High-speed ejecta from the high-mass gamma-ray binary PSR B1259-63/LS 2883

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20 Years of Chandra Science Symposium
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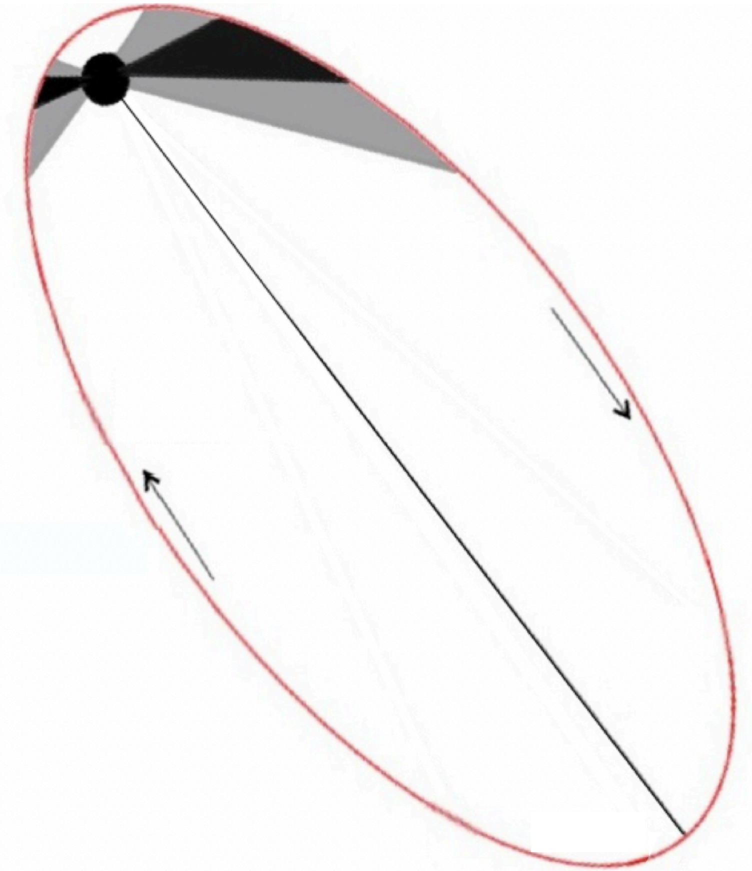
Binary orbit
(sky projection)

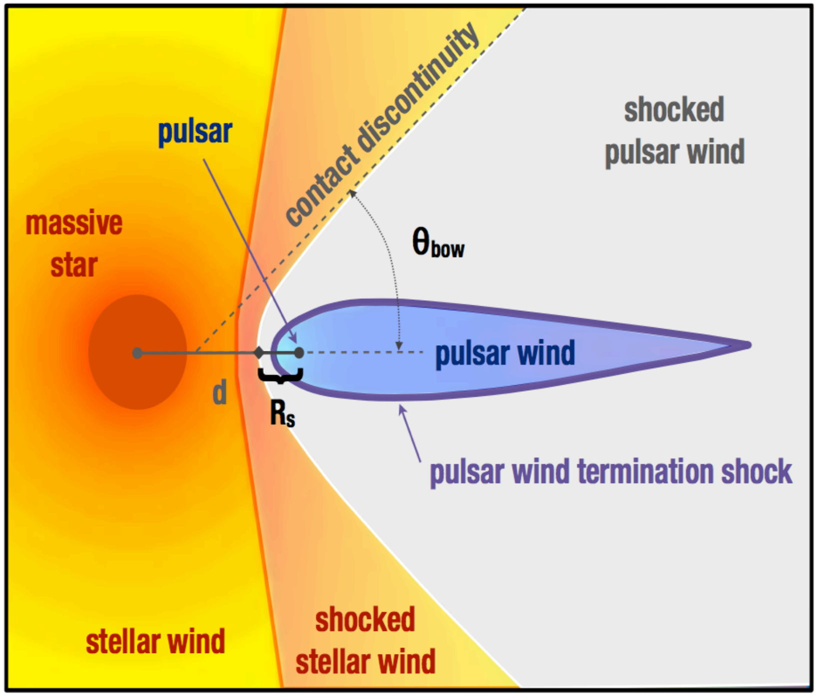


PSR B1259-63: Spin period **48 ms**, spin-down age **330 kyr**, Edot =**8×10^{35} erg/s**, B=**3×10^{11} G**

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** (inclined by **~35°** to the orbital plane), 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°** .
Recent *periastrons*: 2010 Dec 14, 2014 May 4, 2017 Sep 22.

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



(Dubus et al. 2013)

Pulsar wind (PW) is confined by stellar wind if the thrust ratio

$$\eta = \mathrm{Edot}/(\mathrm{Mdot}\ v_w\ c) < 1$$

(vice versa if $\eta > 1$).

(Tavani & Arons 1997)

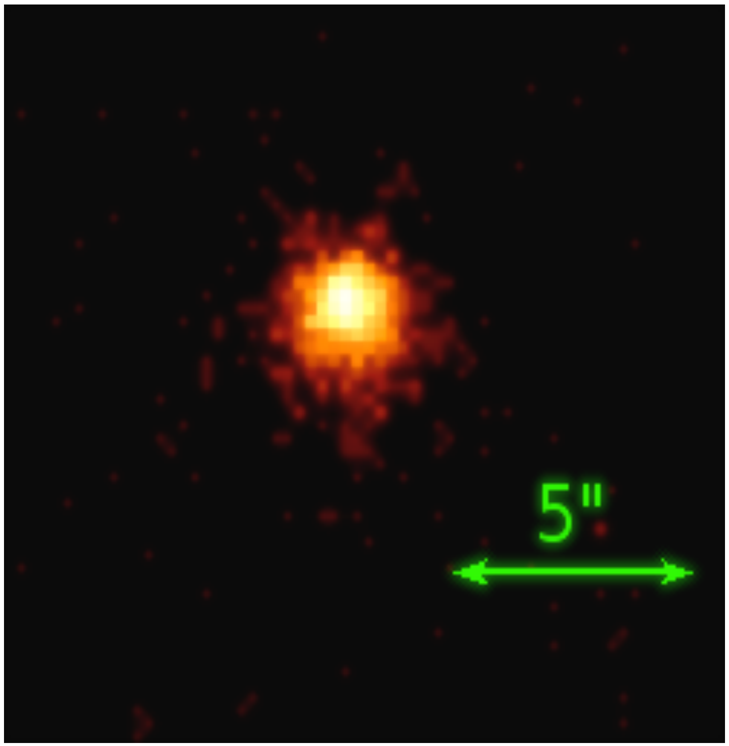
Either shocked or unshocked PW can leave the binary and interact with the ISM forming a pulsar wind nebula (PWN)

We proposed to look for a PWN outside the binary, using the excellent angular resolution of Chandra.

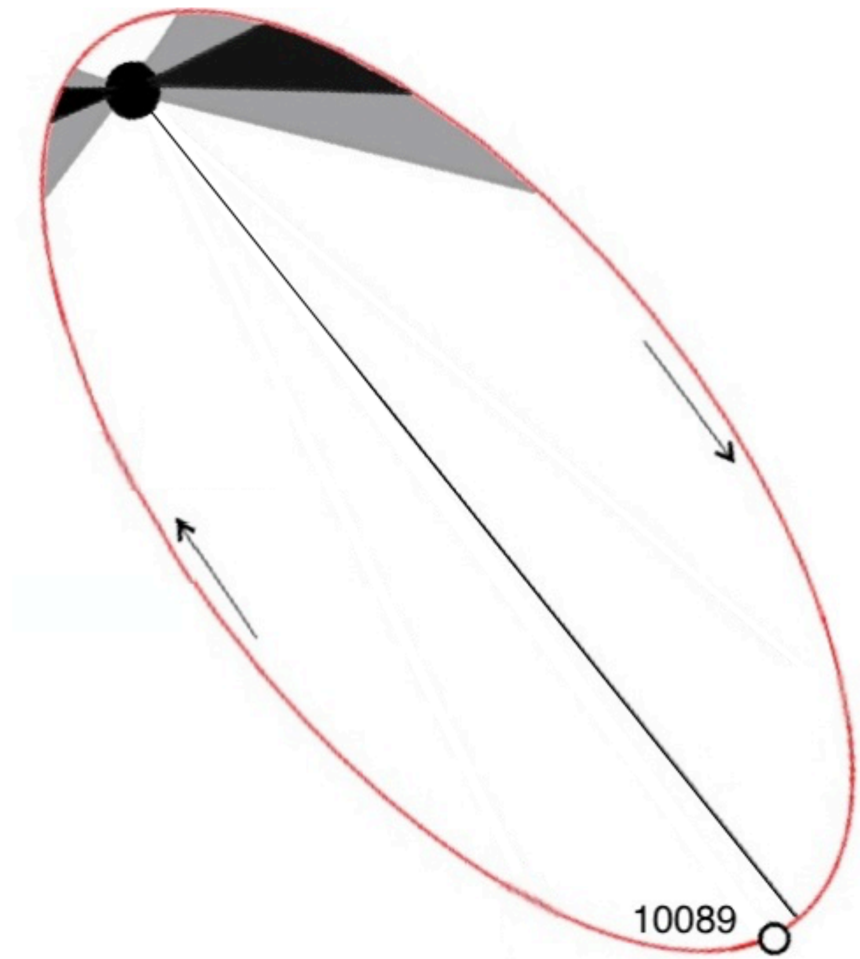
First high-res observation

2009 May 14

25 ks ACIS-I exposure

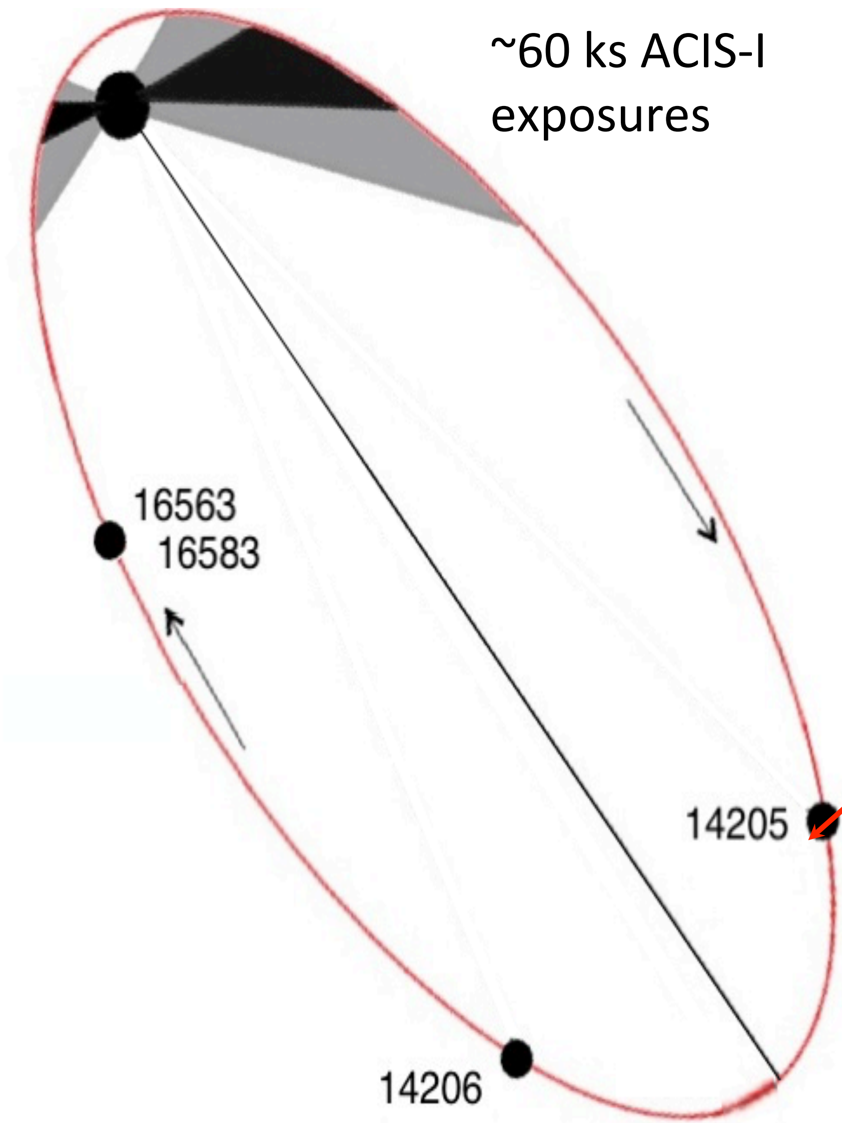


(Pavlov et al 2011)



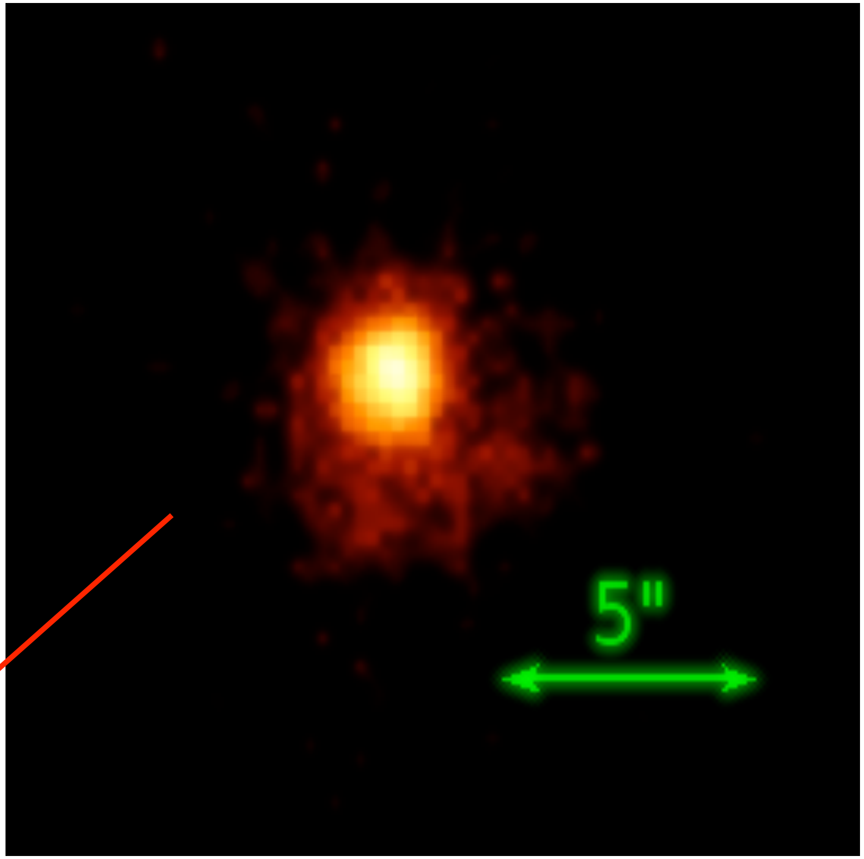
~4σ detection of asymmetric extended emission. Termination shock of PW?

Three observations in binary cycle 2011 - 2014



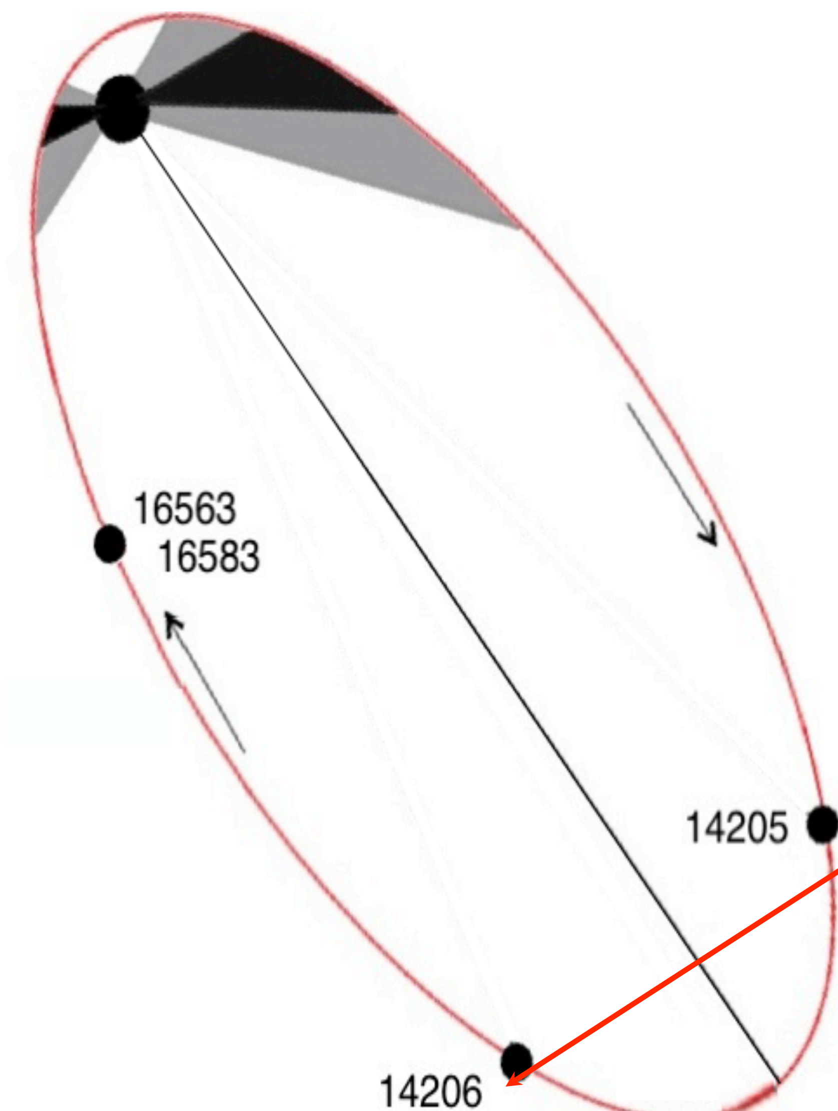
~60 ks ACIS-I exposures

2011 Dec 17

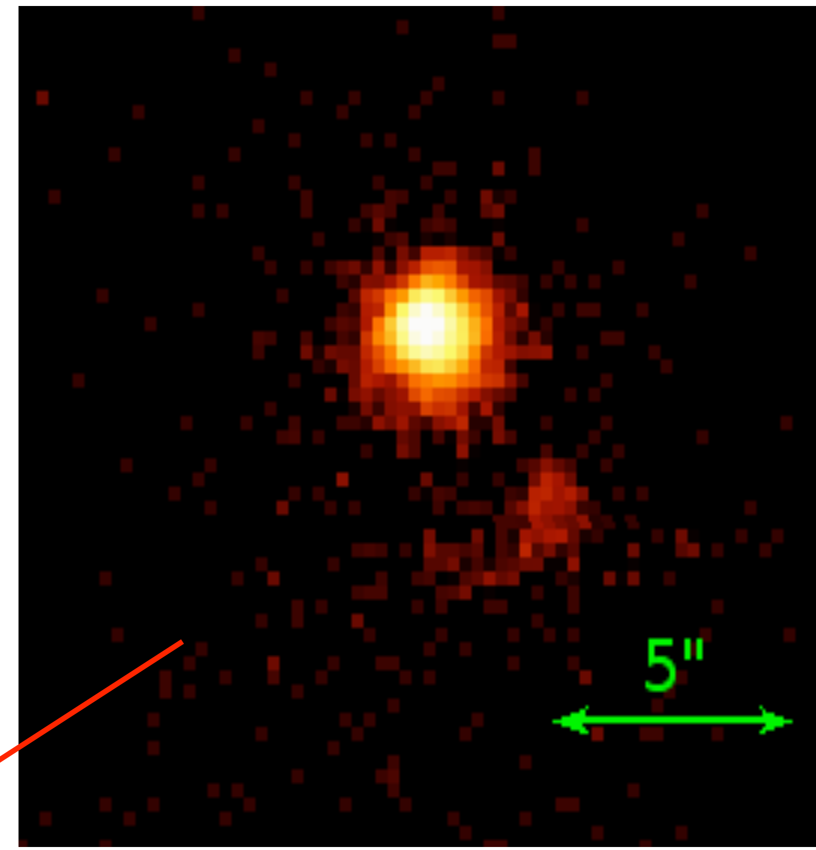


Extension is seen clearly

Three observations in binary cycle 2011 - 2014



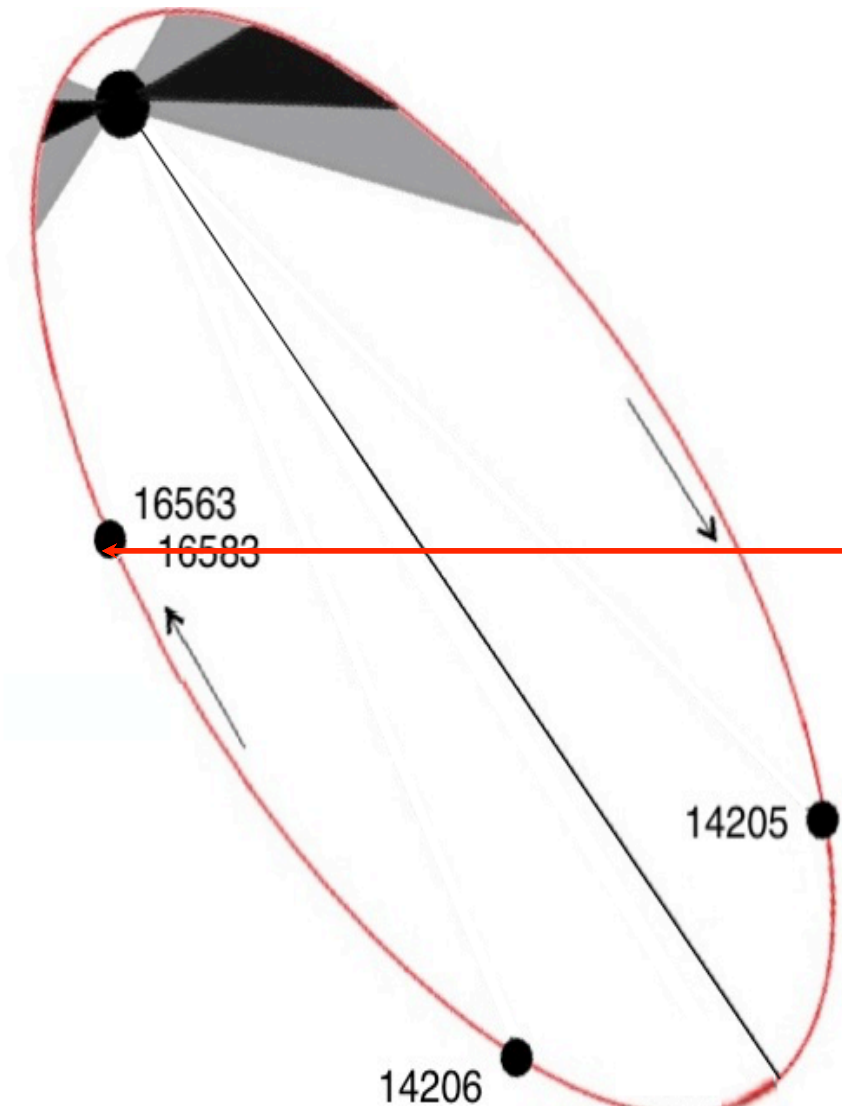
2013 May 19



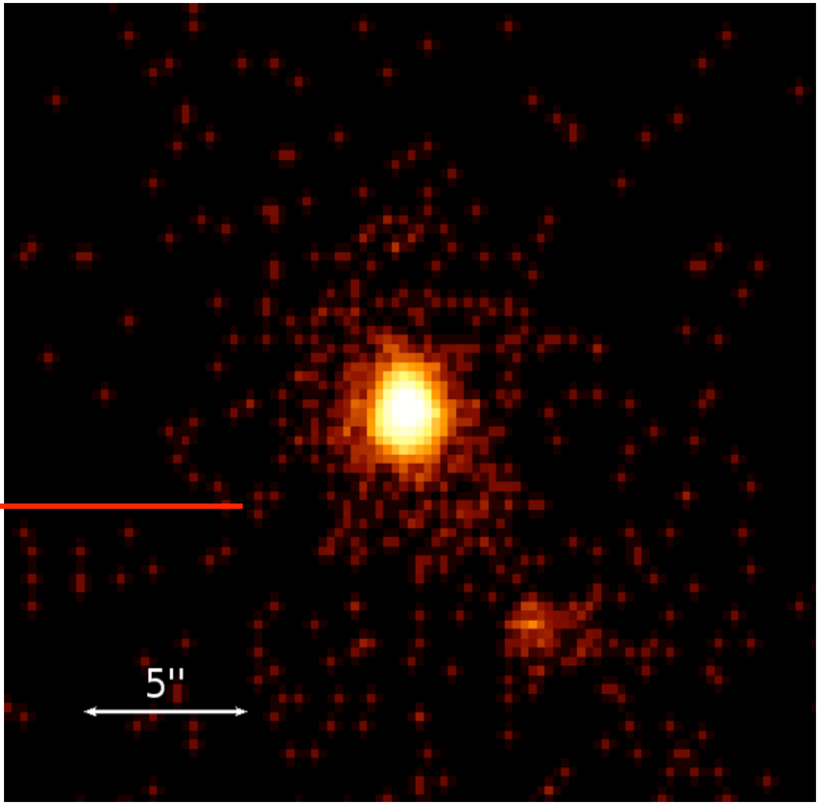
Extended object separated from the binary?

(Kargaltsev et al 2014)

Three observations in binary cycle 2011 - 2014

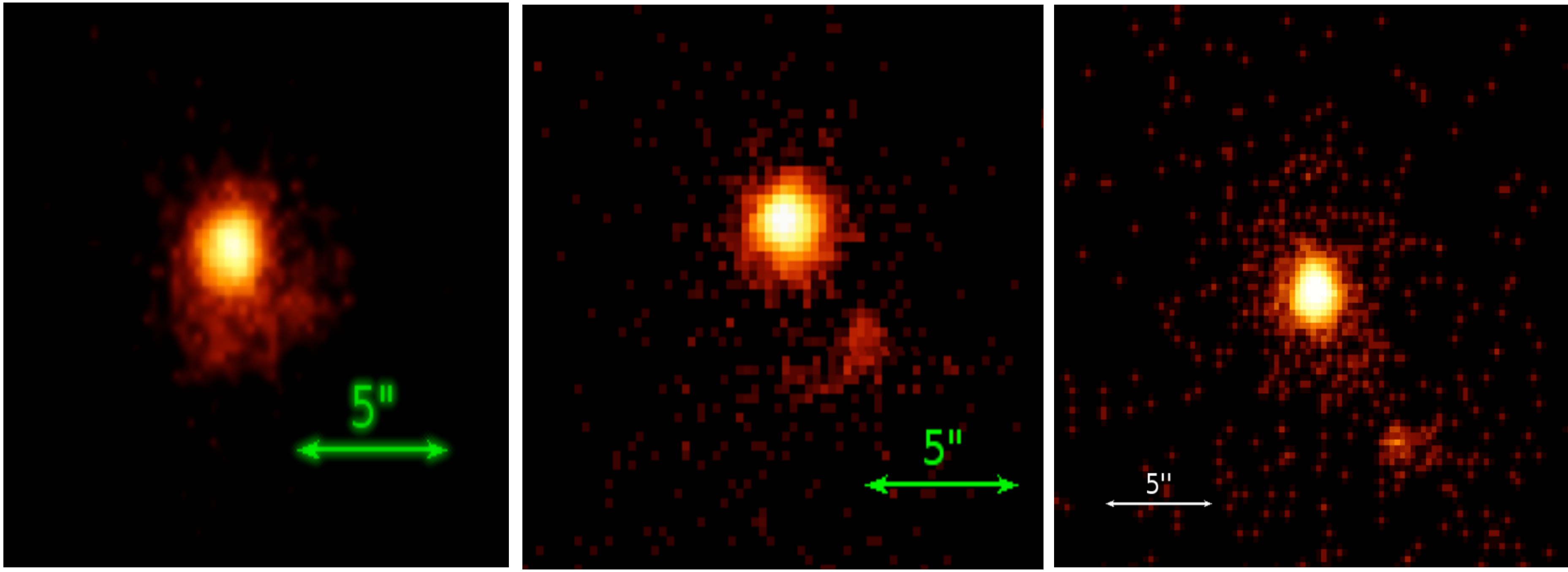


2014 Feb 8 (**DDT**)



Extended object is moving!

(Pavlov et al 2015)



2011 Dec 17 | 2013 May 19 | 2014 Feb 8

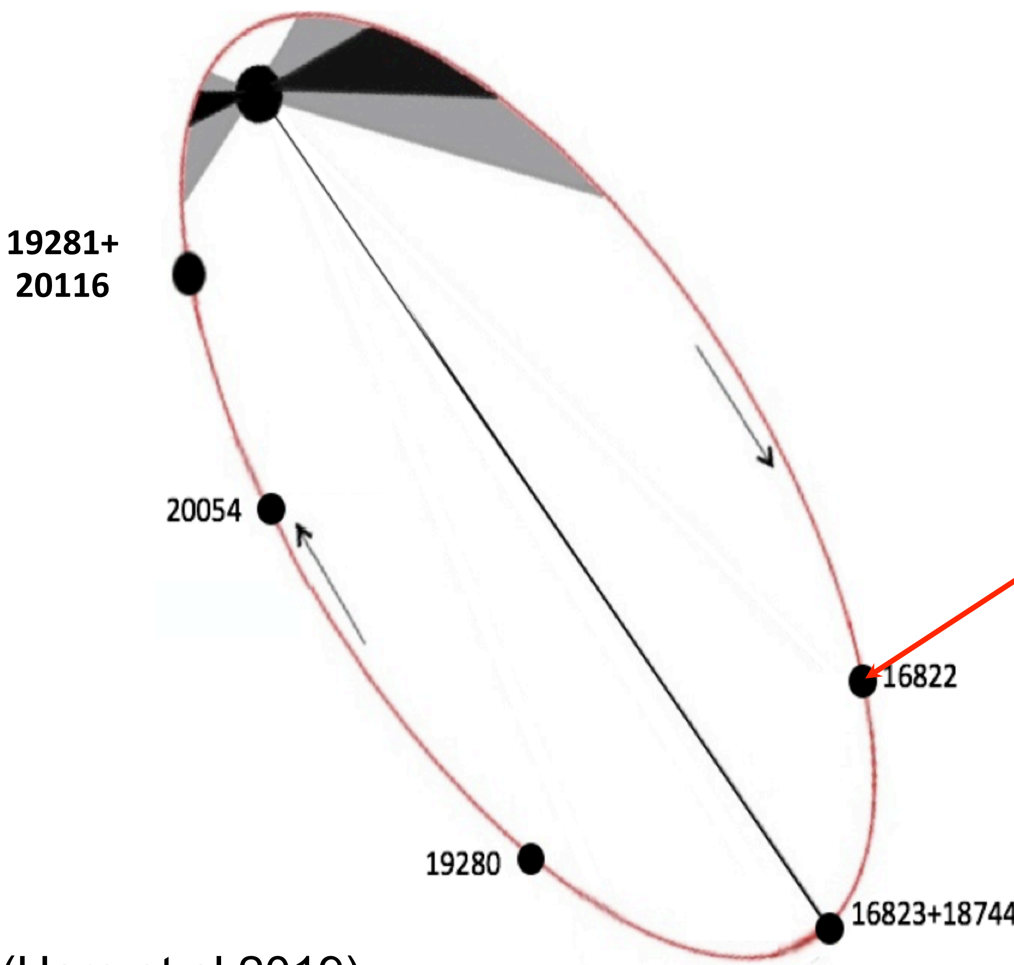
Extended object moving from the binary along its major axis, fading with increasing distance.

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

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

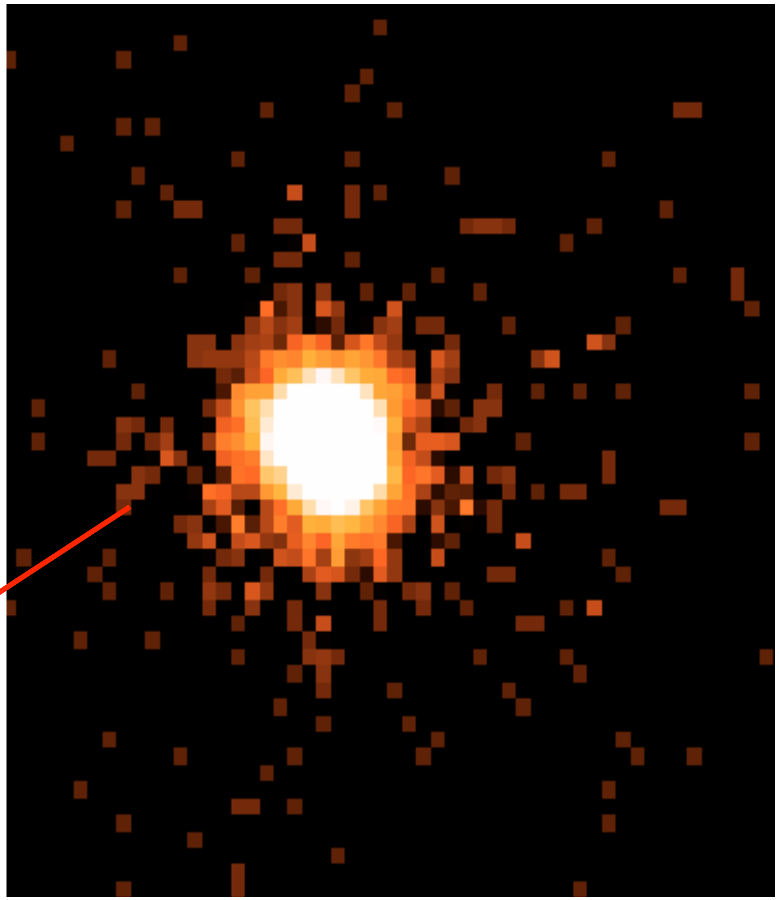
Five observations in the next binary cycle: Apr 2015 – Jul 2017

ACIS-I exposures 60-65 ks



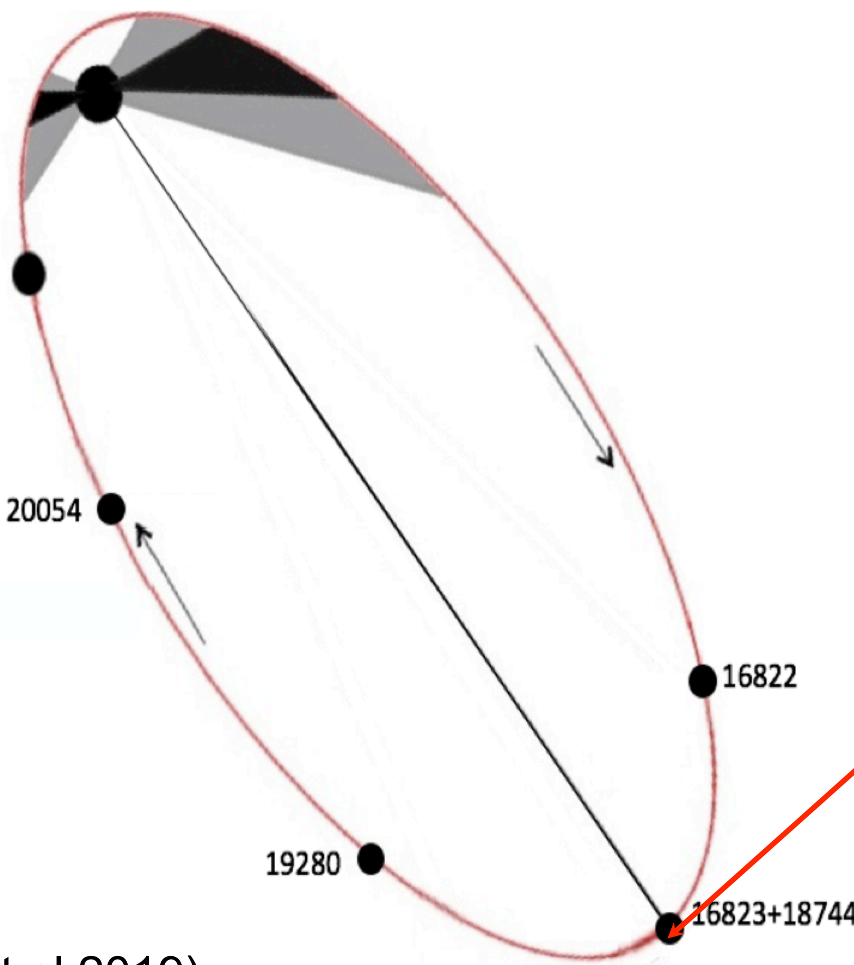
(Hare et al 2019)

2015 Apr 21



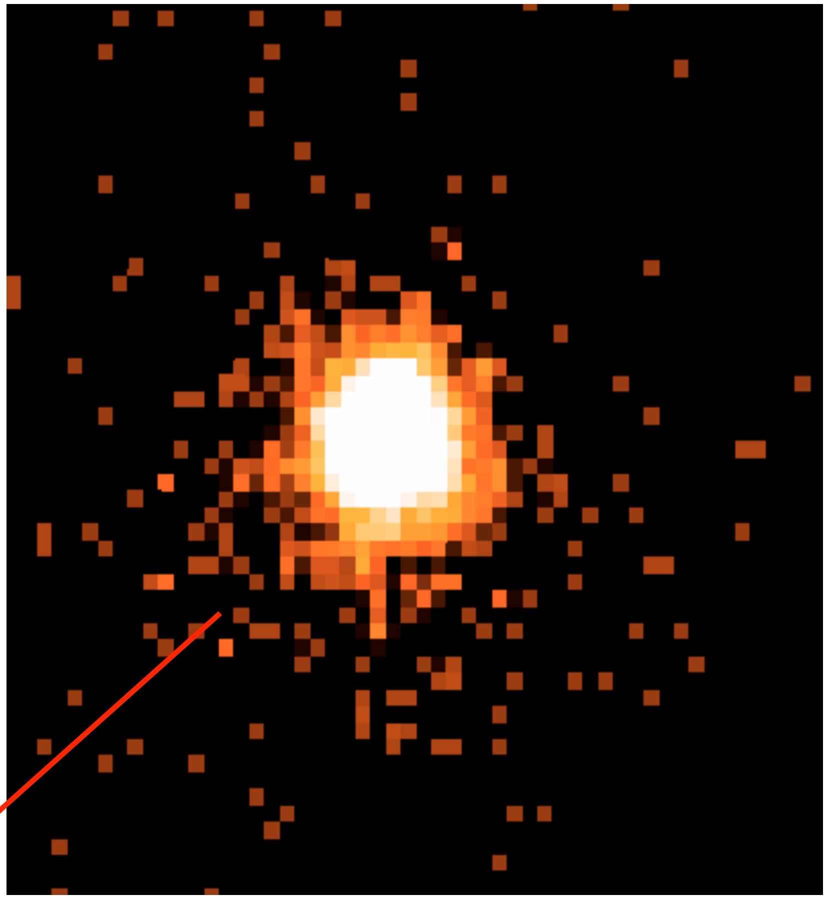
No extended emission?

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



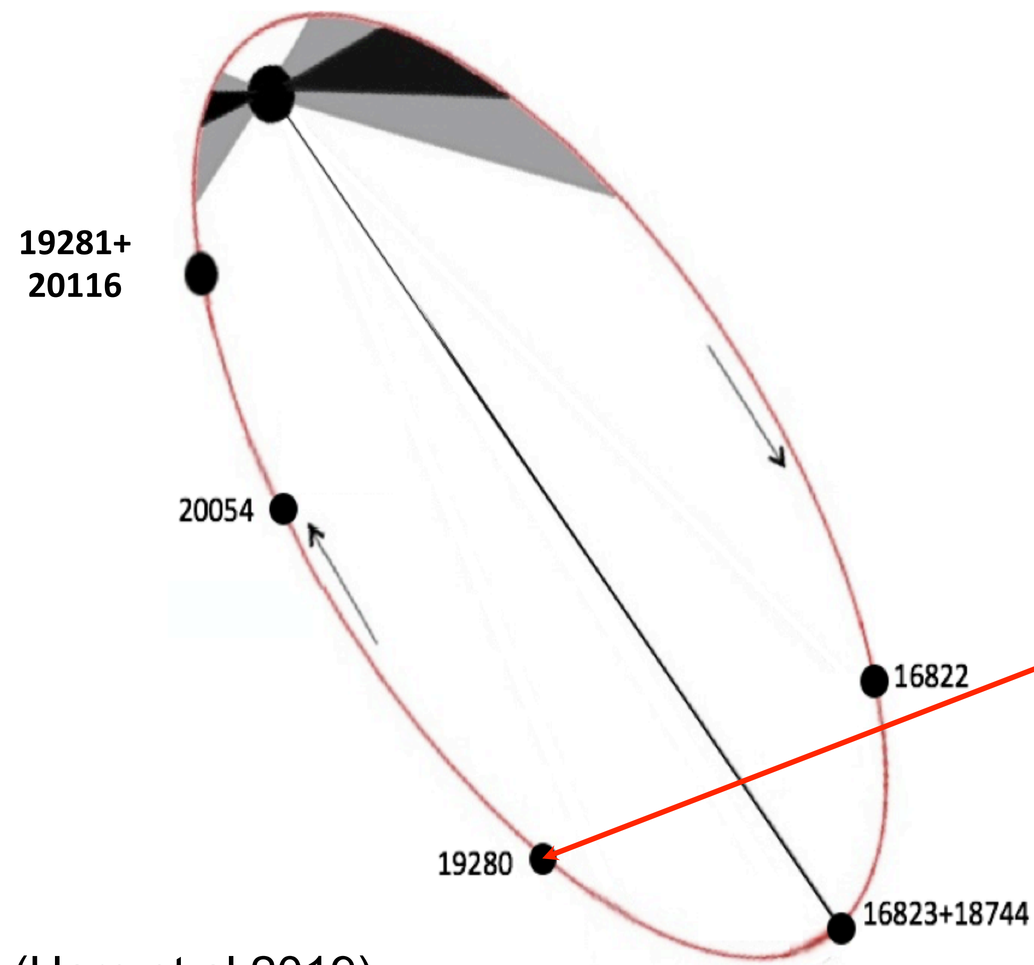
(Hare et al 2019)

2016 Jan 12



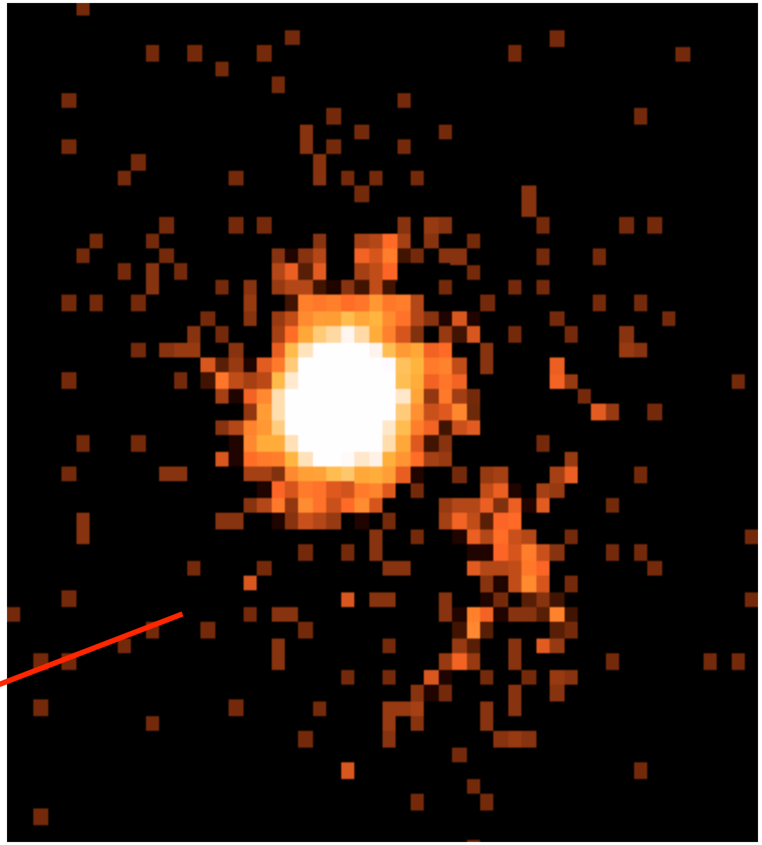
A hint of extended emission

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



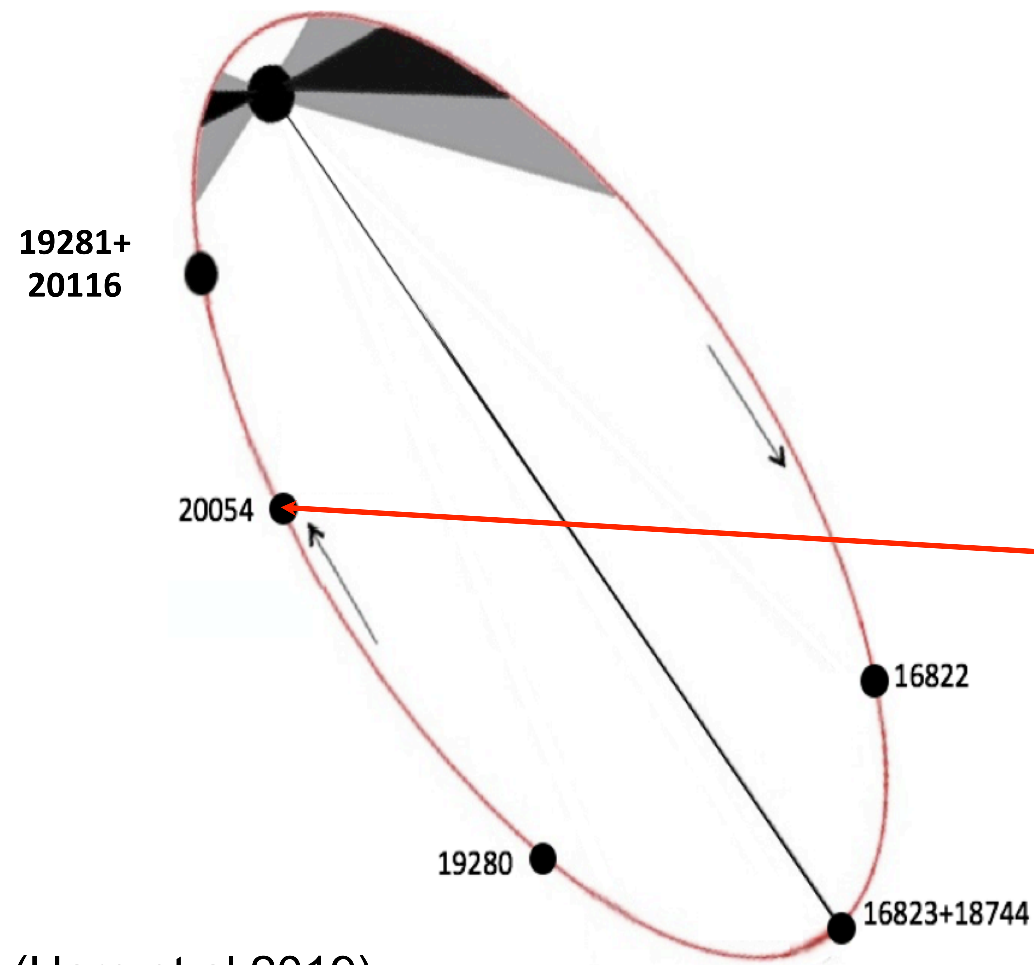
(Hare et al 2019)

2017 Jan 6



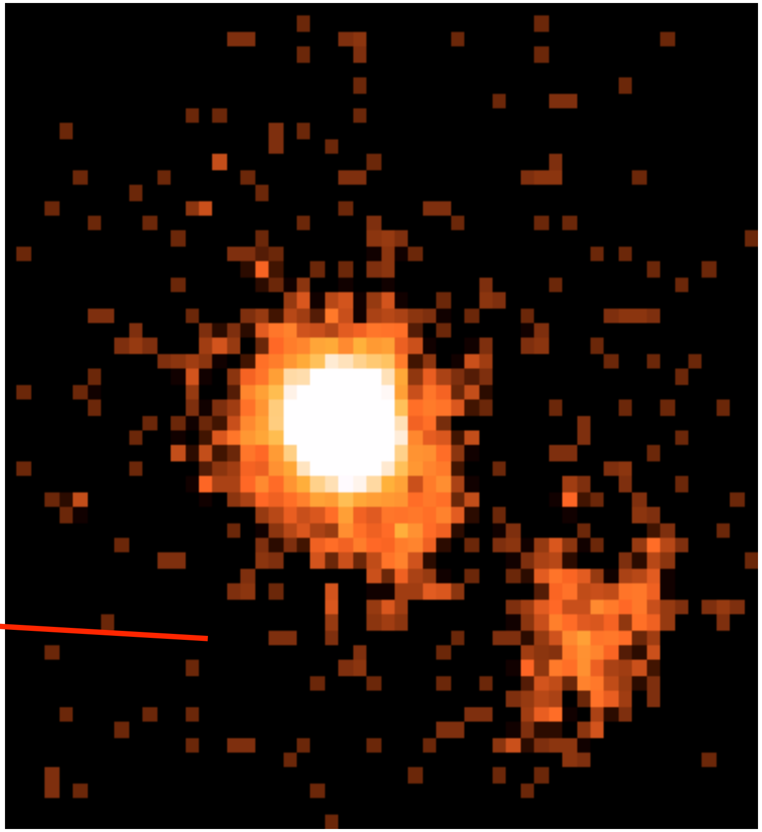
Separated extended object with "whiskers"!

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



(Hare et al 2019)

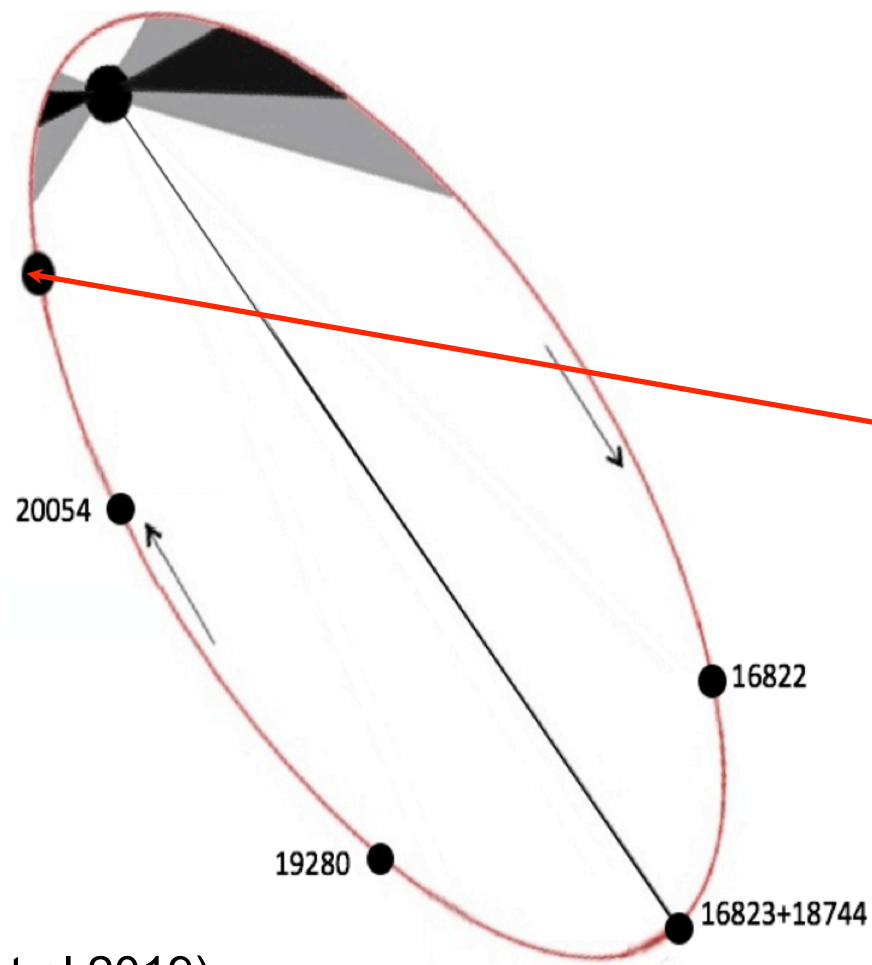
2017 Apr 24 **(DDT)**



Unexpected brightening!
Different shape.
Second "clump" emerging?

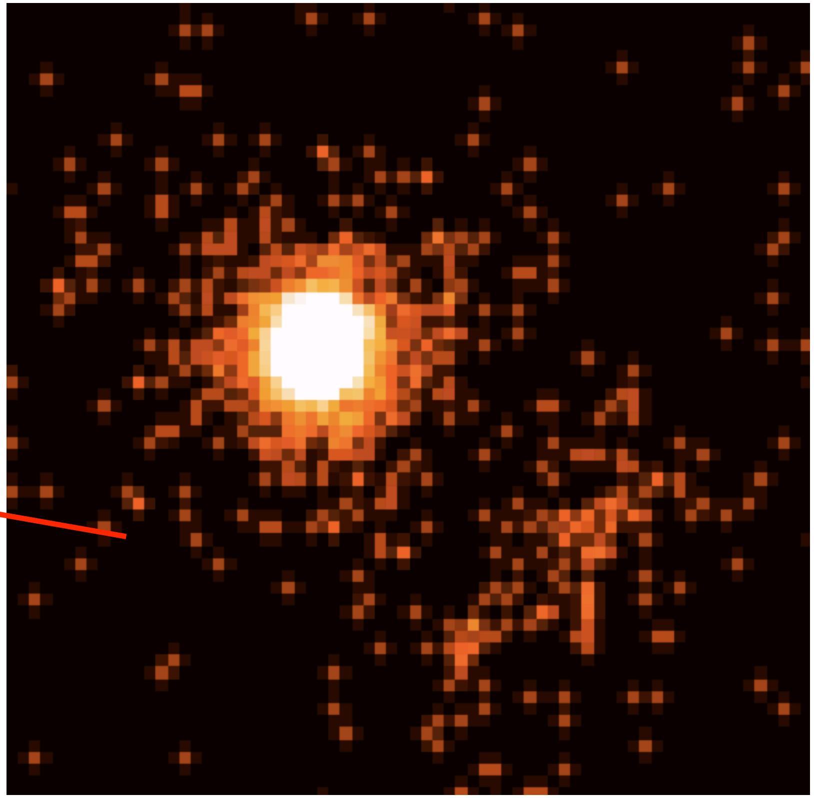
Five observations in the next binary cycle: Apr 2015 – Jul 2017

ACIS-I exposures 60-65 ks

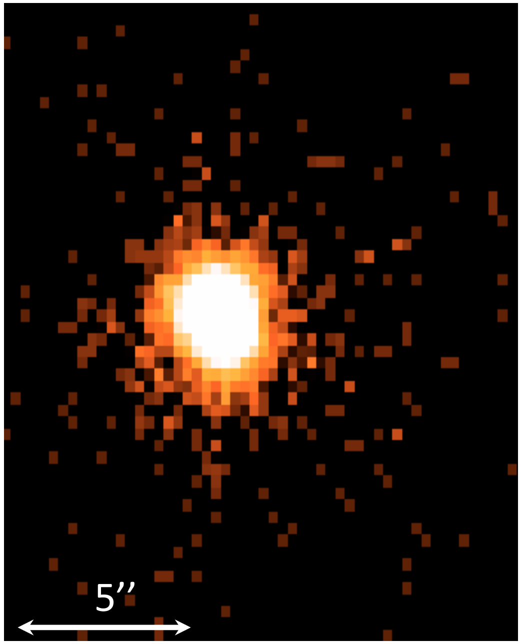


(Hare et al 2019)

2017 Jul 20



Brightening disappeared.
Clump moved further,
Yet another shape.
Second clump disappeared

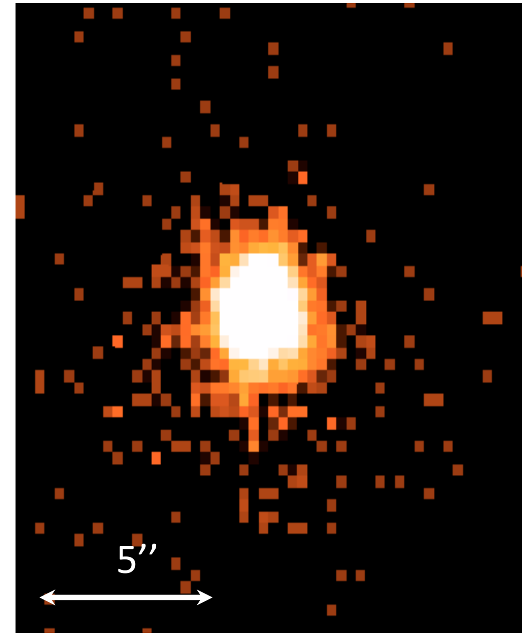


2015 Apr 21

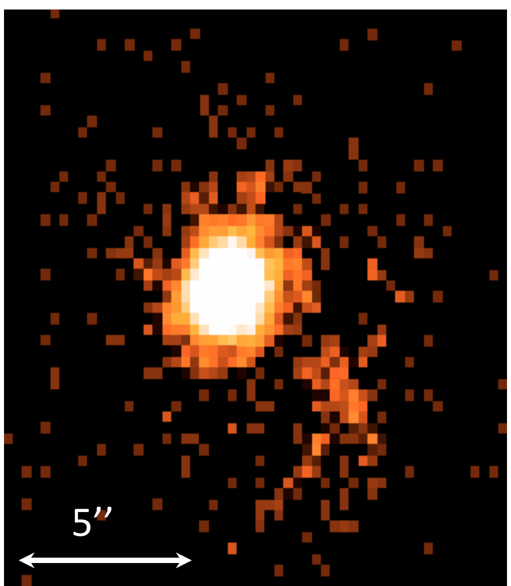
2016 Jan 12

New clump detected moving in *same direction* with *similar velocity*

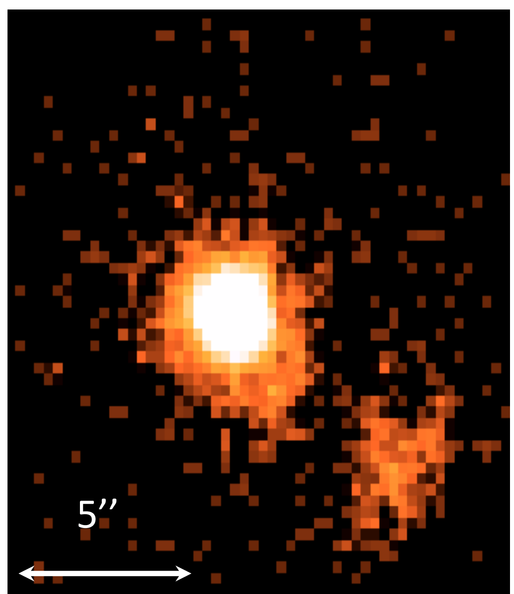
Shows strange "*whiskers*" in Jan 2017, *brightening* and *2nd clump* [?] in Apr 2017



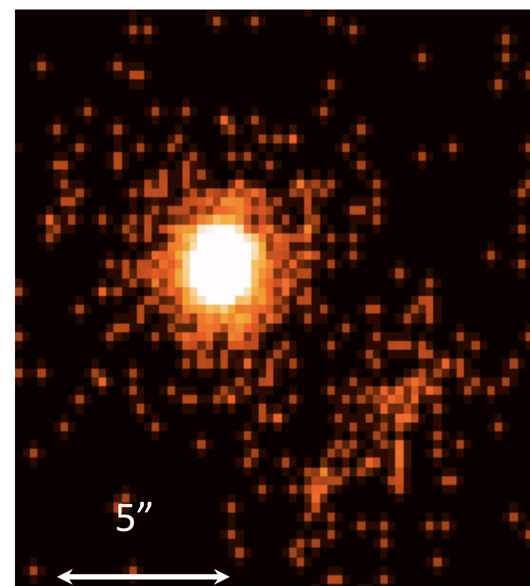
2017 Jan 6



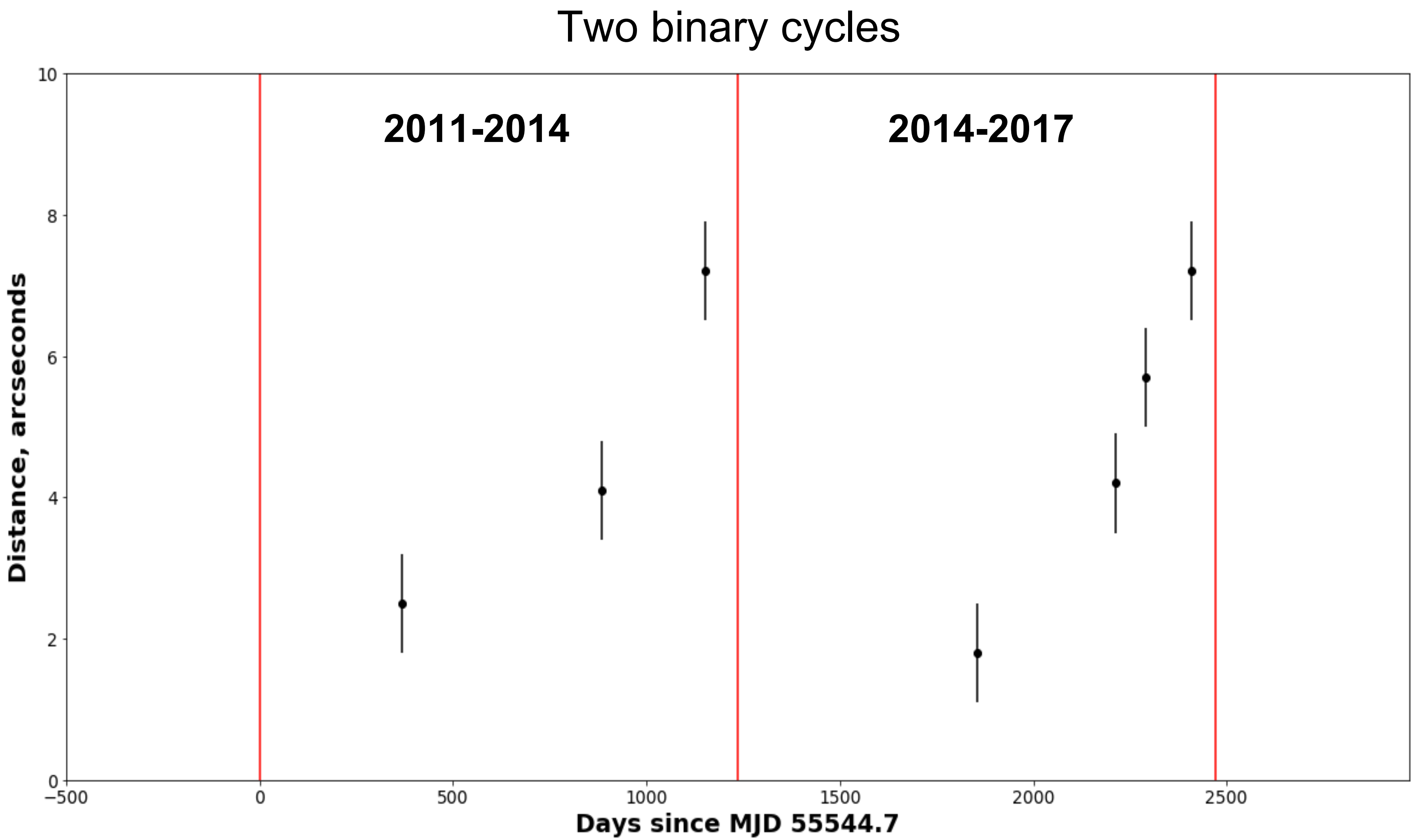
2017 Apr 24



2017 Jul 20



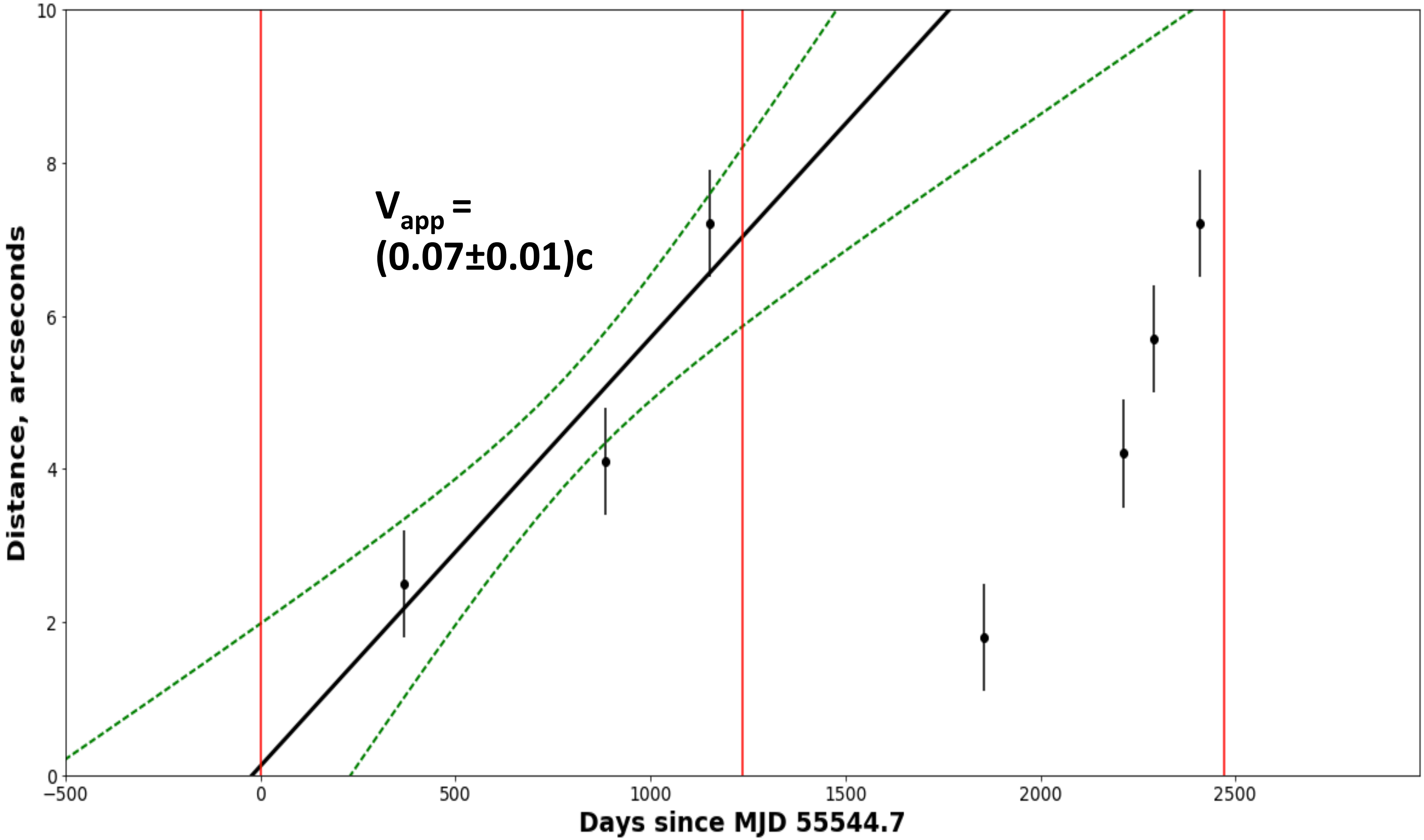
Clump separation from the binary vs time



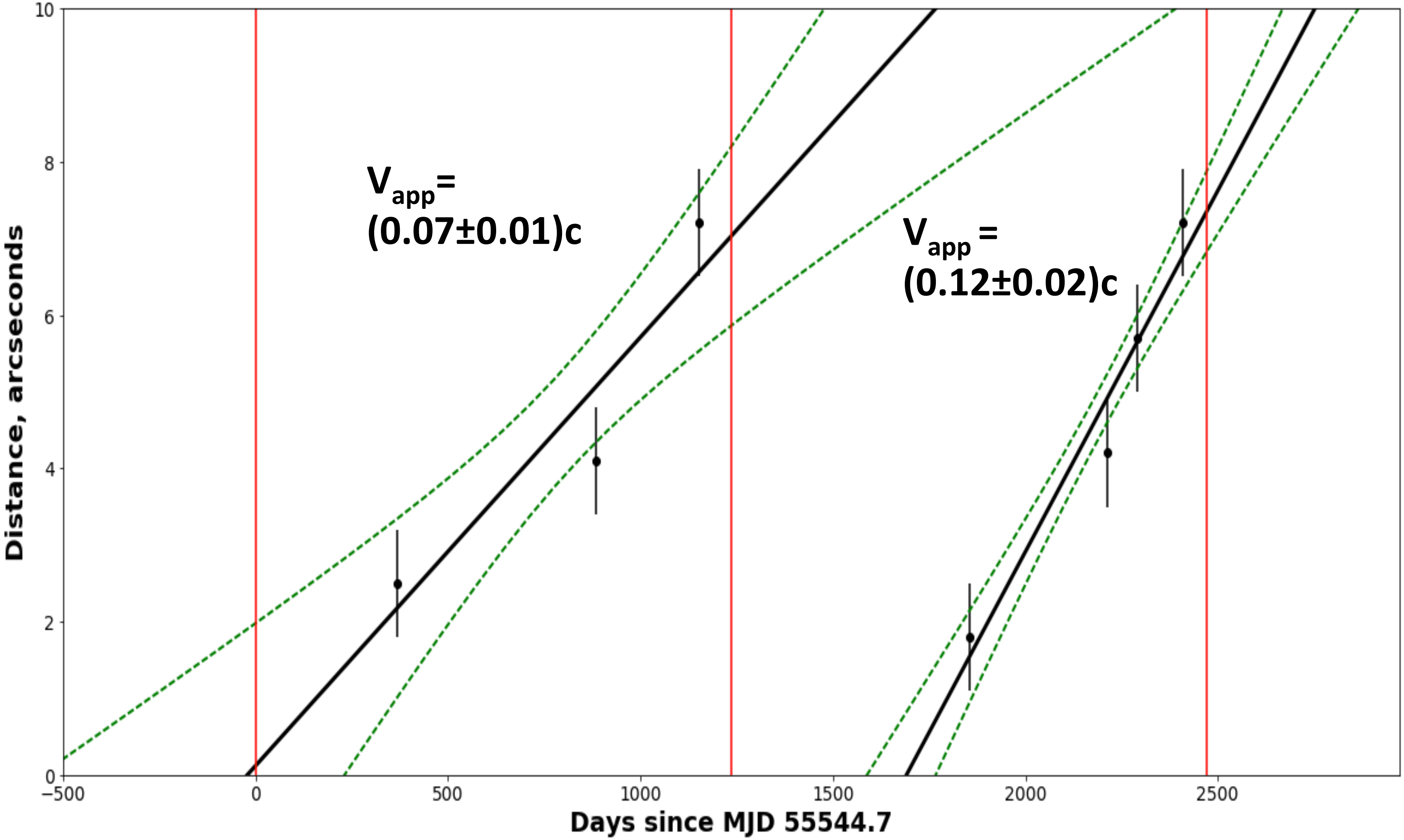
1 arcsec = 3.4×10^{16} cm

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

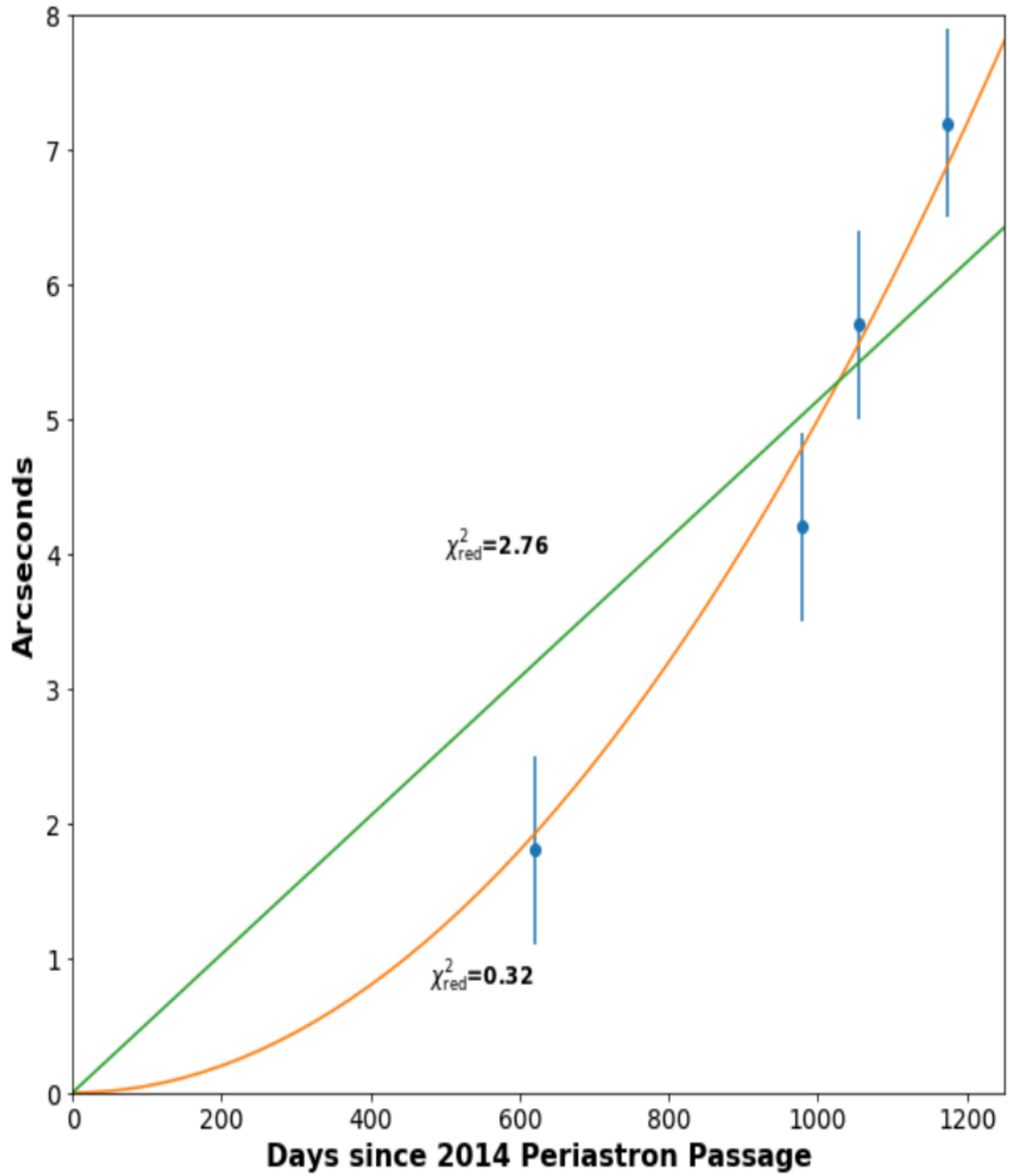
If the clump was launched at 2014 periastron with a low speed, the acceleration is

$$\boldsymbol{a = 47 \pm 2\ \mathrm{cm/s^2}} =$$

$$= \mathbf{14{,}800 \pm 600\ km/s/yr}$$

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

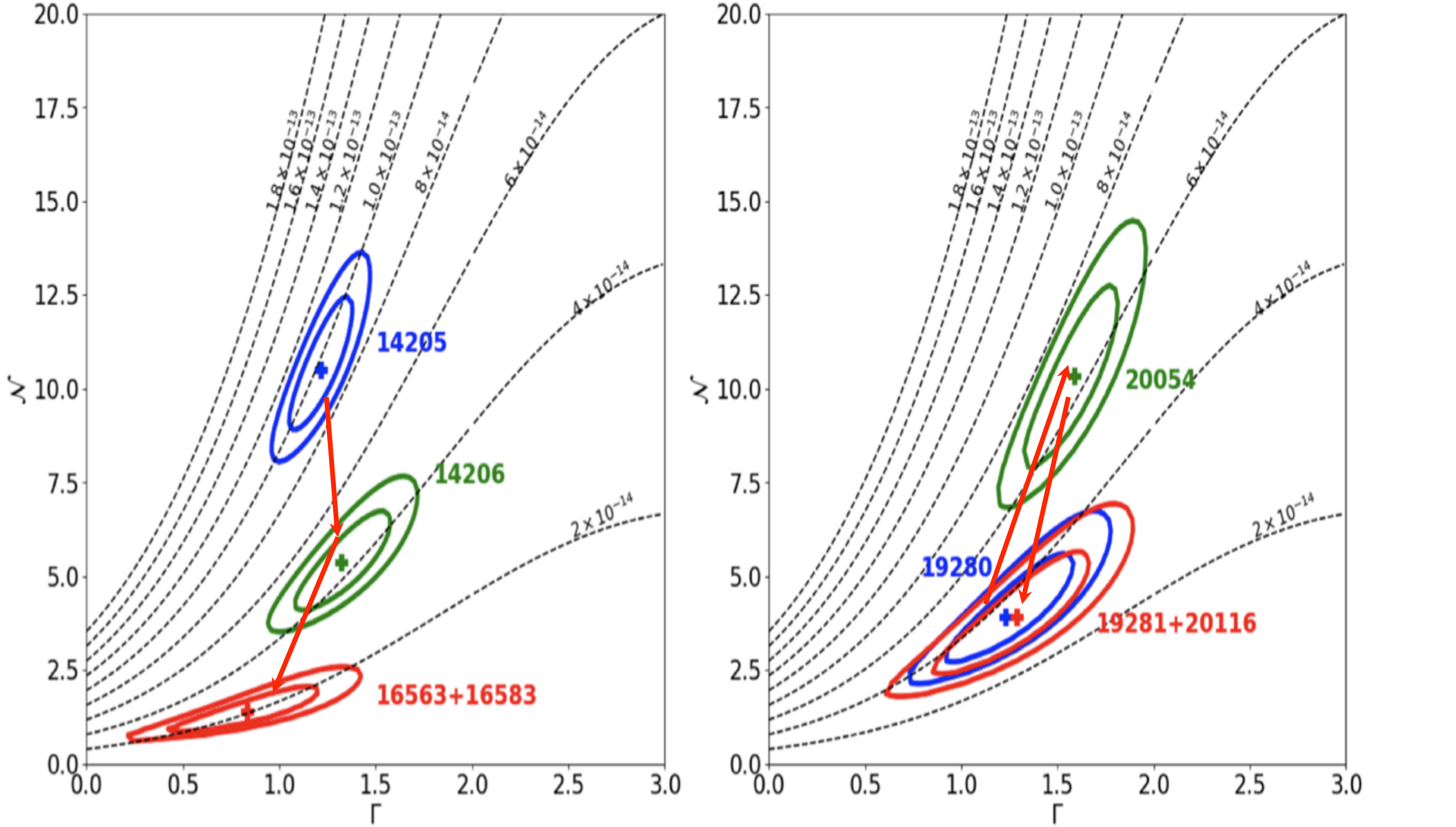
V ≈ 0.2 c if motion in orbital plane



Power-law spectra (confidence contours)

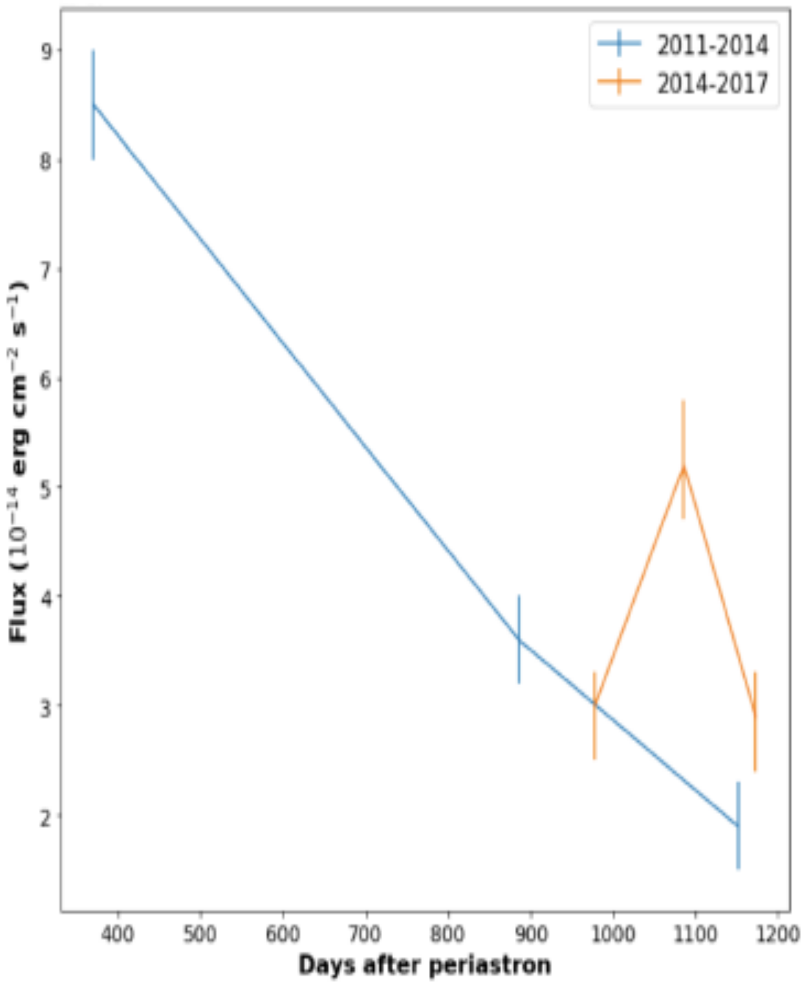
Normalization vs photon index ***Γ***, with lines of constant flux (0.5-8 keV)

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

L_X ~ (2 – 9) × 10^{31} erg/s

at d = 2.6 kpc ;

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

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 ;

$W << P_{bin}\ Edot = 7\times10^{42}$ erg

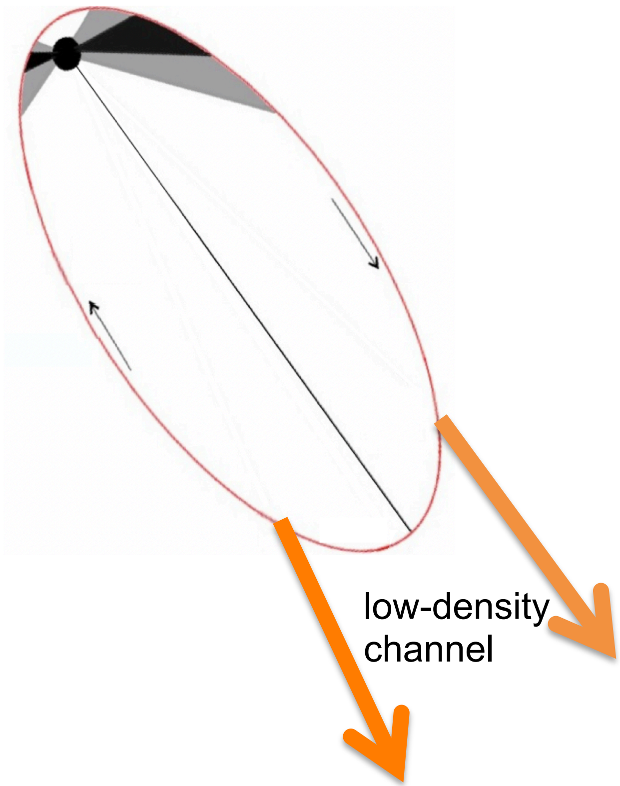
Problem: Isolated e^-/e^+ clump would be immediately decelerated and destroyed by drag force in the interstellar medium: $f \sim \rho_{amb} v^2 A$, but clumps show *no deceleration*!

Likely, they are *loaded with ions from the stellar wind disk* and *move in a very low density medium*

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

Possible scenario:

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

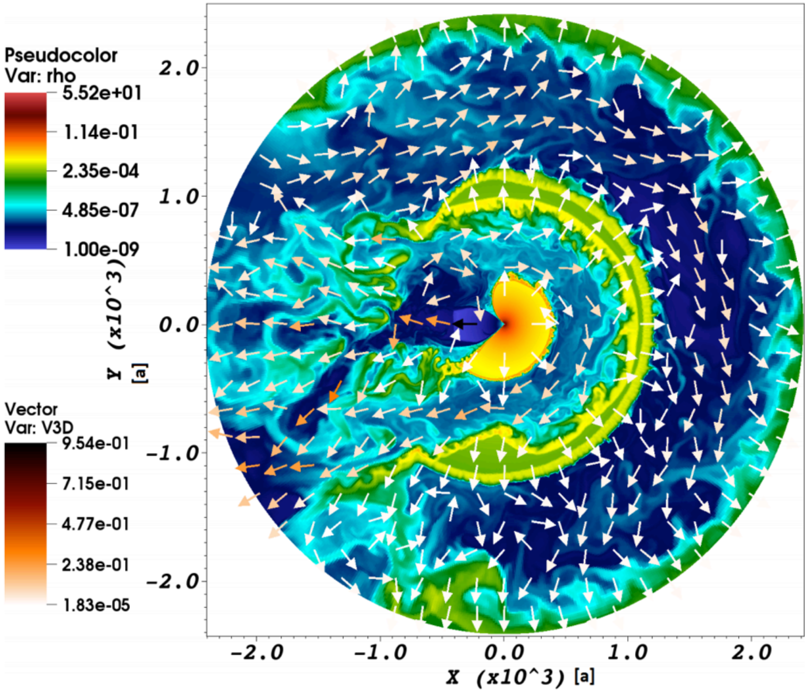


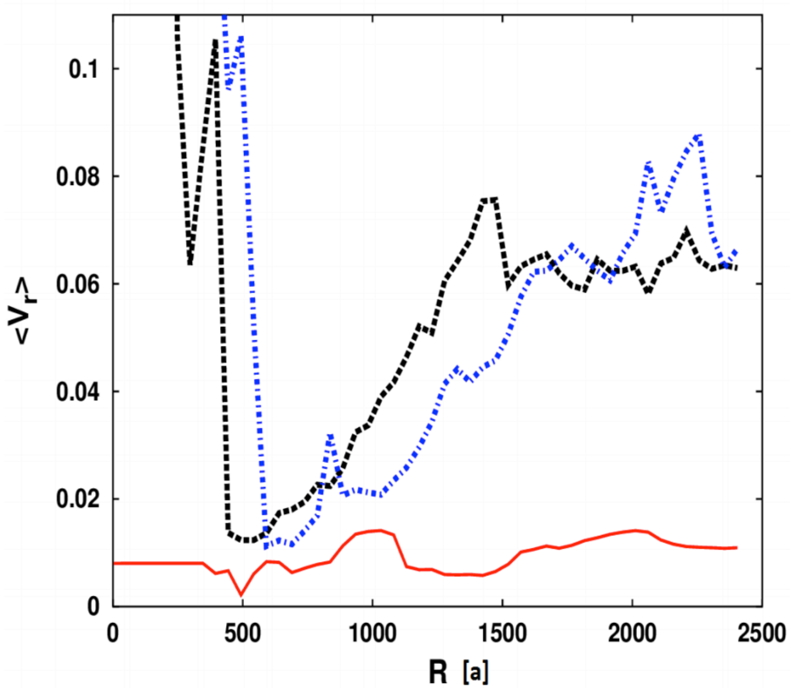
When the pulsar crosses the disk, a clump of mixed disk matter and relativistic electrons (clump mass ~10^{21} g) is formed and ejected into the channel

The clump is pushed "from behind" and perhaps accelerated by the shocked PW along the channel until the clump speed approaches the shocked PW speed, ~0.1c – 0.3 c.

Such a scenario was supported by numerical simulations

(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

- Are the clumps indeed launched near *periastron passages*?

- Do they indeed move with a nearly constant *acceleration*? Why could the acceleration be different in different cycles?

- Is the clump *brightening* due to *internal* processes (e.g., magnetic field reconnection in turbulent plasma) or *external* ones (e.g., collision with a previously launched clump)? How long do the brightening episodes last, what are the peak luminosities?

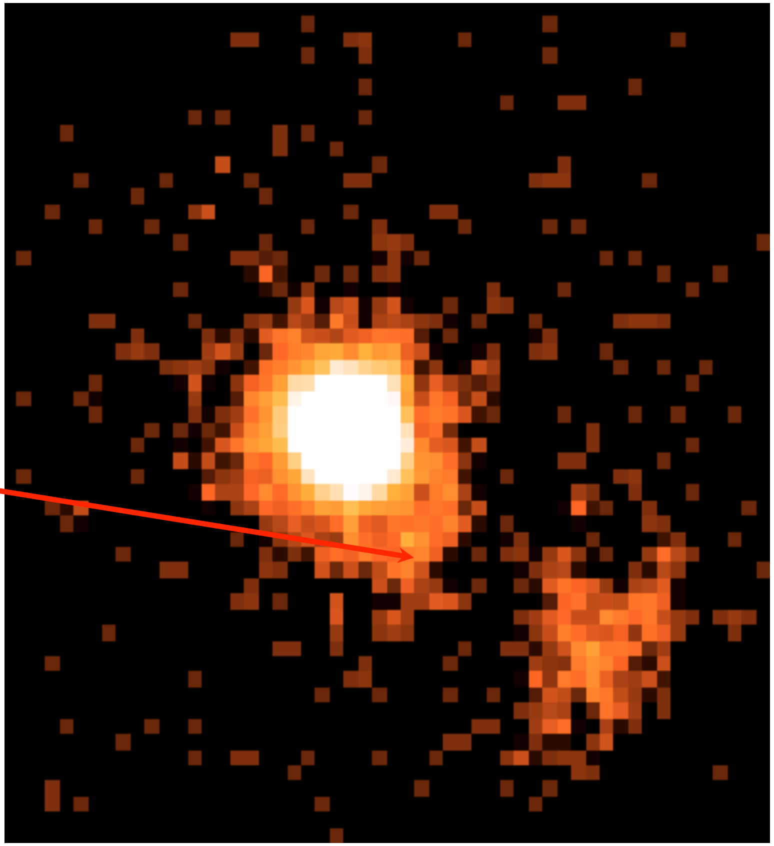
- What is the origin of the *whiskers*? Instabilities in the clump plasma? How fast do they evolve?

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?

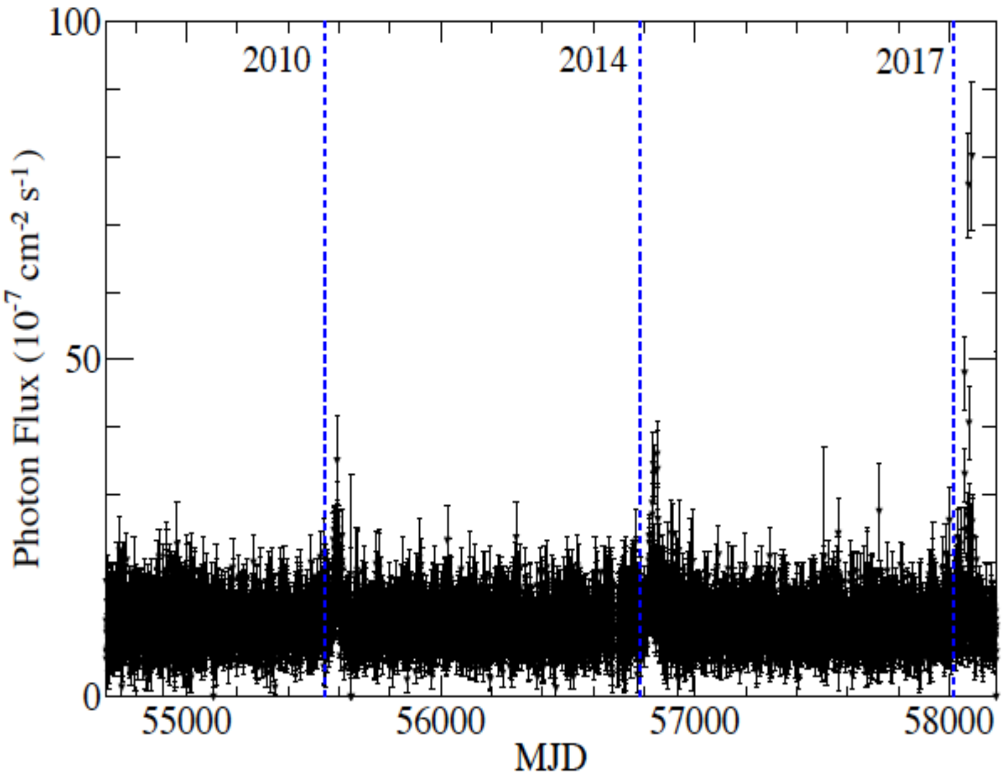
Or launched at a later date, well after periastron?

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

Open Questions

- How clump parameters are connected with the *post-periastron γ-ray flares*?

Fermi GeV γ-ray flares after periastrons of 2010, 2014, 2017

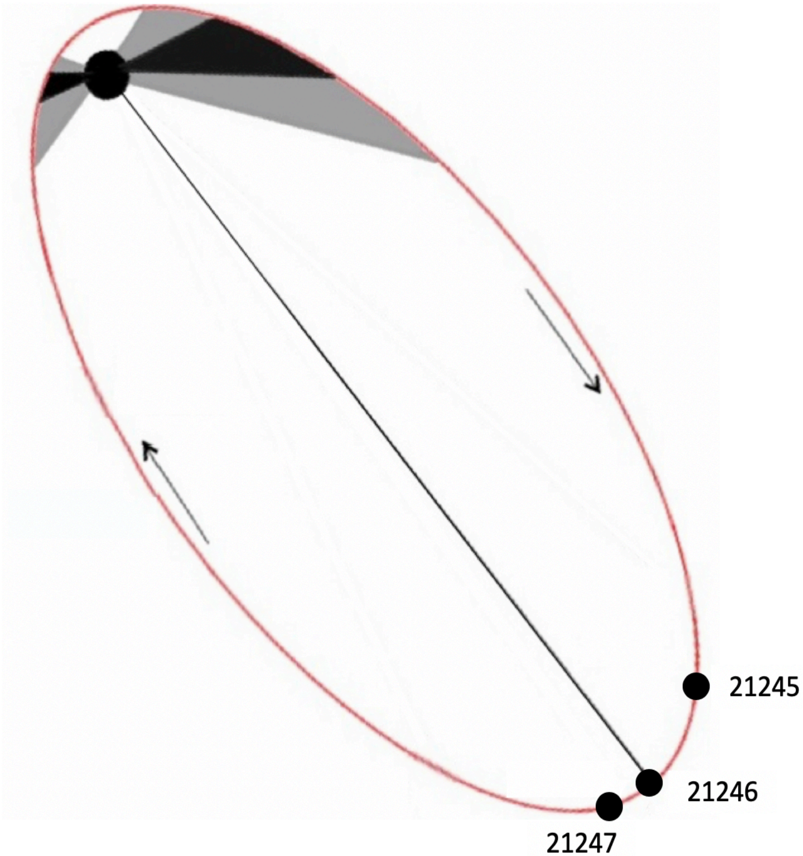


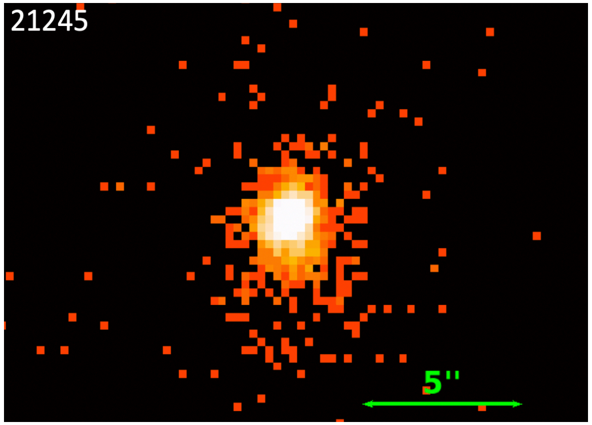
The flares after 2017 periastron had higher photon flux and fluence (**L_γ > Edot** in some of them), faster variability (~1.5 min), lasted longer (up to 90 day after periastron) – Johnson et al 2018.

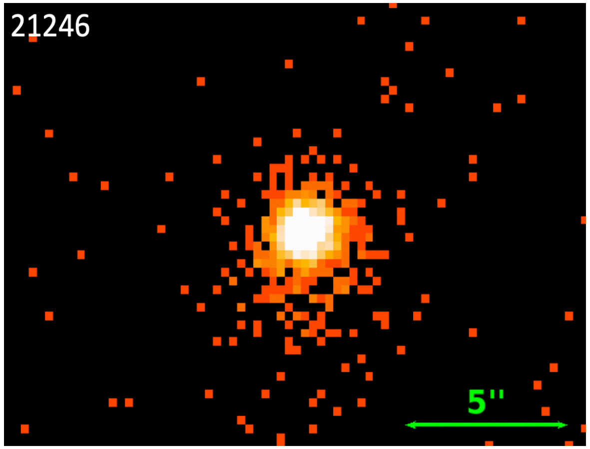
Such differences can affect clump ejection and properties – higher clump mass, lower velocity, higher brightness, larger size in 2017-2021 cycle ?

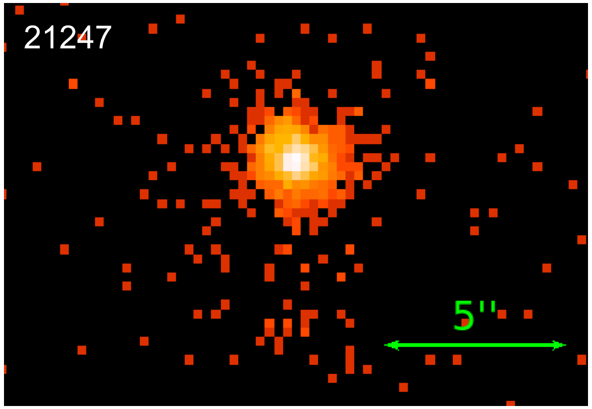
<u>To answer these questions, we should keep monitoring this system with Chandra with short enough cadence</u>

Three observations in the 2017-2021 binary cycle









We see extended emission (perhaps a nascent slow-moving clump) but it is not separated from the binary yet. <u>New observations are needed in the most interesting part of the orbit</u>.

Summary of findings:

- New (so far unique) phenomenon discovered: Ejection of X-ray emitting clumps from a high-mass gamma-ray binary, accelerated to an apparent velocity $\mathbf{V_{app} \sim 0.1c}$
- Typical clump sizes up to **10,000 a.u**. Clumps change their shape and brightness. X-ray luminosity up to $\mathbf{10^{32}}$ **erg/s**, power-law spectra with $\mathbf{\Gamma \sim 1.2 – 1.6}$, no softening with time
- Clumps showed somewhat different behavior in two binary cycles (e.g., different speed/acceleration, steady fading vs occasional brightening)

Possible interpretations:

- Clumps consisting 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
- X-ray emission mechanism is likely synchrotron radiation of relativistic electrons of the shocked pulsar wind mixed with stellar matter; possible internal shocks within the clump

Thank you!