Chandra Results on X-ray Sources in Globular Clusters

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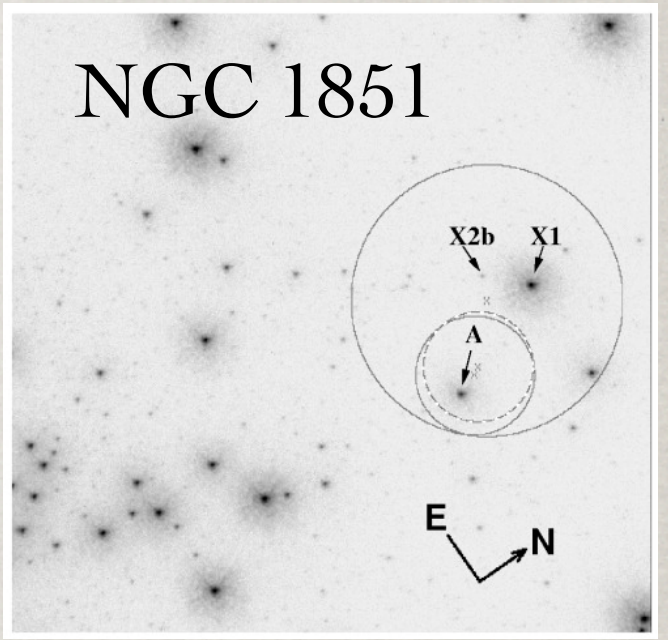
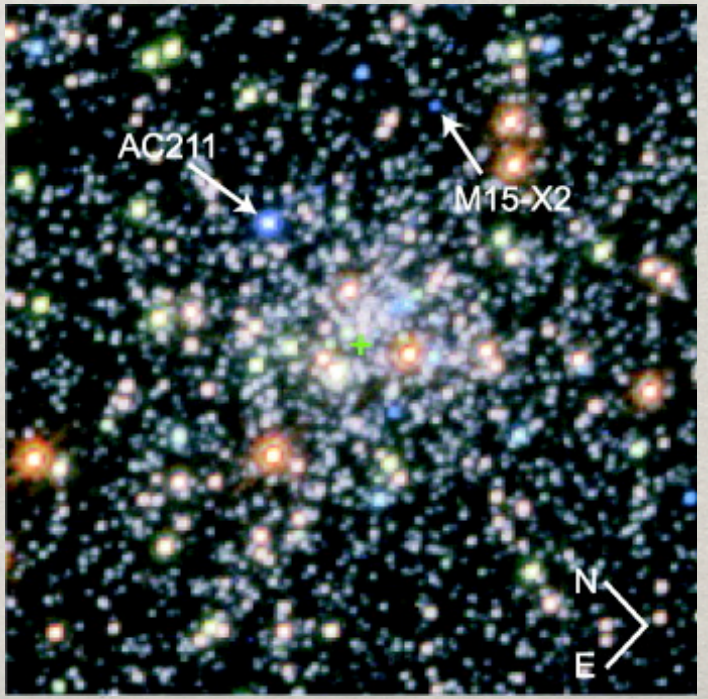
Clusters as LMXB Factories

- 13 of 150 LMXBs are in globular clusters, but only ~1/1000 of Galaxy's stars are in clusters
- LMXB formation linked to high density; theories include
  - Tidal capture: close encounter drains KE into tides (Fabian75)
  - Partner swapping: NS exchanges into existing binary (Hills76)
  - Direct impact: NS strikes giant (Verbunt87)
- Encounter rate parametrized as $\Gamma = \rho^2 r_c^3/\sigma \propto \rho^{1.5} r_c^2$

Chandra on Bright LMXBs

- Chandra allowed separation of two bright LMXBs in M15 (White01)
- Gave precise positions for all bright LMXBs, allowing HST identifications (M15, White01; NGC 1851, Homer01; NGC 6652, Heinke01; NGC 6441, Homer02)
- Two new IDs (4 total) have ultracompact orbital periods (P<1 hour; Dieball05), suggesting direct impact (NS-RG) common in globulars

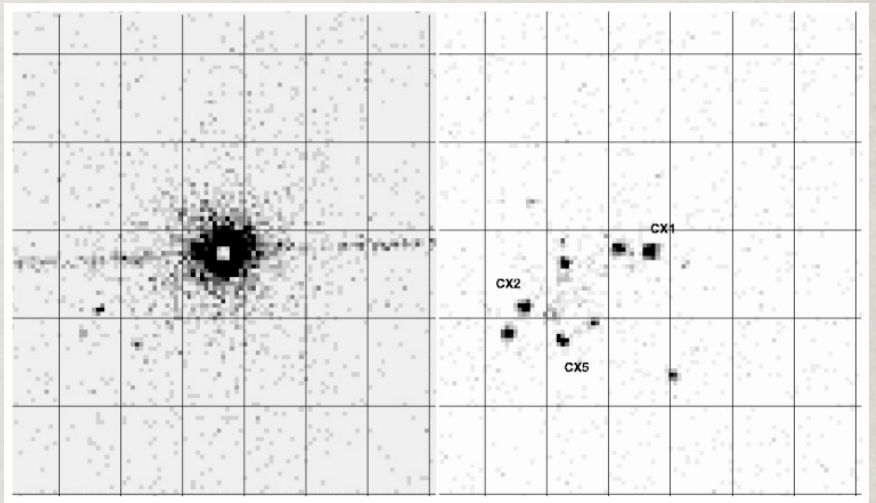




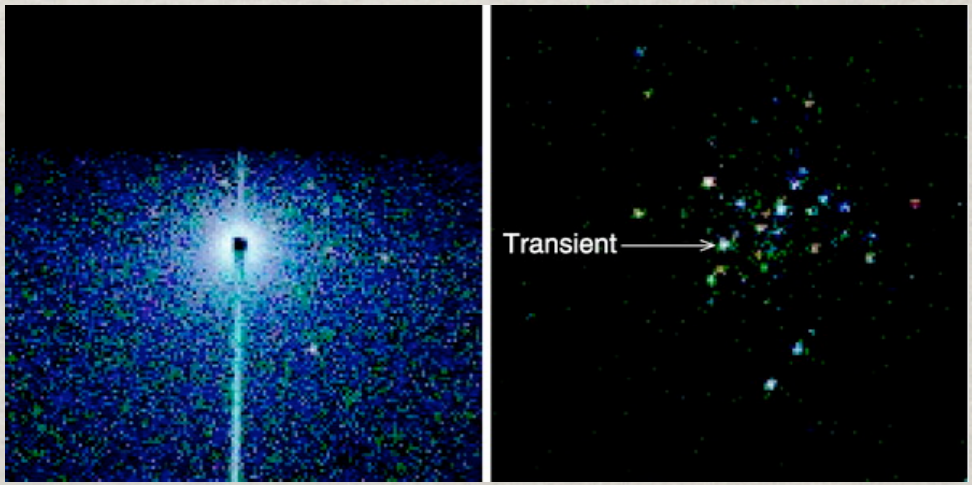
M15

Transient LMXBs in Quiescence

- >5 of 13 LMXBs in globulars are transient
- LMXBs in NGC 6440, Terzan 5, and (probably) Terzan 1 identified in quiescence (in't Zand01, Wijnands05, Cackett06)



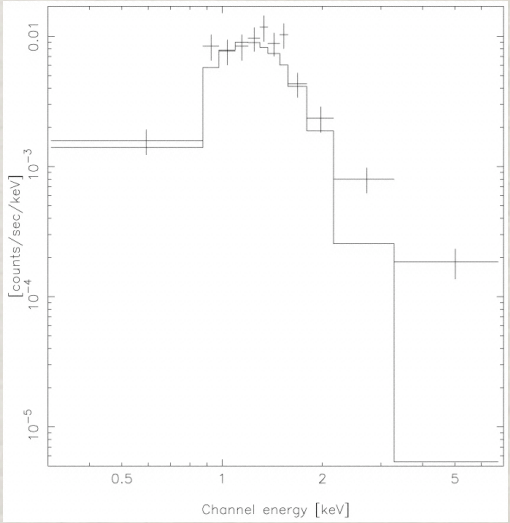
NGC 6440, in't Zand01



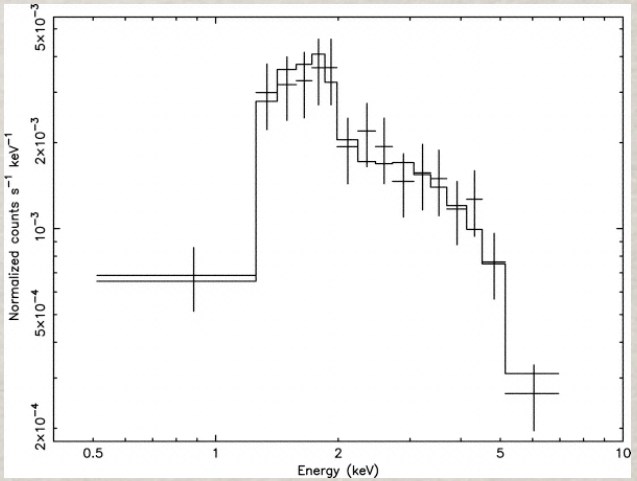
Terzan 5, Wijnands05

QLMXB Spectra

- qLMXBs generally show soft blackbody-like spectral component, modeled as H atmosphere on NS with radius ~10-14 km (Zavlin+96, Brown+98)
- Additional component at high energy often seen, modeled as power-law of index ~1-2
- Accurately describes NGC 6440, Terzan 1 transients (in't Zand+01, Cackett+06)
- Terzan 5 transient, however, shows strong power-law with no soft component required (Wijnands+05)



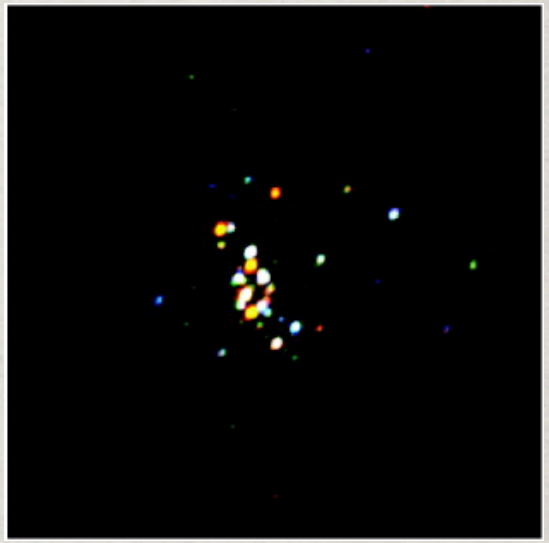
NGC 6440, H-atm



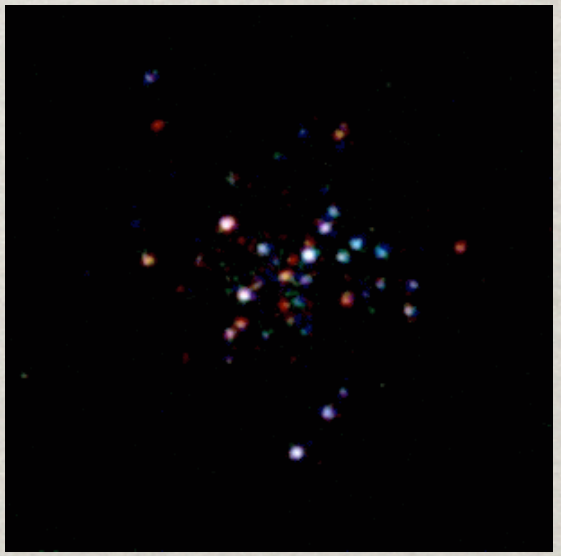
Terzan 5, power-law fit

Additional qLMXBs

- Many faint X-ray sources identified with similar spectra, L_X as known qLMXBs (Grindlay+01a,b, Rutledge+02, Heinke+03a)
- Optical (HST) counterparts identified for two (Edmonds+02, Haggard+04); others have very faint limits
- X-ray eclipses identified in two, with periods of 8.7 and 3.1 hours (Heinke+03b, Heinke+05a)



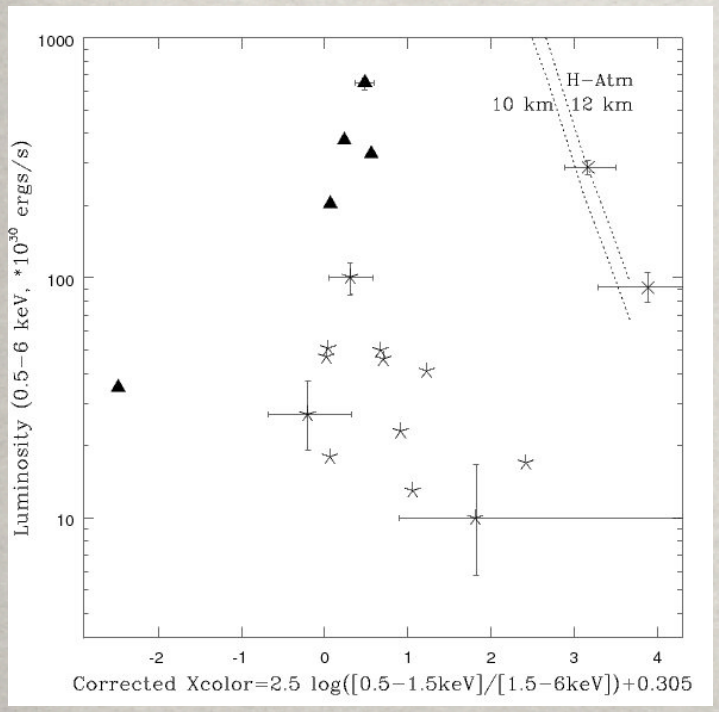
NGC 6266, Pooley03



Terzan 5, Heinke06a

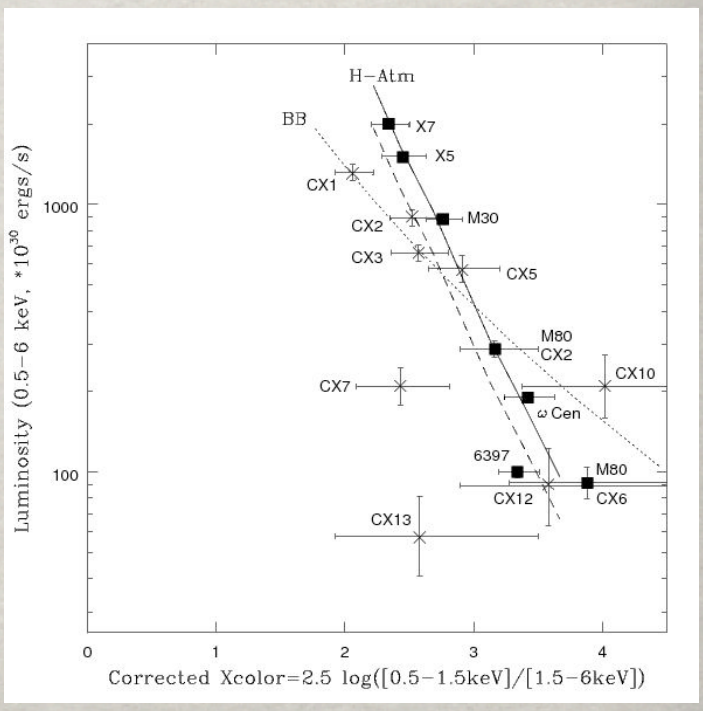
Identifying qLMXBs

- Many qLMXBs in GCs well-fit by H-atm model
- Low-count X-ray srcs' colors match H-atm or typical hard CV X-ray spectrum



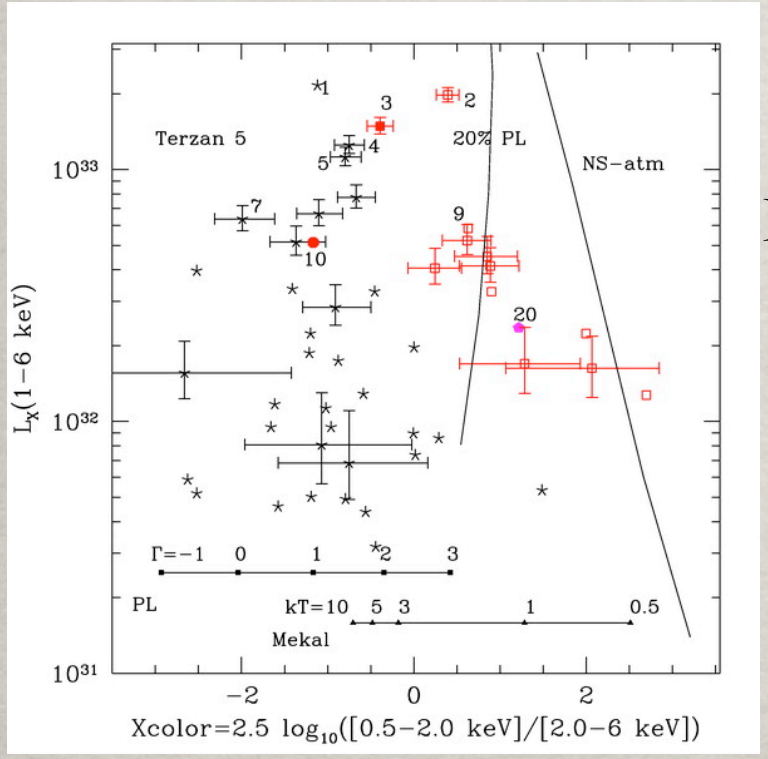
L:M80 XCMD, Heinke+03a

R: XCMD for all GC qLMXBs, Heinke+03b



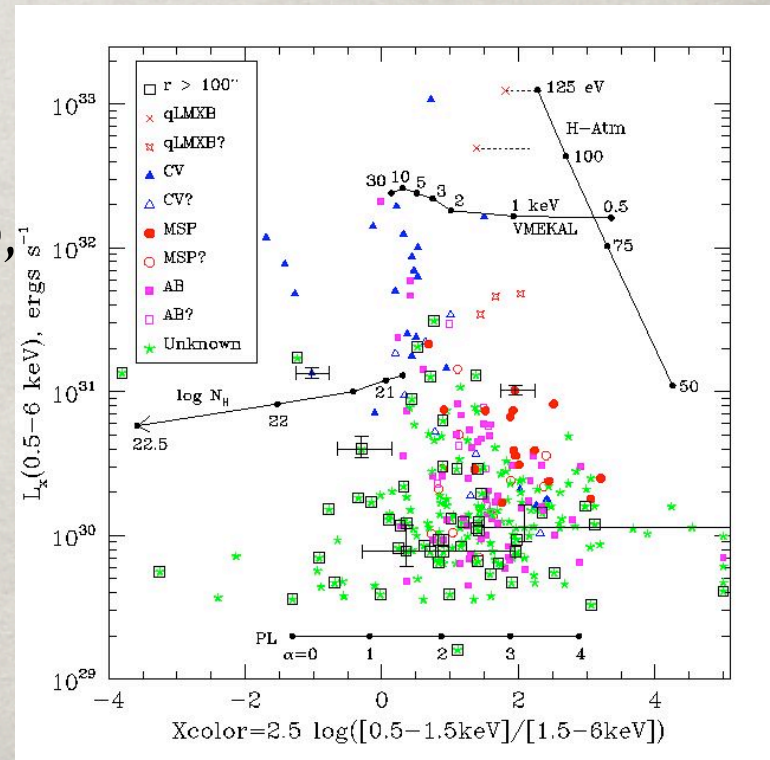
Identifying qLMXBs

- But--Known qLMXBs have power-laws (e.g. Wijnands+05)
- Terzan 5 and *47* Tuc have qLMXBs with hard PL components



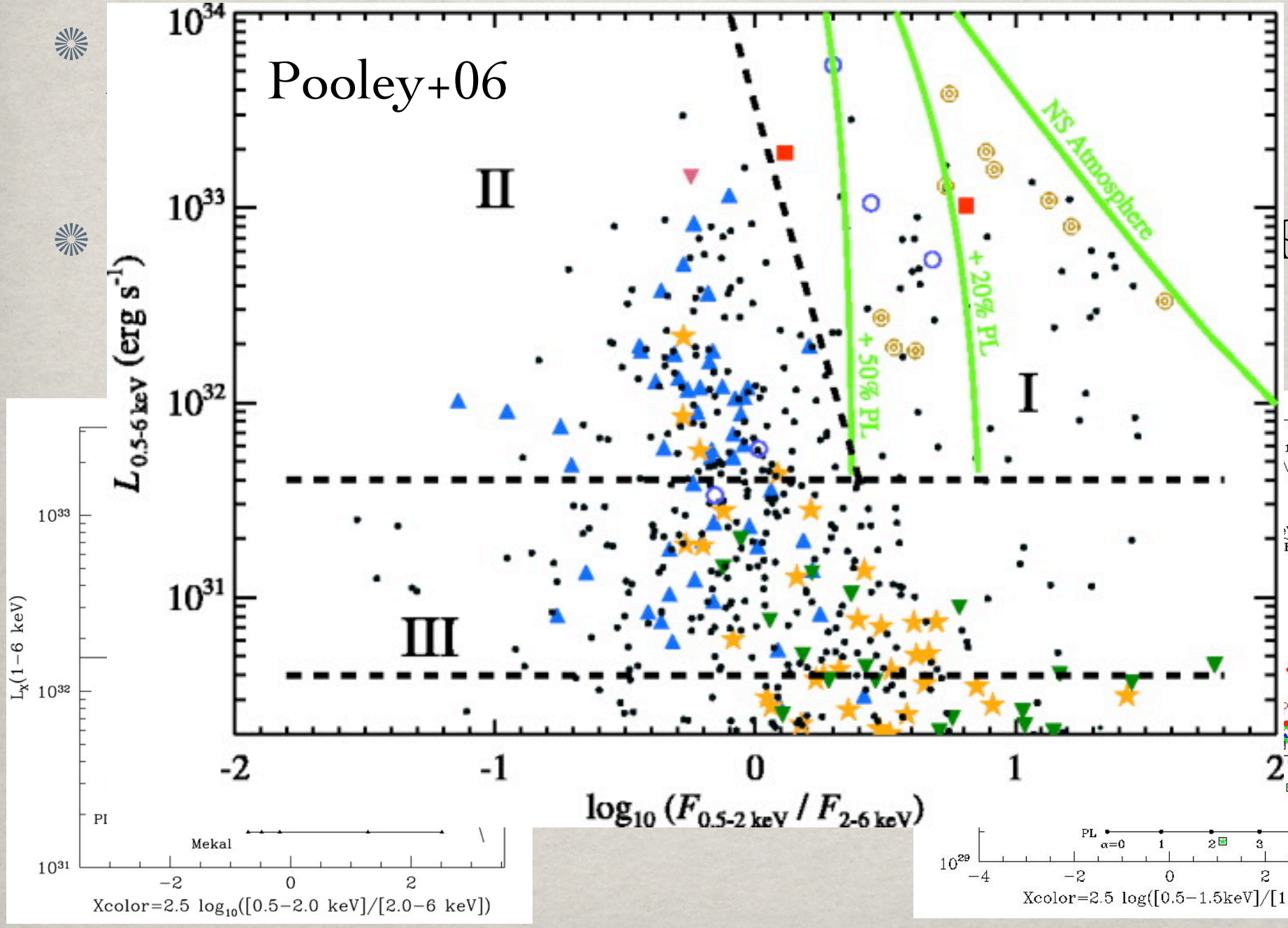
L: Terzan 5 XCMD, Heinke+06

R: *47* Tuc XCMD, Heinke+05



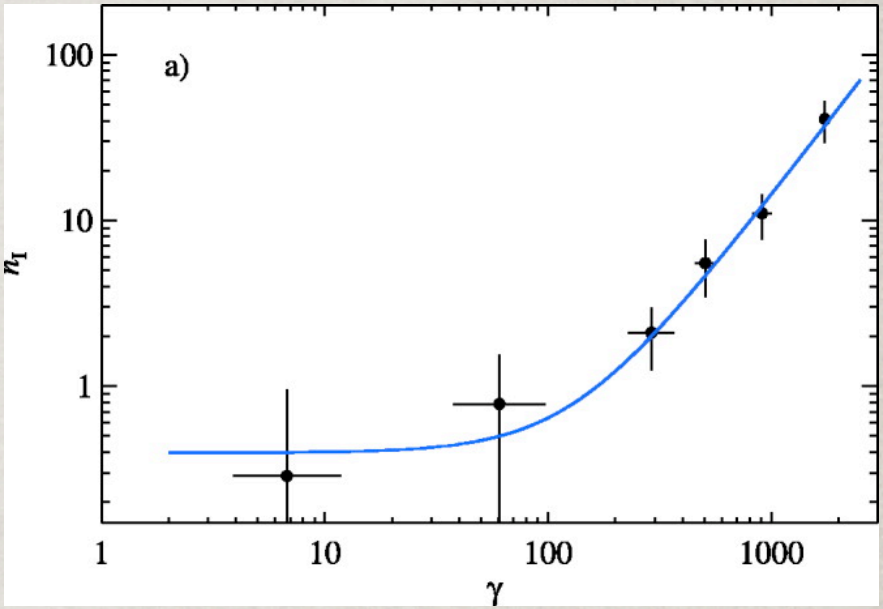
Identifying qLMXBs

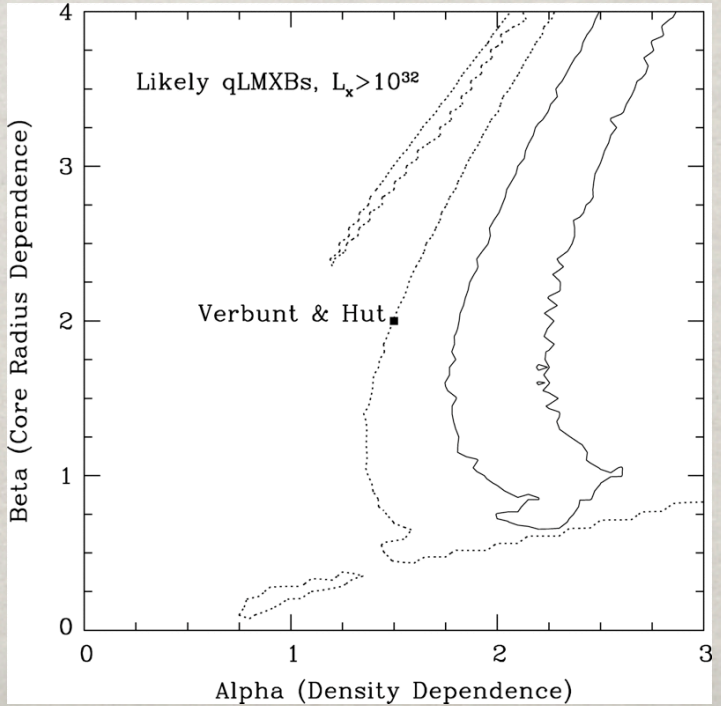
- Pooley+06
- PL



qLMXB Density Dependence

- Pooley+06: $N=C_X+A_X\Gamma^{\alpha}$. Found $\alpha=1.75+0.43-0.36$
- Heinke+06: $\Gamma=\rho^{\alpha}r_c^{\beta}$. Found $\alpha\sim2.1+1-0.6$
- Strong dependence on density, maybe too strong
- Extrapolating: ~100-200 qLMXBs in GC system

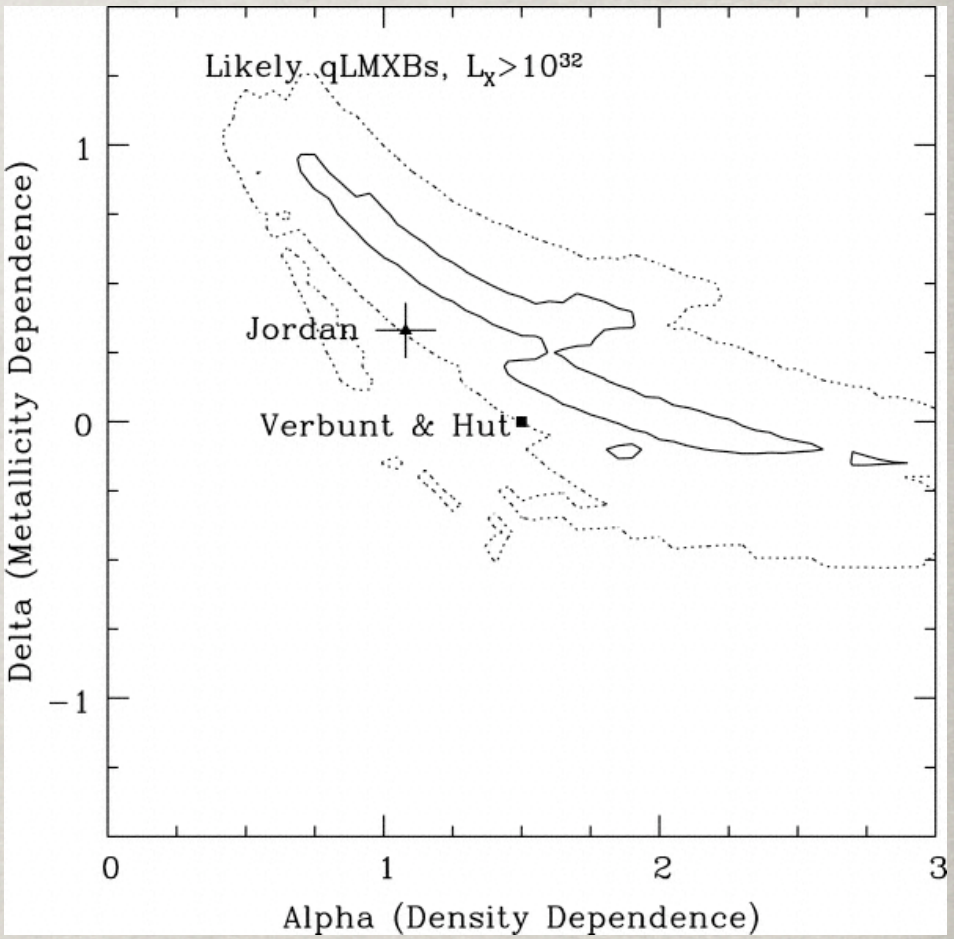




Compare with Extragalactic GCs

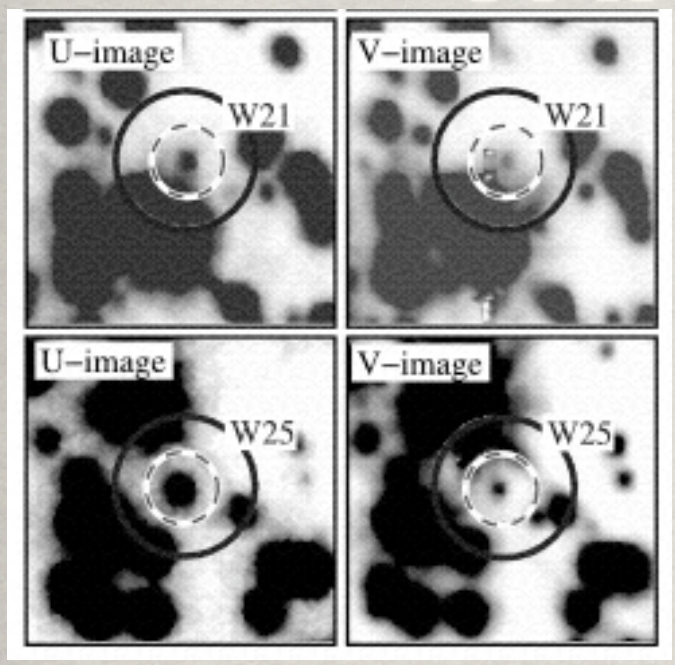
- Clear metallicity dependence (Kundu+03)
- In extragalactic GCs, LMXB $N \propto \Gamma^{0.82\pm0.05} Z^{0.39\pm0.07}$,

  (Sivakoff+07, Jordan+04)
- Set $\Gamma = \rho^{\alpha} r_c^{2} Z^{\delta}$;
  Galactic GCs allow either

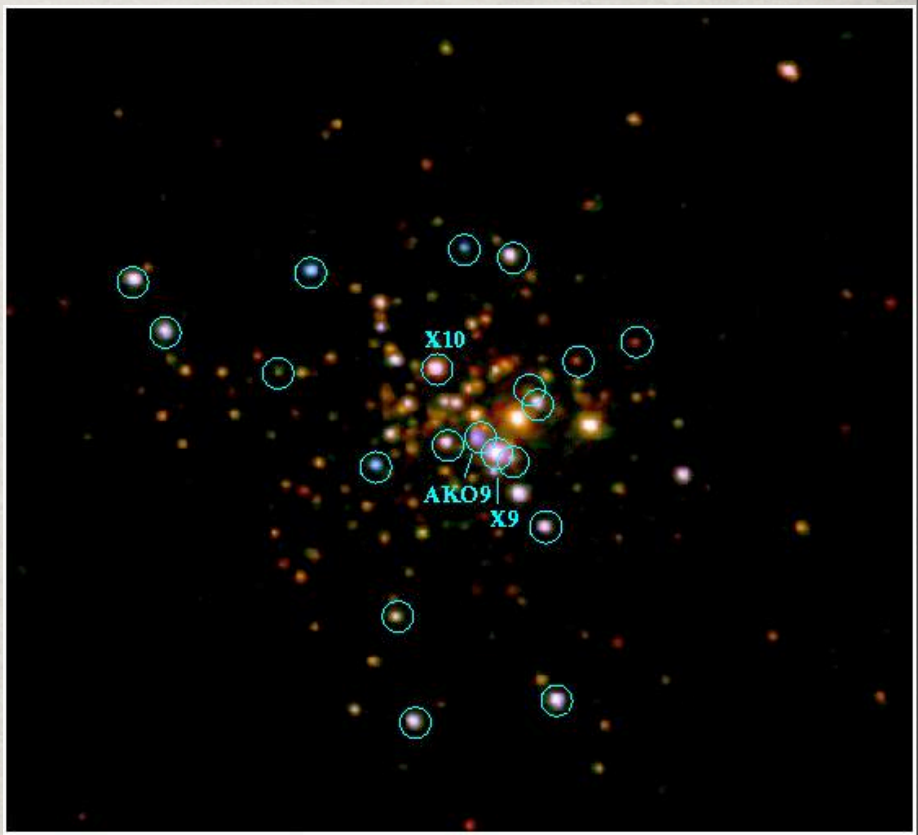


Heinke+06

Cataclysmic Variables (CVs)



Finding charts for 2 CVs in *47* Tuc, Edmonds+03a

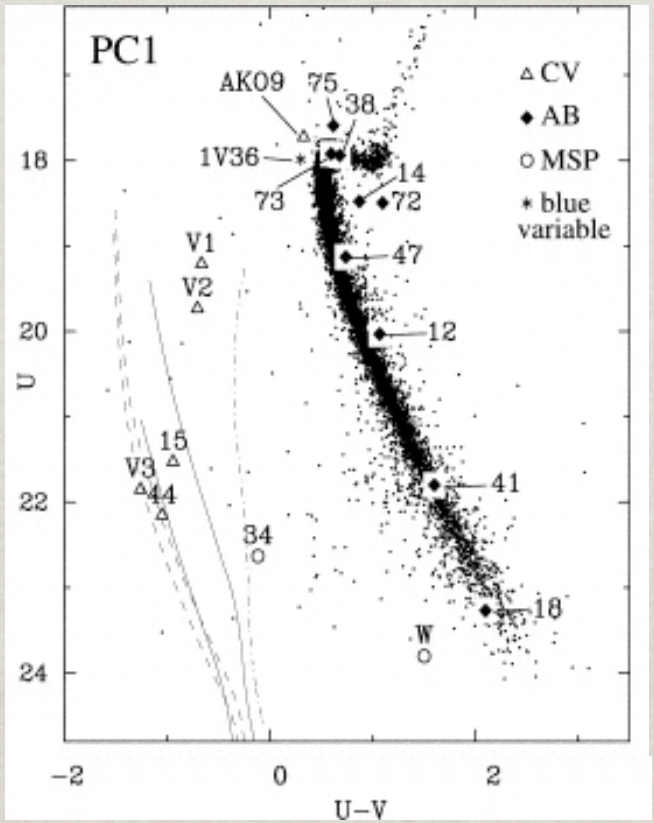


X-ray counterparts of CVs in *47* Tuc

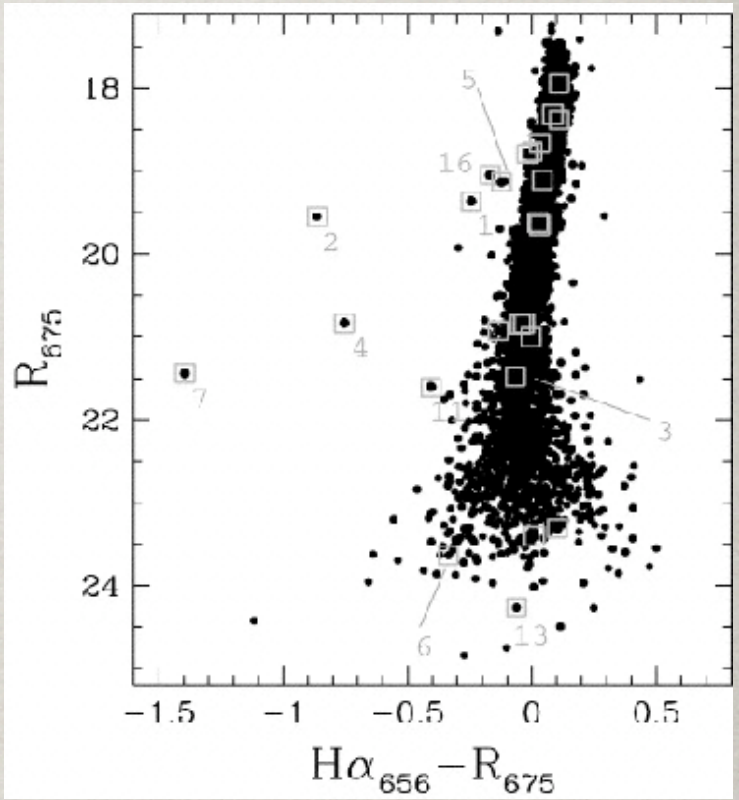
- Faint Einstein, ROSAT X-ray sources suggested to be CVs (Hertz+83, Cool95)
- Chandra and HST confirm blue, variable counterparts to X-ray sources (22 in *47* Tuc: Edmonds03a; 10 in NGC 6752, Pooley02; 9 in NGC 6397,Grindlay01b)

X-ray CV Properties

- Blue in U-V, redder in V-I, Hα emission
- Optical flickering, ellipsoidal variability
- F_X/F_{Opt} ~0.2 to 30
- Periods from 1.7 to 26.6 hours



U vs. U-V CMD,
47 Tuc, Edmonds03a



R vs. Hα-R CMD,
NGC 6752, Pooley02

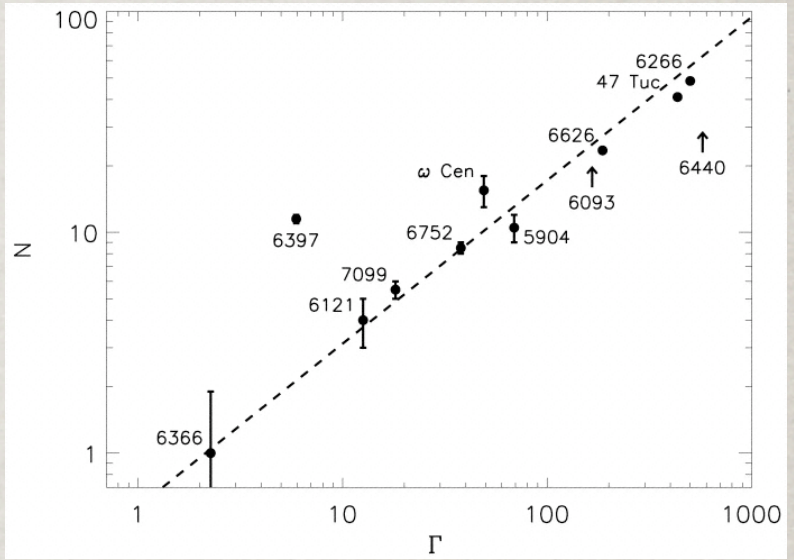
CV Density Dependence

- Total # srcs $\propto \Gamma^{0.74\pm0.36}$,

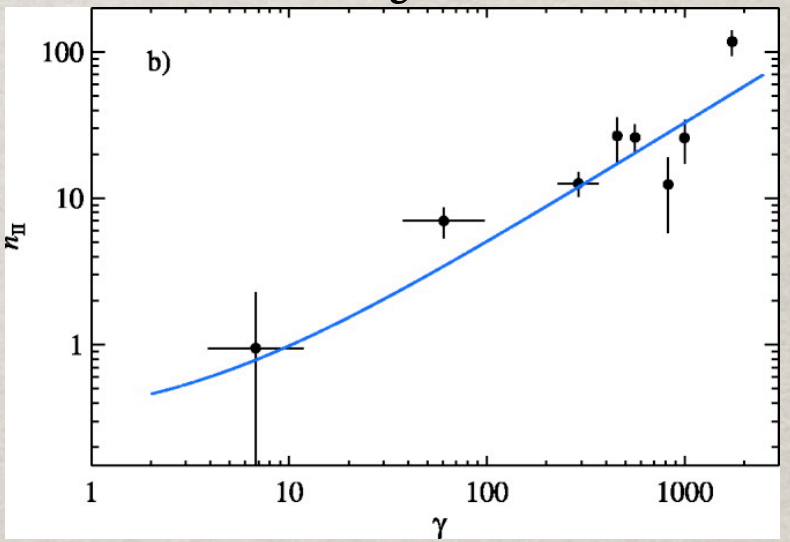
  dominated by CVs (Pooley+03)

- For CV sample: $N=C_X+A_X\Gamma^{\alpha}$, $\alpha=0.83^{+0.29-0.25}$ (Pooley+06)

- Majority of CVs in GCs formed dynamically; some may be primordial



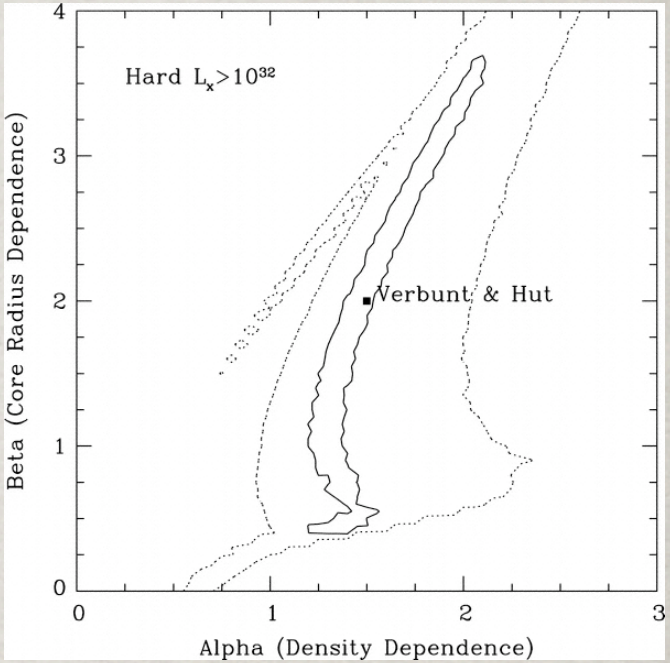
Pooley+03

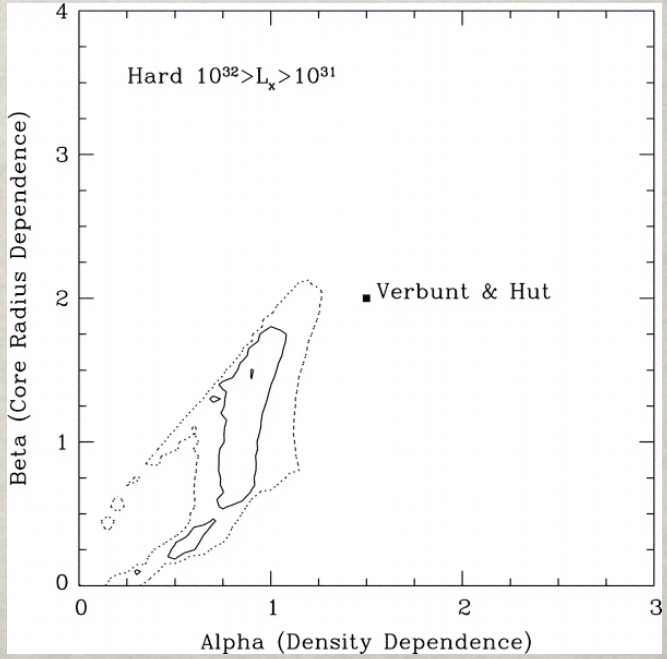


Pooley+06

CV Density Dependence

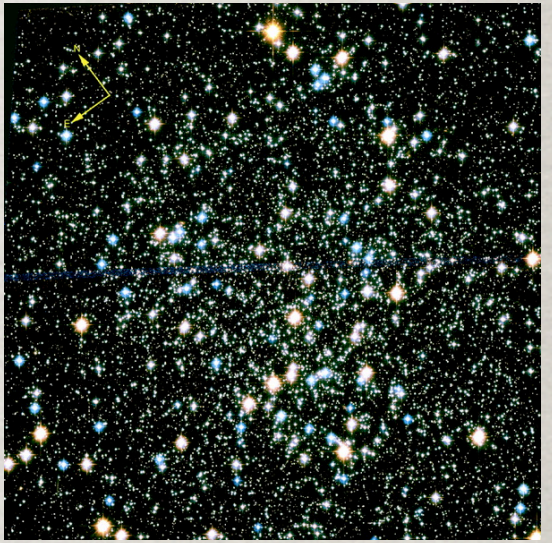
- Heinke+06:Divide CVs @ $L_X=10^{32}$
- Brighter CVs appear dynamical
- Faint CVs lower ρ dependence; some primordial CVs?



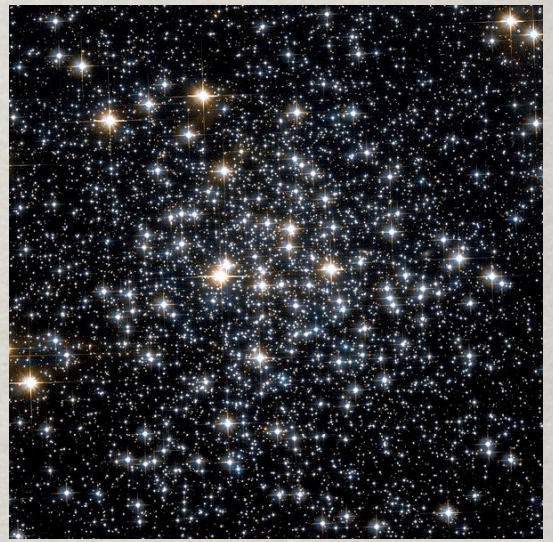


CVs in Sparse Clusters

- Credible CV candidates in 4 sparse clusters; NGC 288 (Kong+06), M55 & NGC 6366 (Bassa+08), M71 (Huang+09)
- 4 to 20% of M4's Γ; M4 has 1 CV
- Evidence some CVs are primordial

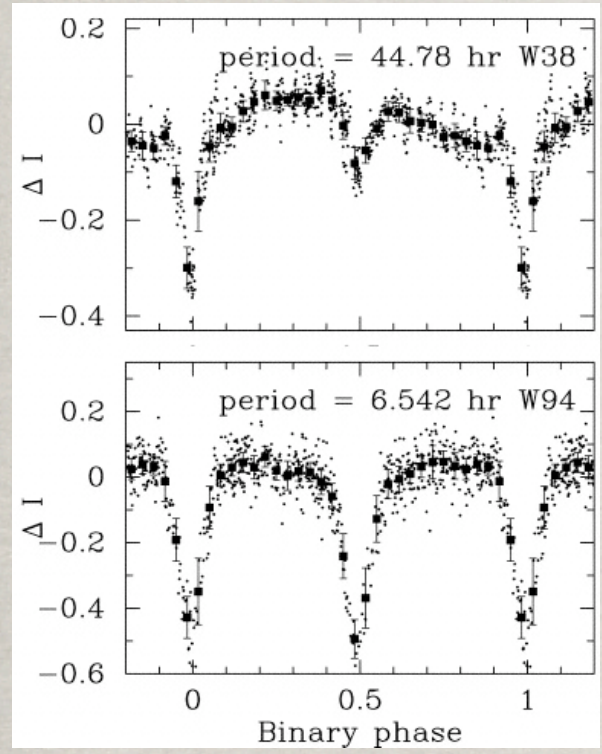


NGC 288; Kong

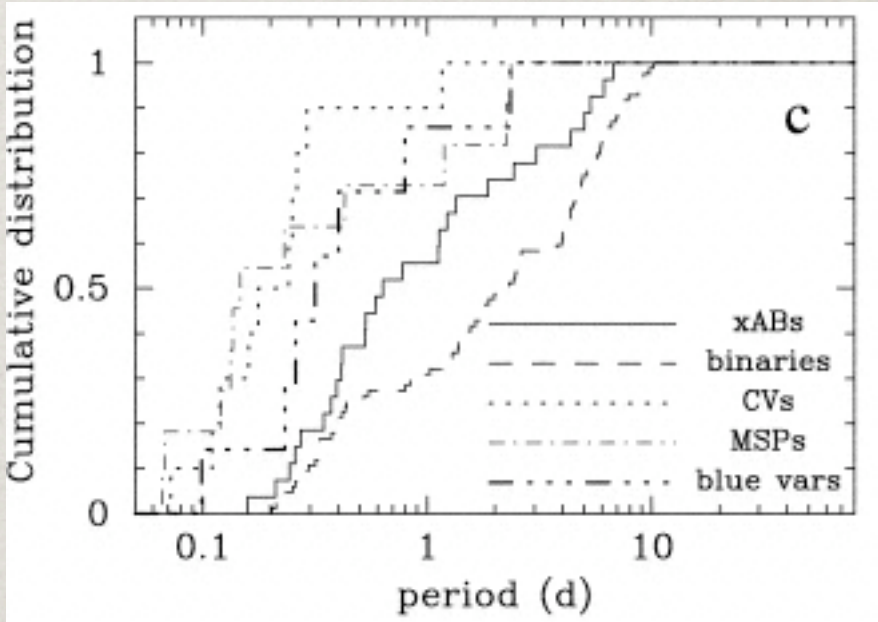


M71; HST

Chromospherically Active Binaries (ABs)



ABs in *47 Tuc*, Edmonds03b

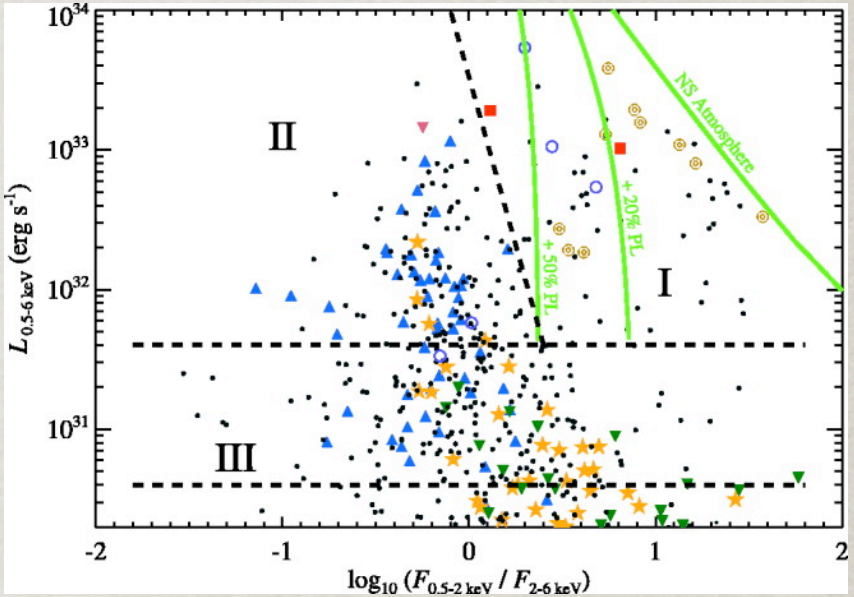


Period distributions in *47 Tuc*, Edmonds03b

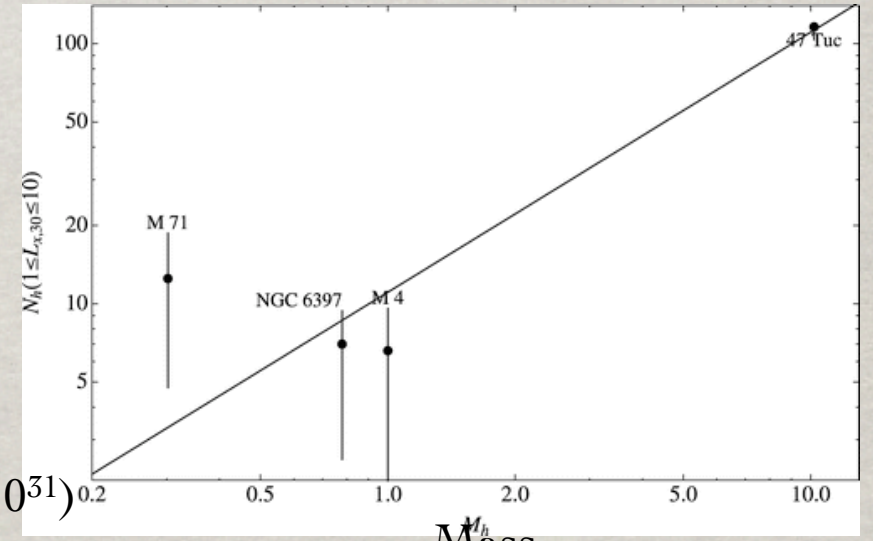
- 60 X-ray ABs identified in *47 Tuc*; also in NGC 6397, NGC 6752, *M4*, NGC 288, *M55*, NGC 6366, *M71*
- Most close binaries (P<1 day) on upper MS detected with Chandra, show chromospheric activity

AB Density Dependence

- Hard to identify pure sample; X-ray faintest sources
- Bassa+04 suggest cluster mass scaling (all primordial)
- M71 shows possible excess



Pooley+06



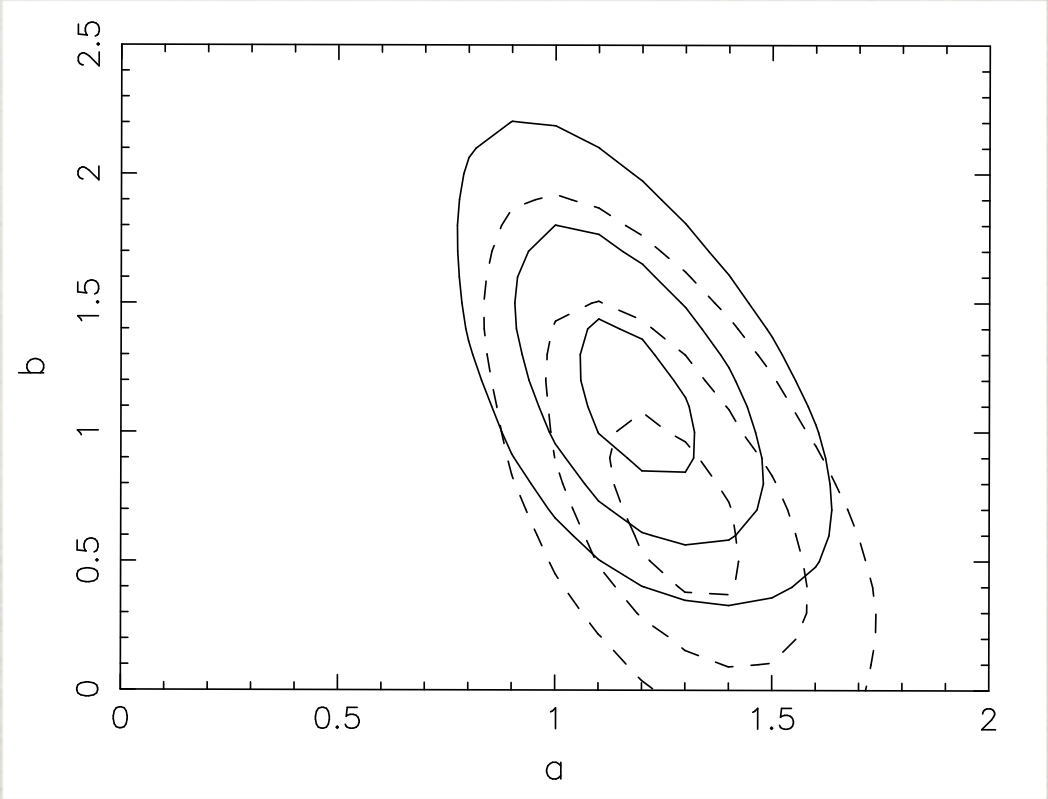
N (10^{30}-10^{31})

Mass

Elsner+08

Primordial + Dynamic

- Using N=aΓ+bM, Bassa fit total cluster X-ray numbers (dashed contours)
- Repeat, forcing N > minimum # optical counterparts (solid); evidence primordial



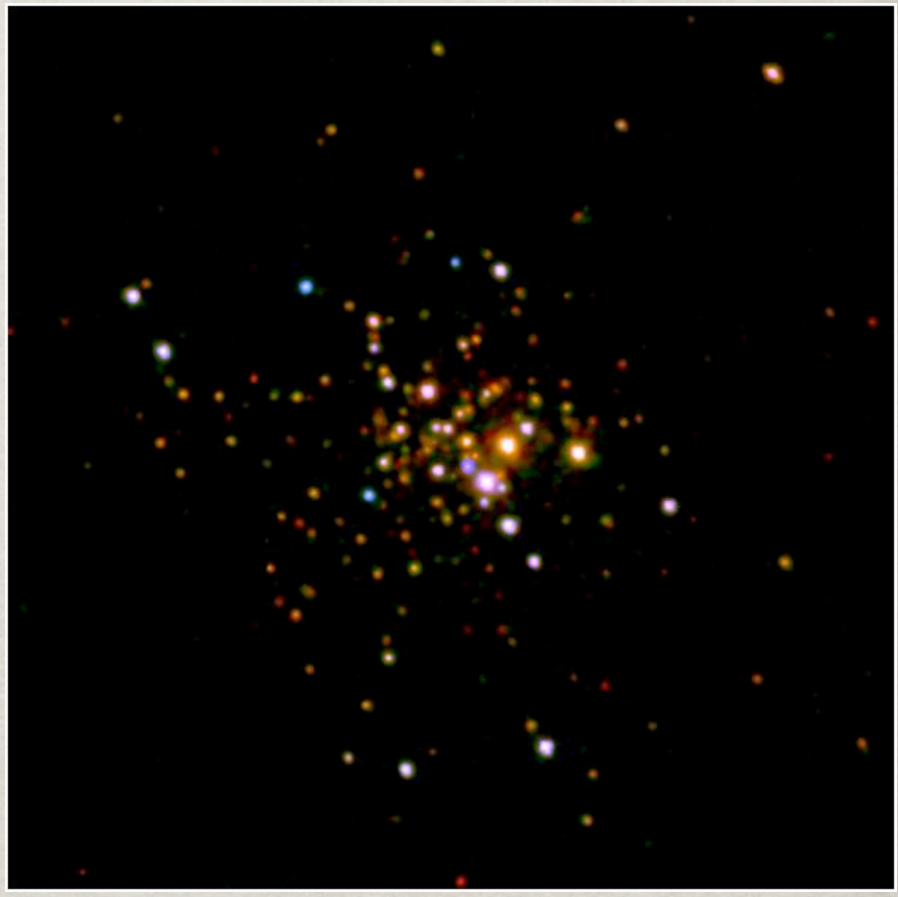
Contours ($\Delta\chi^2$)=1,4,9; Bassa+08

Future Plans

- Very deep Chandra on NGC 6397 (L_X~6e28, Grindlay), reaching AM CVns, faint polars, and post-minimum CVs.
- Deep: (L_X<1e30) M28 (Grindlay), M4 (Pooley), 6752 (Heinke), allowing AB comparisons
- Medium depth on rest of "core-collapsed" clusters (Pooley)
- Shallow depth on ~31 unobserved clusters, to reach 90% of all qLMXBs in Galactic GCs (Pooley)
- XMM observations of 8 open clusters (Pooley)

Conclusions

- Comparing numbers of X-ray sources per cluster to dynamical production rate $\Gamma = \rho^{1.5} r_c^2$ vs. primordial formation
- Quiescent LMXBs produced dynamically (Pooley+03, Heinke03)
- CVs formed both primordially and dynamically (Heinke+06, Pooley+06, Bassa+08)
- Active binaries are primordial, maybe destroyed in interactions (Bassa+04, Kong+06, Huang+09)



Chandra image of 47 Tuc