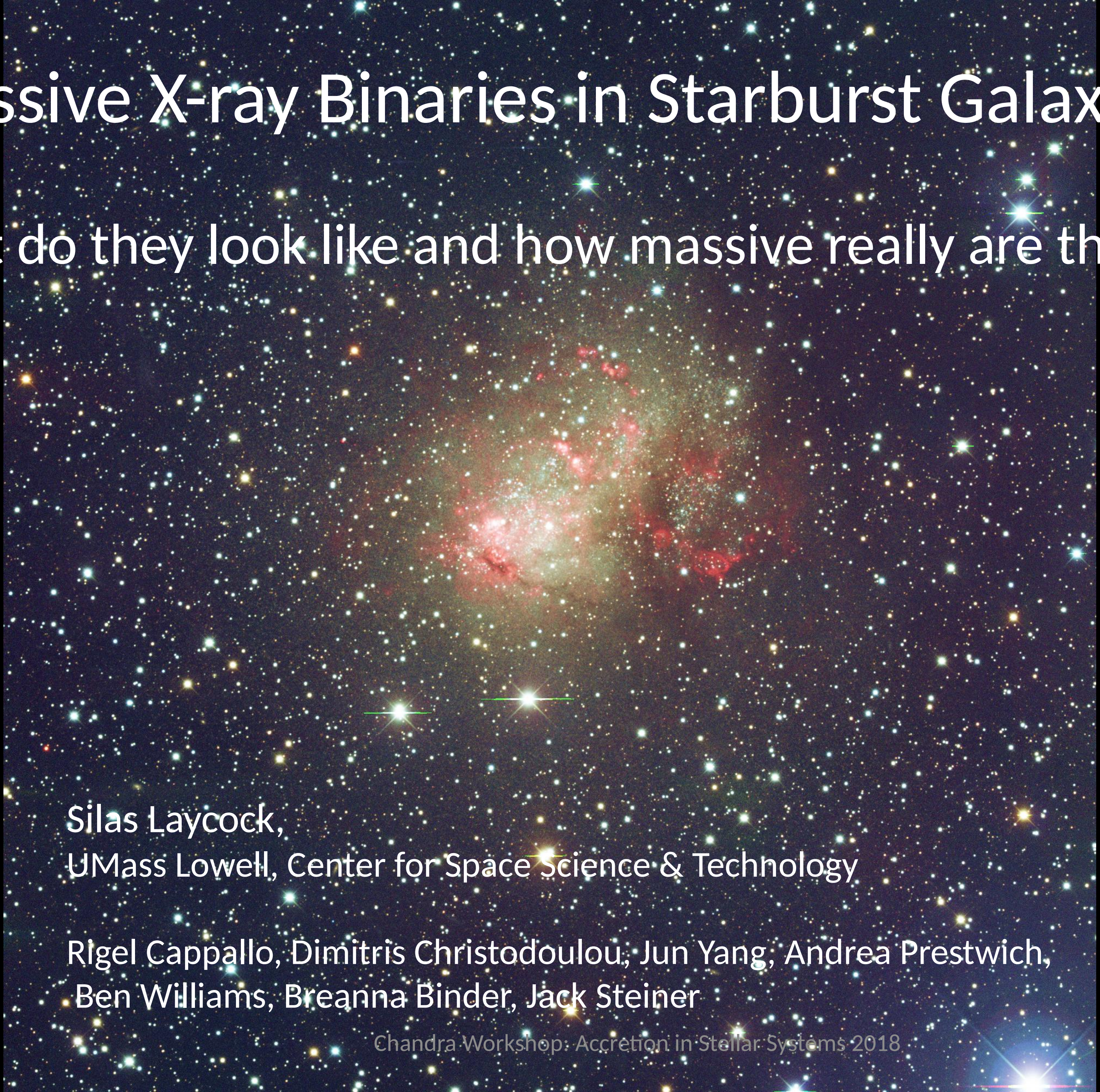
Massive X-ray Binaries in Starburst Galaxies

What do they look like and how massive really are they?



Silas Laycock,
UMass Lowell, Center for Space Science & Technology

Rigel Cappallo, Dimitris Christodoulou, Jun Yang, Andrea Prestwich,
Ben Williams, Breanna Binder, Jack Steiner

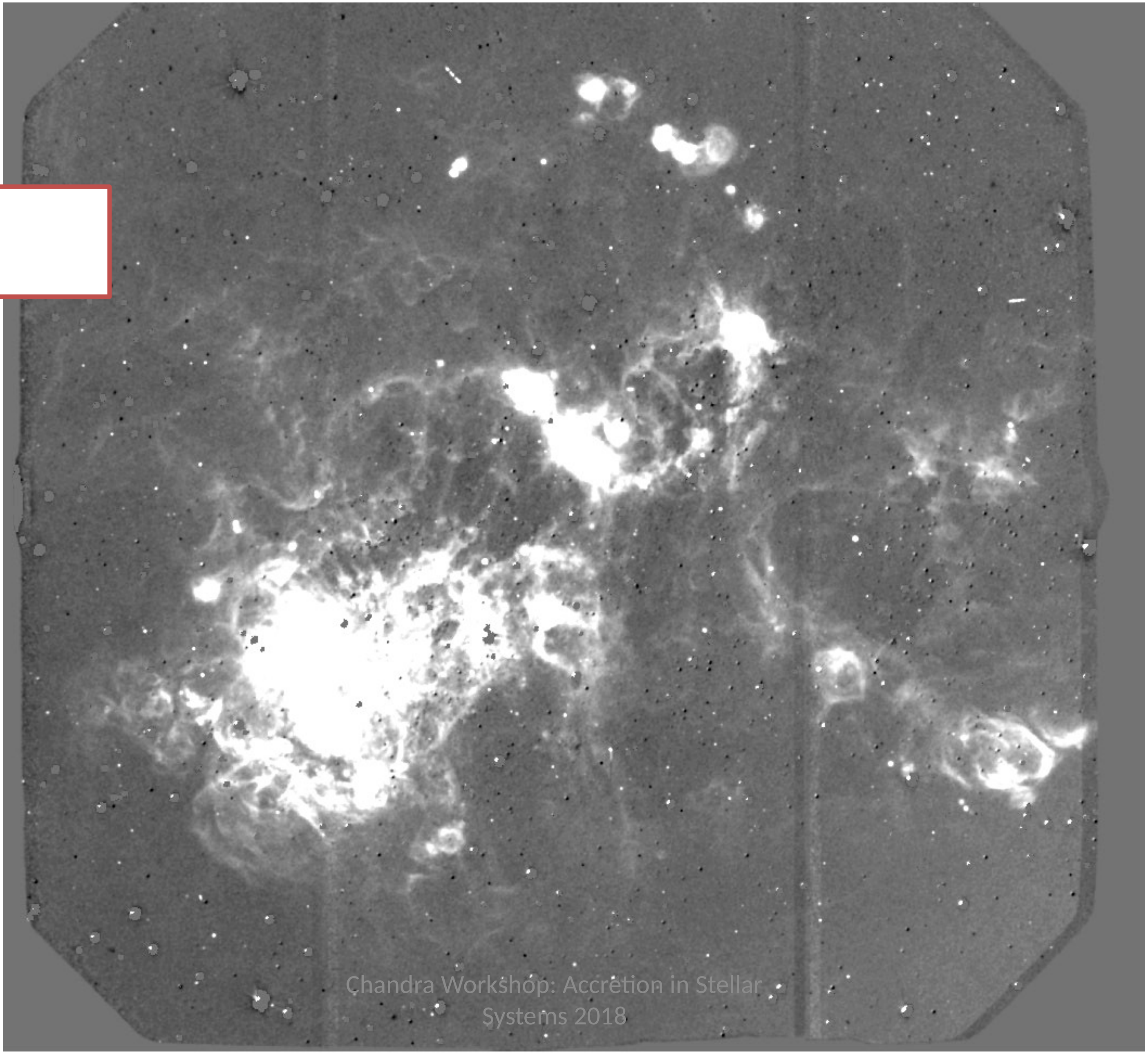
1. Motivation
2. Introducing IC 10: Our nearest dwarf starburst galaxy
3. Blue supergiant HMXBs
4. X-ray variability
5. Pulsars?
6. Summary

1. Motivations for Studying HMXBs in local dwarf starbursts

- Blue compact dwarfs are the most efficient producers of ULX
- Whole galaxy studies possible in single FoV
- Range of metalicity and ages can be probed by comparing e.g. SMC, LMC, IC 10, etc….
- “Most massive” BH HMXB candidates associated with low metalicity environments.
- Precursors of double degenerates (NS+NS, NS+BH, BH+BH)
  - Test observed sample against rate of GW events.
- Reionization of the Early Universe
  - AGN
  - UV flux from first protostars
  - X-ray binaries
- XLF vs SFR relations calibrated with two groups of galaxies. They might not be representative of those early galaxies
  - Massive High redshift galaxies in HDF etc
  - Local resolved galaxies (M31, etc)
  - Dwarfs could be better analogs

2. Introducing our local dwarf starburst laboratory: IC 10

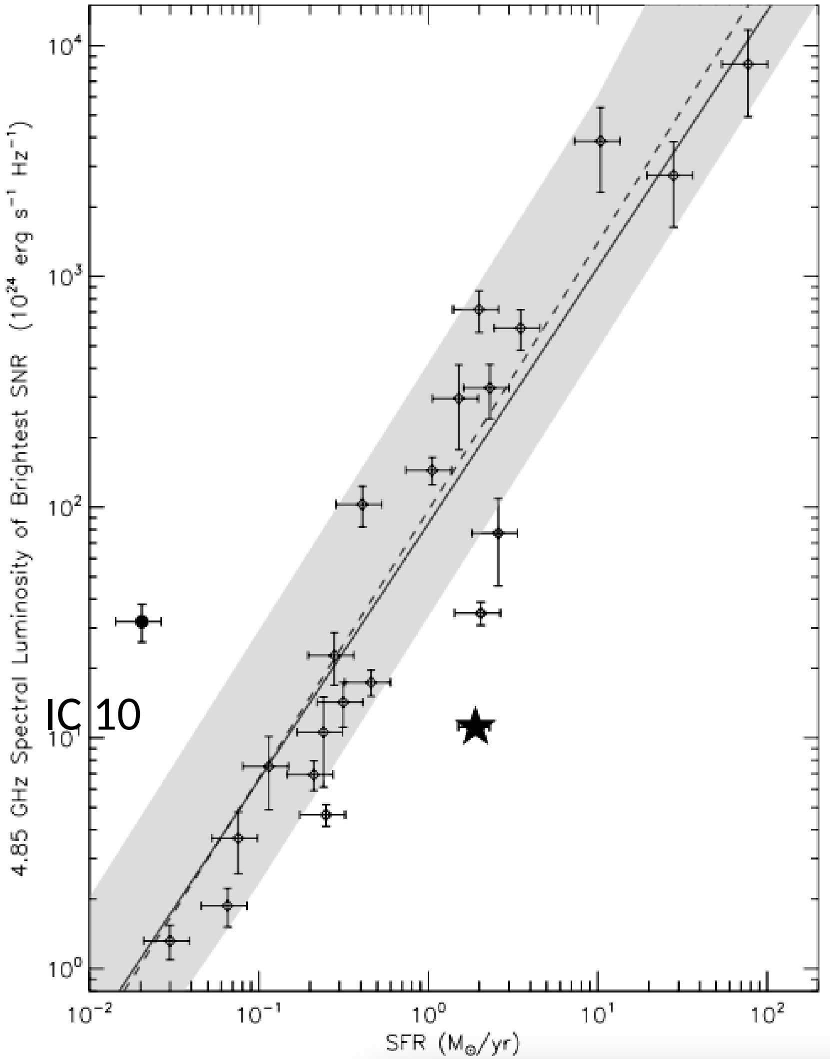
Hα – Cont
(subtracted)



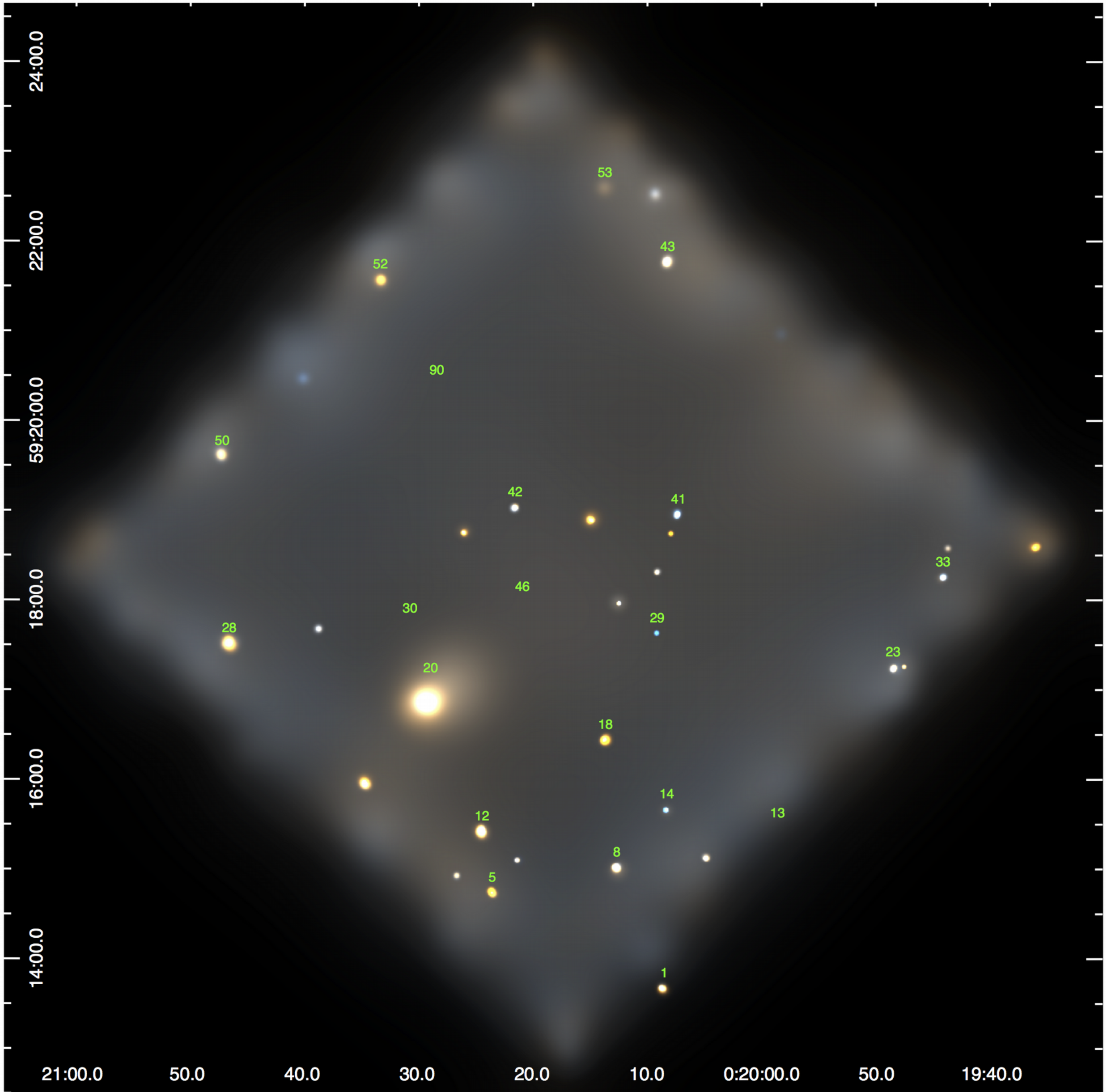
Most stars in IC 10
are < 6 x10^6 yrs old (Massey et al 2006)

IC … rburst

- Young populat …
- Highest knowr … 3)
- SFR as high as … olmes. 2002),
- When normali … etitpas et al. (1997)) yields 2.5 ×10−8 M⊙y … cific SFRs in the local universe excee … mall Magellanic Cloud (SMC), and Lar …
- IC 10 is like an …
- Spatialy conce … rated spectrum (Wang et al 2005)
- Most massive …
- Depending on … an order of magnitude dispersion am … h 2011; Heesen et al. 2007; Leroy et al. 2006).



Deep Chandra image (90 ksec)



- 110 point sources (incl stacked image, and monitoring observations)
- Existing deep multiwavelength surveys: e.g.
  - KPNO+Mosaic (Massey et al. 2007)
  - Gemini GMOS
  - HST
  - Spitzer

3. Evidence for HMXBs in IC 10

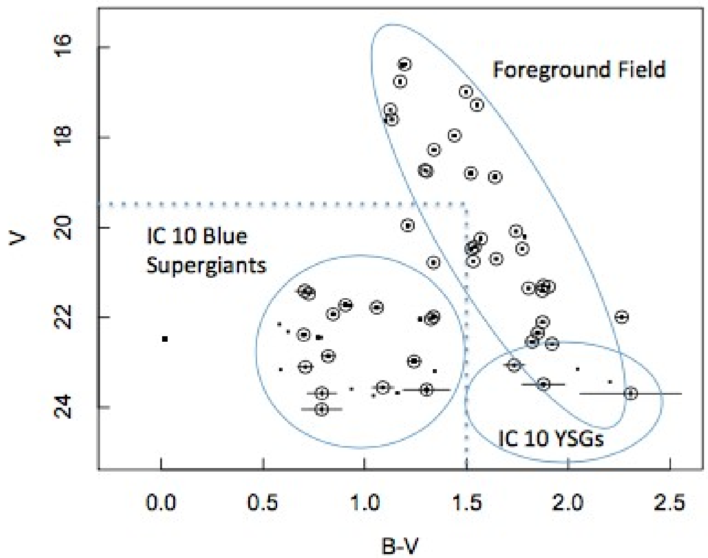
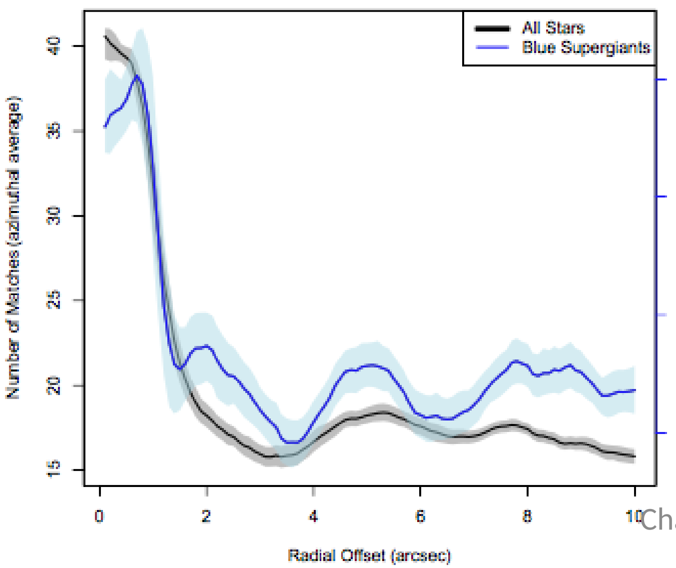
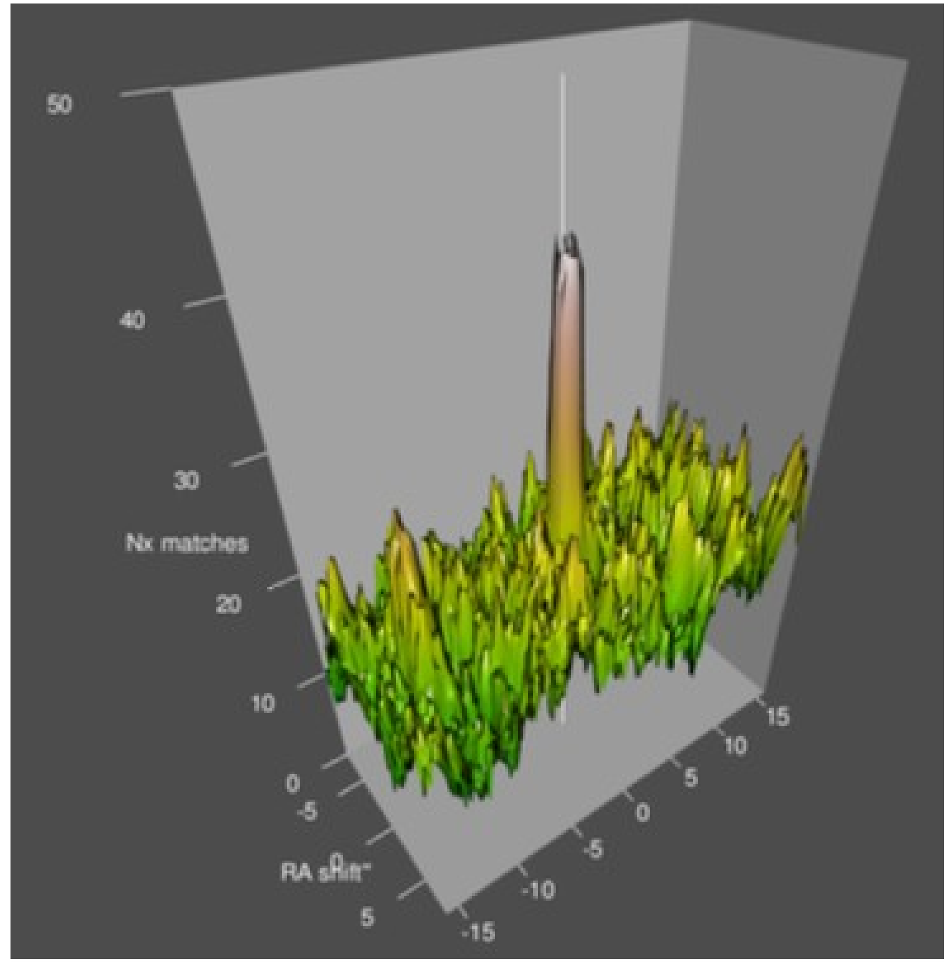


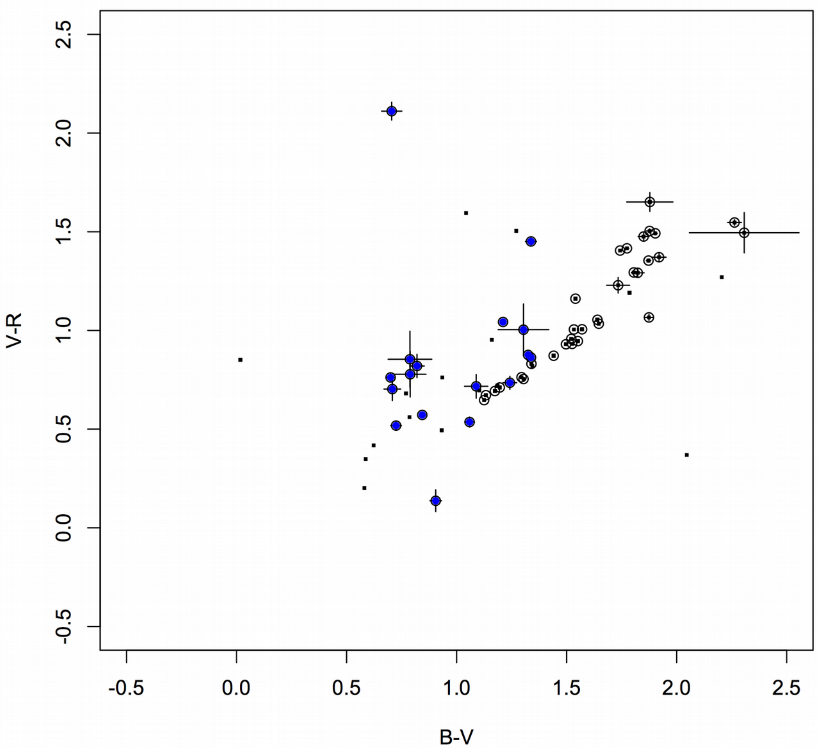
FIG. 1.— Color-Magnitude diagram for positional counterparts to Chandra X-ray sources in the IC 10 field. Ovals indicate the locii of BSGs in IC 10 and the foreground Galactic population which lies atop the yellow SG track for IC 10 (comparison with Massey et al. 2007, Figure 14). A few objects have multiple counterparts; then the one at the smallest offset is retained and the others are indicated by a smaller dot symbol. Dotted lines show the selection B-V<1.5, V>19.5.

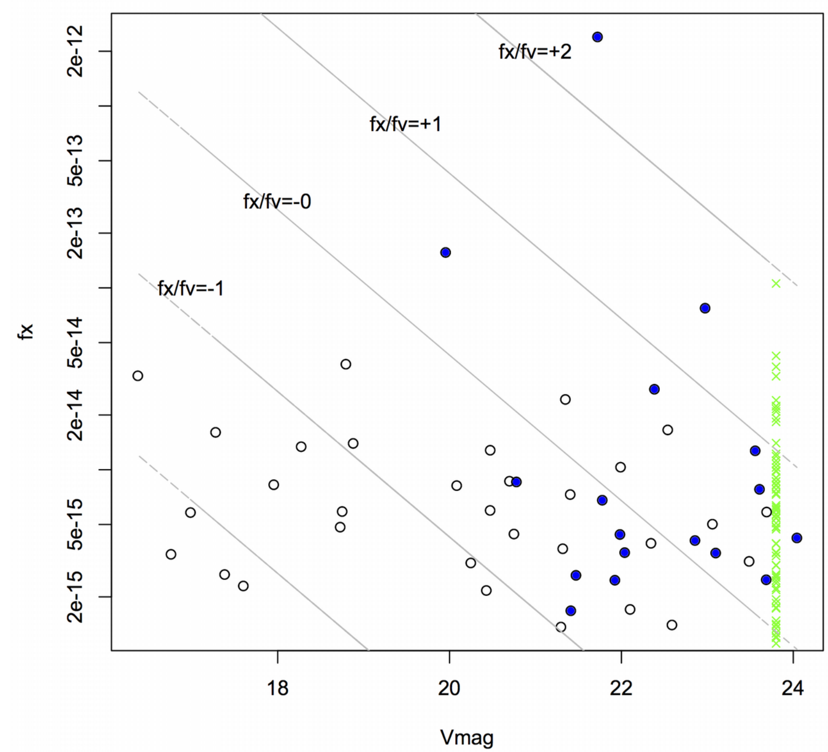




For "all" stars the correlation peak is 8.6σ, and for the blue super giants alone: 6.4σ. (Laycock 2017b, ApJ, 836,51)

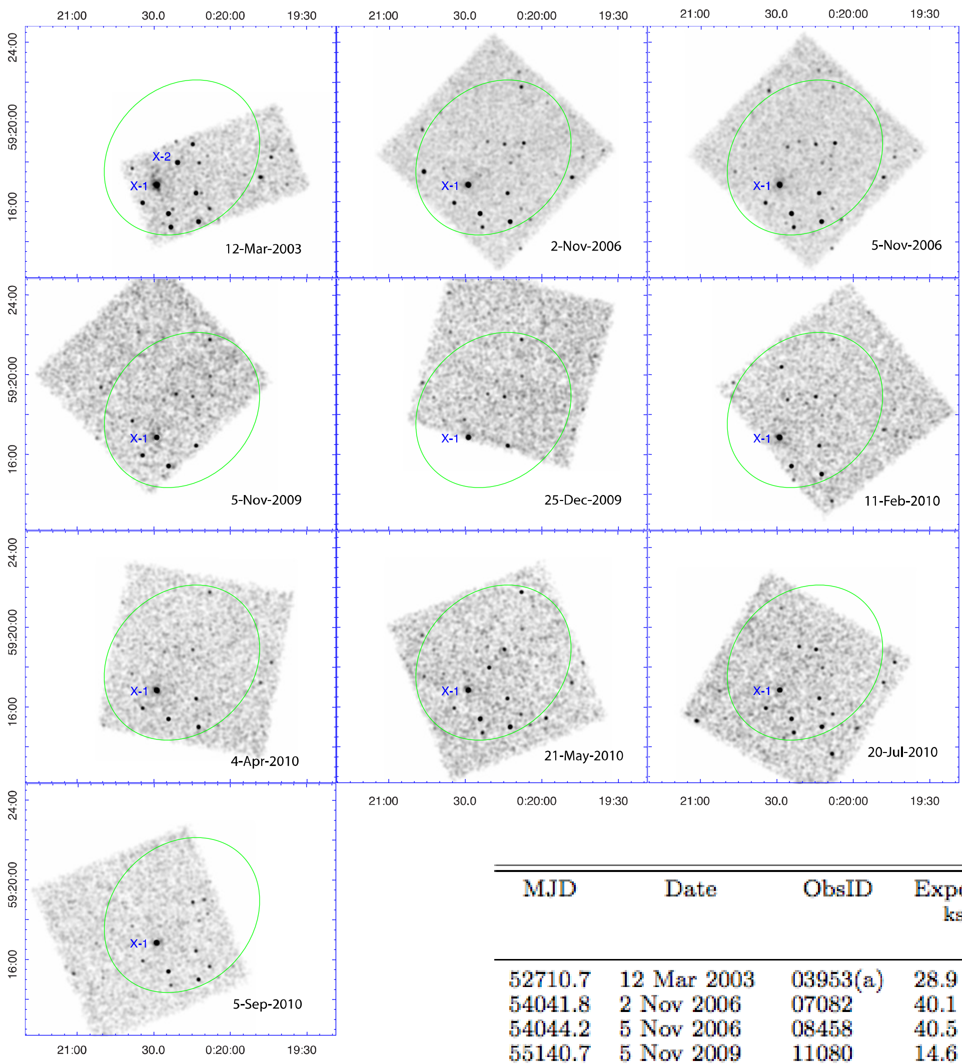
Further Properties of the Blue Supergiant Sample

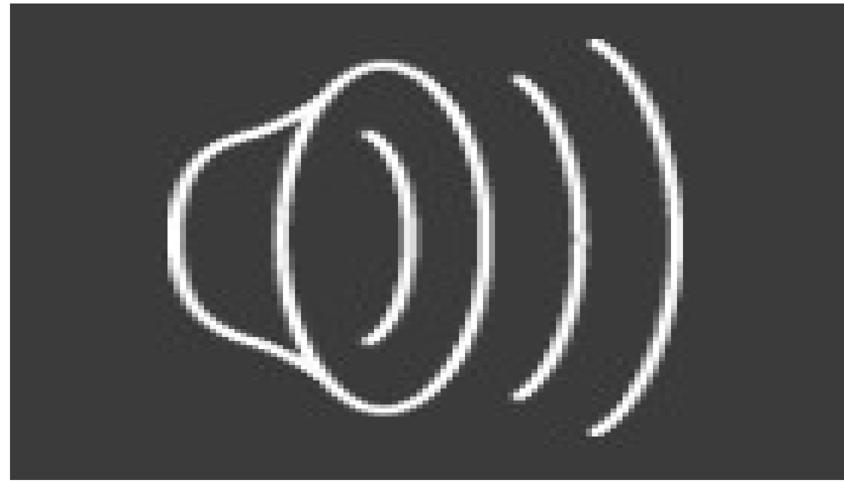




- Systematically elevated X-ray to Optical Flux ratios
- 5 Of the objects are also X-ray variables (among ~20 such in the Chandra survey)
- These include IC10 X-1 (WR+BH?), IC 10 X2 (of which more later),
- Optical Spectroscopy (GMOS, Hydra) is not yet complete for the sample.

Part 4: Variability Survey





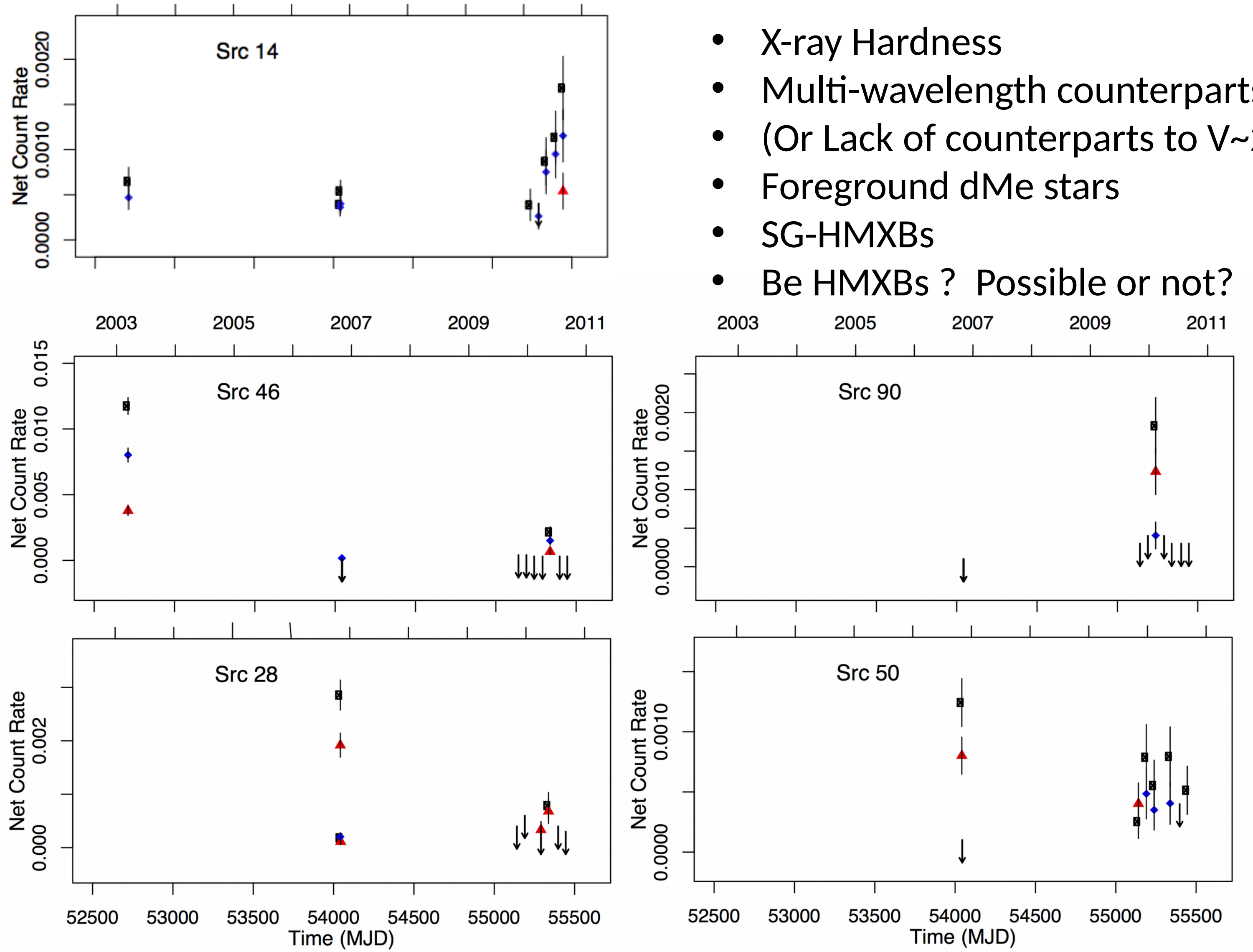
MJD	Date	ObsID	Exposure ksec	R.A. hh:mm:ss	Dec. dd:mm:ss	Roll Angle degrees	N_{Src}
52710.7	12 Mar 2003	03953(a)	28.9	00:20:25	59:16:55	339.27	31
54041.8	2 Nov 2006	07082	40.1	00:20:04	59:16:45	223.70	48
54044.2	5 Nov 2006	08458	40.5	00:20:04	59:16:45	223.70	41
55140.7	5 Nov 2009	11080	14.6	00:20:17	59:17:56	226.53	19
55190.2	25 Dec 2009	11081	8.1	00:20:19	59:18:02	286.15	24
55238.5	11 Feb 2010	11082	14.7	00:20:23	59:17:10	320.56	24
55290.6	4 Apr 2010	11083	14.7	00:20:34	59:19:01	10.32	25
55337.8	21 May 2010	11084	14.2	00:20:25	59:20:16	67.89	27
55397.5	20 Jul 2010	11085	14.5	00:20:11	59:19:13	121.25	22
55444.6	5 Sep 2010	11086	14.7	00:20:15	59:18:11	157.71	27
(b)	2-5 Nov 2009	57082	80.6	-	-	-	63

Variable Chandra (ACIS-S) Sources in IC 10

Source	W05	N_P	N_B	$\bar{R_B}$ $ct\ ks^{-1}$	R_B^{Min} $ct\ ks^{-1}$	R_B^{Max} $ct\ ks^{-1}$	Range $ct\ ks^{-1}$	Ratio	σ_{var}	Total Net Cts	$E50$ keV	Class
46	11C	10	2	1.61	0.1	11.75	11.65	117.5	18.2	370	3.35	T, X
90	-	9	1	0.45	0.1	1.83	1.73	18.3	4.7	26	1.64	T, S
28	24C	8	3	0.73	0.18	2.86	2.67	15.6	9.2	130	1.13	T, S
50	17C, 46X	8	6	0.58	0.1	1.24	1.14	12.4	5.7	88	2.07	T, X?
13	-	7	2	0.39	0.1	0.96	0.86	9.6	3.1	19	1.69	TC,S?
30	19C	10	4	0.36	0.1	0.92	0.82	9.2	3.1	33	1.97	TC, X?
41	-	10	5	0.63	0.2	1.68	1.48	8.4	7.4	154	2.53	TC, X
43	24X	8	7	1.11	0.3	2.45	2.15	8.2	5.1	170	2.06	V, X
20	18C, 39X	10	10	105.8	23.7	179.87	156.17	7.6	55.6	22632	1.75	V, X
53	-	8	1	0.47	0.1	0.66	0.56	6.6	3.7	27	1.38	TC, U
5	14C, 35X	8	8	1.55	0.54	3.17	2.63	5.9	6.7	292	0.89	V, U
29	4C	10	1	0.31	0.1	0.51	0.41	5.1	3.6	22	3.60	TC, X
23	17X	9	7	0.98	0.33	1.62	1.29	4.9	4.9	203	1.86	V, U
52	-	9	2	0.53	0.3	1.21	0.91	4.0	4.7	64	1.24	V, S
14	3C, 25X	8	7	0.76	0.39	1.68	1.29	4.3	3.3	117	3.64	V, X
42	12C, 33X	10	9	0.73	0.4	1.44	1.04	3.6	3.3	144	2.70	V, X/A?
33	16X	9	7	0.87	0.4	1.38	0.98	3.4	3.0	132	2.55	V, X/A?
1	3C, 36X	5	4	1.24	0.68	1.89	1.21	2.8	3.0	70	1.76	V, X
12	15C, 36X	9	9	4.96	2.84	7.93	5.1	2.8	8.1	1137	1.69	V, U
18	8C	10	10	1.99	1.18	2.77	1.59	2.3	3.6	435	1.12	V, U
8	7C, 28X	8	8	4.22	3.1	5.8	2.7	1.9	4.5	863	1.83	V, X

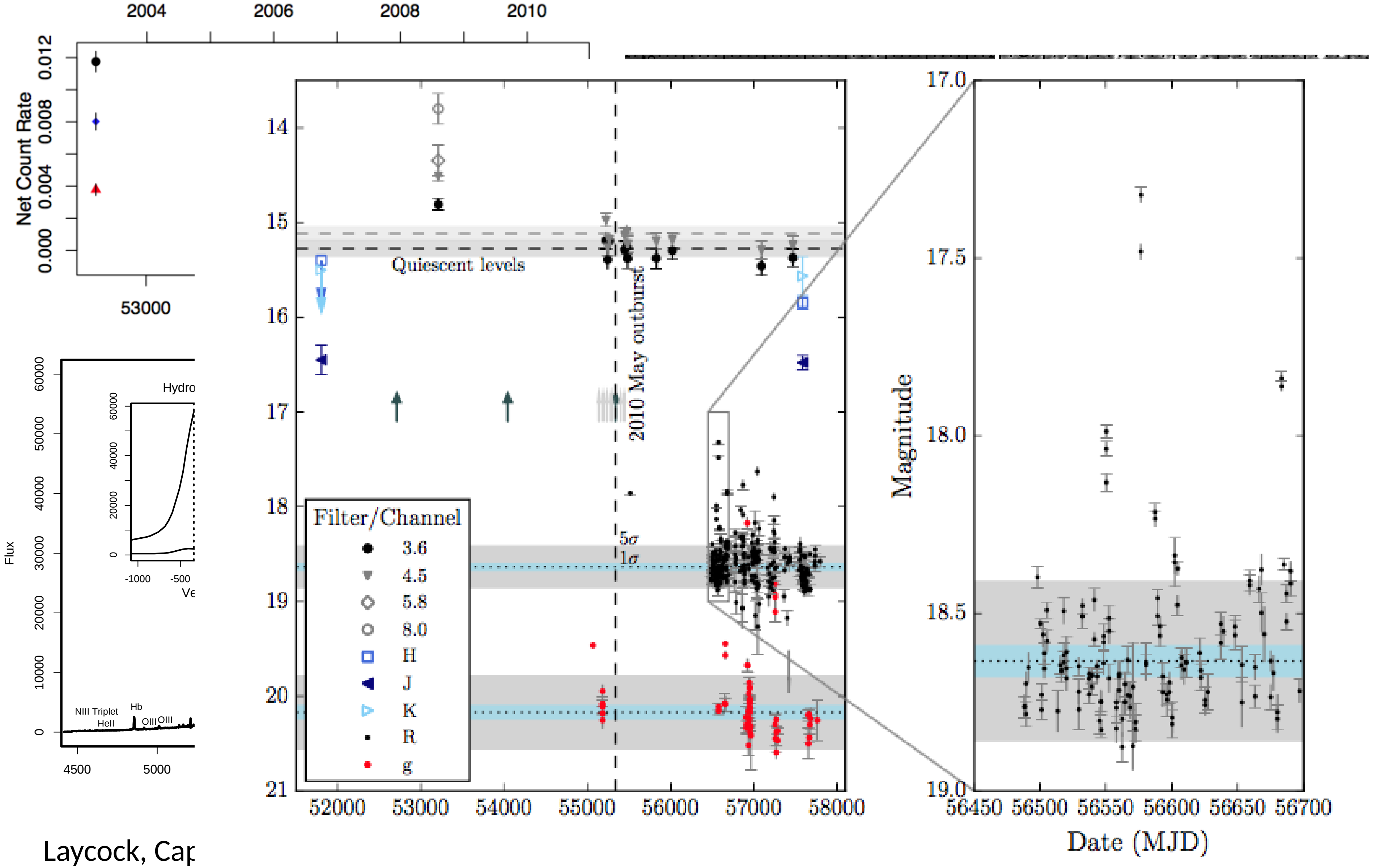
NOTE. — Objects in this table were selected as variable sources accord to $\sigma_{Var} > 3$ and are sorted by *Ratio* in descending order. N_P = number of observations where the source fell on the ACIS-S3 detector; N_B = number of broad-band detections; the remaining columns are computed from those broad-band detections and the upper limits derived for the non-detections. *Class* is a candidate source classification based on the X-ray and optical properties: T = Transient (*Ratio* > 10), TC = Transient Candidate, V = Variable, X = X-ray binary, S = Stellar Corona, A=AGN, U = unclassified. Column *W05* is the source identifier from Wang et al. (2005) where the suffix *C* and *X* denote *Chandra* and *XMM-Newton* respectively. *A full version of this table containing all 110 unique sources, their celestial coordinates, and error bars for all columns is provided in the online journal.*

Sample of variable X-ray lightcurves



- X-ray Hardness
- Multi-wavelength counterparts
- (Or Lack of counterparts to V~24)
- Foreground dMe stars
- SG-HMXBs
- Be HMXBs ? Possible or not?

IC 10 X-2   A LBV/supergiant XRB with similarities to SFXTs and SN Imposters



Laycock, Car

Kwan et al. 2017

Spitzer photometry reveal flaring activity, driven by accretion of wind clumps. IR spectrum shows the star is an LBV

Inferences about double degenerate production rates

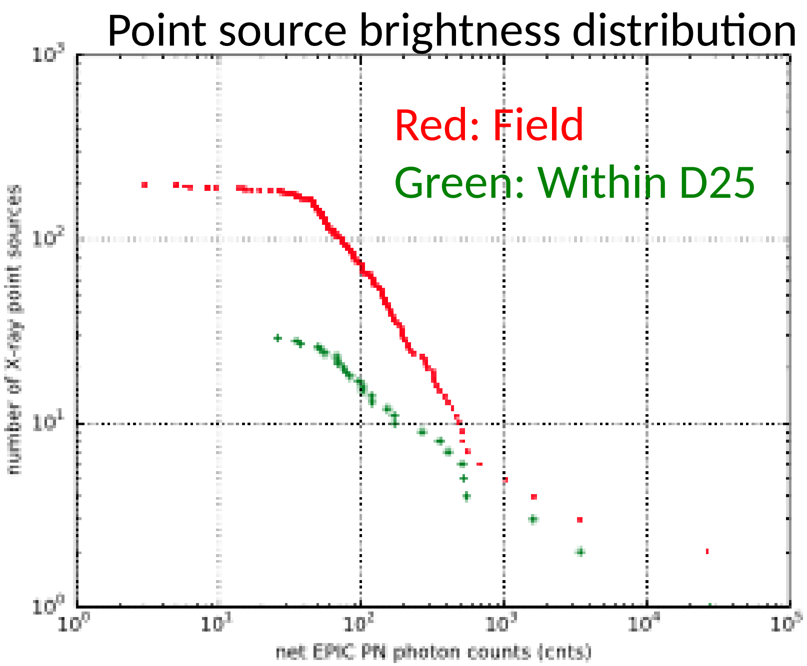
Duty Cycle argument

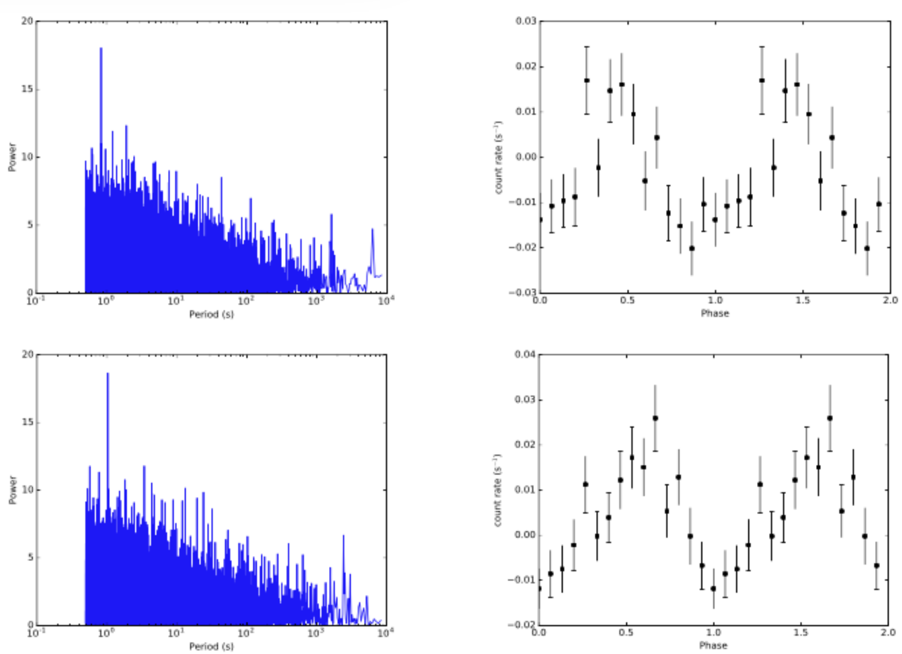
- If IC10 has produced n_{PDD} precursor double- degenerate binaries over the past T ≈ 6 Myr, then the duty cycle during which the LBVs are donating mass to their compact companions is **$D = t_m/T$**
- t_m=0.4 My is the mean lifetime of a typical LBV mass of M_2 = 30 $M_\odot$ (Maeder & Meynet 2001; Fragos et al. 2015; Massey et al. 2016). Hence D = 0.067
- Yielding $n_{PDD} = n_x/D$ = 240 progenitors over the duration of the starburst.

Binary population Distribution argument

- DD precursors require a high mass ratio, and M1 > M2 so that the progenitor will indeed collapse first.
- The close binary fraction of O/B stars with Porb < 20 days and q > 0.1 in the low-metallicity Magellanic Clouds is $F_{cl} = 0.22(M1/10M_\odot)^{0.4}$ (Moe & Di Stefano 2013)
- Using M1 = 35 $M_\odot$ gives F_{cl} = 0.36.
- Proportion F_{tw} of "twin" systems with q > 0.9 is in the range of 0.06-0.16. Adopting a value of 0.1 for q > 0.9, and doubling it to account for additional binaries whose mass ratio falls in the range of q = 0.5−0.9; so below we use an estimate of F_{tw} = 0.2 for q > 0.5. Then we find that $n_{PDD} = nx/(F_{cl}F_{tw})$ = 222 progenitors over the duration of the starburst.

5. Does IC 10 host Pulsars?





- Very deep 130 ksec XMM exposure (2012)
- Few candidates, but consistent with false alarm rate
- Yang et al, 2018 (submitted)

I (Don't) C 10

- Noori et al. (2014, 2017) conducted a deep radio pulsar search of IC 10, but they were unable to identify any continuous pulsed signals.
- Few (if any) normal radio pulsars in IC 10.
- A curious result given the large number of bright young core collapse SN remnants.

6. Summary

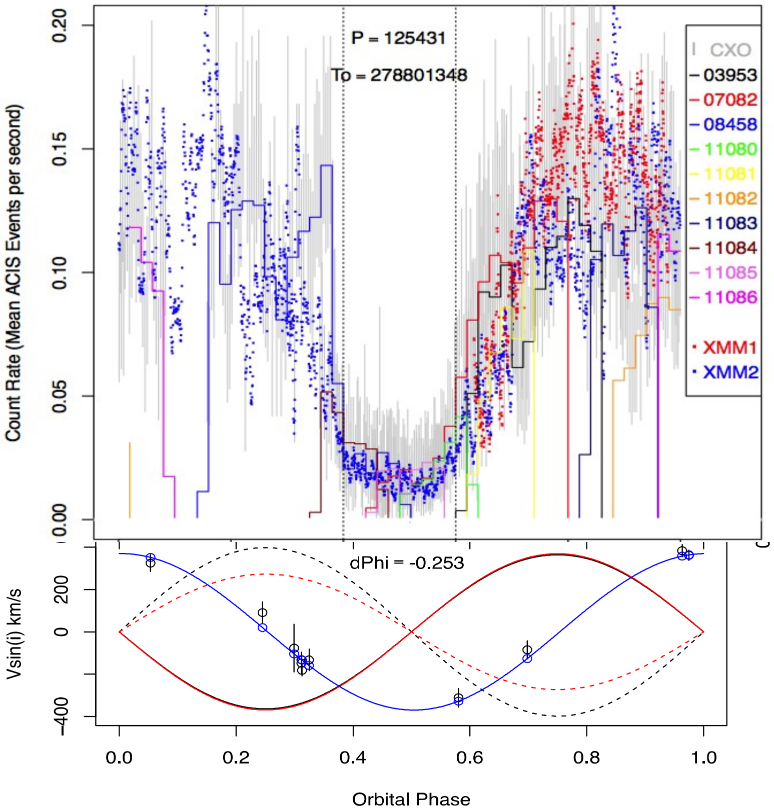
- Dwarf starburst produce HMXB populations at very early ages (a few My), potentially supply a significant portion of the re-ionizing flux in the early universe.

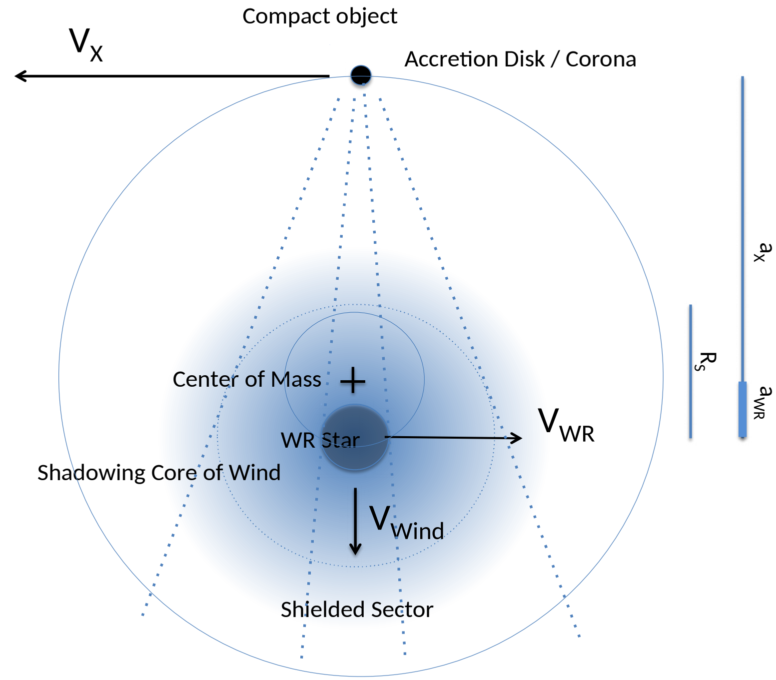
- IC10:
  - 110 point sources, 20 Variables, ~50% optical counterparts to V=24,
  - 16 Supergiant/LBV candidates
  - Implied production rate of ~30 WR/LBV HMXBS per My per dwarf starburst
  - No Pulsars (X-ray and Radio)

- The nature of these XRBs challenge our current understanding of binary evolution and accretion.

- Motivation for extremely large effective-area X-ray missions and timing capabilities for large optical/IR telescopes.

What are the true masses of the compact objects in WR HMXBs?





Our ability to do multi-observatory multi-messenger analyses in the absence of simultaneous observing, hinges on the precision to which data can be lined up in phase space. The goal is to shrink the accumulated phase error across a decade+ to the level of less than 1/10 of an orbital period. This is technically feasible, but thus far has not been attained for many objects. Higher S/N broad-band LCs will improve ephemerides in 2 classes. One small (BH systems with ionizer/scatterer induced modulation), the other very large (X-ray binary pulsars).

BH HMXBs are a key class of object for understanding GW event rates, and understanding the mass function of double degenerates. Recent work on IC 10 X-1 and Cyg X-3 point to the need for new capabilities: ability to resolve X-ray absorption and fluorescence lines in integrations of one hour and less. Steiner et al 2016, Laycock 2015, Barnard 2015. Velocity resolution (McCullough, Hainikainen, etc) however will remain in the realm of gratings and micro-calorimeters.

Similarly at the HEAD meeting we heard from Marianne Heida that phase relationship in the archetype BH XRB GX339-4 between various multi-wavelength timing features does not support the accretion geometry previously adopted by most of the community. Again, orbital phase-resolved observations are needed.

STROBE-X and HMXBs

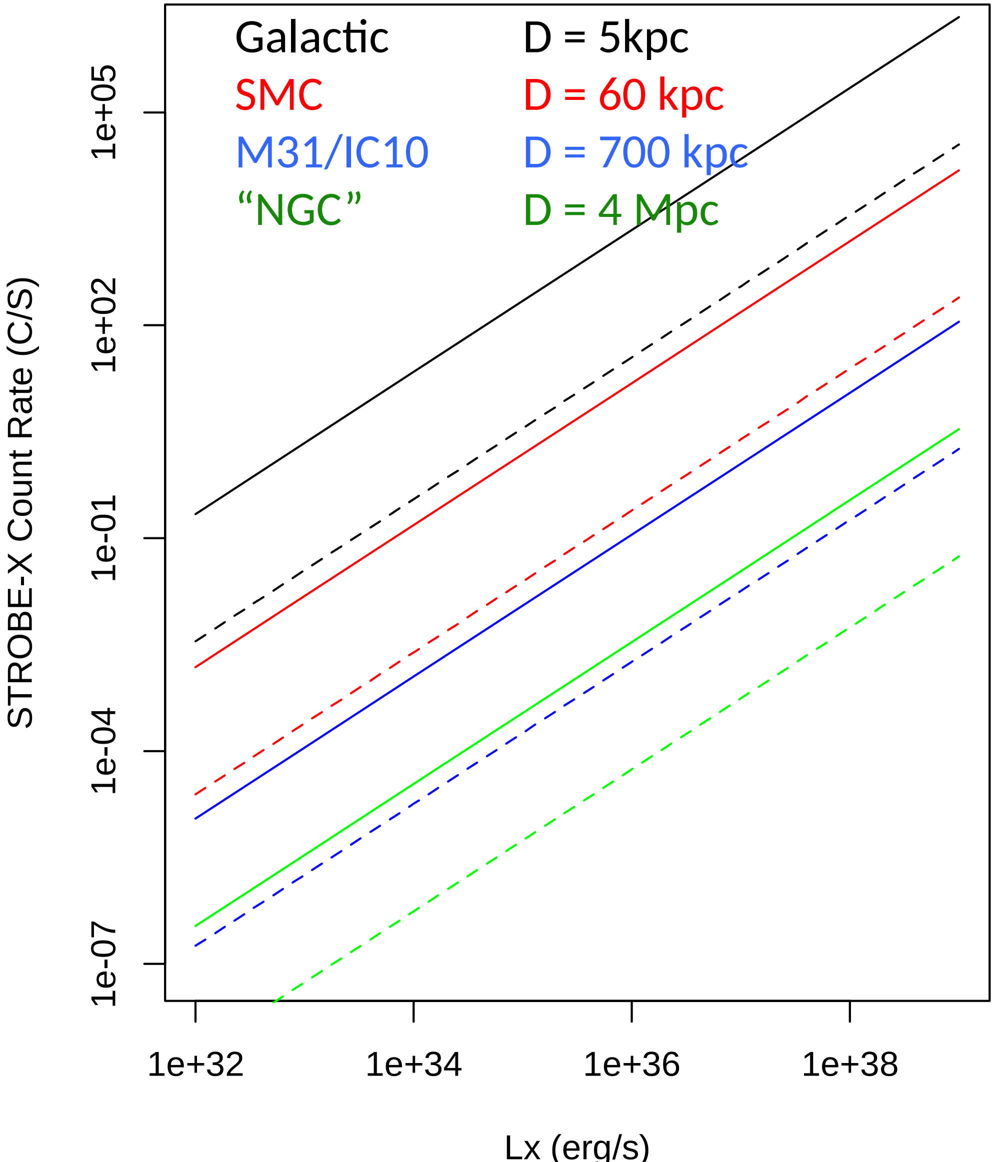
- **End the photon-starvation bottleneck that we have reached**
  - Chandra and XMM have revolutionized the study of XRB populations by isolating and identifying individual sources within many hundreds of galaxies
  - Using these populations as new laboratories requires at least an order of magnitude gain in S/N

- **LAD** FoV is matched to discovering and studying pulsars in active regions within the Magellanic Clouds, M31, and whole dwarf galaxies such as IC 10, and others in the local group.
- **SXRC** with superior S/N can look for pulsations in all Galactic transients, and in luminous extragalactic sources, HMXBs and ULX
- Populations offer the chance to perform controlled "experiments", by accumulating statistical samples of objects.
  - Spin and orbital period distributions
  - Pulse profile modeling of large statistically selected samples
  - other fundamental parameters that can be indirectly inferred such as rotational inertia, magnetic field, radius.

- Cyclotron lines and other features, potentially in single pulsations*
- Dips and Eclipses, disk precession
- Impact of transient sources on Luminosity distributions
- Orbital modulation and QPOs in ULX

- **Rare states become common when the target volume expands**

The HMXB discovery space for STROBE-X



PIMMS simulation*
Powerlaw index = 1.5
NH = 10^{21} atom/cm^2

XRCA = 20 x NICER
LAD = 12 x RXTE PCA

Galactic Systems:
Phase resolved spectroscopy of Individual pulses!

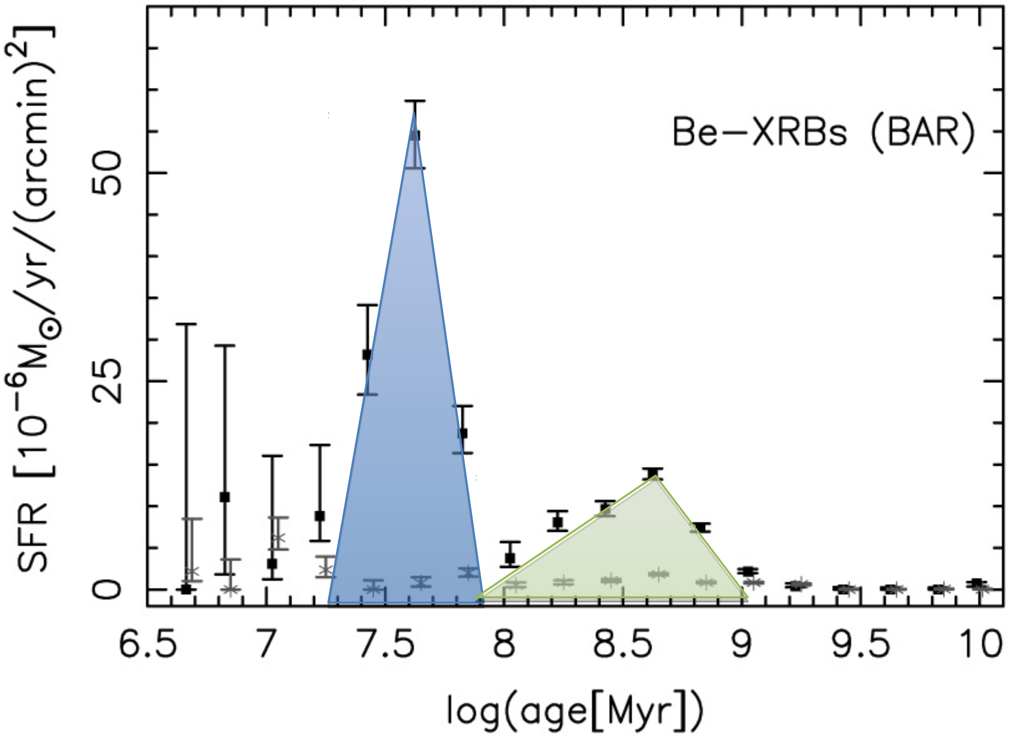
Magellanic Clouds:
Individual pulses during outbursts

Pulsar hunting in Local Group:
If Pulsation detectability per orbit (200 counts in 5 ksec) approx. 6.5x10^{-15} erg/cm2/s we can
At SMC this is 2.6 x 10^{33} erg
at M31 its 3.6 x 10^{35}
at 4 Mpc its 1.2 x10^{37}

(Factor of 4 fainter for 1000 counts in 100 ksec)

(Subject to background)

HMXBs and their progenitor populations
Galactic Archaeology



SMC ~40 My peak

LMC ~20 My

IC10 < 6 My ?

Why? Metals
Rotation
Mass loss

The angular resolution of Chandra enabled large-scale identification of optical counterparts.
Leading to some spectacular science.
E.g. Antoniou et al., 2010, ApJL, 716, L140,
Antoniou & Zezas 2016, 2017