Searching for signs of IMBH astrometric microlensing in M 22

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Intermediate-mass black holes (IMBH)

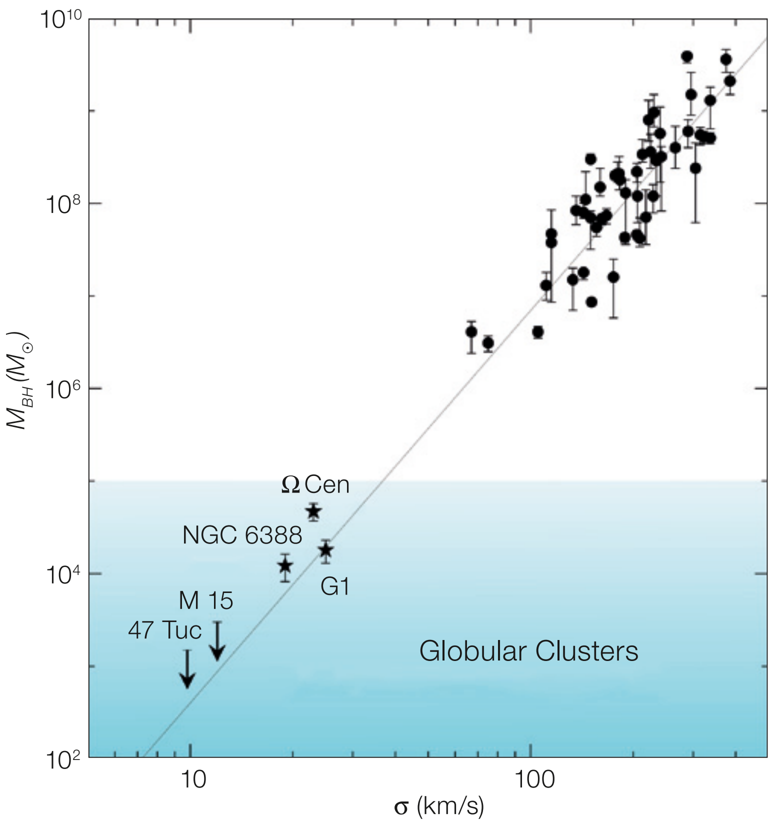
- Supermassive black holes (SMBH; $>10^6\ M_{\odot}$) found at large z – some had formed a few Myr after Big Bang (Fan 2006)
- How did they form so rapidly?
- Maximum accretion (Eddington) rate by stellar-mass BH is not enough to form SMBH
- Preferred scenario is through merger of seed IMBHs
- IMBHs 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



Lützgendorf+ 2012

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)

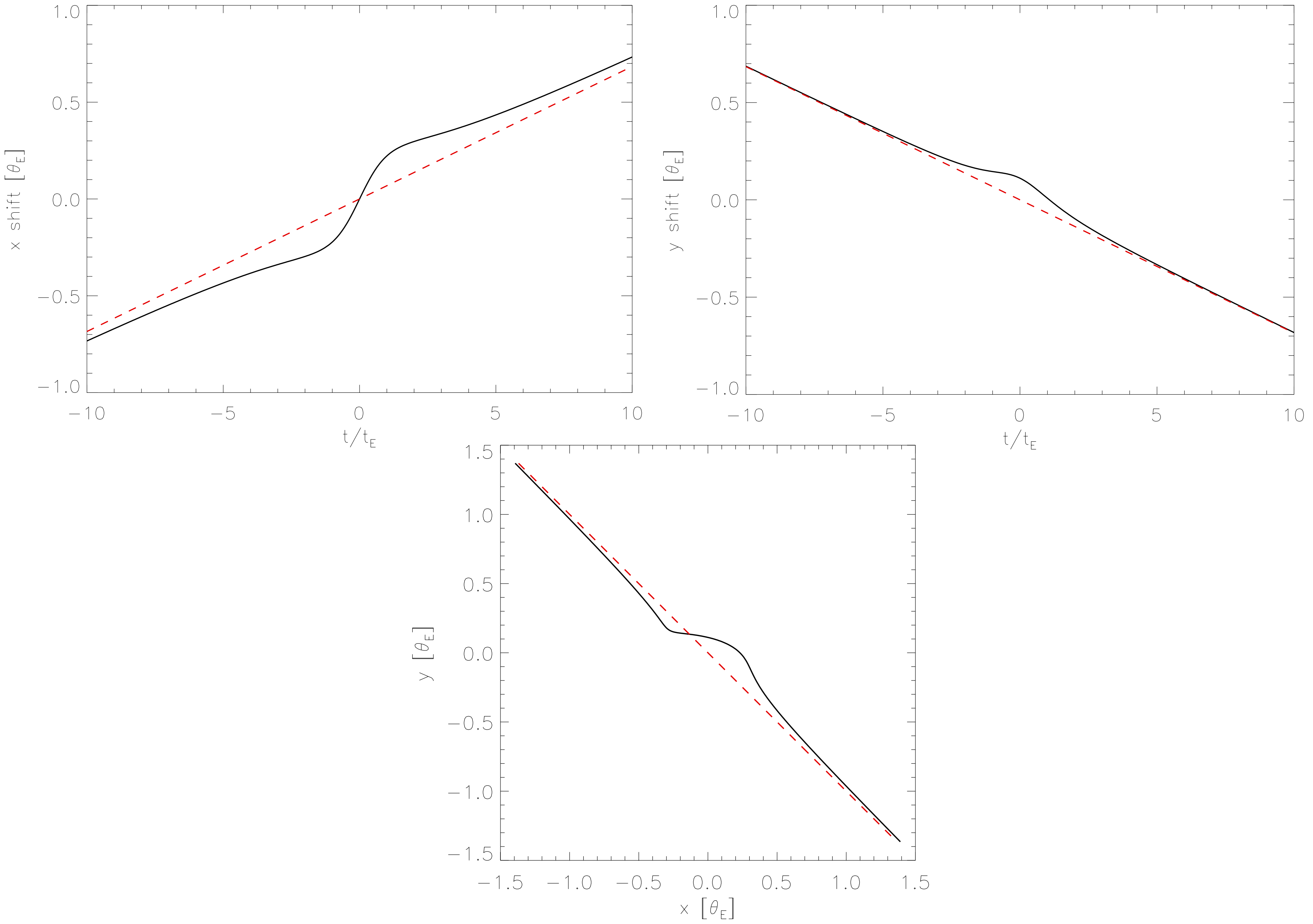
What about microlensing?

- 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/u⁴*)
    - E.g. for M 22, $M=10^4$, t_E~10 yrs, θ_E=125 mas
- Larger masses → larger signals but trade-off between size of shift and ability to distinguish it from rectilinear motion over ~years
- Over reasonable timescales, typically a few mas; still easily detectable with HST
- Self-lensing is negligible: tiny θ_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 θ_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

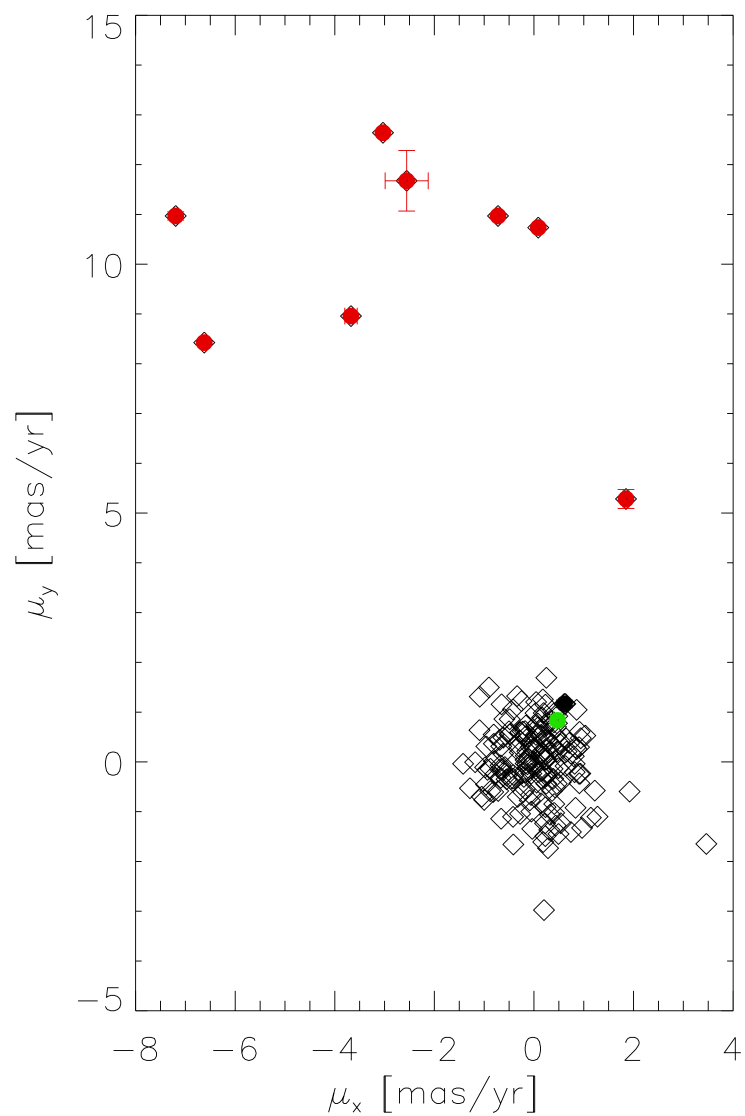
- Data available from 1995 to 2013; different instruments + many different filters/ exposure times, reflecting different science goals of the programs
- Worked with J. Anderson to adapt his reduction software to deal with heterogeneous data set
- Used a reference image from Sarajedini (2006)- ACS GC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

Reduction process in a nutshell

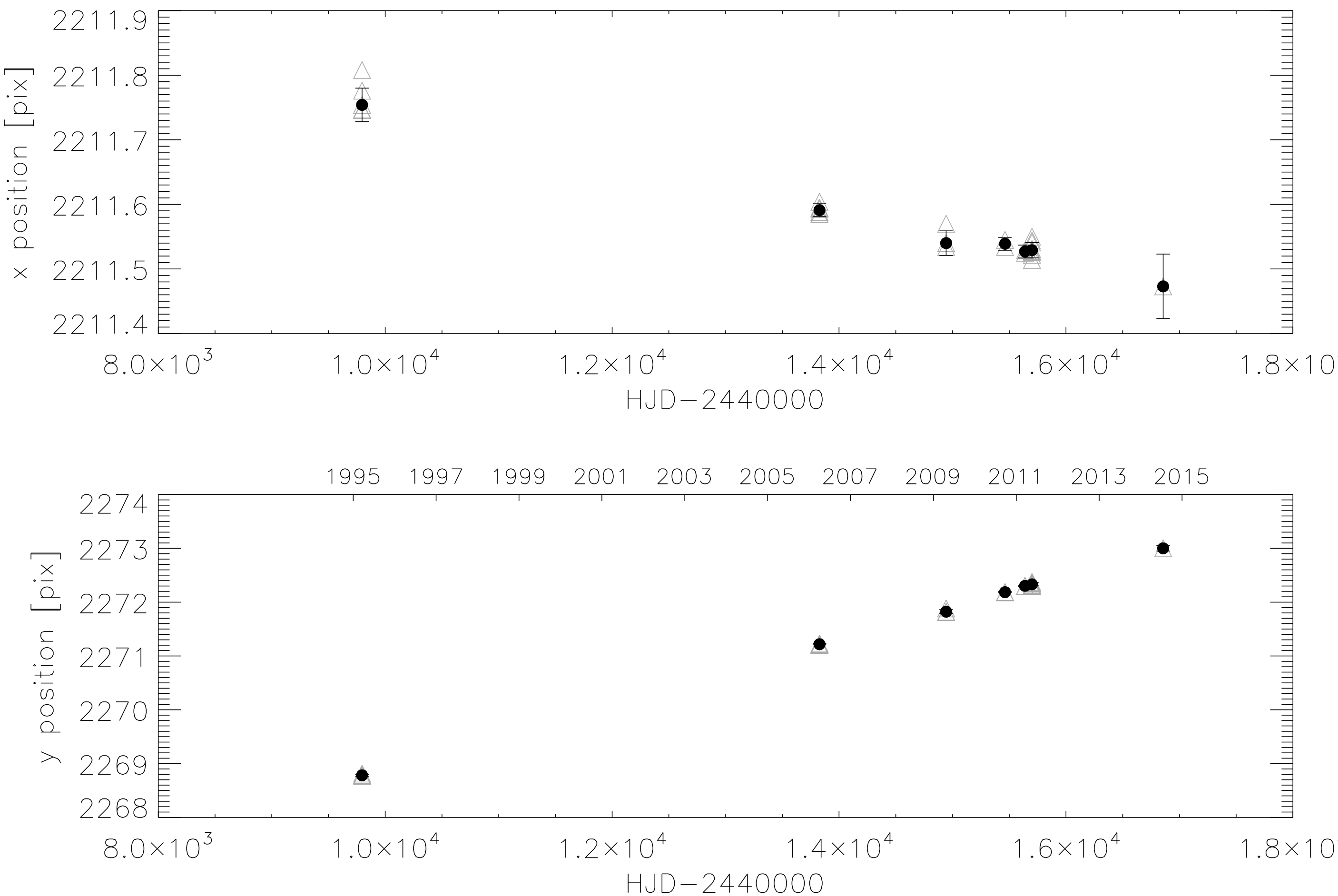
- This worked well for all data except WFPC2/WF chips- large pixel, too much saturation, no dithering
- Unfortunately, this meant throwing away richest data set from 1999/2000 (PI: Sahu), large coverage gap
- Result is 8 unique epochs over the 18 year baseline
- Use cluster stars to derive local corrections 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

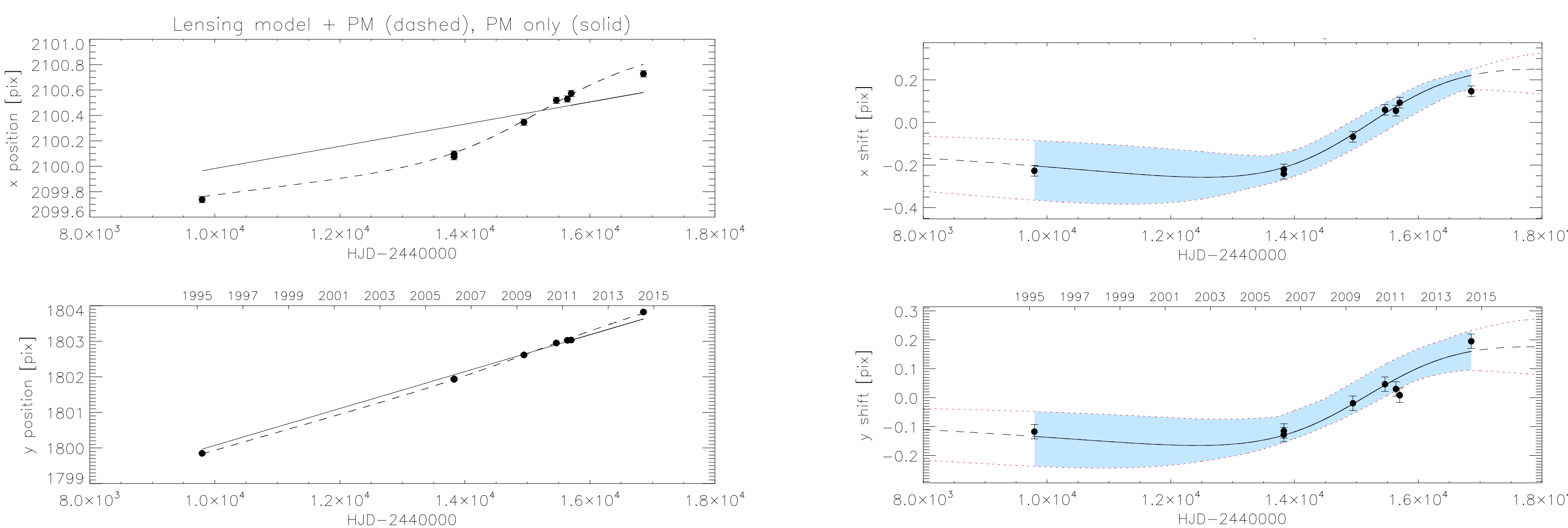


Procedure

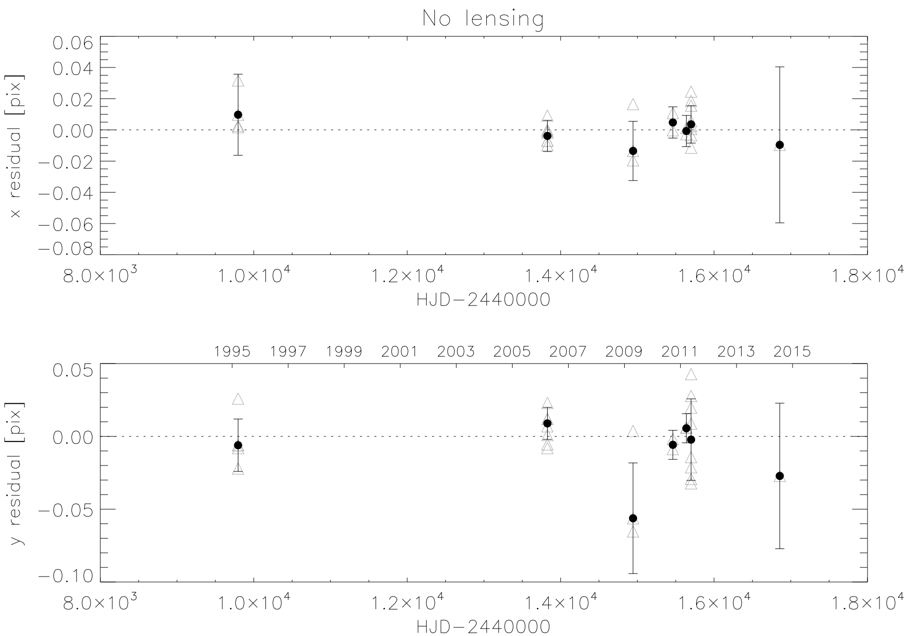
- Fit a straight-line (i.e. proper motion-only) model to each star
    - 4 parameters: x_0, y_0, μ_x, μ_y
- Fit an astrometric lensing model to each star
    - 9 parameters: t_0, t_E, u_0, α, θ_E, x_0, y_0, μ_x, μ_y
- Prior constraints: relative motion (θ_E /t_E) must be consistent with cluster-Bulge 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?

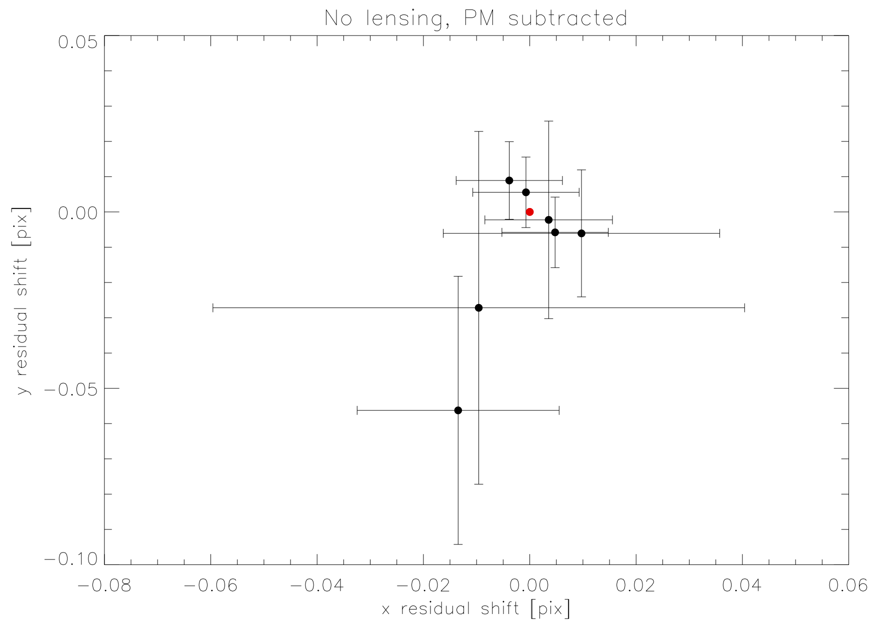
Is that enough data?

- Try with some simulated data with same time coverage
- Real model is recovered, albeit with large uncertainties



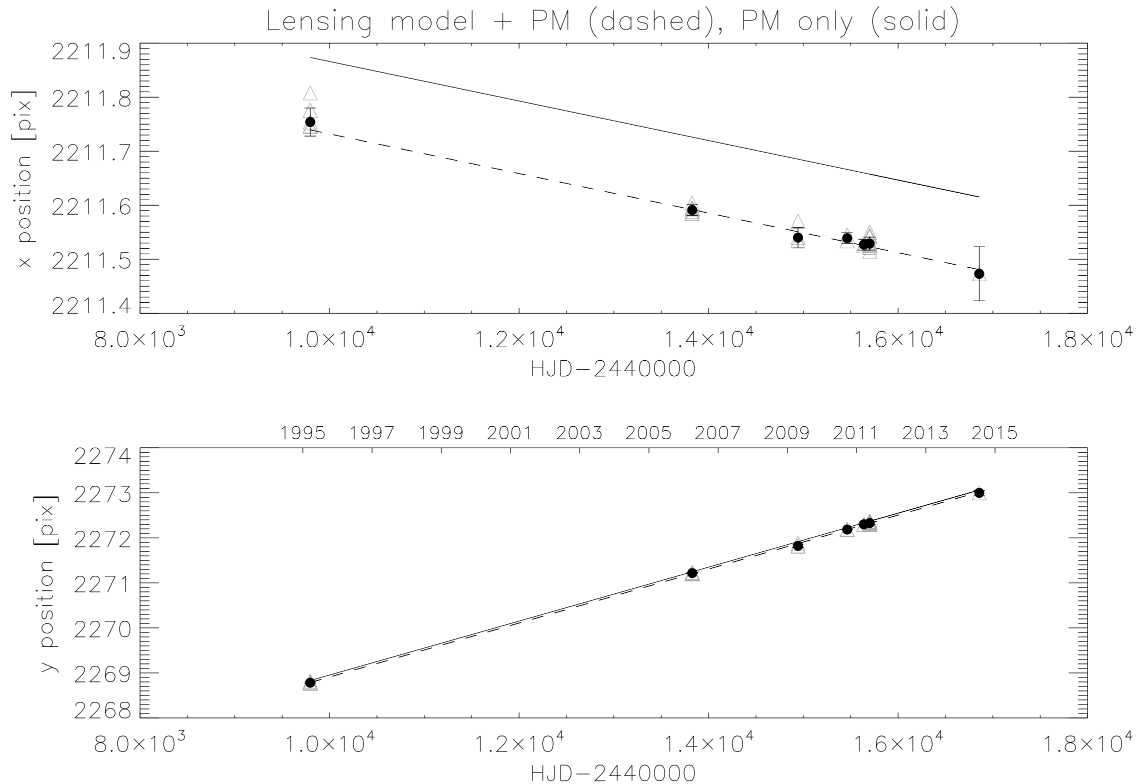
Bulge stars: best-fit PM only model





Best-fit lensing model

- Almost undistinguishable from linear motion
- Would correspond to a very high-mass BH (~10^5 $M_\odot$)
- 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



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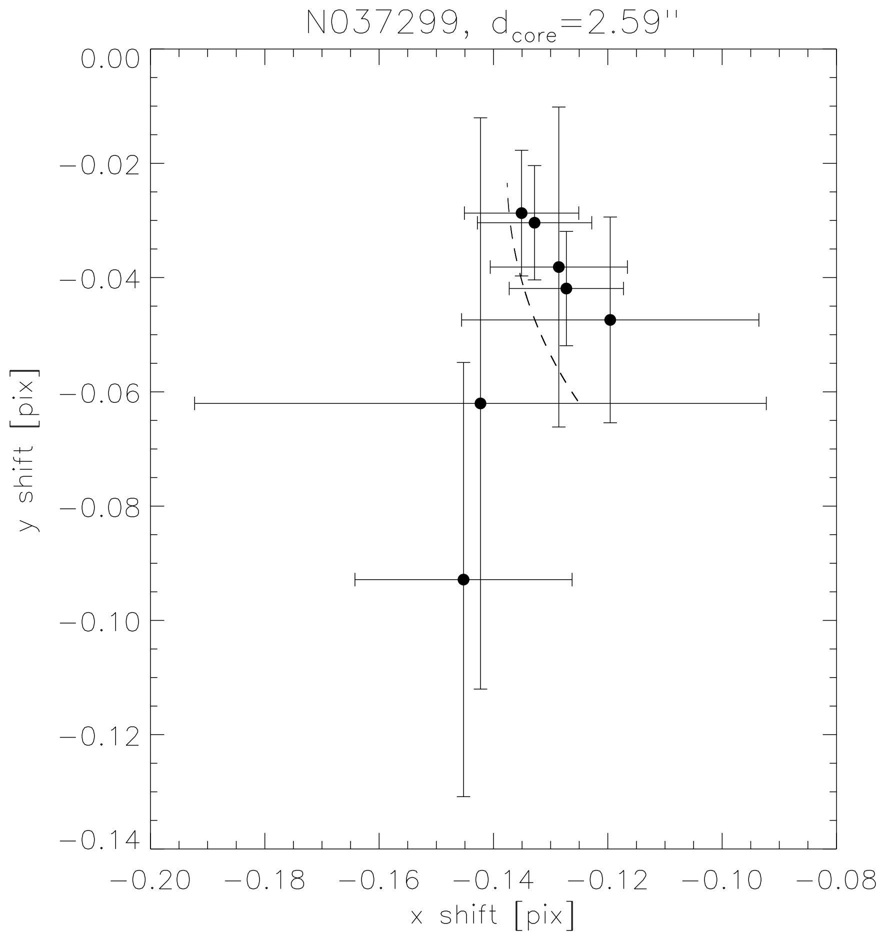

No sign of lensing in M 22

- 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