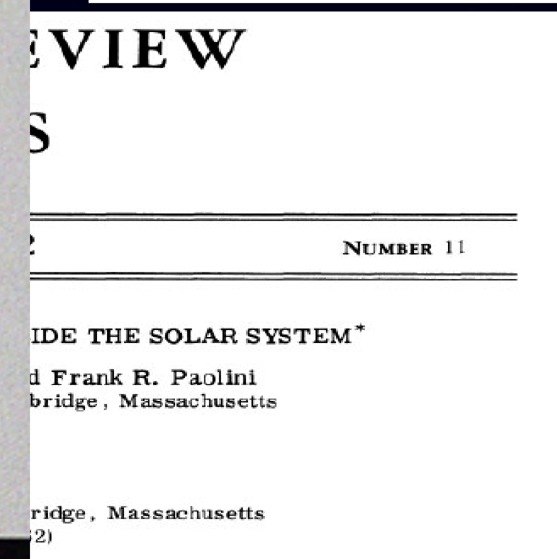
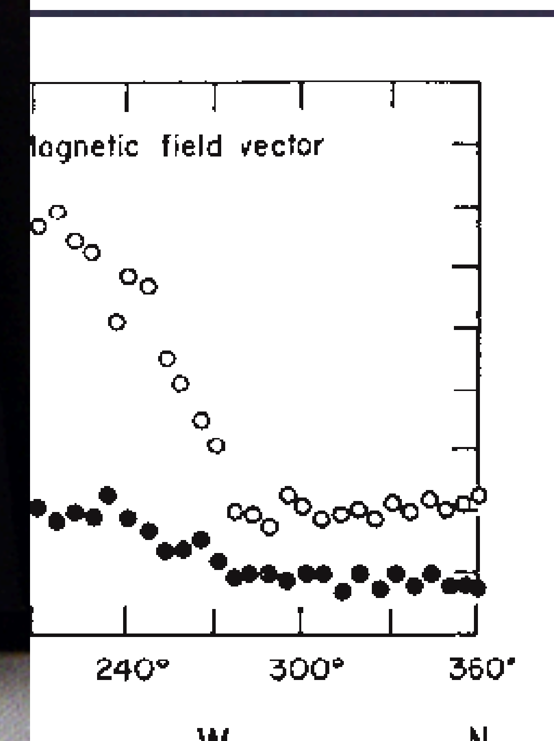
High-Mass X-ray Binaries: nature, formation & evolution

S. Chaty
Université Paris 7 / CEA Saclay

Colloquium APC, 11/10/2011

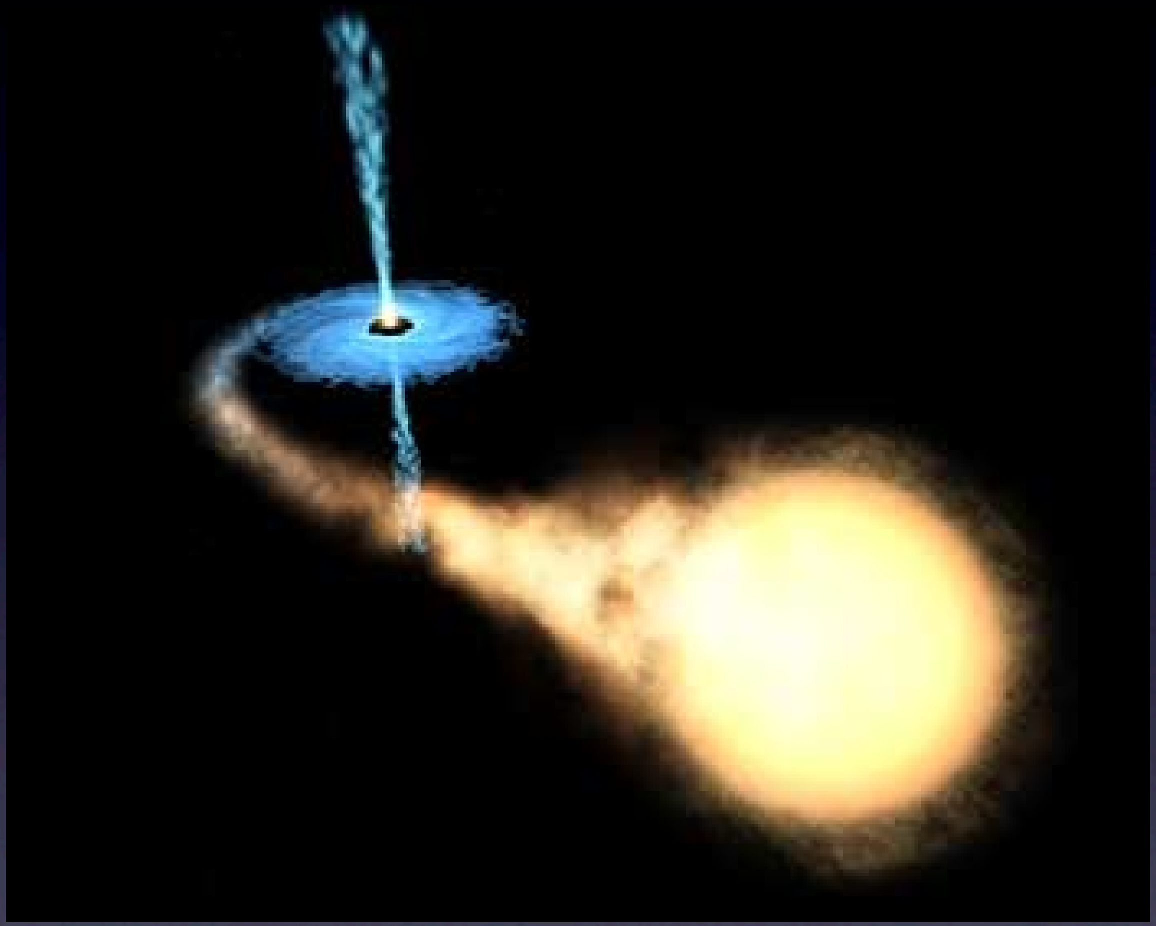
Kick-off of X-ray


EVIEW
S
2 NUMBER 11
IDE THE SOLAR SYSTEM*
d Frank R. Paolini
bridge, Massachusetts
ridge, Massachusetts
2)

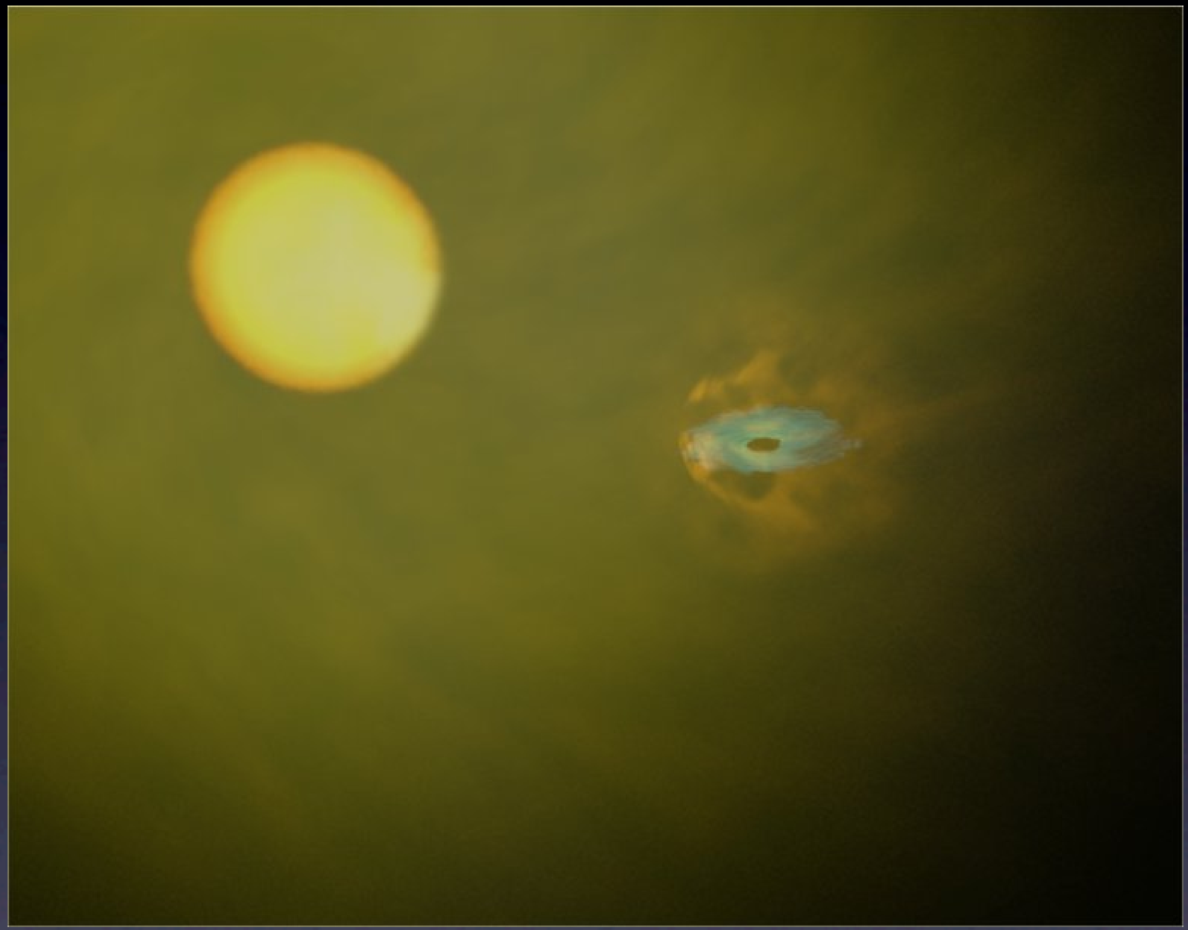


S. Chaty

High energy binary systems



Low-mass X-ray Binaries (LMXBs): Roche lobe overflow

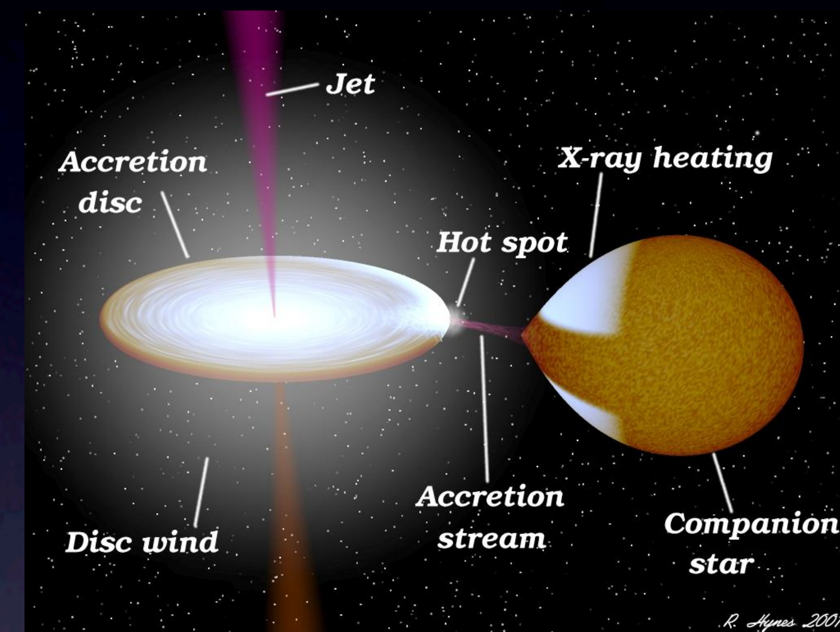


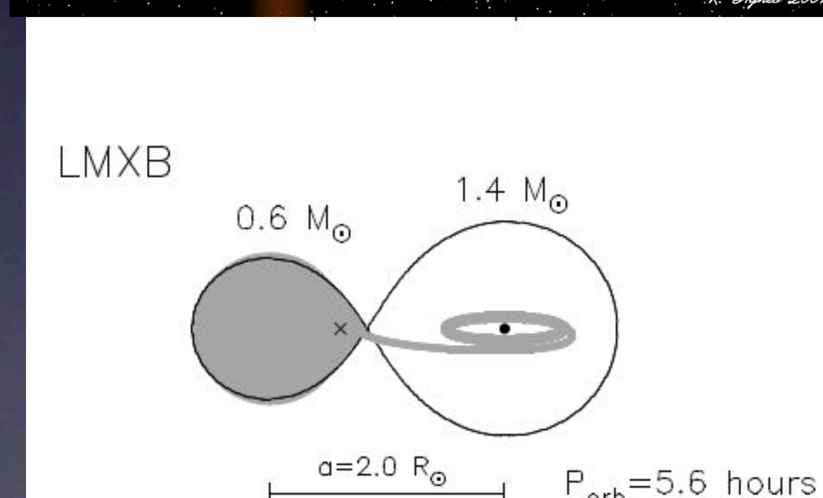
High-mass X-ray Binaries (HMXBs): Stellar wind accretion

S. Chaty

Galactic X-ray binaries

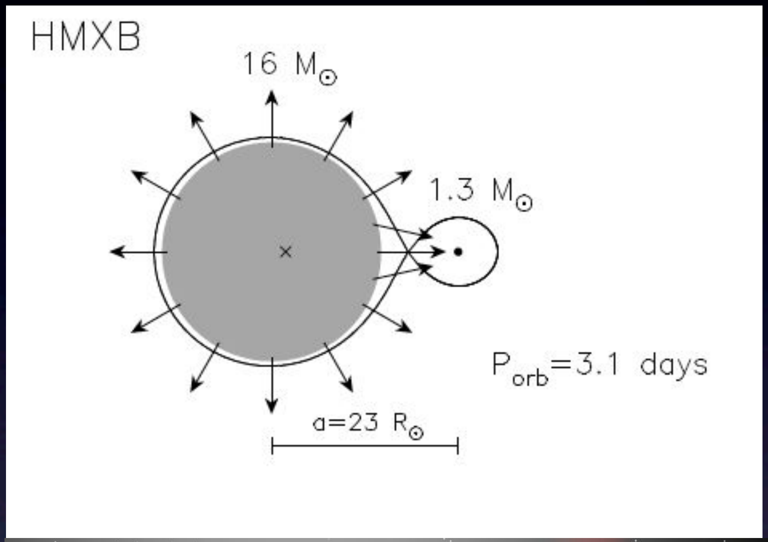
- 300 Galactic X-ray binaries (Liu et al 2006, 2007): LMXBs + HMXBs
- 187 LMXBs (62%):
    - Companion later than B ($M<1M_\odot$)
    - Mass transfer: Roche lobe filling, accretion disk
    - BH or NS LMXBs (Z/Atoll sources...): Sco X-1…
- + IMXBs with intermediate masses...

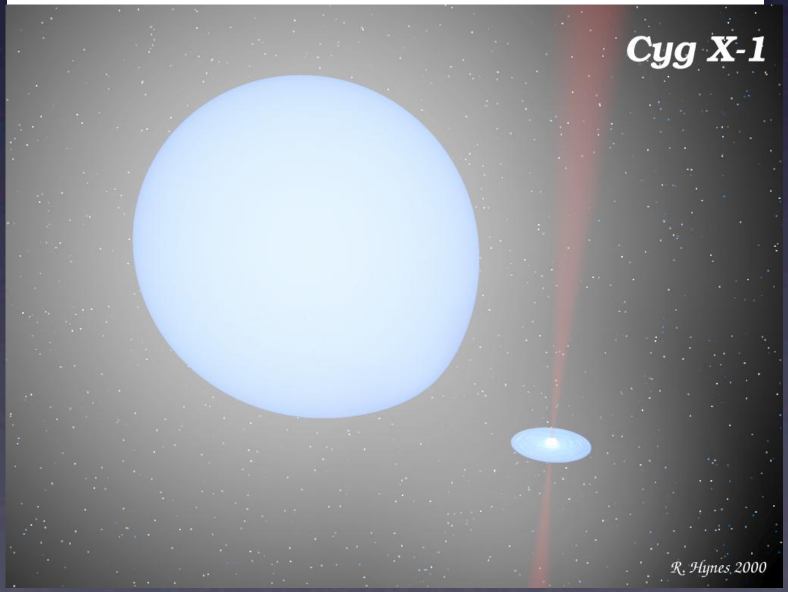




Galactic X-ray binaries

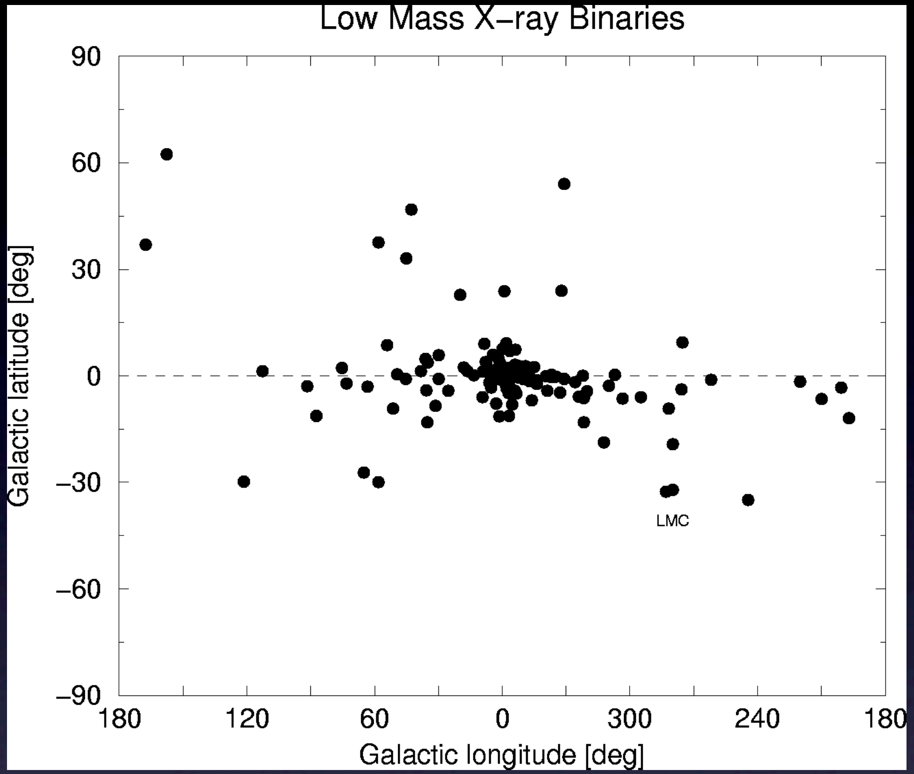
- 114 HMXBs (38%):
  - Luminous early-type OB companion ($M>10M_☼$)
  - Mass transfer:
    - Direct accretion from circumstellar disk (+ Roche lobe overflow) (Be III-V stars): BeXBs
    - Radially outflowing stellar wind or Beginning Atmospheric Roche Lobe Overflow (sg I/II stars): sgXBs



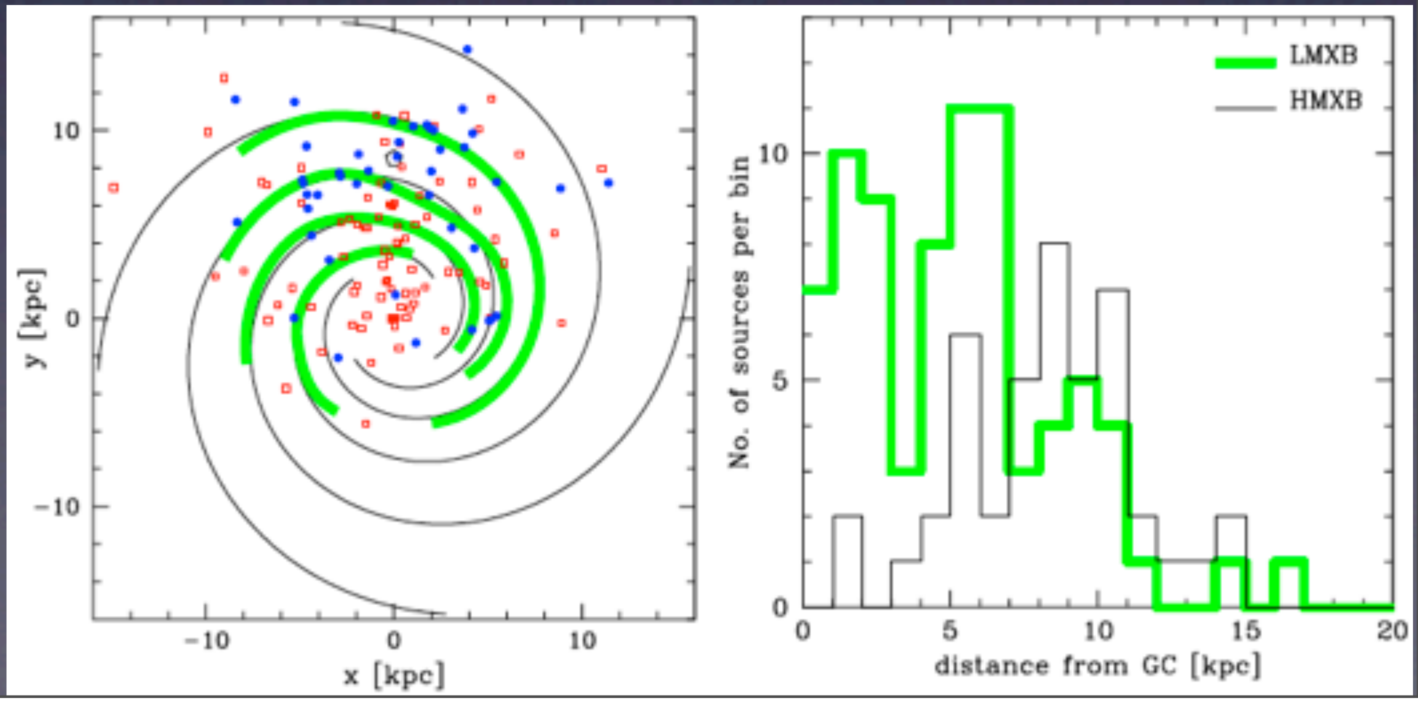


S. Chaty

Galactic distribution of LMXBs



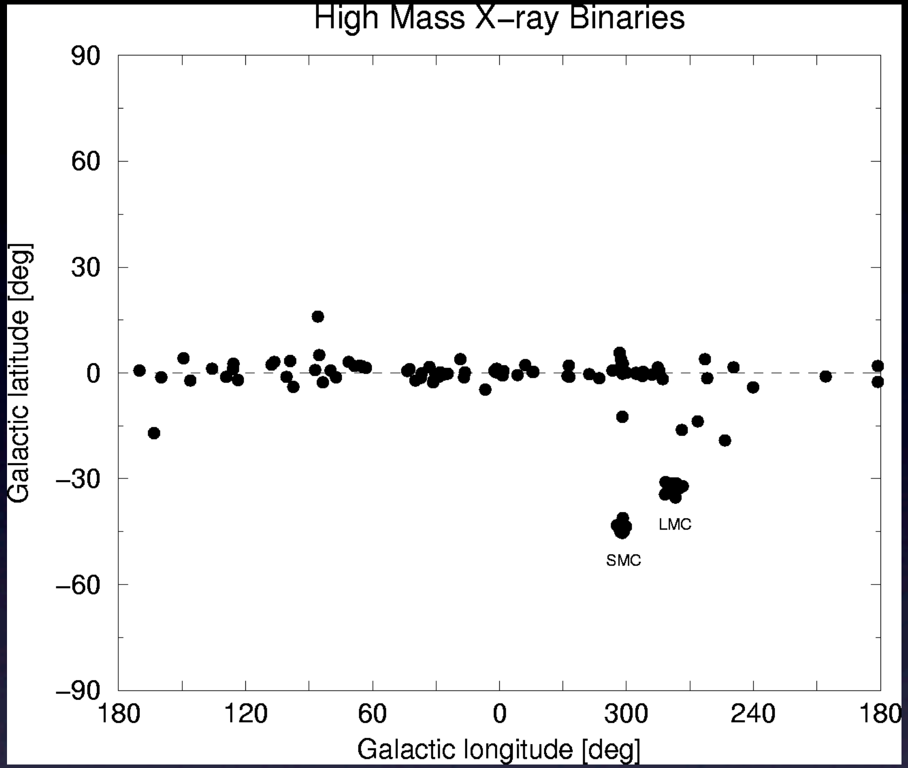
- LMXBs (old companion stars) concentrated in Galactic bulge & migration off the plane (|b|>3-5°)
- LMXBs peak at the center and gradually decrease: association with Galactic bar?



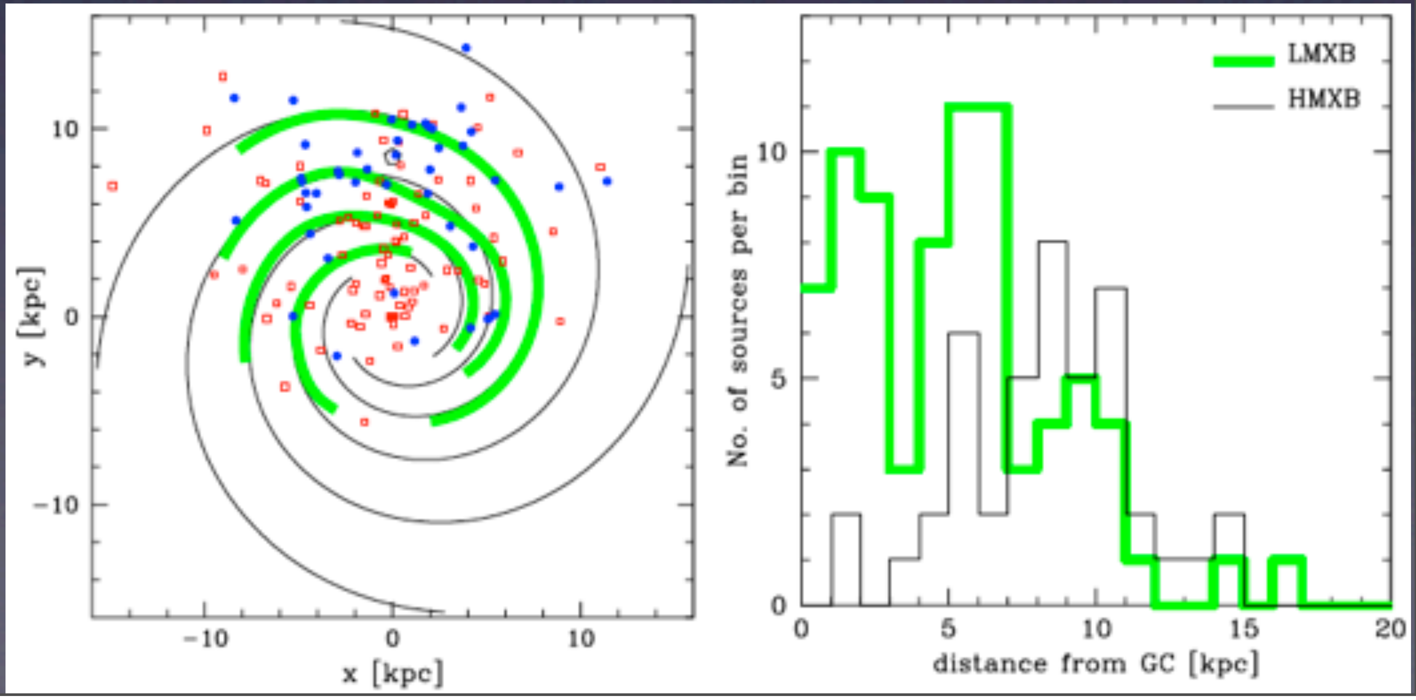
S. Chaty

Galactic distribution of HMXBs

- HMXBs (young companion stars): underabundant in central kpc, uneven distribution on Galactic plane towards tangential directions of spiral arms



- Impact of recent stellar formation & evolution, already noticed with Ginga & RXTE (Koyama et al. 1990; Grimm et al. 2002)



S. Chaty

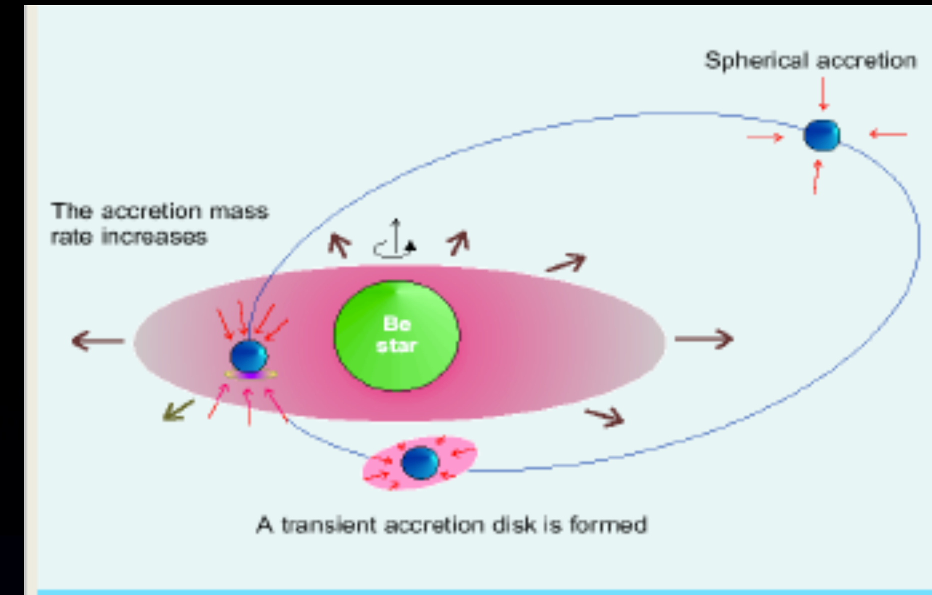
General properties of HMXBs

Type	Percent of all (100) HMXBs	Luminosity class	Pulse periods (s)	Binary period (d)	Binary eccentricity	Log Lx (erg/s)
BeXB	57	III-V	0.05-500	2-260	0.3-0.9	36-38
(XP*)	10	III-V	200-1400	250	0.03	34-35
sgXB	25	I-II	200-700	3-40	0-0.3	34-35
Others	8					

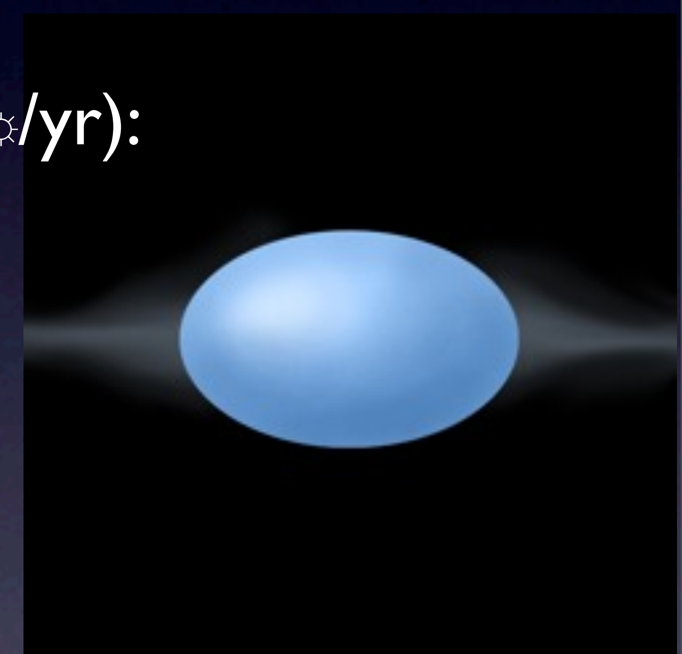
- Taken from the review on X-ray binaries by Charles & Coe 2006
- *X Per-like systems: long pulse periods, persistent low flux, low variability, rare uncorrelated weak X-ray outbursts

S. Chaty

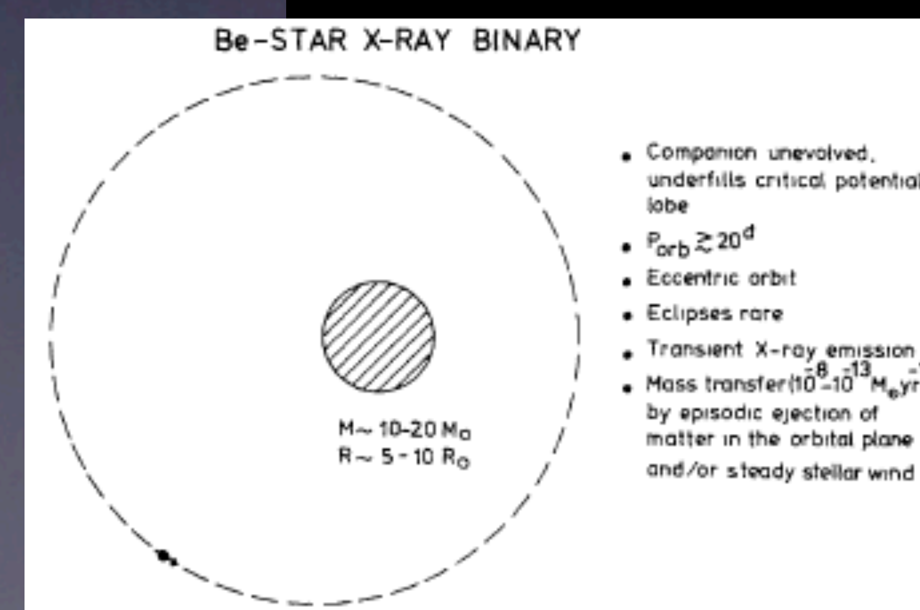
Be X-ray binaries (BeXBs)



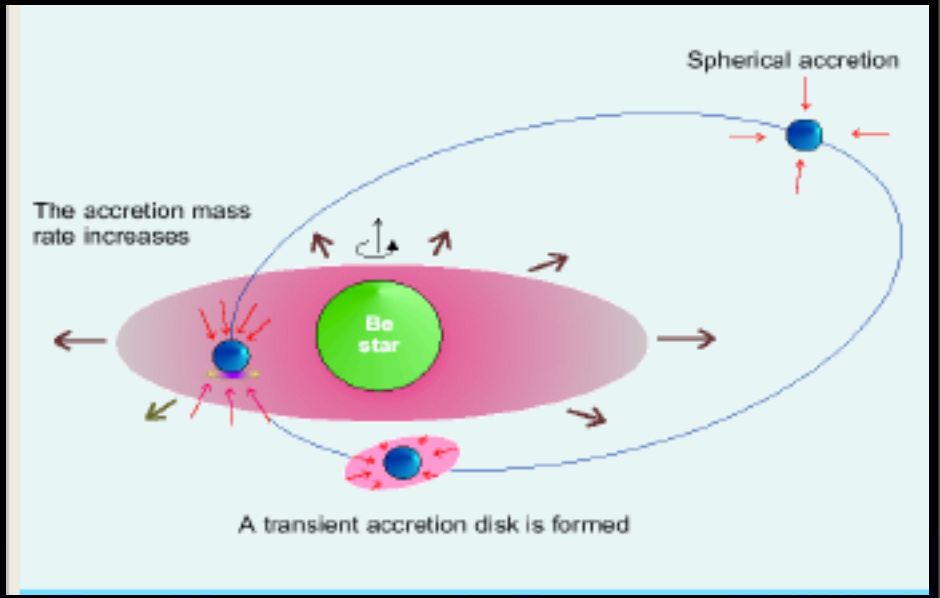
- Donor: B0-B2e star with circumstellar «decretion» disc of gas (Coe 2000, Negueruela 2004)
  - created by low-velocity/high-density wind ($10^{-7}M_\odot$/yr): Hα emission line (disc size)
    + continuum free-free/free-bound (IR excess)



- Compact object: NS in a wide & eccentric orbit
- Transient & bright X-ray outbursts when NS crosses decretion disk
- ~50 in MW, >35 in SMC



BeXBs in X-rays



- <u>Type I</u>: regular periodic outbursts at periastron
- <u>Type II</u>: giant outbursts at any phase: dramatic expansion of circumstellar disc including NS
- <u>«Missed» outbursts</u>: low Hα emission (small disc) or centrifugal inhibition of accretion
- <u>«Shifting phase» outbursts</u>: rotation of density structures in circumstellar disc

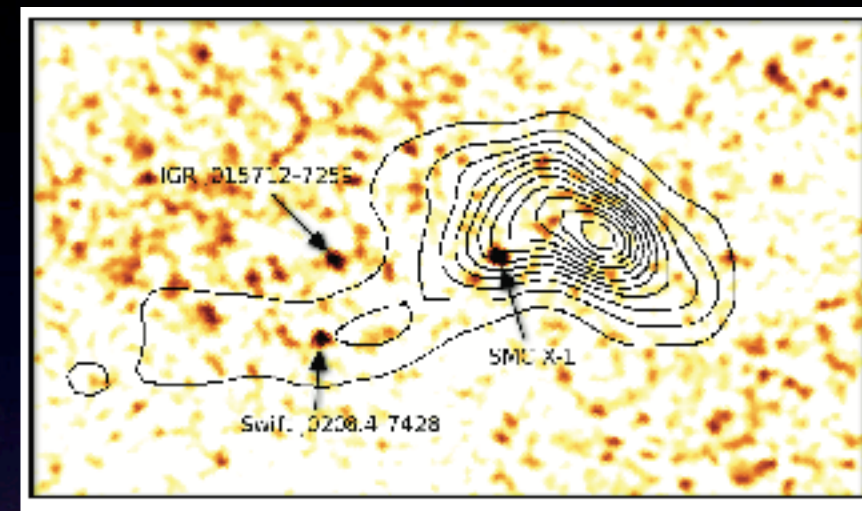
S. Chaty

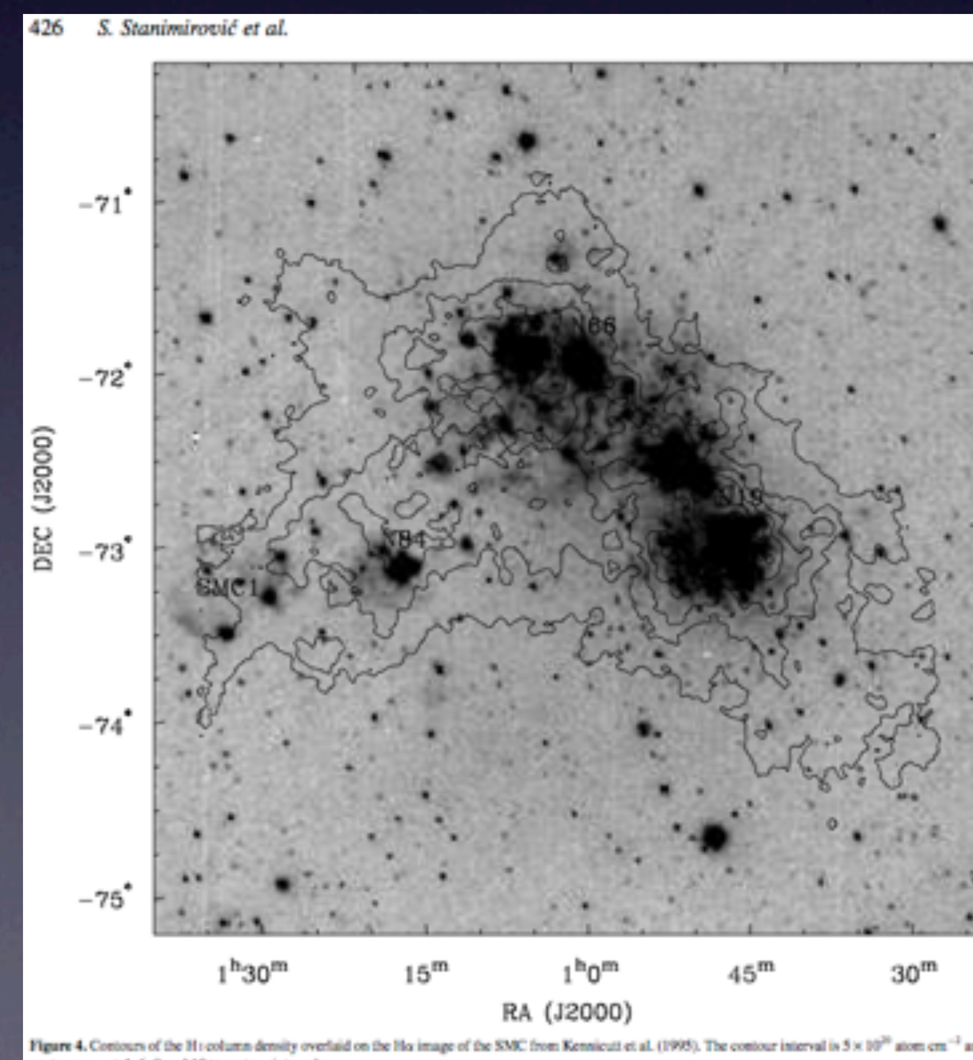
BeXBs:
MW vs S/LMC

- Large number of BeXBs in SMC (>35) instead of ~3 predicted by galactic mass ratio of 50! Probably due to bridge of material MW/MCs (McBride et al. 2008)

- Previous closest SMC/LMC approach ~100 Myr ago: new massive stars formed current HMXB population

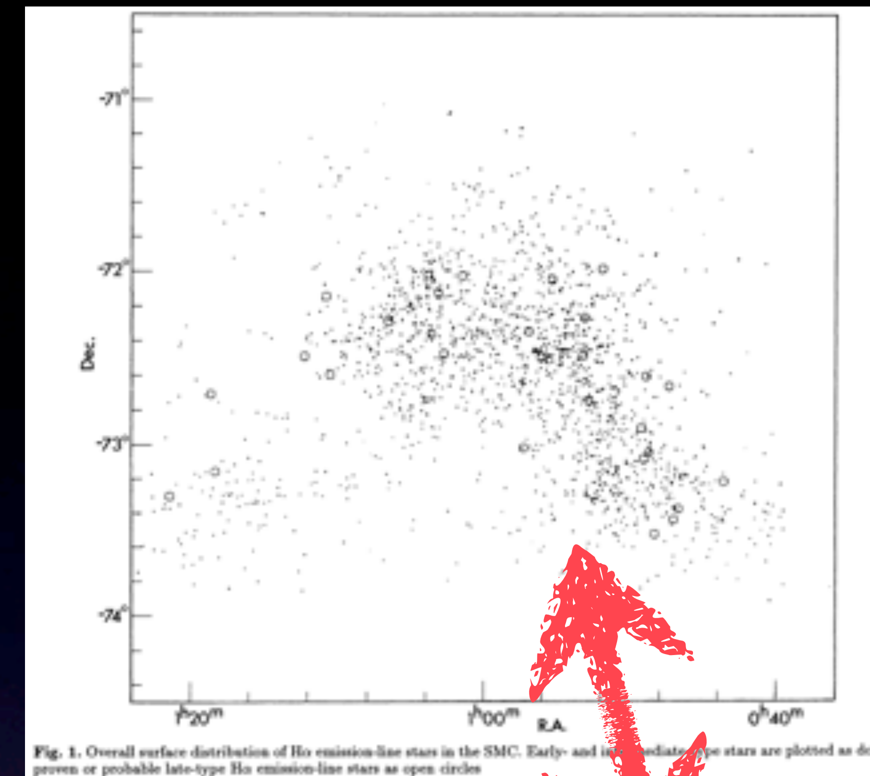
- Large number of SNRs of similar age (~5 Myr): increased starbirth due to tidal interactions (Stavely-Smith et al. 1997; Stanimirovic et al. 1999)

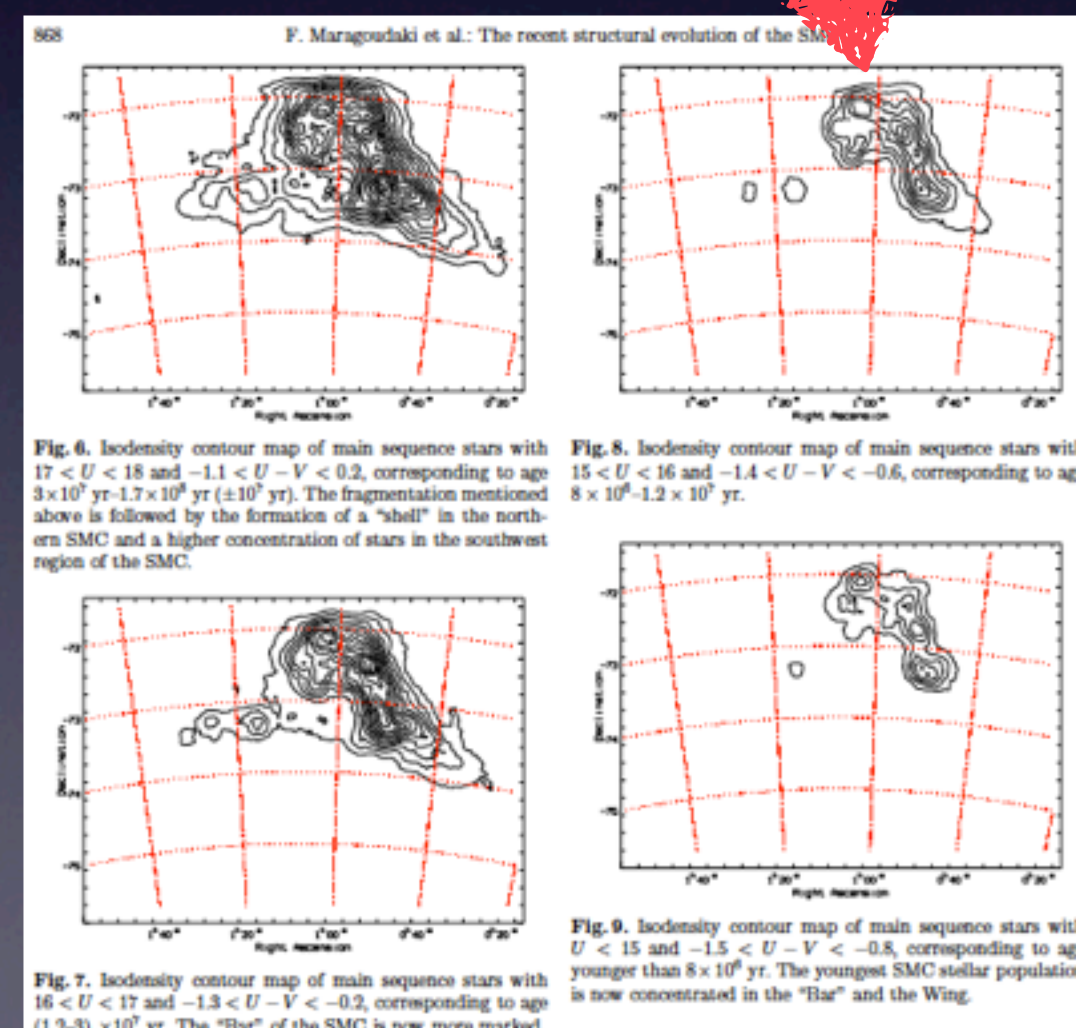




BeXBs: MW vs S/LMC

- Strong spatial correlation between emission line stars & 8-12 Myr stars with BeXBs in SMC (Meyssonnier & Azzopardi 1993, Maragoudaki et al 2001)
- Number of HMXBs: indicator of SFR & starburst activity (Popov et al. 1998, Grimm et al. 2003)
- SMC/LMC provide good sample of BeXBs in a compact region





S. Chaty

BeXBs: MW vs S/LMC

- Similar BeXB populations:
  - MW (solid) & SMC (dashed)
    (McBride et al. 2008)
  - MW (white) & LMC (black)
    (Negueruela & Coe 2002)

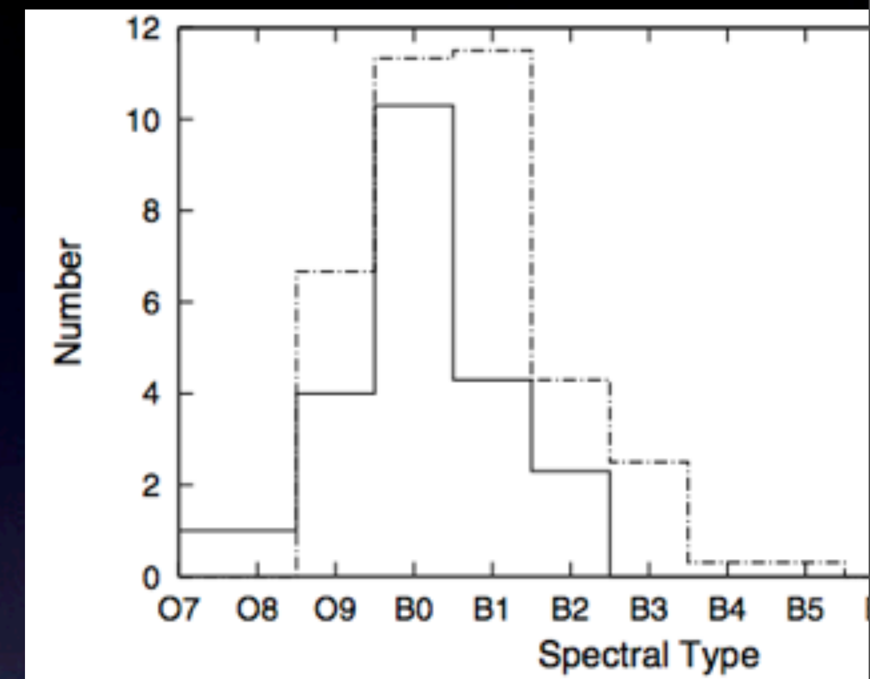
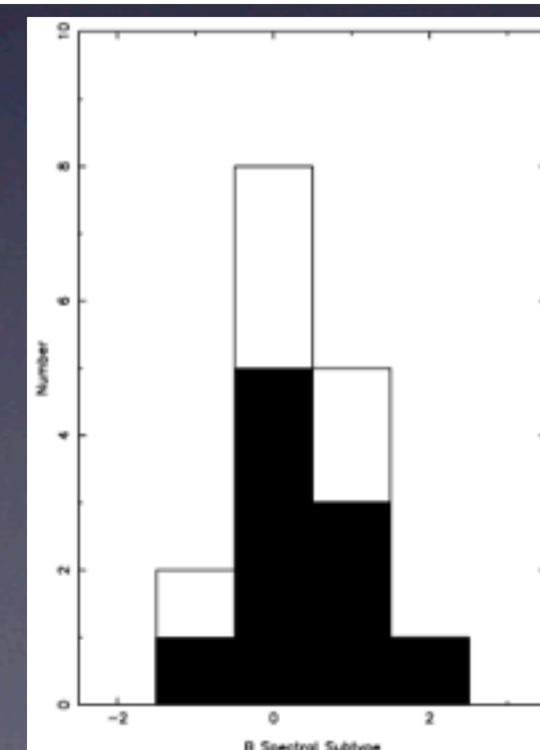
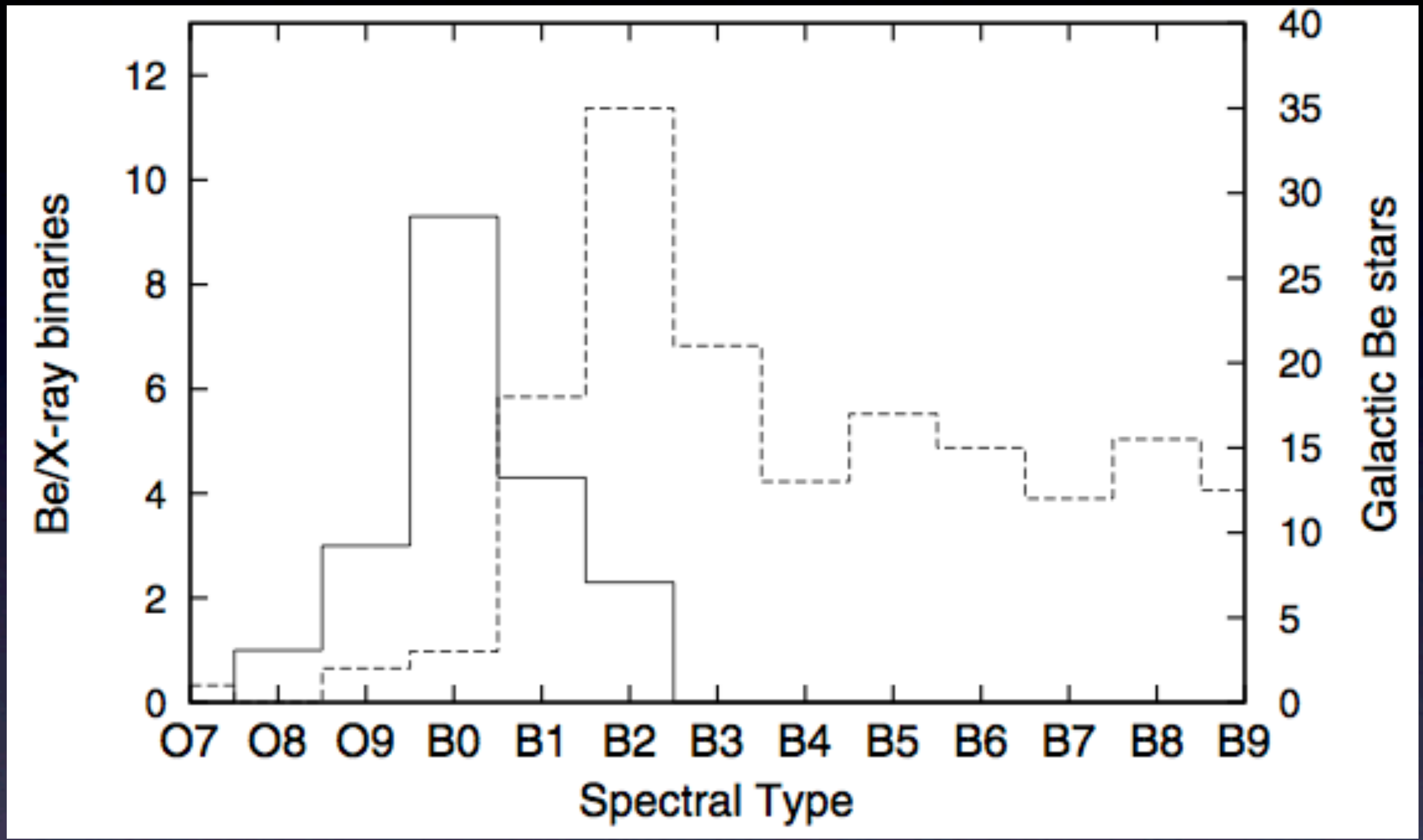


Figure 4. Spectral distribution, as determined from high
tio blue spectra, of Be/X-ray binaries in the SMC (dot–da
the distribution of Be/X-ray binaries in the Galaxy (solid



S. Chaty

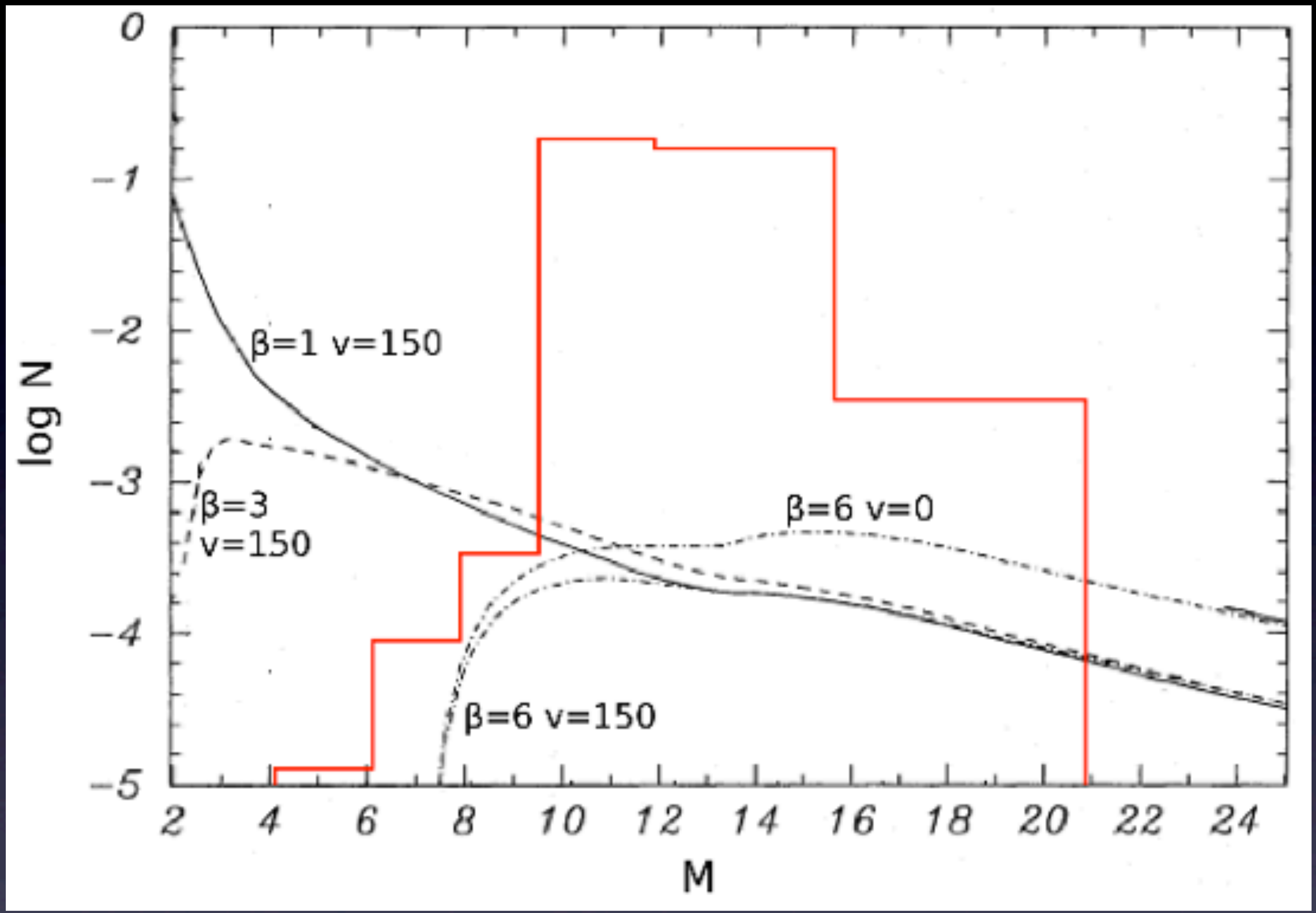
BeXBs vs isolated Be



- MW BeXBs (solid) & isolated Be (dashed) (McBride et al. 2008)
- Narrow spectral type distribution of BeXBs begins at O8 (~22 $M_\odot$), peaks at B0 (~16 $M_\odot$) and stops at B2 (~10 $M_\odot$): wide orbits vulnerable to disruption during SN event, especially for less massive B stars

S. Chaty

Formation of BeXBs

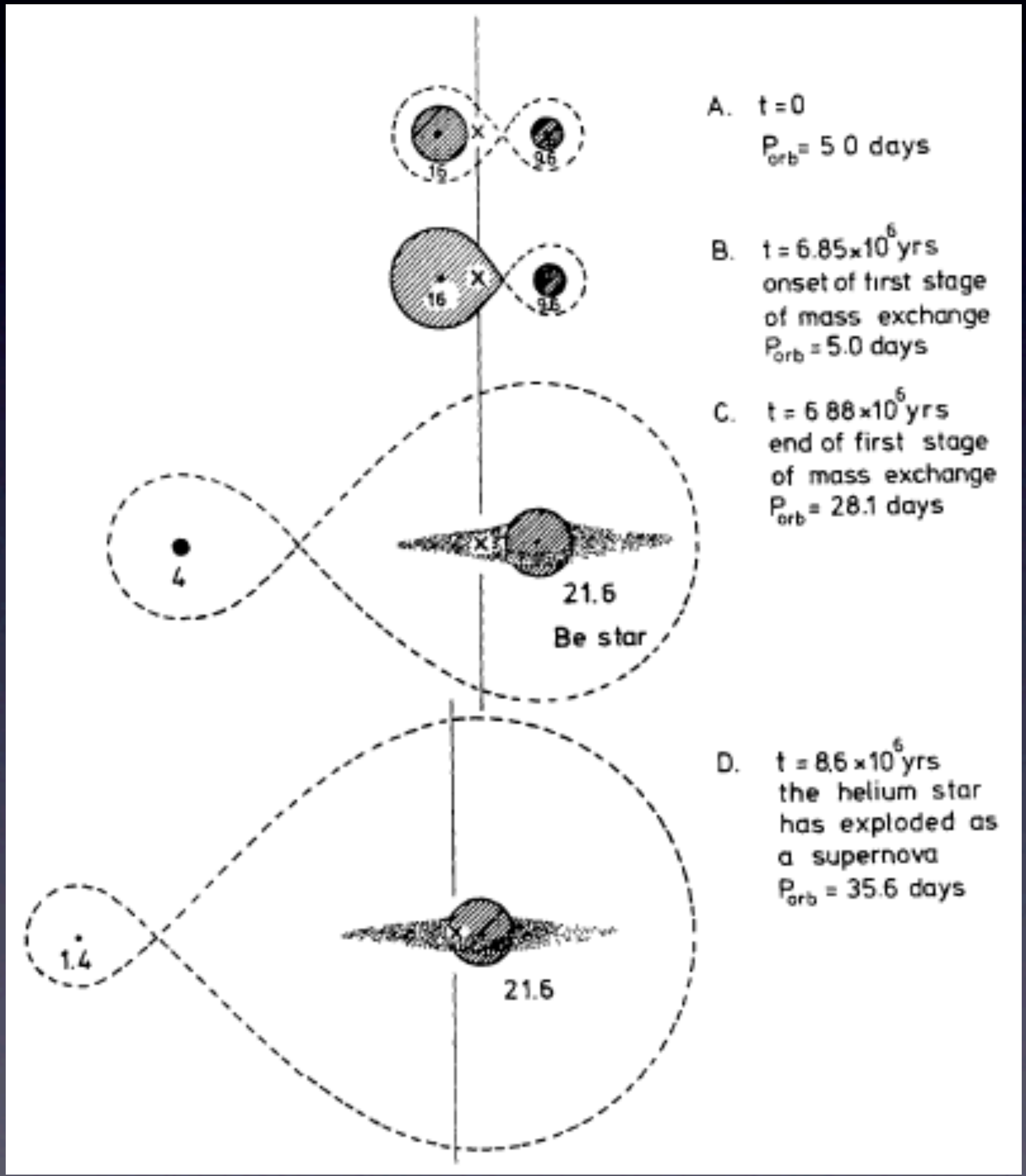


- Distribution of Be stars (Portegies Zwart 1995)
- Low-mass systems (< 8 $M_☉$, later than B2 V): disrupted by SN kick velocities & angular momentum loss
- Heavier systems (> 22 $M_☉$, earlier than 09V): become sgXBs

S. Chaty

Formation of BeXBs

- Model of Rejuvenation: product of binary evolution
- Mass transfer spins up (outer layers of) secondary star => Be phenomenon (not born as fast rotators, nor spun-up in final MS stages)
- Systems formed from moderately massive binaries undergoing semi-conservative mass transfer evolution
  - Wide orbits (200-600d) produced before SN event
  - eccentricity produced by small asymmetries during SN event



(Rappaport & van den Heuvel 1982;
van den Heuvel 1983;
Verbunt & van den Heuvel 1995)

S. Chaty

Be circumstellar disc

- Natural disk truncation due to tidal torques at certain resonance points ($P_{Keplerian}$ = integer fraction of P_{orb}): no transport of matter beyond these points
  - BeXBs with high eccentricities allow size of disc to depend on orbital phase, at periastron the disc can include NS orbit => Type I X-ray outbursts
  - Accretion on NS unlikely for BeXBs with circular orbits always truncated at fixed size, smaller than Roche lobe => Persistent low-level X-ray emission from stellar wind + occasional Type II outbursts

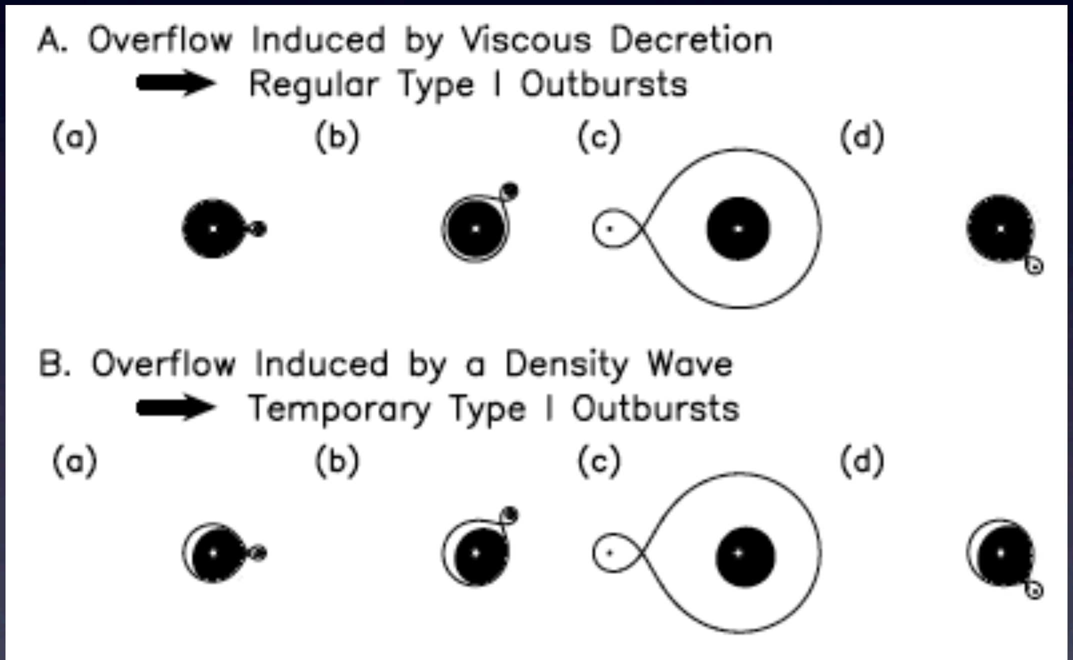
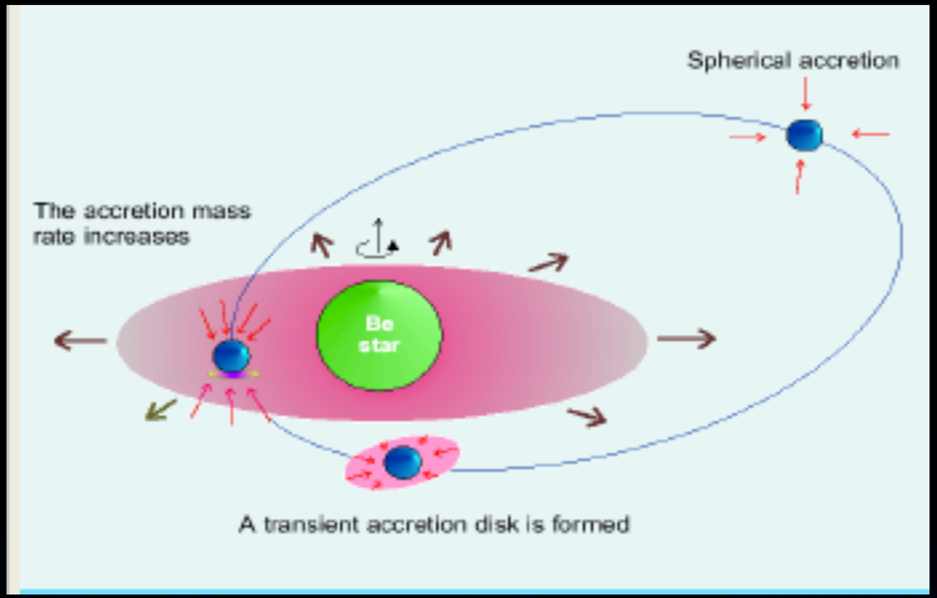


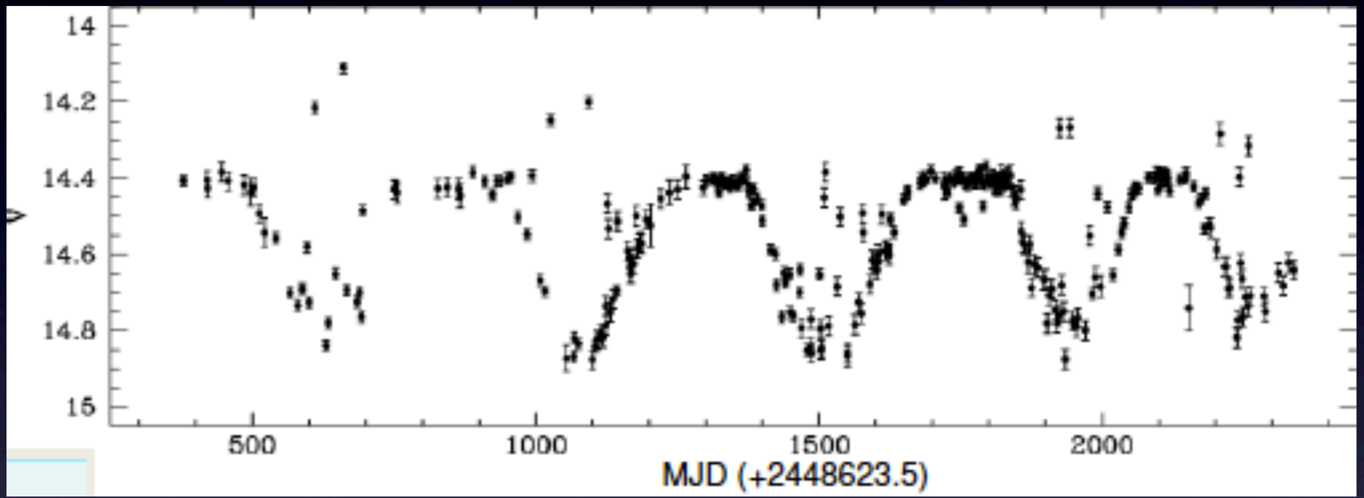
Fig. 3. Scenarios for two families of type I outbursts.

(Okazaki & Negueruela 2001)

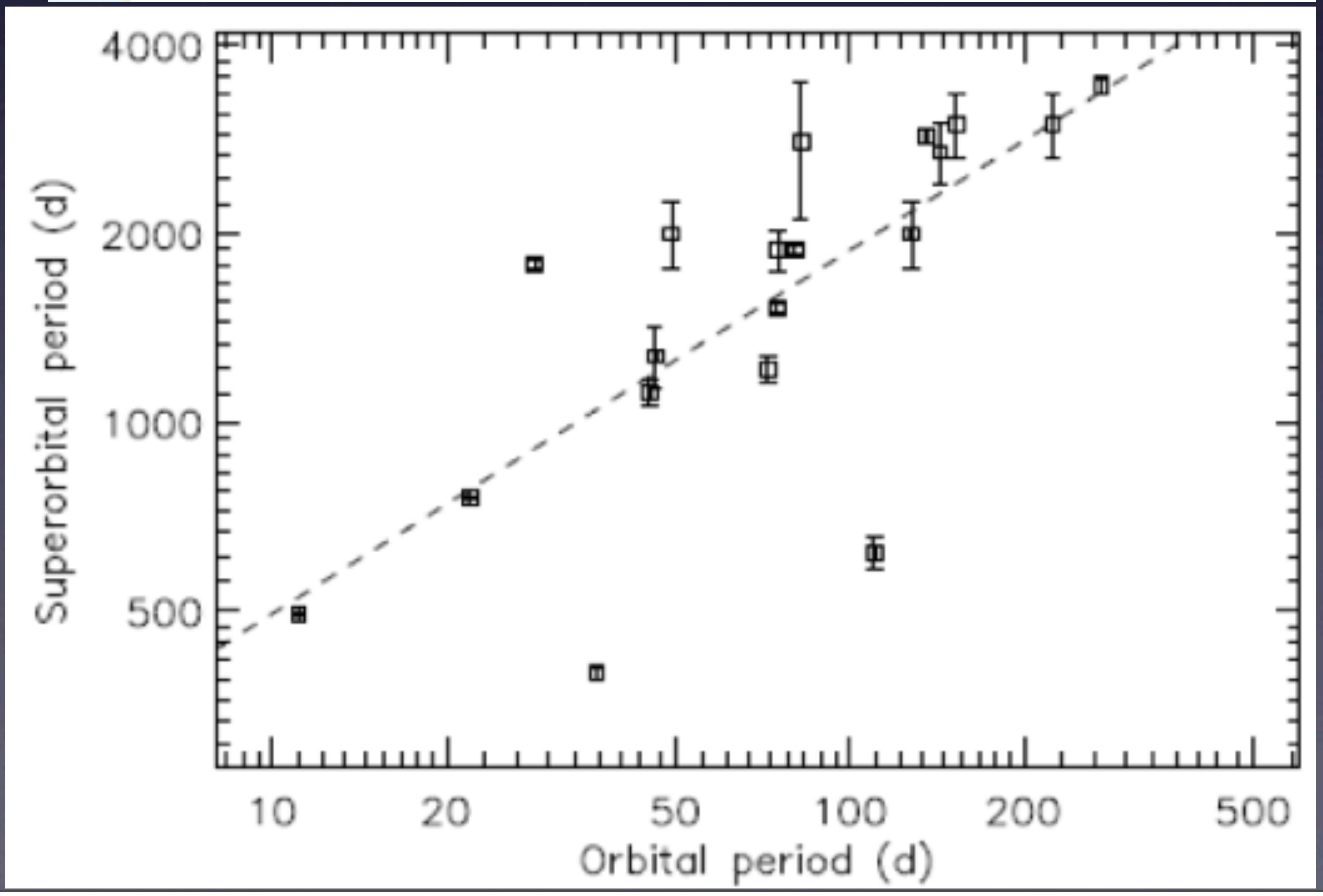
Be circumstellar disc



- Activity cycle variations in Be circumstellar disc, which forms and disperses…



- 3 periods: spin, orbital, and super-orbital
- BeXB A0538-66: P_{orb}=16.65d; P_{sup}=421d
- MACHO + OGLE: 18yr light-curves: P_{sup}: 300-3000d

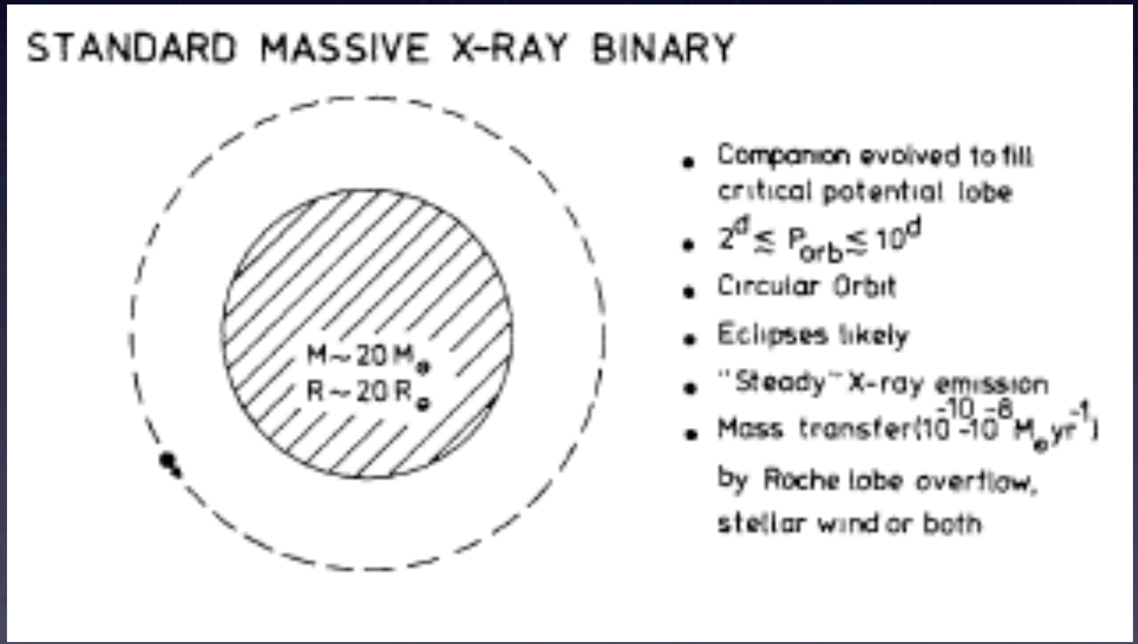


Mc Gowan & Charles 2003
Rajoelimanana et al. 2011

S. Chaty

sg X-ray binaries (sgXBs)

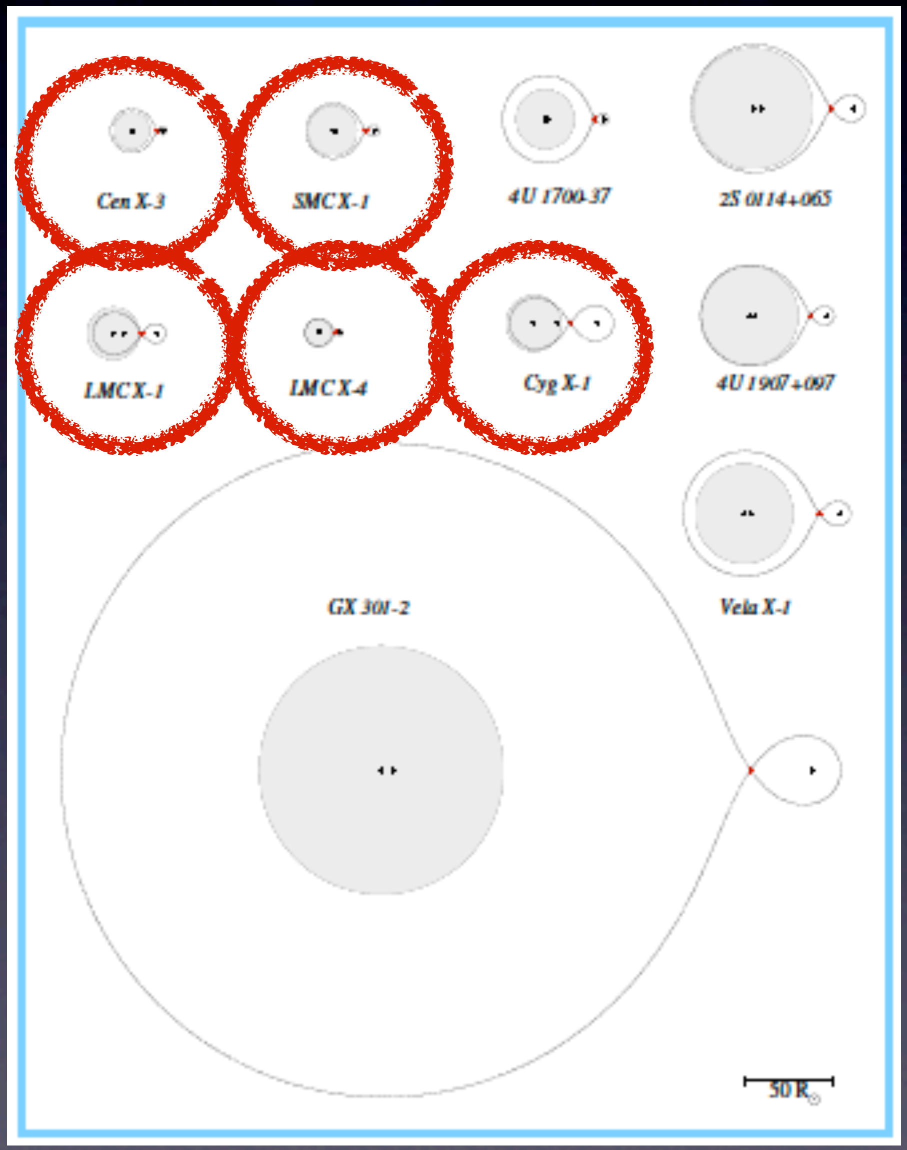
- Donor: early-type sgOB star with steady wind outflow
- Compact object: NS in circular orbit
- 2 distinct groups:
  - Roche-lobe overflow systems
  - Wind-fed accreting systems



S. Chaty

Roche-lobe overflow sgXBs

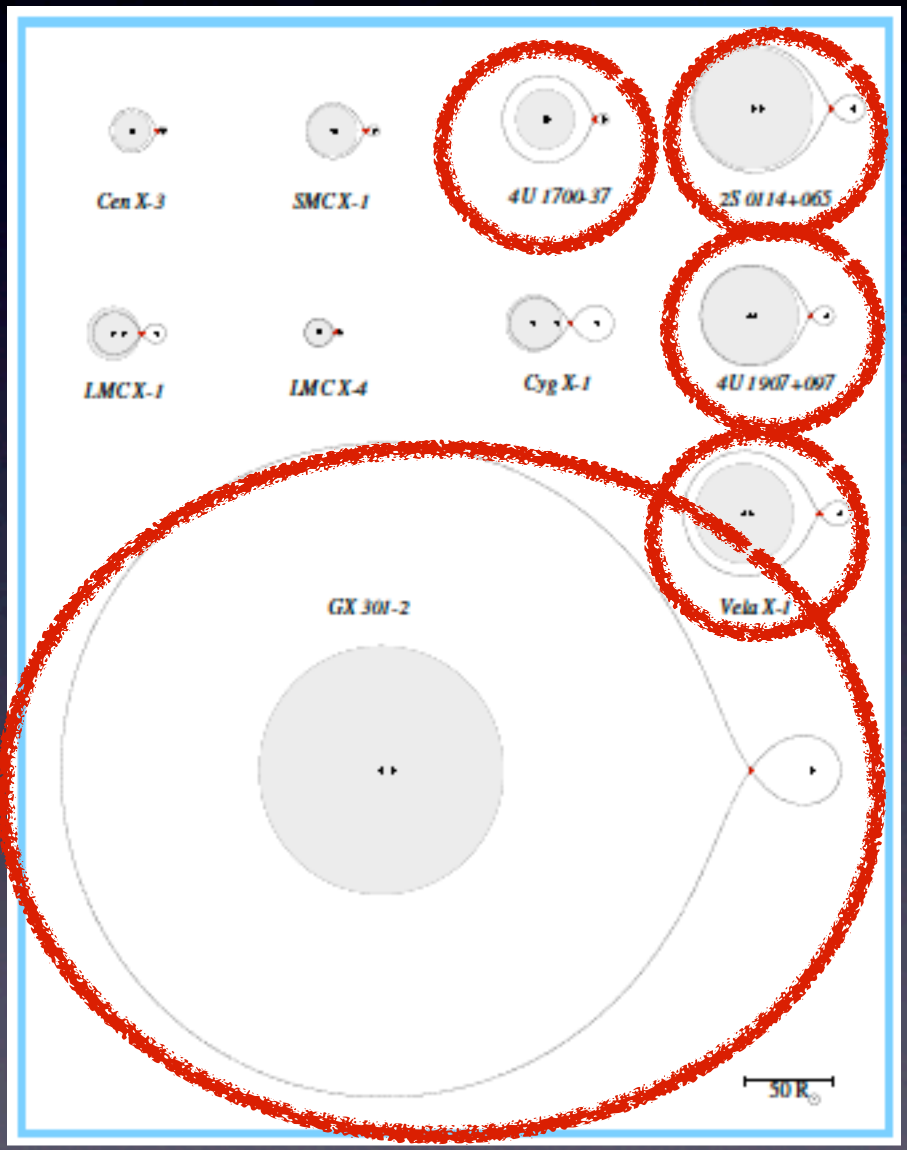
- Classical «bright» sources, NS on circular orbit
- Matter flows via inner Lagrangian point to accretion disc -> high X-ray luminosity ($L_X \sim 10^{38}$ erg/s) during outbursts
- Cyg X-1: the only sgXB with RL overflow (and stellar wind accretion) hosting a confirmed BH



(Kaper et al 2004)

Wind-fed sgXBs

- NS on close orbit (P_{orb}<15d with low eccentricity), accretes deep inside strong steady radiation-driven highly supersonic stellar wind
- Persistent X-ray emission at regular low-level effect ($L_x \sim 10^{35-36}$ erg/s); rare Type II outbursts, no Type I
- Large variations on short timescales (wind inhomogeneities)
- Orbits circularize with time & increasing mass-transfer rate



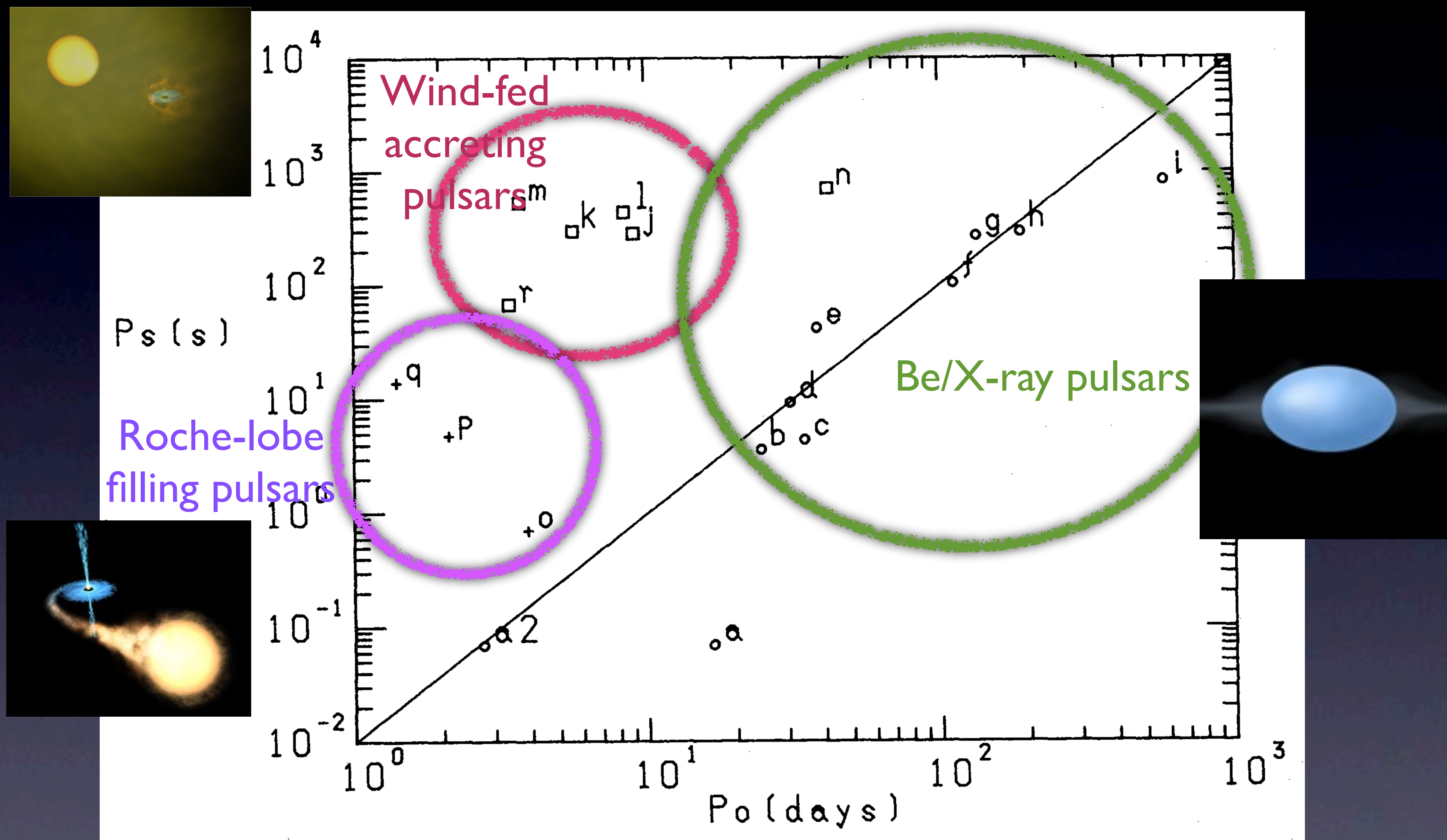
(Kaper et al 2004)

S. Chaty

The Corbet diagram

S. Chaty

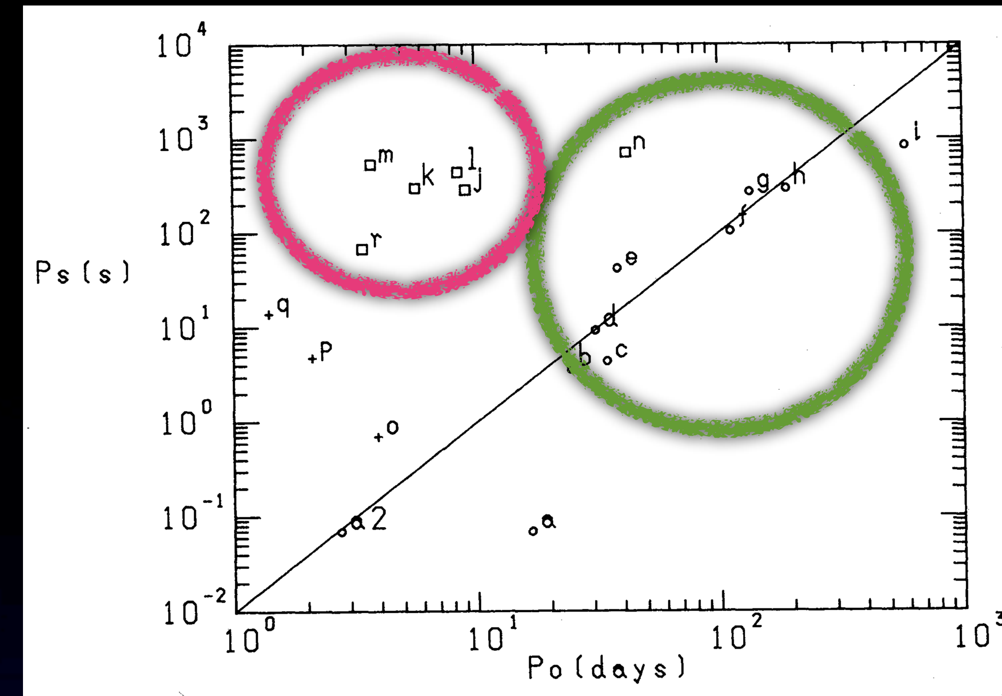
The original Corbet Diagramme (1986)



- 3 types of HMXB populations (X-ray accretion-powered pulsars) in different places due to dominant accretion process

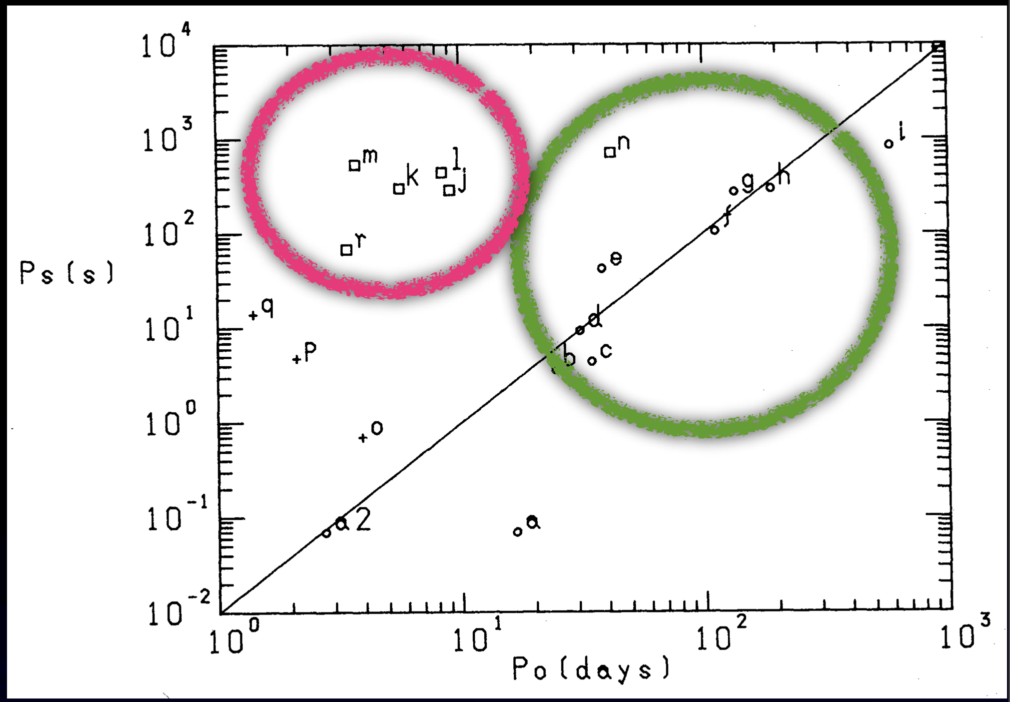
S. Chaty

BeXB correlation



- BeXBs: strong correlation NS $P_{spin} \alpha (P_{orb})^2$
    - Accretion of significant angular momentum
    - Small/wide orbit => high/low average wind density
      => strong/weak accretion pressure
      => low/high P_{spin} (~high/weak centrifugal inhibition)
- sgXBs: no correlation due to low net angular momentum of accreted matter...

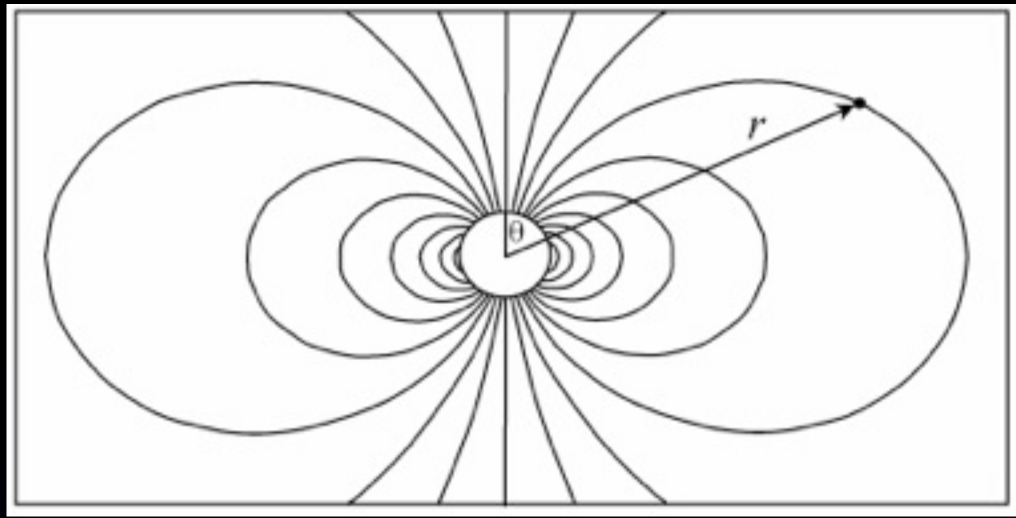
NS P_{spin} on the Corbet Diagramme



- HMXB P_{spin} regulated by stellar wind characteristics:
  - Supergiants: spherically-symmetric wind: density $\rho(r) \alpha\ r^{-2}$; velocity v: ~600-900 km/s
  - Be stars: wind density drops faster: $\rho(r) \alpha\ r^{-3->-3.5}$; v: ~200-300 km/s
- Larger gradients of ρ & v at NS distance in BeXBs => accretion of angular momentum more efficient (Waters et al. 1988; Waters & van Kerkwijk 1989)

S. Chaty

NS P_{spin} on the Corbet Diagramme



- Accretion occurs on magnetized NS only if pressure of infalling material > centrifugal inhibition
  (Alfven radius inside magnetospheric boundary)

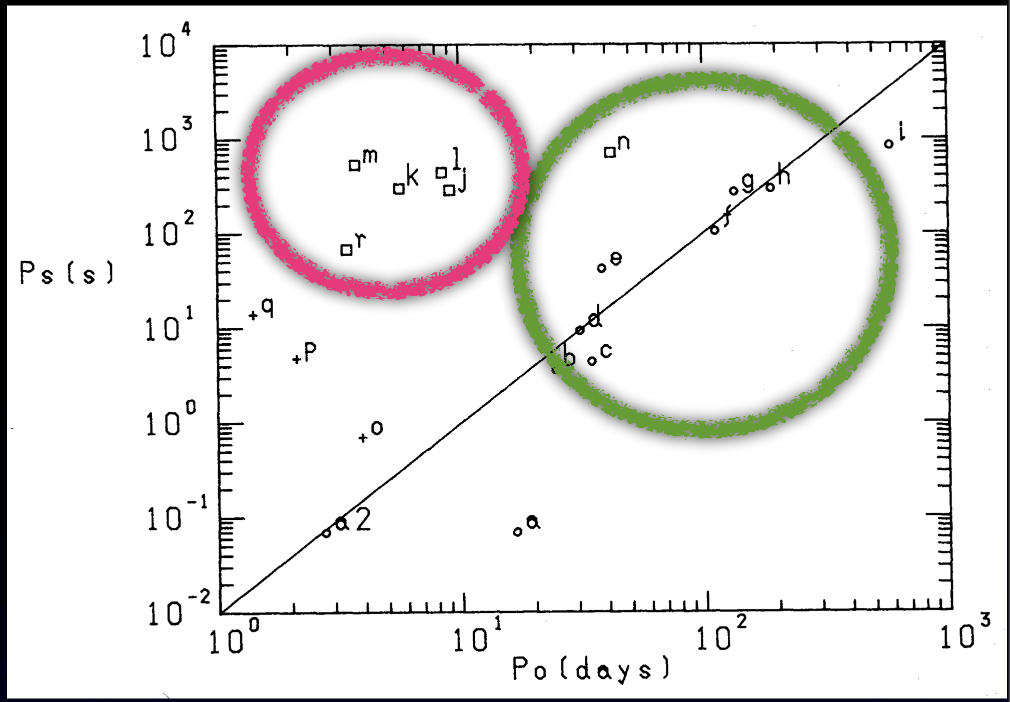
- Equilibrium period P_{eq} for which corotation velocity V_C = Keplerian velocity V_K (at magnetospheric radius)

  - $V_C > V_K$ ($\sim P_{spin} < P_{eq}$): Propeller mechanism increases P_{spin}
    (material spun away taking angular momentum)

  - $V_C < V_K$ ($\sim P_{spin} > P_{eq}$): accretion reduces P_{spin}
    (Illarionov & Sunyaev 1975)

S. Chaty

NS P_{spin} on the Corbet Diagramme



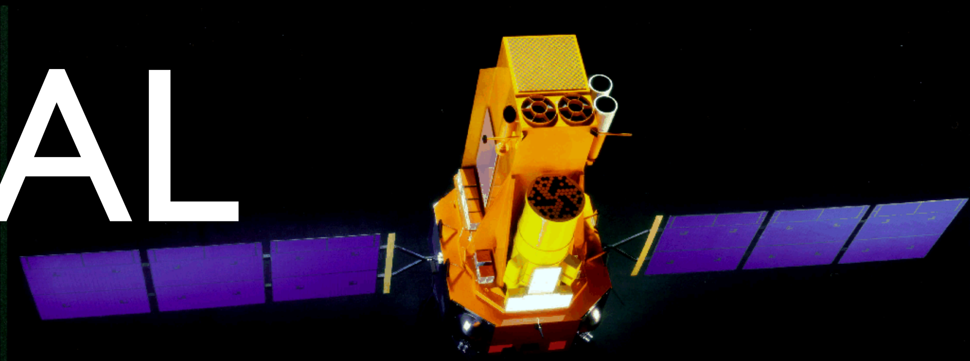
- Given density & steady accretion rate depending on direction of angular momentum vs NS spin: P_{spin} reaches $P_{eq} \alpha \rho^{-3/7}$
  - Current NS P_{spin} in sgXBs longer than predicted, closer to P_{eq} of stellar wind while the star was still a MS O star (Waters & van Kerkwijk 1989)
  - $P_{spin} \neq P_{eq}$ in BeXBs, constantly adjusting to changing conditions in wind: reflect values of earlier evolutionary stage (King 1991)

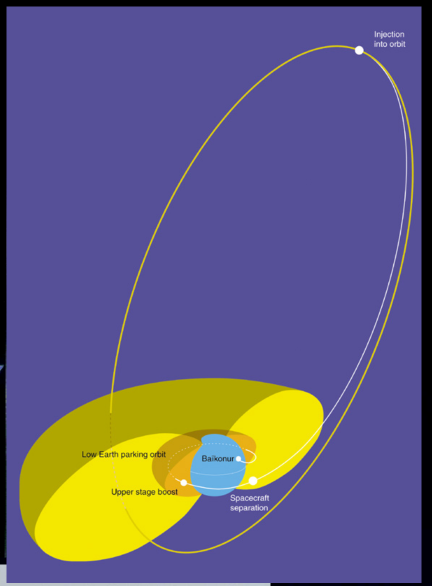
S. Chaty

The INTEGRAL Legacy

S. Chaty

The INTEGRAL observatory

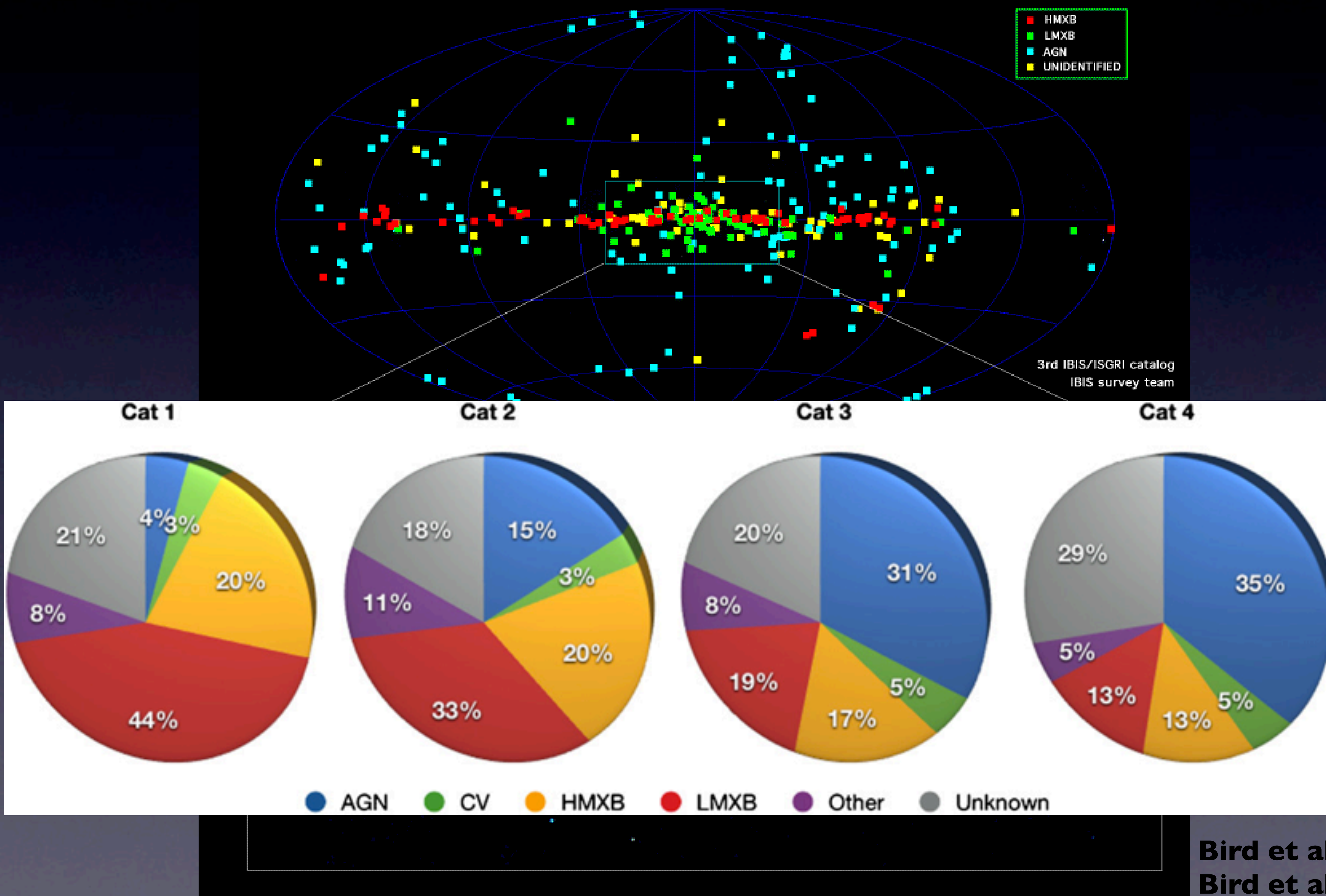




- ESA satellite launched on 17/10/2002 by PROTON rocket on eccentric orbit
- 2 γ-ray coded mask telescopes 10 keV-10 MeV, 12’ resolution, 19° fov

S. Chaty

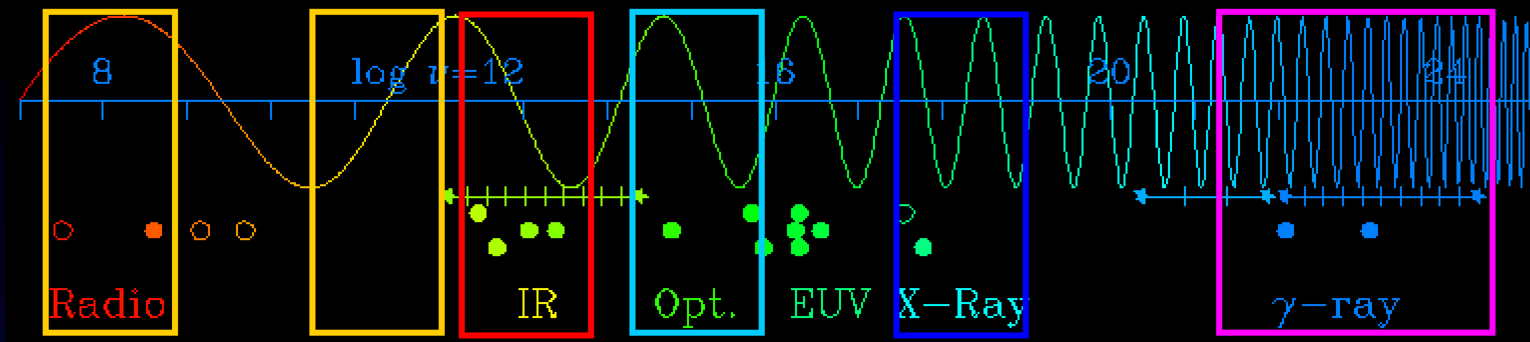
The Milky Way

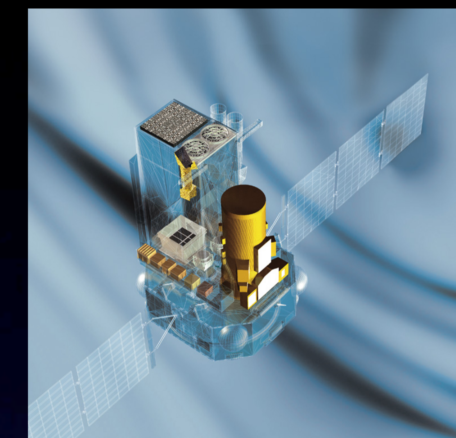


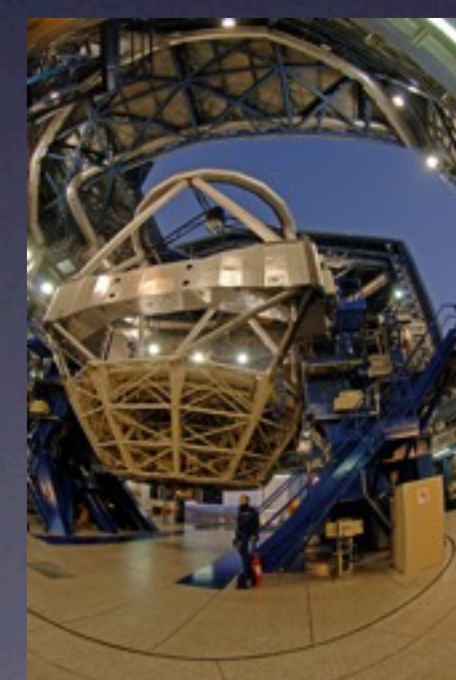
Bird et al. 2007
Bird et al. 2010

S. Chaty

Multiwavelength observations







- Discovery: INTEGRAL (X/γ)
- Localisation: XMM/Swift/Chandra (X)
- Identification: opt/IR (ESO Paranal VLT / La Silla NTT)

Identification of sources

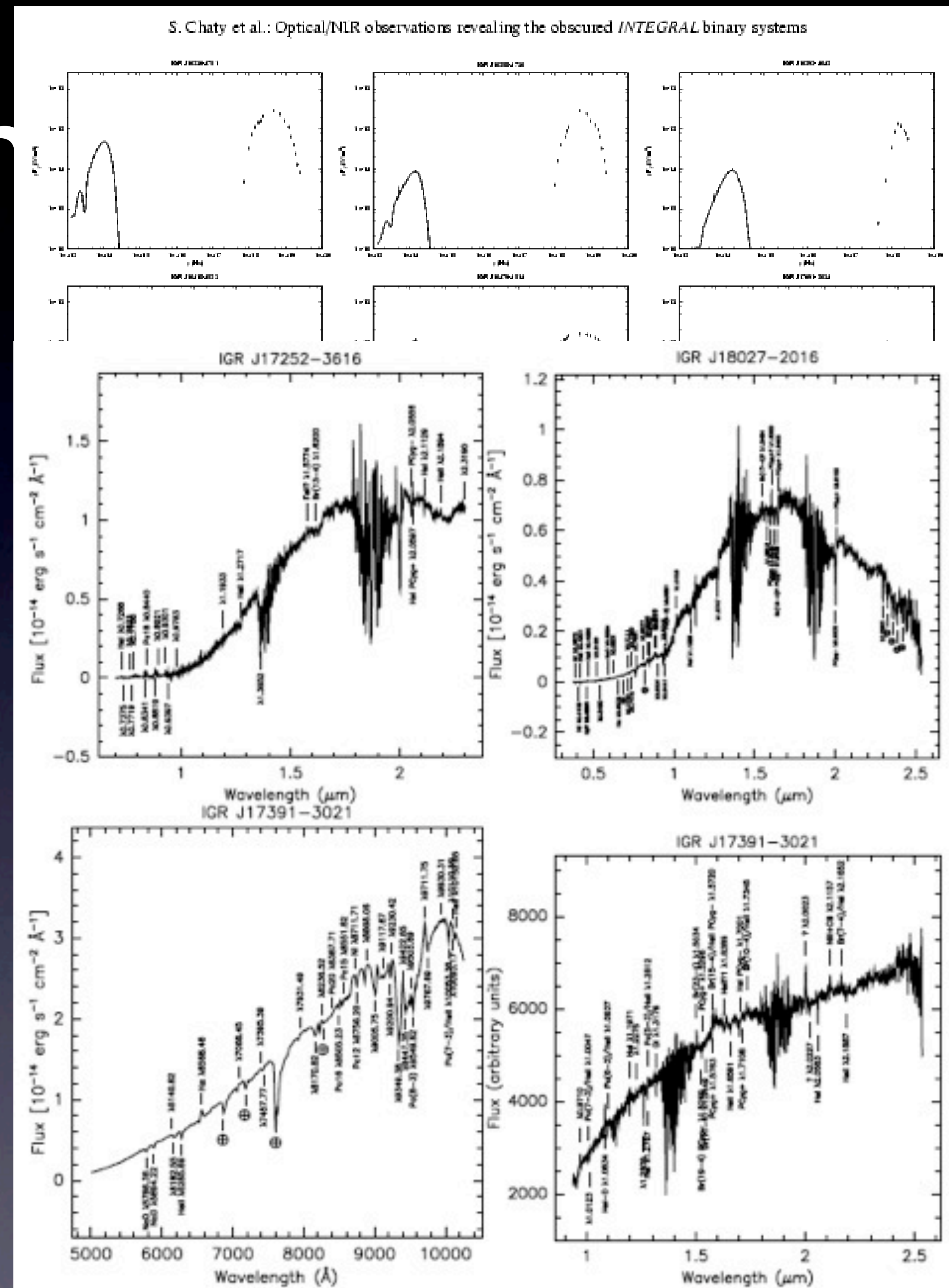
- 4+20+1+5 IGRs localised with Chandra:
  Butler et al. 2009; Paizis et al. 2007; Tomsick, Chaty, Rodriguez et al. ApJ, 2006, 2008, 2009

- 12+17 IGRs localised with Swift:
  Rodriguez, Tomsick, Chaty, A&A, 2008a and 2008b

- Multi-wavelength follow-up of ~50 sources:
  Chaty, Rahoui, Foellmi et al., A&A, 2008; Filliatre & Chaty 2004; Rahoui et al. A&A 2008; Filliatre & Chaty, ApJ 2004, Pellizza, Chaty, Negueruela A&A 2006; Rahoui & Chaty 2010; Zurita Heras & Chaty 2008, 2009; Curran et al. 2011abc

Identification

- Astrometry
- Photometry
- Spectroscopy
- Results: ~20 sgHMXBs, some with MIR excess

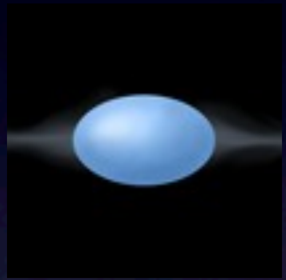


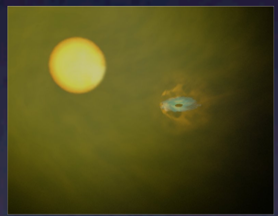
Chaty, Rahoui, Foellmi, Rodriguez, Tomsick, Walter et al. 2008

3 observational facts:

- I. INTEGRAL has quadrupled the known population of sgXBs
- II. INTEGRAL has revealed a previously hidden population of obscured sgXBs
- III. INTEGRAL has discovered huge and fast transient flares in sgXBs

Statistics on HMXBs



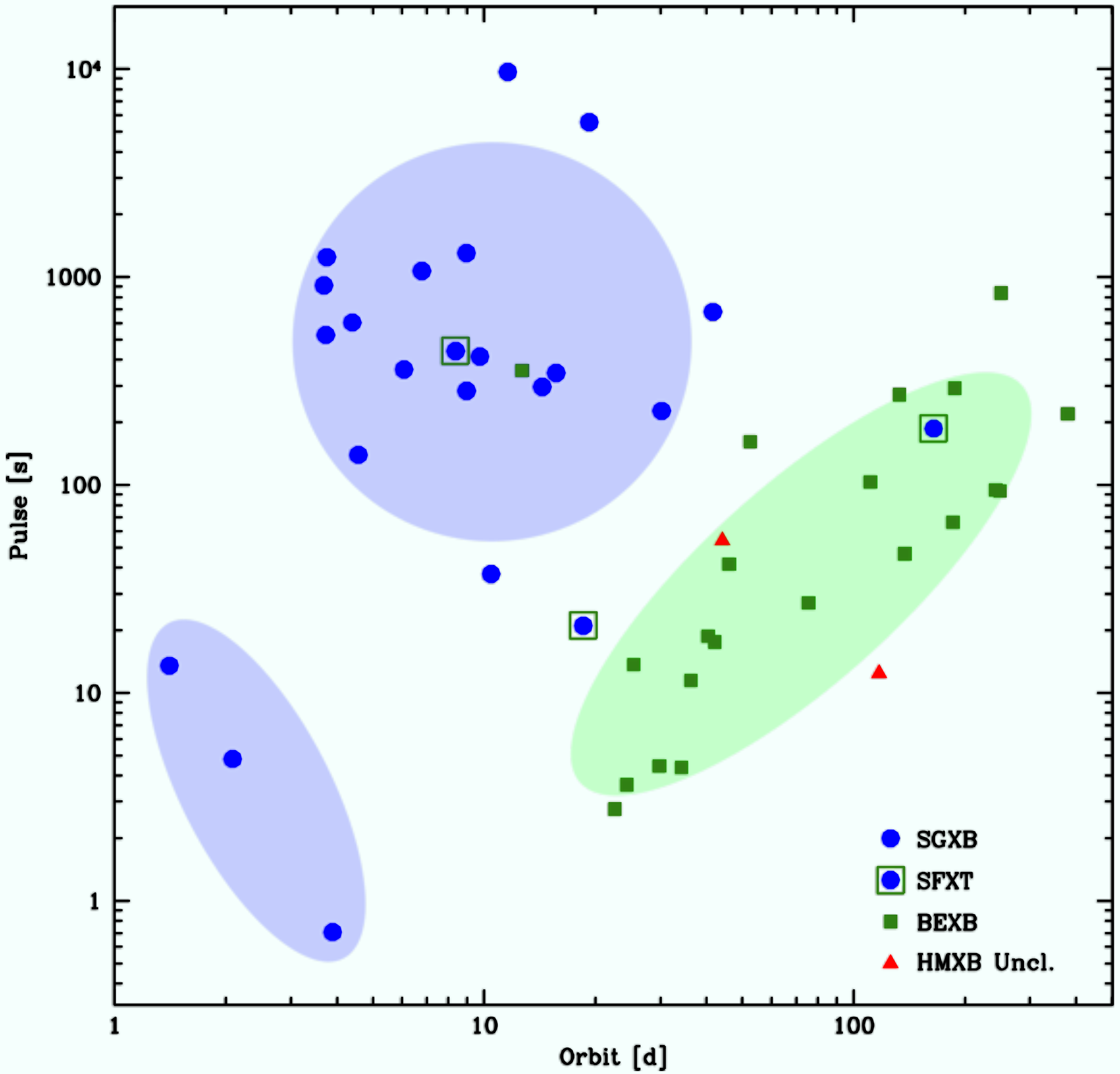


- Before INTEGRAL launch, HMXBs were mostly BeXBs: 54 (42%) BeXBs & 7 (5%) sgXBs (out of 130 HMXBs, Liu et al. 2000)
- 9 years later: 52 (46%) BeXBs & 29 (25%)(x5) sgXBs (out of 114 HMXBs, +128 in MCs, Liu et al. 2006)
- From study of individual sgXBs (GX 301-2, 4U 1700-377, Vela X-1…) to characteristics of whole population...

S. Chaty

The Corbet Diagramme revisited by IBIS/ISGRI

- 22 BeXBs
- 20 sgXBs
- 3 SFXTs
- 2 unclXBs
- P_{spin}: 0.6->10^4s



Bodaghee et al. 2007

S. Chaty

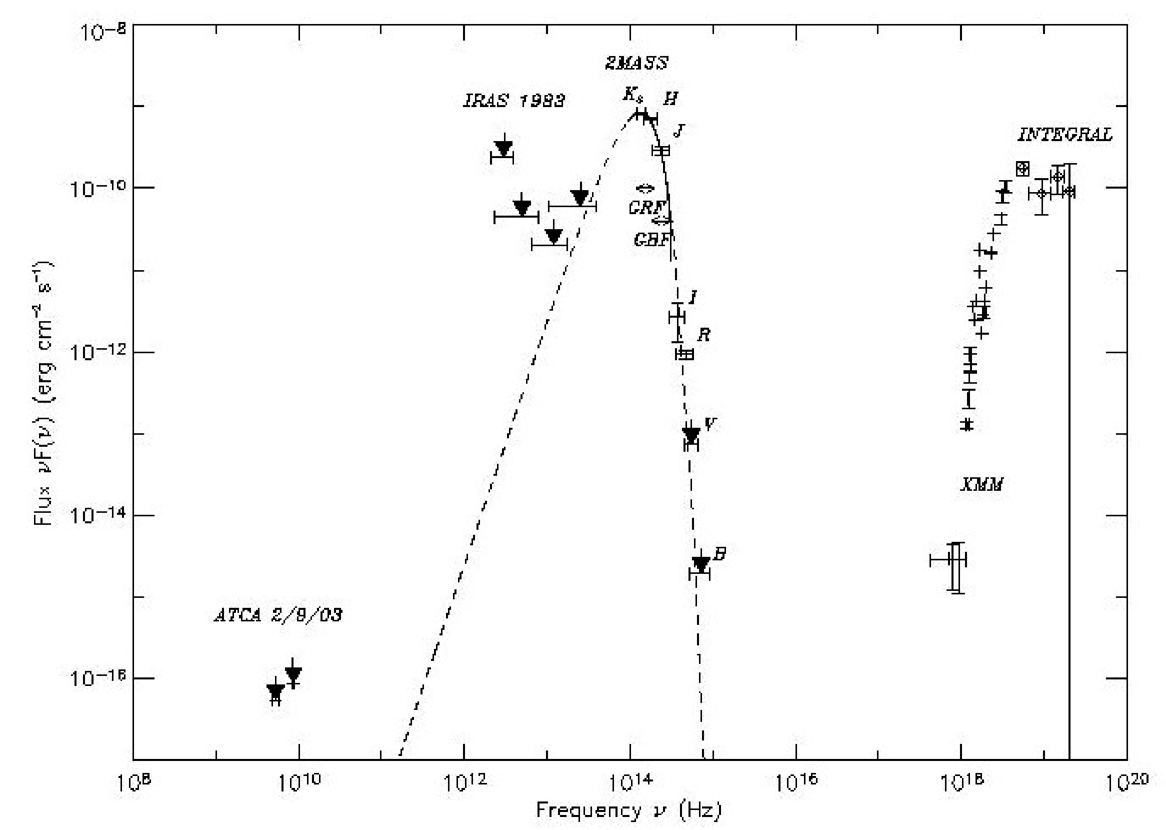
3 observational facts:

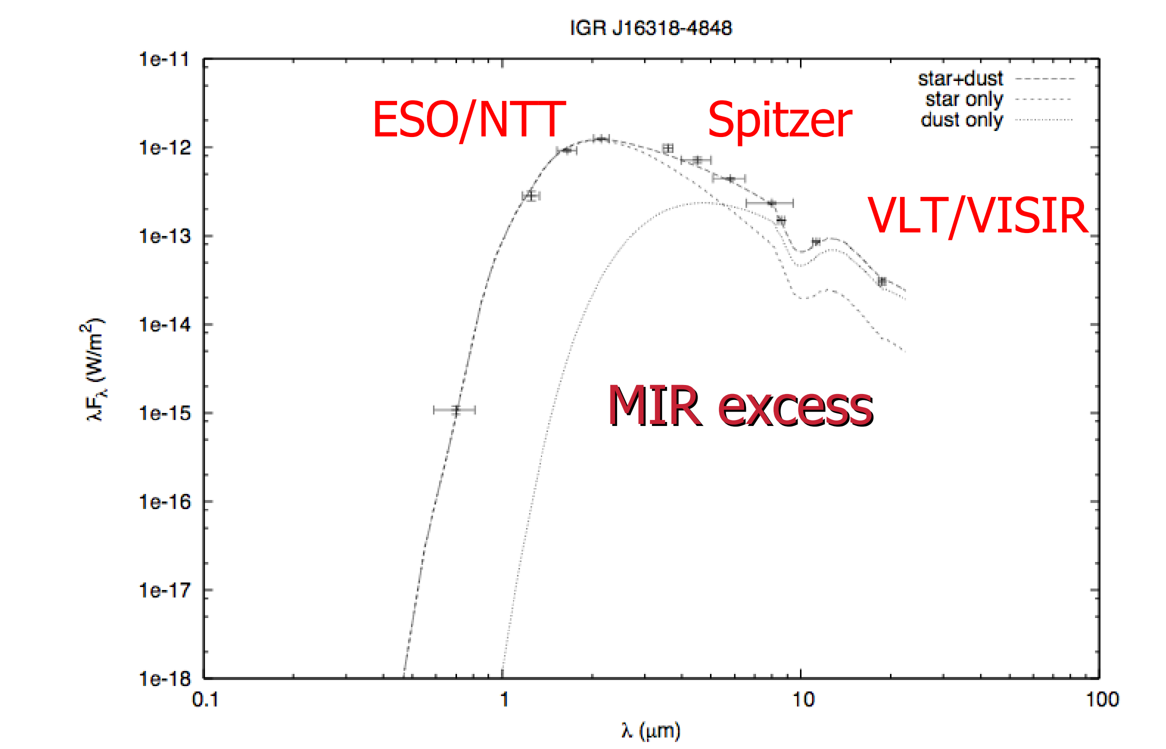
- I. INTEGRAL has nearly quadrupled the known population of sgXBs
- II. INTEGRAL has revealed a previously hidden population of obscured sgXBs
- III. INTEGRAL has discovered huge and fast transient flares in sgXBs

S. Chaty

Obscured source: IGR J16318-4848

- 1st source discovered by INTEGRAL; bright IR counterpart
- Unusual absorption A_V=17 mag, 100x>IS, but 100x<X
- MIR excess (ESO/NTT+VLT & Spitzer observations)

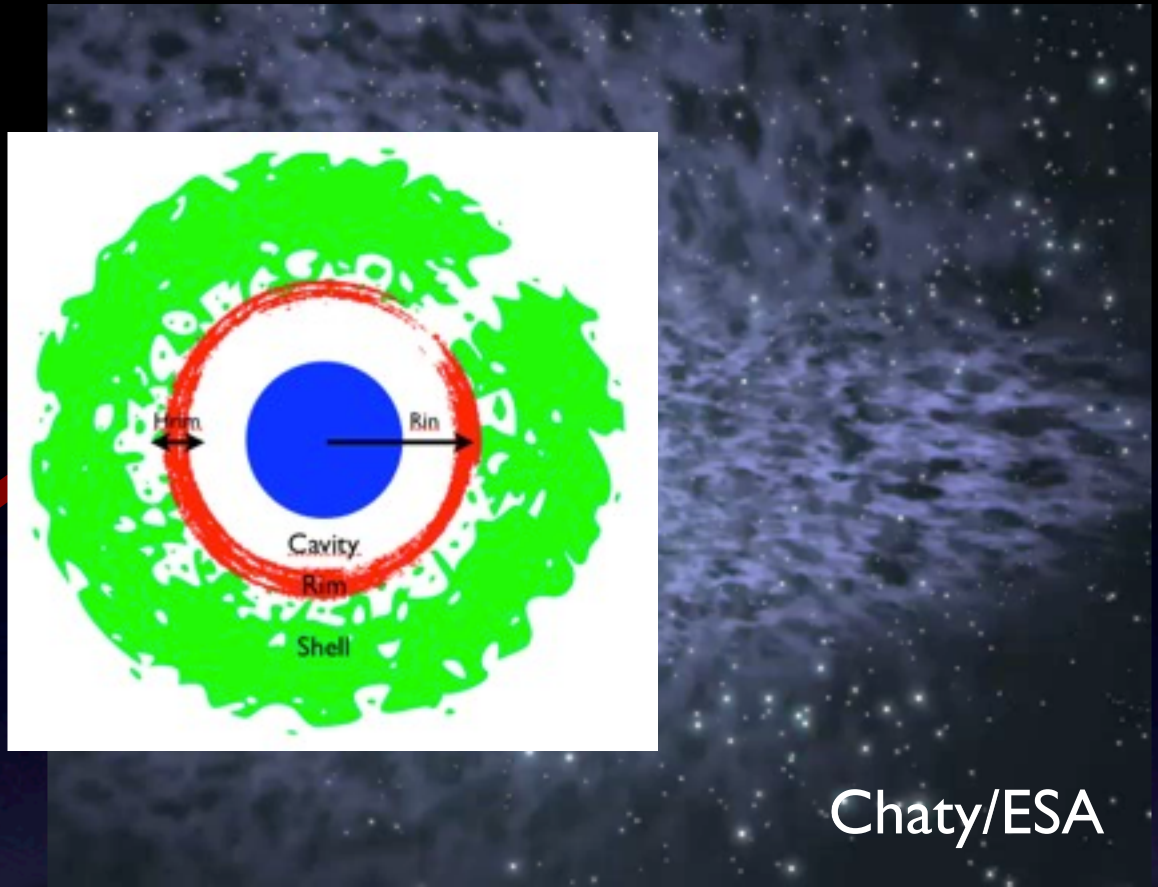


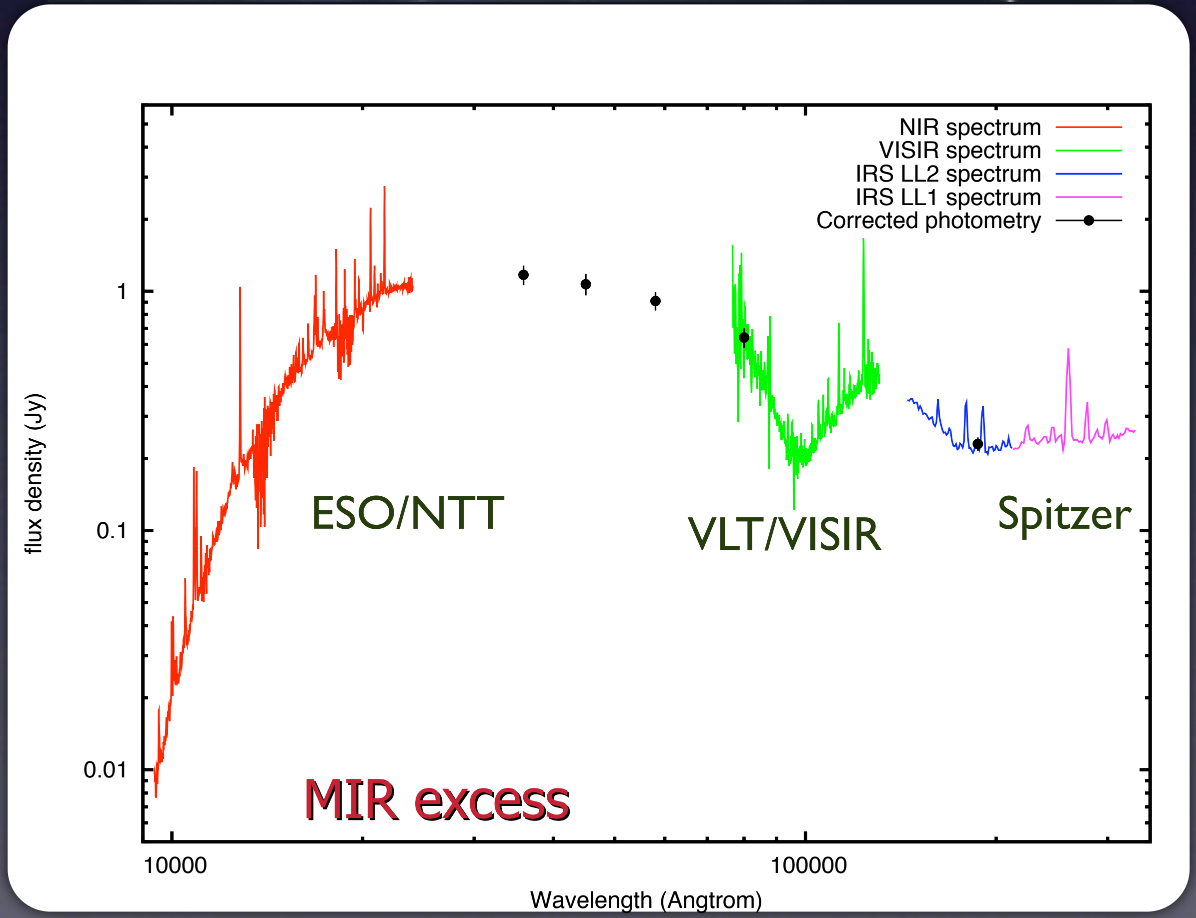


Filliatre & Chaty 2004; Rahoui et al. 2008

Obscured source: IGR J16318-4848

- NIR spectrum: stratified circumstellar enveloppe, wind: Luminous sgB[e] star: $10^6 L_\odot$, $30 M_\odot$, 22000K, $20 R_\odot = 0.1$au
- MIR VISIR photometry: $T_d = 1100$K, $R_d = 12 R_* = 240 R_\odot$ (=1au) If $P_{orb} = 10$d=> $a = 50 R_\odot < R_d$ => dust cocoon enshrouds the whole binary system
- MIR VISIR+Spitzer spectrum: aspheric geometry, disk rim at 5500K, warm dust shell at 900K

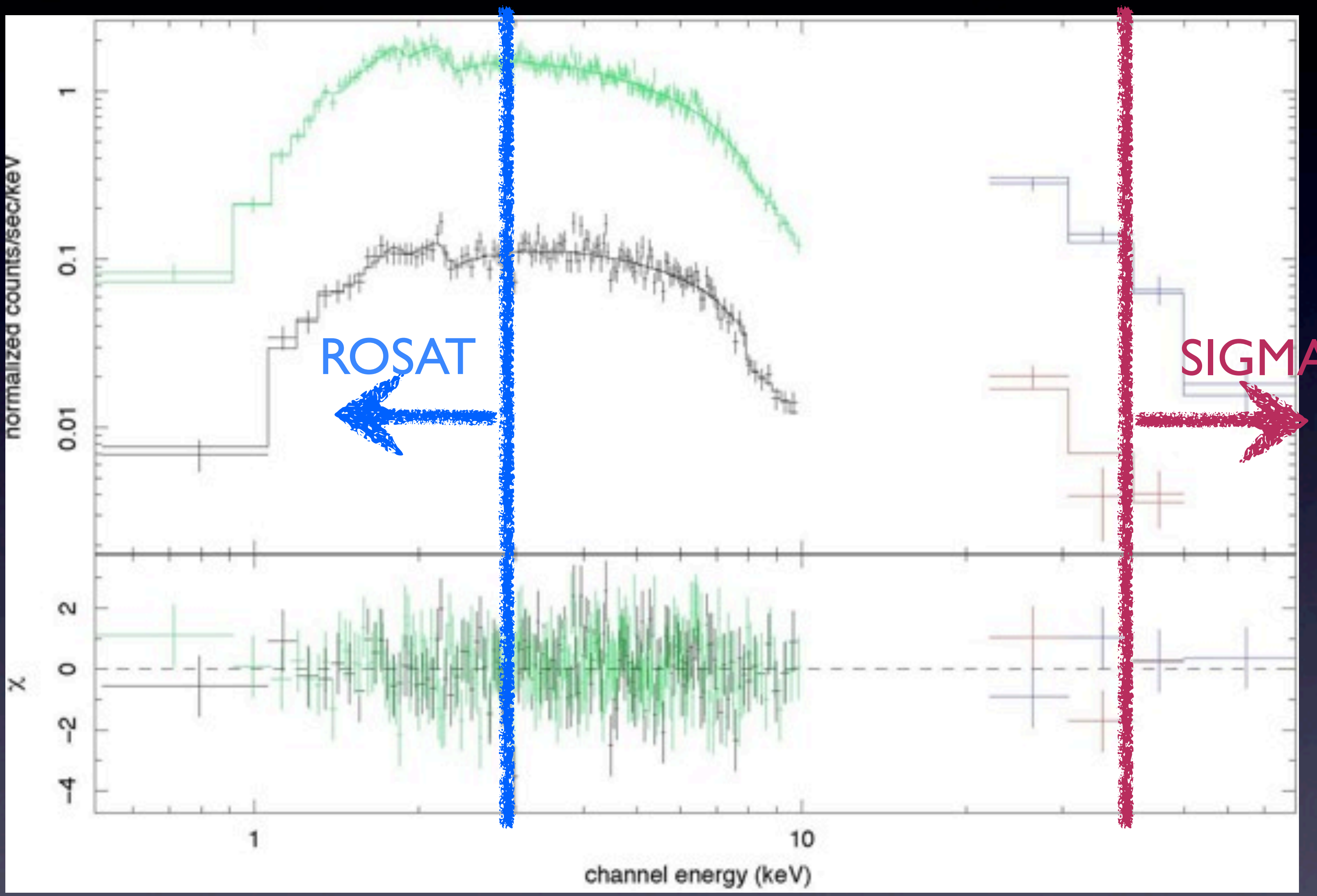




Chaty & Rahoui 2011; Filliatre & Chaty 2004; Rahoui et al. 2008

S. Chaty

Why INTEGRAL?



- ISGRI (>20 keV) immune to absorption that prevented discovery of intrinsically absorbed sources with earlier soft X-ray telescopes (Spectrum IGR J18450-0435)

Zurita Heras & Walter 2009

S. Chaty

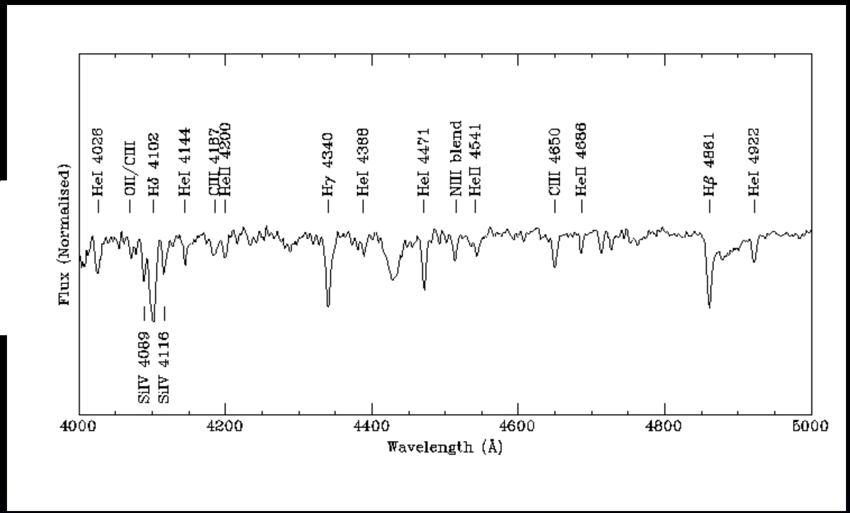
Why INTEGRAL?

- Flux (40-100 keV) in mCrab (Bird et al. 2010)
  - SFXT IGR J17544 = 0.2+/-0.1 (8 Ms) (Peak flux 20-40 keV = 33.7 mCrab)
  - SFXT XTE J1739 = 0.8+/-0.1 (8 Ms) (Peak flux 20-40 keV = 43.9 mCrab)
  - Obscured IGR J16318 = 14.2+/-0.1 (3.4Ms) IGR J16320 = 5.7+/-0.1 (3.3Ms)
  - Vela X-1= 54.3+/-0.2 (3 Ms) 4U1700-377=120.8+/-0.1 (5.5 Ms)
- This explains why only bright sgXBs (~Vela X-1) were known before...

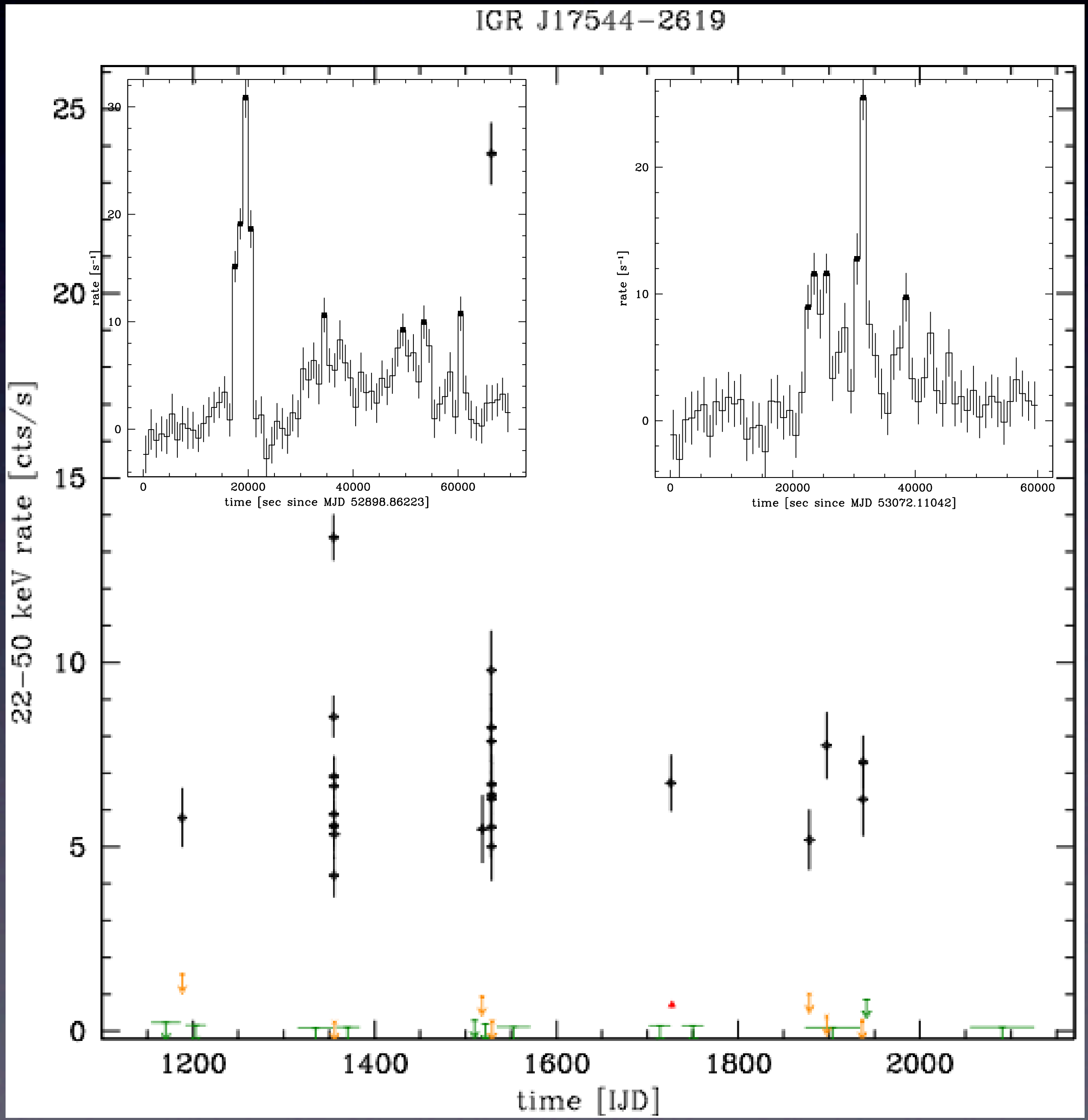
3 observational facts:

- I. INTEGRAL has nearly quadrupled the known population of sgXBs
- II. INTEGRAL has revealed a previously hidden population of obscured sgXBs
- <u>III. INTEGRAL has discovered huge and fast transient flares in sgXBs</u>

SFXTs: IGR J1754



- sgXB: NS + blue O9Ib supergiant star (25M☼, 31000K, 22R☼), P_{orb}=4.9d (½ of bright & persistent source Vela X-1!)
- X-ray study: short (~hr) but complex & intense X-ray flares (factor of 10^{4-5})
- SFXT = Supergiant Fast X-ray Transient 10^{32-34} erg/s



Pellizza, Chaty, Negueruela 2006
Zurita Heras & Chaty 2009

S. Chaty

Accretion processes

- Accretion from clumpy stellar wind:
  study of density, structure & size of clumps
  (Owocki 2009; in't Zand 2005; Walter & Zurita Heras 2007, Negueruela et al. 2008, Ducci et al. 2009)
- Formation of transient accretion disks
  (Ruffert 1997; Ducci et al. 2010)
- Accretion with centrifugal/magnetic barriers
  (Bozzo et al. 2008)

Macro-clumping scenario

- Each SFXT outburst due to accretion of single clump, X-ray lightcurve = direct tracer of wind density
- Very high degree of porosity (macro-clumping) required to reproduce outburst frequency in SFXTs: good agreement with UV line profiles
- Flare/quiescent count rate ratio => clumps/inter-clump density ratio:
  - 15-50 in Intermediate systems
  - 10^{2-4} in SFXTs (~line-driven instabilities at large radii)

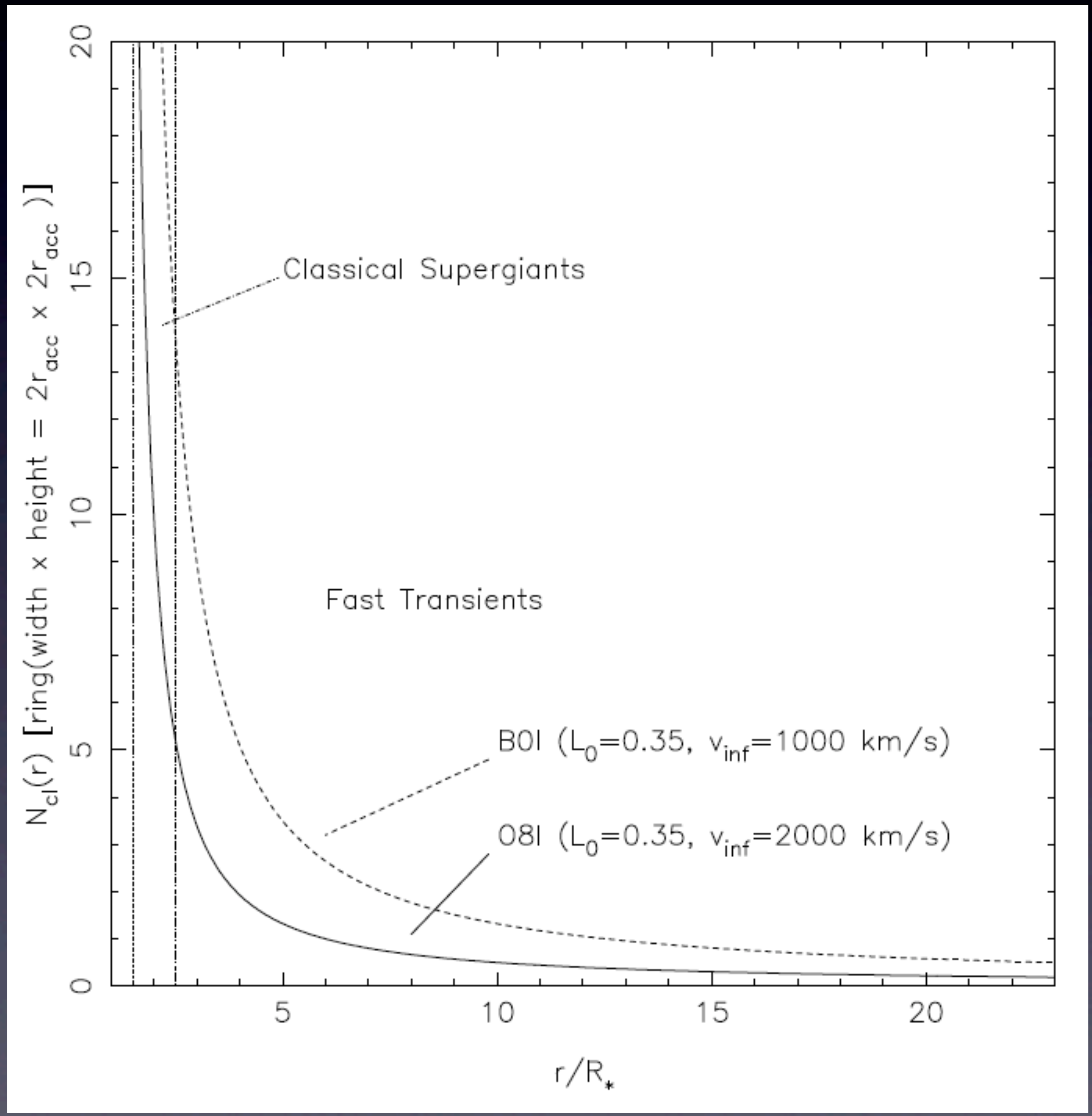
S. Chaty

Macro-clumping scenario

- Typical wind clump parameters:
  - Compact object with large orbital radius: 10 R_*
  - Clump size: few tenths of R_*
  - Clump mass: $10^{22\text{-}23}$ g (for $N_H = 10^{22\text{-}23}$ cm^{-2})
  - Mass loss rate: $10^{-(5\text{-}6)}$ $M_\odot$/yr
  - Clump separation of order R_* (at orbital radius)
  - Volume filling factor: 0.02 -> 0.1

sgXBs vs SFXTs

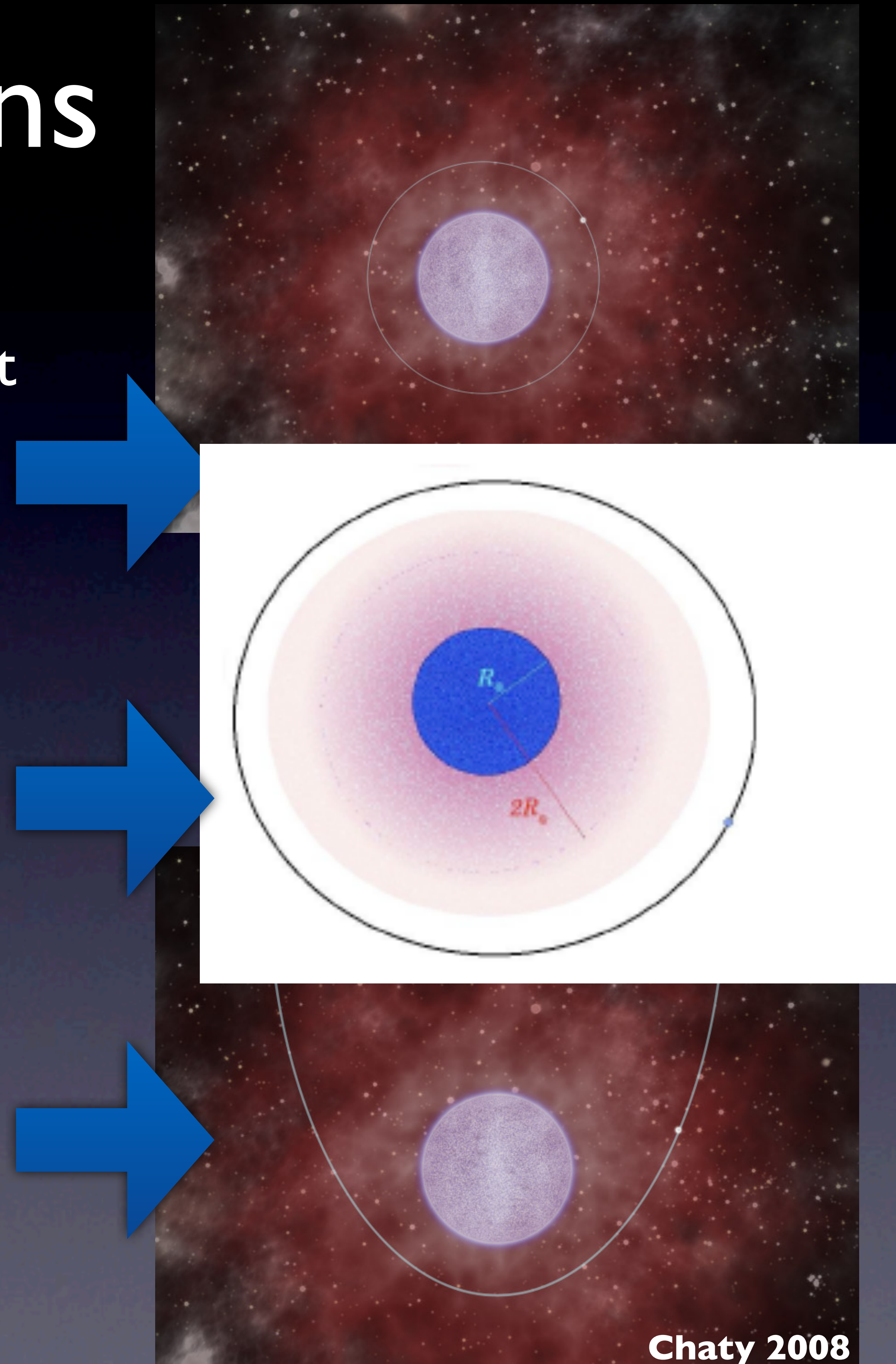
- Basic model of porous wind predicts a substantial change in properties of the wind «seen by NS» at distance r~2R*
    - r<2R*: NS sees a large number of clumps, embedded in quasi-continuous wind
    - r>2R*: clump density so small that NS is effectively in empty space
- sgXBs can only lie within the 2 vertical lines



Negueruela et al. 2008

sgXB configurations

- Classical sgXB: NS on circular orbit inside dust cocoon (10R*) enshrouding whole binary system (~obscured source IGR J16318): persistent X-ray emission
- Intermediate SFXT: NS outside dense region, on circular orbit
- SFXT: NS occasionnally accretes from clumpy stellar wind on wider, eccentric orbit, longer quiescence (~XTE J1739 P_{orb} 50d)

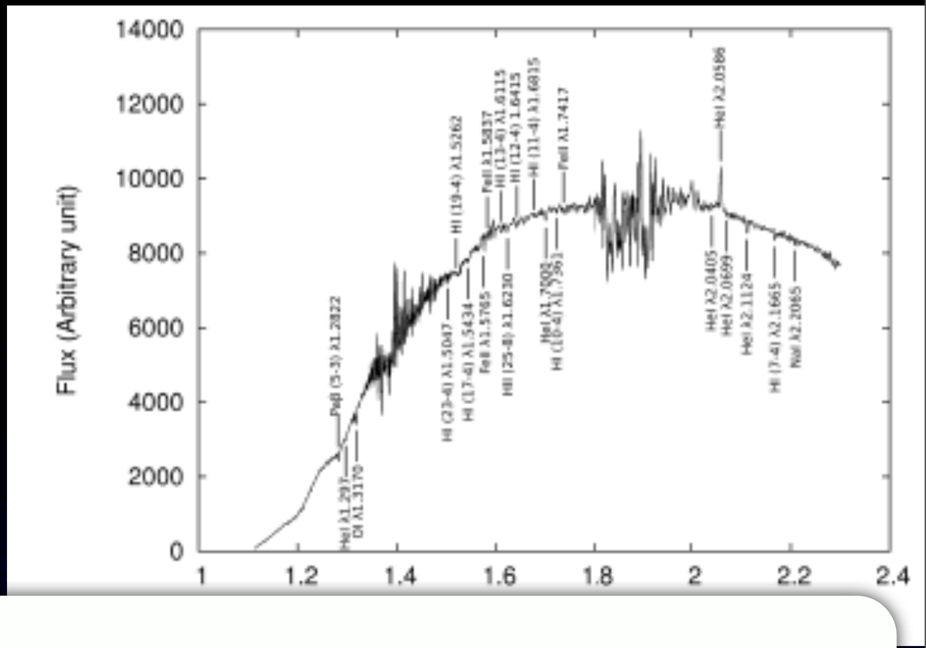


S. Chaty

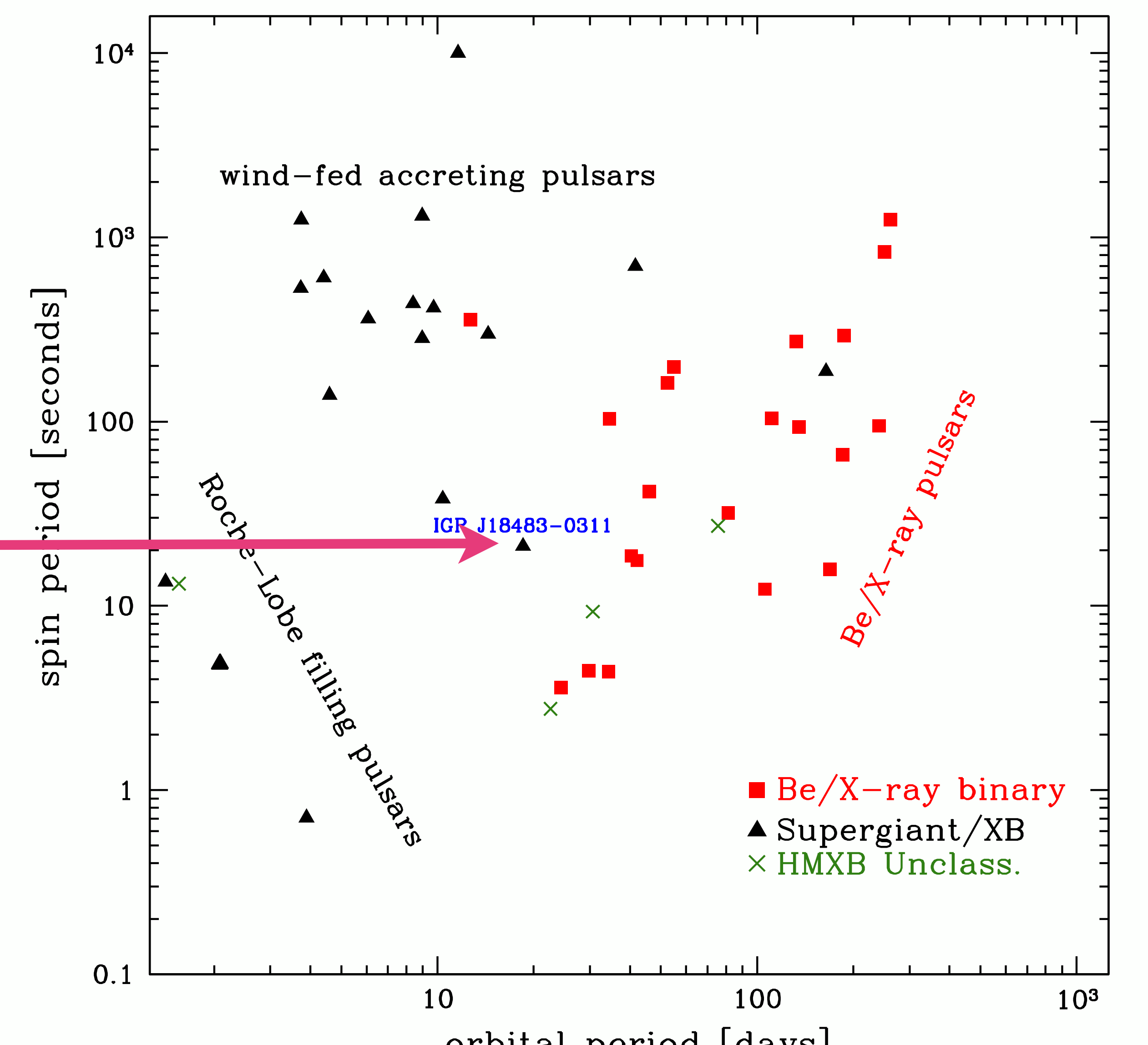
Evolution of HMXBs

S. Chaty

The missing link: IG



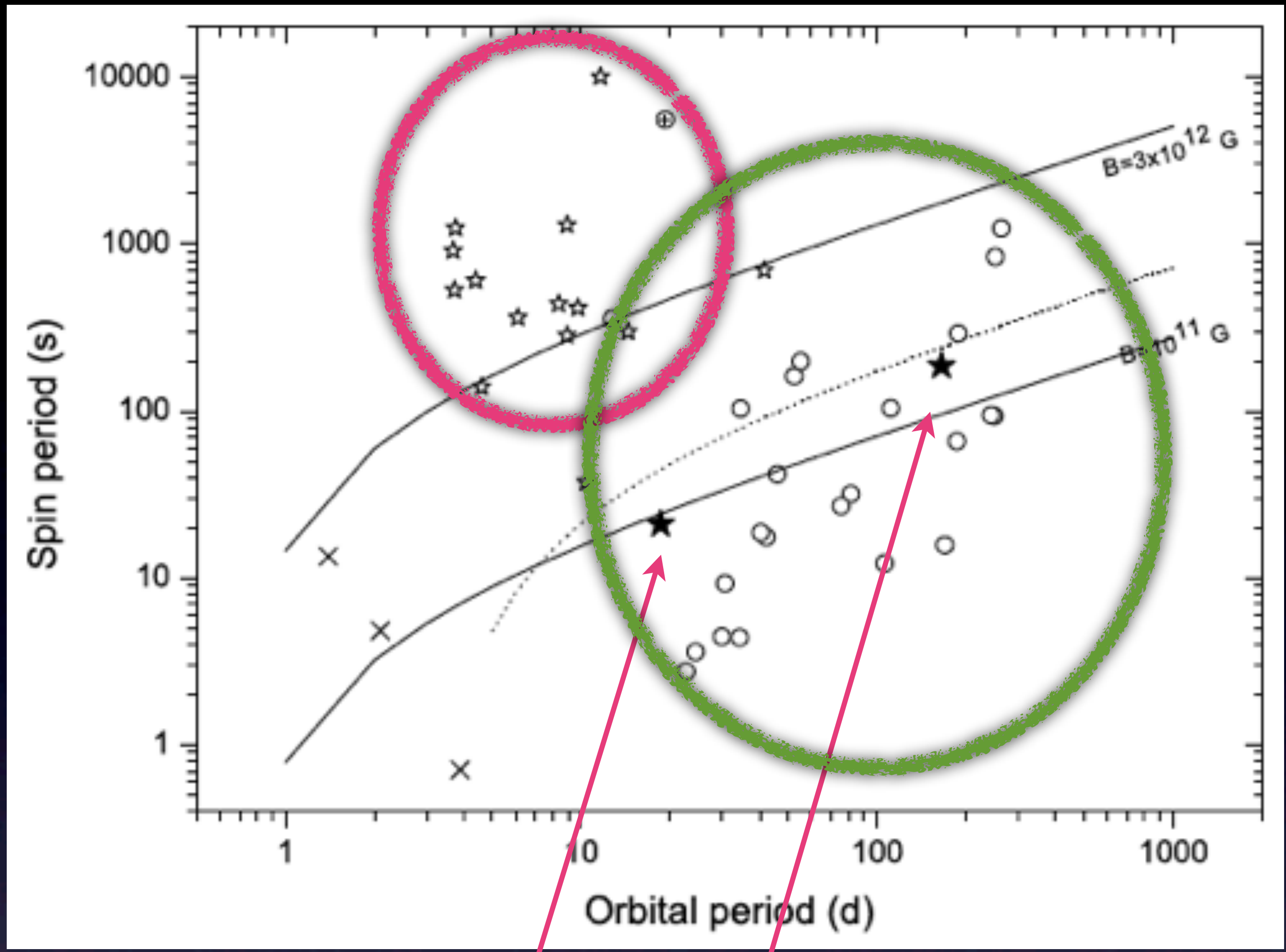
- Unusual SFXT behaviour:
  - outbursts of a few days (usually hours)
  - High level quiescence: $L_{max}/L_{min}=10^3$ (usually 10^4)
- Companion star: sg B0.5Ia; P_{orb}=18.5d, P_{spin}=21.05s
- Intermediate SFXT: NS in narrow transition zone between high/low clump density



Rahoui & Chaty 2008, A&A

S. Chaty

Origin of «misplaced» sgXBs?

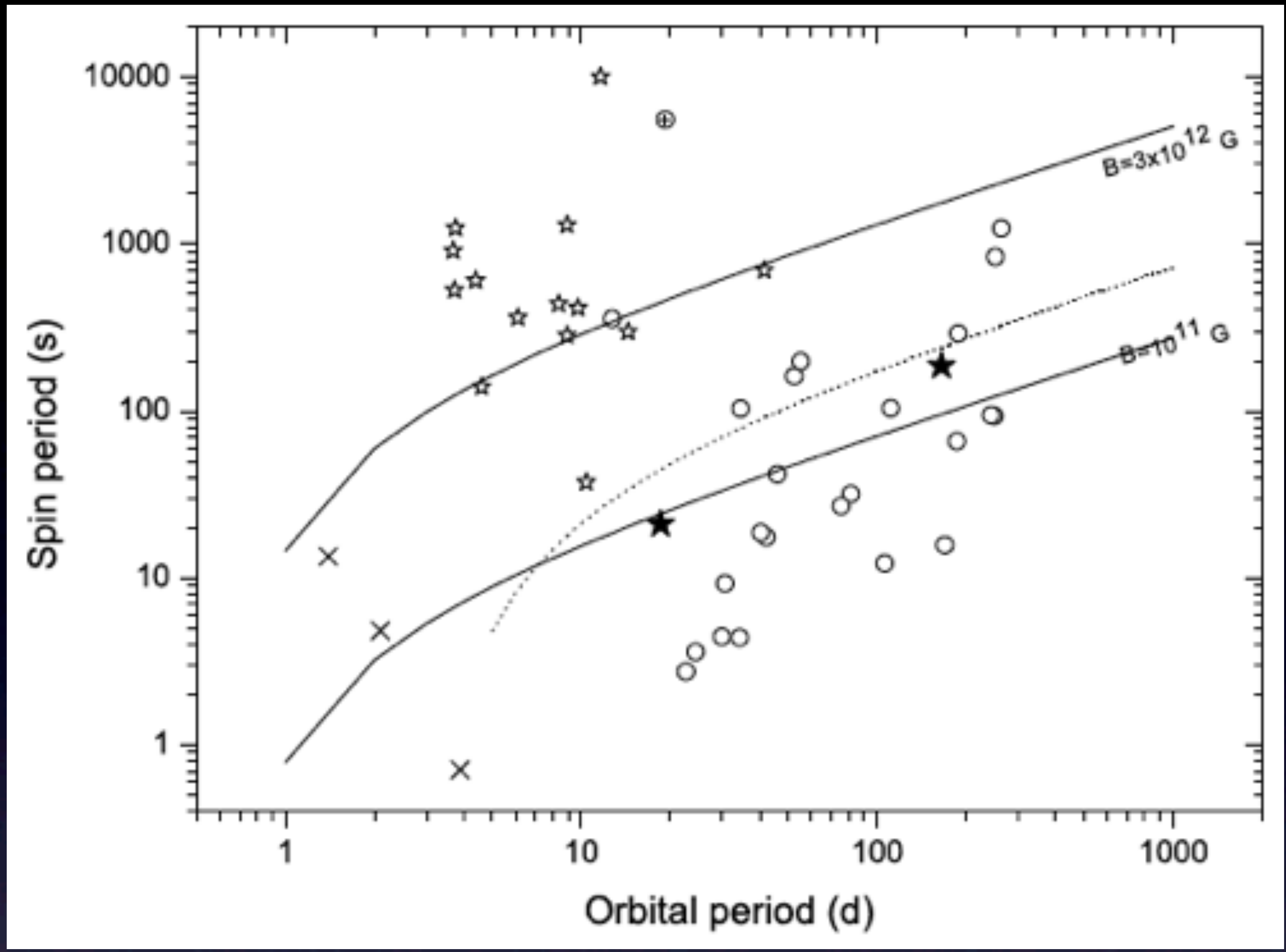


- There are 2 «misplaced» SFXTs: IGR J18483-0311 (B0.5 Ia)
  & IGR J11215-5952 (B1 Ia)

- They should have evolved from normal MS OB-type star

Liu, Chaty, Yan, MNRAS

Origin of «misplaced» sgXBs?

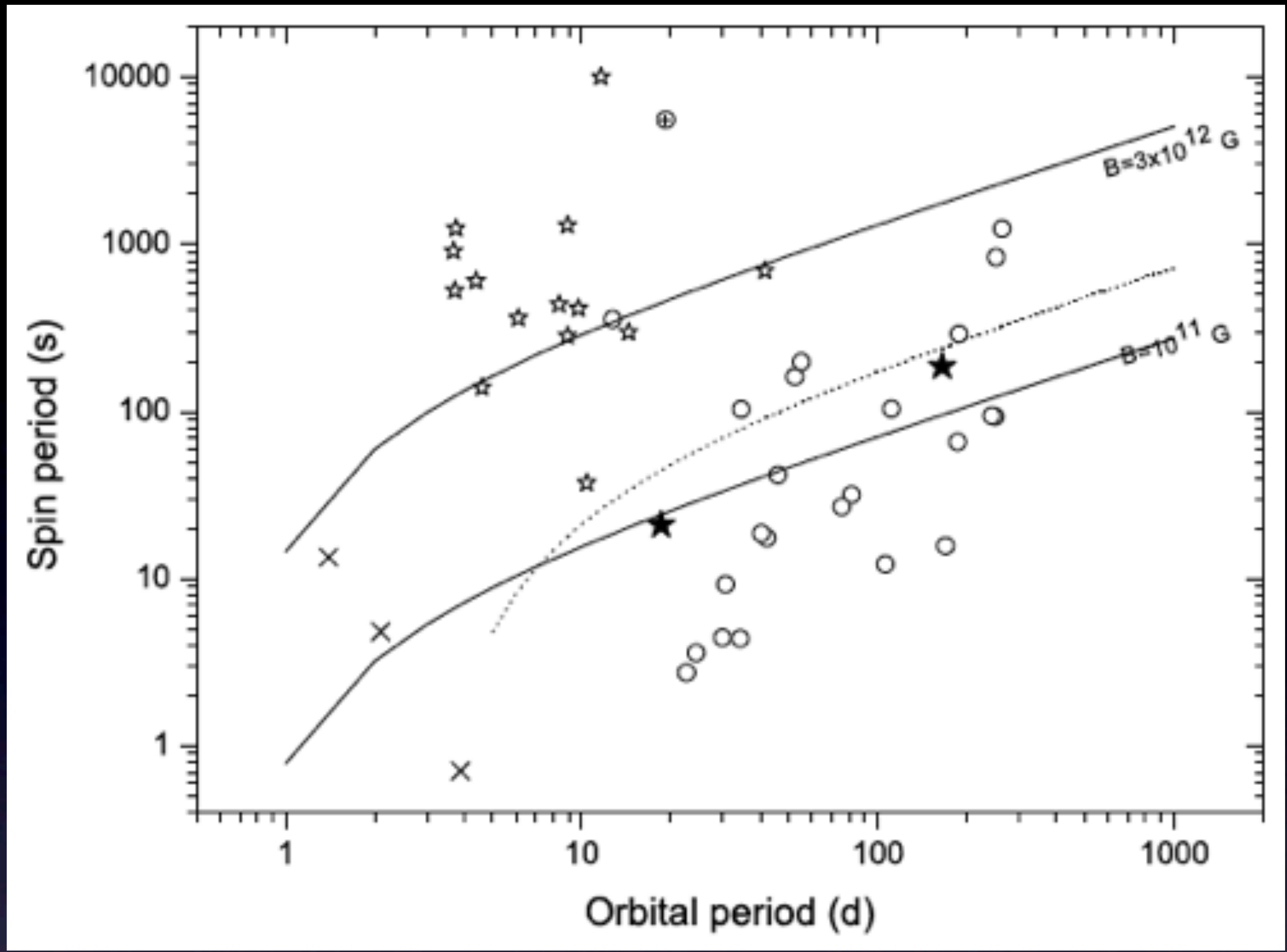


Current Pspin = Peq while on MS
(Waters & van Kerkwijk 1989)
Lines: Theoretical NS Peq for
O7V stars (solid lines) &
B1 Ia with $3x10^{12}$G (dotted line)

- But they are not spinning at P_{eq} of OV stars (or only if low B~10^{11}G)
- They can not have spun up after reaching P_{eq} since stellar wind accretion phases will randomly spin up & down
- The NS have not reached P_{eq}: not enough time due to weak stellar wind and eccentric orbit during MS stage

Liu, Chaty, Yan, MNRAS

Origin of «misplaced» sgXBs?

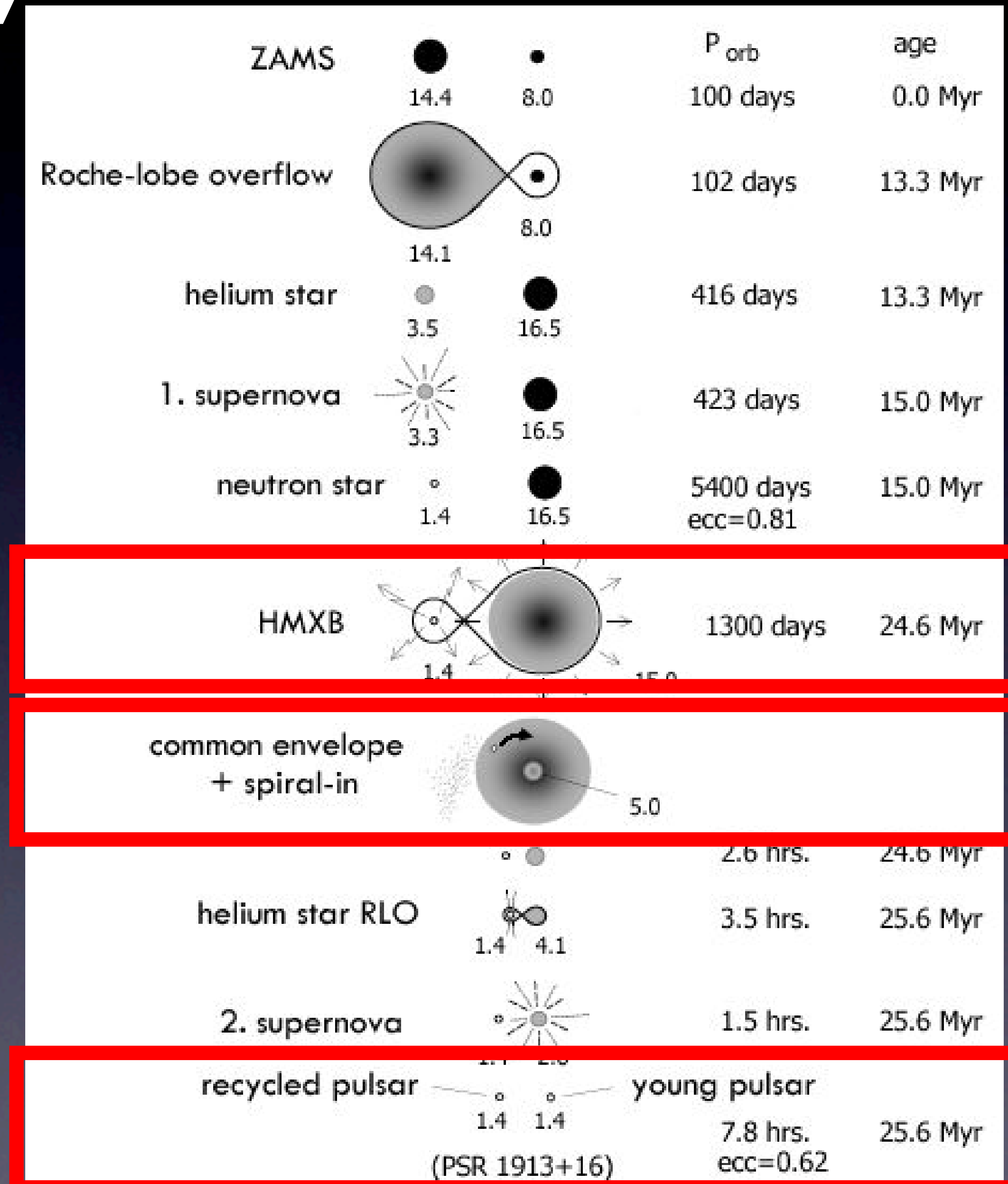


- Therefore they can not have evolved from normal MS OB-type stars as usual sgXBs
- They must be descendants of BeXBs (O-type emission line stars) after NS reaches P_{eq} (i.e. with previous accretion phase)
- And there must be many more such intermediate SFXTs...

Liu, Chaty, Yan, MNRAS

Population Synthesis

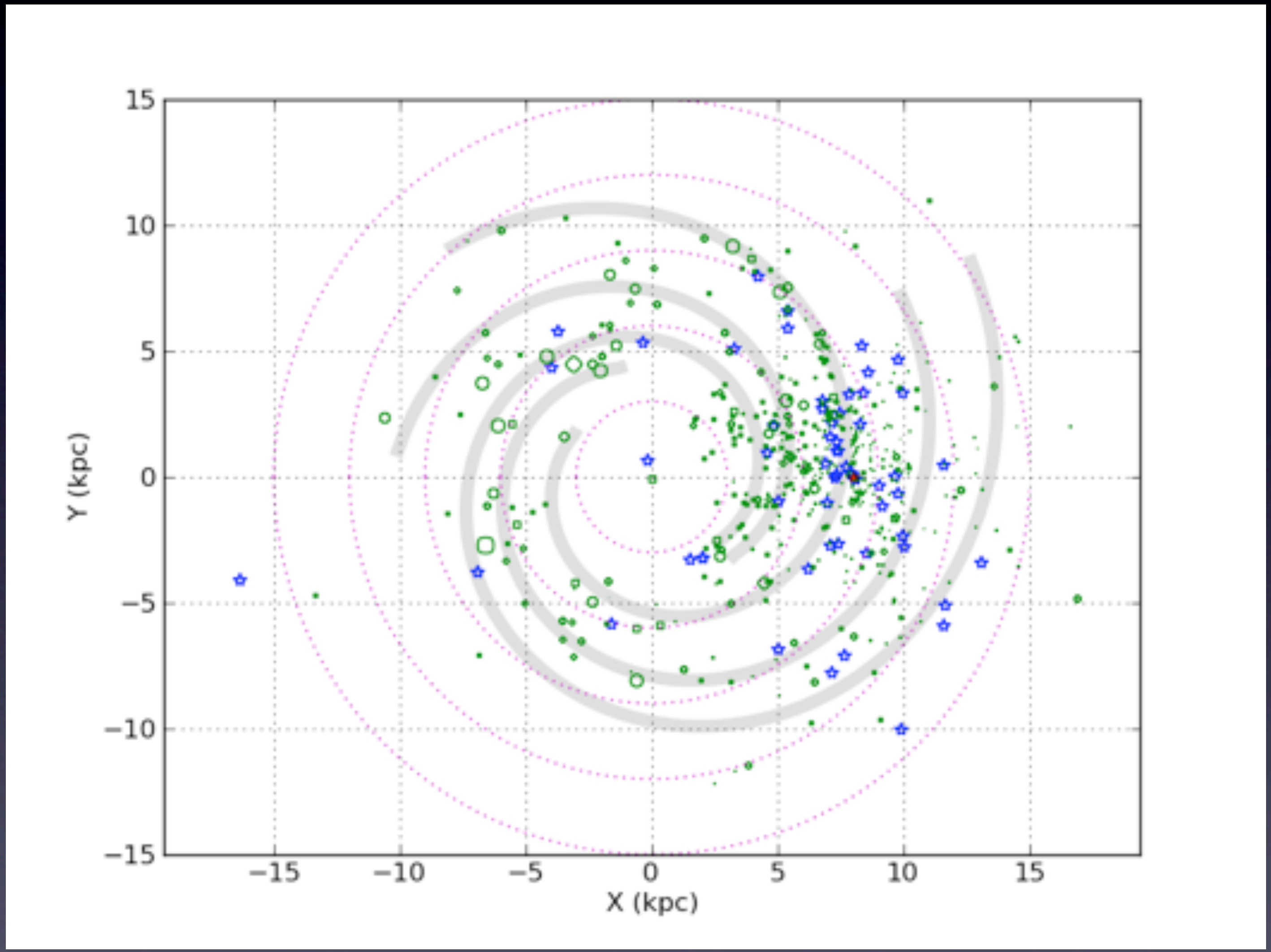
- Long-period ~100d sgXBs require initial systems with Porb~10d
- These systems will survive Common Enveloppe Phase (poorly known phase of stellar evolution)
- End as close eccentric radio pulsar binary systems (double NS or BH/NS)
- Search for massive progenitors



Tauris & van den Heuvel 2006

Galactic distribution

- Study of HMXBs environment & birthplace
- Correlation between HMXBs and active OB stellar complexes
- Typical cluster size: 0.3 kpc
  Inter-cluster distance: 1.7 kpc
  Distance uncert.: 0.65 kpc



Coleiro & Chaty 2011

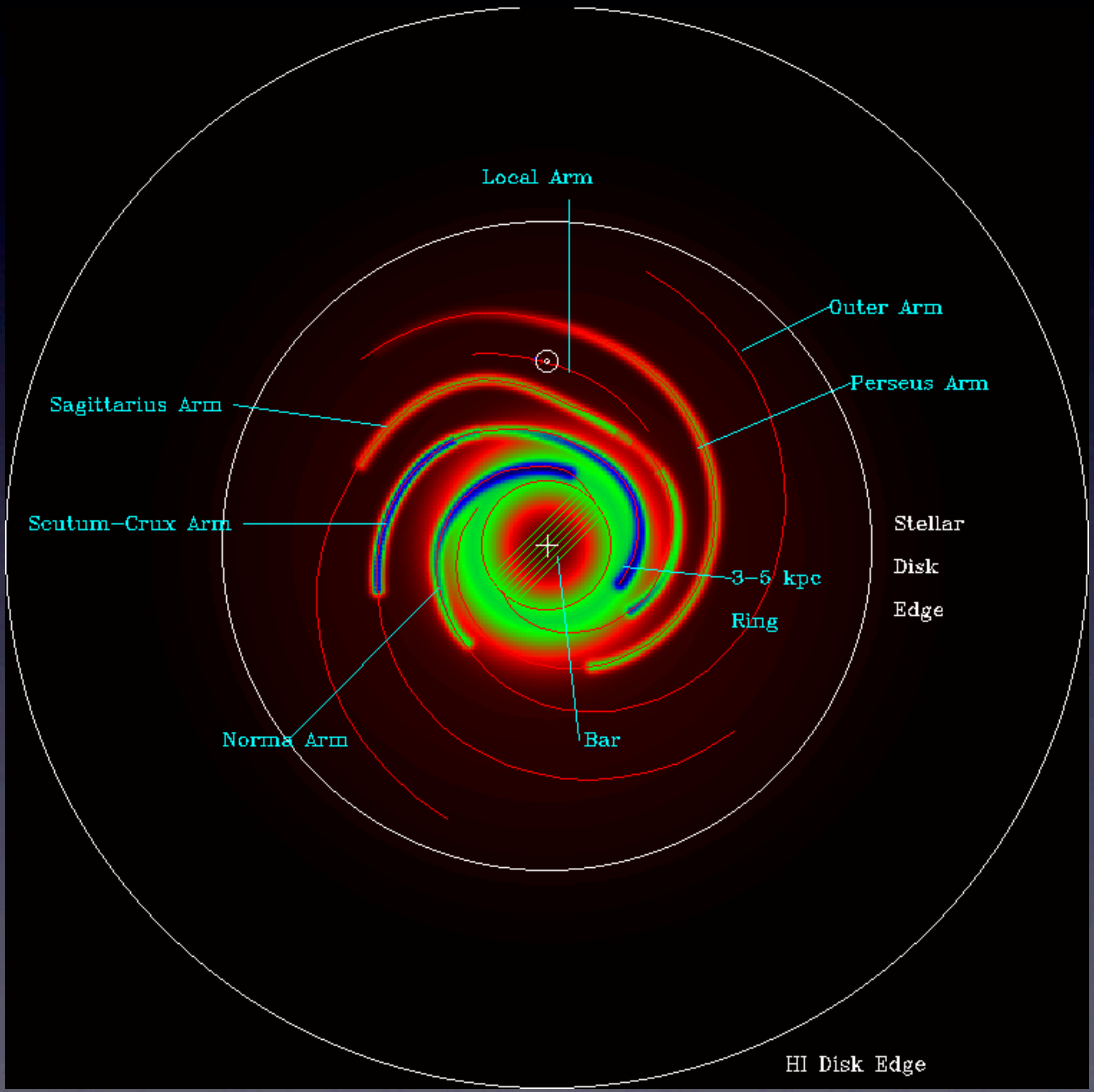
S. Chaty

Galactic rotation

- Propagation of density waves induces star formation in spiral arms (Lin et al 1969): angular velocity of spiral arm pattern Ω~20-60/Gyr (Bissantz et al 2003)
- Delay of ~10 Myr between star formation & maximum number of HMXBs: Galactic rotation changed apparent position of arm
- Distribution of HMXBs should be offset by ~40° with current spiral arm pattern at a distance of ~5 kpc.
- Uncertainties: distance of HMXBs, location of arms, Sun GC distance (Dean et al 2005)

Galactic distribution

- Norma arm region: the most active formation site of young supergiants (Bronfman et al 1996): precursors to HMXBs
- Galactic bulge & Scutum/ Sagittarius arms
- Ongoing Herschel observations of INTEGRAL sources...

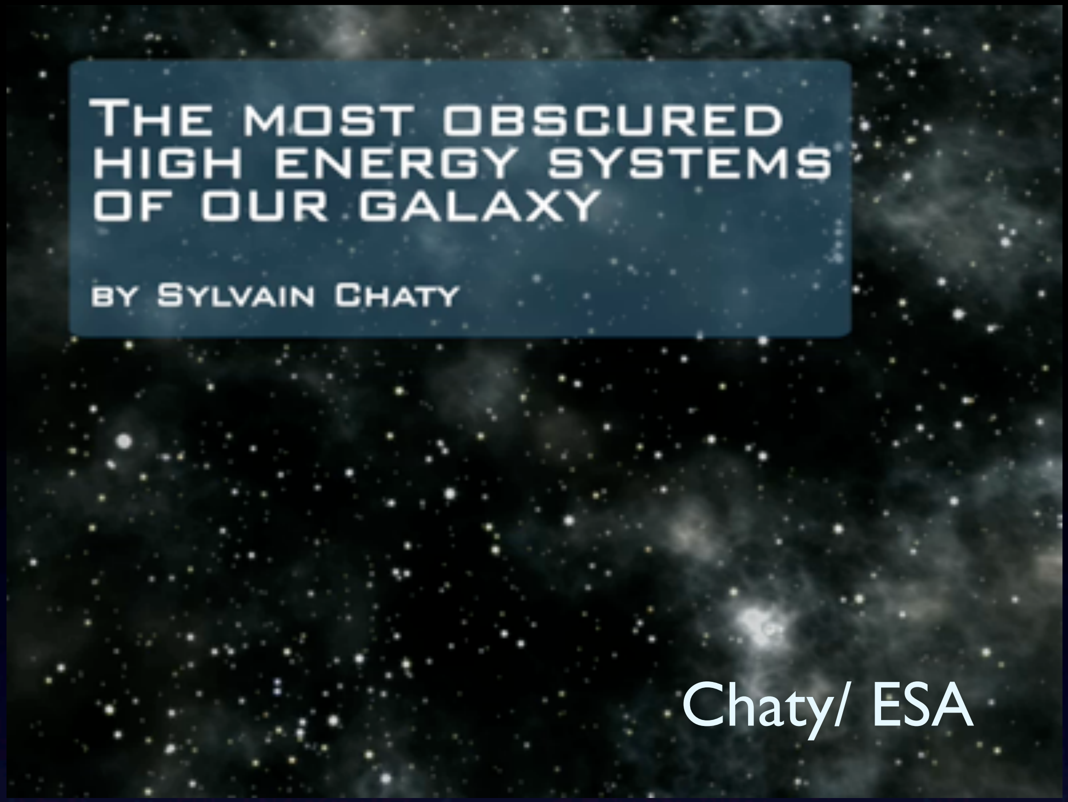


Do we better understand HMXBs?

- Do we better understand the 3 populations of HMXBs?
- Do we better understand accretion processes, in particular in sgXBs?
- Do we understand fast transient flares (clumpy wind/transient accretion disks)?

Probably not fully yet, but at least we now have more sources to play with…
...and study formation and evolution processes...

Conclusions & Perspectives



- Continuity in sgXBs (obscured to SFXTs): differences naturally explained by simple orbital configurations

- Laboratory for studying physics of NS accretion:
  * direct accretion (formation of transitory accretion discs)
  * stellar winds (structure, high/low density, clumps…)

- Study of formation, evolution and final stages of NS/BH binaries

Thank you!