High Mass X-ray Binaries hosting a neutron star: a review

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High Mass X-ray Binary

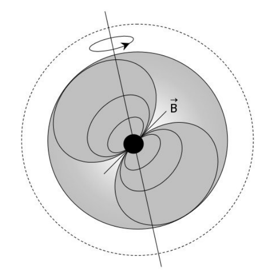
The majority of the HMXB population hosts a neutron star instead of a BH

O or B-type Star

$M_{opt} > 10M_{\odot}$

Accreting magnetized NS

B ~ 10^{12} G



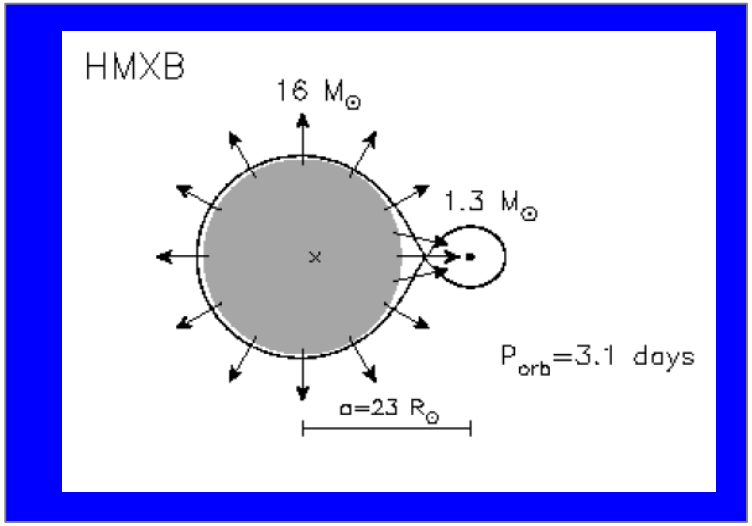
X-ray pulsar

Two types of HMXBs
depending on the massive companion

- **O or B-type supergiant**
  - They loose mass through a **strong** (spherically symmetric) **wind**

    → stellar wind capture by the NS

    → **SgHMXBs** (persistent or transient → Supergiant Fast X-ray Transients, **SFXTs**)

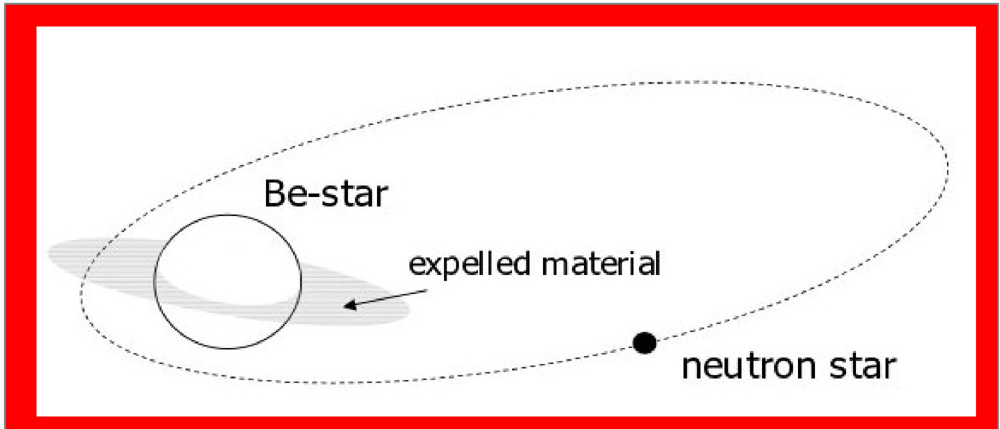


- **Be star** main sequence B stars with Balmer lines in emission
  - Rapidly rotating, they loose mass mainly from the **equatorial** region, through a circumstellar **decretion keplerian disc** (coplanar or misaligned with the orbit). Also a polar wind is present.

    The mechanism for the Be disc formation is unclear (rotation is insufficient)

    → accretion from the Be disc

    → **Be/XRBs** (mostly X-ray transients)



Corbet diagram before INTEGRAL (before October 2002)

sgHMXB

- O, B supergiants
- Porb: 1-15d
- Quasi circular orbits
- Persistent (Lx ~ 10^{36} erg/s)

Be-HMXB

- Be stars with circumstellar discs
- Porb: > 10 days to months
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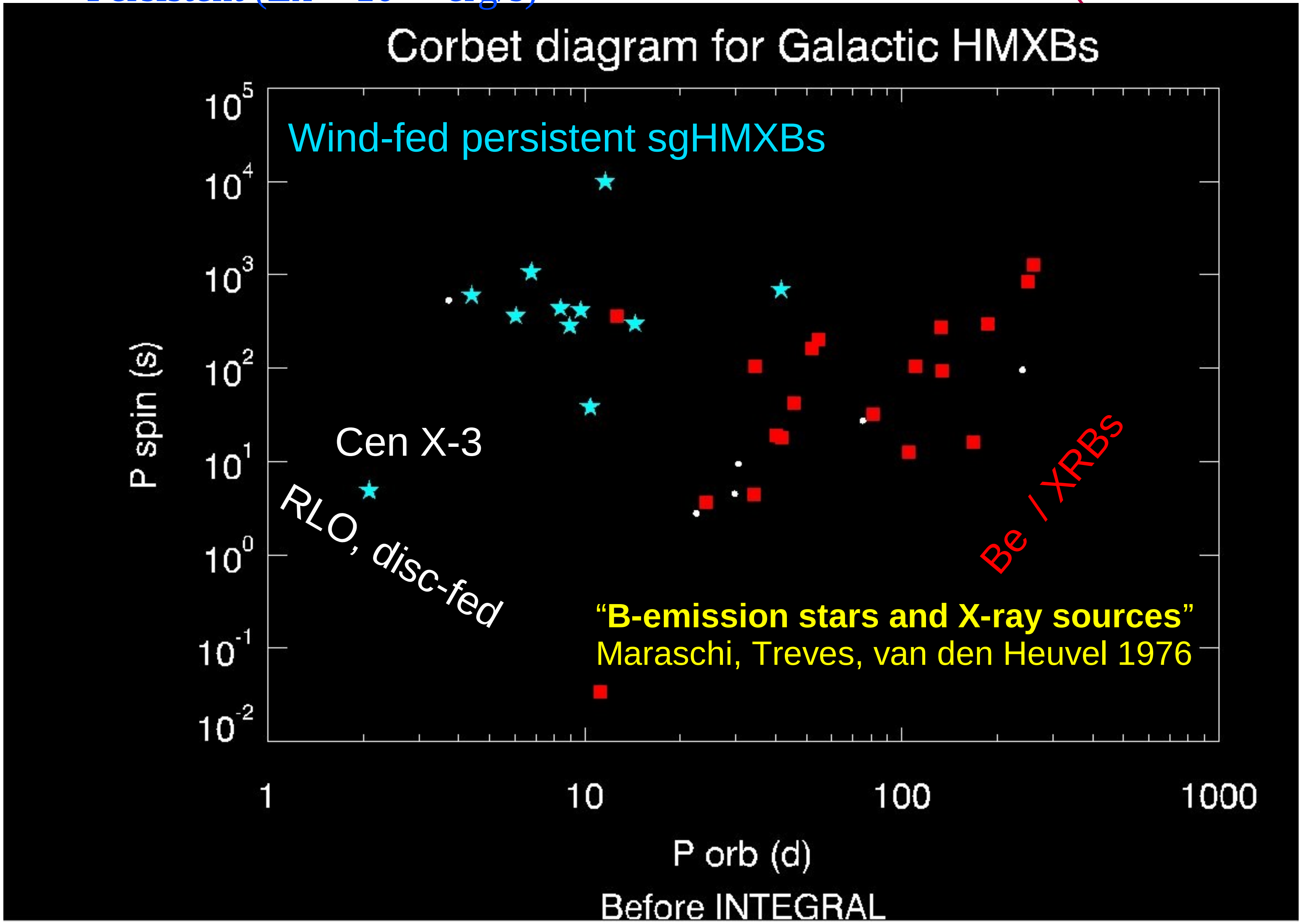
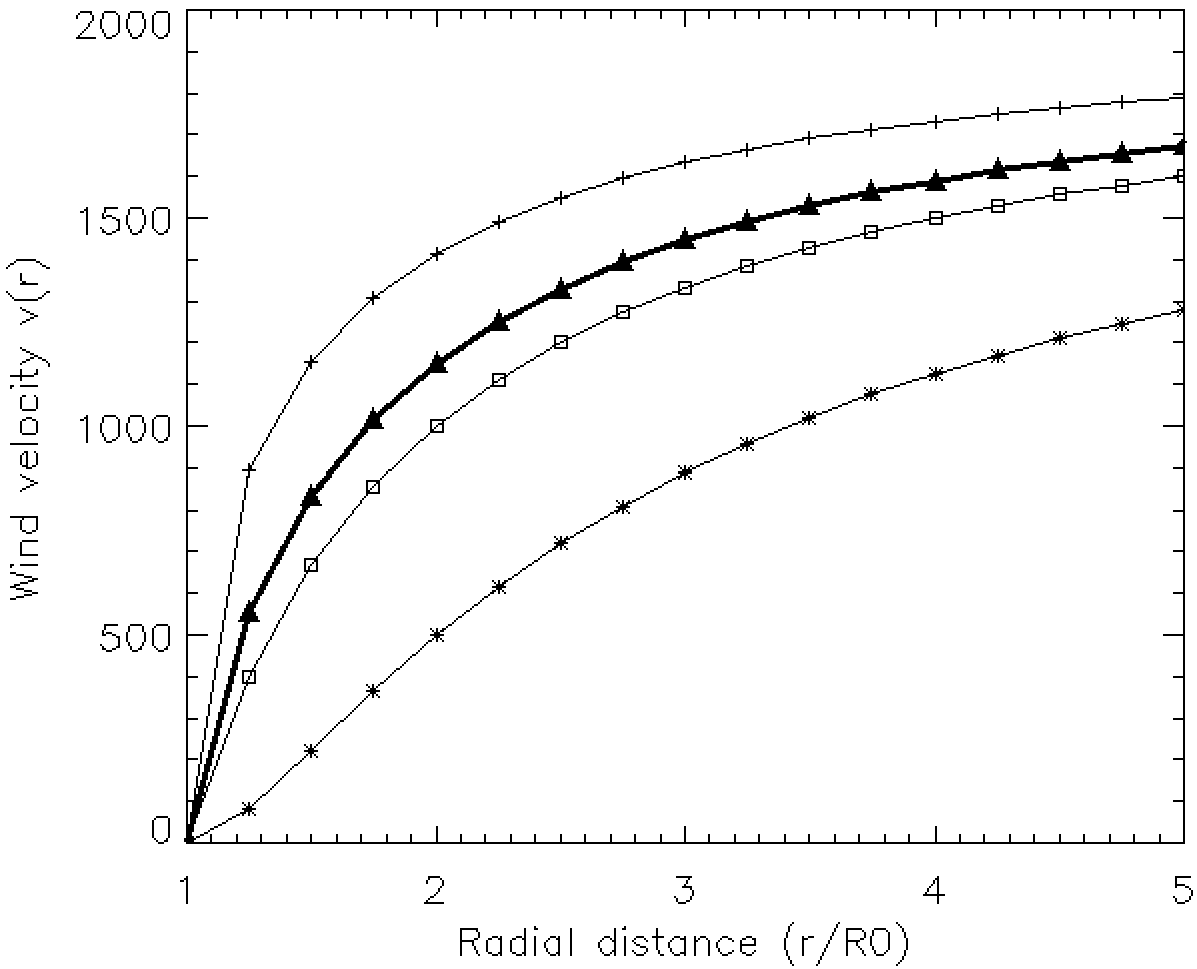


Wind accretion
Sg HMXBs

Wind velocity (beta-law):

$$v_w(r) = v_\infty \left(1 - \frac{R_*}{r}\right)^\beta$$



Wind accretion Sg HMXBs

0.8 – 1.2

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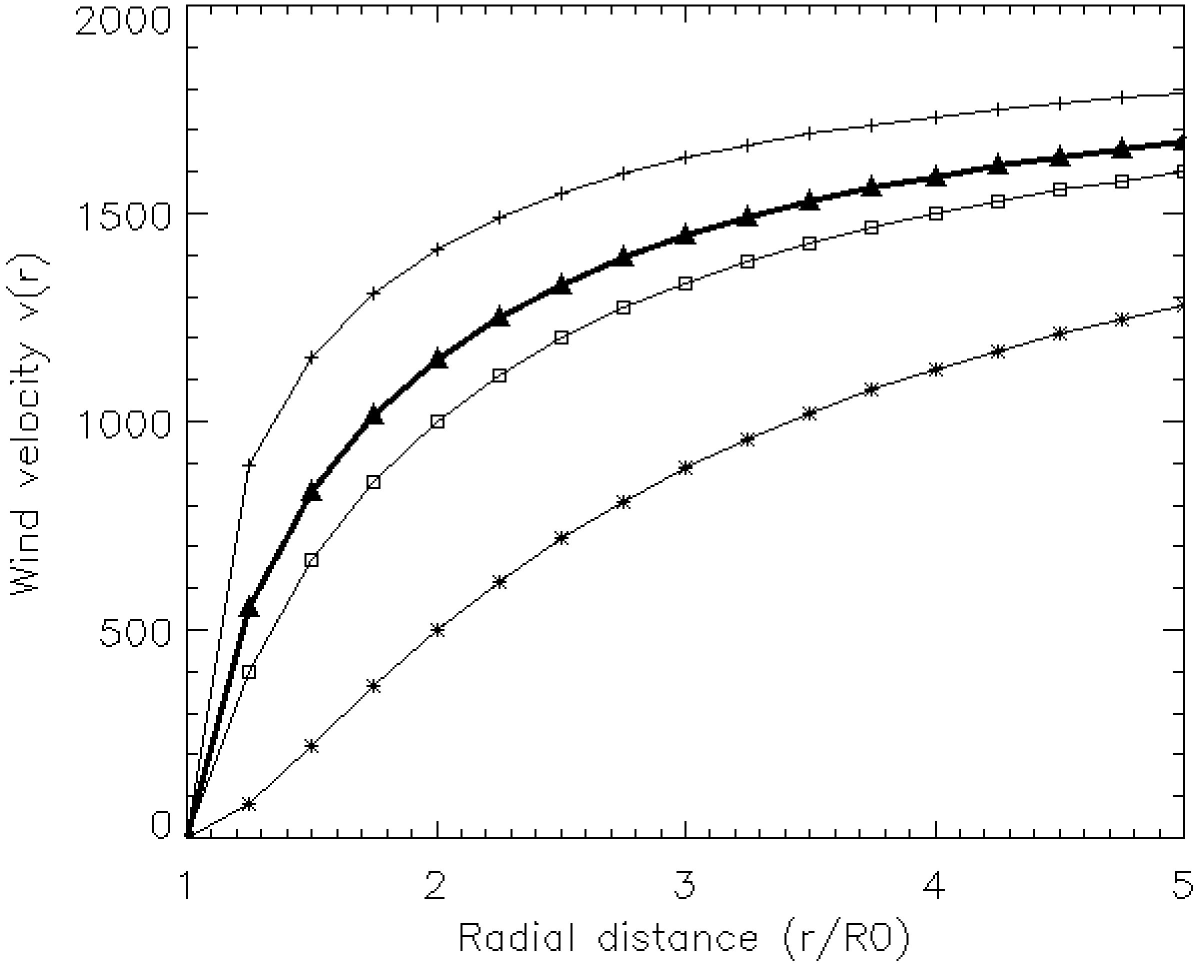


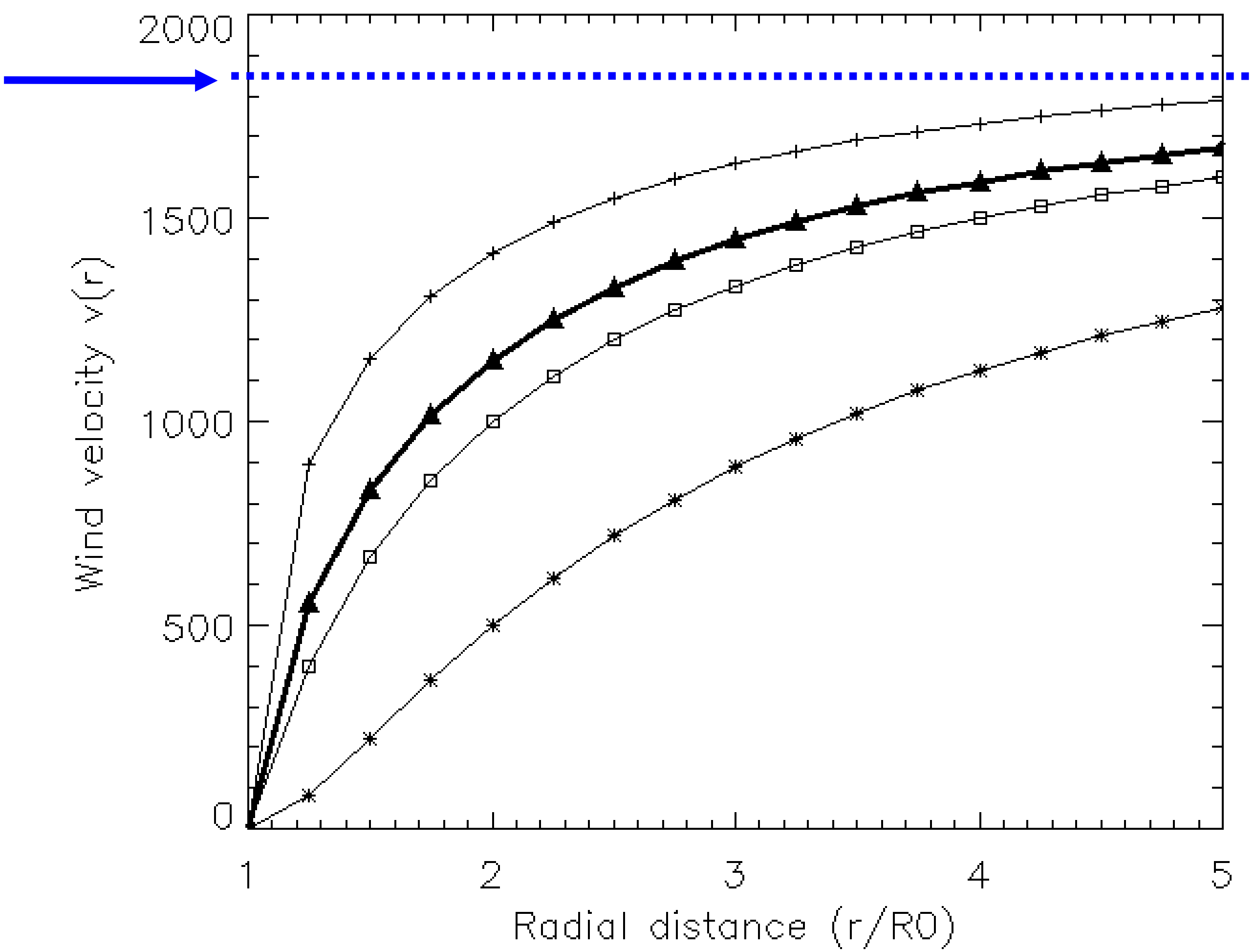
Wind accretion Sg HMXBs

Wind velocity (beta-law):

$$v_w(r) = v_\infty \left(1 - \frac{R_*}{r}\right)^\beta$$

0.8 – 1.2

Terminal velocity ~ 1000 – 2000 km/s



Wind accretion
Sg HMXBs

Mass loss rate from the OB star $\dot{M}_w \sim 10^{-6}\ M_\odot/yr$

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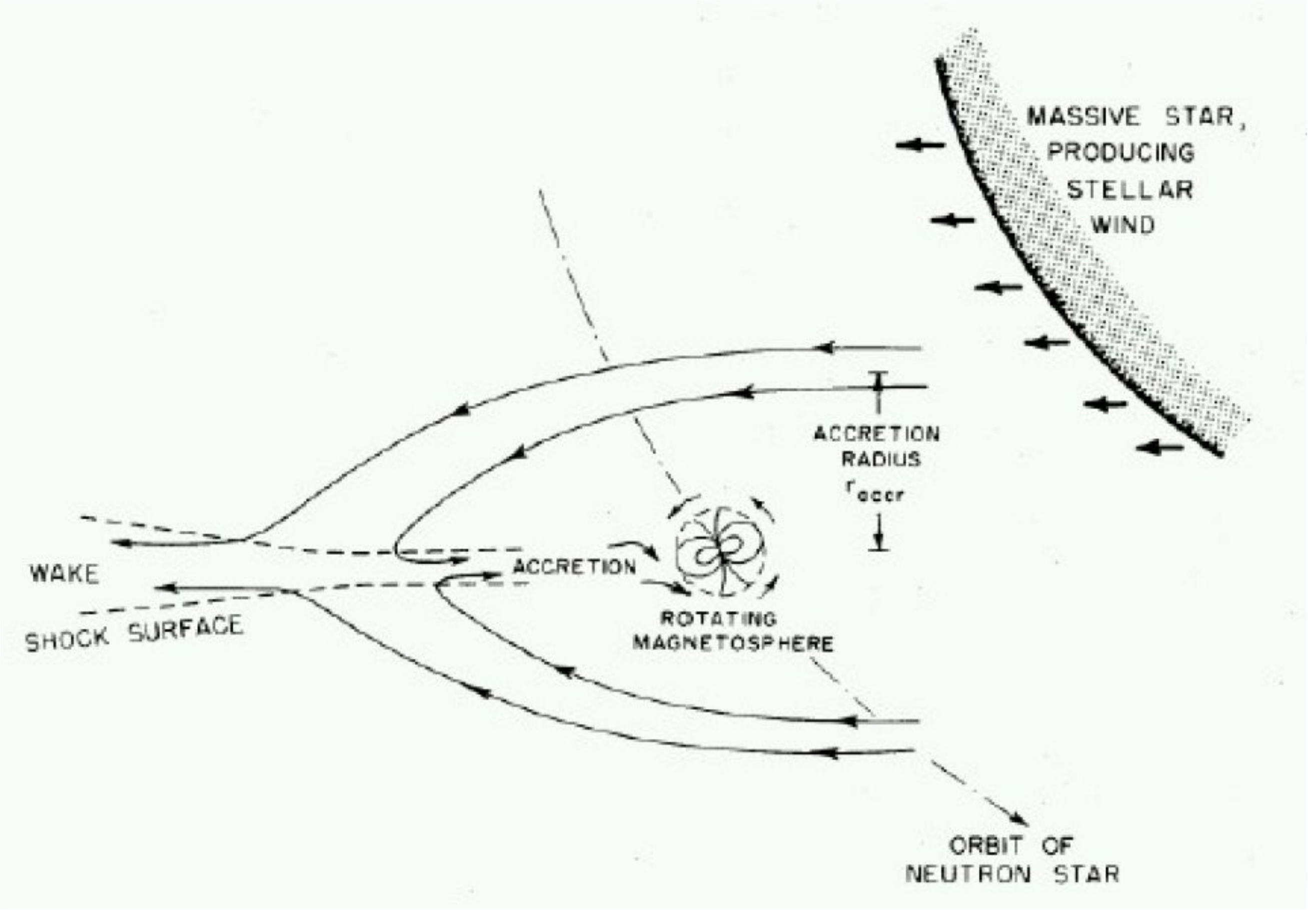

Bondi radius Racc:

$$R_{acc} = \frac{2GM_{NS}}{v_{rel}^2(a)}$$

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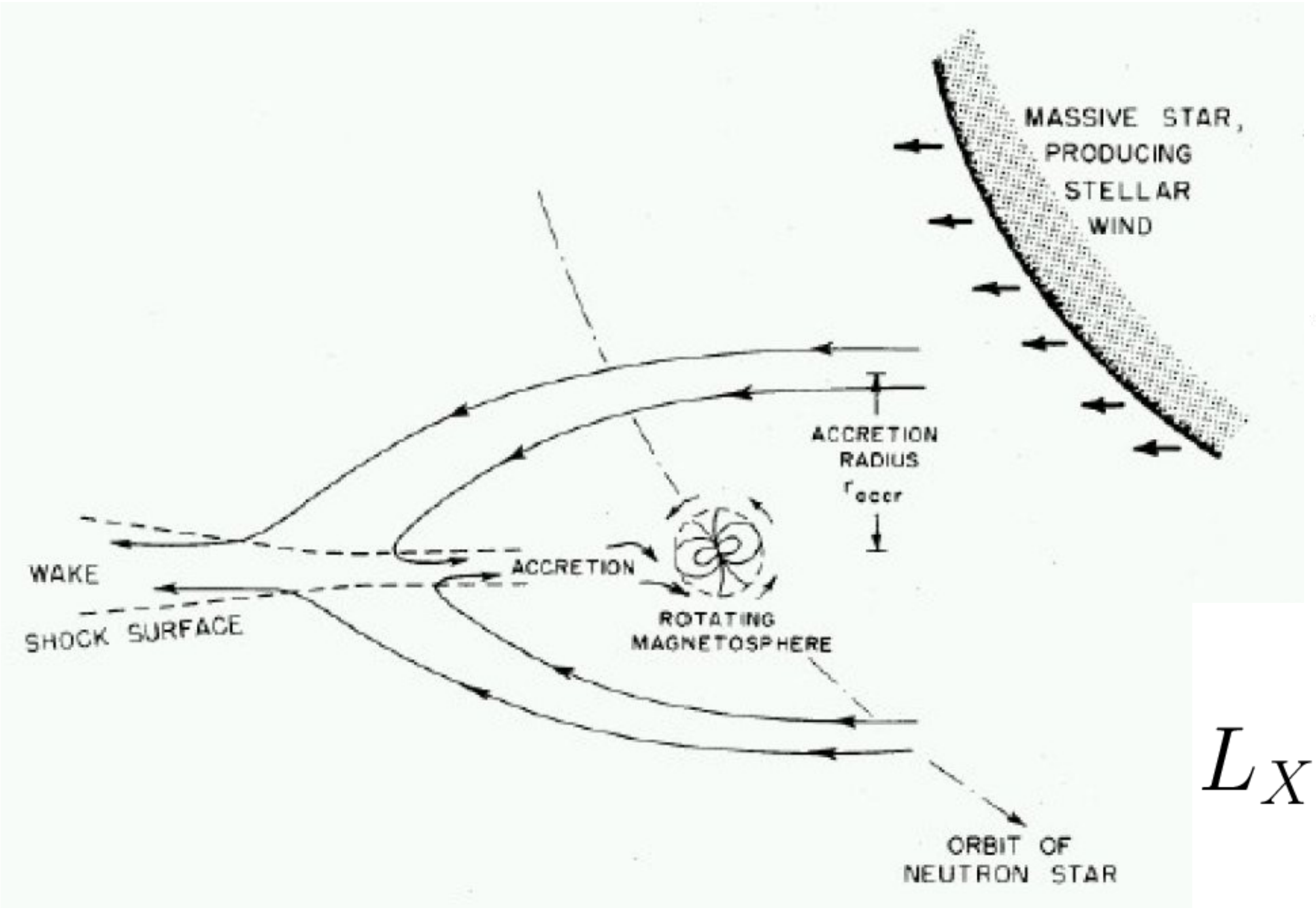


Bondi radius Racc:

$$R_{acc} = \frac{2GM_{NS}}{v_{rel}^2(a)}$$

(a = orbital separation)

Accretion luminosity:

$$L_X \propto \frac{\rho_w(a)}{v_{rel}^3(a)} \propto \frac{\dot{M}_w}{v_w^4(a)}$$

Lx ~ $10^{35} - 10^{36}$ erg/s

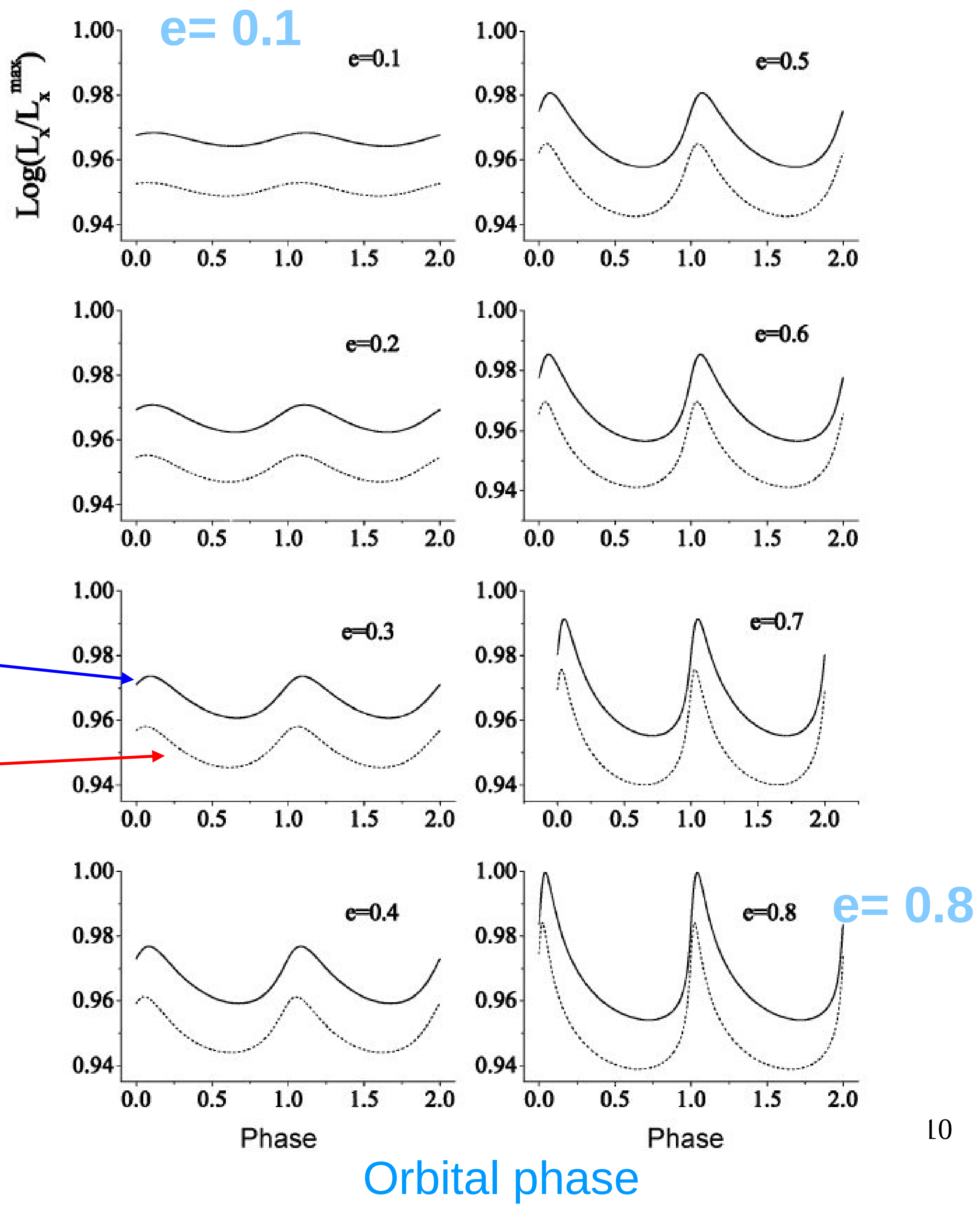
Effect of the binary **eccentricity** on the calculated X-ray light curves

Calculated assuming

spherically symmetric supergiant wind (with beta = 0.5), and
two orbital periods, 20 and 70 days

Porb = 20 days

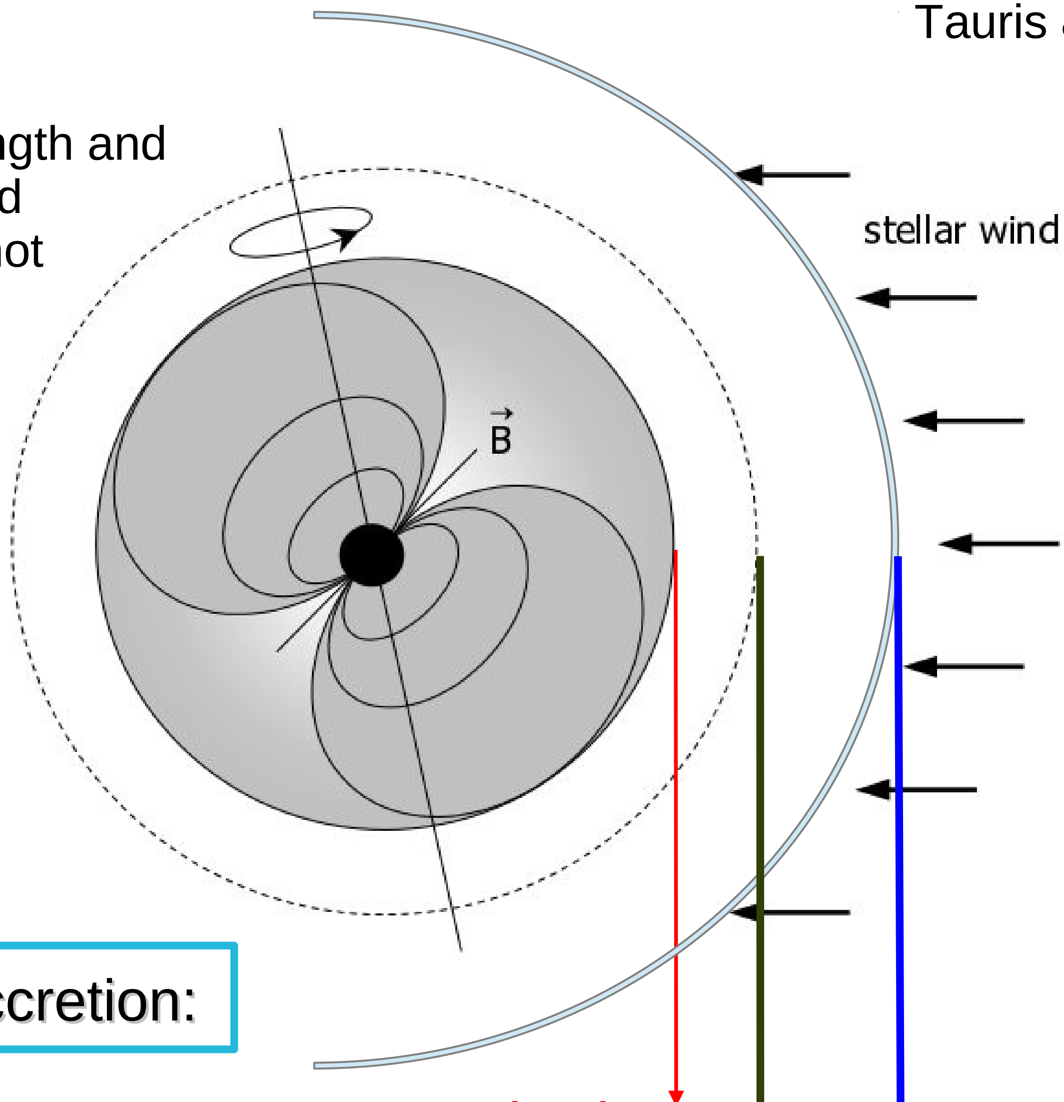
Porb = 70 days



Raguzova & Lipunov 1998

Tauris & van den Heuvel 2006

The rotation period,
the magnetic field strength and
the pressure of the wind
determine whether or not
accretion onto
the NS is possible



In case of direct accretion:

magnetospheric radius (R_M)

$$R_M \simeq 2 \times 10^{10} a_{10\,\mathrm{d}}^{4/7} \dot{M}_{-6}^{-2/7} v_8^{8/7} \mu_{33}^{4/7} \text{ cm.}$$

corotation radius (R_{co})

$$R_{\mathrm{co}} = 1.7 \times 10^{10} P_{s\,3}^{2/3} \text{ cm}$$

accretion (Bondi) radius (R_{acc})

If matter outside the magnetosphere can cool down efficiently,
all matter captured within Racc will accrete

$$R_a = 2GM_{\mathrm{NS}}/v_w^2 = 3.7 \times 10^{10} v_8^{-2} \text{ cm}$$

Transitions between **different regimes**
depending on changes of the relative positions of the three radii

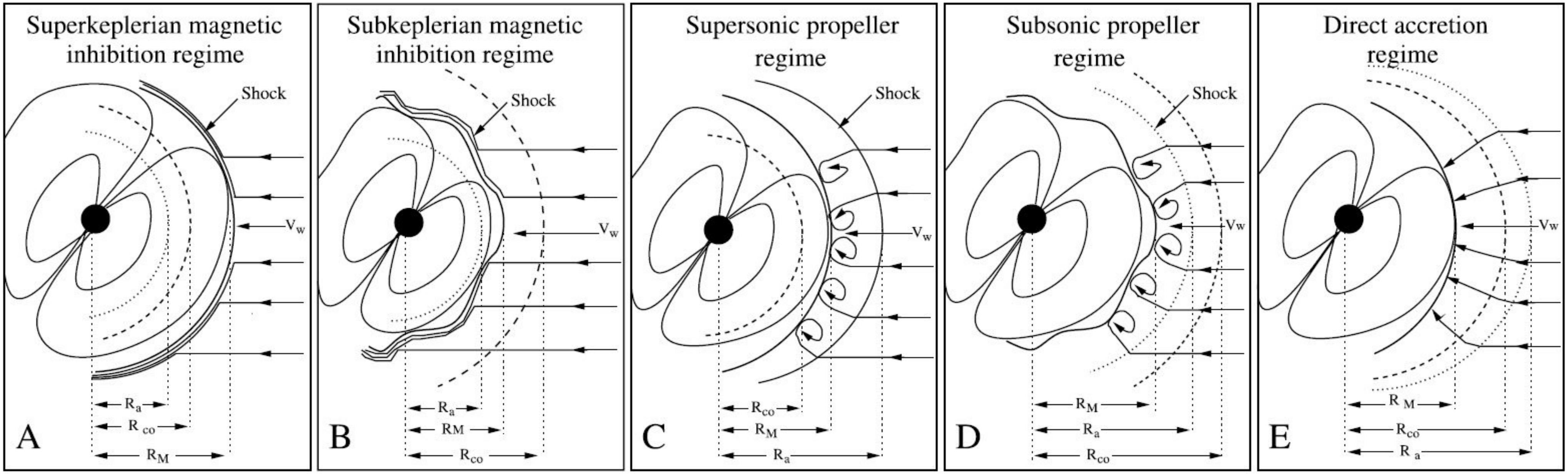
(given a **NS** with its B-field & Pspin,
transitions depend on wind density & velocity at the NS orbit)

Direct accretion

Racc < Rco < RM

Rco < RM < Racc

RM < Rco < Racc



Racc < RM < Rco

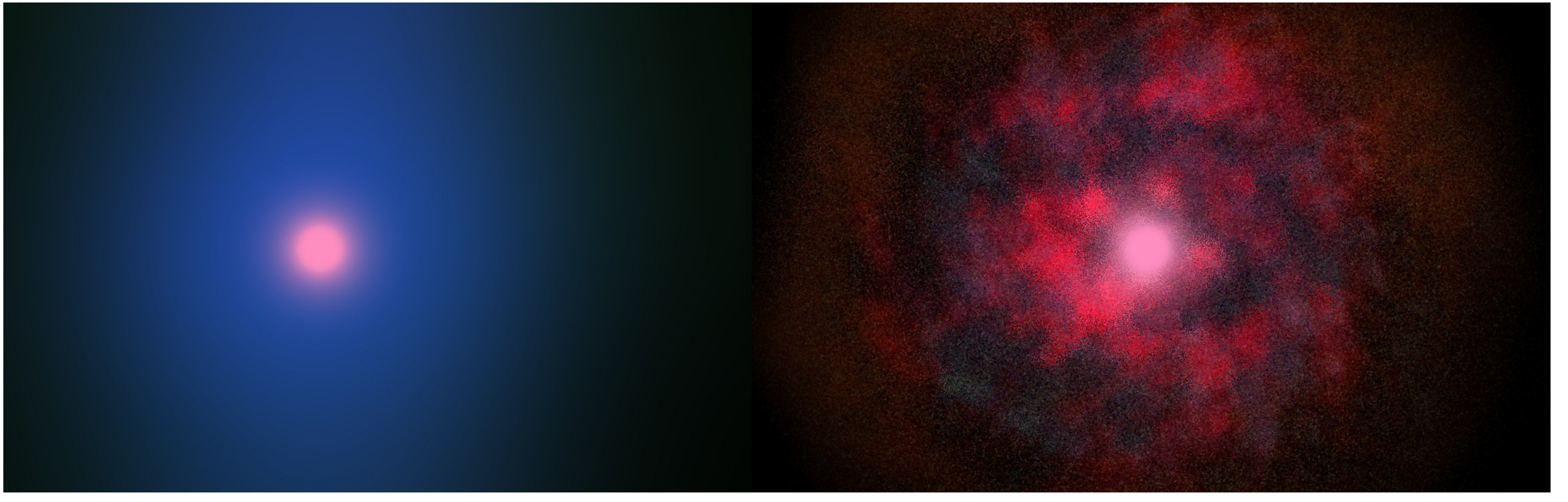
RM < Racc < Rco

Bozzo, Stella & Falanga 2008

Clumpy winds

complicate the picture

Smooth stellar wind — Structured stellar wind

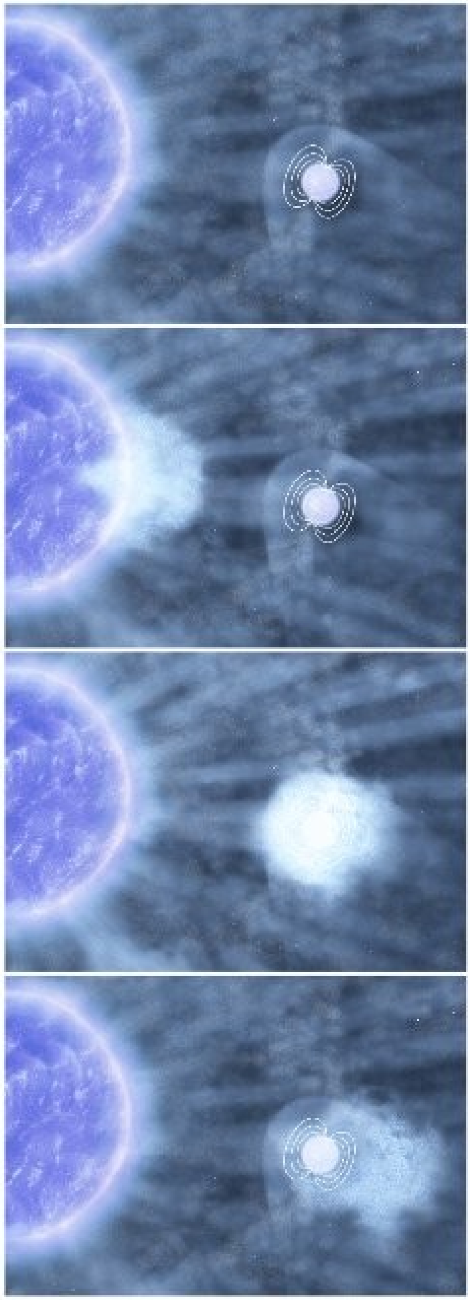


Credits: ESA C. Carreau/Nazé et al.

In principle, HMXBs can probe wind clumpiness (density and velocity wind structure)
- X-ray variability traces the mass inflow rate
- absorbing column density variations due to massive clumps passing in front of the NS

Clumpy winds

complicate the picture



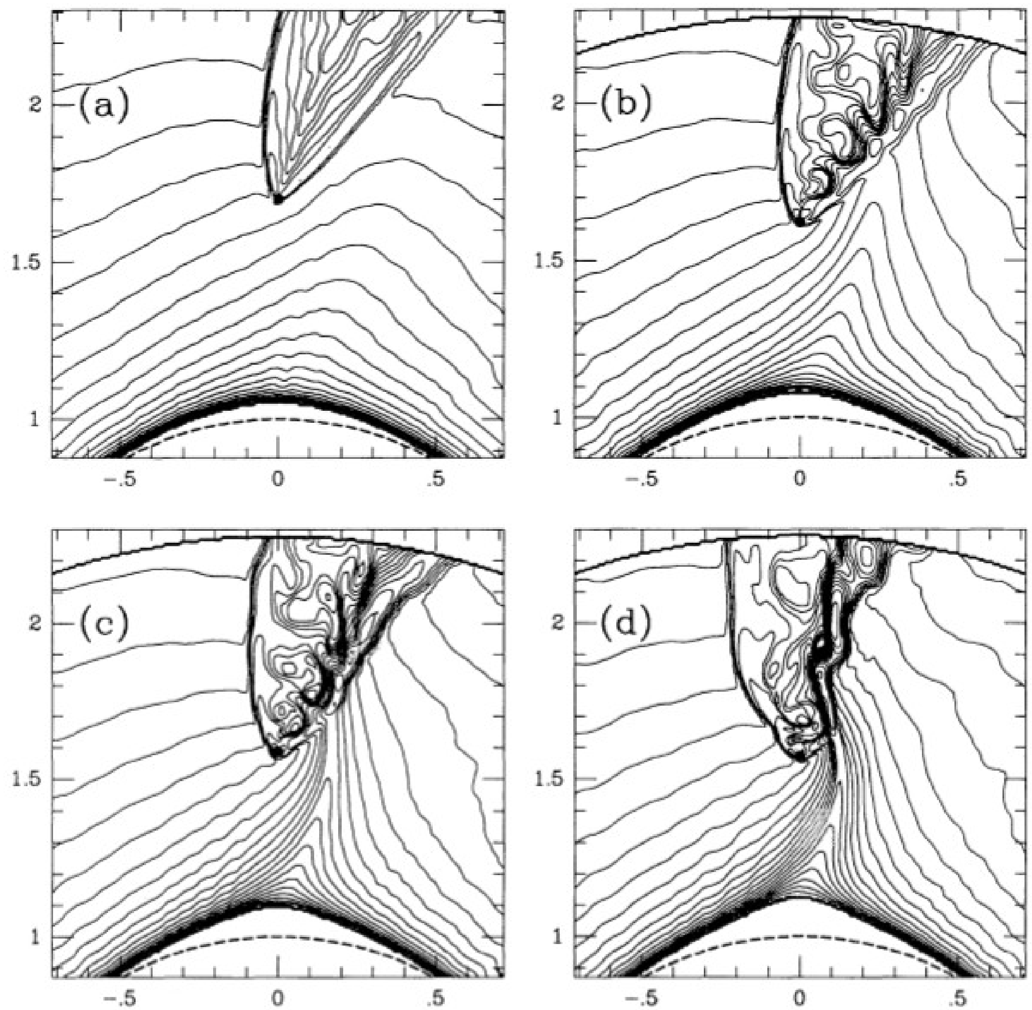
In principle (in absence of any mediating mechanism), **HMXBs** can **probe wind clumpiness** (density and velocity wind structure at the NS separation) by means of:

- X-ray **flux variability** tracing the mass inflow rate

- Absorbing **column density** variations: they can be due to massive clumps passing in front of the NS

Credits: ESA Bozzo et al. 2011

Structures in the stellar wind produced by the interaction with the accretor



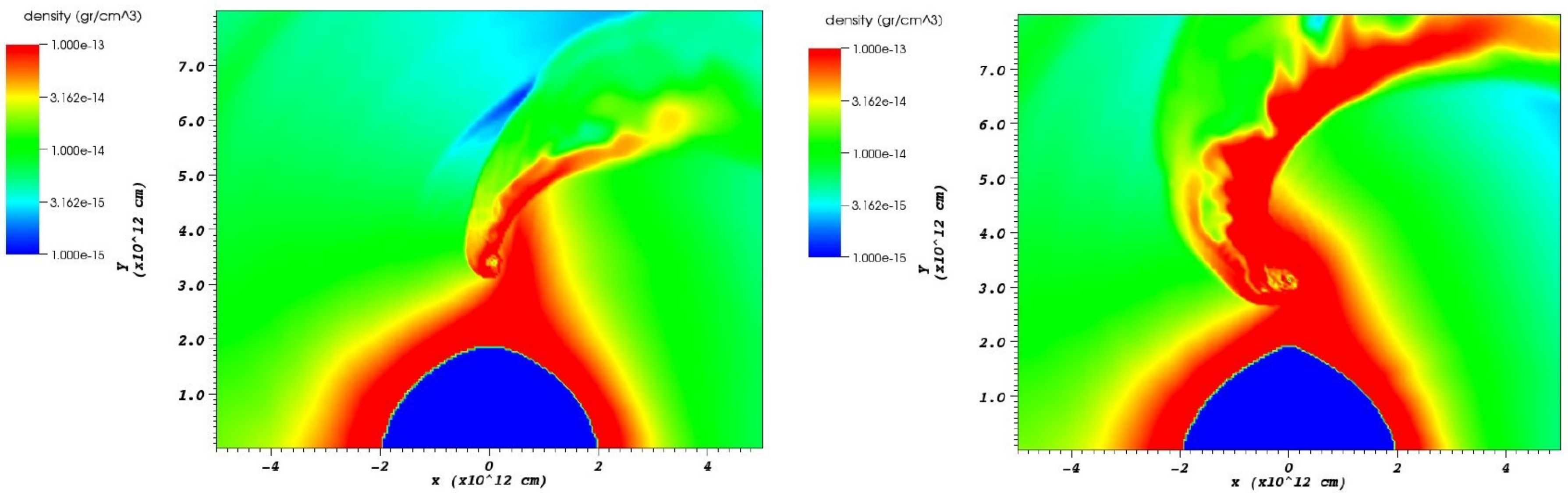
Formation of a **gas stream** as the binary separation is decreased in HMXBs

Stellar wind clumps
are likely disrupted by the accretion wake,
while other bubbles appear to form behind the shock

Blondin, Stevens, Kallman 1991

Sg HMXB simulations

Wind **density distribution** in a Sg HMXB hosting a **neutron star** with different **masses**

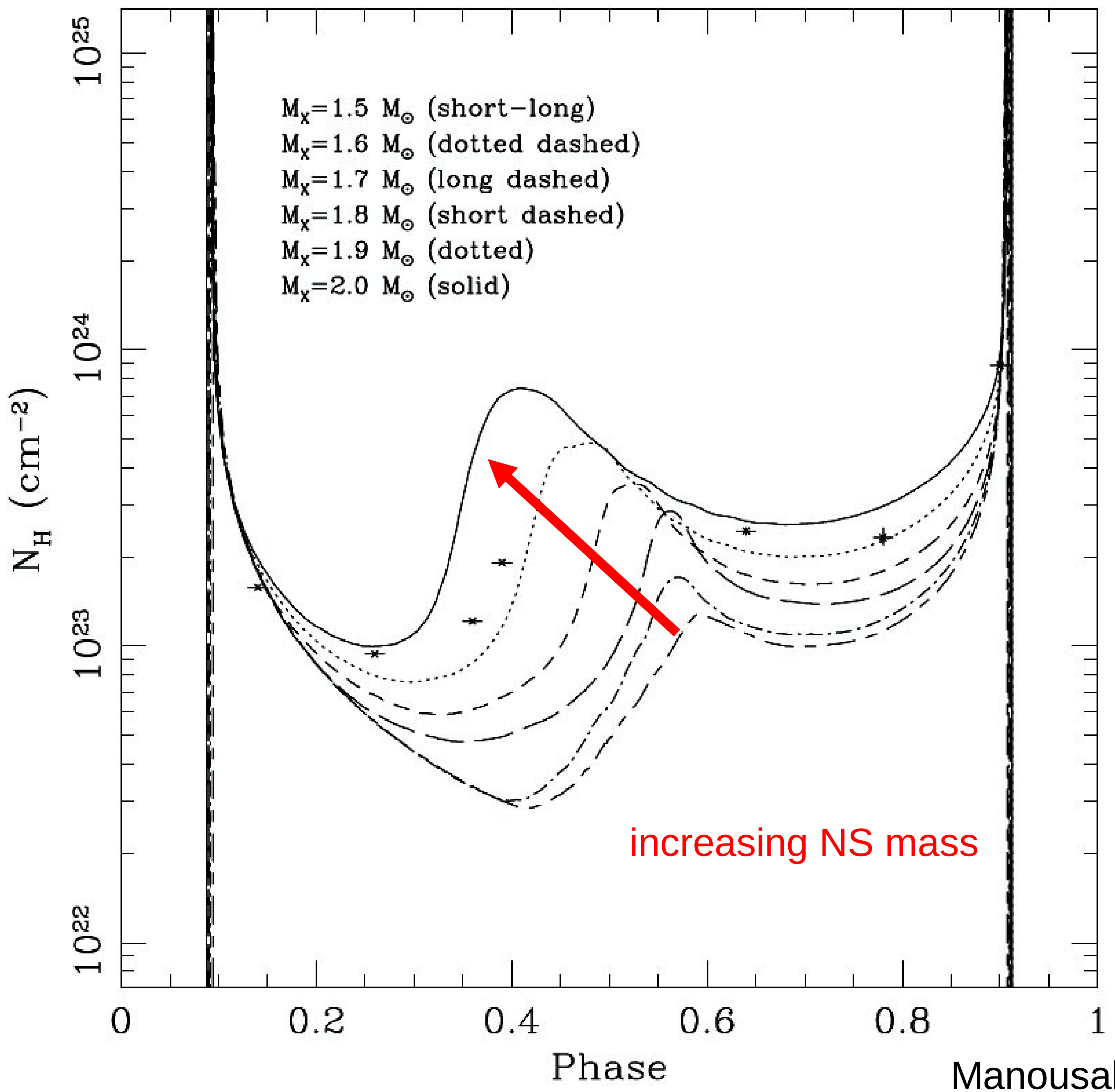


M_{NS} = 1.5 solar masses M_{NS} = 2 solar masses

Figure 1. Density distribution (in gr cm^{-3}; color bar) on the orbital plane after $\sim$ 3 orbits. The wind terminal velocity is $\upsilon_\infty \approx 500$ km s^{-1} and the mass-loss rate is $\dot{M}_w \approx 10^{-6}\, M_\odot$ y r^{-1}. The mass of the neutron star scales from 1.5 (left) to 2.0 $M_\odot$ (right). The color version of this figure is available on-line.

Manousakis et al. 2013

Sg HMXB simulations



Eclipsing system

Manousakis et al. 2013

Corbet diagram before INTEGRAL (October 2002)

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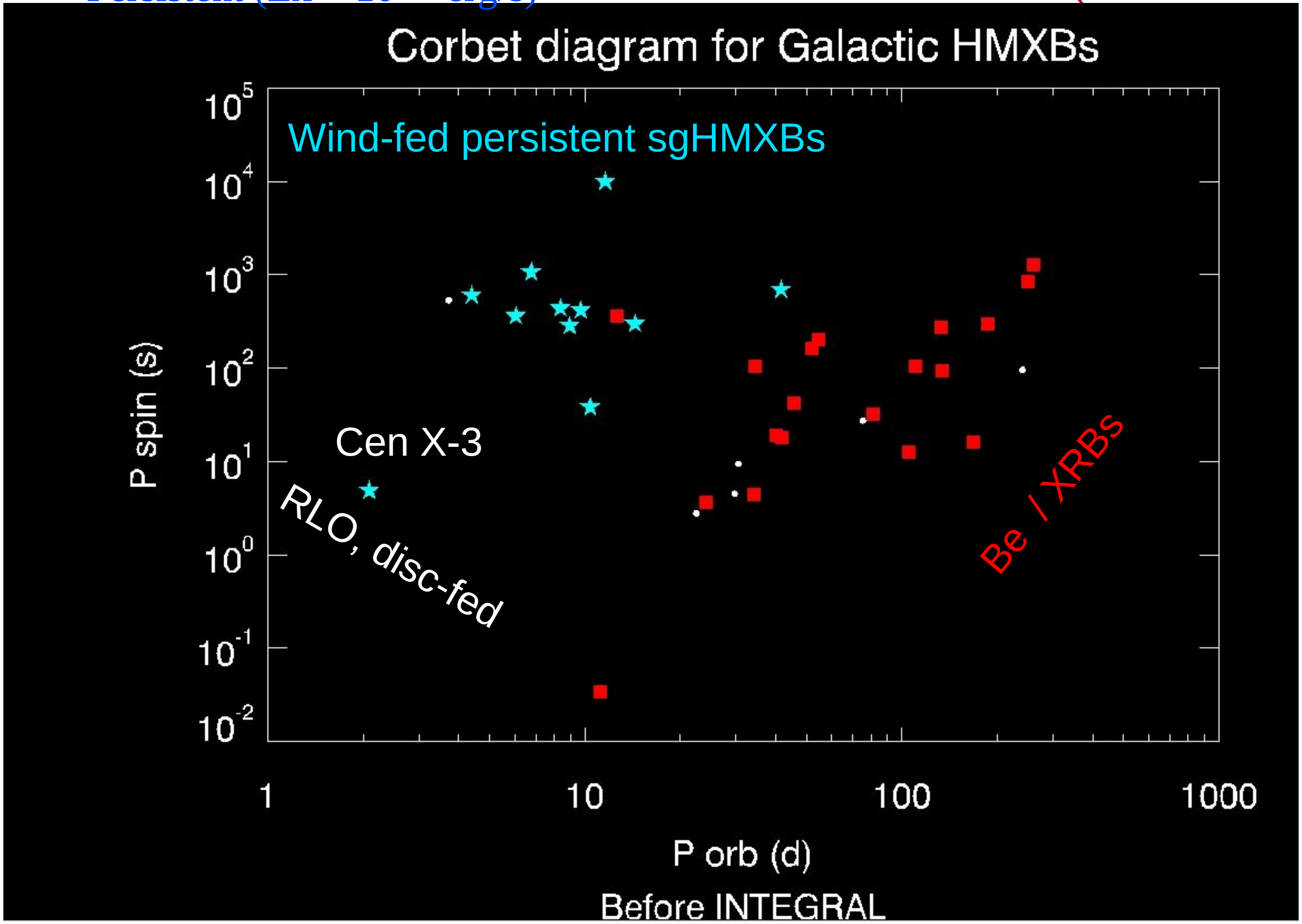
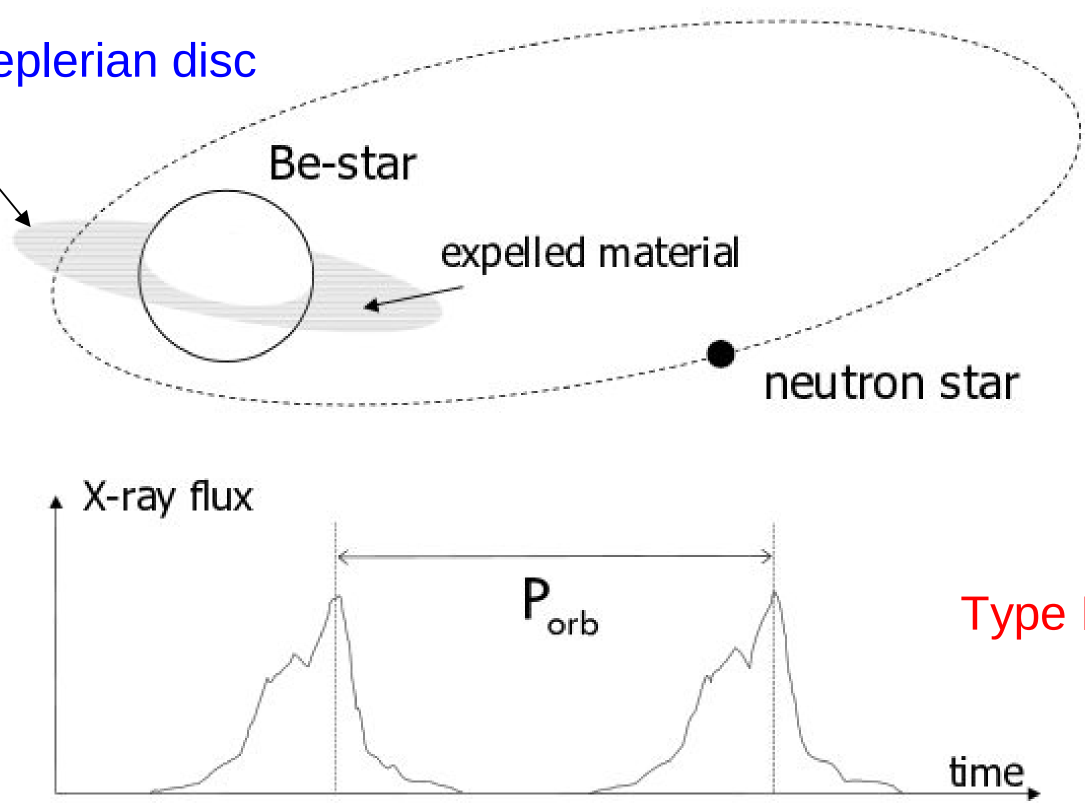


Be/X-ray transients

"**B-emission stars and X-ray sources**"
Maraschi, Treves & van den Heuvel 1976

Be star decretion keplerian disc

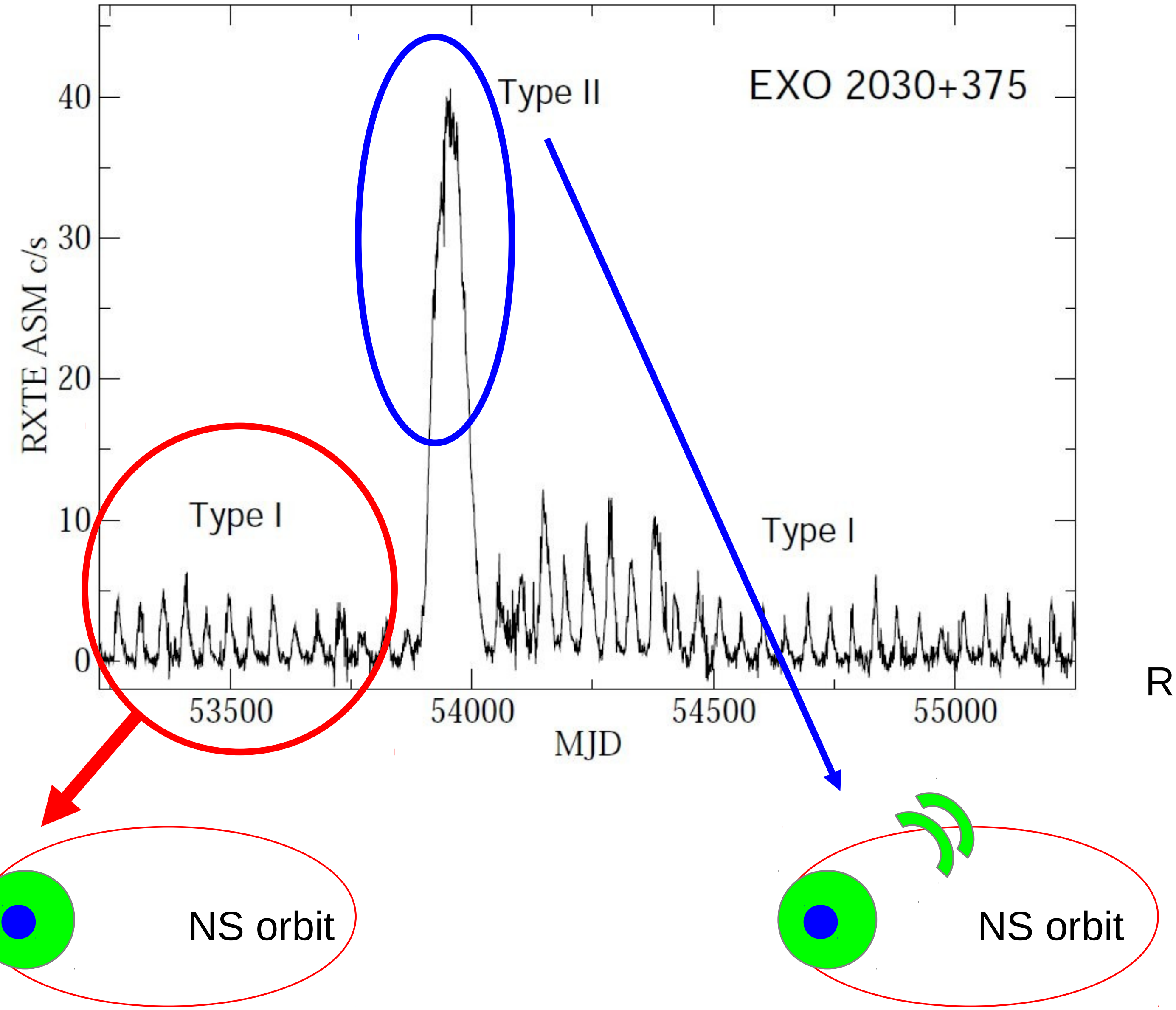


Type I outburst

Most of the accretion takes place during periastron passages

Tauris & van den Heuvel 2006

Be XRBs: two outburst types



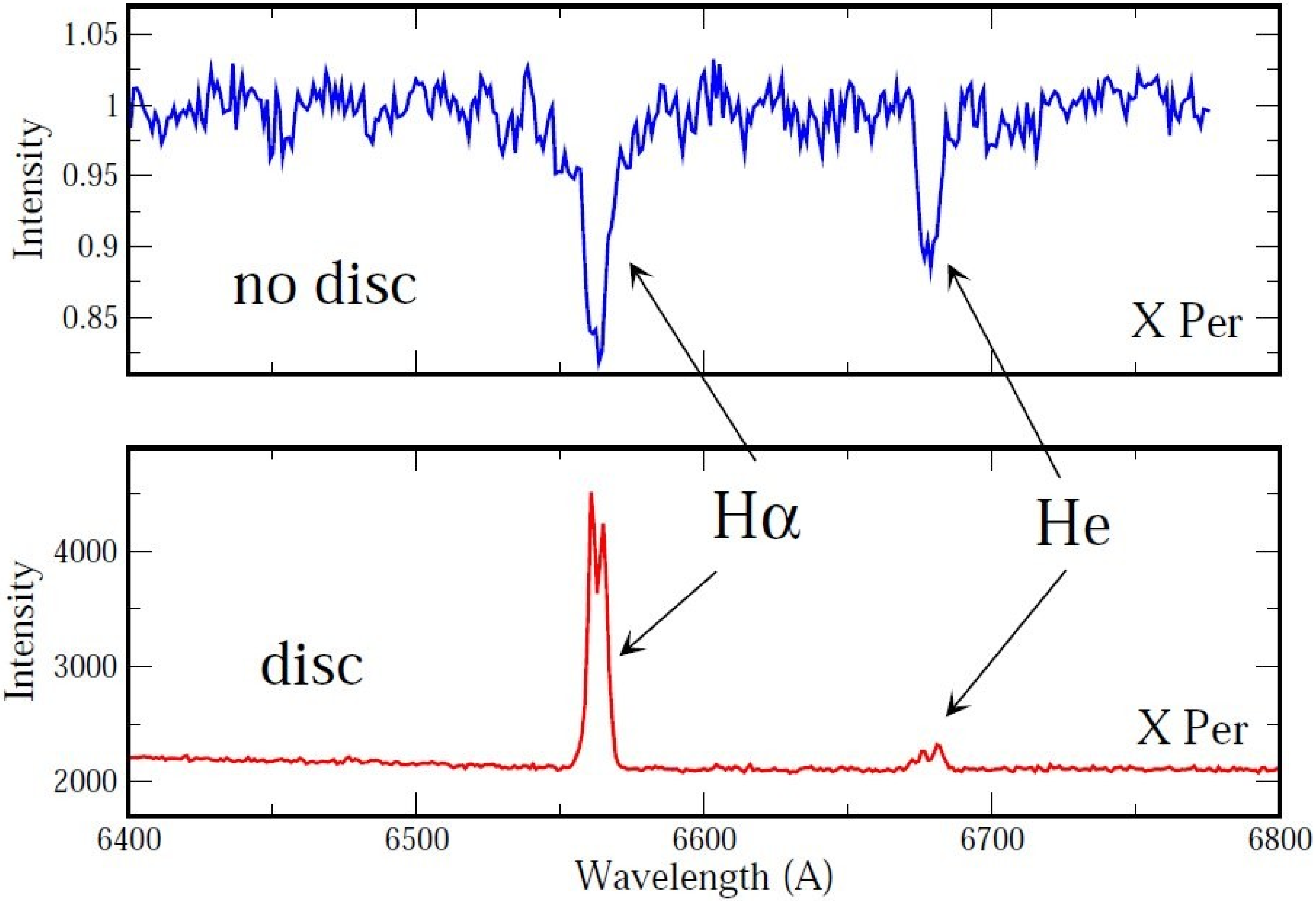
Reig 2011

Type I outbursts:
Periodic on **Porb**

Type II outbursts: No recurrence time
Associated with catastrophic perturbation of the Be disc

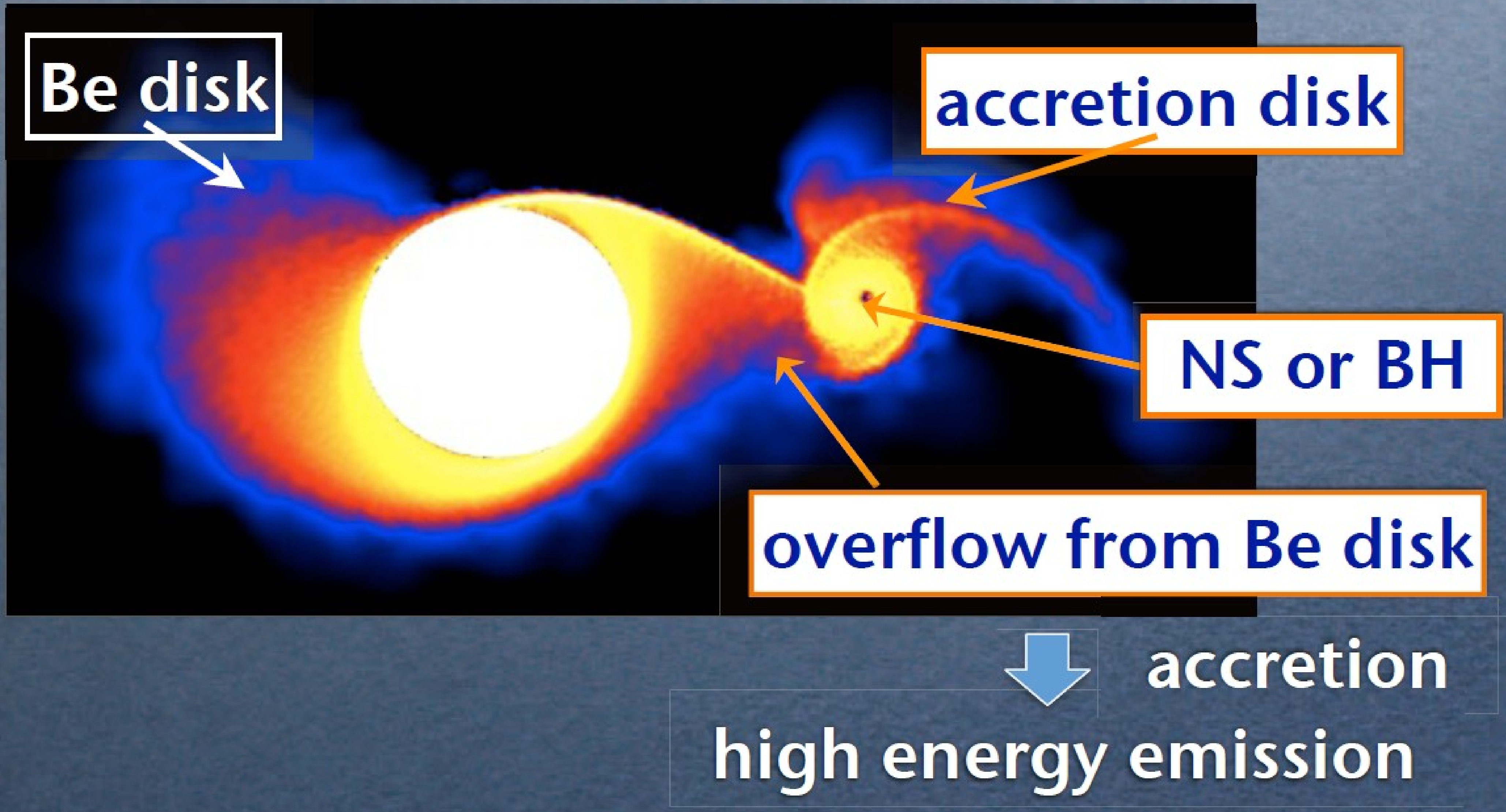
Be star decretion disc

Reig 2011



The viscous decretion disc can undergo formation and dissipation episodes (Negueruela et al. 2001)

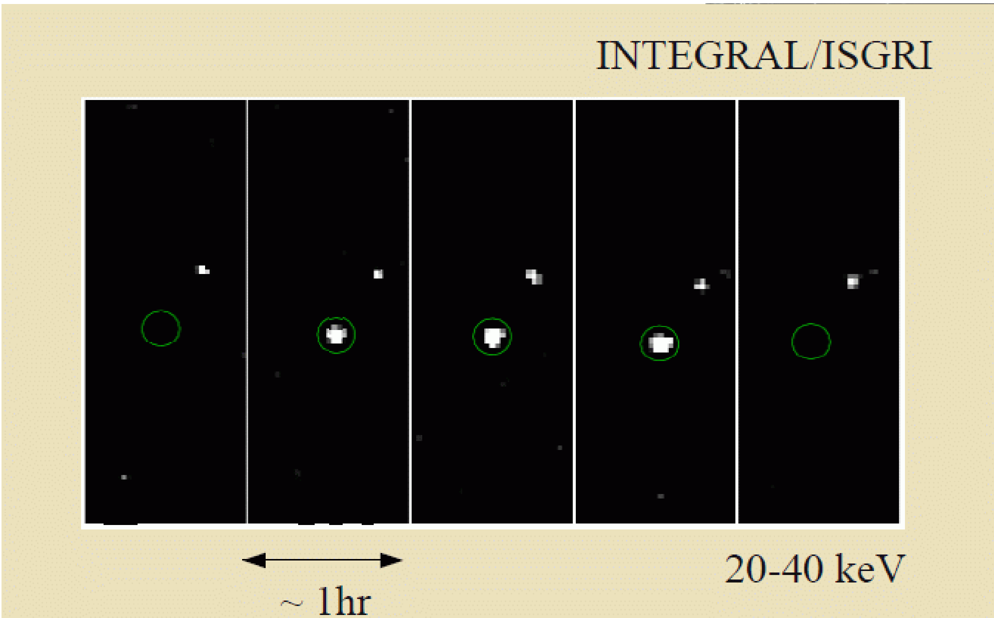
Be/X-ray binaries

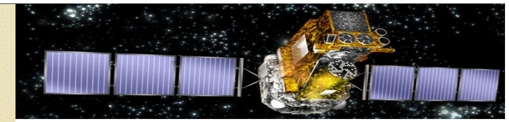


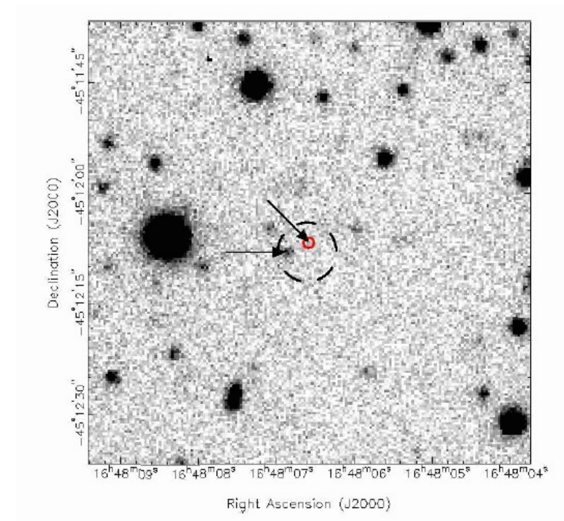
The Be disc is truncated by tidal interaction with the NS
Type II giant outbursts could be due to capture of larger (than in type I) amount of matter from a tilted and warped Be disc

Taken from a talk given by A. Okazaki

Supergiant Fast X-ray Transients







Sguera et al. 2005

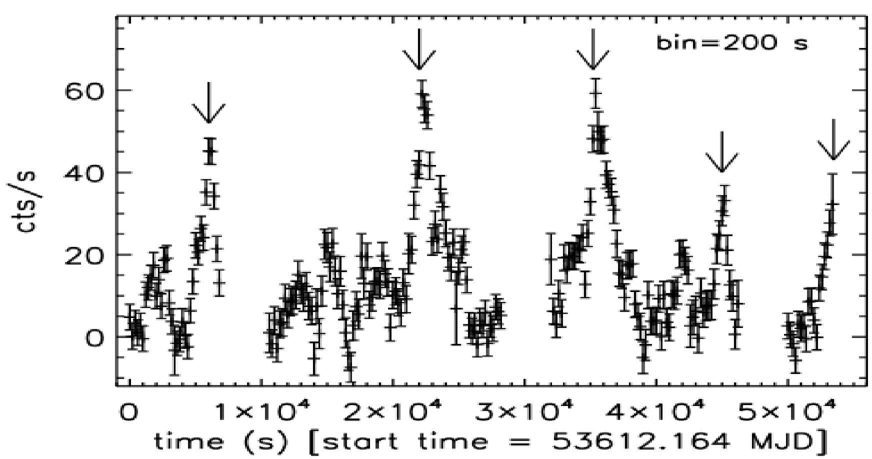
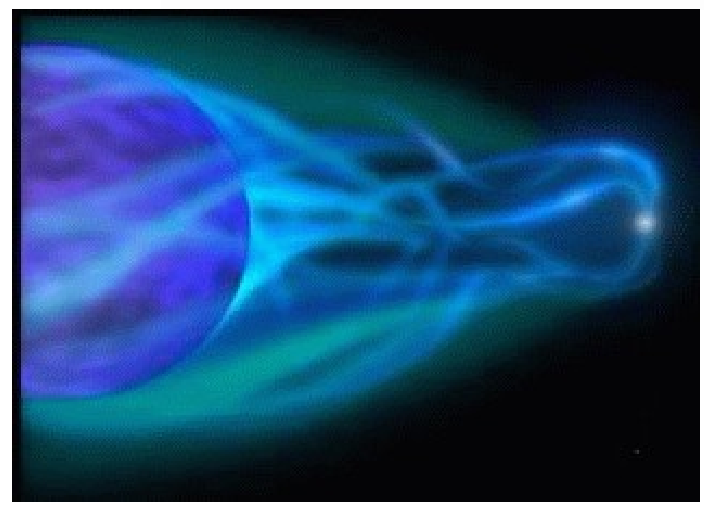


Figure 9. Lightcurve of the observation of XTE J1739−302, in the energy range 18 − 60 keV (IBIS/ISGRI). Arrows indicates the peaks of luminosity.



Negueruela et al. 2006

SgHMXB

- O, B supergiants
- Porb: 1-15d
- Quasi circular orbits
- Persistent

After INTEGRAL

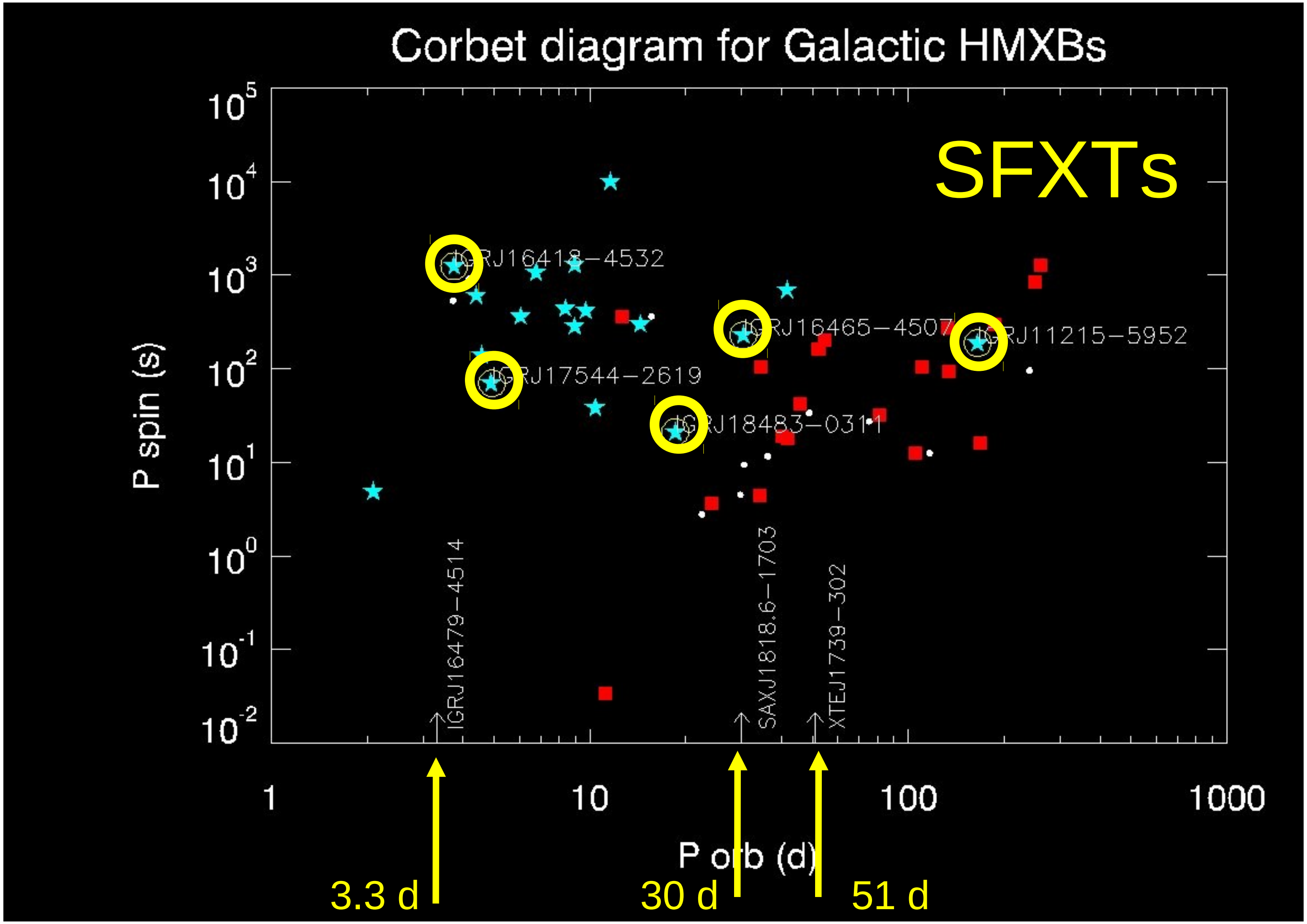
Supergiant Fast X-ray Transients

SFXTs

- O, B supergiants
- Transients

Be-HMXB

- Be stars
- Porb: days-months
- Elliptical orbits
- Transients



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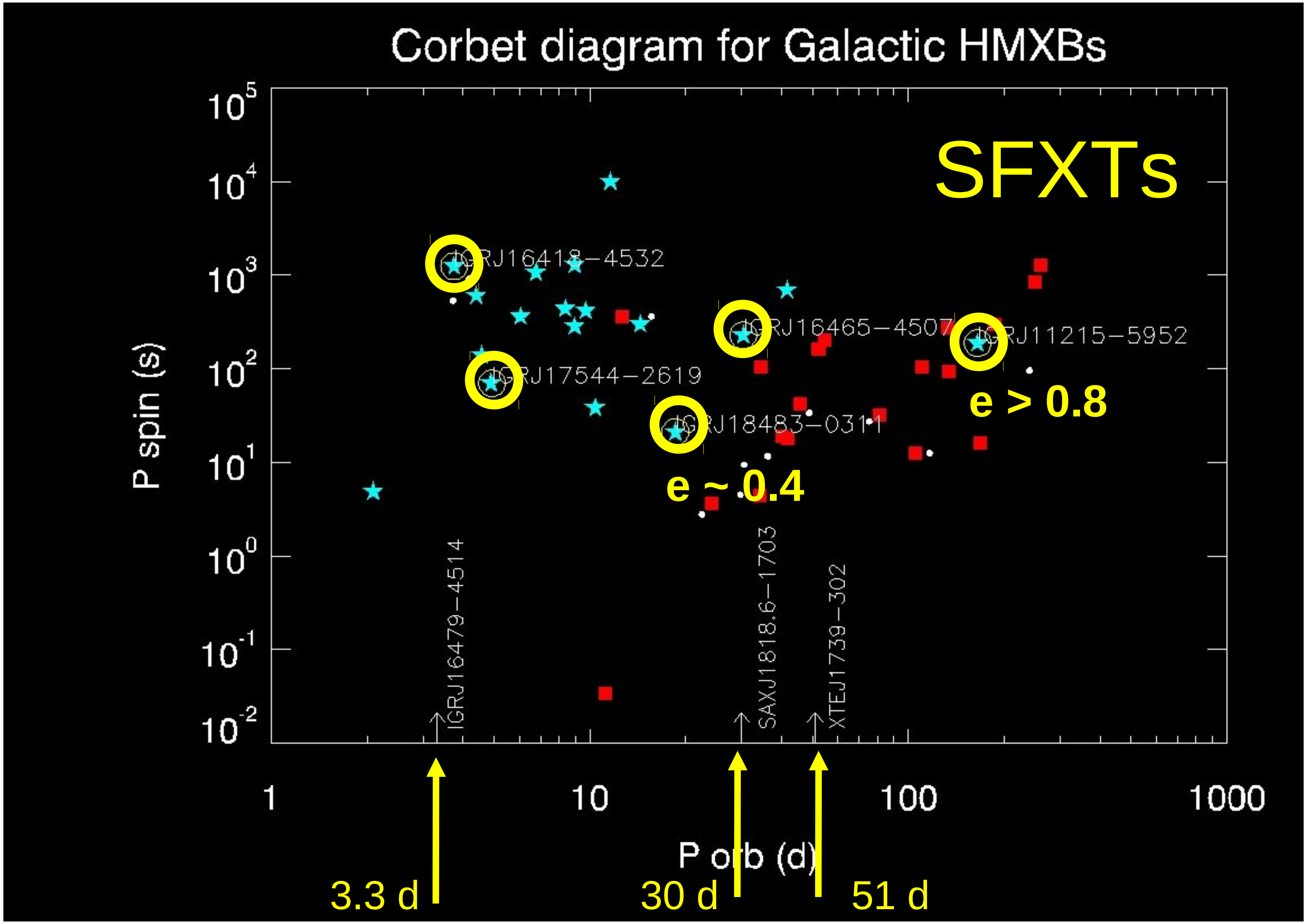
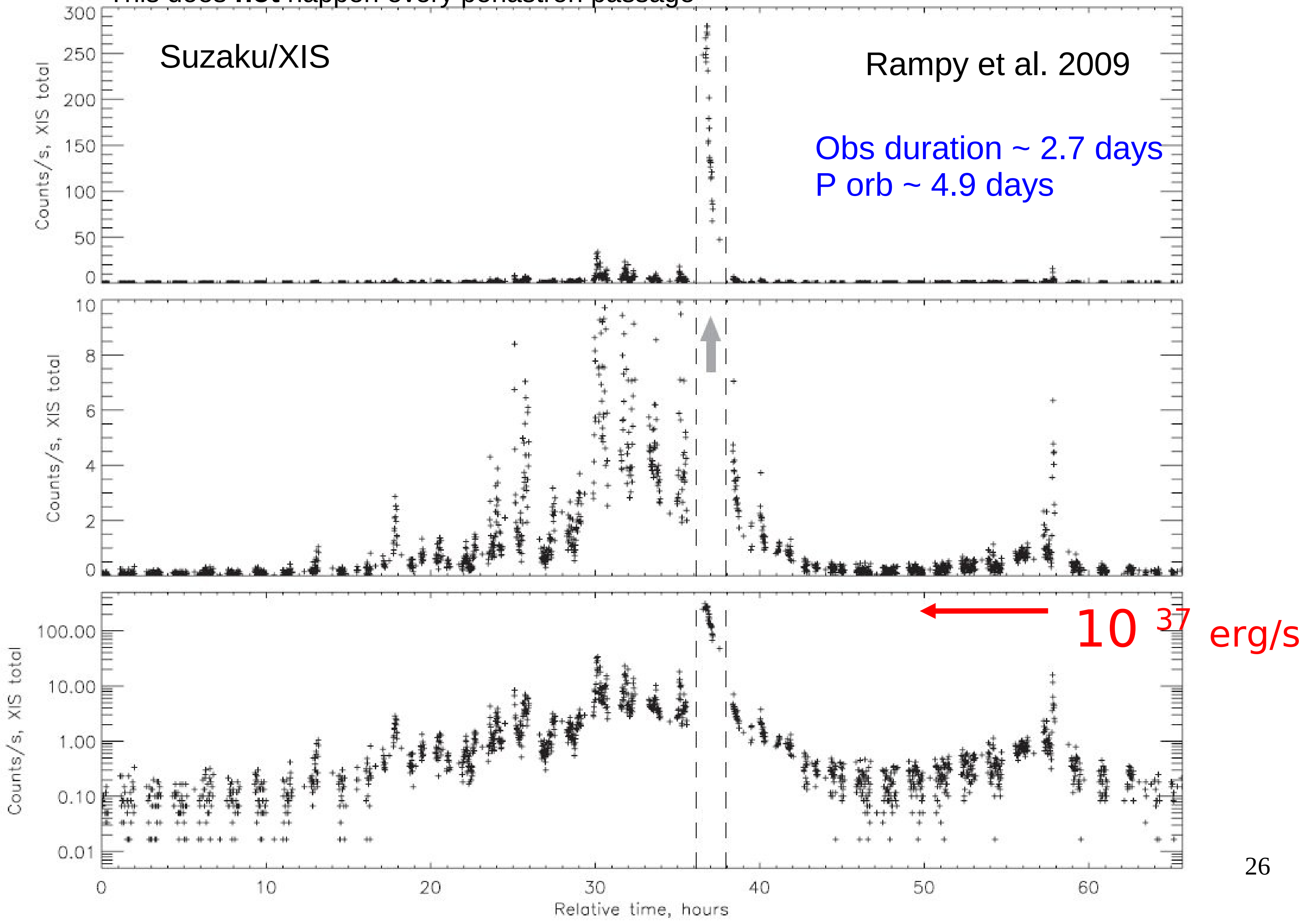


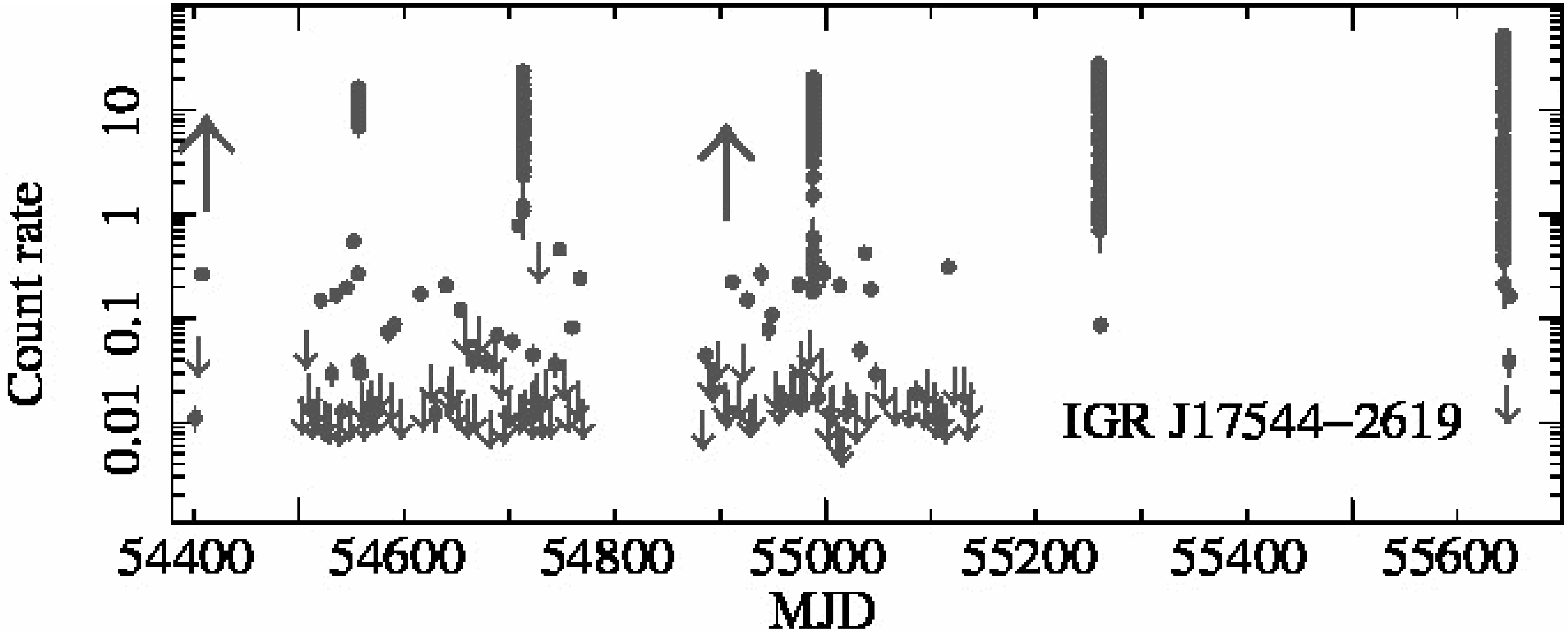
The SFXT IGR J17544-2619

Exceptional outburst from a SFXT near the periastron passage...BUT this occurs rarely!
This does **not** happen every periastron passage



The SFXT IGR J17544-2619

Swift / XRT monitoring of a sample of SFXTs



Sidoli et al. 2008
Romano et al. 2012

Long-term SFXTs X-ray emission:

intermediate luminosity state of 10^{33}-10^{34} erg/s (quiescence is at 10^{32} erg/s in the 1-10 keV band)

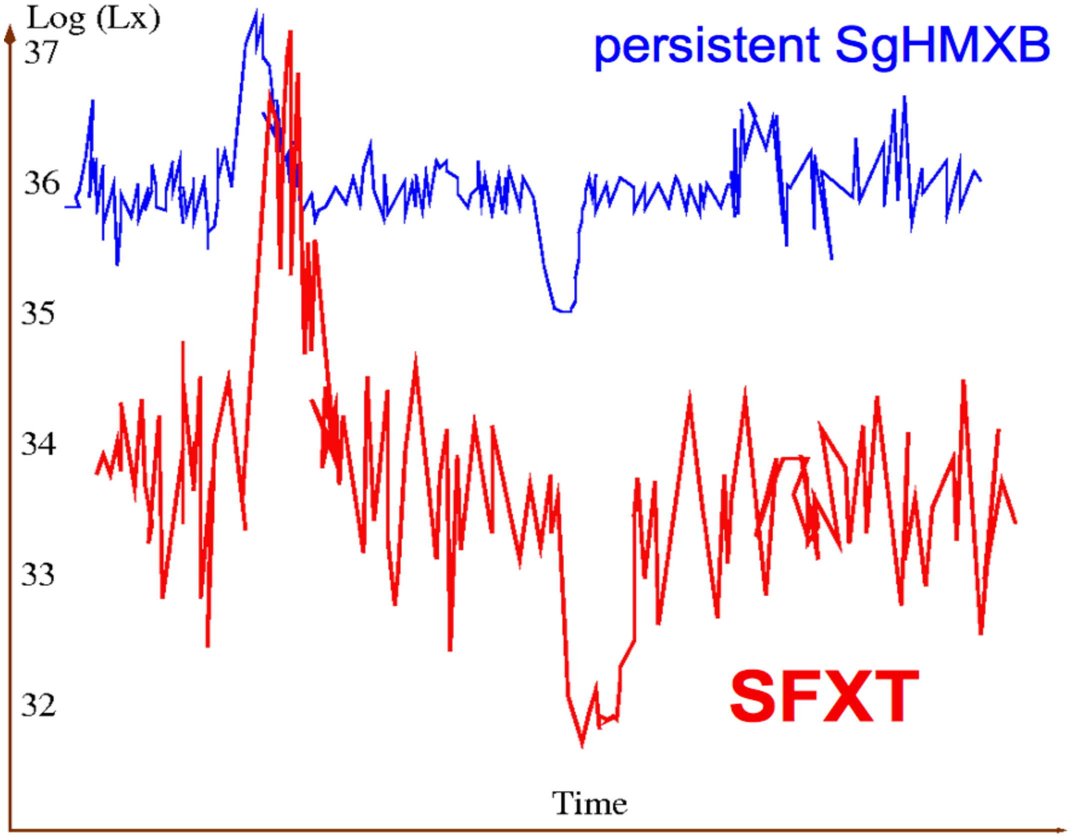
Ada will discuss INTEGRAL results on SFXTs!

SFXT

- O, B supergiants + NS
- Transients

Observationally

- Mostly around 10^{33}-10^{34} erg/s
- Sporadic, short and bright flares (10^{36} - 10^{37} ergs/s)
- Flares: minutes - hours
- Outburst: a few days
- Dynamic range up to $10^{5} – 10^{6}$



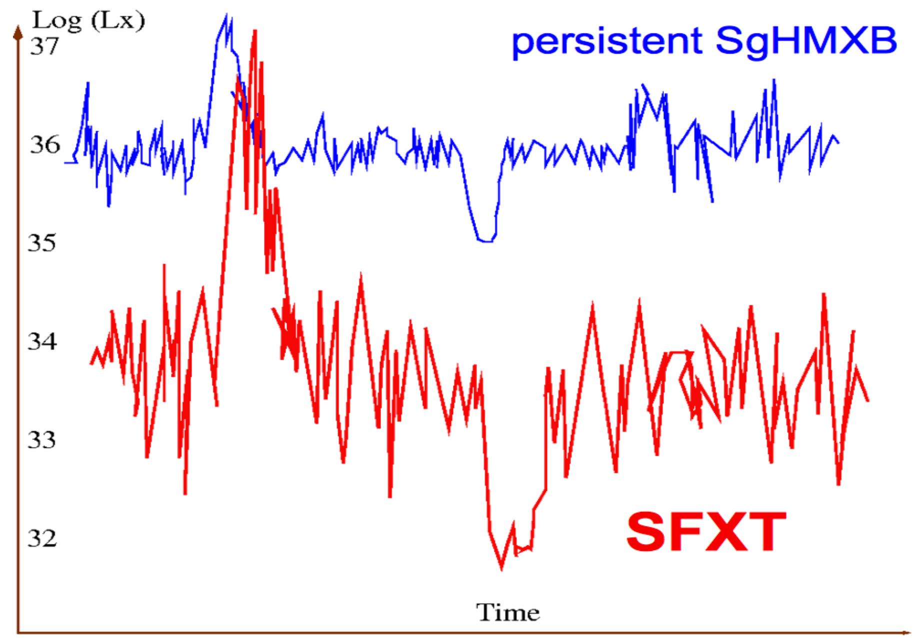
This is only a sketch, no real data!

Wind accretion

- Bondi accretion is an approximation to calculate the time-averaged Lx of classical HMXBs
- If applied to the new class of transient SgHMXBs, the Supergiant Fast X-ray Transients, it results into average Lx ~ 100 times higher than observed → **SFXTs are subluminous**
- The mechanism for

the X-ray **flares** is unclear

The mistery of SFXTs is twofold



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SFXT

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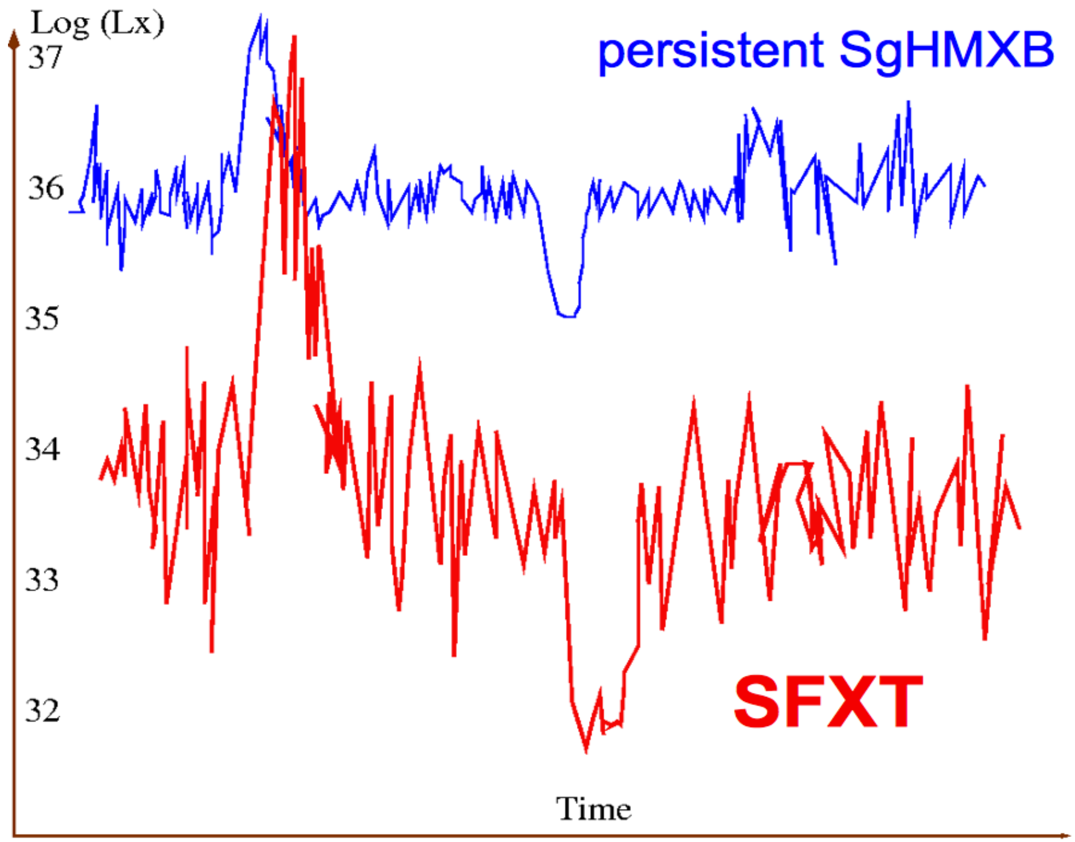
- Mostly around 10^{33}-10^{34} erg/sec
- Sporadic, short and bright flares (10^{36} - 10^{37} ergs/sec)
- Flares: minutes - hours
- Outburst: a few days
- Dynamic range up to 10^5

Physical mechanism debated

- Peculiar wind and/or orbit (in'tZand 05, Walter+07, Sidoli+07, Negueruela+08, …)
- Particular properties of NS (gating mechanism, Grebenev+07, Bozzo+08)
- Subsonic settling accretion regime (Shakura+12, +13, +14)



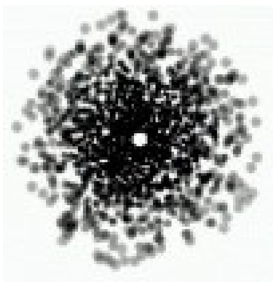
This is only a sketch, no real data!

SFXTs intermittent and sporadic X-ray flares

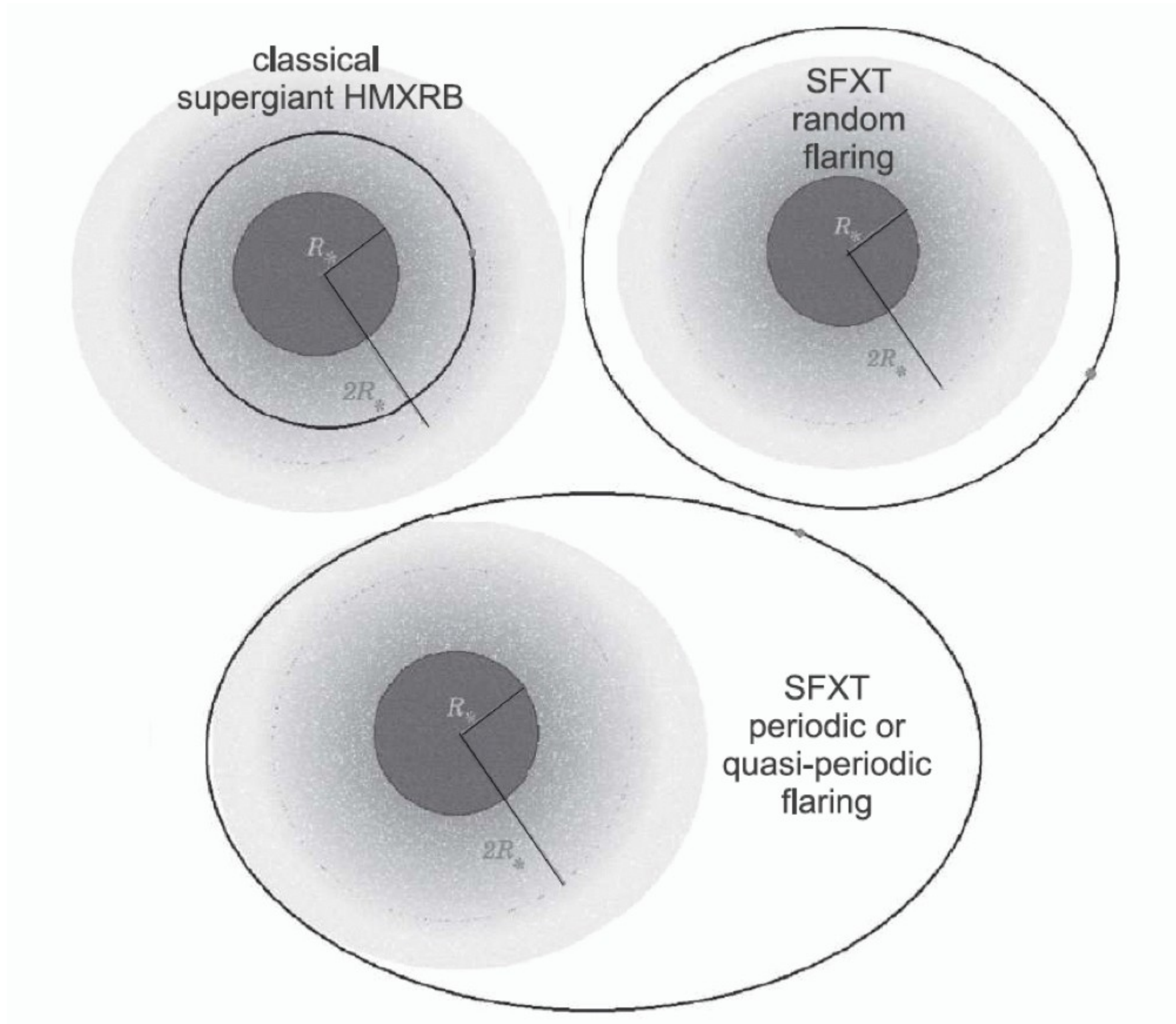
- Are they produced by an intermittent input?

Dense clumps in the wind → X-ray flares ?

Clumpy SG winds + different orbital configurations
are not enough to explain SFXTs **flares** & their **low time-averaged Lx**



Supergiant winds
are clumpy



Blay, Negueruela, Reglero 2012

SFXTs intermittent and sporadic X-ray flares

- Are they produced by an intermittent input?

  Dense clumps in the wind → X-ray flares ?

- Are the flares produced by a gated mechanism?

SFXTs: centrifugal or magnetic barrier?

To explain transitions between quiescence to bright flares in SFXTs in presence of variations in the supergiant wind parameters:

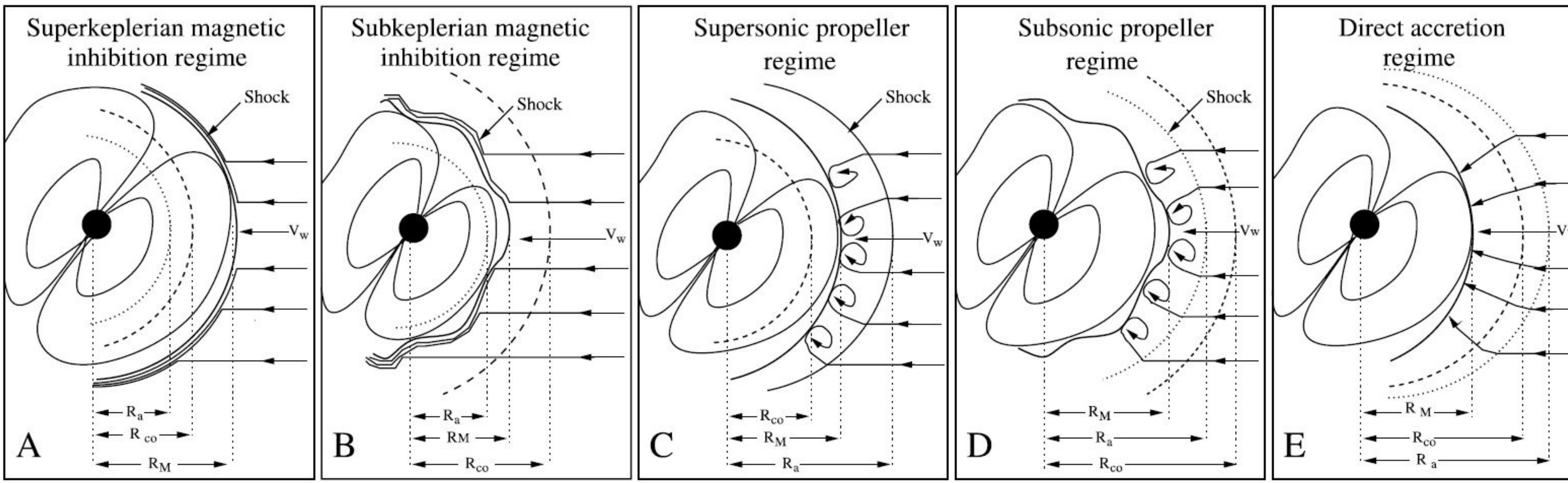
- **either** a **magnetic barrier** (**magnetar** with a **Pspin of ~ 1000 s**)
- **or** a **centrifugal barrier** (neutron star with a **B ~ 10^{12} G** and a **Pspin ~ 10 s**)

Racc < Rco < RM

Rco < RM < Racc

Direct accretion

RM < Rco < Racc



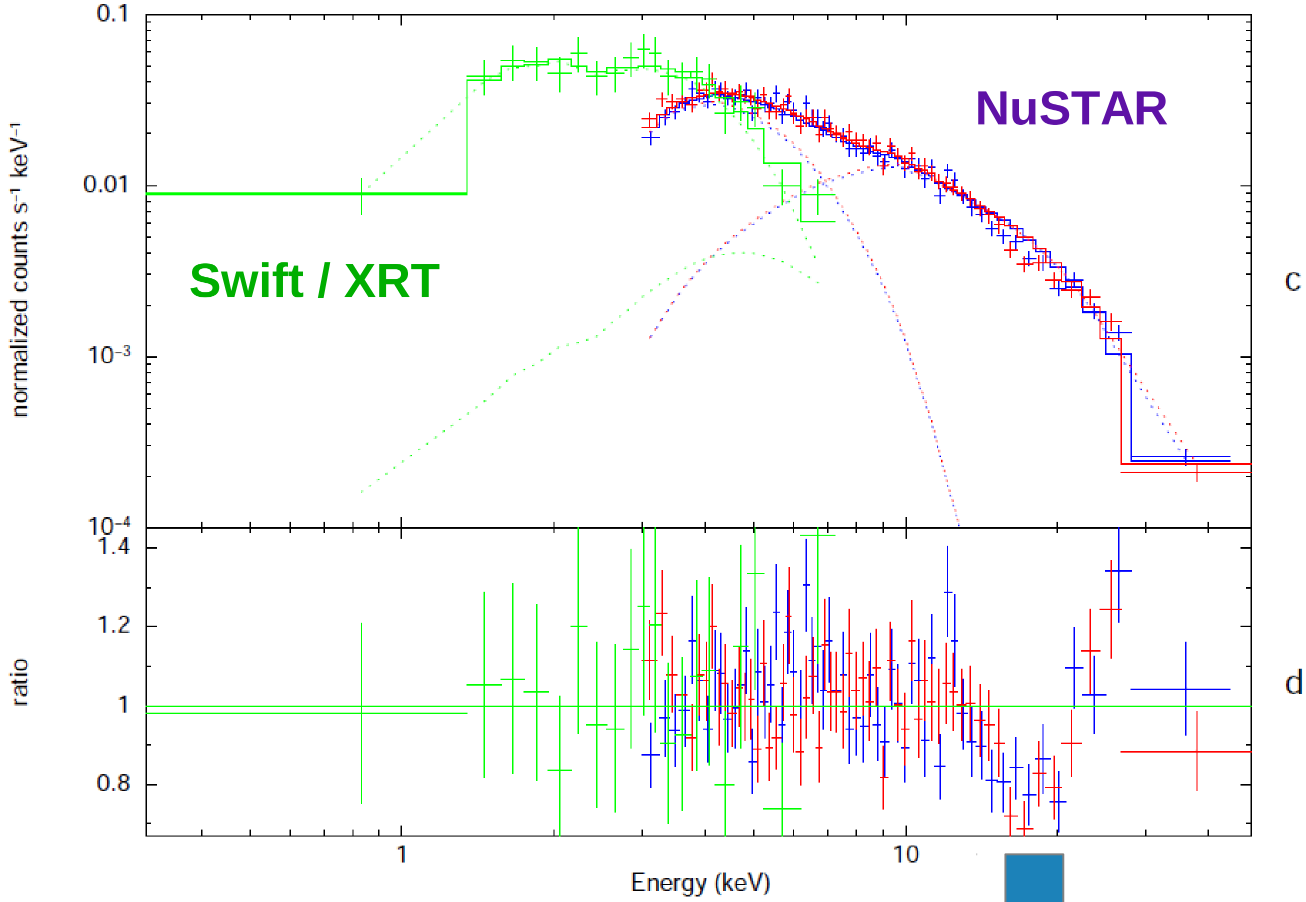
Racc < RM < Rco

RM < Racc < Rco

Racc = accretion radius (Bondi)
RM = magnetospheric radius
Rco = corotation radius

Bozzo, Stella & Falanga 2008

NuSTAR unveils the magnetic field strength in a SFXT



IGR J17544 – 2619

(Bhalerao et al. 2014)

Cyclotron line at ~ 17 keV

$$B = (1.45 \pm 0.03) \times 10^{12}\ G \cdot (1 + z)$$

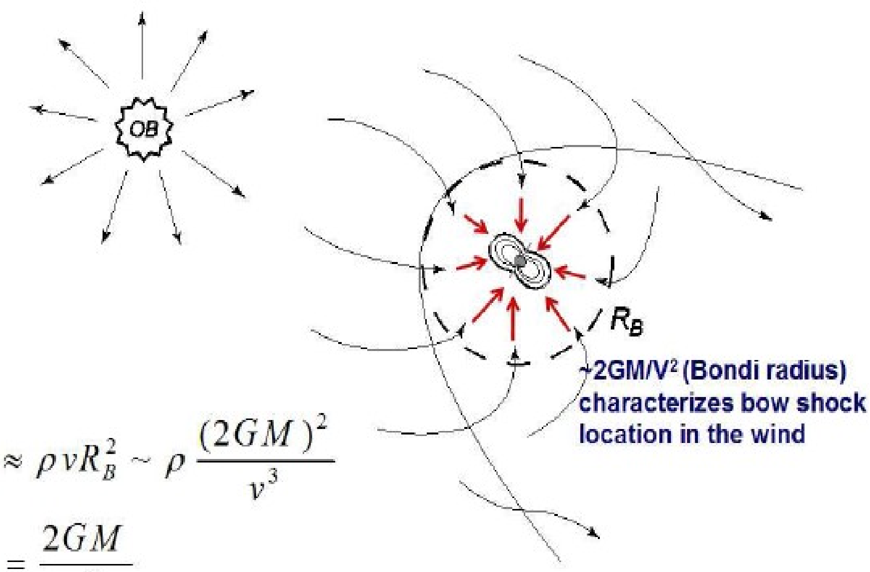
The **magnetar nature** of IGRJ17544 **is ruled out**

Quasi spherical accretion in slow pulsars

$L_x > 4\ 10^{36}$ erg/s

$L_x < 4\ 10^{36}$ erg/s

(usual SFXT state)



$$\dot{M} \approx \rho v R_B^2 \sim \rho \frac{(2GM)^2}{v^3}$$

$$R_B = \frac{2GM}{v^2}$$

Figure 1. Supersonic (Bondi-Hoyle-Littleton) accretion onto magnetized NS

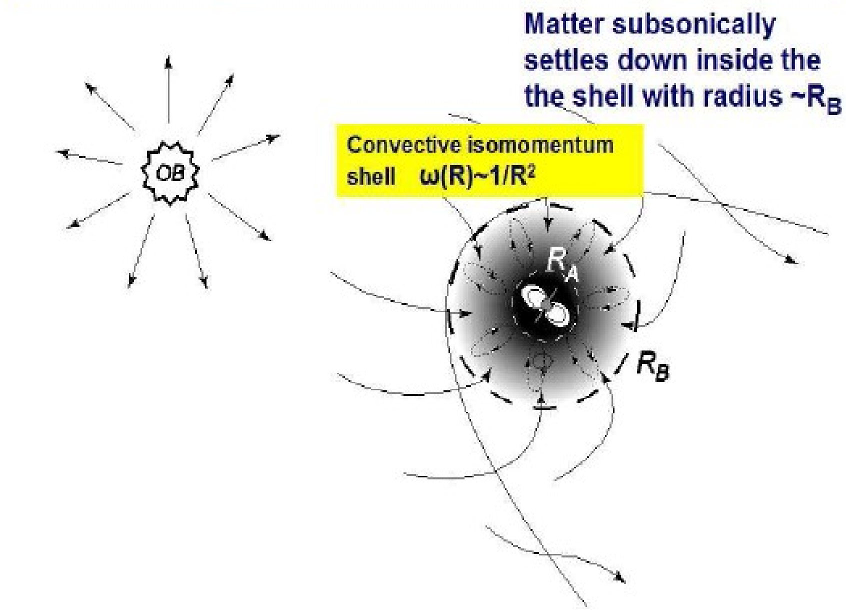
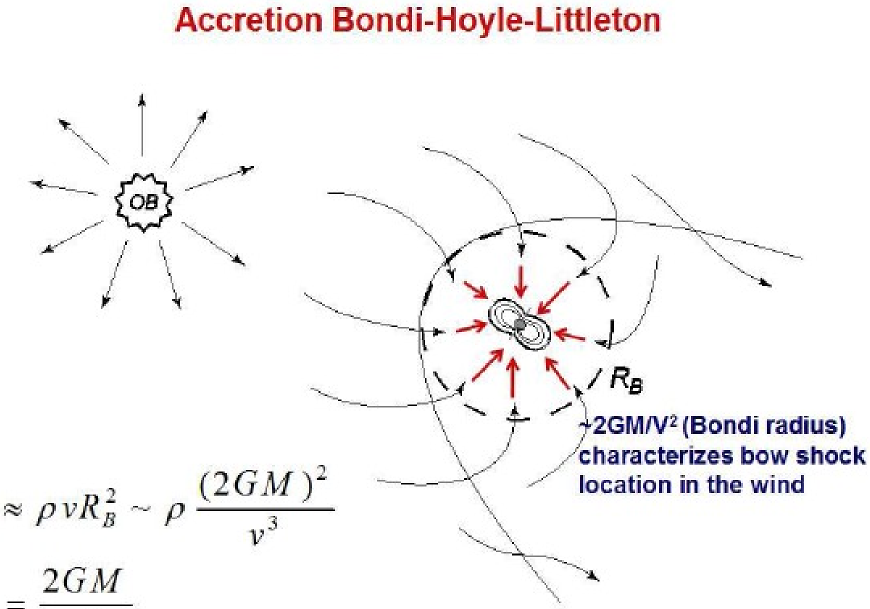


Figure 2. Subsonic settling accretion onto magnetized NS

(Shakura et al. 2012)

$L_x > 4\ 10^{36}$ erg/s

$L_x < 4\ 10^{36}$ erg/s



$$\dot{M} \approx \rho v R_B^2 \sim \rho \frac{(2GM)^2}{v^3}$$

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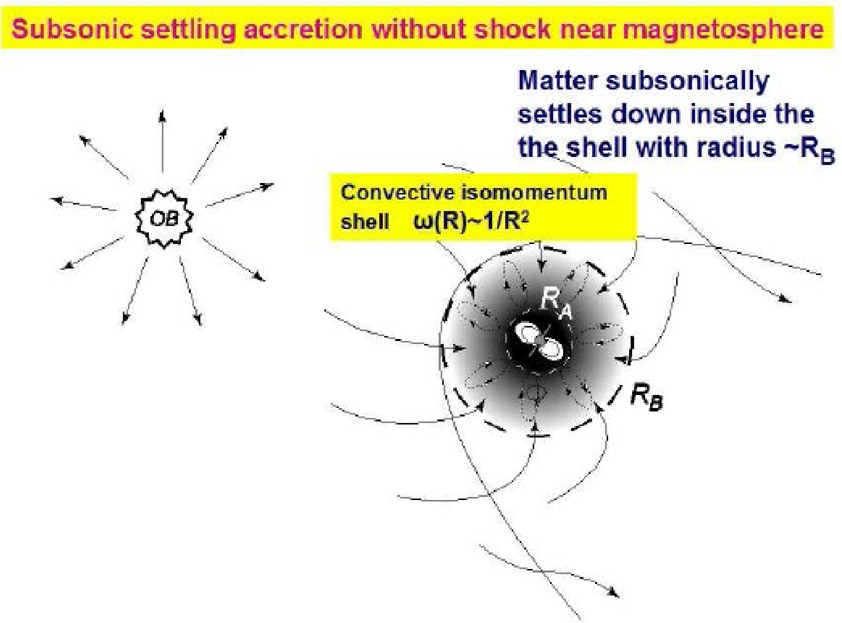
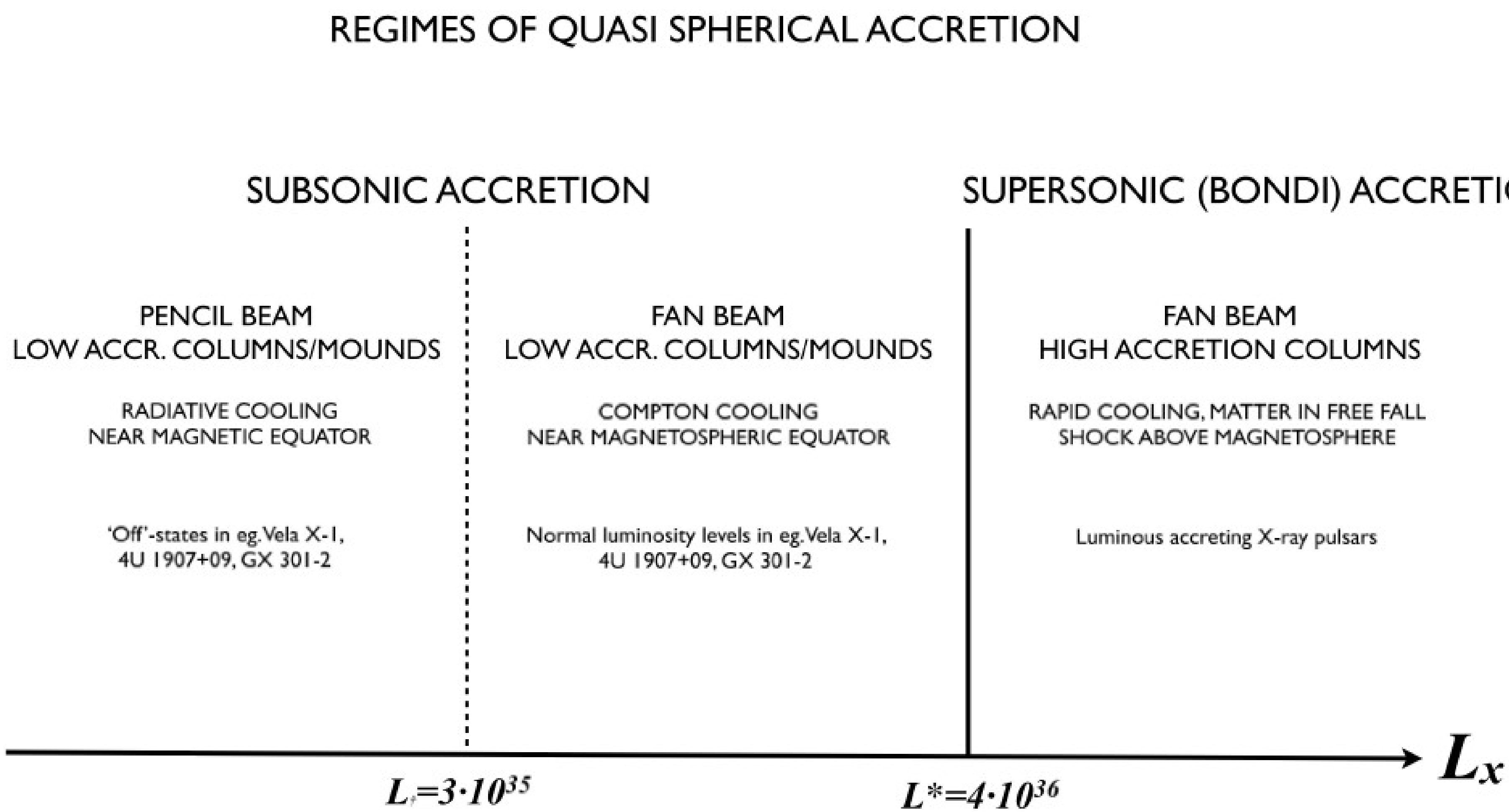


Shell

- Accretion rate controlled by plasma **cooling** (Rayleigh-Taylor instability, matter through magnetosphere: radiative cooling or Compton cooling)
- Mediates angular momentum transfer from/to magnetosphere
- Accretion can be significantly smaller than Bondi direct accretion
- Flares no more “tied” to orbit
- HMXB unified scenario

(Shakura et al. 2012; 2014)



Usual SFXTs state

$10^{33} – 10^{34}$ erg/s

SFXTs bright flare

Brigthest SFXTs flares

Magnetic reconnection is a proposed mechanism to allow the collapse of the Shell of captured matter above the magnetosphere onto the NS in SFXTs

← SFXTs supergiant <u>companions</u> should display higher B stellar field than in other HMXBs

(Shakura et al. 2012, 2014)

COSPAR 2016
event E 1.10 on HMXBs

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