Extended X-ray object ejected from the PSR B1259-63/LS 2883 binary

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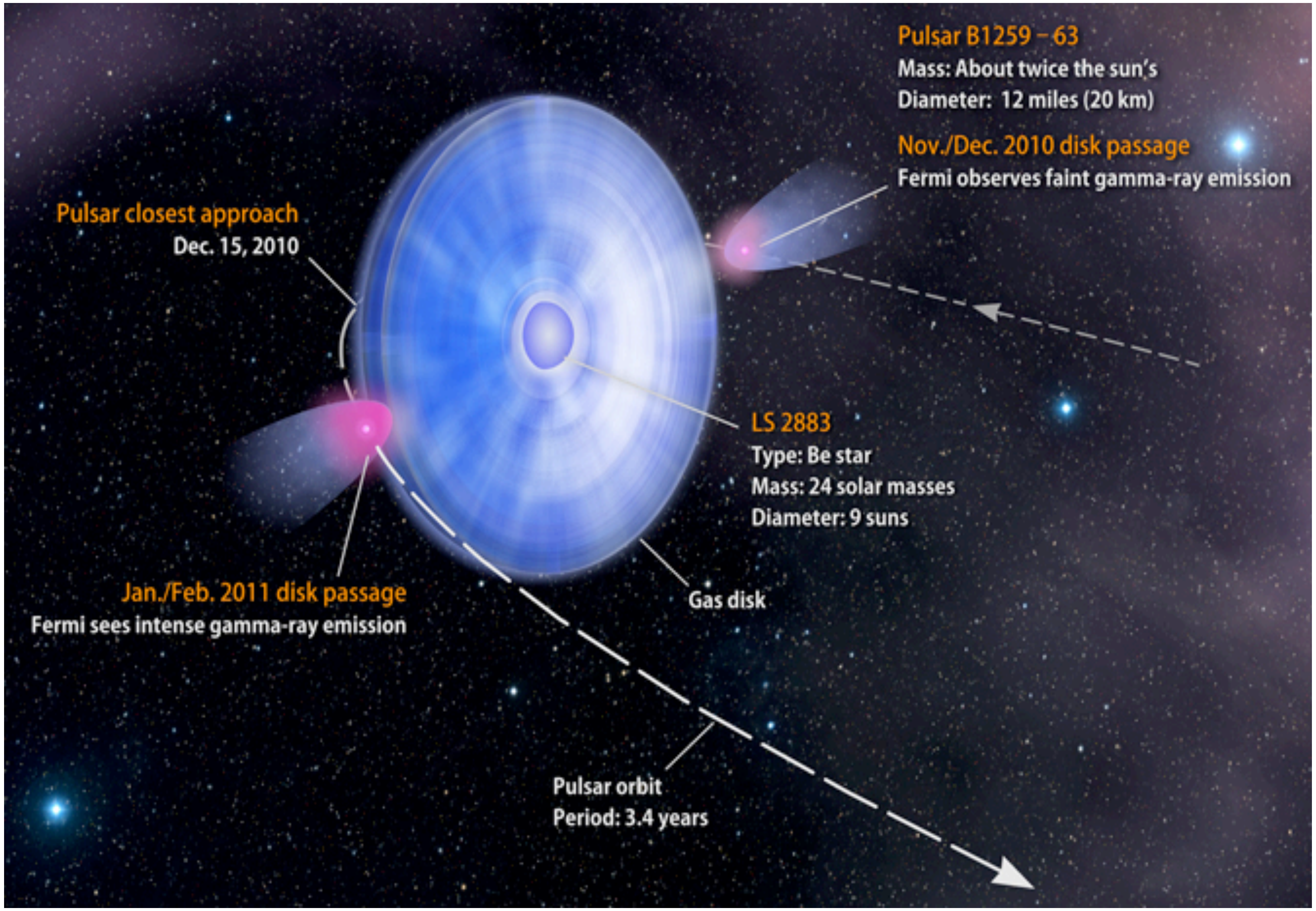
High-mass binary LS 2883 with PSR B1259-63



(Credit: NASA's Goddard Space Flight Center/Francis Reddy)

Fast-spinning, **massive ($M \sim 30\ M_\odot$, $L = 6\times10^4 L_\odot$) star** with a strong wind.

The **wind** is dense and slow in the **decretion disk**, tenuous and fast outside the disk.

Pulsar B1259-63:
Spin period = 48 ms
Edot = 8×10^{35} erg/s
Spin-down age =330 kyr
Should emit pulsar wind

X-ray flux varies with orbital period. **Gamma-ray** flashes near periastron, apparently when the pulsar intreacts with the decretion disk during 2nd passage.

Orbit:
3.4 yr orbital period
7 AU (3 milliarcsec) max. separation
0.87 eccentricity

Imaging observations with Chandra ACIS

4 observations, May 2009 – Feb 2014

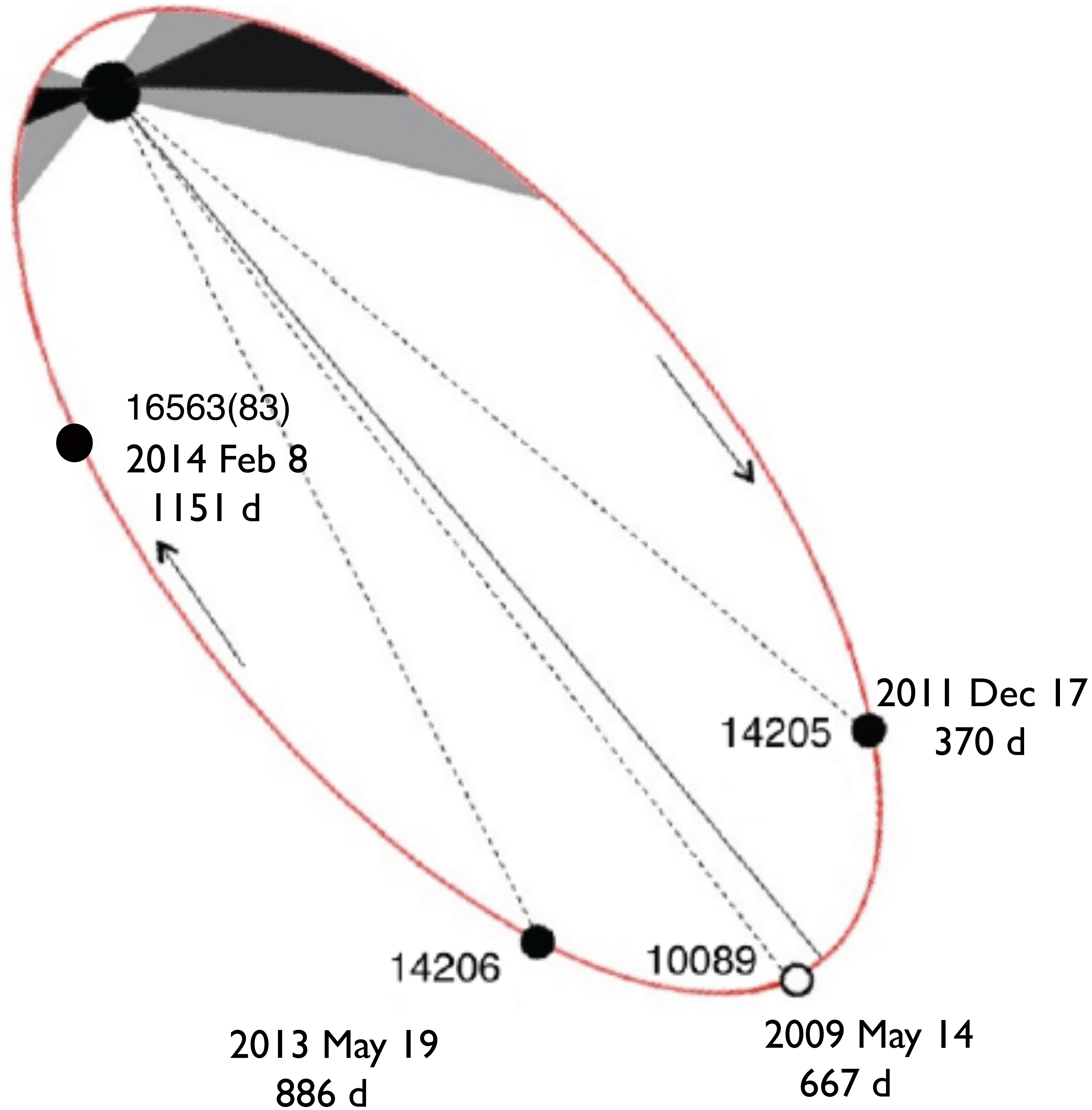
ObsID	MJD	θ^a deg	Δt^b days	Exp.[c] ks	Cts[d]
10089	54965	182	667	25.6	1825 61
14205	55912	169	370	56.3	6551 343
14206	56431	192	886	56.3	4162 144
new[i]	56696	221	1151	57.6	6257 58

[a]True anomaly counted from periastron.

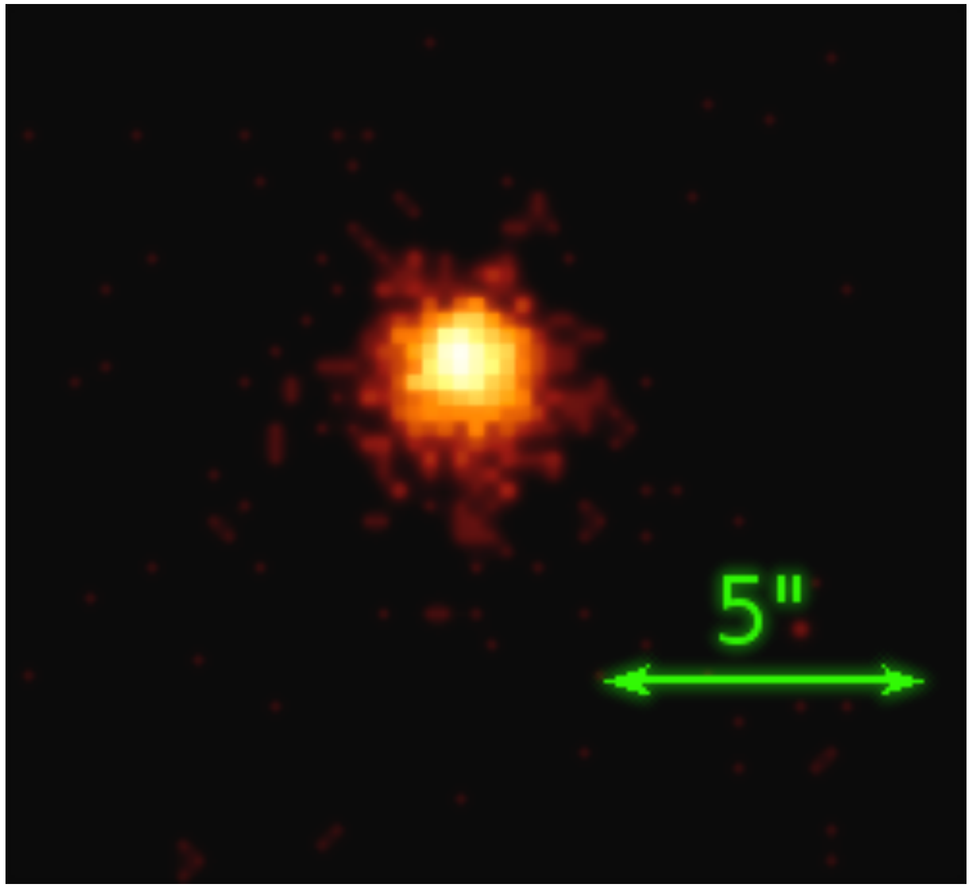
[b]Days since latest preceded periastron.

[c]Exposure corrected for deadtime.

[d]Total (gross) counts.



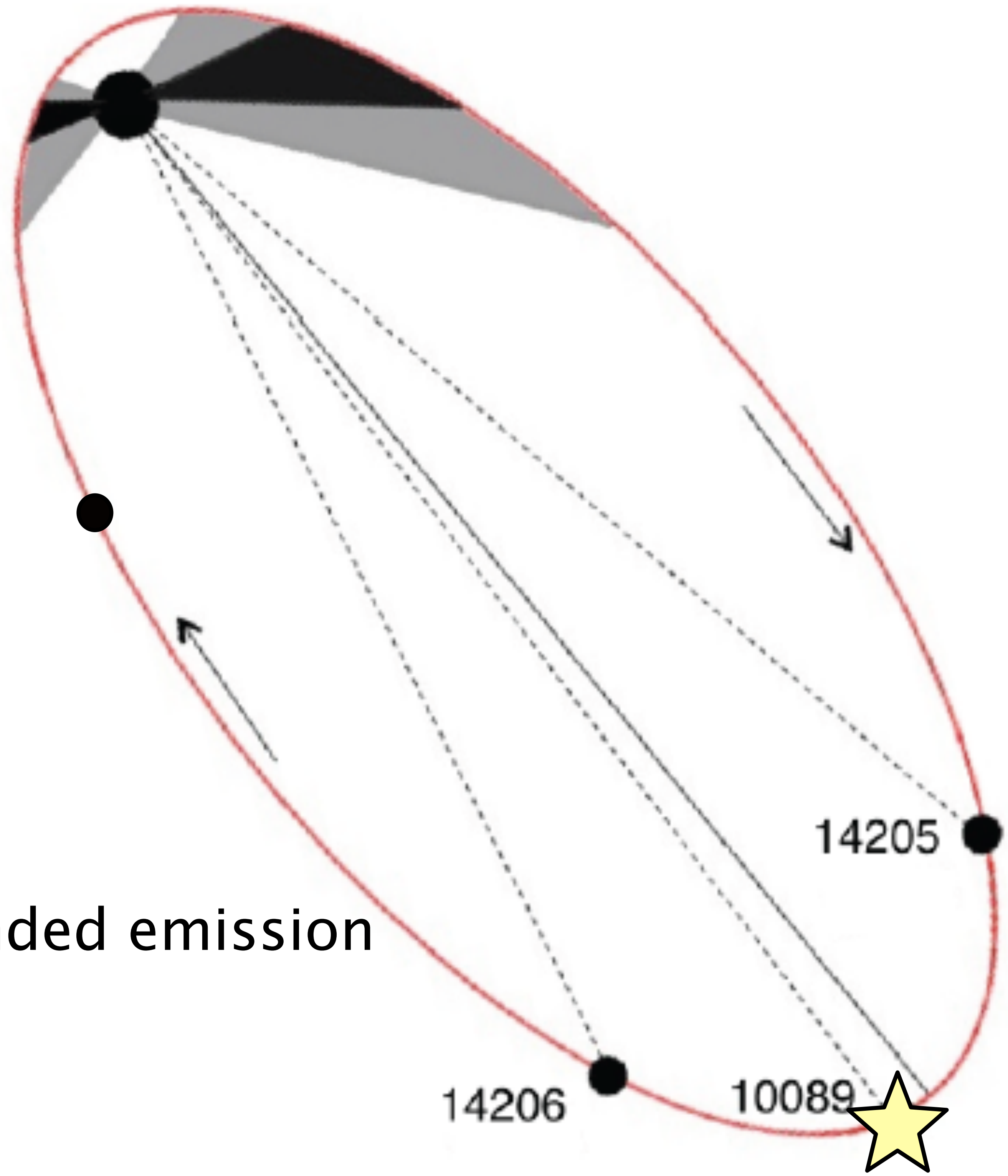
1st Observation (2009 May 14)



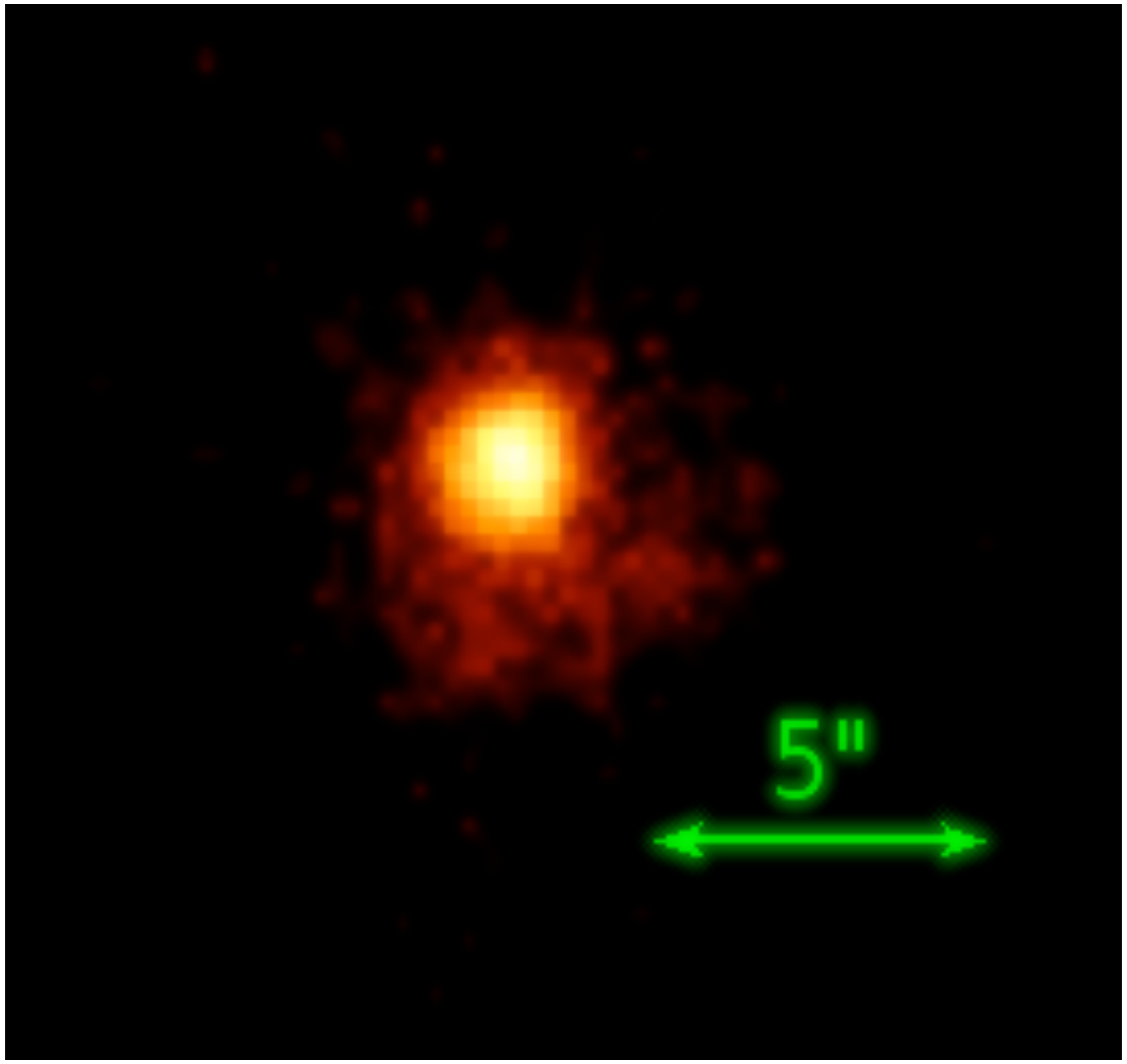
Short 25.6 ks ACIS-I exposure
near apastron, $\theta = 182$ deg

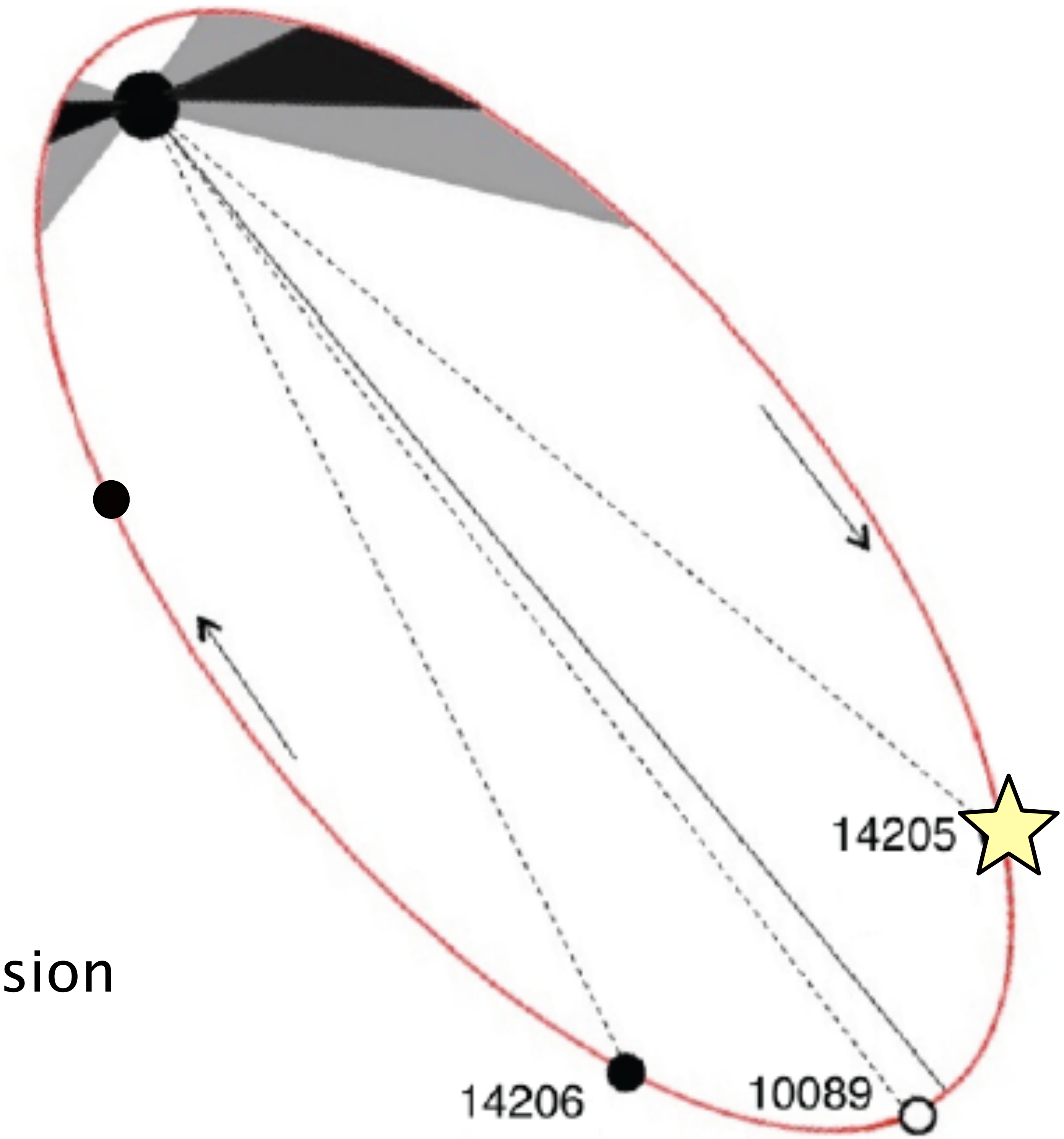
~4σ detection of asymmetric extended emission

(Pavlov et al 2011)



2^{nd} Observation (2011 Dec 17)

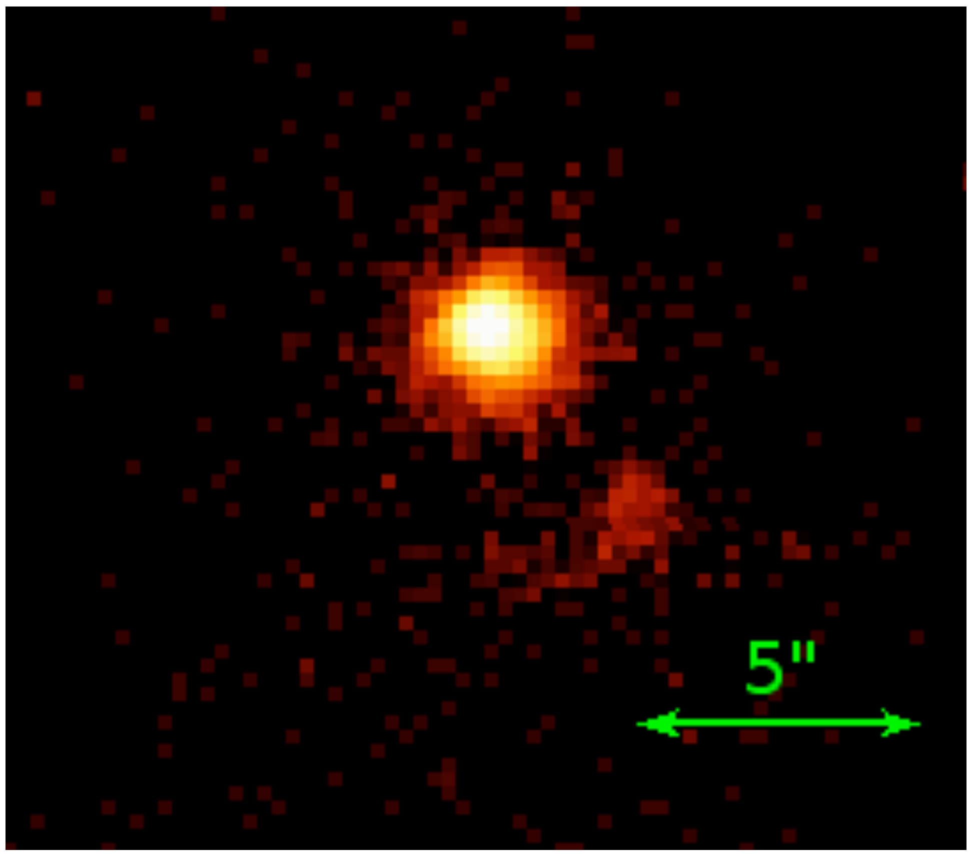




56.3 ks ACIS-I exposure
before apastron, θ =169 deg

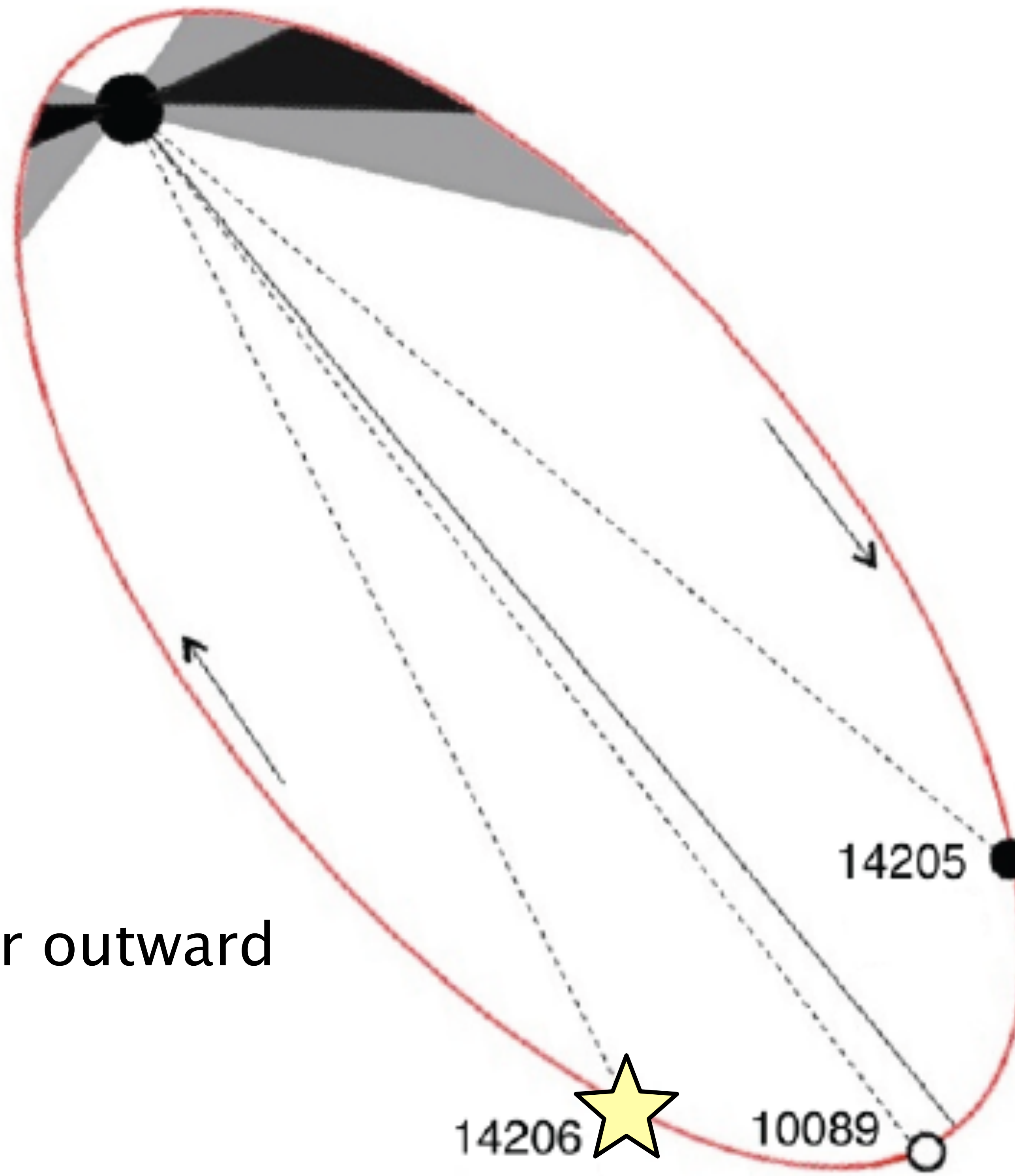
Clear asymmetric extended emission

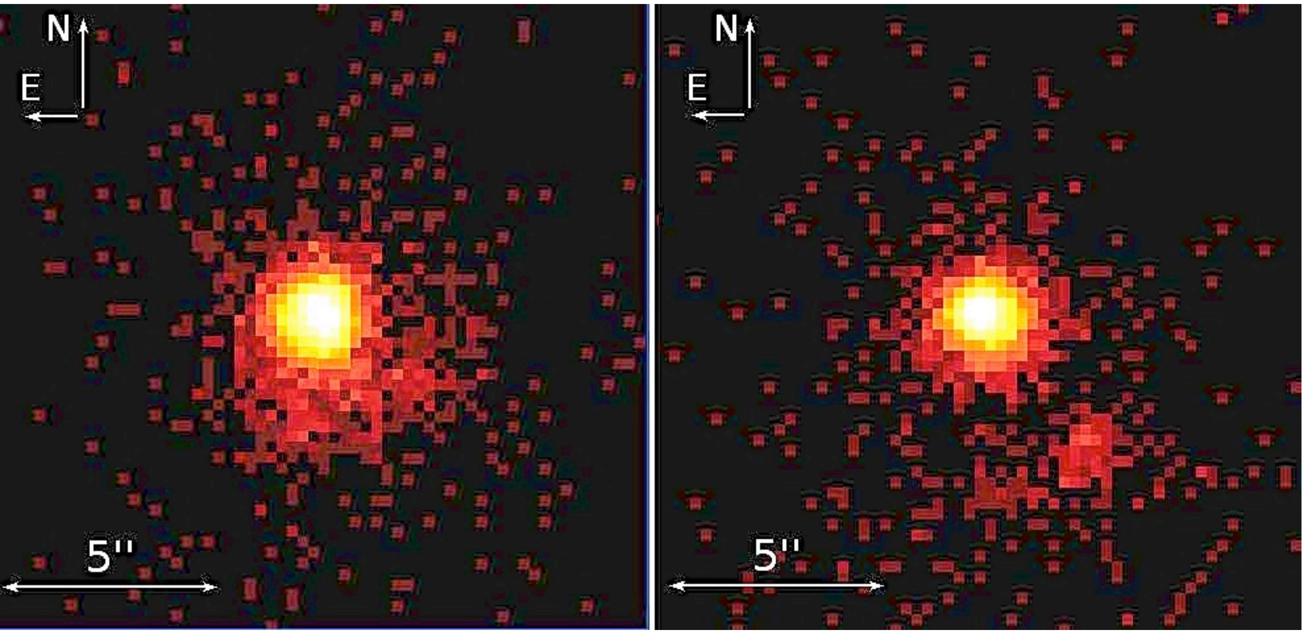
3rd Observation (2013 May 19)



56.3 ks ACIS-I exposure
after apastron, $\theta = 192$ deg

Extended emission moved further outward





2nd and 3rd observations compared

$1\farcs8 \pm 0\farcs5$ shift

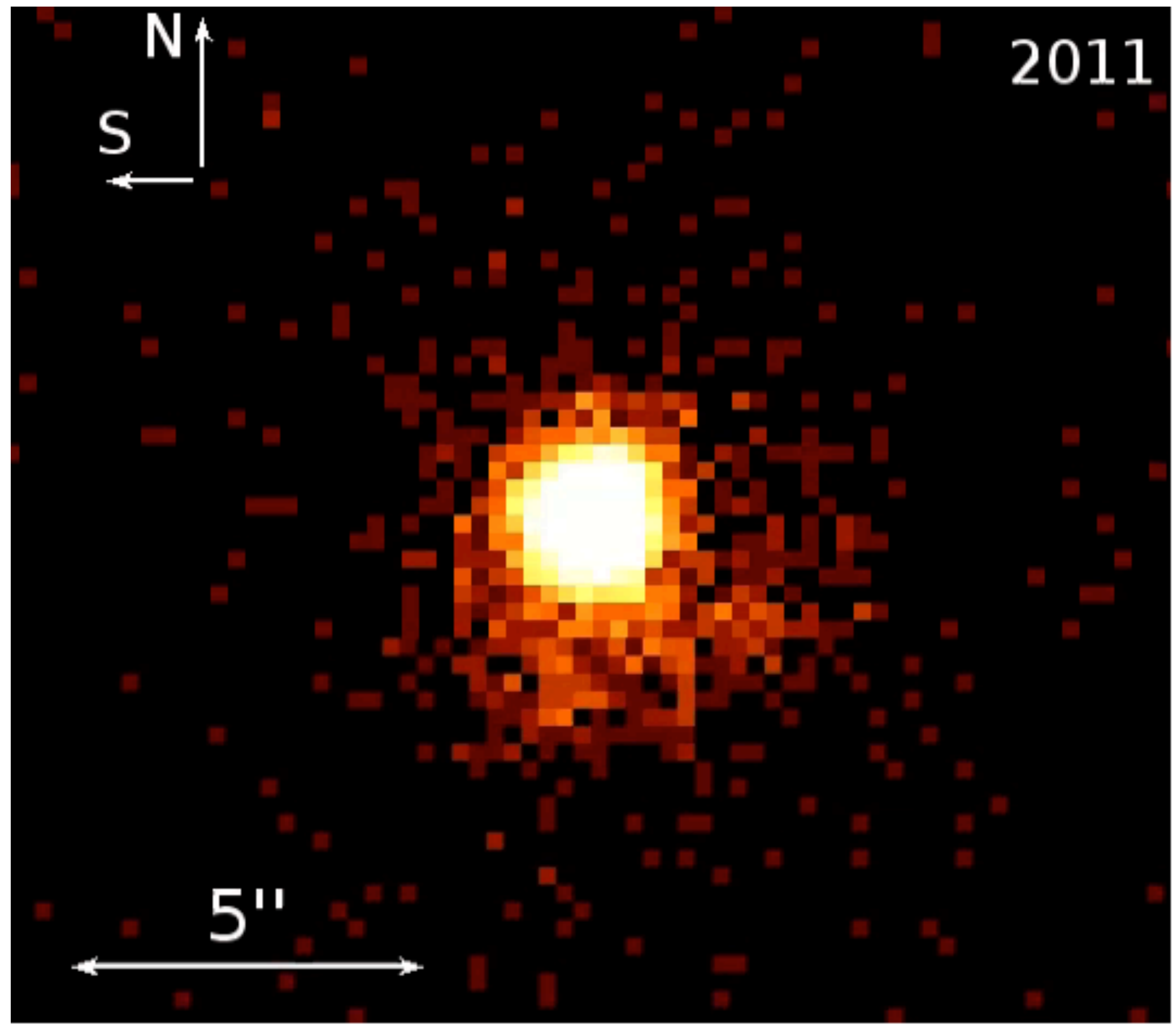
corresponds to the apparent proper motion

$\mu = 1.27 \pm 0.35$ arcsec yr^{-1}

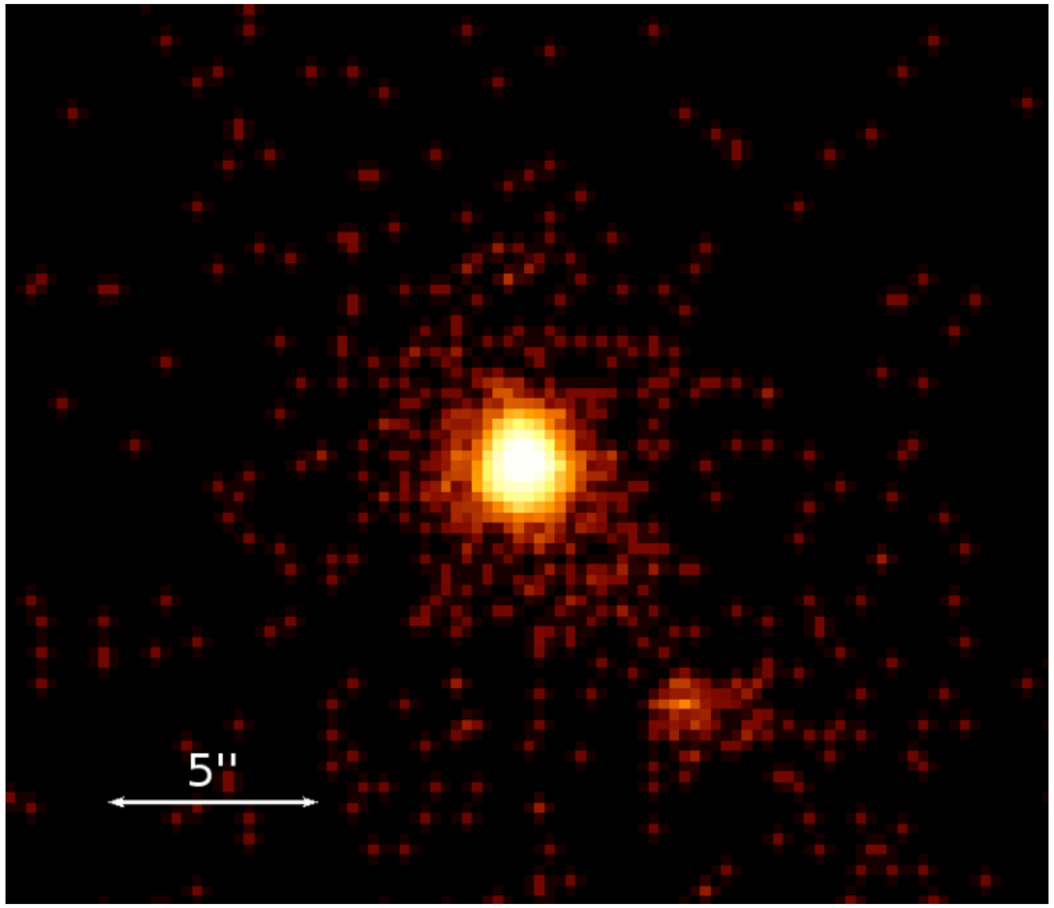
V = (0.046 +/- 0.013)c

at d = 2.3 kpc

(Kargaltsev et al. 2014)

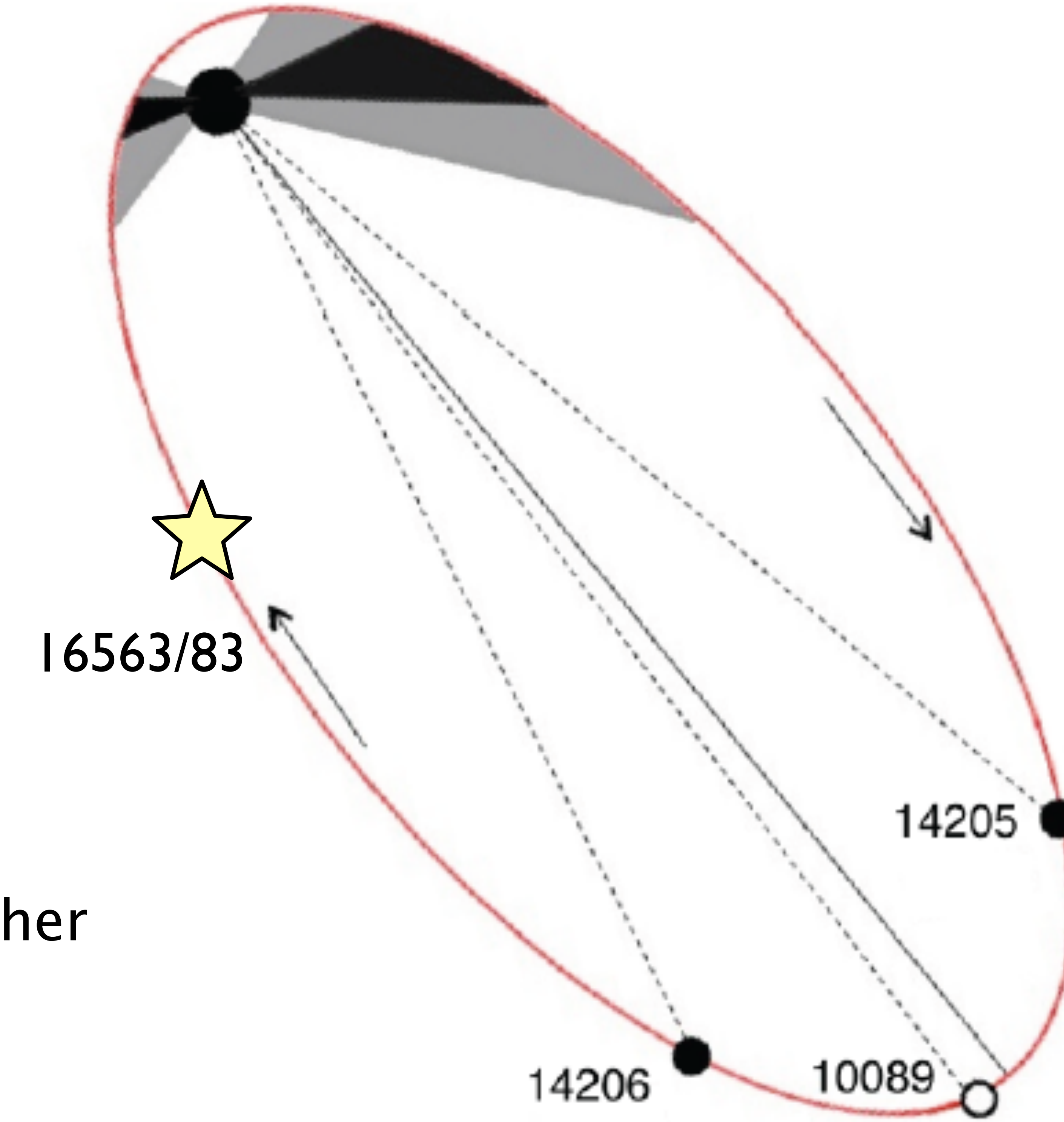


4th Observation (2014 February 8 - 9)

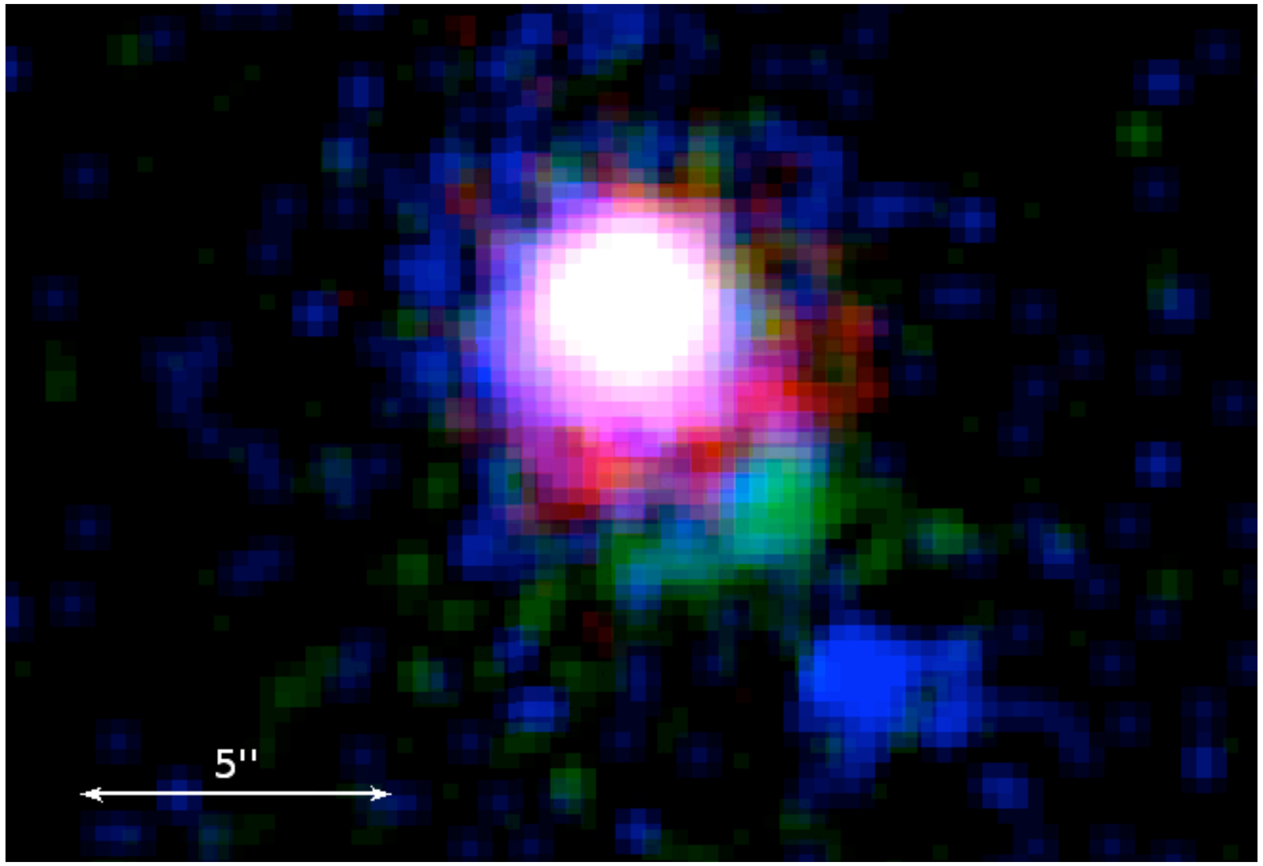


57 ks ACIS-I exposure

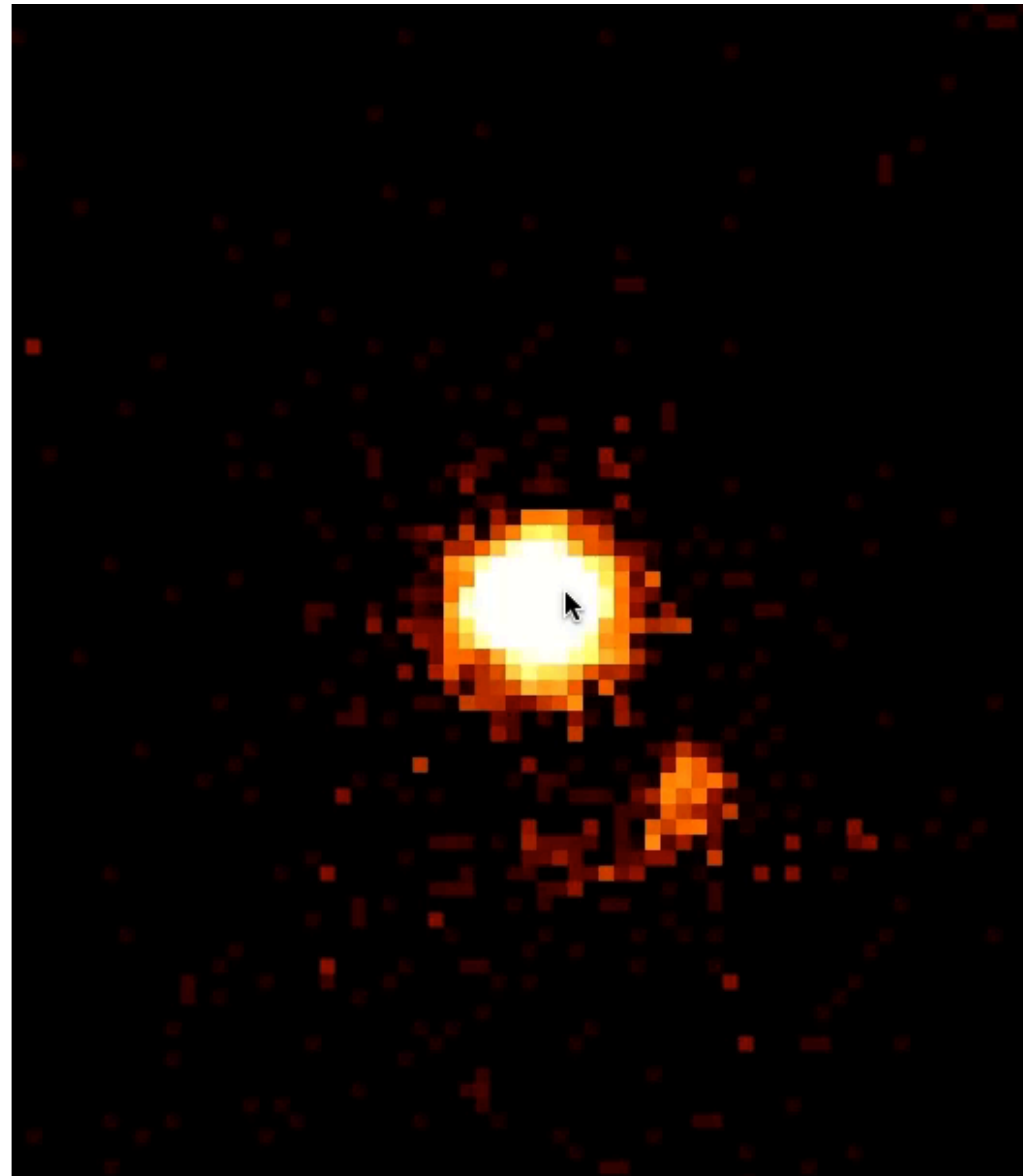
approaching periastron



Extended emission moved farther from the binary, apparently faster than expected from the previous 2 observations



2^{nd}, 3^{rd}, and 4^{th} observations together:



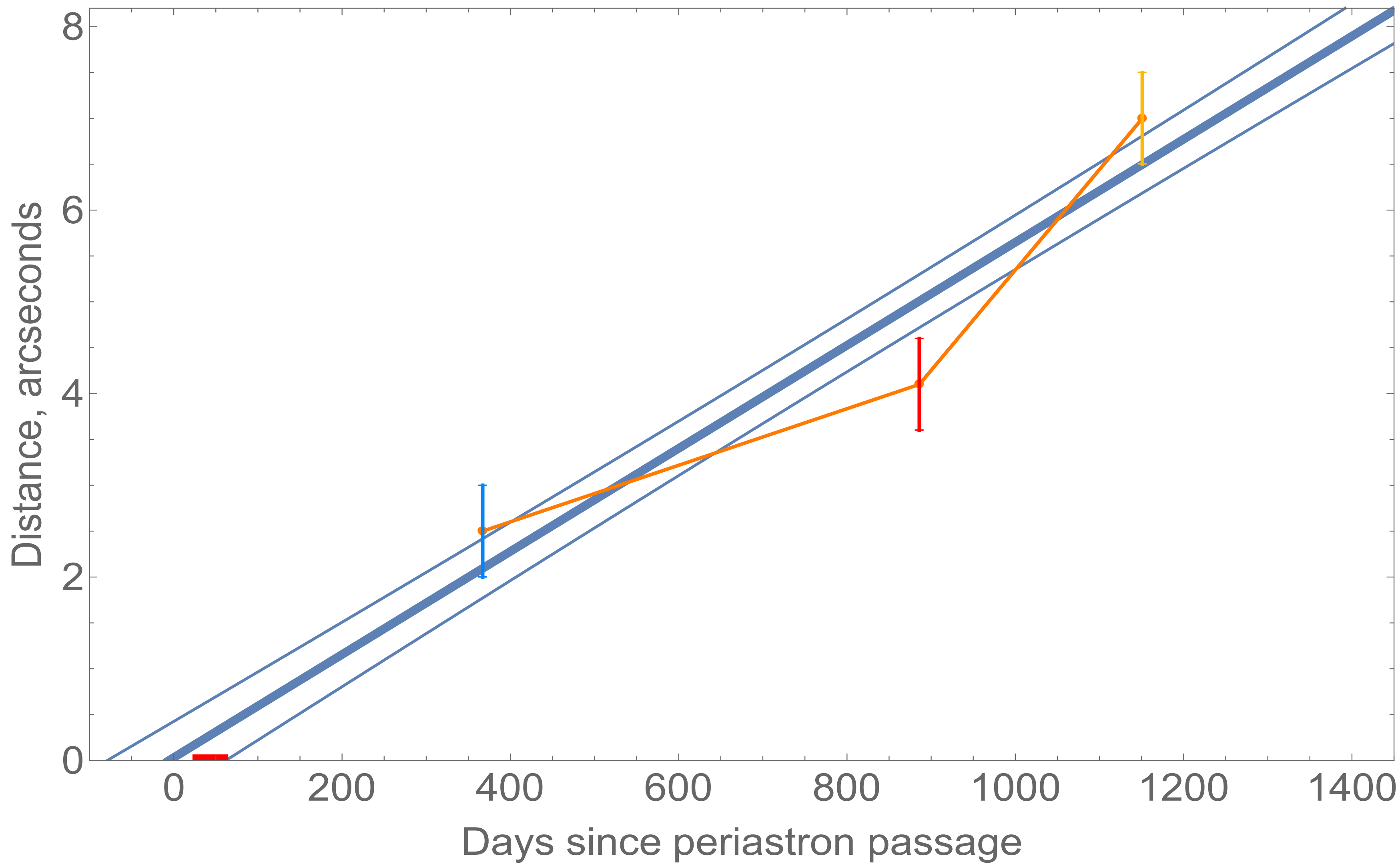
Between 3rd and 4th observations the extended structure moved by 2.5'' ±0.5''.

This corresponds to the apparent proper motion

V=(0.13±0.03)c
at d = 2.3 kpc

Apparent **acceleration (?)**
90±40 cm s^{-2}

Distance of the extended source from the binary versus time



Linear fit: V = (0.07+/-0.01)c

If there is no acceleration, the cloud was ejected from the binary around periastron of 2010 Dec 14

Luminosities and spectra of extended emission

In 3 last observations 0.5 – 8 keV fluxes are

F = 8.5+/-0.5, 3.6+/-0.4, 1.9+/-0.4 $\times$ 10^{-14} erg cm^{-2} s^{-1} ,

corresponding luminosities **L ~ (0.2 – 1) $\times$ 10^{31}erg/s** at d = 2.3 kpc, ~0.7% - 3% of the binary's luminosity.

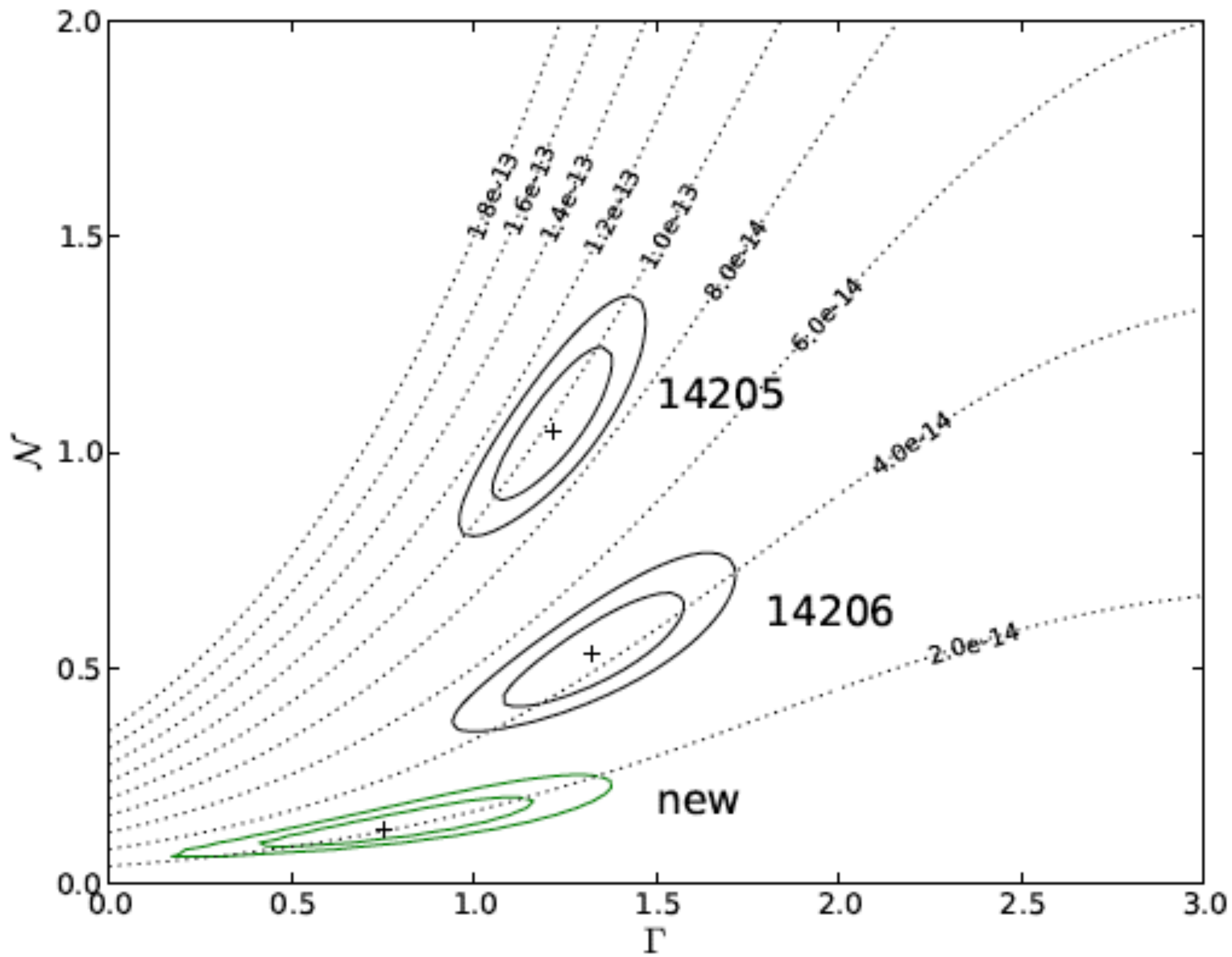
The spectra can be fitted with thermal bremsstrahlung,
kT > 6 keV, n ~ 100 cm^{-3}, **m_{ej} ~10^{28} - 10^{29}** g -- much larger than the mass supplied by the massive star wind during one orbital period, P_{orb} Mdot ~ 10^{26} (Mdot/10^{-8} M_{sol}/yr) g, or a reasonable mass of disk, m_{disk} ~ 10^{24} – 10^{26} g.
Kinetic energy ~10^{46} – 10^{47} erg, improbably large.

The plasma cloud interpretation does not look plausible.

The spectra are also consistent with power laws,
photon indices **Γ = 1.2+/-0.1, 1.3+/-0.2, and 0.8+/-0.4** (no softening!)

Synchrotron radiation?

Confidence contours in Photon Index – Normalization plane



Synchrotron interpretation:

magnetic field $\mathbf{B \sim 80\ k_m^{2/7}}\ \mu\mathbf{G}$, where $k_m = \varepsilon_{mag}/\varepsilon_{kin}$;
electron Lorentz factor $\gamma \sim \mathbf{10^7 - 10^8}$,
total magnetic and electron energies $\mathbf{W_m \sim 5{\times}10^{40}\ k_m^{4/7}}$ and $\mathbf{W_e \sim 5{\times}10^{40}\ k_m^{-3/7}}$ **erg** in volume $\mathbf{V \sim 10^{50}\ cm^3}$ **.**
$W_m + W_e << P_{orb}$ Edot = $9{\times}10^{43}$ erg for a broad range of k_m -- the energy could be supplied by the pulsar.

But, if the ejected object were an **e-/e+ cloud**, it would be difficult to explain the fast motion because of the **drag force,** $\mathbf{f \sim \rho_{amb}\ v^2\ A}$.
Deceleration time

$\mathbf{t_{dec} \sim (W_m + W_e)\ v\ f^{-1}\ c^{-2} \sim 10\ n_{amb}^{-1}\ (k_m^{4/7} + k_m^{-3/7})\ s}$**,**
where n_{amb} is the ambient proton number density.
To reduce the deceleration, the e-/e+ cloud must be loaded with a heavy (electron-ion) plasma, but even in this case the ejected mass should be a substantial fraction of the disk mass, if the ejected clump is moving in a stellar wind blown bubble.

Another hypothesis

Variable termination shock in the circumbinary medium, similar to PWNe around isolated pulsars (Kargaltsev et al 2014)

But, it requires unrealistically high ambient pressure, $p_{amb} \sim 10^{-10}$ dyn cm^{-2}, to explain the shock size; looks artificial now.

Current explanation: Instead of the companion's wind bubble, **ejected clump is moving in the unshocked pulsar wind**

More plausible at larger values of $\boldsymbol{\eta = \mathrm{Edot}/(\mathrm{Mdot}\ v_w\ c) =}$
$\boldsymbol{= 4.4\ (\mathrm{Mdot}/10^{-9}\ M_\odot/\mathrm{yr})^{-1}\ (v_w/1000\ \mathrm{km/s})^{-1}}$
when the companion's wind is confined by the pulsar wind into a narrow cone, while the unshocked pulsar wind fills the rest of the binary volume.

The X-ray emission is due to synchrotron radiation of the pulsar wind shocked by the collision with the clump.
X-ray luminosity $\boldsymbol{L_{X,cl} = \xi_X\ \mathrm{Edot}\ (r_{cl}/2r)^2}$, $\boldsymbol{\xi_X \sim 1.5\times10^{-3}}$

The interaction with unshocked pulsar wind with ejected clump can also **accelerate** the clump: **vdot ~ p_{pw} A m_{cl}^{-1}**.

m_{cl} ~ 10^{21} g for the apparent (low-significance) estimated acceleration.

The clump could be ejected due to interaction of the pulsar with the decretion disk. When the pulsar enters the dense disk, a shock is created, with a radius exceeding the disk's vertical size →
→ Disruption of the disk in the first passage, further fragmentation in the second passage, γ-ray flares from shocked pulsar wind, entrainment of clumps in the pulsar wind, then acceleration by the pulsar wind ram pressure to ~0.1 c.

Summary

- We discovered a new phenomenon: Ejection of an X-ray emitting clump from a high-mass γ-ray binary with a velocity $v \sim 0.1c$ and a hint of acceleration.
- The clump's luminosity faded with time but the power-law-like spectrum ($\Gamma \sim 0.8 - 1.3$) did not show softening.
- The clump was likely ejected due to interaction of the pulsar (pulsar wind) with the equatorial decretion disk of the high-mass star.
- We suggest that the clump is moving in the unshocked pulsar wind, whose pressure accelerated the clump to the very high speed. This scenario requires large η.
- The most likely emission mechanism is synchrotron radiation of relativistic electrons ($E_e \sim 10$ - 100 TeV, $B \sim 10^2$ μG) of pulsar wind shocked in the collision with clump.
- We expect a new clump has been ejected during the recent periastron passage (May 2014), new Chandra observations are planned.