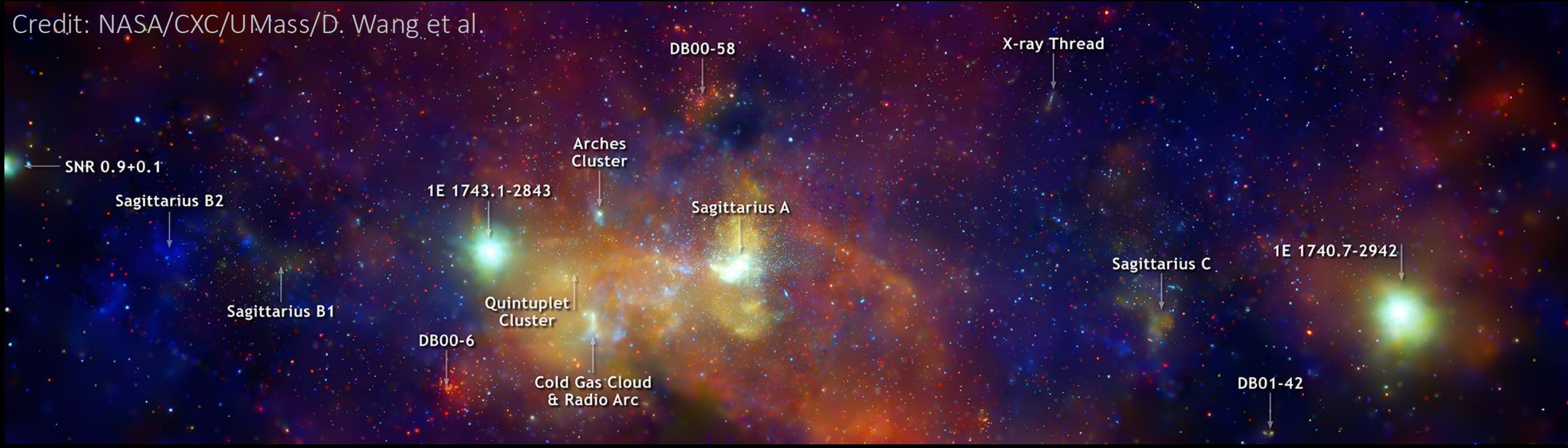


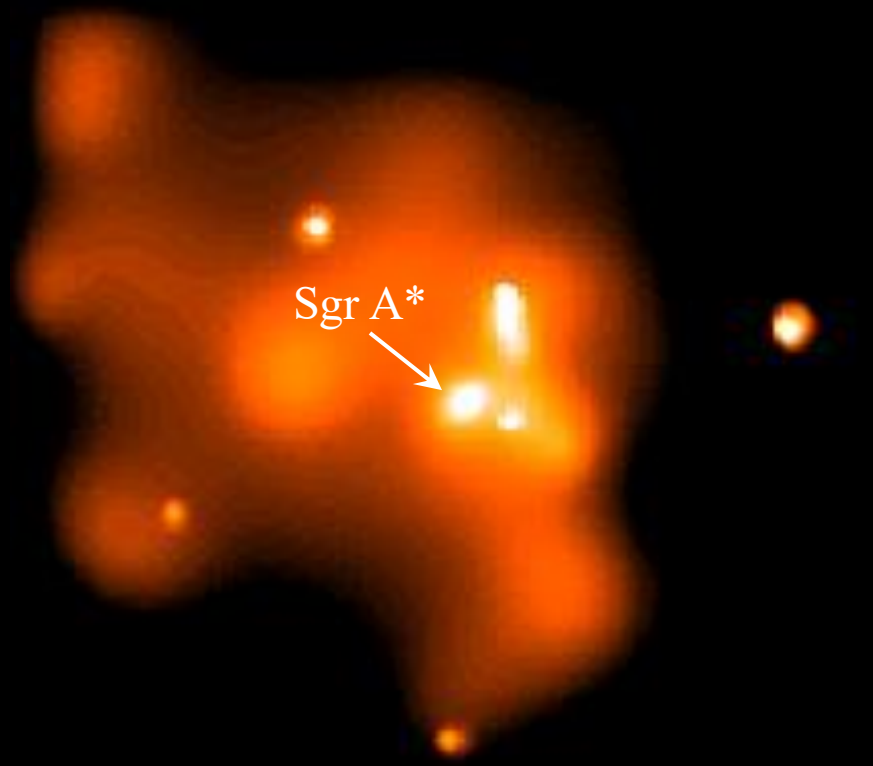
A Comprehensive Study of the X-ray Sources in the Galactic Center

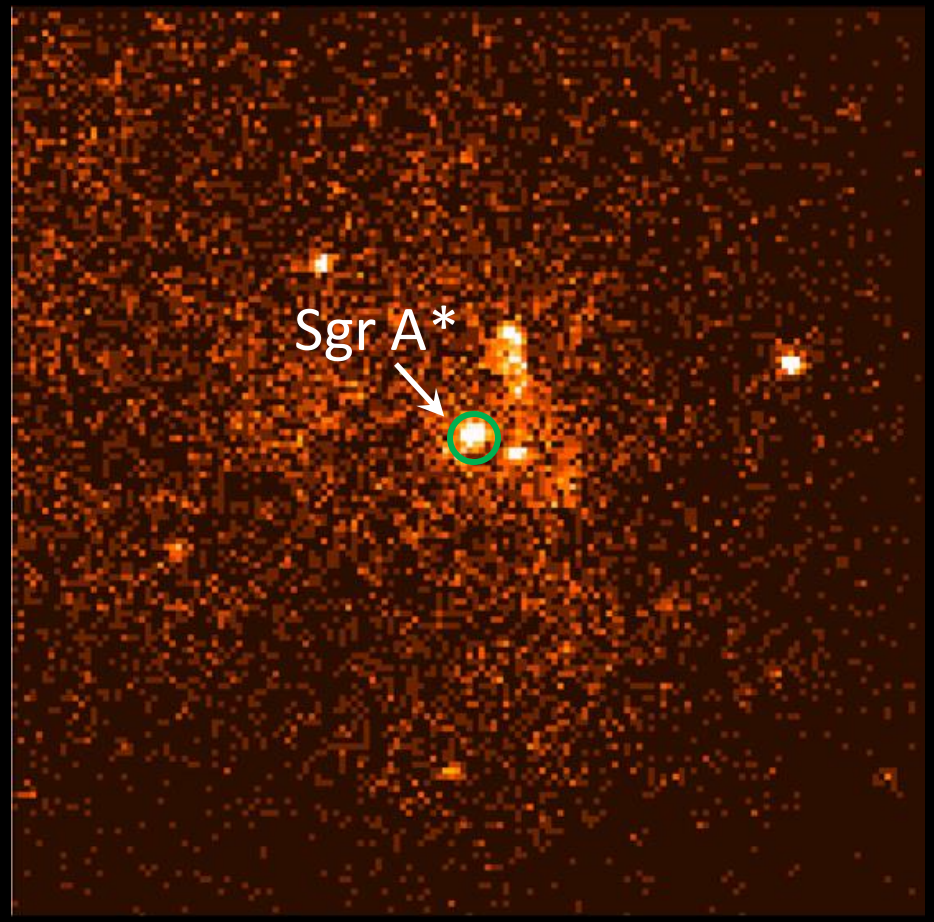
Shifra Mandel
Columbia University

December 5, 2024

Retrospective: *Chandra* and the GC

2000: First X-ray detection of Sgr A*
(Baganoff et al.)

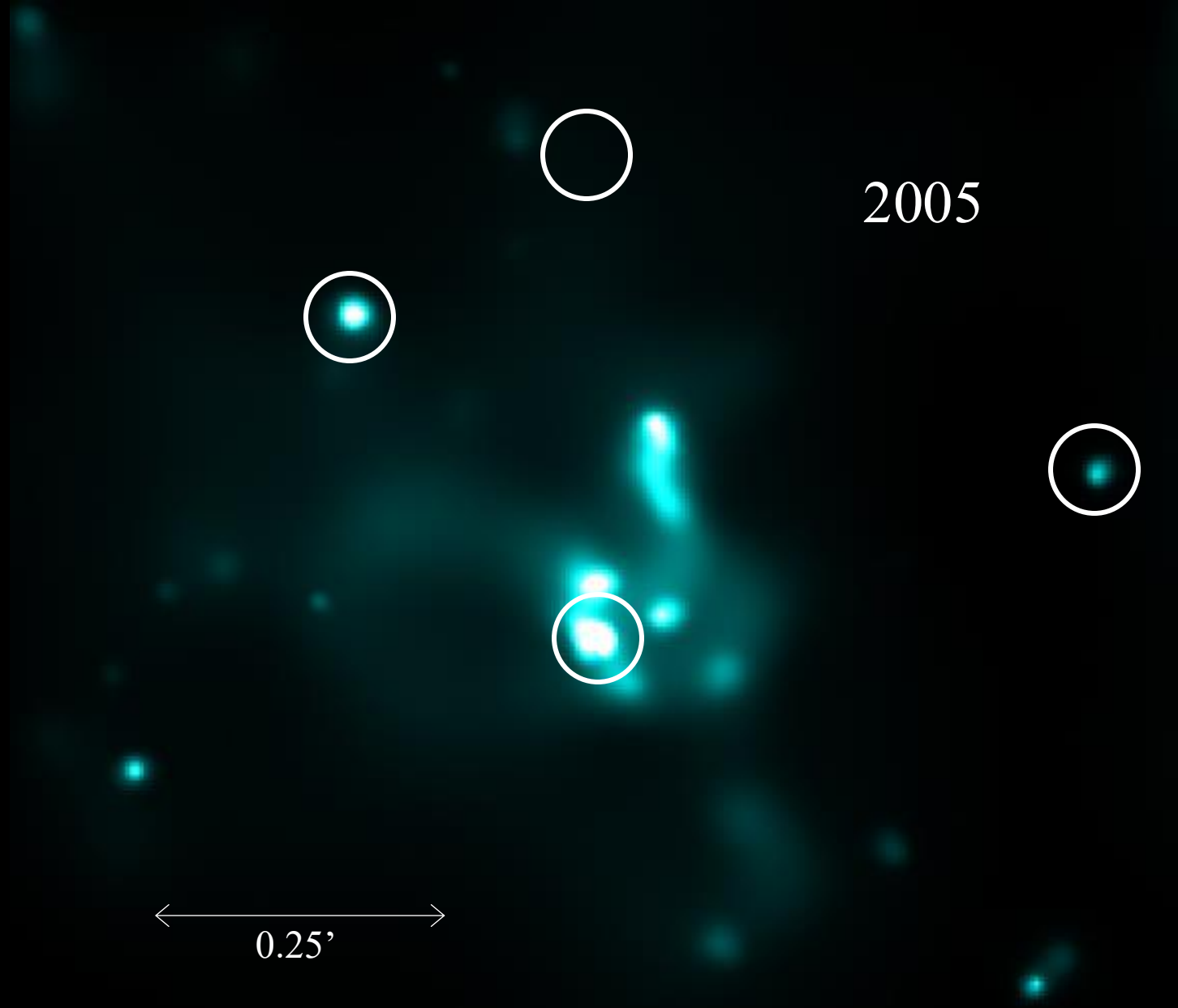




Credit: NASA/F. Baganoff (MIT) /G. Garmire (PSU)

Hello transients!

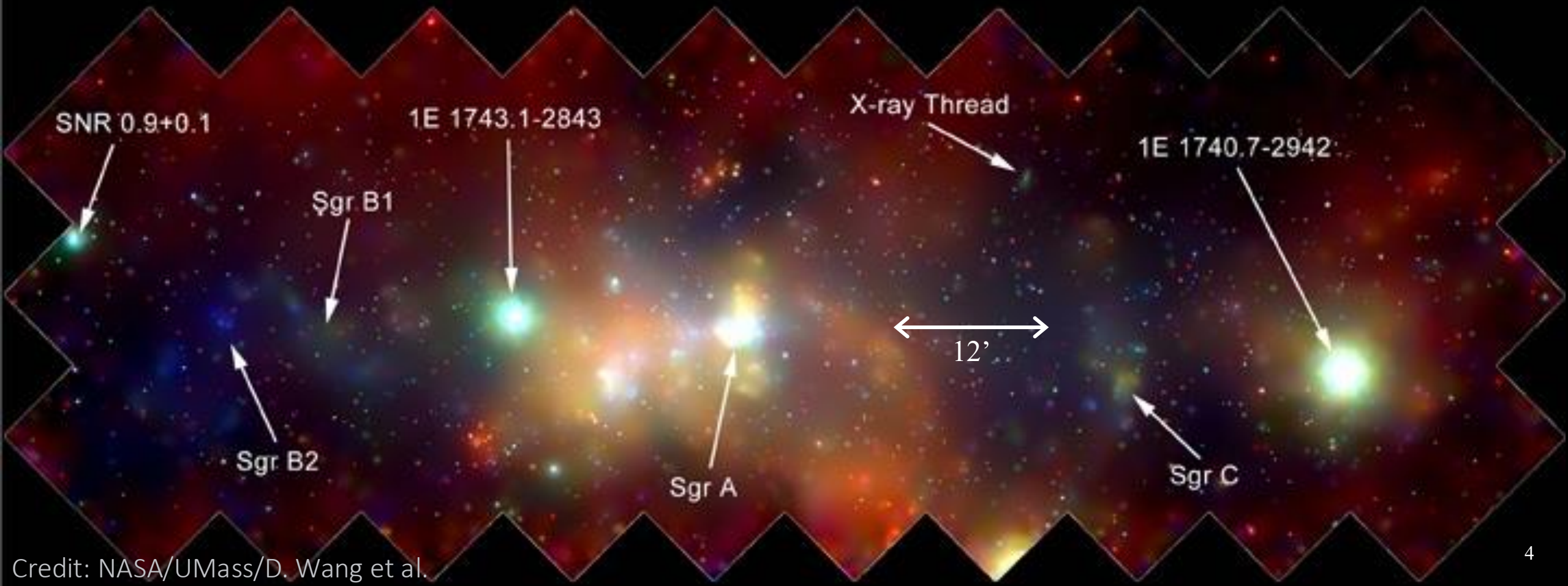
New or recurrent transients?
Only *Chandra* can determine
(Muno et al. 2005)



Credit: NASA/CXC/UCLA/M. Muno et al.

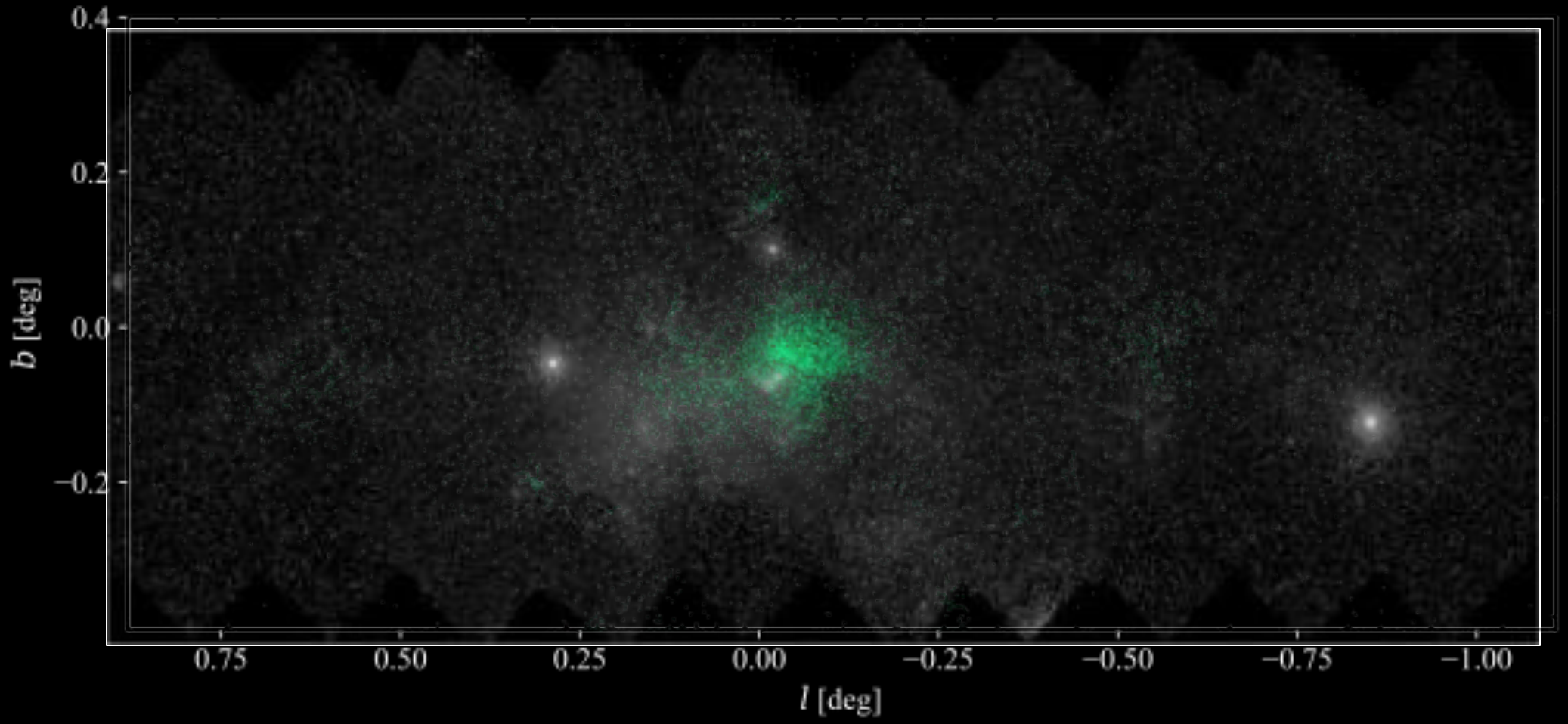
Wang survey (2002): Detection of ~1000 discrete (point) sources

Accreting compact objects (white dwarfs, neutron stars or black holes) – & AGN…



Credit: NASA/UMass/D. Wang et al.

Muno survey (2009): ***9000*** point sources



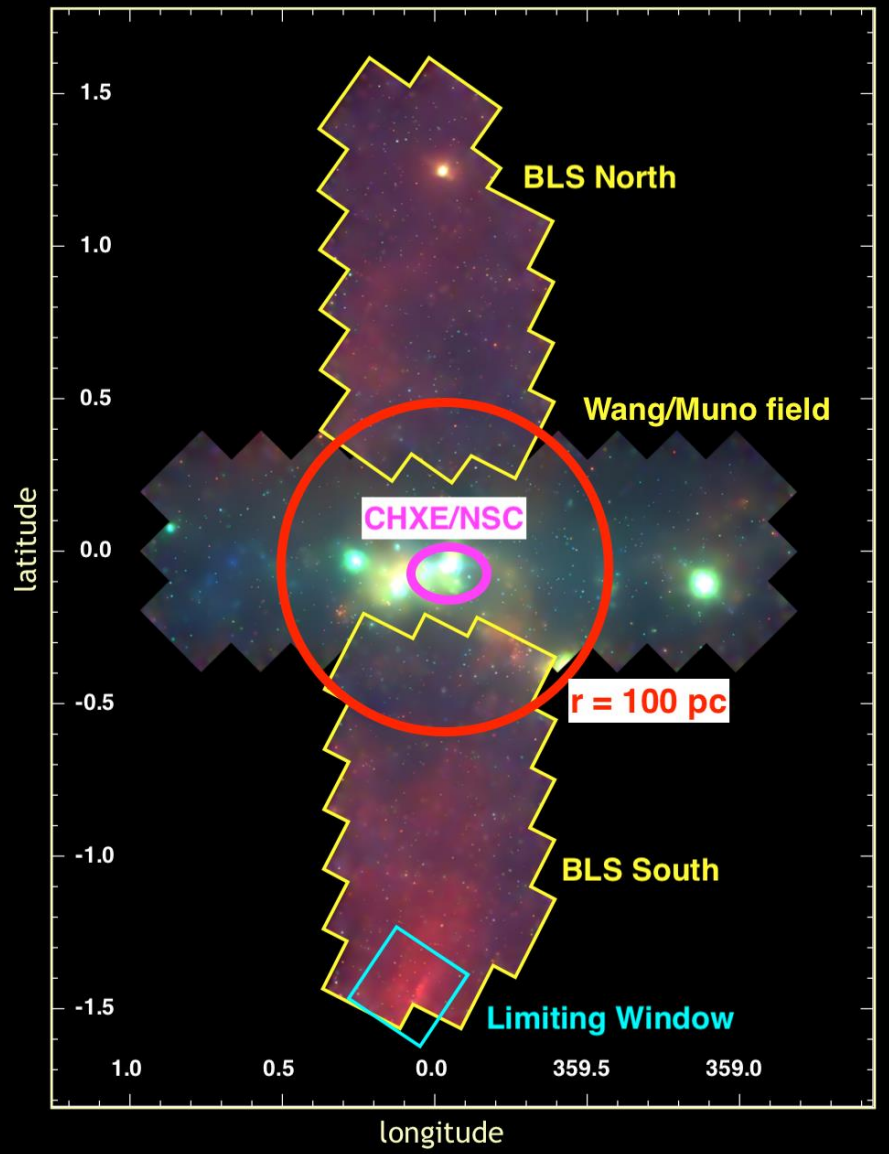
Limiting Window and Bulge Latitude Surveys

Bulge Latitude Survey (BLS):

- $l \pm 0.3$; $b \pm 1.5$ degrees
- 2500 point sources
- CV dominated

Limiting Window (LW) survey:

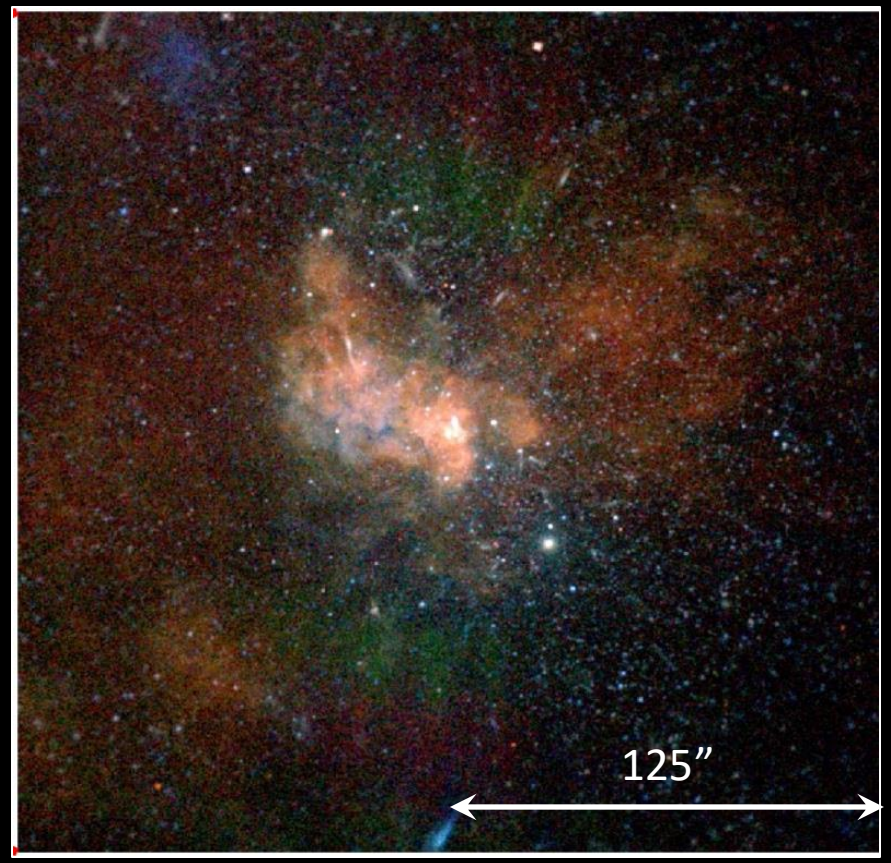
- Low extinction region
- Diffuse emission resolved into discrete sources (Revnivtsev+ 2009)
- 1 Ms exposure reveals faint mCV population (Hong et al. 2012)



Chandra/ACIS-I mosaic R=1-3 keV G=3-5 keV B=5-8 keV

Zhu catalog (2018): ultradeep observation of the Nuclear Star Cluster (NSC)

- Inner 500” (~20 pc)
- An *additional* 1300 sources
- New understanding of **faint** GC X-ray population



Zhu et al. (2018)

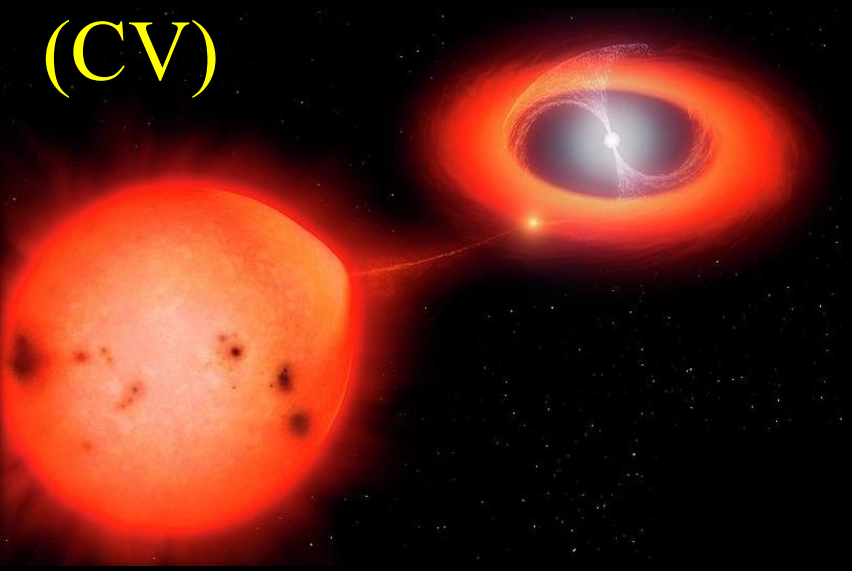
What are they?

- Accreting compact objects

What are they?

- Accreting compact objects

Cataclysmic variable
(CV)

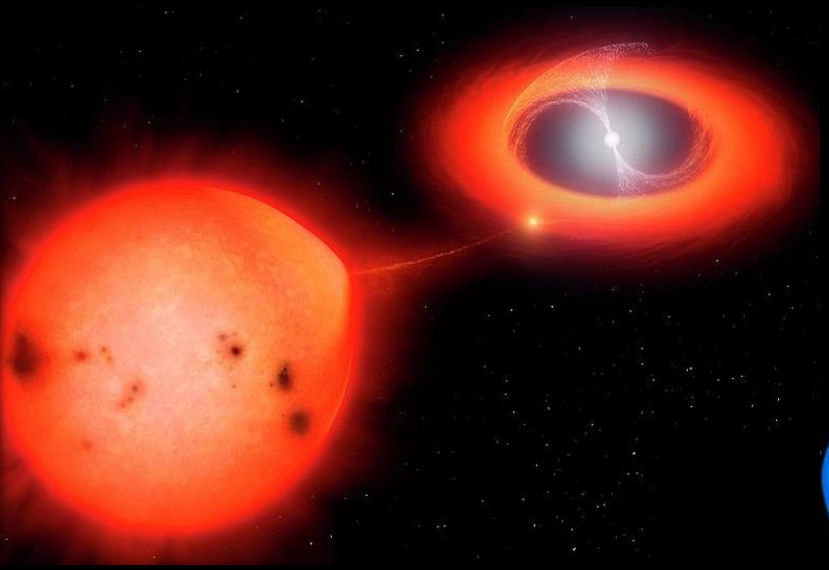


Science Photo Library

What are they?

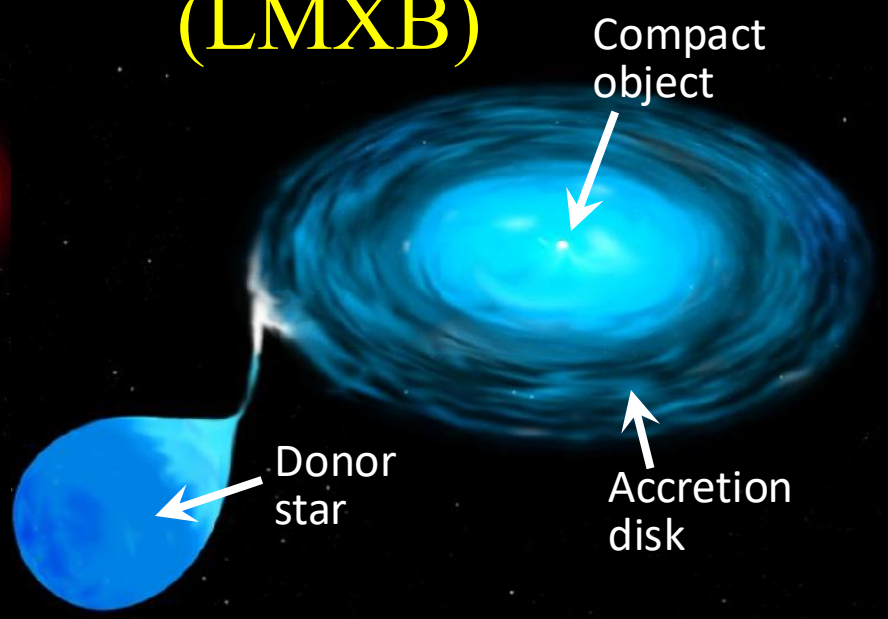
- Accreting compact objects

CV



Science Photo Library

Low-mass X-ray binary (LMXB)

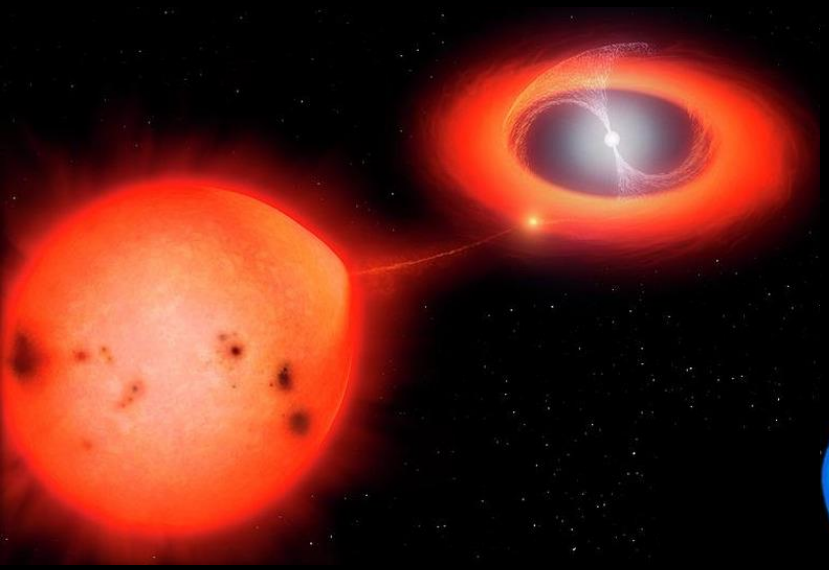


Credit: STScI

What are they?

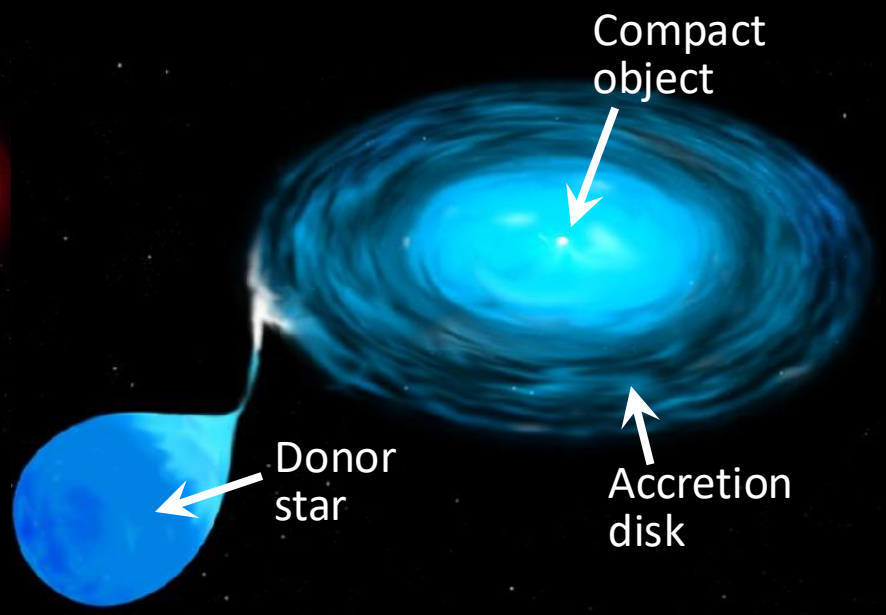
- Accreting compact objects

CV



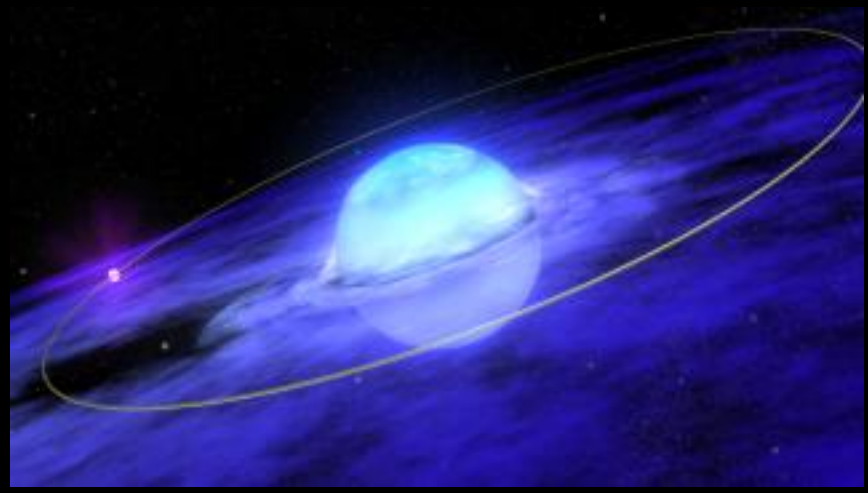
Science Photo Library

LMXB



Credit: STScI

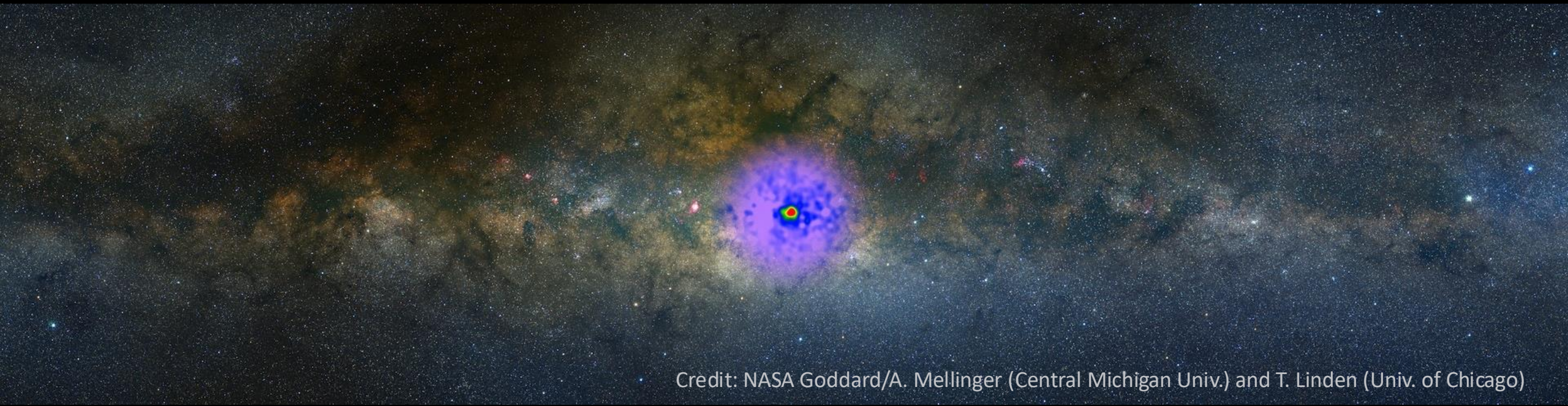
High-mass X-ray binary (HMXB)



Credit: Walt Feimer, NASA/Goddard Space Flight Center

What are they?

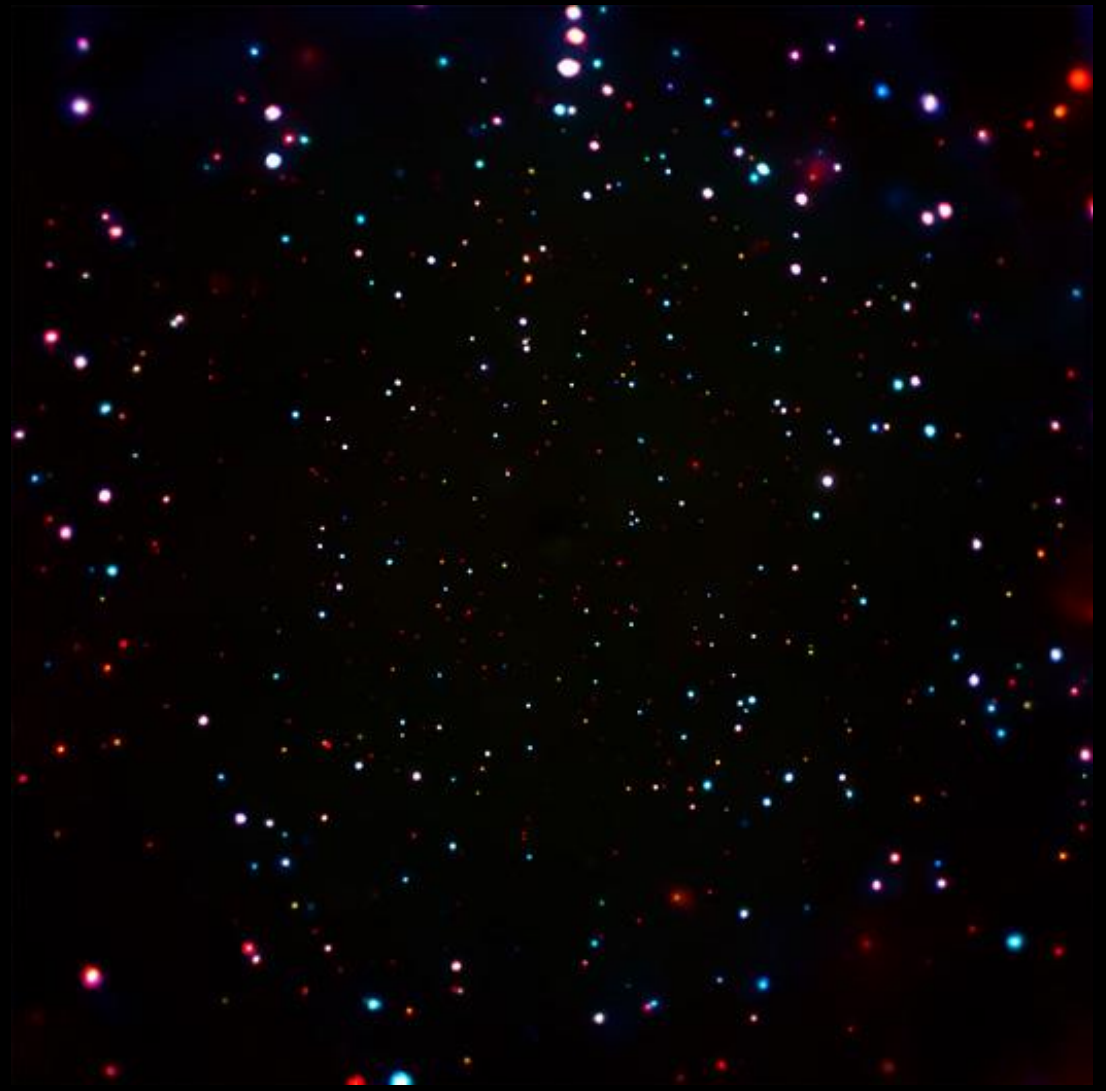
- Accreting compact objects
- Pulsars (missing pulsar problem; Fermi GeV excess)
  – see poster 9 by Amruta Jaodand



Credit: NASA Goddard/A. Mellinger (Central Michigan Univ.) and T. Linden (Univ. of Chicago)

What are they?

- Accreting compact objects
- Pulsars
- AGN



Credit: NASA/CXC/Penn State/B.Luo et al.

What are they?

- Accreting compact objects
- Pulsars
- AGN
- X-ray active stars (O/B stars, WR stars)

Wolf-Rayet star WR 124

Credits: NASA, ESA, CSA, STScI, Webb ERO Production Team

What are they?

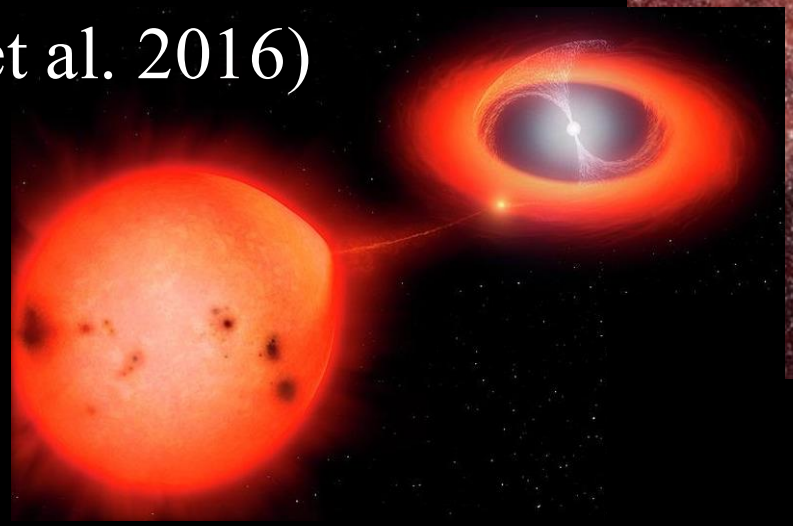
- Accreting compact objects
- Pulsars
- AGN
- X-ray active stars (O/B stars, WR stars)
- Planetary Nebulae

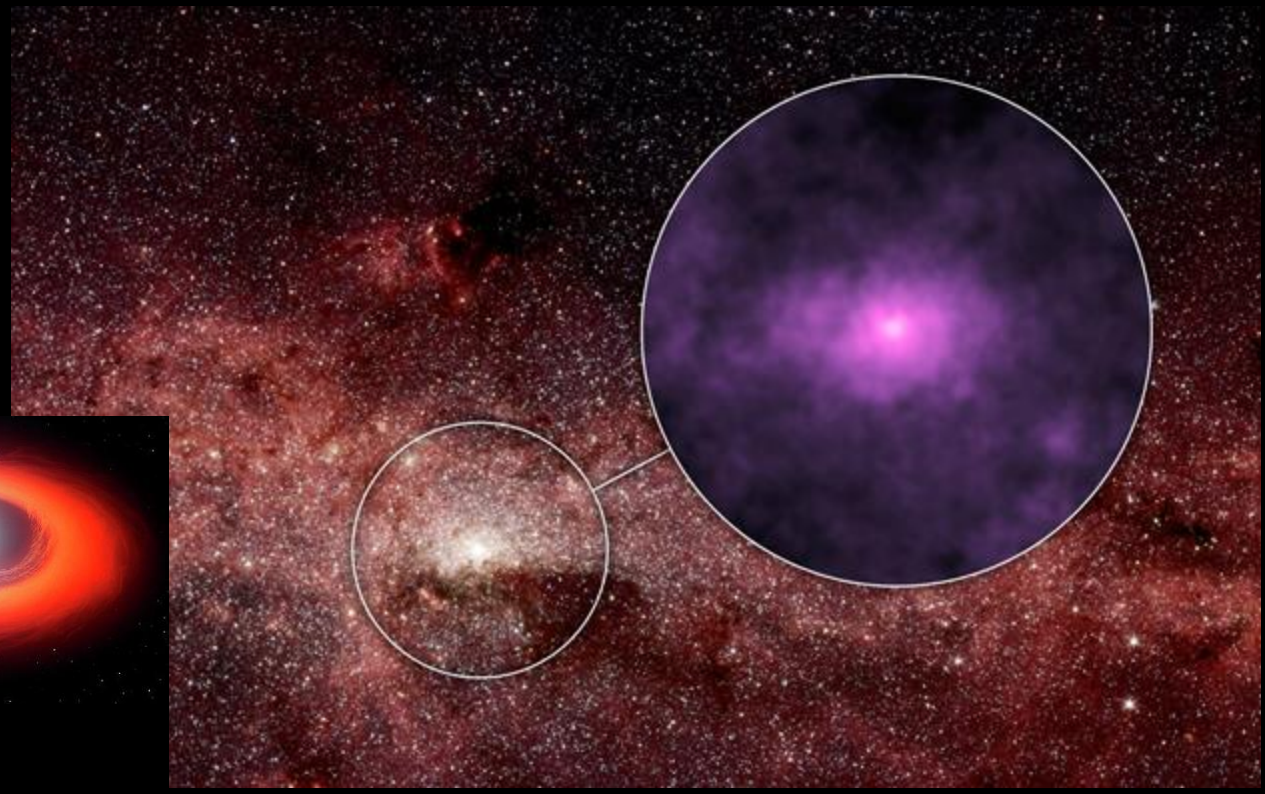
Credit: X-ray: NASA/CXC/RIT/J.Kastner et al.;
Optical: NASA/STScI

NGC 6543

2015: *NuSTAR* discovers the **Central Hard X-ray Emission** (CHXE)

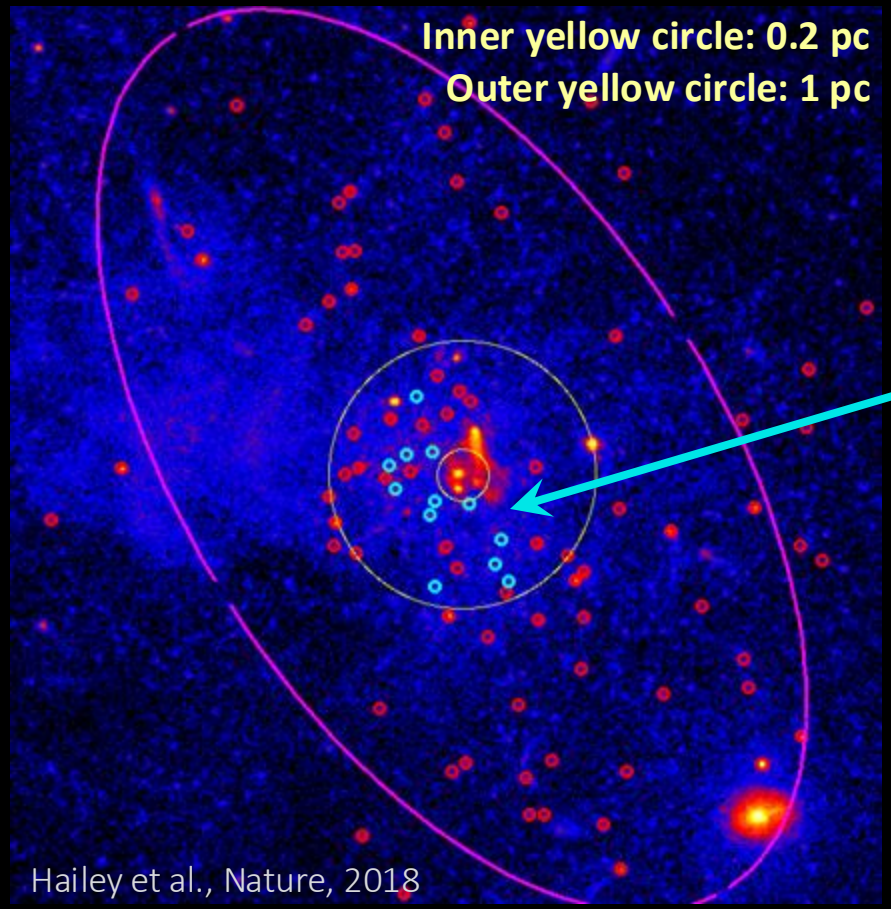
- kT > 35 keV
- Consistent with *intermediate polars* (IPs)
- $M_{WD} \geq 0.9 M_{\odot}$ (Hailey et al. 2016)





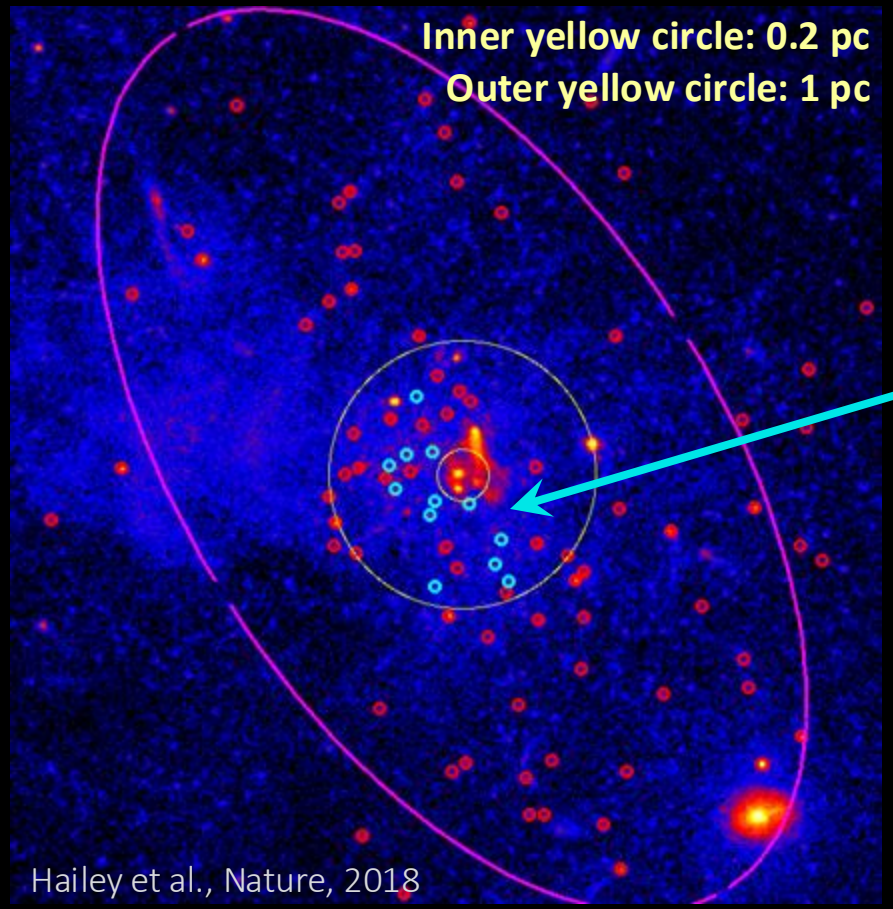
Credit: NASA/JPL-Caltech

Searching for IPs with *Chandra* – Oops, we find quiescent black hole LMXBs



- Hard, thermal sources (IPs?) ~evenly distributed throughout central pcs
- Soft, non-thermal sources (BH-LMXBs?) all located within ~1 pc of Sgr A*

Hailey+ 2018: Searching for IPs with *Chandra* – Oops, we find quiescent black hole LMXBs



Hailey et al., Nature, 2018

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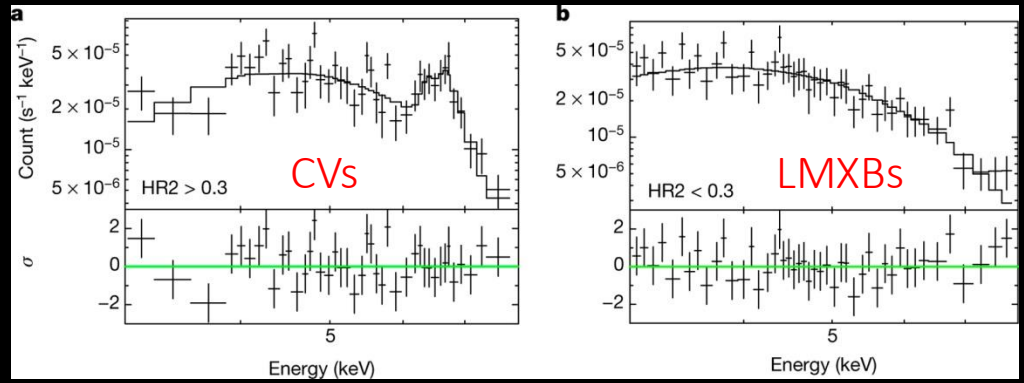

Hailey et al. (2018)

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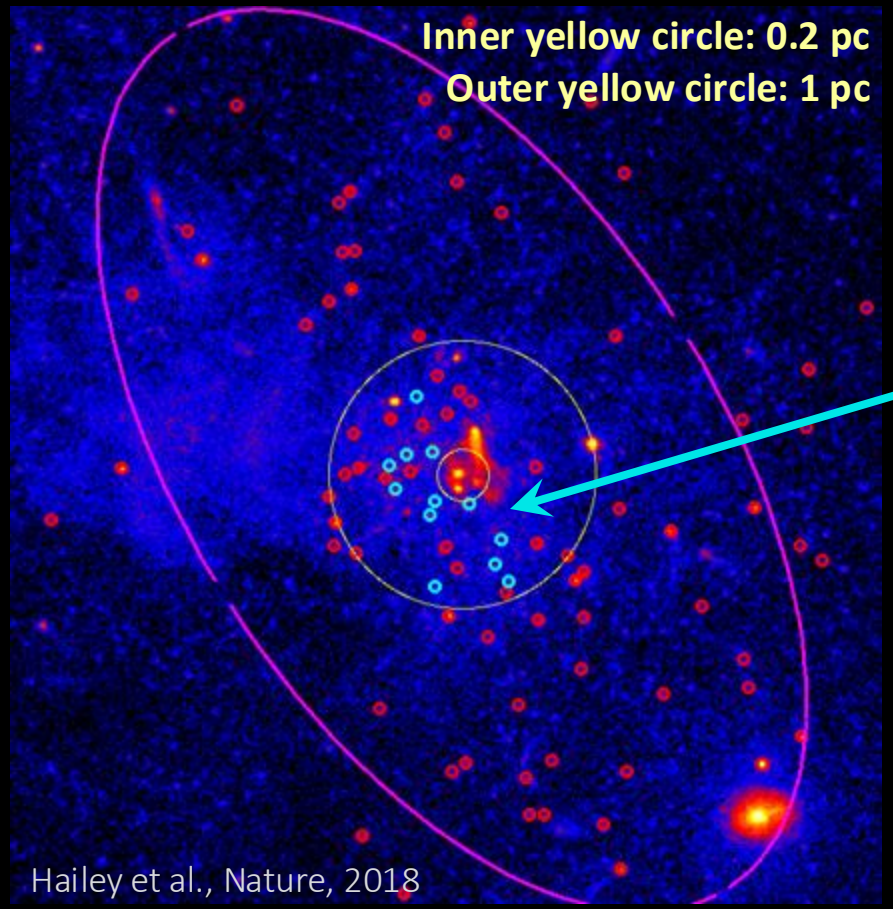

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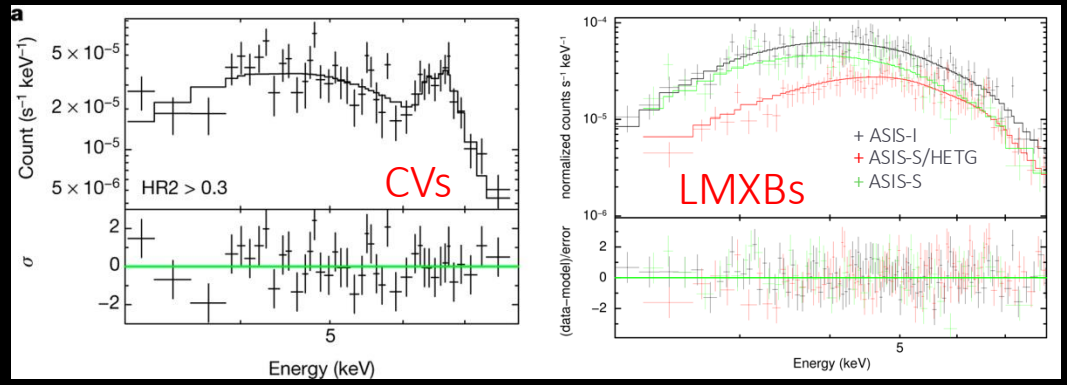
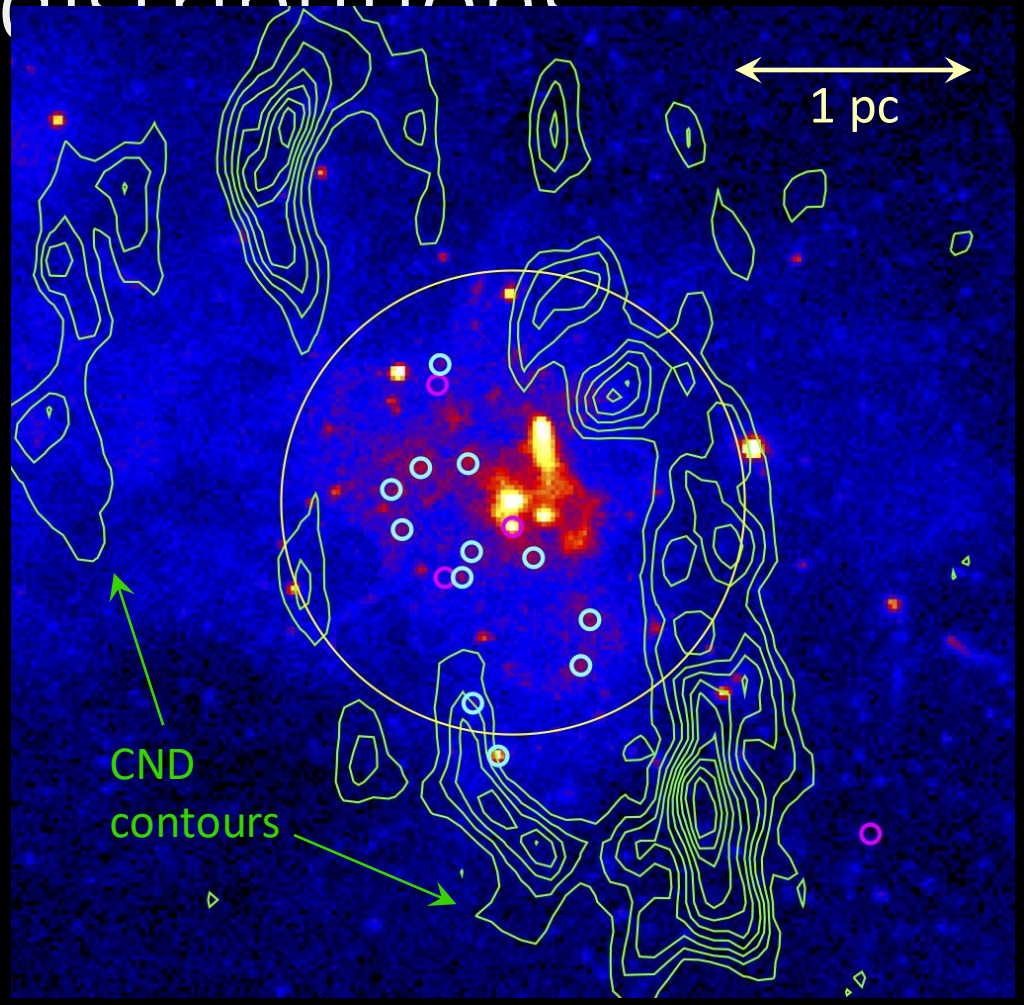


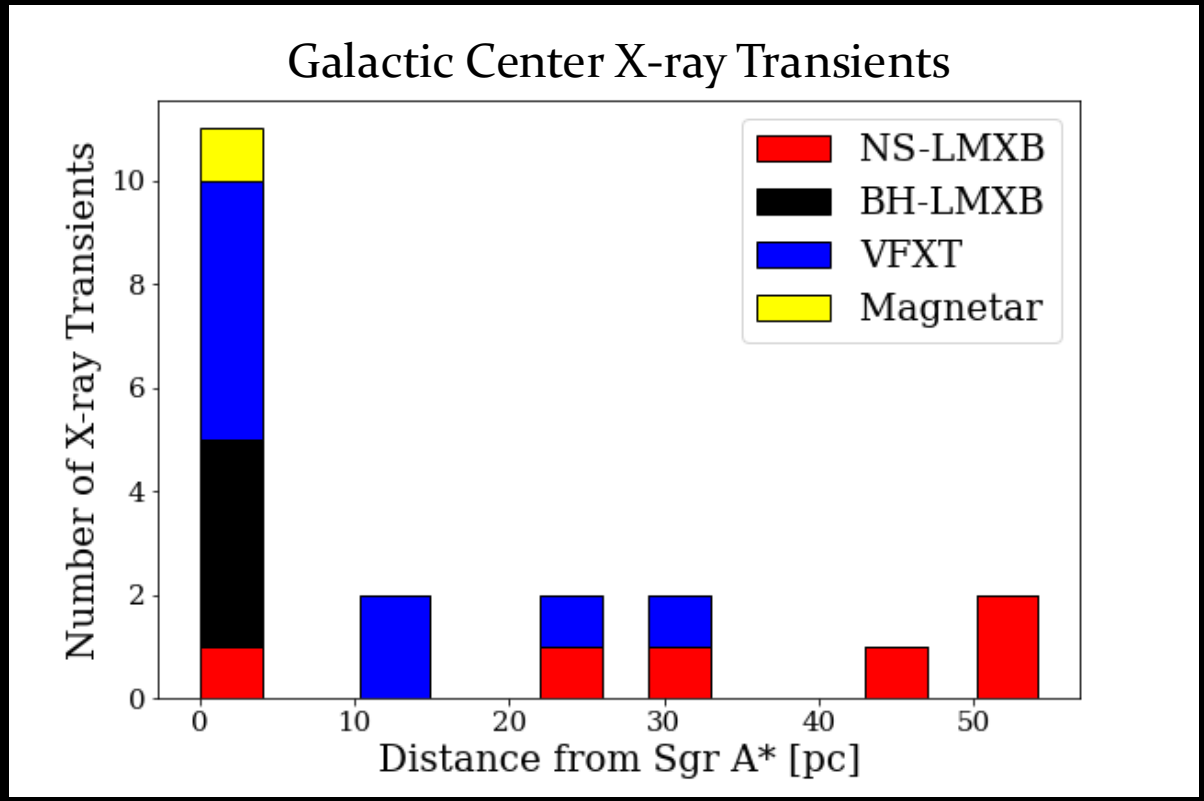
Hailey et al. (2018) Mori et al. (2021)

Mori+ 2021: study of GC X-ray binary distributions



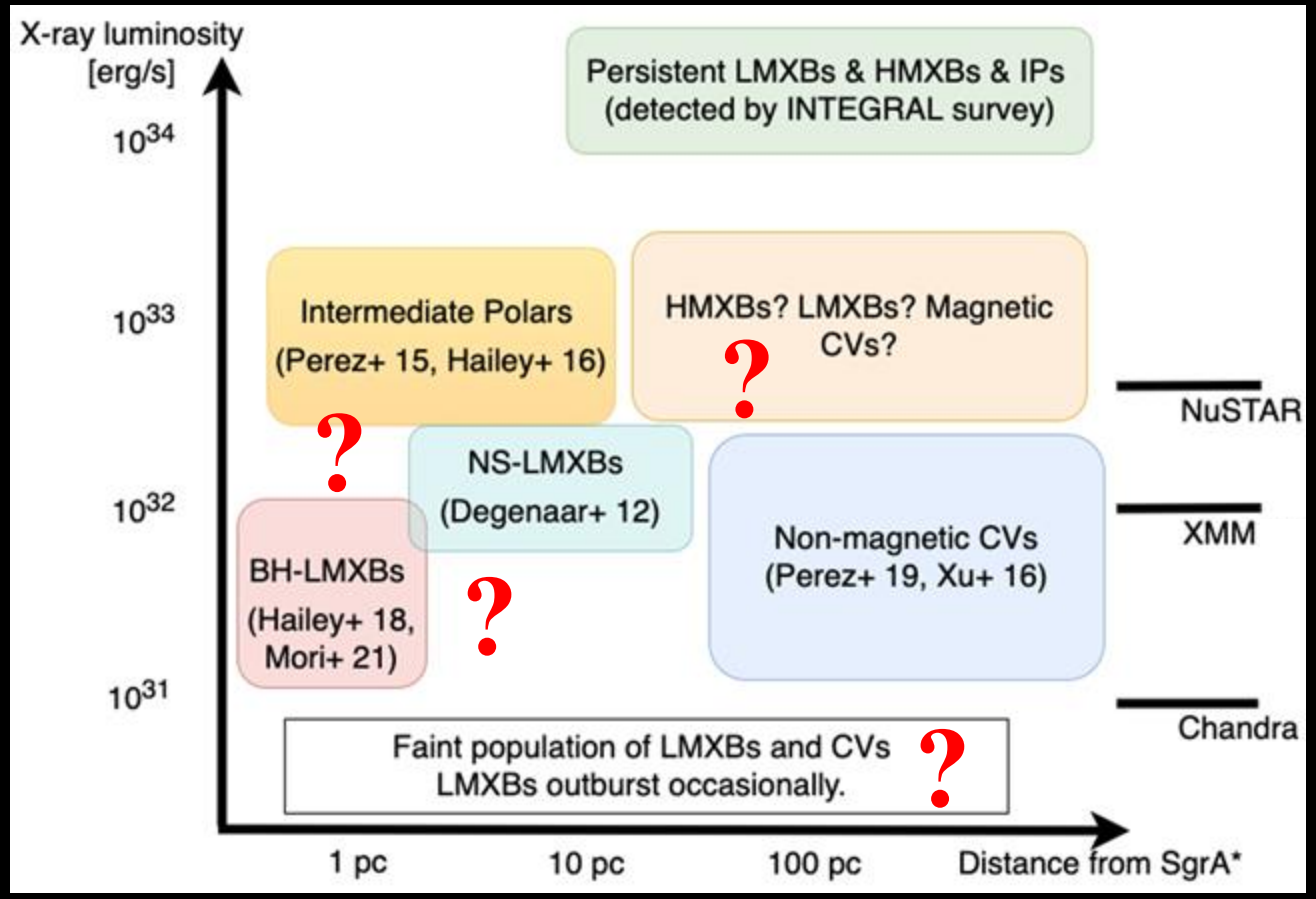
Magenta: BH transients. Cyan: quiescent BH-LMXBs.

Identified X-ray transients in the GC: BH sources concentrated in the central few pc



What about the other ~9000 sources?

- What are the thousands of "other" X-ray sources?
- How and why do their distributions vary?



Identified X-ray sources present only a small fraction of the thousands detected so far, but already indicate significant differences in luminosity and location.

New Ponti Surveys (2024)

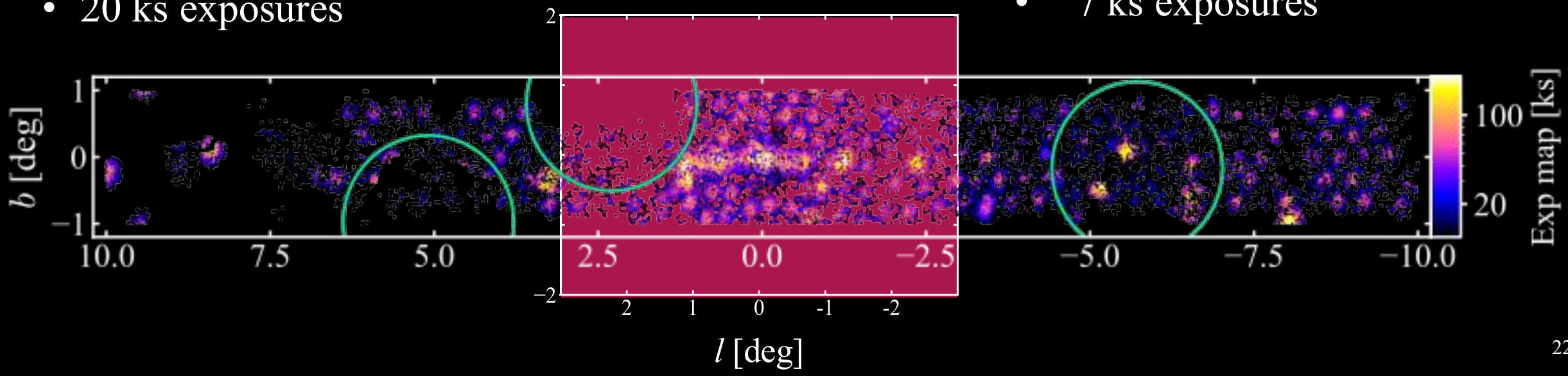
- Unprecedented coverage beyond the CMZ

XMM Heritage Survey:

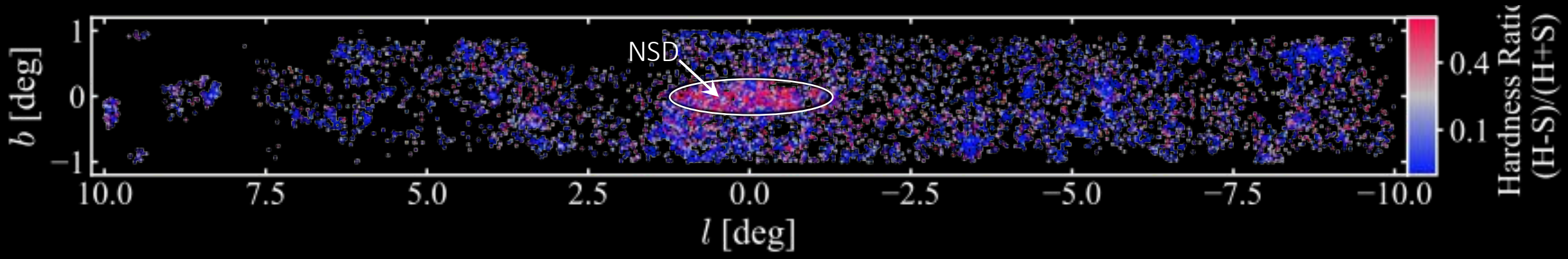
- $l \pm 10;\ b\ \pm 1$ degrees
- 20 ks exposures

Chandra Legacy Survey:

- Central 4 x 6 degrees
- 7 ks exposures

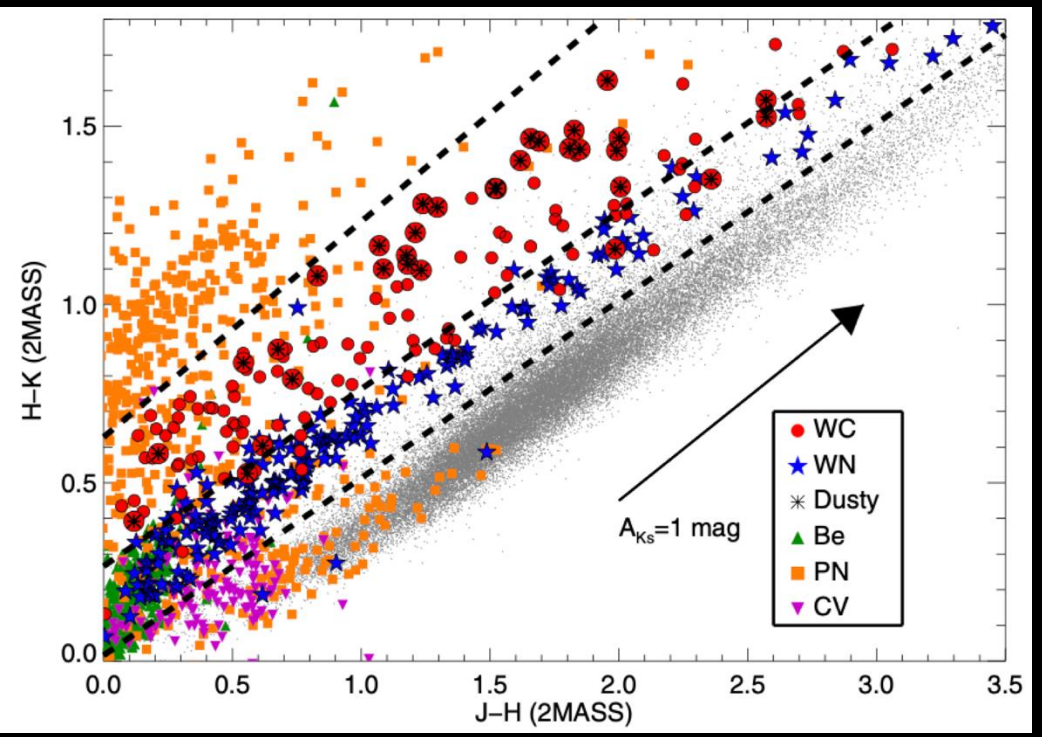


XMM data indicates distinct X-ray population in nuclear stellar disk (NSD) region – *Chandra* can bridge X-ray/NIR data to add another dimension



Multi-band data can differentiate between source types

- NIR **colors**, plus
- X-ray **hardness**, plus
- **Flux** ratios f_X/f_{NIR}



Faherty et al. (2014)

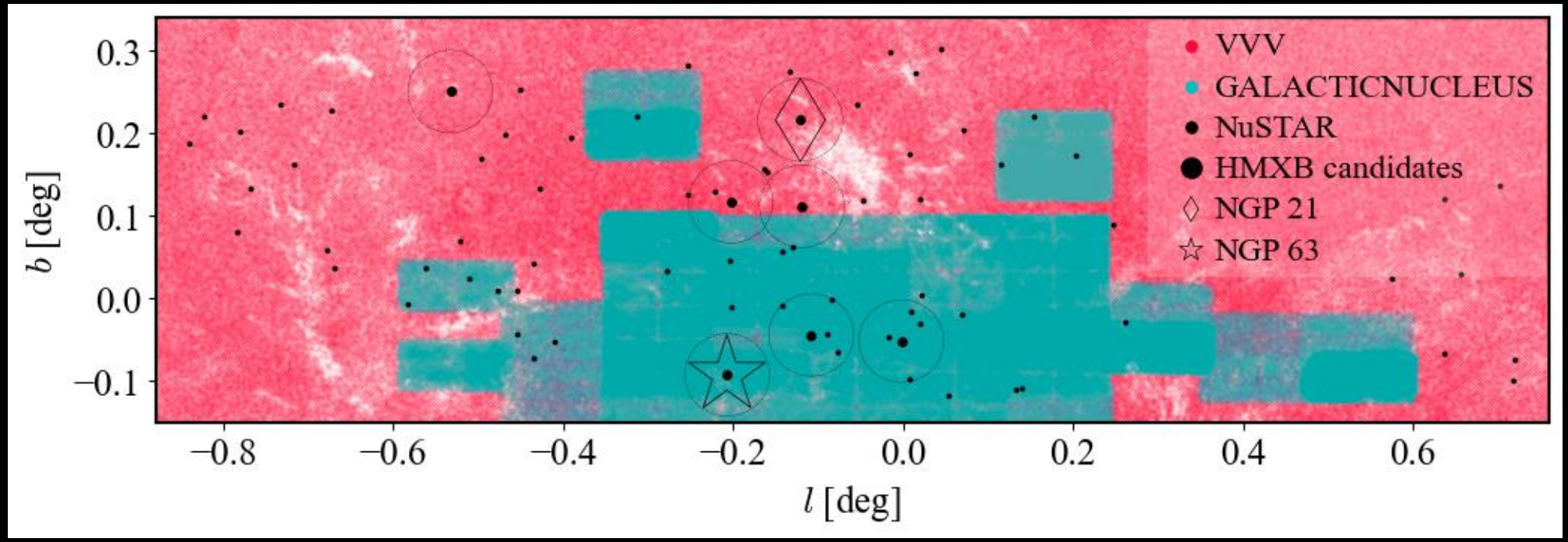
X-ray:

- *XMM-Newton* for hardness
- *Chandra* for source localization

NIR:

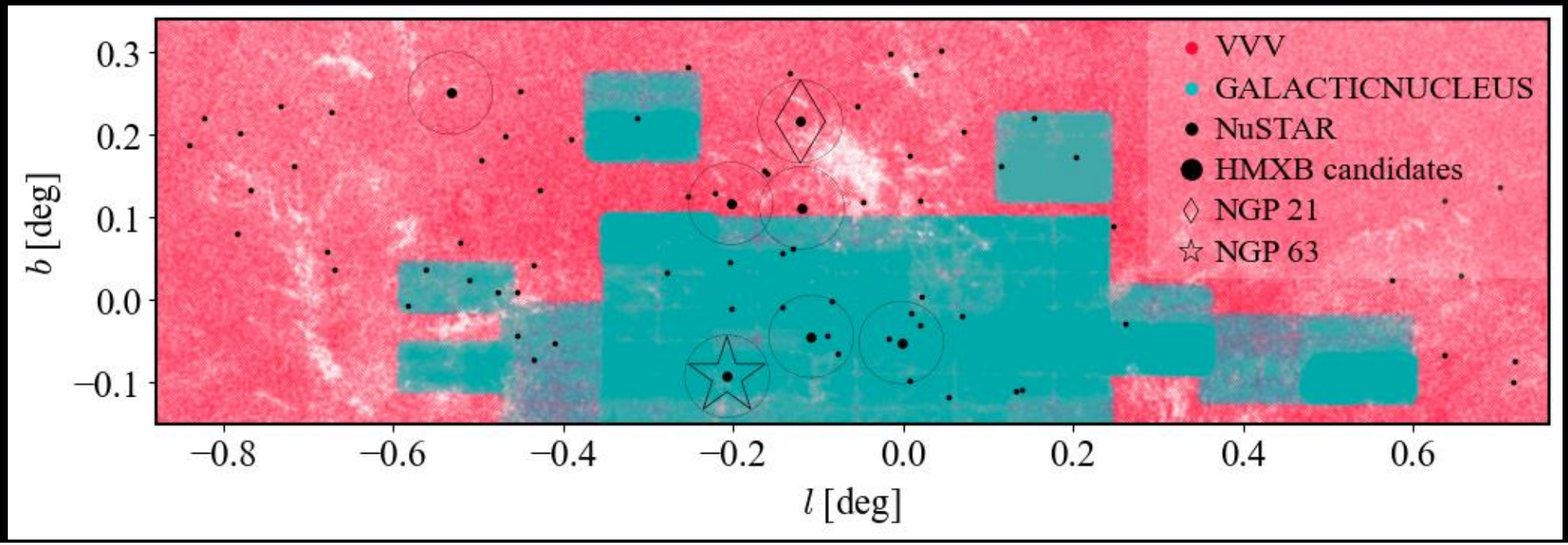
- VVV survey: photometric colors
- VVV survey: X-ray/NIR flux ratios
- Herschel: extinction maps

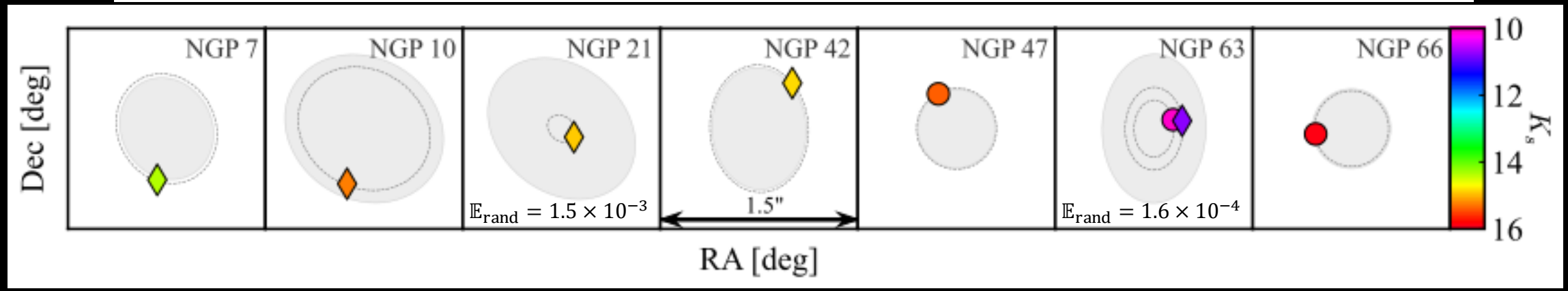
HMXBs in the GC: A Case Study



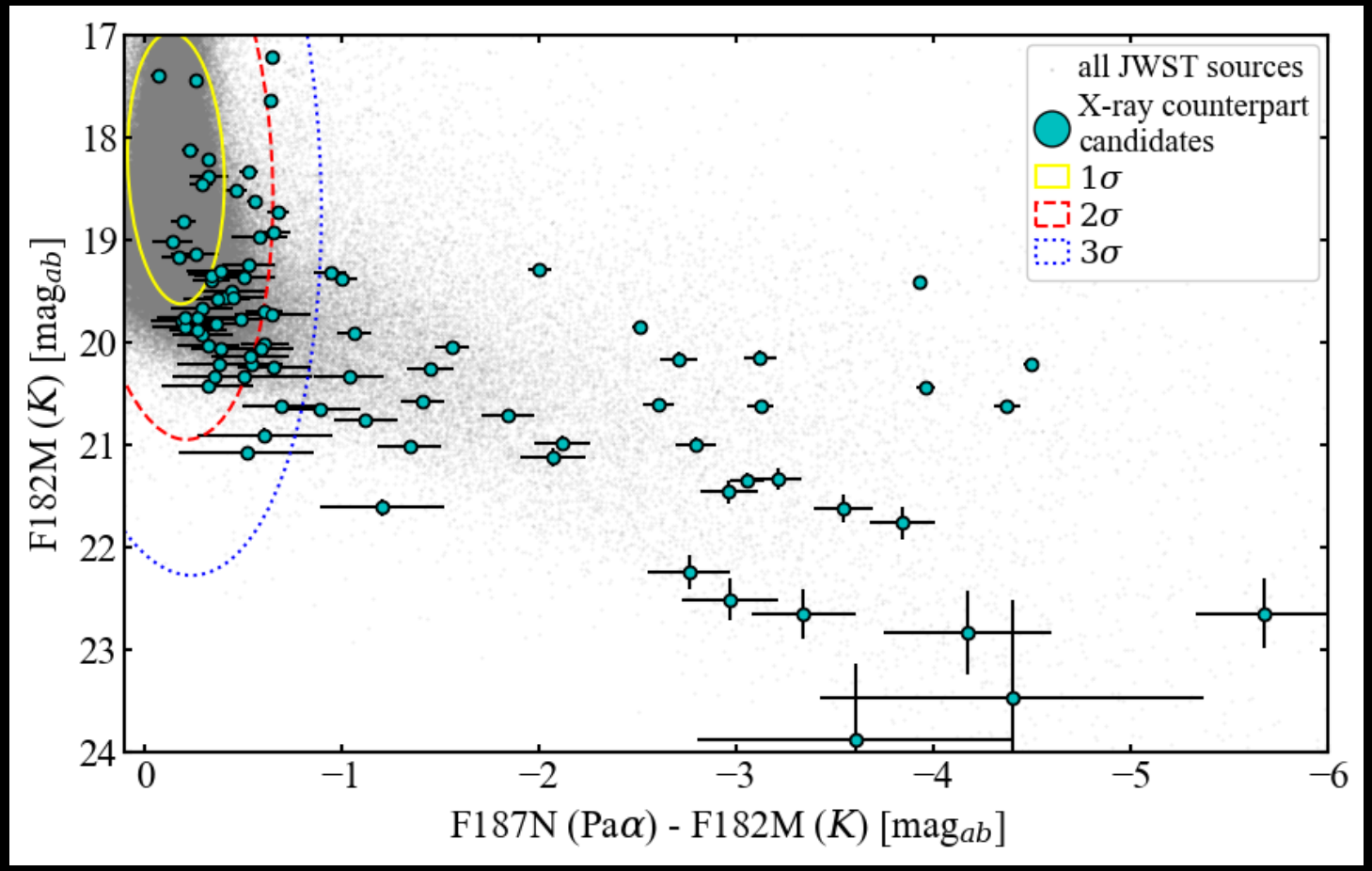
77 *NuSTAR* hard X-ray point sources → *Chandra* counterparts: CSC2.1 positions & uncertainties → Cross-matching *Chandra* positions with NIR catalogs → Evaluating random match probability for NIR matches

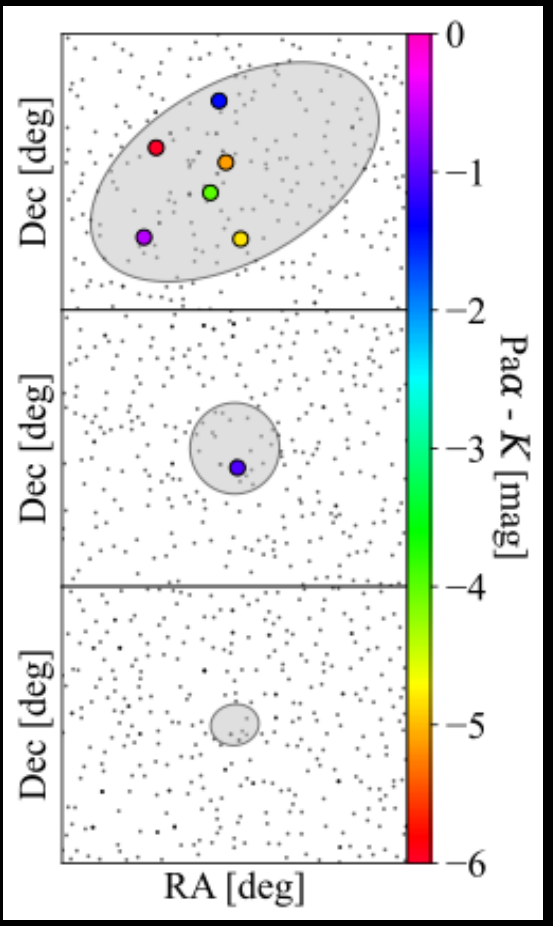
HMXBs in the GC: A Case Study



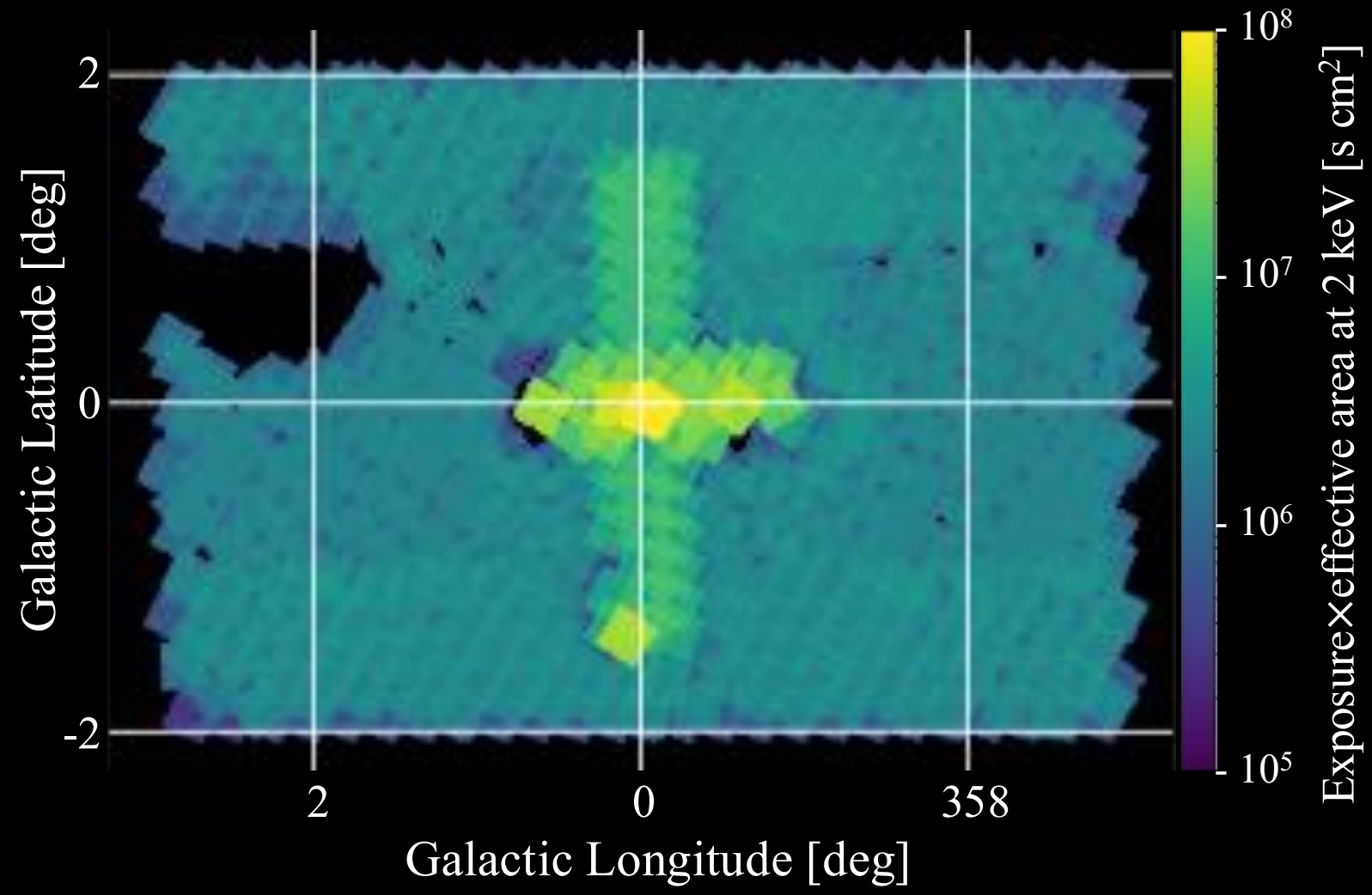


Multi-wavelength studies with *JWST*





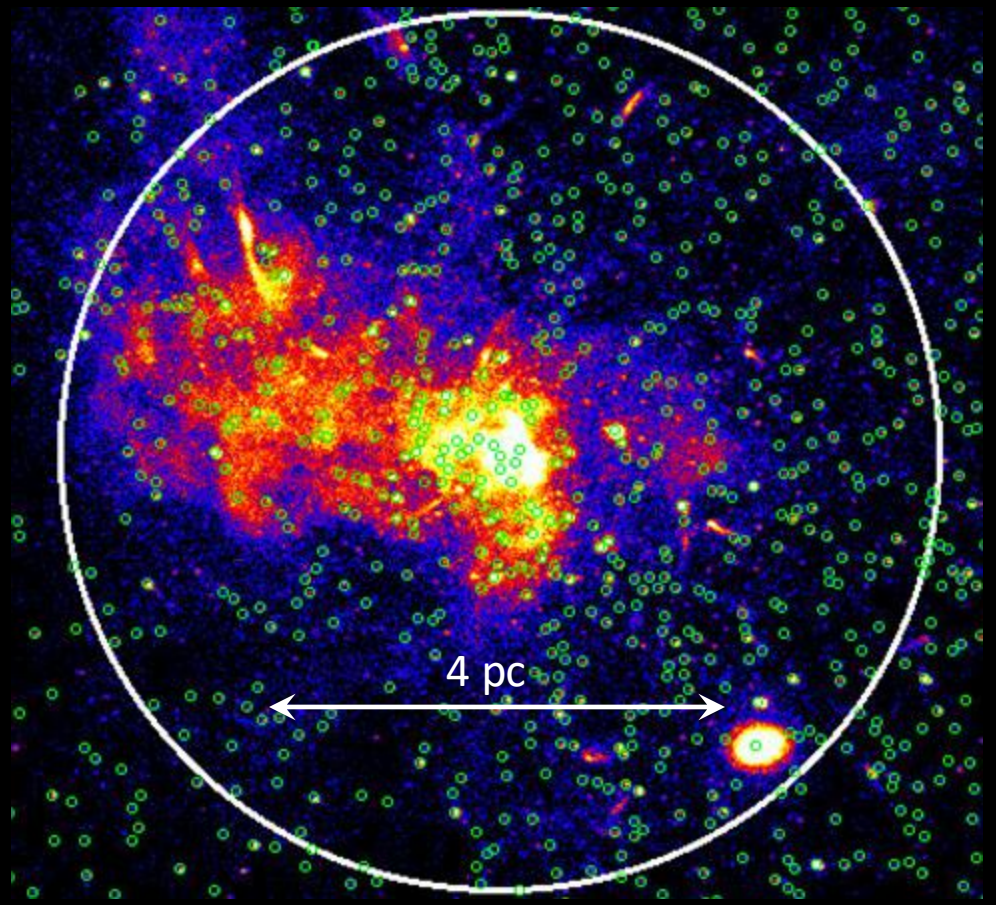
Chandra Ponti survey: a preliminary look



Exposure map by Xueying Zheng (MPE)

Key takeaways

- *Chandra* revolutionized our understanding of Galactic center X-ray sources
- New and ongoing studies continue to shed light on X-ray source populations
- *Chandra* data remains crucial for the multi-wavelength studies required for X-ray source identification



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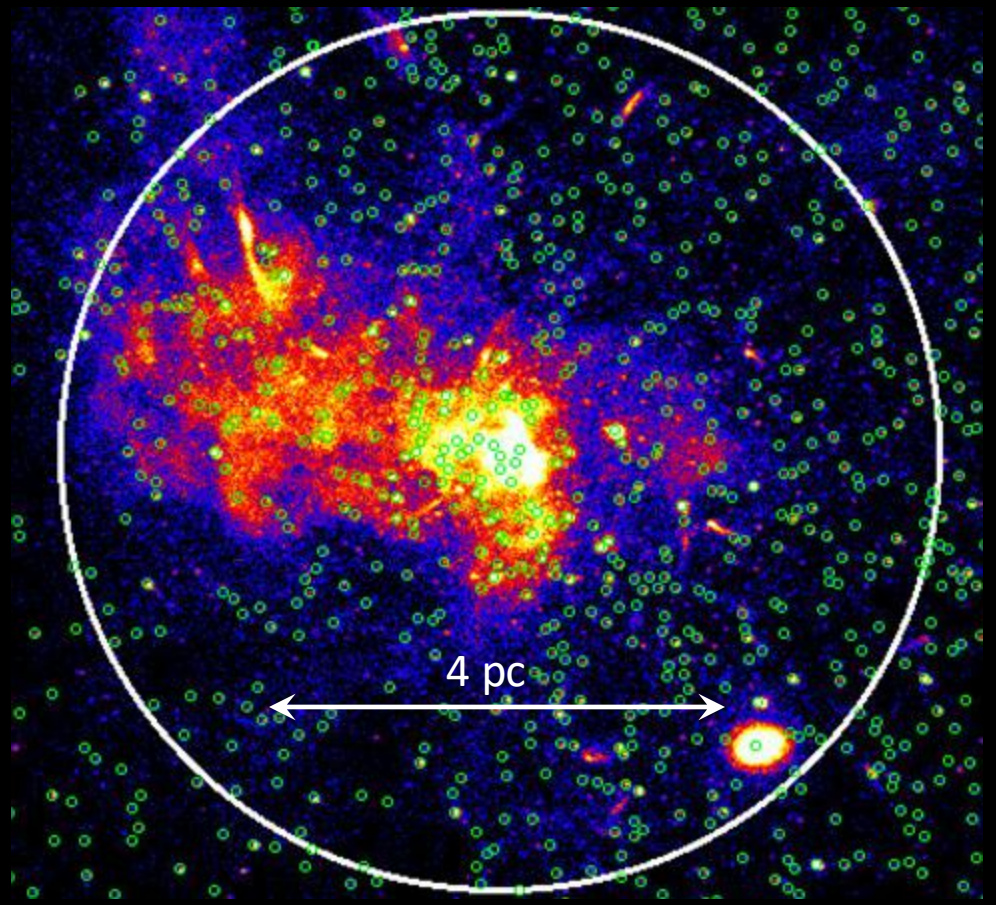
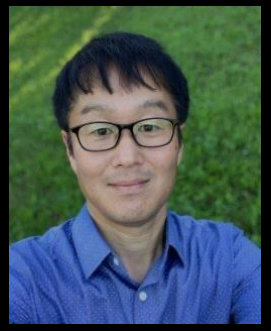


What's next?

- Multiwavelength (NIR) studies (*JWST* etc.)
- Legacy data: updated CSC crucial for optimized astrometry

Acknowledgements

Chuck Hailey & Kaya Mori (Columbia)



Mimi

Gabriele Ponti , Heshou Zhang, Samaresh Mondal (INAF)