MATTEO BACHETTI

THE ULTRALUMINOUS PULSAR

A REALLY ULTRALUMINOUS X-RAY SOURCE

TEXAS SYMPOSIUM, GENEVA, DEC.15th 2015

NO AGN

Single sources

Definition:

Ultraluminous X-ray sources are off-nuclear, point-like X-ray sources exceeding the (isotropic) Eddington limit for a stellar-mass Black Hole (StBH)

NO AGN

Single sources

Definition:

Ultraluminous X-ray sources are off-nuclear, point-like X-ray sources exceeding the (isotropic) Eddington limit for a stellar-mass Black Hole (StBH)

$$L_{Edd} \approx 1.38 \cdot 10^{38} \frac{M}{M_\odot} \mathrm{erg/s}$$

$$\approx 1.38 \cdot 10^{39} \frac{M}{10 M_\odot} \mathrm{erg/s}$$

Extreme ULXs (eULXs): $L_{Edd} > 10^{40}$ erg/s

*Hyper*luminous X-ray sources: $L_{Edd} > 10^{42}$ erg/s

NO AGN

Single sources

Definition:

Ultraluminous X-ray sources are off-nuclear, point-like X-ray sources exceeding the (isotropic) Eddington limit for a stellar-mass Black Hole (StBH)

$$L_{Edd} \approx 1.38 \cdot 10^{38} \frac{M}{M_\odot} \mathrm{erg/s}$$

$$\approx 1.38 \cdot 10^{39} \frac{M}{10 M_\odot} \mathrm{erg/s}$$

Extreme ULXs (eULXs): $L_{\mathrm{Edd}} > 10^{40}$ erg/s

*Hyper*luminous X-ray sources: $L_{\mathrm{Edd}} > 10^{42}$ erg/s

ULTRALUMINOUS X-RAY SOURCES

IMBH?

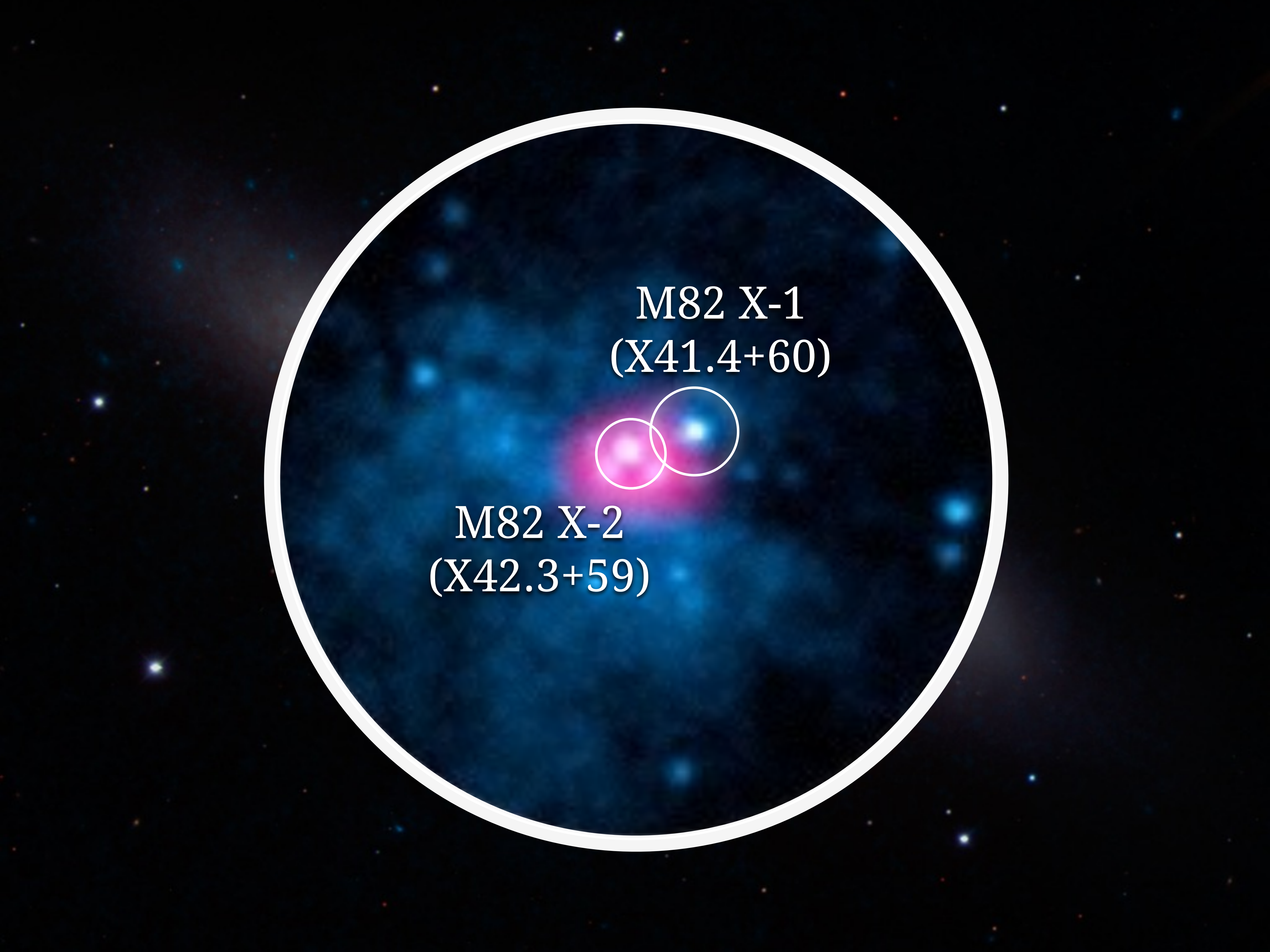
Soft excess
Low-frequency variability
High luminosity (of course)

More likely above 10^{42} erg/s

>EDDINGTON?

Hard turnover
"Strange" variability!
High luminosity (of course)

More likely below 10^{40} erg/s



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

THE ULXs IN M82

Famous ULXs, showing interesting spectral and timing behavior:

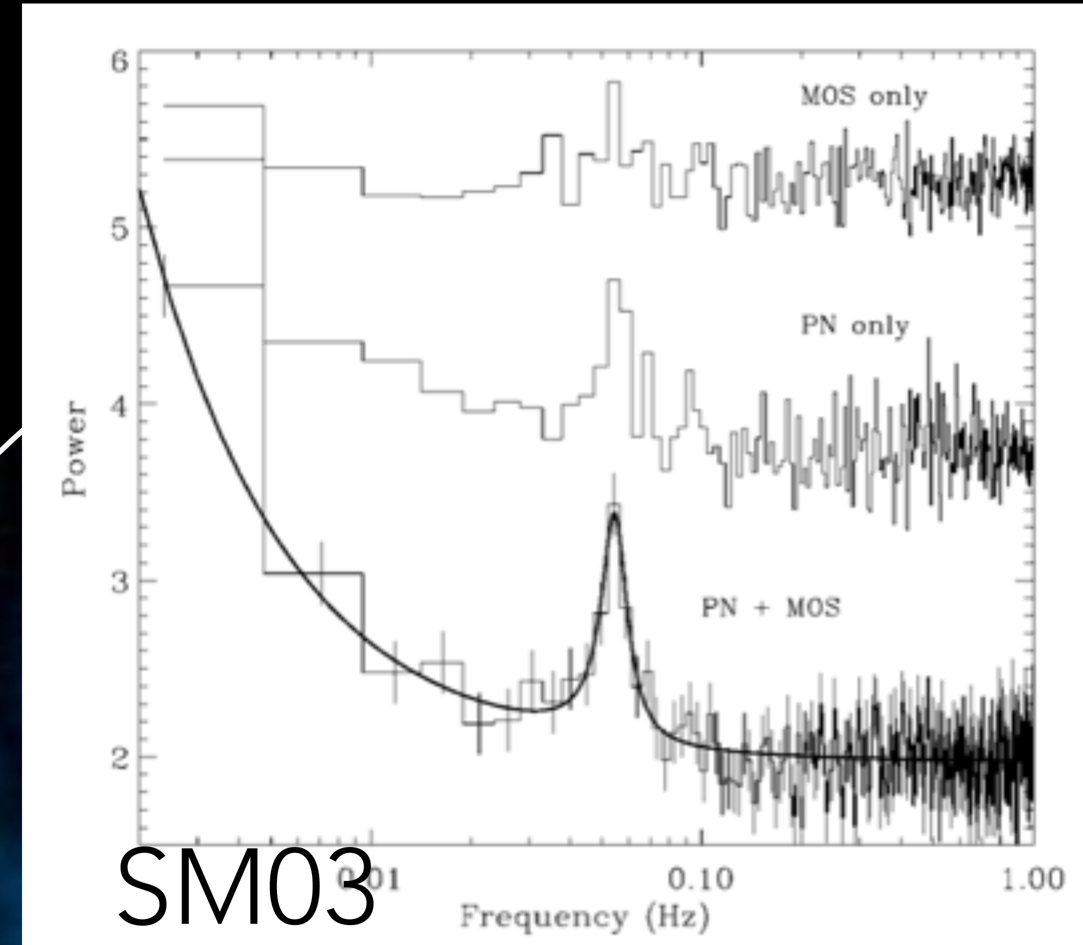
- **M82 X-1/X41.4+60:** $L_X \sim 10^{41}$ f_{QPO}: **50—190 mHz** (SM03, K+06)
- **M82 X-2/X42.3+59:** $L_X \sim 10^{40}$ f_{QPO}: **3—4 mHz** (FK10)
- Both used to infer masses of the BHs in the **IMBH range** (FK07, FK10)

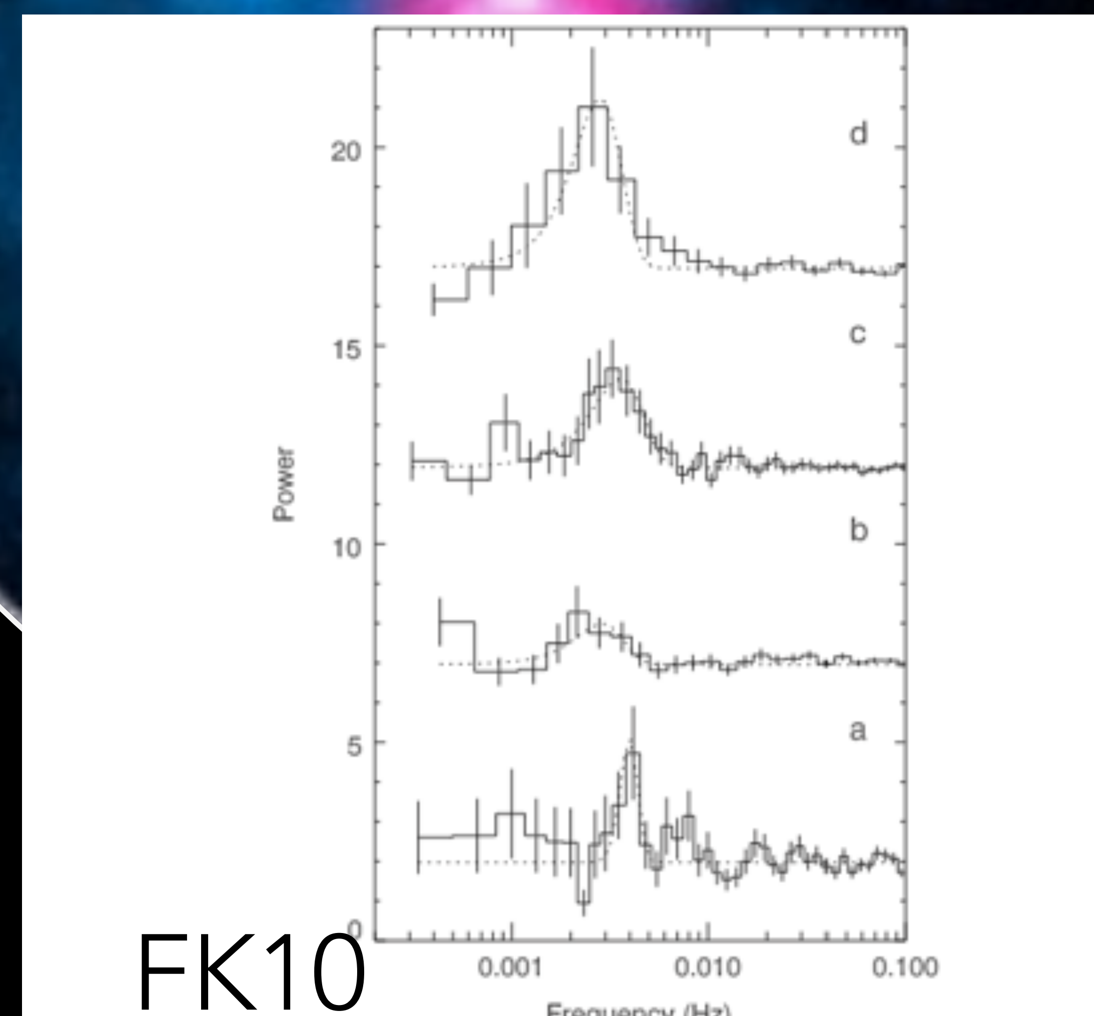
- SM03: Strohmayer, T. E. & Mushotzky, R. F., ApJ 586, L61–L64 (2003).
- K+06: Kaaret, P., Simet, M. G. & Lang, C. C., ApJ 646, 174–183 (2006).
- FK07: Feng, H. & Kaaret, P., ApJ 668, 941–948 (2007).
- FK10: Feng, H., Rao, F. & Kaaret, P., ApJL 710, L137–L141 (2010).

THE ULXs IN M82

Famous ULXs, showing interesting spectral and timing behavior:

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

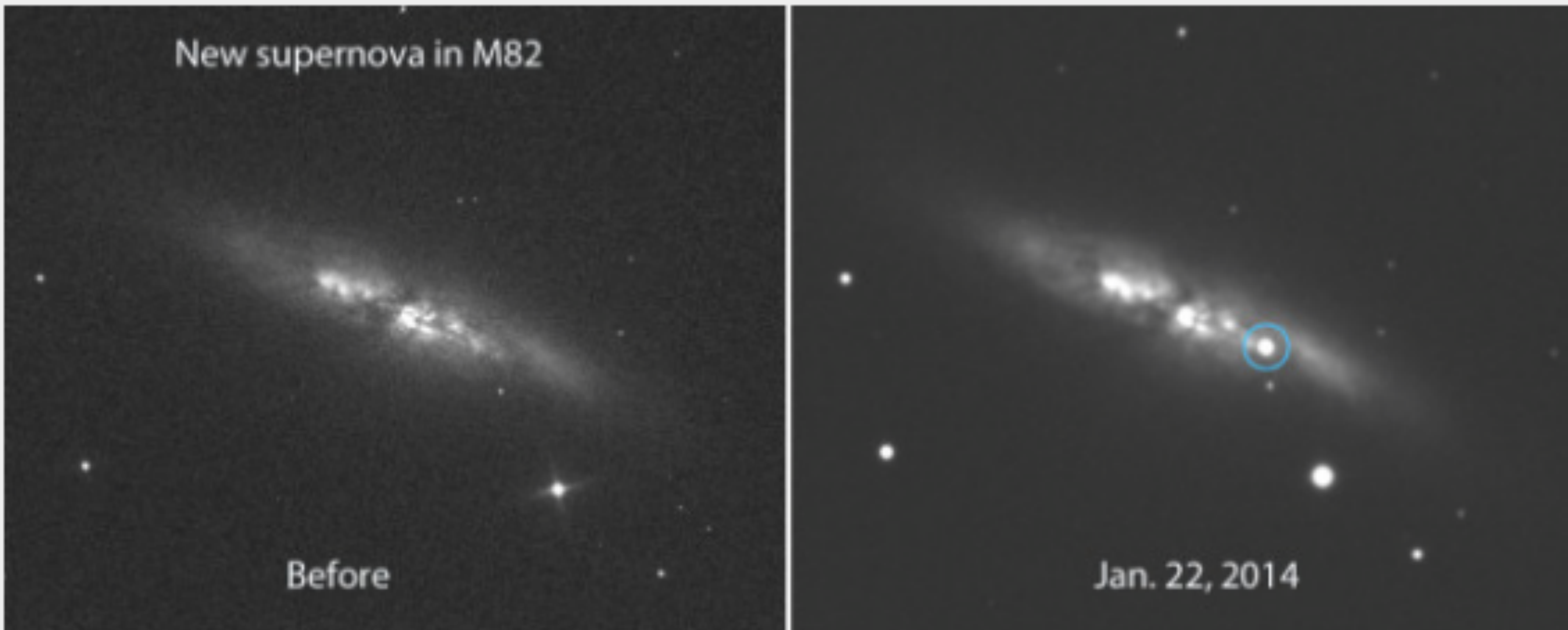




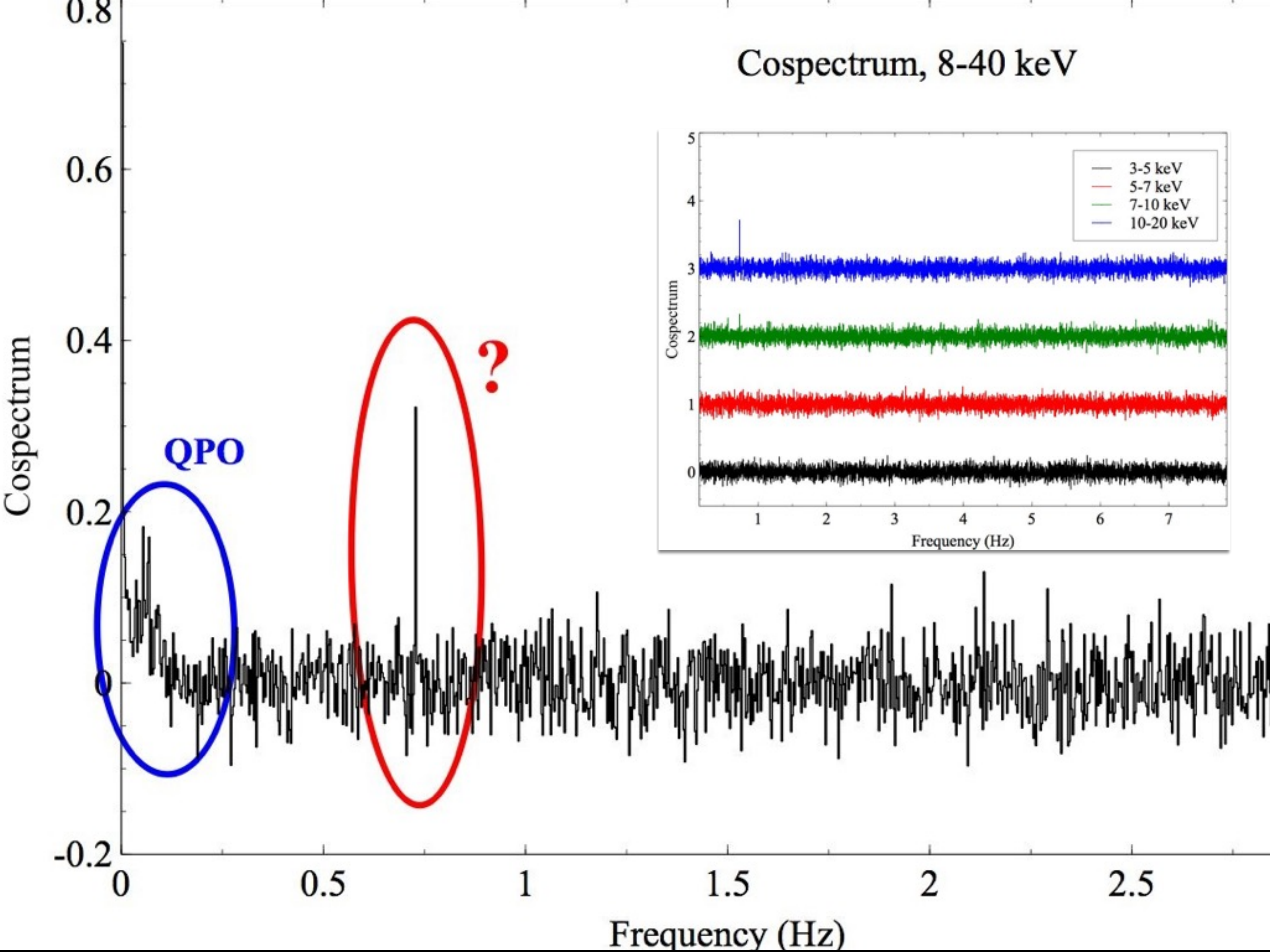
- SM03: Strohmayer, T. E. & Mushotzky, R. F., ApJ 586, L61–L64 (2003).
- K+06: Kaaret, P., Simet, M. G. & Lang, C. C., ApJ 646, 174–183 (2006).
- FK07: Feng, H. & Kaaret, P., ApJ 668, 941–948 (2007).
- FK10: Feng, H., Rao, F. & Kaaret, P., ApJL 710, L137–L141 (2010).

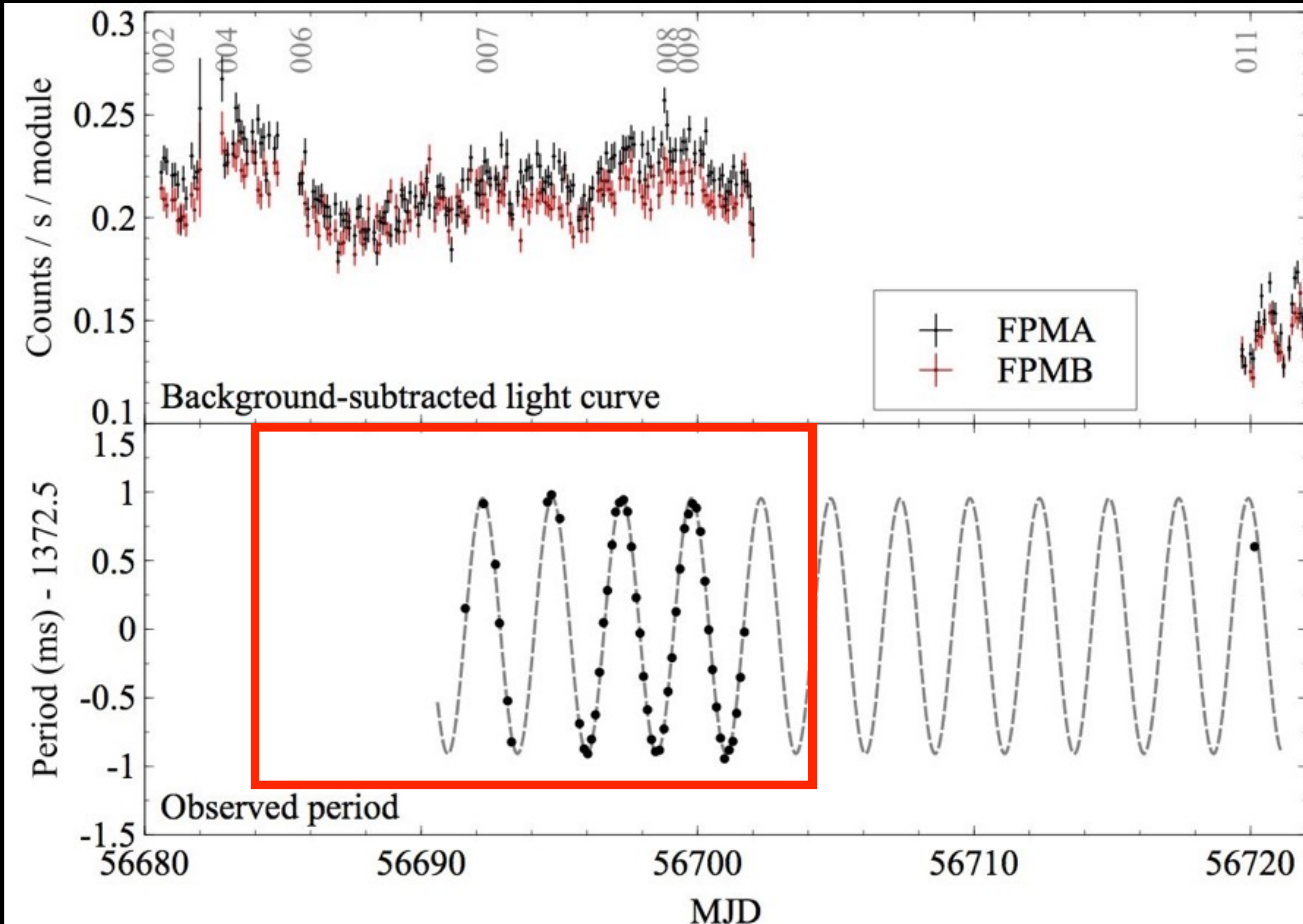
Bright New Supernova Blows Up in Nearby M82, the Cigar Galaxy

by BOB KING *on* JANUARY 22, 2014

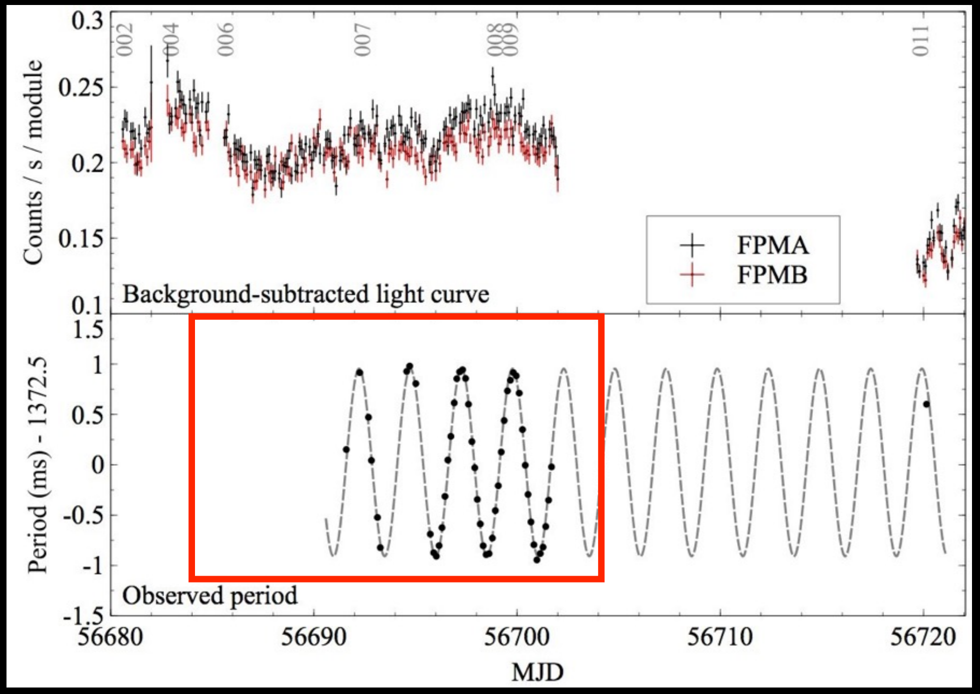


Before and after photos of the galaxy M82 showing the appearance of a brand new 11.7 magnitude supernova. The object is located in the galaxy's plane 54″ west and 21″ south of its

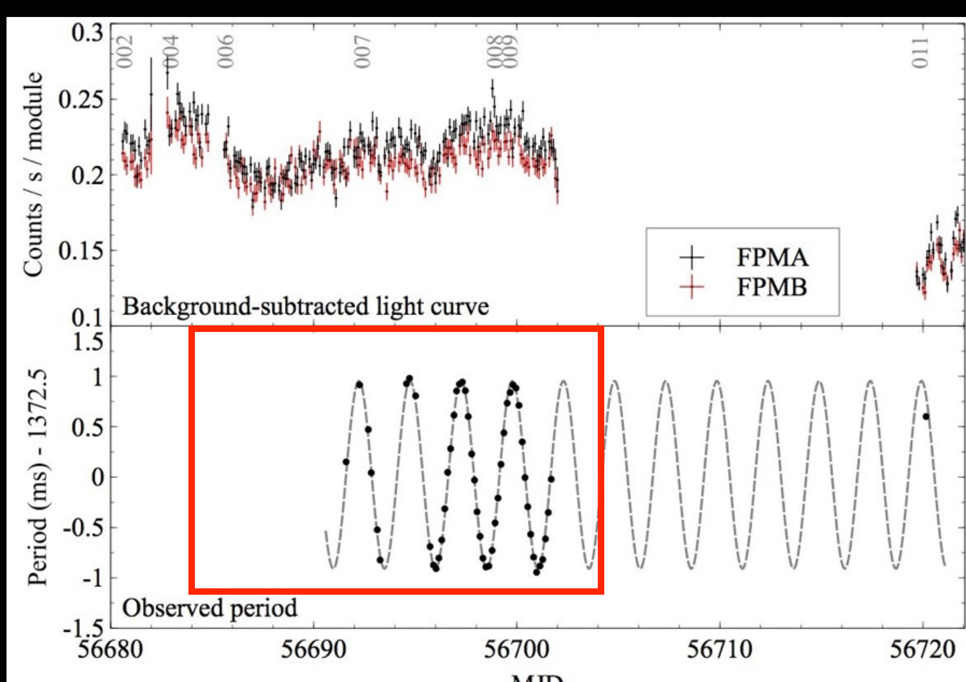

Cospectrum, 8-40 keV
QPO
?
Cospectrum
Frequency (Hz)
0.8
0.6
0.4
0.2
0
-0.2
0
0.5
1
1.5
2
2.5
3-5 keV
5-7 keV
7-10 keV
10-20 keV
Cospectrum
Frequency (Hz)

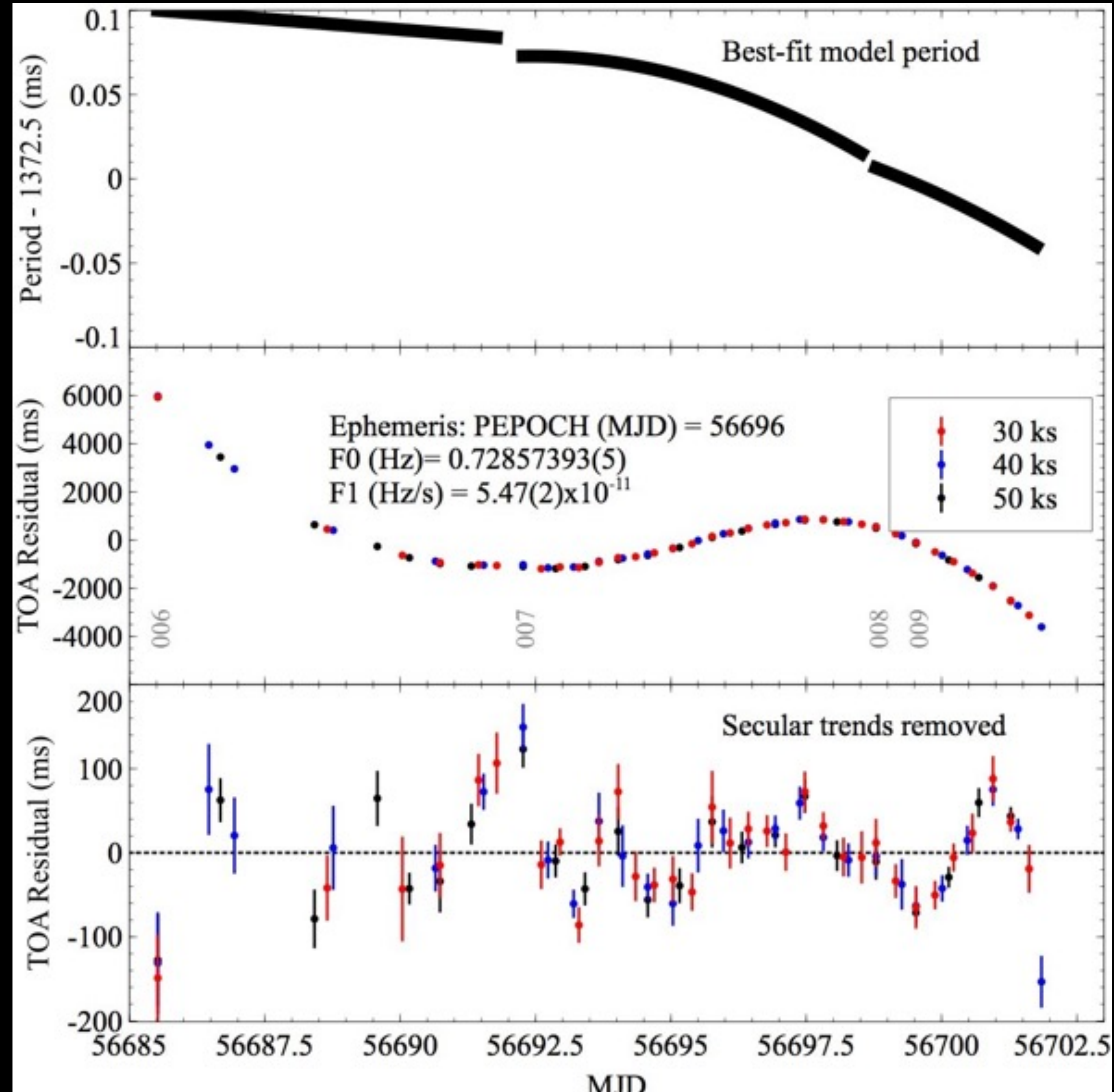


002
004
006
007
008
009
011
0.3
0.25
0.2
0.15
0.1
Counts / s / module
FPMA
FPMB
Background-subtracted light curve
1.5
1
0.5
0
-0.5
-1
-1.5
Period (ms) - 1372.5
Observed period
56680
56690
56700
56710
56720
MJD



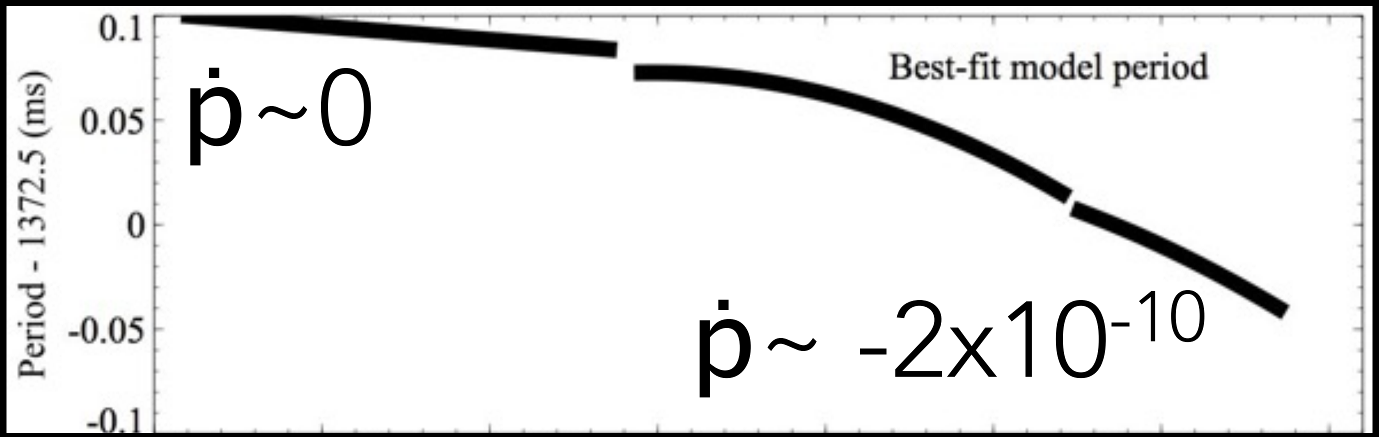
002
004
006
007
008
009
011
FPMA
FPMB
Background-subtracted light curve
Counts / s / module
Period (ms) - 1372.5
Observed period
MJD

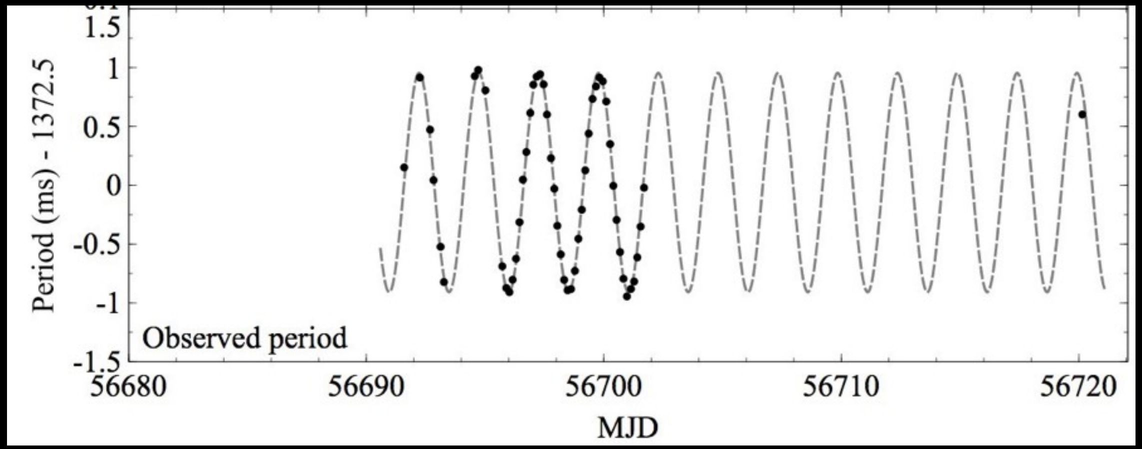

Counts / s / module
002
004
006
007
008
009
011
FPMA
FPMB
Background-subtracted light curve
Period (ms) - 1372.5
Observed period
MJD


Period - 1372.5 (ms)
Best-fit model period
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
TOA Residual (ms)
Secular trends removed
MJD

INGREDIENTS:

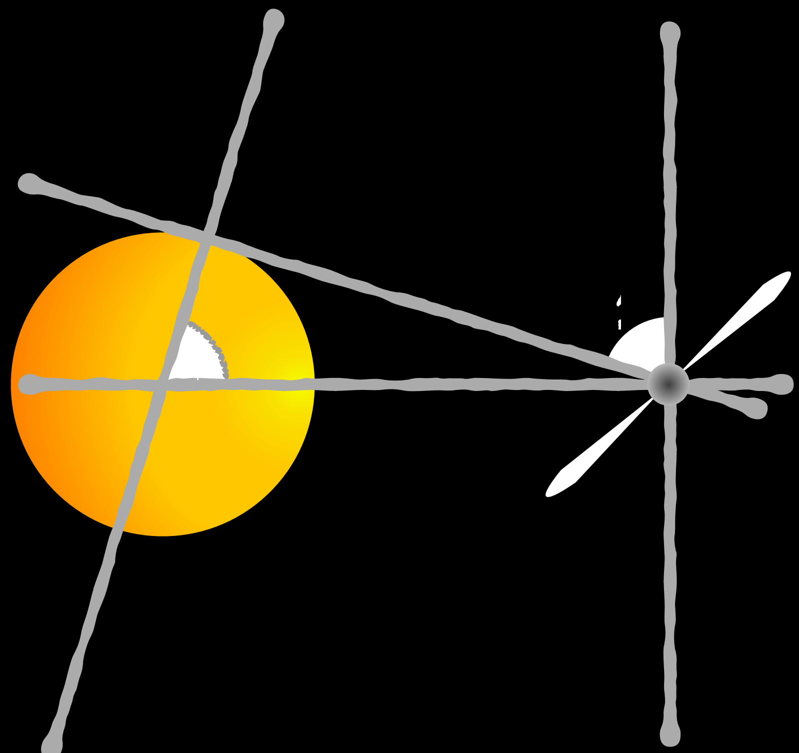
- Pulsation found ubiquitously, around **1.37 s**
- Strong and variable **spin up:** $\dot{p}$: 0-> -2×10^{-10} ($\dot{f} \sim -10^{-10}$ Hz/s)

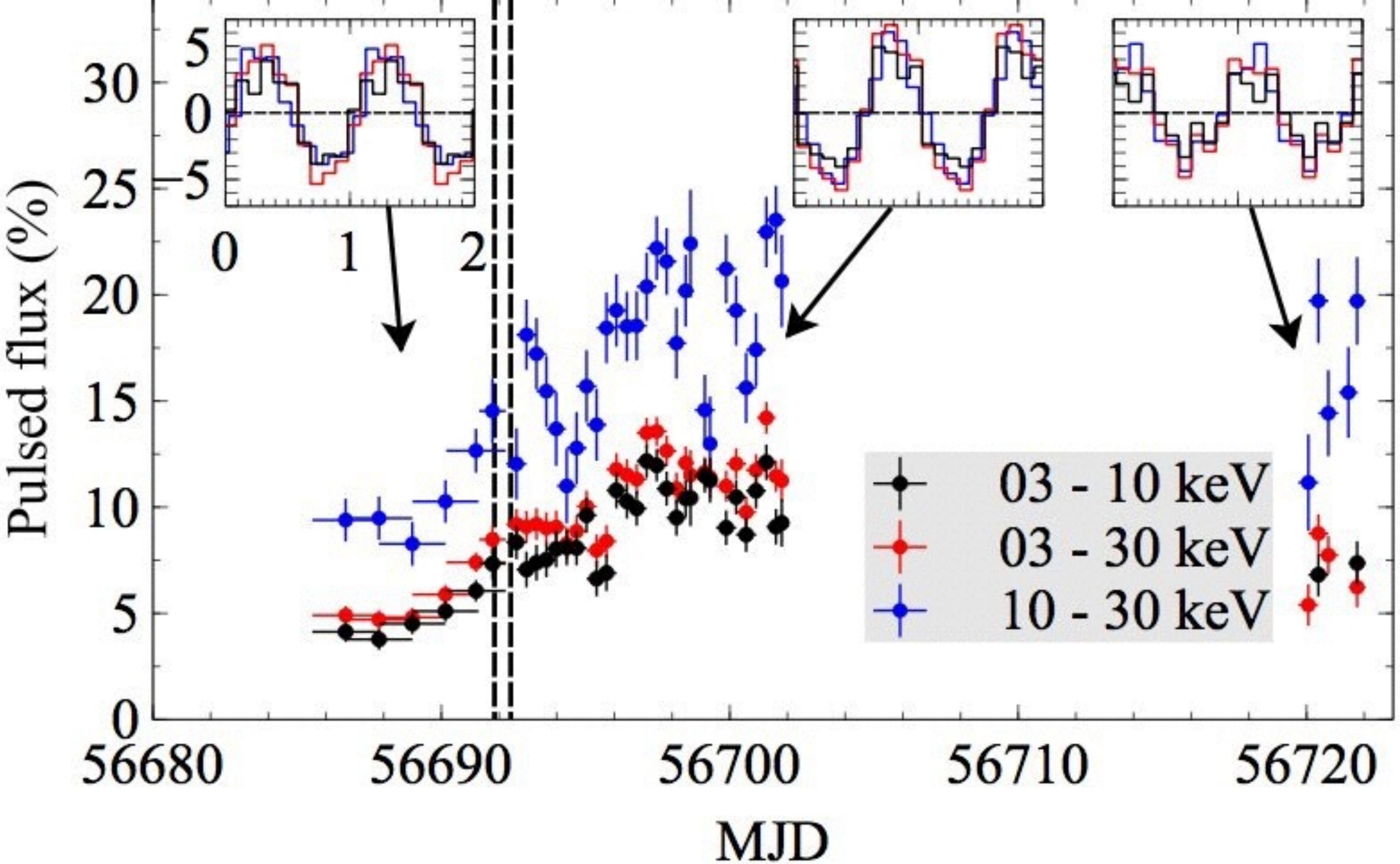




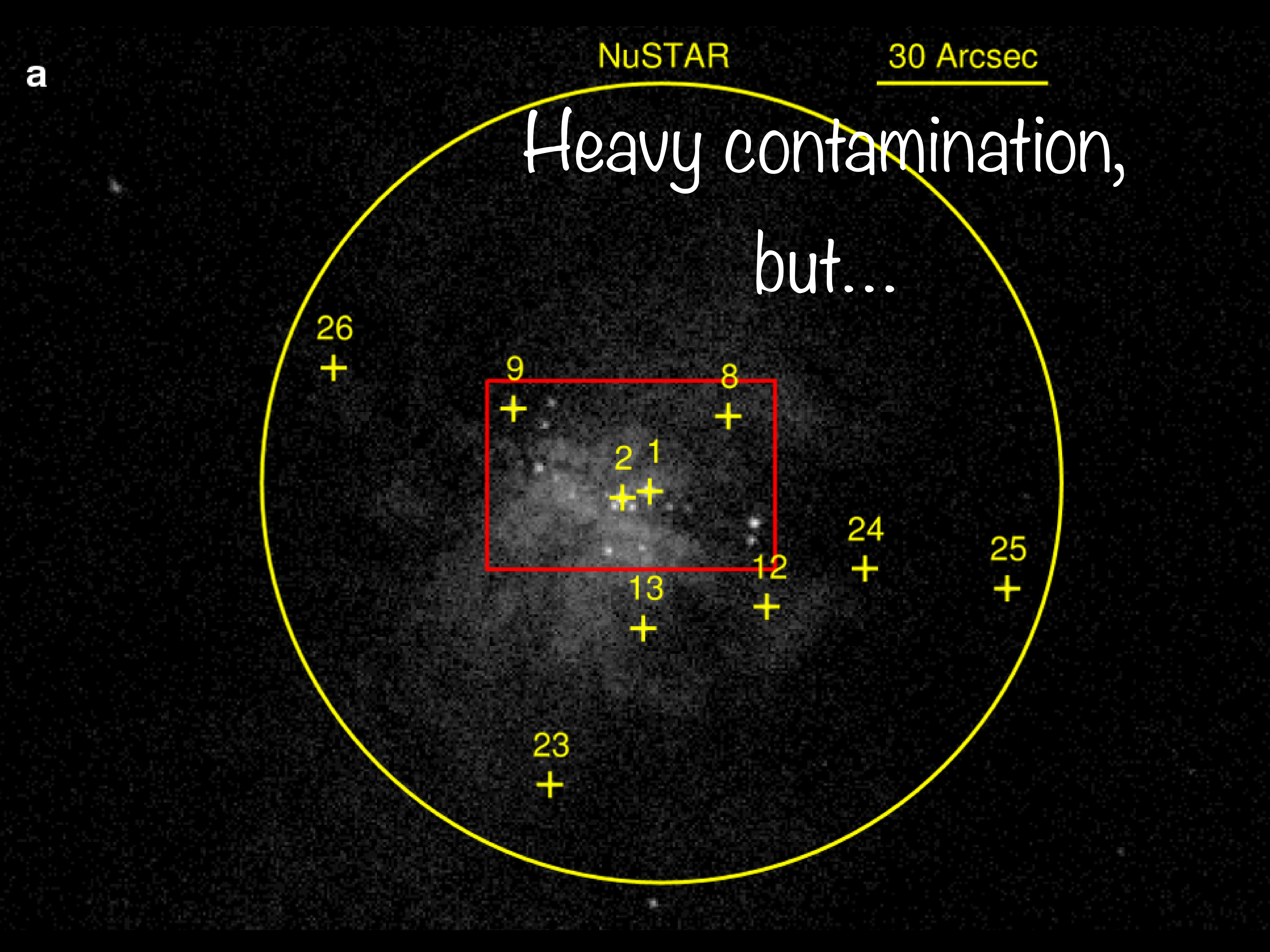
- P_{orb} = 2.54 d
  $a \sin i / c$ = 23 l-sec
- No eclipses

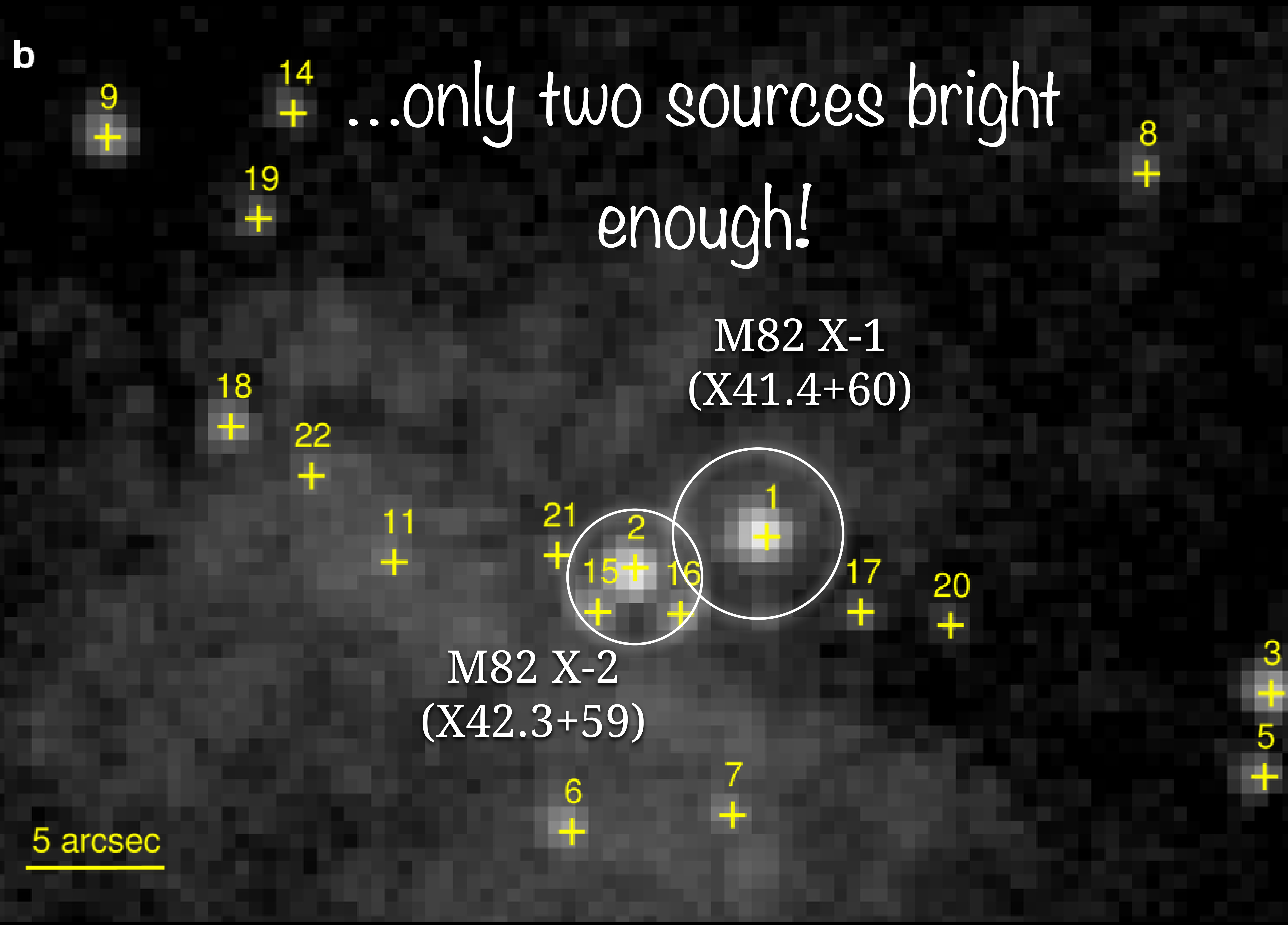
Companion star
$5\ M_\odot \lesssim M_C \lesssim 25\ M_\odot$



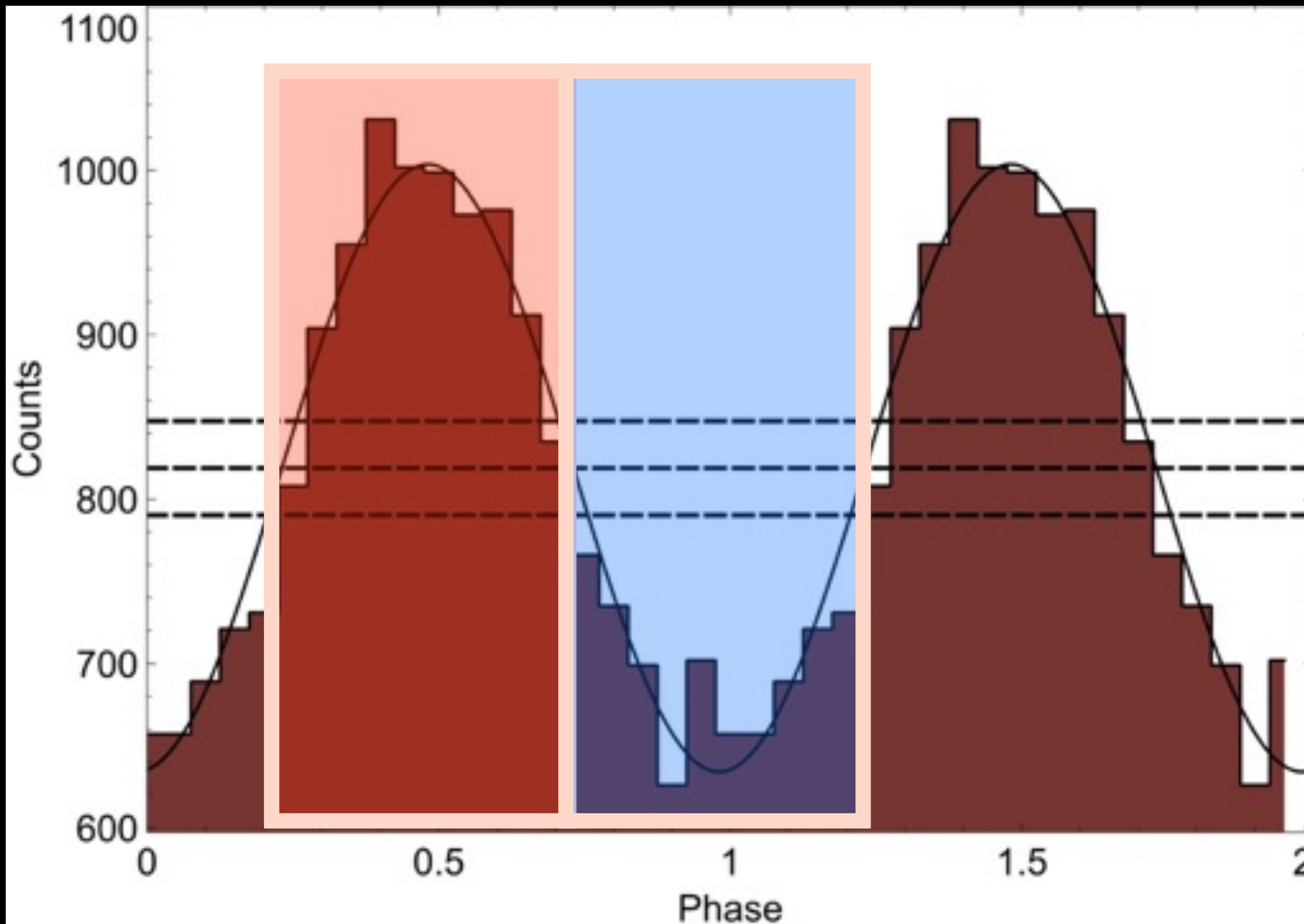


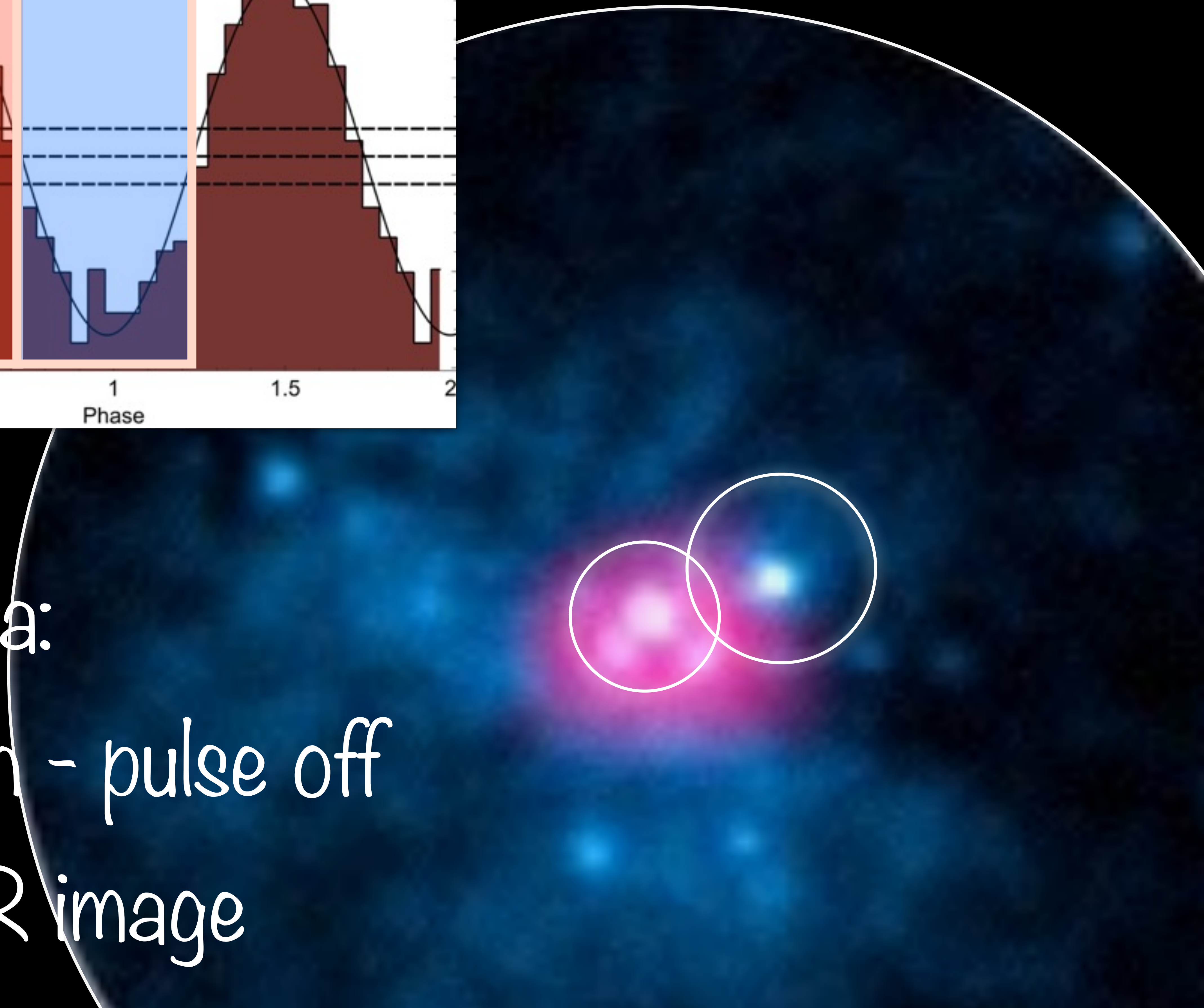
- Pulsed flux is ~10-20% of total flux
- **≳5x10^{39} erg/s in the pulse alone!**


a
NuSTAR
30 Arcsec
Heavy contamination,
but...
26
9
8
2
1
24
25
12
13
23

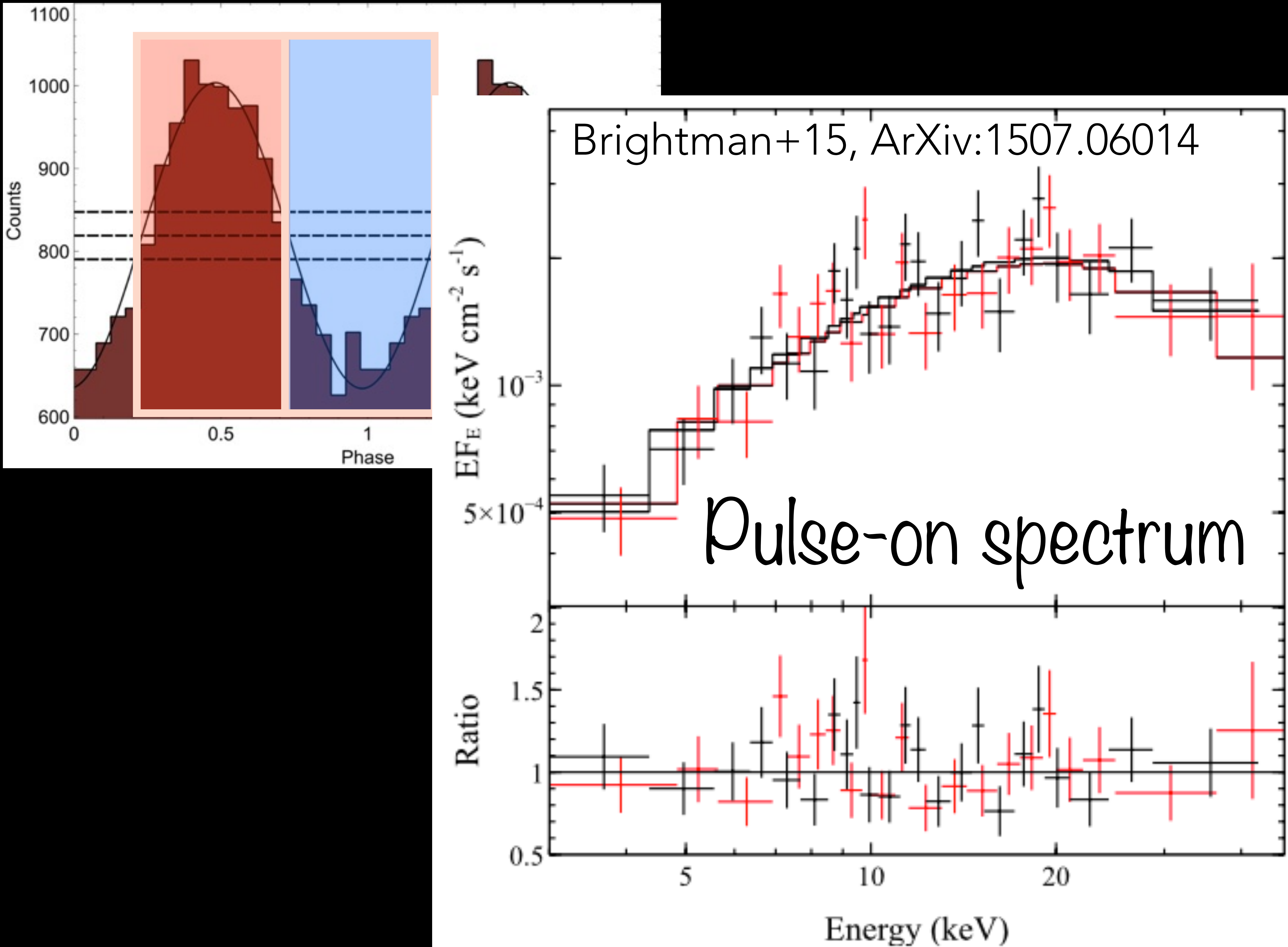


b
...only two sources bright enough!
M82 X-1
(X41.4+60)
M82 X-2
(X42.3+59)
9
14
19
8
18
22
11
21
2
1
15
16
17
20
3
5
6
7
5 arcsec

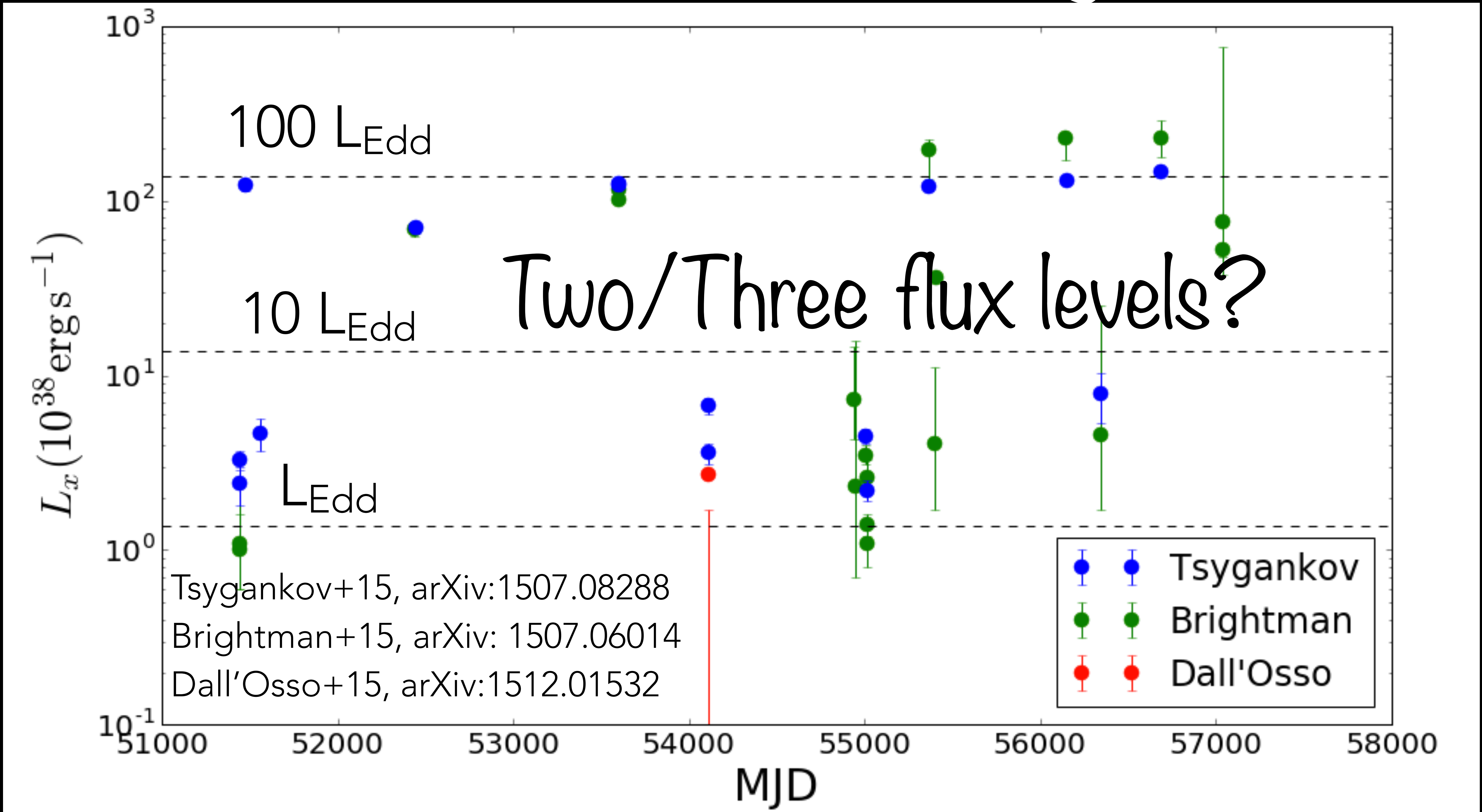




Magenta:
pulse-on - pulse off
NuSTAR image


Brightman+15, ArXiv:1507.06014
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)

Maximum $L_X > 10^{40}$ erg/s



>100L_{Edd} for a neutron star

PROBLEM

10 times the maximum luminosity for an accreting Neutron Star (Basko & Sunyaev ’76, MNRAS 175, 395)

PROBLEM

10 times the maximum luminosity for an accreting Neutron Star (Basko & Sunyaev ’76, MNRAS 175, 395)

See Mushtukov+15, Abolmasov & Chashkina for recent developments

MODELS?

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

MODELS?

- **High magnetic field**:
  - Dall'Osso+15, … -> $B \sim 10^{13}$G
  - Eksi+15, Tsygankov+15, … -> magnetar
- **Low magnetic field (**$B \sim 10^{9}$G**)**:
  - Kluzniak & Lasota 15
- **"Standard" magnetic field** ($B \sim 10^{12}$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?**

Tsygankov+15, ArXiv:1507.08288

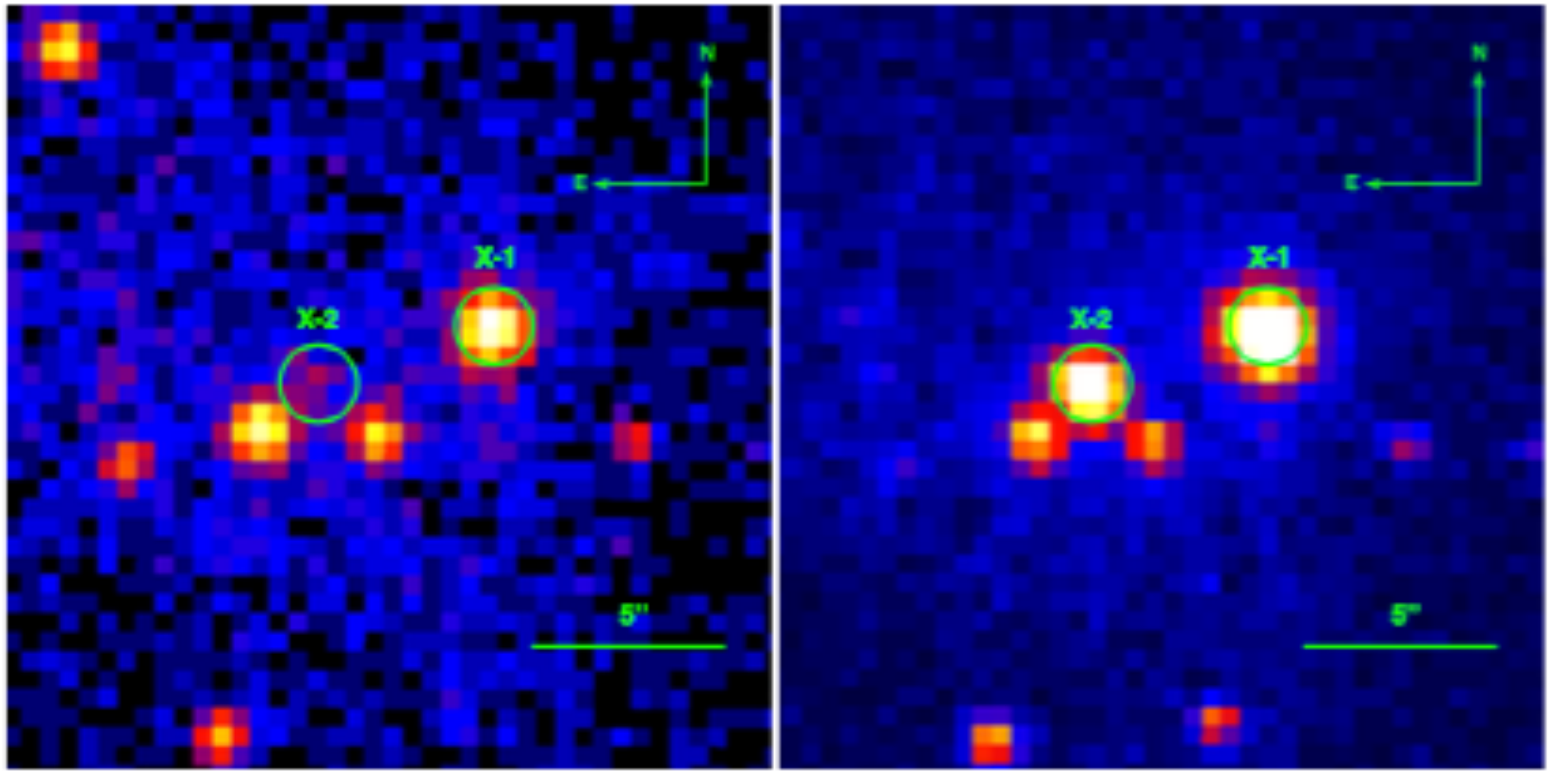
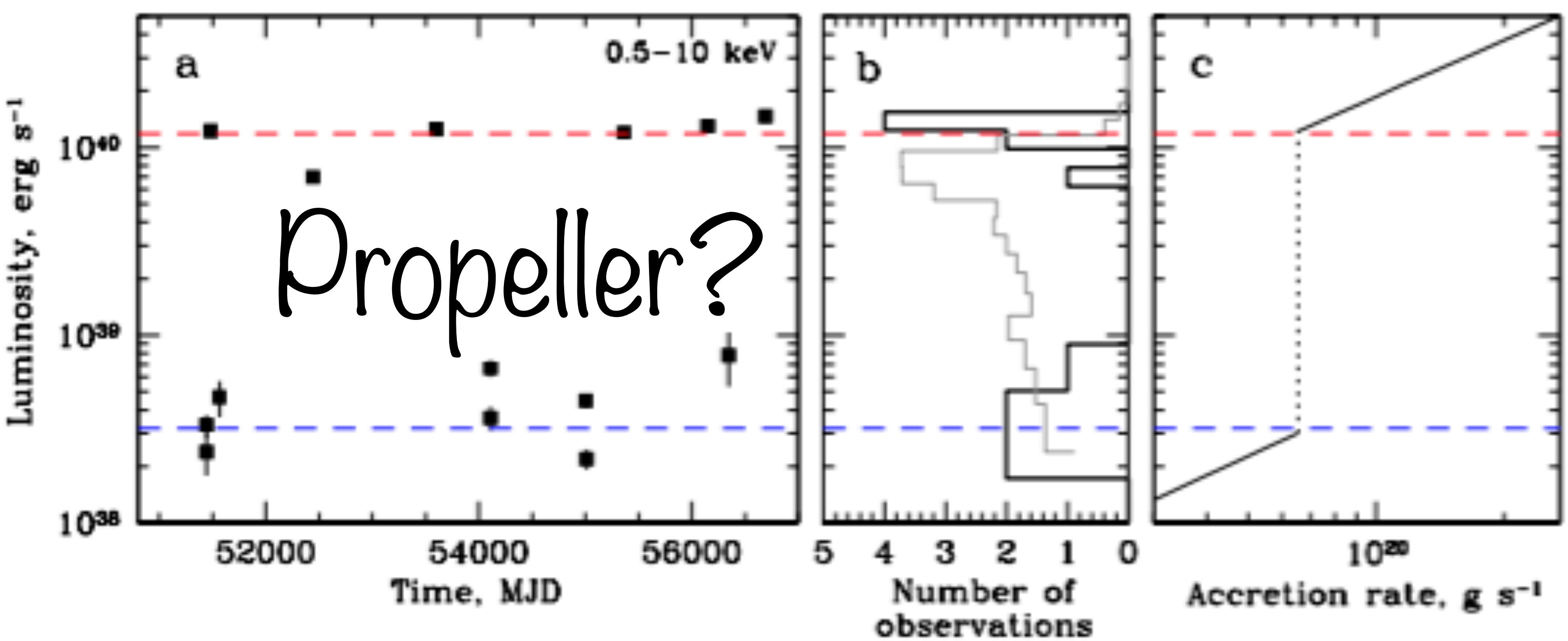


Figure 1. *Chandra* images of M82 galaxy's centre during observations performed on September 20, 1999 (MJD 51441.47) when M82 X-2 was in a low-luminosity state (left) and August 17, 2005 (MJD 53599.04) when it was in a high-luminosity state (right). Circles indicate the positions of M82 X-1 and X-2 ultra-luminous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



Tsygankov+15, ArXiv:1507.08288

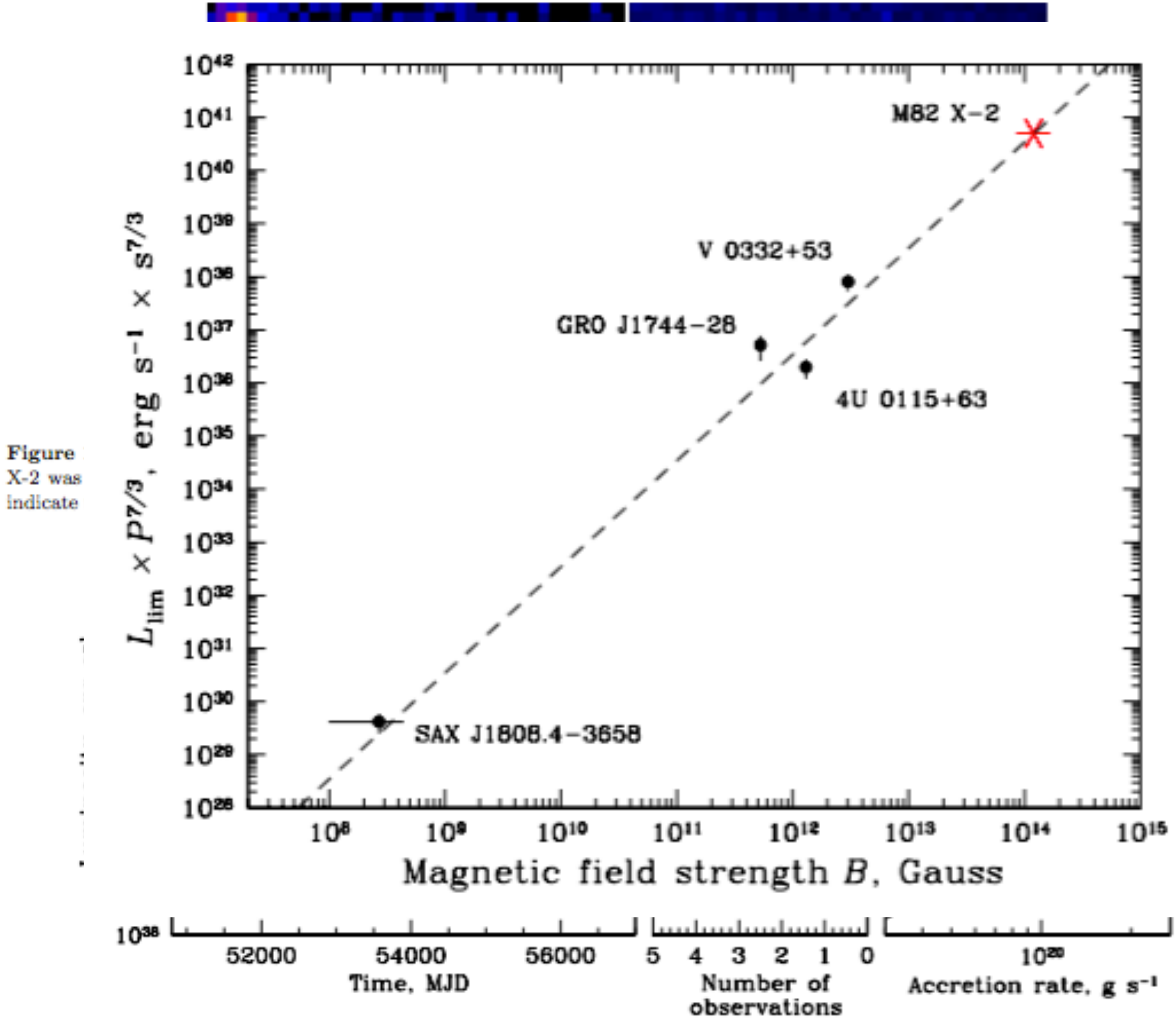
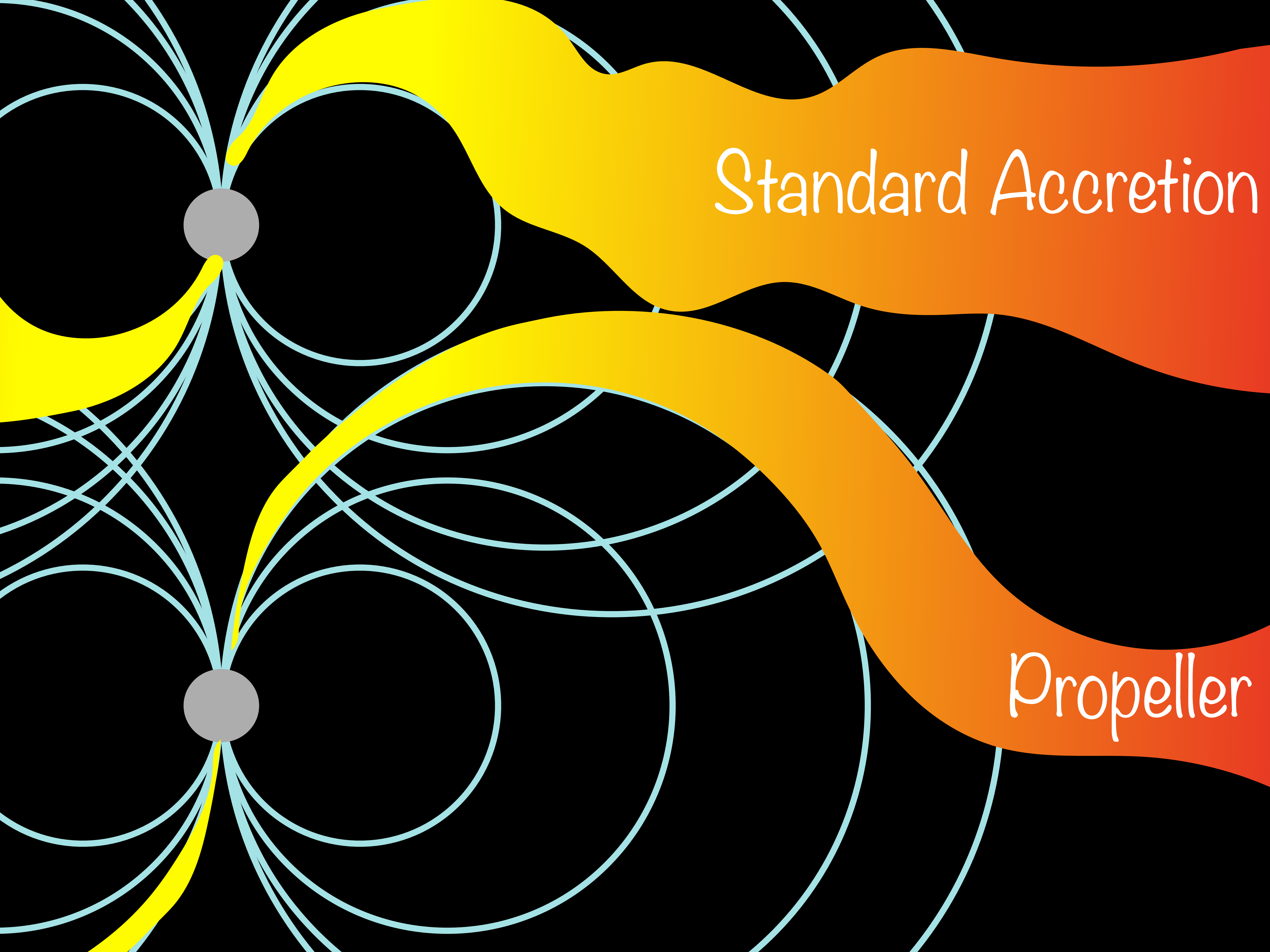
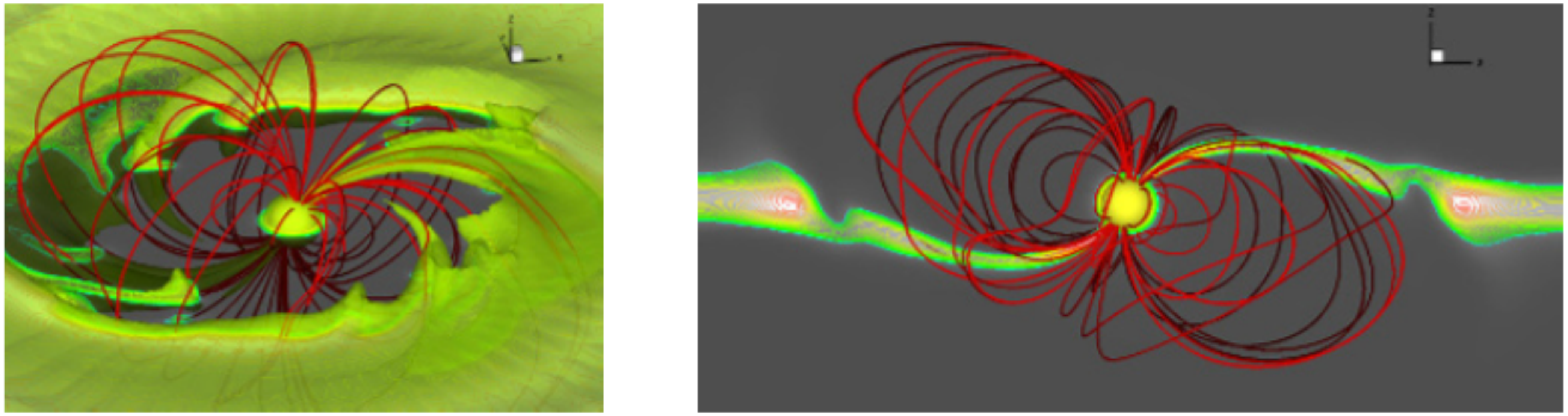


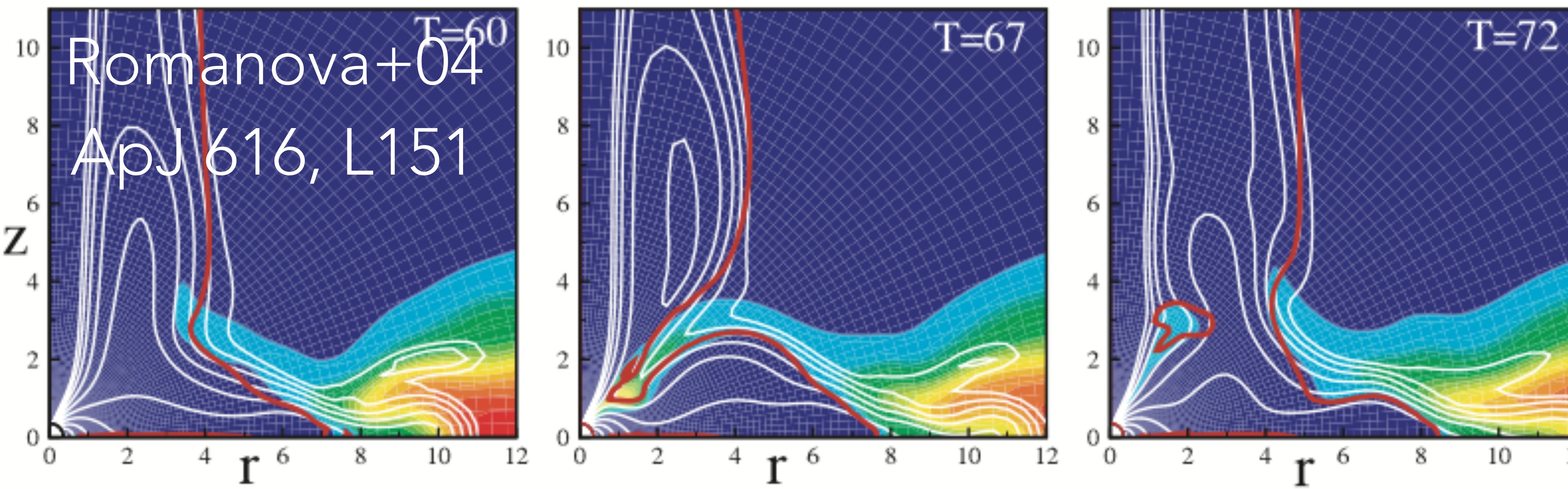
Figure
X-2 was
indicate

M82
rcles

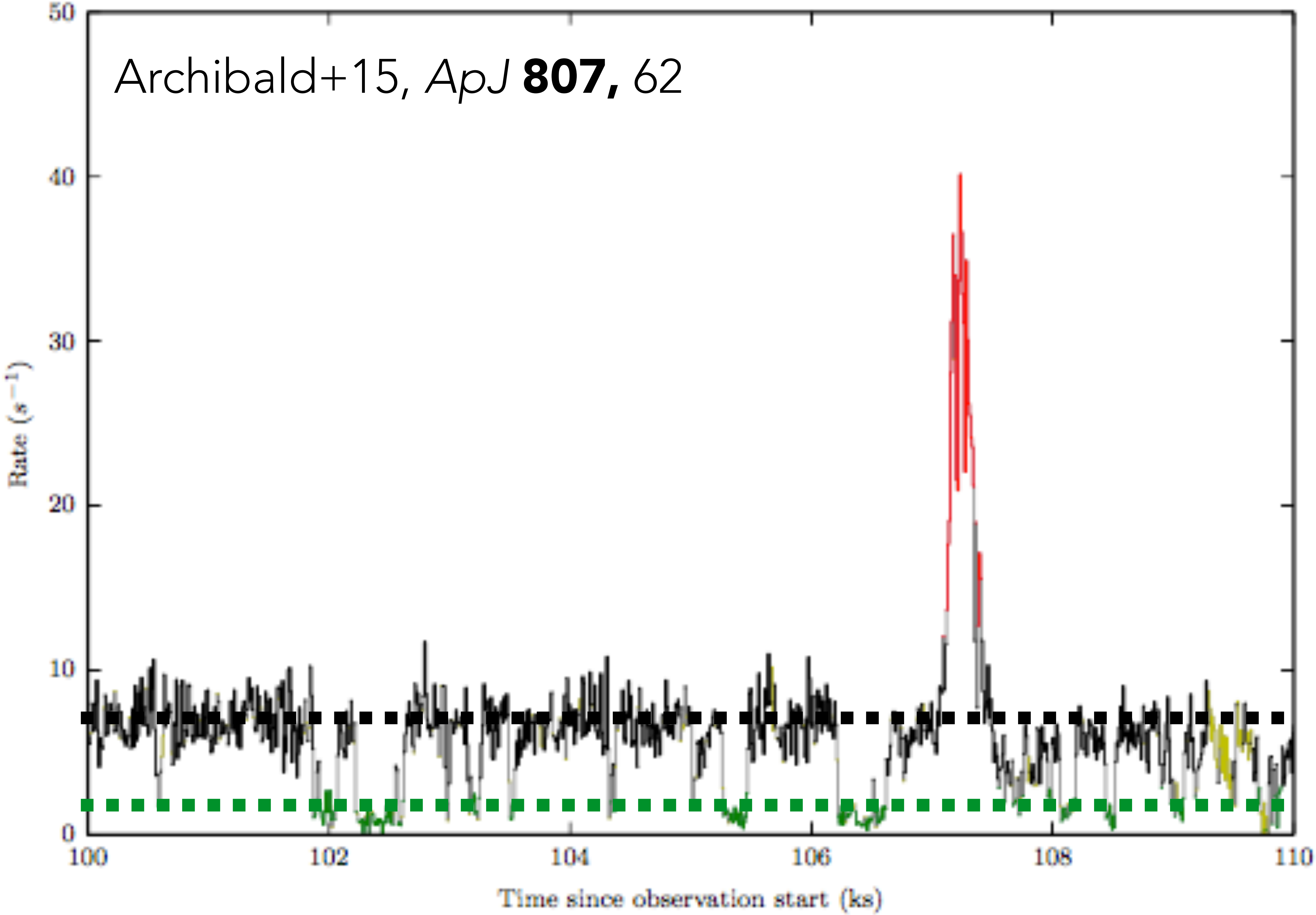

Standard Accretion
Propeller

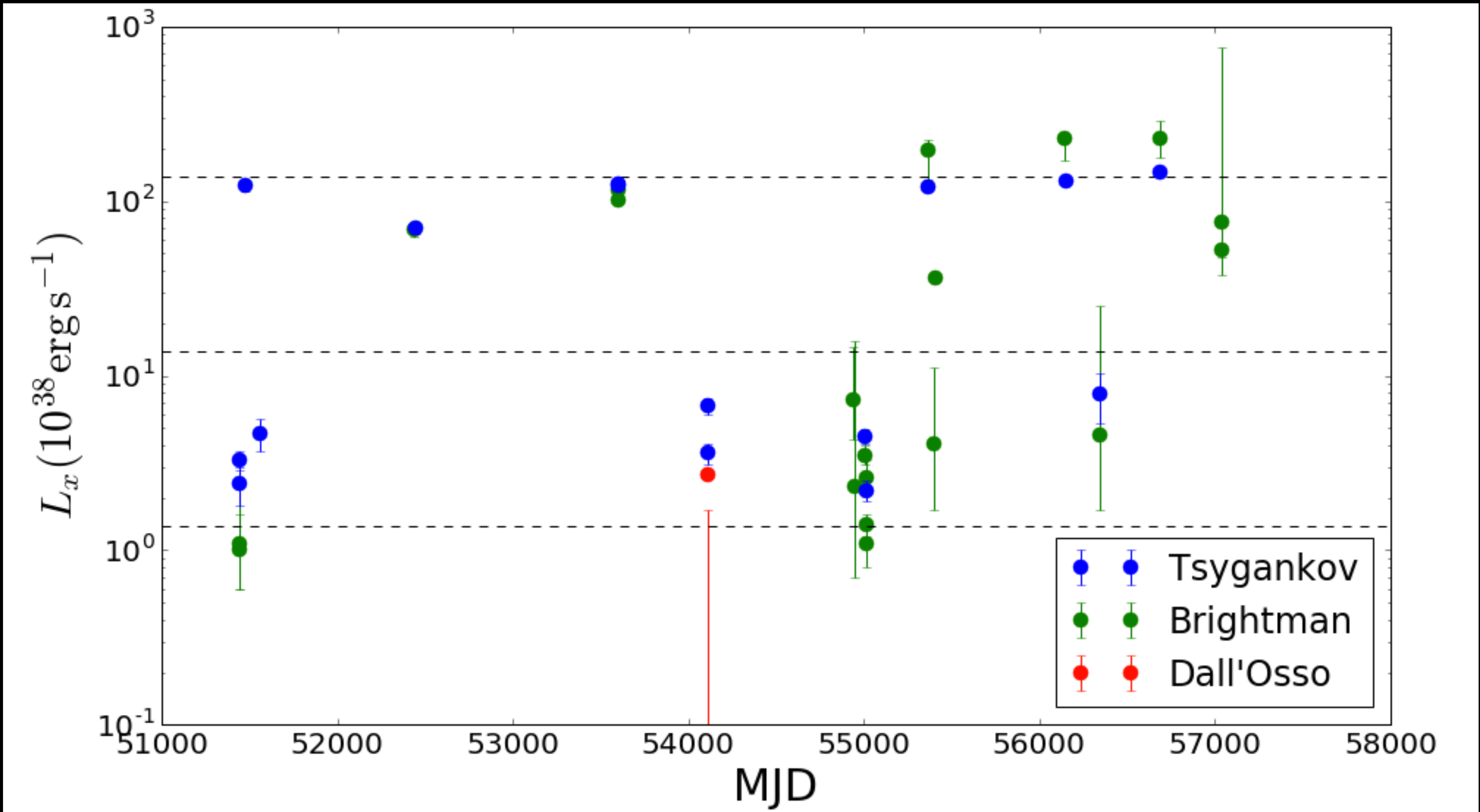


Romanova+14, EPJ WoC **64,** 05001

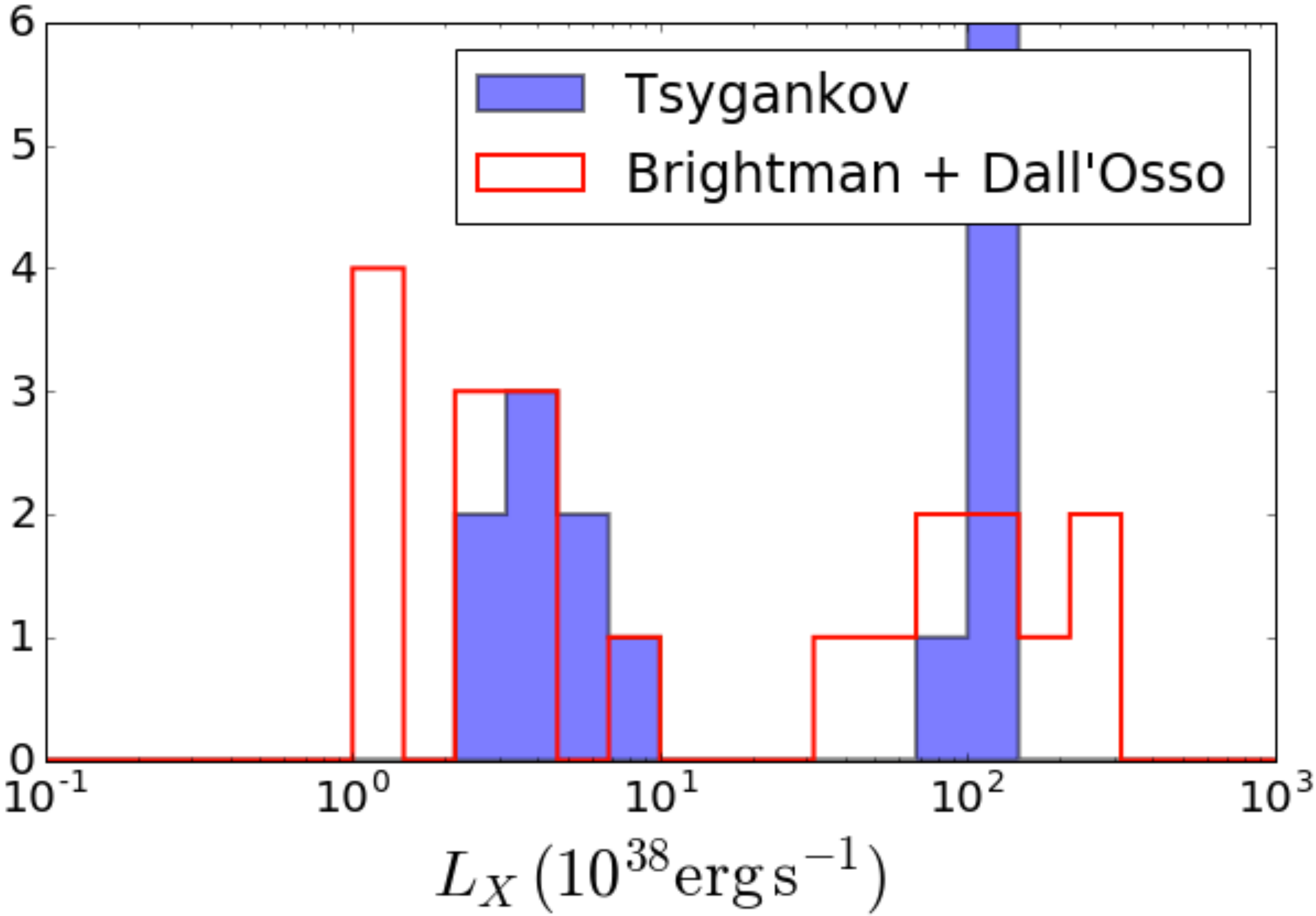


Romanova+04
ApJ 616, L151

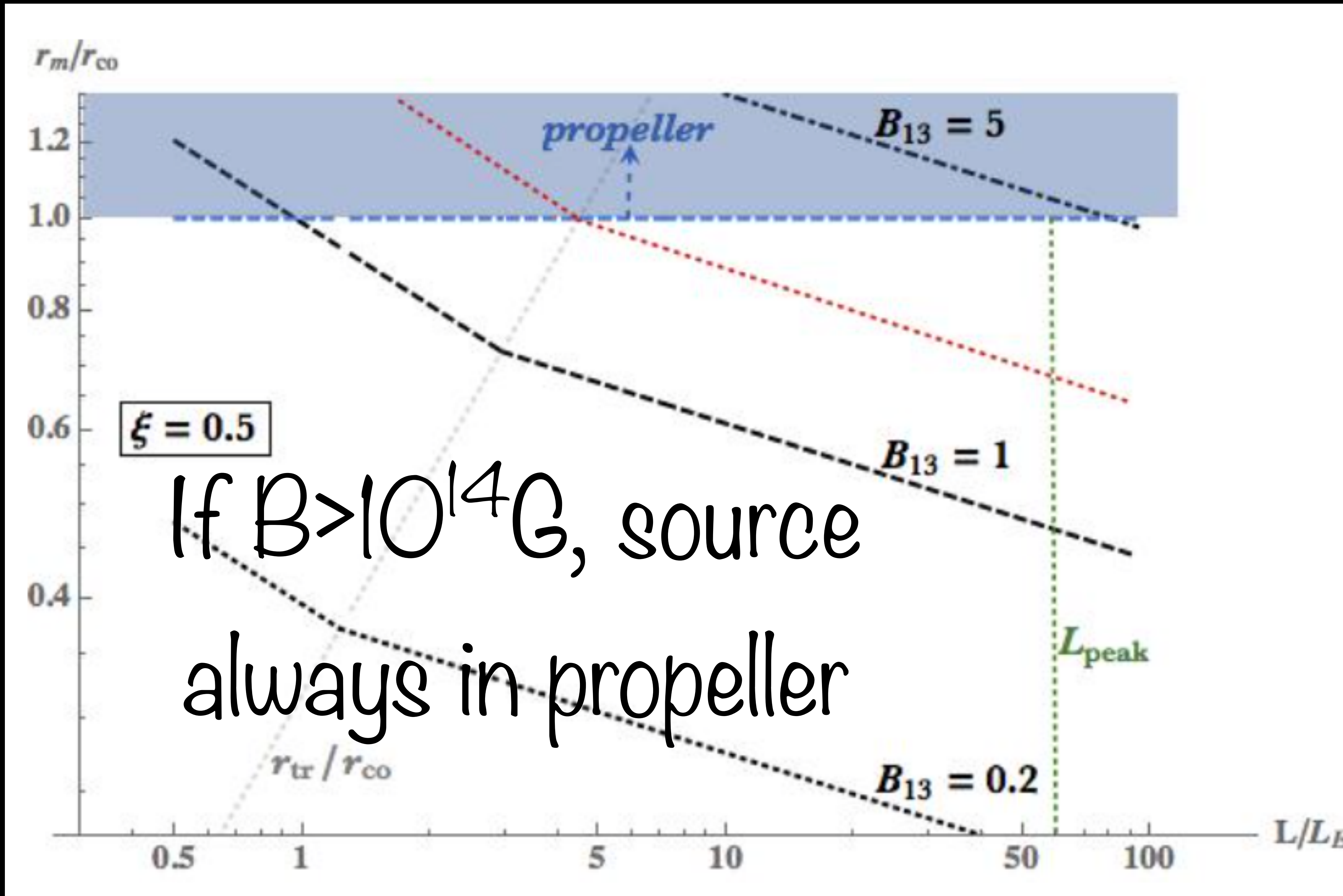

Archibald+15, *ApJ* **807,** 62
Rate (s^{-1})
0
10
20
30
40
50
100
102
104
106
108
110
Time since observation start (ks)



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



Tsygankov
Brightman + Dall'Osso
0
1
2
3
4
5
6
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
$L_X\,(10^{38}\mathrm{erg\,s^{-1}})$



Dall'Osso+15, arXiv:1512.01532

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 ≲ 60°
  - companion star mass:
  $5\ M_\odot \lesssim M_C \lesssim 25\ M_\odot$
- Large luminosity variations: why?
- Various models for magnetic field, probably $>10^{13}$

FUTURE WORK

- Flux Monitoring (look for orbital/super orbital periodicities): accepted Chandra large program (PI Harrison)

- Pulsar monitoring and timing (constrain mass exchange, average spin evolution, …) accepted NuSTAR observation (PI Bachetti),

- Multi-wavelength observations (“bubbles”, spectral lines, masers, jets?) Tendukar+, ….