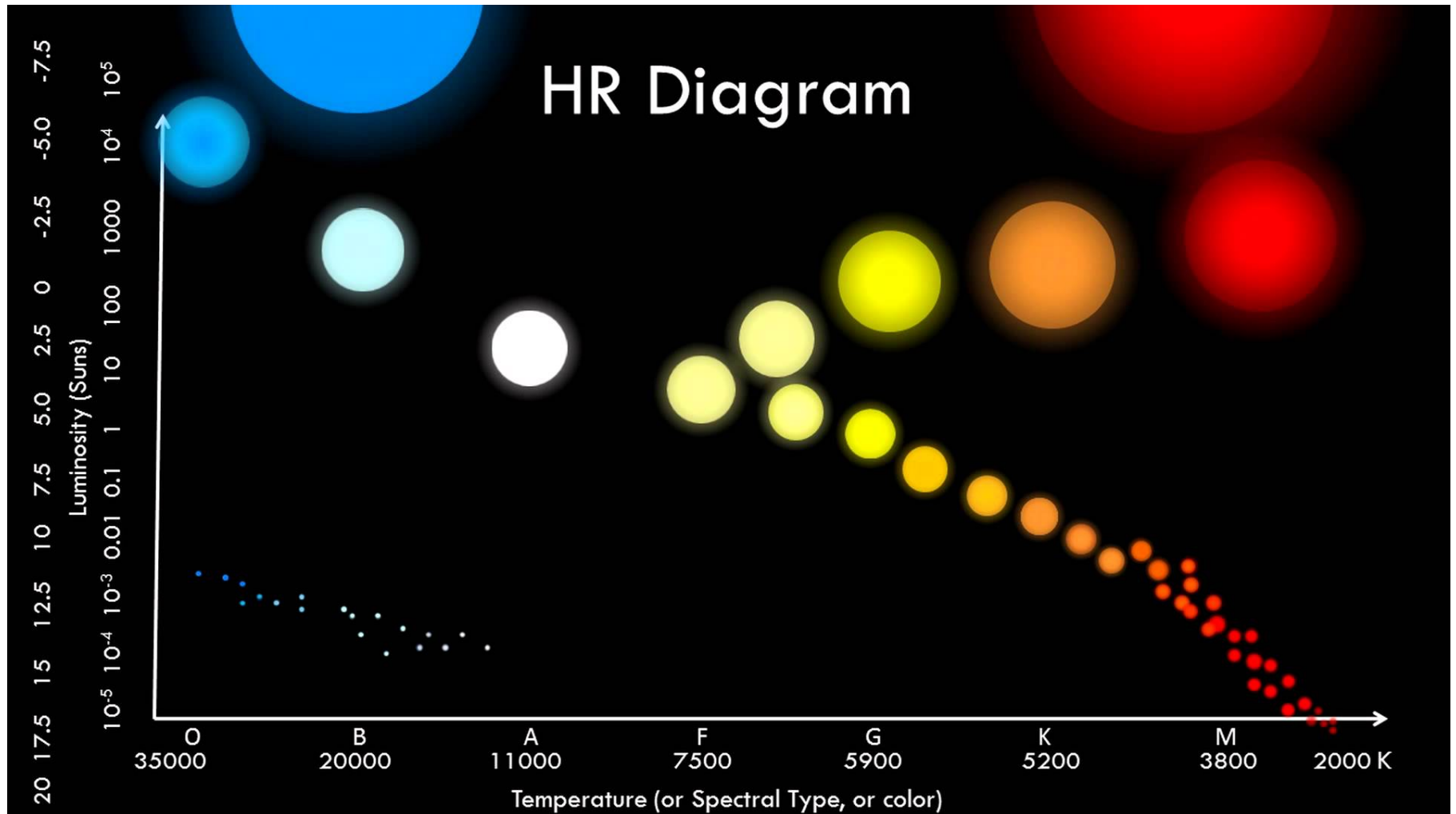


Accretion and X-Ray Binaries

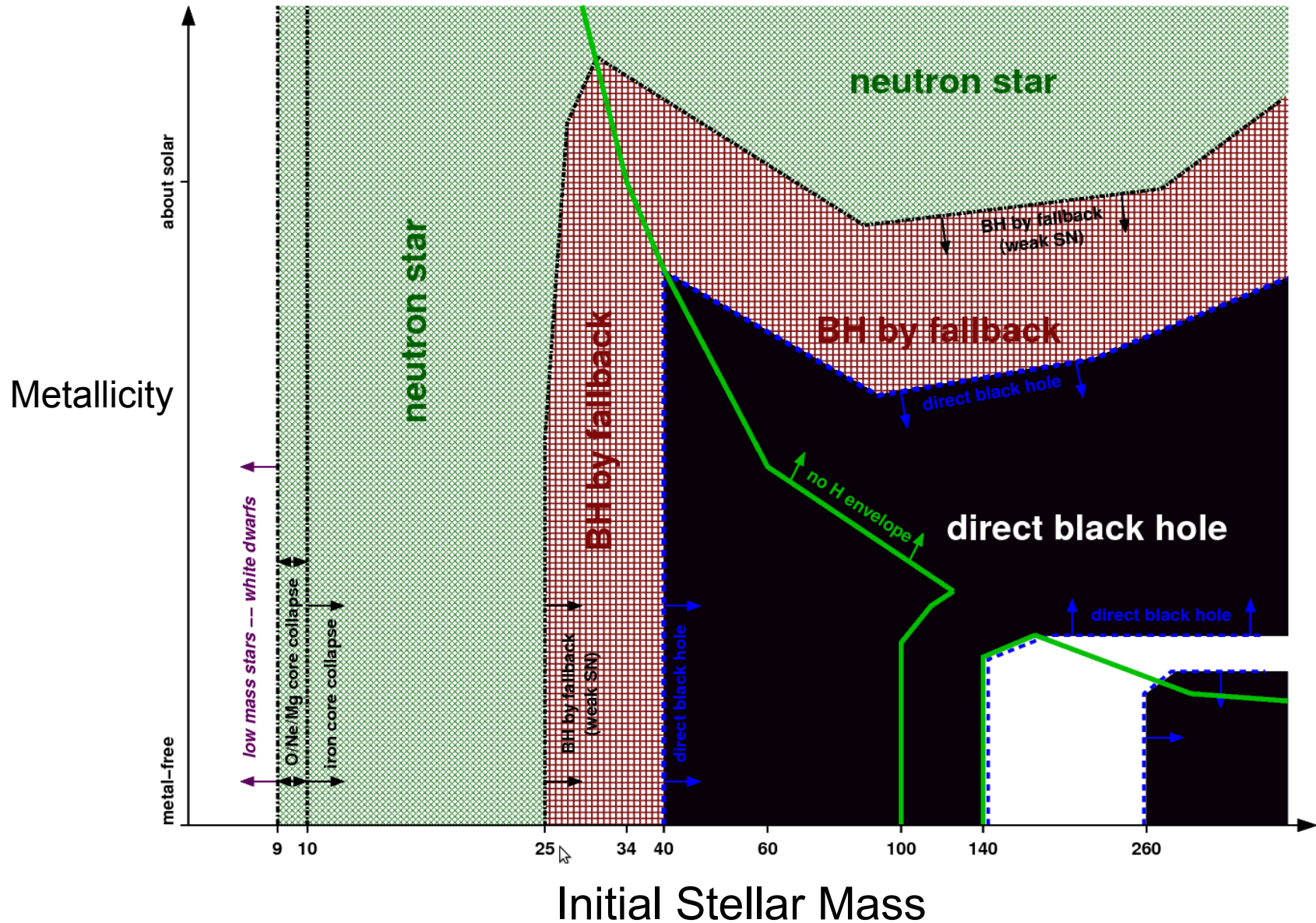
An artistic rendering of an X-ray binary system. In the upper right, a large, bright yellow-orange star is partially visible. In the center, a smaller, intensely bright blue-white compact object, likely a neutron star or black hole, is surrounded by a glowing blue and purple accretion disk. The background is a deep blue space filled with distant stars.

How Compact Objects are Formed



How Massive *Single* Stars End their Lives

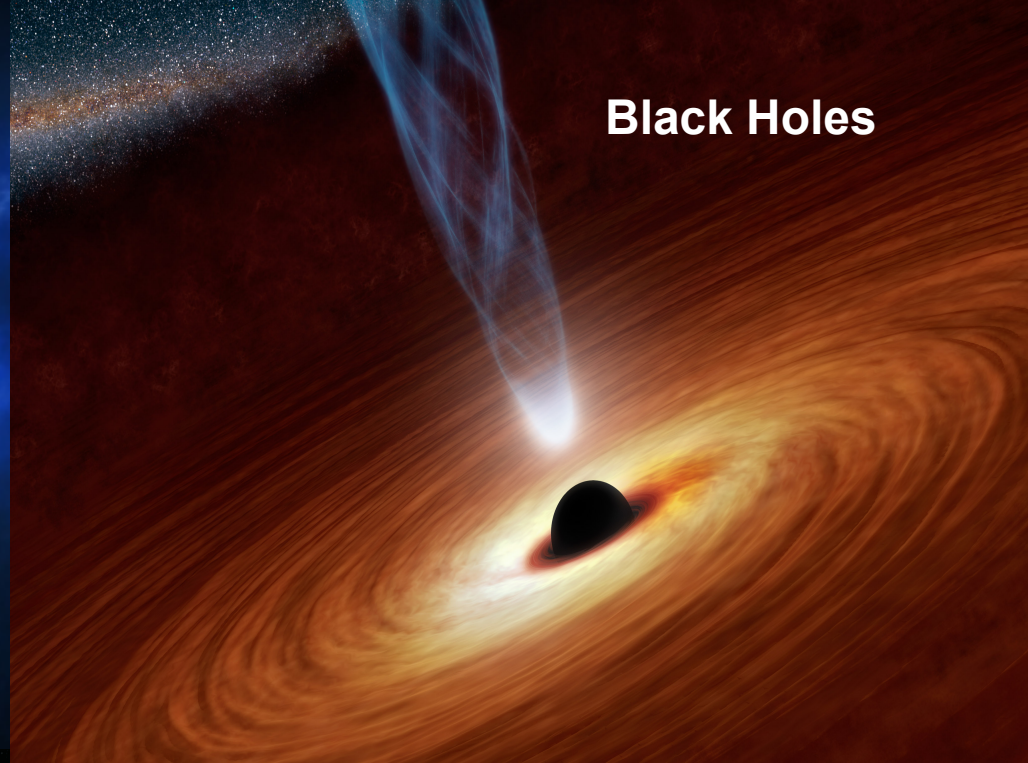
Heger et al. (2003), *The Astrophysical Journal*, Volume 591, Issue 1, pp. 288-300



White Dwarfs



Black Holes



Neutron Stars

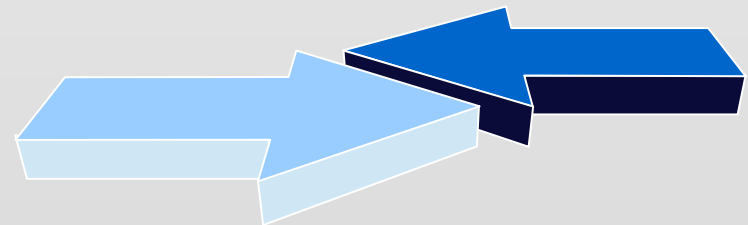


Astrophysics

- § Accretion Flows
- § Compact objects
- § Binary evolution

Fundamental Phys.

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

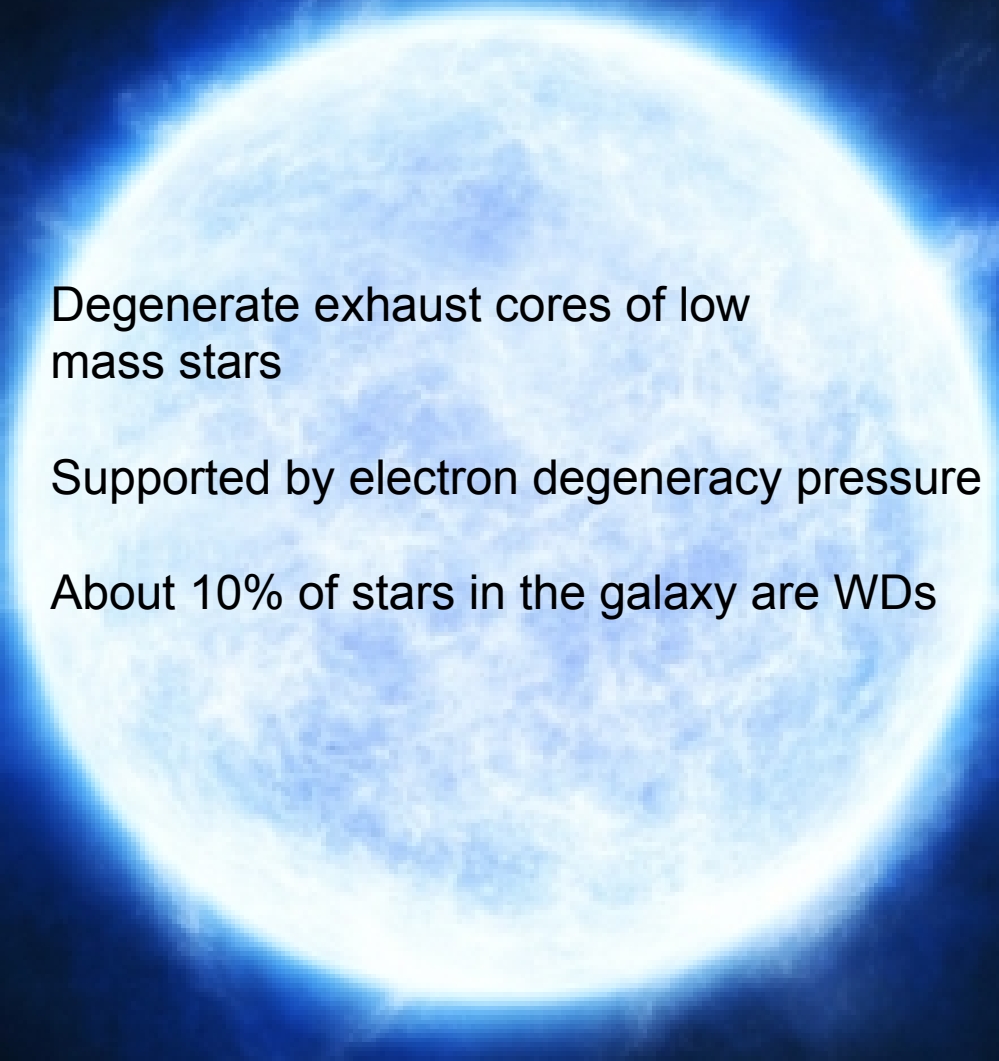


White Dwarfs

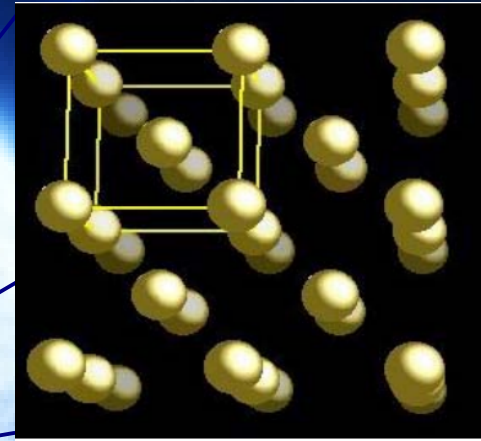
Degenerate exhaust cores of low mass stars

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 $\sim 0.1\text{-}1\text{ Msun}$

Diameter $\sim 10,000\text{ km}$ (very similar to Earth)

Central Density up to 10^8 g/cm^3

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-Dirac distribution



“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 M_{sun}

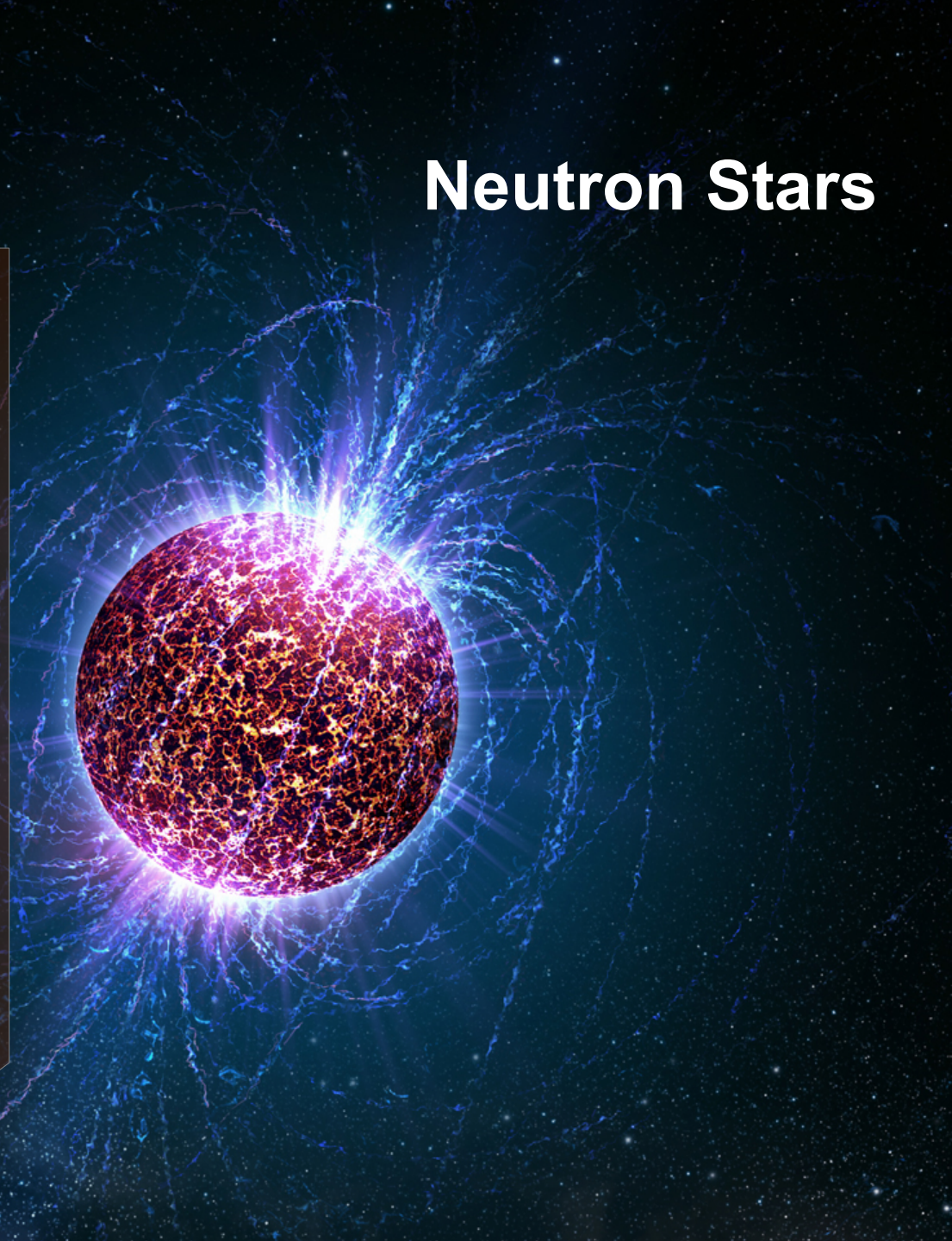
Tiny Size: 10-15 km

Huge Density: 2-10 nuclear density

Strong Gravity: surface radius at just 2-3 R_s

Strong Magnetic Field: $10^{12} - 10^{15}$ Gauss

Fast rotations: 0.001 – 10 s



Neutron Stars

Mass: 1.2-2.0 M_{sun}

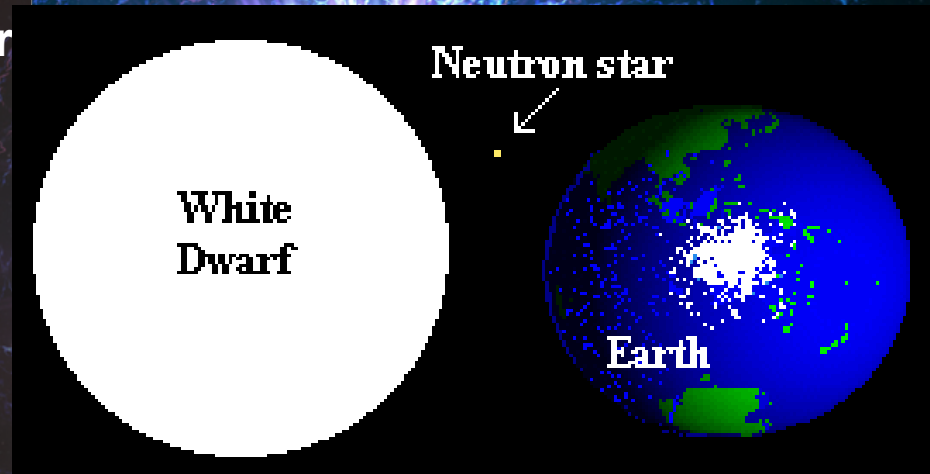
Tiny Size: 10-15 km

Huge Density: 2-10 nuclear density

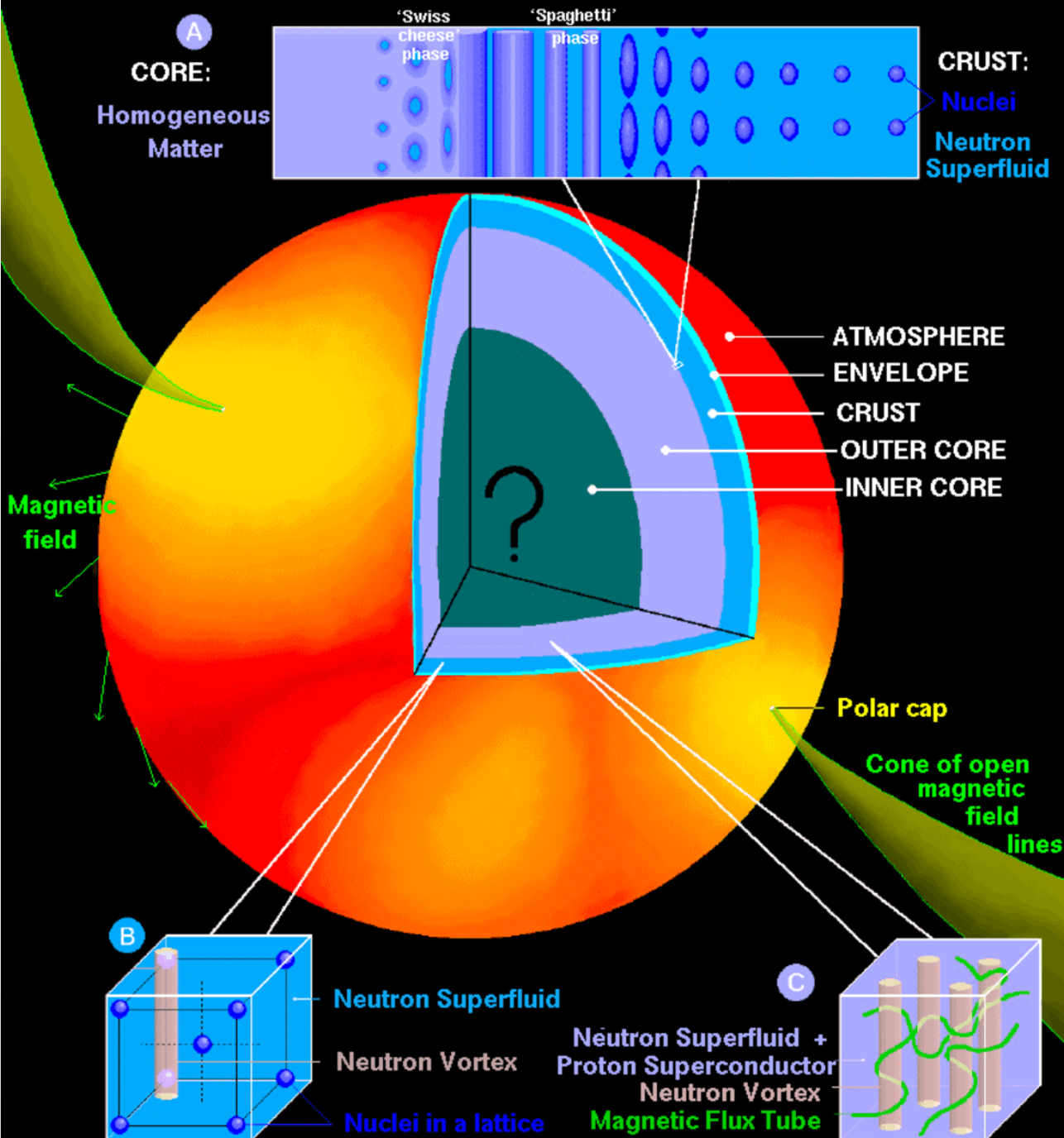
Strong Gravity: surface radius at just 2-3 R_s

Strong Magnetic Field: $10^{8} - 10^{**15}$ Gauss**

Fast rotations: 0.001 – 10 s



A NEUTRON STAR: SURFACE and INTERIOR



Neutron Stars

Neutron Star Structure

Accreting Black Holes

- X-rays (spectra, timing)



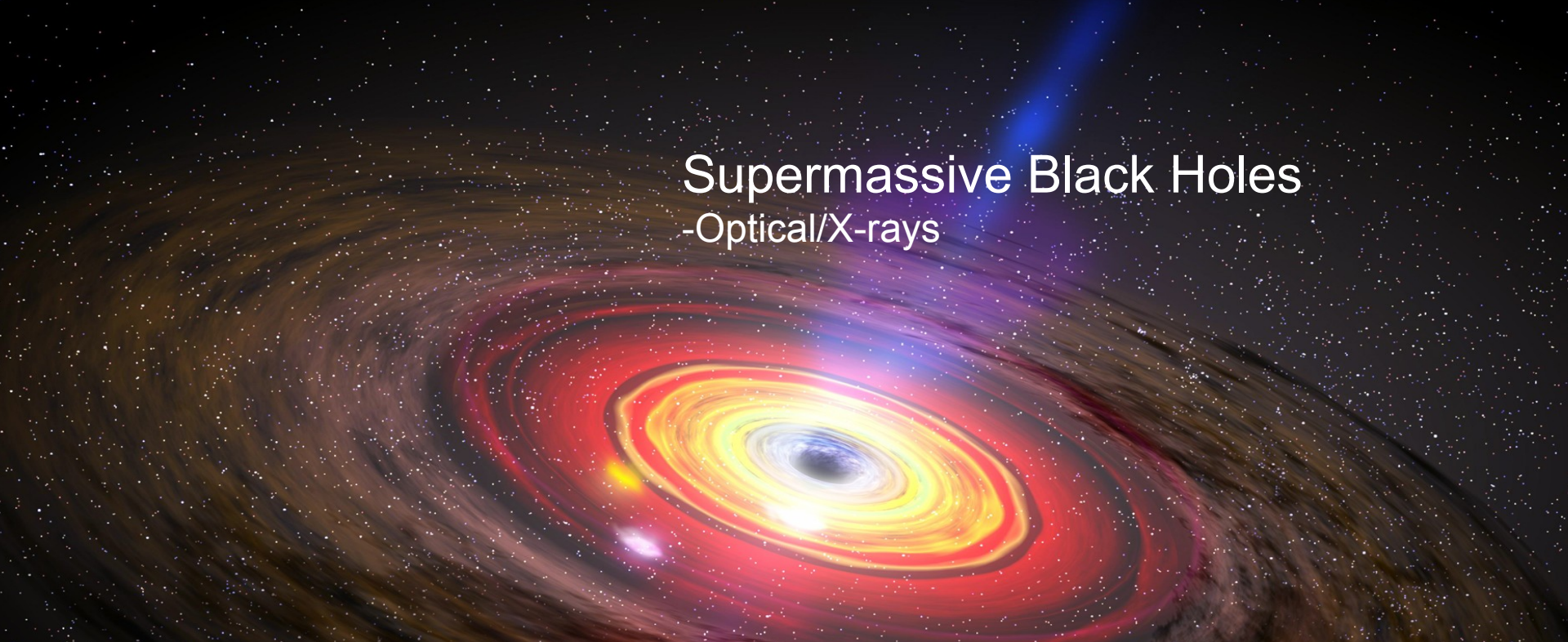
Binary Black Holes

-Gravitational Waves

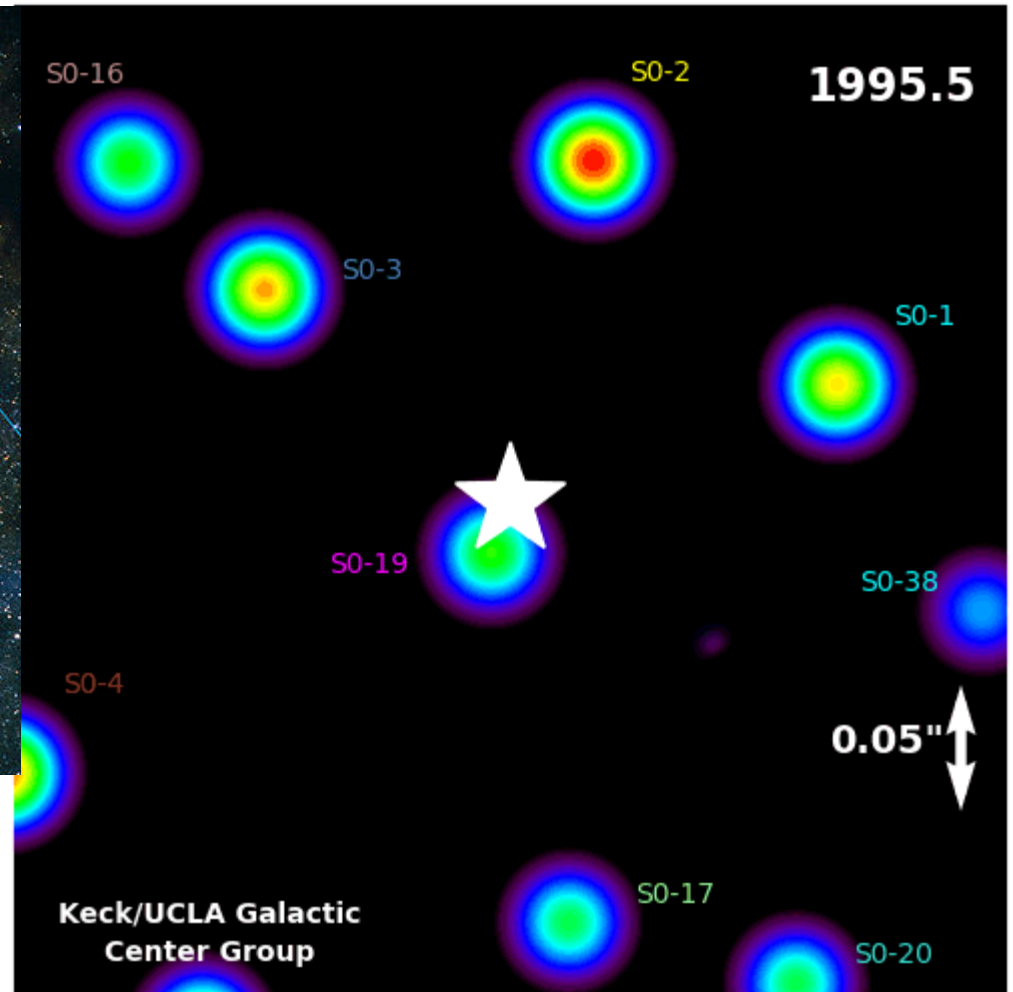
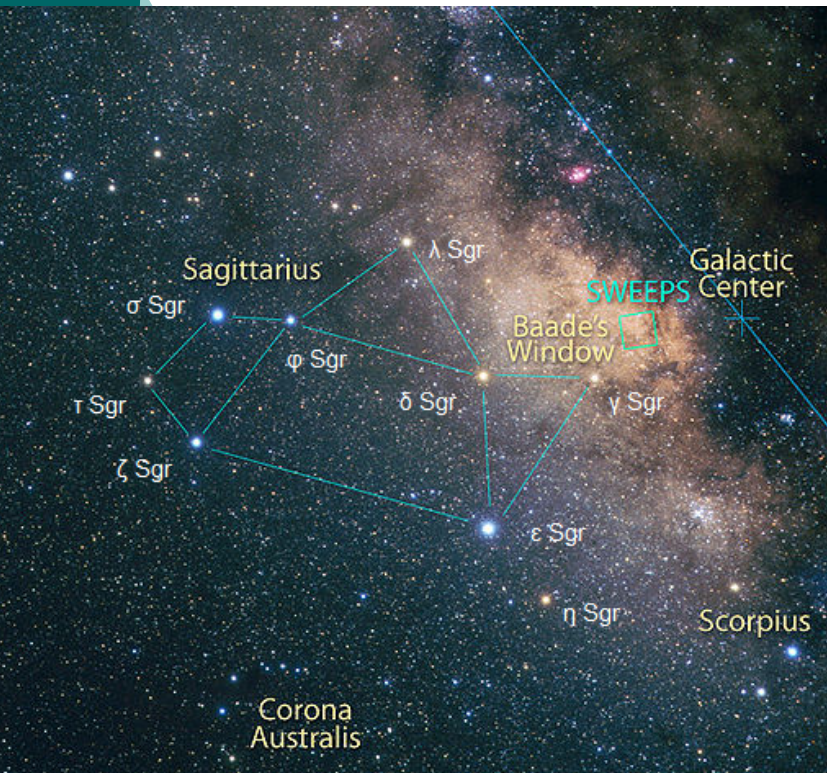


Supermassive Black Holes

-Optical/X-rays

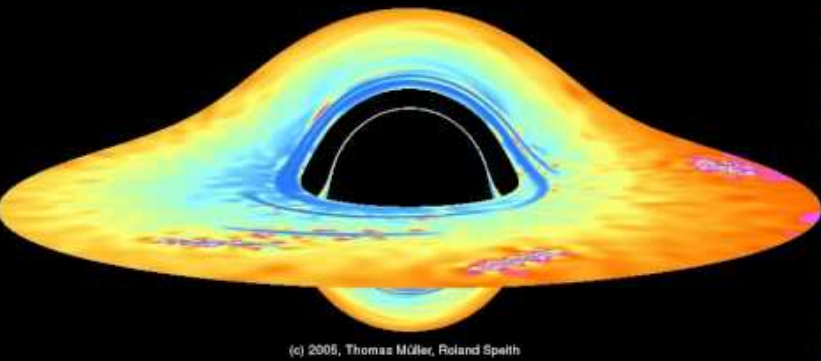


Supermassive BH in the Galactic Center



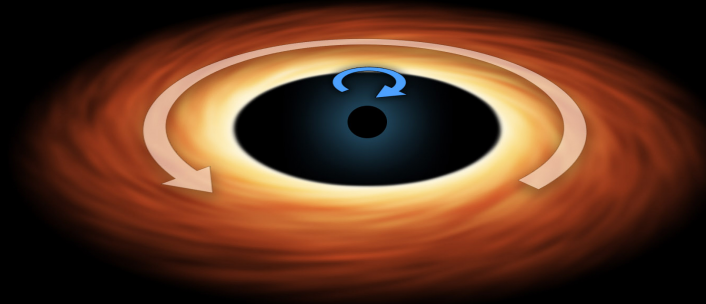
Central Mass of ~ 4 Million M_{sun}

Innermost Stable Circular Orbit

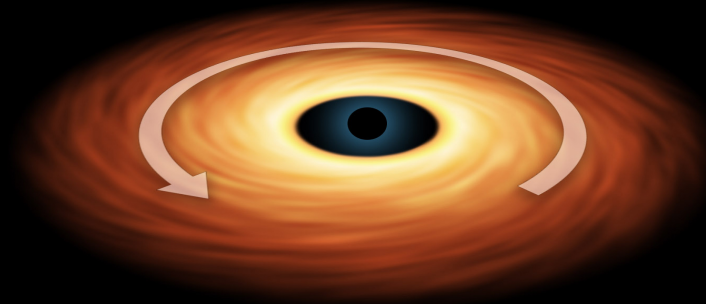


(c) 2008, Thomas Müller, Roland Speith

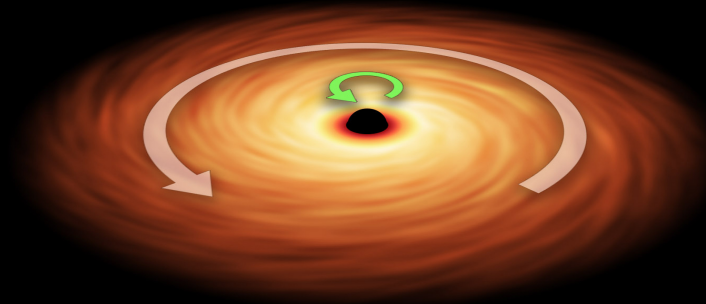
Innermost stable circular orbit (ISCO): *smallest orbit in which a test particle can stably orbit a massive object in general relativity.*



Retrograde Rotation



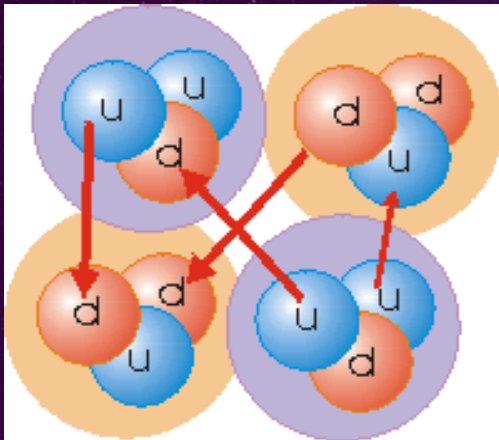
No Black Hole Rotation



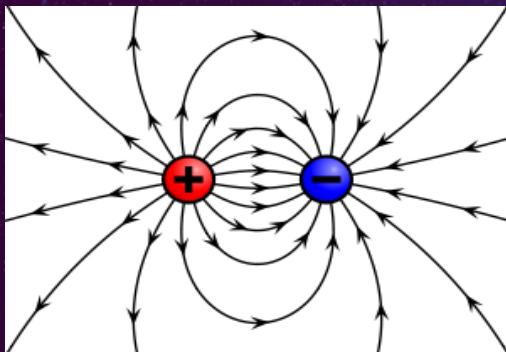
Prograde Rotation

Fundamental Forces

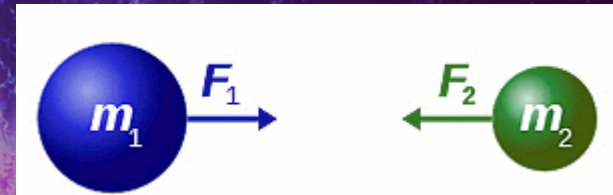
STRONG INTERACTION



ELECTROMAGNETISM

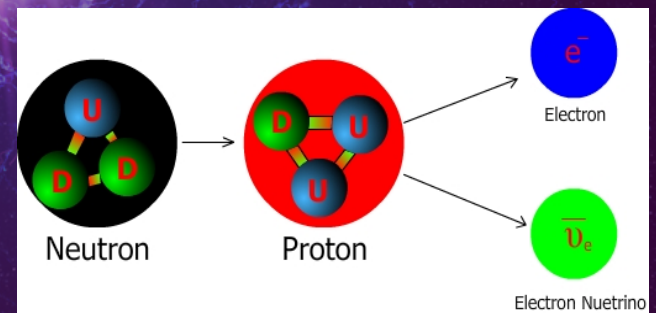


GRAVITY



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

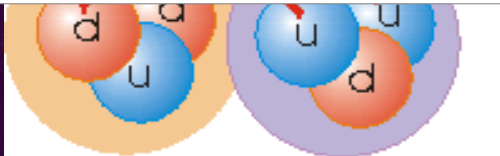
WEAK INTERACTION



Fundamental Forces: Key Questions

STRONG INTERACTION

What is the ground state of ultra-dense matter?



ELECTROMAGNETISM

Behaviour of plasma in ultra-strong magnetic fields



GRAVITY

Test GR in strong gravity regime

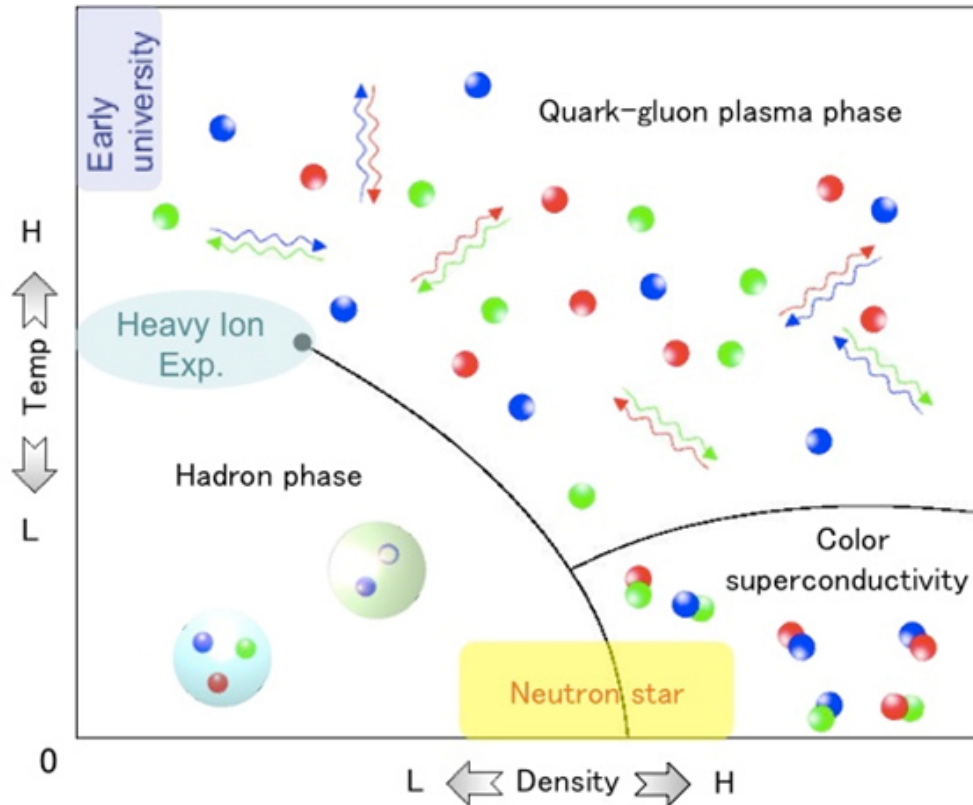


WEAK INTERACTION

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

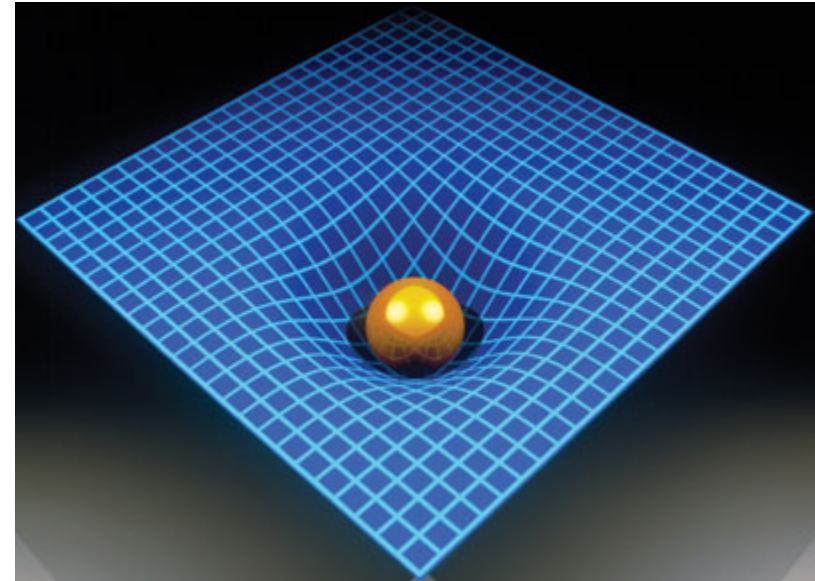
Extreme Regimes

STRONG INTERACTION



Which properties does Ultra-Dense Matter have ?

GRAVITY



Is General Relativity the correct theory of gravity ?

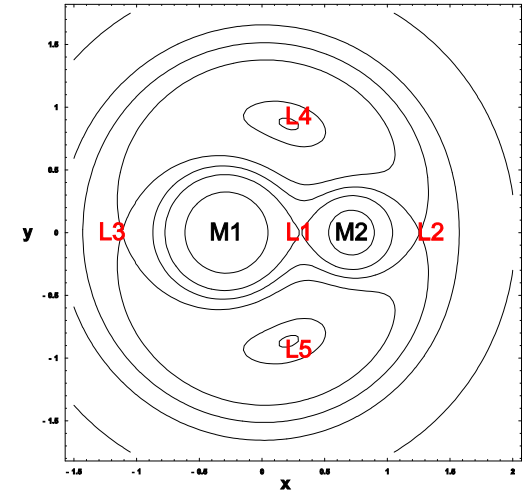
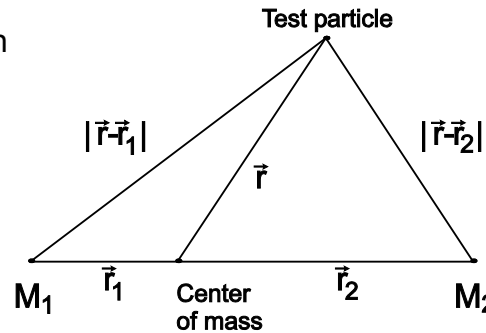
Cataclysmic Variables & Low Mass X-Ray Binaries



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:

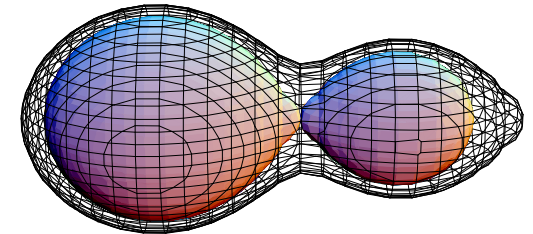
$$\rho \frac{\partial \vec{v}}{\partial t} + \rho (\vec{v} \cdot \nabla) \vec{v} = -\nabla P - 2\omega \times \vec{v} - \rho \nabla \phi_R$$

Convection of momentum through the fluid by velocity gradients

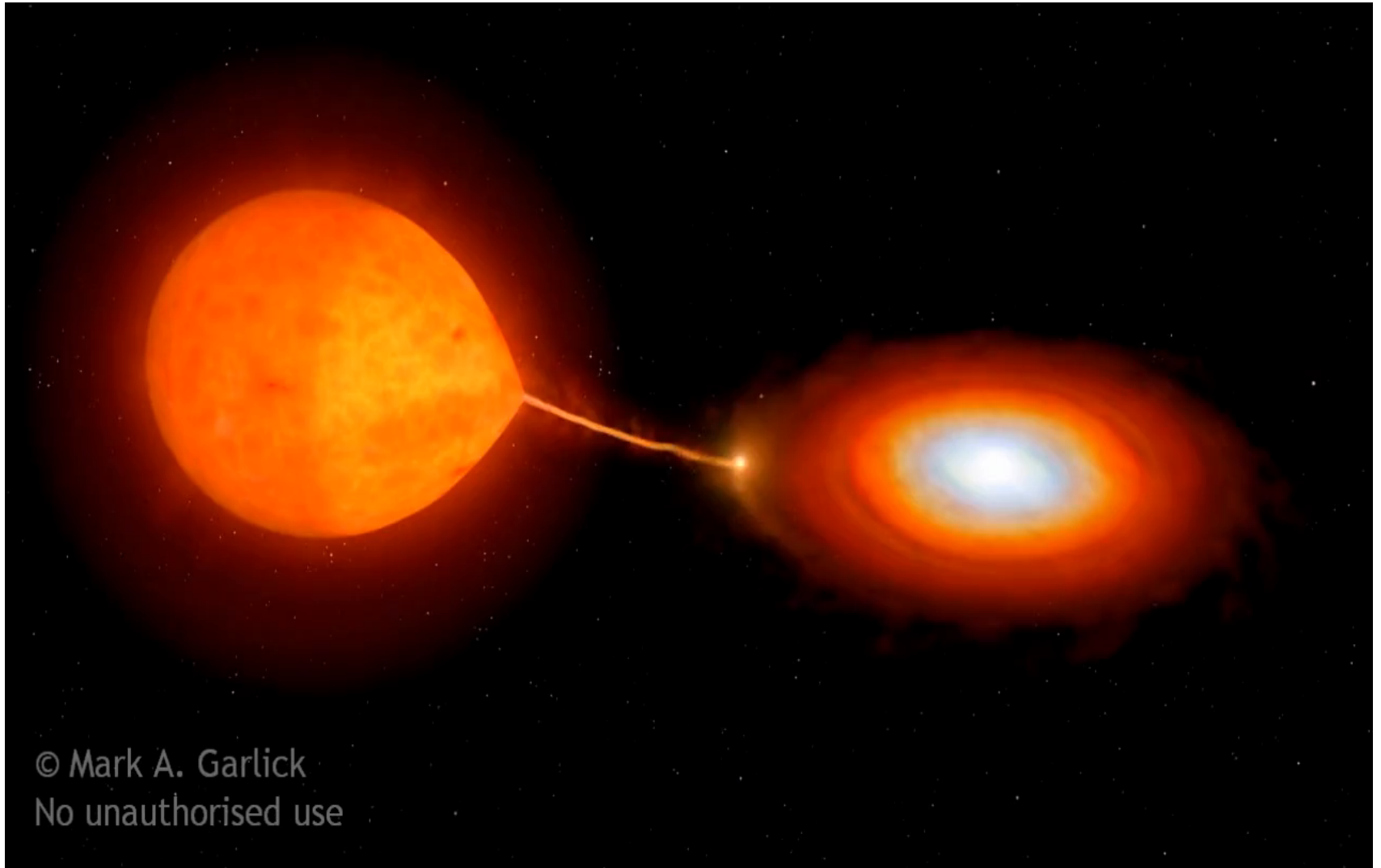
Coriolis force

Gravitational +centrifugal potential

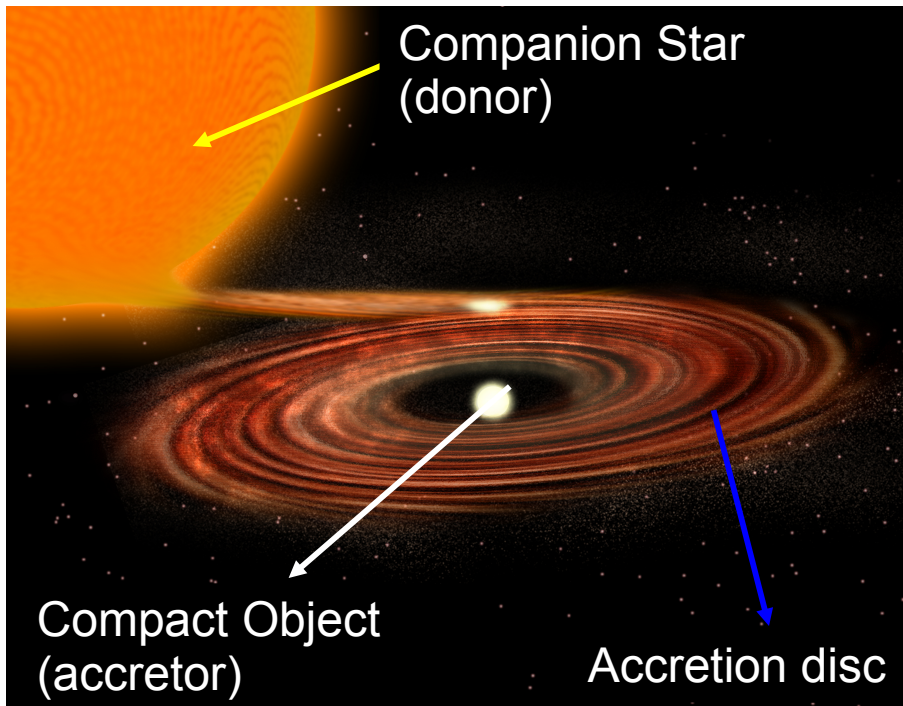
$$\phi_R = -\frac{GM_1}{|\vec{r}-\vec{r}_1|} - \frac{GM_2}{|\vec{r}-\vec{r}_2|} - \frac{1}{2}(\vec{\Omega}_B \times \vec{r})^2$$



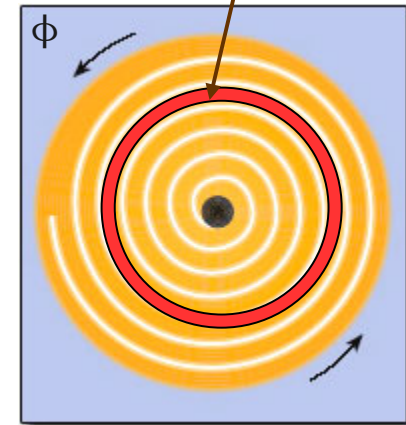
X-ray binaries: the Roche potential



Accretion discs



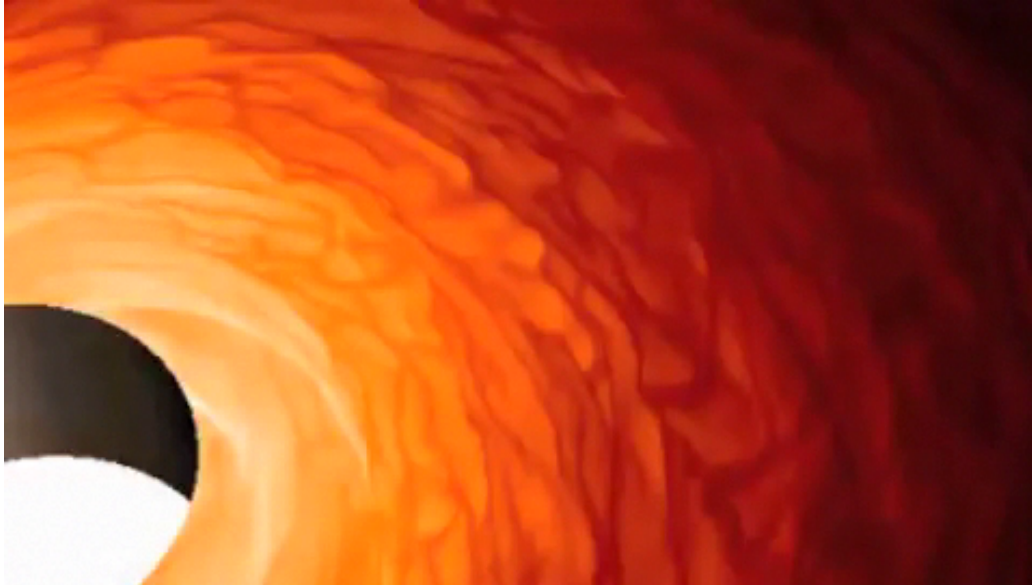
Circularization radius $R_{circ.} = \frac{GM}{v_{\phi}}$



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 discs 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).

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

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

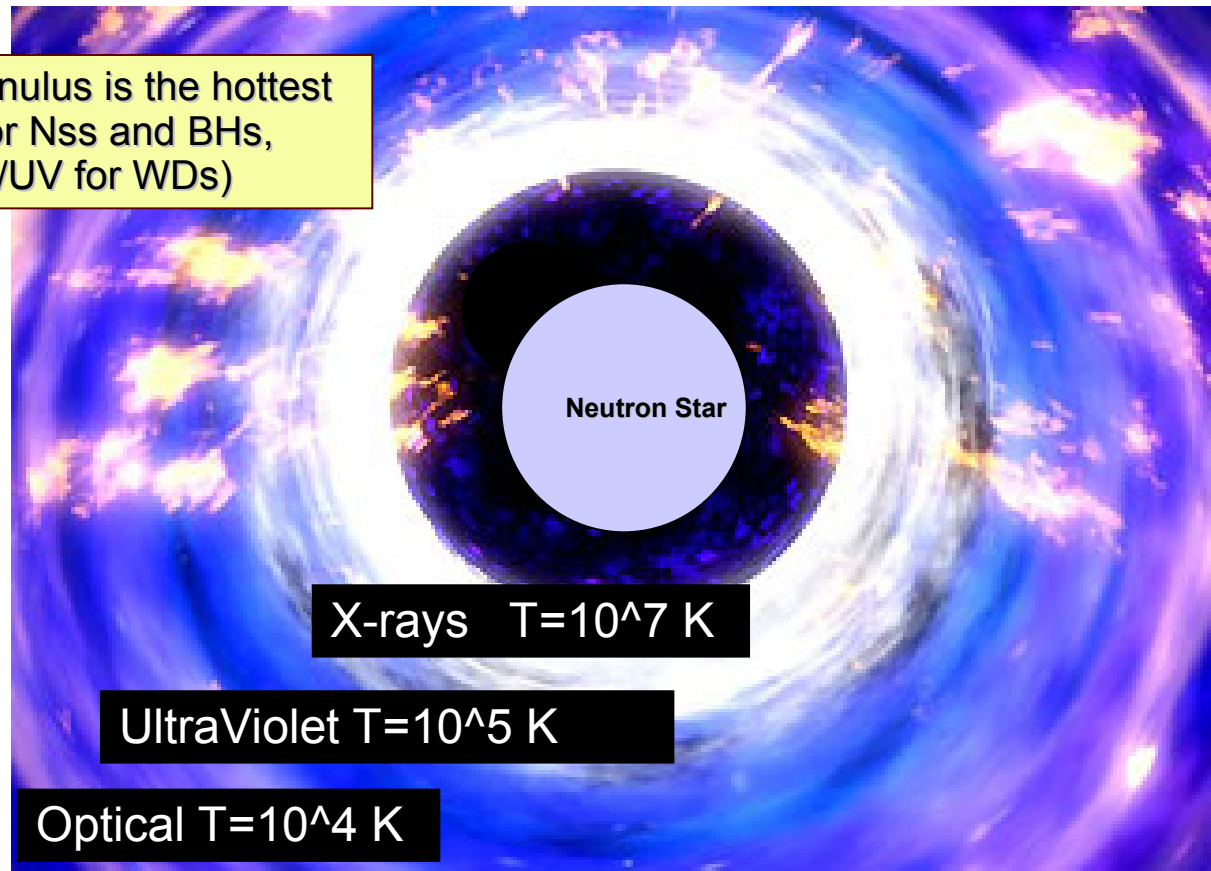
Accretion disc structure

Gas rotates in the disc with “Keplerian frequency”, i.e., the inner annulus rotates faster than the outer one.

$$\longrightarrow \Omega_K = \sqrt{\frac{GM}{r^3}}$$

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)

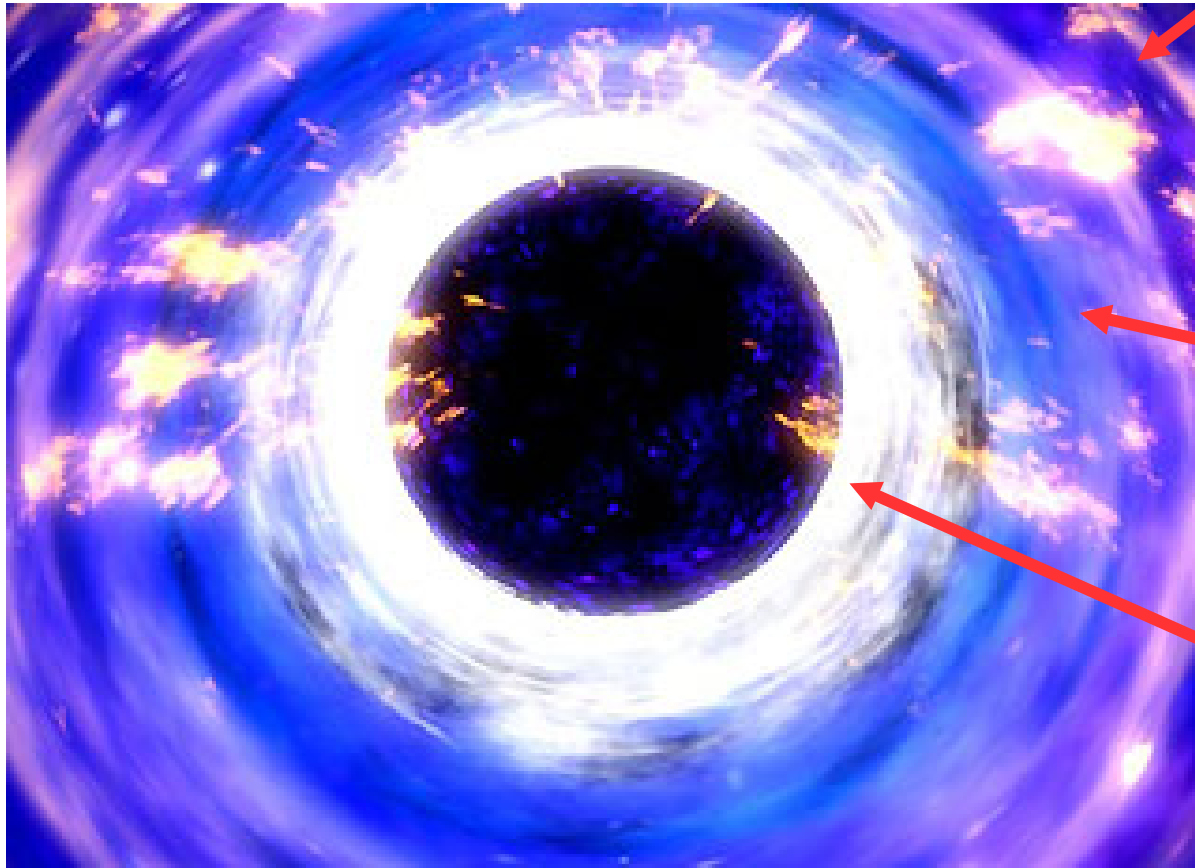


X-rays $T=10^7$ K

UltraViolet $T=10^5$ K

Optical $T=10^4$ K

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:

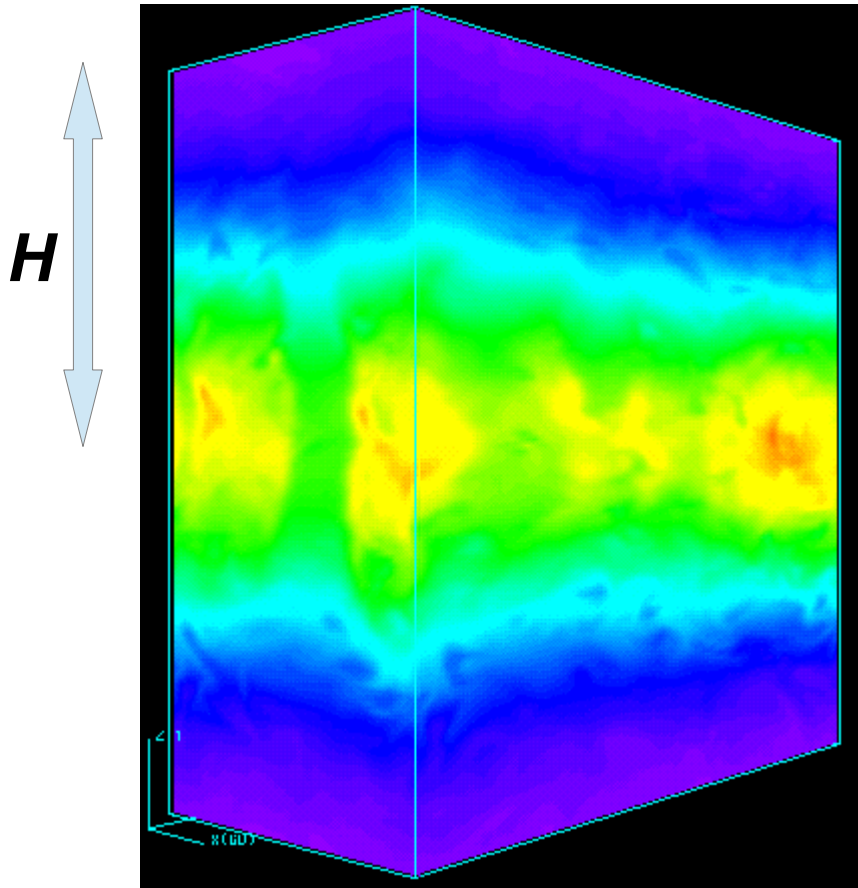
$$f = \frac{L}{4 \pi r^2}$$

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

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

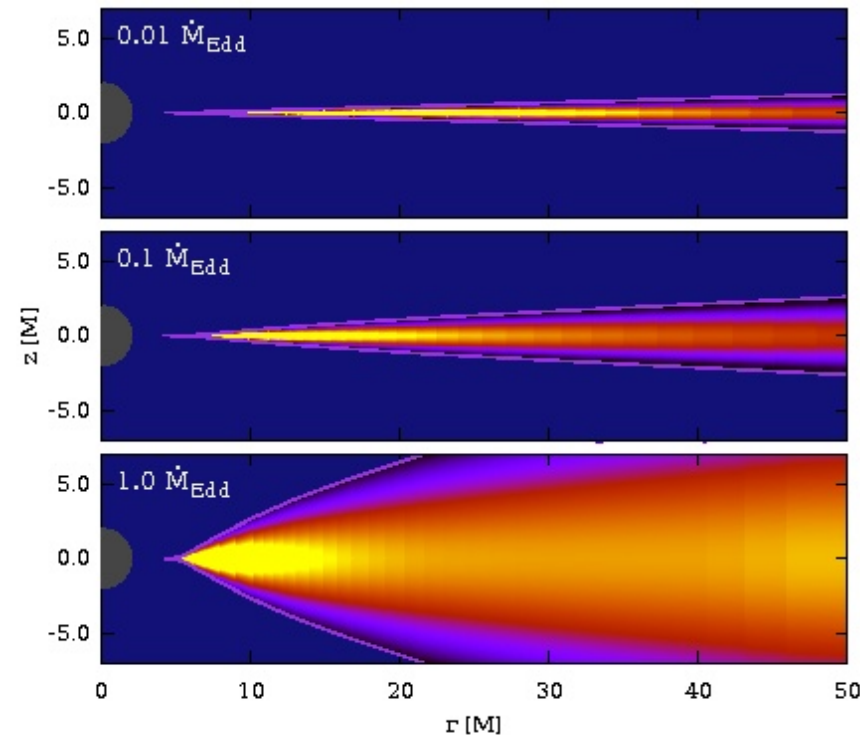
At greater luminosities the outward pressure of radiation would exceed the inward gravitational attraction and accretion would be halted. If all the luminosity of the source were derived from accretion this would switch off the source; if some, or all, of it were produced by other means, for example 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



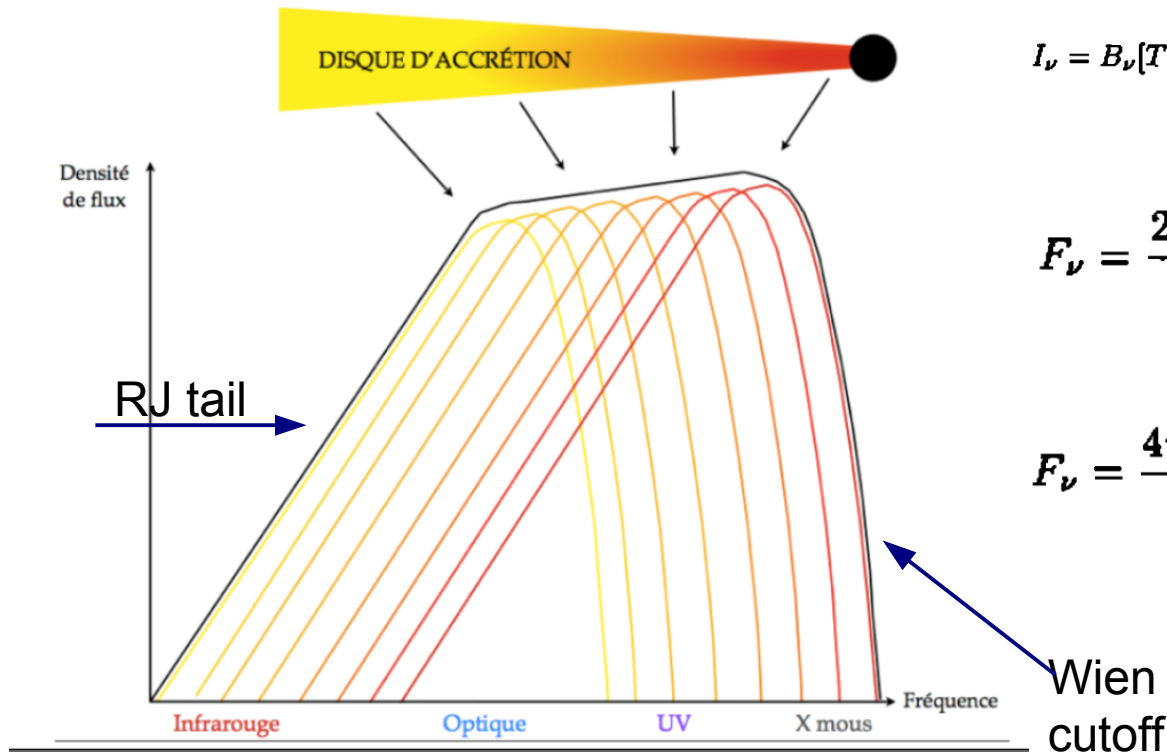
$$\frac{1}{\rho} \frac{dP}{dz} = -\frac{GM}{r^2} \frac{z}{r}$$

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



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

Spectrum of Accretion Disks



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

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

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

See Compact Objects course

Intermediate part:

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

Low Mass X-Ray Binaries



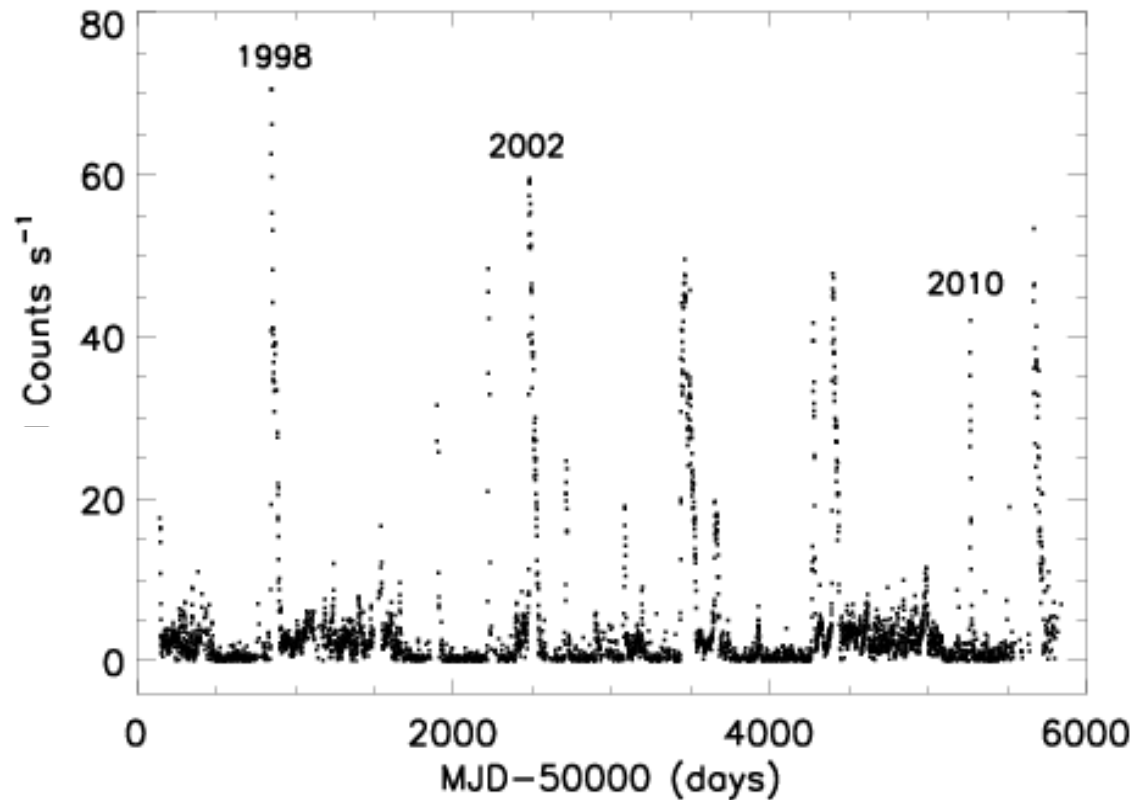
$$T > T_H \sim 6500 K$$

Onset of ionization instability
Gas fully ionized
Viscosity increases
High X-ray activity

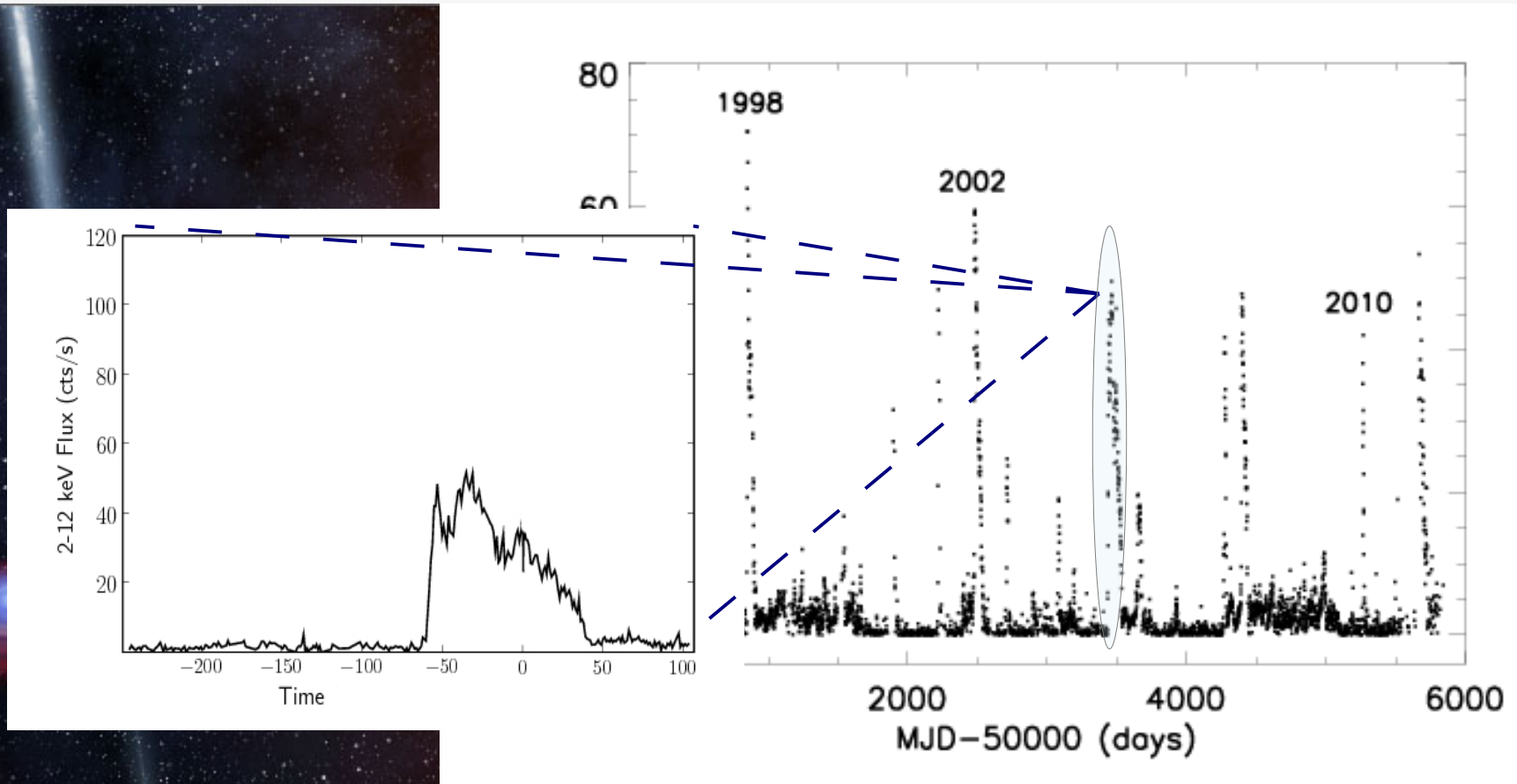
Lasota 2001

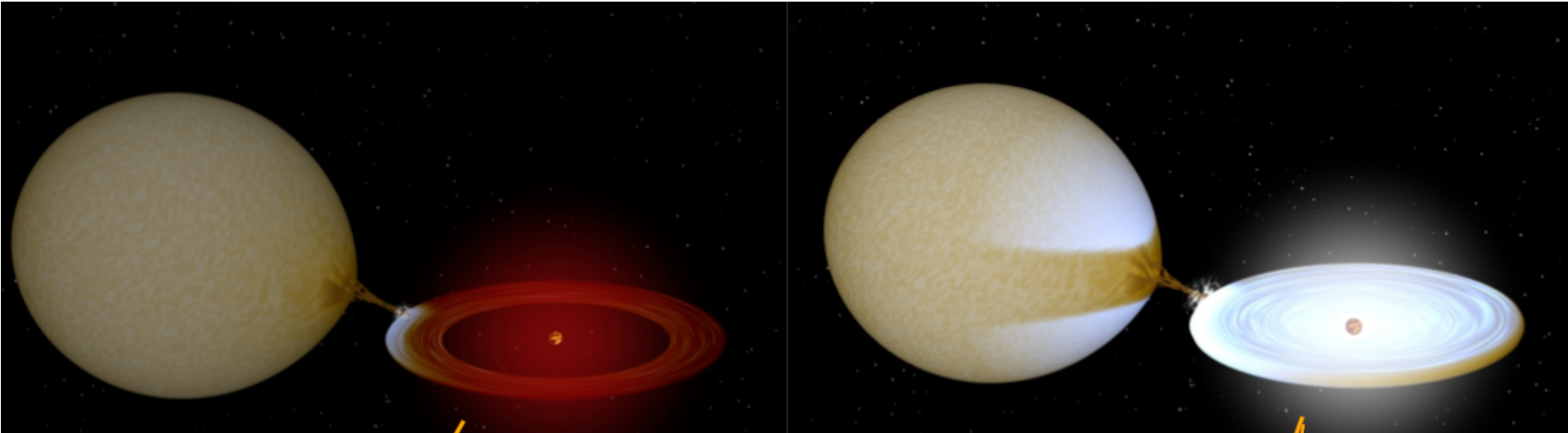
Hameury & Lasota 2016

Low Mass X-Ray Binary Transients

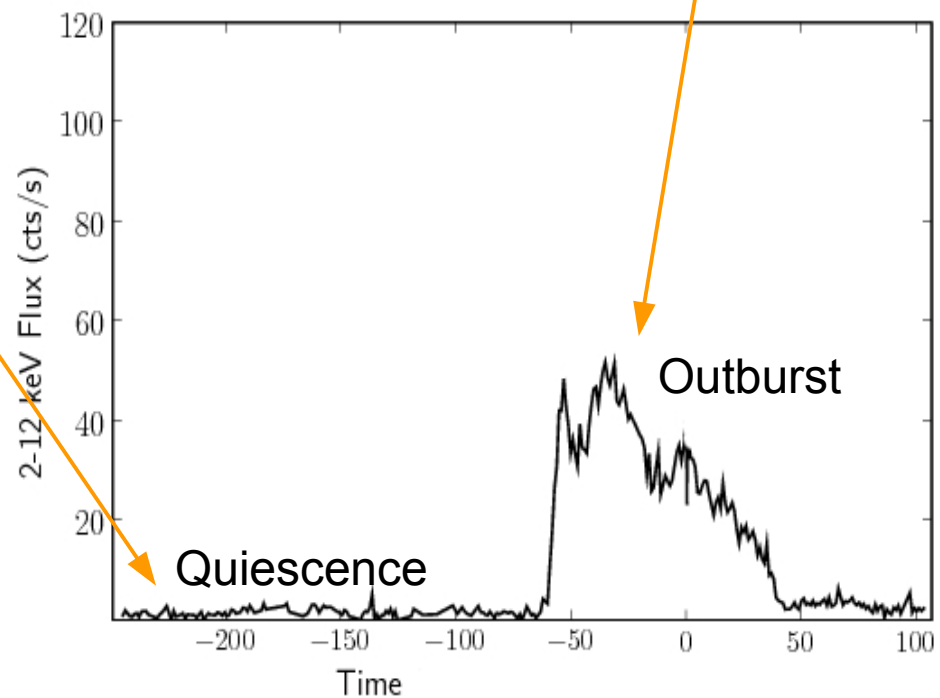


Low Mass X-Ray Binaries

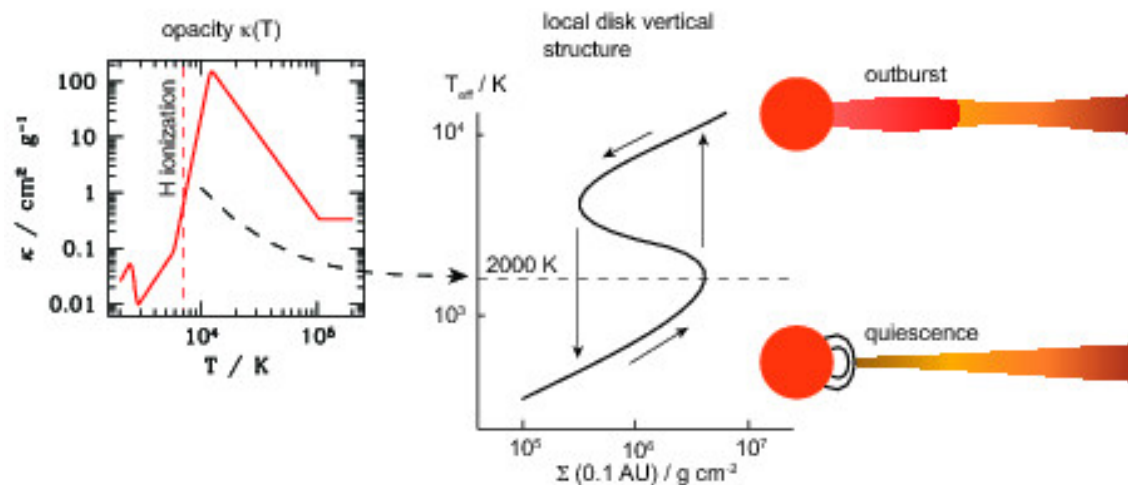


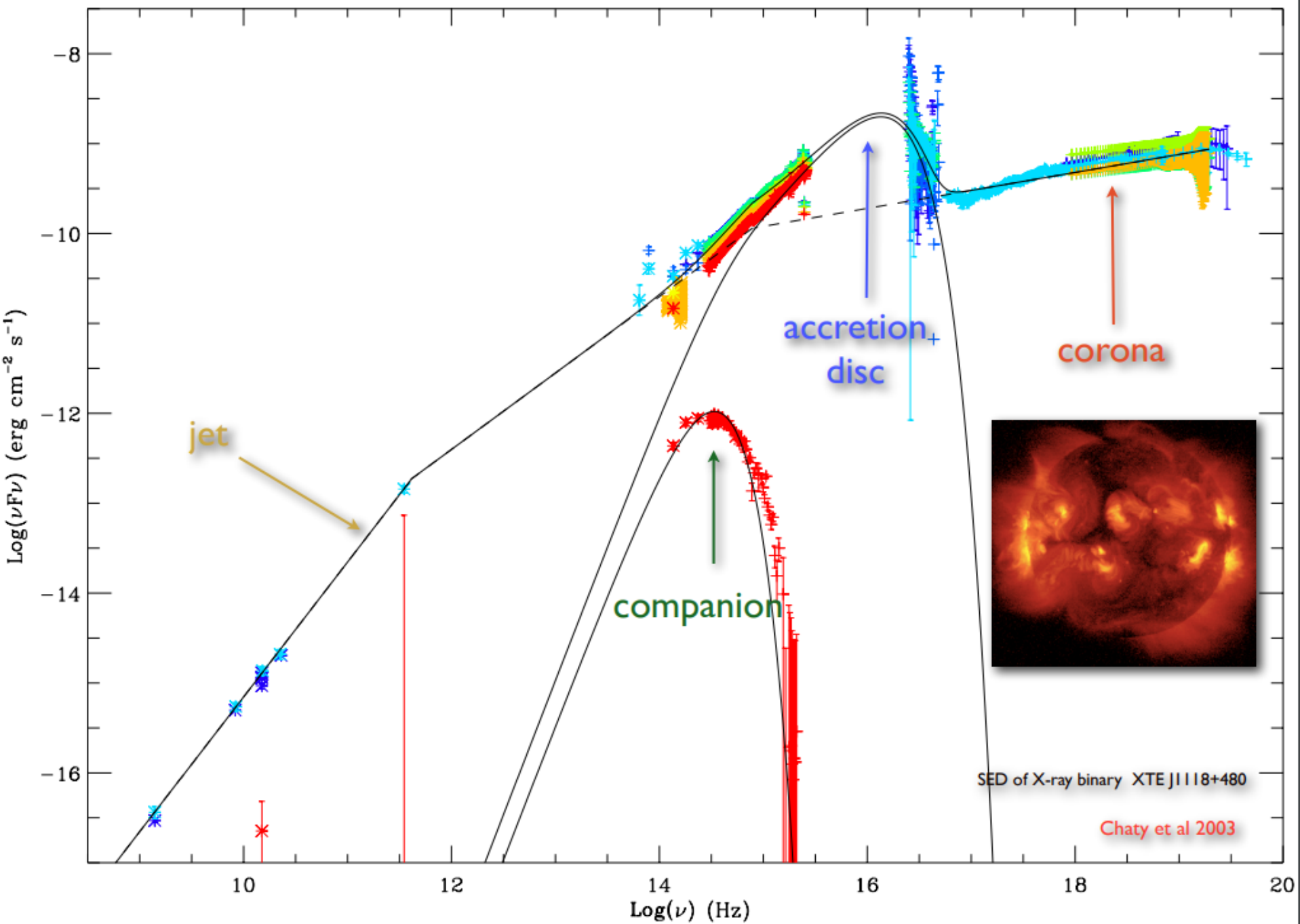


Transient behavior is common, but X-ray binary systems can also be persistent (disk always ionized).

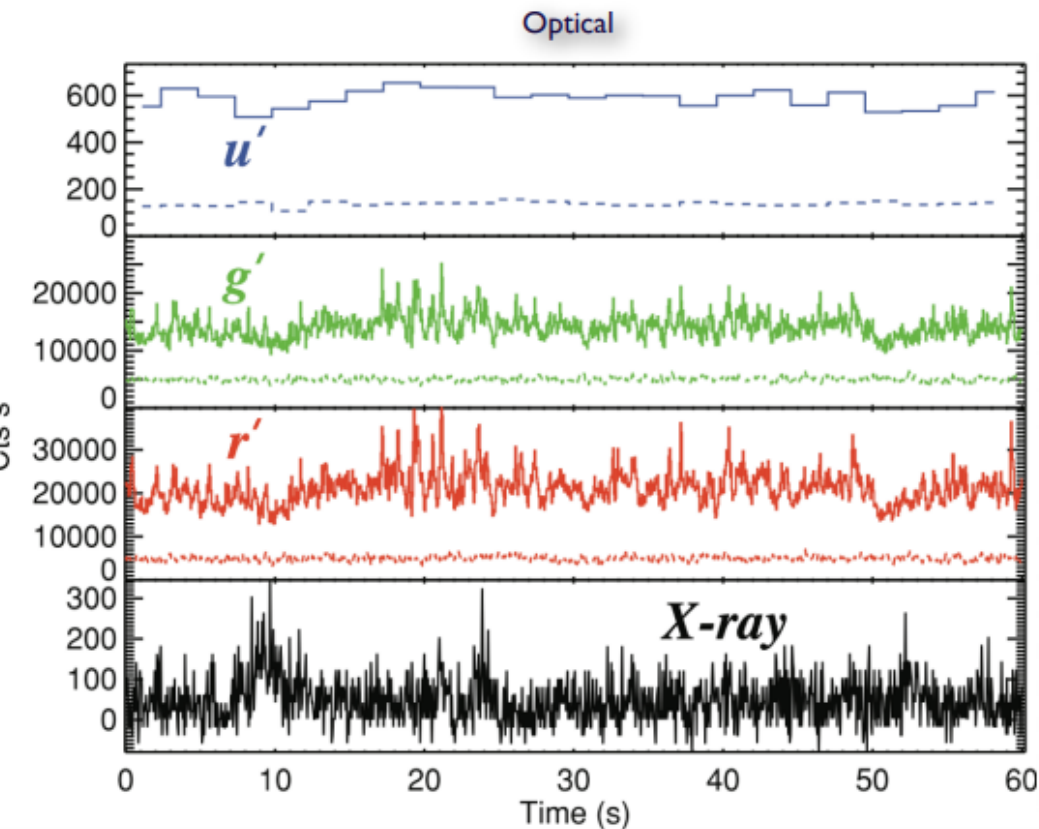


Disk Instability and Production of X-rays

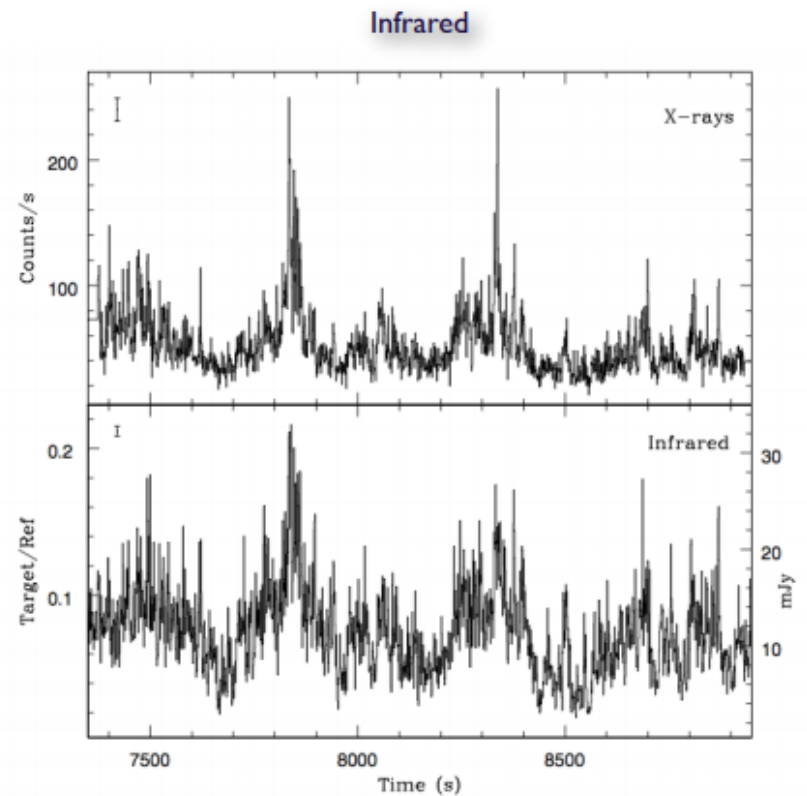




IR, Optical and X-ray Flickering



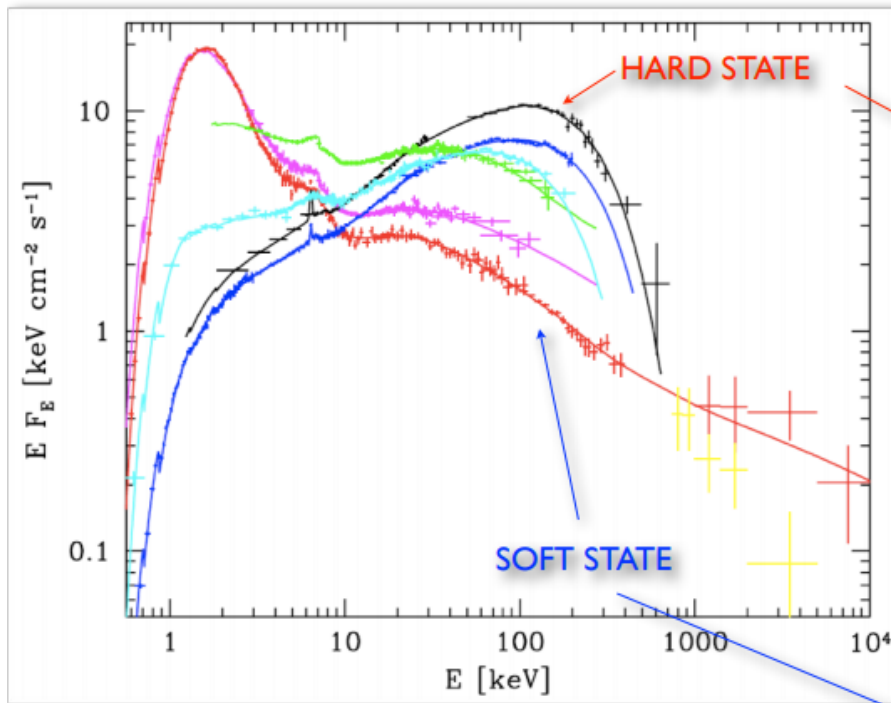
Gandhi et al. 2010



Casella et al. 2010

Observations of GX 339-4

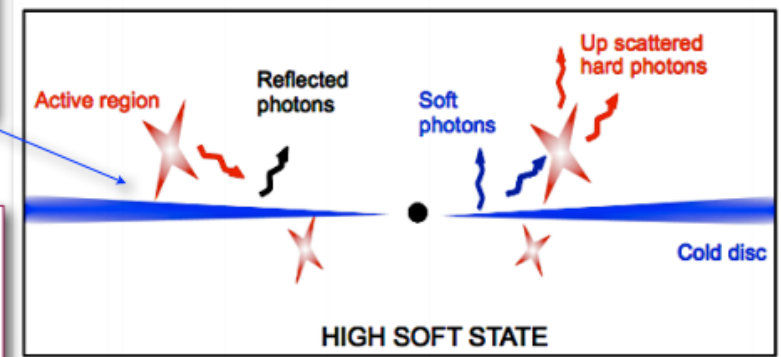
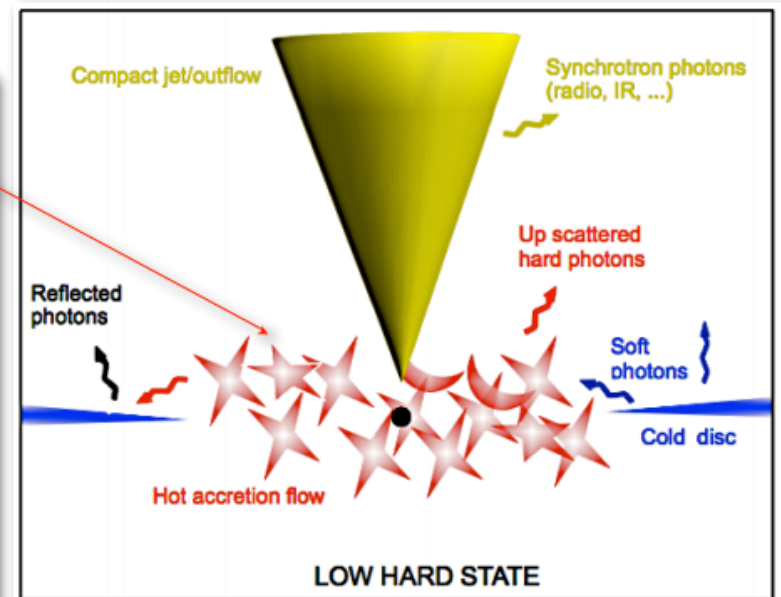
Corona and Thermal/Non-thermal electrons



Zdziarski et al 2003

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

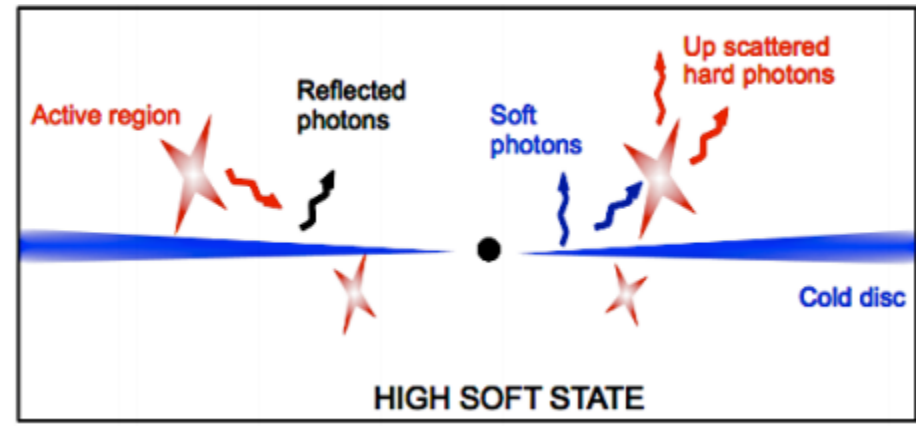
SOFT STATE:
disc blackbody: strong / Corona: mostly NON-THERMAL electrons



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

Observed in a narrow range of luminosities
($\sim 0.01 - 0.1 L_{\text{Edd}}$)

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 $L < 0.1 L_{\text{Edd}}$

Thermal emission from accretion disc barely detected ($T_{\text{in}} \sim 0.1 \text{ KeV}$)

X-ray emission dominated by power-law $\Gamma = 1.4 - 1.9$

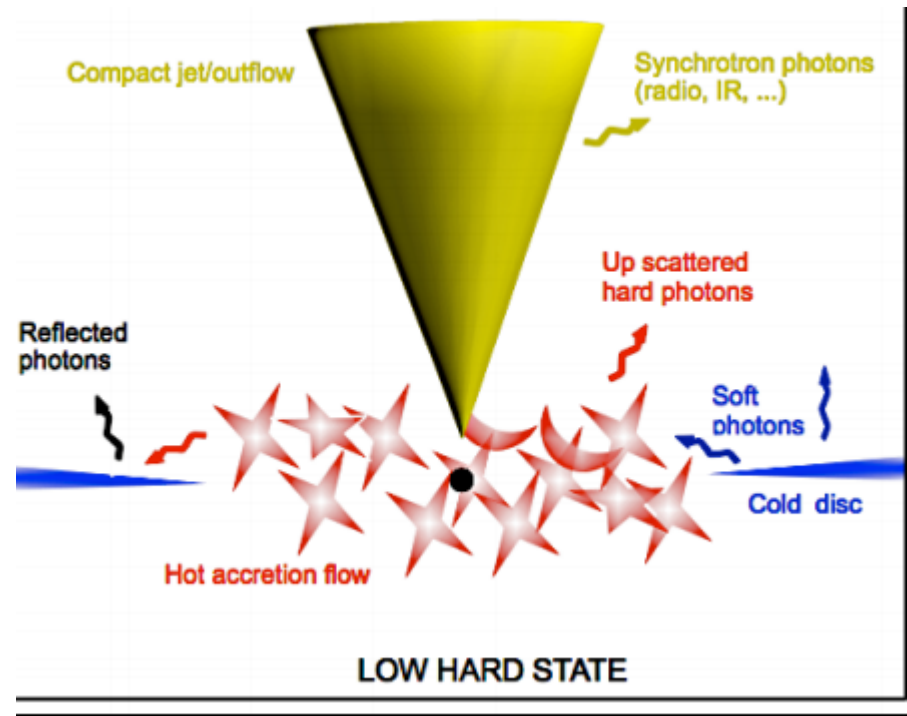
High energy cut-off at $\sim 100 \text{ keV}$

Fits with Thermal comptonisation models:

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

Reflection amplitude is small $R \sim 0.3$

Associated with the presence of a compact radio jet

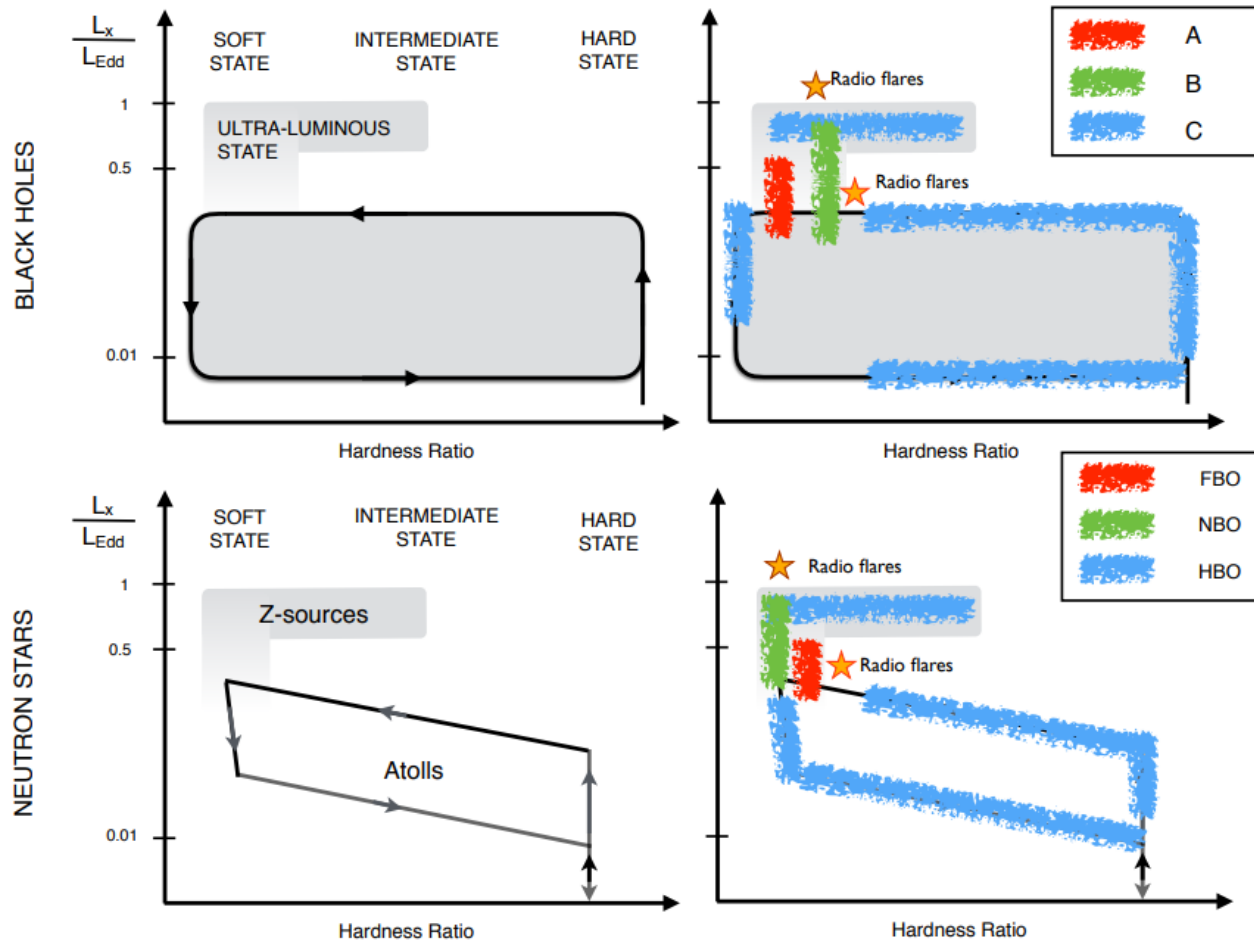


Reflection component is usually small (“reflection” in the sense that it is the result of radiation that is returned from the accretion disk by fluorescence or electron scattering)

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 $R < 100R_G \simeq 1500 \left(\frac{M}{10M_\odot} \right) \text{ km}$

Time scales in X-ray emitting region:

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

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

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

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

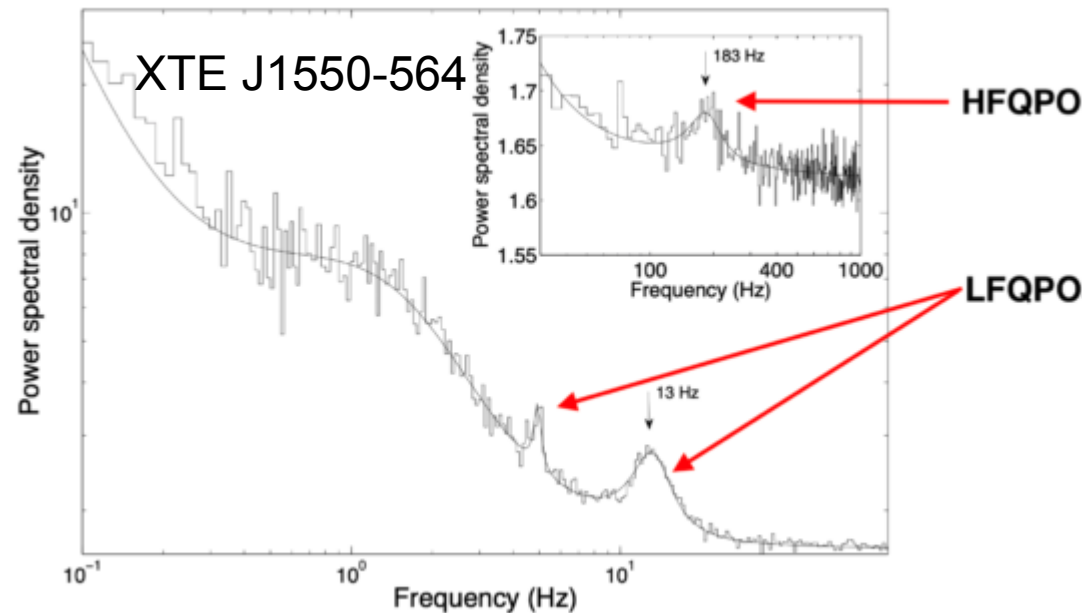
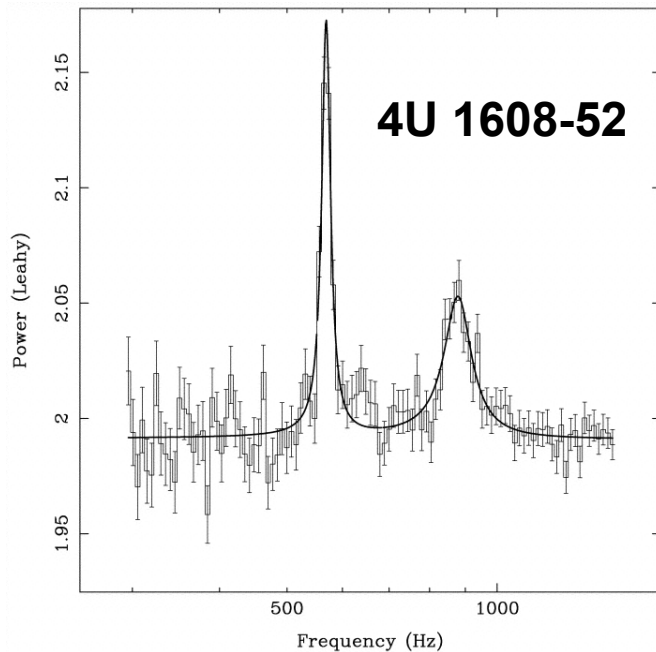
High Fourier frequencies can be produced in this region

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

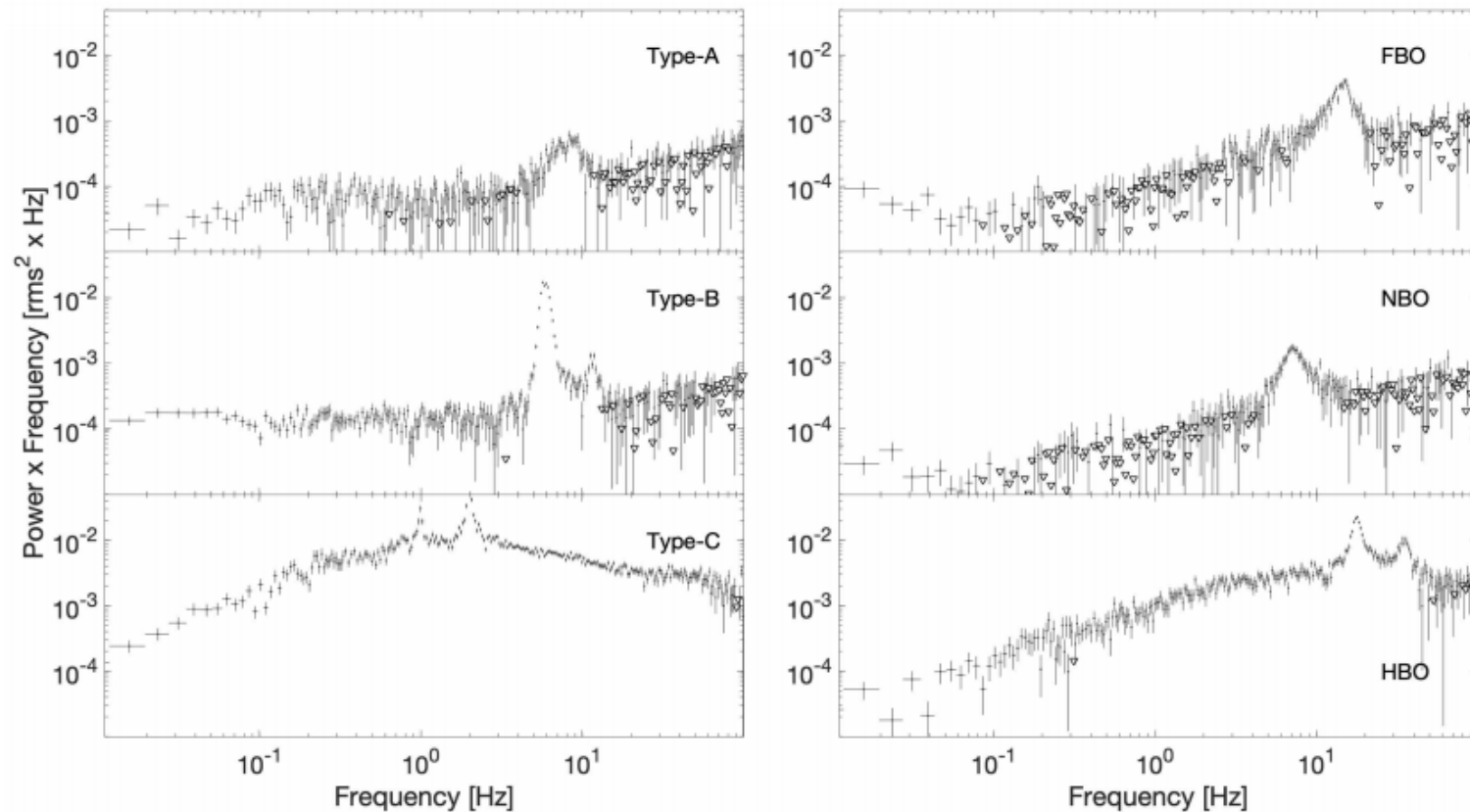
Quasi Periodic Oscillations: High Frequencies

QPOs are interesting because they track variability in the disk.
The highest frequency QPOs track the closest 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:

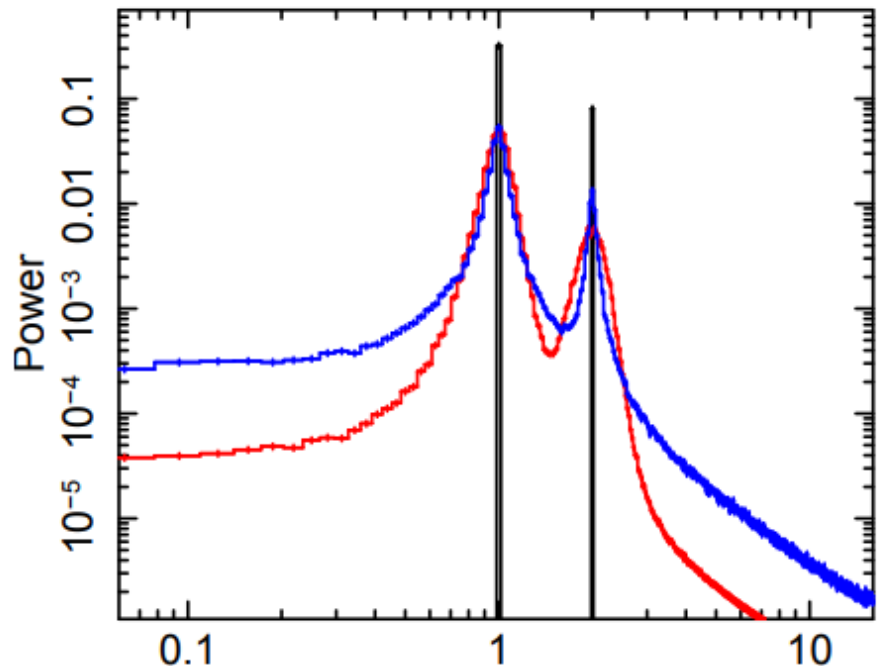
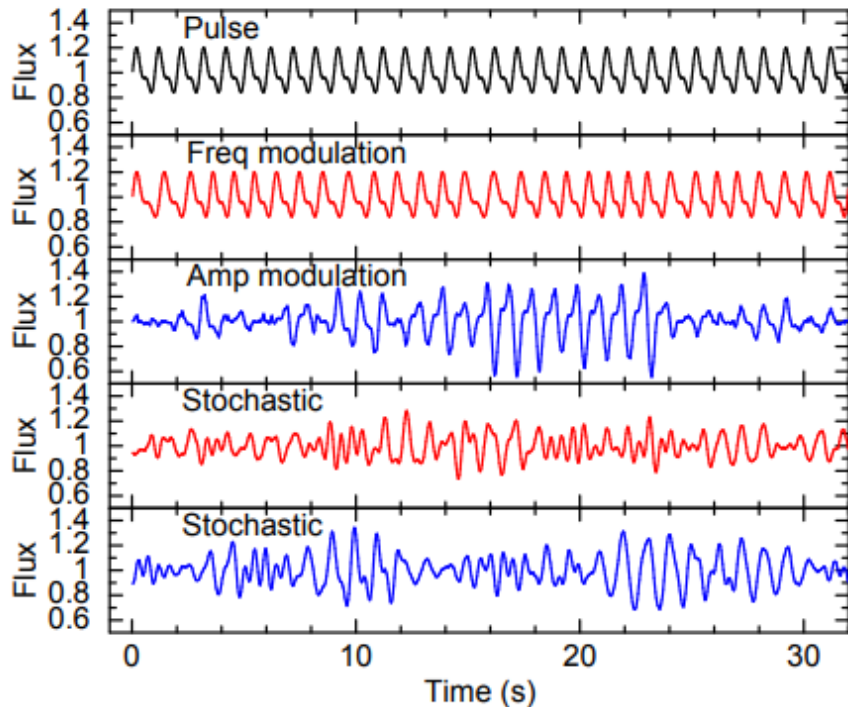
$$\varphi(t) = \varphi_0 + 2\pi \int_0^t \nu_{\text{qpo}}(t') dt',$$

where φ_0 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.

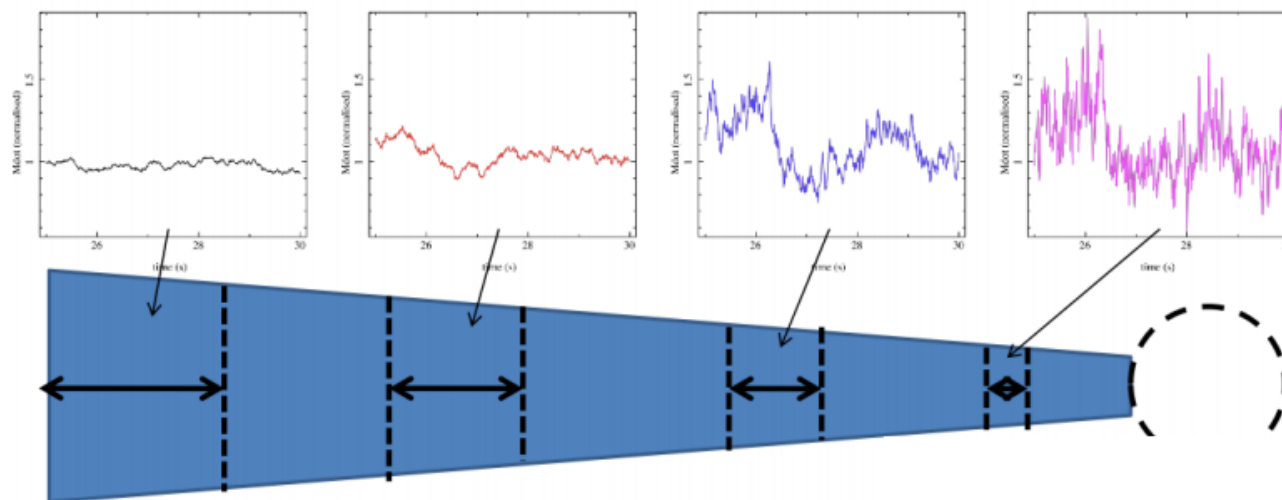
What happens if φ , ψ , $a_1(t)$ and $a_2(t)$ are held constant all the time?

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?



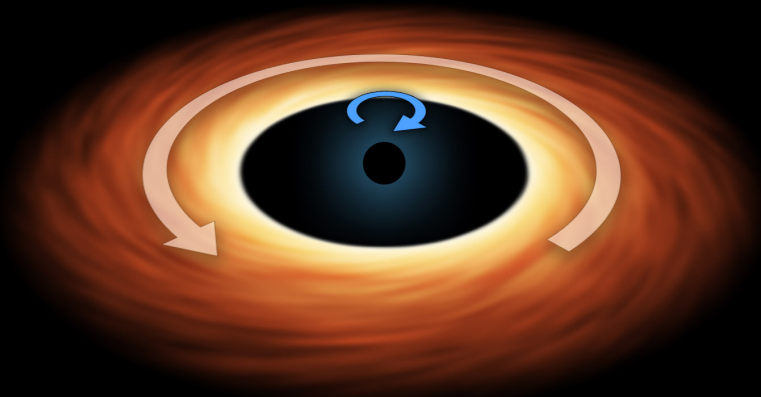
X-Ray Variability: Propagating Fluctuations?



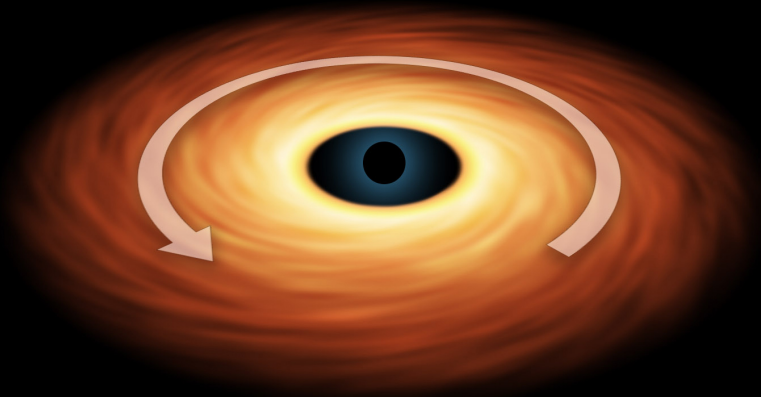
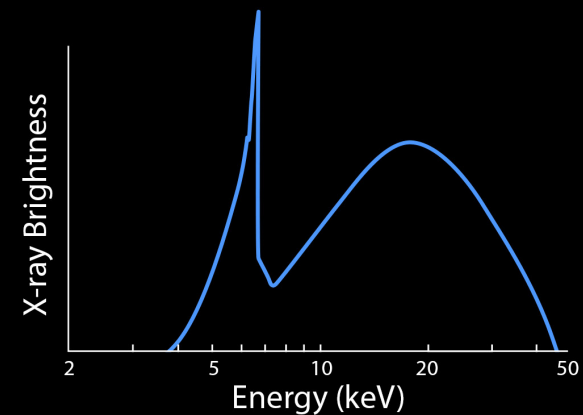
Long times scales produced at large distances (turbulent fluctuations of mass accretion rate ?) and propagate inward on viscous time scale until they reach X-ray emitting region (within 100 R)

Accretion disks model may produce 1/f noise (Lyubarskii 1997; King et al. 2004; Arevalo & Uttley 2006, Mayer & Pringle 2006, ...)

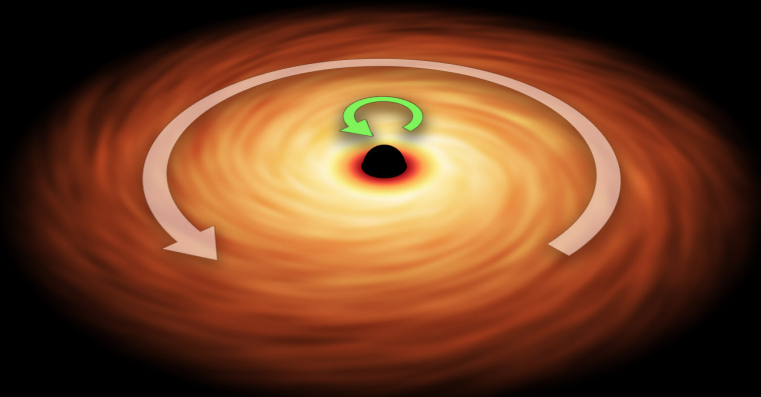
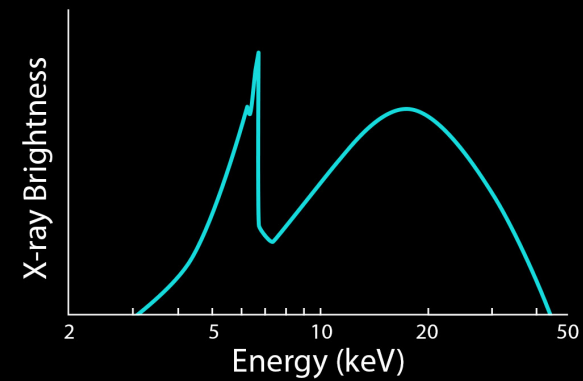
Explains observed rms-flux correlation (Uttley et al. 2005)



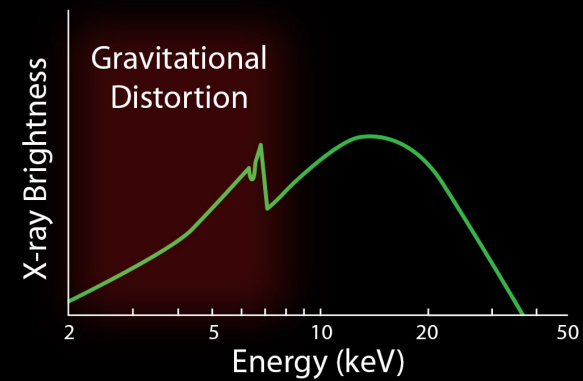
Retrograde
Rotation



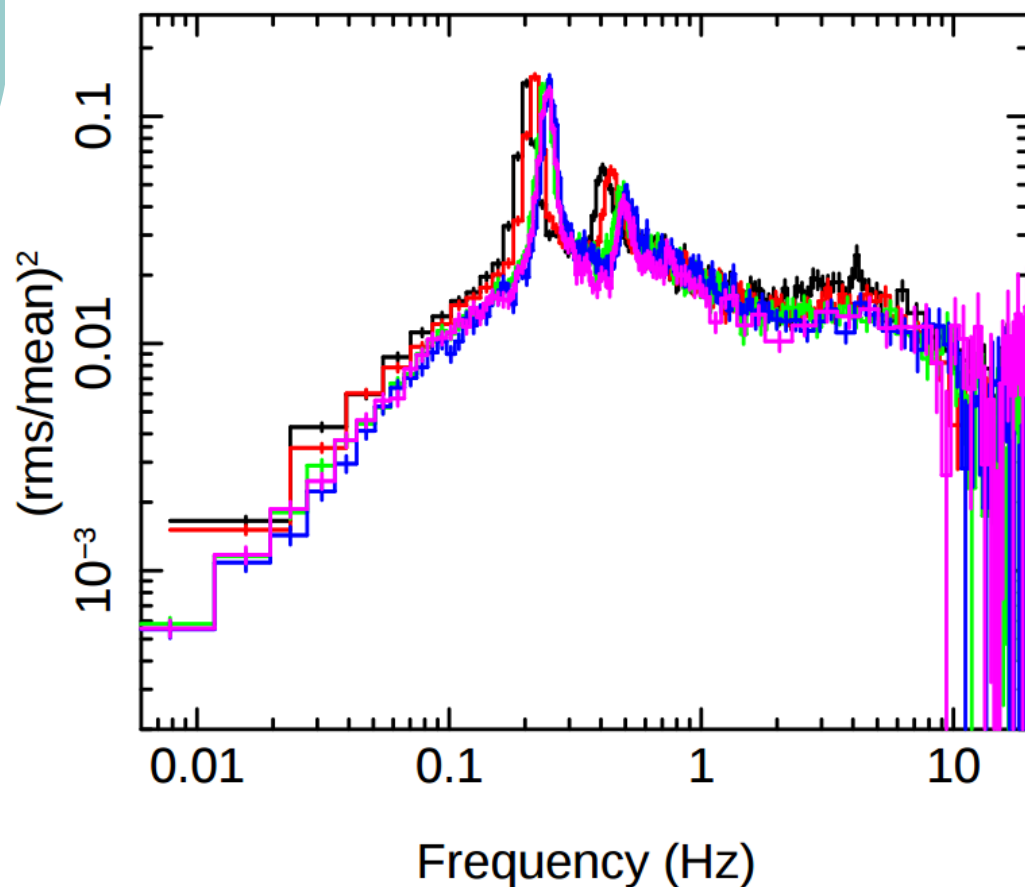
No Black Hole
Rotation



Prograde
Rotation



Type-C QPO (Quasi Periodic Oscillation)

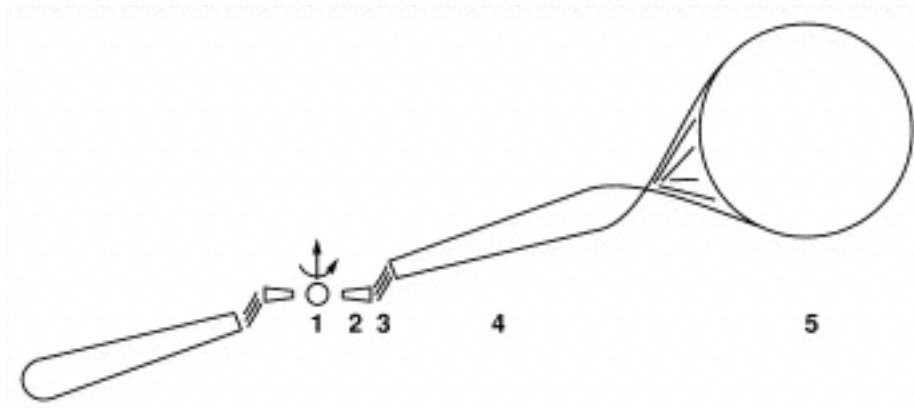


Observed in several
Black hole binaries.

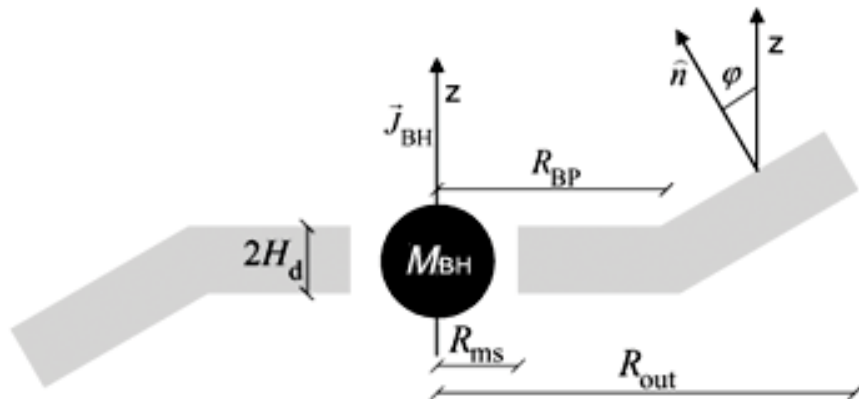
Mysterious origin

0.25 Hz QPO \rightarrow ~ 4 s modulation

Bardeen-Patterson Effect

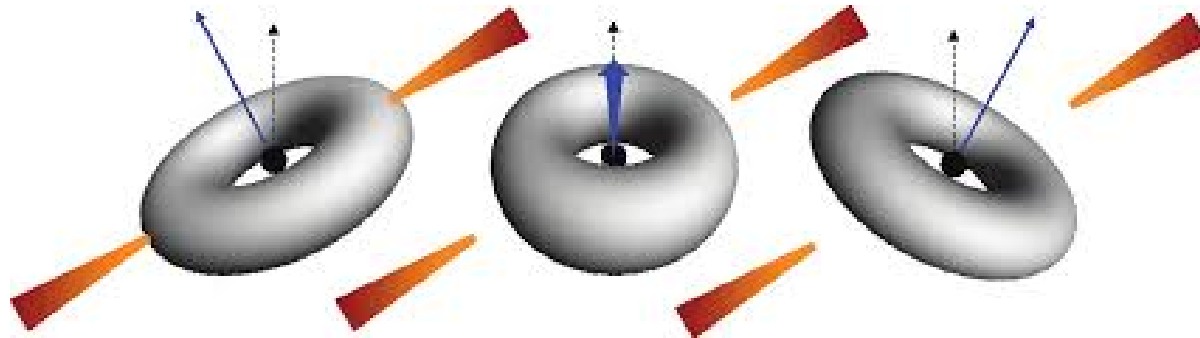


Bardeen & Patterson 1975



Nealon, Price and Nixon (2015)

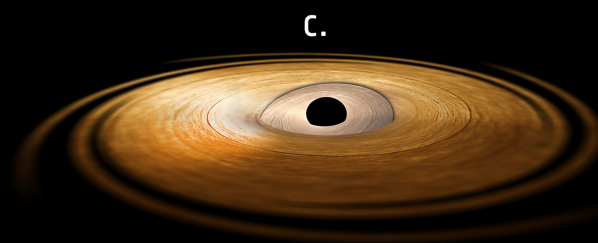
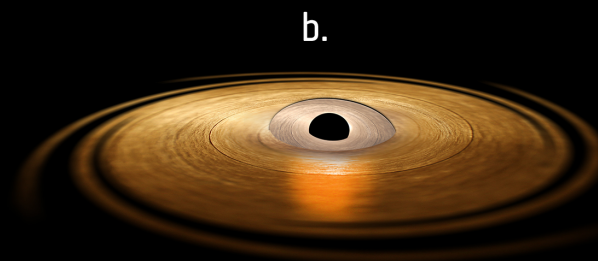
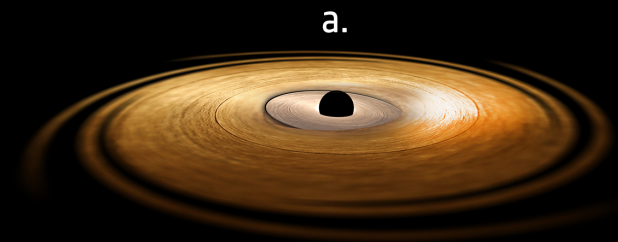
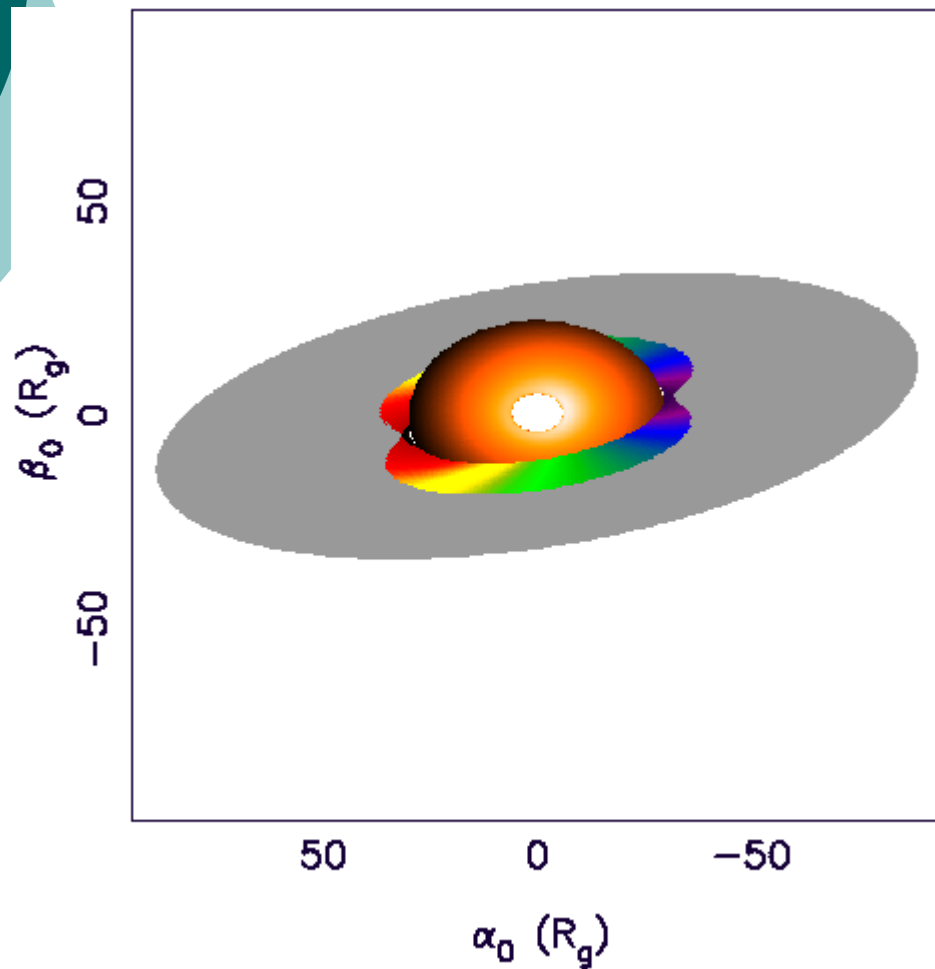
Lense-Thirring Precession

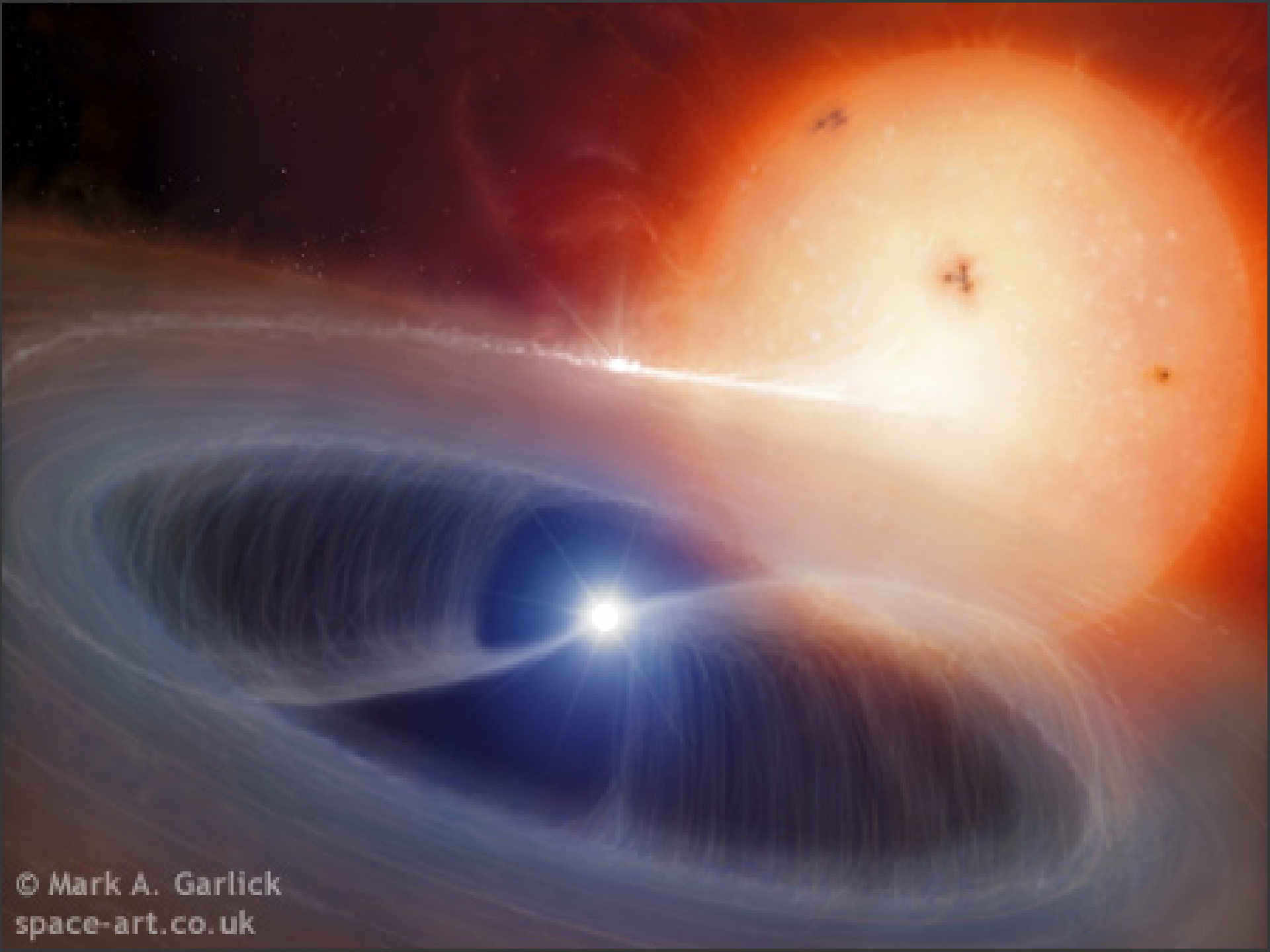


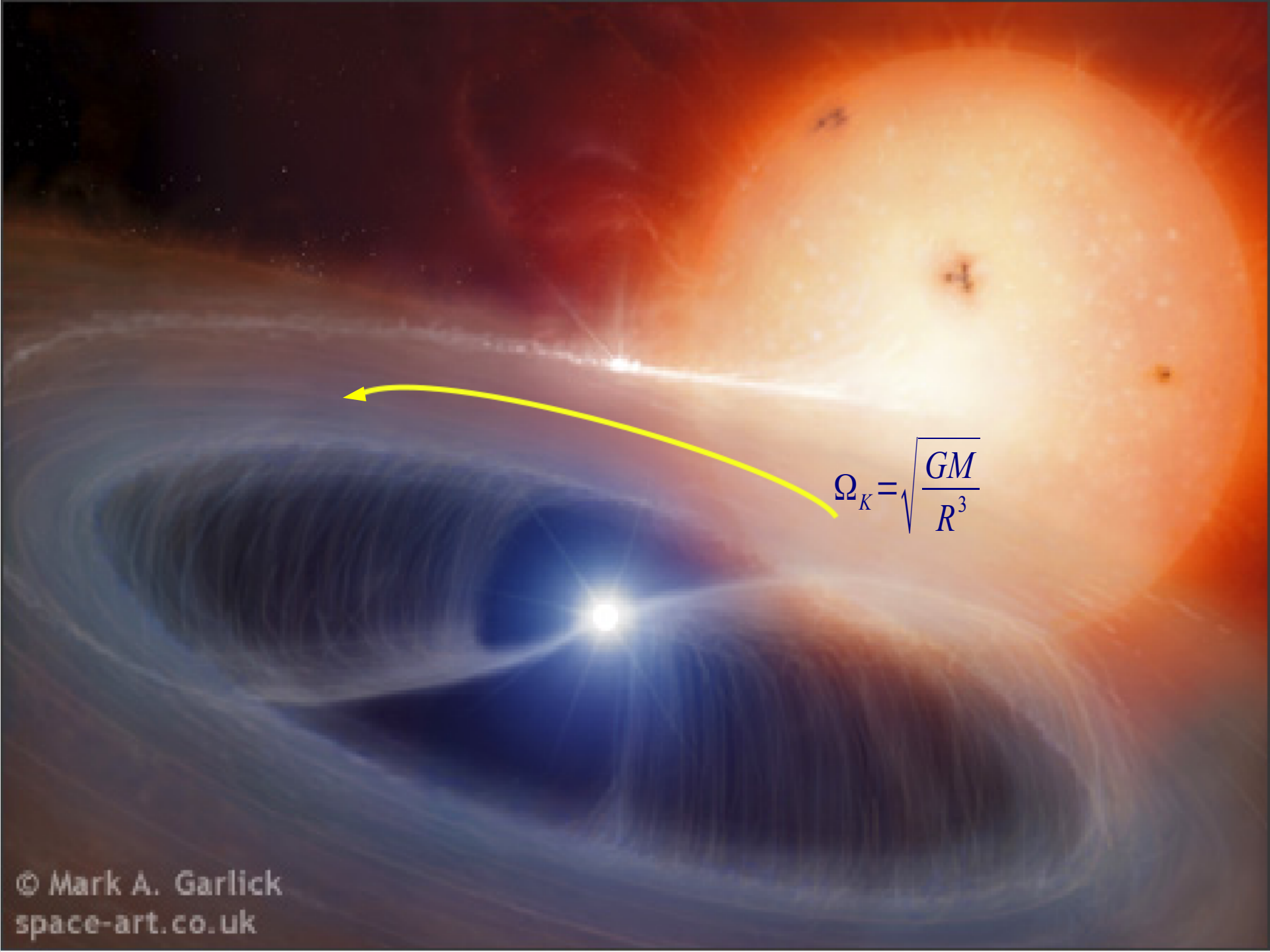
In general relativity, Lense–Thirring precession is a relativistic correction to the precession of a gyroscope near a large rotating mass..

Example Period of Lense-Thirring precession
around Earth ~ 33 Myr
around a 10 Msun Black Hole ~ few seconds

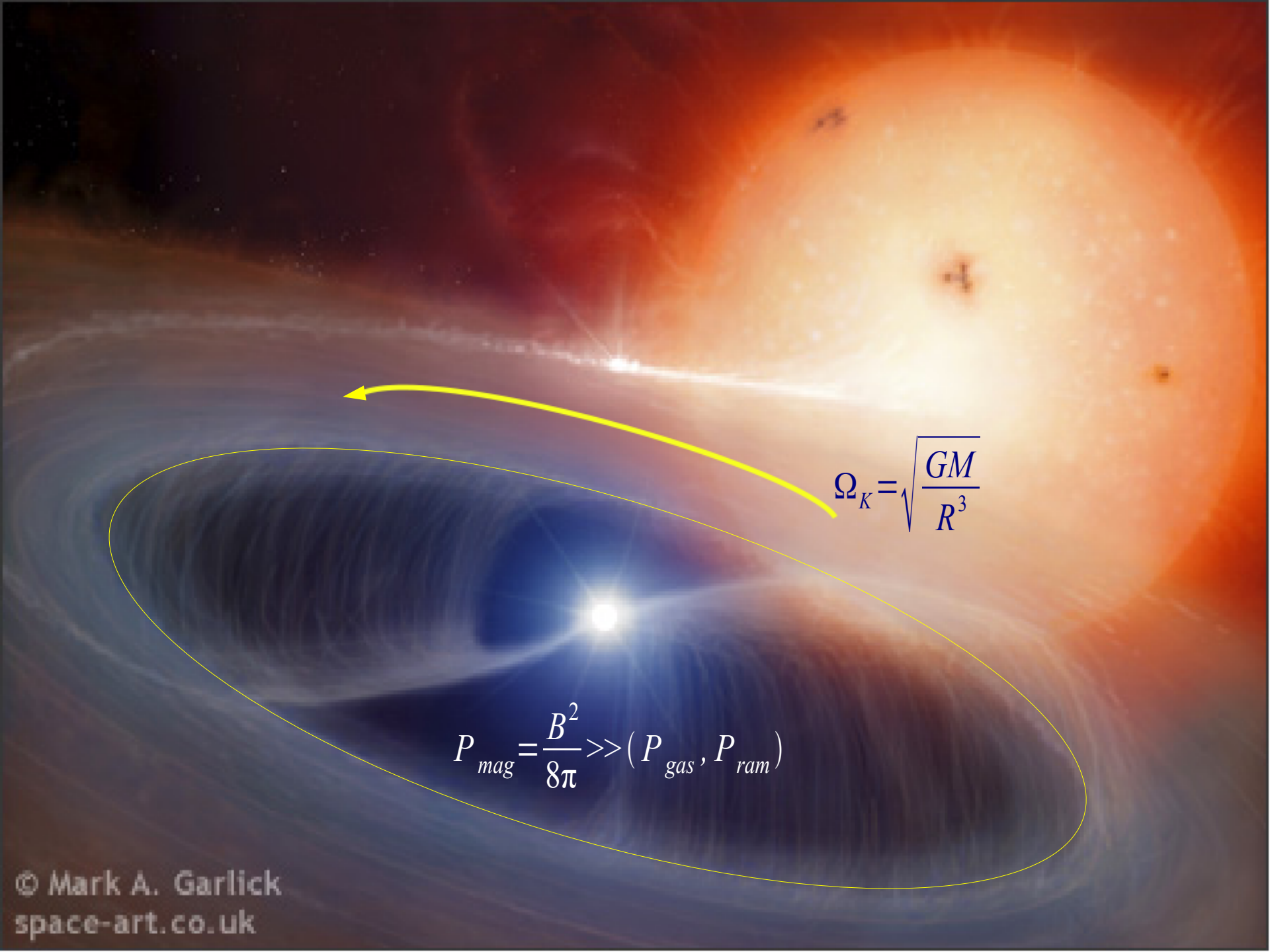
Lense-Thirring Precession around H 1743-322





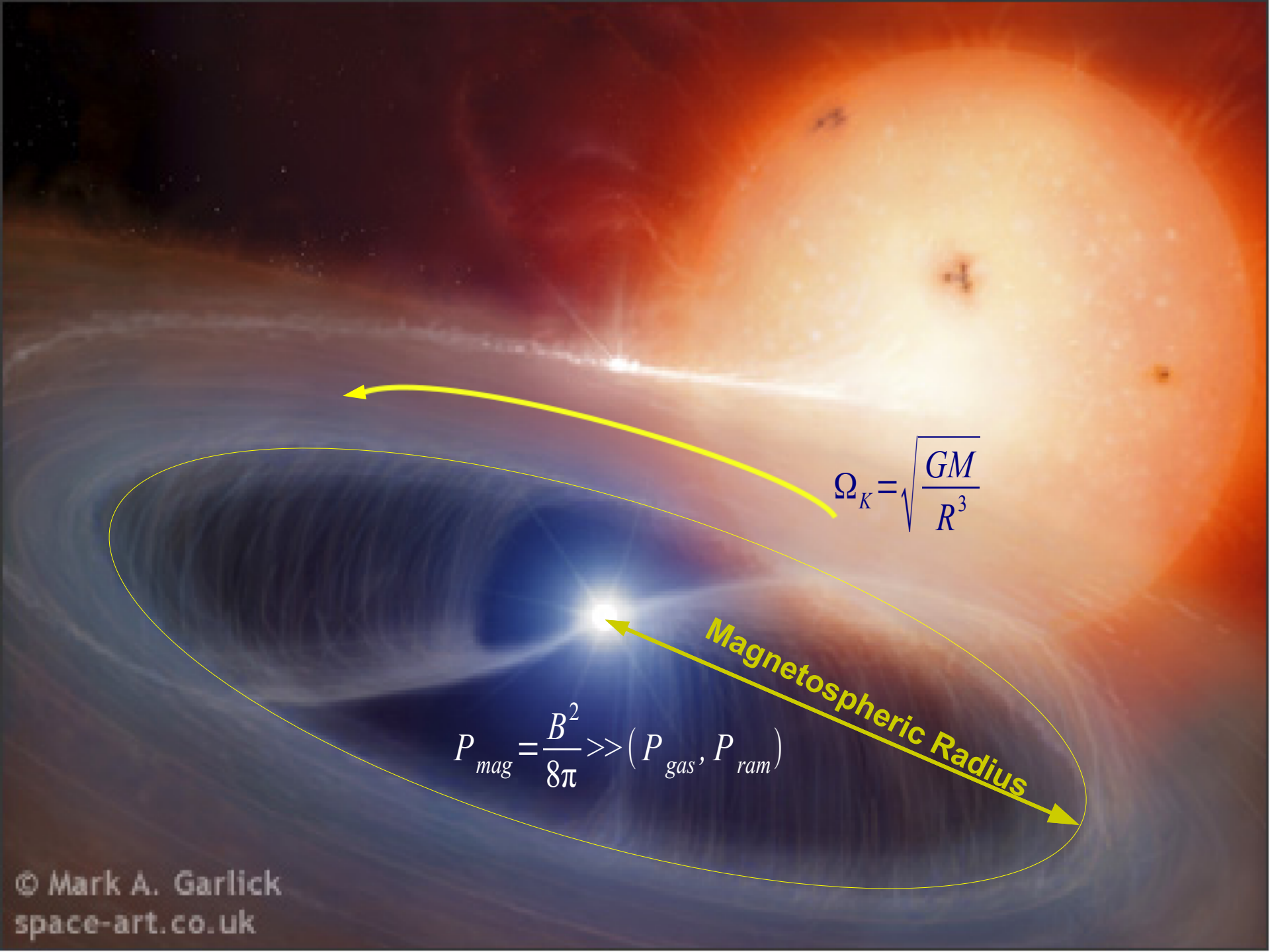


$$\Omega_K = \sqrt{\frac{GM}{R^3}}$$



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$$P_{mag} = \frac{B^2}{8\pi} \gg (P_{gas}, P_{ram})$$



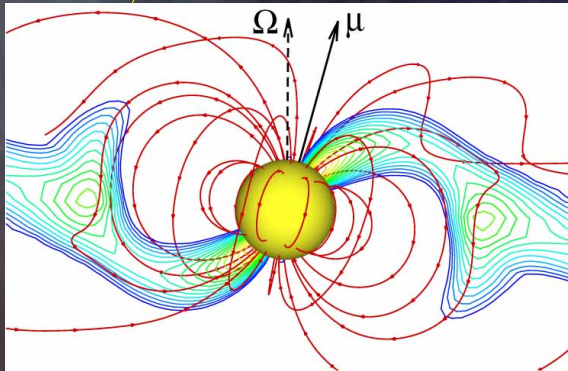
$$\Omega_K = \sqrt{\frac{GM}{R^3}}$$

$$P_{mag} = \frac{B^2}{8\pi} \gg (P_{gas}, P_{ram})$$

Magnetospheric Radius

Hot Spots

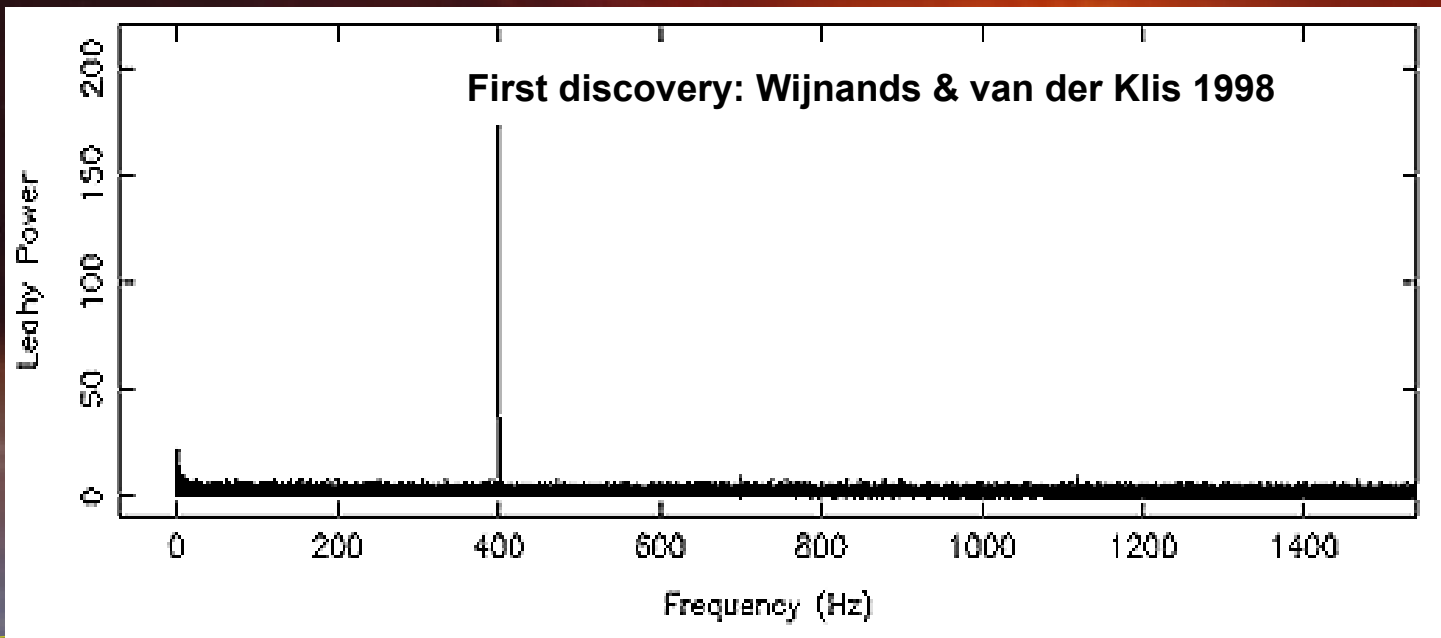
$$\Omega_K = \sqrt{\frac{GM}{R^3}}$$



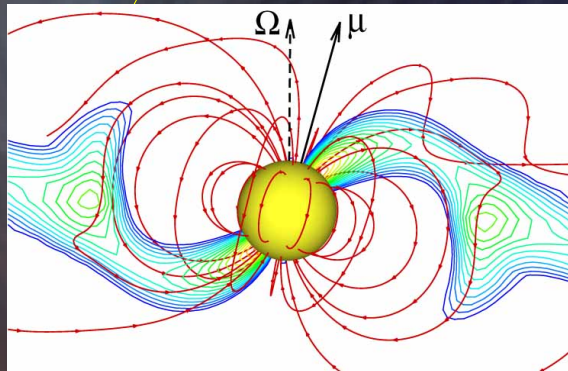
Magnetospheric Radius

$$P_{mag} = \frac{B^2}{8\pi} \gg (P_{gas}, P_{ram})$$

$$\dot{v} \propto \dot{M}^{6/7}$$



Hot Spots



$$\Omega_K = \sqrt{\frac{GM}{R^3}}$$

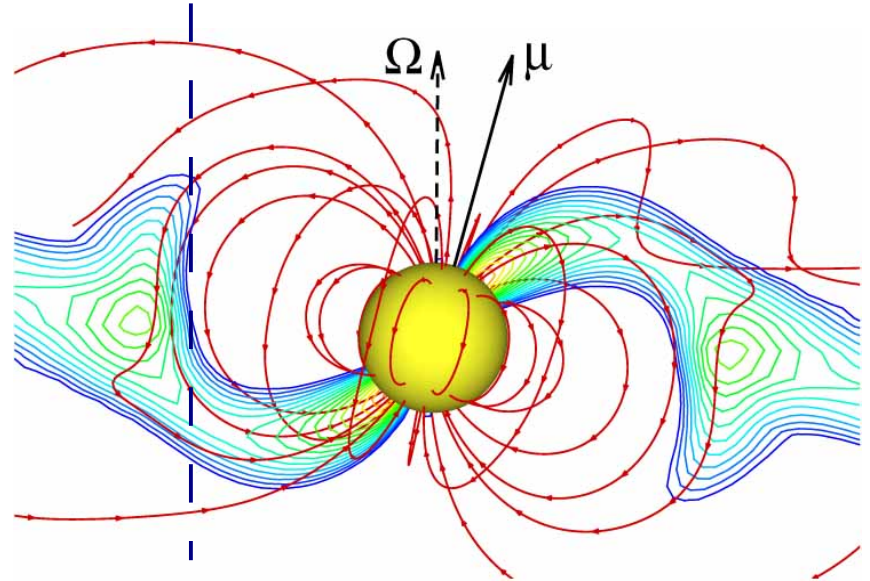
Magnetospheric Radius

$$P_{mag} = \frac{B^2}{8\pi} \gg (P_{gas}, P_{ram})$$

$$\dot{v} \propto \dot{M}^{6/7}$$

Magnetospheric Accretion

$$N_{acc} \approx \dot{M} l(r_m) \approx \dot{M} \sqrt{G M r_m}$$



$$r_m < r_{co}$$

Accretion is possible. Plasma flows along field lines before landing on the surface.

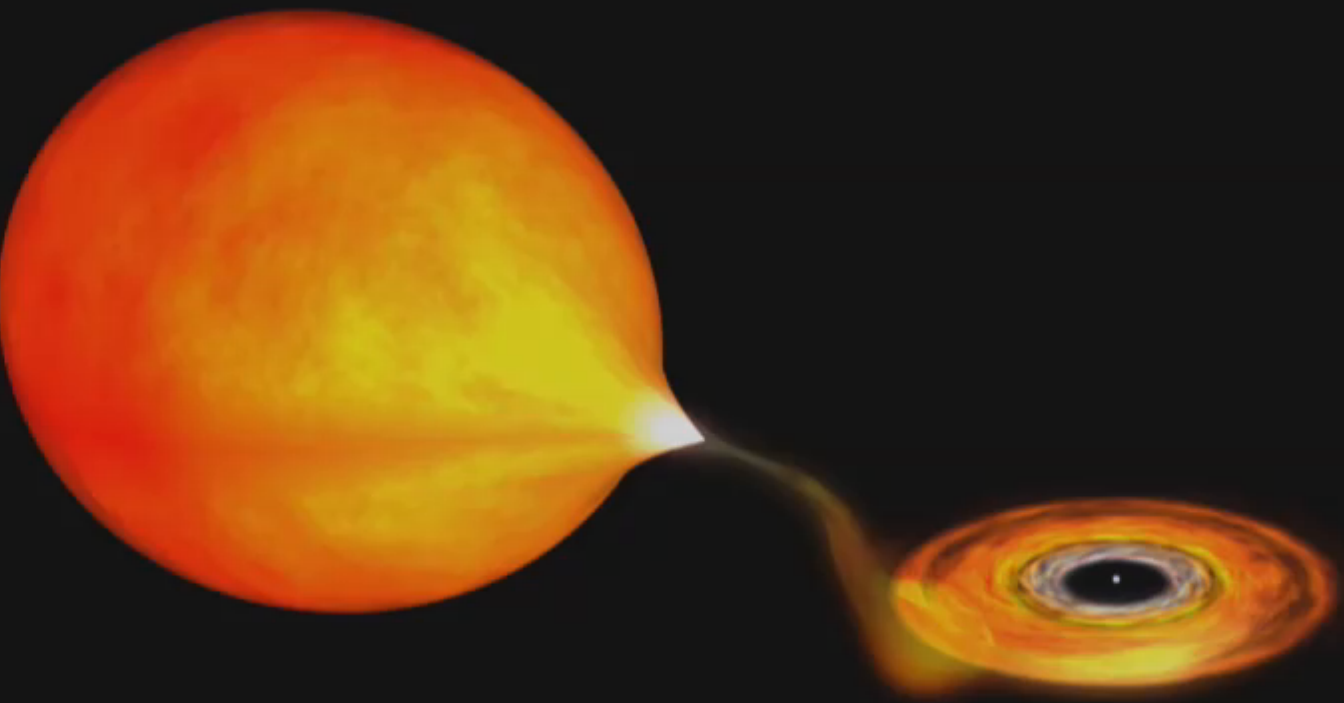
$$r_m > r_{co}$$

Strong propeller: Accretion is prevented. Plasma is **ejected** by the centrifugal barrier of the magnetic field

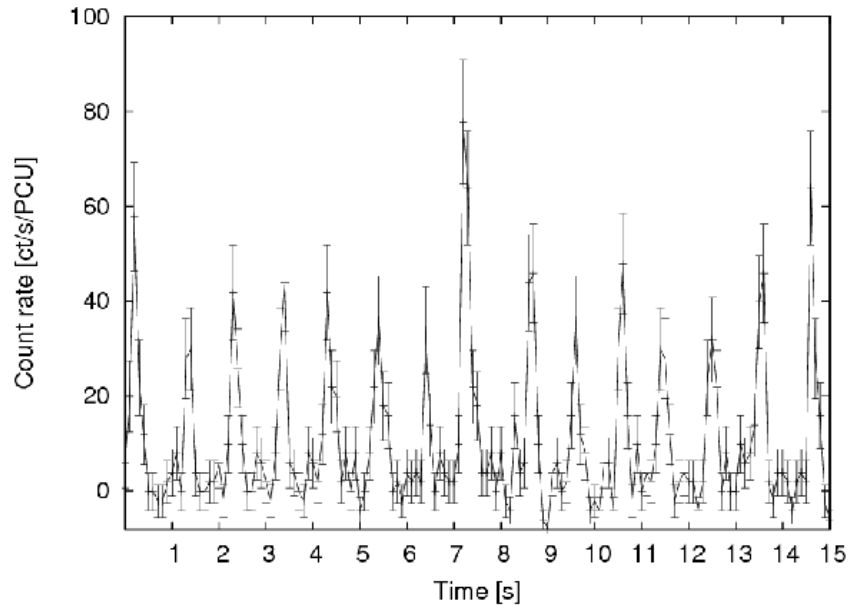
Illarionov & Sunyaev '75

Weak propeller: Material is stopped but **not ejected** from the system

Spruit & Taam '93
Rappaport+ 04
Ustyugova+ '06

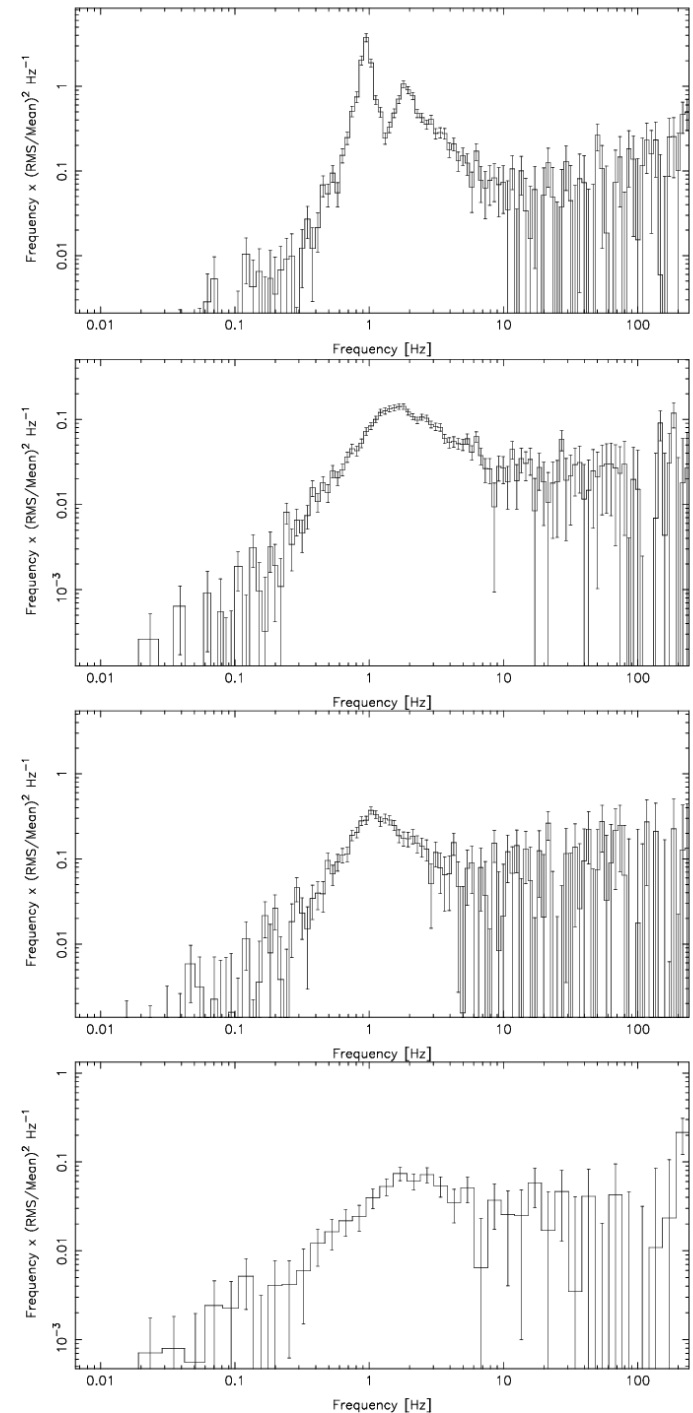


1 Hz QPO in Accreting ms Pulsars

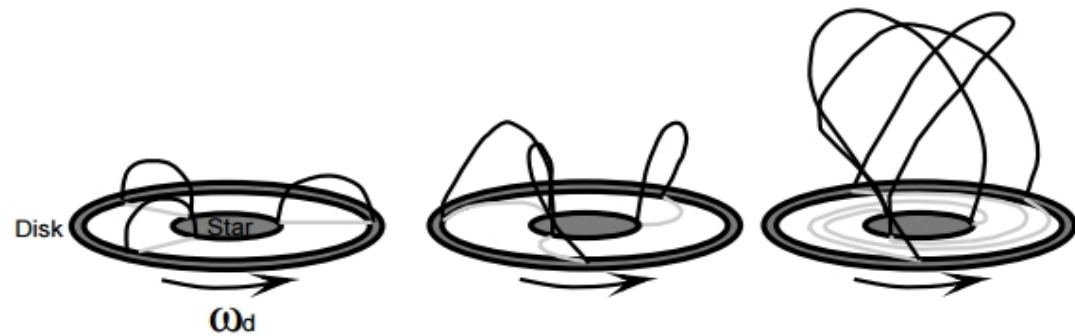


Useful to probe different region of the accretion disk!

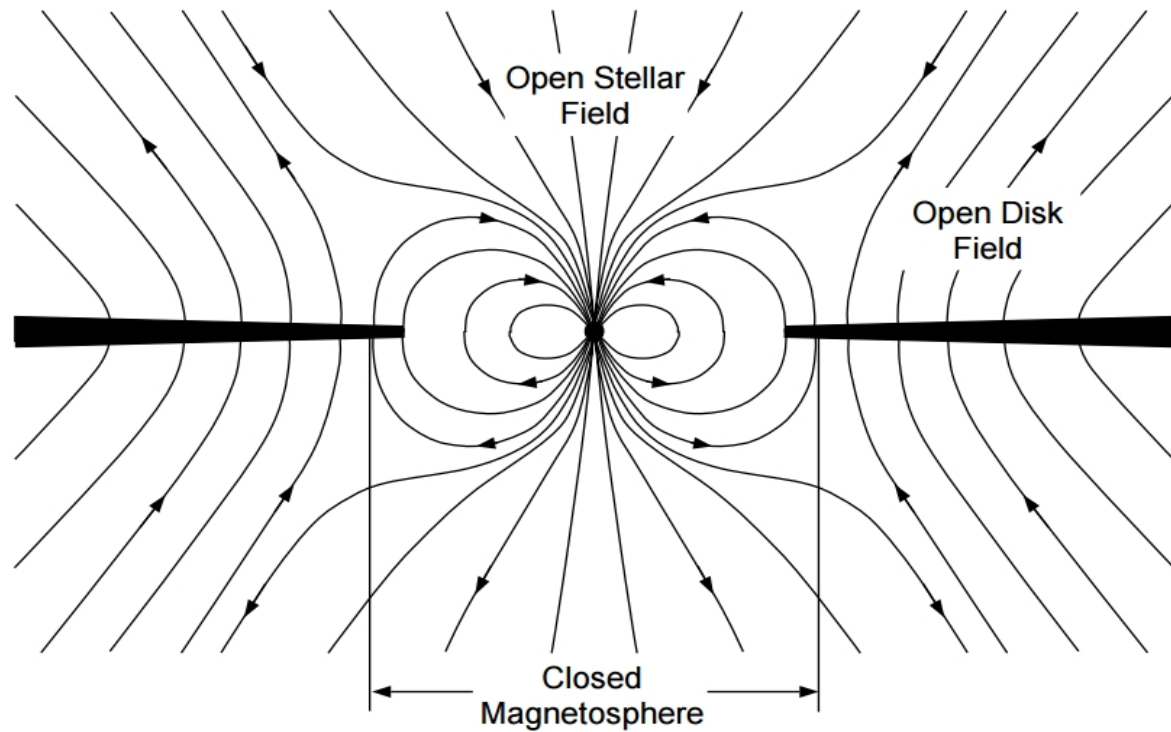
Can also help to measure physical characteristics of disk/magnetosphere interaction region (for magnetized neutron stars)



Field inflates almost immediately (ms timescale)



Pulsar field hardly connected at all with the disk.
Field line opening unavoidable



E.g., Aly '85, Lovelace+ '95, Goodson+ '97, D'Angelo & Spruit 2010, Romanova et al. 2008, Patruno et al. 2016

Hydrostatic Equilibrium

with Hydrostatic Equilibrium + EoS you can build a model for your star (and calculate Mass and Radius)

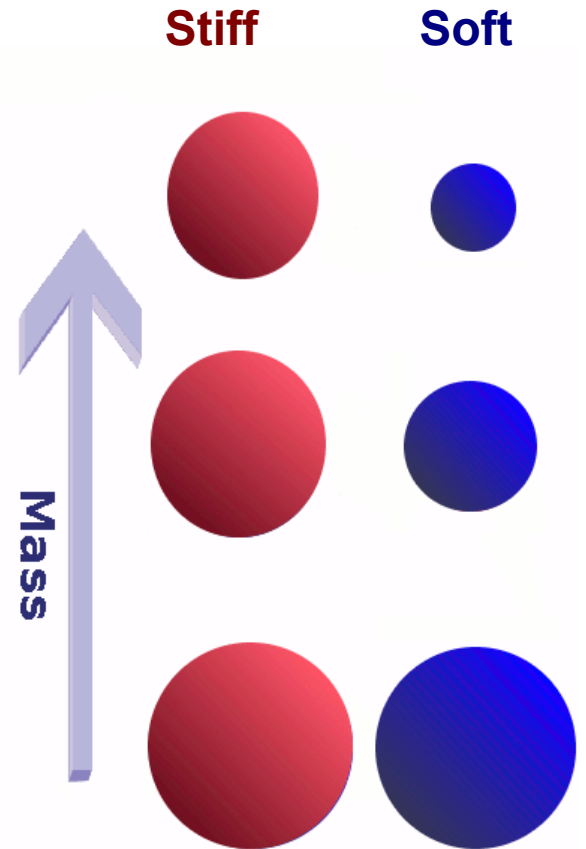
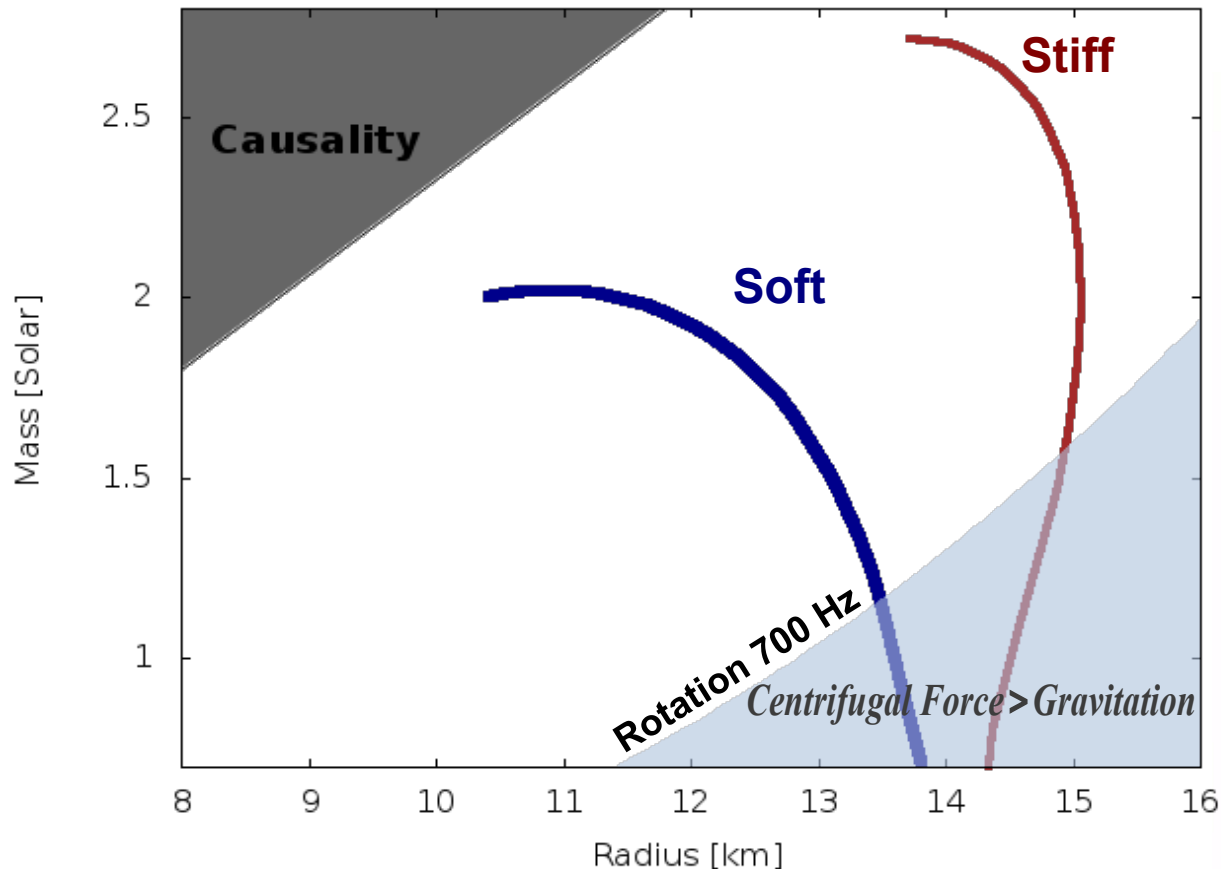
$$m(r) = \int_0^r \rho 4\pi r'^2 dr' \rightarrow \frac{dm(r)}{dr} = 4\pi r^2 \rho$$
$$\frac{dP}{dr} = -\frac{G m(r) \rho}{r^2}$$

$$\frac{1}{r^2} \frac{d}{dr} \left(\frac{r^2}{\rho} \frac{dP}{dr} \right) = -4\pi G \rho$$

+
Equation of State

Structure of a star (e.g., M-R relation)

Neutron Stars and Strong Force

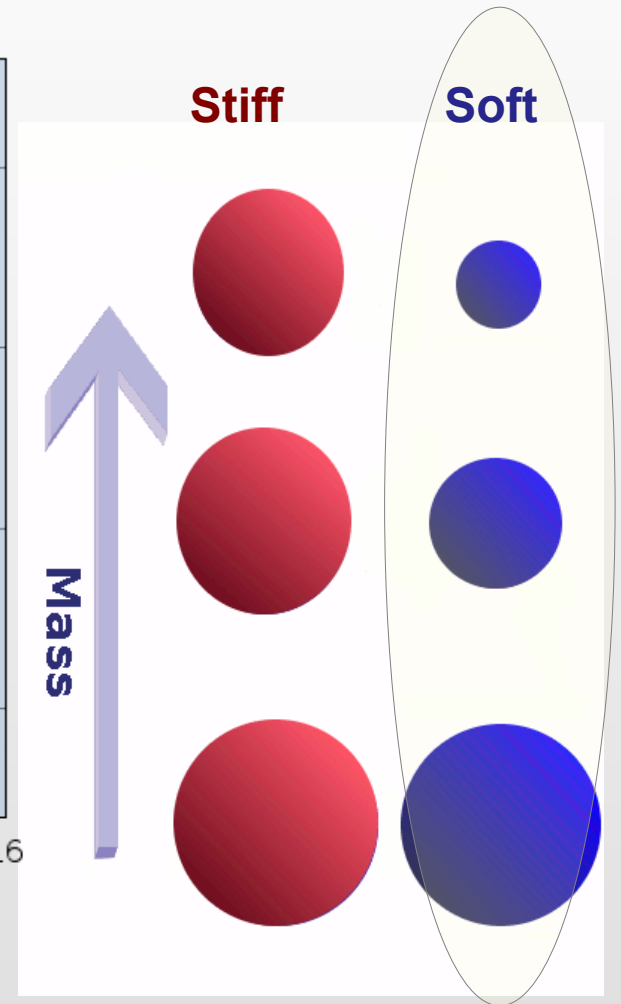
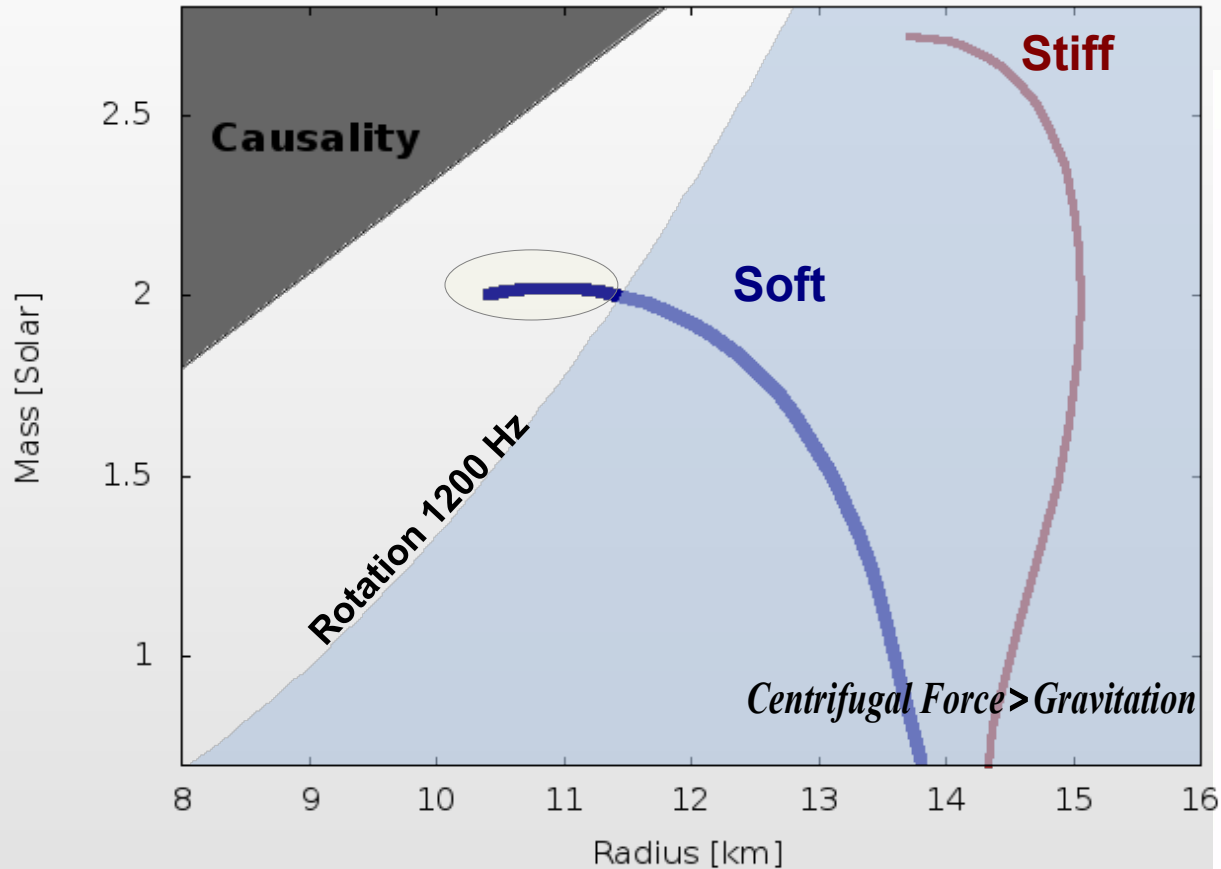


e.g., Lattimer & Prakash 2011

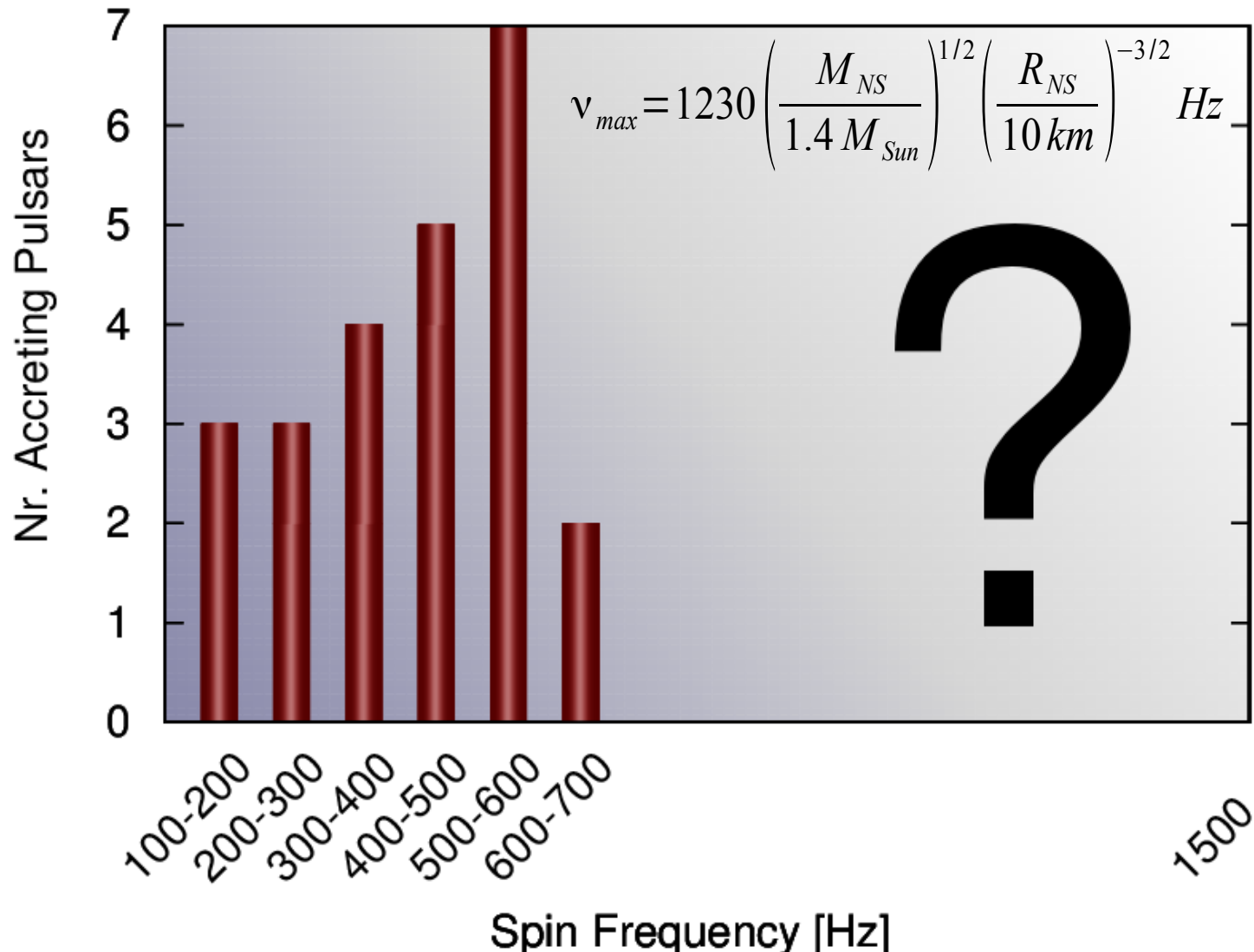
Gravity + EoS \rightarrow Neutron Star Structure (M-R).

Invert problem: Gravity + M-R \rightarrow EoS

Neutron Stars and Strong Force

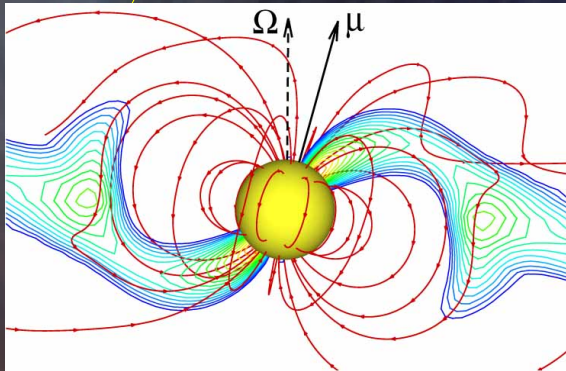


Where are the fastest known pulsar?



Source Name	Spin Freq. Derivative (Expected) [Hz/s]	Spin Freq. Derivative (Measured) [Hz/s]
SAX J1808.4-3658	9e-14	< 2.5e-14
XTE J1807-294	1e-13	< 4e-14
XTE J1814-338	4e-14	<1.5e-14
IGR J00291+5934	1e-12	5e-13

Hot Spots



$$\Omega_K = \sqrt{\frac{GM}{R^3}}$$

$$P_{mag} = \frac{B^2}{8\pi} \gg (P_{gas}, P_{ram})$$

$$\dot{v} \propto \dot{M}^{6/7}$$

Magnetospheric Radius

See Patruno & Watts 2012 for a review
 Patruno et al. 2012, Patruno 2010
 Patruno, Wijnands & van der Klis 2009

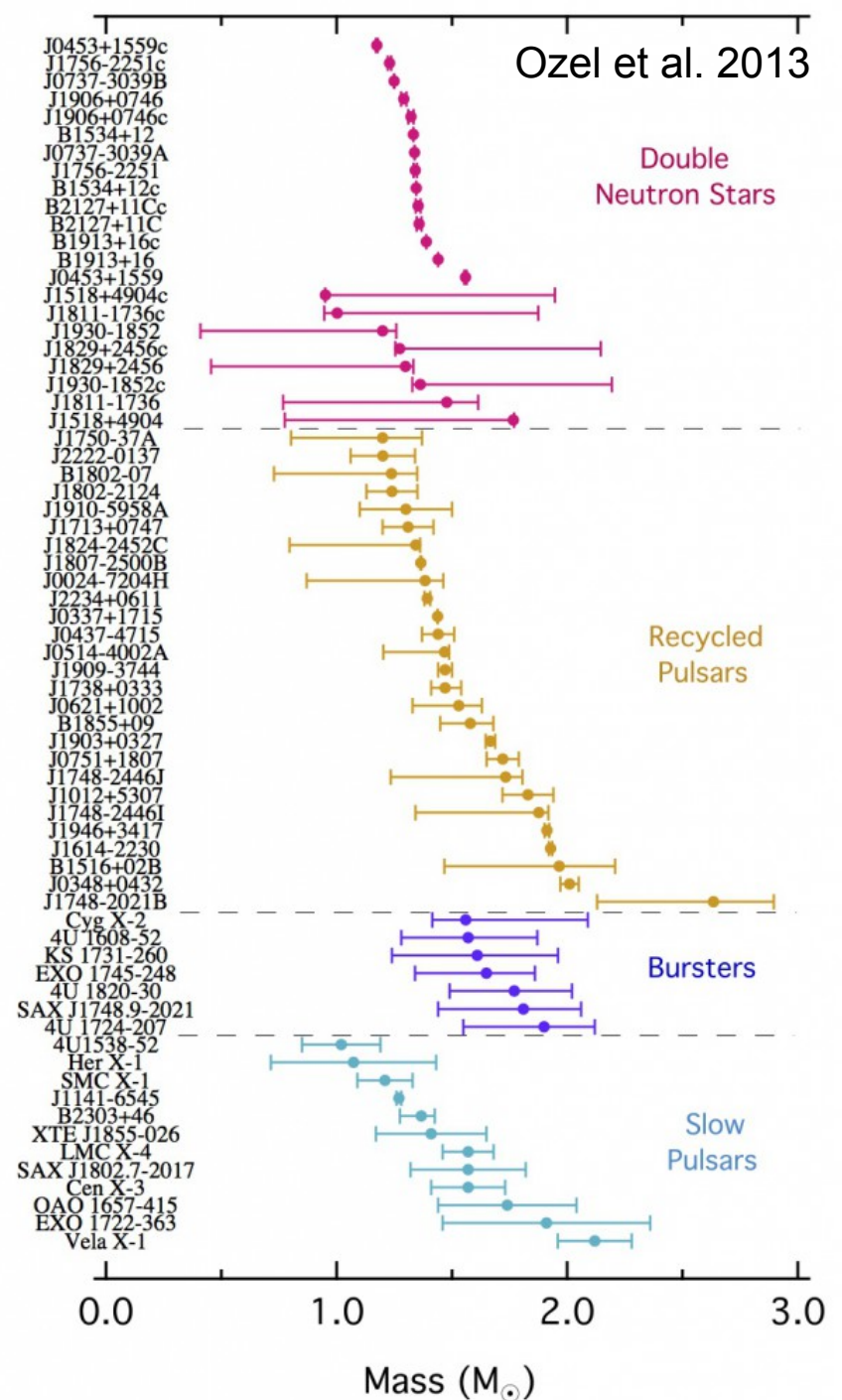
Neutron Stars Masses

So far biggest neutron star has a mass of 2 Msun (e.g., Demorest et al. 2010).

Maximum theoretical limit is 3 Msun (more massive → collapse to black hole).

Almost **any** EoS predicts masses > 2Msun

There must be massive neutrons stars out there!



Constraints from Neutron Star Mass

