Searching for signs of IMBH astrometric microlensing in M 22

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Intermediate-mass black holes (IMBH)

- Supermassive black holes (SMBH; $>10^6 \, M_\odot$) found at large $z$ – some had formed a few Myr after Big Bang (Fan 2006)
- How did they form so rapidly?
- Maximum accretion (Eddington) rate by stellar-mass BH is not enough to form SMBH
- Preferred scenario is through merger of seed IMBHs
- IMBHs are missing link in our understanding of SMBH formation, insights into galaxy formation and evolution
Where are the IMBHs?

• IMBH themselves could form through runaway star mergers (Miller & Hamilton 2002, Portegies Zwart & McMillan 2002)

• Need dense stellar environments like globular clusters (GC); e.g. Silk & Arons (1975)

• GC are similar age as host galaxies— they could have delivered seed IMBHs to galaxy centers to form SMBHs (Capuzzo Dolcetta+ 2001)
Where are the IMBHs?

• Further motivation to look in GCs: M-σ relation (e.g. Ferrarese & Merritt 2000)
• Velocity dispersion is related to the mass of central black hole (galaxies and their SMBH)
• Extrapolate to low-mass → σ range of GCs
Current evidence for IMBHs

- X-ray accretion signatures
  - Only upper limits, crucial dependence on assumption accretion processes (Grindlay+ 2001, Maccarone+ 2005, Haggard+ 2013)

- Surface-brightness profiles: IMBH would produce weak central cusp (Bahcall & Wolf 1976, Baumgardt+ 2005)
  - But cusp is not unique signature- could be sign of e.g. ongoing core-collapse (Trenti+ 2010), mass segregation (Baumgardt+ 2003), anisotropic orbit (Ibata+ 2009)
Current evidence for IMBHs

- Photometry + spectroscopy comparison to dynamical models have yielded a few candidates (e.g. Noyola+ 2010, Lützgendorf+ 2013)
  - Conflicting results e.g. in ω Cen (Anderson+ 2010, Kamann+ 2014)
- Dynamics and spatial distribution of pulsars in 47 Tuc compared to models (Kiziltan+ 2017)
  - Controversy as to uniqueness of this signature
- Other techniques with important caveats
  - X-ray quasi-period oscillations (Strohmayer & Mushotzky 2014)
  - Molecular cloud velocity dispersion (Oka+ 2016)
What about microlensing?

• No unambiguous detection of an IMBH yet
• Astrometric microlensing could help (e.g. Hog+ 1995, Dominik & Sahu 2000, Kains+ 2016)
• Determine lens mass without relying on assumptions on nature of system
• Carried out simulations for all non-core-collapsed GC along Bulge line of sight
• Estimated detection rates for each, assuming various IMBH masses, and using known relative GC - Bulge motions
IMBH lensing signal

- Extremely long $t_E$ — years; usually won’t detect photometric event ($1/u$ vs. $1/u^4$)
  - E.g. for M 22, $M=10^4$, $t_E\sim10$ yrs, $\theta_E=125$ mas
- Larger masses $\rightarrow$ larger signals but trade-off between size of shift and ability to distinguish it from rectilinear motion over $\sim$years
- Over reasonable timescales, typically a few mas; still easily detectable with HST
- Self-lensing is negligible: tiny $\theta_E$ even for large mass
- Focus on lensing of Bulge source stars by cluster IMBH
What shifts would look like...
Getting the IMBH mass

• Astrometric detection constrains the Einstein ring radius $\theta_E$
• The lens distance is known (GC distance)
• Therefore, an astrometric detection *only* could yield a lens (IMBH) mass
• No model assumptions → could yield an unambiguous IMBH detection
HST Archival Project

• Many GC have been observed frequently with HST since the early 1990s
• M 22 was identified by Kains+ (2016) as the best candidate cluster
  • Not core collapsed
  • High density of background Bulge stars
  • Large cluster-Bulge relative motion
HST Archival Project

• In this archival proposal (PI: Kains), we analyzed 20 years of HST archival data of M 22
• Challenging- spans different instruments with different dynamic ranges, pixel scales (WFPC2 vs. WFC3)
• Aim: obtain 20-year astrometric time series determine if we can find signs of astrometric lensing of Bulge stars
• Blind astrometric search- no hope of detecting photometric events with such timescales
Reduction process in a nutshell

- Data available from 1995 to 2013; different instruments + many different filters/exposure times, reflecting different science goals of the programs
- Worked with J. Anderson to adapt his reduction software to deal with heterogeneous data set
- Used a reference image from Sarajedini (2006)-ACS GC Treasury Program
- Derived transformations for each image
- Measured position on each transformed image
Reduction process in a nutshell

• This worked well for all data except WFPC2/WF chips- large pixel, too much saturation, no dithering

• Unfortunately, this meant throwing away richest data set from 1999/2000 (PI: Sahu), large coverage gap

• Result is 8 unique epochs over the 18 year baseline

• Use cluster stars to derive local corrections for systematics
Bulge stars

- Cluster-Bulge relative motion is large (12 mas/yr), so Bulge stars are easily identified by the proper motions
- Look at stars within 5” of cluster core
- 8 Bulge stars, but 2 are too close to saturated stars
Bulge stars time-series
Procedure

• Fit a straight-line (i.e. proper motion-only) model to each star
  • 4 parameters: \( x_0, y_0, \mu_x, \mu_y \)
• Fit an astrometric lensing model to each star
  • 9 parameters: \( t_0, t_E, u_0, \alpha, \theta_E, x_0, y_0, \mu_x, \mu_y \)
• Prior constraints: relative motion \( \left( \frac{\theta_E}{t_E} \right) \) must be consistent with cluster-Bulge relative motion
• Use (arbitrary) condition that lensing model be 1000 times more probable, i.e. -2*\( \ln(0.001) \) penalty
• Is lensing model favoured for any (Bulge) star?
Is that enough data?

- Try with some simulated data with same time coverage
- Real model is recovered, albeit with large uncertainties
Bulge stars: best-fit PM only model
Almost undistinguishable from linear motion
Would correspond to a very high-mass BH (~10^5 M☉)
Does not improve fit enough to be favoured over PM model
When no lensing is taking place, lensing fits converge toward very slow models, since those are essentially undistinguishable from PM-only
No photometric counterpart, blind astrometric search
Best-fit lensing model

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No sign of lensing in M 22

- All stars consistent with PM-only motion
- Large 10-year gap in data means no useful mass limits can be obtained
- With better time coverage, could place mass limits (Kains+ 2016)- similar to planet detection efficiency analyses (e.g. Gaudi & Sackett 2000)
Conclusions

• Still no black hole found through astrometric microlensing 😞
• Astrometry is tough, especially with WFPC2 (only PC useful)
• We now have tools to look for these signals in other clusters (plus a general astrometric lensing fitting code that could be incorporated to open codes)
• We are reaching expected astrometric precision with HST (e.g. Kains+ 17, Sahu+ 17, Kuijken & Rich 2002)
• Will look at other Bulge clusters with enough archival data, especially those identified as good candidates in Kains+ (2016)
• Worth extending baselines with JWST- many clusters will be frequent observing targets anyway for stellar population studies