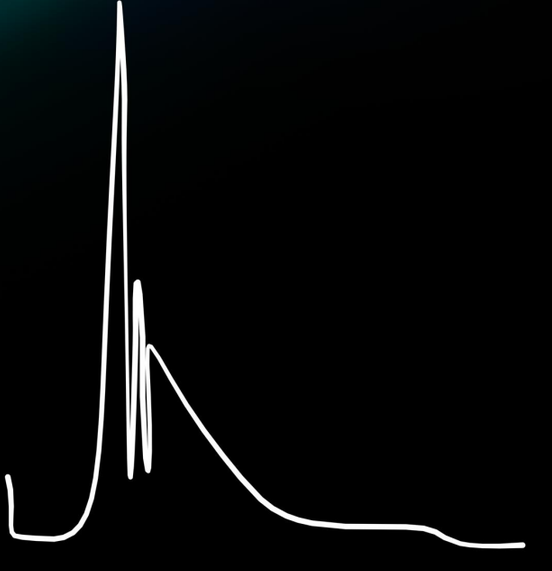
15 May 2006

Lidia Oskinova

IGRs: γ-ray selected High-Mass X-ray Binaries



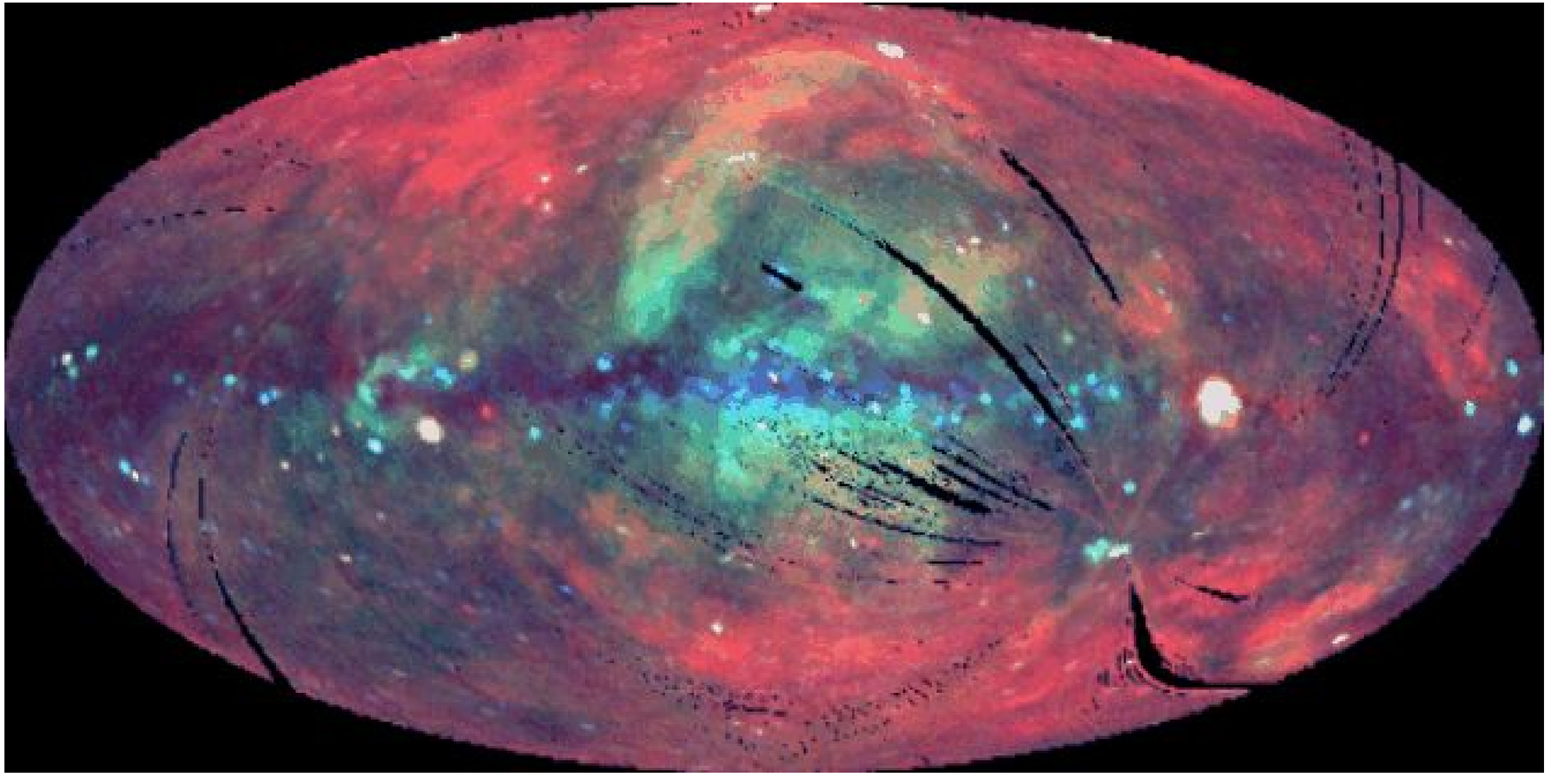
University Potsdam

Contens

- Introduction: X-ray binaries in the sky
- High-mass X-ray binaries: HMXBs
  - Phenomenology
  - Basic Physics
- HMXBs as stellar wind probe
- Integral discovery of new obscured sources
- IGRs: new class of HMXBs
  - Distribution
  - Properties
  - Consequences

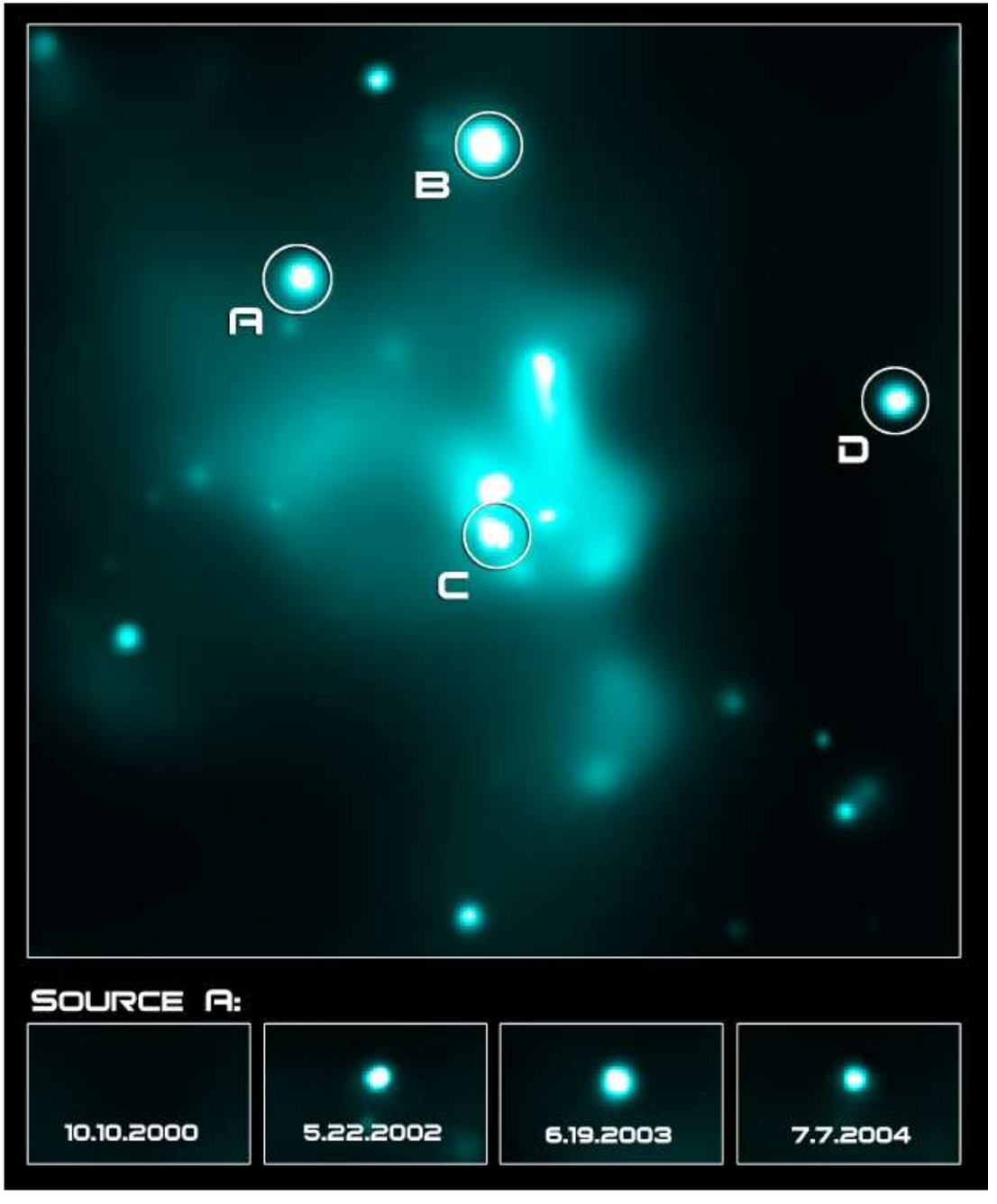
X-ray Sky: Rosat All-Sky Survey

Rosat (1990-1999): all sky survey RASS (0.2-2.4 keV)



- Galactic plane: high abosorption
- Point sources: XRB, stars; Diffuse: SNR, extragalactic
- Diffuse background

Low-Mass X-ray Binaries (LMXB)



NS/BH + $M_* \leq 10 M_\odot$

E.g. XTE J1550-564: KIII + BH

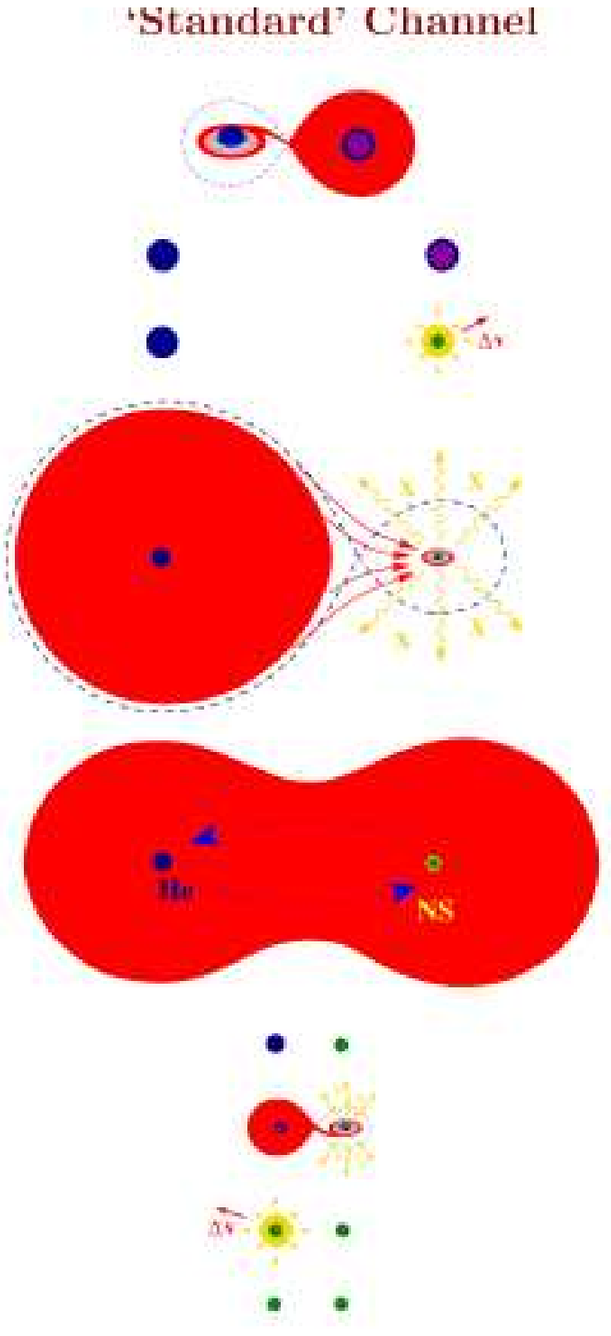
$10^{32} < L_X < 10^{39}$ erg/s

- Origin: dynamical interactions in clusters?
- Primary's low stellar mass $\Rightarrow$ Long feeding time
- Transients, complex geometry

← **Milky Way Center**

(Chandra)

High-Mass X-ray Binaries (HMXB)



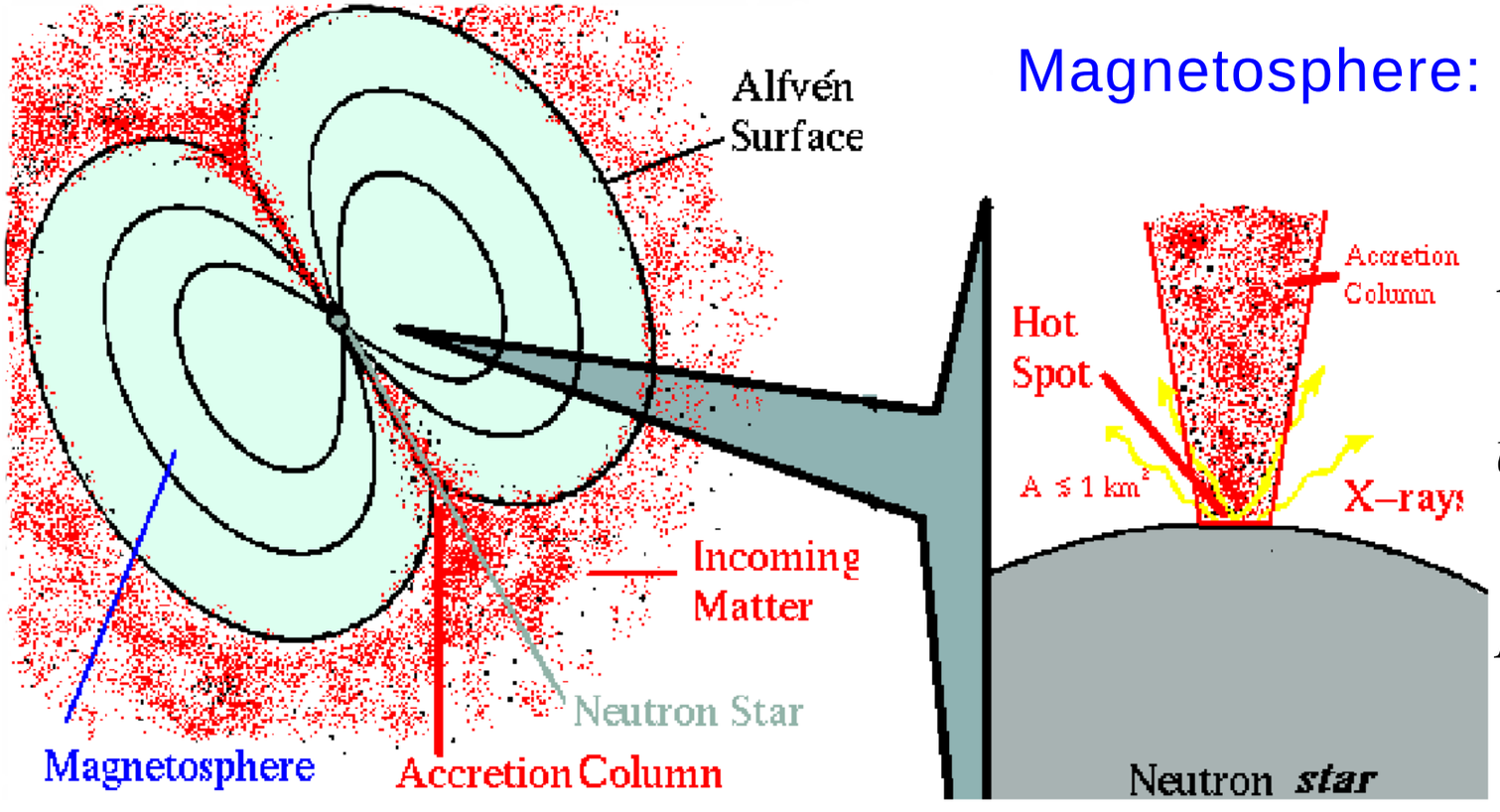
NS/BH + $M_* \geq 10 M_\odot$

E.g. Vela X-1: B0I + NS
$L_X \approx 10^{36}$erg/s, a=0.6 R_*!

- Origin: binary evolution
  - $\geq 50\%$ binaries
  - $\leq 10\%$ bound after SN kick
- Massive primary $\Rightarrow$ short feeding time $(\sim 10^5 \mathrm{yr}) \Rightarrow$ traces of recent star formation

← Podsiadlowski et al. (2006)

Neutron-Star Accretion (Davidson & Ostriker 73)



Magnetosphere: $\frac{B_{\rm m}^2}{8\pi} > \rho v_{\rm infall}^2$

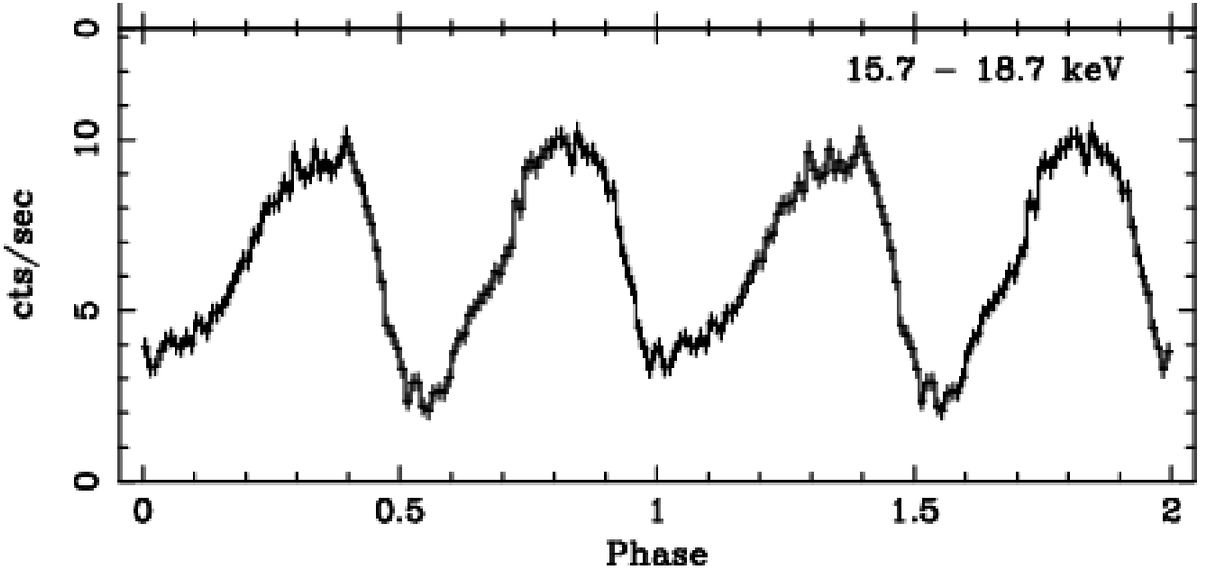
$$B(r) = \frac{BR_{\rm X}^3}{r^3}$$

$$v_{\rm infall} \approx \sqrt{\frac{2GM_{\rm X}}{r}}$$

$$R_{\rm m} \approx 10^3 \text{ km}$$

- NS gravity accelerates gas particles to high velocities
- Gas cannot penetrate magnetosphere $\Rightarrow$ Moves along B lines
- Focused at poles $\Rightarrow$ Accretion column
- Hot $\bar{e}$ $\Rightarrow$ Iinverse Compton scattering $\Rightarrow$ X-ray beams
- NS rotation $\Leftarrow$ at $R_{\rm m}$ Keplerian velocity = NS rotational velocity

X-ray Pulsars



- P(Vela X-1)=283 s, P(Cen X-3)=4.8 s, P(A0538-66)=0.07 s
- $P \geq (G\bar{\rho})^{-1/2} \Rightarrow \bar{\rho} \geq 10^6\,\mathrm{g\,s^{-3}} \Rightarrow$
- Orbital motion $\Rightarrow$ Phased pulse variation
- Pulse periods: Doppler-shifted (optic analog SBI)
- Observed velocity (projected) and period
- Mass

  NS $\approx 1.4\,M_\odot$

  BH $> 7\,M_\odot$ HMXBs LMC X-3, LMC X-1, Cyg X-1

X-ray Luminosity

- Zeldovich & Novikov (1971) Accretion onto Neutron Star
- Spherically symmetric accretion: max Eddington Luminosity:

$$L_{\rm edd} = \frac{4\pi G M_{\rm X}(m_{\rm p}+m_{\rm e})c}{\sigma_{\rm T}} = 3.23\times10^{4}\left(\frac{M_{\rm X}}{M_{\odot}}\right)L_{\odot}$$

- Efficiency $\eta = \frac{GM}{Rc^2}$ of accretion process $L = \eta \dot{M}_{\rm acc} c$

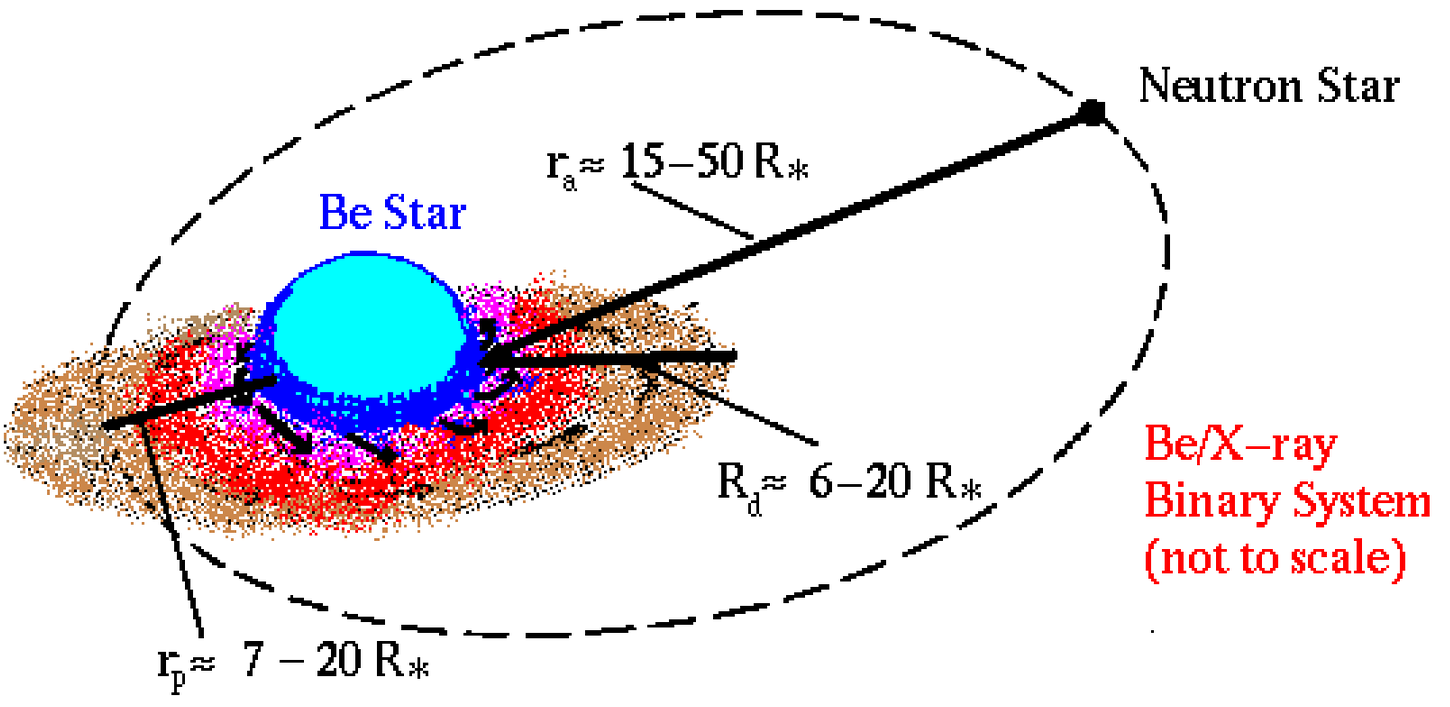
BH η=0.4; NS η=0.1; WD η=0.1; nuclear fusion η=0.007;

- Obsevrved luminosity: $10^{36} \le L_{\rm X} \le 10^{39}$ erg/s

$\Rightarrow \dot{M}_{\rm acc} \sim 10^{-7}..10^{-9}\, M_{\odot}{\rm yr}^{-1}$

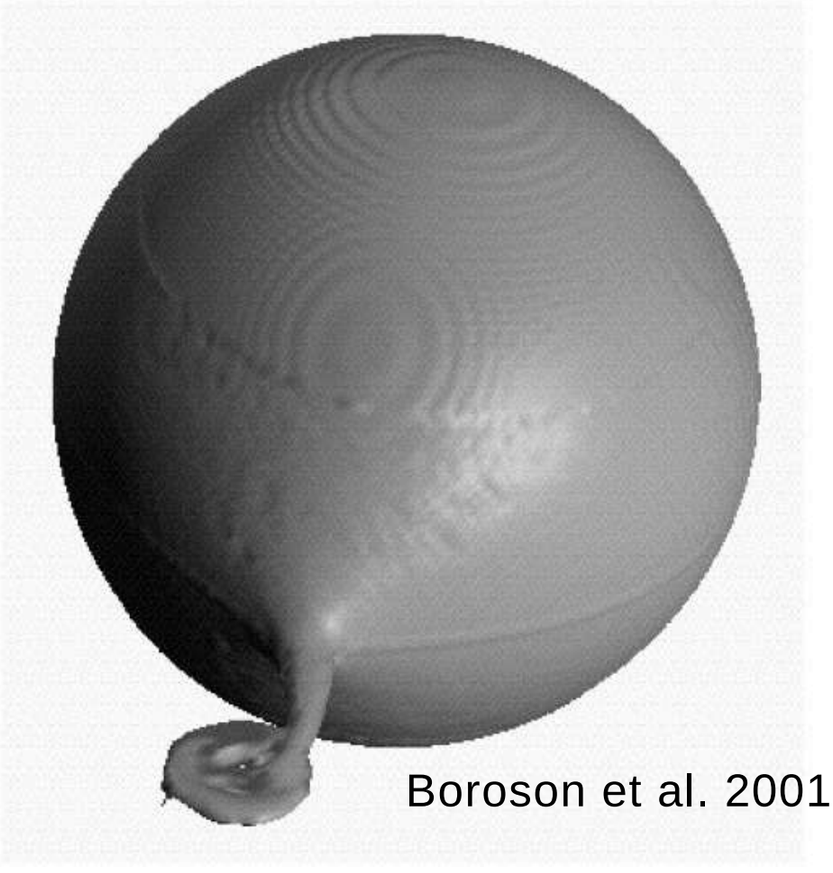
- In a massive star close binary via
  - Be stars discs
  - Roche Lobe Overflow
  - Stellar Wind

Be/X-ray Binaries



- O9- B2 stars with high rotation rate $\Rightarrow$ disk / Be phenomenon
- Collision of compact object with disk: Transients. Outbursts $L_X \sim 10^{37}$ erg/s / Persistent $L_X \sim 10^{34}$ erg/s
- Physics is poorely understood
- 80 per cent all HMXBs, e.g. X Per, A0535+2

Roche-Lobe Overflow



Boroson et al. 2001

- Specific angular momentum

Peterson (1978): $J \approx \Omega_{\rm orb}(a - r_{\rm L})^2$

$r_{\rm L}$ - Roche lobe radius

- Circularisation: $R_{\rm circ} = \frac{J^2}{GM_{\rm X}}$
- Disk: $R_{\rm circ} > R_{\rm X}$

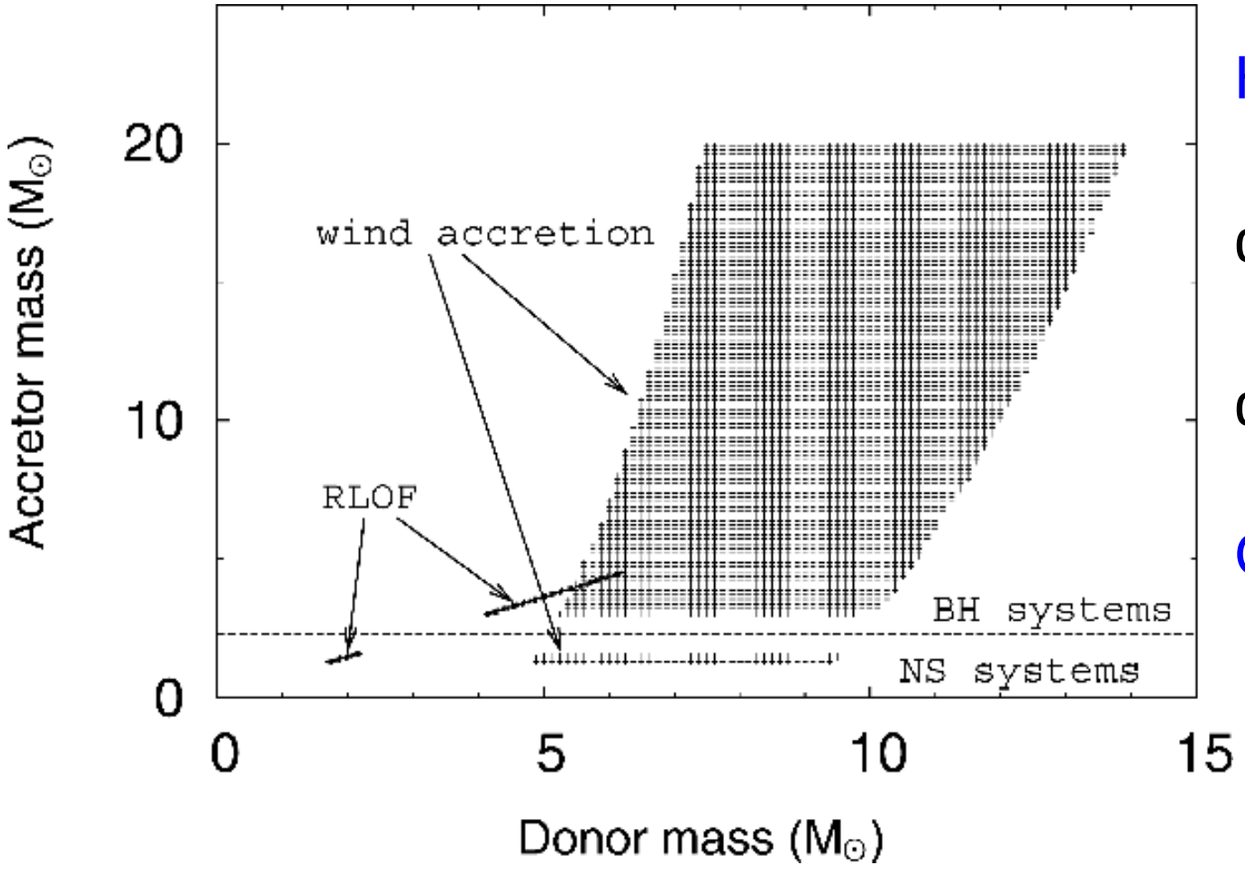
$$R_{\rm circ}^{\rm roche} = r_{\rm L}^4 \frac{\Omega_{\rm orb}^2}{GM_{\rm X}}$$

- Donor $\rightarrow L_1 \rightarrow$ NS/BH

$$R_{\rm circ}^{\rm roche} \approx 3.5 \times 10^9 \left(\frac{M_*}{M_\odot}\right)^{1/3} \left(\frac{P_{\rm orb}}{1\,{\rm hr}}\right)^{2/3} {\rm cm} \gg r_{\rm NS} \approx 10^6\,{\rm cm}$$

- angular momentum $\rightarrow$ beyond $R_{\rm circ}$ transported to the secondary orbit through tides

Roche-Lobe Overflow: Evolutionary Scenario



He-burning

- $M_{\rm He} \leq 0.8 M_\odot$

do not expand

- $M_{\rm He} \geq 5.8 M_\odot$

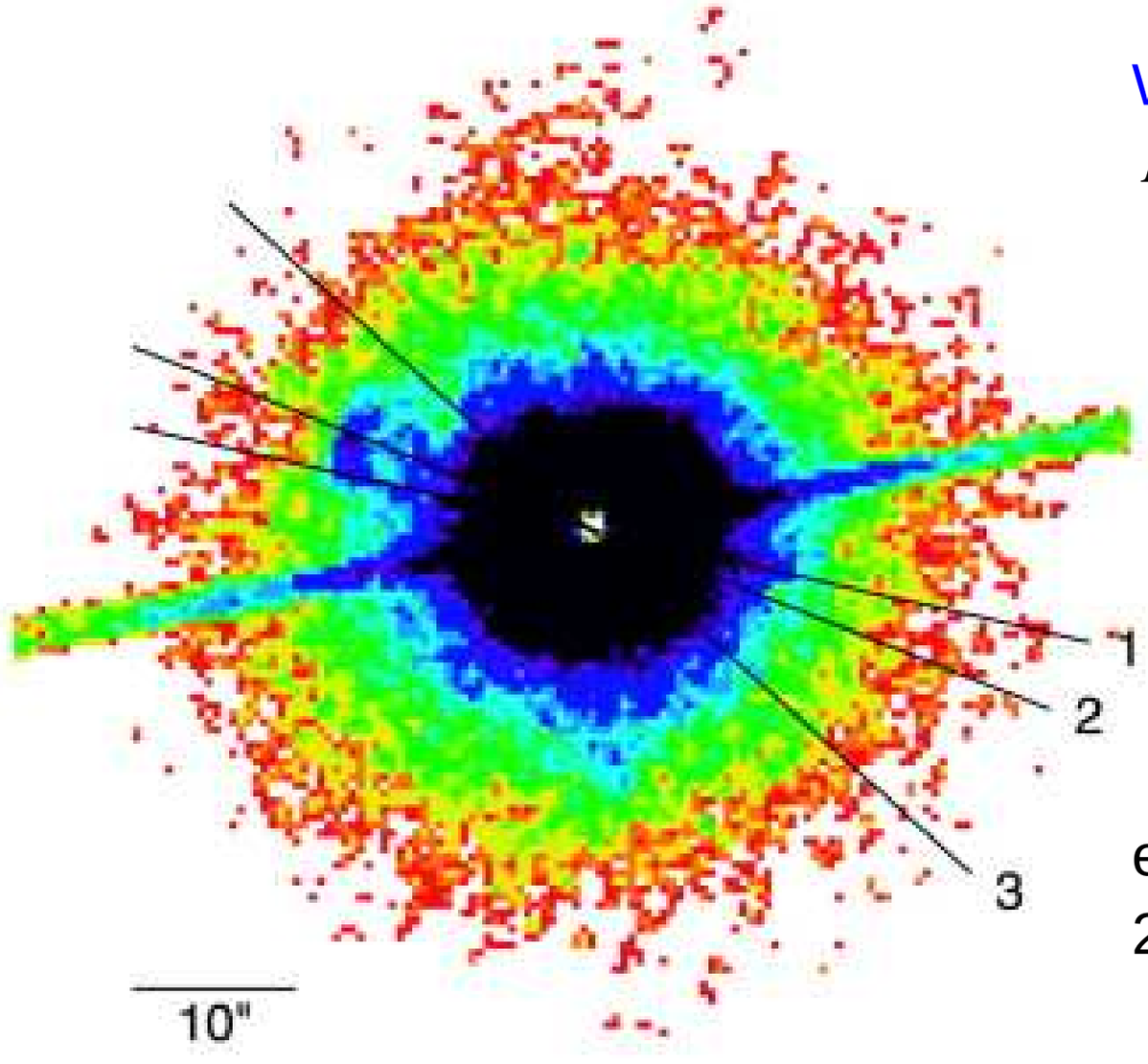
do not expand

C-burning: very short time

- $M_{\rm He} \geq 7 M_\odot$ expand (Dewi et al. 2002)

- RLOF in He- burning: $0.8 \leq M_{\rm He} \leq 5.8 M_\odot$
- $\dot{M}_{\rm acc} \sim 10^2 \dot{M}_{\rm wind}$
- Population synthesis $\rightarrow 10^0$ stars in the Galaxy (Lommen et al. 2005)

Microquasar Cygnus X-3



Wolf-Rayet+BH/NS

$L_X = 10^{38}$ erg/s

- Jets (0.8c) $\Rightarrow$ Disk
- Disk $\Rightarrow$ RLOF or Wind
- Wind $\Rightarrow$ BH + WR

$$M_{He} \geq 7\, M_\odot$$

- RLOF $\Rightarrow$ NS + He

$$M_{He} \leq 1.5\, M_\odot$$

← Chandra: extended emission (Heindl etal. 2003)

- Rare objects: SS433, Cyg X-1, SMC X-1, LMC X-4

Massive star winds

OB, WR $M_* \geq 10 M_\odot$

- Intrinsic X-ray sources

$L_{\rm X} \sim 10^{32}$ erg/s

- Radial velocity profile

$v_{\rm w}(r) = v_\infty (1 - R_*/r)^\beta$

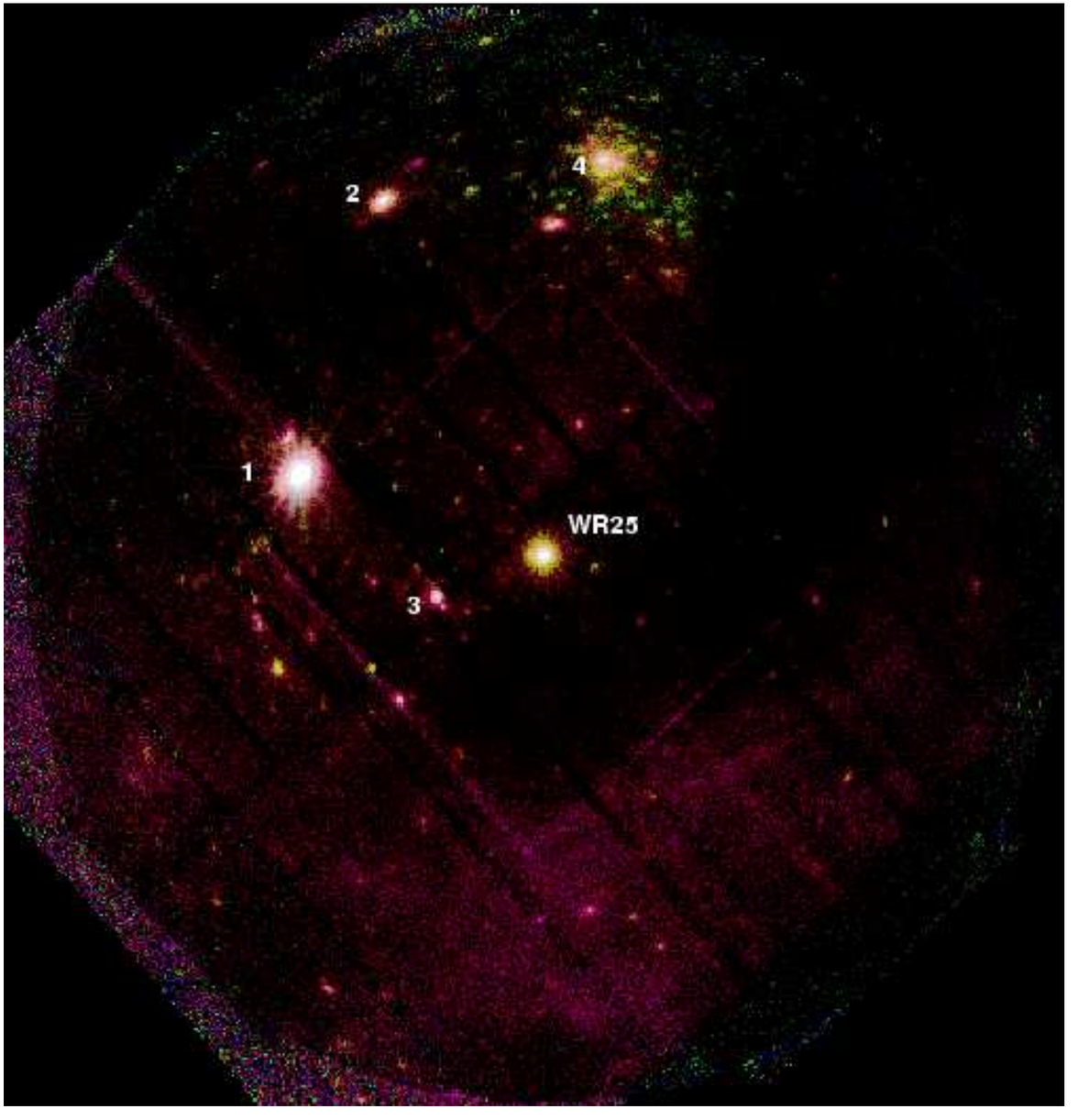
$v_\infty \sim 0.01c, \;\; \beta \sim 1$

- Radiatively driven wind

$\dot{M}_{\rm w} = 10^{-7..-5} M_\odot \, {\rm yr}^{-1}$

- Continiuty equation

$$\rho_{\rm w} = \frac{\dot{M}_{\rm w}}{4\pi v_{\rm w}(r) r^2}$$

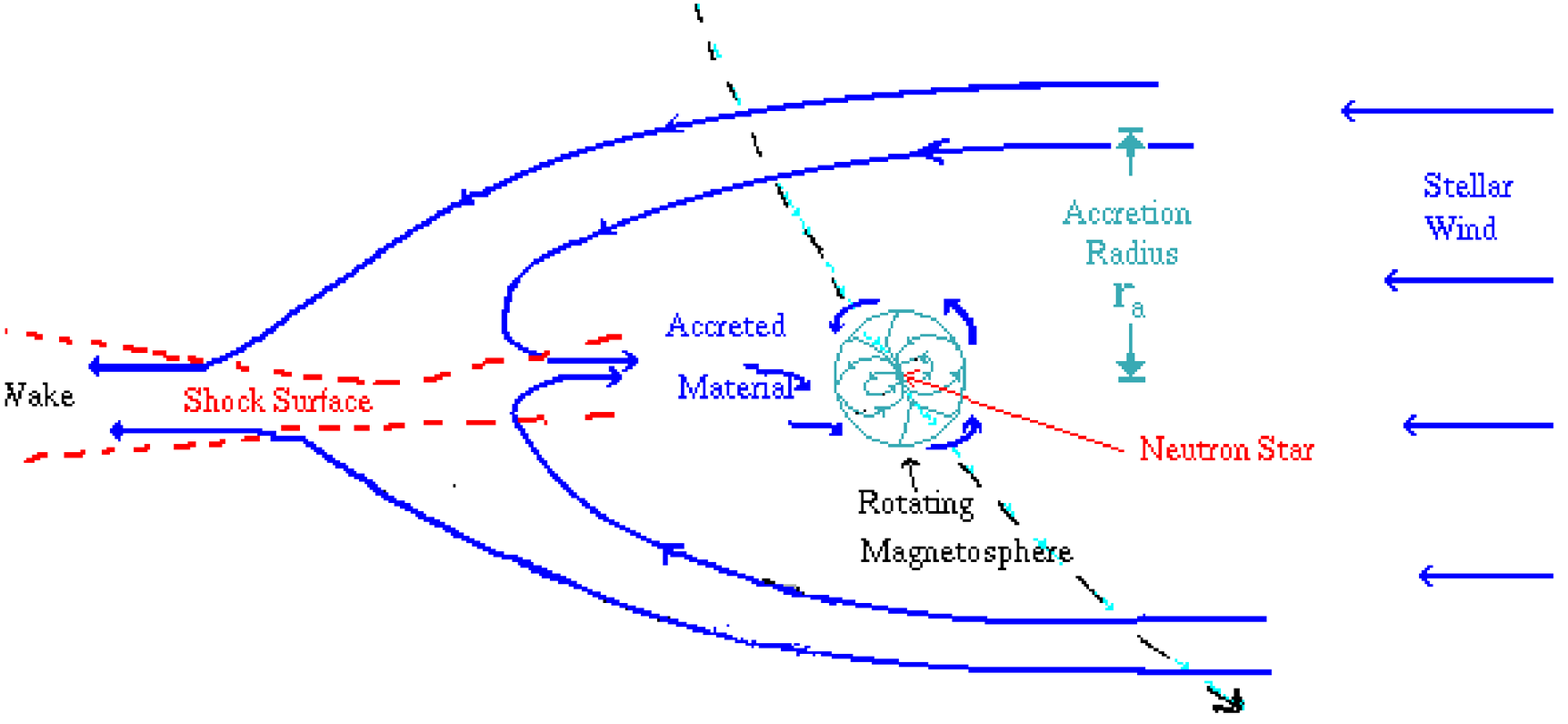


Carina region

WR25, η Car, O-stars

XMM-Newton (Raassen et al. 2003)

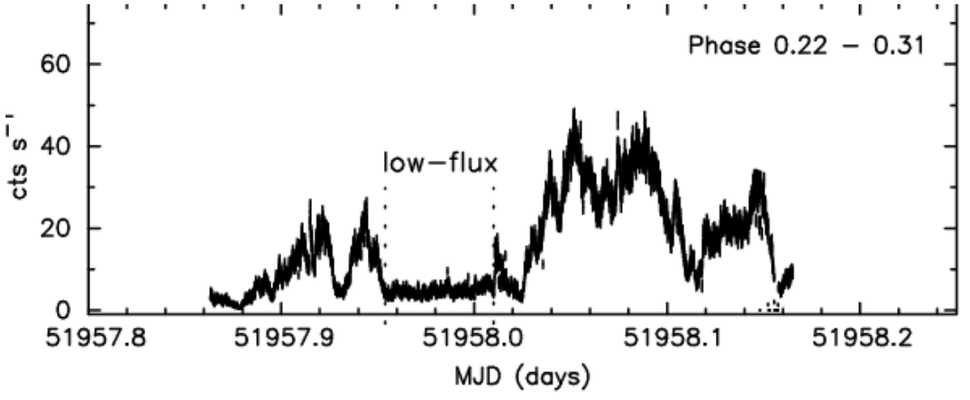
NS accretion in a stellar wind (Davidson & Ostriker 73)

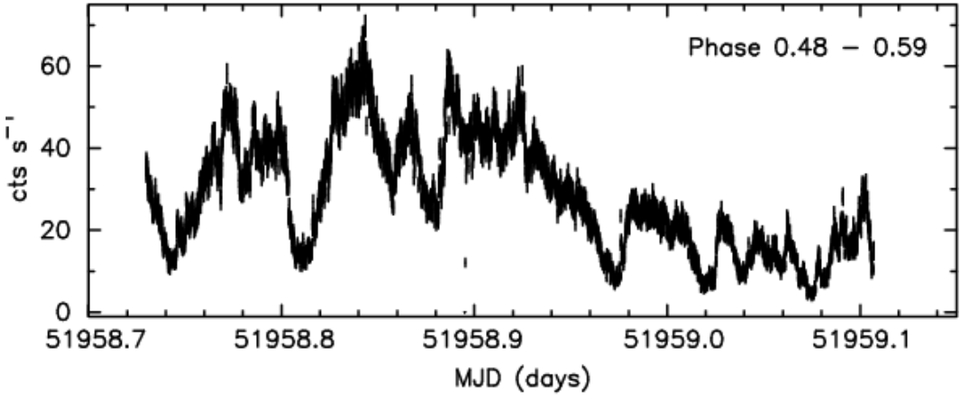


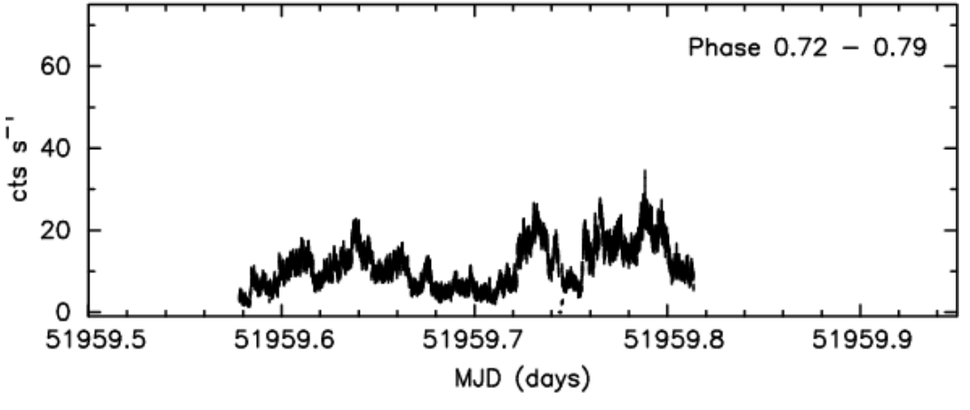
- Bondi- Hoyle accretion: non- radial flow $v_{\rm rel}$ past $M_{\rm X}$
- Accretion $E_{\rm tot} < 0 \Rightarrow \quad r_{\rm acc} = \frac{2GM_{\rm X}}{v_{\rm rel}^2}$
- Accretion rate $\dot{M}_{\rm acc} \approx \pi r_{\rm acc}^2 v_{\rm rel}\, \rho_{\rm w}(a)$
- Luminosity $L_{\rm X} = 0.1 \dot{M}_{\rm acc} c^2$

$$L_{\rm X} \propto \frac{\dot{M}_*}{v_{\rm w}(a)^4}$$

Stochastic variability



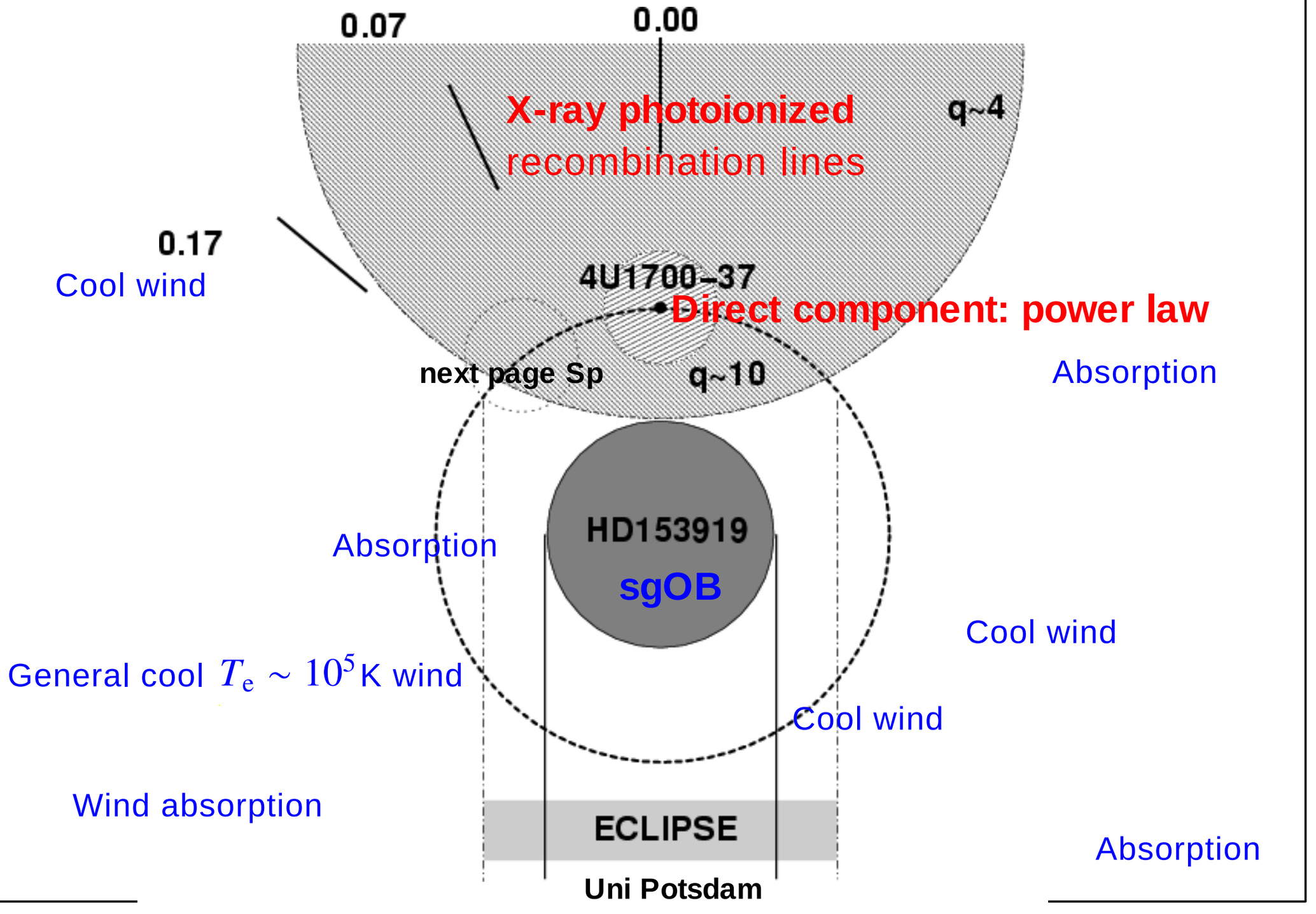




- 4U 1700-37/HD 153919 O6I+NS
- XMM Light Curves
  van der Meer et al. 2005
- Varying density and/or velocity structure
- Flaring/stochastic variability common among HMXBs
- Clumped wind

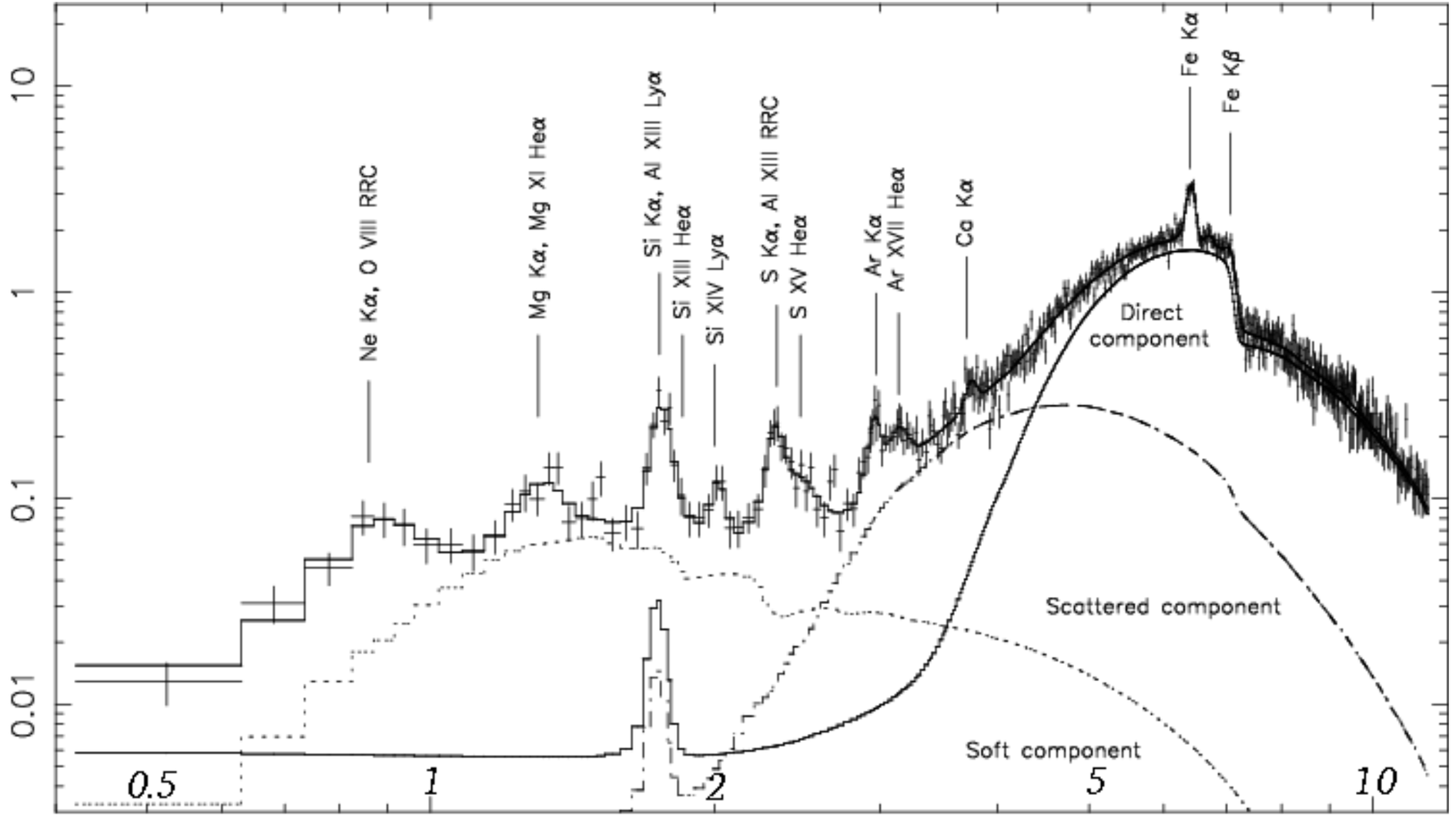
Let us consider X-ray spectra!

HMXB geometry



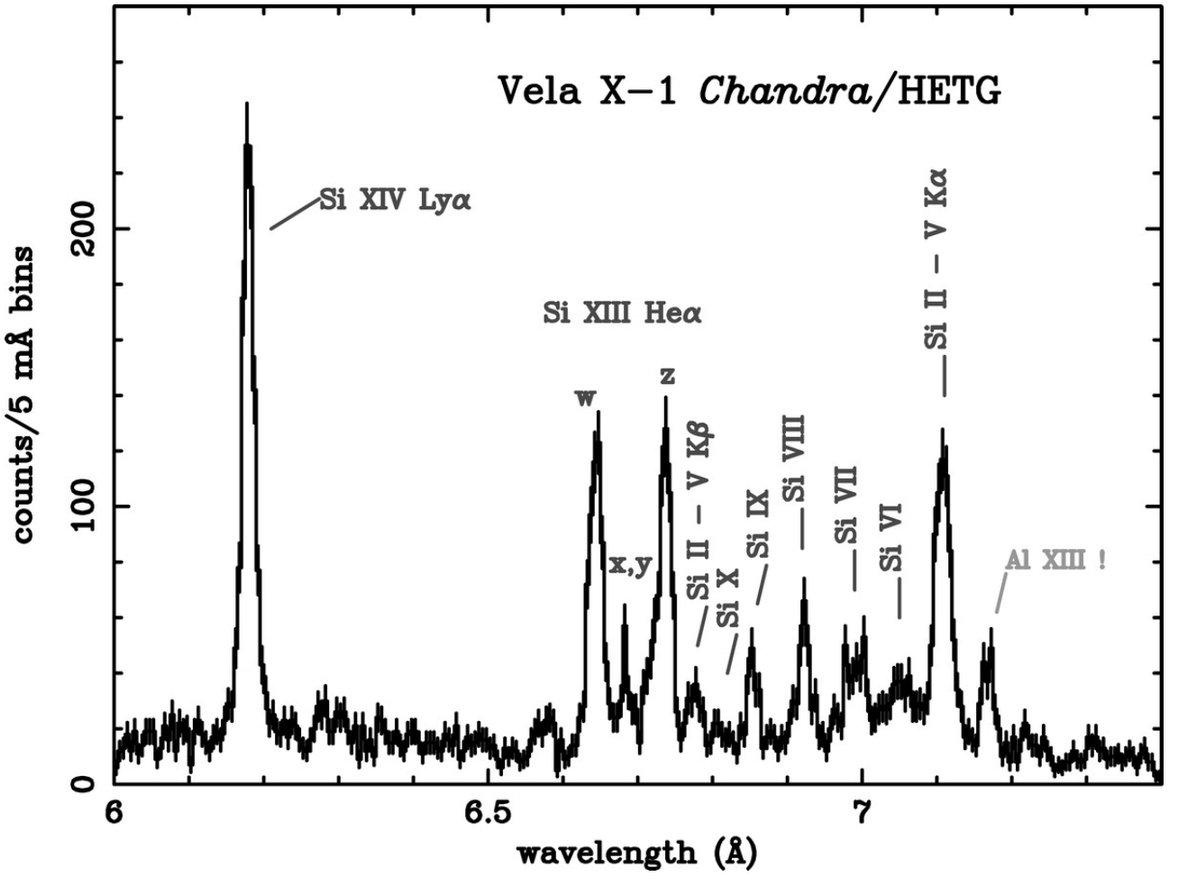
X-ray Spectrum

van der Meer et al. (2005)



- Absorbed direct component
- RRC - radiative recombination continuum
- Orbital variable fluorescence → close to NS

Stellar winds are strongly clumped



Observational evidence:

- Single stars: UV spectra (Bouret et al. 2005)
- X-ray emission line profiles (Oskinova et al. 2006)
- Vela X-1 fluorescence spectrum (Sako et al. 1999)

Clumping reduces empirical mass- loss rate → affects stellar evolution models

On the size of photoionized region in a clumped-wind HMXB

- Ionization parameter:
  $\xi = \frac{L_X}{nr^2}$

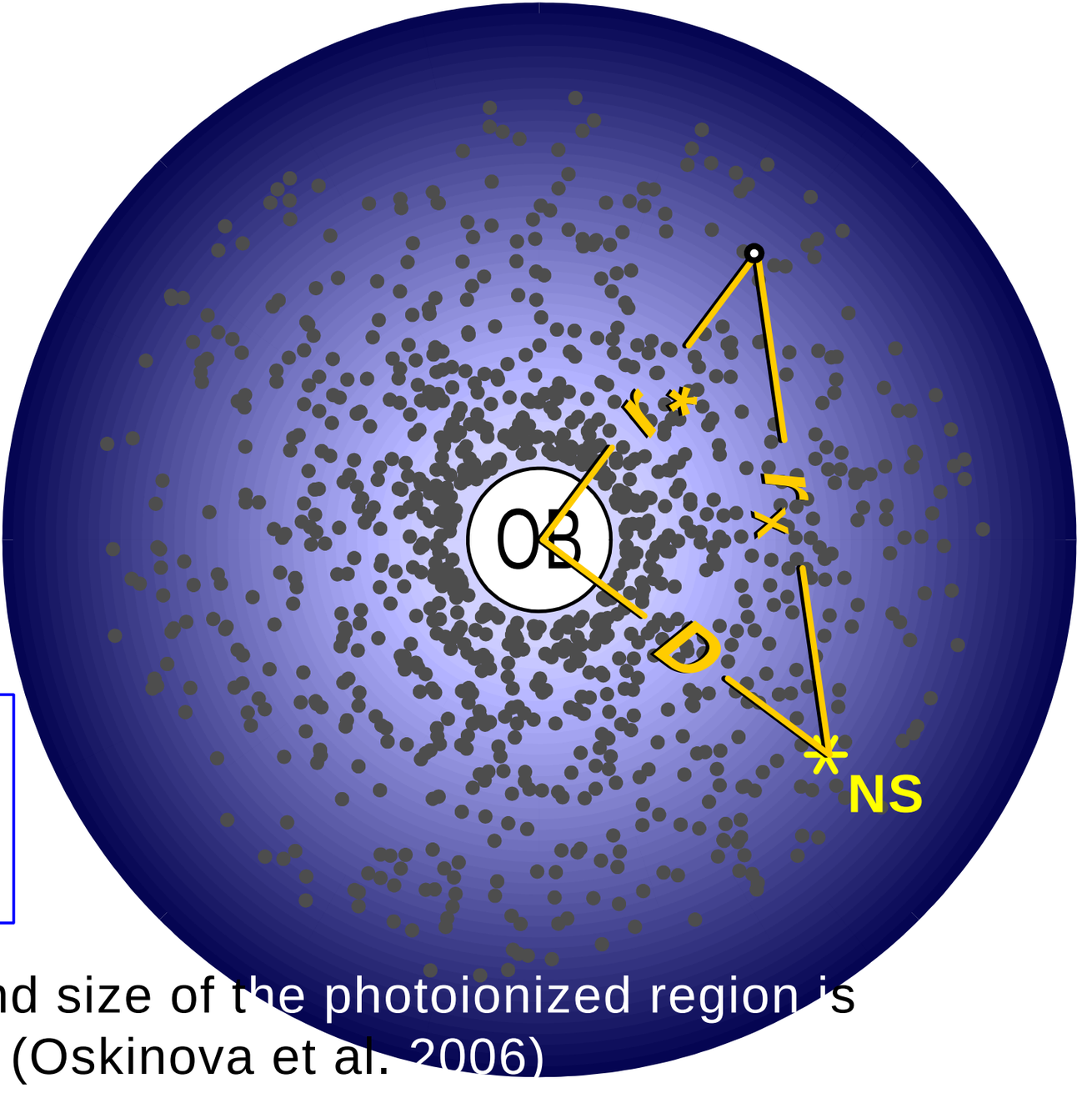
- Interclump gas:

$$\xi_{ic} = \xi \cdot \frac{\exp(-\bar{\tau})}{1 - D f_V}$$

D density contrast
f_V filling factor
$\bar{\tau} = \frac{r_X}{h}$
h porosity length

- Photoionized zone

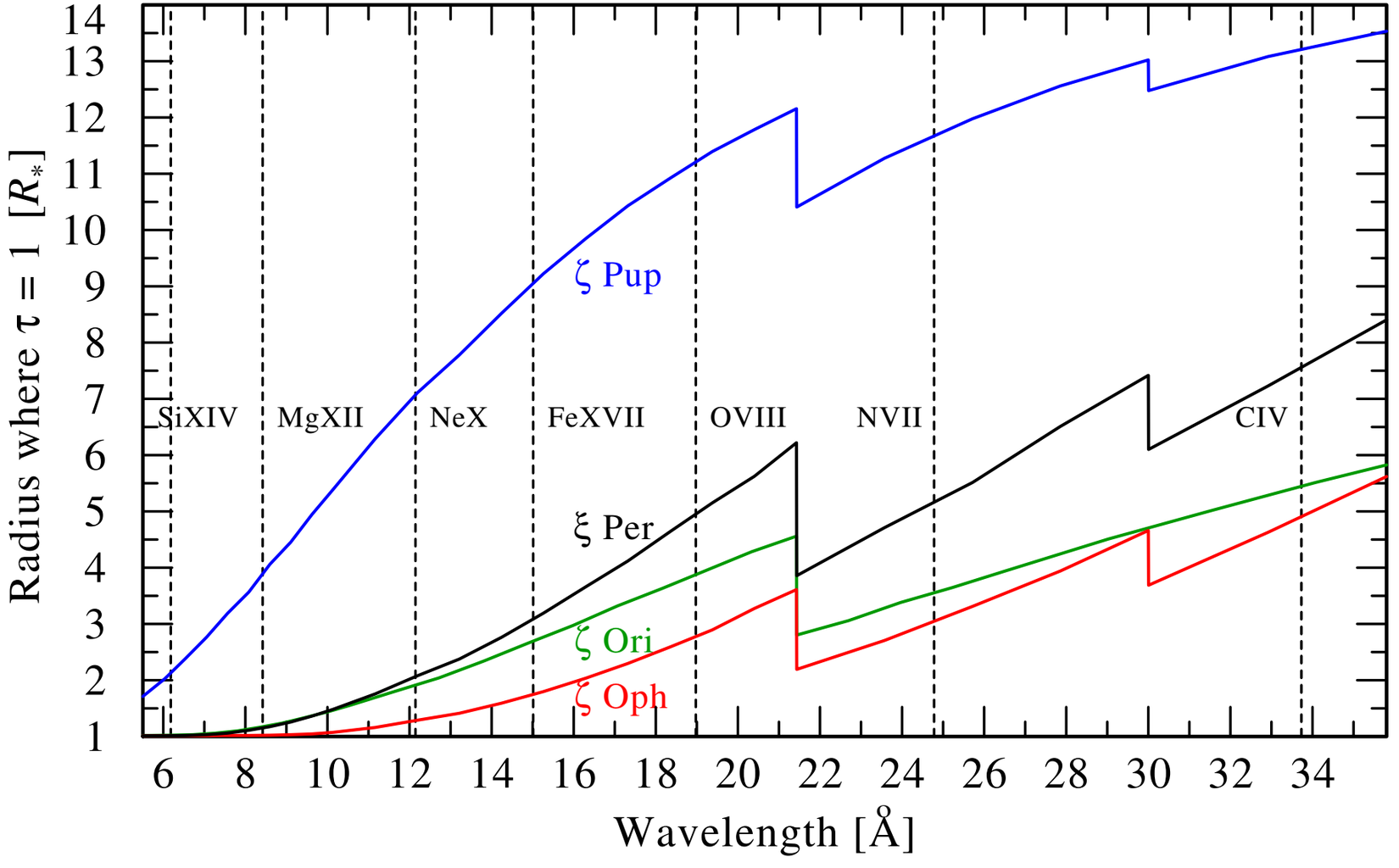
$$q_{ic} = \frac{\exp(-\frac{r_X}{h})}{1 - D f_V} \cdot \frac{r_*^2}{r_X^2}$$



Ionization balance and size of the photoionized region is affected by clumping (Oskinova et al. 2006)

OB stellar wind opacity for X-rays

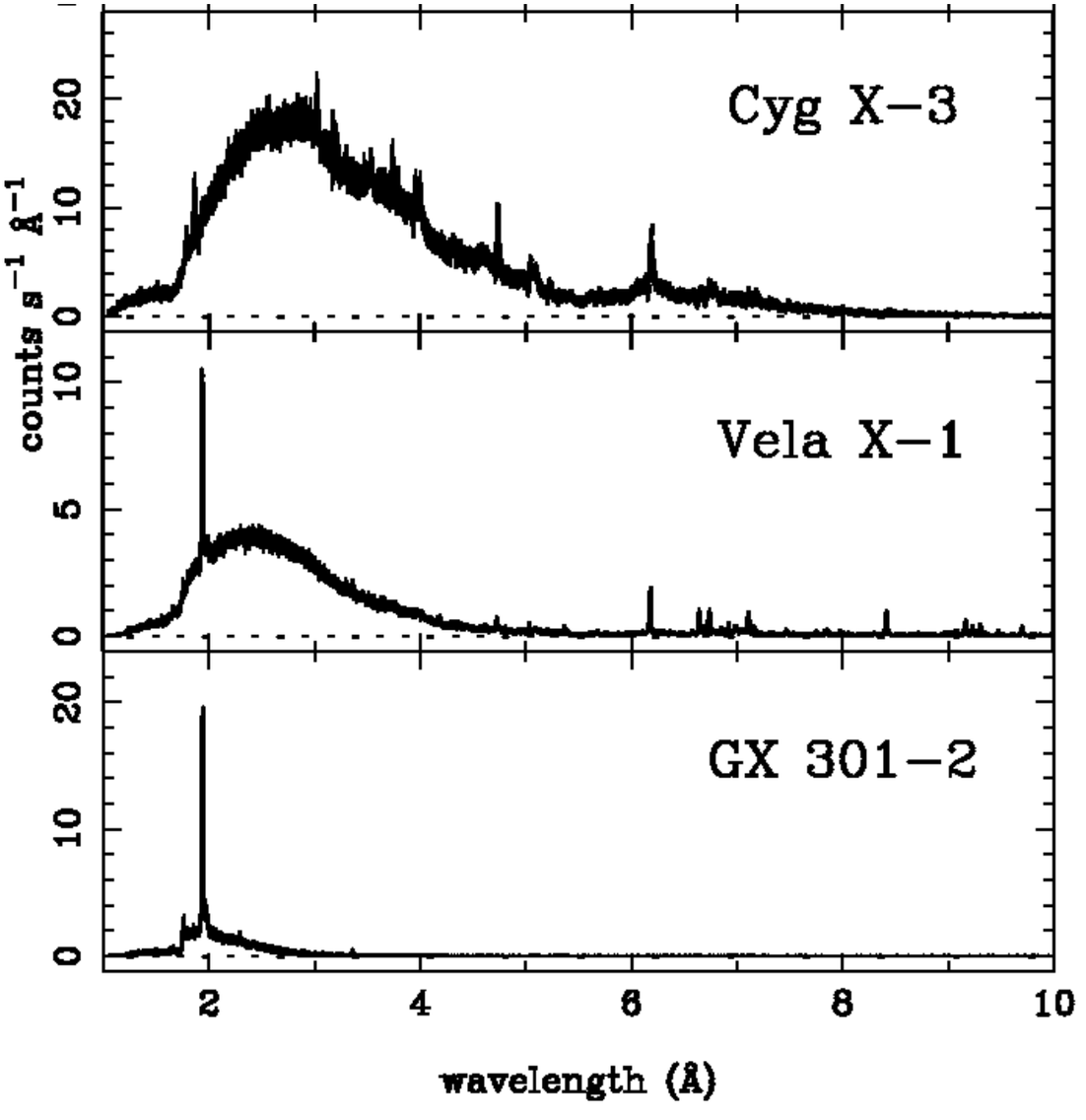
From stellar atmosphere models (PoWR, here maximum opacity)



Clumping: smaller optical depth, grey opacity! (Feldmeier+ ’02)

Agreement with X-ray data of "normal" OB stars (Oskinova + ’06)

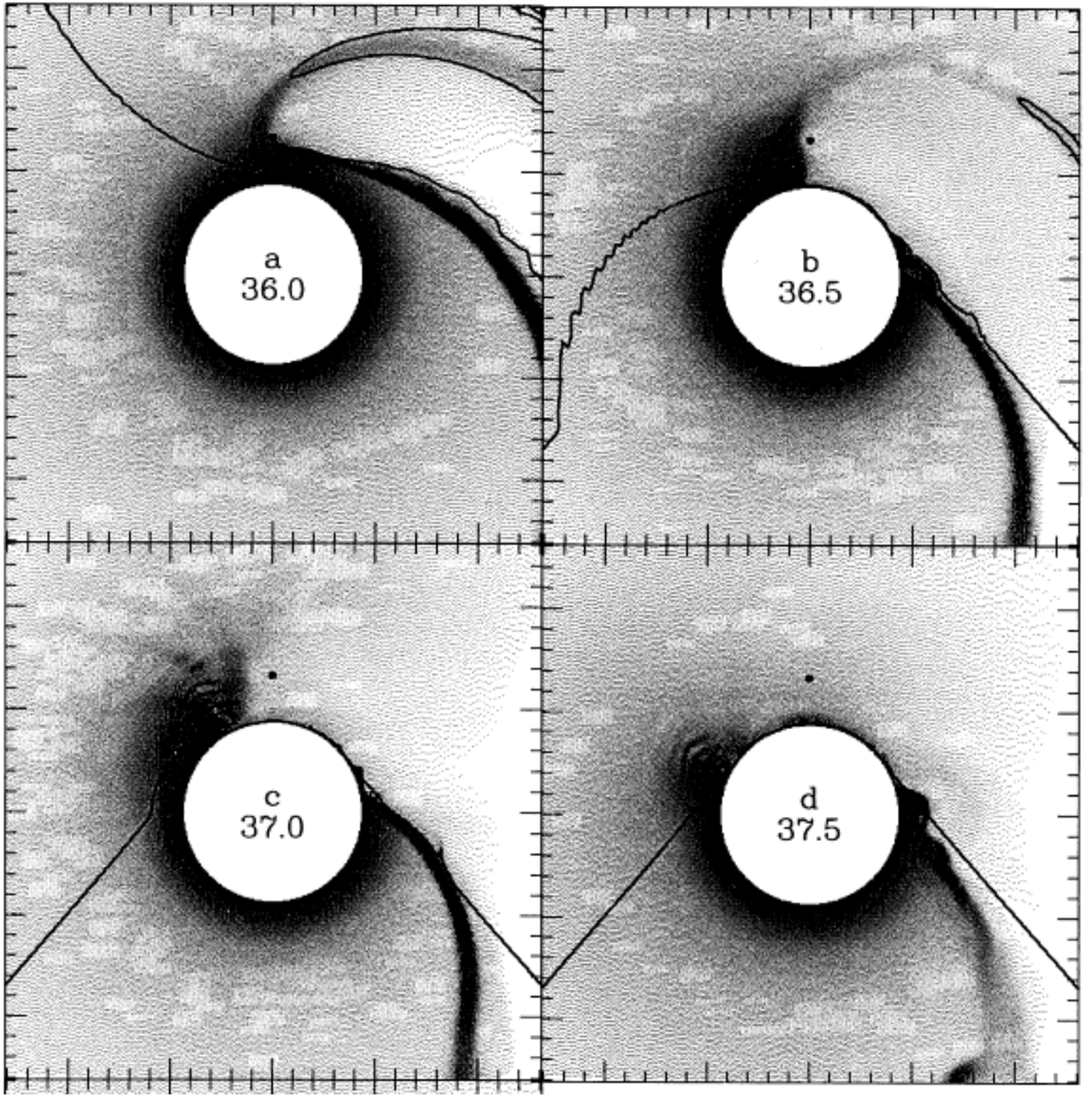
Strong absorption in HMXB X-ray spectra



- Absorption depends on orbital phase
- Measured $N_{\rm H} \Rightarrow$ too high $\dot{M}$
- Clumping not included! so far
- Compact object distorts wind
- X-ray field distorts the wind

Apparent contradiction between high absorption infered from X-ray spectra and clumped nature of the wind

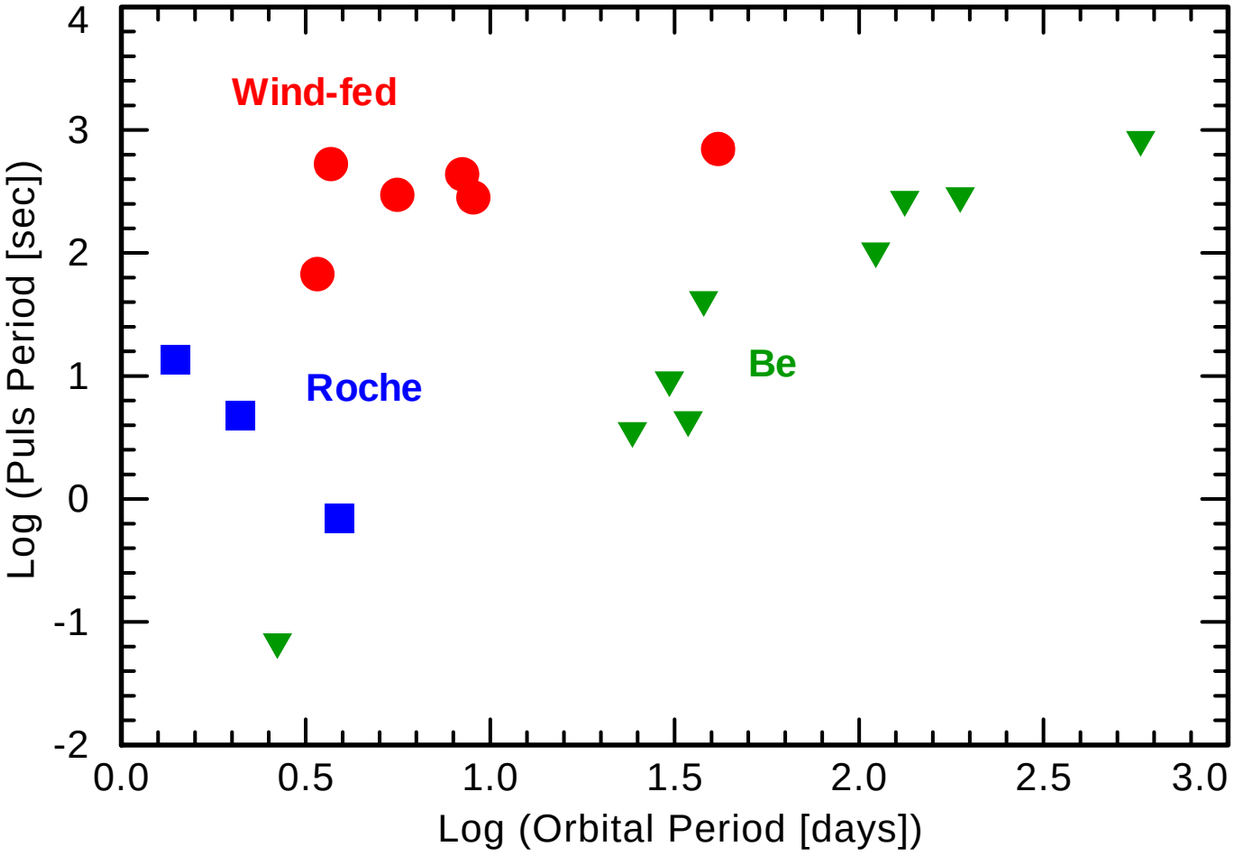
The shadow wind in high-mass X-ray binaries



- Blondin (1994)
- Feldmeier etal (1996)

- Accretion wake
- Photoionization wake
- Agreement with light curves (?)
- Is it explanation?

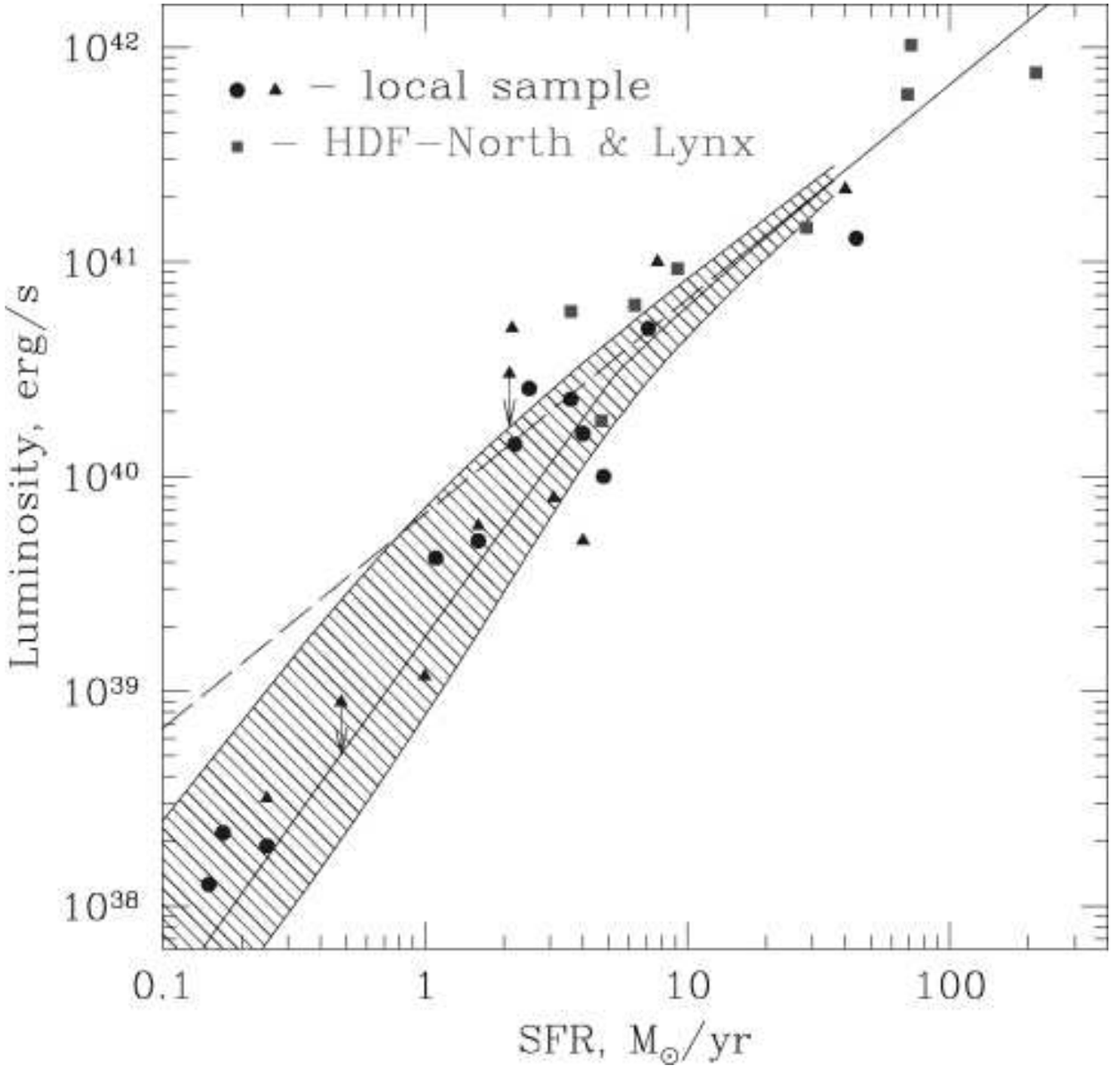
Three types of X-ray pulsator



- Empirical diagram Puls-Period
  Corbet (1986)
- New data agree
- Physics???
- 2004: 130 HMXBs
  (Goldstein et al. 2004)
  ≈ 11 sgOB
  ≈ 3 RLOF

- Life- time $\sim 10^5$ yr → second SN → IF! bound → double NS/BH
- Gravitational waves. Be/XRB & LMXBs in Globulars: far better statistics

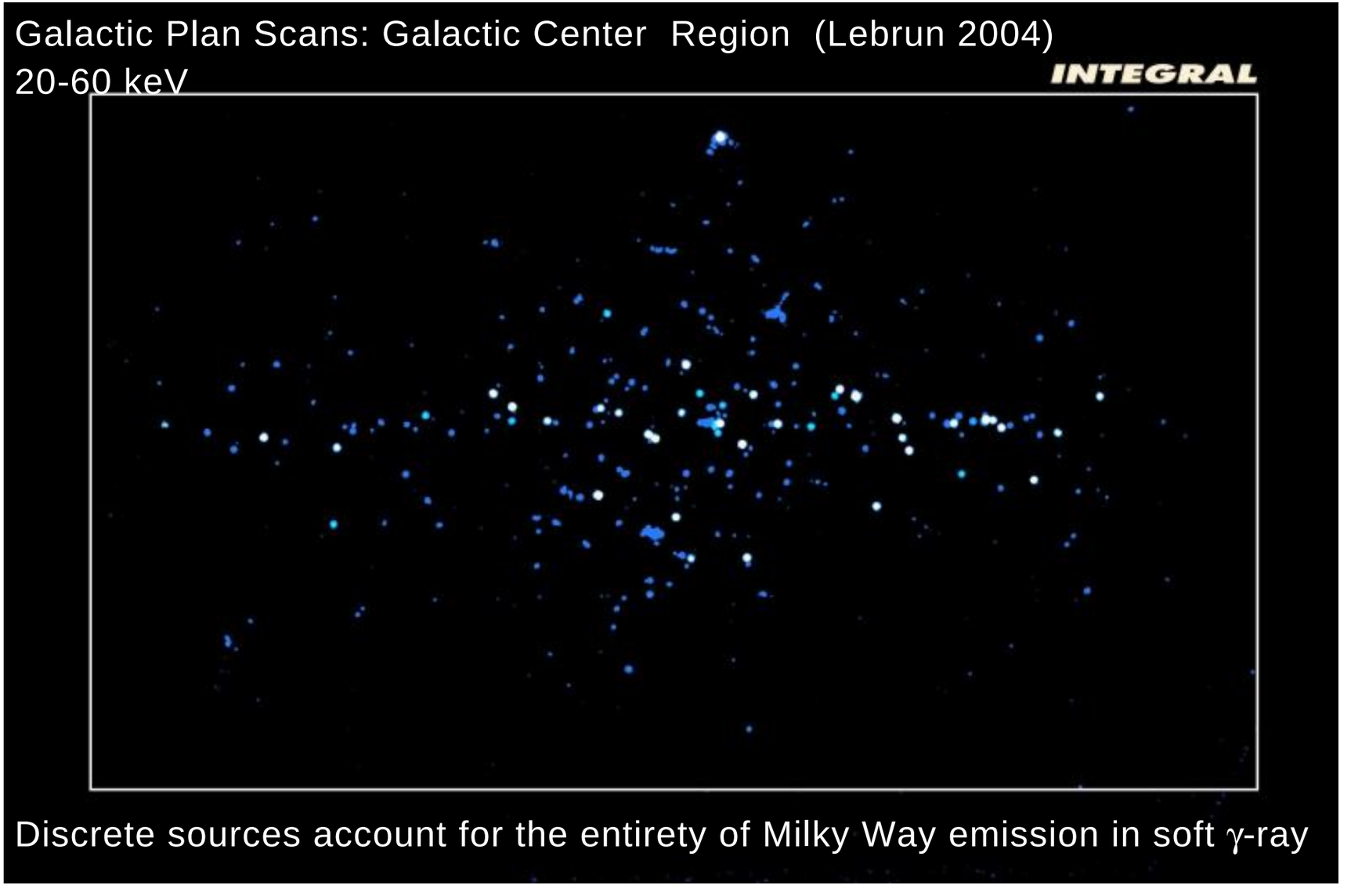
HMXBs: star formation rate indicator in distant galaxies



- sgOB 10^5 yr lifetime
- HMXB $L_X \sim 10^{38}$ erg/s
  Detection
  $F_X = 10^{-16}$ [cgs]
  individual: 100 Mpc
- Cummulative: 10^3 Mpc
- Flux - SFR
  (Hα, UV, IR, radio)
- L_X - SFR
  (Grimm et al. 2003)

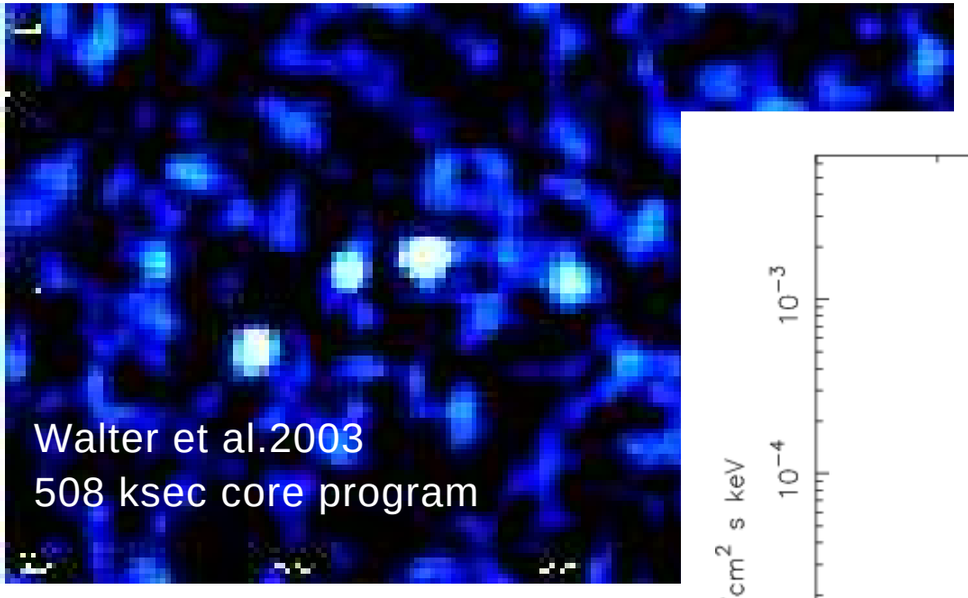
Soft γ-ray emission of the Mylky Way

- Imager on Board of Integral Sattelite (IBIS 15keV-10MeV)

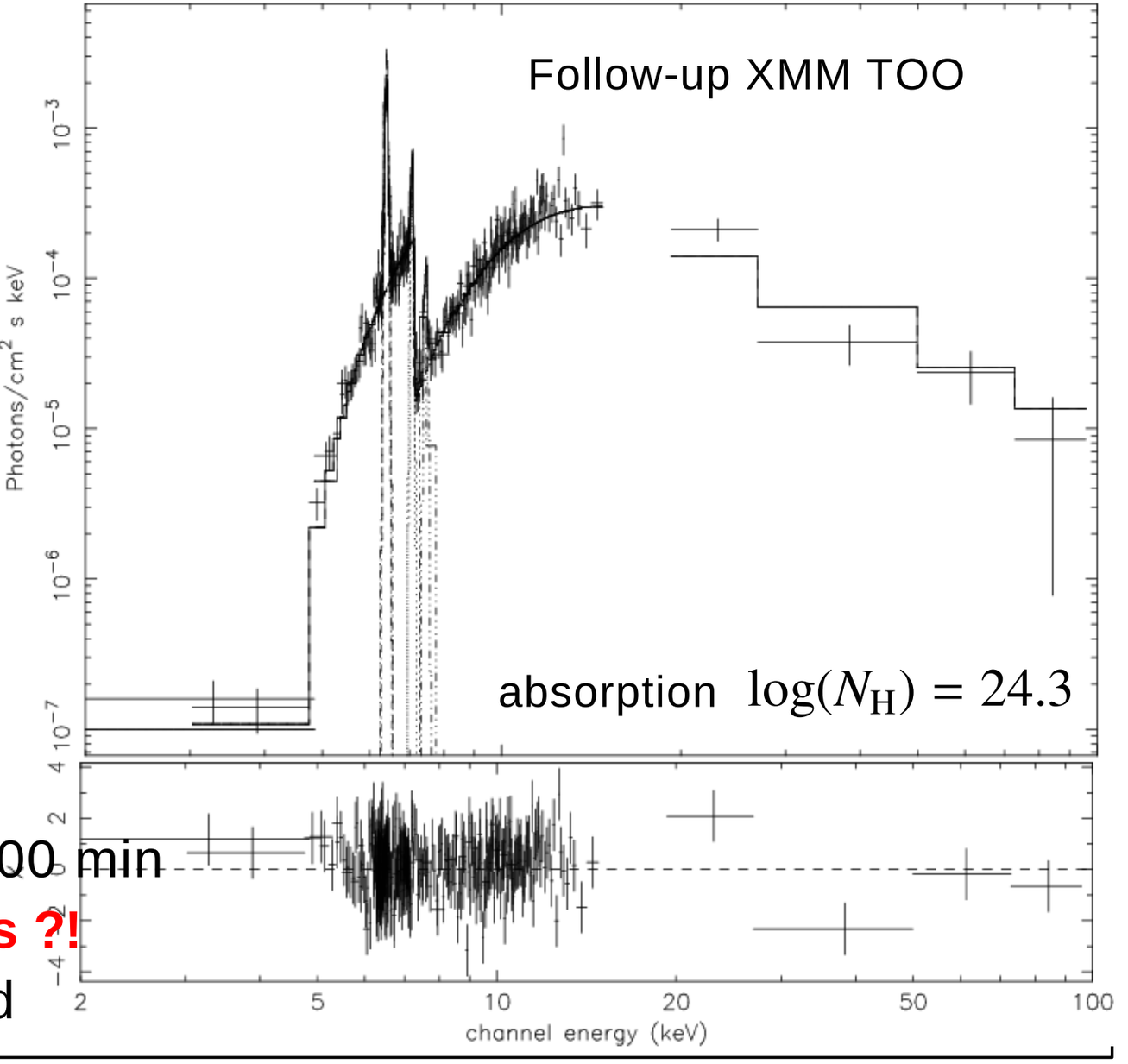


- $8^\circ \times 8^\circ$FoV, $12'$ resolution, 1 milliCrab $\rightarrow$ 120 new sources

New, highly absorbed Integral sources



IGR J16318-4848
01/03 beginning of science operation

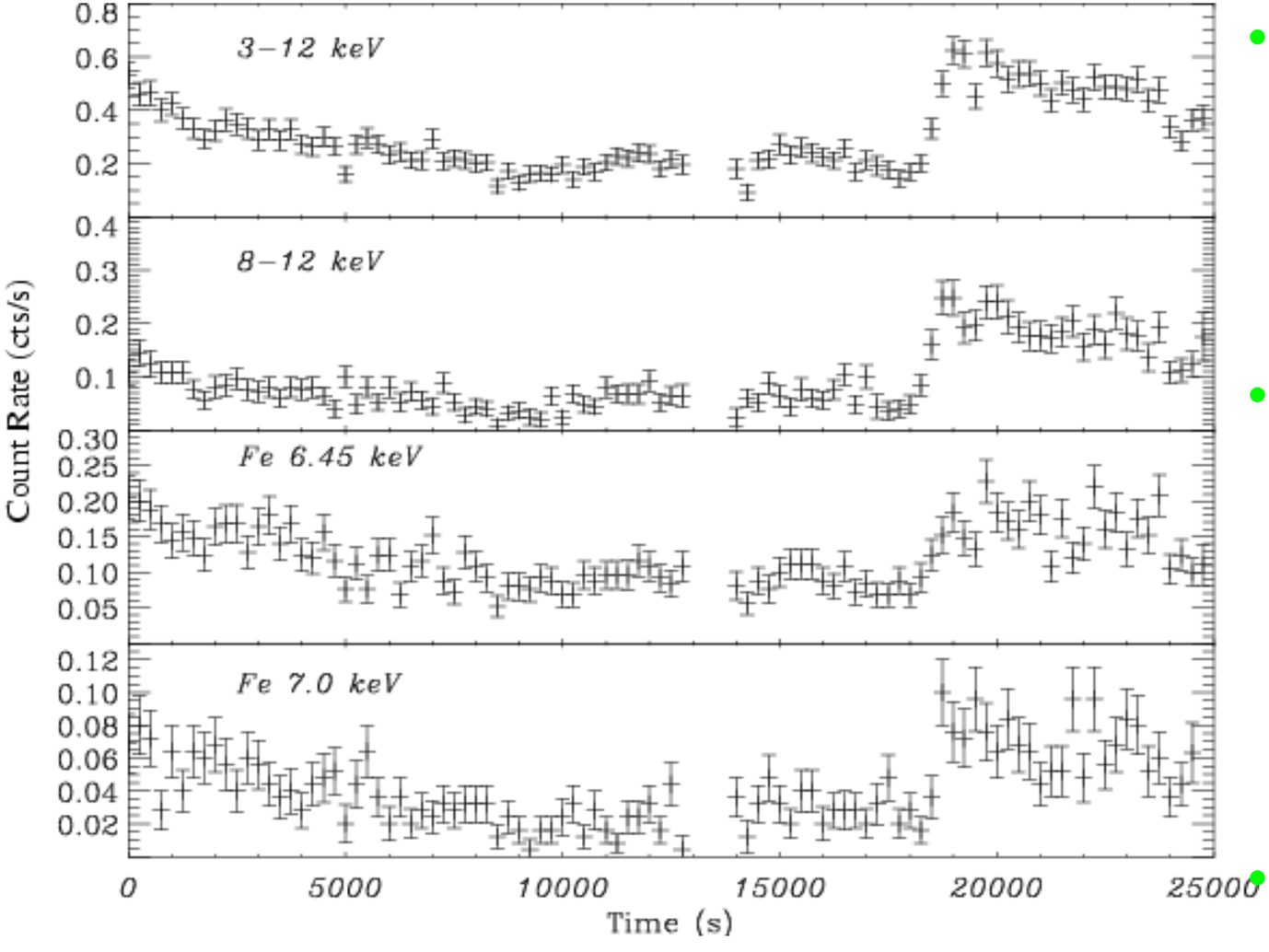


- ~10 IGRs Norma-Arm varaiable $\log(N_{\rm H}) \geq 23$
Galactic value $\log(N_{\rm H}) \approx 22$
- Hard X-rays power-law ($\Gamma \leq 2$) emission lines
- 4 IGRs: pulses (?) 4-100 min

High-Mass X-ray binaries ?!

Corbet diagram: wind-fed

On the nature of the source IGR J16318-4848



- X-ray light curve
  Time T< 200 s
  continuum & Fe Kα
  small size
  NOT a galaxy
- Optical/NIR spectra
  NTT SOFI (Filliatre '04)
  Interstellar $A_V = 11.6$
  Source $A_V = 17.4$
  $L_{bol} \sim 10^5 L_\odot$ d>2 kpc
  Hydrogen emission lines + fo
  Supergiant Of/B[e]
- X-ray luminosity
  $L_X \approx 10^{35}$ erg/s
  Accreting NS
  Be/X-ray ?

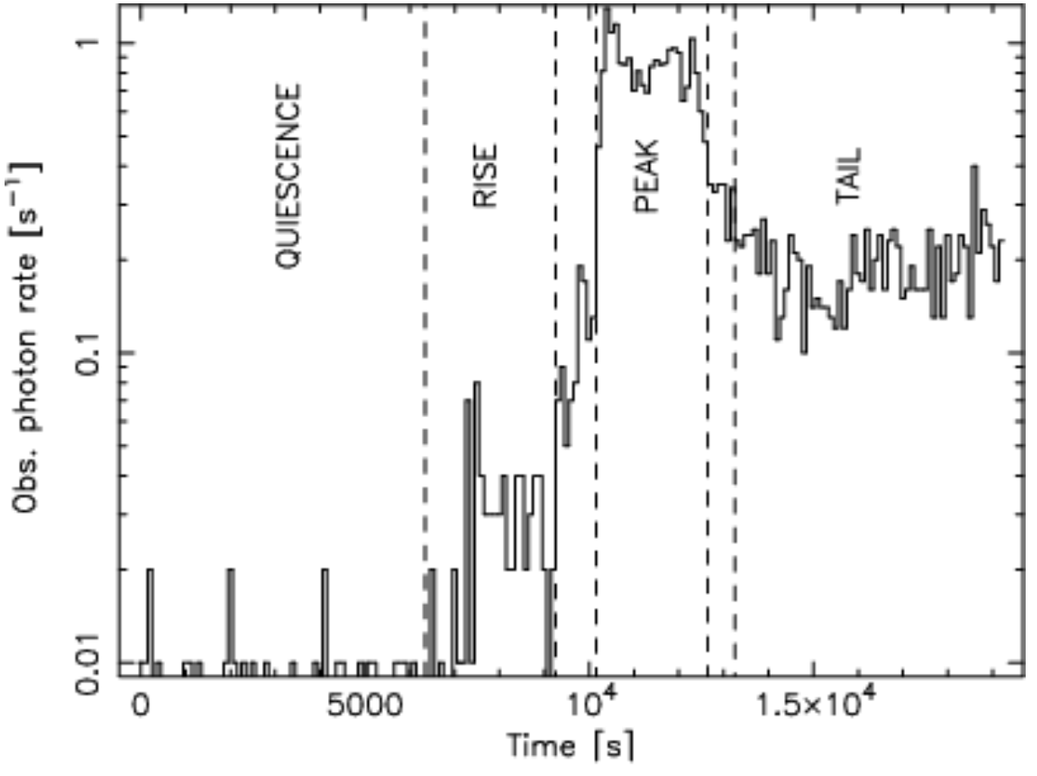
Supergiant donors, short outbursts

Supergiant Fast X-ray Transients

(Negueruela et al.'06)

Assymetric wind? Radio? Why absorption??

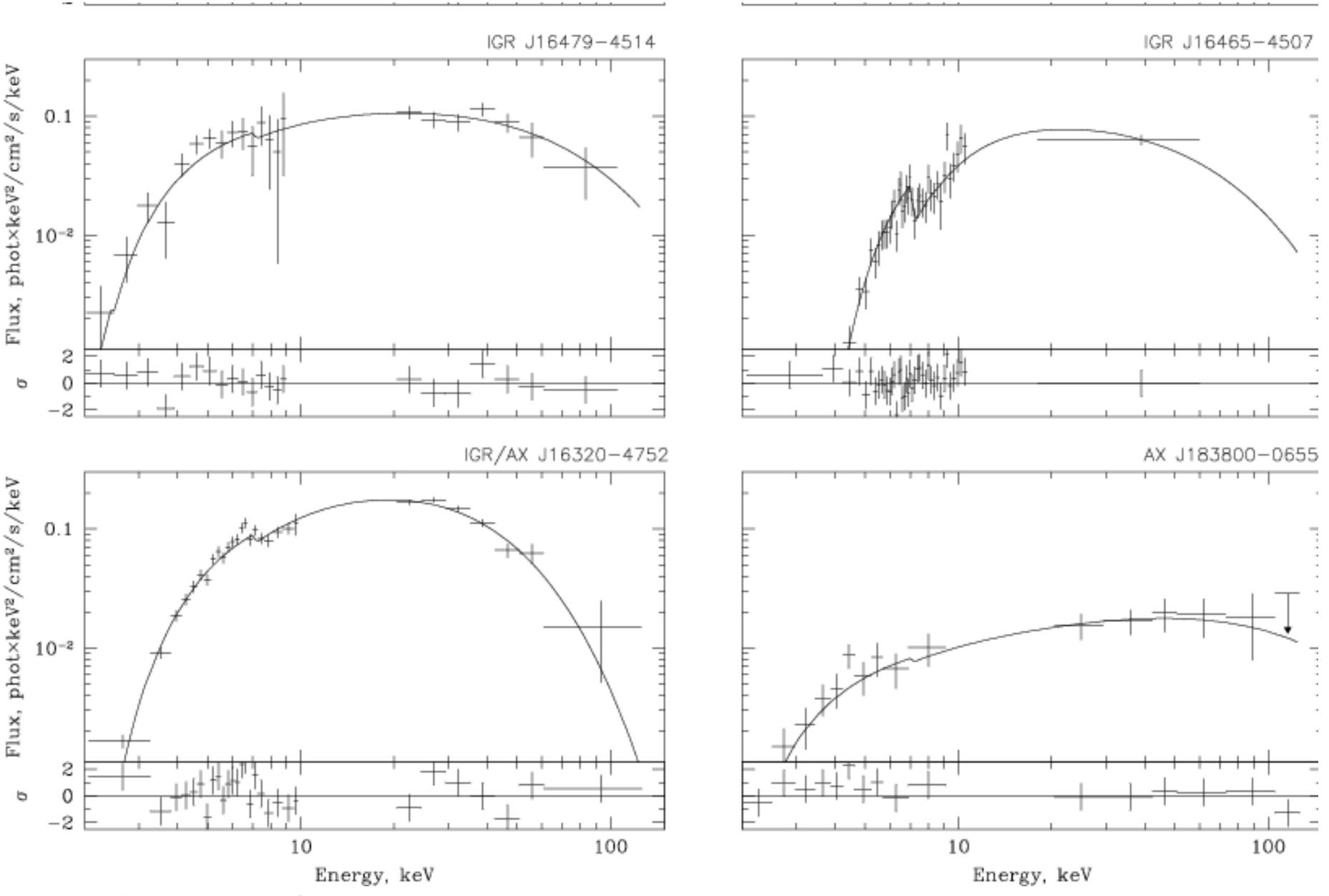
IGRs with optical identifications



- IGR J17544-2619
  O9Ib
  Brief outbursts 100x
  in 't Zand '05: **clumps**
  $L_X \approx 5 \times 10^{32}$ erg/s
- IGR J19140+0951
  OB stars (in 't Zand '06)
  ISM reddening
  Source $A_V = 17.4$
- XTE J1739-302
  O8Iab(f) optic $N_H = 22.3$,
  X-ray spectra $N_H = 22.54$
  variable absorption (Neg. + '06)

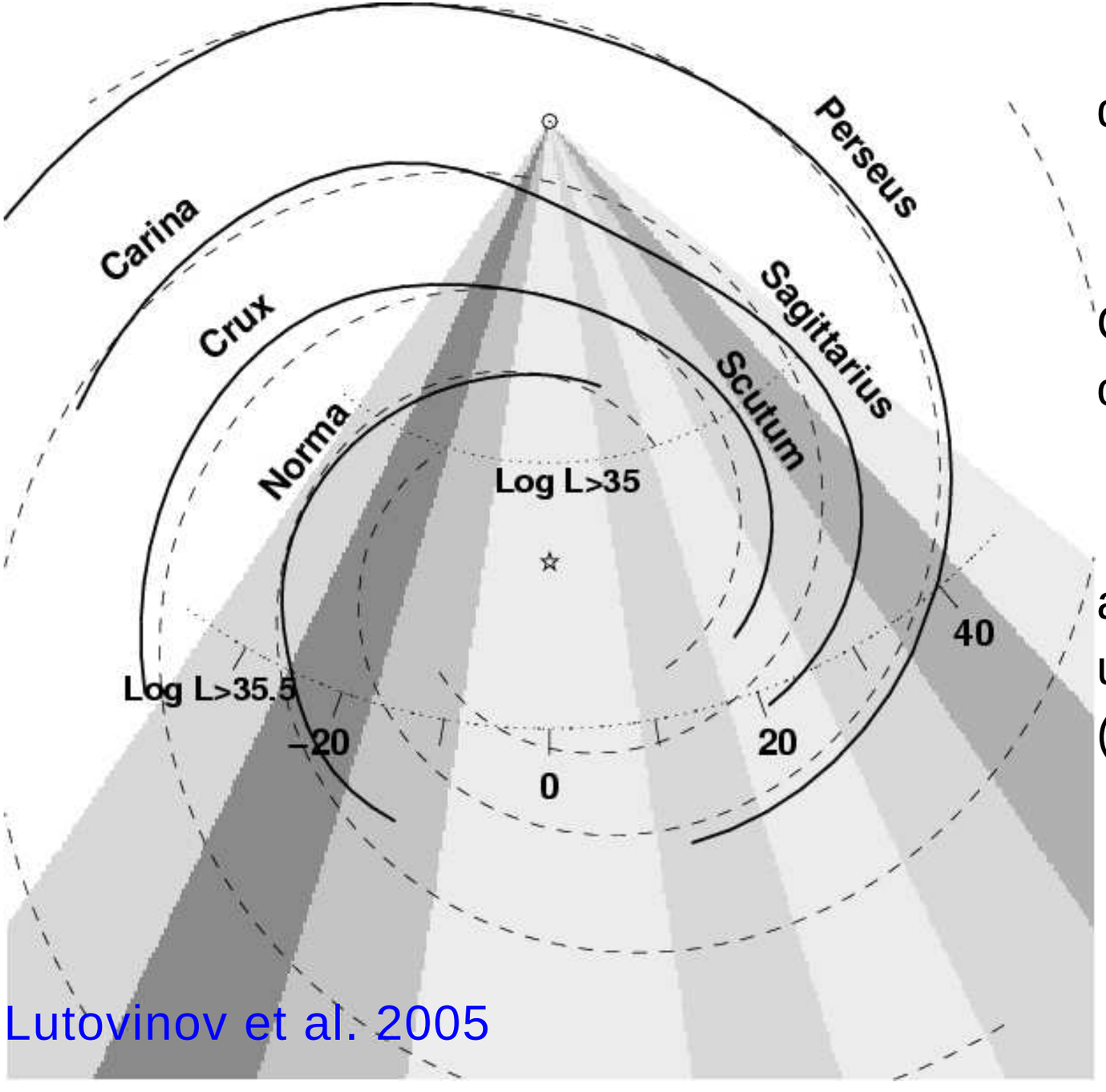
Supergiant Fast X-ray Transients
- OB supergiant donors
- High-absorption
- Flaring
- Low-quiescence X-ray luminosity

Broadband energy spectra of highly absorbed sources



Lutovinov et al. 2005

Galactic distribution



Lutovinov et al. 2005

- HMXBs disribution different form LMXBs
- 50% of all Galactic HM Galactic HMXBs: obscured sources
- Total number agreement universal XRLF (Grimm 03)
- Star formation sites

Our XMM-Newton Program

- Five IGRs pulsars

- Two systems have eclipses:
  - IGR J17252-3616 $P_{\rm orb} = 9.7$d and $P_{\rm spin} = 413$s
  - IGR J18027-2016 $P_{\rm orb} = 4.6$d and $P_{\rm spin} = 139$s

- Coordinated XMM-Newton VLT observations:
  - X-ray and ISAAC NIR spectra
  - 8×10 ksec exposure around orbit

- Stellar wind probe

- Physics of NS accretion

- NS masses

Conclusions

- Integral Galactic Plane Probe doubled number of known HMXBs
- X-ray spectroscopy of HMXBs is snesitive tool to probe stellar wind
- Clumping of the wind is infered from analysis of emission spectrum.
- The large-photoelectric absorption seen in IGRs cannot be explained by stellar clumped wind
- Do IGRs represent the new class of HMXBs?