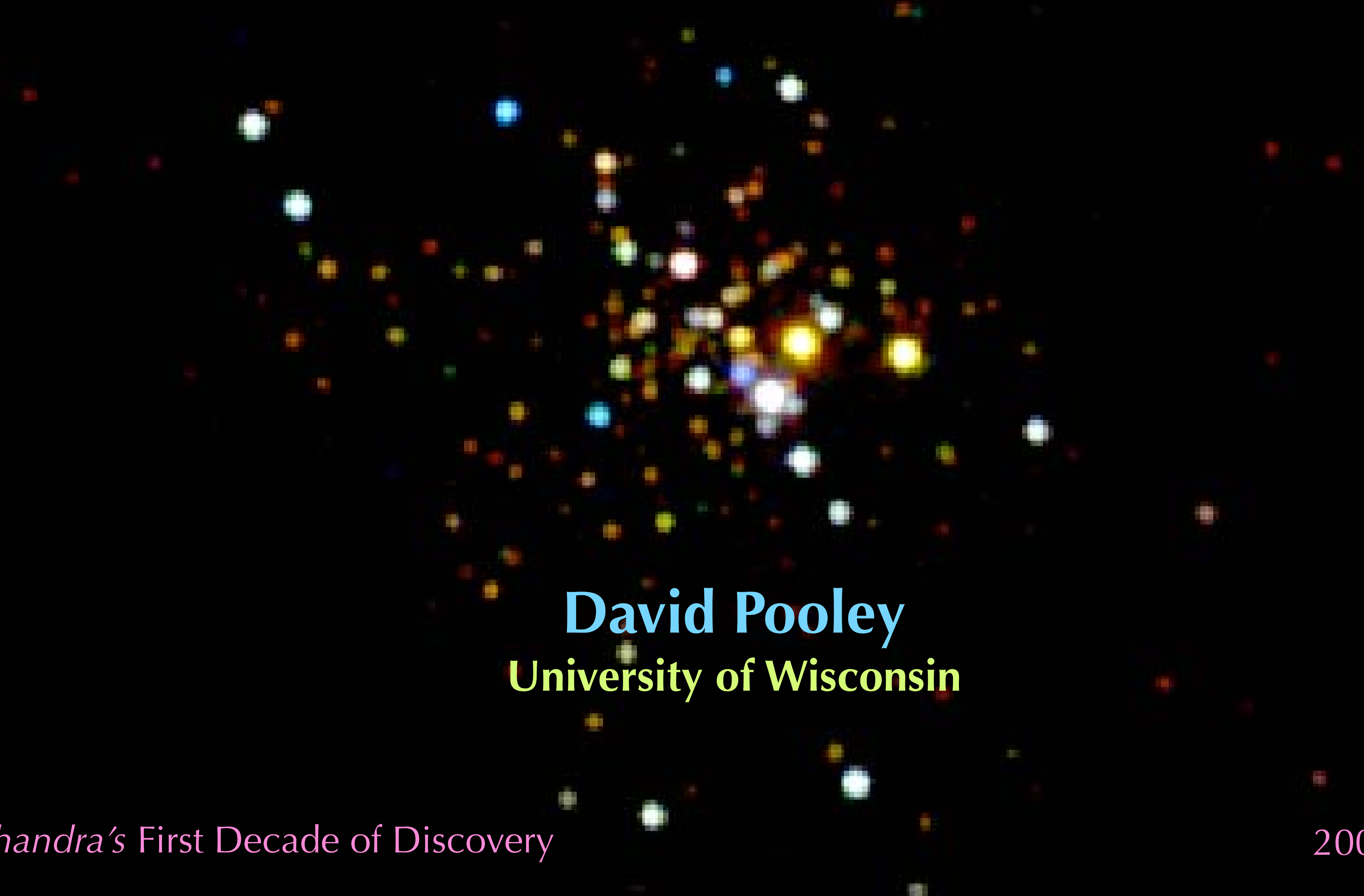
Globular Cluster X-ray Sources

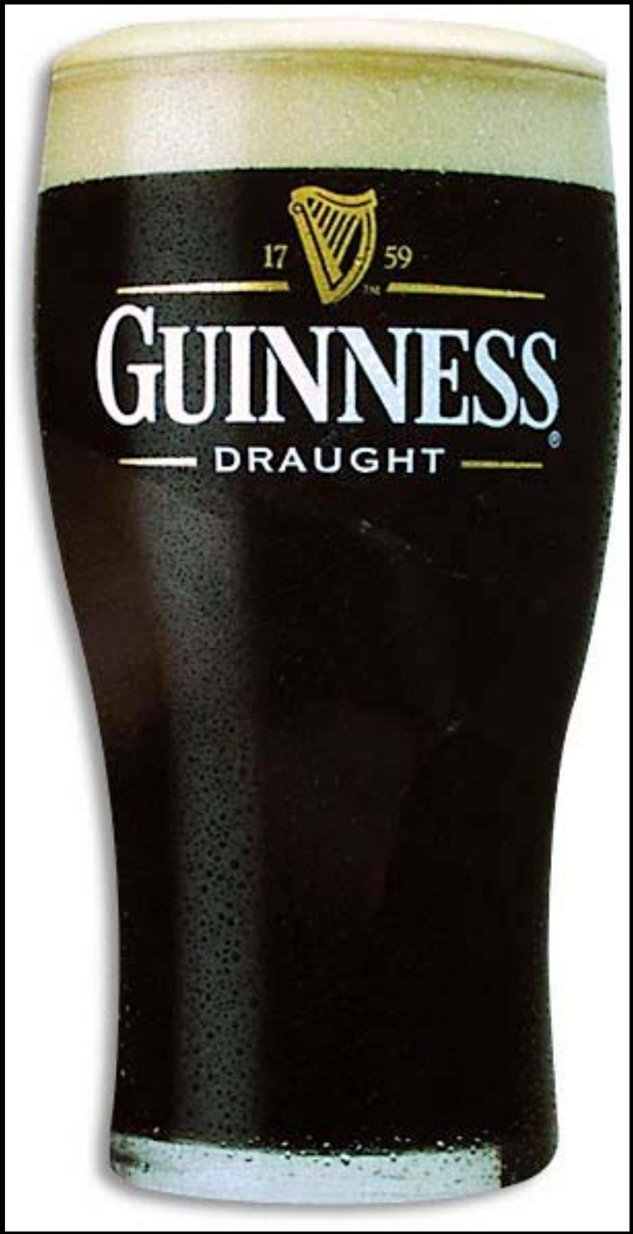


David Pooley
University of Wisconsin

Chandra's First Decade of Discovery

2009 Sep 24

September 24, 1759



with thanks to friends, colleagues, and collaborators:

Walter Lewin
Frank Verbunt
Cees Bassa
Lee Homer
Scott Anderson
Bruce Margon
Vicky Kaspi
Brian Gaensler
Derek Fox
Rudy Wijnands
Ed Cackett
Jeroen Homan

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Peter Edmonds
Steve Murray
Haldan Cohn
Phyllis Luger
Adrienne Cool
Daryl Haggard

Albert Kong
Ting-Ni Lu
Shih Hao Lan

Didier Barret
Bruce Gendre
Natalie Webb
Mathieu Servillat

Piet Hut
Simon Portegies Zwart
John Fregeau
Natalia Ivanova

Harvey Tananbaum and the entire CXC staff

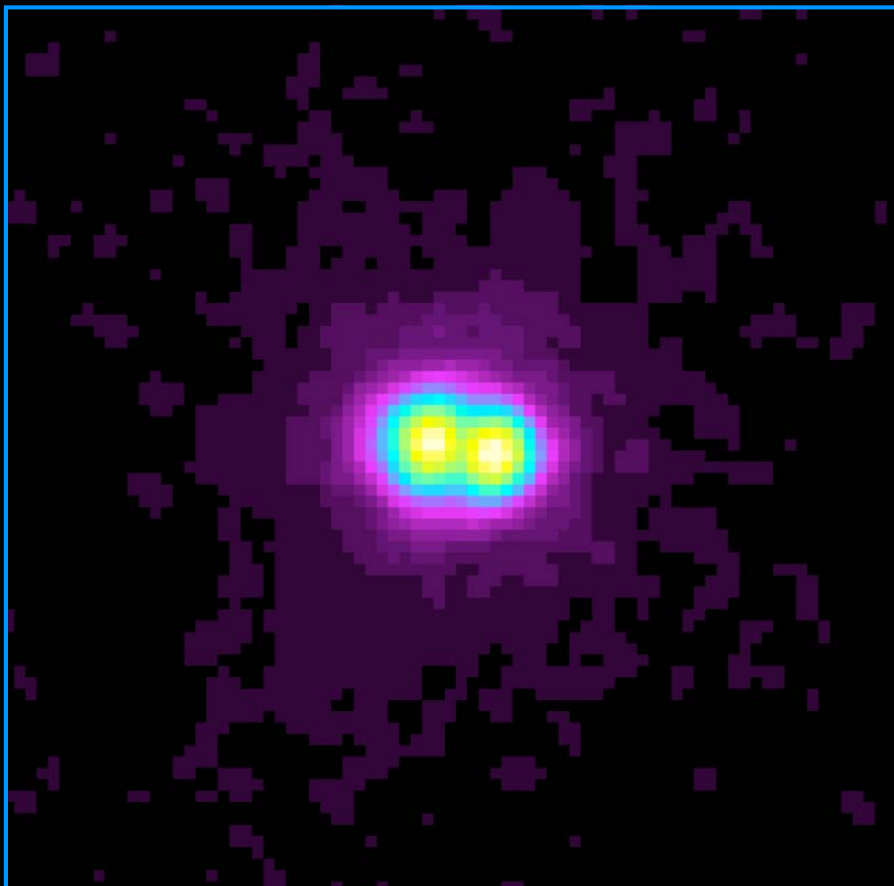
X-ray astronomy & globular clusters

Luminous X-ray sources ($L_X > 10^{36}$ erg s^{-1})

- Discovered by *Uhuru* and *OSO-7*; argued to be formed via cluster dynamics
  Gursky 1973, Clark 1975, Katz 1975
- Stimulated flurry of theoretical work
  Fabian, Pringle, & Rees 1975, Sutantyo 1975, Hills 1975, 1976, Heggie 1975, Verbunt & Hut 1983
- 12 globular clusters thought to contain one each
- All but one show Type-I X-ray bursts $\Rightarrow$ NS-LMXBs ***e.g., Kuulkers et al. 1996***

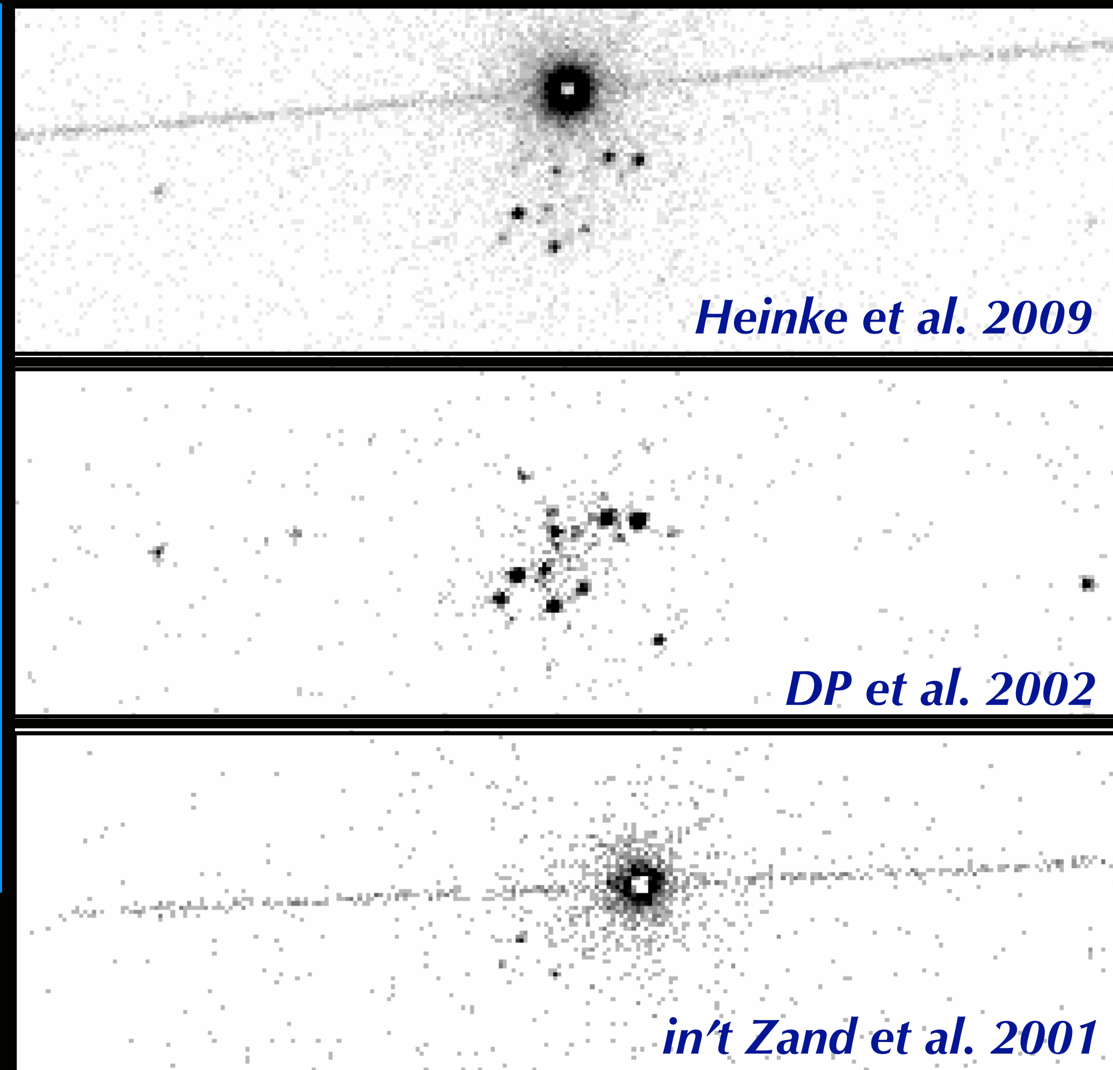
Bright X-ray Sources:
New *Chandra* discoveries

M15



White & Angelini 2001

NGC 6440



X-ray astronomy & globular clusters

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Discovered by *Uhuru* and *OSO-7*; argued to be formed via cluster dynamics

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12 globular clusters thought to contain one each

All but one show Type-I X-ray bursts ⇒ NS-LMXBs ***e.g., Kuulkers et al. 1996***

Low Luminosity X-ray sources ($L_X < 10^{34}$ erg s^{-1})

Discovered by *Einstein* **Hertz & Grindlay 1983** More found with *ROSAT* **e.g., Verbunt 2001**

No secure identifications

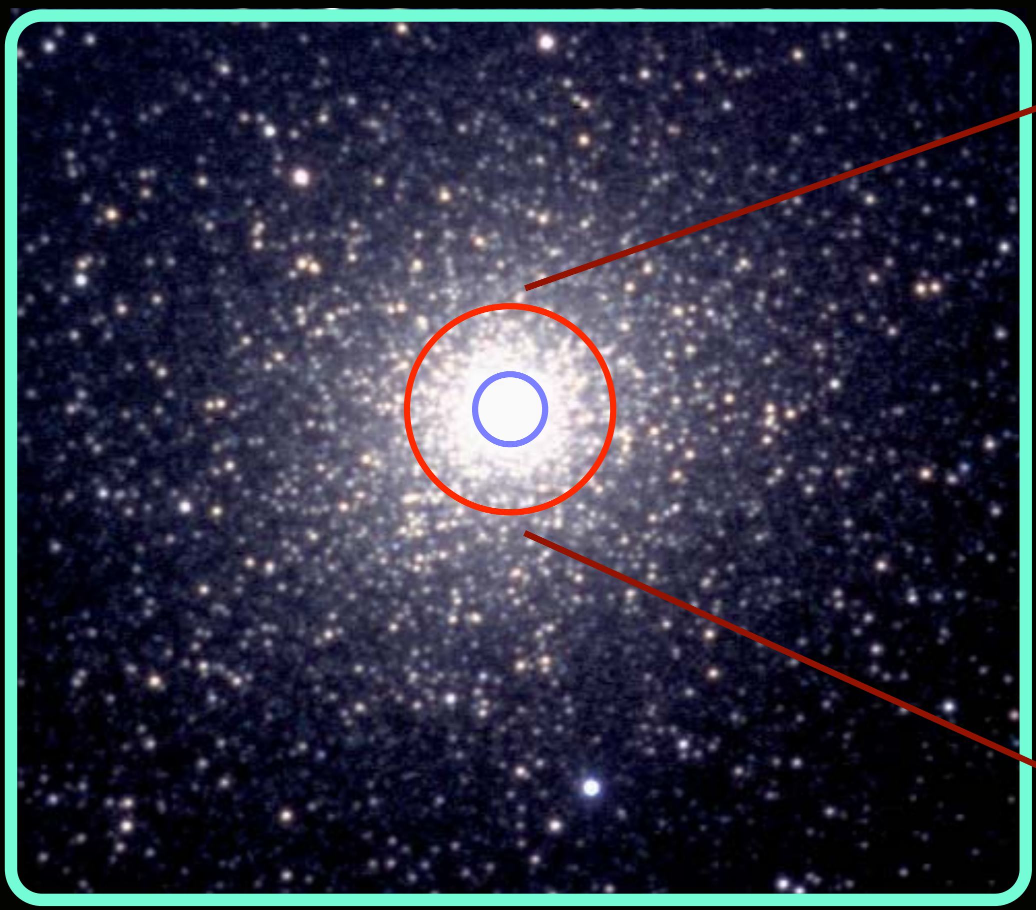
Suggested to be CVs ***(Hertz & Grindlay 1983)***, qLMXBs ***(Hertz & Grindlay 1983, Verbunt et al. 1984)***, ***radio*** MSPs ***(Saito 1997)***, magnetically active binaries ***(Bailyn et al. 1990)***

Extragalactic globular cluster X-ray sources ***(T. Maccarone)***

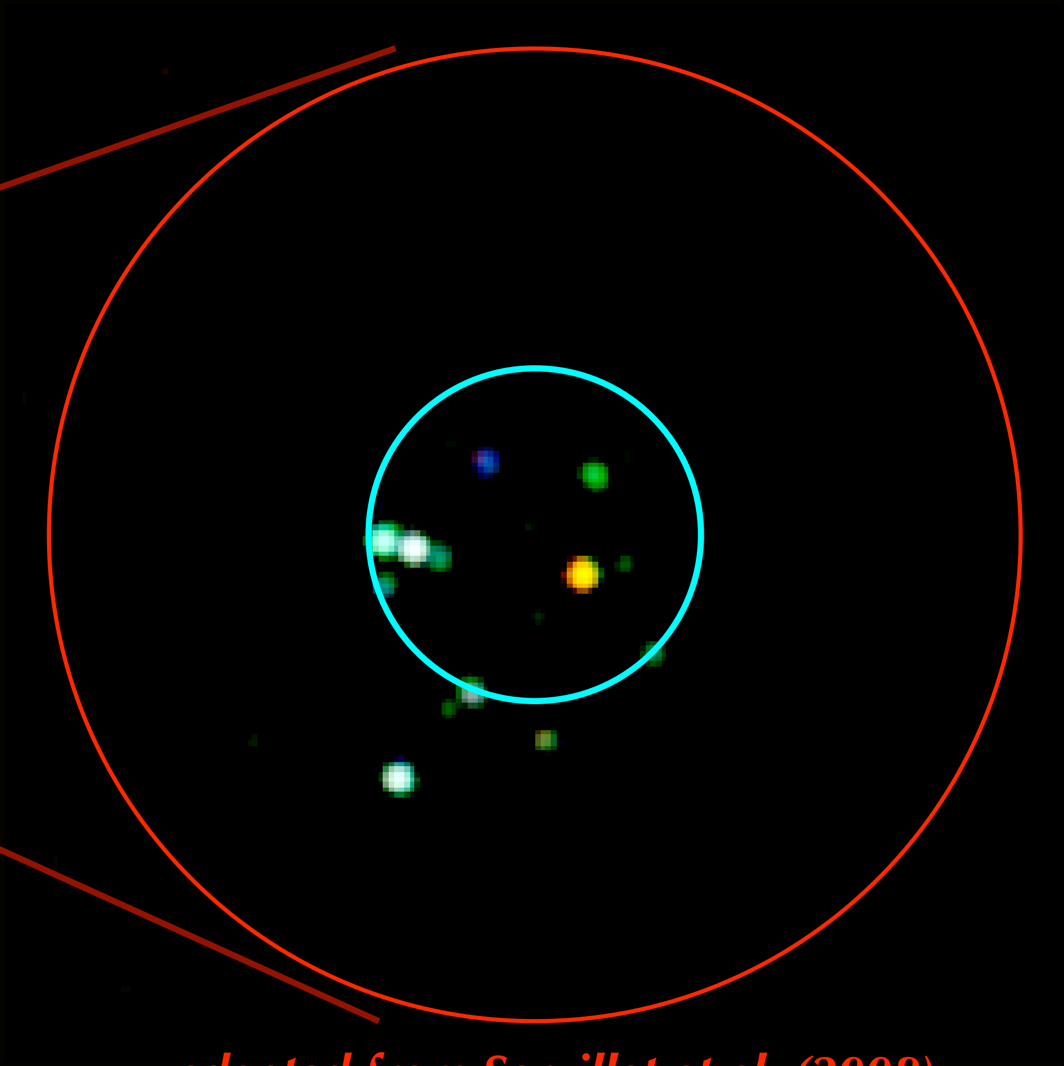
Detailed MSP studies ***(S. Bogdanov)***

Intermediate Mass Black Holes

Globular Cluster NGC 2808

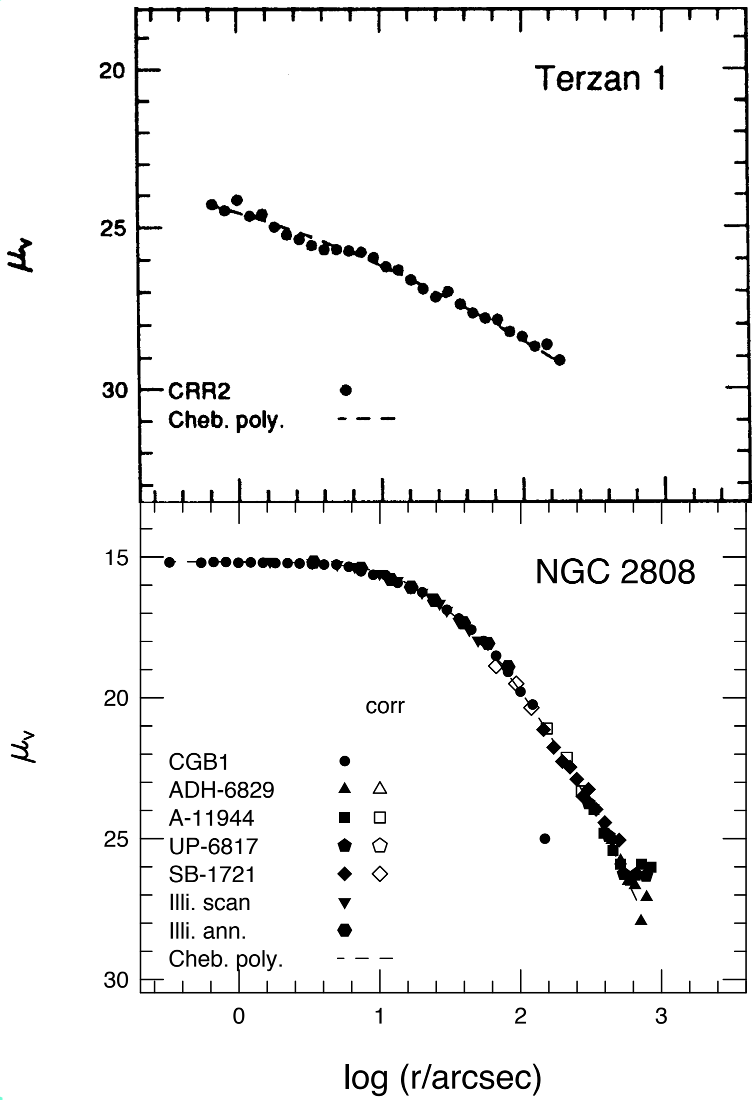


credit: S. Juchnowski



adapted from Servillat et al. (2008)
see poster by M. Servillat

Surface Brightness Profiles



"core collapsed"

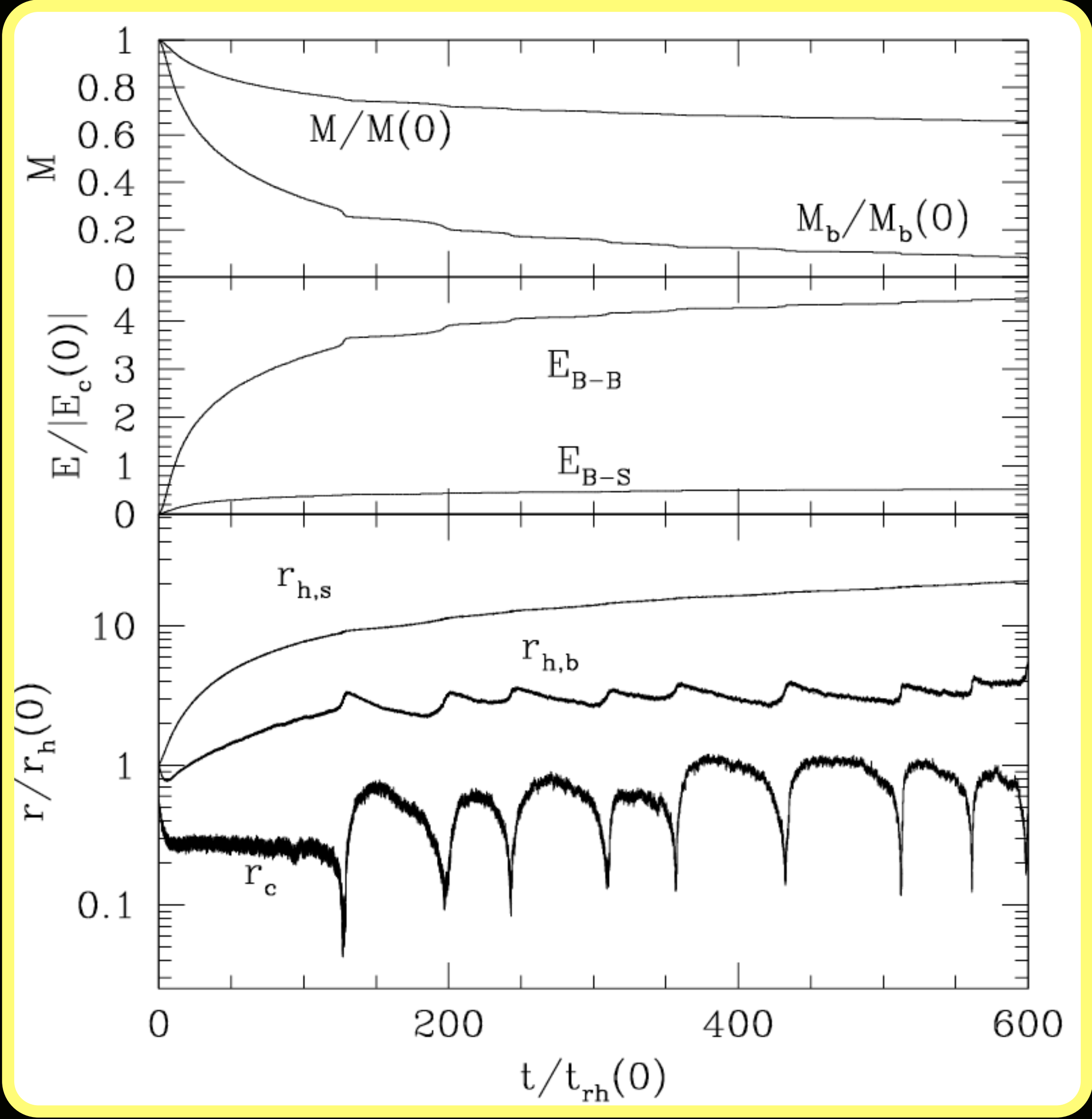
20% of globular clusters

"normal"

80% of globular clusters

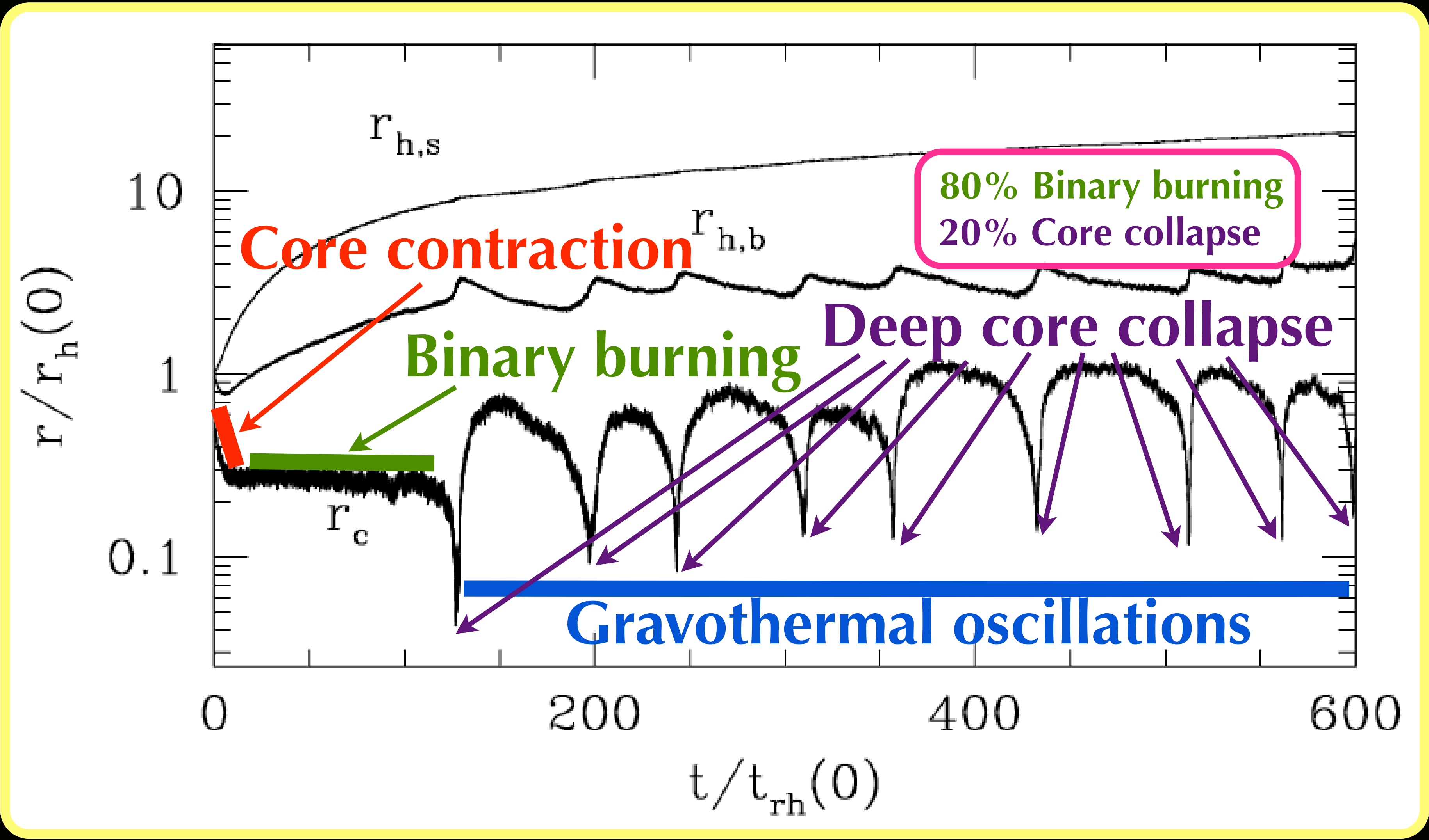
Trager, King, & Djorgovski 1995

Simulating Globular Clusters



Fregeau et al. 2003

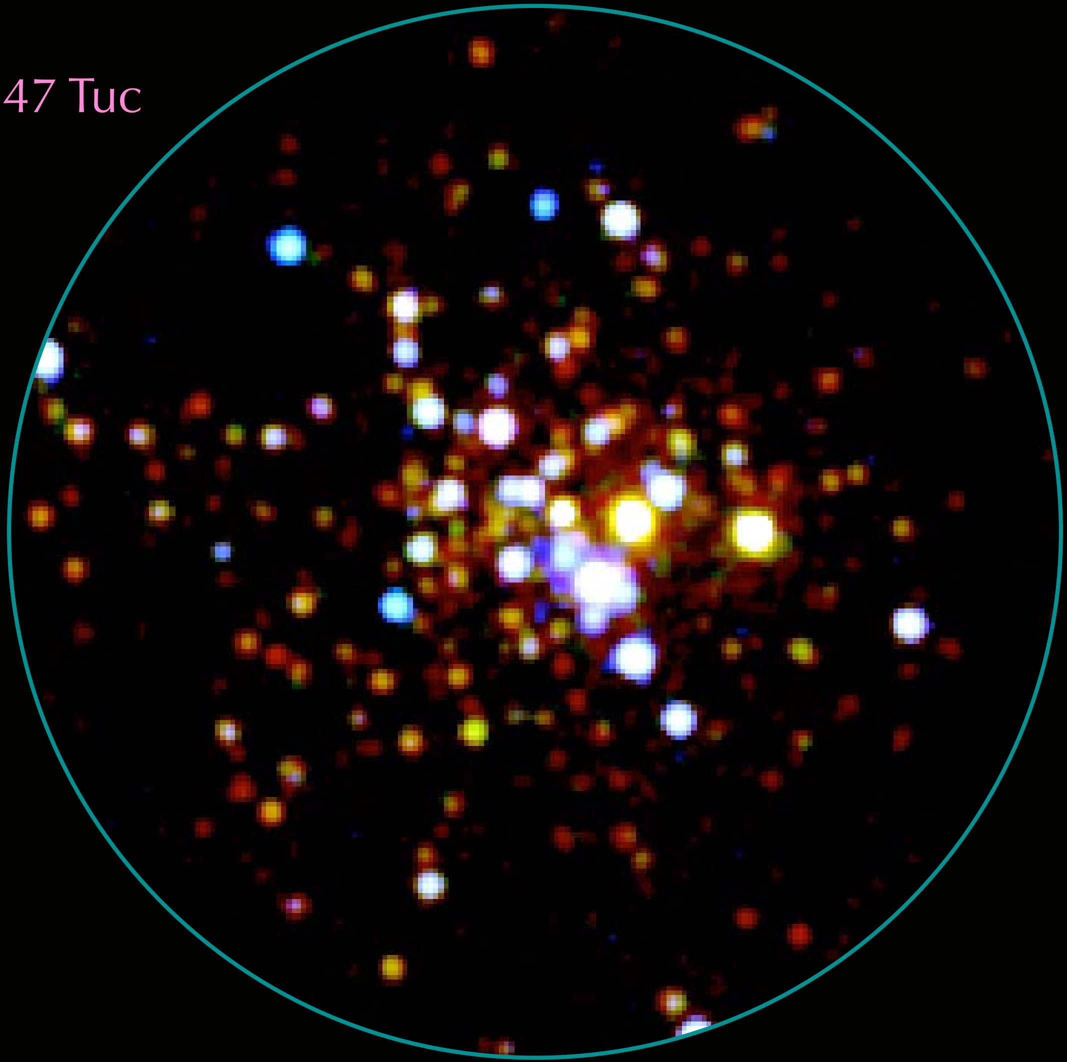
Globular Cluster Life Stages



Fregeau et al. 2003

X-ray Sources in Globular Clusters

Chandra image of 47 Tuc



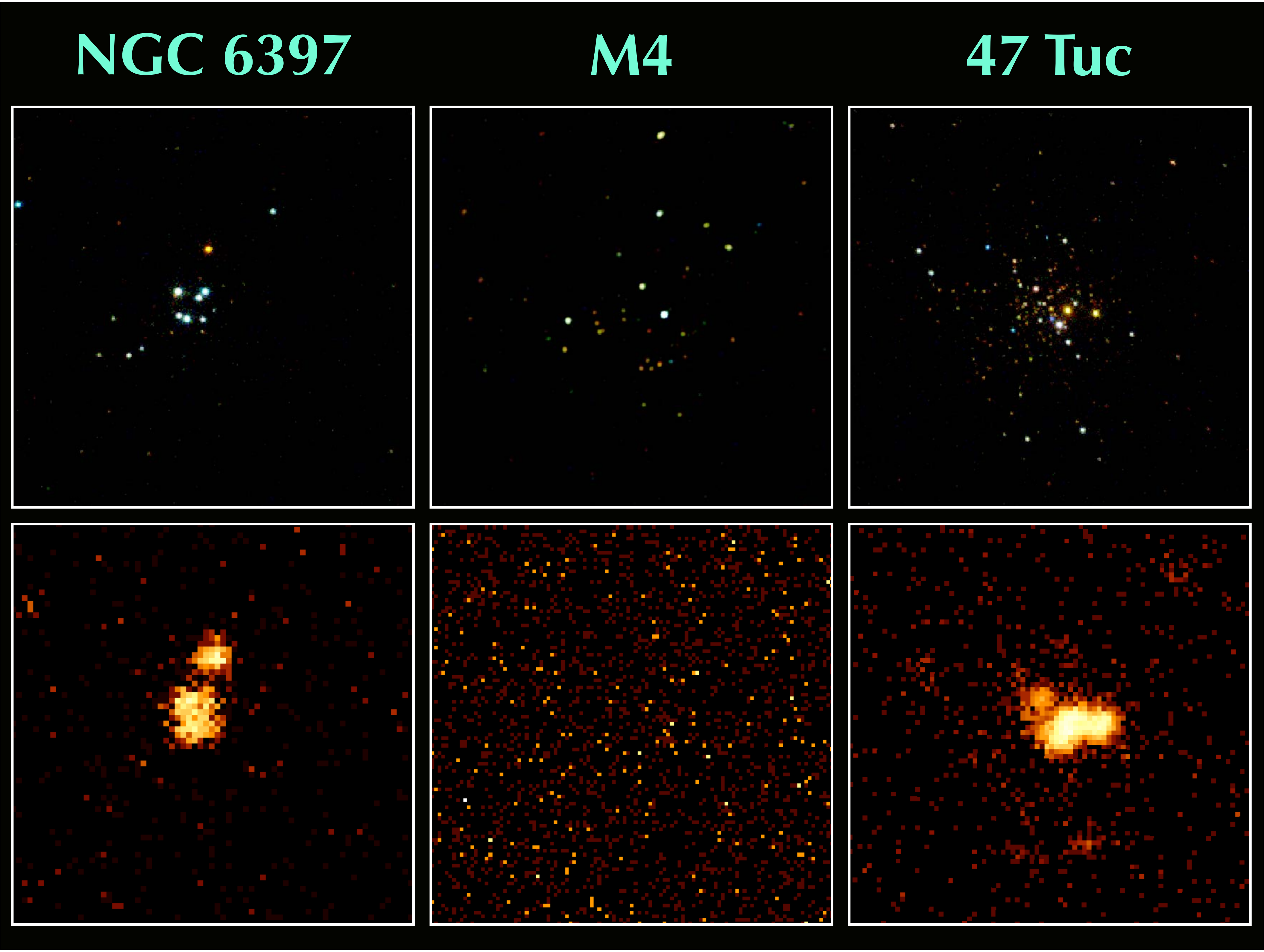
Low-mass X-ray Binaries

Millisecond pulsars

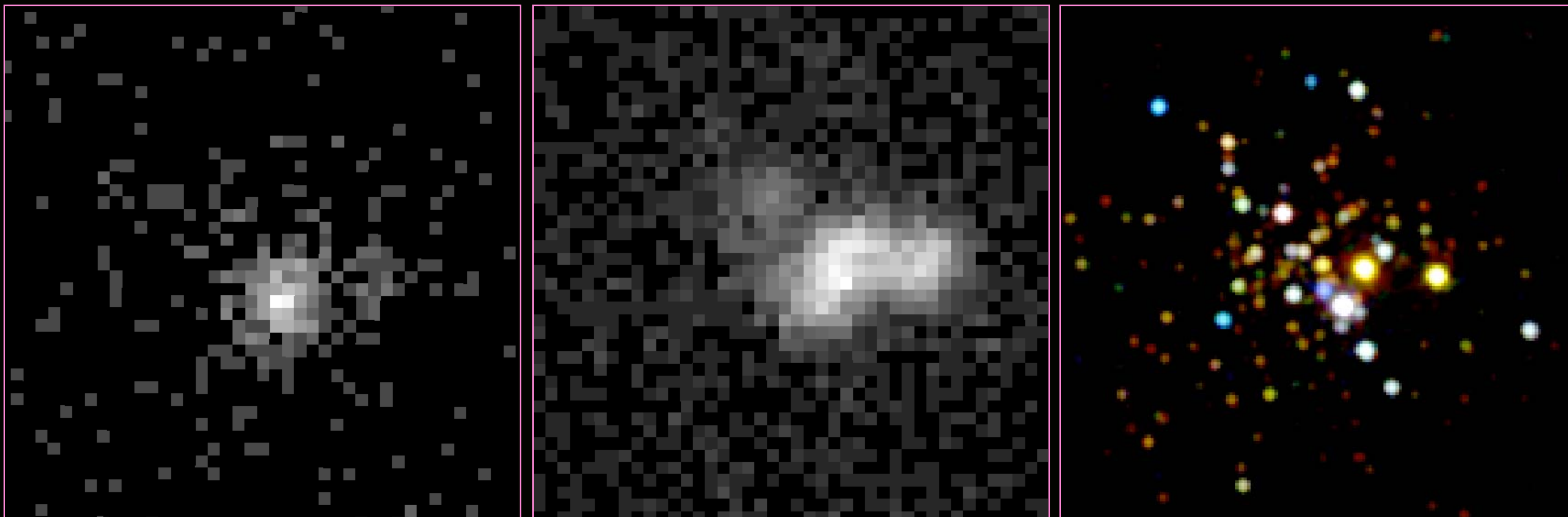
Cataclysmic Variables

Active main-sequence binaries

adapted from Grindlay et al. 2001


NGC 6397
M4
47 Tuc

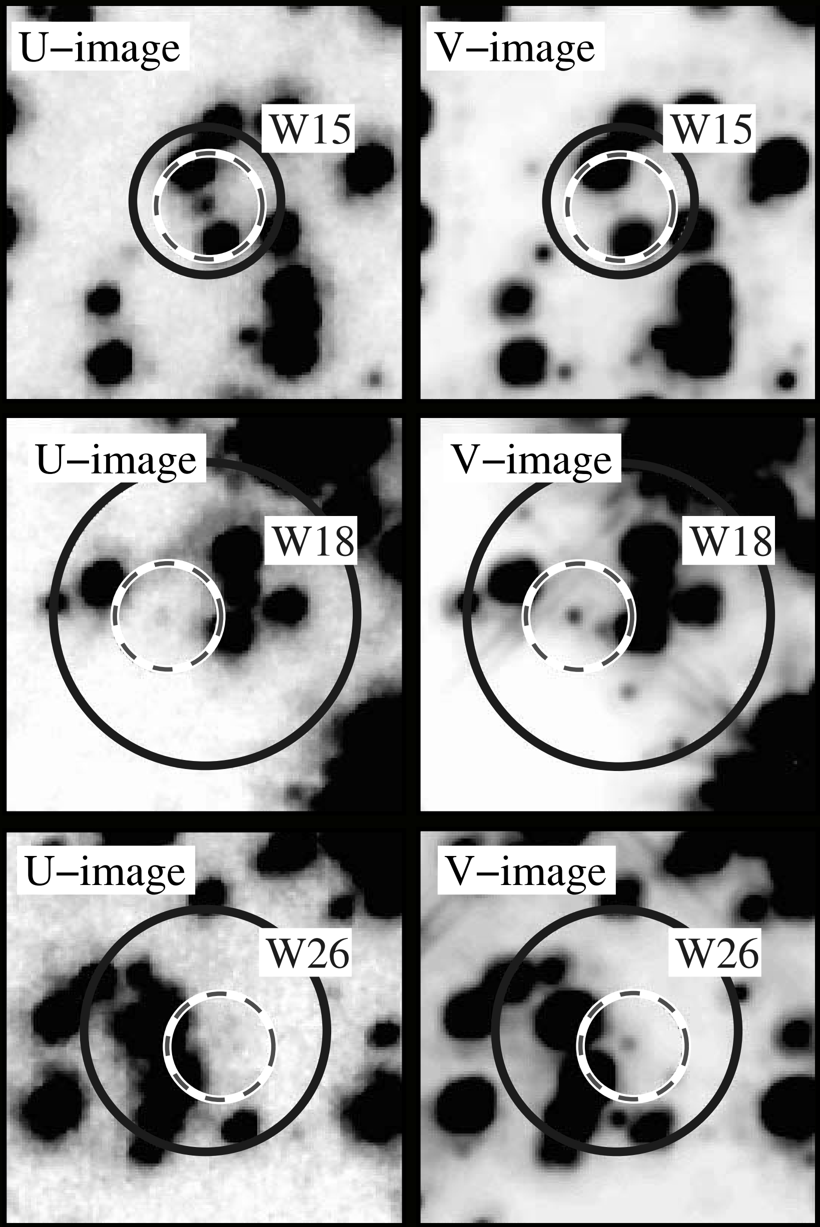
47 Tuc in X-rays



Einstein (8 ksec) *ROSAT* (77 ksec) *Chandra* (240 ksec)

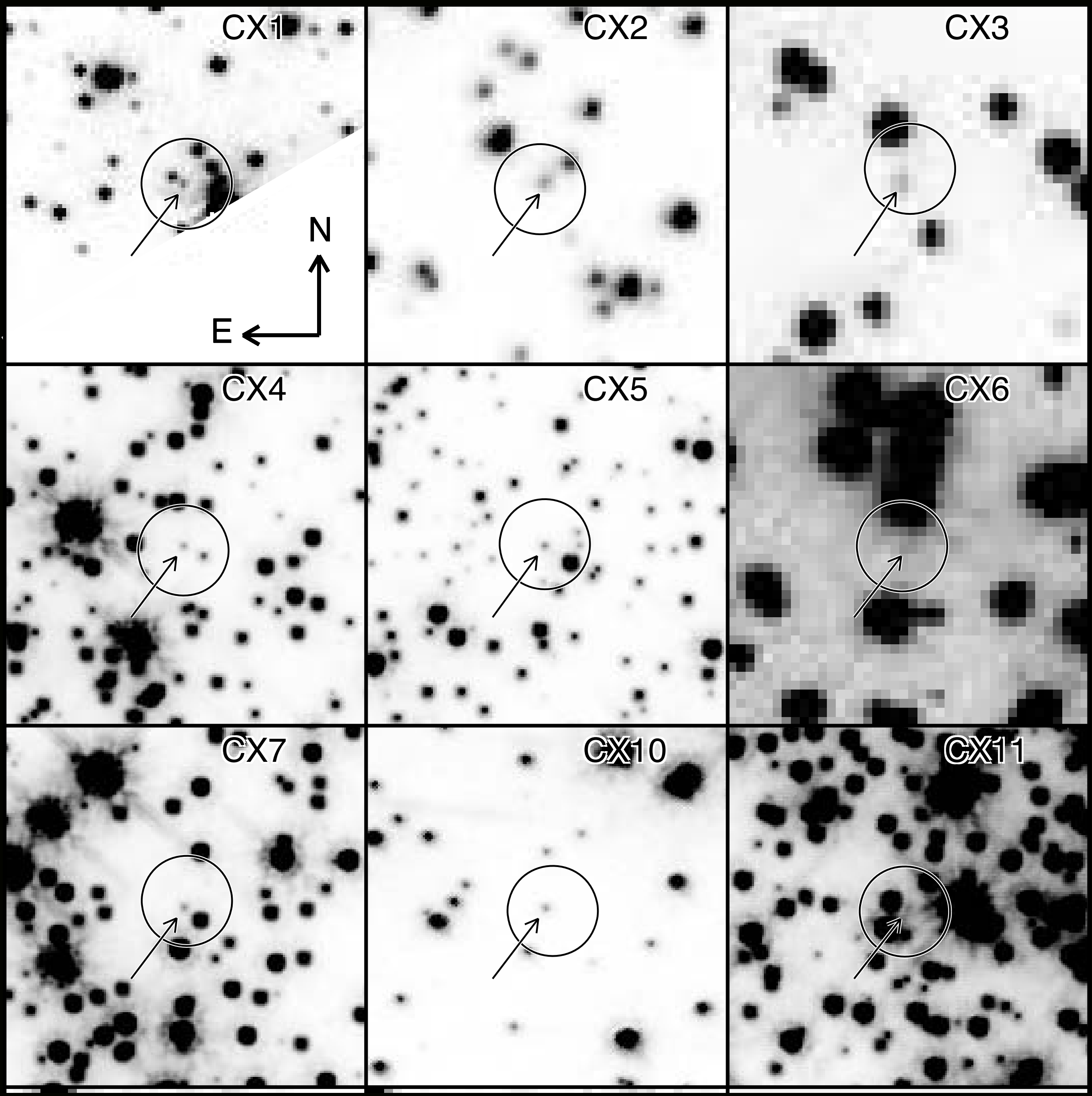
Identifying the X-ray Sources

47 Tuc



Edmonds et al. (2003)

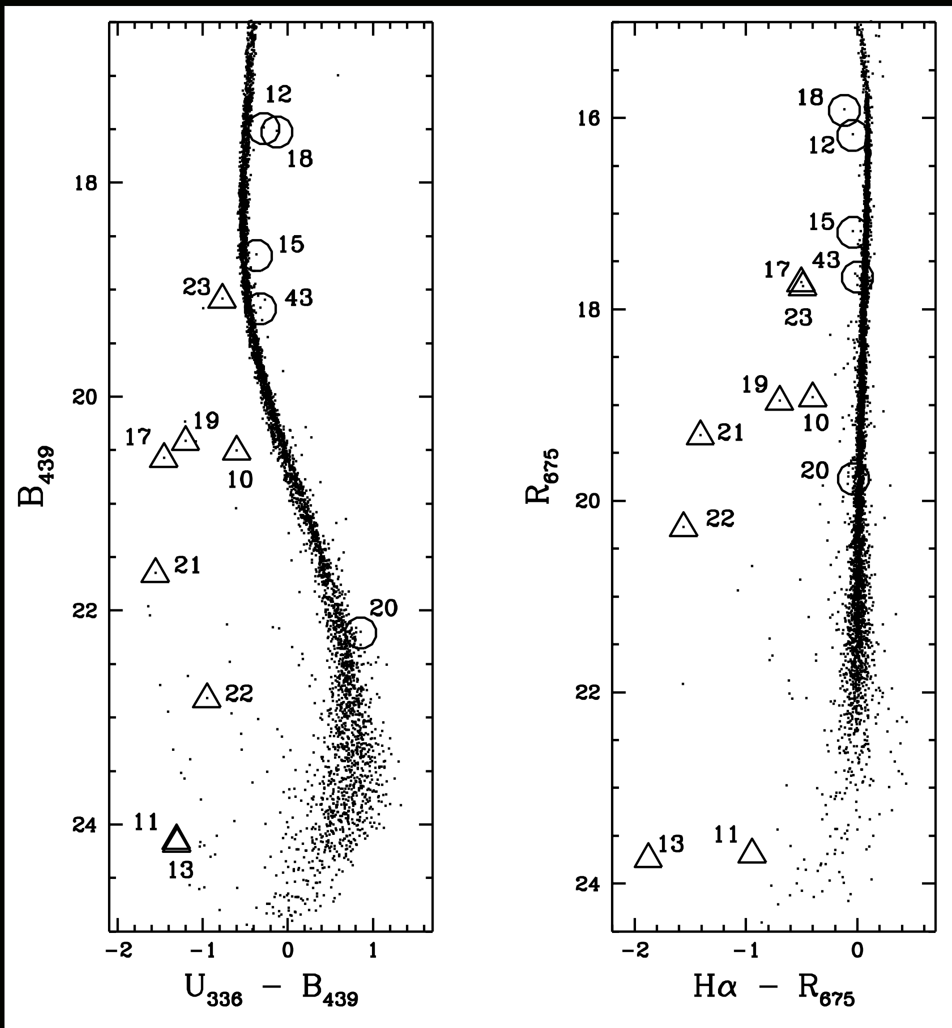
NGC 6752



DP et al. (2002)

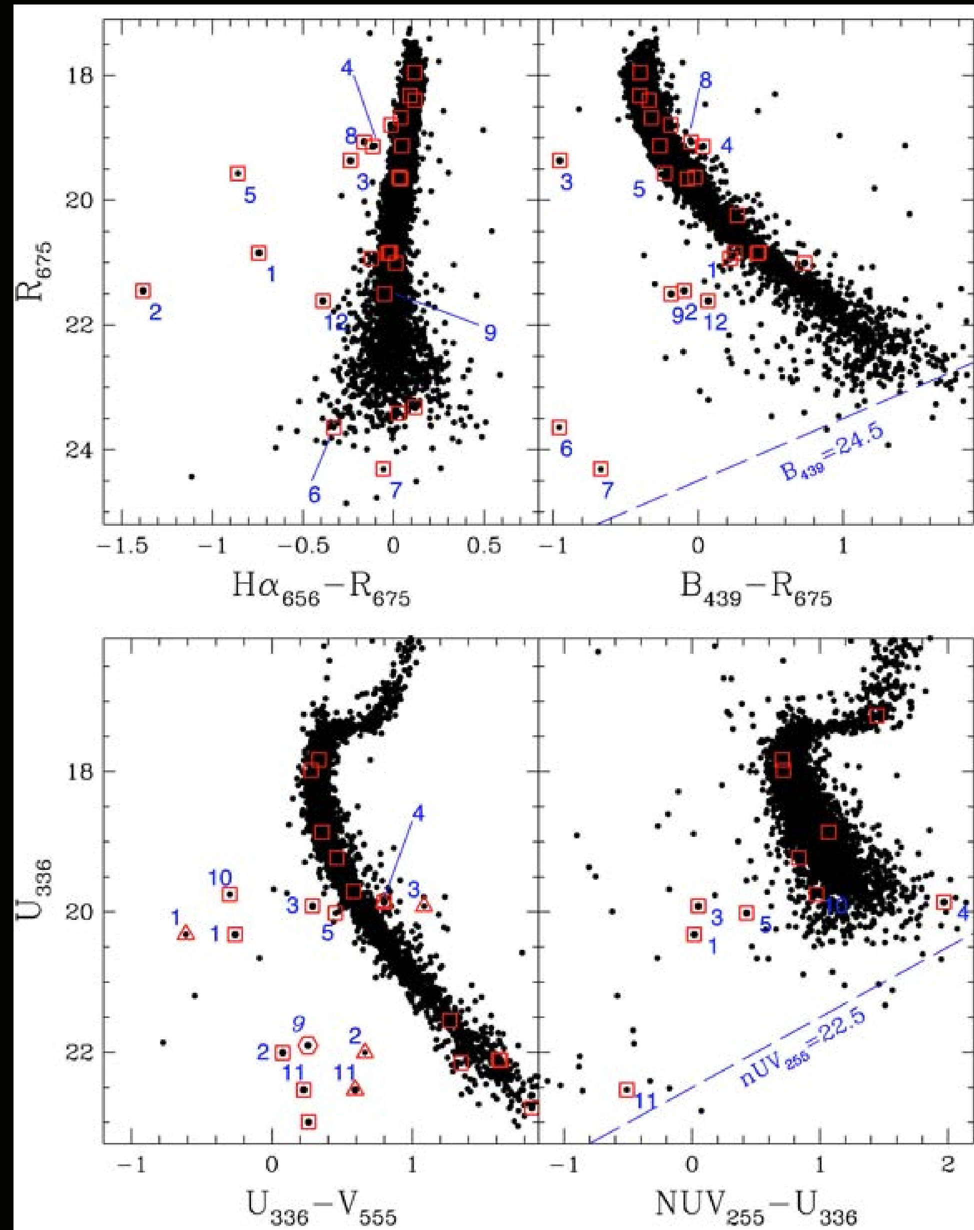
Identifying the X-ray Sources

NGC 6397



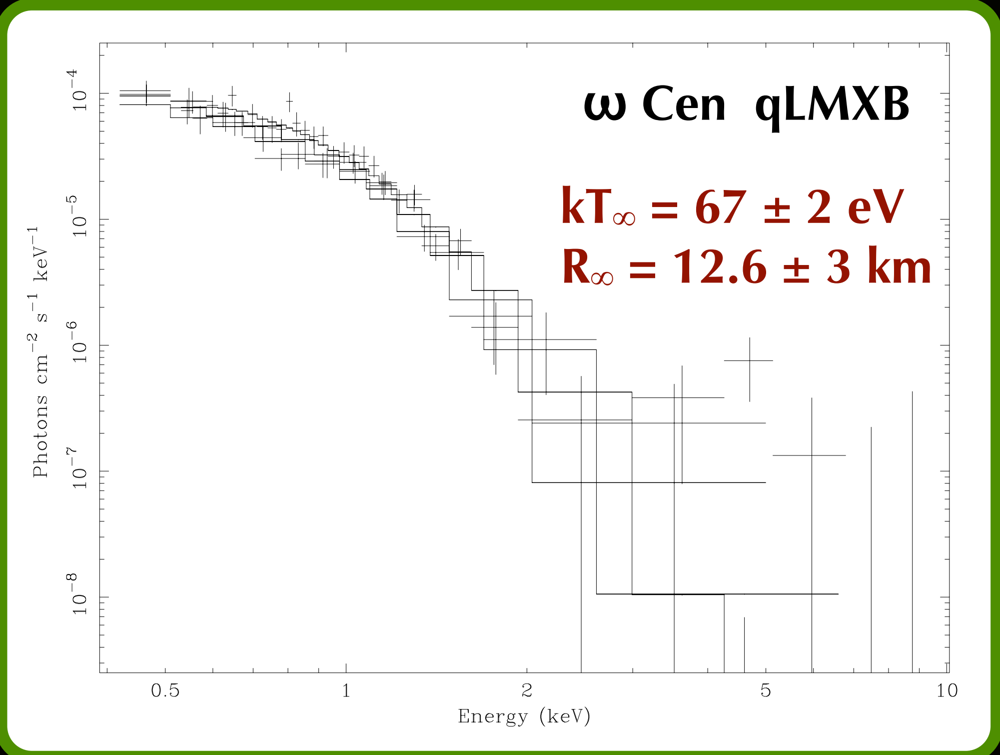
Grindlay et al. (2001)

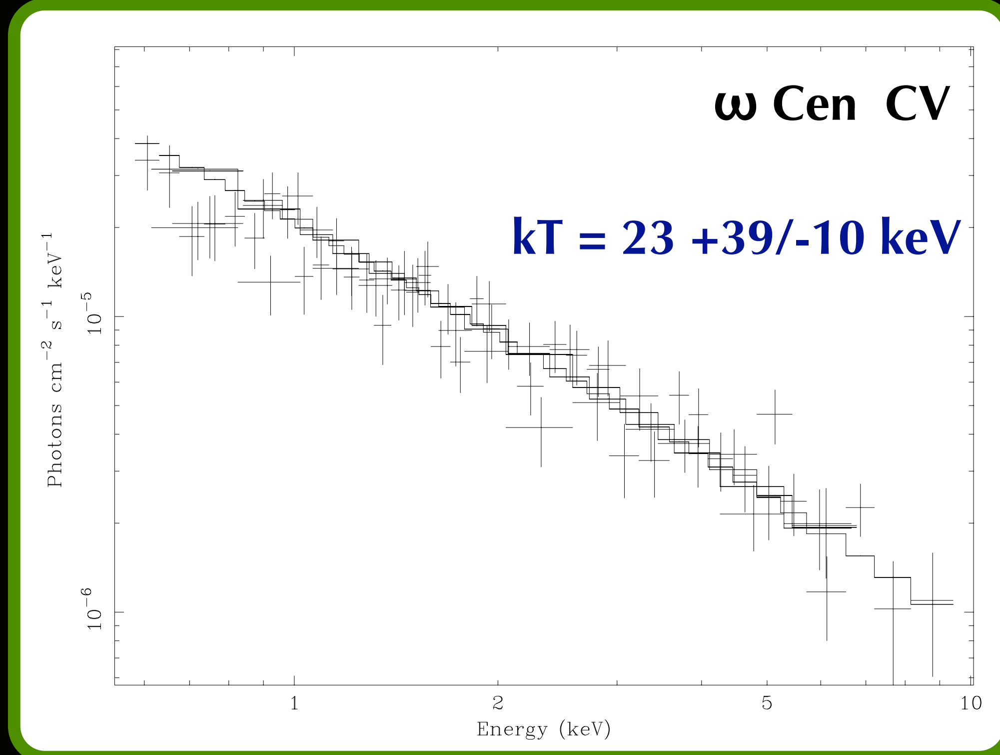
NGC 6752



DP et al. (2002)

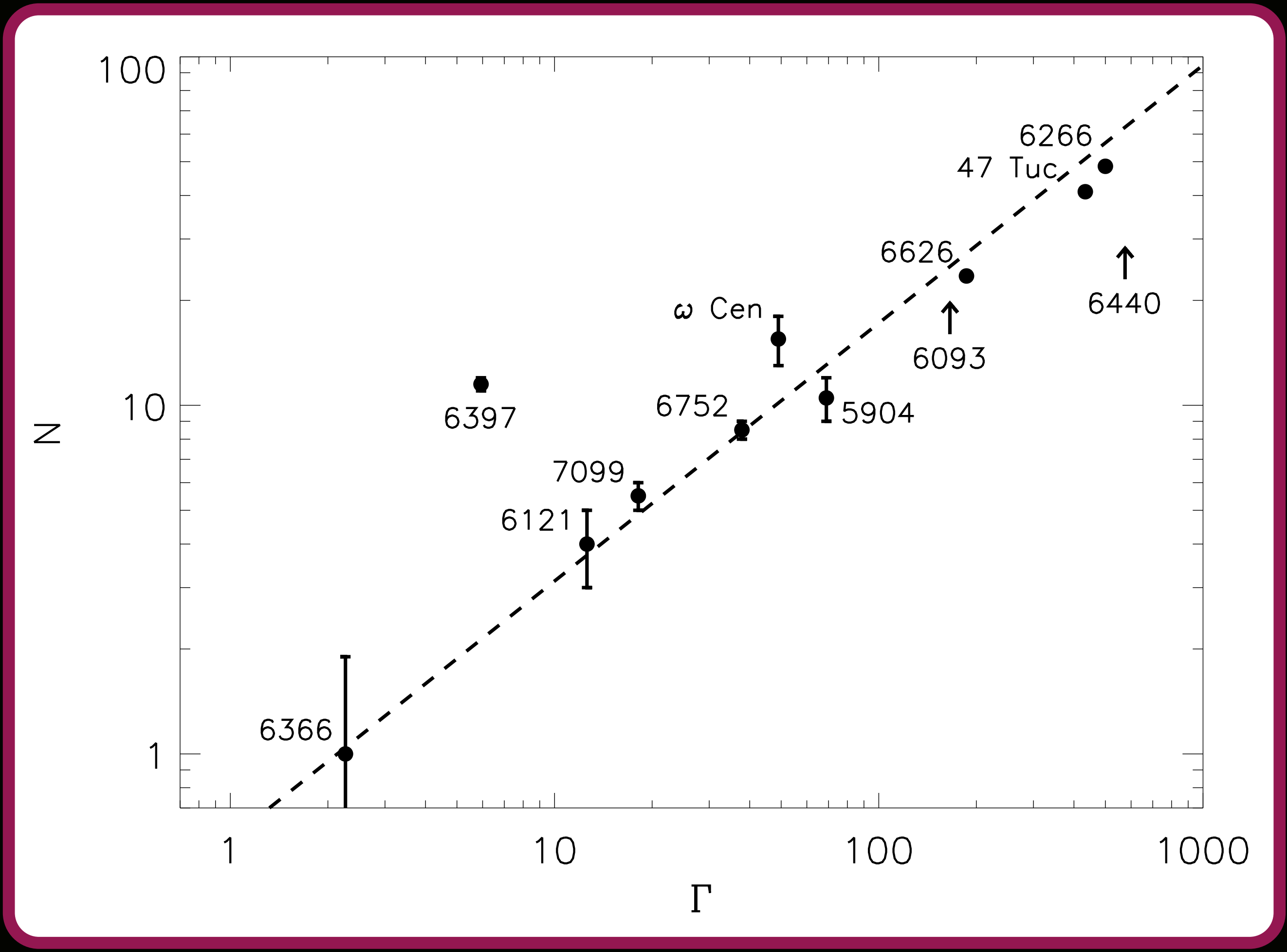
Source Identification via X-rays





Webb & Barret 2004 (from Gendre et al. 2003)

A Link to Stellar Dynamics



DP et al. 2003

Heinke et al. 2003

Gendre et al. 2003

X-ray CMD

To Date:

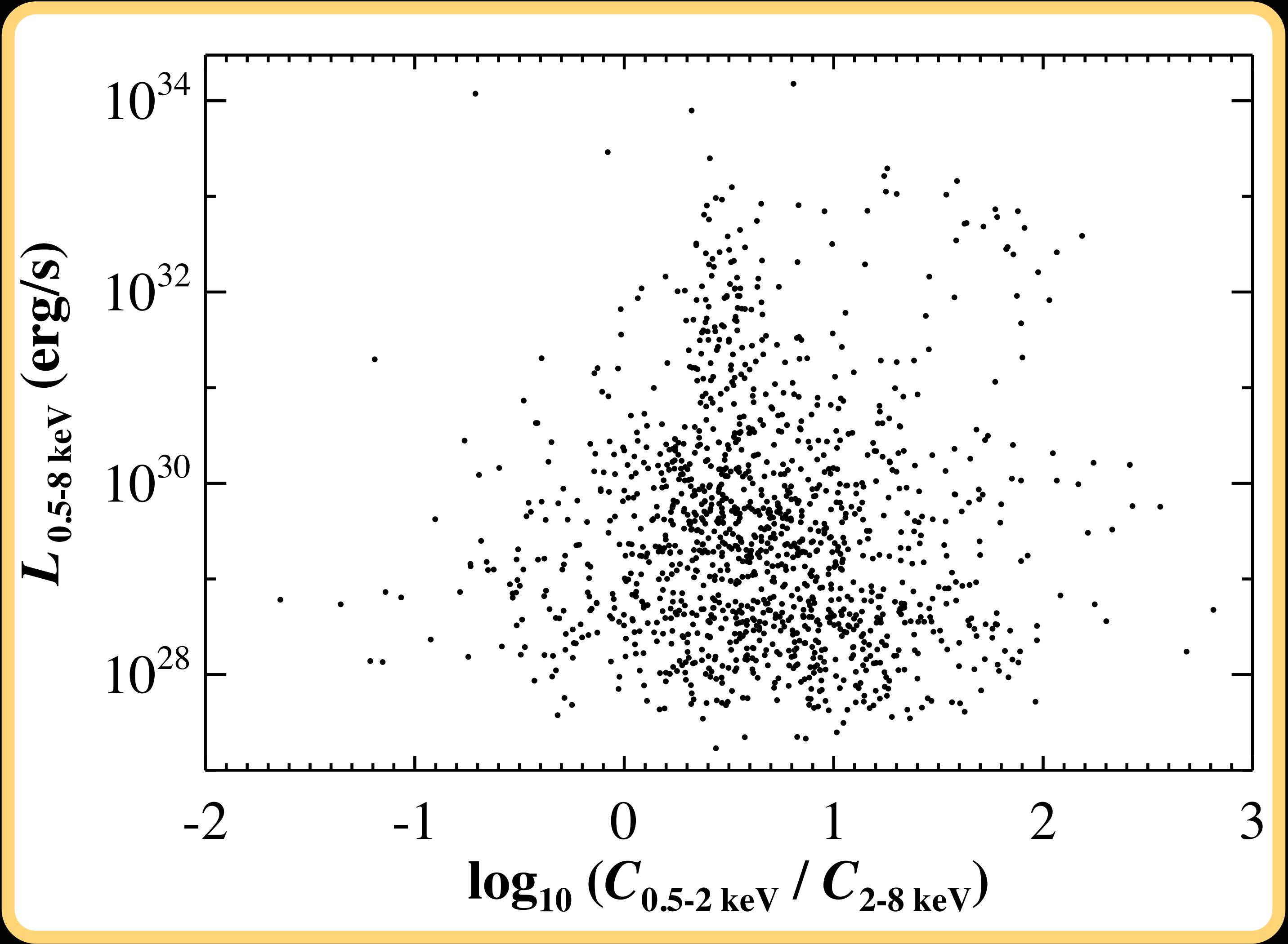
77 GCs

114 ACIS Obs.

3 Msec

>1500 sources

~250 background



X-ray CMD

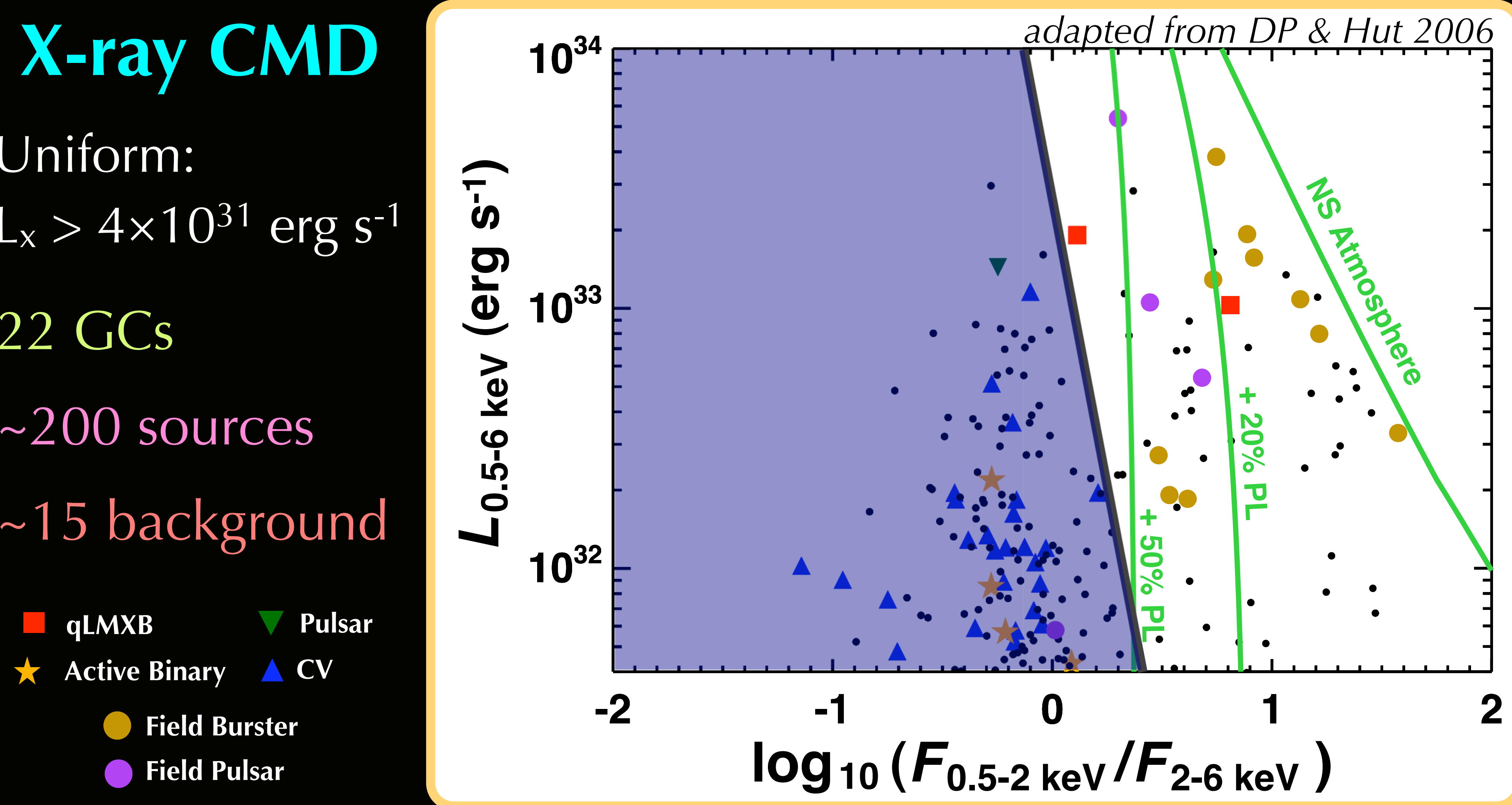
Uniform:

$L_X > 4\times10^{31}$ erg s^{-1}

22 GCs

~200 sources

~15 background

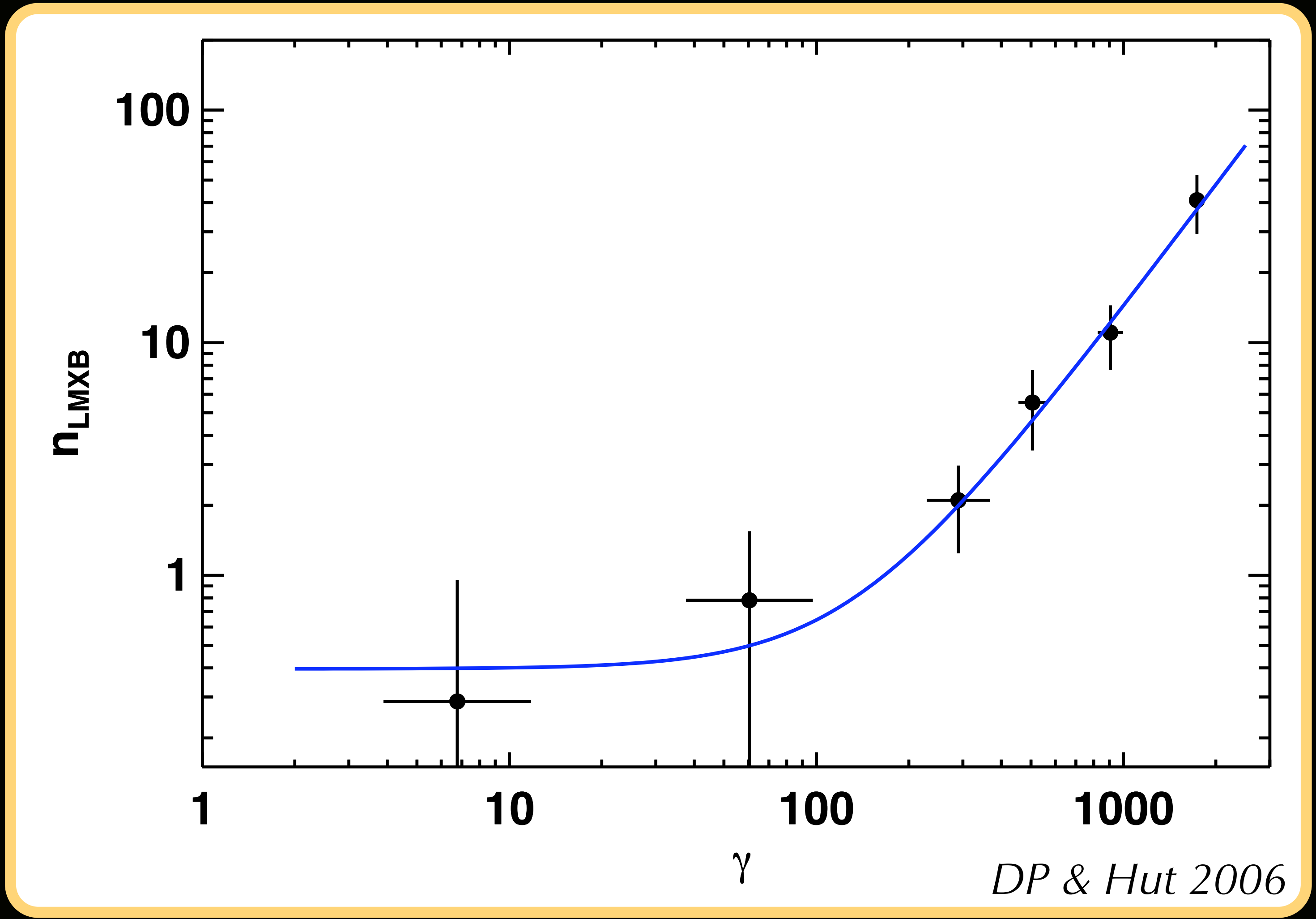


Cluster LMXBs

Can rule out constant n at 4σ

$n = a\gamma^s + c$

$s = 1.8 \pm 0.4$
$c = 0.4 \pm 0.5$



Specific units: $n = N/M \quad \gamma = \Gamma/M$
M in units of $10^6\ M_\odot$

building on Gendre et al. 2003, Heinke et al. 2003, DP et al 2003

Are Globular Cluster CVs overabundant?

They should be:

Hut & Verbunt 1983

White dwarfs and neutron stars in globular cluster X-ray sources

Piet Hut
Institute for Advanced Study, Princeton, New Jersey 08540, USA

Frank Verbunt*
Sterrenkundig Instituut, Utrecht & Sterrenkundig Instituut, Amsterdam, The Netherlands

We predict here that globular clusters contain at least as many cataclysmic variables, which contain white dwarfs, as bright (L_x>10^{36} erg s^{-1}) X-ray sources, which contain neutron stars. Globular clusters contain many more white dwarfs than neutron

Di Stefano & Rappaport 1994

PREDICTIONS OF A POPULATION OF CATACLYSMIC VARIABLES IN GLOBULAR CLUSTERS

R. DI STEFANO[1,2] AND S. RAPPAPORT
Department of Physics and Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139;
e-mail: rd@space.mit.edu., sar@eagle.mit.edu

Received 1993 July 19; accepted 1993 September 13

results to the Galactic globular cluster system. Although there is at present little *direct* observational evidence of CVs in globular clusters, we find that there should be a large number of active systems.

Are Globular Cluster CVs overabundant?

They're not:

Before HST resolved the cores of many Galactic globular clusters, theorists had predicted a plethora of cataclysmic variables in their cores. While a few CVs have now been found, the numbers appear to be one to two orders of magnitude less than the early expectations. Deeper searches with HST will soon show if tidal capture binaries, and in particular CVs, are truly rare, or if most CVs are intrinsically very faint.

Shara 1996

elliptical galaxies. Likewise, we predict that there should be 60–180 CVs for every 10^6 $L_{\odot,K}$ in an old stellar population. The population of X-ray–identified CVs in the globular cluster 47 Tuc is similar to this number, showing no overabundance relative to the field. The observed CN $P_{\rm orb}$ distribution also contains evidence for a CV population

Townsley & Bildsten 2005

Maybe a little?

With our simulations, we predict that the formation rates of CVs and AM CVn systems in GCs are not very different from those in the field population. The numbers of CVs and AM CVn systems per mass unit are comparable to numbers in the field if the whole cluster population is considered, and they are only two to three times larger in the core than in the field. Dynamical formation is responsible only for 60–70 per cent of CVs in the core. This fraction decreases

Ivanova et al. 2006

X-ray CMD

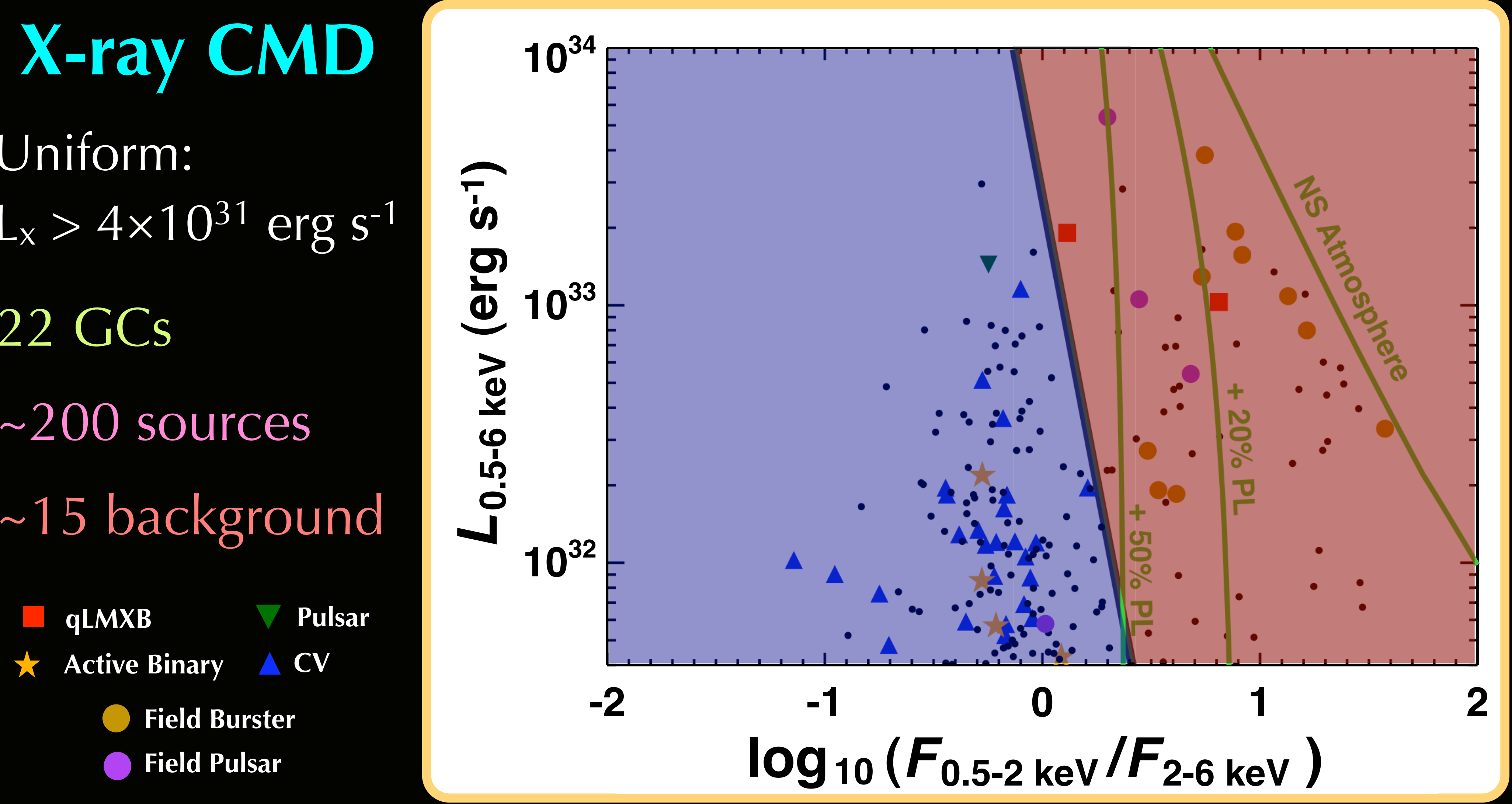
Uniform:

$L_X > 4\times10^{31}$ erg s^{-1}

22 GCs

~200 sources

~15 background

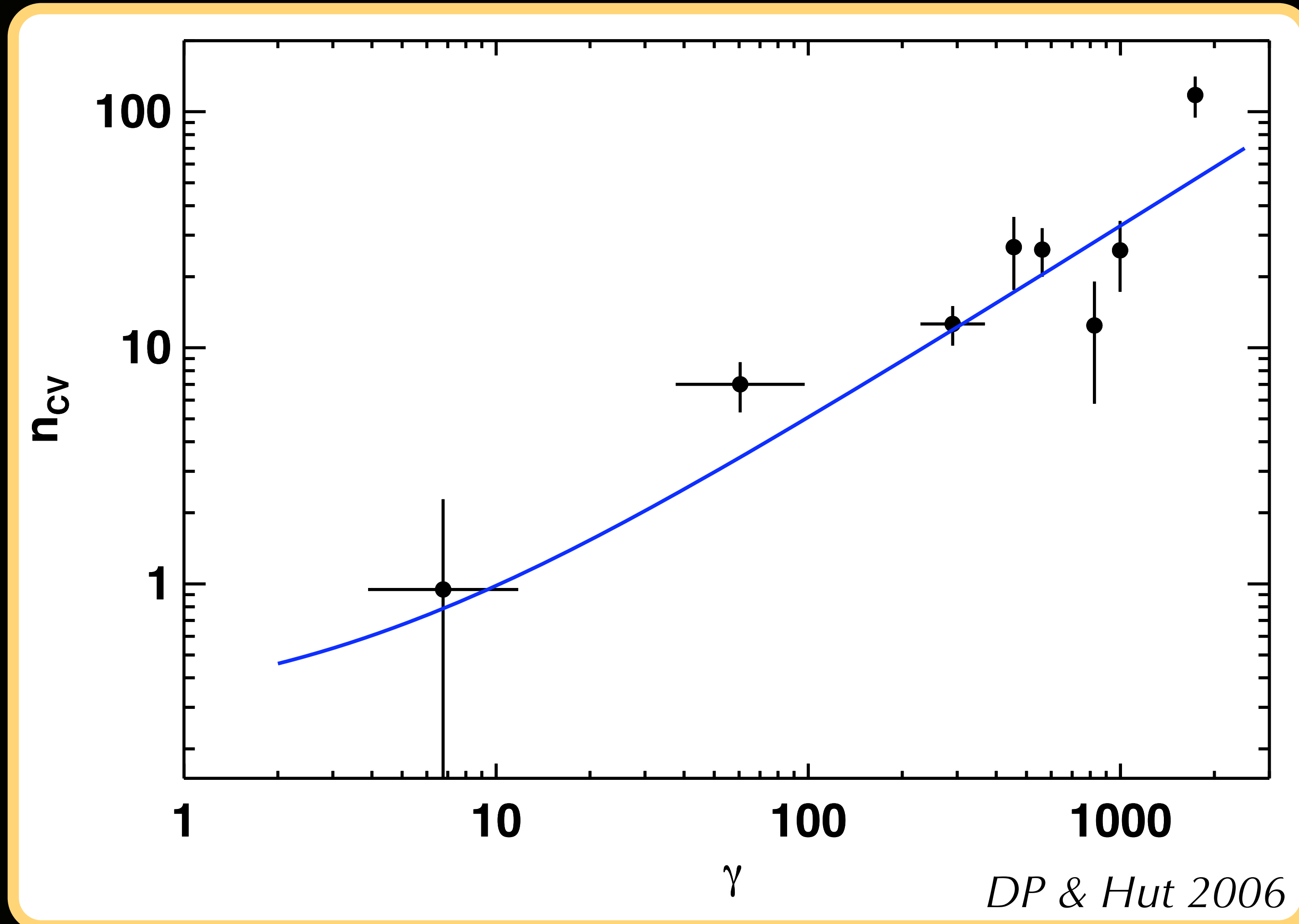


Bright, hard sources
(mostly CVs)

Can rule out constant n at 6σ

$n = a\gamma^s + c$

$s = 0.8 \pm 0.2$
$c = 0.3 \pm 1.4$



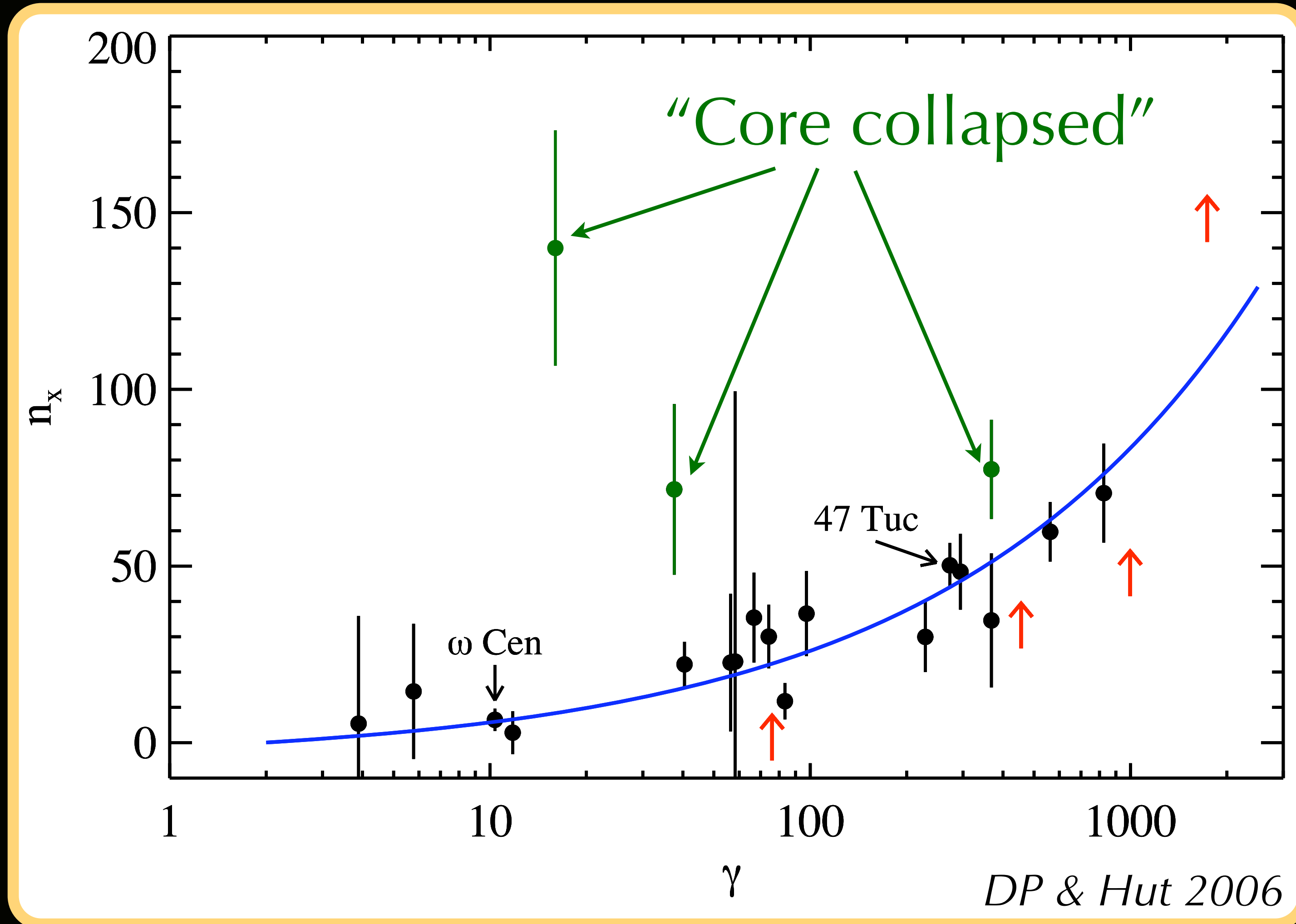
Specific units: $n = N/M$ $\gamma = \Gamma/M$
M in units of 10^6 $M_\odot$

Dynamical Formation

All sources with
$L_X > 4\times10^{30}$ erg s^{-1}

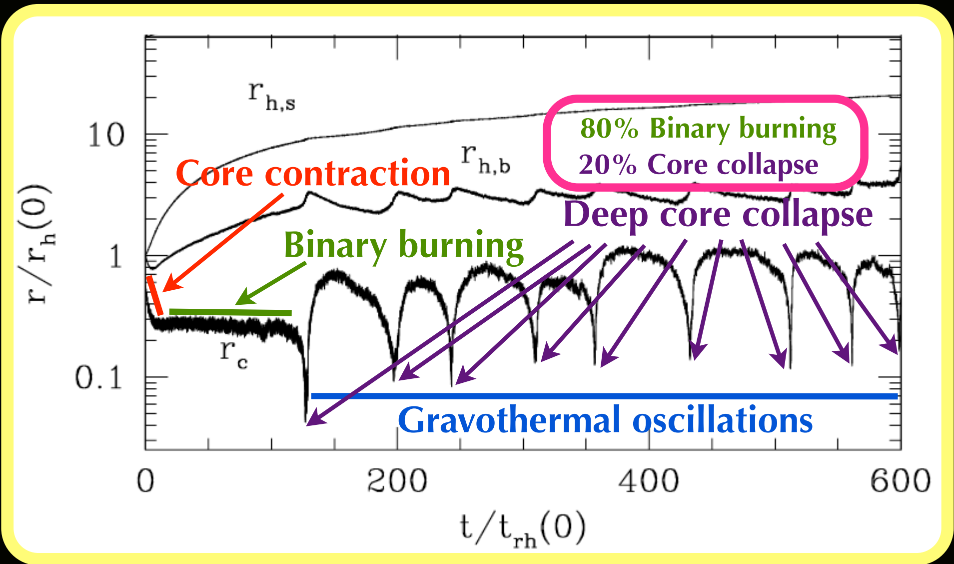
$n = a\gamma^s + c$

$s = 0.45 \pm 0.17$
$c = -5.3 \pm 7.7$



Specific units: $n_X = N_X/M$ $\gamma = \Gamma/M$
M in units of $10^6\ M_\odot$

Globular Cluster Life Stages *Revisited*



Fregeau et al. 2003

Fregeau (2008) pointed out:

- ✳ Better simulations reveal r_c was over-estimated by ≥10× in binary-burning phase
- ✳ Production of X-ray sources in binary burning phase is 2–20× higher than in core contraction phase
- ✳ *Chandra* reveals that "core collapsed" clusters have many more binaries than the N-Γ relation predicts

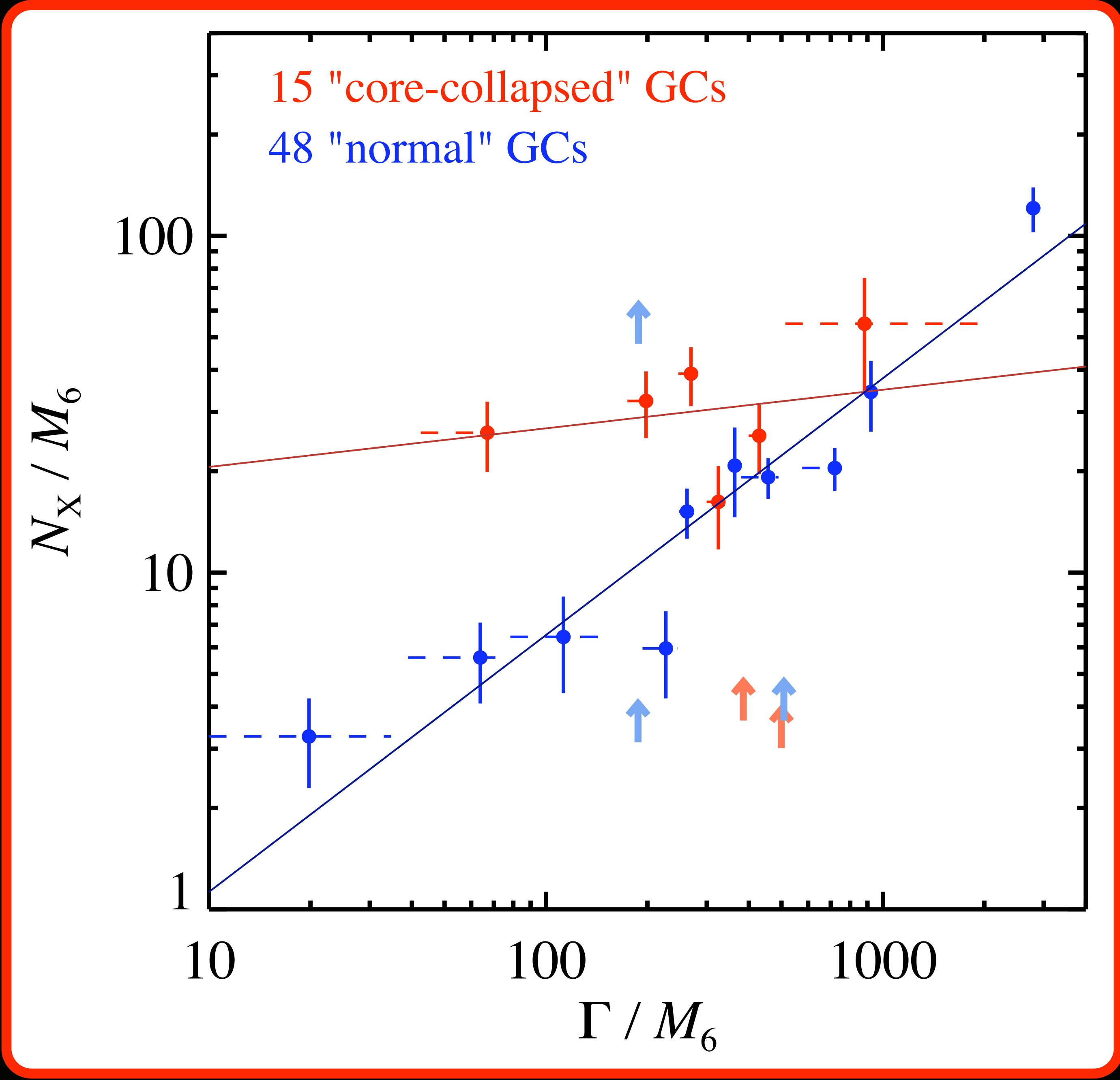
Paradigm shift?

80% Binary burning + 20% Core collapsed → **80% Core contraction + 20% Binary burning**

Dynamical Formation

All sources with
$L_X > 4\times10^{31}$ erg s^{-1}

PRELIMINARY



DP et al. in prep.

Future Work

- Individual identifications
  - Subpopulation dynamics
  - Investigate importance of other parameters (e.g., metallicity)
- Fast (~3 day) transients ***Heinke et al.***
- Low density clusters (primordial binaries) ***Kong, Lu, Lan et al.***
- Deep exposures of M4 ***(DP et al.)*** and NGC 6397 ***(Grindlay et al.)***
- Extending into rich open clusters: **see poster by N. Gosnell**
- *Fermi* survey to determine overall MSP population

Summary

- It's Guinness's 250th birthday!
- X-ray sources are dynamically formed
  - ➡ *Great tracers for large scale simulations (especially LMXBs)*
- CVs are finally being found in large numbers in globular clusters and **are** overabundant
- *Chandra* is the most efficient and effective means of finding the important close binaries in a globular cluster
- Possible revolution in our understanding of the current dynamically states of globular clusters

Understanding Globular Clusters (is tough)

No Thermodynamic Limit

$M \propto R^3$ $E_{kin} \propto M$ but $E_{pot} \propto M^2/R \propto M^{5/3}$ ⇒ "Infrared Divergence"

Negative Heat Capacity

Mass segregation → stratified system → dense core

Encounters extract energy from core, increasing temperature

Nearly Unlimited Reservoir of Binary Binding Energy

3-body encounters tap into binary energy ⇒ "Ultraviolet Divergence"

Feedback between Stellar Dynamics and Stellar Evolution

No Easy Way to Compare Theory to Observation

Input theory to simulations

Compare simulations to observations

Bright X-ray Sources: Neutron Star LMXBs

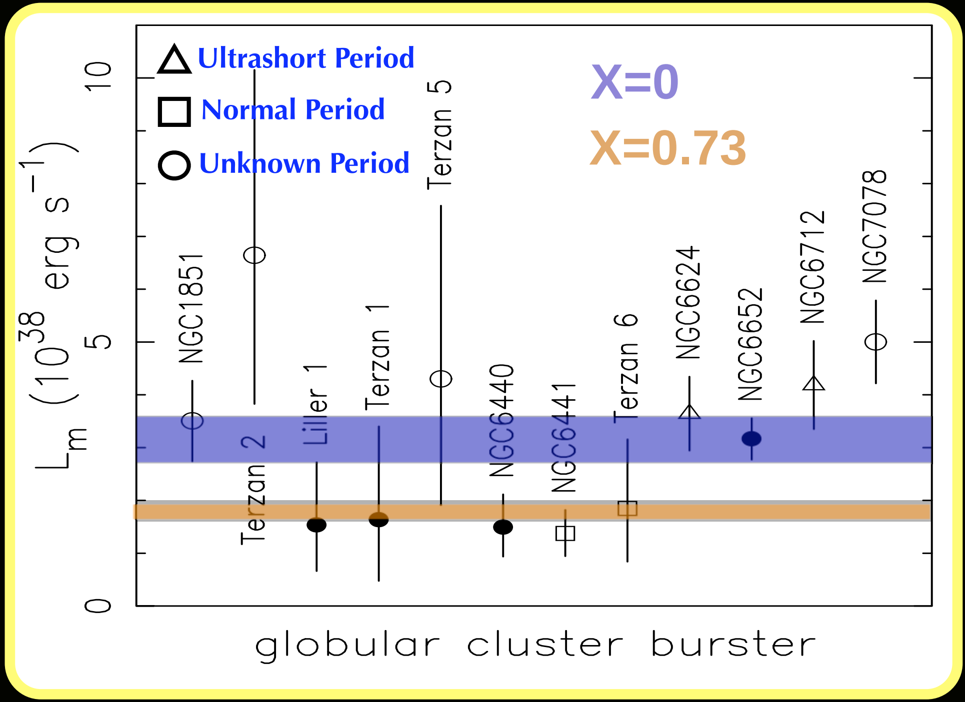
Discovered by *Uhuru* and *OSO-7*; argued to be formed via cluster dynamics
Gursky 1973, Clark 1975, Katz 1975

Stimulated flurry of theoretical work
Fabian, Pringle, & Rees 1975
Sutantyo, 1975
Hills, 1975, 1976
Heggie 1975
Verbunt & Hut 1983

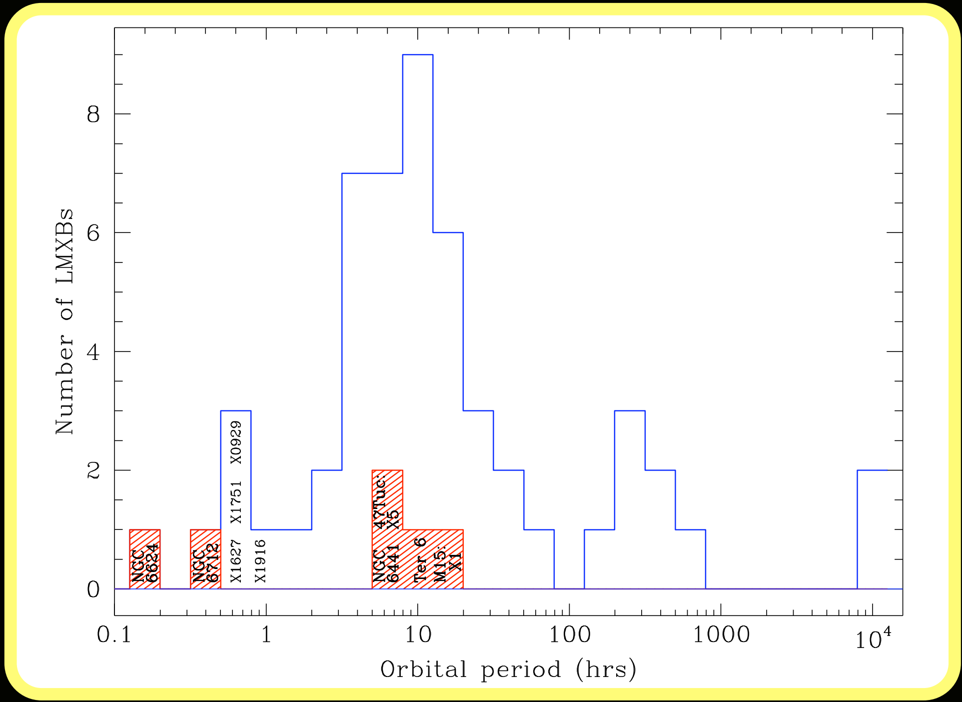
12 globular clusters thought to contain one each

All but one show Type-I X-ray bursts
⇒ NS-LMXBs ***e.g., Kuulkers et al. 1996***

Good evidence that many have ultra-short periods: $P_{orb} < 80$ min
e.g., Deutsch et al. 1996

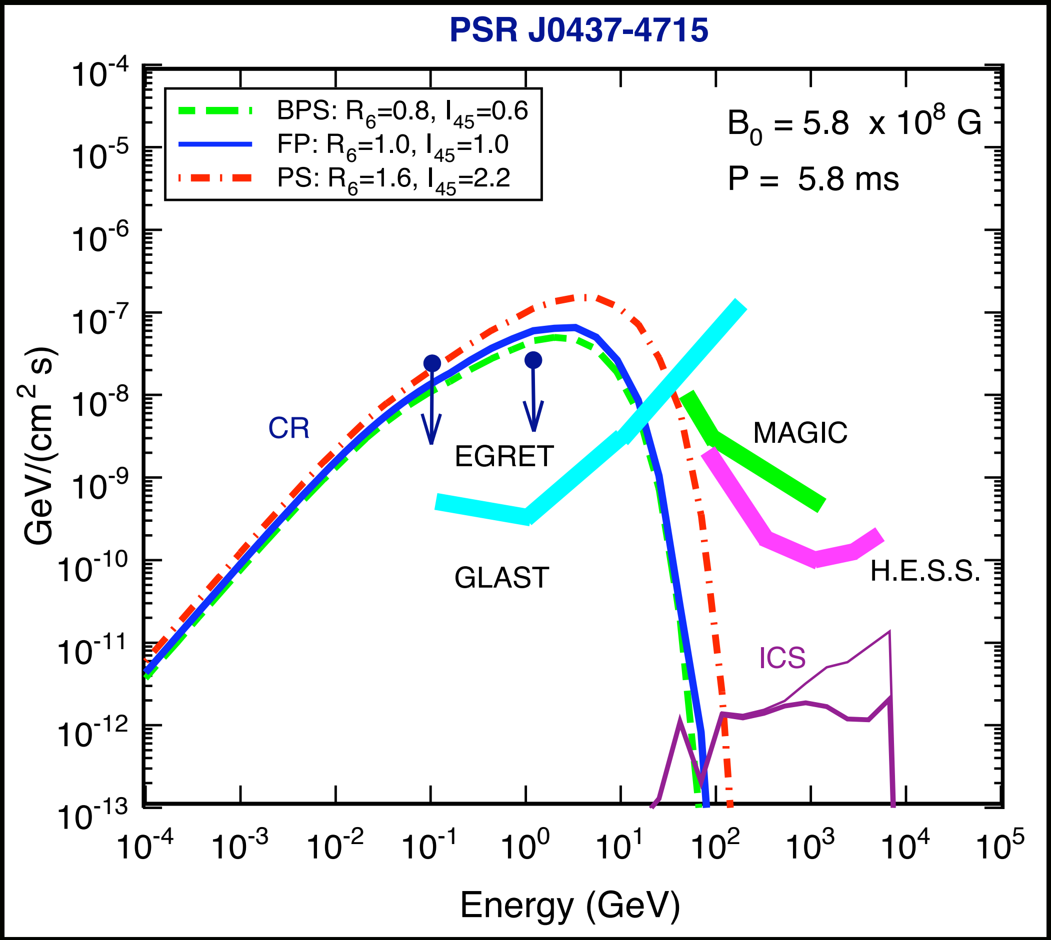


Kuulkers et al. 2003



courtesy L. Homer

GLAST Observations of Globular Cluster MSPs



Harding, Usov, & Muslimov 2005

d = 0.18 kpc

F_{CR} (1 GeV) = 0.145×10^{-8} cnts cm^{-2} s^{-1} MeV^{-1}

Glob. clusters @ 2–10 kpc
BUT with 100s of MSPs!

$$F_{clus} = F_{0437} \times \left(\frac{0.18}{5}\right)^2 \times 100$$

$$= F_{0437} \times 0.13$$

Most Promising *GLAST* Clusters

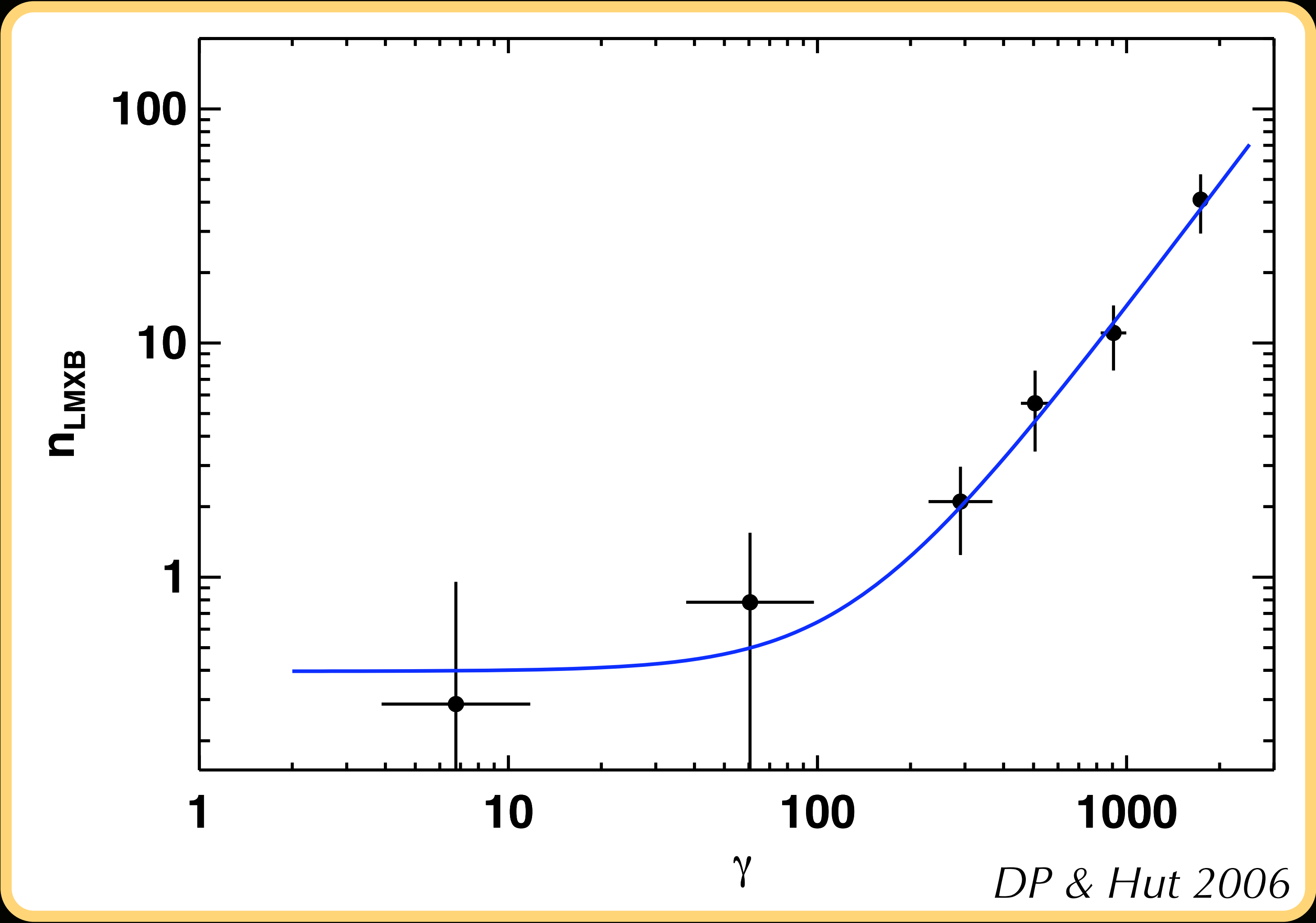
Cluster	N_{LMXB}	d (kpc)	MSP Flux Fig. of Merit
Terzan 5	15.3	8.7	0.203
NGC 6440	10.2	8.4	0.144
47 Tuc	2.7	4.5	0.132
NGC 6388	13.0	10.0	0.130
NGC 6540	1.6	3.7	0.120
Liller 1	10.5	9.6	0.114
NGC 6266	5.4	6.9	0.113
NGC 6544	0.5	2.7	0.064

Cluster LMXBs

Can rule out constant n at 4σ

$n = a\gamma^s + c$

$s = 1.8 \pm 0.4$
$c = 0.4 \pm 0.5$



Specific units: $n = N/M$ $\gamma = \Gamma/M$
M in units of $10^6\ M_\odot$

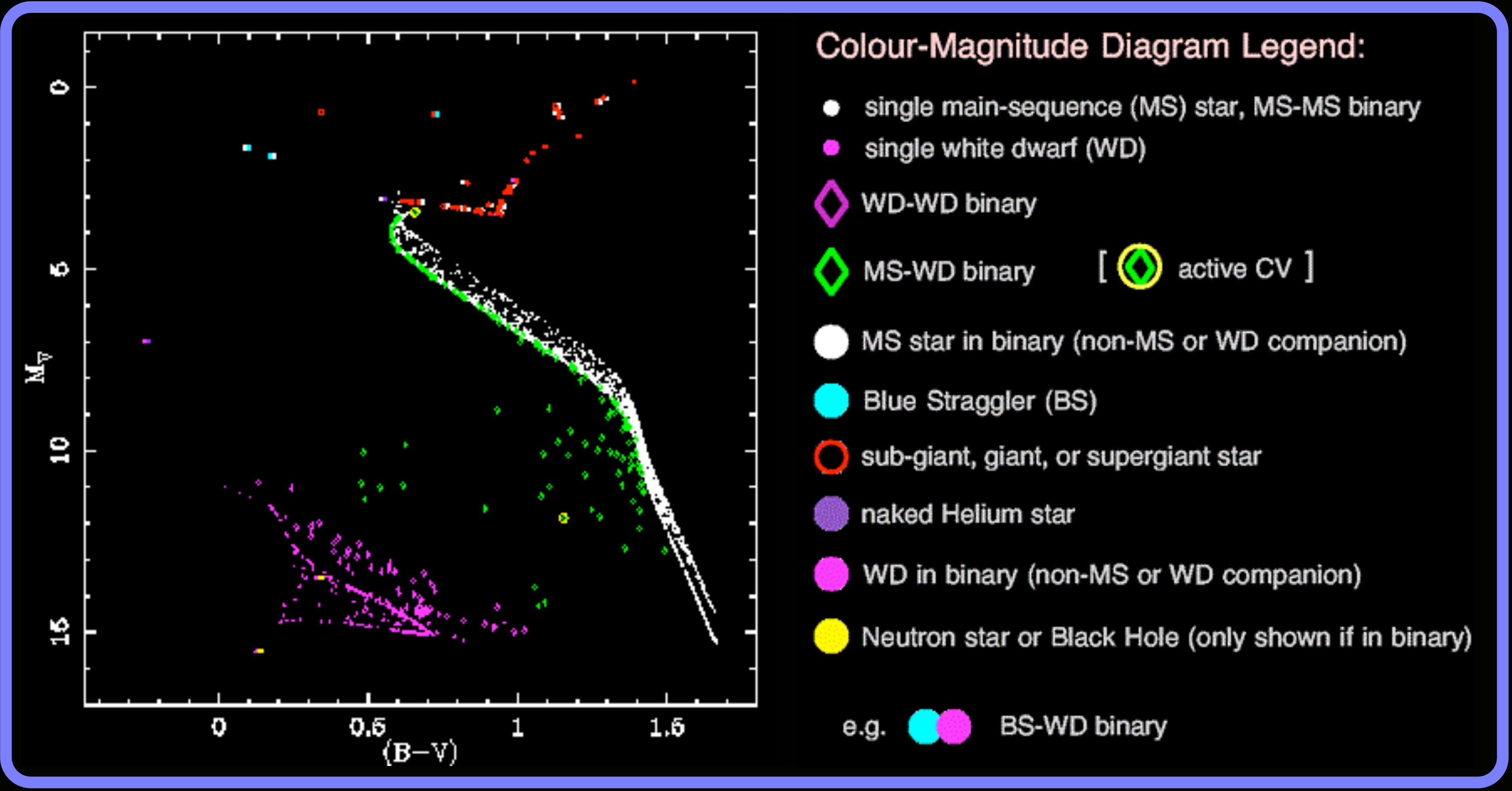
“Kitchen Sink” simulations coming soon...

GRAPE-6
supercon

See www
for more

Simulation by S. Portegies Zwart

"Kitchen Sink" simulations coming soon...



M67 Simulation by J. Hurley

Brief History of Binaries in Globular Clusters

1960s, 70s: Theory predicted the inevitable collapse of cluster of single stars ***e.g., Hénon 1961, 1965***

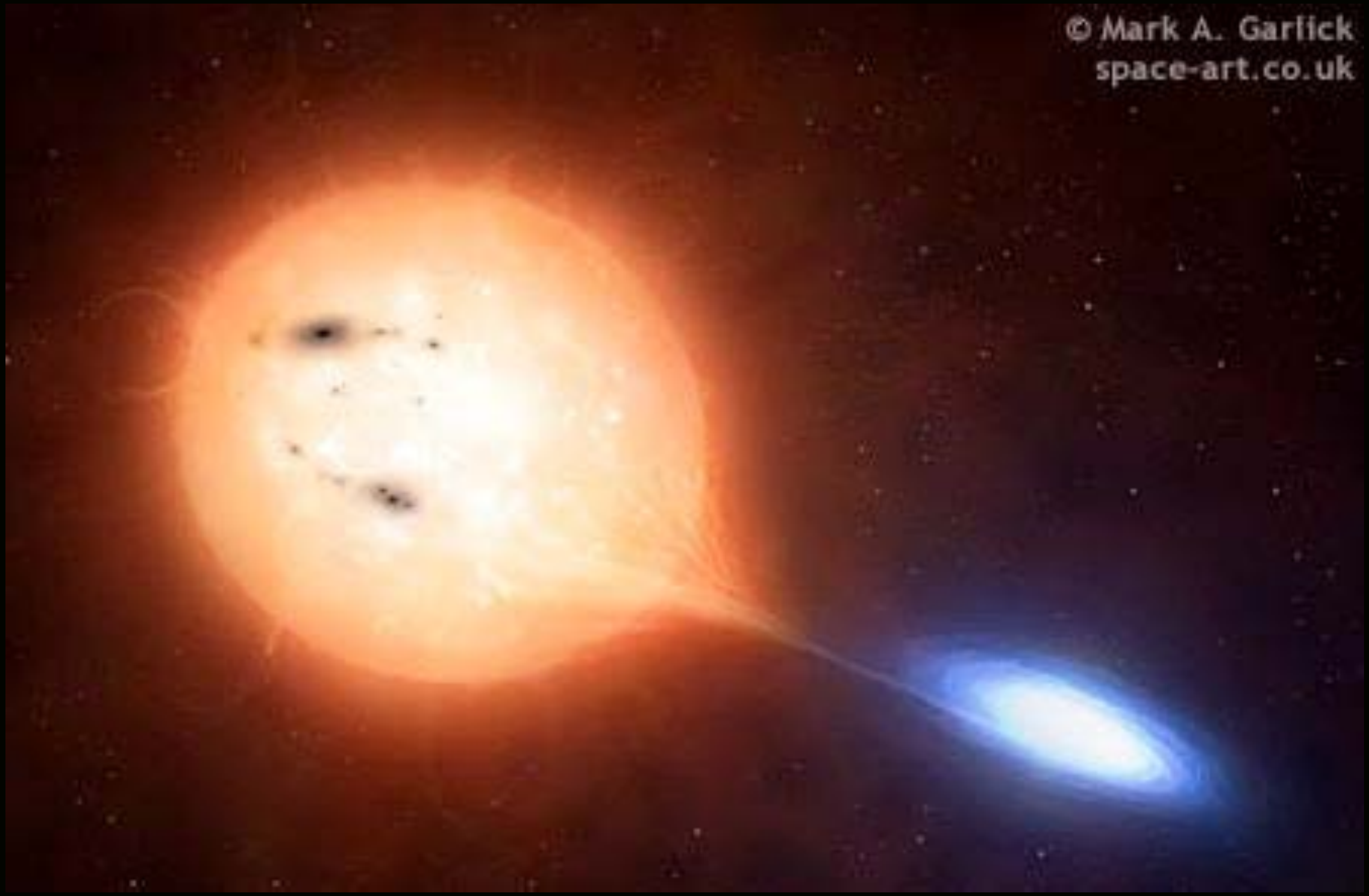
1980s: Computer simulations confirmed this and gave rich understanding of collapse ***e.g., work by Goodman, Heggie, Hut, Spitzer ...***

1970s, 80s: Observers found no binaries ***e.g., Gunn & Griffin 1979***

1990s: Observers found some binaries ***see Hut et al. 1992***

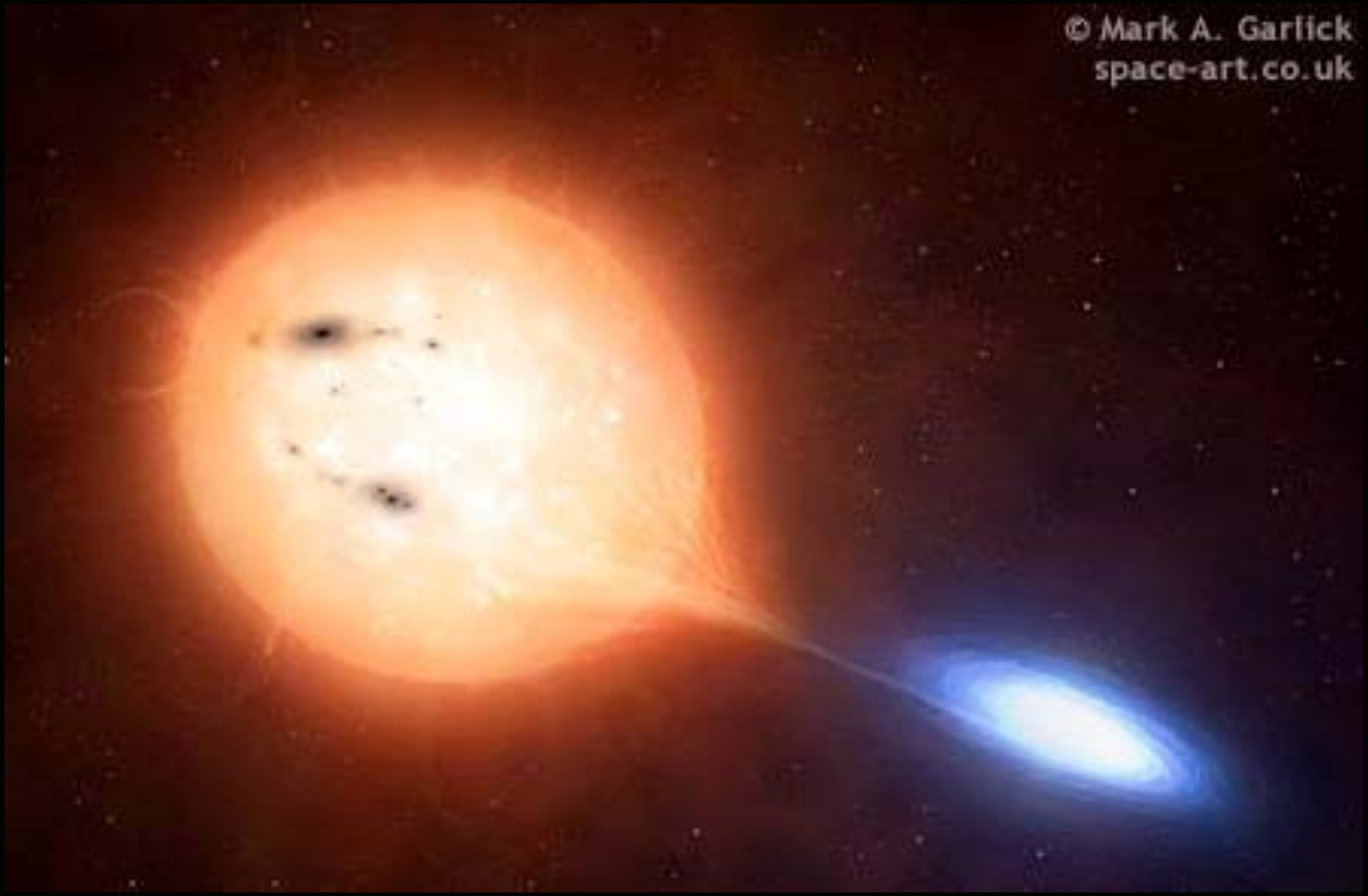
1990s: Simulations showed how binaries postpone core collapse ***e.g., Goodman & Hut 1989***

Low Mass X-ray Binary (LMXB)



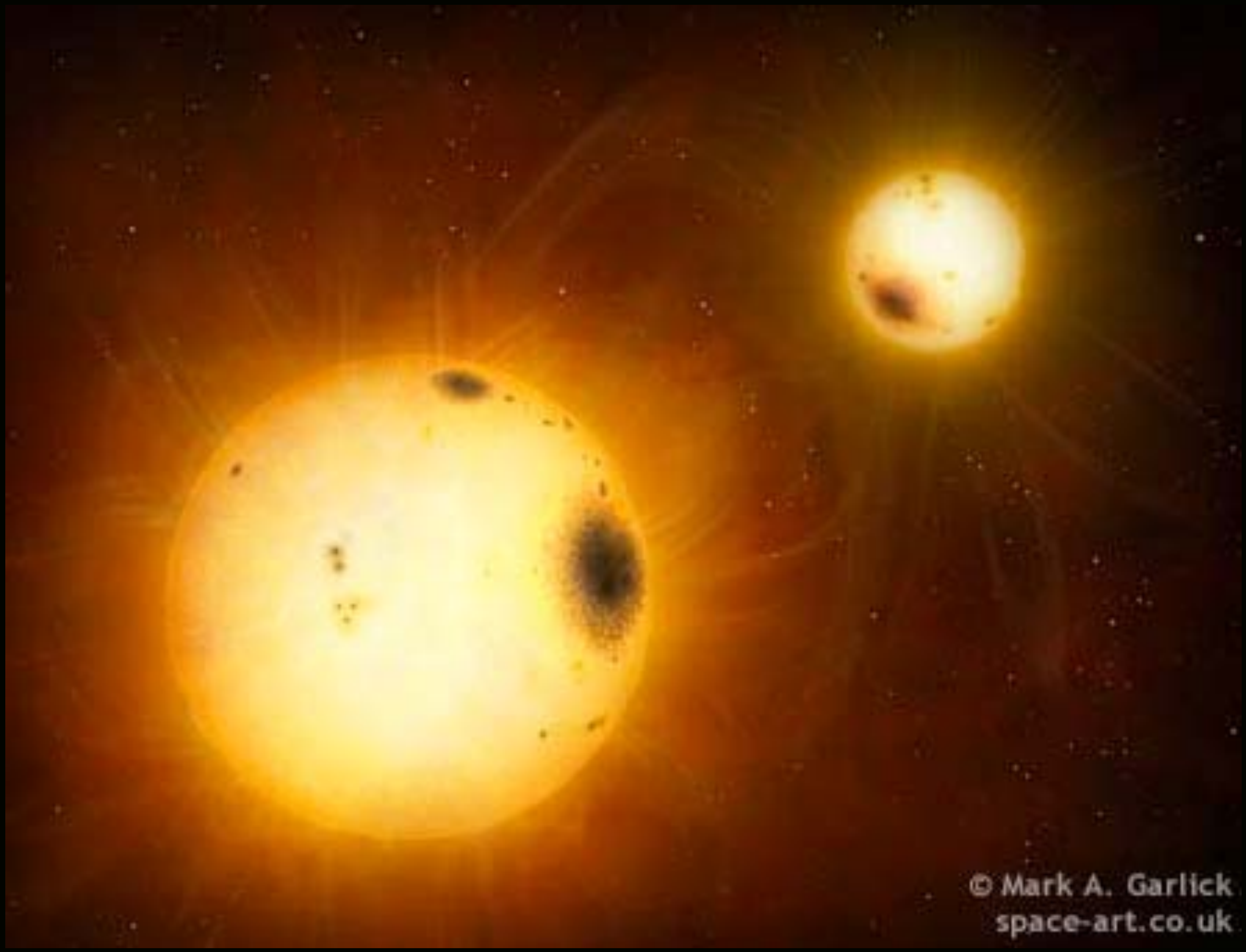
low mass star + neutron star

Cataclysmic Variable (CV)



low mass star + white dwarf

Active Main Sequence Binary



two stars with strong magnetic fields

What is a "close" binary?

We can divide globular cluster binaries into two broad groups, based on binding energy:

$$\frac{Gm_1m_2}{a} > \frac{1}{2}\left\langle mv^2\right\rangle$$

"Hard" or "Close" binaries

$$\frac{Gm_1m_2}{a} < \frac{1}{2}\left\langle mv^2\right\rangle$$

"Soft" binaries

We shall later find it meaningful to divide this range into two, applying to those binaries satisfying the inequality $\beta x \leqslant 1$ the description 'soft', while those for which $\beta x > 1$ will be called 'hard'. We shall see that hard binaries are highly resilient to encounters with other stars, while soft binaries are somewhat fragile.

Heggie (1975)

Γ ("Encounter Frequency")

$$R = n_1 n_2 v_{\rm rel} \sigma$$

$$\sigma = \pi d^2 \left(1 + \frac{2G(m_1 + m_2)}{v_{\rm rel}^2 d}\right) \approx \pi d \frac{2G(m_1 + m_2)}{v_{\rm rel}^2}$$

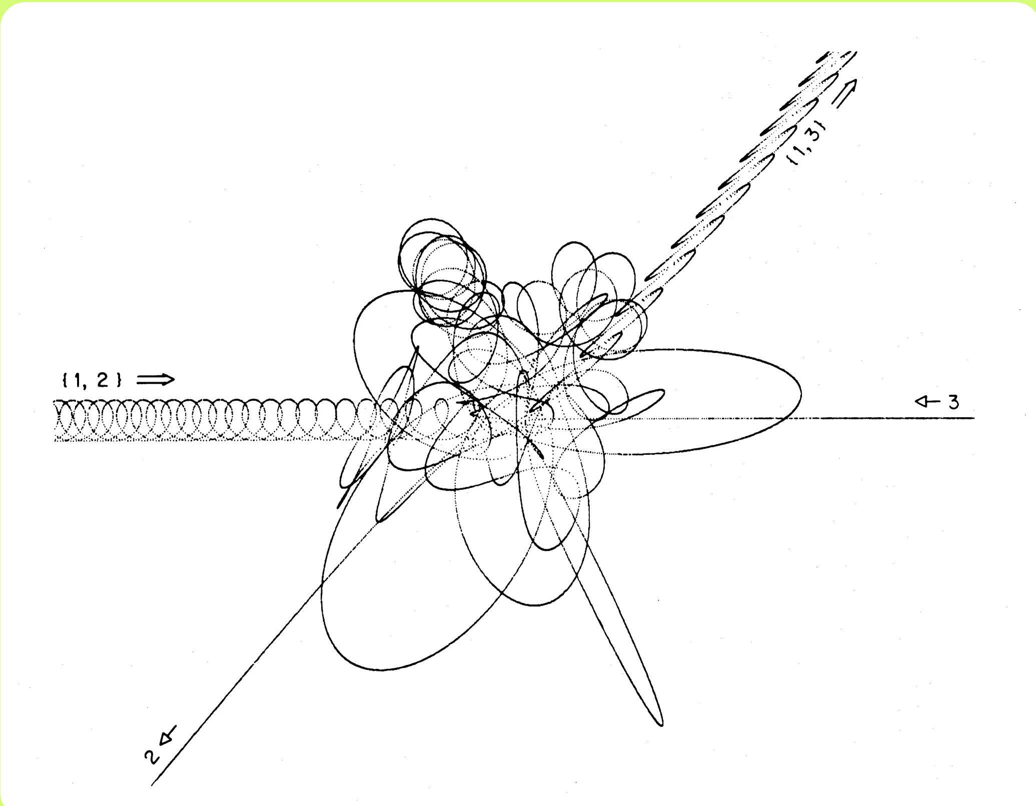
$$\Rightarrow R \sim \rho^2 / v$$

$$\Gamma = \int_0^{r_h} R dV$$

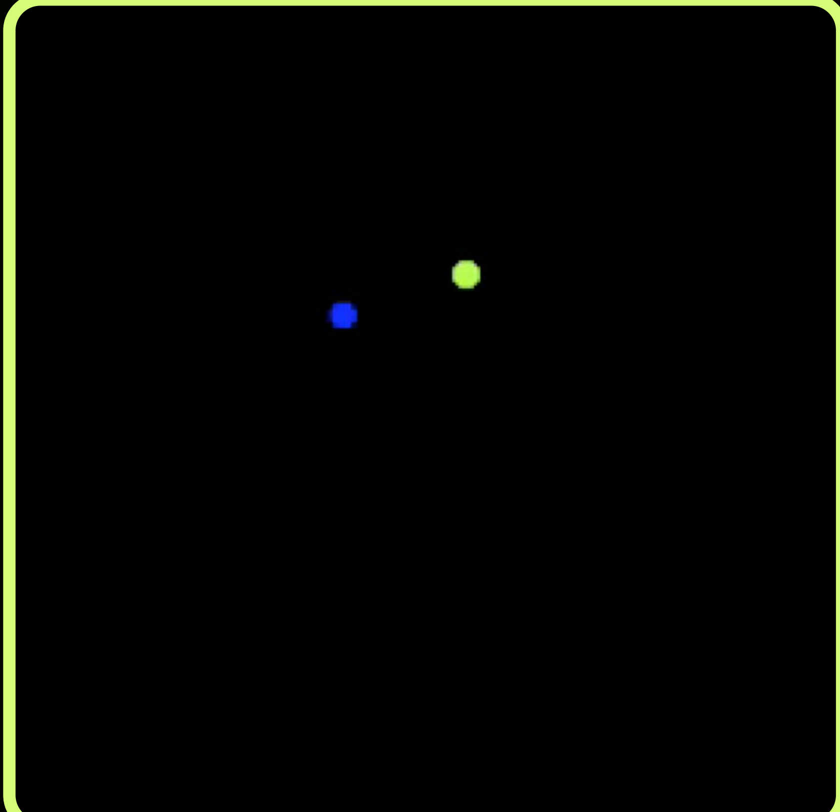
$$\Gamma = \int_0^{r_c} R dV \approx \rho_0^2 r_c^3 / v = \rho_0^{1.5} r_c^2$$

“Heggie’s Law” in action (numerically):

Perform scattering experiments for different initial parameters.

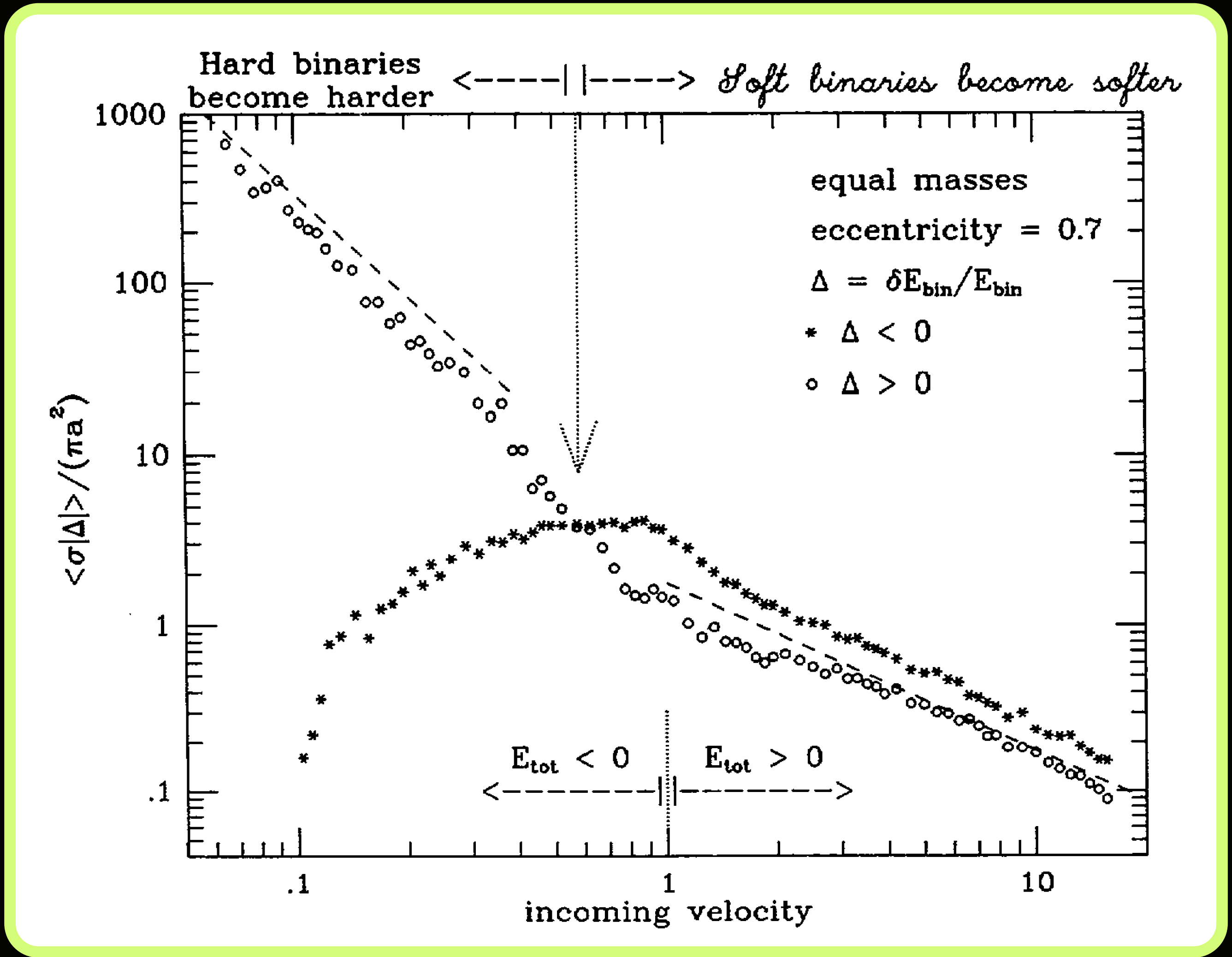


Hut & Bahcall (1983)



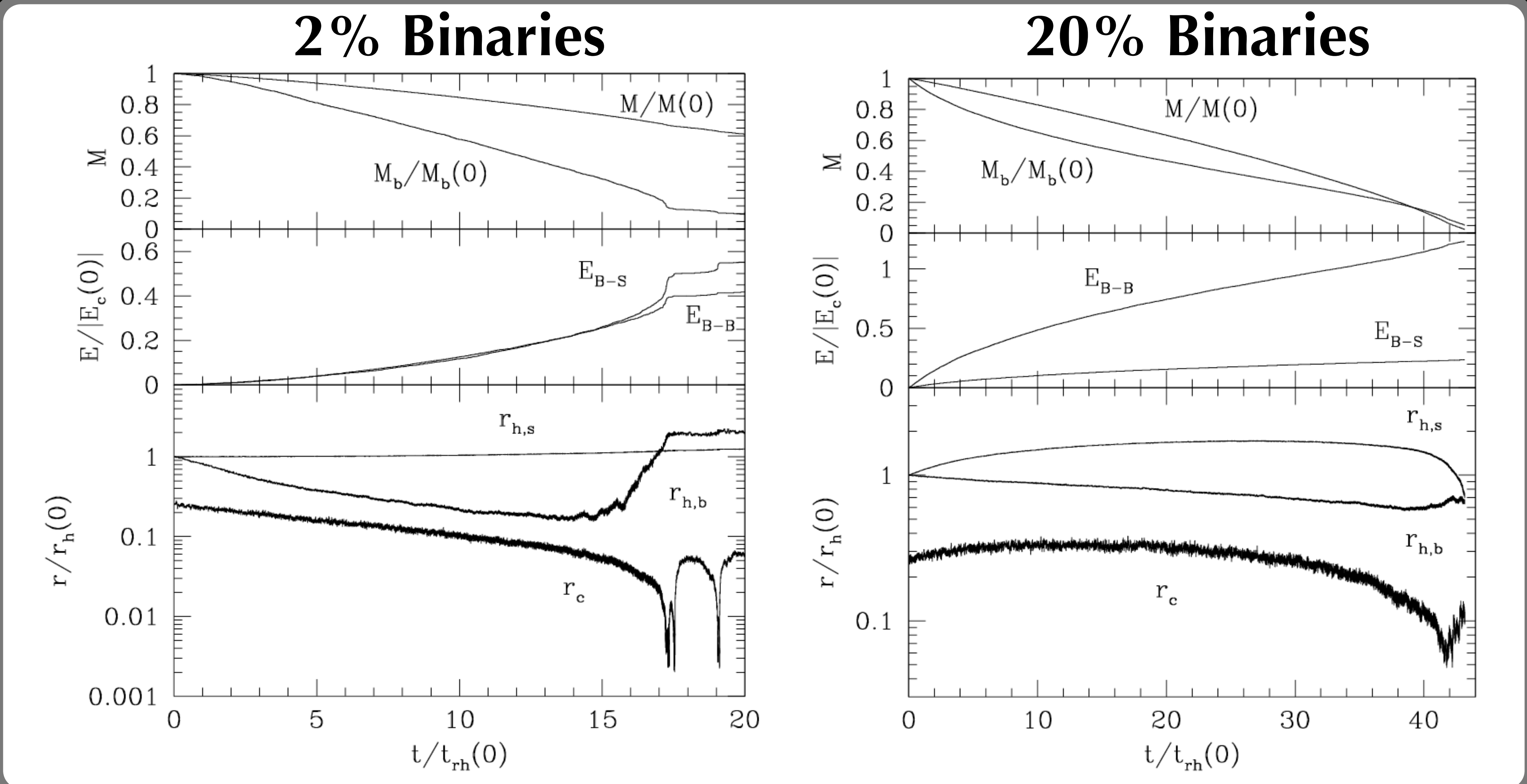
from A. Gualandris
(http://staff.science.uva.nl/~alessiag/)

“Heggie’s Law” in action (numerically):



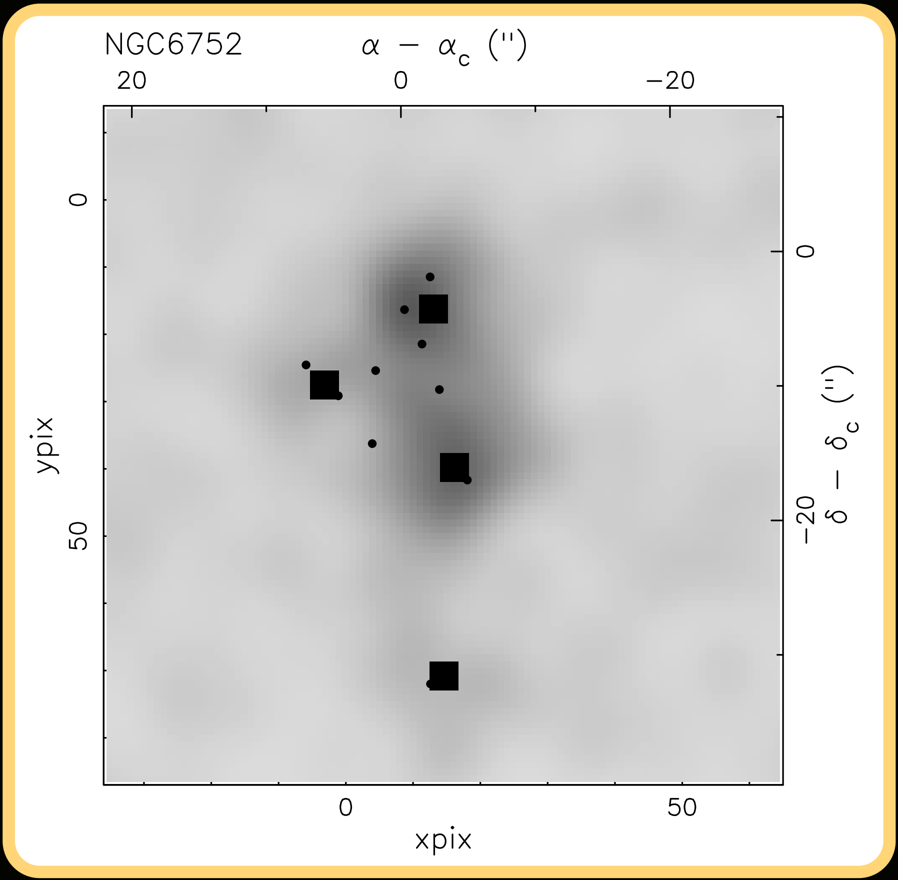
Hut (1983)

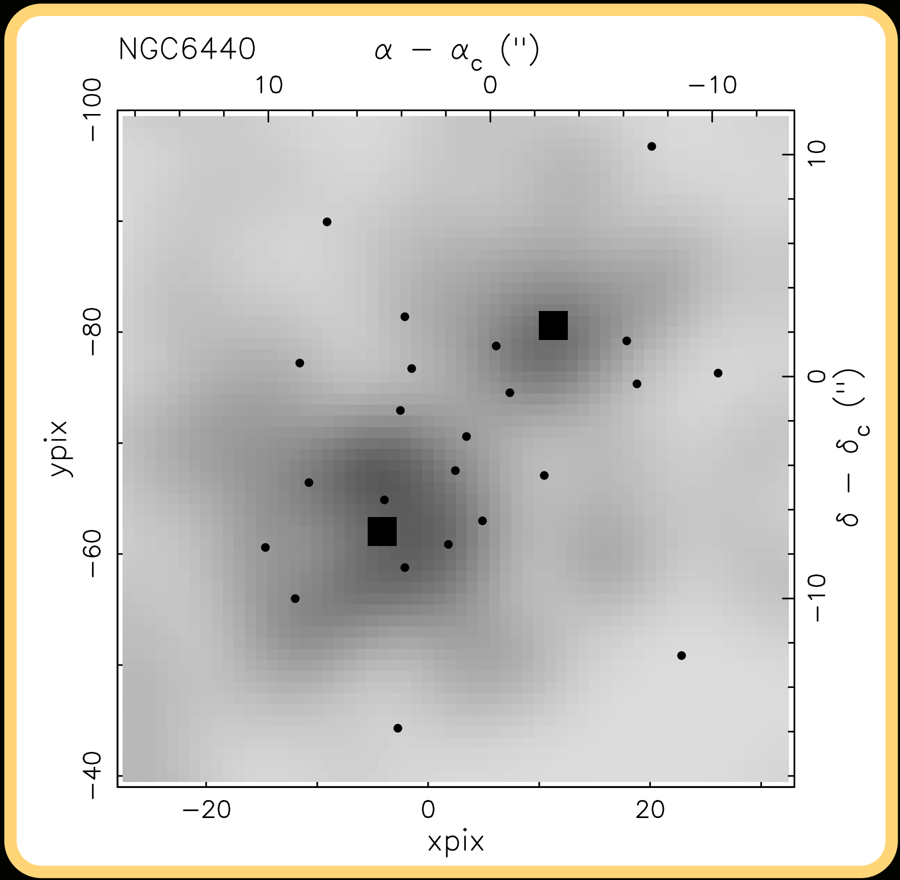
Key Role of Binaries in GCs



Fregeau et al. 2003

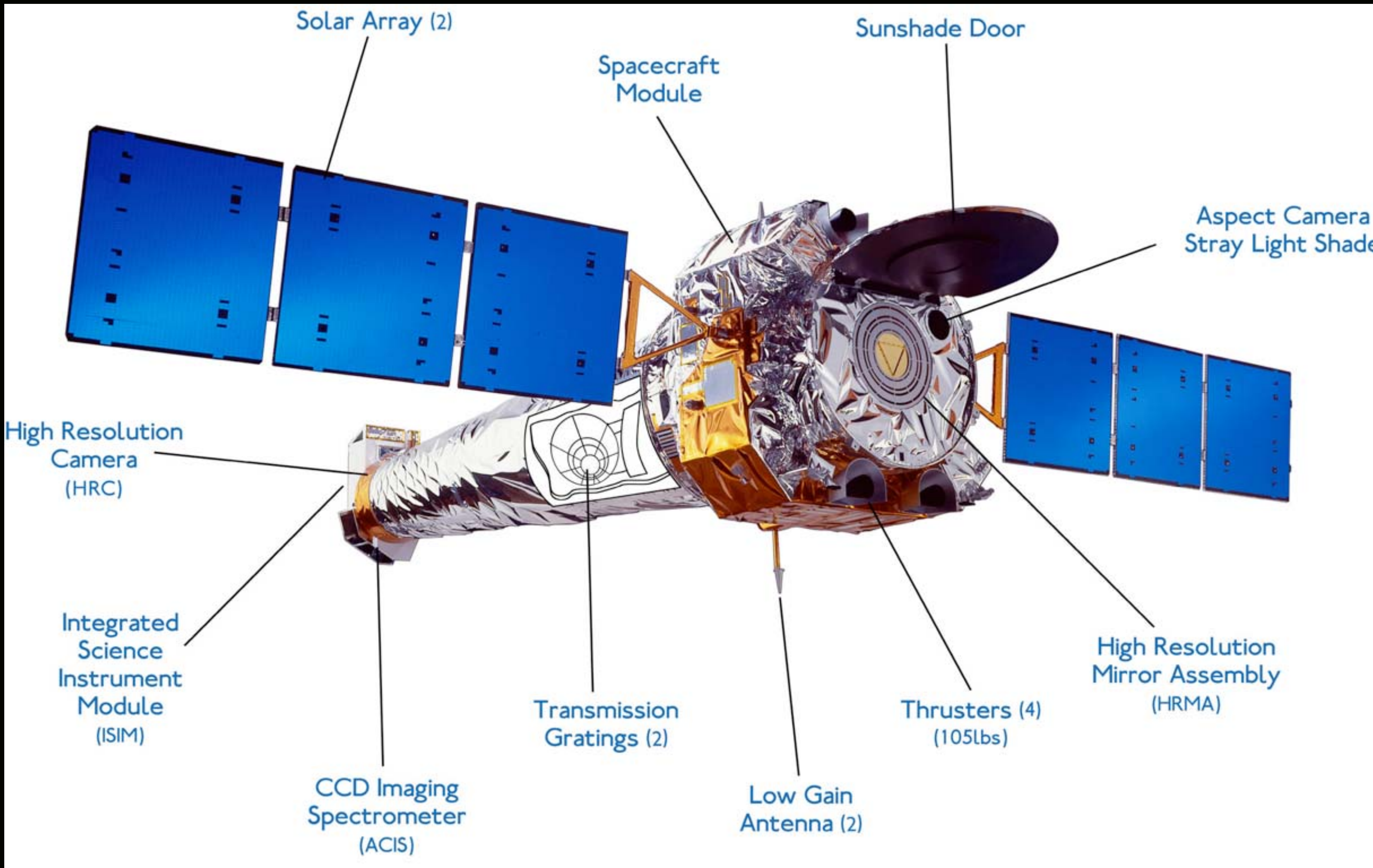
ROSAT grayscale + *Chandra* point sources





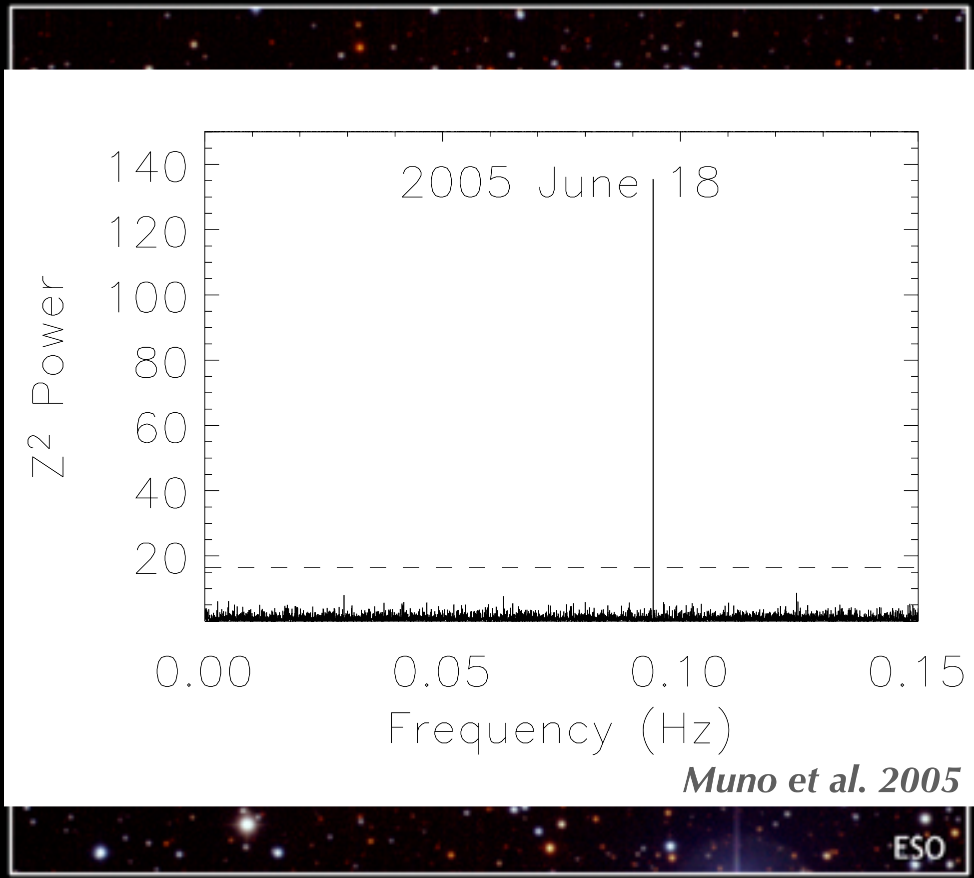
Verbunt 2004

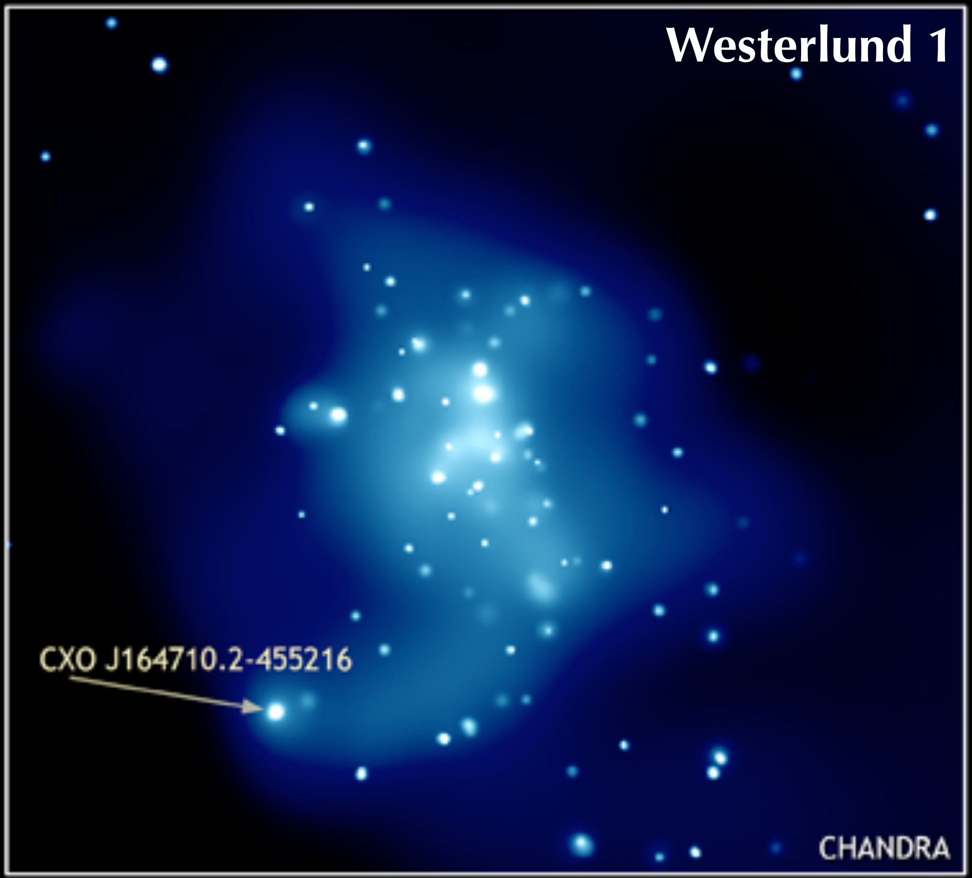
The Revolutionary *Chandra X-ray Observatory*



Related Work: Young Massive Clusters

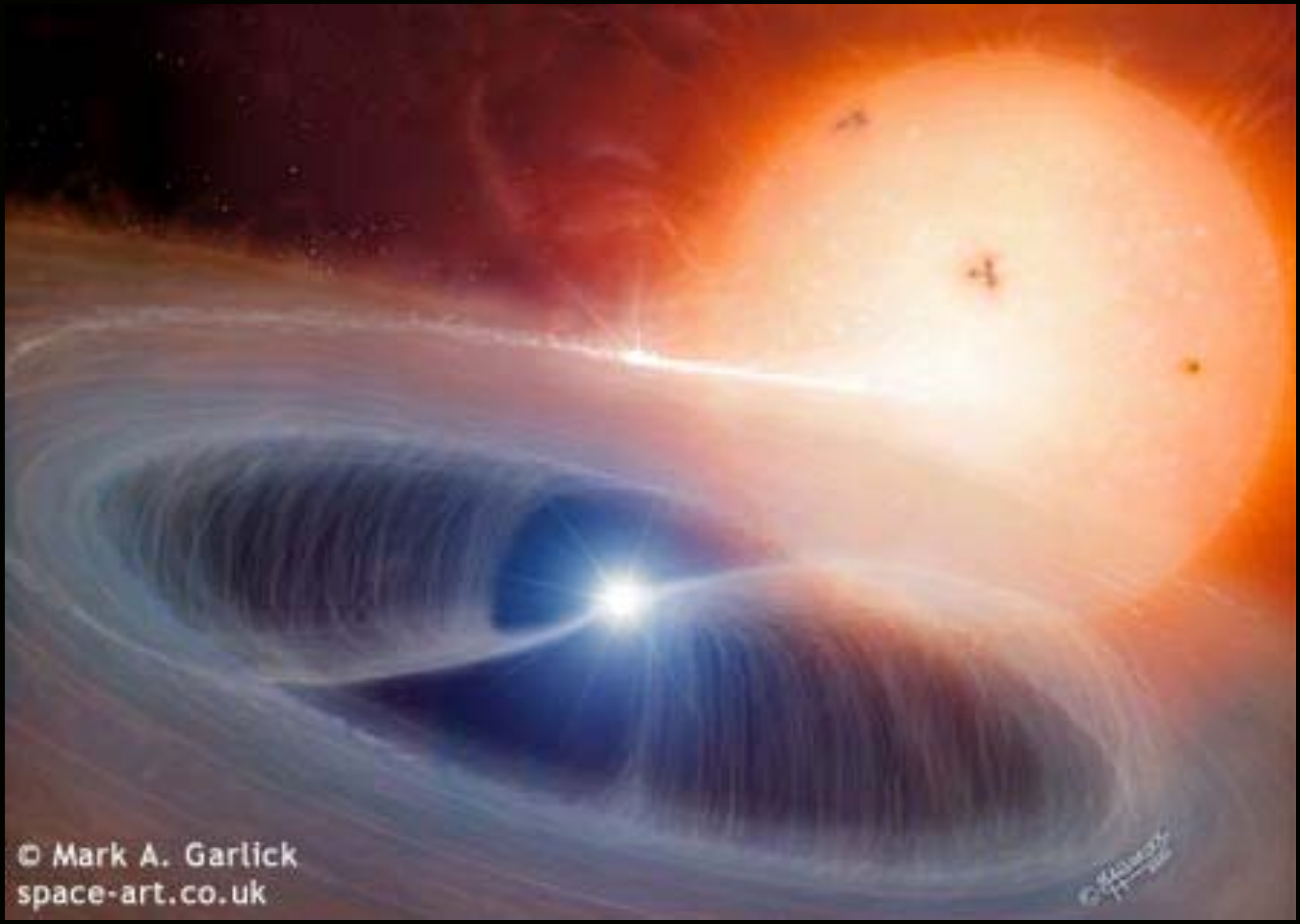
The Search for Black Holes





Cataclysmic Variable (CV)

Intermediate Polar



low mass star + magnetic white dwarf

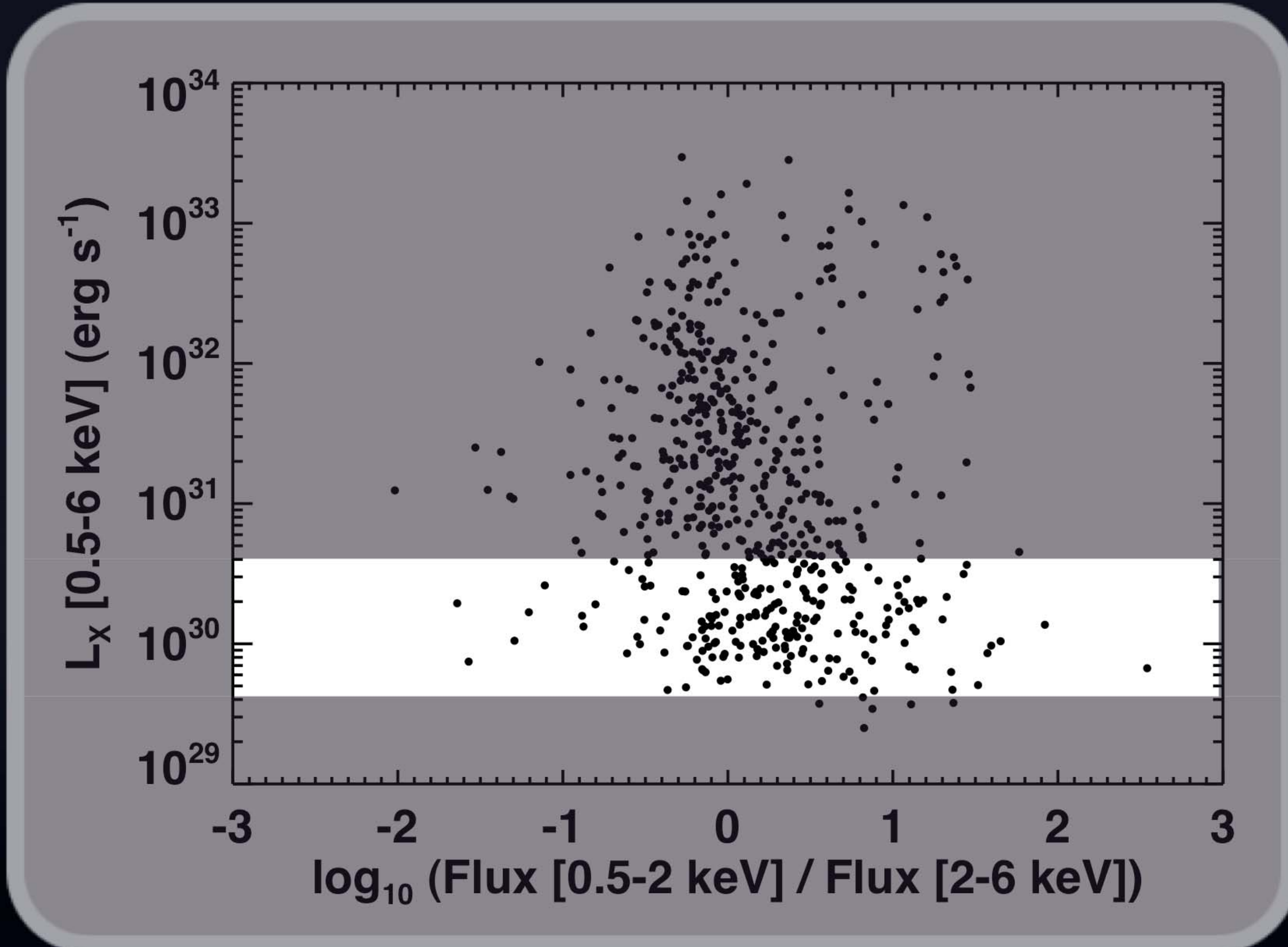
X-ray CMD

Very low L_x
$4\times10^{29} - 4\times10^{30}$ erg s^{-1}

3 GCs

243 sources

~35 background



Very Low Luminosity: $4 \times 10^{29} - 4 \times 10^{30}$ erg s^{-1}

(Mostly Active Main-sequence Binaries)

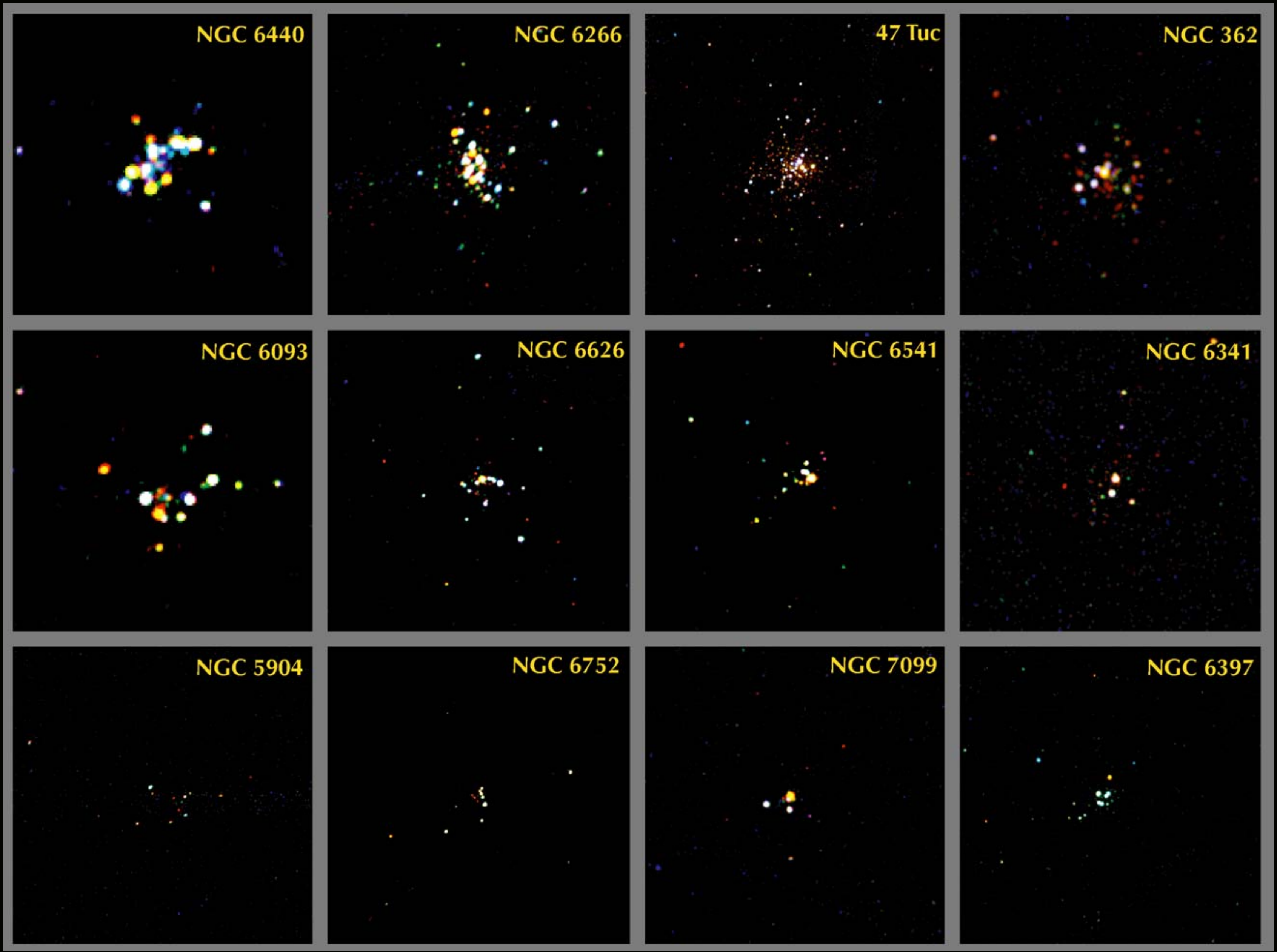
Cluster	Γ/Γ_{6121}	$L_V/L_{V,6121}$	N_{srcs}	$N_{srcs}/N_{srcs,6121}$
47 Tuc	34	10	180 – 200	12 – 13
NGC 6121	1	1	12 – 18	1
NGC 6397	0.45	0.77	4 – 6	0.3 – 0.4

Heinke et al. 2005, Bassa et al. 2004, Grindlay et al. 2001

Complication: Variability

Cluster	Obs.	$N_{min} – N_{max}$	$\langle N \rangle \pm \sigma_N$	N_{unique}
47 Tuc	14	70 – 88	78.9 ± 6.4	180
NGC 6121	5	7 – 14	10.2 ± 2.1	22
NGC 6397	11	10 – 16	13.3 ± 2.1	25

X-ray Sources in Globular Clusters



X-ray CMD

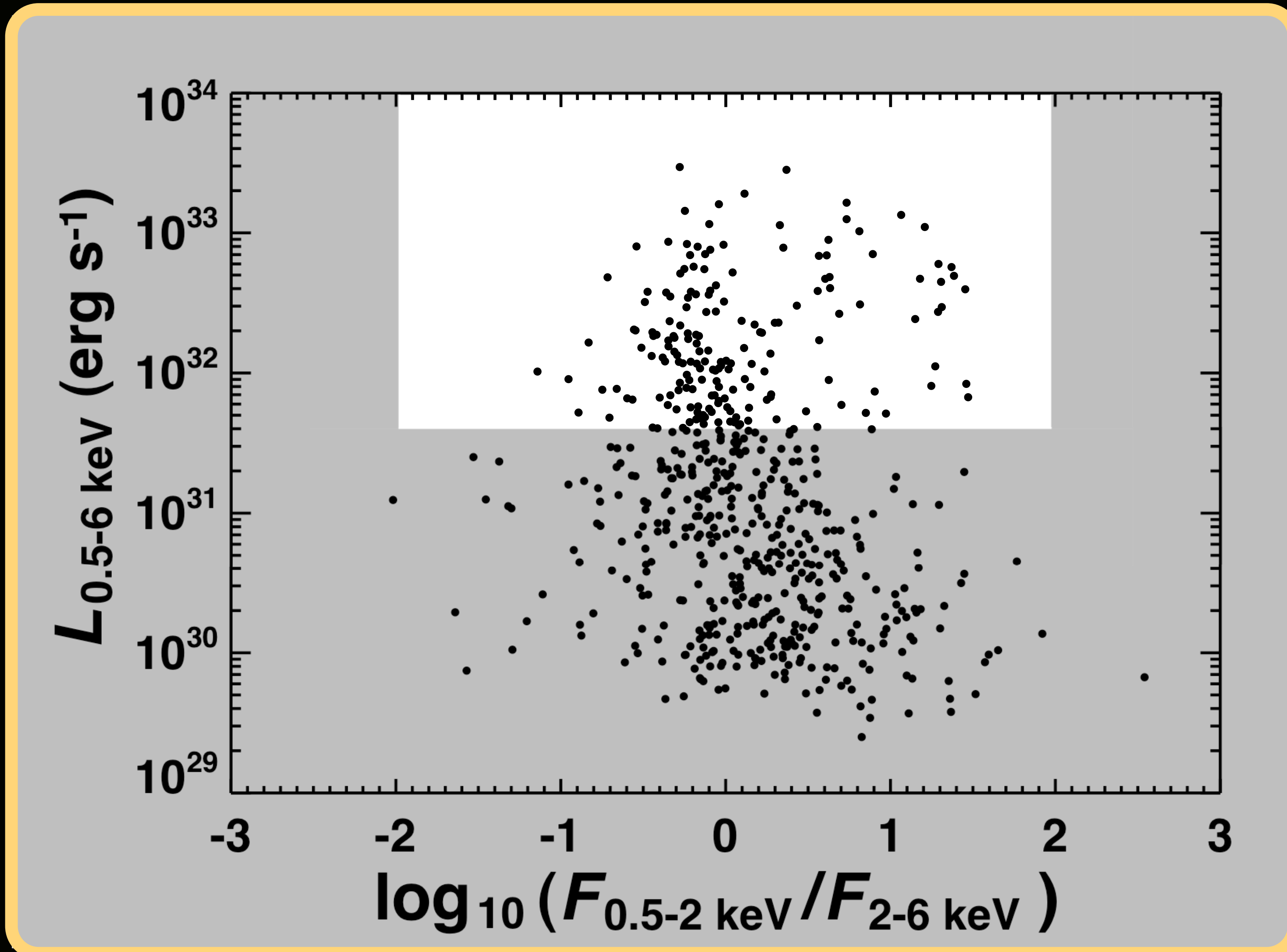
Uniform:

$L_x > 4\times10^{30}$ erg s^{-1}

12 GCs
28 GCs

~200 sources
~500 sources

~100 background
~150 background



X-ray CMD

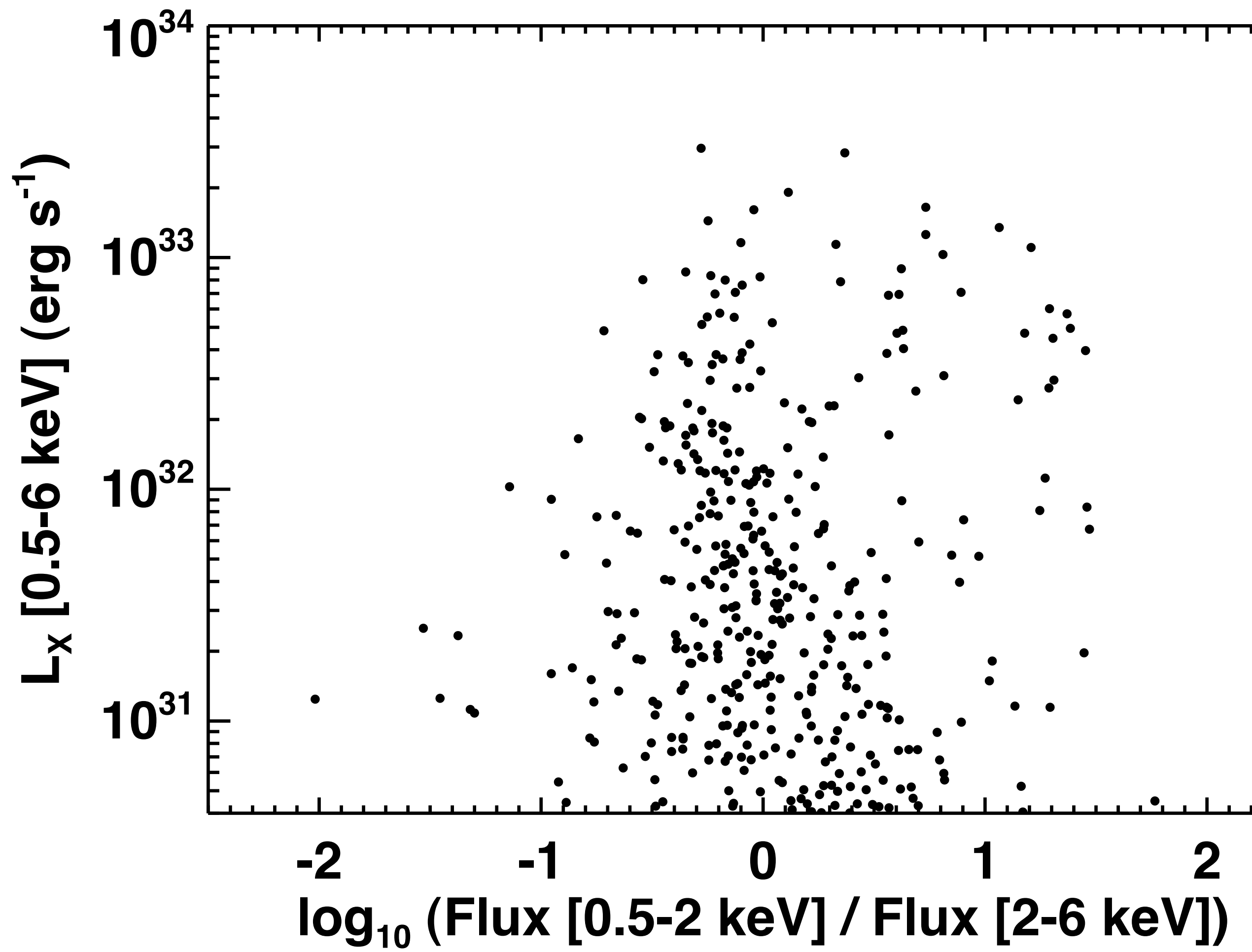
Uniform:

$L_X > 4\times10^{30}$ erg s^{-1}

21 GCs

~500 sources

~100 background



Primordial vs. Dynamical Formation

Compare number of sources (N) per cluster to

Primordial quantity: mass of cluster (M)

Dynamical quantity: encounter frequency of cluster (Γ)

Problem — M and Γ are correlated

Solution — use "specific" units $n \equiv N/M$ $\gamma \equiv \Gamma/M$

Method — primordial: $n = c$

dynamical: $n(\gamma) = a\gamma^s + c$