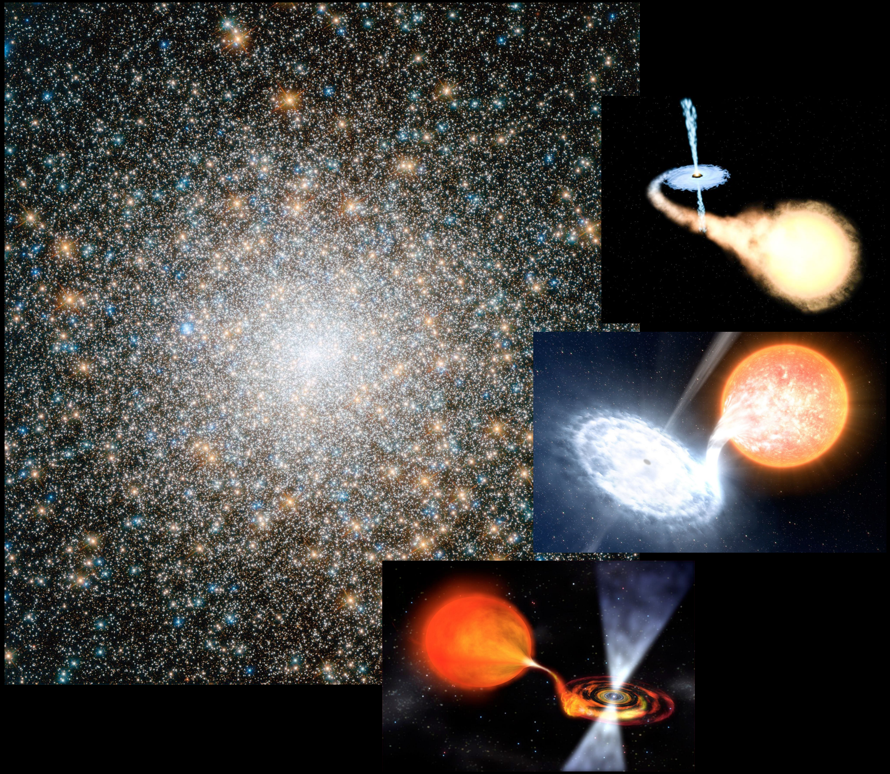
X-ray binaries and black holes in globular clusters



Arash Bahramian

Towards formation of black-hole binaries workshop

July 2021

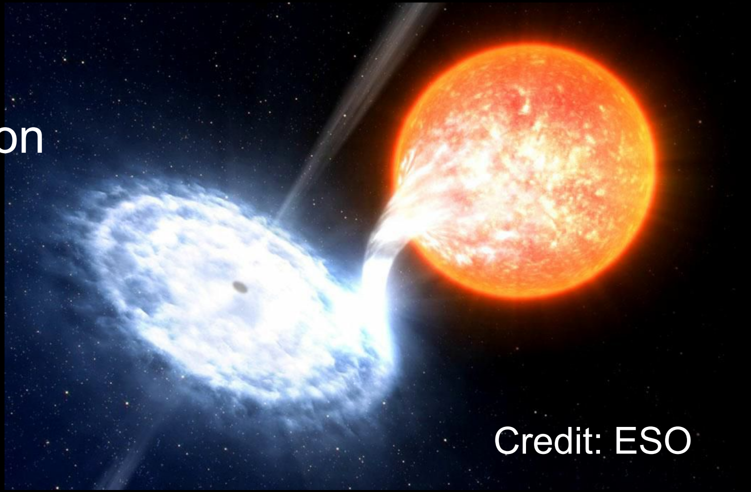
ICRAR International Centre for Radio Astronomy Research

Curtin University

X-ray Binaries

- Binary star systems with significant X-ray luminosity ($L_X > 10^{30}$ erg/s).
- Typically a massive stellar object (BH, NS, WD) and a companion star.

- Some of different types:
  - BH/NS and a low or high mass companion
  - Cataclysmic variables
  - Millisecond radio pulsars
  - Chromospherically active binaries



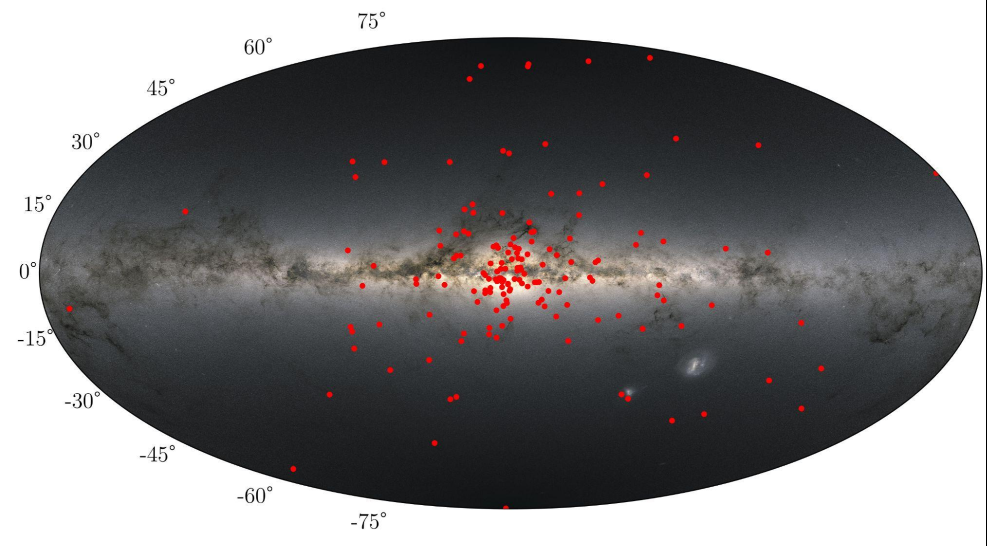
Credit: ESO

Globular clusters

- Dense spherical **old** (~10 Gyrs) collections of stars orbiting the Galactic center.

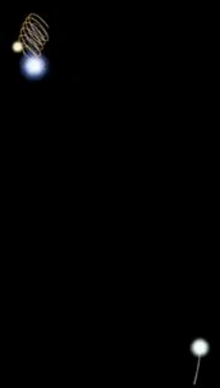
- High stellar densities toward their centers, up to a million times local densit around the sun.

- About 150-200 in our Galaxy, hundreds t thousands in other galaxies



Formation and evolution of XRBs in GCs

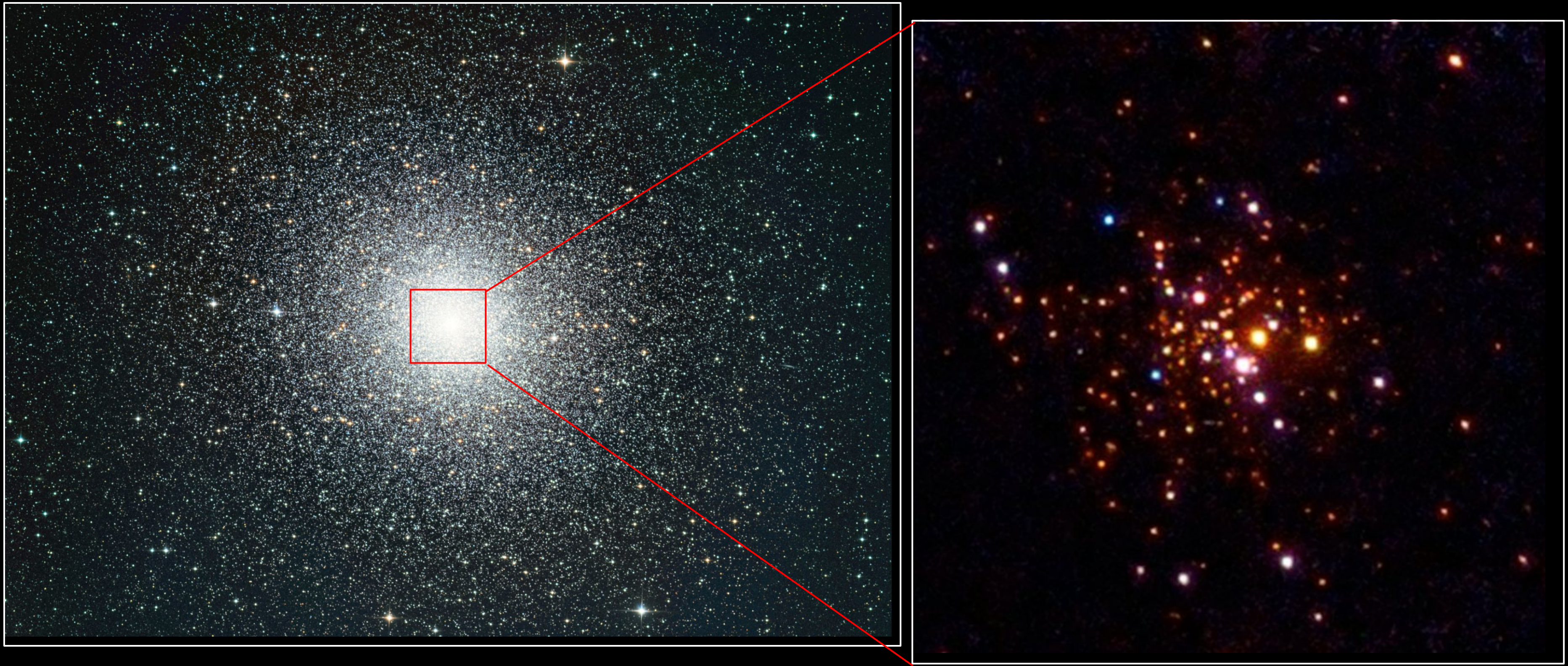
In contrast with the rest of the Galaxy, in GCs, binaries are formed mainly through encounters (and can be disrupted through them)



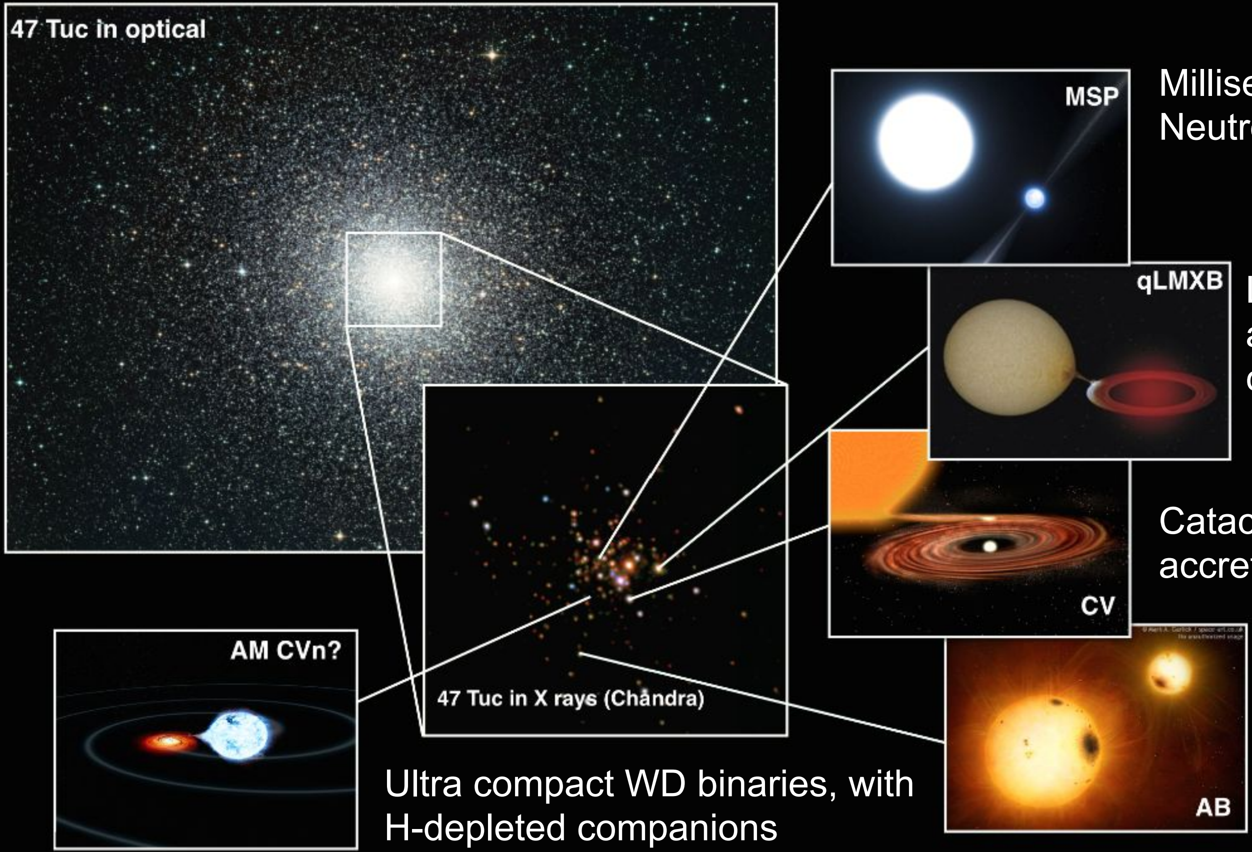
Credit: Aaron Geller

GC binaries are a key component in our understanding of compact objects, accretion and globular cluster properties.

Globular clusters: binary system factories



Globular clusters: binary system factories



Visualization courtesy of L. Rivera Sandoval

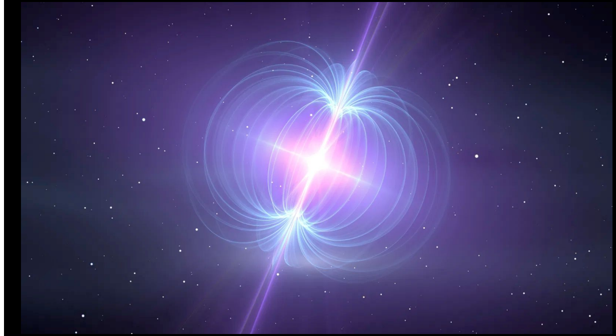
Globular clusters: binary system factories

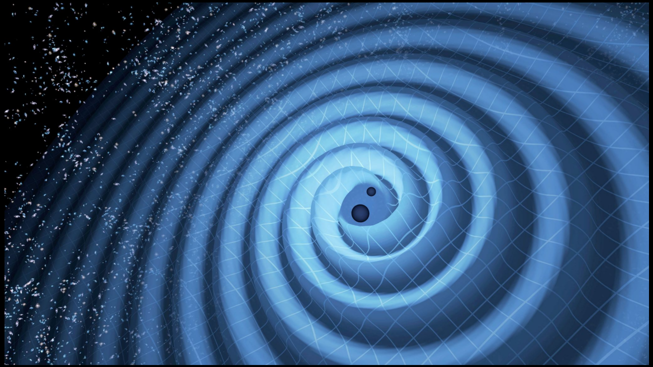
24 May 2021

A repeating fast radio burst source in a globular cluster

F. Kirsten,[1] B. Marcote,[2] K. Nimmo,[3,4] J. W. T. Hessels,[4,3] M. Bhardwaj,[5,6] S. P. Tendulkar,[7,8] A. Keimpema,[2] J. Yang,[1] M. P. Snelders,[4] P. Scholz,[9] A. B. Pearlman,[5,6,10,11,12] C. J. Law,[13,14] W. M. Peters,[15] M. Giroletti,[16] D. M. Hewitt,[4] U. Bach,[17] V. Bezukovs,[18] M. Burgay,[19] S. T. Buttaccio,[20] J. E. Conway,[1] A. Corongiu,[19] R. Feiler,[21] O. Forssén,[1] M. P. Gawroński,[21] R. Karuppusamy,[17] M. A. Kharinov,[22] M. Lindqvist,[1] G. Maccaferri,[16] A. Melnikov,[22] O. S. Ould-Boukattine,[4] Z. Paragi,[2] A. Possenti,[19,23] G. Surcis,[19] N. Wang,[24] J. Yuan,[24] K. Aggarwal,[25,26] R. Anna-Thomas,[25,26] G. C. Bower,[27] R. Blaauw,[3] S. Burke-Spolaor,[25,26,28] T. Cassanelli,[9,29] T. E. Clarke,[15] E. Fonseca,[5,6,25,26] B. M. Gaensler,[9,29] A. Gopinath,[4] V. M. Kaspi,[5,6] N. Kassim,[15] T. J. W. Lazio,[30] C. Leung,[31,32] D. Li,[13] H. H. Lin,[33] K. W. Masui,[31,32] R. Mckinven,[9] D. Michilli,[5,6] A. Mikhailov,[22] C. Ng,[9] A. Orbidans,[18] U. L. Pen,[33,9,28,34] E. Petroff,[4,5,6,35] M. Rahman,[36] S. M. Ransom,[37] K. Shin,[31,32] K. M. Smith,[34] I. H. Stairs,[38] and W. Vlemmings[1]

[1] *Department of Space, Earth and Environment, Chalmers University of Technology, Onsala Space Observatory, 439 92, Onsala, Sweden*
[2] *Joint Institute for VLBI ERIC, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands*
[3] *ASTRON, Netherlands Institute for Radio Astronomy, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, The Netherlands*
[4] *Anton Pannekoek Institute for Astronomy, University of Amsterdam, Science Park 904, 1098 XH, Amsterdam, The Netherlands*
[5] *Department of Physics, McGill University, 3600 rue University, Montréal, QC H3A 2T8, Canada*
[6] *McGill Space Institute, McGill University, 3550 rue University, Montréal, QC H3A 2A7, Canada*
[7] *Department of Astronomy and Astrophysics, Tata Institute of Fundamental Research, Mumbai, 400005, India*
[8] *National Centre for Radio Astrophysics, Post Bag 3, Ganeshkhind, Pune, 411007, India*
[9] *Dunlap Institute for Astronomy & Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON M5S 3H4, Canada*





20 Jan 2021

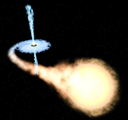
The Observed Rate of Binary Black Hole Mergers can be Entirely Explained by Globular Clusters

Carl L. Rodriguez,[1] Kyle Kremer,[2,3] Sourav Chatterjee,[4] Giacomo Fragione,[5] Abraham Loeb,[6] Frederic A. Rasio,[5] Newlin C. Weatherford,[5] and Claire S. Ye[5]

[1] *McWilliams Center for Cosmology and Department of Physics, Carnegie Mellon University, Pittsburgh, PA 15213, USA*
[2] *TAPIR, California Institute of Technology, Pasadena, CA 91125, USA*
[3] *The Observatories of the Carnegie Institution for Science, Pasadena, CA 91101, USA*
[4] *Tata Institute of Fundamental Research, Homi Bhabha Road, Navy Nagar, Colaba, Mumbai 400005, India*
[5] *Center for Interdisciplinary Exploration & Research in Astrophysics (CIERA) and Department of Physics & Astronomy, Northwestern University, Evanston, IL 60208, USA*
[6] *Astronomy Department, Harvard University, 60 Garden Street, Cambridge, MA 02138*

ABSTRACT

Since the first signal in 2015, the gravitational-wave (GW) detections of merging binary black holes (BBHs) by the LIGO and Virgo collaborations (LVC) have completely transformed our understand-



The BH conundrum in globular clusters

- GCs are Gyrs old ⟶ plenty of BHs should have formed
- They are dense ⟶ plenty of encounters for BHs to form XRBs

But

All bright (Lx > 1e35 erg/s) accreting binaries in GCs have been neutron star XRBs so far

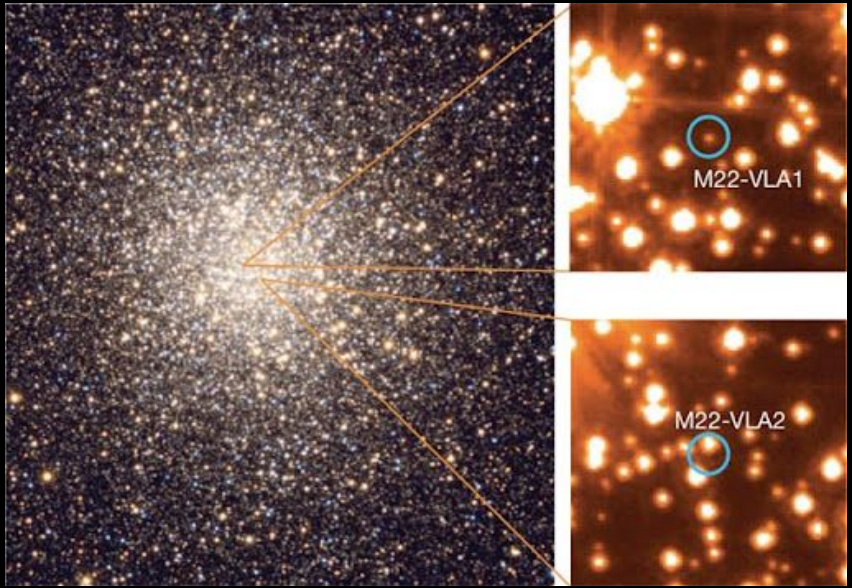
Confirmed via pulsation or X-ray bursts

(see next talk by Adelle!)

X-ray binaries and BHs in globular clusters

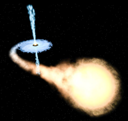
2007: Discovery of RZ2109
a super-eddington X-ray source (BH candidate) in an extragalactic GC

2012: Discovery of BH-like radio sources in Galactic GCs M22 and M62
(faint/inefficiently accreting BHs?)



BH candidates in M22
Strader et al. 2012

X-ray binaries and BHs in globular clusters

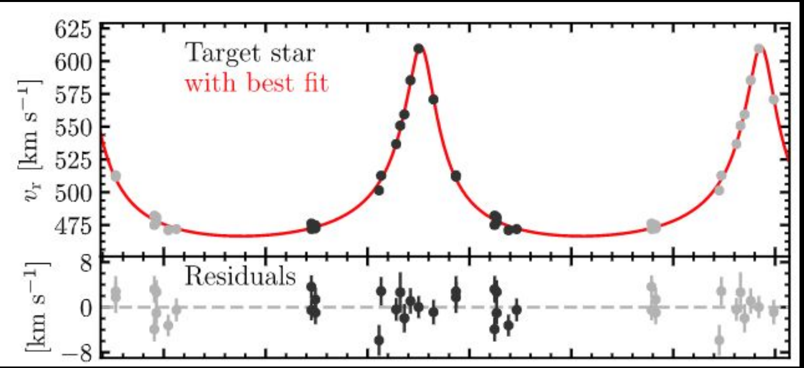


2007: Discovery of RZ2109
a super-eddington X-ray source (BH candidate) in an extragalactic GC

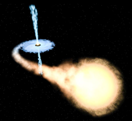
2012: Discovery of BH-like radio sources in Galactic GCs M22 and M62
(faint/inefficiently accreting BHs?)

2018: Discovery of dynamically **confirmed** detached black holes in NGC 3201
(~4.5 M☉ in 167 day orbit, 7.6 M☉ in 2 day orbit)

Radial velocity curve for one of the BHs in N3201 (Giesers et al. 2018, 2019)

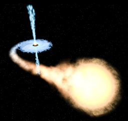


X-ray binaries and BHs in globular clusters



2012: Discovery of BH-like radio sources in Galactic GCs M22 and M62
(faint/inefficiently accreting BHs?)

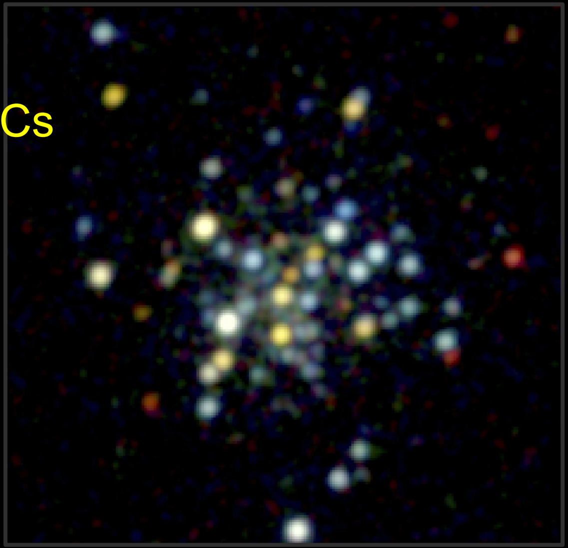
X-ray binaries and BHs in globular clusters



2012: Discovery of BH-like radio sources in Galactic GCs M22 and M62
(faint/inefficiently accreting BHs?)

hundreds of **faint (Lx < 1e35 erg/s)** X-ray sources in Galactic GCs
Are BHs lurking among them?

If so, how do we search for them?

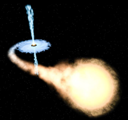


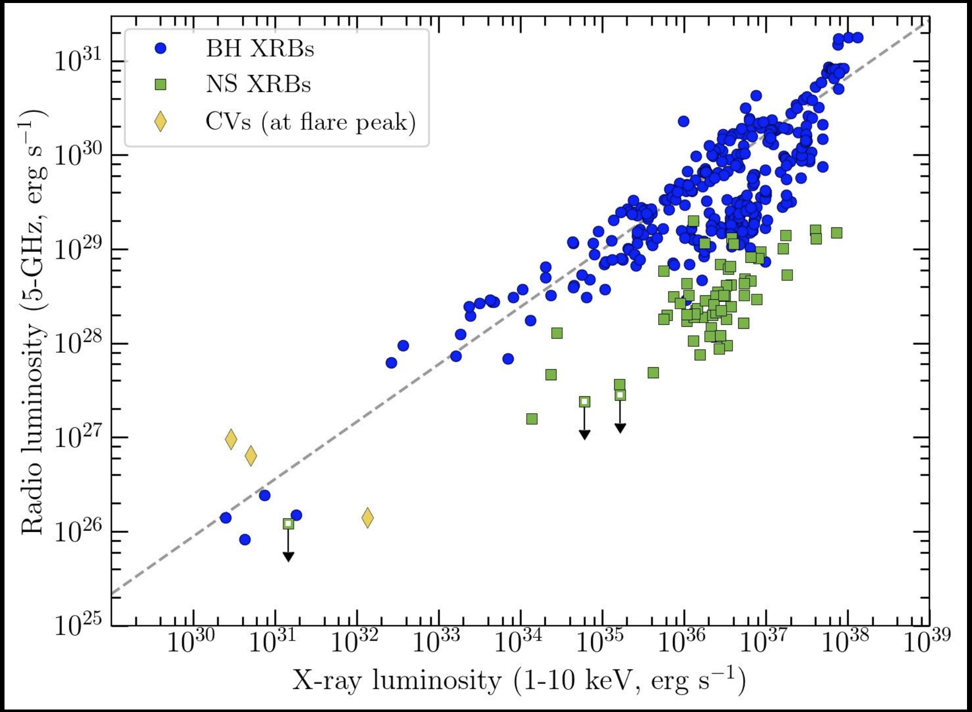
Core of Terzan 5 as seen in the X-rays
(Chandra, Bahramian et al.)

Observational signatures of accreting BHs vs. NSs

- Accreting black holes have brighter radio emission compared to neutron stars associated with jets

- Correlated with X-ray luminosity (linked to accretion rate)





Jet vs. accretion in BHs and NSs
Radio - X-ray luminosity
correlation in X-ray binaries

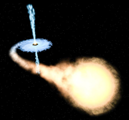
The MAVERIC Survey

Milky-way ATCA VLA Exploration of Radio-sources In Clusters

Arash Bahramian (ICRAR)
Laura Chomiuk (MSU)
Craig Heinke (Alberta)
Tom Maccarone (Texas Tech)
James Miller-Jones (ICRAR)
Alessandro Paduano (ICRAR)
Laura Shishkovsky (MSU)
Gregory Sivakoff (Alberta)
Jay Strader (MSU)
Evangelina Tremou (Paris Diderot)
Vlad Tudor (ICRAR)
Ryan Urquhart (MSU)
Yue Zhao (Alberta)

VLA in New Mexico

ATCA in New South Wales

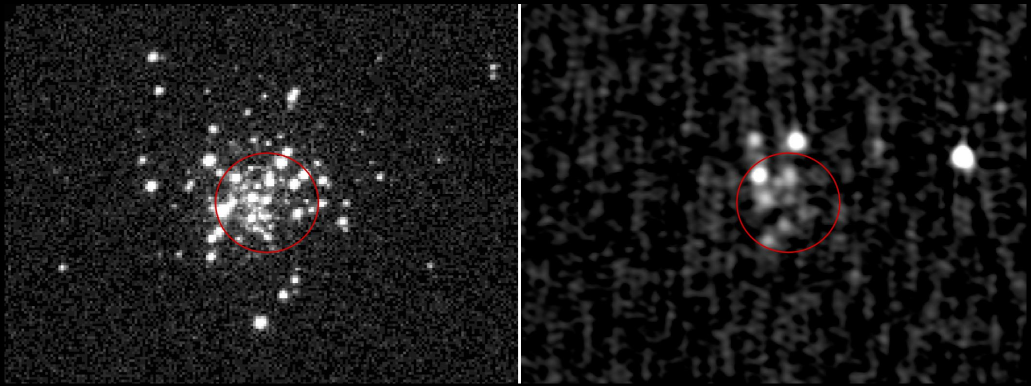


The MAVERIC Survey

Surveying a sample of 50 nearby GCs

Looking for candidates showing signatures of accretion:

- Distinct separation from Pulsars and AGNs in radio spectrum
- X-ray brightness and spectrum
- Optical/NIR counterpart
- Optical emission lines (e.g., H-alpha)



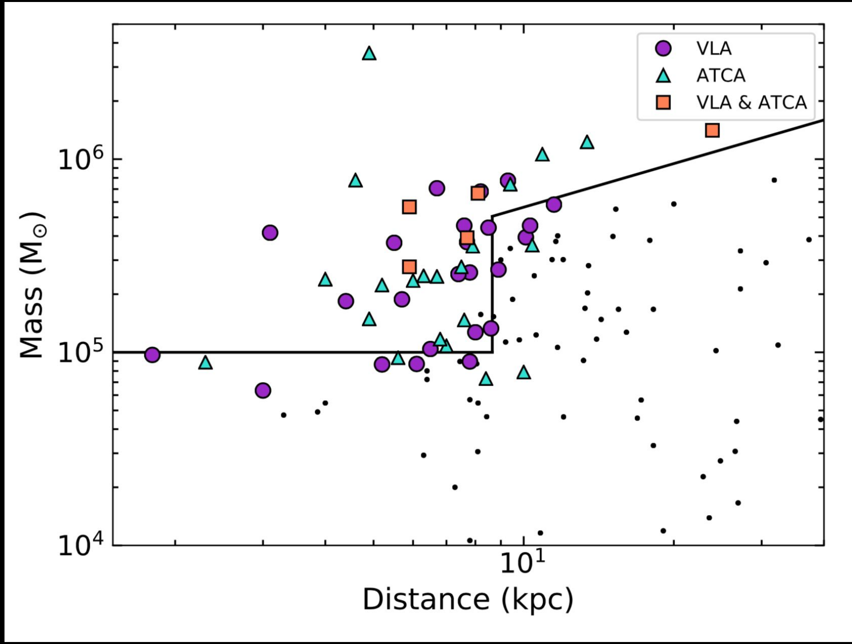
Terzan 5 as seen
in Radio (VLA, right)
X-rays (Chandra, left)

Bahramian et al. 2018
Urquhart et al. 2020

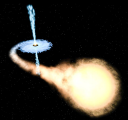
The MAVERIC Survey

Surveying a sample of 50 nearby GCs

- Catalogs of radio sources (~2000 sources)

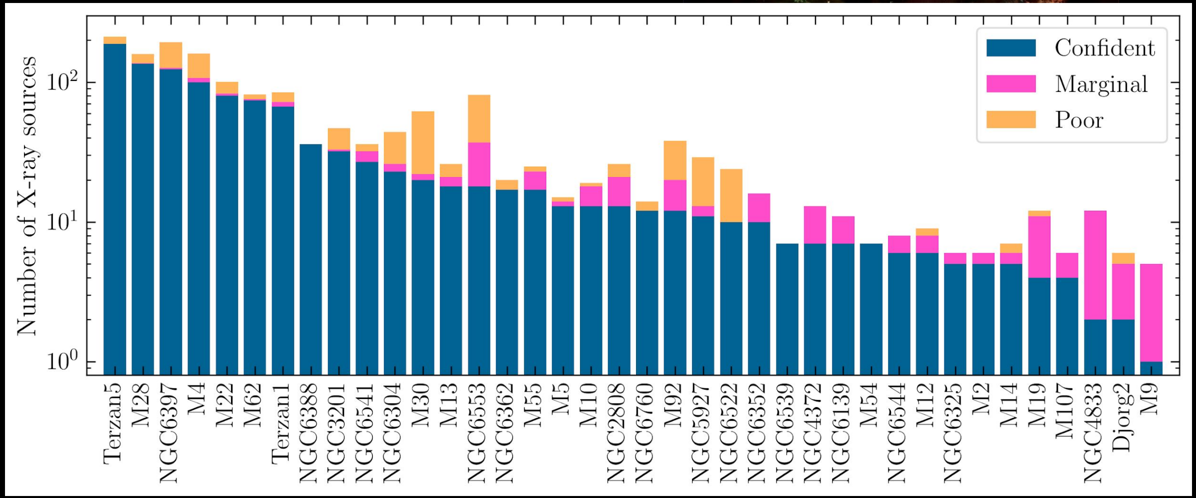


The MAVERIC Survey



Surveying a sample of 50 nearby GCs

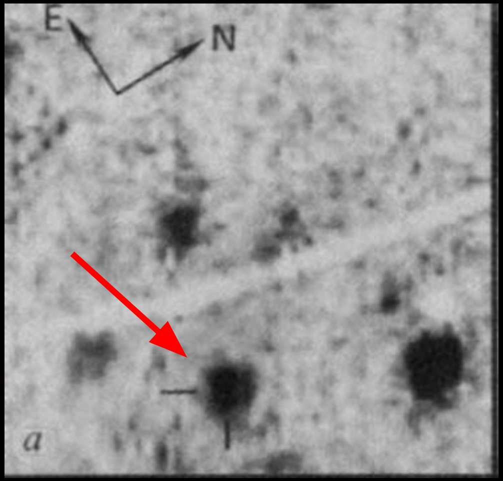
- Catalogs of radio sources (~2000 sources)
- A catalog of X-ray sources (~1800 sources)



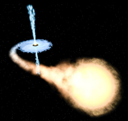
47 Tuc X9

- The brightest hard X-ray source in the cluster
- A bright blue star identified as the UV counterpart
- Significant variability in UV and X-rays
- C & O emission lines in UV and X-ray spectrum

Core of 47 Tuc in X-rays
Chandra (2002)

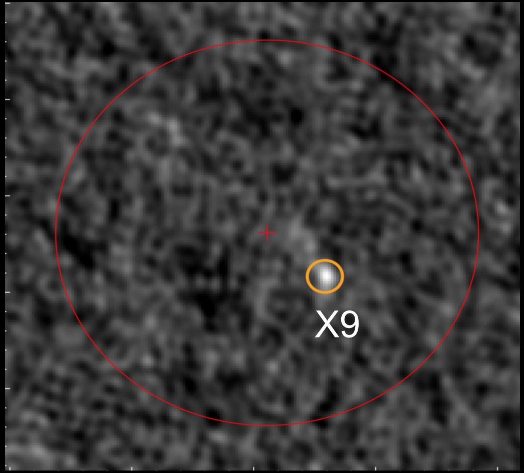


X9 in UV
Hubble (1990)

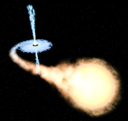


47 Tuc X9

- The brightest hard X-ray source in the cluster
- A bright blue star identified as the UV counterpart
- Significant variability in UV and X-rays
- C & O emission lines in UV and X-ray spectrum
- Detected as a bright radio source in the MAVERIC survey

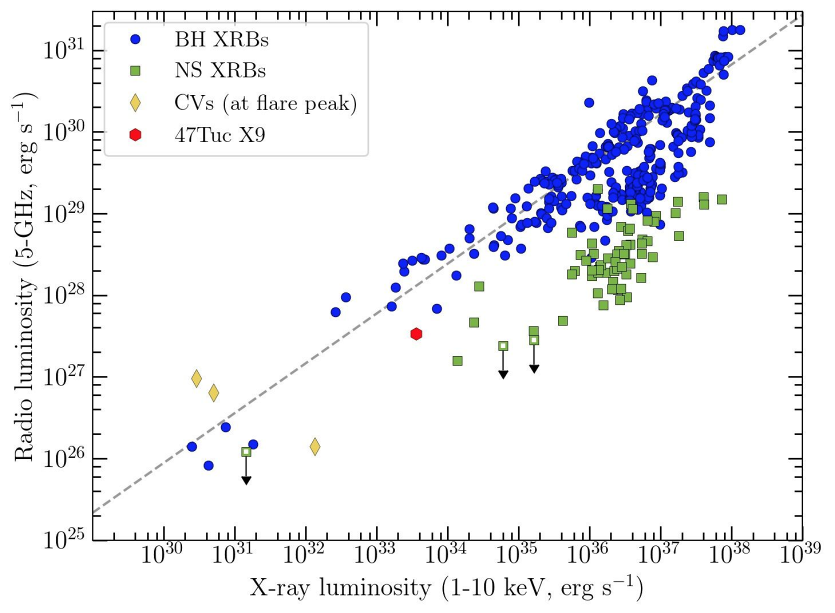


Core of 47 Tuc in radio
Miller-Jones et al. 2015

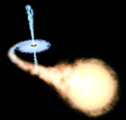


47 Tuc X9

- The brightest hard X-ray source in the cluster
- A bright blue star identified as the UV counterpart
- Significant variability in UV and X-rays
- C & O emission lines in UV and X-ray sp
- Detected as a bright radio source in the I
- Radio vs. X-ray suggest a BH

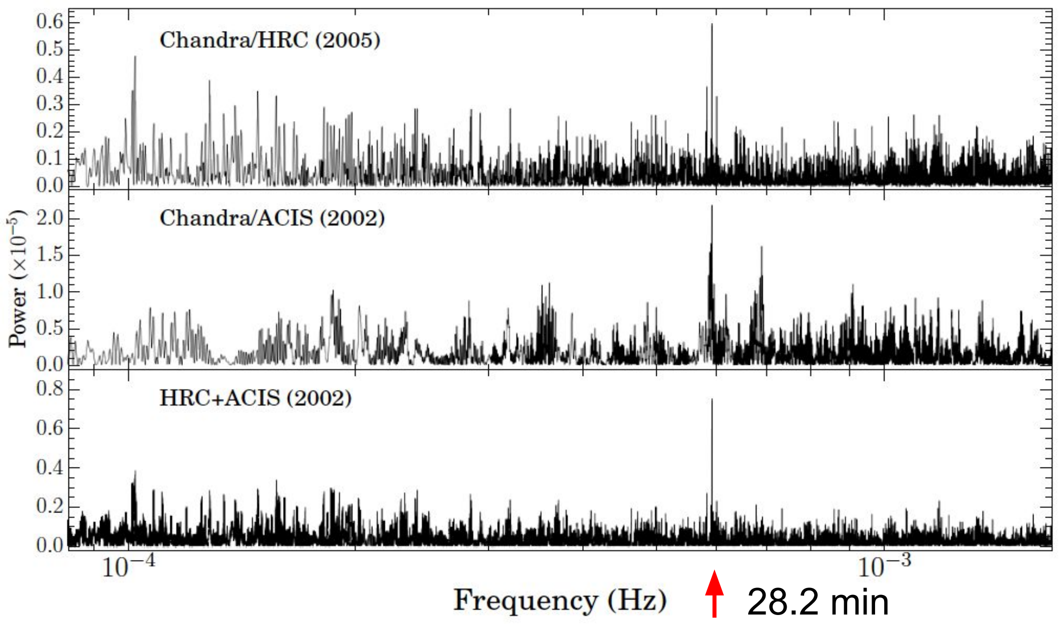


47 Tuc X9 on the Radio/X-ray correlation plane
Bahramian et al. 2016



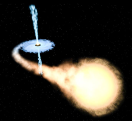
47 Tuc X9

- The brightest hard X-ray source in the cluster
- A bright blue star identified as the UV counterpart
- Significant variability in UV and X-rays
- C & O emission lines in UV and
- Detected as a bright radio sour
- Radio vs. X-ray suggest a BH
- Orbital period of 28.2 min

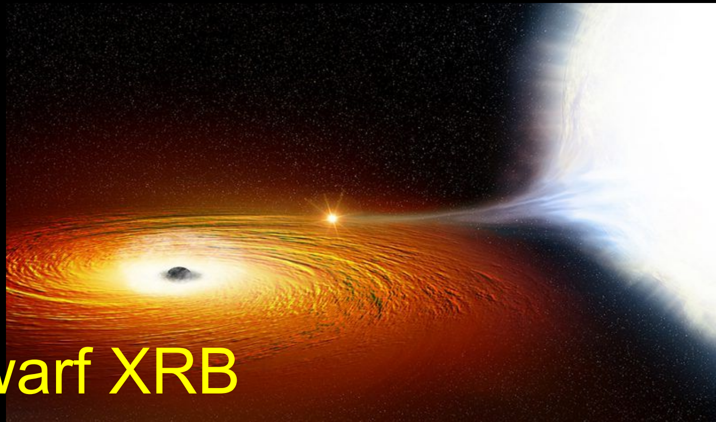


X-ray power spectrum for X9
Bahramian et al. 2016

47 Tuc X9

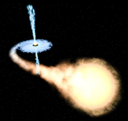


- The brightest hard X-ray source in the cluster
- A bright blue star identified as the UV counterpart
- Significant variability in UV and X-rays
- C & O emission lines in UV and X-ray spectrum
- Detected as a bright radio source in the MAVERIC survey
- Radio vs. X-ray suggest a BH
- Orbital period of 28.2 min
- Evidence of photo-ionized overabundant oxygen
- Featureless Optical spectrum



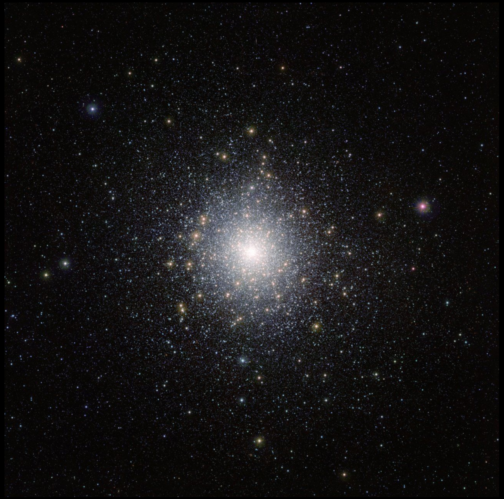
Black hole - C/O White dwarf XRB

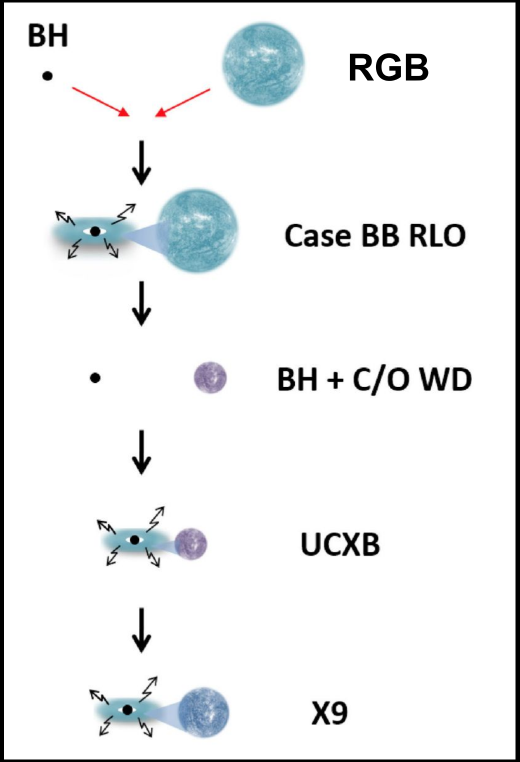
Formation of X9



47 Tuc X9

Ultracompact BH-WD binary
In a dynamically active GC





Tudor et al. 2018, Church et al. 2018

Some of the black holes found so far

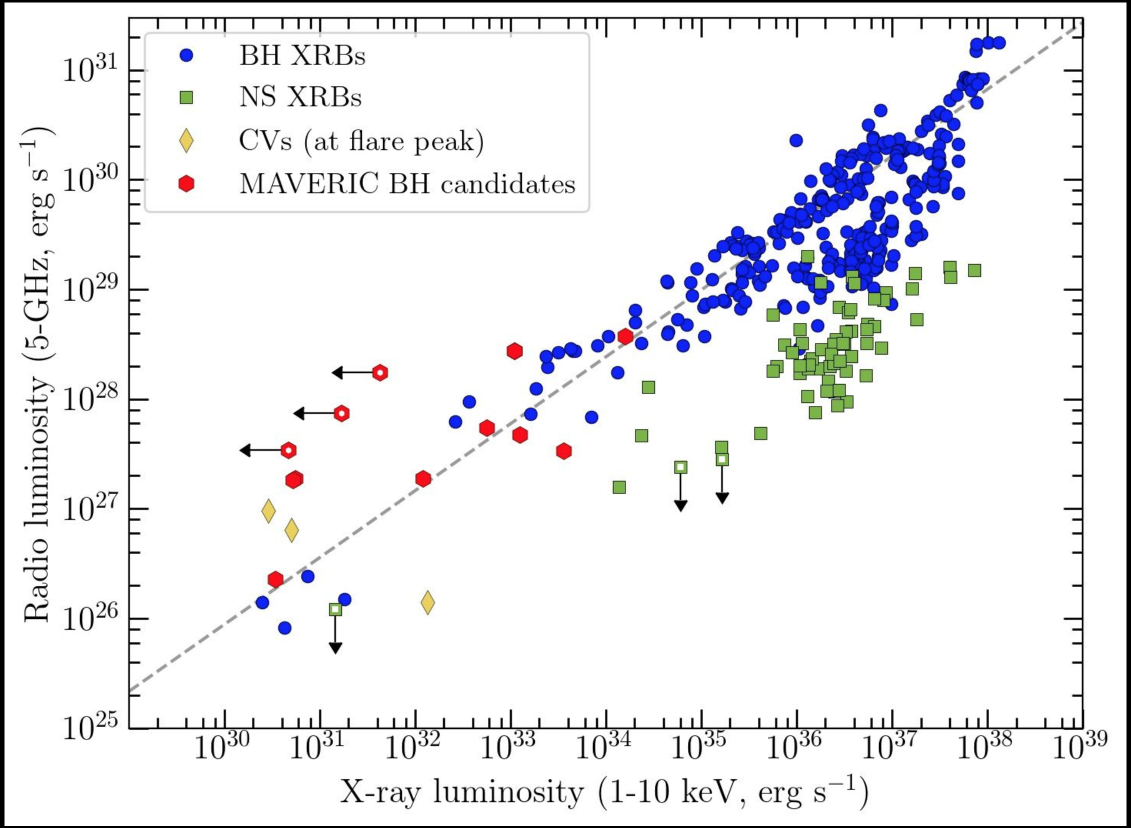
M22-VLA1 (Strader+2012)
BH-red dwarf binary

M62-VLA1 (Chomiuk+2013)
BH-subgiant binary

47 Tuc X9 (Miller-Jones+2015)
Ultracompact BH-WD binary

M10 - VLA1 (Shishkovsky+2018)
BH-red straggler binary

And many more under study.



What about their host GCs?

47 Tuc X9

Ultracompact BH-WD binary

In a dynamically active, massive, metal-rich cluster

M10 - VLA1

BH-red straggler binary

Relatively Low encounter-rate, low mass, metal-poor cluster

M22-VLA1

BH-red dwarf binary

Relatively metal-poor, low mass,
low encounter-rate cluster

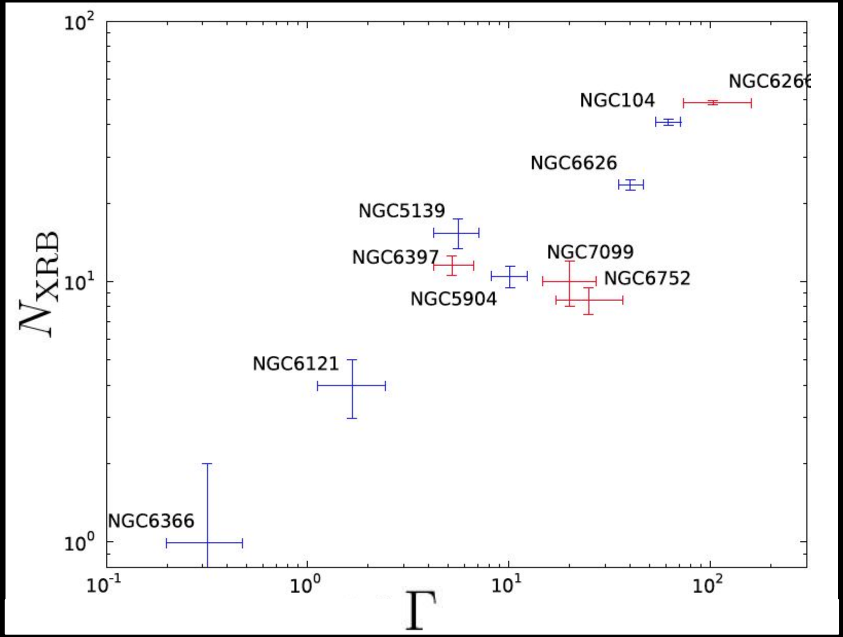
M62-VLA1

BH-subgiant binary

Dynamically active, massive cluster

Why cluster properties matter?

Encounters: main channel for XRB formation in GCs



Encounter rate vs. #XRBs in Galactic GCs

Cluster density

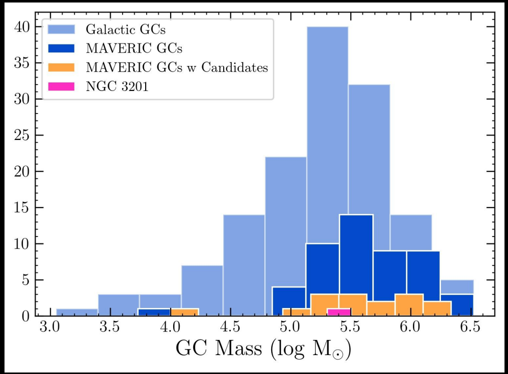
$$\Gamma = \int \frac{\rho^2}{\sigma} dV$$

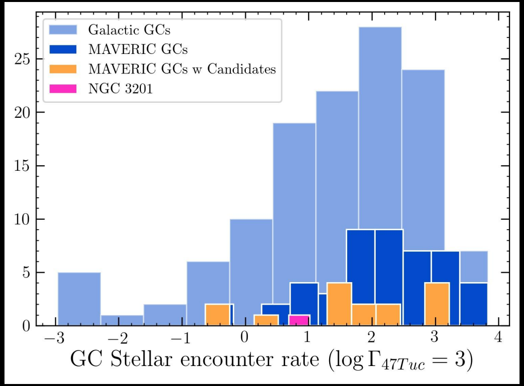
Velocity dispersion

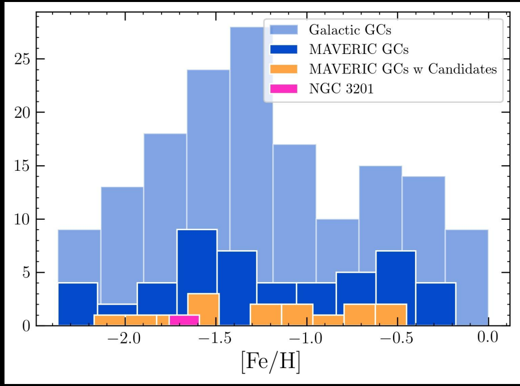
What about the BH-XRBs alone?

No apparent connection between BH candidates and properties of clusters

(Preliminary results)







BHs in GCs

- They are lurking around in GCs in unusual configurations
- We have identified ~ a dozen accreting BH candidates,
  more study to confirm their nature is underway
- Currently no apparent link has been noticed
  between BHs population and GC properties (observationally)
  More rigorous analysis underway