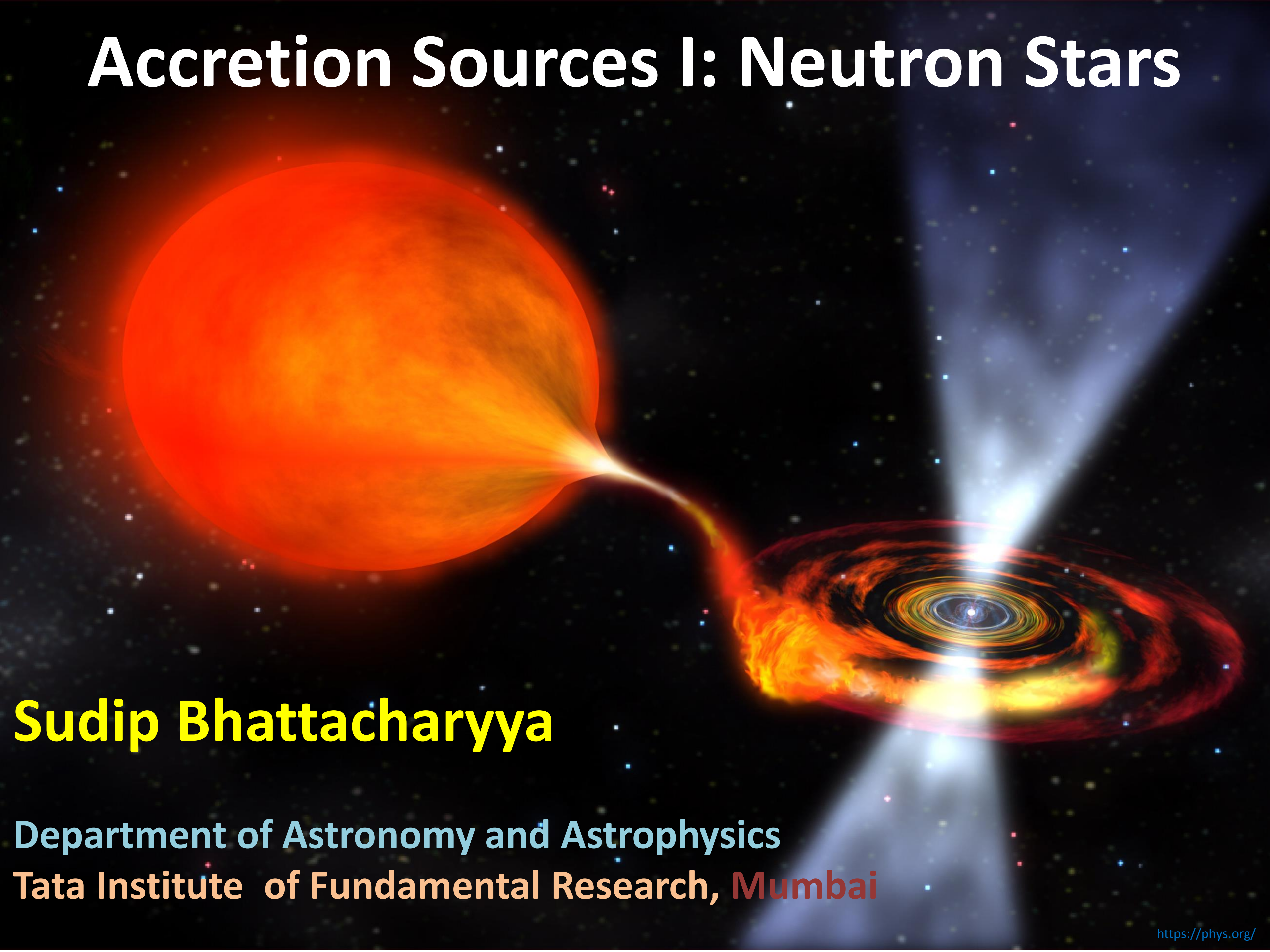
Accretion Sources I: Neutron Stars



https://phys.org/

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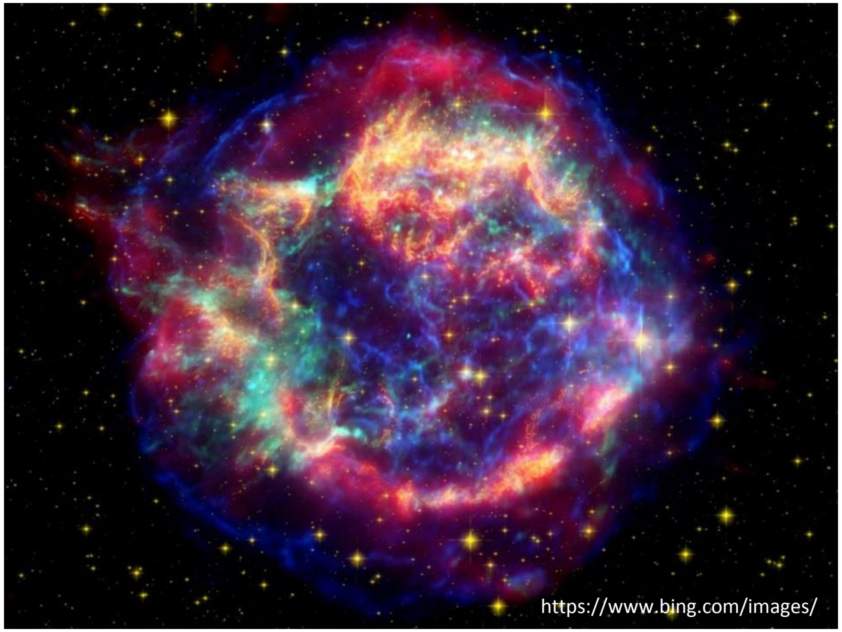
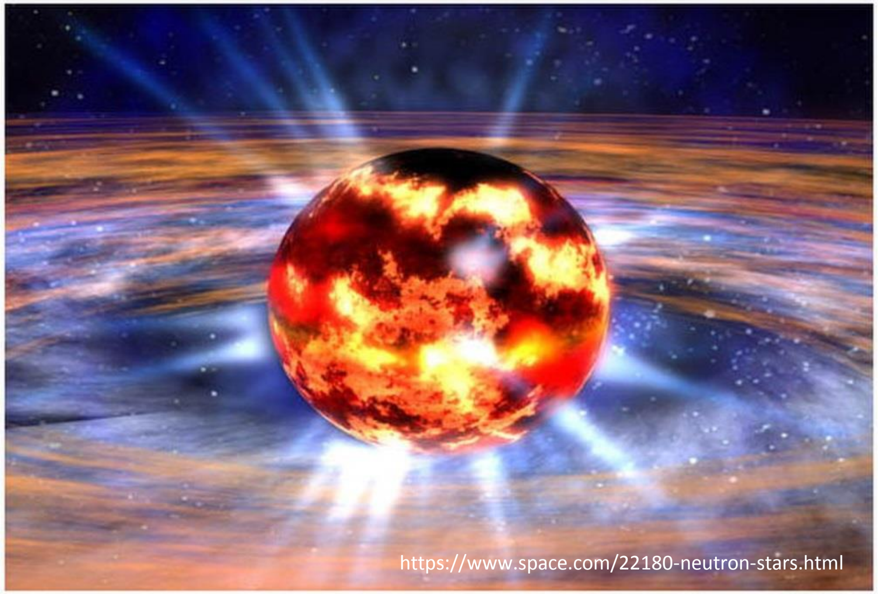
Neutron star

A neutron star is created when a massive star dies by a supernova explosion, and its core collapses.



https://www.bing.com/images/

Supernova



https://www.space.com/22180-neutron-stars.html

Neutron star

A “dead” star (no fuel burning), but more alive than a normal star!

Neutron star:
more than one solar mass crammed into a sphere of the size of a city

Neutron star vs. a city

Figure courtesy: M. Coleman Miller

Radius ~ 10 - 20 km

Mass ~ 1.4 - 2.0 solar mass

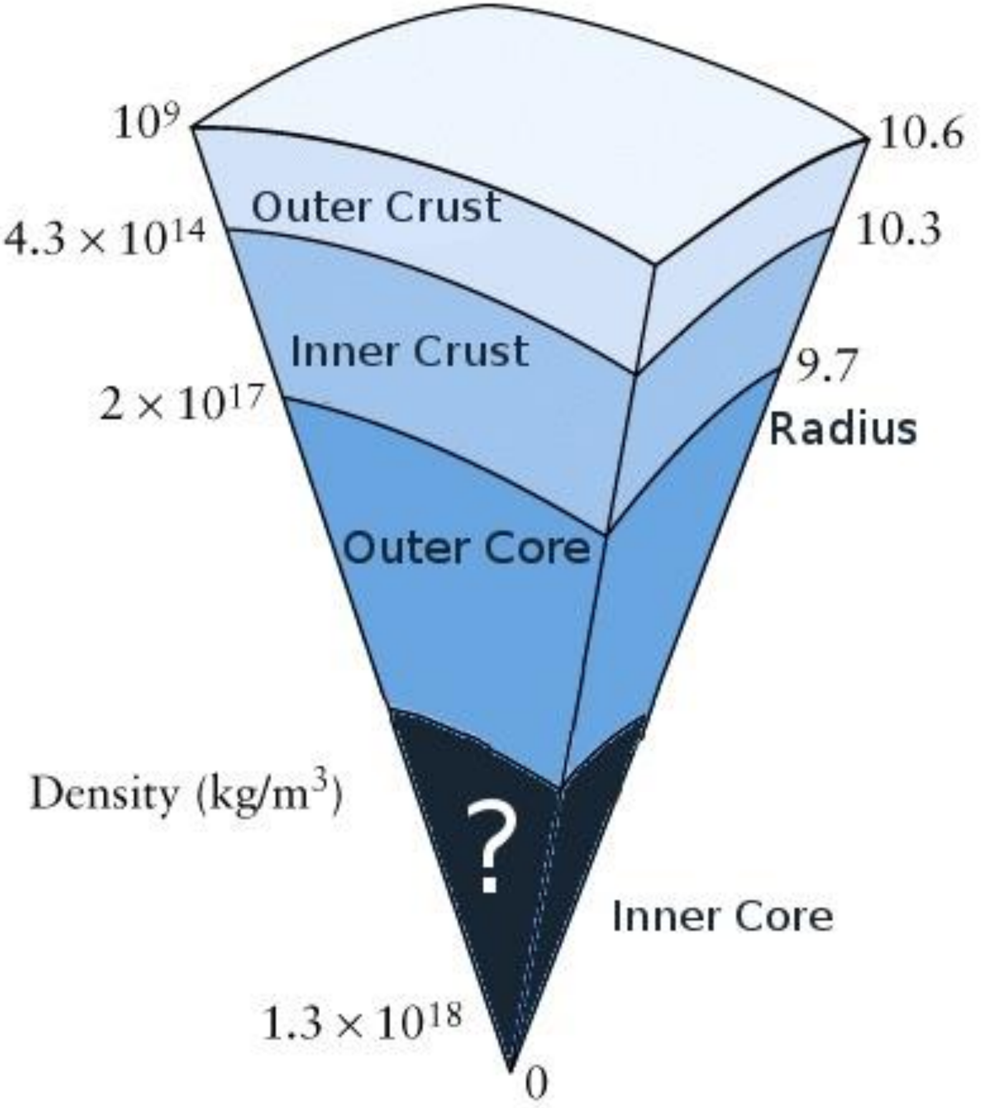
Core density ~ 5 -10 times the nuclear density

Magnetic field ~ 10^{7} - 10^{15} G

Spin frequency
(for fast-spinning neutron stars or millisecond pulsars)
~ 200 - 700 Hz

Some of the most extreme conditions of the universe exist in neutron stars.

There is possibly no branch of physics, that is not useful for neutron star study.



Astrophysics

Gravitational physics

Nuclear physics

High-energy physics

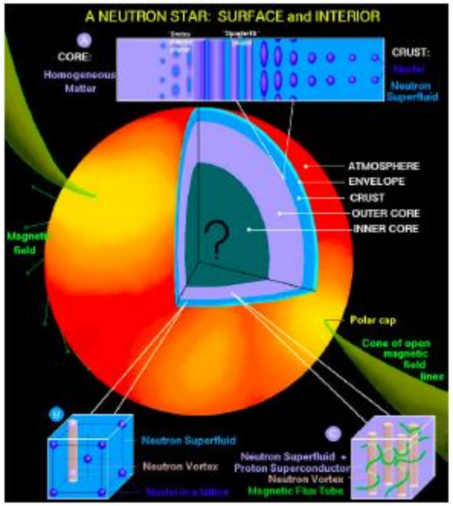
and even

Solid state physics
(neutron star crust is the strongest known solid in the universe.)

https://www.bing.com/images/

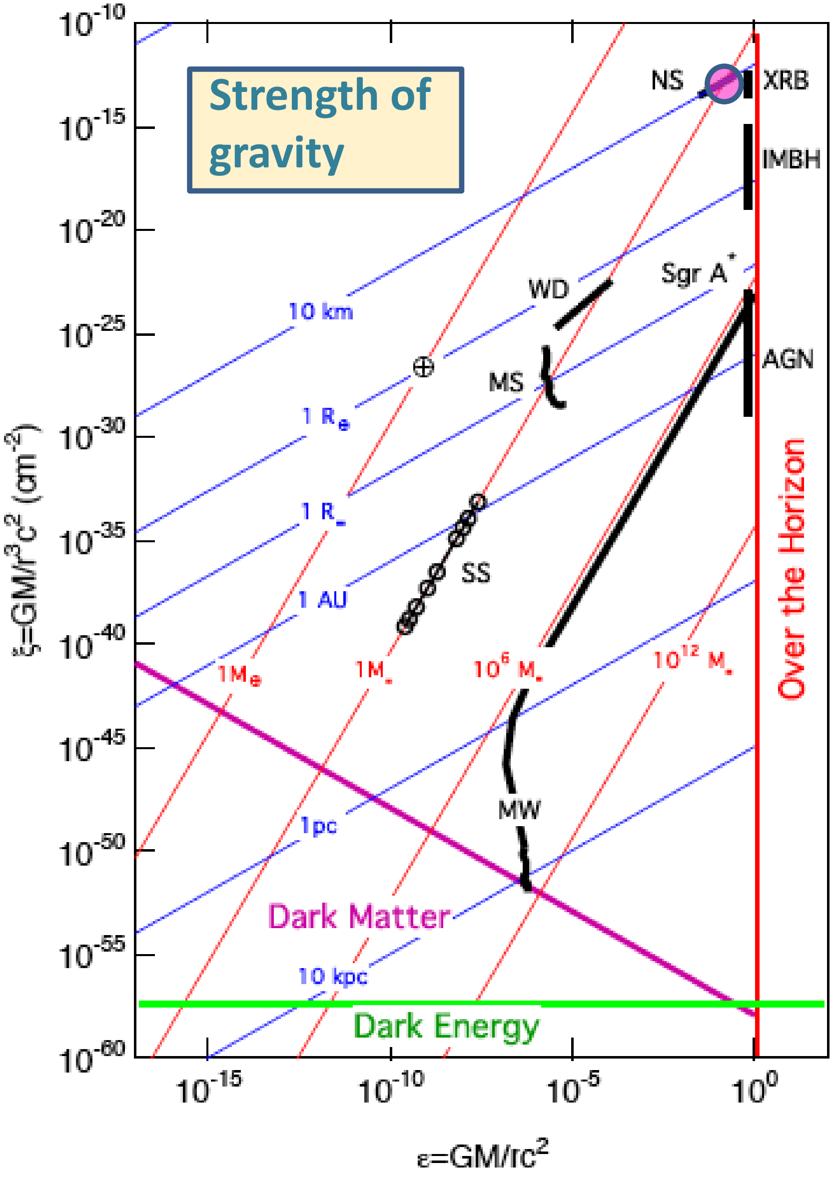
Neutron star: a unique laboratory

What are the properties of the relatively cold matter at a density 5-10 times the density of an atomic nucleus?



Is the neutron star core a bag of ~ 10^{57} free quarks? Are there new types of particles?

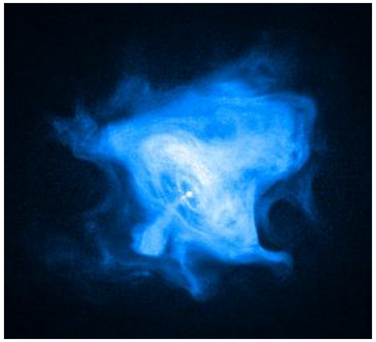
To answer these questions, we need to measure the mass and radius of the same neutron star.



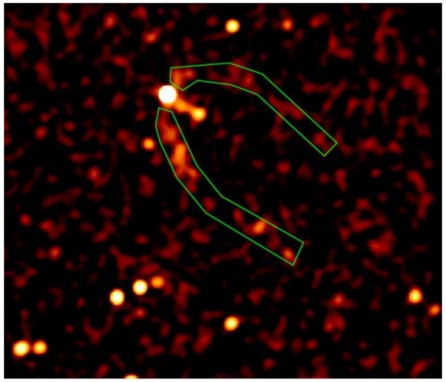
Psaltis (2008)

Neutron stars: many incarnations, emit in all EM wavelengths (radio to gamma-rays), multi-messenger astronomy (EM, neutrino, gravitational waves), many branches of astronomy (do not forget life/exoplanet).

Various neutron star systems observed in X-rays



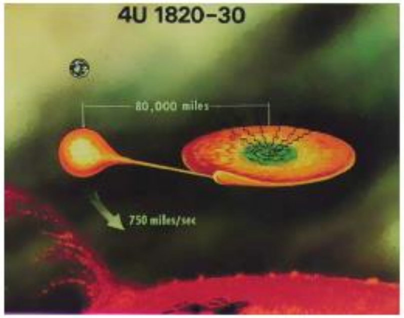
Crab pulsar
(real image)



Geminga pulsar
(*Chandra* image)

Pavlov, SB, Zavlin,
ApJ (2010)

Low-mass X-ray binary (LMXB)
(artist's impression)

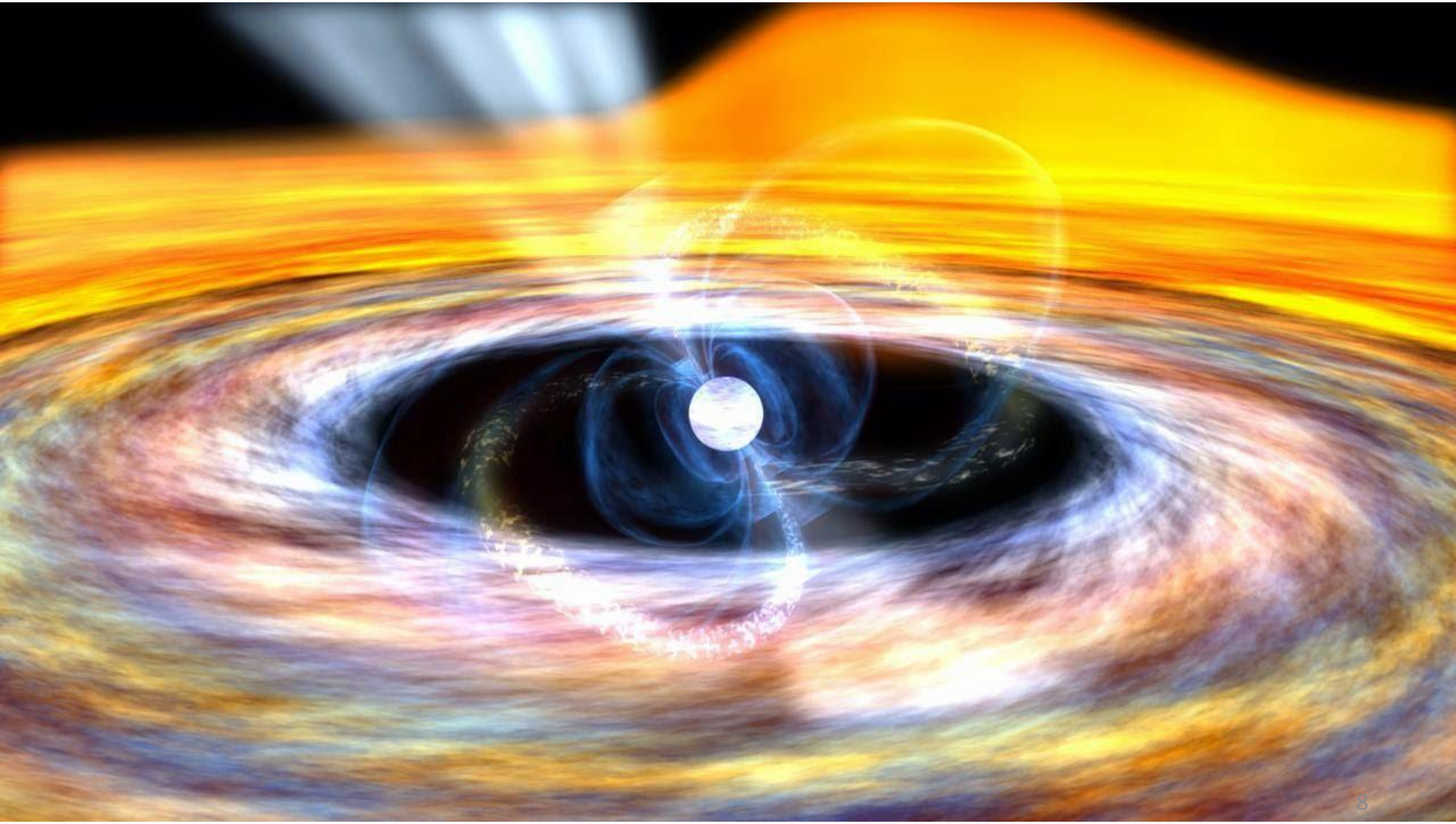


High-mass X-ray binary (HMXB)
(artist's impression)

Two types of neutron star X-ray binaries

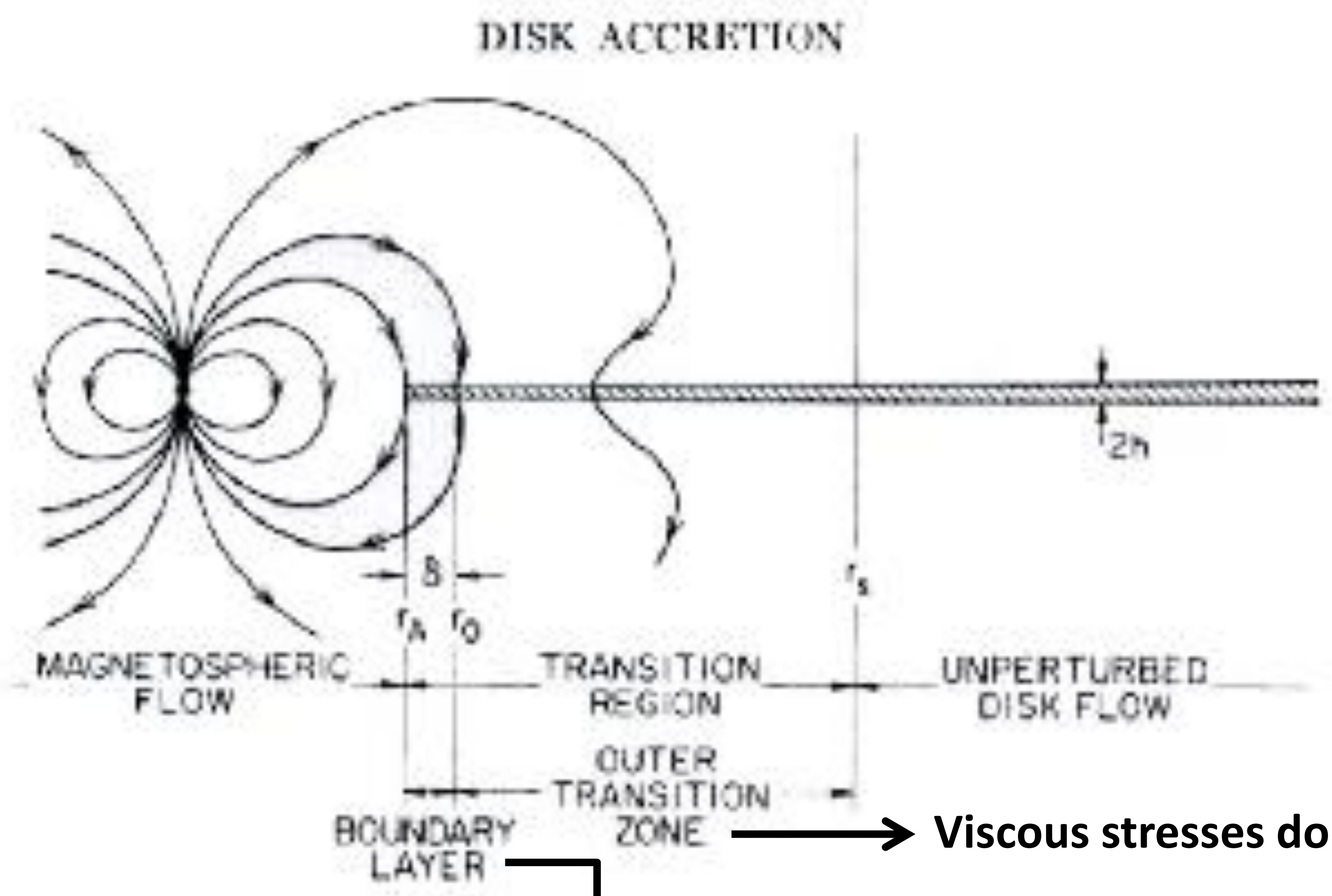
	LMXB	HMXB
Optical companion	Later than A	O or B
Mass of companion	$< 3\ M_\odot$	$> 10\ M_\odot$
Orbital period	~ 10 minutes - 10 days	~ 1 day – 1 year
L_{Opt}/L_X	0.001-0.01	0.1-1000
X-ray spectra	Soft ($kT < 5$ keV)	Hard ($kT > 15$ keV)
NS magnetic field	Low ($10^{7\text{-}9}$ G)	High (10^{12} G)
Age	~10^9 years	$< 10^7$ years
Accretion mechanism	Roche-lobe overflow	Beginning atmospheric Roche-lobe overflow; stellar wind; Be-disk
Accretion disk	Present	Usually absent or far
Pulsations	For some sources; Spin period ~ 2-3 ms	For many sources Spin period ~ 1-500 s

Accretion disk around a neutron star with a magnetosphere



https://aasnova.org/wp-content/uploads/2016/03/fig16.jpg

Disk-magnetosphere interaction



Viscous stresses dominate

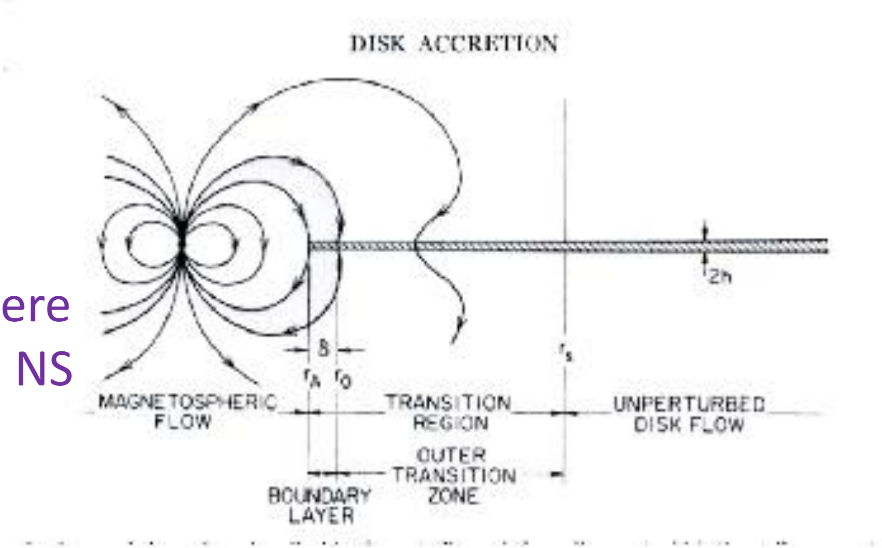
Magnetic stresses dominate ($\delta << r_A$)

Ghosh and Lamb (1978)

Disk-magnetosphere interaction

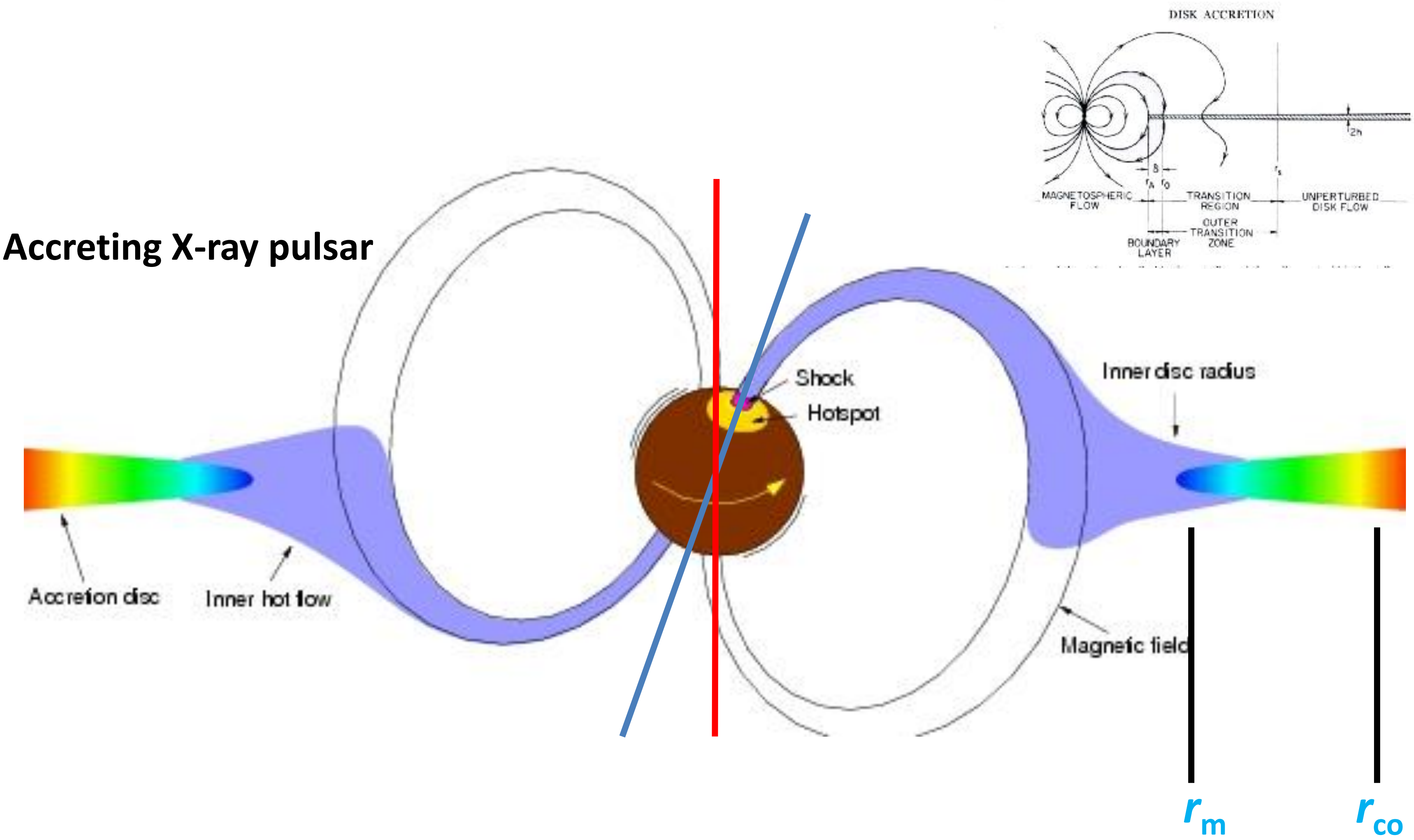
Magnetospheric radius
$r_m = \xi.[(B^2R^6)/(\dot{M}.\ (2GM)^{0.5})]^{2/7}$, where the accretion disk stops. ($\xi \sim 0.5\text{-}1.4$).

Corotation radius $r_{co} = [(GM)/(2\pi\nu)^2]^{1/3}$, where the Keplerian spin frequency is equal to the NS spin frequency.



Disk-magnetosphere interaction

Accreting X-ray pulsar



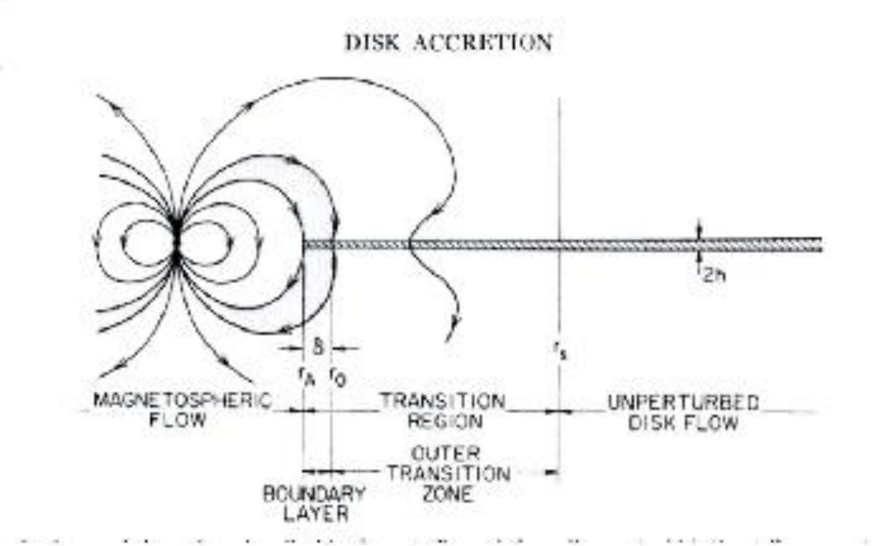
Standard scenario of X-ray pulsation: R or $r_{ISCO} < r_m < r_{co}$

http://www.issibern.ch/teams/observephysics/ns_nolgm.jpg

Disk-magnetosphere interaction

Magnetospheric radius

$r_m = \xi.[(B^2R^6)/(\dot{M}.(2GM)^{0.5})]^{2/7}$, where the accretion disk stops. ($\xi \sim 0.5\text{-}1.4$).



Corotation radius $r_{co} = [(GM)/(2\pi\nu)^2]^{1/3}$, where the Keplerian spin frequency is equal to the NS spin frequency.

For $r_m < r_{co} \Rightarrow$ positive torque (for example, $\dot{M}.[GMr_m]^{0.5}$) $\Rightarrow$ spin up $\Rightarrow r_{co}$ decreases

For $r_m > r_{co} \Rightarrow$ negative torque and propeller effect $\Rightarrow$ spin down $\Rightarrow r_{co}$ increases

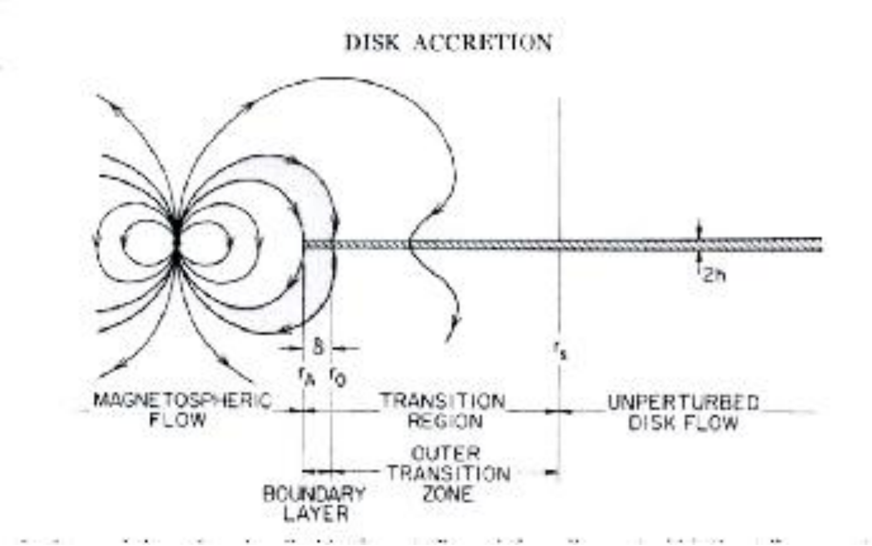
So a self-regulated mechanism operates:

r_{co} tends to r_m. At $r_m = r_{co}$: no torque $\Rightarrow$ spin equilibrium.

Spin equilibrium frequency $\nu_{eq} = 3000\ \text{Hz}\ .\ \xi^{-3/2}.B_8^{-6/7}.\ R_6^{-18/7}.(M/M_\odot)^{5/7}.(\dot{M}/\dot{M}_{Edd})^{3/7}$

Here, $B_8 = B/(10^8\ \text{G})$ and $R_6 = R/(10^6\ \text{cm})$

Disk-magnetosphere interaction



Magnetospheric radius

$r_m = \xi.[(B^2R^6)/(\dot{M}. (2GM)^{0.5})]^{2/7}$, where the accretion disk stops. (ξ ~ 0.5-1.4).

Corotation radius $r_{co} = [(GM)/(2\pi\nu)^2]^{1/3}$, where the Keplerian spin frequency is equal to the NS spin frequency.

At $r_m = r_{co}$: no torque ⇒ spin equilibrium.

Spin equilibrium frequency $\nu_{eq} = 3000\ \mathrm{Hz}\ .\ \xi^{-3/2} .B_8^{-6/7}.\ R_6^{-18/7}.(M/M_\odot)^{5/7}.(\dot{M}/\ \dot{M}_{Edd})^{3/7}$

For LMXBs, tyically $B = 10^8$ G, $R_6 = 1$, $M/M_\odot = 1.4$ and $\dot{M}/\ \dot{M}_{Edd} = 0.01$

Spin equilibrium frequency $\nu_{eq} \approx 530$ Hz [spin period ≈ 1.9 ms]

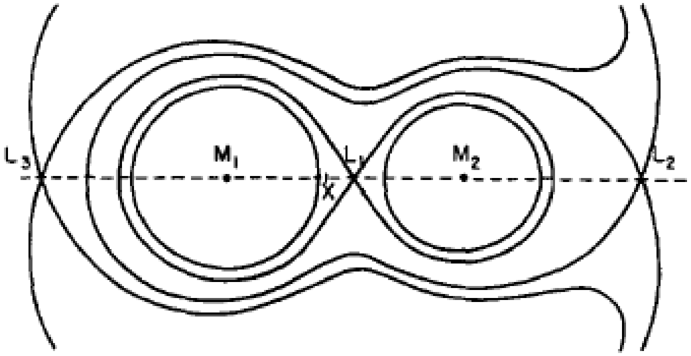
For HMXBs, tyically $B = 10^{12}$ G, $R_6 = 1$, $M/M_\odot = 1.4$ and $\dot{M}/\ \dot{M}_{Edd} = 0.01$

Spin equilibrium frequency $\nu_{eq} \approx 0.2$ Hz [spin period ≈ 5 s]

Low-mass X-ray binary

Low-mass X-ray binary (LMXB)

Equipotential surfaces in a binary system

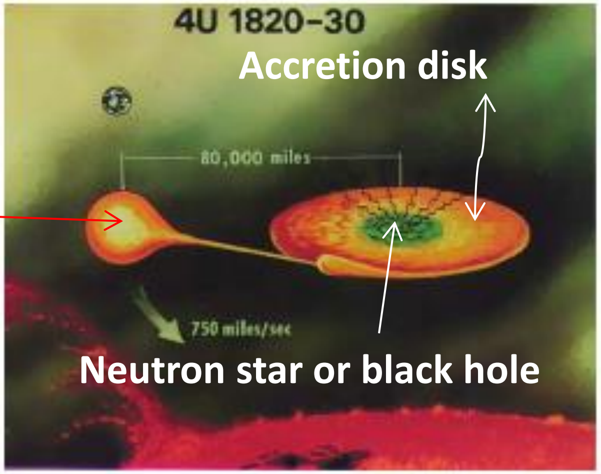


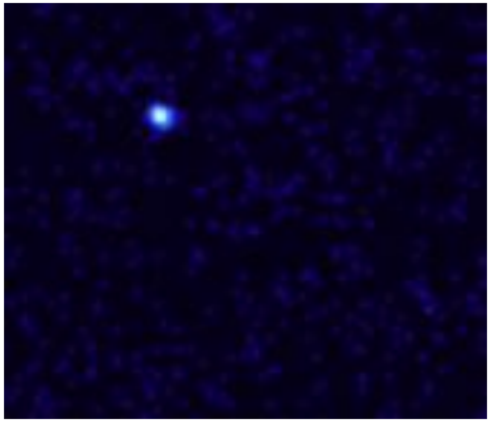
Courtesy: Bhattacharya & van den Heuvel (1991)

Low-mass X-ray binary (LMXB)

(Artist's impression)

Low-mass (≤ 1 solar mass) companion star





Chandra image of KS 1731-260
Courtesy: NASA website

Angular size is so small that an LMXB cannot be spatially resolved.

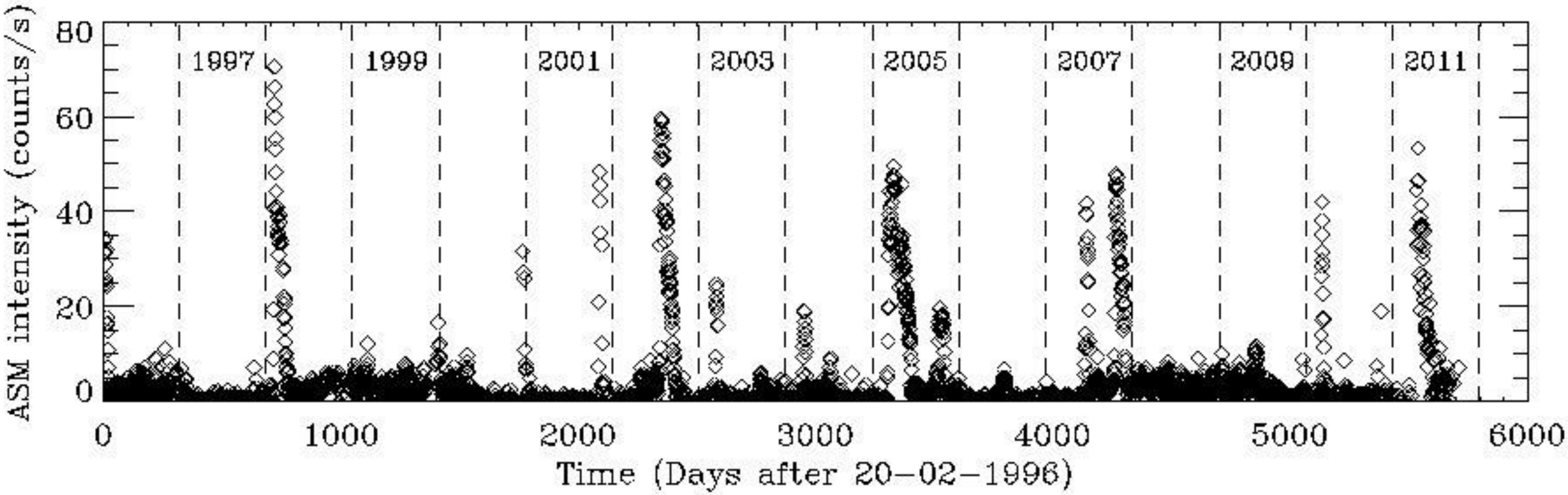
Only spectral and timing methods are available to probe LMXBs.
(Exception: some jets).

Primarily emits X-rays. But also emits in other wavelengths.

A reasonably clean accretion process with disk extended close to the compact object →
Ideal to probe strong gravity and compact object properties.

Transient accretion

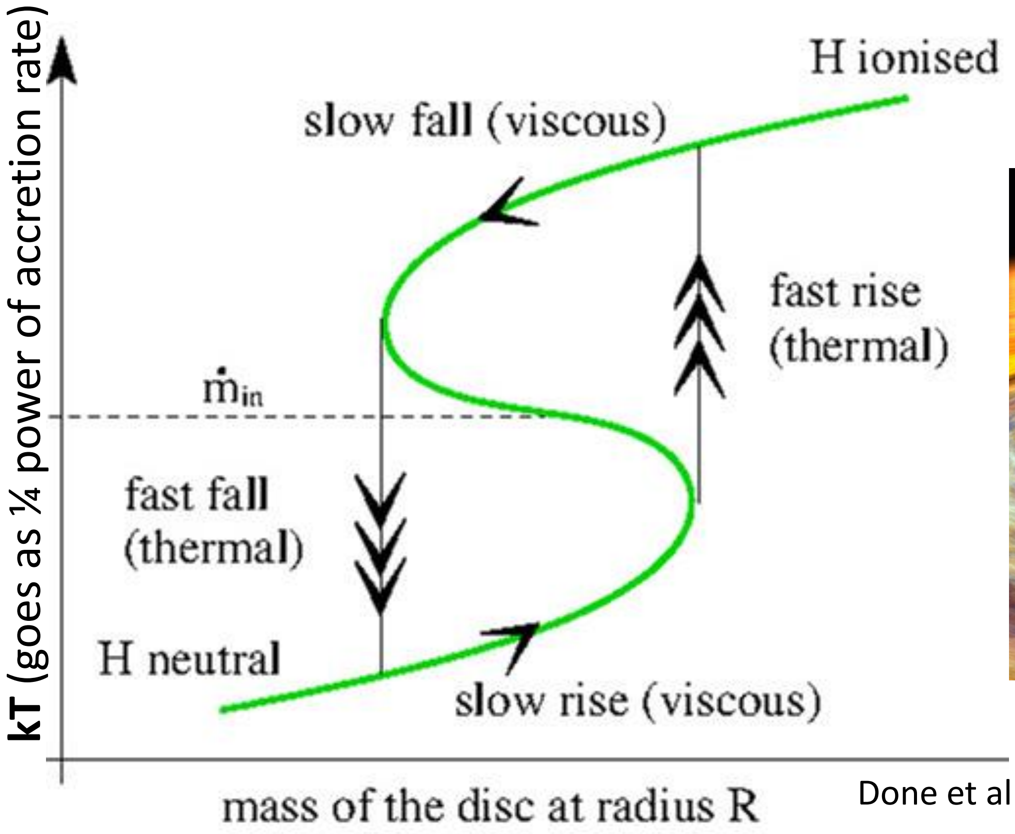
4U 1608-522

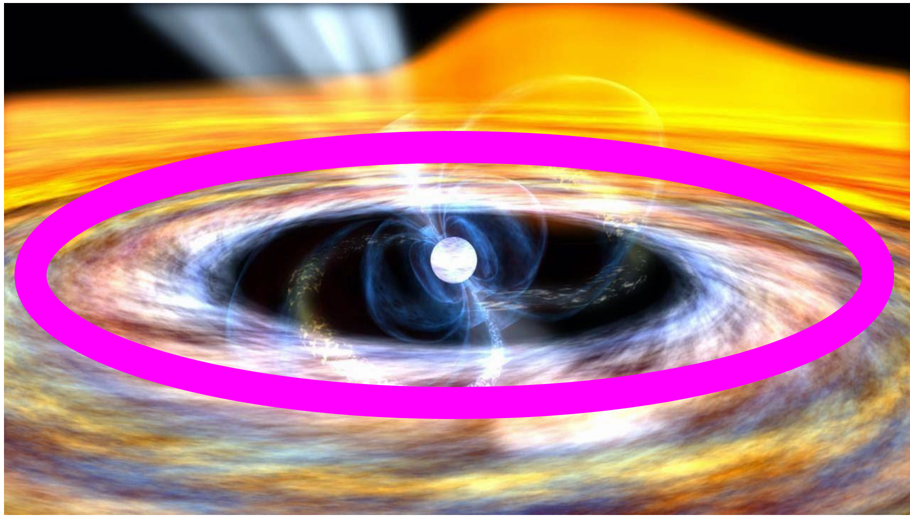


Most of the neutron star LMXBs are X-ray transient sources.

Moreover, almost all the X-ray ms pulsars (in fact all known accreting ms pulsars) are transients.

Transient accretion: thermal-viscous instability





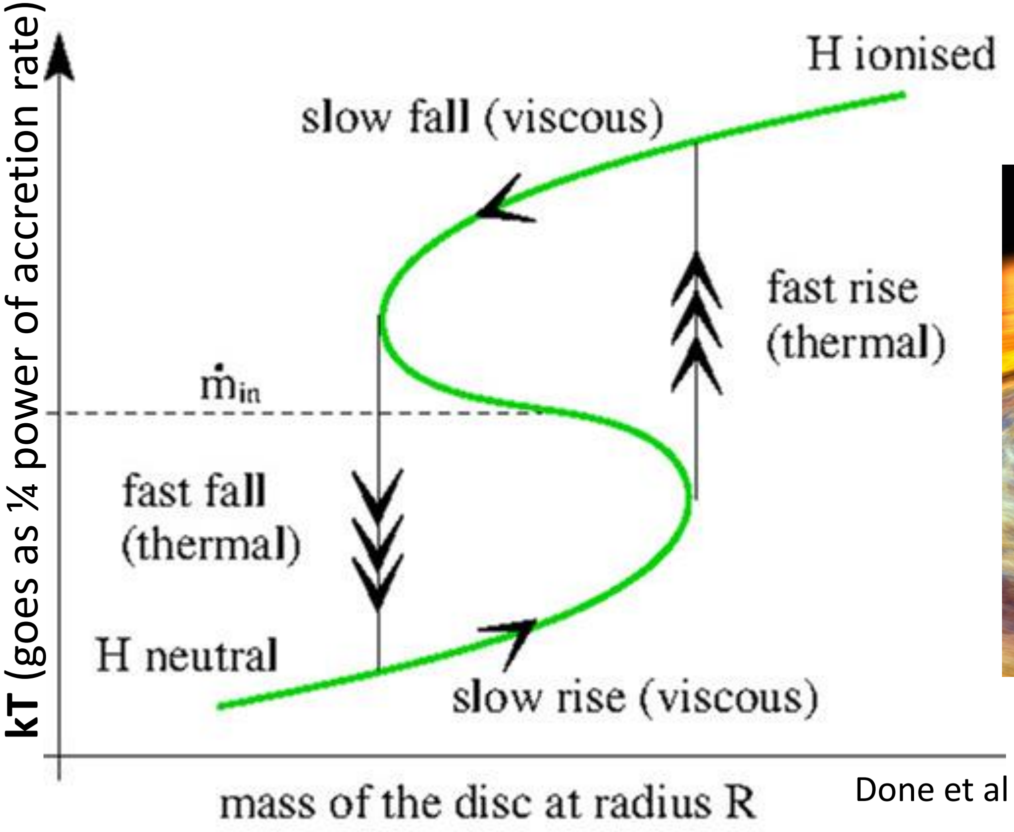
Done et al (2007)

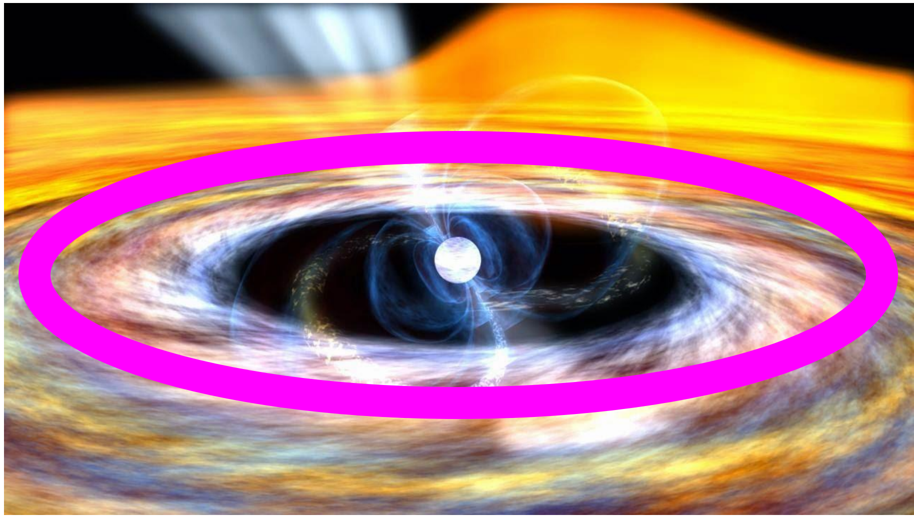
Thermal instability: at a disk radius, a little increase in disk temperature causes a further rise in temperature, and vice versa.

Viscous instability: at a disk radius, a small increase in the mass accretion rate leads to a further increase in mass accretion rate.

For a thin disk: Thermal instability timescale << Viscous instability timescale

Transient accretion: thermal-viscous instability



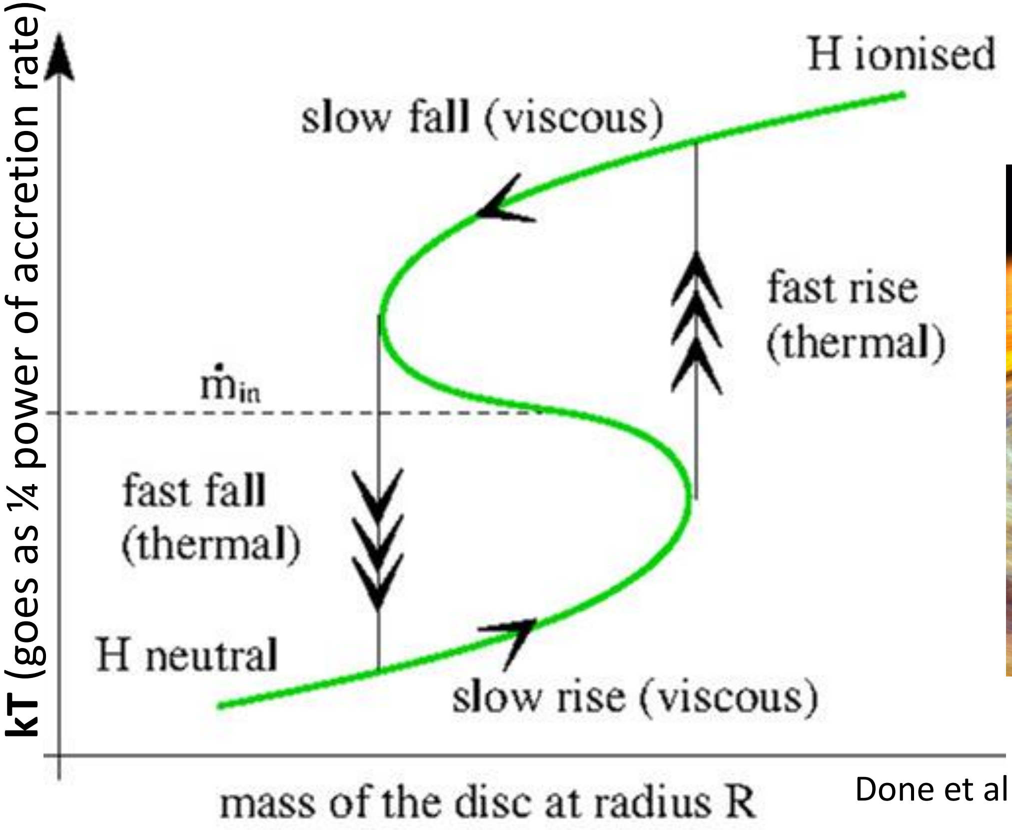


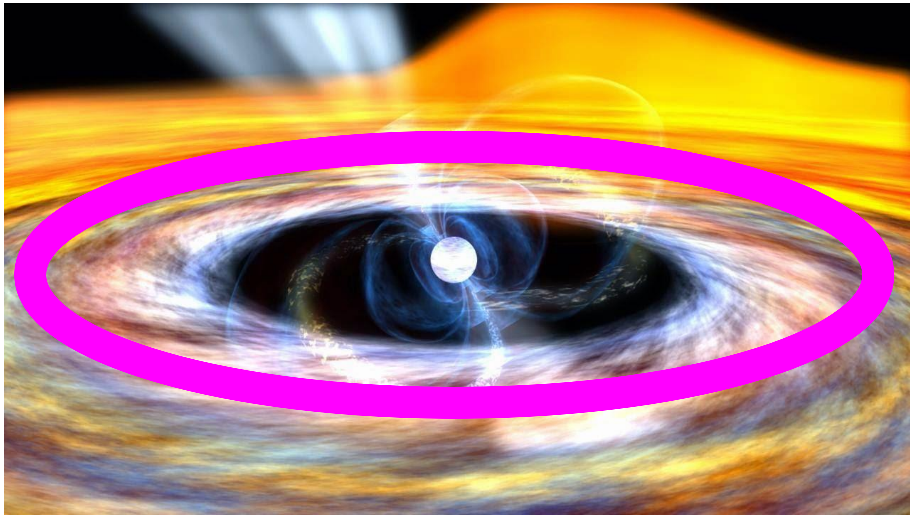
Done et al (2007)

Initially, the accretion rate is low (lower than the long-term average accretion rate). So, the disk temperature is low. Hence, viscous stress is low and matter accumulates. The disk hydrogen is mostly neutral (below a temperature about 10^4 K), and disk opacity is low.

As more matter comes from the companion star, the disk temperature slowly increases at each radius.

Transient accretion: thermal-viscous instability



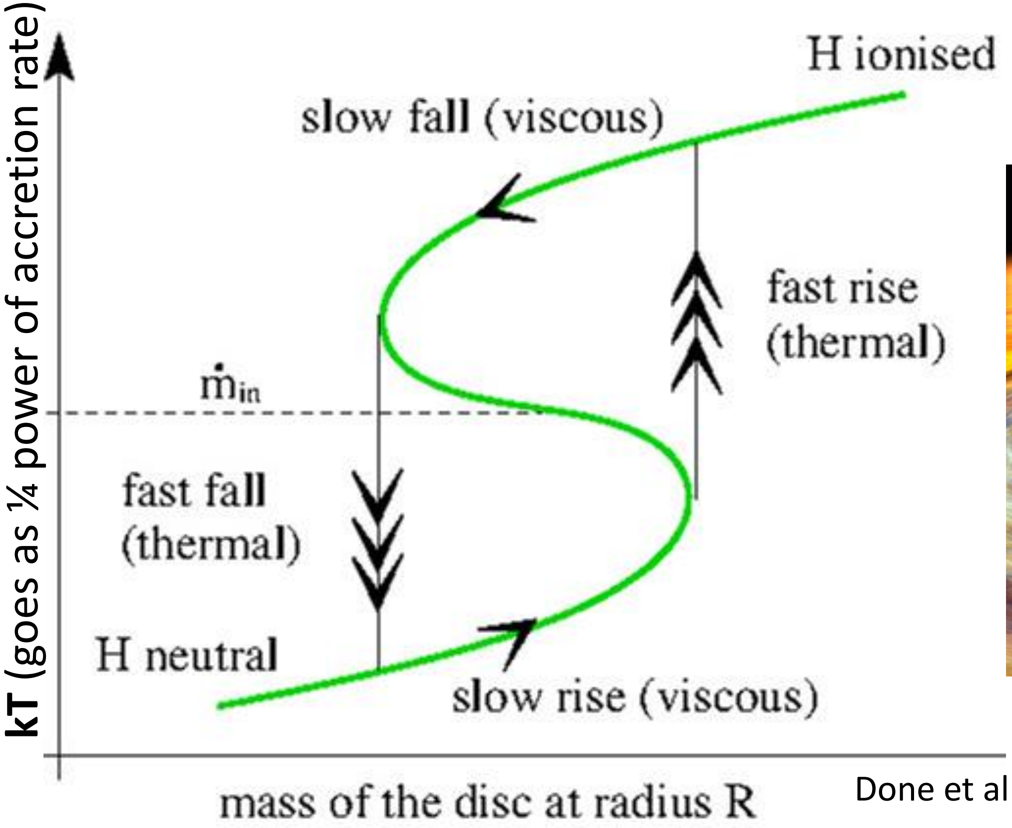


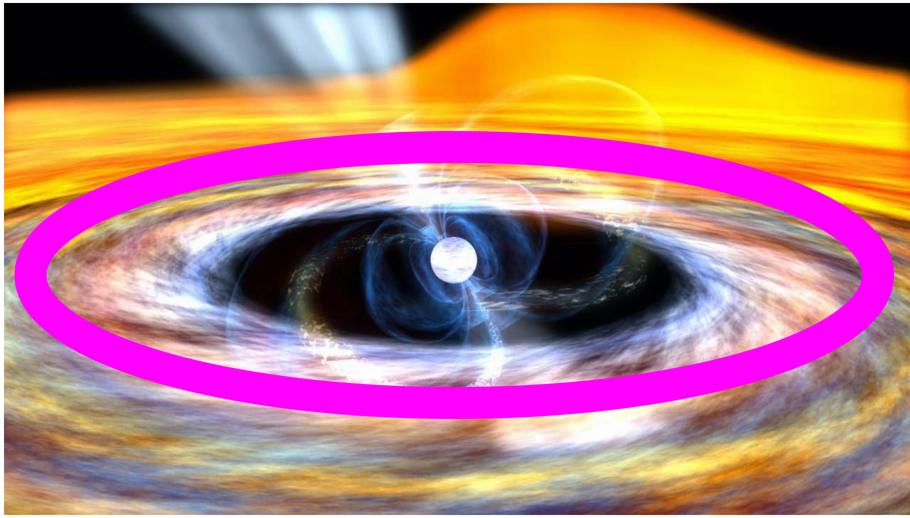
Done et al (2007)

When the disk temperature at a certain radius becomes more than the hydrogen ionization temperature, the hydrogen becomes ionized, opacity increases sharply, photons cannot escape anymore, and hence the disk temperature increases by a large amount almost instantly.

This thermal instability triggers the viscous instability, as the viscous stress increases with the pressure, and the accretion rate increases enormously.

Transient accretion: thermal-viscous instability





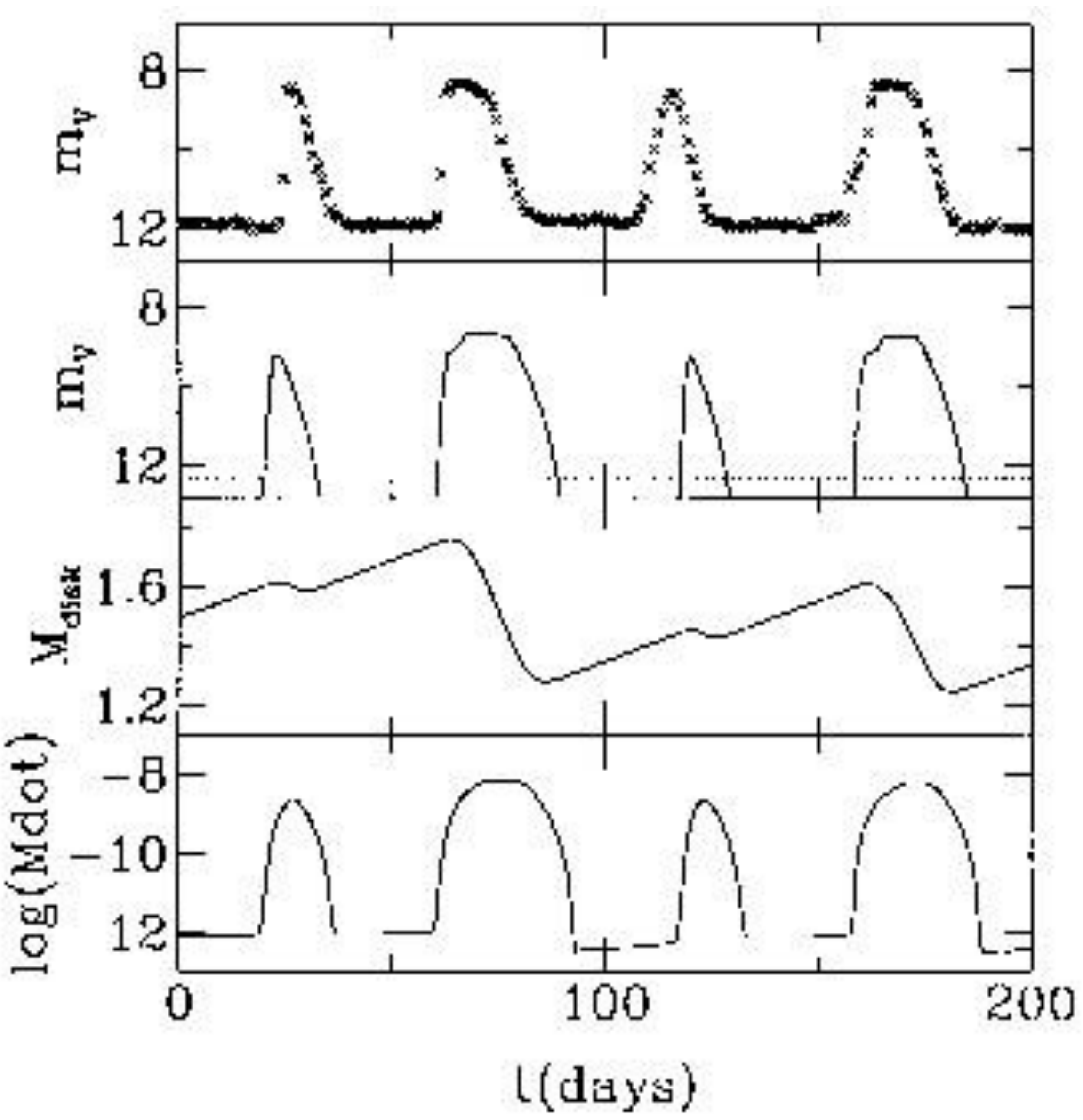
Done et al (2007)

This local phenomenon becomes global, as the matter flows inwards through all radii at a rate much higher than the long-term average accretion rate, and the entire disk is accreted onto the neutron star in a relatively short time. This is the outburst.

As the disk is consumed, the temperature falls below the hydrogen ionization temperature, a thermal instability occurs in the opposite direction, the mass accretion rate decreases enormously, and the quiescence period begins.

LMXB

Transient accretion: thermal-viscous instability



So the neutron star LMXB alternates between periods of outburst and quiescence.

The model can explain the observation, as seen in this figure (Cannizzo 1993).

Energy spectrum of NS LMXBs

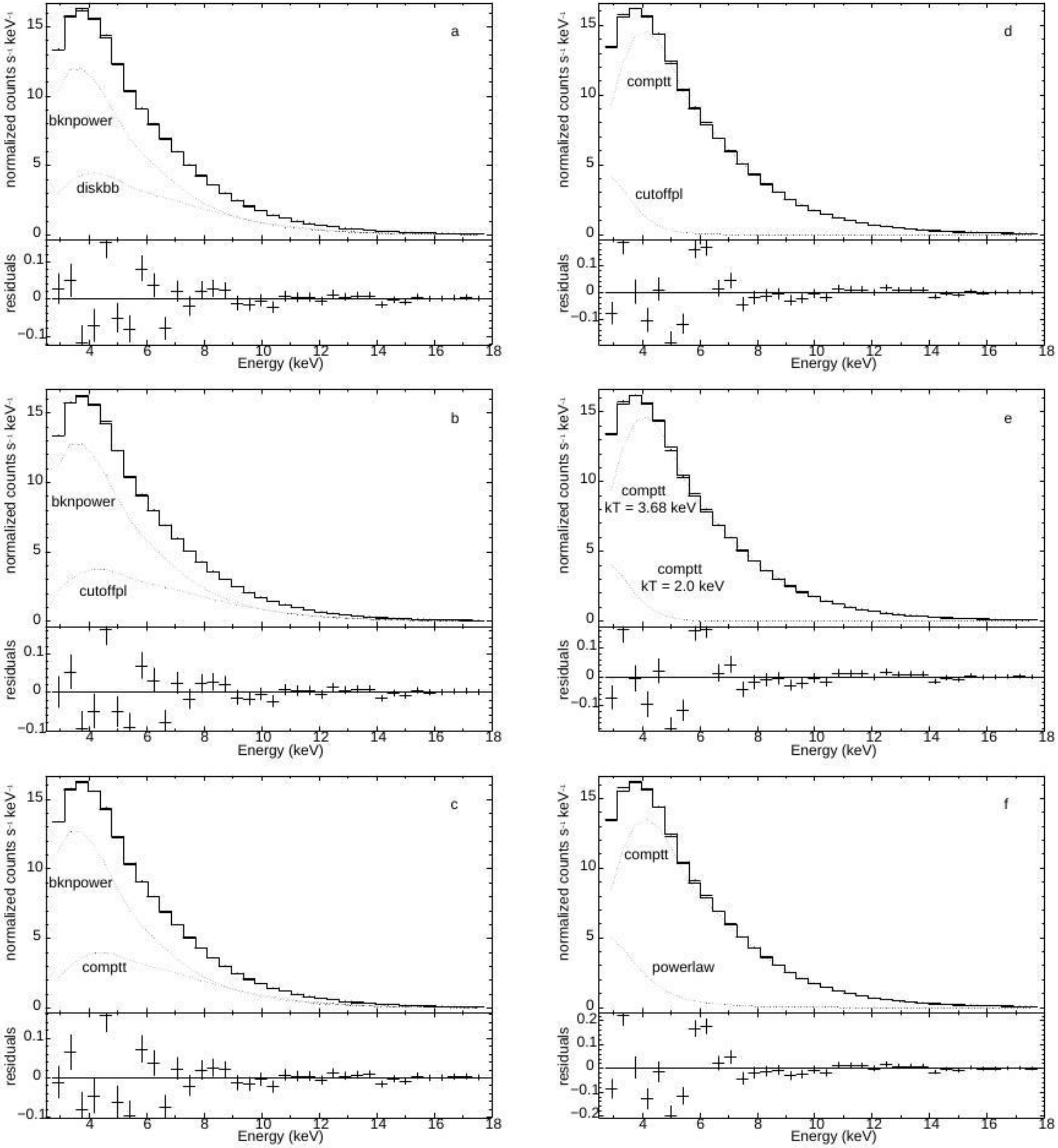
Two emission components: accretion disk and NS surface: each of them can emit blackbody; each of them can be partially or fully covered with a Comptonizing corona. No spectral model uniquely fits the data.

NS LBXB XB 1254-690: an example with RXTE PCA data

Model	χ_ν^2(dof)	Model	χ_ν^2(dof)
diskbb+comptt	1.95(30)	diskbb+powerlaw	1.95(32)
diskbb+cutoffpl	1.97(31)	diskbb+bknpower	0.52(30)
comptt+bbody	1.50(30)	powerlaw+bbody	2.24(32)
cutoffpl+bbody	1.65(31)	bknpower+bbody	2.39(30)
diskbb+bbody	2.75(32)	comptt+comptt	0.91(28)
powerlaw+comptt	0.95(30)	cutoffpl+comptt	0.91(29)
bknpower+comptt	0.54(28)	powerlaw+powerlaw	32.31(32)
cutoffpl+powerlaw	2.33(31)	bknpower+powerlaw	3.47(30)
cutoffpl+cutoffpl	1.54(30)	bknpower+cutoffpl	0.53(29)
bknpower+bknpower	3.73(28)		

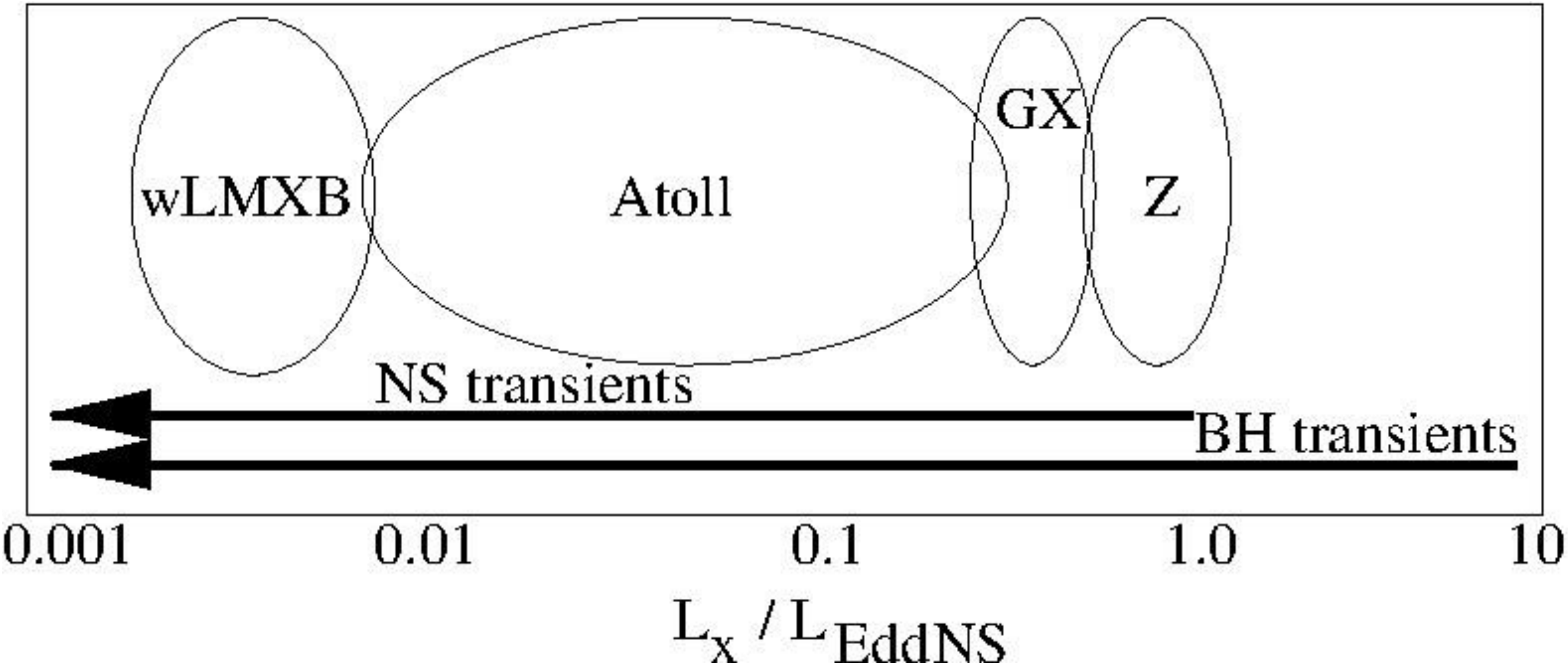
Mukherjee and SB (2011)

LMXB



Mukherjee and SB (2011)

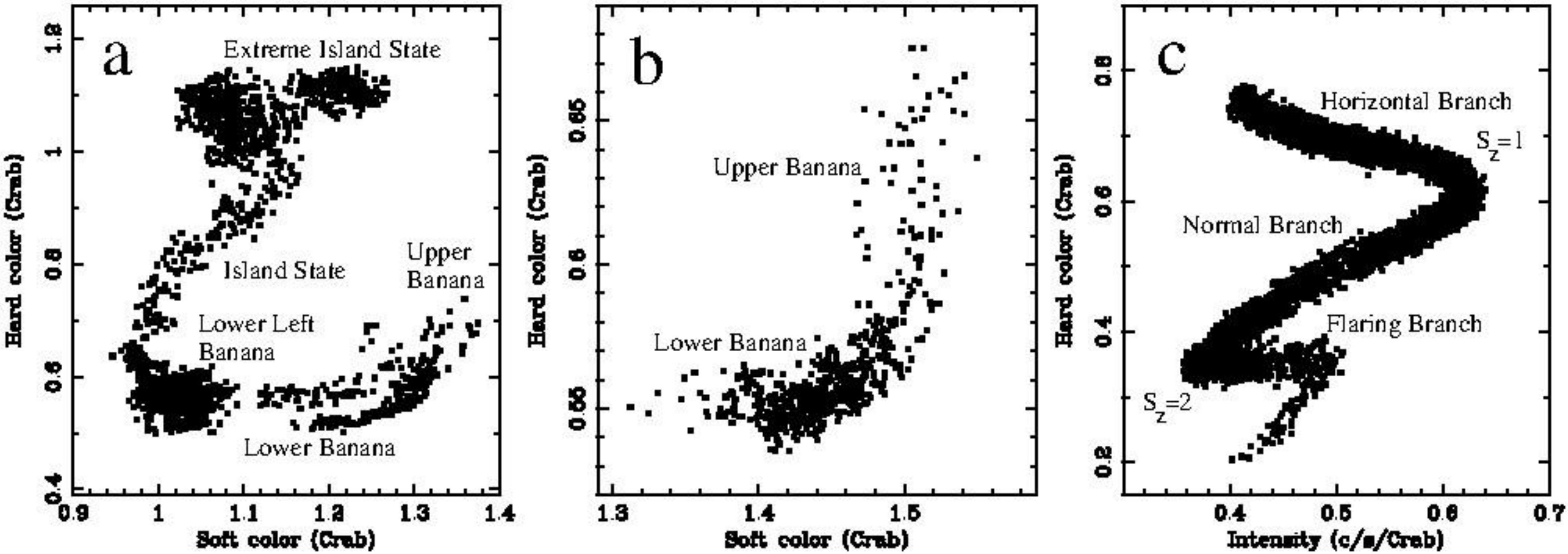
Atoll and Z sources: two types of neutron star LMXBs



van der Klis (2004)

Atoll and Z sources: two types of neutron star LMXBs

Color-color diagram (CD) and hardness-intensity diagram (HID)



Suppose we identify five photon energy values: $E1 < E2 < E3 < E4 < E5$.

Suppose, the background subtracted count rates in the energy ranges E1-E2, E2-E3, E3-E4 and E4-E5 are A, B, C and D respectively.

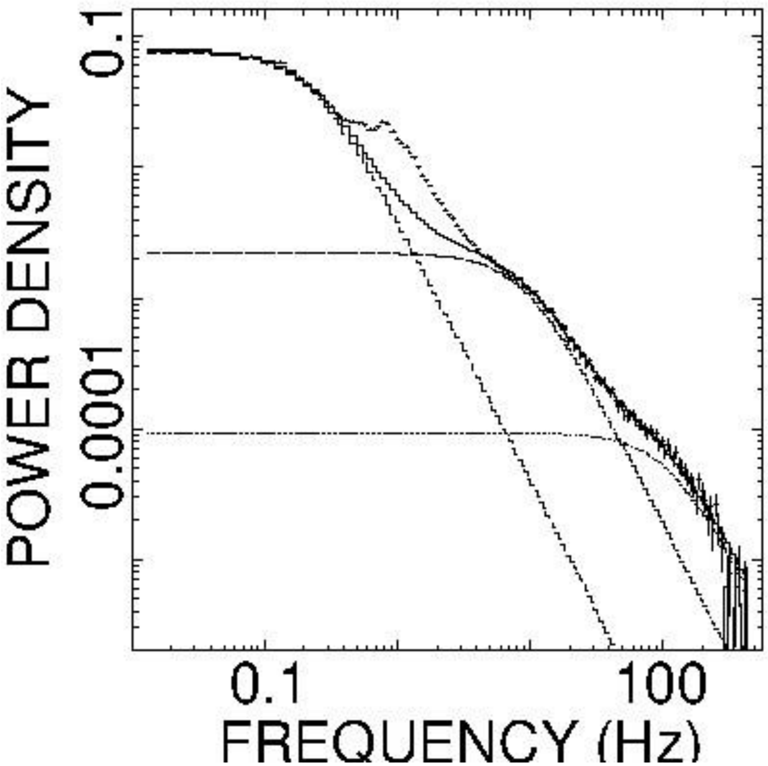
Then the soft color, hard color and intensity can be defined as B/A, D/C and A+B+C+D respectively.

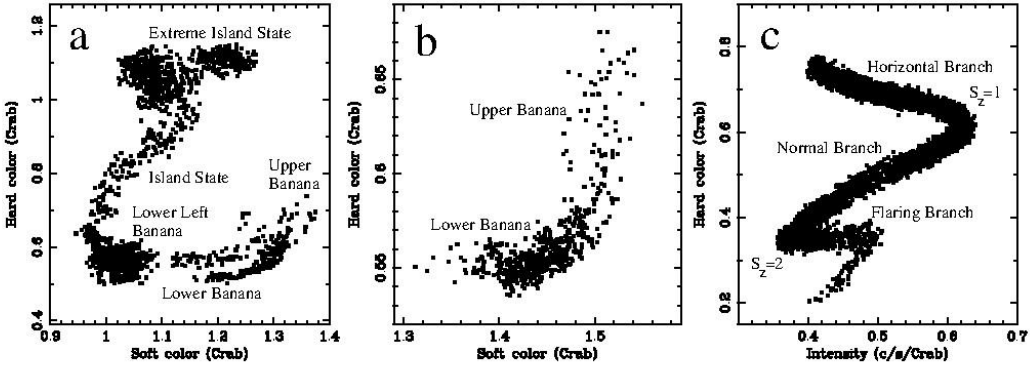
CD and HID show how the spectral state of the source evolves.

van der Klis (2004)

Atoll and Z sources: two types of neutron star LMXBs

Color-color diagram (CD) and hardness-intensity diagram (HID)





Broad and narrow (quasi-periodic oscillation or QPO) timing features are correlated with locations on CD and HID.

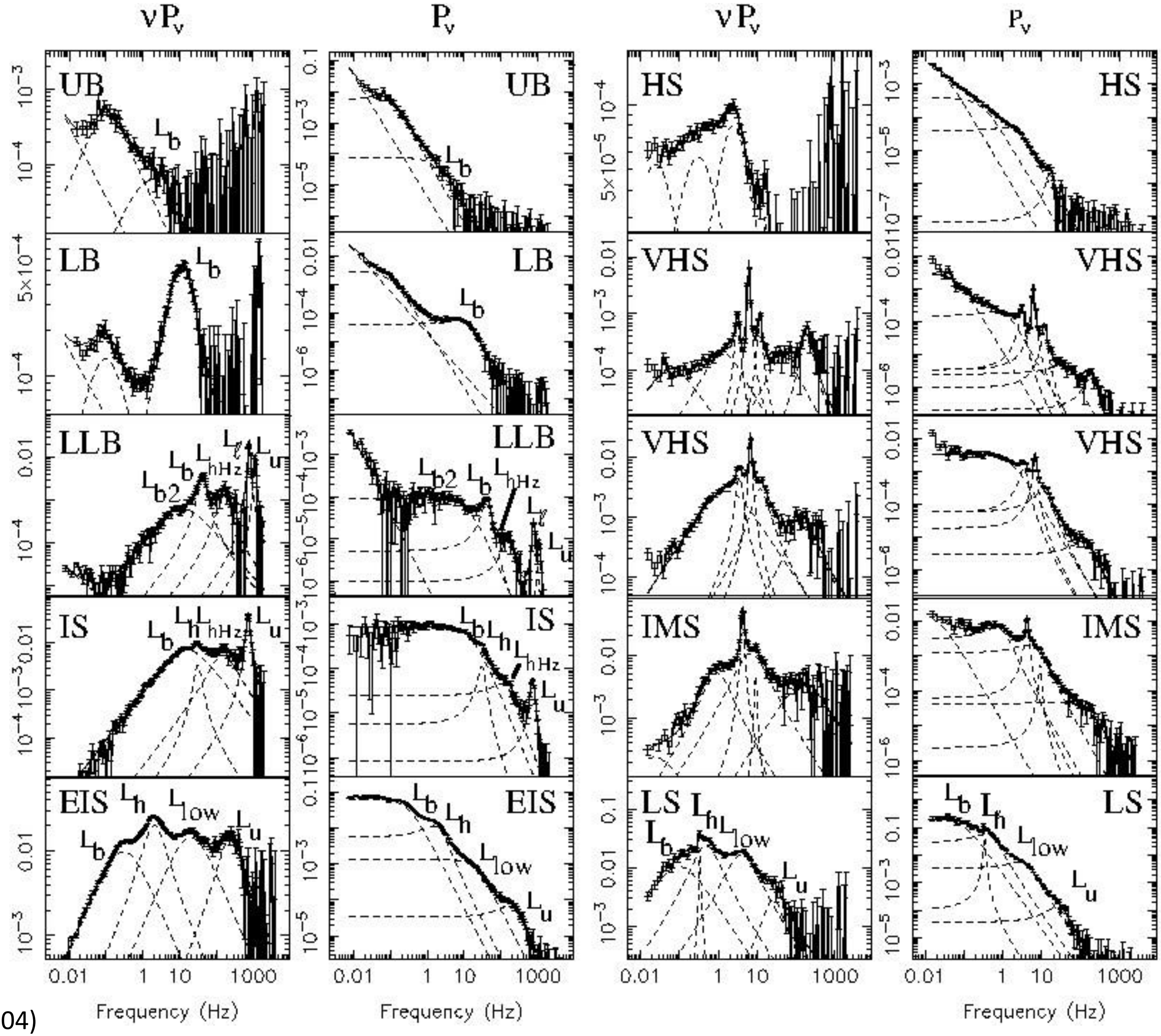
Examples:

Horizontal branch oscillation (HBO): 15-60 Hz

Normal branch oscillations (NBO): ~6 Hz

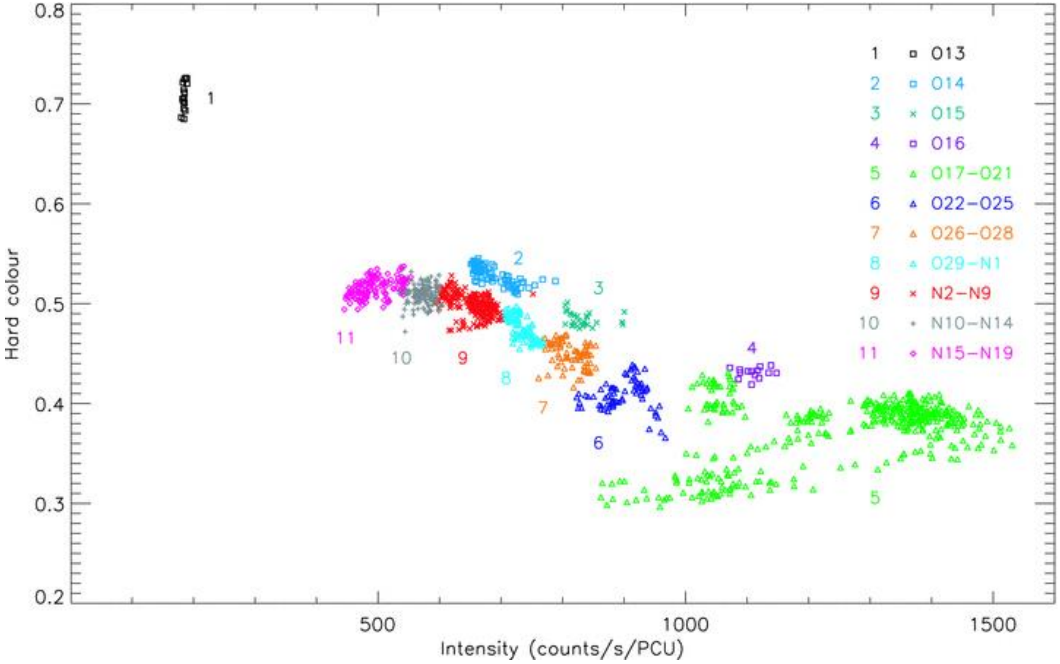
van der Klis (2004)

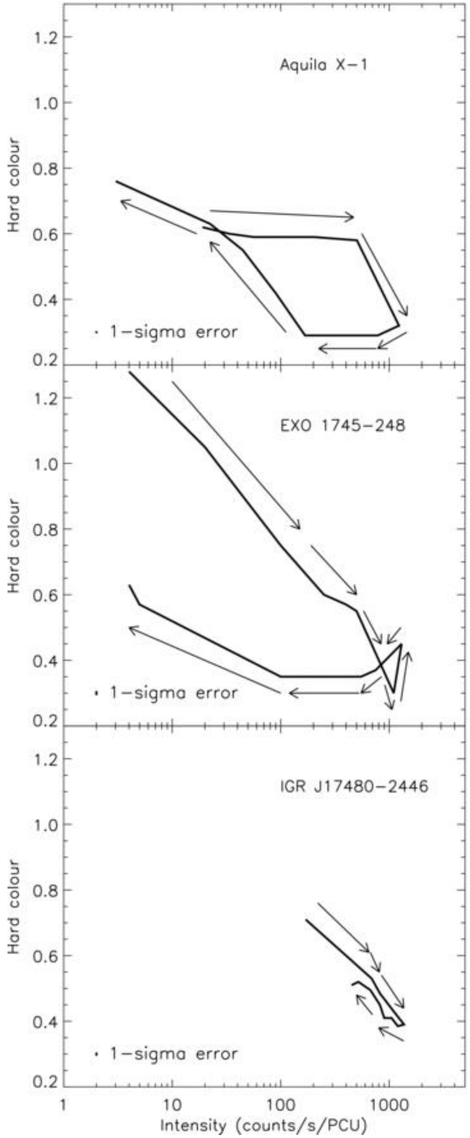
LMXB



van der Klis (2004)

Hysteresis in HID and atoll – Z transition



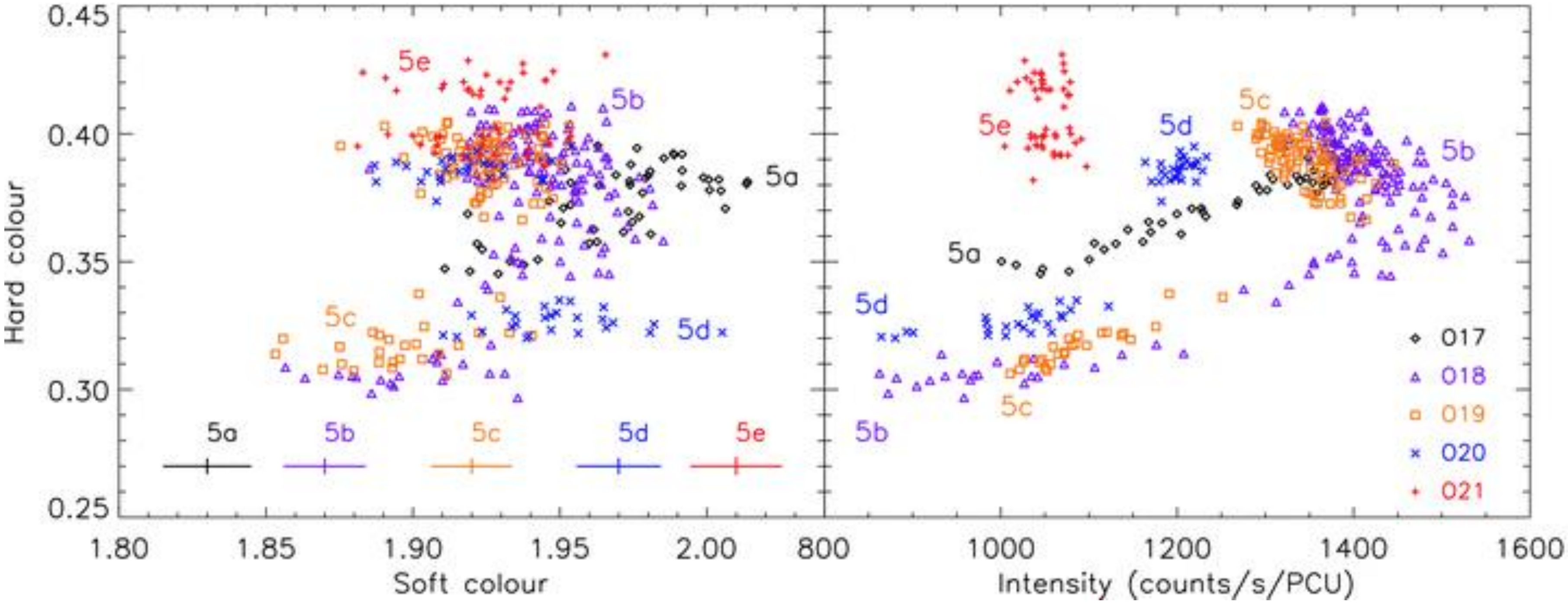


Chakraborty, SB, Mukherjee (2011)

Hysteresis in hardness-intensity diagram was observed for IGR J 17480-2446. Such hysteresis of accreting black holes and neutron stars may be a useful tool to probe time-dependent accretion-ejection mechanism. The figure on the right shows that even for similar peak luminosities, the hysteresis path may be drastically different.

Hysteresis in HID and atoll – Z transition

Z states of IGR J17480-2446

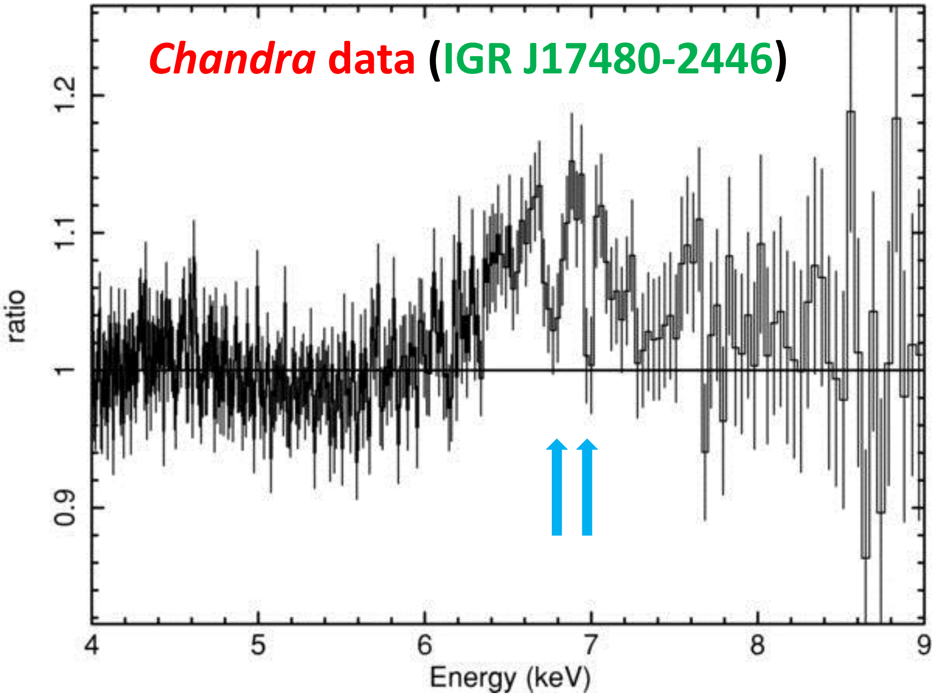


Chakraborty, SB, Mukherjee (2011)

LMXB

Blueshifted narrow absorption line: signature of accretion disk wind

Miller, Maitra, Cackett, SB, Strohmayer (2011)



Recent works have suggested that jet (mostly observed in X-ray spectrally hard state) and disk wind (mostly observed in X-ray spectrally soft state) are mutually exclusive (Neilsen & Lee 2009; King et al. 2012).

It was suggested that wind carries enough mass away from the disk to halt the flow of matter into the jet.

So disk wind could be important to probe the jet launching mechanism, and the accretion-ejection mechanism in general.

Continuum spectra: the simplest model which fits well is blackbody+powerlaw (*RXTE* data: Chakraborty & SB 2011; *Chandra* data: Miller, Maitra, Cackett, SB, Strohmayer 2011). A broad iron emission line is detected.

Blueshifted He-like Fe xxv (3100±400 km s^{-1}) and H-like Fe xxvi (1000 ±200 km s^{-1}) absorption features indicate a disk wind.

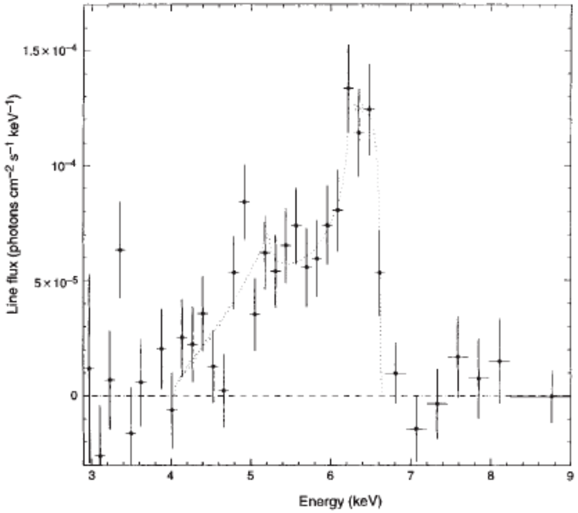
LMXB

Broad relativistic spectral iron emission line from inner disk

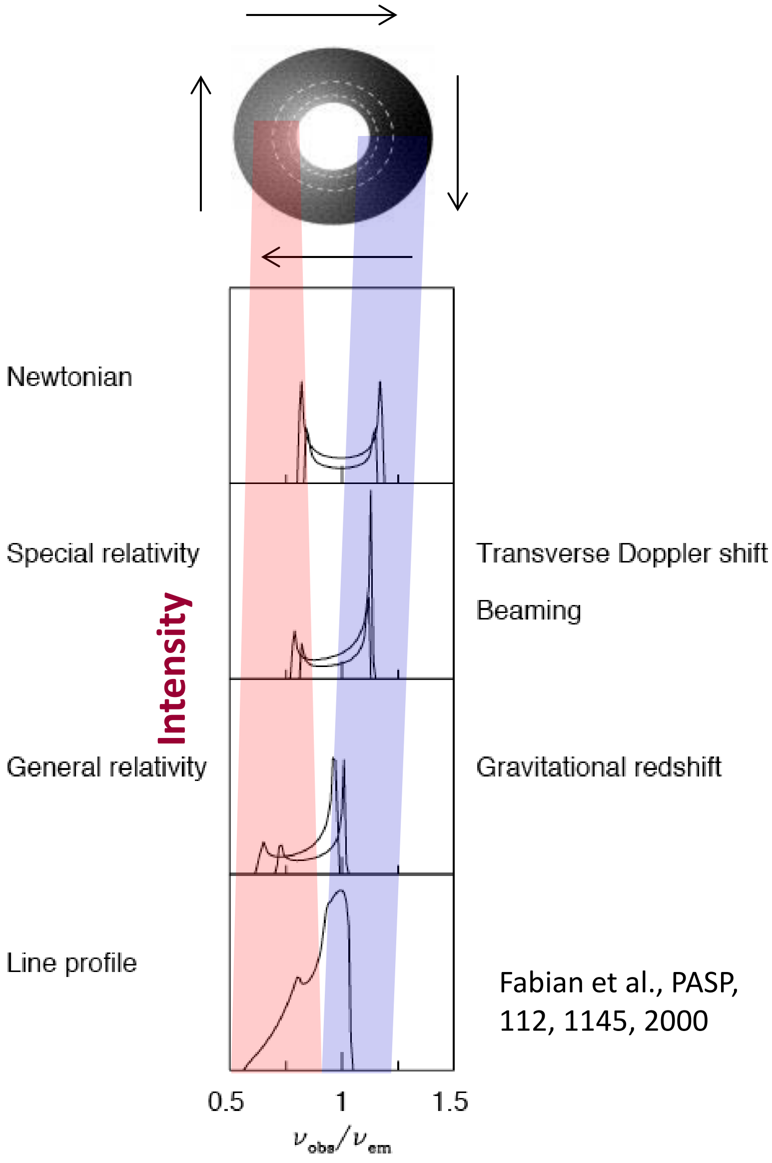
Broad asymmetric iron Kα emission lines are observed from accreting super-massive black hole (AGN) and stellar-mass black hole (black hole LMXB) systems.

They are believed to originate from the inner part of the accretion disk.

MCG-6-30-15: ASCA data



Tanaka et al., Nature, 375, 659, 1995



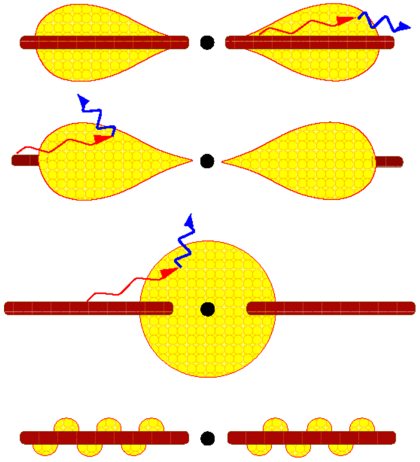
Fabian et al., PASP, 112, 1145, 2000

Origin of broad iron line

Main requirements:

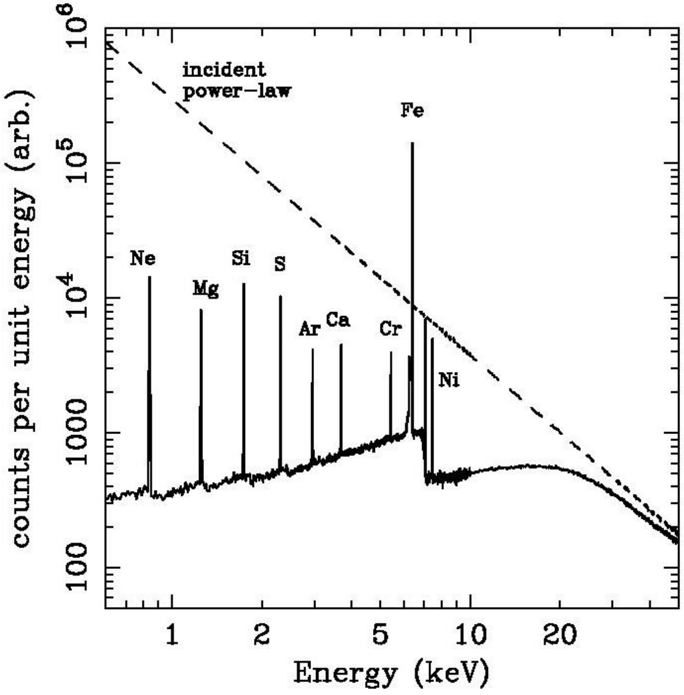
1. A geometrically thin, optically thick accretion disk, which is radiatively efficient down to the ISCO.

2. A hard X-ray source.



A reflection spectrum off the disk, in which a Fe $K\alpha$ line is the most prominent feature due to high abundance and fluorescent yield.

Right: An example of simulated reflection spectrum: A power-law X-ray continuum with photon index 2 is reflected from a cold semi-infinite slab of gas with cosmic abundances.

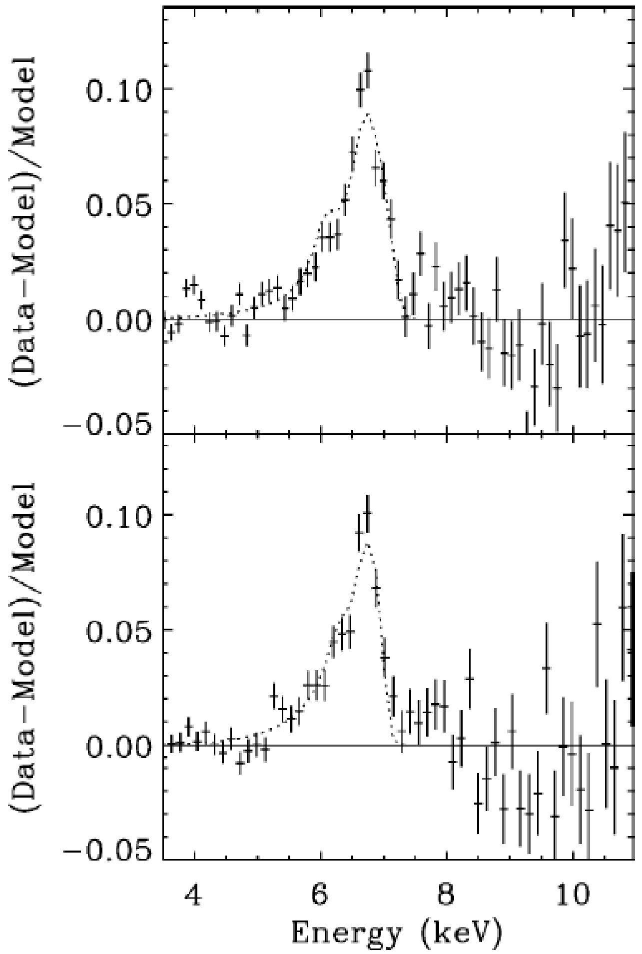


Reynolds and Nowak (2003)

Broad Iron Lines from neutron Star LMXBs

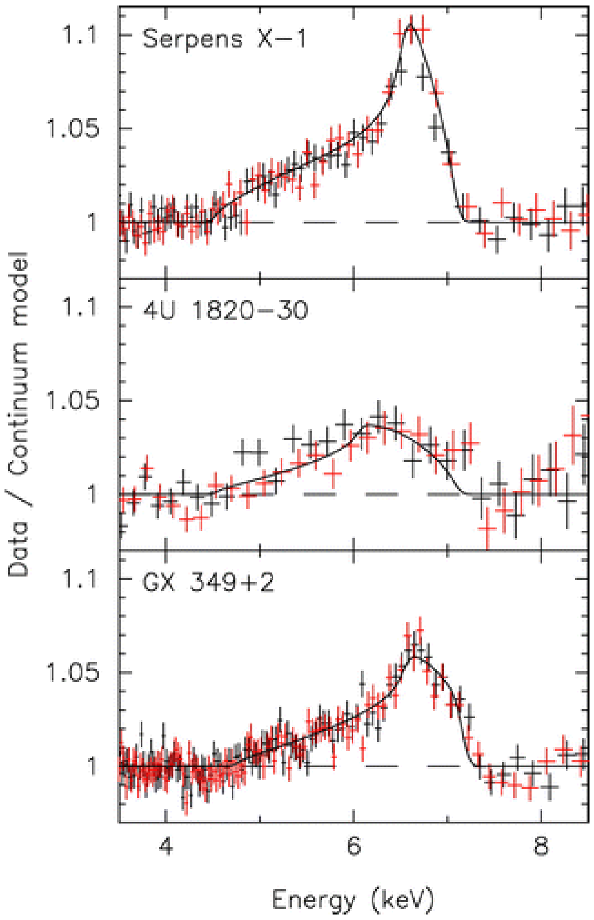
Relativistic nature at last!

Serpens X-1: XMM-Newton EPIC pn data



SB and Strohmayer, ApJ, 664, L103, 2007

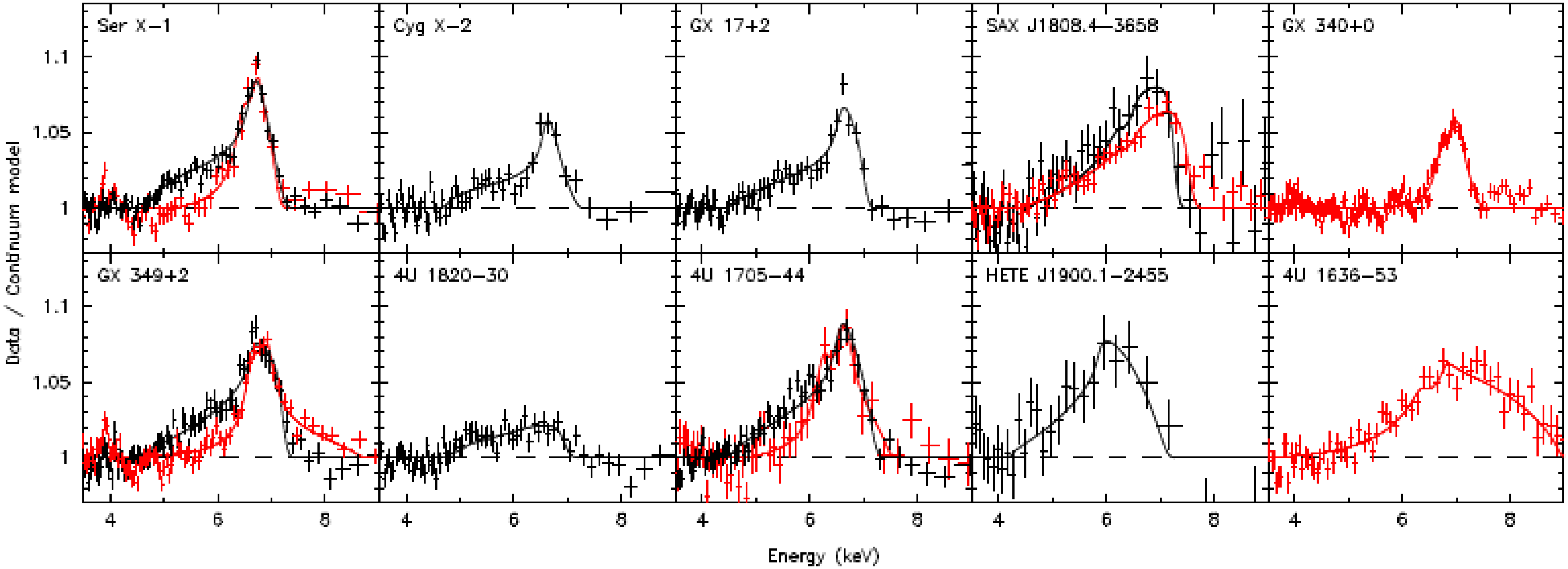
Suzaku data



Cackett, Miller, SB et al., ApJ, 674, 415, 2008

Broad Iron Lines from neutron Star LMXBs

XMM-Newton data (red) and Suzaku data (black)

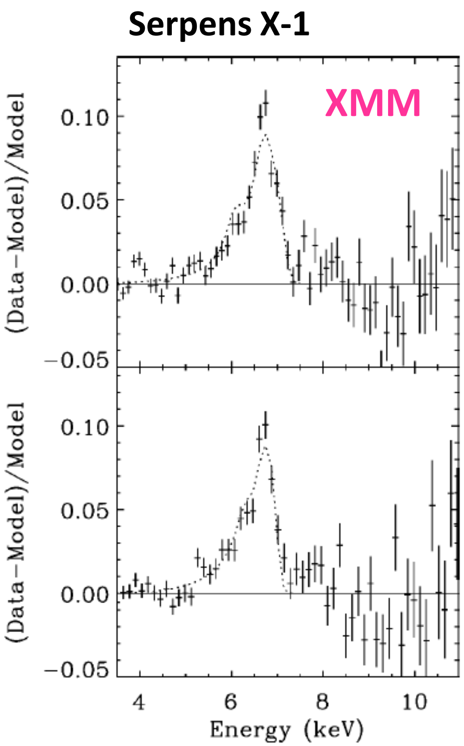


Cackett, .., **SB** et al., ApJ, 720, 205, 2010

Since 2007, the relativistic nature of broad iron lines has been confirmed for more than ten neutron star LMXBs.

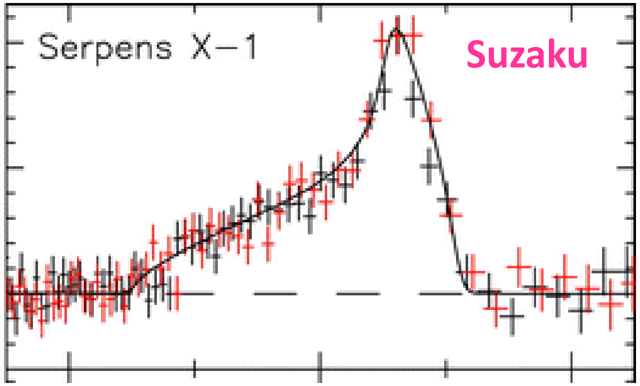
LMXB

Broad Iron Lines from neutron Star LMXBs

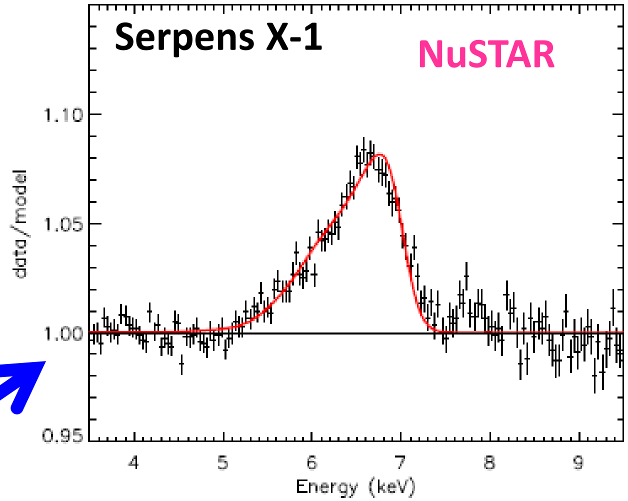


(Discovery of relativistic line from a neutron star)

SB and Strohmayer, ApJ, 664, L103 (2007)

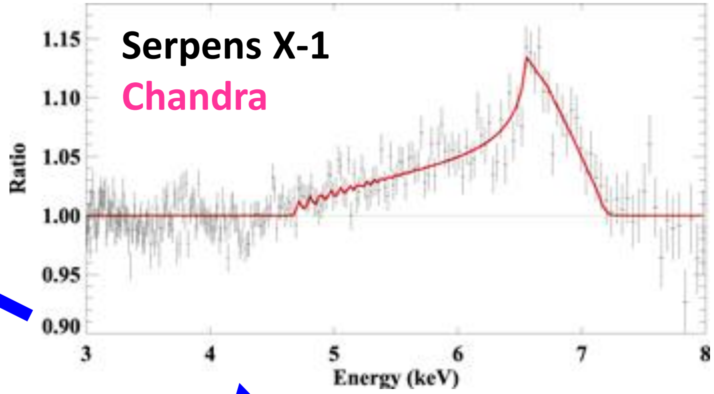


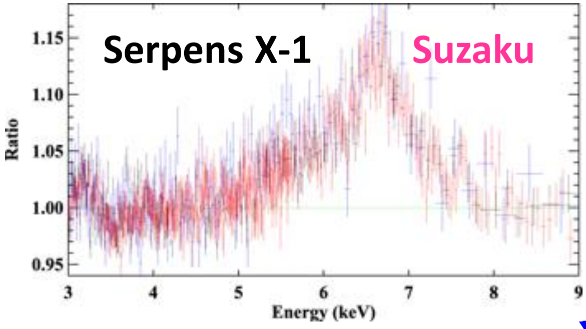
Cackett, Miller, SB, ApJ, 674, 415 et al. (2008)



Miller et al. (2013)

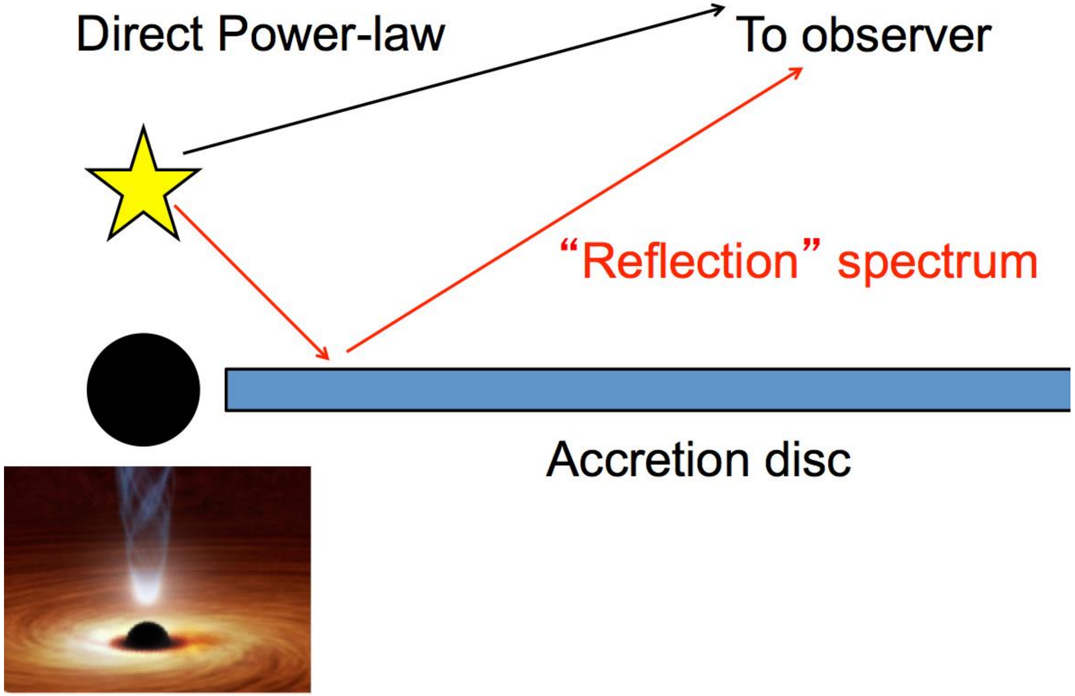
Chiang,..., SB, et al., ApJ, 821, 105 (2016)





Chiang,..., SB, et al., ApJ, 831, 45 (2016)

Time lag due to reflection



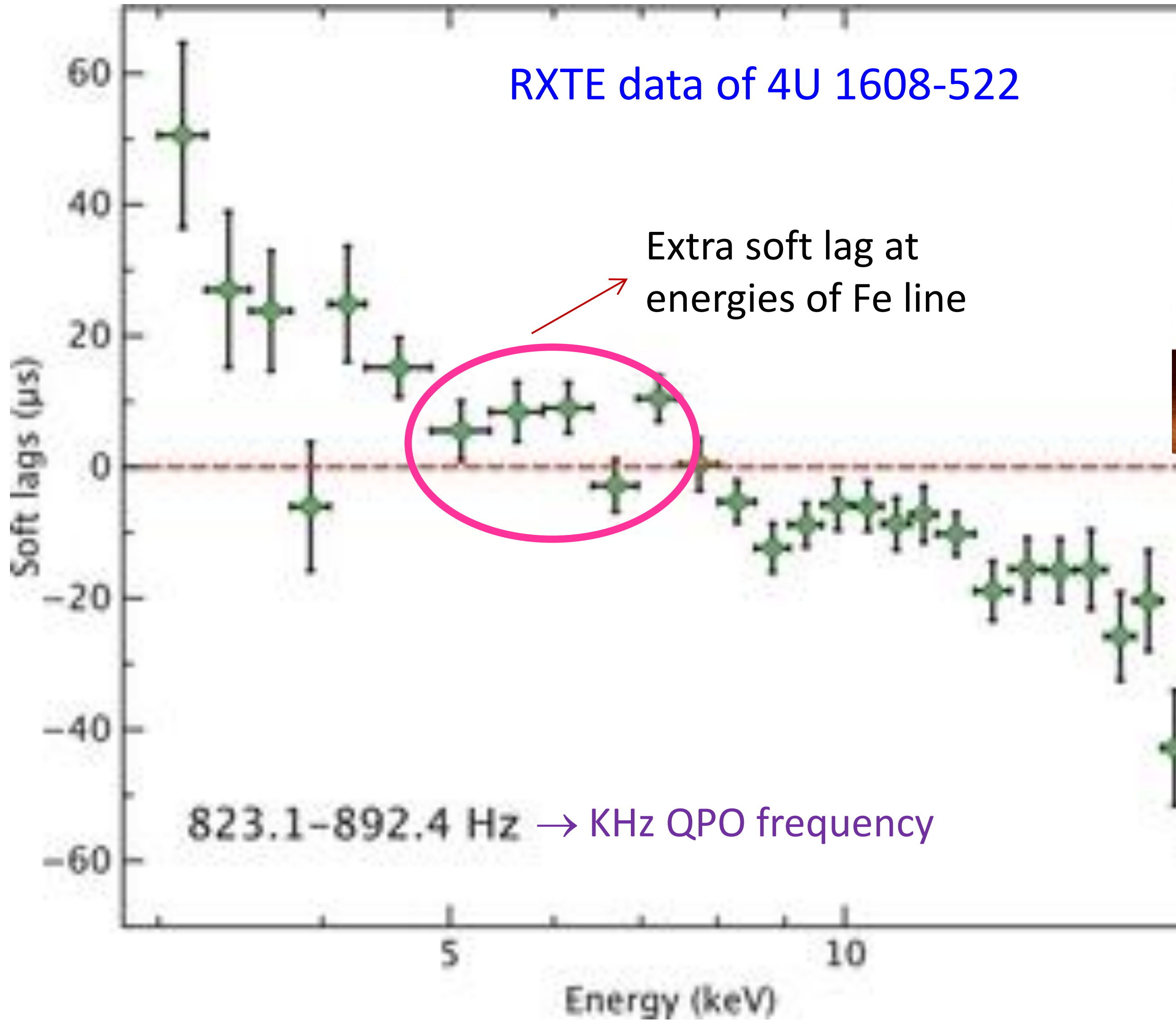
Direct Power-law

To observer

“Reflection” spectrum

Accretion disc

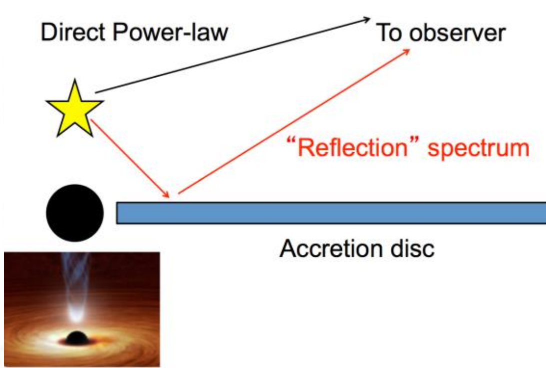
Broad Iron Lines from neutron Star LMXBs



RXTE data of 4U 1608-522

Extra soft lag at energies of Fe line

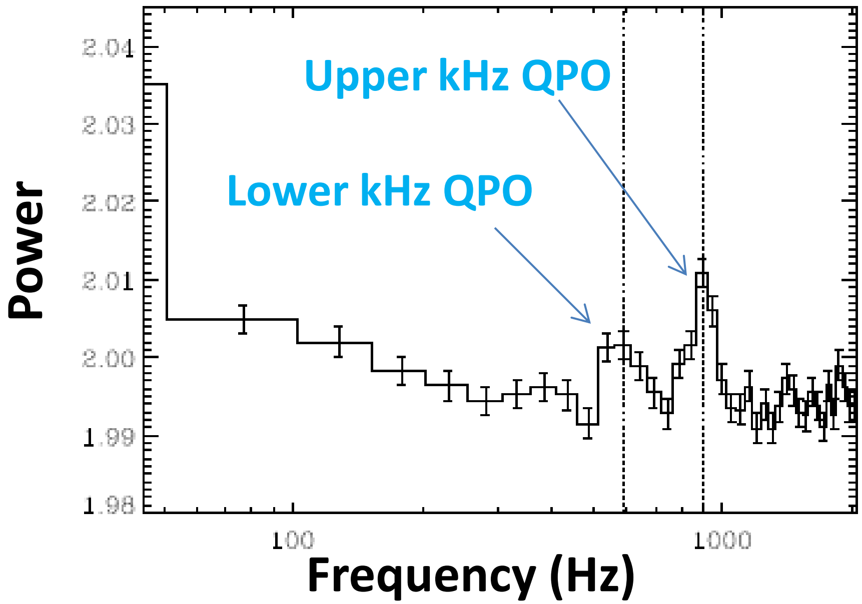
→ KHz QPO frequency



Barret (2013)

High-frequency quasi-periodic oscillations

Kilo-Hertz Quasi-Periodic Oscillations (KHz QPO)



High-frequency (400-1200 Hz) quasi-periodic oscillations of X-ray intensity have been observed from many neutron star LMXBs.

Their high frequencies strongly suggest that they originate within a few Schwarzschild radii of the neutron star, and are possibly related to the following accretion disk frequencies.

So kHz QPOs will be an important tool to probe the strong gravity and dense matter, if their actual origin is known.

Spectro-timing studies can be particularly useful to find their origin.

$$\nu_\phi = \frac{\sqrt{GM/r^3}/2\pi}{1+j(r_g/r)^{3/2}} = \nu_K(1+j(r_g/r)^{3/2})^{-1}$$

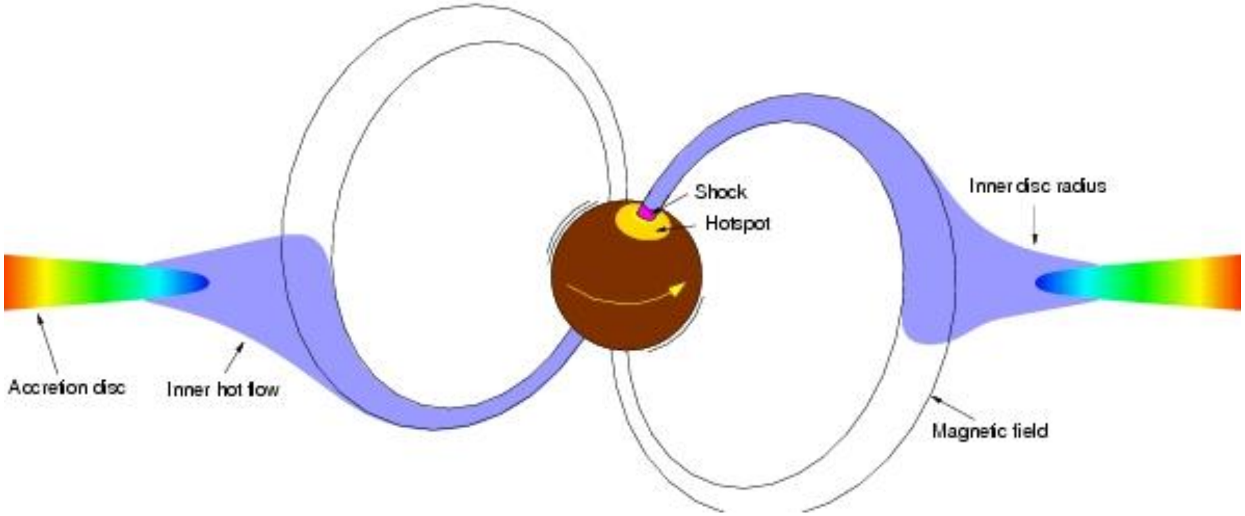
$$r_g \equiv GM/c^2$$

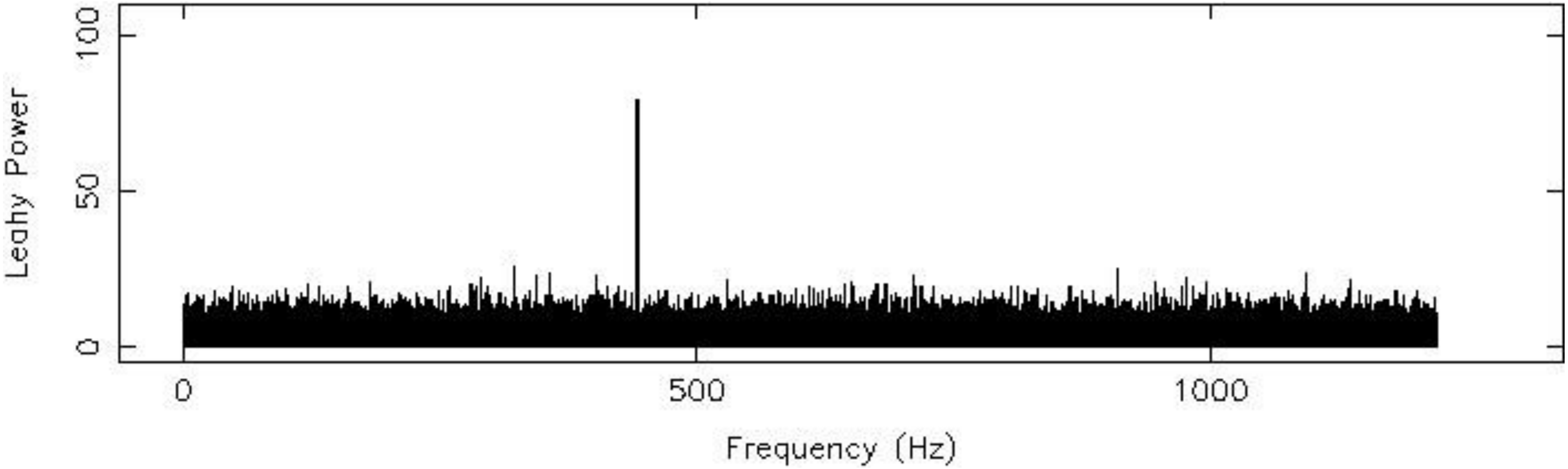
$$\nu_r = \nu_\phi\left(1-6(r_g/r)+8j(r_g/r)^{3/2}-3j^2(r_g/r)^2\right)^{1/2}$$

$$j \equiv Jc/GM^2$$

$$\nu_\theta = \nu_\phi\left(1-4j(r_g/r)^{3/2}+3j^2(r_g/r)^2\right)^{1/2}$$

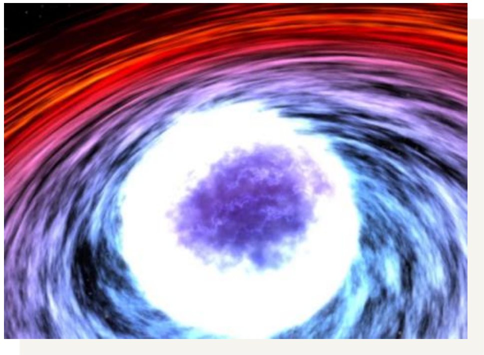
Accretion-powered pulsars





Altamirano et al. (2008)

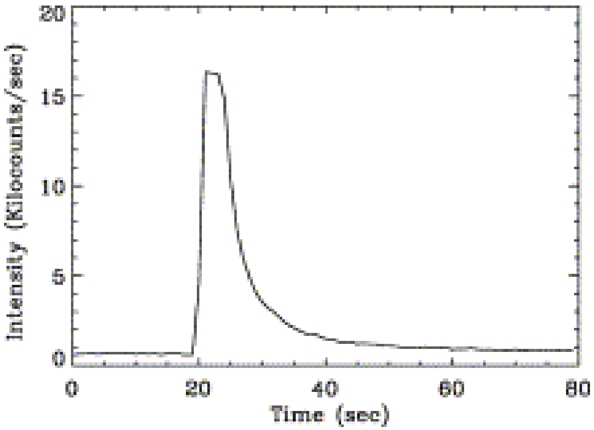
Thermonuclear X-ray Bursts



Accretion on neutron star

Unstable nuclear burning of accreted matter on the neutron star surface causes type I (thermonuclear) X-ray bursts.

Burst light curve



Rise time ≈ 0.5 - 5 seconds
Decay time ≈ 10 - 100 seconds
Recurrence time ≈ hours to day
Energy release in 10 seconds
≈ 10^{39} ergs

↓

Sun takes more than a week to release this energy.

Why is *unstable* burning needed?

Energy release:
Gravitational ≈ 200 MeV / nucleon
Nuclear ≈ 5 MeV / nucleon

Accumulation of accreted matter for hours → Unstable nuclear burning for seconds ⇒ Thermonuclear X-ray burst.

Thermonuclear X-ray Bursts

CNO cycle: : $T > 10^7$ K, **Q = 26.73 MeV**

$^{12}C + p \rightarrow {}^{13}N + \gamma$

$^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$

$^{13}C + p \rightarrow {}^{14}N + \gamma$

$^{14}N + p \rightarrow {}^{15}O + \gamma$

$^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$

$^{15}N + p \rightarrow {}^{12}C + \alpha$

Thermonuclear X-ray Bursts

Parameters which set the ignition condition:

(1) chemical composition of accreted matter,
(2) temperature (~ 10^8 K),
(3) column depth (~ 10^8 gm cm^{-2}), and
(4) initial conditions set by the previous bursts.

Various regimes of burning:

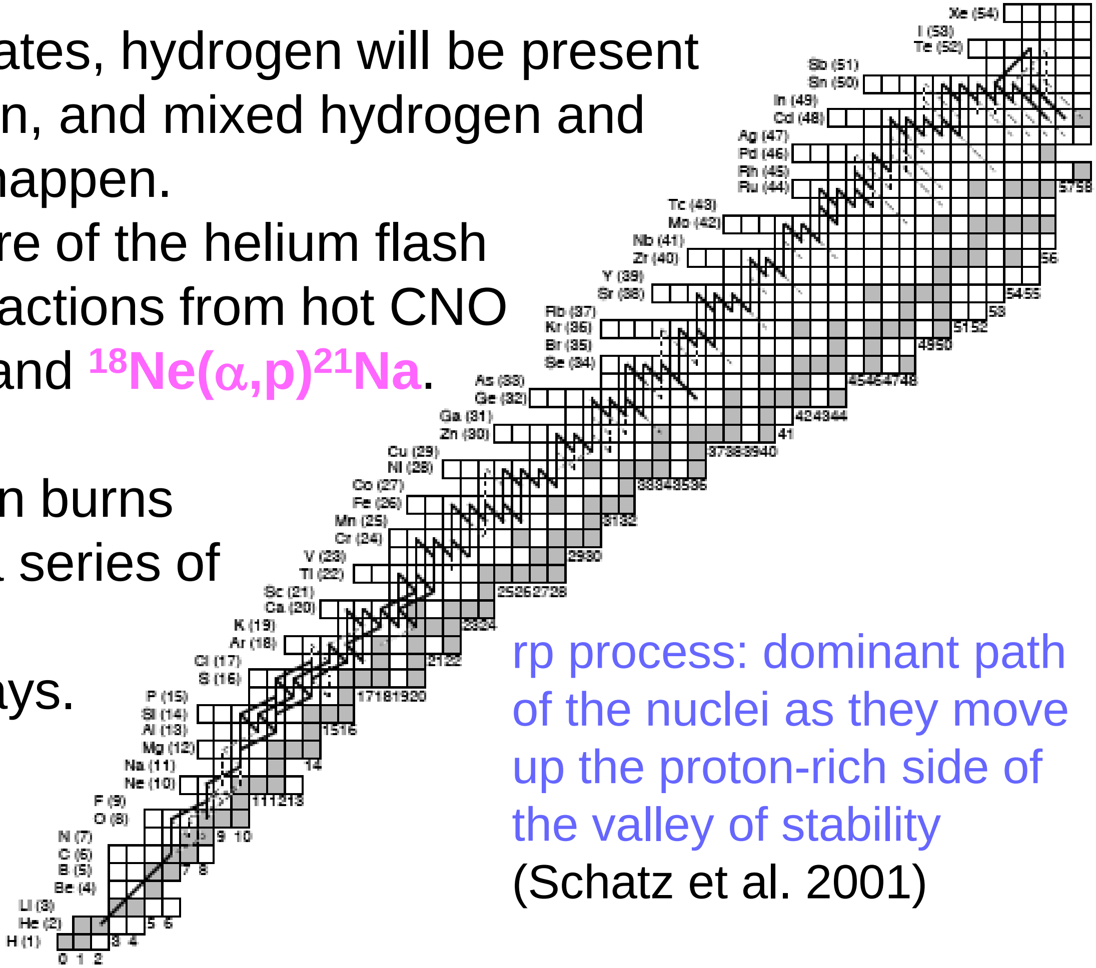
(1) At T > 10^7 K : Mixed hydrogen and helium burning triggered by thermally unstable hydrogen ignition; hydrogen burns via the CNO cycle.
(2) At T > 8 x 10^7 K, hydrogen burns in a stable manner via hot CNO cycle:
$^{12}C(p,\gamma)^{13}N(p,\gamma)^{14}O(\beta^+)^{14}N(p,\gamma)^{15}O(\beta^+)^{15}N(p,\alpha)^{12}C$
(3) When helium ignition condition is met, and hydrogen is depleted, (happens at a small window of accretion rate) pure helium bursts occur (identified by high intensity, short duration and long recurrence time) : $3\alpha \rightarrow {}^{12}C$

Thermonuclear X-ray Bursts

(4) At higher accretion rates, hydrogen will be present during helium ignition, and mixed hydrogen and helium burning will happen.

High temperature of the helium flash causes break-out reactions from hot CNO cycle: $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$ and $^{18}\mathrm{Ne}(\alpha,p)^{21}\mathrm{Na}$.

As a result, hydrogen burns via the rp process: a series of successive proton captures and β decays.



rp process: dominant path of the nuclei as they move up the proton-rich side of the valley of stability (Schatz et al. 2001)

(5) At very high accretion rates, the helium burning temperature sensitivity becomes weaker than cooling rate's sensitivity. So the stable burning sets in.

Burst continuum spectrum

Burst spectra are normally well fitted with a blackbody model.

In principle, neutron star radius can be measured from the observed bolometric flux (F_{obs}) and blackbody temperature (T_{obs}), and the known source distance (d):

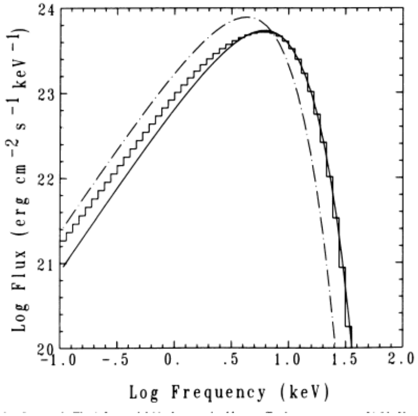
$$R_{obs}=d.(F_{obs}/(\sigma T^4_{obs}))^{1/2}$$

But there are systematic uncertainties:
- (1) unknown amount of spectral hardening;
- (2) effect of unknown gravitational redshift;
- (3) unknown distance;
- (4) if part of the surface emits.

$$\begin{matrix} T = T_{obs}.(1+z)/f \\ R = R_{obs}.f^2/(1+z) \end{matrix} \left\{ \begin{matrix} z > 0;\ f \sim 1.0 - 2.0 \\ 1+z = [1 - (2GM/Rc^2)]^{-1/2} \end{matrix} \right.$$

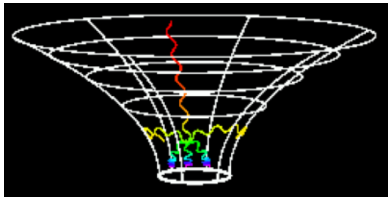
Atmospheric chemical composition, surface gravity, temperature ⇒ f (primary problem)

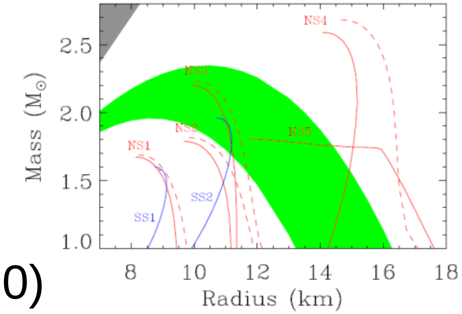
Burst spectra



London, Taam & Howard (1986)

Gravitational redshift





SB, AdSpR, 45, 949 (2010)

Burst oscillations

Fast Timing Properties of X-ray Bursts (Burst Oscillations)

What are burst oscillations?

These are millisecond period variations of observed intensity during thermonuclear X-ray bursts.

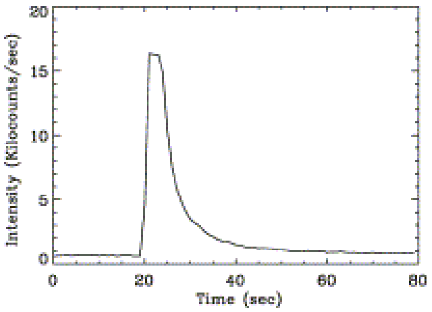
What is their origin?

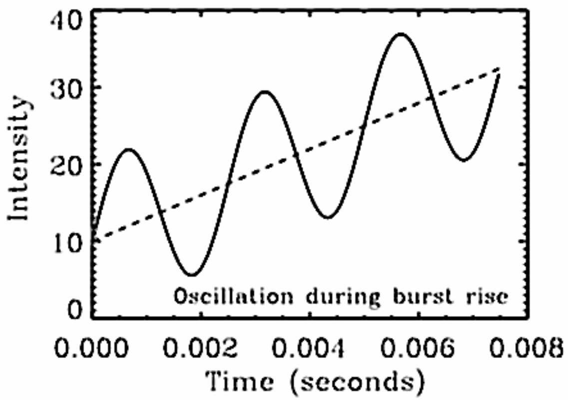
Asymmetric brightness pattern on the spinning neutron star surfaces.

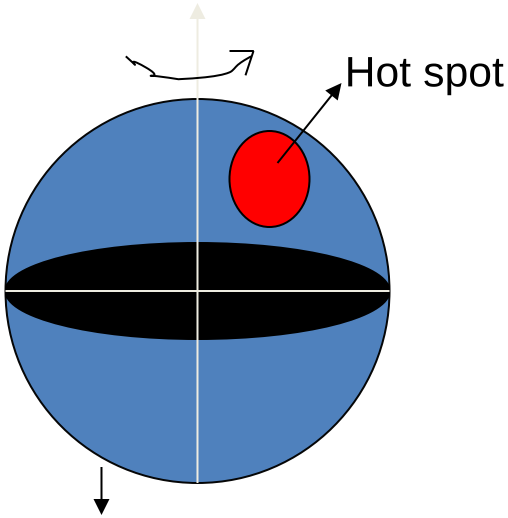
Neutron star spin frequency

= Burst oscillation frequency

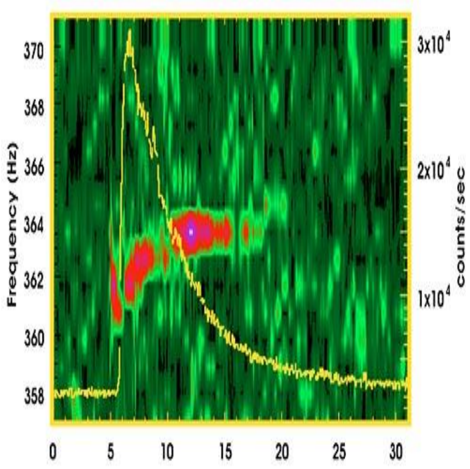
Burst light curve





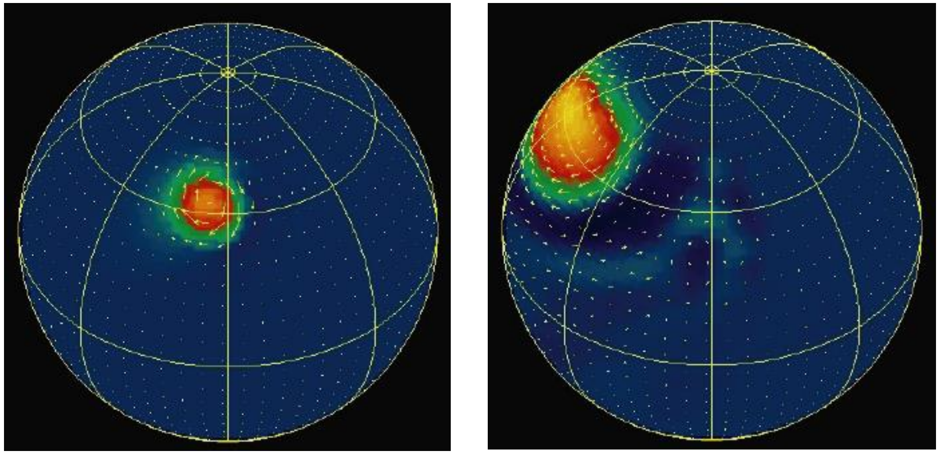


Spinning neutron star

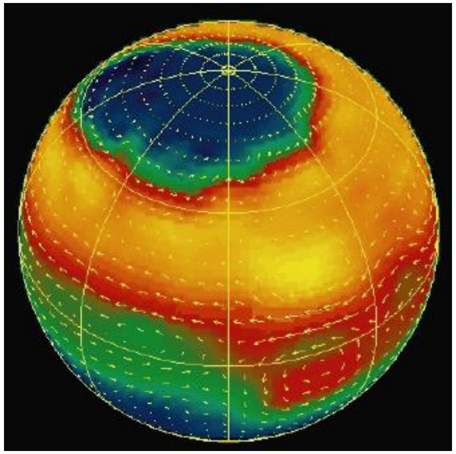


NASA website

Burst oscillation during rise: thermonuclear flame spreading?



Spitkovsky, Levin & Ushomirsky (2002)

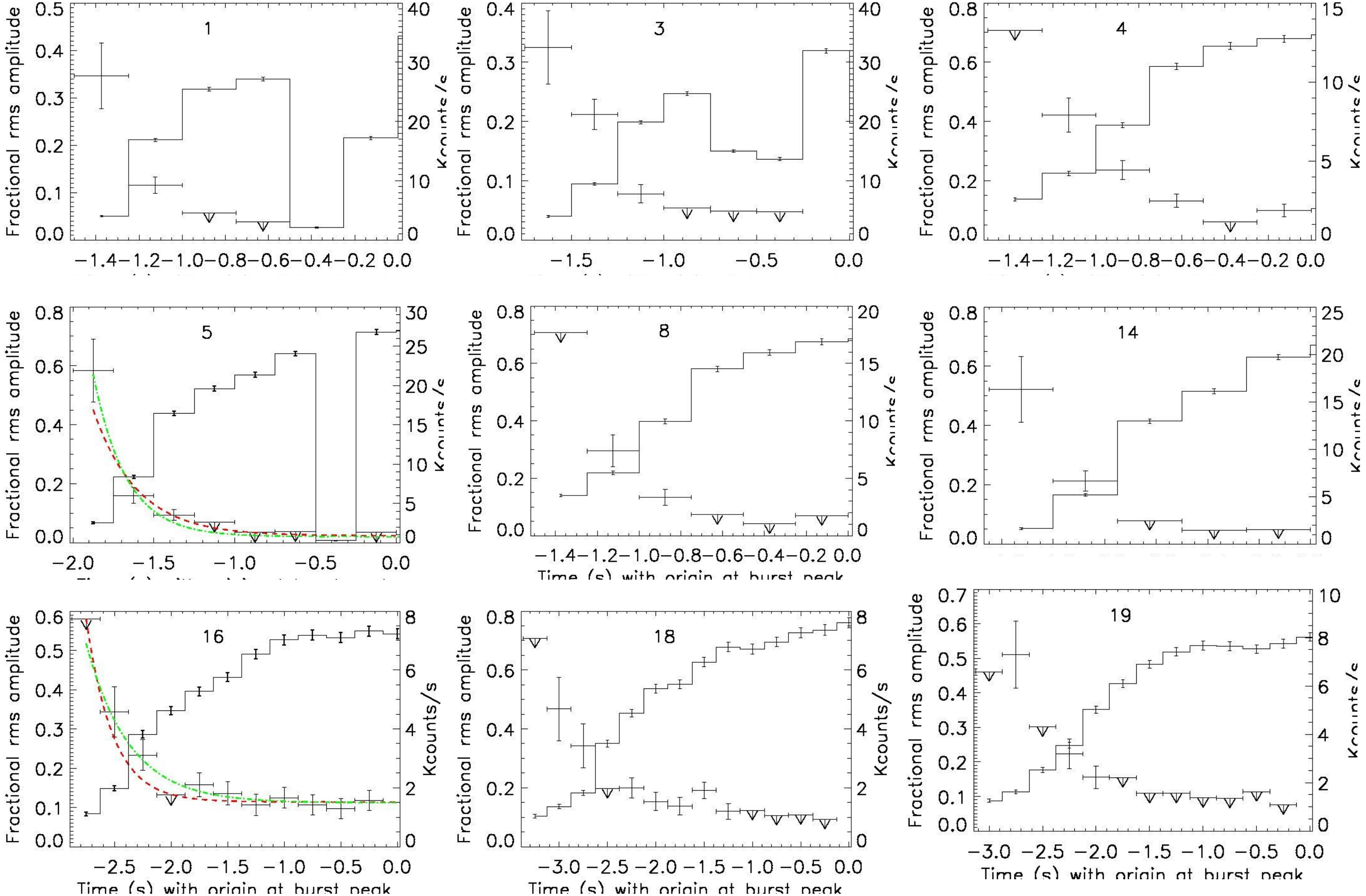


Courtesy: A. Spitkovsky

1. **Modeling of burst oscillation light curve can be useful to measure neutron star mass and radius, which is possibly the only way to address the fundamental physics of super-dense degenerate core matter of neutron stars.**

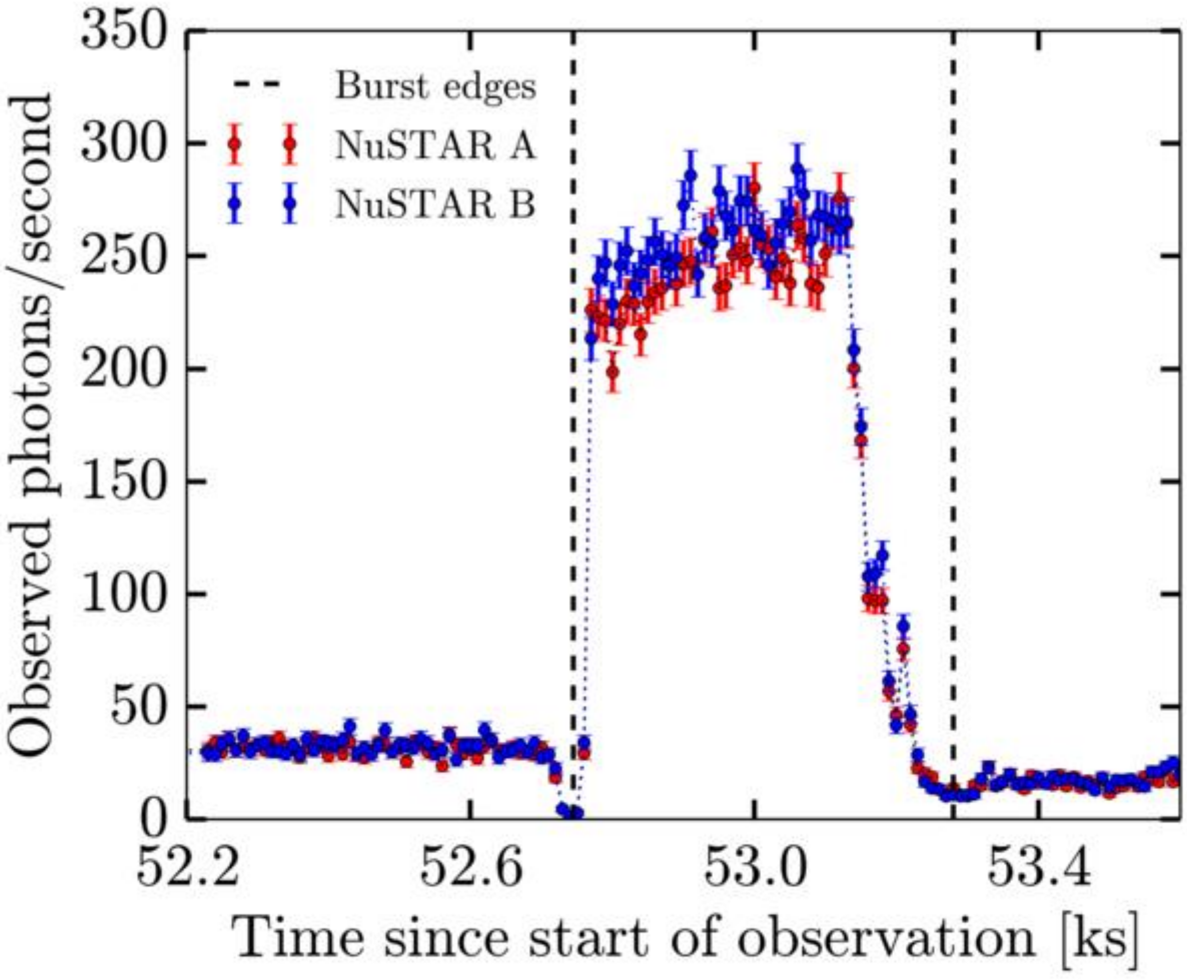
2. **Thermonuclear flame spreading is an interesting science on its own; it combines various fields, such as, astrophysics, nuclear physics, fluid dynamics, gravitational physics, etc., and can be useful to constrain neutron star surface parameters, such as the turbulent viscosity for flame spreading.**

All bursts show a decreasing trend for fractional rms amplitude for burst rise oscillations: **examples of nine bursts from 4U 1636-536 are shown.**



Chakraborty, SB, ApJ, 792, 4 (2014)

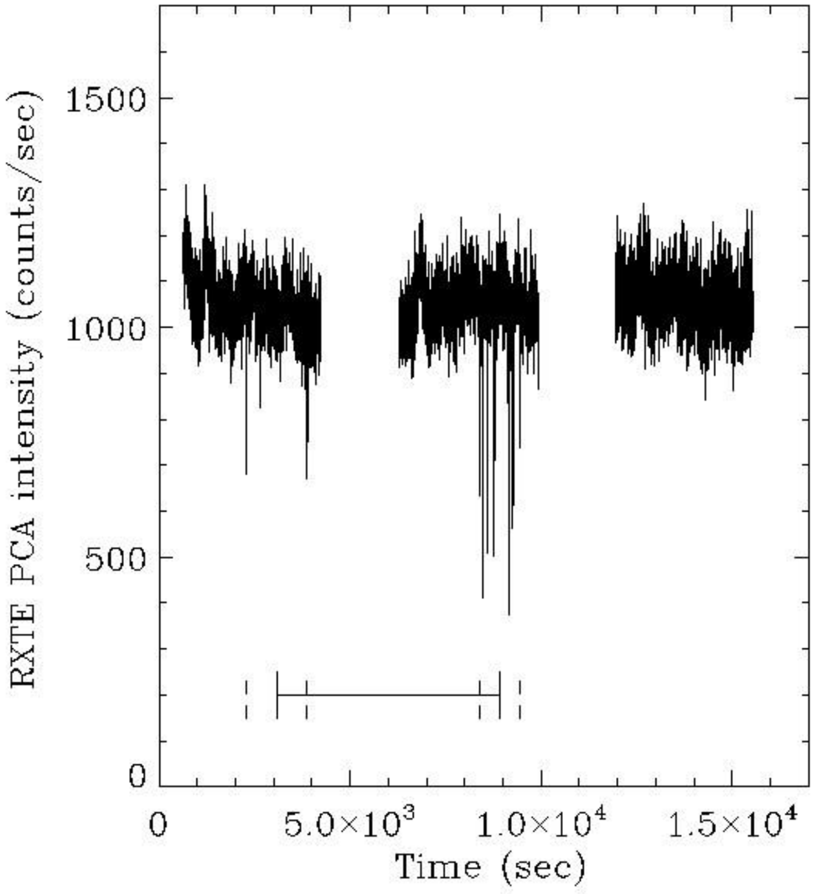
Type-II bursts



Bursts caused by spasmodic accretion.

A type-II burst from the Rapid Burster.
(http://sci.esa.int/xmm-newton/58749-light-curve-of-the-rapid-burster/)

Dips and eclipses



X-ray intensity dips observed from A neutron star LMXB 1A 1744-361. (SB et al. 2006).

Some neutron star LMXBs show periodic X-ray intensity dips and/or (partial or total) eclipses.

Dips are due to obscuration by structures above the disk, when the source inclination angle is greater than about 60°.

Eclipses are due to obscuration by the companion star, when the source inclination angle is greater than about 75°.

Both the features can be useful to measure the binary orbital period, and the source inclination angle.

These high inclination systems show spectral lines, which can be used to probe LMXBs.

High-mass X-ray binary

High-mass X-ray binary (HMXB)

Two classes:

1. **Supergiant X-ray binaries (SGXBs):**

   Have supergiant companion (luminosity class I, II) with a stellar wind (10^{-6}– 10^{-8} $M_{\odot}$/yr).

2. **Be/X-ray binaries (BeXBs):**

   Have O or B type non-supergiant companion (mass ~ 10–20 $M_{\odot}$; luminosity class III-V). These OB stars have circumstellar disk of expelled material in the equatorial plane. Hydrogen emission lines, originated from such a decretion disk, are observed in the optical/IR spectra of such stars, and hence these stars are called Oe and Be stars.

High-mass X-ray binary (HMXB)

Two classes:

1. **Supergiant X-ray binaries (SGXBs):**

   Have supergiant companion (luminosity class I, II) with a stellar wind (10^{-6}– 10^{-8} $M_{\odot}$/yr).

(a) Wind-fed accretion:

When the companion star does not fill the Roche lobe.

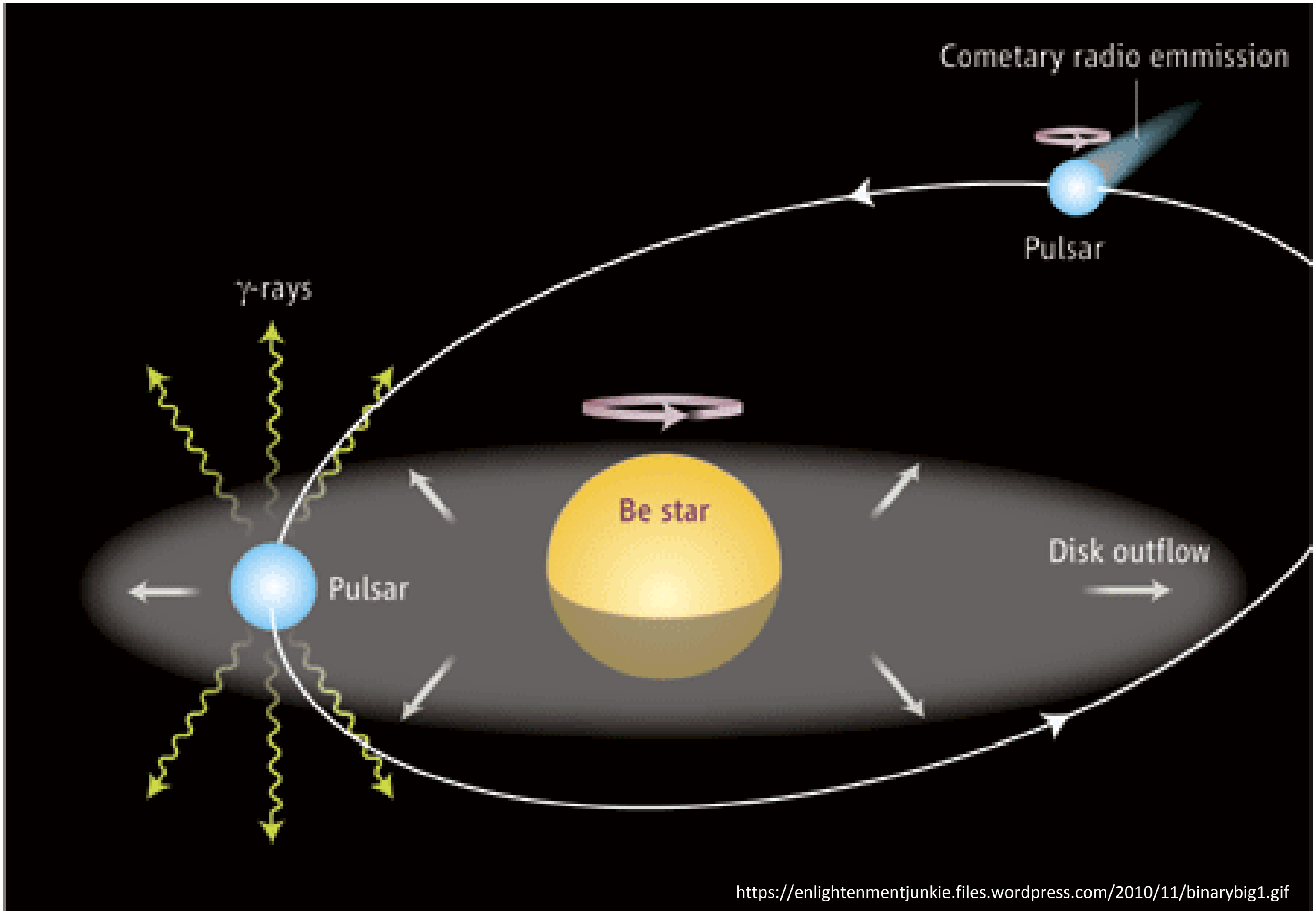
(b) Disk-fed accretion:

By beginning atmospheric Roche-lobe overflow (when the stellar photosphere does not fill the Roche lobe, but the stellar atmosphere does).

High-mass X-ray binary (HMXB)

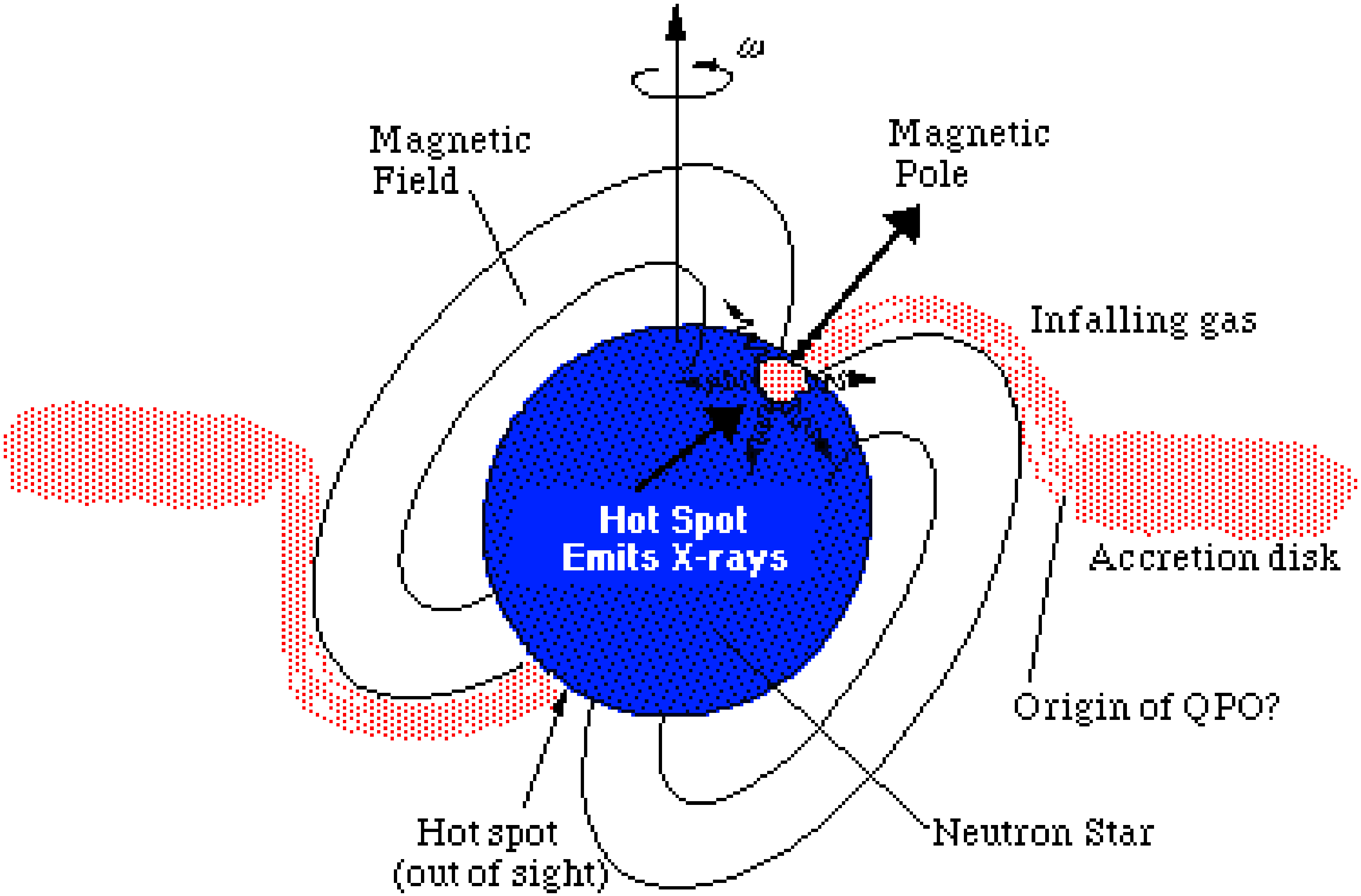
2. Be/X-ray binaries (BeXBs):

Have O or B type non-supergiant companion (mass ~ 10–20 $M_\odot$; luminosity class III-V).



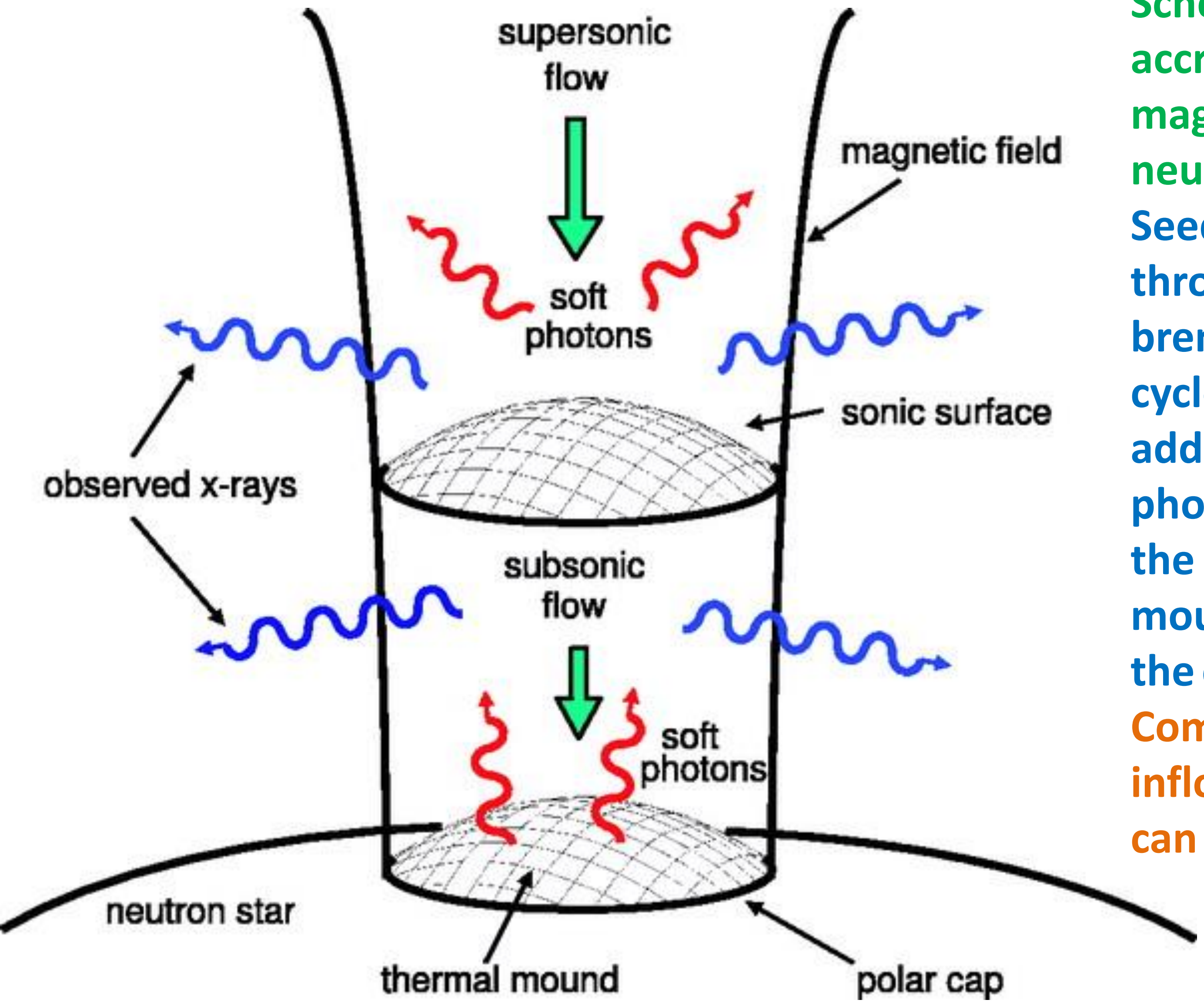
https://enlightenmentjunkie.files.wordpress.com/2010/11/binarybig1.gif

High-mass X-ray binary (HMXB)



https://www.bing.com/images

High-mass X-ray binary (HMXB)



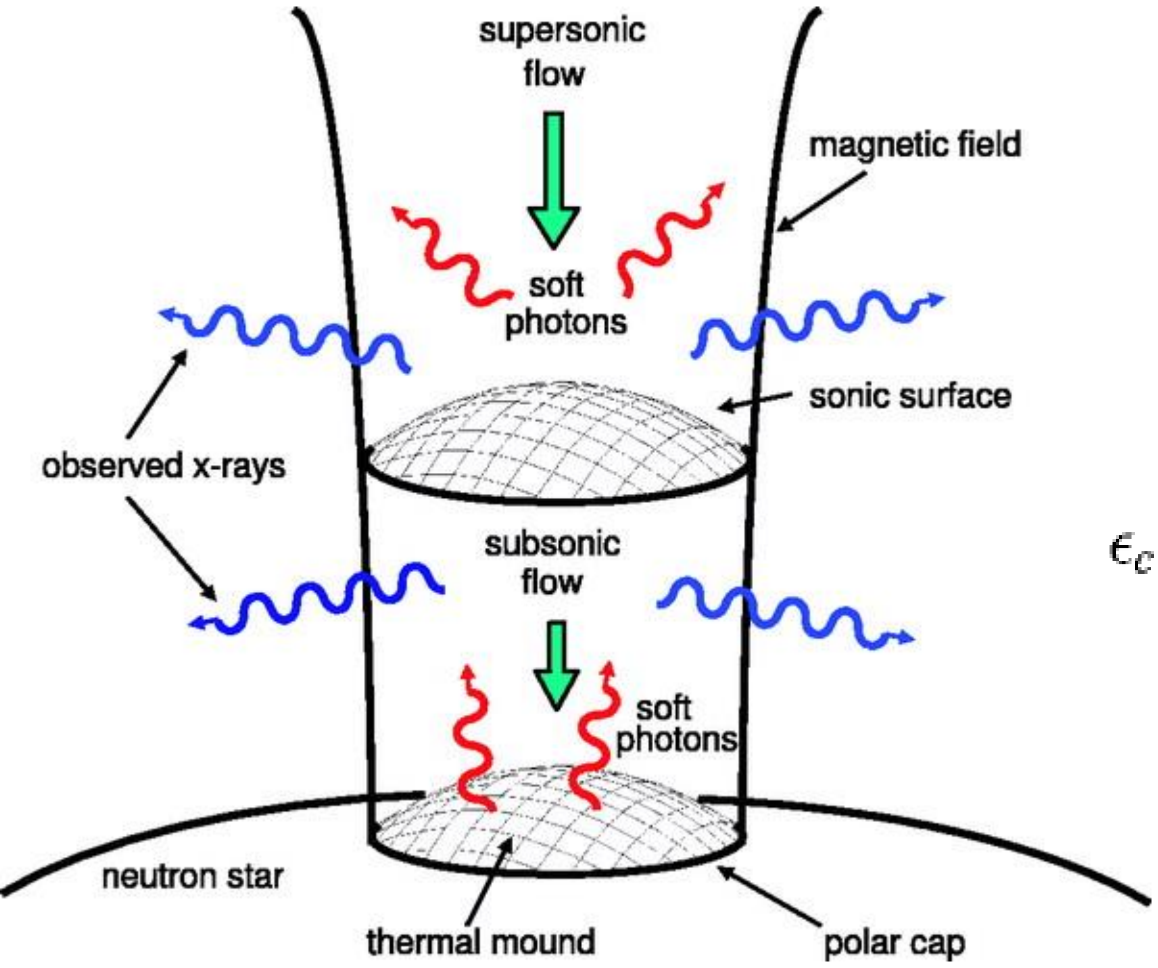
Schematic depiction of gas accreting onto the magnetic polar cap of a neutron star.

Seed photons are created throughout the column via bremsstrahlung and cyclotron emission, and additional blackbody seed photons are emitted from the surface of the thermal mound near the base of the column.

Comptonization by bulk inflow of accreted matter can happen.

Becker and Wolff (2007)

High-mass X-ray binary (HMXB)



Schematic depiction of gas accreting onto the magnetic polar cap of a neutron star.

Cyclotron absorption feature at the following energy can be observed:

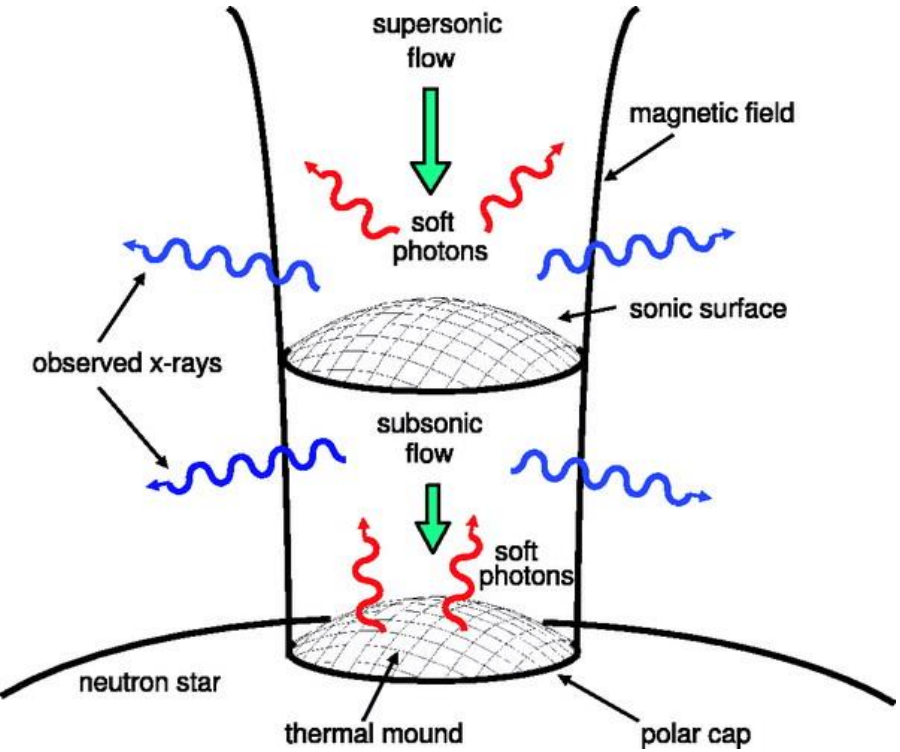
$$\epsilon_c \equiv \frac{eBh}{2\pi m_e c} \approx 11.57\, B_{12}\ \mathrm{keV}$$

This is a direct way to measure the neutron star magnetic field.

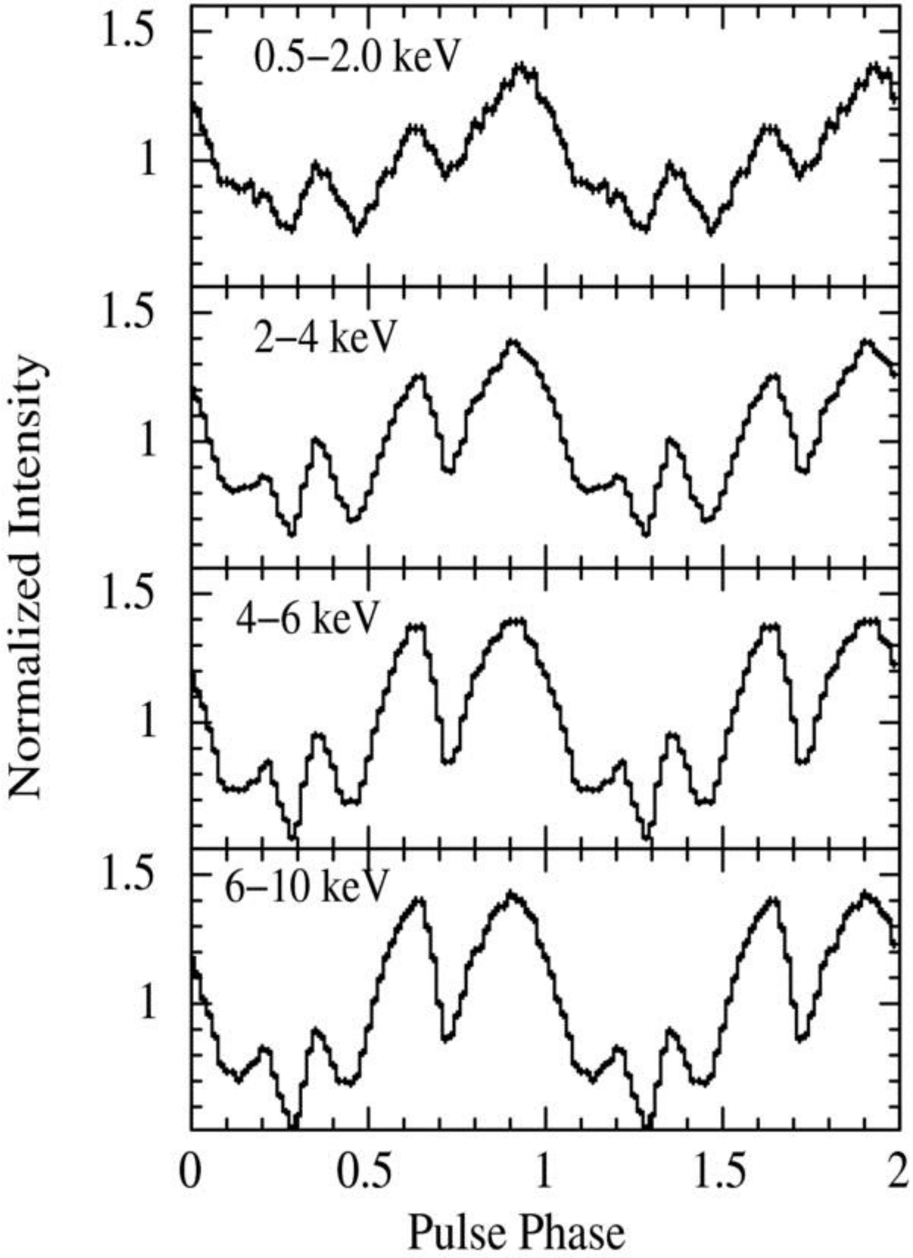
The dependence of the cyclotron feature on pulsar spin phase and luminosity can be used to probe the source physics.

Becker and Wolff (2007)

High-mass X-ray binary (HMXB)



Becker and Wolff (2007)



Energy-dependent pulsar pulse profiles are useful to probe the emission mechanism and geometry.

Naik et al. (2013)

Thank you!