INSIGHTS INTO THE HIGH-MASS X-RAY BINARY POPULATION OF THE MAGELLANIC CLOUDS

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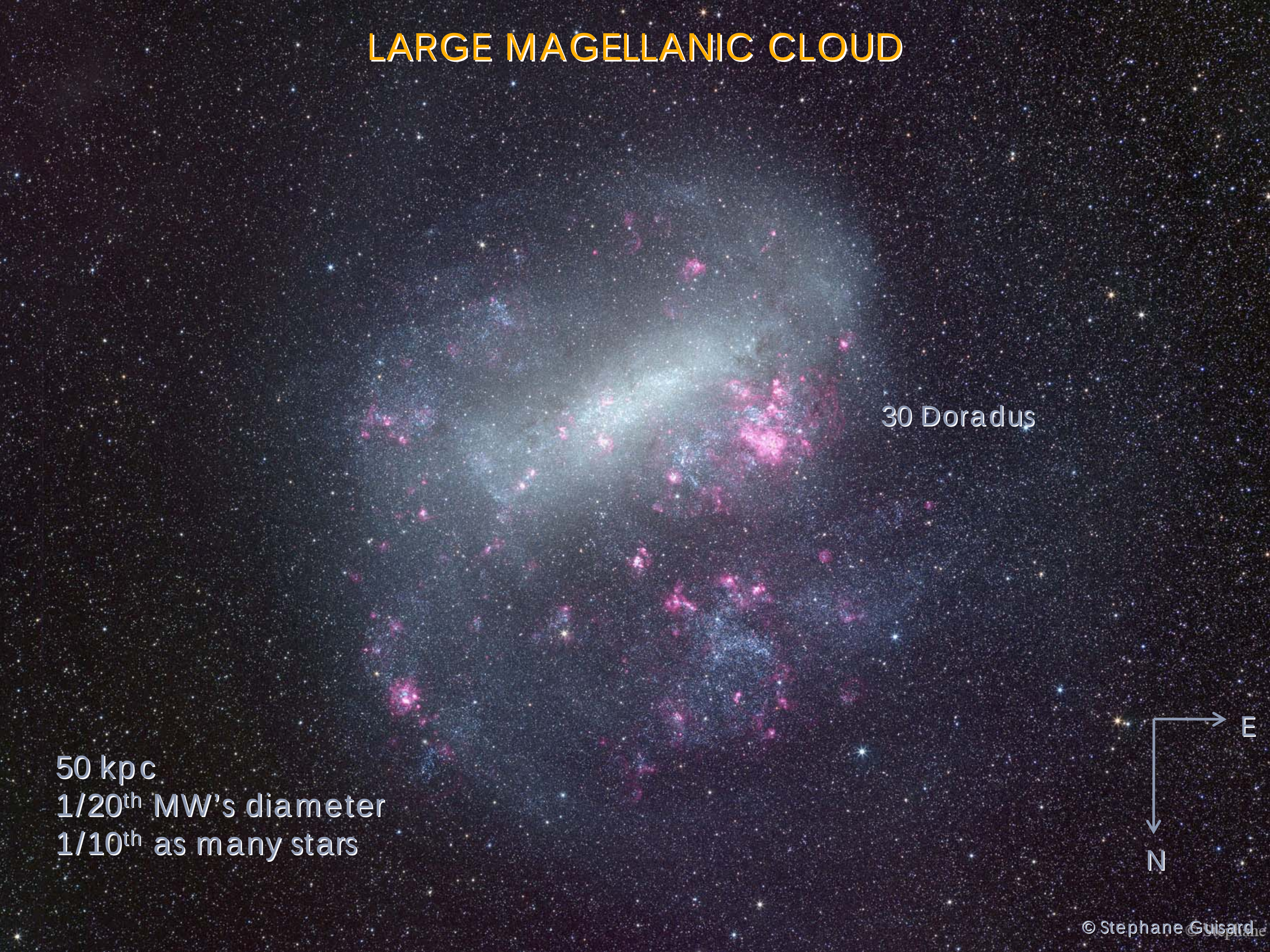
LARGE MAGELLANIC CLOUD
30 Doradus
50 kpc
1/20th MW's diameter
1/10th as many stars
E
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THE HMXB POPULATION OF THE MAGELLANIC CLOUDS

* Spectral fits or X-ray color-color diagrams → hard X-ray sources

* Cross-correlate their position with optical and/or near-IR photometric catalogs (e.g., OGLE-II/-III, MCPS, 2MASS) → identify their counterparts

* Position of counterparts on their

-*V vs. B-V* CMD with respect to a spectroscopically identified locus of OB stars (e.g., Antoniou et al. 2009)

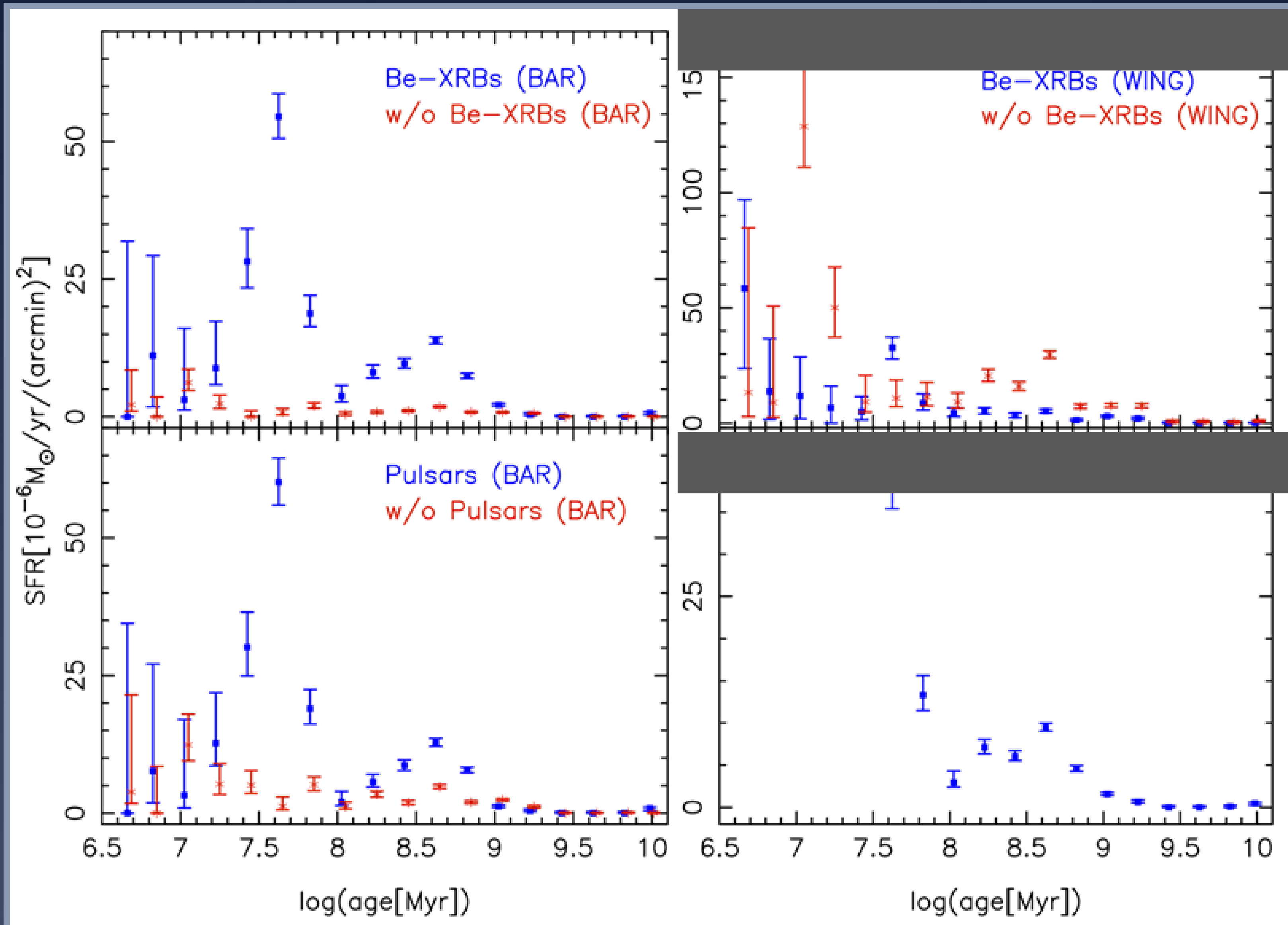
- $R\text{-}H_\alpha$ *vs. B-V* 2CD (e.g., Reig et al. 2005)

- $R\text{-}H_\alpha$ *vs. V-I* 2CD (e.g., Iqbal & Keller 2013)

* Selected based on their photometric variability (e.g., Subramaniam et al. 2012)

* optical spectroscopy of counterparts → early-type companions

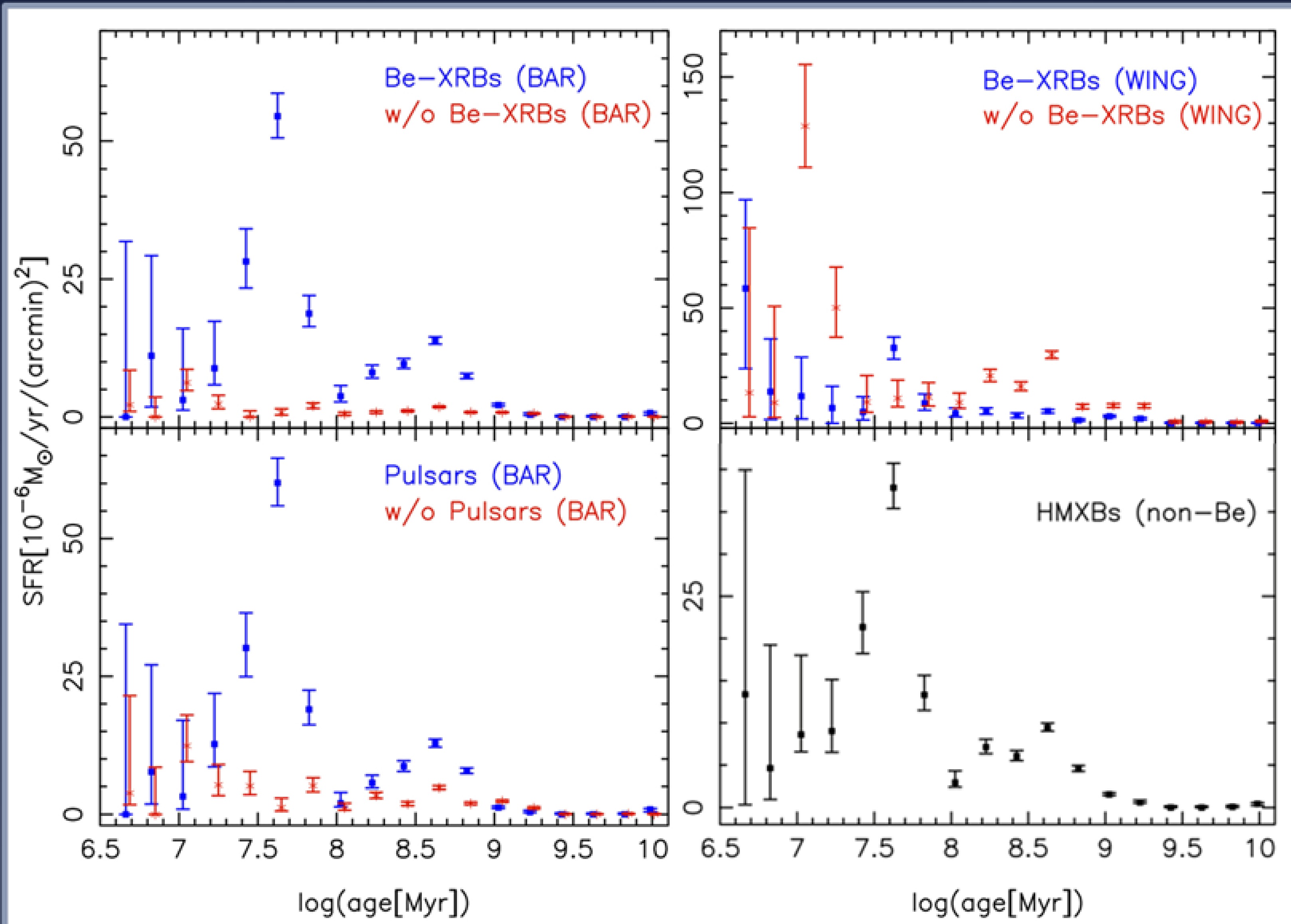
TRACING THE YOUNG HMXBs IN THE SMC



Average SFH (using data from Harris & Zaritsky 2004)

Antoniou et al. (2010)

TRACING THE YOUNG HMXBs IN THE SMC



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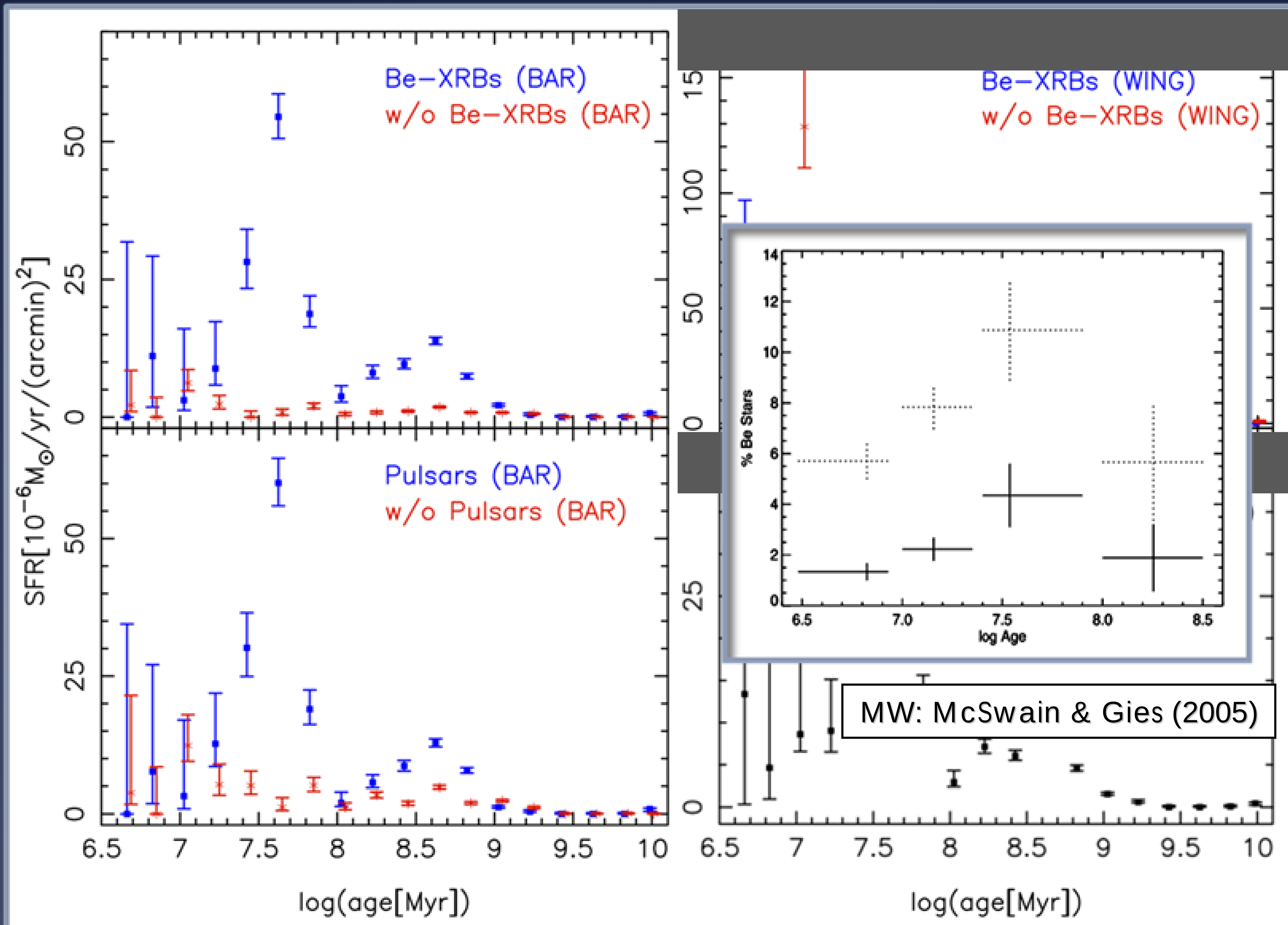

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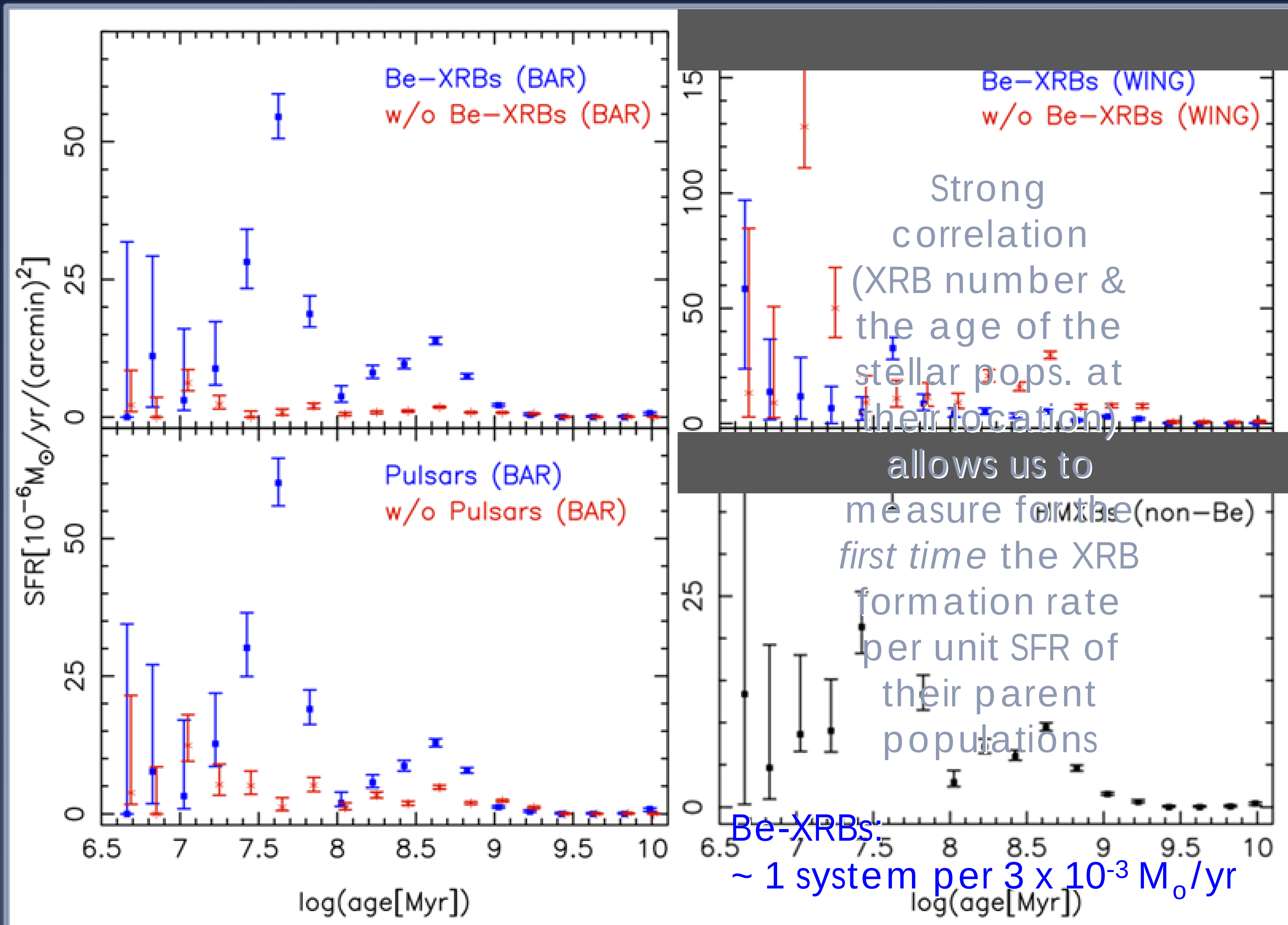


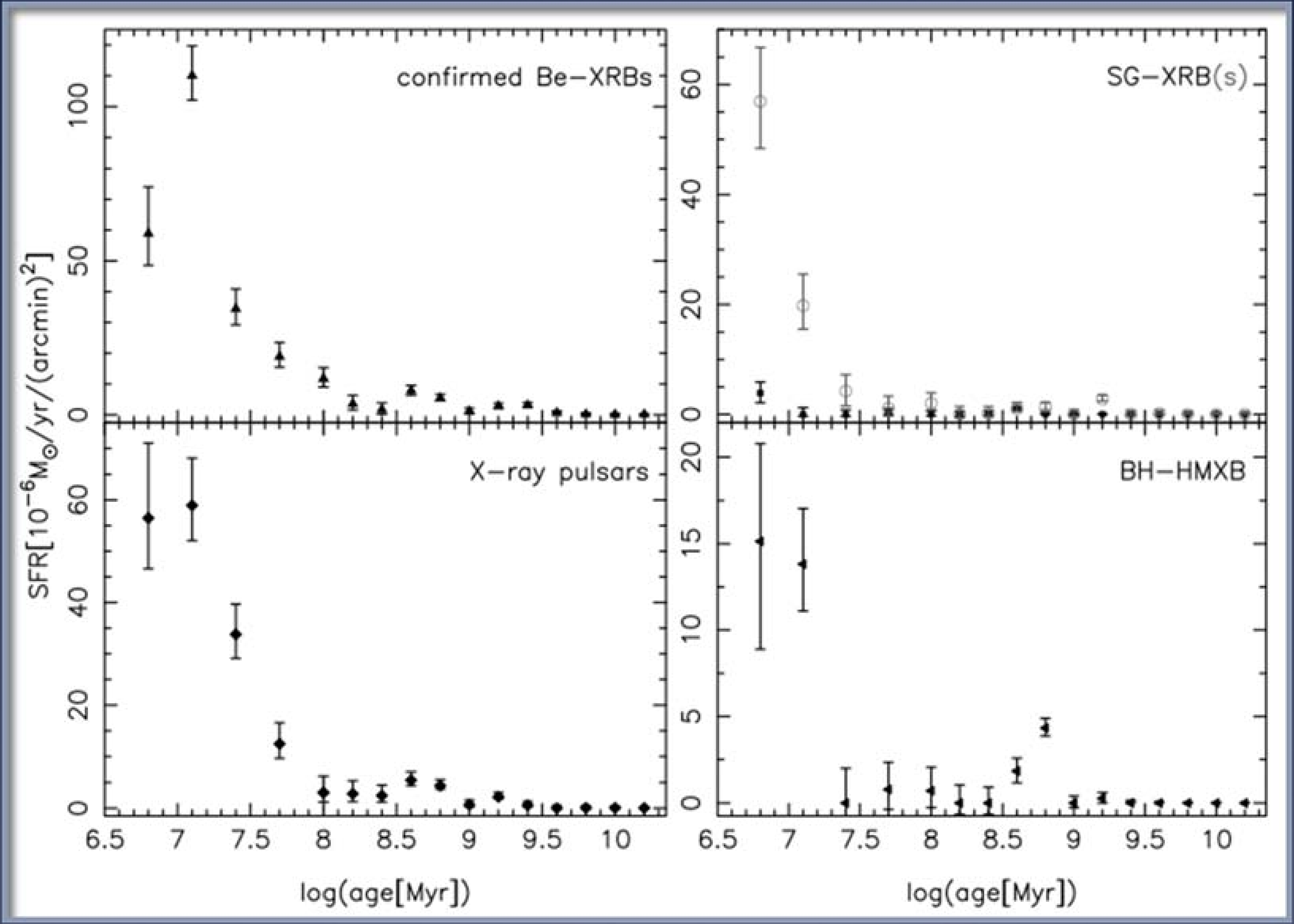
Strong correlation (XRB number & the age of the stellar pops. at their location) allows us to measure for the *first time* the XRB formation rate per unit SFR of their parent populations

Be-XRBs:
~ 1 system per 3 x 10^{-3} M_o/yr

Average SFH (using date from Harris & Zaritsky 2004)

Antoniou et al. (2010)

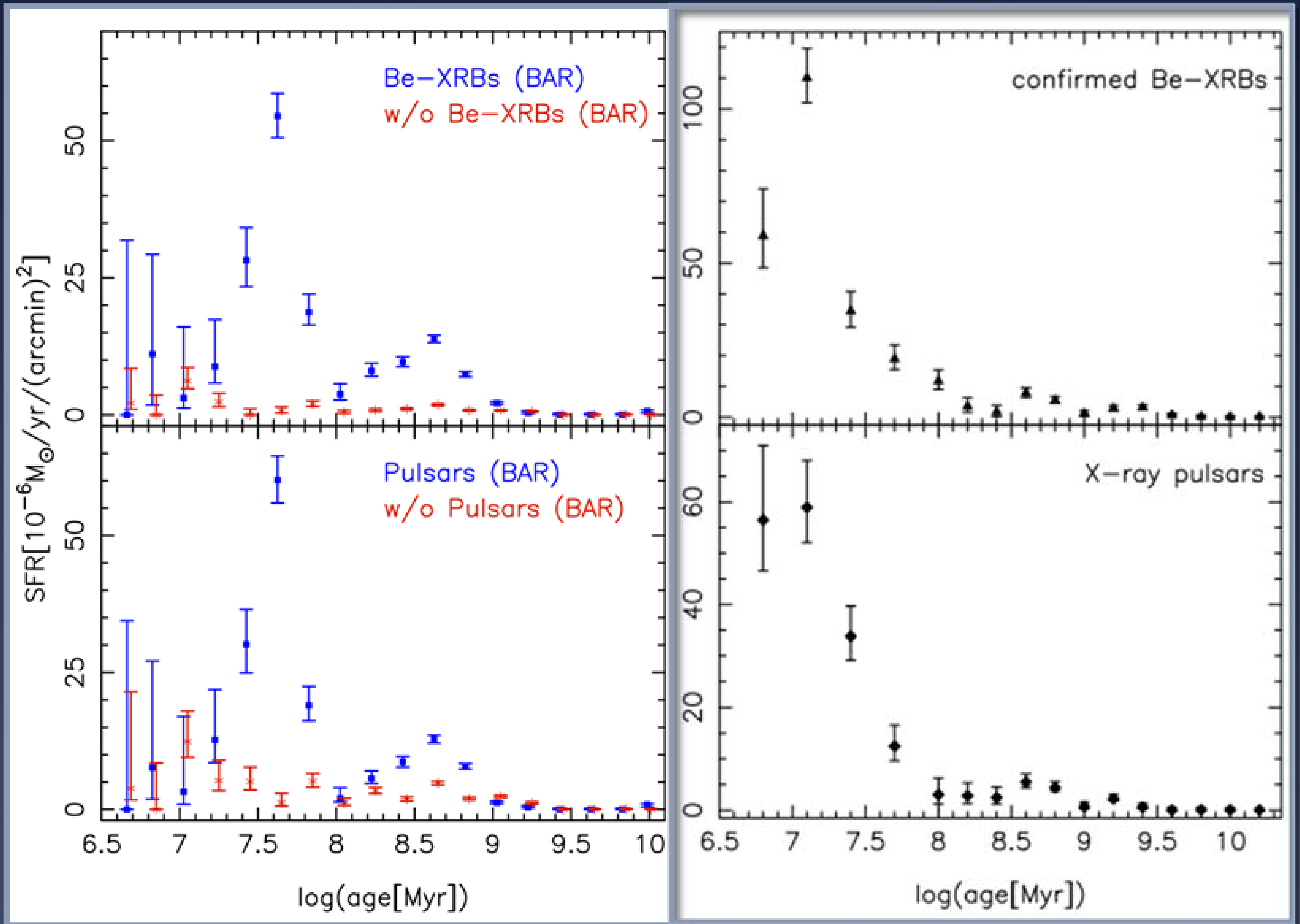
TRACING THE YOUNG HMXBs IN THE LMC



Average SFH (using data from Harris & Zaritsky 2009)

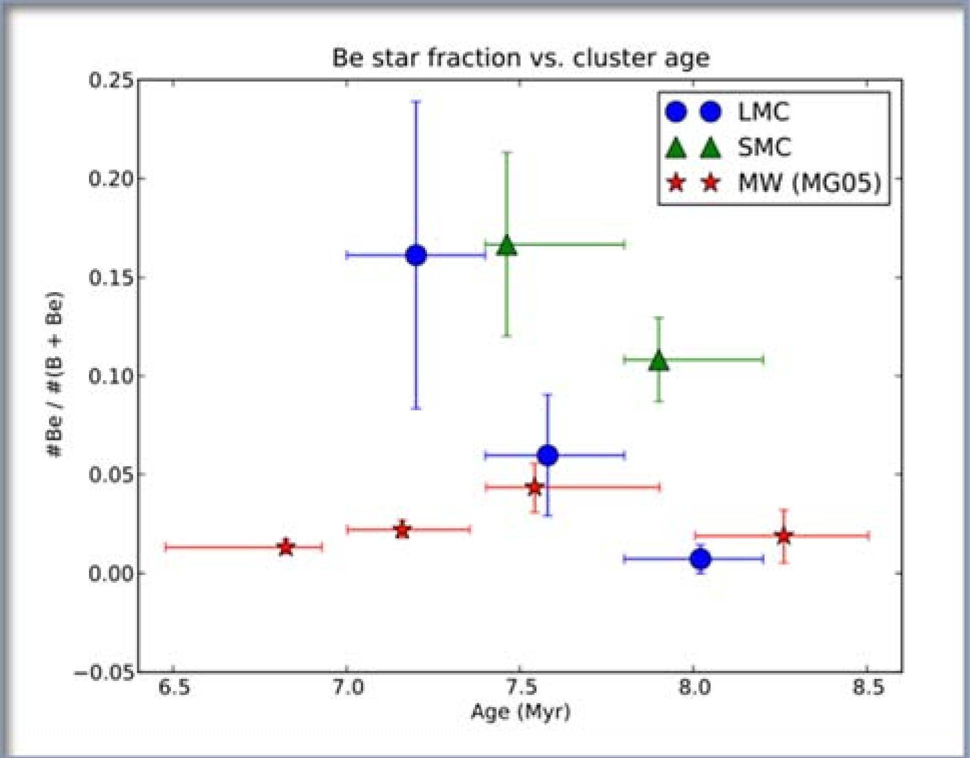
Antoniou & Zezas (2013)

TRACING THE YOUNG HMXBs IN THE MCs



SMC LMC

BE STARS IN THE MAGELLANIC CLOUDS



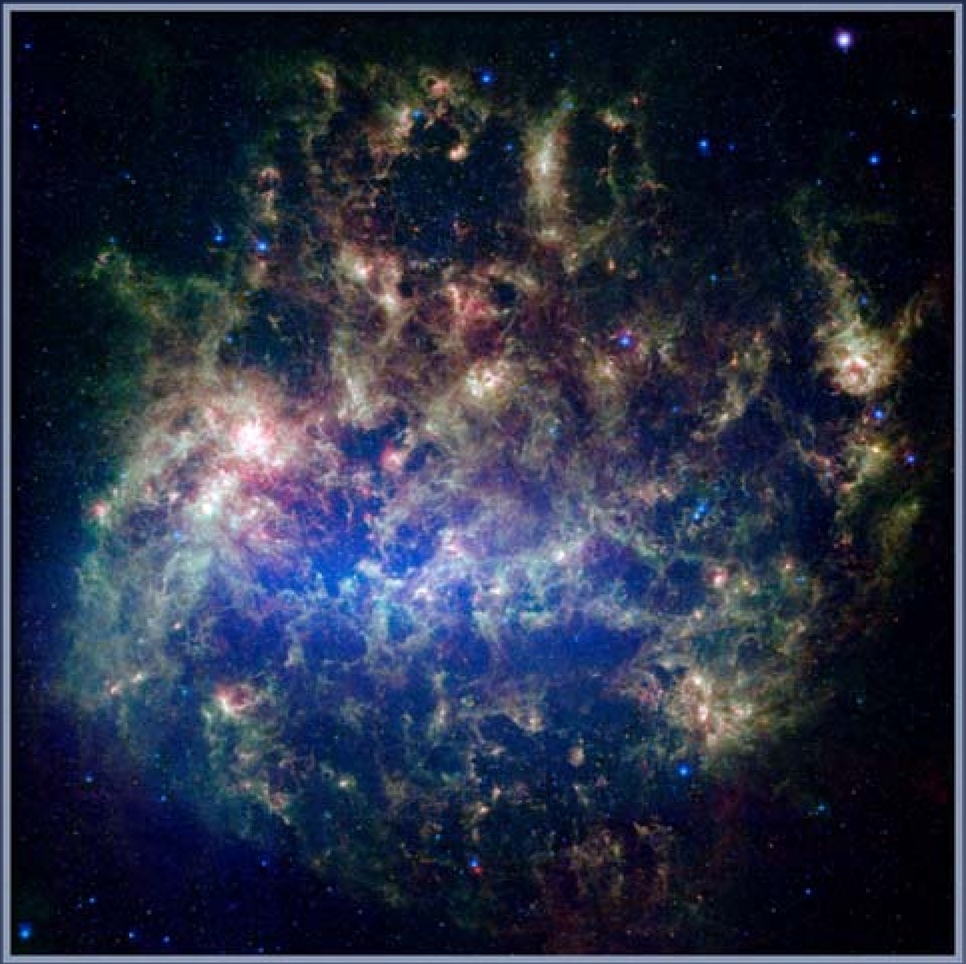
Iqbal & Keller (2013)

A narrow-band Hα filter to identify Be star candidates in 11 LMC & 14 SMC clusters:

✧Trend of higher Be star fractions with lower metallicity

✧ The highest fractions of Be stars occur in the SMC clusters and decrease with increasing metallicity through the LMC and MW

SURVEYING THE AGENTS OF GALAXY EVOLUTION (SAGE)



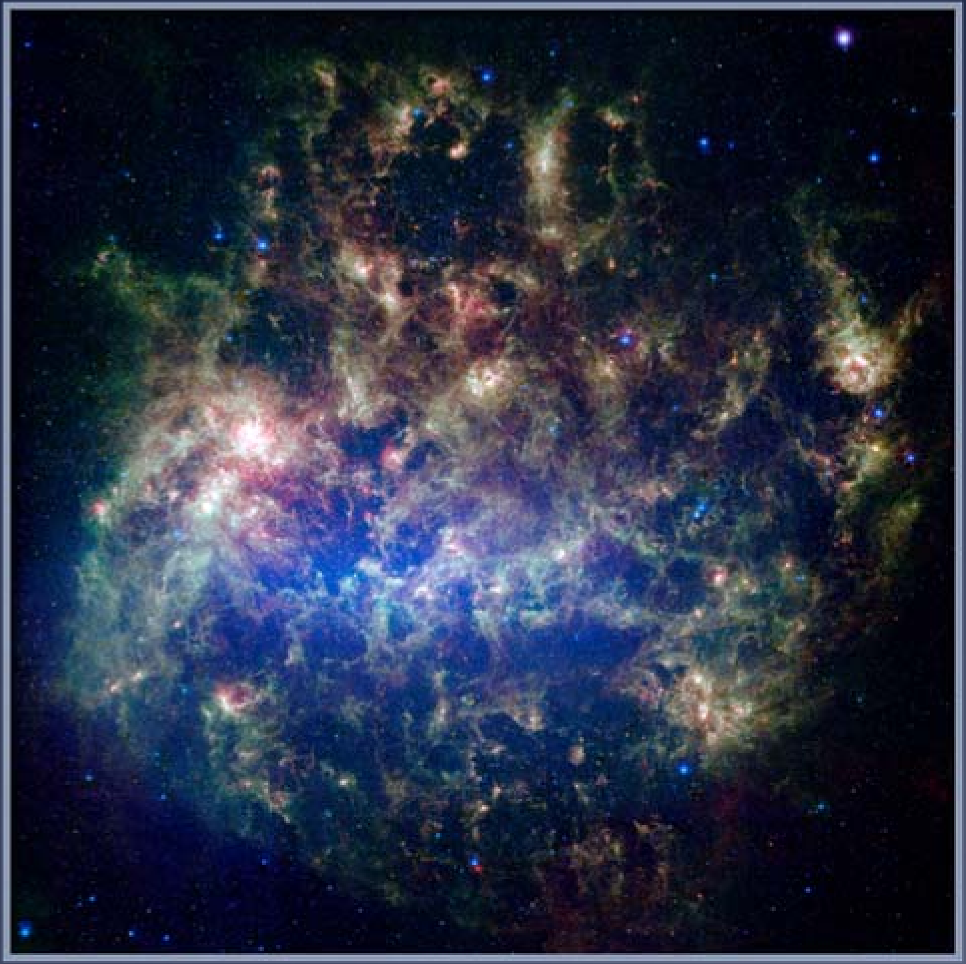
- ✧ Unbiased imaging survey (PI M. Meixner)
- ✧ ISM & stellar content in order to trace the lifecycle of observable matter in the LMC
- ✧ IRAC (3.6, 4.5, 5.8 & 8.0 μm) & MIPS (24, 70 & 160 μm) instruments on board Spitzer Space Telescope
- ✧ Composite ~7.4 deg x 7.4 deg image assembled from >300,000 frames:

3.6 μm, 8.0 μm, 24.0 μm

PHOTOMETRIC CLASSIFICATION OF THE SAGE SOURCES

SAGE-Spec: PI C. Kemper; Coordinator M. Marengo

…To classify as many SAGE sources as possible!



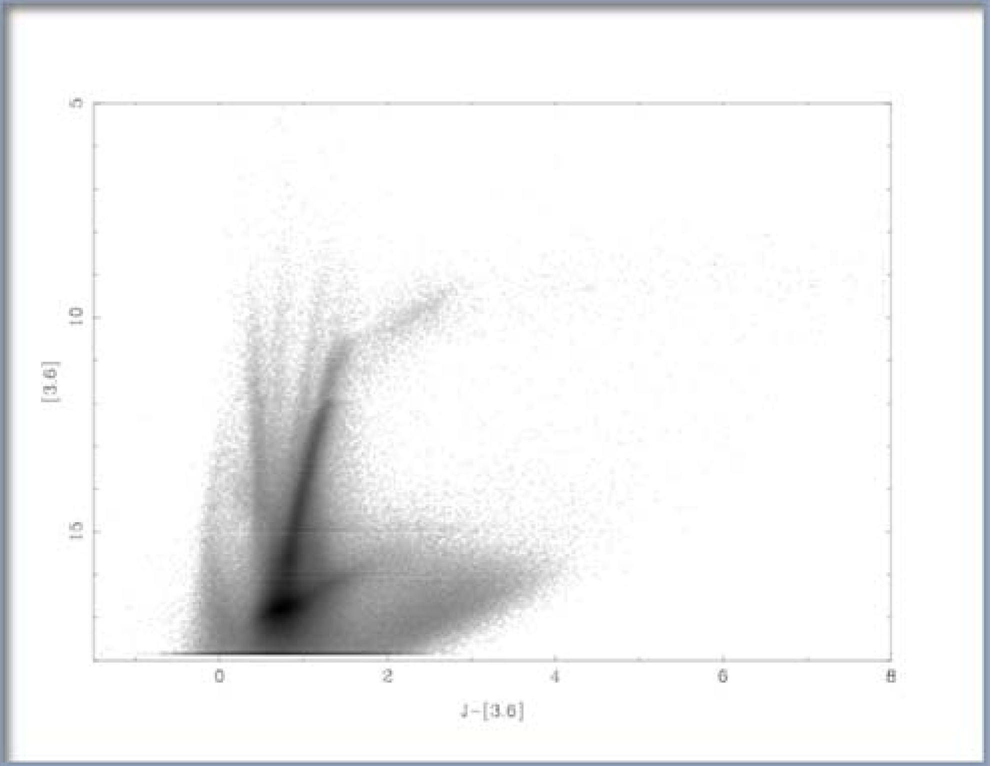
✧ >7M sources: Spitzer SAGE (IRAC 3.6, 4.5, 5.8 & 8.0 μm and MIPS 24μm), 2MASS (JHK) and MCPS (UBVI)

✧ Sensitivity not uniform across bands: only a fraction of sources has photometry across all bands: e.g., 80% have 3.6 & 4.5μm mags, <30% have JHK mags, <5% have 8.0μm photometry and only ~0.5% have 24μm mags.

…Have to use a staggered approach with different combinations of photometric bands for sources of different classes.

PHOTOMETRIC CLASSIFICATION OF THE SAGE SOURCES

k-Nearest Neighbor (k-NN) method: a non-parametric classifier



✧ Avoid cuts in CMDs and 2CDs

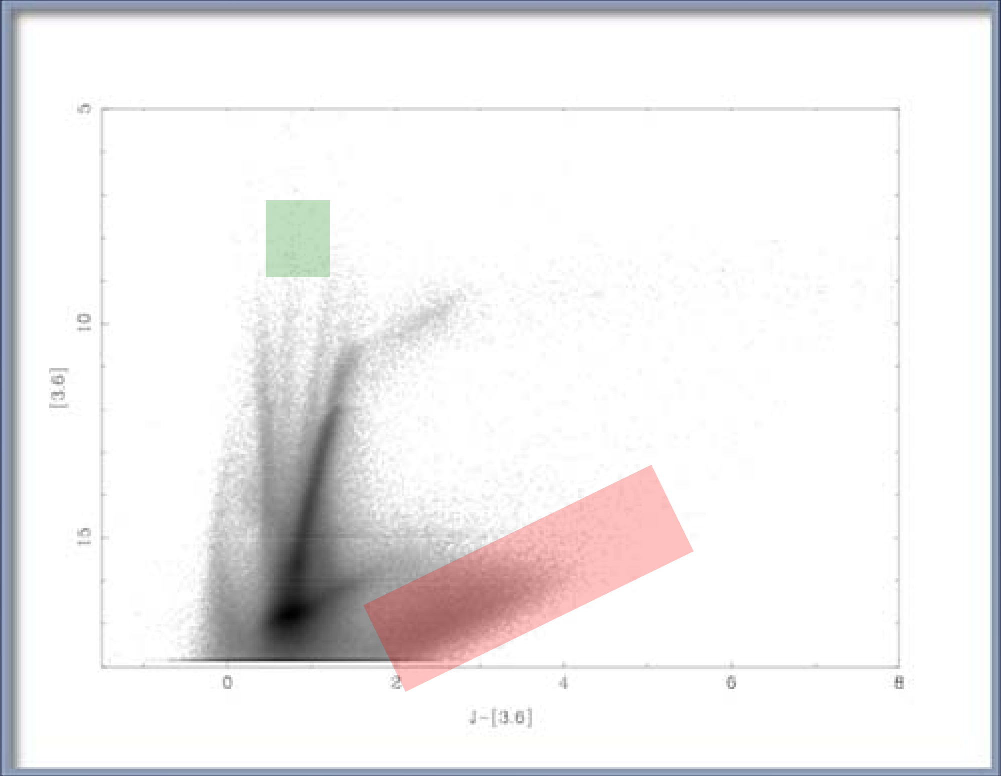
- often srcs of different classes overlap
- their choice can bias the final classification

...Have the cuts draw themselves following more closely the separation between classes & using simultaneously a large number of variables...

The k-NN method allows this kind of classification by using the “distance” of each src to be classified from a number of “template” srcs of known class

PHOTOMETRIC CLASSIFICATION OF THE SAGE SOURCES

Main stellar populations



✧ identified in various CMDs and 2CDs, e.g.:

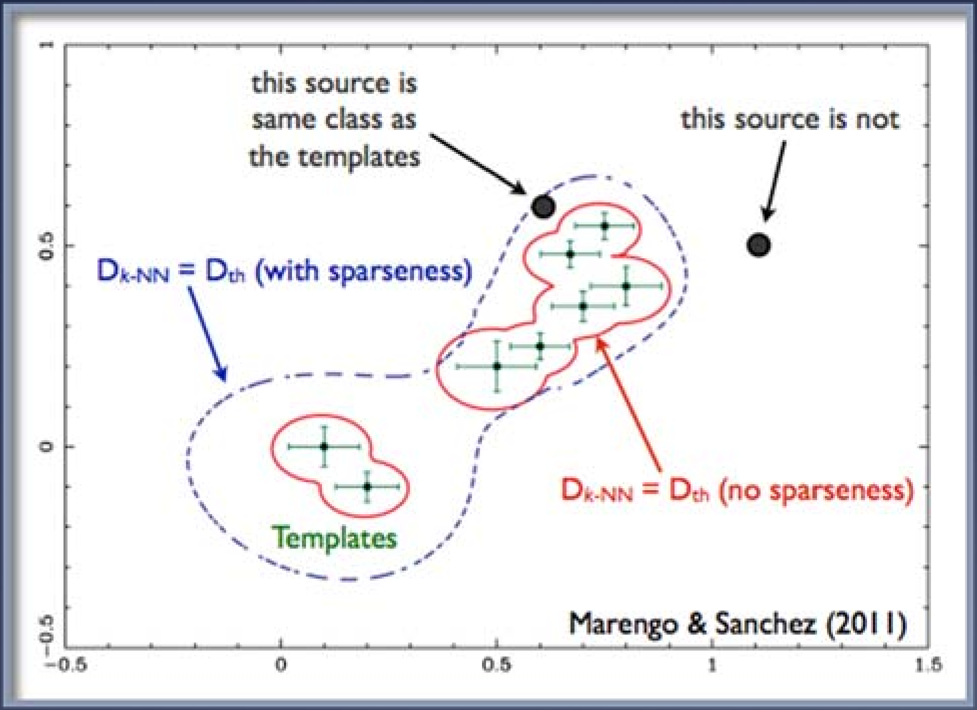
- Massive stars: Bonanos et al. (2009)
-YSOs: Whitney et al. (2008)
- PNe: Hora et al. (2008)
- Evolved stars: Boyer et al. (2011), Matsuura et al. (2011)
- etc.. etc..

→ Extensive literature search of spectroscopically confirmed members for each class of objs

✧ LMC srcs overlap with both fg and bkg contaminants → they can only be “cleaned” on a statistical basis

PHOTOMETRIC CLASSIFICATION OF THE SAGE SOURCES

How does it work?



A source with $D_{k\text{-}NN} < D_{th}$ is of the same class as the templates

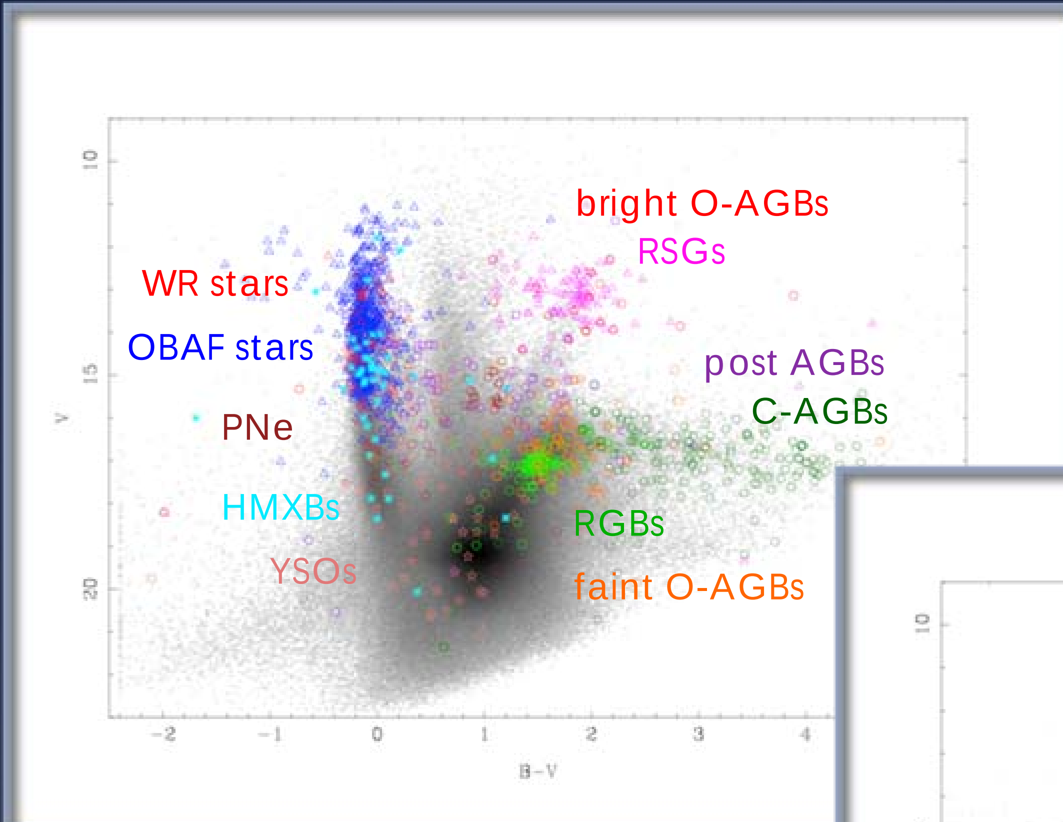
✧ Each point in *n-dimensional color/magnitude space has associated "distance" from k closest templates. Distance normalized over photometric uncertainty of templates and data.*

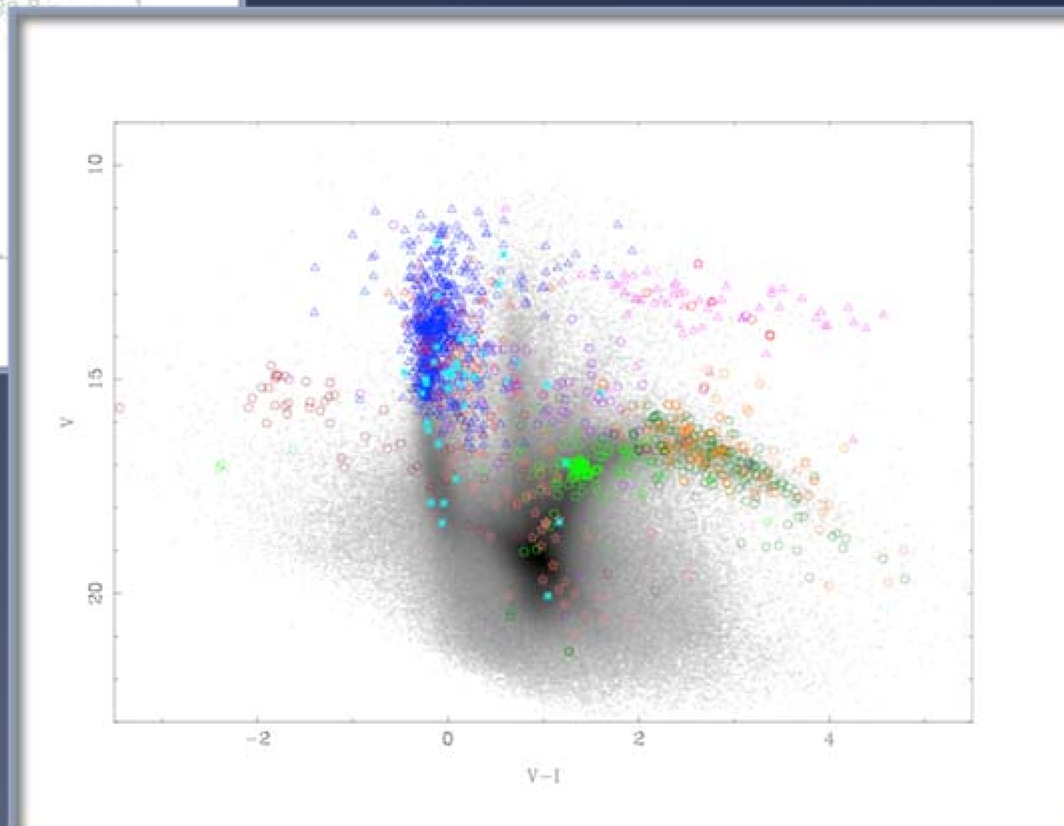
✧ *"Sparseness factor" (average separation between templates) added to avoid excessive fragmentation of regions.*

✧ *Dth determined by balancing selection completeness and rejection efficiency.*

PARENT STELLAR POPULATIONS OF HMXBS

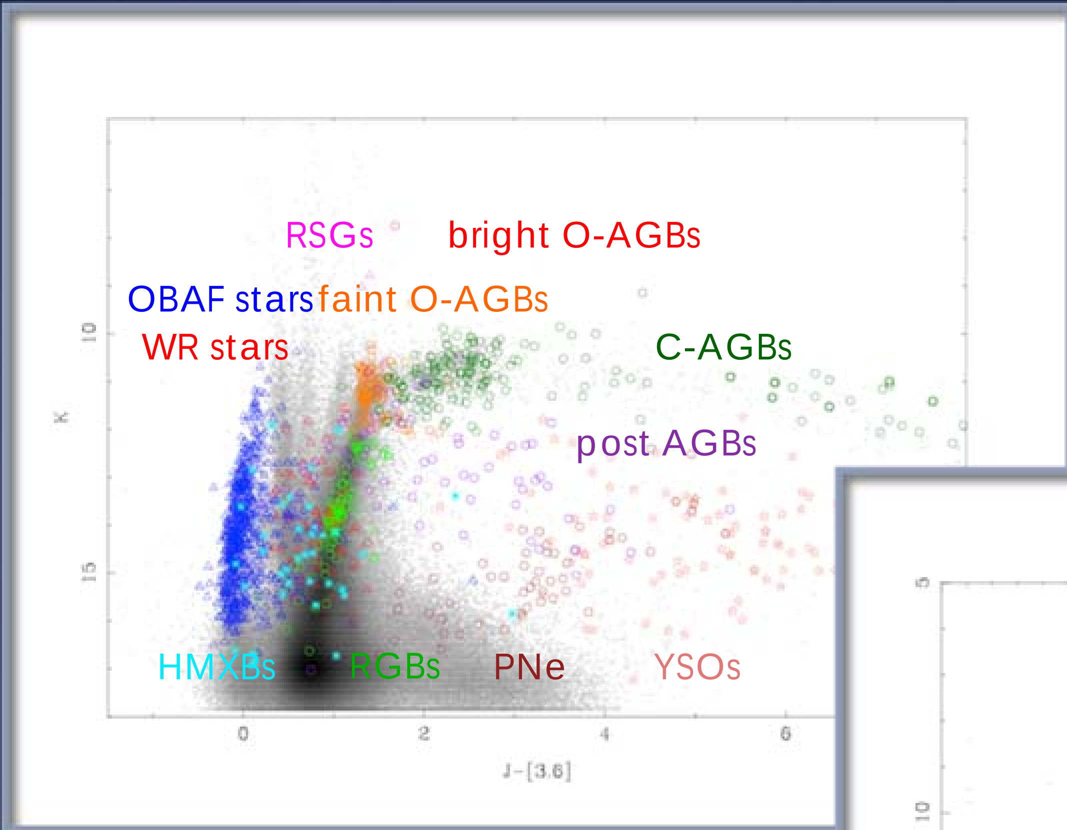
OPTICAL PROPERTIES

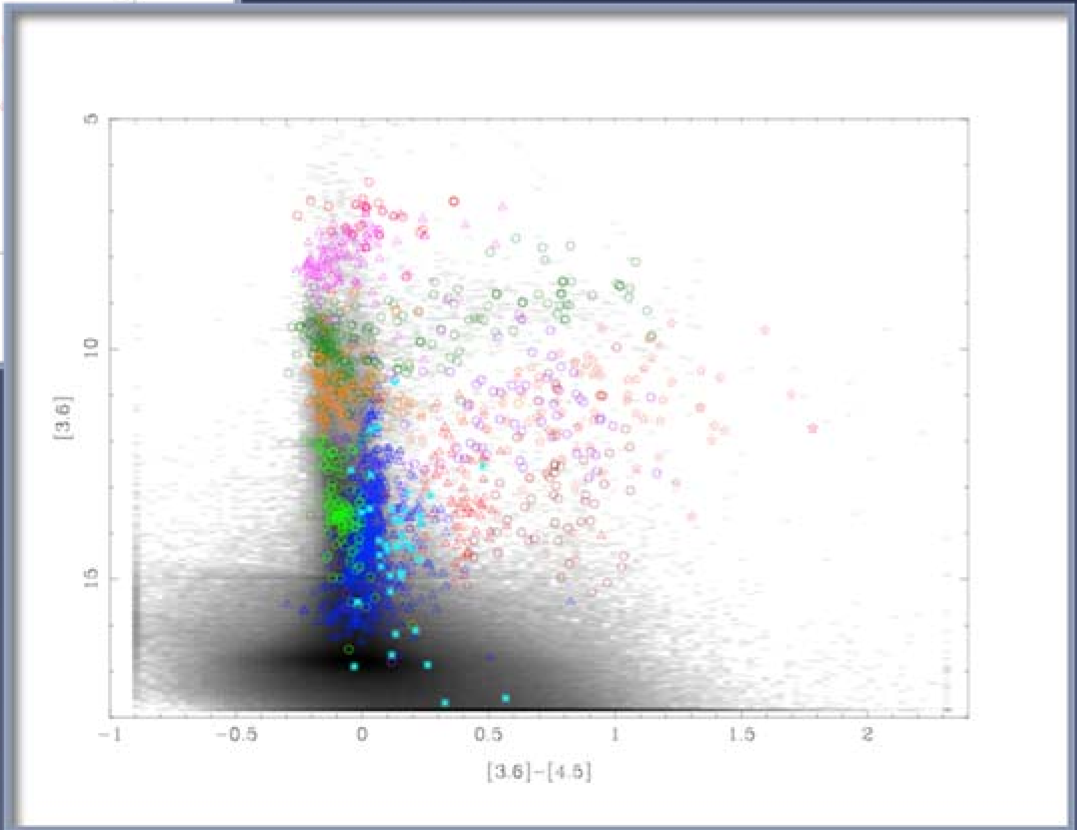




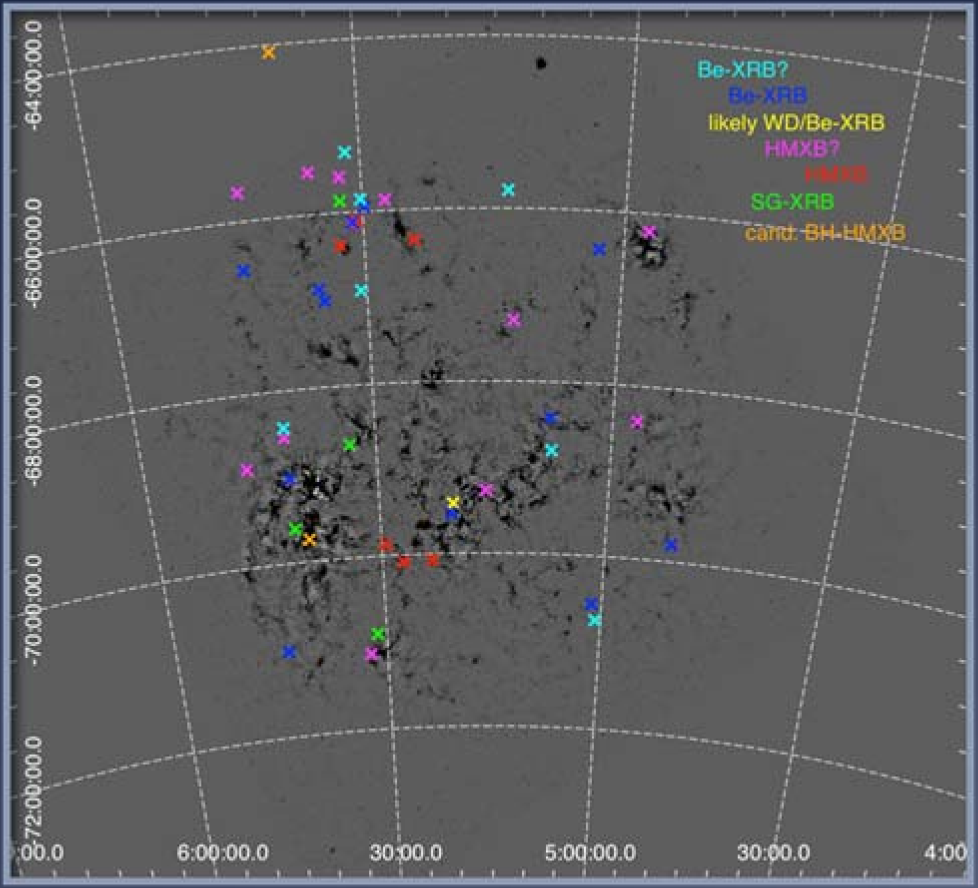
PARENT STELLAR POPULATIONS OF HMXBS

NEAR/MID-IR PROPERTIES





THE HMXB POPULATION OF THE LMC



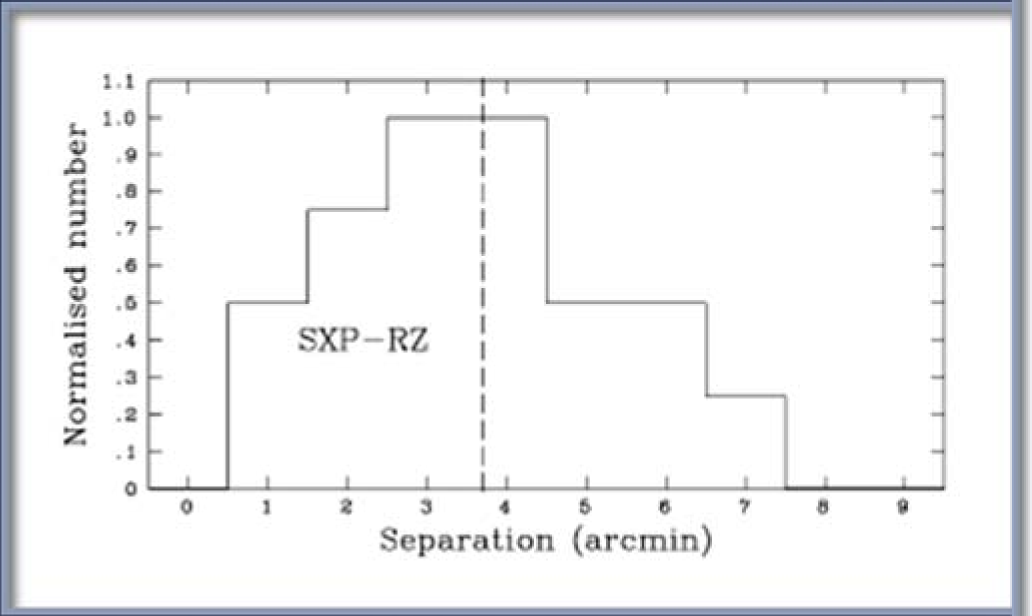
8.0 μm IRAC image

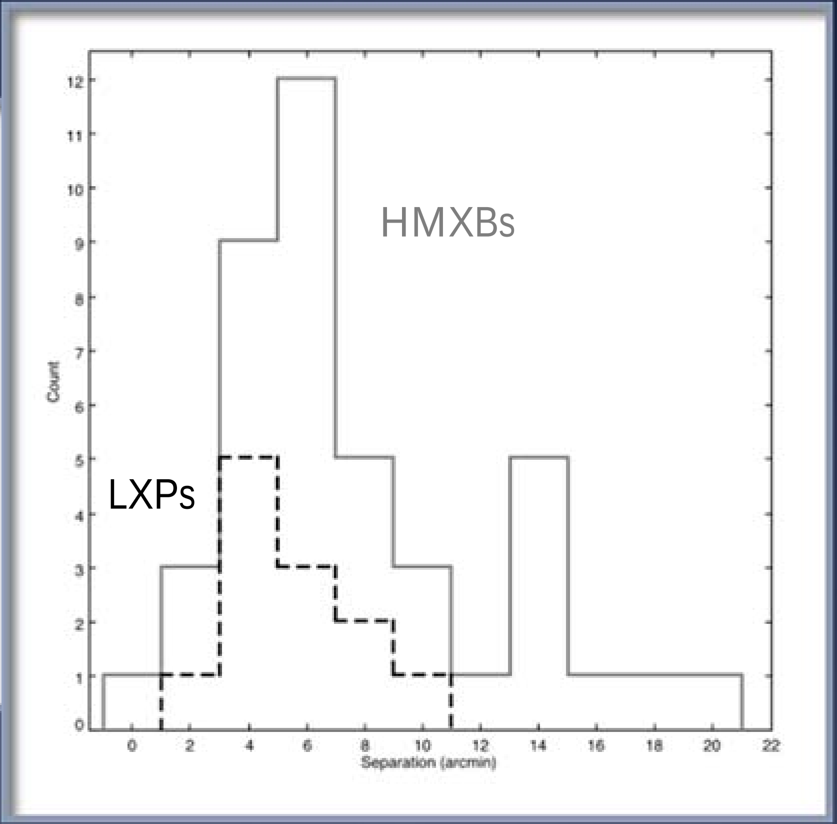
✧ Previous census (36 HMXBs published till Apr. 2005):
Liu et al. (2005)

✧ 44 HMXBs (including candidate systems)

✧ 12 X-ray pulsars

KICK VELOCITIES OF NEUTRON STARS IN HMXBS





SMC (Coe 2005) @ 60 kpc

- Mean separation ~ 3.9' ~ 65 pc
- Travel time of SXP since birth ~ 5 Myr

→$v_{transverse}$ ~ 16 km/s

Moving in completely random directions

→v_{space} ~ 32 km/s

LMC (Antoniou & Zezas 2013) @ 50 kpc

- Mean separation ~ 5.6'~ 81 pc
- SF burst ~ 12.6 Myr
- Min. pulsar birth timescale (after the SF burst) ~ 10 Myr

→$v_{transverse}$ ~ 26 km/s

MW (van den Heuvel 2000)

→v~15+/-6 km/s (Be-XRBs, but most-if not all-XBPs in the MCs have Be companions)

CONCLUSIONS

✧ The first direct determination of the number of XRBs per unit SFR of the *parent* population

✧ For the same metallicity $Z \sim 0.4 Z_{\odot}$, the number of HMXBs (and Be-XRBs) peaks at earlier ages in the LMC (~12 Myr) than in the SMC (~42 Myr)

...indicates lower formation efficiency in these ages

...NEED detailed metallicity studies of regions with HMXBs

✧ The X-ray pulsar population of the LMC is connected with a SF burst ~6-25 Myr ago

...Do current population synthesis models predict X-ray pulsars at that young ages? No, they predict BHs instead of NSs as compact objects!

COLLABORATORS

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  University of Crete & CfA
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  Northwestern University
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  Iowa State University
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- Jeremy Drake, Jose Galache
  CfA
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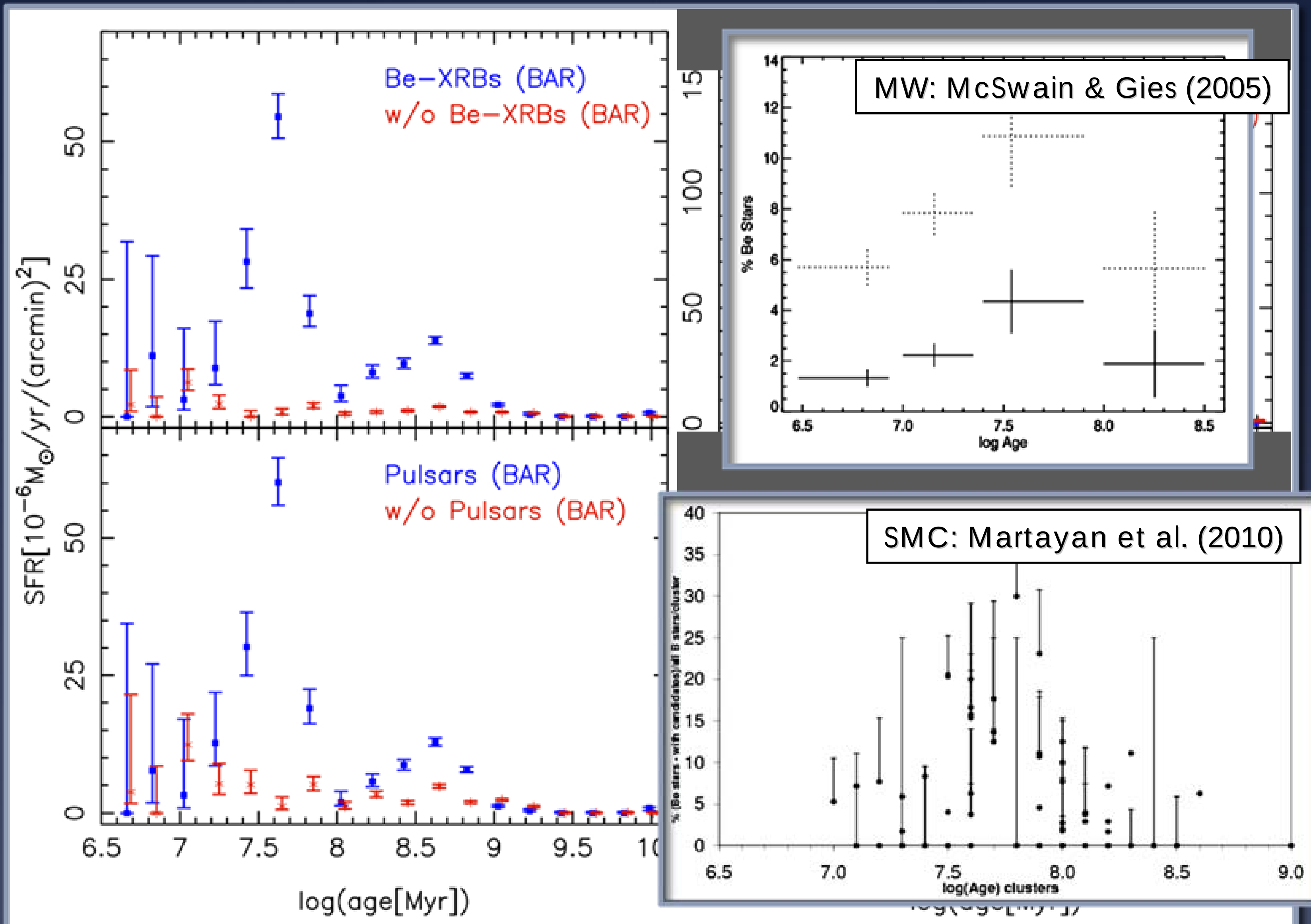
  Academia Sinica, Institute of Astronomy & Astrophysics (ASIAA)

MAGELLANIC CLOUDS: OUR NEAREST STAR-FORMING GALAXIES

- Thought to be gravitationally bound to the Milky Way
- High 3D velocities indicate that instead they are “just passing through”
- Rather than forming stars continuously (like the MW), the MCs have undergone several burst of SF followed by long quiet periods
- *Interactions between the SMC and LMC may be the primary force driving star formation in both galaxies*

Besla et al. (2007, ApJ, 668, 949)

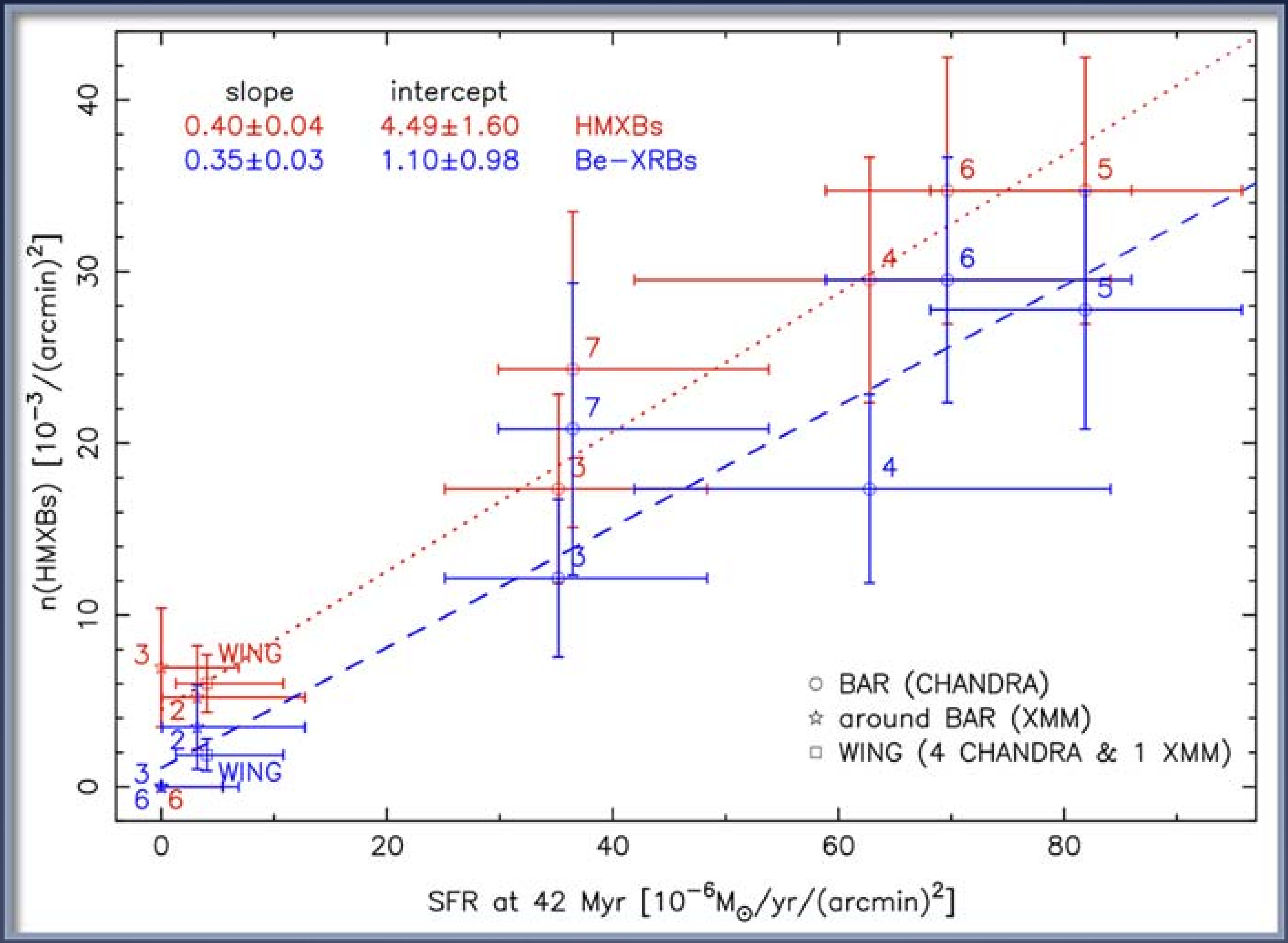
TRACING THE YOUNG HMXBs IN THE SMC



Average SFH (using date from Harris & Zaritsky 2004)

Antoniou et al. (2010)

HMXB FORMATION RATE IN THE SMC

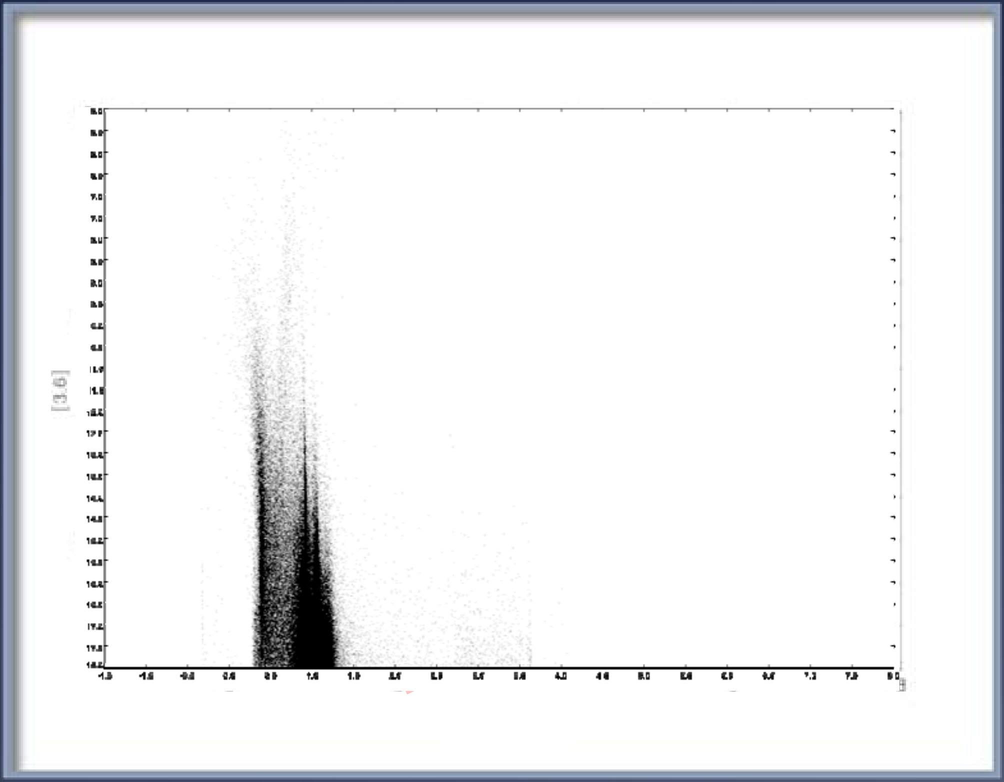


Be-XRBs: ~ 1 system per 3 x 10^{-3} M_o/yr

Antoniou et al. (2010)

PHOTOMETRIC CLASSIFICATION OF THE SAGE SOURCES

TRILEGAL simulations (PI L. Girardi) for foreground contamination
http://stev.oapd.inaf.it/cgi-bin/trilegal_1.6



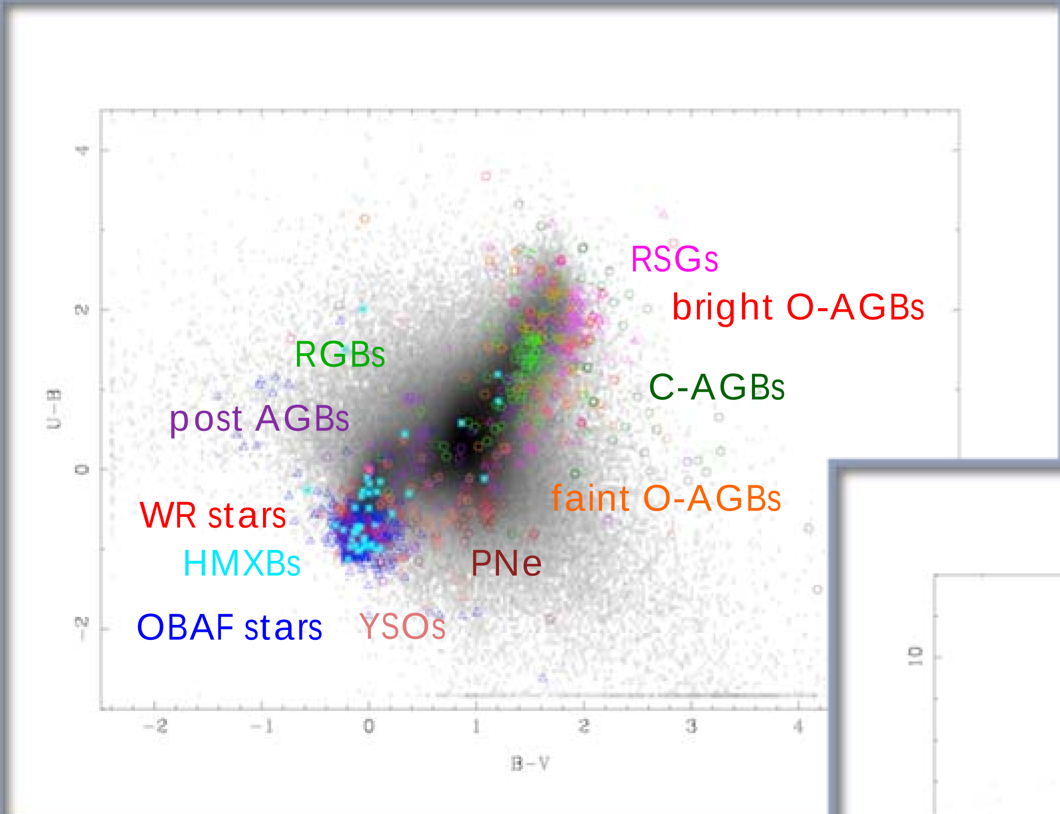
✧ A population synthesis code for simulating the stellar photometry of any Galactic field (Girardi et al. 2005)

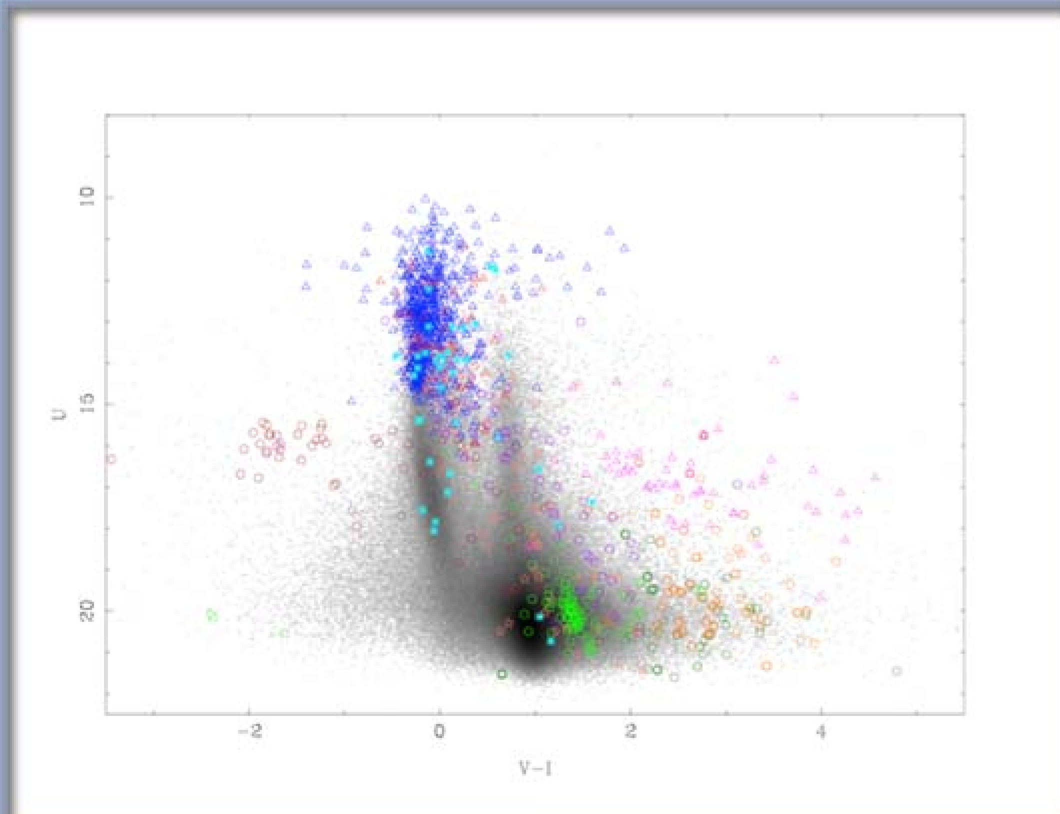
✧ Input parameters:
- coordinates
- photometric system
- extinction calibration: Av taken from extinction maps http://irsa.ipac.caltech.edu/applications/DUST/

✧ Output parameters:
- a series of population and physical parameters of the stars
- the apparent photometry in the selected system

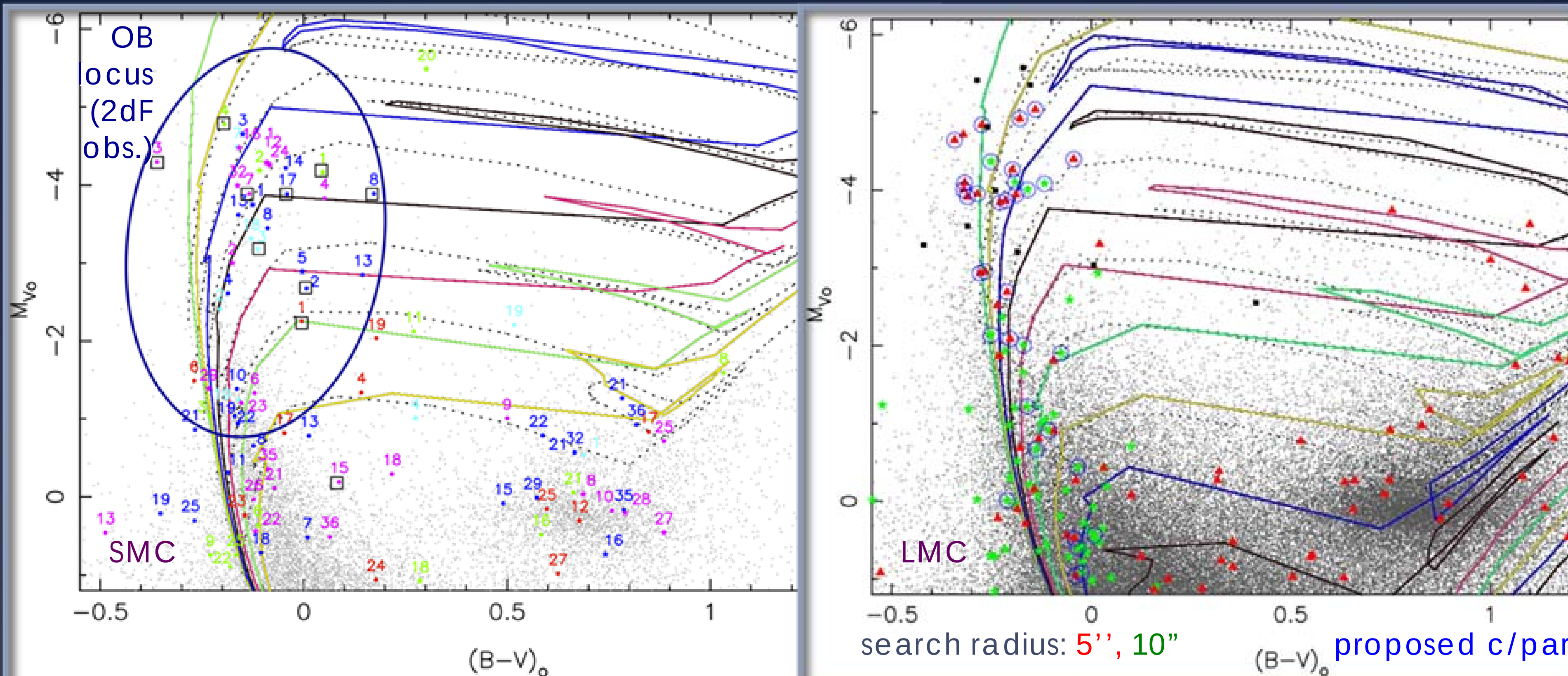
PARENT STELLAR POPULATIONS OF HMXBS

OPTICAL PROPERTIES





PARENT STELLAR POPULATIONS OF HMXBs



$Z = 0.004 = 0.2Z_\odot$

Geneva isochrones (top to bottom):
8.7 Myr, 15.5 Myr, 27.5 Myr, 49.0 Myr,
87.1 Myr, 154.9 Myr, 275.4Myr, …

$Z = 0.008 = 0.4Z_\odot$

black squares: OGLE-II (type-4) candidate Be stars from
SMC: Mennickent et al. (2002); LMC: Sabogal et al. (2005)

Antoniou et al. (2009)

Antoniou & Zezas (2013)

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  SSL@ Univ. of California, Berkeley
- Jeremy Drake, Jose Galache, Paul Plucinsky
  CfA
- Ciska Kemper
  Academia Sinica, Institute of Astronomy & Astrophysics (ASIAA)
- Ann Hornschmeier, Andy Ptak, Bret Lehmer
  Goddard Space Flight Center
- Tom Maccarone
  Texas Tech University

CONCLUSIONS

The low-metallicity MCs are excellent analogs of the low-metallicity star-forming galaxies that dominate in the early Universe. Unlike those distant systems, in the MCs we can study in great detail their XRB populations.

✧ The first direct determination of the number of XRBs per unit SFR of the *parent* population

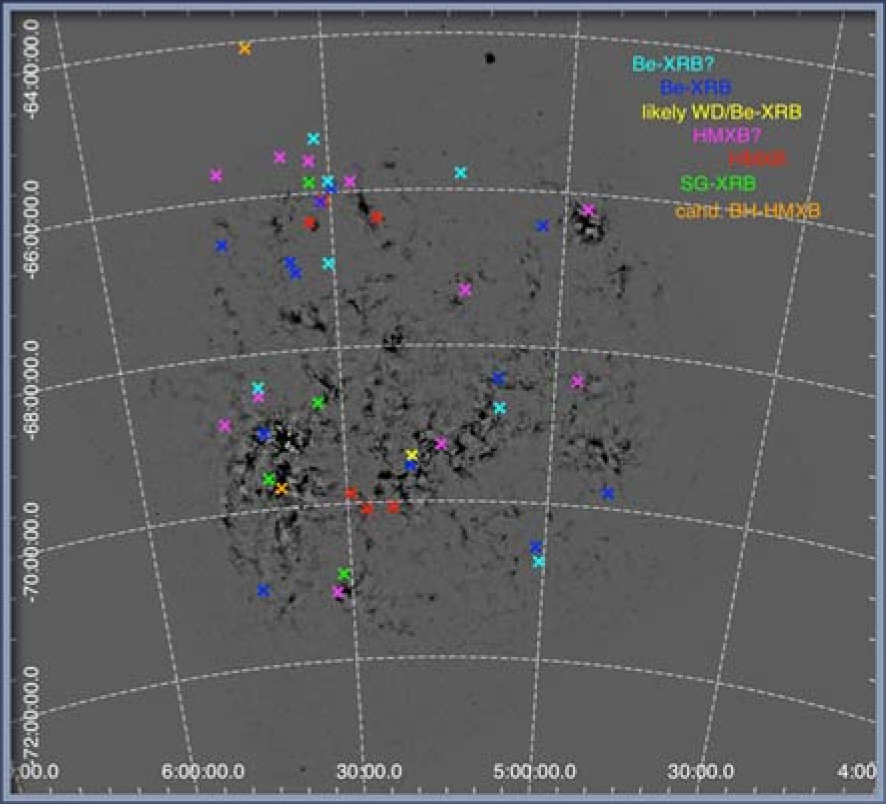
✧ For the same metallicity $Z \sim 0.4 Z_{\odot}$, the number of HMXBs (and Be-XRBs) peaks at earlier ages in the LMC (~12 Myr) than in the SMC (~42 Myr)

…Why? Simply because at these ages the SFR is higher in each of the 2 galaxies! In any case, “same metallicity” is a simplifying assumption!

…NEED for detailed metallicity studies of regions with HMXBs

CONCLUSIONS

✧ Based *solely* on the higher star-formation rate of the parent stellar populations in the LMC, a significant number of Be-XRBs and X-ray pulsars is expected to be discovered



✧ What is the formation rate of HMXBs in the LMC?

...Limited by small number statistics

...NEED for a systematic study of the LMC X-ray source population in *young* stellar regions