Intermediate-Mass Black Holes in the Local Universe

Lessons from G1

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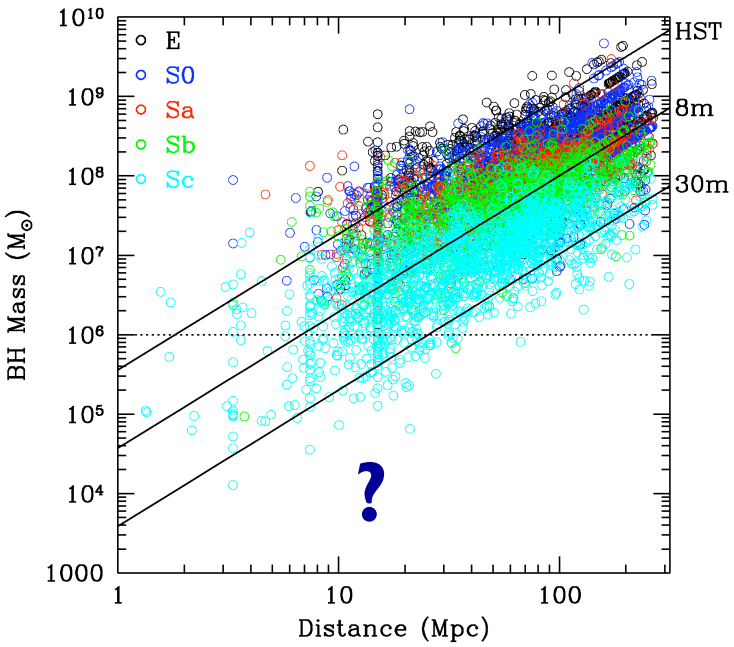
Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NRAO

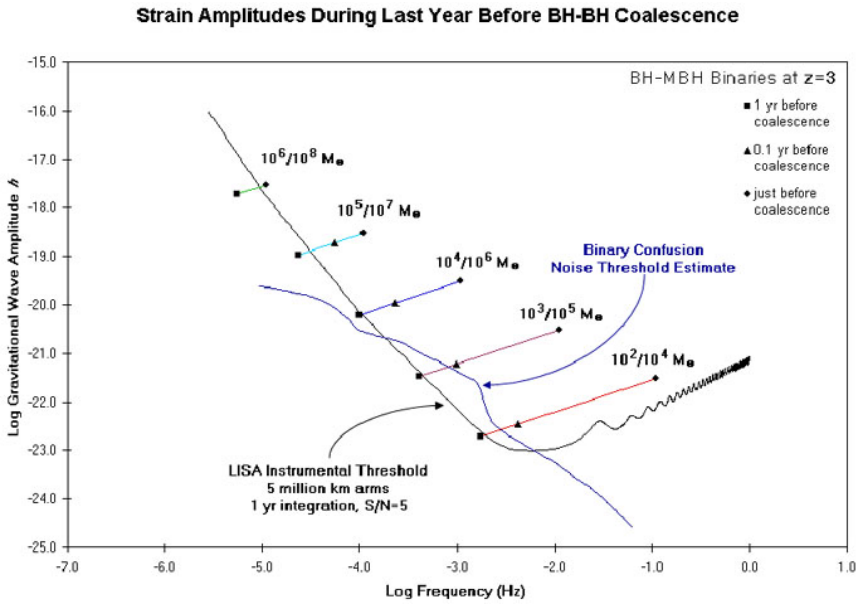
Range of Black Hole Masses M_{BH}

- Stellar mass black holes $M_{BH} < 40\ M_\odot$
  - Silverman & Filippenko (2008)
- Massive black holes $M_{BH} > 10^6\ M_\odot$
  - Megamasers (Lo 2005)
  - Stellar dynamics
    - Ferrarese & Ford (2005) CfAz
    - Resolve sphere of influence
    - Access $M_{BH} \sim 10^5\ M_\odot$ with 30m
- Intermediate-mass black holes (IMBHs)
  - $40\ M_\odot < M_{BH} < 10^5\ M_\odot$
  - Almost no access via stellar dynamics beyond Local Group
  - Hindrance to demographic studies



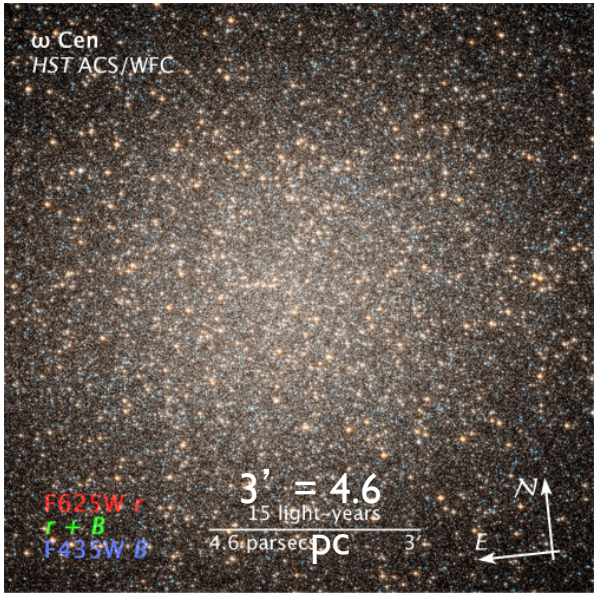
Importance of Intermediate-Mass Black Holes

- Predictions of gravity wave signals for Laser Interferometer Space Antenna (Bender & Pollack 2003)
- Formation of seed black holes
  - Volonteri et al. (2008), Bellovary et al. (2010)
- Simulations of gravity wave recoil
  - Holley-Bockelmann et al. (2008)



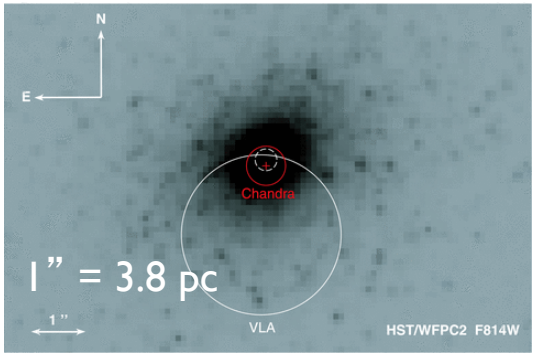
Candidate Intermediate-Mass Black Holes
Globular cluster ω Cen at distance d = 5 kpc

- Most luminous globular cluster in Milky Way
- Stellar dynamics via HST and VLT
  - Noyola et al. (2010)
    - Radial velocities
    - $M_{BH} \sim 4.7 \times 10^4\ M_\odot$
  - Van der Marel & Anderson (2010)
    - Radial velocities and proper motions
    - $M_{BH} < 1.2 \times 10^4\ M_\odot$
  - Origin of differences unclear

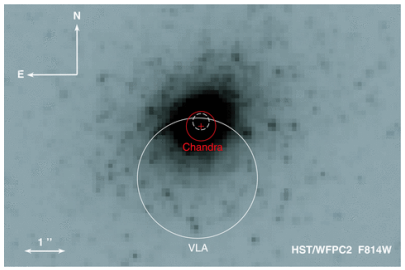


Candidate Intermediate-Mass Black Holes
Globular cluster G1 at d = 780 kpc

- Amongst the most luminous globular clusters in M31
- Stellar dynamics via HST and Keck
  - Gebhardt et al. (2002, 2005)
    - Radial velocities
    - $M_{BH} \sim 1.8 \times 10^4\ M_\odot$
- X-ray counterpart via XMM and Chandra
  - Pooley & Rappaport (2006), Kong et al. (2010)
  - $L_X \sim 2 \times 10^{36}$ ergs/s
  - Low-mass stellar binary? Viable
  - Accretion onto candidate IMBH? Viable



Candidate Intermediate-Mass Black Holes
Globular cluster G1 at d = 780 kpc



- Radio counterpart via NRAO VLA (Ulvestad et al. 2007)
  - Observed flux density S ~ 30 μJy
- Use empirical radio – X-ray – mass relation for accreting black holes to predict S (Merloni et al. 2003, Falcke et al. 2004)
  - Stellar binary with $M_{BH} \sim 10\ M_\odot$?
    - Not viable: predicted S too low
  - IMBH with $M_{BH} \sim 1.8 \times 10^4\ M_\odot$?
    - Viable: predicted S about right

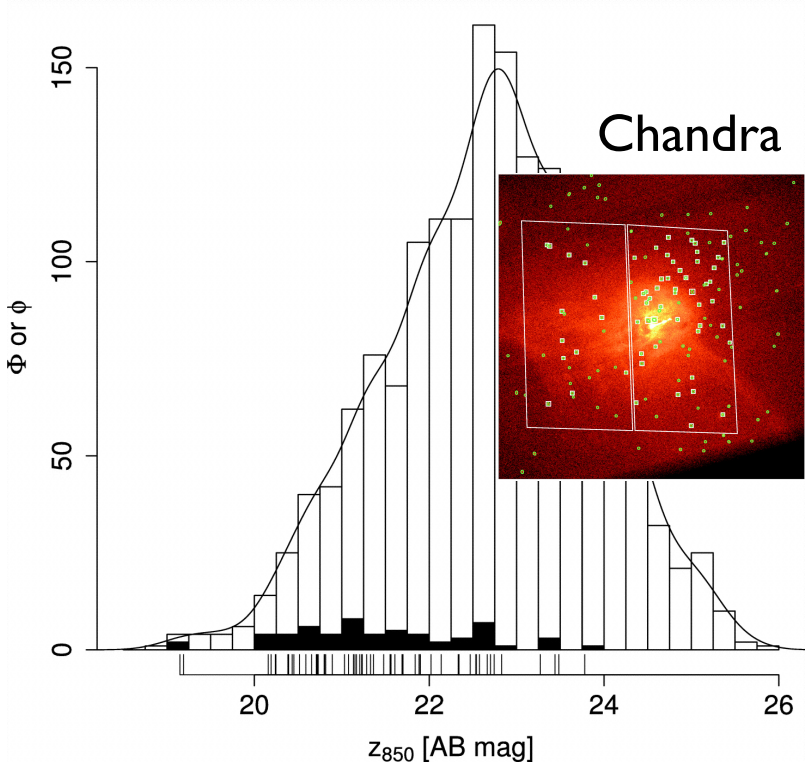
$$S_{5\,\mathrm{GHz}} = 52 \left(\frac{L_X}{10^{36}\ \mathrm{ergs\ s^{-1}}}\right)^{0.6} \left(\frac{M_{BH}}{10^4\ M_\odot}\right)^{0.78} \times \left(\frac{d}{600\ \mathrm{kpc}}\right)^{-2} \mu\mathrm{Jy}.$$

± factor of 8

- Planetary wind nebula?
  - Unlikely in an old stellar population but can test via VLBI

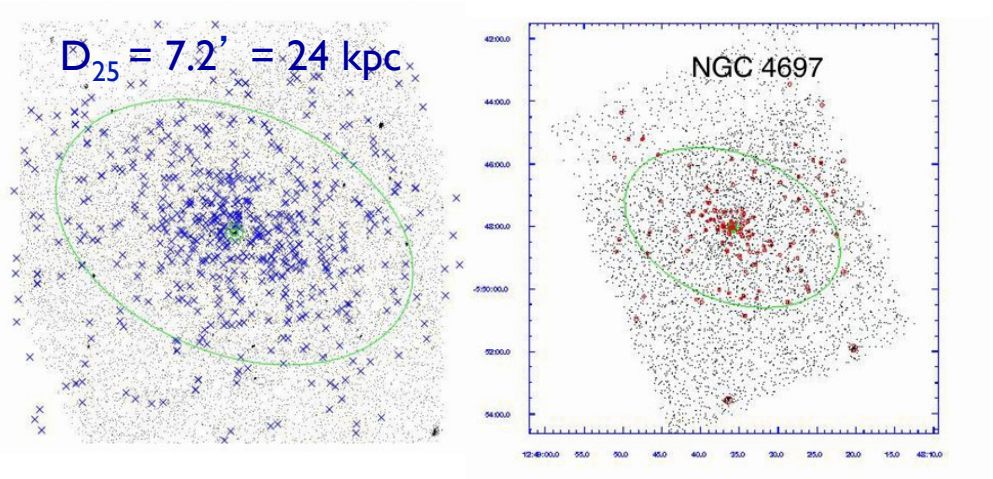
Candidate Intermediate-Mass Black Holes
Globular clusters at d = 4 – 40 Mpc

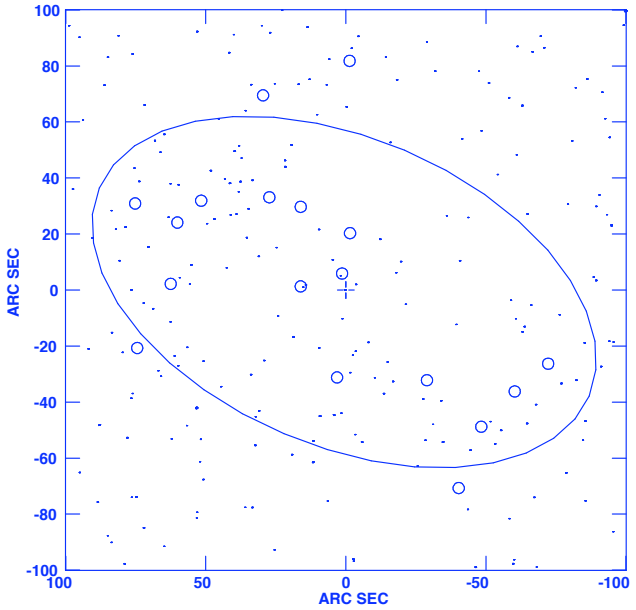
- 1000s localized via HST
  - Jordan, Humphrey, Masters …
  - Eg, globular clusters in M87
- 100s have X-ray counterparts
  - Kundu, Sarazin, Kim, Sivakoff …
  - Eg, M87 $L_X > 5 \times 10^{38}$ ergs/s
- X-ray sources reside preferentially in the most luminous globular clusters
- Mainly low-mass stellar binaries
- But could some be G1 analogs?
  - $M_{BH} \sim 1.8 \times 10^4\ M_\odot$



$$S_{5\,\mathrm{GHz}} = 52 \left(\frac{L_X}{10^{36}\ \mathrm{ergs\ s^{-1}}}\right)^{0.6} \left(\frac{M_{BH}}{10^4\ M_\odot}\right)^{0.78} \times \left(\frac{d}{600\ \mathrm{kpc}}\right)^{-2}\ \mu\mathrm{Jy}.$$

Candidate Intermediate-Mass Black Holes
Globular clusters in NGC 4697 at d = 11 Mpc





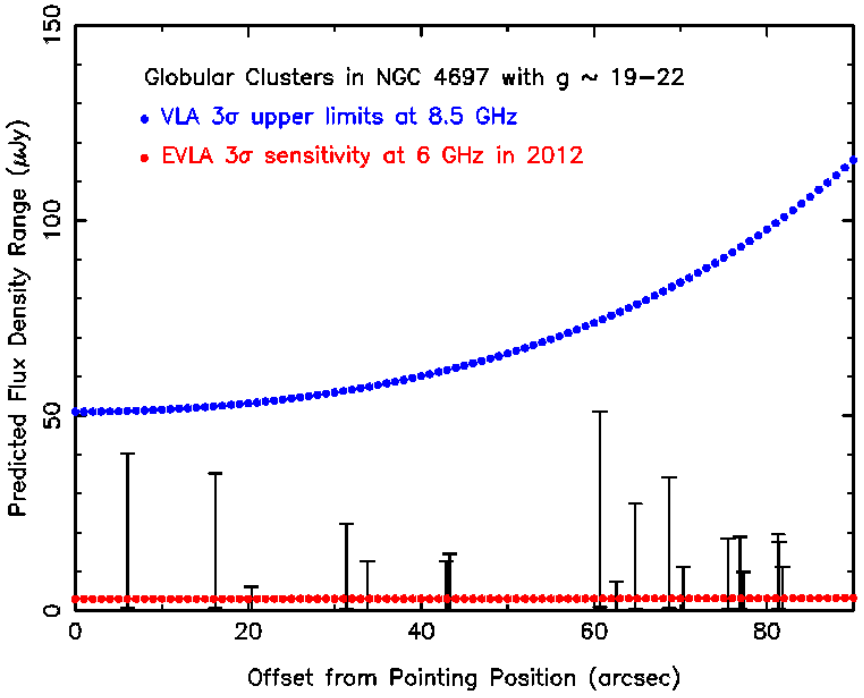
- Elliptical galaxy studied via HST and Chandra (Sivakoff et al. 2008)
- 34 globular clusters with X-ray counterparts
  - g ~ 19 – 25 mag
  - $L_X > 10^{37}$ ergs/s

- VLA 8.5 GHz (Wrobel et al. 2008)
- Resolution 0.3 arcsec = 16 pc
- G1 g ~ 20 mag
- 18 clusters with g ~ 19 – 22 mag

Candidate Intermediate-Mass Black Holes
Globular clusters in NGC 4697 at d = 11 Mpc

- $M_{BH} \sim 1.8 \times 10^4\ M_\odot$ like G1
- L_X from Chandra
- Predict radio flux density S

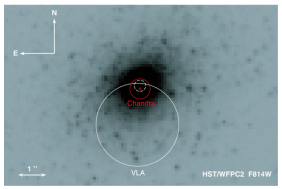
$$S_{5\,\mathrm{GHz}} = 52 \left(\frac{L_X}{10^{36}\ \mathrm{ergs\ s^{-1}}}\right)^{0.6} \left(\frac{M_{BH}}{10^4\ M_\odot}\right)^{0.78} \times \left(\frac{d}{600\ \mathrm{kpc}}\right)^{-2}\ \mu\mathrm{Jy}.$$

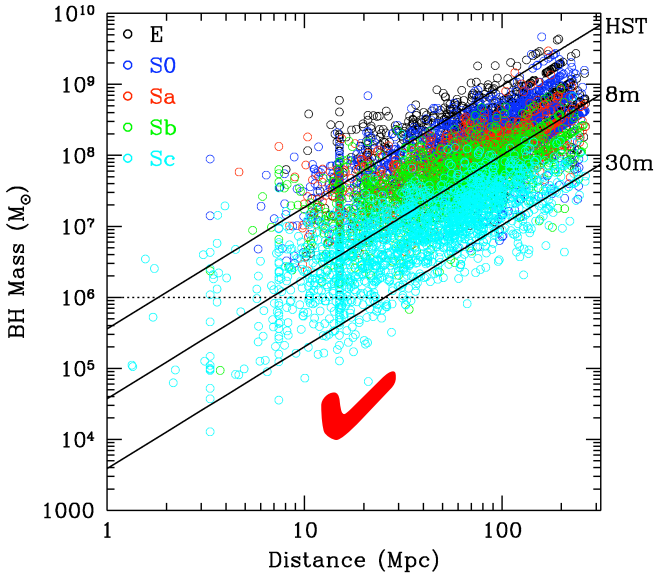


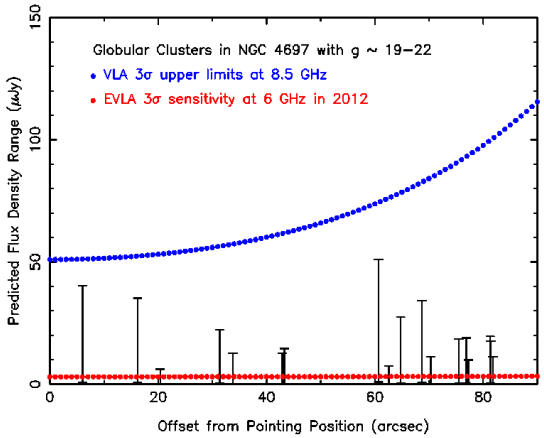
- Predicted S ~ 1 – 7 μJy
- Each S uncertain by ± factor of 8
- Detections of G1 analogs feasible with NRAO Expanded VLA

Summary

Globular Cluster G1 in M31







- Intermediate-mass black holes (IMBHs) have masses 40 $M_\odot$ < M_{BH} < 10^5 $M_\odot$
- Demographics key for gravity waves, seed black holes, recoiling black holes
- Almost no access via stellar dynamics beyond Local Group, even with 30m
- Radio and X-ray properties of G1 consistent with M_{BH} ~ 1.8 x 10^4 $M_\odot$
- EVLA detections of G1 analogs beyond Local Group are feasible