Detecting planet with microlensing

OUTLINE:

Principle

Example of planet discoveries

Microlensing surveys projects

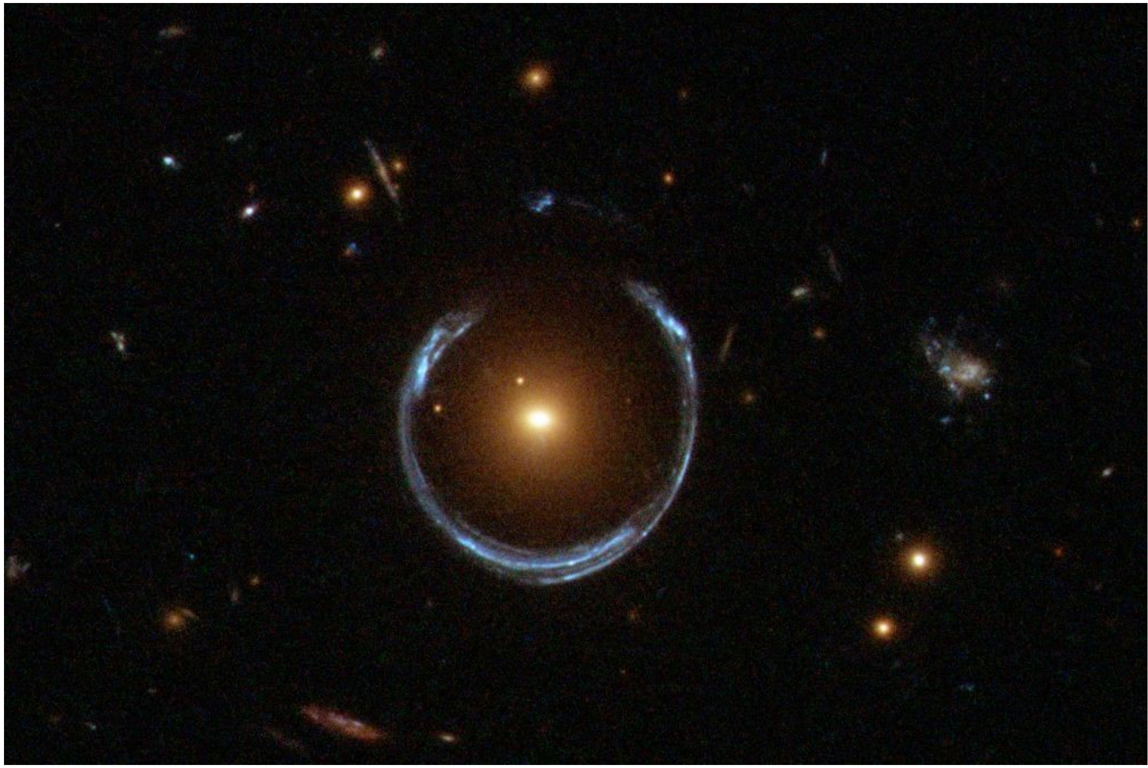
Gravitational Microlensing principle

Masses act as lenses by bending light

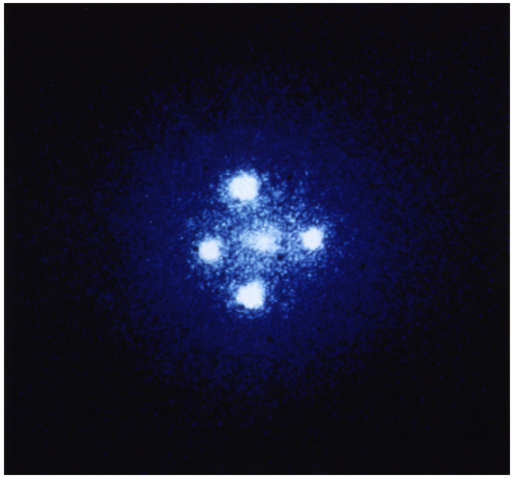
Strong lensing:
Images of background distant galaxies strongly distorted by foreground mass (massive galaxy or galaxy cluster)

Weak lensing:
Images of background galaxies weakly distorted (slight stretch) by foreground mass. This technique is used to measure and map the mass of galaxy clusters.

Microlensing:
Flux of star is modulated by foreground star/planet passing along the line of sight.
Technique is used to identify planets



Examples of strong lensing



Microlensing geometry (lens = mass point, source = point source)

Grav. lens creates two images of the source

- If impact parameter is large: one image is very close to lens and very faint, the other image is almost co-located with true source position
- General case: 2 images, one outside Einstein radius, one inside
- If impact parameter is = 0: the two images become a ring of radius = Einstein radius

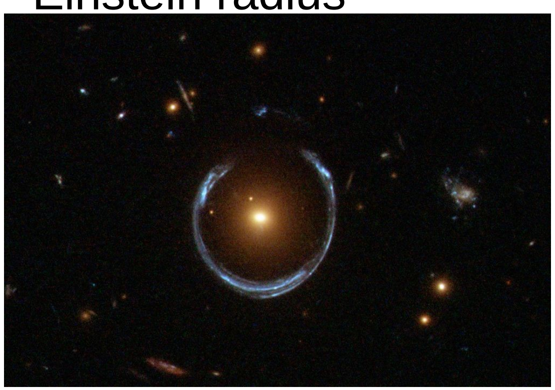
$$R_E = 2\sqrt{\frac{GMD}{c^2}} = 4.03\ \mathrm{AU}\ \sqrt{\left(\frac{M}{M_\odot}\right)\left(\frac{D}{2\ \mathrm{kpc}}\right)}$$

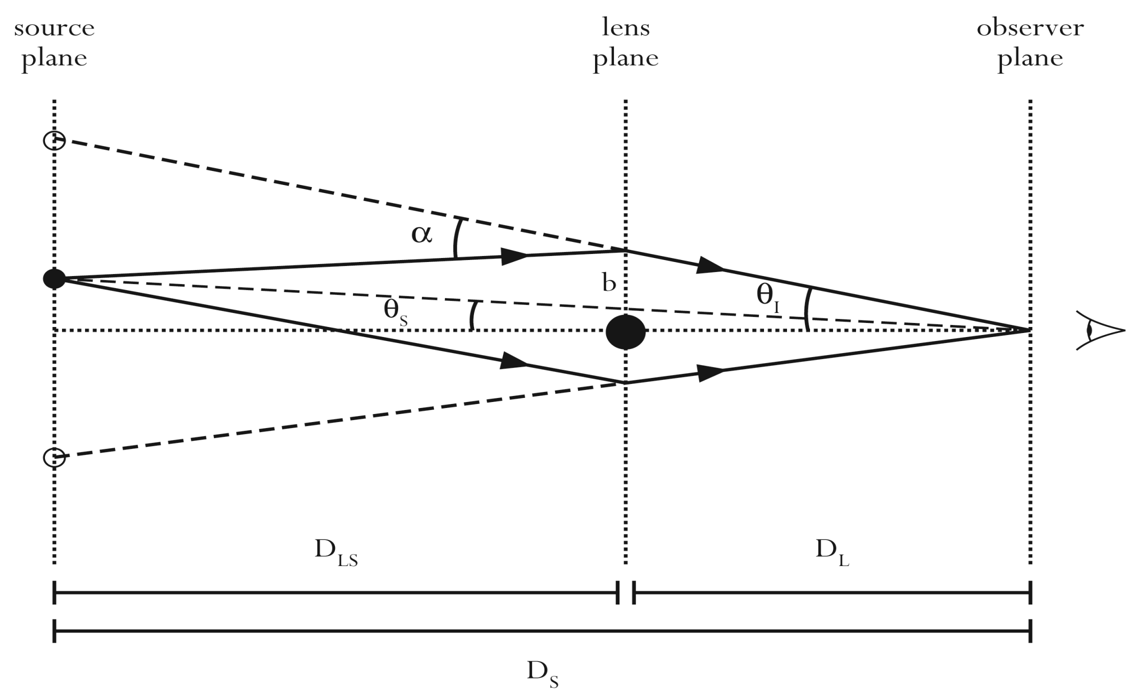
reduced distance

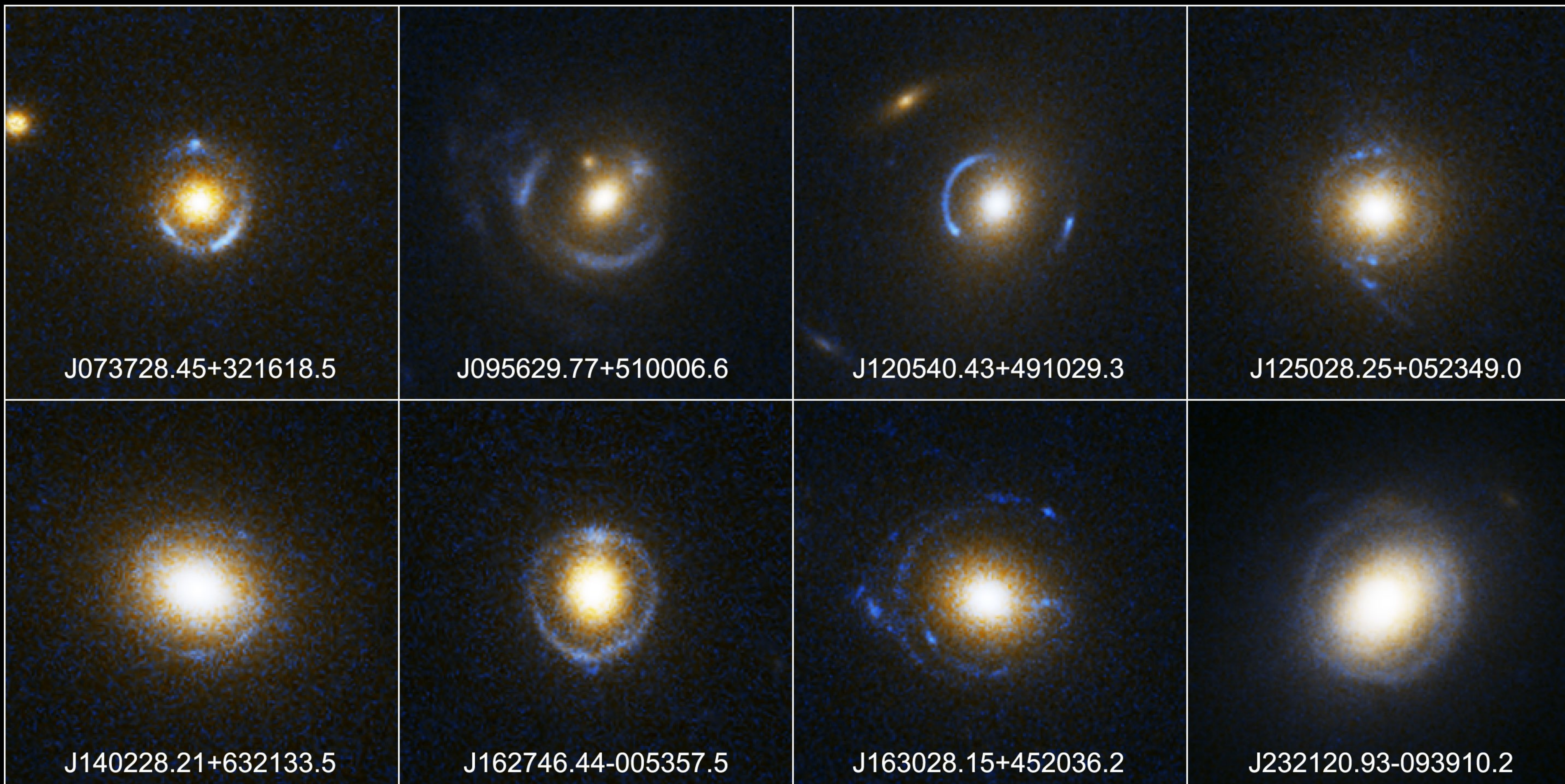
$1/D = 1 / D_L + 1/D_{LS}$

Einstein radius

Lens mass / Solar mass







Einstein Ring Gravitational Lenses

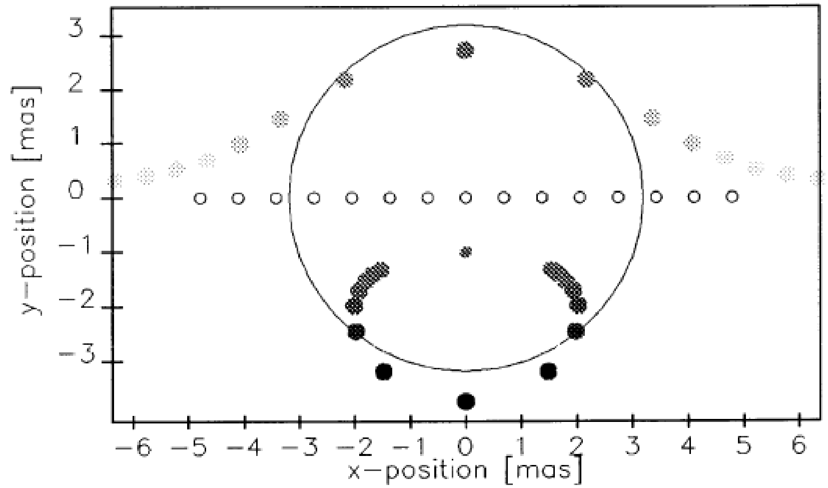
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team

STScI-PRC05-32

Microlensing geometry

Einstein radius is usually too small to be resolved
Planet detection with microlensing relies on photometry



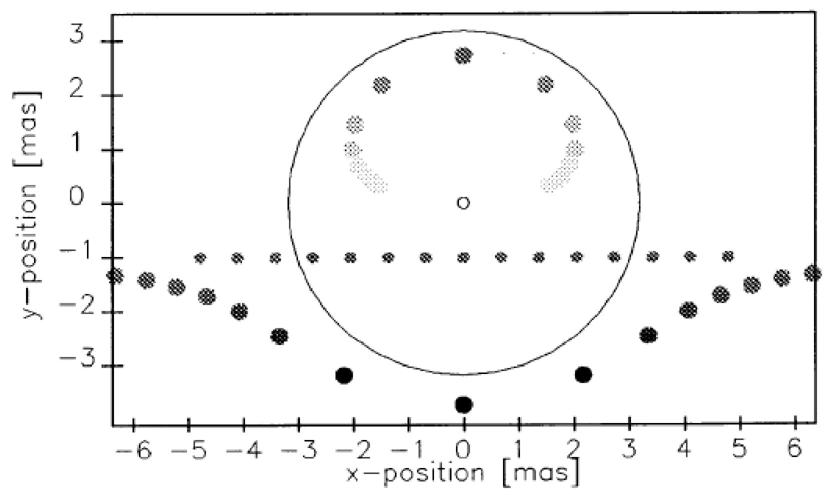


Fig. 1. Two representations of a microlensing event with $D_{\rm source} = 8$ kpc, $M_{\rm lens} = 10\,M_\odot$, $D_{\rm lens} = 4$ kpc, and impact parameter of 1 mas. The radius of the Einstein ring for this event is $r_{\rm E} = 3.2$ mas. Top panel — The background source position is fixed on the sky (small grey dot at $(x, y) = (0, -1)$ mas), and the lens is moving along the x axis. Instantaneous pairs of lensed images are connected by the lines passing through the consecutive lens positions. Bottom panel — The lens position is fixed at the center of the frame, and the source position is shown moving along the line $y = -1$ mas.

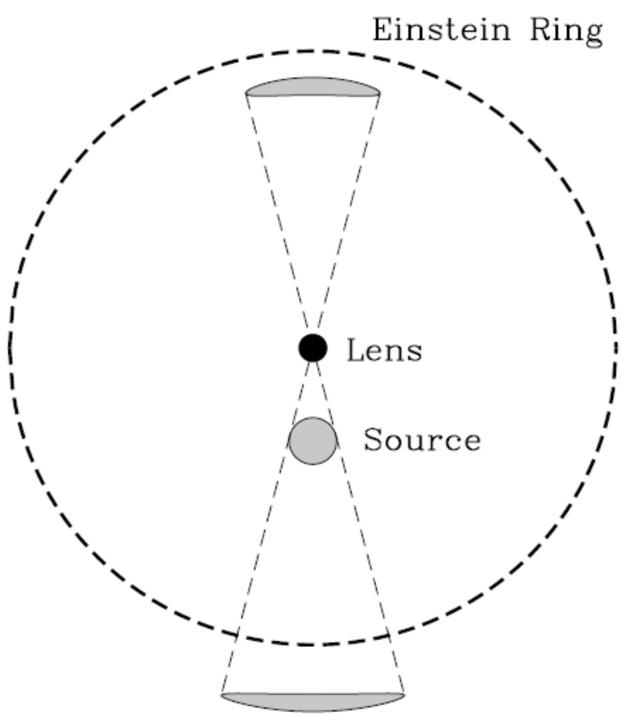


Fig. 6. Elongation of the two background source images for the microlensing event model (case 1) discussed in Sect. 3.3, and also shown in Fig. 4. The unlensed source diameter is 500 μarcsec. The image elongation is shown at the moment of the smallest lens-source separation, and the largest magnification during the event.

Delplancke et al. 2001

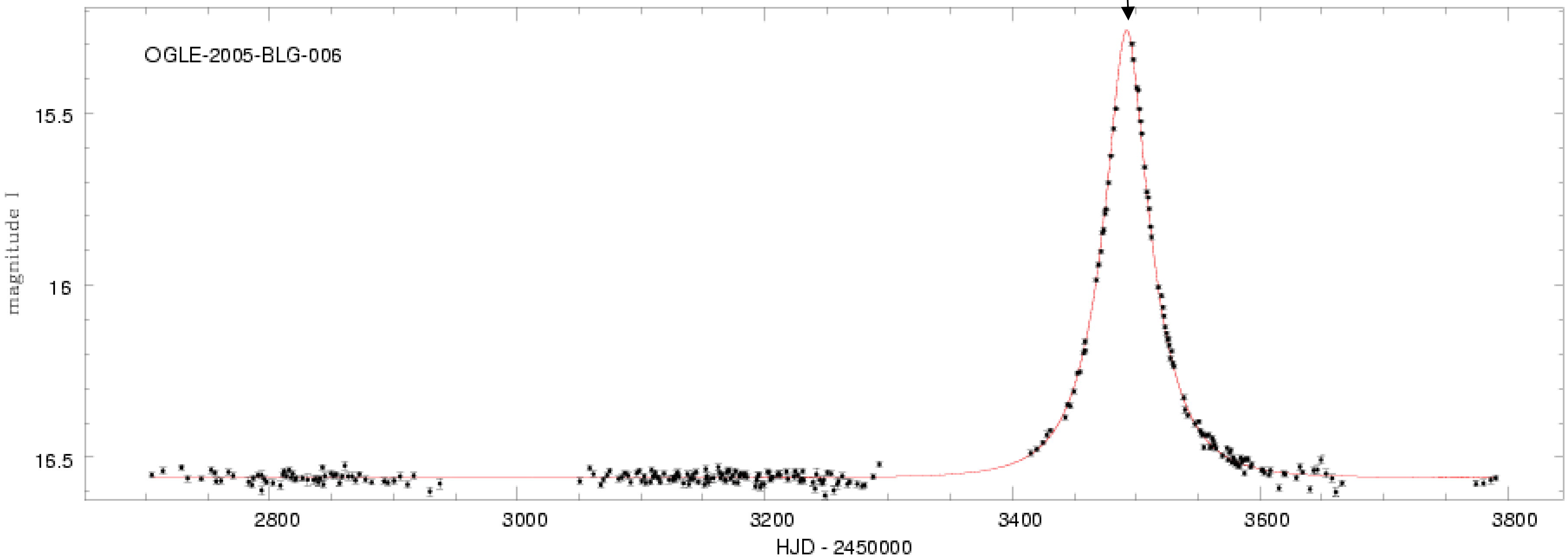
Microlensing geometry : Flux amplification

Einstein radius crossing time

$$A = \frac{u^2 + 2}{u\sqrt{u^2+4}}\ ; \quad u = \sqrt{u_{\min}^2 + [2(t-t_0)/\hat{t}]^2}$$

separation of the lens from source-observer line in unit of Einstein

time of max amplification



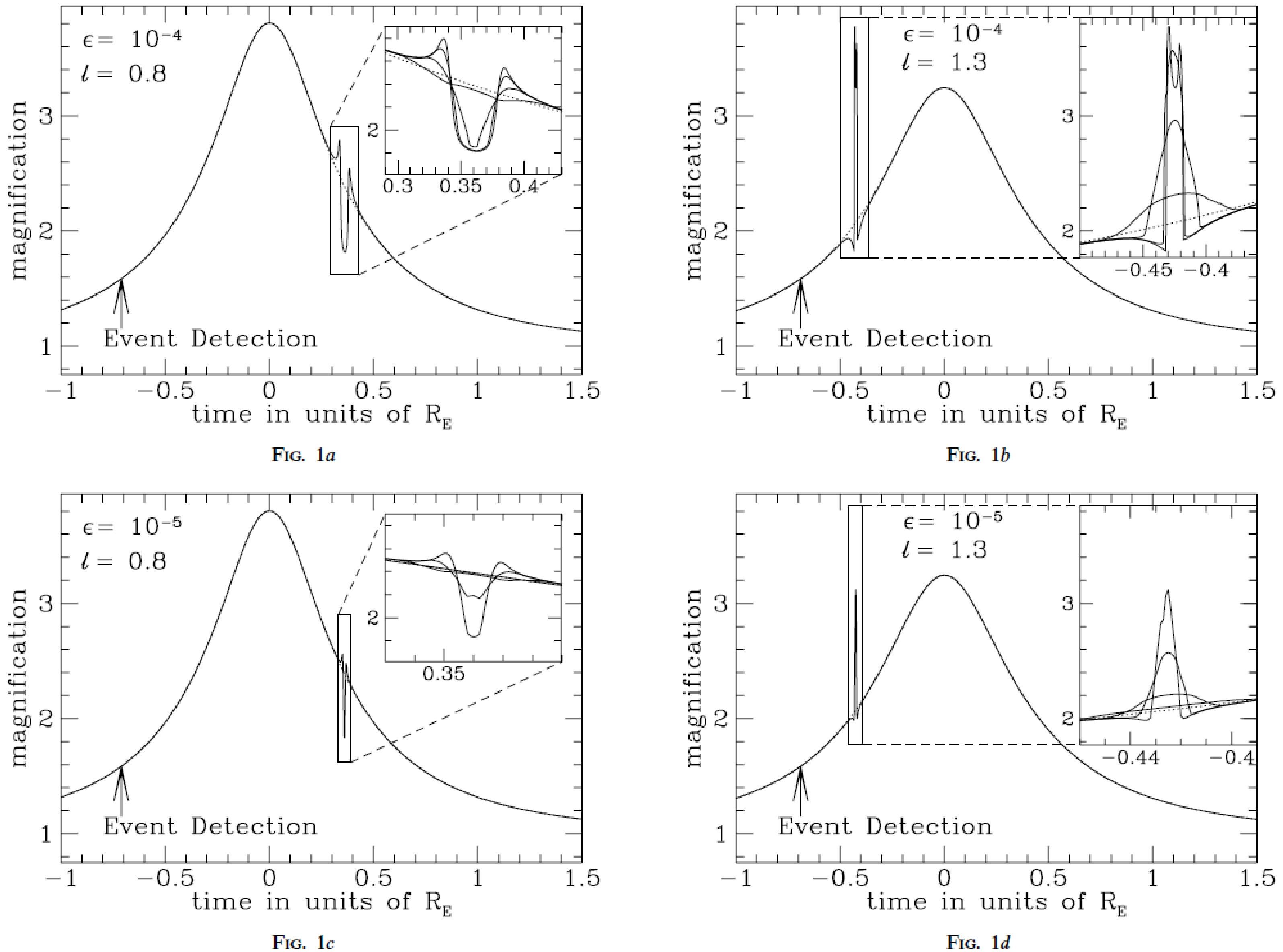
Microlensing geometry : Flux amplification with planet

planet has its own microlensing event

Event is short due to smaller planet mass

Einstein radius is small → source angular size can affect lightcurve

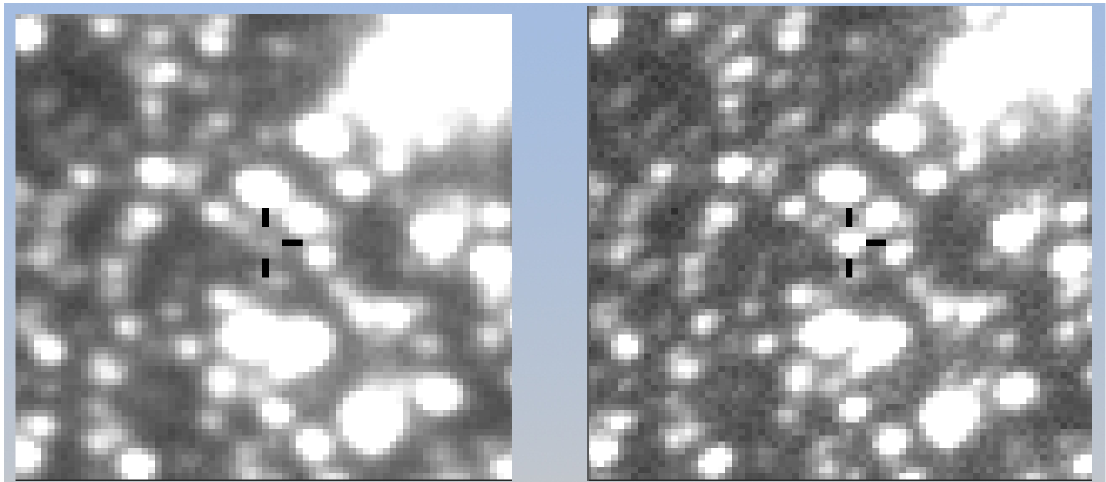
Bennett & Hung Rhie 1996

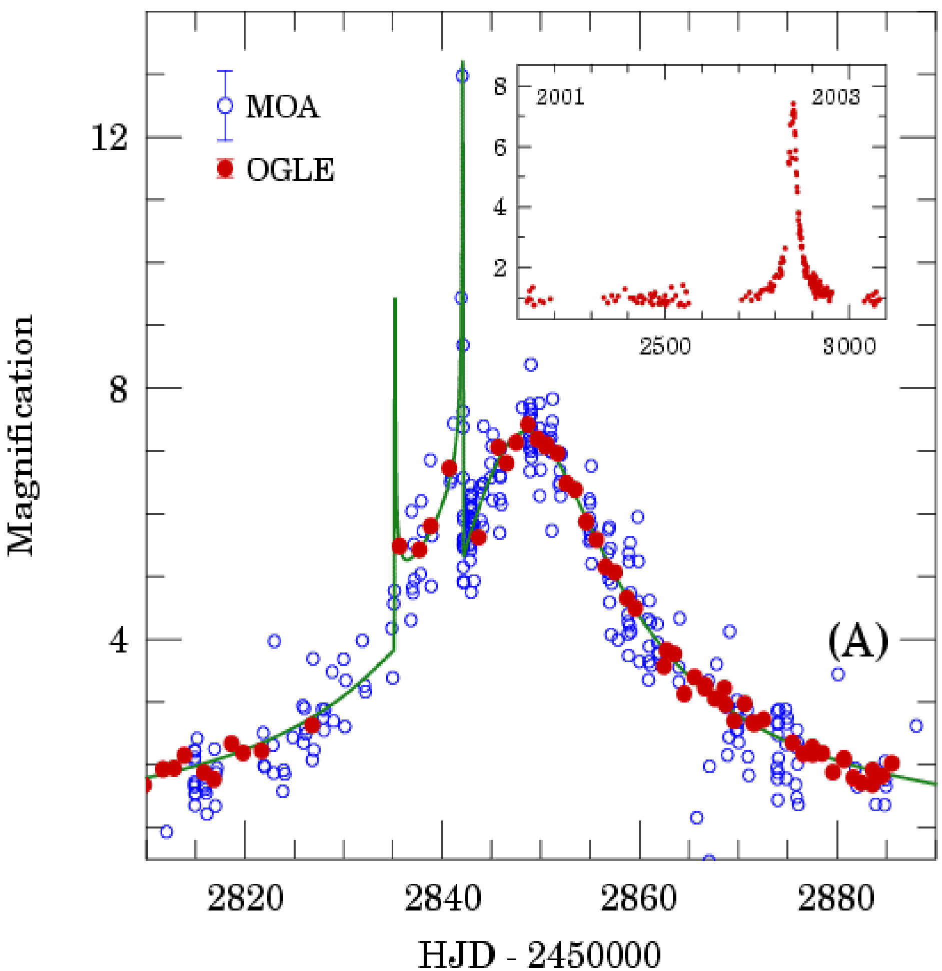


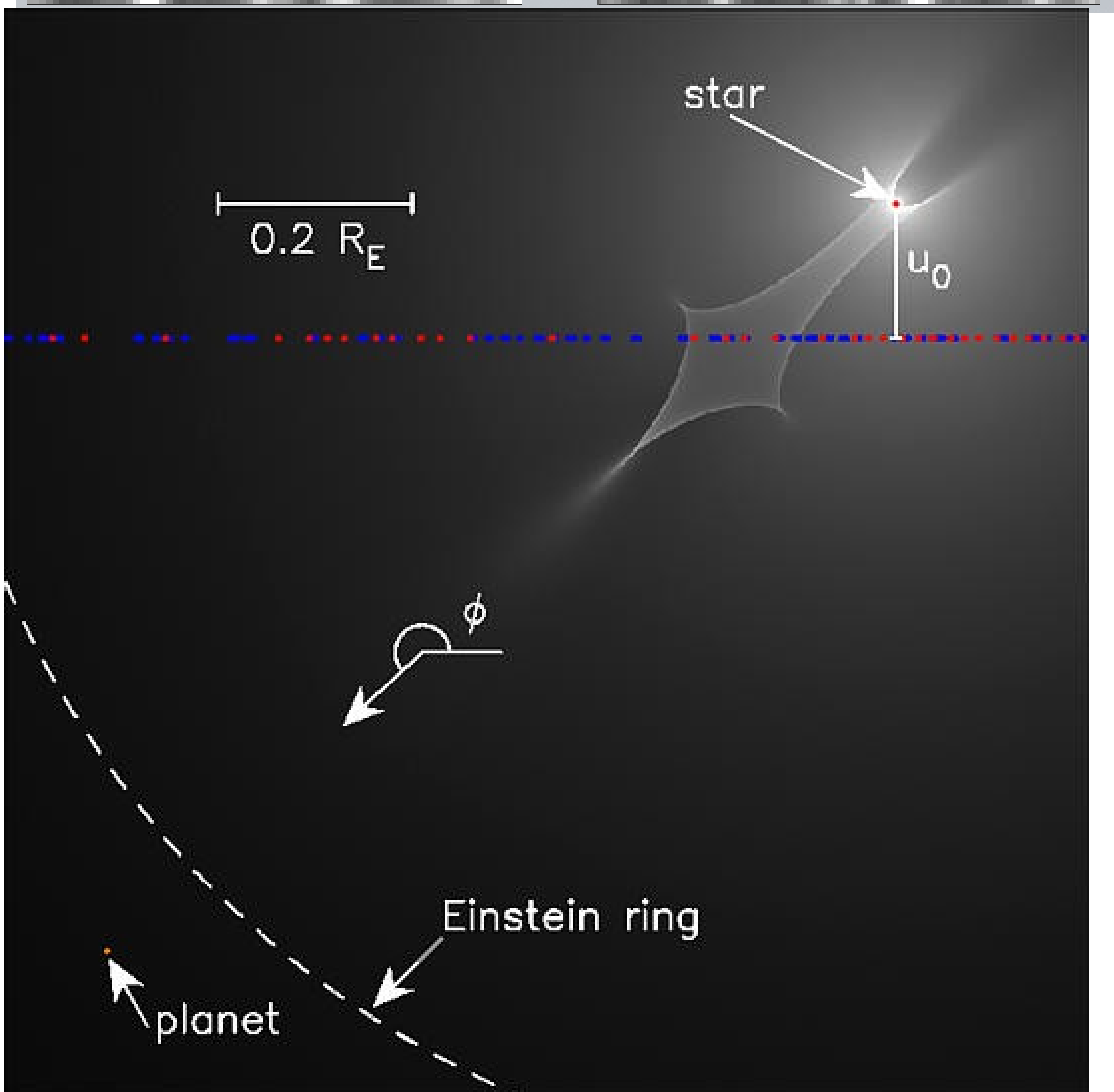
Fɪɢ. 1.—Microlensing light curves that show planetary deviations are plotted for mass ratios of $\epsilon = 10^{-4}$ and 10^{-5} and separations of $l = 0.8$ and 1.3. The main plots are for a stellar radius of $r_s = 0.003$ while the insets show light curves for radii of 0.006, 0.013, and 0.03 as well. (The amplitude of the maximum light curve deviation decreases with increasing r_s.) The dashed curves are the unperturbed single lens light curves, $A_0(t)$. For each of these light curves, the source trajectory is at an angle of $\sin^{-1} 0.6 = 36^\circ.9$ with respect to the star-planet axis. The impact parameter $u_{min} = 0.27$ for the $l = 0.8$ plots and $u_{min} = 0.32$ for the $l = 1.3$ plots.

Microlensing geometry :
Flux amplification with planet

First microlensing detection of massive planet (OGLE+MOA)

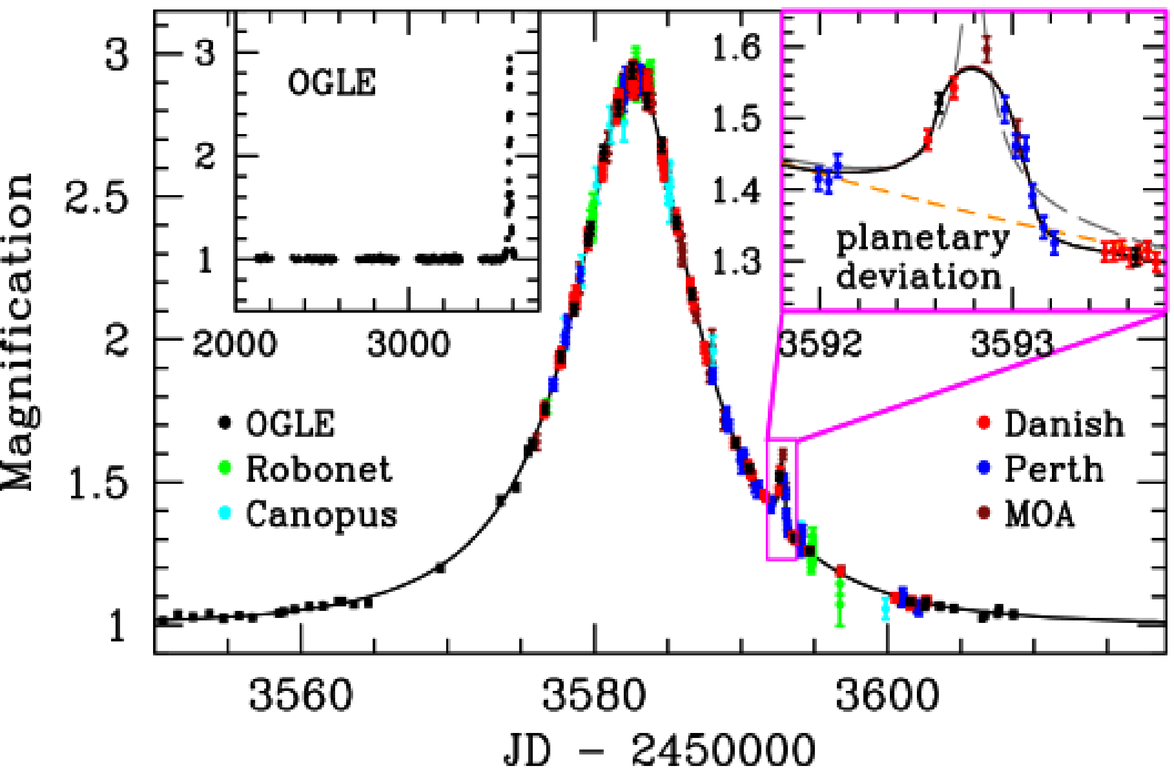


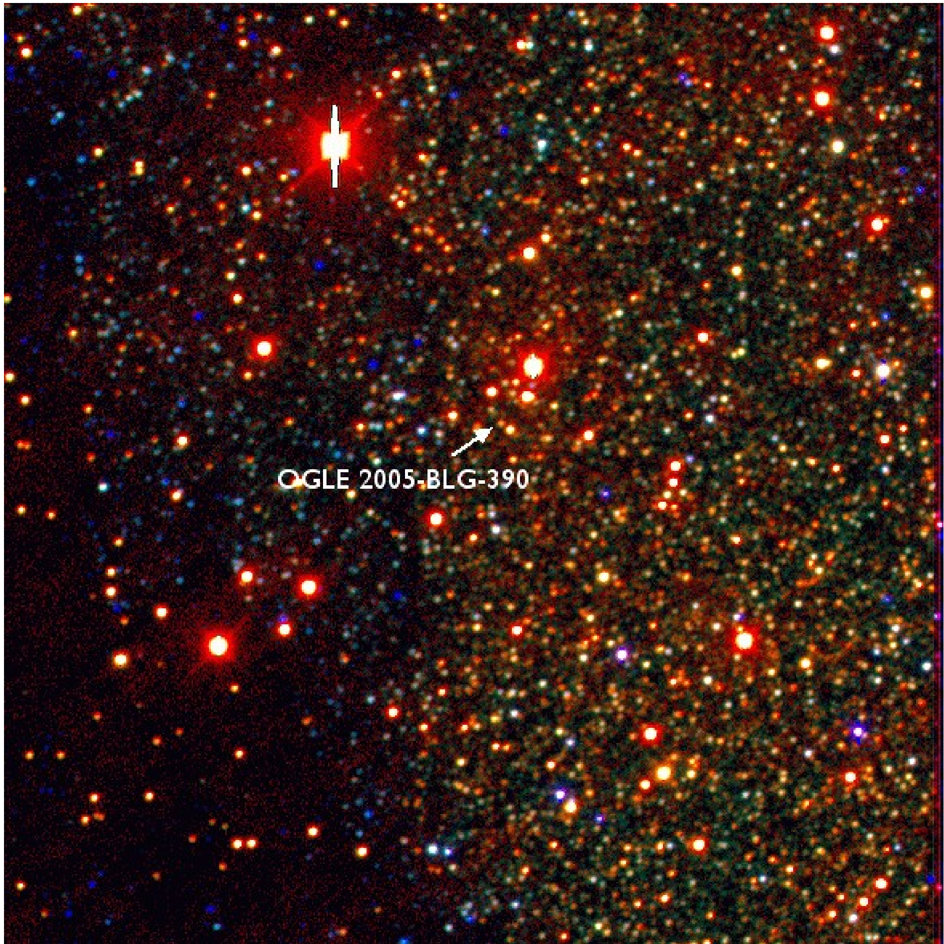




Discovery of a 5.5 Earth mass planet

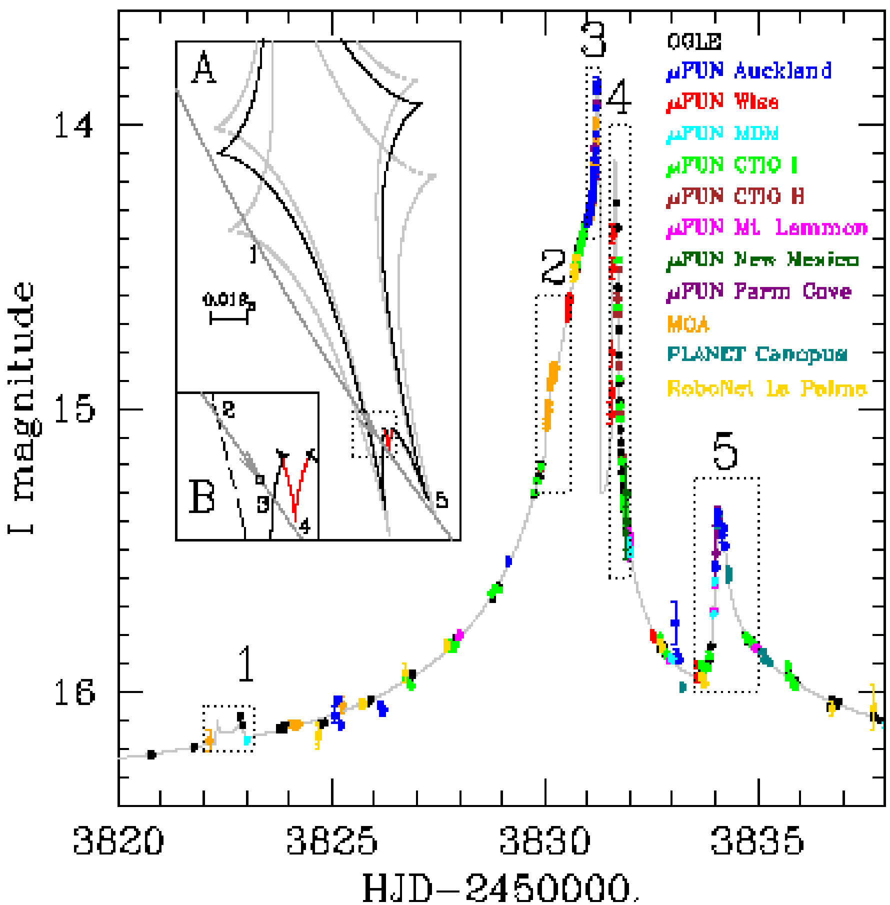
Search strategy: first, identify microlensing event (slow rise in flux seen by OGLE)
Then, follow-up photometry with multiple telescopes.





Discovery of a 2-planet system (Gaudi et al. 2008)

Complicated light curve, with large flux amplification as background source moves across caustics.
→ allows detailed derivation of system geometry, including orbital motion seen during event



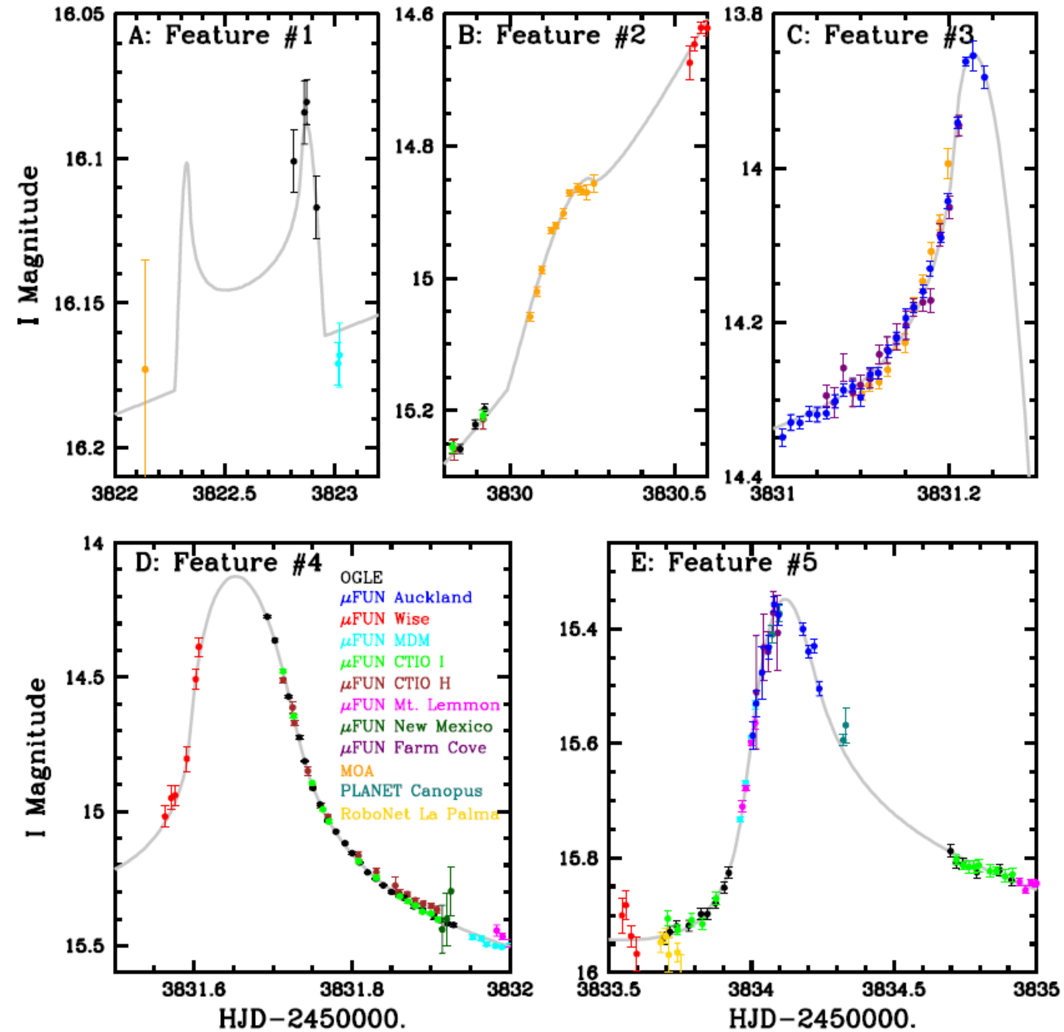


Figure 2: Five features of light curve from Fig. 1, which determine planetary geometry. A) Feature 1: weak cusp crossing; B) Feature 2: weak caustic entrance; C) Feature 3: strong caustic exit; D) Feature 4: strong cusp approach; E) Feature 5: moderate cusp approach. Features 1, 2, 3, and 5, are explained by the black portion of the caustic seen in in Fig. 1A. Feature 4 requires an additional cusp in the caustic, which is shown as the red curve. Data have been binned for clarity.

Microlensing surveys: goals and challenges

Low probability event: need to monitor large number of stars

- probability is smaller than transit
- signal is usually much stronger (amplification ~2x), easily detectable

No follow-up possible after event: planet is only detectable during microlensing event, and host star often cannot be seen
Note: Ground-based imaging after event can identify host star as its image drifts away from background source

Microlensing is **sensitive to outer and isolated planets** that cannot be detected by other techniques → provides valuable complementary information on statistical occurrence of exoplanets, even with small number of detections
(transit, RV and astrometry are biased to detect planets at small separation)

→ microlensing data suggests that free-floating planets are common
(Nature 473, 349 (2011))

The Optical Gravitational Lensing Experiment (OGLE)

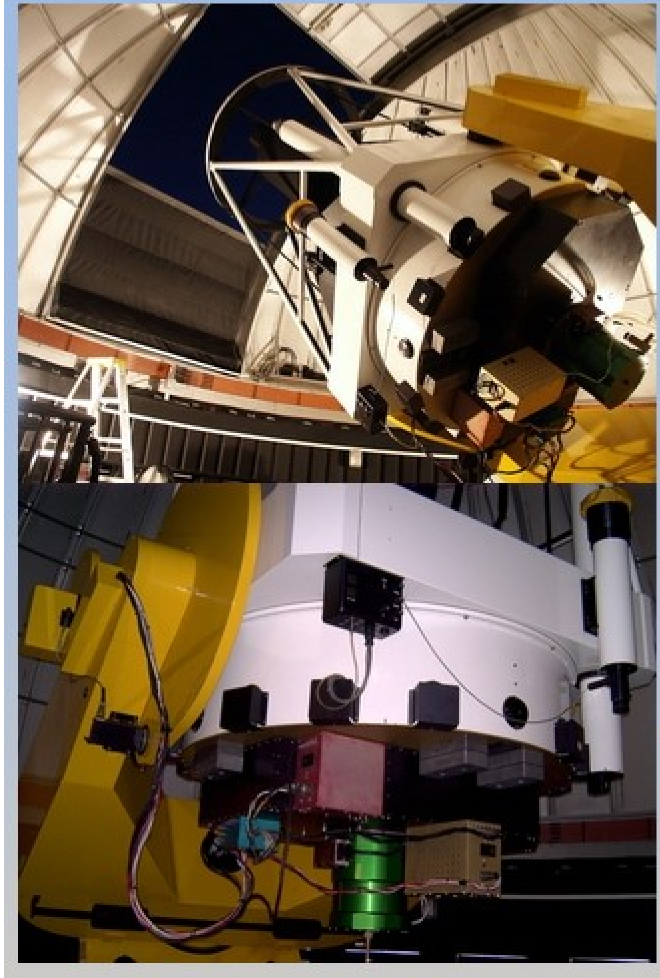
1.3 m Warsaw University Telescope Las Campanas Observatory, Chile

Telescope technical data:

- 1.3m (51") primary mirror diameter
- 1:9.2 (1:2.8 primary) Ritchey-Chretién system; 17.4 arcsec/mm focal scale
- 3-element field corrector - 1.5° diffraction limited field (80% of light within 0.5 arcsec diameter)
- Ultra Low Expansion (ULE) glass mirrors
- Fully automated, computer controlled operation
- Fork, paralactic mount, friction drives (no backlash) allowing any tracking rate in RA and DEC
- Light, steel enclosure with Ash-dome dome, easy ventilation (louvers on telescope and ground level). Minimalization of heat sources in the telescope building
- Remote control of the telescope and instruments from "control building" located 15 m away from the telescope building. Possibility of remote control over the Internet
- First "optical" light Feb 9, 1996, first "electronic" light Jul 18, 1996

Control building (left) and the dome

The Optical Gravitational Lensing Experiment (OGLE)



The telescope and its instruments

CCD Camera

- Single chip camera (OGLE-II, 1997-2001)
  - SITe 2048×2049 thin chip
  - 90% QE over wide range from *B* to *I*, also some sensitivity in *U*
  - 0.4 arcsec/pixel scale
  - 5 e^- readout noise at 3.8 e^-/ADU (16-bit ADC: 65535 levels)
  - modular control system developed at Warsaw University Observatory - easily expandable to multi-chip mosaic, next generation cameras
- "Second generation" mosaic camera (OGLE-III, 2001-2009)
  - eight thin SITe 2048×4096 CCD chips (total of 8192×8192 pixels)
  - 0.26 arcsec/pixel scale, 35'×35' total field of view
  - 6-9 e^- readout noise (depending on chip) at 1.3 e^-/ADU gain
  - 98 seconds readout time
- "Third generation" mosaic camera (OGLE-IV, 2009-...)
  - 32 thin E2V44-82 2048×4096 CCD chips
  - 0.26 arcsec/pixel scale, 1.4 square degrees total field of view
  - 4.5-6.5 e^- readout noise (depending on chip) at 1.0 e^-/ADU gain
  - 20 seconds readout time

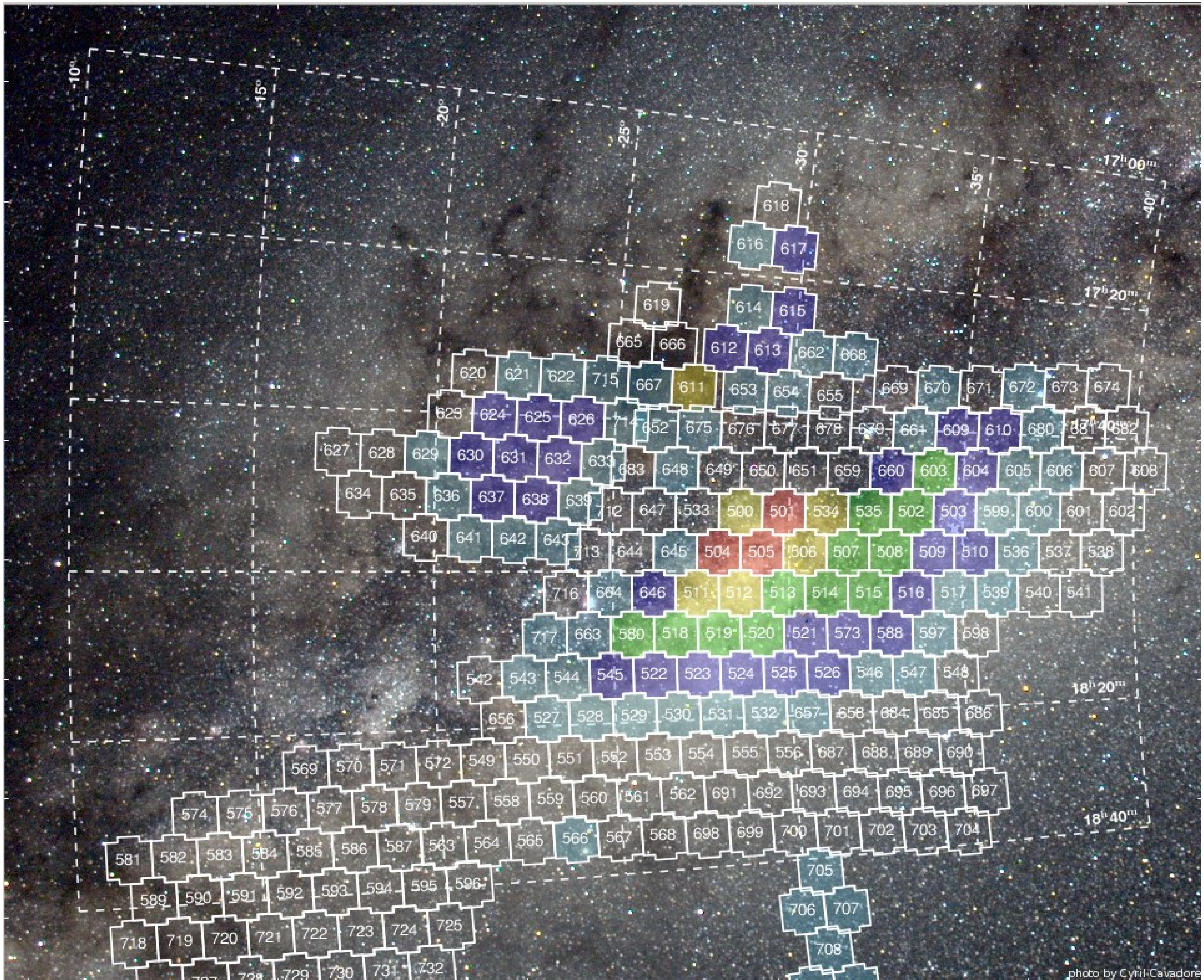
Auto-Guiding System and Filter Wheel (OGLE-II and OGLE-III)

- 512×512 pixels EEV CCD37 detector driven by the same electronics as scientific CCD (2.2 by 2.2 arcmin field)
- Automatic positioning of the guider probe with accuracy of 2 pixels over the entire field of view
- Automatically positioned filter wheel with 7 slots for up to 16 cm diameter filters. Standar *UBVRI* filters installed

Auto-Guiding System and Filter Holder (OGLE-IV)

- Automatically positioned filter holder with two slots for 31 cm × 31 cm size filters. Standard *VI* interferometric filters installed

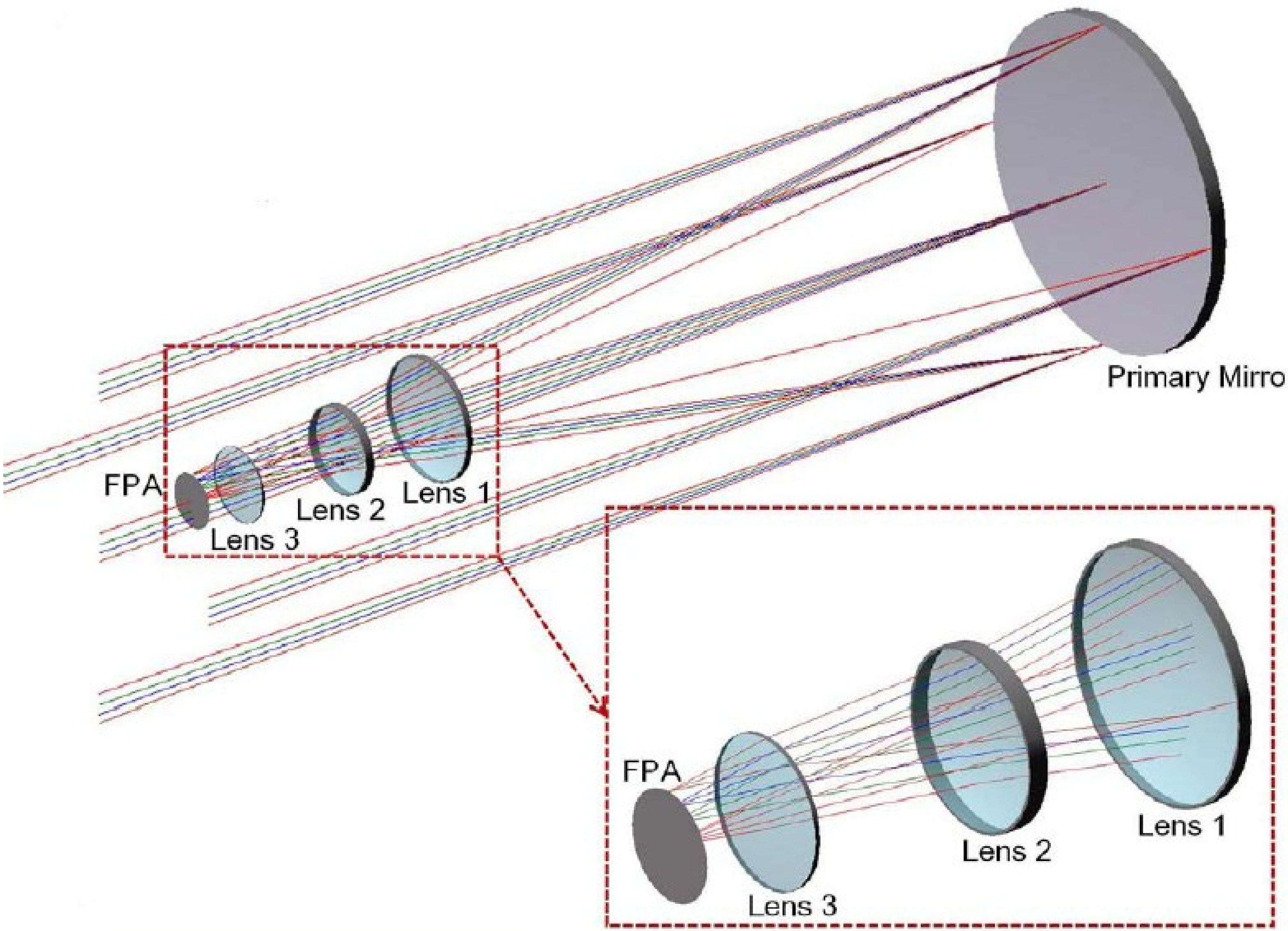
OGLE galactic bulge field (OGLE also includes other fields)



MOA telescope

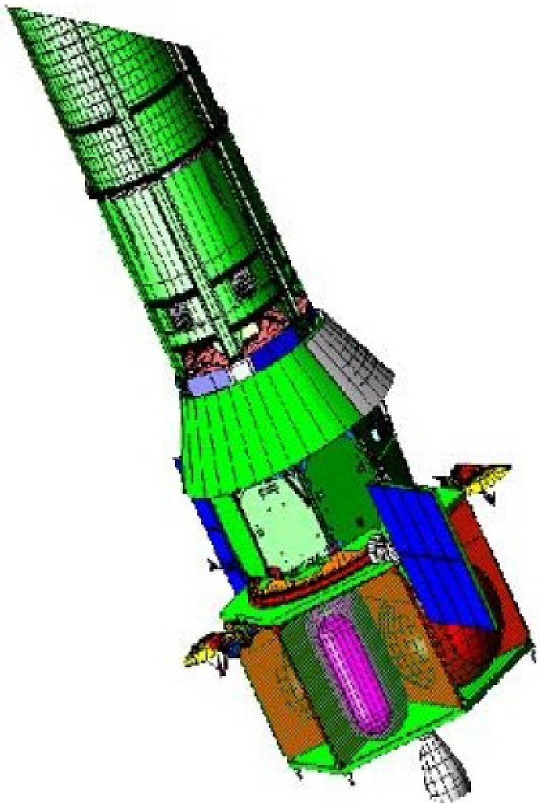
1.8-m telescope in New Zealand

KMTnet (Korean project, 3 wide field telescope, 1.6-m diam each)



One of the optical design with 1.6m, f/3.25, prime focus and 4 deg^2 field of view

Space mission concepts for microlensing



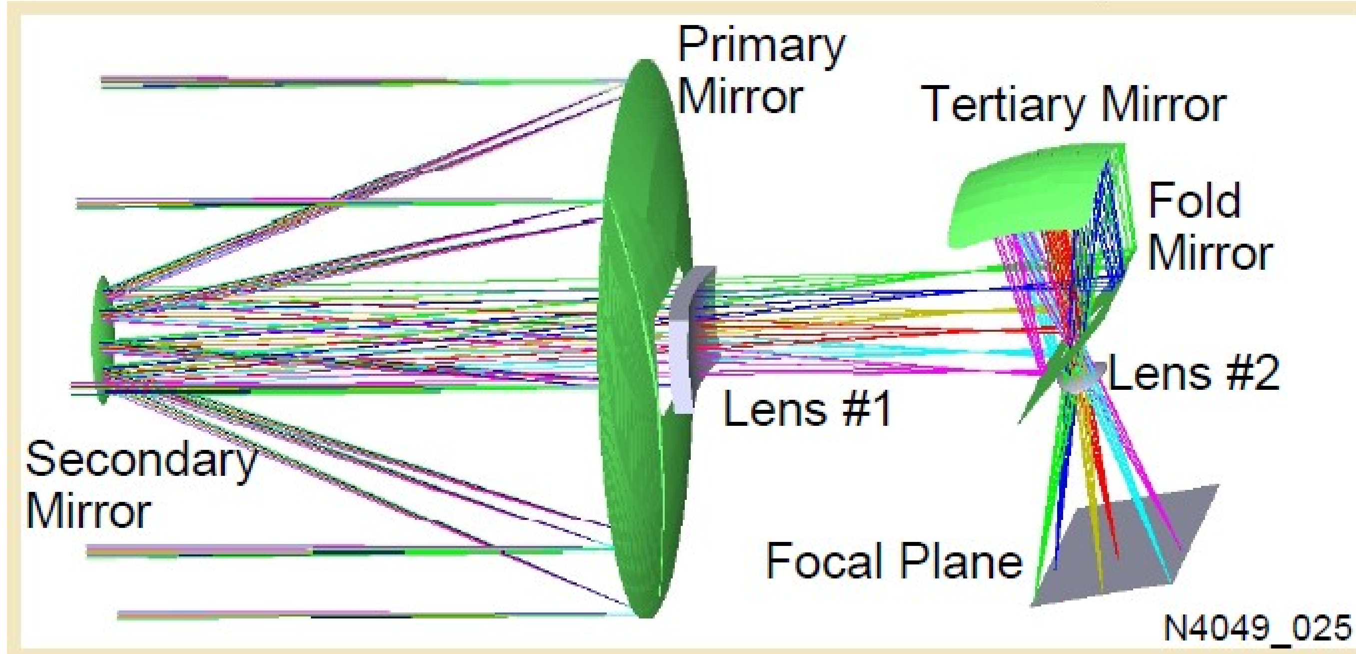
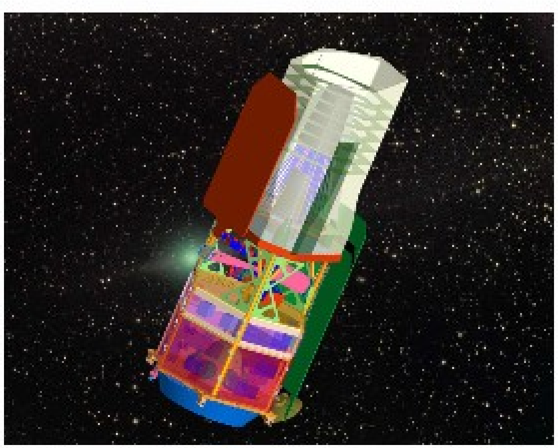


Fig. 14: *MPF Telescope Configuration.*

Microlensing Planet Finder (MPF): 1.1-m telescope,
1.25 sq deg FOV (proposed to NASA)



WFIRST observatory. This is the JDEM-Omega design as specified by the NWNH Decadal Survey. It is a baseline design that is being studied and modified by the Science Definition Team (SDT).

Wide field infrared survey telescope (WFIRST) mission, recently identified as a priority for future mission development, would include a microlensing component.