X-ray Studies of Millisecond Pulsars in Globular Clusters

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(with special thanks to collaborators:
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Neutron Stars and Pulsars   363rd Heraeus-Seminar

Overview of talk

- Introduction to bright vs. dim X-ray binaries in Globular Clusters (MSP origins…)
- Chandra views of 47Tuc & NGC6397: the compact binary population revealed
- Quick comparison with Terzan 5
- MSPs in 47Tuc & NGC6397: re-recycled?
- MSPs & NS binaries in GCs: origin of short GRBs?
- Why the fastest MSPs may not pulse: B_{NS} vs. M_{NS}?
- Conclusions and future questions/opportunities

Luminous (Lx >10^{35}) X-ray binaries in GCs

13 LMXBs in 12 globular clusters: *all bursters (NSs), no BHs*

...the future MSPs:

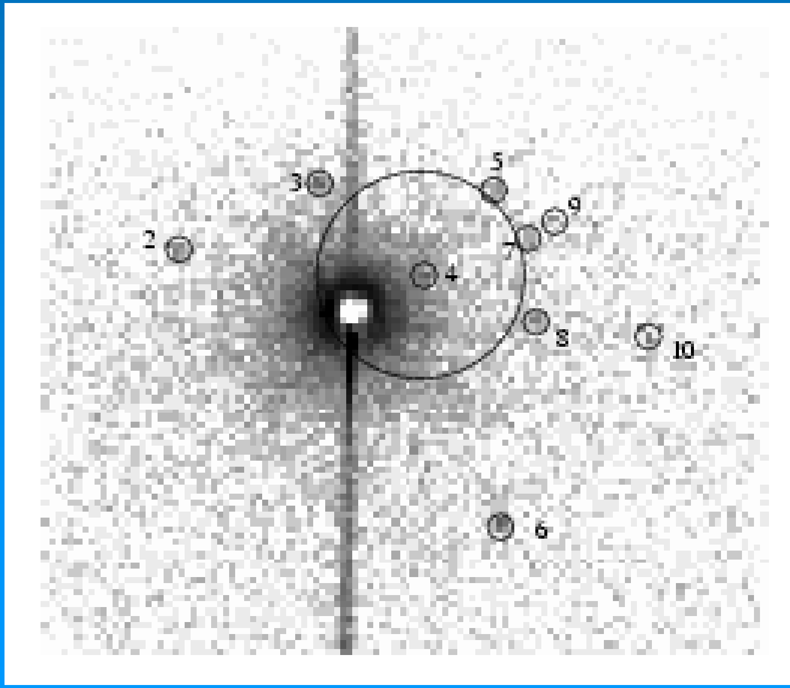
Cluster	LogLx	P_binary	LogRho_c	[Fe/H]	R_galctr	Z_disk
	(erg/s)		(Msun/pc^3)		(kpc)	(kpc)
N1851	36.2	~82min?	5.3	**-1.2**	16.7	-6.9
N6440	32.5-37		5.3	**-0.3**	1.3	0.6
N6441	36.5	5.5hours	5.2	**-0.5**	3.5	-1
N6652	32.5-36	42min(??)	4.5	**-1**	2.4	-1.9
N6624	37-37.5	11min+~1d*	5.3	**-0.4**	1.2	-1.1
N6712	36	21min	3.1	**-1**	3.5	-0.5
N7078	36.5, 36	17.2d	5.4	**-2.2**	10.4	-4.7
Ter1	32-36		3.5	**-0.3**	1.8	0.1
Ter2	36		4.7	**-0.4**	0.9	0.3
Ter5	32-37		5.5	**-0.3**	0.7	0.2
Ter6	32-36		5.4	**-0.5**	1.6	-0.4
Liller1	32-36		5.4	**0.2**	2.6	0
		*probable triple with ~1d outer binary period				

Primary correlation with [Fe/H], not ρ_c or R_{GC} or Z_{disk} ?
(strongly supported by external GC systems)

Luminous vs. quiescent LMXBs …or CVs?

"Dim" sources discovered (1983) with Einstein survey & suggested to be primarily CVs but also qLMXBs (e.g. Lx ~10^{37} transient in N6440) (Hertz and Grindlay 1983)

Chandra can resolve *both* populations in single GCs:



Terzan 5: LMXB in outburst (L_x ~10^{36} erg/s) with 9 faint sources at L_x ~10^{32-33} erg/s. (Heinke et al 2003, ApJ, 590, 809). *Deeper followup obs. (see below; Heinke et al 2006)*

***M15*: 2 Luminous LMXBs plus 2-3 CVs & qLMXB(?) in core (Hannikainen et al 2005)**

Chandra Studies of Globular Clusters

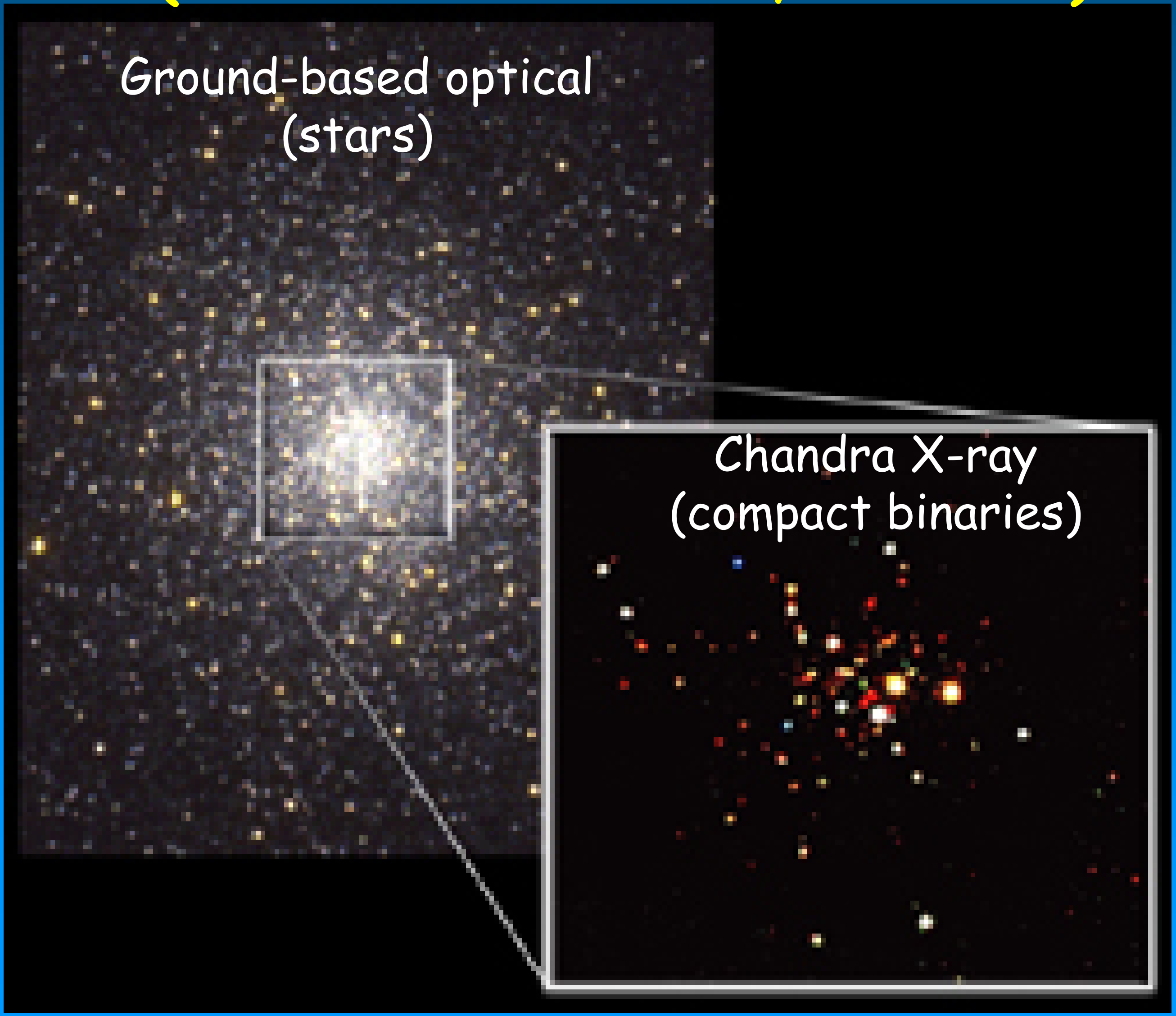
Incomplete list of Chandra GC observations include:

- 2 luminous LMXBs in M15 (Angelini and White 2000)
- >2 qLMXBs (ejected?) in NGC 6652 (Heinke et al 2001);
  MSPs ejected from core in NGC 6752 (Colpi et al 2003)
- Multiple MSPs, progenitor qLMXBs, & CVs in 47Tuc and NGC6397 (Grindlay et al 2001a,b, 2002, 2006; Grindlay 2006) and X-ray CMDs
- Sources vs. collision rates in GCs (Pooley et al & Heinke et al 2003)
- GCs in ext. galaxies: LFs, [Fe/H], ULXs(?) (Sarazin et al, Kundu et al, Maccarone et al 2003, 2004, 2005)
- Deep survey of 47 Tuc (Heinke et al 2005), MSPs in depth (Bogdanov et al 2006); qLMXBs vs. NS-EOS (Heinke et al 2006); and more…

First deep look a Globular with Chandra:

47Tuc, March 16-17, 2000

(Chandra ACIS-I, 70ksec)



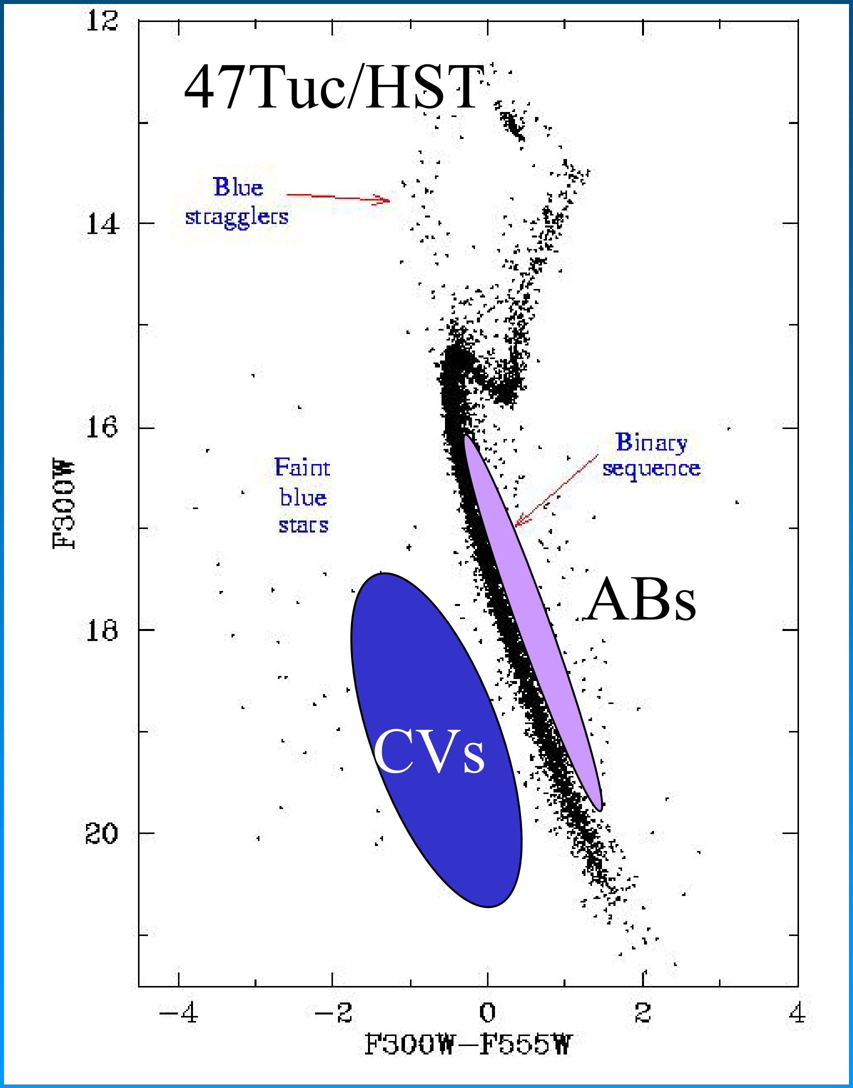
ACIS-I image
2 x 2.5 arcmin

0.5-1.2 keV

1.2-2.0keV

2.0-6.0keV

Chandra GC Binary Roadmap in Color Mag Diagram



CVs: blueward of main sequence (m-s); Hα

ABs = active binaries: within binary m-s; weak Hα emission

MSPs: have WD or m-s companions, like CVs; confused with ABs

qLMXBs: between CVs and m-s

BSs = blue stragglers: NOT detected?

How to make a Compact Binary (e.g., MSP) in a GC

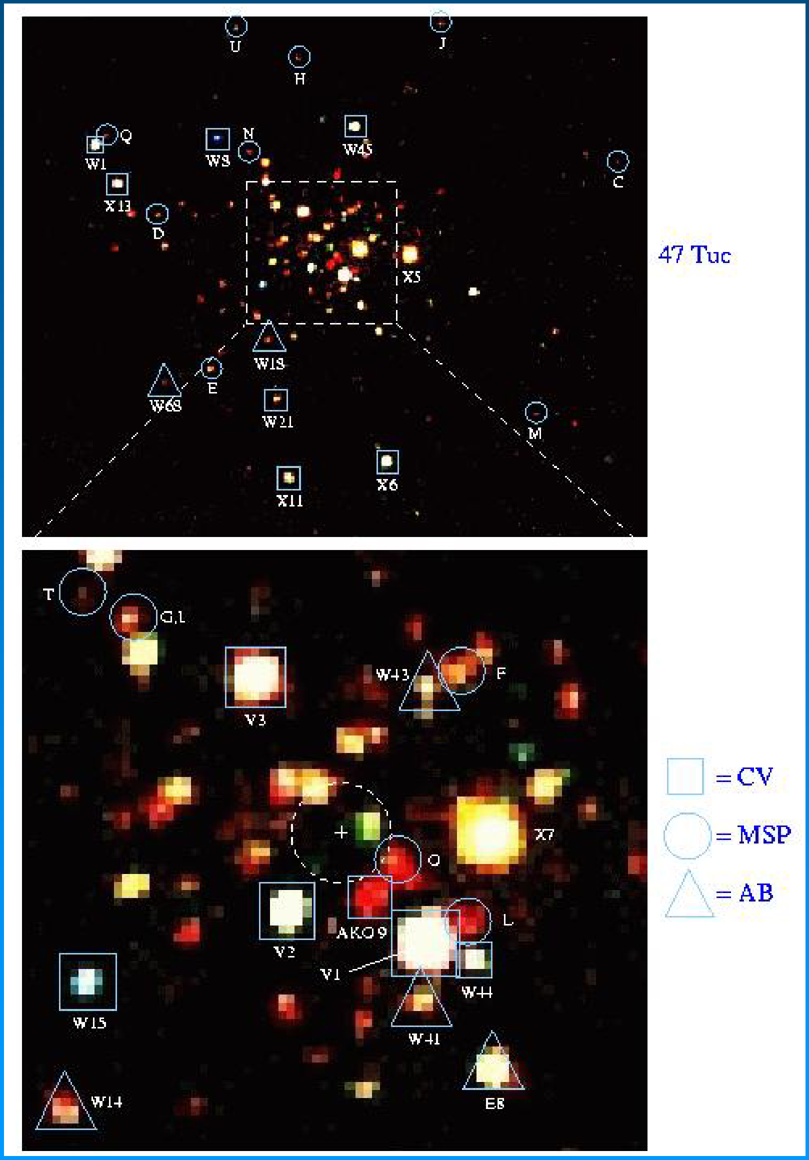
- Start with primordial binary mix (~20% of GC stars)
- "Darwinian" dynamical evolution: only the tightly bound survive [with $V_{orb} \geq (GM_{core}/R_{core})^{0.5}$]; others disrupted in binary-star encounters
- NSs (or WDs) *exchange* with mainseq (MS) star in binary to form low mass X-ray binary (LMXB) or cataclysmic variable (CV)
- NS *partly* spunup by Roche-lobe (RL) overflow accretion from MS *
- MS secondary evolves to RG; higher Mdot from RG-RL completes spinup leaving HeWD secondary detached after common envelope
- Spunup MSP "free" to be detected as radio MSP *and thermal (hot PC) X-ray source, possibly with non-thermal comp. (3 mechanisms…)*
- MSP may itself *exchange* into another MS-MS or MS-NS binary…!

47Tuc: initial Chandra data results

- BY Dra stars (active m-s binaries = *ABs*) detected in large numbers: 29 HST IDs.
L_x ~1-10 x 10^{30}, kT ≤1keV (usually), P_{binary}~0.5-2d

- Limit on central BH from Bondi accretion & n ~0.1cm^{-3} from variable DM of MSPs
M_{BH} < 470 M_O, but dependent on uncertain (advection?) $\varepsilon_{accretion}$

NEW RESULT from NEW data:
MBH < 150 M_o since bright Neighbor source identified as qLMXB



MSPs in 47Tuc: the *initial* Chandra view

• 9 of the 16 MSPs with precise radio timing positions detected firmly, 5 marginally (2 un-resolved)

• All but 1 (MSP-J) very ***soft***: kT~0.2keV emission from polar caps. L_x ~1-4 x 10^{30} and *new* fit to L_x – Edot: $Lx \sim Edot^{0.5}$

• Significant underlying "red" Chandra source pop. and incompleteness:

→ ***~35-90 MSPs, total?***

vs. Deep Exposure on 47Tuc

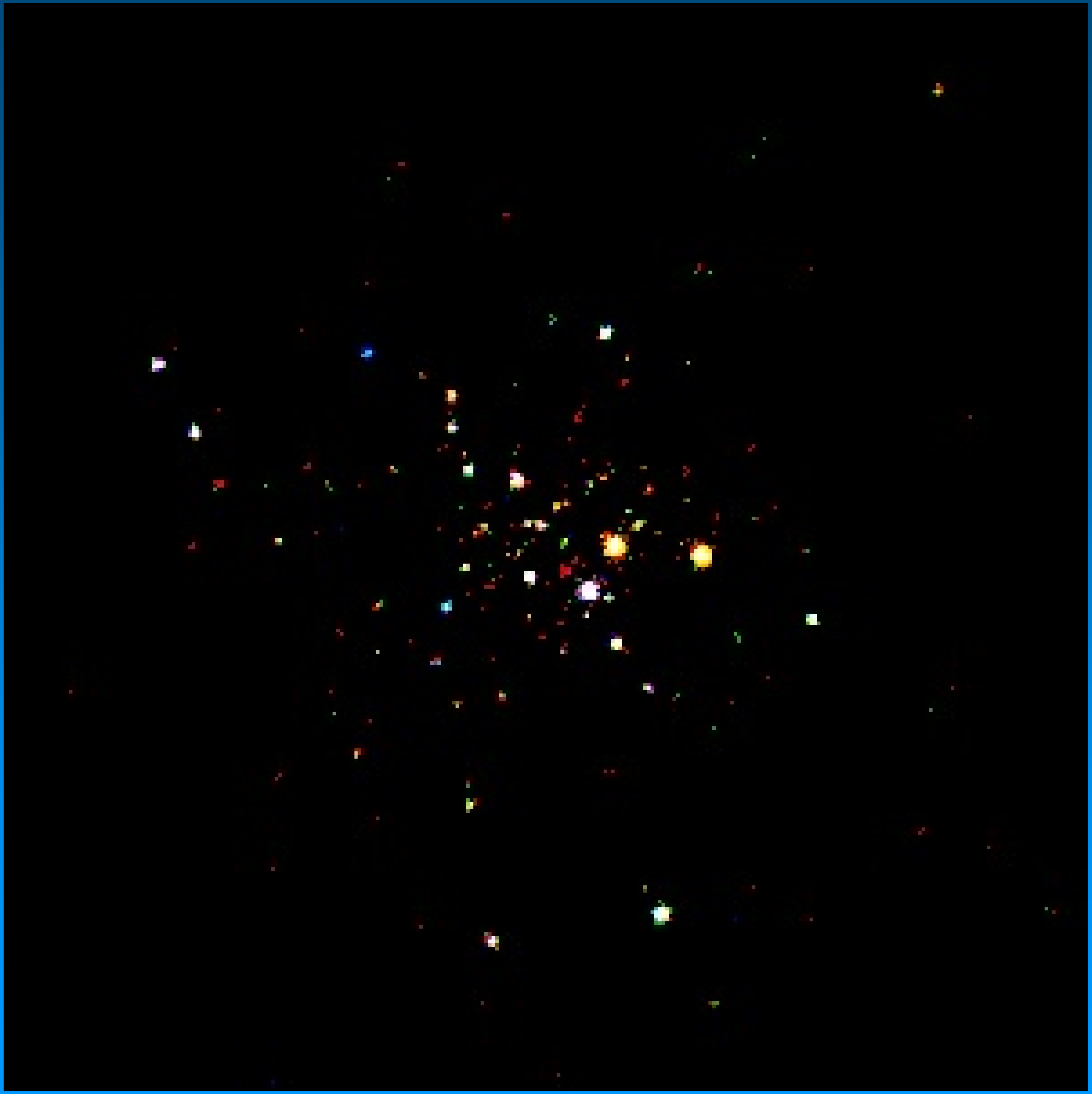
4 x 65 ksec exposures with ACIS-S (better soft response) with ~1, 3, 10d separations (Sept. 30 - Oct. 10, 2002). Initial analysis and Catalog by Heinke et al 2005

and

HST-ACS imaging (V, R, Hα), for 3 (of Chandra's 4) visits at 3 orbits each (new IDs in progress by van den Berg et al 2006)

⇒ *Scroll through Chandra images...*

Compare: March 2000, ACIS-I (70ks)



(Grindlay et al 2001a)

0.5-1.2 keV

1.2-2.0keV

2.0-6.0keV

To: Sept. 30 - Oct. 10, 2002, ACIS-S (280ks)

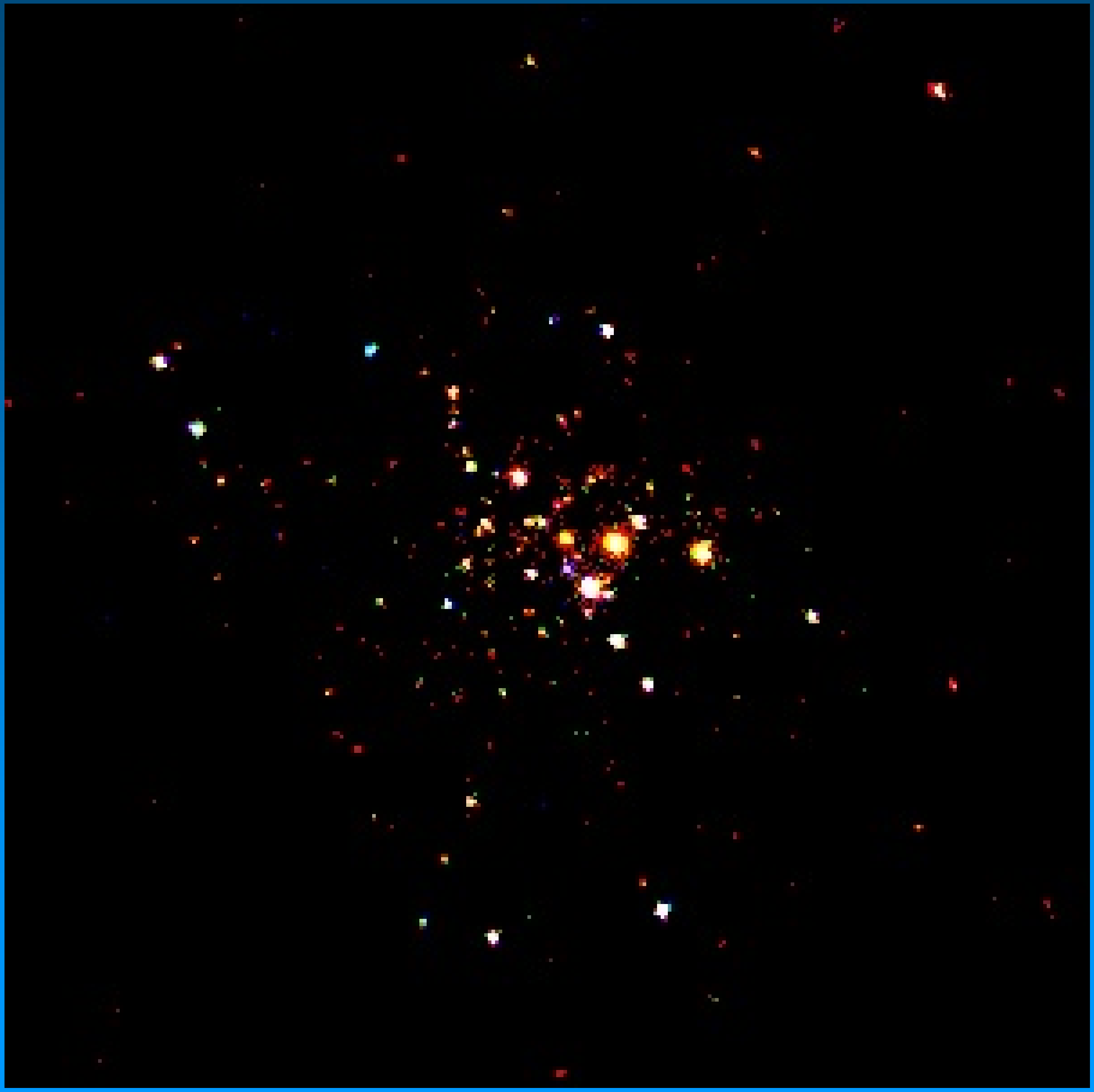
0.3-1.2 keV

1.2-2.0keV

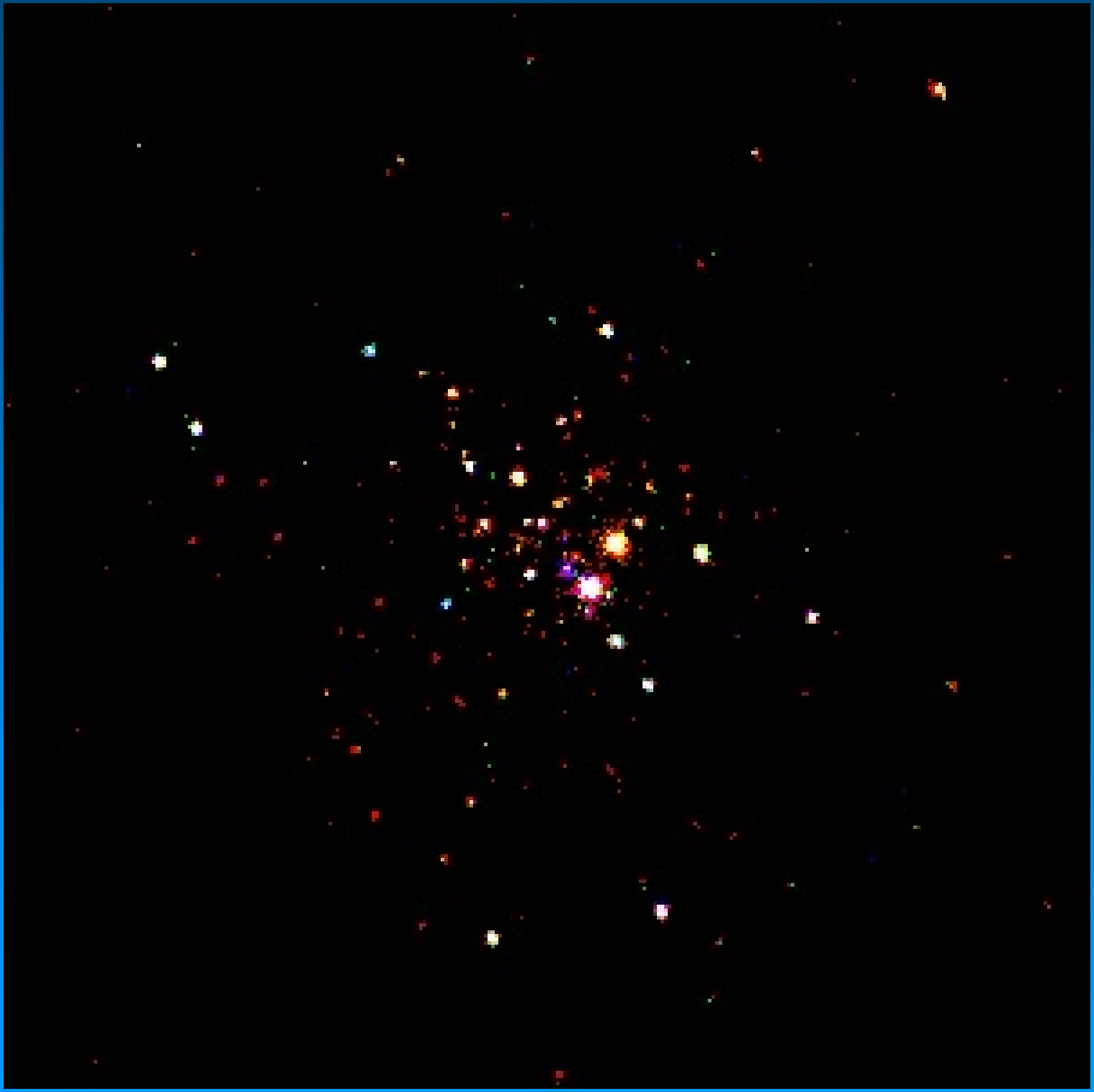
2.0-6.0keV

(Heinke et al 2005)

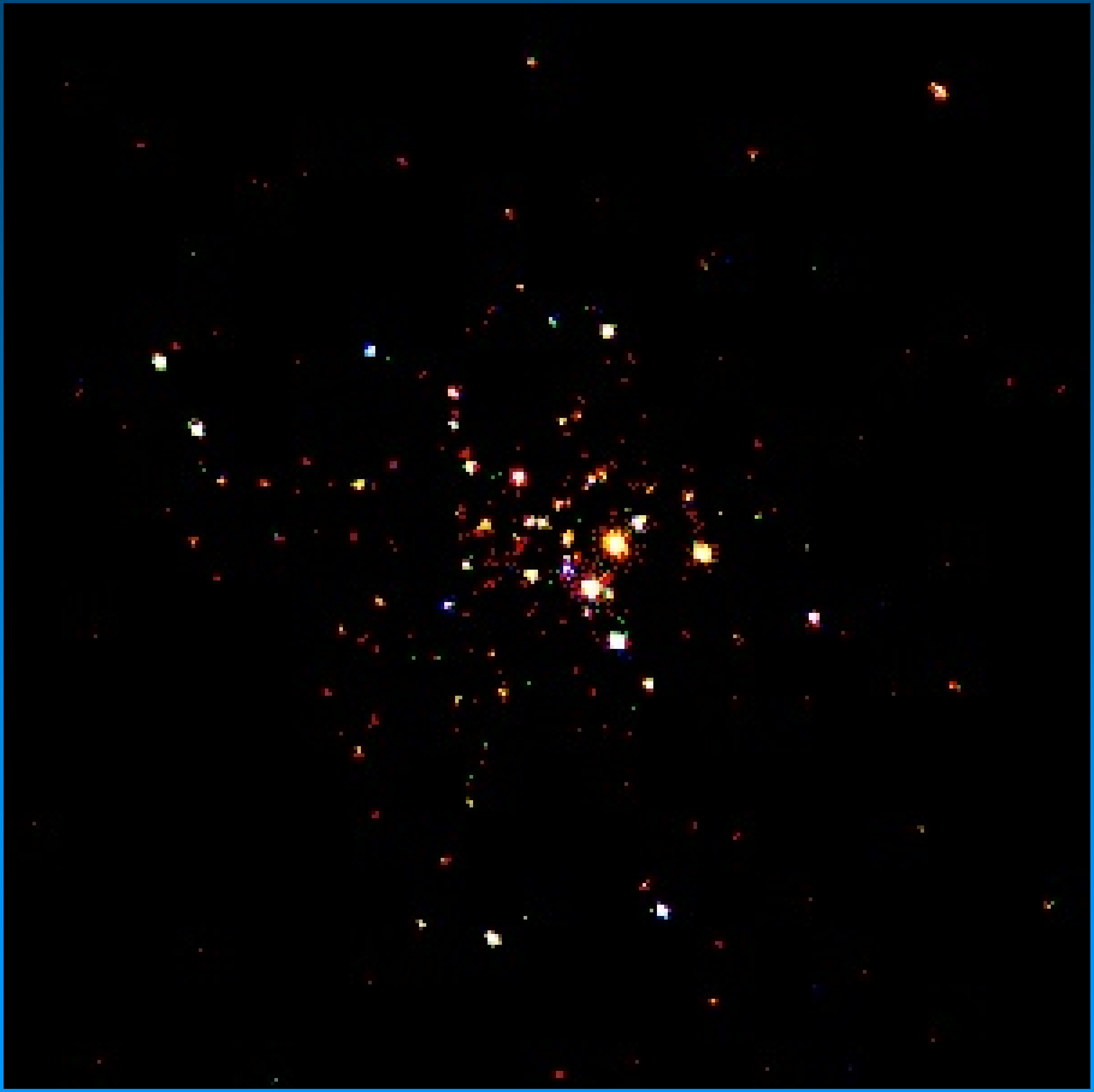
Time variability: Sept. 30, 2002 (65ks)



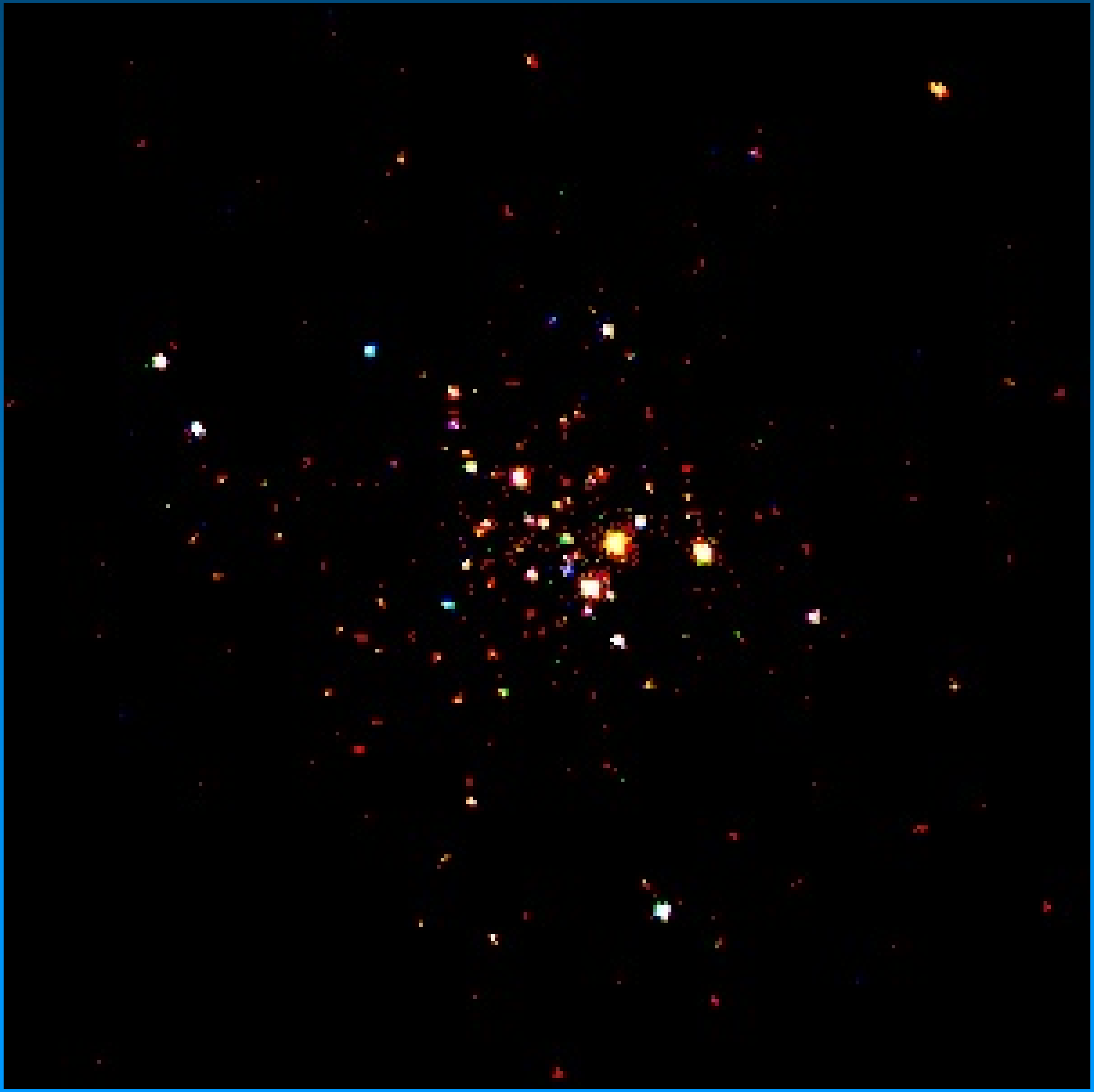
Oct. 1, 2002 (65ks)



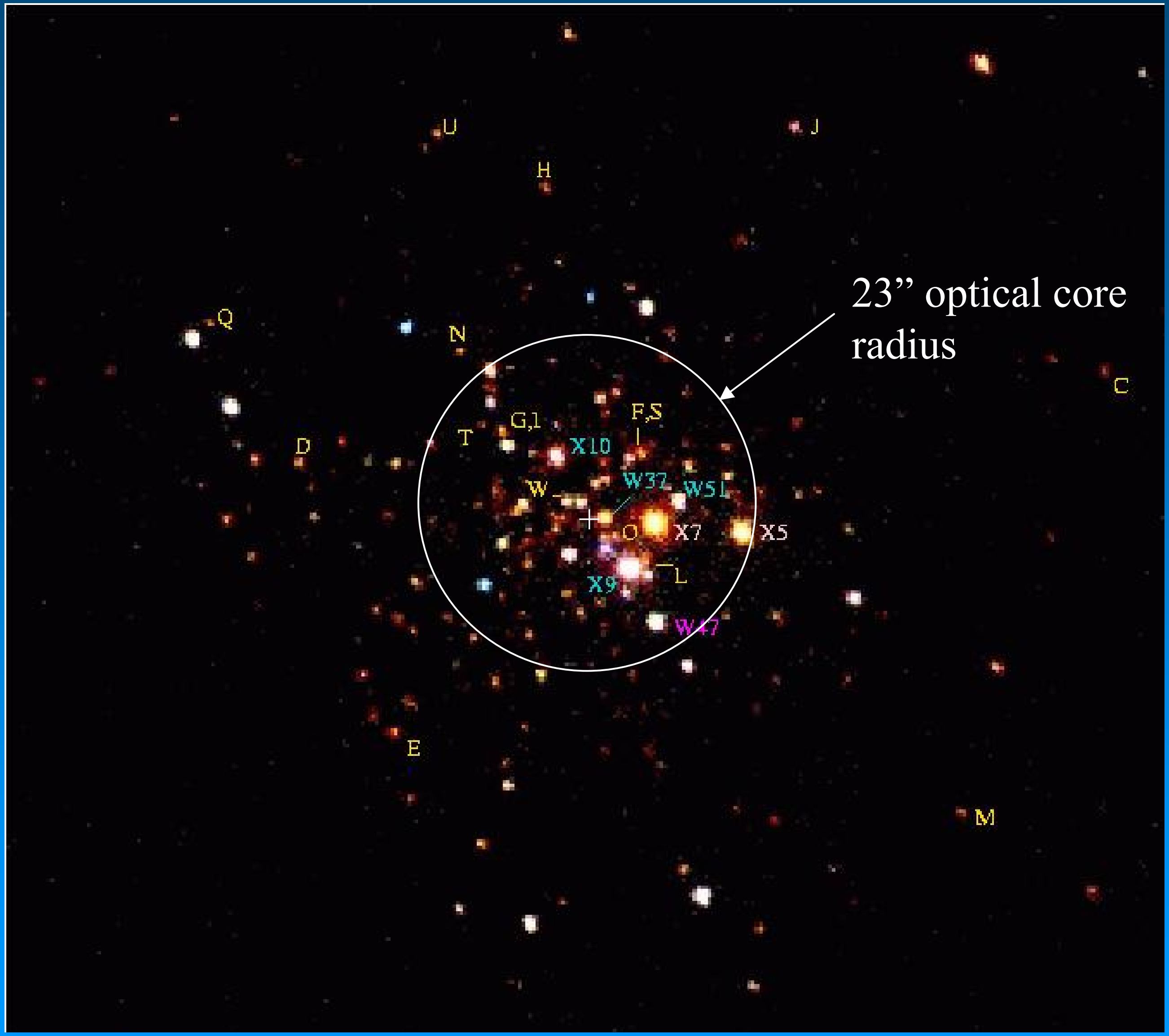
Oct. 3, 2002 (65ks)



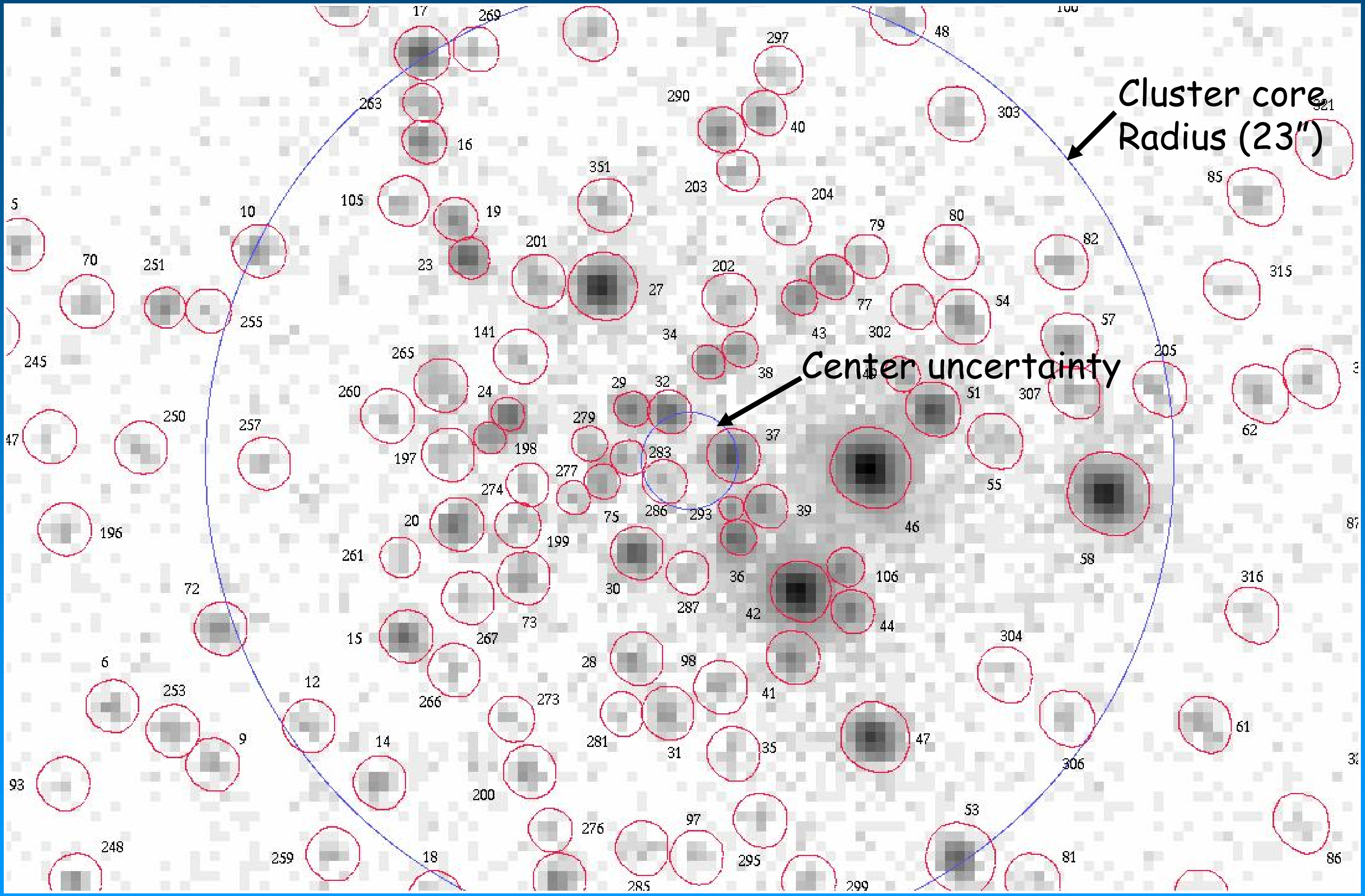
Oct. 10, 2002 (65ks)



Total ACIS-S, 2002 (260ks), & Sample IDs

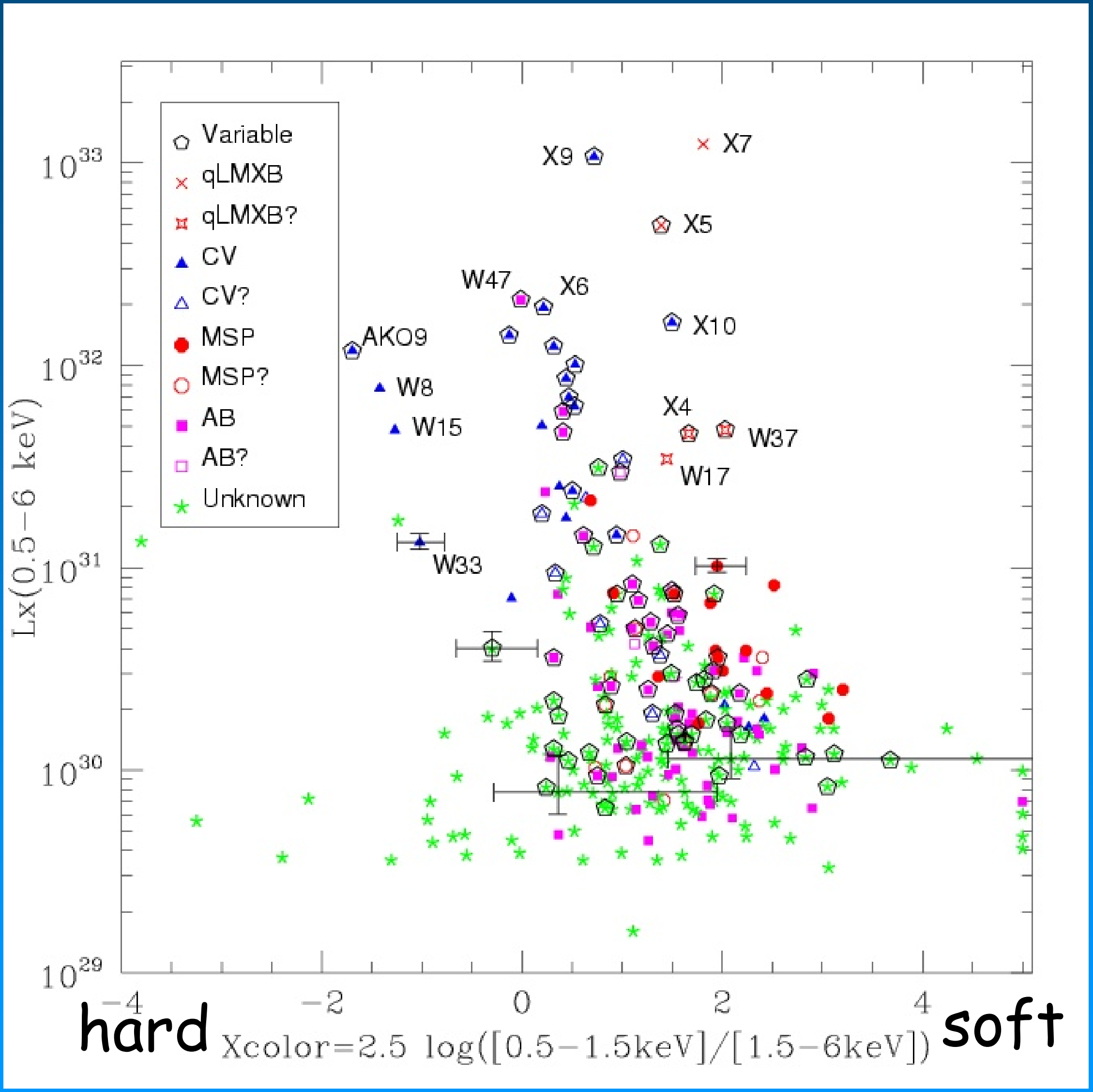


Zoom in on 47Tuc core….



Improved limit on central black hole: ≤ 150 Msun (Grindlay 2005, AIPCP, 797, 13)

X-ray Lx-Color Magnitude Diagram



Classify sources (with Parkes or HST IDs):

Active binaries = ms-ms, P<2d (≥40 ABs)

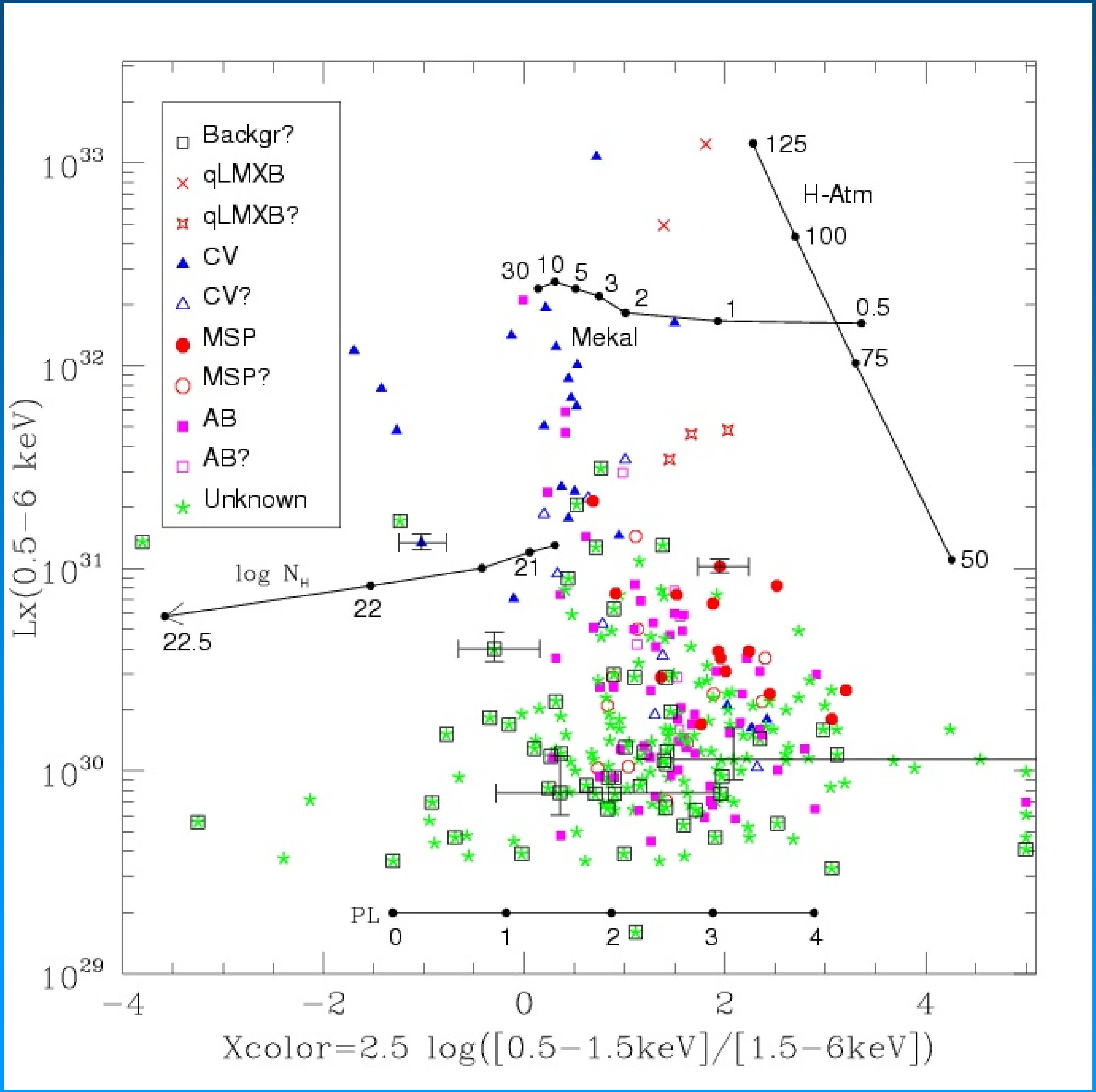
Cataclysmic vbls = WD+ms, P<2d (≥25 CVs)

Quiescent LMXBs= NS+ms, P<0.5d (≥5 qLMXBs)

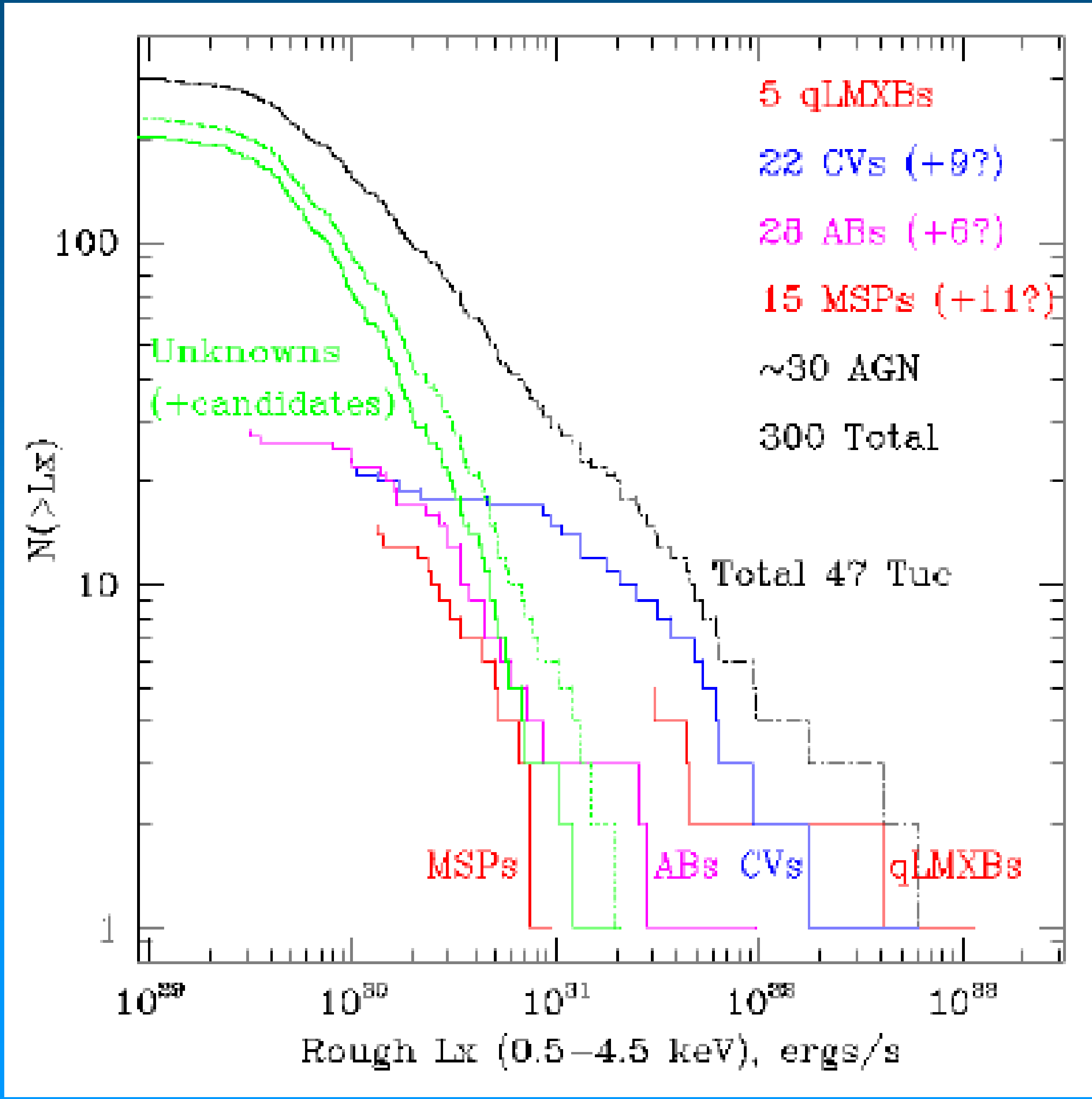
Millisecond pulsars (≥19-30 MSPs)

(Heinke et al 2005, ApJ, 625, 796)

47Tuc X-ray CMD with Models



X-ray Luminosity Distributions vs. IDs



Survey limit:
Lx > 3 x 10^{29} erg/s

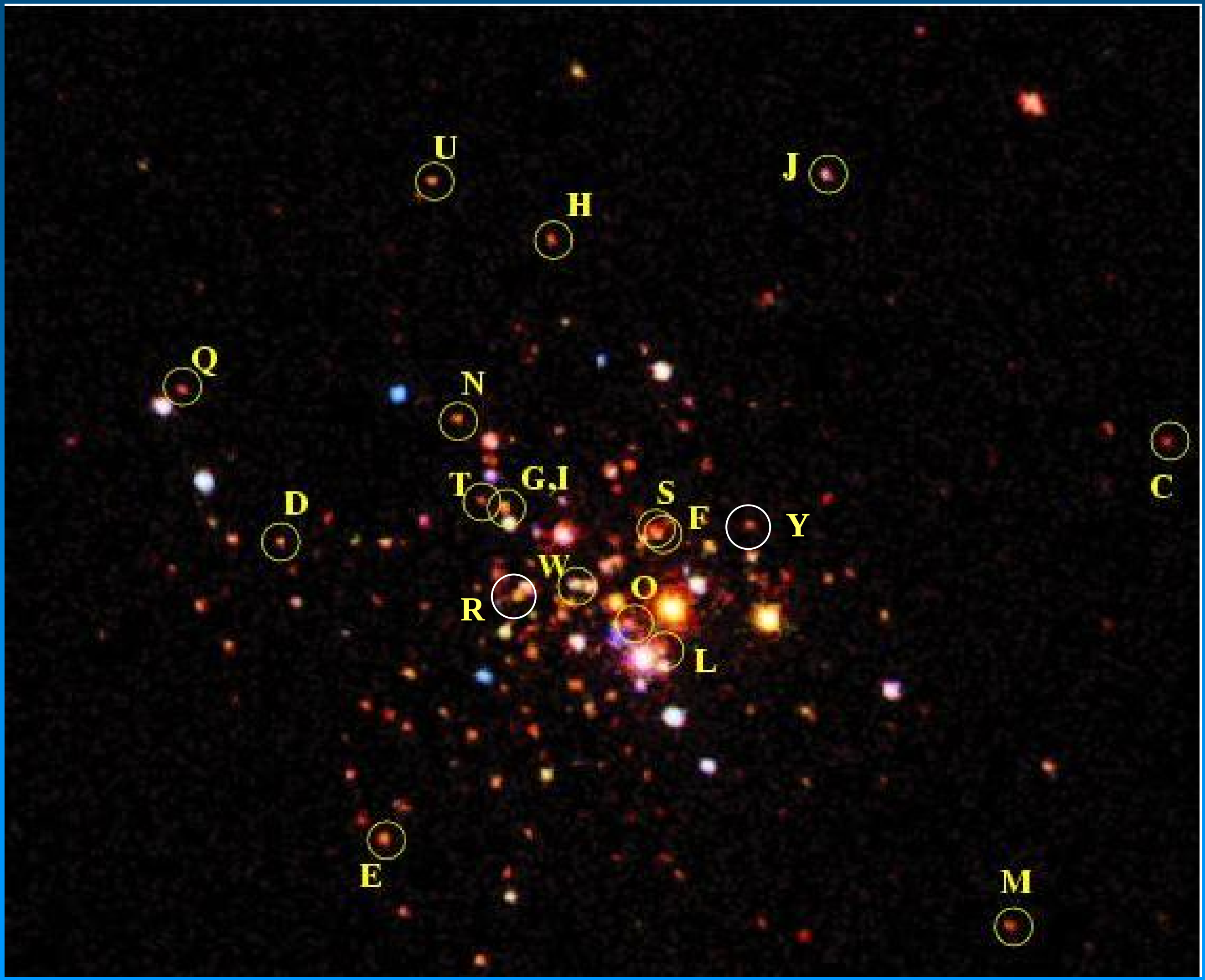
Unknown IDs?
Steeper XLF suggests MSPs, ABs

but…
flatter XLF for CVs partly due to limits on HST-WFPC2 and Fx/Fv constraints; new ACS data & Hα will improve

Initial results from deep 47Tuc Chandra data

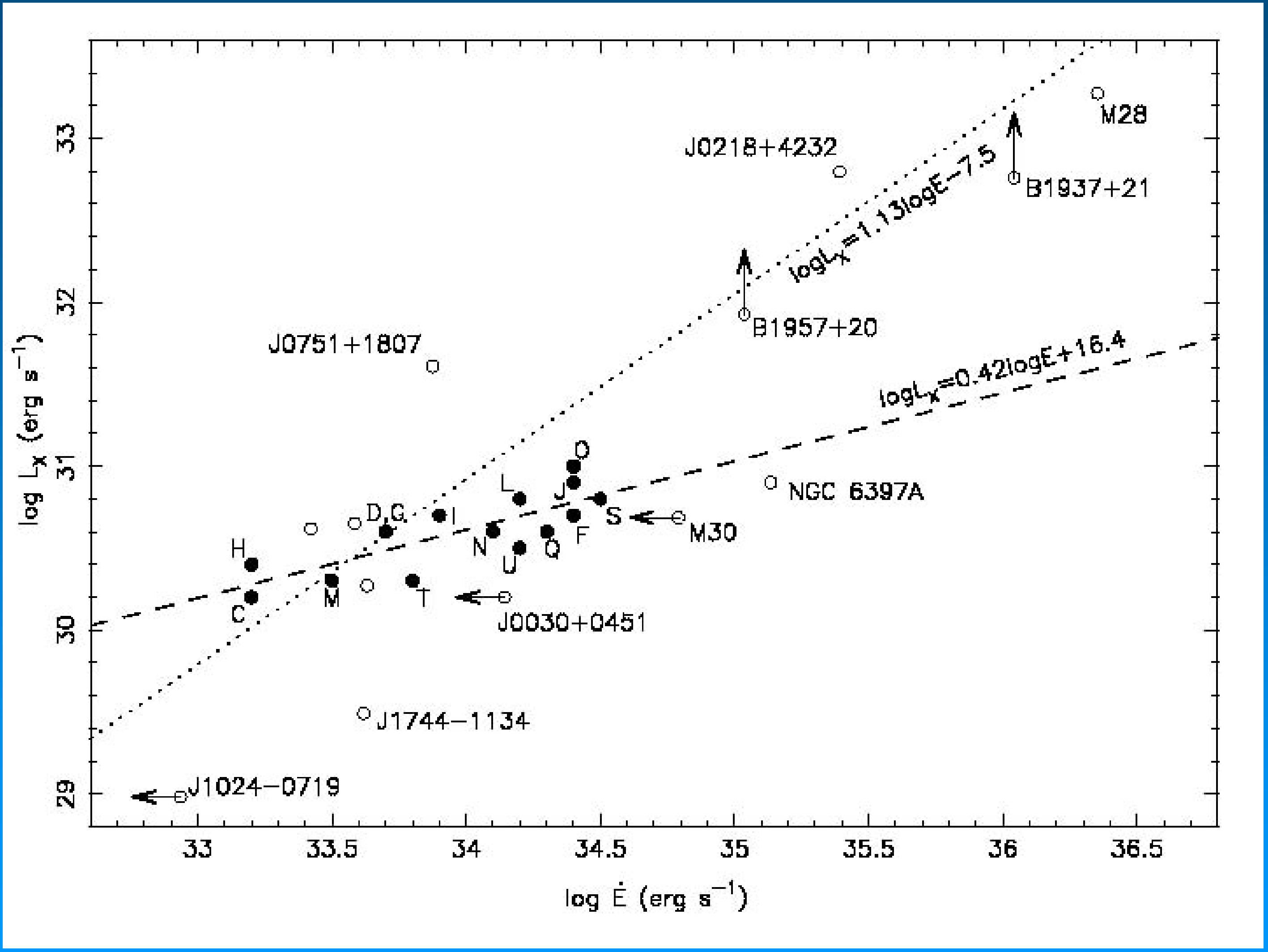
- *At least 225 sources detected significantly by WAVDETECT in ~same 2.5 x 2.5 arcmin central box (vs. 108 for ACIS-I)*
- *301 sources (Lx >~3 x 10 ^{29} erg/s) inside half-mass radius (2.8arcmin) vs. 146 in ACIS-I data*
- *New flaring (some ABs, but also CVs) and steady (MSPs, qLMXBs, & CVs?) sources detected*
- *All resolved MSPs (17/19) detected; spectra on summed MSP images: BB/NSA fits & faint PL components measured*
- *HST-ACS data much higher resolution: new IDs*

All 19 Radio MSPs with Radio/optical positions well-detected (>30-150 cts each)



No significant variability of any MSP except W

ACIS-S MSP data (Bogdanov et al 2006a,ApJ, in press)



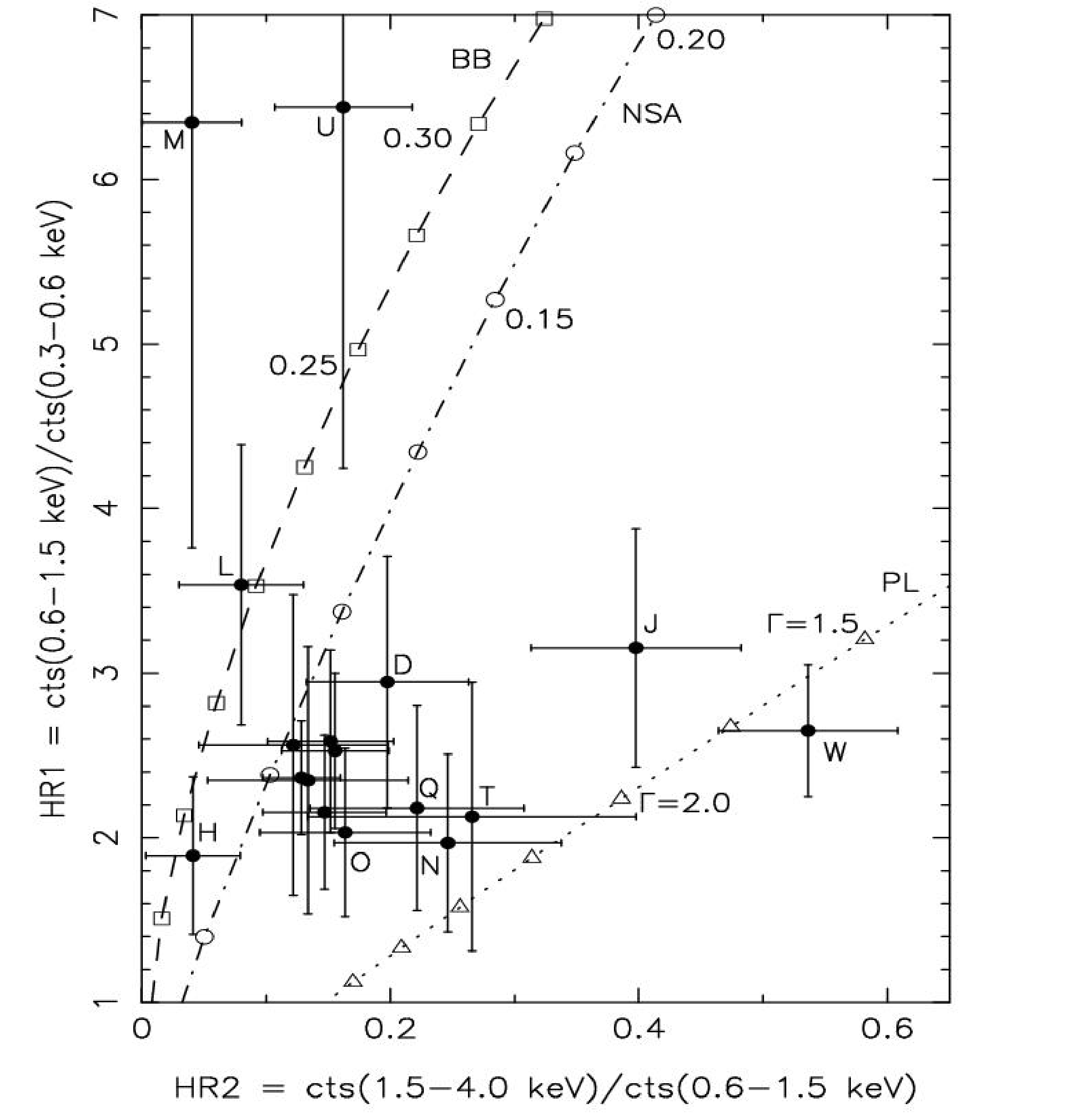
Similar to ACIS-I result: Lx ~ Edot$^{0.5}$ (Grindlay et al 2002) but less scatter. Consistent with Harding-Muslimov model for PC heating ~ Edot$^{0.5}$

47Tuc MSPs color-color diagram vs. models

MSPs all Thermal EXCEPT MSP-O with ~50% PL component

- and -

vs. J and W with >70% PL spectra from MSP wind shock at companion (Bogdanov et al 2006a)



47 Tuc MSP X-ray spectra: thermal vs. PL

MSP	Best fit model	T_{eff} ($\times 10^6$ K)	Radius (km)	Γ	χ_ν^2	dof	F_X (0.3-8.0 keV) ($\times 10^{-15}$ erg cm^{-2} s^{-1})	L_X ($\times 10^{30}$ erg s^{-1})
C	NSA	1.12	0.57	-	0.68	3	0.73	2.00
D	NSA	1.29	0.61	-	1.4	8	1.54	4.24
E	NSA	0.88	1.75	-	1.03	6	2.28	7.37
F+S	NSA	1.27	1.03	-	0.77	10	4.09	10.49
G+I	NSA	1.28	0.84	-	0.98	7	2.78	7.71
H	NSA	1.04	0.94	-	0.59	6	1.39	3.78
J	NSA+PL	0.89	1.43	1.0	1.0	6	4.69	13.5
L	NSA	1.42	0.78	~	0.87	17	3.70	13.8
M	NSA	1.27	0.53	-	0.45	4	1.08	2.97
N	NSA	1.20	0.61	-	1.38	5	1.09	3.00
O	NSA+PL	0.98	1.48	1.3	1.33	11	4.55	13.3
Q	NSA	1.30	0.51	-	0.78	5	1.10	3.06
R	NSA	1.54	0.60	~	1.60	7	3.19	8.93
T	NSA	0.80	0 – 2.4	-	1.52	2	0.67	1.86
U	NSA	1.82	0 .28	-	0.49	6	1.40	3.96
W	NSA+PL	0.94	0 – 2.1	1.15	1.17	14	11.3	33.9
Y	NSA	1.35	0.47	~	0.98	4	1.10	3.08

MSP Variability: 47Tuc-W shows *hard* eclipse

- No long term variability (days, weeks, years), except for 47 Tuc O (due to adjacent CV?);
- 47 Tuc J, –O are eclipsed at (some) radio frequencies (Camilo et al. 2000; Freire et al. 2003) but not in X-rays
- 47 Tuc-W partially eclipsed in hard X-rays but not thermal emission from NS. Shocked gas from MSP wind on L1 stream and qLMXB J1809-369 (Bogdanov, Grindlay and van den Berg 2005)
- similar to hard X-ray emission from MSP-6397A in NGC 6397 (Grindlay et al 2001b, 2006)

47Tuc-W: Total cts. & Energy vs. binary phase

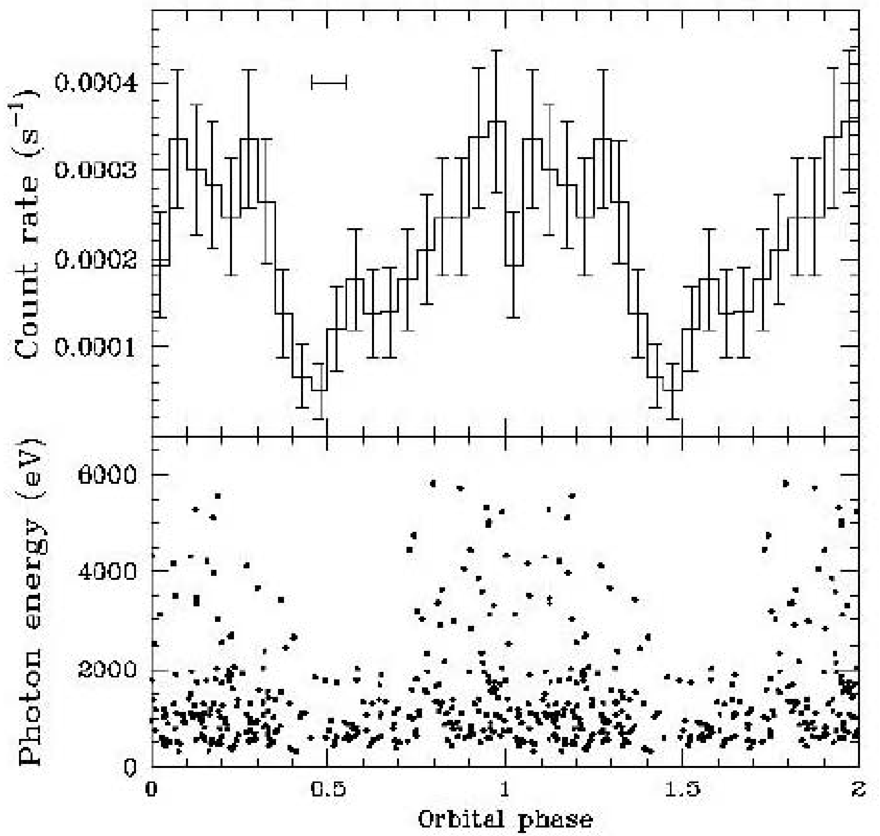


Fig. 1.— Upper panel: X-ray lightcurve of PSR J0024-7204W in the 0.3-8 keV band, folded over its binary period. The horizontal errorbar at phase 0.5 represents the uncertainty in the orbital phase of the optical minimum at the time of the Chandra ACIS-S observations. Lower panel: the energy of each photon detected within 1″ of the optical position of 47Tuc W plotted versus orbital phase. Note the complete absence of photons with energies above 2 keV and the reduction in the number of soft photons between orbital phases 0.4 and 0.7. Two orbital cycles are shown for clarity.

(Bogdanov, Grindlay and van den Berg 2005, ApJ, 630, 1029)

HST- ACS photometry: MSP-W heating its companion star

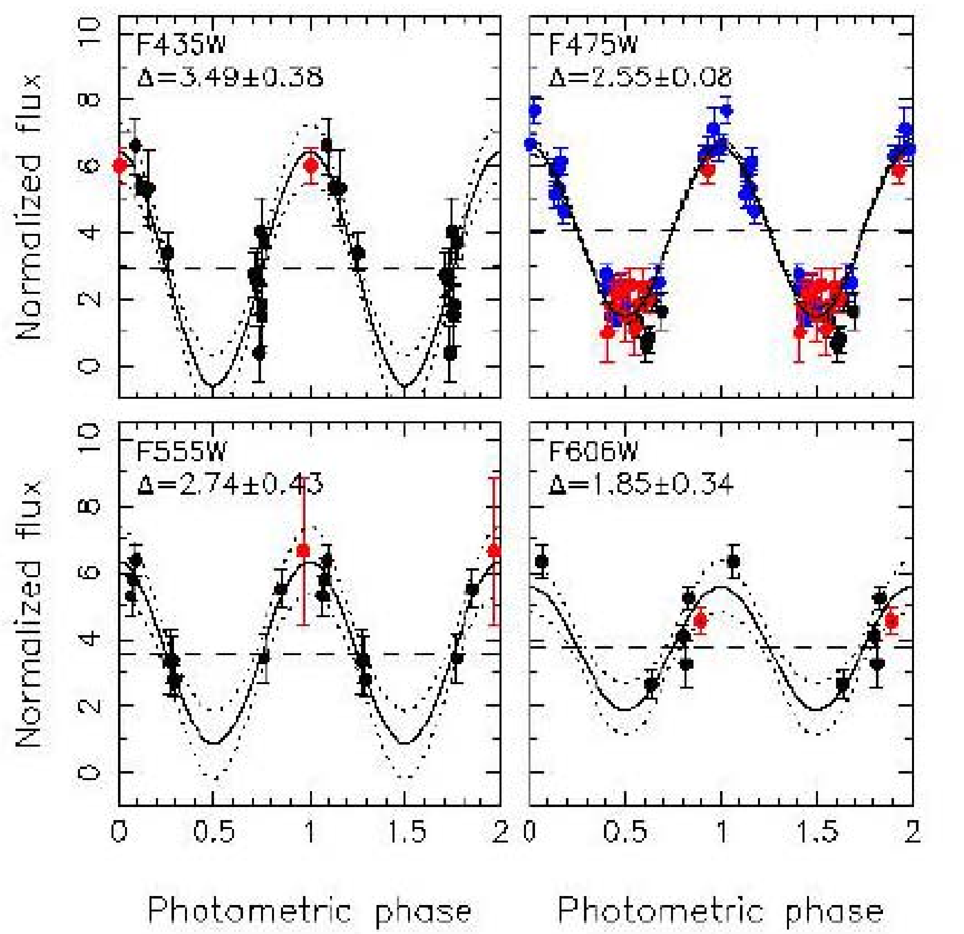


Fig. 3.— HST/HRC light curves of the optical counterpart of 47 Tuc W in different filters folded at the photometric period. The flux is in units of 10^{-18} erg s^{-1} cm^{-2} Å^{-1}. The data from observing programs 9019, 9028, and 9443 are plotted in black, blue, and red, respectively. For each filter the solid line is the sine curve with the best-fit amplitude and average flux level, with period and phasing as in Edmonds *et al.* (*8*). The dotted lines represent 2σ error margins while the dashed lines give the average flux levels. The HST filter and Δ, the amplitude of variation ($\pm 1\sigma$), are given in the upper left corner of each panel. Note the trend of decreasing amplitude with increasing wavelength. Two orbital cycles are shown for clarity.

X-ray/optical (ACS) spectrum of MSP W

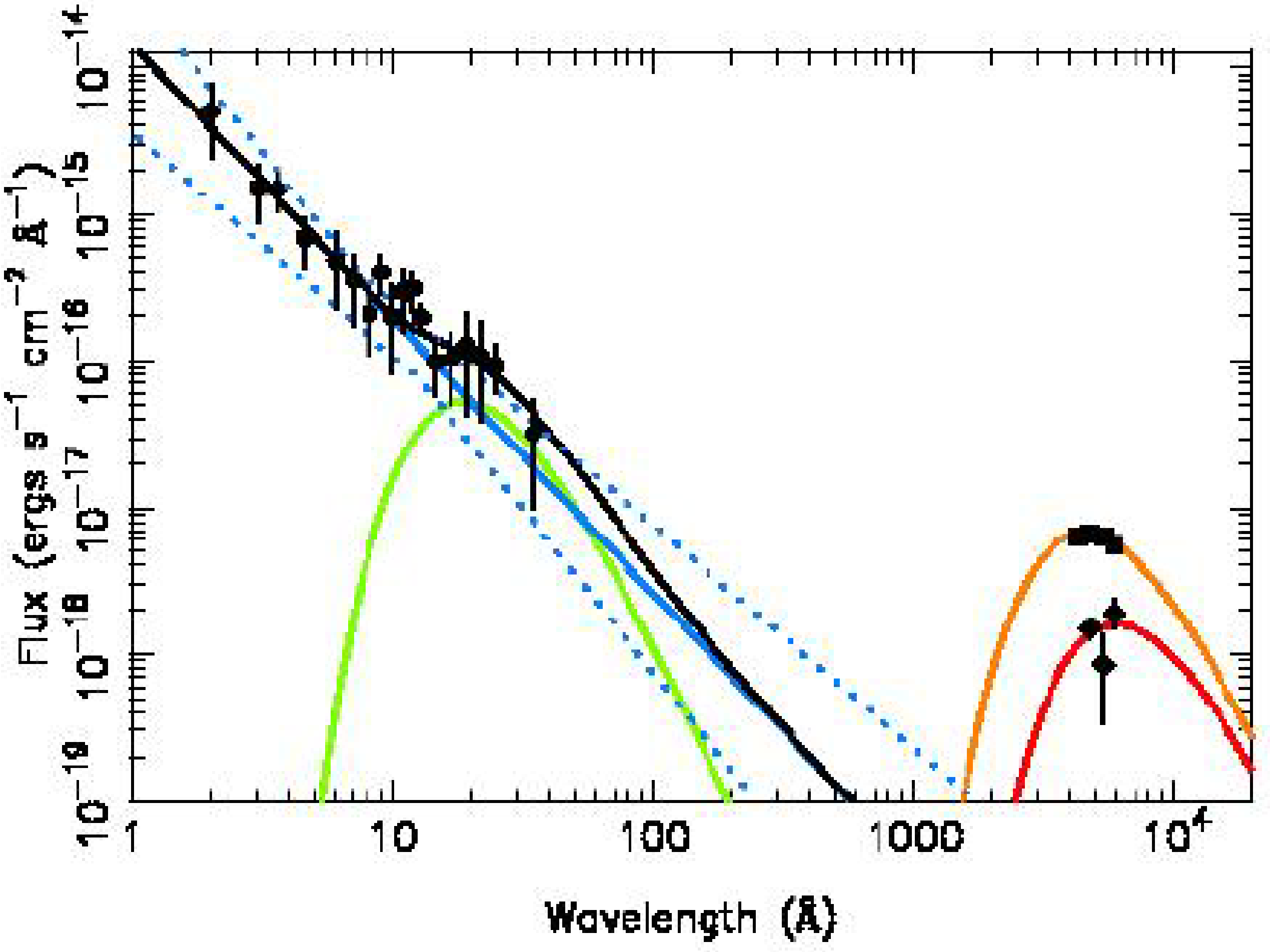
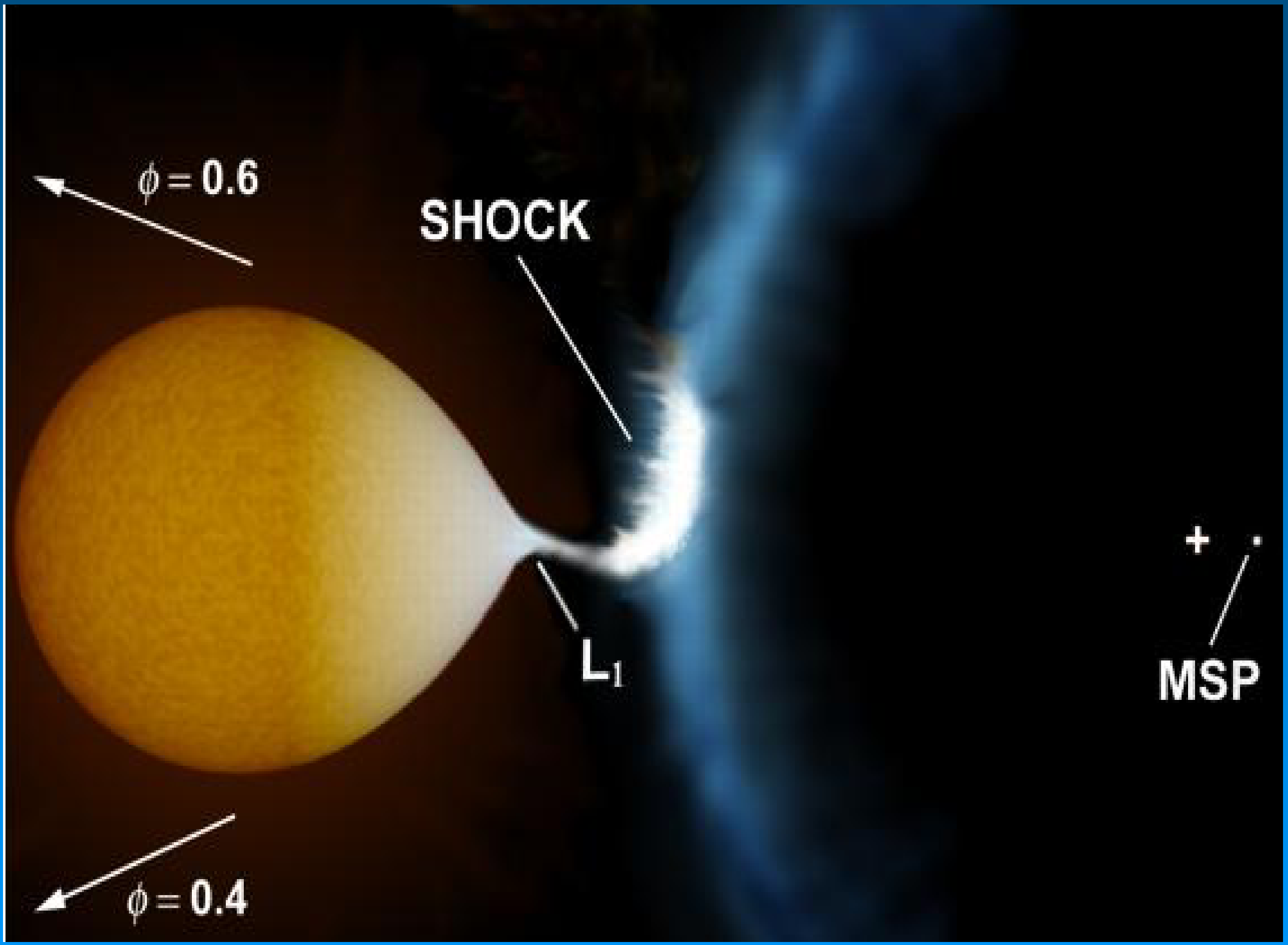


Fig. 4.— The broadband spectrum of 47Tuc W showing the X-ray (circles) and optical data at maximum (squares) and minimum (diamonds). Also shown is the best fit model for the total emission (black line), as well as for the individual emission components: thermal emission from the MSP (green line), blackbody emission from the secondary star at optical maximum and minimum (orange and red line, respectively), and non-thermal emission from the intrabinary shock (blue line). The dashed blue lines delineate the bounds of the 1σ uncertainty in the best fit non-thermal (power-law) model.

47Tuc-W: Cartoon (to scale) of shocked gas at L1



Asymmetric eclipse of *hard* flux: swept-back shock at L1
(Bogdanov, Grindlay and van den Berg 2005)

47Tuc-W ~same as accreting MSP J1808.4-3658!

(cf. Campana et al 2004 for XTEJ1808)

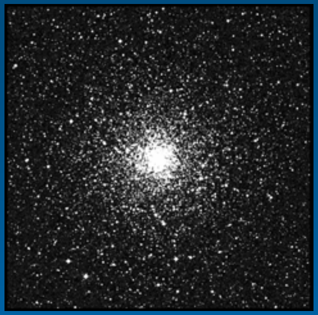
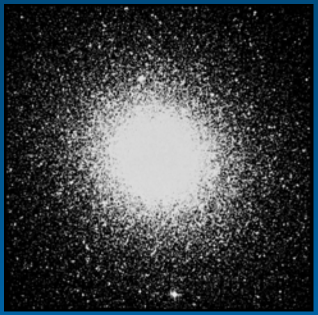
- Virtually identical X-ray/optical spectra: MSP wind (not X-rays) heats companion & provides hard synchrotron spectrum from shock

- "Symmetry" of MSPs and qLMXBs: shocked gas from MSP wind gives PL in (some) qLMXBs

- Hard PL X-ray spectrum, Lx and Fx/Fopt for MSP W *resembles CVs* -- contamination of both populations in GCs?

- Main sequence companion of "W" shows it has *re-exchanged its binary partner* (like MSP in NGC 6397). Degenerate dwarf secondary for XTEJ1808 is as expected for original partner. Possibly ~8% of MSPs in 47 Tuc have acquired new secondaries (Freire 2005)

47Tuc (King model) vs. NGC6397 (core collapsed)

	 NGC 6397	 47Tuc
distance (kpc)	~ 2.5	~ 4.6
mass (M_{sun})	~ 2 x 10^5	~ 10^6
core radius (pc)	~ 0.06	~ 0.5
central density (M_{sun}/pc^3)	~ 2 x 10^5	~10^5
central velocity dispersion (km/s)	~ 5	~ 12
relative collision rate ($\Gamma \sim \rho_c^2\, r_c^3/\sigma$)	1	~ 30

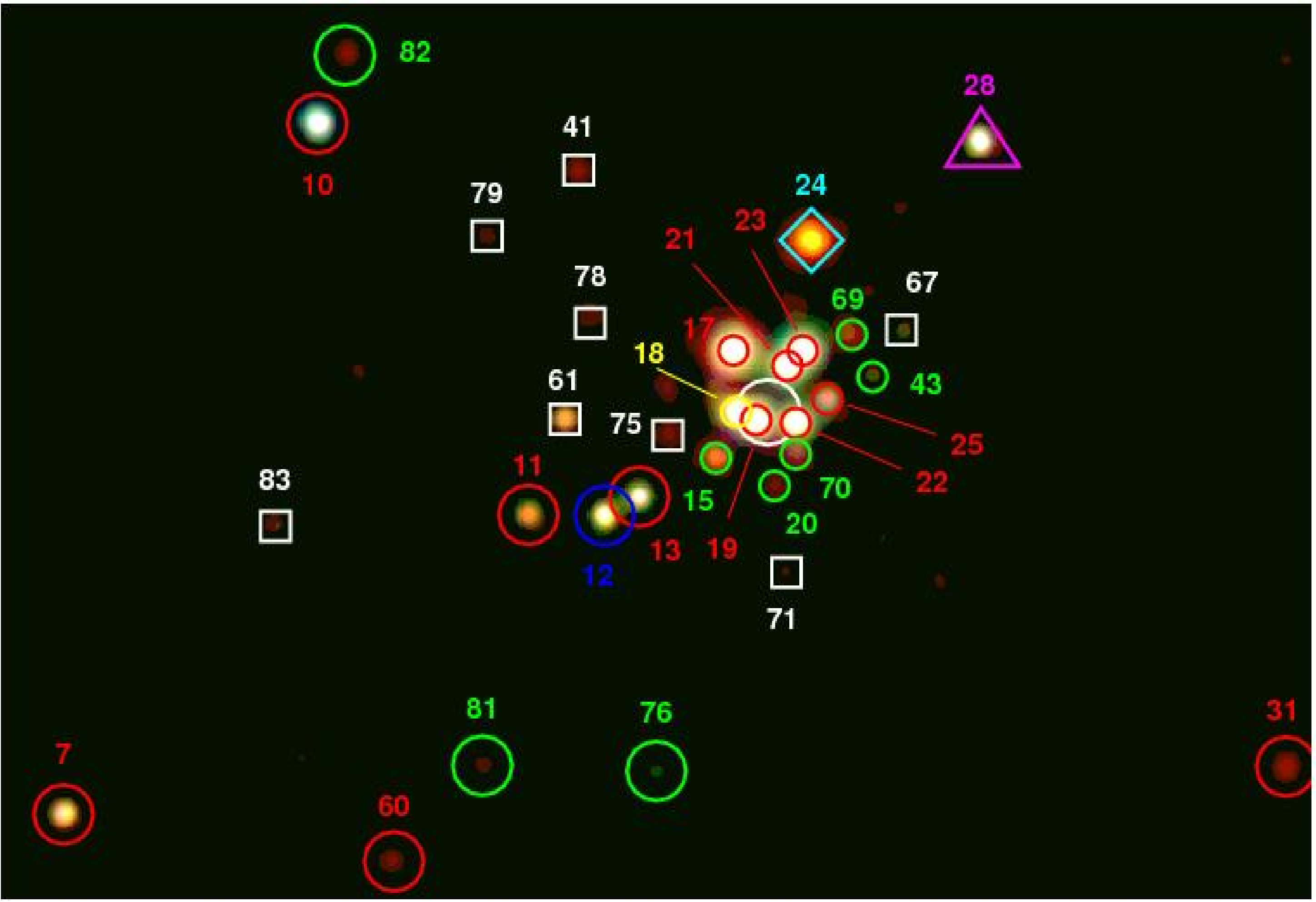
NGC 6397 followup Chandra and HST Study

2 x 28 ksec exposures with ACIS-S with 2d separation (May 13, 15, 2002) & HST processing:

- 12 CVs (4 new, 1 removed as background AGN!)
- 12 ABs (10 new IDs with HST or LCO variables)
- 1 MSP and 1 qLMXB (still; unchanged), but evidence for 2^{nd} MSP (U18) strengthened…
- ~15 unID for total of ~32 cluster sources

Combine with orig. (Grindlay et al 2001b) ACIS-I

NGC 6397 core: combined ACIS-I+S



Source IDs:

12-13 CVs

8 ABs +4 outside image

1 MSP + U18?

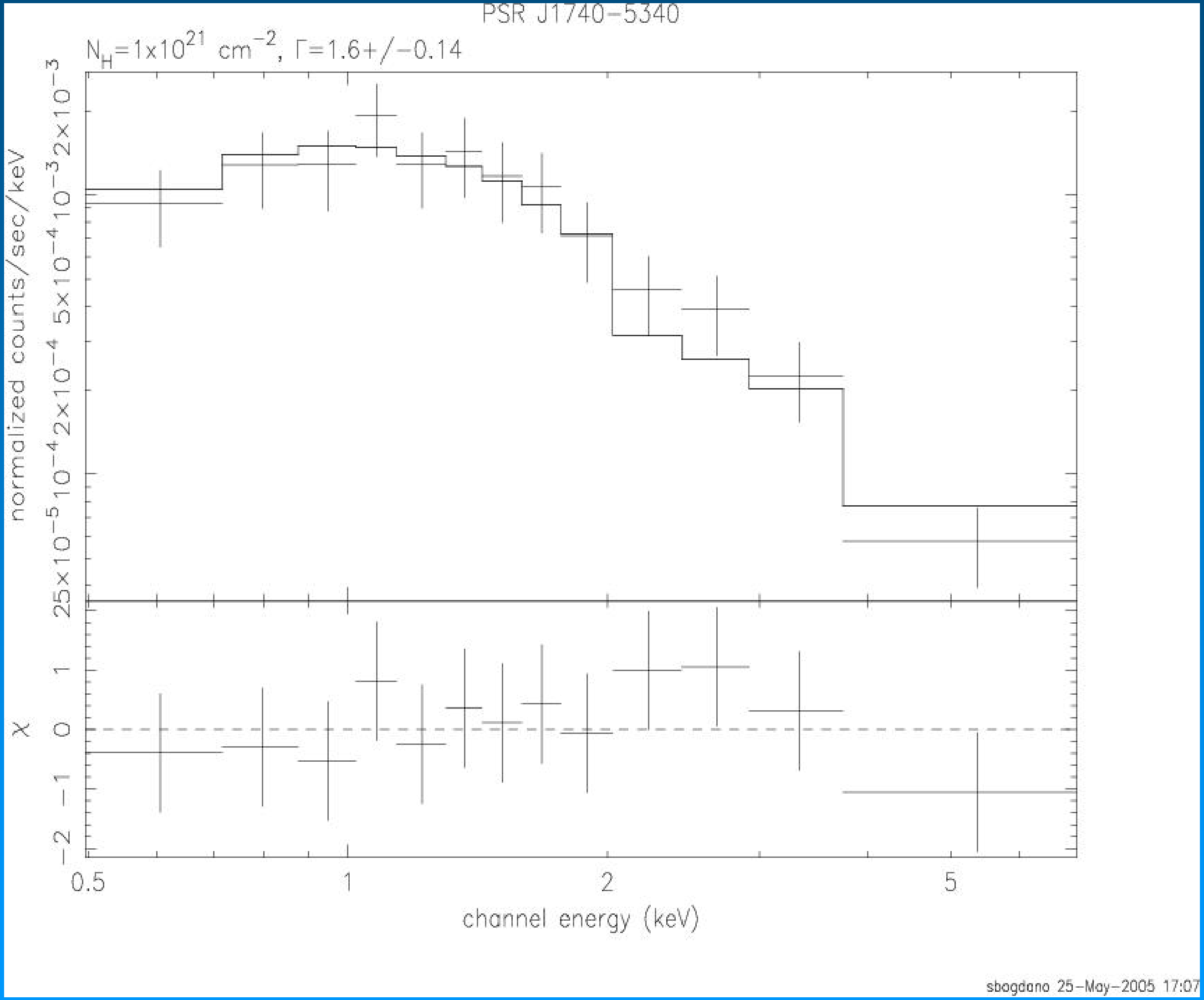
1 qLMXB

7 UNIDs +12 outside image

1 AGN (bkgd)

Major puzzle: anisotropic distribution of compact binaries? NO CVs, etc. to NW ??

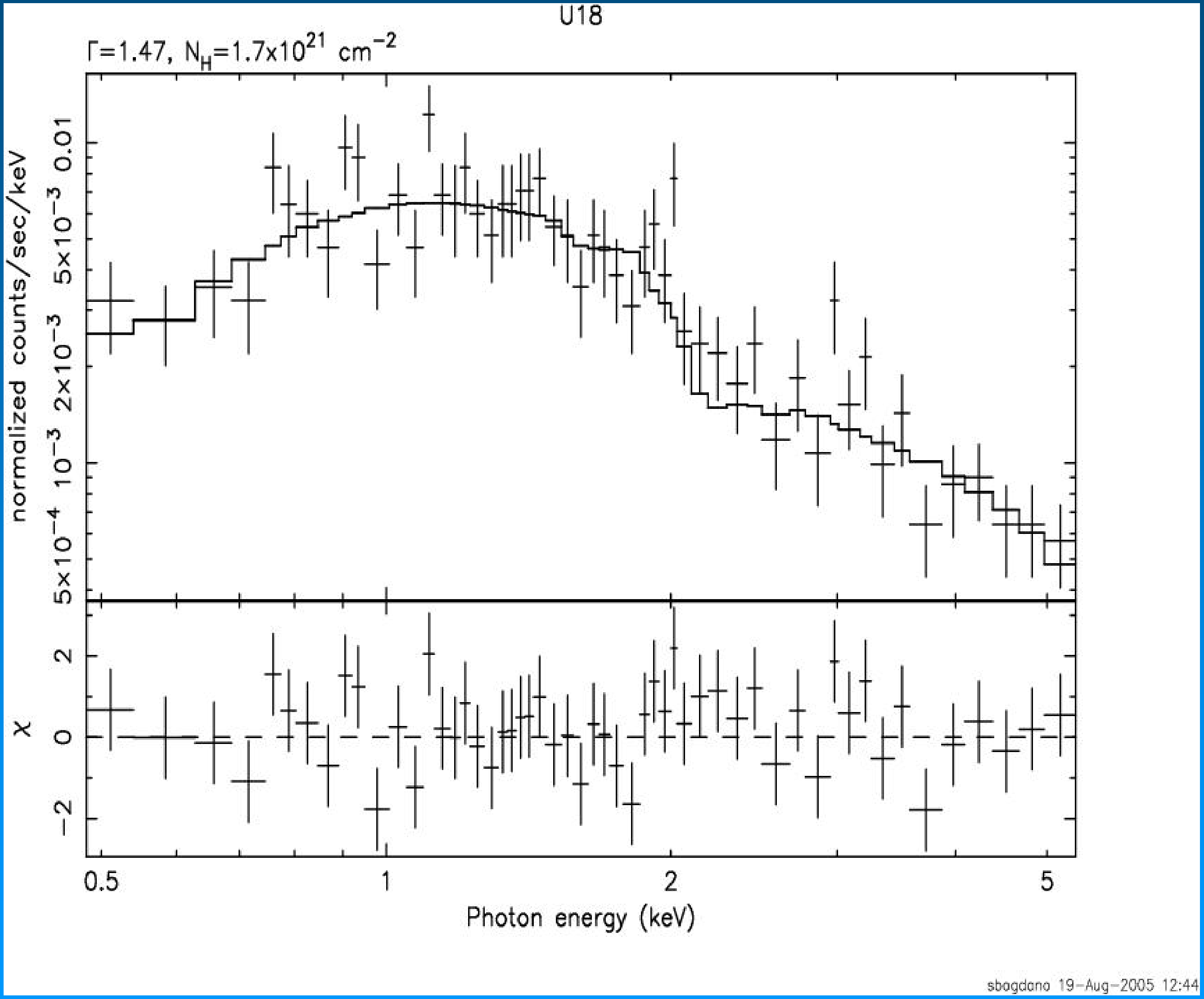
PL spectrum of MSP-6397A: PW shock at L1



Similar to 47Tuc-W: X-ray synch. radn. from shock (Grindlay et al 2006)

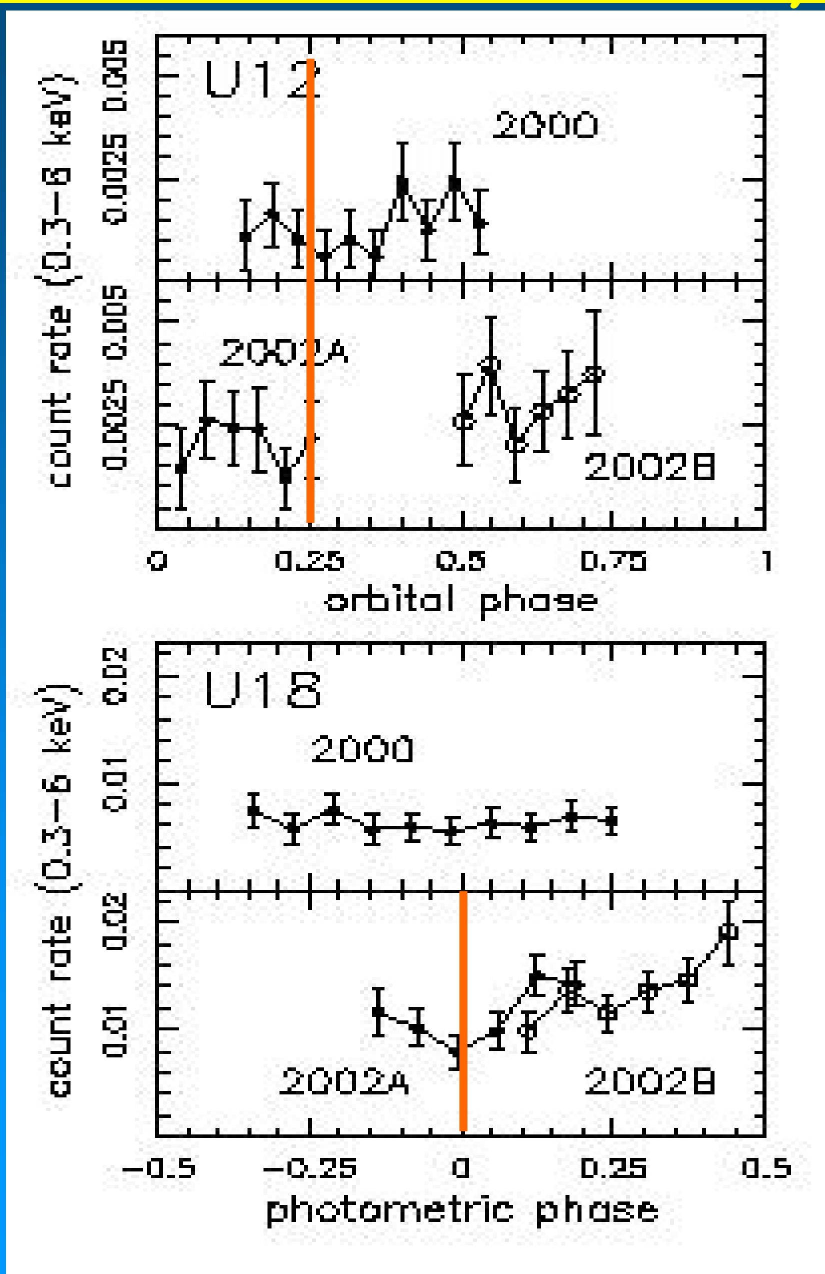
implies MSP PW has electrons with $\gamma_0 \sim 10^6$!

Candidate twin (X-ray/opt.) MSP-6397B?



Chandra source U18 (Grindlay et al 2001b, 2006) has ~same PL X-ray spectrum as MSP *& HST/optID also a "Red Straggler" : Enshrouded MSP?*

Both U12 (MSP) & U18 *may* have X-ray eclipses



Predicted X-ray eclipse on radio ephemeris for its known 33h binary Period of N6397-A.

Clearly better statistics needed & obs. proposed…

Predicted X-ray eclipse on optical ephemeris for *approximate 21.2h HST binary period for the optical ID* -- phasing possible *only* for the 2002 obs. ~2d apart.

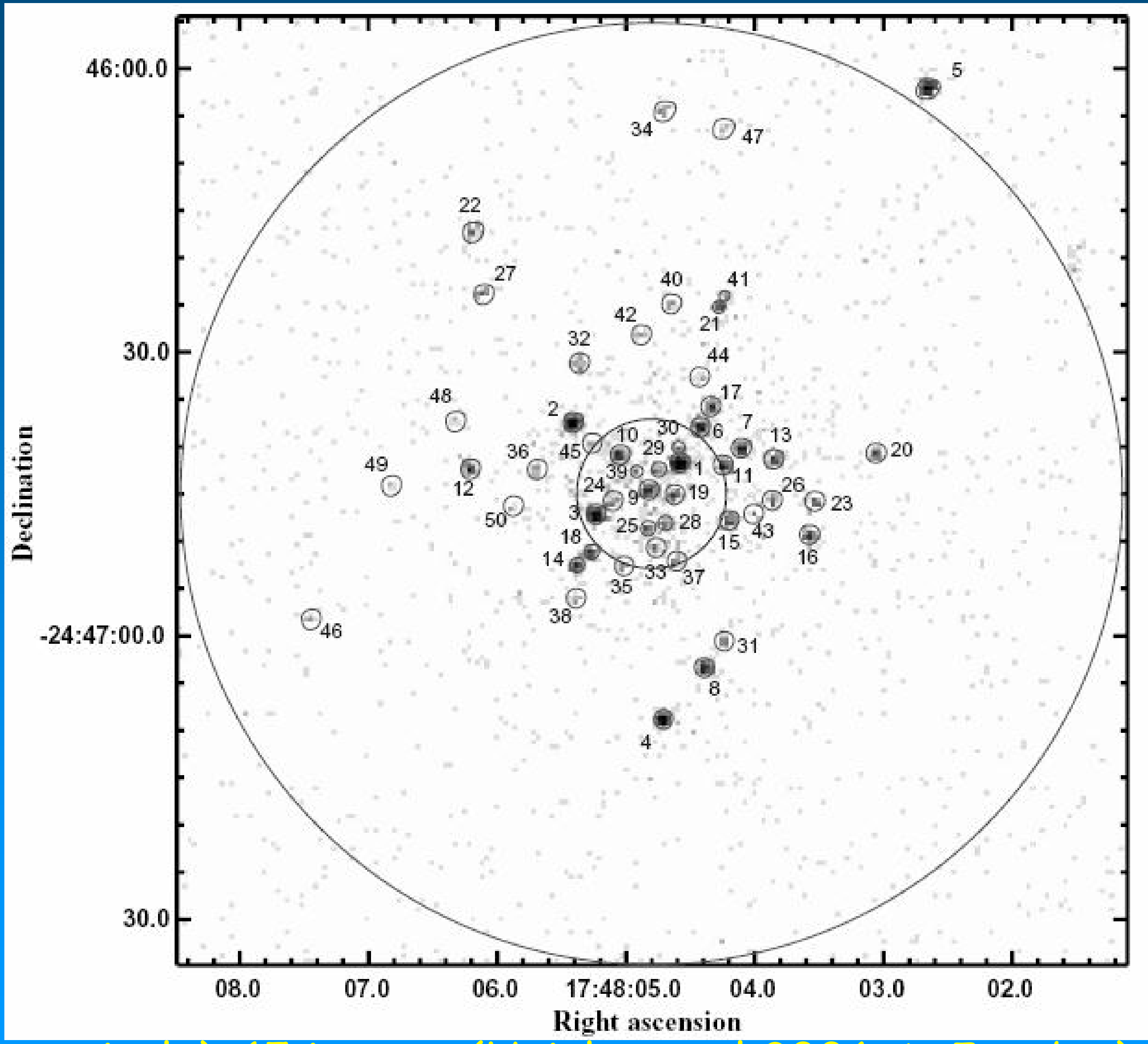
Results from ACIS-S on NGC6397

- *CVs highly variable; 4/6 CVs show binary modulation! New CVs (N ~12-13 total in cluster); low Lx (AM CVn?)*
- *CVs interior to ABs: ABs "burned" in core collapse by exchanging MS star for a WD*
- *U18 relatively constant: consistent with being like U12=known MSP: a doubly-exchanged secondary*
- *MSP –A shows variability consistent with radio eclipse*
- *Small number ABs (binary burning in core collapse?)*
- ***Ratio NSs/WDs in compact binaries ~0.1 of 47Tuc!***

→ so NS/WD ratio depleted by IMF (Grindlay et al 2006)

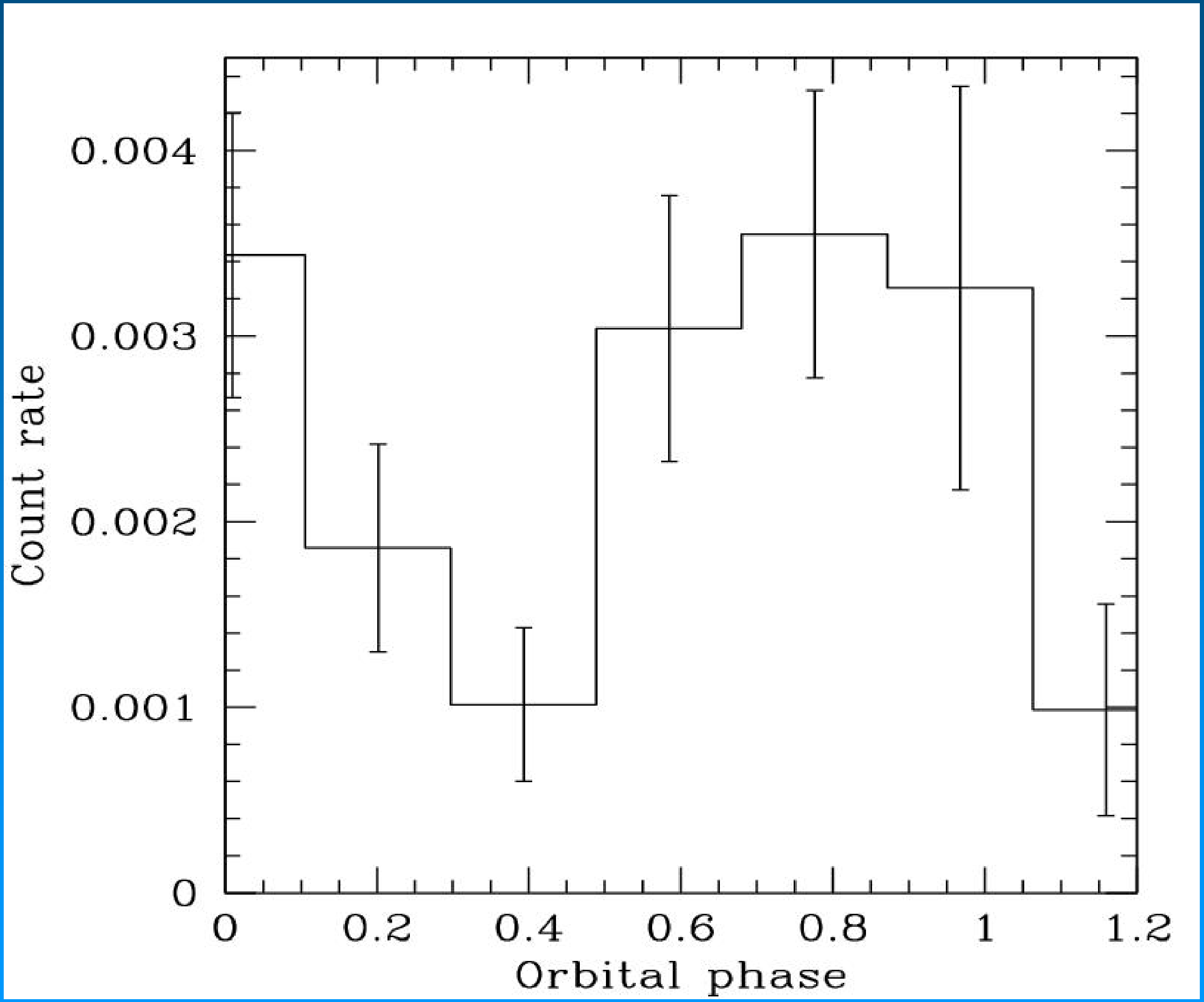
And… a deeper Chandra exposure of Terzan 5

- 50 sources with $L_x \geq 3 \times 10^{31}$ inside half-mass radius
- possibly 12 qLMXBs suggests ~120 MSPs!
- original MSPs A, C *not detected due to high NH*
- BUT eclipsing binary MSP-P probably ID with source 10; timing positions will allow check of full set



50 sources inside r_h (large circle), 15 in core (Heinke et al 2006,ApJ, subm)

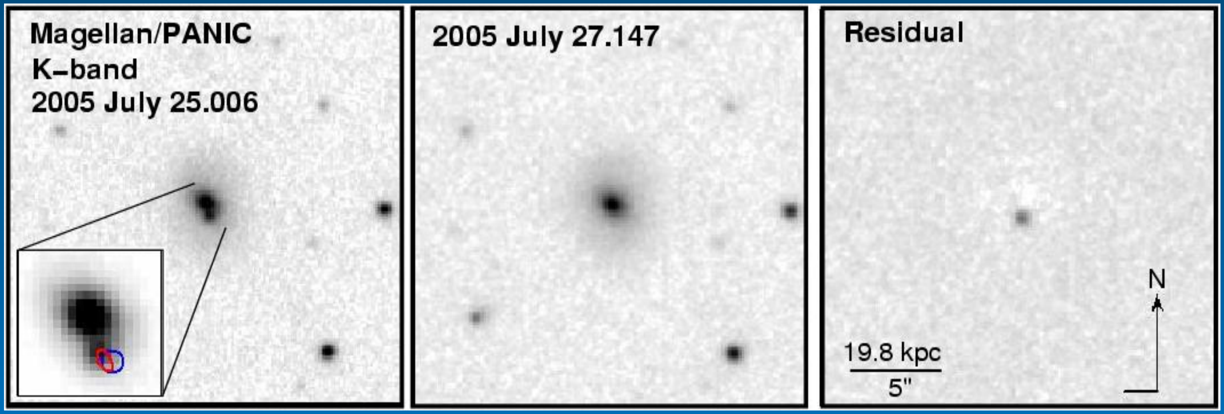
And… Ter5 MSP-P like 47Tuc MSP-W?



Chandra hard flux for source CX10 folded on 0.3626d binary period of Ter5 MSP-P:

Likely modulation suggests it is like 47Tuc-W and thus also has a re-exchanged MS companion

Swift: Short GRBs from *old* stellar systems…



- Berger et al, astro-ph/0508115 show that *Swift* short GRB050724 is from *elliptical* galaxy at z=0.257 (at R ~0.4 galaxy offset from center) from optical afterglow

- Most probably, first short GRB050509b also from halo of giant *elliptical* at z=0.225 (Bloom et al, astro-ph/0505480)

- And 3rd short GRB within 3kpc of star-formation galaxy can also be from old stellar system (globulars there too…)

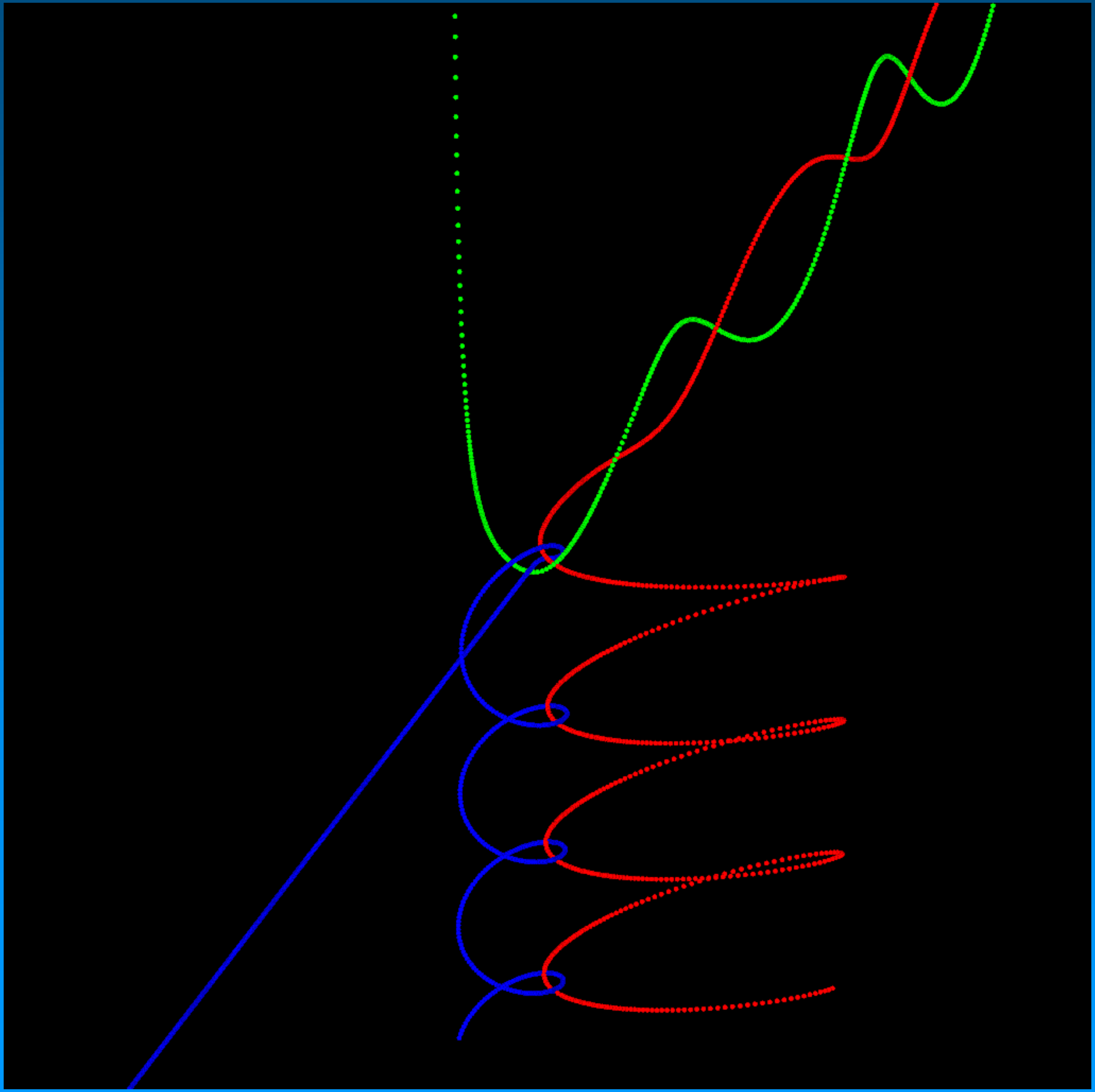
- And 2 more short GRBs in galaxy clusters: PopII origin for short GRBs

MSPs ⇨ Double NS Binaries in GCs: short GRBs

- Now clear that MSPs (and likely also CVs) are swapping partners in dense cluster cores
- *Thus MSPs can acquire NEW NS companions in globulars: single NS or MSP exchanges into MSP-WD ⇨ DNS !*
- This is likely origin of MSP M15C: P =0.33d, e=0.7 and large offset from core all consistent with NS swap, not (just) scattering of primordial DNS
- Thus, *GCs* "grow" DNS binaries in compact orbits which will *coalesce* , and thus *are likely source of NS mergers: short GRBs (and gravitational waves)*

(Grindlay, Portegies Zwart & McMillan 2006, Nature Physics, 2, 116)

Exchange of MSP into MSP-MS (LMXB)



LMXB (= NS + MS) encounters isolated NS in dense core of a globular cluster.

Exchange interaction produces double NS (NS + NS) in eccentric orbit which merges by gravitational wave inspiral after ~100My to produce a Short GRB!

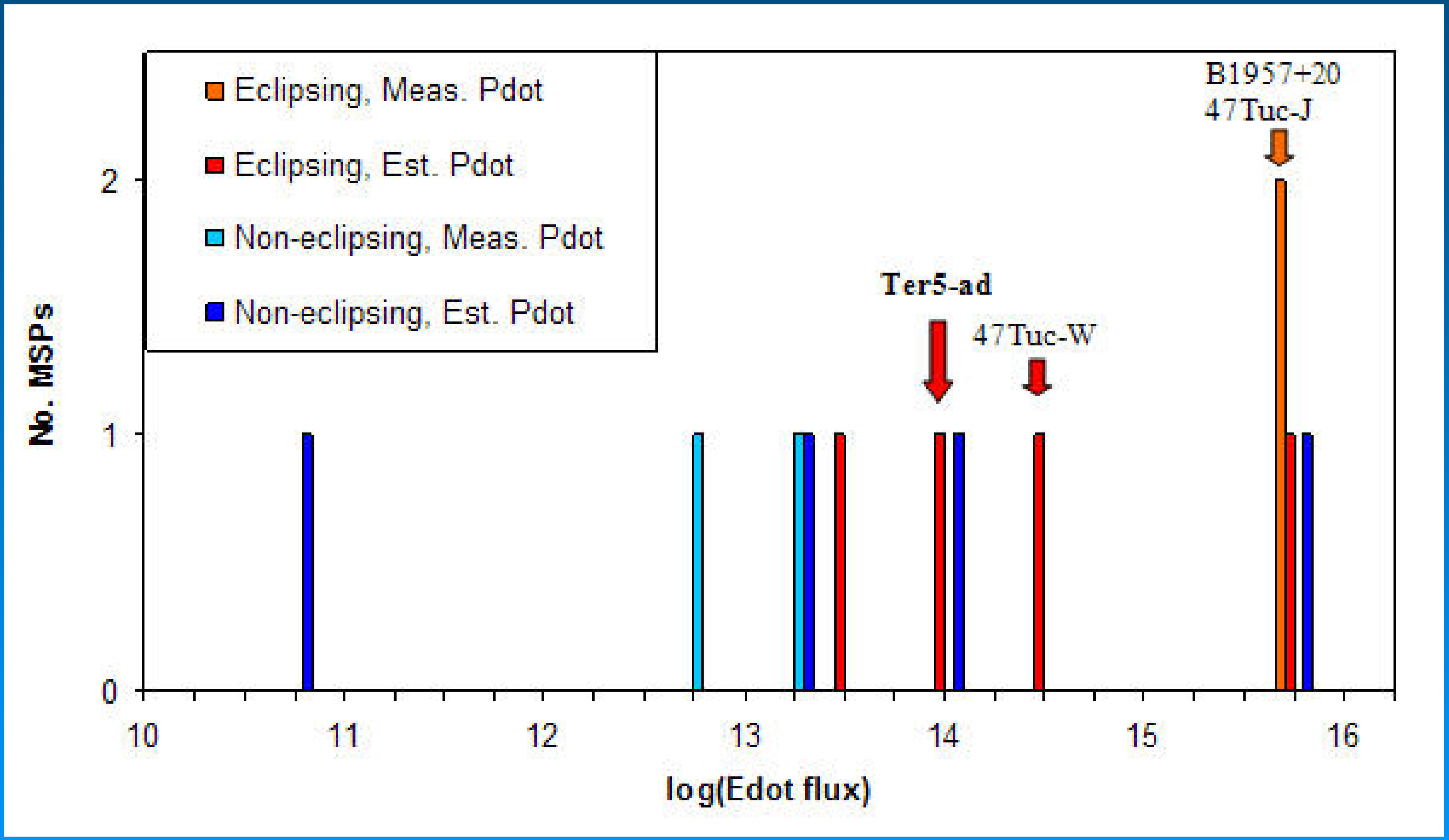
And, finally: what sets fastest MSP spin?

- Newly discovered 716Hz MSP in Ter 5-ad (Hessels et al 2006, Science, 311, 1901) further pushes ~760Hz limit suggested by Chakrabarty et al 2003, Nature, 424, 42

- Are faster MSPs “prevented” from discovery by
  - Gravitational radiation loss of J (Chakrabarty et al)?
  - Enhanced PW ablating binary companion? (No; see Figure…)

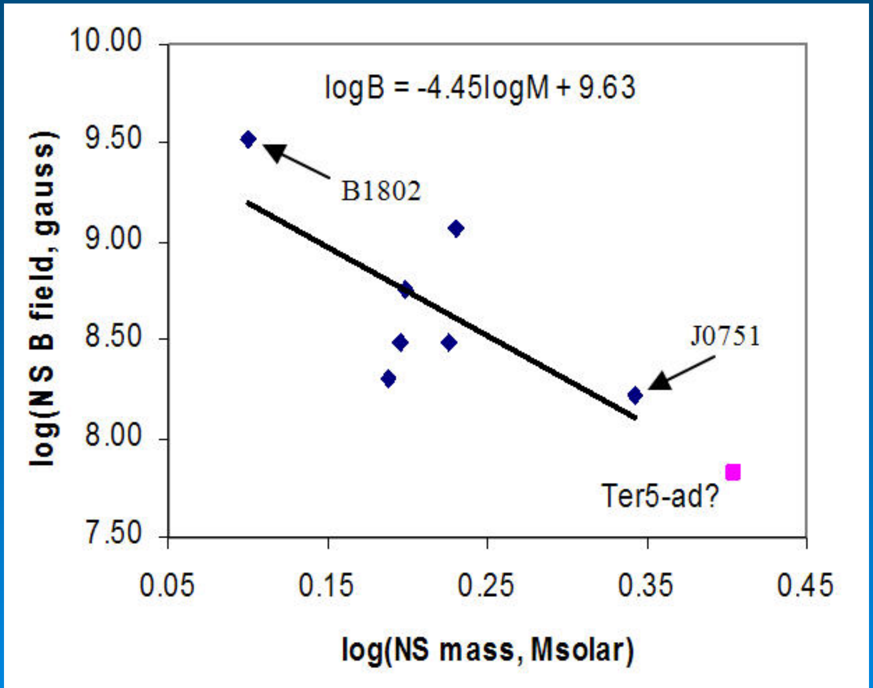
- Or, does the continued Mdot for further spinup continue to reduce (bury) B below threshold for pulsar to pulse?! (Yes; see Figure and Grindlay 2006, Science, 311, 1876)

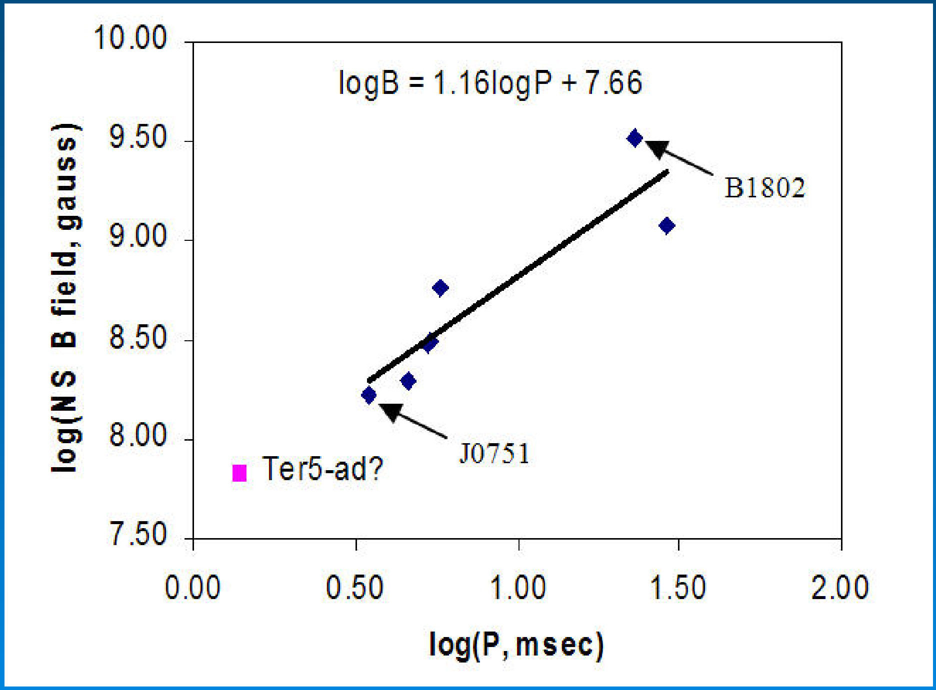
Are faster MSPs hidden by PW?



Probably not: Ter5-ad does not have largest PW flux at companion, even for upper limit on Pdot used here.

Or, is B reduced by continued Mdot for shorter P?





Possibly YES: Plot (above) 7 MSPs with NS mass measures with $\delta M_{NS}/M_{NS} \leq 10\%$ (masses from Lattimer & Prakash 2004, Science, 304, 536): B appears inversely correlated with M_{NS}!

Ter5-ad predicted (by correlations) to have M ~ 2.4M. and B ~ 7 x 10^7 G and thus Edot ~3 x 10^{-21} s/s – confirm with timing solution. *B becomes too small to pulse!* (Grindlay 2006, Science, 311, 1876)

Conclusions and Questions…

- *Active binaries are bright x-ray markers of compact binary formation/destruction (destroyed in NGC6397?)*
- *MSPs (as oldest pop.) have most multiple encounters. Confuse with CVs when acquire m-s partners; observed X-ray MSP numbers thus lower limits ?*
- *MSPs vs. CVs in 47Tuc vs. N6397 vs. Ter5: probe IMFs in GC s and/or cluster dynamical evolution ?*
- *Binary partner swapping common (~8% of known GC –MSPs?): What are effects on MSP spin history and B field topology?*
- *Short GRBs produced by DNS mergers primarily(?) from MSPs in GCs*
- *MSP max spin freq. may be natural result of decreasing B (by continued accretion to spinup NS) to below critical pulsar value*