High-mass X-ray Binaries in star-forming galaxies

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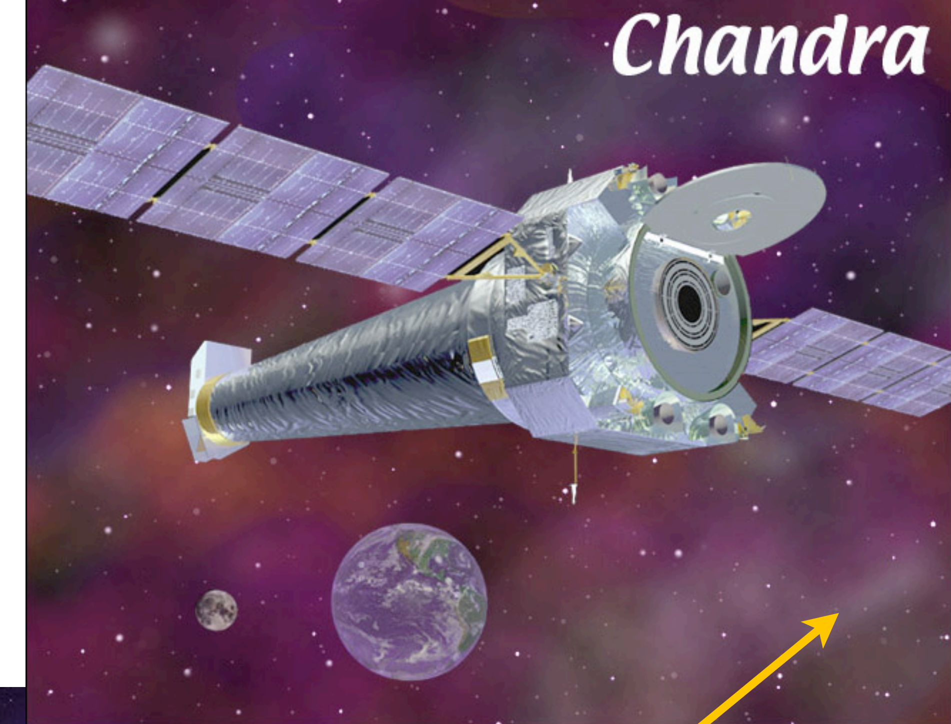
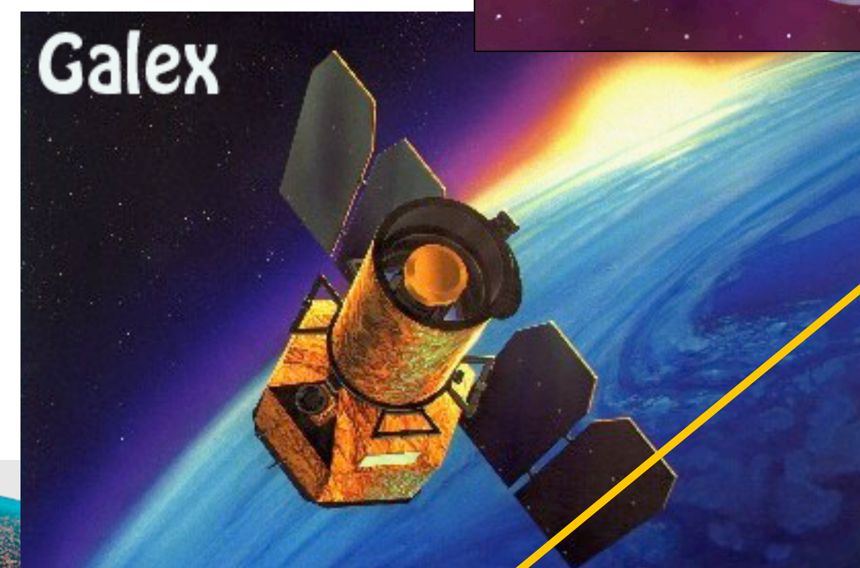
Science goals

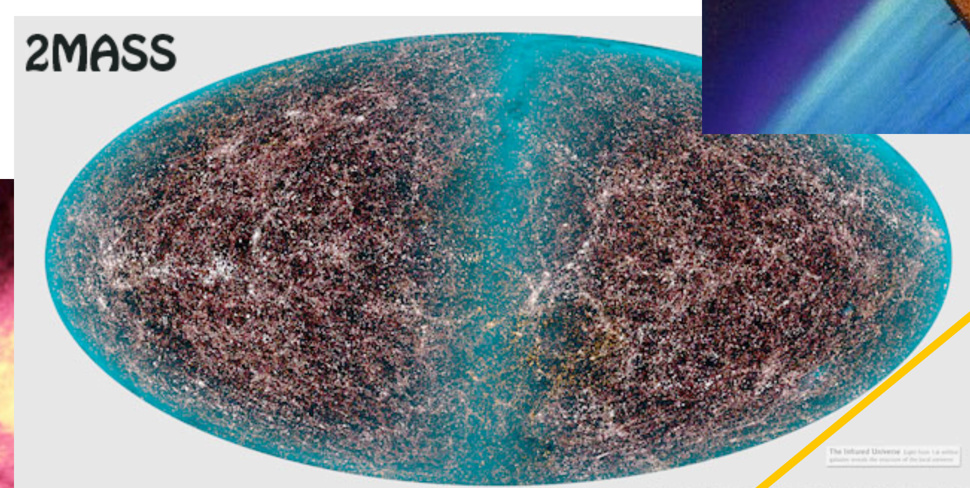
- L_X-SFR relation HMXBs, diffuse gas and total emission
- HMXB luminosity function



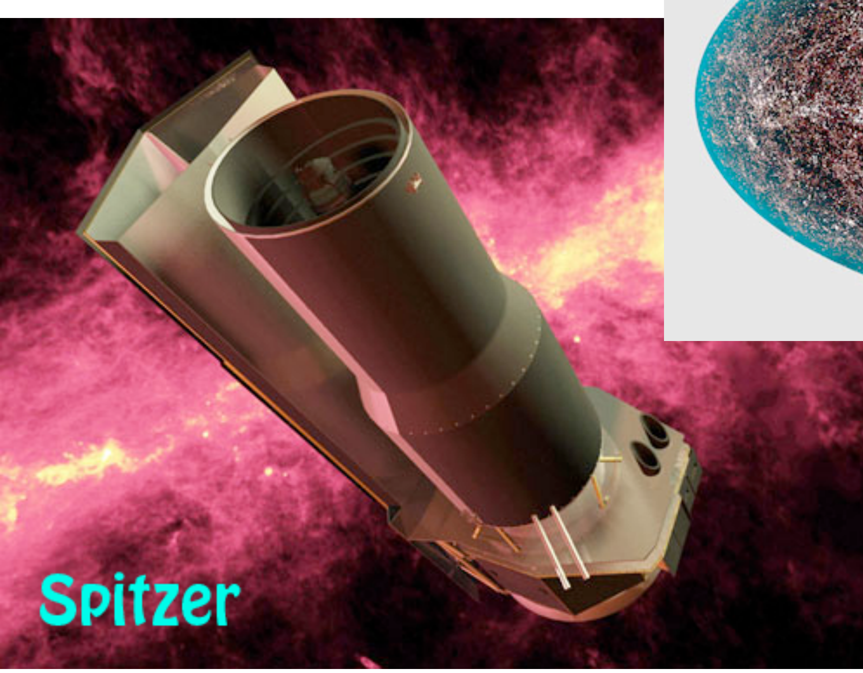
0.5-8 keV



NUV (2312 Å)
FUV (1529 Å)



NIR
2.16μm



FIR
70μm
24μm

multiwavelength study of archival data

Sample selection criteria

- Hubble type: late-type only (S and Irr) $\Rightarrow$ star-forming
- Specific SFR: $\frac{\mathrm{SFR}}{M_\star} > 10^{-10}\,\mathrm{yr}^{-1}$ $\Rightarrow$ HMXB dominated

τ_{HMXB}~10-50 Myr $\Rightarrow$ $N_{HMXB} \propto$ SFR (Grimm, Gilfanov & Sunyaev 2003)

τ_{LMXB}~1-10 Gyr $\Rightarrow$ $N_{LMXB} \propto M_\star$ (Gilfanov 2004)

- Exposure time: $t_{exp} \geq 15$ ks
- Distance: *Resolved galaxies:*
  $D < 40$ Mpc, discriminate AGN, low SFR, $L_{TOT}=\Sigma L_i$ $\Rightarrow$ 29 galaxies

  Unresolved galaxies:
  $D > 40$ Mpc, high SFR, spectra $\Rightarrow$ 8 galaxies (LIRGs, ULIRGs)

Chandra Deep Field galaxies:
$0.2 \leq z \leq 1.3$ $\Rightarrow$ 12 late-type galaxies from CDF-South and 13 CDF-North

62 star-forming galaxies
0.1 < SFR ($M_\odot$/yr) < 10^3
~1000 resolved X-ray point sources

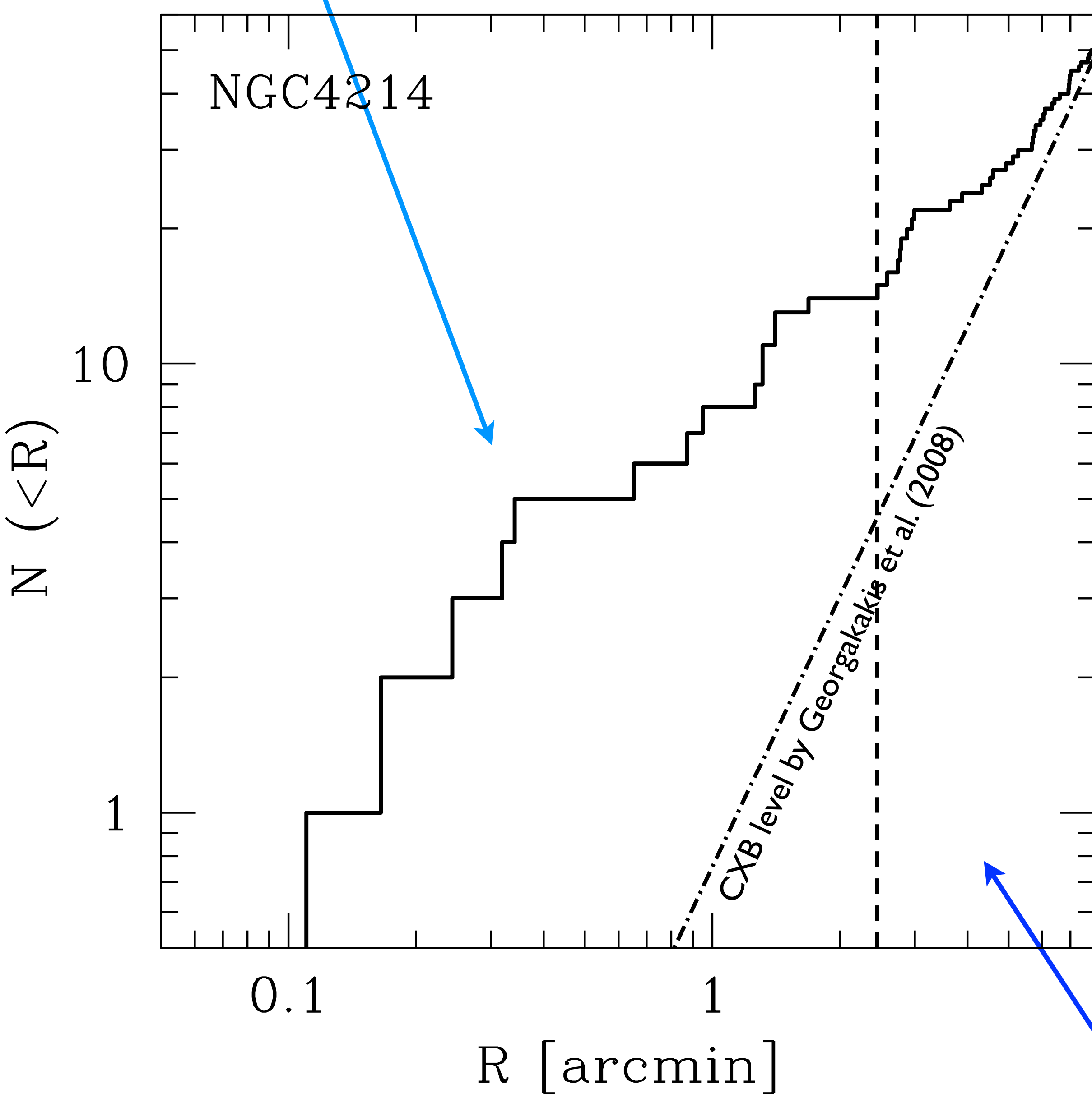
Spatial Analysis

minimizing the CXB contribution

central regions

- high surface density of XRBs
- negligible contribution of CXB sources

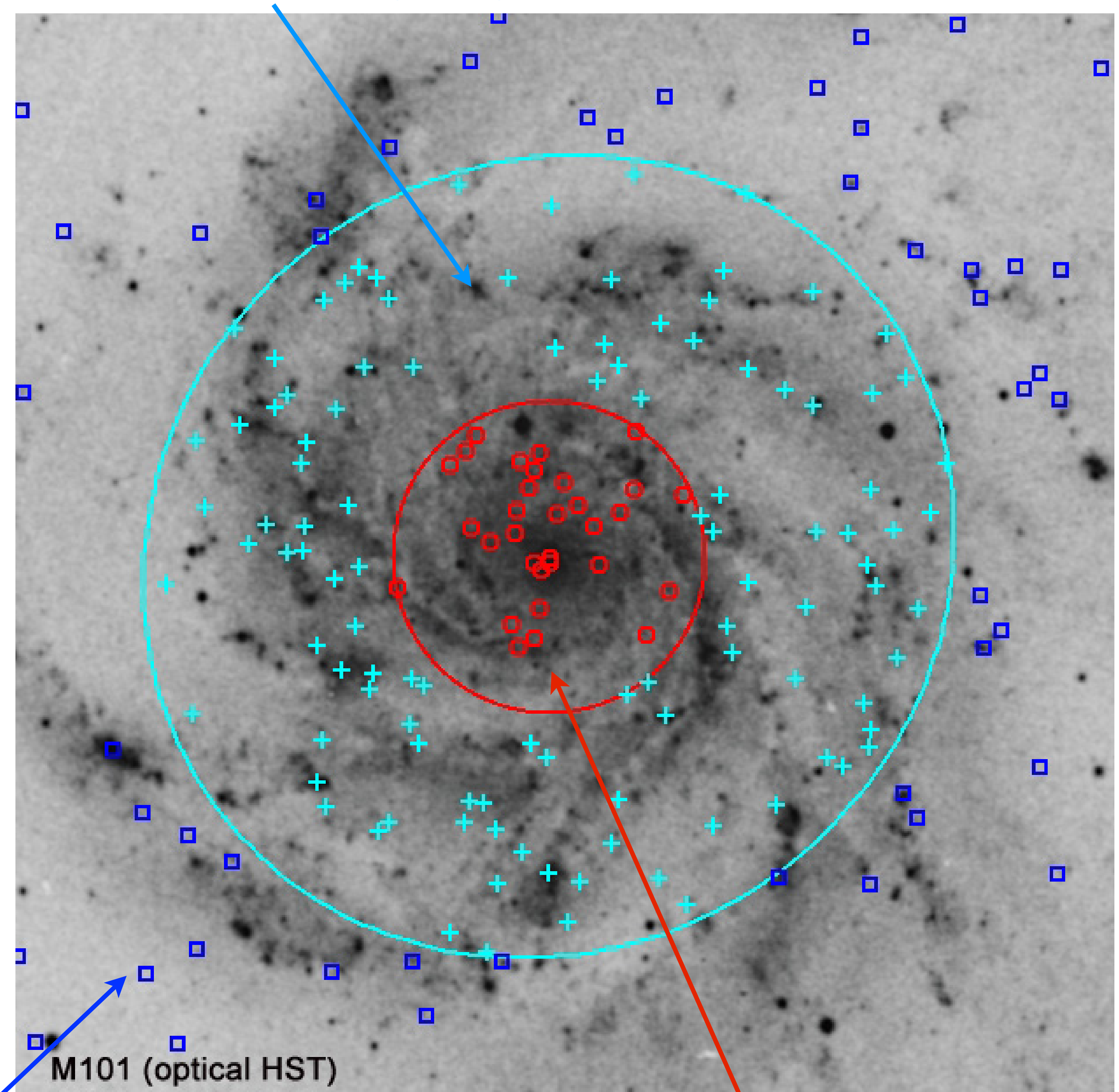
$$\frac{N_{\rm CXB}}{N_{\rm tot}} \leq 30\%$$



outer regions
detected sources dominated by CXB

minimizing the LMXB contribution

disk population
XRBs of a wide range of age



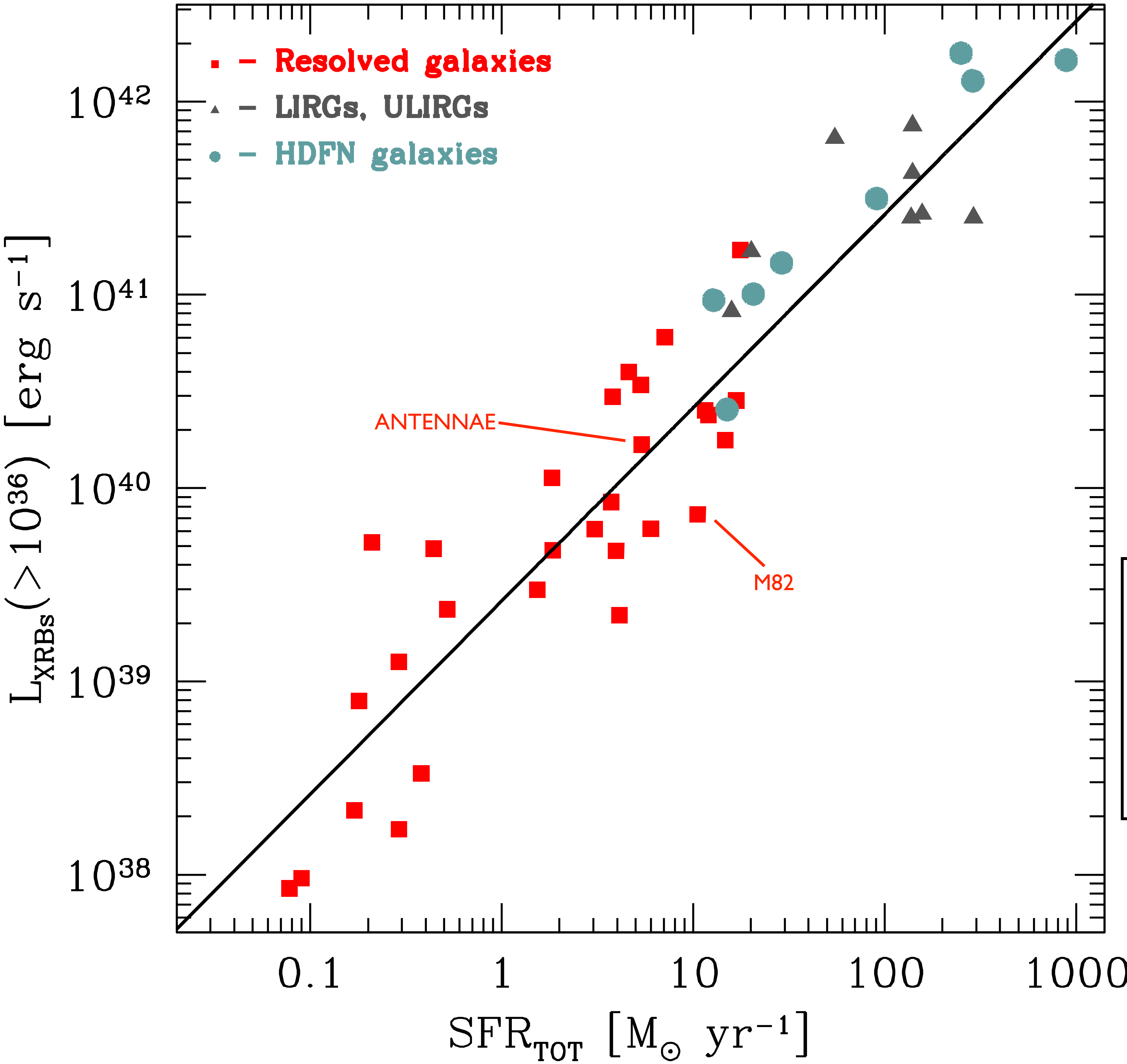
bulge population
dominated by LMXB

L_X-SFR relation for HMXBs, hot ISM and total emission

Mineo, Gilfanov & Sunyaev (2012a) - MNRAS 419,2095
Mineo, Gilfanov & Sunyaev (2012b) - arXiv:1205.3715 - MNRAS submitted
Mineo, Gilfanov & Sunyaev (2012c) - arXiv: 1207.2157 - MNRAS submitted

The L_{XRB}-SFR relation

$$L^{XRB}_{0.5-8\,keV}(\mathrm{erg\,s^{-1}}) = 2.61 \times 10^{39}\,\mathrm{SFR}\,(\mathrm{M_\odot\,yr^{-1}})$$



- consistent with L_X-SFR relation of Grimm et al. (2003), Ranalli et al. (2003), Lehmer et al. (2010)
- we also see the dispersion around the L_X-SFR relation found in earlier studies

$$\mathrm{SFR_{TOT}} = \mathrm{SFR^0_{UV}} + (1-\eta)\,\mathrm{SFR_{IR}}$$

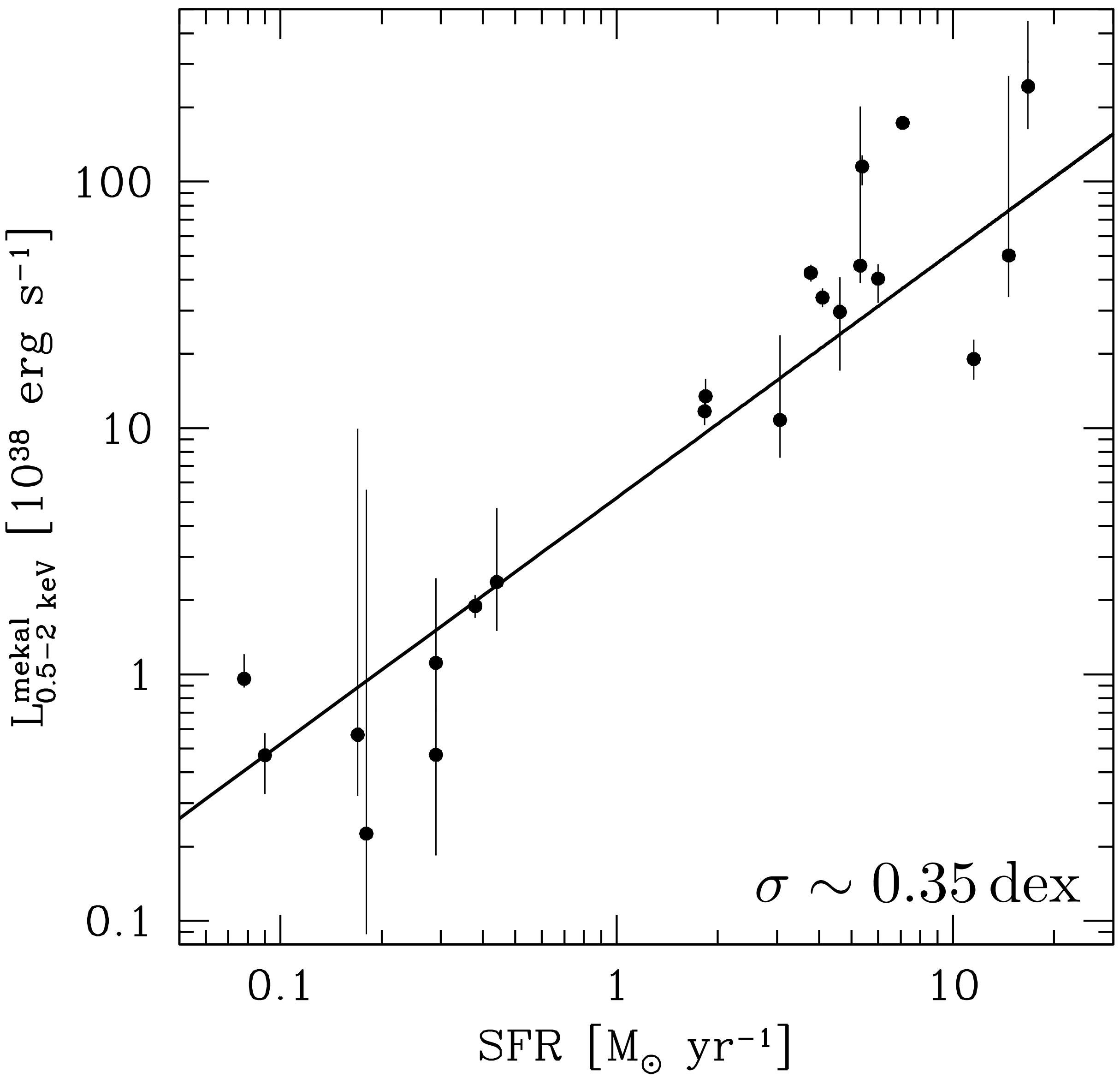
[Salpeter IMF, 0.1-100 $M_\odot$]
Hirashita et al. (2003), Bell (2003), Iglesias-Paramo et al. (2006)

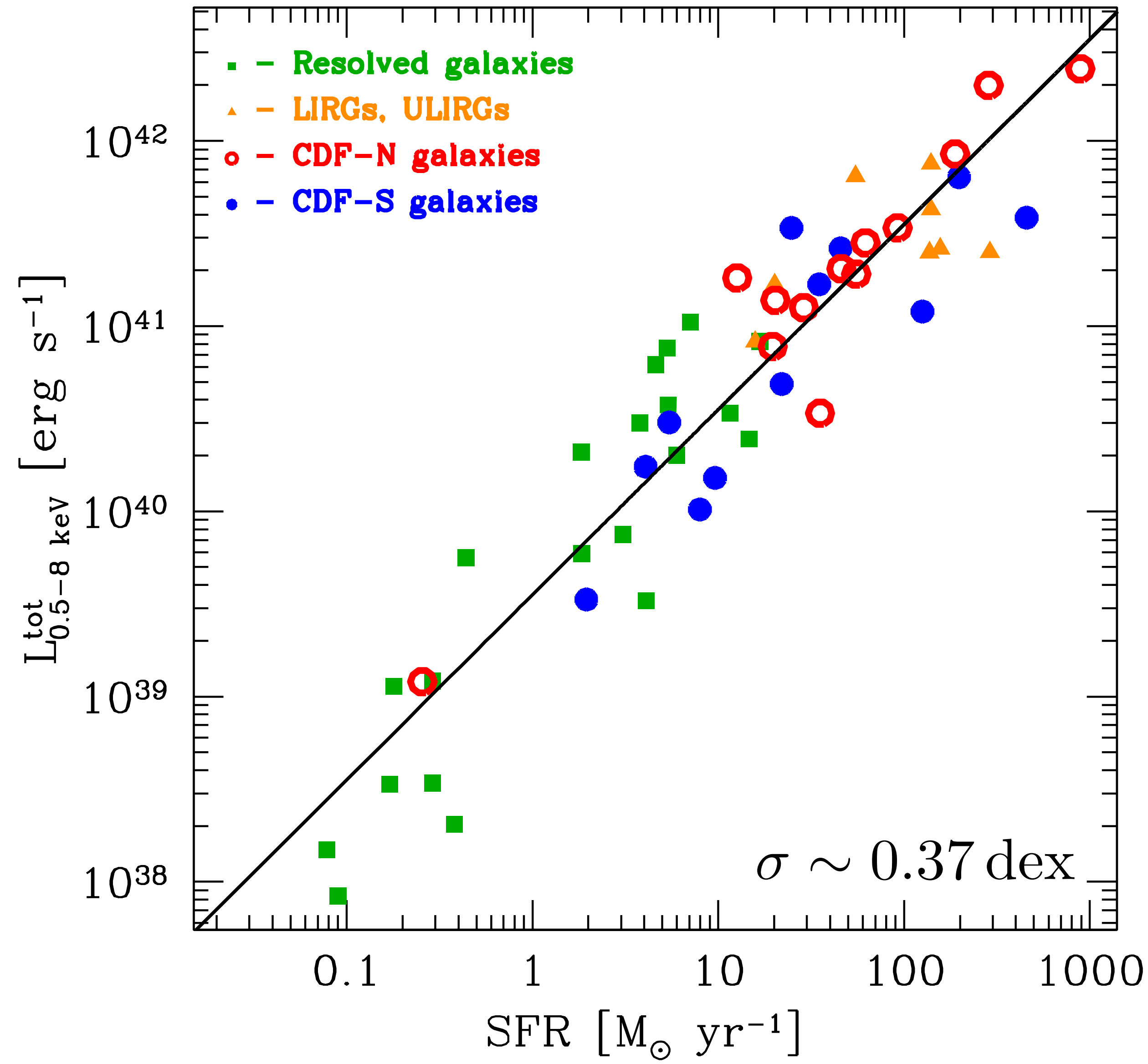
Mineo et a. (2012a)
MNRAS 419,2095

$$L_{XRB} = \int_{10^{36}}^{L_{lim}} L\frac{dN}{dL}dL + \sum_{L_i \geq L_{lim}} \frac{L_i}{K(L_i)} - 4\pi D^2 \int_{F_{lim}}^{F_{cut}} F\frac{dN_{CXB}}{dF}dF$$

L_X-SFR relations for hot ISM and total emission

HMXBs provide ~3/4 of the 0.5-8 keV luminosity generated per unit SFR





$$L^{mekal}_{0.5-2\,keV}(\mathrm{erg\,s^{-1}}) = (5.2 \pm 0.2) \times 10^{38}\,\mathrm{SFR}\,(\mathrm{M_\odot\,yr^{-1}})$$

21 galaxies resolved by Chandra (D<40Mpc)

Mineo et al. (2012b) - MNRAS submitted
arXiv:1205.3715

$$L^{tot}_{0.5-8\,keV}(\mathrm{erg\,s^{-1}}) = (3.5 \pm 0.4) \times 10^{39}\,\mathrm{SFR}\,(\mathrm{M_\odot\,yr^{-1}})$$

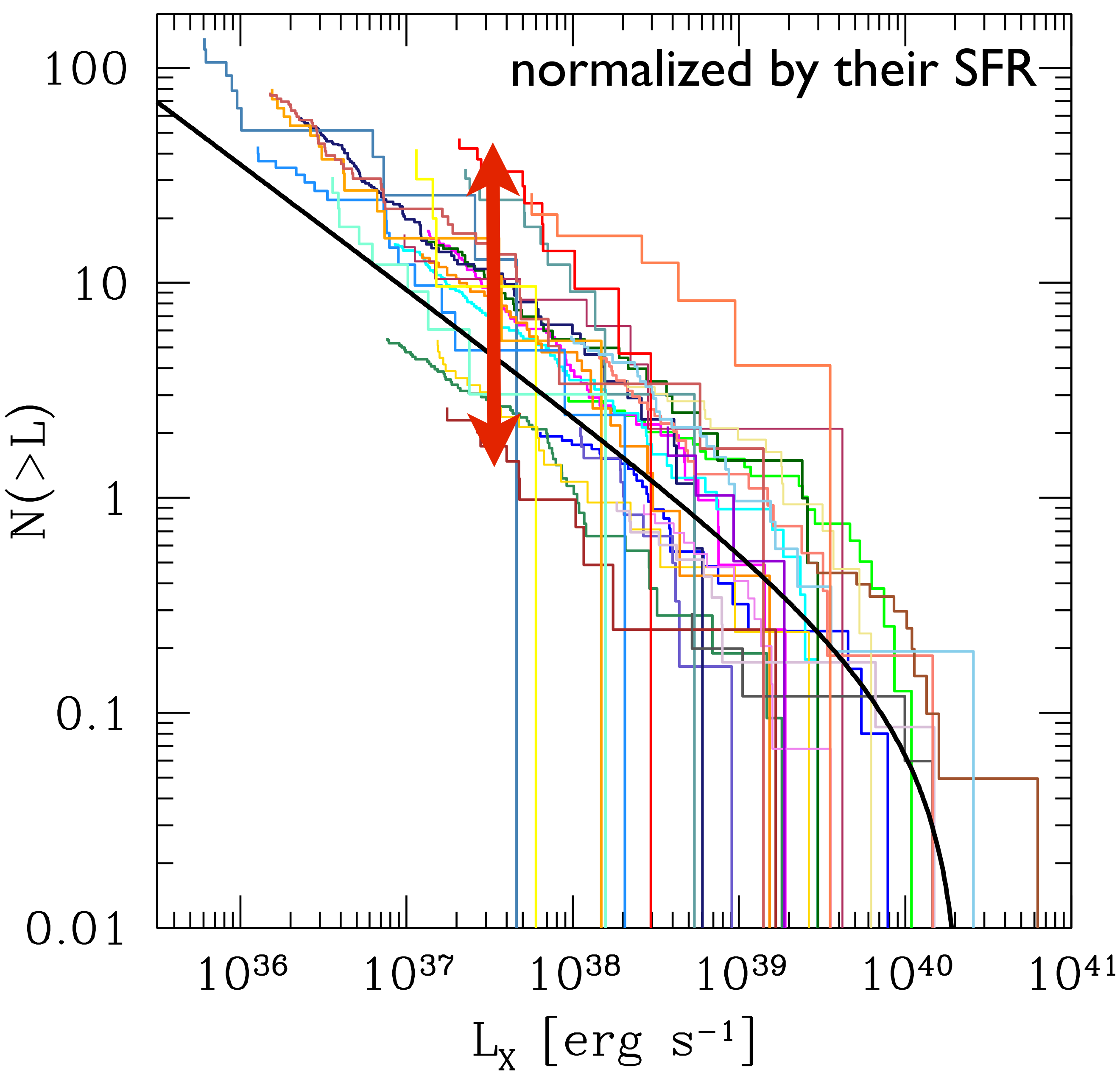
54 galaxies: 21 resolved, 8 ULIRGs, 25 CDFs $z \leq 1.3$

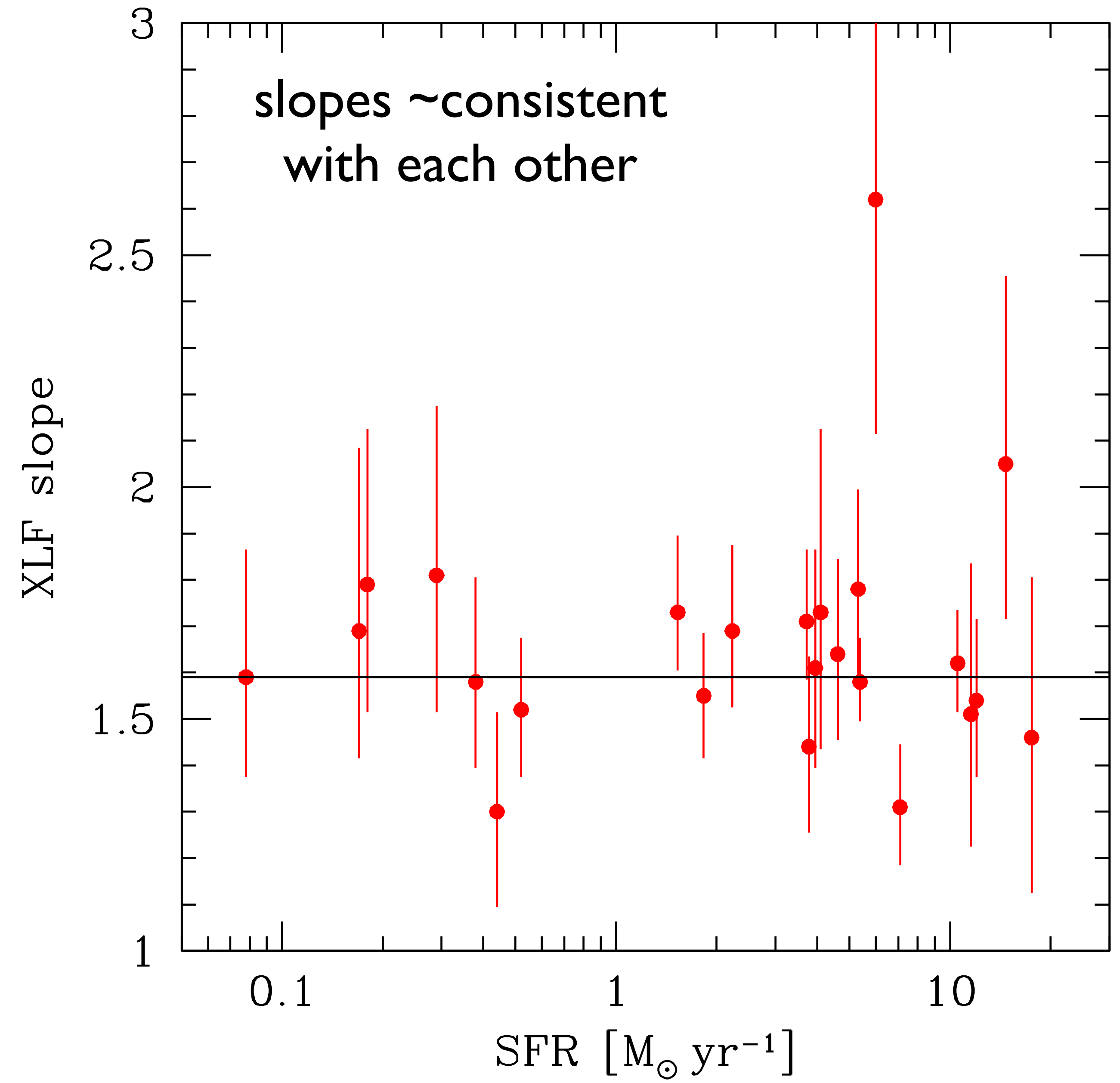
Mineo et al. (2012c) - MNRAS submitted
arXiv: 1207.2157

Luminosity function of HMXBs

Mineo, Gilfanov & Sunyaev (2012) - MNRAS 419,2095

Cumulative individual XLFs and their slopes





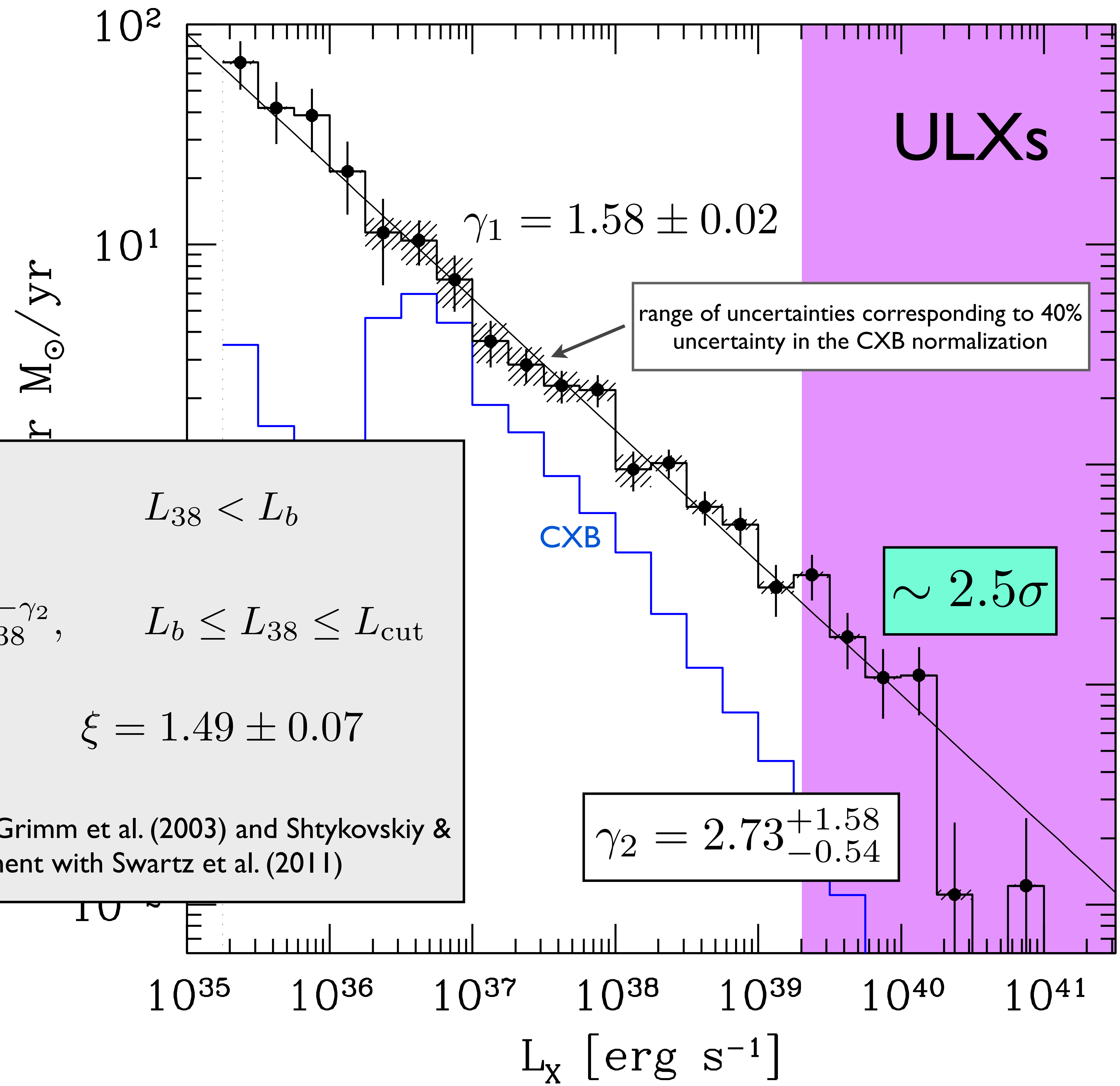
factor of ~10 difference in individual XLF normalization but RMS is ~2

$$\langle\gamma\rangle \approx 1.6 \quad rms \approx 0.22$$

is the average XLF of HMXBs universal?

Average differential luminosity function of HMXBs

- ~ 700 compact sources
- detected in 29 galaxies
- normalized by SFR
- CXB subtracted



$$\frac{dN}{dL_{38}} = \xi\,\mathrm{SFR} \times \begin{cases} L_{38}^{-\gamma_1}, & L_{38} < L_b \\ L_b^{\gamma_2-\gamma_1}\, L_{38}^{-\gamma_2}, & L_b \leq L_{38} \leq L_{\rm cut} \end{cases}$$

$$L_b = 1.1^{+0.57}_{-0.34} \times 10^{40}\,\mathrm{erg/s} \qquad \xi = 1.49 \pm 0.07$$

slope and normalization consistent with Grimm et al. (2003) and Shtykovskiy & Gilfanov (2005), break in agreement with Swartz et al. (2011)

Implications for the theory of binary evolution

How many black holes and neutron stars become X-ray sources?

Mineo, Gilfanov & Sunyaev (2012) - MNRAS 419,2095

Specific frequency of X-ray bright compact objects in HMXBs

$$N_{\rm HMXB} \sim \dot{N}_{co}\, f_{\rm X}\, \bar{\tau}_{\rm X}$$

$$\bar{\tau}_{\rm X} = \frac{\sum_k f_{{\rm X},k}\, \tau_{{\rm X},k}}{\sum_k f_{{\rm X},k}}$$

- $N_{\rm HMXB}$: number of HMXBs observed at any time
- $\dot{N}_{co}$: birth rate of compact objects
- $f_{\rm X}$: total fraction of HMXBs
- $\bar{\tau}_{\rm X}$: average duration of X-ray active phase ($\tau_X \sim 10^4$ yr supergiant systems, $\tau_X \sim 10^5$ yr Be/X systems)

from the HMXB luminosity function (Mineo+ 2012):

$$N_{\rm HMXB}(>10^{35} {\rm erg\, s^{-1}}) \approx 135 \times {\rm SFR} = {\rm N_{NS+BH}}$$

assuming Kroupa IMF:

$$\dot{N}_{co} \approx \dot{N}_{*}(M > 8\, M_{\odot}) \approx 7.4 \cdot 10^{-3} \times {\rm SFR} = {\rm \dot{N}_{NS+BH}}$$

→

$$f_{\rm X} \sim 0.18 \times \left(\frac{\bar{\tau}_{\rm X}}{0.1\,{\rm Myr}} \right)^{-1}$$

fraction of compact objects that on the time scale of ~10^2 Myr after their formation (e.g. Shtykovskiy & Gilfanov 2007) become X-ray sources with $L_X > 10^{35}$ erg/s powered by accretion from a massive donor star

Specific frequency of X-ray bright compact objects in LMXBs

$$N_{\rm LMXB} \sim N_{co}\, f_{\rm X}$$

number of LMXBs observed at any time

number of compact objects

total fraction of LMXBs

considering only LMXBs in the bright state
(no objects in transient systems)

from the Nx-M$_*$ relation (Gilfanov 2004):

$$N_{\rm LMXB}(> 10^{35} {\rm erg\,s^{-1}}) \approx 50 \times {\rm M_*}/(10^{10}{\rm M_\odot}) = {\rm N_{NS+BH}}$$

assuming Kroupa IMF:

$$N_{co} \approx N_*(M > 8\, M_\odot) \approx 5 \cdot 10^{-3} \times M_* = N_{\rm NS+BH}$$

$$f_{\rm X} \sim 10^{-6}$$

~5 orders or magnitude smaller than the specific frequency of HMXBs

Constraints on the mass-ratio distribution in binaries

$$f_X(\text{HMXBs}) \leq f_{\text{bin}}(m_2 \gtrsim 5M_\odot)$$

total fraction of HMXBs

fraction of binaries with compact object, having a massive companion

for a Kroupa IMF:

$$f(m > 5M_\odot) \approx 5.5 \cdot 10^{-3} \sim f_X/(30-100)$$

for general power-law mass distribution:

$$\psi(m) \propto m^{-\gamma}, \quad f_X = 0.2 \rightarrow \gamma < 0.3$$

if the mass transfer does not significantly change m_2, this excludes the possibility that the masses in the HMXB are independent from the IMF

assuming that the number of binaries obeys the following distribution:

$$dN \propto \psi(m_1)dm_1\, f(q)dq, \qquad q = m_2/m_1$$

mass distribution of the primary

distribution of the mass ratio

for a Kroupa IMF and $f(q) = 1$**, for** $m_1 > 8M_\odot$**,** $m_2 > 5M_\odot$**:**

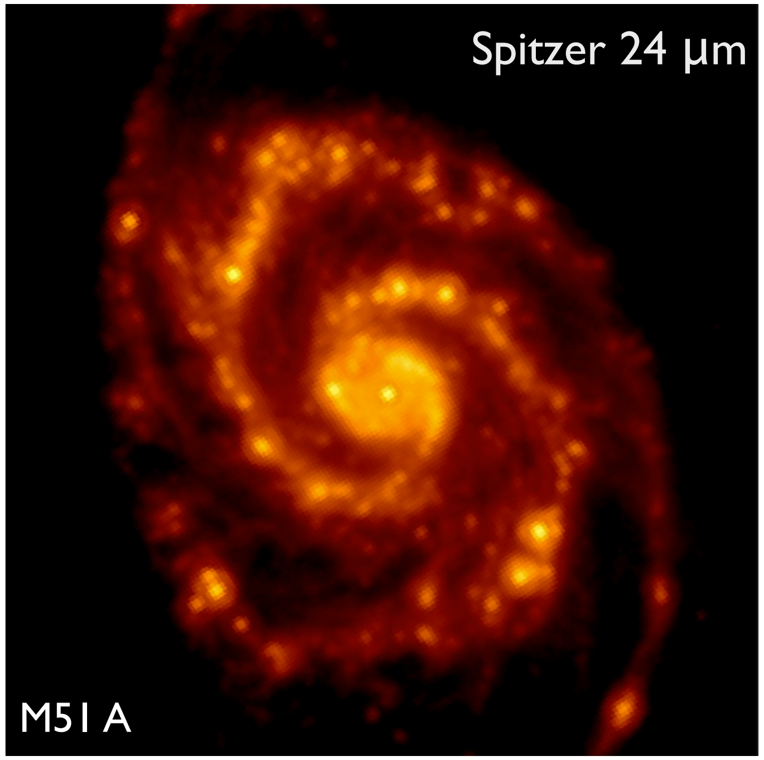
$$f_{\text{bin}}(m_2 \gtrsim 5M_\odot) = \frac{\int_8^{100} dm_1 \psi(m_1) \int_{5/m_1}^{1} f(q)dq}{\int_{0.1}^{100} \psi(m)dm} \approx 0.6$$

consistent with f_X ~0.2

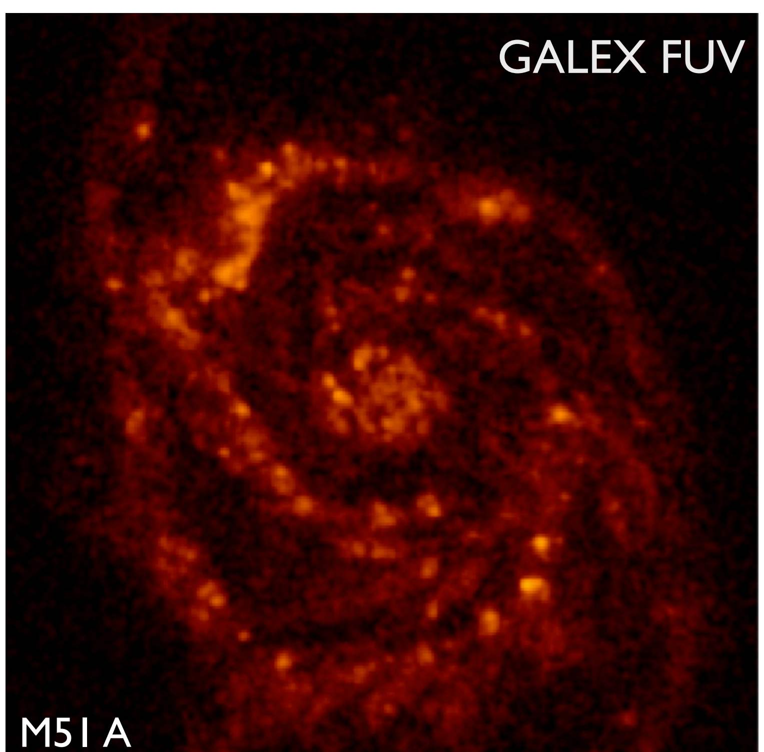
Spatially resolved N_X-SFR relation

Mineo, Fabbiano, Gilfanov, Zezas (2012) - ApJ in preparation

Spatially resolved N_{XRB}-SFR relation

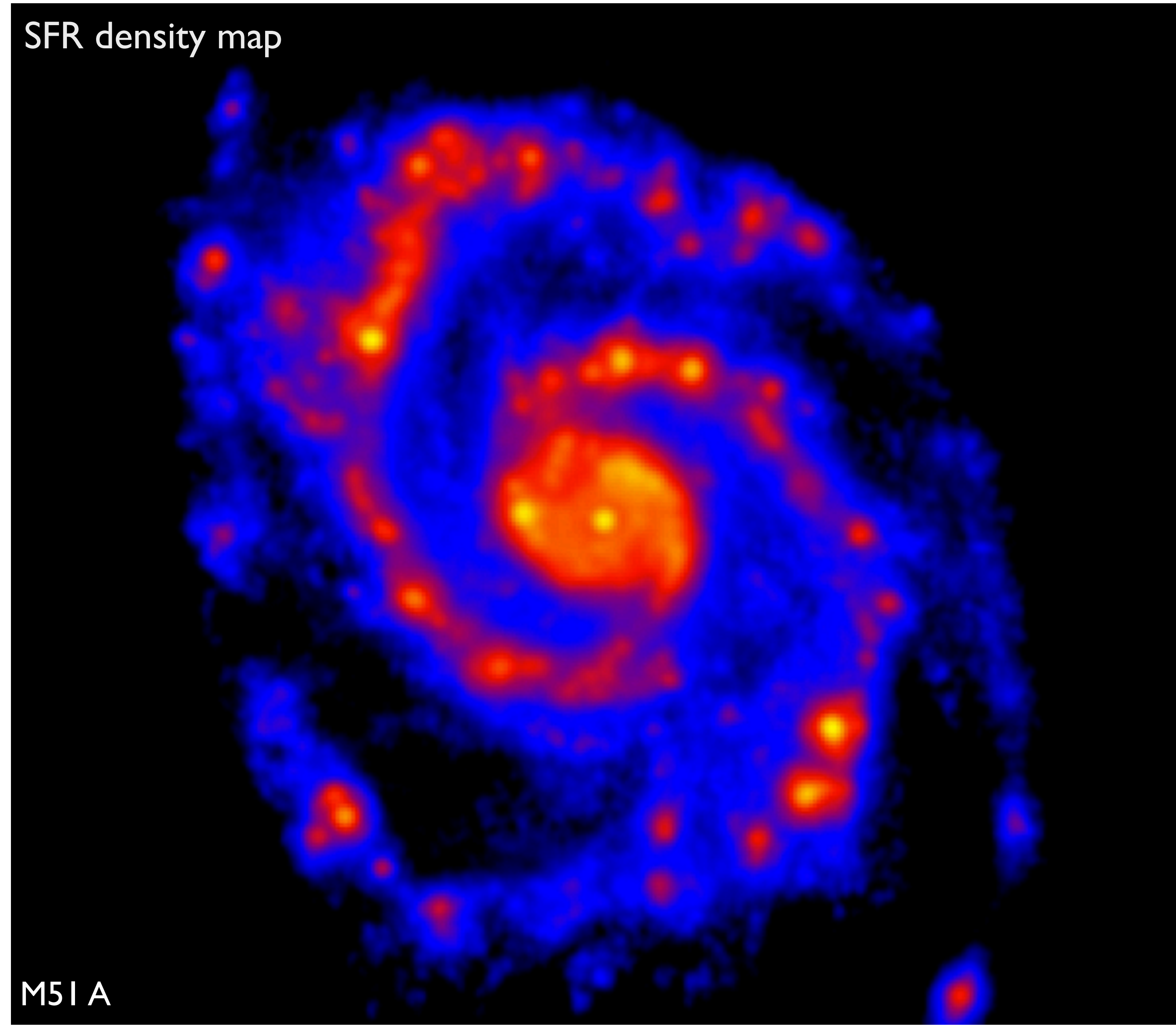


τ(24 µm)~10 Myr (Calzetti et al. 2007)



τ(FUV)~50-100 Myr (Calzetti et al. 2005)

FIR+FUV →

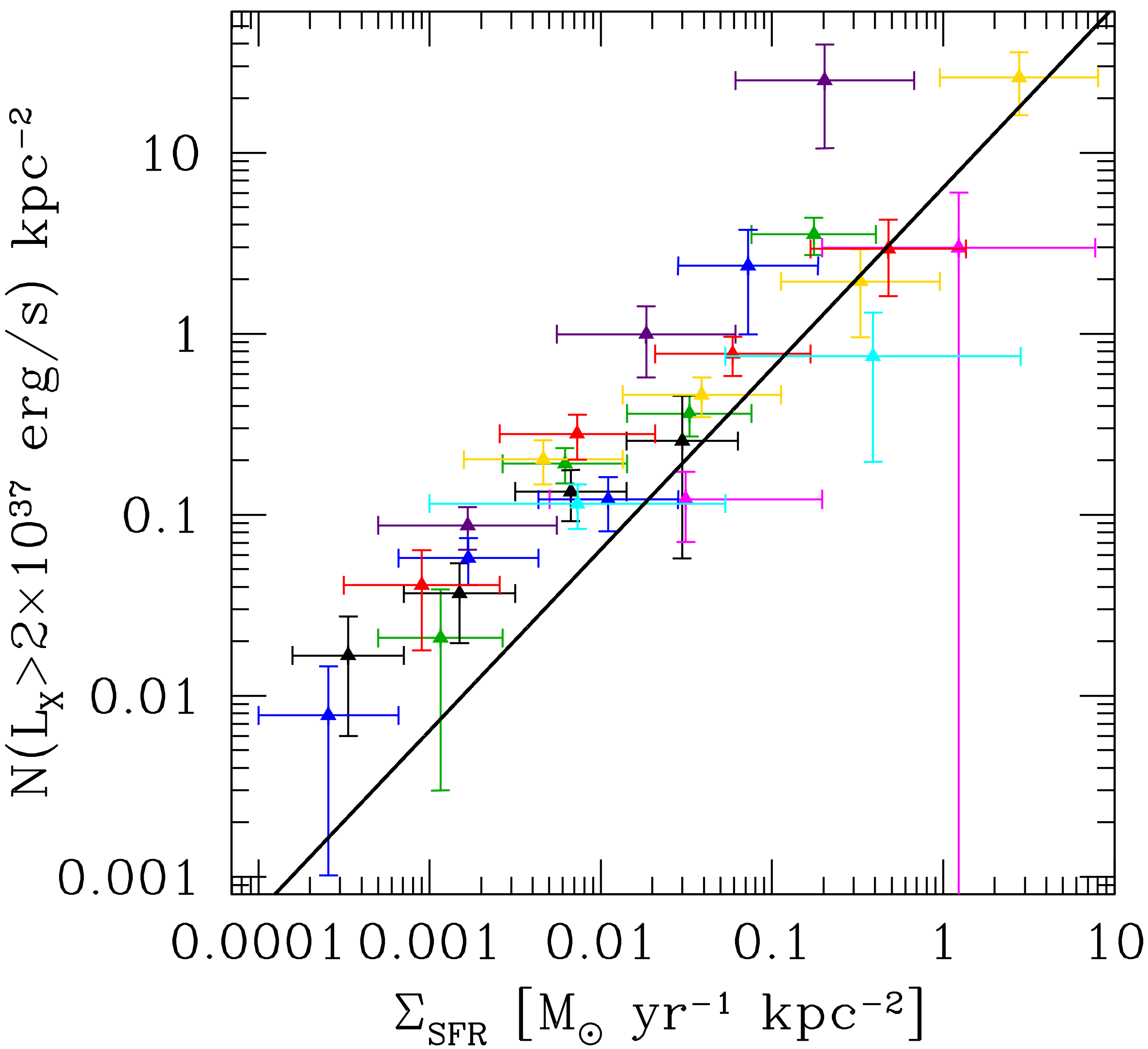


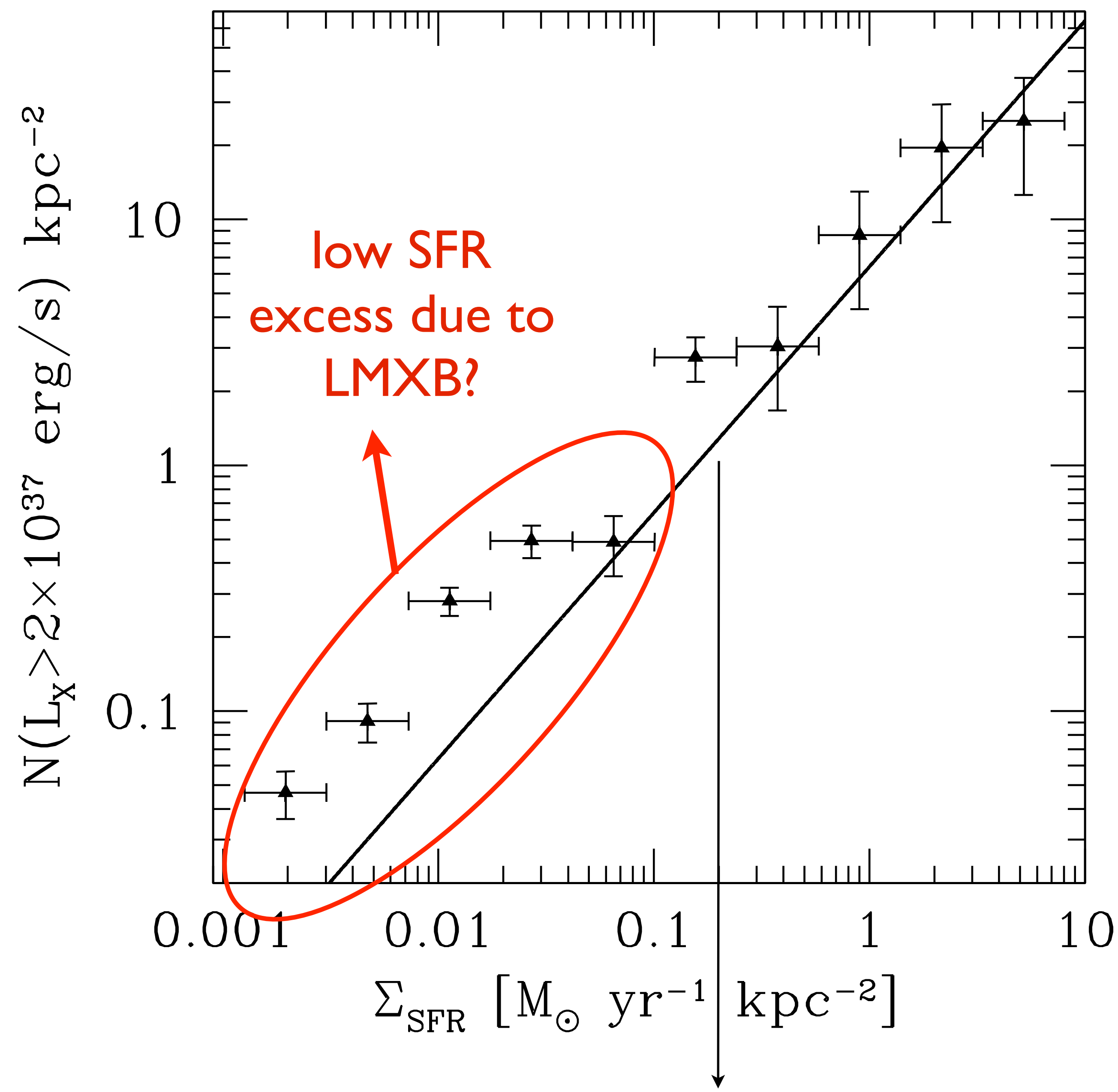
$$\Sigma_{\rm SFR}(M_\odot\,{\rm yr}^{-1}\,{\rm kpc}^{-2}) = 8.1\times10^{-2}{\rm I}_{\rm FUV} + 3.2\times10^{-3}{\rm I}_{24\,\mu{\rm m}}$$

(Leroy et al. 2008)

Spatially resolved N_{XRB}-SFR relation

X-Ray source density vs SFR density





- 8 galaxies, D<12 Mpc
- face-on, grand design spiral
- ~450 X-ray point sources
- CXB subtracted

N-SFR relation for HMXB-dominated population

$$N_{\rm XRB}(L > 2 \times 10^{37} {\rm erg\,s^{-1}}) = 6.42 \times {\rm SFR}\,({\rm M_\odot\,yr^{-1}})$$

Conclusions

- Largest sample of multi-wavelength data for X-ray resolved star-forming galaxies to date.
- X-ray luminosity function of HMXBs:
  - substantially improved statistical accuracy and control of systematic effects than achieved in previous studies
  - power law with slope of 1.6 in the 10^{35}-10^{40} erg/s luminosity range
  - evidence for a break near 10^{40} erg/s
- Collective luminosity and number of HMXBs scale with the star formation rate of the host galaxy
- The fraction of compact objects that once upon their lifetime experienced an X-ray active phase powered by accretion from a high mass companion is ~ 5 orders of magnitude more frequent than in LMXBs.

Catalog of XRBs - includes 1055 compact sources

(VizieR On-line Data Catalog: J/MNRAS/419/2095)

Work in progress

- spatially resolved N_X-SFR density relation for separate arm and inter-arm sources
  Correlation with the X-ray color-color analysis outcome?

Thank you for your attention!