Variability in X-ray binaries with *Theseus*

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THESEUS CONFERENCE 2021, VIRTUAL - 23-26 March 2021

The Zoo of X-ray binaries

- **HMXBs**
  - Persistent:
    - Disk accretion, ROFL, incl. microquasars
    - Wind accretion, Supergiant X-ray binaries (SGXBs)
  - Transients
    - Black hole transients (BHTs)
    - Be-X-ray binaries (BeXRBs)
    - Supergiant fast X-ray transients (SFXTs)
    - Very faint X-ray transients (VFXTs)
    - Gamma-ray binaries
- **LMXBs**
  - Persistent sources (ROFL, disk accretion)
  - transients
    - Soft X-ray transients (SXTs)
    - Ultracompact binaries (UCXBs)
    - Black hole transients (BHTs)
    - Accretion-powered millisecond pulsars (AMXPs)
    - X-ray bursters
- **CVs**
  - Zoo of it’s own…

Another level of diversity:

- NS/BH?
- Magnetic field
- Pulsations
- Spin
- ……

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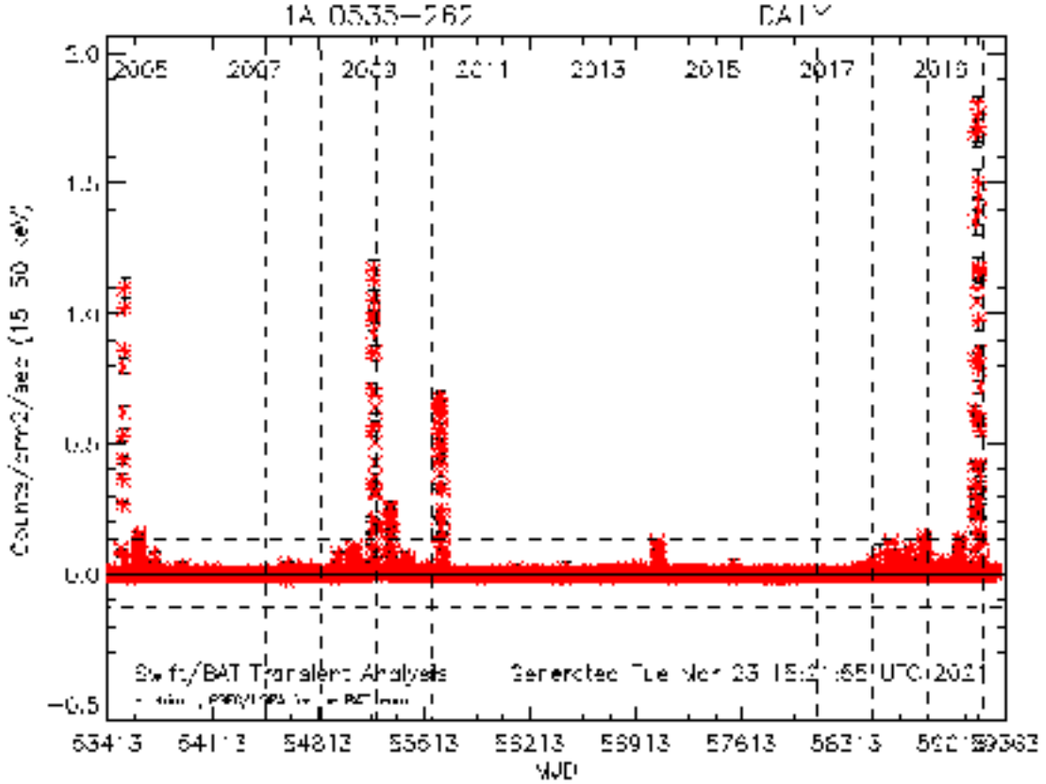
Today focus mostly on time variability of transient NS XRBs accessible to *Theseus*

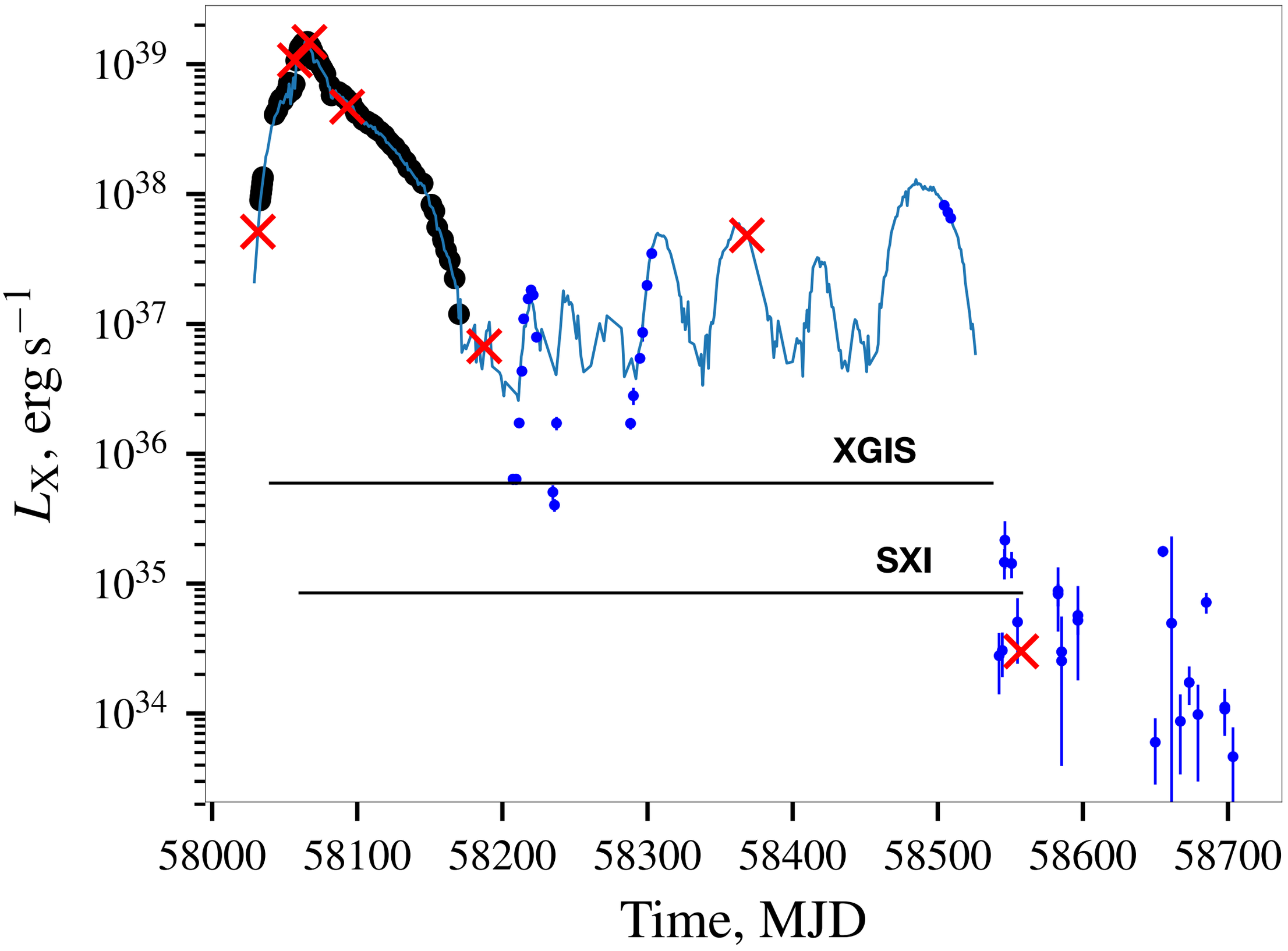
Be X-ray binaries (BeXRB)

- Traditional and easy target for all-sky monitors (fluxes up to 10^{-7} erg/cm^2/s)
  - Quiescent luminosities $10^{32\text{-}35}$ erg/s
- X-ray pulsar + Be binary, accretion from circumbinary Be disk when NS crosses it
  - ~100 known (50 Galactic, and 50 in MC)
  - Regular or irregular outbursts
    - peak luminosities of up to 10^{39} erg/s (normally below 10^{37} erg/s)
    - Lasts several weeks to months
    - Rich phenomenology (spectra/timing)
    - Many unanswered questions (also in context of PULXs science)

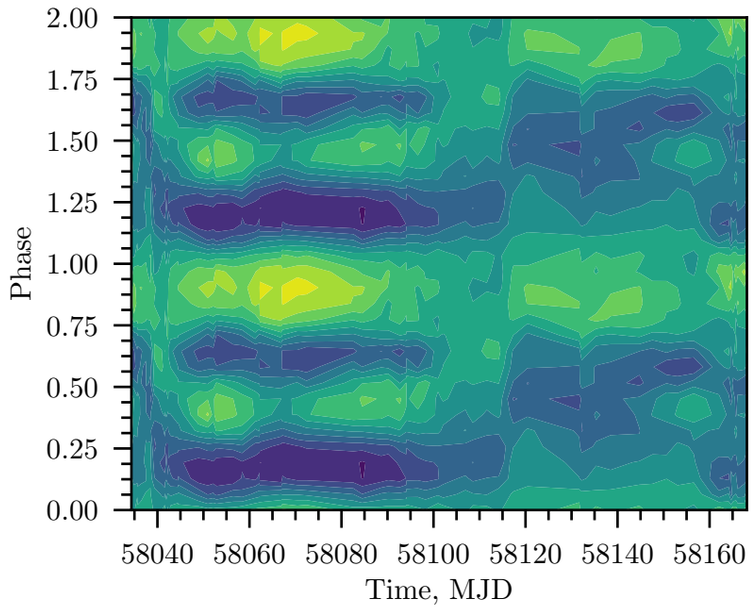
- Transient, bright, broadband: *Theseus!*
  - detailed studies with *Theseus* alone
  - Discovery of new sources
  - Monitoring of BeXRBs in MCs (to follow-up with other facilities)

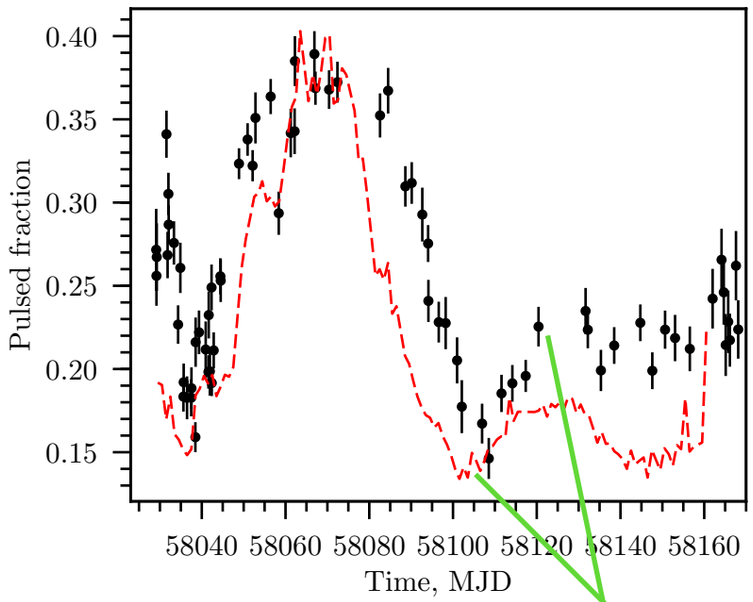


Be X-ray binaries (BeXRB)

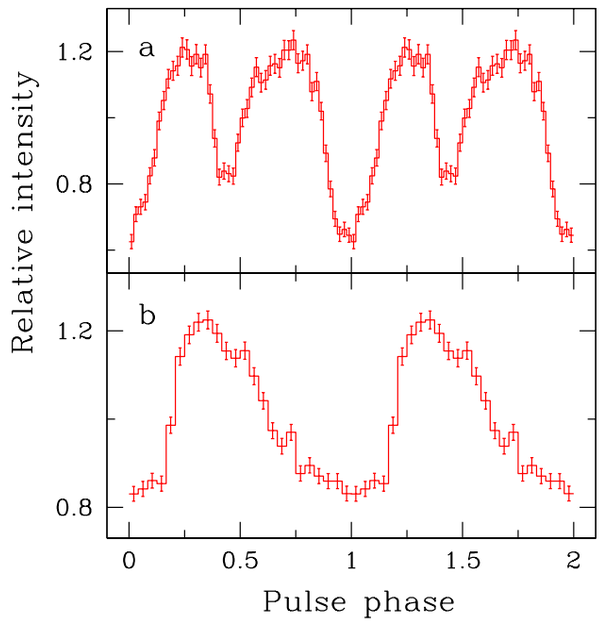


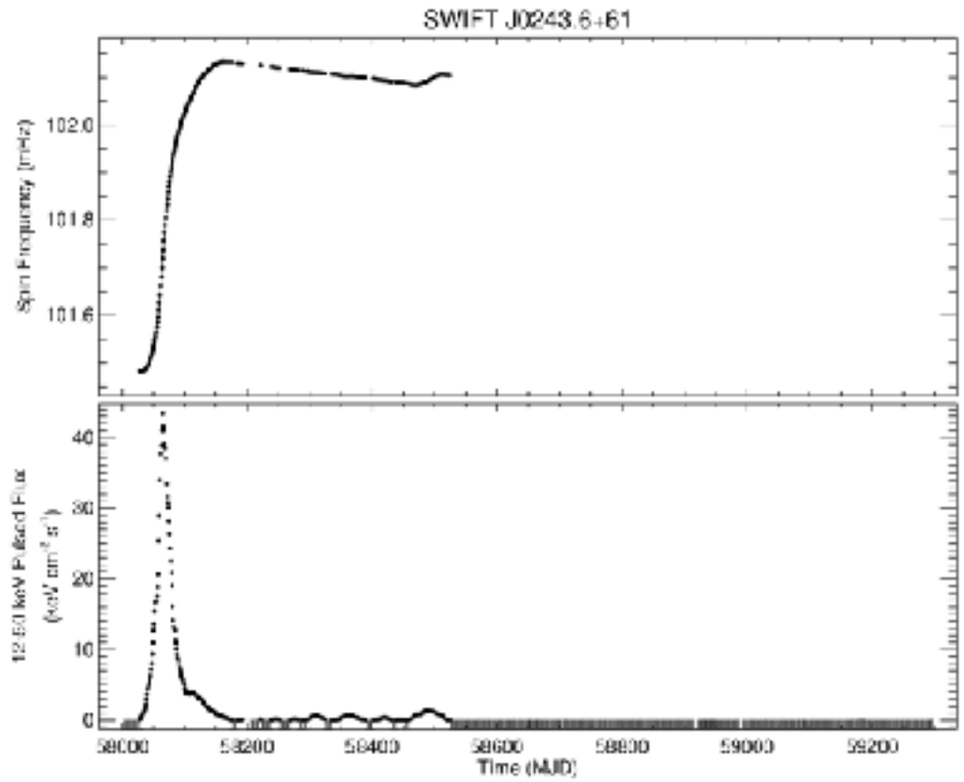
Swift J0243.6+6124 (Swift + MAXI + NICER)

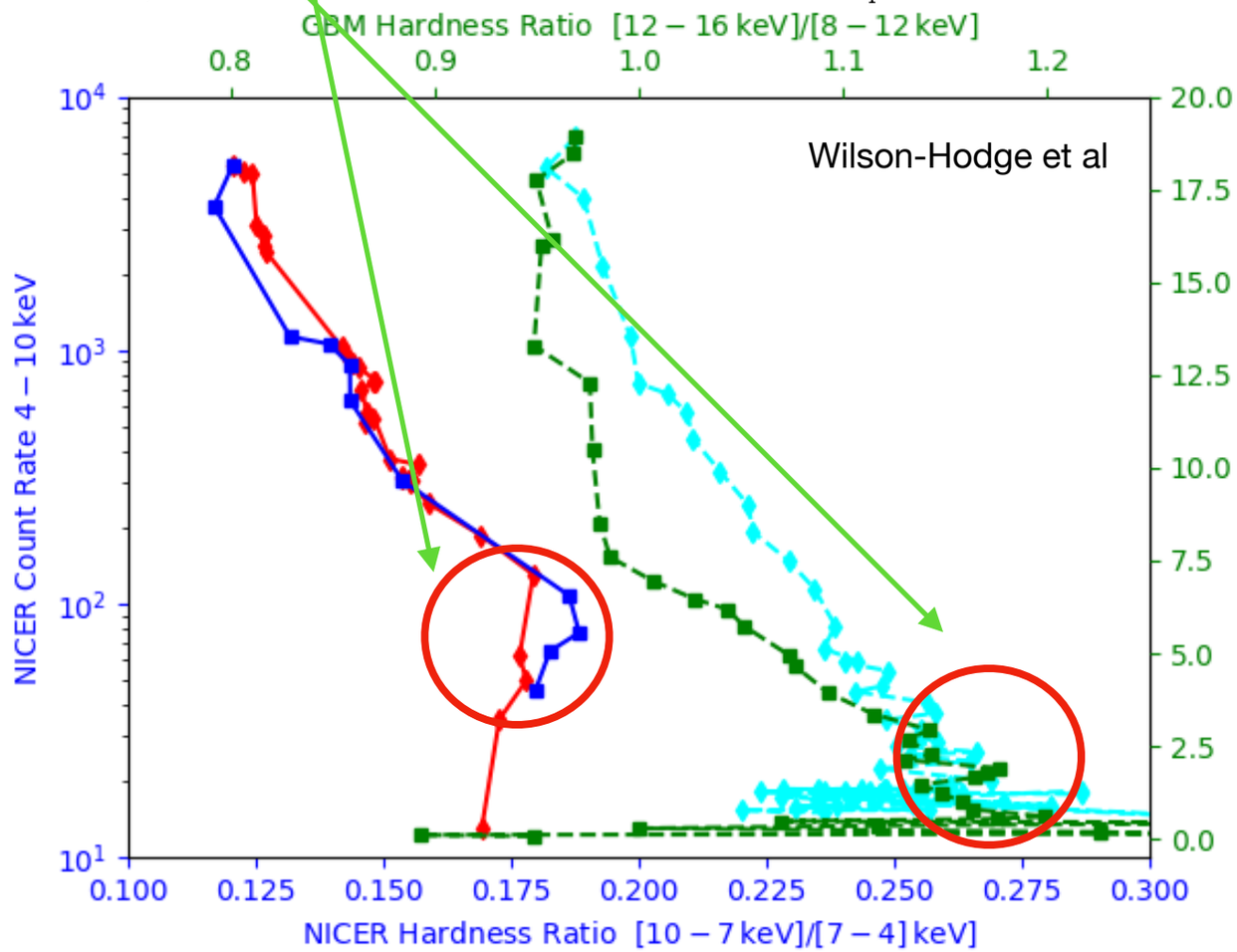




Tsygankov et al

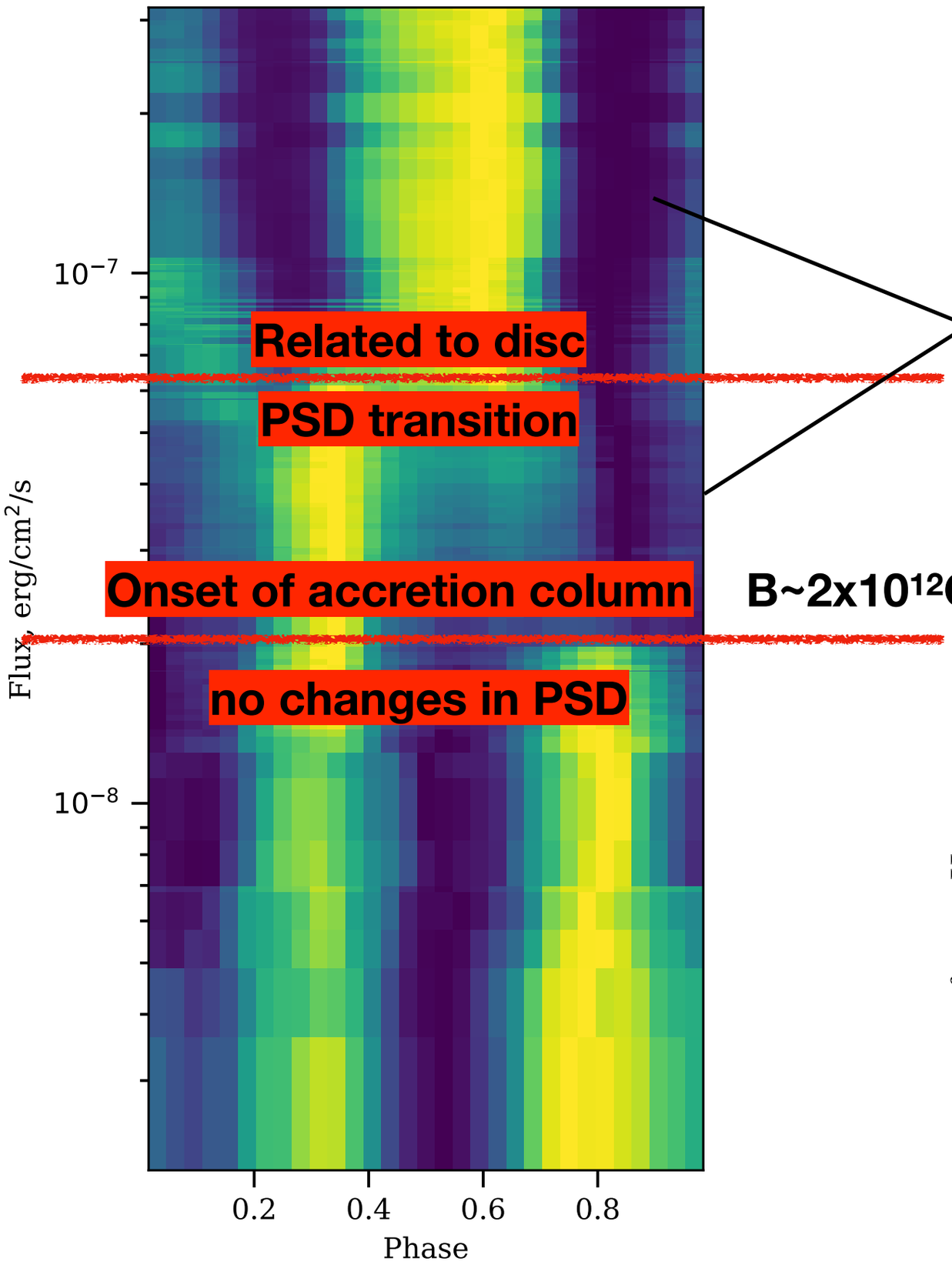


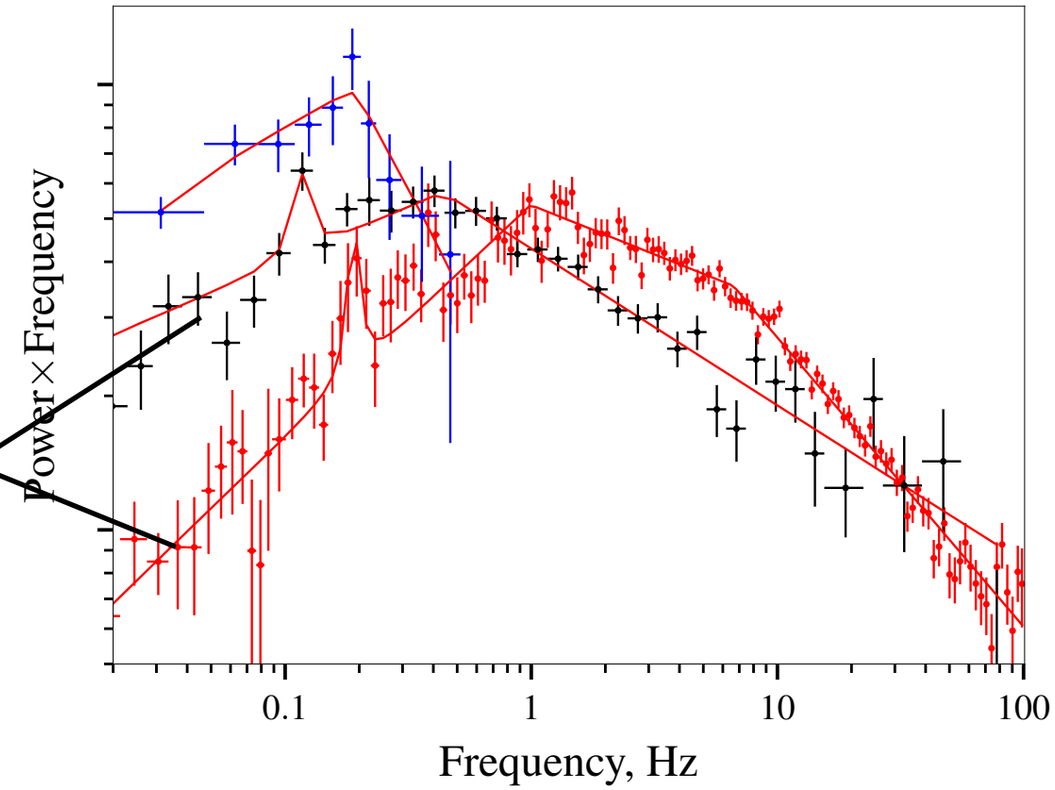


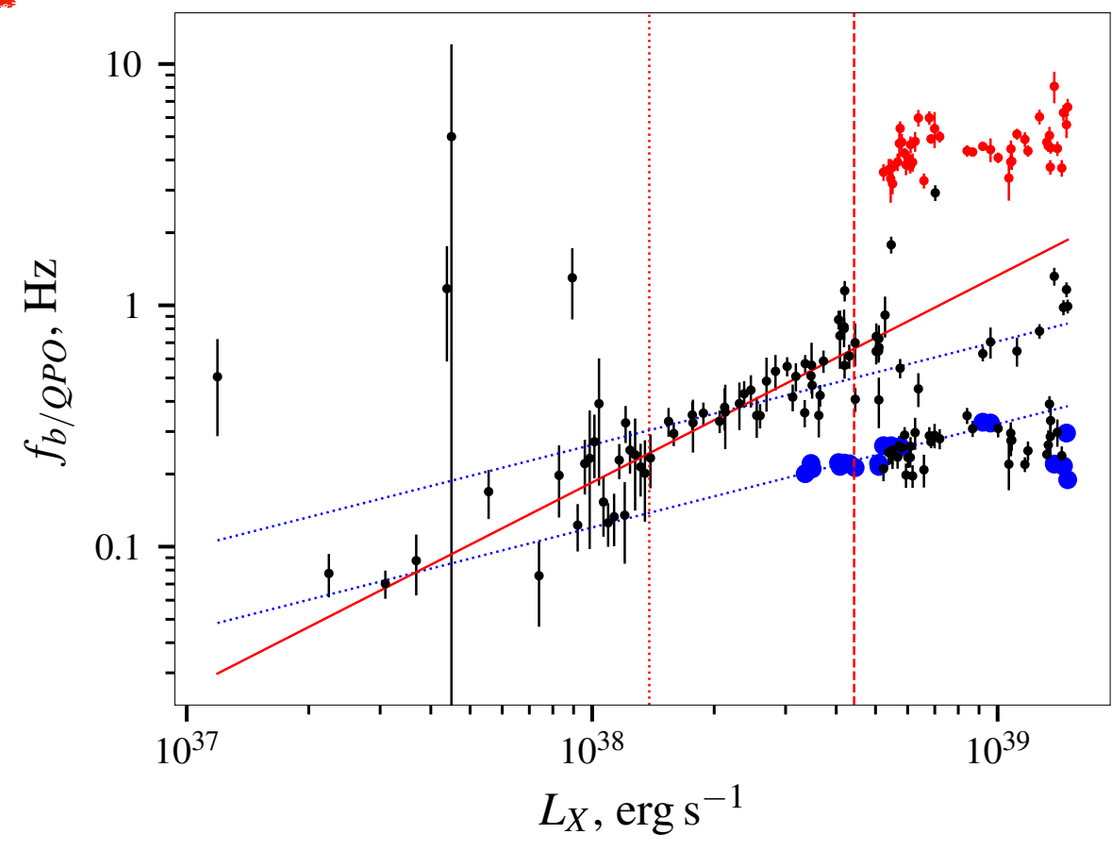


Could be done with *Theseus*

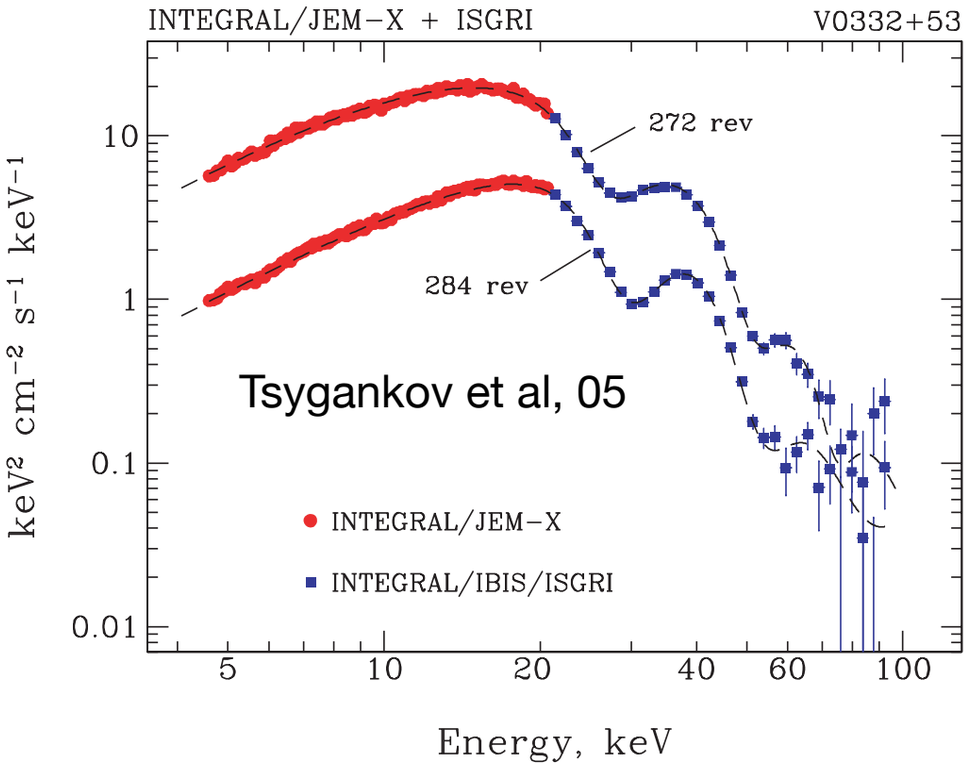
Swift J0243.6+6124 (Swift + MAXI + NICER)

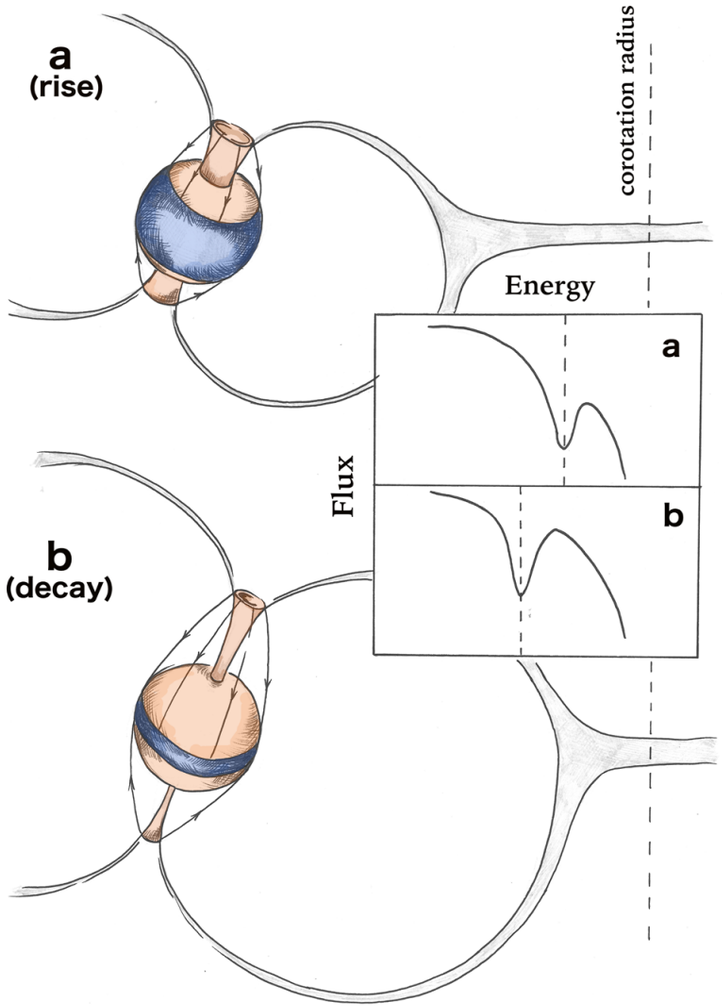


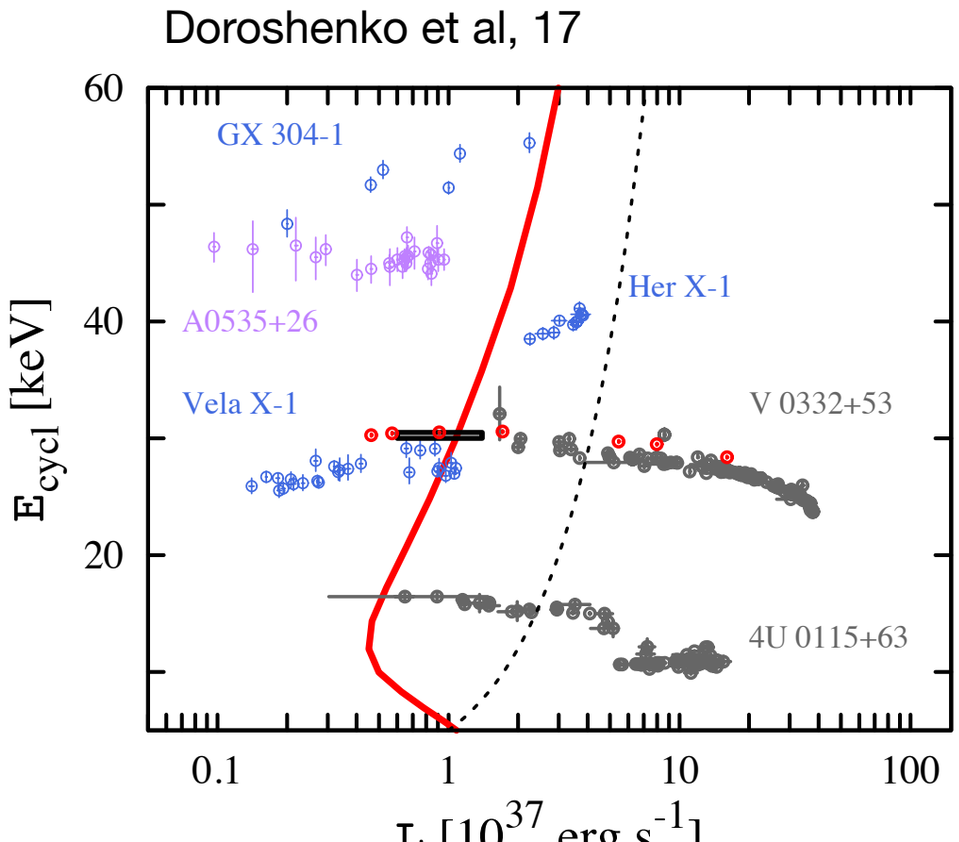


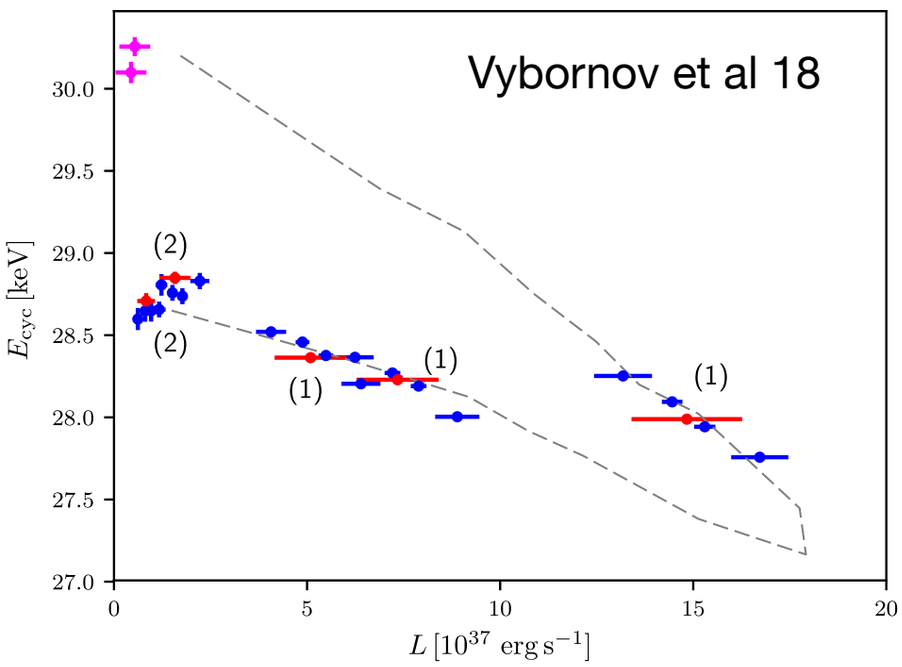


V 0332+53, BAT + NuSTAR

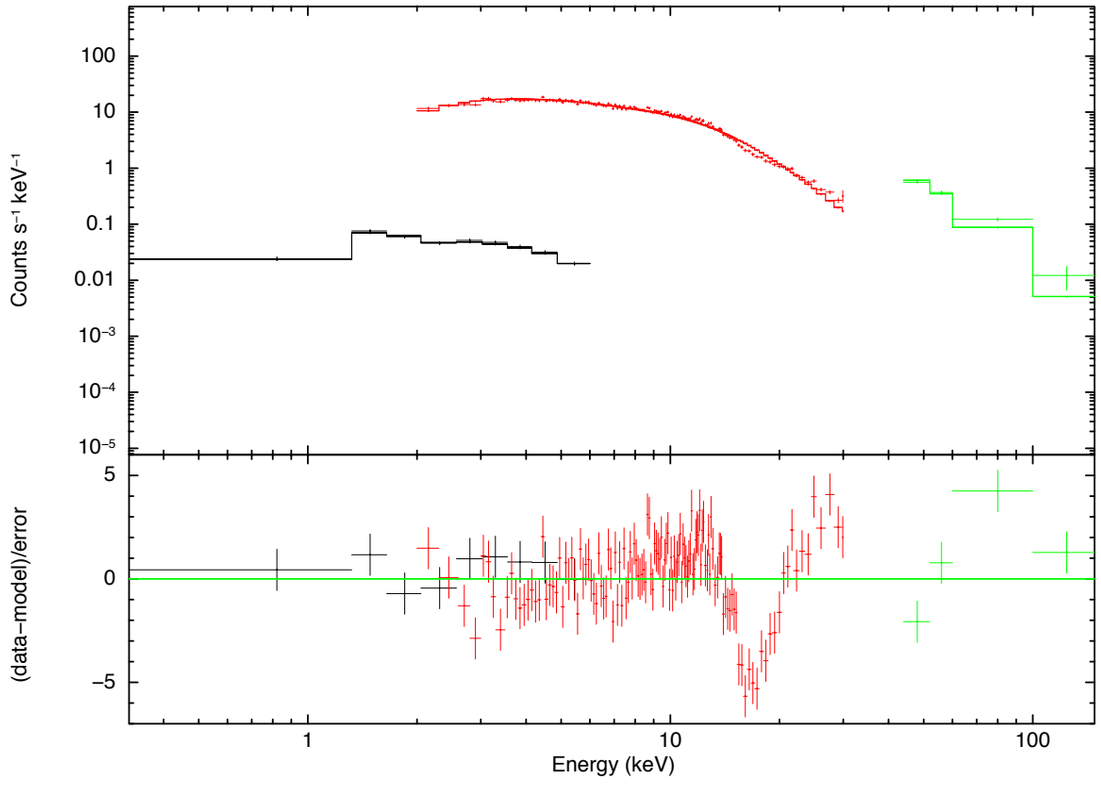




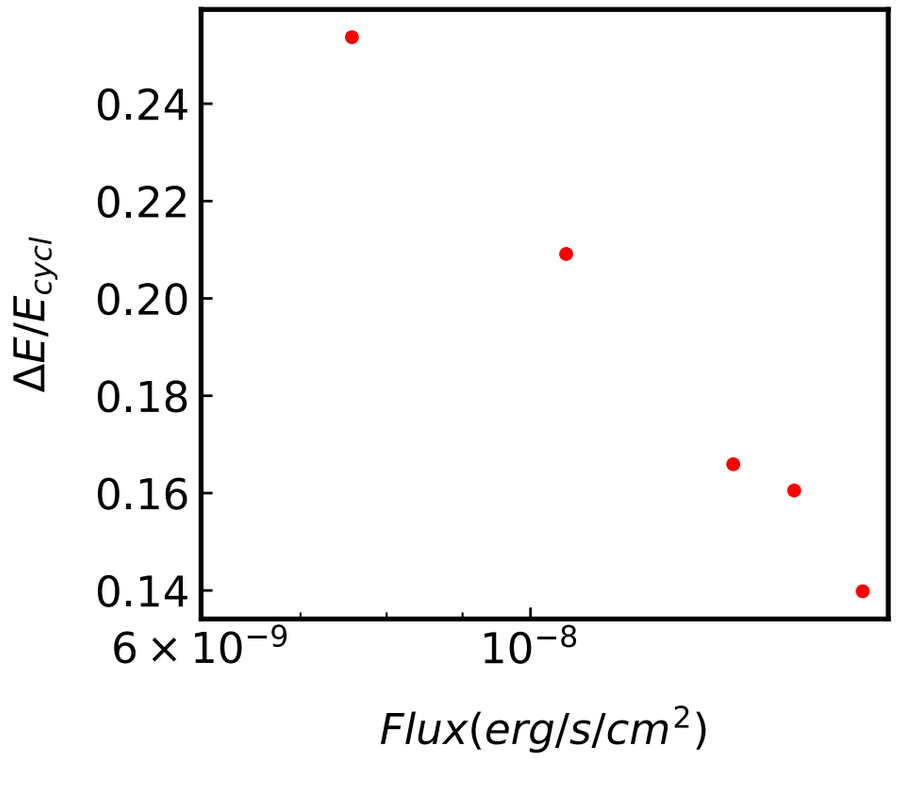




Cyclotron line and continuum evolution in BeXRBs



10ks simulation for 10^{-9} erg/cm^2/s flux and CRSF at 17 keV

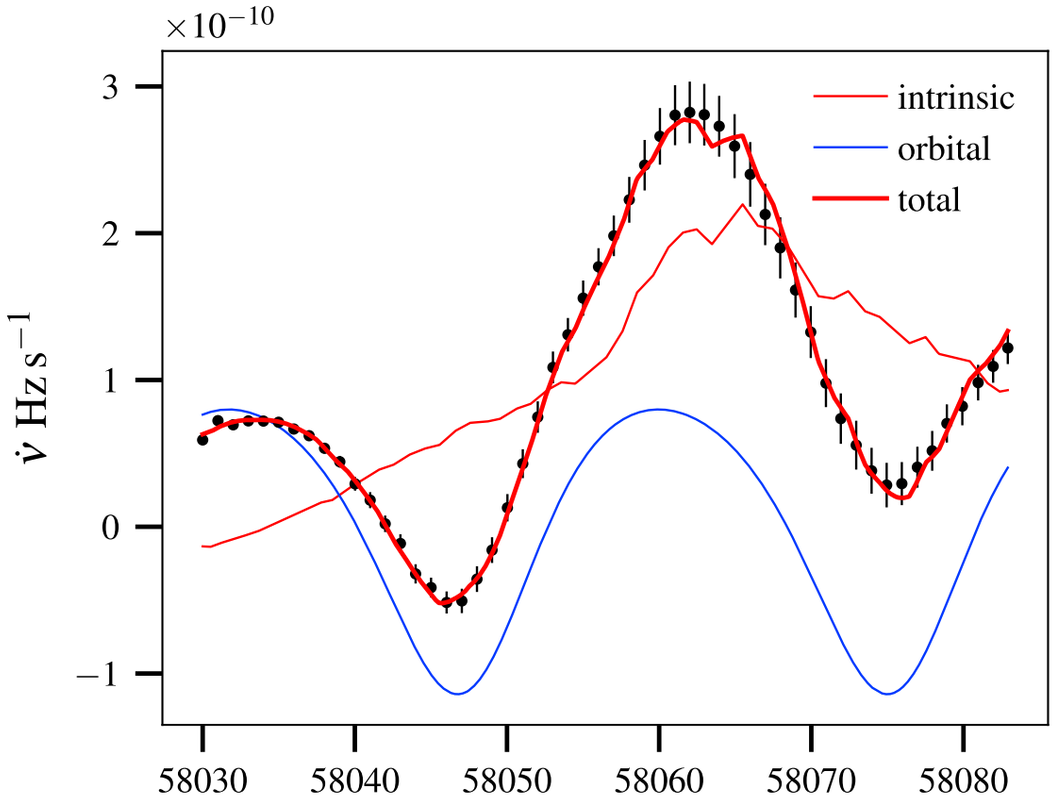


Accuracy of the 30 keV CRSF centroid in 70 ks
(Based on Cen X-3)

- Currently 1 source with robustly measured L*. A handful of candidates. To expand this small sample *Theseus* could (for bright sources)
  - measure **photon index/color variations** for Galactic BeXRB
  - **CRSF variations** are more tricky: only sources with CRSFs <~30 keV are feasible (~ 10 objects, but new transients with CRSFs might appear)
  - Follow **pulse-profile/pulsed fraction variations**
- **Mostly interesting for new/exceptional outbursts/sources** (regularly bursting ones will likely be studied in great details before *Theseus* launch)

Be X-ray binaries (BeXRB)

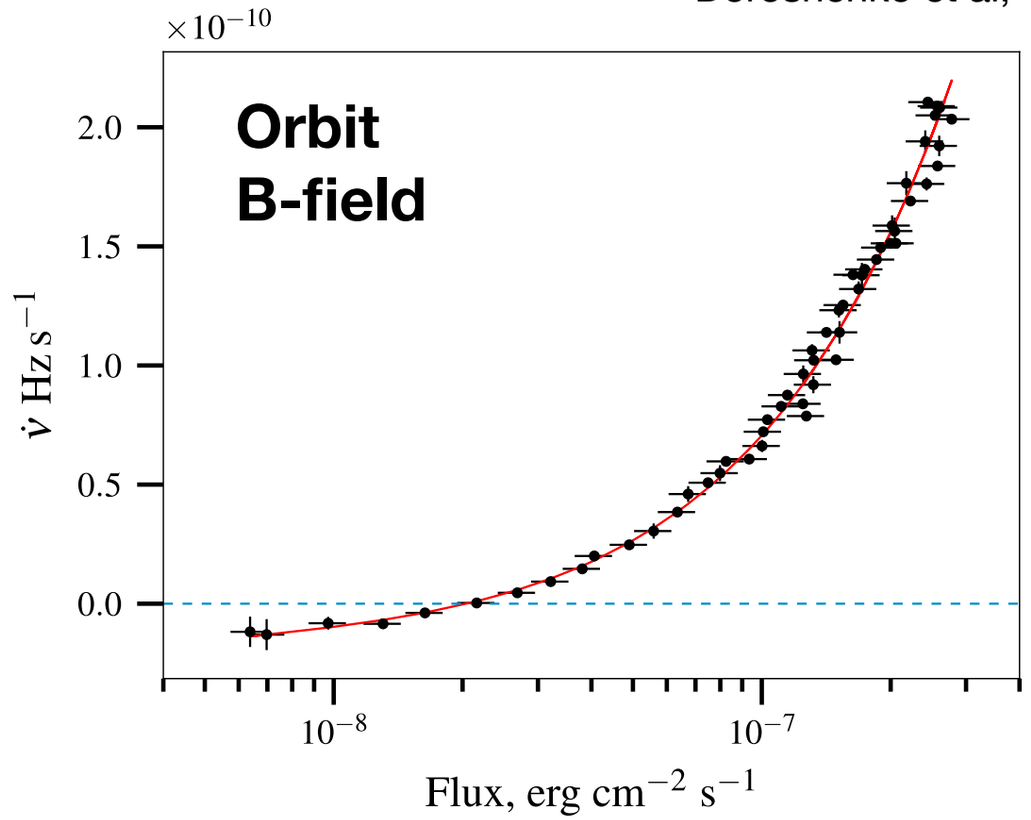
- Rapid spin-up during outbursts
  - interaction of the disk with magnetosphere
- Possibility to measure orbital parameters
- Measure magnetosphere radius and magnetic field



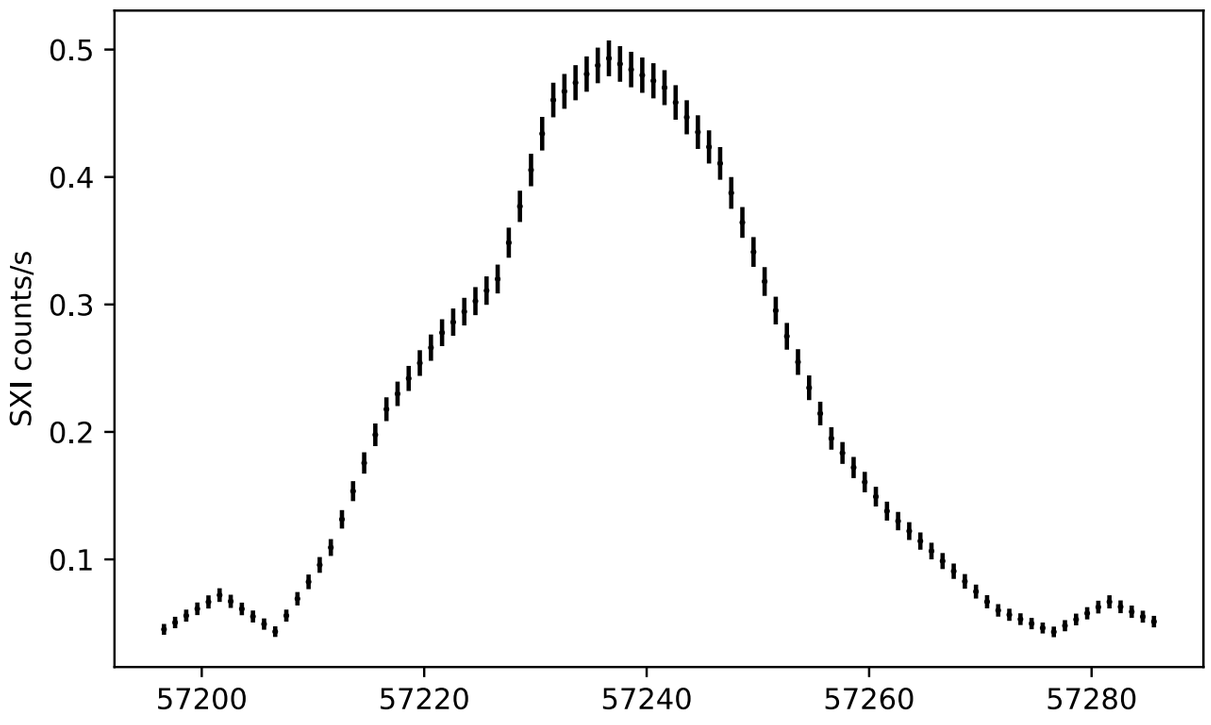
$$I\dot{\omega} \propto \dot{M}\sqrt{GMR_m}$$

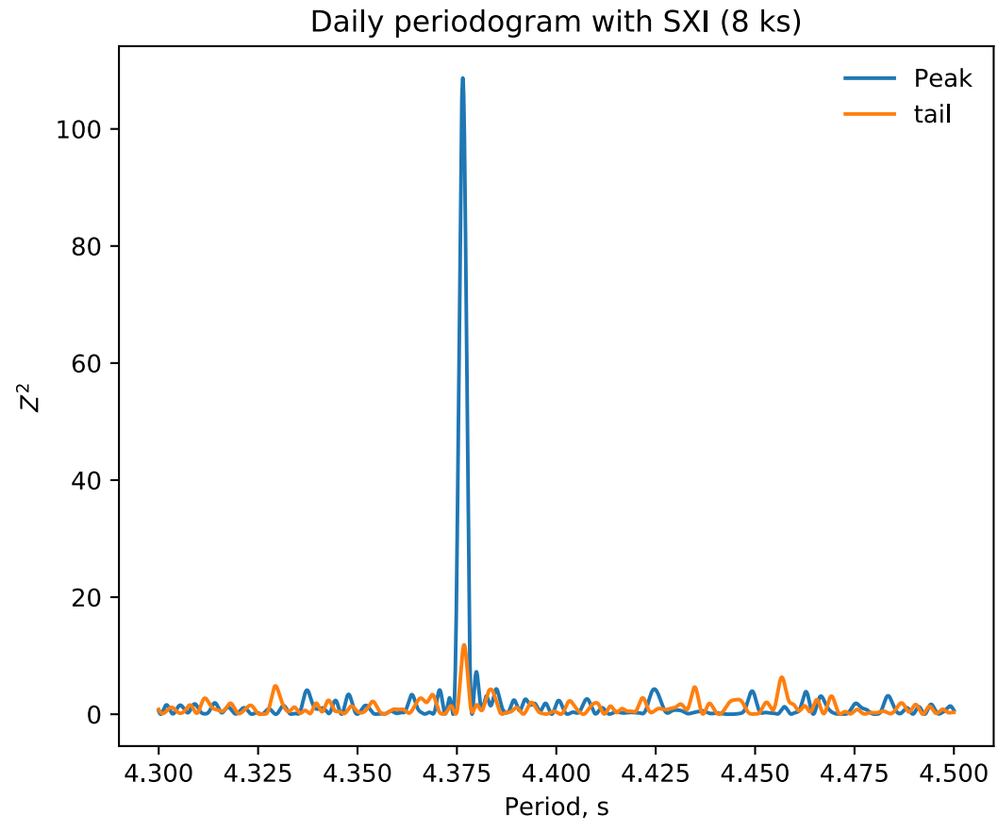
- Often the only way to assess the field (or accretion rate/distance)
  - Important to understand spin evolution of XRPs in binaries

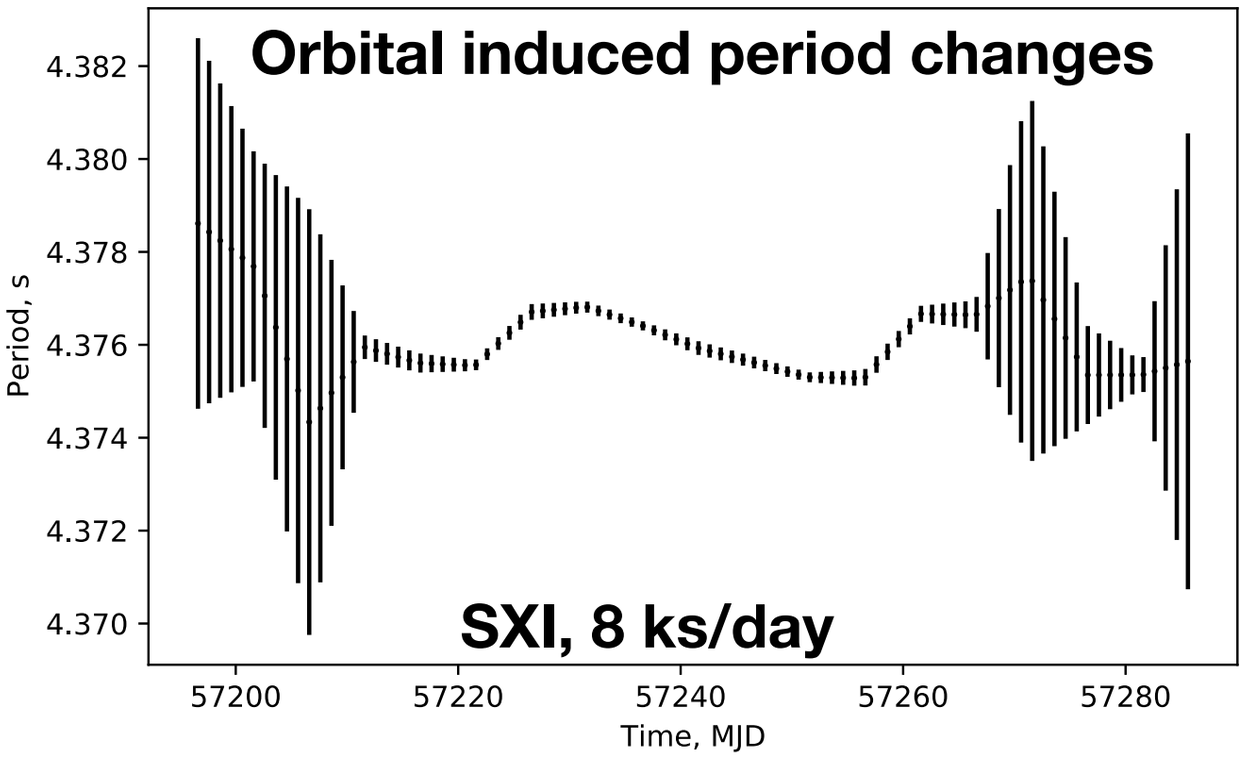
Doroshenko et al, 18



Spin evolution in BeXRBs



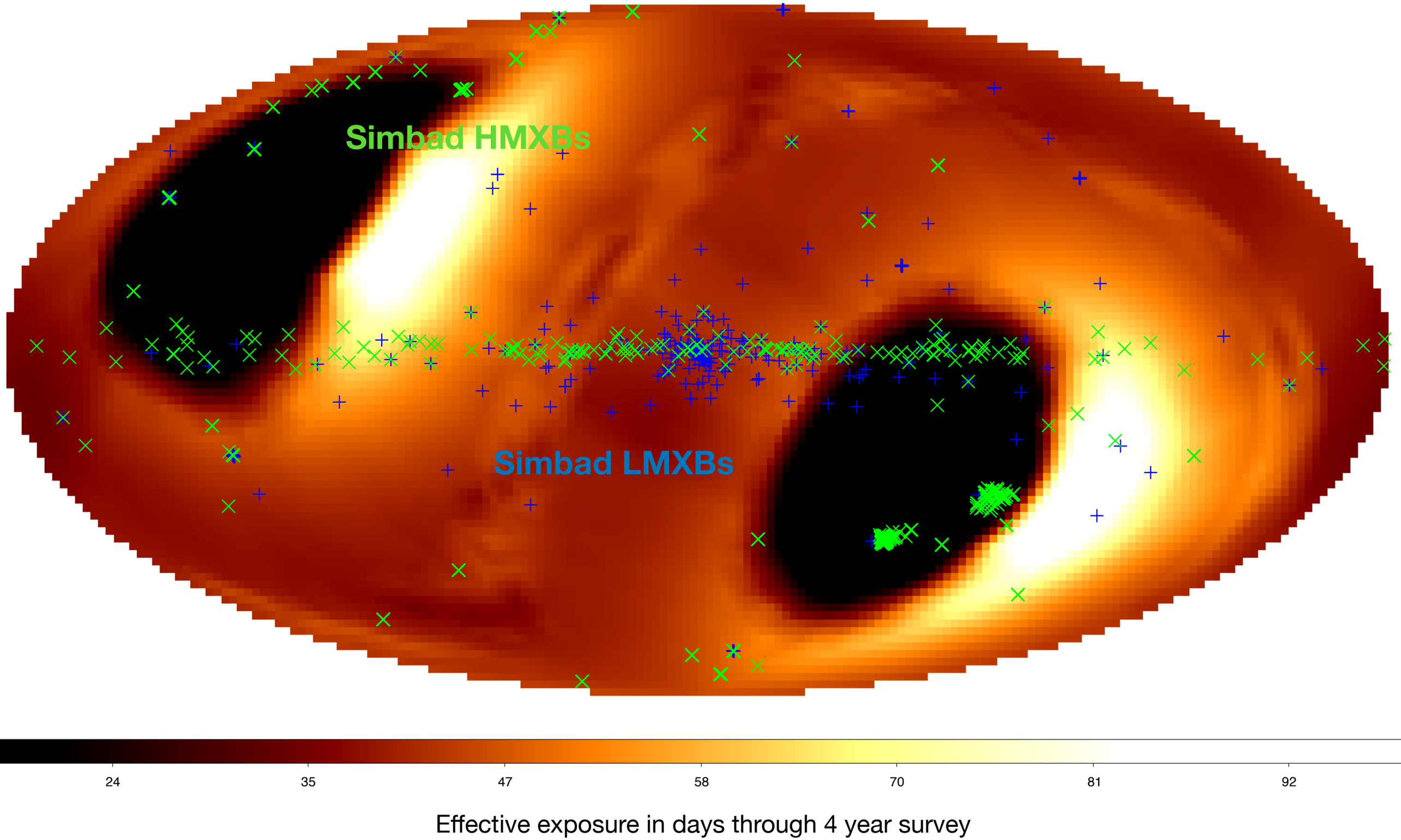




- Low background makes SXI preferred instrument
- approx. equivalent to Fermi/GBM, but with better cadence (~1d vs 2-4 d for individual points if region is observed)
- Mostly relevant for new transients (orbit, accretion torques)
- Requires dt<0.1s and >0.1 counts/s (for pulsed fraction of ~50%)

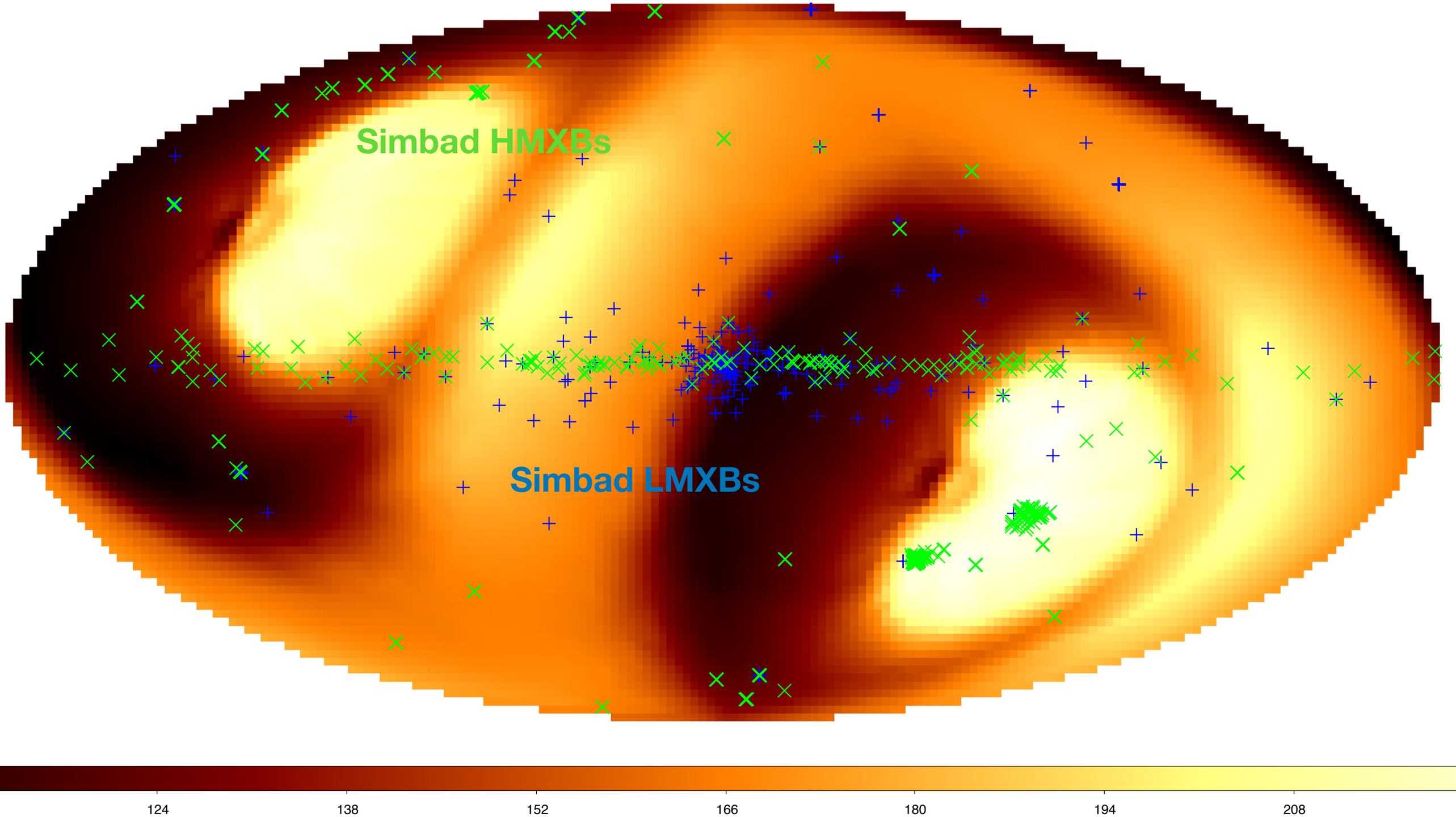
Theseus observing pattern and its impact on BeXRB science

Coverage of the Galactic sky by Theseus/SXI is highly non-uniform, MCs not covered



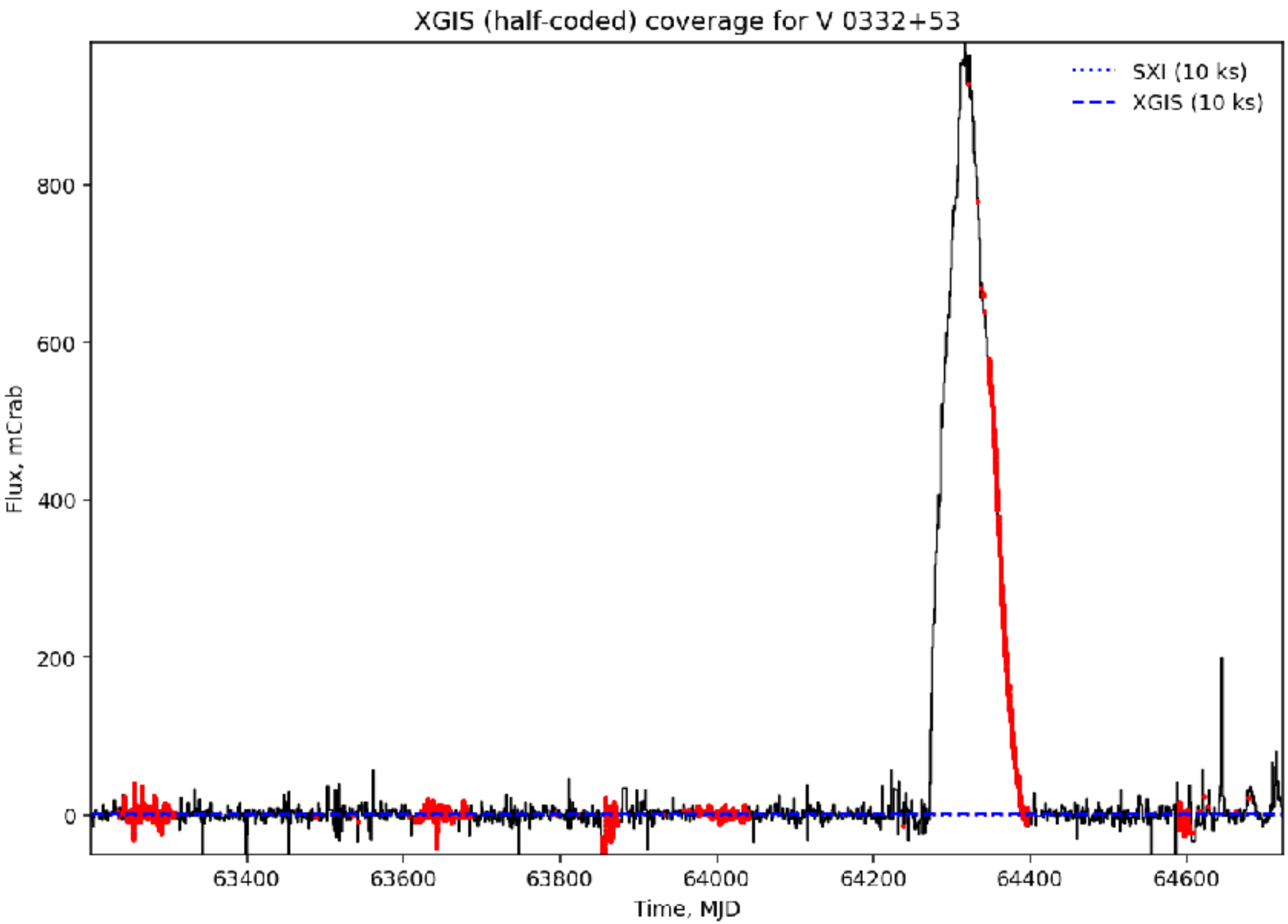
Theseus observing pattern and its impact on BeXRB science

Coverage of the Galactic sky by Theseus/XGIS is non-uniform, MCs covered



Theseus observing pattern and its impact on BeXRB science

But exposure maps don't tell the complete story!



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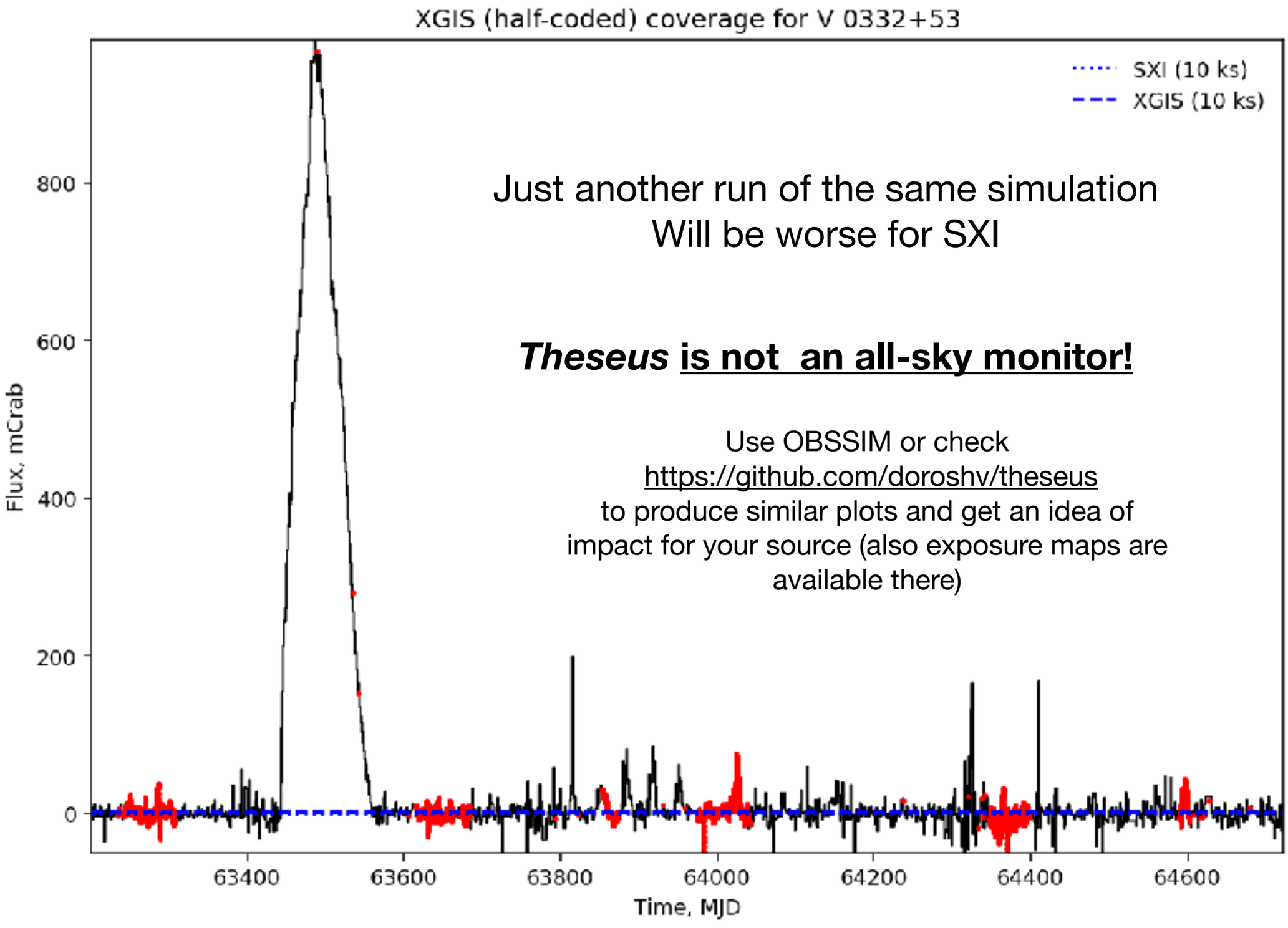


Just another run of the same simulation
Will be worse for SXI

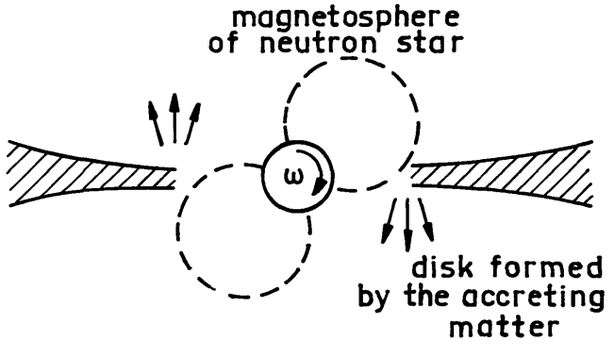
***Theseus* <u>is not an all-sky monitor!</u>**

Use OBSSIM or check
<u>https://github.com/doroshv/theseus</u>
to produce similar plots and get an idea of impact for your source (also exposure maps are available there)

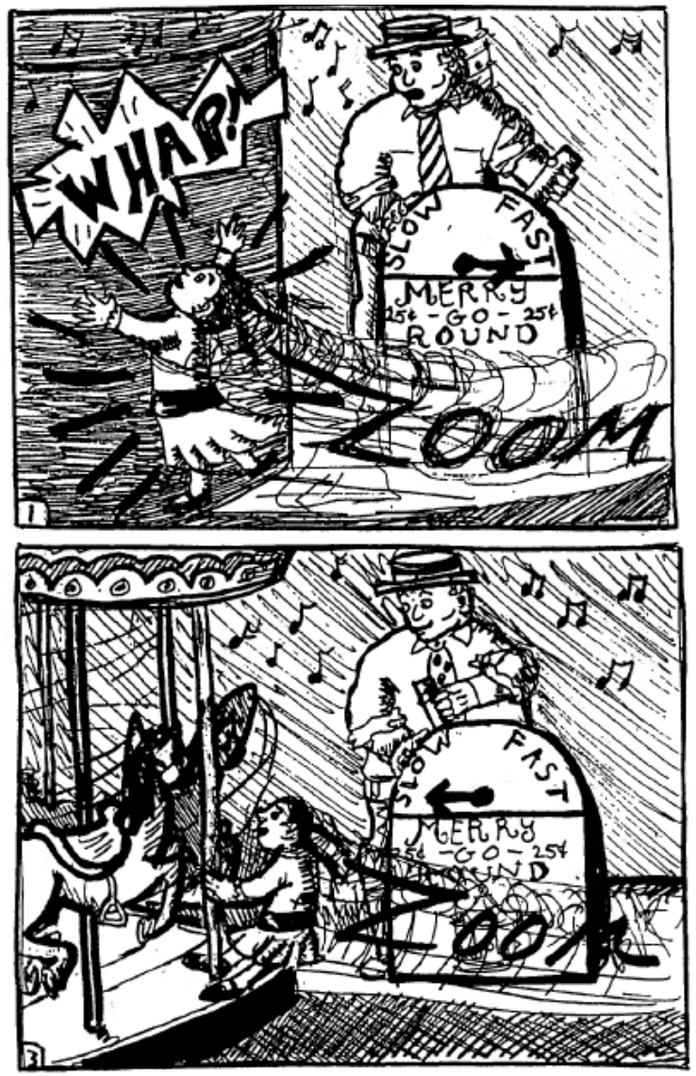
Theseus observing pattern and its impact on BeXRB science

- Duration of BeXRB outbursts is comparable with the length of *Theseus* observing seasons
  - If you are lucky - entire outburst with unprecedented cadence can be observed
    - detailed time-resolved spectral/timing analysis
    - perhaps some surprises (as was the case with V 0332+53, Swift J0243.6)
  - **Most likely you are not:**
    - We estimate ~10-20 outburst in total will be observed by *Theseus*
    - some examples for expected number of observed outbursts from known sources in 4 years: V 0332+53 ~ 0.5, 4U 1538-52 - 2; 1A 0535+262 - 2; IGR J16320-4751 - 4 …
- **most of the BeXRBs will only be observed in quiescence**
- **This might apply also to your science case**
  - Probably not if the variability timescale is <days not weeks

Quiescence might also be interesting, however…

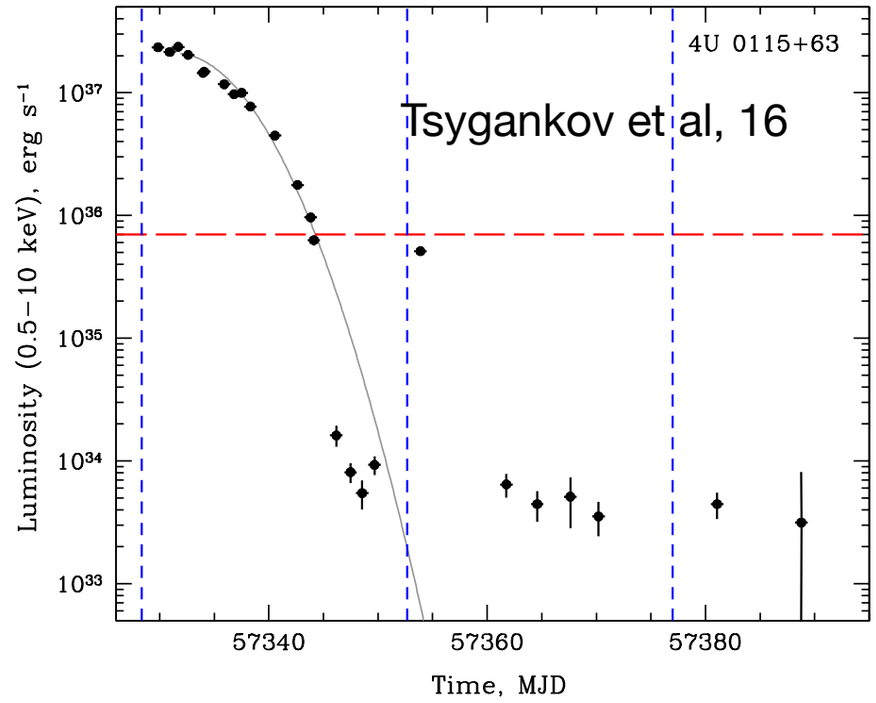


Illarionov&Sunyaev 1975

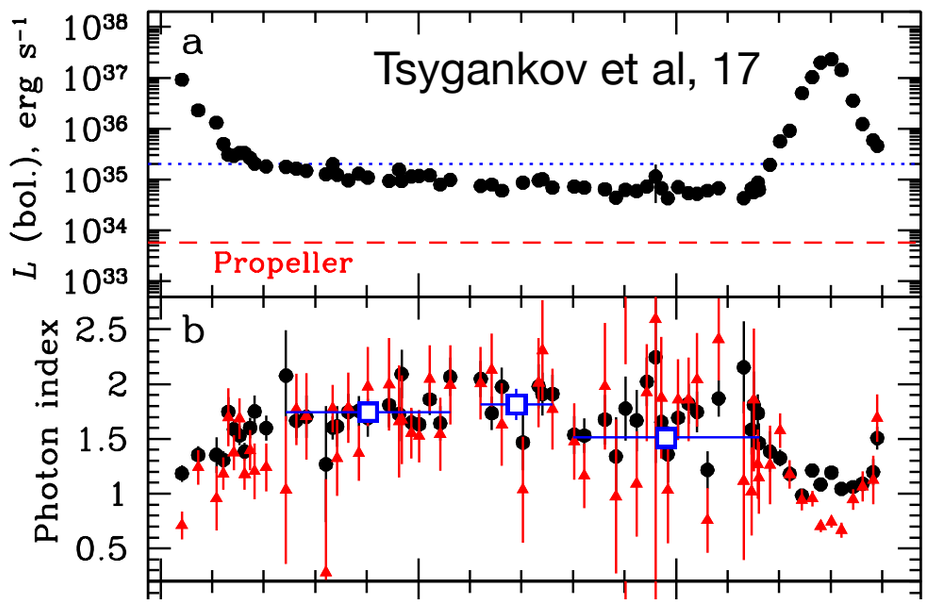


Patterson, 1994

Propeller effect

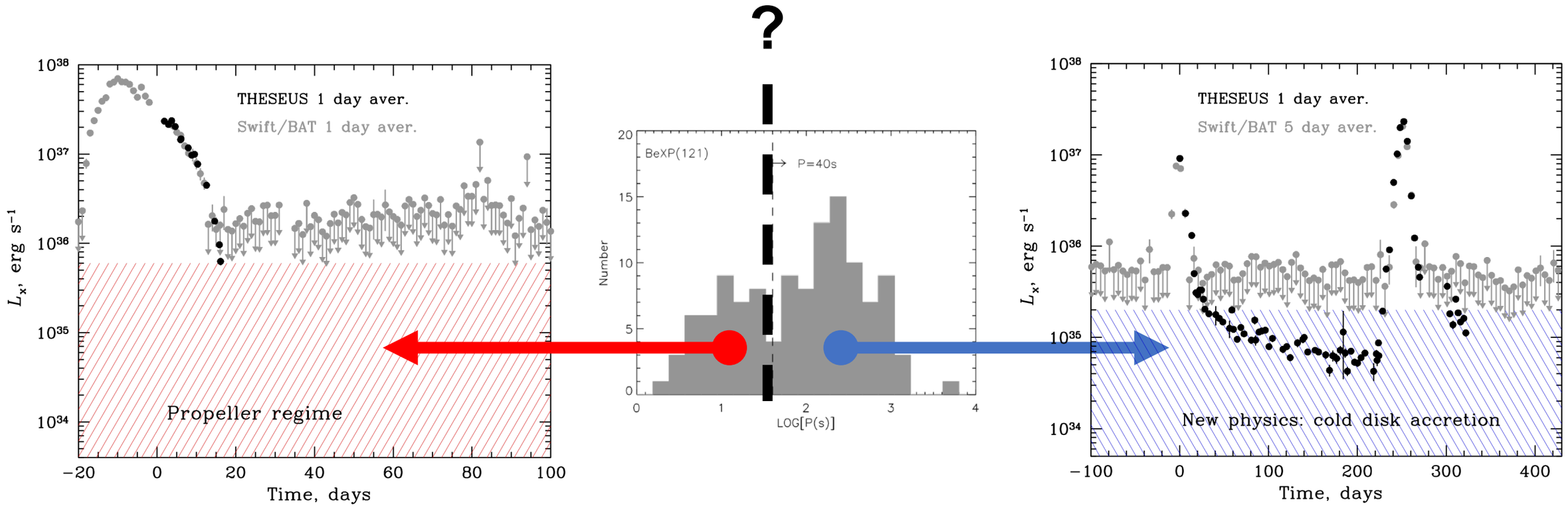


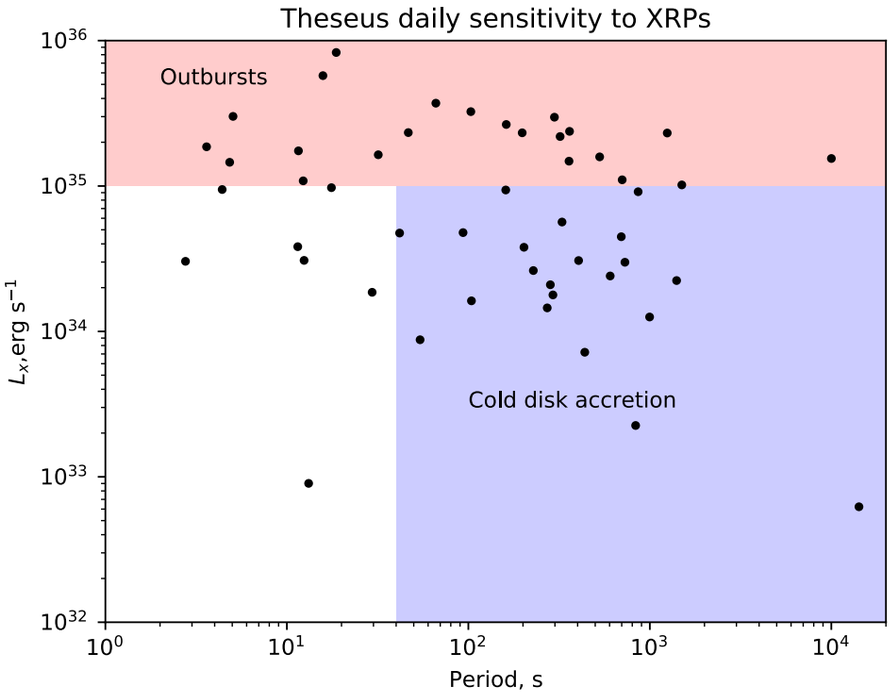
$$P^* = 40.7\, k^{21/23}\, B_{12}^{6/13}\, M_{1.4}^{-5/13}\, R_6^{18/13}\, A^{3/13}\, T_{6500}^{-12/13} \quad \text{s.}$$

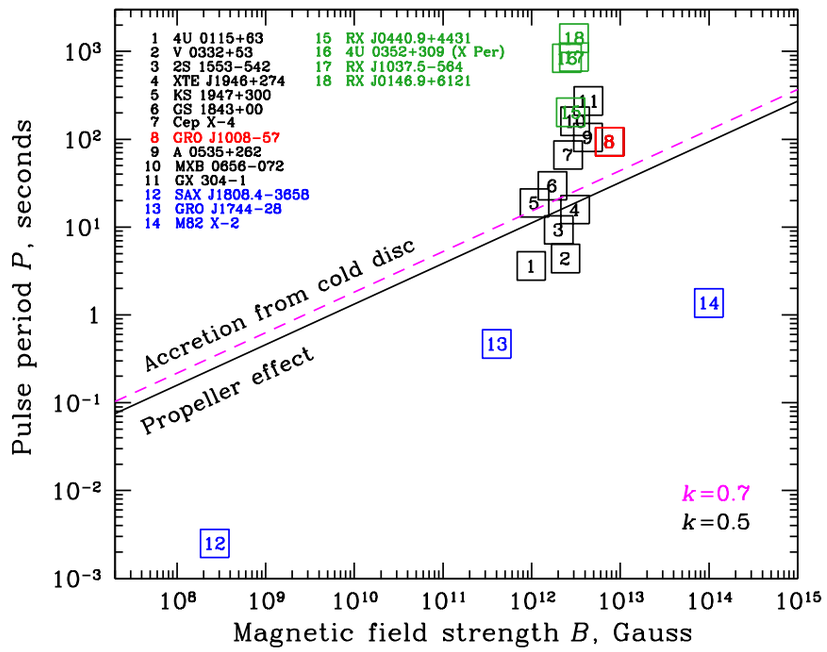


“Cold disk” accretion

Propeller effect and cold disk accretion

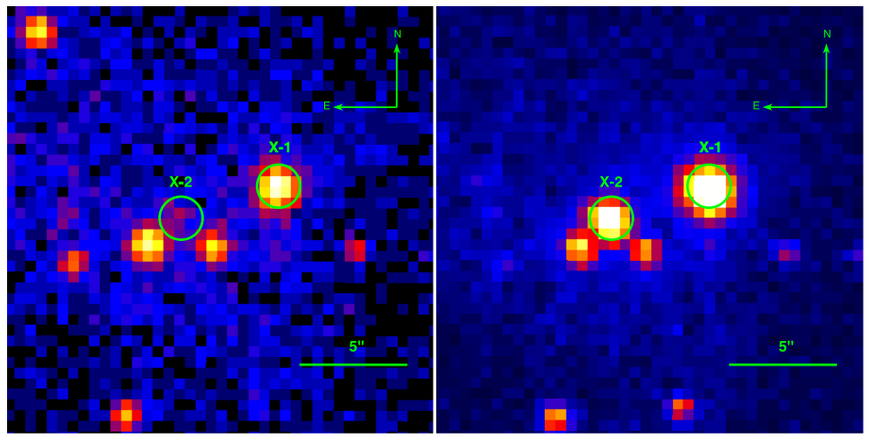




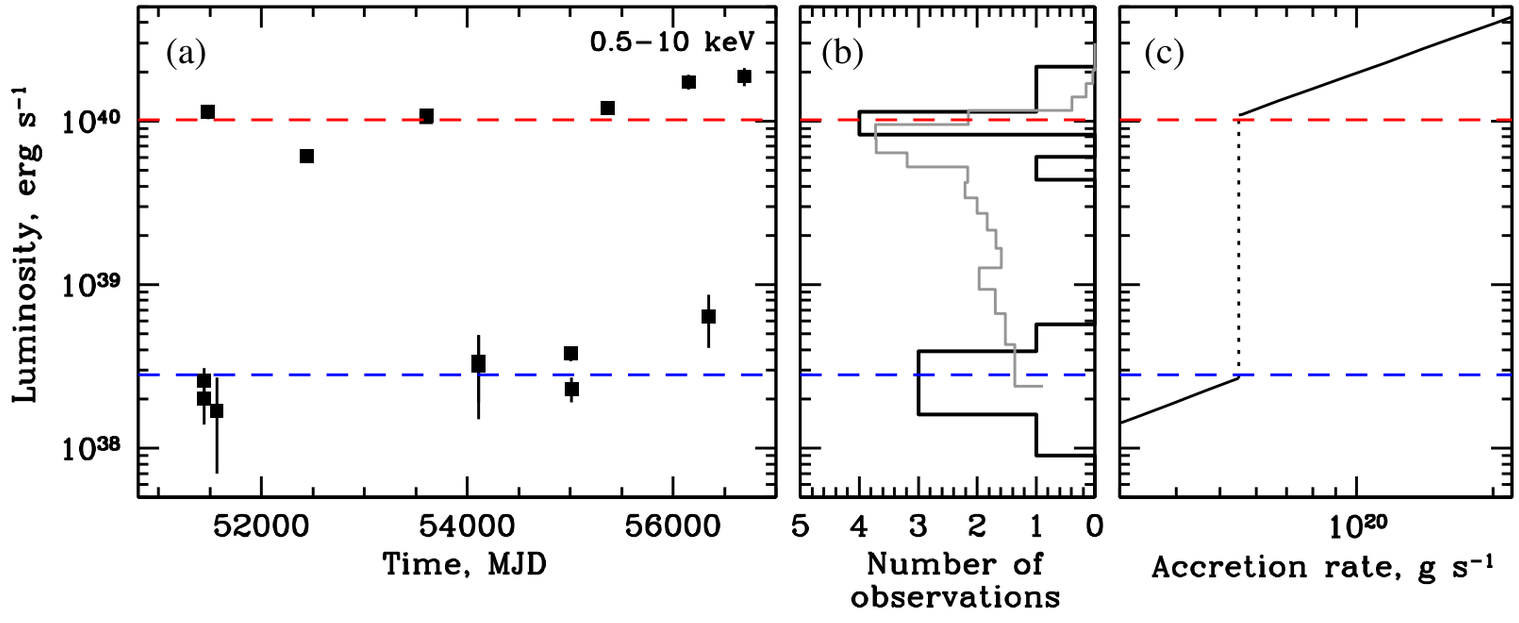


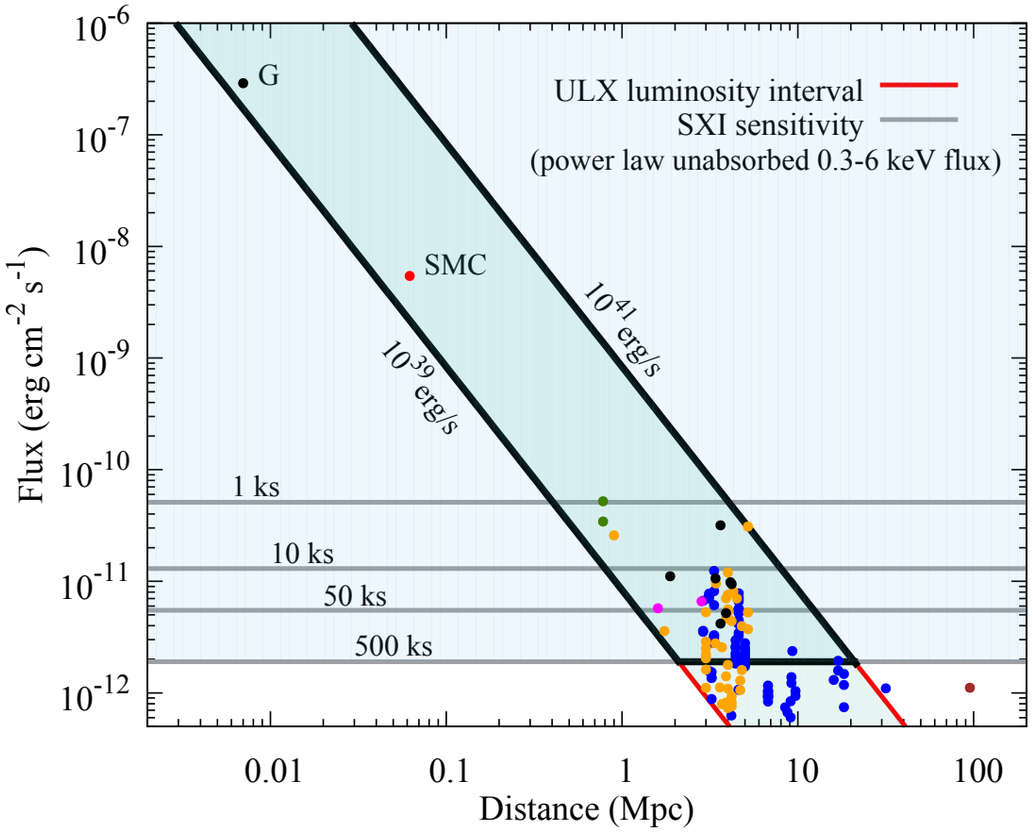
Takeaway: will detect all outbursts in FOV, some sources in cold-disk state, Quiescence is unreachable with SXI, will be done by eRosita anyway

pULXs as transient X-ray binaries



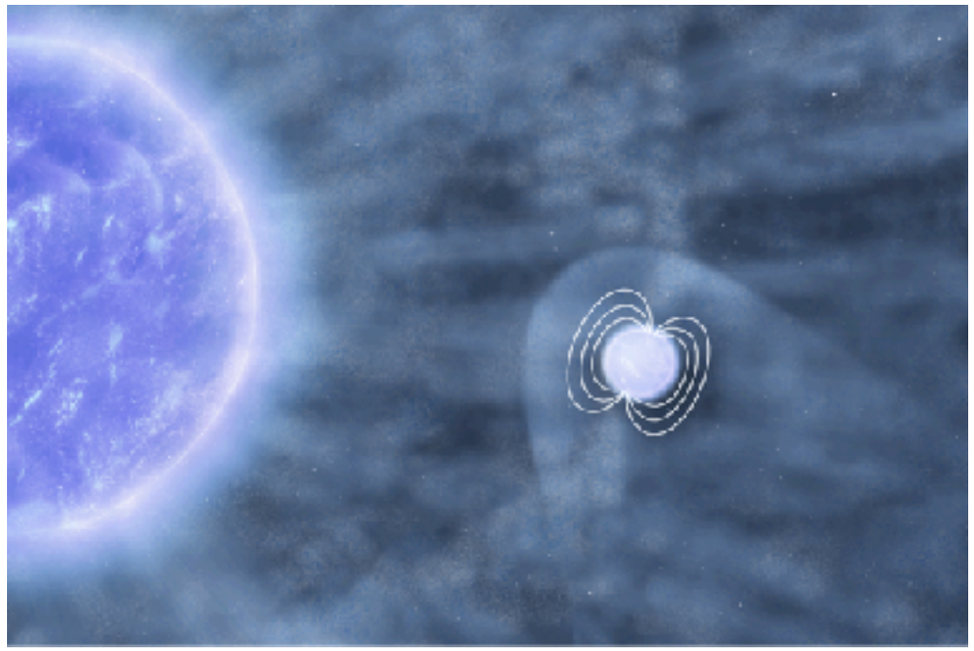
Tsygankov et al, 15



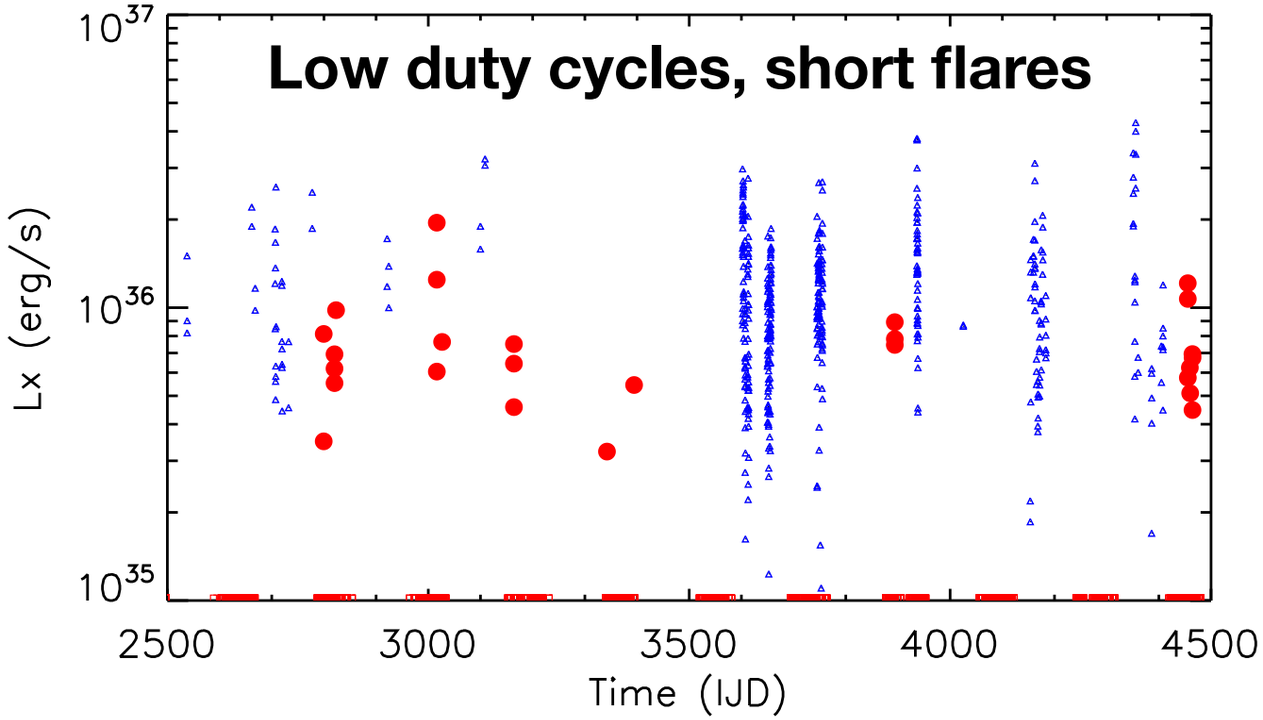


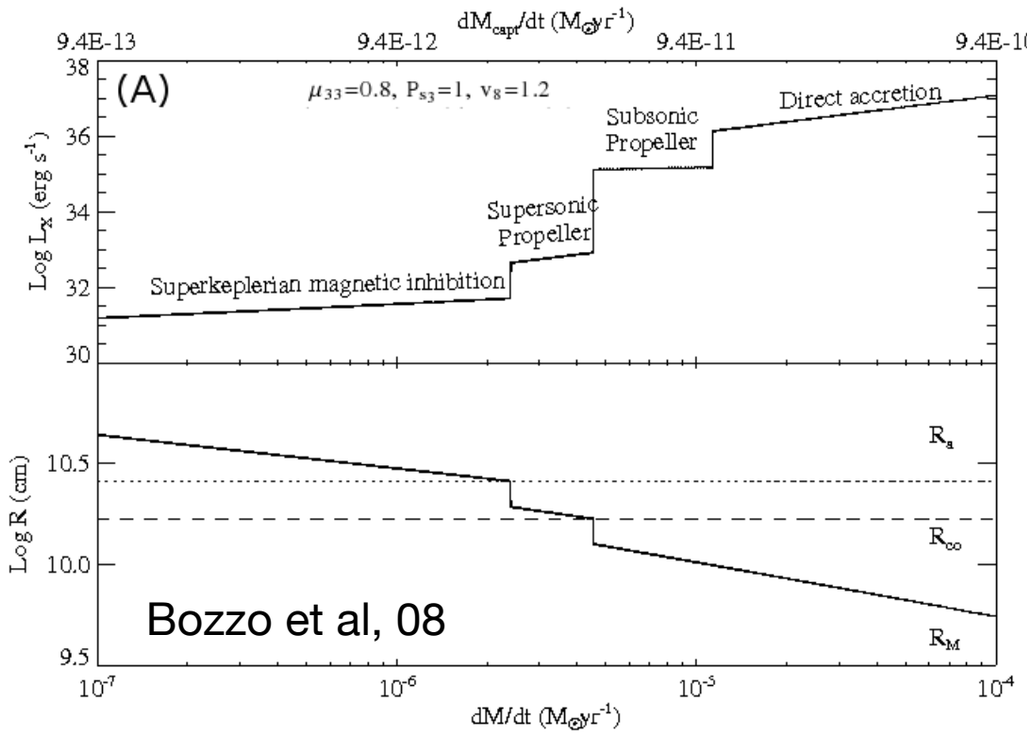
- PULXs = extra-Galactic XRBs
- Same physics, can hunt for variability to discover more pULX candidates
- SXI will be sensitive down to 10^{39} erg/s for many ULXs. Frequent drops of flux below the detection limit - candidate for follow-up and pulsations search with Athena/eXTP
- Here the caveat with observing pattern also applies, but there are significantly more pULX candidates than BeXRBs

Supergiant fast X-ray transients

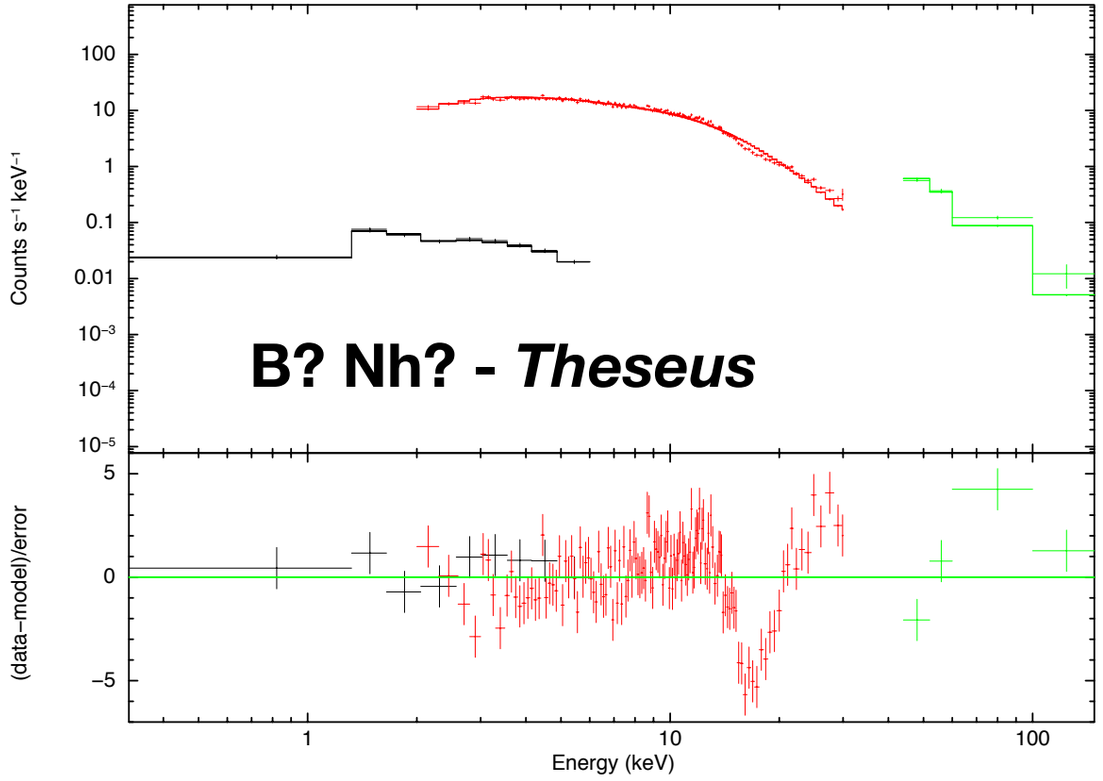


ESA/AOES Medialab





Magnetiospheric gating vs clumpy wind



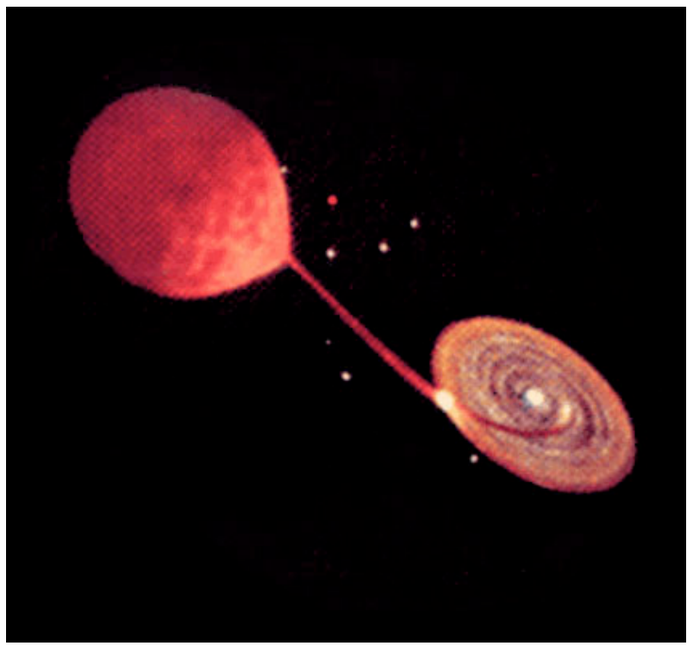
10ks simulation for 10^{-9} erg/cm²/s flux and CRSF at 17 keV

Supergiant fast X-ray transients

Name	SXI exposure (Ms)	N SXI (BAT/XRT)	XGIS exposure (Ms)	N XGIS
SAXJ1818.6-1703	5.2	2.1/694-2700	10.6	4.3
IGRJ08408-4503	6.9	2.0/667-2596	15.6	4.5
IGRJ16328-4726	4.5	0.2/63-247	11.4	0.5
IGRJ17544-2619	6.4	4.0/1323-5148	11.5	7.3
AXJ1845.0-0433	1.2	0.2/57-222	13.8	2.0
IGRJ16479-4514	5.2	6.2/2053-7990	11.4	13.6
IGRJ16465-4507	5.2	0.1/22-86	11.4	0.1
AXJ1841.0-0536	1.5	0.6/187-728	13.2	4.9
IGRJ18483-0311	0.8	0.7/215-836	14.7	12.6
XTEJ1739-302	6.6	5.1/1680-6539	11.6	9.1
IGRJ16418-4532	5.1	1.0/326-1269	11.4	2.2

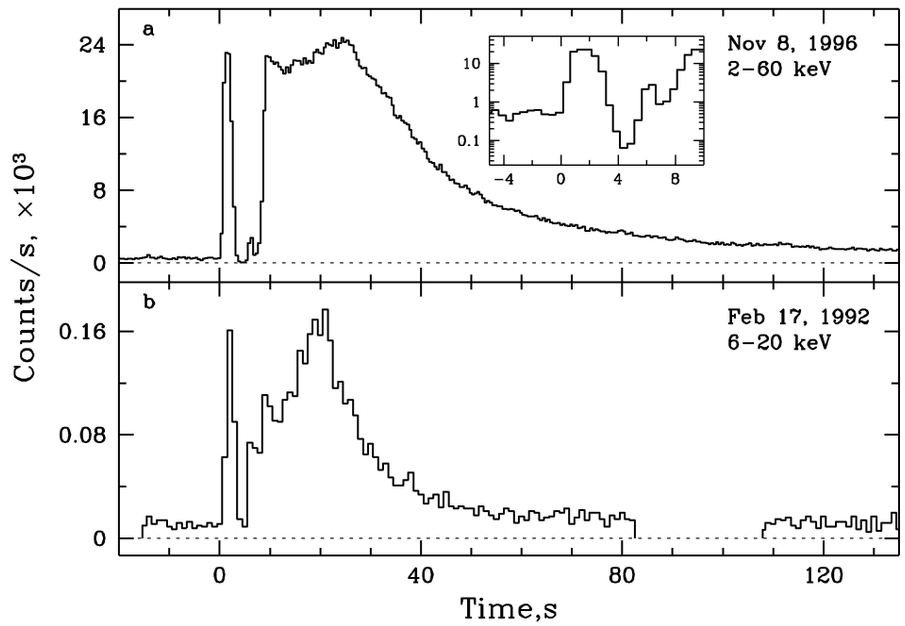
- SFXTs origin is currently unclear, largely because of observational challenges
  - low duty cycles imply these objects are studied with ASMs
- **SXI** has an order of magnitude better sensitivity plus large overall exposure time, so may be able to i**ncrease sample of SFXT flares observed** and refine duty cycle estimates
- Predictions are hard, because we don't know now what happens at low Lx. Extrapolating XRT data **thousands of flares will be detected**
  - those are biased to outburst periods, so that's over-optimistic
- We'll only see that when *Theseus* flies!

Bursts and super bursts



Low Mass X-ray Binary (artist veiw)

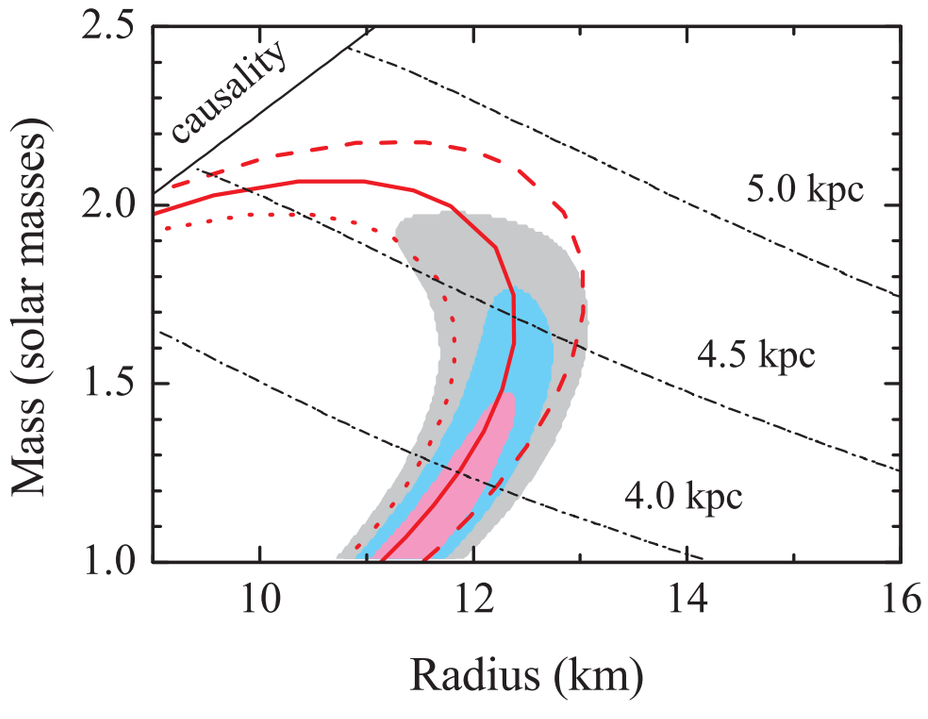
Fig courtesy V. Suleimanov

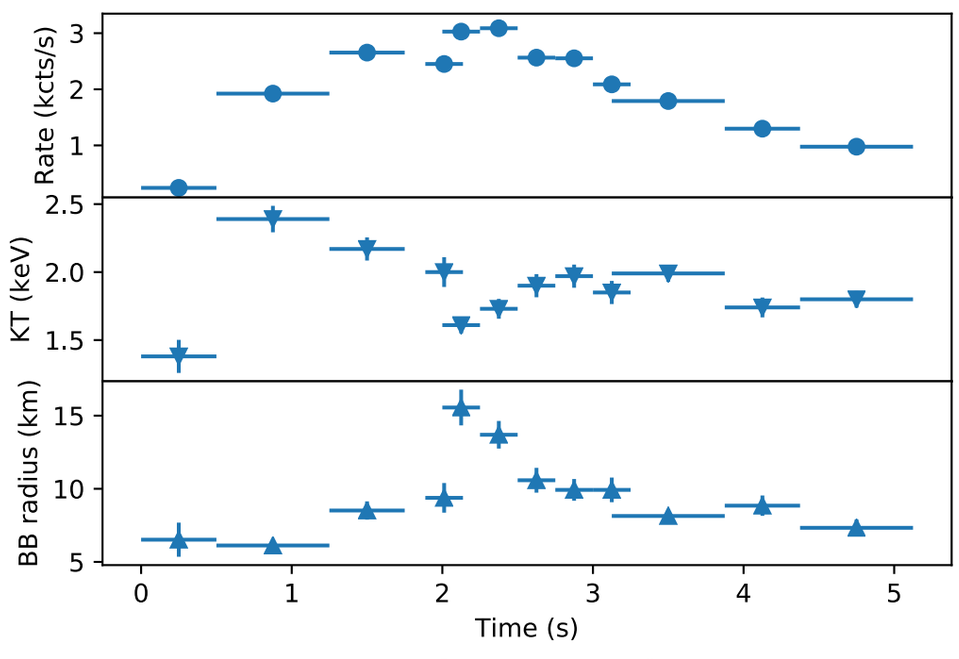


4U 1724-307 in Terzan 2

Figure from Molkov et al (2000)

Cooling tail method to get EOS constrains from bursters





Theseus simulation of a pre-burst

Conclusions

- *Theseus* is not an all-sky monitor if your sources are not “all-sky” like GRBs!
  - This makes it more sensitive than ASMs
  - With some luck, broadband capabilities and comparatively high sensitivity will allow detailed studies of bright sources with *Theseus* alone, but probably eXTP/WFM + pointed observations are more suitable for that
  - Same probably applies to BHTs (Maria’s talk)
- Most suitable to study variability on short timescales in fainter sources. For XRBs this means that strong *Theseus* side is mainly (not exclusively)
  - For HMXBs:
    - variability of BeXRBs in quiescence
    - in particular, SFXTs are of interest: duty cycles and burst spectroscopy
    - detection of outbursts in MC BeXRBs (essentially all of them)
    - Monitoring of variability in ULXs to find pULX candidates
  - For LMXBs:
    - Transitional millisecond pulsars (Domitilla talk)
    - detection and time-resolved spectroscopy of bursts and super-bursts
    - Characterisation of VFXT population
- Last but not least: while *Theseus* will operate in parallel to eXTP where WFM is quite similar to XGIS for Galactic science. Both will, however, be complementary rather than competing due to different observing strategy