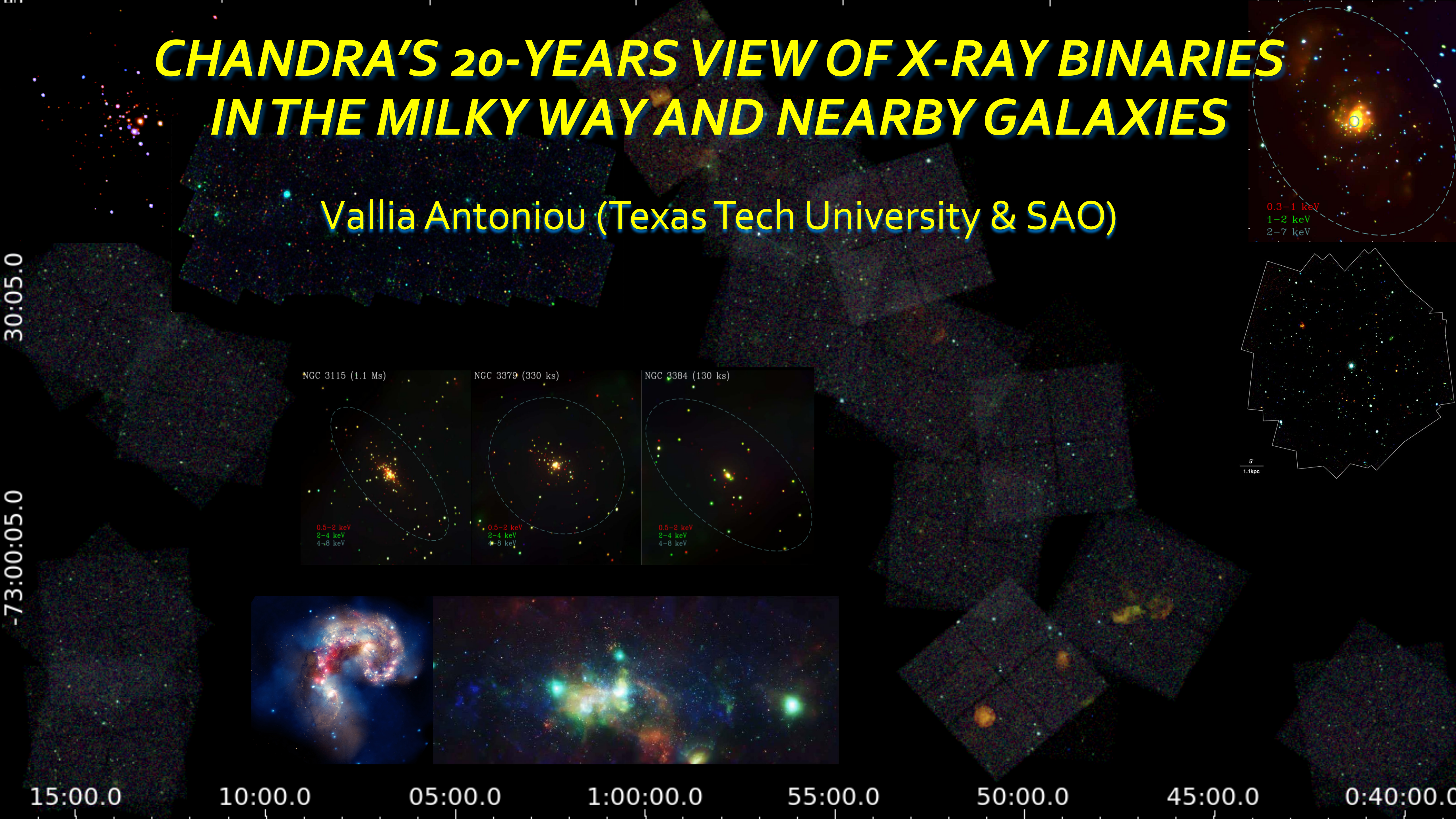
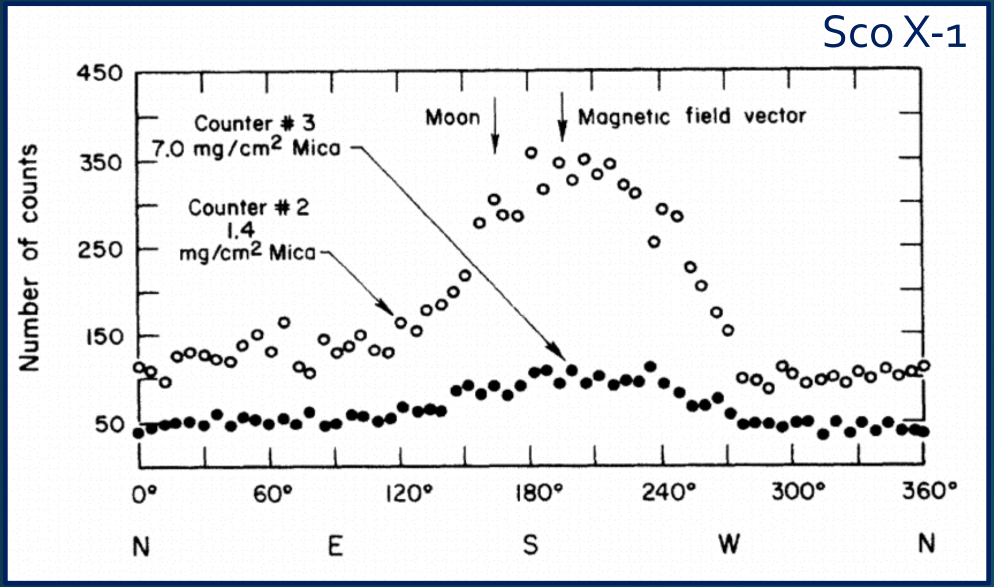
CHANDRA'S 20-YEARS VIEW OF X-RAY BINARIES IN THE MILKY WAY AND NEARBY GALAXIES

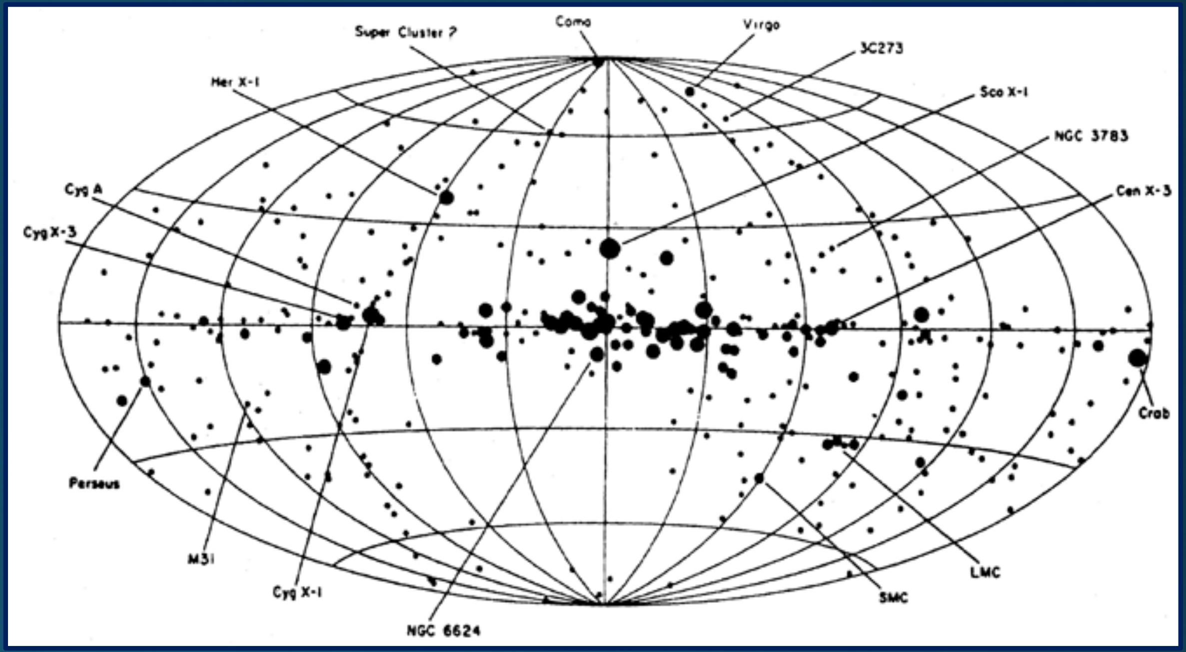
Vallia Antoniou (Texas Tech University & SAO)



How it all started…



Giacconi et al. 1962, PhRvL, 9, 439



Forman et al. 1978, ApJS, 38, 357

In the late 1970's and 1980's, following the advent of imaging X-ray astronomy with the *Einstein Observatory*, **XRBs were detected in a number of nearby galaxies** (Fabbiano 1989, ARAA, 27, 87)

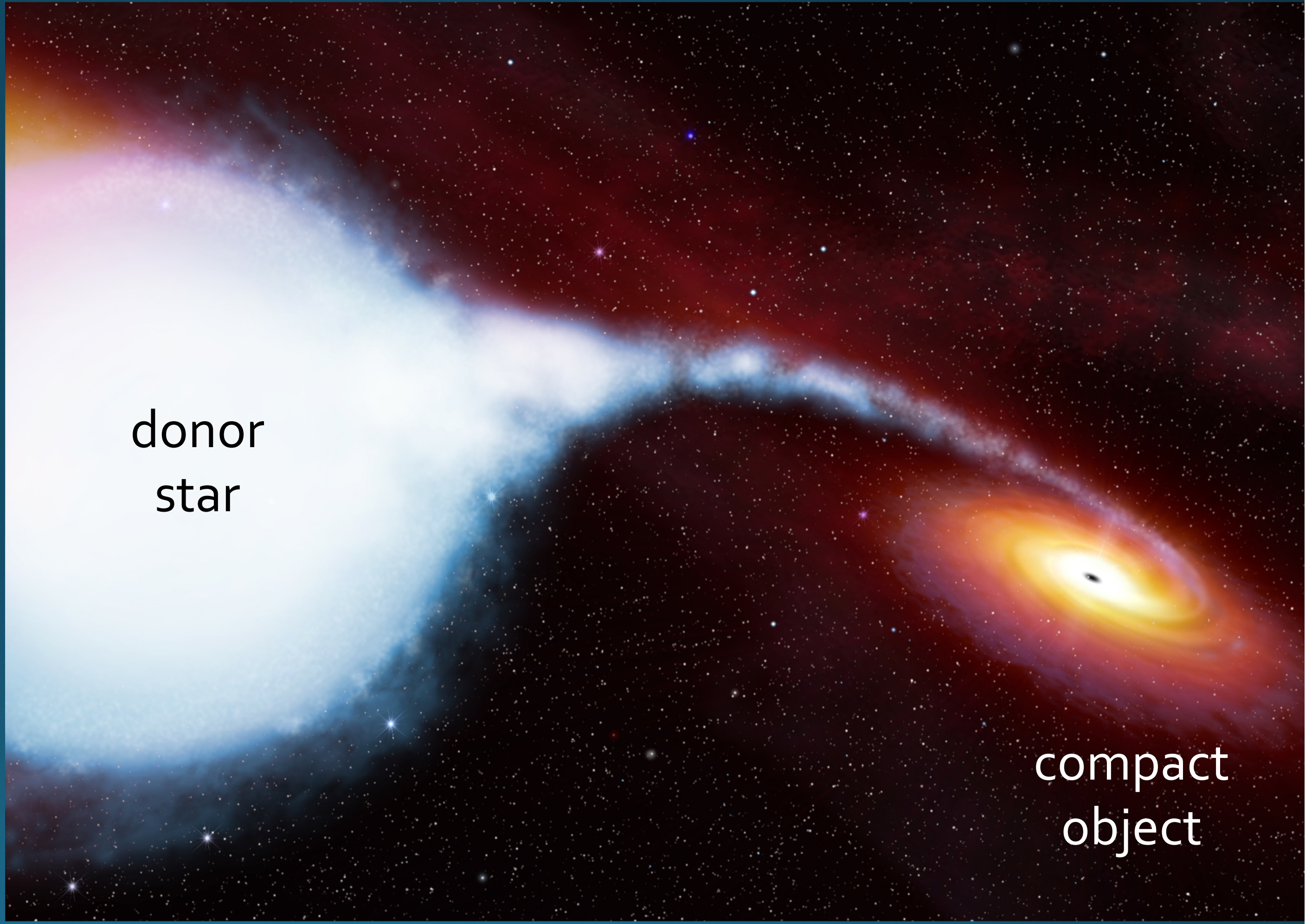
X-ray Binaries

HMXBs ($\gtrsim$8-10$M_\odot$)

short-lived (few Myr), young stellar populations

LMXBs ($\lesssim$1$M_\odot$)

- Field-LMXBs (stellar binary systems evolution; old systems; $t_{lifetime}$~10^8-10^9 yr)
- GC-LMXBs (dynamical interactions in Globular Clusters; can be formed any time → some could be short lived)



Fabbiano arXiV: 1903.01970

Why study X-ray Binaries

Key tools for several areas of Astrophysics. XRBs provide information on:

1. star-formation processes
2. late stages of stellar evolution
3. compact object formation
4. compact object mergers, and thus sources of gravitational waves
5. behavior of matter at extreme magnetic fields
6. XRB feedback in the early Universe
7. ….

Zezas et al. 2019, Astro2020 WP

Pre-*XMM-Newton*/*Chandra* Era Science Highlights

Einstein, *ROSAT*, *RXTE*, *ASCA* have contributed to the study of XRBs in the Milky Way and our local neighborhood:

- Discovery of numerous **Super-Soft X-ray Sources** (SSS; most of their luminosity is below ~0.5 keV)

- Detection and monitoring of **discrete sources in nearby galaxies** (ROSAT HRI)
  - Spectral & temporal variability studies of compact Galactic and Magellanic Clouds objects
    - Census of X-ray pulsars in the Magellanic Clouds

- Discovery of Ultra-Luminous X-ray sources (**ULXs**; $L_X > 10^{39}$ erg s^{-1})

XMM-Newton Science Highlights

- **First solid evidence (through a serendipitous discovery) for the existence of intermediate-mass black holes** (Farrell et al. 2009, Nature, 460, 73).

- **Uncovered a new class of novae** (while monitoring M31 center), which turn-on and off in only a few months (Pietsch et al. 2007, A&A 465, 375; 2008, AN, 329, 170).

- **Detection of a WD with a dynamical mass of $1.2M_\odot$** (Mereghetti et al. 2009, Science, 325, 1222).

- **First detection of strong winds gusting at very high speeds (~0.2c) from two ULXs** (Pinto et al. 2016, Nature, 533, 64).

- **First detection of a BH in a Globular Cluster** (Maccarone et al. 2007, Nature, 445, 183). NOTE: *Chandra* was needed to get a firm association.

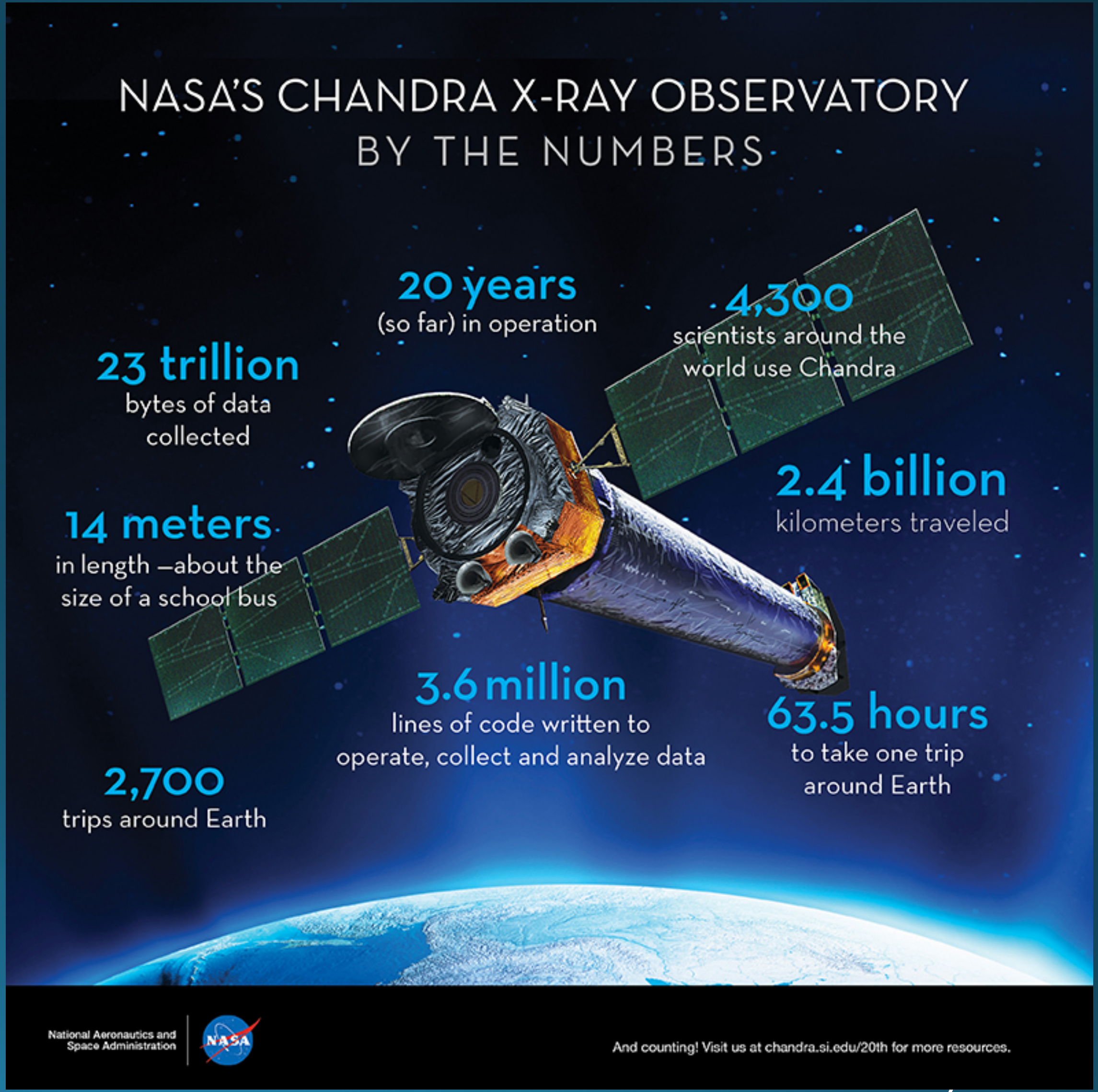
Schartel, 2012, MmSAI, 83, 97

Chandra X-ray Observatory

However, **it was *Chandra*'s subarcsecond resolution that revolutionized our understanding of accreting binaries!**

Chandra detected luminous ($L_X > 10^{37}$ erg s^{-1}) point sources in *all* galaxies within 50 Mpc.

Most of them are associated with XRBs.



Fabbiano arXiV: 1903.01970

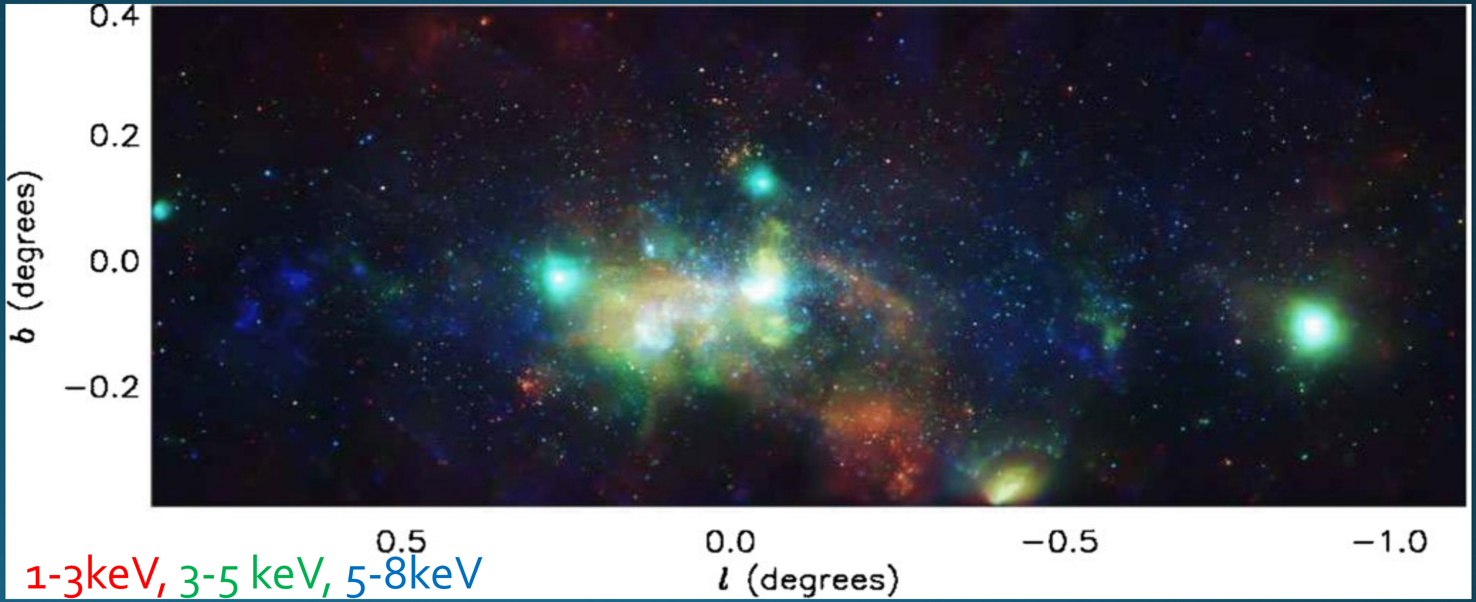
2Ms of *Chandra* observations of the Galactic Center

- $2^\circ \times 0.8^\circ$ field around the Galactic center (d~8kpc)
- $L_{X,limiting}$~4 × 10^{32} erg s^{-1} (0.5–8 keV) over an area of 1 deg^2
- An order of magnitude more sensitive in the deepest (1 Ms) exposure around Sgr A∗.

Muno et al.2009, ApJS, 181, 110

✓ 9,017 sources: increased the number of known X-ray sources in the region by a factor of 2.5

✓ 19 transients with $L_X > 10^{34}$ erg s^{-1}, which varied by at least an order of magnitude in F_X



1-3keV, 3-5 keV, 5-8keV

→ Have identified all XRBs that are active on timescales of a decade

Faint X-ray Transients

4-yr monitoring campaign of the Galactic Center

transient X-ray sources down to $L_{X,2\text{-}10keV}$~10^{34} erg s^{-1}

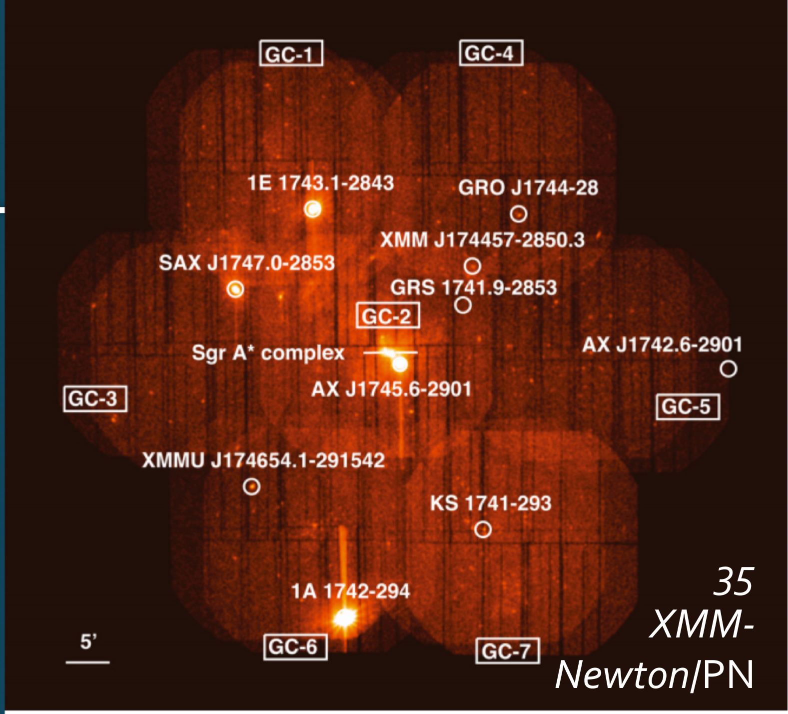
→ factor of ~100–1000x deeper than the sensitivity of widefield monitoring instruments; e.g. Swift/BAT

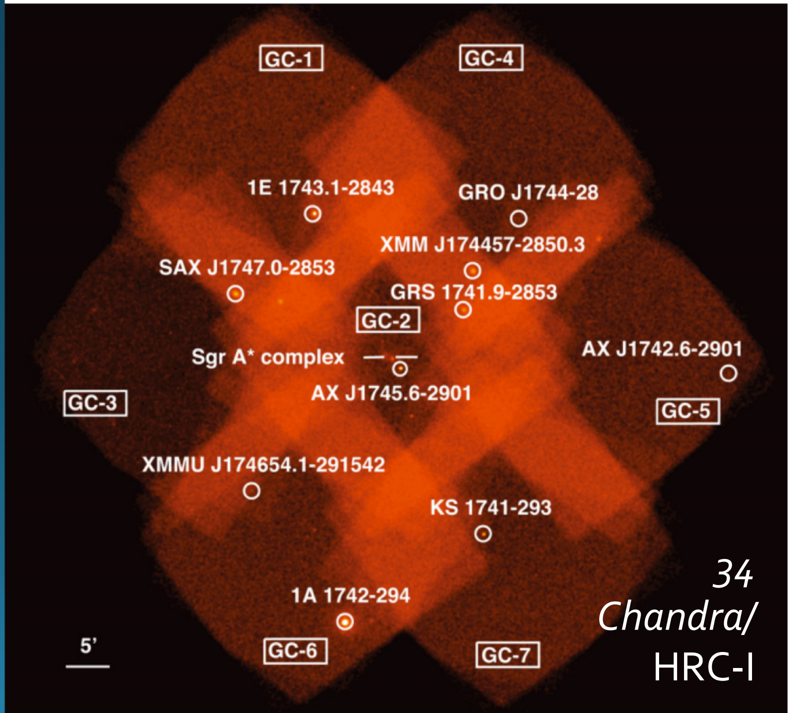
central 1.2 sq.degrees

10 different epochs (2005-2008)

- 17 known X-ray transients
  - 8 in outburst
    - 6 active each year
- a number of variable sources remained below $L_X \sim 5 \times 10^{33}$ erg s^{-1}

Degenaar et al. 2012, A&A, 545, 49





What we can gain from extragalactic studies…

… of accreting binary populations?

- Possible to obtain **a complete census**
- Not hampered by **distance uncertainties**
- **Increased parameter space of interest** for the formation and evolution of XRBs (e.g. age of parent stellar populations, metallicity, star-formation rate)
- Probe **extreme objects**

focus on nearby, normal (non-active) galaxies

What we have learned so far… #1

Link between the total number of XRBs and star-formation rate (SFR) of the stellar population of the galaxy

Grimm et al. 2003, MNRAS, 339, 793

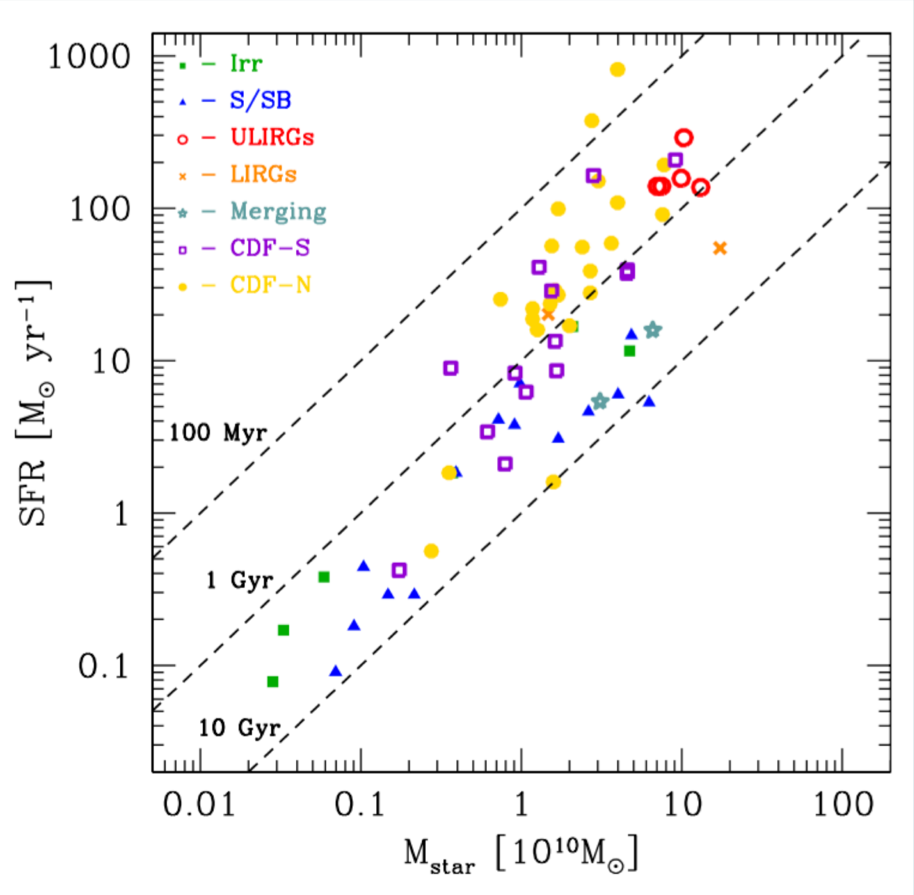
20 nearby late-type/starburst galaxies: *Chandra* & *ASCA*

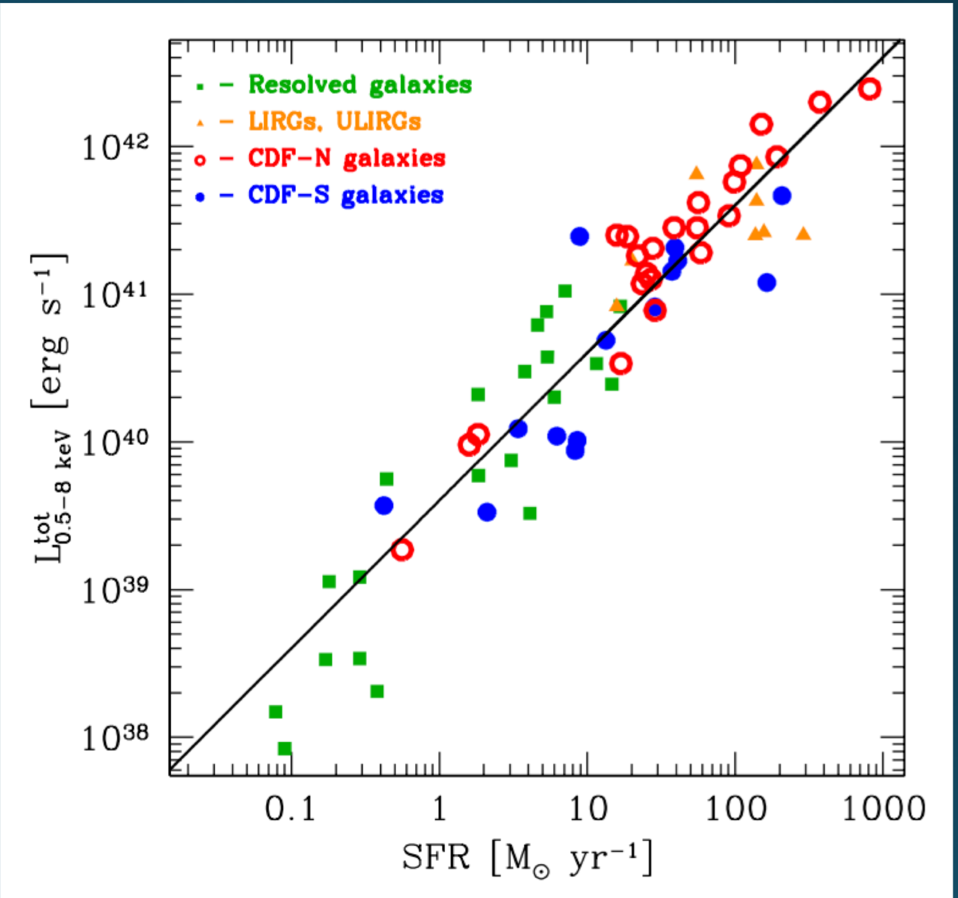
Milky Way & Magellanic Clouds: *RXTE, ASCA* & *MIR-KVANT*

→ the number and/or the collective L_X of **HMXBs** can be used to measure the SFR of a galaxy

What we have learned so far… #1

66 galaxies spanning the redshift range $z \approx 0–1.3$





X-ray observations are a powerful tool for measuring the SFR in normal star-forming galaxies that dominate the source counts at faint fluxes

Mineo et al. 2014, MNRAS, 437, 1698

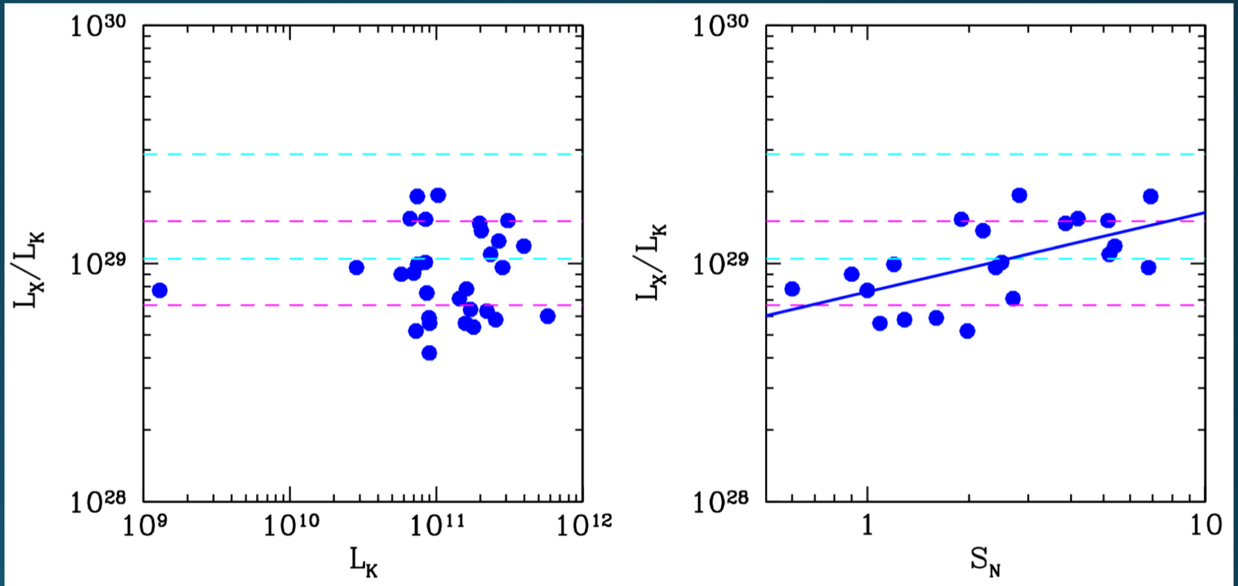
What we have learned so far… #2

Link between the total number of XRBs and total stellar mass (M⋆)

Kim et al. 2009, ApJ, 703, 829
3 old, nearby ellipticals with *Chandra*
Boroson et al. 2011, ApJ, 729, 12
30 normal early-type galaxies
optical spectroscopy + *Chandra* → detection of bright LMXBs > 10^{38} erg s^{-1}

To a lesser degree, the normalization of the LMXBs XLF also depends on the GC specific frequency, S_N (# GCs/ M⋆)

Both formation channels important



L_K: K-band stellar luminosity; a proxy for M⋆
S_N: GC specific frequency
cyan lines: Kim & Fabbiano 2004, ApJ, 611, 846
magenta lines: Boroson et al. 2011, ApJ, 729, 12

What we have learned so far… #3

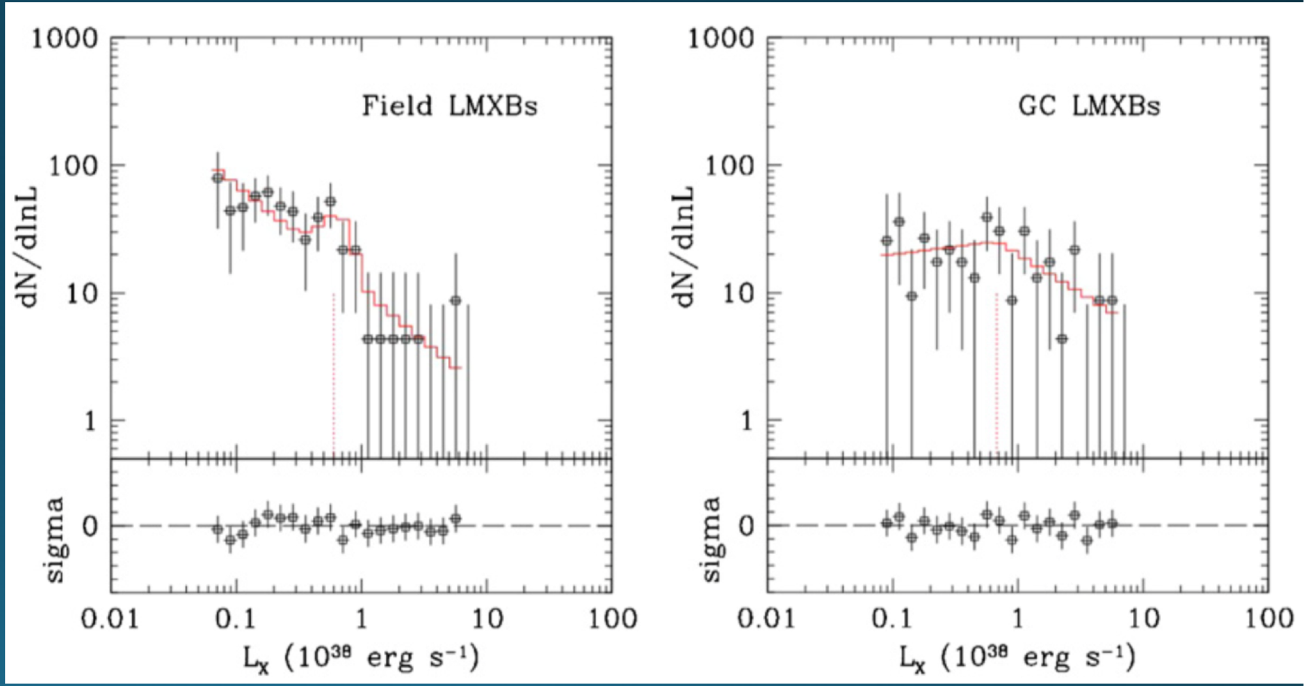
The GC-LMXBs XLF is flatter than that of the field-LMXBs

Kim et al. 2009, ApJ, 703, 829

3 nearby, old elliptical galaxies with ~1 Ms *Chandra* time

- A fraction of the field sources are likely to have originated in GCs
- Break of the XLF at ~5 × 10^{37} erg s^{-1} may be explained by the contribution of red giant donors (Fragos et al. 2008, ApJ, 683, 346)

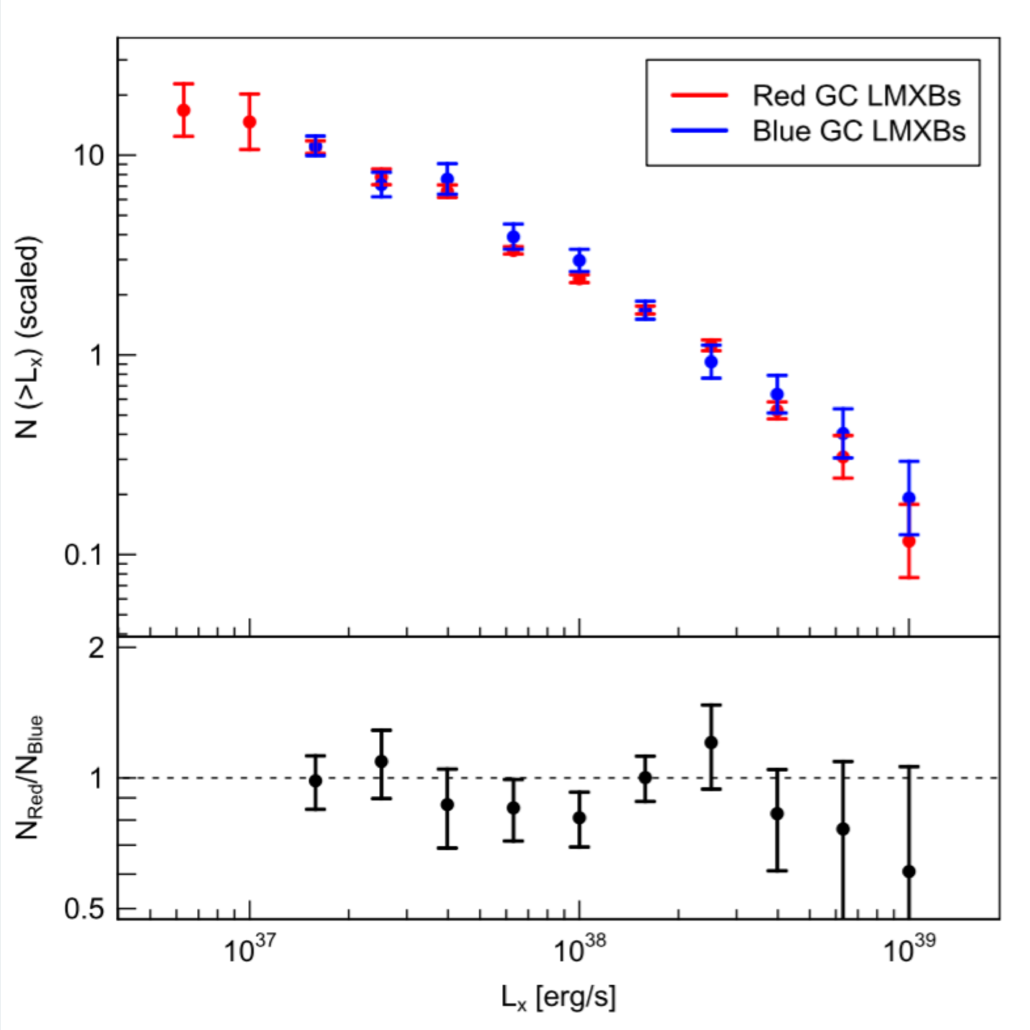
Voss et al. 2009, ApJ, 701, 471
Paolillo et al. 2011, ApJ, 736, 90
Lehmer et al. 2014, ApJ, 789, 52
Peacock & Zepf 2016, ApJ, 818, 33



Field LMXBs: single power-law+Gaussian model
GC LMXBs: broken power-law model

What we have learned so far… #4

Red, metal-rich GCs vs. blue, metal-poor GCs & their LMXBs



Chandra-HST

- 7 local, old, early-type galaxies:

No statistically significant difference in the shape of the LMXBs XLF in metal-rich and metal-poor clusters

Peacock & Zepf 2016, ApJ, 818, 33

- 6 ellipticals (d~17-20 Mpc):

RGCs on average have 3x higher probability of harboring an LMXB than BGCs

Kim et al. 2016, ApJ, 647, 276

What we have learned so far… #5

But what about **normal galaxies with mixed stellar populations** (e.g. Milky Way)?

XRBs consist of both HMXBs and LMXBs → the total XRB X-ray luminosity can be parameterized as a function of both M⋆ & SFR:

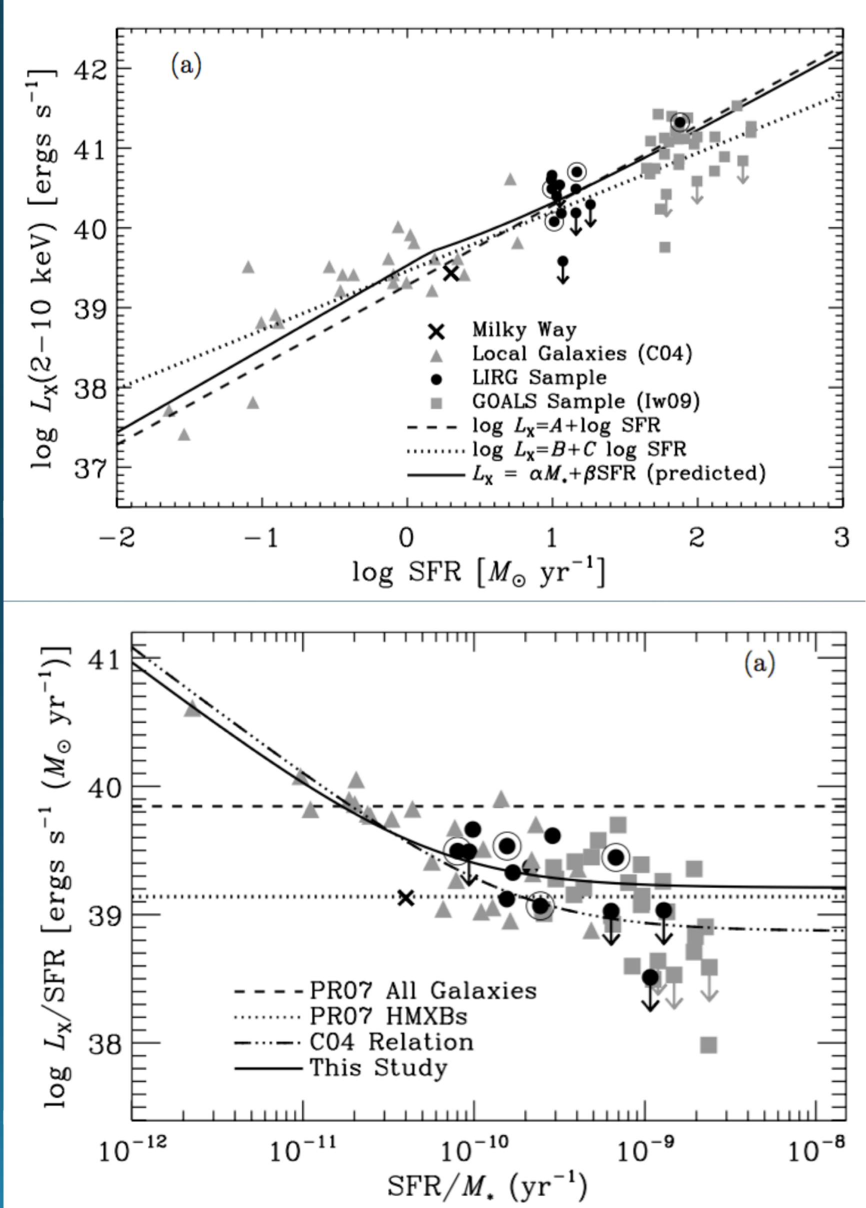
$$L_{X,gal} = L_{X,gal}(LMXBs) + L_{X,gal}(HMXBs)$$
$$= \alpha M_\star + \beta SFR$$

Chandra: 17 LIRGs; D<60Mpc; $N_H \lesssim 5 \times 10^{20}$ cm^{-2}

$\alpha = (9.05 \pm 0.37) \times 10^{28}$ (erg/s)/M⊙

$\beta = (1.62 \pm 0.22) \times 10^{39}$ (erg/s)/(M⊙/yr)

Lehmer et al. (2010, ApJ, 724, 559)



What we have learned so far… #5

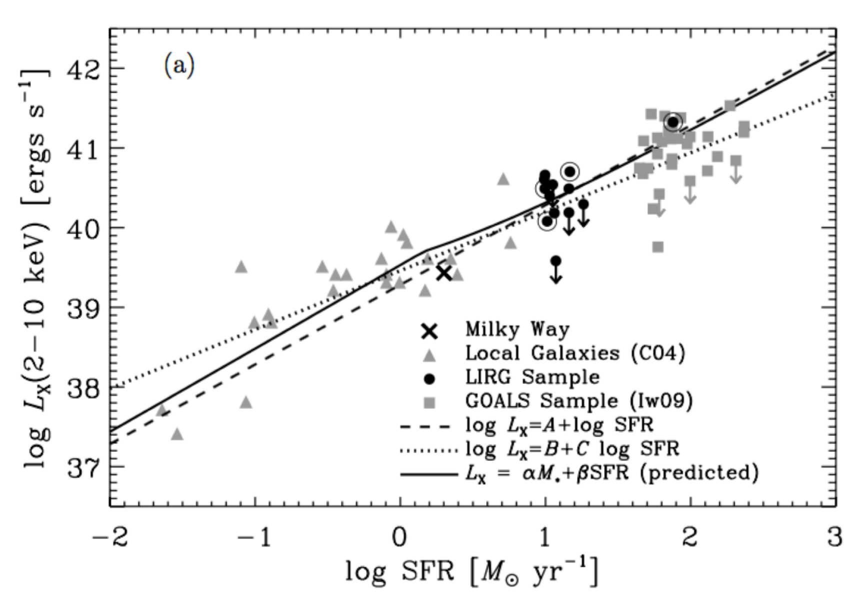
$$L_{X,gal} = L_{X,gal}(\text{LMXBs}) + L_{X,gal}(\text{HMXBs})$$
$$= \alpha M_\star + \beta \text{SFR}$$

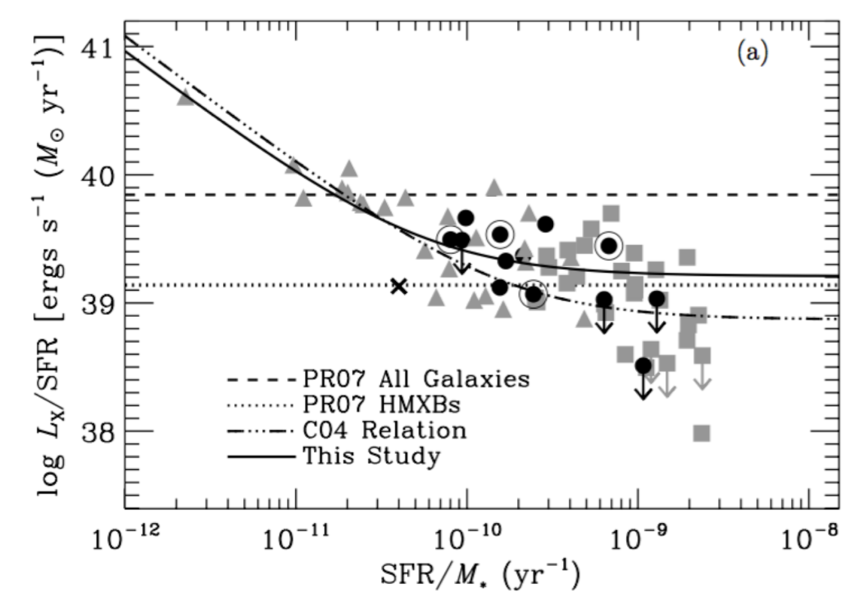
$\alpha = (9.05 \pm 0.37) \times 10^{28}$ (erg/s)/$M_\odot$

$\beta = (1.62 \pm 0.22) \times 10^{39}$ (erg/s)/($M_\odot$/yr)

These values suggest that the HMXBs dominate the galaxy-wide X-ray emission for galaxies with $\text{SFR}/M_\star \gtrsim 5.9 \times 10^{-11}\ \text{yr}^{-1}$

Can be used to investigate the evolution of XRB populations at different redshifts

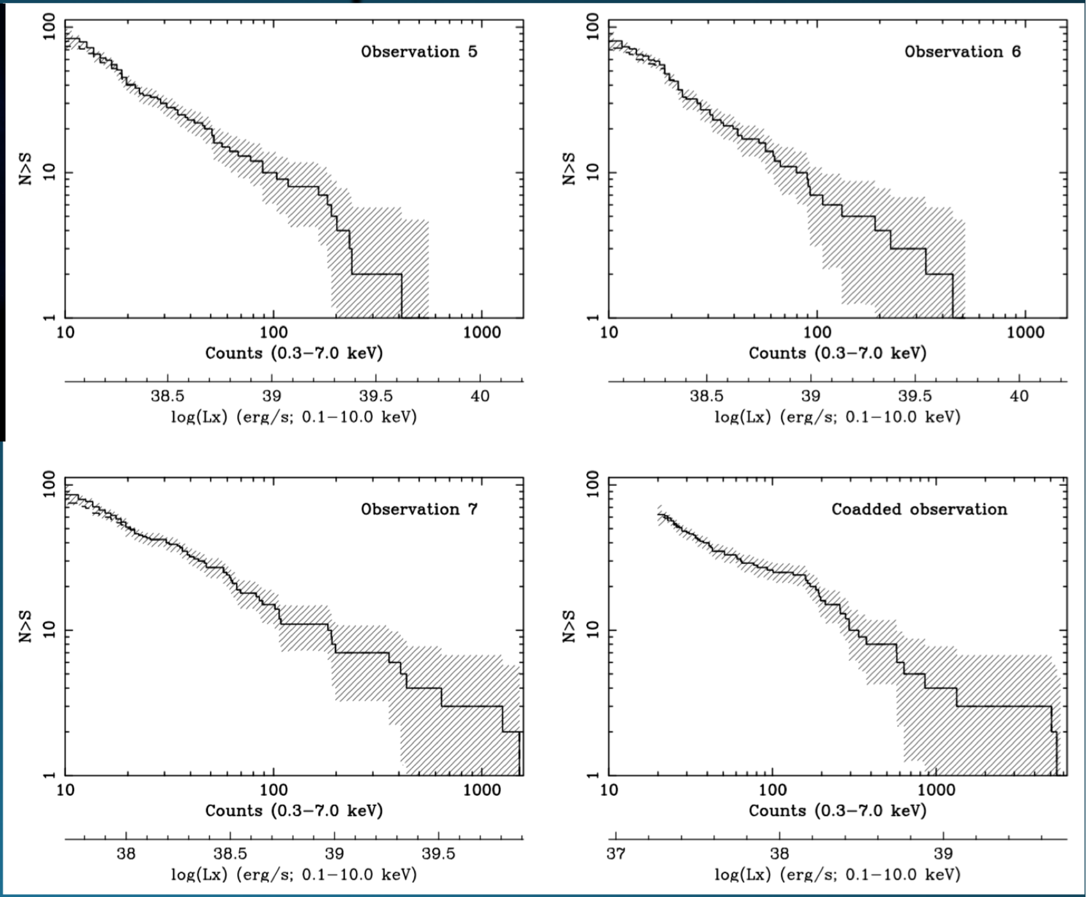




Lehmer et al. (2010, ApJ, 724, 559)

What we have learned so far… #6

Long-term variability of XRBs
Even a strong source variability does not affect the shape of the XLF



Zezas+2007, ApJ, 661, 135

- NGC 4038/4039 (the Antennae; 19 Mpc): 7 *Chandra* observations; $L_{X,limiting}$~10^{37} ergs s^{-1}

Fridriksson et al. 2008, ApJS, 177, 465

- spiral galaxy NGC 6946 (~8 Mpc): 5 *Chandra* observations; few times 10^{36} ergs s^{-1}
- irregular/spiral interacting galaxies NGC 4485/4490 (~8 Mpc): 3 *Chandra* observations; ~10^{37} ergs s^{-1}

Sell et al. 2011, ApJ, 735, 26

- M81 (3.6 Mpc): 15 *Chandra* observations; ~10^{37} ergs s^{-1}

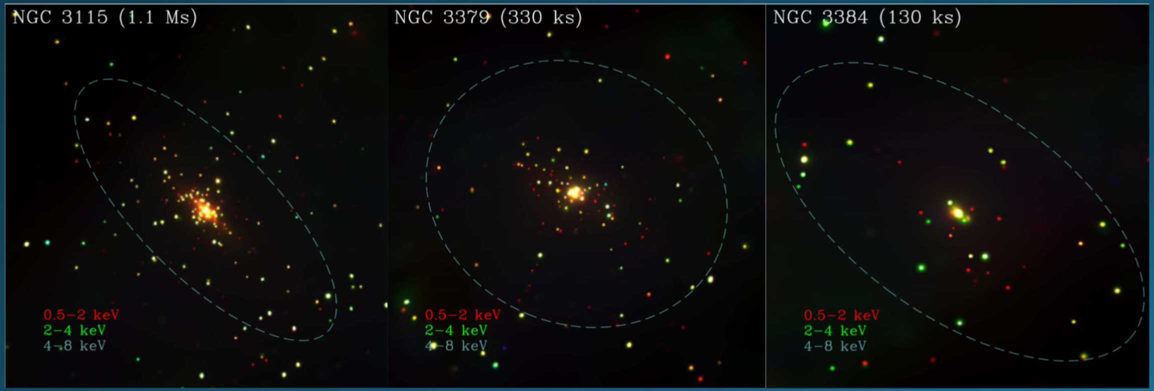
What we have learned so far… #8

Age effects on XRBs: the case of LMXBs

(Kim & Fabbiano 2010, ApJ, 721, 1523; Zhang et al. 2012, A&A, 546, 36)

Evolution of the number of LMXBs & their XLF with age:

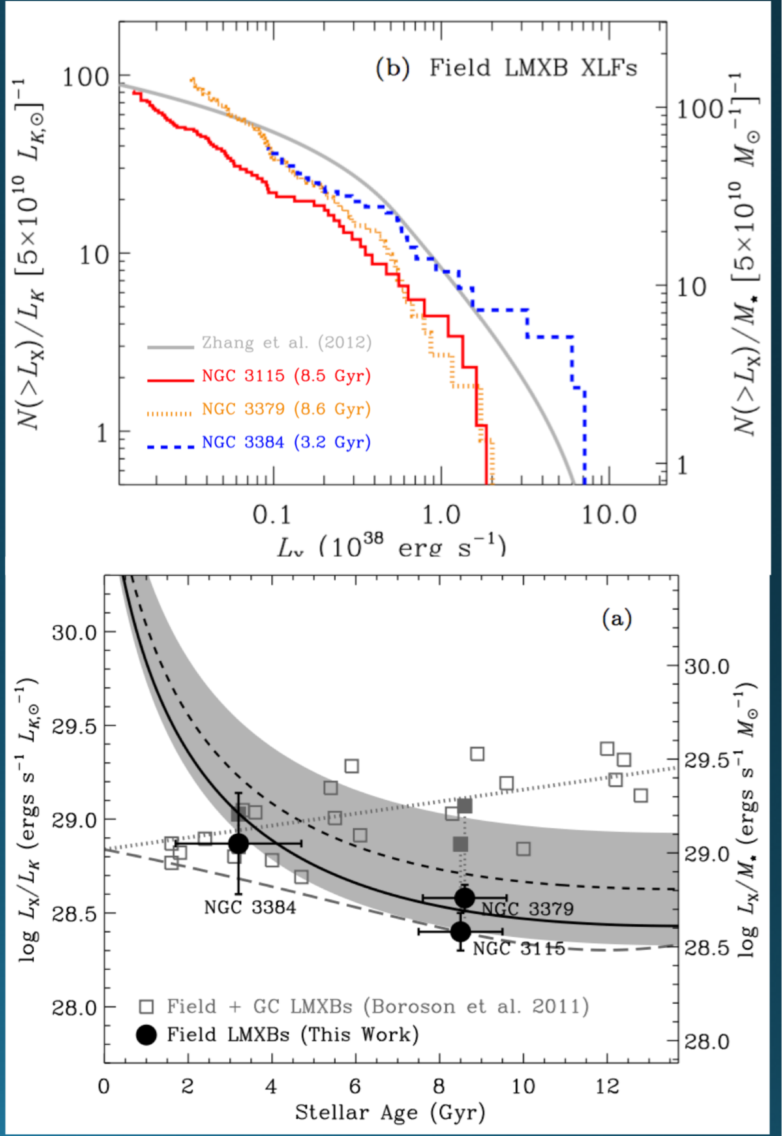
Young early-type galaxies have more numerous & luminous field LMXB populations than old early-type galaxies



Lehmer et al. 2014, ApJ, 789, 52

Chandra-HST

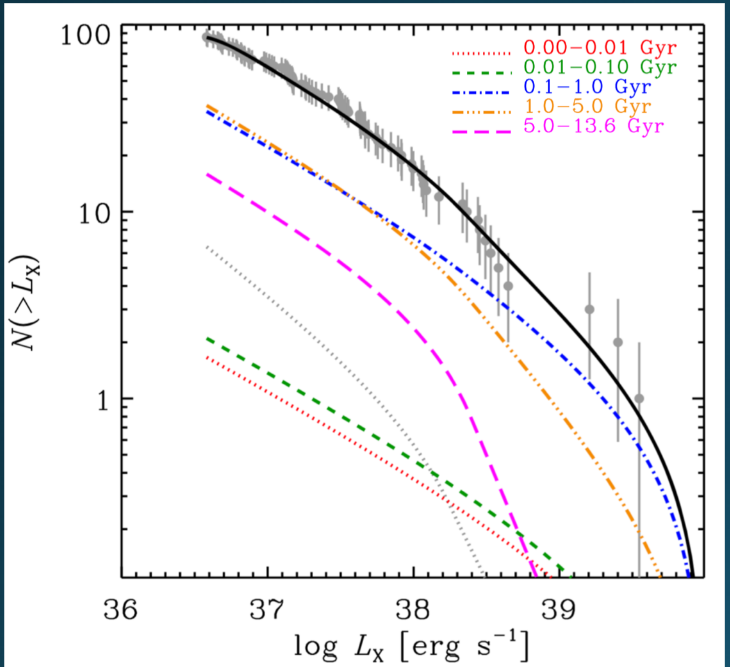
3 nearby early-type galaxies



What we have learned so far… #9

Age effects on XRBs: the case of HMXBs

≈850 ks cumulative *Chandra* exposure of M51 (d=8.6Mpc; Z~2-3Z⊙)



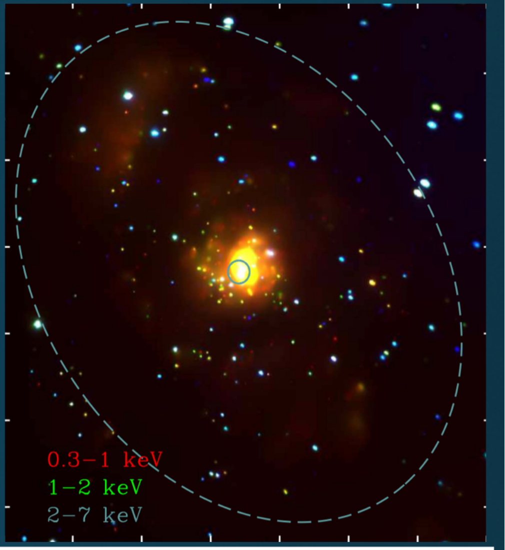
black: SFH XLF model folded in with M51 SFH with contributions from all 5 stellar-age bins

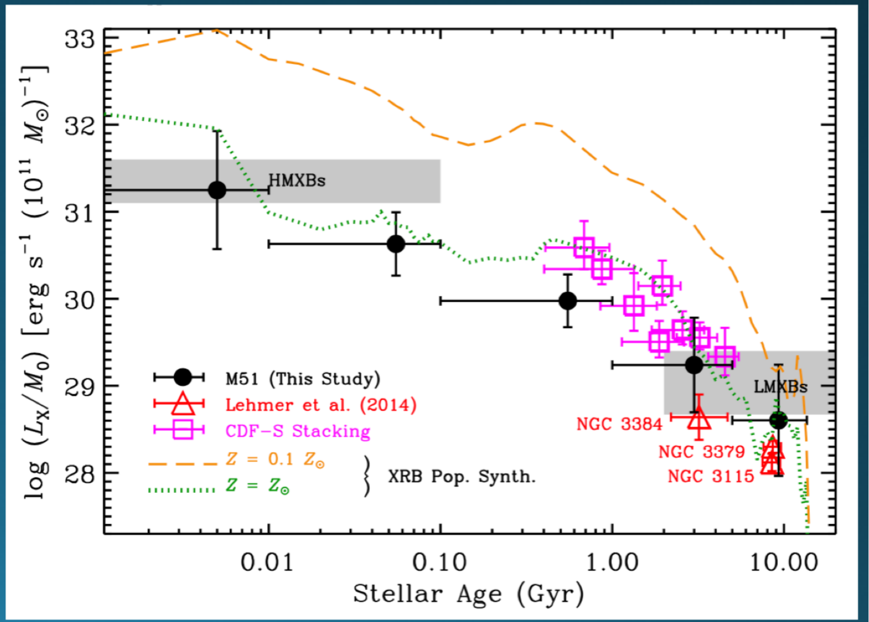
X-ray power output evolution for XRB populations, normalized by a birth mass of $M_0 = 10^{11}$M⊙.

Estimates from

- HMXB and LMXB scaling relations
- field LMXBs in 3 ellipticals
- X-ray stacking analyses in the ≈6 Ms CDF-S

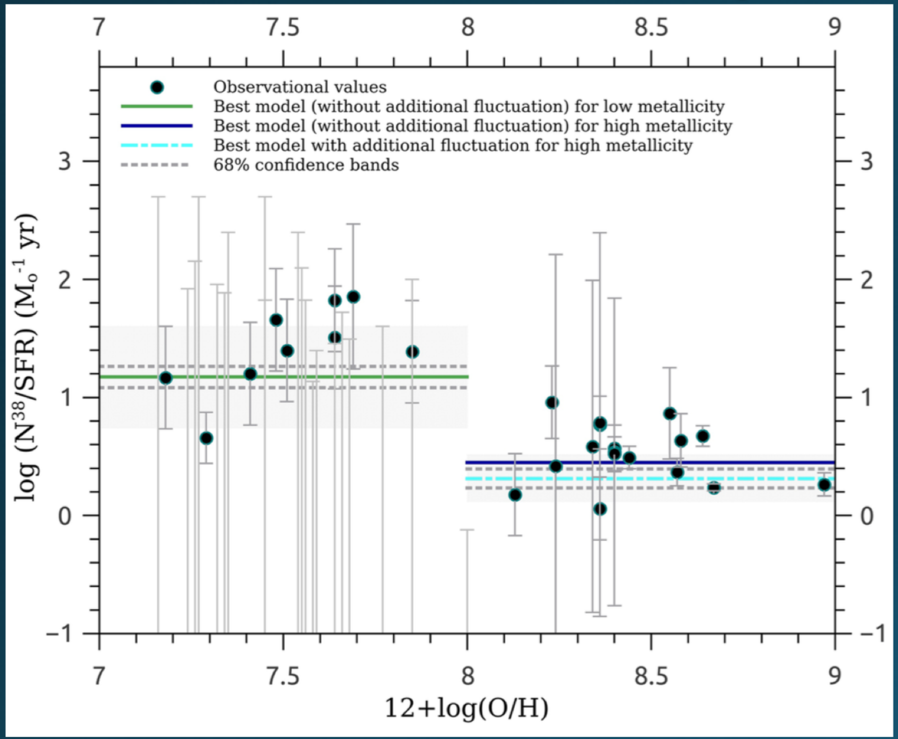
Lehmer et al. 2017, ApJ, 851, 11





What we have learned so far… #10

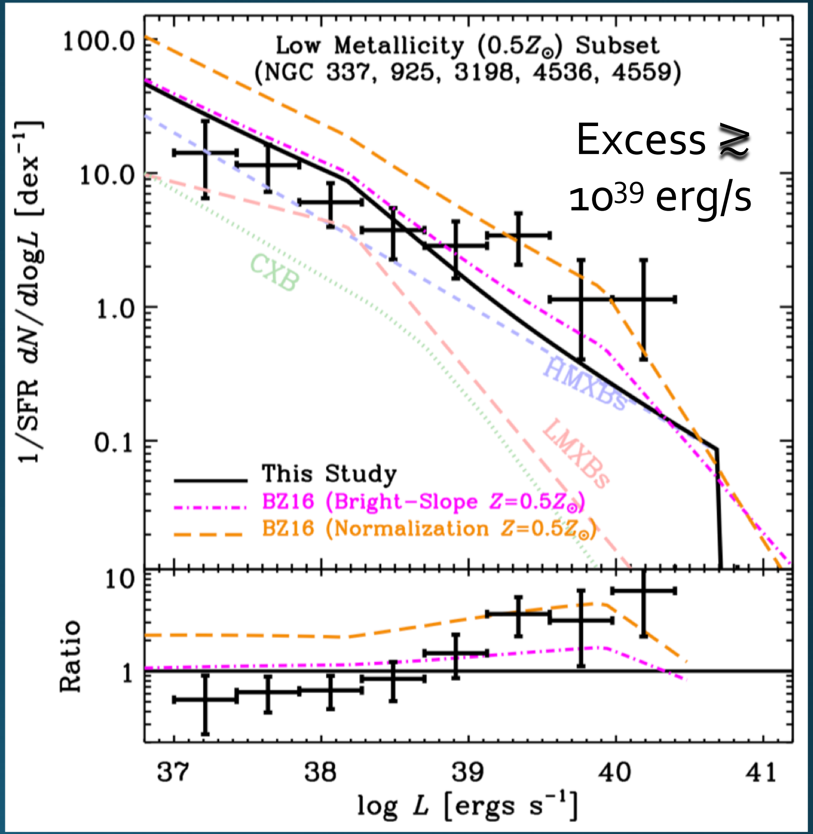
Enhanced HMXB production at low metallicity



Douna et al. 2015, A&A, 579, 44

~10x more HMXBs (per unit SFR) with $L_X > 10^{38}$ erg s^{-1} in low-metallicity galaxies (12+log(O/H)<8, i.e. < 20% Z⊙)

Kaaret+2011, ApJ, 741, 10;
Basu-Zych+2013, ApJ, 774, 152;
Prestwich+2013, ApJ, 769, 92;
Brorby+2014, MNRAS, 441, 2346;
Ponnada et al. 2019,
MNRAS acc., arXiV: 1910.06925

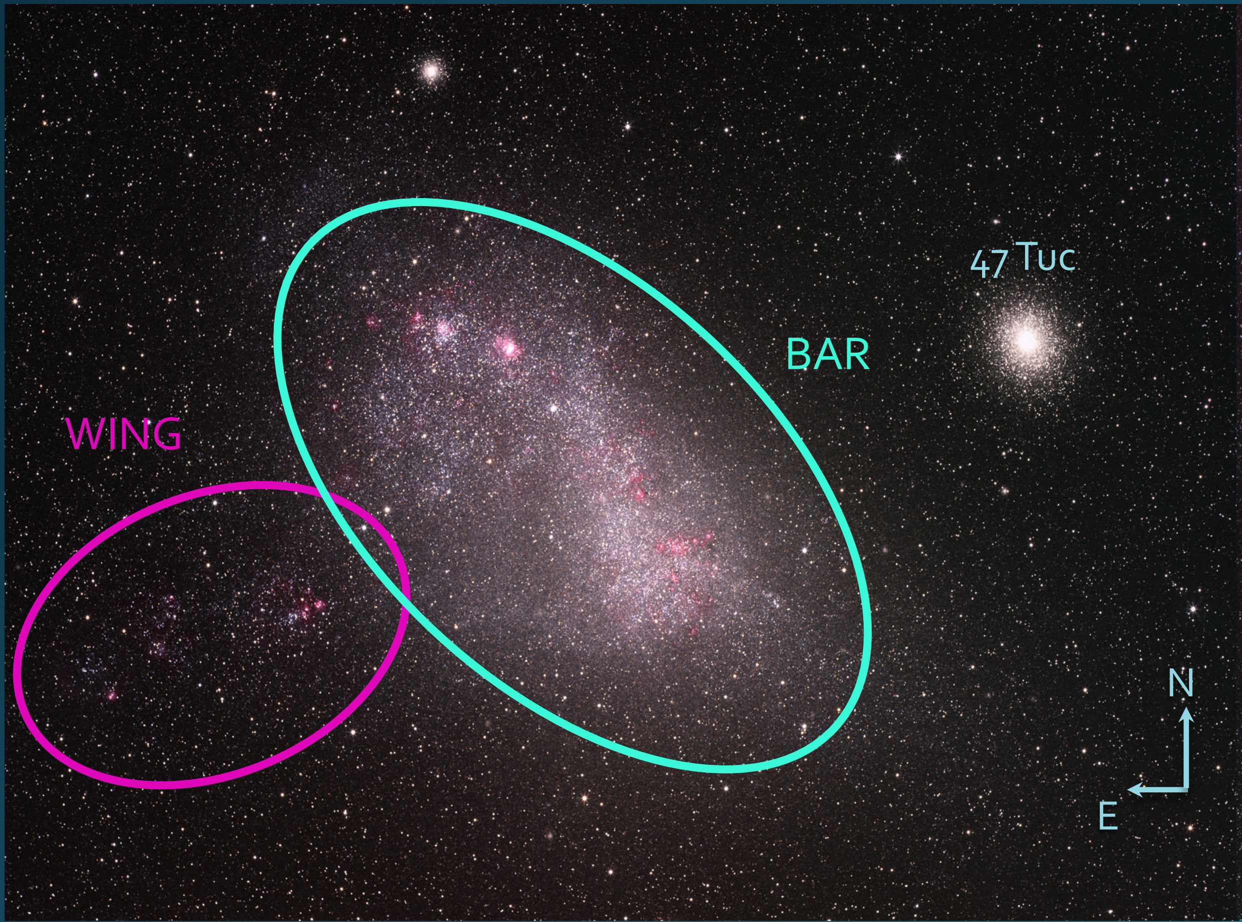


Lehmer et al. (2019, ApJS, 243, 3)

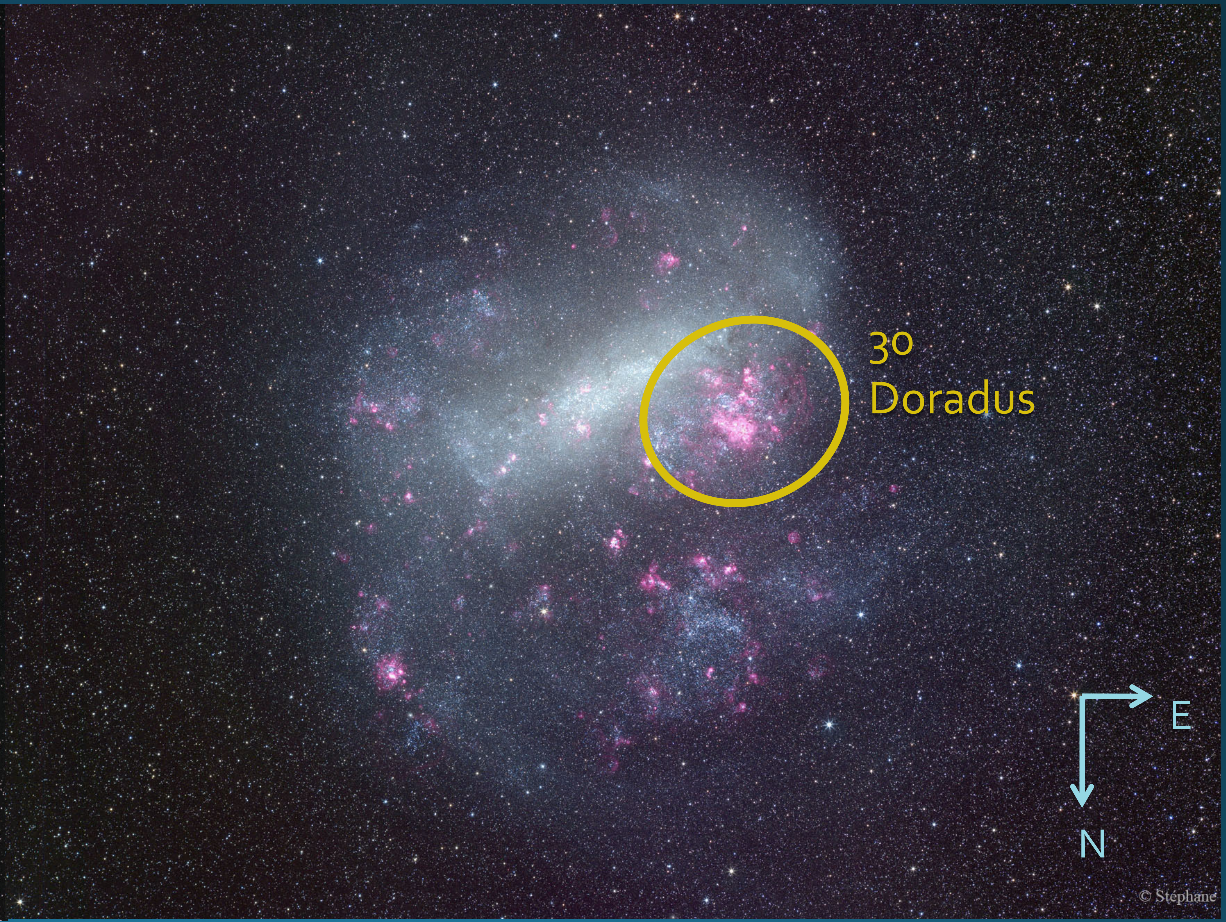
38 galaxies from SINGS sample: SFR-normalized total XLF for the 5 lowest-metallicity galaxies (≈0.5Z⊙)

Our nearest star-forming galactic neighbors

Small Magellanic Cloud
(SMC; ~60 kpc)

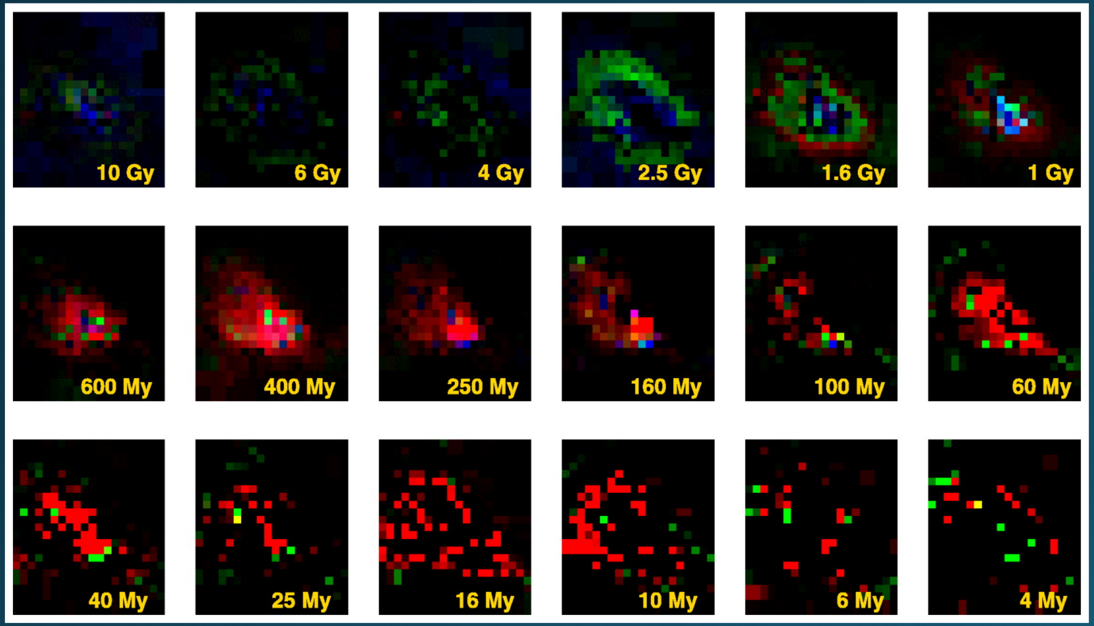


Large Magellanic Cloud
(LMC; ~50 kpc)



Spatially-resolved SFH maps of the MCs

Small Magellanic Cloud
(SMC; ~60 kpc)

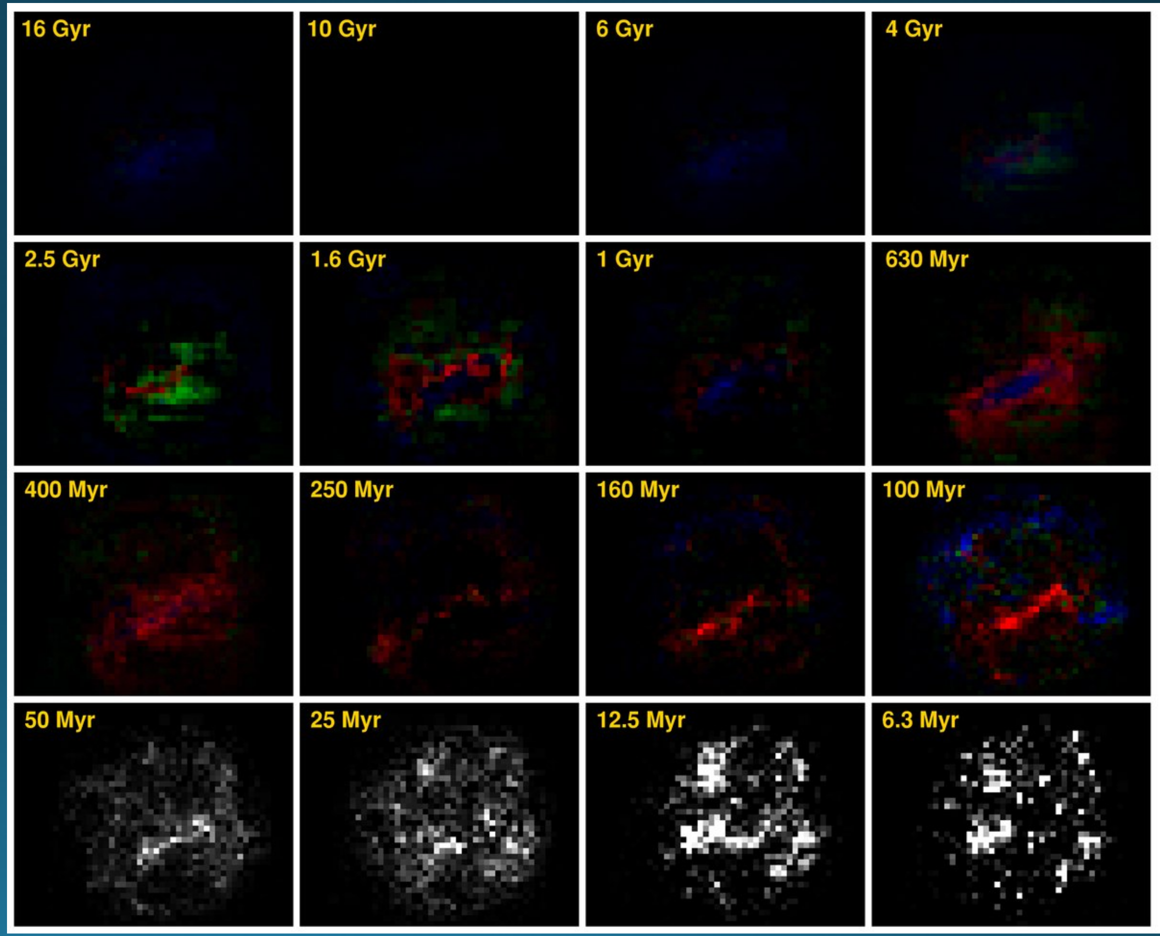


pixel (12’x12’) intensity proportional to the subregion's SFR

Z = 0.008, Z = 0.004, Z = 0.001

Harris & Zaritsky 2004, AJ, 127, 1531

Large Magellanic Cloud
(LMC; ~50 kpc)

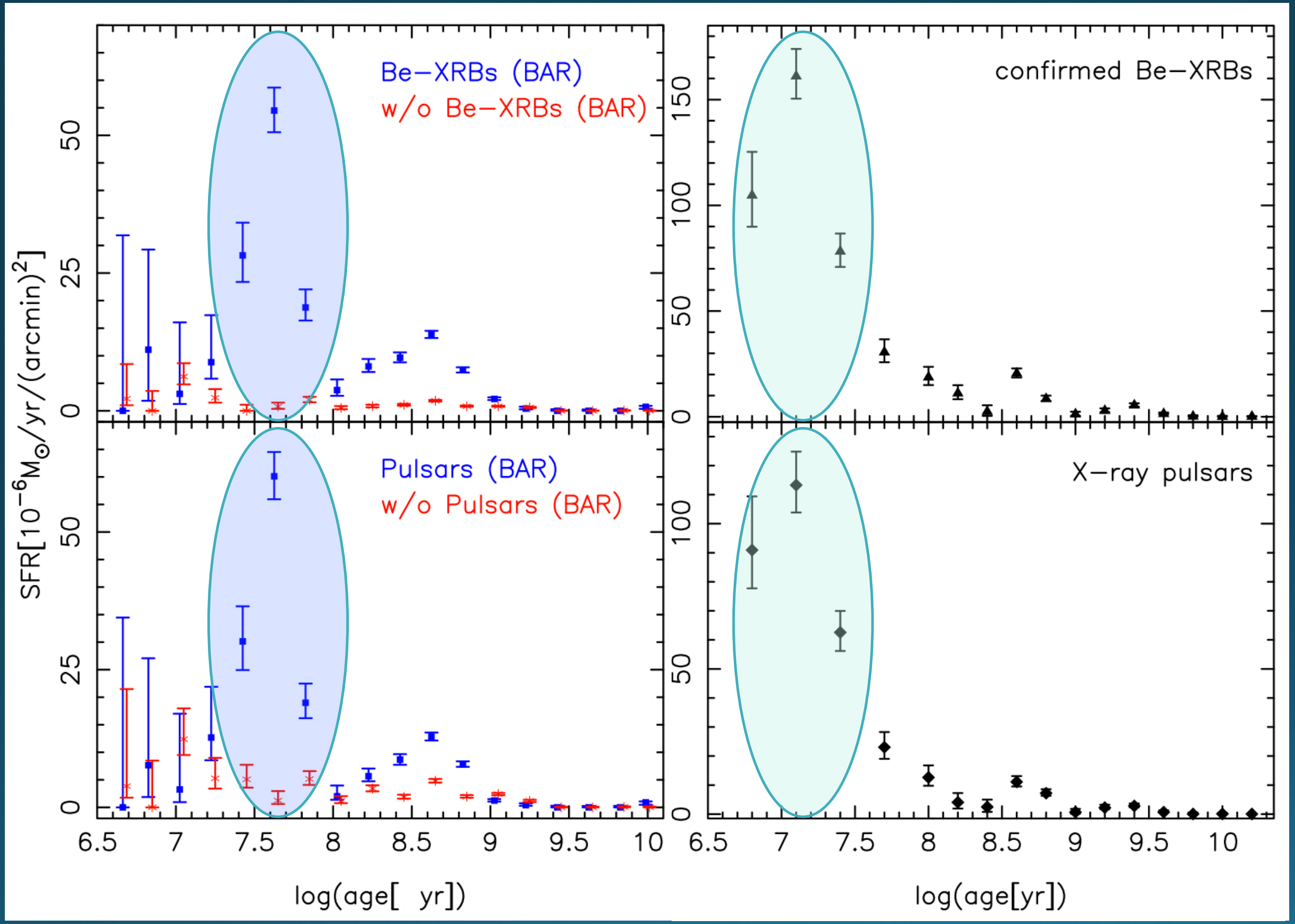


Harris & Zaritsky 2009, AJ, 13, 1243

Highest formation rate of HMXBs

SMC ~ 42.2 Myr; Z~1/5Z⊙ LMC ~ 12.6 Myr; Z~1/2.5Z⊙

Strong correlation (XRB number & age of stellar pops. at their location) allows us to measure for the *first* time the XRB formation rate per unit SFR of their parent stellar populations



The formation efficiency of HMXBs (Be-XRBs) in the LMC is ~17x (7x) lower than that in the SMC, primarily due to the different ages and metallicity of the HMXB populations in the two galaxies

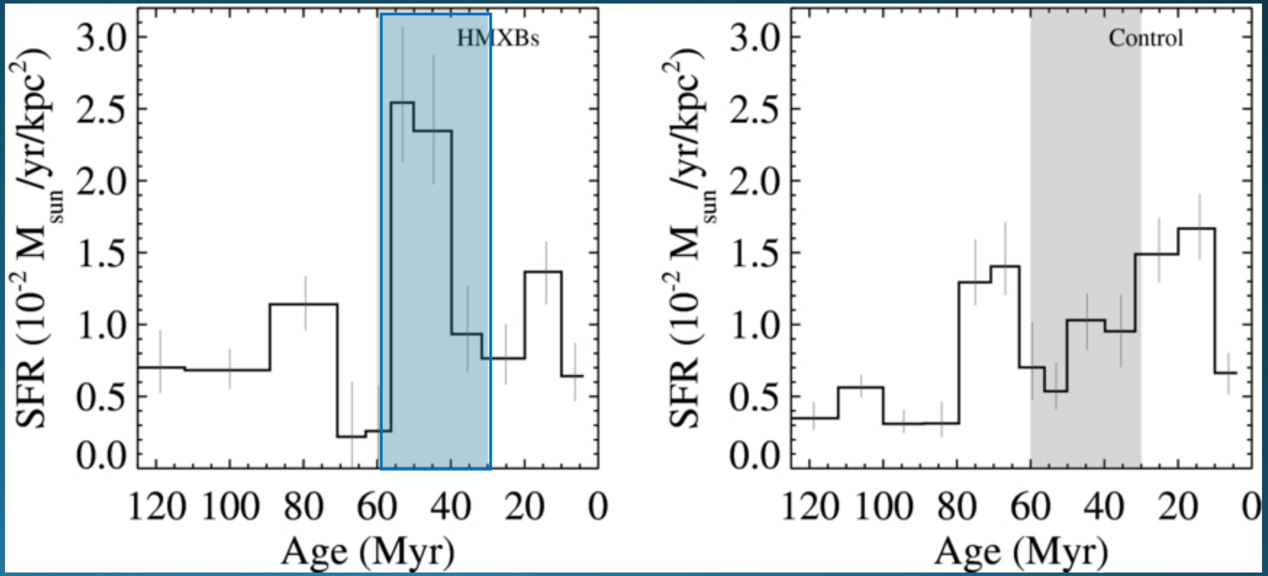
Antoniou et al. 2010, ApJL, 716, 140; 2016, MNRAS, 459, 528

Highest formation rate of HMXBs

NGC 300 & NGC 2403 ($Z\sim(1/5\text{-}1/2)Z_\odot$)

Williams et al. (2013, ApJ, 772, 12): deep *Chandra* observations as part of the *Chandra* Local Volume Survey (CLVS)

- NGC300 (2 Mpc): 63 ks with *Chandra* + *HST*; limiting $L_{X,\mathrm{unabs}(0.35\text{-}8\mathrm{keV})} \sim 10^{36}$ erg s^{-1} (Binder et al. 2012, ApJ, 785, 15)
- NGC2403 (3.3 Mpc): 190 ks with *Chandra* + *HST*; limiting $L_{X,\mathrm{unabs}(0.35\text{-}8\mathrm{keV}} \sim 5\times10^{35}$ erg s^{-1} (Binder et al. 2015, AJ, 150, 94)



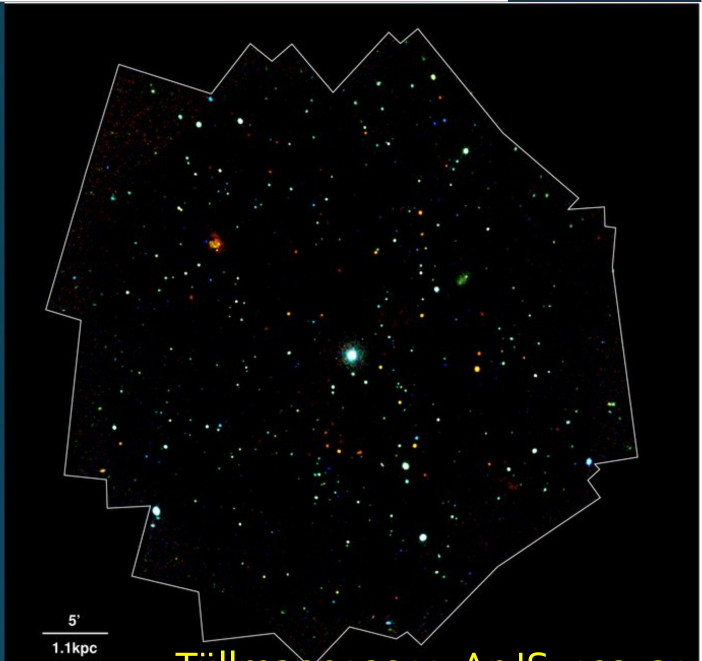
increased HMXB formation efficiency at an age of ~40 Myr

Highest formation rate of HMXBs

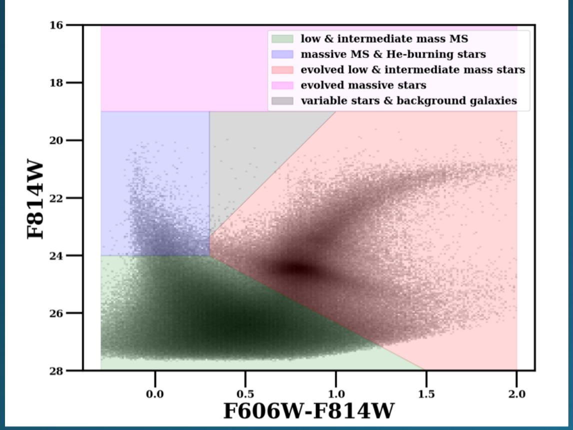
M33 (Z~1/20Z⊙)

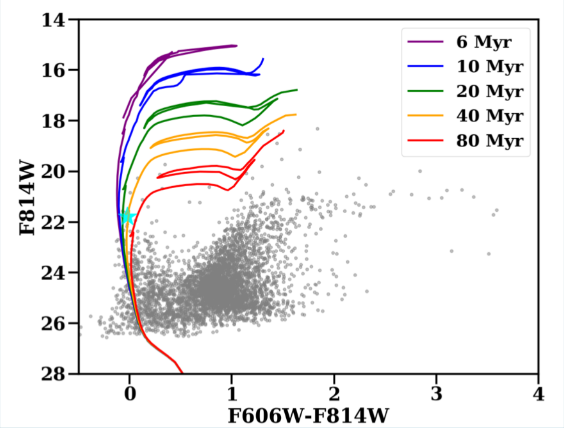
Garofali et al. (2018, MNRAS, 479, 3256): archival *Chandra* & HST data

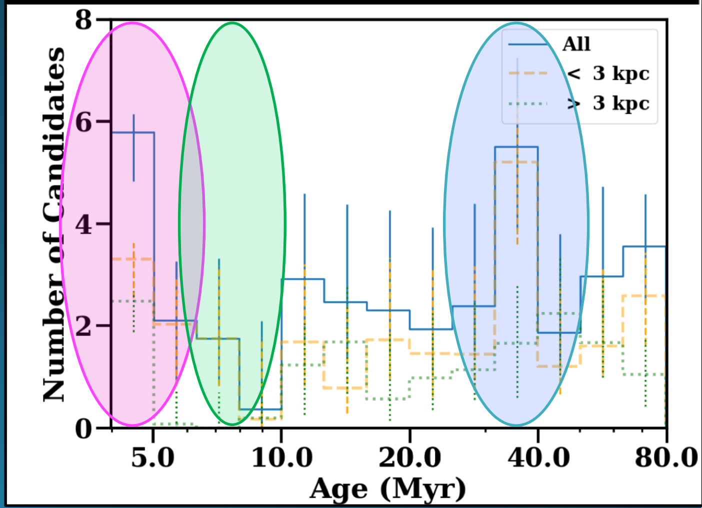
- a peak in production at <5 Myr
- few, if any, sources between 6-10 Myr
- another peak at ~40 Myr



Tüllmann+2011, ApJS, 193, 31







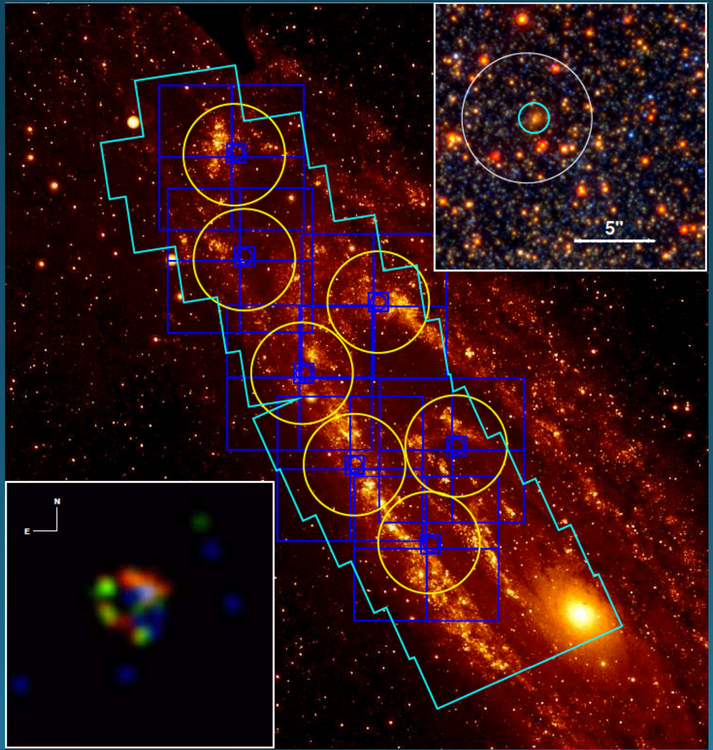
Highest formation rate of HMXBs

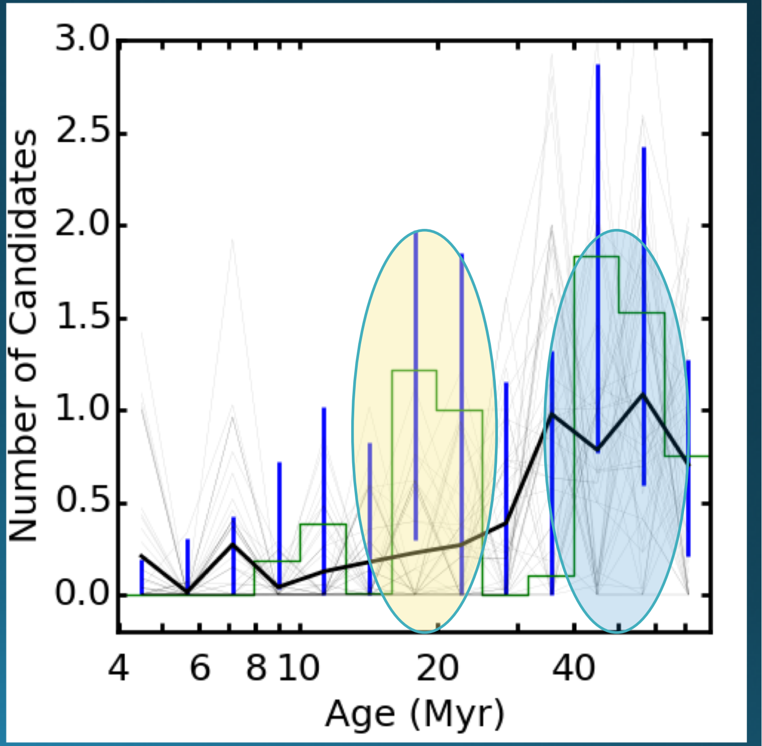
M31 ($Z \sim 1/3.5 Z_\odot$)

...the only other galaxy in our Local Group that resembles our own

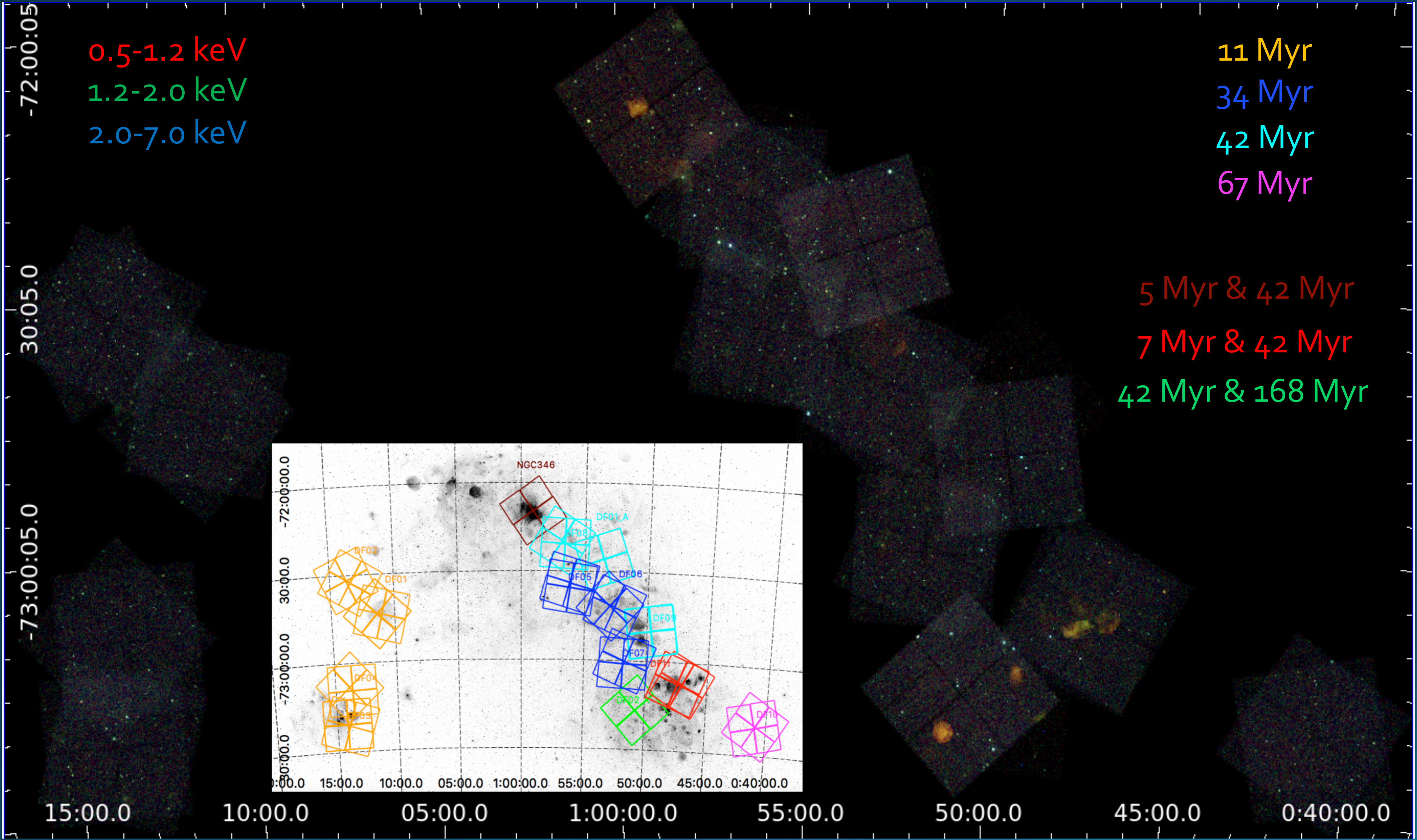
Williams et al. (2018, ApJS, 239, 13): *Chandra* Legacy Survey (350 ks; $L_{X,limit} \sim 5 \times 10^{35}$ erg/s) & Panchromatic Hubble Andromeda Treasury survey (Multi-epoch UV to NIR photometry; SFHs derived on 50-100 pc scales)

age distribution has two peaks at 15-20 Myr and 40-50 Myr





Formation rate of HMXBs as a function of age



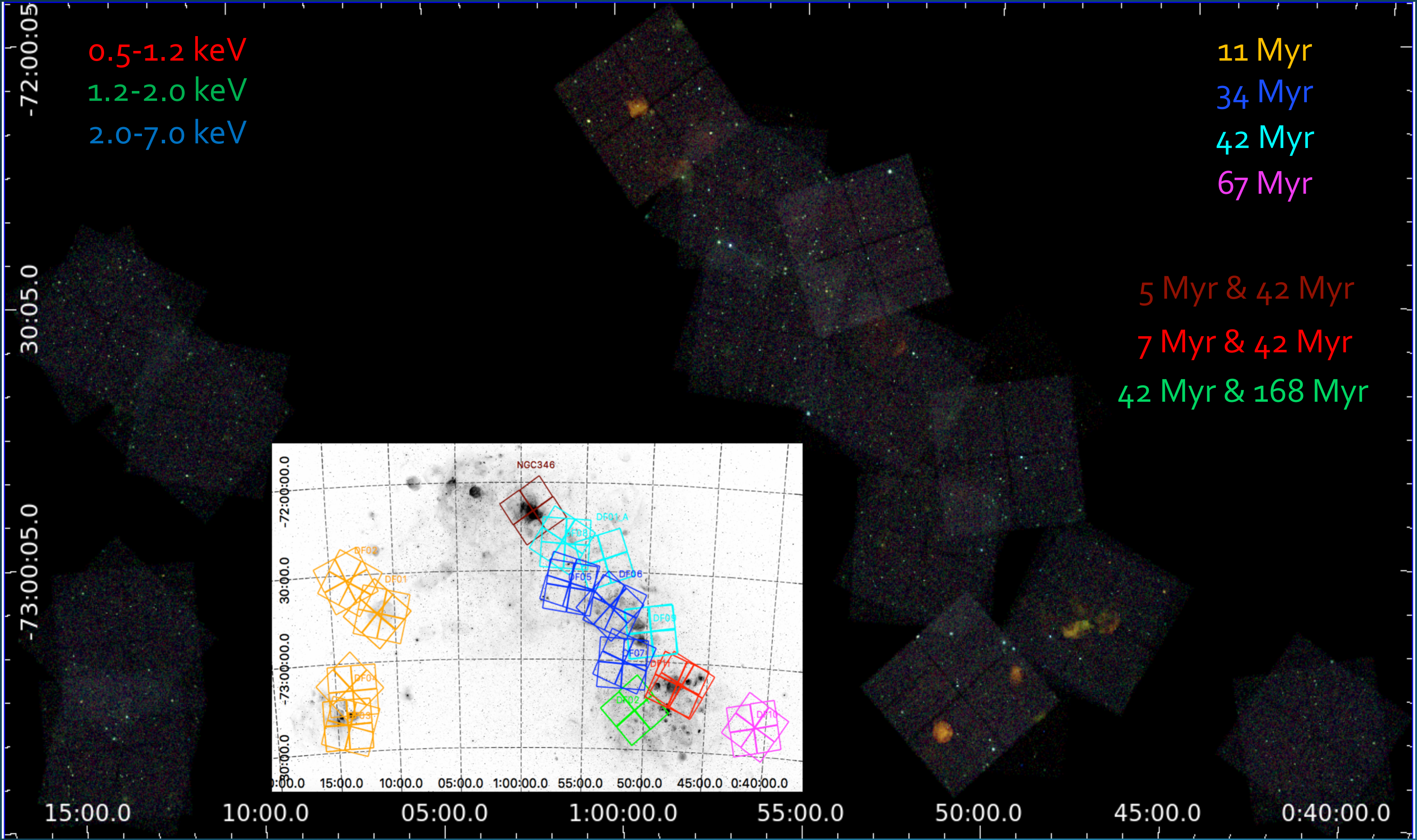
XVP Program (1.1 Ms)

PI A. Zezas

A comprehensive survey of sources brighter than ~ few times 10^{32} erg s^{-1} in 11 fields in the SMC representing young (<100 Myr) populations of different ages

Antoniou et al. 2019, ApJ acc.; arXiV: 1901.01237

Formation rate of HMXBs as a function of age



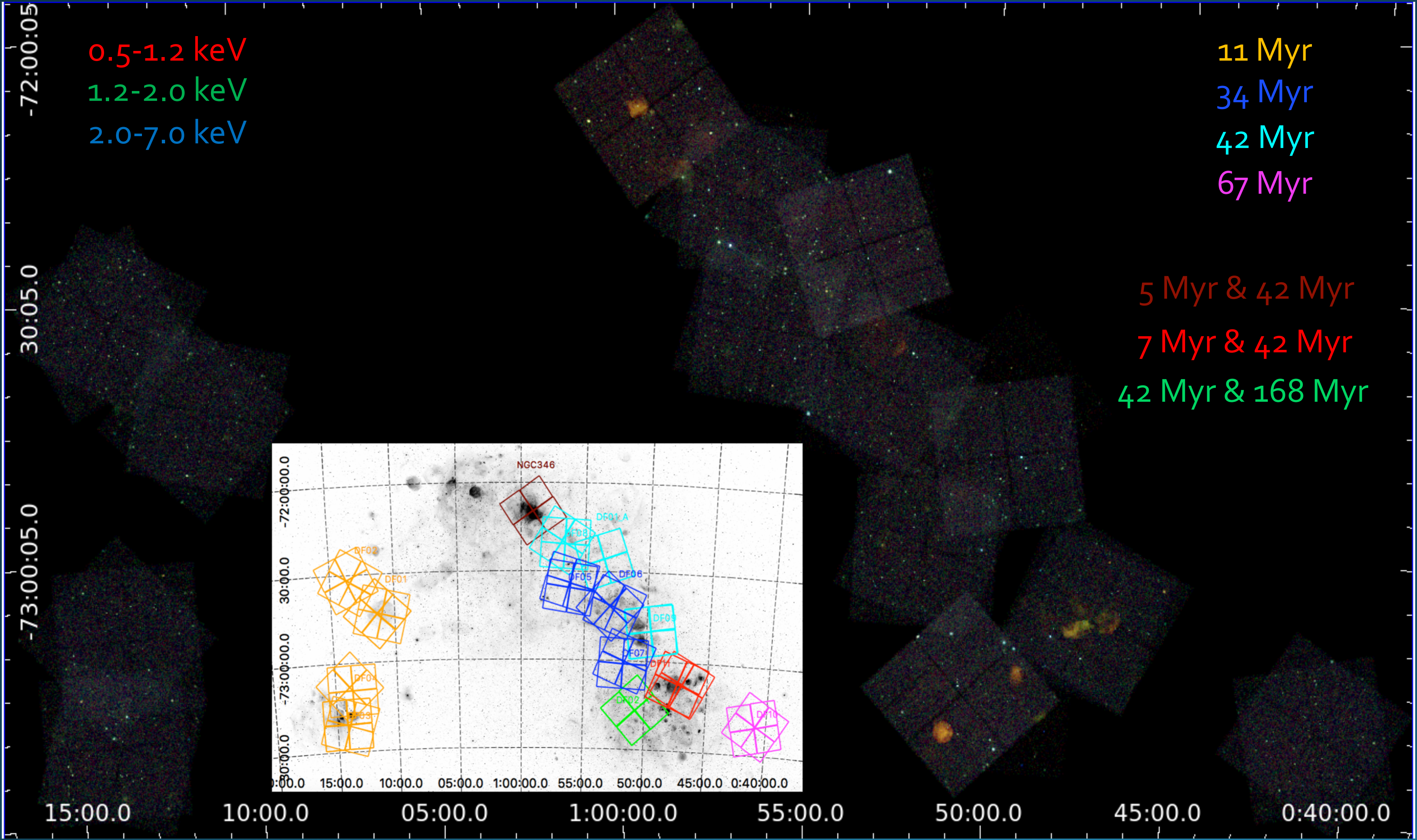
XVP Program (1.1 Ms)

PI A. Zezas

11 fields (each 2 x 50ks) + 3 archival fields with similar exposure times

All active HMXBs and a large fraction of their quiescent population in regions sampling "clean" stellar populations

Formation rate of HMXBs as a function of age



XVP Program (1.1 Ms)

PI A. Zezas★

- 2,393 unique sources down to $L_X \sim 2 \times 10^{32}$ erg/s
- 903 sources with >20 net cnts
- ~140 candidate HMXBs down to $L_X \sim 5 \times 10^{32}$ erg/s

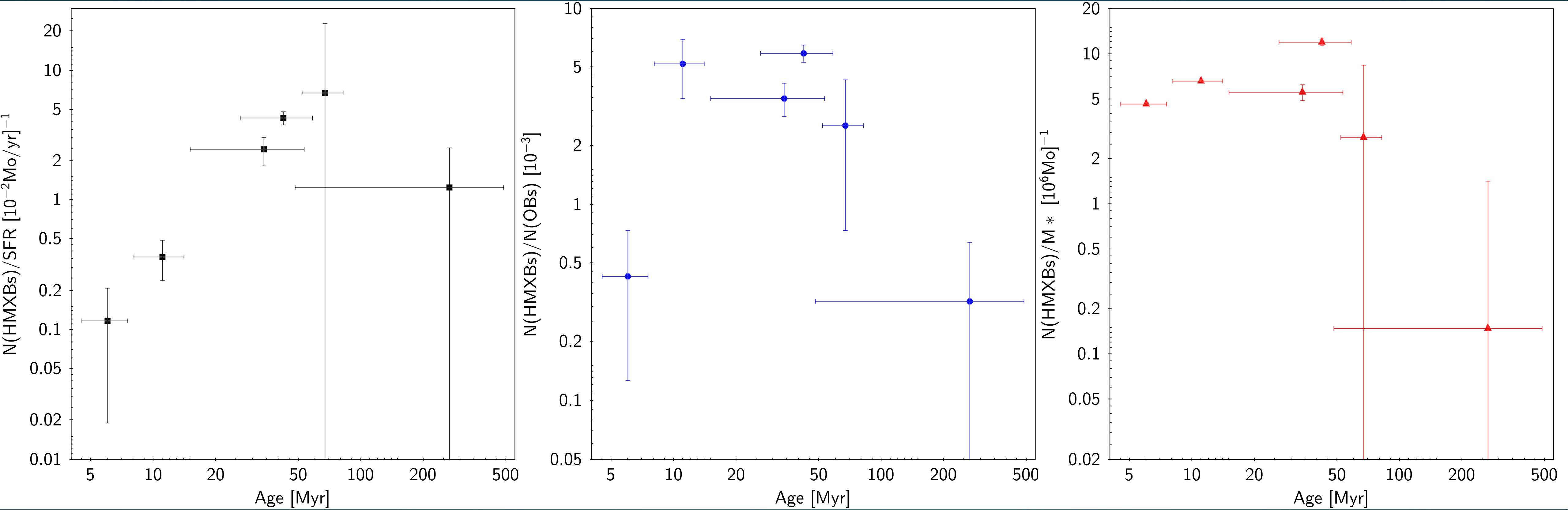
★ see poster!

Antoniou et al. 2019, ApJ acc.; arXiV: 1901.01237

Formation rate of HMXBs

Antoniou et al. 2019, ApJ acc.; arXiV: 1901.01237

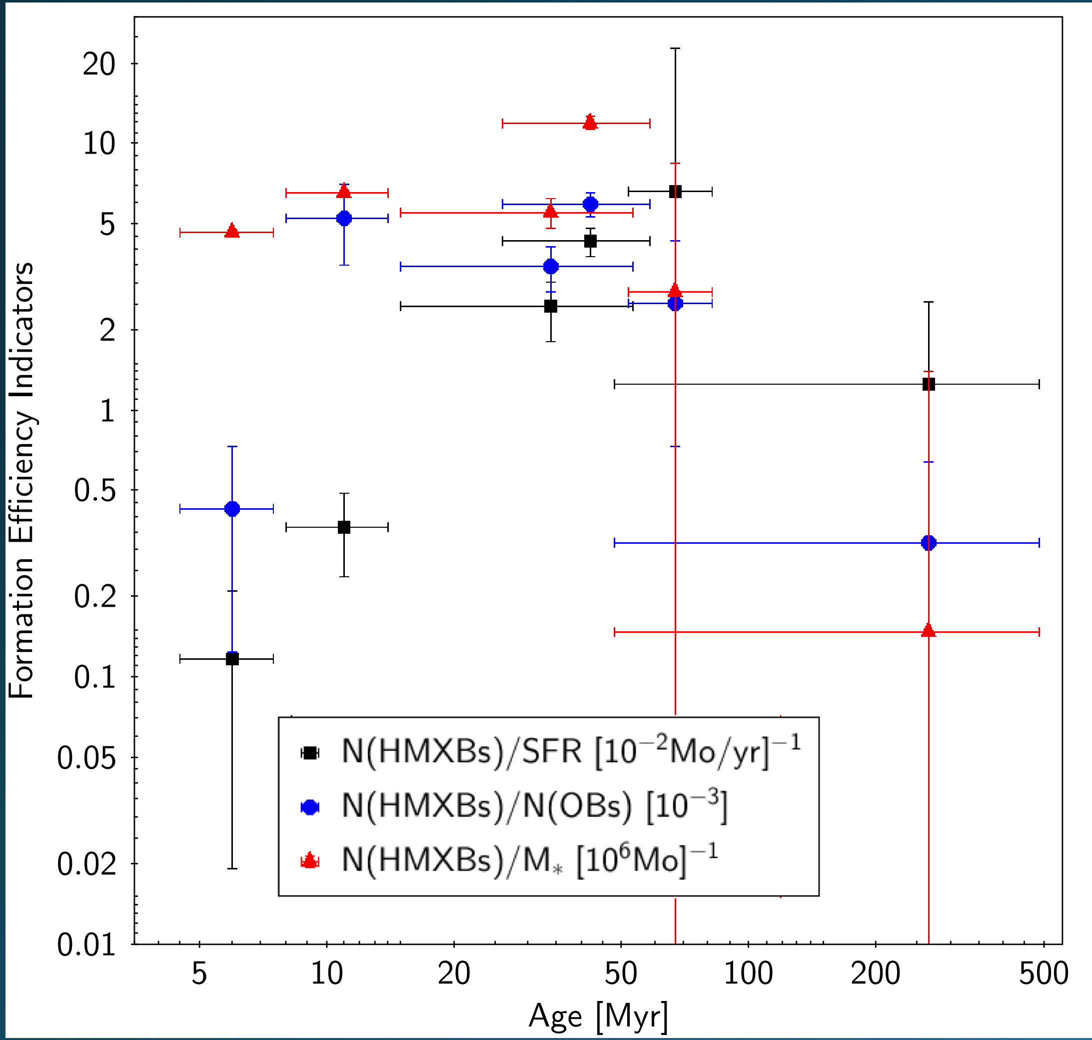
for the *first* time as a function of age of their associated SF burst



Formation rate of HXMBs

Antoniou et al. 2019, ApJ acc.; arXiV: 1901.01237

for the *first* time as a function of age of their associated SF burst



Formation efficiency: increase up to an age of ~40–60 Myr, and a gradual decrease thereafter

$(N(HMXB)/SFR)_{peak}$ = (430 ± 52) $(M_\odot/yr)^{-1}$ at 42 Myr

$(N(HMXB)/SFR)_{average}$ = 339^{+78}_{-83} $(M_\odot/yr)^{-1}$ in the 30–40 Myr age range

Looking into the future

Chandra has demonstrated that ***high spatial resolution is critical for studies of accreting binary populations***.

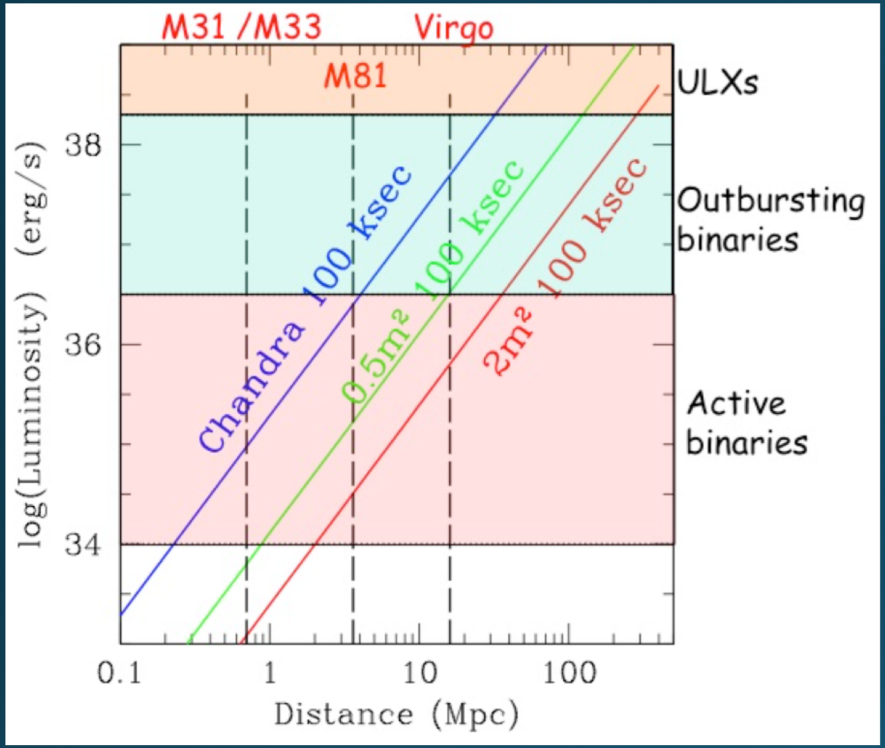
However, due to its relatively low effective area, ***Chandra allows us to study in great detail only nearby galaxies***.

In order to make the next leap forward in our understanding of the accreting binaries, we need larger source populations that cover a wider range of the galactic environment parameter space (stellar age, metallicity, SFR).

A new high-resolution, high-throughput telescope will increase the discovery space!

Zezas et al. 2019, Astro2020 WP

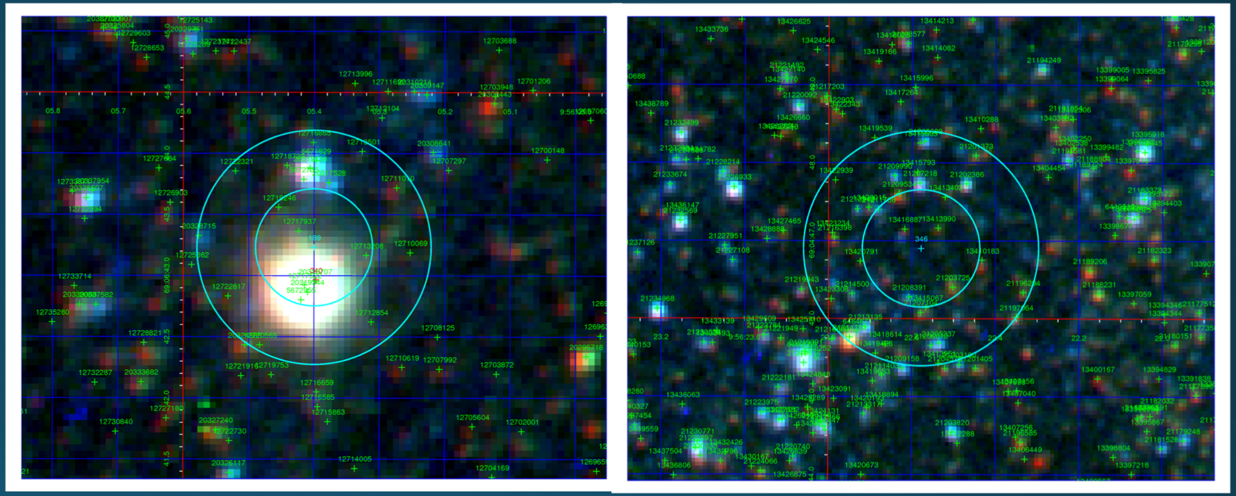
A high-resolution, high-throughput X-ray mission



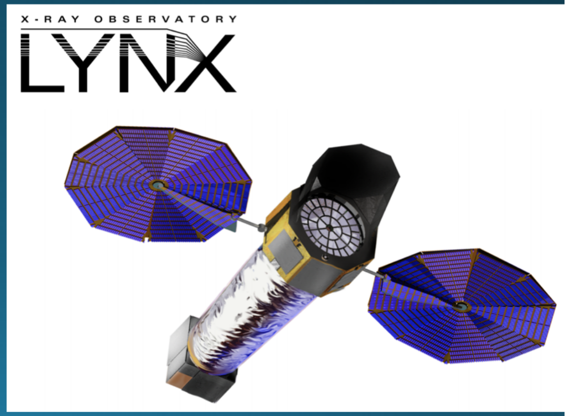
Distances to nearby objects and different source types that will be probed at various luminosities

Black curves: $L_{X,\mathrm{limiting}}$ (3σ level) for different effective areas and 0.5" resolution

For the characterization of the XRBs, we need high resolution



Zezas et al. 2019, Astro2020 WP



Looking forward to 20+ more years with *Chandra*!

Thank you for your attention