Microlensing: Some Scientific Highlights

- **Microlensing Can Detect Compact Objects (Stellar Remnants) (Dark Matter MACHOs)**
- **Dark Matter Candidates Include Stellar Remnants and Exotic Particles Created in the Big Bang (WIMPS)**
- **Microlensing Places Significant Limits on Stellar Remnants**
  - **Detection Probabilities are Low: Even If Entire Halo is Composed of Stellar Remnants P ~)10^{-6} events/year**
  - **MACHO Team (c. 1990) Detected ~ 50 events/year Against Galactic Bulge (Baade's Window; Hewitt & Warren 1997)**
  - **Stellar Remnants Cannot Account for Milky Way's Massive Halo (Pietrzynski 2018)**
- **Dark Matter Sub-halos (clumpy DM) May be Detectable via Lensing (Croon, McKeen & Raj 2020)**
  - **Extended Mass Distribution Means They Would be More Difficult to Detect Than Point Masses**

Microlensing: Exoplanets

- Most Stars are in Binary Systems so Let's Consider Binary Lens
- With Two Masses the Deflection Angle is the Vector Sum of All the Individual Deflections:

$$\hat{\boldsymbol{\alpha}}(\boldsymbol{\xi}) = \frac{4G}{c^2}\sum_i M_i \frac{\boldsymbol{\xi} - \boldsymbol{\xi}_i}{|\boldsymbol{\xi} - \boldsymbol{\xi}_i|^2}$$

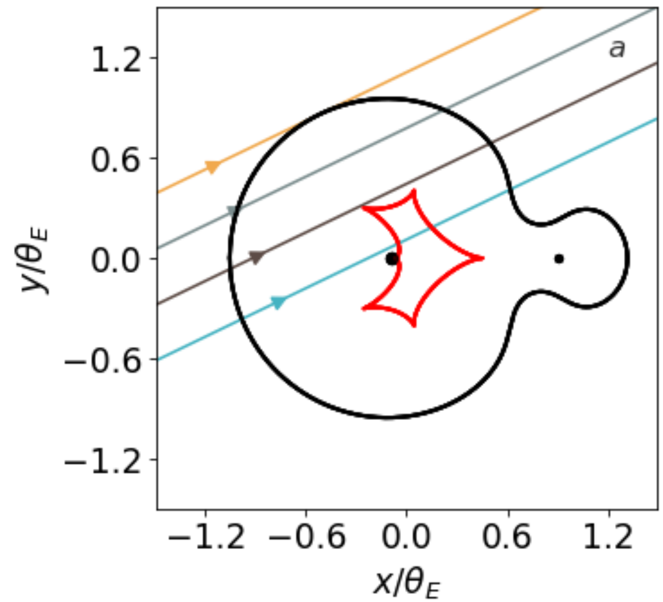
For the Case of Two Lensing Masses:

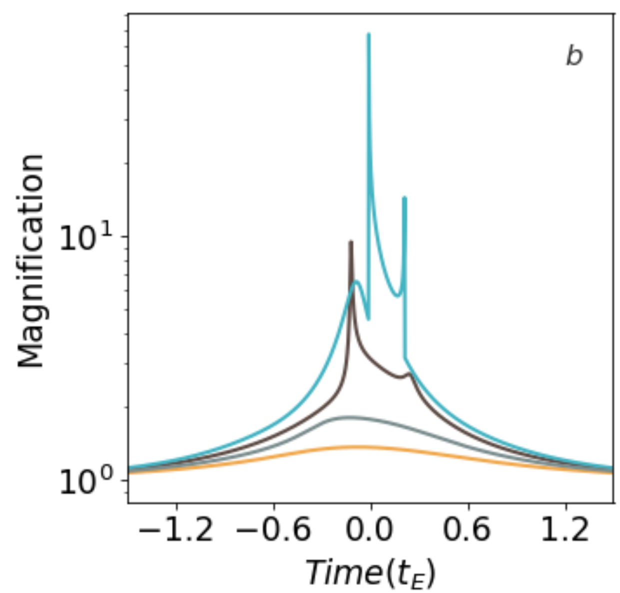
$$\hat{\boldsymbol{\alpha}}(\boldsymbol{\xi}) = \frac{4G}{c^2}\left[M_1 \frac{\boldsymbol{\xi} - \boldsymbol{\xi}_1}{|\boldsymbol{\xi} - \boldsymbol{\xi}_1|^2} + M_2 \frac{\boldsymbol{\xi} - \boldsymbol{\xi}_2}{|\boldsymbol{\xi} - \boldsymbol{\xi}_2|^2}\right]$$

- Similarly, the Jacobian Matrix for Multiple Lens Masses is Just the Sum of Individuals:

$$A = \sum_i^n A_i = \sum_i^n |J|^{-1}$$

- The Lens Plane Can Be Traced With the Jacobian Computed at Each Point. When the Determinant Vanishes, i.e., the Magnification Diverges, These Points can be Stored and a Contour of Them Reveals the Critical Curve (black curve at right). Upon Application of the Lens Mapping Equation the Critical Curve Becomes the Caustic in the Source Plane (red curve at right)
- Magnification for Sources vs Position in Top Figure are Plotted vs Time in Bottom Figure.





Microlensing: Exoplanet Examples

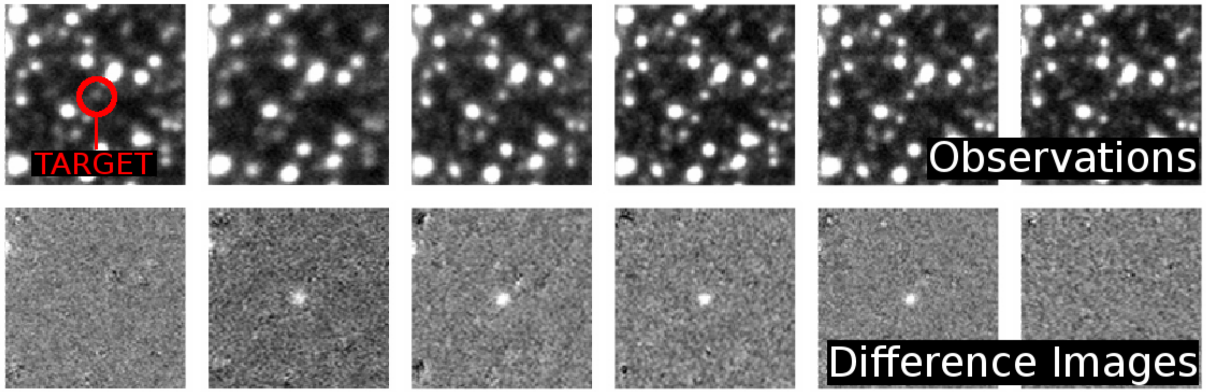
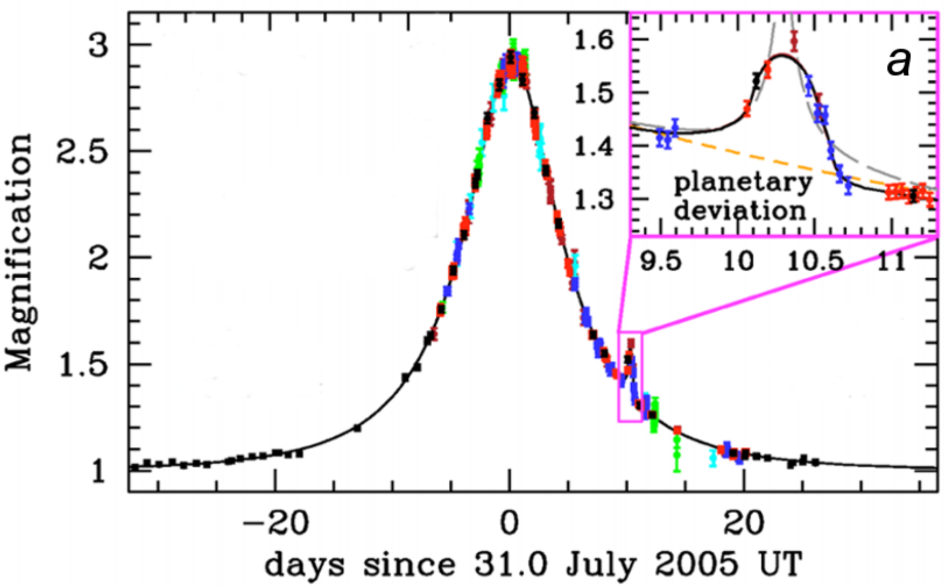


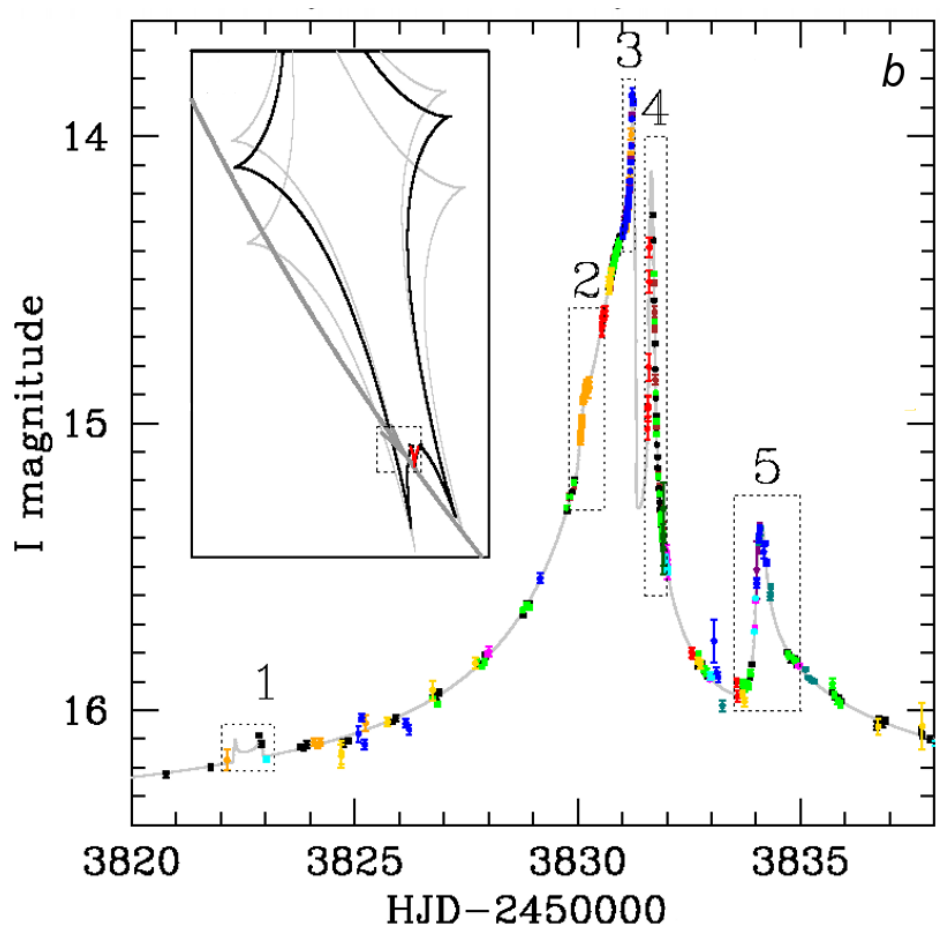
Image sequence showing microlensing event

- **Example at Right: OGLE-2005-BLG-390 (Baulieu et al. 2006)**
  - **M star host**
  - **Single 5.5 M_E Planet**
  - **Temp. ~ 50K (Icy Super-Earth)**
  - **For the time one of the lowest mass planets discovered**



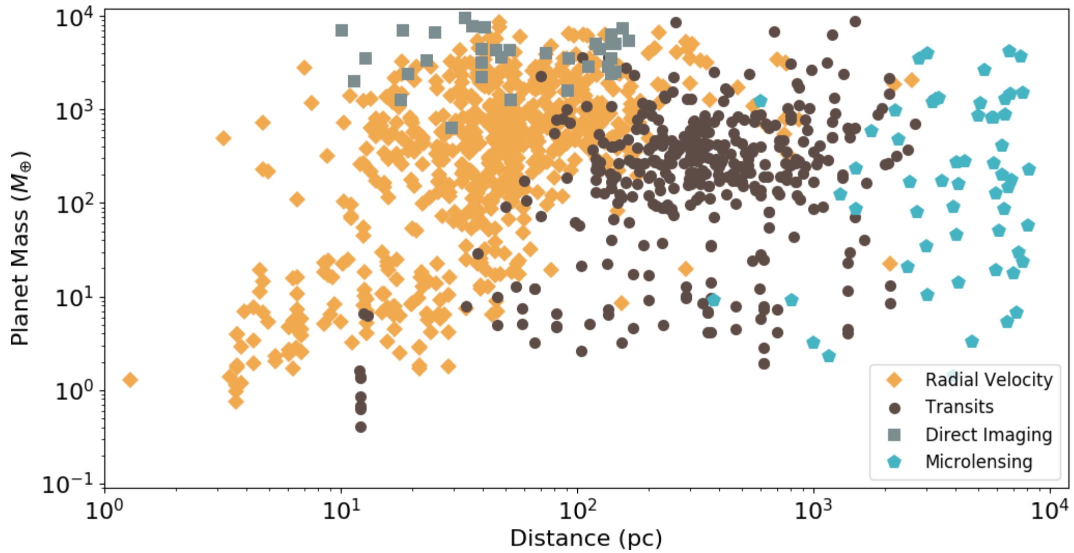
Microlensing: Exoplanet Examples

- **Example at Right: OGLE-2006-BLG-109 (Gaudi et al. 2008)**
- **Five Distinct Model Residuals Seen**
  - **Mass Range: ~2 M_E – 0.7 M_J**
  - **Separations: 2 – 5 AU**
  - **Two giant planets located beyond snow line**
  - **Additional Planets with a > 10 AU cannot be excluded**



OGLE-2006-BLG-109 light curve. Inset shows model caustics in the source plane. Light grey curves show the shifts introduced by the motion of the most massive planet.

Microlensing: Exoplanet Results



Exoplanet mass vs. host star distance. Note that microlensing samples a broad range of planet masses but is limited to distant host stars.

- **More than 60 Exoplanets Have Been Detected with Microlensing (c. 2006)**
  - **Separations: 0.5 < a < 18 AU (largely unexplored with Transits & RV)**
  - **Masses: ~1.4 M_E < M < 13 M_J**
  - **Limited to Distant Host Stars Due to Requirement of Foreground Lensing Mass**

Microlensing: Future of Exoplanet Detections

- **Advantages**
  - Provides a Large-scale, Unbiased Sampling of Host Stars
  - Discovery Timescale is Short (Snapshot)
  - Relatively Cheap in Telescope Resources & Independent of Period
  - Sensitive to Earth-mass Planets
  - Sensitive to Planets Beyond Snow Line

- **Disadvantages**
  - Detection Probability is Low, $\sim 10^{-8}$ (monitoring 10^9 stars -> a few events/year)
  - Events Only Last a Few Hours, Need for Worldwide Monitoring
  - Targets Too Far Away for Follow-up on System (with Other Techniques), Host Stars Faint
  - Limited Orbital Range: $0.4 < a < 100$AU
- **Future**
  - Ground-based Surveys Will Continue
  - Astrometric Signal (e.g., Paczynski 1998; Dominik & Sahu 2000)
  - WFIRST Offers Stable PSF, Uninterrupted Coverage: Should Find 1000s

References

- **Hewitt, P. & Warren, S. 1997, Science 275, 626**
- **Pietrzynski, G. 2018, Nature 562, 349**
- **Croon, D., McKeen, D. & Raj, N 2020, arxiv:2002.08962v2**
- **Tsapras, Y. 2018, Microlensing Searches for Exoplanets, arXiv:1810.02691**
- **Beaulieu, et al. 2006, Nature 439, 437**
- **Gaudi et al. 2008, Science 319, 927**
- **Wambsganss, J. 2006, astro-ph/0604278, from Gravitational Lensing, Strong, Weak and Micro, 33rd Saas-Fee Advanced Course, 2003**
- **NASA Exoplanet Archive: https://exoplanetarchive.ipac.cqltech.edu**
- **Paczynski, B. 1998, ApJL 494, L23**
- **Dominik, M. & Sahu, K.C. 2000, ApJ 534, 213**
- **Poleski & Yee, MulensModel (software package for modeling microlensing), Ast. & Comp. 26, 35**
- **Street, R. et al. 2018, LSST & Microlensing White Paper,** https://lsst-tvssc.github.io/MS_DDF_proposals/LSST-Special-Project-MW-Microlensing-Science.pdf