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An Isolated Stellar-mass Black Hole Detected through Astrometric Microlensing*

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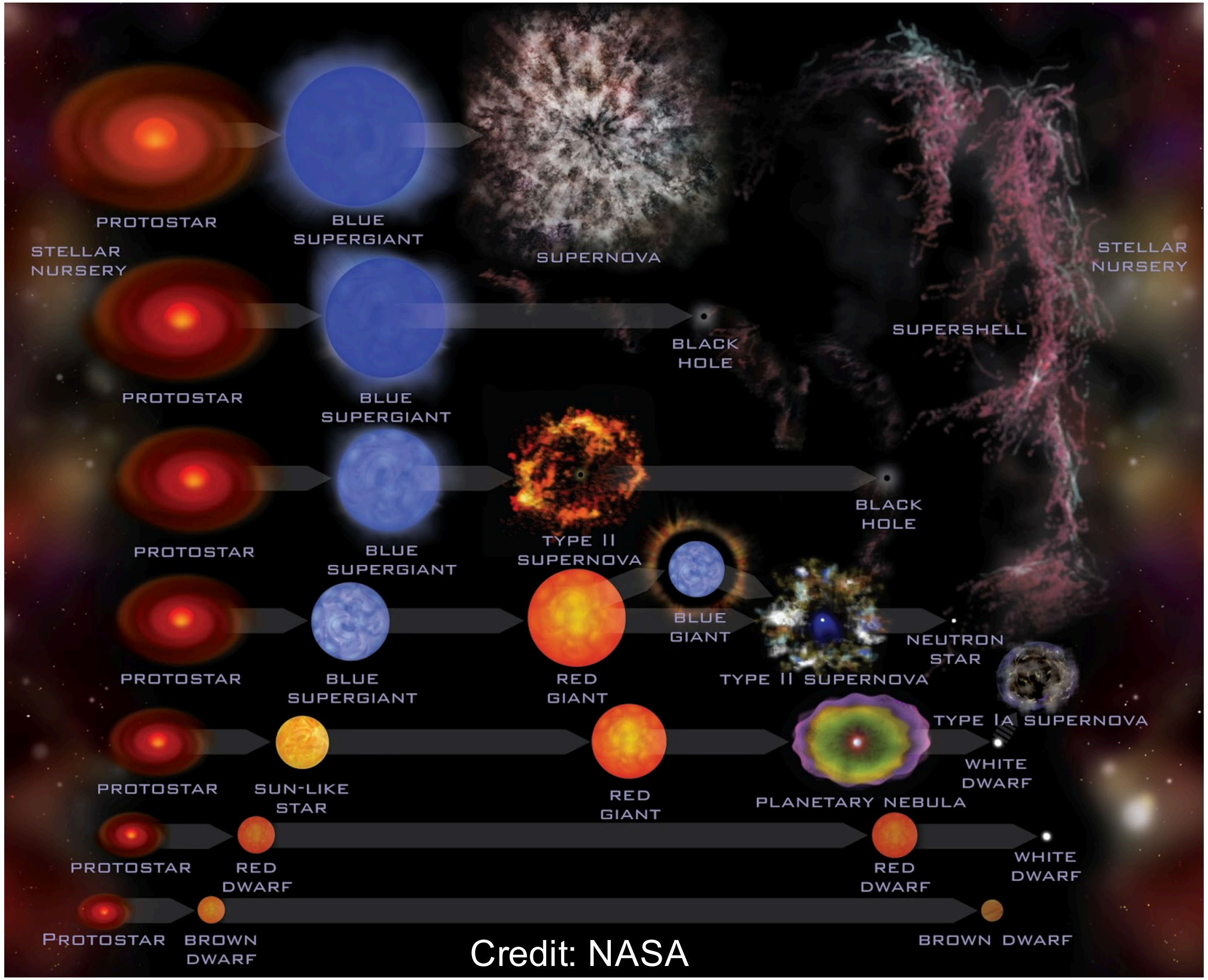
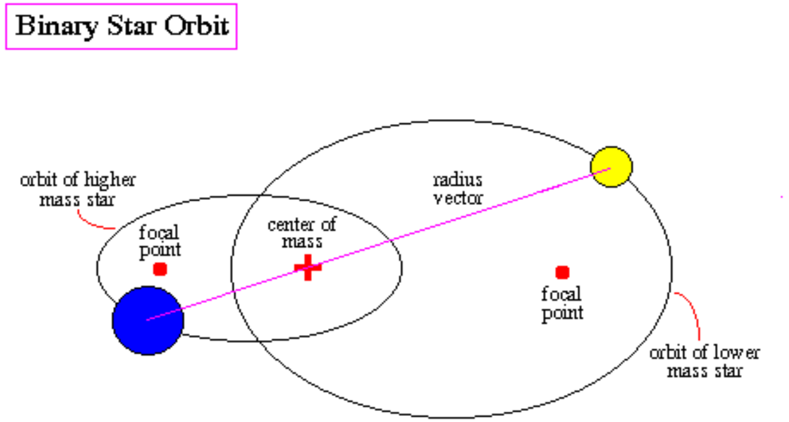
Stellar black hole -- remants of massive stars

- ➢ Stellar evolution
- ➢ Supernova physics
- ➢ Gravitational wave prediction
- ➢ Initial mass function...

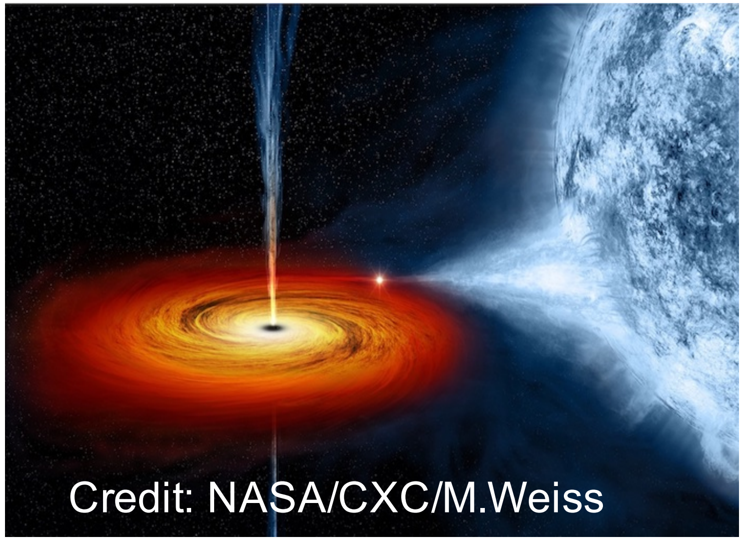


Search for stellar black hole

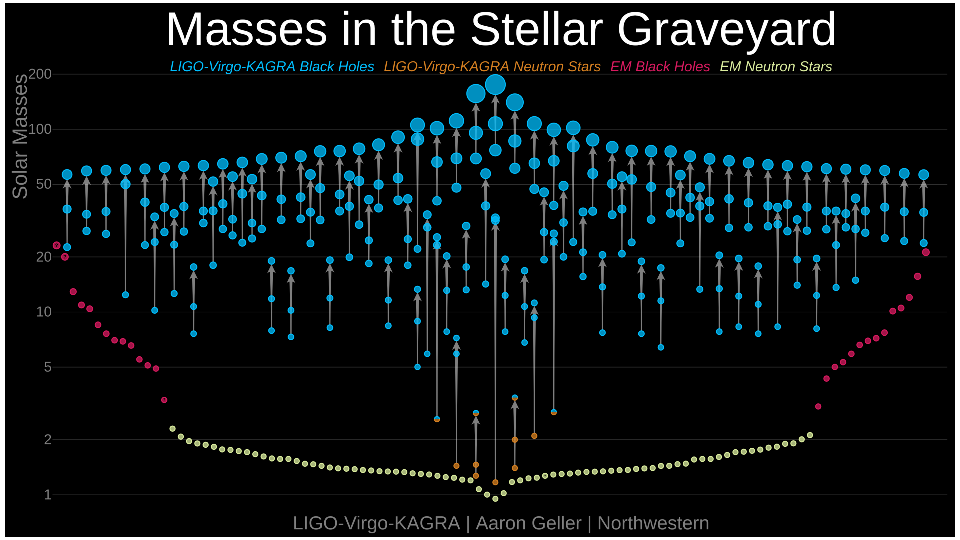
Wide-binary



X-ray binaries (~20 candidates)



Gravitational wave



Are stellar BHs all in binaries?

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Not likely

- ~30% massive stars are born single
- In close binaries, the pair may merge before SN explosion
- In wide binaries, BH may be detached when the natal kick by SN to the companion is large enough

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How to search for isolated BHs?

No isolated BH has been unambiguously found before this work

Search for isolated stellar BH

Astrometric microlensing

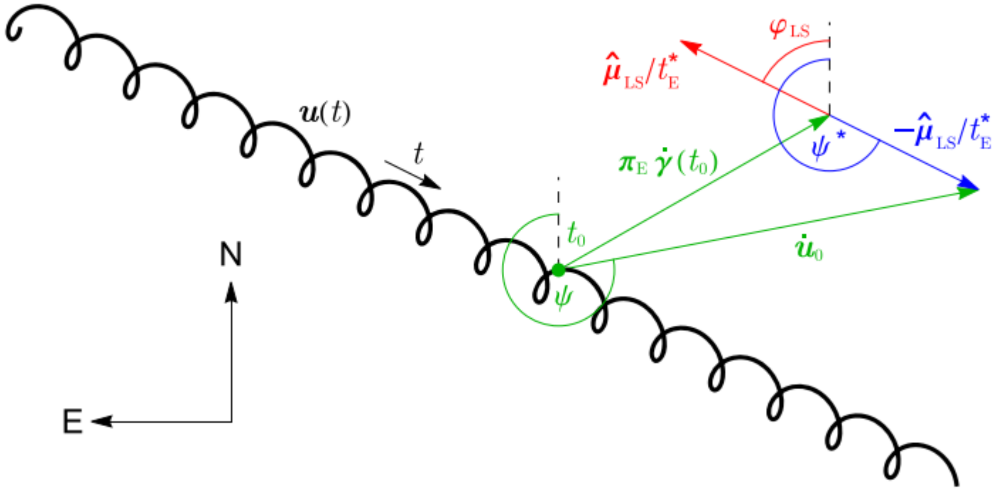


Figure 1. Source–lens trajectory $\boldsymbol{u}(t)$ as seen by the observer, showing the effect of annual parallax. At epoch t_0, the tangent to the source–lens trajectory $\dot{\boldsymbol{u}}_0$ is not (anti)parallel to the direction of the lens–source proper motion $\hat{\boldsymbol{\mu}}_{\rm LS}$ but differs by $\pi_{\rm E}\,\dot{\boldsymbol{\gamma}}(t_0)$ (Equation (11)), related to the orbital velocity of Earth at t_0. Consequently, we distinguish the direction angles ψ, $\psi^{\star}$, and $\varphi_{\rm LS}$, referring to $\dot{\boldsymbol{u}}_0$ and $\mp\hat{\boldsymbol{\mu}}_{\rm LS}$, respectively. Furthermore, $t_{\rm E} = 1/|\dot{\boldsymbol{u}}_0|$ and $t_{\rm E}^{\star} = \theta_{\rm E}/|\boldsymbol{\mu}_{\rm LS}|$.

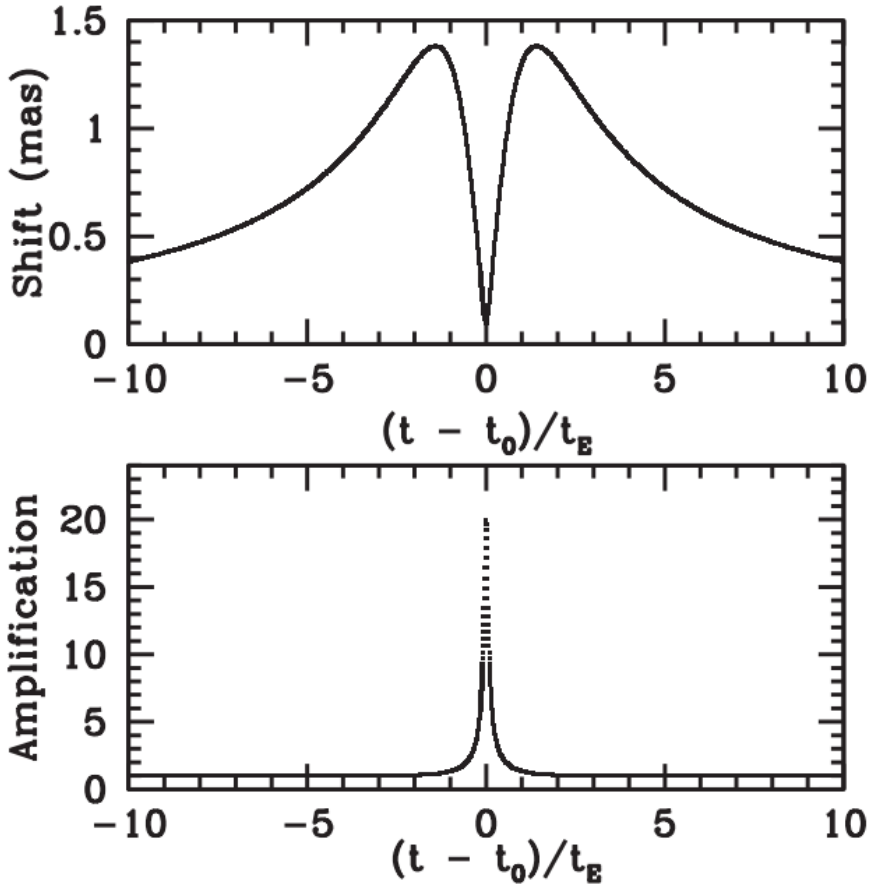
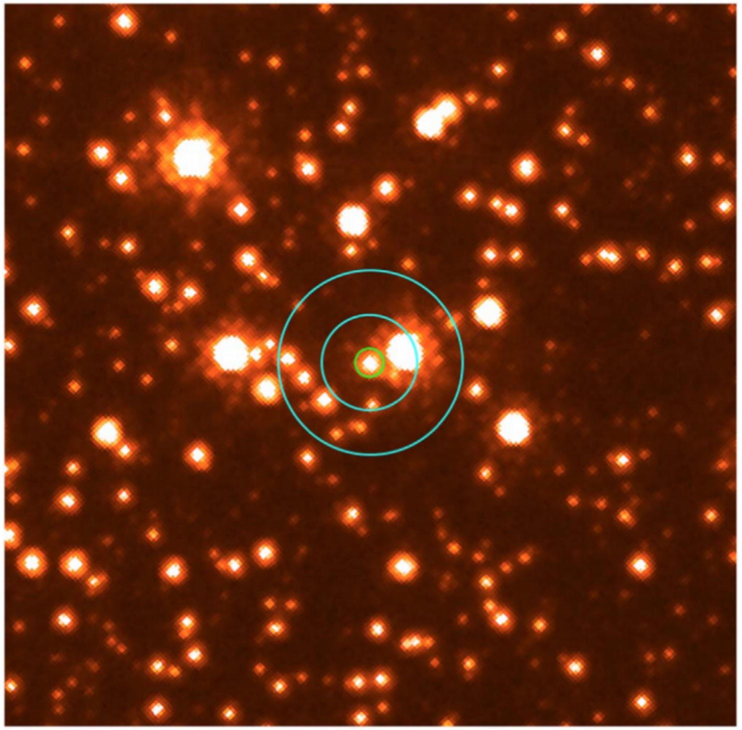


Figure 2. Astrometric shift (top panel) and light magnification (bottom panel) for a microlensing event produced by a $5\,M_{\odot}$ BH at a distance of 2 kpc passing in front of a background star at 8 kpc. The assumed minimum impact parameter is $u_0 = 0.05$. The maximum astrometric shift of the source is $\sim$1.4 mas, at $u = \sqrt{2}$, and the maximum magnification is $\sim$20, at the time of closest angular approach. Note the much longer duration for the astrometric shift, compared to that of the light magnification.

One astrometric microlensing event

Ongoing microlensing programs: OGLE, MOA, KMTNet, yielding >2000 events/yr, 30000 events in total so far.



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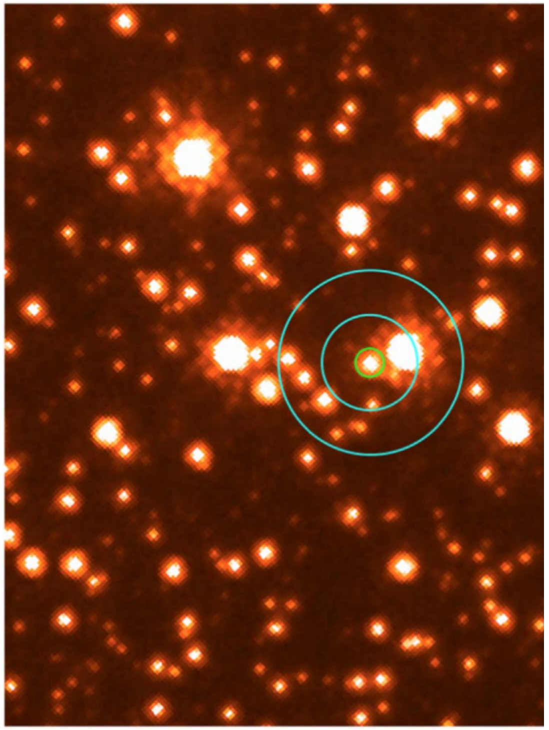
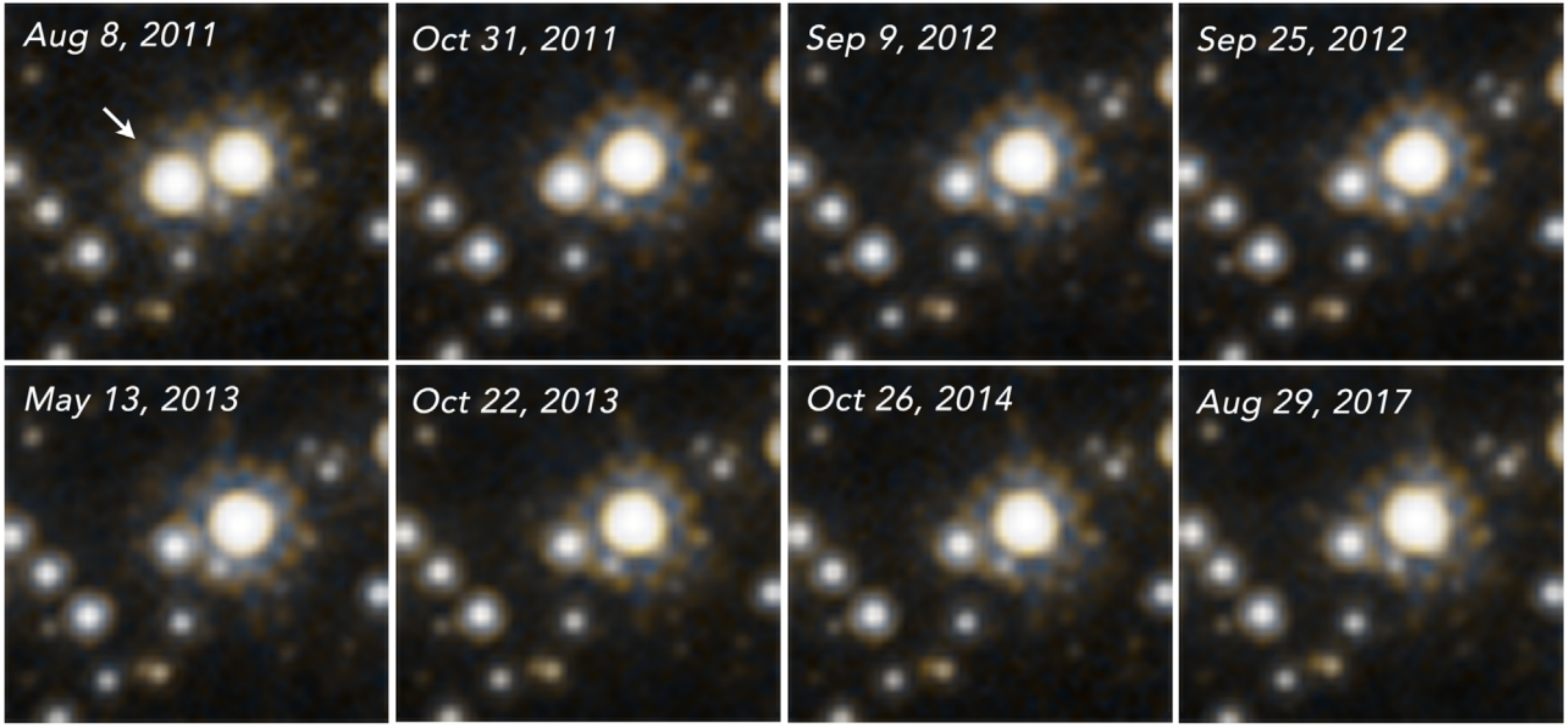
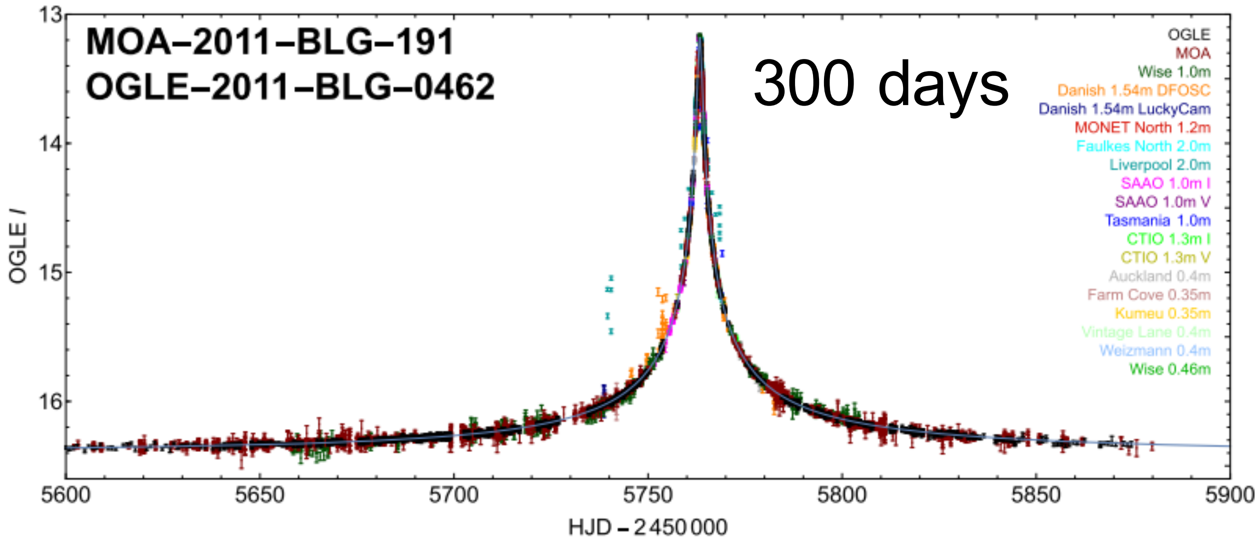




Light-curves

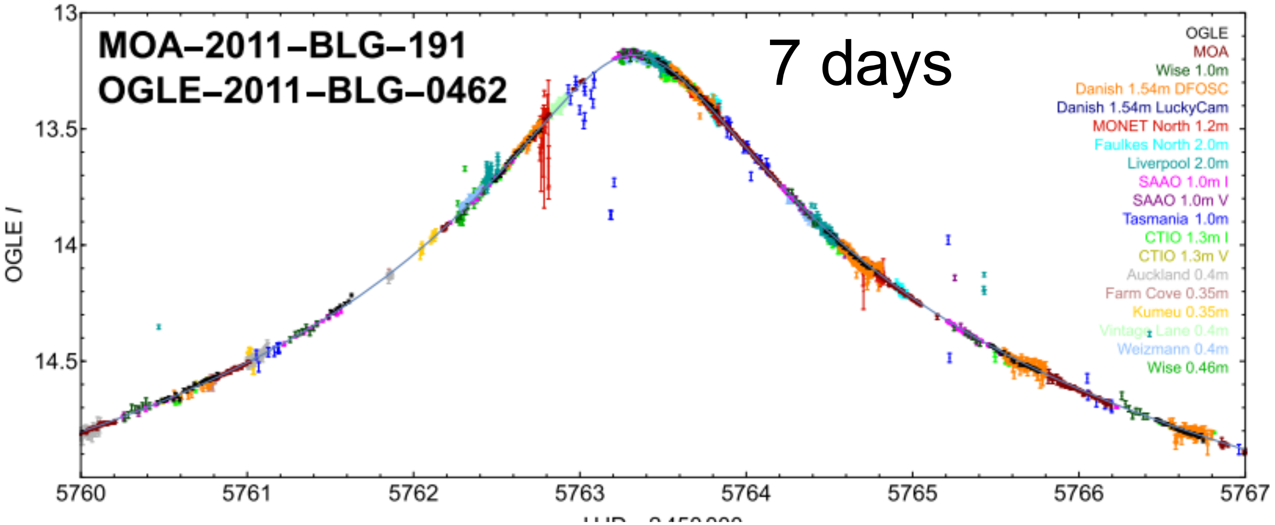
Ground-based light curve

300 days

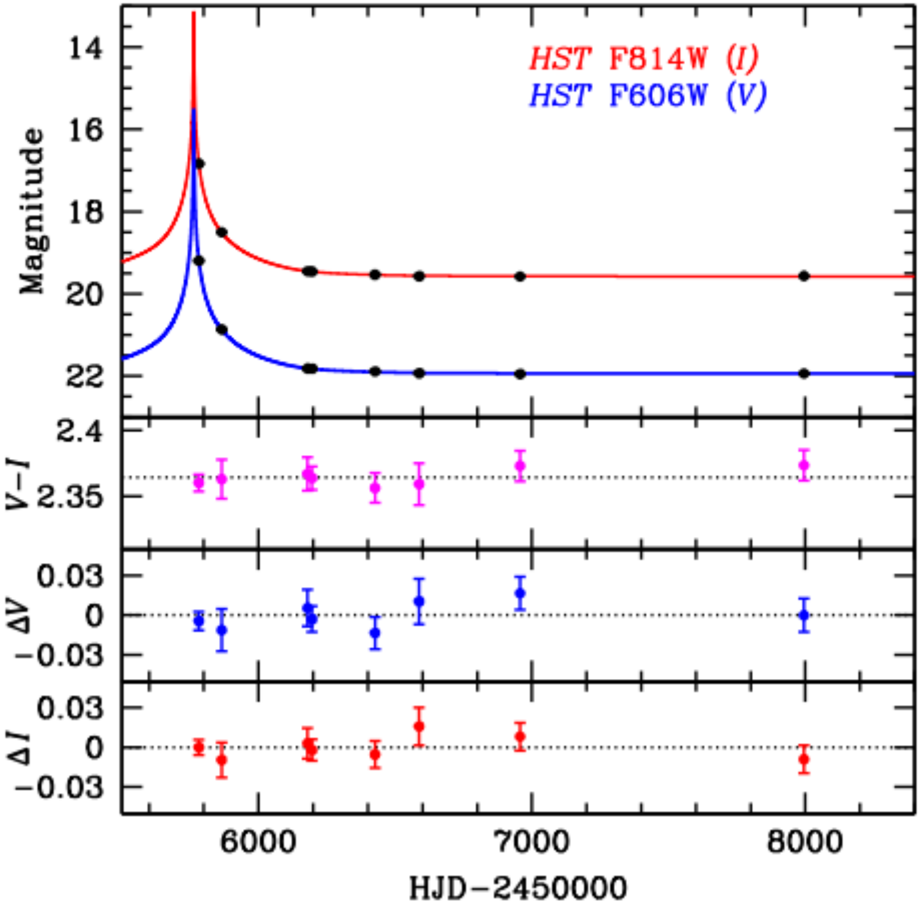


R or I bands

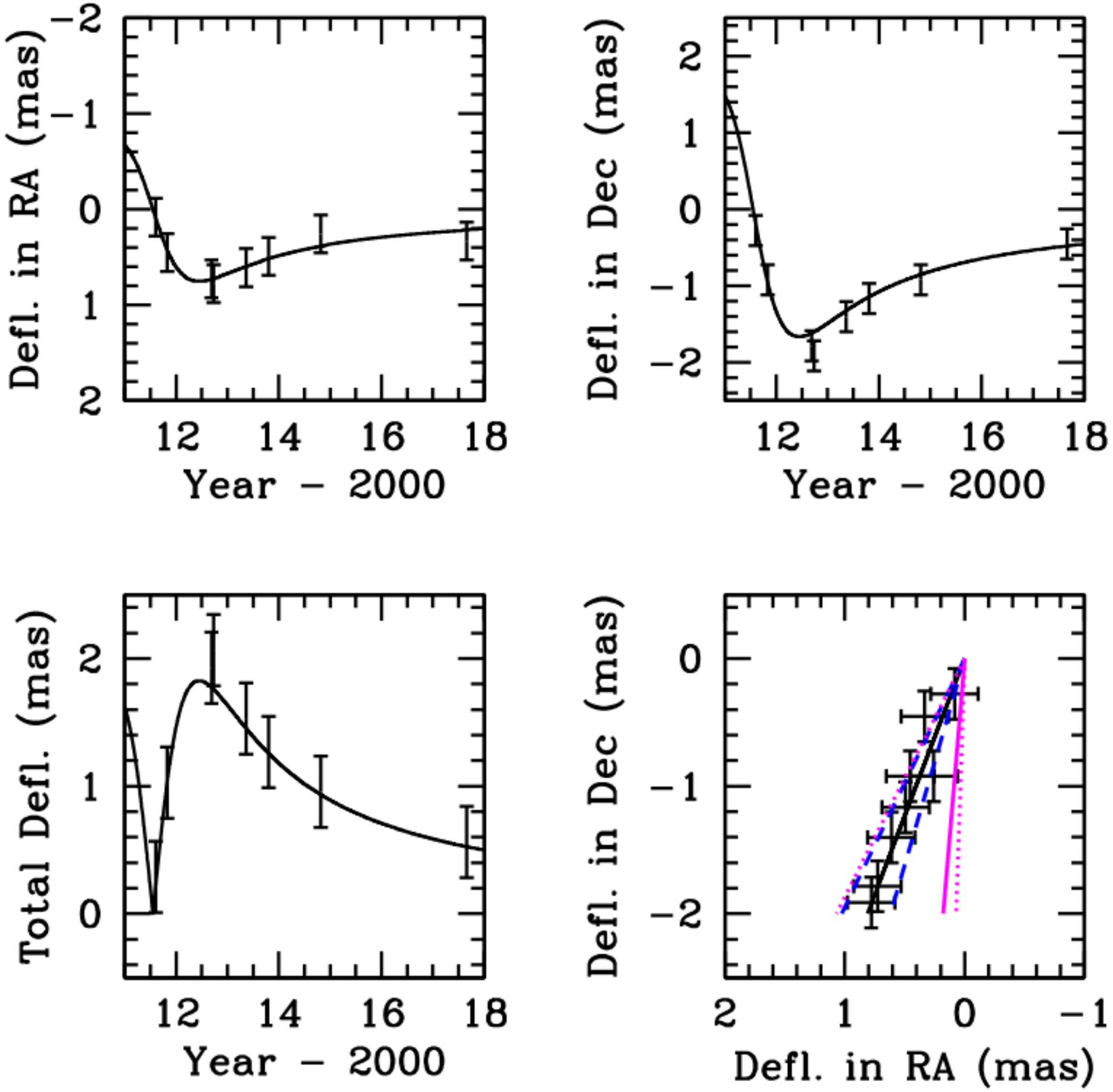
7 days



HST light curve



Deflection measured from HST obs.



Source and lens on the sky

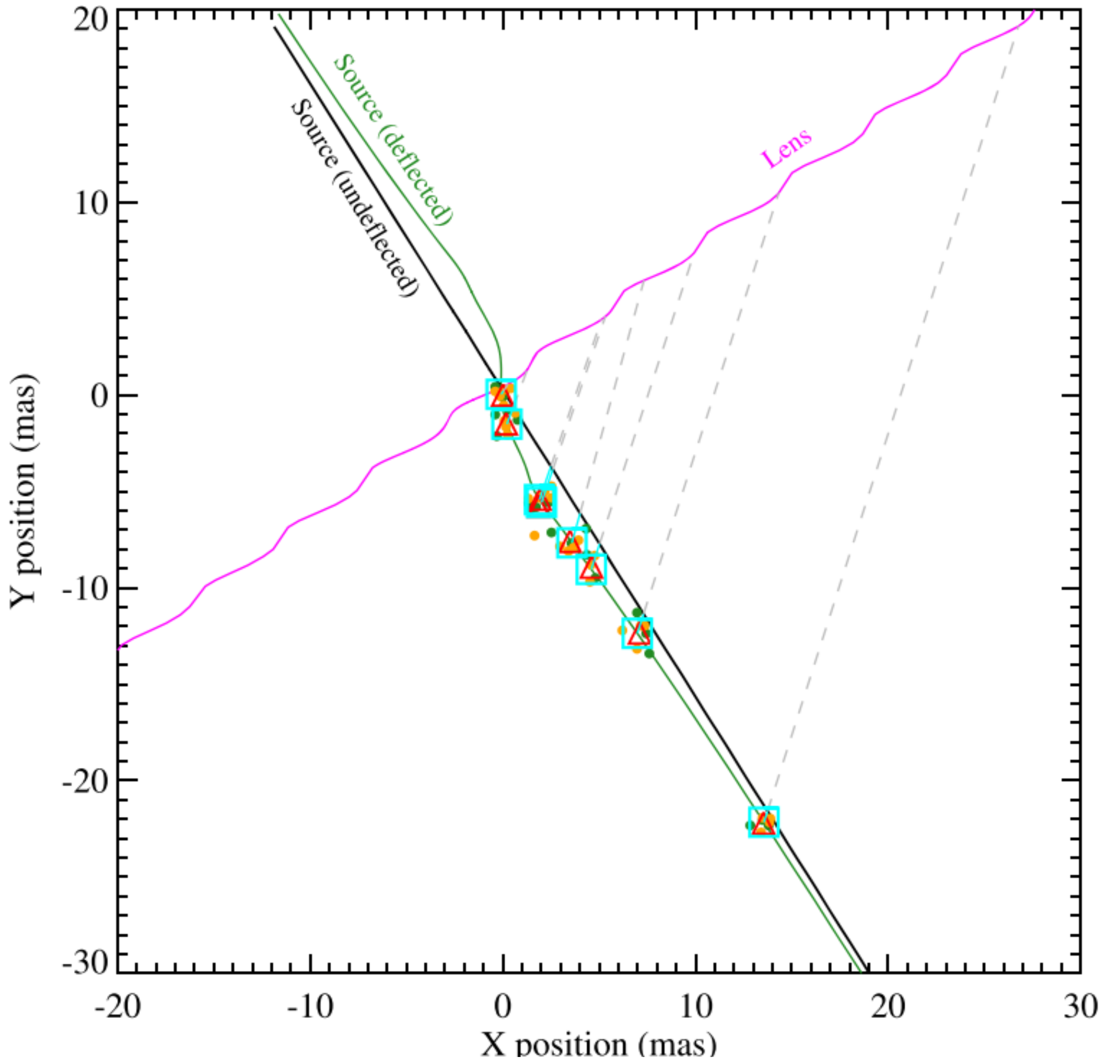


Figure 17. Representation of the reconstructed motions of the lens and of the source on the plane of the sky. The reference point is the undeflected position of the source at time t_0. The small circles are the individual measurements from HST images (green for F606W, orange for F814W); the larger red triangles represent the average positions for each epoch. The cyan squares are the fitted positions at each epoch. The gray lines connect the undeflected source and lens positions at each HST epoch.

Nature of the lens

The first ever confirmed isolated BH

Properties of the MOA-11-191/OGLE-11-462 Black Hole Lens

Property	Value	Sources and Notes[a]
Mass, $M_{\rm lens}$	$7.1 \pm 1.3\ M_\odot$	(1)
Distance, D_L	1.58 ± 0.18 kpc	(2)
Einstein ring radius, $\theta_{\rm E}$	5.18 ± 0.51 mas	(3)
Proper motion, (μ_α, μ_δ)	$(-4.36 \pm 0.22, +3.06 \pm 0.66)$ mas yr^{-1}	(4)
Galactic position, (X, Y, Z)	$(-4, -1580, -45)$ pc	(5)
Space velocities, (V, W)	$(+3, +40)$ km s^{-1}	(6)

Note.
[a] Sources and notes: (1) This paper, Section 10.1. (2) This paper, Section 10.2. (3) This paper, Table 5. (4) This paper, derived from model in Table 5; absolute proper-motion components in Gaia EDR3 J2000 frame. (5) Galactic position relative to Sun: X in direction of Galactic rotation, Y in direction away from Galactic center, Z perpendicular to Galactic plane toward north Galactic pole. (6) Space velocity components relative to Sun, assuming zero radial velocity: V in direction of Galactic rotation, W toward north Galactic pole; U component toward Galactic center is undetermined owing to unknown actual radial velocity.

Formation of $7M_{sun}$ BH?

1. Through fallback in a weak SN explosion

2. In a close binary that lost mass through a common-envelope mass ejection. the binary evidently became unbound, when its lower mass companion itself became an SN, and its mass loss and SN kick detached the binary.

Future work

- The GRAVITY instrument with Very Large Telescope Interferometer (VLTI) will make it possible to measure θ_E from spatially resolved microlensed images.

- Roman will observe 2 deg^2 region in the Galactic bulge with a 15-minute cadence for several months each year, yielding several thousand microlensing events.

- Rubin's wide-angle survey will provide deep, long baseline photometry and consistent data reduction, ideal for the discovery and photometric characterization of microlensing events.

- Microlensing with extended source?