Periodic X-ray sources:

diagnosing the nature and evolution for exotic binaries in dense environments

Tong Bao

I.N.A.F - Osservatorio Astronomico di Brera;
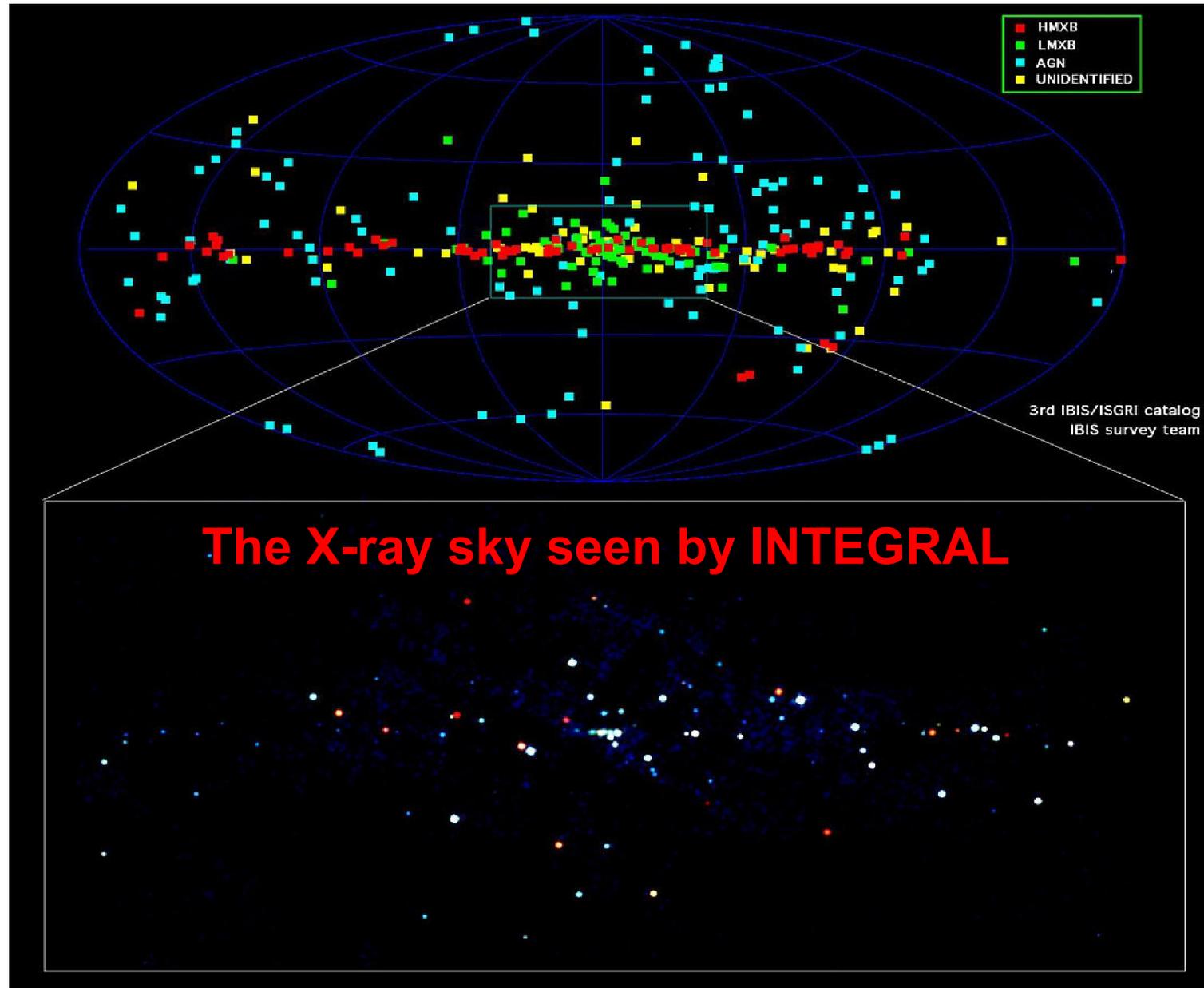*tong.bao@inaf.it*

X9

X-RAY

ILLUSTRATION

2024/12/03

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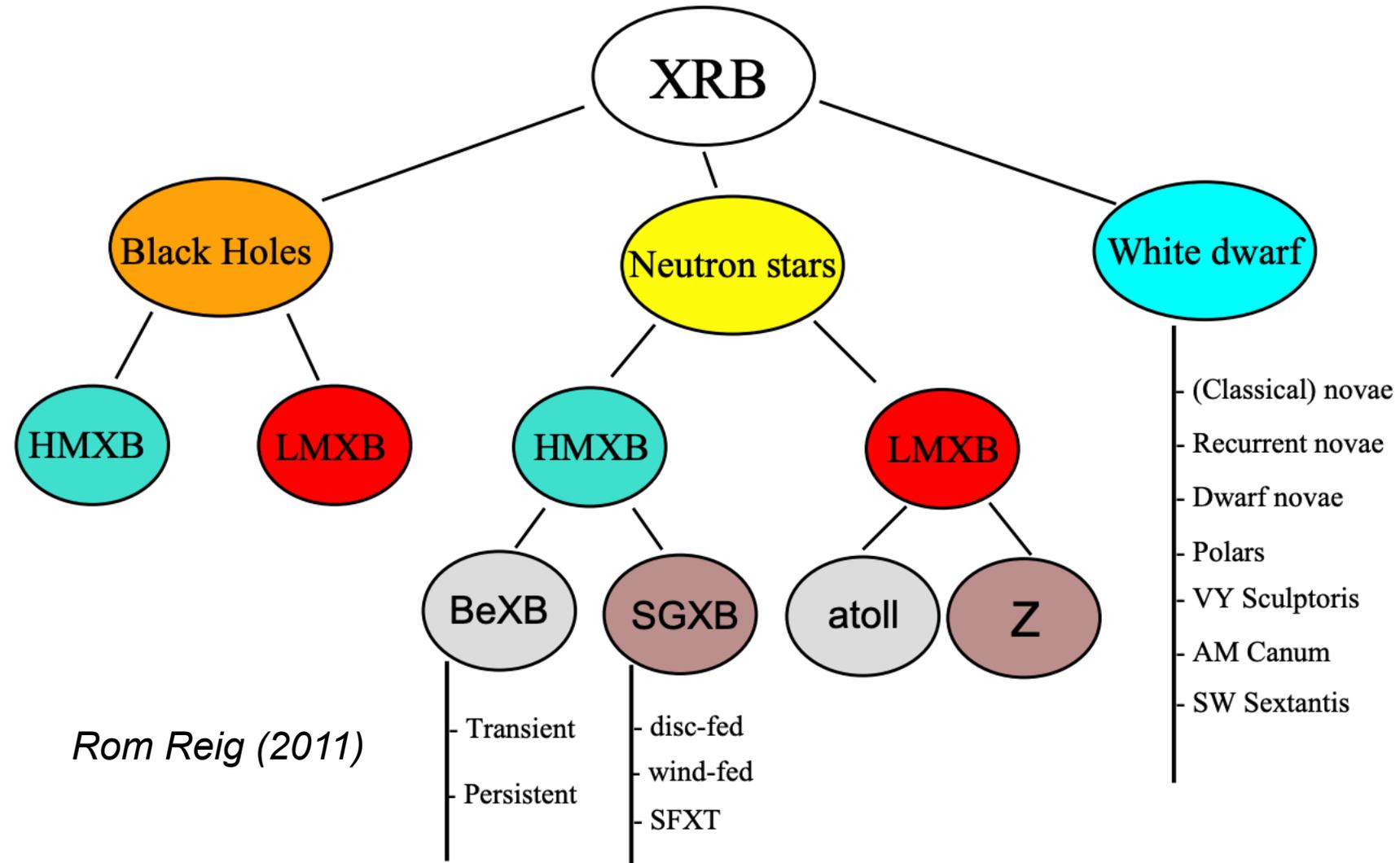**Outline**

1、 **Background**

2、 **Techniques**

3、 **CVs in the Galactic bulge**

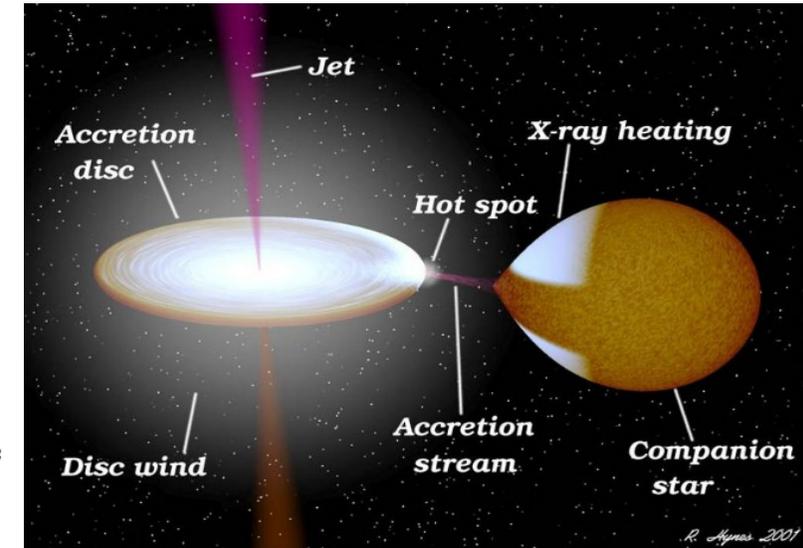4、 **Periodic X-ray sources in Milky Way globular clusters**

5、 **Some exotic binaries**

1. Background

The X-ray sky seen by INTEGRAL

3rd IBIS/ISGRI catalog
IBIS survey team
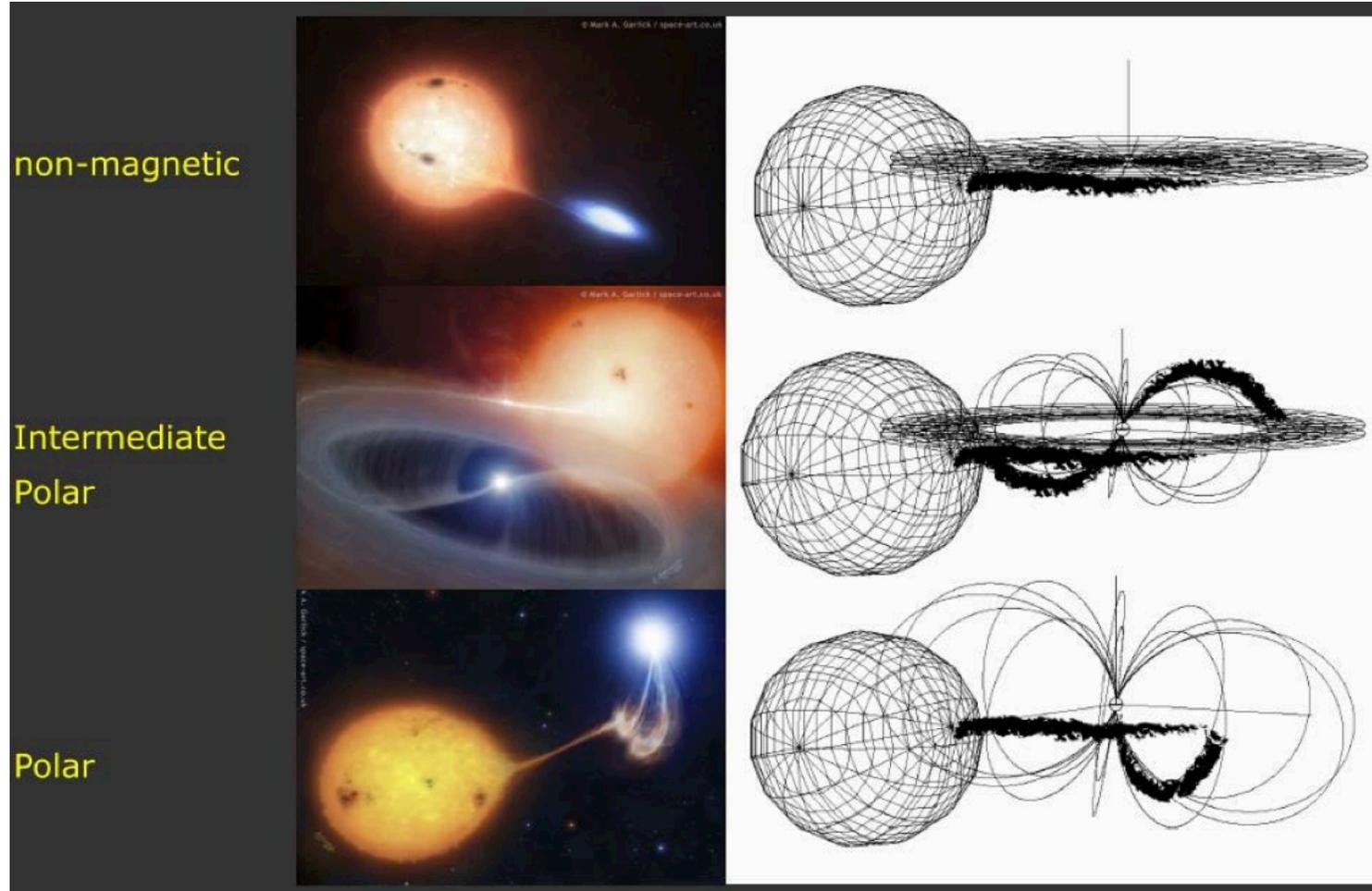
Classification of XRBs

Rom Reig (2011)

Credit: NASA/R. Hynes

CVs: what are they?

Cataclysmic Variables are
-semi-detached binaries accreting from a main-sequence-like secondary star
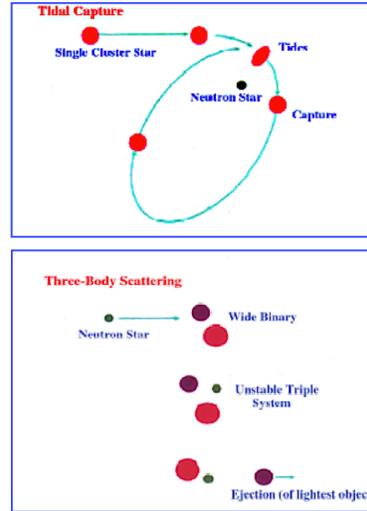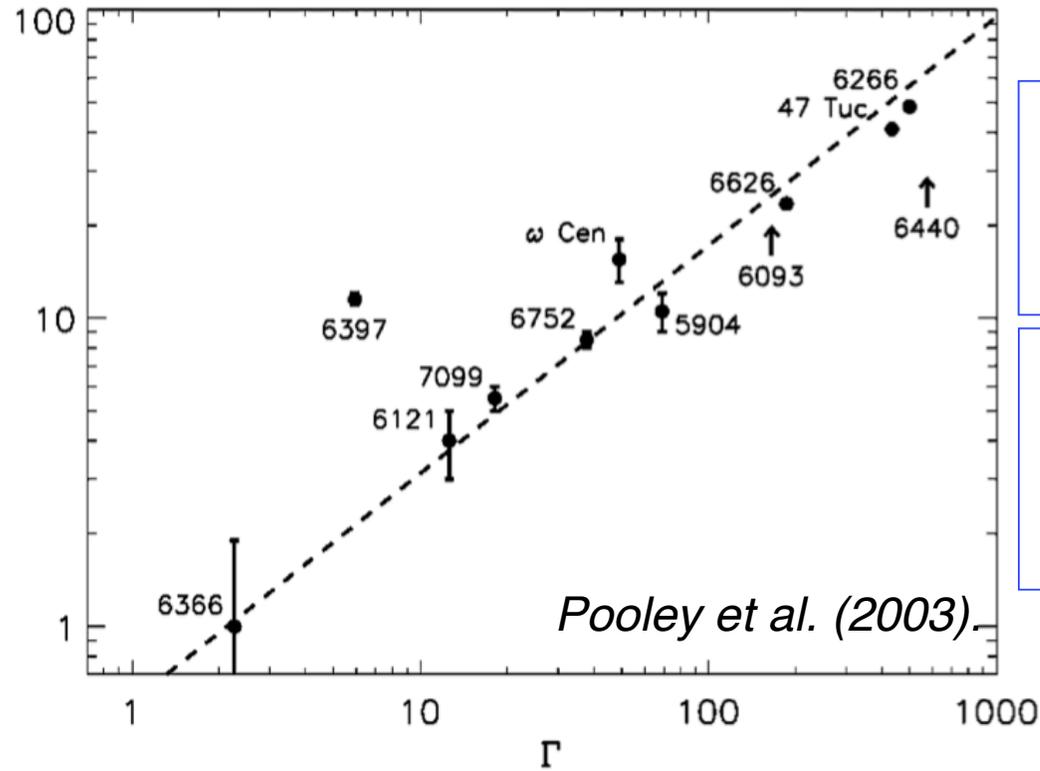**to a more massive WD primary star**

Main types:
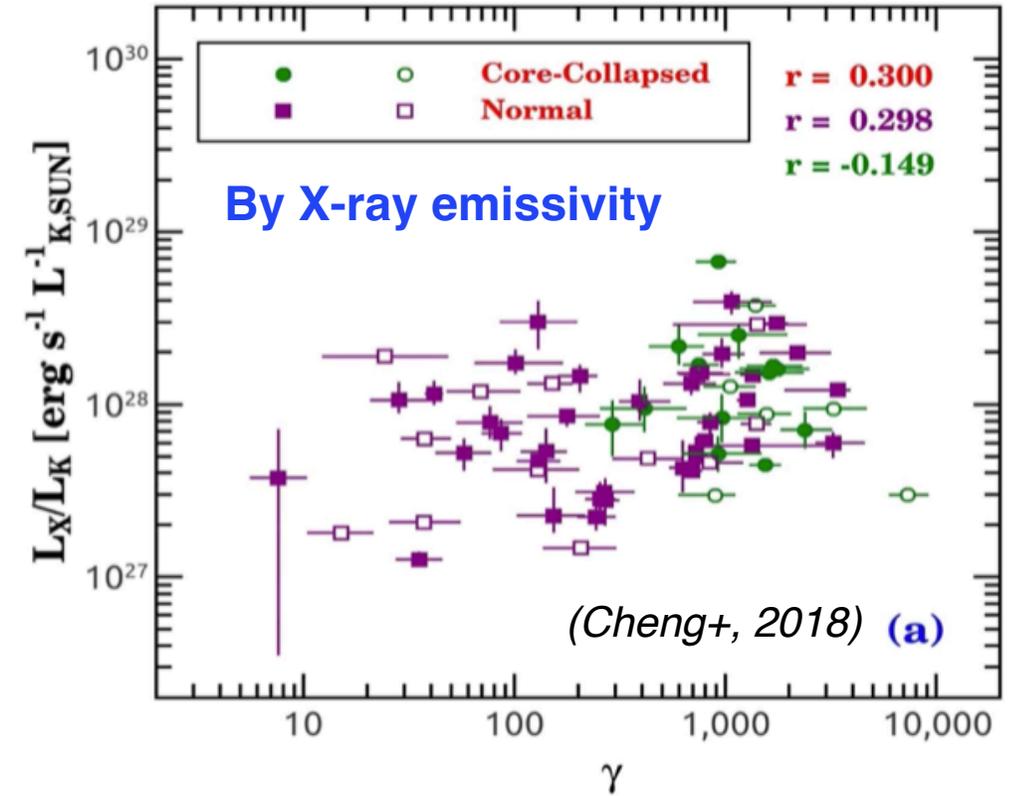
Are X-ray population in GCs similar to Galactic-field?

1. **Bright LMXBs are $\simeq$ 100× overabundant in GCs.**   **2. Not so sure for CVs**

Pooley et al. (2003)

(Cheng+, 2018) **(a)**

By X-ray emissivity

Number of X-ray sources (N) with Lx $\gtrsim$ 4 × 10^{34} erg/s vs. the normalized encounter rate Γ of the cluster.

Tidal capture or exchange encounter in cluster core favor the production of LMXBs.

Unlike LMXBs, no correlation between the faint X-ray source (mostly CVs) abundance and the normalized stellar encounter rate.

Identification of CVs in globular clusters

(1) Variability (optical outburst): only a few detected while hundreds are expected
(2) Emission line: narrow-band Hα imaging surveys
(3) Blue color: FUV band with HST, while small FoV

X-ray emission: identified by Chandra

Difficulties:
1. CVs are optically-faint ;
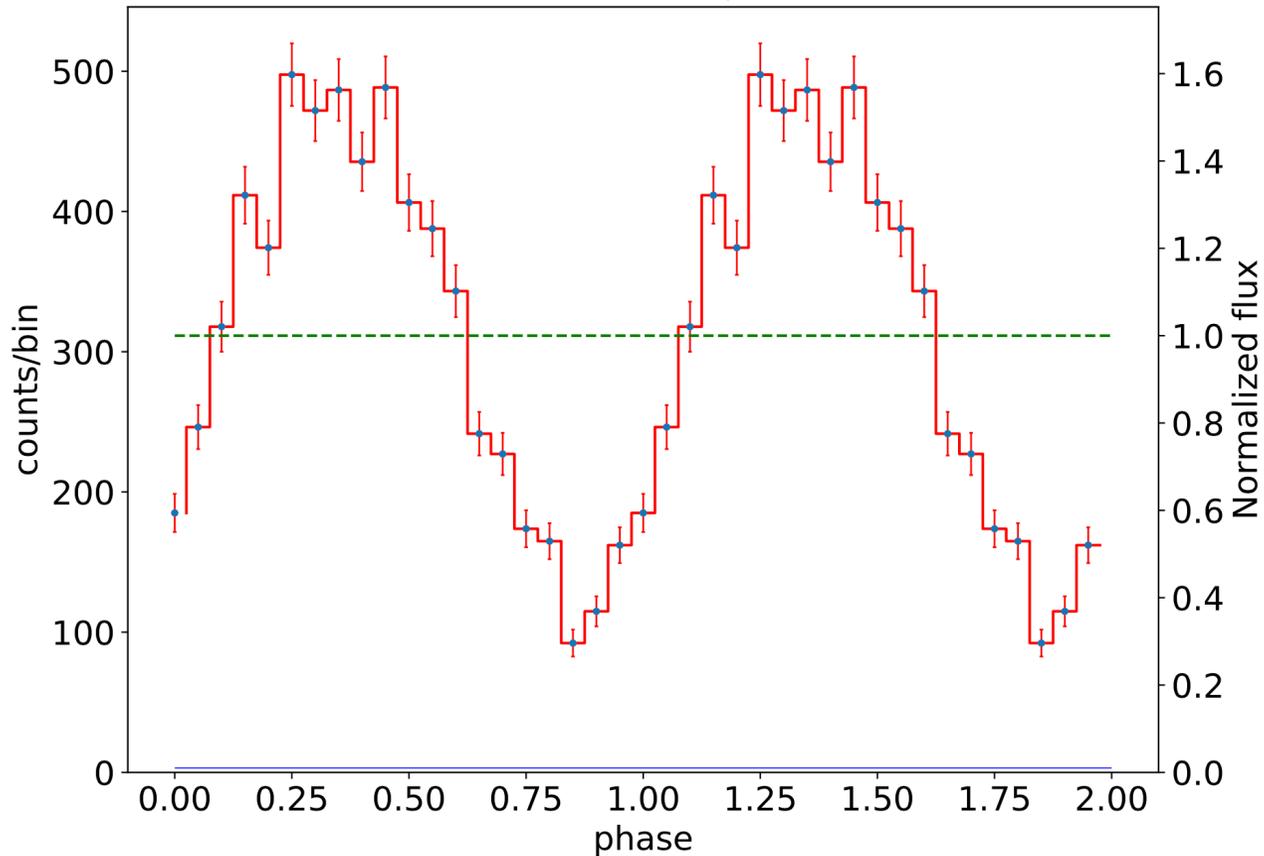**2. crowded nature of the GC.**

**Small and biased CV sample by different methods…**

OPTICAL
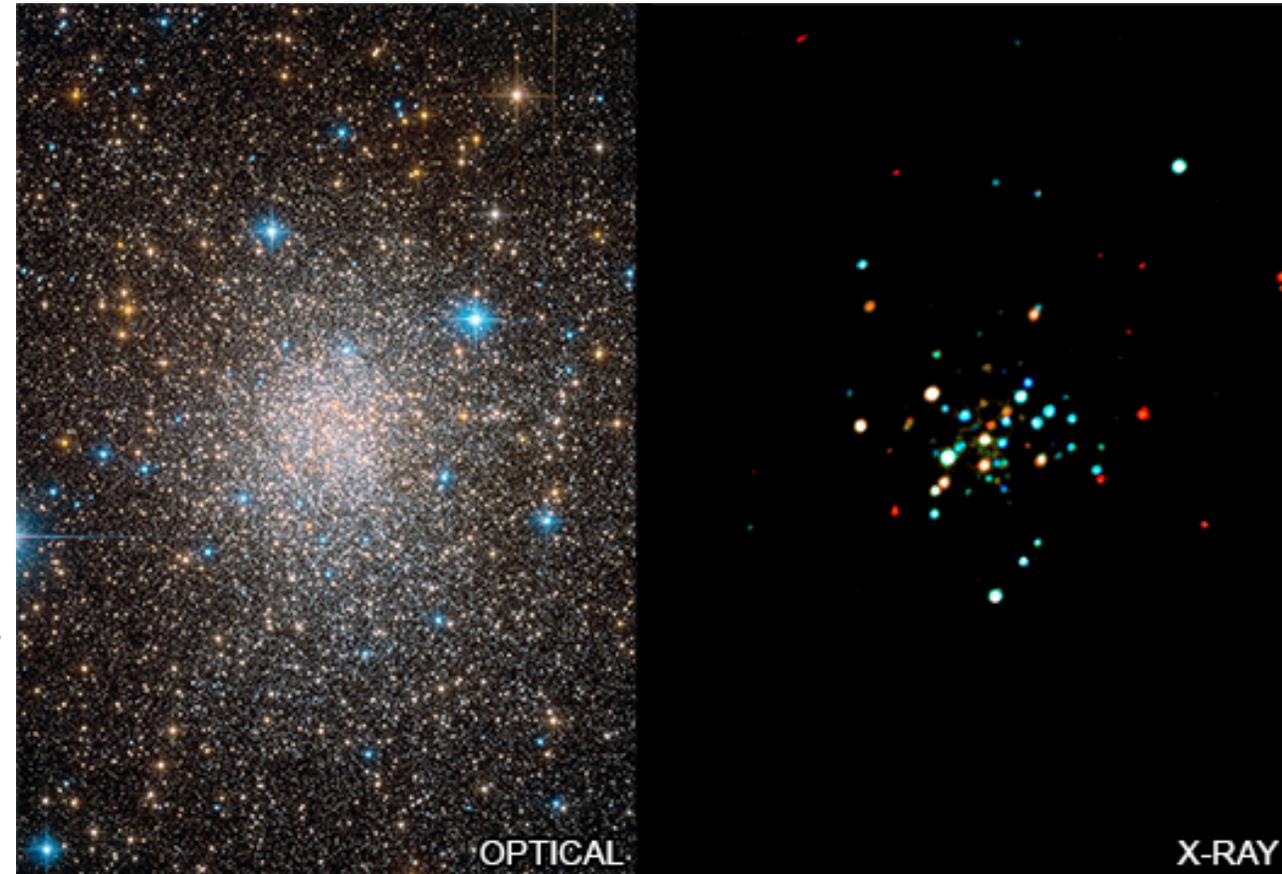
X-RAY

X-ray periods: a powerful observational tool

1. Great probe for identifying CVs from X-ray sources. 2. Hint for binary formation and evolution
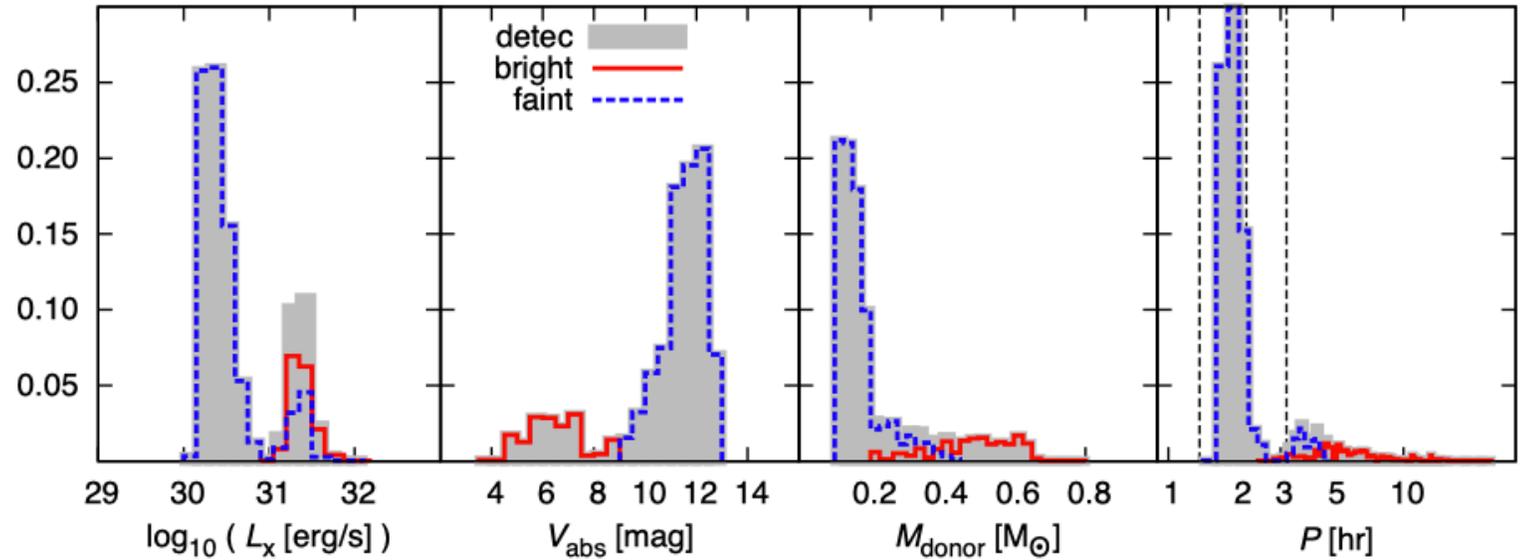
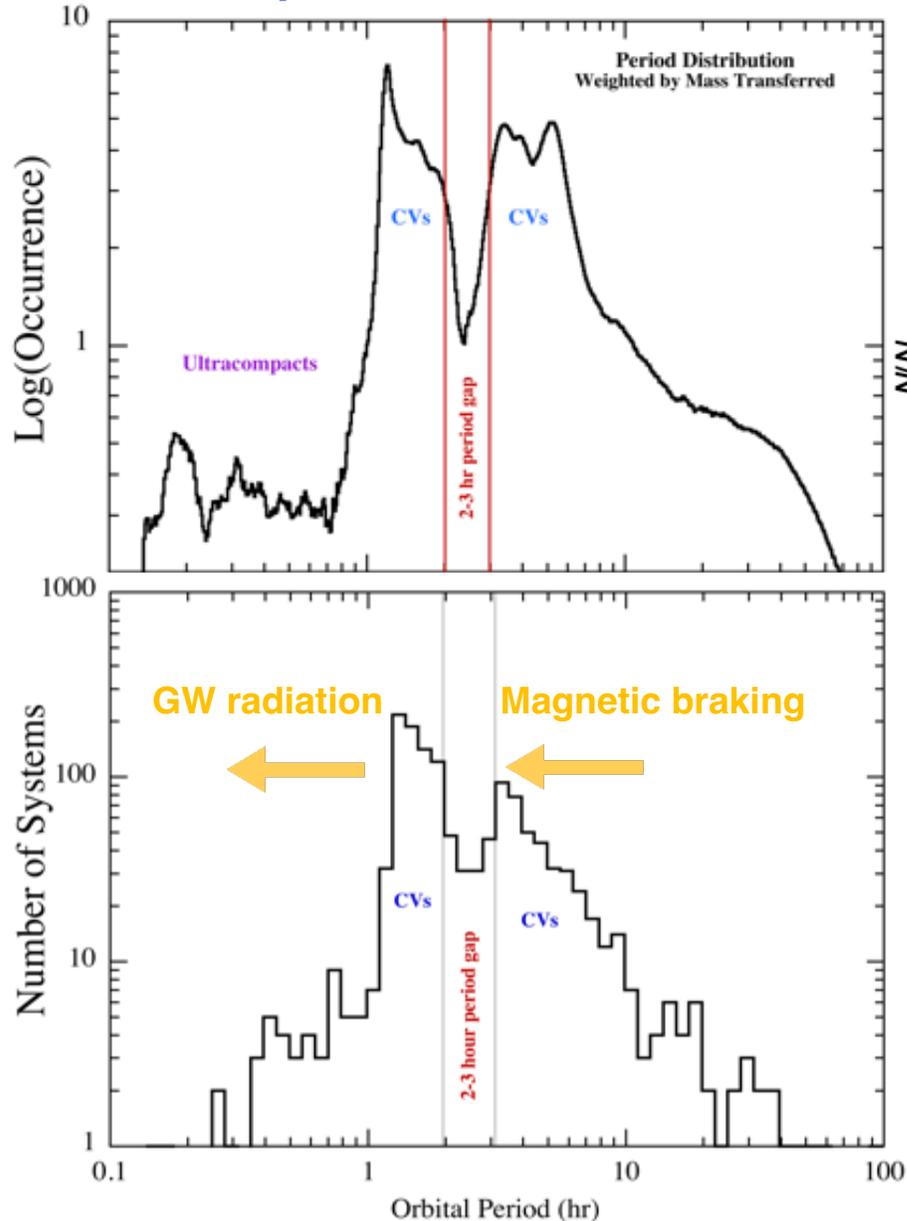**Typical periodic variation from magnetic CVs**

Orbital periods are known for only 12 CVs in the Galactic GCs before. (Kinnge,2012)

Globular Cluster CVs

More dynamical-formed CVs in GCs?
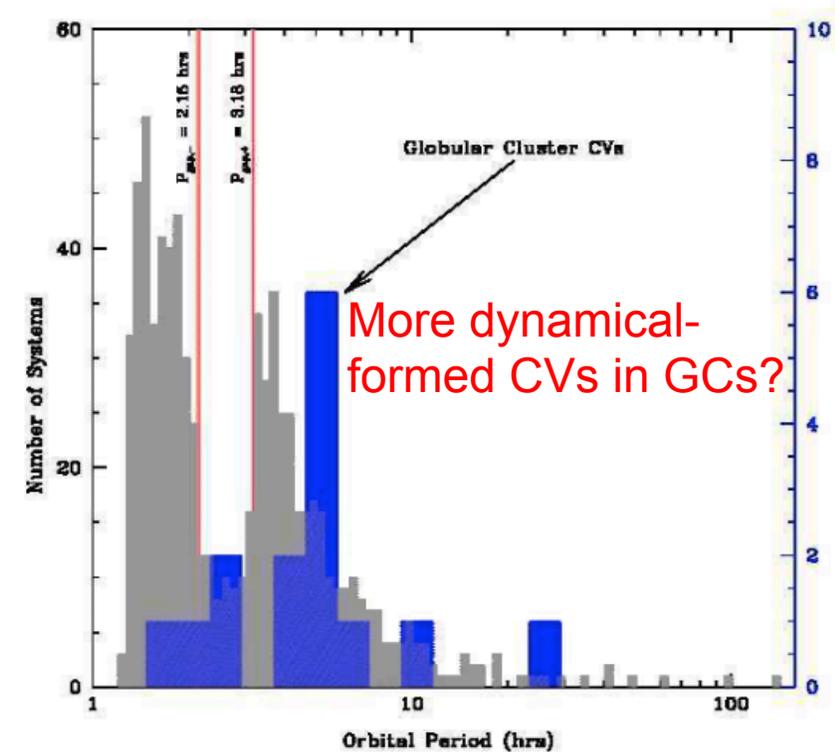
What is the expected P_{orb} distribution?

Field CVs: primordial channel

GC CVs:

Simulation by (Belloni+, 2020)

The dominant formation channel amongst detectable CVs is typical common-envelope phase (i.e., primordial binaries, ~88 percent)
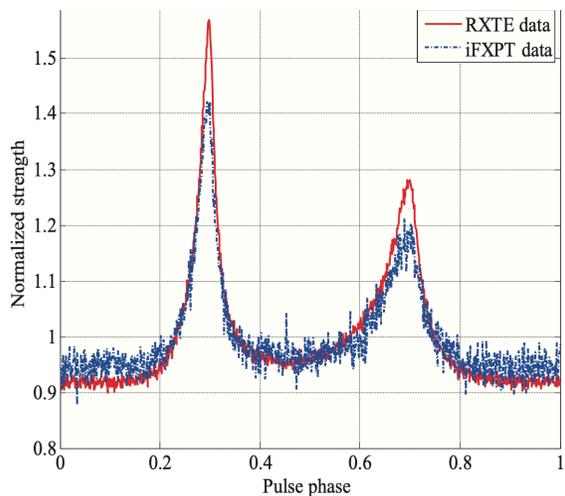
2. GL algorithm

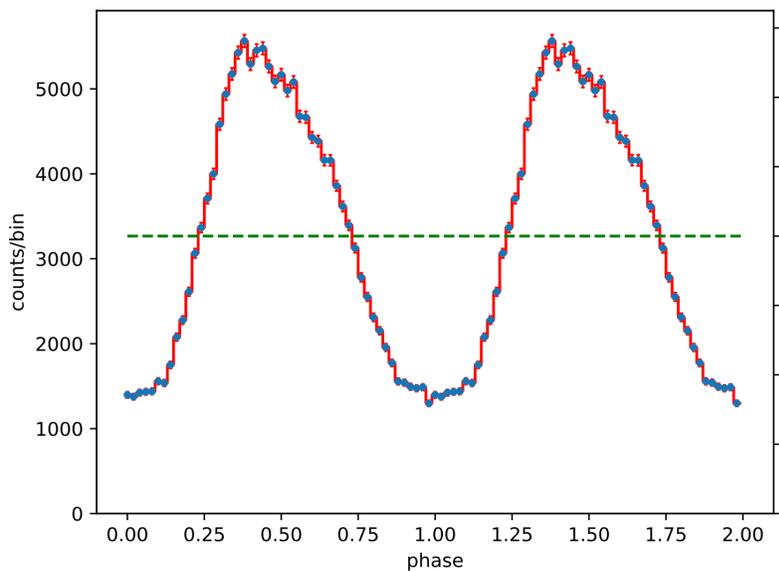- a phase-folding method applying Bayesian probability theory

(Gregory & Loredo,1992)

Phase-folded light curve of periodic X-ray sources

The eclipsing of LMXBs

X-ray Pulsars: (The Crab pulsar, P~33ms)

Quasi-periodic oscillations (QPOs) in AGN

RE J1034+396, P~3733s

WD's spin in magnetic CVs:
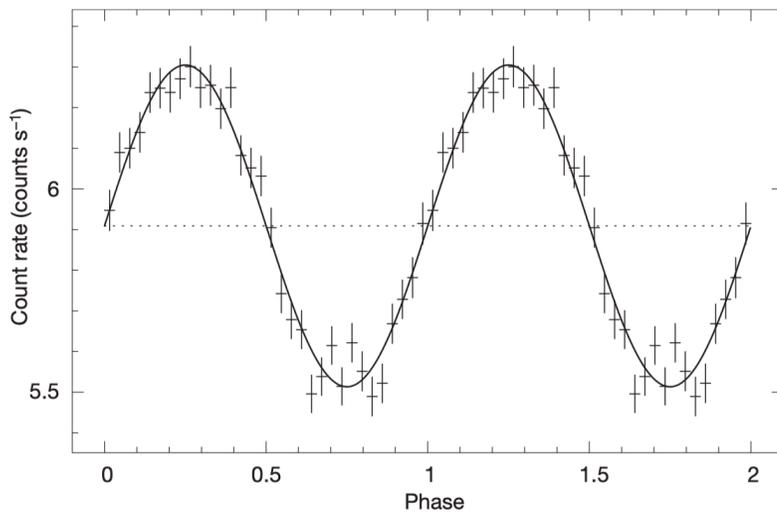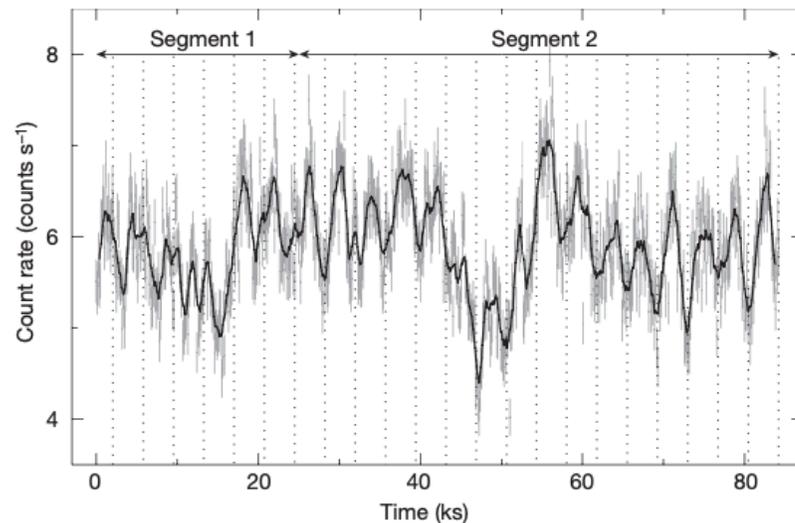
(AO Psc, P~805s)
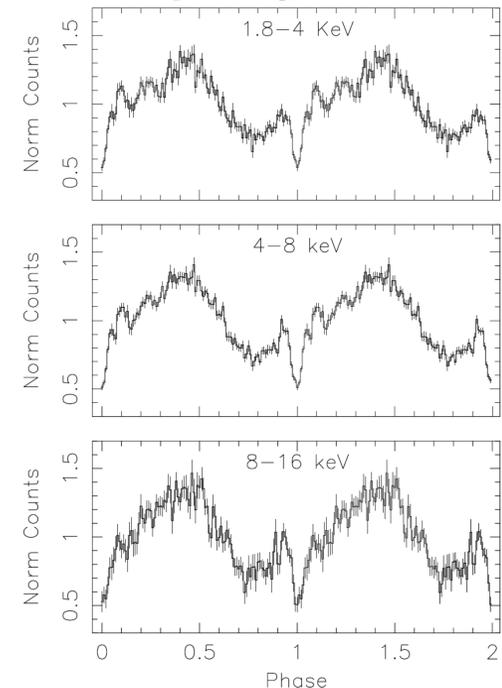
4U 1822-37, P~5.6 hrs

Super orbital period of HMXBs:
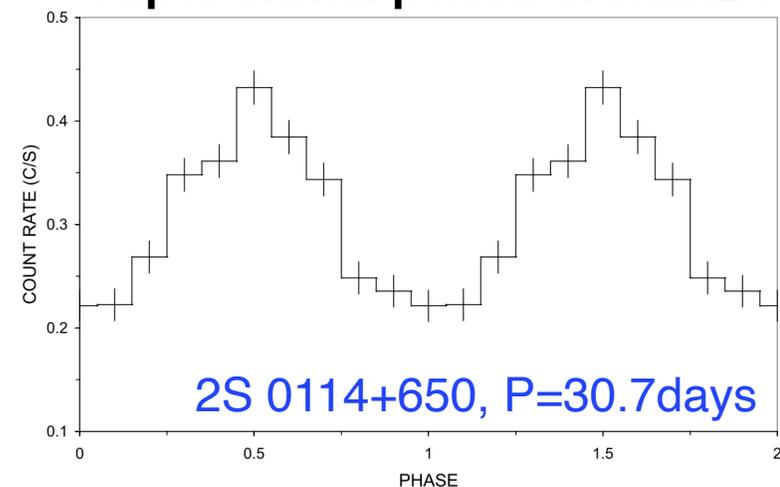
2S 0114+650, P=30.7days

And so on·····

The outline of GL method

KEY: The "multiplicity" :
$$W_m(\omega, \phi) = \frac{N!}{n_1! \, n_2! \, n_3! \cdots n_m!}, \quad \text{where} \quad \sum_{i=1}^{m} n_i(\omega, \phi) = N$$

$n_i(\omega, \varphi)$**:** the number of counts falling into the ith phase bins.

The more the values of n_i differ from each other (indicating periodicity), the smaller the multiplicity.
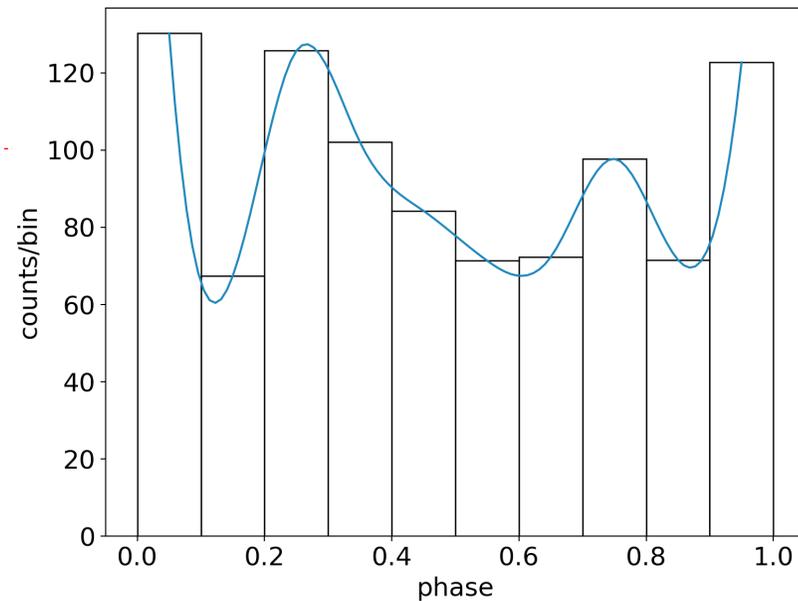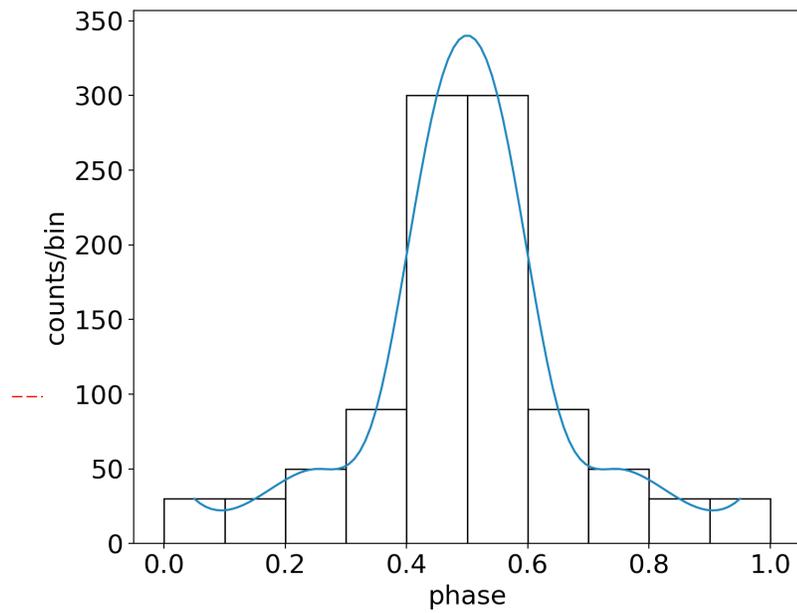
Probability of periodic signal can be derived numerically.

(Gregory & Loredo,1992)

(Bao&Li, 2020)   12

Application of GL method

Cautions:

1. Non-periodic variations among observations
2. Intrinsic aperiodic noise (red noise)
3. The satellite dithering (~707s and 1000s for *Chandra*)
4. The CCD frame time (~3.2s for *Chandra*).

Solution:

- Define and derive the **false alarm probability**, based on a large set of simulated light curves. *(with/without red noise, long-term flux variation.)*

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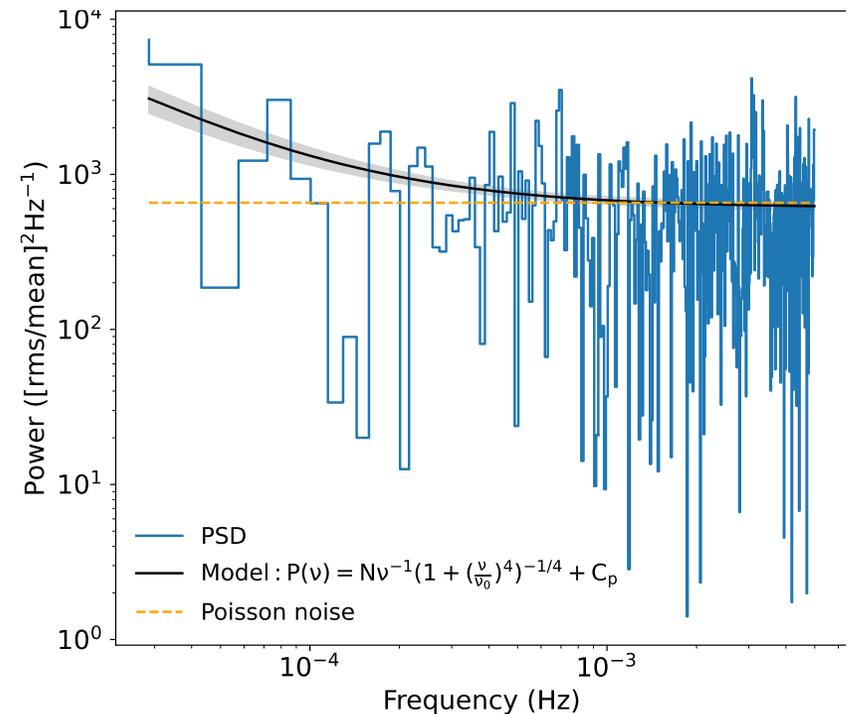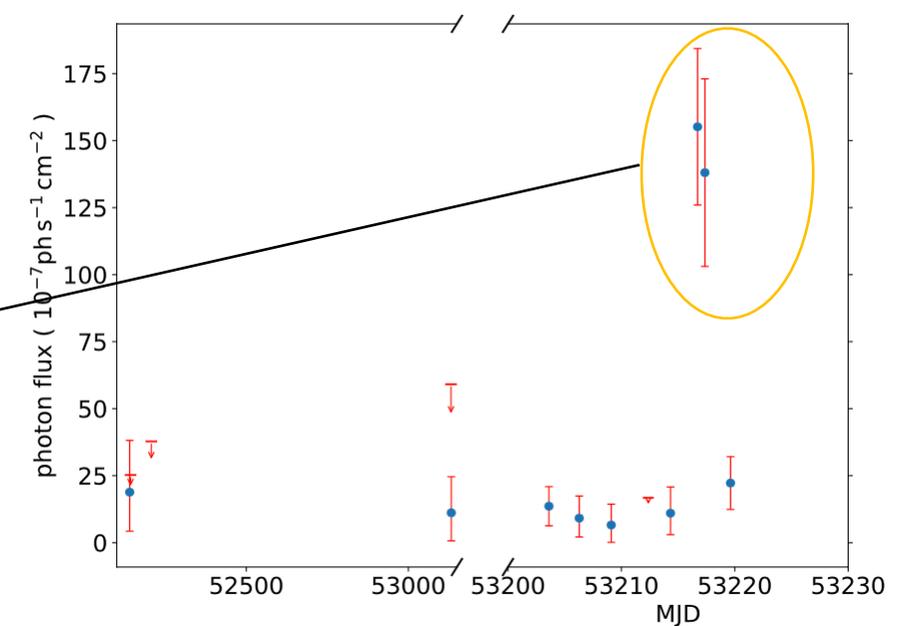
Detection efficiency of GL method *(Bao T & Li Z., 2020, MNRAS, 498, 3513)*
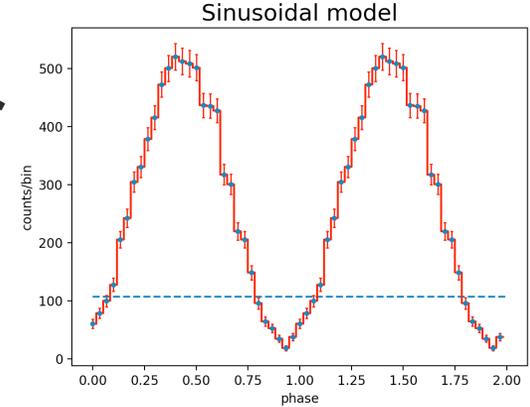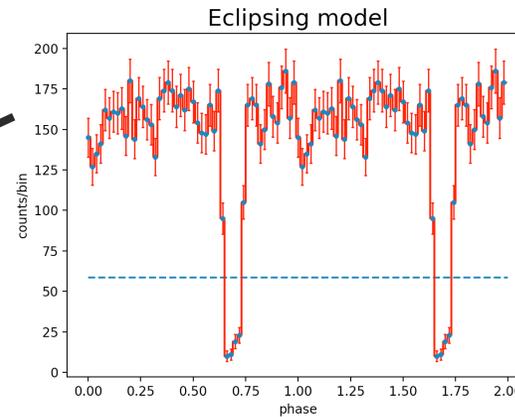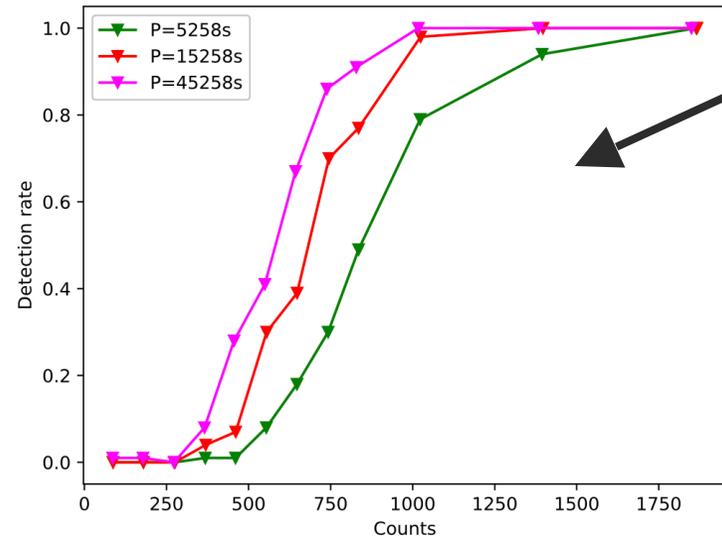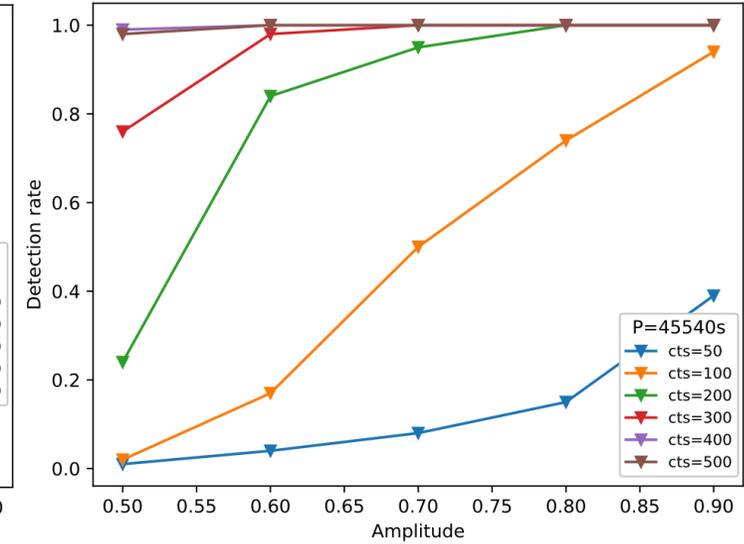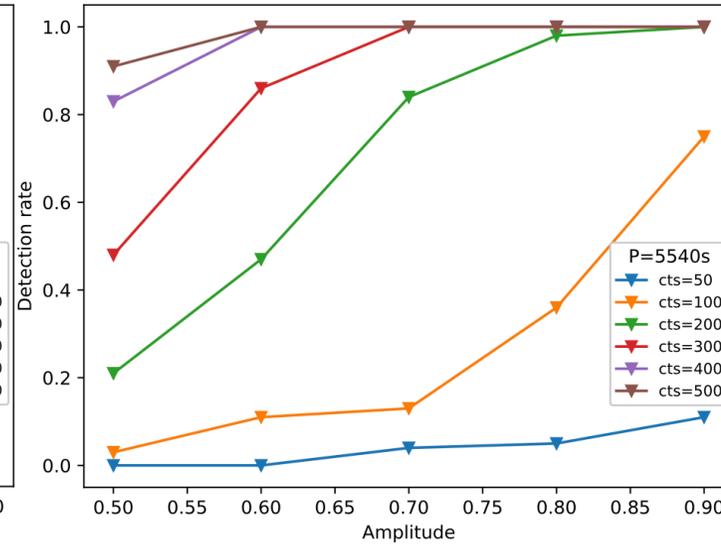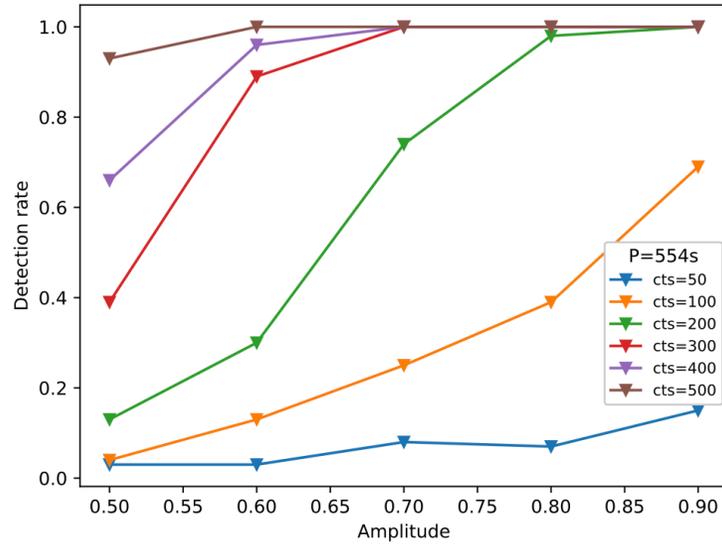
1. **Low detection rate of eclipsing signal (unless N>1000)**
2. **Higher detection rate for longer period**
3. **Adequate detection efficiency only for N>100 (sinusoidal variation)**

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3. CV population in the Galactic bulge
- the first application of the GL algorithm for period searching
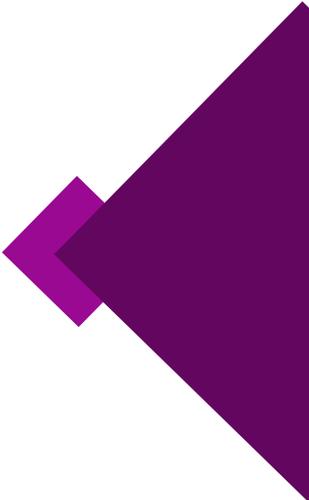
The "Limiting Window"

- a low-extinction *window* in the Galactic Bulge

Total: ~ 1 Ms Chandra observation
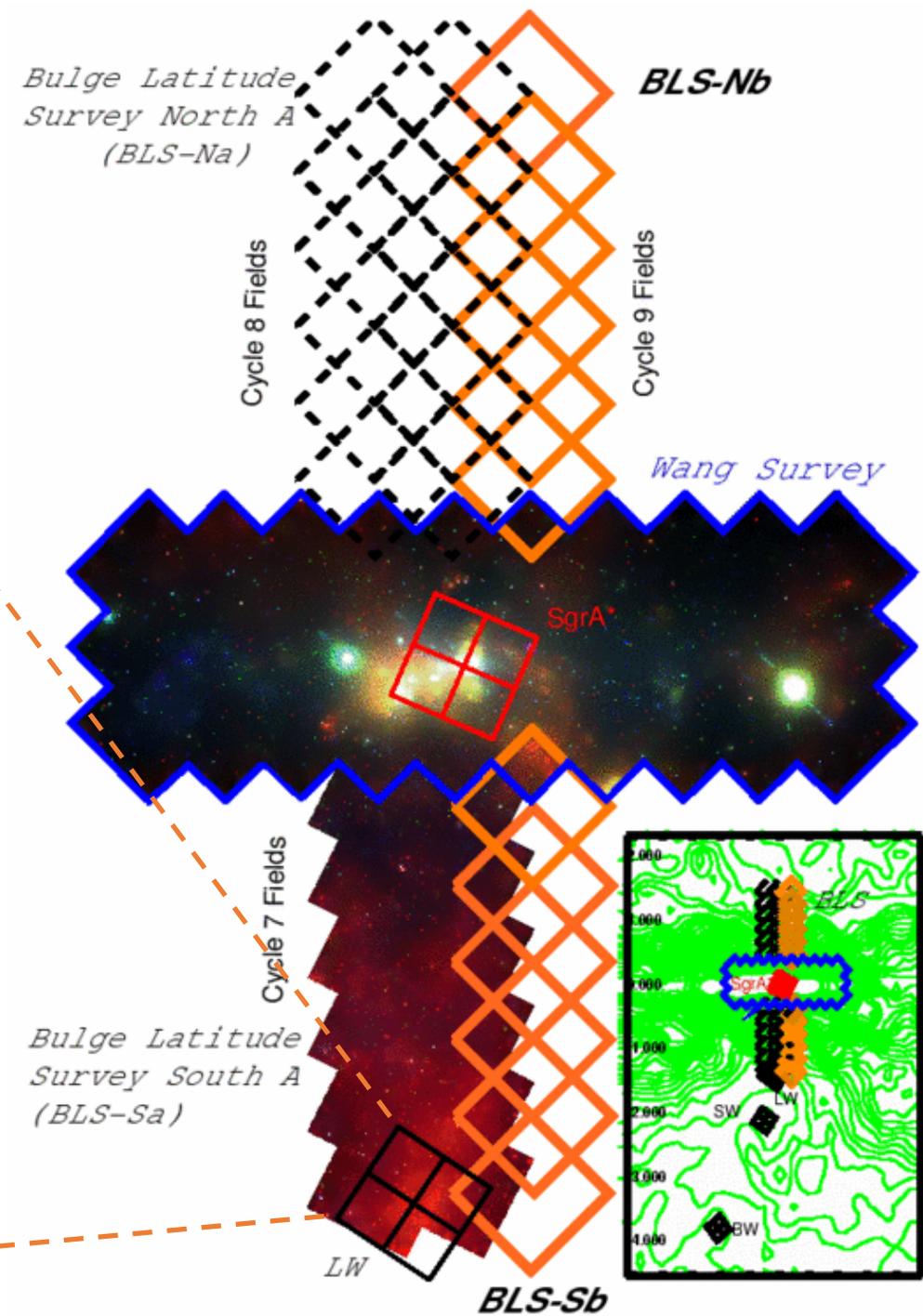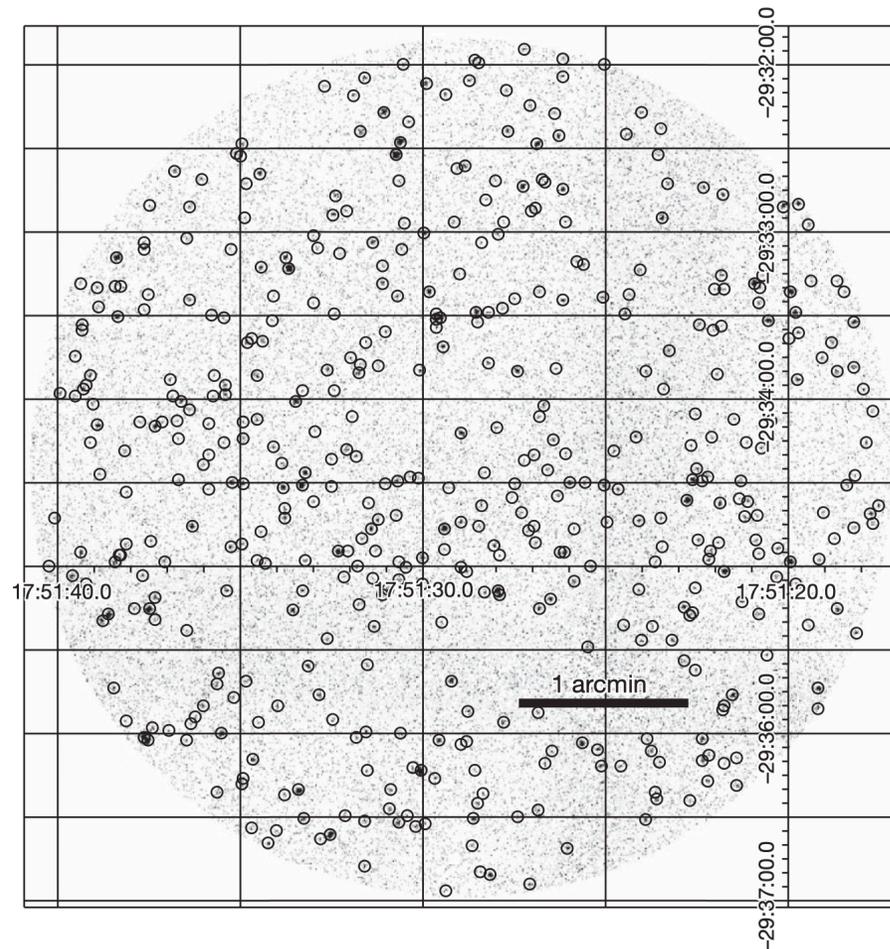
Periodic sources in the LW

(Bao T & Li Z., 2020, MNRAS, 498, 3513)
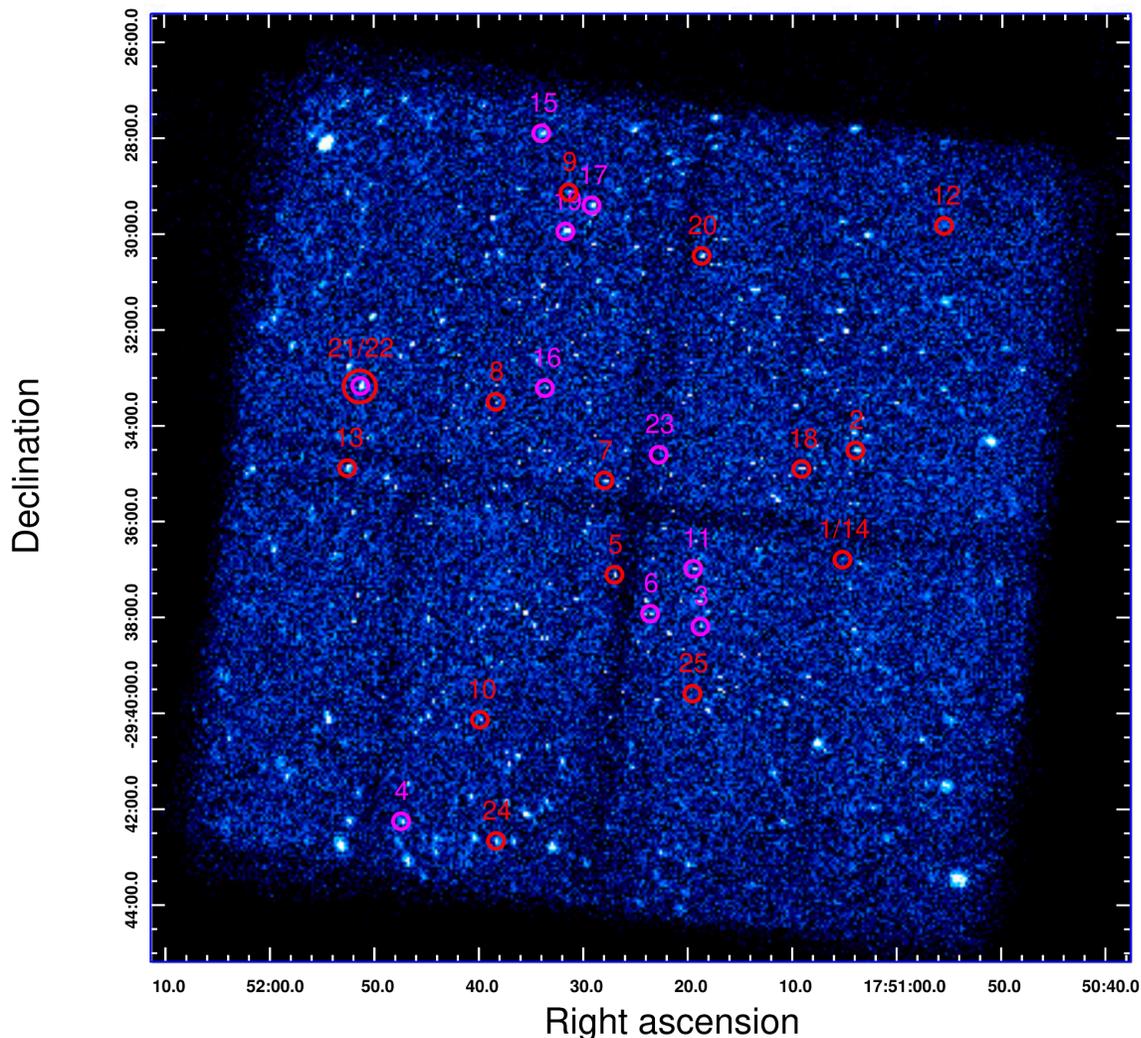
We detect 25 periodic signals in 23 discrete sources in the LW, most of them are classified as mCVs.
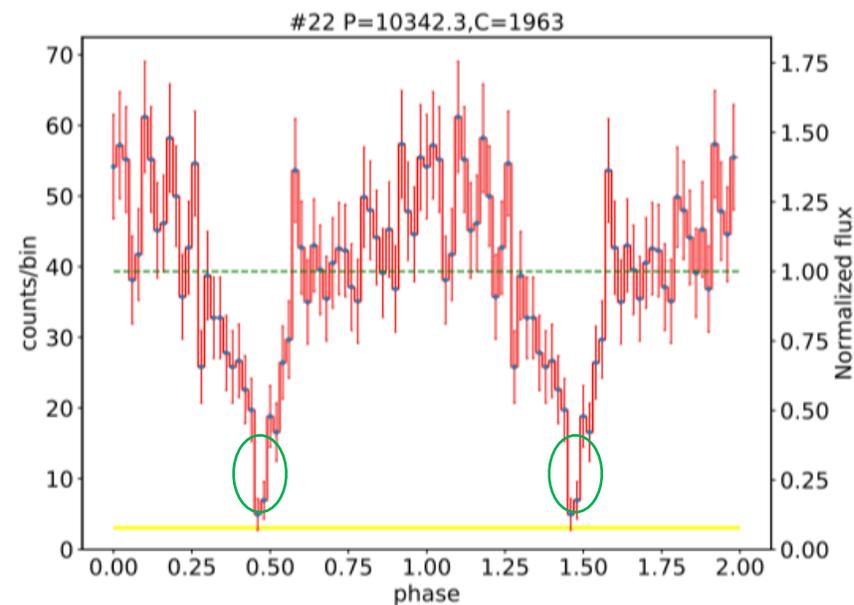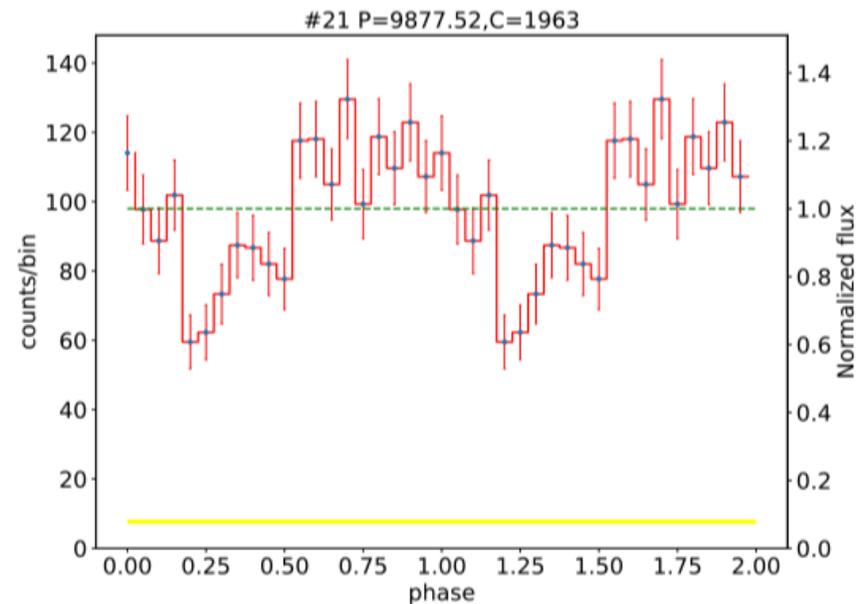
The one with eclipsing behavior and dual period

Orbital period distribution of LW CVs
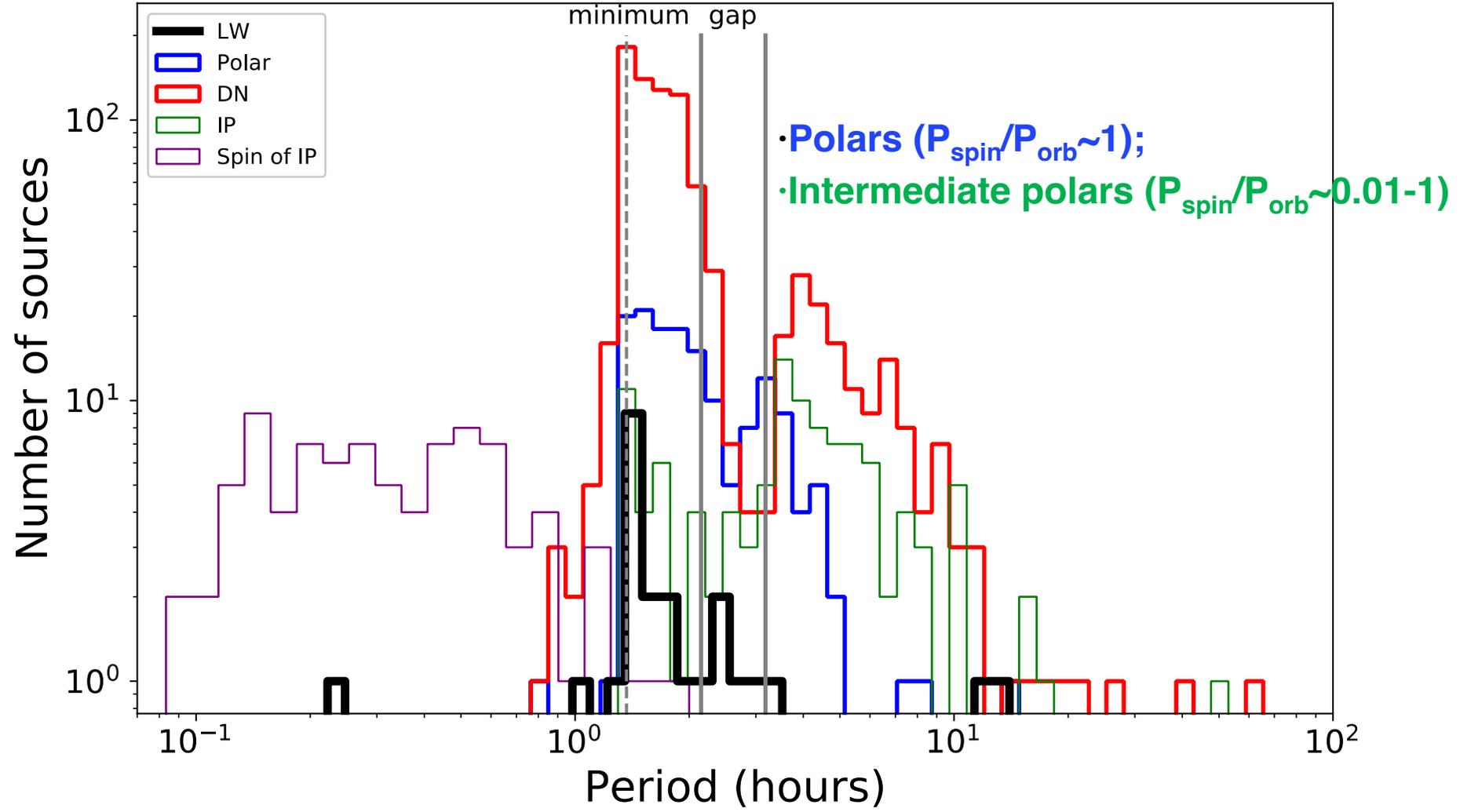
The apparent lack of long-period CVs in the LW suggest that CVs in the inner bulge are predominantly old and have substantially shrunk their orbits.

Estimating fraction of mCVs in the LW

Detection completeness

e.g.
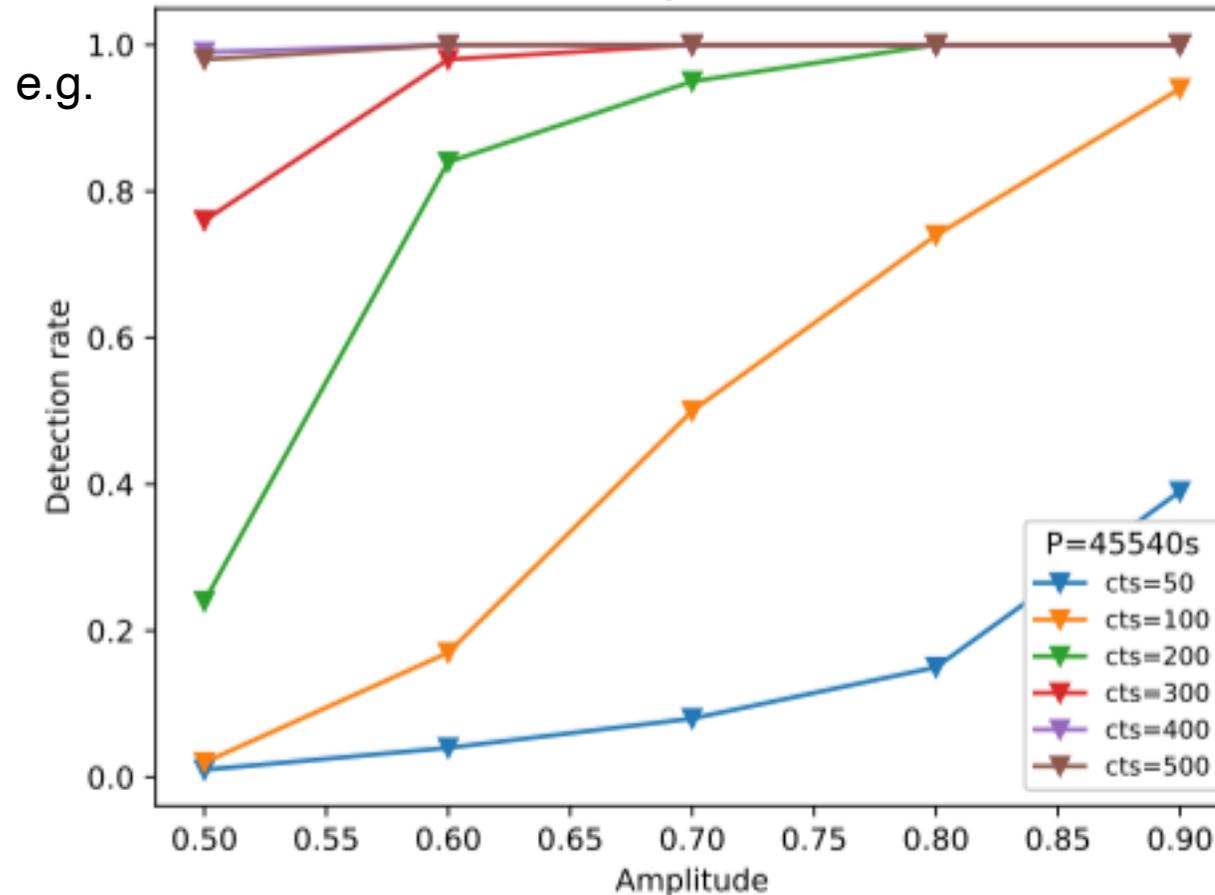
Fraction of polars

$$N_{det,polar} = P_{det} \times g \times \alpha_{polar} \times N_{tot}$$

geometric factor

Based in the global detection rate of GL method obtained, we are able to estimate **the fraction of mCVs in the LW $\lesssim$ 23%, similar to that in the solar neighborhood (~20%).**

How much is the contribution from background AGN?

(Bao T & Li Z., 2022, MNRAS, 509, 3584)

AGN QPO: between 200s and 20000s

(Luo+,2017)
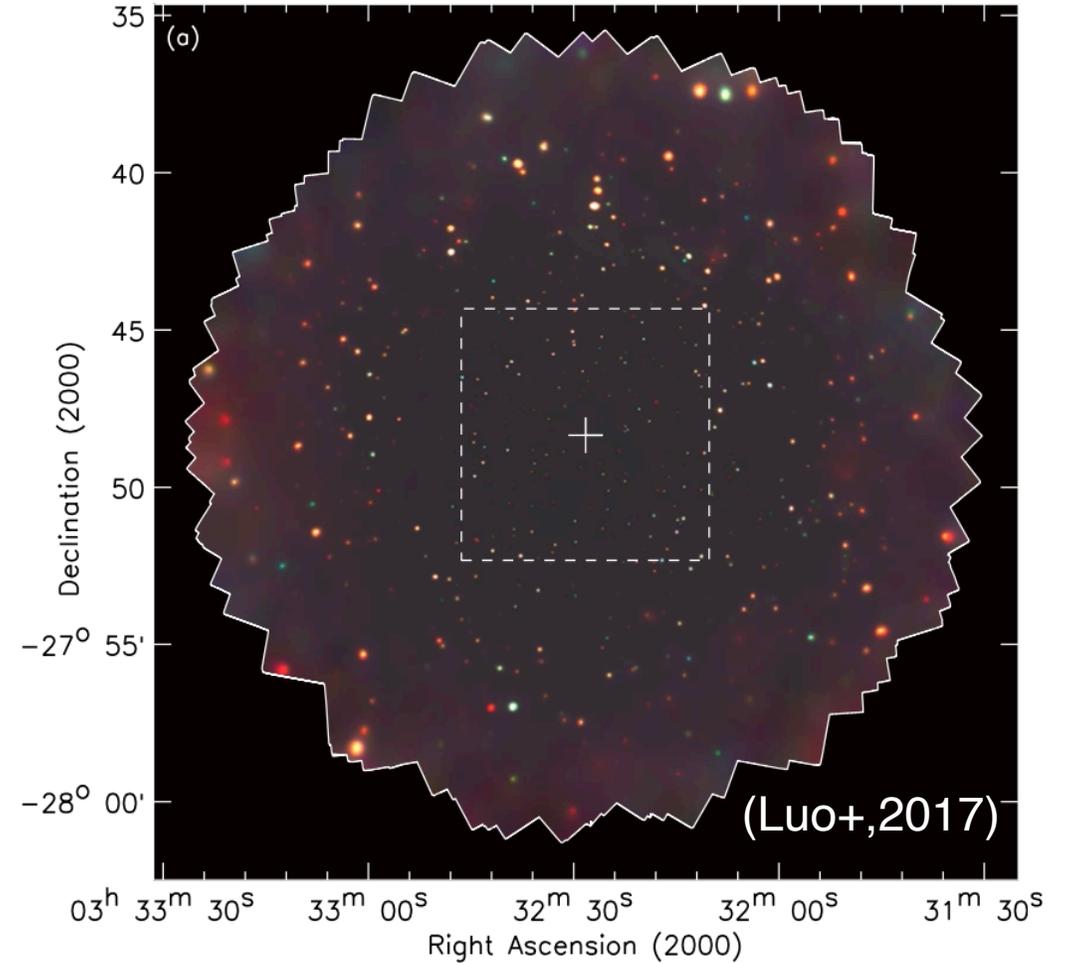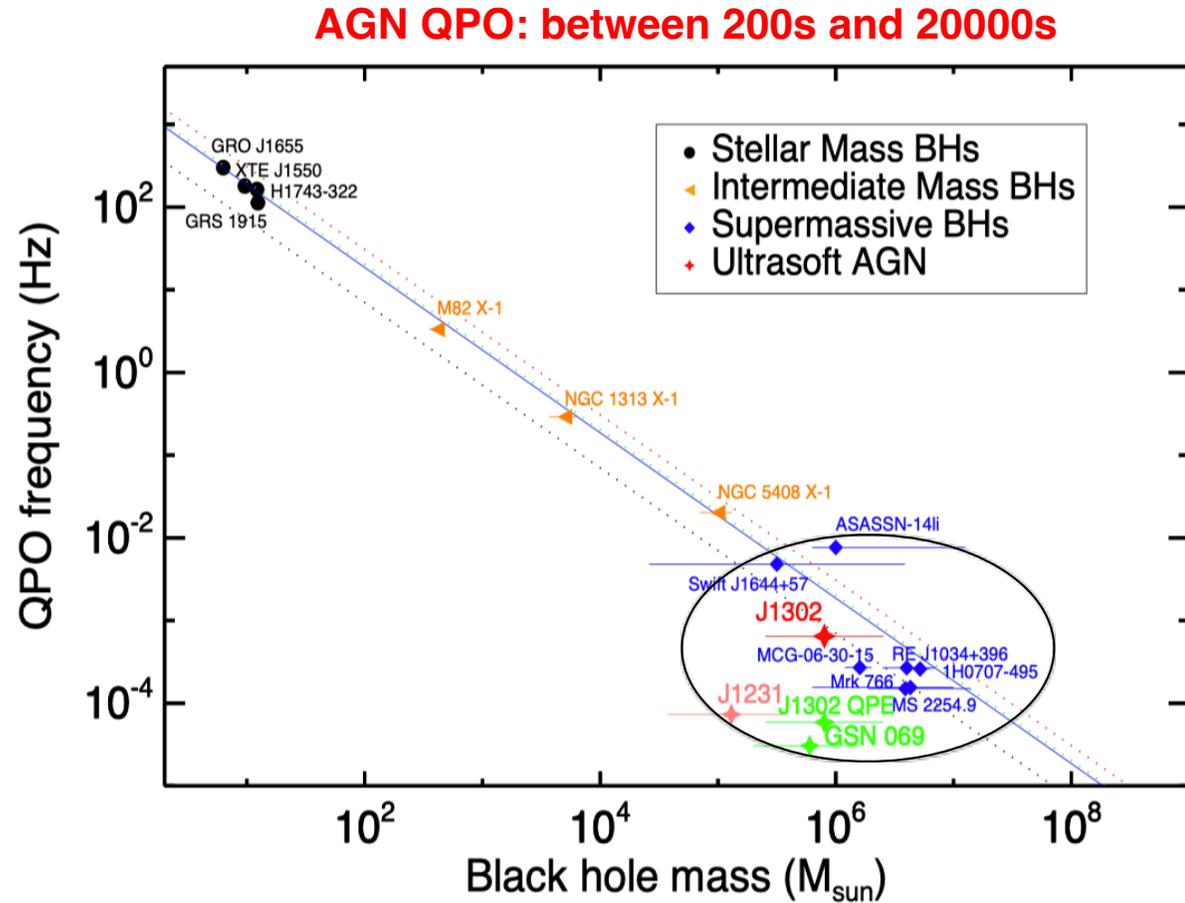
Result: 0 QPOs in ~1000 sources over a span of ~ 20yrs (7 Ms exposure).

QPO occurrence rate in AGNs

Simulating light curves with QPOs:
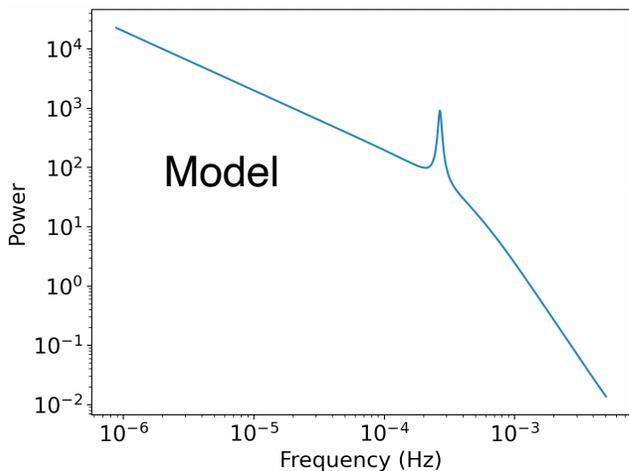
Typical PSD of AGNs with QPO:

bending powerlaw (M_{BH}, λ_{Edd})
+Lorentzian function
(QPO frequency, width)

Model

Power spectra

Light curve
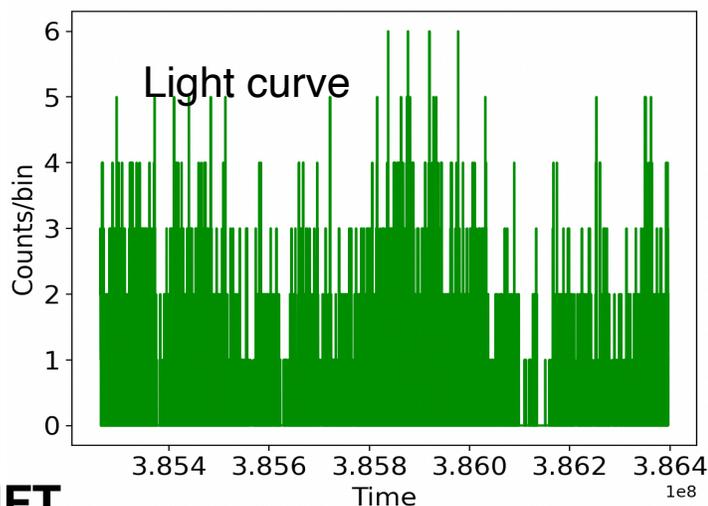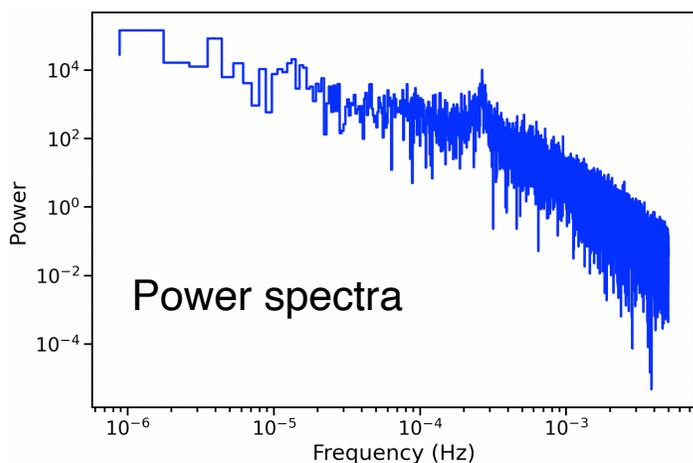
IFT
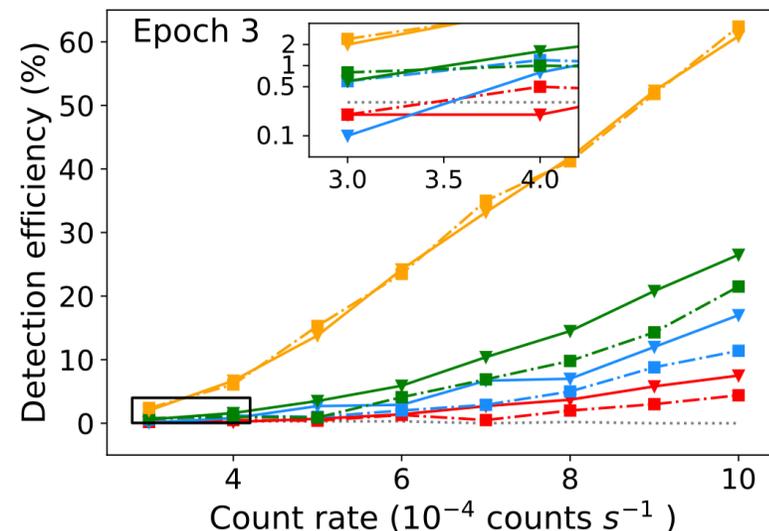
Detection efficiency

$$N_{\text{QPO,det}} = DE \times f_{\text{QPO}} \times N_{\text{sou}}$$

$$f_{\text{QPO}} \approx N_{\text{QPO,det}} / (\sum_i DE(\bar{x}_i, P) \times N_i)$$

$$\approx N_{\text{QPO,det}} / (\sum_i \overline{DE}(\bar{x}_i) \times N_i)$$

Intrinsic fraction of AGNs with QPO

f_{QPO}< 15-20%

The first constraint on the intrinsic occurrence rate of AGN QPOs.

Summary I

1. Using ~1Ms observation of "LW", we advocate the priority of GL method for period-searching by multiple X-ray observations.

2. Based on GL method, dozens of magnetic CVs are detected, constraining the fraction of mCVs in the bulge ~23%.

3. The lack of long-period CVs hint for the parent old stellar population.

4. The contribution from background AGN is negligible.

5. The first constrain on occurrence rate of AGN QPO: ~15-20%

4. Periodic X-ray sources in Milky Way globular clusters

4.1、X-ray observation of the massive GC: 47 Tuc

eROSITA image: ~150ks

Saeedi et. al, 2021
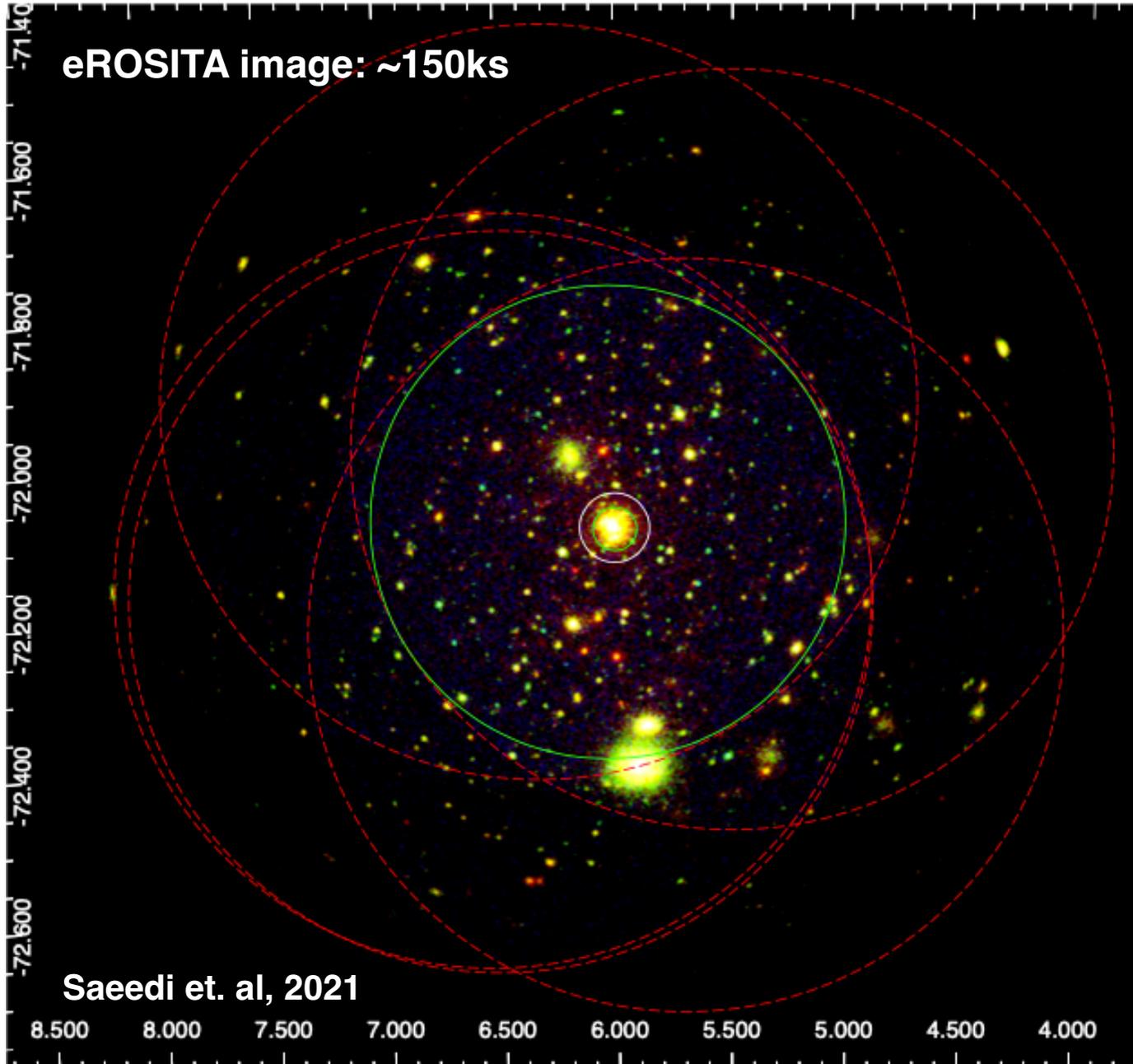
Chandra image of the central 2′ × 2.5′ of 47 Tuc.
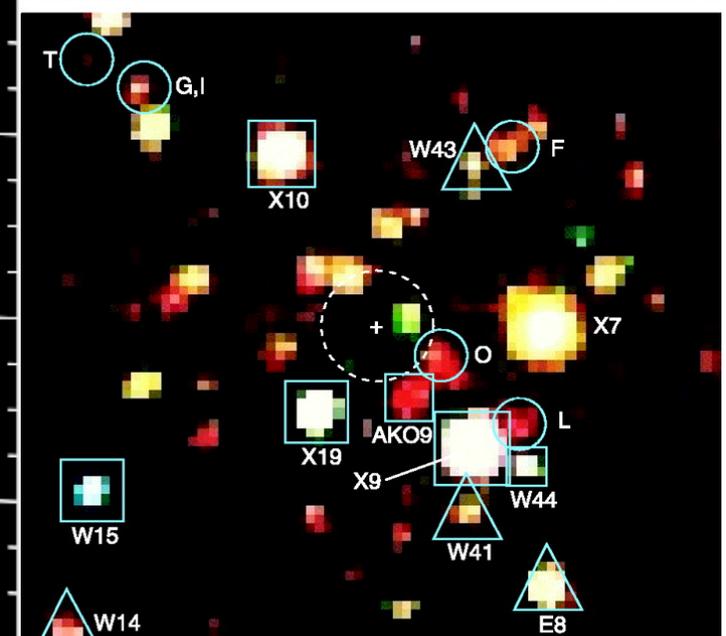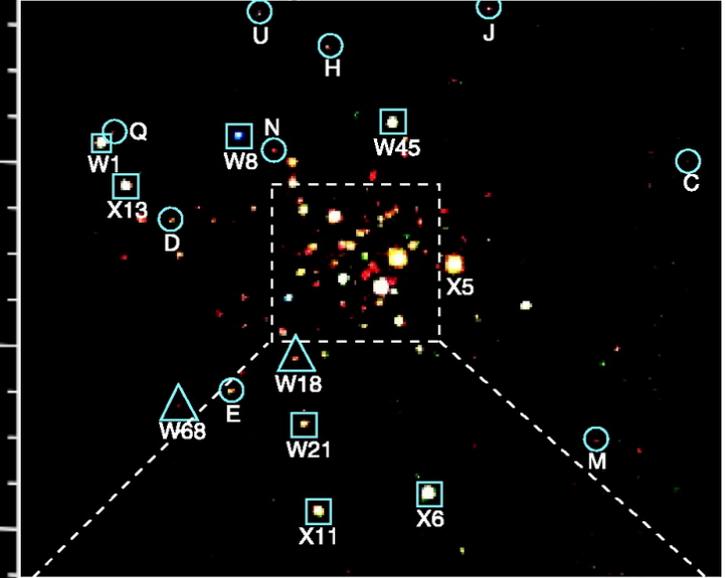
Jonathan E. Grindlay et al. Science 2001

eROSITA study of the 47 Tucanae

eROSITA pointing observation:
~888 sources, locating beyond the central 1.7'region.

The brightest one in the central region.
(an eclipsing XRB)
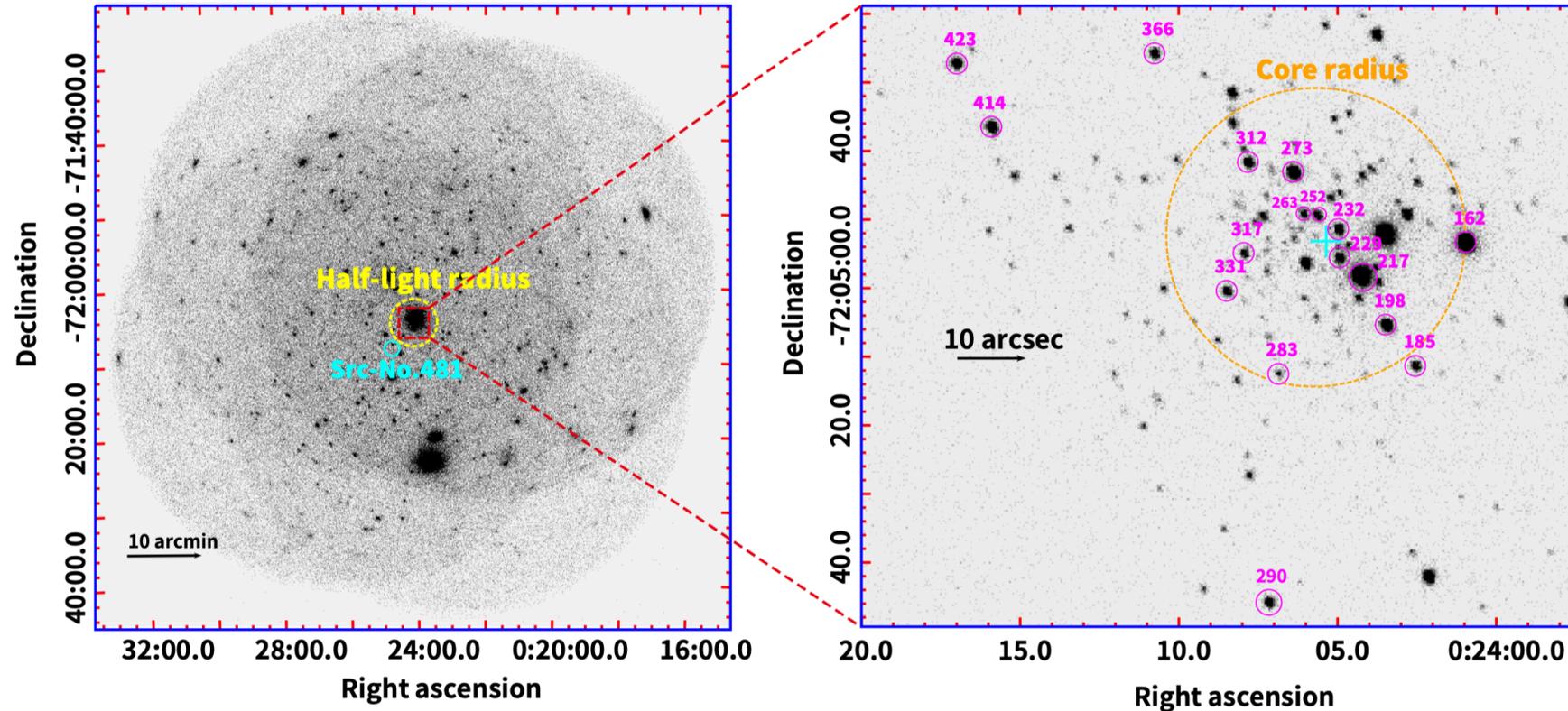
The cluster core is unresolved due to source crowding and the limited angular resolution of eROSITA
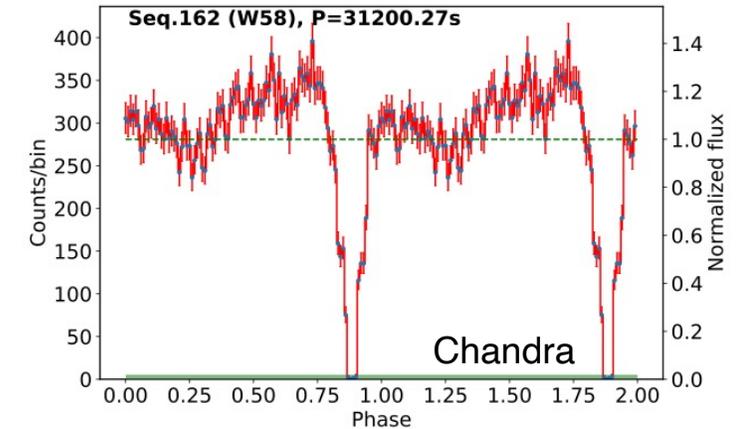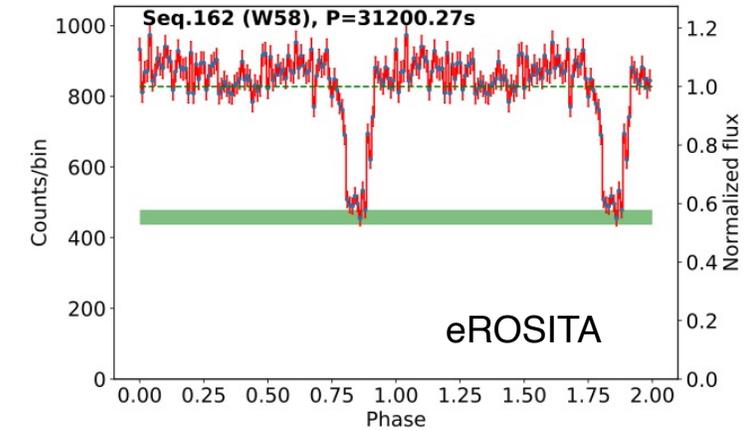
Confirming the validity of period searching process using eROSITA data.

eROSITA study of the 47 Tucanae

Src-No.481, P=14388.49s
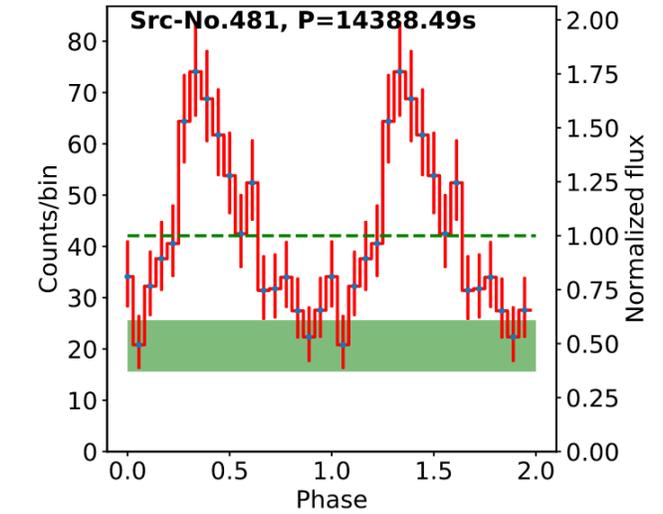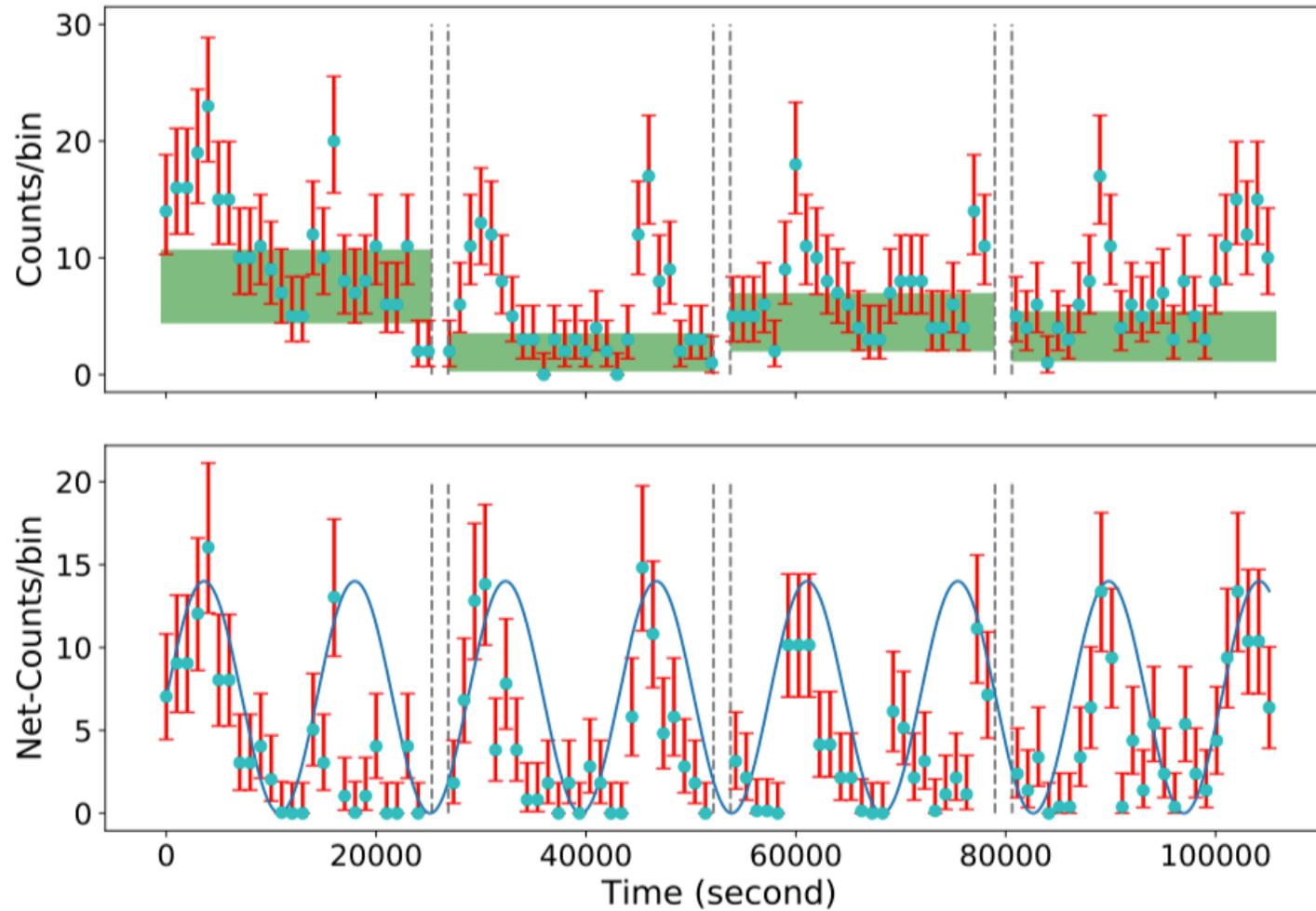
Both the sinusoidal-like light curve and soft spectra (**kT~0.06 keV**) indicates it as a MSP.

Low occurrence rate (1/888) of periodic sources in outskirts of 47 Tuc:
(1) Higher background in light curves;
(2) Most of sources are background AGN

Period searching results: 17+1 periodic sources
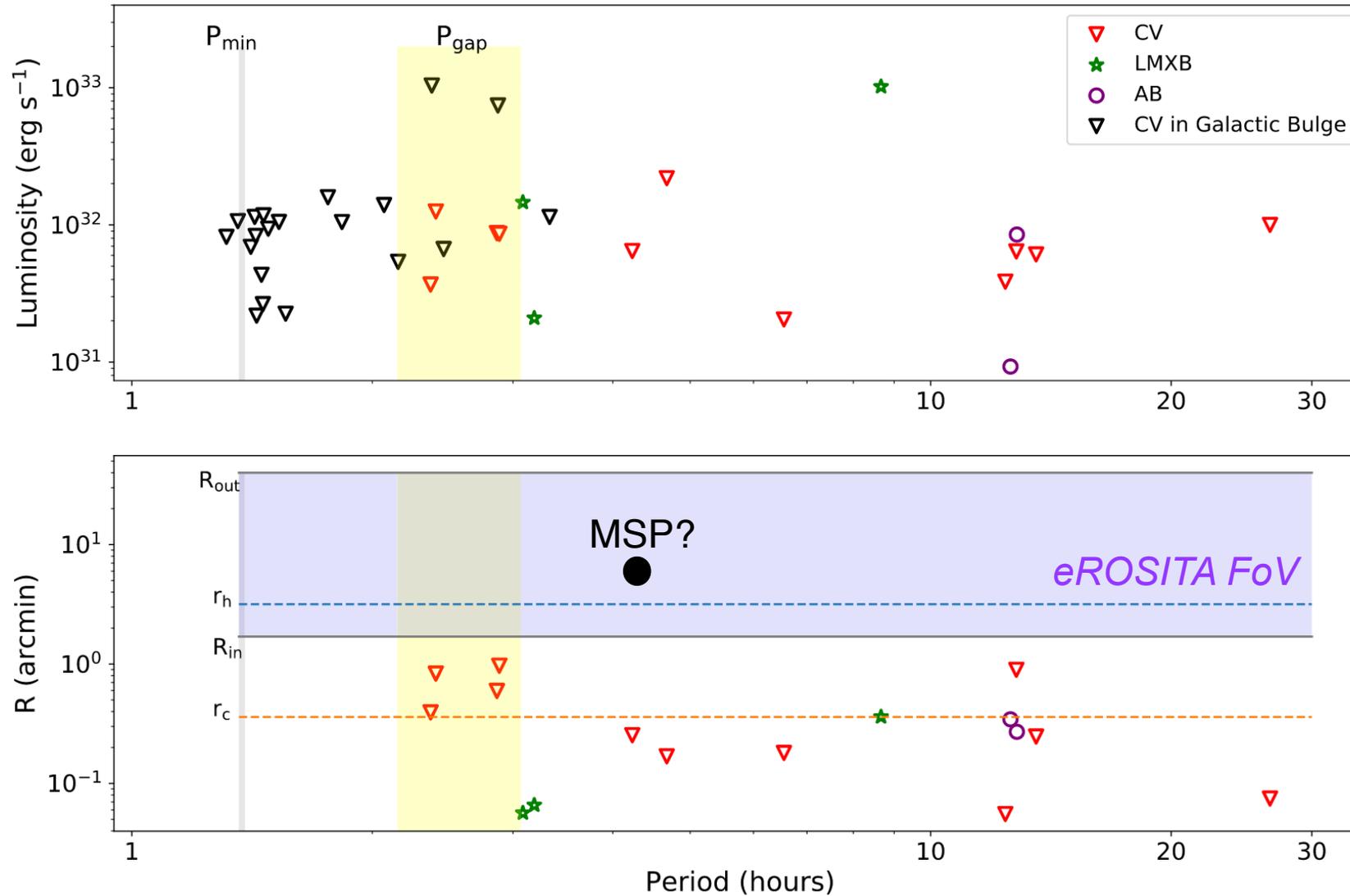
11 CVs+ 4 LMXBs+1MSP+2 ABs are identified from their UV counterpart, periodicity and spectra.

The long period CV population (P>12h) needs subgiant donor (>0.9 M$_{sun}$) to fullfill Roche-lobe, should be a dynamical formed, young, massive population.

Evident as dynamically-formed CVs
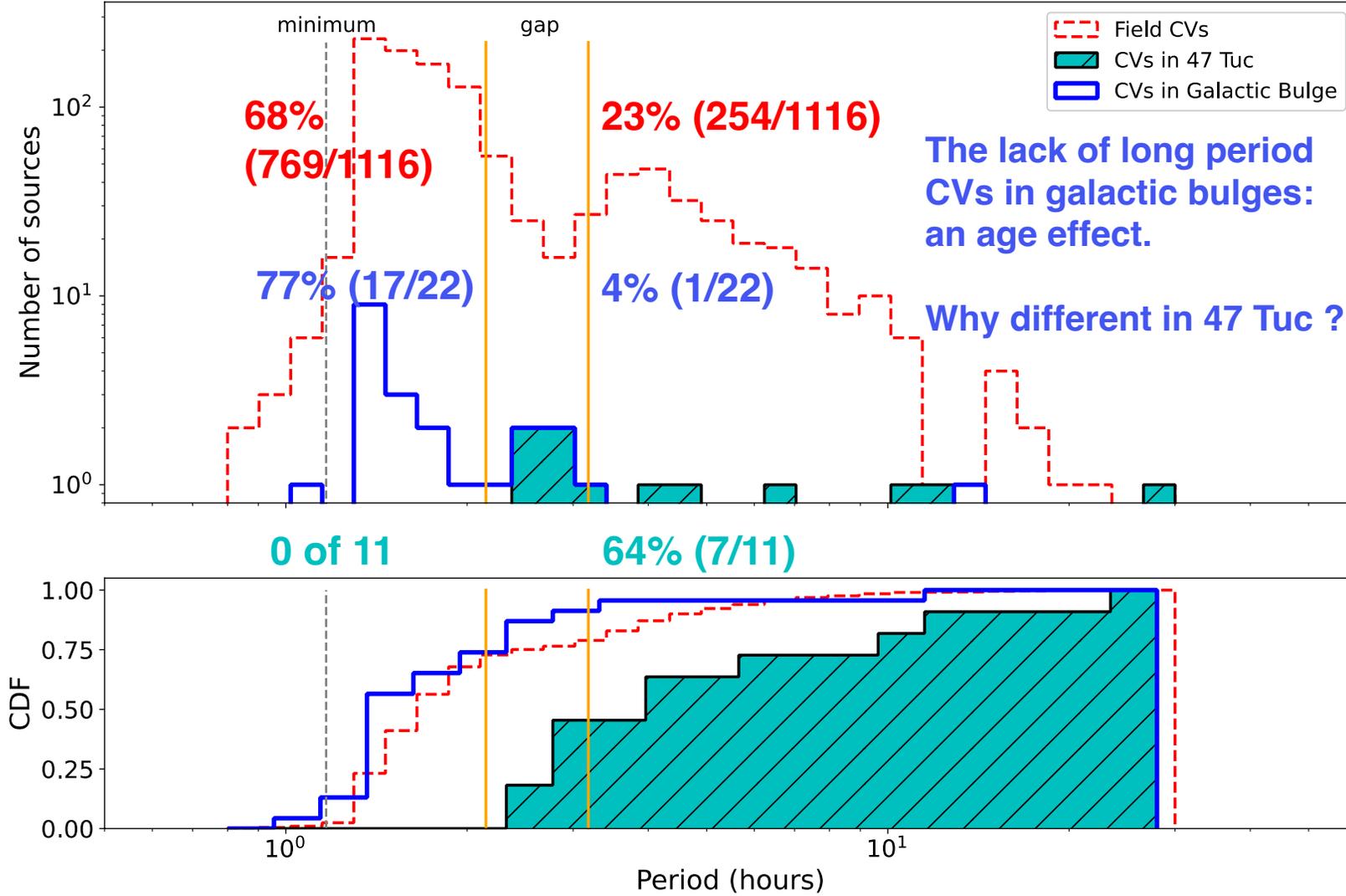
Steeper radial profile for these CVs

The lack of long period CVs in galactic bulges: an age effect.

Why different in 47 Tuc ?
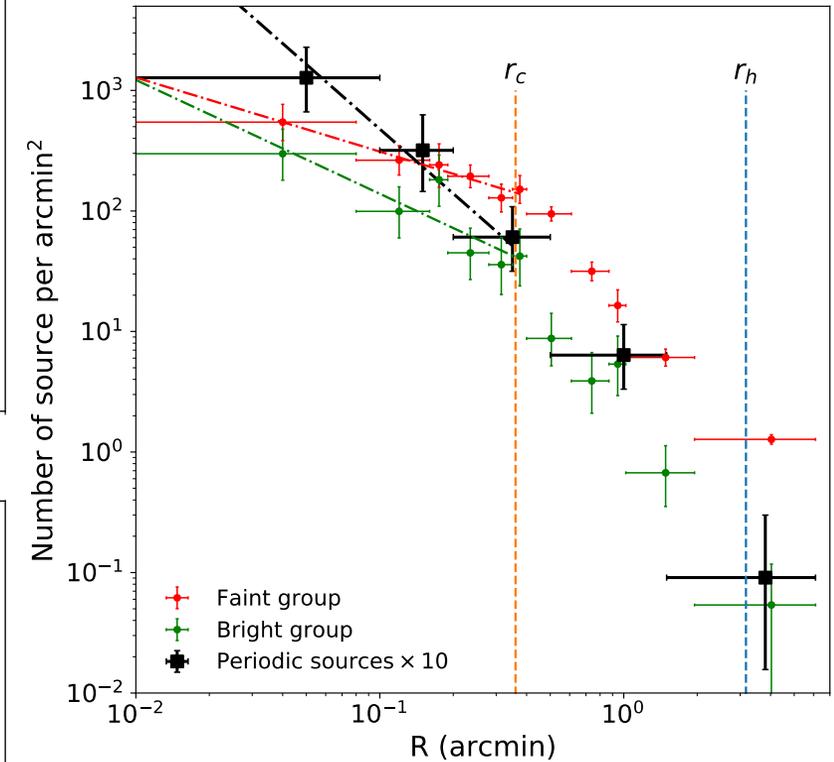
Both period and spatial distribution indicate CV are severely affected by dynamical interactions.

4.2、A Chandra survey of the Galactic globular clusters: Periodic X-ray sources

Sample selection: 11 Galactic GCs with Chandra exposure > 100 ks, covering at least 2-3 cycles for most CV orbits

Results: **46 periodic sources** (classified as CVs, LMXBs, MSPs and ABs.)

| GC Name	RA (deg)	DEC (deg)	ObsID	Exposure (ks)	D (kpc)	r_h (arcmin)	r_c (arcmin)	[Fe/H]	Mass (10^5 M$_\odot$)	Number of sources
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
47 Tuc (NGC 104)	6.02363	-72.08128	78, 953, 954, 955, 956, 2735, 2736, 2737, 2738, 3384, 3385, 3386, 3387, 15747, 15748, 16527, 16528, 16529, 17420	535.1	4.5	3.17	0.36	-0.76	11.8	537 (184)
ω Cen (NGC 5139)	201.69683	-47.47958	653, 1519, 13727, 13726	290.9	5.2	5.00	2.40	-1.62	25.7	300 (86)
NGC 6121	245.89675	-26.52575	946, 7446, 7447	119.2	1.9	4.33	1.17	-1.20	1.52	117 (29)
M62 (NGC 6266)	255.30333	-30.11372	2677, 15761	144.4	6.4	0.92	0.22	-1.29	9.50	146 (36)
NGC 6304	258.63438	-29.46203	8952, 11073	102.7	5.8	1.42	0.21	-0.59	1.68	183 (24)
NGC 6397	265.17538	-53.67433	79, 2668, 2669 7461, 7460	339.7	2.4	2.97	0.05	-1.95	0.91	376 (129)
Terzan 5	267.02042	-24.77917	3798 10059 13225, 13252, 13705, 13706, 14339, 14475, 14476, 14477, 14478, 14479, 14625, 15615, 15750, 16638, 17779, 18881,	745.6	5.5	0.72	0.21	-0.23	20.0	489 (130)
M 28 (NGC 6626)	276.13671	-24.86978	2683, 2684, 2685, 9132, 9133, 16748, 16749, 16750	325.9	5.4	1.97	0.24	-1.45	3.71	502 (139)
NGC 6656	279.09975	-23.90475	5437, 14609	100.7	3.2	3.36	1.34	-1.64	5.08	138 (20)
NGC 6752	287.71712	-59.98456	948 6612 , 19014 20121 20122 20123	344.4	4.3	1.91	0.17	-1.56	2.50	244 (62)
M30 (NGC 7099)	325.09217	-23.17986	2679, 20725, 18997, 20726, 20732, 20731, 20792, 20795, 20796	330.1	8.0	1.03	0.06	-2.12	1.93	84 (20)

Identified CVs in the Galactic globular clusters
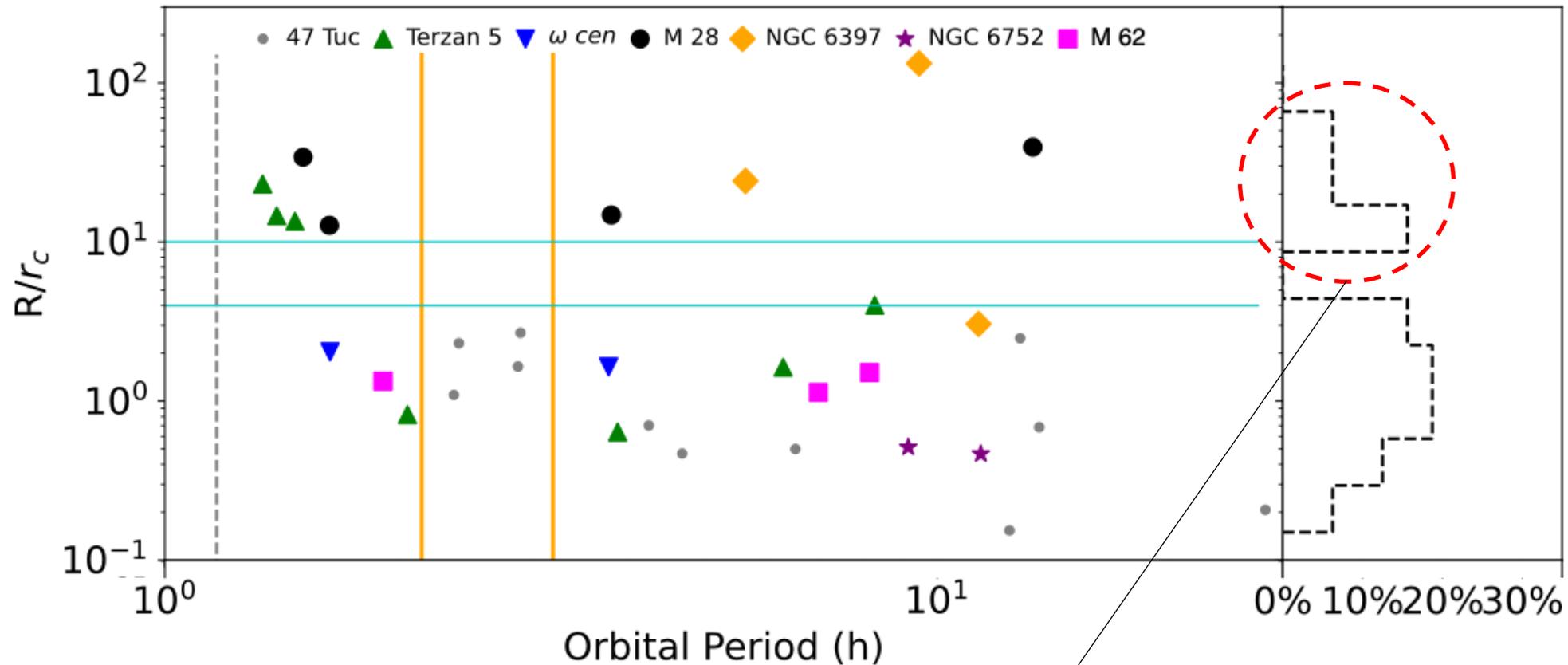
1. The largest sample of periodic CVs so far, i.e., **32 periodic CVs in 7 GCs**, enlarging the previous sample in GCs by 3 times.

2. **Dynamically-ejected CVs are firstly found in the GC's outskirts**, confirming the predictions by MOCCA simulation (Belloni+, 2019).

Orbital period distribution of known GC CVs
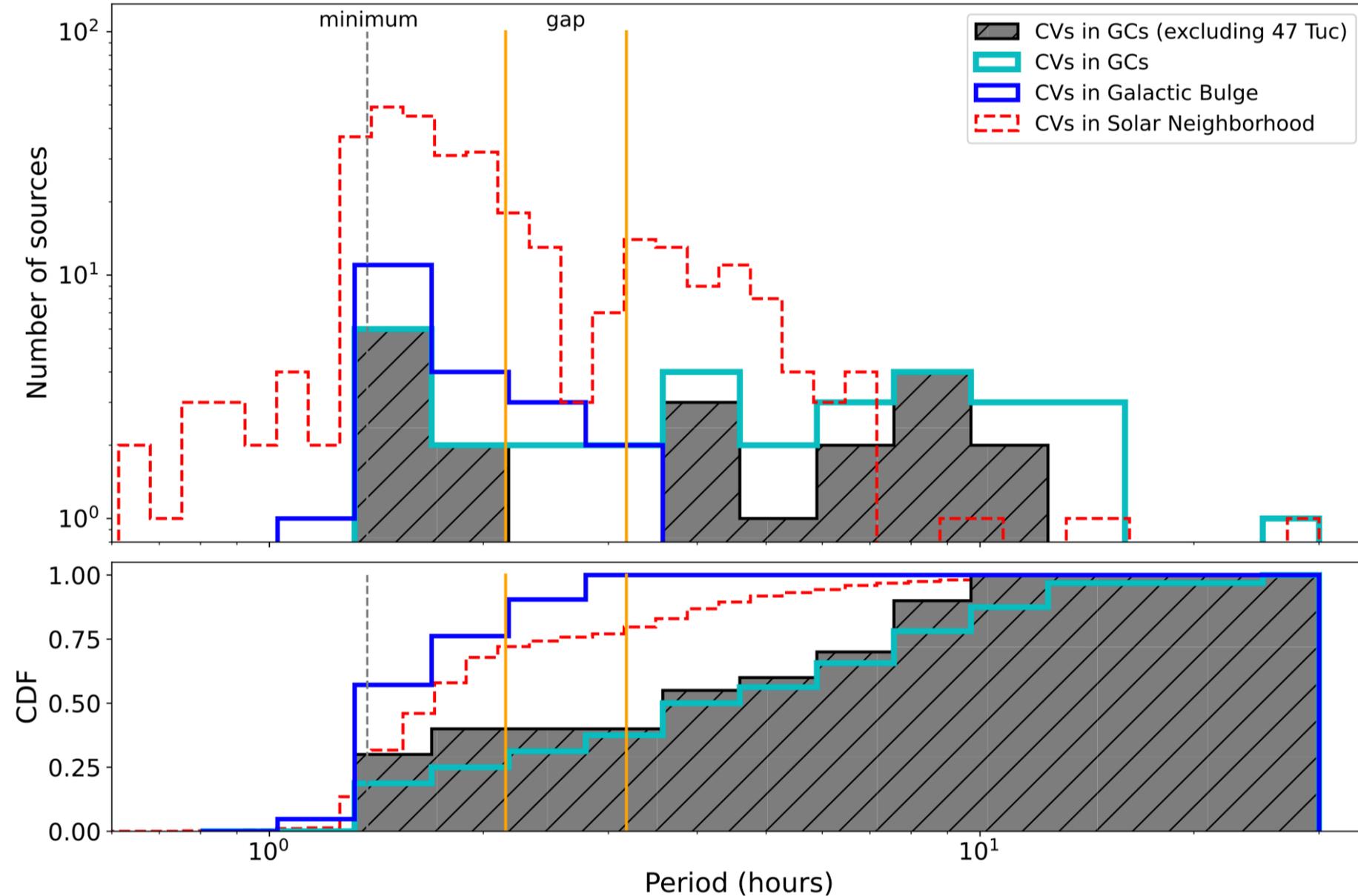
This disparity can be attributed to

(i) selection bias favouring younger, dynamically formed systems;

(ii) suppression of the pathway for CV formation through primordial binary evolution by dynamical interactions.

Higher proportion of long-period CVs compared to the local CV sample.

New observational constraint on the dynamics:
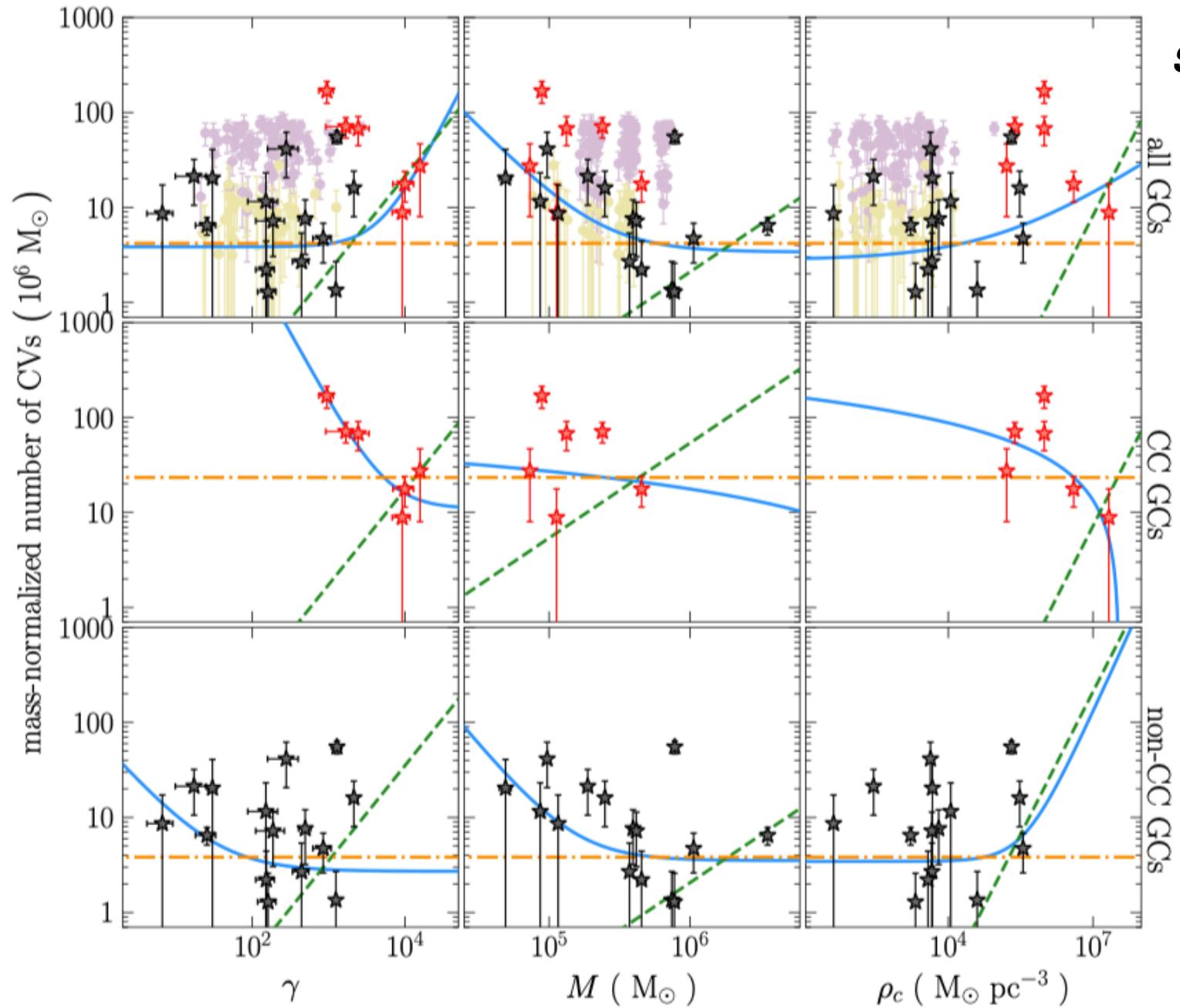
Sandoval+, 2024

1. No correlation between number of CVs and stellar encounter rate

2. Fewer CVs with higher encounter rate in core-collapsed GCs

Hint for outstanding questions

1. Are most GC CVs formed by dynamical channels?

   --Not supported by newly confirmed GC CV sample.

2. Are GC CVs predominantly magnetic?

   -- still biased to magnetic CVs if by X-ray periodicity

   -- still no bright IPs (intrinsic?)
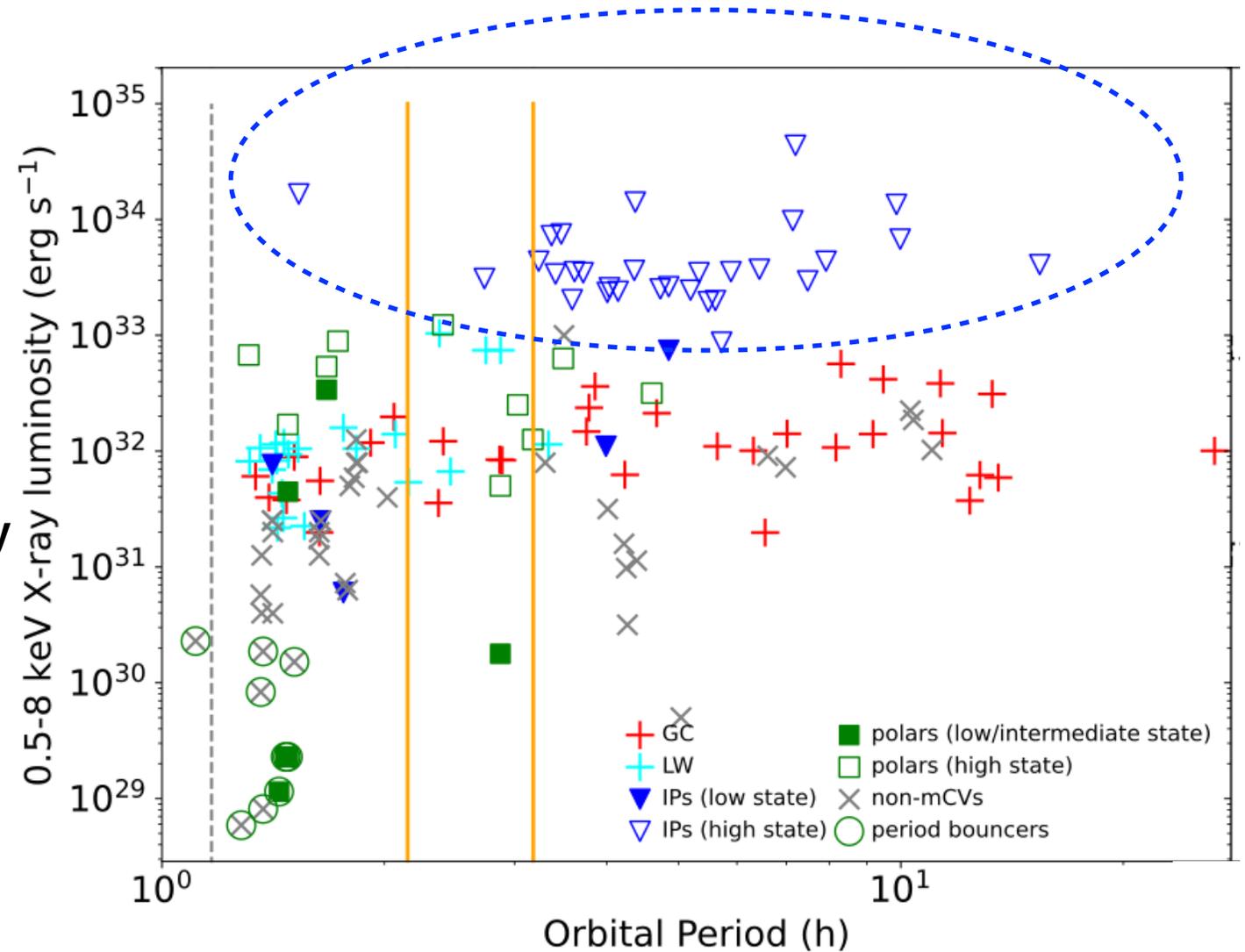
Summary II

1. The largest sample of GC CVs with orbital periods.

2. First observational evidence for dynamically-formed CVs in 47 Tuc.

3. Dynamically-ejected CVs are observed as predicted.

4. **Most GC CVs are formed by primordial channels.** Growing evidence for suppression of primordial CVs by dynamical interactions.

My research proves that mining compact binaries by their periodicities would be an effective approach, for both studying the parent stellar population and discovering new exotic binary systems (UCXBs, MSPs, ···).

5. Some exotic X-ray bianries

(Related "by products")
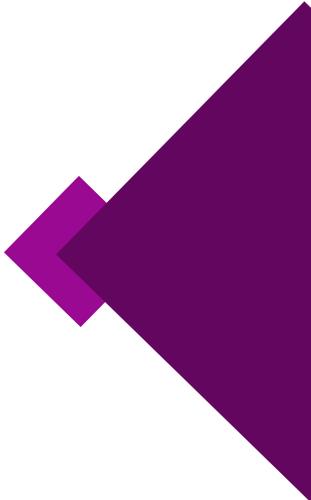
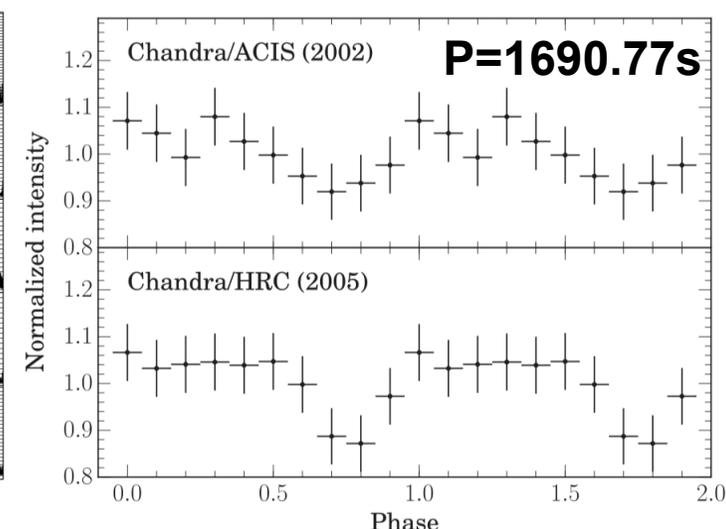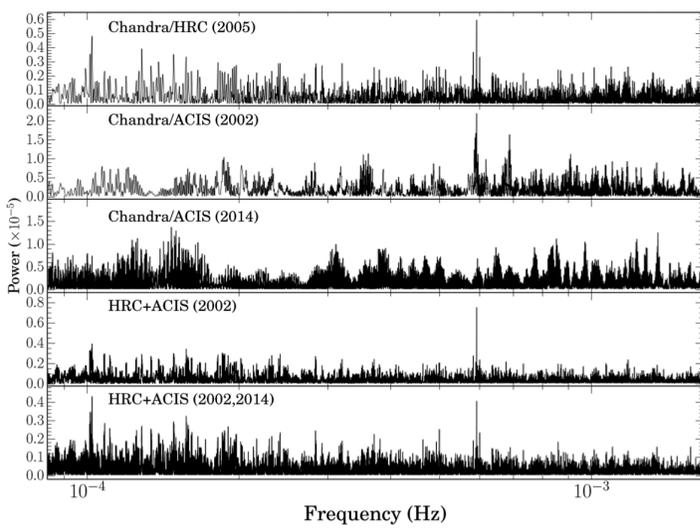# (1) 47 Tuc X9: an UCXB with multiple period?

Seq.217, P=205.02s

(Bao,T et al., 2023)

P~6.8 day

(Bahramian, et al., 2017)

Chandra/HRC (Jan 2006)

Chandra/HRC (2005)

Chandra/ACIS (2002)

Chandra/ACIS (2014)

HRC+ACIS (2002)

HRC+ACIS (2002,2014)

Chandra/ACIS (2002) P=1690.77s

Chandra/HRC (2005)
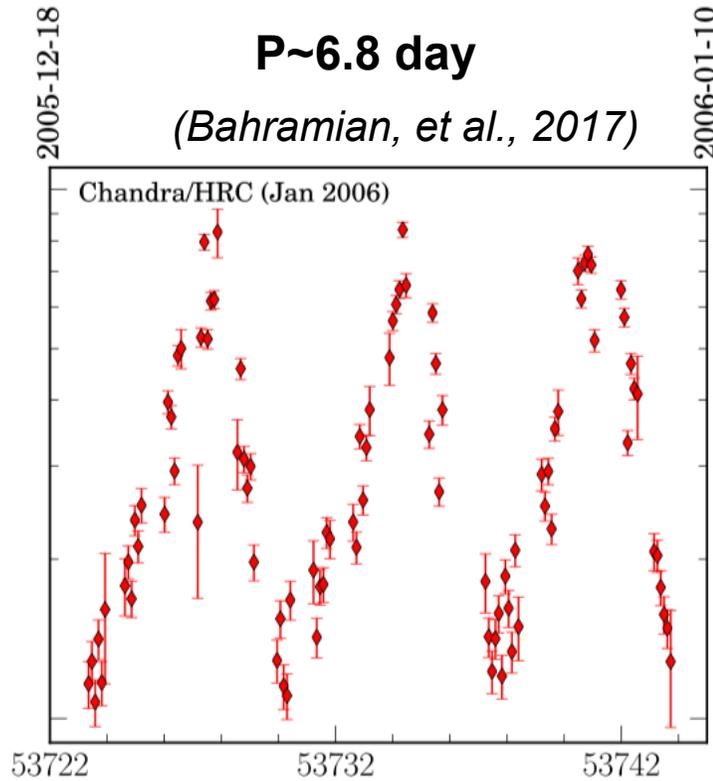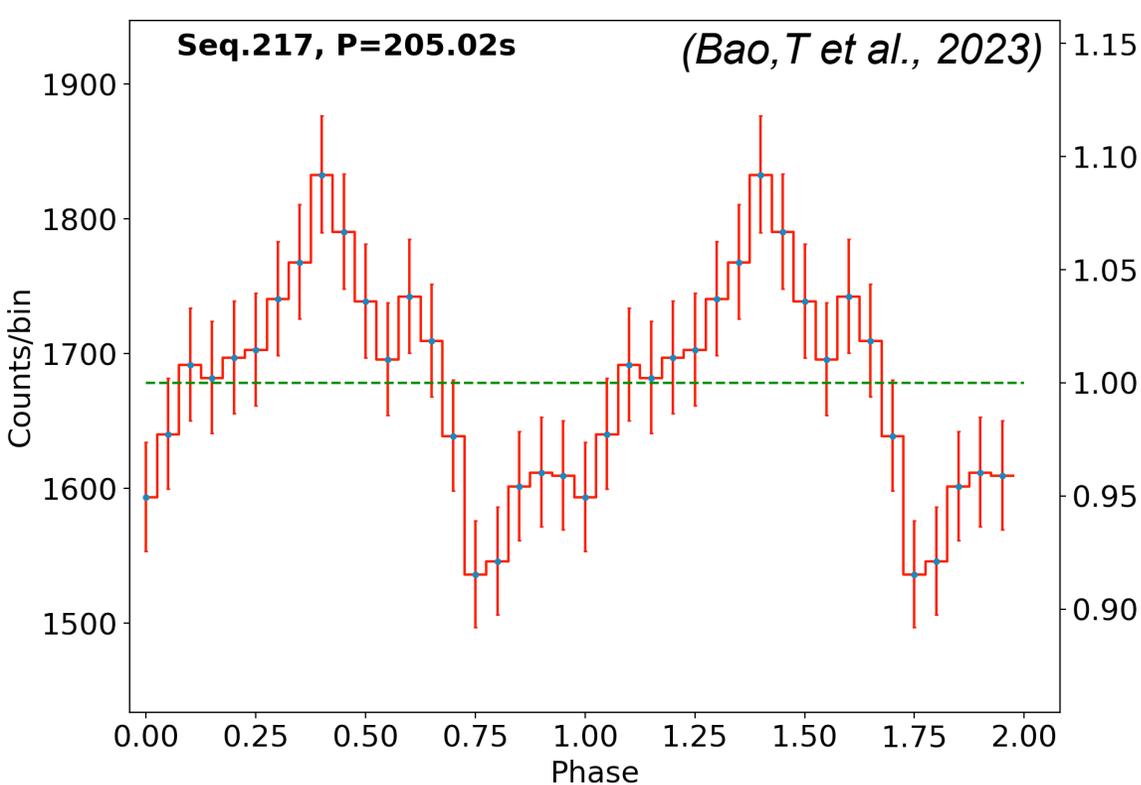
The presence of strong carbon lines and lack of H or He lines suggest a CO WD as the donor star.
(Knigge et al. 2008; Miller-Jones et al. 2015)

(2) Two dip in one period ?

A X-ray binary system found near the core of M31.*(Zhang, Bao, Li., 2024)*

All

Folded at P ~ 19.28h

Model: tbabs*powerlw
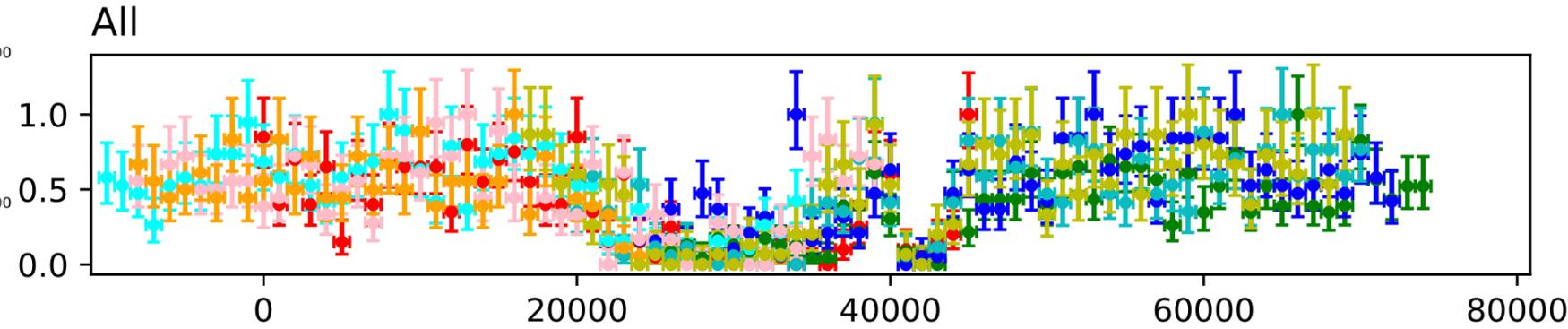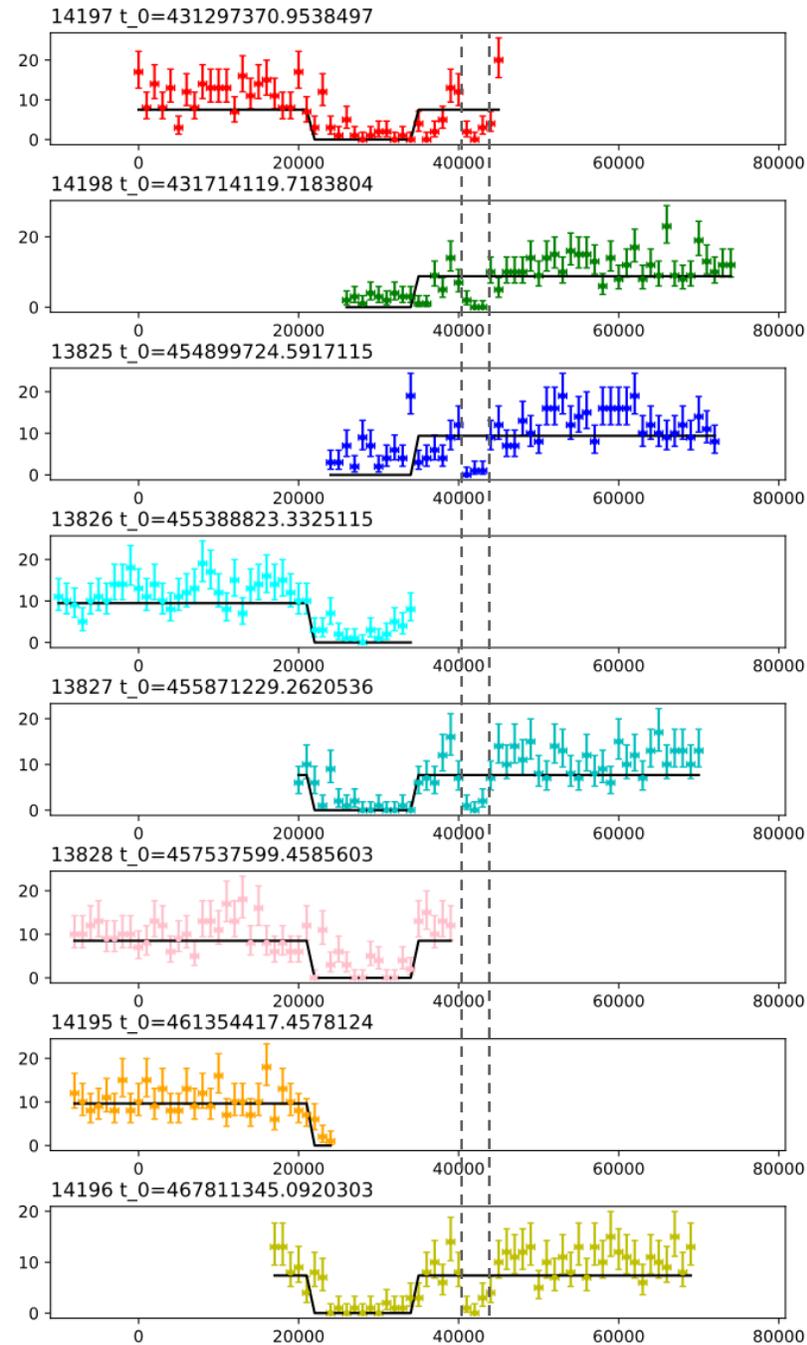
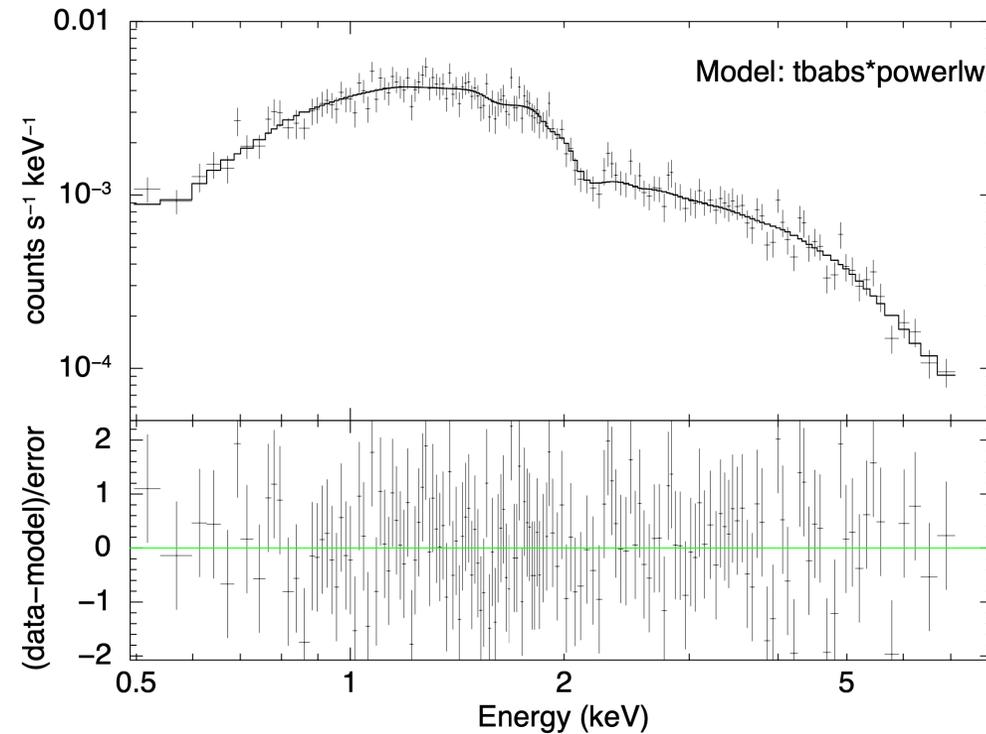$\Gamma \sim 1.6$; $L_x \sim 7 \times 10^{36}$ erg/s

The first extragalactic ultra-compact X-ray binary: A candidate black hole-white dwarf system

Qian-Qi Ma,[1,6] Jiachang Zhang,[2,3,6] Wei-Min Gu,[1,*] Zhiyuan Li,[2,3,*] Shan-Shan Weng,[4] and Tong Bao[5]

*Correspondence: guwm@xmu.edu.cn (W.-M.G.); lizy@nju.edu.cn (Z.L.)

(3) An UCXB system in M31

(Zhang, Bao, Li., 2024)
(Ma,Q, Zhang J, et al. 2025)

GRAPHICAL ABSTRACT

PUBLIC SUMMARY

- M31 UCXB-1 is the first extragalactic ultra-compact X-ray binary (UCXB) candidate.

- M31 UCXB-1 is in excellent agreement with the black hole/neutron star-white dwarf system.

- The primary in M31 UCXB-1 is more likely to be a black hole than a neutron star.

- This source hosts the shortest orbital period and the most massive white dwarf among the known UCXBs.

38

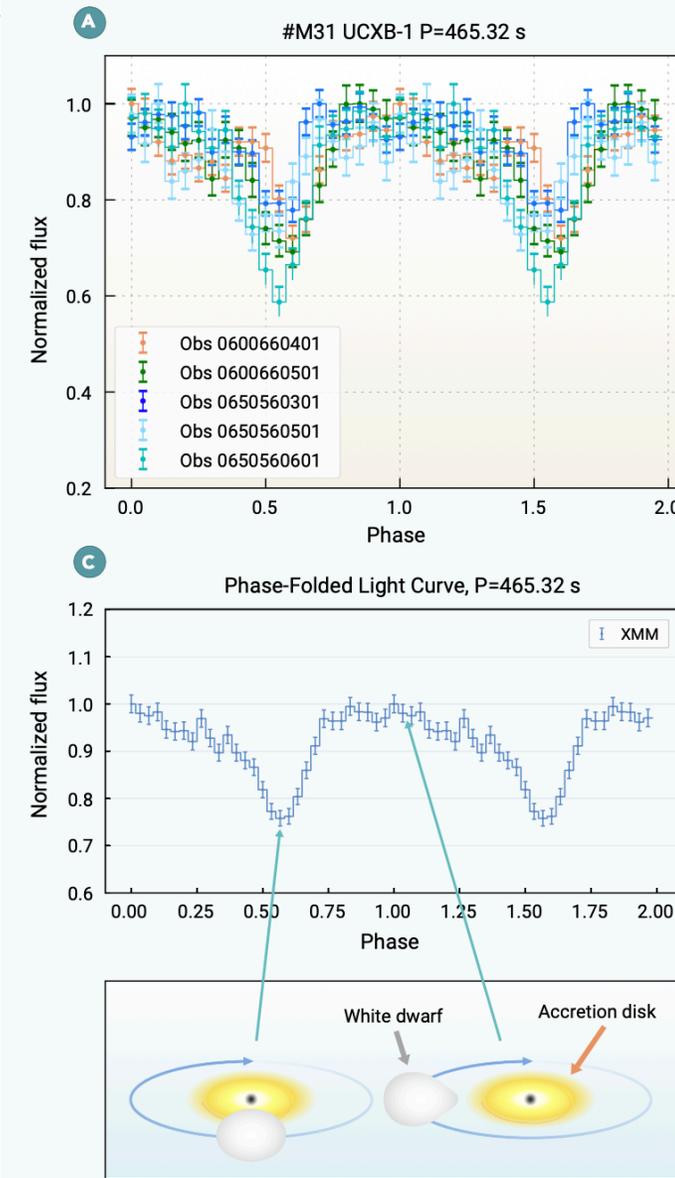# Detection of X-ray emission from a bright long-period radio transient

Ziteng Wang[1✉], Nanda Rea[2,3], Tong Bao[4], David L. Kaplan[5], Emil Lenc[6], Zorawar Wadiasingh[7,8,9], Jeremy Hare[9,10,11], Andrew Zic[6,12], Akash Anumarlapudi[5], Apurba Bera[1], Paz Beniamini[13,14,15], A. J. Cooper[16], Tracy E. Clarke[17], Adam T. Deller[12,18], J. R. Dawson[6,19], Marcin Glowacki[1,20,21], Natasha Hurley-Walker[1], S. J. McSweeney[1], Emil J. Polisensky[17], Wendy M. Peters[17], George Younes[10,22], Keith W. Bannister[6,23], Manisha Caleb[12,23], Kristen C. Dage[1], Clancy W. James[1], Mansi M. Kasliwal[24], Viraj Karambelkar[24], Marcus E. Lower[6,18], Kaya Mori[25], Stella Koch Ocker[24,26], Miguel Pérez-Torres[27,28], Hao Qiu[29], Kovi Rose[6,23], Ryan M. Shannon[18], Rhianna Taub[30], Fayin Wang[31], Yuanming Wang[12,18], Zhenyin Zhao[31], N. D. Ramesh Bhat[1], Dougal Dobie[12,23], Laura N. Driessen[23], Tara Murphy[12,23], Akhil Jaini[18], Xinping Deng[6,32], Joscha N. Jahns-Schindler[18], Y. W. Joshua Lee[6,12,23], Joshua Pritchard[6], John Tuthill[6] & Nithyanandan Thyagarajan[33]

~43 mins

https://www.media.inaf.it/2025/06/05/due-minuti-ogni-44/
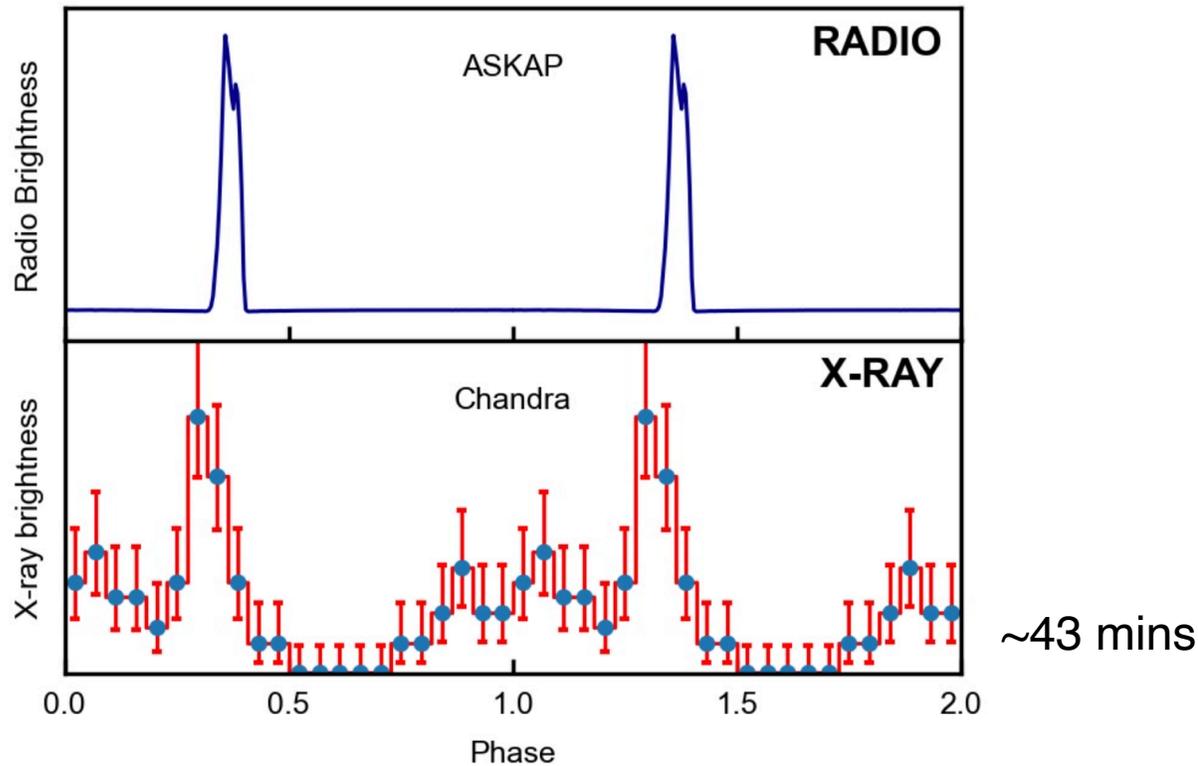
(4) The first detection of X-ray emission from a bright long-period radio transient

LPT is a type of radio transient exhibiting periodic radio emission thousands of times longer than radio pulsars.
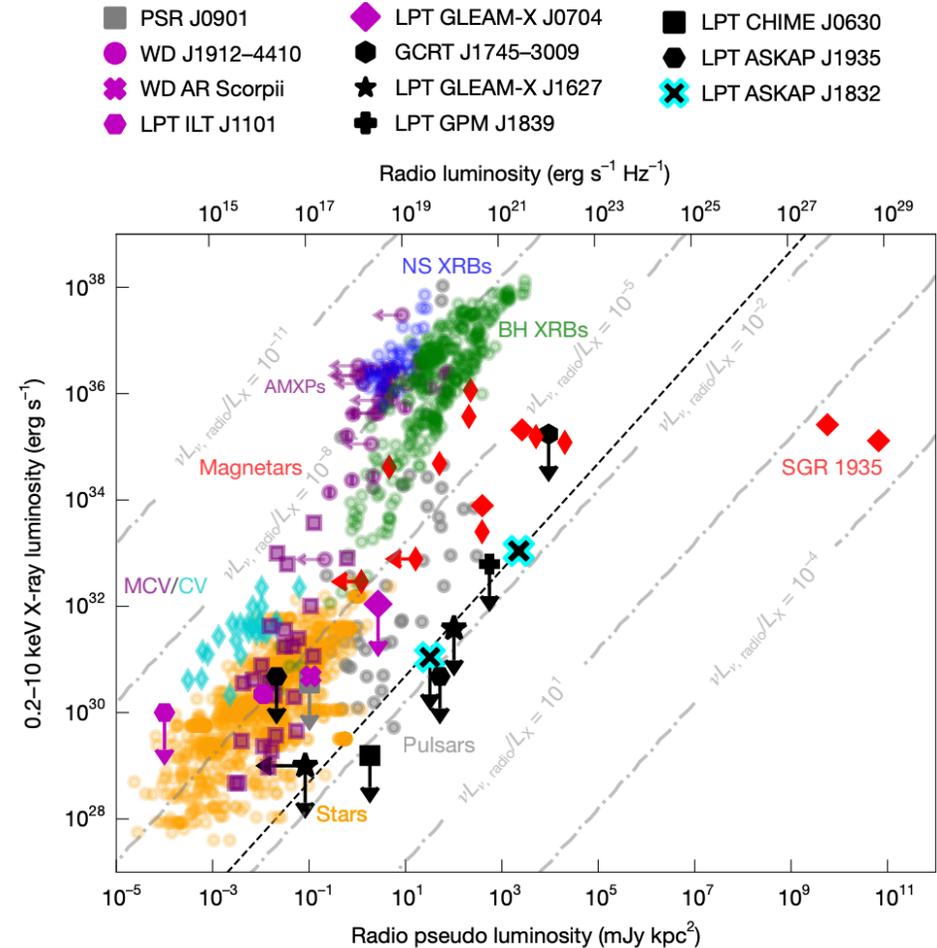
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3. **Bao T.*,** & Li Z. 2022, MNRAS, 509, 3504, "Searching for quasi-periodic oscillations in active galactic nuclei of the Chandra Deep Field South"

4. **Bao T.*,** & Li Z. 2020, MNRAS, 498, 3513, "Periodic X-ray sources in the Galactic bulge: application of the Gregory-Loredo algorithm"

5. Zhang J., **Bao T.*,** Li Z., 2024, MNRAS, 530, 2096, "A Chandra Search for Periodic X-ray Sources in the Bulge of M31"

6. Mondal S.*, Ponti, G., **Bao, T.**, et al., 2024, A&A, 686, A125

7. Ma. Q, Zhang. J, Gu*. W, Li, Z, Weng. S, **Bao, T.,** 2025, The Innovation, 101181

8. Wang Z.*, Rea N, **Bao T.,** et al., 2025, Nature, 642, 583

Thank you!