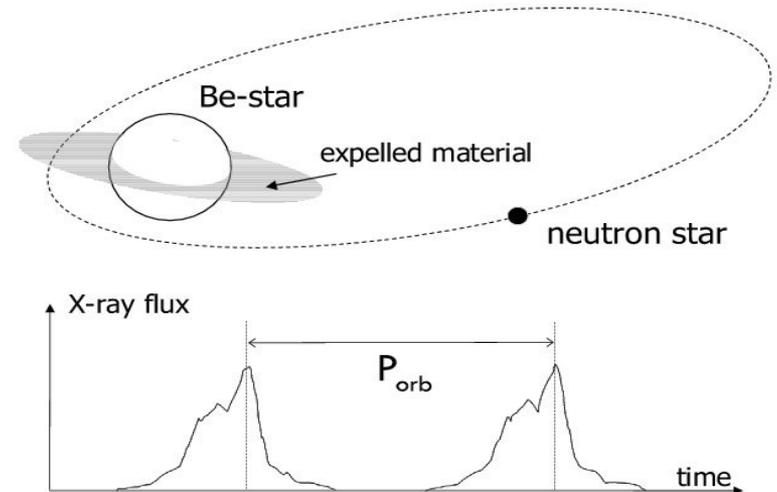
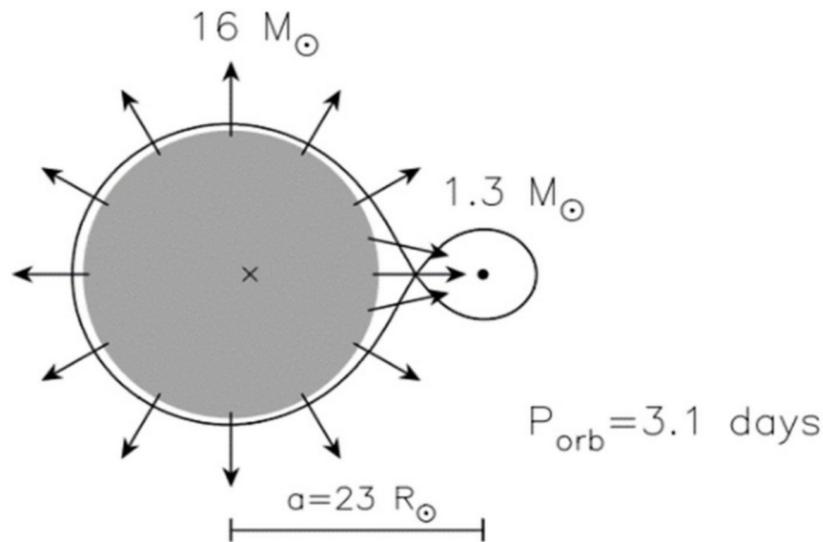




# Probing massive star winds with SgXBs: current status, recent efforts, and future perspectives

E. Bozzo  
University of Geneva 

# Some background: High Mass X-ray Binaries



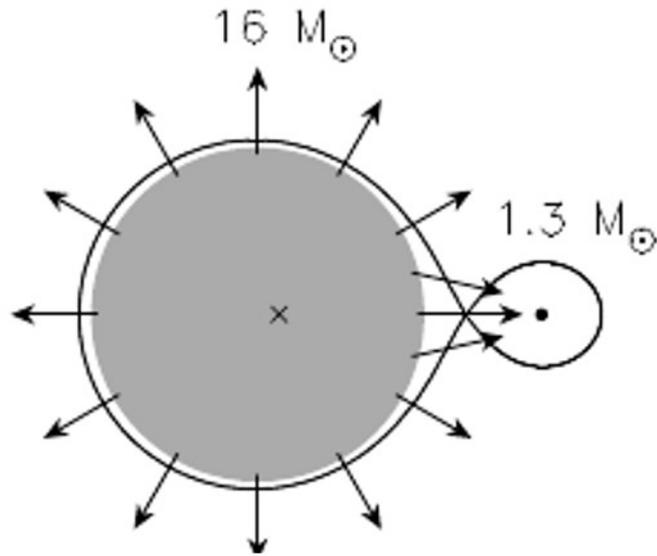
## “Classical” supergiant X-ray binaries

- OB supergiant with a compact object
- (mostly) wind accretion
- **Persistent** objects with variability in the X-ray luminosity by a factor of  $\sim 10$ - $100$
- Average persistent luminosity depends from the orbital period
- Typically  $\sim 10^{35}$ - $10^{38} \text{ erg s}^{-1}$

## Be X-ray binaries

- Be stars with a compact object
- Disk accretion
- **Transient** sources with regular outbursts (weeks to months)
- Typically:
  - $\sim 10^{32}$ - $10^{33} \text{ erg s}^{-1}$  (quiescence)
  - $\sim 10^{36}$ - $10^{38} \text{ erg s}^{-1}$  (outbursts)

# Wind-fed Supergiant High Mass X-ray Binaries

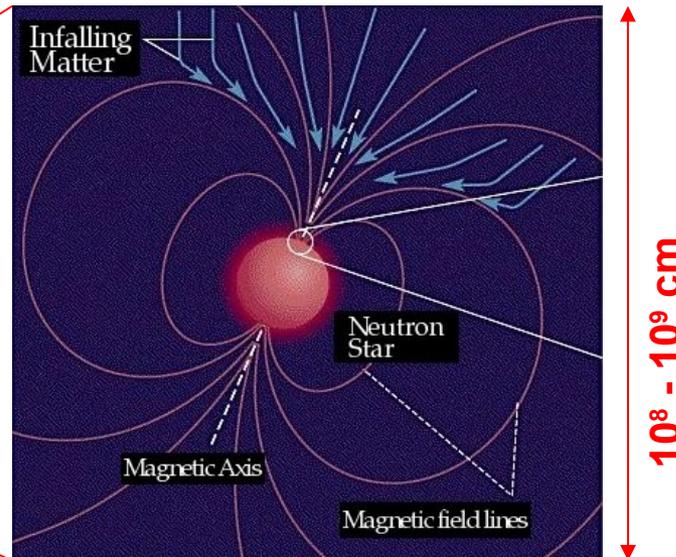
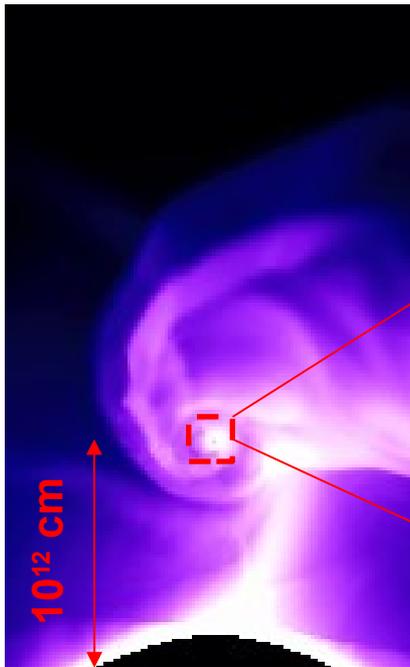


Neutron star (NS) orbiting a O-B supergiant  
 Orbits are nearly circular  
 Orbital periods few to tens of days  
 Young systems (few  $10^6$  yrs)  
 Highly magnetized NS expected  
 Spin Periods are long,  $>100$  s

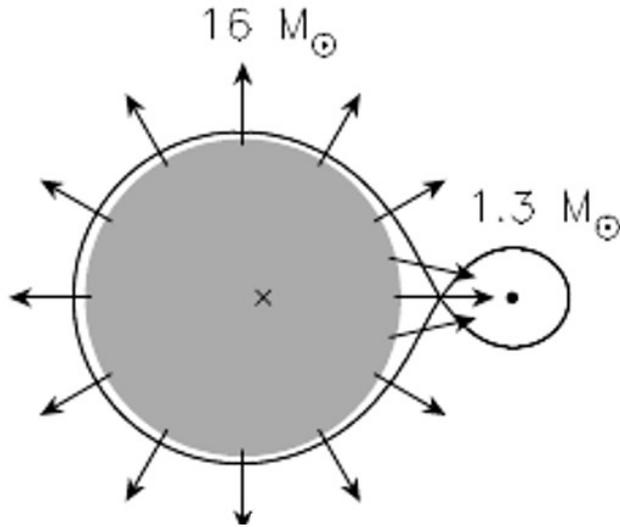
Typical stellar wind parameters:

$V_\infty \sim 1000\text{-}3000$  km/s

$\dot{M}_W \sim 10^{-6}\text{-}10^{-5} M_\odot/\text{yr} \sim 10^{19}\text{-}10^{20}$  g/s



# Wind-fed SgXBs: the «direct accretion»



Relatively bright X-ray sources due to wind mass accretion onto the NS

$$V_{\infty} \sim 1000-3000 \text{ km/s}$$

$$\dot{M}_W \sim 10^{-6}-10^{-5} M_{\odot} / \text{yr} \sim 10^{19}-10^{20} \text{ g/s}$$

The classical «**direct wind accretion**»

$$\dot{M}_W \sim 4\pi r^2 V W \quad \text{Spherically symmetric wind}$$

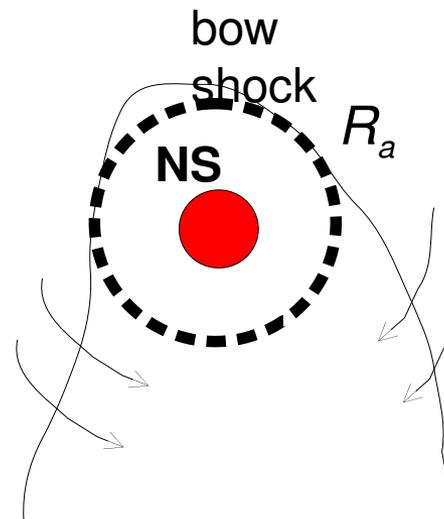
$$R_a = \frac{2GM_{NS}}{V_W^2} \sim 10^{10} \text{ cm} \quad \text{Accretion radius}$$

$$\dot{M}_{capt} / \dot{M}_W = \frac{R_a^2}{r^2} \sim 10^{-4} \quad \text{Wind accretion efficiency}$$

$$\sim 10^{35} - 10^{37} \text{ erg/s}$$

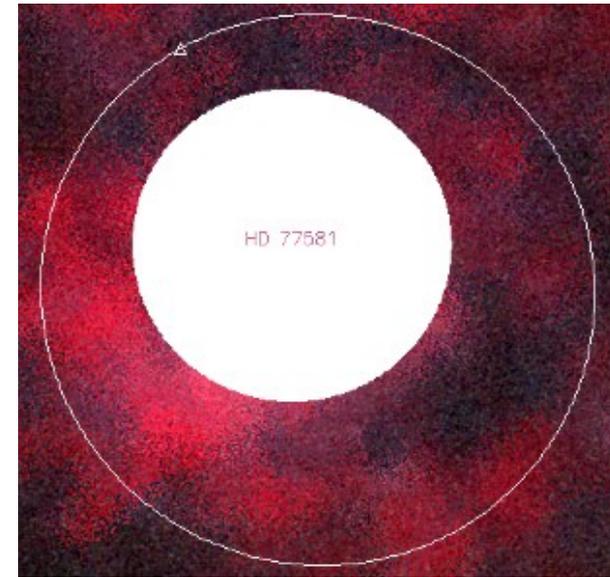
Accretion luminosity

(Bondi 1952)

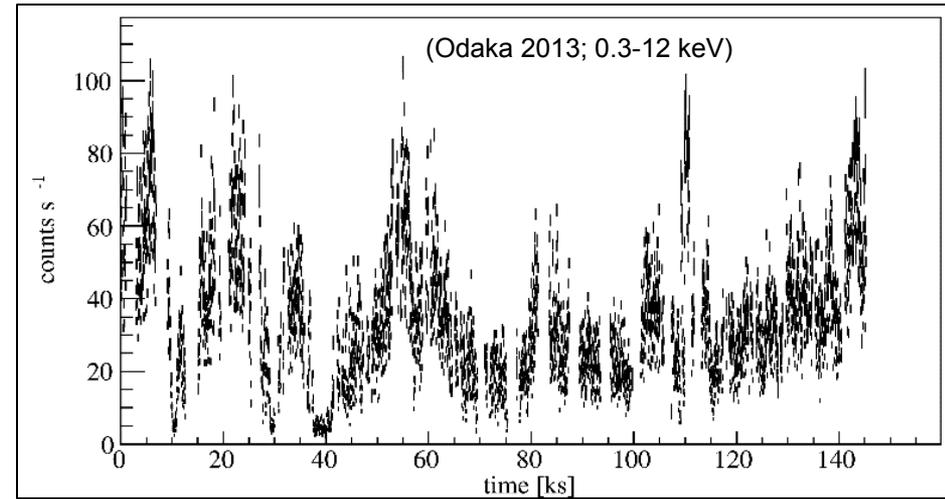


Typical  
variability  
timescale  
 $R_a / V_W \sim 100 \text{ s}$

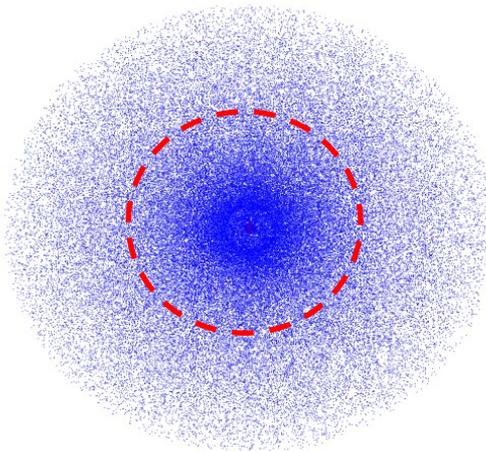
# The SgXB prototype: Vela X-1



$P_{\text{orb}} \sim 8.9 \text{ d}$   
 $P_{\text{spin}} \sim 283 \text{ s}$   
 $e = 0.09$   
**B0.5Ib**



- Averaged  $L_X \sim 4 \times 10^{36} \text{ erg/s}$
- Variations in flux  $\sim 20-50$  on time scales of 100-1000 s



## Clumpy Wind Accretion (Lucy & White 1980)

$$\dot{M}_{\text{capt}} \propto \dot{M}_w \left( \frac{R_{\text{NS}}}{r} \right)^2 \frac{V}{V_w}$$

$$L_{\text{acc}} = \frac{GM_{\text{NS}} \dot{M}_{\text{capt}}}{R_{\text{NS}}}$$

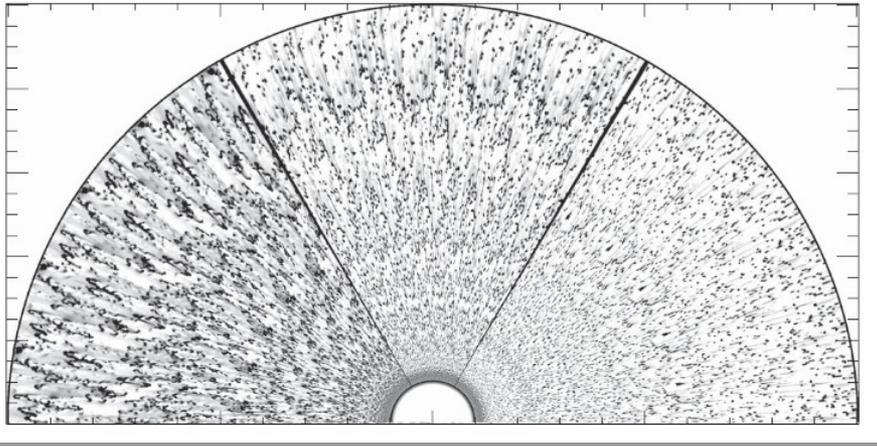
$$\Rightarrow \epsilon \sim 10 \Rightarrow L_X \sim 10-100$$

$$\Rightarrow \frac{v}{v_w} \sim 2-3$$

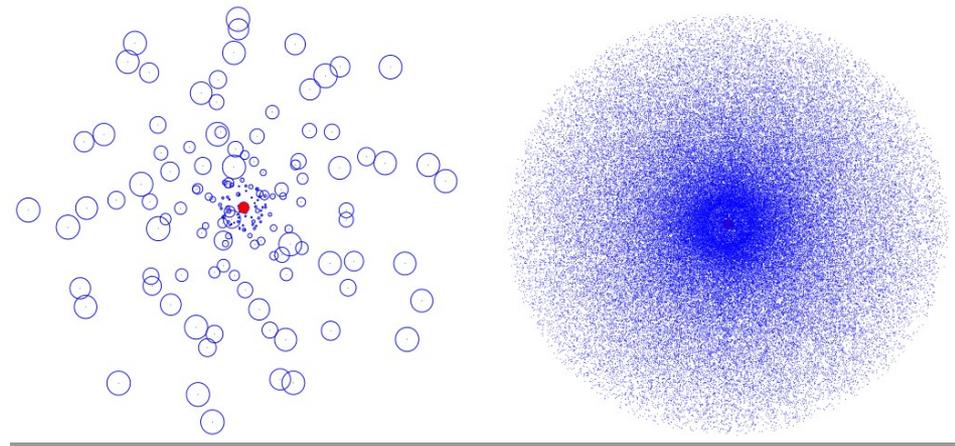
(in't Zand 2005; Negueruela 2008, Walter 2007)

# Clumps in supergiant stellar winds

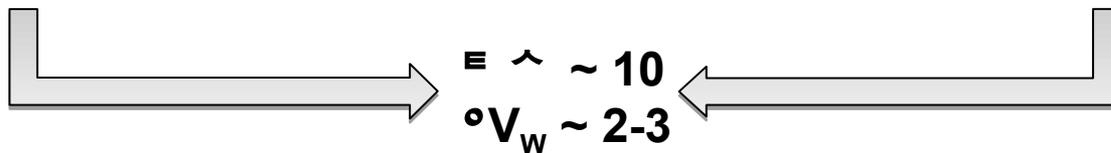
- Predicted theoretically ~1980: instabilities of radiatively driven winds (Lucy & White 1980)
- Observational features in Opt./UV spectra: «outward moving inhomogeneities» (Eversberg 1998)



Hydrodynamical simulations:  
**1D**: very massive clumps ( $\epsilon \sim 10^4$ )  
**2D**: instabilities prevent large clumps  
 (Feldmeier 1997; Oskinova 2012; Dessart 2002, 2005)

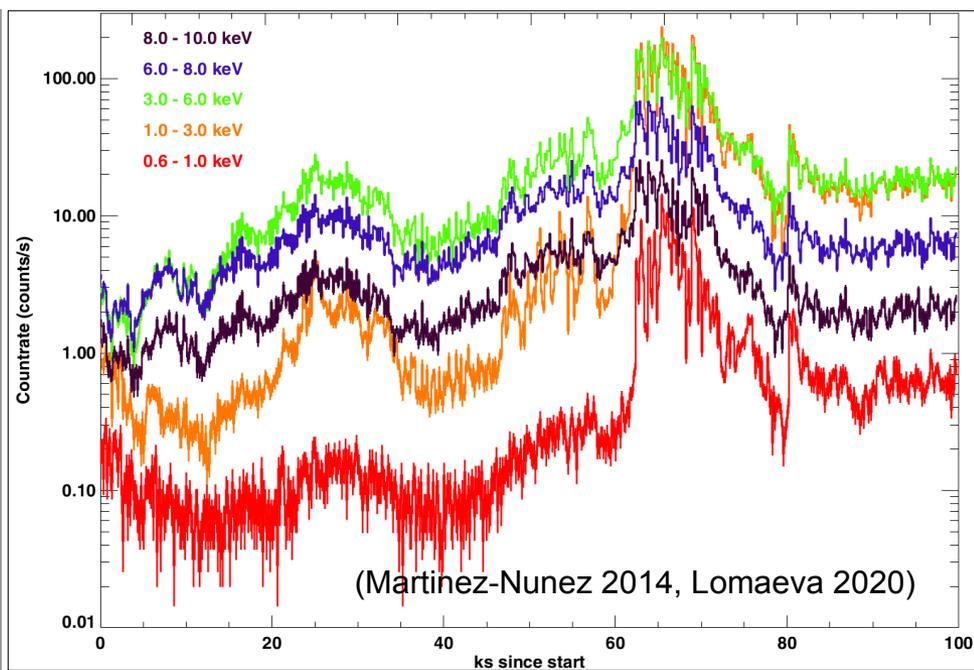
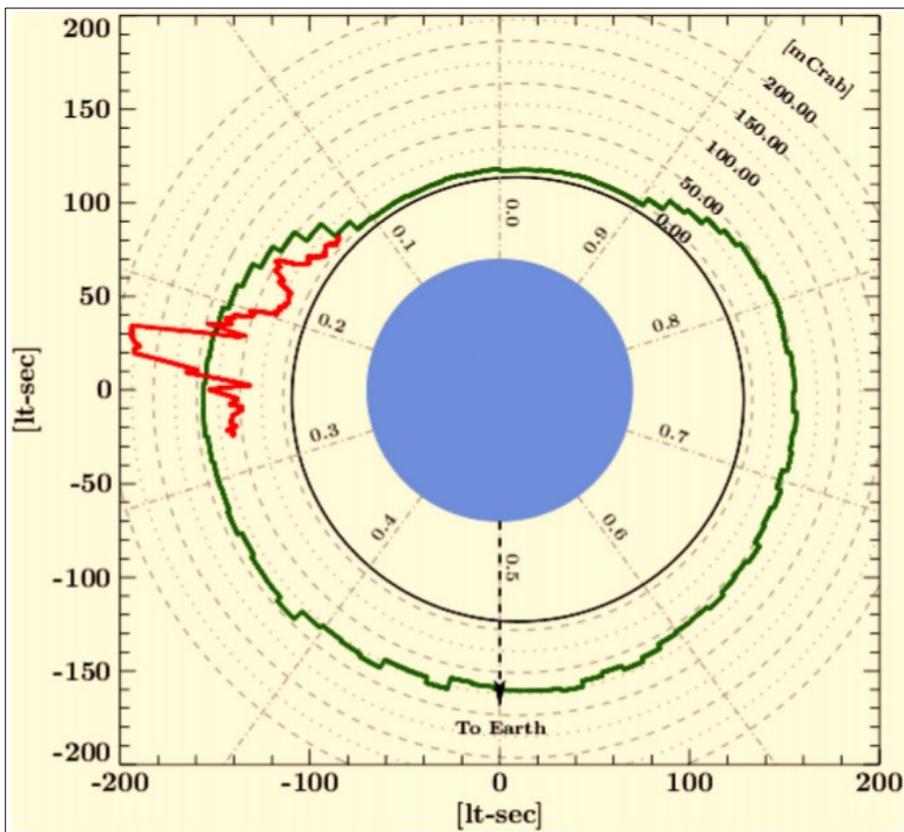


Quantitative spectroscopy:  
*Ad hoc* clumps distributions + radiative transport to simulate Opt./UV spectra  
 (Surlan 2013)

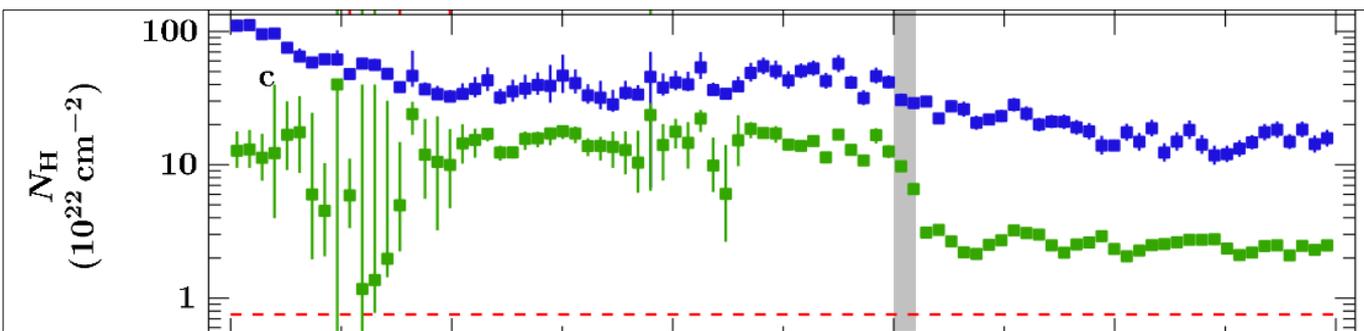


Clumps affect estimates of mass loss rates from massive stars, which in turns impact our understanding of: Galaxy evolution and chemical enrichment, Universe evolution, GWs

# Clumpy winds: Vela X-1 observations



Giant flare interpreted as due to the accretion of a massive clump



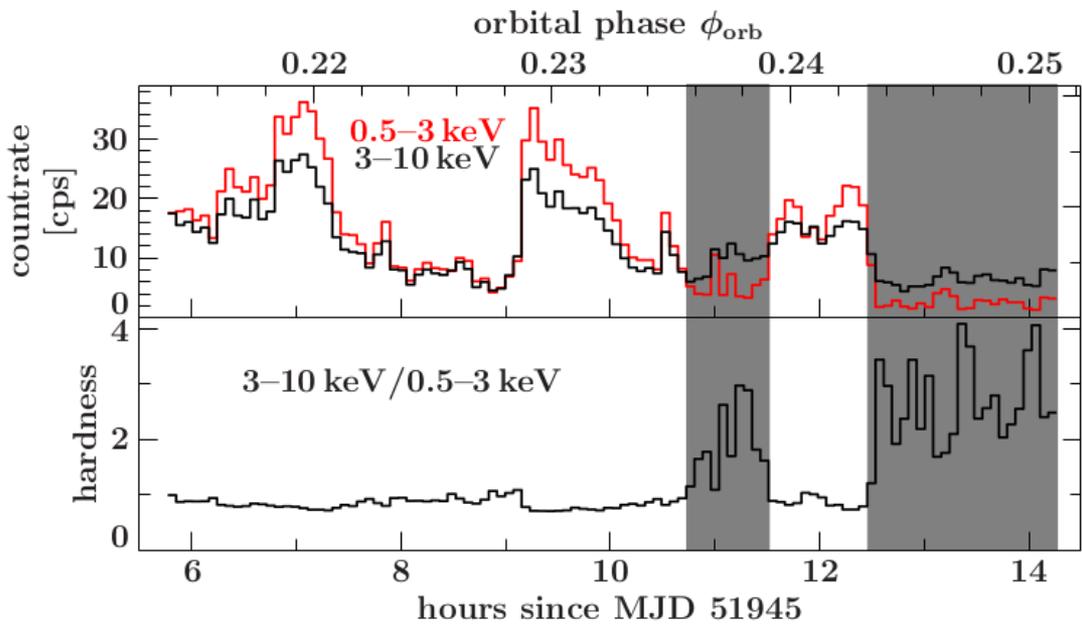
$$l_{cl} \sim t_{rise} v \approx 5 \times 10^{10} \text{ cm}$$

$$m_{cl} \sim 10^{21} \text{ g}$$

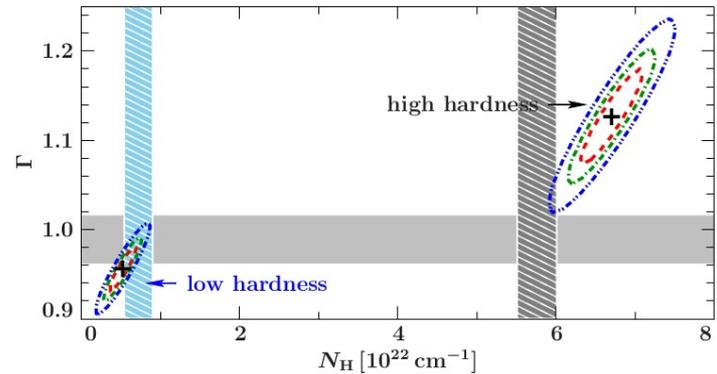
Other studies (Fuerst 2010)

$$5 \times 10^{19} - 10^{21} \text{ g}$$

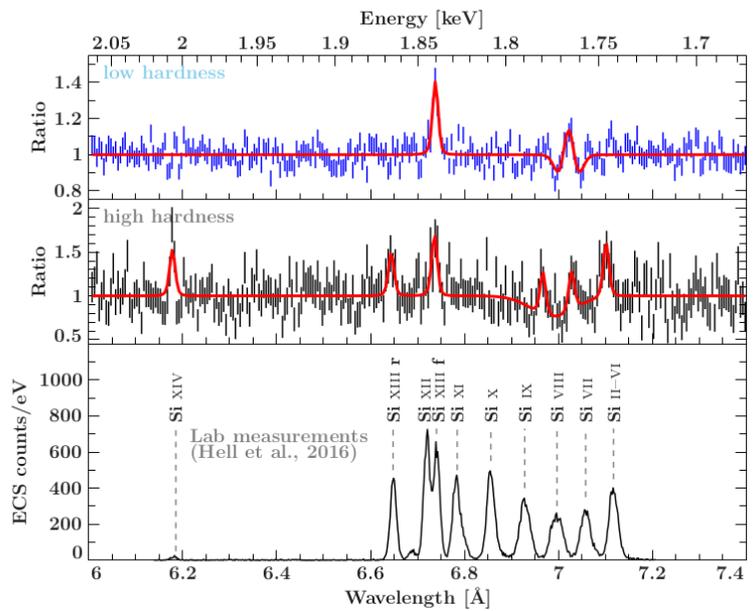
# Clumpy winds: Vela X-1 observations



Increased HR due to increased absorption largely variable on few ks timescale



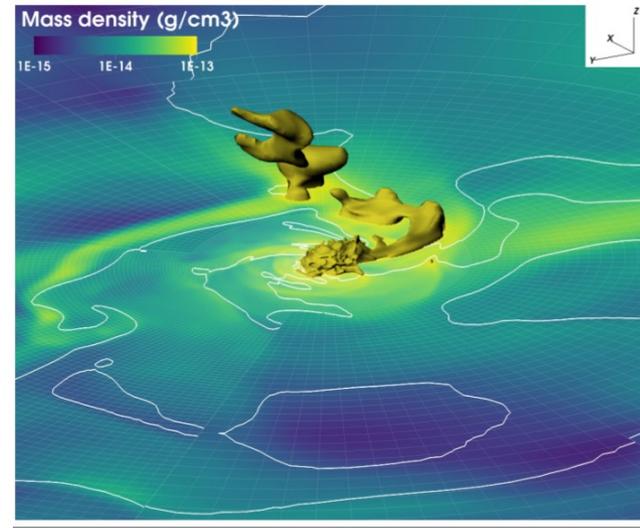
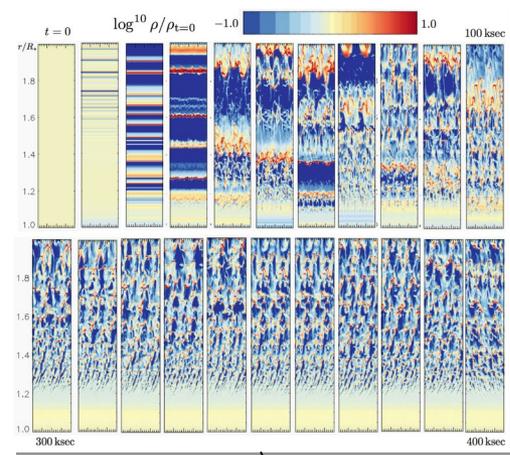
(Grimberg 2017, Amato 2021)



High resolution spectroscopy reveals how stellar wind respond to X-rays:

- Dual cold/hot medium with different ionizations states
- Ionized medium distributed also in relatively large region between the Supergiant and the NS

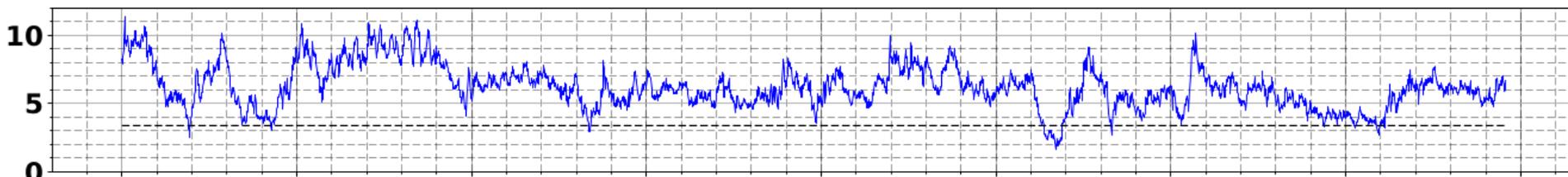
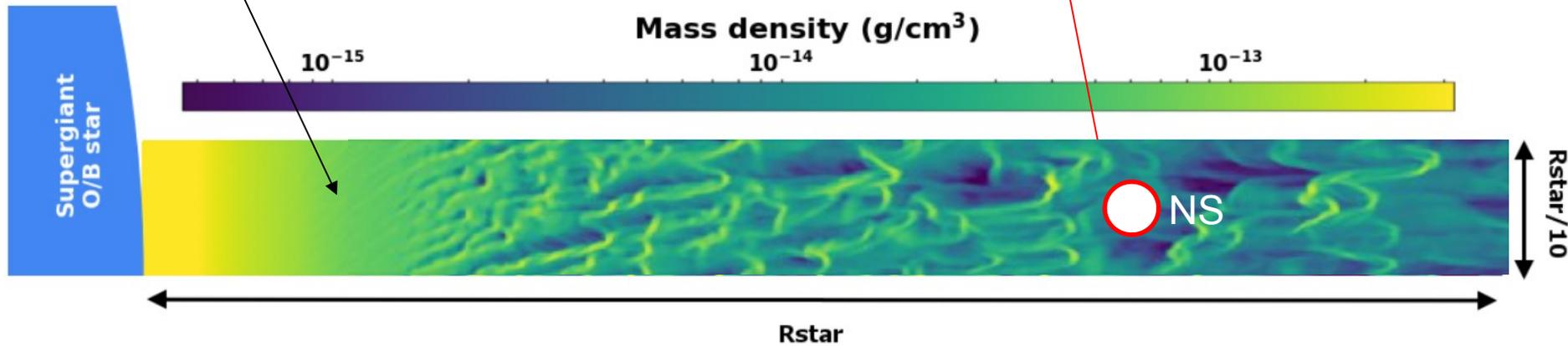
# Clumps in supergiant stellar winds



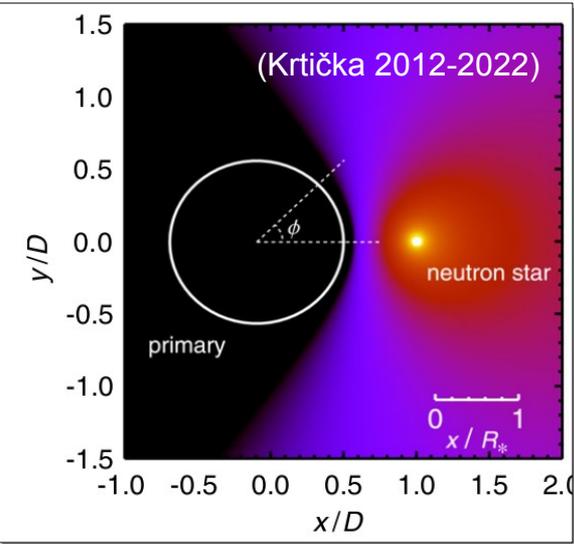
3D simulations from the  
2D hydro+radiation wind

Promising results in the  
computation of synthetic  
lightcurves (El Mellah 2017)

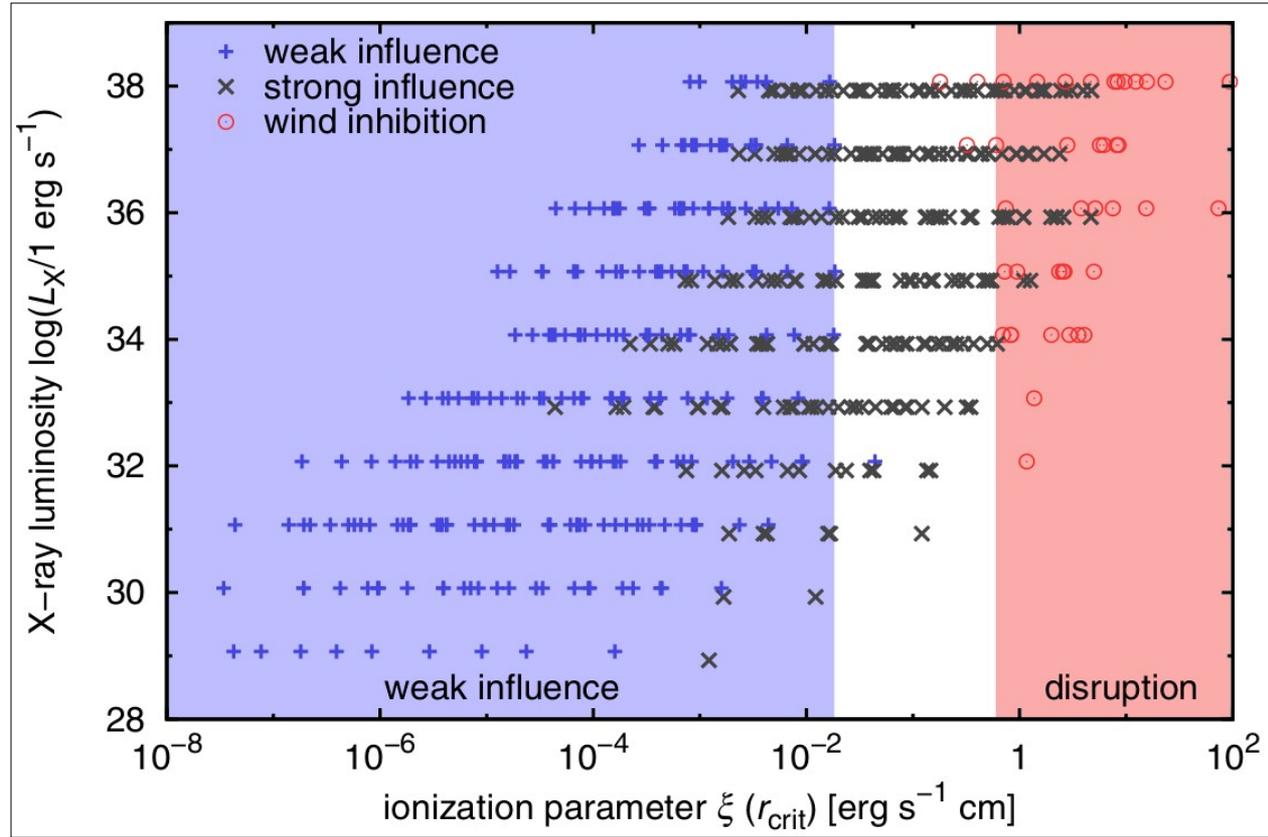
X-ray feedback onto the  
wind not included



# X-ray feedback into the stellar wind

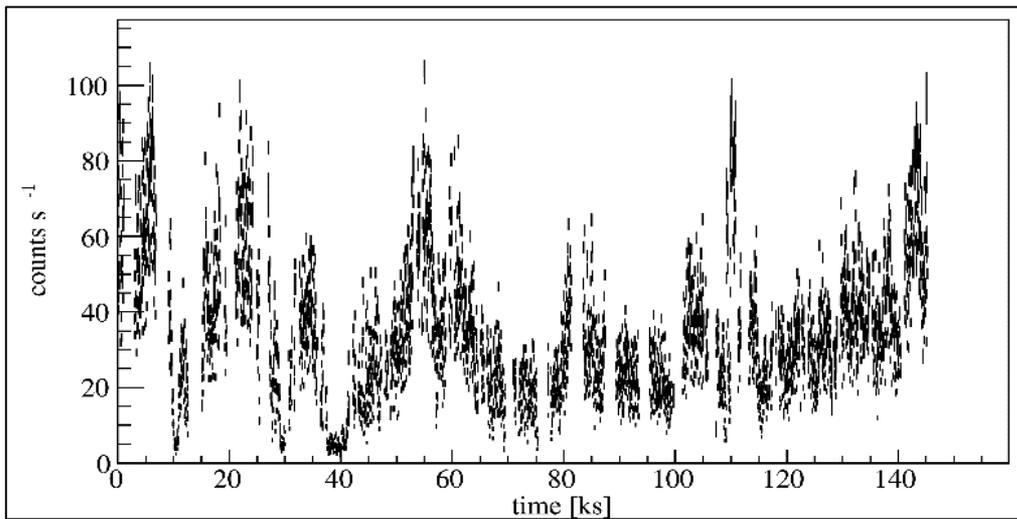


- X-rays from the compact object photoionize the stellar wind
- At higher luminosities this might inhibit the wind
- Low luminosity systems are less affected by this effect (i.e. SFTXs!)



Fainter sources are better suited to use the neutron star as a probe of the stellar wind

# The Supergiant Fast X-ray Transients



(Suzaku/XIS; 0.5-12 keV; Odaka 2013)

**Vela X-1** (classical SgXBs prototype)

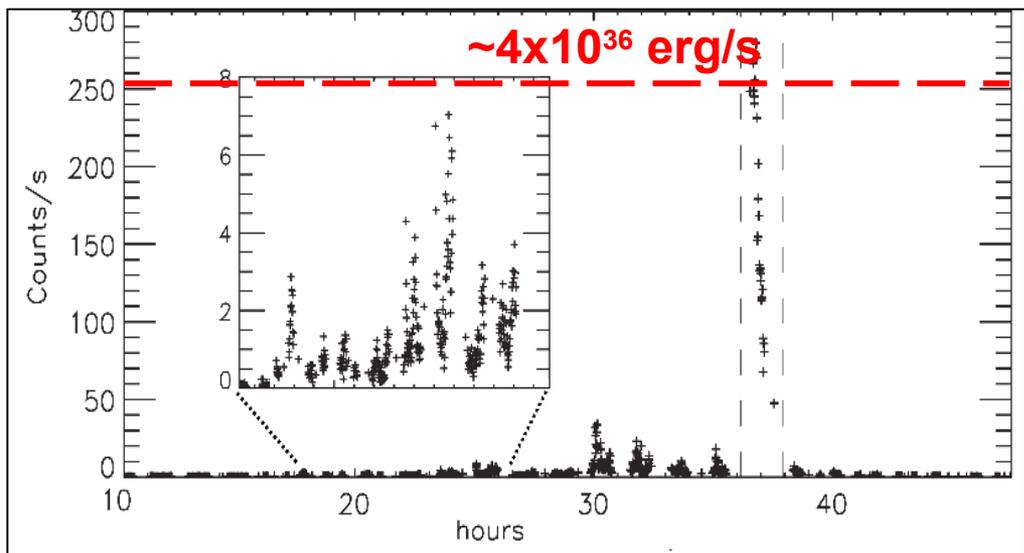
Orbital period 8.9 days

Average luminosity  $4 \times 10^{36}$  erg/s

Luminosity variations  $\sim 20-50$

NS accreting from supergiant wind

Variability due to wind clumps



(Suzaku/XIS; 0.5-12 keV; Rampy 2009)

**IGRJ17544-2619** (SFXT prototype)

Orbital period 4.9 days

Average luminosity:  $4 \times 10^{34}$  erg/s

Luminosity variations  $\sim 10^4-10^6$

NS accreting from supergiant wind

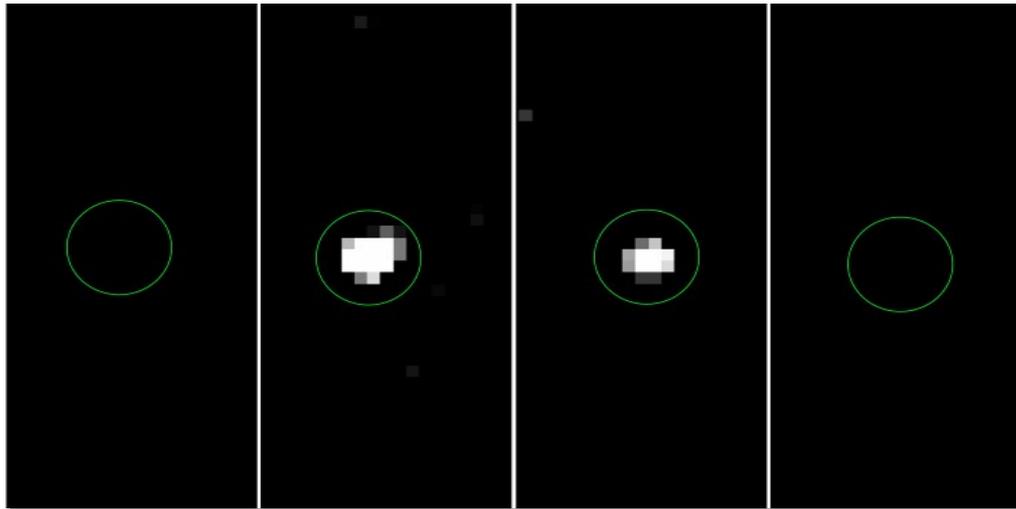
Sporadic hour-long flares

Variability due to clumps ??

# The INTEGRAL discovery (almost 20 years!)



INTEGRAL IBIS/ISGRI (Ubertini 2003, Lebrun 2003)  
 Coded mask instruments (20 keV – 1 MeV)  
 Field of view  $30^\circ \times 30^\circ$   
 Regularly monitoring a large fraction of the sky  
 Including Norma and Sagittarium regions  
 (hosting many HMXBs)  
 Perfectly suited to discover transient sources



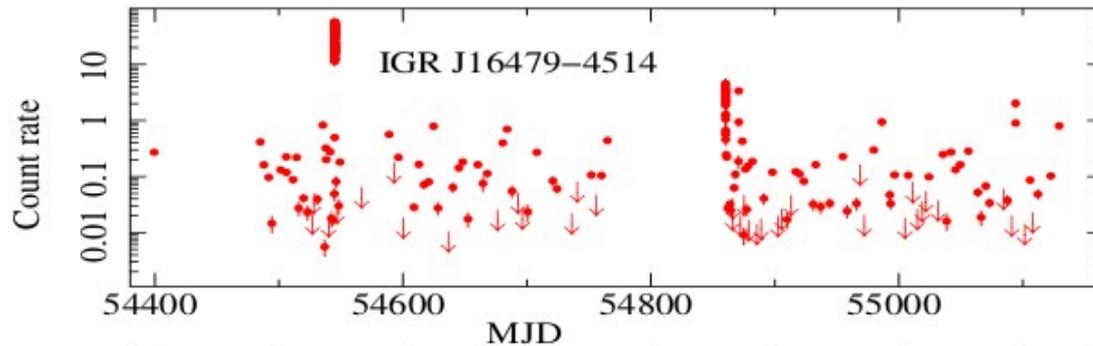
ISGRI – 4 SCWs – 8 ks sequence (Sguera 2005)

- Short X-ray transients (1-2 h)
- 15 sources identified in 20 years
- Follow-up associated them with massive O-B supergiants
- Sub-class of SgHMXBs (similar orbital periods)
- X-ray spectra of accreting NS

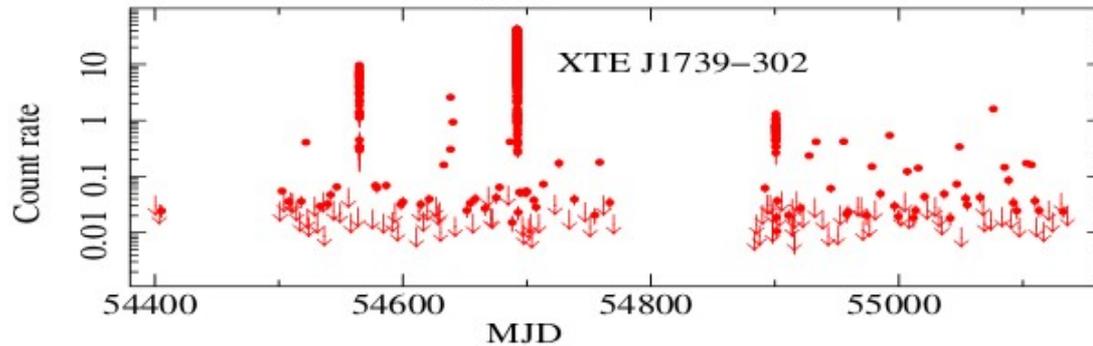
→ SFXTs!

→ Still hunting for them! (Sguera 2020)

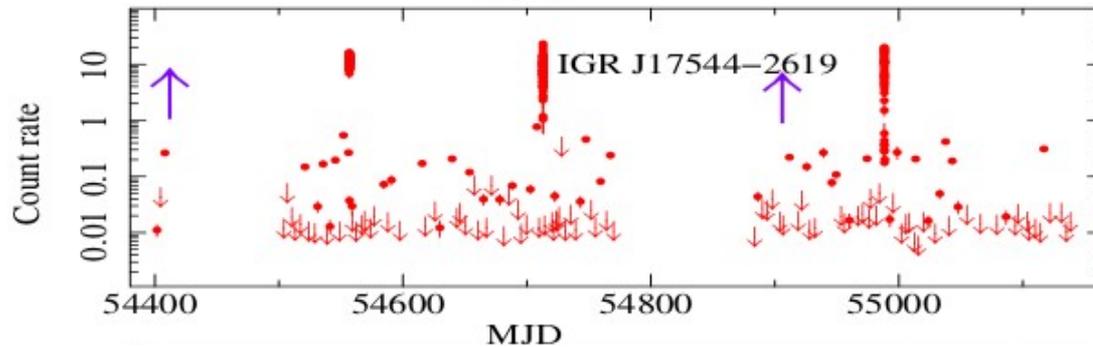
# Follow-up and monitoring campaigns



Porb  $\sim 3.3$  days  
Average luminosity  $8 \times 10^{34}$  erg/s

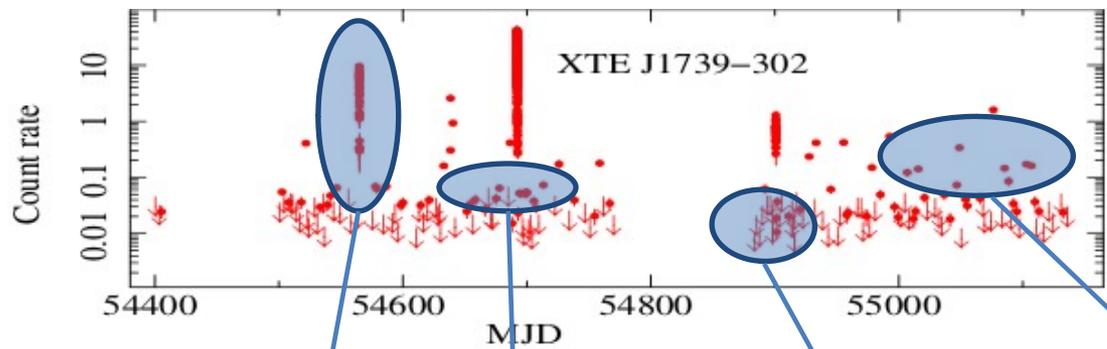


Porb  $\sim 57$  days  
Average luminosity  $8 \times 10^{33}$  erg/s



Porb  $\sim 4.9$  days  
Average luminosity  $2 \times 10^{34}$  erg/s

(Romano 2010, 2011, 2012, 2014)



Outbursts

$$L_x > 10^{36} - 10^{37} \text{ erg/s}$$

Intermediate state

$$L_x \sim 10^{33} - 10^{34} \text{ erg/s}$$

Quiescence

$$L_x \sim 10^{32} \text{ erg/s}$$

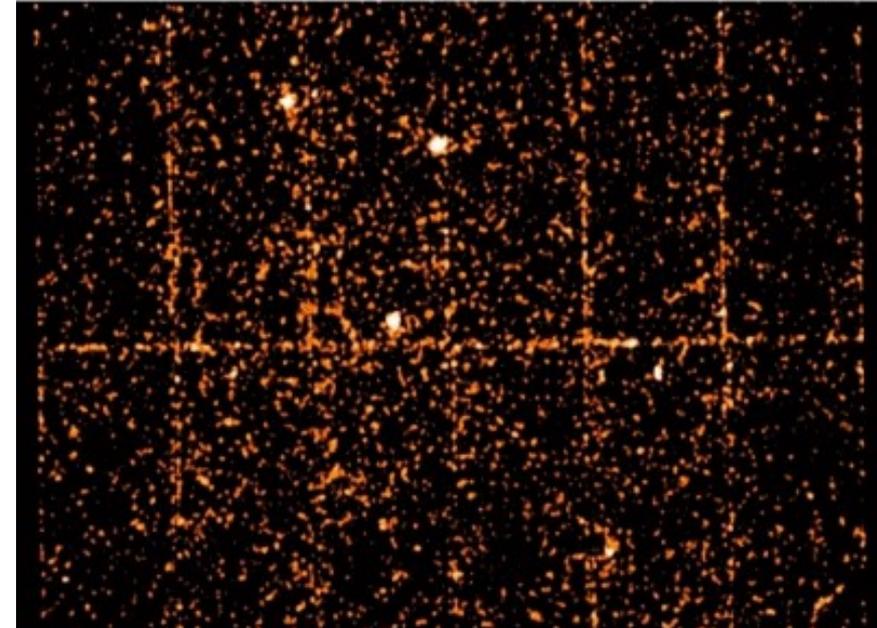
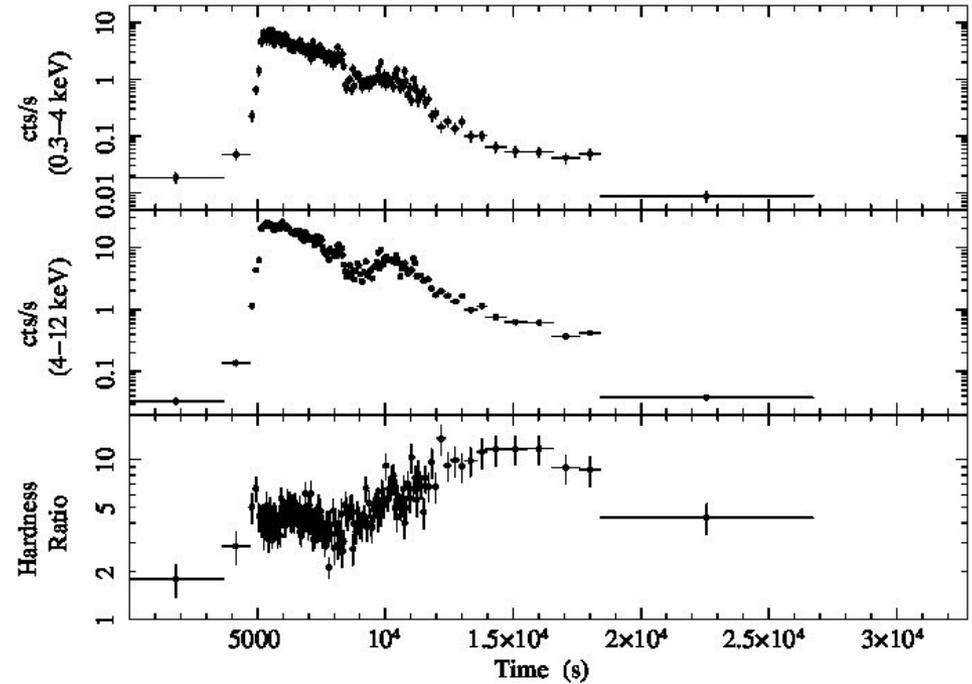
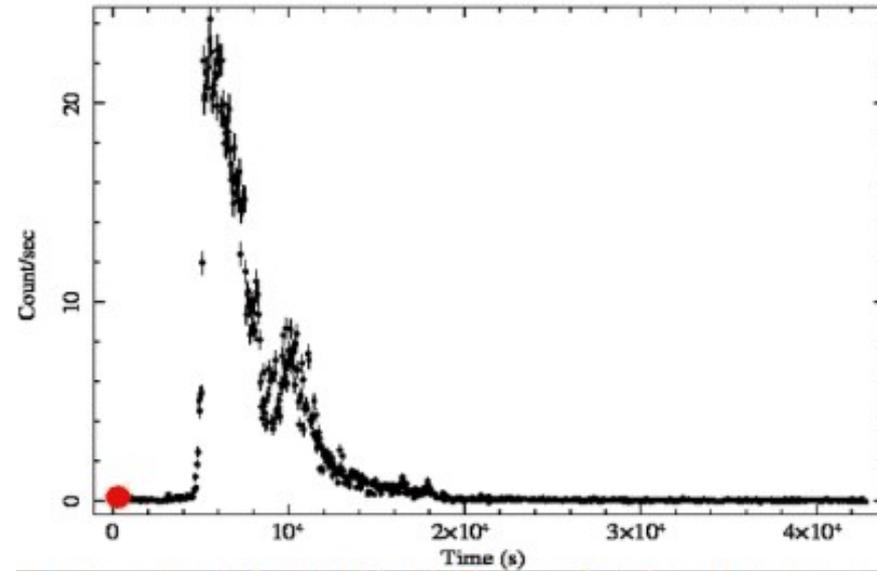
Flares

$$L_x \sim 10^{35} \text{ erg/s}$$

Monitoring with *Swift* critical: require rapid repointing

# Stellar wind clumps in action: direct evidence

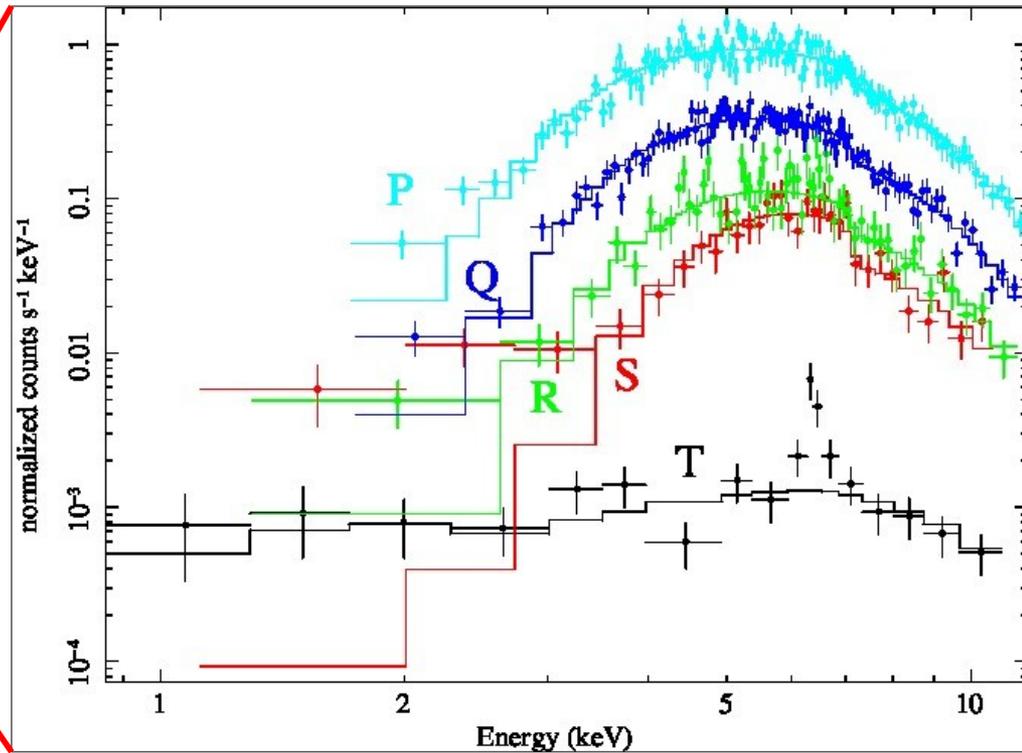
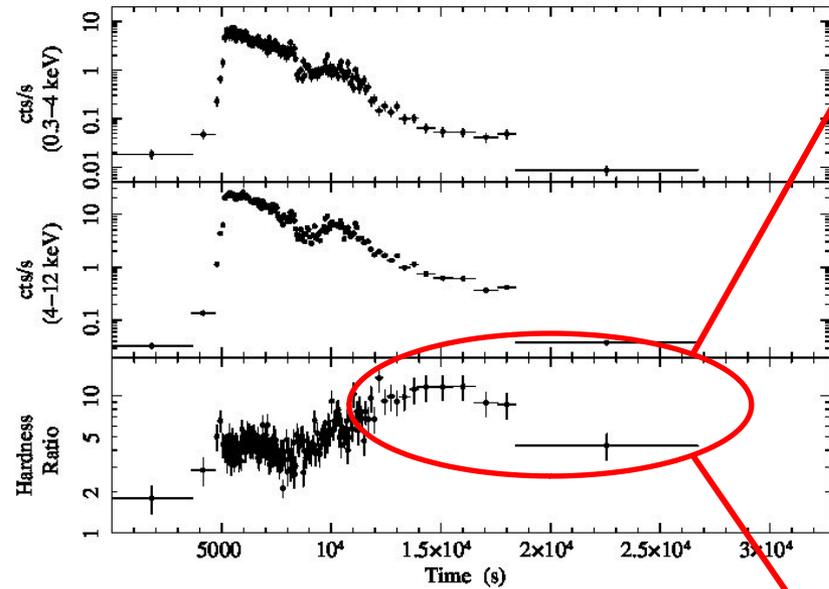
AXJ1841.0-0536 (Epic-pn)



Flare from the SFXT IGRJ18410-0535  
 15 ks XMM, total variation in luminosity  $10^5$   
 Peak luminosity  $\sim 10^{35}$  erg/s

(Bozzo 2011)

# Stellar wind clumps in action: direct evidence



Observations suggest the NS “ingested” a massive clump:

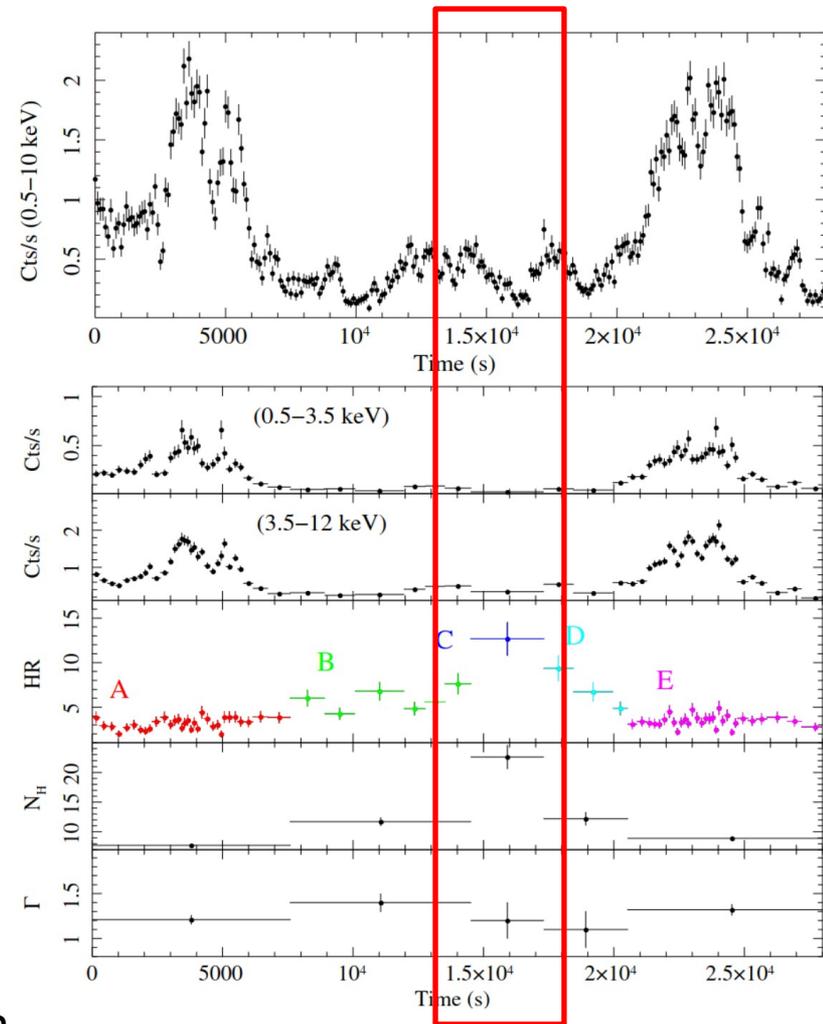
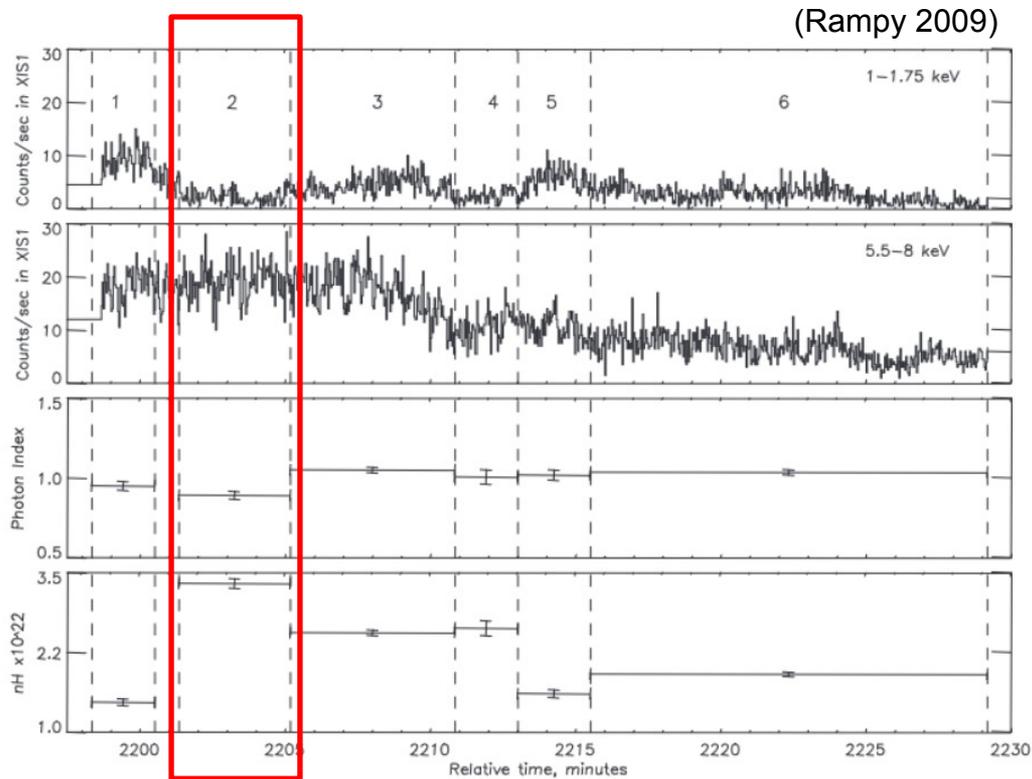
$$M_{cl} \simeq 1.4 \times 10^{22} \text{ g}$$

$$R_{cl} \simeq 8 \times 10^{11} \text{ cm}$$

About 0.6 x Supergiant Radius!!

# Stellar wind clumps in action: indirect evidence

Involving sudden increases in the local absorption column density for few x100 s



Similar events detected in many sources with different instruments

Monitoring campaign on-going with XMM-Newton

(Bozzo 2017, 2022)

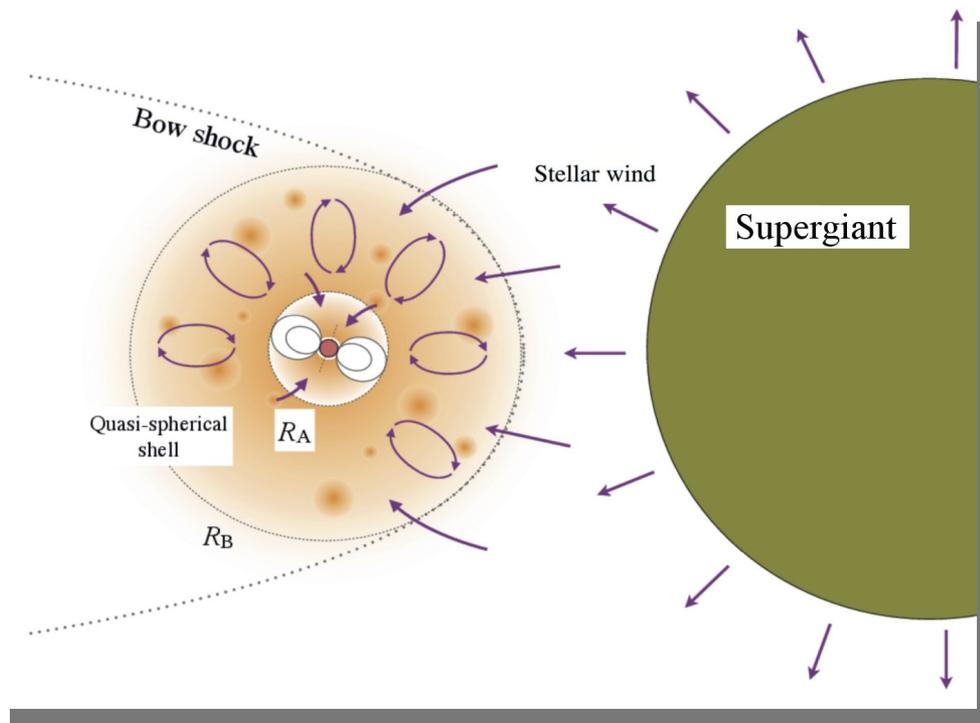
## Revisiting direct accretion: the **quasi-spherical settling accretion model**

(Shakura 2011,2013,2014)

Assuming low ( $L_x < 4 \times 10^{36}$  erg/s) and slowly rotating NS

Hot shell inhibits accretion:

- $1/30 \times Bondi$  in the radiative inefficient regime
- $1/3 \times Bondi$  in the Compton cooling regime
- = *Bondi* with reconnection between magnetized stellar clumps and neutron star magnetosphere



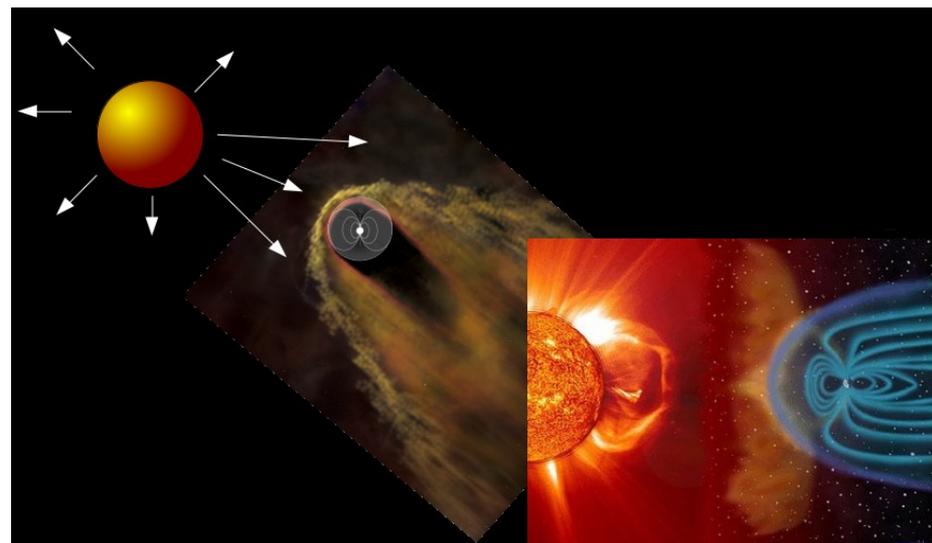
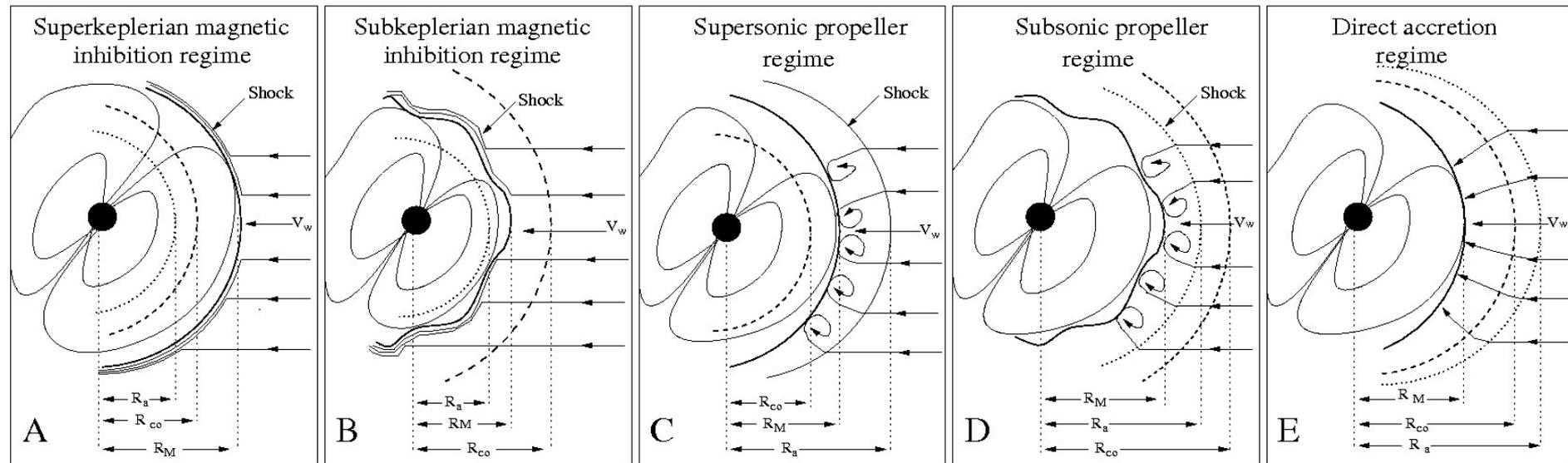
Mass outflow rate from the supergiant companions should be systematically lower in SFXTs than SgXBs (no dichotomy identified in classical and SFXT companions!)

Or long elliptic orbits needed to largely modulate the accretion rate (IGRJ08408 is an eccentric system with  $e=0.63$ ; Sidoli 2021)

**(magnetized) Clumps are needed for reconnection and flares/outbursts!** (Hubrig 2018)

# Theoretical modeling: the gating inhibition of accretion

## The centrifugal/magnetic gated accretion model (Bozzo 2008)



Centrifugal gating  $\equiv$  “propeller effect”

Magnetic gating  $\equiv$  no gravitational focusing of wind material

Favors NS with long spin periods ( $>1000$  s) and strong magnetic fields ( $\sim 10^{14}$  G – NO EVIDENCE!) to achieve a luminosity dynamic range of  $10^6$

**Stellar wind clumps required to trigger switch between different accretion regimes**

# Theoretical modeling: the gating inhibition of accretion

The centrifugal/magnetic gated accretion model + Clumpy wind (Oskinova 2012, Bozzo 2016)

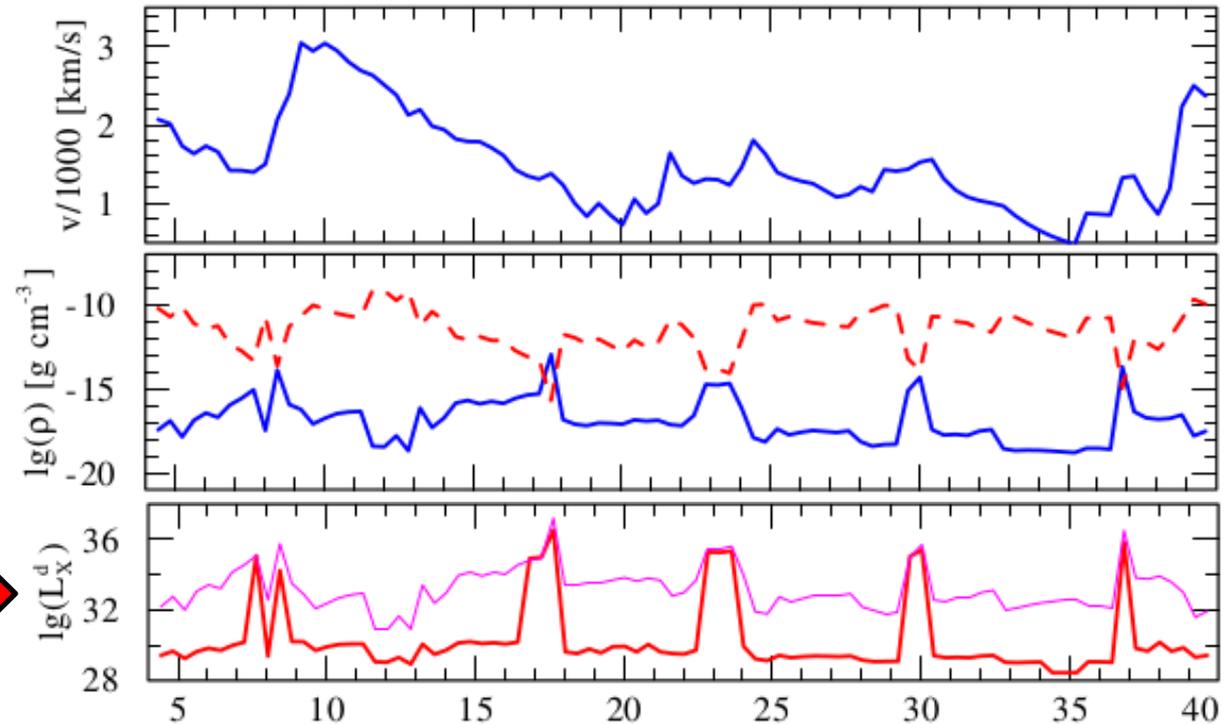
$$a=5 R_* \quad \mu_{33}=0.1 \quad P_{\text{spin}}=1000\text{s}$$

Neutron star immersed in  
1D hydro stellar wind  
(Feldmeier 1995, 1997)

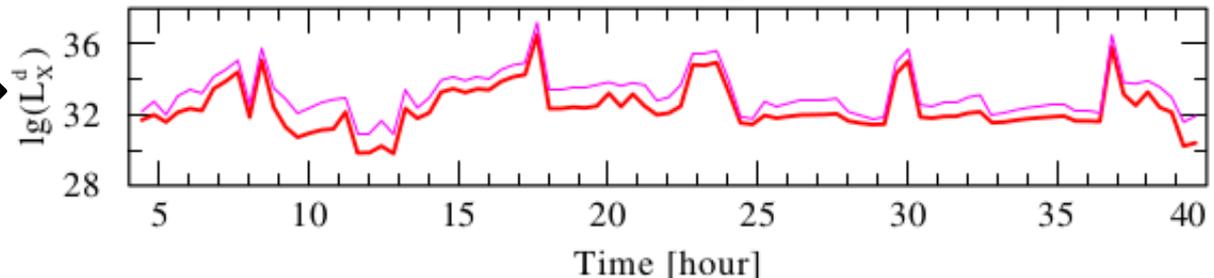
Long spin periods  
and strong magnetic  
fields give rise to  
**SFXT**-like variability



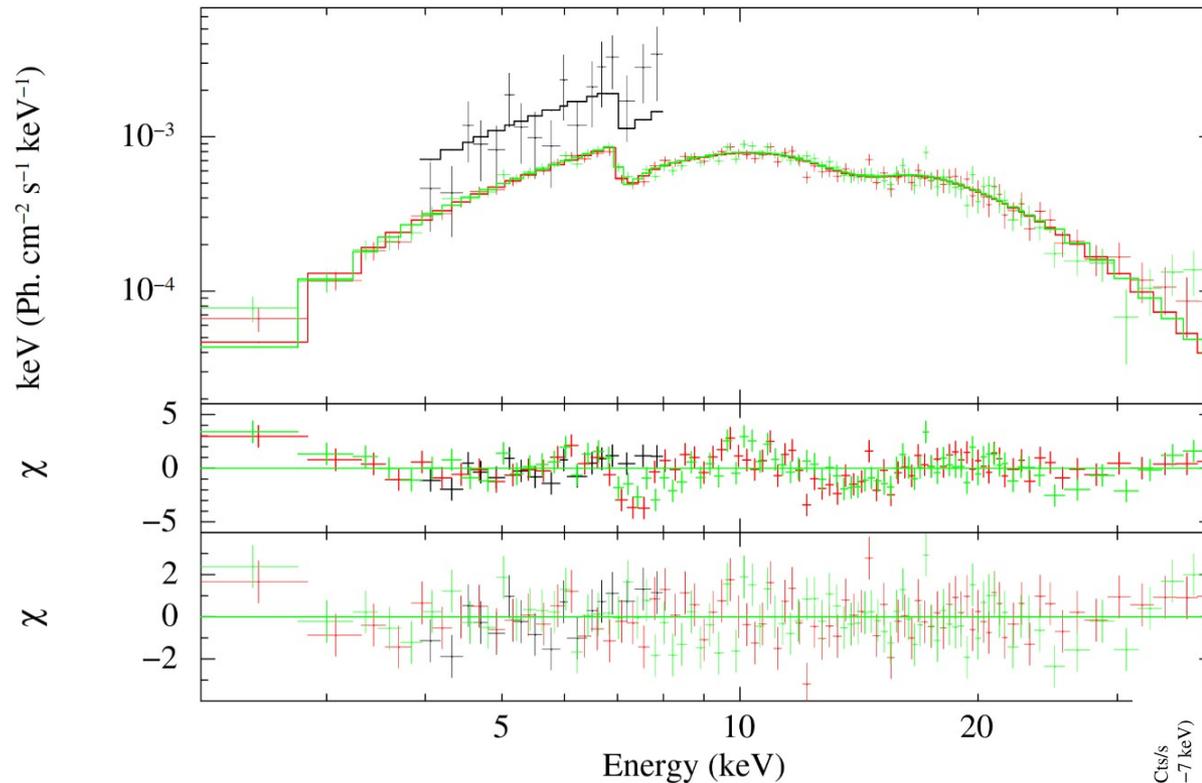
**Classical SgXBs** are  
recovered with  
weaker magnetic  
fields and/or shorter  
spin periods



$$a=5 R_* \quad \mu_{33}=0.001 \quad P_{\text{spin}}=1000\text{s}$$



- Archival NuSTAR observations revealed a very likely Cyclotron Resonant Scattering Feature in the SFXT SAXJ1818.6-1703



CRSF at 14 keV  
 $B=10^{12}$  G  
 NOT a magnetar!

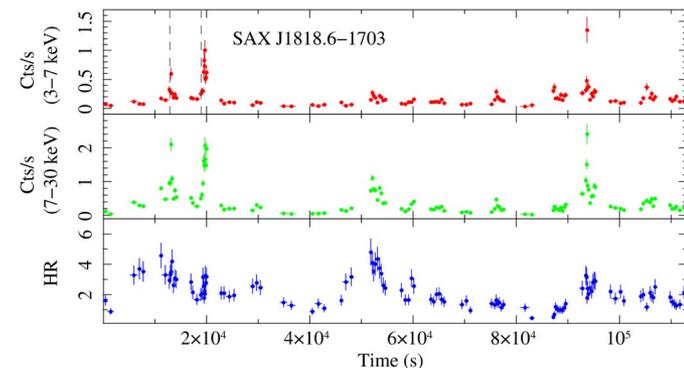
JUST SUBMITTED!

## Swift and NuSTAR observations of AX J1841.0-0536 and SAX J1818.6-1703

E. Bozzo,<sup>1\*</sup> C. Ferrigno,<sup>1</sup> P. Romano,<sup>2</sup>

<sup>1</sup>Department of Astronomy, University of Geneva, Chemin d'Ecogia 16, CH-1290 Versoix, Switzerland

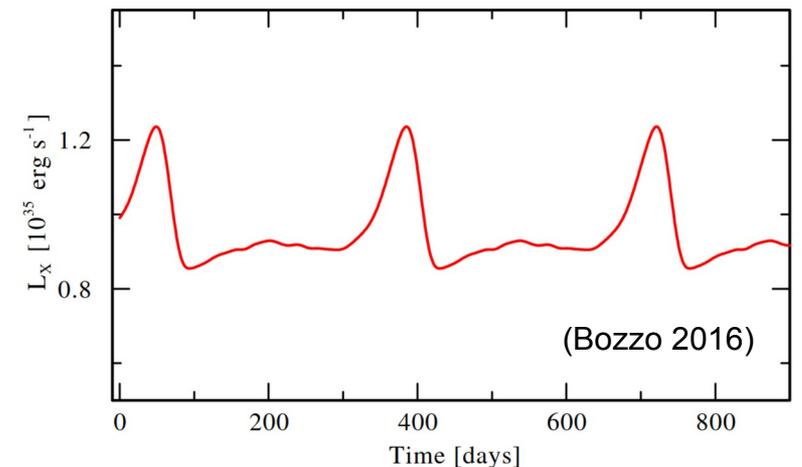
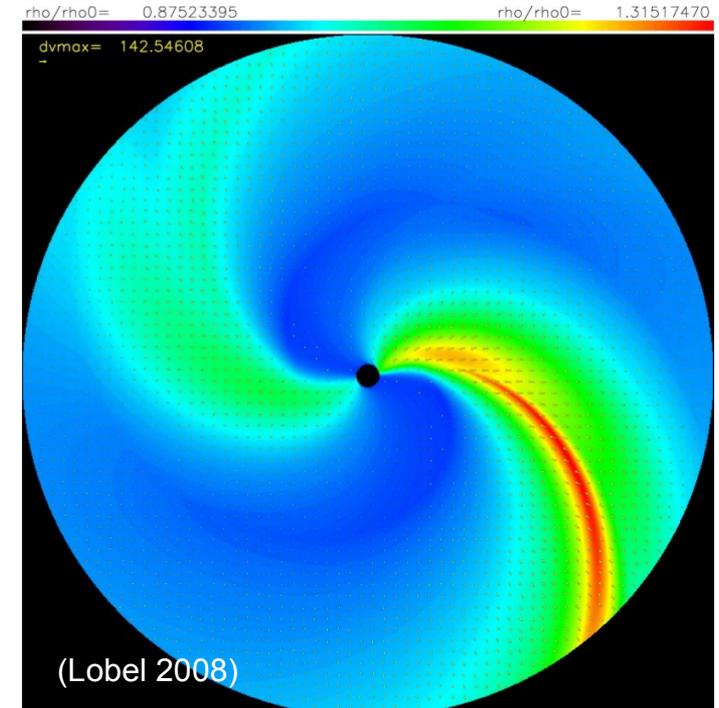
<sup>2</sup>INAF, Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-23807, Merate, Italy



# Corotating interaction regions

Are CIR of O-B supergiant playing any role in the X-ray variability?

- Discrete Absorption Components (obs.)
- Present in all (observed) O-B supergiants
- Corotating Interaction Regions (model)
- Co-rotating pattern: explains spectroscopic and time modulations
- Time-scale = rotational period, days
- Corotating Interaction Regions (Mullan 1984, Cranmer & Owocki 1996, Hamann et al. 2001)
- Azimuthal variation of wind velocity and density
- Collision of fast / slow winds
- **Produce super-orbital modulations!**



## Superorbital modulations in the wind-fed supergiant X-ray binary 2S 0114+650

P. Romano,<sup>1\*</sup> E. Bozzo,<sup>2,3</sup> N. Islam,<sup>4,5</sup> R.H.D. Corbet,<sup>6,5,7</sup>

<sup>1</sup>INAF, Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-23807, Merate, Italy

<sup>2</sup>Department of Astronomy, University of Geneva, Chemin d'Ecogia 16, CH-1290 Versoix, Switzerland

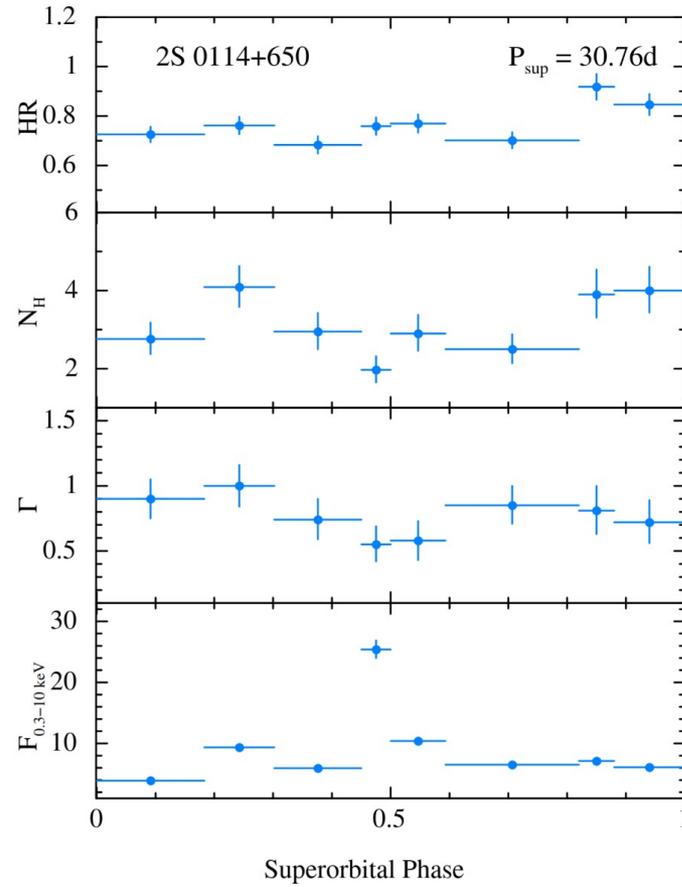
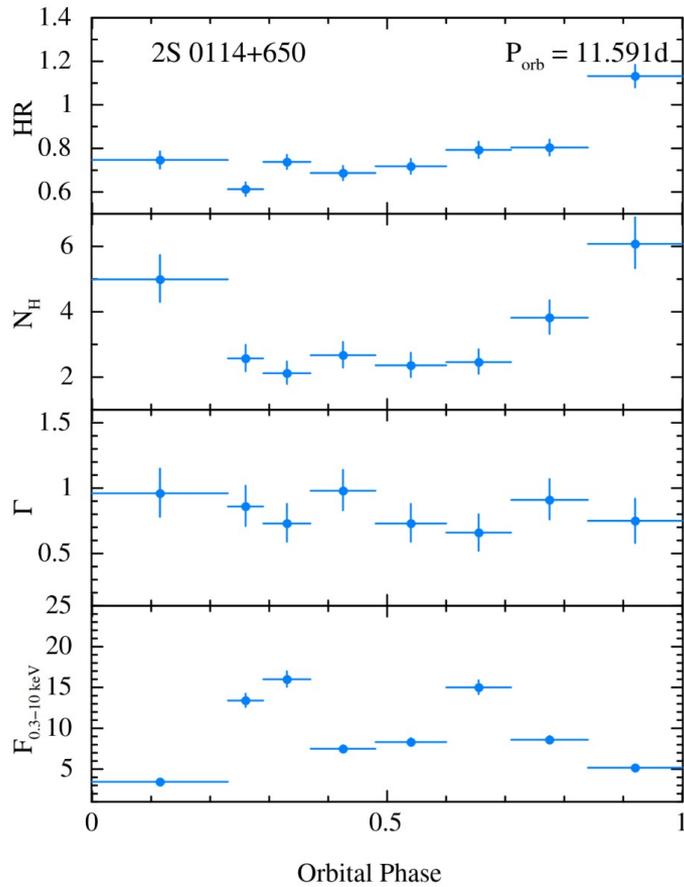
<sup>3</sup>INAF-OAR, Via Frascati, 33, 00078 Monte Porzio Catone, Rome, Italy

<sup>4</sup>Center for Space Science and Technology, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA

<sup>5</sup>X-ray Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

<sup>6</sup>CRESST and CSST, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA

<sup>7</sup>Maryland Institute College of Art, 1300 W Mt Royal Ave, Baltimore, MD 21217, USA



## Superorbital modulations in the wind-fed supergiant X-ray binary 2S 0114+650

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<sup>1</sup>INAF, Osservatorio Astronomico di Brera, Via E. Bianchi 46, I-23807, Merate, Italy

<sup>2</sup>Department of Astronomy, University of Geneva, Chemin d'Ecogia 16, CH-1290 Versoix, Switzerland

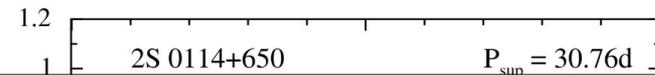
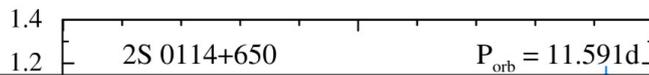
<sup>3</sup>INAF-OAR, Via Frascati, 33, 00078 Monte Porzio Catone, Rome, Italy

<sup>4</sup>Center for Space Science and Technology, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA

<sup>5</sup>X-ray Astrophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

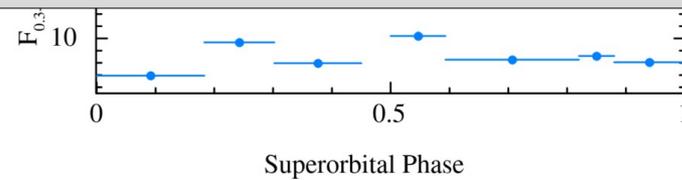
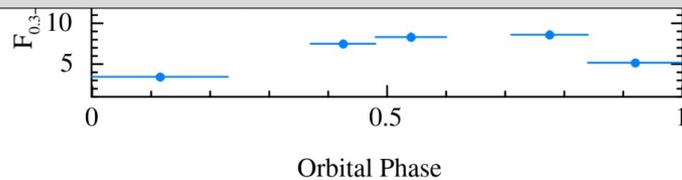
<sup>6</sup>CRESST and CSST, University of Maryland, Baltimore County, 1000 Hilltop Circle, Baltimore, MD 21250, USA

<sup>7</sup>Maryland Institute College of Art, 1300 W Mt Royal Ave, Baltimore, MD 21217, USA



A NiCER proposal approved last Friday on the classical SgXB 4U1538-522 to study superorbital variability

Effective area is about 10 times larger than XRT giving us 10 times more counts to improve statistics



# Conclusions

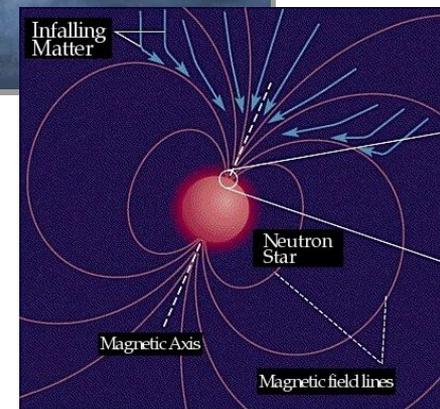
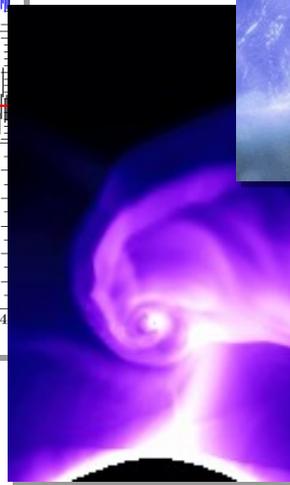
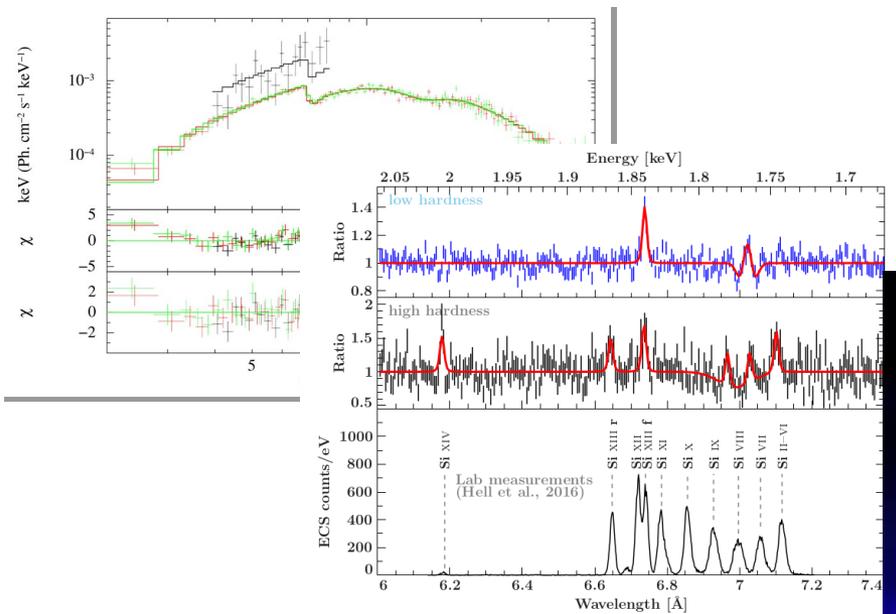
- Renewed interest for wind-fed HMXBs due to their role as independent probes of massive star winds (beside being precious laboratories for accretion processes in highly magnetized environments)
- Classical SgXBs provides promising insights into clumpy winds but ...
  - «high» luminosity in X-ray can disrupt the wind: photoionization shall be folded in the calculations
- Supergiant Fast X-ray Transients (SFXTs) could help ...
  - Lower luminosity can reveal the «naked» supergiant wind
  - We do not fully understand accretion processes, thus hampering realistic estimates of clumpy wind parameters
- Superorbital modulations could be linked to additional stellar wind structures, widening the role of NSs in SgXBs as probes of the massive star winds



# The (near) Future of SgXB research

Requires:

- X-rays photons = **large effective area!**
- High **sensitivity** in the **soft X-rays**: clumps & absorption
- **Broad-band** X-ray coverage: CRSF
- **large FoV**: discovery of transients sources
- good **energy resolution** at least (<150-200 eV): fluorescence
- high energy resolution (few eV): ionization state of stellar wind components
- Good **timing** capabilities: pulsations



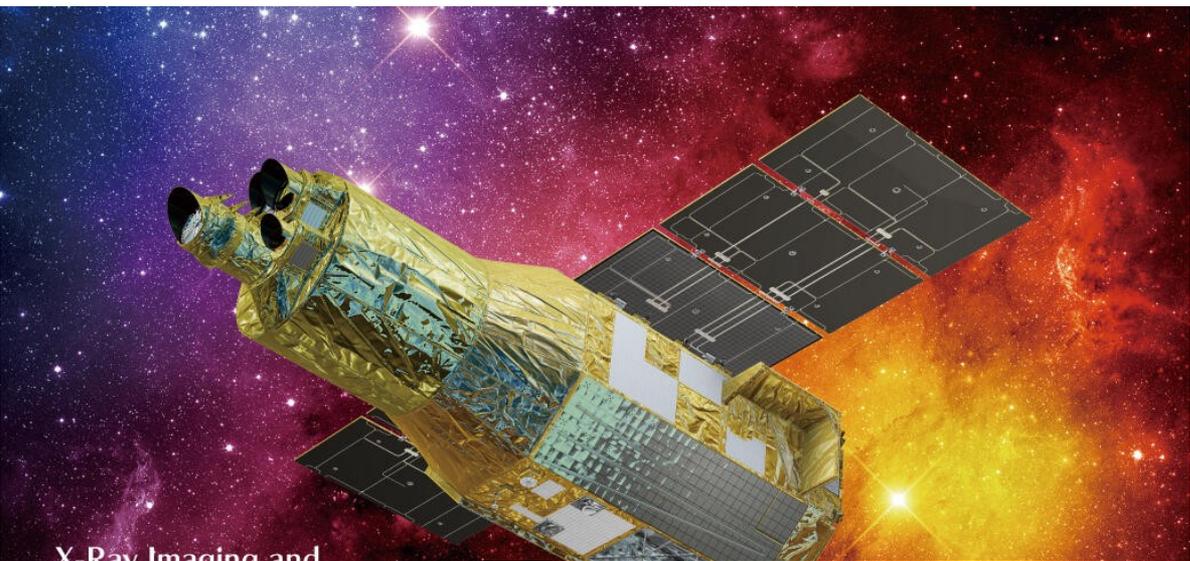
# XRISM: launched

High spectroscopic resolution  
Down to 5-7 eV

Relatively low effective area

No wide FoV

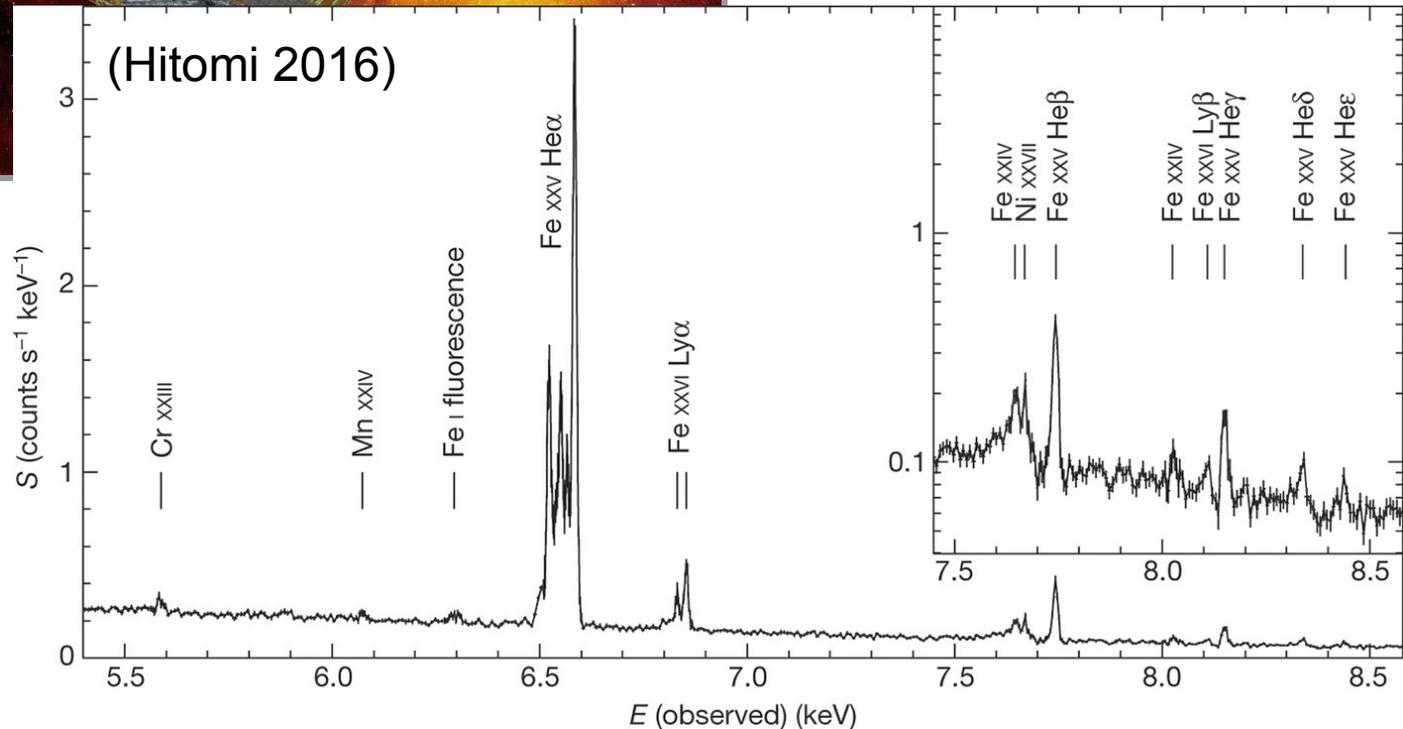
Preferentially bright sources



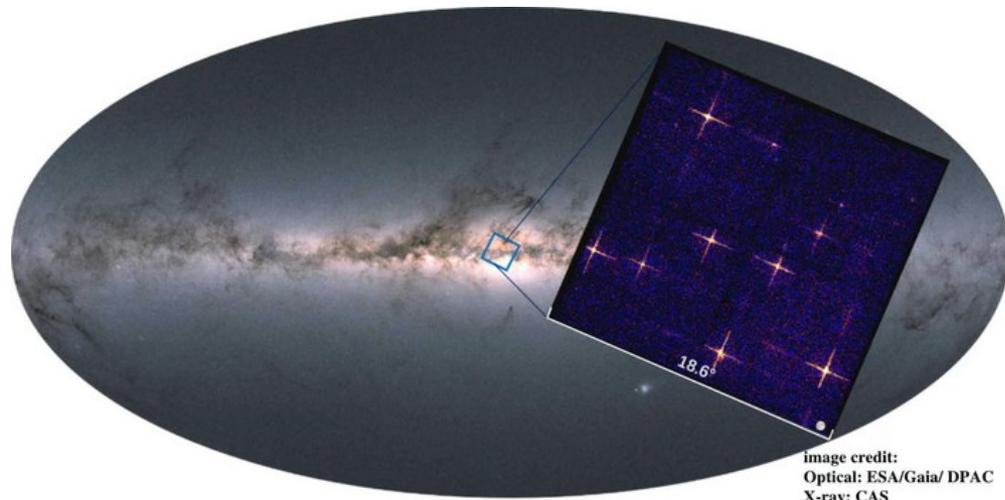
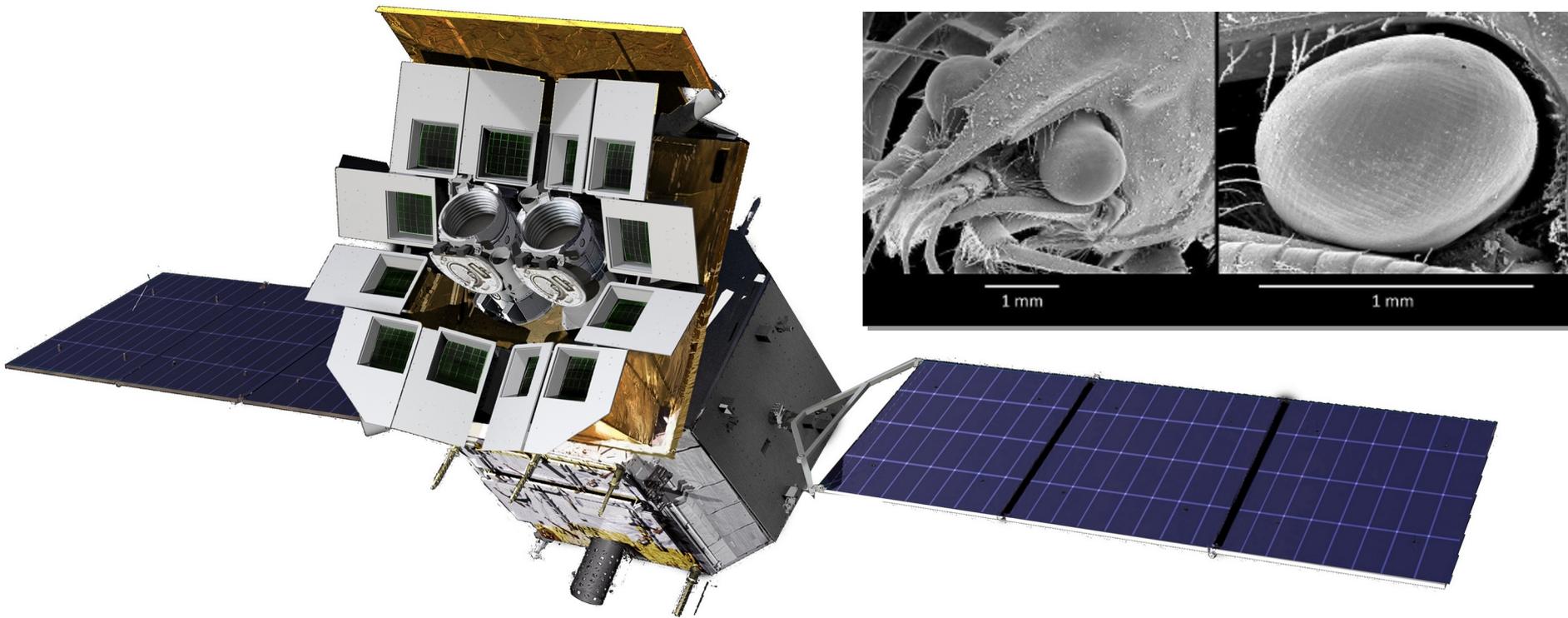
X-Ray Imaging and  
Spectroscopy Mission  
**XRISM**

Characterization of  
bright sources

Improves over  
Chandra/HETG



# Einstein Probe: should come soon!



Large FoV to hunt for transients  
Characterization is difficult  
Many transients expected, their nature difficult to unveil quickly

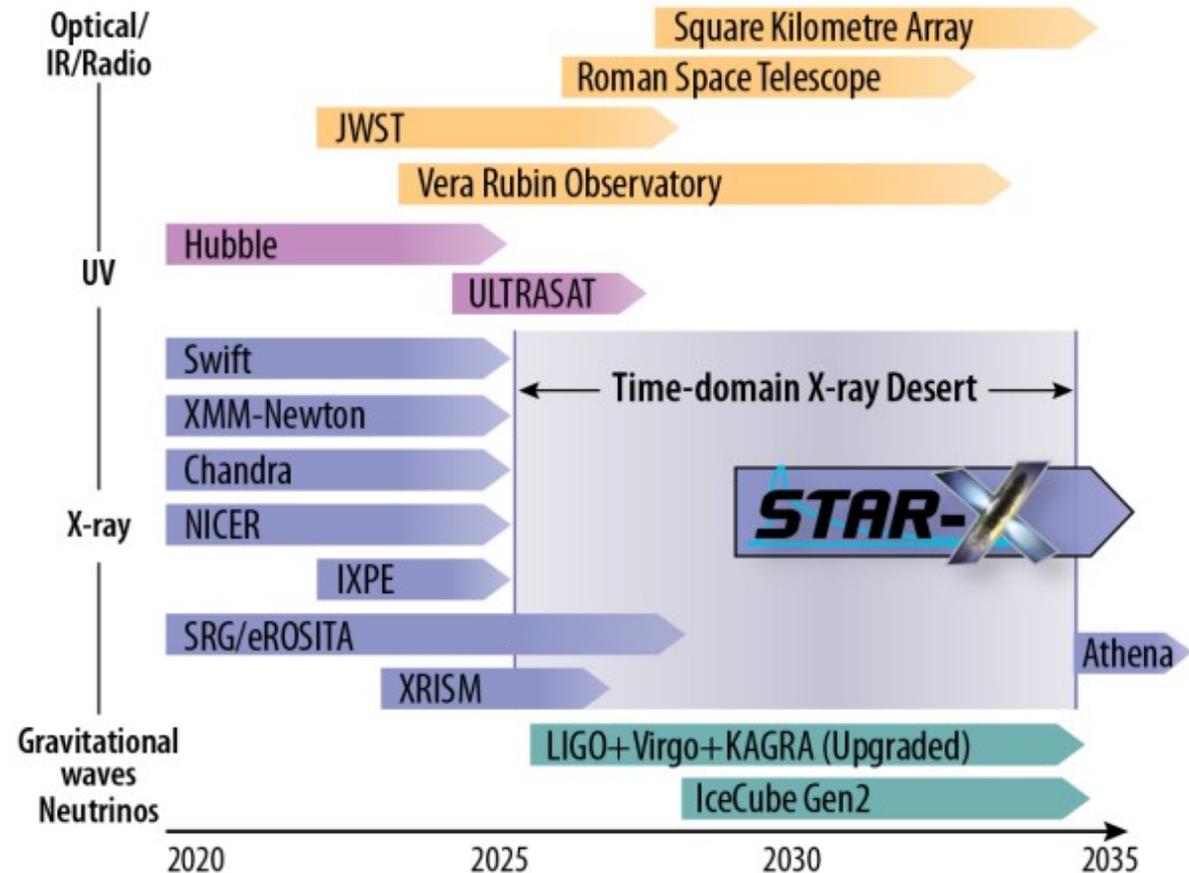
High sensitivity, low effective area

First lobster-eye telescope to fly  
Pathfinder showed beautiful results!

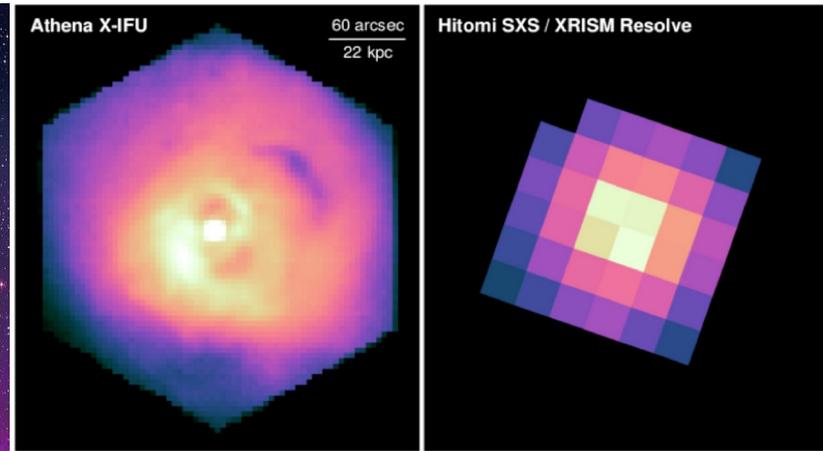
# The (far) Future of HMXB research

HMXB research requires:

- X-rays photons = large effective area!
- large FoV: discovery of transients sources
- good energy resolution at least
- high energy resolution (if possible!)
- Good timing capabilities for pulsations studies



# Athena (ESA - 2037 pending adoption in 2027)

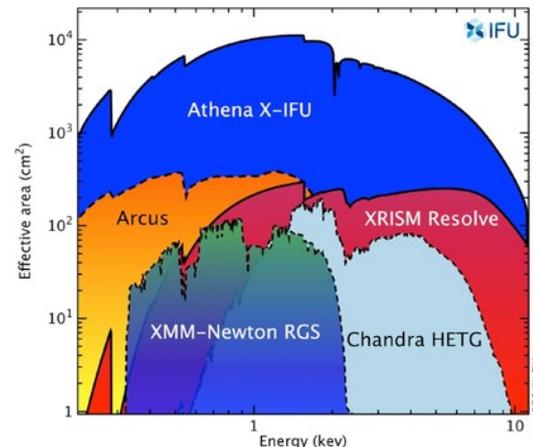
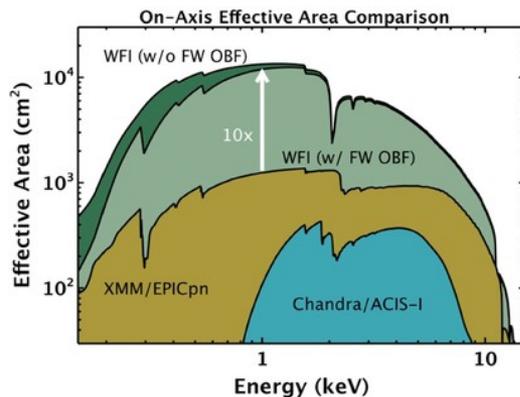


X-ray imaging and spectroscopy at high resolution (3 eV) in the 0.2-12 keV range

Large area especially in soft X-rays

Can observe bright sources with minimal degradation with uninterrupted exposures

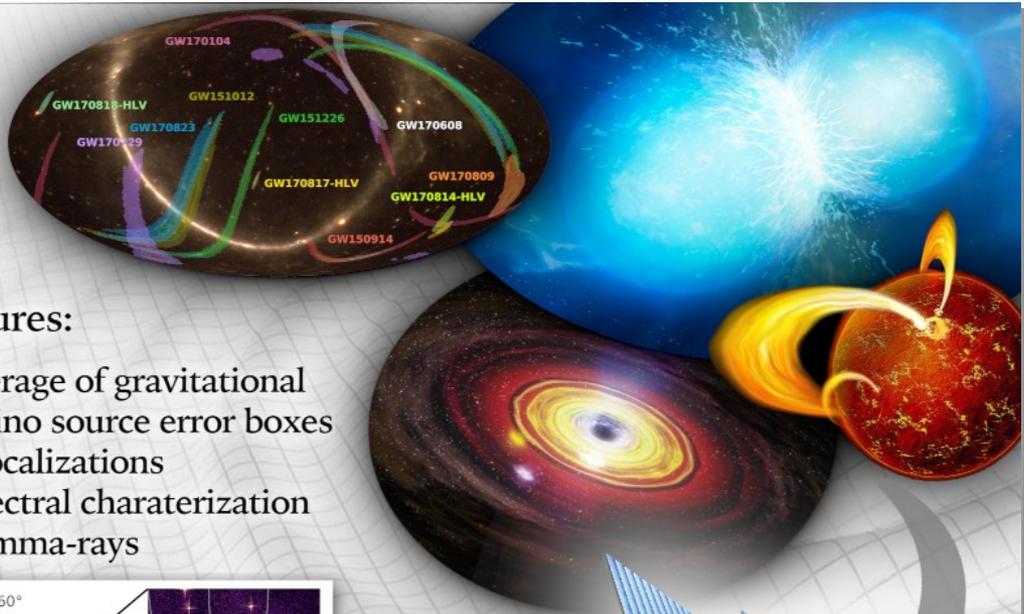
Fast spectral variability, access to faint sources for high resolution spectroscopy, pulsations



2 instruments:

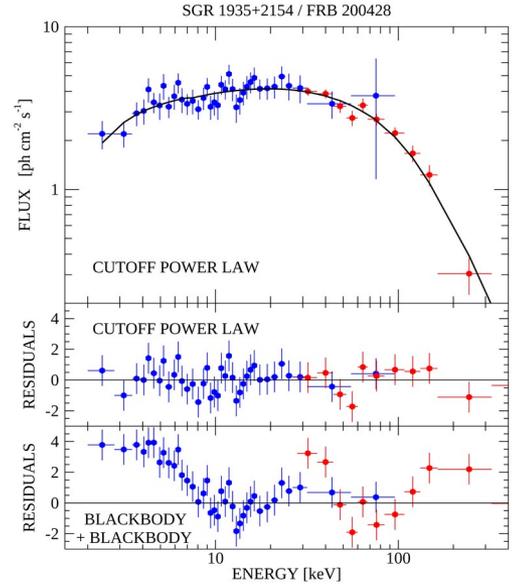
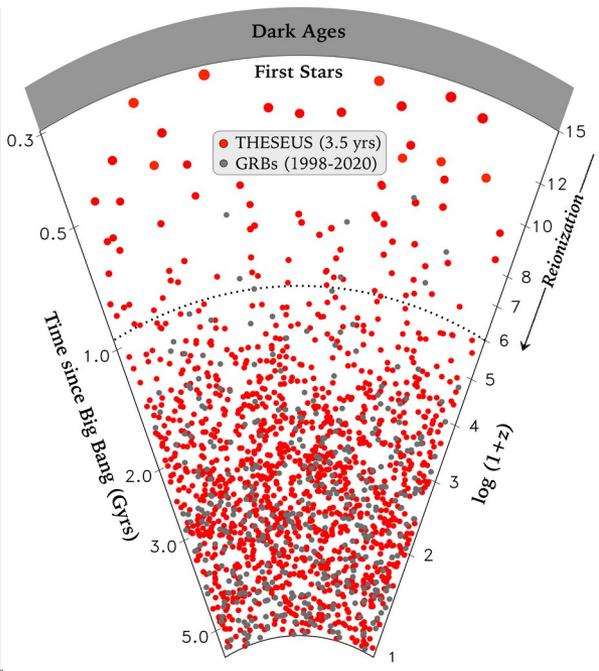
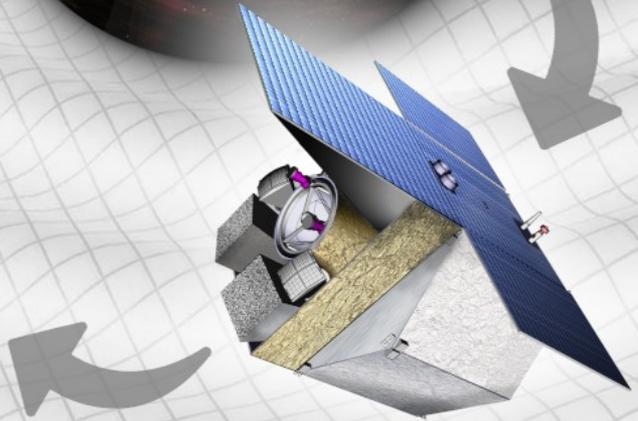
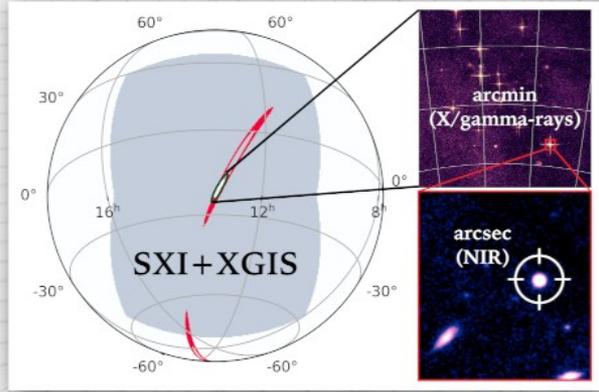
- X-IFU: spectroscopy
- WFI: imaging

# Theseus (ESA - 2037 pending adoption in 2027)



## THESEUS ensures:

- Immediate coverage of gravitational wave and neutrino source error boxes
- Real time sky localizations
- Temporal & spectral characterization from NIR to gamma-rays



Designed to identify, localize and characterize X-ray transients with fast autonomous repointing, large FoV and wide energy band instruments ... From high redshift GRBs to Galactic transients

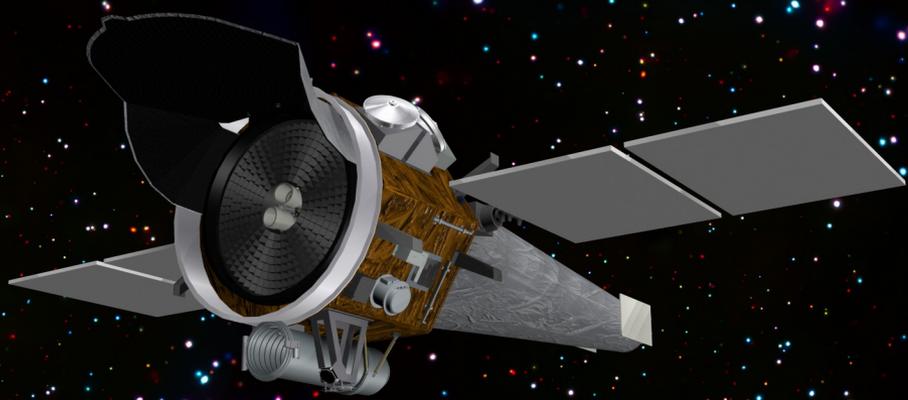
Dedicated mainly to time domain astrophysics

Modest area

Fine imaging over 1 deg FoV

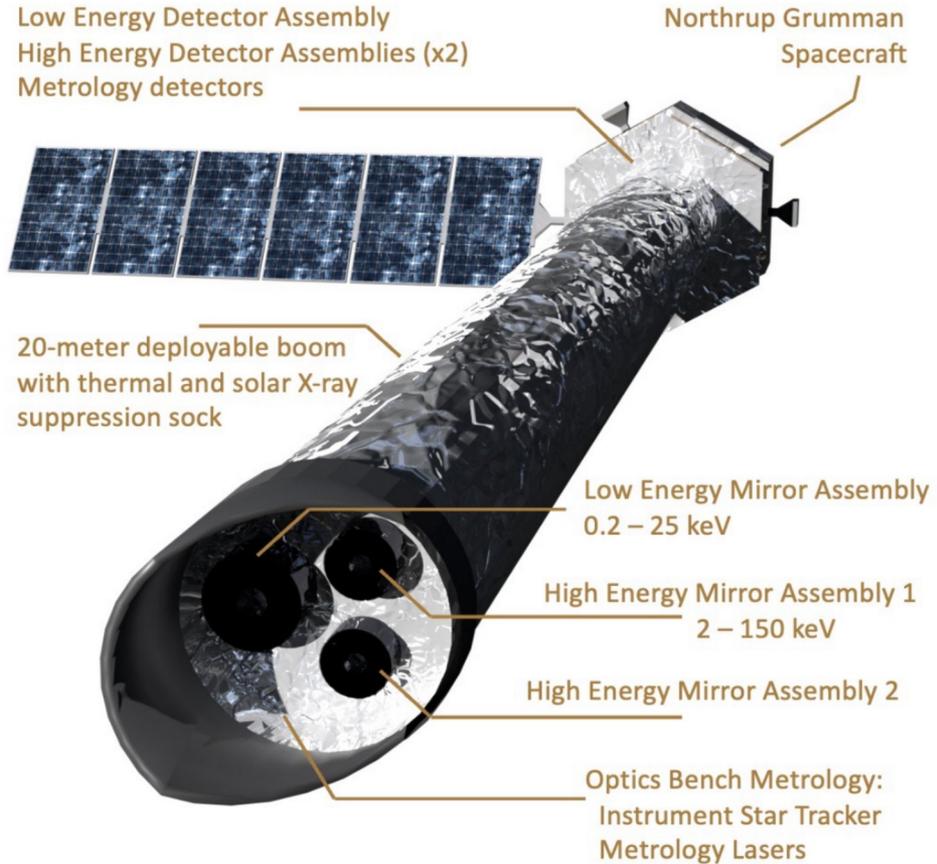
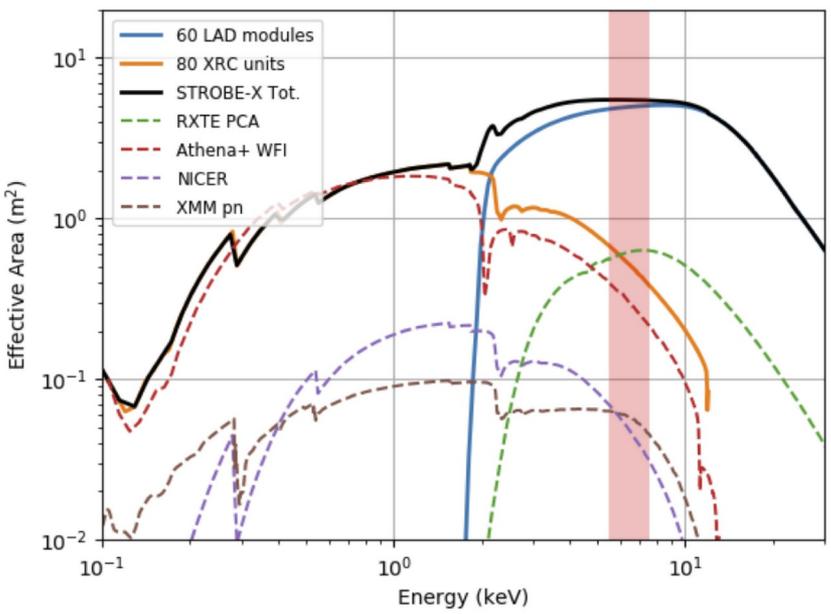
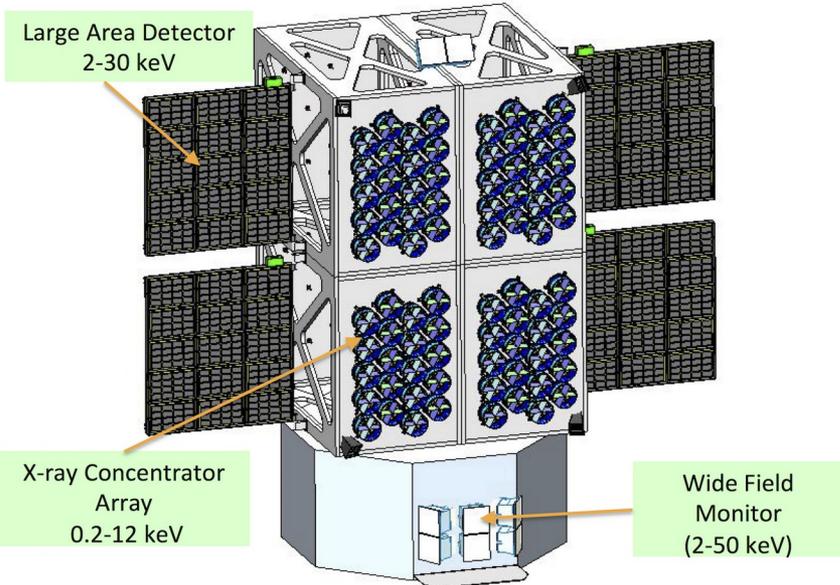
CCD-like energy resolution

UV imager to complement



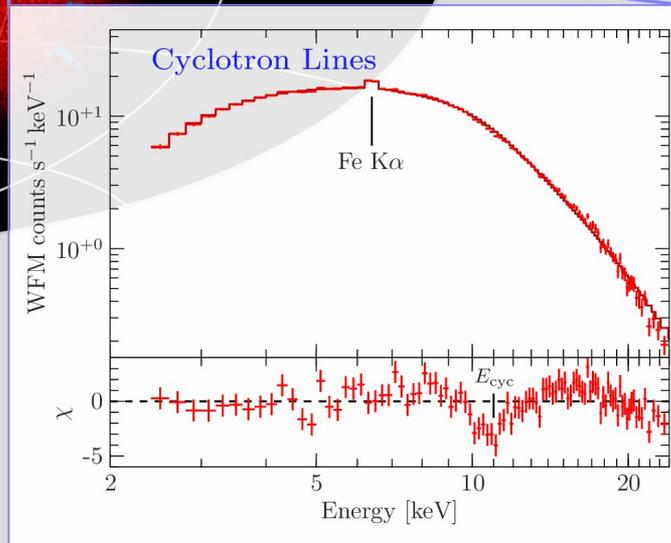
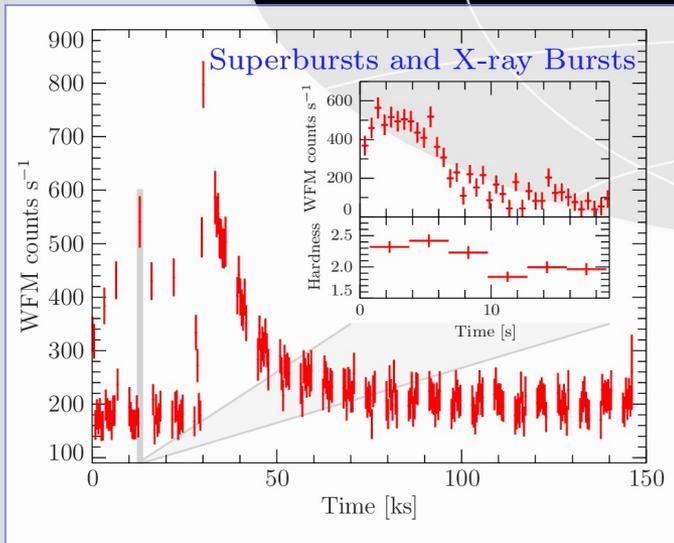
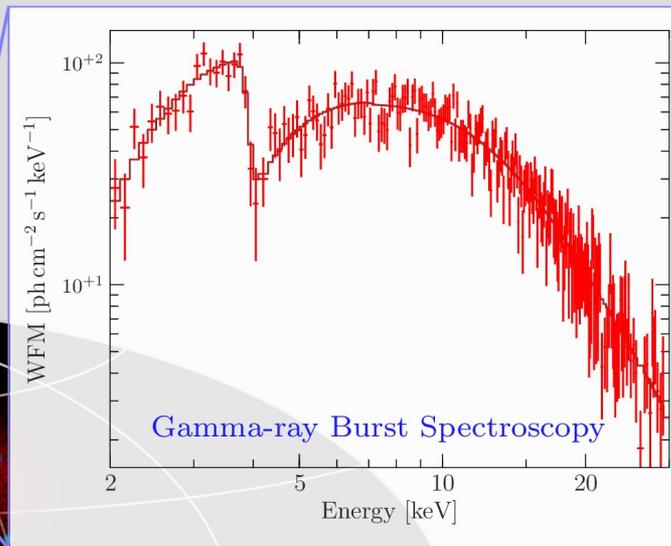
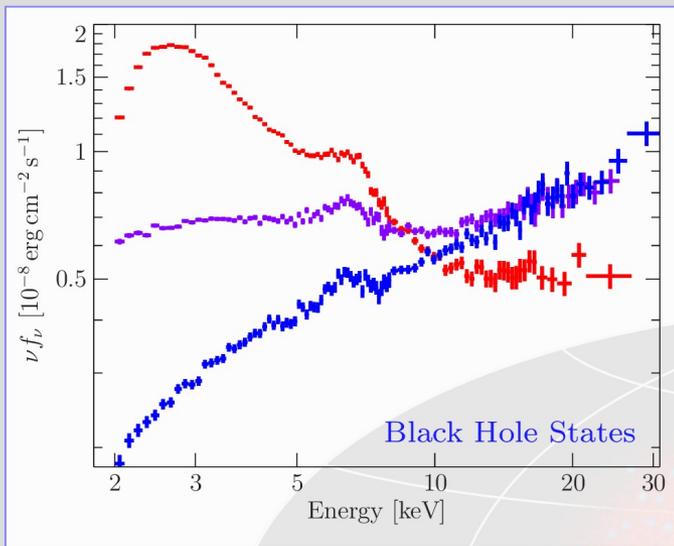
|                           |   |  |  |
|---------------------------|---|--|--|
| <b>STAR-X Goals</b>       | <b>1.</b> Determine how stellar explosions work and how they fuel cosmic chemistry  | <b>2.</b> Understand the accretion processes that allowed massive black holes to form so early in the Universe                   | <b>3.</b> Determine how the largest bound structures in the Universe form  |
| <b>Decadal Priorities</b> | <br><i>Pathways to Habitable Worlds</i> | <br><i>New Windows on the Dynamic Universe</i> | <br><i>Unveiling the Drivers of Galaxy Growth</i> |
| <b>STAR-X Objectives</b>  | <b>STAR-X:</b><br>Stellar activity survey from exoplanet hosts  | <b>STAR-X:</b><br>First light from supernovae, GW counterparts, Tidal Disruption Events, Extreme AGN Accretion                   | <b>STAR-X:</b><br>Nuclear black hole growth, Galaxy cluster formation from z=6   |

selection)

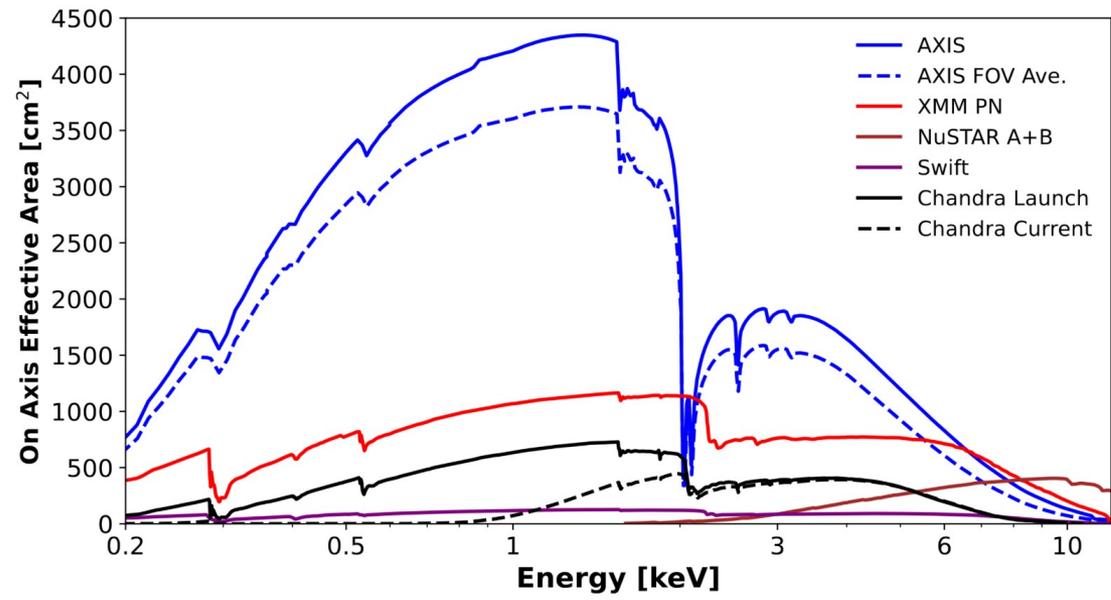
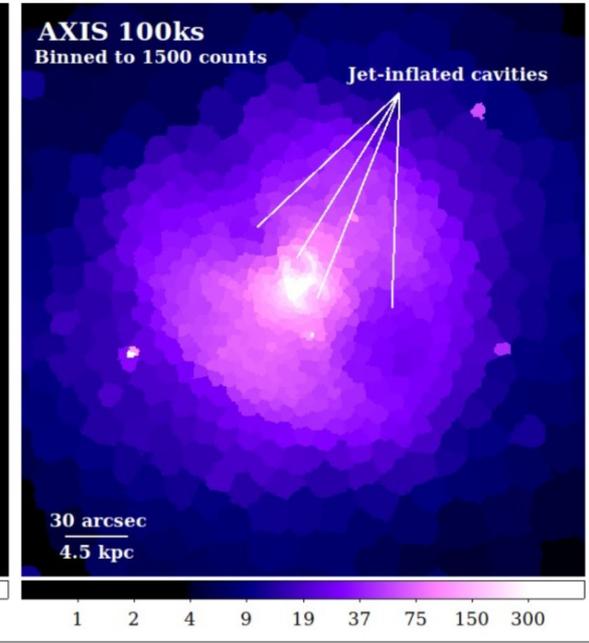
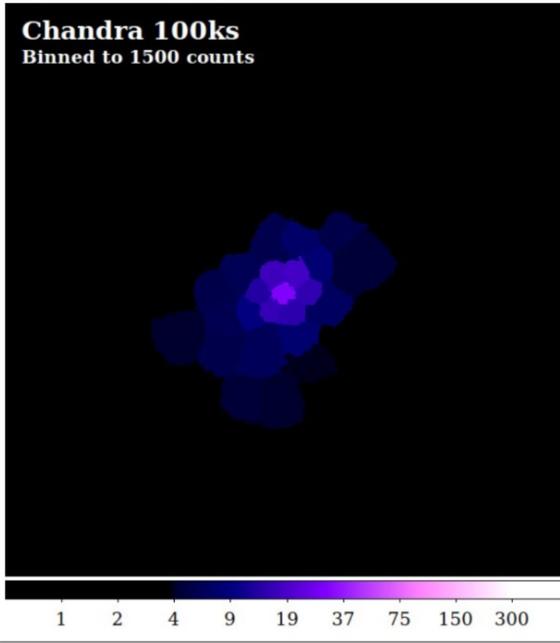
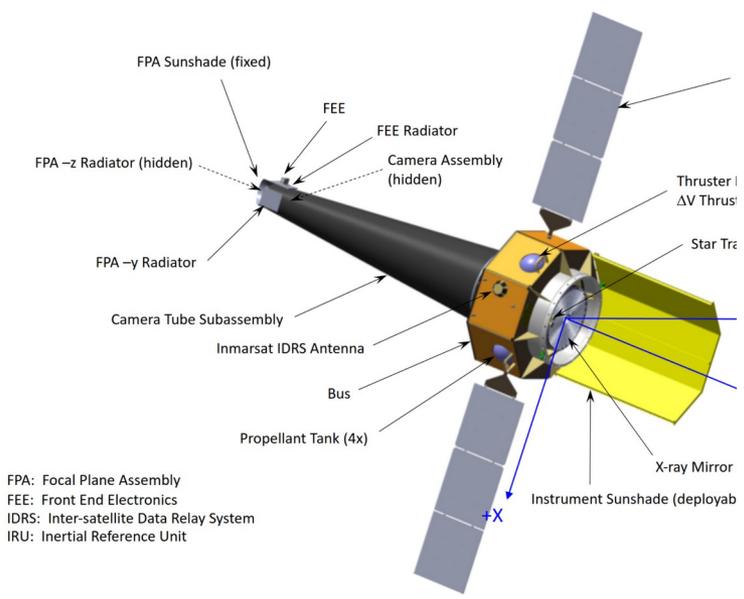


Search for transient HMXBs & pulsations  
Fast timing-spectral variability  
CRSFs down to low fluxes (=many sources)

# STROBE-X & eXTP Wide Field Monitor



# The USA PROBES: AXIS (>2032, pending selection)



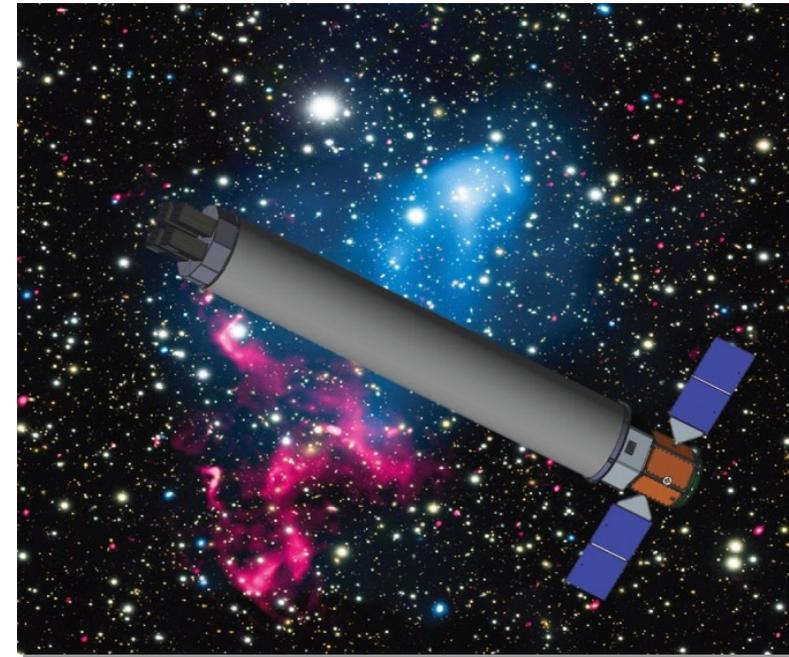
Fine imaging over 24 arcmin FoV

CCD-like energy resolution

High sensitivity for faint and spatially resolved sources

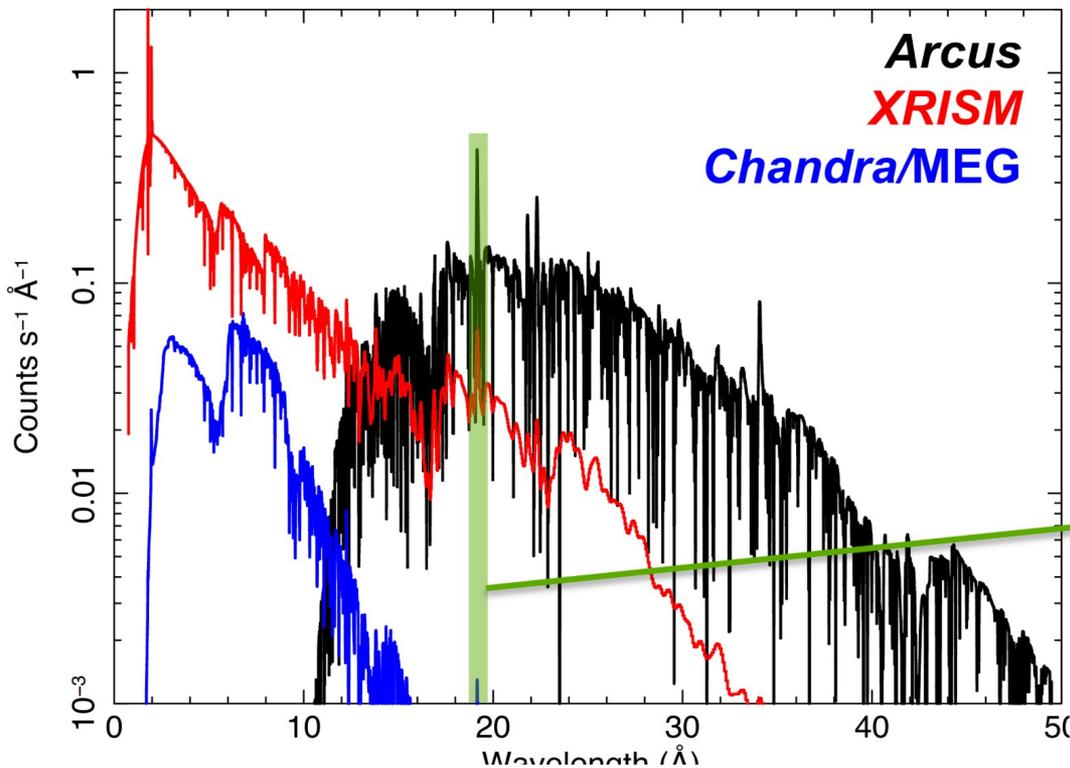
“super STAR-X” or “super-Chandra”

# The USA PROBES: ARCUS (>2032, pending selection)



Gratings energy resolution with large area in X-rays and UV

Better sensitivity than previous gratings instruments and larger area than XRISM



*Thank you!*

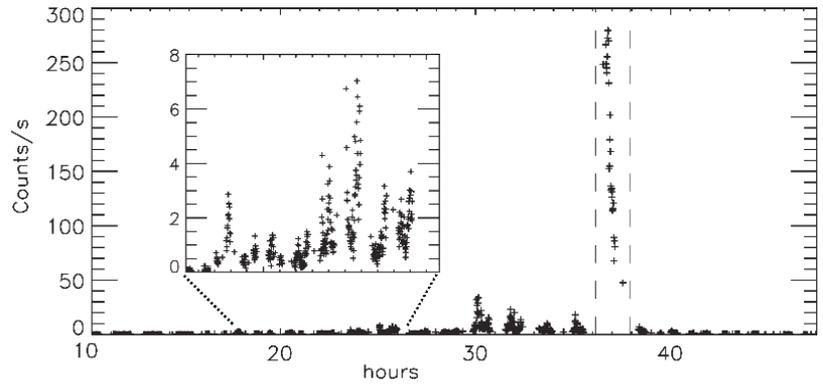
Enrico.Bozzo@unige.ch

# Theoretical modeling summary

Two models proposed so far:

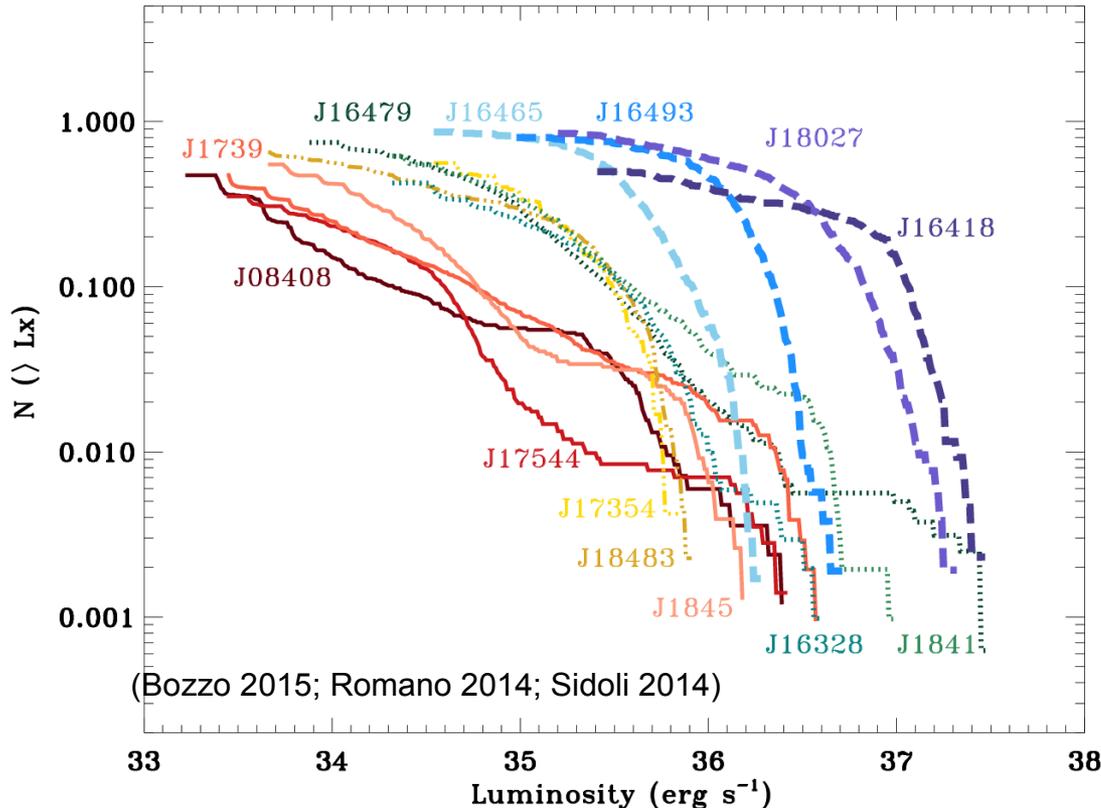
- Focus on inhibition of accretion and switch between different accretion regimes
- No smoking gun in favor of one or the other:
  - **Gating accretion:**
    - Cyclotron lines for magnetar fields outside coverage of current instrumentation
    - “Long” spin periods known for classical SgXBs, but no spin period confirmed for any SFXT
  - **Quasi-spherical accretion:**
    - No evidence of systematically different winds between classical SgXBs and SFXTs
    - Some evidence of possibly magnetized stellar winds in 1 SFXT
    - Application to eccentric systems ease the constraints, 2 SFXTs have eccentric orbits
- Switch between different accretion regimes manifested by drops/rises in the X-ray luminosity but physical mechanism(s) causing the switches are hidden behind observational limitations
- Stellar wind clumps must have a role, and for this at least we have both direct and indirect evidences!

# luminous



Individual observations show an extreme variability, at odds with the longer known classical supergiant X-ray binaries. Flickering at different scales in all states resemble what expected in case of clumpy wind accretion

□ Clumps must play an important role!



Cumulative luminosity distributions

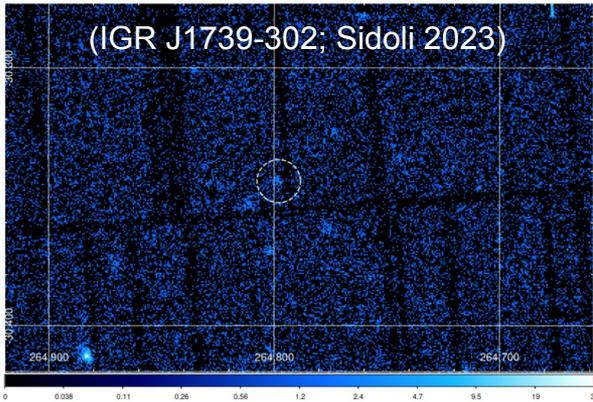
Built after several years of intense high-sensitivity monitoring (INTEGRAL & Swift)

Substantial differences in the distributions of SFXTs and classical systems. SFXTs are dramatically sub-luminous □ Accretion must be inhibited!

# Follow-up and monitoring campaigns: quiescence

**Quiescence:** soft spectral components directly from the stellar winds ( $\sim 10^{31}$ - $10^{32}$  erg/s)

□ Largely inhibited accretion + X-ray emission from the stellar wind?



**Fig. 2.** Central part of the *XMM-Newton* mosaic of the three EPIC exposures (0.3–12 keV), with the faint XTE J1739–302 marked by the white, dashed circle.

