THE (?) ULTRALUMINOUS PULSAR

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FUN FACTS 2001-2002

Chandra High-Resolution Camera observations of the luminous X-ray source in the starburst galaxy M82

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ABSTRACT
We analyse *Chandra* High Resolution Camera observations of the starburst galaxy M82, concentrating on the most luminous X-ray source. We find a position for the source of RA = $09^{\rm h}55^{\rm m}50^{\rm s}.2$, Dec. = $+69^{\circ}40'46''.7$ (J2000) with a 1σ radial error of 0.7 arcsec. The accurate X-ray position shows that the luminous source is neither at the dynamical centre of M82 nor coincident with any suggested radio AGN candidate. The source is highly variable between observations, which suggests that it is a compact object and not a supernova or remnant. There is no significant short-term variability within the observations. Dynamical friction and the off-centre position place an upper bound of 10^5–$10^6\,M_{\odot}$ on the mass of the object, depending on its age. The X-ray luminosity suggests a compact object mass of at least $500\,M_{\odot}$. Thus the luminous source in M82 may represent a new class of compact object with a mass intermediate between those of stellar-mass black hole candidates and supermassive black holes.

ULTRALUMINOUS X-RAY SOURCES IN EXTERNAL GALAXIES

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ABSTRACT

We investigate models for the class of ultraluminous nonnuclear X-ray sources (i.e., ultraluminous compact X-ray sources [ULXs]) seen in a number of galaxies and probably associated with star-forming regions. Models in which the X-ray emission is assumed to be isotropic run into several difficulties. In particular, the formation of sufficient numbers of the required ultramassive black hole X-ray binaries is problematic, and the likely transient behavior of the resulting systems is not in good accord with observation. The assumption of mild X-ray beaming suggests instead that ULXs may represent a short-lived but extremely common stage in the evolution of a wide class of X-ray binaries. The best candidate for this is the phase of thermal-timescale mass transfer that is inevitable in many intermediate- and high-mass X-ray binaries. This in turn suggests a link with the Galactic microquasars. The short lifetimes of high-mass X-ray binaries would explain the association of ULXs with episodes of star formation. These considerations still allow the possibility that *individual* ULXs may contain extremely massive black holes.

SUPER-EDDINGTON FLUXES FROM THIN ACCRETION DISKS?

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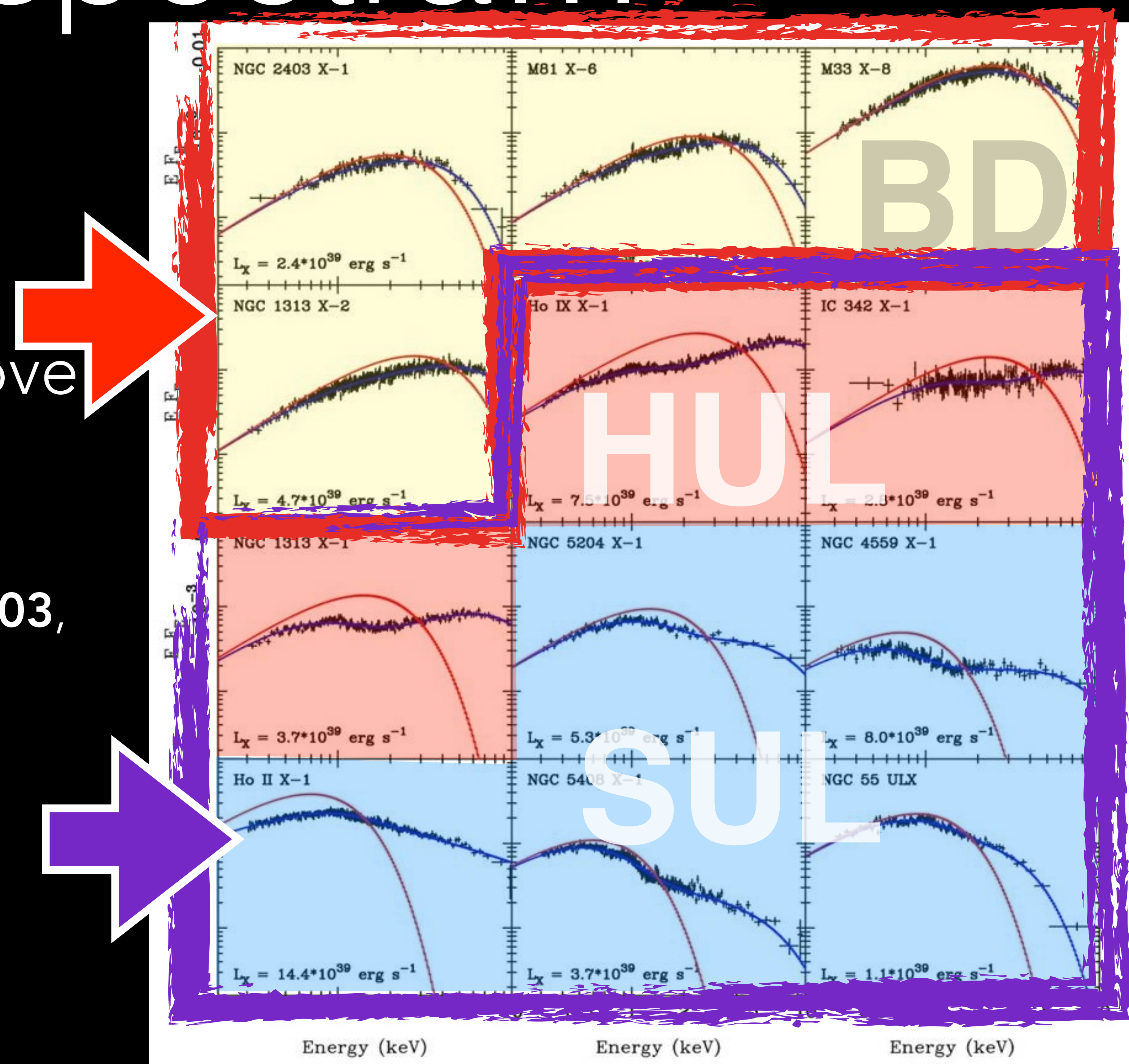
ABSTRACT

Radiation pressure–dominated accretion disks are predicted to exhibit strong density inhomogeneities on scales much smaller than the disk scale height as a result of the nonlinear development of photon-bubble instability. Radiation would escape from such a "leaky" disk at a rate higher than that predicted by standard accretion disk theory. The disk scale height is then smaller than that of a similar disk without small-scale inhomogeneities, and the disk can remain geometrically thin even as the flux approaches and exceeds the Eddington limit. An idealized one-zone model for disks with radiation-driven inhomogeneities suggests that the escaping flux could exceed $L_{\rm Edd}$ by a factor of up to ~10–100, depending on the mass of the central object. Such luminous disks would develop strong mass loss, but the resulting decrease in accretion rate would not necessarily prevent the luminosity from exceeding $L_{\rm Edd}$. We suggest that the observed "ultraluminous X-ray sources" are actually thin, super-Eddington accretion disks orbiting stellar-mass black holes and need not indicate the existence of a class of intermediate-mass black holes.

ULX spectra…

- Low-luminosity ULXs: BHs with luminosities around or slightly above Eddington
  (e.g. Middleton *et al. Nat.* **493,** 187–190 (2013); Liu et al. *Nat.* **503**, 500–503 (2013).)

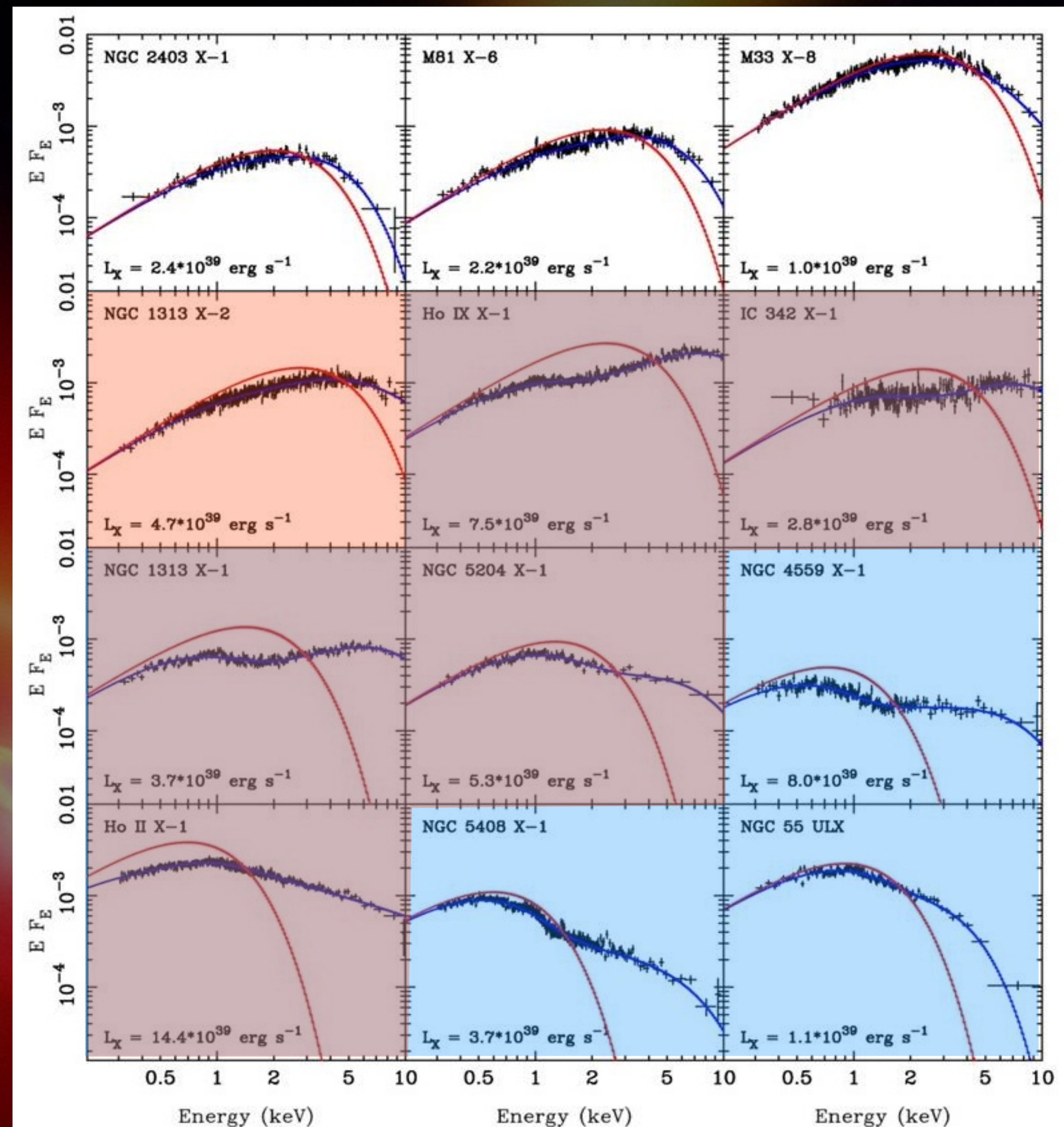
- "Extreme" ULXs — $L_X > 10^{40}$ erg/s

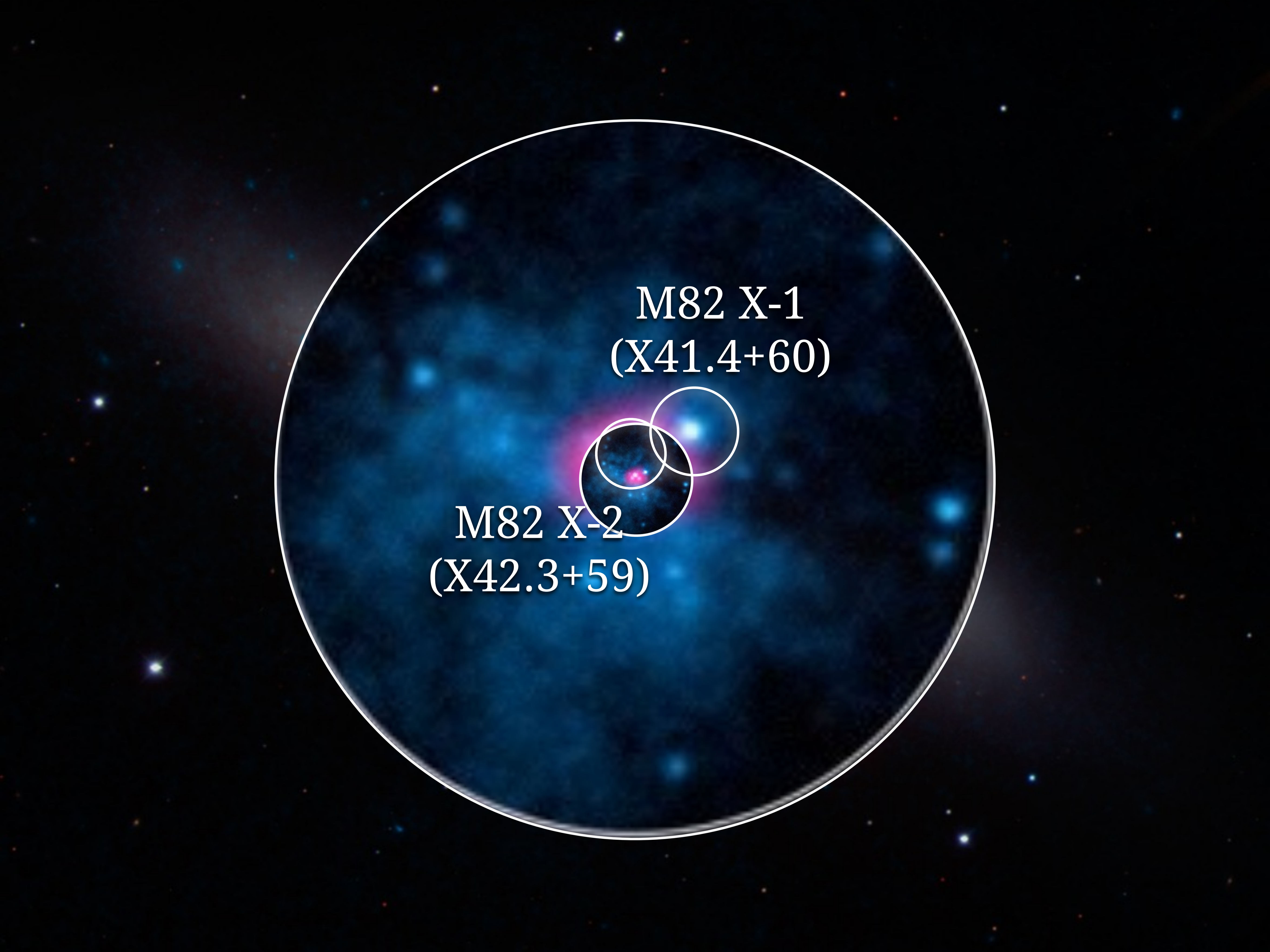


Gladstone, Roberts & Done, *MNRAS* **397**, 1836–1851 (2009).

ULXs in the NuSTAR program

- **eULXs**
- Chosen for **distance** and **hardness**

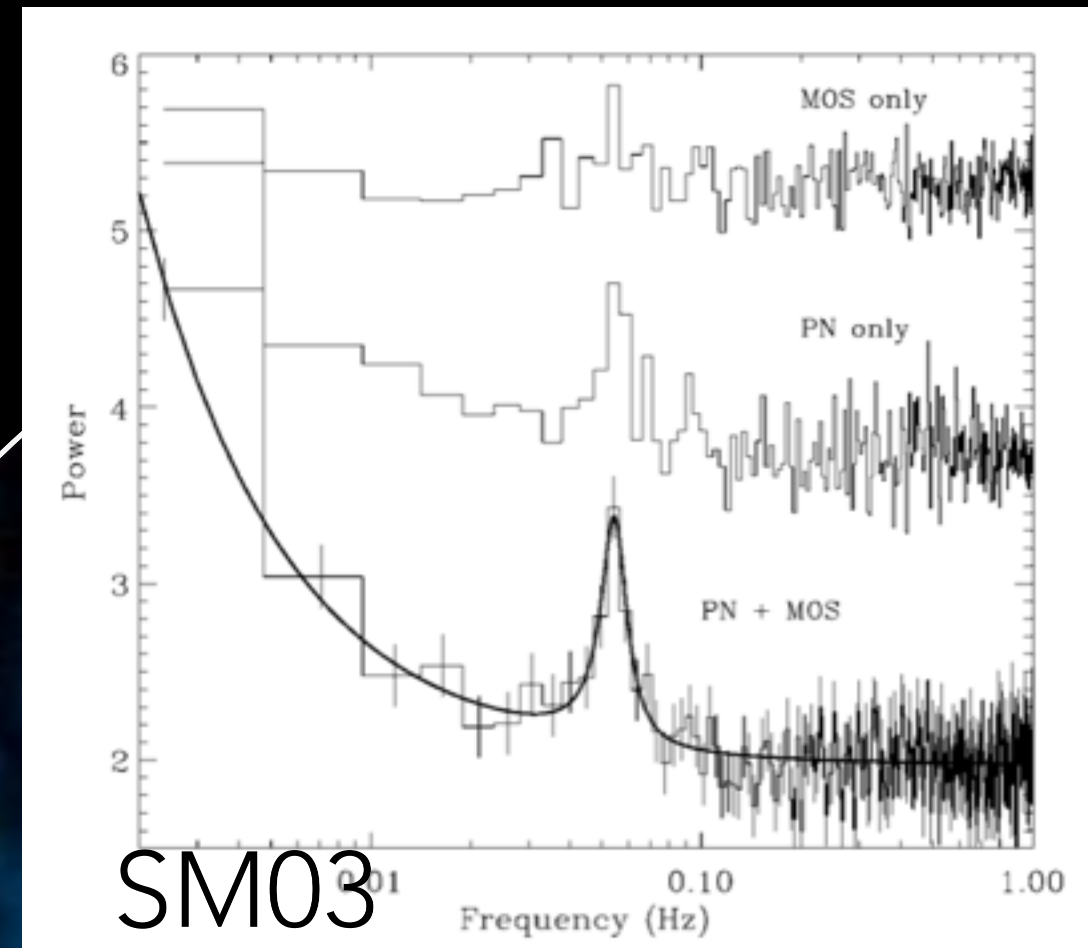


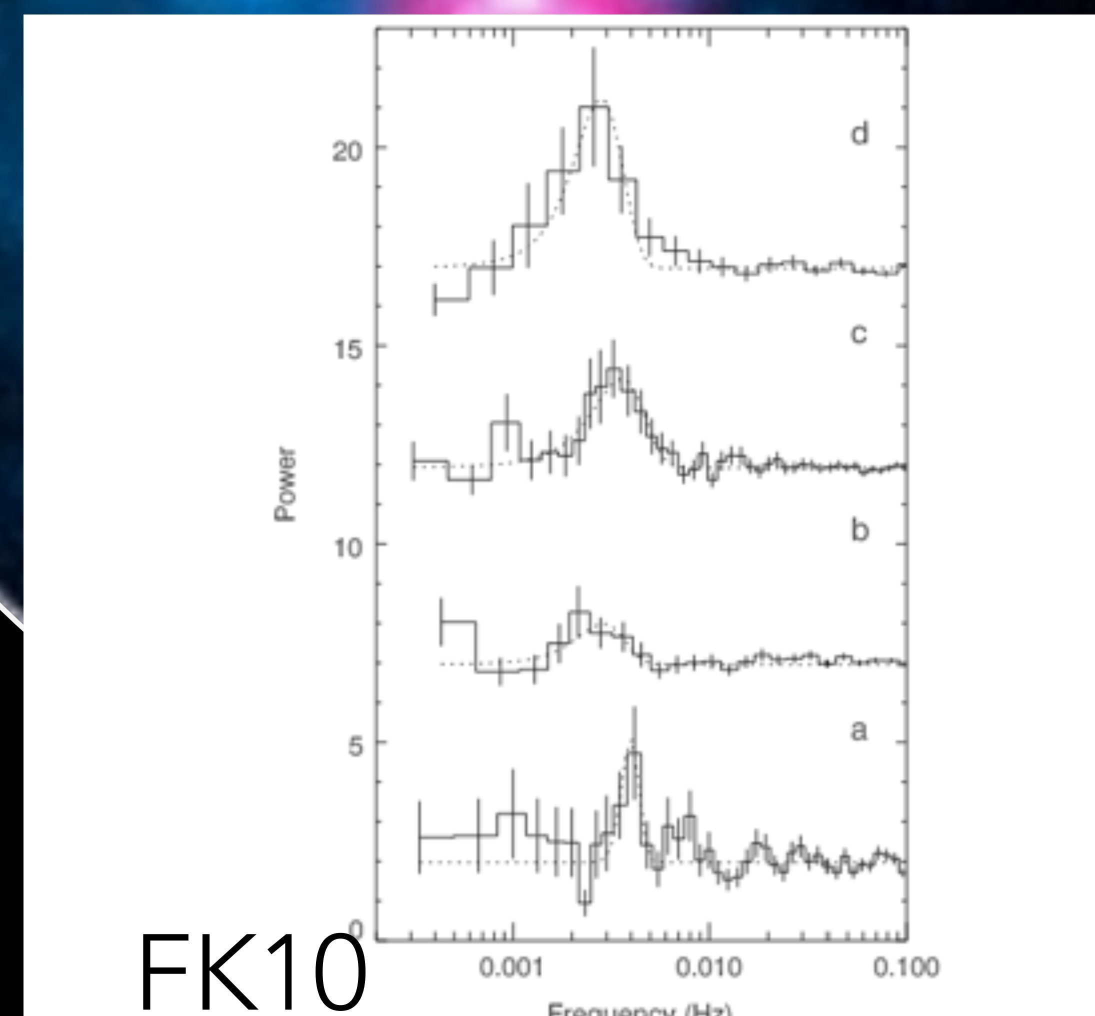

M82 X-1
(X41.4+60)
M82 X-2
(X42.3+59)

THE ULXs IN M82

Famous ULXs, showing interesting spectral and timing behavior:

- **M82 X-1/X41.4+60:** L_X ~10^{41} f_{QPO}: **50—190 mHz** (SM03, K+06)
- **M82 X-2/X42.3+59:** L_X ~10^{40} f_{QPO}: **3—4 mHz** (FK10)
- Both used to infer masses of the BHs in the **IMBH range** (FK07, FK10)

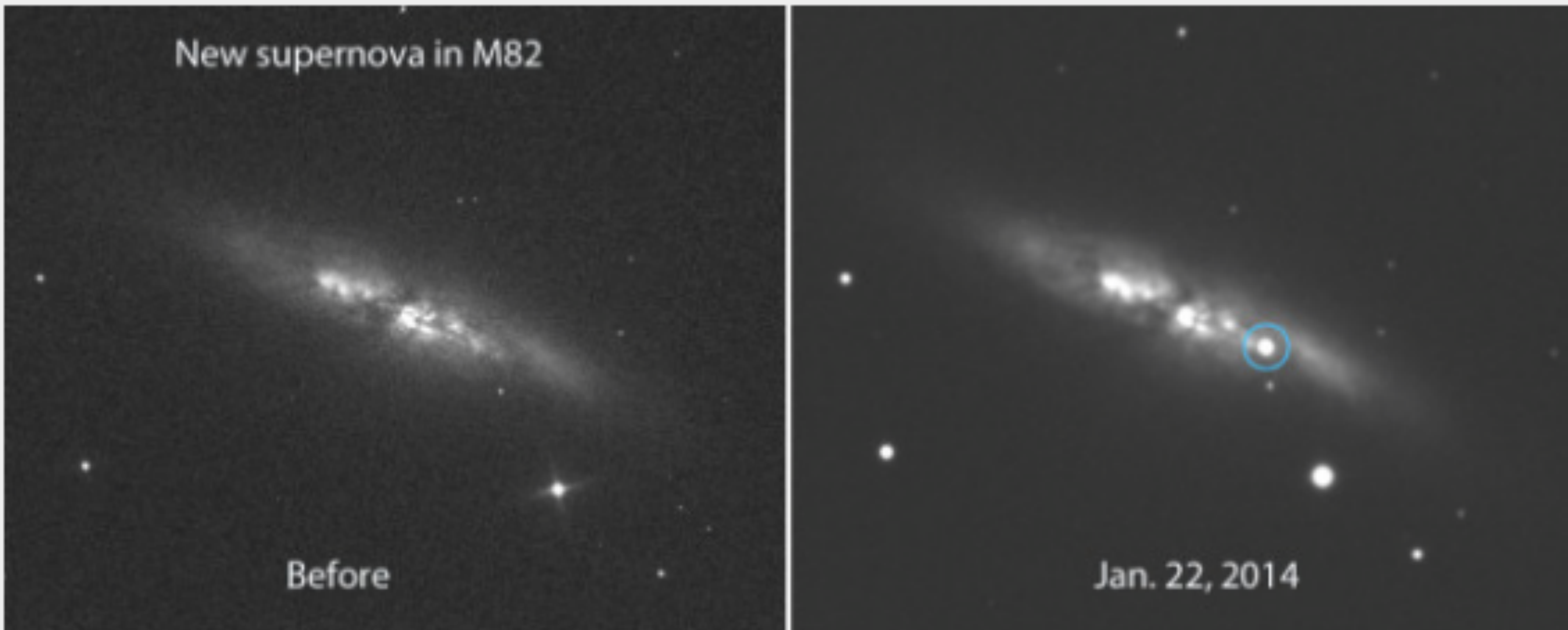




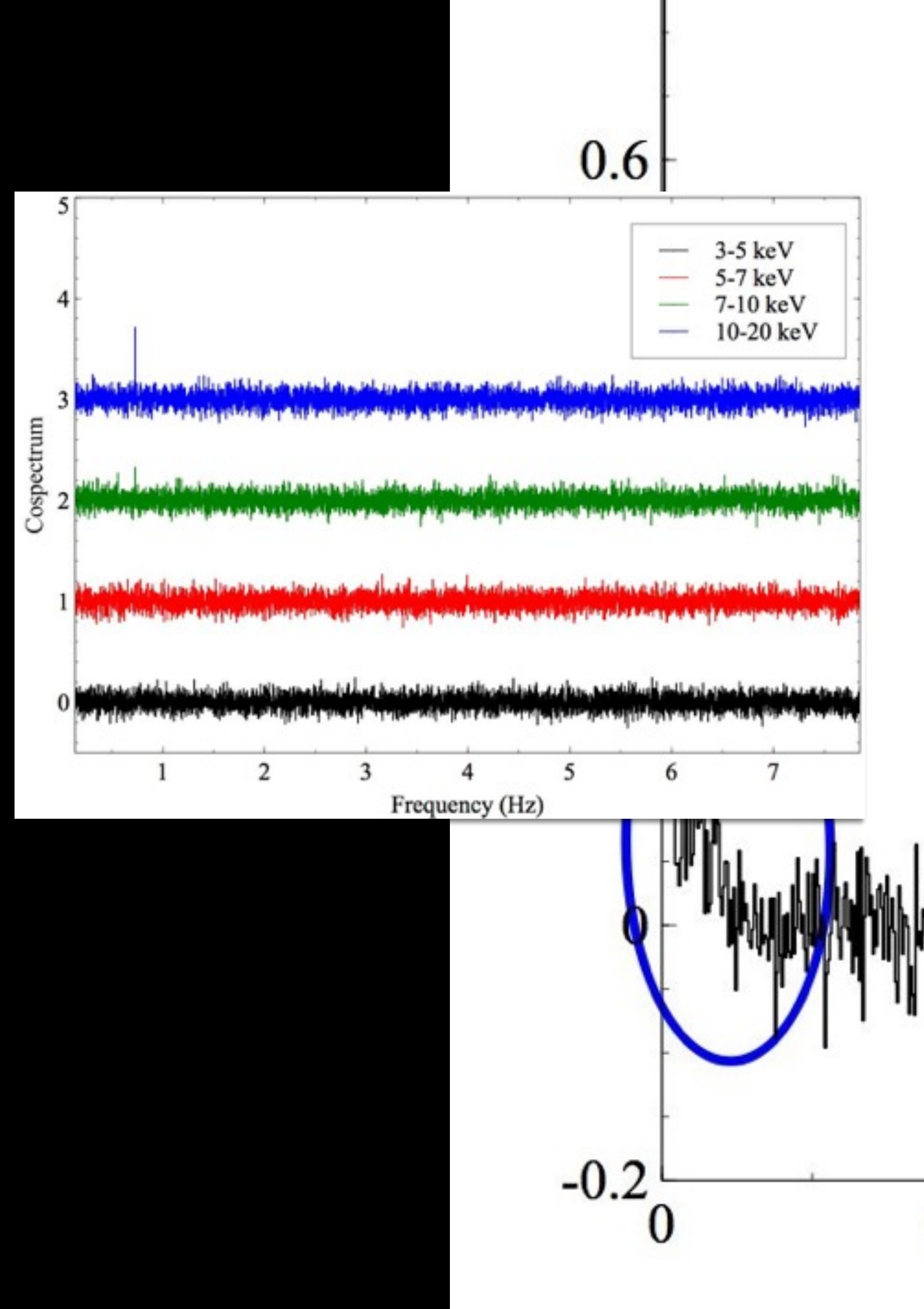
- SM03: Strohmayer, T. E. & Mushotzky, R. F., ApJ 586, L61–L64 (2003).
- K+06: Kaaret, P., Simet, M. G. & Lang, C. C., ApJ 646, 174–183 (2006).
- FK07: Feng, H. & Kaaret, P., ApJ 668, 941–948 (2007).
- FK10: Feng, H., Rao, F. & Kaaret, P., ApJL 710, L137–L141 (2010).

Bright New Supernova Blows Up in Nearby M82, the Cigar Galaxy

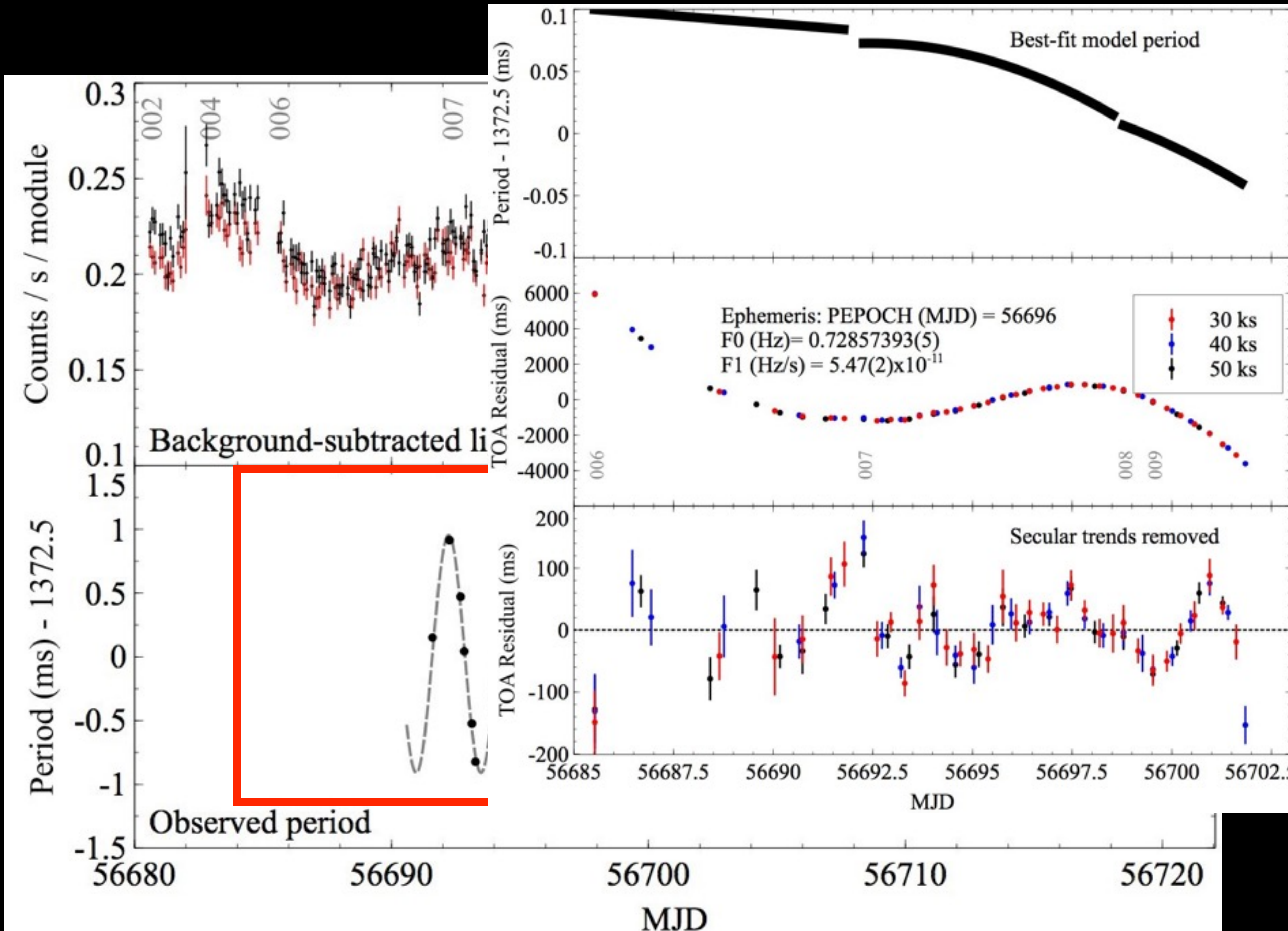
by BOB KING *on* JANUARY 22, 2014



Before and after photos of the galaxy M82 showing the appearance of a brand new 11.7 magnitude supernova. The object is located in the galaxy's plane 54″ west and 21″ south of its

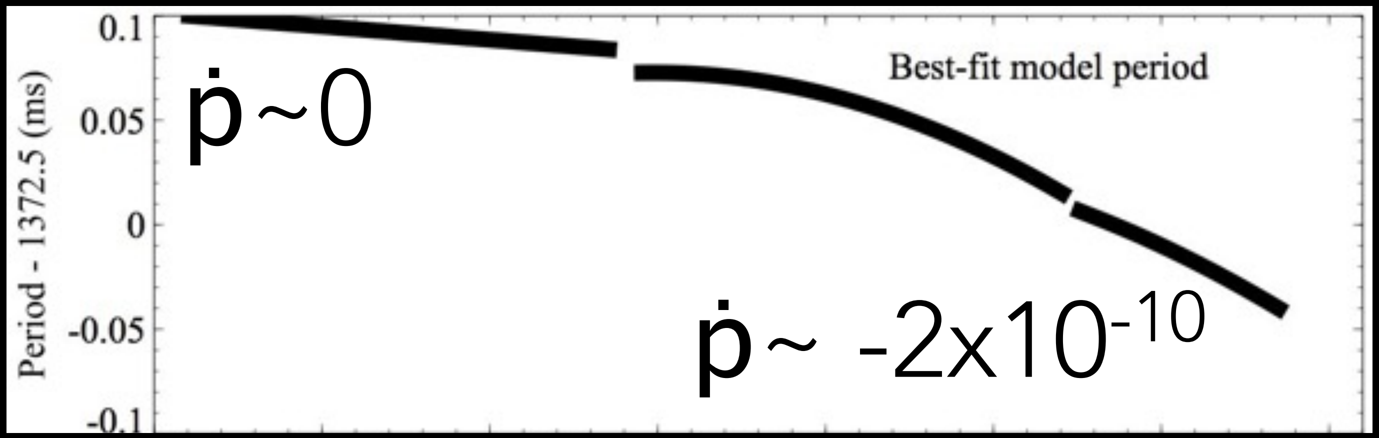


0.6
0
-0.2
0
5
4
3
2
1
0
Cospectrum
3-5 keV
5-7 keV
7-10 keV
10-20 keV
1
2
3
4
5
6
7
Frequency (Hz)

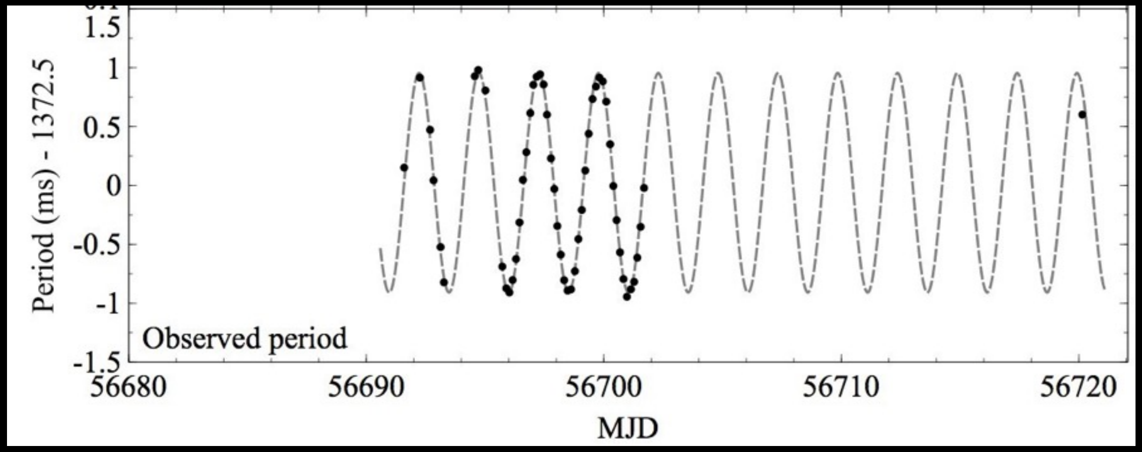

Counts / s / module
Background-subtracted li
002
004
006
007
Period (ms) - 1372.5
Observed period
MJD
Best-fit model period
Period - 1372.5 (ms)
TOA Residual (ms)
Ephemeris: PEPOCH (MJD) = 56696
F0 (Hz)= 0.72857393(5)
F1 (Hz/s) = 5.47(2)x10^-11
30 ks
40 ks
50 ks
006
007
008
009
Secular trends removed
MJD

INGREDIENTS:

- Pulsation found ubiquitously, around **1.37 s**

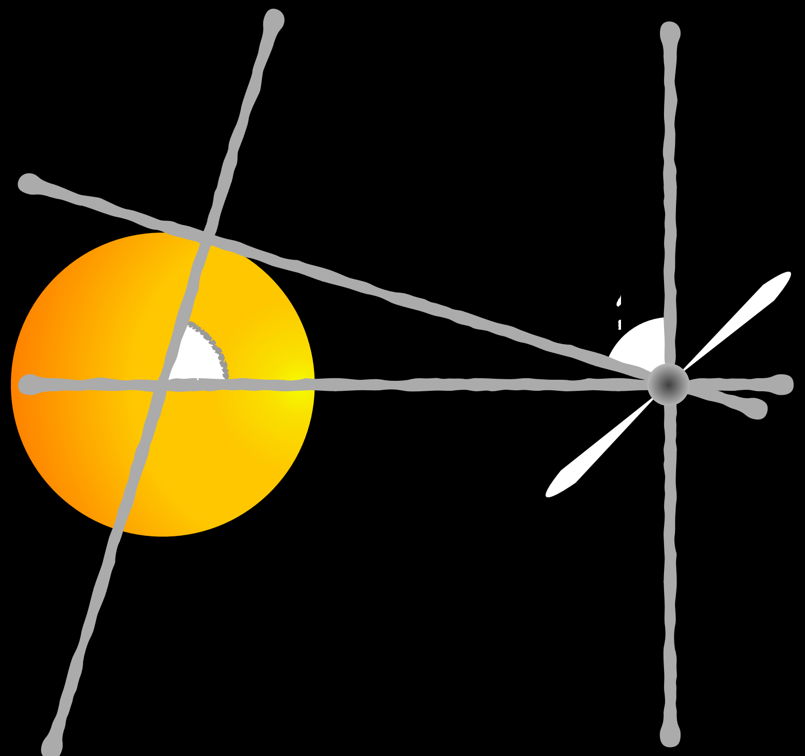


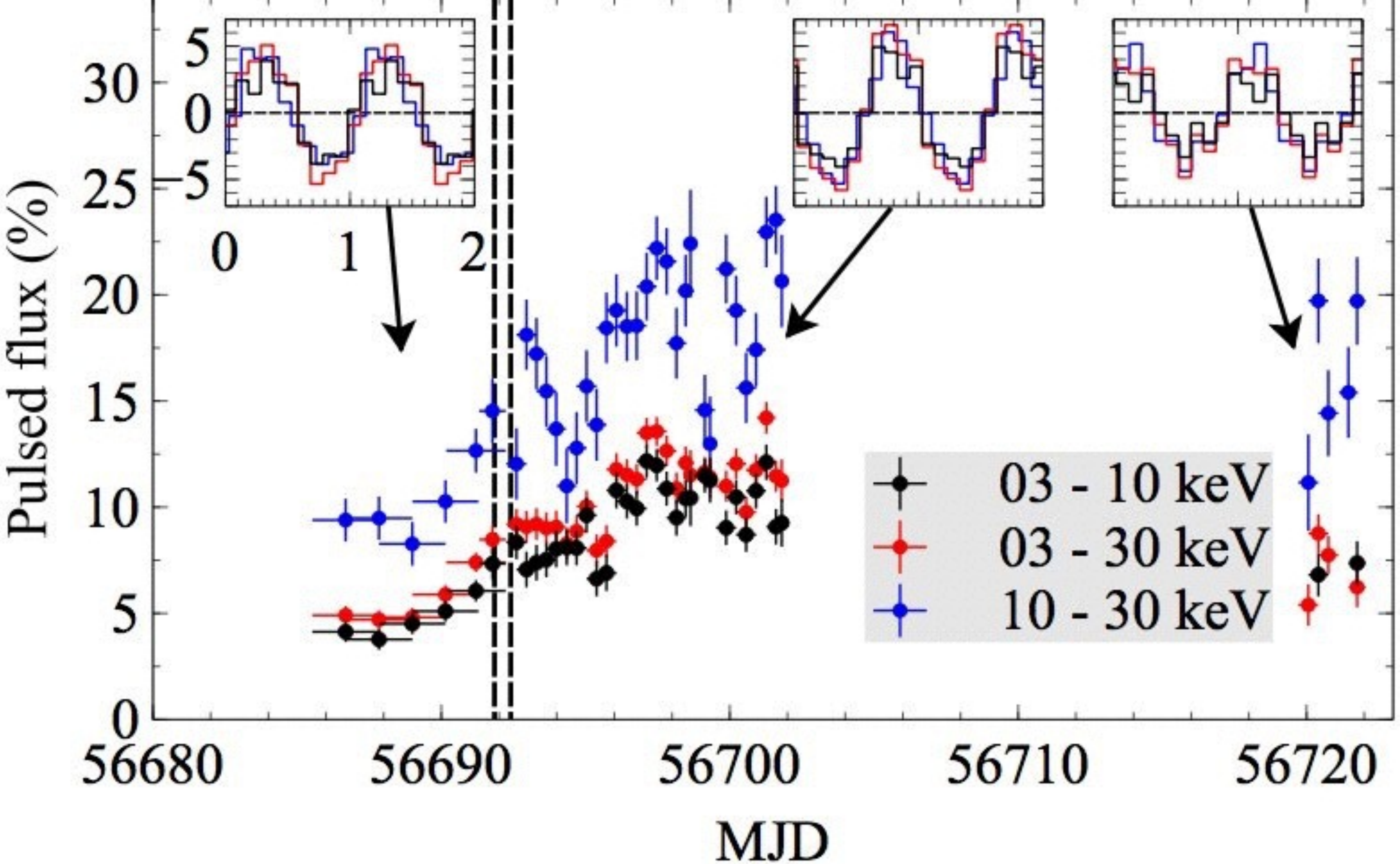
- Strong and variable **spin up:** $\dot{p}$: 0-> -2×10^{-10} ($\dot{f}\sim-10^{-10}$ Hz/s)



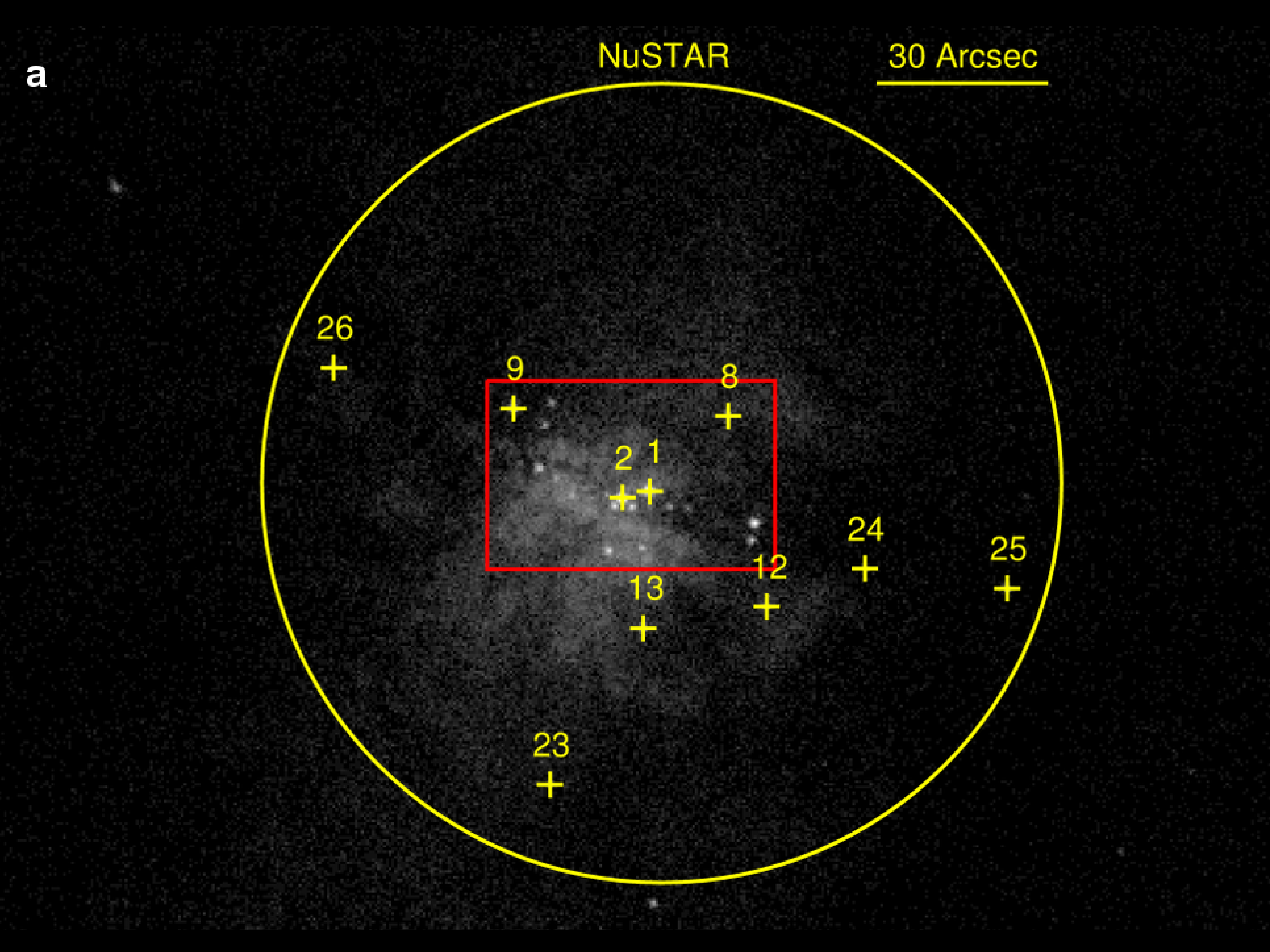
- P_{orb} = 2.54 d
  $a \sin i / c$ = 23 l-sec
- No eclipses

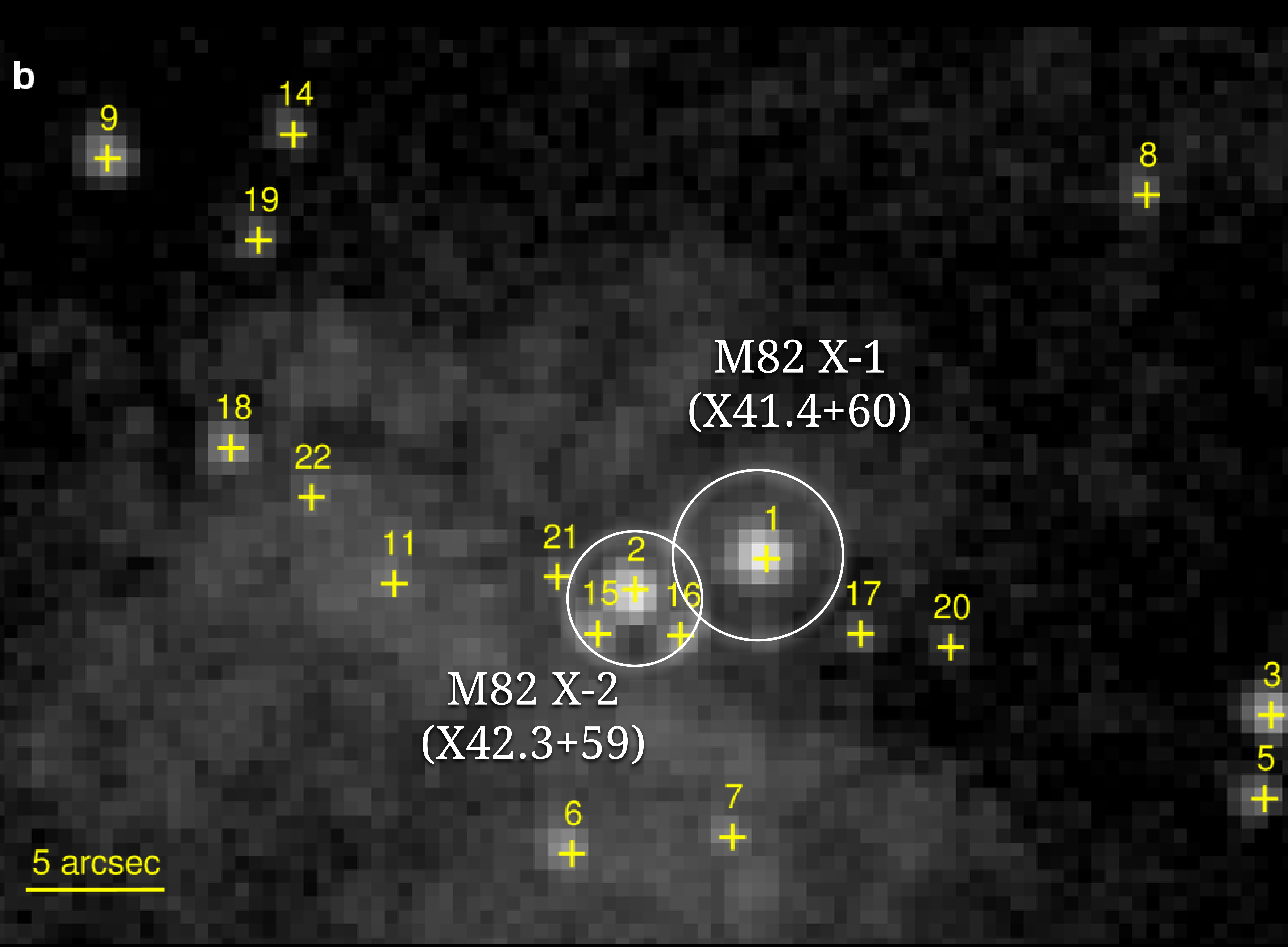
Companion star
$5\ M_\odot \lesssim M_C \lesssim 25\ M_\odot$



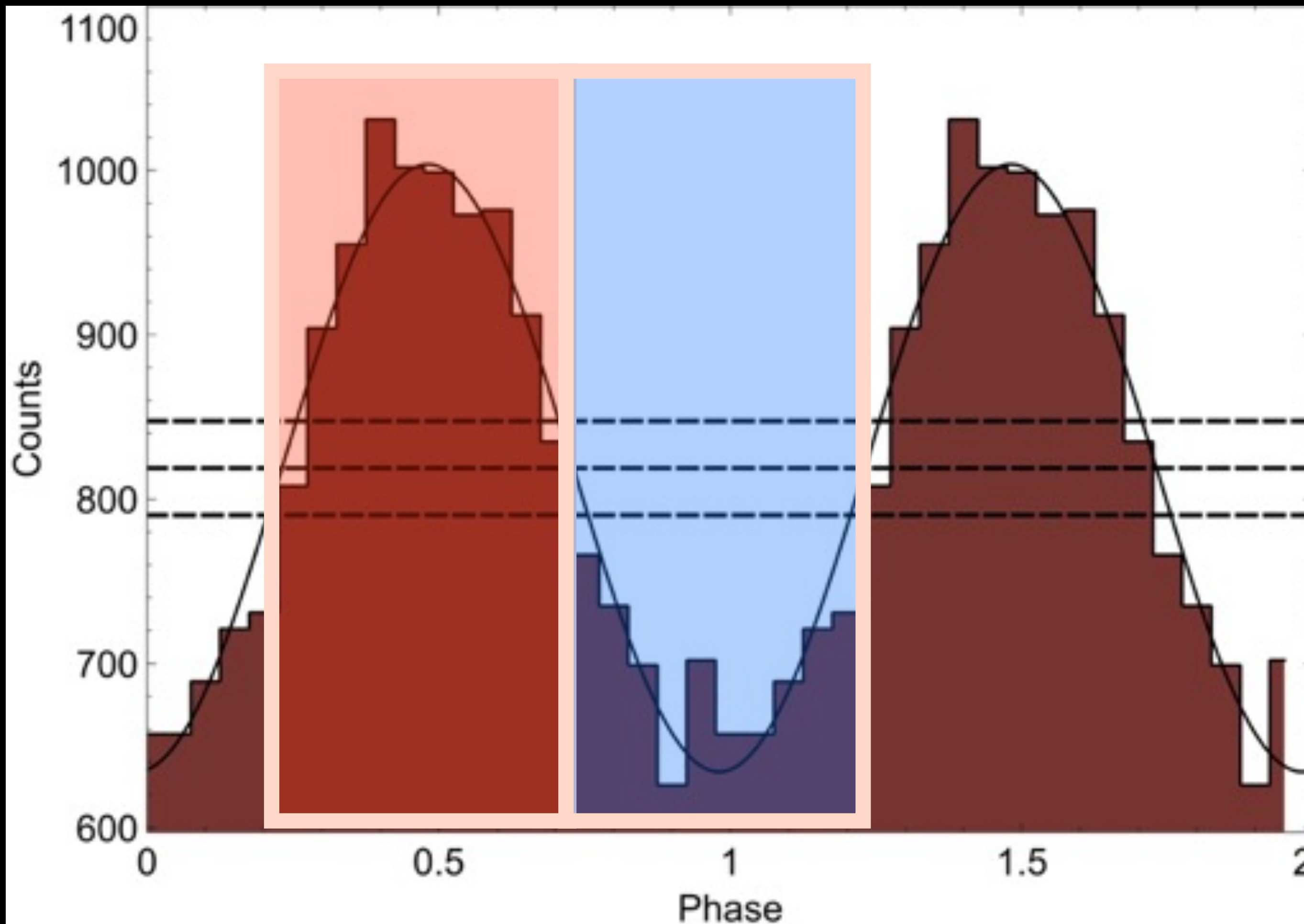


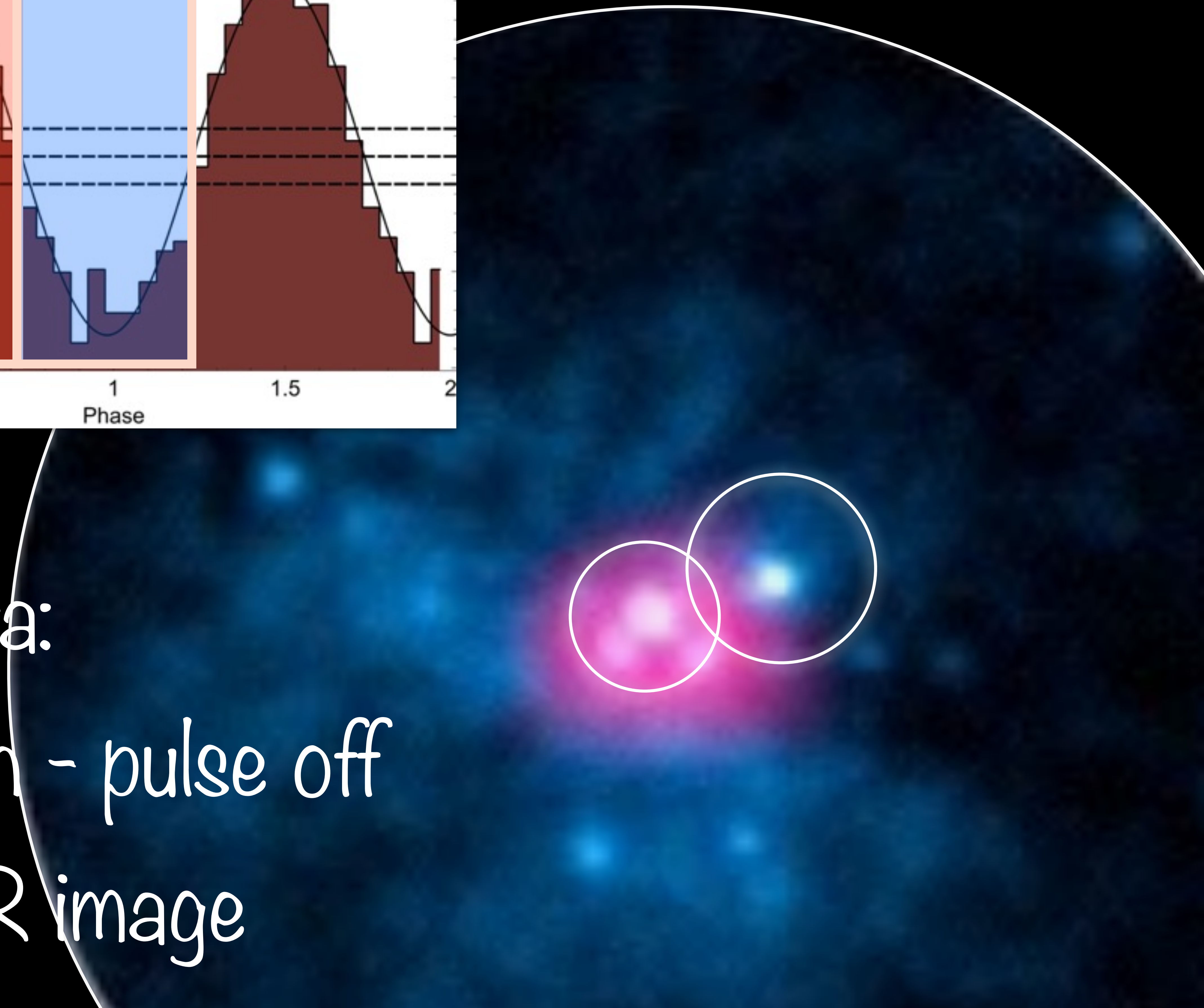
- Pulsed flux is ~10-20% of total flux
- **≳5x10^{39} erg/s in the pulse alone!**


a
NuSTAR
30 Arcsec
26
9
8
2
1
24
25
12
13
23



b
9
14
19
8
M82 X-1
(X41.4+60)
18
22
1
11
21
2
15
16
17
20
M82 X-2
(X42.3+59)
3
5
7
6
5 arcsec

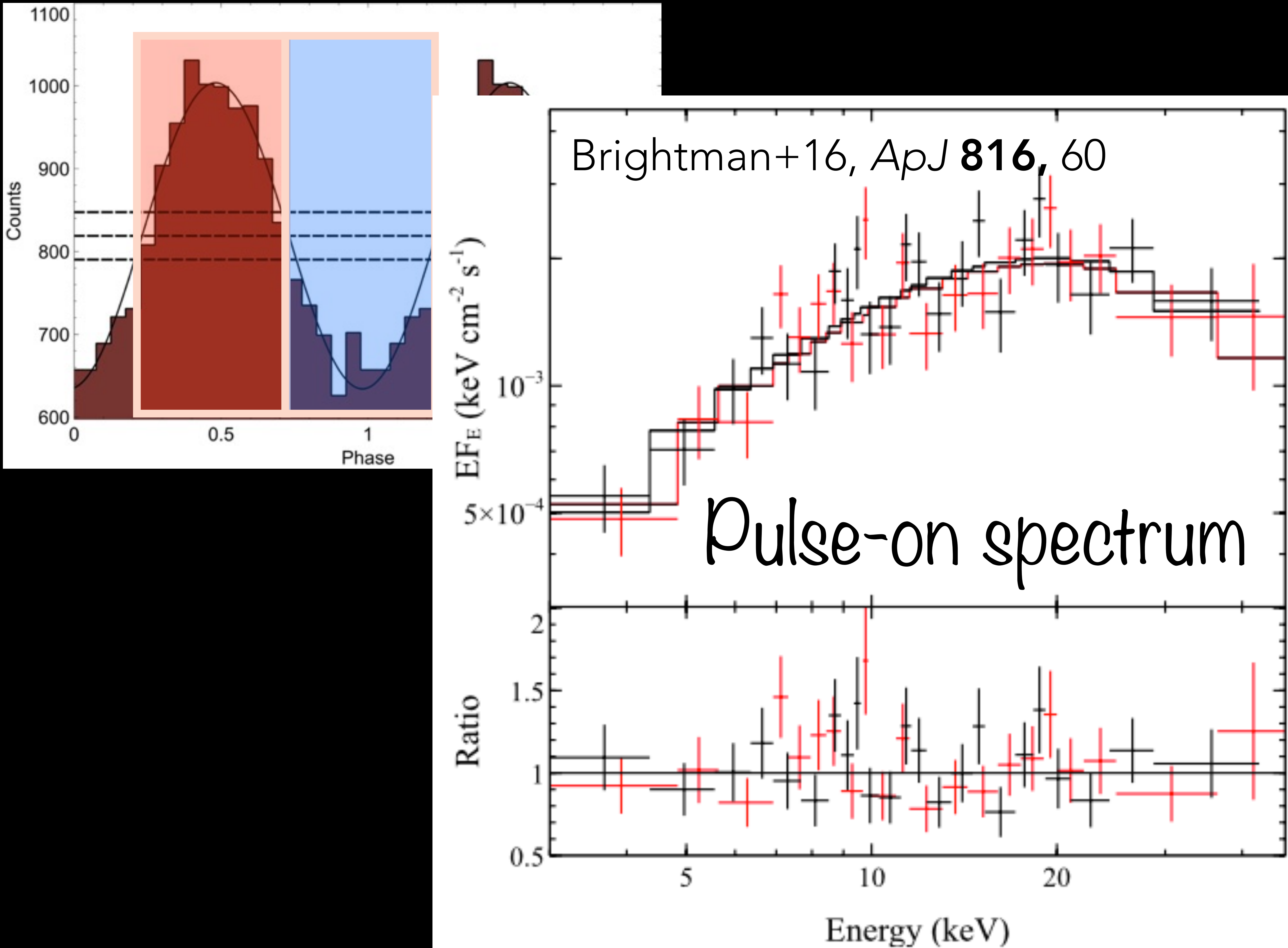




Magenta:

pulse-on - pulse off

NuSTAR image


Brightman+16, *ApJ* **816**, 60
Pulse-on spectrum
Counts
Phase
1100
1000
900
800
700
600
0
0.5
1
EF_E (keV cm^-2 s^-1)
10^-3
5×10^-4
Ratio
2
1.5
1
0.5
5
10
20
Energy (keV)

100 X EDDINGTON LIMIT?

- **Feeding: no problem**
  Roche Lobe overflow
  (e.g. Tauris+00, ApJ 530, 93)

  Be-like
  (e.g. Karino & Miller, MNRAS ArXiv:1605.05723)

- **Overcoming Local Eddington limit:**
  + Radiation “simply” escaping from sides o accretion column
  Kawashima+16, *PASJ*.
  + High magnetic field
  (e.g. Mushtukov+15, MNRAS 454, 2539)

MAGNETIC FIELD?

- **High magnetic field**:
  - Dall'Osso+15, … -> $B \sim 10^{13} G$
  - Eksi+15, Tsygankov+15 (+Mushtukhov+15) -> magnetar
- **Low magnetic field (**$B \sim 10^{9} G$**)**:
  - Kluzniak & Lasota '15, MNRAS, 448, 43
    King & Lasota '16, MNRAS
- **"Standard" magnetic field** ($B \sim 10^{12} G$):
  - Bachetti+14, Christodolou+14, Lyutikov+14, …

MAGNETIC FIELD?

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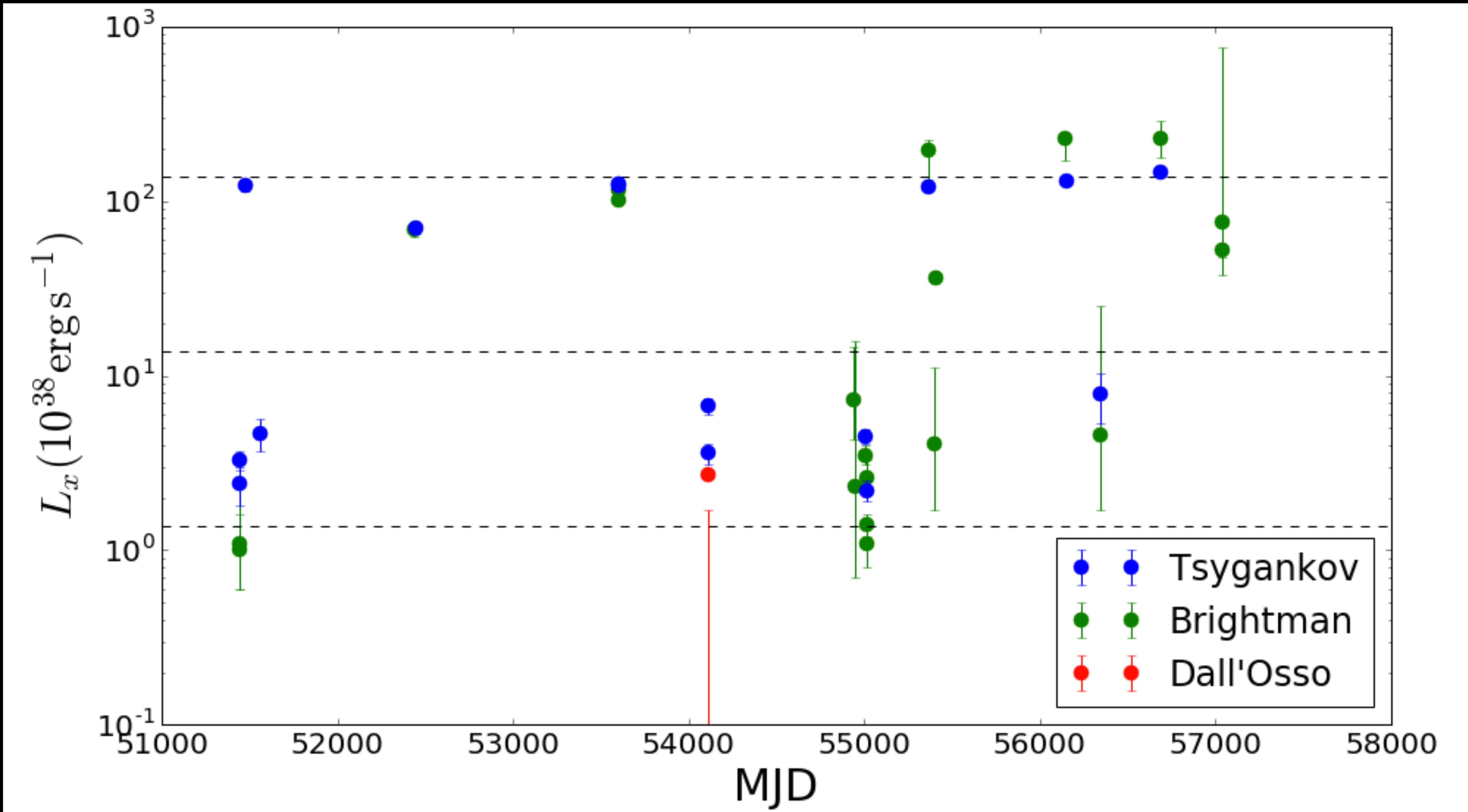
    King & Lasota '16, MNRAS
    Kawashima+16
- **"Standard" magnetic field** (B~10^{12}G):
  - Bachetti+14, Christodolou+14, Lyutikov+14, …

three flux levels correspond to radiation-dominated, gas-dominated and quiescence

two flux levels as signature of the **propeller regime**

a new channel to form **MSPs?**
progenitor of **low-M BHs?**



10^3
10^2
10^1
10^0
10^{-1}
$L_x\,(10^{38}\mathrm{erg\,s^{-1}})$
51000
52000
53000
54000
55000
56000
57000
58000
MJD
Tsygankov
Brightman
Dall'Osso

Tsygankov+16, *MNRAS* **457**, 1101

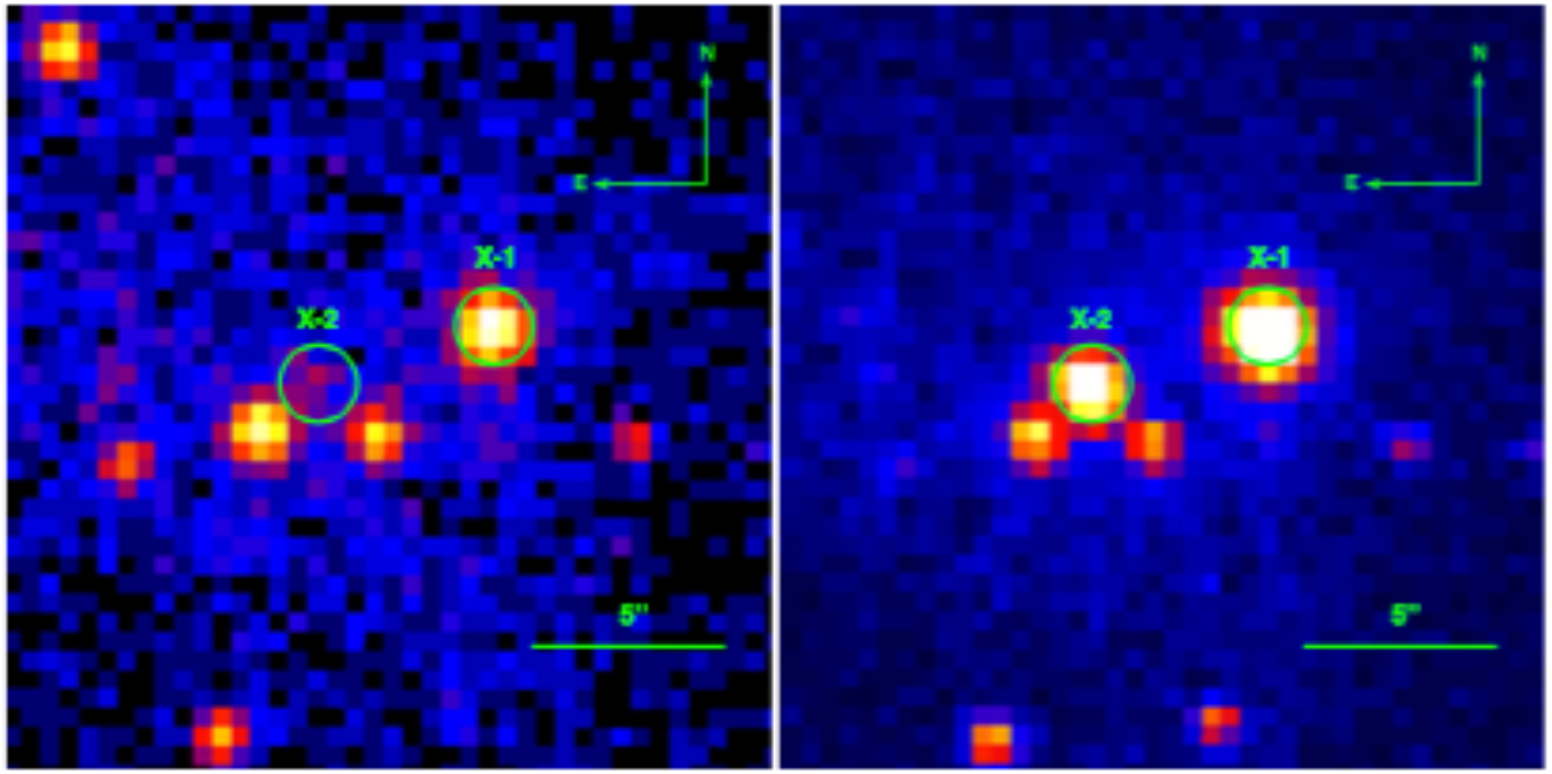
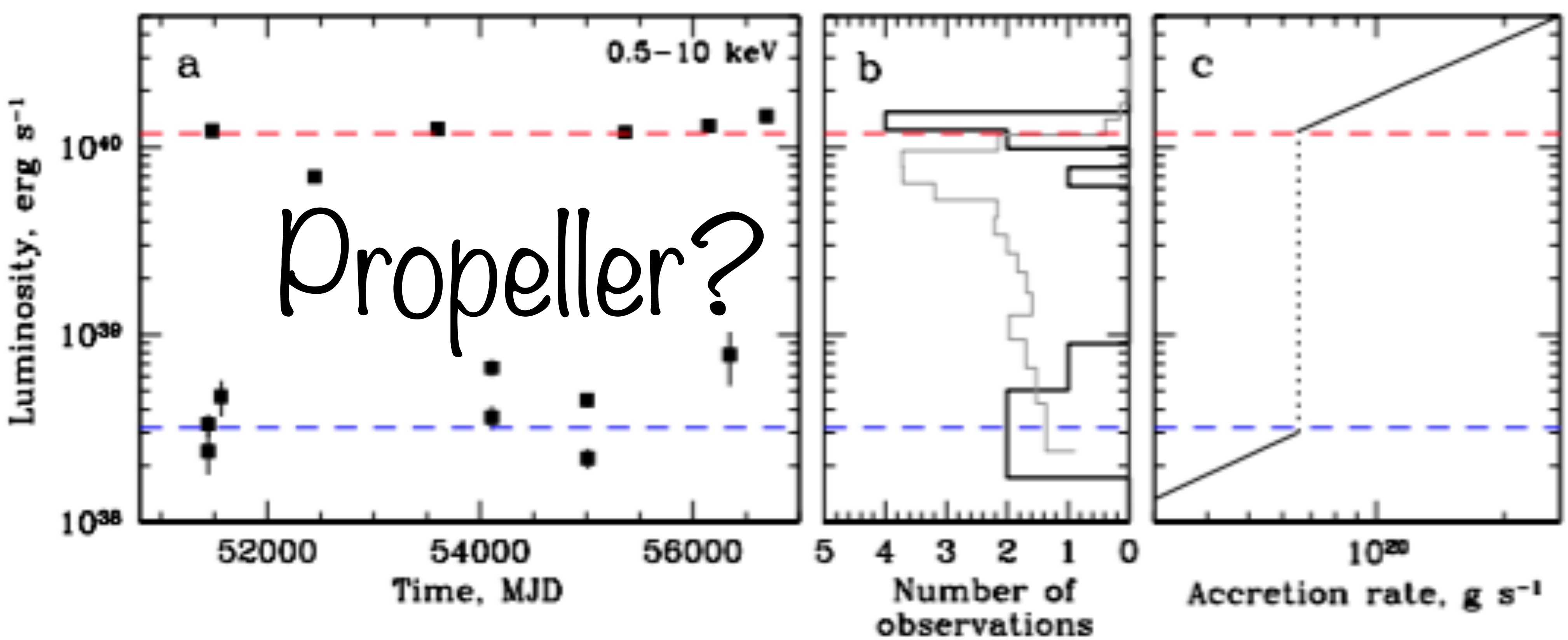
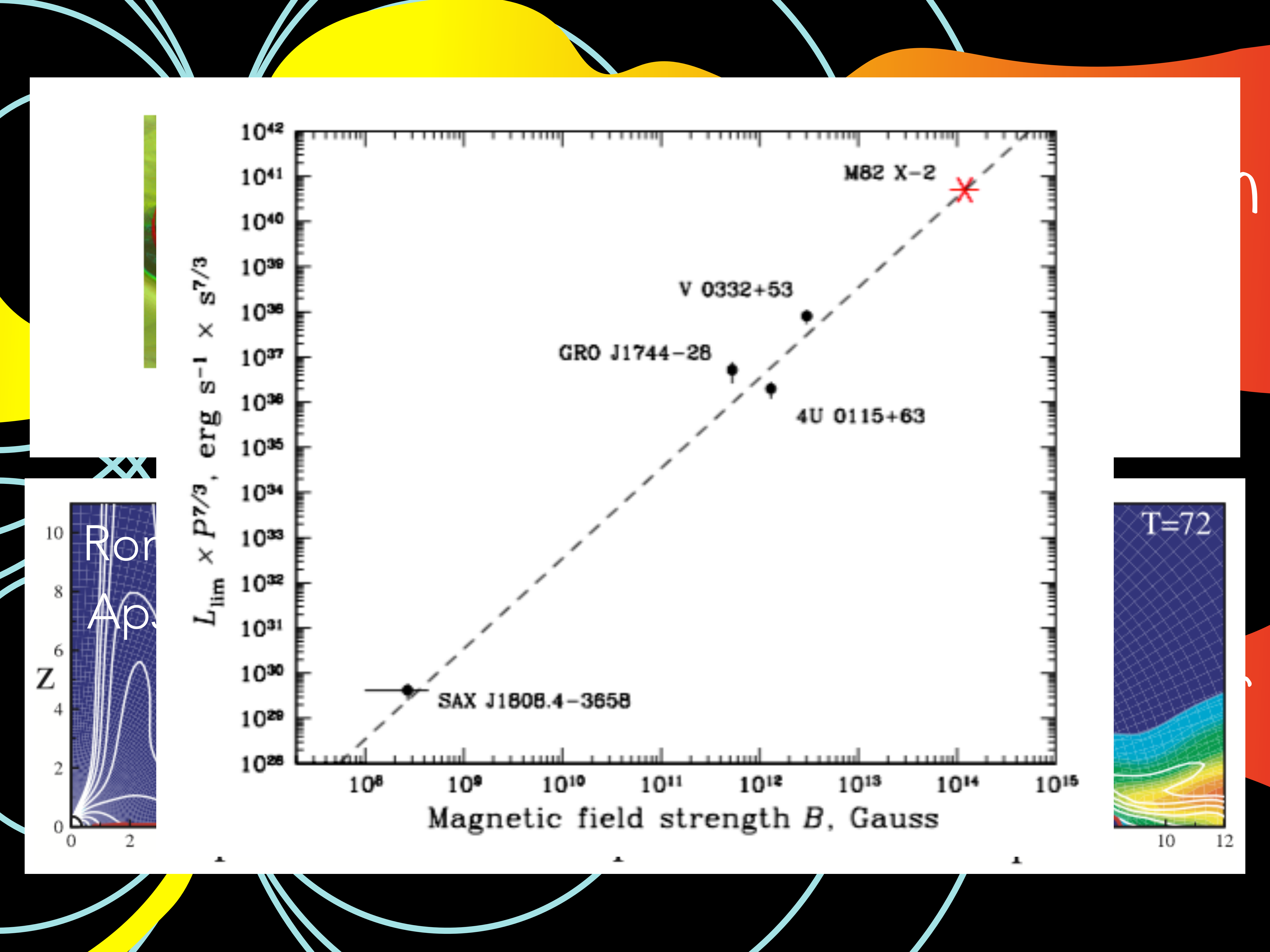


Figure 1. *Chandra* images of M82 galaxy's centre during observations performed on September 20, 1999 (MJD 51441.47) when M82 X-2 was in a low-luminosity state (left) and August 17, 2005 (MJD 53599.04) when it was in a high-luminosity state (right). Circles indicate the positions of M82 X-1 and X-2 ultra-luminous X-ray sources.





M82 X-2
V 0332+53
GRO J1744-28
4U 0115+63
SAX J1808.4-3658
$L_{\rm lim} \times P^{7/3}$, erg s^{-1} × s$^{7/3}$
Magnetic field strength B, Gauss
T=72
Z

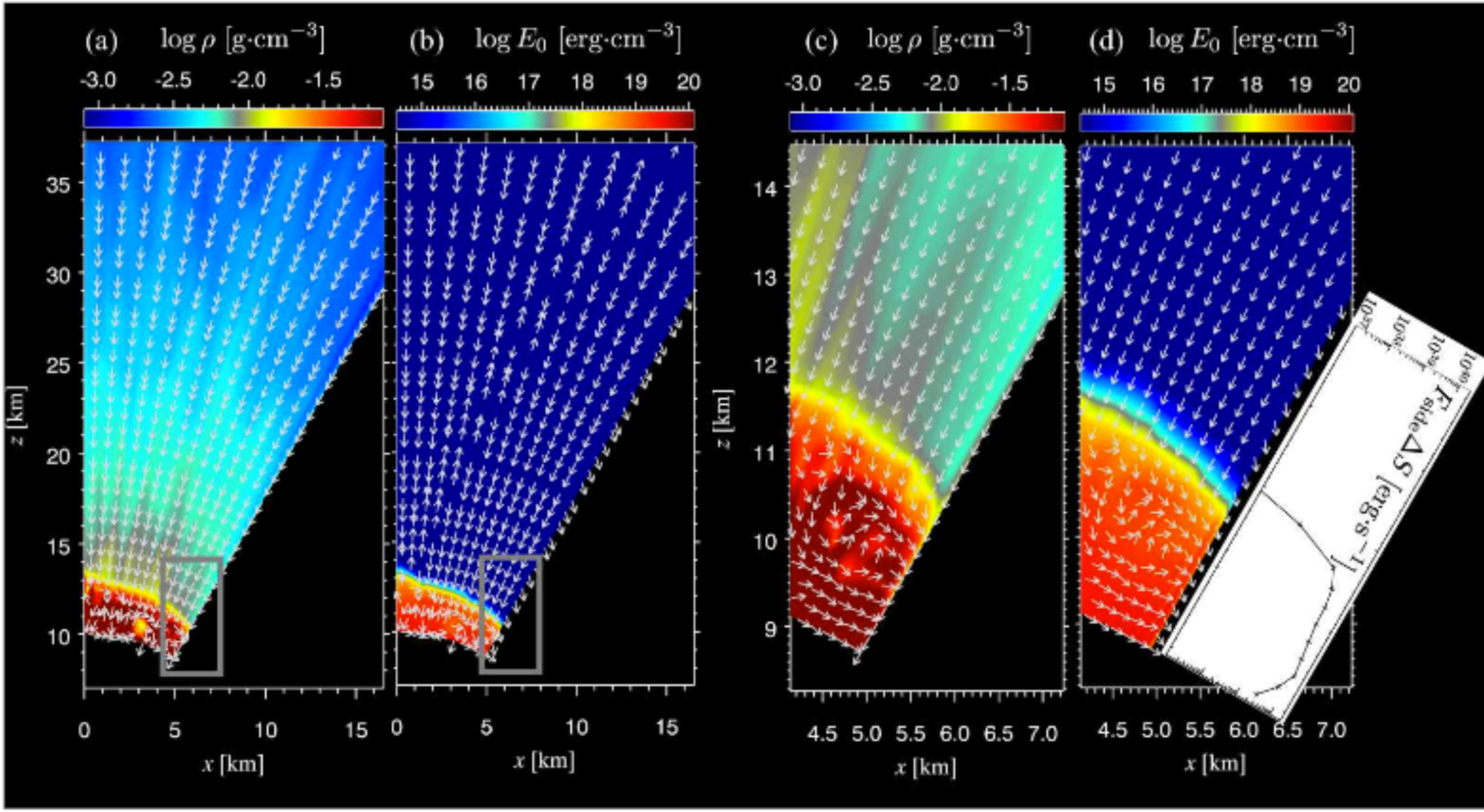


Fig. 1. Two-dimensional diagrams displaying mass and energy flow of super-critical column accretion at the elapsed time of 0.0335 sec. The left two panels show the structure of a column within $r = 37\mathrm{km}$, whereas the right two are magnified views of the innermost region enclosed by the gray squares in the left ones. In each pair of panels, the left panels show matter density color contours overlaid with matter velocity, while the right ones show color contours of radiation energy density overlaid with radiation flux in the laboratory frame (i.e., $\boldsymbol{F}_0 + \boldsymbol{v}E_0$), respectively. Radial profile of the radiation luminosity leaked from the side of accreting column with an area of $\Delta S \equiv 2\pi r \sin\theta \Delta r$ is shown in the inserted figure, where $\Delta r \sim 0.2$ km is the mesh spacing.

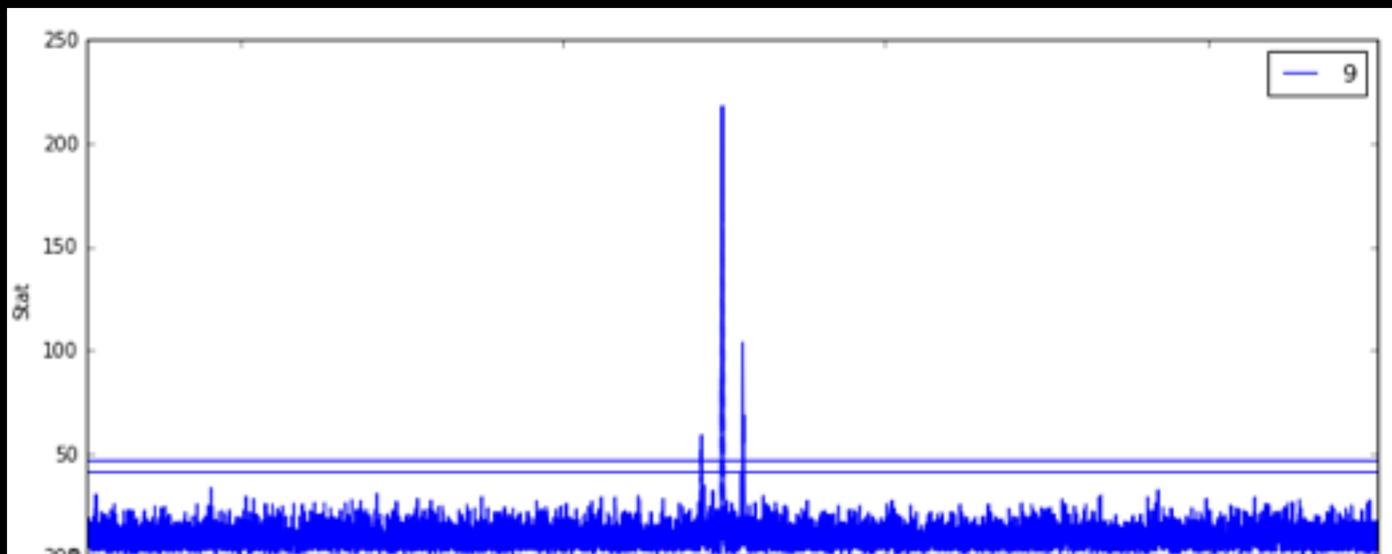
Kawashima+16 *PASJ*

BOTTOM LINE

- A ULX with $L_X > 10^{40}$ erg/s ->**Extreme ULX** range…
- also a **Pulsar** —> NS!!
- in a binary system
  - orbital modulation: likely $i > 26°$ (90% c. l.)
  - no eclipses: $i \lesssim 60°$
  - companion star mass:
  $5\ M_\odot \lesssim M_C \lesssim 25\ M_\odot$ (Most probably ~6, see Tauris+00, *ApJ* **530**, 93)
- Large luminosity variations: why?
- Various models for magnetic field, probably $>10^{13}$ but very uncertain

PRELIMINARY RESULTS - AO1

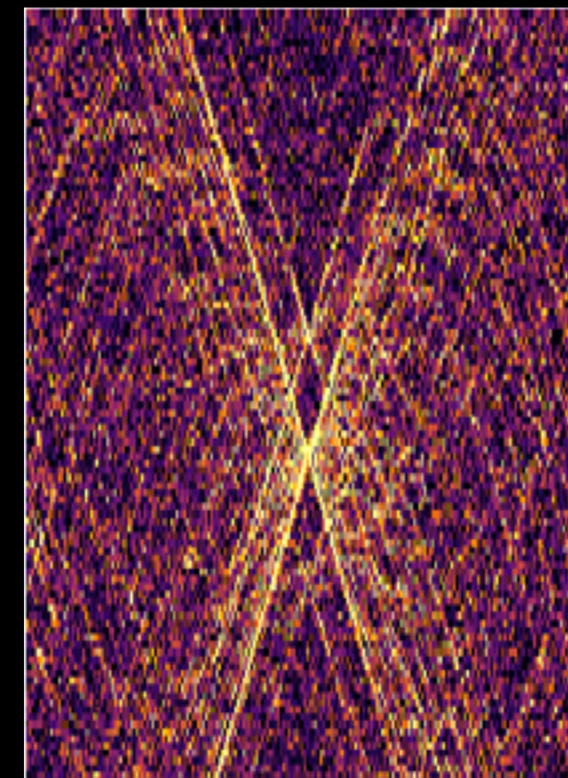
Stat ->



Pulse period ->

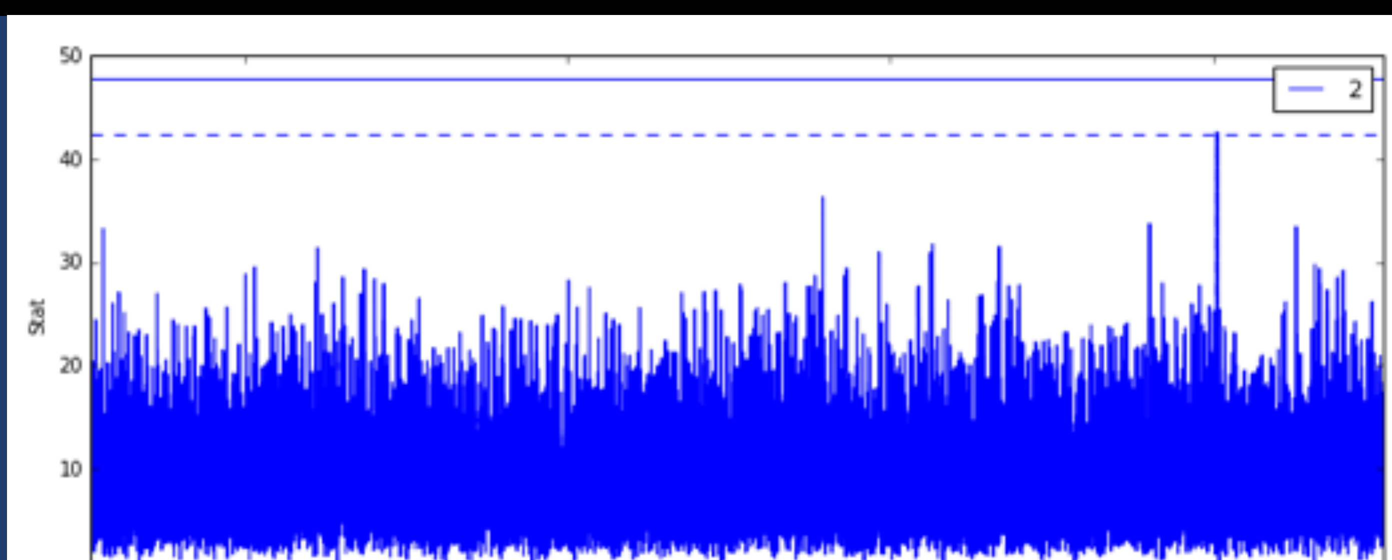
T_0 ->

Pulse period ->



2014

Stat ->



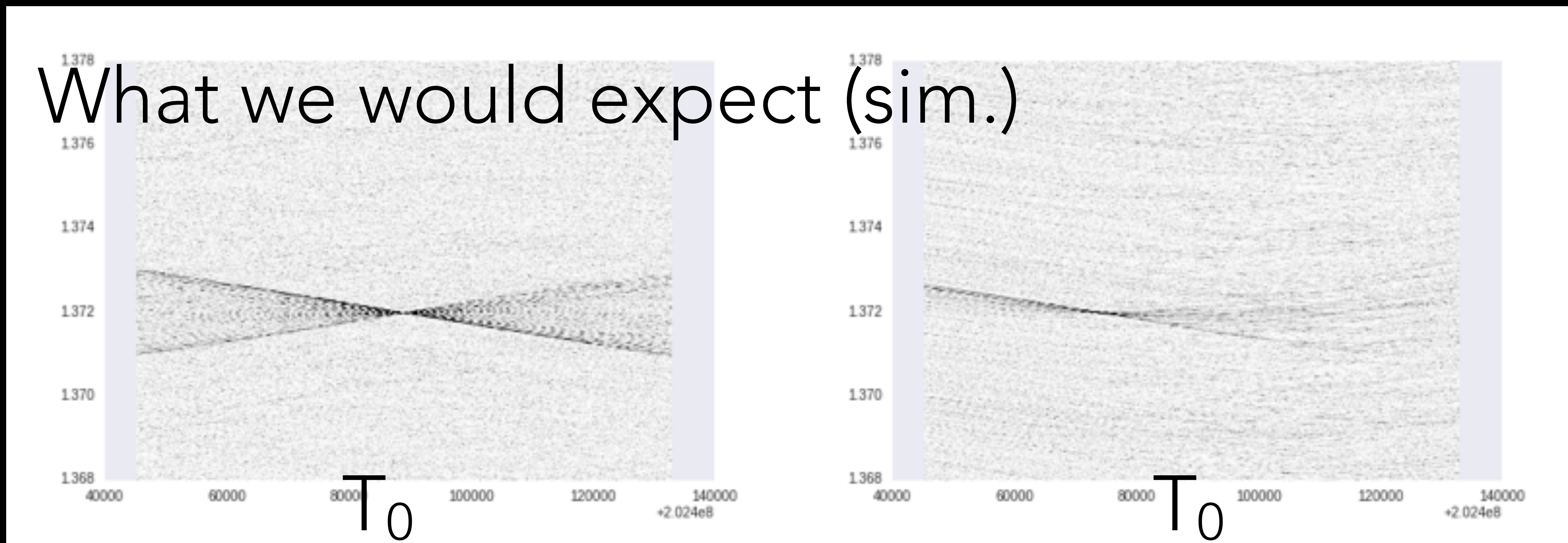
Pulse period ->

2016-AO1

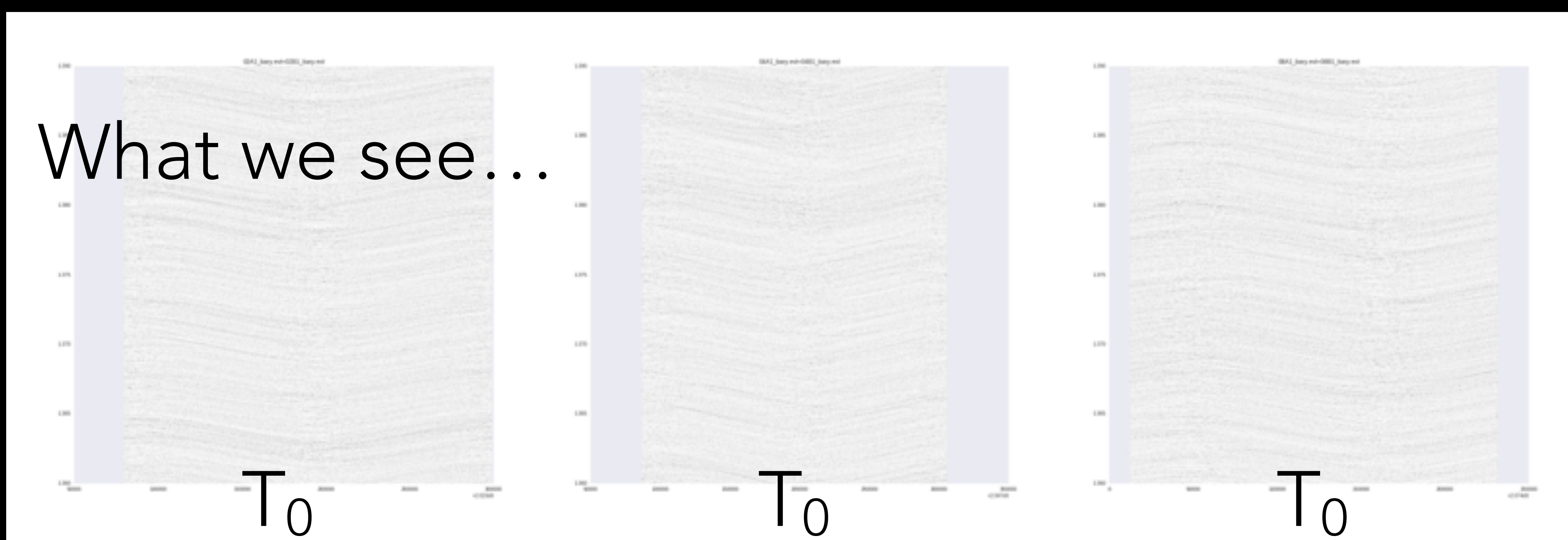
A full orbit NuSTAR~2.5d

PRELIMINARY RESULTS - AO2

pulse period



pulse period



PULSATIONS DISAPPEAR? WHY?

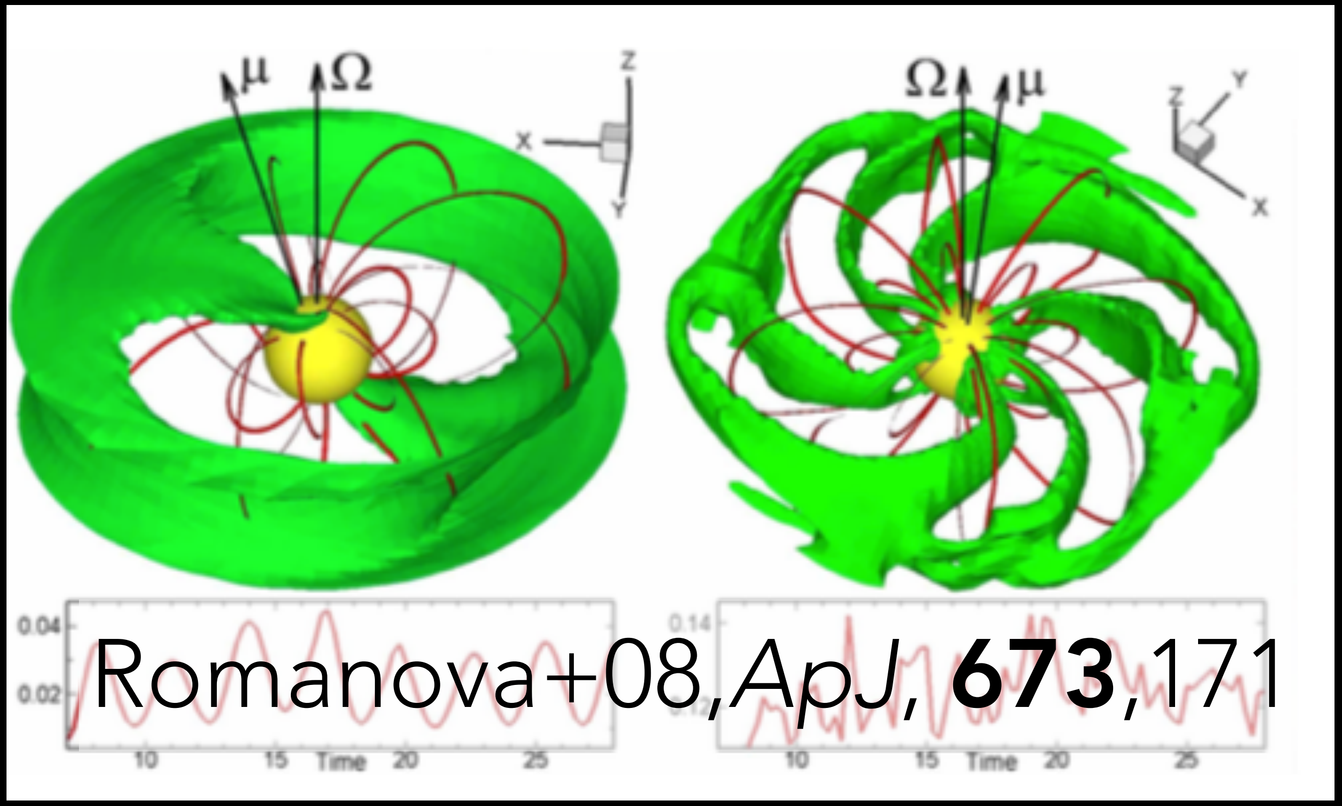
Examples:

- Aql X-1: 150 s over several Ms of RXTE data. (Casella+0 8, *ApJ*, **674**, 41)
- AO 0538-66: pulsations at 69.2 ms observed only once in the seventies. HMXB with Be binary companion. (e.g. Campana et al. 2002. *ApJ*, **580**, 389)

Possibilities:

★ Change of magnetic field configuration?
★ Different accretion regime (Instabilities disrupting accr. col.)?
★ Partial occultation from disk, precession?
★ Others? (Asks the audience ;))

Bachetti+16 in prep.



Romanova+08,*ApJ*, **673**,171