Study of white dwarfs, neutron stars and black holes through astrometricmicrolensing

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Tests of General Theory of Relativity

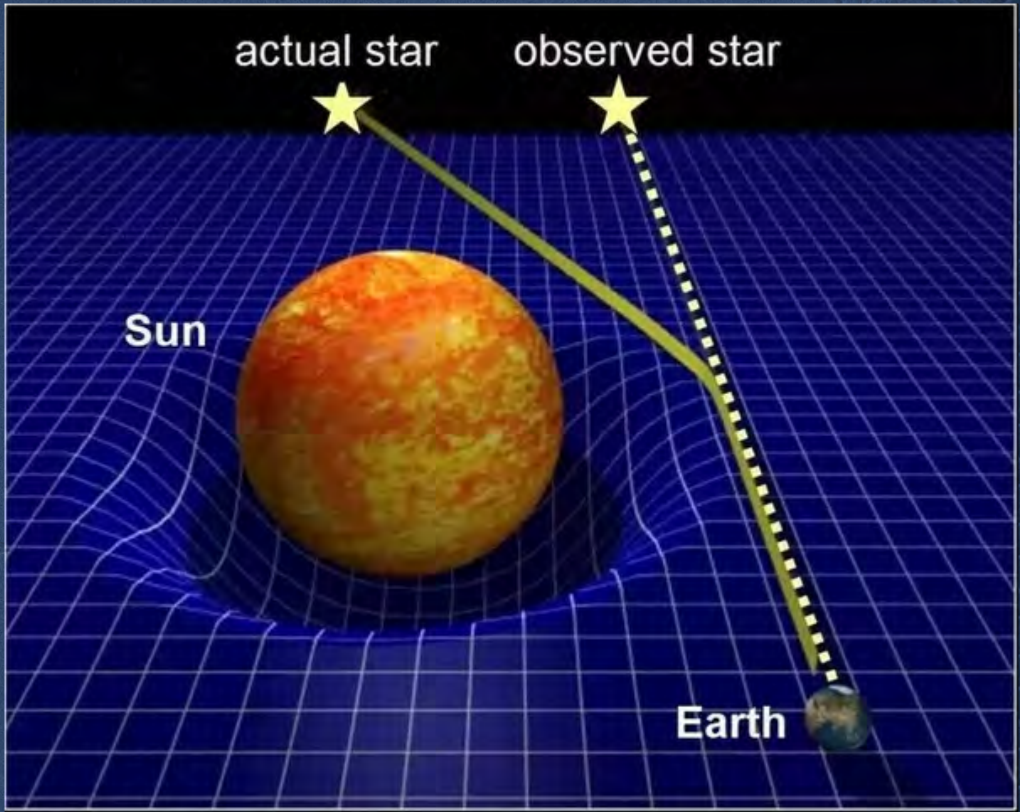
Einstein postulated his General Relativity in 1915, which was a ground-breaking theory. This clearly needed experimental verification.

One of the crucial tests for GR was the curvature test: a massive body causes warping of space leading to bending of light-rays.

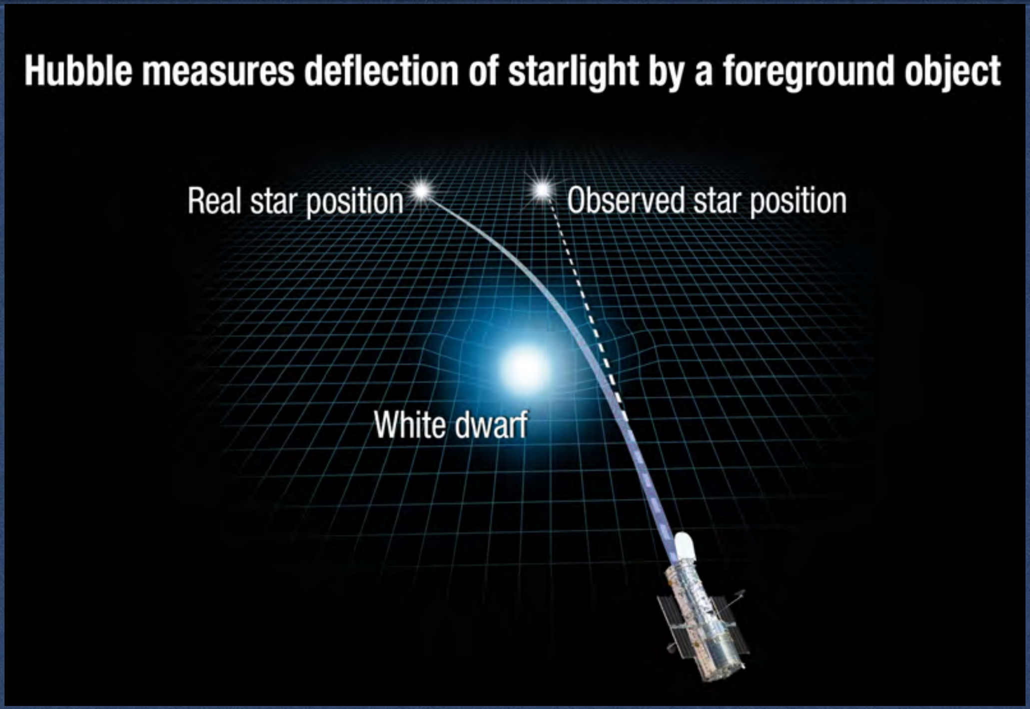
………………..

A ray of light going past the sun will be deflected by 1.75 arcsec.

- First measurement of this deflection during 1919 solar eclipse by a team led by Eddington: 1.98+/—0.18 arcsec.
- This provided the first clear confirmation of general relativity.



Gravitational Bending of Light

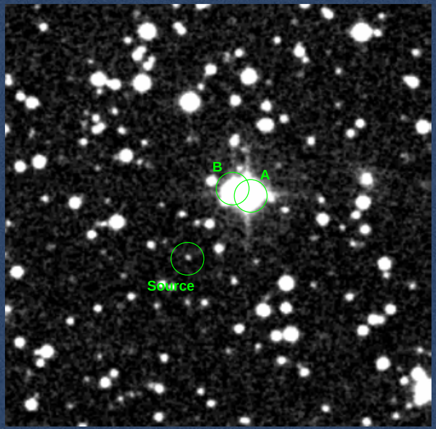


- Measurement of such deflection by a star outside the solar system would provide a direct method to measure the mass of the star.
- However, the expected deflections are tiny, about 1000 times smaller than what Eddington measured.
- So no such deflection caused by a star outside the solar system (astrometric microlensing) had been observed until now.
- Hubble's high angular resolution capability allows us to observe such a phenomenon.

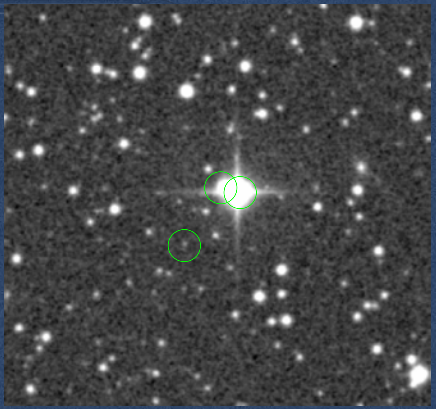
Search for Microlensing Events by Stars

- Nearby and higher proper-motion stars are the most interesting because the expected deflection is large, and measurable with HST.

- Input catalog: ~5000 high-proper motion stars from Luyten's Catalog, with improved coordinates from Lepine and Shara (2005) and Bakos, Sahu and Nemeth (2002).



1992



1995

Importance of White Dwarf Mass Determination

- All stars with mass less than 8 solar mass end their lives as white dwarfs.

- Existence of a mass-radius relation is a key prediction of the white dwarf theory; however, this lacks firm observational support.

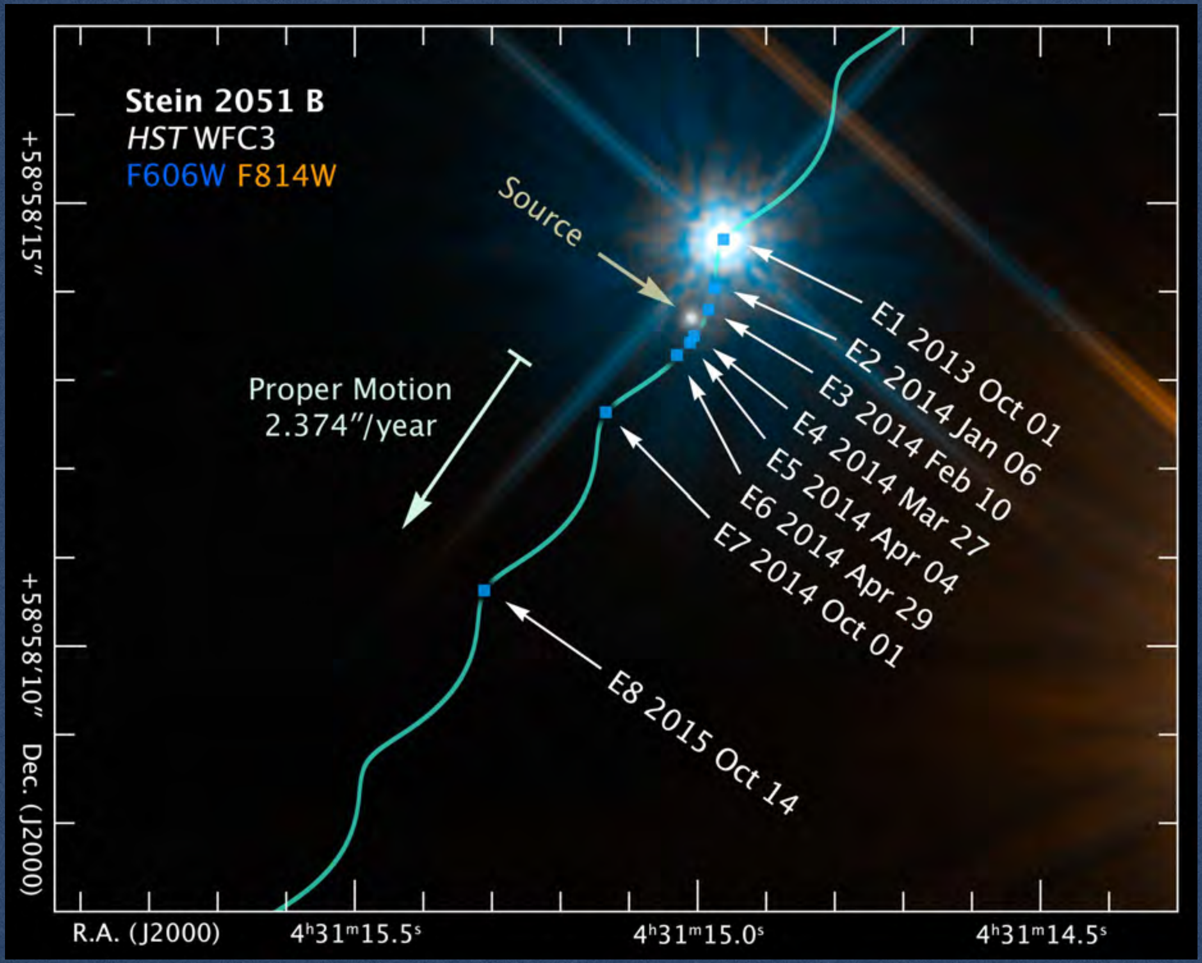
- Until now, all (~3) masses for white dwarfs have come from binaries.

- Stein 2051B is the 6th nearest white dwarf (D~ 17 light yr).

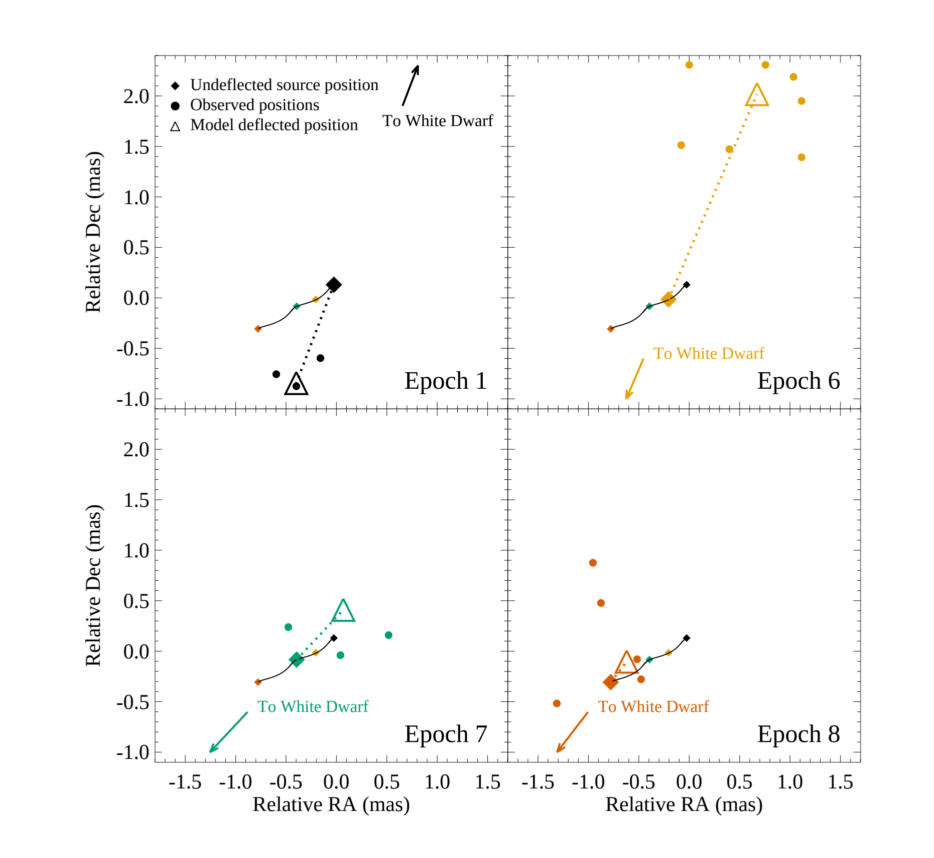
- Stein 2051B is a binary, but the companion is >55 AU away, so the binary is unlikely to have affected the evolution. Mass of Stein 2051B has been a matter of debate.

- So Stein 2051B's mass determined through microlensing will provide a crucial test for the theory of white dwarfs, and can also be used to determine its age.

Motion of STEIN 2051B



Observed deflections by STEIN 2051B

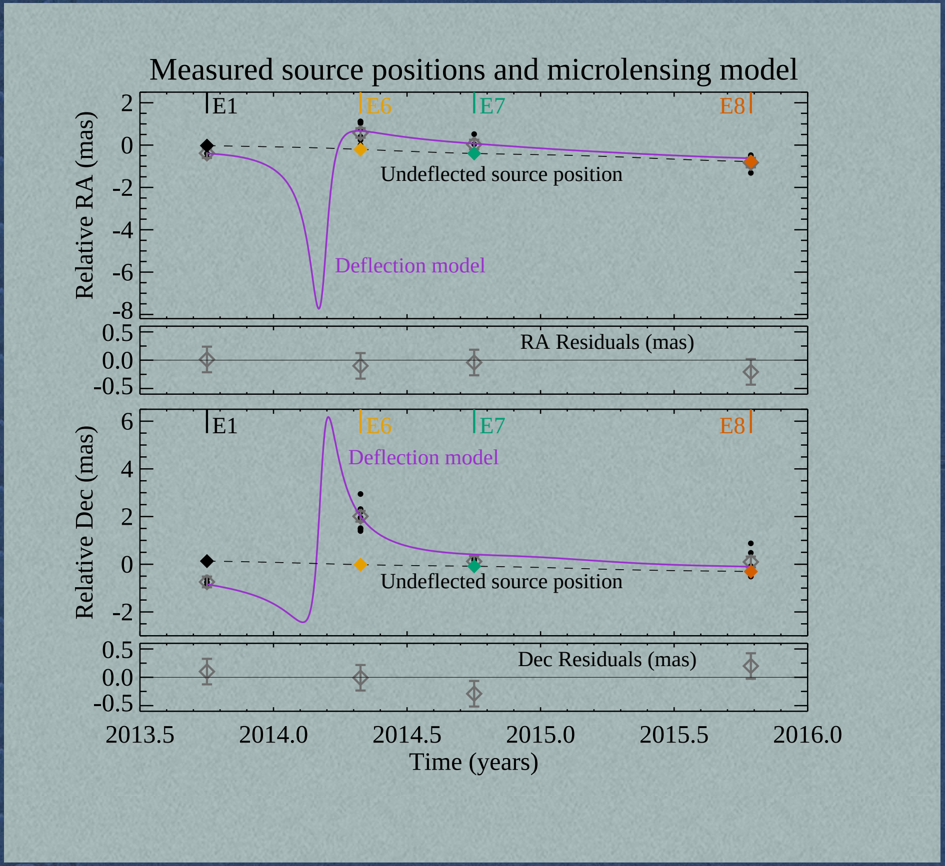


Deflections at the four observed epochs.

Deflection is:
(i) away from the WD, and
(ii) inversely proportional to the distance beween the WD and the source.

The source shows a small proper motion and parallax with respect to the 26 reference stars.

Time Evolution of the Observed Deflection



Time-evolution of the deflection is consistent with the model.

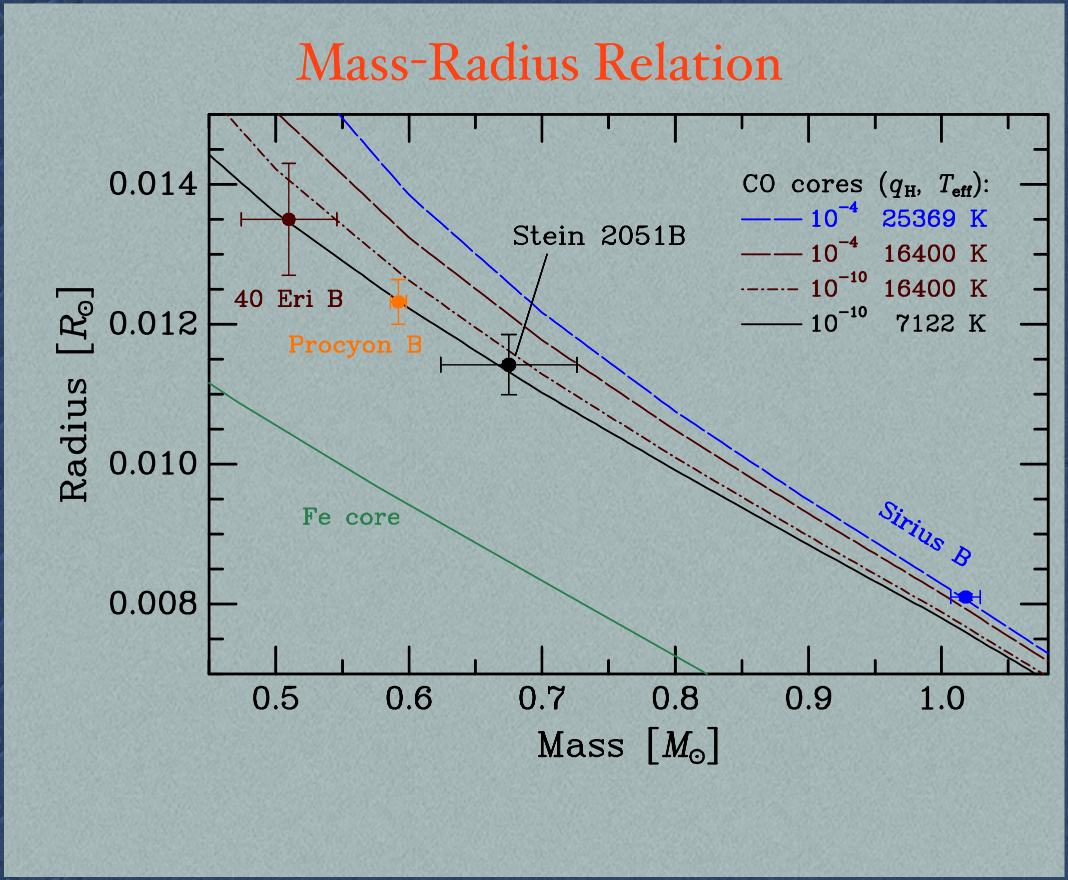
All other 26 stars in the image show no such motion.

This suggests that

$\Theta_{E} = 31.3 \pm 0.5$ mas

Mass = 0.675 +/− 0.051 solar mass.

Results



Mass = 0.675 +/- 0.051 $M_\odot$.

This provides a confirmation of the WD evolutionary theory.

White Dwarf Theory by S. Chandrasekhar

In 1930, 19-year old Subrahmanyan Chandrasekhar calculated the theoretical structure of white dwarfs taking into account the relativistic effects of degenerate matter. His calculations showed that the radius should decrease as the mass increases, and there is an upper limit to the mass (now known as Chandrasekhar limit). This theory ultimately led to his 1983 Nobel prize.

Eddington thought this to be a strange result and publicly ridiculed Chandrasekhar during the meeting: "..there should be a law of nature to prevent a star from behaving in this absurd way".

As astronomers found more examples of white dwarfs, it became clear that Chandrasekhar's model worked. However, most are binaries, and Stein 2051B seemed to be an exception. Its estimated mass would suggest a strange composition (iron core) if Chandrasekhar's theory is correct.

Our results confirmed that the mass is exactly consistent with theoretical calculations.

We used the same experiment that Eddington used to confirm general relativity!

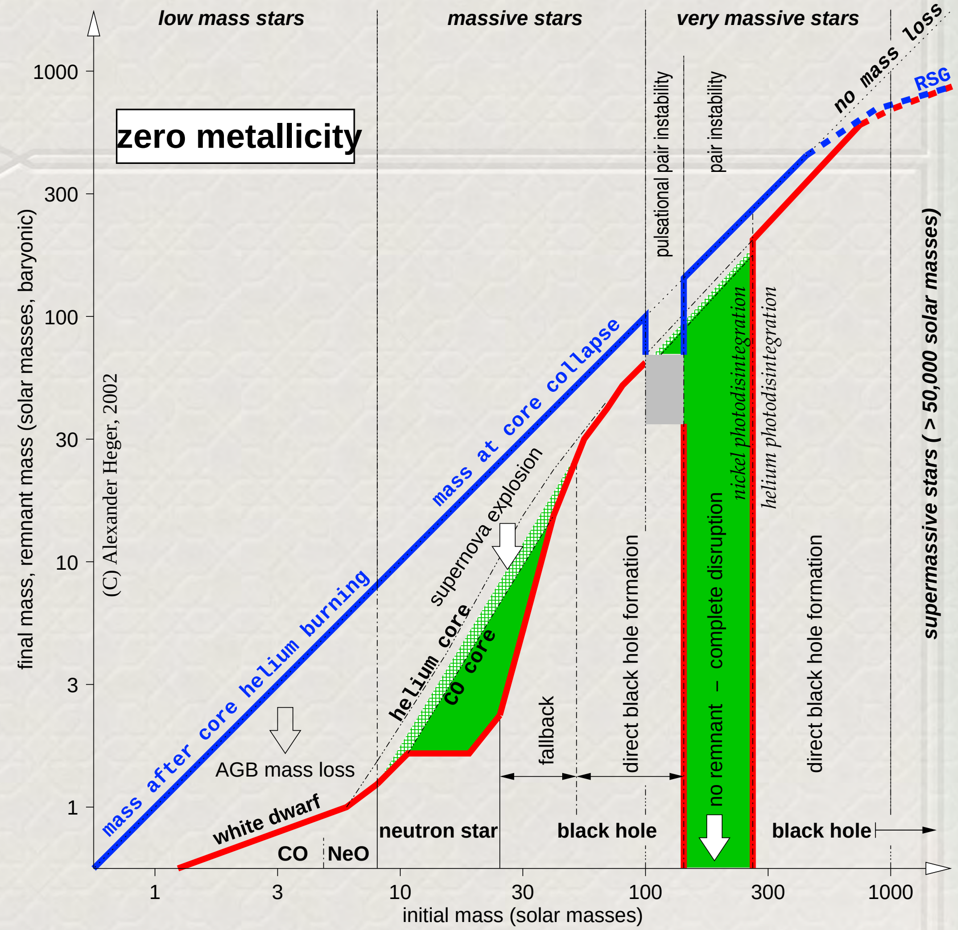
As Forbes put it:
It is perhaps poetic justice that Chandrasekhar's model has been vindicated by the very experiment Eddington so famously first used.

Summary

- Stein 2051B passed close to an 18th mag background star in 2014 causing astrometric microlensing.
- The event was observed with HST at 8 epochs to measure the astrometric deflections.
- This is the very first astrometric deflection measurement of a Milky Way source beyond solar system.
- This is the first mass measurement through astrometric microlensing, of an effectively-isolated WD.

Isolated Stellar Mass Black Holes

- **Stars with M > 20 M⊙ 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".**
- **Yet, an isolated BH has never been unambiguously detected.**
- **Microlensing is the only method capable of detecting solitary BHs**



Initial-Final Mass Relation (Heger, 2010)

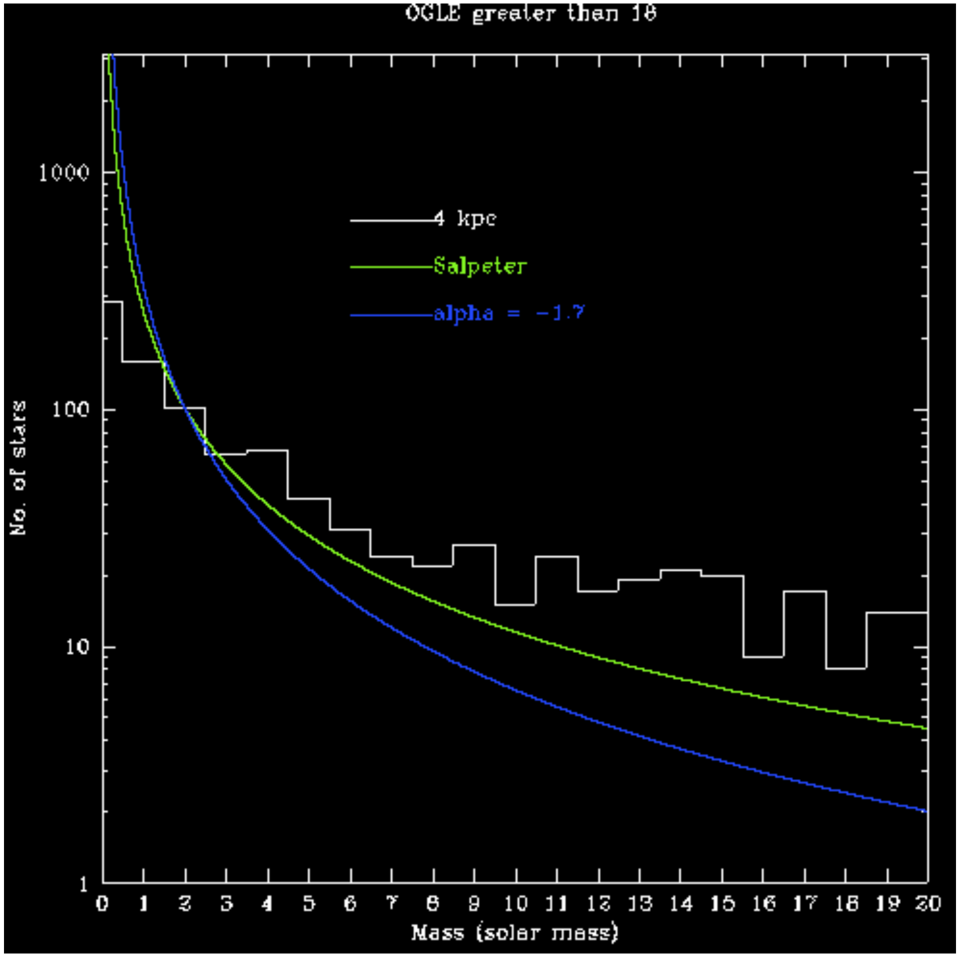
Mass discrepancy of stellar remnants

- Masses of BHs in binaries in our Galaxy: ~8 +/- 1$M_\odot$
- Theoretical Models for BH masses: ~3 to 20 $M_\odot$
- BHs detected by LIGO have masses 10-35 $M_\odot$

- Observed BH masses have their own biases. Mass determination of a few isolated BHs will provide important insights.

- We have 2 HST programs to provide an unbiased mass and velocity distribution for isolated NSs and BHs, through microlensing.

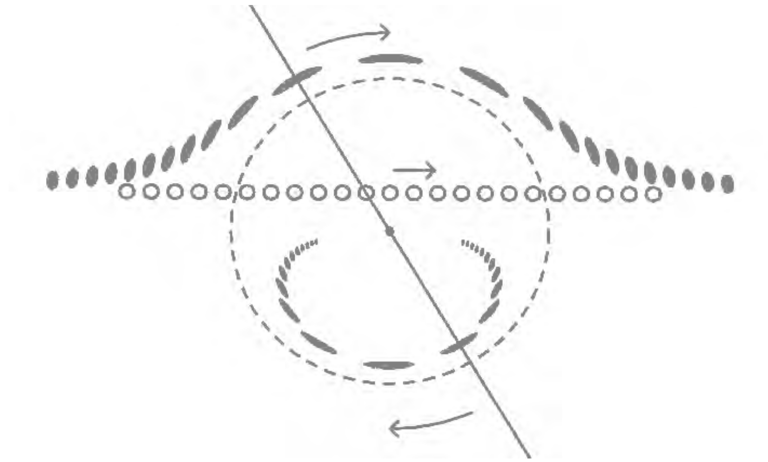
Stellar Mass Black Holes and Microlensing



MOA and OGLE collaborations have detected ~20,000 microlensing events.

Some events must be due to isolated neutron stars and stellar-mass black holes.

Stellar Mass Black Holes and Microlensing



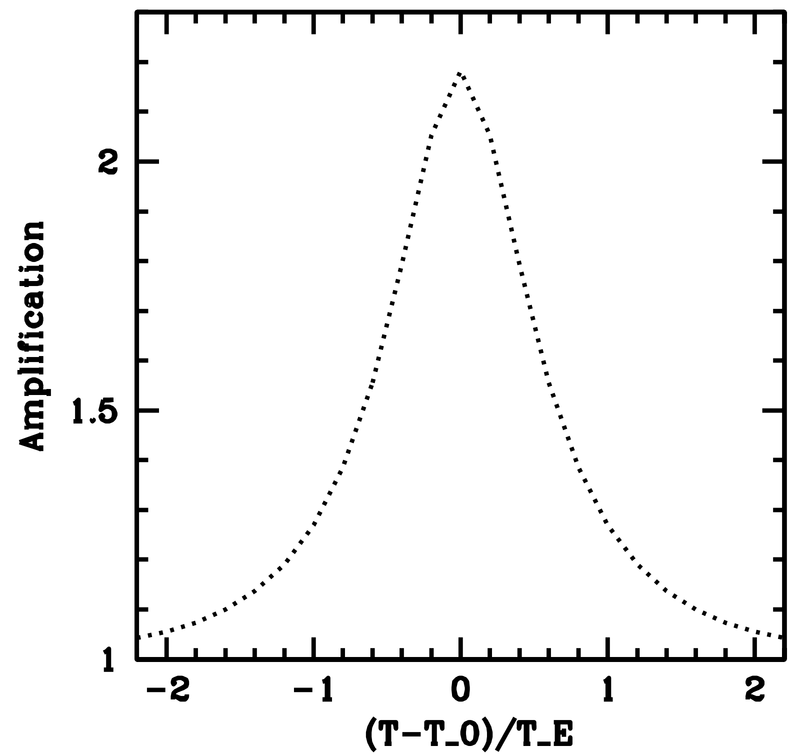
From Light curve:

$$M_{lens} = (T_E\ V\ C)^2\ \mathbf{D_S} / (4G\ \mathbf{D_L}\ D_{LS})$$

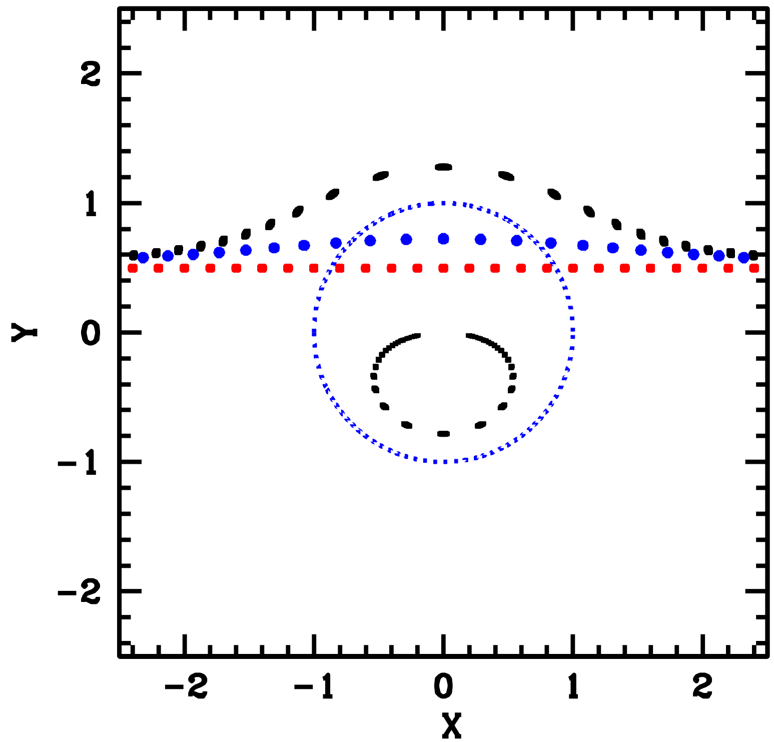
Long-duration events, with no light from the lens, have been claimed to be due to Black Holes.

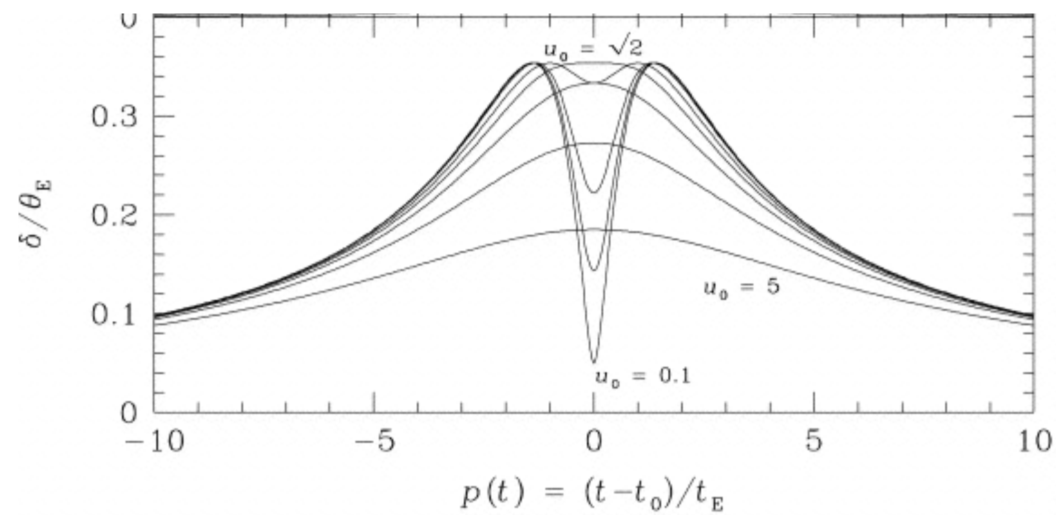
M depends on 4 parameters (T_E, D_L, D_S, V). Photometry provides only 1 (T_E)!

So the mass estimates from timescales are statistical. Long-durations events can also be due to slow-moving, low-mass objects.



Astrometric Microlensing

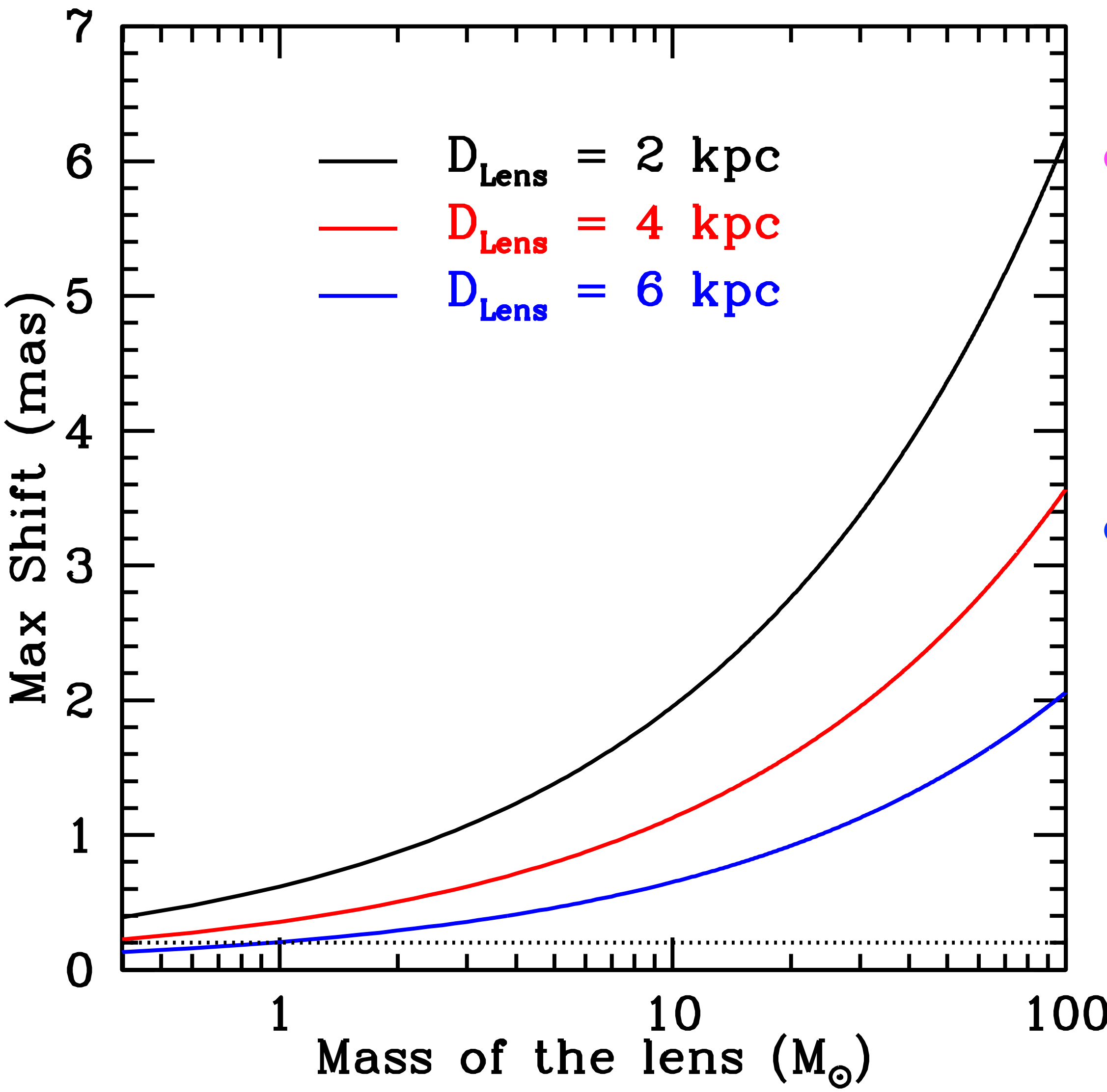




- Microlensing causes an astrometric shift in the position of the source.

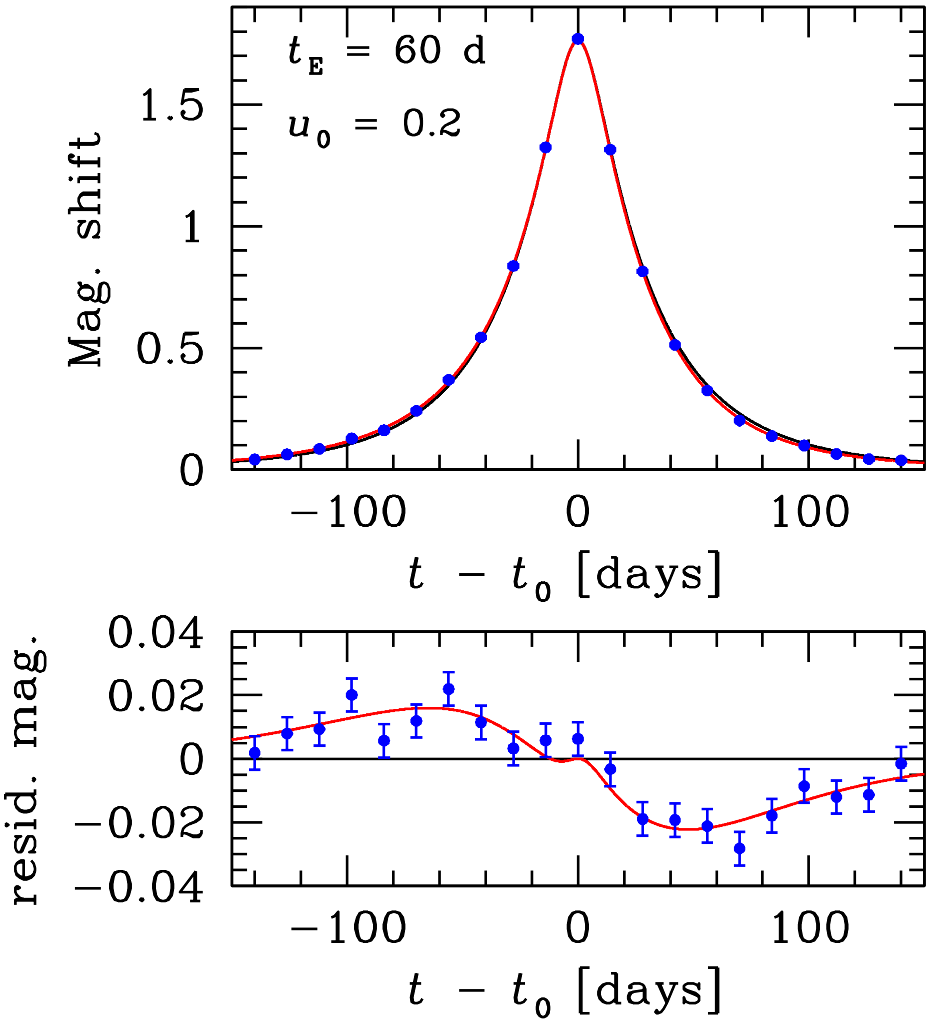
$$\Theta_E = R_E/D_L = [(4GM/C^2)\, D_{LS}/(D_L\, D_S)]^{0.5}$$

- Astrometric shift provides a measure of Θ_E, and hence the mass as a function of the distances.



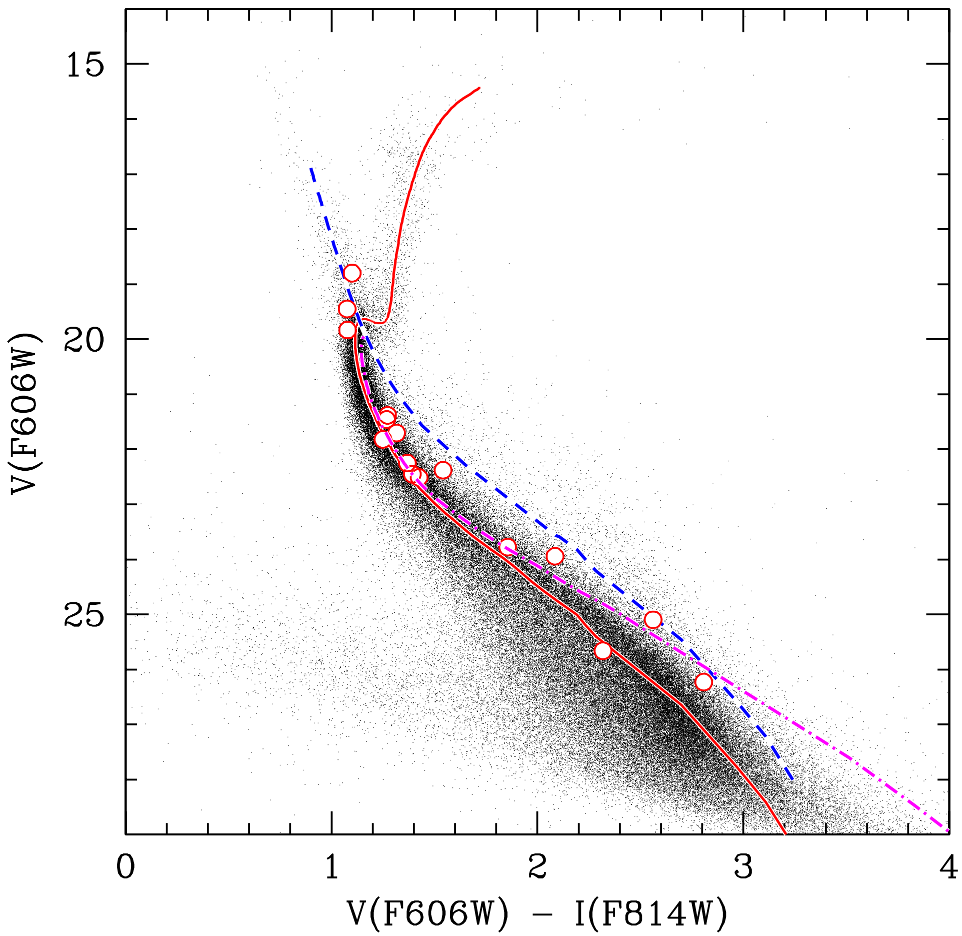
- However, astrometric shifts caused by BH lenses are a few mas.
- HST has routinely measured such astrometric deflections.

Distance to the Lens



- Earth's motion around the Sun introduces a distortion on the microlensing light curve.
- Such "parallax" measurements provide an estimate of the distance to the lens.
- Ground-based follow-up observations can be used for parallax measurements.

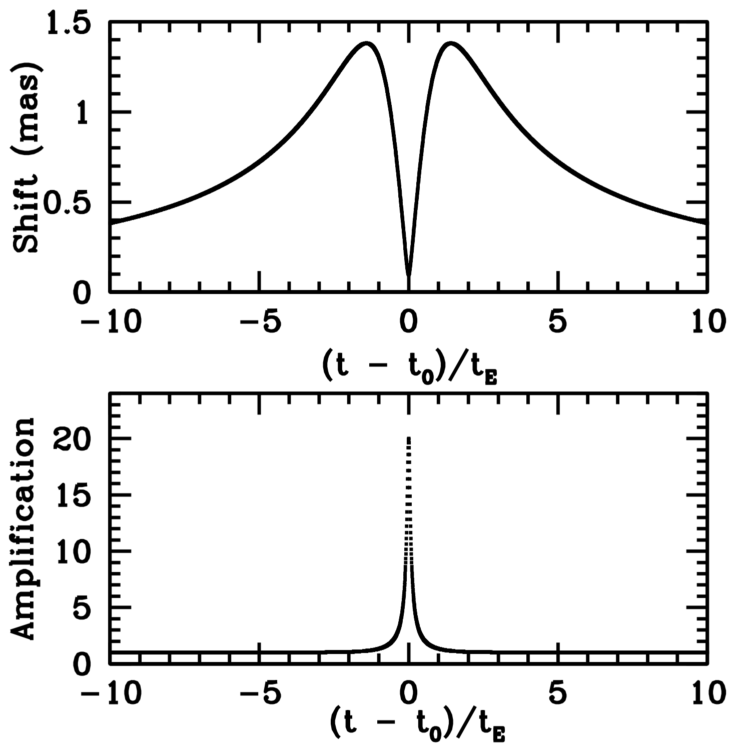
Distance to the Source

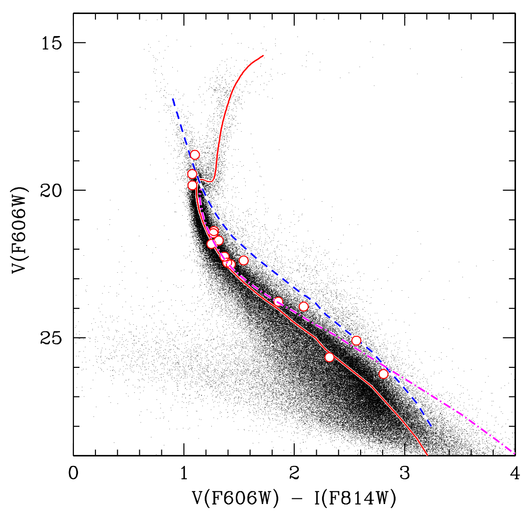


Sahu et al. 2006, Nature, 443, 534

- For microlensing events observed towards the Galactic bulge, >95% of the sources lie within the bulge.
- The observed CMD is often useful in confirming that the source is indeed in the bulge.
- Spectroscopic observations can also be used for spectral type/distance measurements.

Physical parameters from astrometric microlensing





$\Theta_E = [(4GM/C^2)\, D_{LS}/(D_L\, D_S)]^{0.5}$

- δ, A $\Rightarrow$ Θ_E
- Parallax signal $\Rightarrow$ D_L
- CMD $\Rightarrow$ D_S

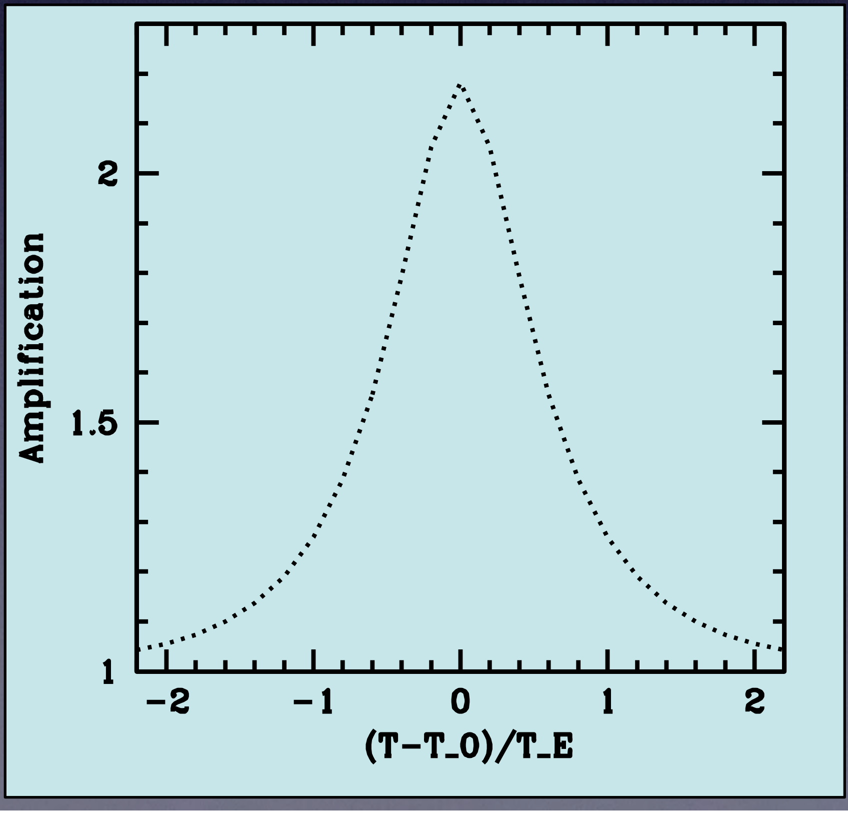
➡Mass of the Lens

- $T_E \Rightarrow V_L$
- Unequivocal detection of BHs with measurements of:
  - the mass,
  - the distance and
  - the velocity

from a single technique.

The Method

- Observe microlensing events with
  - long-duration (T_E>100 days)
  - No blending
- Detected before the peak
- Measure photometric and astrometric deflections
- Conceptually simple, but observationally tough!



HST Programs

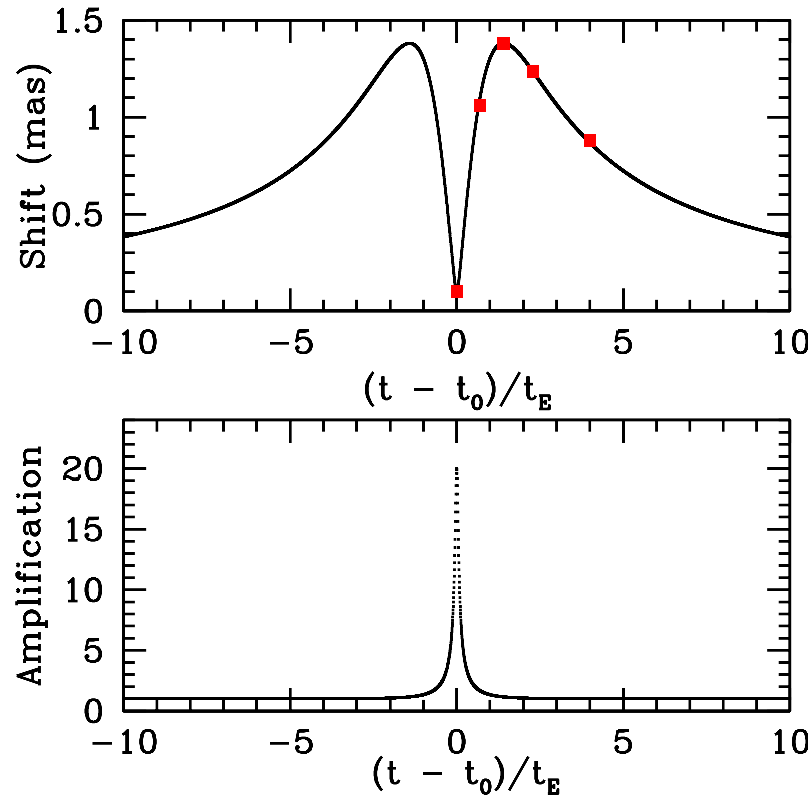
I. Follow-up observations of ongoing, long-duration, microlensing events

(GO-11707, PI: Sahu)

Observe ongoing, long-duration (t_E>100 days) events with WFC3/HST , and measure:

- *i. Blending (from V & I observations)*
- *ii. Parallax motion (millimag)*
- *iii.Distance to the source*
- *iv. Astrometric motion (milliarcsec)*

Measure the mass of the potential BH, along with its distance and velocity.



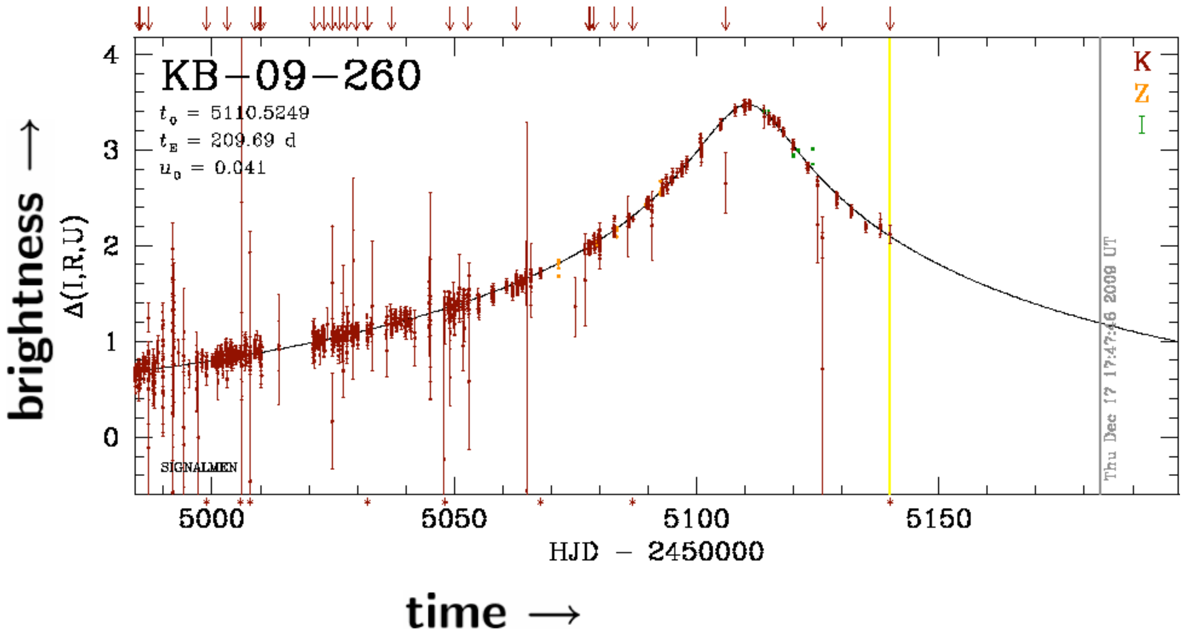
HST Observations of MOA 2009-BLG-260

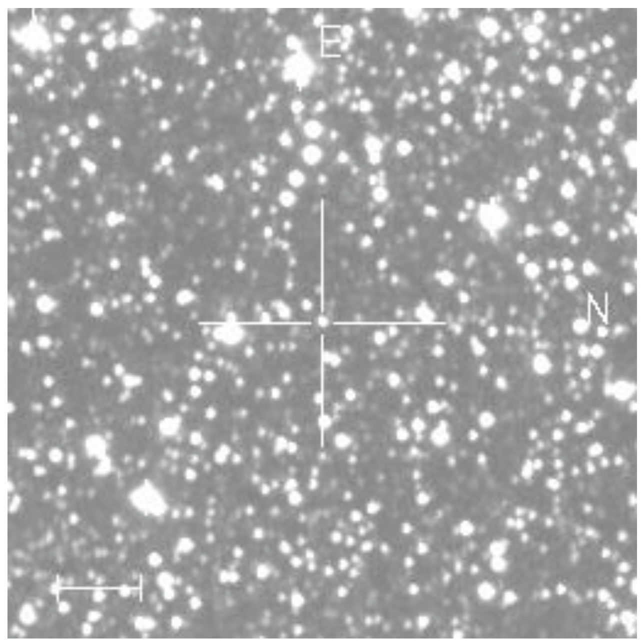
First event being followed: MOA 2009-BLG-260

Problems:
predicted amplification: 5
blending: ~0.5

Duration >130 days

Peak amplification ~16





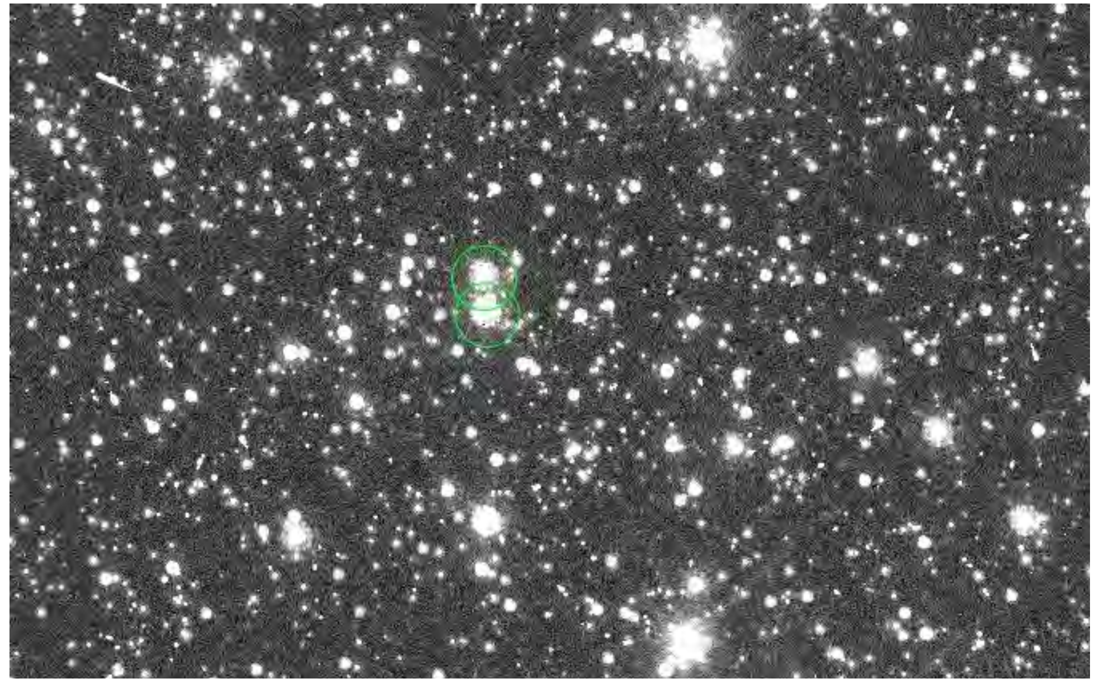
MOA Finding chart

HST Observations

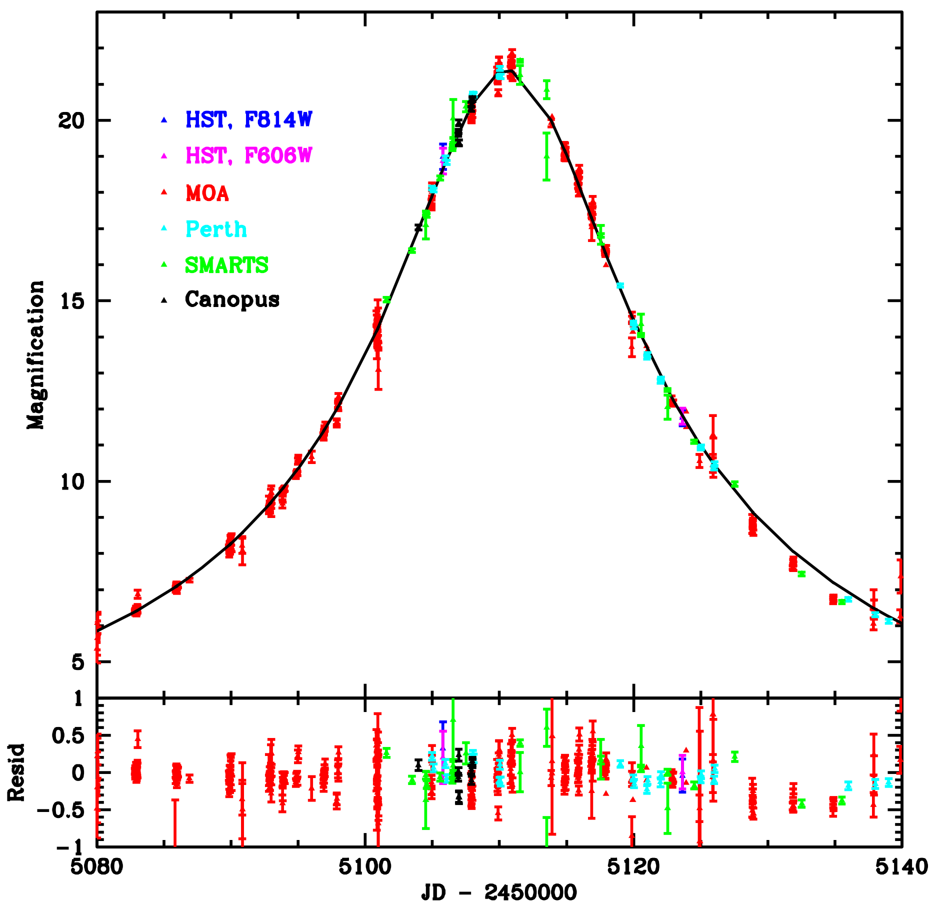
- **There is another object close to the source, which is brighter than the source by 1.16 mag in I, and by 2.5 mag in V.**

- **Consistent with no light from the lens.**

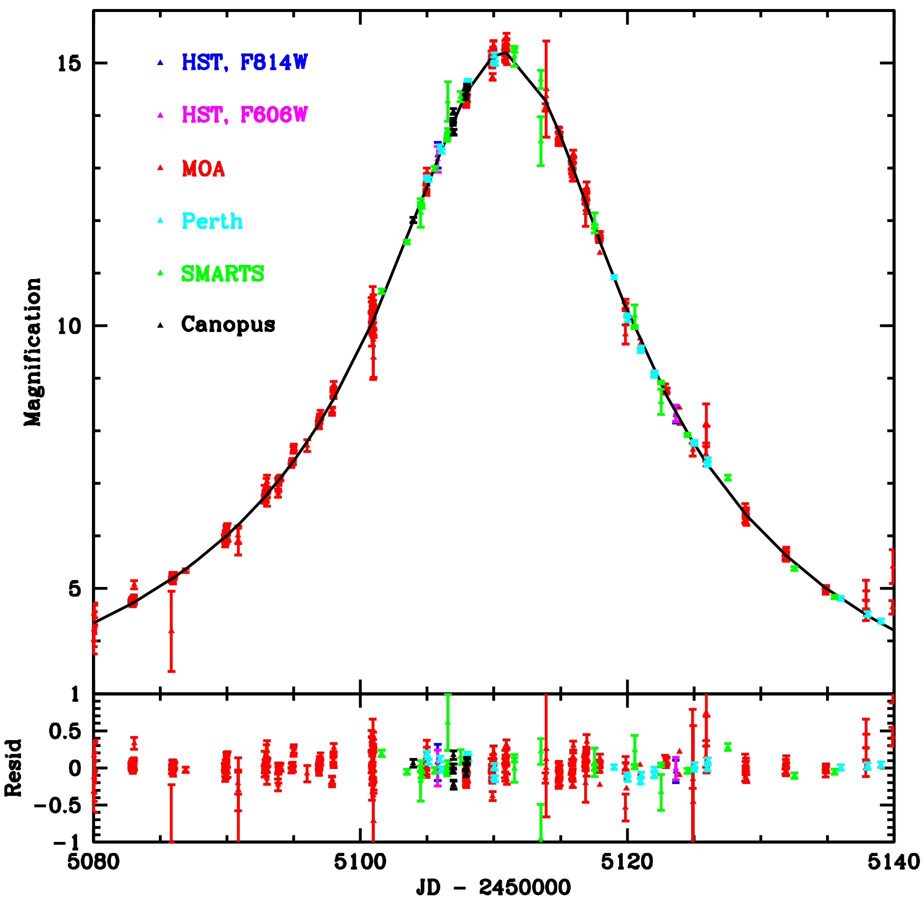
-> *Blending close to zero.*



HST Image, Oct 2010



Fit without parallax
~6000 pts

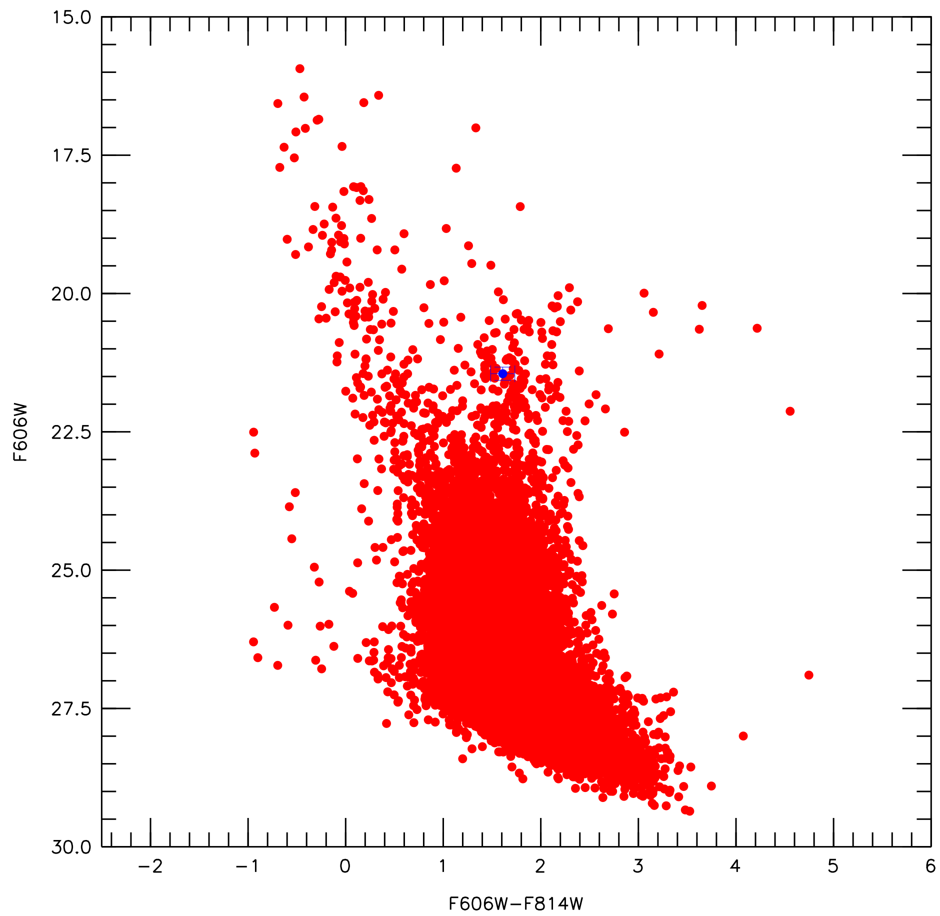


Fit with parallax
(delta-chi)^2 ~900

Light curve is sensitive to Earth's parallax.

D_{Lens} ~ 1.5 kpc

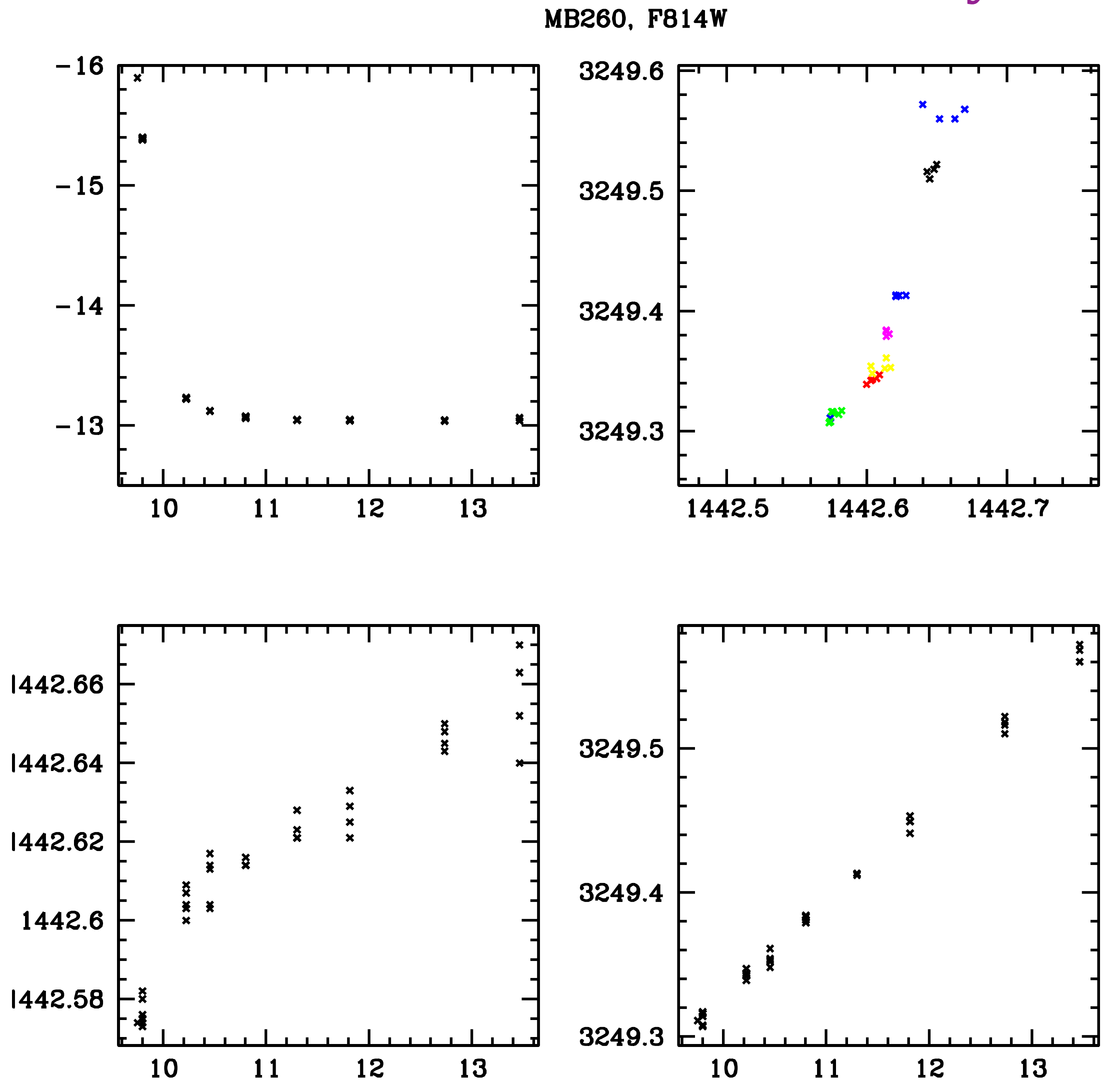
Color-Magnitude Diagram from HST Photometry



Source is within the Galactic bulge.

D_{Source} ~ 8.5 kpc

HST observations over ~4 years



Work in progress!

Deflection ~ 0.02 pix (~ 0.45 $M_\odot$).

Deflections by BHs would be easily detectable.

We are monitoring 7 long-duration events.

The first 5 are not BHs, but they were mostly 100<t_E<150 days.

A few more are being monitored with t_E~300 days.

Bias in such BH mass measurements

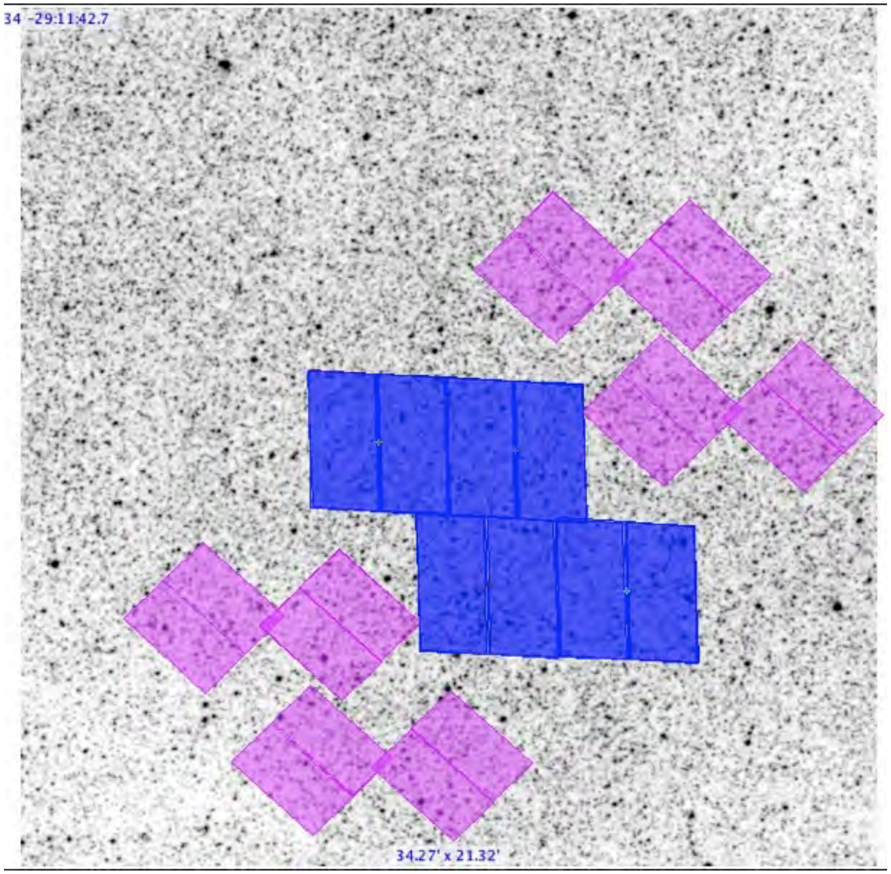
- **Unfortunately, the choice from ground-based observations has its own selection effects. In particular, we inherently assume that the stellar remnants have the same velocity distribution as normal stars.**

- **The correct method to get the mass function of stellar remnants is to simultaneously detect a large number of microlensing events, and measure their astrometric motions.**

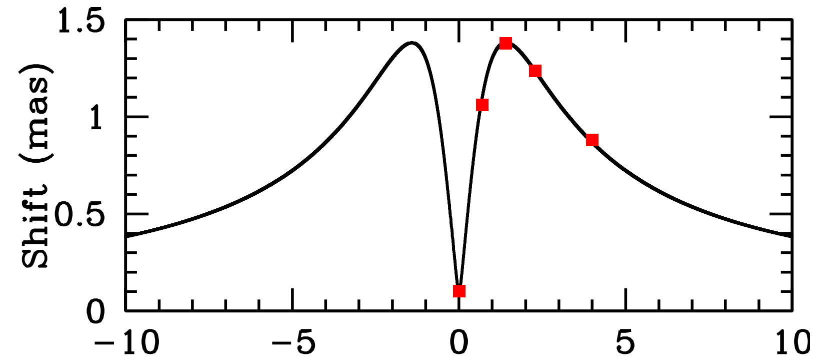
- **The best method to measure the real frequency of black holes and their mass distribution is to discover and measure their masses through HST alone.**

II. Detecting and Measuring the Masses of Stellar Remnants (HST-GO-12586, PI: Sahu)

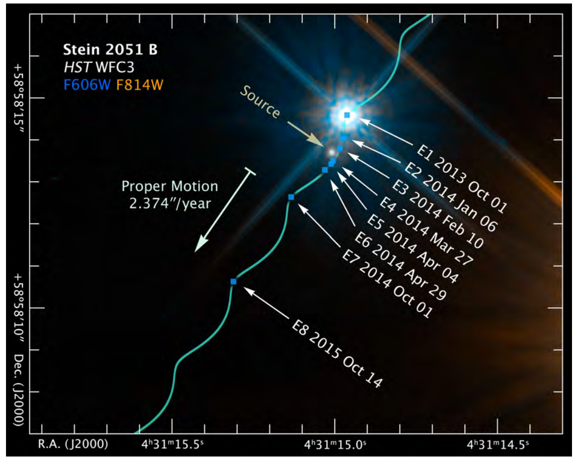
- **Fields/ Targets**
  - **Monitored a total of 1.7 million stars, 50% with astrometric measurements**
- **Observing Cadence**
  - One visit every 2 weeks over two 4-month windows
  - 64 visits per year, for 3 years
  - Optimized for long-duration events
- **Expectation:**
  - Found ~15 events in the brightest ~15% of data, many OGLE (Kains et al. 2016).
  - So we expect to find a total of ~100 events, some by NSs and BHs.



Summary



Astrometric microlensing is a powerful tool to:
i. Measure masses of lenses, and
ii. To detect isolated black holes
and measure their masses and velocities.



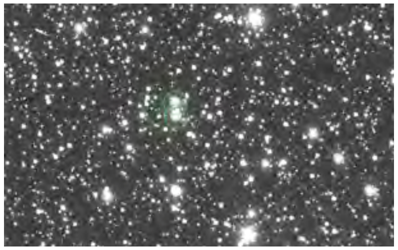
We measured the mass of the nearby WD Stein 2051B through astrometric microlensing.

We have two HST programs currently under way:

I. We are observing a few long-duration microlensing events.

II. We detected astrometric deflections, but the lens is ~0.45 solar mass.

III. None of the 5 events observed so far are BHs.



IV. Through a *multi-cycle HST program we monitored 1.7 million stars. ~15 events are found among the brighter stars, further analysis is in progress.*