Recent X-ray observations of three high-mass gamma-ray binaries

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Variable Galactic Gamma-ray Sources V
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1. PSR B1259-63/LS 2883

PSR B1259-63: Spin period **48 ms**, spin-down age **330 kyr**,
Edot =**8×10^{35} erg/s**, B=**3×10^{11} G**

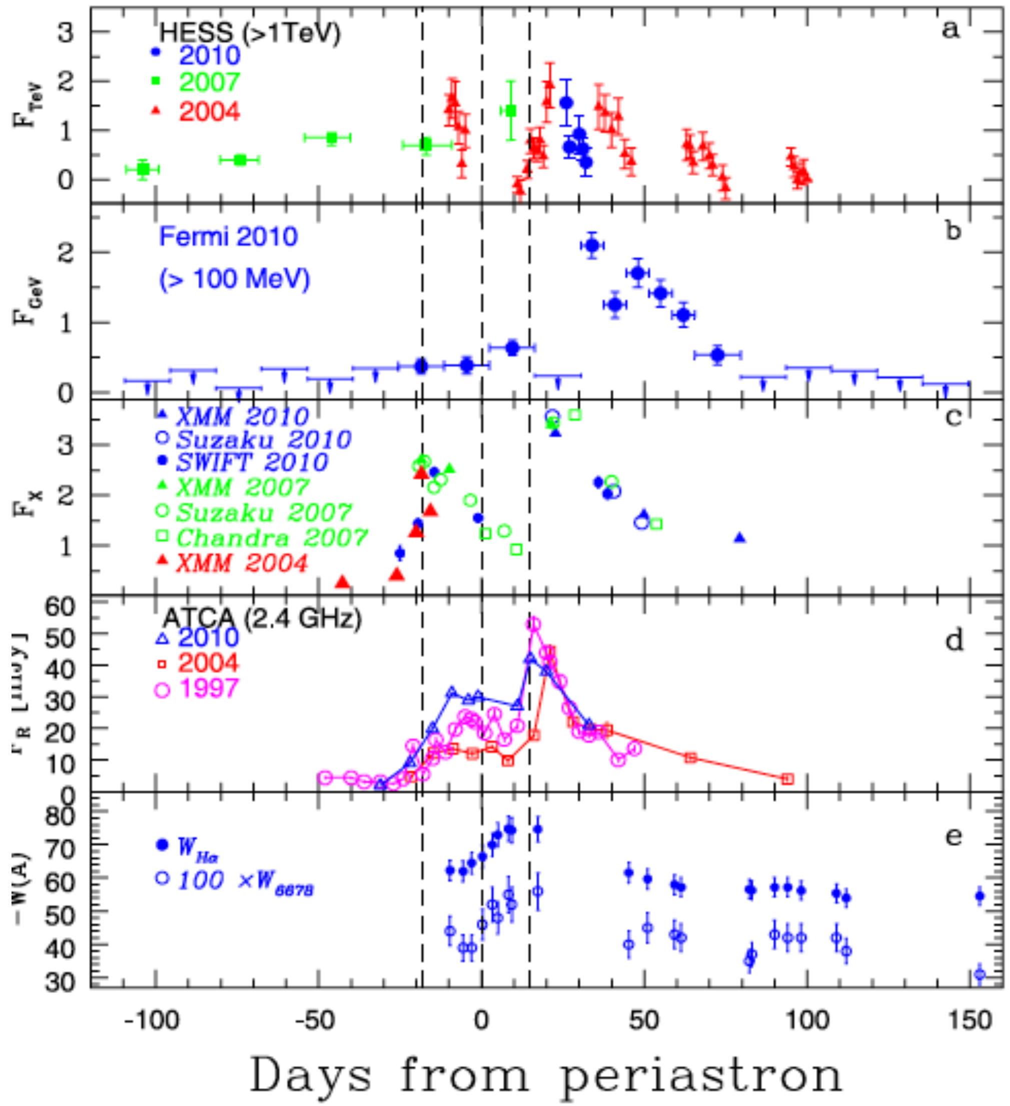
LS 2883: M = **15 – 31 $M_\odot$**, L = **6×10^4 $L_\odot$**, d = **2.6 kpc**, fast-spinning Be (late O) star, stellar wind dense and slow in the **equatorial disk**, tenuous and fast outside the disk

Binary parameters: Orbital period **3.4 yrs**, semi-major axis **6 au** (3 mas), eccentricity **0.87**, inclination **153°**

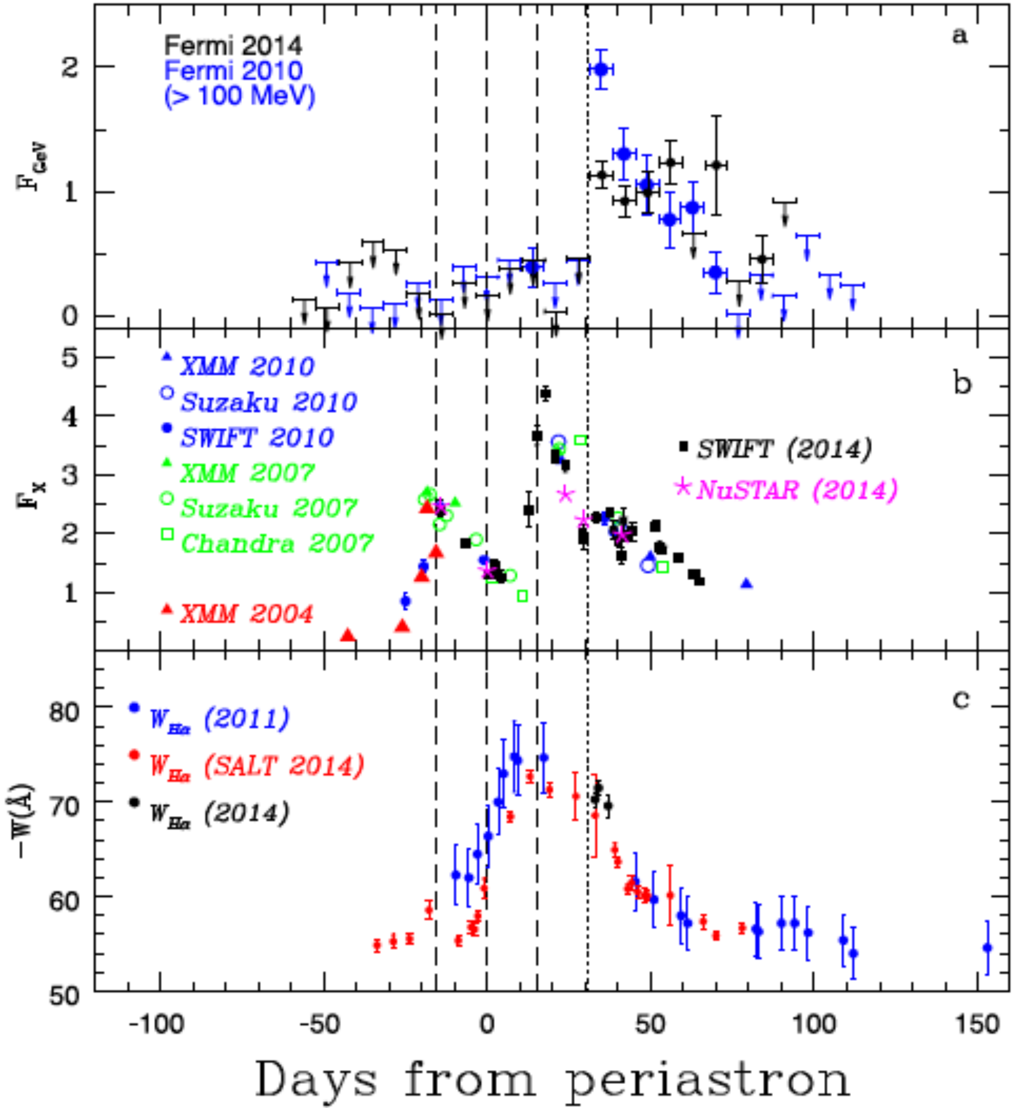
Collision of pulsar wind with stellar wind ➔intrabinary shock ➔ particle acceleration ➔ nonthermal emission from radio to gamma-rays

Multiwavelength emission shows peculiarities around periastrons, when the pulsar crosses the equatorial disk inclined at 35^o to the orbital plane

Periastrons 2004, 2007, 2010 (Chernyakova et al 2014)

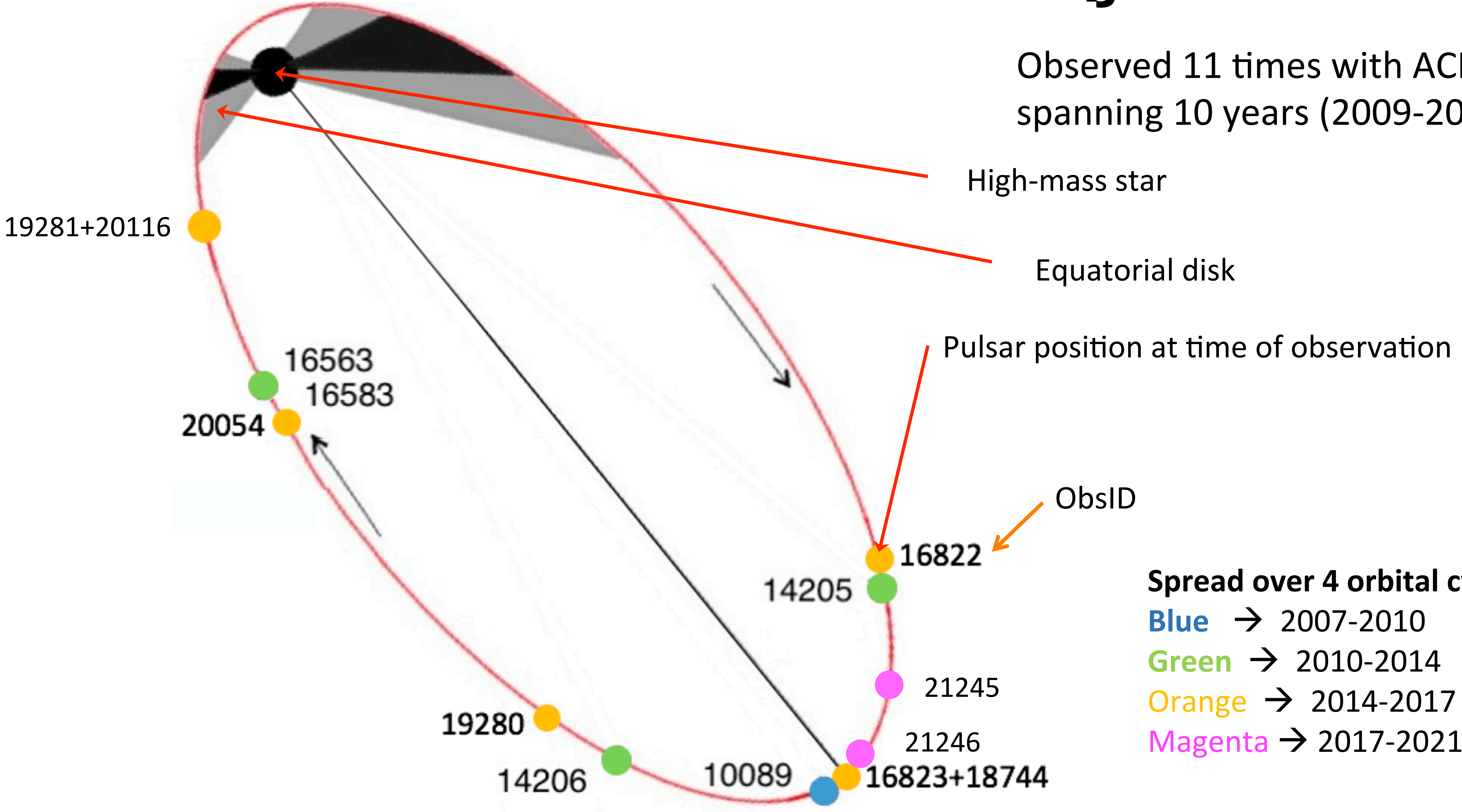


Periastrons of 2007, 2010, 2014 (Chernyakova et al 2015)



Chandra Monitoring

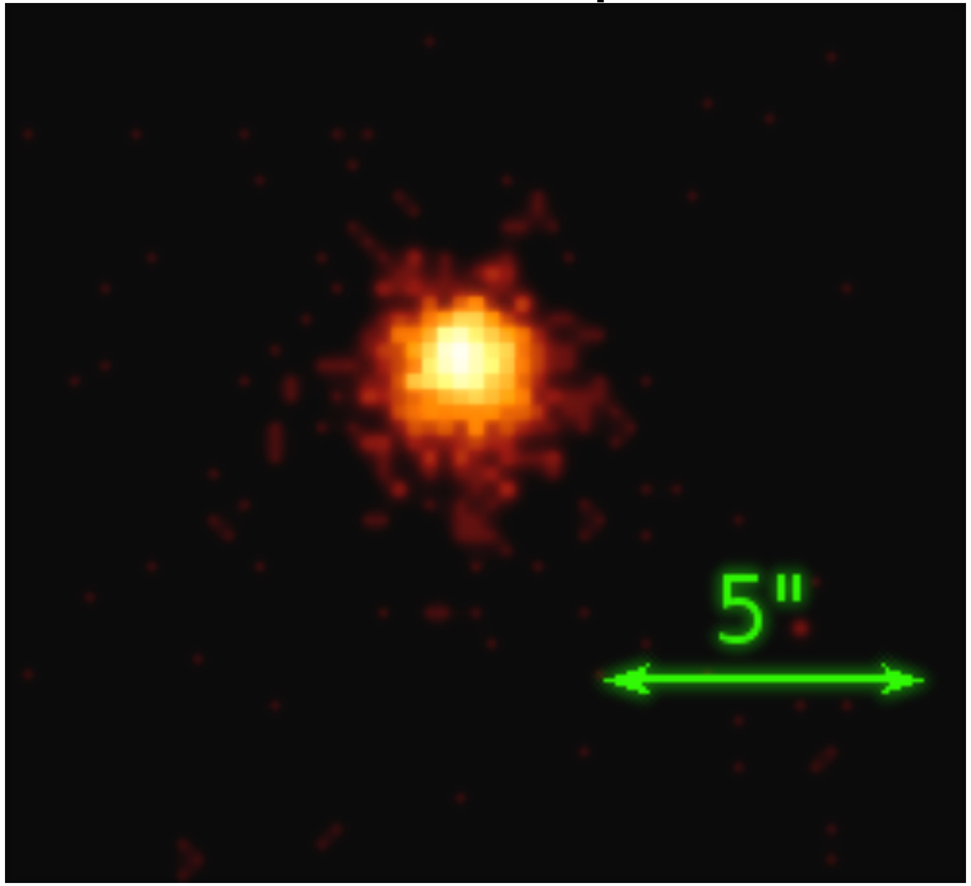
Observed 11 times with ACIS-I, spanning 10 years (2009-2019)



Spread over 4 orbital cycles:
Blue → 2007-2010
Green → 2010-2014
Orange → 2014-2017
Magenta → 2017-2021

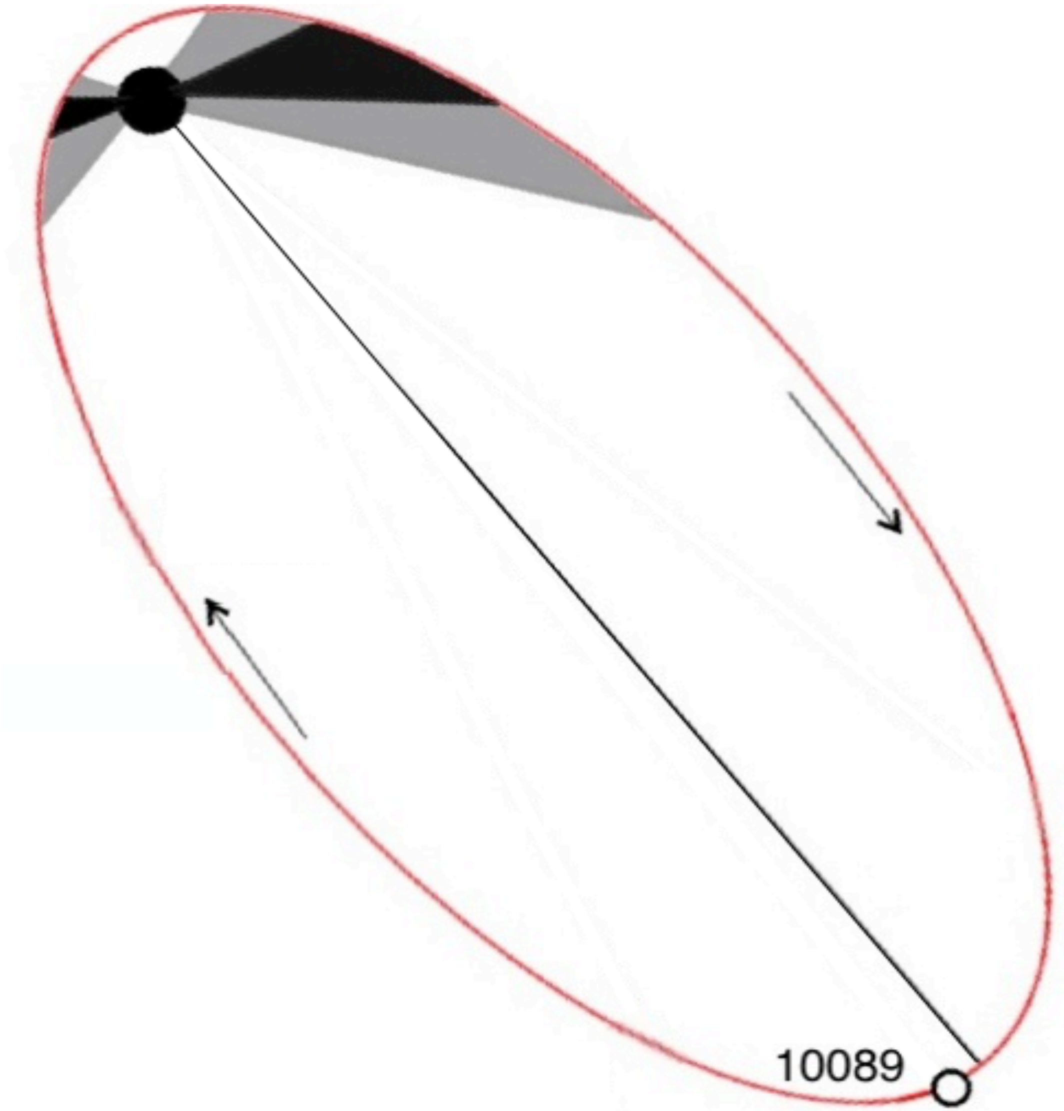
2009 May 14

25 ks ACIS-I exposure



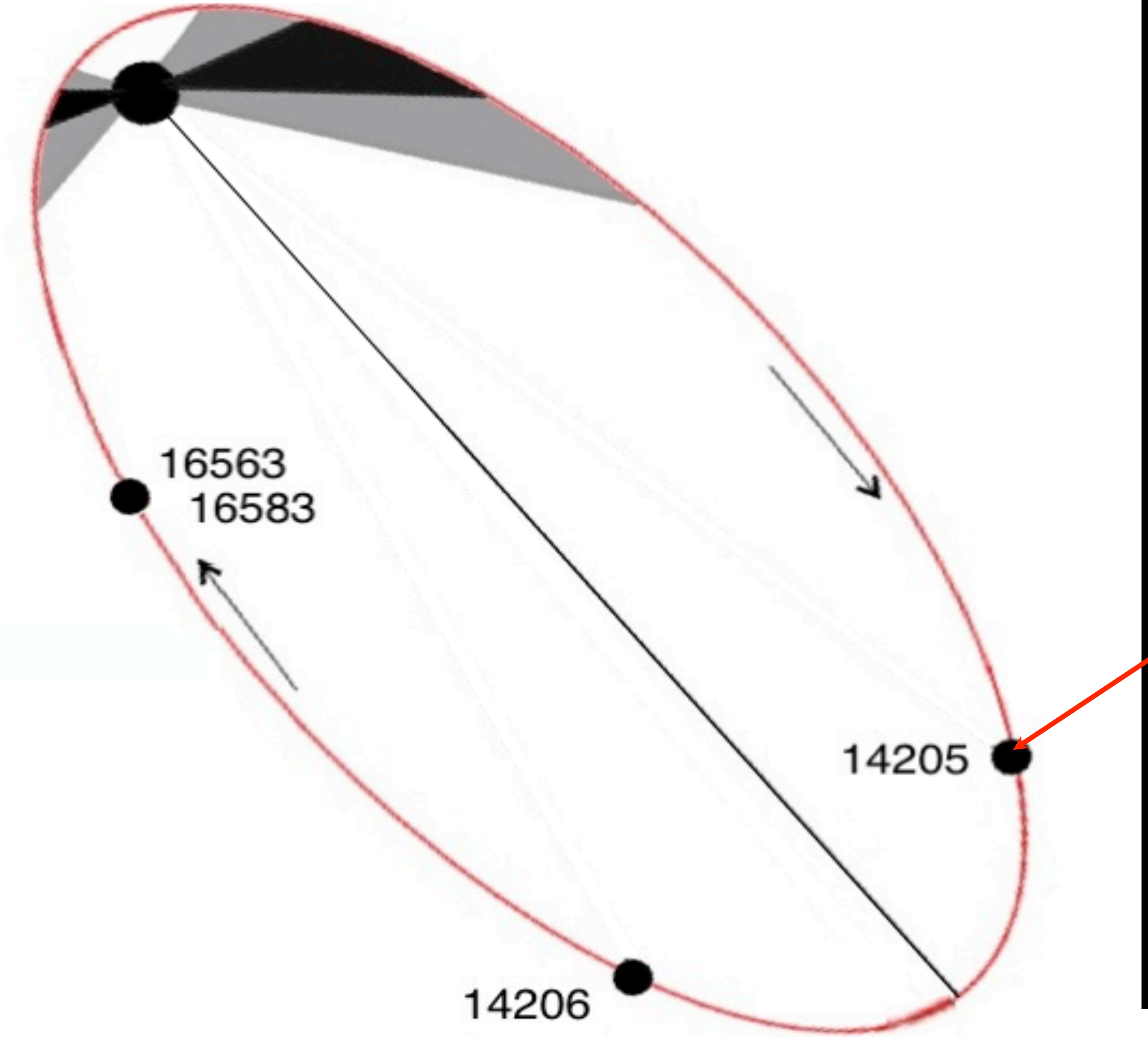
(Pavlov et al 2011)

~4σ detection of asymmetric extended emission. Termination shock of PW?

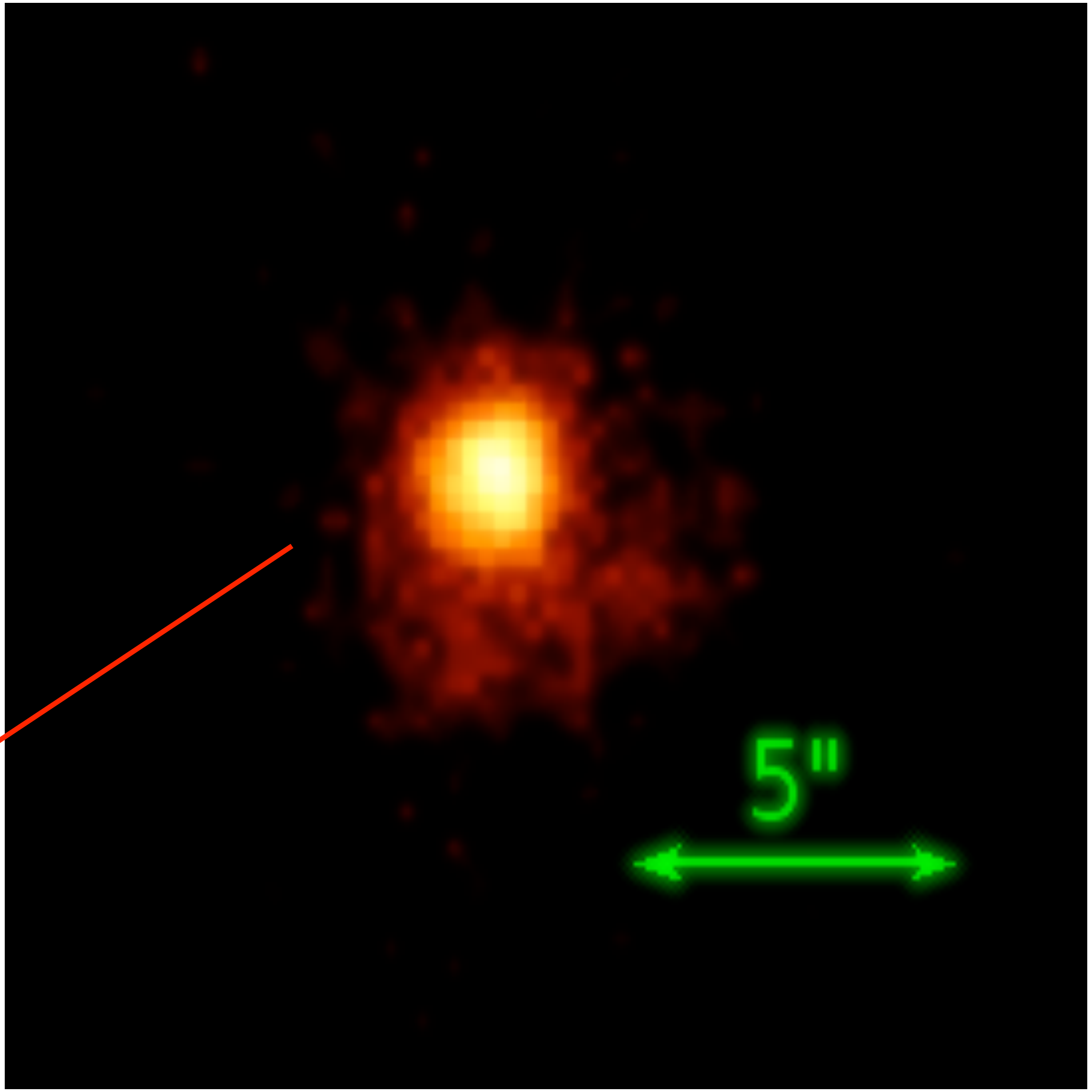


Three observations in 2011 - 2014

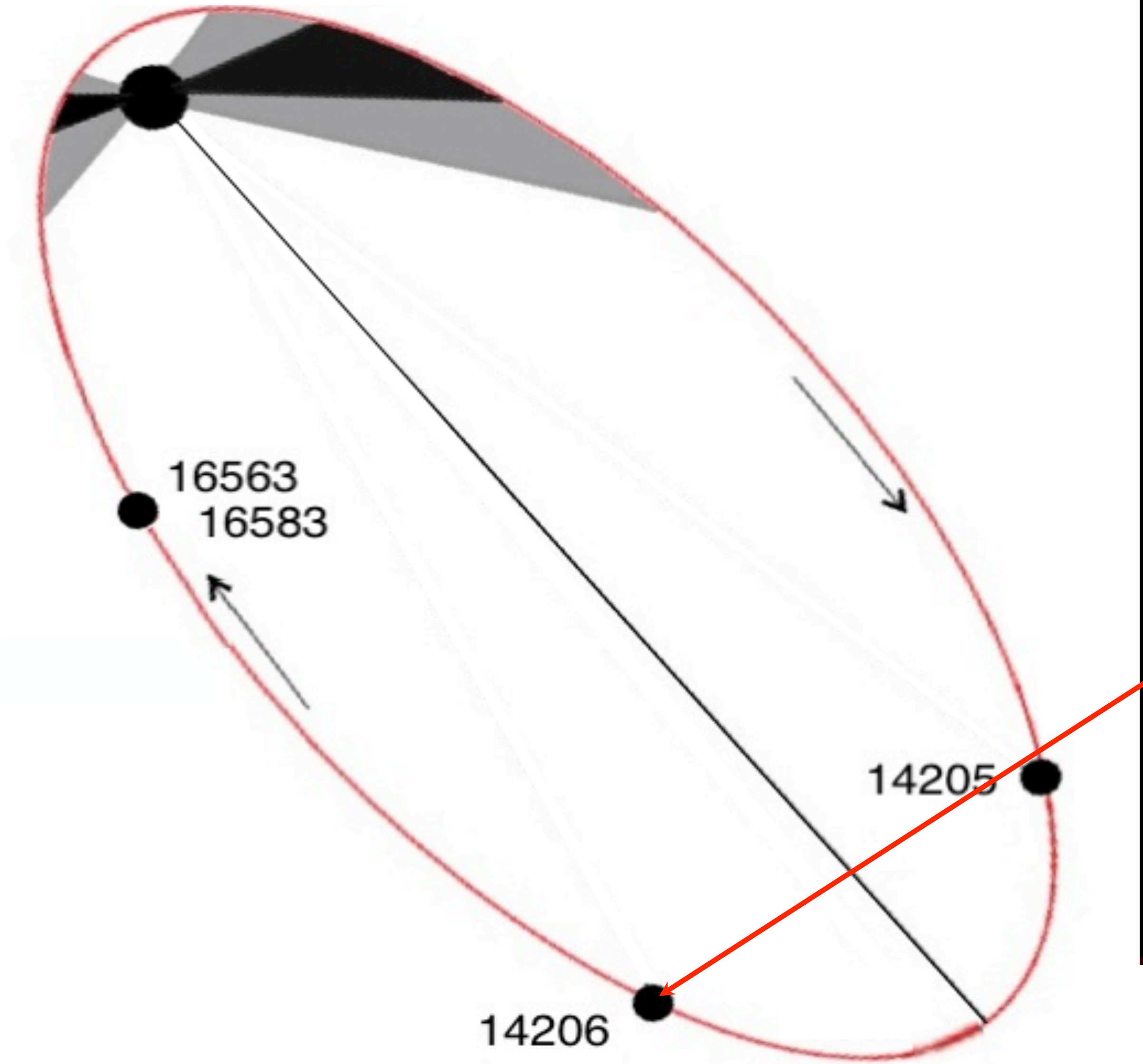
~60 ks exposures



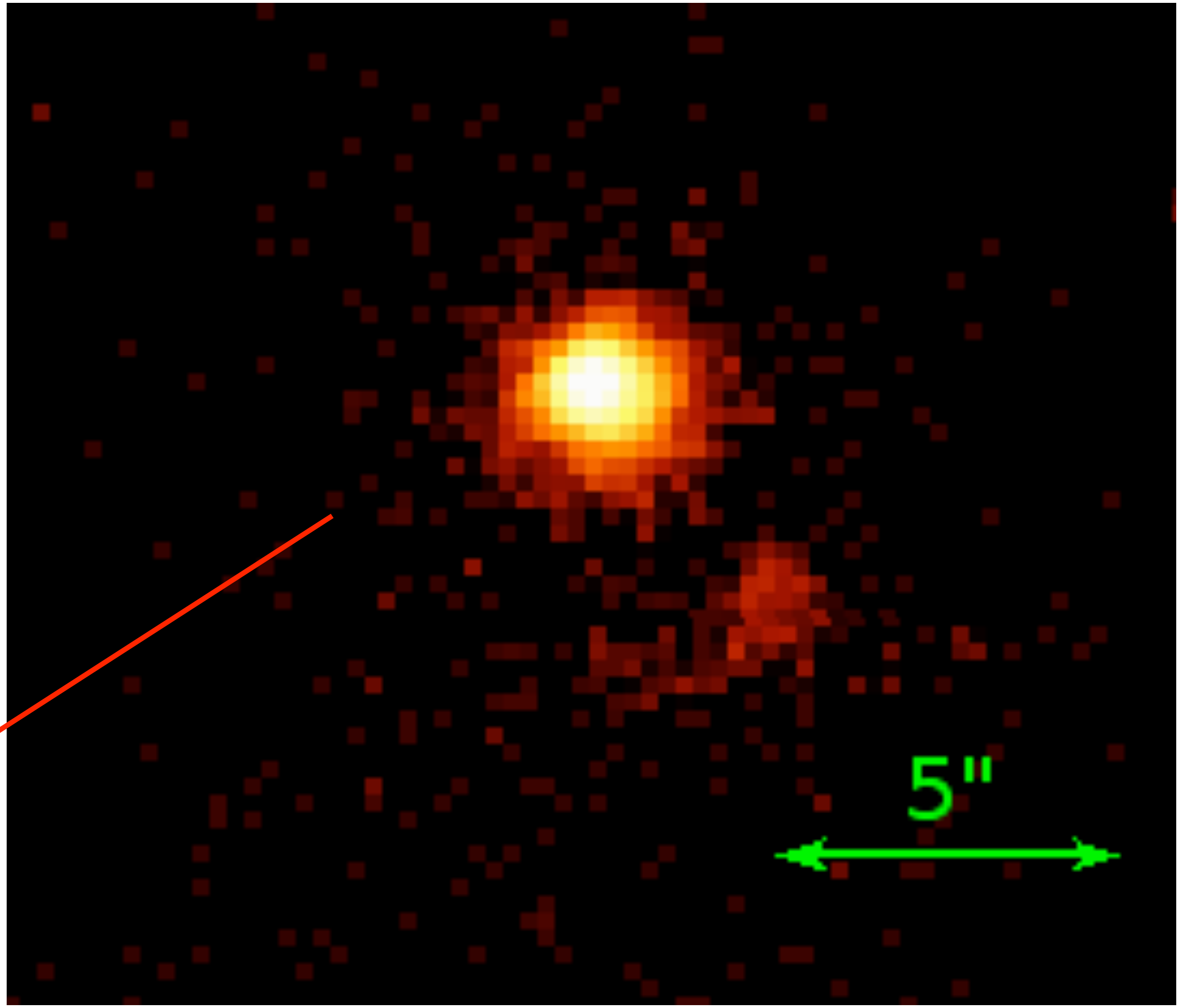
2011 Dec 17



Three observations in 2011 - 2014



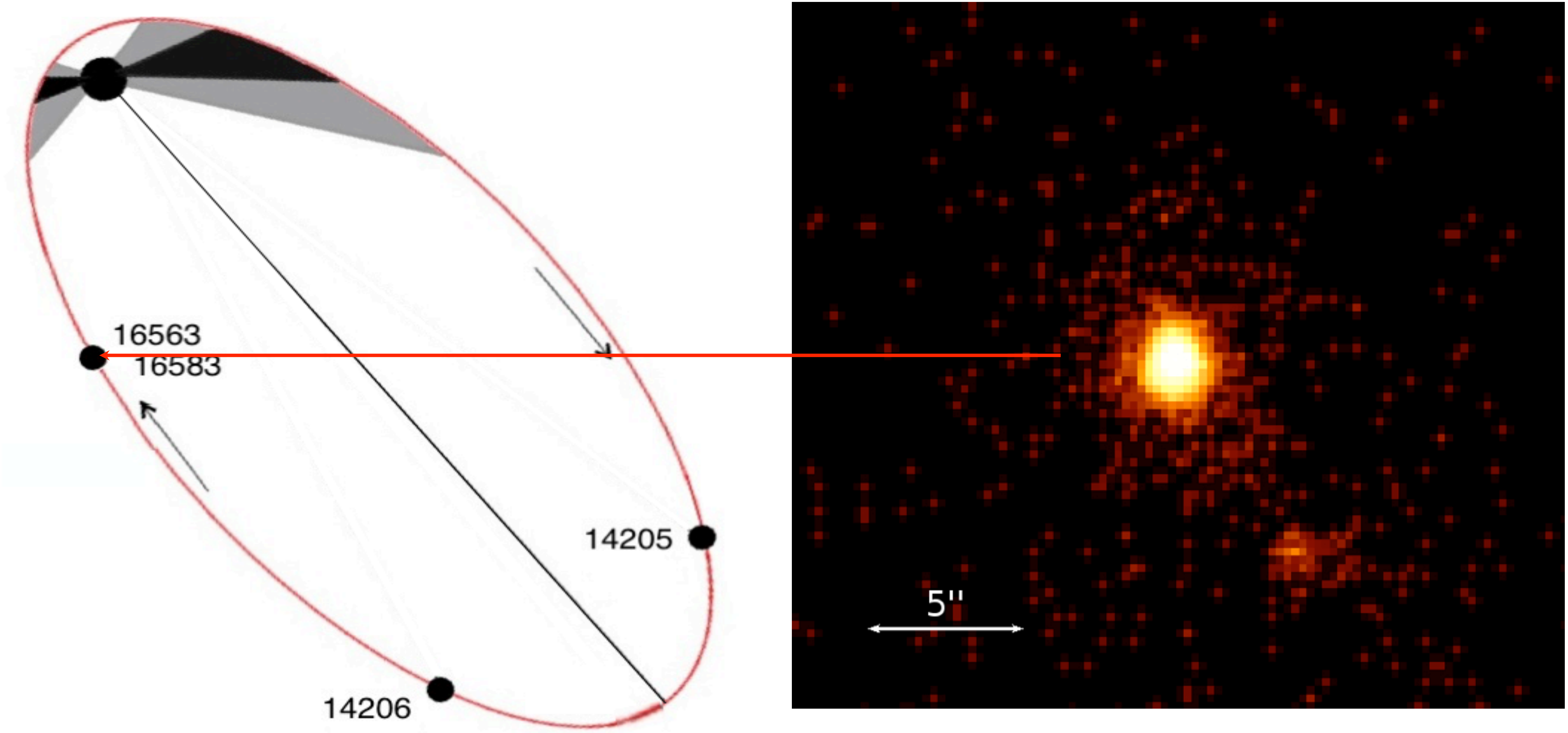
2013 May 19

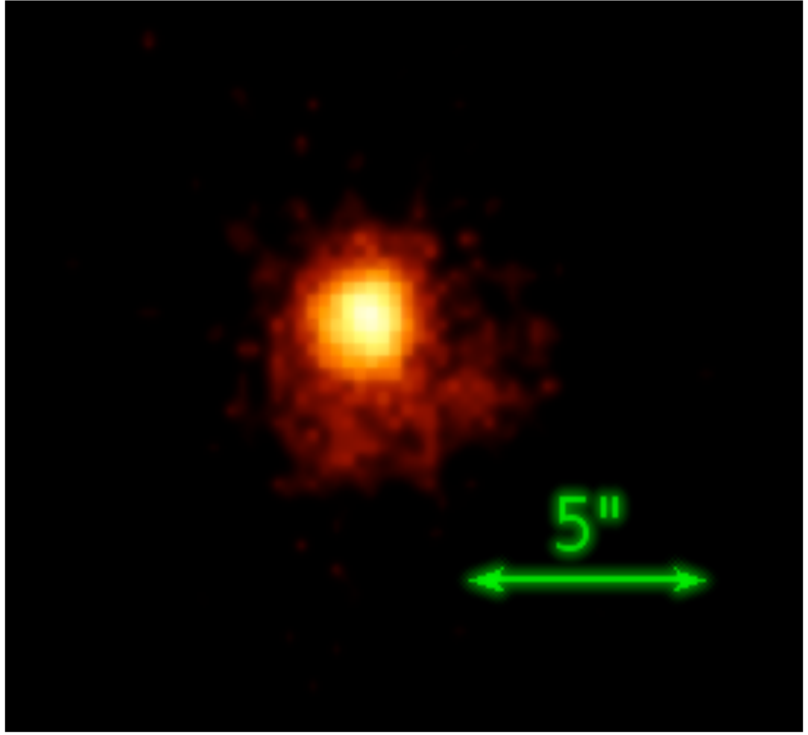


Three observations in 2011 - 2014

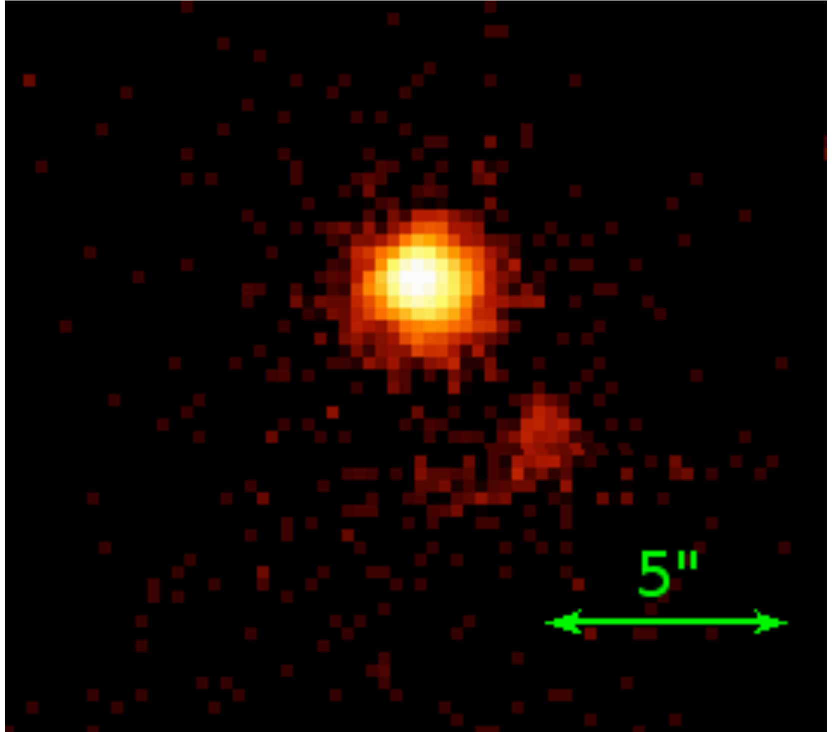
The blob is moving!

2014 Feb 8

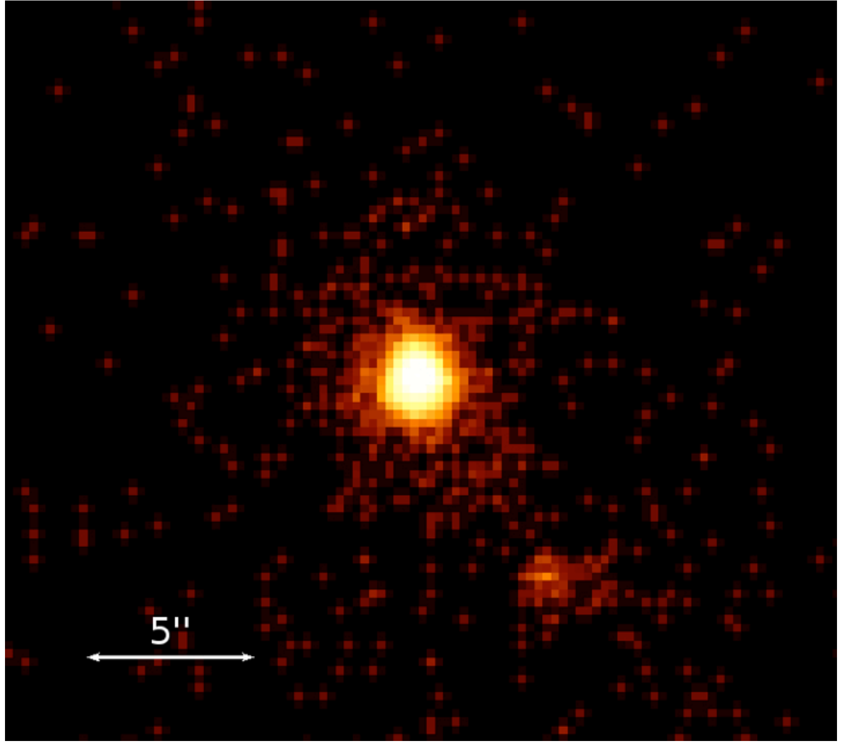




2011 Dec 17



2013 May 19



2014 Feb 8

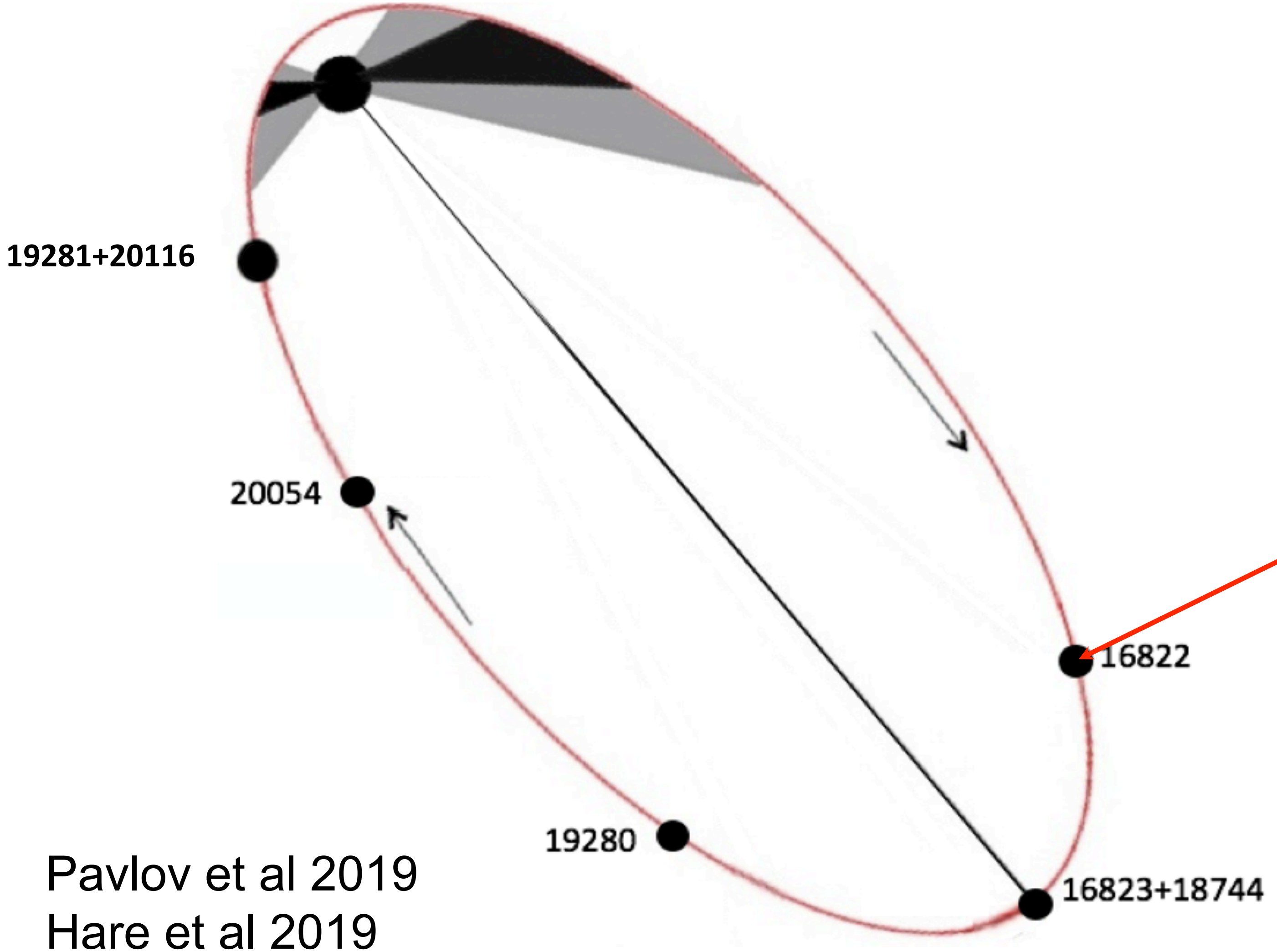
Extended ‘clump’ is moving from the binary along its major axis and fading .

High apparent velocity, ~0.1 c, perhaps with acceleration. No evidence of deceleration.

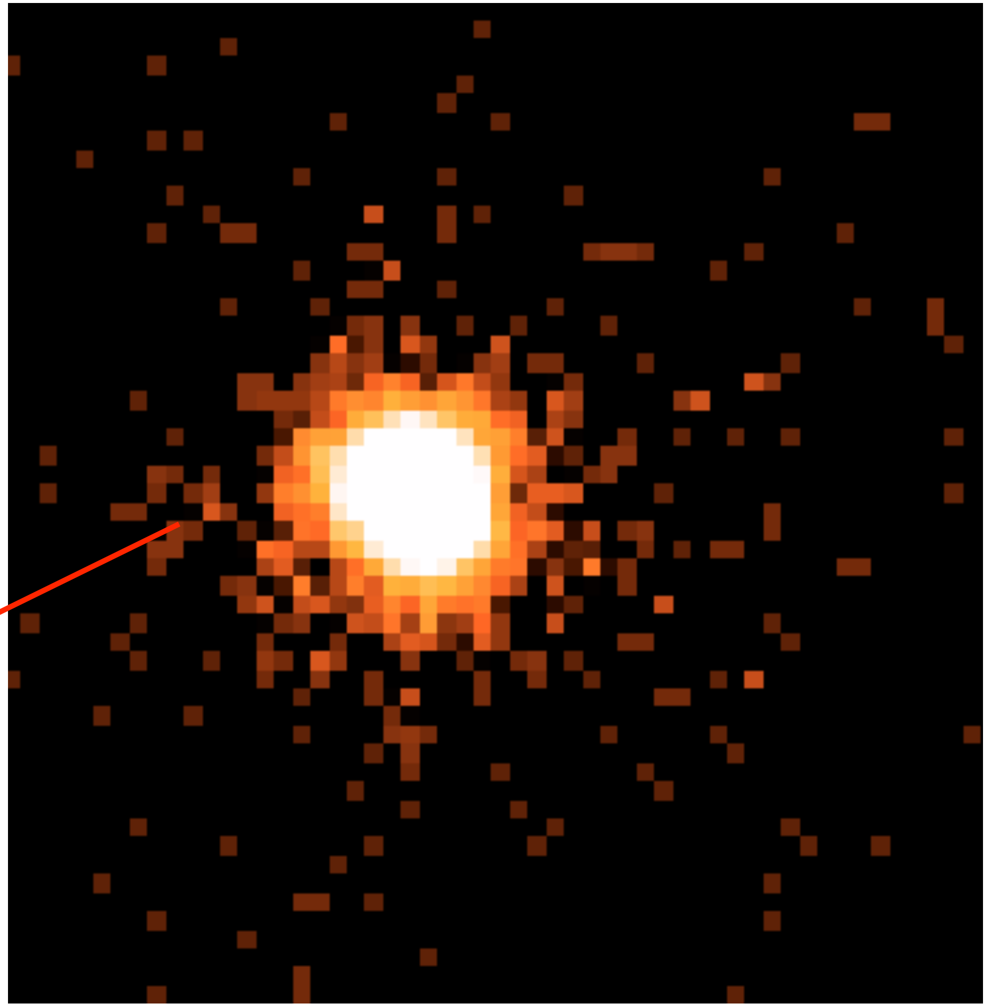
(Kargaltsev et al. 2014; Pavlov et al. 2015)

Five observations in the next binary cycle: Apr 2015 – Jul 2017

ACIS-I exposures 60-65 ks

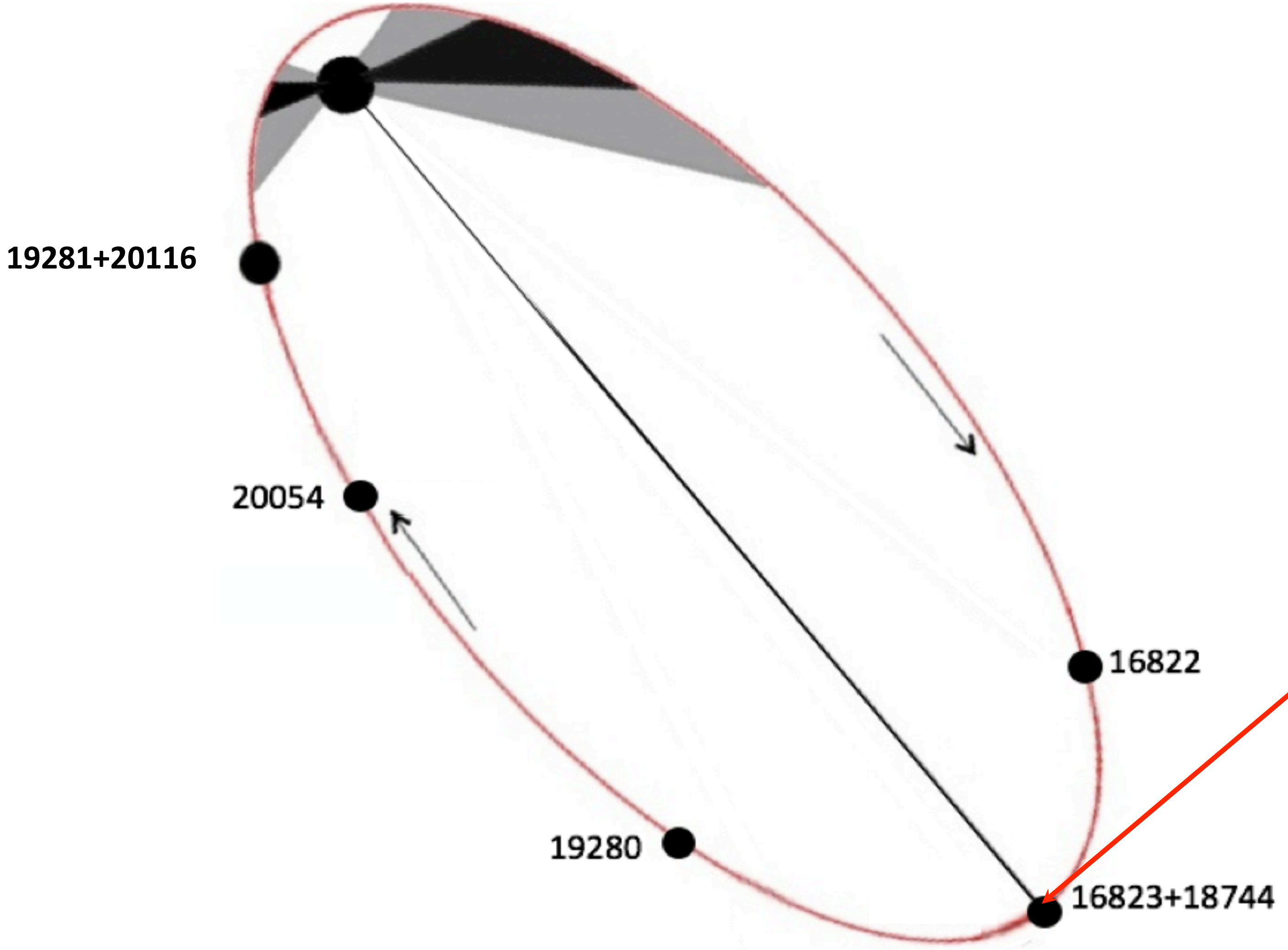


2015 Apr 21

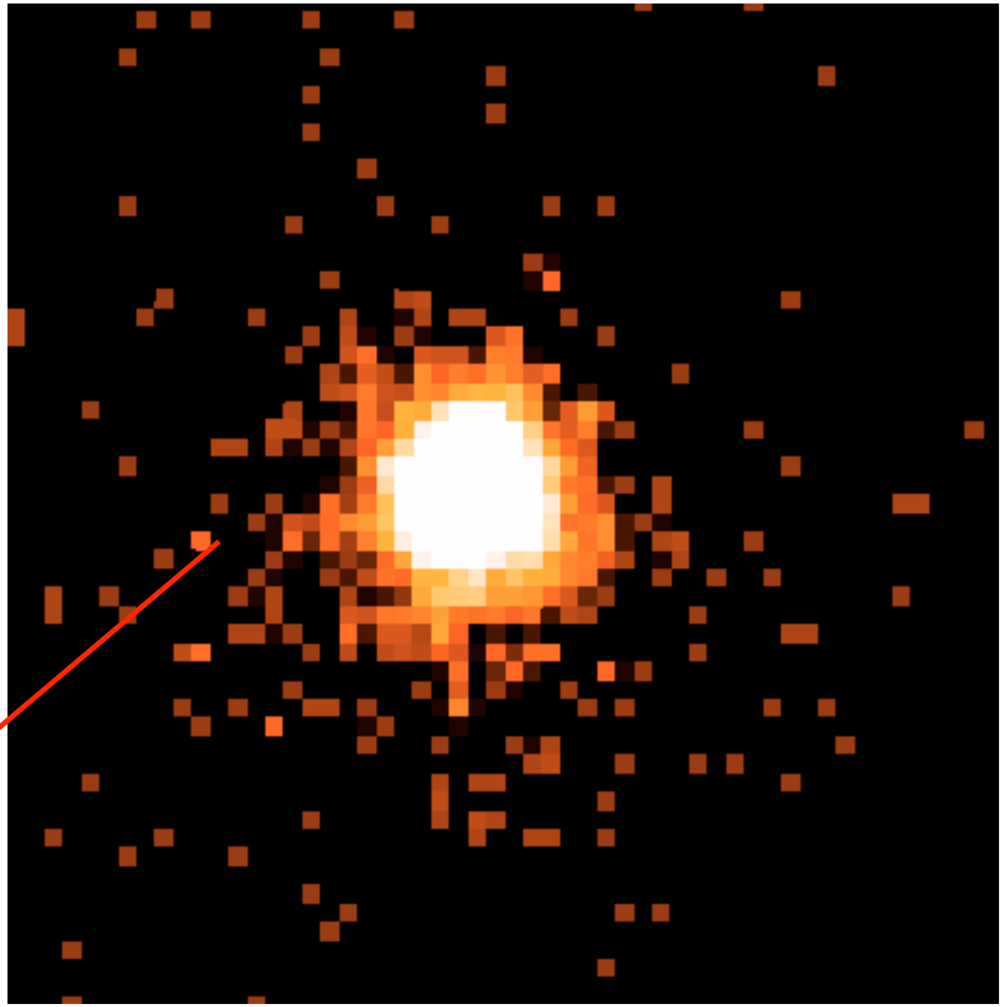


Pavlov et al 2019
Hare et al 2019

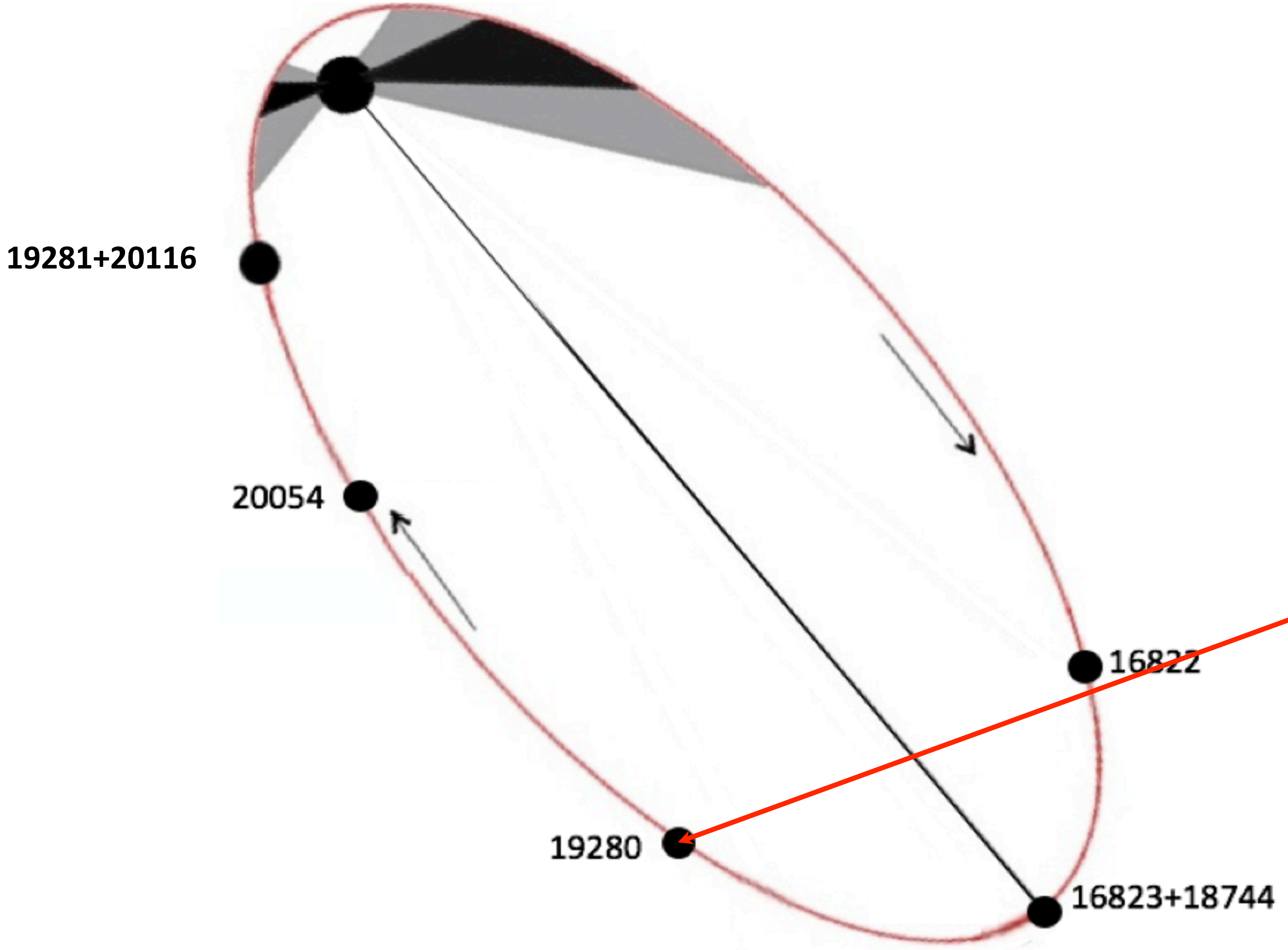
Five observations in the next binary cycle: Apr 2015 – Jul 2017



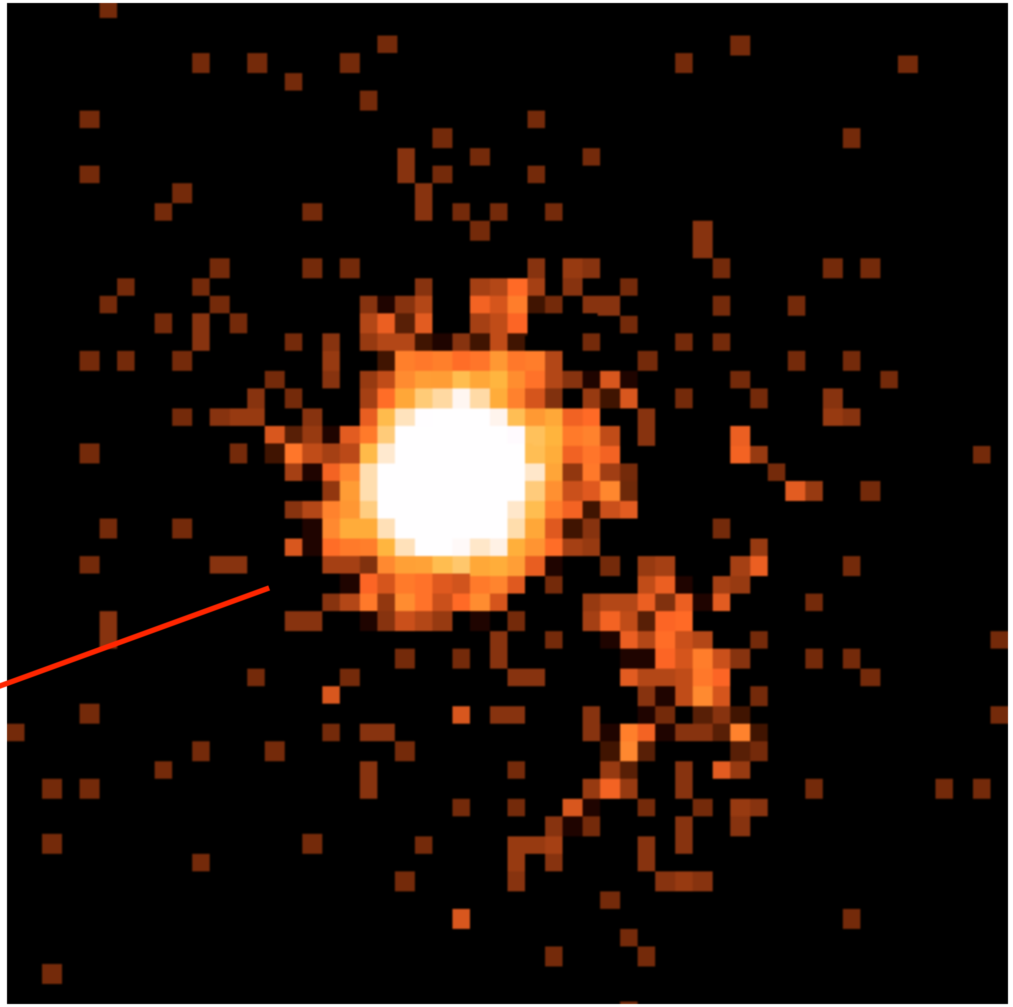
2016 Jan 12



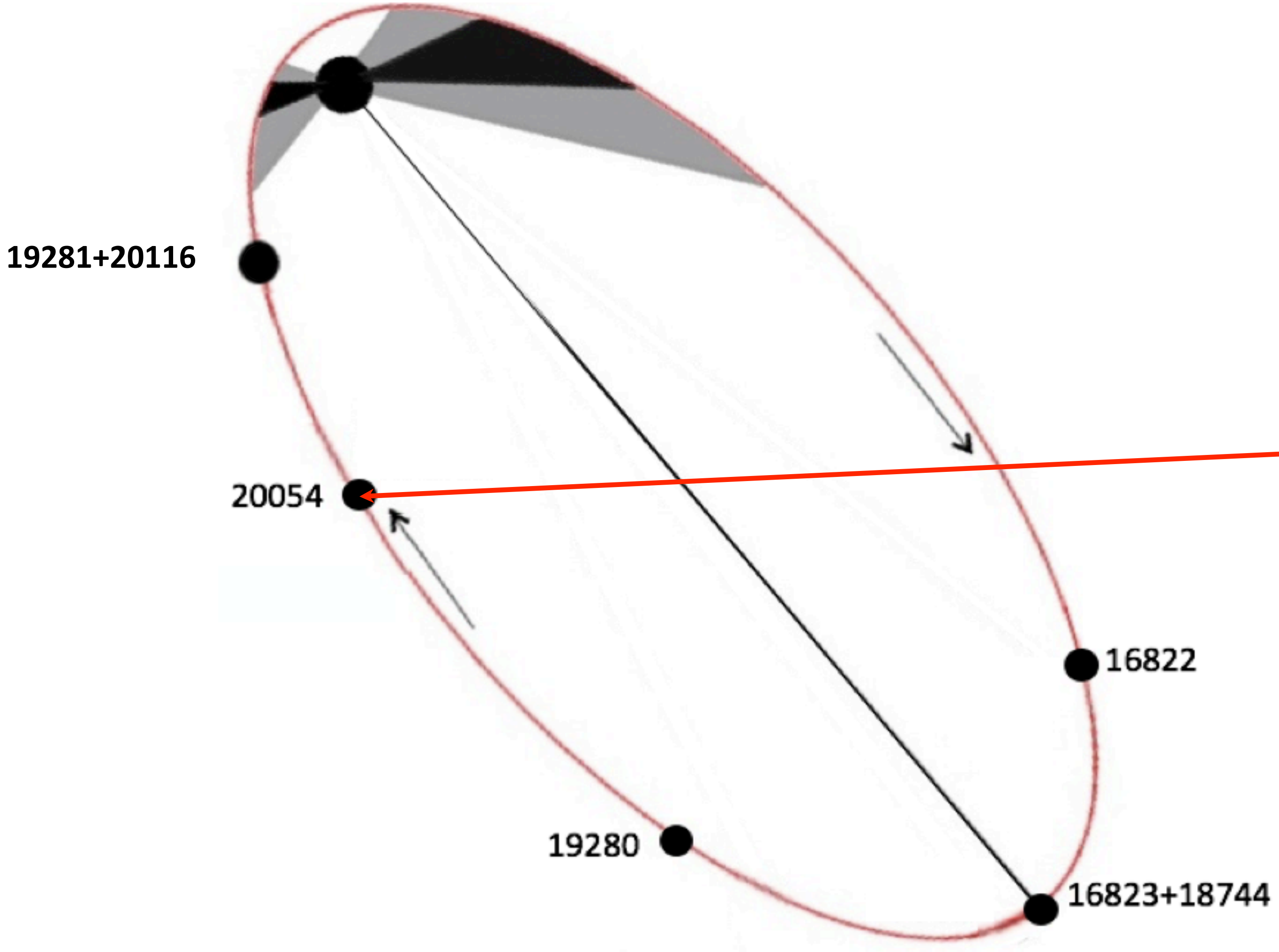
Five observations in the next binary cycle: Apr 2015 – Jul 2017



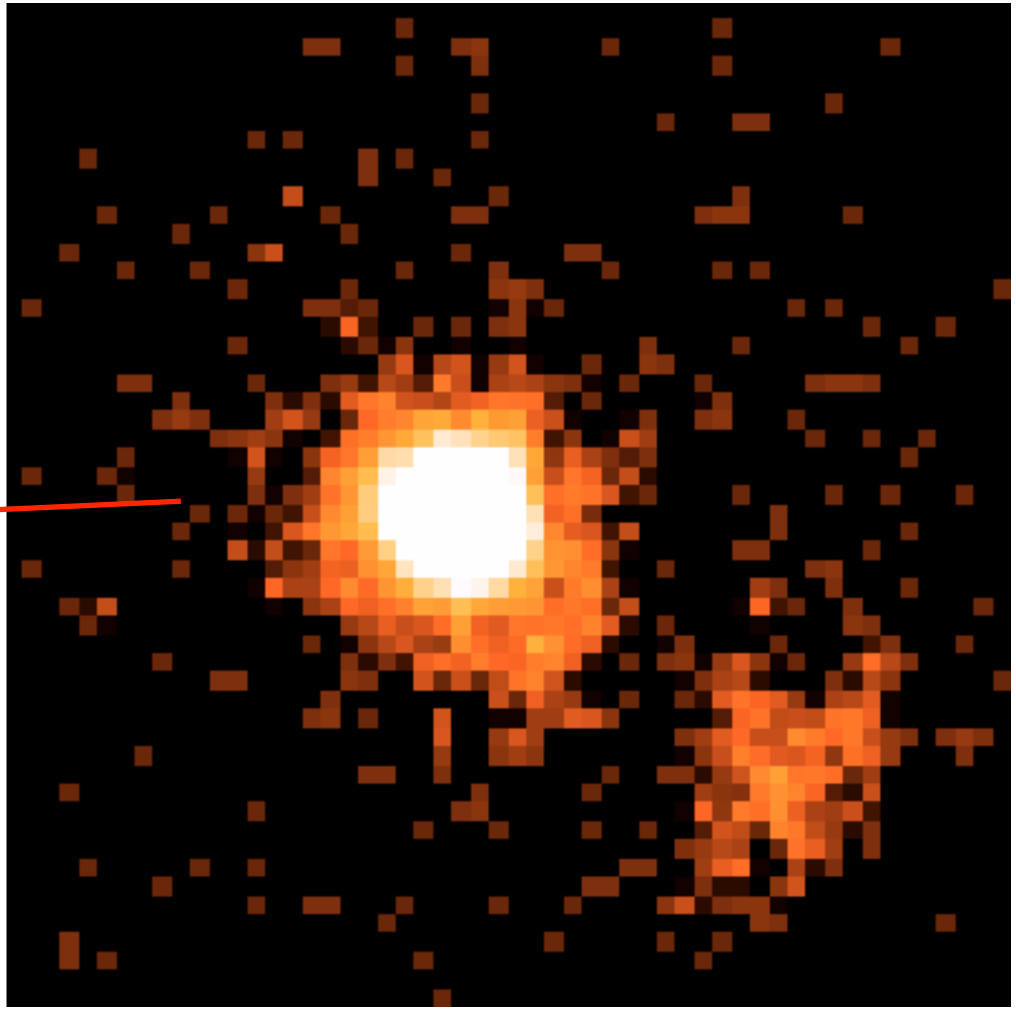
2017 Jan 6



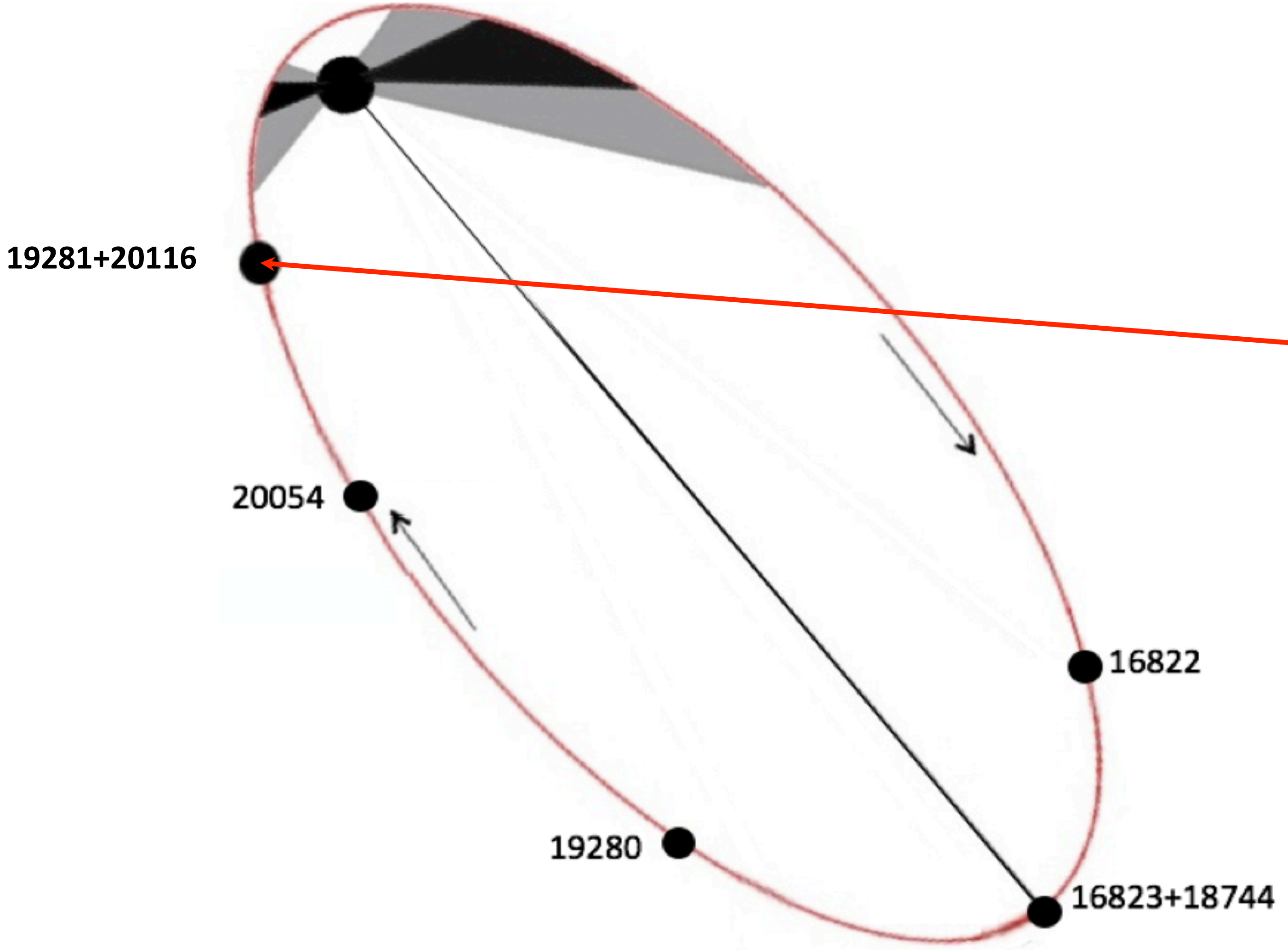
Five observations in the next binary cycle: Apr 2015 – Jul 2017



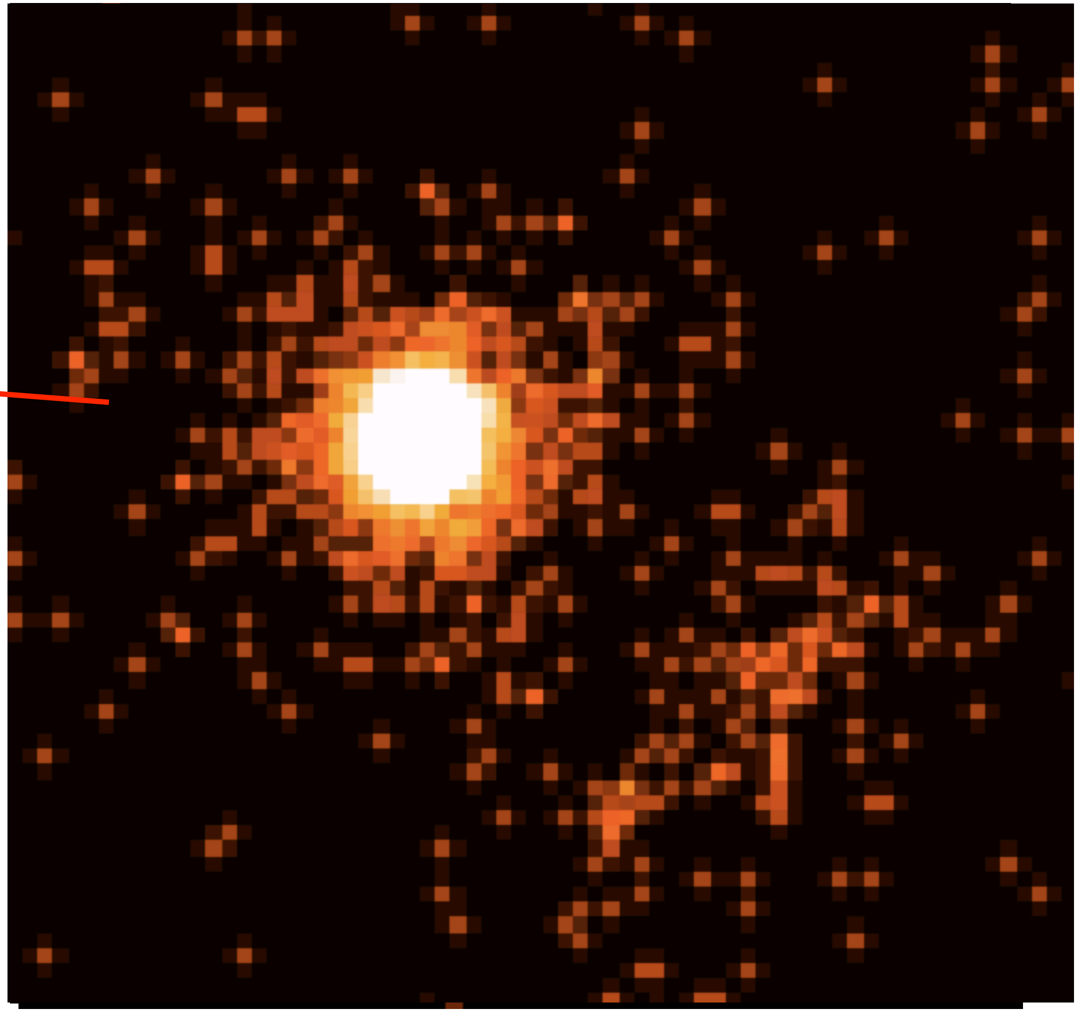
2017 Apr 24



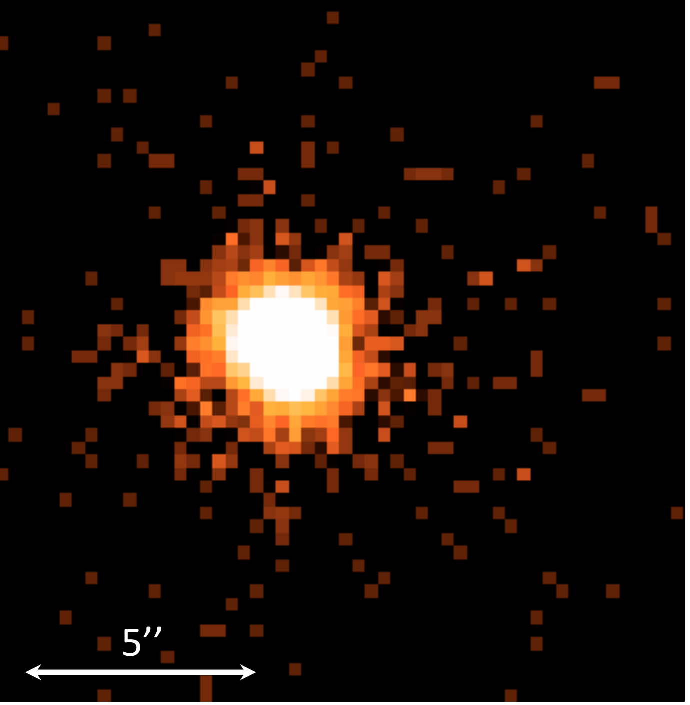
Five observations in the next binary cycle: Apr 2015 – Jul 2017



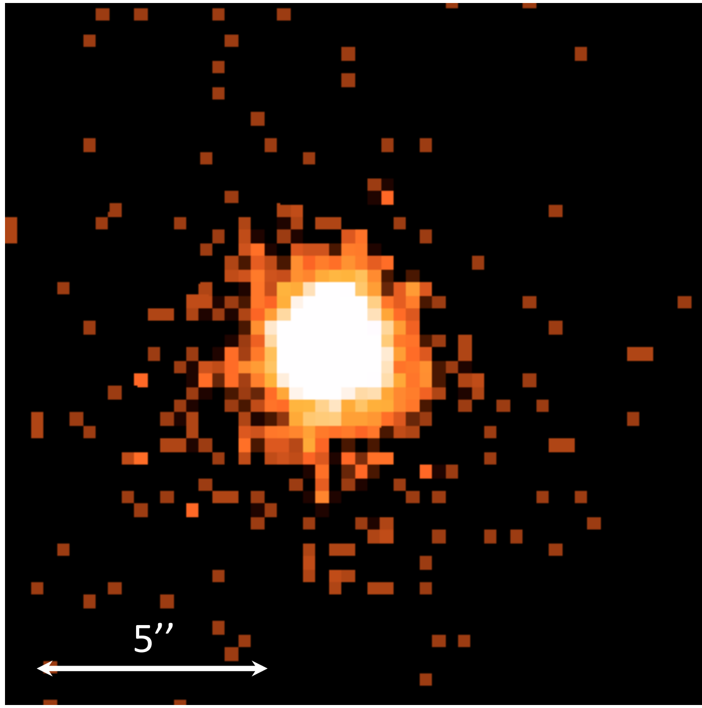
2017 Jul 20



2015 Apr 21



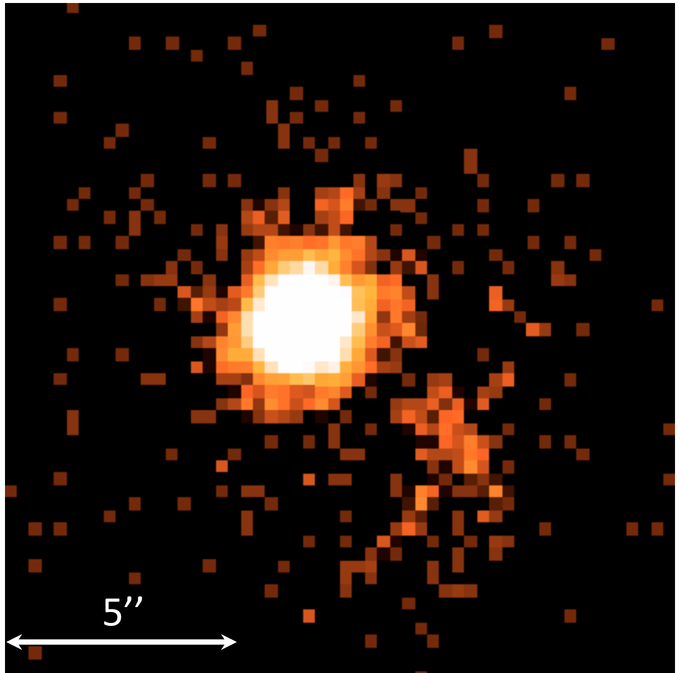
2016 Jan 12



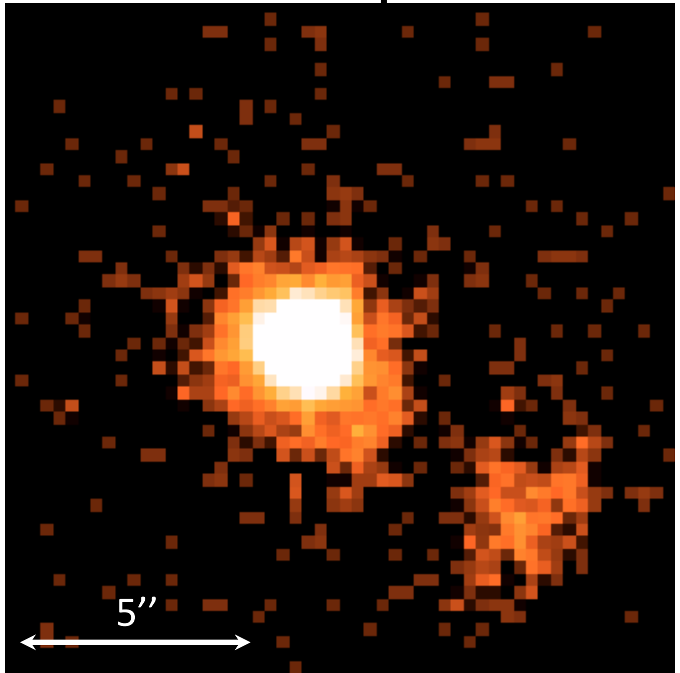
New clump detected moving in same direction with similar velocity

Shows strange “whiskers” in Jan 2017, brightening and 2nd clump [?] in Apr 2017

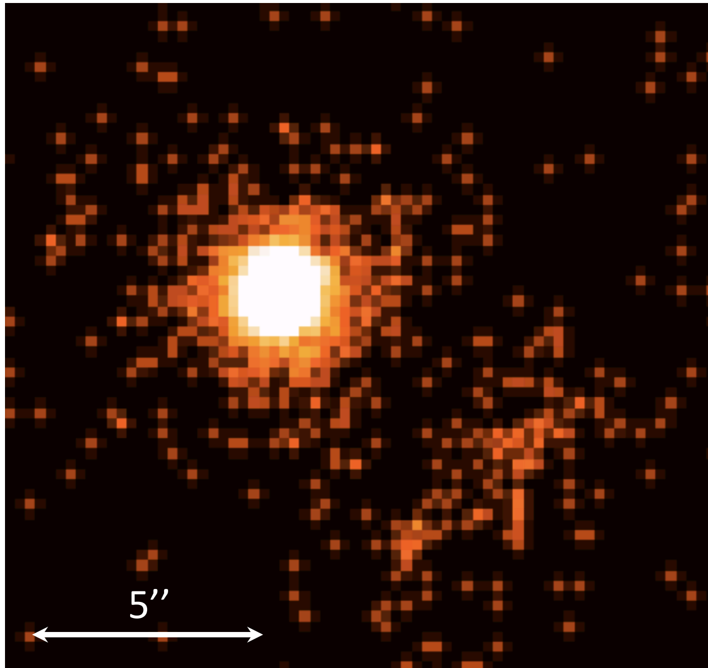
2017 Jan 6



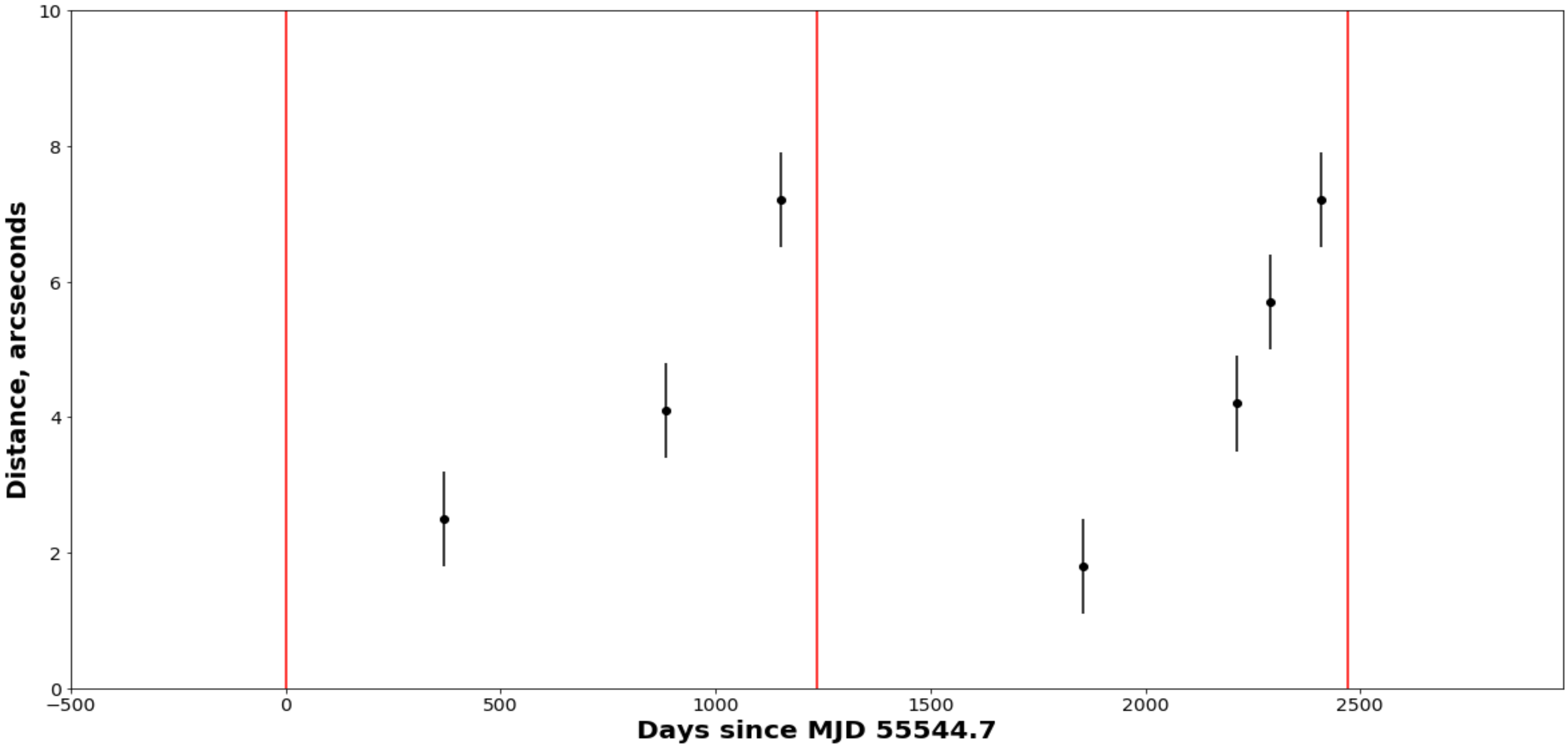
2017 Apr 24



2017 Jul 20



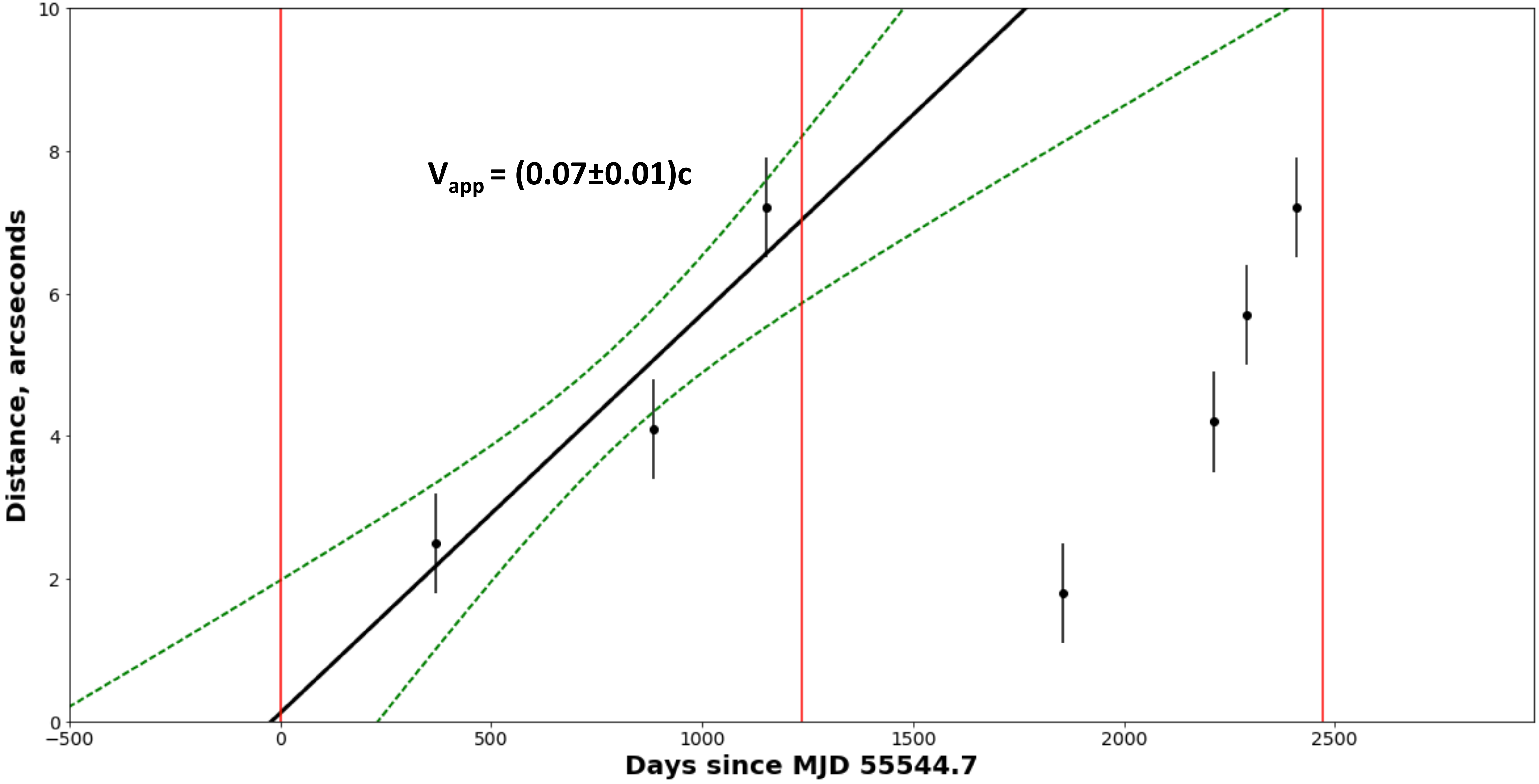
Clump separation from the binary vs time.



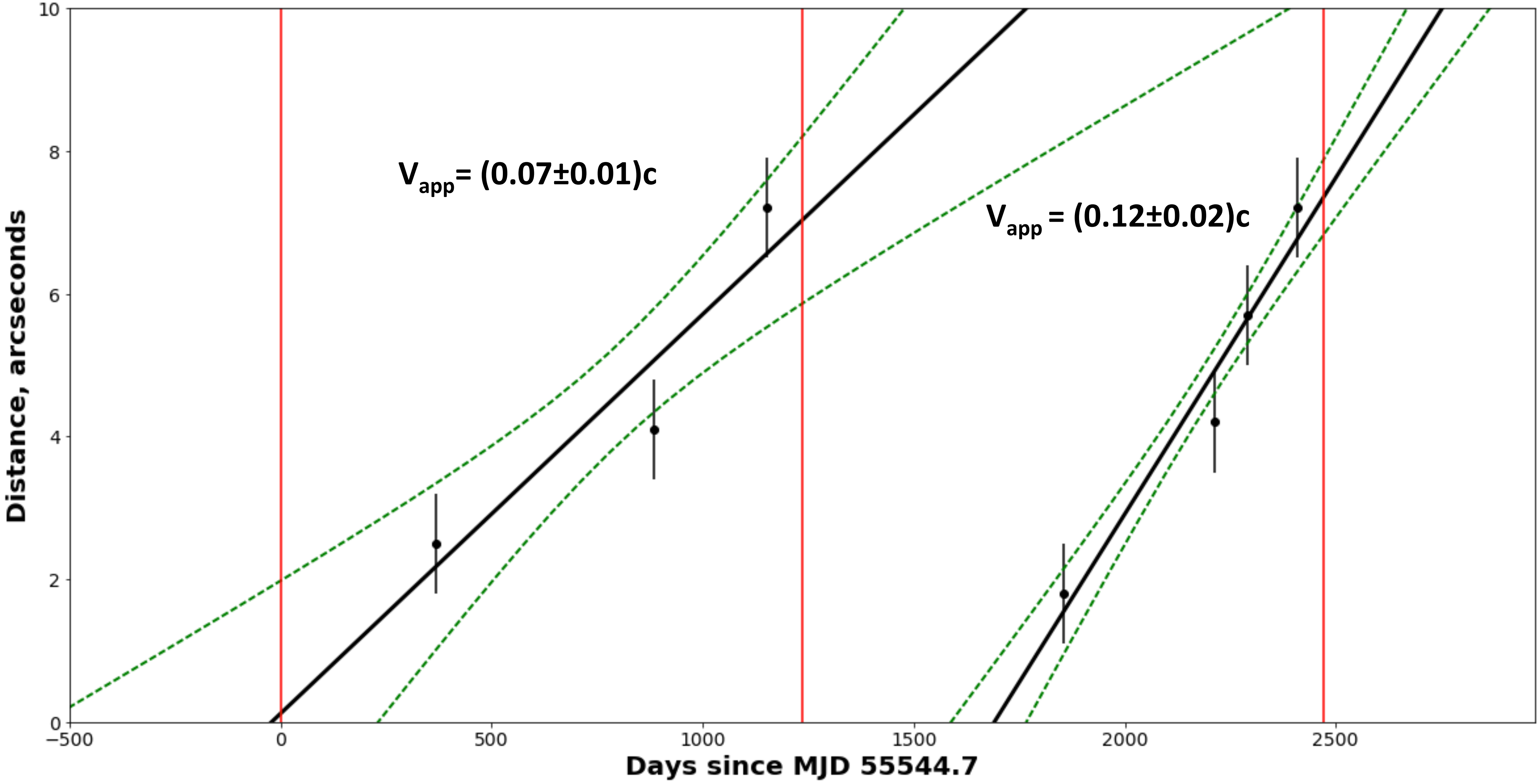
1 arcsec = 3.4×10^{16} cm

Characteristic size of the "clump" ≈ **3"≈ 10^{17} cm**

Clump separation from the binary vs time.



Clump separation from the binary vs time.



Accelerated motion: a better model

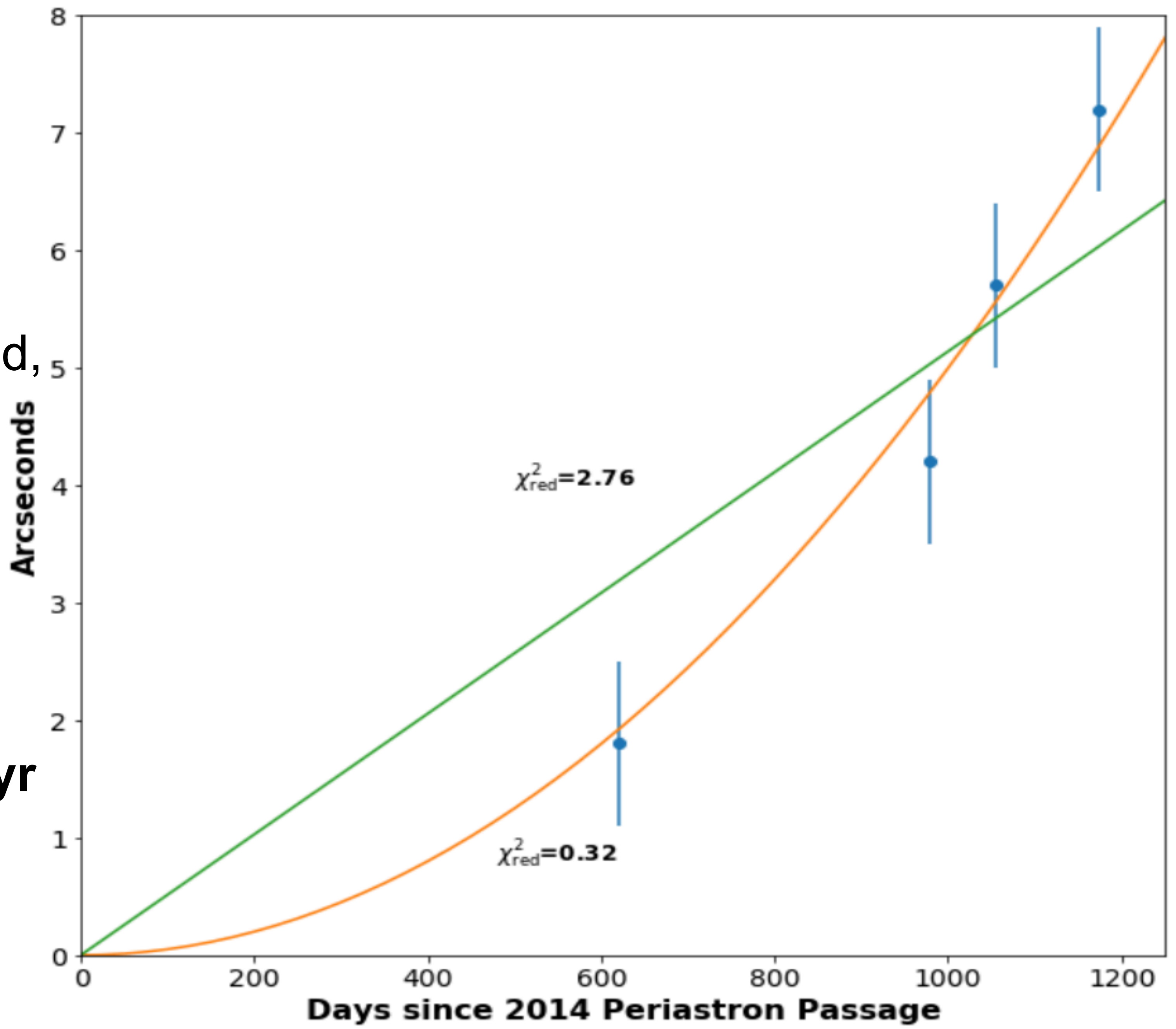
If the clump was launched at 2014 periastron with a low speed, acceleration is

a **= 47±2 cm/s²** =

= **14,800±600 km/s/yr**

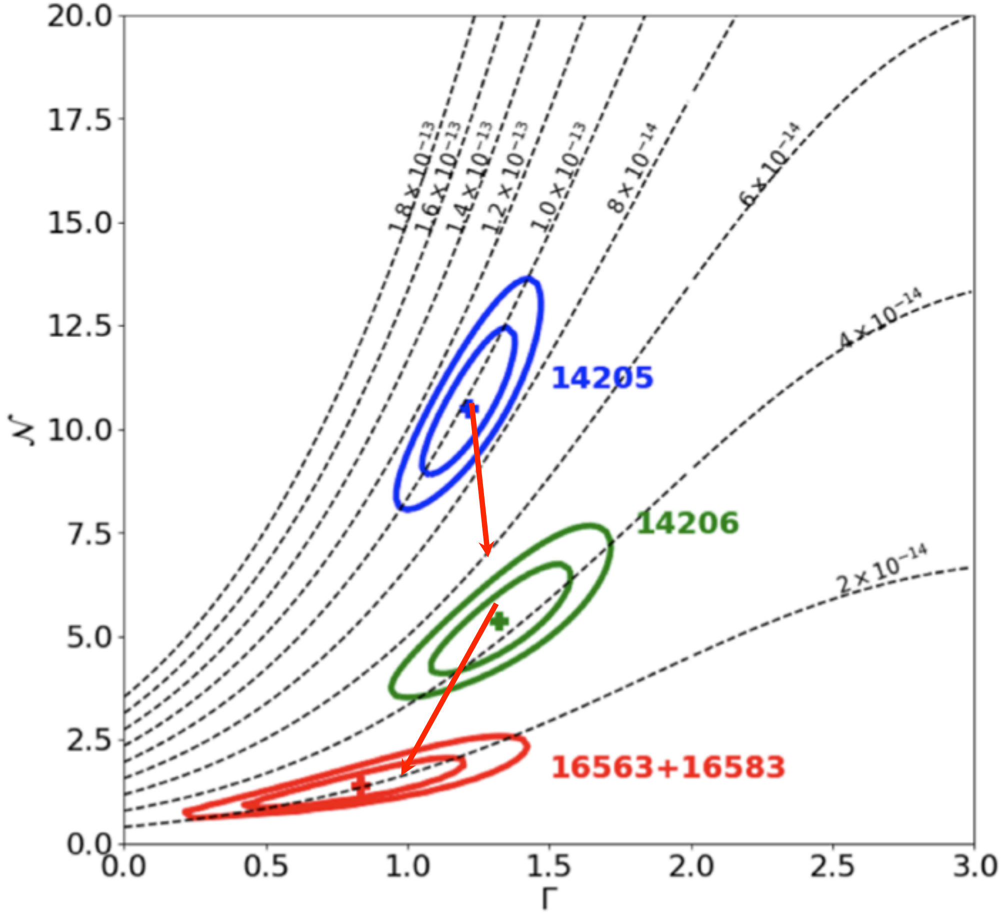
$\mathbf{V_{app} \approx 0.16c \text{ at } t = P_{orb} = 3.4 \text{ yr}}$

V ≈ 0.2 c if motion in orbital plane

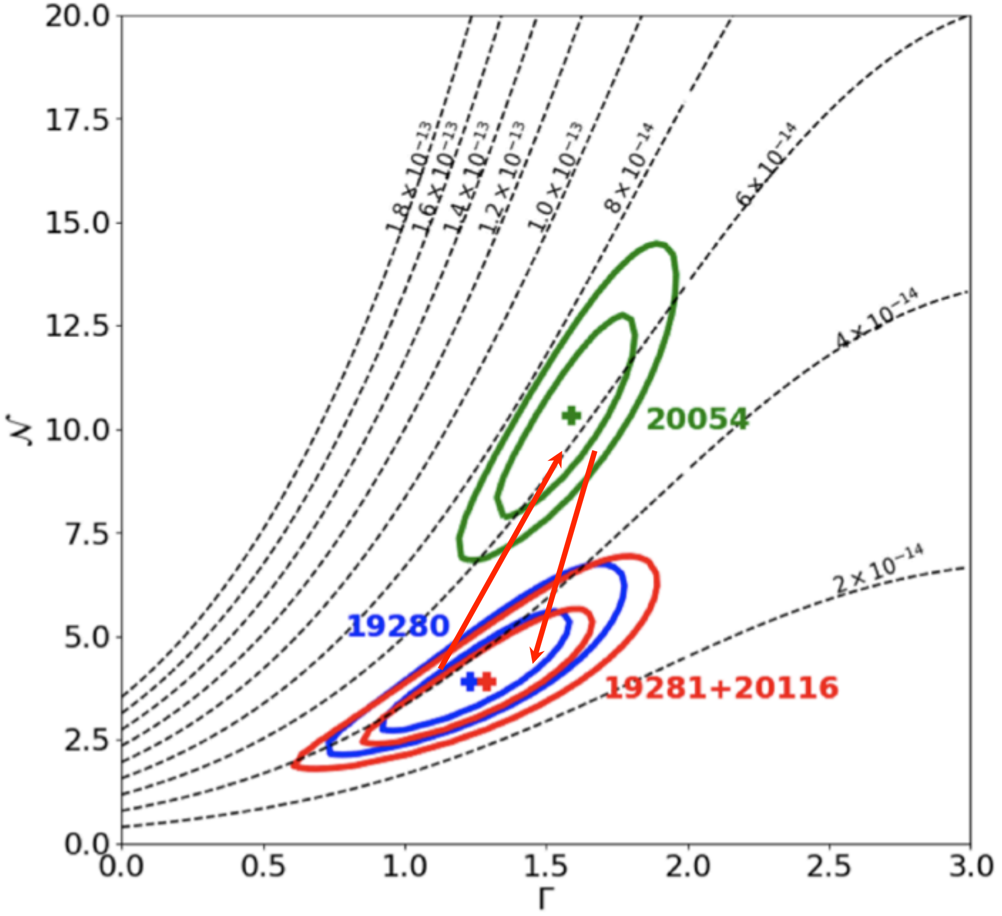


Power-law normalization vs photon index Γ, with lines of constant flux in the 0.5-8 keV band

2011- 2014

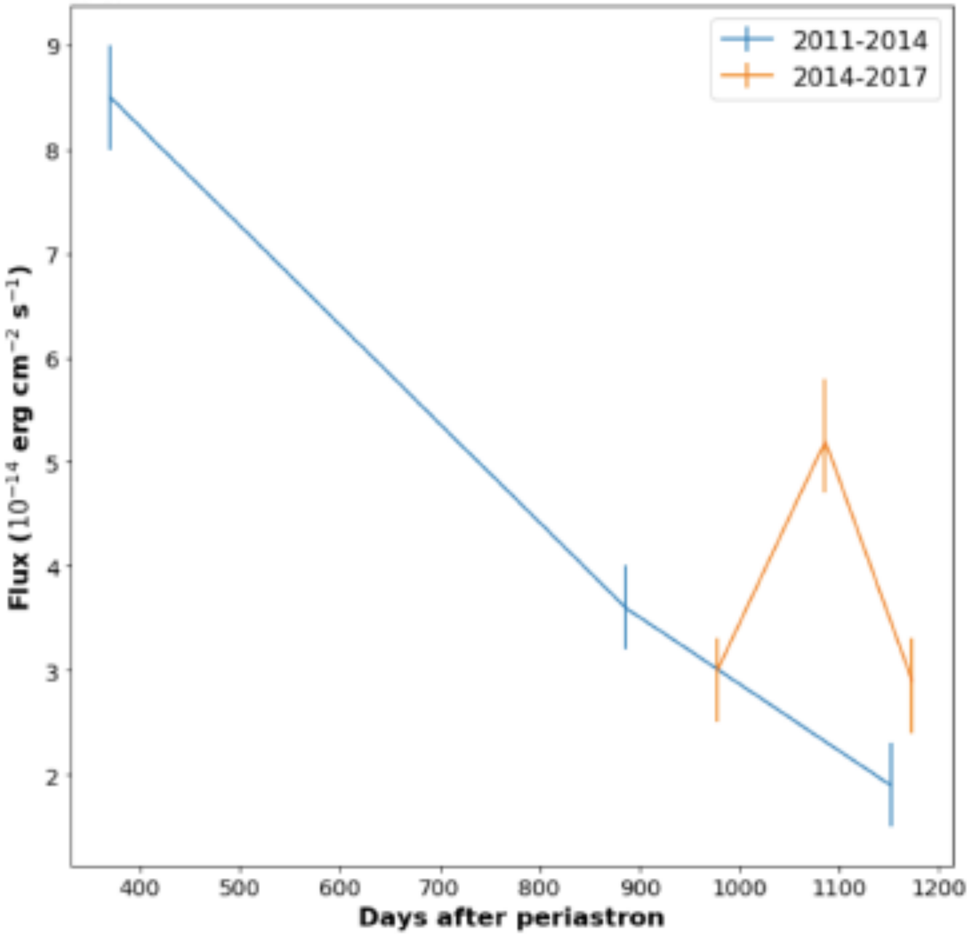


2017 Jan - Jul



Variations of Γ are statistically insignificant; average **Γ = 1.45±0.11**.

0.5 – 8 keV flux evolution in 2 binary cycles



Luminosities
at d = 2.6 kpc

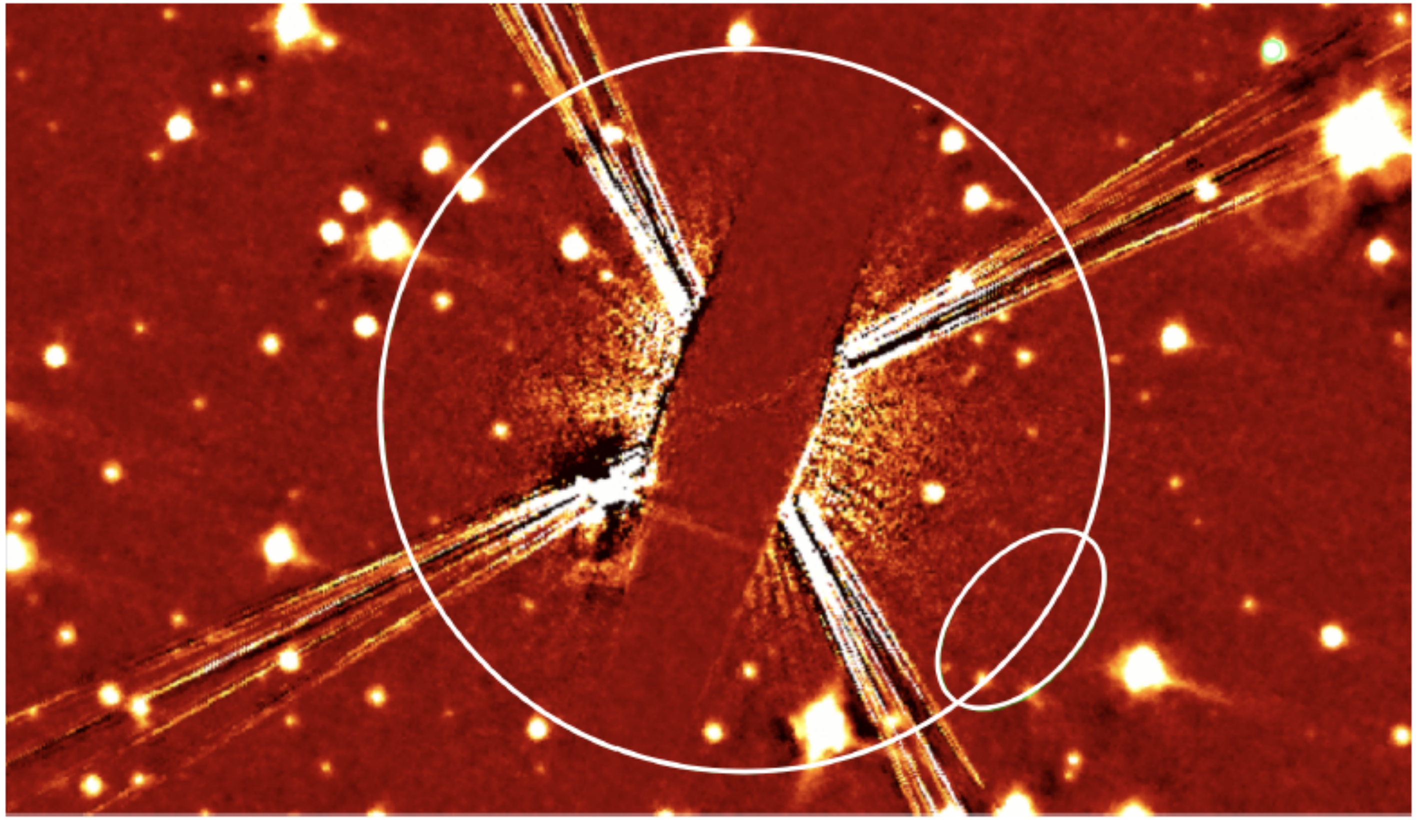
L_X ~ (2 – 9) × 10^{31} erg/s

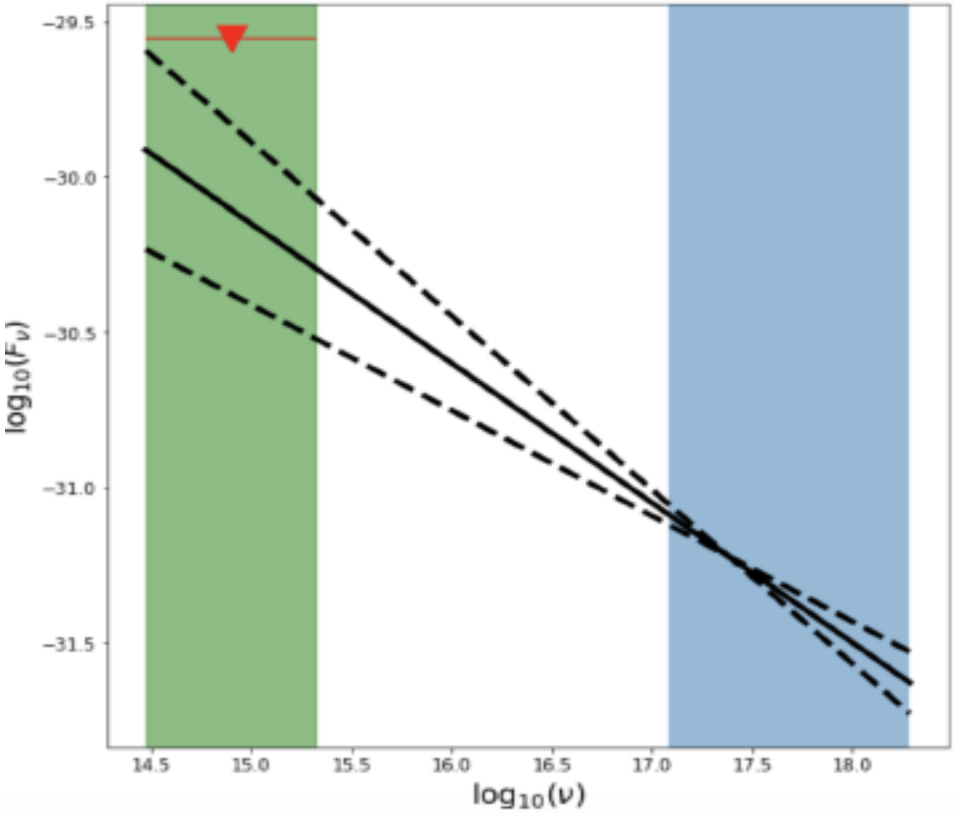
~0.7% - 3% of the binary's X-ray luminosity far from periastron.

HST STIS CCD observation with Coronograph in a 2000 – 10000 A band

F_ν < 29 nJy; F_ν^{unabs} < 280 nJy at λ = 5769 A E(B-V) =0.85

2017 July 24

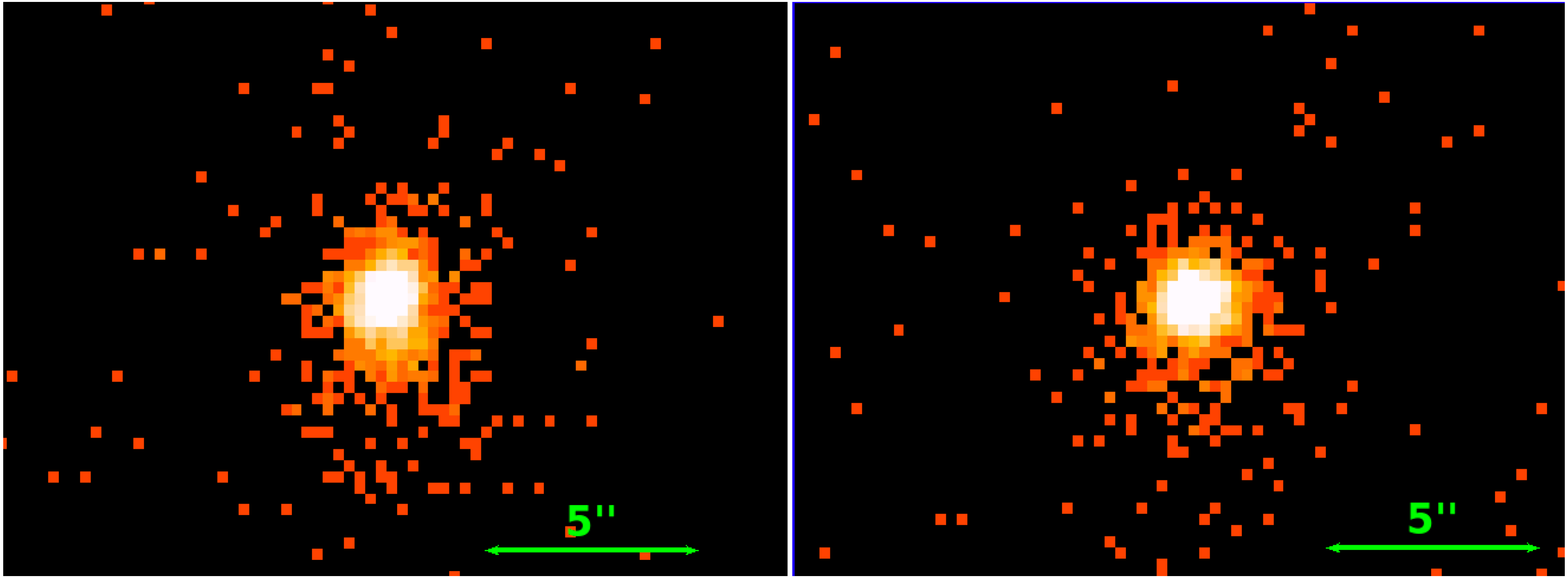




Two recent observations in the current 2017-2021 binary cycle

2018 Dec 29 Δt = 463 d

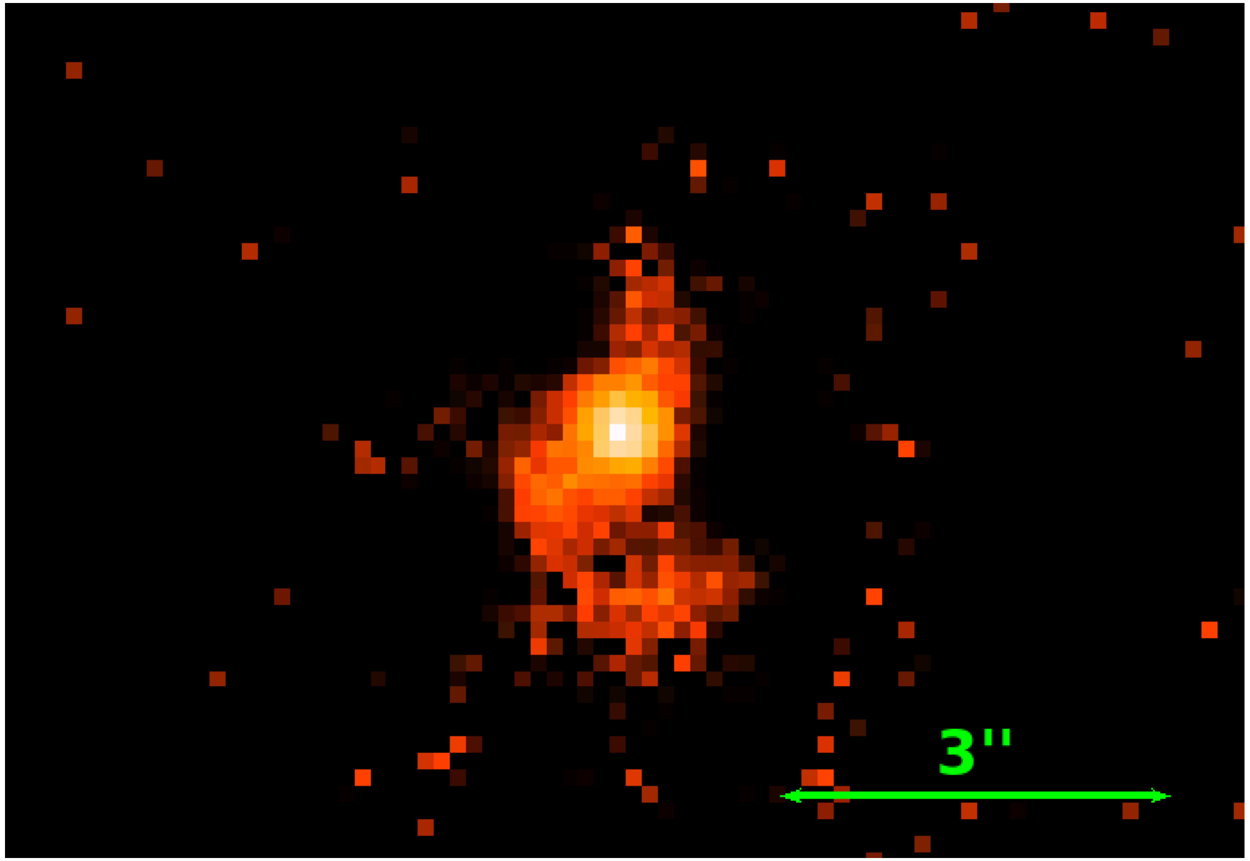
2019 May 25 Δt = 610 d



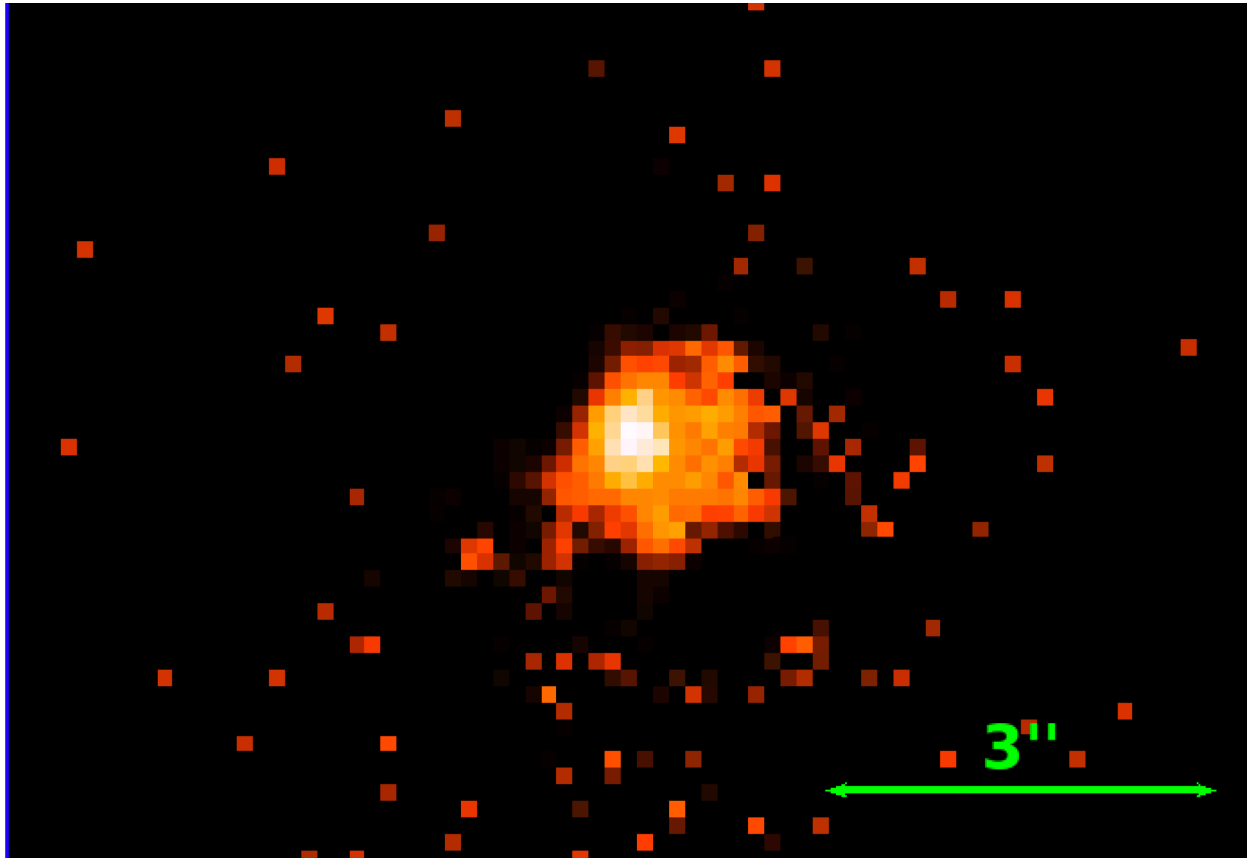
No separated clumps. Possible extensions in apastron direction
(larger in earlier image?)

The same images deconvolved (using PSF model)

2018 Dec 29 Δt = 463 d



2019 May 25 Δt = 610 d



Earlier image shows southward extension (nascent clump?) and northward extension, both disappear in 147 days (??). The later image shows no real extension.

Most likely emission mechanism is synchrotron radiation from a cloud of e^+/e^- supplied by pulsar (Inverse Compton would require too many e^+/e^-).

Physical parameters: B_{eq} ~ **100 μG**, $E_{electron}$ ~ **10 – 100 TeV**,
total energy W ~ **10^{41} erg** in volume ~10^{51} cm^3 ;
W << P_{disk} Edot = 7×10^{42} erg

Isolated e^-/e^+ clump would be immediately decelerated and destroyed by drag force in the interstellar medium: $f \sim \rho_{amb} v^2 A$, but clumps show no deceleration!

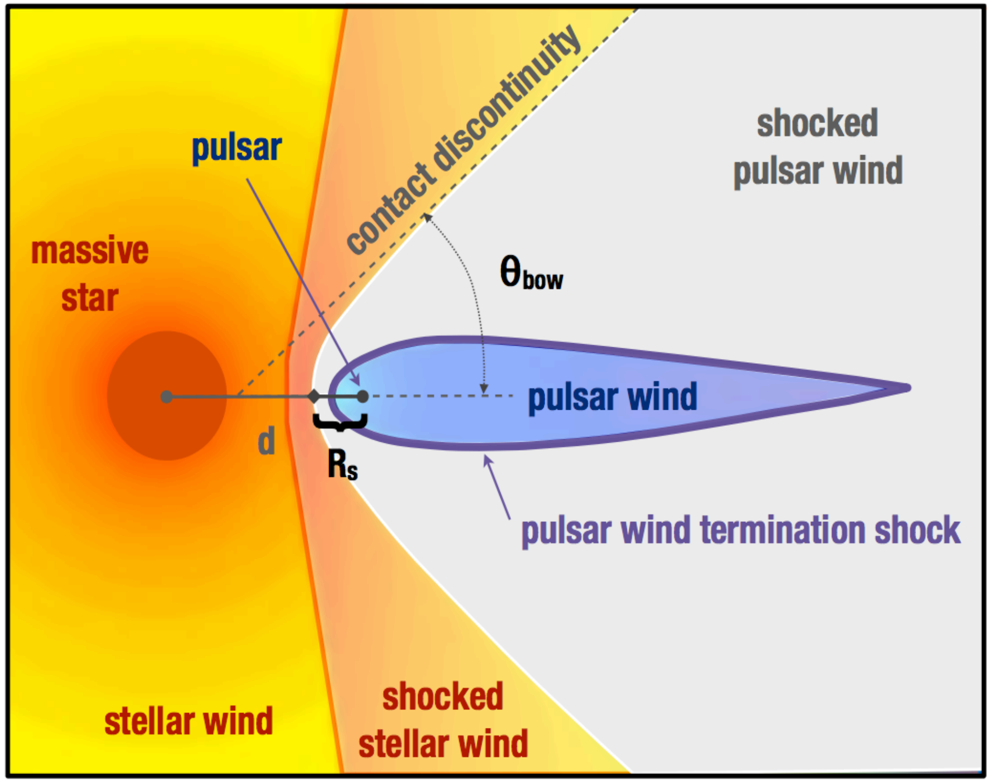
Likely, they are loaded with ions from the stellar wind disk and move in a very low density medium (or not isolated)

If the acceleration is real, it could be due to ram pressure of pulsar wind (but not a ‘Compton rocket’)

Possible scenario:

Pulsar wind (PW) within the binary is confined by powerful stellar wind:

$$\eta = \text{Edot}/(\text{Mdot}\ v_w\ c) \cong 0.1\ (\text{Mdot}/2\text{x}10^{-8}\ M_\odot/\text{yr})^{-1}\ (v_w/2400\ \text{km/s})^{-1} < 1$$ (Tavani & Arons 1997)



Dubus et al. (2013)

During most part of binary period the shocked PW leaves the binary in the apastron direction and carves a <u>low-density channel</u> in ambient medium.

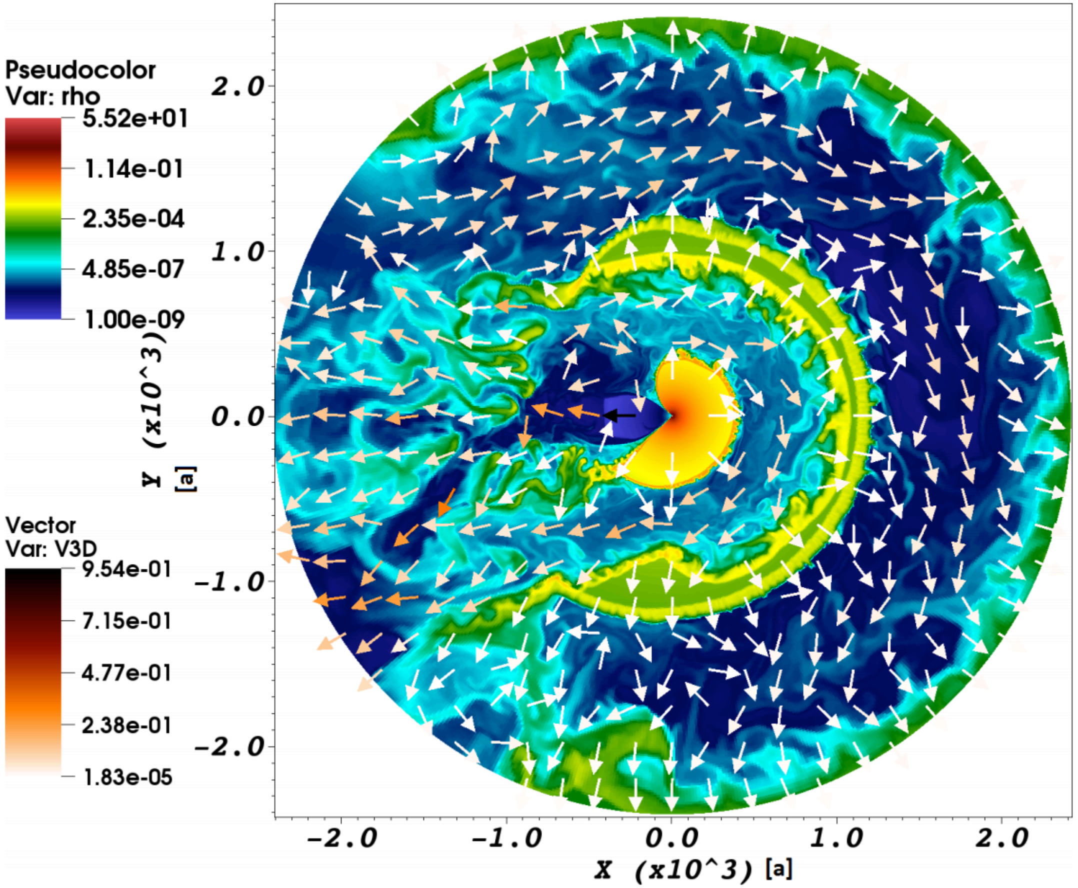
When the pulsar crosses the disk, a cloud of <u>mixed disk matter and relativistic electrons</u> (cloud mass ~10^{21} g) is formed and ejected into the channel

The cloud is pushed “from behind” and perhaps <u>accelerated by the shocked PW</u> along the channel until the cloud speed approaches the shocked PW speed, ~0.1c – 0.3 c.

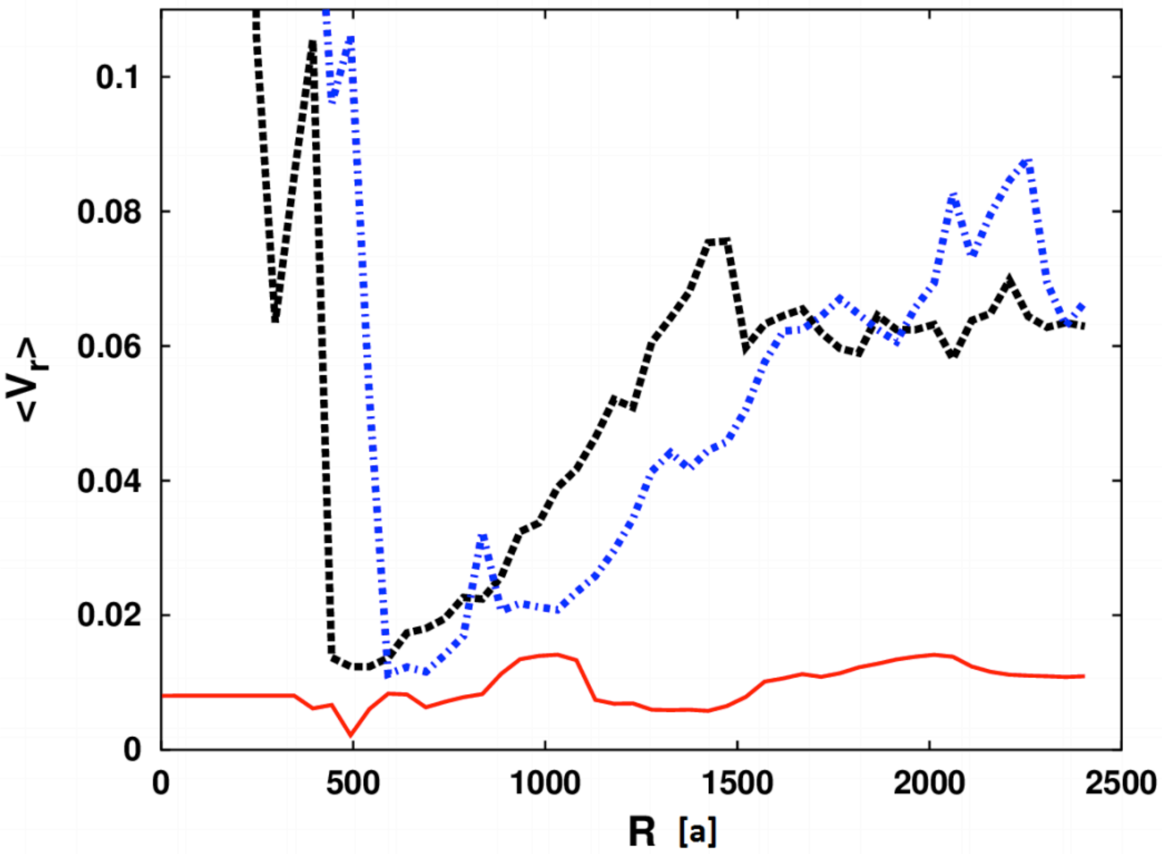
<u>Internal shocks</u> produced by turbulent motions within the cloud might explain shape change (“whiskers”) and brightenings.

Such a scenario was supported by numerical simulations (do not include circumstellar disk)

Barkov & Bosch-Ramon 2016



Density distribution (colors) and velocities (arrows) in the orbital plane 680 d after periastron.



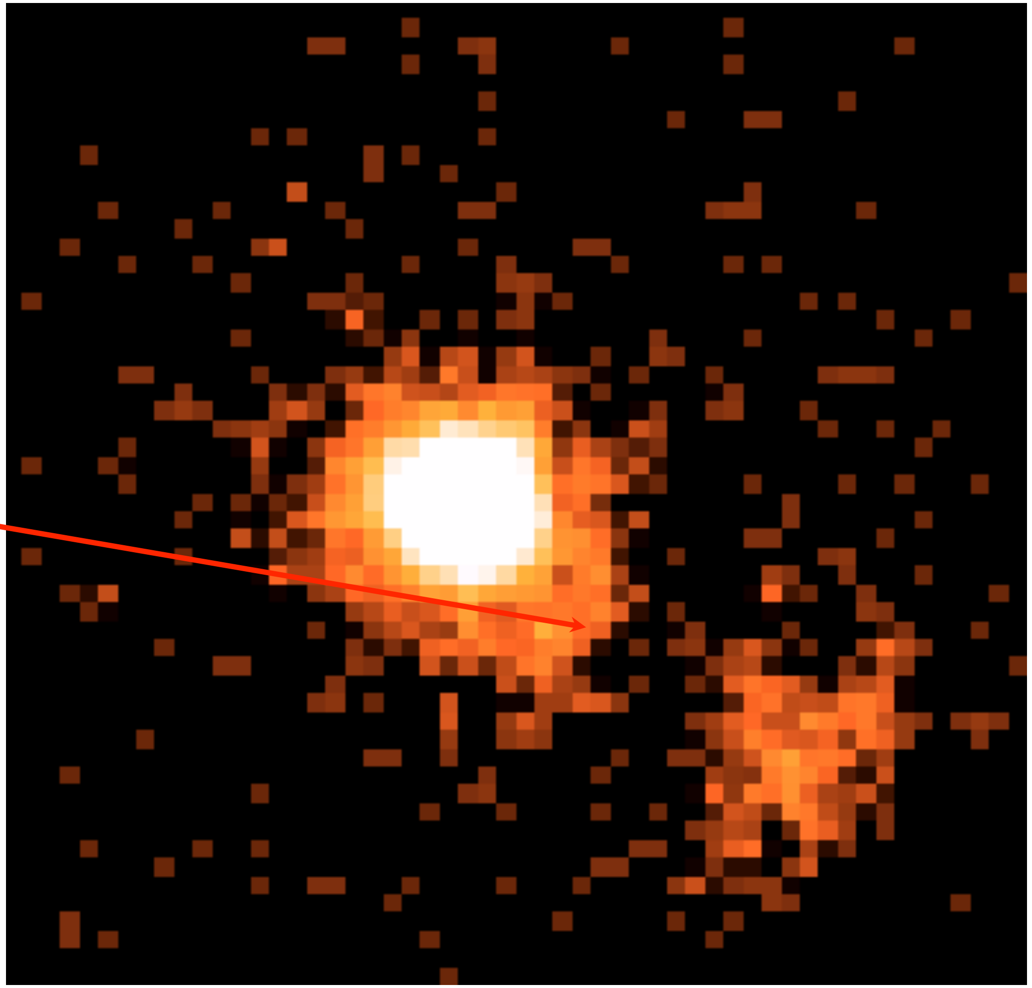
Azimuthally averaged radial velocities for two sectors of orbital plane at different times.

Open Questions

What is the nature of the apparent 2nd clump observed on 2017 Apr 24?

Possible new clump 2'' from binary

Not seen in next observation 97 days later



Possible ejection of another, slower moving clump?

Or launched at a later date, well after periastron?

Or a projection effect (different clumps are launched in different directions and fade with different rates)?

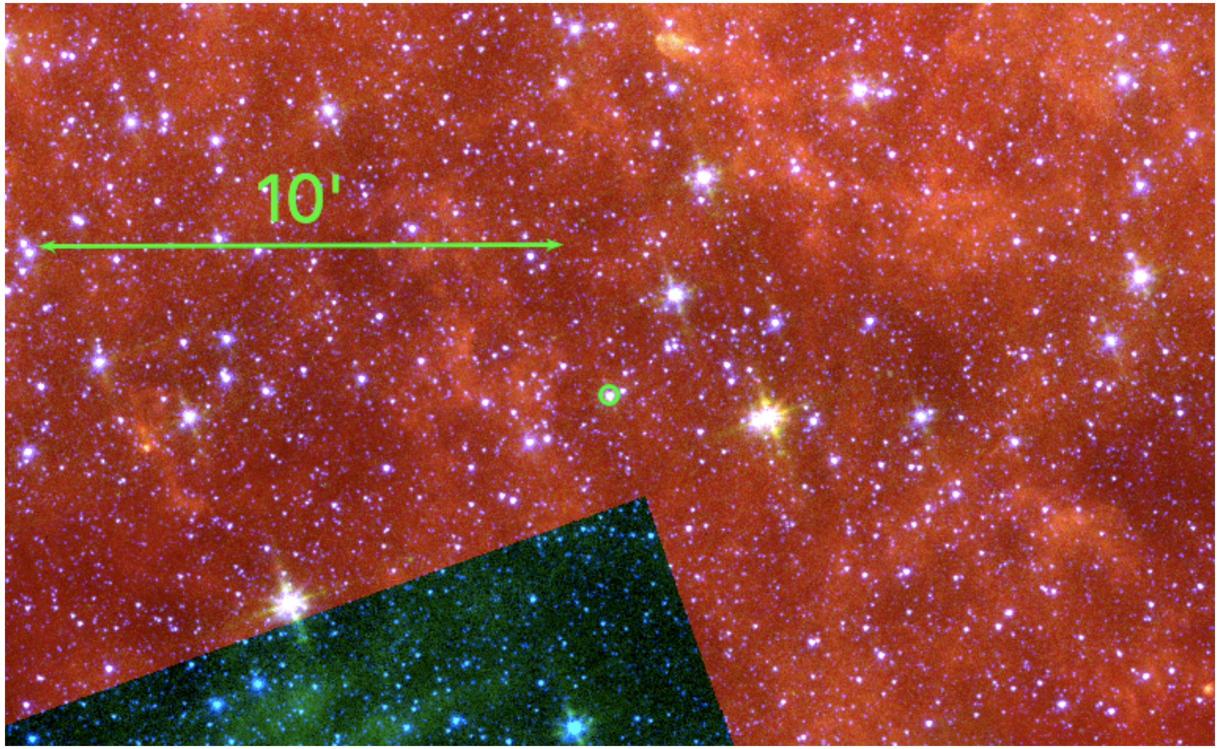
What is the nature of northern extensions seen in some deconvolved images?

Open Questions

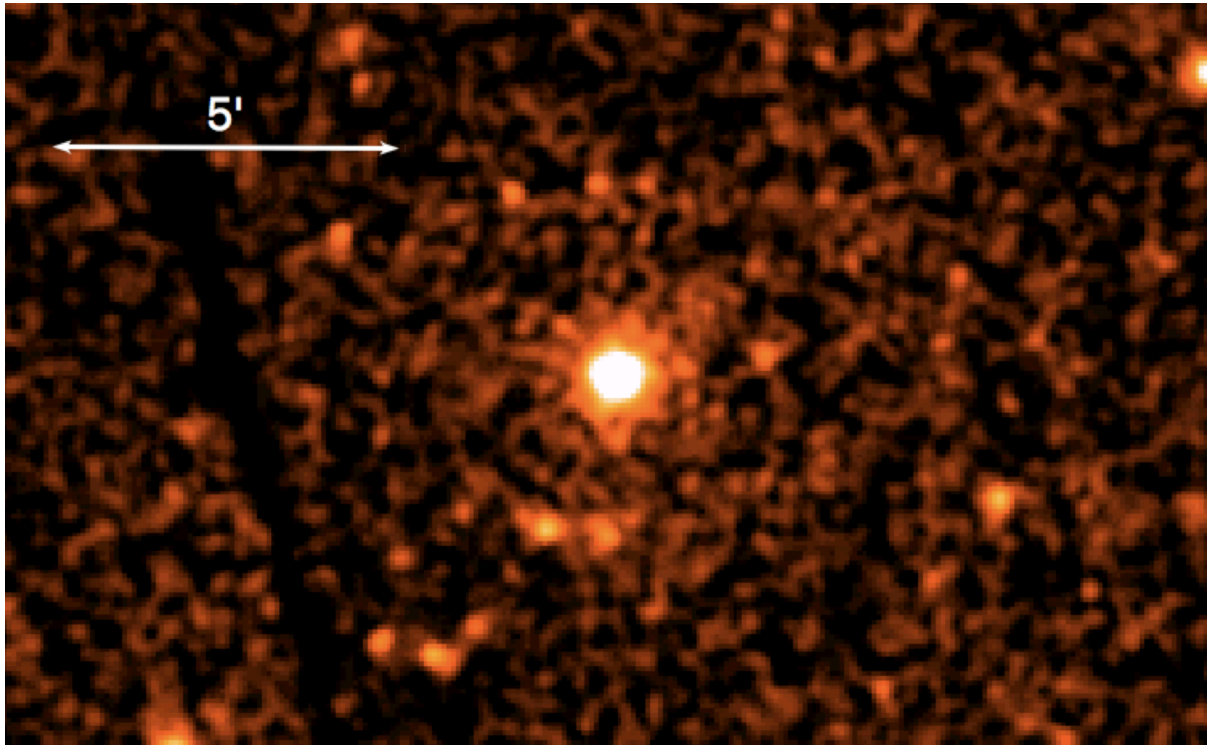
Where the large amount of clump energy is deposited?

Should happen at ≅2’-5’ for channel opening angle ≅ 20-50 degrees.
Nothing seen observationally at those distances, neither in X-rays nor in IR

Spitzer IRAC



XMM-Newton MOS1

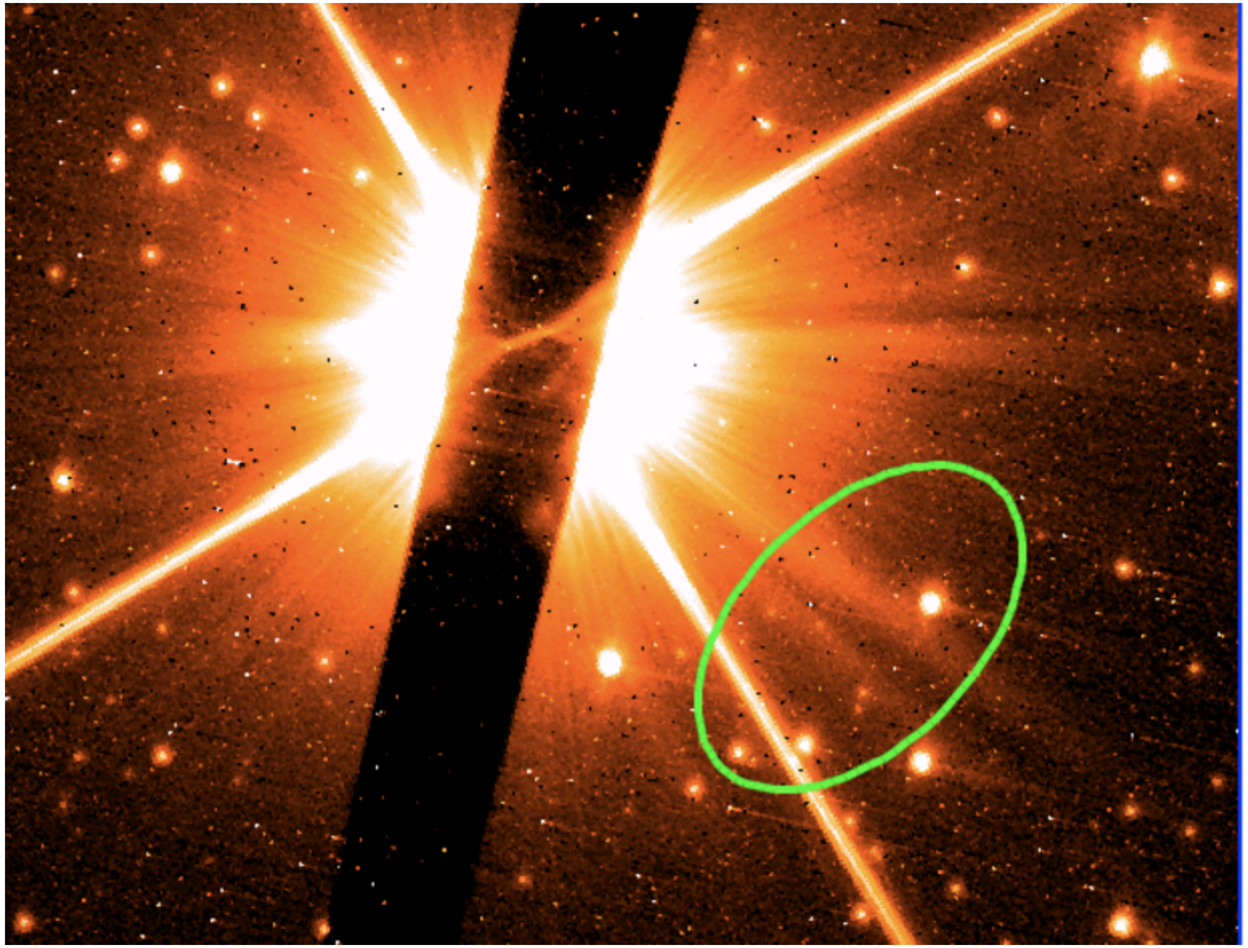


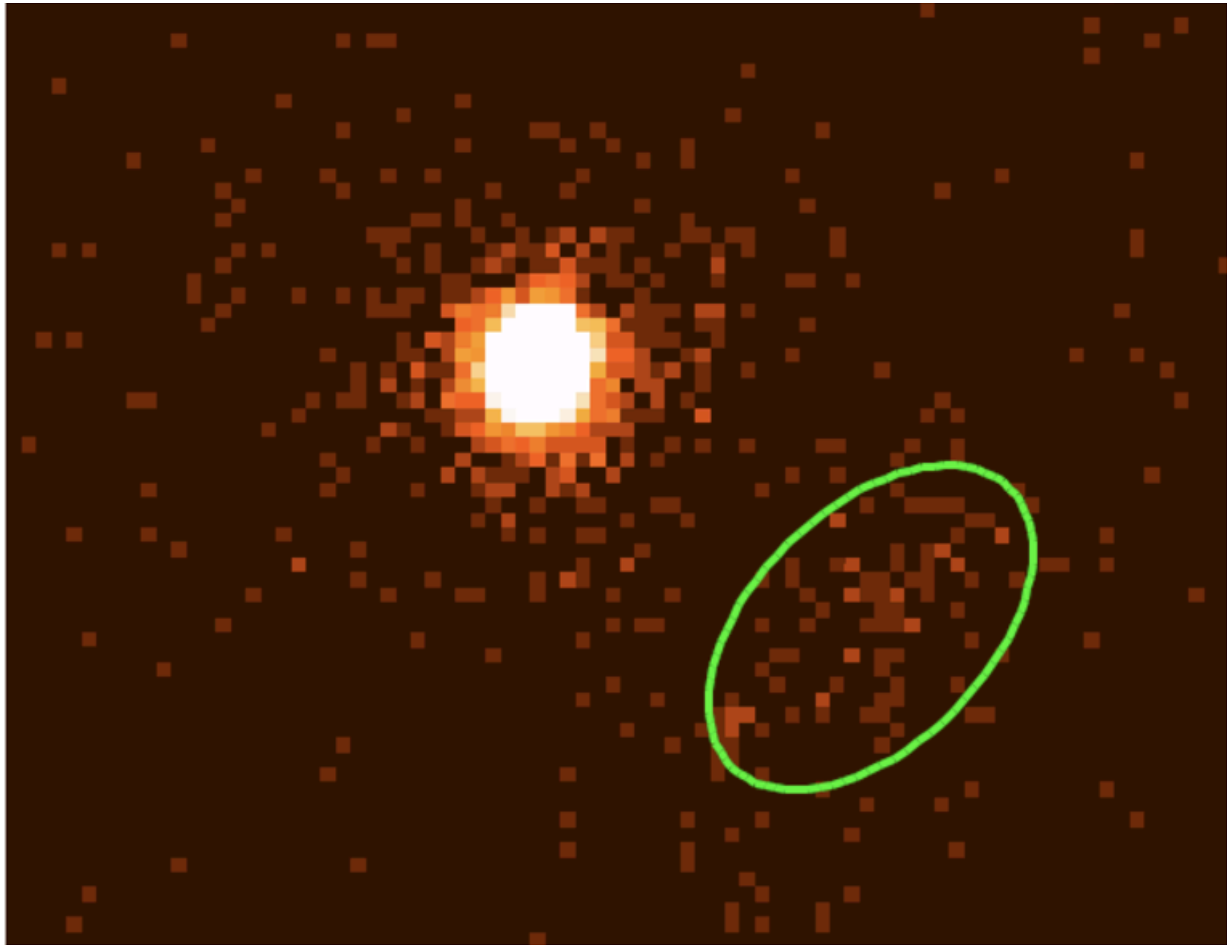
Open Questions

What is the SED toward lower energies?

Clump could be detected with HST STIS coronograph if the same spectral slope in optical/X-rays

Not detected in coronagraph image observed 2017 Jul 24

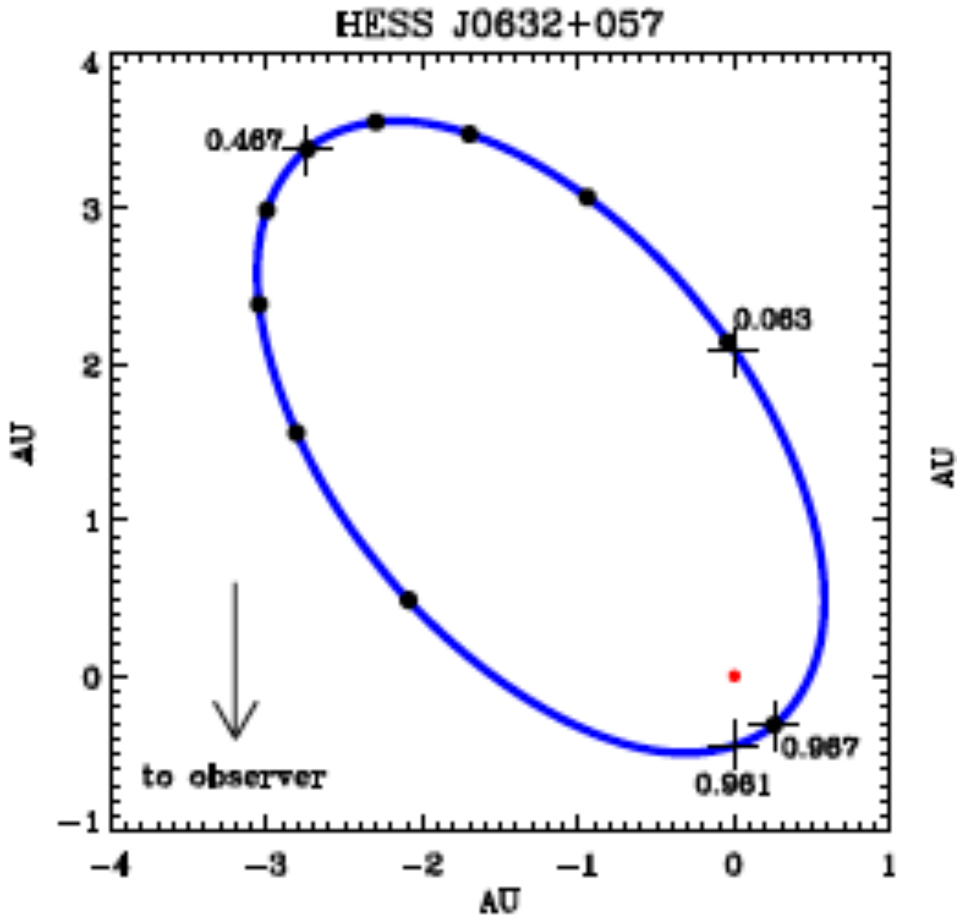




Summary on PSR B1259-63/LS 2883

- New (so far unique) phenomenon: Ejection of X-ray emitting clumps from a high-mass gamma-ray binary, accelerated to an apparent velocity $\mathbf{V_{app} \sim 0.1c}$
- Clumps consisting of a mixture of relativistic electrons and stellar (disk) matter are ejected during periastrons passages due to interaction of the pulsar wind with the equatorial disk of the high-mass star
- Clumps are possibly moving in the pulsar wind, whose ram pressure accelerates them to the very high speed
- Clumps have shown somewhat different behavior in the two binary cycles (e.g., different speed/acceleration, steady fading vs occasional brightening)
- Typical clump sizes up to **10,000 a.u**., X-ray luminosity up to $\mathbf{10^{32}}$ **erg/s**, hard power-law spectra with $\mathbf{\Gamma \sim 1.1 – 1.7}$, no softening with time
- X-ray emission mechanism is likely synchrotron radiation of relativistic electrons of the shocked pulsar wind mixed stellar matter; possible internal shocks within the clump.

2. HESS J0632+057



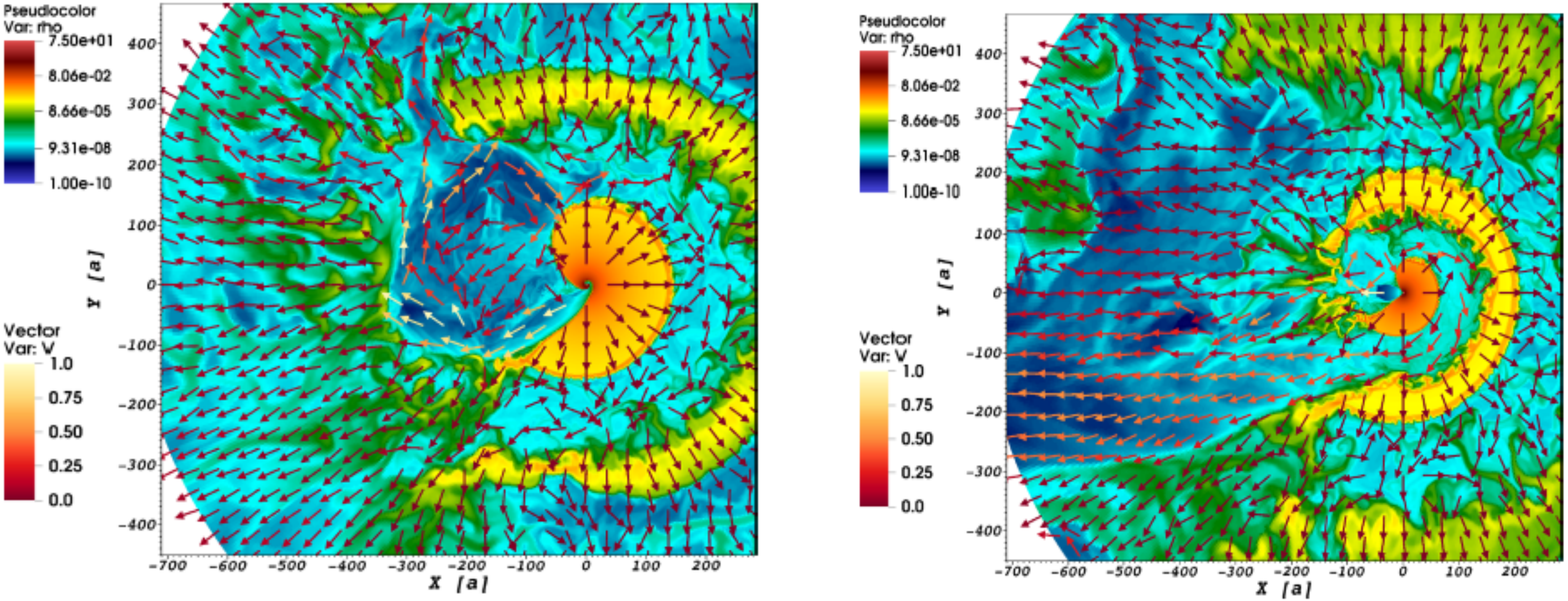
Binary: P_{orb} ~ 315 – 320 days,
e ~ 0.8 [0.6], d = 1.1-1.7 kpc, i ~ 70° [35°],
a ~ 1 - 7 au

Massive companion: B0Vpe star MWC 148,
M = 13-19 $M_{\odot}$, $L \sim 10^{38}$ erg/s

Compact companion: M = 1.3 – 7.1 $M_{\odot}$,
NS (pulsar) or BH?

Casares et al. 2012)
[Moritani et al. 2018]
Malyshev et al. 2019

If pulsar, we can expect outflows, possibly in apastron direction, similar to B1259-63.

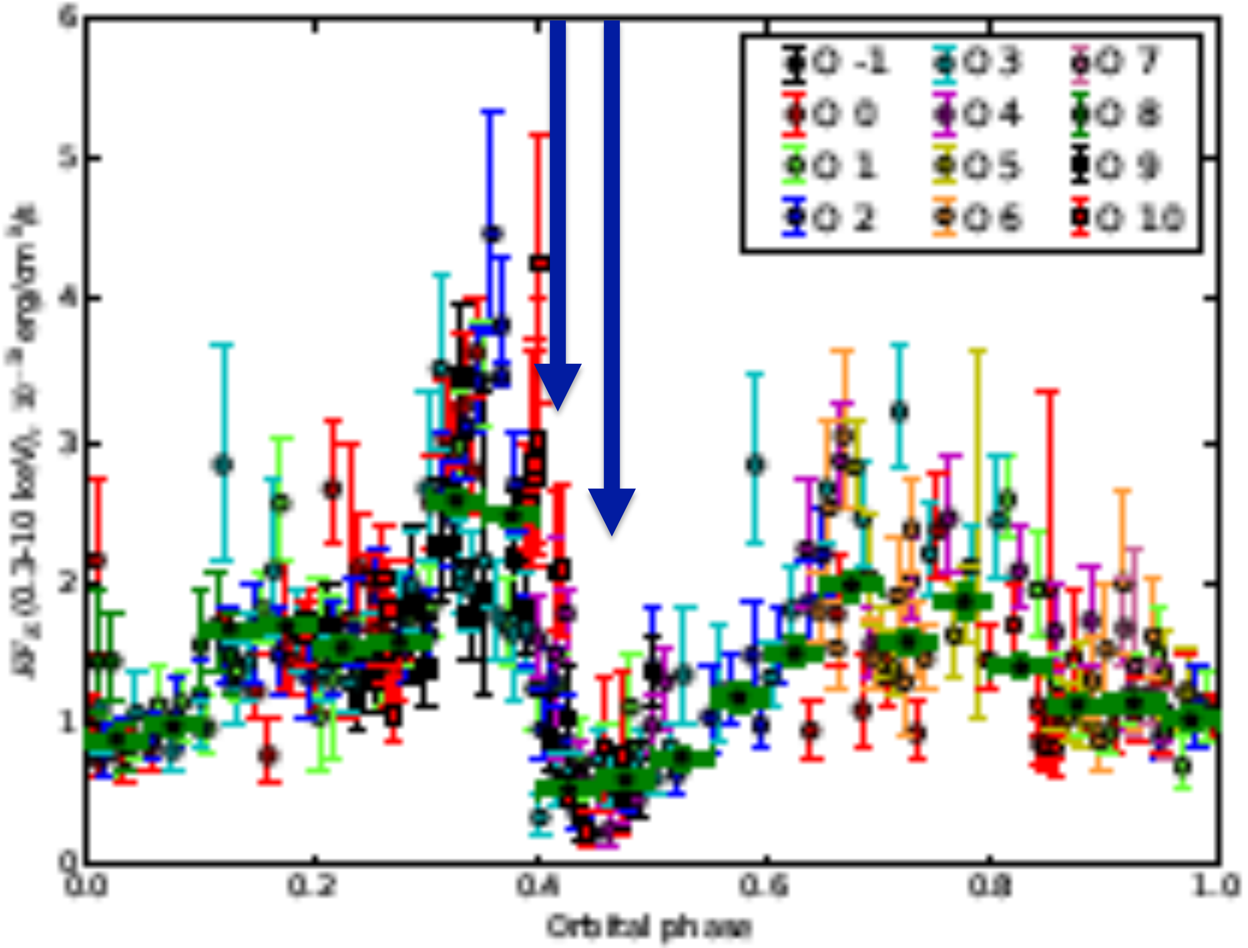


ϕ=0.026

ϕ=0.46

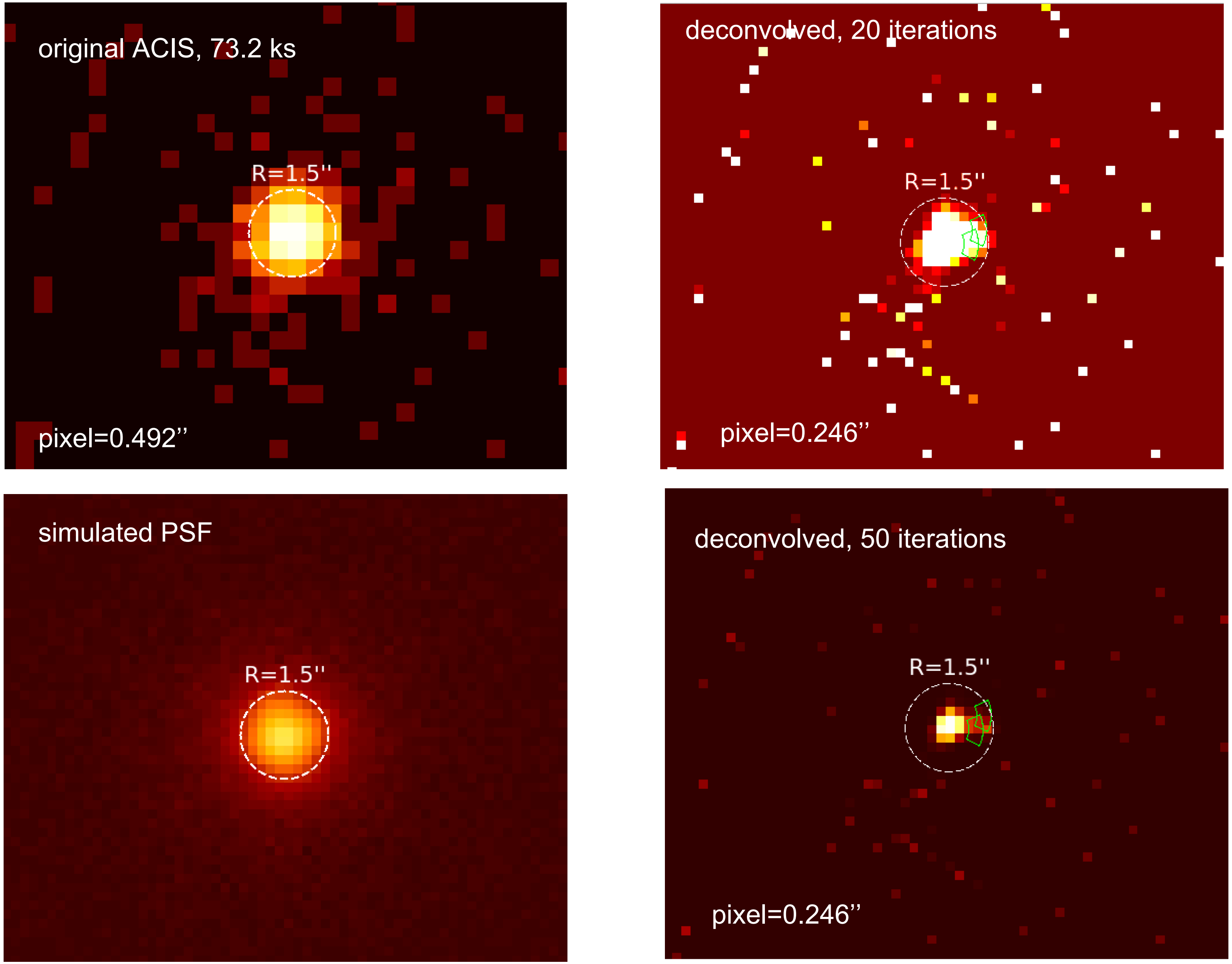
Barkov & Bosch-Ramon 2018

We observed J0632 with **Chandra ACIS-I** on 2018 Feb 3, 4, 19, 21
(binary phases **ϕ = 0.41, 0.46**, near flux minimum before apastron, for P=317 d)
total exposure **152 ks** (J0632 in chip gap during ~40 ks).



The phase intervals are near the minimum of the binary's X-ray flux to reduce PSF wings

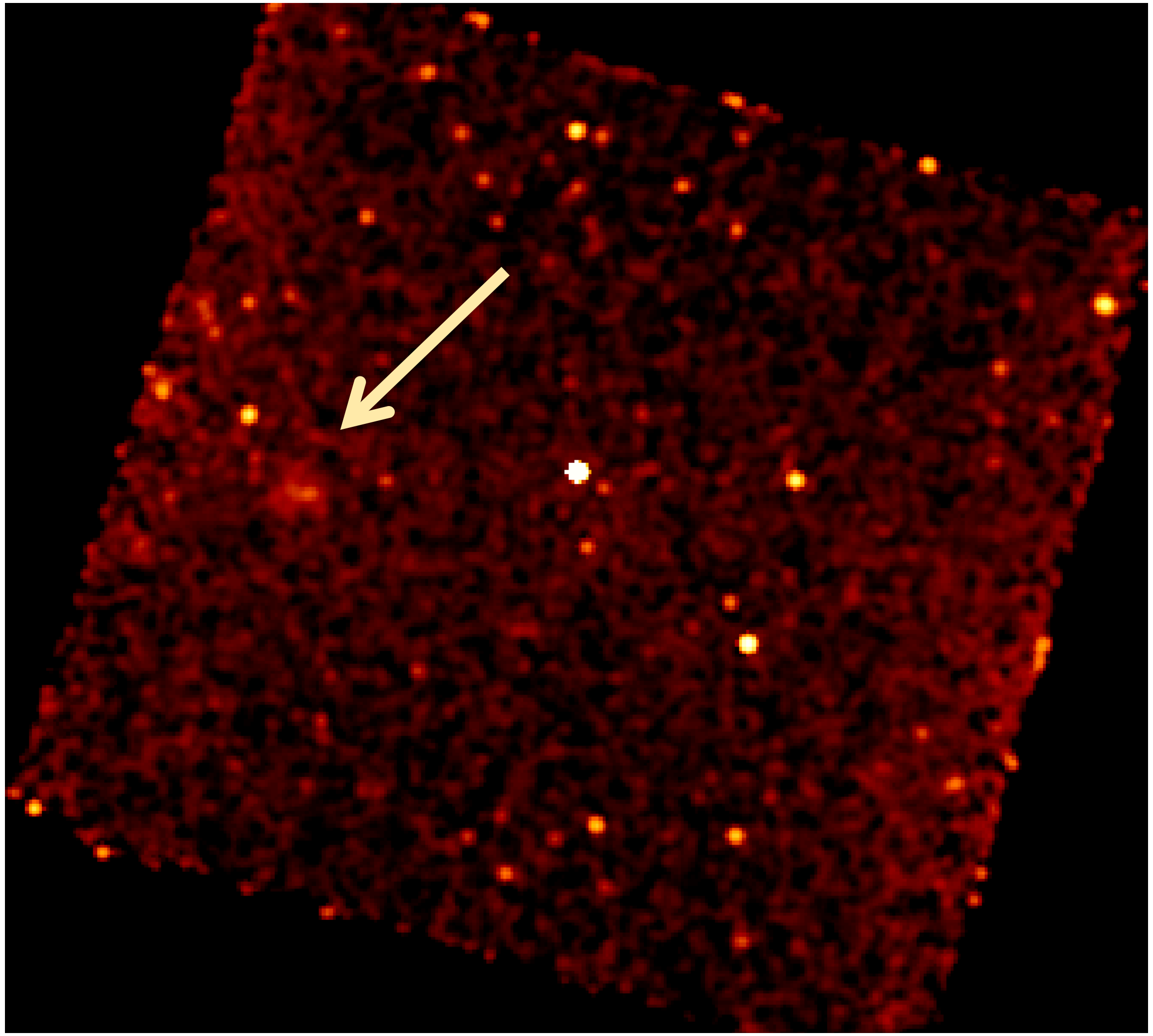
(Malyshev et al 2019)



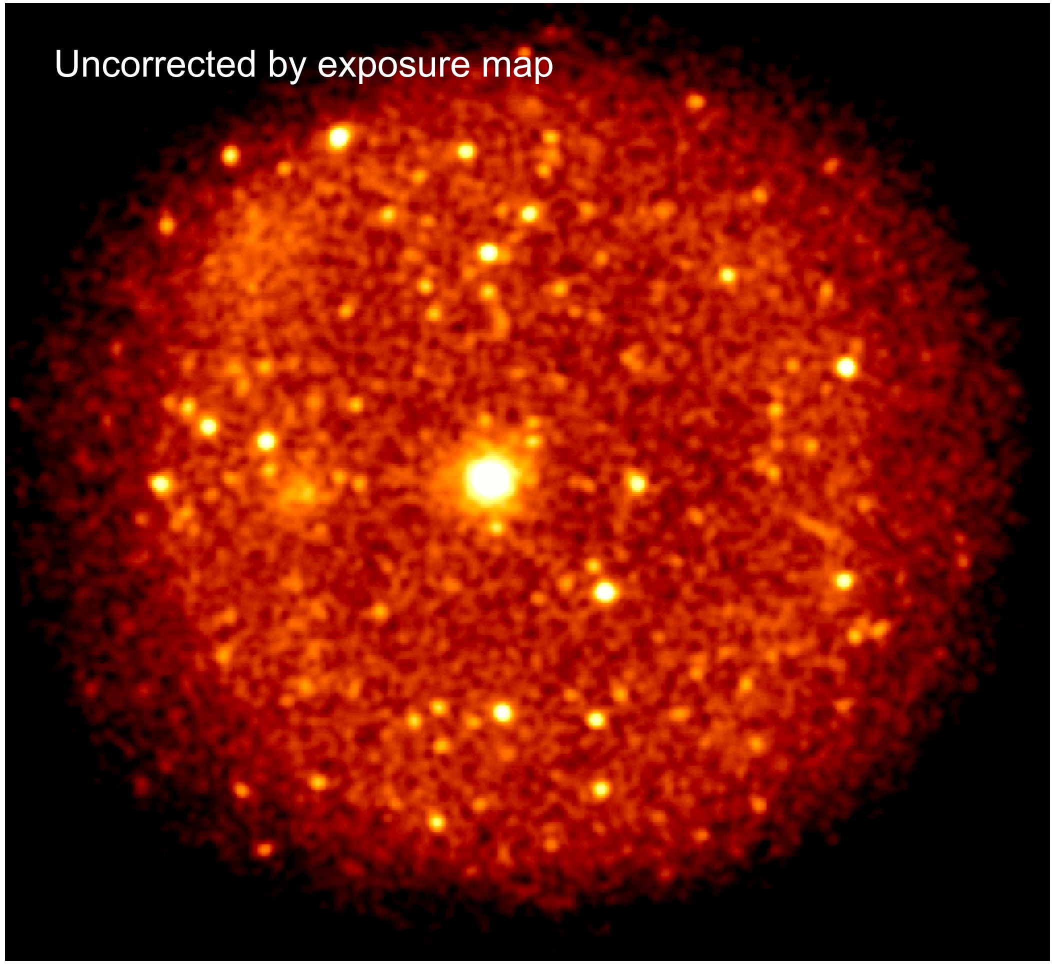
No convincing evidence for extended emission at a few arcsec scale, in neither original nor deconvolved images

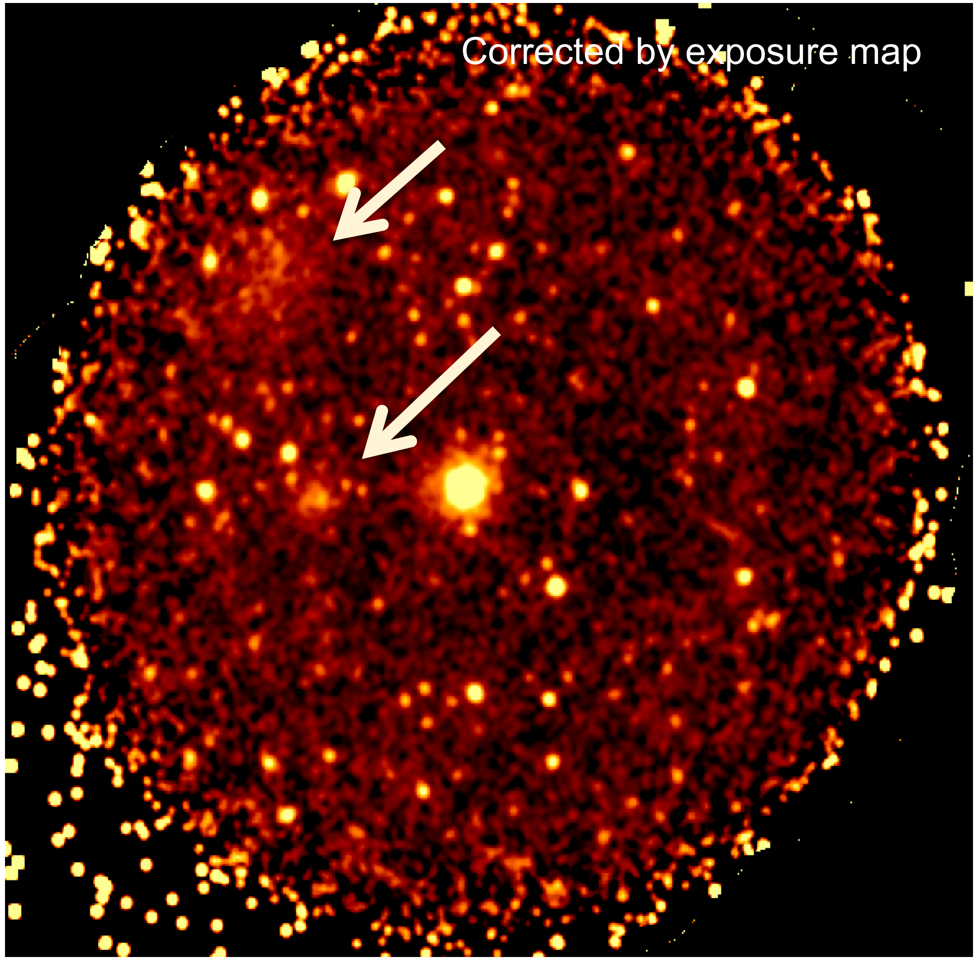
However, extended emission is seen in the large-scale Chandra ACIS-I image ~5 arcmin from J0632 (2.3 pc at d = 1.6 kpc)

152 ks



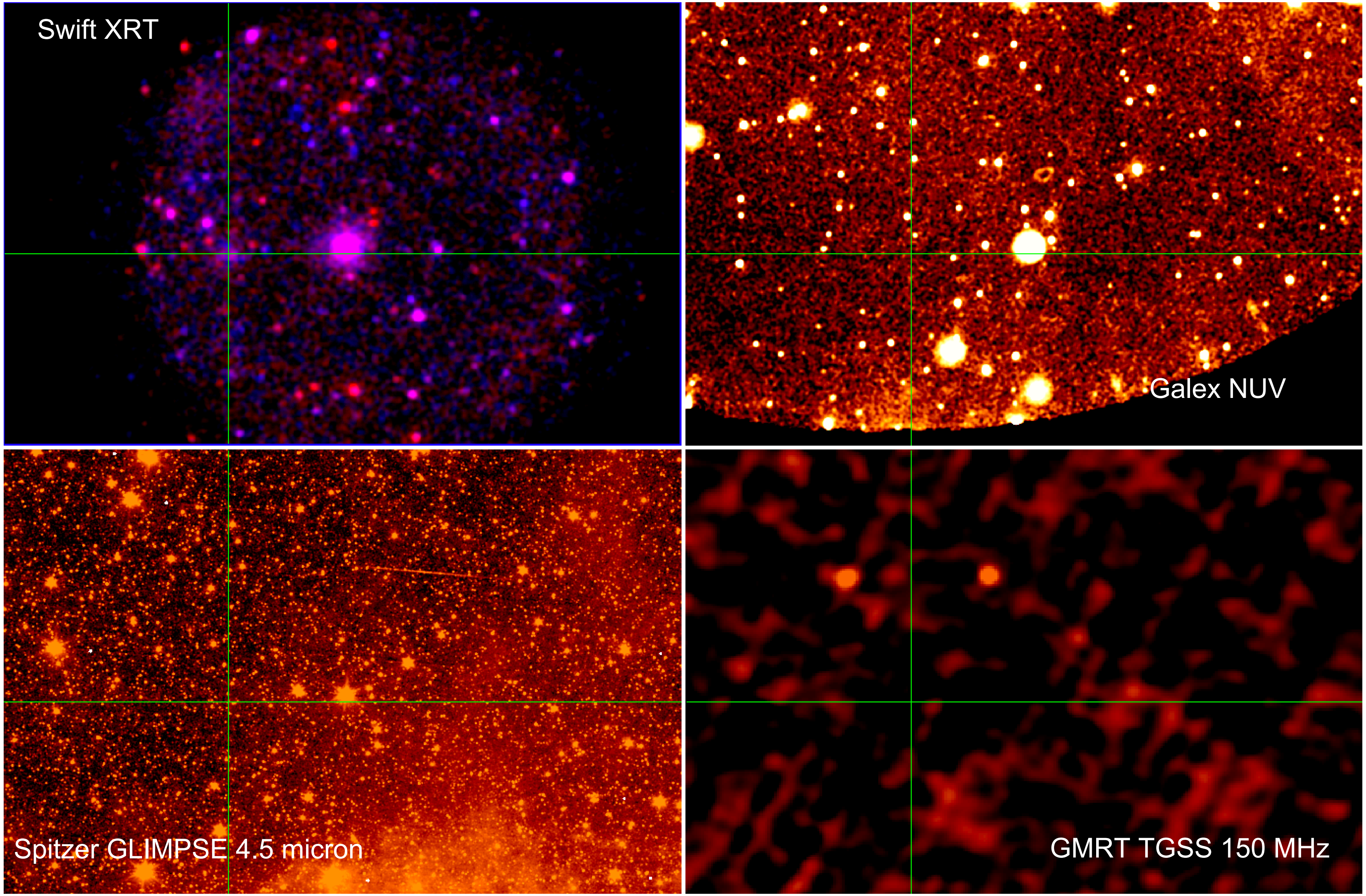
To check this, we collected archival Swift XRT data from **271 observations** spread over **2009 Jan 26 – 2018 Dec 14** ,0.3-10 keV, total exposure **980 ks**

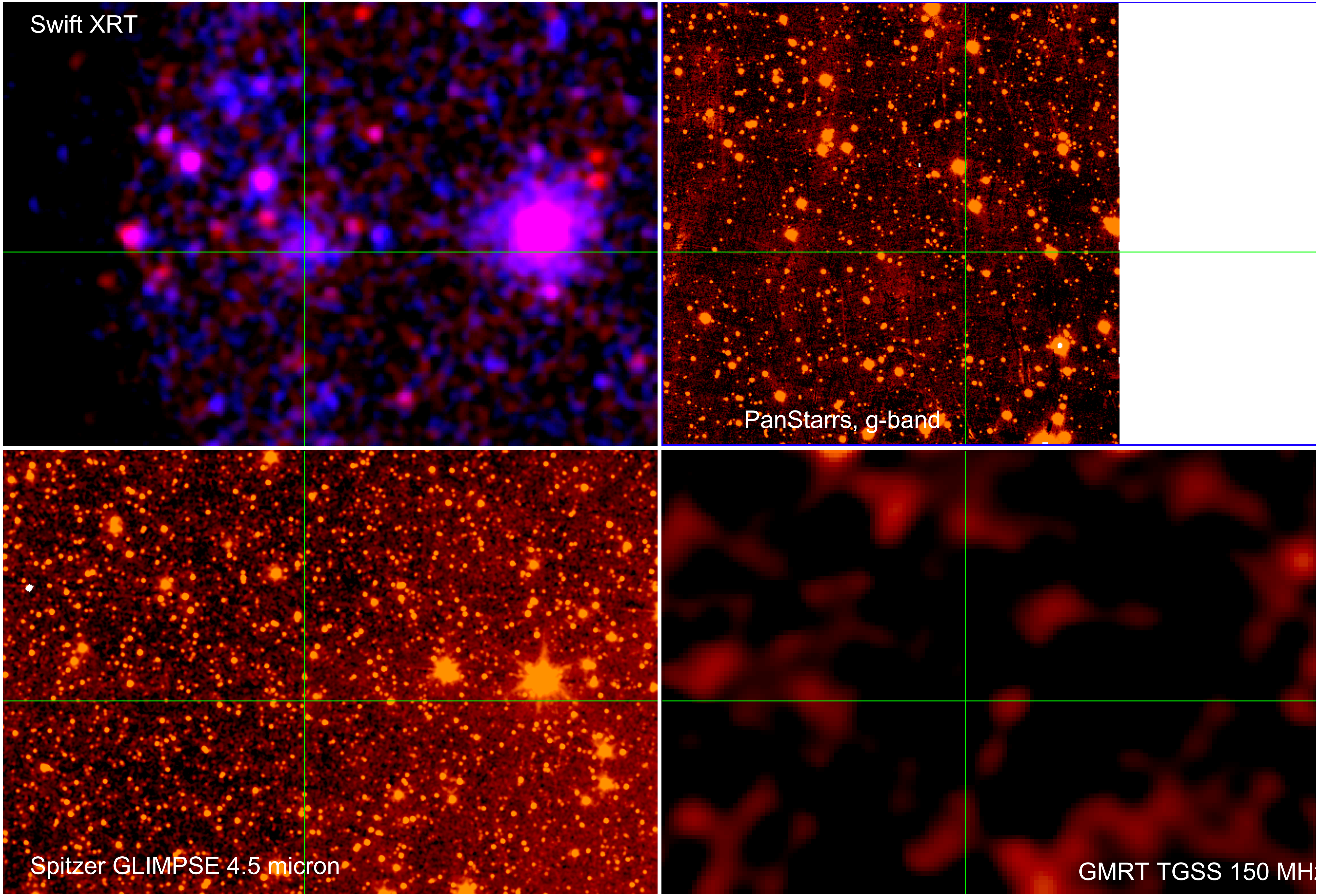


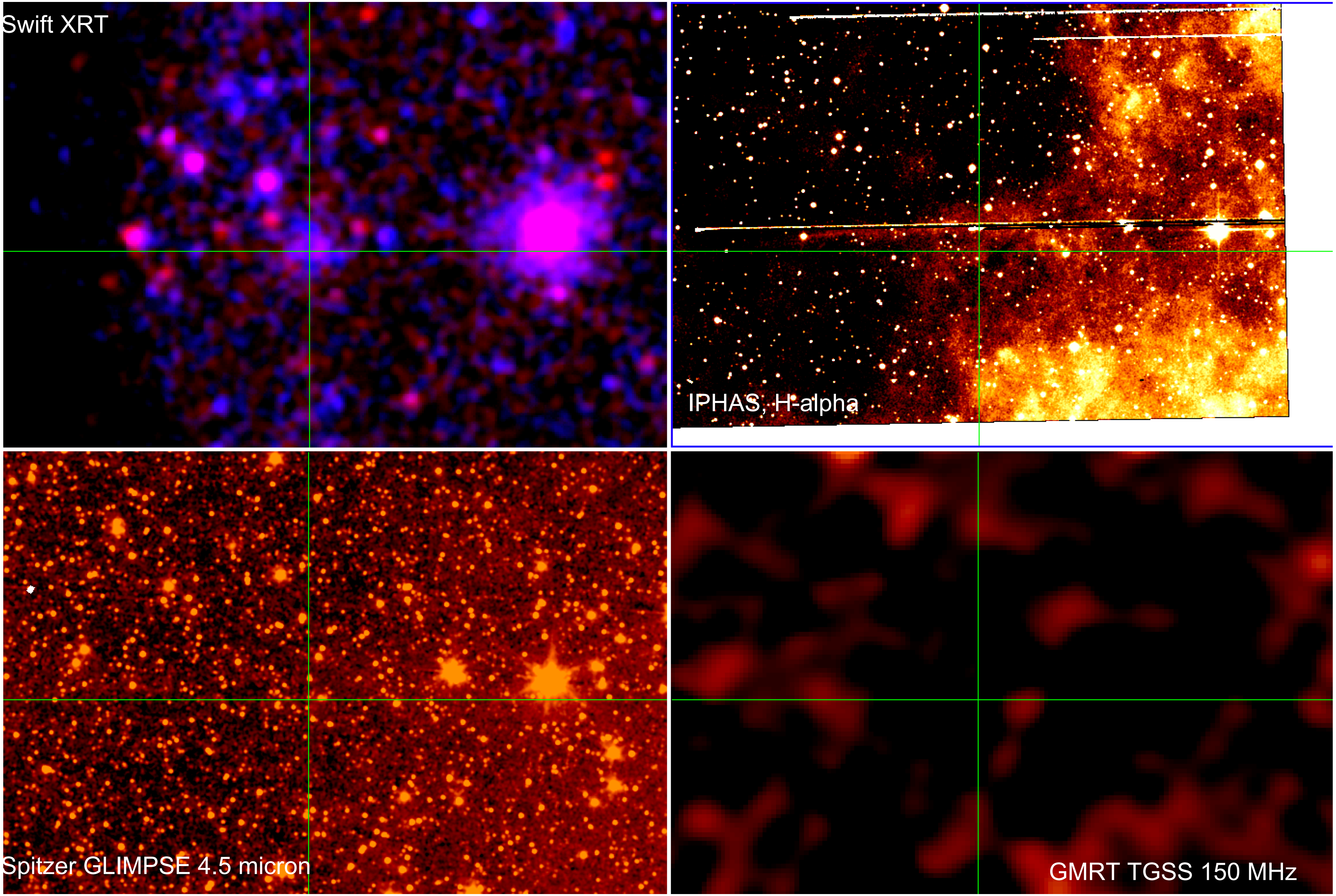


In the Swift image we see **two extended objects**

No counterparts in the NUV, g-band, Hα, IR, radio.




Swift XRT
PanStarrs, g-band
Spitzer GLIMPSE 4.5 micron
GMRT TGSS 150 MH


Swift XRT
IPHAS, H-alpha
Spitzer GLIMPSE 4.5 micron
GMRT TGSS 150 MHz

Spectral parameters from our Chandra observations (power-law fits)

J0632+057

$N_H = (5.3\pm0.8)\times10^{21}$ cm^{-2}

$\Gamma = 1.32\pm0.06$

$F_{0.5-8\ keV} = (4.95\pm0.11)\times10^{-13}$ erg/cm^2/s

Extended emission east of J0632

$N_H = (2.0\pm0.8)\times10^{22}$ cm^{-2}

$\Gamma = 2.6\pm0.6$

$F_{0.5-8\ keV} = (3.9\pm0.11)\times10^{-14}$ erg/cm^2/s

Extended emission is likely farther than the binary – not related ?
Its spectrum much softer, origin remains unknown so far (possibly extragalactic – a galaxy cluster?)

No pulsations are found (but time resolution is too coarse)

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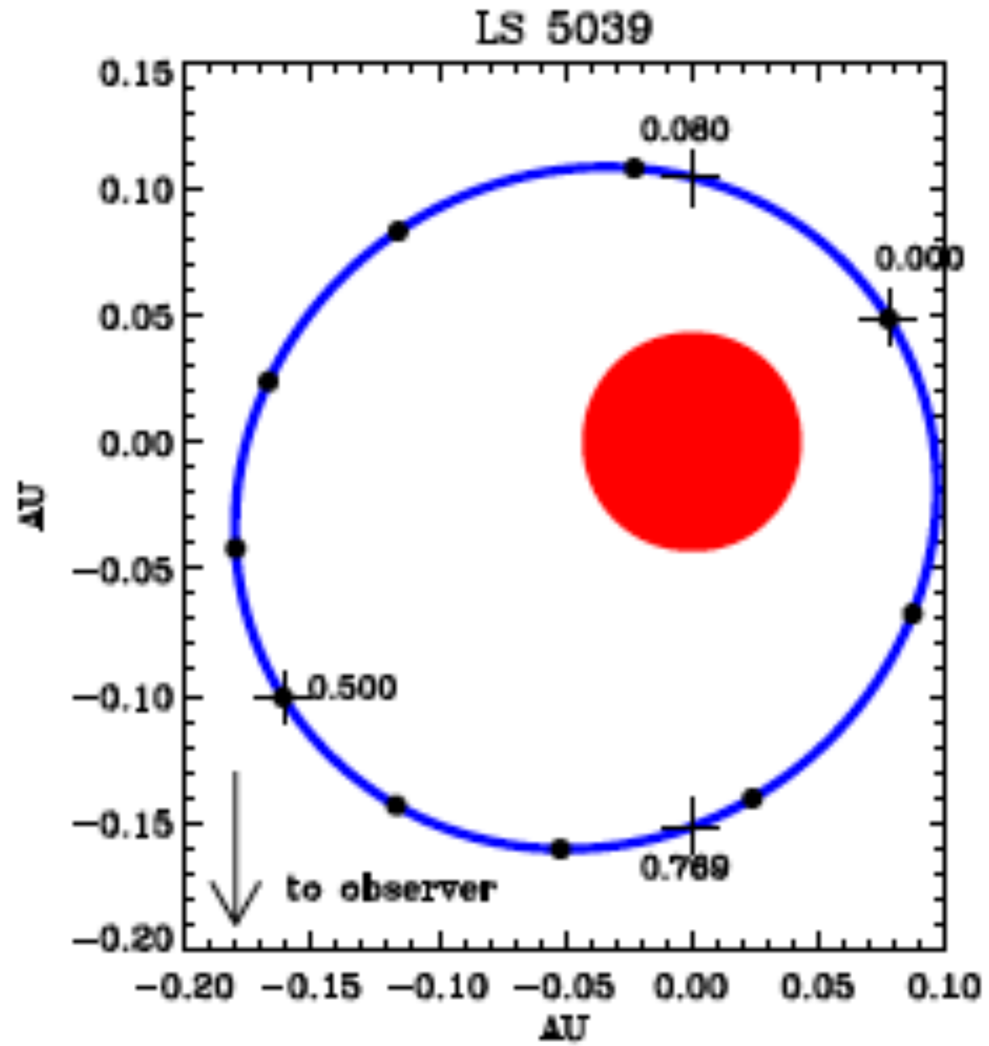
3. NuSTAR observations of LS 5039



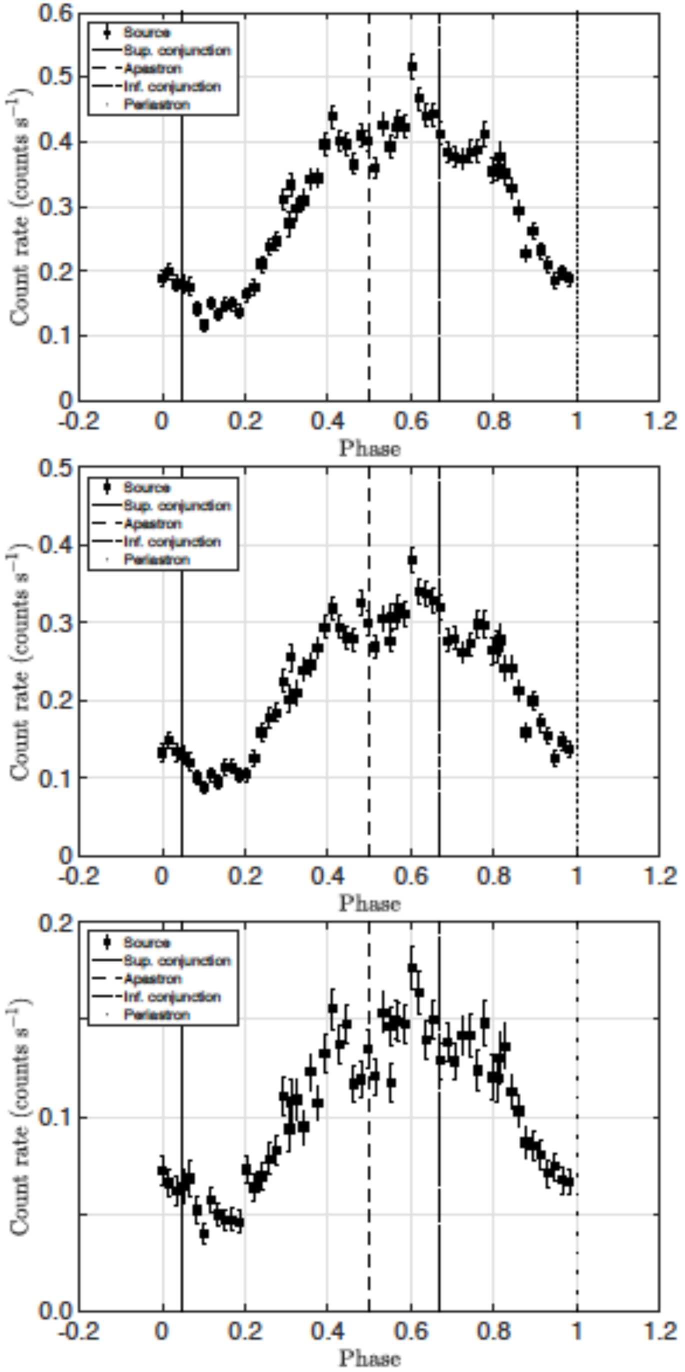
P_{orb} = 3.9 days, e ~0.34, i ~30°, d ~2.9 kpc

M = 23 $M_{\odot}$ O6.6 V((f)), L ~7×10^{38} erg/s, separation 0.1 – 0.2 au

Compact object NS (pulsar) or BH

Goals: search for pulsations, measure orbital dependence of spectral parameters

(Casares et al 2011)



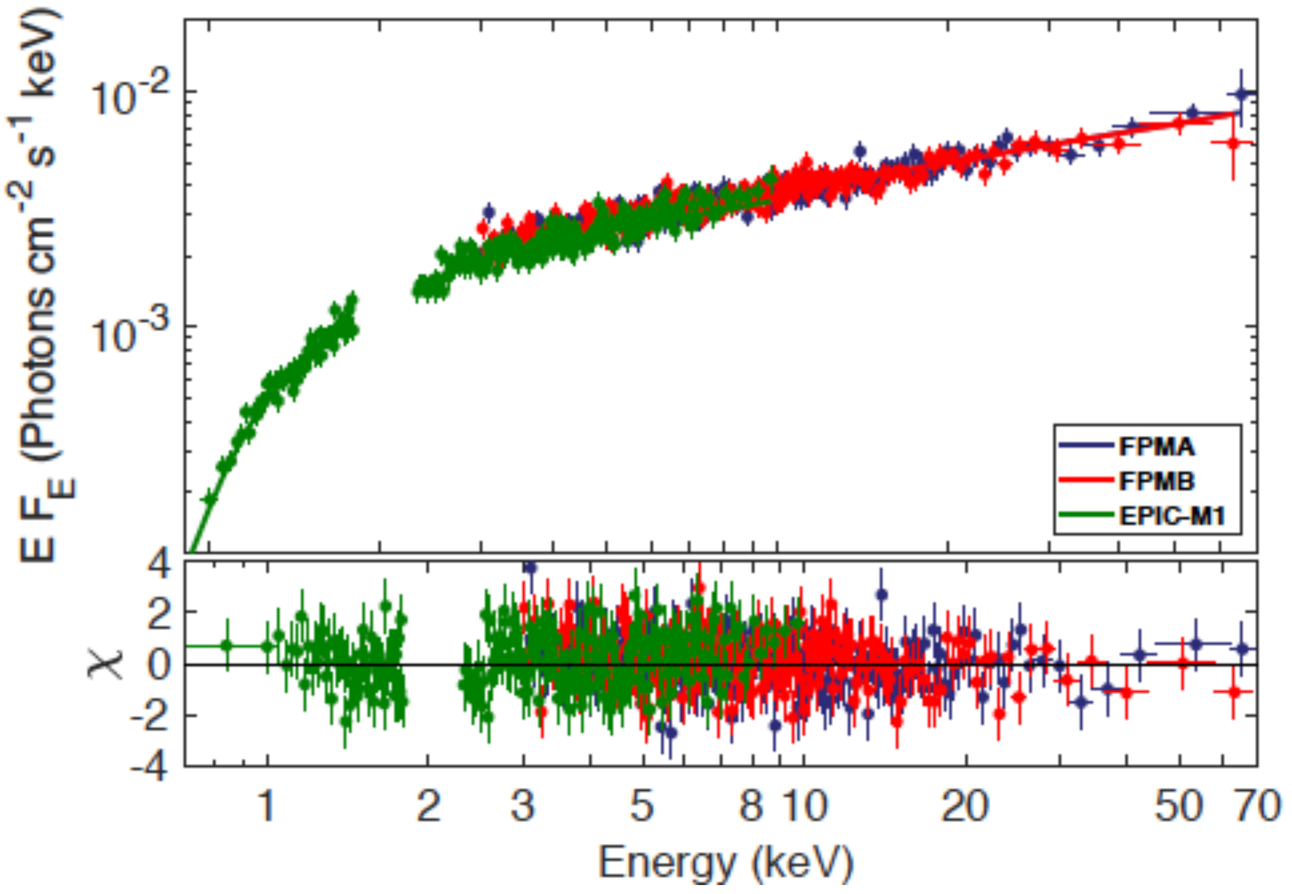
NuSTAR observation: 2016 Sep 1-5

Time span 346 ks (4 days, 60 NuSTAR orbits); GTI 166 ks

Folded light curves in **3-60 keV**, **3-10 keV**, **10-60 keV** (top to bottom).
No substantial dependence on energy.

Timing: No other periodicities found.
Possible small bursts of a few sec duration

Phase-averaged PL spectrum (NuSTAR + Suzaku XIS)



$N_H = (1.18 \pm 0.01) \times 10^{22}\ cm^{-2}$

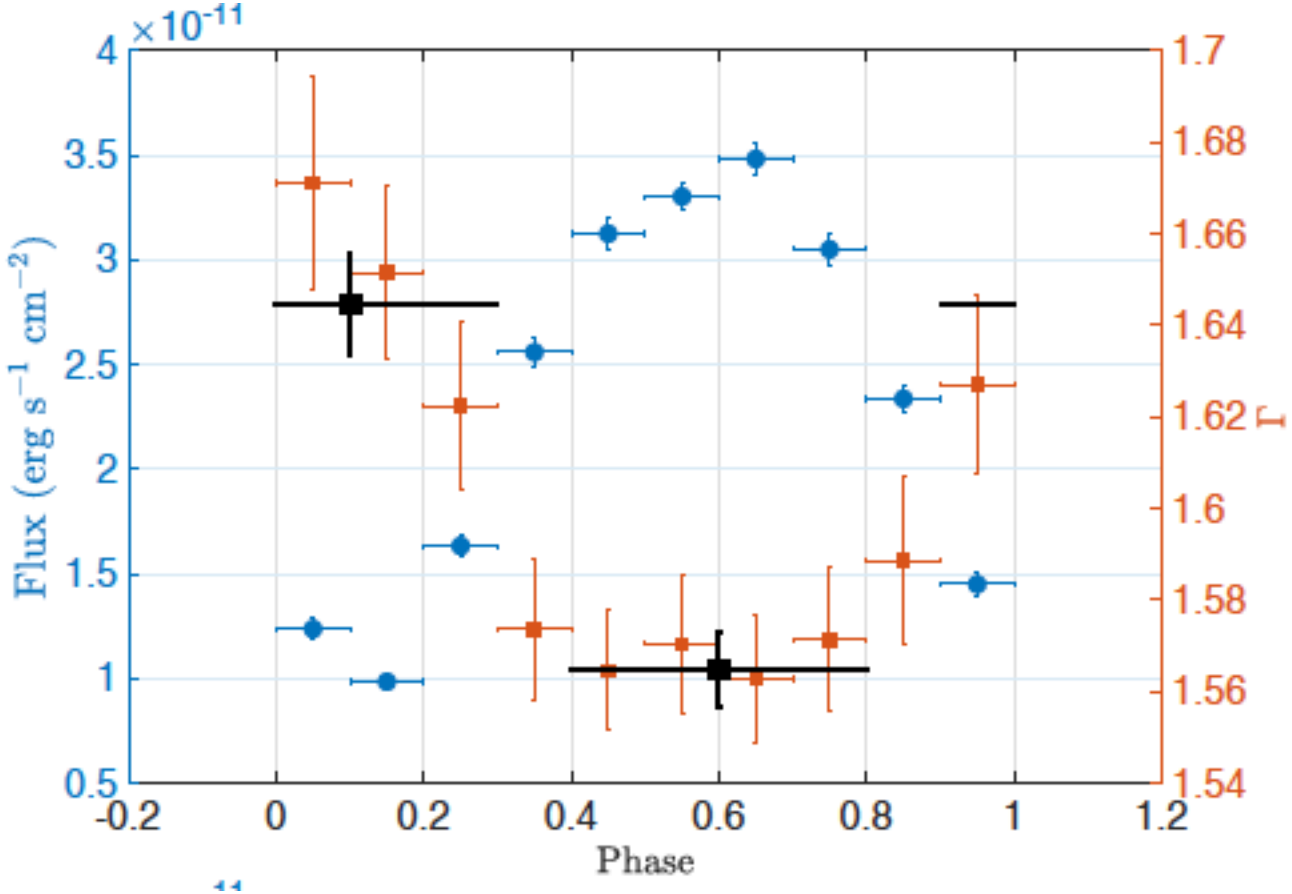
$\Gamma = 1.59 \pm 0.01$

$F_{0.5-10\ keV} = (9.64 \pm 0.05) \times 10^{-12}$ c.g.s.

$F_{10-70\ keV} = (18 \pm 0.2) \times 10^{-12}$ c.g.s.

$L_{0.5-70\ keV} \sim 2 \times 10^{33}$ erg/s

Phase dependence of 3-70 keV flux and PL slope



Slope anticorrelated with flux

Qualitatively consistent with Suzaku XIS+HXD observations (Takahashi et al 2009) but Γ is larger in the NuSTAR data – a hint of spectral cutoff at ~100-200 keV?

Thank you!!