INAF
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The CATS @ BAR WR/BH X-ray binaries

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+

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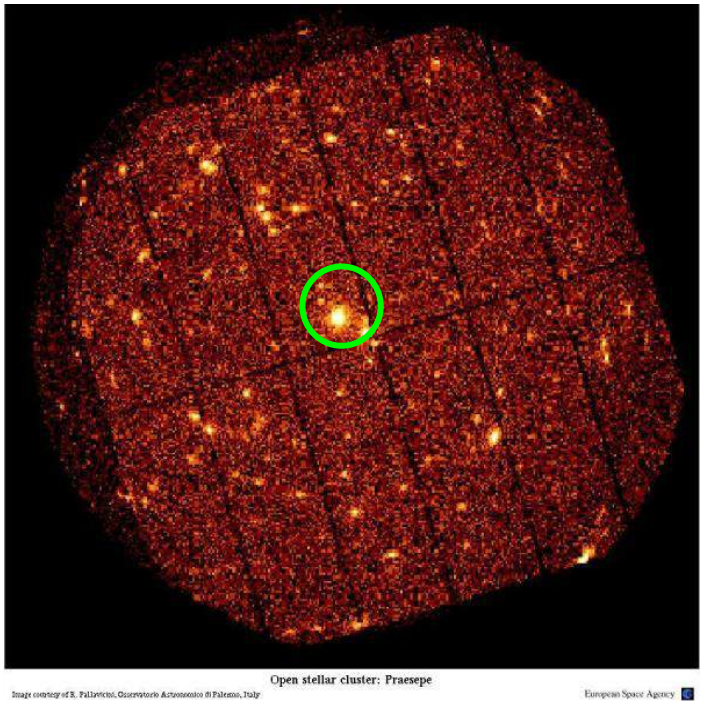
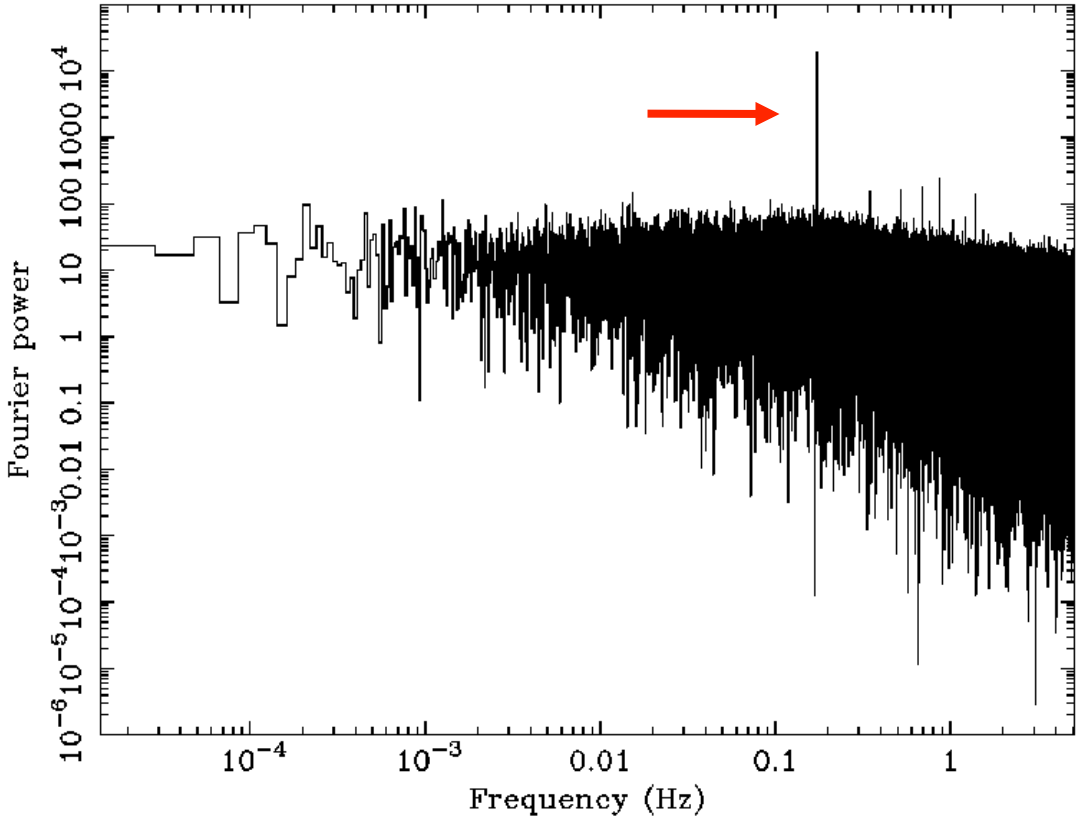
X-ray pulsators

Periodic signals are key to understand the nature of a source!

In general, modulation is discovered through timing analysis of the source targeted by an observation





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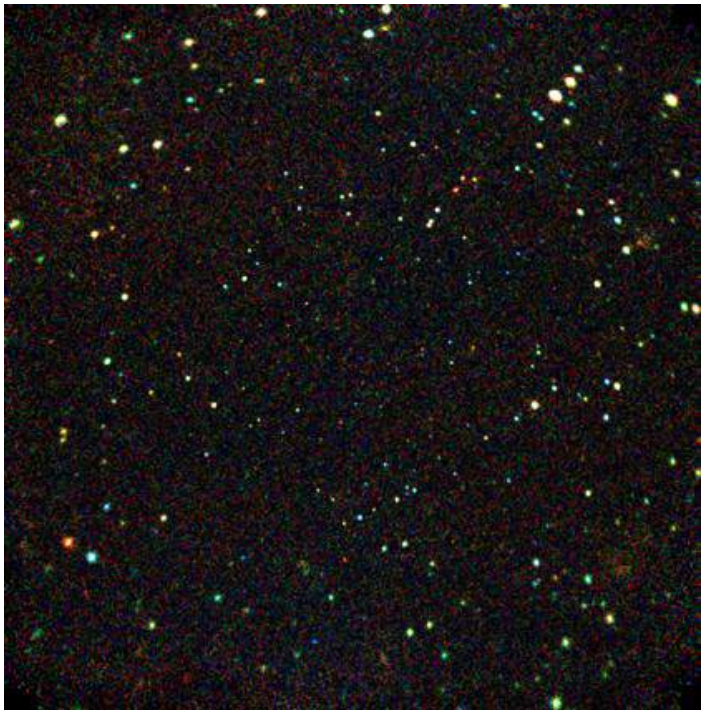


CXO DFS - CXC/NASA/Giacconi

Faint X-ray sources can remain unidentified for years

~50,000 objects from past missions

>500,000 with XMM, Chandra, Swift

- Different populations of X-ray sources
- Interesting sources might lurk among them

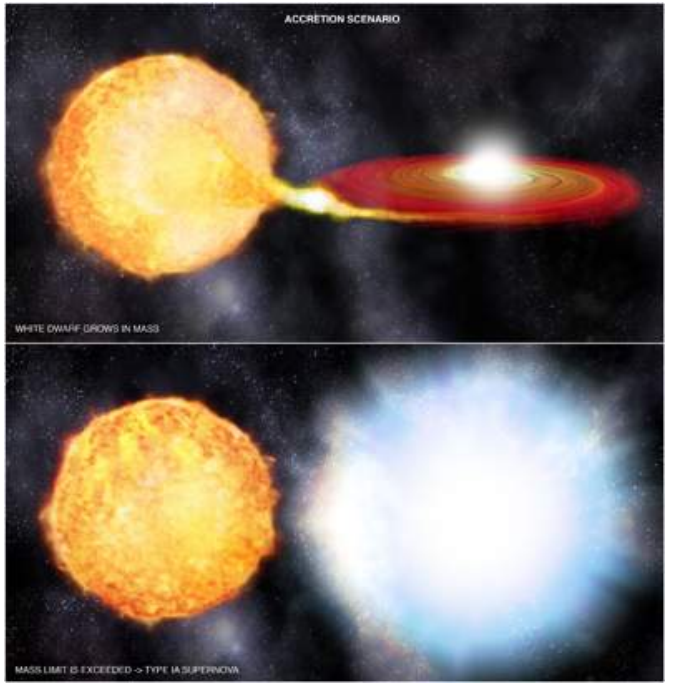
Enormous discovery space in serendipitous sources

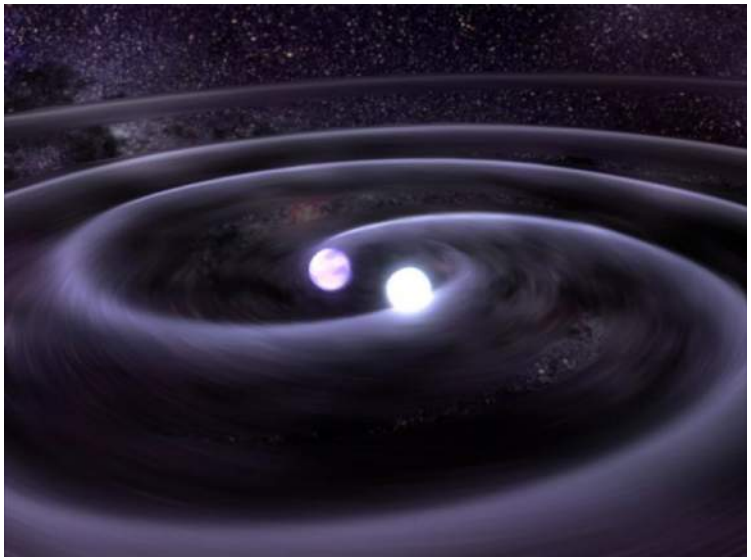
Highlights from previous searches

• EXOSAT: 4U 0142+614, prototype of the AXP class (I+94)

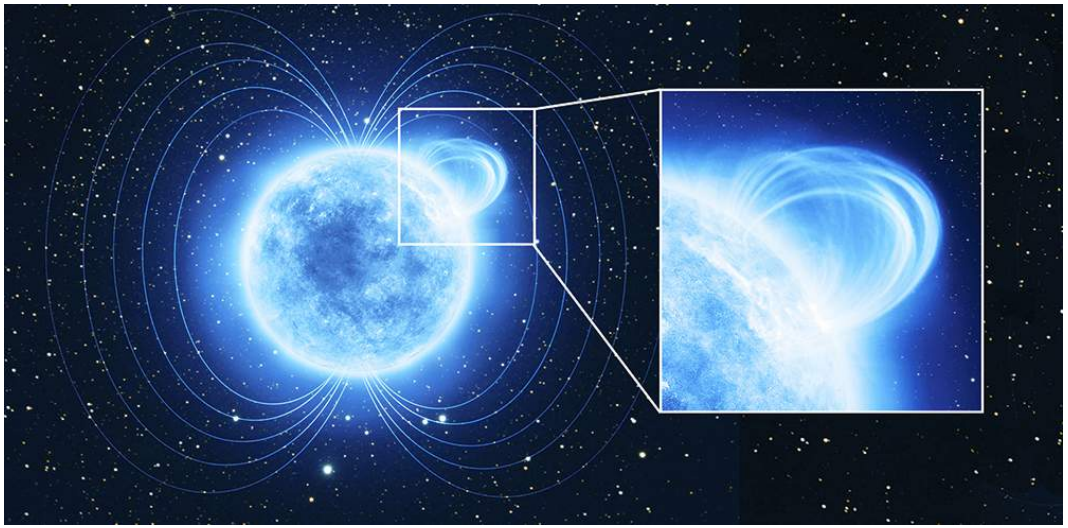
• ROSAT PSPC: HD 49798, a very massive WD in a post common envelope phase (I+96, Mereghetti+09)

• ROSAT HRI: the 2-WD system HM Cnc (I+99,02; E+14), the binary with the shortest orbital period known: 5.4 min!





← GSFC/D. Berry ESA/A. Tiengo ↓ NASA/CXC/M. Weiss ↑



Our recent results

1RXS J225352.8+624354
(E+13, MNRAS 433, 2028)

X Persei-like low-luminosity persistent Be/XRB in a wide and circular orbit

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Be/XRBs in the SMC, a whole type I burst fortuitously recorded in 17 obs

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A 6.4-h part-time, borderline ULX, most likely a WR + BH system

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An HMXB with off-states due to sudden transitions to ineffective accretion regime

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The fourth totally eclipsing intermediate polar discovered in ~60 yr

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New polars and another ULX / WR+BH candidate in the Circinus region

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1st X-ray NS/psr in M31, likely an intermediate XRB akin to Her X-1

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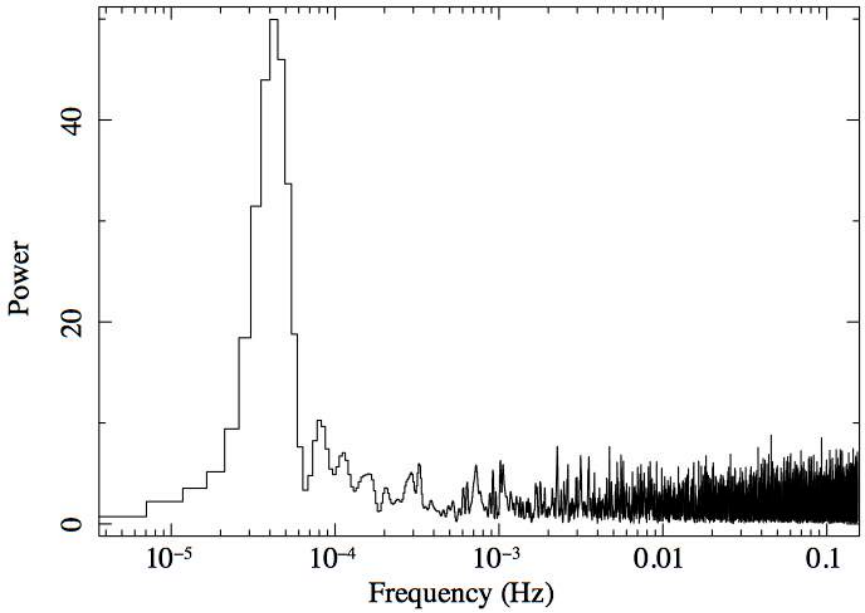
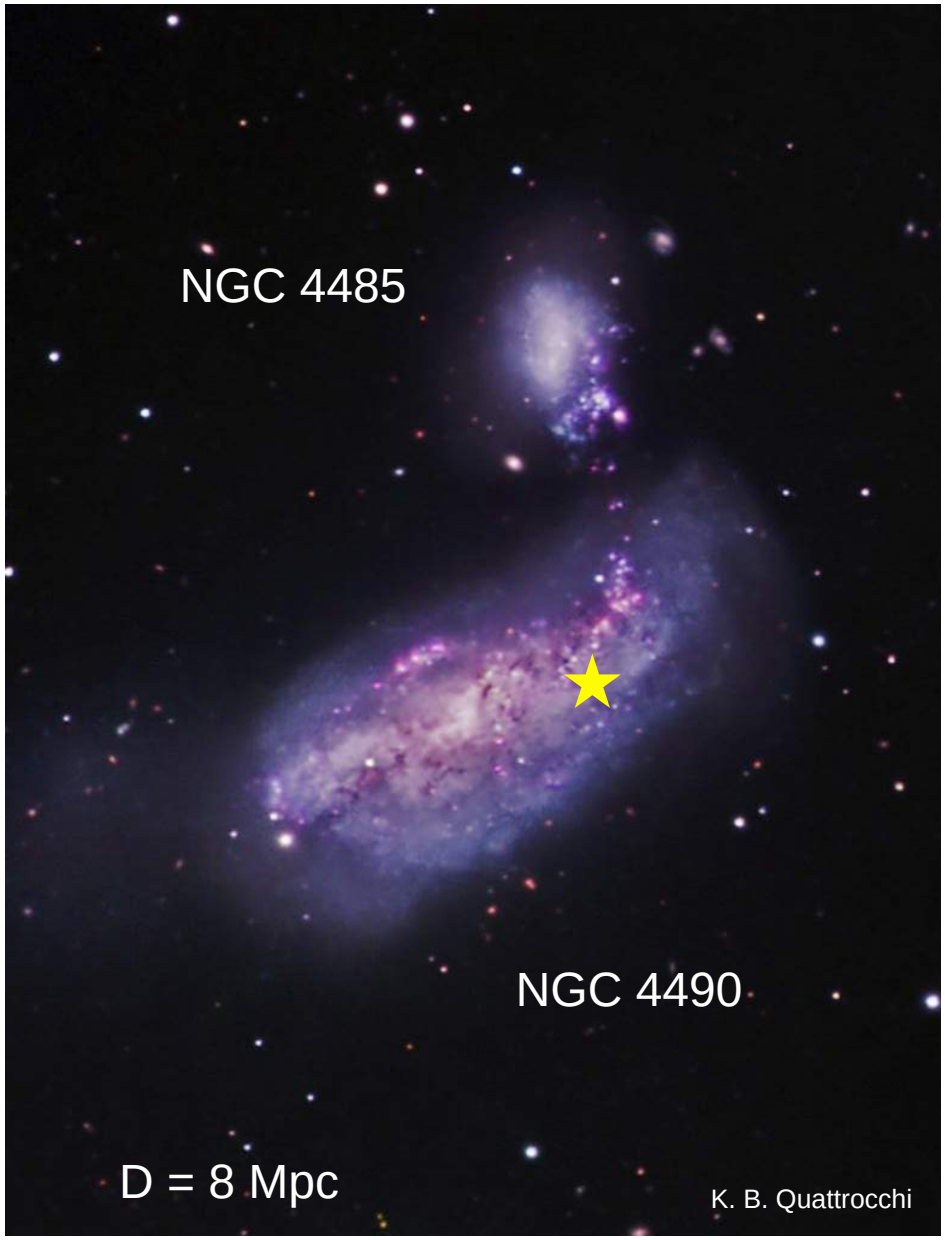


- Multiple CXO observations
- Modulation at P = (6.4 ± 0.1) h
  (confirmed also by XMM)
- Pulsed fraction: ~90 per cent

(First observed by Roberts et al. 2002)



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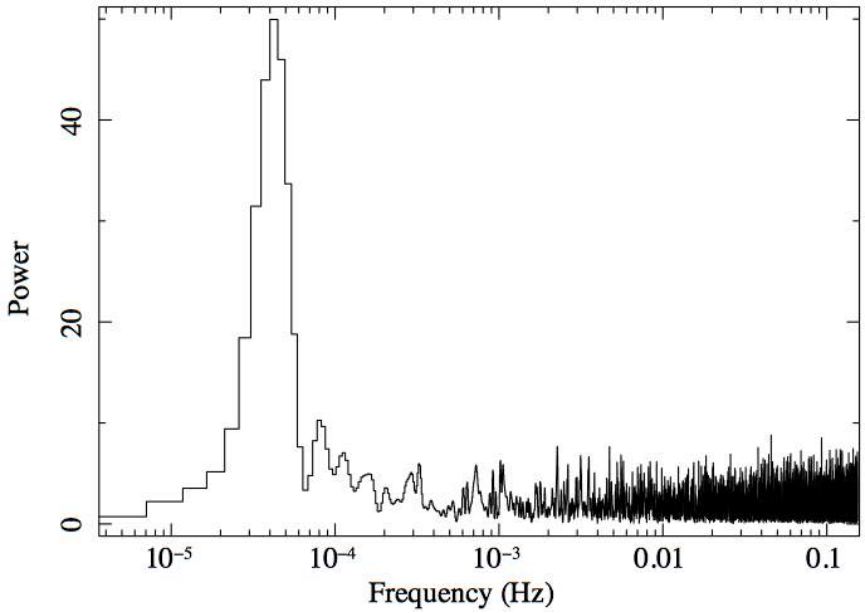

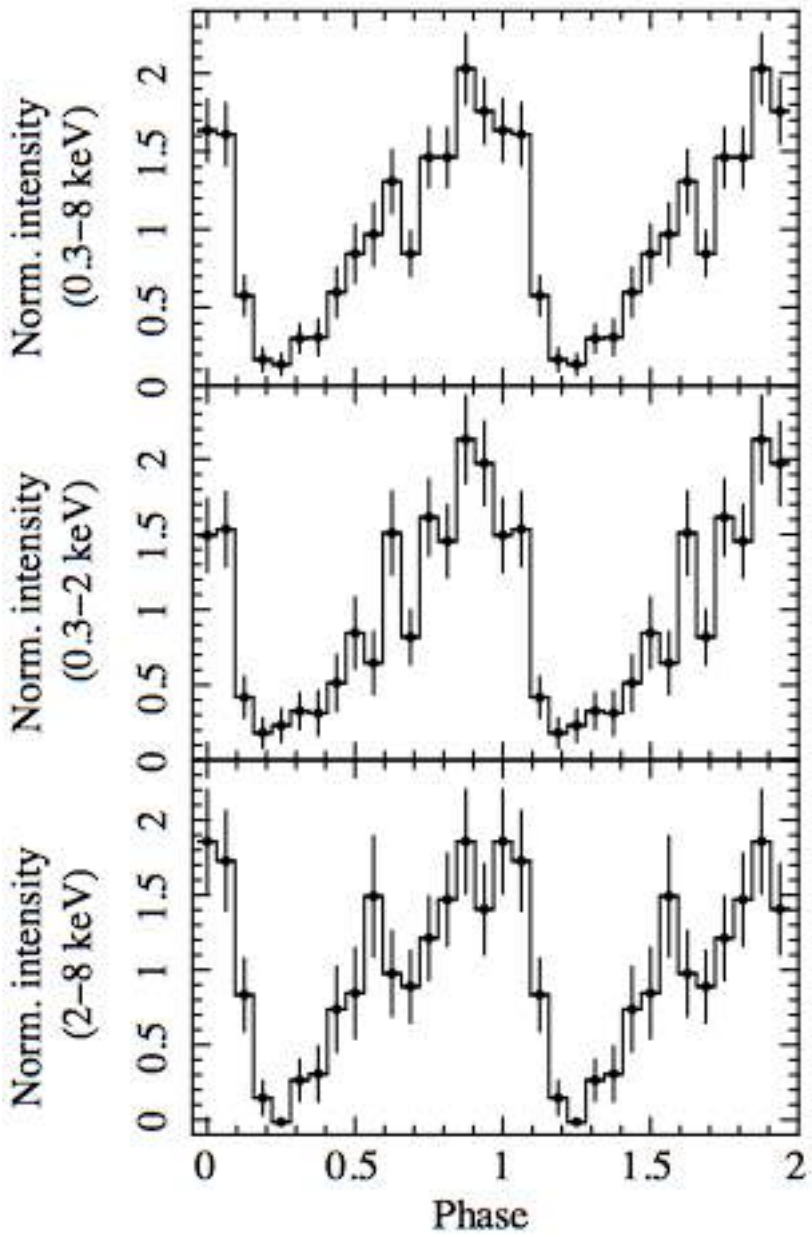

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A 6.4 hr BH binary in NGC 4490

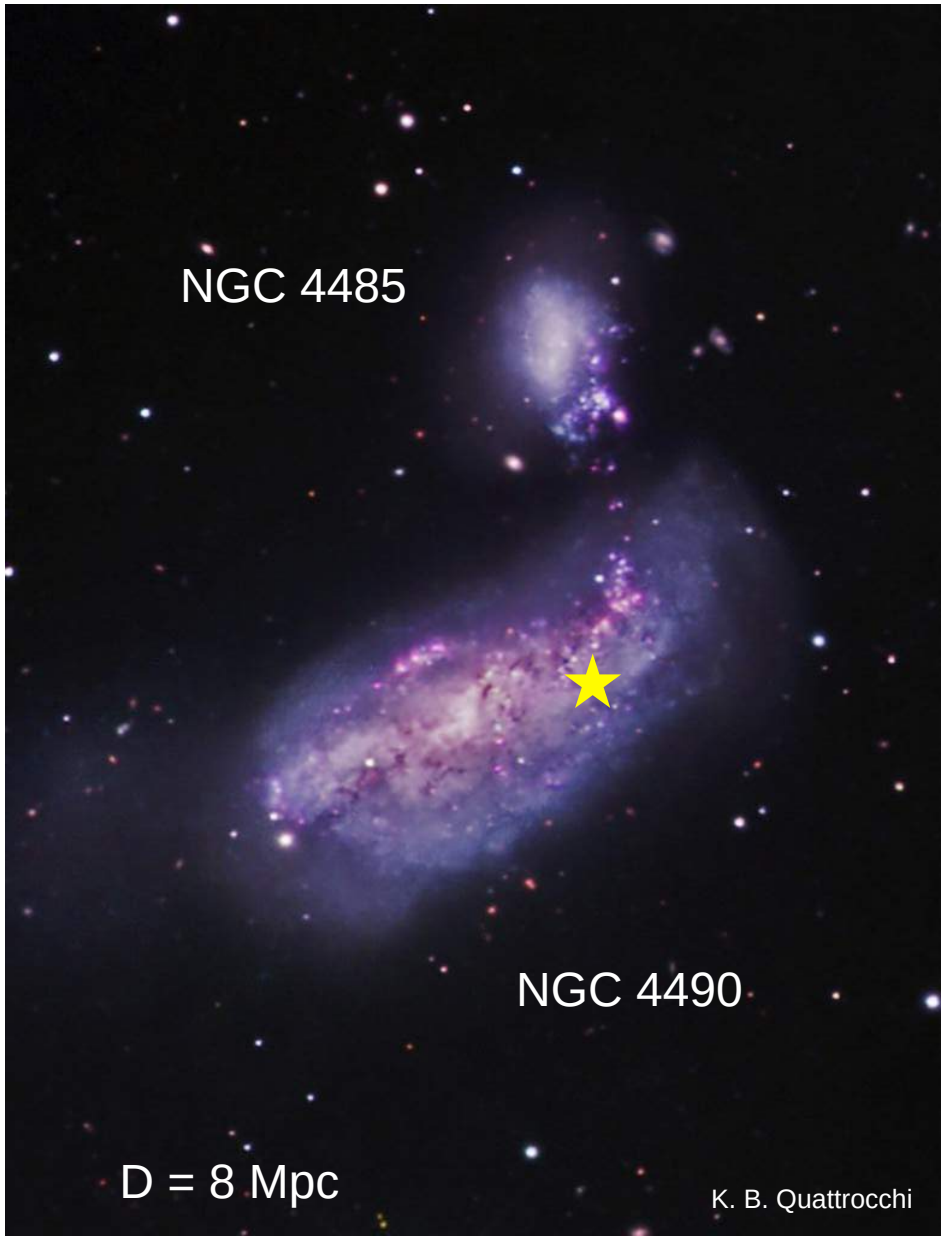
NGC 4490 is a spiral galaxy interacting with the irregular NGC 4485

P = 6.4 h, 90% PF

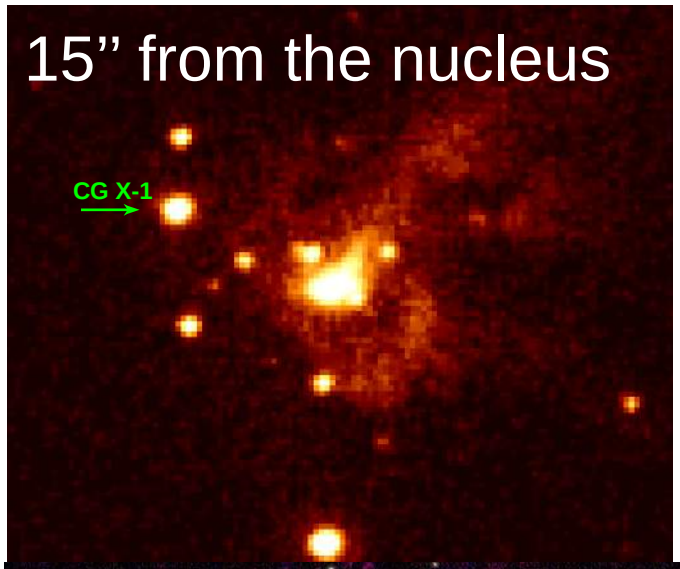
~2.5 kpc from NGC 4490's nucleus

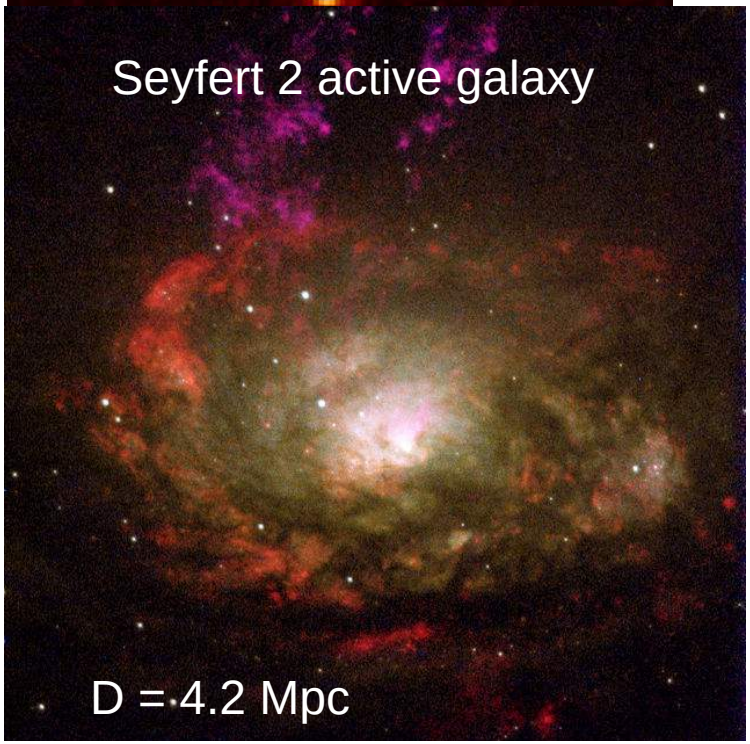
L from ~0.2 to 2×10^{39} erg s^{-1}

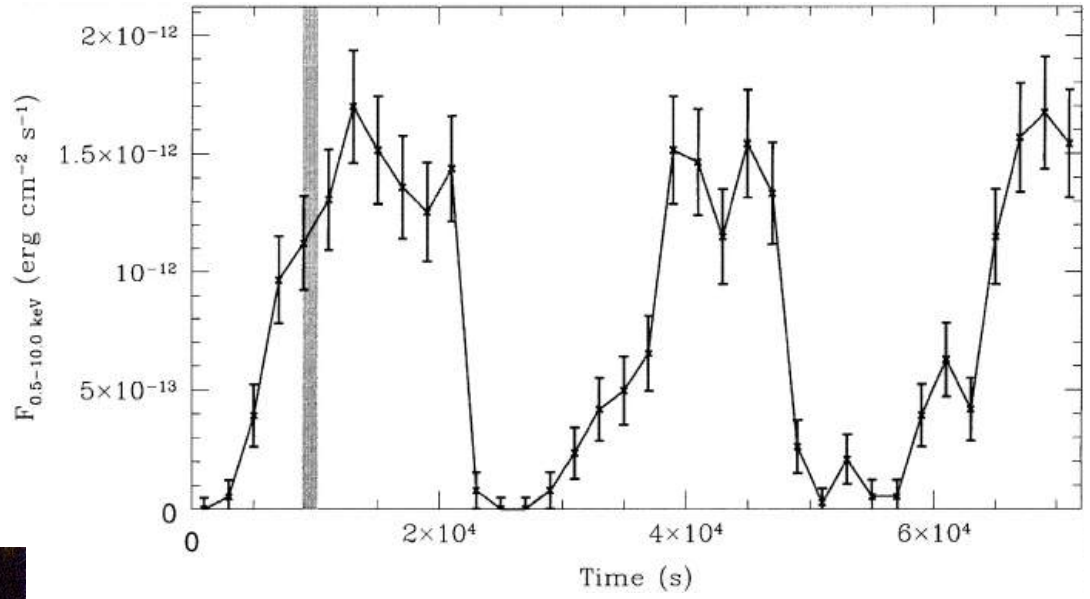
$L > L_E$ for a 5–10 $M_\odot$ object
(similar lower limit from diskbb fit)



Circinus Galaxy X−1







Bauer et al. 2001: **P ~ 7.2 h**

$L_X = (1–5) \times 10^{40}$ erg s^{-1}

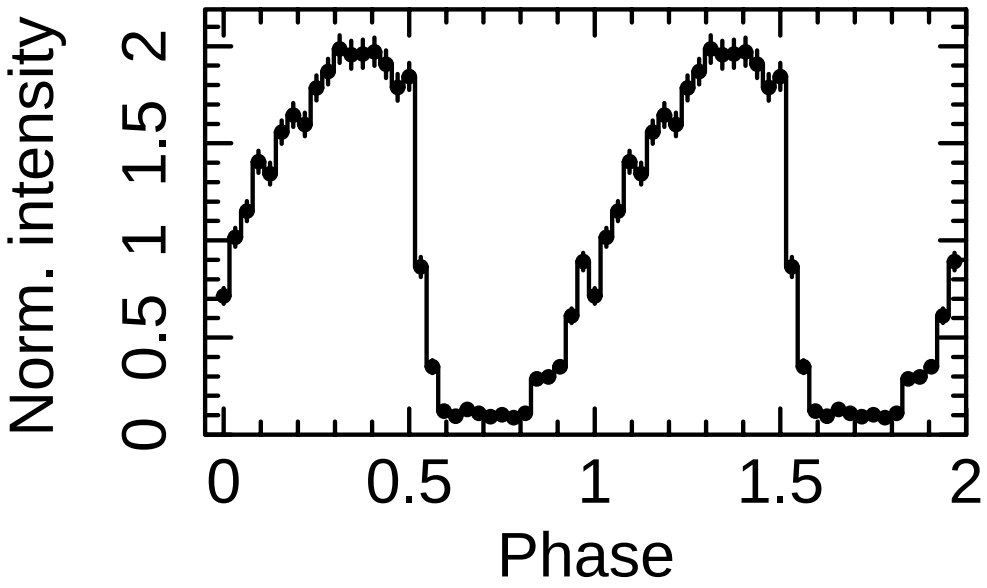
See Weisskopk+2004

Strictly speaking, not a CATS@BAR source, we sort of bumped into it

NGC 4490's J123030 & CG X−1

P = 6.4 / 7.2 h, ~90% PF

L ~$10^{38/39}$ and $10^{39/40}$ erg s^{-1}



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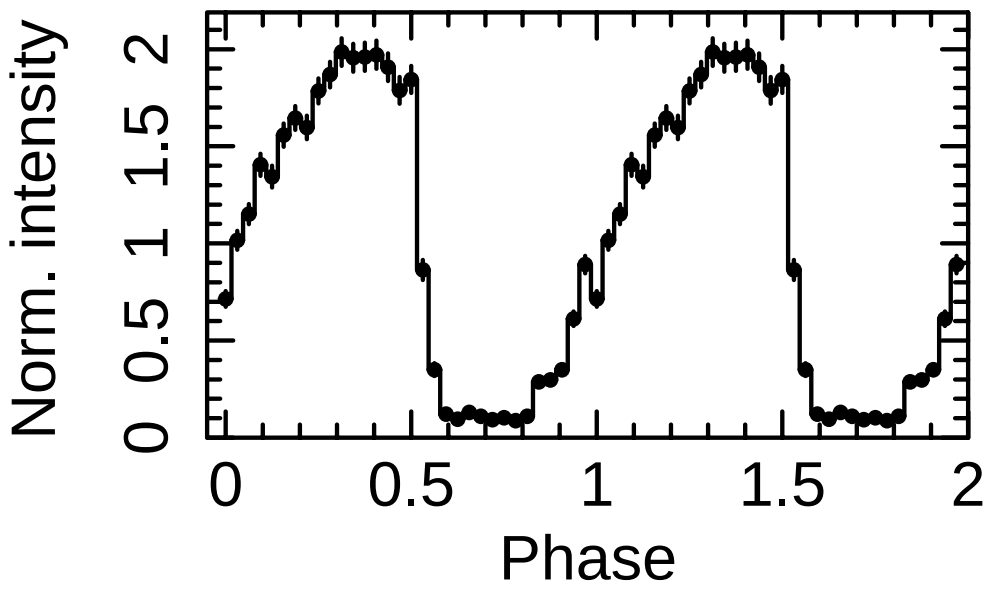

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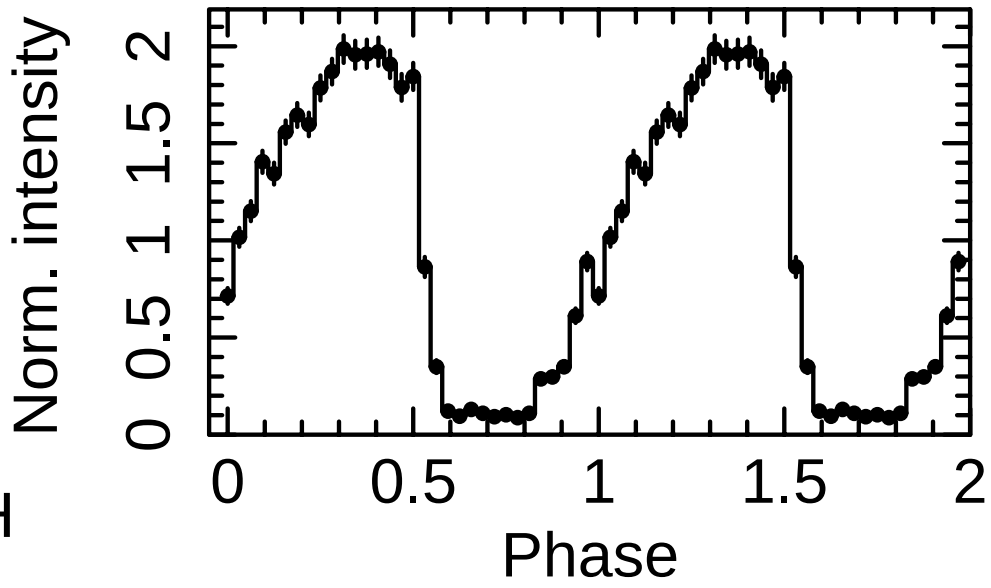
P < 0.03%

no counterparts, nH > Gal. nH



LMXBs:

- Transients;
- Very different pulse profiles!

low-amplitude orbital modulation (if any): sharp eclipse ingresses/egresses (small X-ray emitting regions), dips

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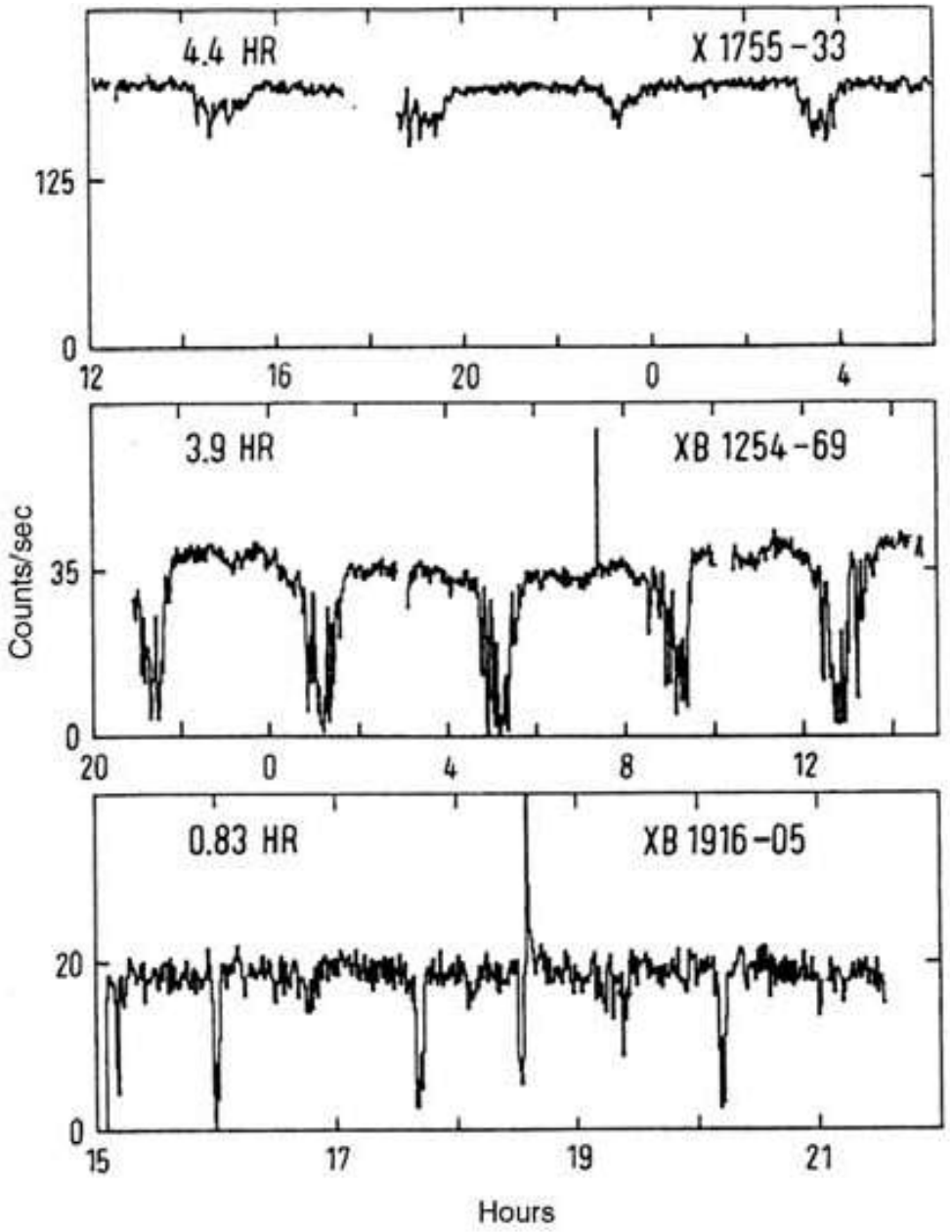

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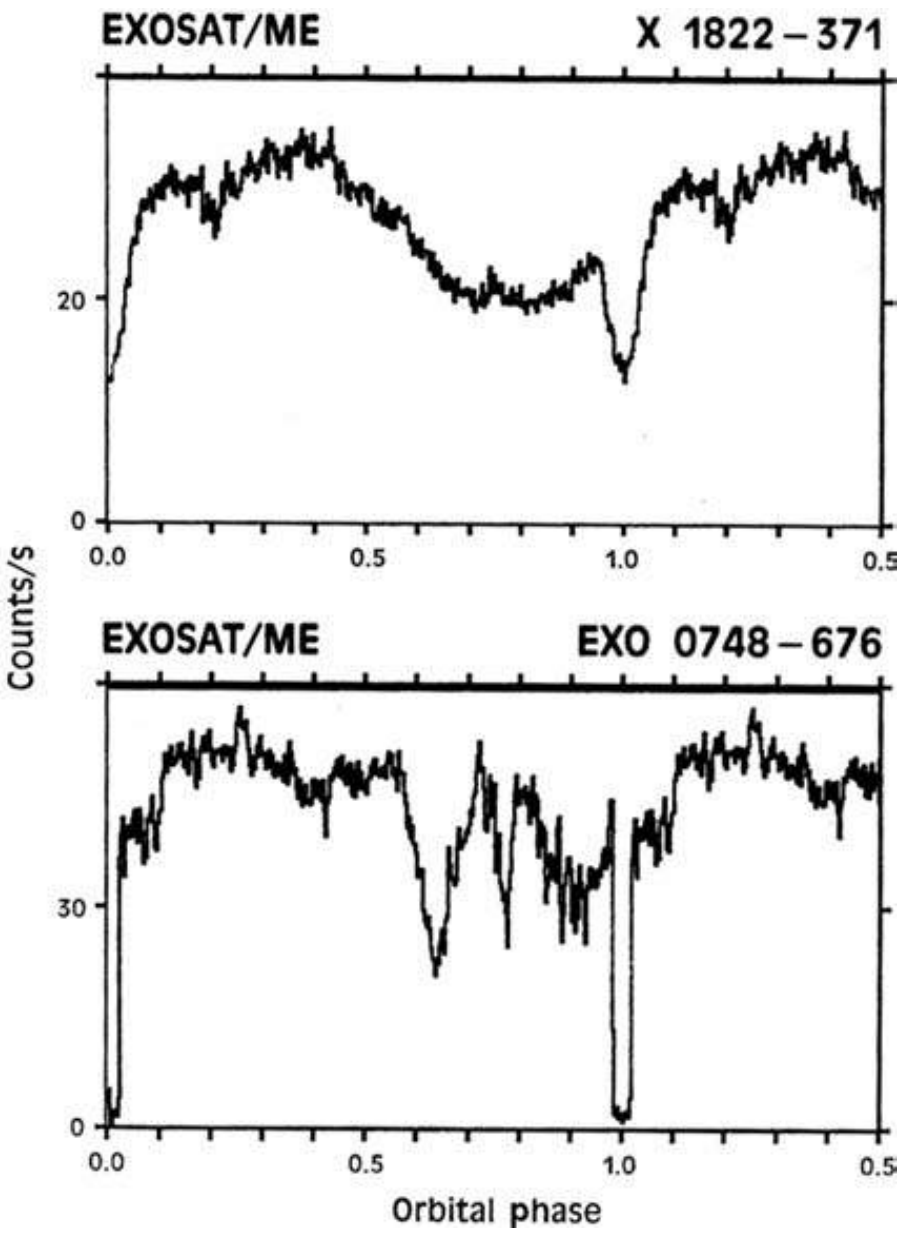

ADC source

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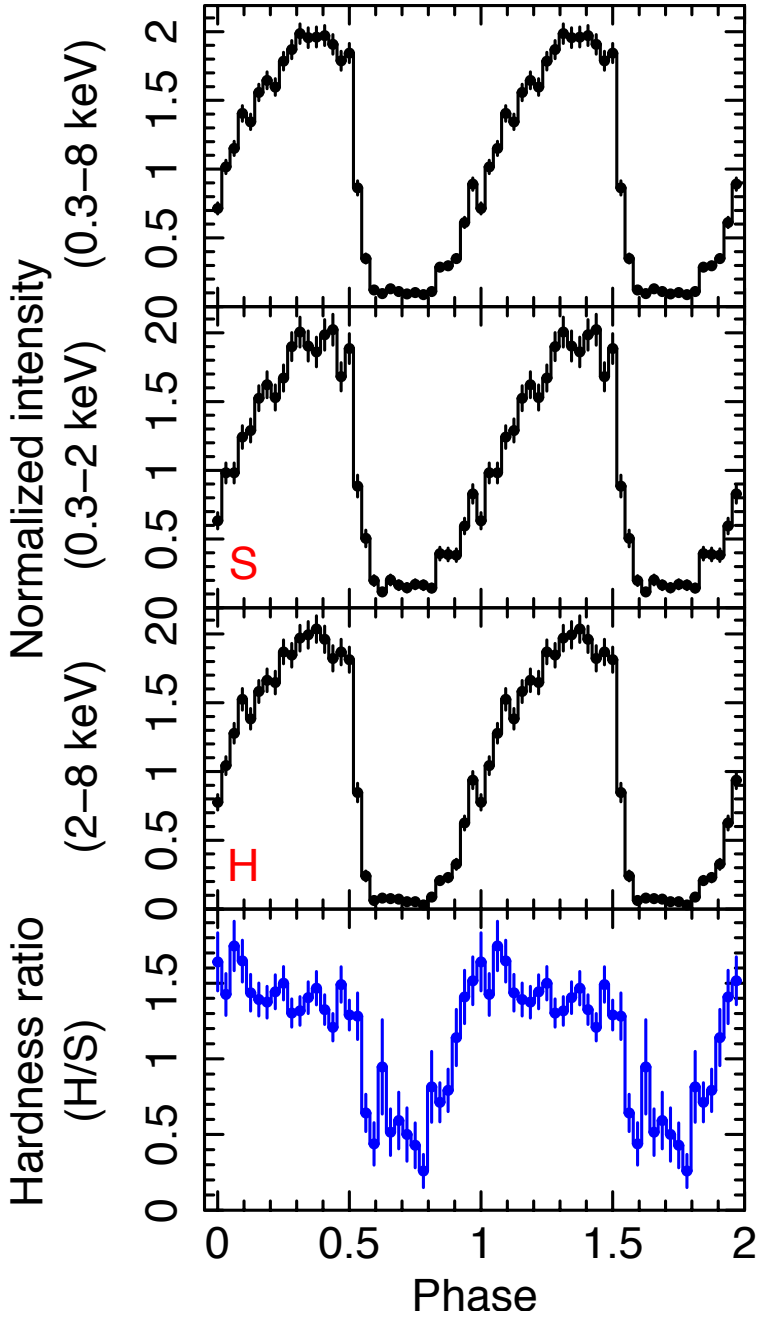

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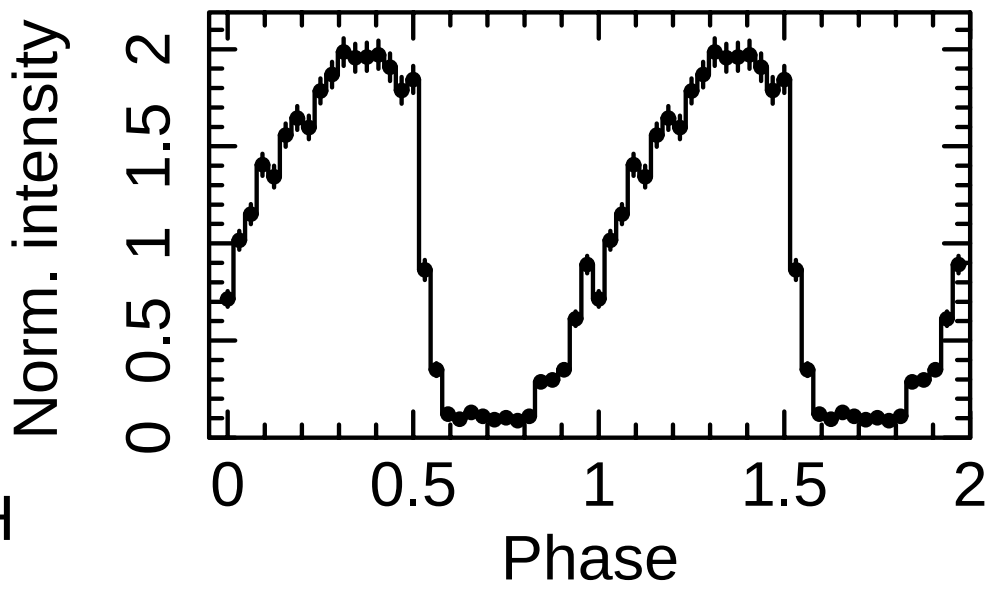

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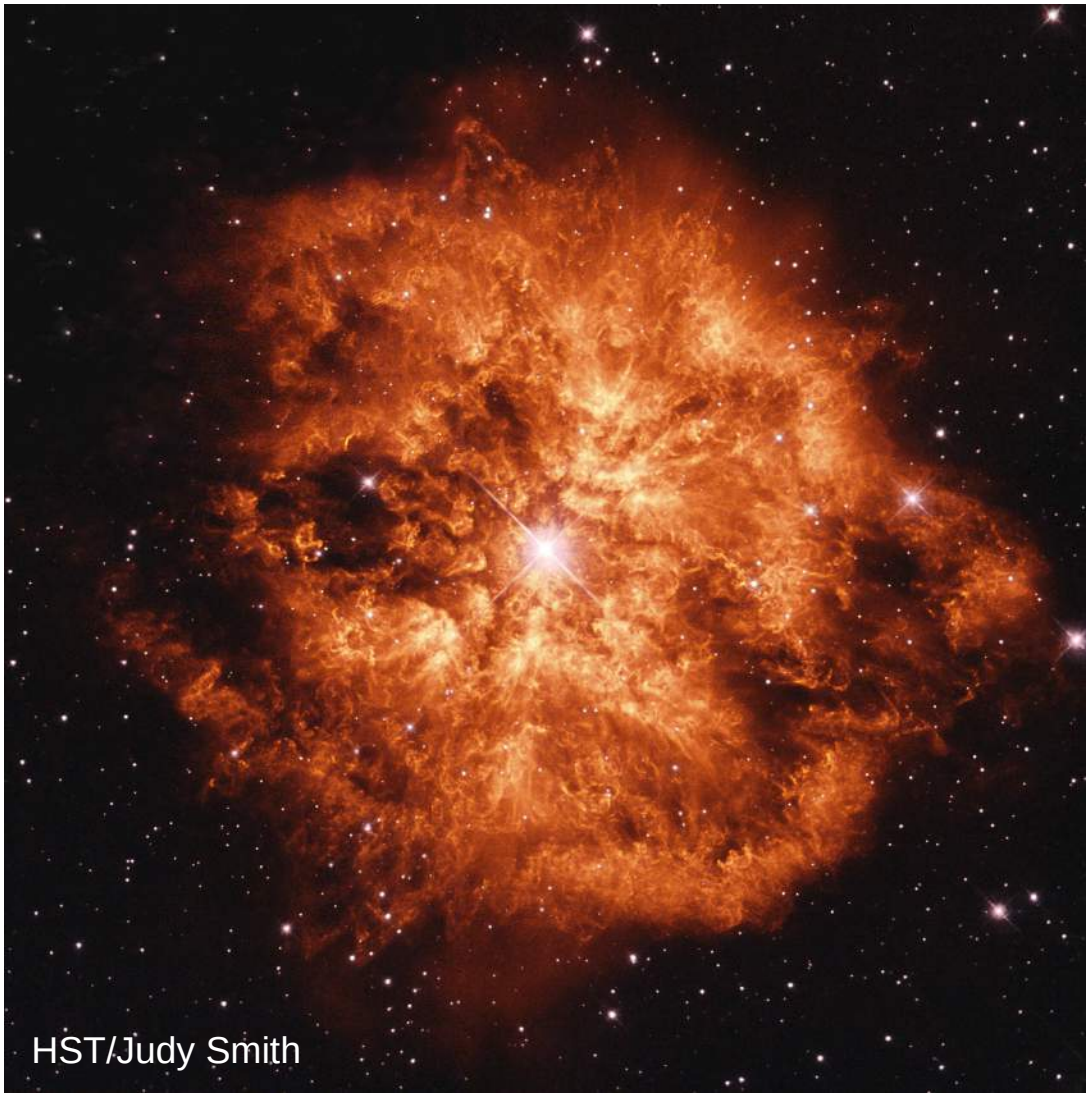
HMXBs:

Possible only with a WR star

Wolf−Rayet stars



- Final phase (prior to core collapse) of massive stars
- H envelope stripped away via stellar wind or close binary evolution, revealing products of CNO (WN) or He burning (WC)
- Strong emission lines, intense ($10^{-5}\ M_{\odot} yr^{-1}$), fast ($\sim(1-3)\times10^{3}$ km s^{-1}) winds
- Compact, $R < 2R_{\odot}$ for $M \sim 20M_{\odot}$

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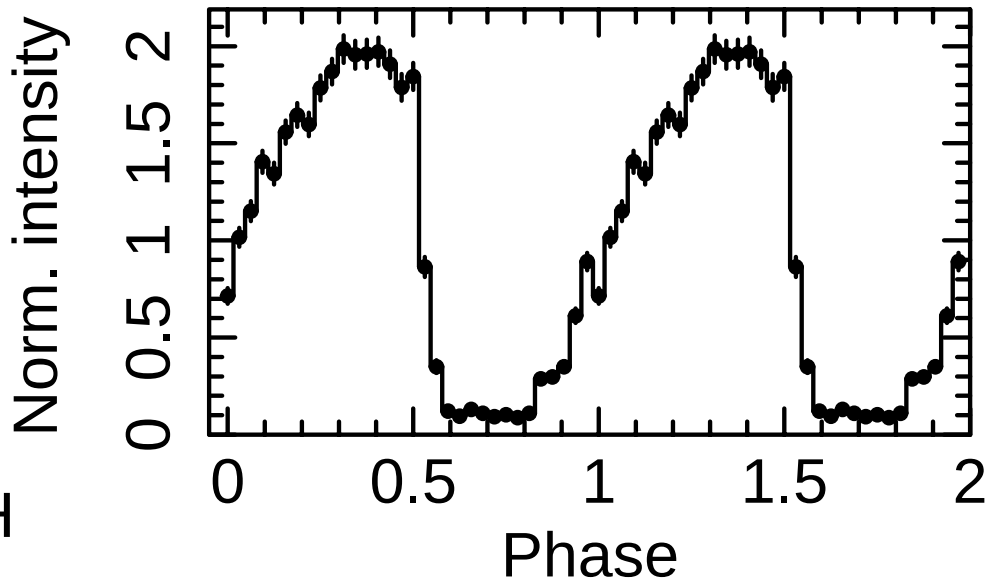

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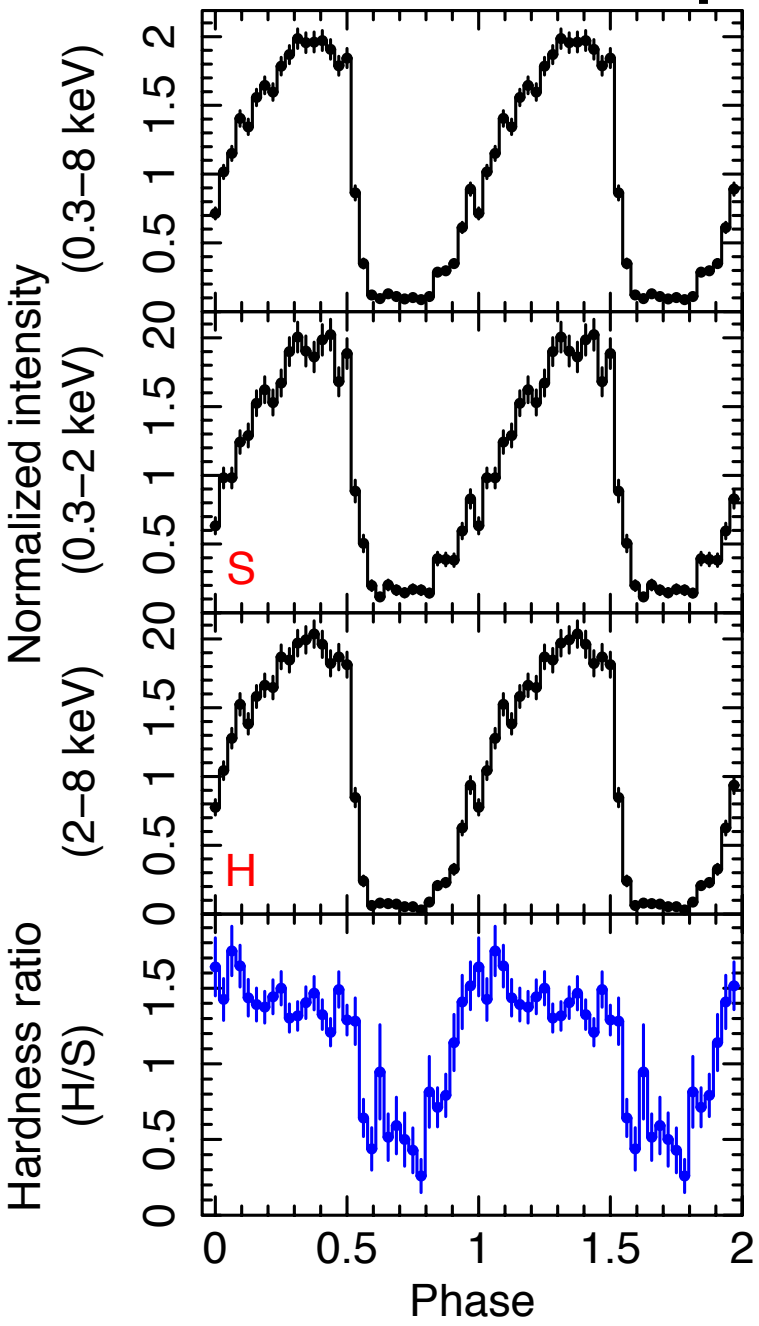
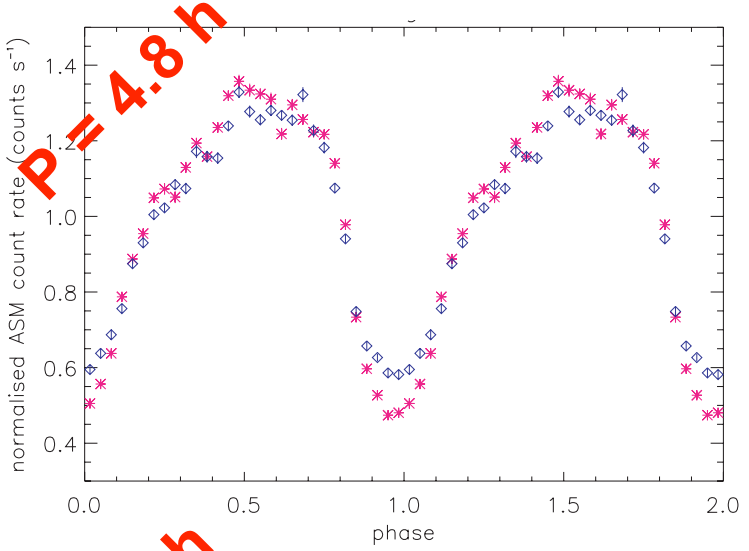
WR + BH

A NS cannot be excluded, L_X~10^{39} maybe 10^{40} erg s^{-1} for the NuSTAR one in M82 (Bachetti+14)

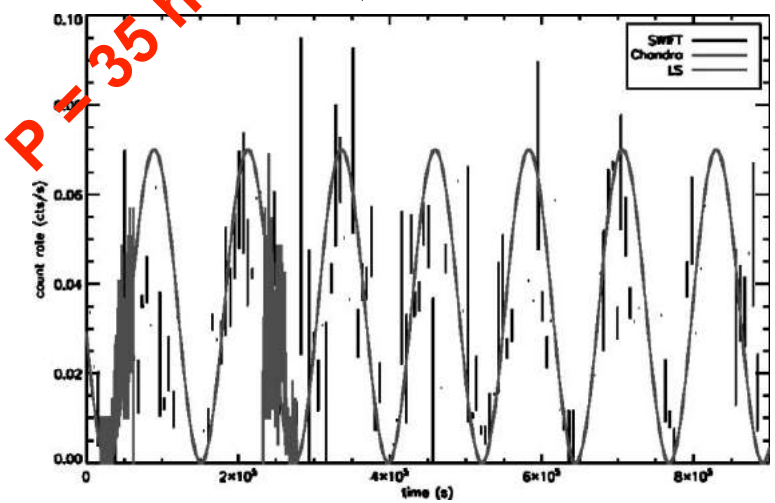
Pulse profile



Carbon copy of the WR/HMXB light curves!

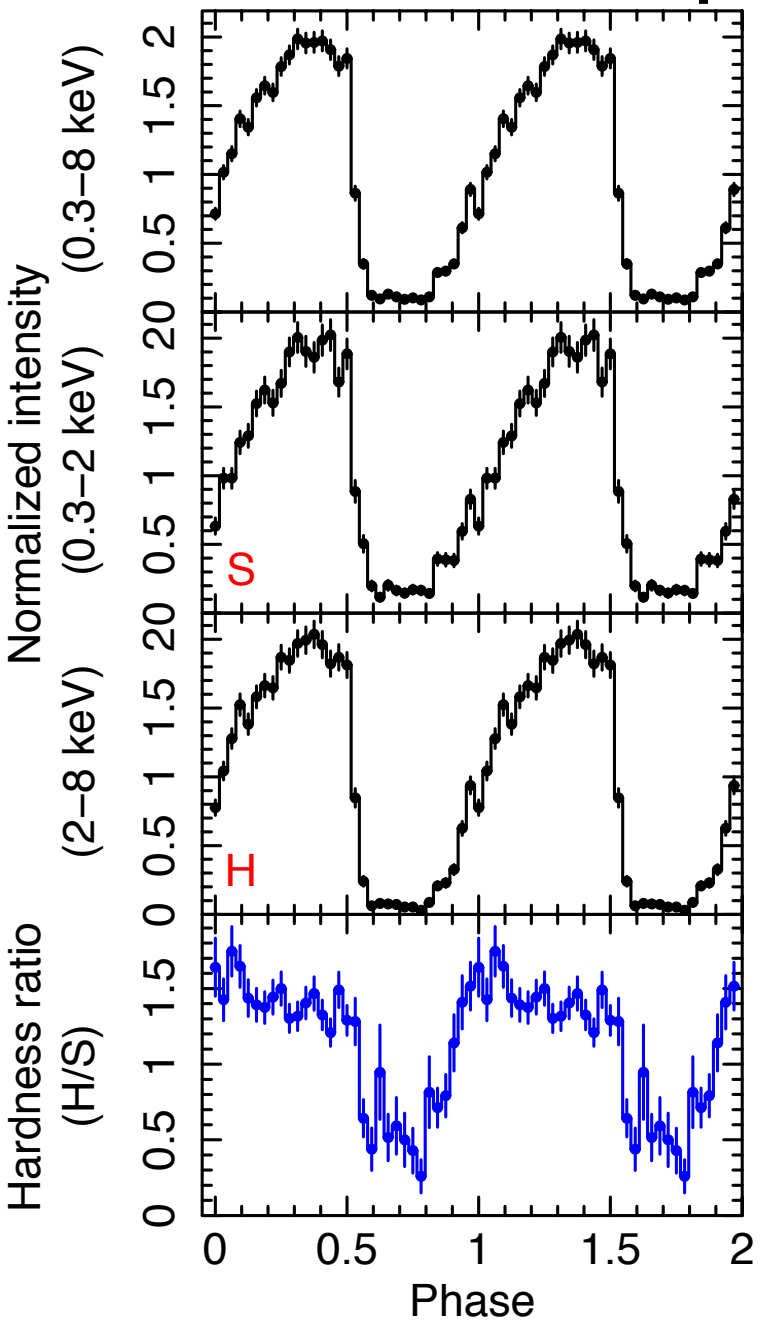


Cyg X−3
Hjalmarsdotter+08



IC10 X−1
Prestwich+07

Pulse profile



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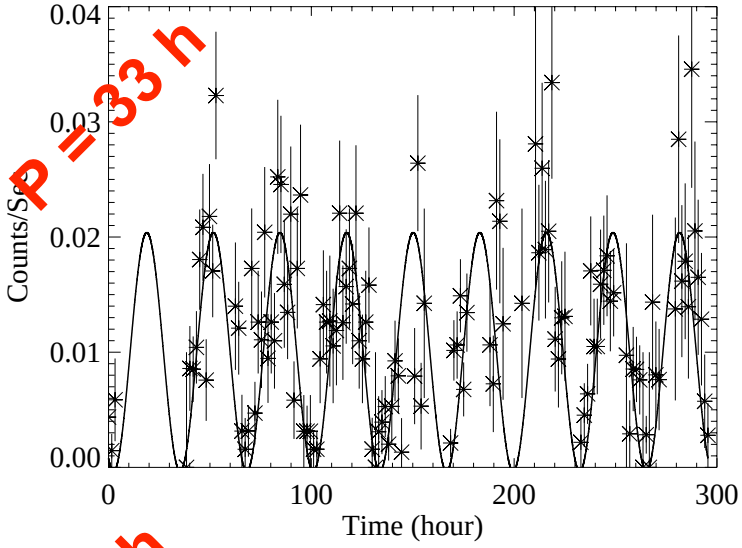
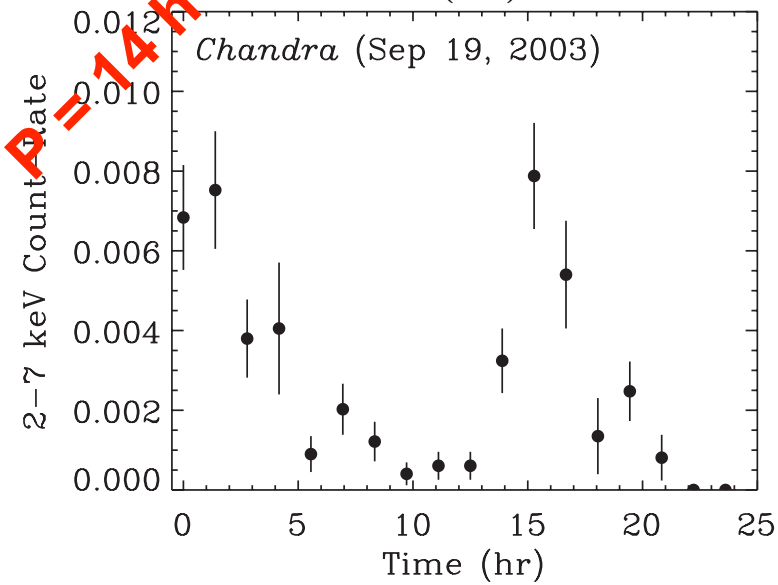
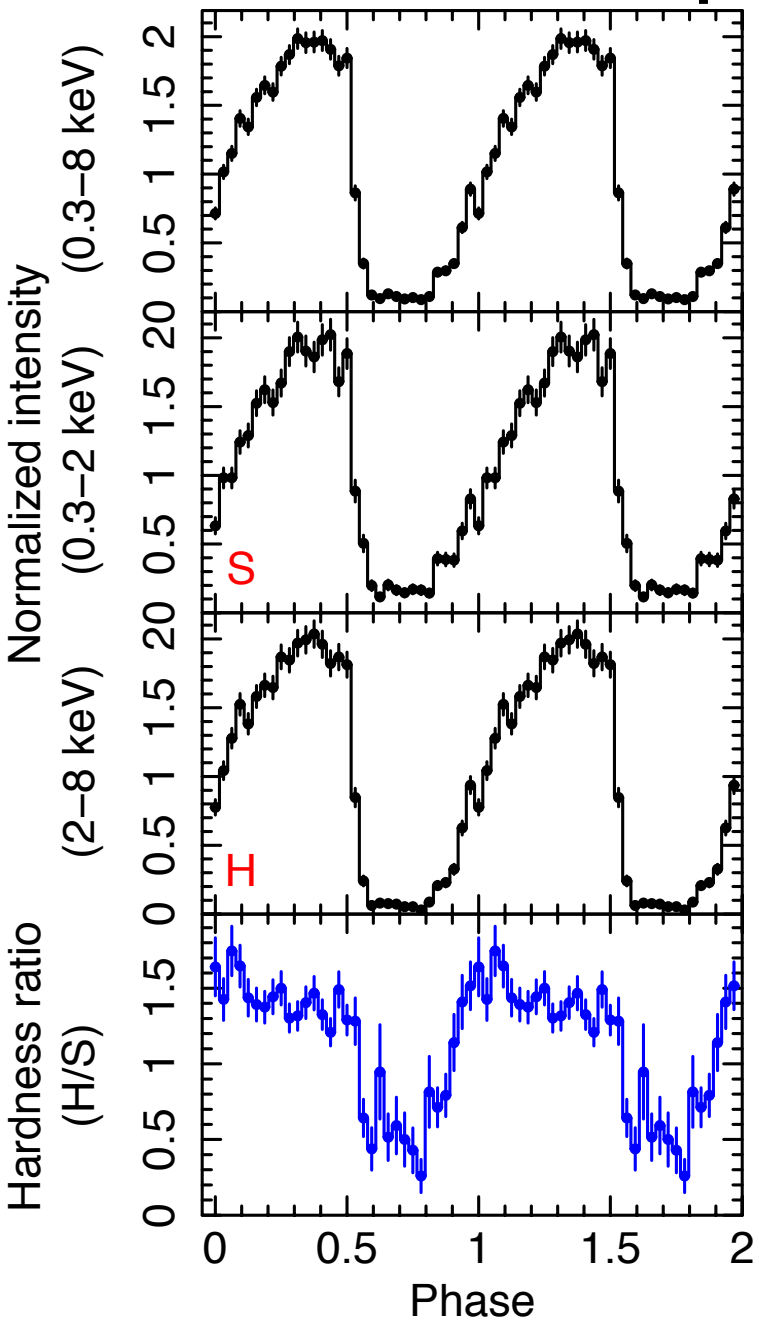


NGC300 X−1
Carpano+07



NGC 253
Maccarone+14

Pulse profile



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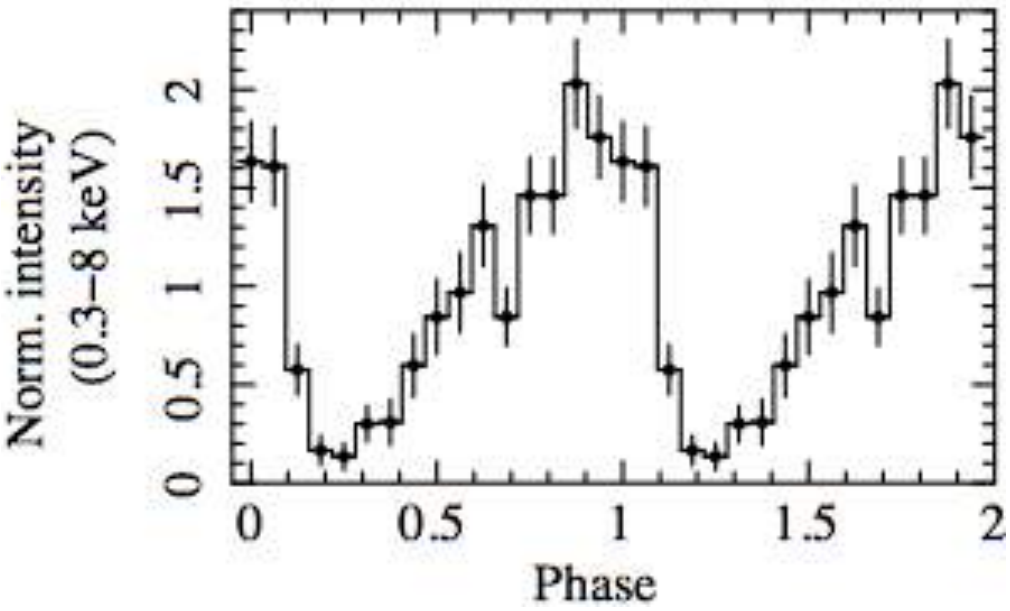
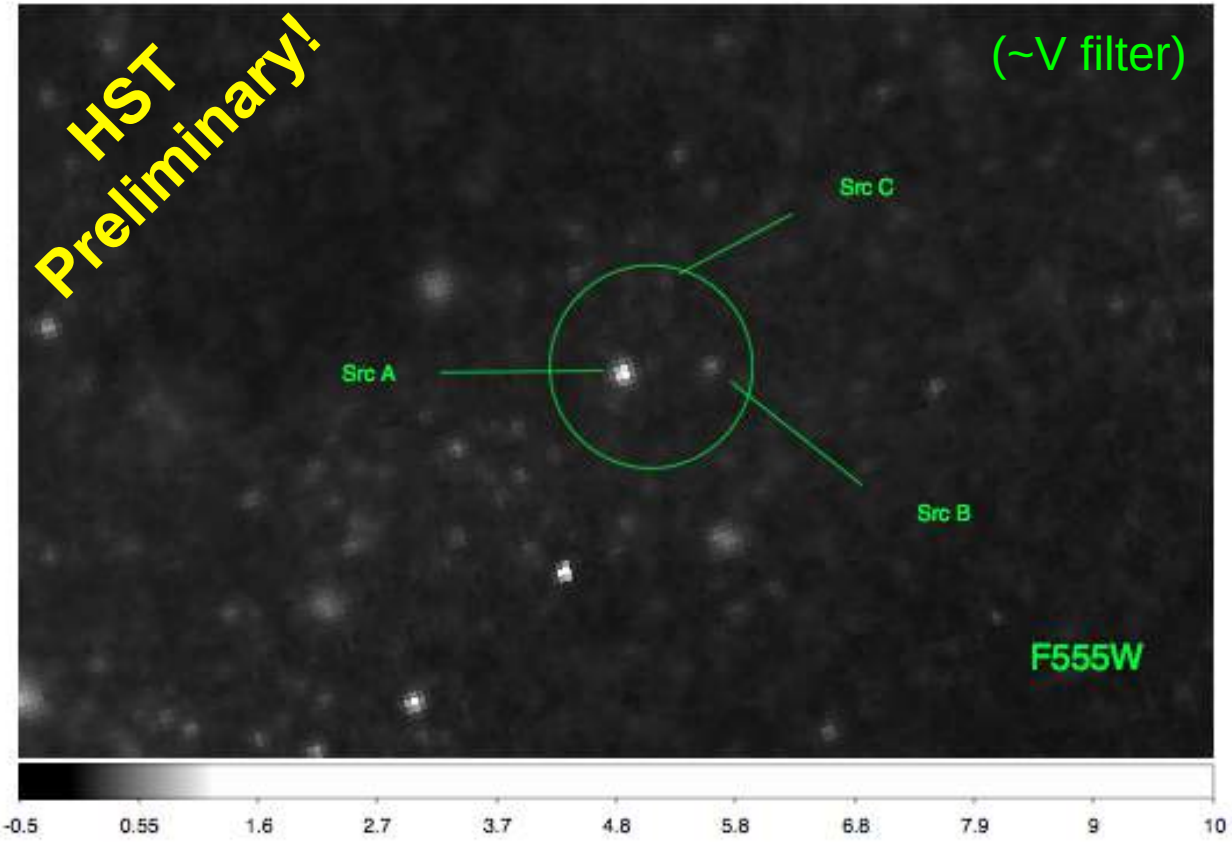


Signature pulse profile produced by absorption and Compton scattering of the X-rays through the WR stellar wind (even for $i \sim 30°$; Zdziarski et al. 2010)

Counterparts

M_V from −2.5 to −7 for WRs

NGC 4490's J123030



3 rather bright and blue objects

A $M_V = -6.4$, $B-V = -0.4$

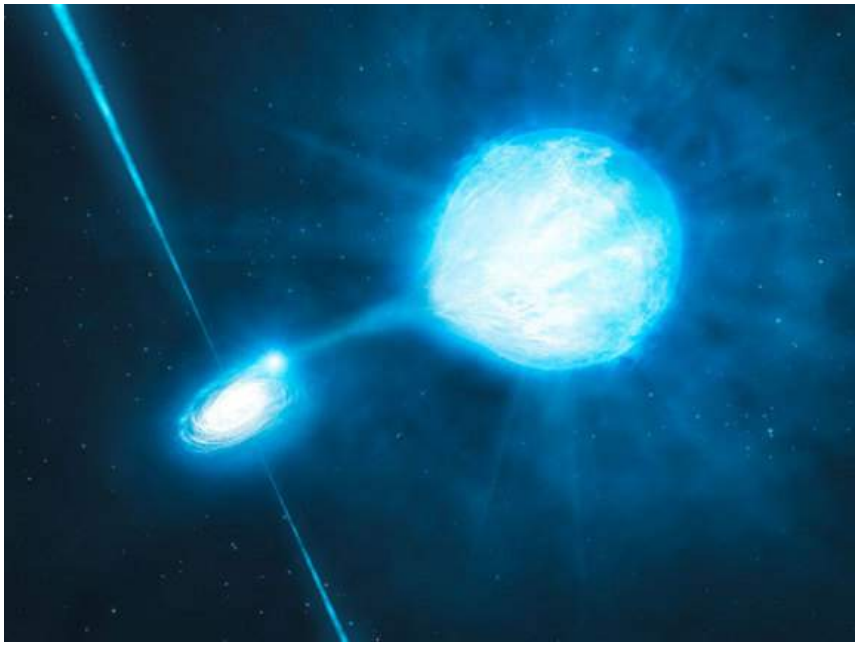
B $M_V = -4.8$, $B-V = -0.1$

C $M_V = -3.0$, $B-V = -1.2$

CG X–1

HST: $M_V > -6.8$

Luminosity



A BH needs a disc to shine

$$M_{\rm BH} \gtrsim 1.5\, v^4_{\rm w,\,1000} \delta^2\ {\rm M}_\odot$$

Carpano+2007; Illarionov & Sunyaev 1975

$$L_{\rm X} \approx \eta \frac{\dot{M}_{\rm w} c^2 G^2 M^2_{\rm BH}}{a^2 v^4_{\rm w}}$$

$\dot{M}_{\rm w} = 10^{-5}\ {\rm M}_\odot\ {\rm yr}^{-1}$

$v_{\rm w} = 1000\ {\rm km\ s}^{-1}$

(e.g. Crowther 2007)

$L_X > 3 \times 10^{39}$ erg s^{-1} for M > 10 $M_\odot$

For CG X–1, L_X up to 2×10^{40} erg s^{-1}
If L_E holds, M > 75 $M_\odot$ for a He or C/O donor
For 75 $M_\odot$: $L_X = 2 \times 10^{40}$ erg s^{-1}

Easily more with RLO
Canonical stellar-mass BH if moderately beamed / super-Edd

WR/BH binaries

Cyg X–3
2 $M_\odot$ NS or a 3–5 $M_\odot$ BH
P = 4.8 h, L ~ 10^{38} erg s^{-1}

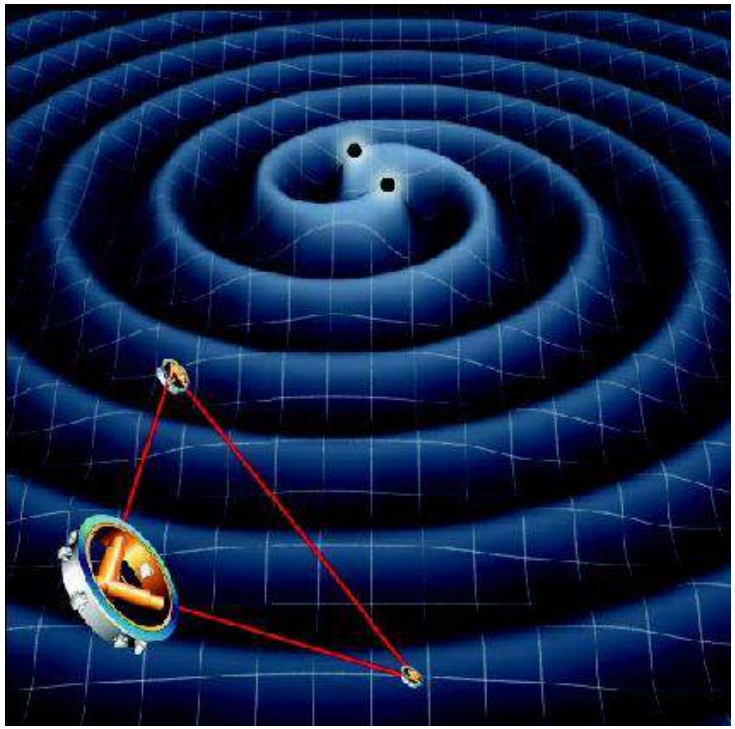
M101 ULX–1
>5 $M_\odot$ BH; P = 8.2 d
(Liu et al. 2013)

+ NGC 4490 and CG X–1
+ candidate in NCG 253:
P ~ 15 h, L ~ 10^{38} erg s^{-1}
(Maccarone et al. 2014)

WR/BH binaries are the progenitors of 2BHs with merger time scales shorter than a Hubble time

NGC300 X–1
20 $M_\odot$ BH; P = 32.3 h
(Carpano et al. 2007)

IC 10 X–1
33 $M_\odot$ BH; P = 34.9 h
(Prestwich et al. 2007)



WR/BH binaries

Theoretical predictions from population synthesis:
0.4 < **20** < 1000 events/yr for aLIGO or Virgo
(Abadie+2010)

Host galaxy	Source	Period (h)	BH mass ($M_\odot$)	WR mass ($M_\odot$)	SFR ($M_\odot$ yr^{-1})	Z ($Z_\odot$)	t_{GW} (Gyr)
IC 10	X–1	34.9	33	35	0.07	0.22	1.4
NGC 300	X–1	32.8	20	26	0.14	0.19	1.7
NGC 4490	CXO J123030 *	6.4	–	–	4.5	0.23	0.038
NGC 253	CXO J004732 *	14.5	–	–	4.0	0.24	0.33
Circinus	CG X–1 *	7.2	–	–	1.5	0.10	0.052
M 101	ULX–1	196.8	20	19	3.1	0.17	200
Milky Way	Cyg X–3	4.8	3	7	0.25	0.31	0.051

Natal kick? Mass of the 2nd compact object?

- WR forms a 10 $M_\odot$ BH via direct collapse
  - Orbital parameters left unchanged
- If BH mass unknown, we assume 10 $M_\odot$

WR/BH binaries

Host galaxy	Source	Period (h)	BH mass ($M_\odot$)	WR mass ($M_\odot$)	SFR ($M_\odot$ yr^{-1})	Z ($Z_\odot$)	t_{GW} (Gyr)
IC 10	X–1	34.9	33	35	0.07	0.22	1.4
NGC 300	X–1	32.8	20	26	0.14	0.19	1.7
NGC 4490	CXO J123030 *	6.4	–	–	4.5	0.23	0.038
NGC 253	CXO J004732 *	14.5	–	–	4.0	0.24	0.33
Circinus	CG X–1 *	7.2	–	–	1.5	0.10	0.052
M 101	ULX–1	196.8	20	19	3.1	0.17	200
Milky Way	Cyg X–3	4.8	3	7	0.25	0.31	0.051

$$R = \rho_{\rm SFR}(z) \sum_i (t_{\rm GW,\,i} + t_{\rm evol,\,i})^{-1} \, ({\rm SFR}_i)^{-1} \ {\rm yr}^{-1} \ {\rm Mpc}^{-3}$$

$$t_{\rm GW} = \frac{5}{256} \frac{c^5 \, a^4 \, (1-e^2)^{7/2}}{G^3 \, m_1 \, m_2 \, (m_1 + m_2)}$$

(Peters 1964)

- $\rho_{SFR}(z)$ cosmic SFR density
- t_{evol} ~ 3 Myr

(Mapelli+2010)

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(Peters 1964)

- $\rho_{SFR}(z)$ cosmic SFR density
- $t_{evol} \sim$ 3 Myr

(Mapelli+2010)

$\rho_{SFR}(z = 0.3) \sim 3.6 \times 10^{-2}\ M_\odot\ {\rm yr}^{-1}\,{\rm Mpc}^{-3}$ (Hopkins & Beacom 2006)

WR/BH binaries

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(Peters 1964)

- $\rho_{SFR}(z)$ cosmic SFR density
- t_{evol} ~ 3 Myr

(Mapelli+2010)

<16 yr^{-1} for distance range 1 Gpc

0.4 <**20** <1000 yr^{-1} (Abadie+2010) / **~10 yr^{-1}** (1.4 Gpc) (Maccarone+2014)

The Future - I

CATS @ BAR

- Every 3/4 months we run the pipeline on the new ACIS data; new pulsars are coming
- Z^2-like algorithms, better suited for low-counts sources
- X-ray/optical follow-ups & classification
- Search the XMM EPIC archive (EXTraS)

NGC 4490's 6.4 h BH binary

- Identification of the companion star
- Dynamical measurement of the BH mass
- New estimates of the metallicity of NGC 4490/85

The Future - II

- Dearth of WR HMXBs. Yet they should be relatively common and very bright. Are there others known systems which may have been misclassified?
- The sample is still small, but growing (from 3 to 7 in 2 yr!)
- Can a significant fraction of ULXs be powered by WRs?
- Stellar massive BHs >20 $M_{\odot}$
- Population synthesis and common envelope phase
- Rate of (stellar) 2-BH mergers to be seen (Advanced Ligo)