Detection and Mass Measurement of an Isolated Stellar-Mass Black Hole Using HST

Kailash Sahu

Jay Anderson

Stefano Casertano

Annalisa Calamida

Varun Bajaj

Andrea Bellini

Howard Bond

Tom Brown

Harry Ferguson

(STScI)

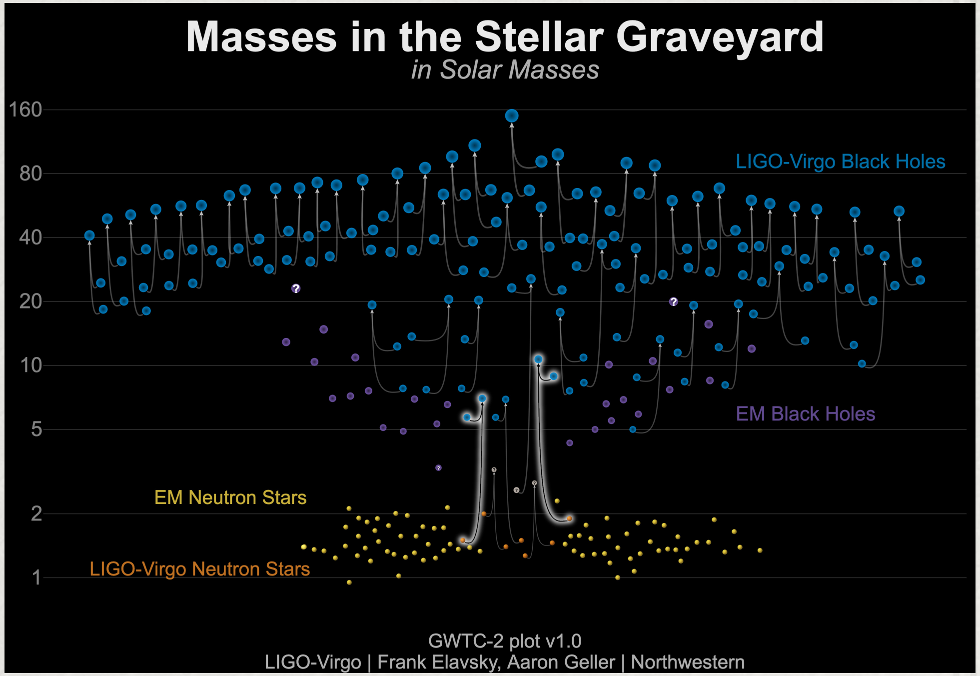
Total 91 Authors

Isolated Stellar Mass Black Holes

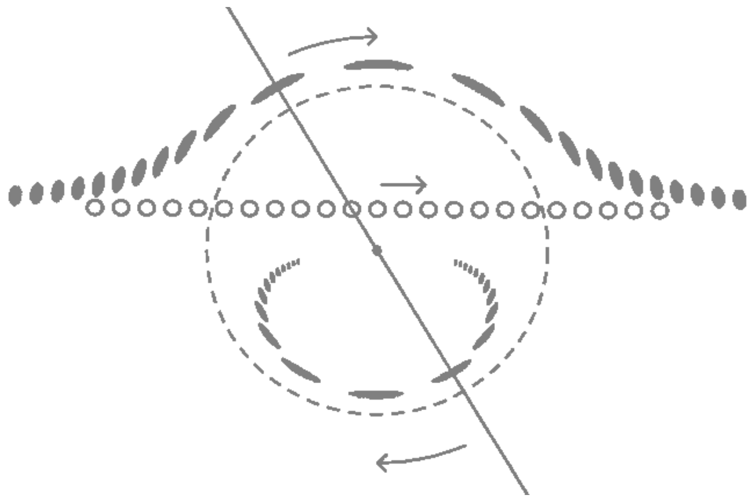
- Stars with $M > 20\ M_\odot$ are thought to end their lives as black holes. There should be 100 million BHs in the Galaxy.

- A large fraction of them are expected be isolated, because:
  - ~30% start as single stars
  - close binaries lead to merging during SN explosion
  - wide binaries produce single BHs due to orbital separation by the "kick velocity".
- Not a single isolated BH has ever been detected.

- All the BH detections so far are in binaries, including the BHs detected by LIGO.

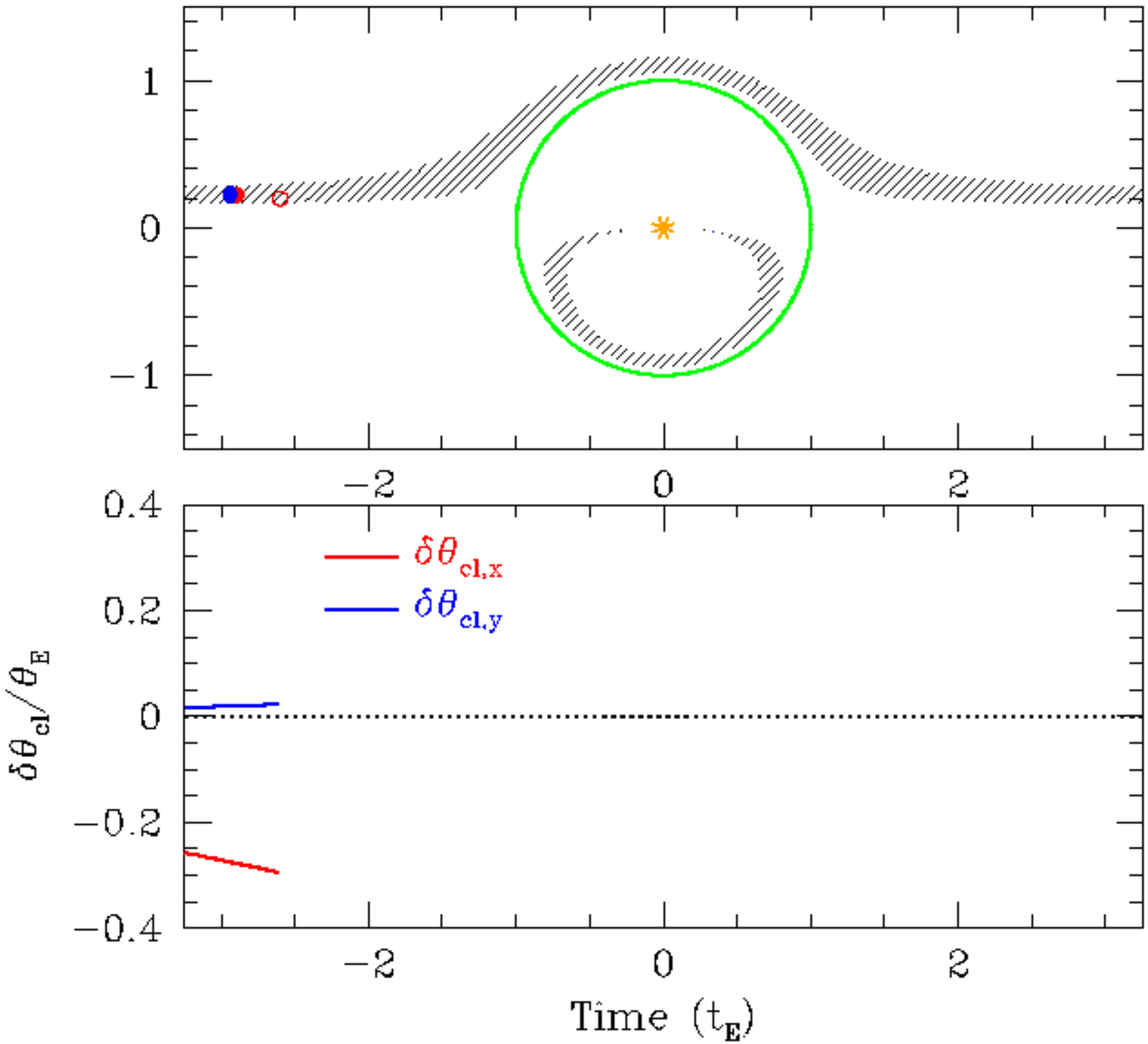


Astrometric microlensing

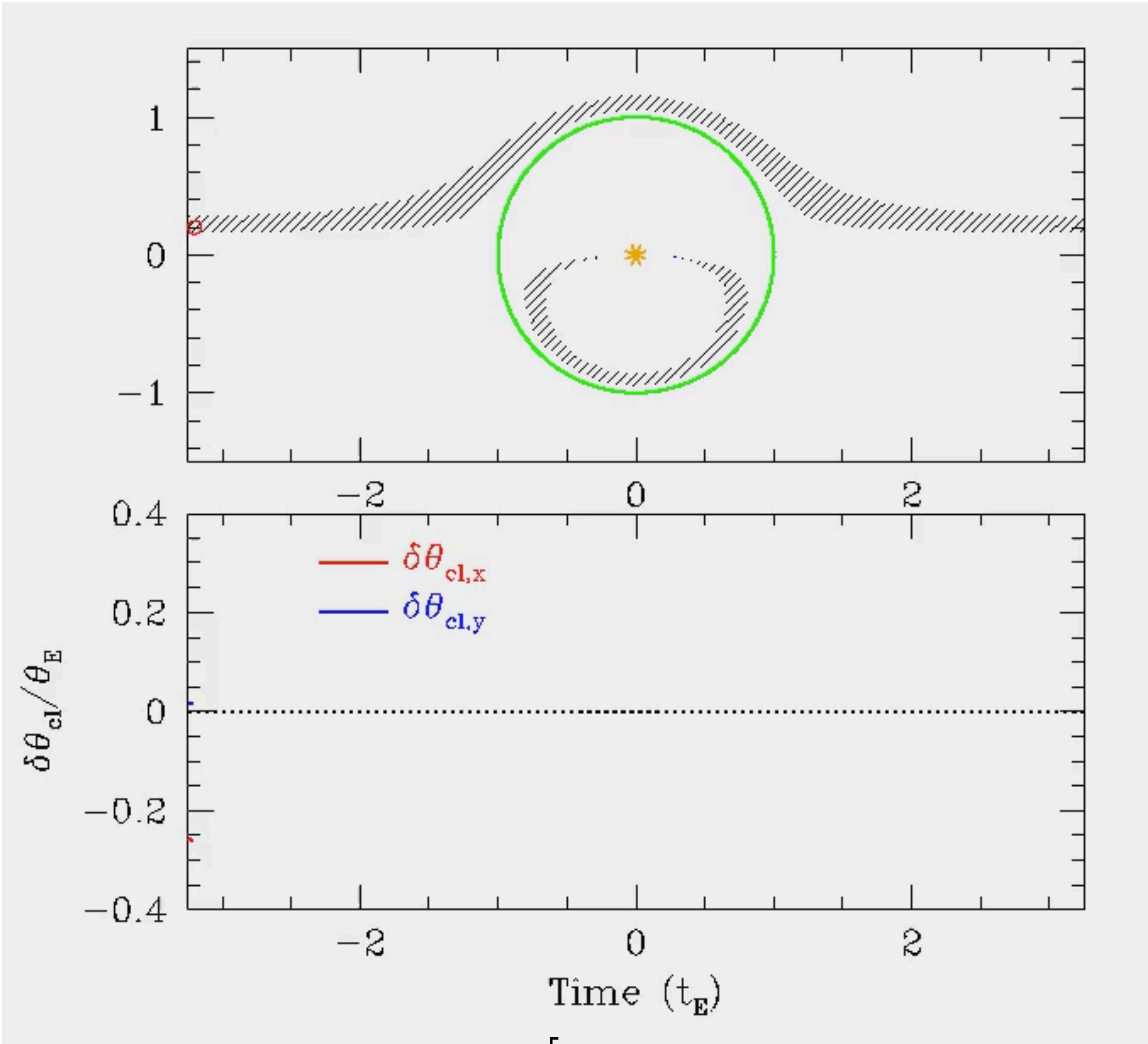


- **Microlensng is the only technique which is capable of detecting isolated BHs.**
- **Traditional photometric microlensing does not give any information on the the mass of the lens.**
- **Astrometric Microlensing breaks the degeneracies.**

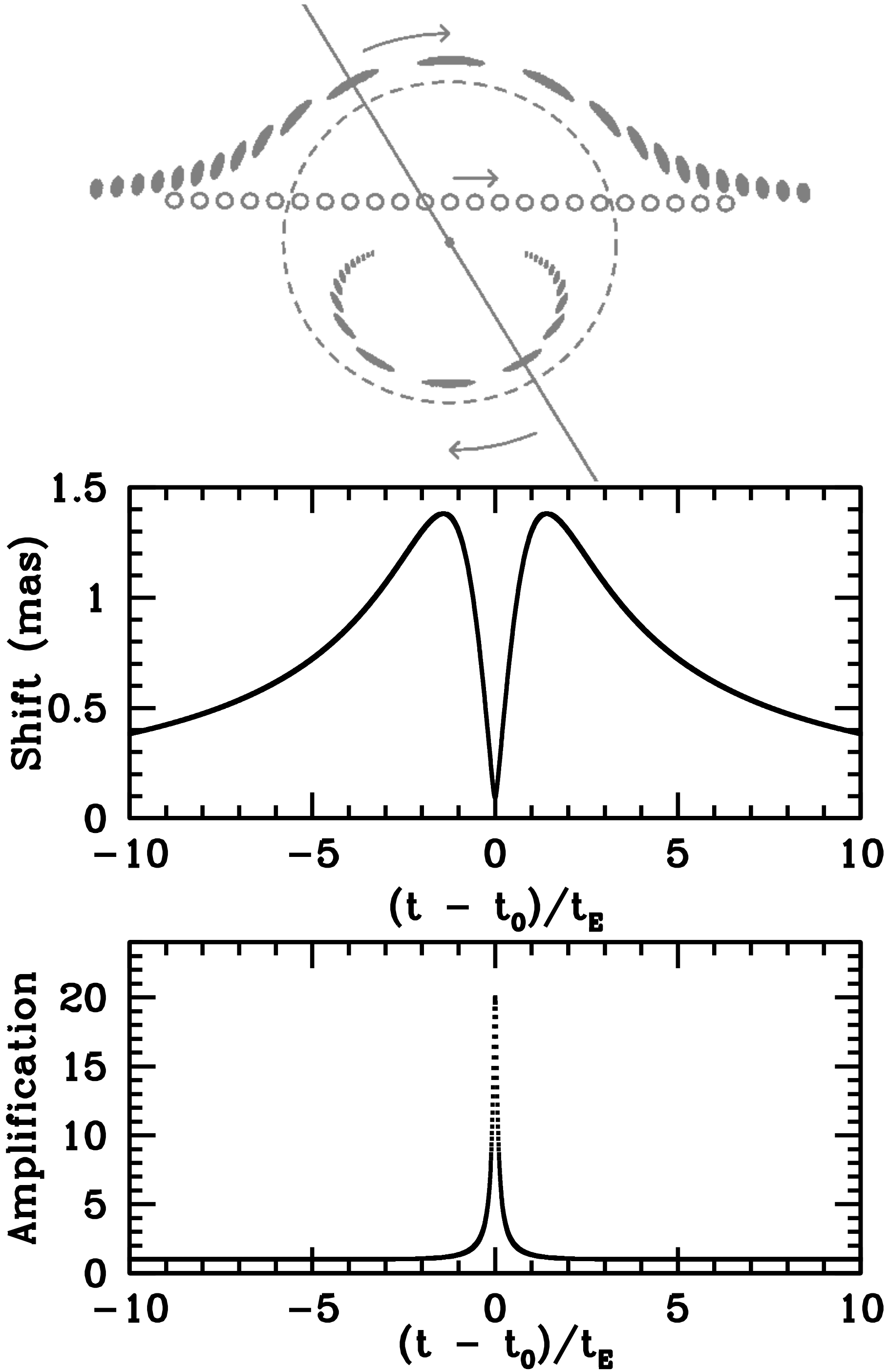
Astrometric microlensing



Astrometric microlensing



Astrometric microlensing



- **Astrometric microlensing gives the size of the Einstein ring, which provides measurements of:**

  the mass,

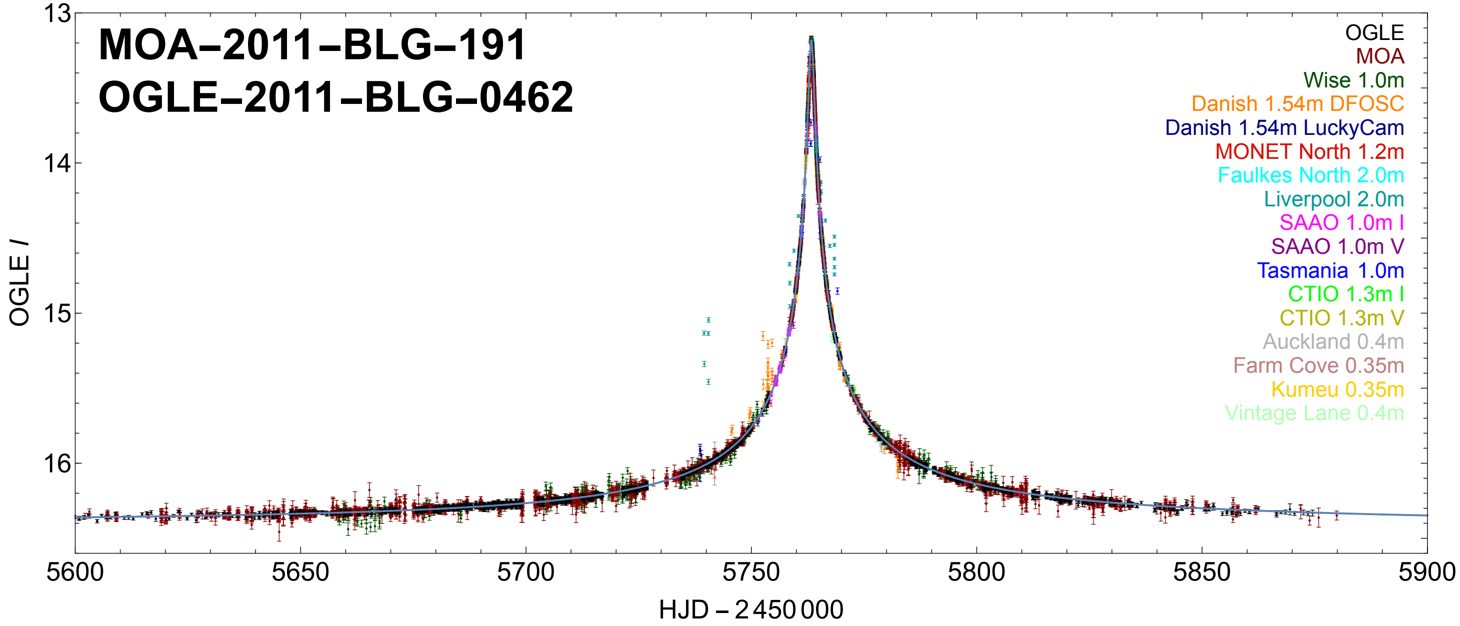
  the distance and

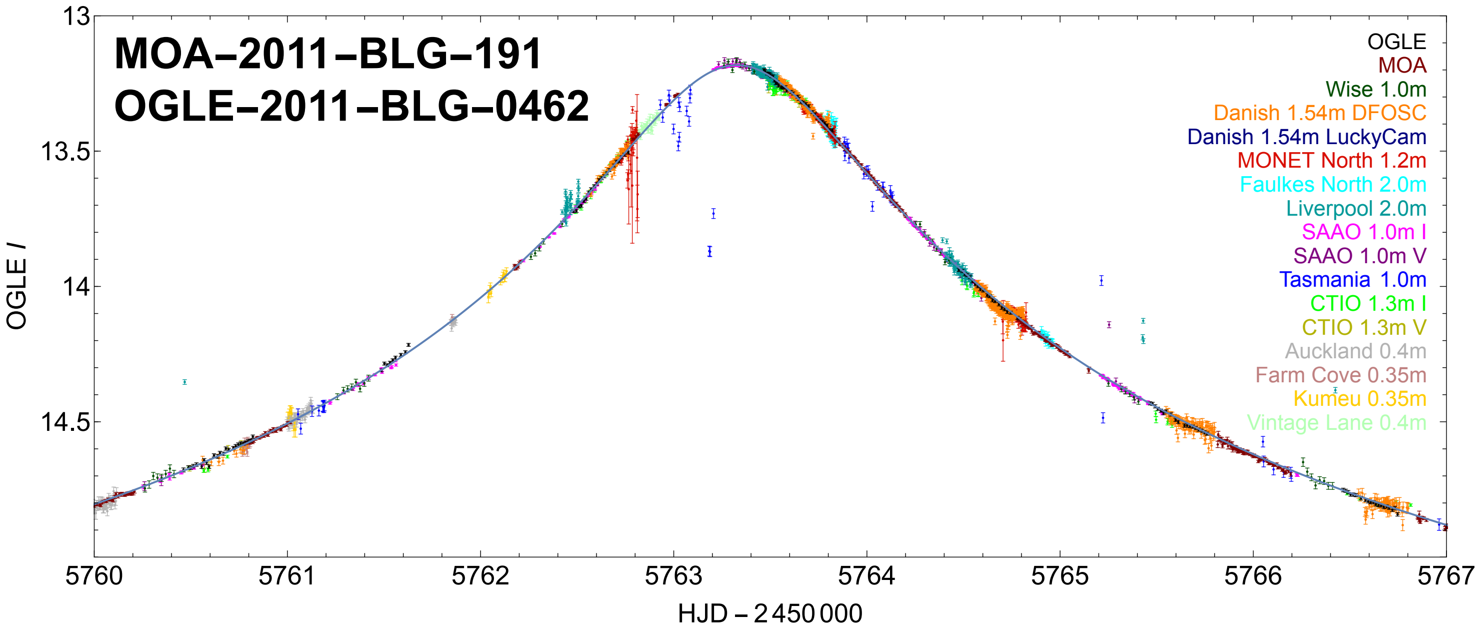
  the velocity

from a single technique.

HST Program

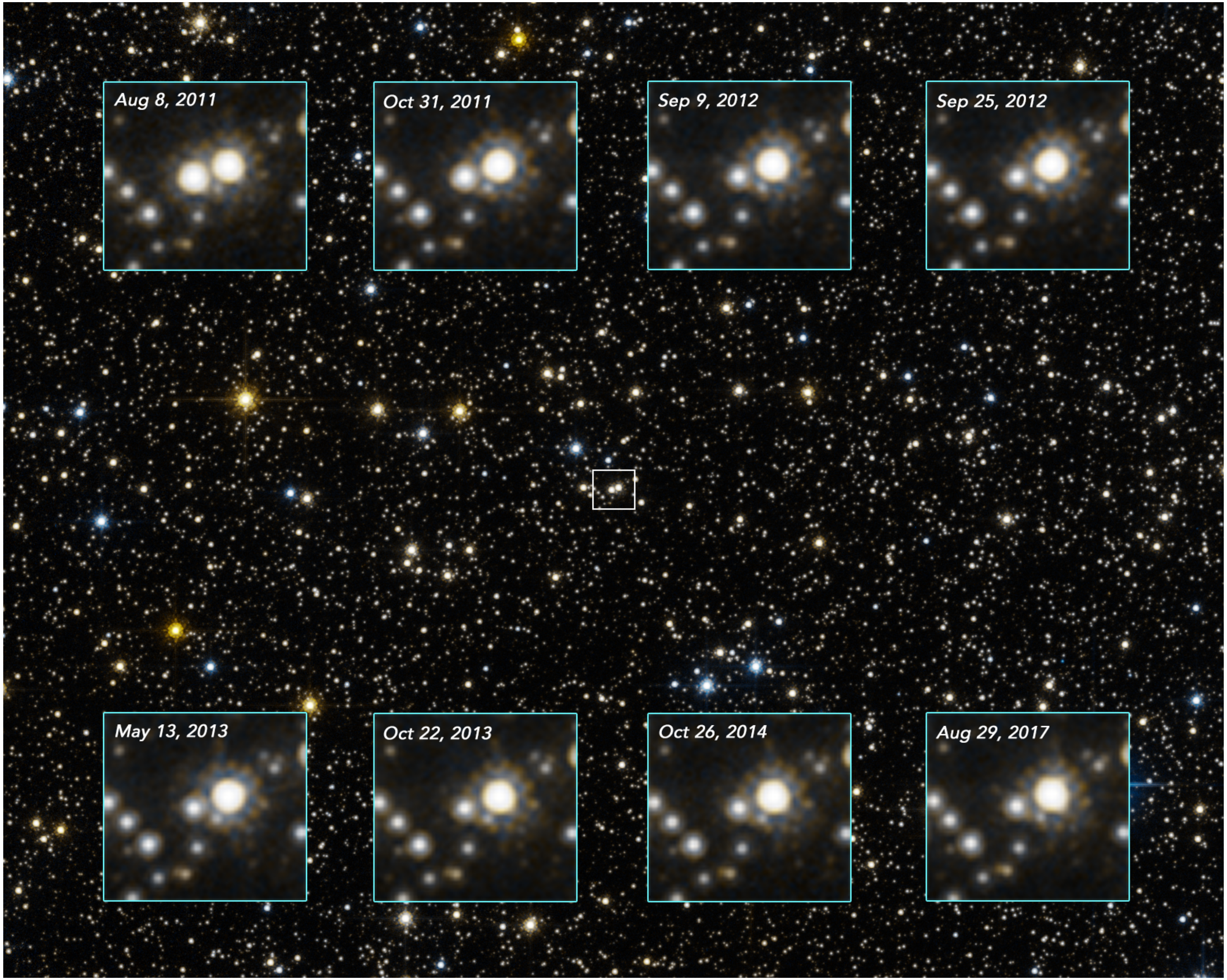
- Microlensing survey programs find thousands of microlensing events per year.
- BH events are expected to be long-duration ($T_E > 200$ days), No blending.
- We have a HST program to observe such events, and measure relativistic deflections.
- Deflections are very small, about 1 to 2 mas. And we need observations over several years.
- Conceptually simple, but observationally tough!



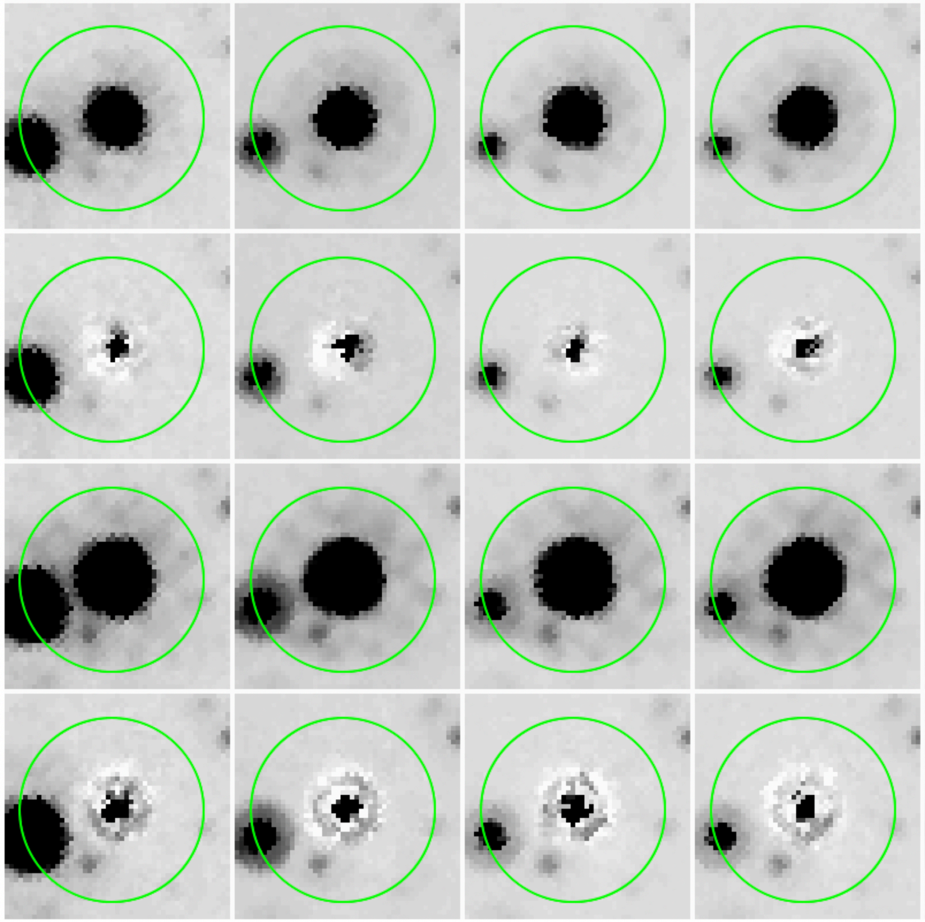


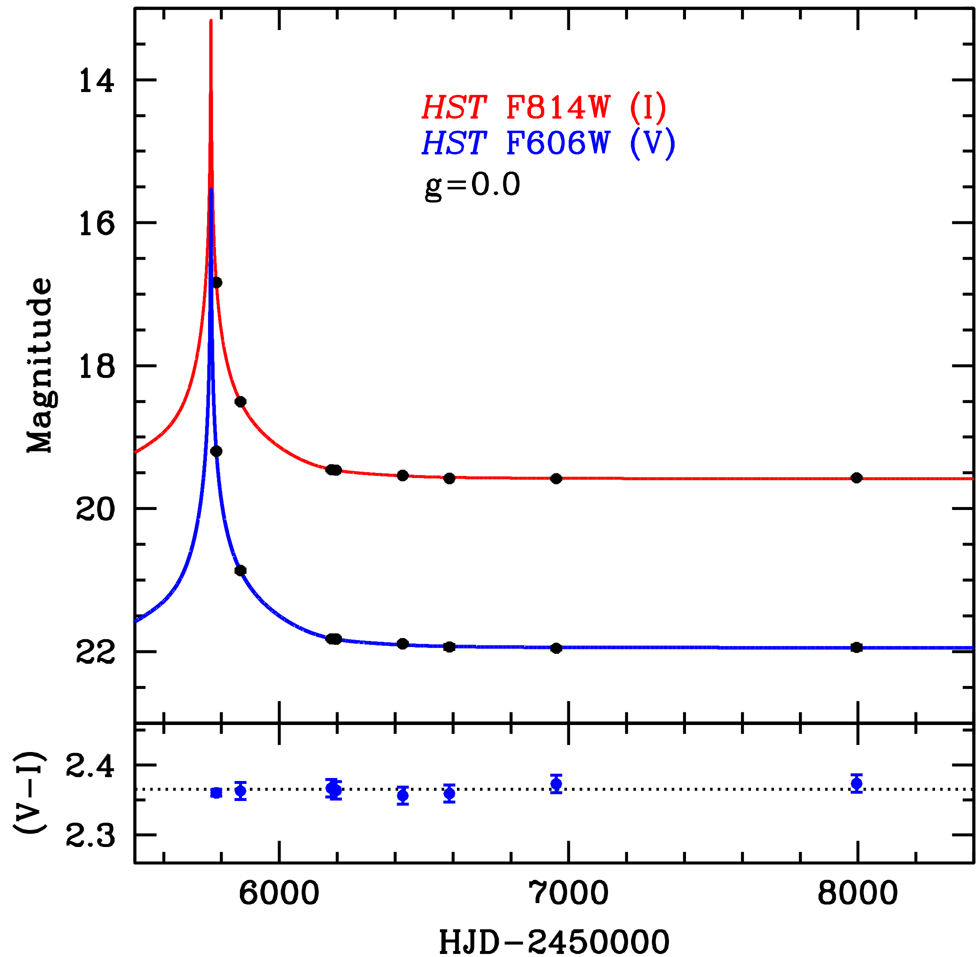
MOA-11-191

- T = 270 days
- Amp=400
- Heavily blended in ground-based data



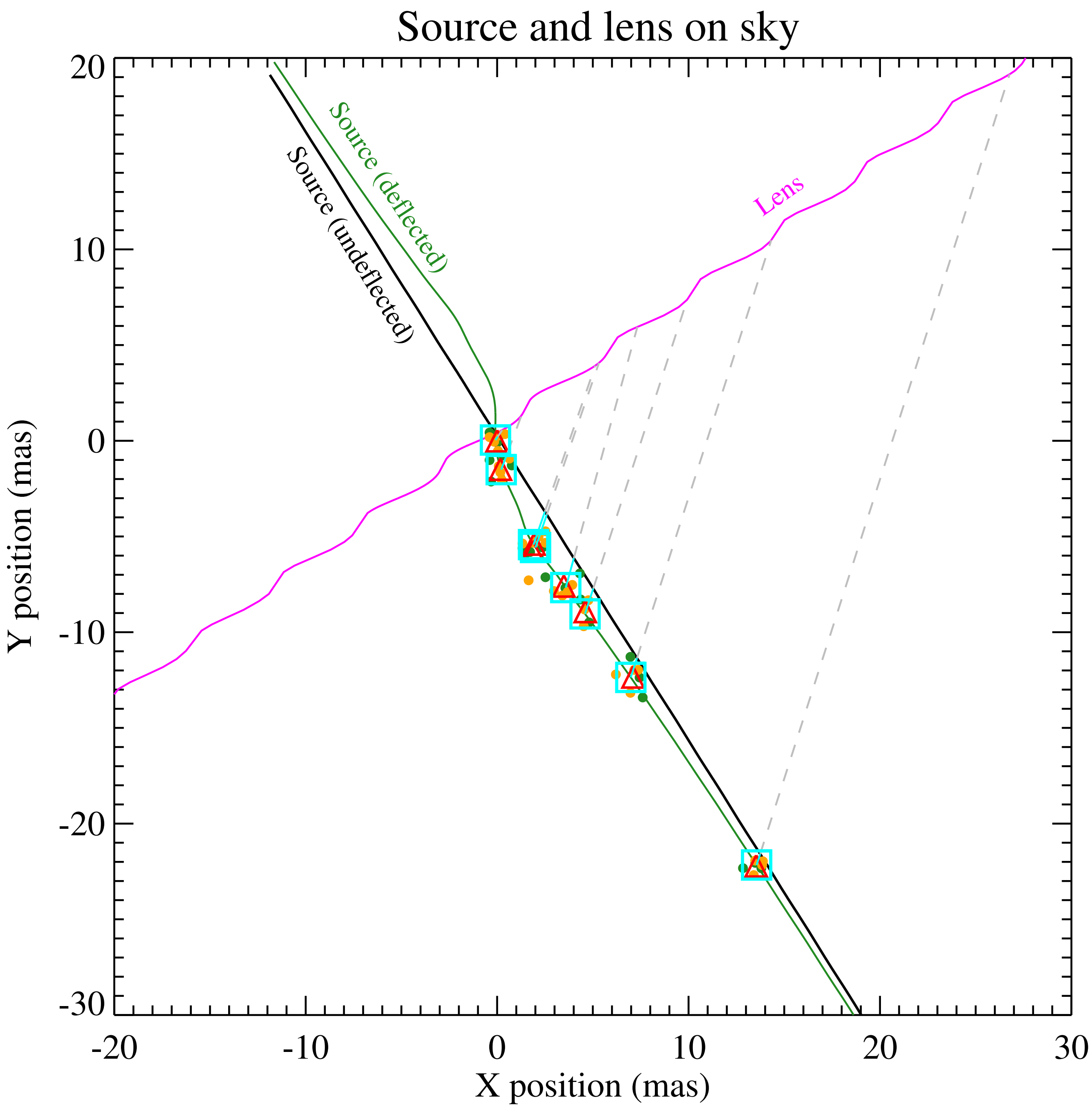
- HST observations showed that the blending in ground-based data is due to a nearby star, ~20 times brighter than the source, 0.4" away from the source.
- Blending is unrelated to the lens or source.





- It’s critical to accurately subtract the bright star, to correctly measure the position of the source.
- Jay Anderson did a superb job in making an extended PSF for this subtraction.

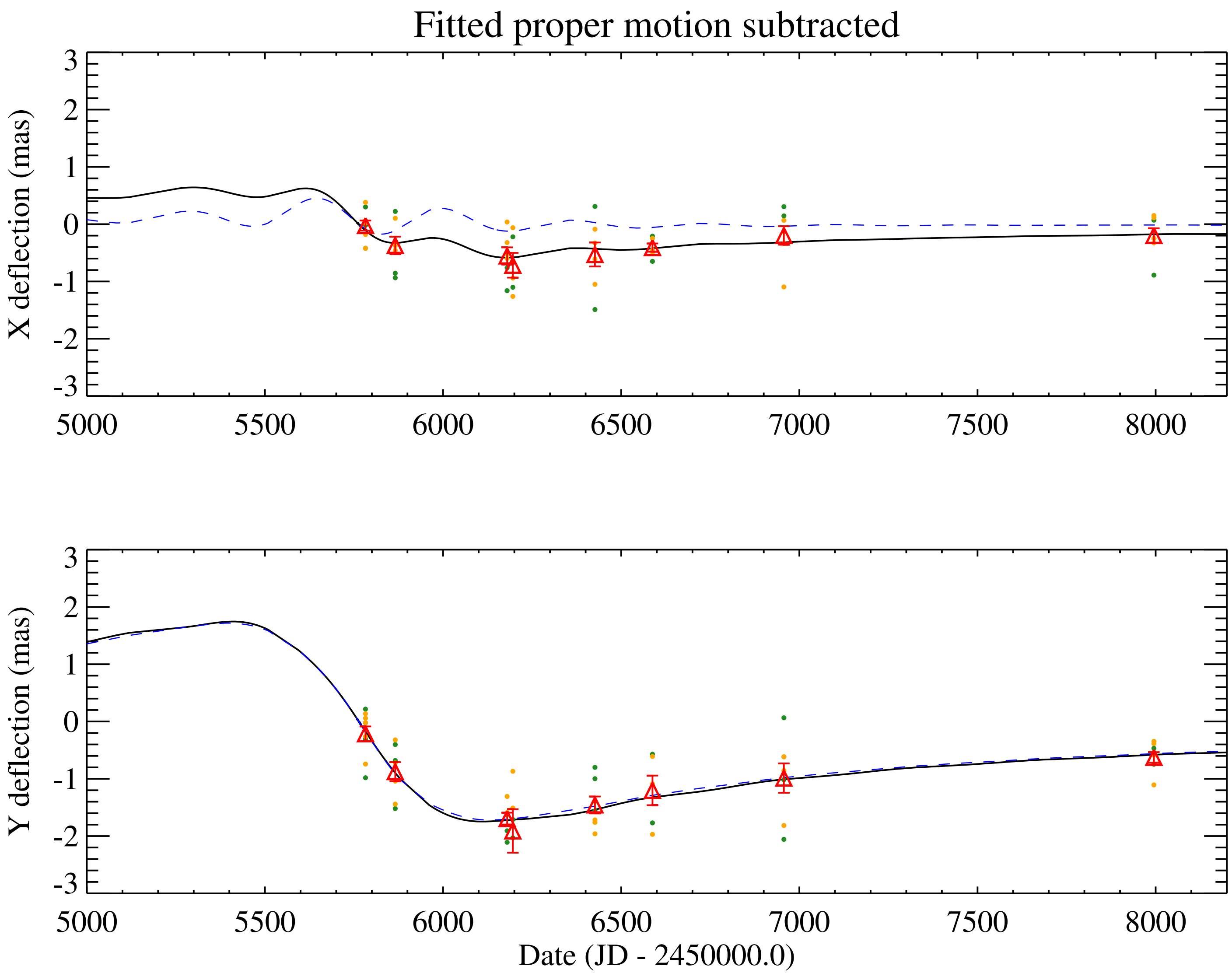
- HST observations were taken in F606W and F814W.
- The HST light curve shows that the light curve is achromatic to within 0.002 magnitudes during the entire duration of six years.



HST observations spanning 6 years enable clear separation of PM and deflection.

Path of the source includes PM and deflection (parallax is negligible).

Path of the lens includes PM and parallax.



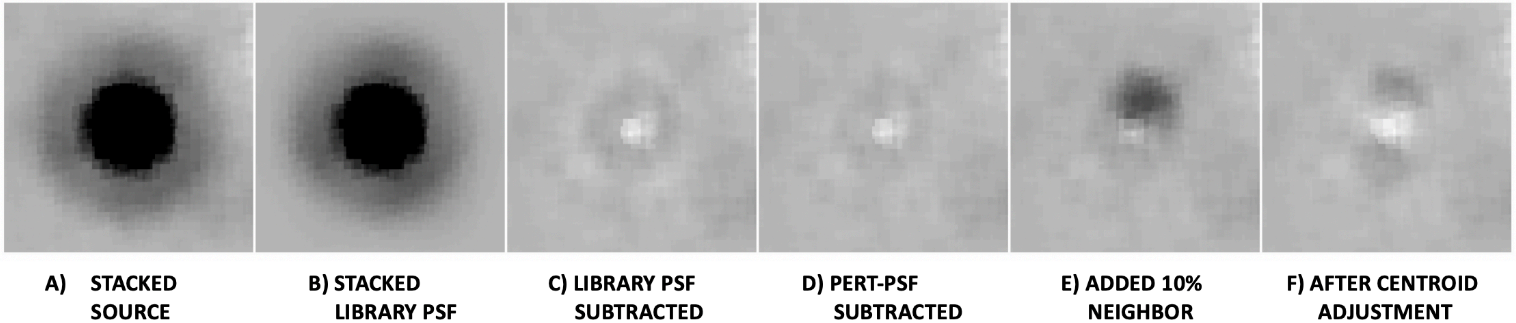
Excellent (combined) model fit to the observed deflections.

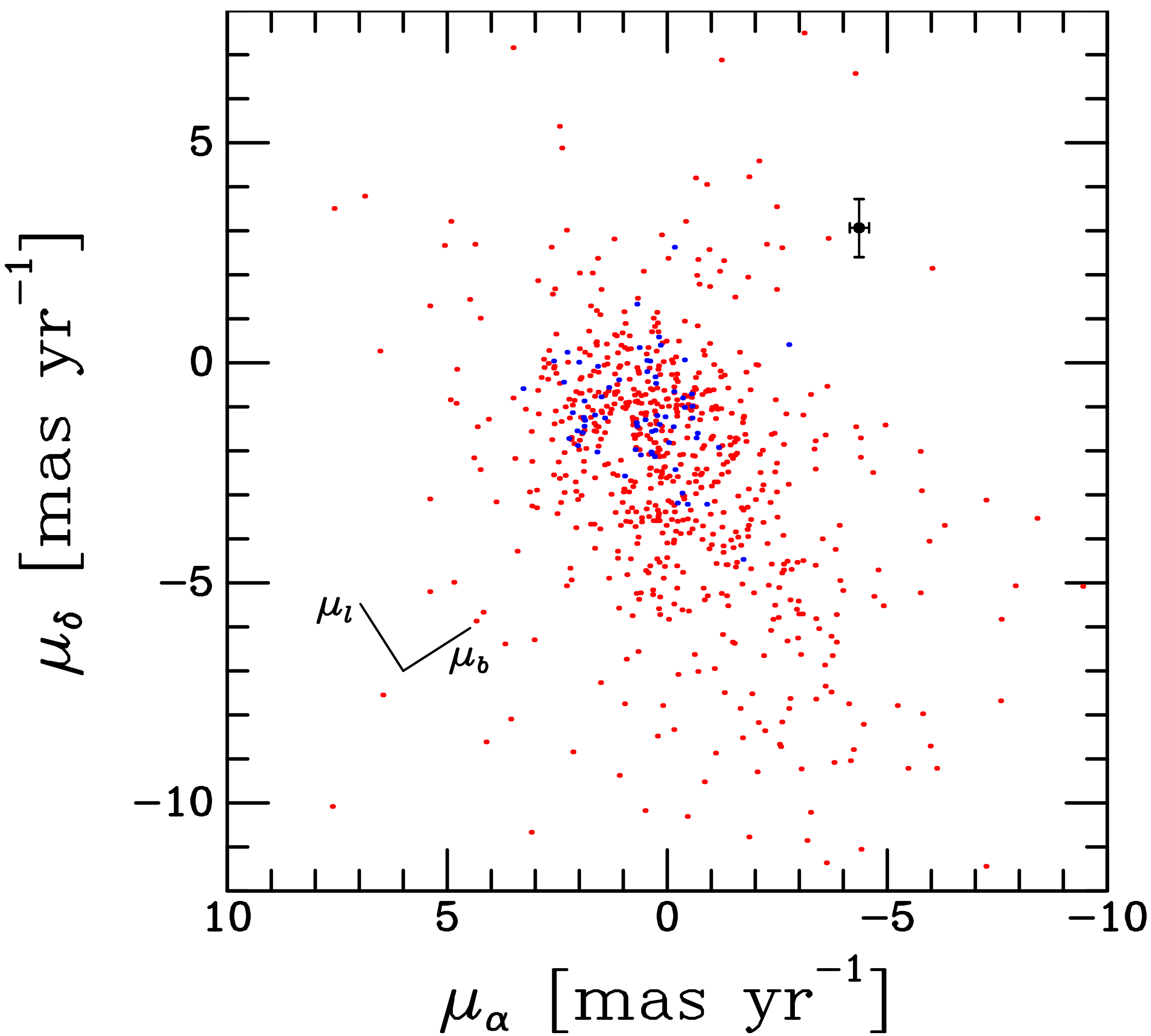
Derived parameters:
Theta_E = 5.18 mas
Parallax (pi_E) = 0.089

PMRA= -2.26 mas/yr
PMDEC=-3.60 mas/yr

Dist=1.58 +/- 0.15 kpc
Mass = 7.1 +/-1.3 M_sun
Transverse vel =45 km/s

(Blue curve is photometric-only fit, which shows that it's important to include astrometry).



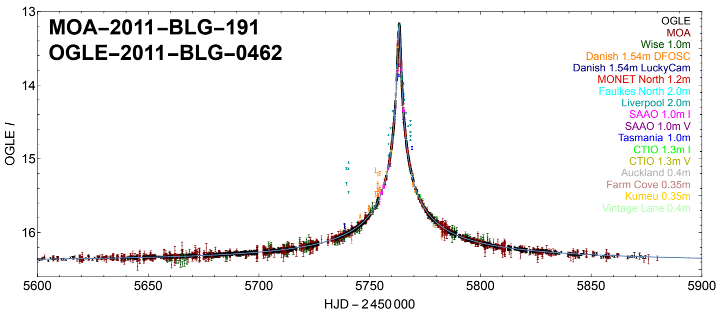


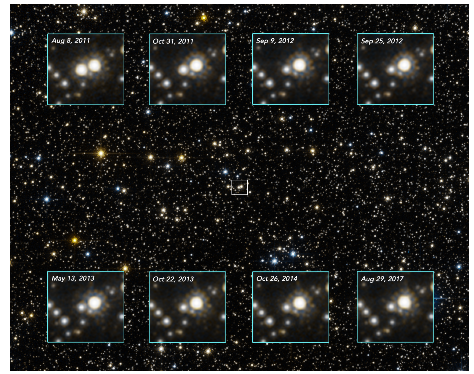
No detection of the lens at the last HST epoch.
The lens cannot be a MS star of mass > 0.2 M_sun.

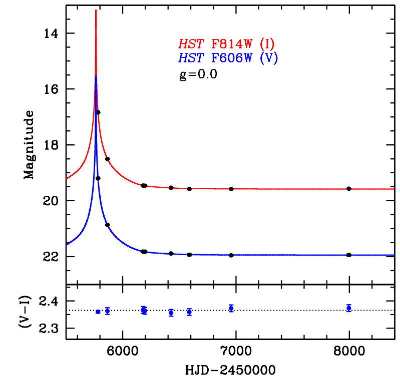
Proper motions of all Gaia stars at distance similar to the BH.

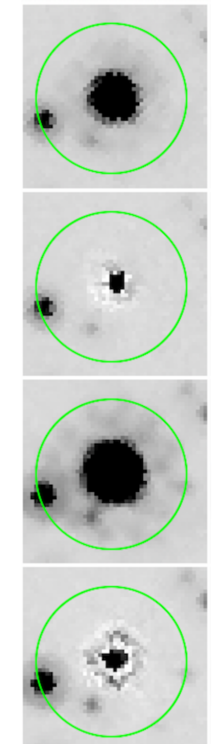
The BH moves at 45 km/s w.r.t. the mean, which suggests it received a modest ‘natal kick’ during the SN explosion.

SUMMARY

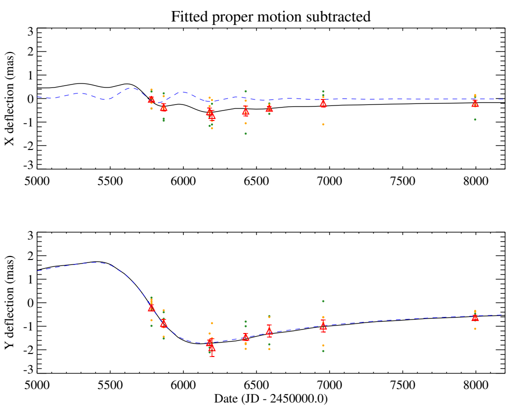


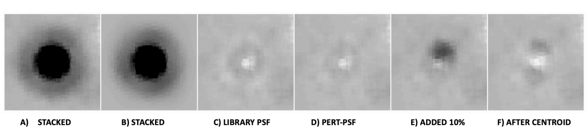






MOA-11-191 is a high-amplification, long-duration microlensing event, which we monitored with HST for 6 years to look for astrometric deflections.



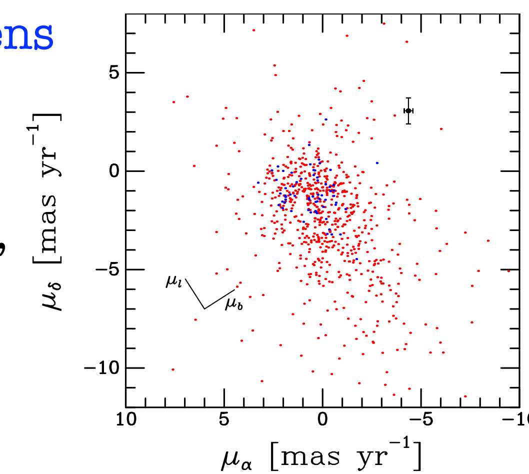


There is a bright star 10 pixels away, and its subtraction was critical for accurate astrometry of the source.

Combination of photometry and astrometry gives the mass of the lens as 7.1 solar mass, and its distance as 1.58 kpc.

Lack of blending and non-detection of the lens after 6 years shows that it's non-luminous, confirming its BH nature.

Its velocity is 45 km/sec w.r.t. the stars in that region, suggesting that it got a natal kick at the time of SN explosion.



This is the first unambiguous detection and mass measurement of an isolated BH by any technique.

After our paper was placed on arXiv, several stories appeared in Science journals, including Nature and Scientific American. Here is one of my favorite pieces (from Michelle Starr, a Science Journalist from Australia): https://www.sciencealert.com/for-the-first-time-a-lone-black-hole-has-been-found-wandering-the-milky-way

“The black hole, they found, has a mass about 7.1 times the mass of the Sun. That would make its event horizon around just 42 kilometers (26 miles) across. Take a moment to marvel at that. Scientists were able to detect an invisible object less than a tenth the length of the Grand Canyon from over 5,000 light-years away by studying the changing light of a more distant star. That's freaking awesome.”

Thank you!!