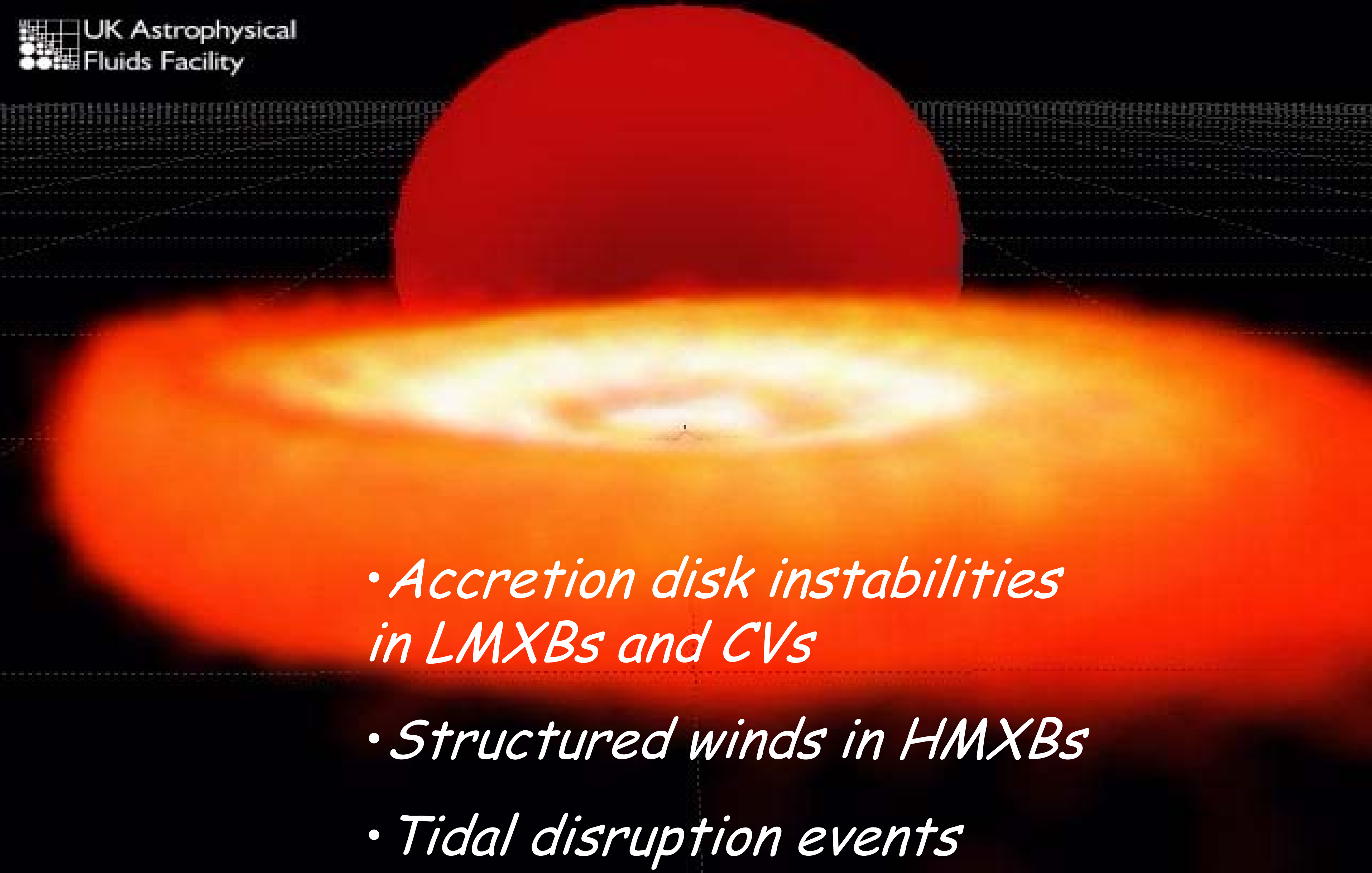
Transient accretion events



UK Astrophysical Fluids Facility

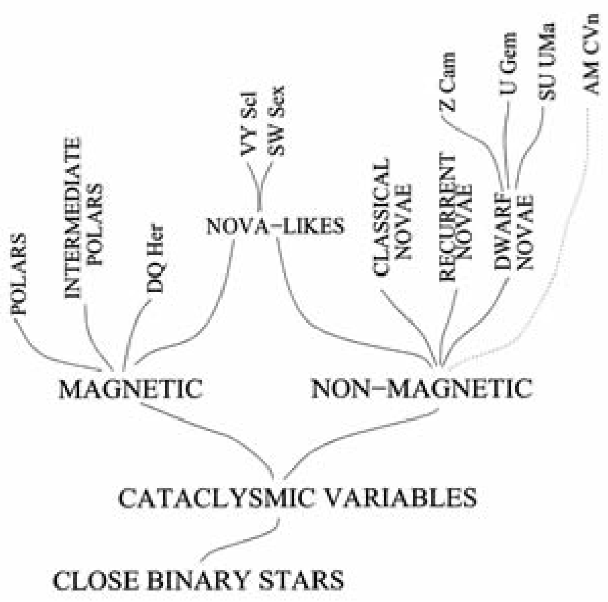
- *Accretion disk instabilities in LMXBs and CVs*
- *Structured winds in HMXBs*
- *Tidal disruption events*

A few accretion generalities..

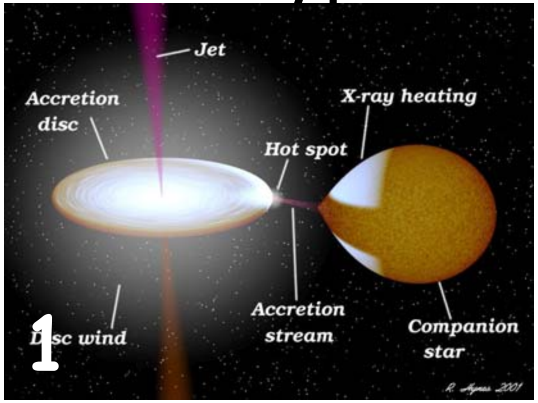
- Dropping a point mass from infinity on a central mass liberates GM/R energy per gram → compact central masses (M/R large) are most energetic → WD, NS, BH, super-massive BH as accretors (between ~0.1 and few hundred MeV per nucleon)
- If the point mass has velocity v, it will be captured if within $R=2GM/v^2$ from the central mass → small v will result in much accretion → Roche lobe overflow very efficient
- If the point mass has angular momentum, it will not fall directly on the central mass but circulate in an accretion disk first
- If the central mass has a substantial magnetic field, the capture process may be channeled by it and motion may not be Keplerian
- Accretion is most energetic if the compact star accretes from another star, not from ISM → we are always dealing with binaries. The next slide provides a taxonomy of mass-transferring binaries
- At the end of the lecture we discuss briefly other accretion events on a bigger but more distant scale

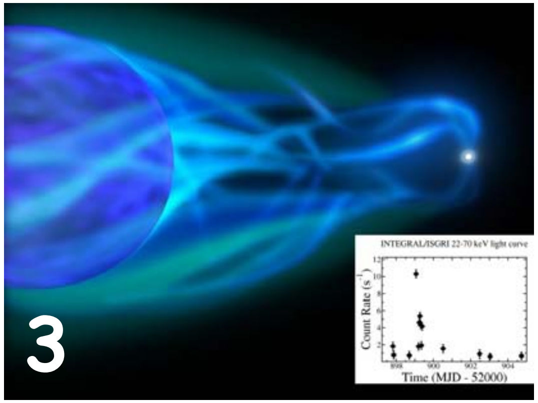
Taxonomy of mass-transferring binaries with compact accretors (**CVs, LMXBs, HMXBs**)

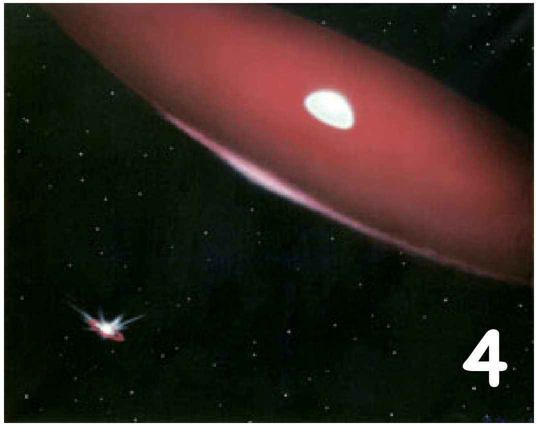
- Donors: either low-mass (<1.4 $M_\odot$) or high mass (>20 $M_\odot$), either main-sequence or evolved. Compact stars with companions between 1.4 and 20 $M_\odot$ do exist, but are not mass-transferring
- Accretors: WD (0.1-1.4 $M_\odot$)/NS (1.4 $M_\odot$)/BH (>3 $M_\odot$)
- Transfer: via accretion disk, magnetosphere, or wind
- Orbits: narrow (sometimes 'ultracompact') or wide. P_{orb} between few minutes and 100s of days.
- Special donor: WD
- Donor usually loosing mass continuously; nevertheless, accretor may receive mass *dis*continuously → transient
- Low-mass donor (<1 $M_\odot$) → **low-mass X-ray binary (LMXB)** if accretor is a NS or BH, **cataclysmic variable (CV)** if accretor is WD
- High-mass donor (>20 $M_\odot$) → **high-mass X-ray binary (HMXB)** for NS or BH accretor; no system identified yet with WD accretor

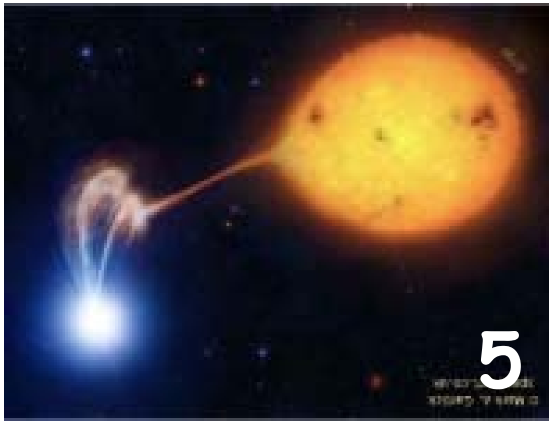


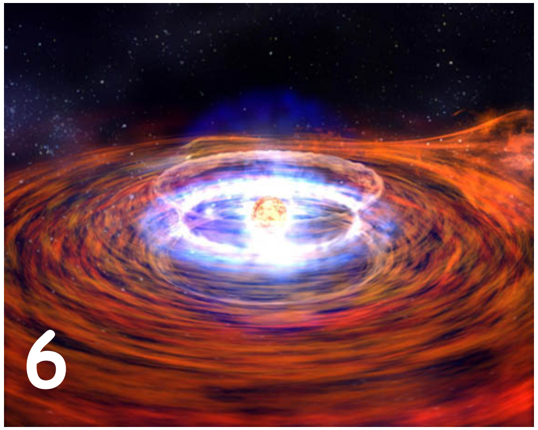
Types of transfer channels in binaries











1. Low-mass X-ray binary with a Roche-lobe filling $<1.4\ M_\odot$ star transferring matter to an accretion disk which buffers that matter and dumps it on the compact object only if a critical mass column density is reached (otherwise accretion is inhibited by conservation of angular momentum)
2. Roche-lobe overflow onto a strongly magnetized compact accretor. The accretion disk is truncated by the magnetic field at the 'Alven radius' which is prescribed by B and M-dot. This type of accretion is only observed in cataclysmic variables (the so-called intermediate polars)
3. High-mass X-ray binary. The donor star is a supergiant with a heavy and structured wind giving rise to variable accretion.
4. A HMXB with a 'Be' star as donor. Be stars are fast rotators wind strong anisotropic winds giving rise to 'secretion disks'. A compact object in a wide eccentric/inclined orbit will only accrete if it traverses the disk
5. CV where the Alfven radius is outside the Roche lobe of the accretor. These are called 'AM Her' systems
6. Same kind of system as in 1., but due to an X-ray burst the inner accretion disk is temporarily blown up and accretion ceases for a limited amount of time (up to 15 mins).

Differences between Roche-lobe overflowing WD and NS/BH systems (LMXBs and CVs)

- Main difference: size of accretor → delimits inner radius of accretion disk
  - white dwarf is of order 10^4 km
  - Neutron star is of order 10^1 km
  - Innermost stable orbit around BH: $6GM/c^2$ *for a non-rotating black hole* → 4.5 km for a 3 $M_\odot$ BH. For a spinning BH this size is smaller (Kerr metric instead of Schwarzschild)

→ WDs are orders of magnitude larger than NS/BHs

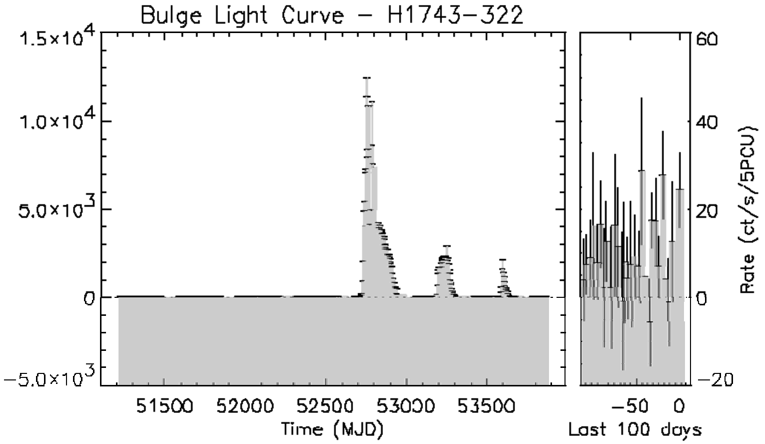
→ Since T_{disk} (:) $r^{-3/4}$, disks around NS/BHs are up to ~200 times hotter than around WDs

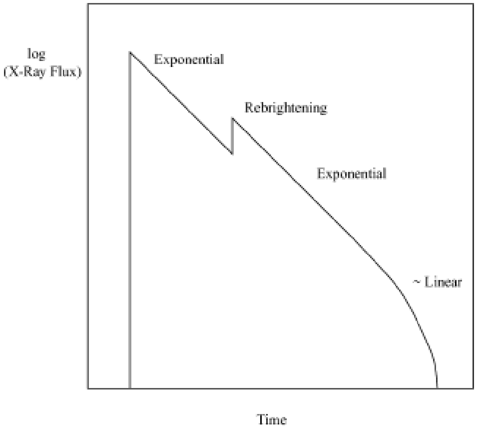
Differences between NS/BH and WD outbursts (in LMXBs and CVs, respectively)

- Since the disk around a NS or BH is up to 200 times hotter (see earlier in this lecture), the spectra of outbursts in NS/BH systems peak at X-ray instead of optical wavelengths
- Since the gravitational well is at least 10^3 times deeper, the energy output is proportionally higher (being proportional to $GM/R_{\text{compact-object}}$)
- The higher energy output makes self-irradiation of accretion disks effective in NS/BH systems (i.e., X-ray photons from the inner disk can photo-ionize the outer cooler disk), while irradiation is unimportant in WD systems. Since irradiation is not effective in a completely flat disk, the disk must contain some level of 3-dimensional structure (warping may occur due to tidal forces)
- Mass transfer and accretion rates are similar between LMXBs and CVs, but outburst durations and duty cycles are different

Irradiation effects

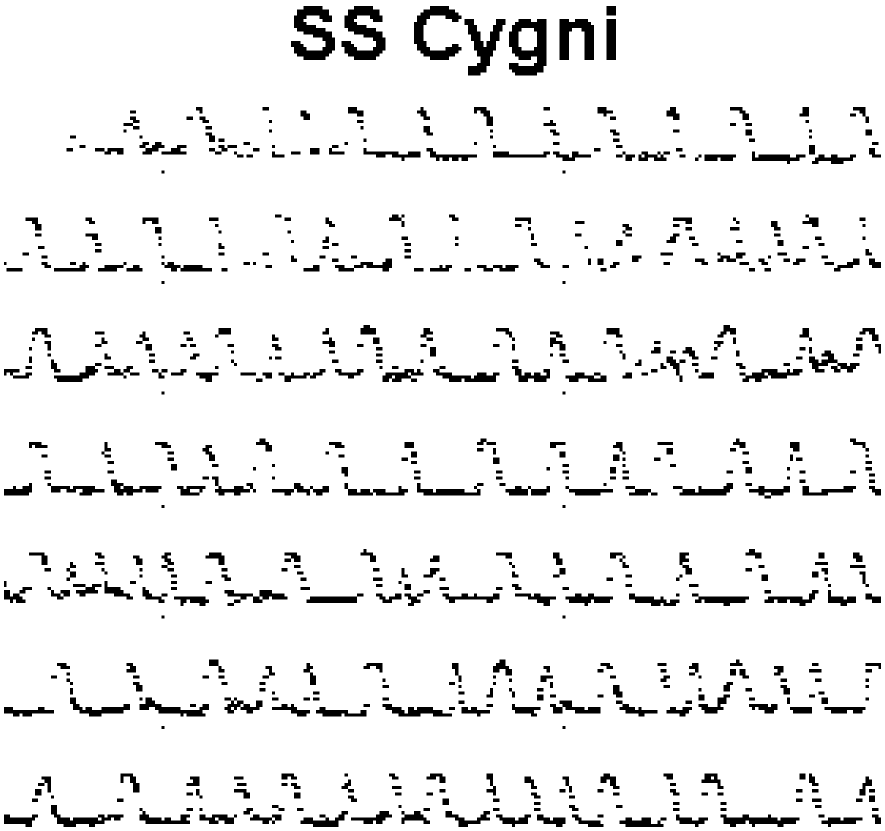
- SXTs in LMXBs seem to empty disk completely → difficult to understand → invoke irradiance of disk → keep ionization at high level → keep accretion going untill there is nothing left
- Sometimes there are rebrightenings or multiple outbursts → disk did not empty initially → shielding of outer disk by puffed-up disk during initial outburst; later shielding re-oriented and irradiation of that part of disk possible





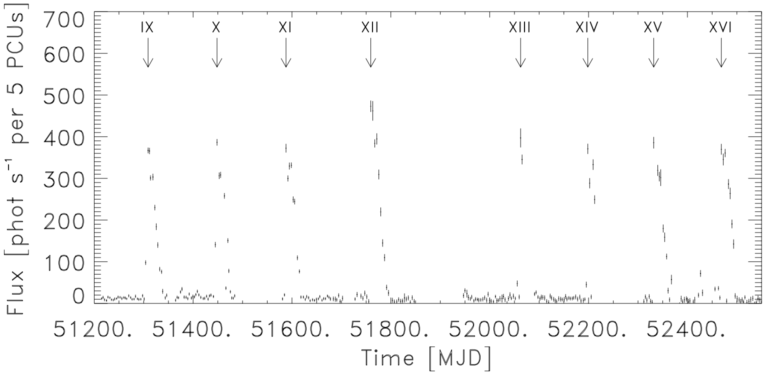
Observations: classical example of a 'dwarf nova' = accretion disk instability around a WD

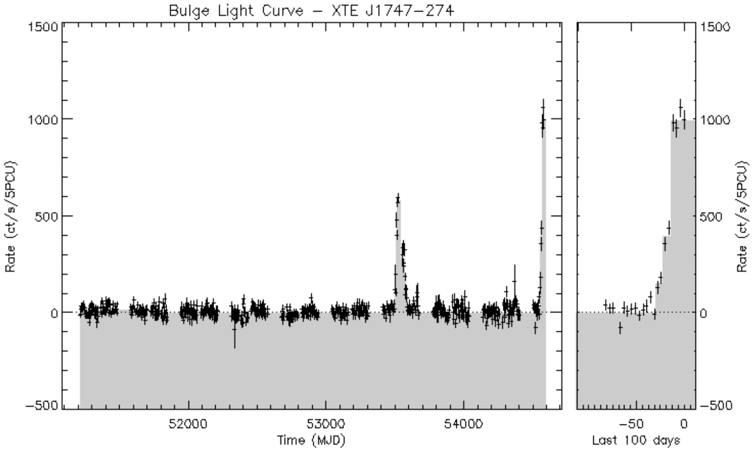
- SS Cygni is the brightest dwarf nova, with m_V ranging between 8 and 12, the distance being about 30 pc
- Discovered in 1896, more than 800 outbursts have been detected sofar
- Recurrence is 4-10 weeks, outburst duration 2 weeks → the duty cycle is about 25%
- Orbital period 6.5 hr, M_{WD}=0.6 $M_\odot$, M_{donor}=0.4 $M_\odot$



Observations of NS X-ray novae

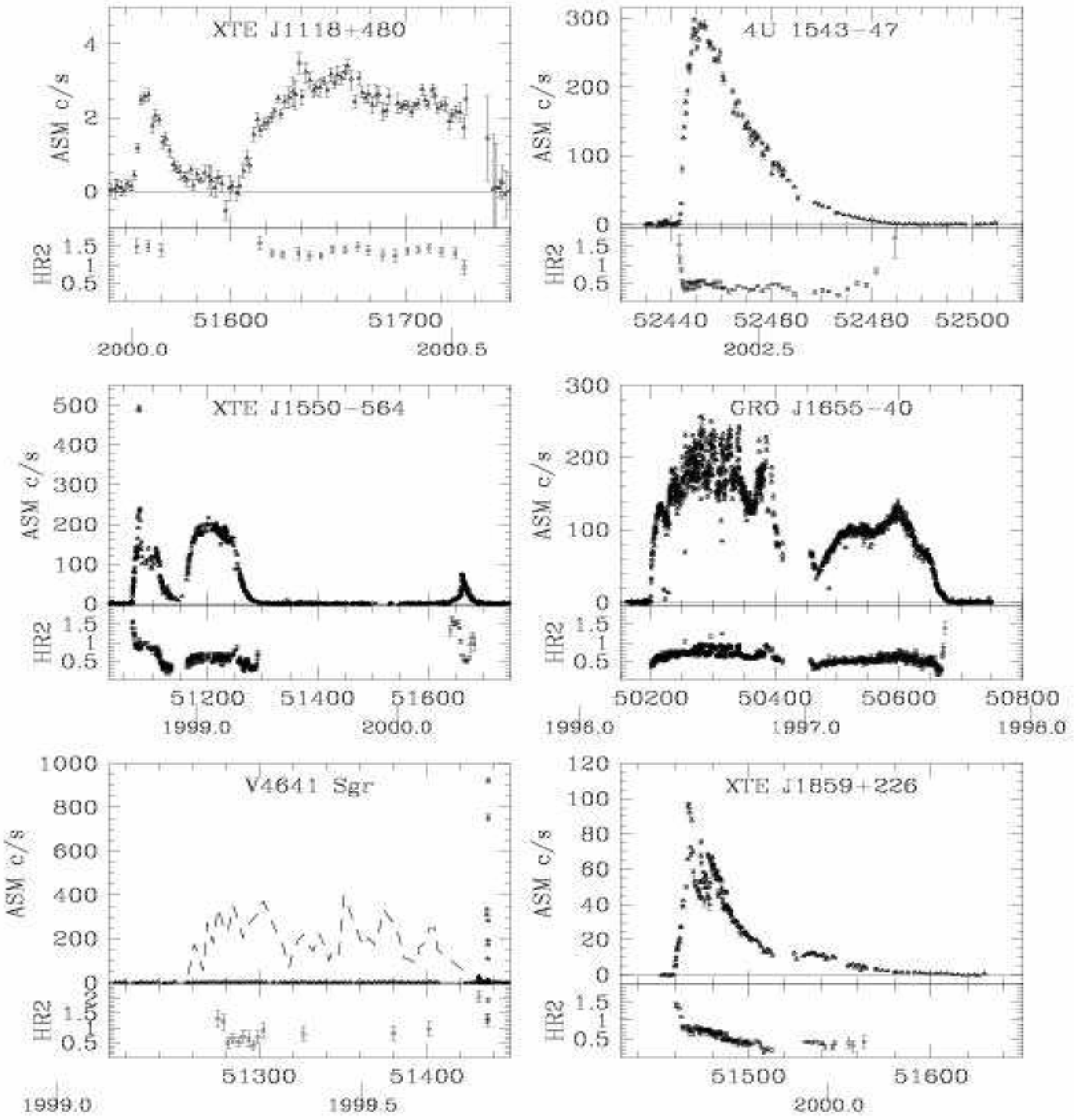
- At the right two novae from NS systems are shown
- Sometimes the outbursts are very regular with recurrence times of a few months, but mostly they irregular with (per source) varying recurrence times, durations, peak fluxes
- NS systems known: ~80





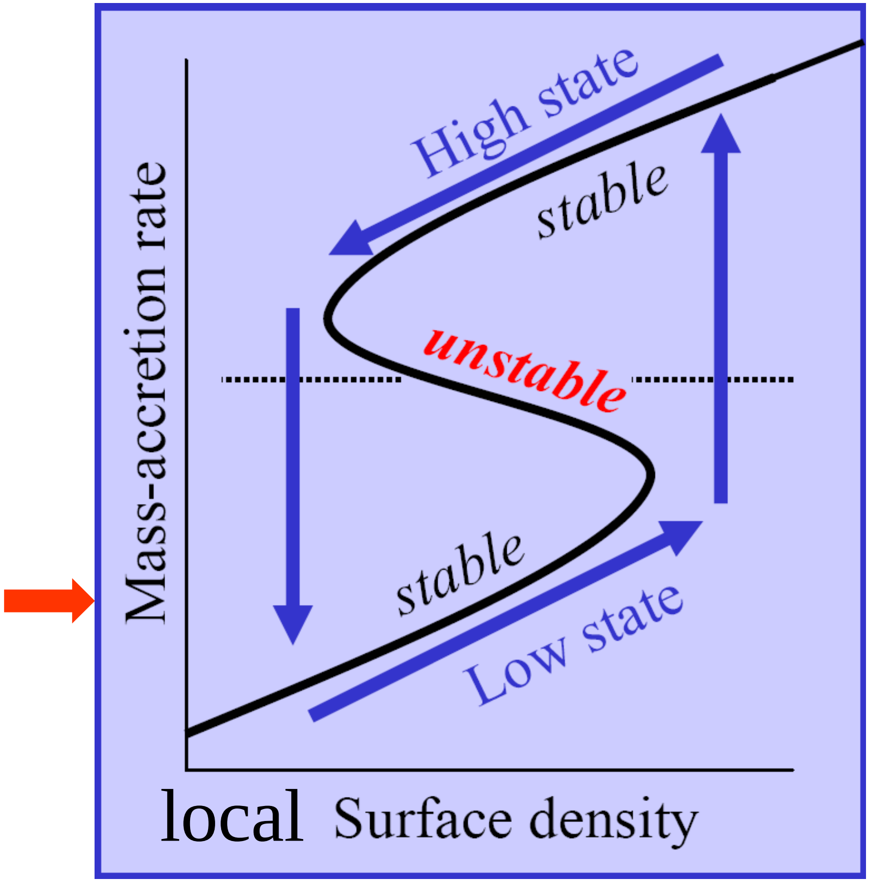
Observations of BH novae

- Comparison BH to NS novae:
  - Softer
  - Brighter
  - Often eddington-limited
  - Less frequent
  - More often multiple peaks
- Systems known: ~30
- These transient outbursts are often called ‘soft X-ray transients’



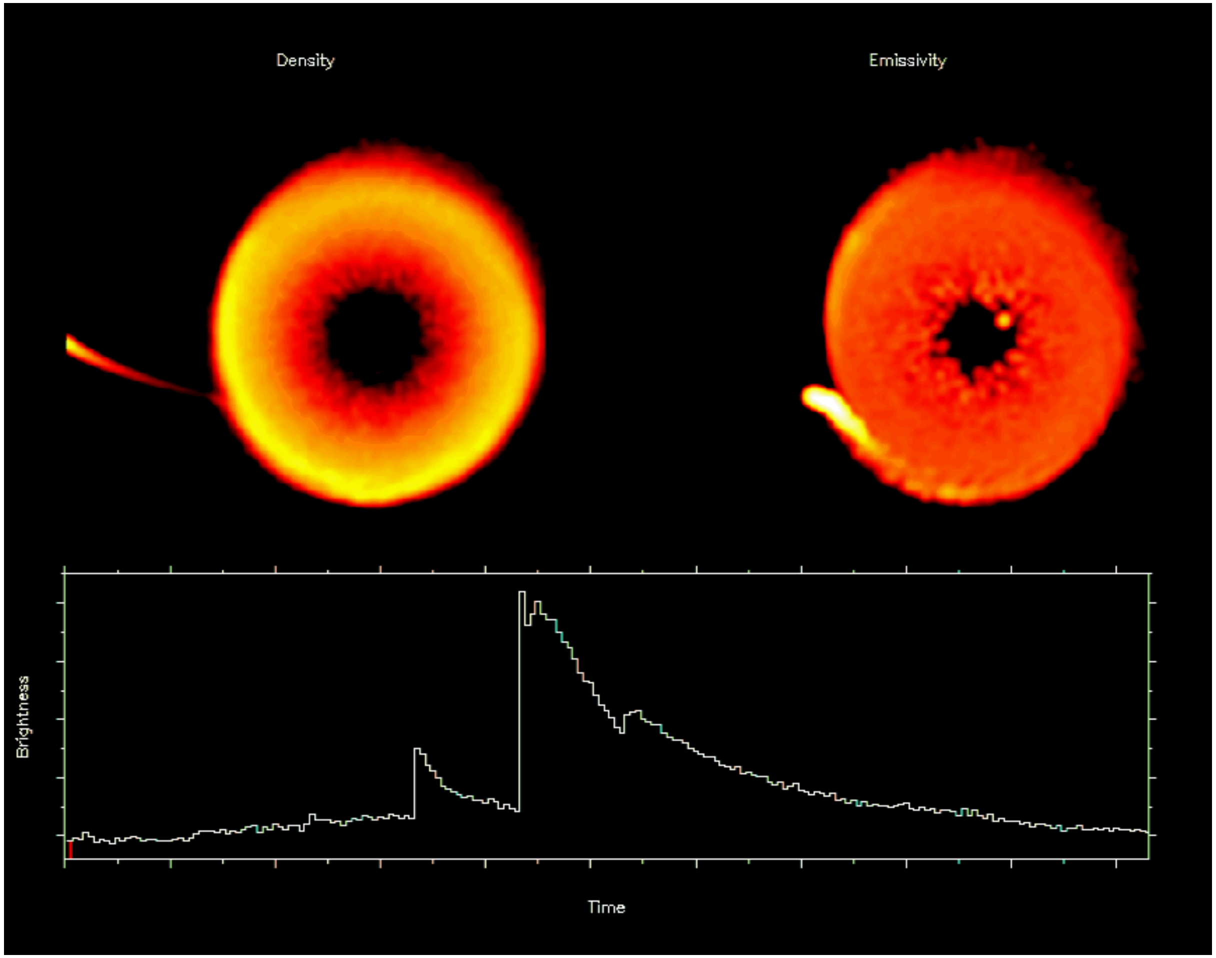
These novae are transients in Roche-lobe overflowing systems. The transient nature is due to an instability in the accretion disk

- Roche-lobe overflow: mass transferred from secondary arrives in circular orbit around compact object and due to angular momentum conservation extends to a disk
- Matter only transfers efficiently to closer orbits if it is braked through 'viscosity'
- Prime suspect for viscosity: magnetic turbulence → need ionization
- Hydrogen ionizes if $T_{eff} > 6500$ K
- T_{eff} reaches that value due to thermal instability in disk → S curve
- Two types of disks: hot & active / cool & quiescent
- $T = T_i \, (r_i/r)^{3/4}$ without irradiance, flatter with irradiance
- Outburst spectrum often dominated by multi-T black body from disk



Accretion disk instability movie

- This movie (see website) shows model calculations of the evolution of surface density (left picture) and emissivity (right) and resulting lightcurve (below)
- The movie starts with quiescence, when the disk is being filled. Then, halfway through the disk the critical surface density (gr/cm^{-2}) is surpassed and the inner portion of the disk is dumped onto the compact object as a result. The outer portion at first is preserved (perhaps because it is shielded from irradiation from the inner edge), but a little later it becomes hot (perhaps because the geometry has altered and irradiation becomes effective, or because there too the critical surface density is surpassed)



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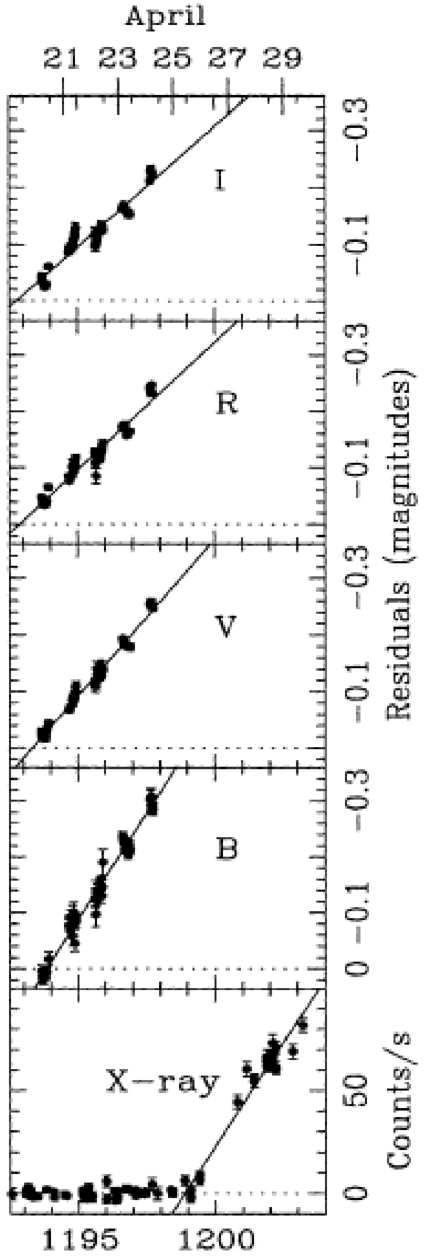
Inside-out and outside-in scenarios

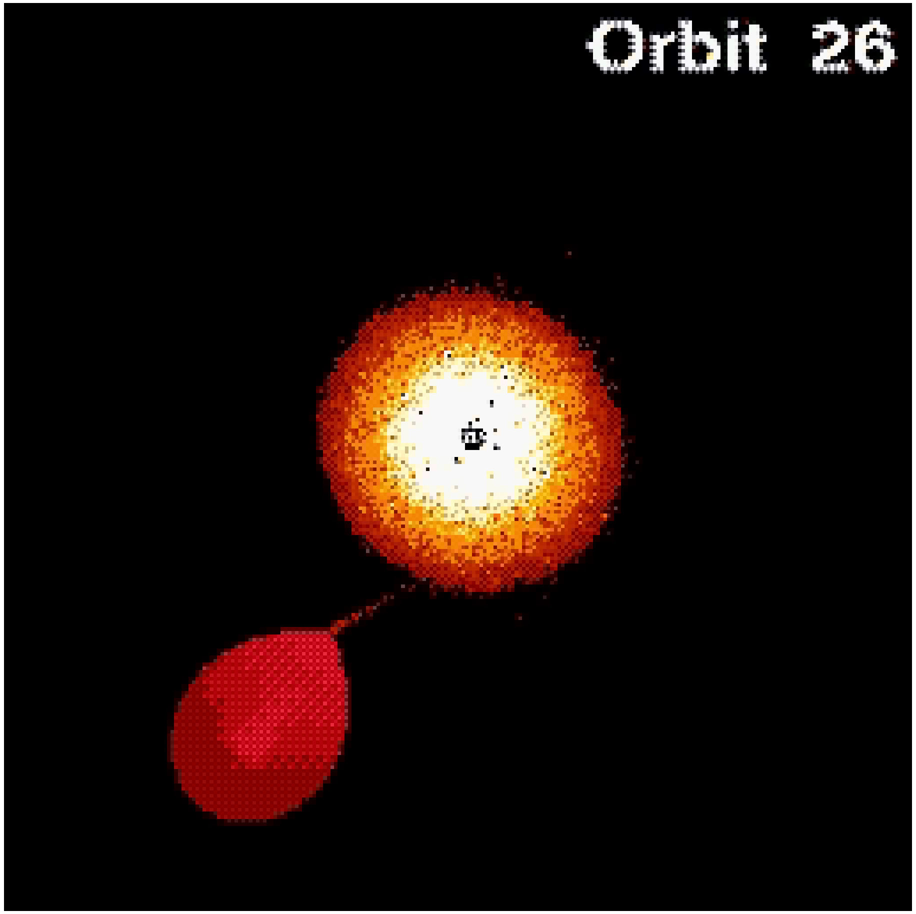
- Optical light traces the outer disk, X-rays the inner disk
- The example to the right shows that the optical outburst precedes the X-ray one
  - → Critical density is surpassed first in outer disk

(this is not always the case)



Disk resonances

- An accretion disk is affected by tidal forces
- Simulations show that this is particularly the case if the mass ratio between the donor and the accretor is less than 0.25
- The resulting effect may be elongated outer rims and warping
- The simulation at right shows the development of such asymmetries after the onset of mass transfer (movie available at website)
- The asymmetry will precess, introducing for instance periodicities in nova light curve slightly off the orbital period



How about the persistent accretors?

- LMXBs and CVs can also accrete persistently
- These are systems that have higher mass transfer rates so that the critical surface density of the accretion disk is <u>permanently</u> surpassed
- Apart from M-dot, P_{orb} is also a critical parameter in setting the persistent nature of a source: the smaller P_{orb}, the smaller the disk, the easier it is to keep the disk in a hot/viscous state through irradiation (after all, the ionizing flux goes as r^{-2})
- For LMXBs, the approximate threshold for persistent accretion is equal to $10^{-10}\ M_\odot\ yr^{-1}$ ($\approx 10^{16}$ g s^{-1}). The relation with P_{orb} is graphed to the right.

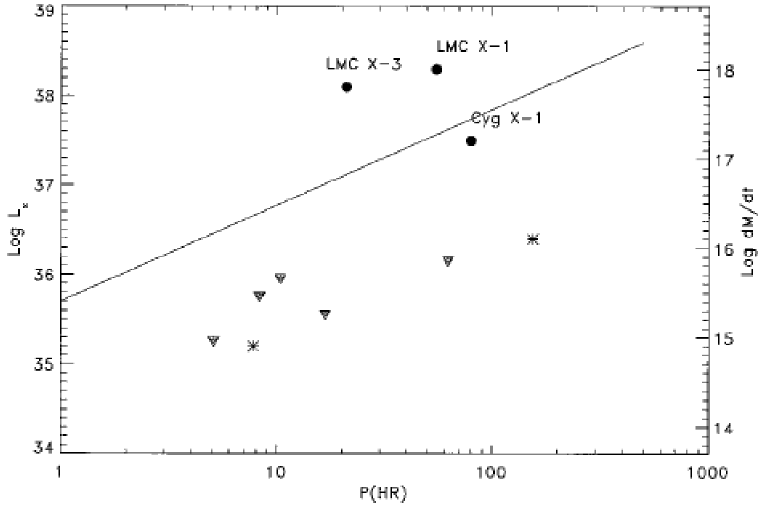
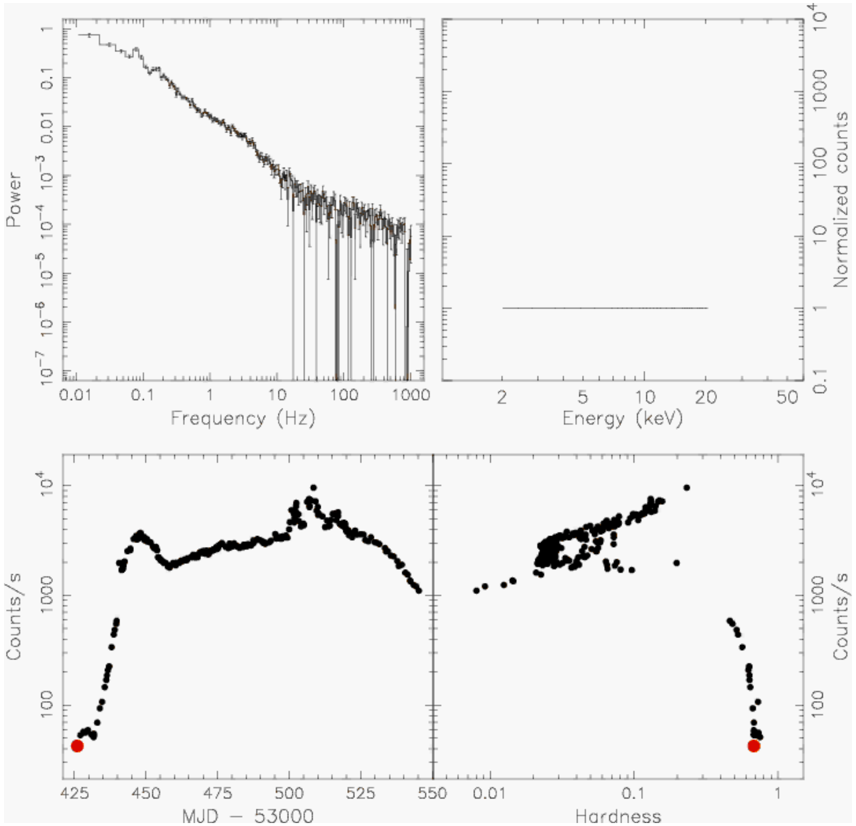


FIG. 2.—X-ray luminosity (and average mass transfer rate) as a function of orbital period for persistent and transient LMXBs with black holes. The transients with known recurrence times have been indicated with asterisks, the other transients with triangles. The straight line indicates the separation between persistent and transient sources derived here for black holes of 10 $M_\odot$ (eq. [3]). The figure also includes (*filled circles*) the three persistent high-mass X-ray binaries Cyg X-1, LMC X-1, and LMC X-3, at the fiducial positions that they would have occupied if they had been LMXBs with an equally large accretion disk, i.e., Roche lobe of the X-ray source. Since LMC X-1 and Cyg X-1 likely transfer mass by a (possibly focused) stellar wind instead of fully developed Roche lobe overflow, the radius of any accretion disk in these systems is likely to be smaller than the 80% of the Roche lobe radius assumed in the calculations (see text); as a result their fiducial positions are likely to be too far to the right in this diagram.

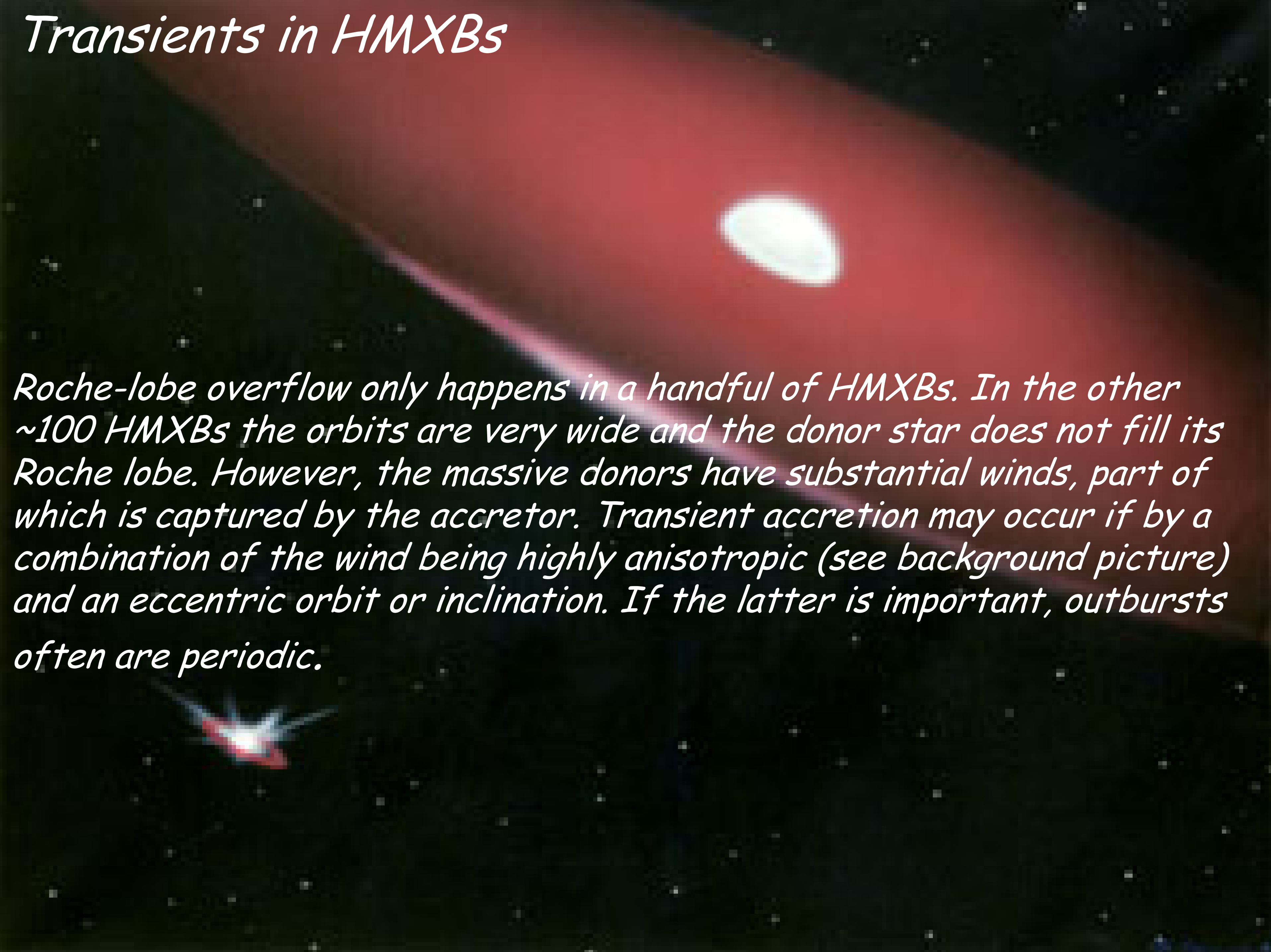
(Van Paradijs 1996)

Movie of measurements of the 2005 outburst of GRO J1655-40, a BH transient

- This movie shows the evolution of the Fourier power density spectrum (top left), energy spectrum (top right), light curve (bottom left) and color-color diagram (bottom right) as a function of time
- The movie illustrates different states of the disk, as is often seen in BH transients. For instance, the low-flux part is characterized by a hard spectrum (shallow power law) and relatively much variability at high frequencies (including a QPO). The high-flux part shows a much softer spectrum, presumably because the inner radius of the accretion disk becomes smaller and thus the temperatures of the inner edge reach the X-ray domain (the hard spectrum being due to a corona, not the disk)
- Movie available at web site



Transients in HMXBs



Roche-lobe overflow only happens in a handful of HMXBs. In the other ~100 HMXBs the orbits are very wide and the donor star does not fill its Roche lobe. However, the massive donors have substantial winds, part of which is captured by the accretor. Transient accretion may occur if by a combination of the wind being highly anisotropic (see background picture) and an eccentric orbit or inclination. If the latter is important, outbursts often are periodic.

Wind accretion

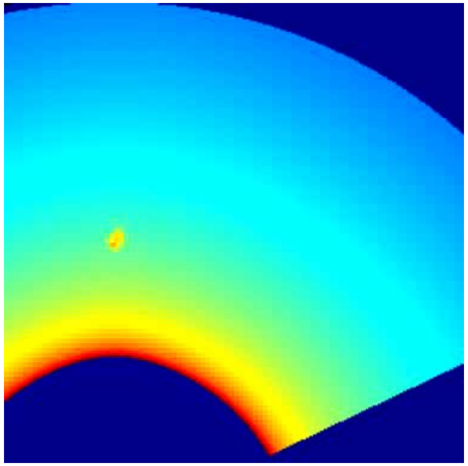
- Capture radius $R_{capture}=2GM_{accretor}/v_{rel}^2$
- For a typical HMXB of $M=20\ M_\odot$ and $v_{rel}=1500$ km, $R_{capture}=2.5\times10^6$ km. For a typical $P_{orb}=10$ d and a NS with mass 1.4 $M_\odot$, $a=3.8\times10^7$ km and approximately a fraction of 10^{-3} of the wind is accreted
- Capture may be influenced by NS magnetic field. Matter is captured by the magnetic field at the so-called Alfven radius

$$r_A = \left(\frac{\mu^4}{2GM\dot{M}^2}\right)^{1/7} = 3.2\times10^8 \dot{M}_{17}^{-2/7}\mu_{30}^{4/7}\left(\frac{M}{M_\odot}\right)^{-1/7}\ \mathrm{cm}$$

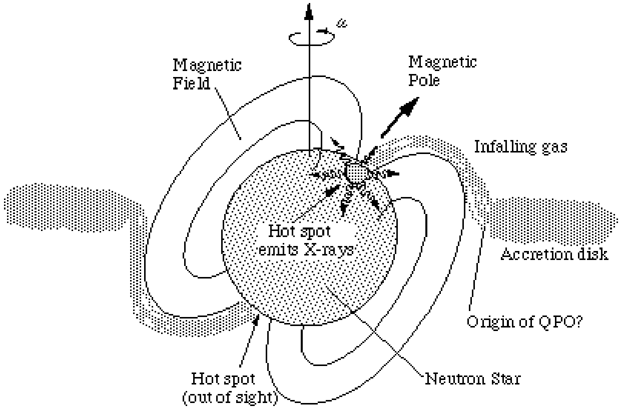
- with the NS magnetic moment mu in units of 10^{30} G cm3 (typical value for a NS with $B=10^{12}$ G) and M-dot in units of 10^{17} g $s^{-1.}$
- r_A is of order 10^3 km, so magnetic capture occurs at much smaller distances from the NS than gravitational capture

Structure in the wind due to accretor

1) In reality wind capture is complicated, as movie at right shows
2) Structure in wind induced by accretor will result in variability in the accretion
3) If $r_A > R_{cor}$ with co-rotation radius R_{cor} equal to radius where Keplerian period is equal to NS spin period → material is flung out by magnetic field → no accretion is possible → 'propeller effect'
4) The combination of 2) and 3) may result in transient X-ray sources

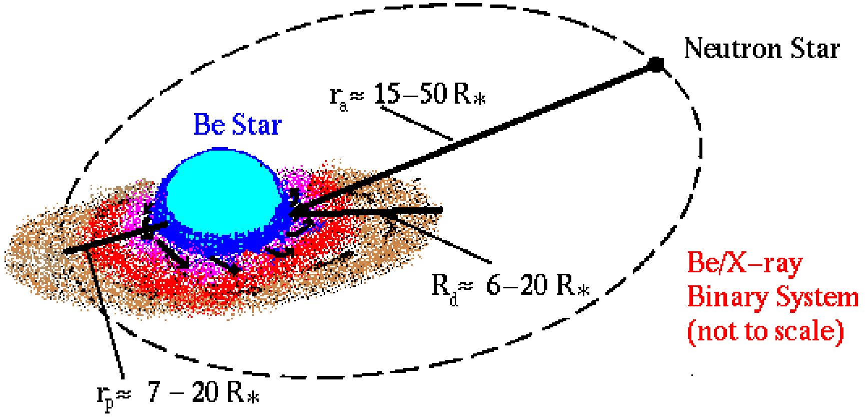


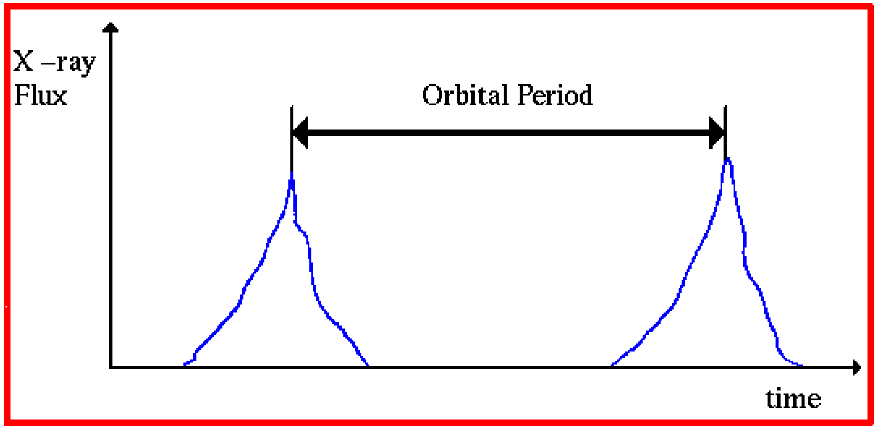
- *Movie by Blondin (see website)*



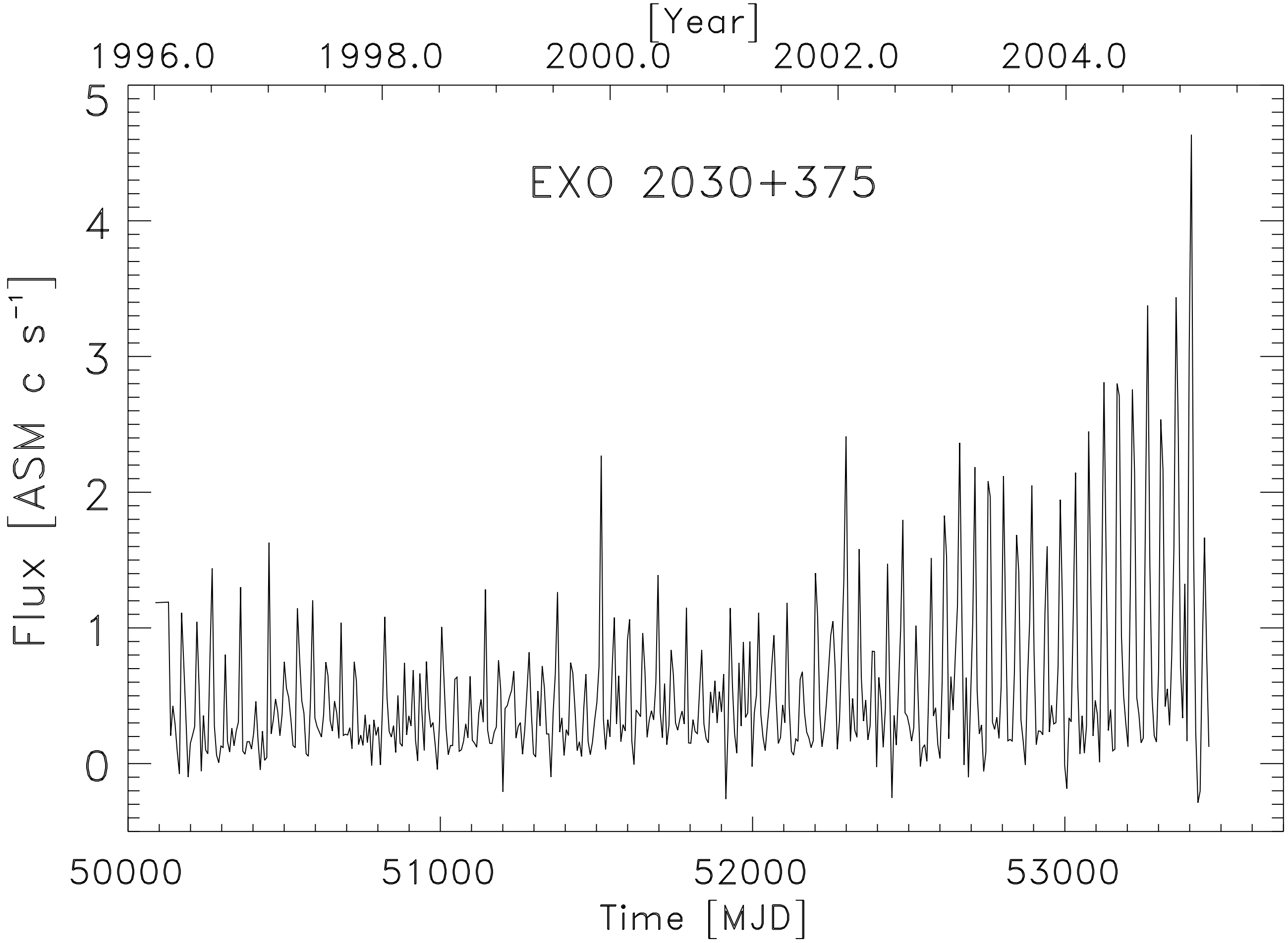
Hard X-ray transients

- A substantial fraction of HMXBs (~50%) are 'B[e]' stars which are known to exhibit 'secretion' disks
- This will result in periodic recurrence of outbursts
- Outbursts reveal accretion-powered X-ray pulsar (P = 0.2-1400 s) with spin up during outbursts





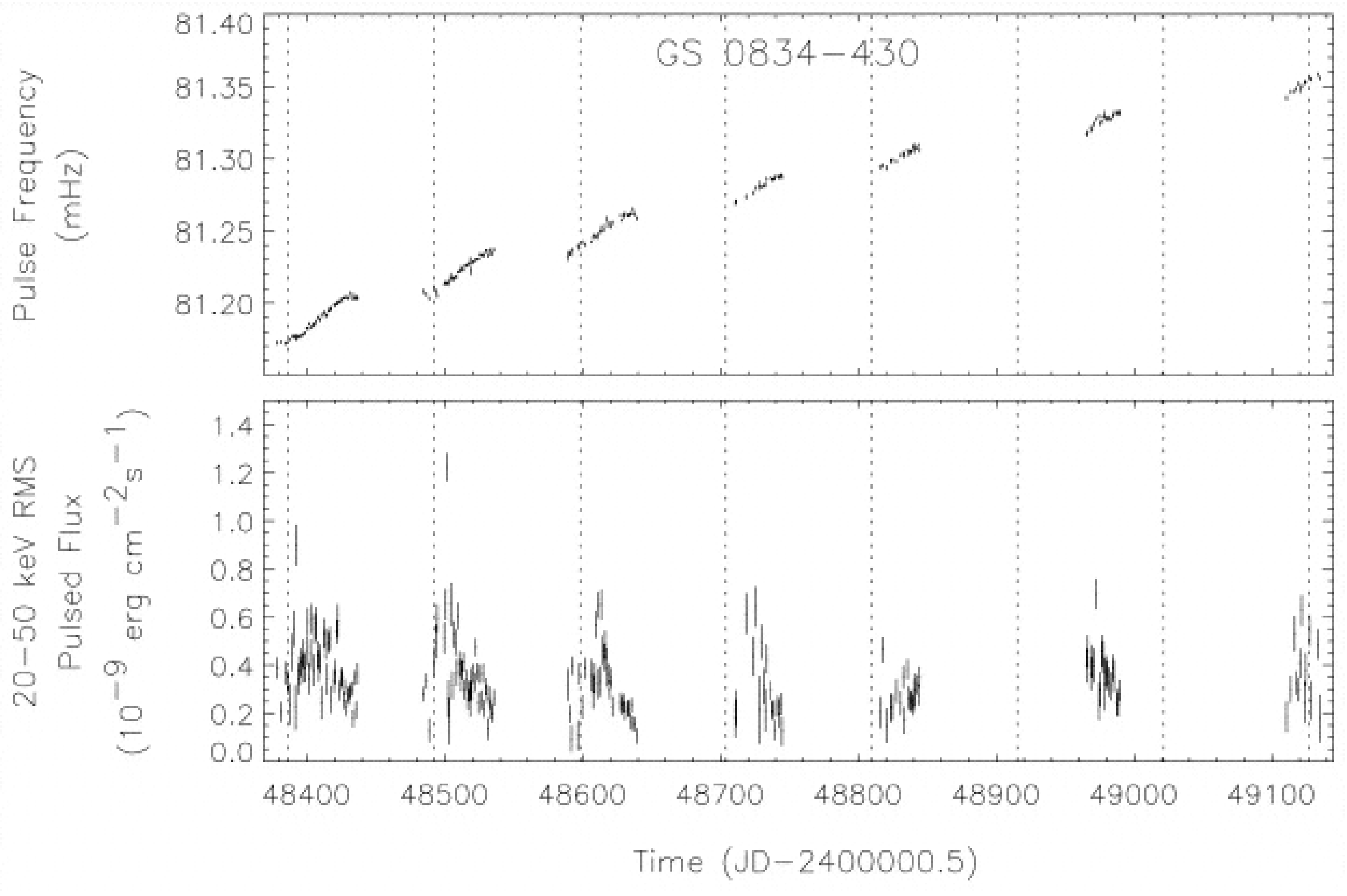
HXTs - lightcurves



orbital period 46.0 d

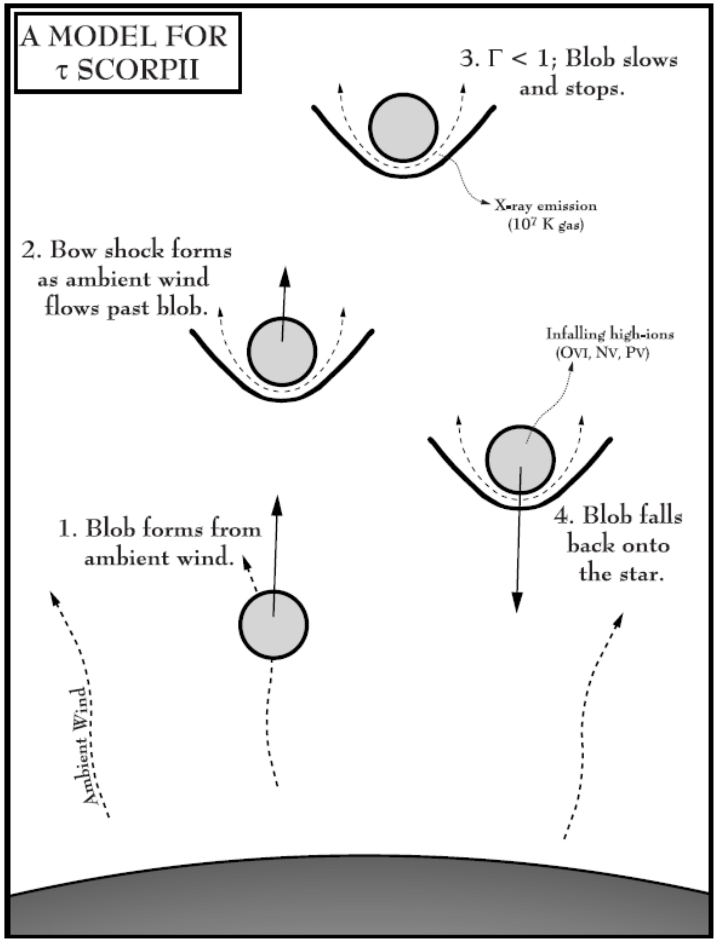
RXTE/ASM

NS spin changes during HXT outbursts



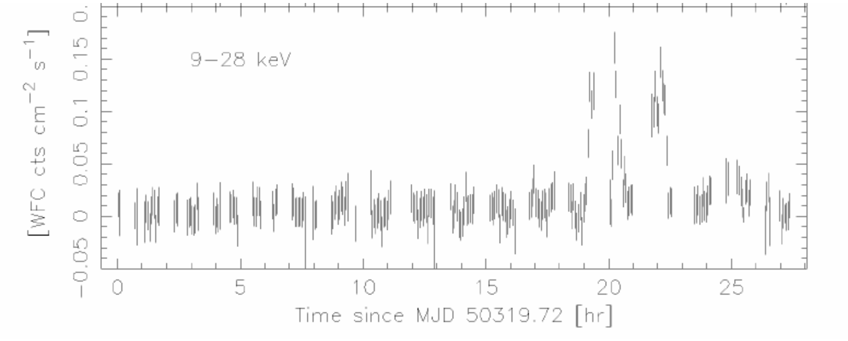
Bildsten et al. 1997 (CGRO/BATSE)

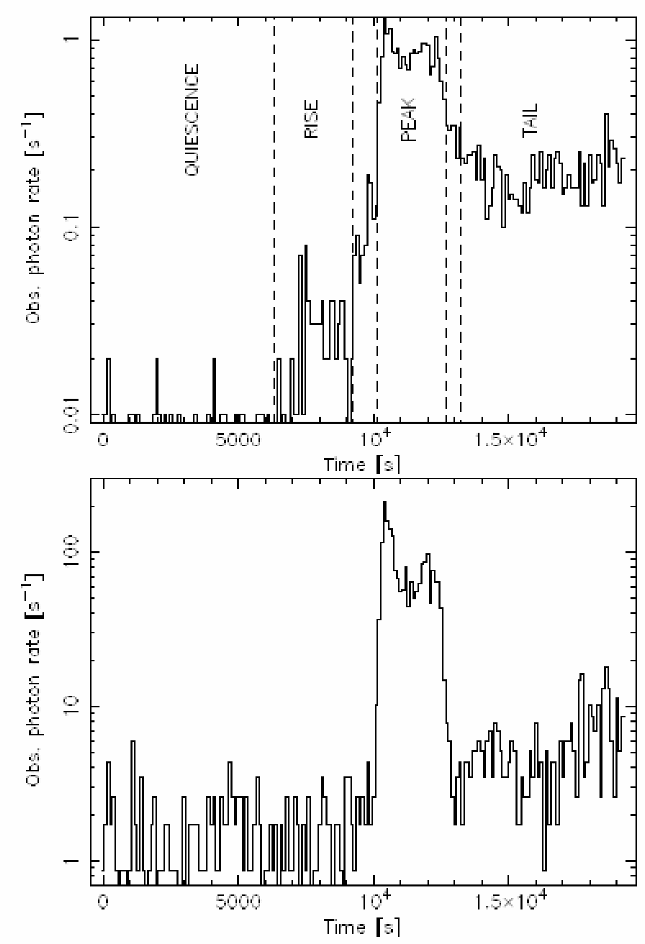
Intrinsic structure in the wind



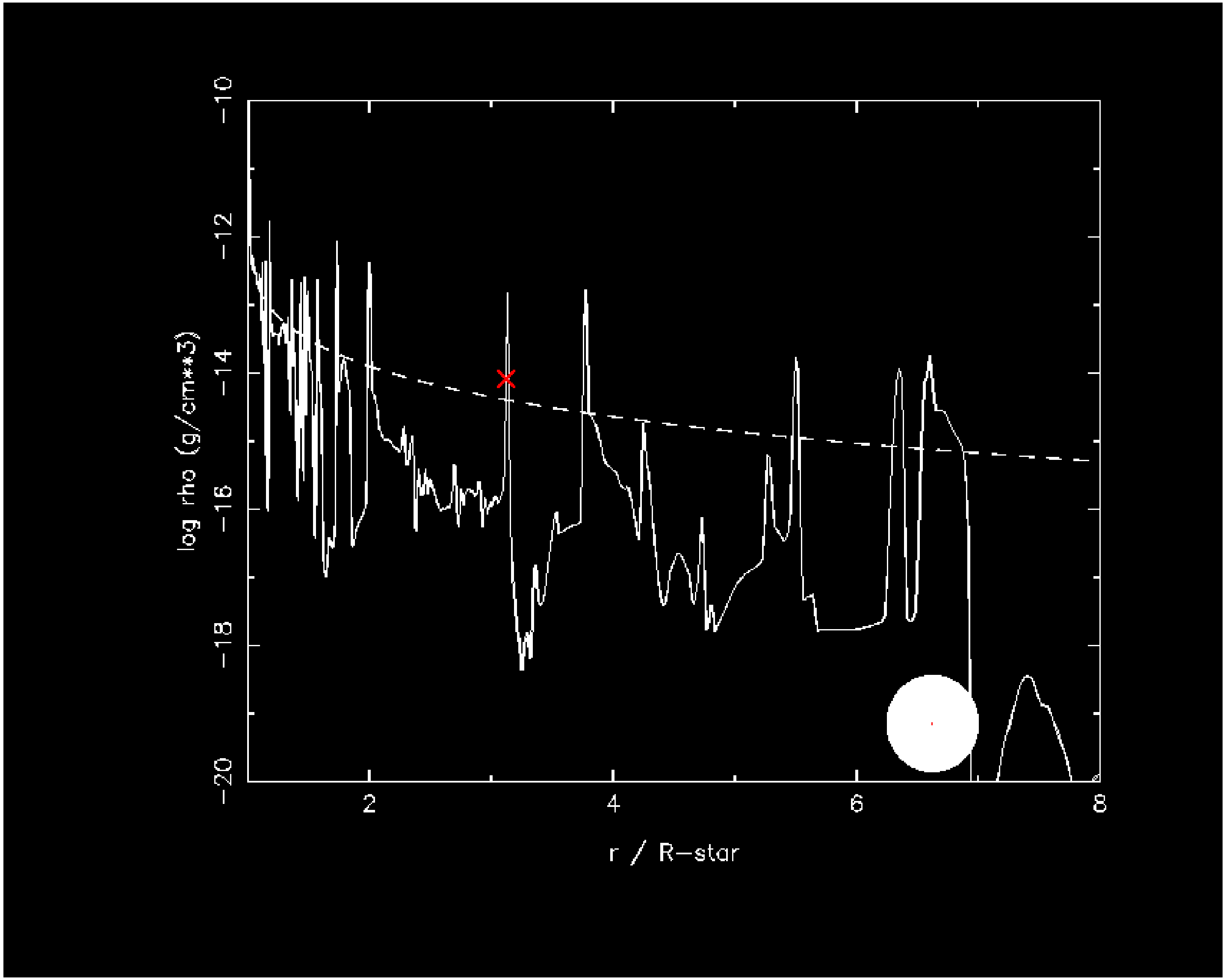
- From optical line profiles of supergiant early type stars there are strong indications that they can be clumpy
- For most spectral types those clumps are expected to fall back to the supergiant. For a narrow range in types, around A9-B1, they may escape
- A compact object may accrete such a clump, giving rise to a 'supergiant fast X-ray transient' which is a subclass of HMXBs containing ~10 known objects
- This scenario is still speculative. Recently an alternative scenario was proposed: subtle propellor effects

Example SFXT: IGR J17544-2619





- *Further ~10 cases detected since late 1990s*
- *Optical counterparts are late O or early B supergiants*

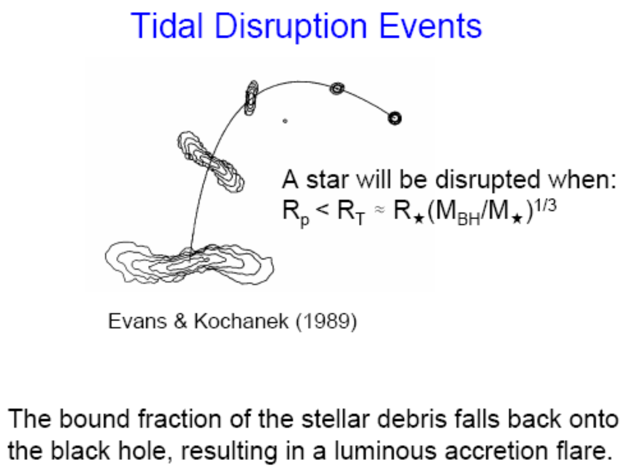


- *Movie by Feldmeier of 1-dimensinal calculations on clumps in supergiant winds (see website)*

Cartoon of tidal disruption

Tidal disruption event

- Consider a supermassive black hole (10^6-10^9 $M_\odot$) and a passing typical star
- When that star comes within a few pc, tidal forces become important
- If the Roche-lobe of the star becomes smaller than the star (i.e. when tidal forces become similar to the surface gravity force) during the star's approach to the BH, tidal forces disrupt the star
- If $M_{BH} > 10^8$ $M_\odot$, star will enter event horizon before it can be disrupted → no accretion energy visible
- Otherwise, a debris accretion disk will form, which will shine in far UV



Tidal Disruption Events

A star will be disrupted when:

$R_p < R_T \approx R_\star (M_{BH}/M_\star)^{1/3}$

Evans & Kochanek (1989)

The bound fraction of the stellar debris falls back onto the black hole, resulting in a luminous accretion flare.

Properties of a Tidal Disruption Flare

- For 10^6-$5\mathrm{x}10^7\ M_\odot$ black holes, the stellar debris accretes in a thick disk (Ulmer 1999)

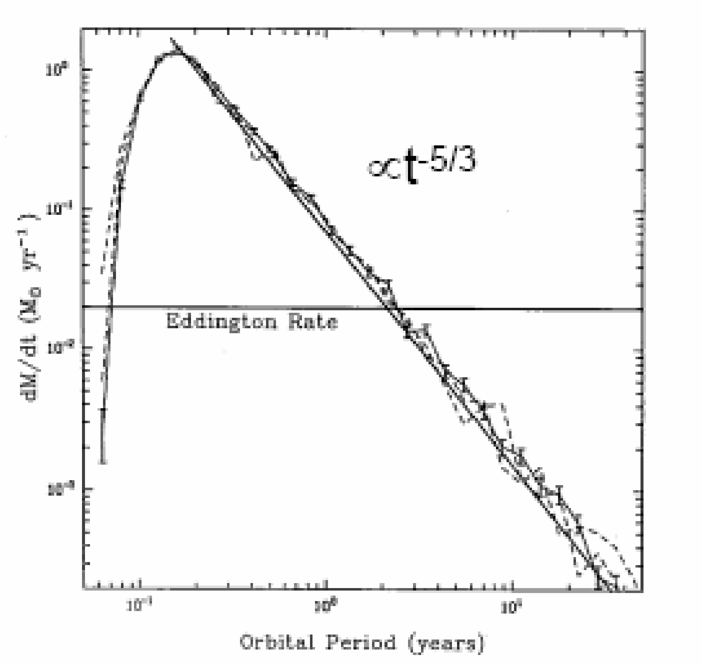
- $L_{\rm flare} \approx L_{\rm Edd} = 1.3\times10^{45}\ M_7$ erg s^{-1}

- $T_{\rm eff} \approx (L_{\rm Edd}/4\pi R_T^2\sigma)^{1/4} = 3\times10^5\ M_7^{1/12}$ K

- $L(t) = \varepsilon(dM/dt)c^2 \propto t^{-5/3}$

- $dN/dt \propto \sigma^{7/2} M_{BH}^{-1} \propto M_{BH}^{-1/4} \approx 10^{-4}$ yr^{-1} (Wang & Merritt 2004)

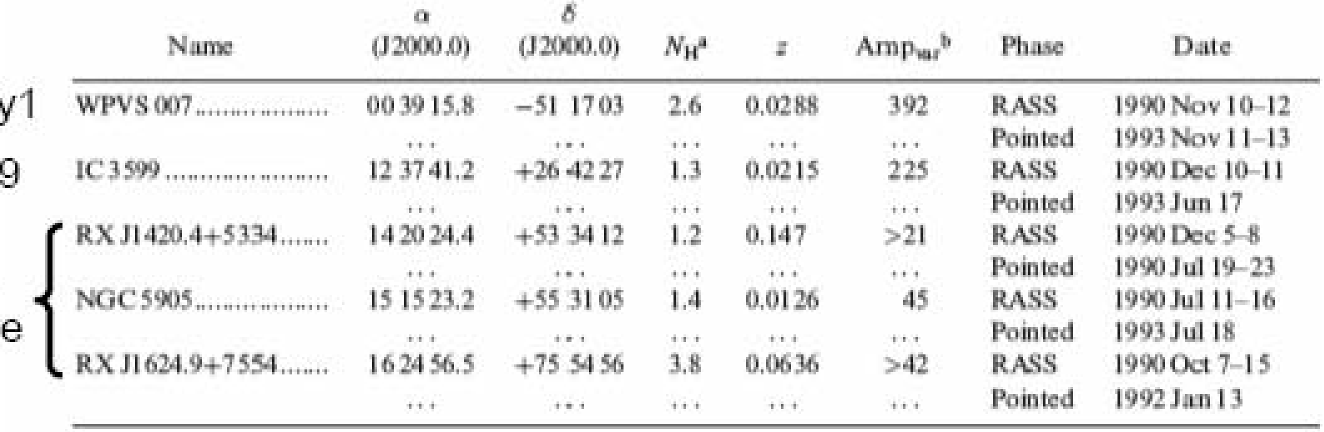
Tidal disruption theory predicts rare but luminous flares that peak in the UV/X-ray domain, with decay timescales ~ months.



Evans & Kochanek (1989)

Flares Detected by ROSAT

The ROSAT All-Sky Survey (RASS) conducted in 1990-1991 was an excellent experiment to detect TDEs since it sampled 3x10^5 galaxies in the soft X-ray band (0.1 - 2.4 keV).



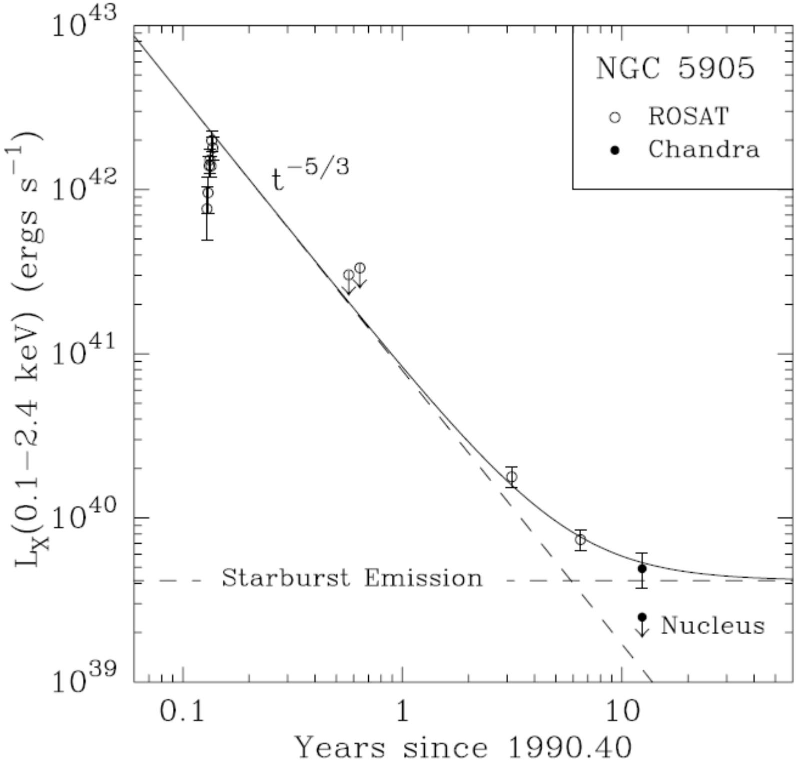
	Name	α (J2000.0)	δ (J2000.0)	$N_H{}^a$	z	$\mathrm{Amp}_{\mathrm{sxr}}{}^b$	Phase	Date
NLSy1	WPVS 007	00 39 15.8	−51 17 03	2.6	0.0288	392	RASS	1990 Nov 10–12
		…	…	…	…	…	Pointed	1993 Nov 11–13
Sy1.9	IC 3599	12 37 41.2	+26 42 27	1.3	0.0215	225	RASS	1990 Dec 10–11
		…	…	…	…	…	Pointed	1993 Jun 17
non-active	RX J1420.4+5334	14 20 24.4	+53 34 12	1.2	0.147	>21	RASS	1990 Dec 5–8
		…	…	…	…	…	Pointed	1990 Jul 19–23
	NGC 5905	15 15 23.2	+55 31 05	1.4	0.0126	45	RASS	1990 Jul 11–16
		…	…	…	…	…	Pointed	1993 Jul 18
	RX J1624.9+7554	16 24 56.5	+75 54 56	3.8	0.0636	>42	RASS	1990 Oct 7–15
		…	…	…	…	…	Pointed	1992 Jan 13

- T_{bb} = 6 - 12 x 10^5 K
- $L_x = 10^{42} - 10^{44}$ ergs s^{-1}
- t_{flare} ~ months
- Event rate ≈ 1 x 10^{-5} yr^{-1} (Donley et al. 2002)

} **Properties of a tidal disruption event!**

Best candidate for TDE..

- .. Until recently when it was identified as a ultraluminous X-ray binary
- → observational tests are inconclusive, unless the event can be unambiguously located at the core of a galaxy, at the supermassive black hole
- More candidates (200 ?) will be detected with the launch of Spectrum-X-Gamma in 2011/12 (Russian / German / Dutch / USA mission)



NS-NS/BH merger

- Theoretical predictions, the occurrence of short gamma-ray bursts (see later lectures) and the measurements of the double pulsar binary show the possible existence of mergers between a NS and another NS or BH
- See movie of model calculations at website (picture at right)
- These would be strong sources of gravitational waves
- Released energy similar to that of a SN, within 1 second → very bright but short events
- Within our galaxy the predicted rate is 10^{-6}-10^{-4} yr^{-1}.

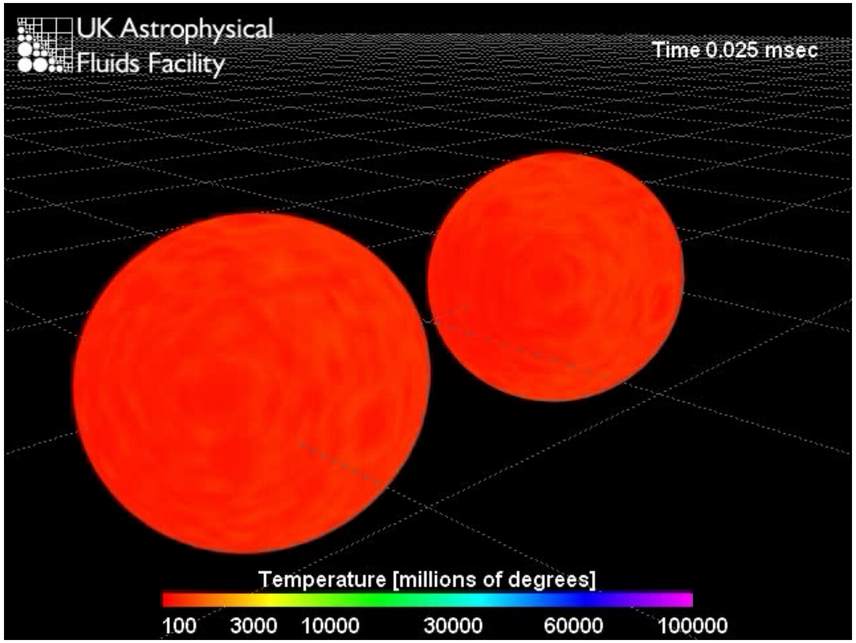
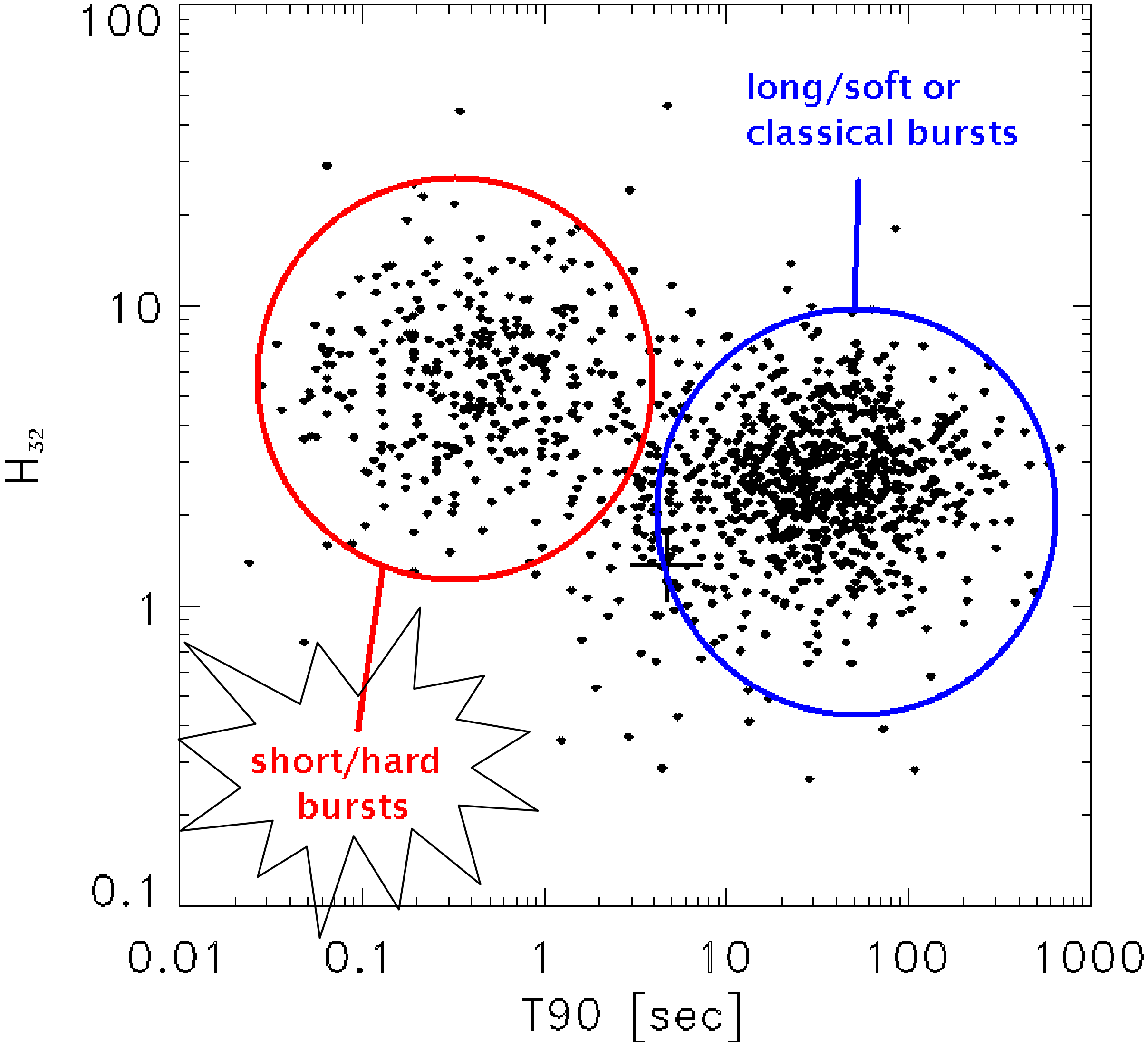


Diagram of short and long GRBs (see later lecture)



long/soft or classical bursts

short/hard bursts

Summary

- The brightest transient events are:
  - Dwarf novae: disk instabilities in CVs
  - X-ray novae: disk instabilities in LMXBs
  - Hard X-ray transients: structured winds / eccentric orbits in HMXBs
  - Short gamma-ray bursts? (in other galaxies)
- Tidal disruption events around supermassive black holes in other galaxies are fainter because they last longer
- Except for the galactic events, our understanding of transient events is just beginning because they are harder to observe