XRB populations in galaxies

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Harvard-Smithsonian CfA

Cargese, April 2006

X-ray Binaries

HMXB - Young

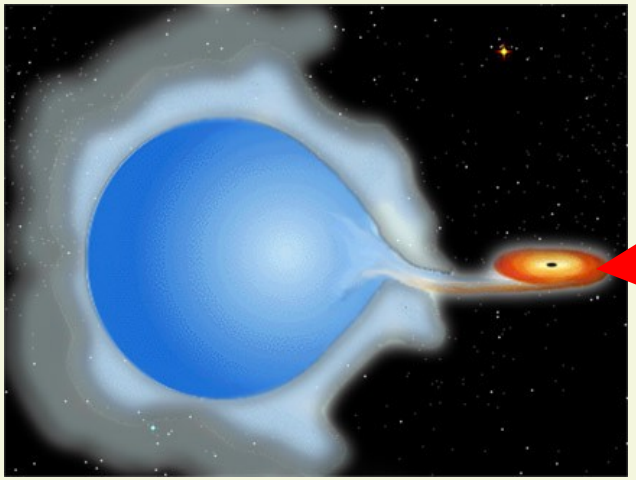
- Early type star donor
- Wind or Roche lobe overflow
- Short lifetimes ~10^7 yrs

Tracer of star formation

LMXB - Old

- Late type star donor
- Roche lobe overflow
- Long lifetimes ~$10^{9\text{-}10}$ yrs

Tracer of mass



Neutron star
Or
Black Hole

Outline

- X-ray emission of galaxies
  - Pre-*Chandra*
  - *Chandra* (*XMM-Newton*) population studies/tools
  - Color-Color diagrams
  - XLFs
- Old populations (E & S0 galaxies)
  - Properties
  - XLFs
  - GC connection
  - Evolution theories

Outline

- Younger & Mixed populations (S and Irr galaxies)
  - Properties
  - XLFs
- Drivers of XLFs and effects of statistics
- Peculiar classes of sources
  - SSS
  - ULX
- High z galaxies and XRB evolution
- Future prospects

General Points

- Go to review papers and use them to find important papers to read
- I will point out a couple of papers that are important to look at for methods/data analysis approaches
- If you are an observer
  - It is important to be aware of relevant theory
  - It is more important to consider all possibilities when reading the data, and to consider the allowed uncertainties - let the data guide you

History - 1

- X-ray study of galaxies began in 1978 with the *Einstein Observatory* (~0.5 -4 keV; ~45" & ~5" res.) the first imaging X-ray telescope
  - (see Fabbiano 1989 ARAA; Einstein Catalog; many correlation-based papers, e.g. Shapley et al 2001, Fabbiano & Shapley 2002 for S)
  - Populations of X-ray sources in S galaxies
  - XRB-star-formation connection
  - ULXs
  - Hot gaseous outflows
  - Hot ISM/halos in some E galaxies
    - Debated mass estimates (see Trinchieri, Fabbiano & Canizares)
  - Inferred LMXB populations in E galaxies

History - 2

- *Rosat* (~0.1 - 2 keV; ~35” & ~5” res.) allowed study of softer component
  - Discovery of SSS
- *ASCA* (arcmin res. But good CCD spectra)
  - Spectral/variability study of nearby luminous ULXs
  - Spectral studies of halos/ hot ISM
    - Puzzling low metal abundances

Now

- We have two telescopes in orbit that can study galaxies (see review Fabbiano 2006, ARAA in press)
  - *Chandra* - the best because of its sub-arcsecond resolution (0.3'' at focus), ~0.1sqm collecting area
  - *XMM* - only ~15'' resolution, but >3 x larger collecting area
    - Good for nearby galaxies
    - Nearby ULXs

most of the emission of a galaxy is in the OIR
why do we observe galaxies in X-rays?

A very efficient way to study extreme forms of matter

The only way to study the hot (~10 Mk) gaseous component

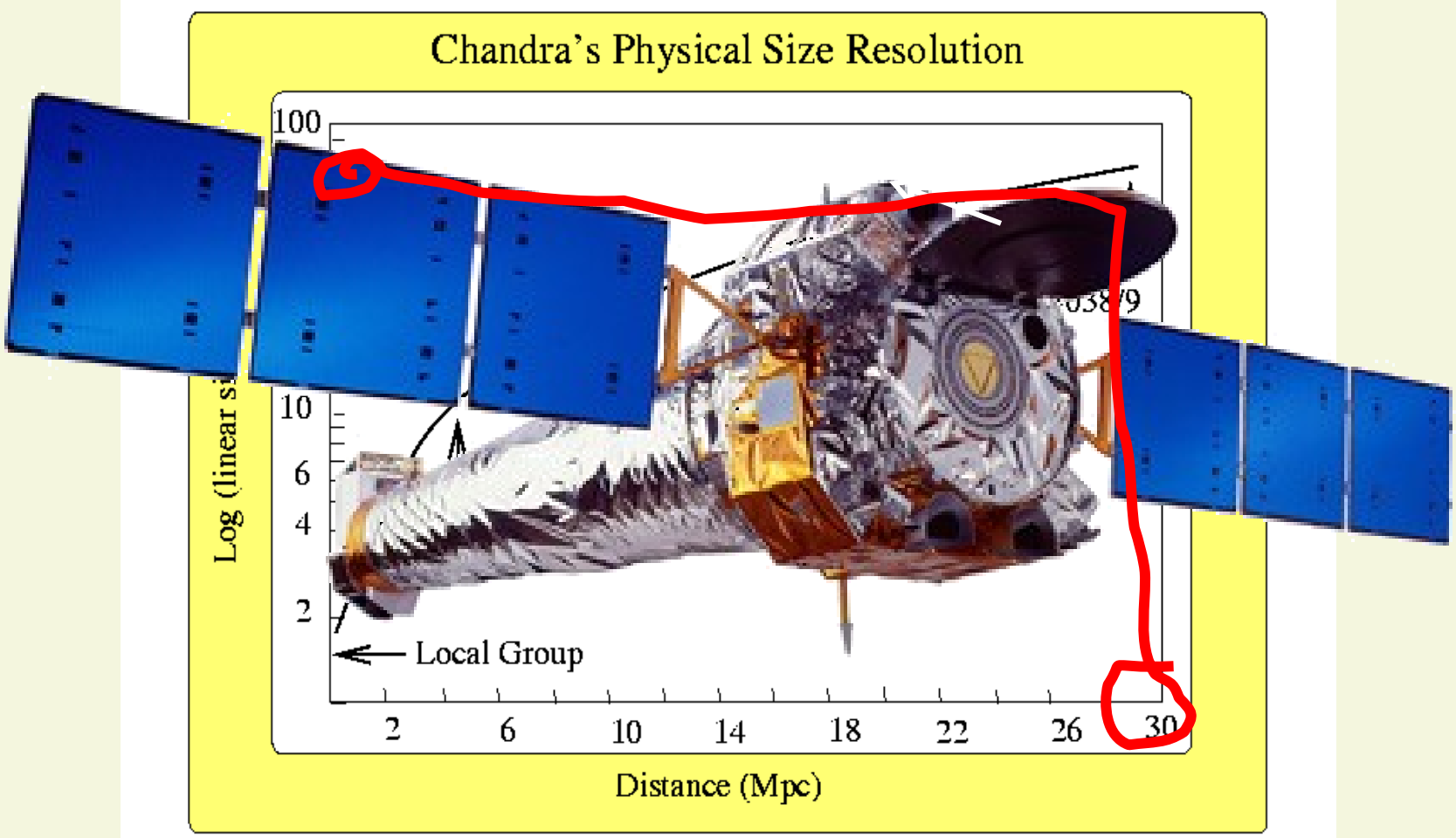
Why is sub-arcsecond resolution important?

…field XRBs are relatively sparse

nuclear regions and GC can be resolved in nearby galaxies…

we can individually detect and study populations of sources

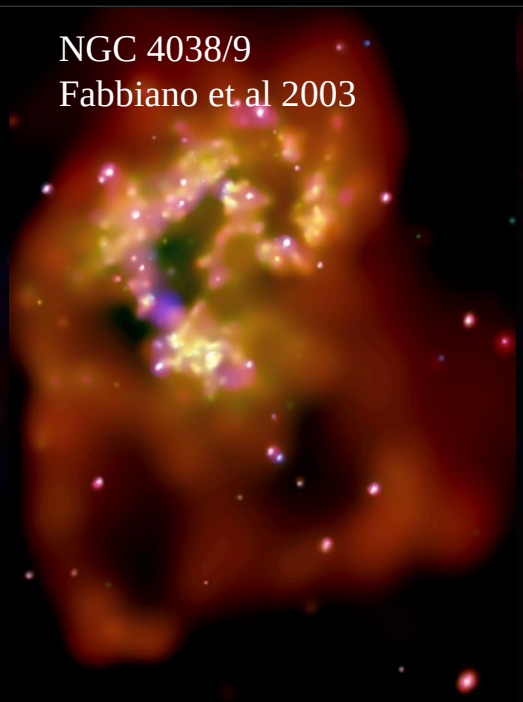
and we can subtract them from the hot ISM emission



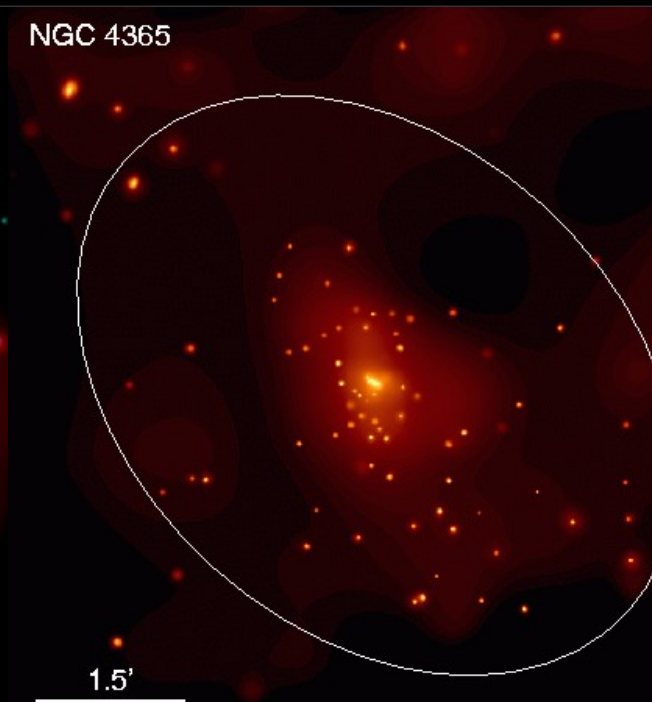
X-ray source populations

The Milky Way
Warwick et al 2002

M 83
Soria & Wu 2002



NGC 4038/9
Fabbiano et al 2003



XRB Populations in Nearby Galaxies

- External galaxies provide `cleaner' samples
  - Distances uncertain for Galactic XRB
  - Extinction a major problem
- Association of XRB with stellar populations
- We can find and study `extreme' sources
  - ULXs

Approaches

X-ray colors / spectra

Variability / spectral variability

X-ray Luminosity Functions

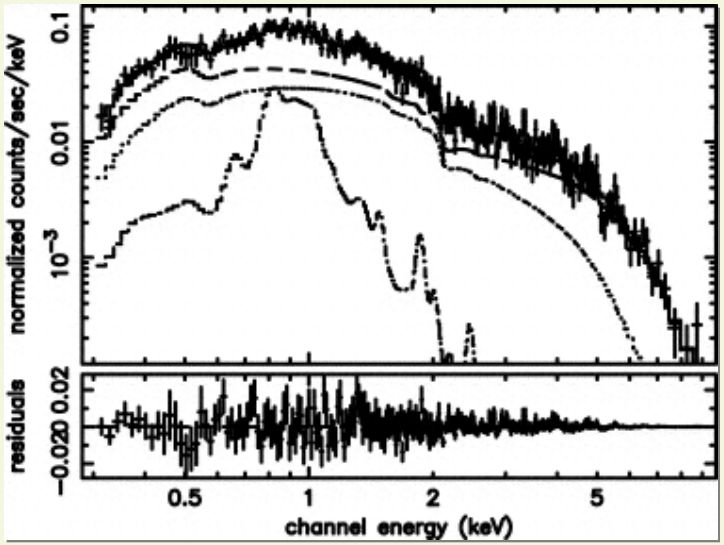
Association with optical / radio counterparts

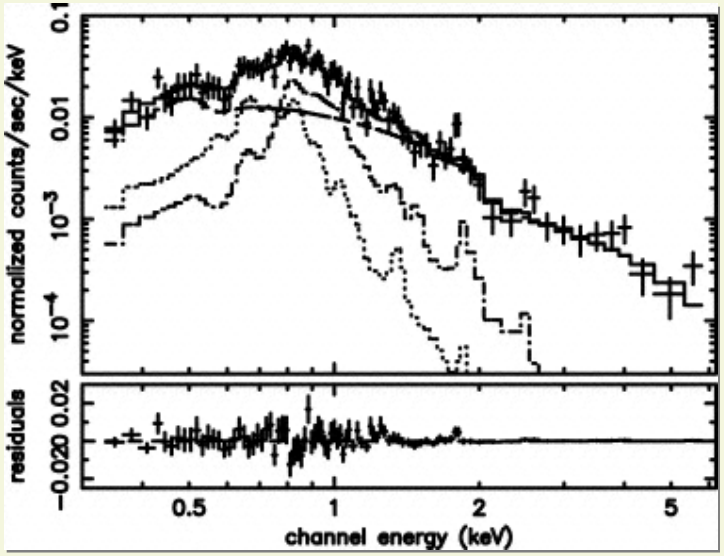
X-ray spectra

X-ray spectra can only be derived for the most luminous sources (e.g. ULXs)

Composite spectra average properties

- Is the sample reasonably chosen?
- E.g., sources in 2 luminosity bins in the Antennae (Zezas et al 2002)





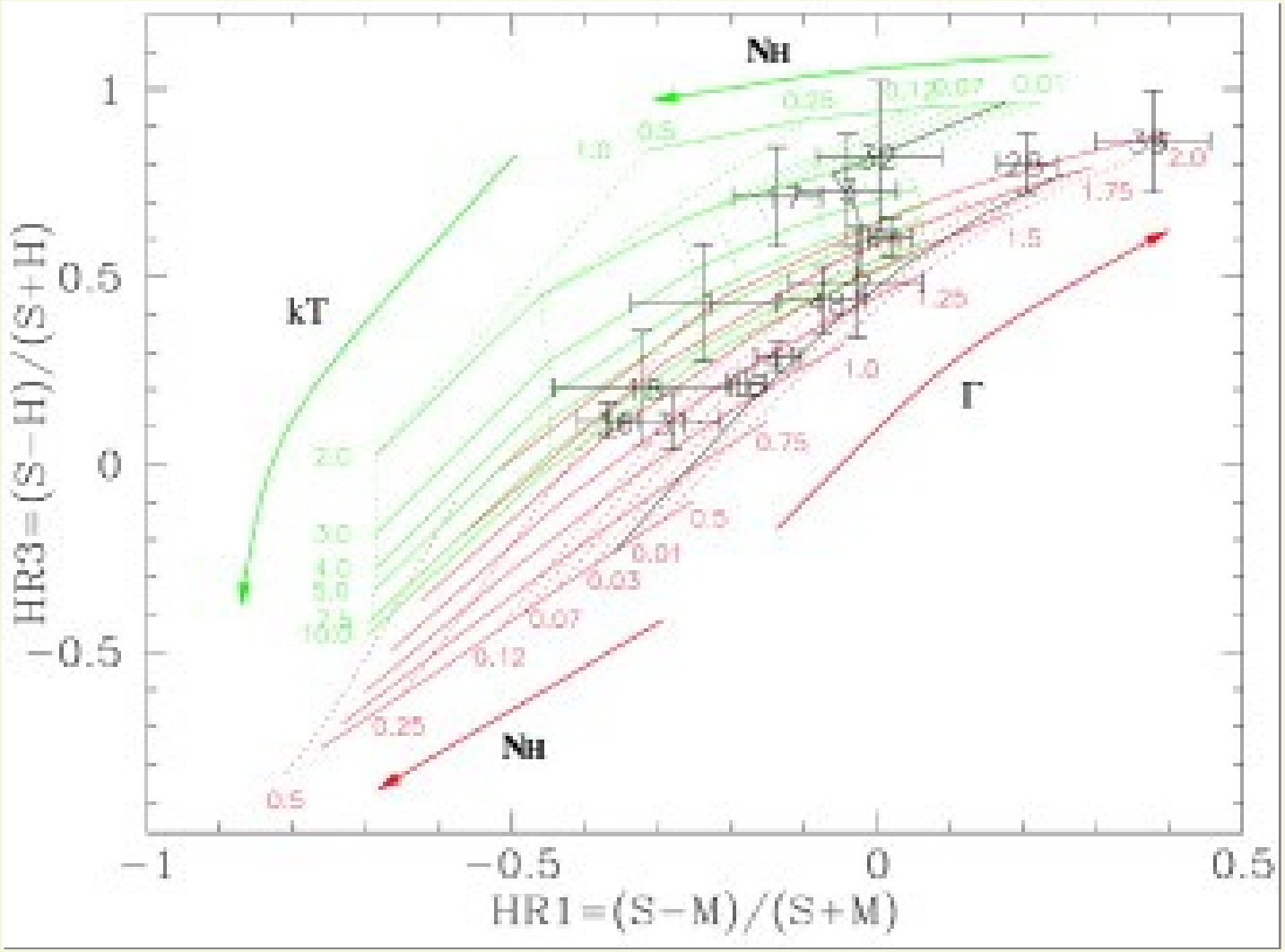
X-ray colors

Hardness ratios and colors to study fainter populations

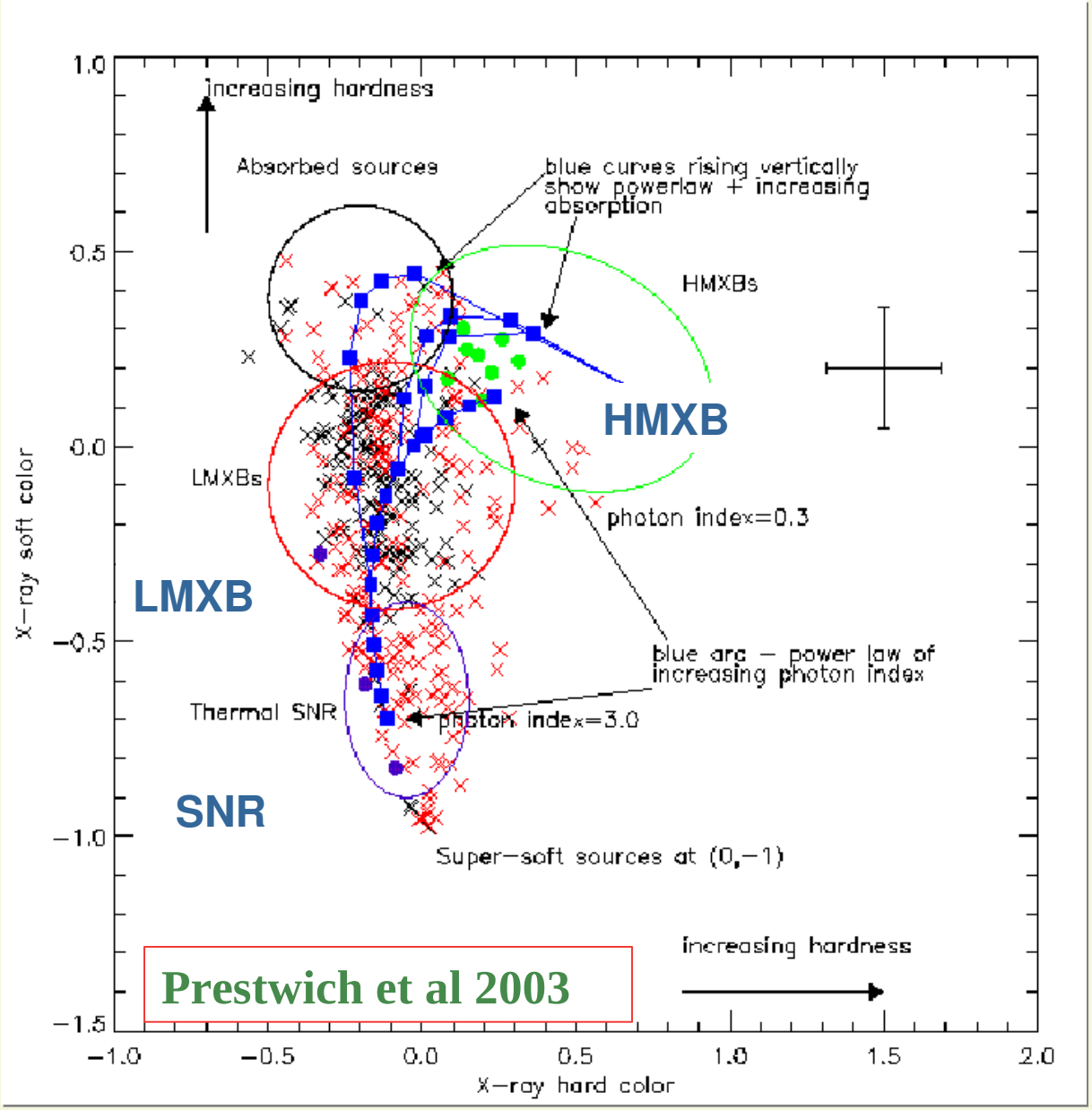
- Model-independent approach
- HR = H-S/H+S
- Colors from 3 bands, e.g. H-M/H+M+S, M-S/H+M+S
  - No standard X-ray photometry yet
  - Instrument dependent comparisons
- Define loci in color-color diagram
- Compare with model ‘grids’
- Follow sources in color-magnitude diagrams

Ratio diagram with model grids

(Zezas et al 2002, for the Antennae*)*

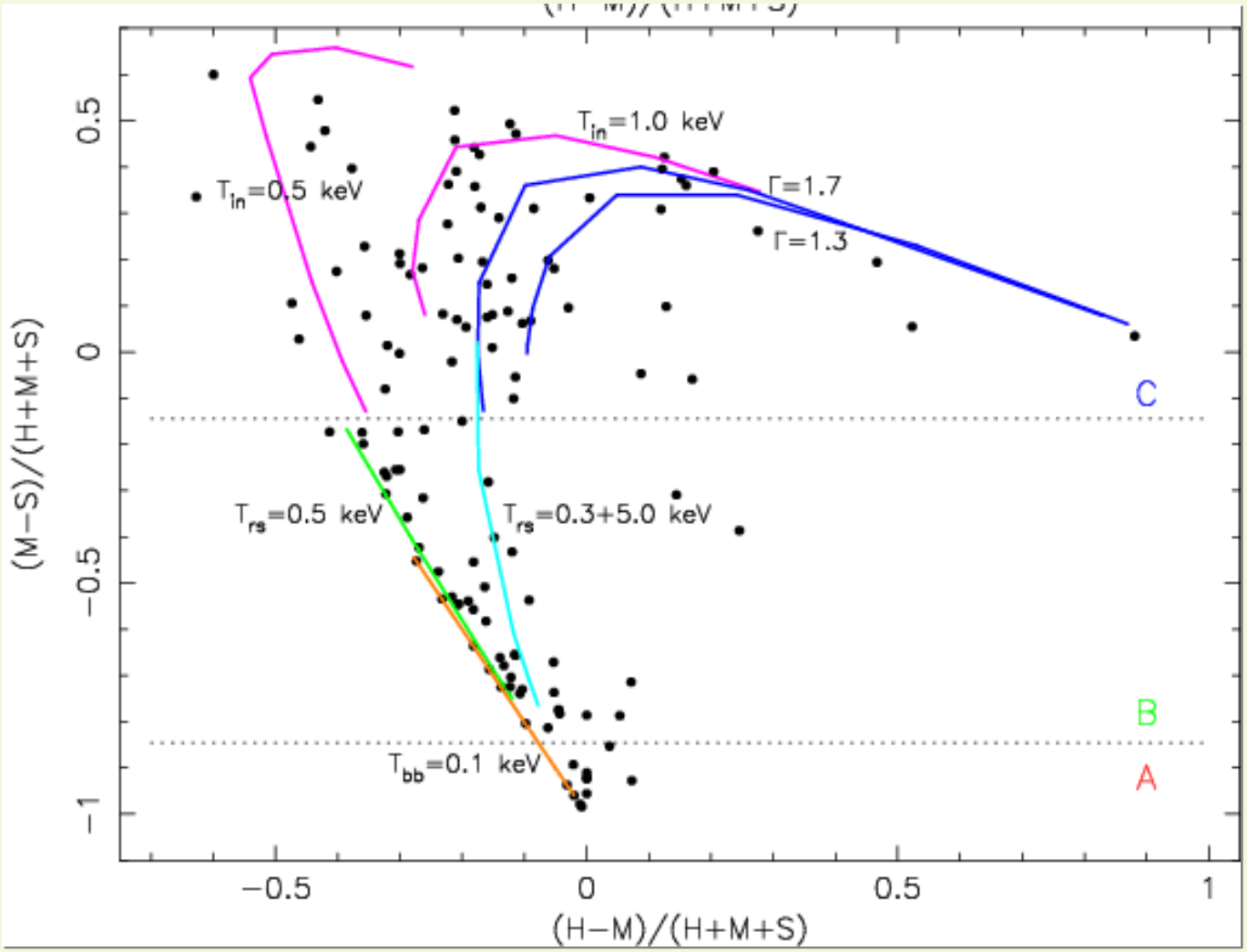


Example of color-color diagram



Color-color diagram for M83

Soria & Wu 2003



X-ray Luminosity Functions

Differential

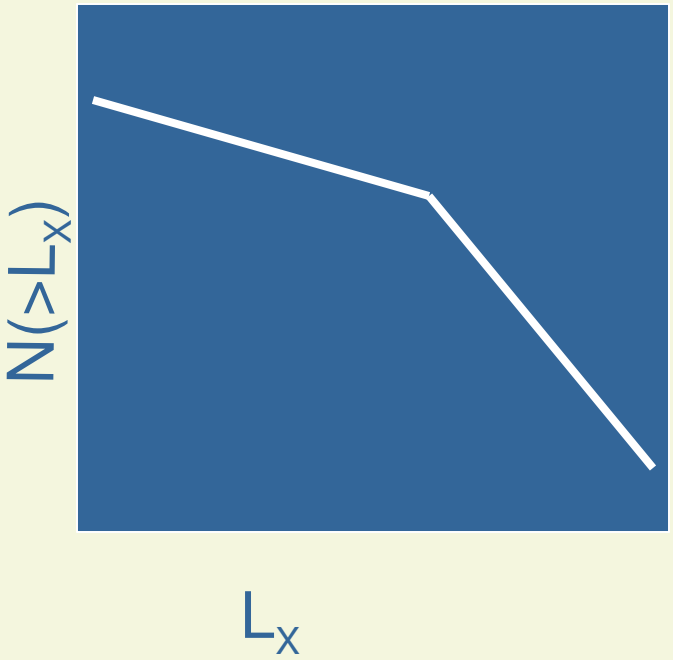
- Number of X-ray sources at a given L_X

Cumulative

- Integral of the differential XLF
- Number of X-ray sources with L_X > given value

Functional parameters

- Slope(s)
- Breaks
- Normalization

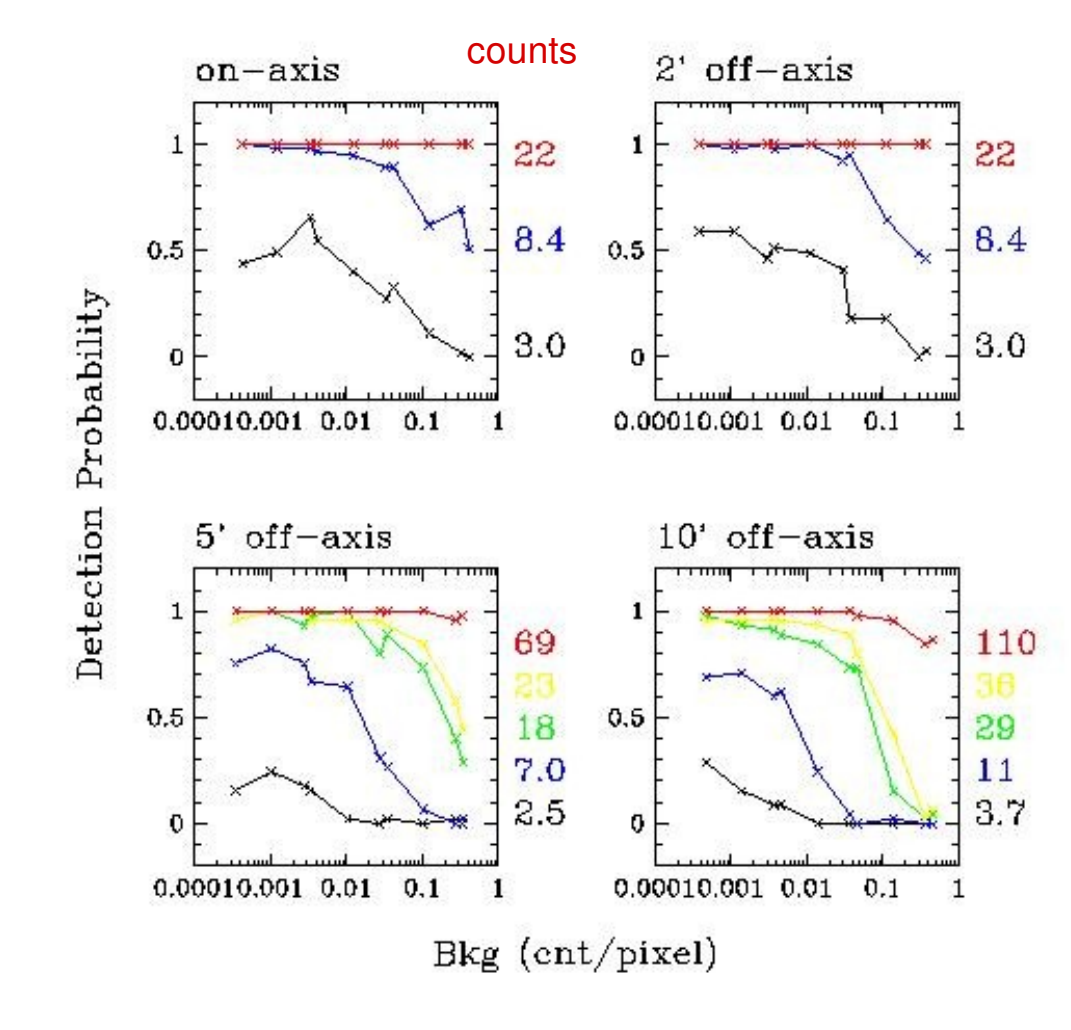


Slope and breaks - be careful about incompleteness biases …

Kim & Fabbiano 2003, ApJ - read Appendix!

XLF of NGC1316, an early-type galaxy

- Break in XLF disappears when proper corrections are applied
  - Background
  - Beam bias

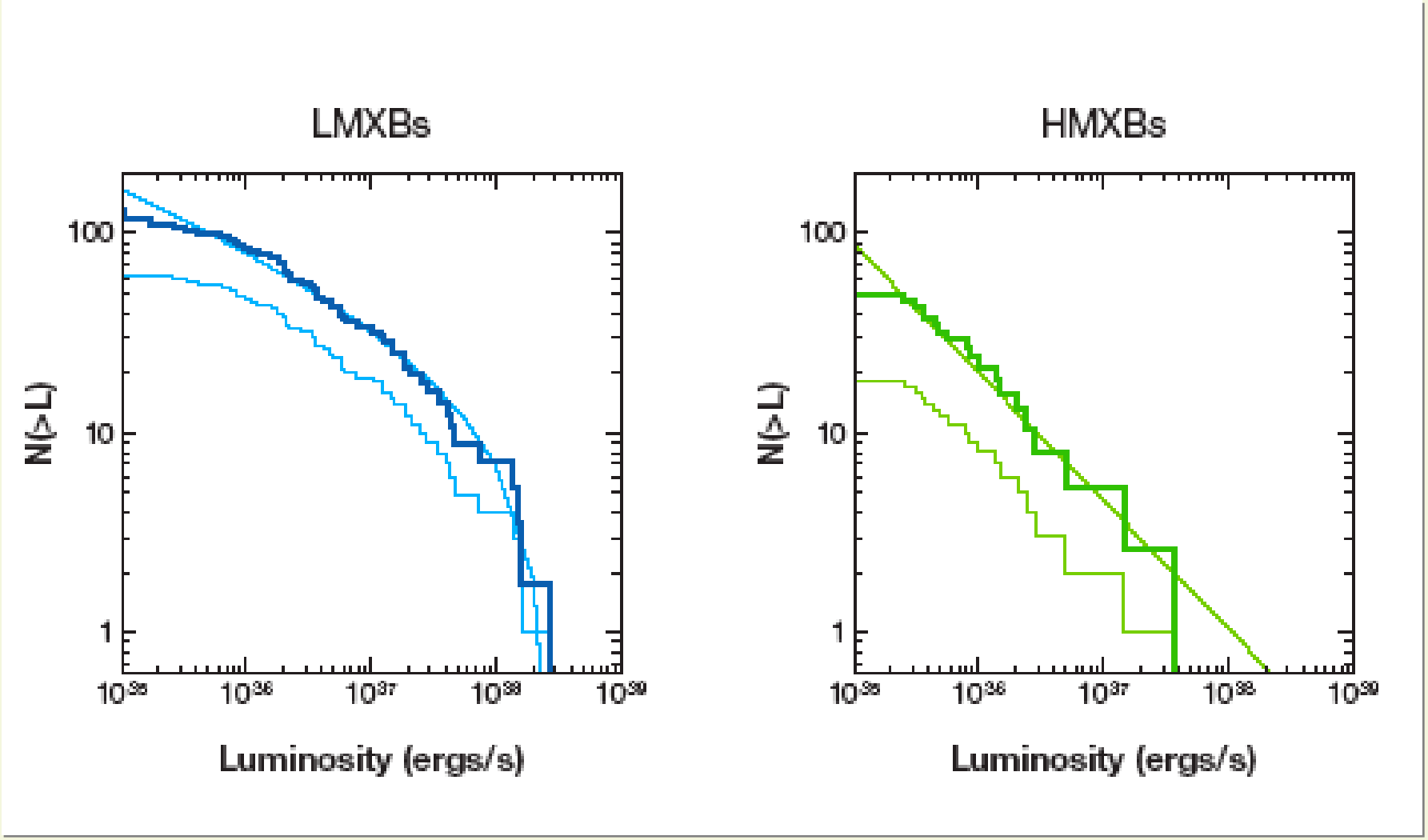


Normalization

It may be affected by small number statistics and effect of source variability if only most luminous few sources are detected (we'll get back to this)

The HMXB and LMXB XLF in the Galaxy

(Grimm, Gilfanov & Sunyaev 2002)

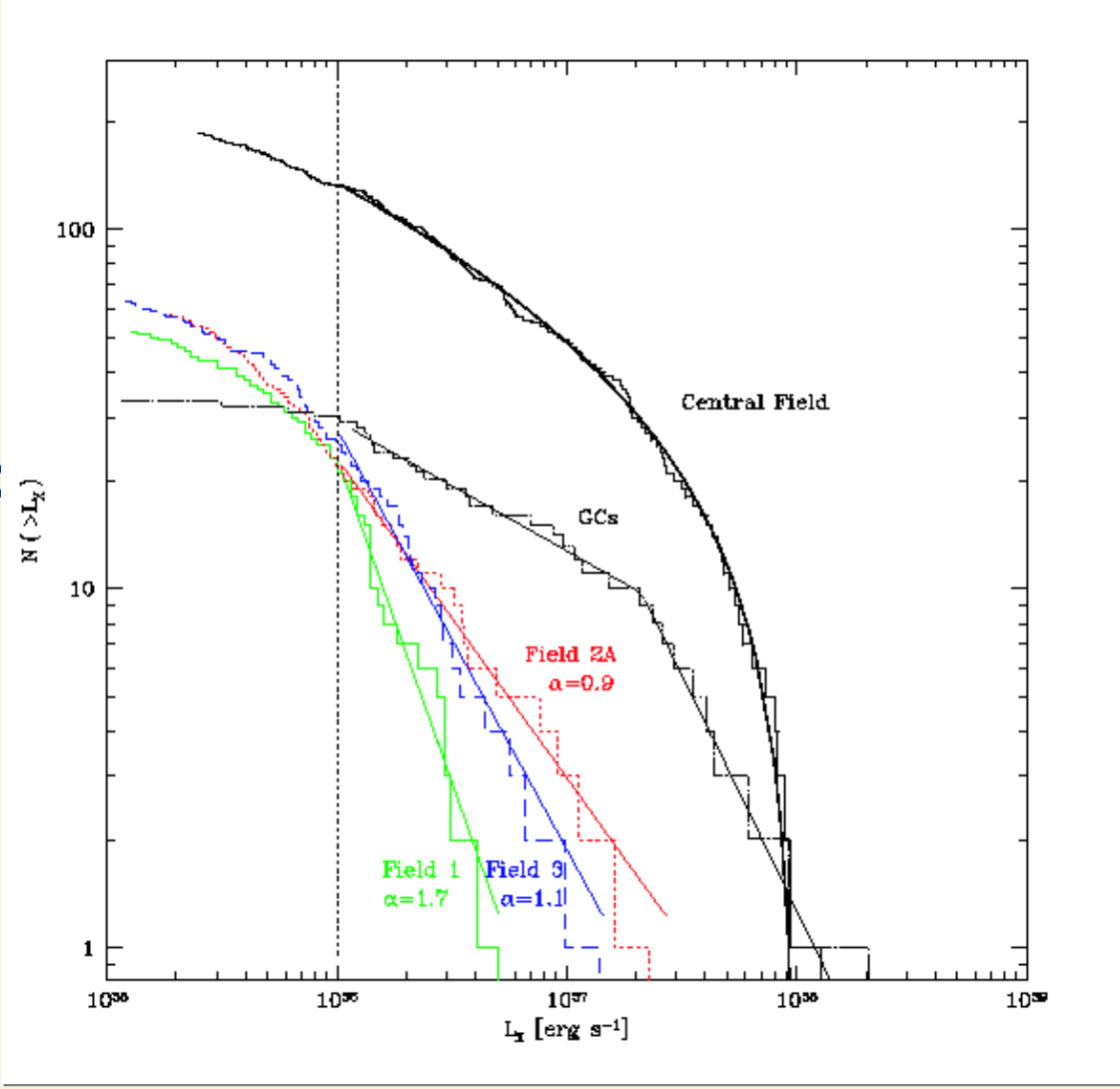


XLF & parent stellar populations in M31

(Kong et al 2003)

Different stellar populations have different XRB populations

See review by Fabbiano & White in CUP X-ray binary book (ed. Lewin et al), just published



LMXB populations

Old low-mass binaries

Uniform populations

Chandra detects LMXB populations in Elliptical Galaxies

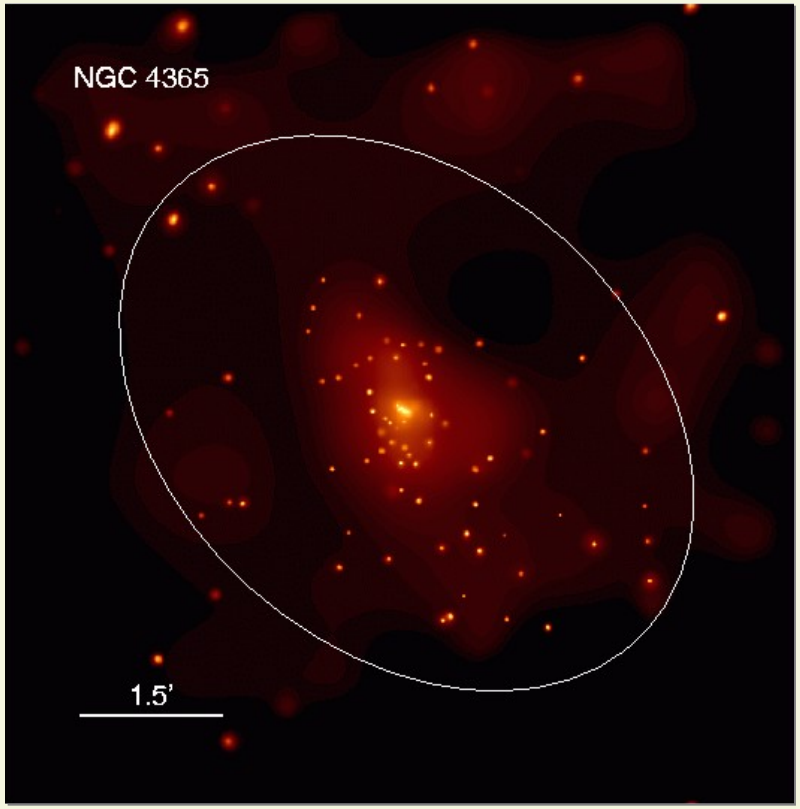
Inferred 20 yrs ago
(Trinchieri & Fabbiano 1985)

Detected with Chandra (e.g. Sarazin et al 2000; etc.)

Spectra kT~7 keV
(e.g. Irwin et al 2003)

More luminous sources are softer (BH binaries?)

Variability detected in some cases, long term, flares
(e.g. Kraft et al 2001; Sivakoff et al 2005)

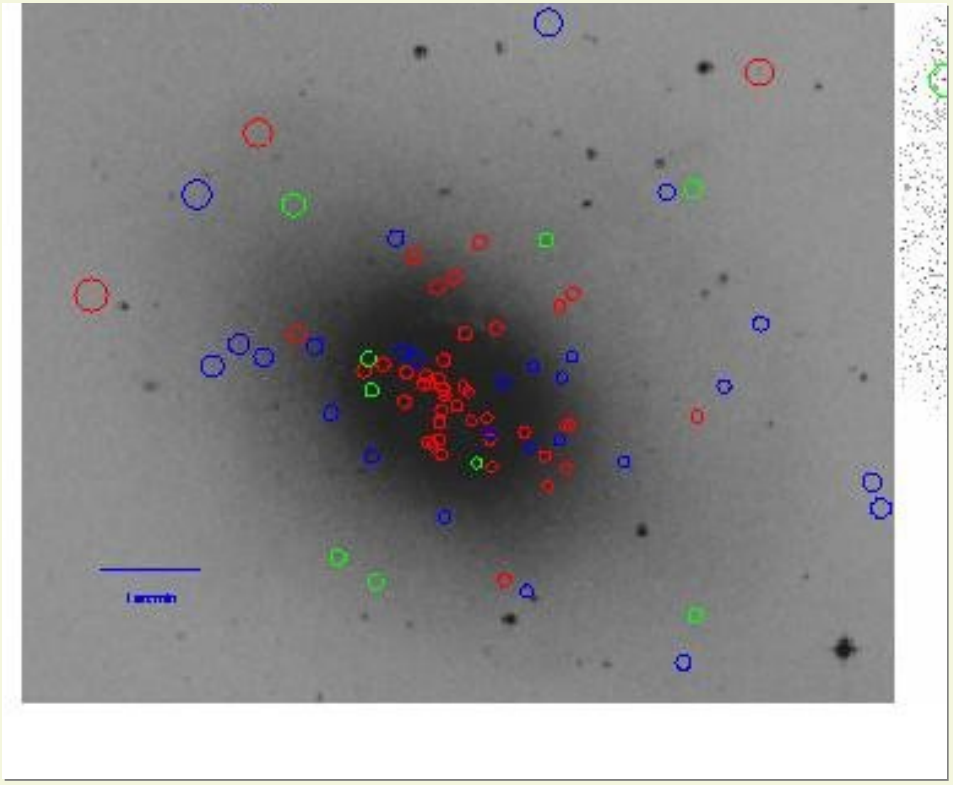


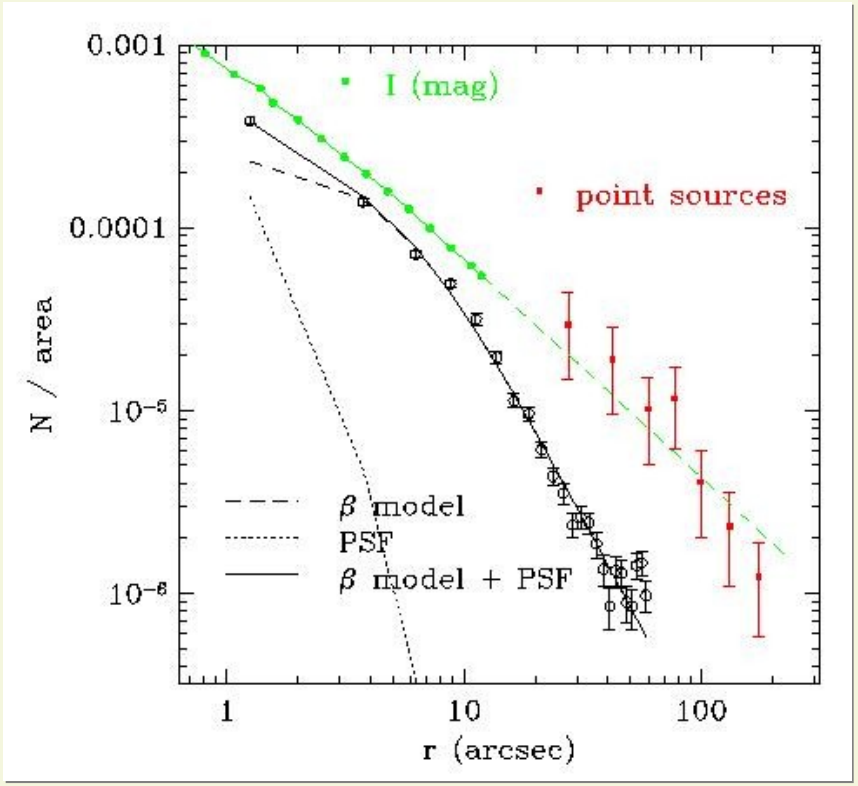
LMXB populations in E and S0 galaxies

..once controversial, now no more

they trace the old stellar population

if you don't remove them, you can't study ISM
T, space distribution, Z



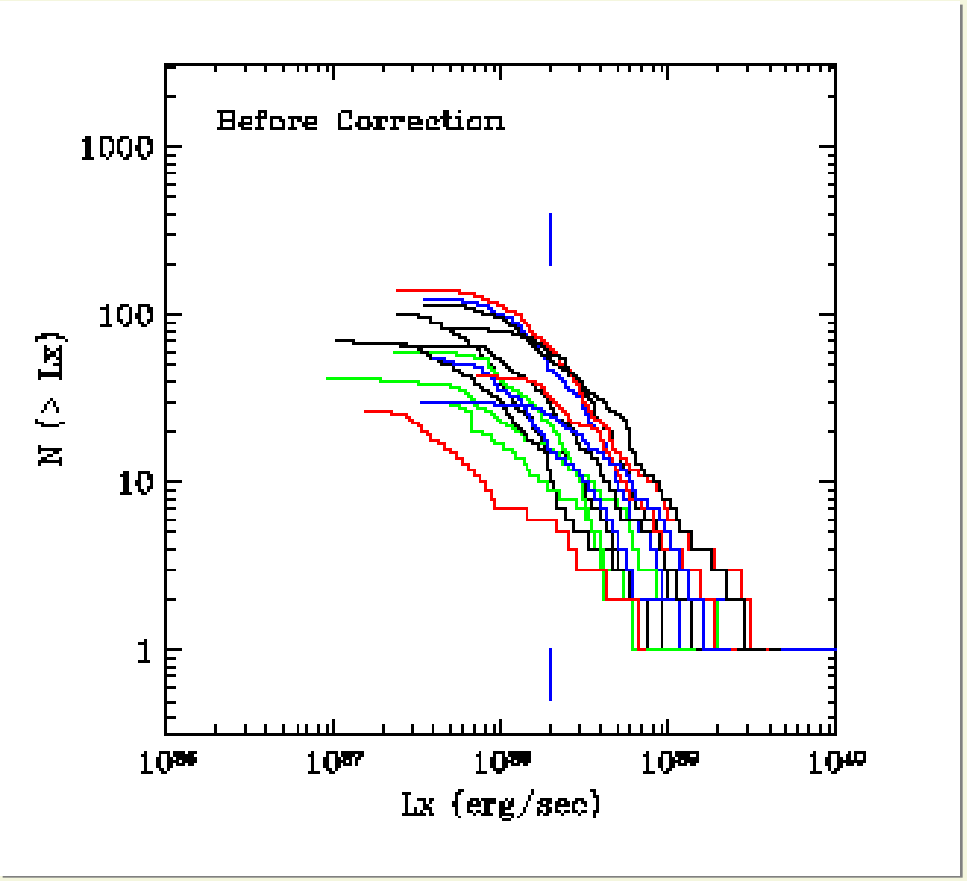


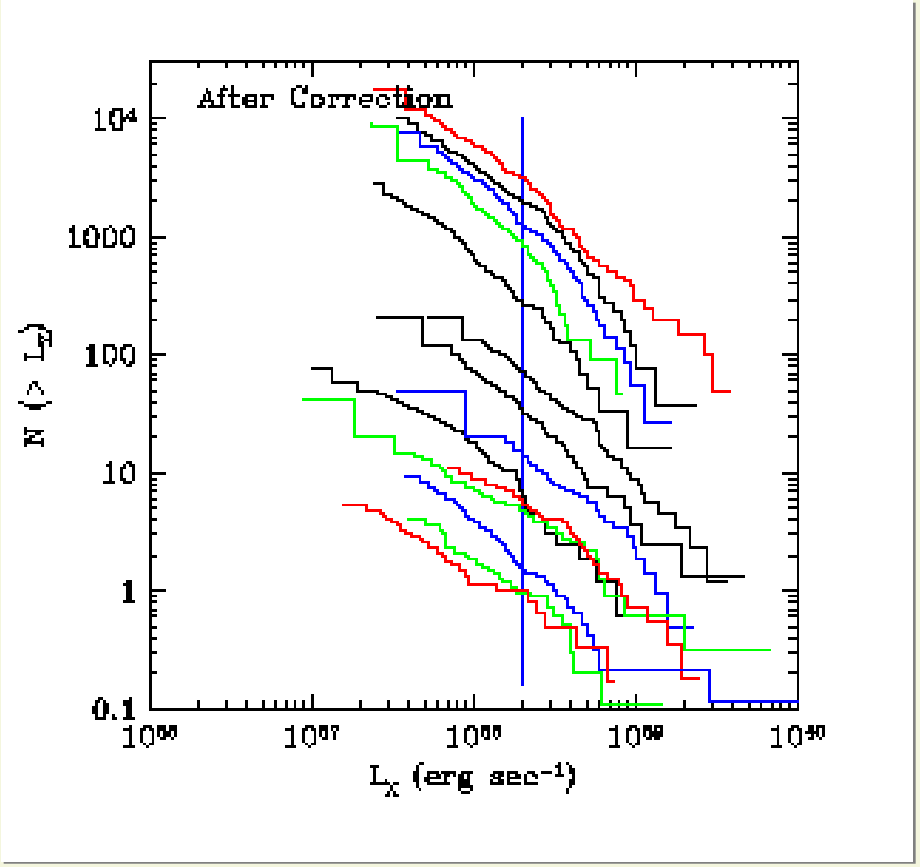
NGC 1316 – Kim & Fabbiano 2003

XLFs of 14 E and S0s

Kim & Fabbiano 2004

XLFs (> 6 10^{37} ergs/s) are similar, no break visible





Composite XLF of 14 E and S0s

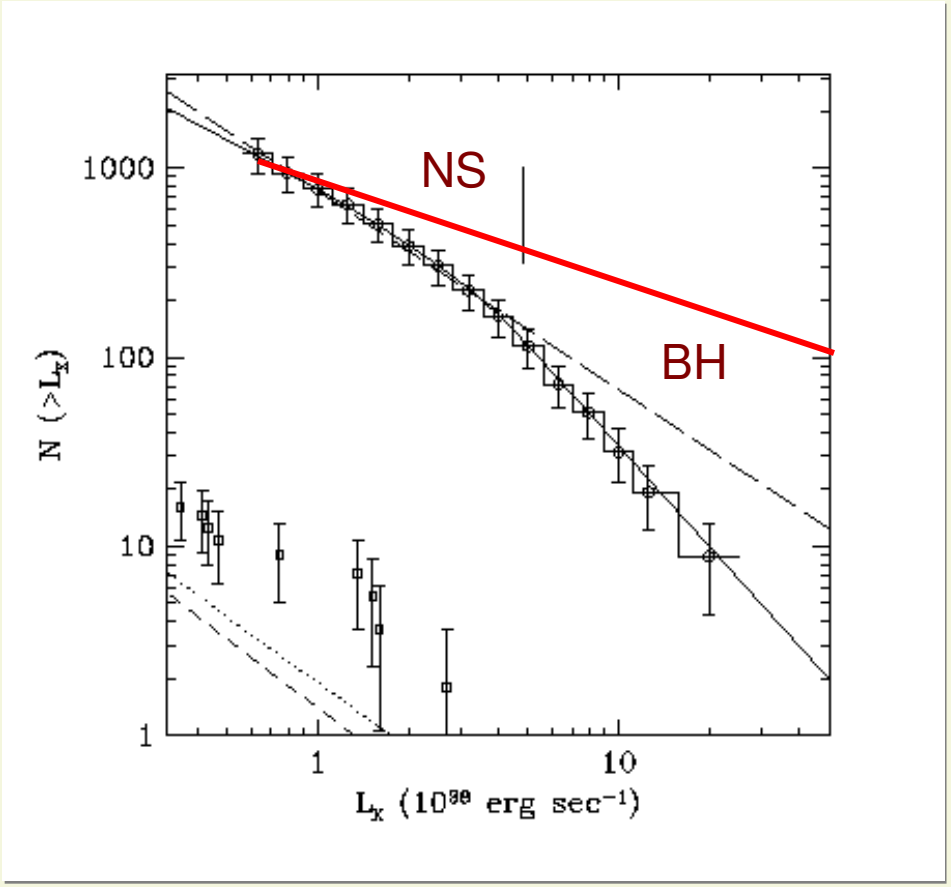
Kim & Fabbiano 2004

XLFs (> 6 10^{37} ergs/s) are similar

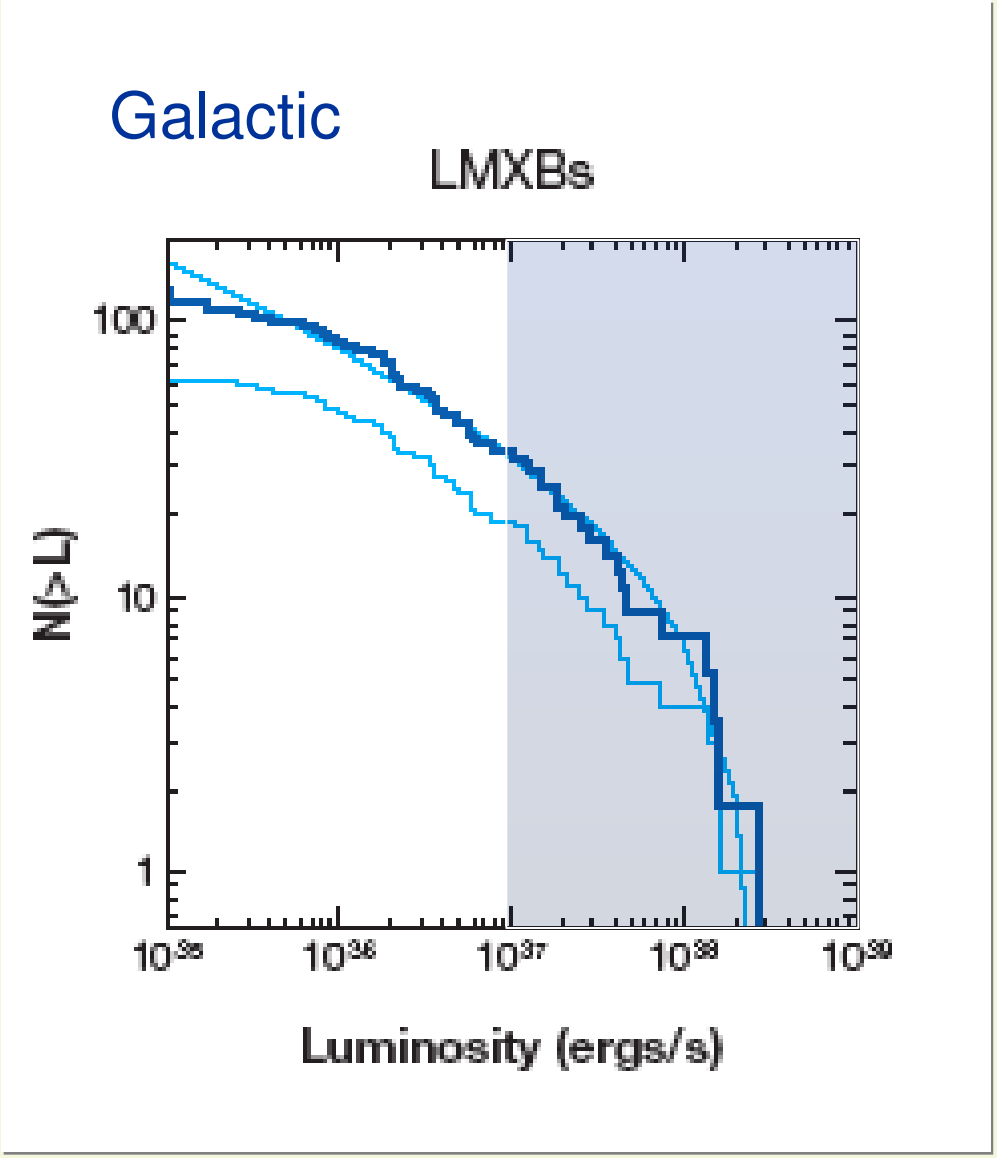
Break at 4.5 10^{38} ergs/s seen in composite XLF

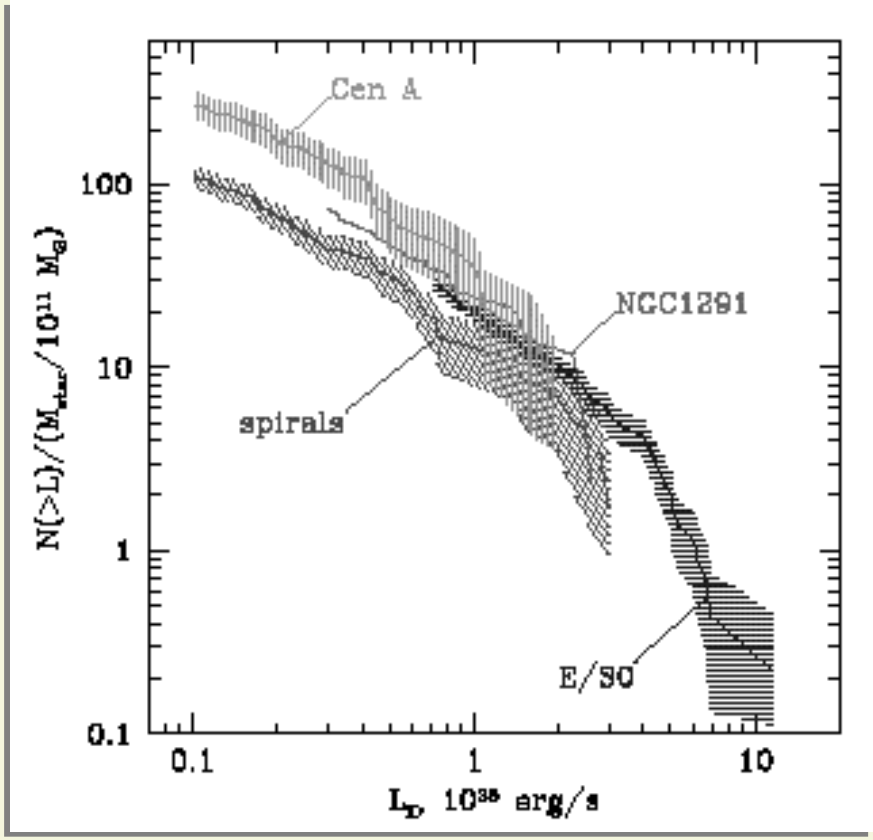
Low luminosity slope consistent with Galactic and M31 LMXB XLFs

Overall cumulative slope ~ -1
(-0.5 is slope for HMXB populations)



The Gilfanov (2004) composite LMXB XLFs





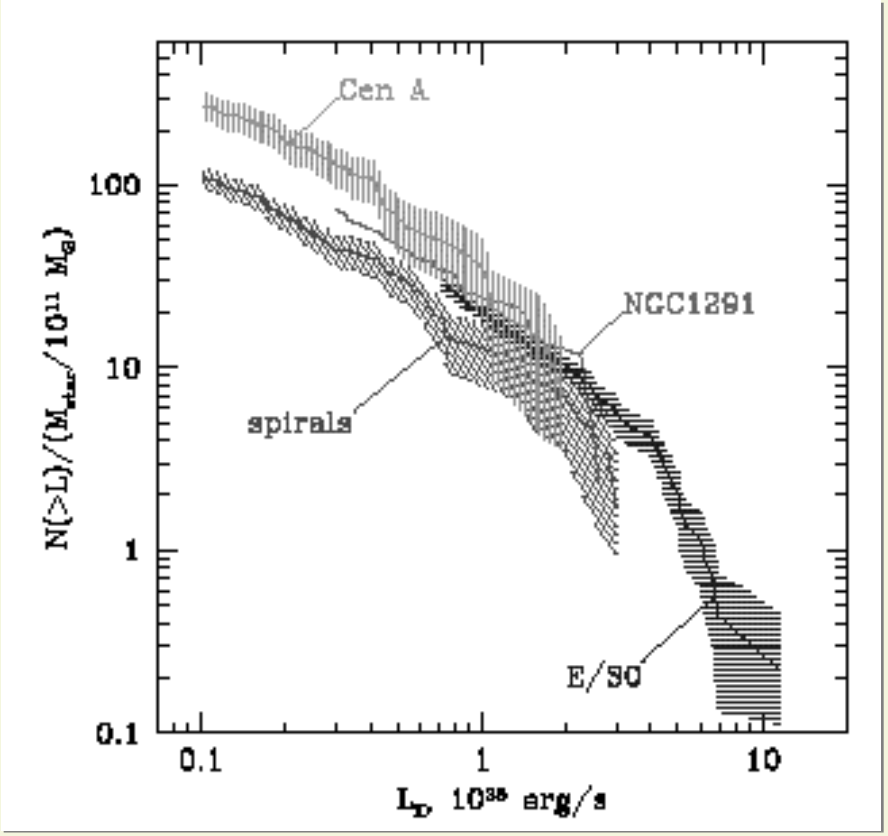
XLFs -norm. ($L_{X,gal.}$) driven by stellar mass

Similar XLF shapes (LMXBs of M.W., spirals, ellipticals)

Normalization is function of global stellar mass

$L_X(>10^{37}\text{erg/s}) = (8.0 +/- 0.5) \times 10^{39}$ erg/s per 10^{11} M

Gilfanov 2004



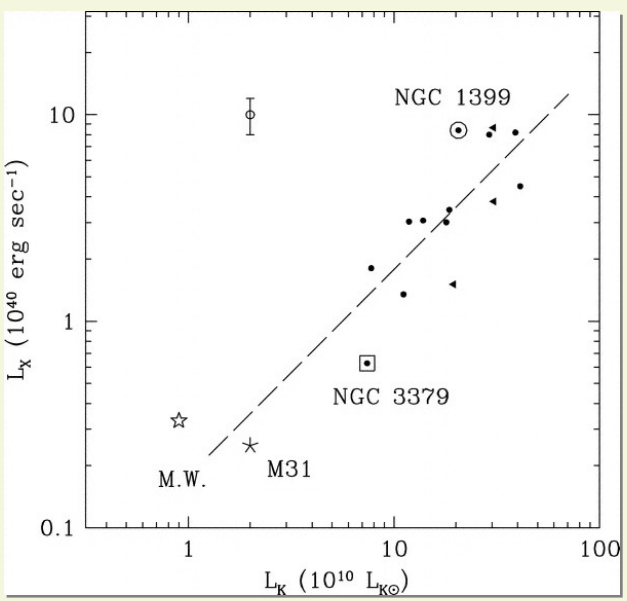
..but $L_{X,\ gal.}$ is also related to S_{GC}

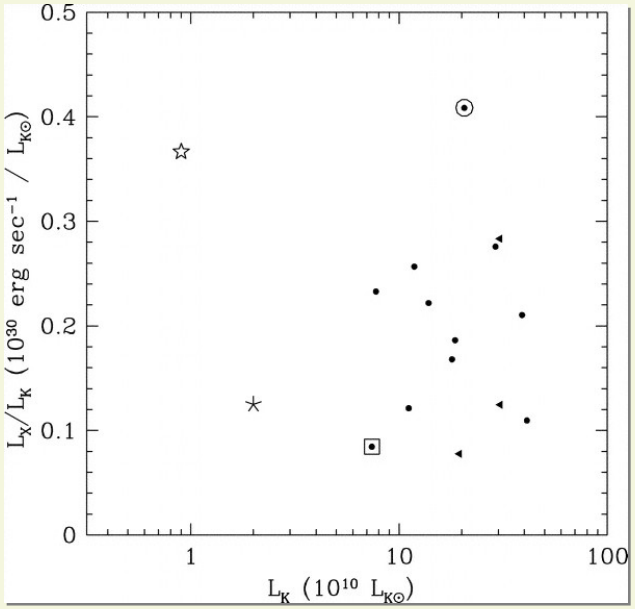
Kim & Fabbiano 2004

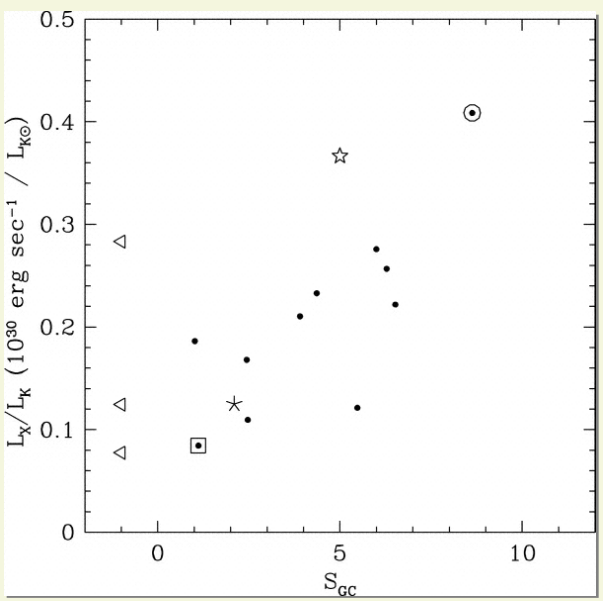
Sources detected both in the stellar field and in GC

LMXB content depends on both stellar content (galaxy mass) and GC content of galaxy (see also Irwin 2004)

Field binary evolution and formation in GC may both be important







The LMXB - GC connection in the Galaxy

- First suggested for Galactic LMXB
  - Formation more efficient than in the field (Clark 1975)
  - Capture binaries; do all LMXB originate in GCs?
  - Metallicity connection (Grindlay 1987; more LMXBs in high z GCs)
  - GC disruption or formation kicks would disperse LMXBs in the field
- But evolution of native field binary can also form a LMXB (see review by Verbunt & van den Heuvel 1995)

The LMXB - GC connection in E and S0 galaxies

White et al 2002 suggested a correlation of the L_X/L_B scatter with S_{GC}

LMXB content depends on both stellar content and GC content of galaxy (Kim & Fabbiano 2004; Irwin 2004)

- Field binary evolution and formation in GC may be both important

LMXBs and GCs - the facts (1)

~5% of GCs have an LMXB

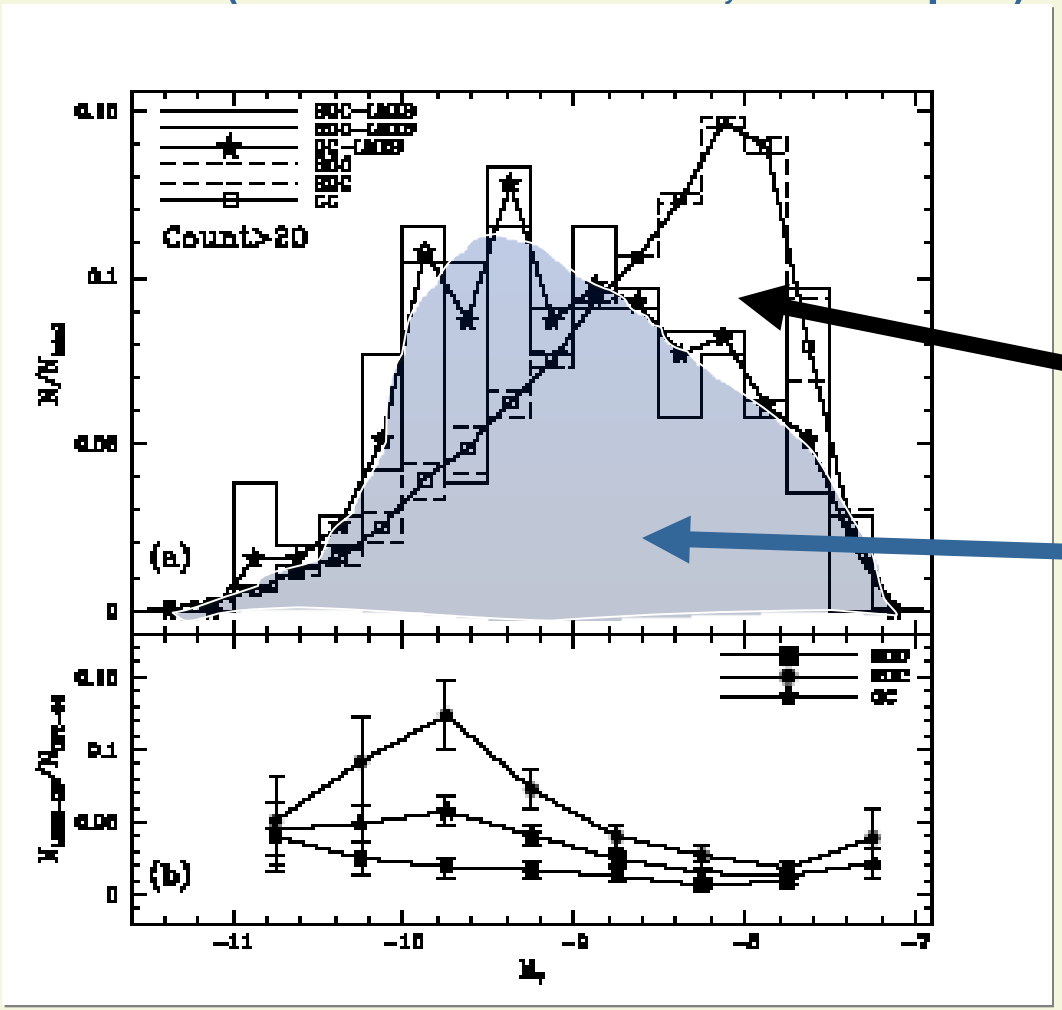
- The number of LMXBs-GC increases with the number of GCs in a galaxy (~10% in MW up to 70% in the cD NGC1399)

More luminous GCs are more likely to host a LMXB

- Probability of association is ~100 times than in the field (per unit stellar light); Sarazin et al 2003

More luminous GC are more likely to host a LMXB - histogram of GC vs M_V in sample of 6 ellipticals

(Kim et al 2005, astroph)



All GCs

GC-LMXB

More luminous

LMXBs and GCs - the facts (2)

Probability is function of GC color (metallicity)

- Red/metal-rich clusters are more likely to host an LMXB
  (e.g. Kundu et al 2002; Maccarone et al 2003)
- in a sample of 6 E with 285 LMXB-GC
  (E. Kim et al 2006)
  - P(blue)~5%
  - P(red)~3-13%

LMXBs and GCs - the facts (3)

Spectra

- Harder LMXB (blue GC) spectra suggested in NGC4472 (Maccarone et al 2003)
  - Led to suggestion of absorption by radiatively induced winds in metal poor stars
  - Winds would speed up binary evolution resulting in a smaller number of LMXBs in metal poor blue clusters
- ...But, no color dependence found in large Kim et al (2006) sample

LMXBs and GCs - the facts (4)

Spatial distribution shows central concentration
(Kim et al 2006, next slide)

Dynamical effects?

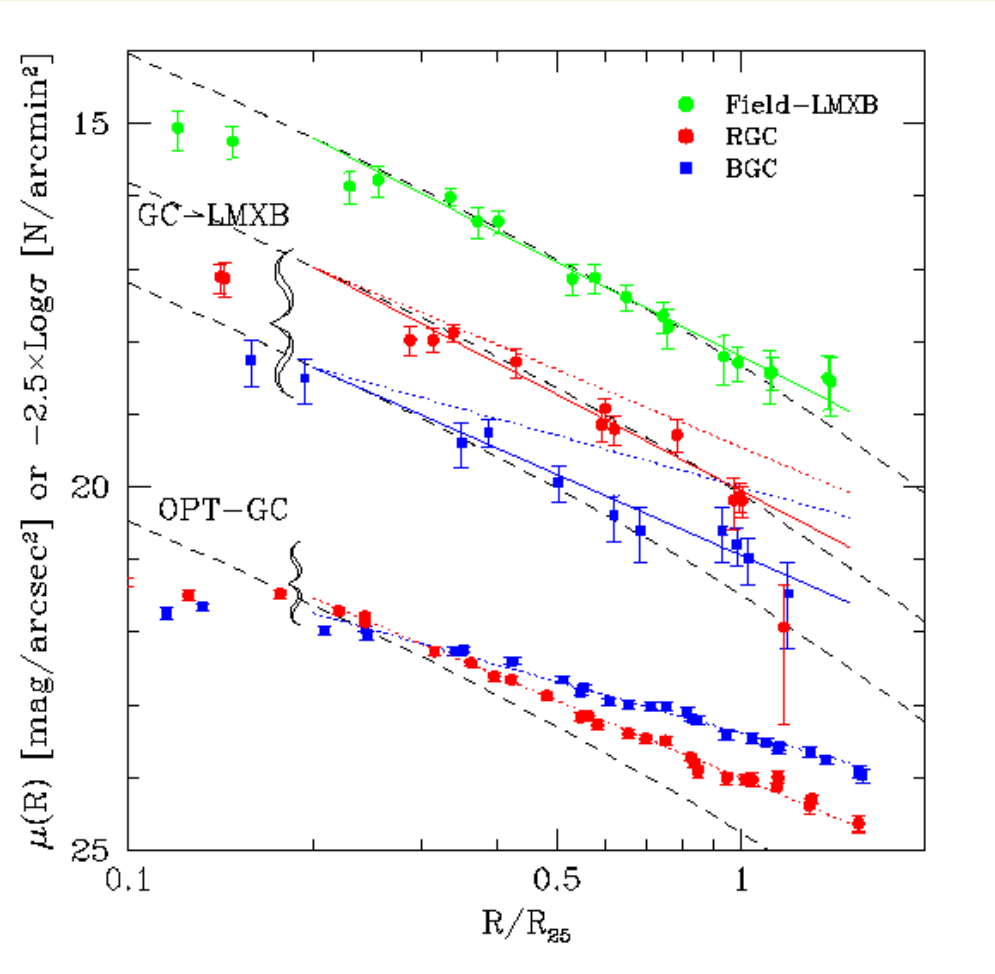
Spatial distribution of LMXBs

E. Kim et al 2006 (astro-ph)

Field LMXBs follow stellar distribution

GC LMXBs (both red and blue GCs) are more centrally concentrated than GCs

- Dynamical effects?
  - Larger cores, resist disruption

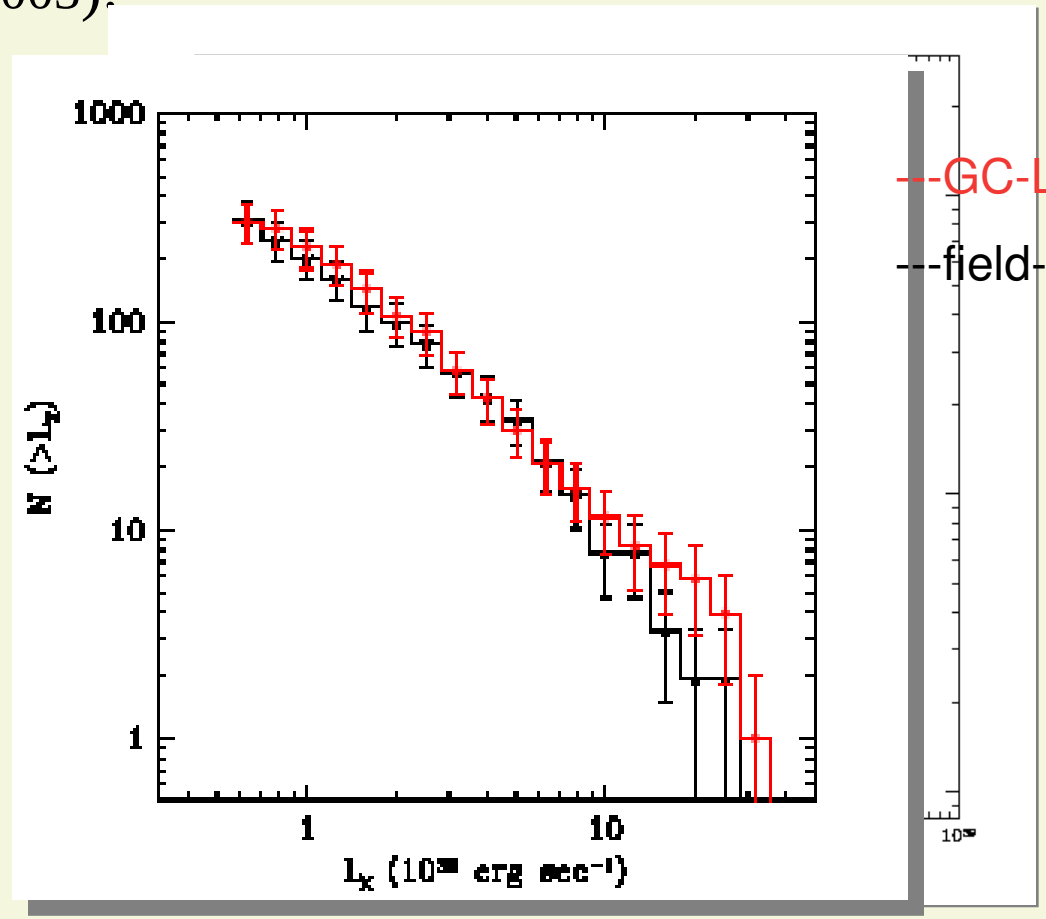


LMXBs and GCs - the facts (5)

XLFs of field and GC LMXBs are consistent in E and S0s (E. Kim et al 2006)

but differ in the Sa Sombrero galaxy (DiStefano et al 2003) and M31 (e.g., Kong et al 2003).

M31



Constraints on LMXB formation and evolution (1)

Field sources (Piro & Bildsten 2002, King 2002)

- High L_X, high accretion rates
- Detached binaries with large unstable disks
- Recurrent transients (recurrence time >100yr, outburst 1-100 yr)
- Transients detected in NGC5128 (Kraft et al 2001)
- More time monitoring needed (it's happening)

Constraints on LMXB formation and evolution (2)

Bildsten & Deloye 2004

- Ultra-compact binaries formed in GCs
  - Probability per unit light is larger in GCs than field
  - White dwarf orbiting NS or BH
    - Filling Roche lobe
    - 5-10 min orbit
    - Lifetime 10^7, therefore tracing their birth rate
  - Reproduce XLF of Kim & Fabbiano (2004) and Gilfanov (2004)
- Predict a low-luminosity break in XLF at ~10^{37} erg/s
  - Onset of transient behavior
  - See composite XLF of Gilfanov (2004)
  - Needs to be checked in normal E - in progress
- Other explanations for the break have been proposed in field binary evolution scenarios
  - Irradiation of donor from X-rays flattens low-luminosity XLF (population synthesis of Pfahl, Rappaport & Podsiadlowski 2003)
  - Gravitational wave emission effects at low L_X (Postnov & Kurazon 2005)

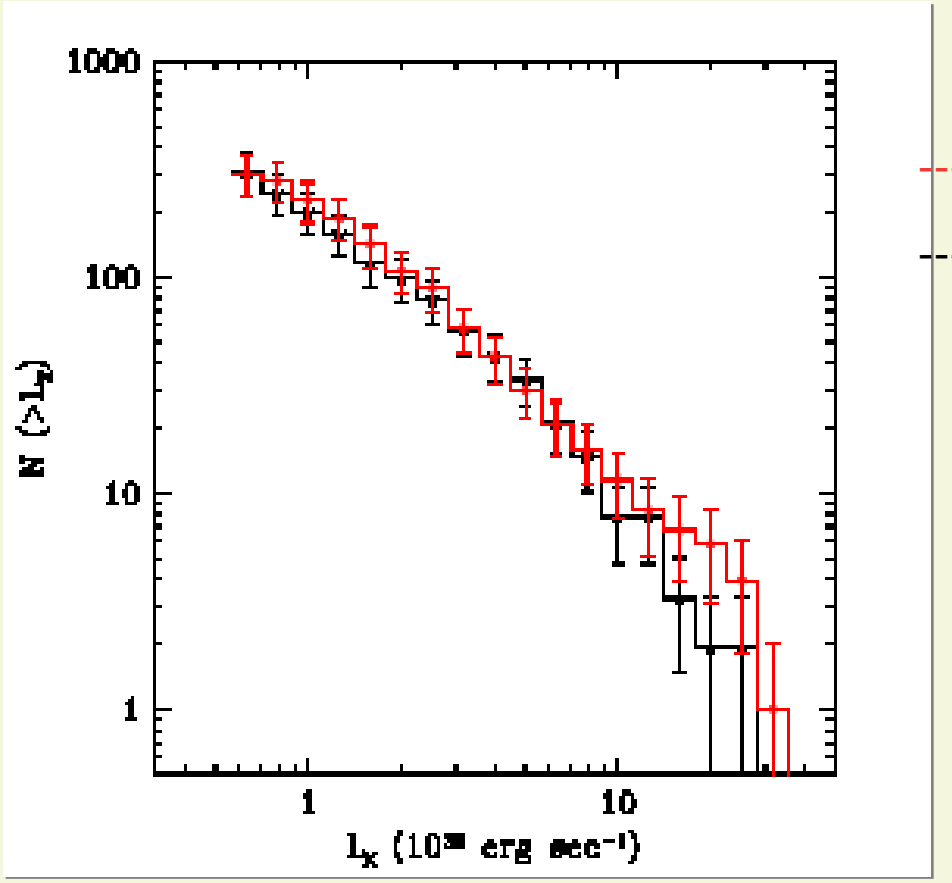
The most luminous sources (> 5 10^{38} erg/s)

Ivanova & Kalogera (2005)

- Too luminous to be NS systems
- BH binaries unlike to form in GC(Kalogera, King & Rasio 2004)
- Donor mass 1-1.5 M
  - Transients populating XLF only at outburst
  - XLF footprint of BH mass function
    - Differential mass function slope -2.5
    - Upper BH mass cut-off 20 M

The most luminous sources (> 5 10^{38} erg/s)

…but?- XLFs of GC and field LMXBs are consistent => BH sources in GC? (Kim et al 2006)

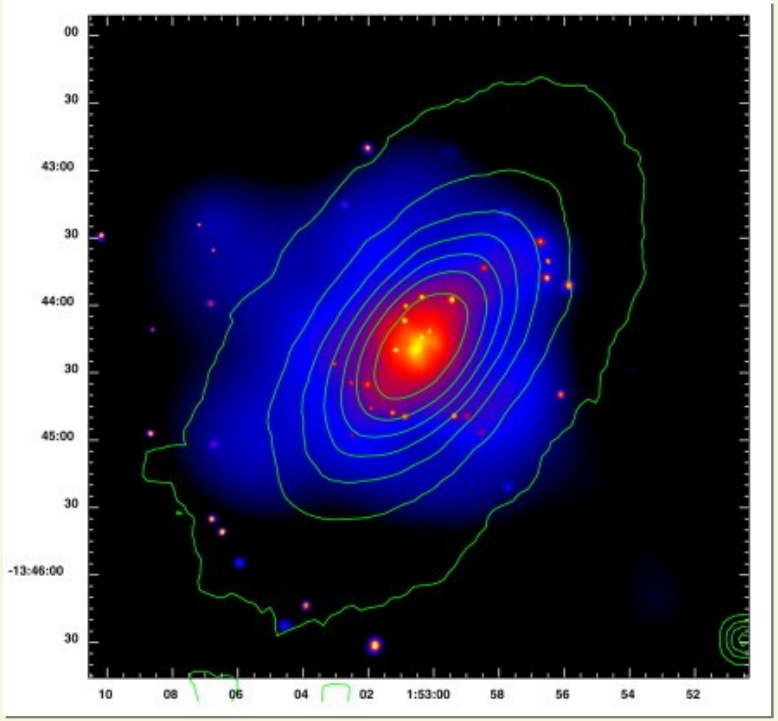


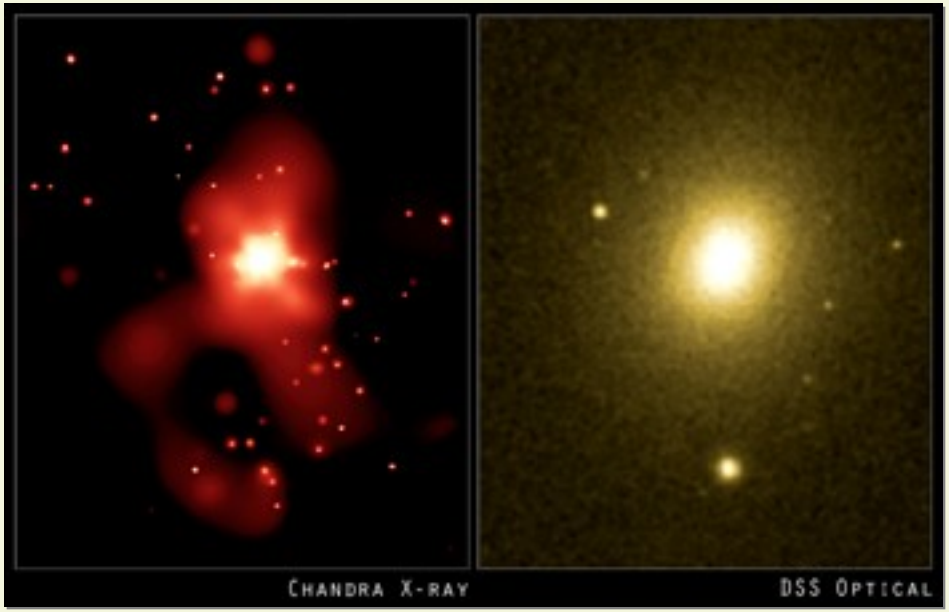
---GC-LMXBs

---field-LMXBs

Finding the effect of merging in the XRB populations in E and S0 galaxies?

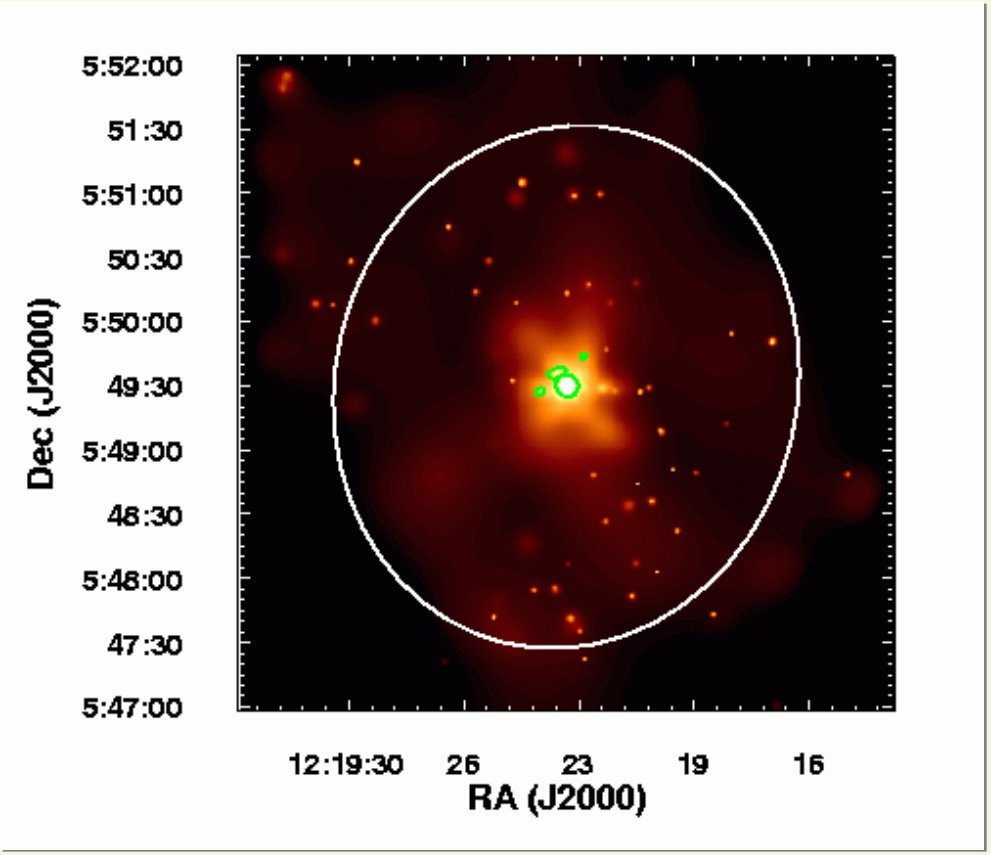
Luminous sources in some galaxies are not distributed like the stellar light (e.g. NGC 720, Jeltema et al 2003; NGC 4261, Zezas et al 2003)

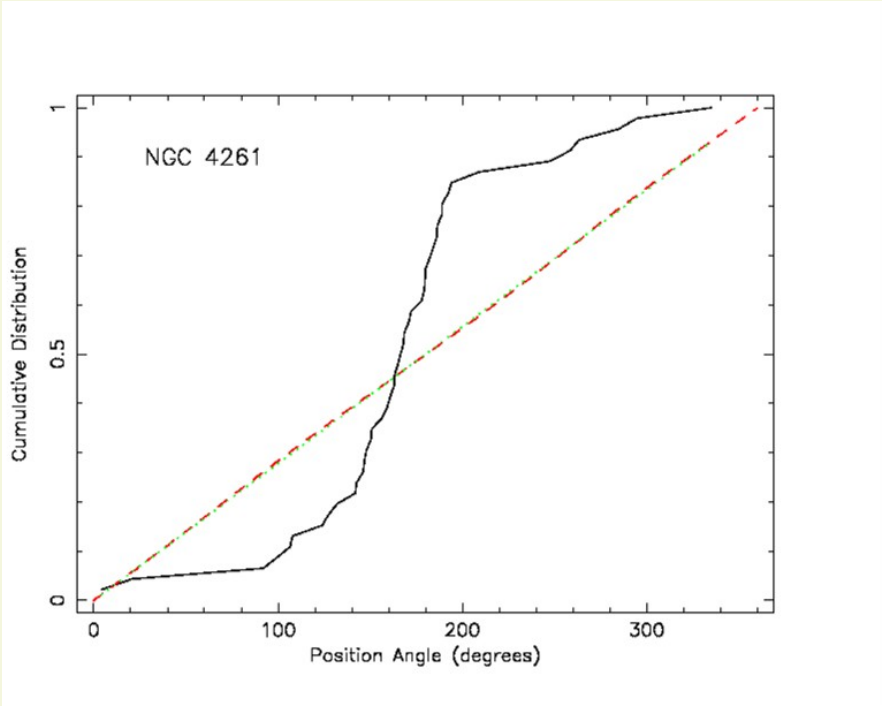




Finding the effect of merging in the XRB populations in E and S0 galaxies?

rejuvenation? Or the results of dry merging (Giordano et al 2005)?





NGC4261 – Zezas, Hernquist, Fabbiano & Miller 2003

XRB populations of ‘young’ galaxies: HMXBs

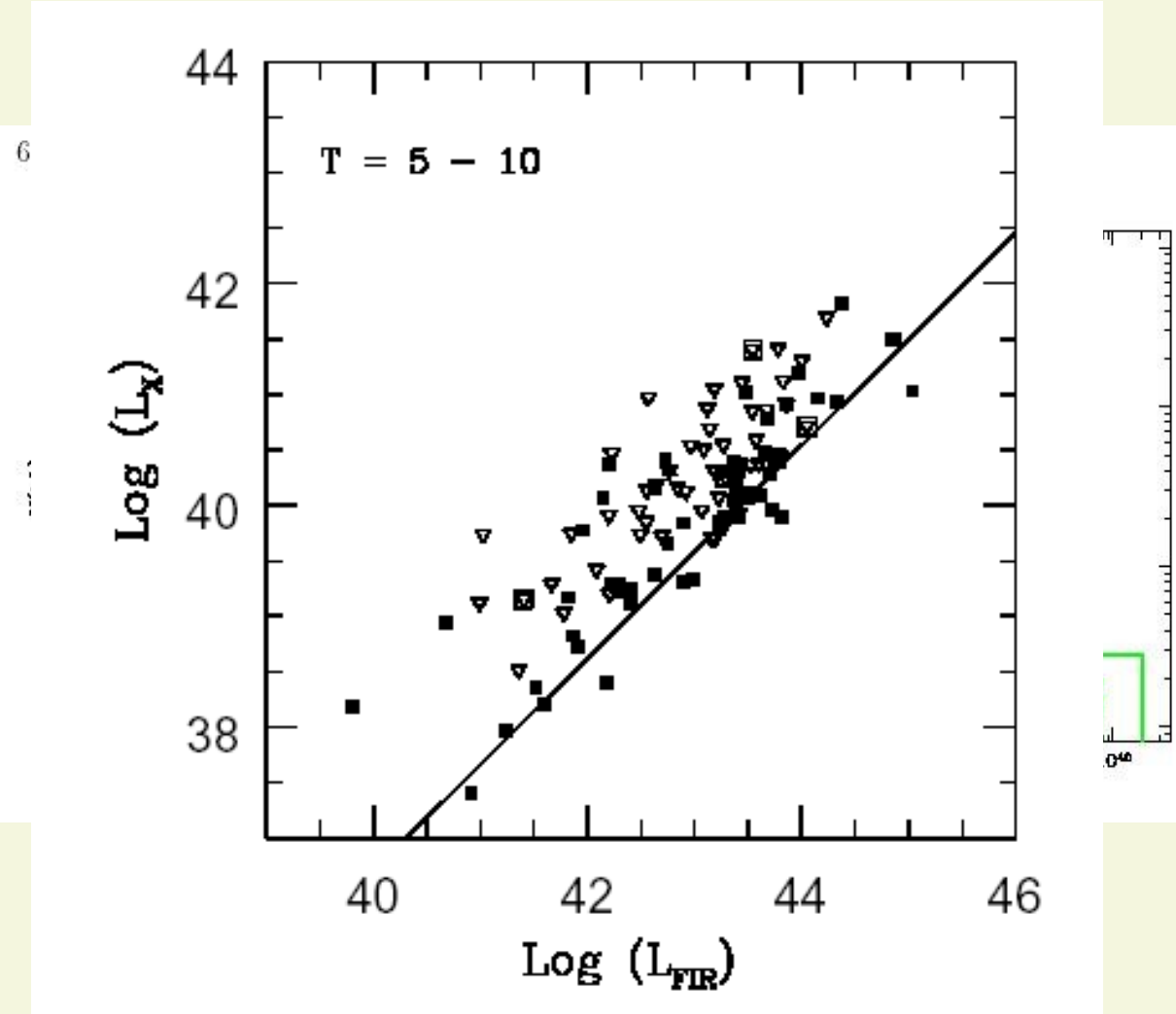
The SFR connection

XLF and Star Formation

Lx ~FIR correlations in Sc-Irr (e.g., Fabbiano et al 1988; Fabbiano & Shapley 2002)

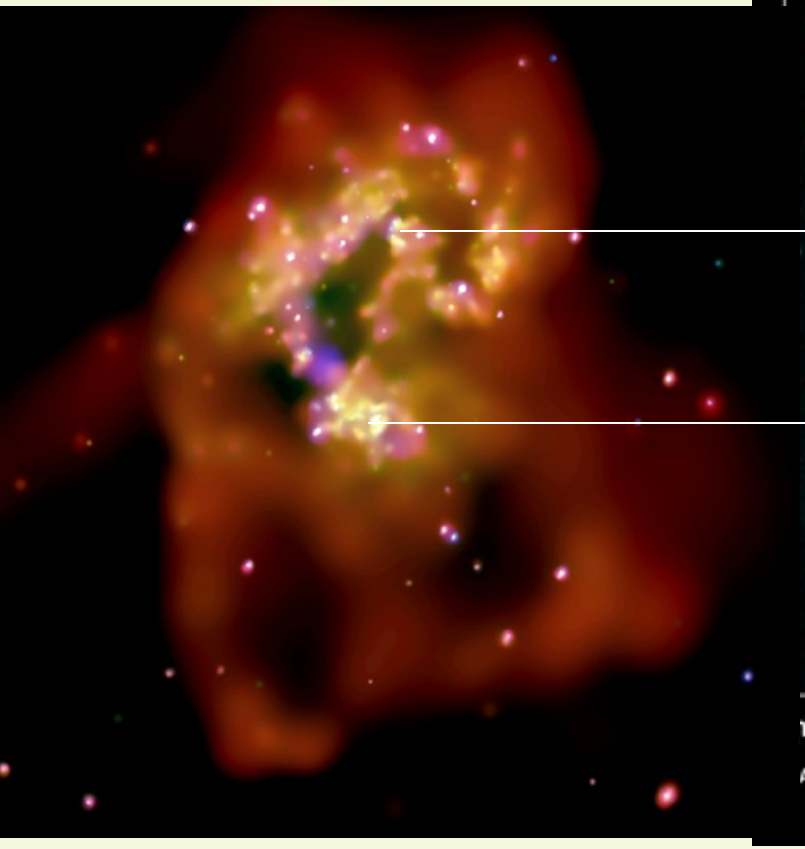
XLF ~ SFR in actively star forming galaxies (Grimm, Gilfanov & Suniaev 2003)

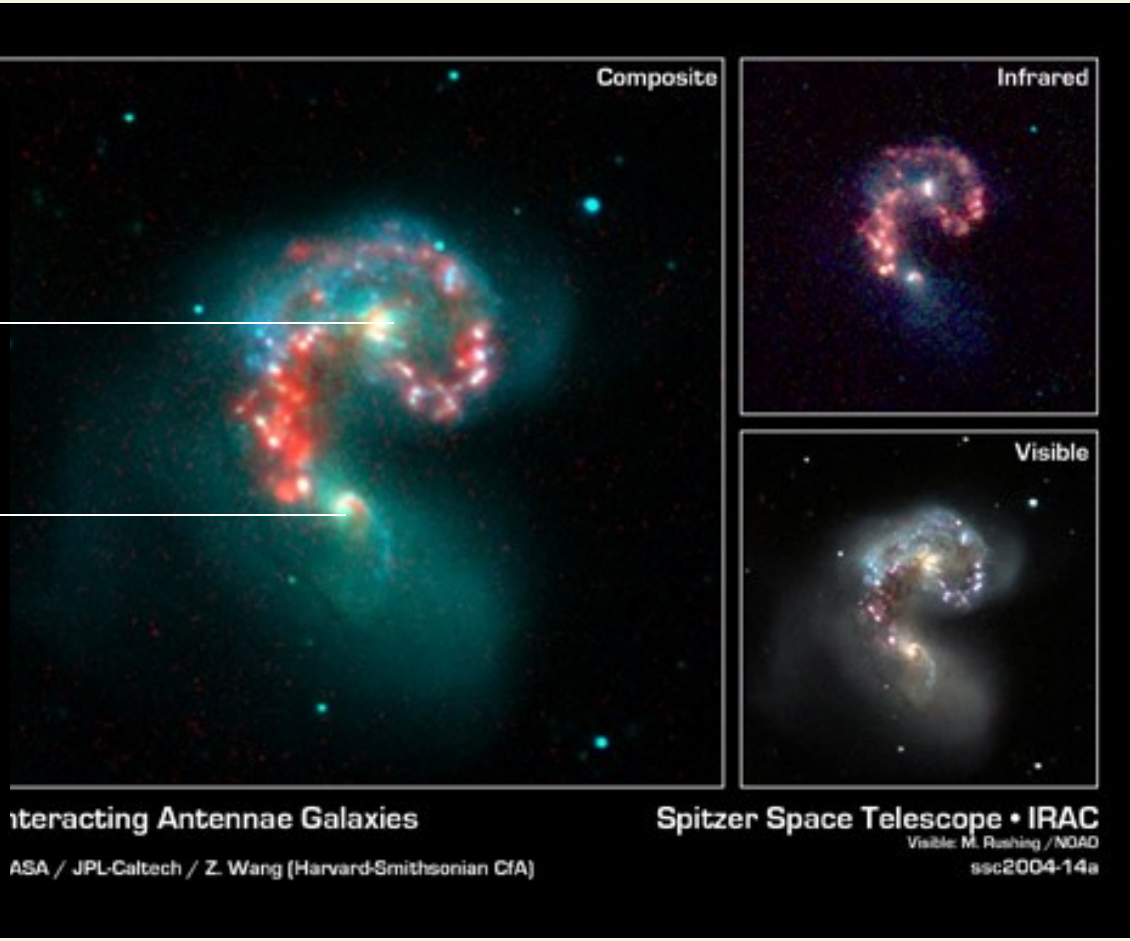
Universal XLF cum. Slope -0.6



The Antennae –very active star formation

Chandra/Spitzer/Optical





The X-ray source population of the Antennae galaxies

2 year monitoring with Chandra ACIS-S

- 410 Ks
- 7 exposures (~40 sources/exposure)

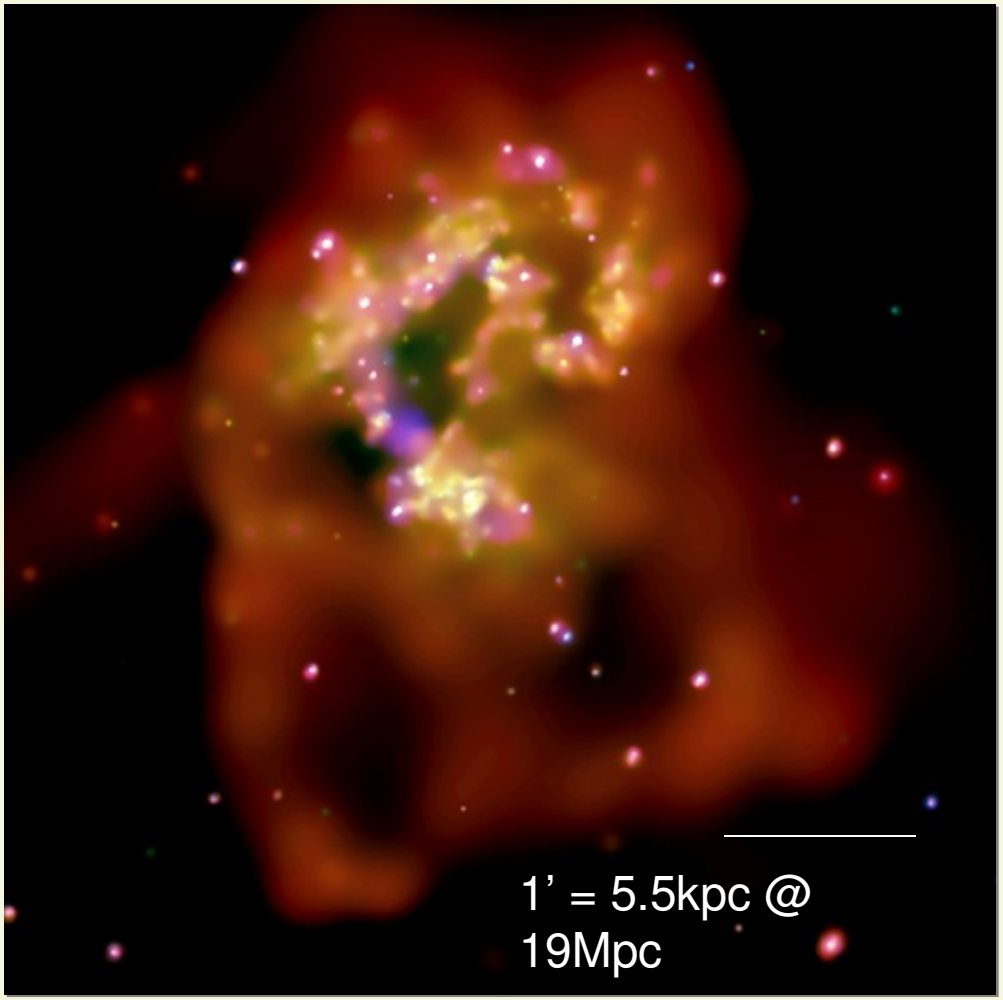
120 sources

>60% variable

Spectral variability

ULX are all variable

- 7 LX>10^{39}cgs
- 7 occasional ULXs



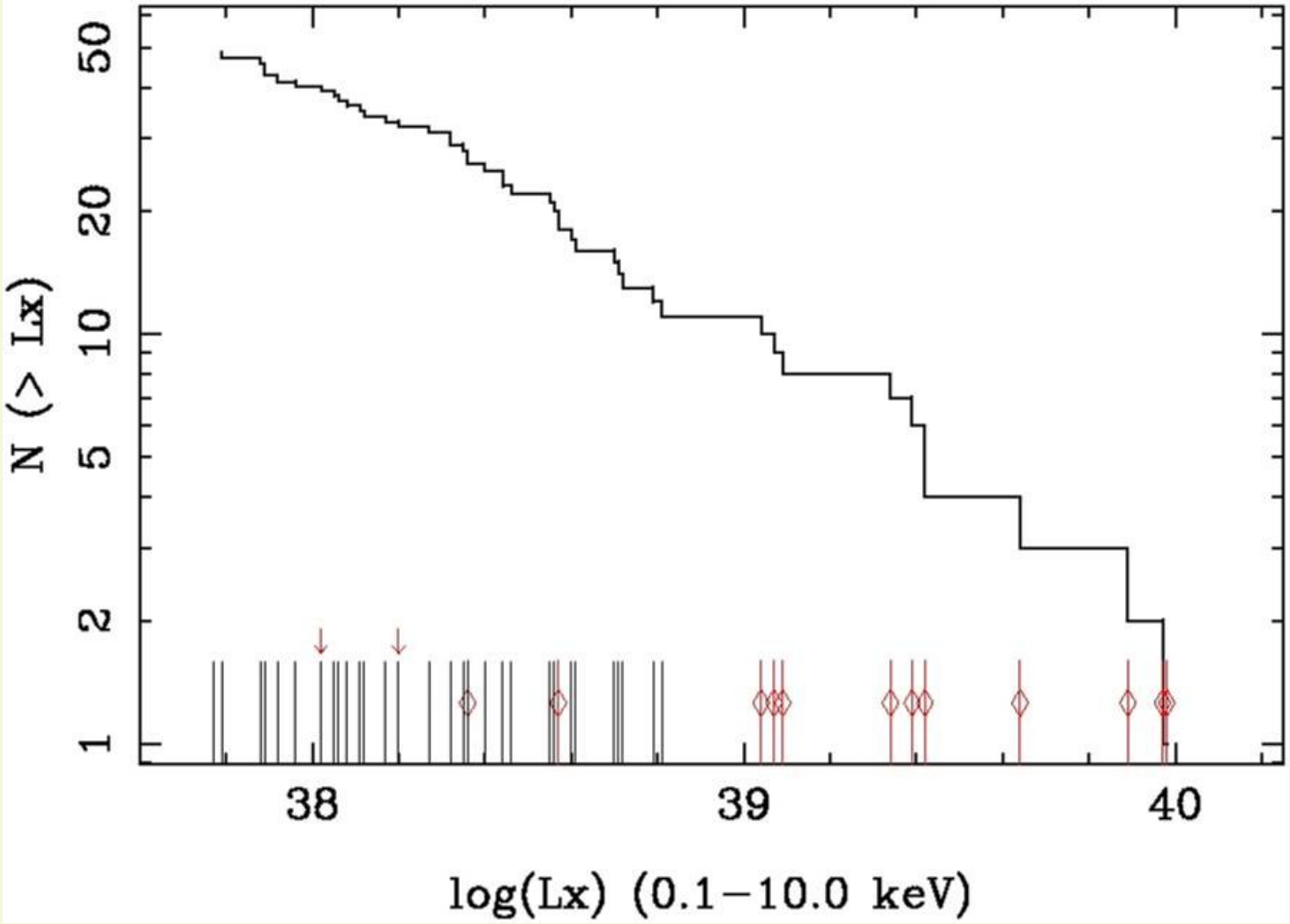
Fabbiano et al 2003, ApJ letters

The Antennae: The Movie
ULX Variability

Thanks to
Andreas Zezas
&
Roy Kilgaard

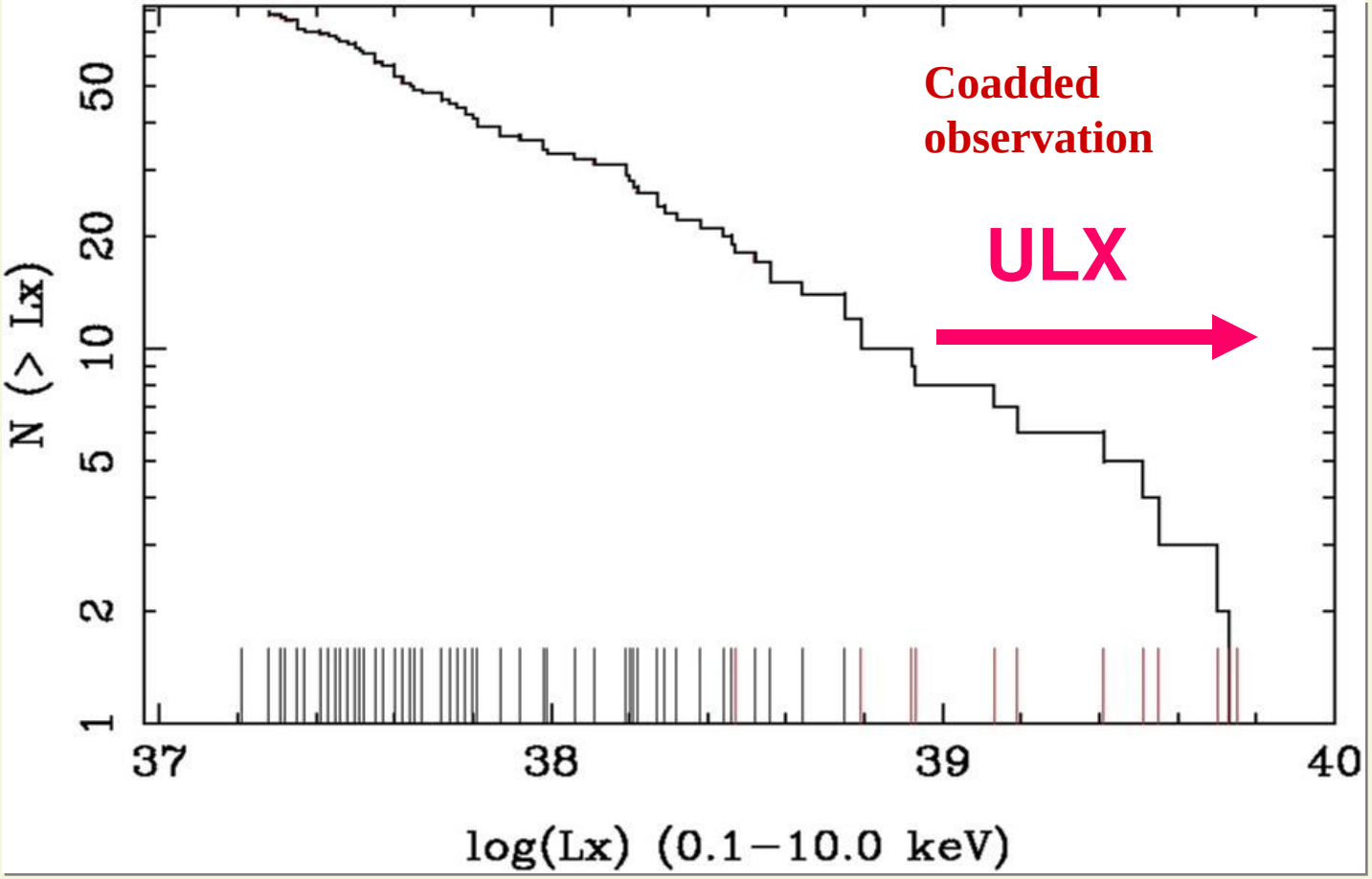
30”

The Antennae XLF is not affected by XRB variability
XLFs statistically consistent (Zezas et al in prep.)



The XLF of the Antennae

Zezas et al in prep.



Cumulative XLF slope ~-0.5

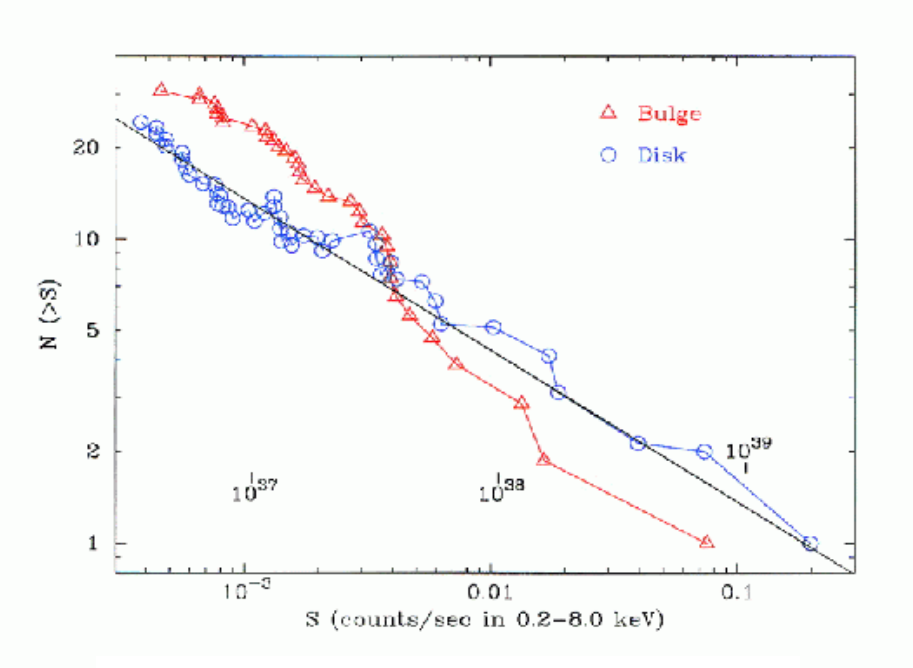
XRB populations of spiral galaxies: LMXBs & HMXBs

Complex X-ray source populations

Studying the evolution of XRBs with XLFs

XLF different in different stellar populations

Younger populations, flatter XLFs



M81 – Tennant et al 2001

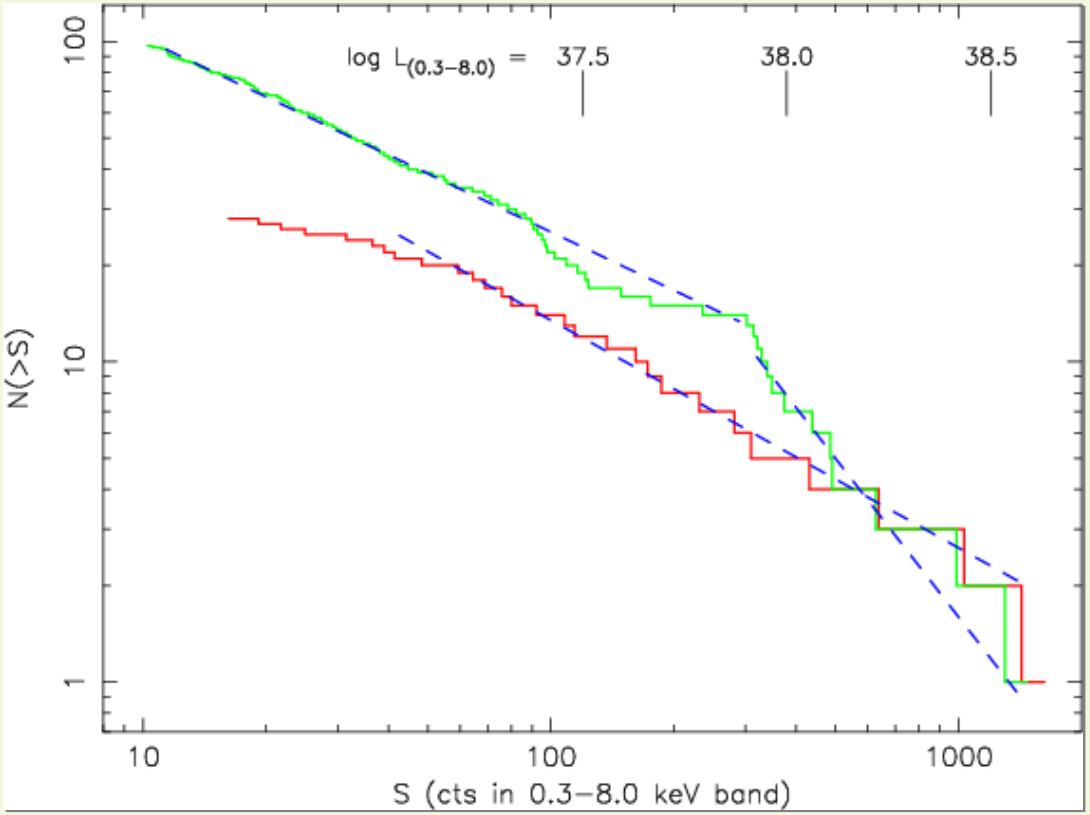
M81 – Willner et al 2004 – Spitzer/UV

The XLFs of M83 - a composite population

Soria & Wu 2003

XLF of inner regions (red, d<60'') follows a -0.7 power-law

The XLF of the outer disk (green) follows a -0.6 power-law below a break at 3 x 10^{37} erg/s



A young XRB population: M33

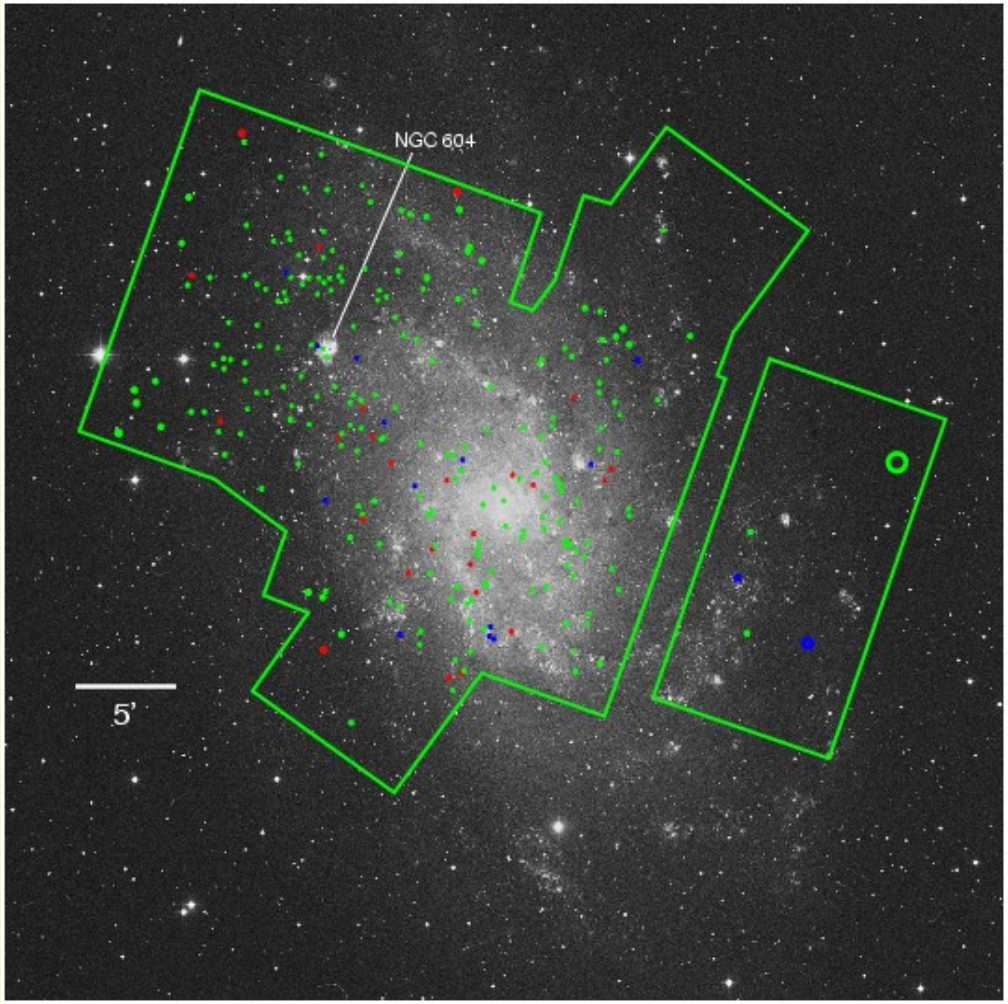
Grimm et al 2005

3 *Chandra* observations

- 261 sources
- $L_X > 2\ 10^{34}$ erg/s
- (D = 840 pc)

X-ray colors

- Few LMXBs
- HXMBs (+ background AGN contamination)
- SNRs



X-ray source population and XLF of M33

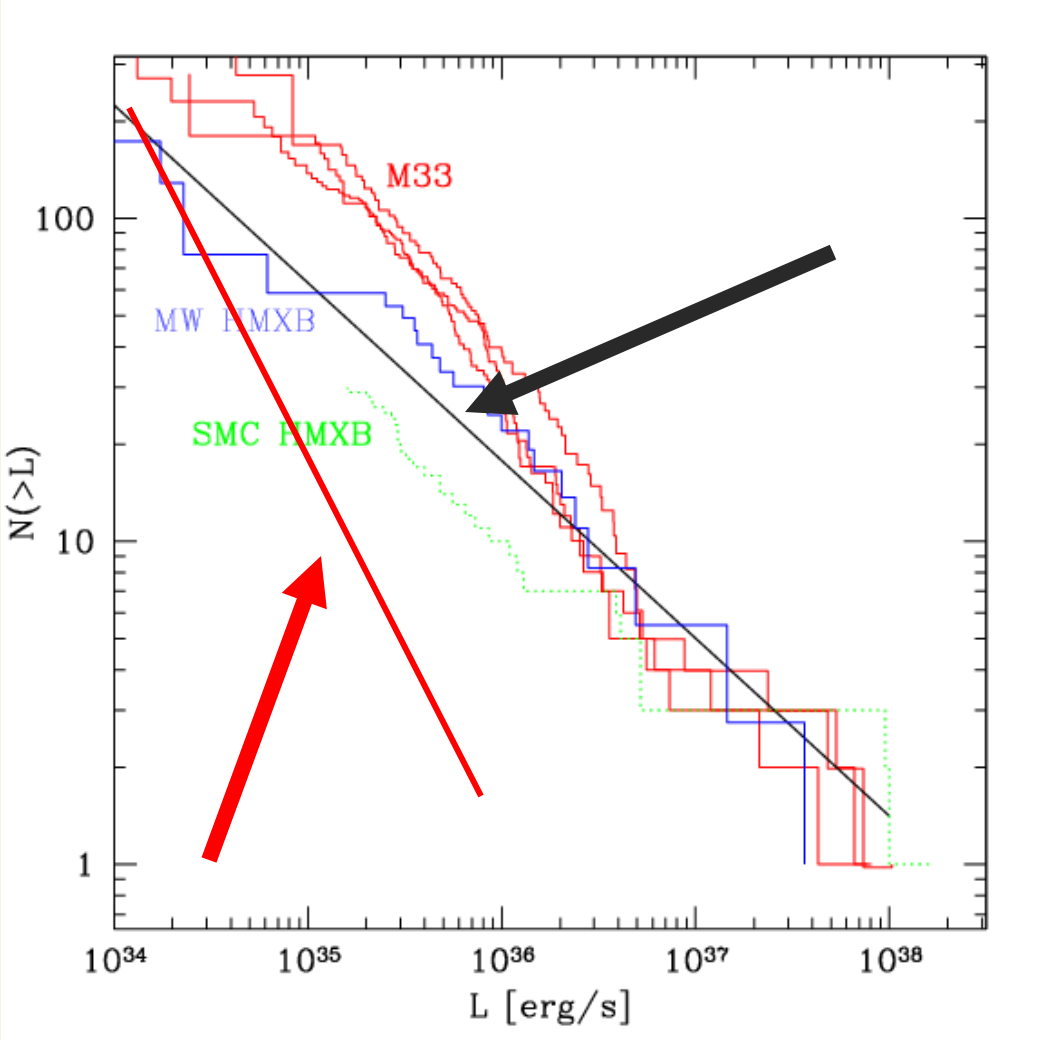
Grimm et al 2005

Bias-corrected XLFs of 3 *Chandra* observations are self-consistent

Background-corrected XLF consistent with MW and SMC HMXB XLFs

Cumulative slope ~ -0.5

Slope of LMXB population ~ <-1.

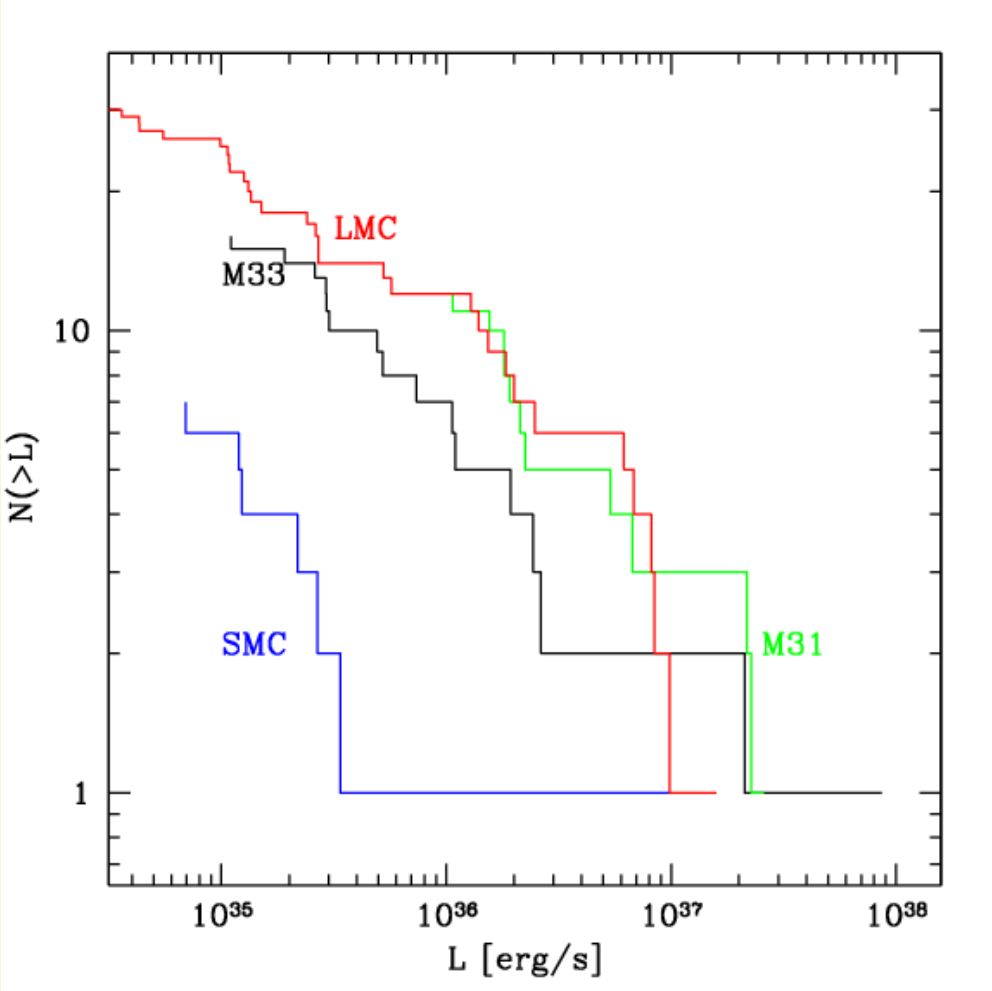


X-ray source population and XLF of M33

Grimm et al 2005

SNRs have little effect on overall XLF (5-10%)

SNR XLF comparison suggest differences in slope between young (M33, LMC, SMC) and older (M31) stellar populations



The lowest reaches of the HMXB XLF

LMC (Shtykovskiy & Gilfanov 2005, with *XMM-Newton*)

- Suggest flattening at the lower luminosities (< 10^{37} erg/s)
  - Propeller effect? Magnetic field stopping accretion flow onto pulsar for low accretion rates
- Age effect:Halpha and FIR maxima deficient of HMXBs
  - Regions too young for binary evolution
    (see also Tyler et al 2004, 12 nearby spirals)

X-ray Luminosity functions

Drivers and statistics

Drivers of the X-ray Luminosity Functions

Slope - star formation
luminous short-lived HMXB

Flatter slope (e.g. Zezas & Fabbiano 2002; Colbert et al 2004)

Normalization

Star-forming galaxies - SFR (Grimm et al 2003)

Old stellar populations - Stellar mass (Gilfanov 2004; Kim & Fabbiano 2004) - GC content?

Breaks

Multiple XRB populations or population evolution
The trickiest to detect and most affected by biases

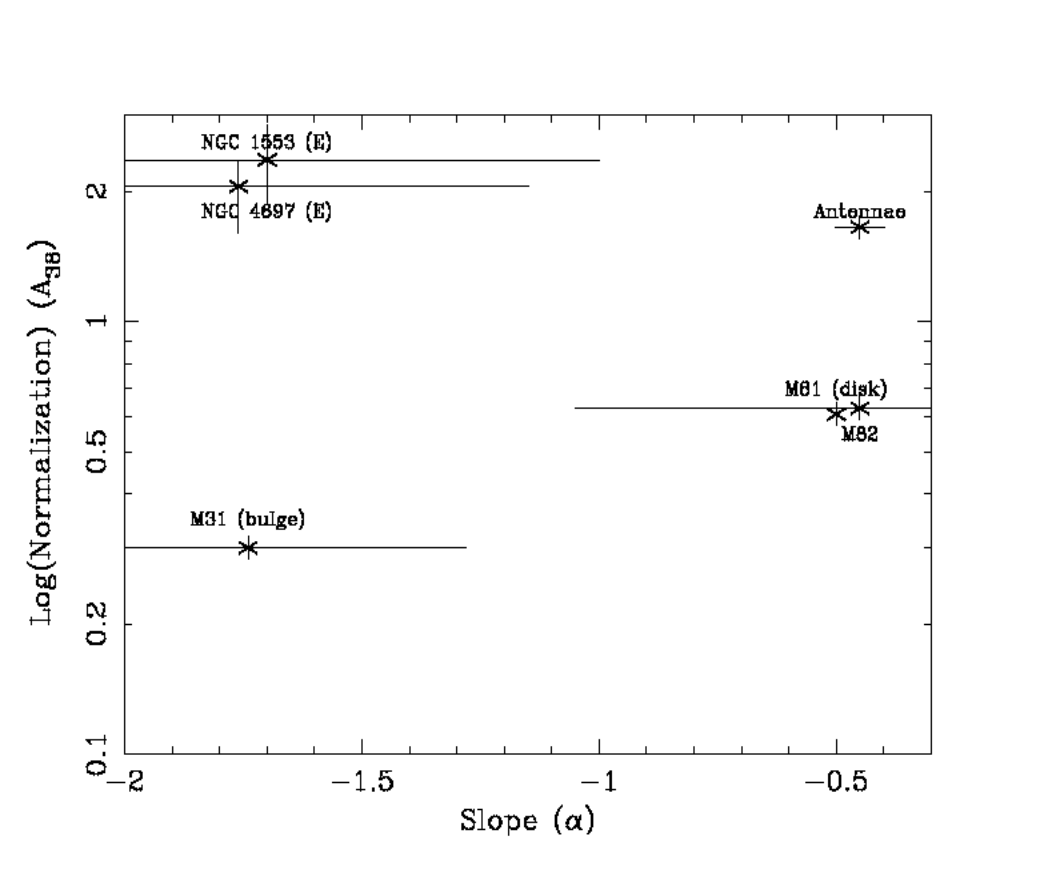
Drivers of the XLF

Slope

More active star formation results in more and more luminous XRBs

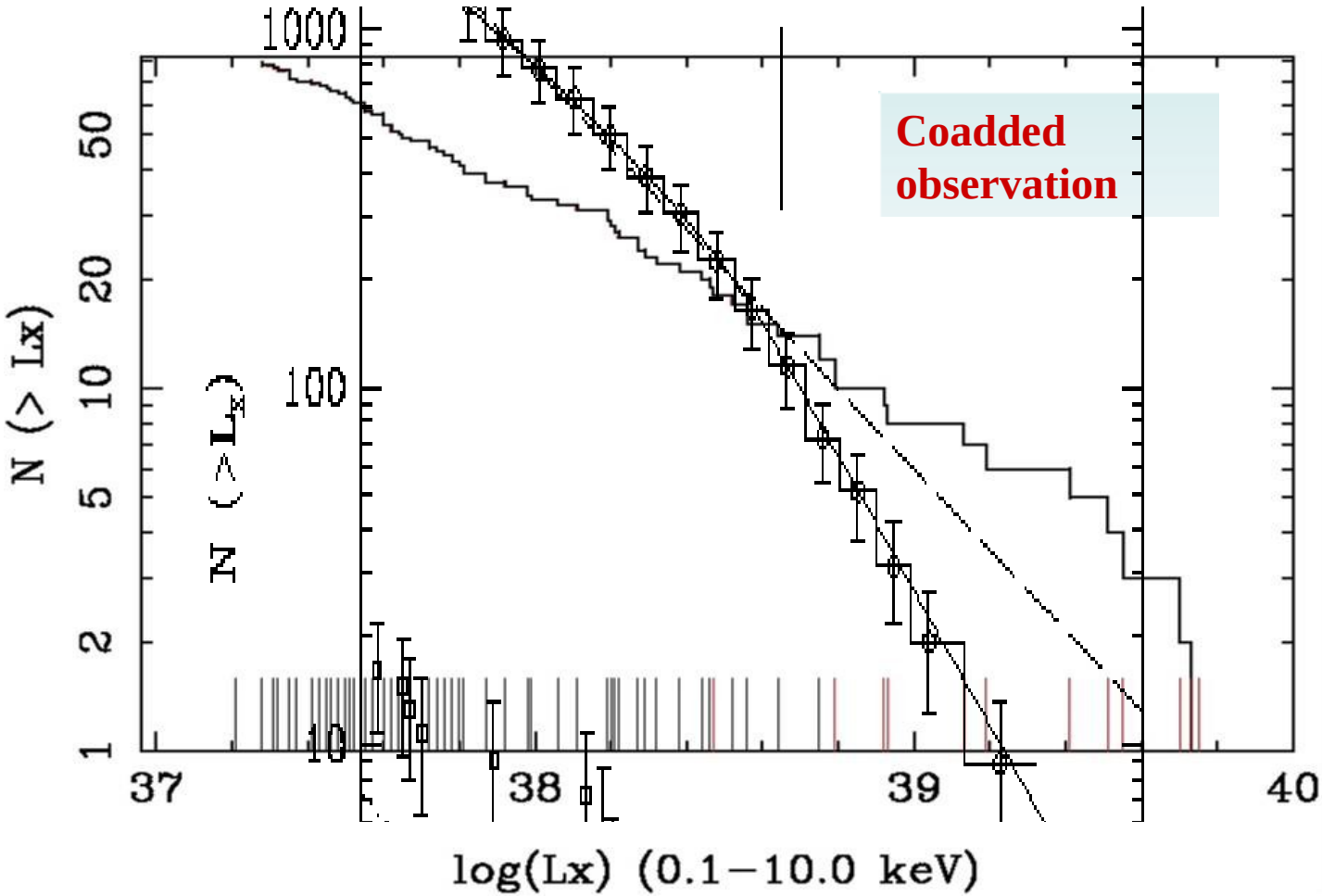
Normalization

If star formation is not important, galaxy mass / stellar content is the driver.



Zezas & Fabbiano 2002

The Luminosity functions



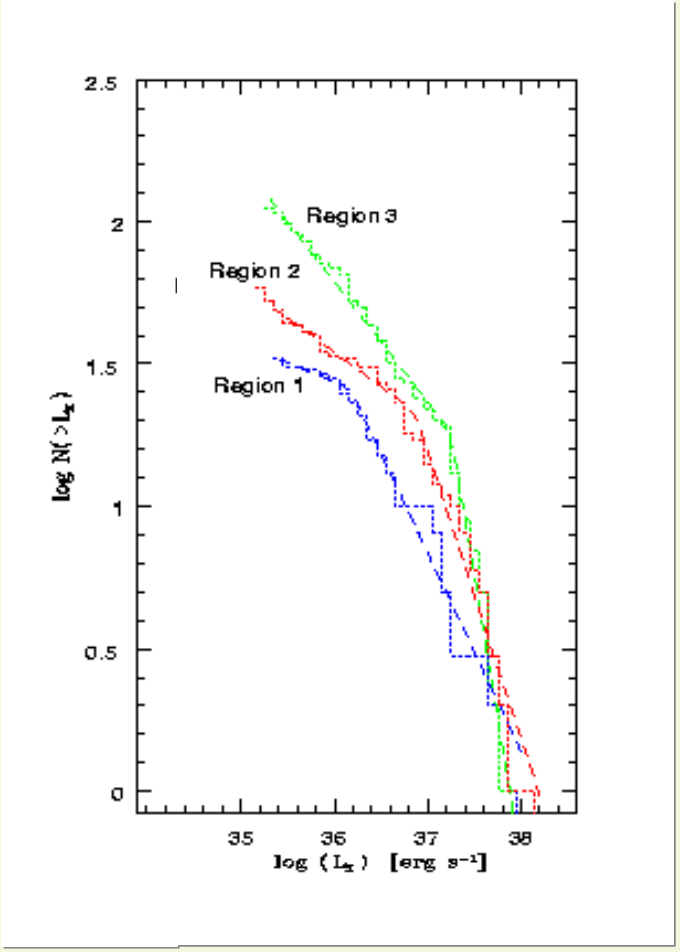
$\forall \Rightarrow$ E and S0 galaxies lack very luminous sources

X-ray Luminosity Functions: Breaks

E.g. low luminosity breaks in the bulge of M31

- R1 < 2’
- R2 < 8’
- R3 >8’

Disappearance of more luminous sources because of aging?



M31 – Kong et al 2002

Effects of statistics
(Gilfanov, Grimm & Sunyaev 2004)

Dependence of total galaxy L_X on the number of sources *n* for different XLF slope

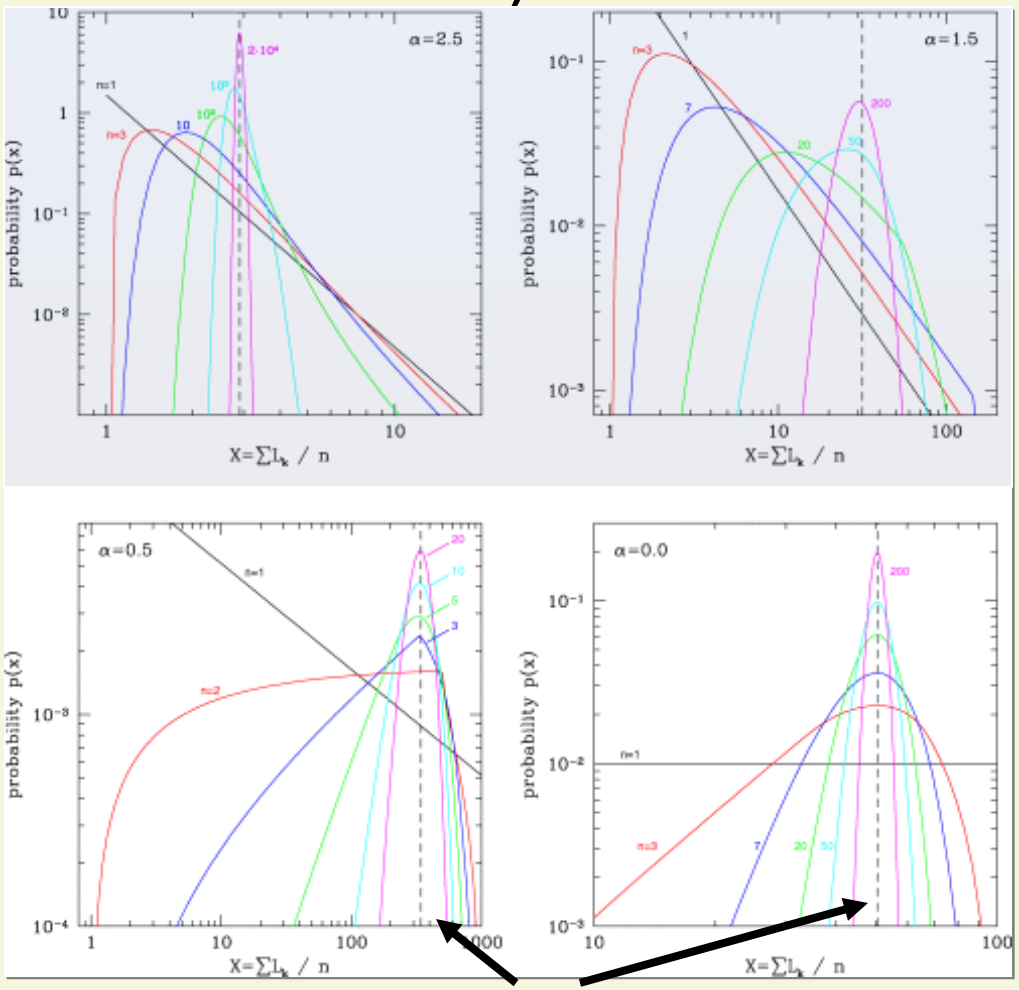
Effect on L_X-SFR, L_X-mass relations

Relation of $L_{X(total)}$ to detected *n*

(Gilfanov et al 2004)

Effect of small *n* number of luminous sources (Poisson statistics) and power-law of differential XLF

$\langle L_{X(total)} \rangle \neq$ most probable $L_{X(total)}$



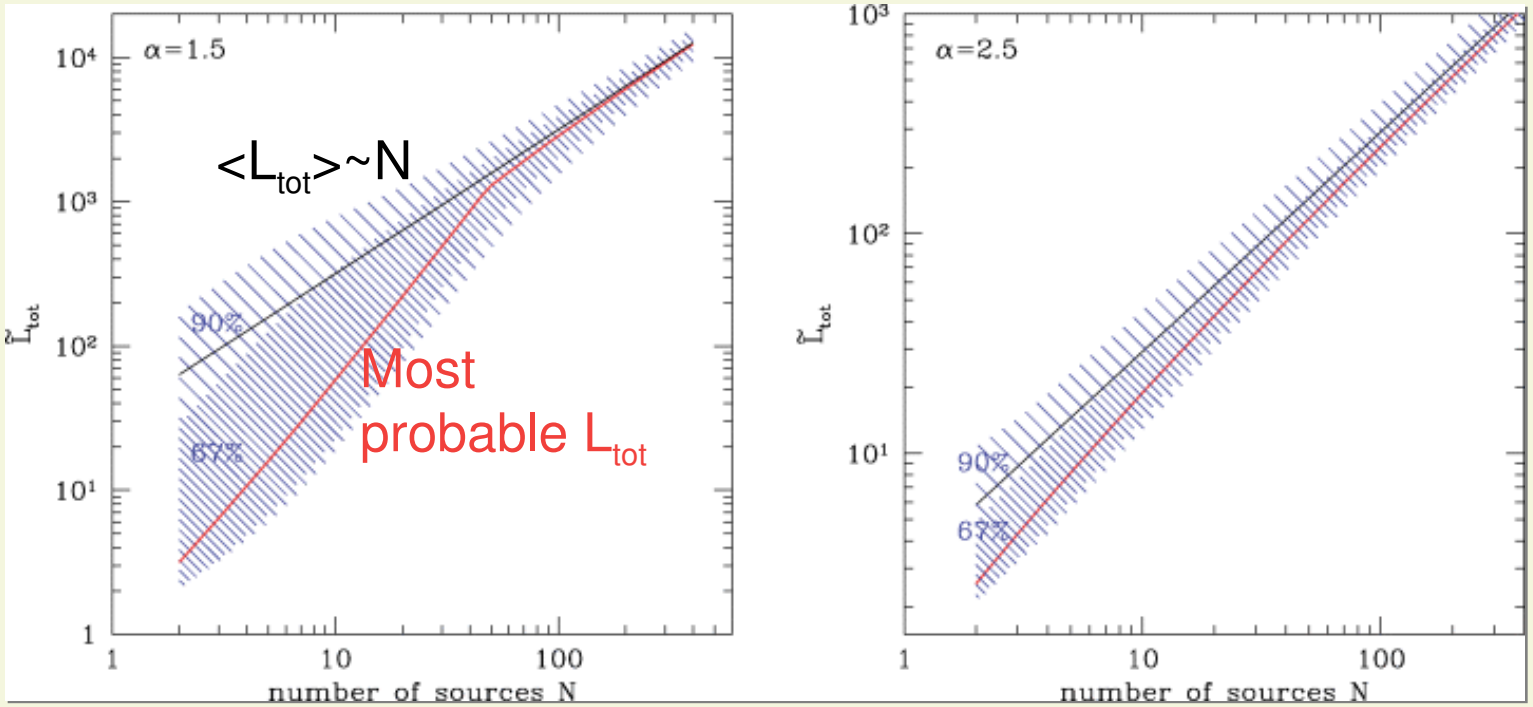
$\langle L_{X(total)} \rangle / n$

Relation of L_X(total) to *n*

(Gilfanov et al 2004)

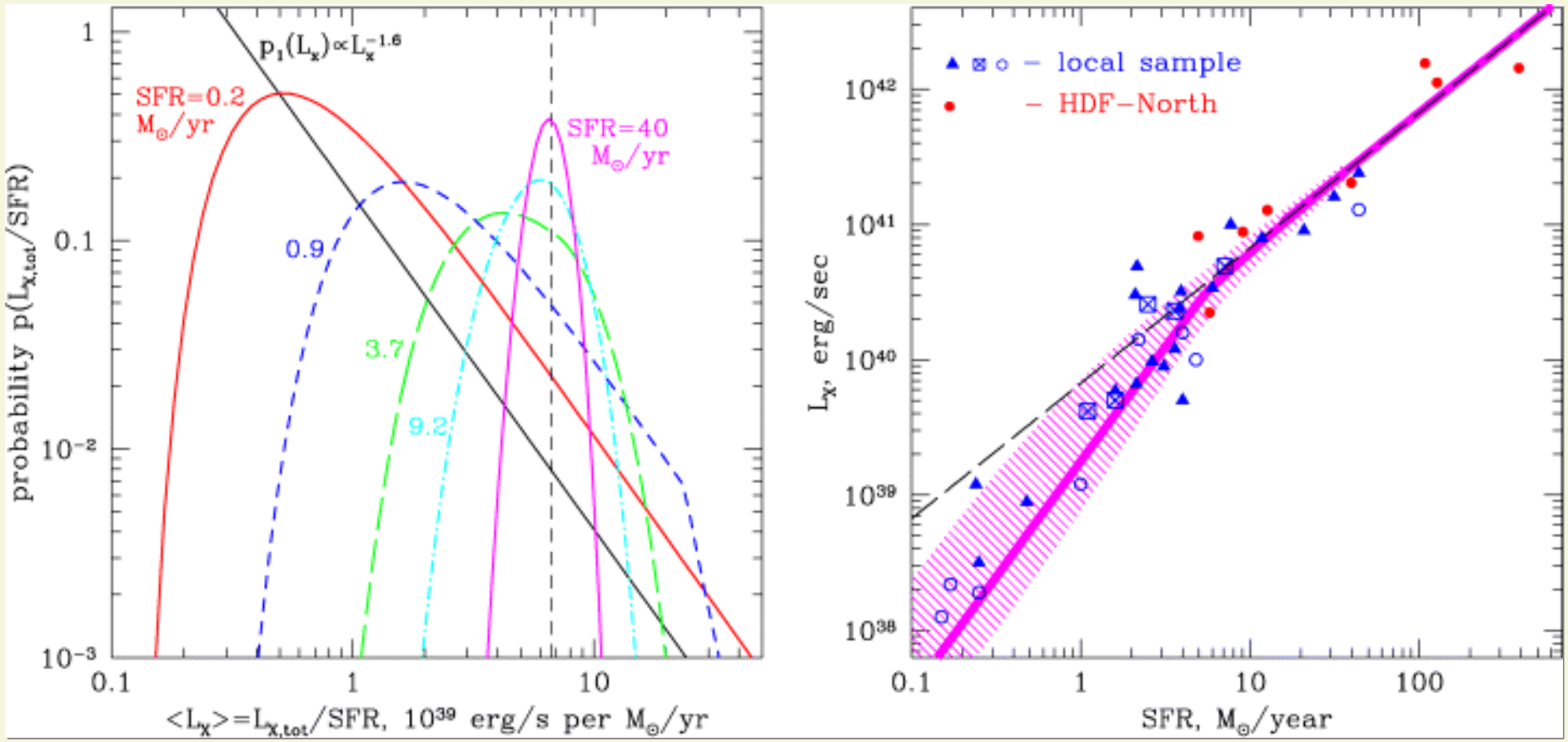
Linear and non-linear regimes

Effect of small number of luminous sources and power-law XLF (differential, 1.5 ~HMXB, 2.5 ~ LMXB)



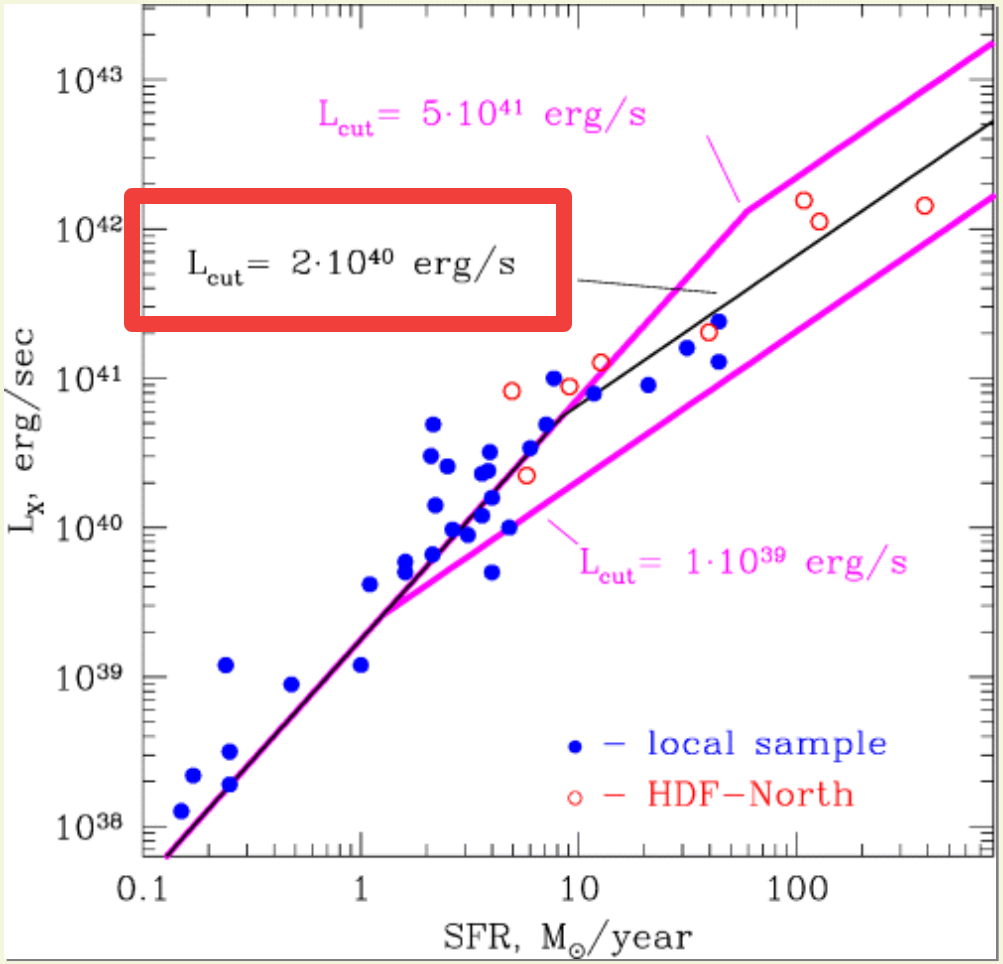
The L_X, total-SFR relation

(Gilfanov et al 2004)

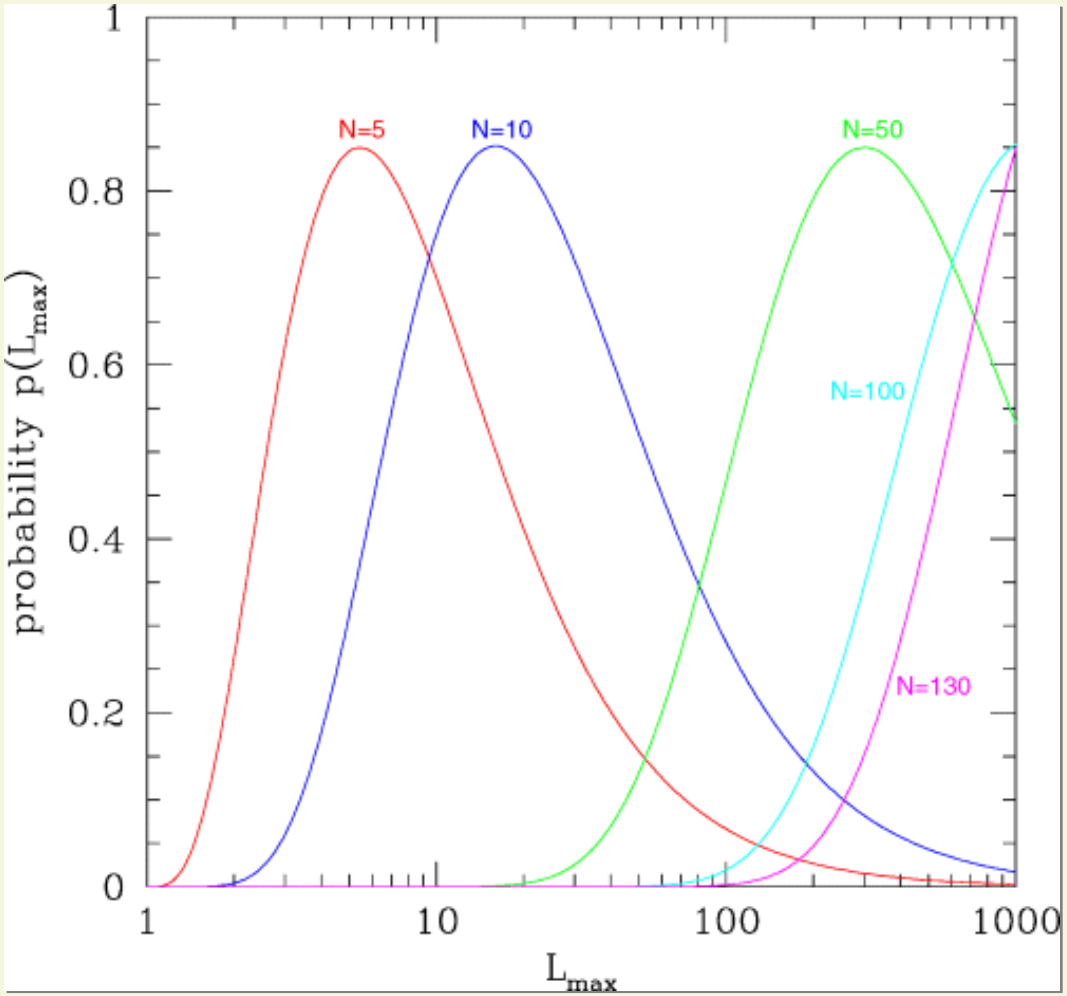


Dependence on the XLF cut-off

(Gilfanov et al 2004)



Probability distribution for the most luminous sources as function of the number of sources for a 1.5 differential XLF (Gilfanov et al 2004)

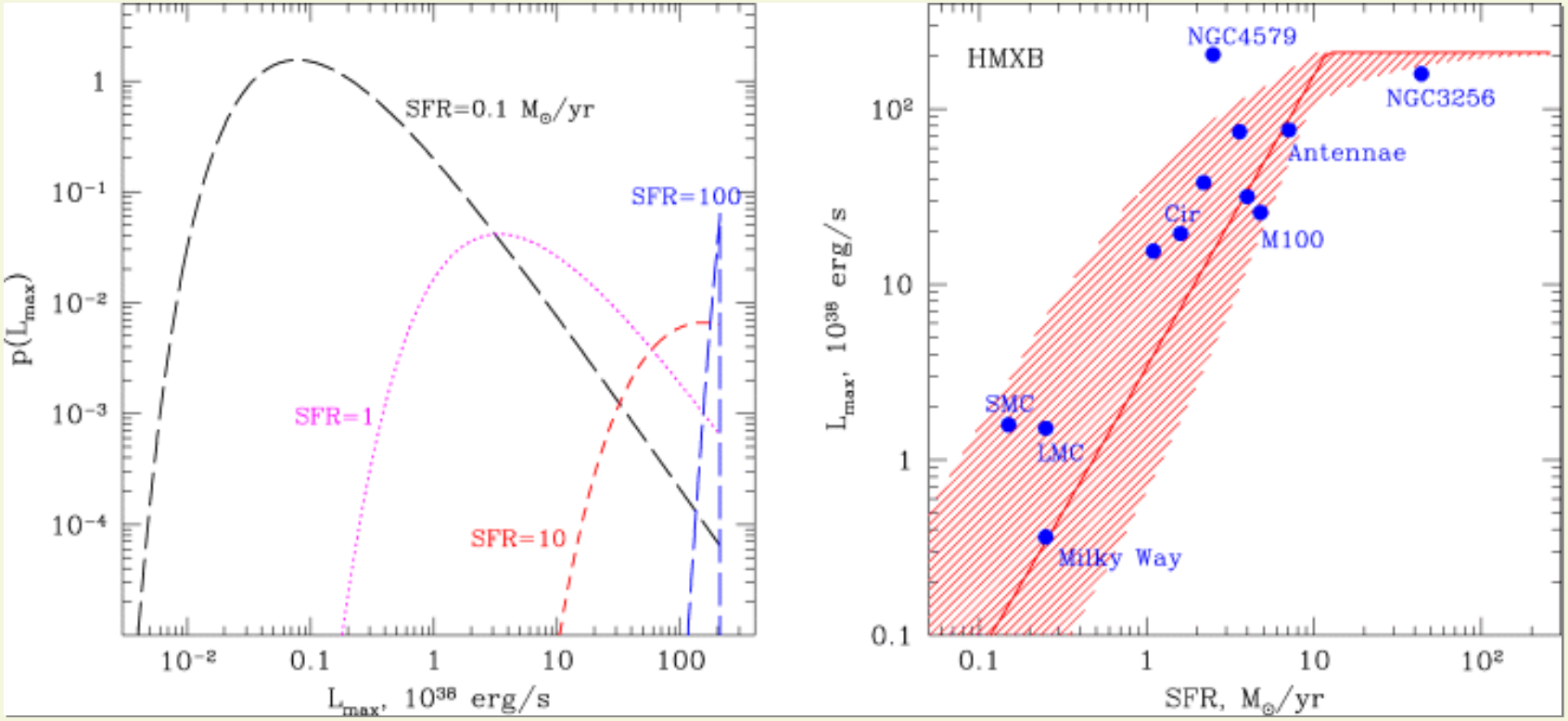


Expected L_X of brightest source vs SFR for HMXBs

(Gilfanov et al 2004)

Shaded area is 67% intrinsic dispersion

Sources up to 10^{40} erg/s expected

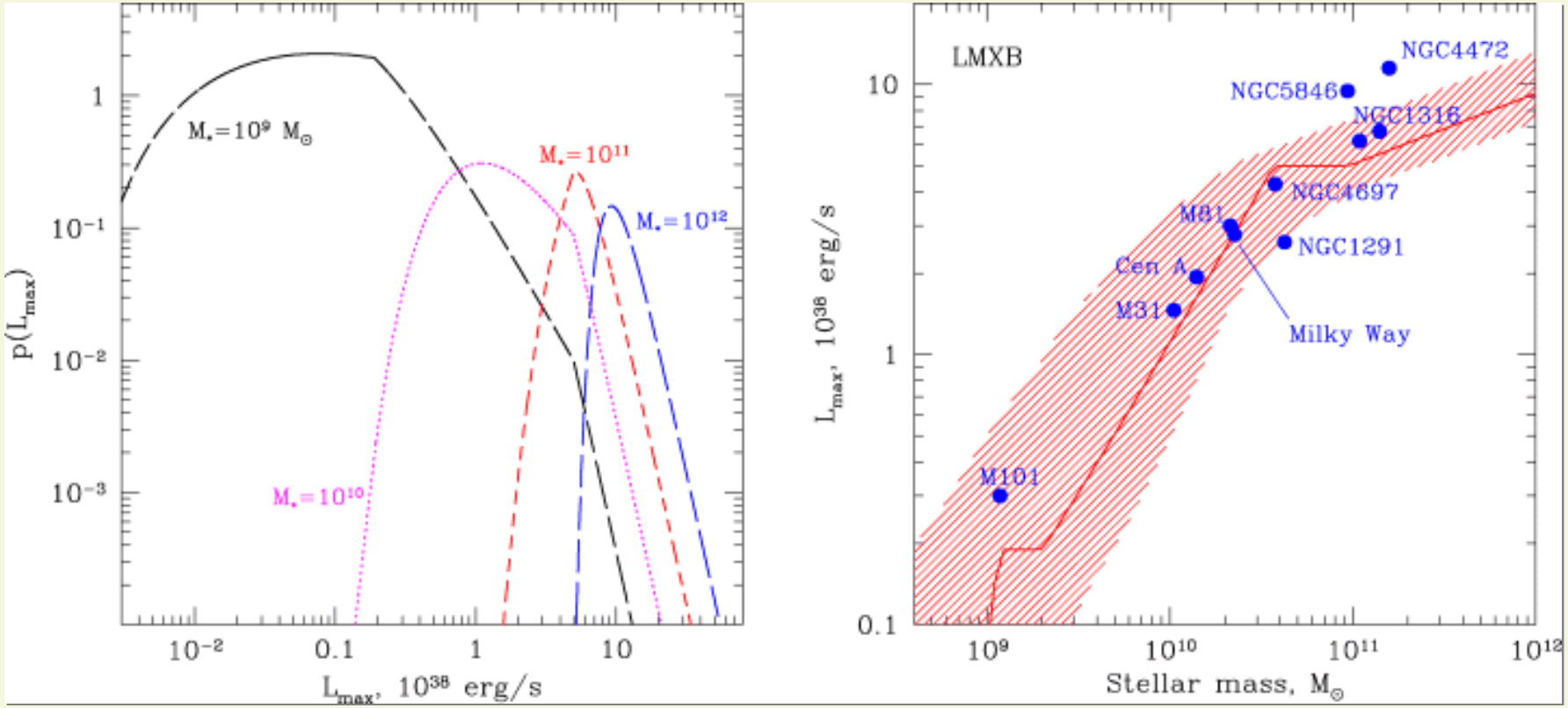


Expected L_X of brightest source vs Mass for LMXBs

(Gilfanov et al 2004)

Shaded area is 67% intrinsic dispersion

Sources a few 10^{39} erg/s expected



Outline

- X-ray emission of galaxies
  - Pre-*Chandra*
  - *Chandra* (*XMM-Newton*) population studies/tools
  - Color-Color diagrams
  - XLFs
- Old populations (E & S0 galaxies)
  - Properties
  - XLFs
  - GC connection
  - Evolution theories

Outline

- Younger & Mixed populations (S and Irr galaxies)
  - Properties
  - XLFs
- Drivers of XLFs and effects of statistics
- Peculiar classes of sources
  - SSS
  - ULX
- High z galaxies and XRB evolution
- Future prospects

‘New’ classes of X-ray sources that have come of age

SSS & QSS

ULX

SSS

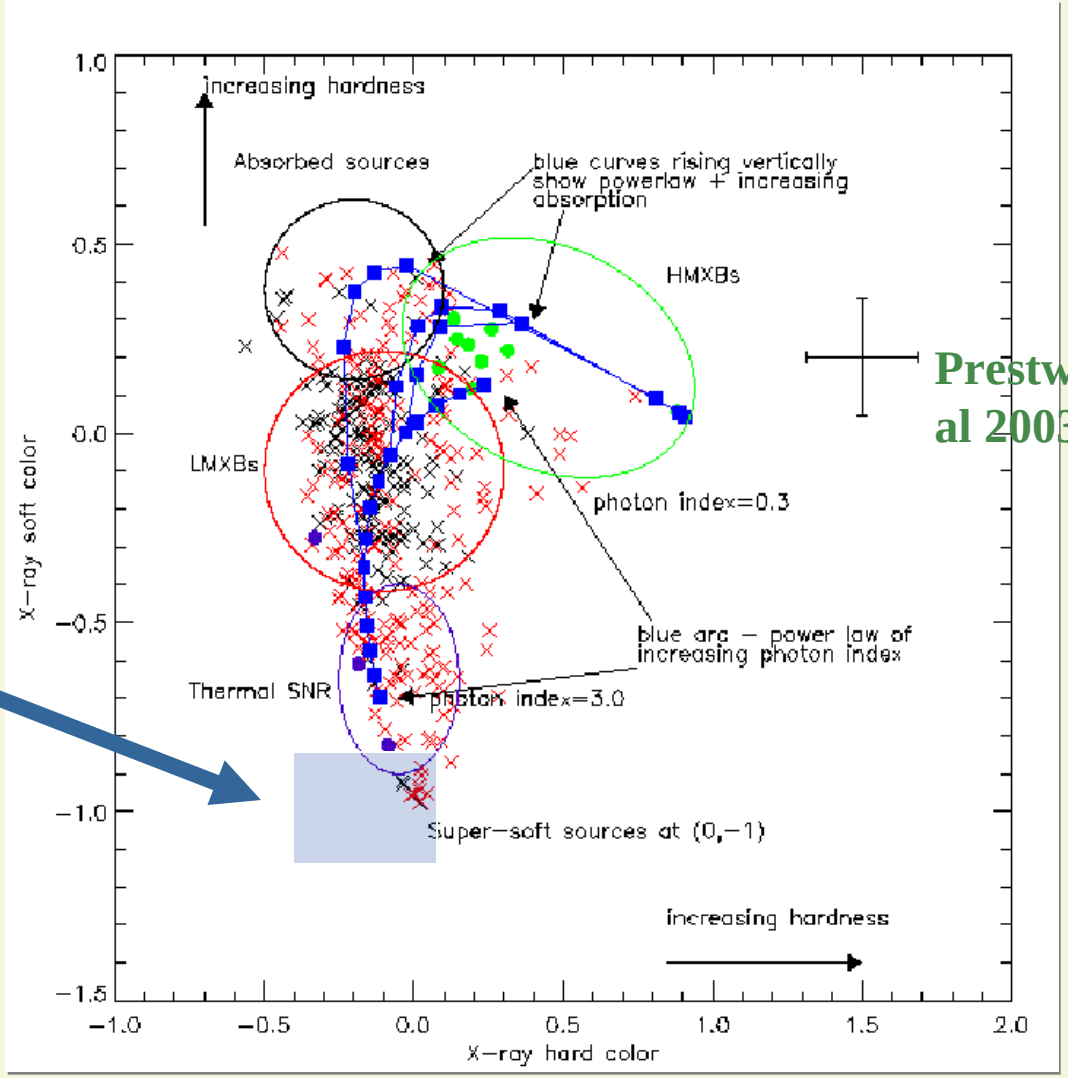
SSS - emission <1kev

Discovered with *Rosat*

- MW, M31, MCs
- 15-80 eV BB spectra
- $L_{bol} \sim 10^{36\text{-}38}$ erg/s
- Model: nuclear burning WD
- See review by Kahabka & van den Heuvel 1992

SSS & QSS

Very soft sources discovered with *Chandra* in many galaxies



Prestwich et al 2003

SSS & QSS

Very soft sources discovered with Chandra in many galaxies

- SSS
- QSS (e.g. Di Stefano & Kong 2003)
  - 100-300 eV BB
  - + small hard power-law
- Super-soft ULXs
  - In the Antennae (Fabbiano et al 2003)
  - M101 (Mukai et al 2003)
  - We'll discuss these with the ULXs

Stellar population of very soft sources

They are found everywhere
(see review Fabbiano 2006 for refs.)

- E galaxies: NGC1332, NGC4967
- The Sa Sombrero galaxy
- Spirals: M31, M81, M101, M83, M51, IC341, NGC300, NGC4449
  - Halos, bulges
  - Spiral arms, disks
  - One GC association
  - Associated with optical novae in M31 & M33 (Pietsch et al 2005)

What are these very soft sources?

A heterogeneous group

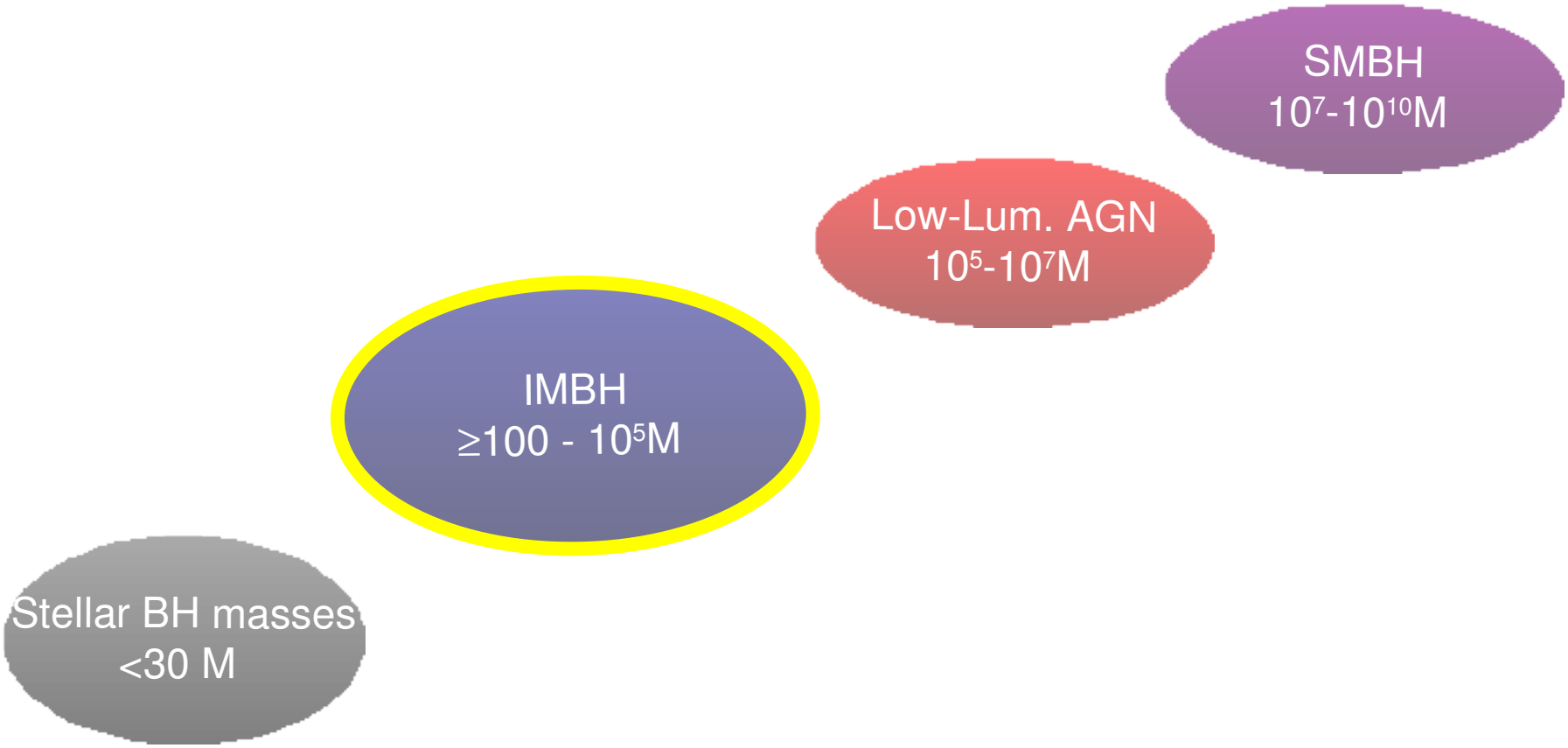
- SSS: hot WD
- QSS: NS or BH binaries
- SS ULXs: BH or IMBH(?) binaries

Ultra-**L**uminous **X**-ray Sources

Are we detecting IMBHs

(M ~ 100 - 1000 M)?

Black Hole Mass Distribution



ULX definition

- Non-nuclear X-ray sources in galaxies with 'isotropic'

$L_X > 10^{39}$ up to 10^{41} erg s^{-1}

  – Well above L_E of a neutron star (~2×10^{38}erg s^{-1})
  – If taken at face value…

Mass > 8 - 500 M

ULXs could be IMBHs !

Some recent ULX literature

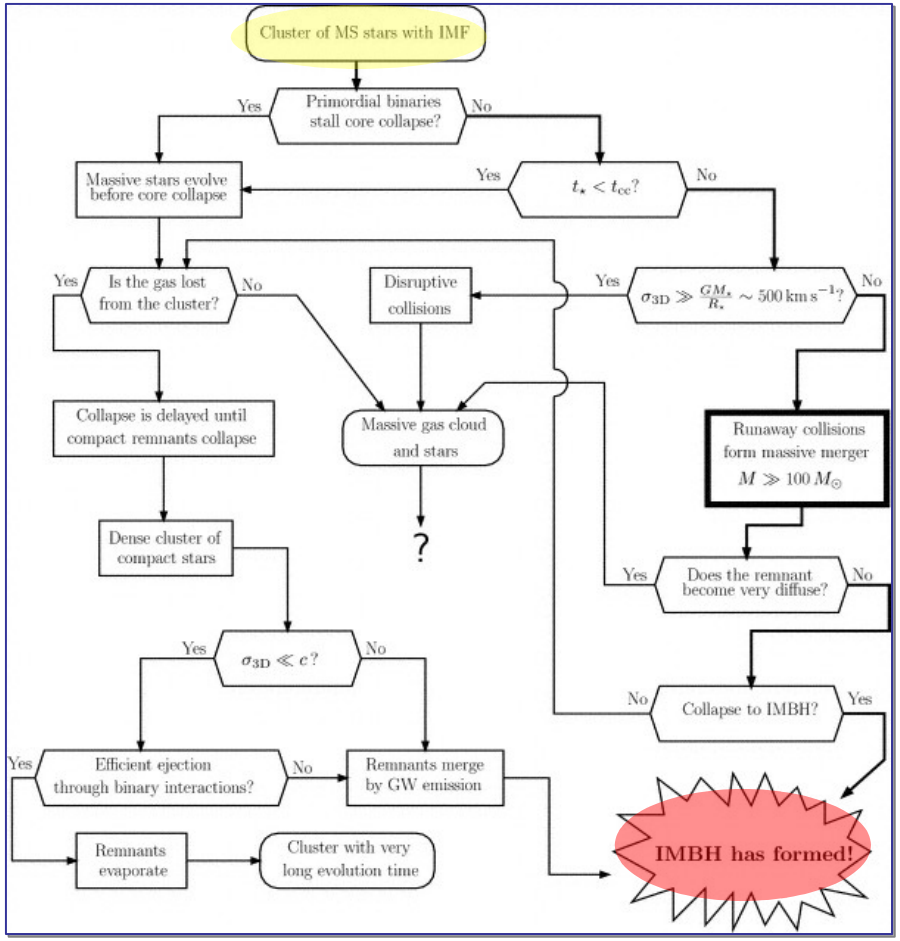
- Reviews: Miller & Colbert 2004, Mushotzky 2004, Fabbiano & White 2004, Fabbiano 2006
- Catalogs: Swartz et al 2004, Liu & Bregman 2005, Liu & Mirabel 2005

Formation of IMBH

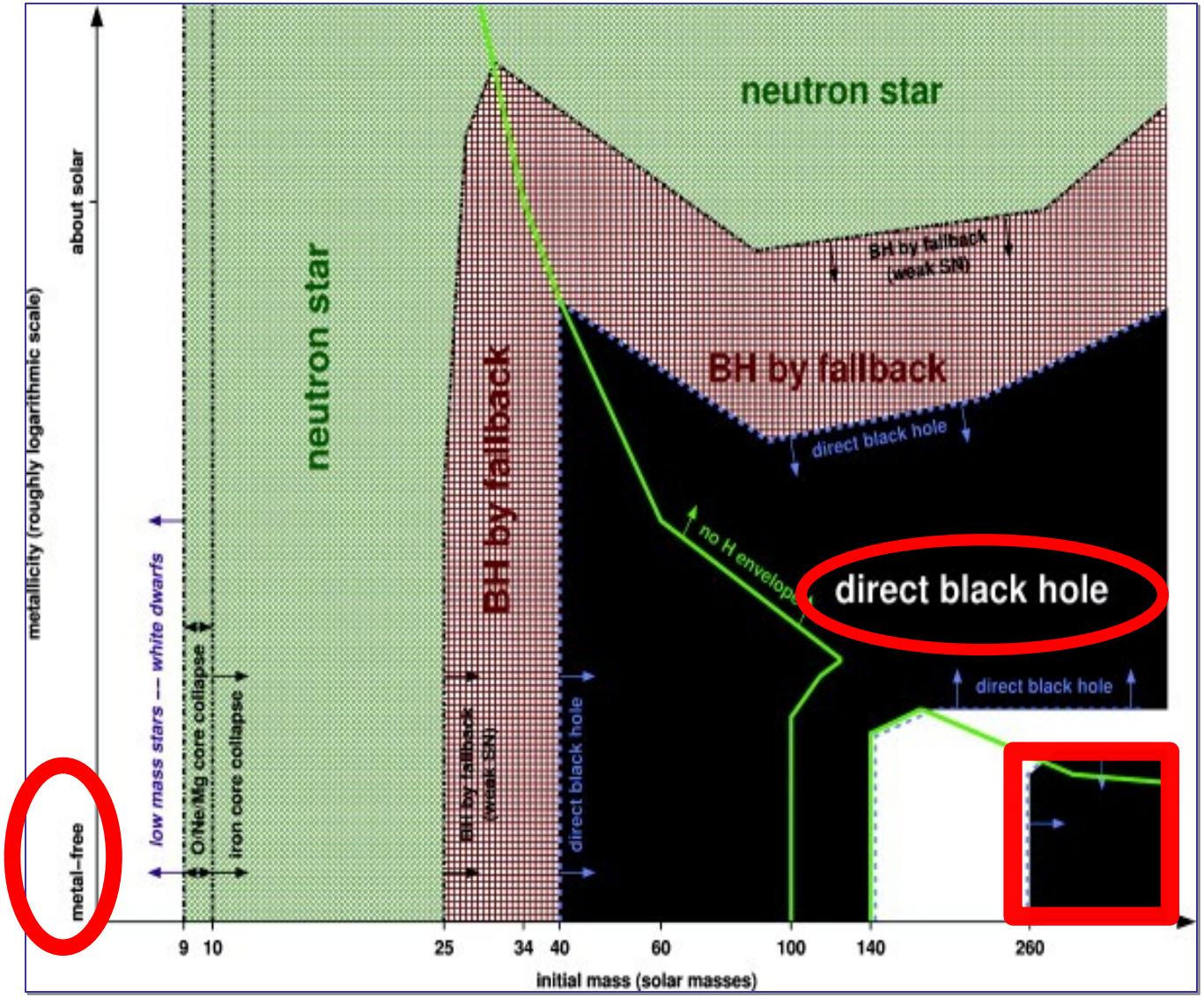
- Core collapse in Globular Clusters
- Remnants of Pop III stars and subsequent mergers (ΛCDM)

Core collapse in GCs

- First discussed in mid-70s
  - Bahcall & Ostriker 1975
  - Silk & Aarons 1975
  - Grindlay & Gursky 1976
    - X-ray burster in NGC6624, later discovered to be NS
- Revived by ULXs
  - PortegiesZwart et al 1999
  - PortegiesZwart & McMillan 2002
  - Gurkan, Freitag & Rasio 2004
  - Can we really have collapse to IMBH?

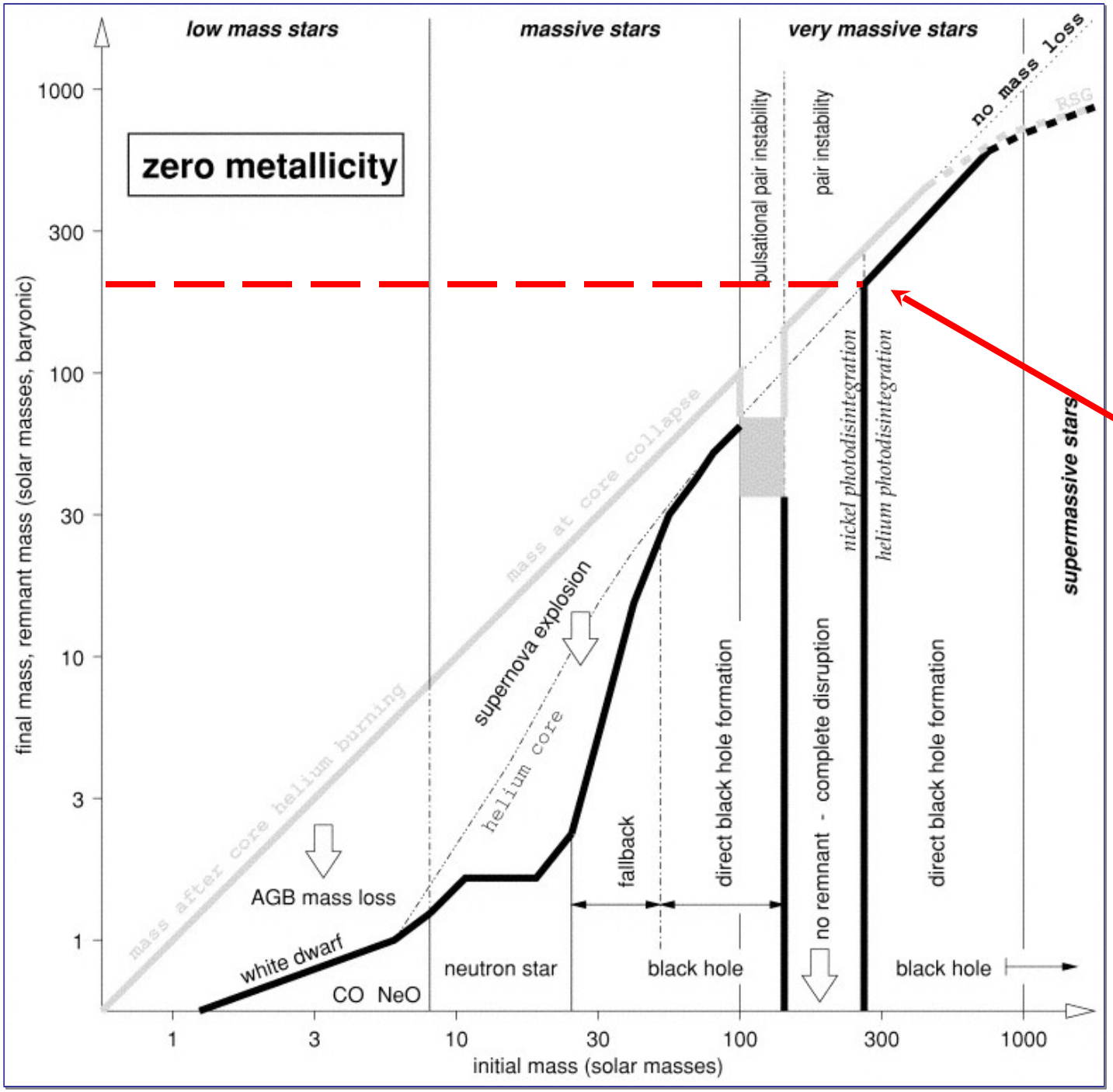


Stellar remnants as function of metallicity and mass



Heger et al. 2003

Courtesy: Marta Volonteri



Metal free dying stars with M>260M leave remnant BHs with $M_{seed} \approx 100M$

(Fryer, Woosley & Heger)

Courtesy: Marta Volonteri

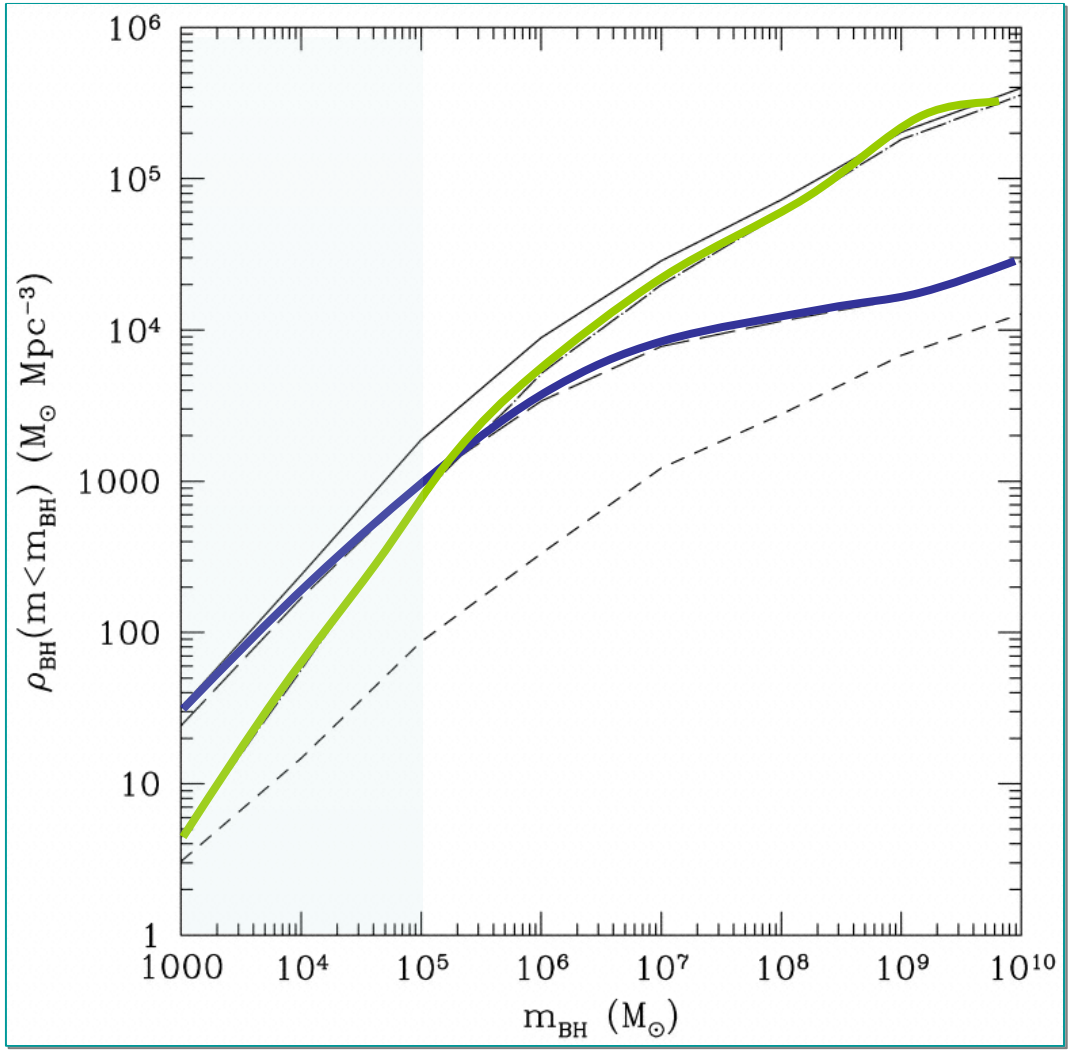
Remnants of Pop III stars and mergers

- Madau & Rees 2001
- Volonteri, Haardt & Madau 2003
- Islam, Taylor & Silk 2003
- Volonteri & Perna 2005

IMBHs would be found in large bulges
Tidal capture of stars **in inner bulges**
↓
ULX

Remnants of minor mergers **in halos**
Predicted numbers model dependent
Accreting halo gas or own fuel
↓
ULX

Halo IMBH dominate mass density
Volonteri et al 2003



Nuclear BH

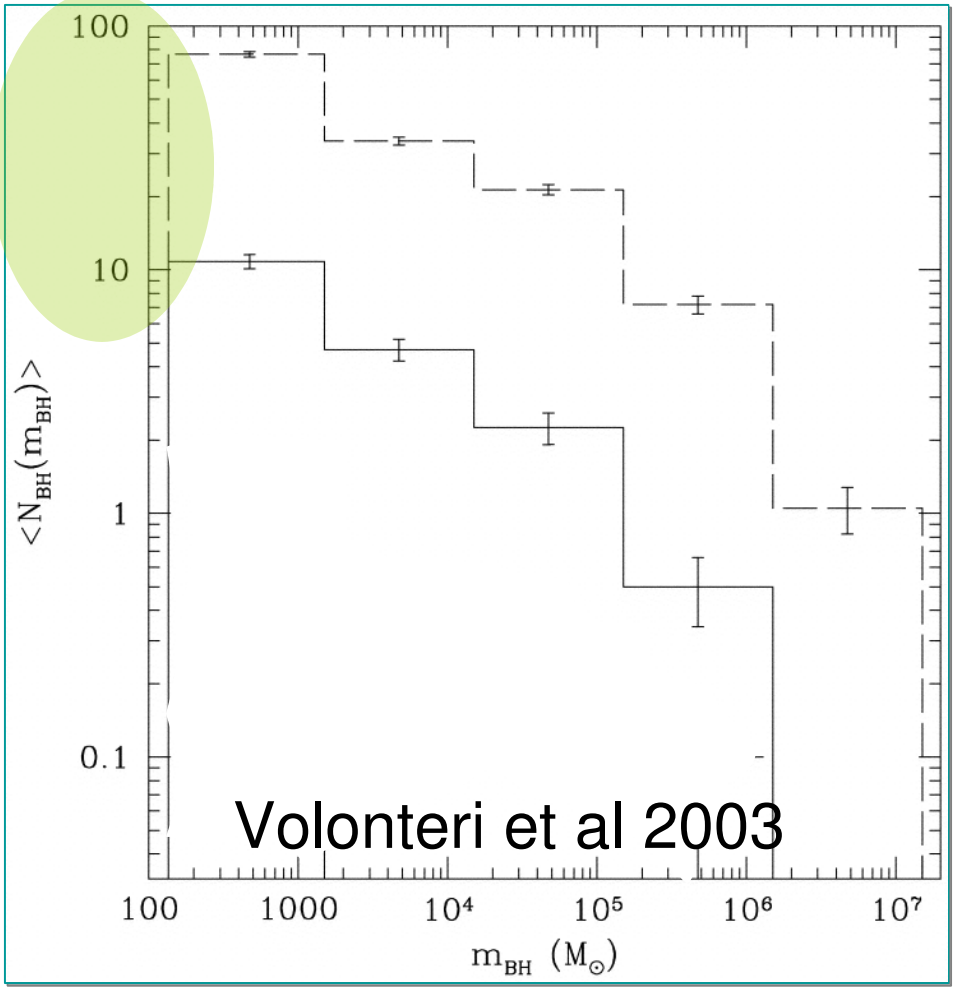
Halo BH

Primordial remnants - Numbers of IMBH

- Discrepancies in predictions
  - Depend on the assumptions of the model

Halo mass	***M*** **,seed**	***M*** **,seed**
	260 M	**1300 M**
1.6×10^{10}	88 ± 22	72 ± 16
1.6×10^{11}	330 ± 50	420 ± 70
1.6×10^{12}	1560 ± 550	1370 ± 340
1.6×10^{13}	1130 ± 100	1430 ± 310

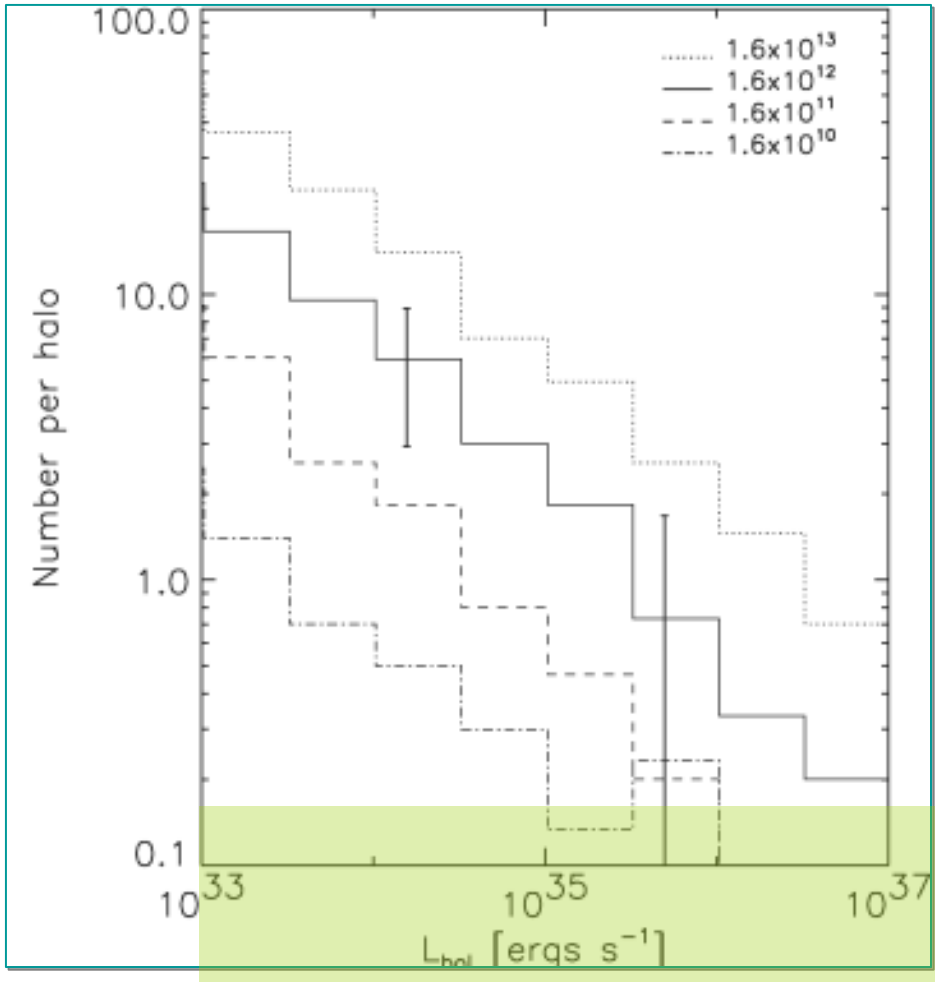
Islam et al 2003



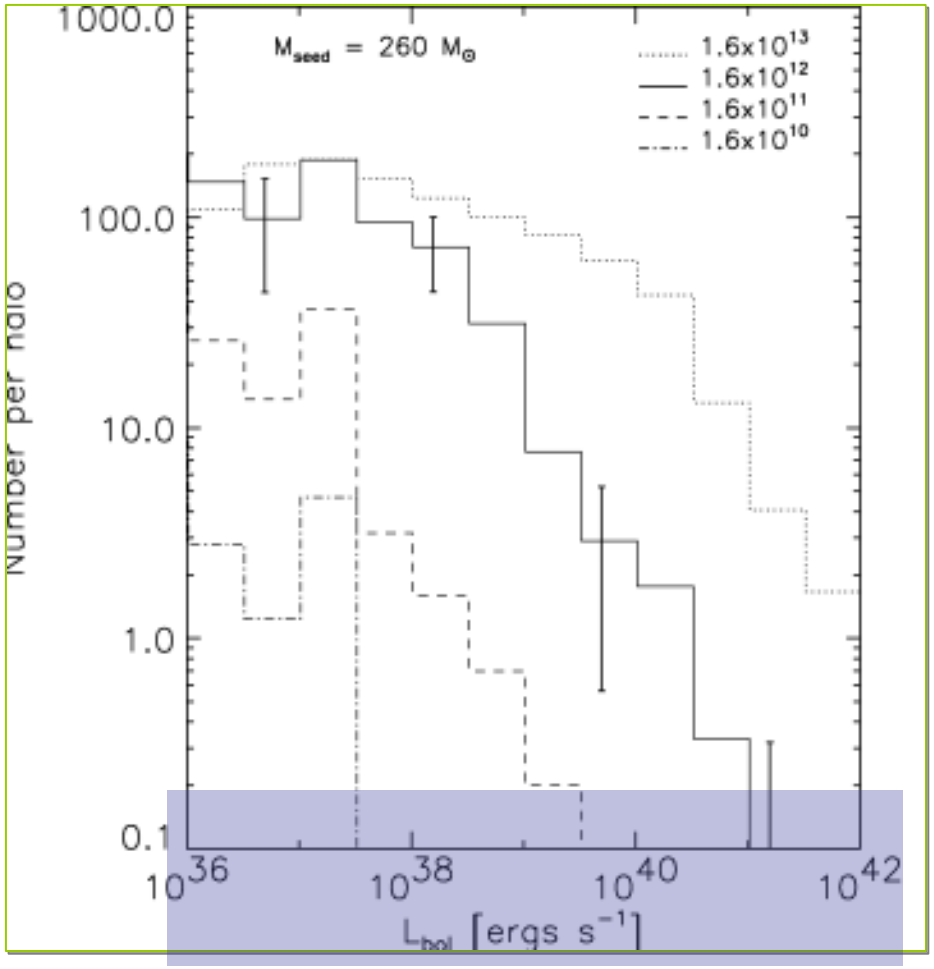
Luminosities of Halo IMBH

Islam et al 2003

- naked



- With baryonic core



ULX controversy

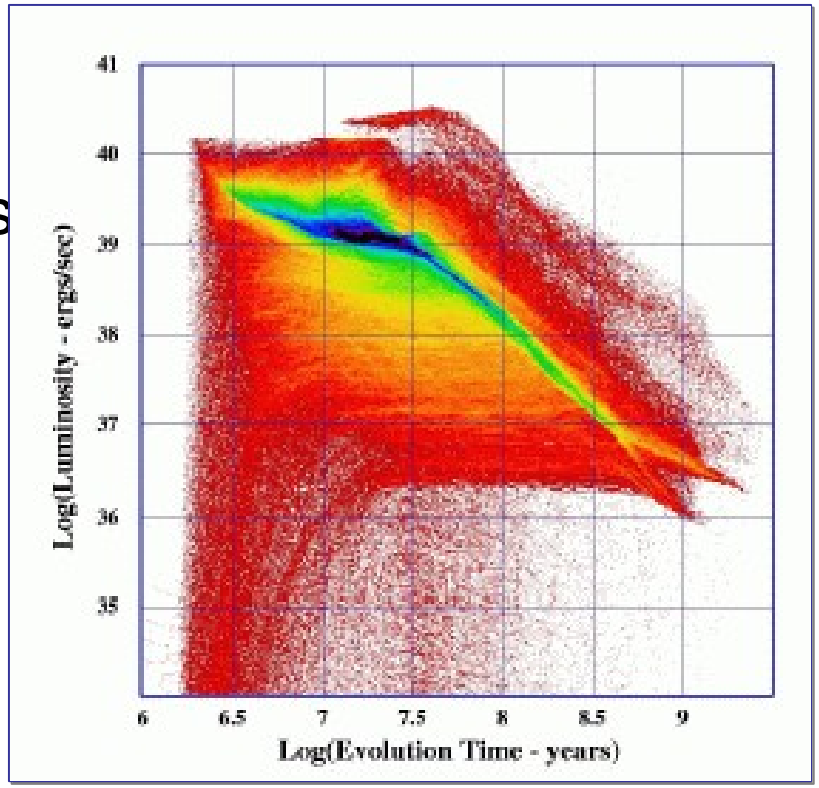
- Intermediate Mass Black Holes?
  (IMBH: 100 – 10^4 M)?
- Normal ‘stellar’ Black Holes?
  - Beamed emission at high accretion rates?
    King et al 2001
  - Relativistic jets?
    Koerding et al 2002
  - Super-Eddington accretion disks?
    Begelman 2002
  - Young rotation-powered Crab-like pulsars?
    Perma & Stella 2004

‘Extraordinary claims require extraordinary evidence’
(Carl Sagan, 1979; Broca’s brain, page 73)

ULX Luminosity -

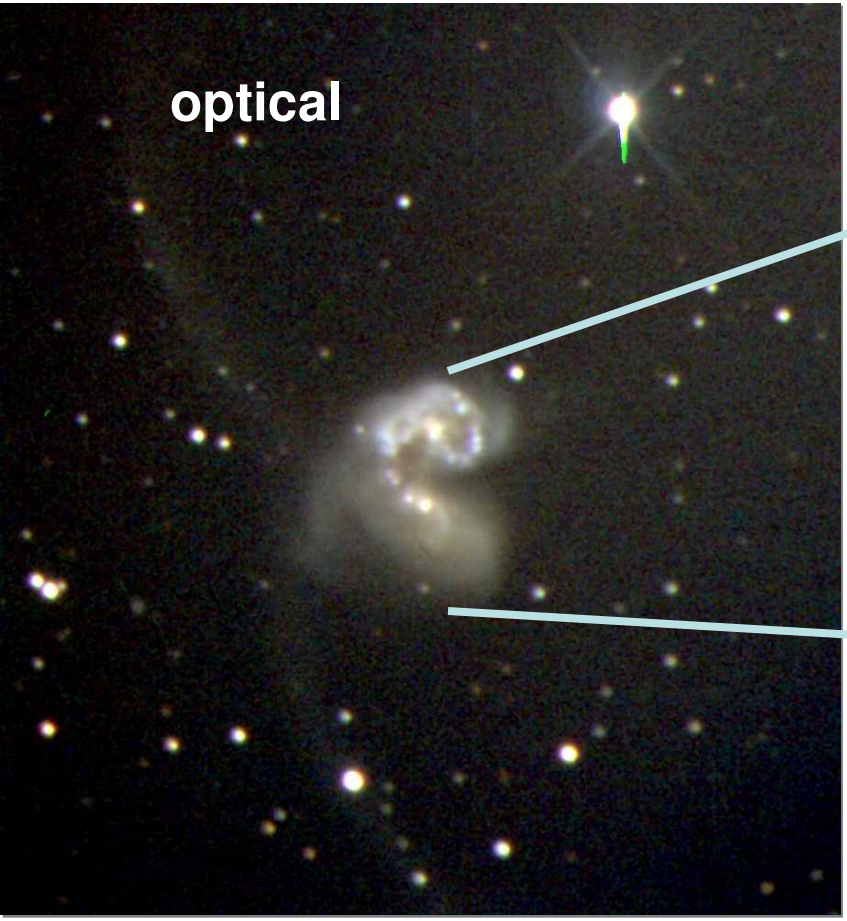
can be reached in stellar BH XRBs

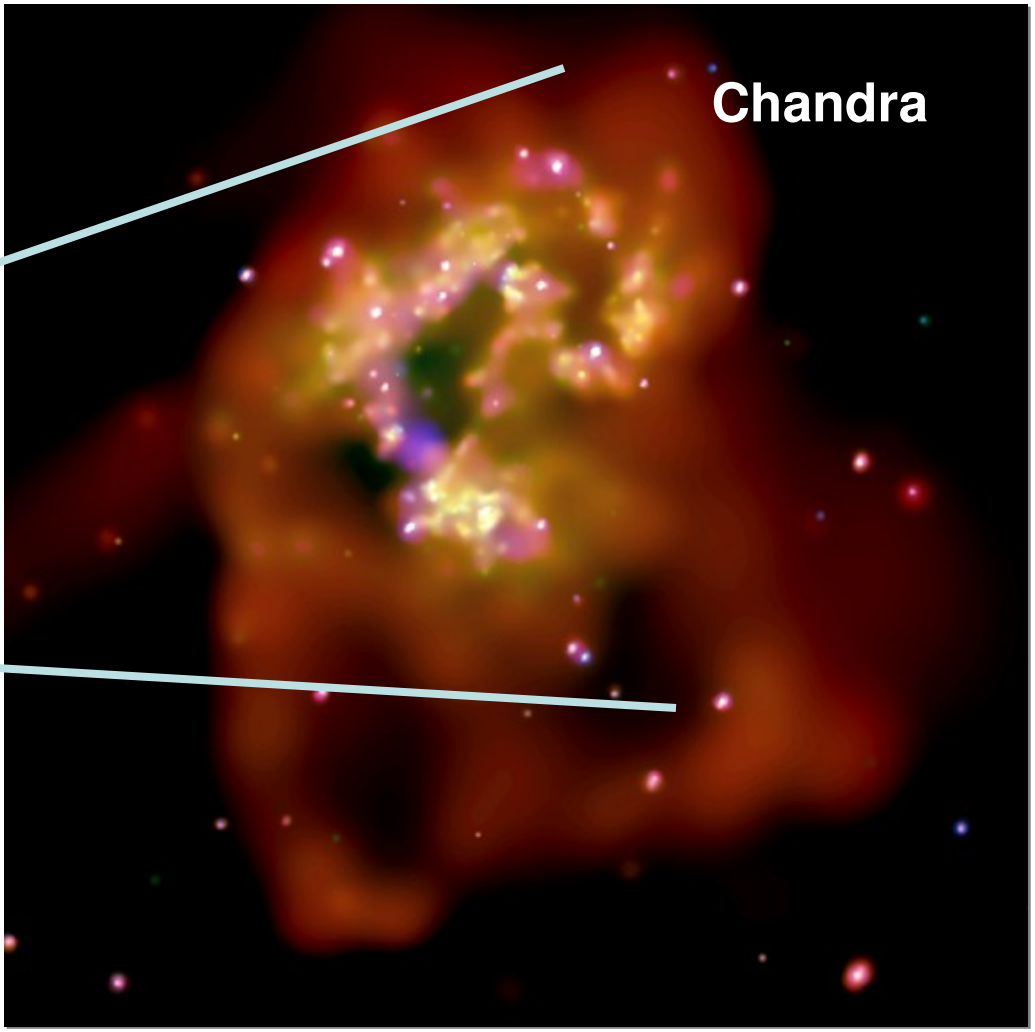
- ***Only*** **luminosities $L_x > 10^{40}$ erg/s *require* IMBHs**
  - Stellar evolutionary calculations produce ~30 (70?) M stellar BHs (Balczynski et al 2004)
  - Evolutionary calculations can produce luminous BH binaries (e.g. Rappaport, Podsiadlowski, Pfahl 2005)
  - Moderate beaming (King 2001) or super-Eddington disk emission (Begelman 2002)



ULX are mostly found in star-forming galaxies

14 ULXs in the Antennae

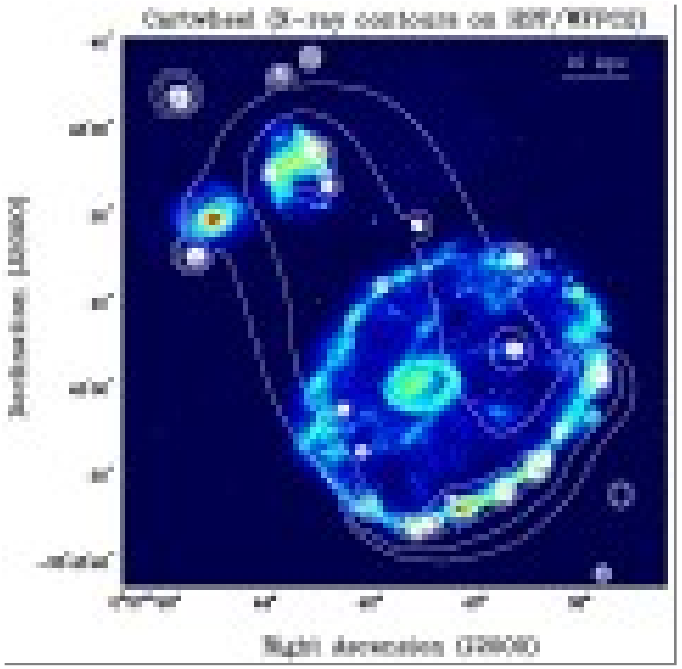


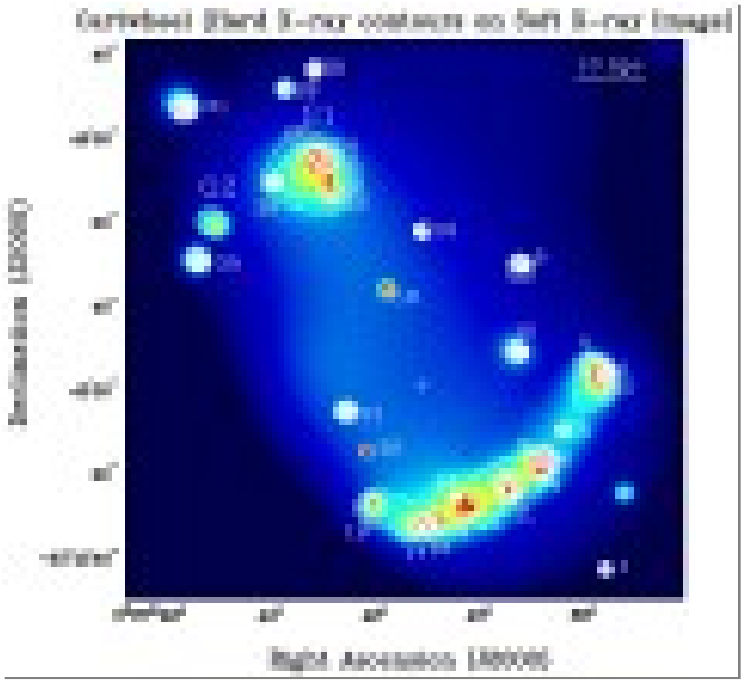


- Young systems or re-awakened IMBHs?

The Cartwheel ULXs

- ~20 ULXs (> 3 x 10^{39} -10^{41} erg/s) in the `ring' (Gao et al 2003)
- Most near but not coincident with Halpha knots
- Stellar ages < 10^7 yr
- … but D=122 Mpc (0.5'' = 300 pc)





A. Zezas & R. Kilgard

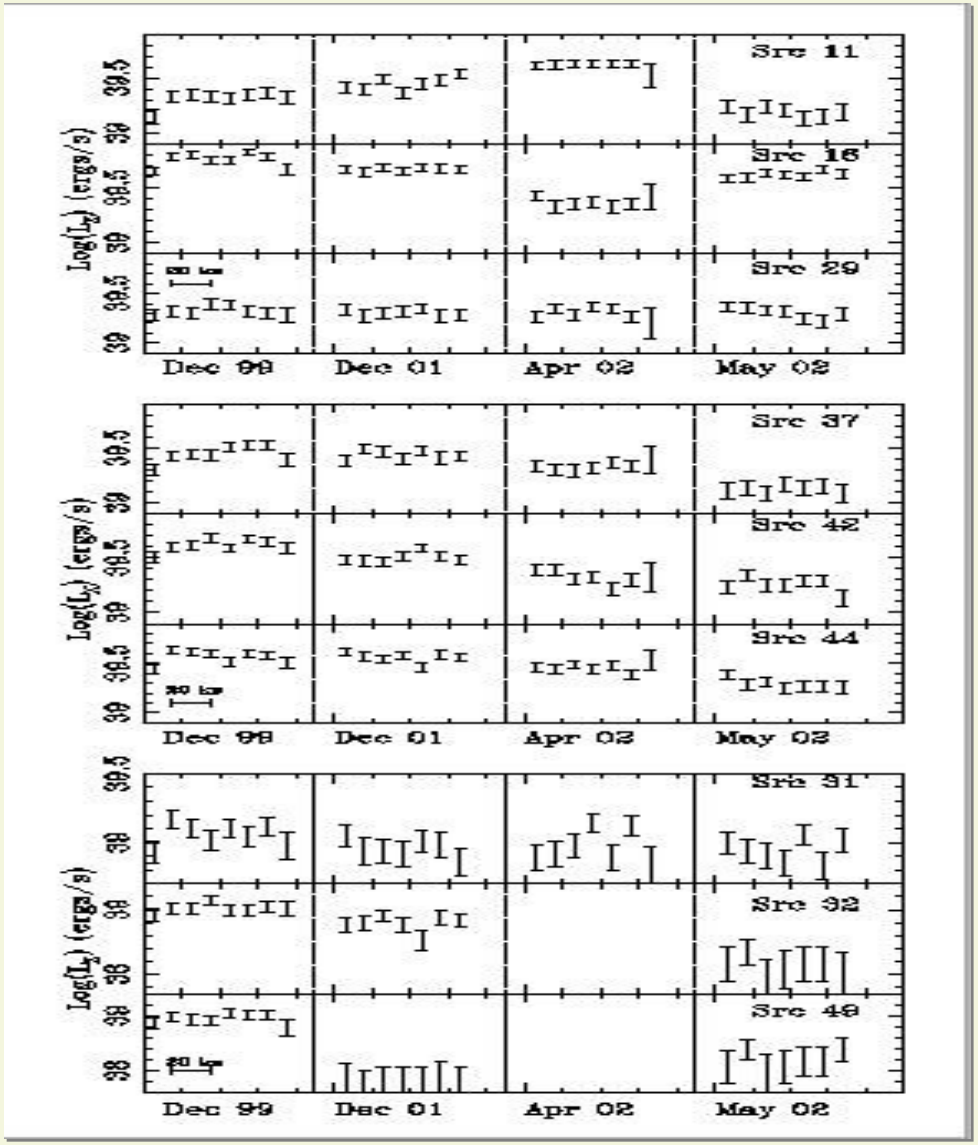
30”

- Variability and spectral variability
- Reminiscent of BH binaries
- Accreting systems

The Antennae: ULX –Variability

Fabbiano et al 2003

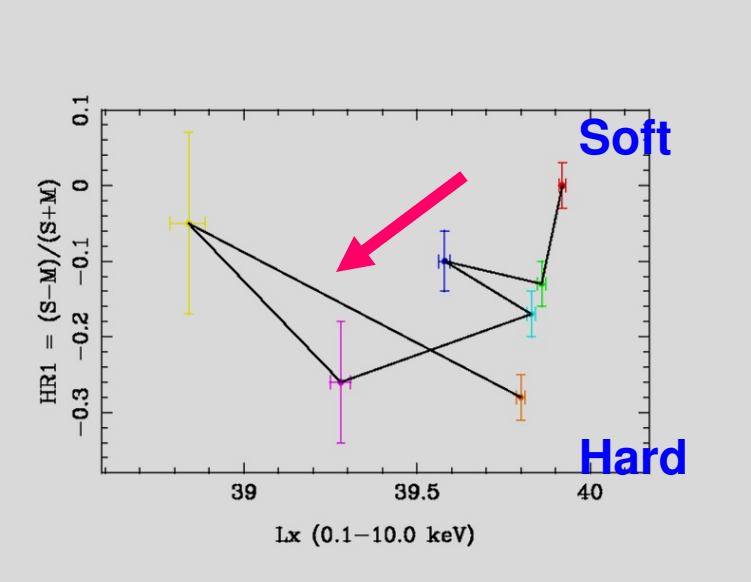
Light curves show bumps, dips, long-term trends

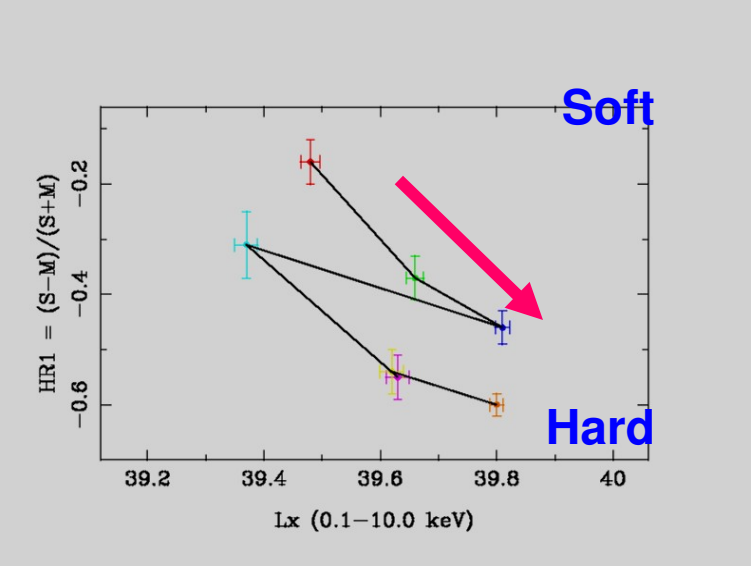


The Antennae: ULX –Variability

Fabbiano et al 2003

Instances of both hardening and softening with increasing LX can be seen in the same source

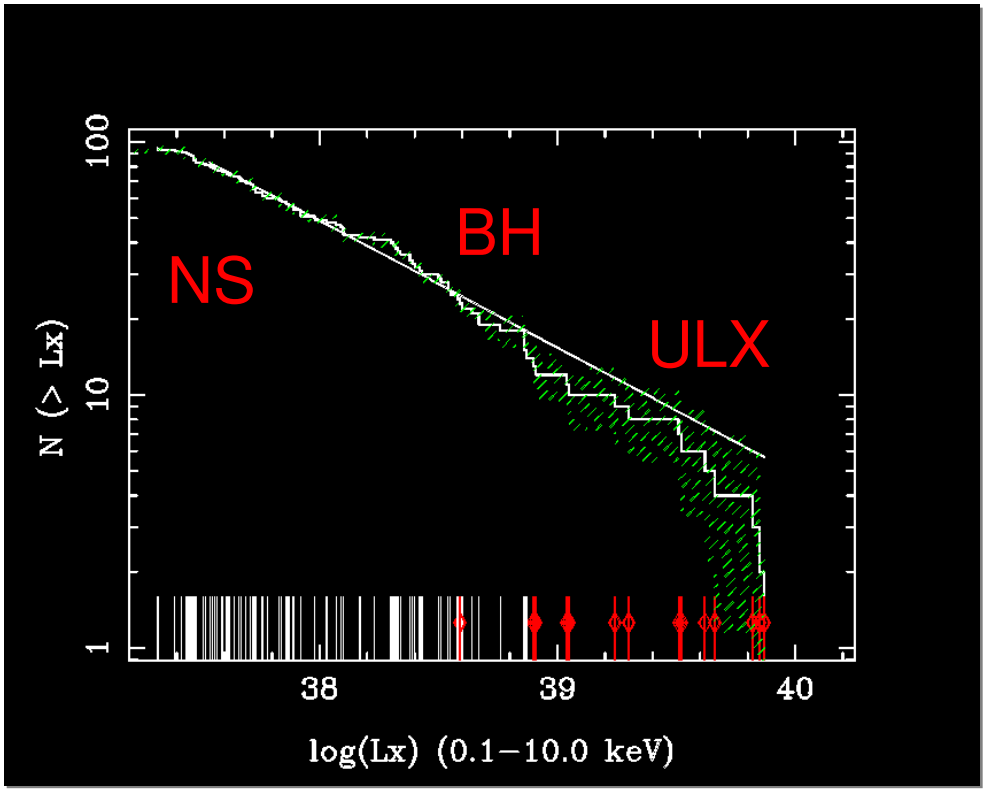




ULXs and X-ray binary populations

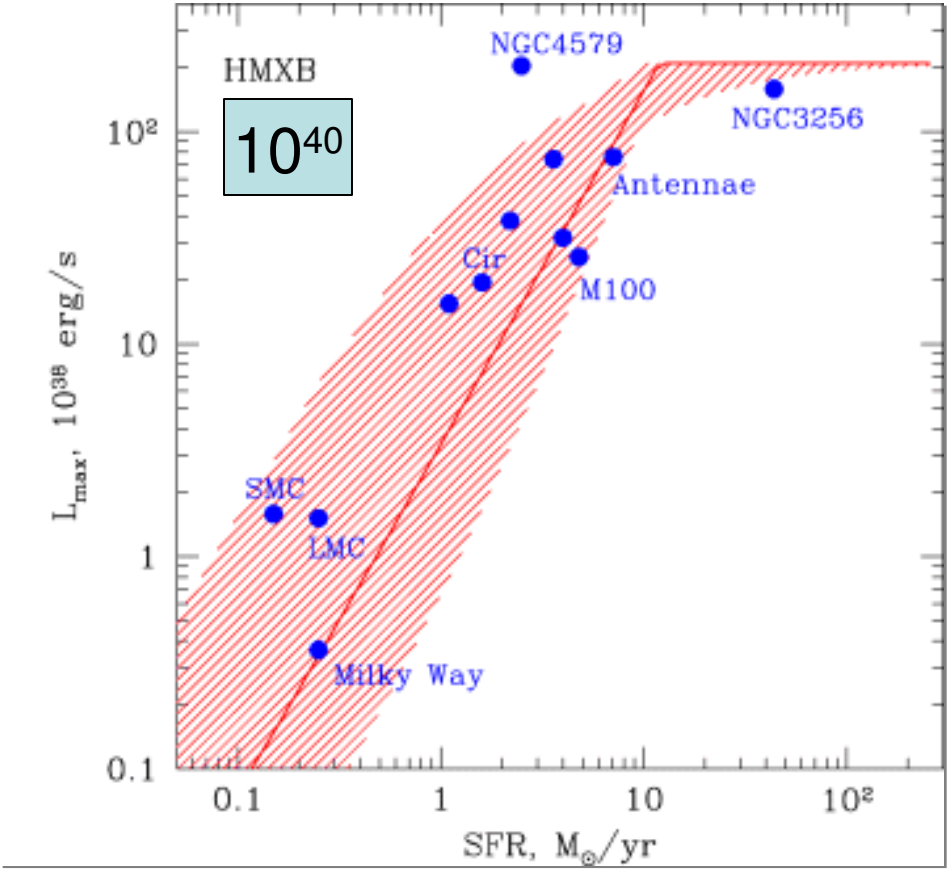
- ULXs do not appear to be a different XRB population in star-forming galaxies
- The larger the SFR, the larger the number of XRB and of ULXs (e.g. Grimm et al 2003)
  - E.g., The Antennae

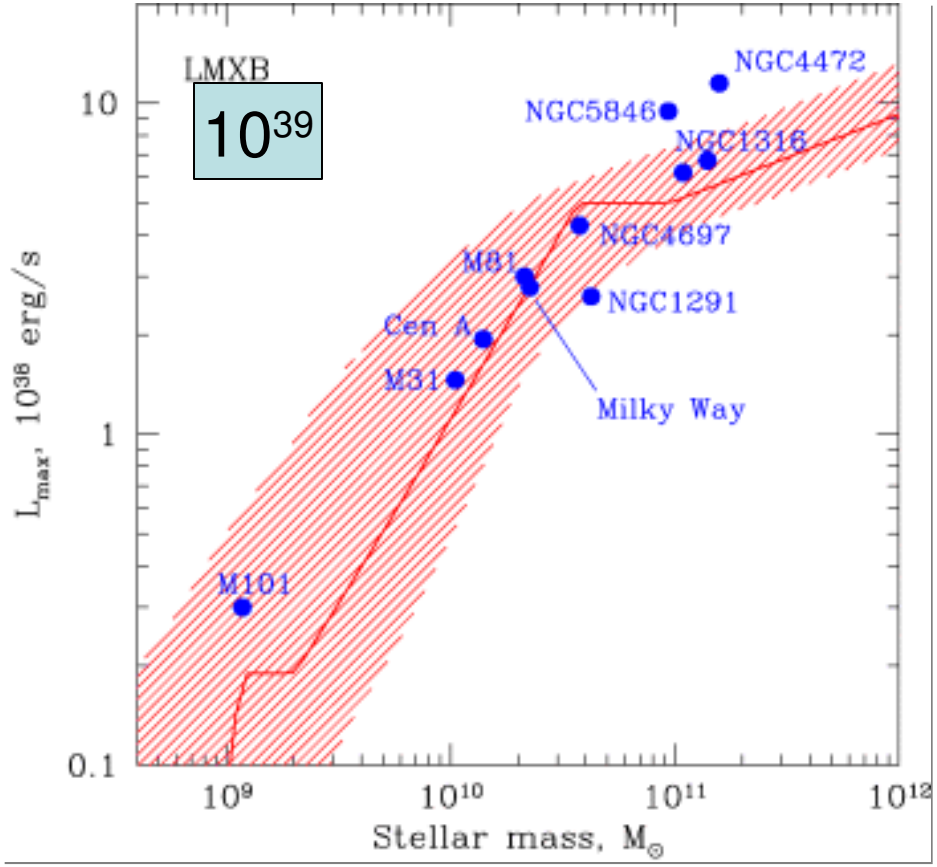
- In E galaxies, the larger the galaxy mass, the larger the number of high lum. Sources (Gilfanov 2004)



Highest L_X of XRB from XLFs

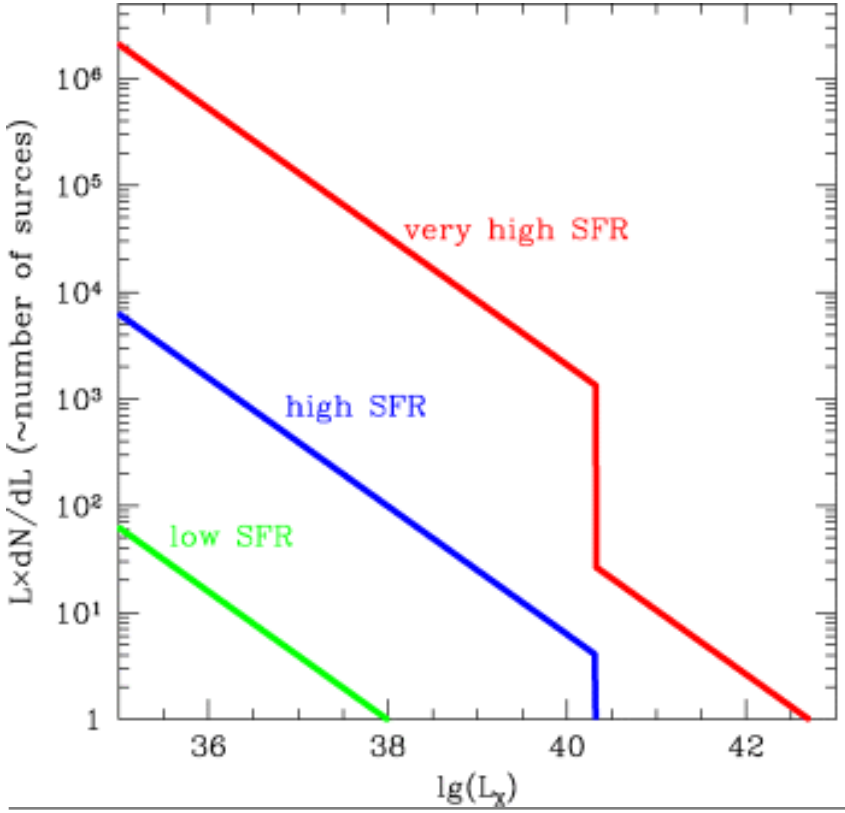
(Gilfanov et al 2004)

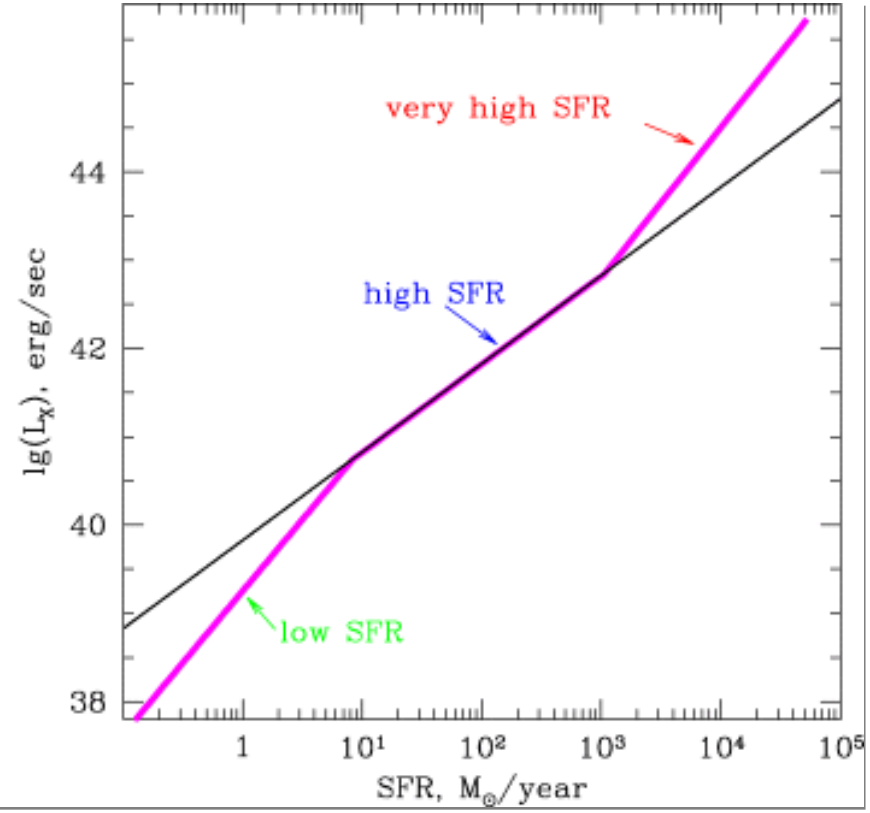




Effect of a population of IMBHs in the XLF and Lx-SFR

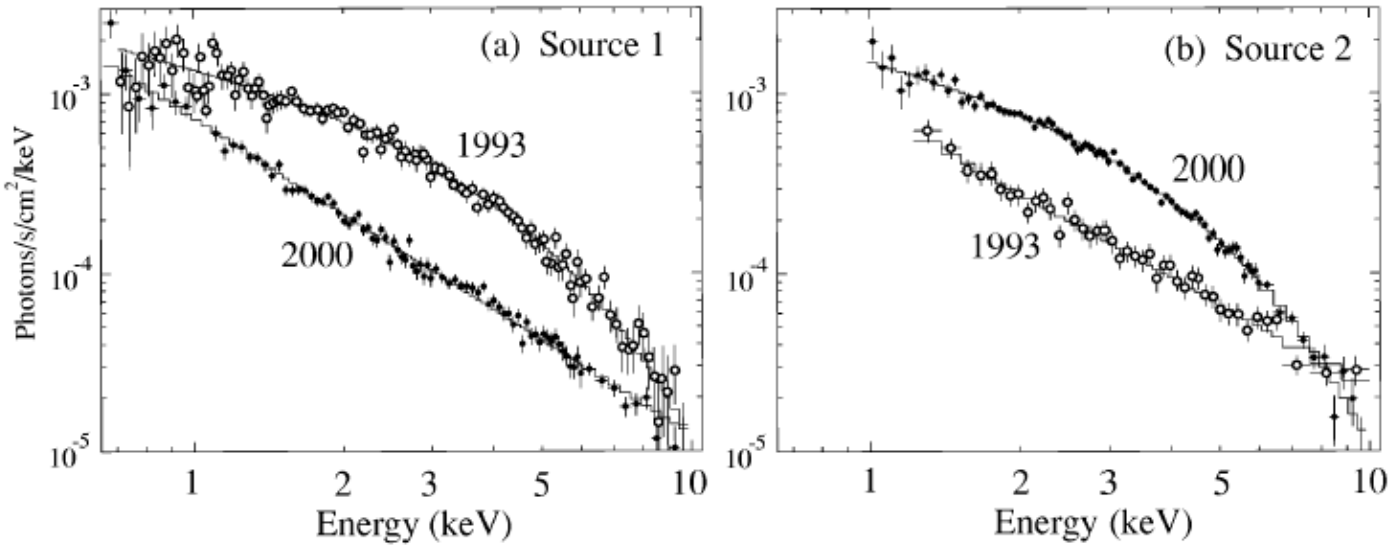
(Gilfanov et al 2004)





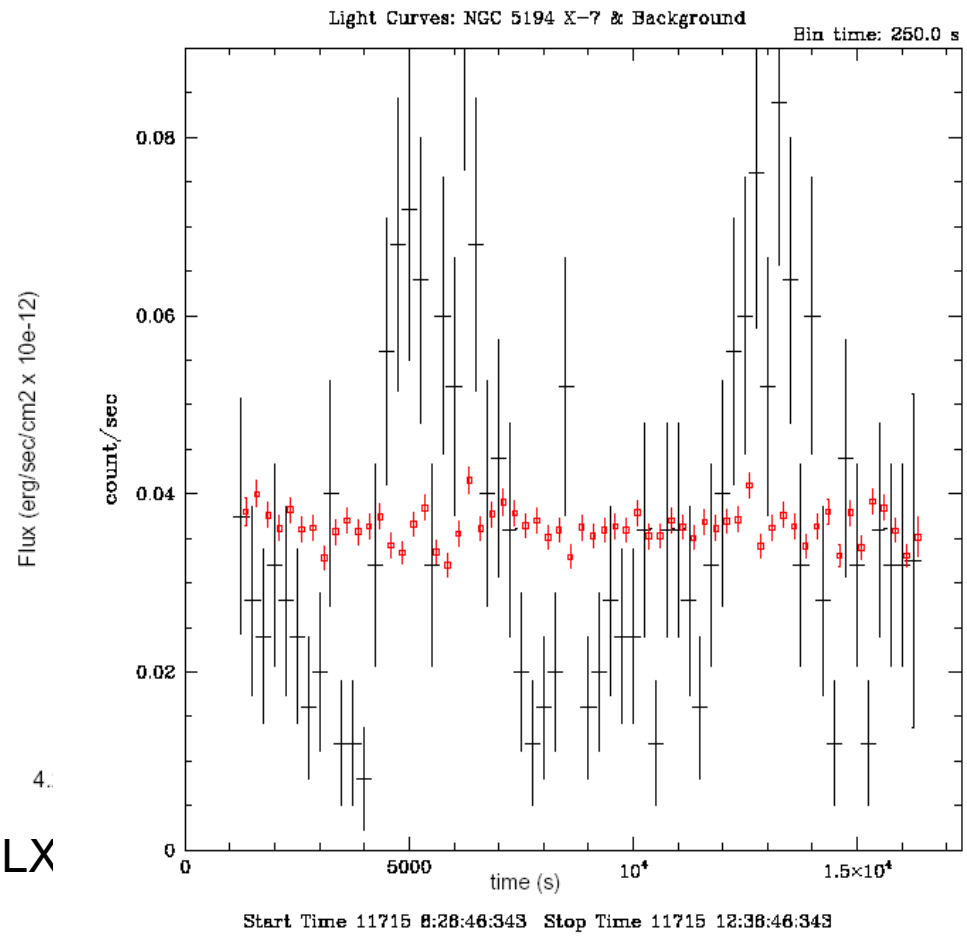
ULX Spectral Variability XRBs

- **High/soft – low/hard**
  - IC342 ULXs (*ASCA* – Kubota et al 2001)



ULX Variability Compact accretors

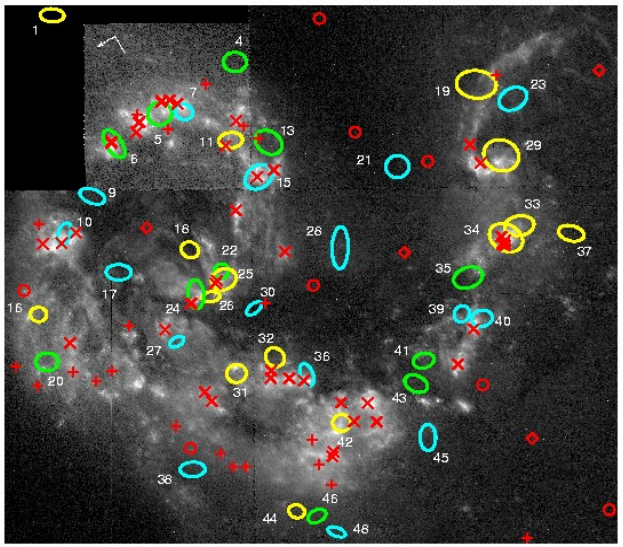
- M81 X-9
  (La Parola et al 2001)
  - years
- NGC5194 X-7
  (Liu et al 2002)
  - hours
- ULXs in M82
  - Months
  - 62 days period? (Karet 2006)
  - 54mHz QPO (Strohmayer & Mushot 2003)
    - But it may be associat with nearby variable ULX (Kaaret et al 2006)



The Antennae ULX are displaced from star clusters

(Zezas et al 2002)

10/14 ULXs (Ho=75/50) observed with Hubble WFPC2 have nearby (2") stellar cluster, but only 3 can be securely associated with a cluster



U-band HST-WFPC2 image

Yellow ellipses -- ULXs (Lx>10**39)

Green ellipses Lx~3x10**38-10**39

Blue ellipses Lx<3x10**38 ergs/s

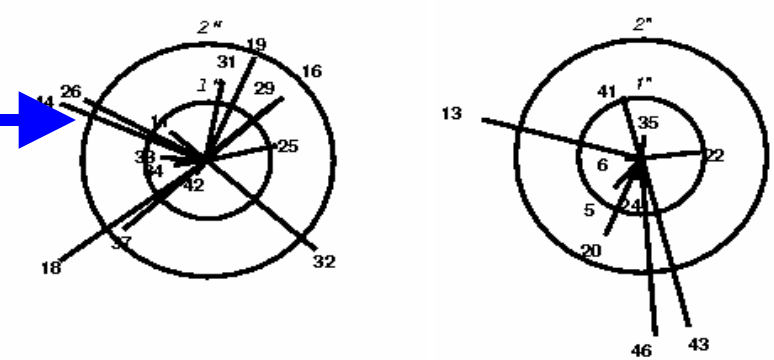
Red crosses -- young clusters (Whitmore et al 1999)

X -- intermediate age clusters

Diamonds -- globular clusters

Circles --foreground stars

Cluster offset -ULXs



ULX counterparts ambiguous evidence

- **IMBH?**
  - Ionized nebulae (NGC 1313 ULXs; M81 X-9; Pakull & Mirioni 2003)
  - Expanding molecular cloud around M82 ULX (Matsushita et al 2001)

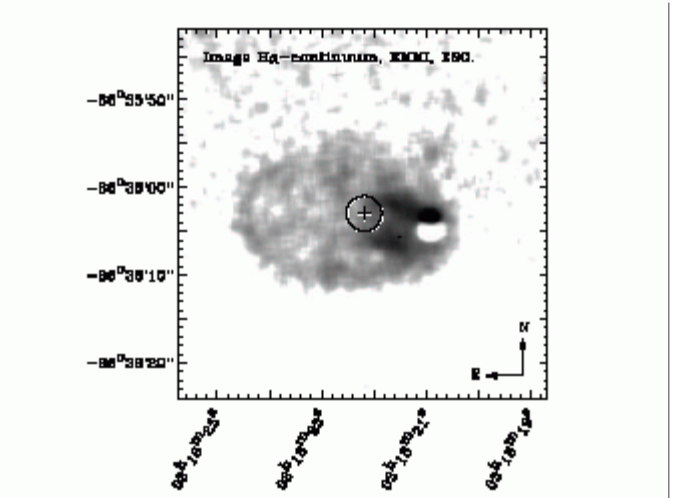
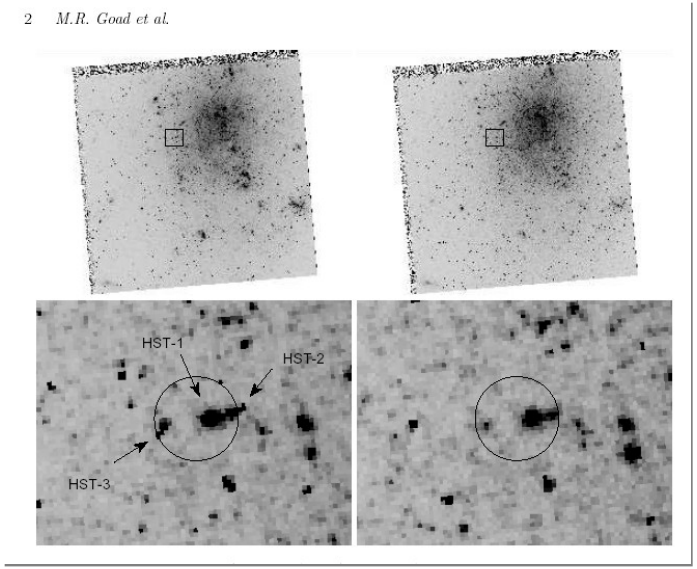


Fig. 3. The huge, 600 pc diameter Hα bubble around the ULX NGC 1313 X-2. The nebula expands with 80 km s^{-1} and is largely shock excited.

- **normal XRB; beamed?**
  - HMXB (in NGC5204, Goad et al 2002; in M81 X-1, Liu et al 2002)
  - Radio emission and SED of 2E1400.2-4108 in NGC5408
    - relativistic beaming, microquasar (Kaaret et al 2003)



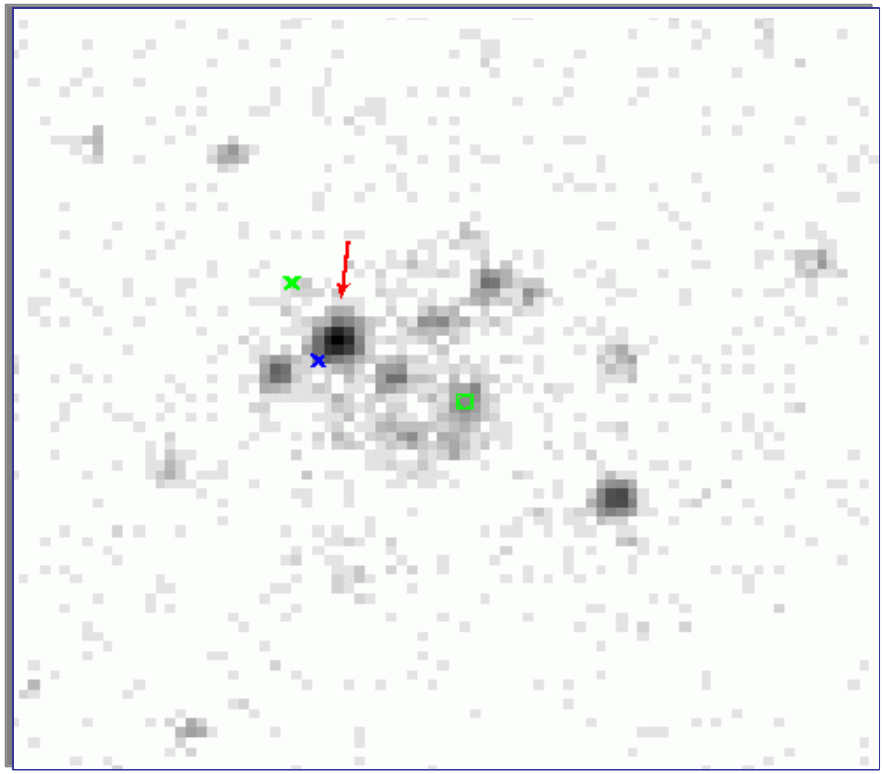
ULXs are rare in E galaxies

- Statistical argument (Irwin et al 2004)
  - Sources with $L_X > 2\ 10^{39}$ erg/s consistent with background AGNs
  - Fainter sources - high L_X end of LMXBs
- Theory predictions - Old population
  - ULXs if any are likely to be soft transients

  (Piro & Bildsten 2002; King 2002)

The eclipsing ULX of the E galaxy NGC3379

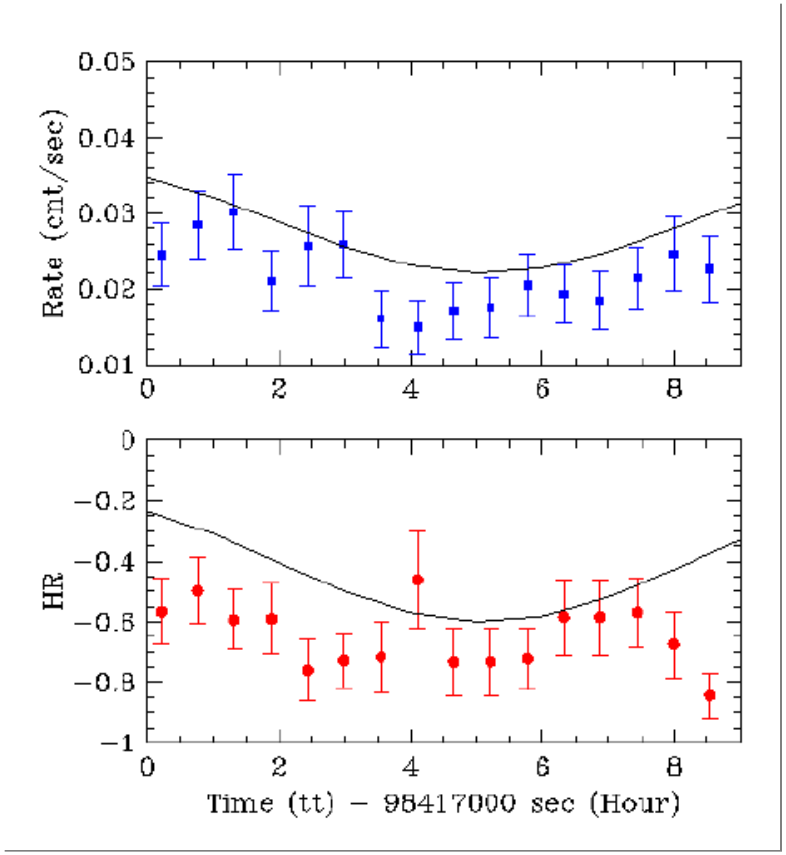
- Seen in 3 observations, each 5 yr apart
  - Swartz et al 2004
  - David et al 2005
  - Fabbiano et al 2006
- Similar flux (with factors of a few variability)
  - M_{BH}~30 M
- No GC counterpart
- No AGN counterpart
- Old stellar population

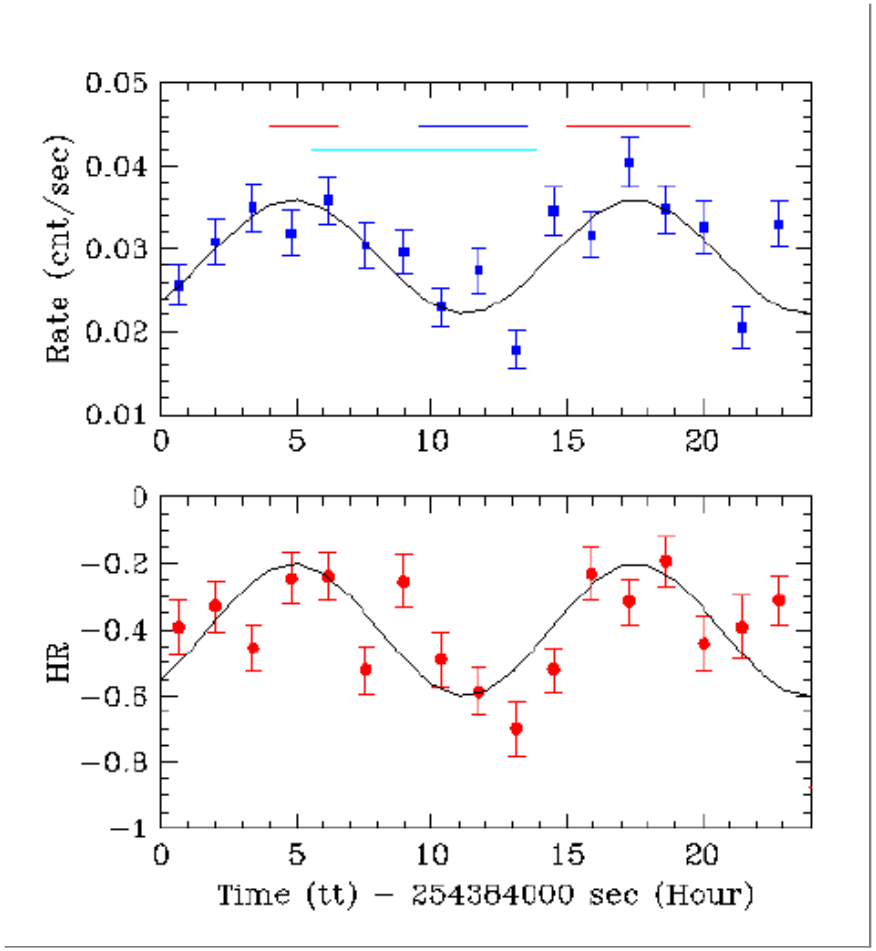


The eclipsing ULX of NGC3379

2001 2006

- Period ~ 12.6 hr
- Spectral variability - low/soft-high/hard





The eclipsing ULX of NGC3379

- Light curve
  - ADC (accretion disk corona) source?
  - but the dim/soft behavior is unusual
- Wind feedback model?
- Expected to be a transient
  - ON period 10yr so far
- Future planned observation will give good spectral variability information

Is there a ULX accretion disk IMBH?

- **The ASCA spectral conundrum**

$kT_{in} \sim 1.2\ keV\ (M / 10M_{\odot})^{-1/4}$

spectra too `hot'

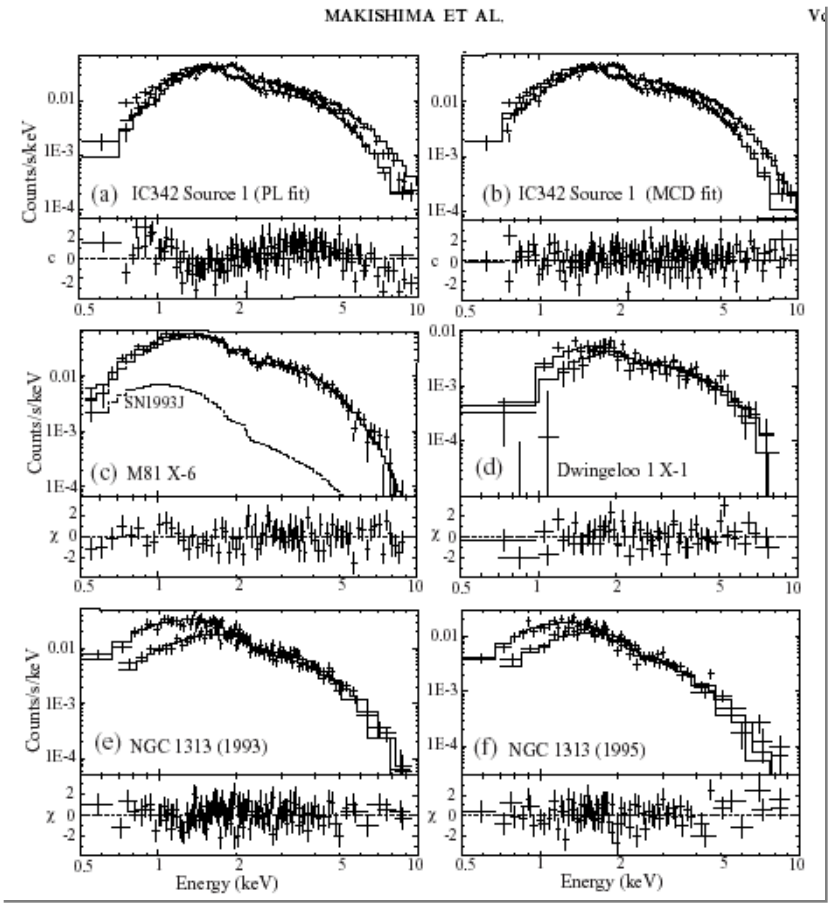
kT ~ 1.5 keV

Consistent with stellar BH

Discrepant with luminosity

(Makishima et al 2000)

Kerr BH?

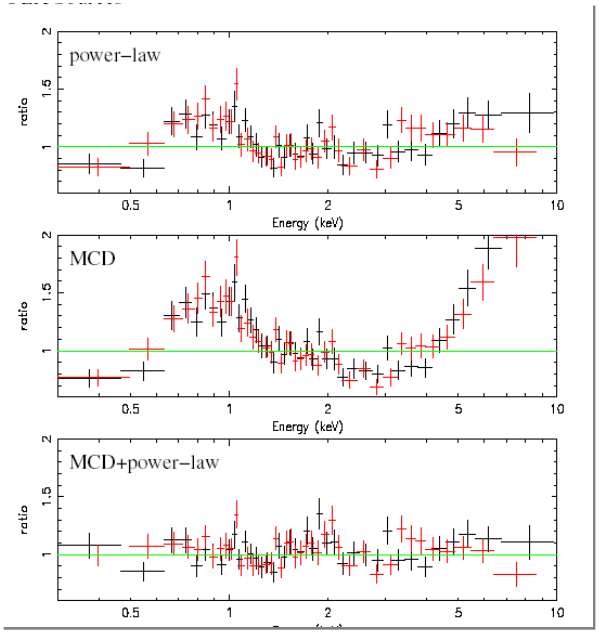


Is there a ULX accretion disk IMBH?

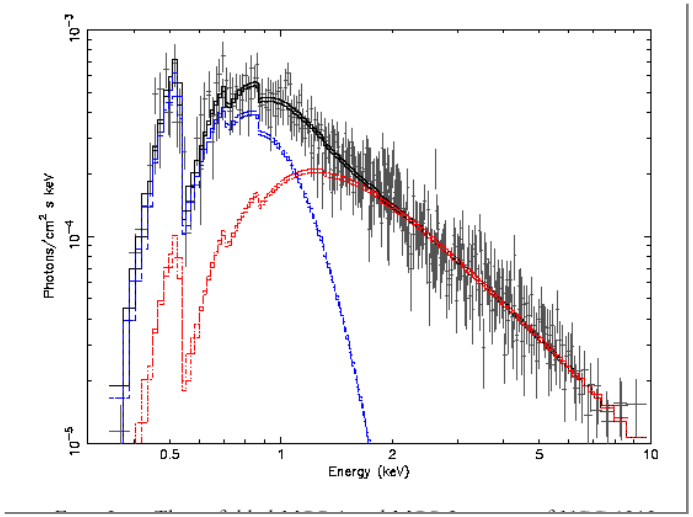
- Accretion disk temperature

$$kT_{in} \sim 1.2\ \text{keV}\ (M / 10\ M_\odot)^{-1/4}$$

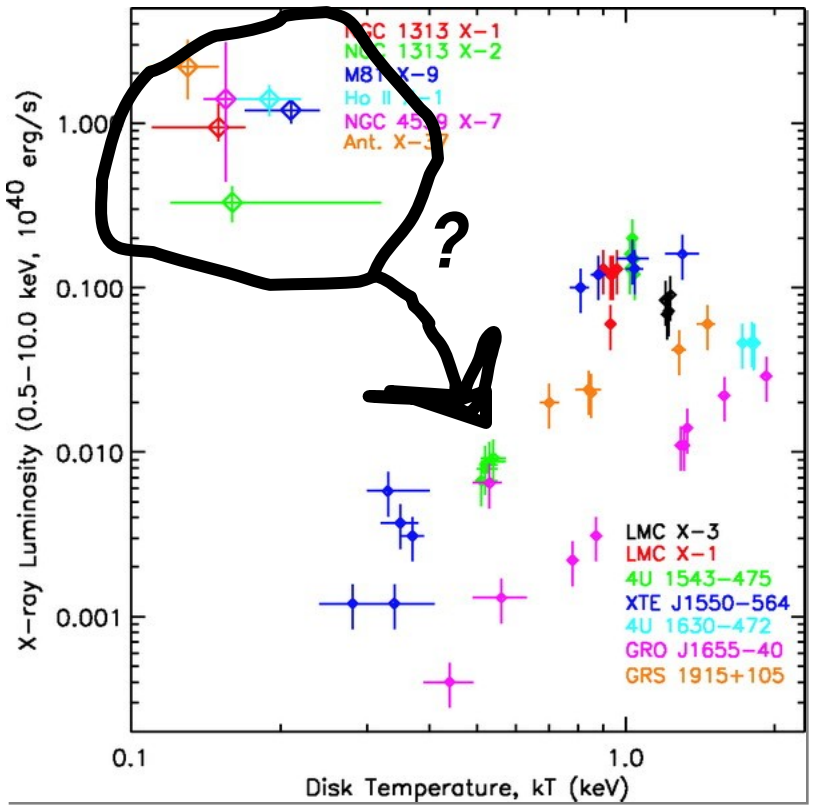
100-1000 M IMBH --> kT ~ 700-400 eV



- Soft components are found
  - (kT ~150 eV; e.g., Miller et al 2003 in NGC 1313)
    IMBH
- **But these components are crucially dependent on the assumed spectral model**



Do we have the right spectral model?



Miller, Fabian & Miller 2004

- Spectra consistent with Stellar Black Holes for
  - Ken Ebisawa's slim disk model (advection dominated)
  - Chris Done's comptonized disk model

A cautionary tale: the SSS ULX of M101

- Discovered by Mukai et al 2003
  - Expanding BH photosphere
- + power-law and low/hard-high/soft variability
  - Comptonized accretion disk
- IMBH (power-law+accretion disk model)?
  - Kong et al 2004(L_X ~ 10^{41}erg/s, but high N_H)
- 20-40 M (Mukai et al 2005)
  - Accretion disk + line model
  - Colors of optical counterpart exclude high absorption

ULXs the facts

Variability
Spectral variability
XRB accretion disk
No information on mass!

Luminosity
Only Lx $\geq 10^{40}$erg s^{-1} require IMBHs

Environment
Star-forming galaxies
Rarely Ellipticals

Soft spectral components
Model dependent

X-ray Luminosity Functions (XLF)
High L_X extension of high mass XRB XLF

Counterparts
Ionized nebulae
high intrinsic L_X
OB star or disk
No stellar cluster

ULX
a single umbrella for different phenomena?

Iron-clad solution?

- Find optical star and follow up with measurement of mass function (as for Galactic BHs)

$$f = PK^3 / 2\pi G = M \sin^3 i / (M_p / M + 1)^2 < M$$

where P= orbital period

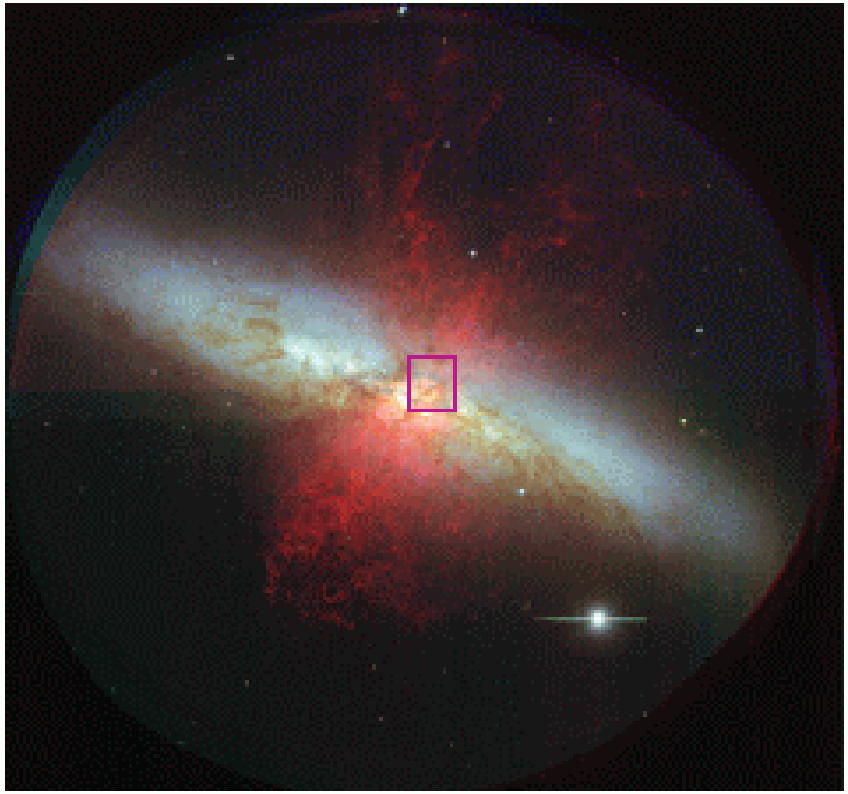
K= 1/2 amplitude of change in radial v

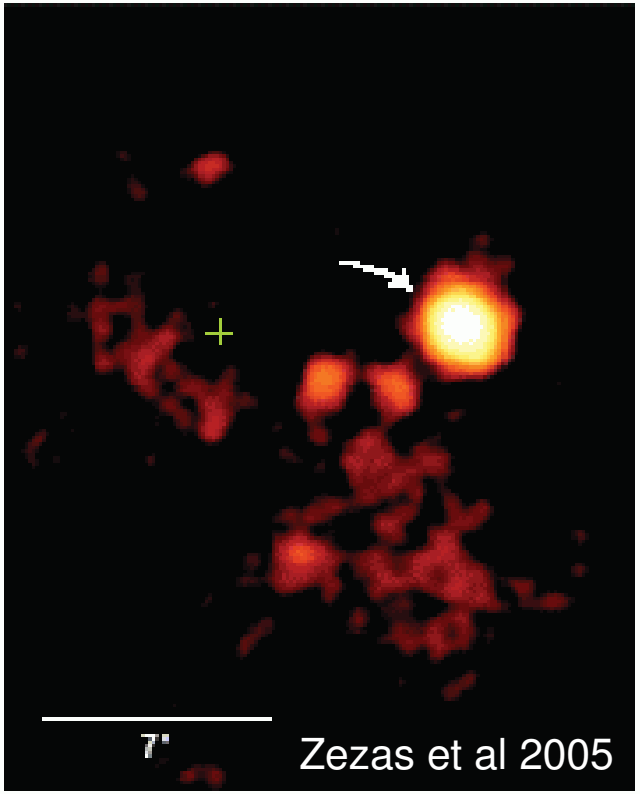
M_p= mass of star with known spectrum

M = mass of BH

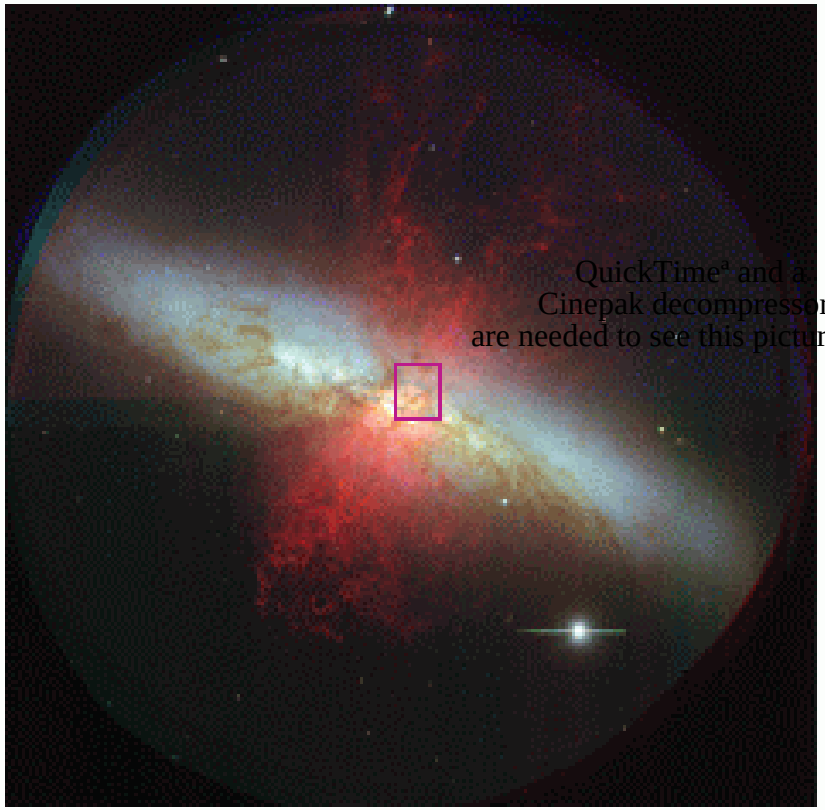
Will need future very large area and high resolution optical telescopes

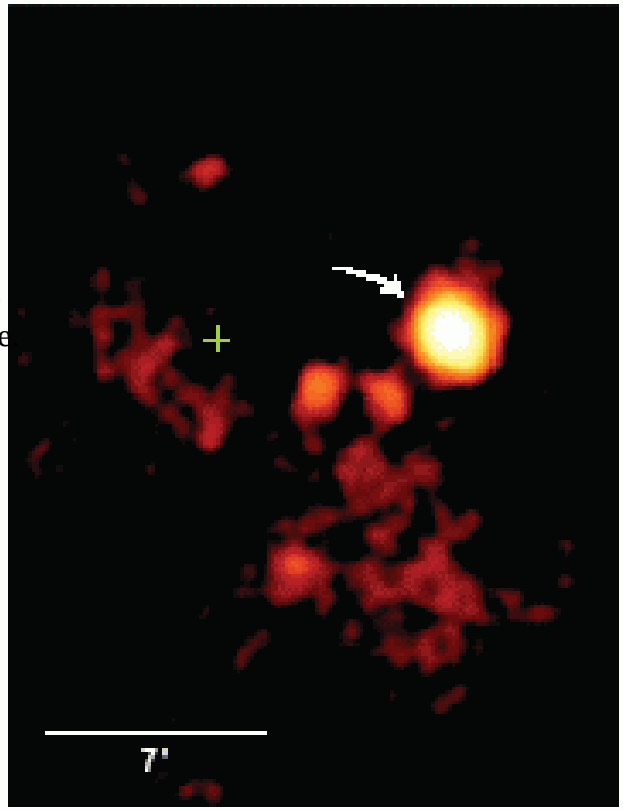
M82 ULX: the best IMBH candidate





- $L_X > 10^{41}$ erg s^{-1}
- Displacement from nucleus limits mass to < 10^5 M (Kaaret et al 2001)
- QPO 0.05 - 0.1 Hz - accretion disk and possibly 100-1000 M (Strohmayer & Mushotzky 2003) but may not be in this ULX (Kaaret et al 2006, astro-ph)
- Report of a binary period of ~62 days (Kaaret et al 2006)





Zezas et al 2005

Galaxy evolution in X-rays

X-ray population synthesis

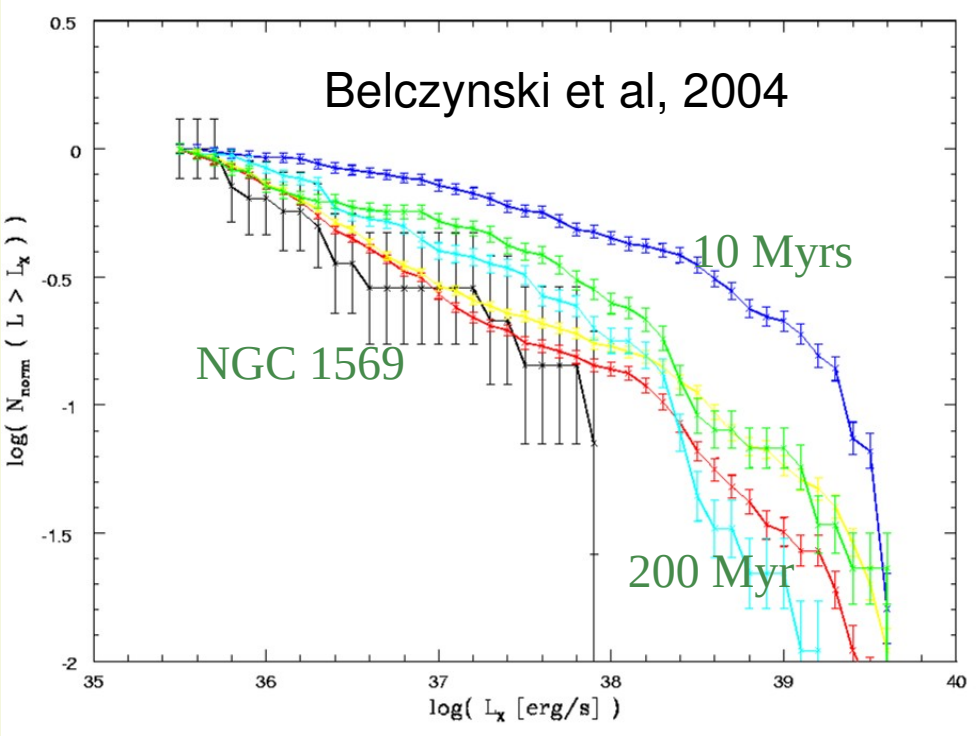
Evolution with red-shift

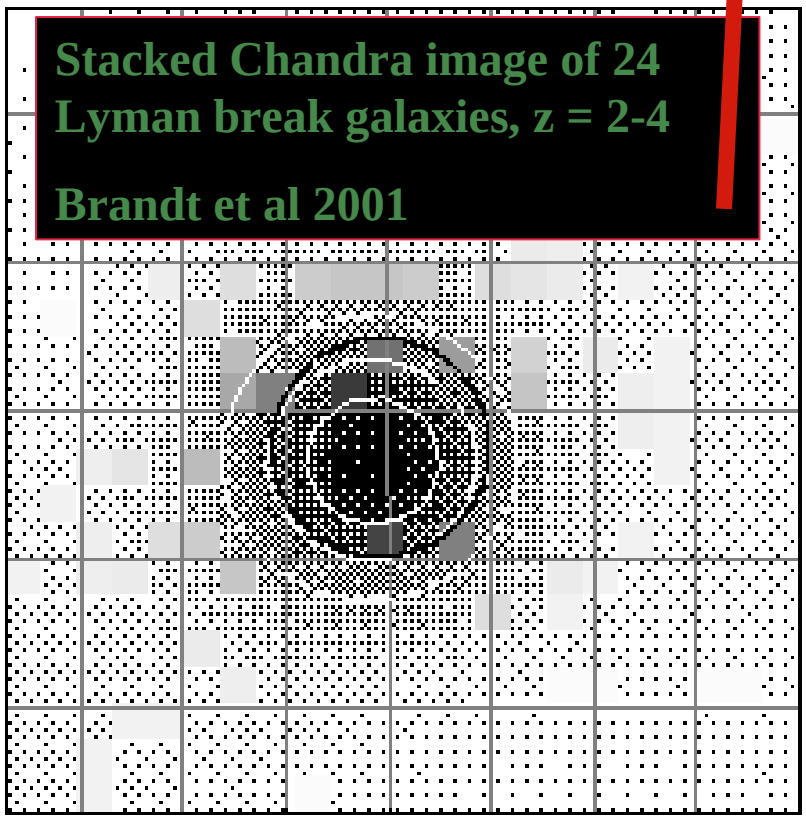
X-ray population synthesis

Synthetic X-ray Luminosity Functions
e.g. Vicky Kalogera's work

Comparison with high z galaxies
they're there, modelling will come

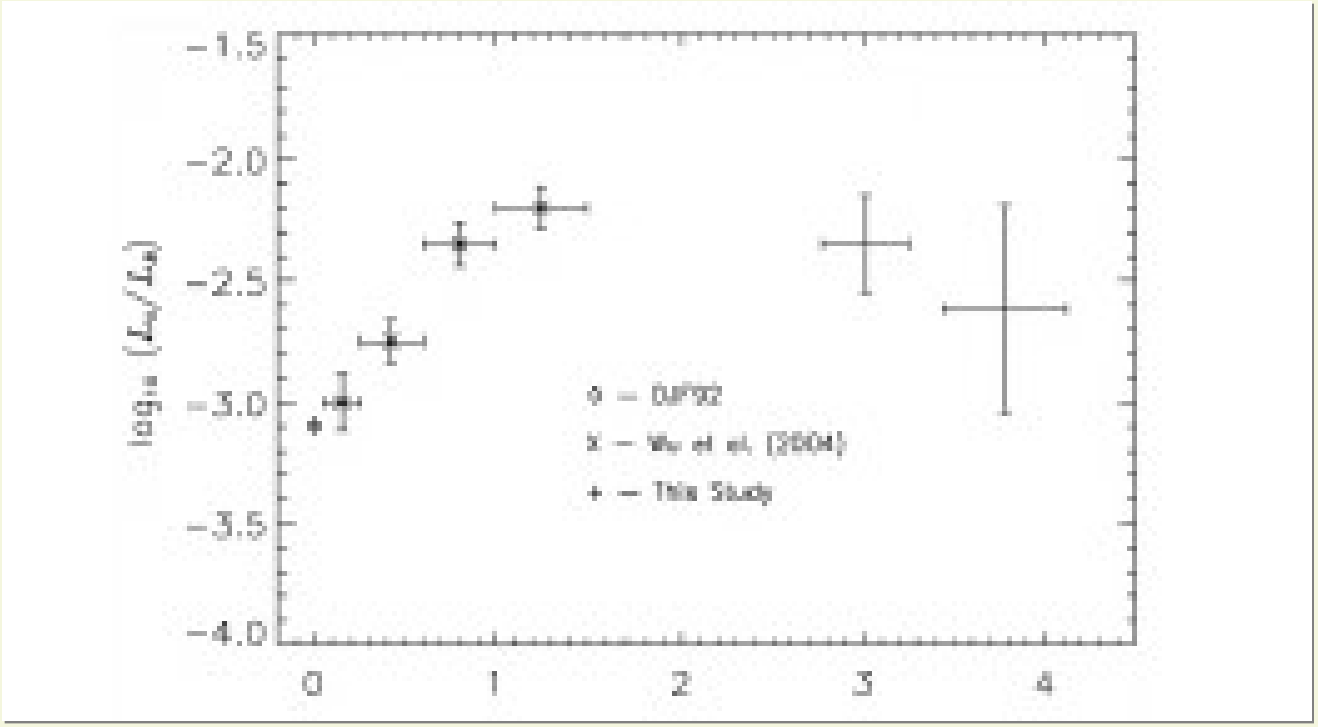
- **We need the next generation of X-ray telescopes to really study them**
- **X/B > nearby galaxies (e.g. Shapley & Fabbiano 2001)**





Evolution of L_X/L_{opt} with z

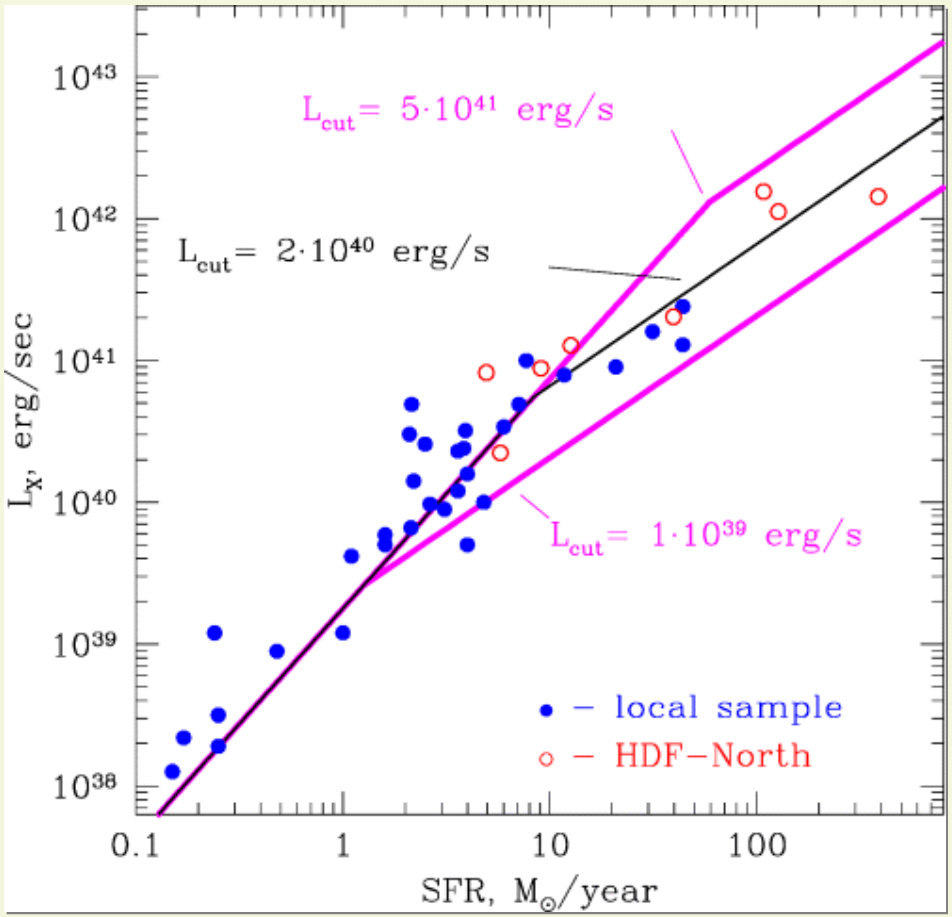
Lehmer et al 2005



redshift

Maximum L_X of HMXB

(Gilfanov et al 2004)



but small

What's next?

Chandra is beautiful, but small (0.1 sqm area)

Very deep exposures are needed
e.g. 410 ks images of the Antennae

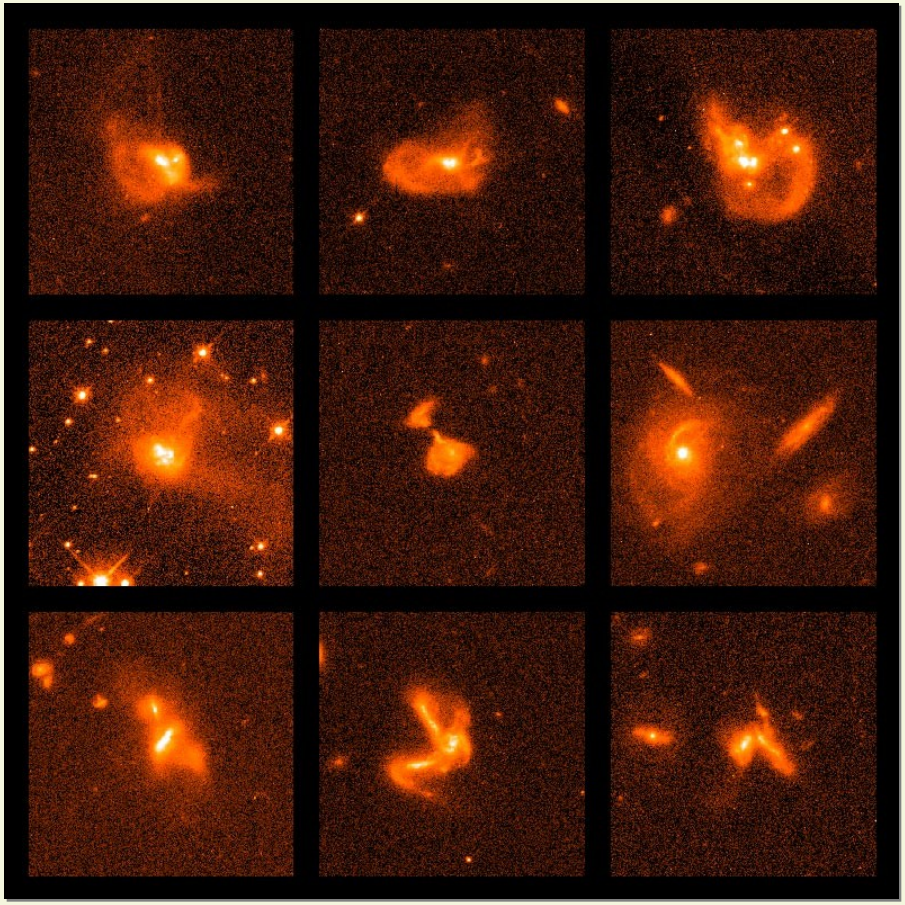
Post

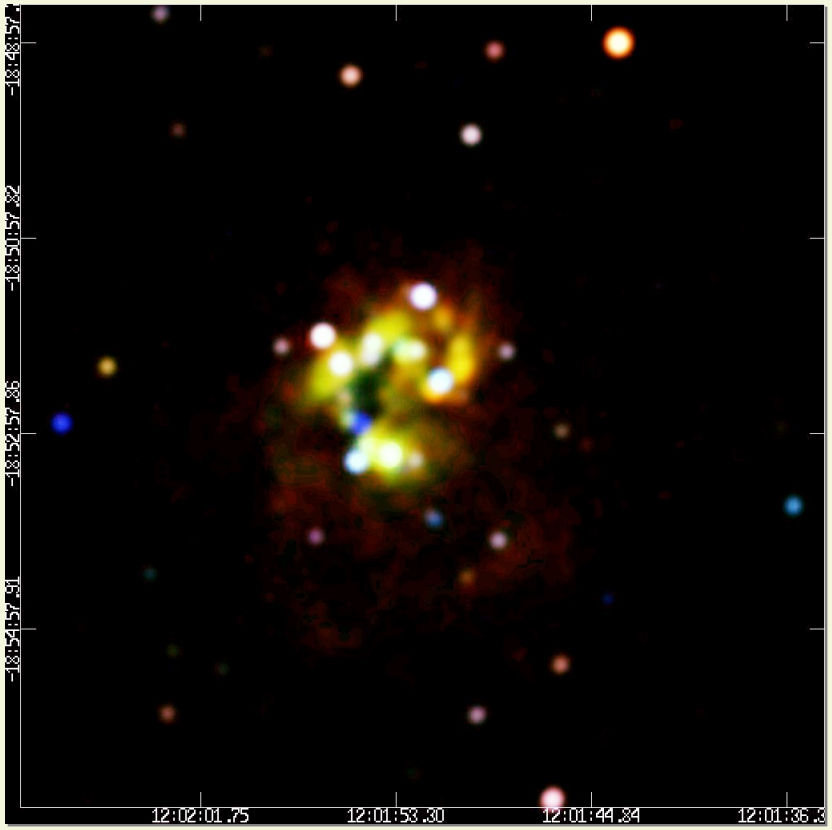
We need to preserve high angular resolution (~ 0.1")

And increase the collecting area (~100 sqm)

Generation-X NASA study

Looking Ahead: Studying galaxy evolution in X-rays – *Gen-X*





What do the Ly break galaxies look like?

The Antennae at z=1 with 0.1” res. and 100sqm area

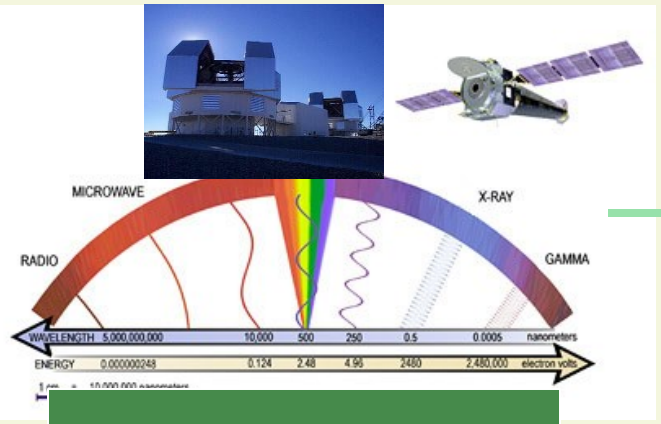
The Virtual Observatory

To exploit fully the data archives

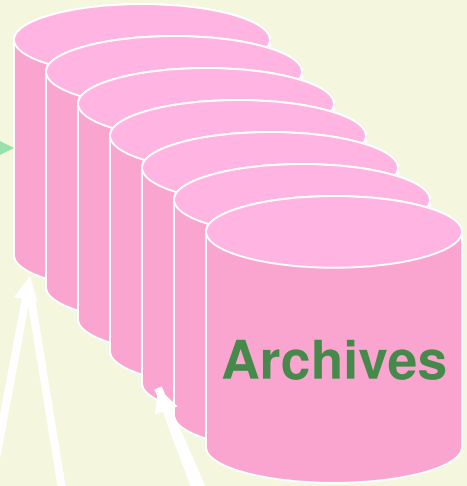
To give access to tools and simulations

To simplify multi-instrument studies

The Present Archival Paradigm



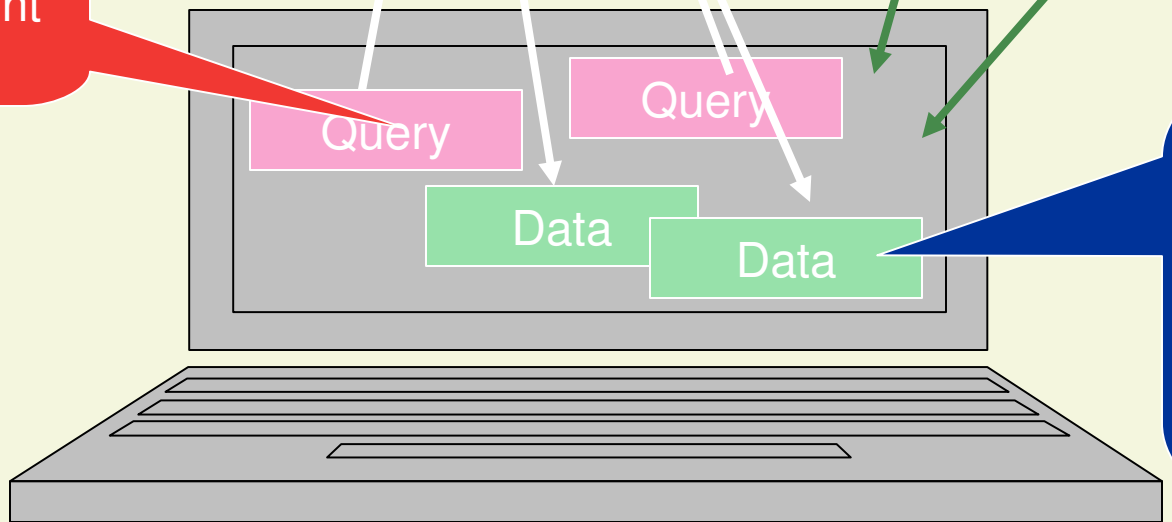
Observatories
Radio – γ rays
Ground and Space



Theory and Simulation

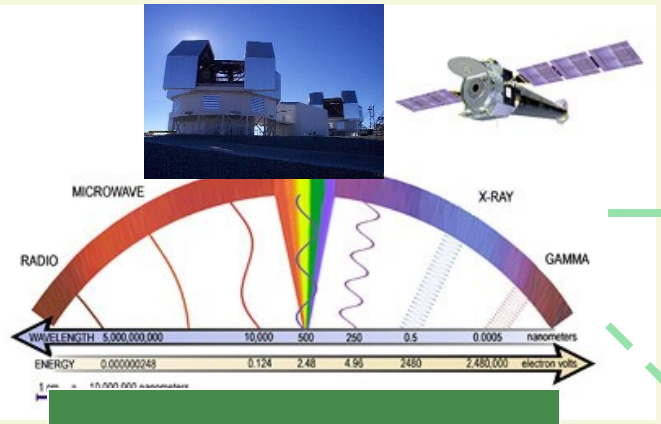
Literature ADS

Each archive has a different interface



Different software tools needed for each dataset

The Virtual Observatory Paradigm



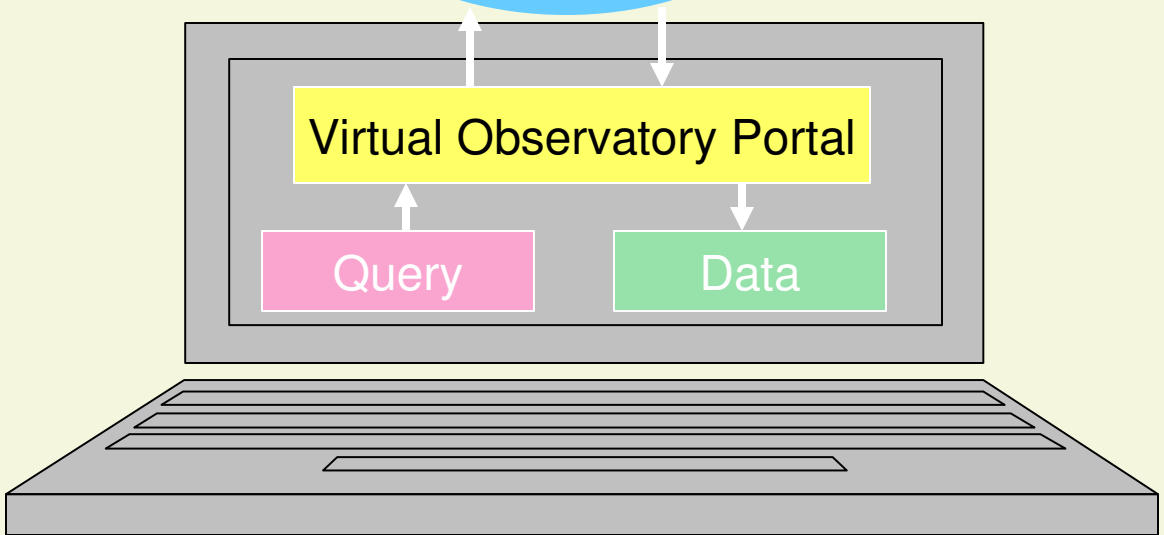
Observatories
Radio – γ rays
Ground and Space

Archives

Theory and Simulation

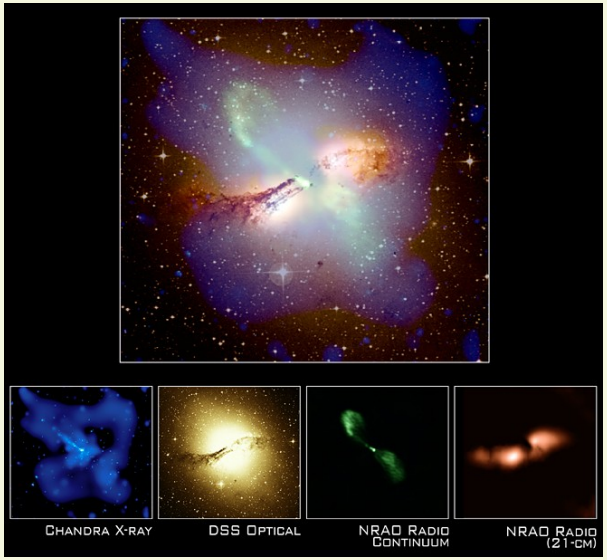
Virtual Sky
Archival Data
Simulated Data
Realtime Data

Literature
ADS



Multi-wavelength Astronomy

Give access to the multi-wavelength data accumulated world-wide in state of the art observatories



Reveal a more complete physical picture

Formed
June 2002
>14 projects