Detecting Multiple Planets: OGLE-2006-BLG-109

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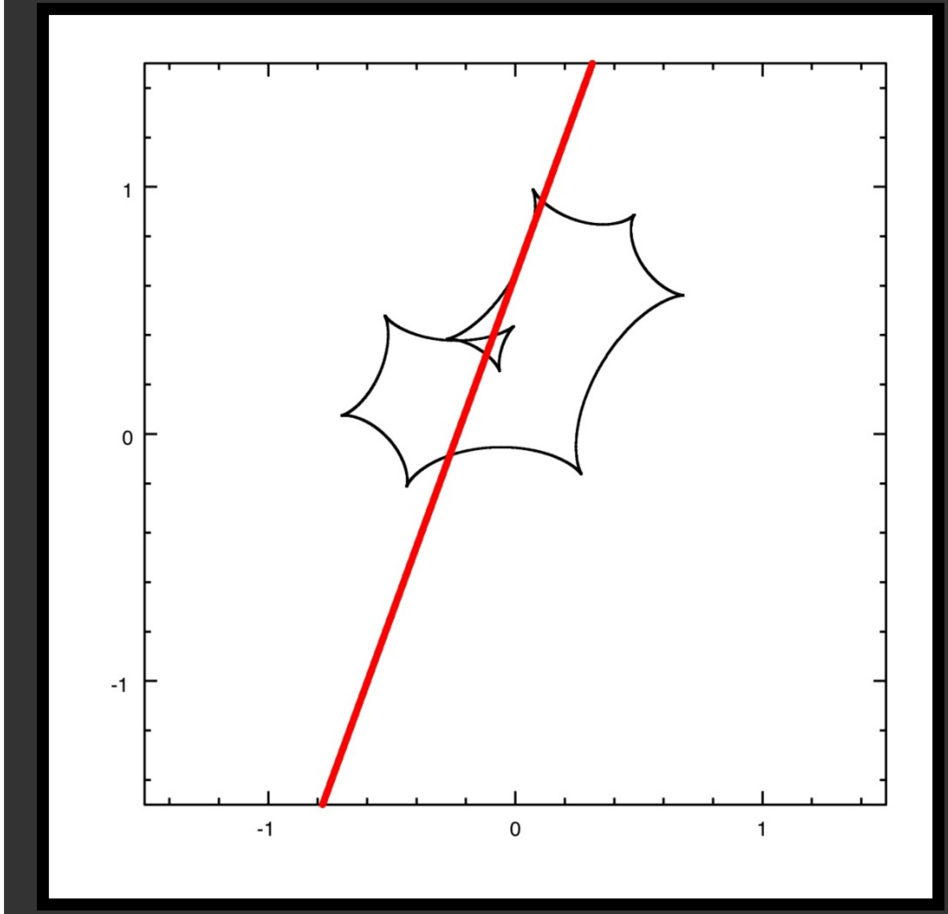
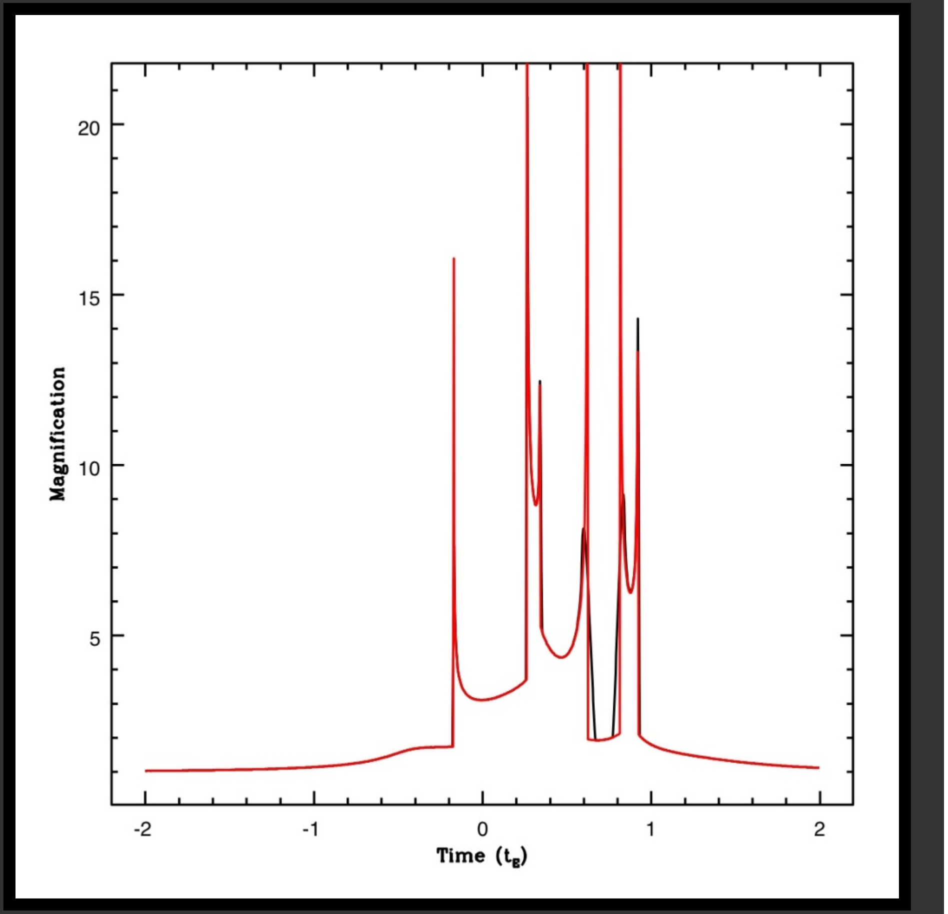
General Triple Lenses - Hard!

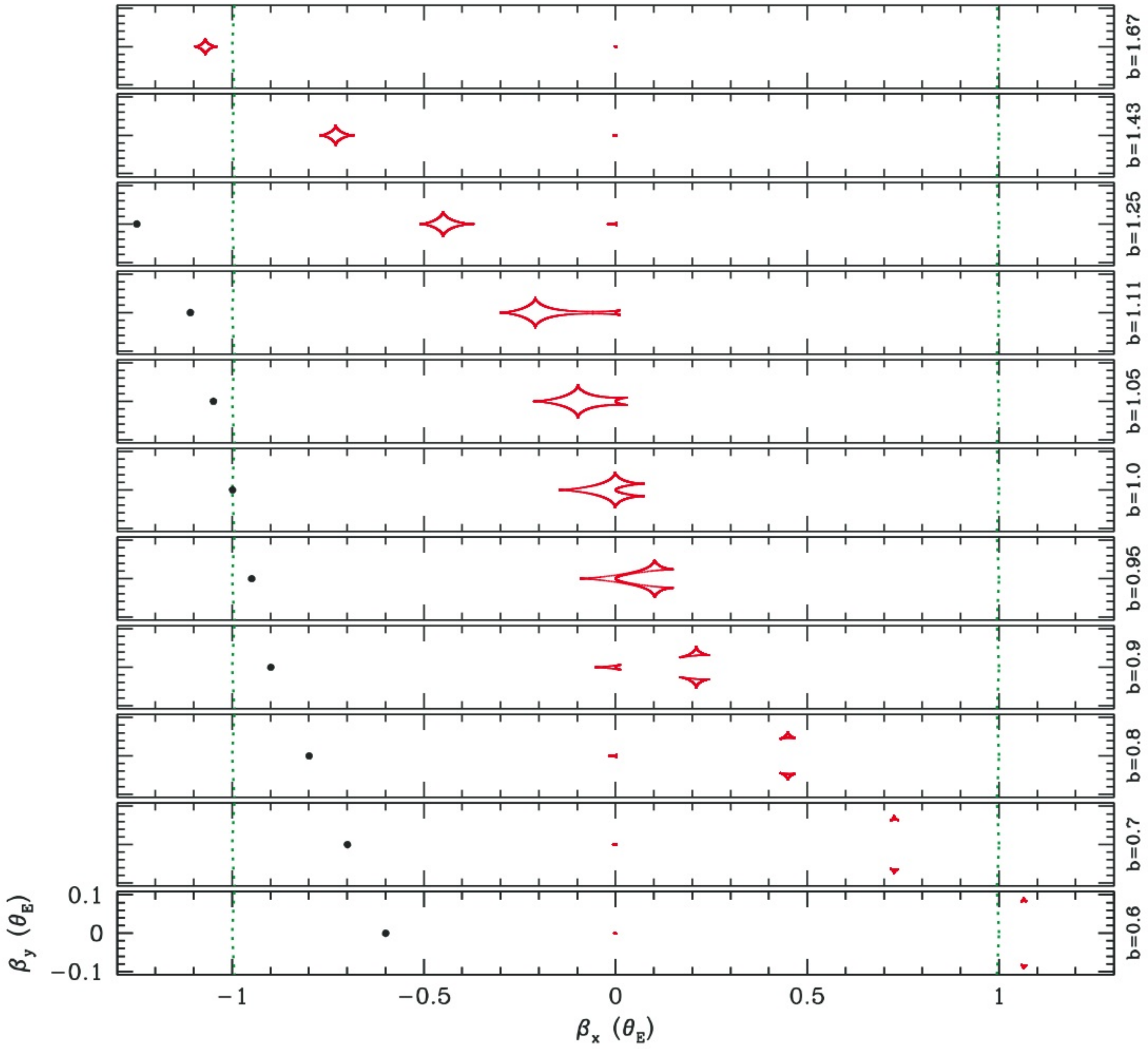
- Parameters d_1, q_1, d_2, q_2, ϕ
- Caustics - messy!
  - Self-intersection
  - Nesting
- Lightcurves - complicated!


1
0
-1
-1
0
1

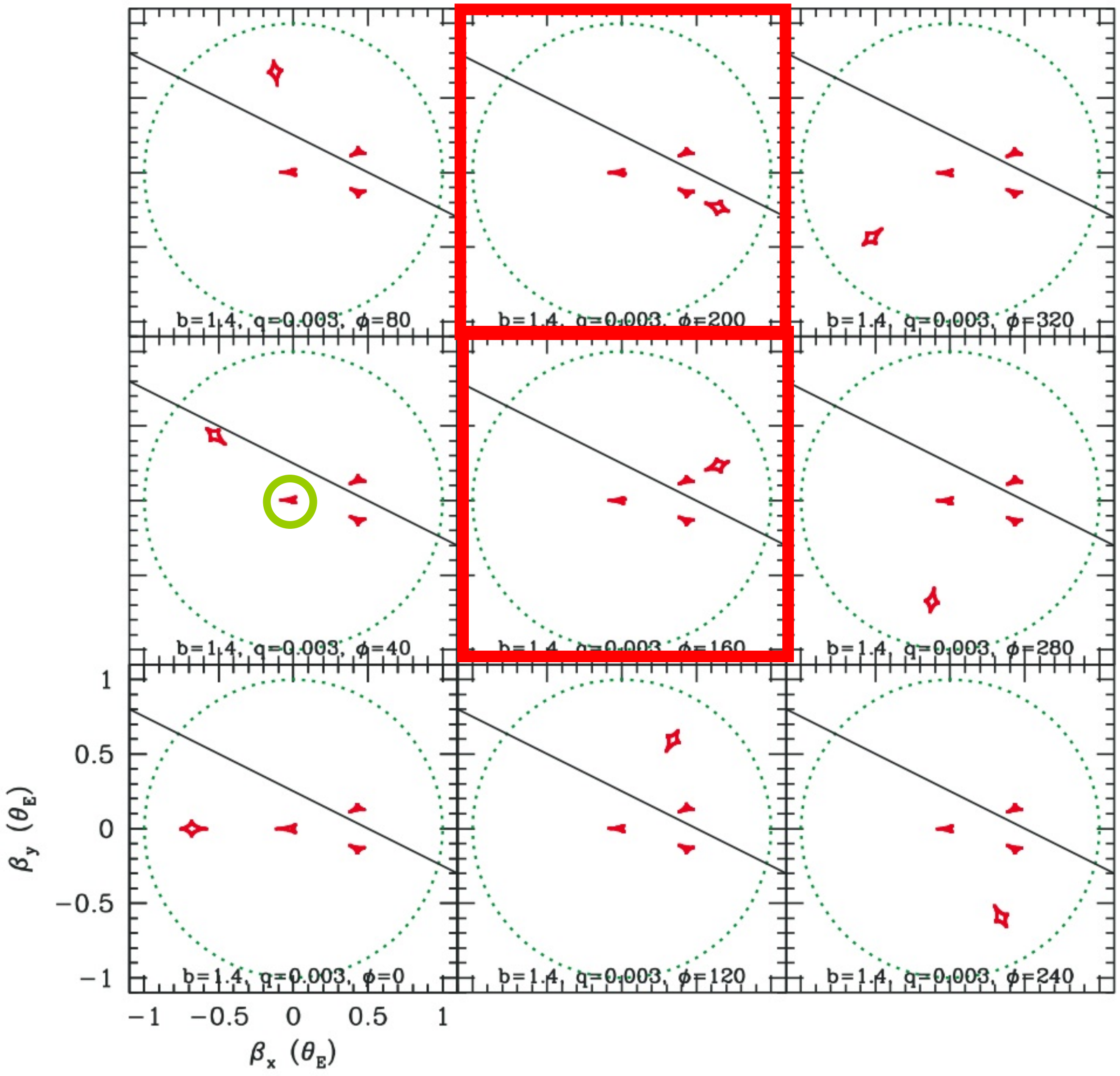

20
15
10
5
Magnification
-2
-1
0
1
2
Time (t_E)

Multiple Planets

- Mass ratios are small.
- Both planets are small perturbations to the overall lightcurve (or mapping).
- Therefore, can essentially be considered a superposition of two planets.
- Makes understanding the properties of lightcurves by multiple planets much easier.



b=1.67
b=1.43
b=1.25
b=1.11
b=1.05
b=1.0
b=0.95
b=0.9
b=0.8
b=0.7
b=0.6
0.1
0
−0.1
β_y (θ_E)
−1
−0.5
0
0.5
1
β_x (θ_E)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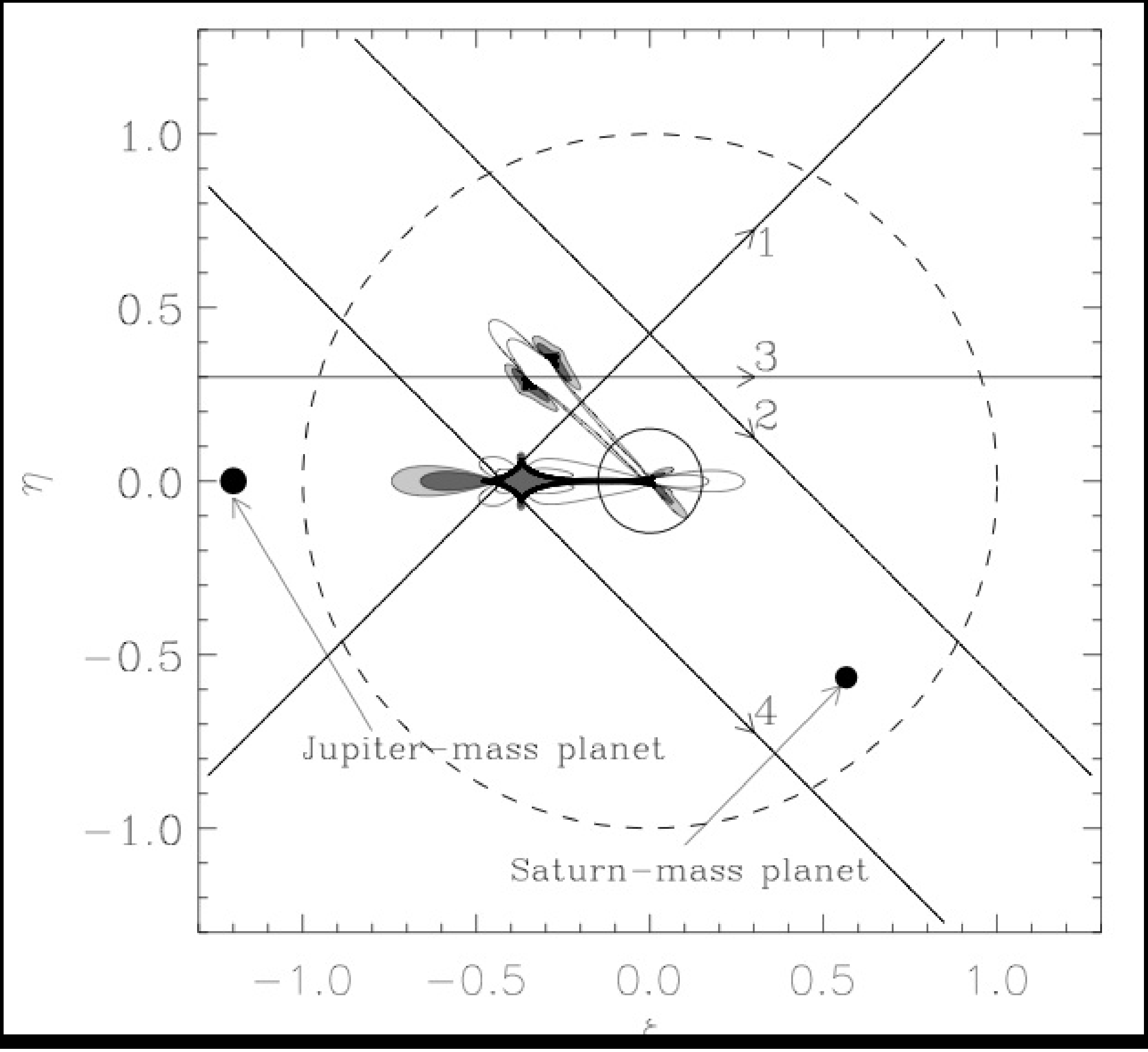
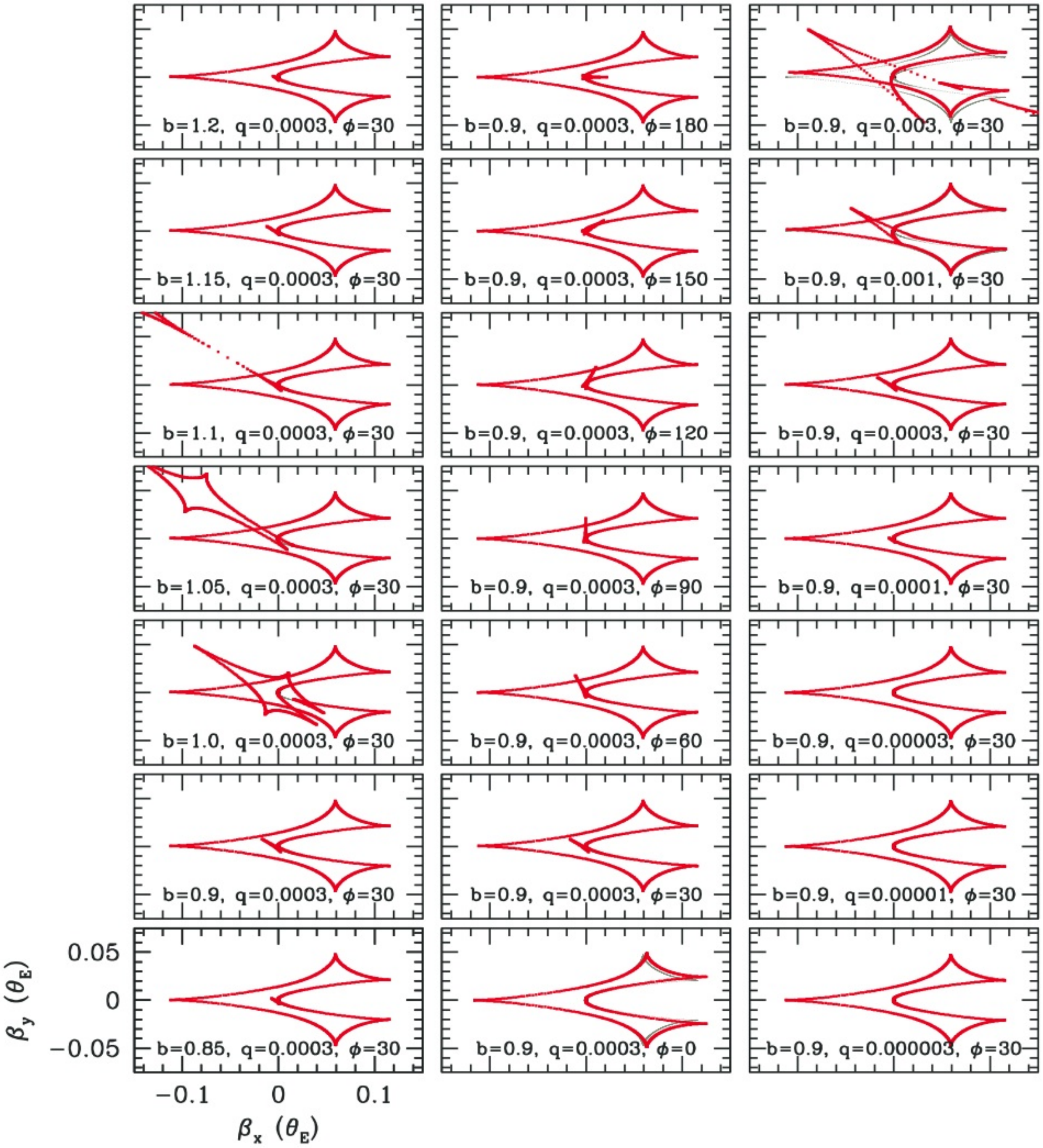
b=1.4, q=0.003, ϕ=200
b=1.4, q=0.003, ϕ=320
b=1.4, q=0.003, ϕ=40
b=1.4, q=0.003, ϕ=160
b=1.4, q=0.003, ϕ=280
b=1.4, q=0.003, ϕ=0
b=1.4, q=0.003, ϕ=120
b=1.4, q=0.003, ϕ=240
1
0.5
0
−0.5
−1
β_y (θ_E)
−1
−0.5
0
0.5
1
β_x (θ_E)

Microlensing by Multiple Planets



Gaudi, Naber & Sackett 1998; Han et al. 2001; Han & Park 2002; Han 2005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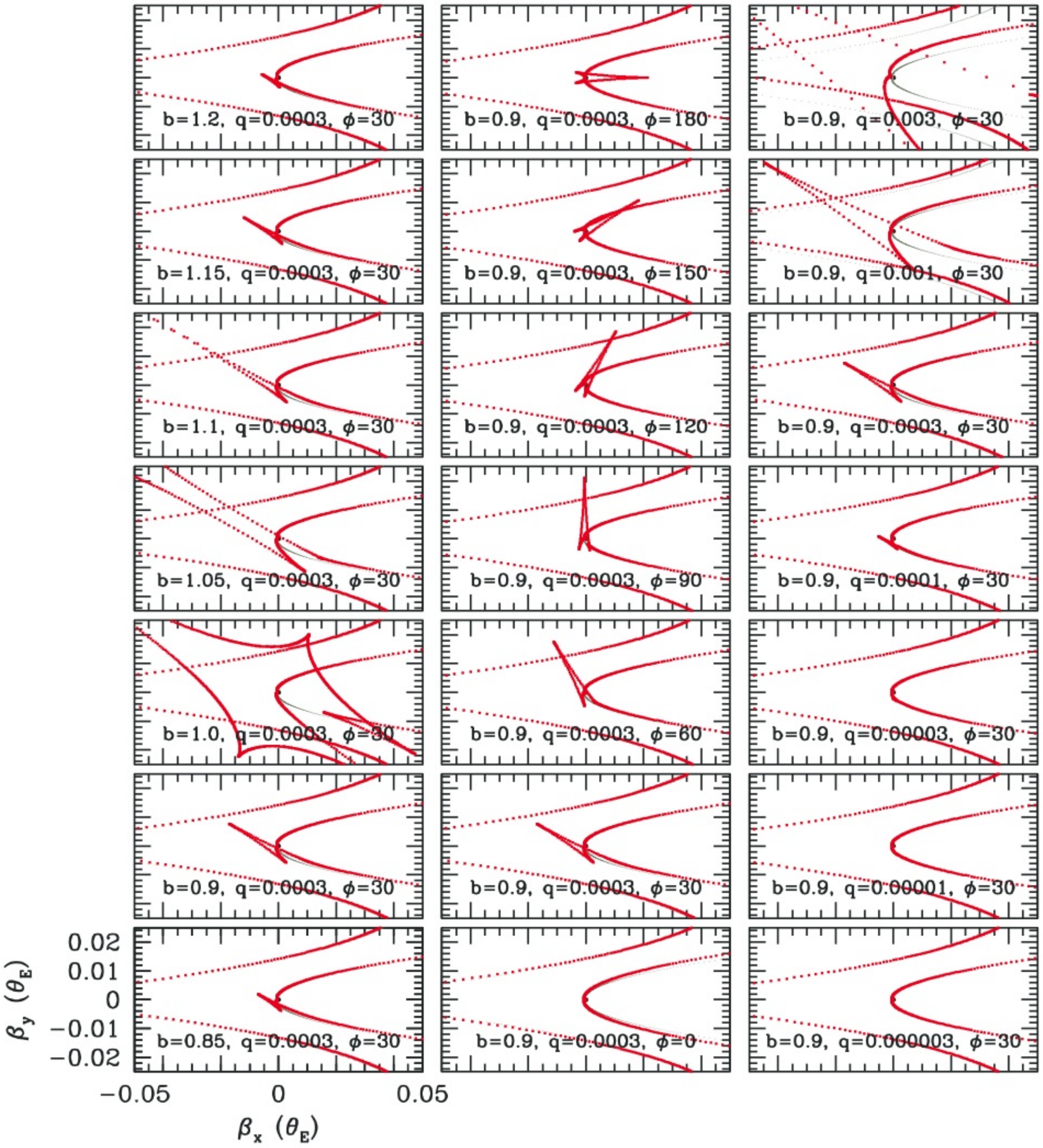
b=0.9, q=0.0003, φ=180
b=0.9, q=0.003, φ=30
b=1.15, q=0.0003, φ=30
b=0.9, q=0.0003, φ=150
b=0.9, q=0.001, φ=30
b=1.1, q=0.0003, φ=30
b=0.9, q=0.0003, φ=120
b=0.9, q=0.0003, φ=30
b=1.05, q=0.0003, φ=30
b=0.9, q=0.0003, φ=90
b=0.9, q=0.0001, φ=30
b=1.0, q=0.0003, φ=30
b=0.9, q=0.0003, φ=60
b=0.9, q=0.00003, φ=30
b=0.9, q=0.0003, φ=30
b=0.9, q=0.0003, φ=30
b=0.9, q=0.00001, φ=30
b=0.85, q=0.0003, φ=30
b=0.9, q=0.0003, φ=0
b=0.9, q=0.000003, φ=30
0.05
0
−0.05
β_y (θ_E)
−0.1
0
0.1
β_x (θ_E)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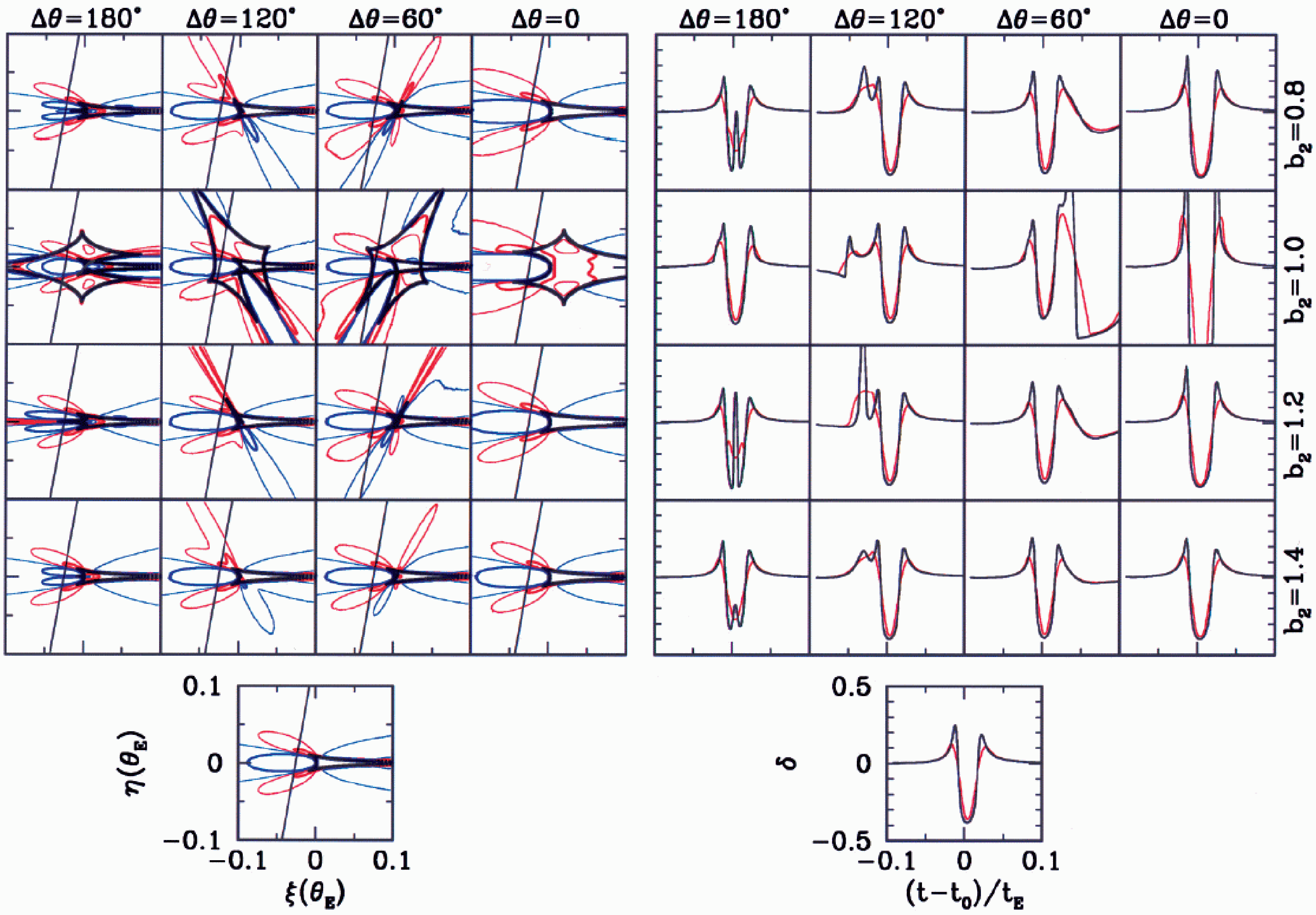
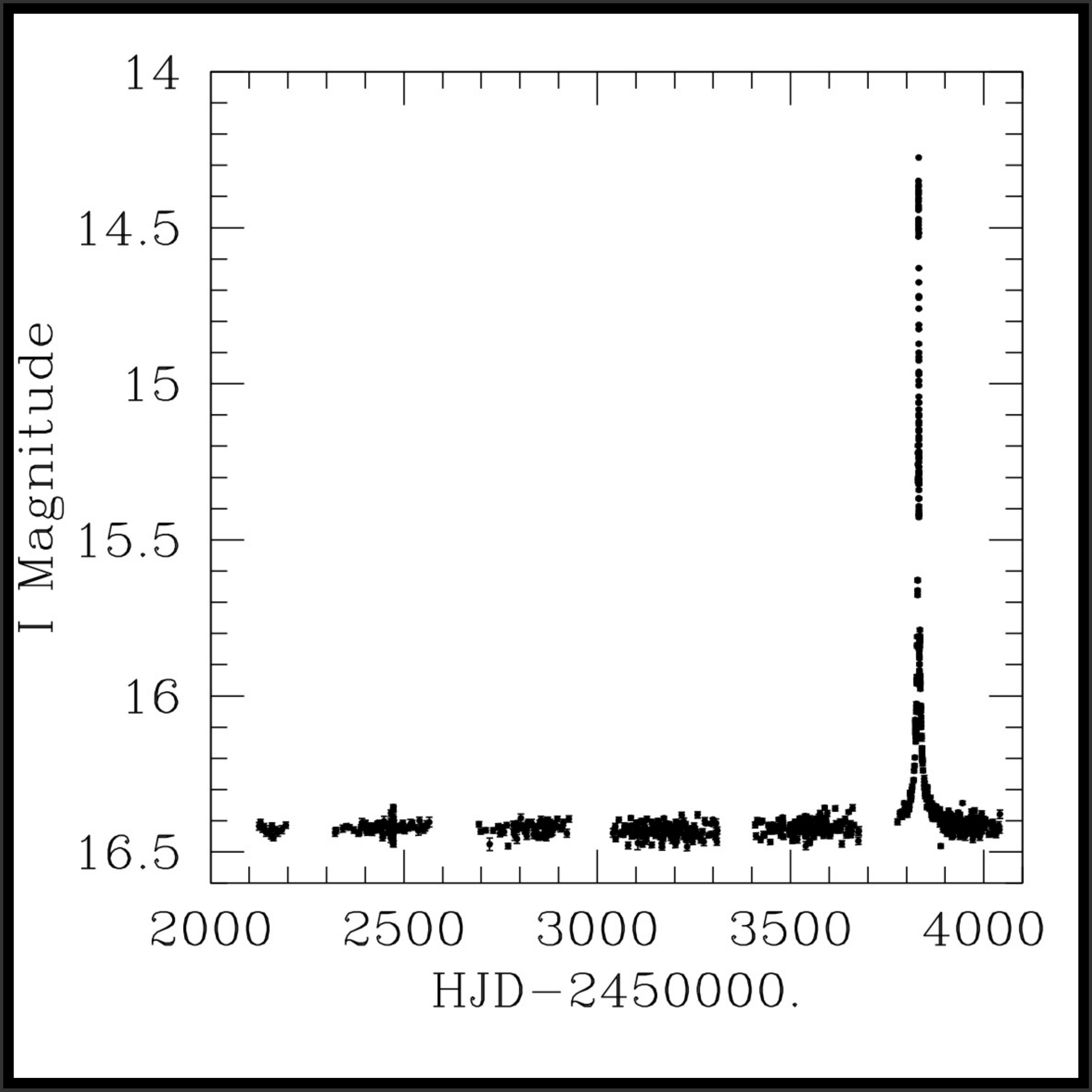
b=0.9, q=0.0003, φ=180
b=0.9, q=0.003, φ=30
b=1.15, q=0.0003, φ=30
b=0.9, q=0.0003, φ=150
b=0.9, q=0.001, φ=30
b=1.1, q=0.0003, φ=30
b=0.9, q=0.0003, φ=120
b=0.9, q=0.0003, φ=30
b=1.05, q=0.0003, φ=30
b=0.9, q=0.0003, φ=90
b=0.9, q=0.0001, φ=30
b=1.0, q=0.0003, φ=30
b=0.9, q=0.0003, φ=60
b=0.9, q=0.00003, φ=30
b=0.9, q=0.0003, φ=30
b=0.9, q=0.0003, φ=30
b=0.9, q=0.00001, φ=30
b=0.85, q=0.0003, φ=30
b=0.9, q=0.0003, φ=0
b=0.9, q=0.000003, φ=30
0.02
0.01
0
−0.01
−0.02
β_y (θ_E)
−0.05
0
0.05
β_x (θ_E)

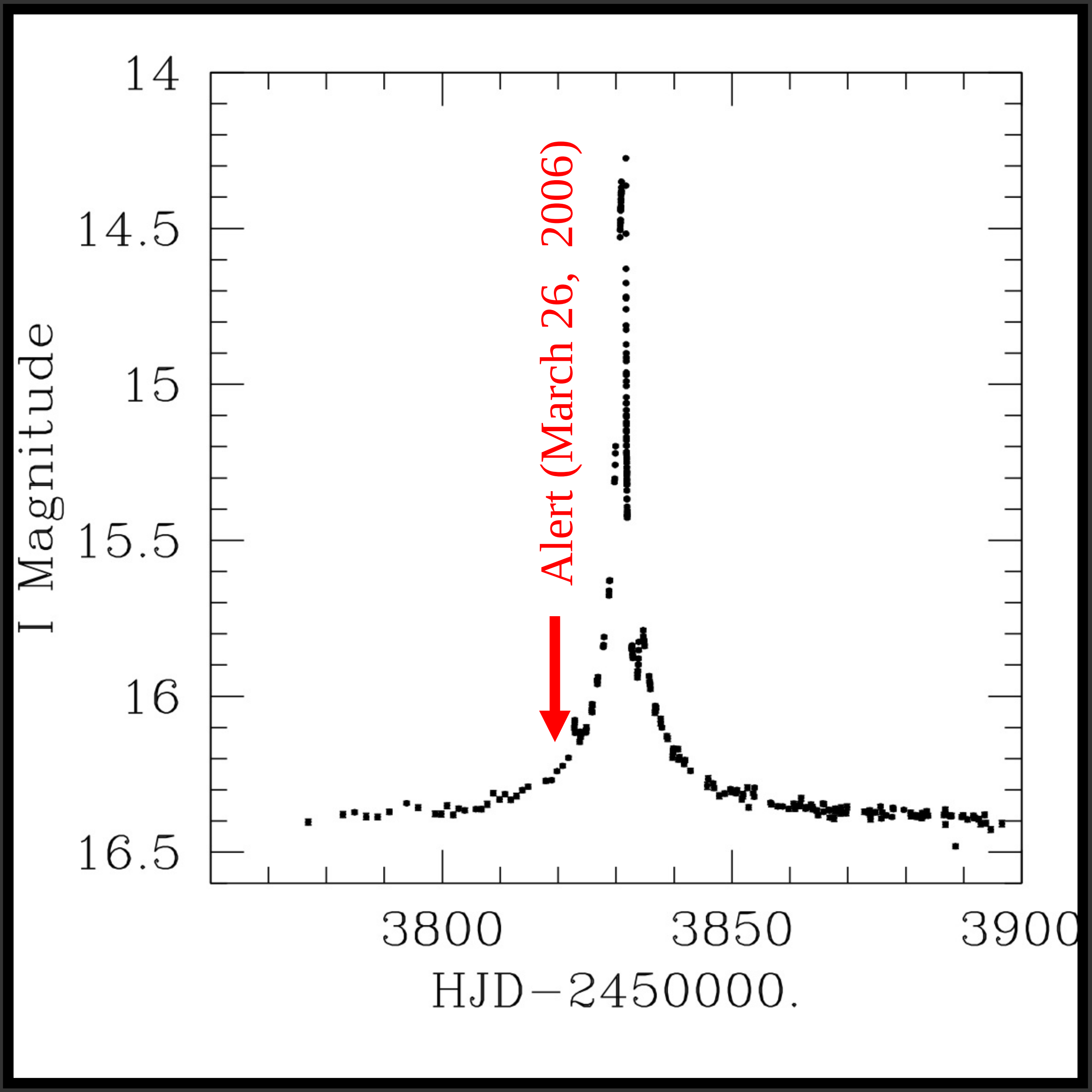


(Gaudi et al. 1998)

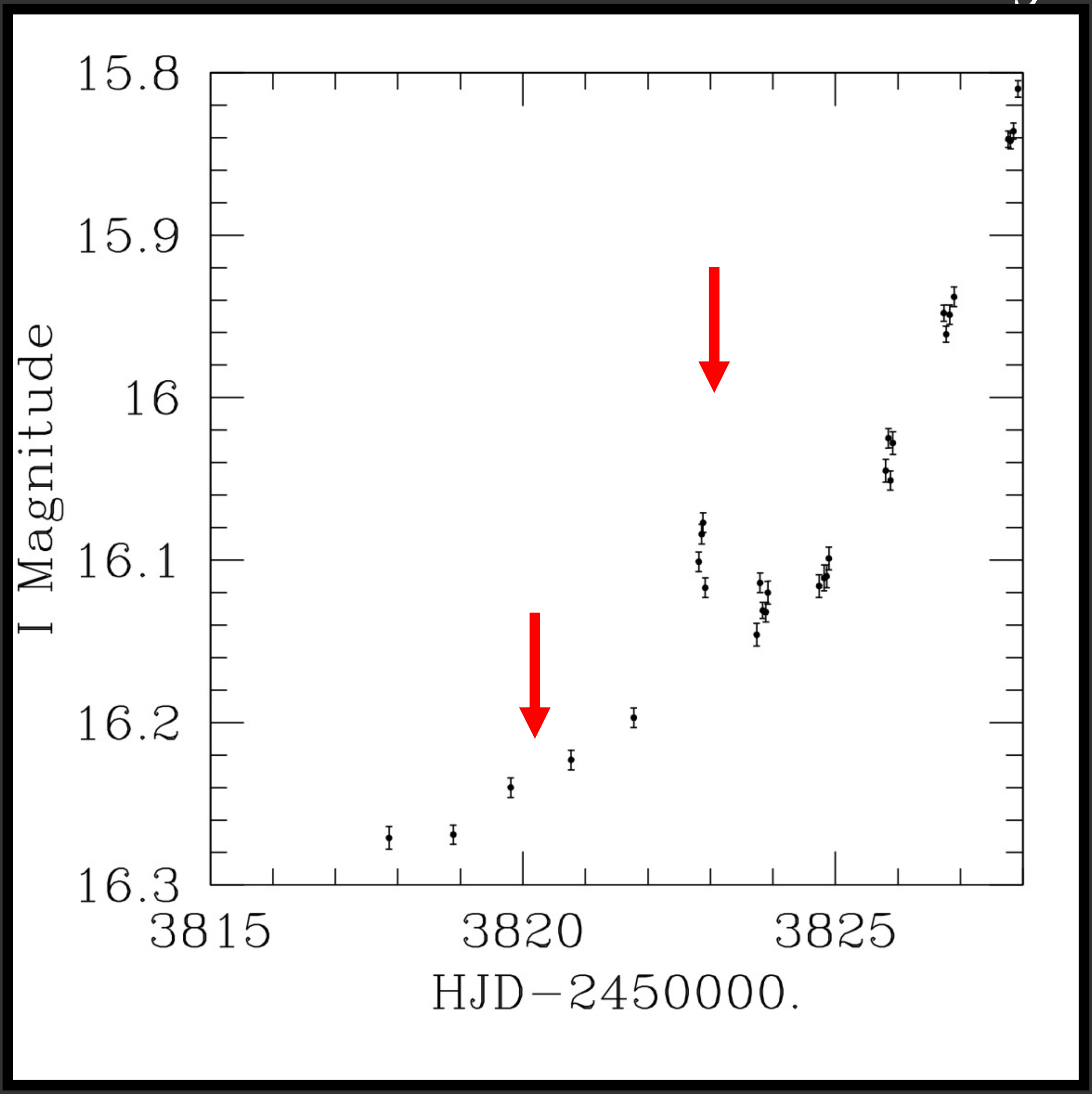
OGLE-2006-BLG-109



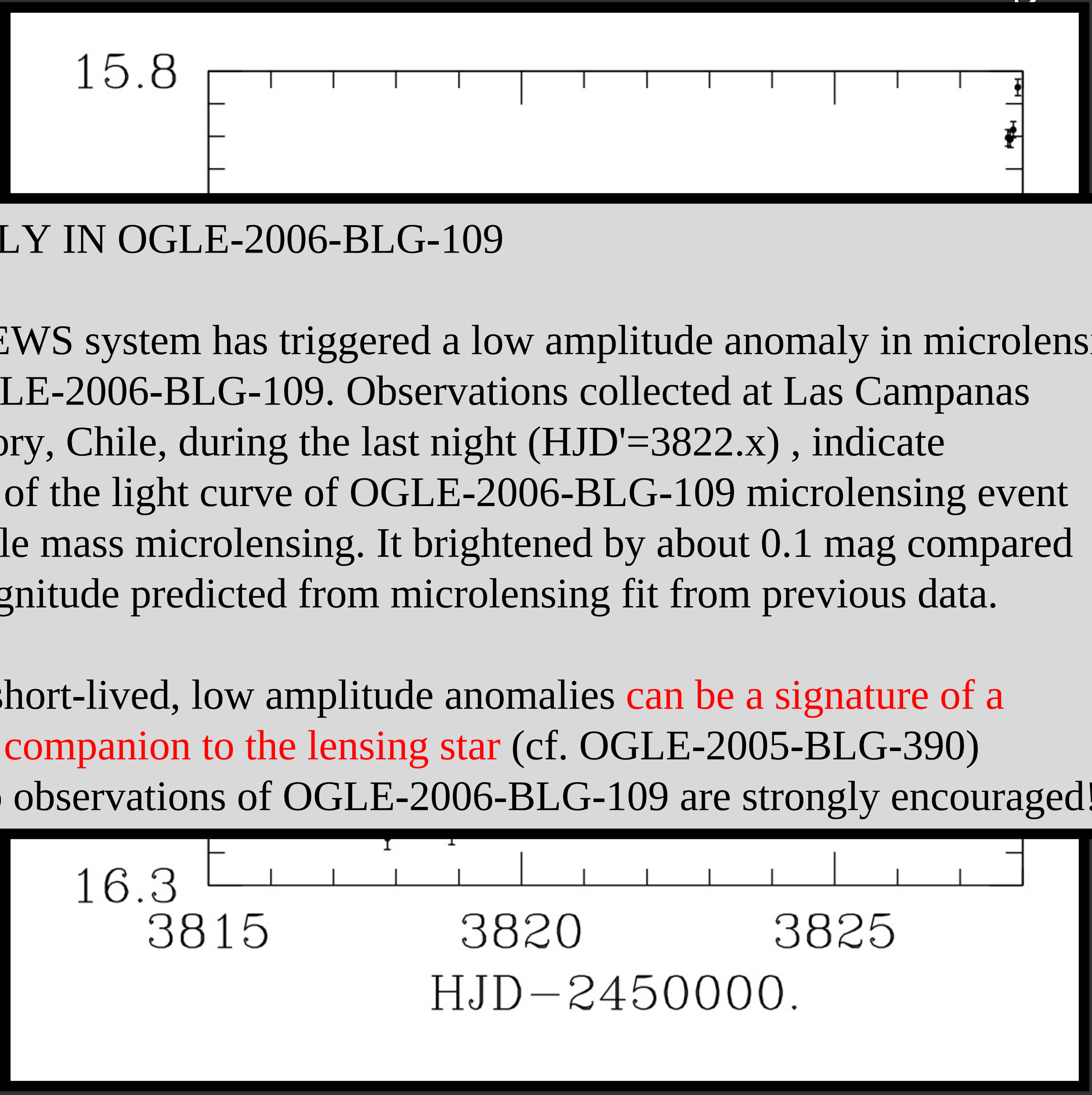
EWS Alert #109 of 2006



EEWS Alert of Anomaly



EEWS Alert of Anomaly

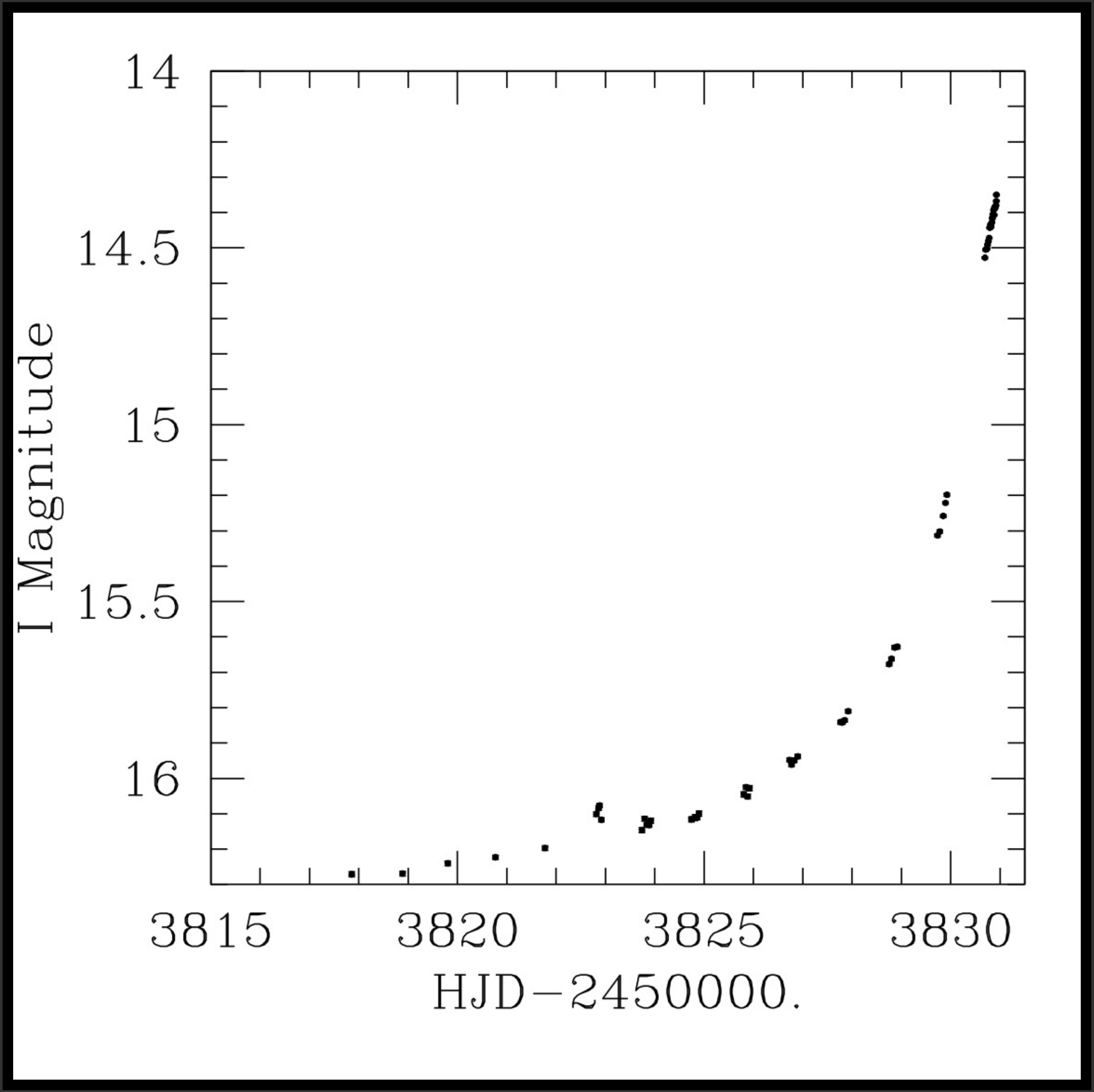


ANOMALY IN OGLE-2006-BLG-109

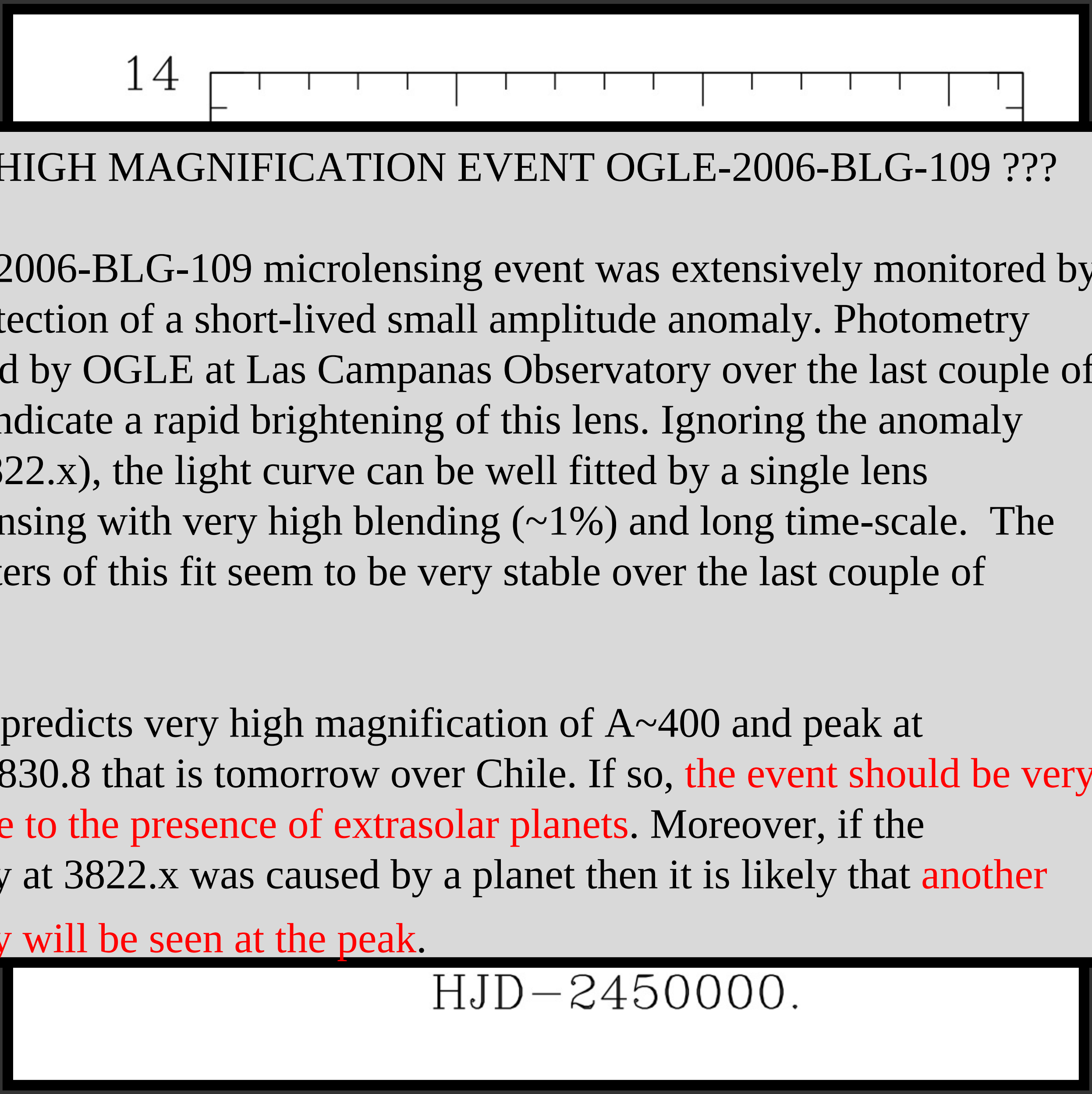
OGLE EEWS system has triggered a low amplitude anomaly in microlensing event OGLE-2006-BLG-109. Observations collected at Las Campanas Observatory, Chile, during the last night (HJD'=3822.x) , indicate deviation of the light curve of OGLE-2006-BLG-109 microlensing event from single mass microlensing. It brightened by about 0.1 mag compared to the magnitude predicted from microlensing fit from previous data.

Because short-lived, low amplitude anomalies can be a signature of a planetary companion to the lensing star (cf. OGLE-2005-BLG-390) follow-up observations of OGLE-2006-BLG-109 are strongly encouraged!!!

Rise to Peak



Rise to Peak

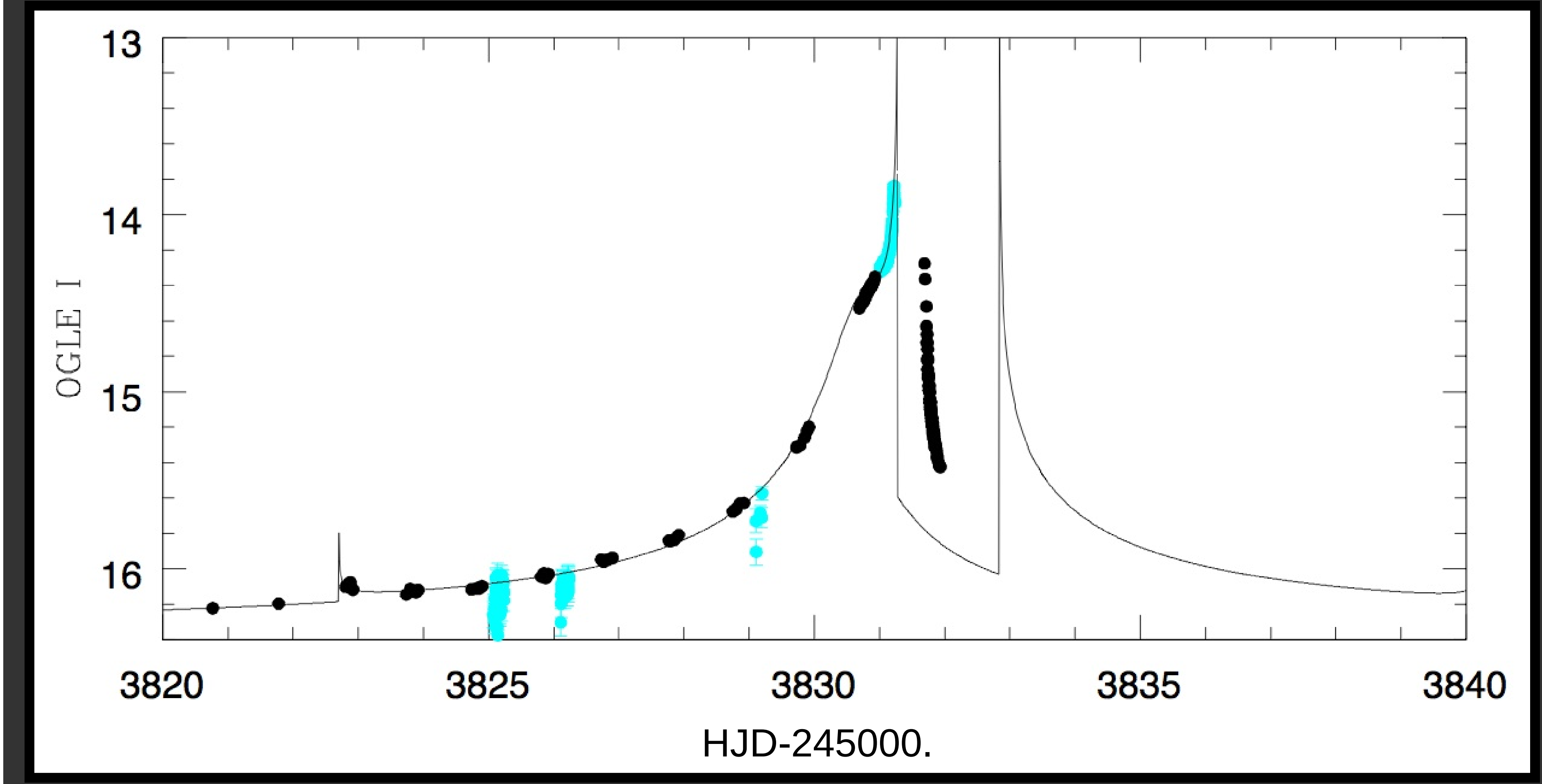


VERY HIGH MAGNIFICATION EVENT OGLE-2006-BLG-109 ???

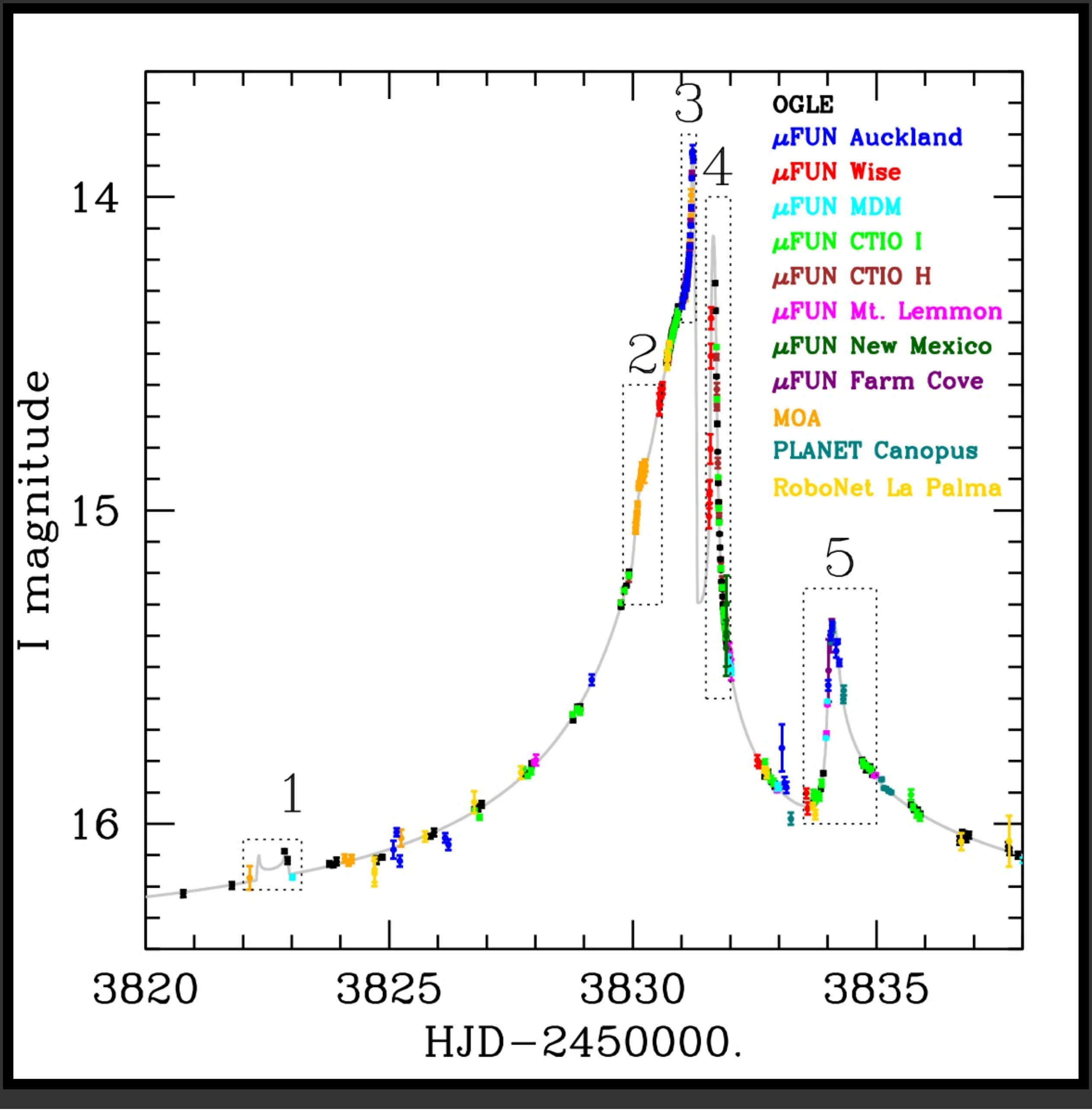
OGLE-2006-BLG-109 microlensing event was extensively monitored by OGLE after detection of a short-lived small amplitude anomaly. Photometry collected by OGLE at Las Campanas Observatory over the last couple of nights indicate a rapid brightening of this lens. Ignoring the anomaly data (3822.x), the light curve can be well fitted by a single lens microlensing with very high blending (~1%) and long time-scale. The parameters of this fit seem to be very stable over the last couple of nights.

This fit predicts very high magnification of A~400 and peak at HJD'=3830.8 that is tomorrow over Chile. If so, the event should be very sensitive to the presence of extrasolar planets. Moreover, if the anomaly at 3822.x was caused by a planet then it is likely that another anomaly will be seen at the peak.

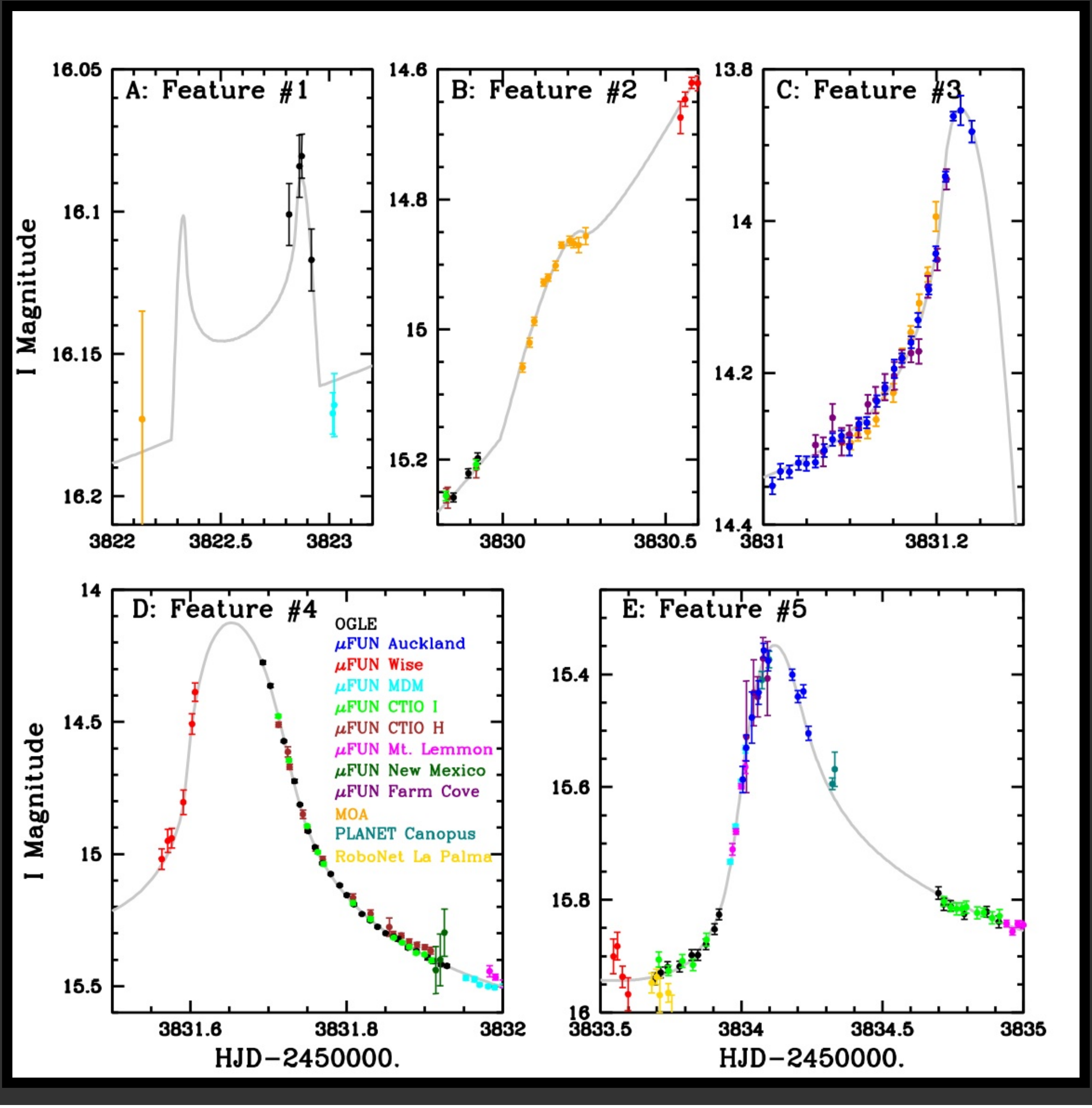
Caustic Crossing & Real-Time Modeling



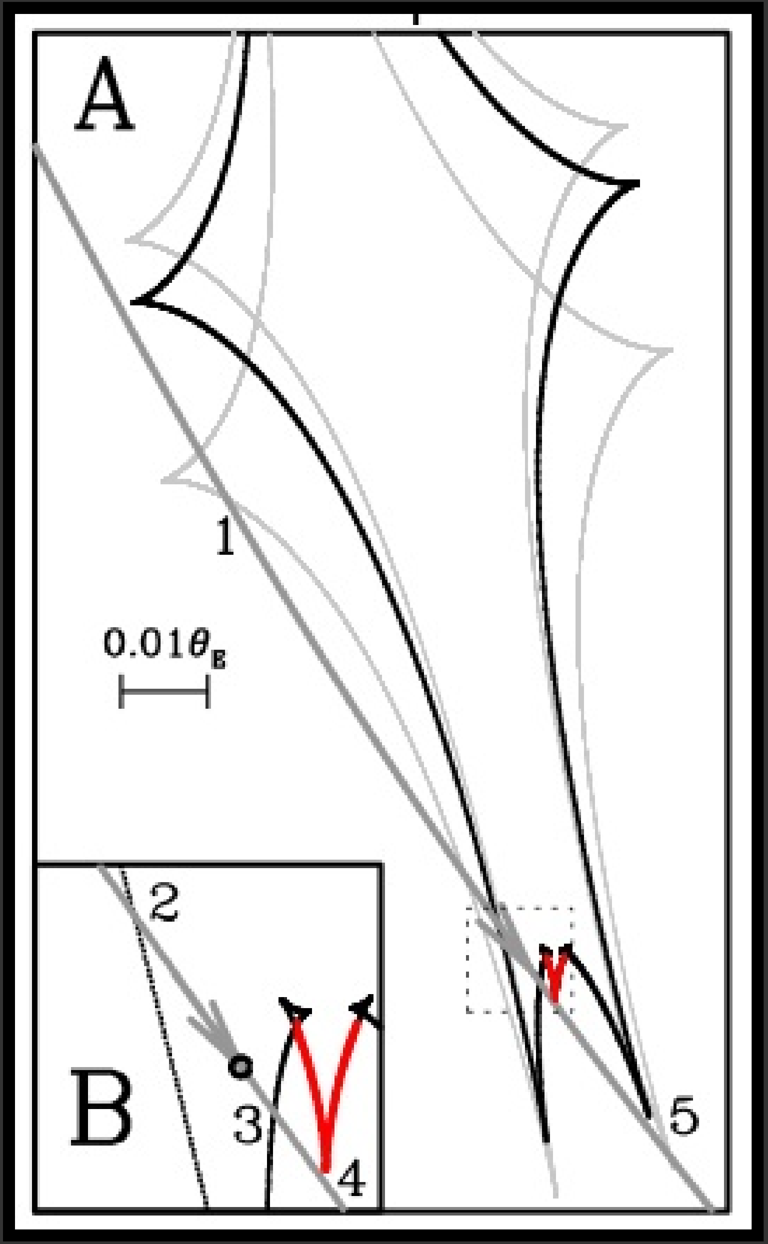
Full Dataset



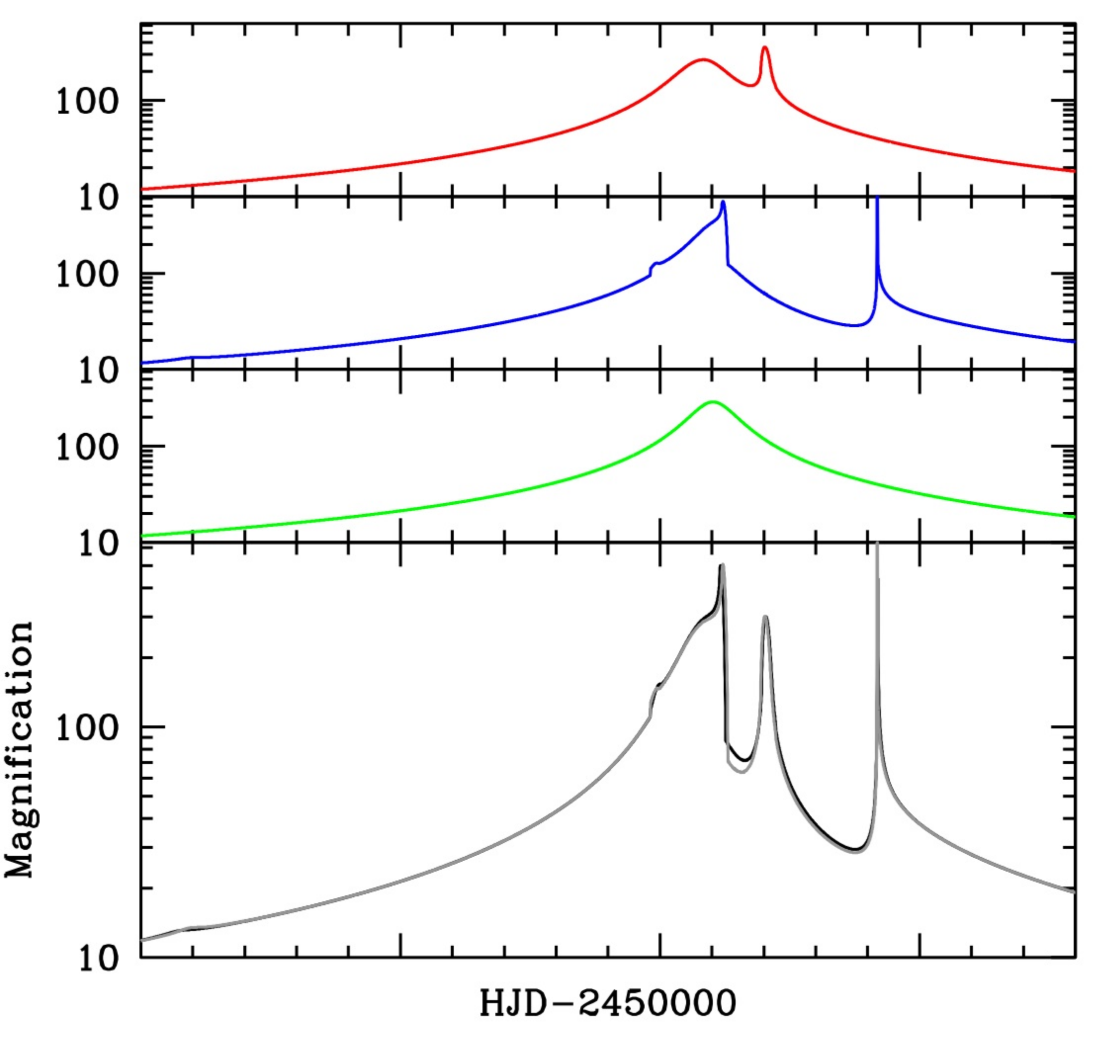
Five Features



Caustics



Finding the Model



(Han et al. 2001; Rattenbury et al. 2002; Han 2005)

Detailed Modeling

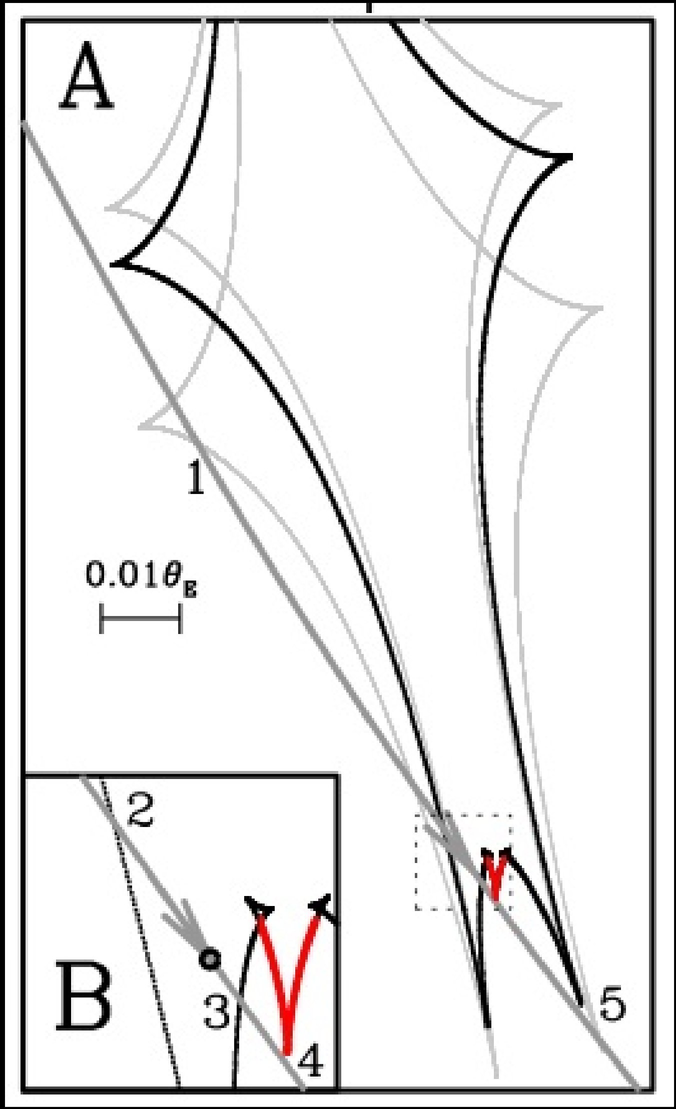
(Dave Bennett)

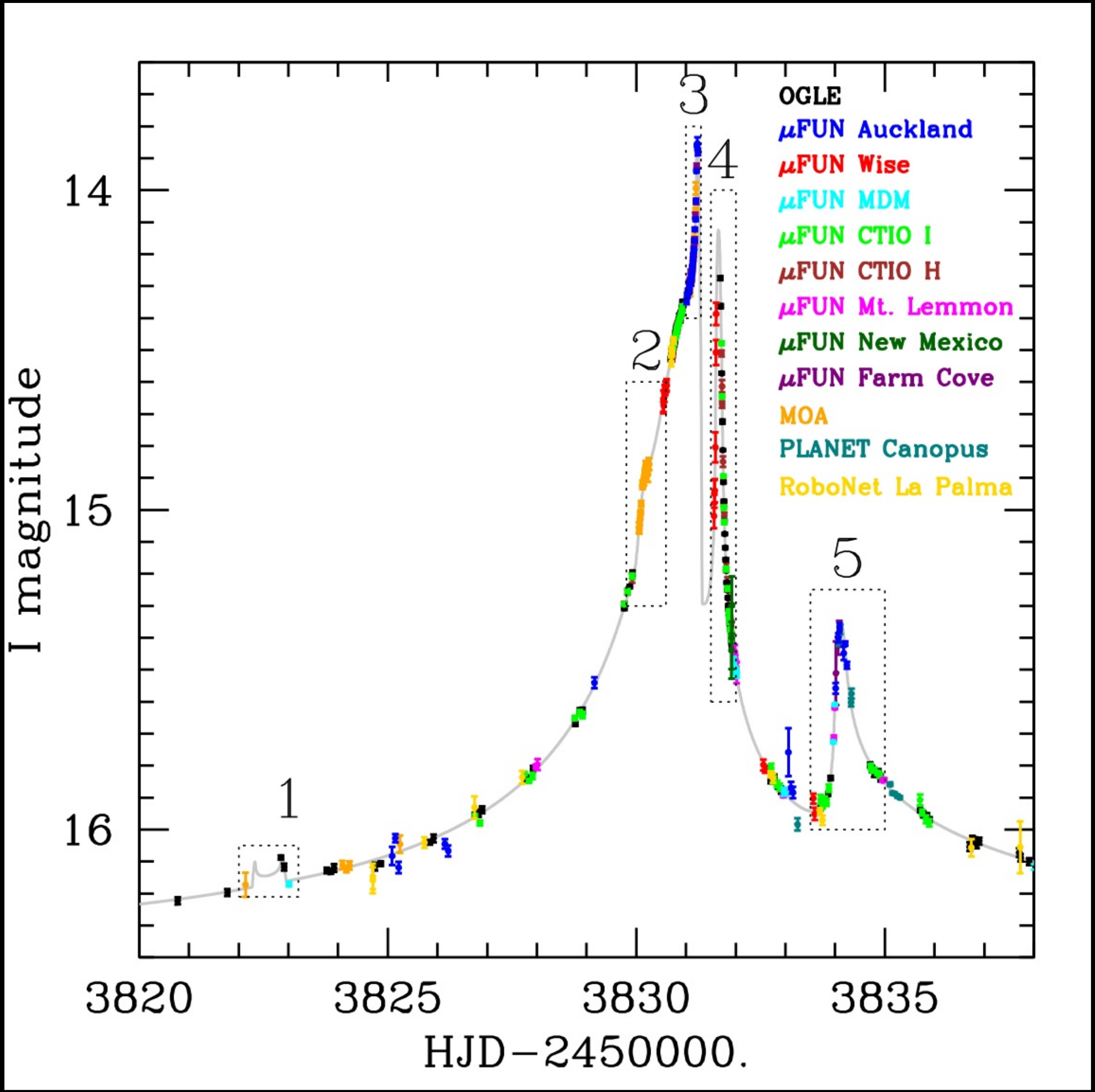
Orbital Motion.

Finite source effects.

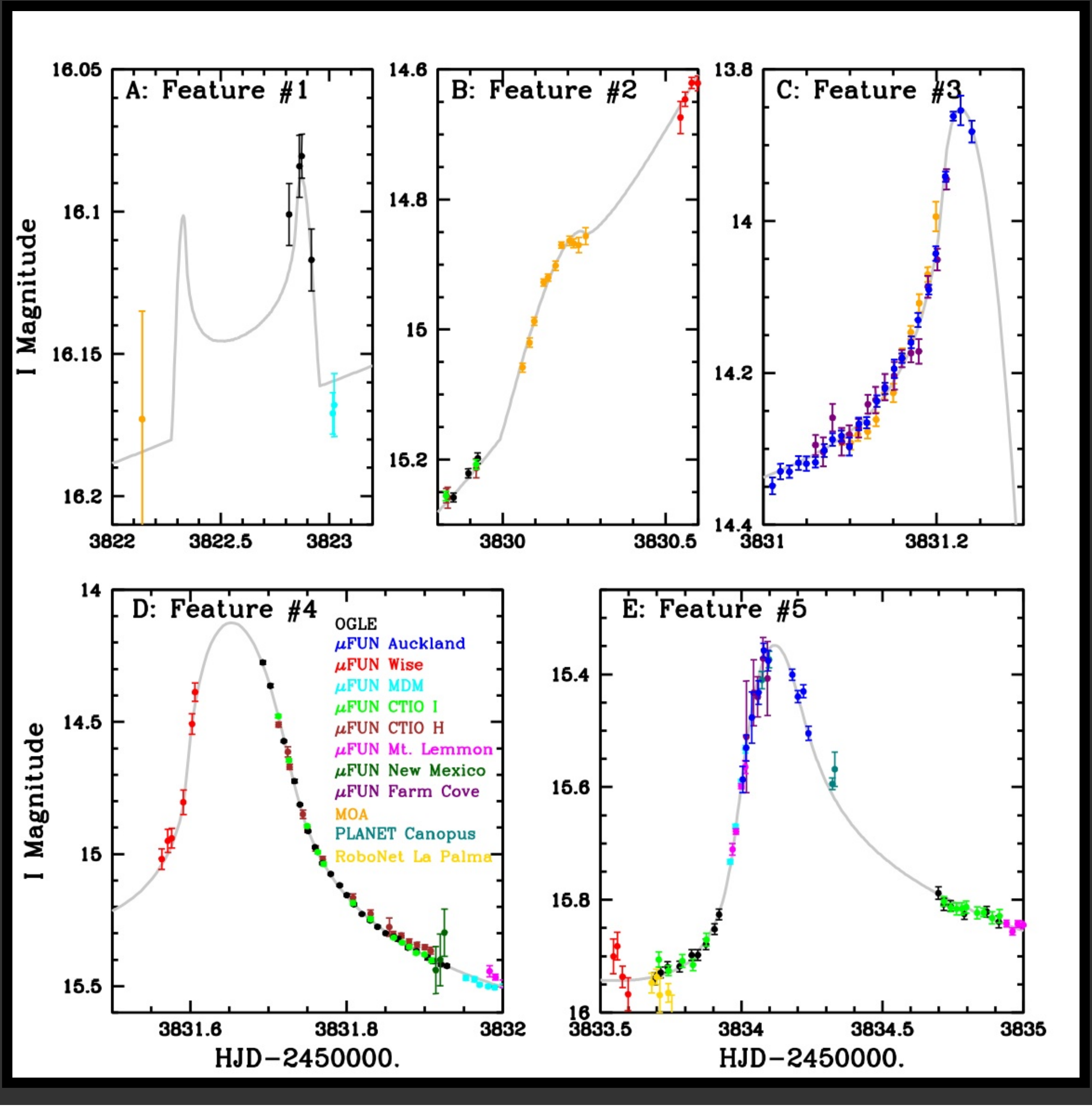
Parallax.

Rotation


A
1
0.01θ_E
B
2
3
4
5

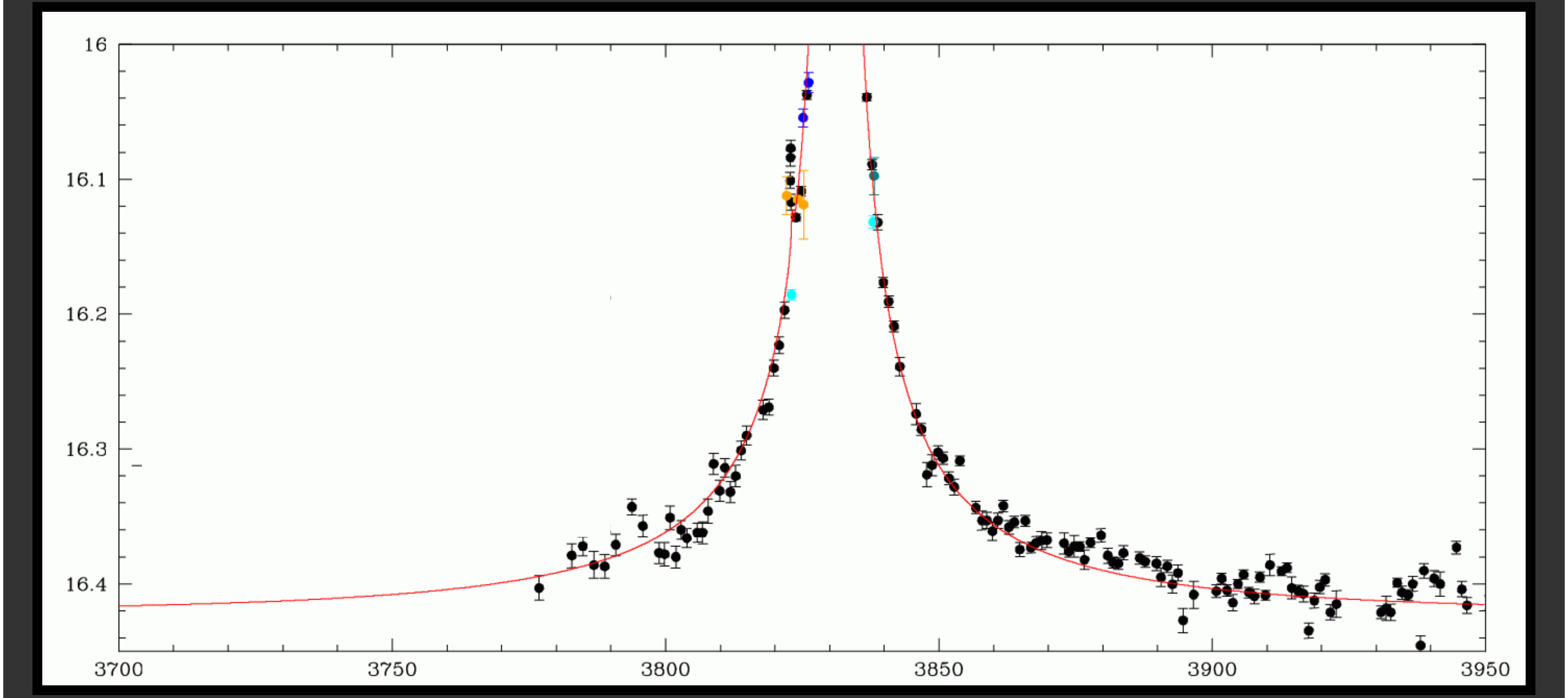

I magnitude
14
15
16
3820
3825
3830
3835
HJD−2450000.
1
2
3
4
5
OGLE
μFUN Auckland
μFUN Wise
μFUN MDM
μFUN CTIO I
μFUN CTIO H
μFUN Mt. Lemmon
μFUN New Mexico
μFUN Farm Cove
MOA
PLANET Canopus
RoboNet La Palma

Finite Source Effects



$$\theta_E = \frac{\theta_*}{\rho_*}$$

Parallax



$$\boxed{\tilde{r}_E = \theta_E D}$$

Properties of the Primary

Finite source effects.

$$\boxed{\theta_E = \frac{\theta_*}{\rho_*}}$$

Parallax.

$$\boxed{\tilde{r}_E = \theta_E D}$$

Mass.

$$\boxed{M = \left(\frac{c^2}{4G}\right)\tilde{r}_E\theta_E}$$

Distance.

$$\boxed{D_l = \left(\theta_E / \tilde{r}_E + D_s^{-1}\right)^{-1}}$$

Microlens Constraints on the Primary

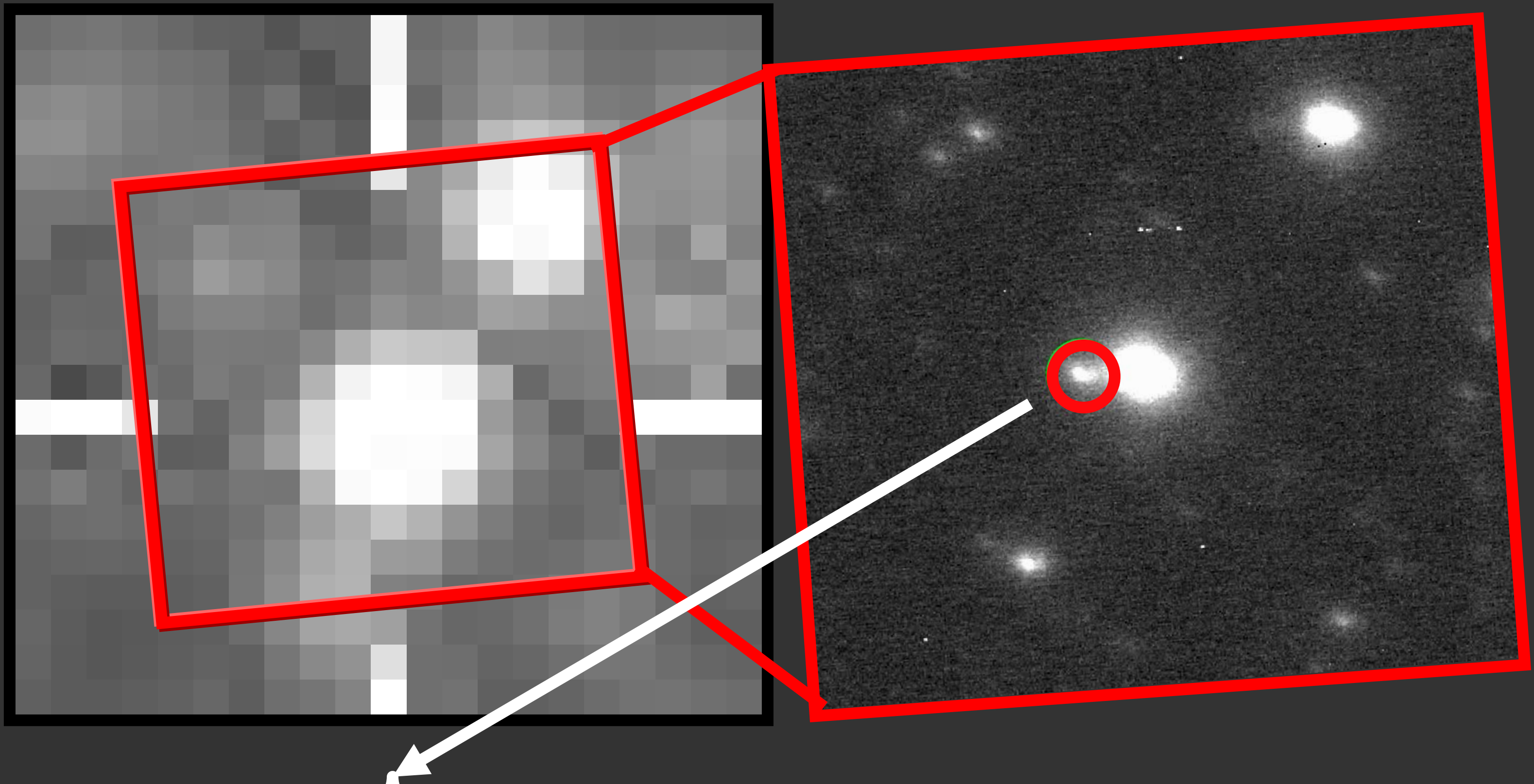
Finite Source. Parallax.

$$\underbrace{\boxed{\theta_E \cong 1.49\ \text{mas}}\quad\boxed{\tilde{r}_E \cong 2.92\ \text{AU}}}$$

$$\boxed{M \cong 0.53 M_\odot}$$

$$\boxed{D_l \cong 1.57\ \text{kpc}}$$

Keck AO Imaging



$$\overbrace{\text{Source + Lens}} - \underbrace{\text{Source}}_{\text{Light Curve.}} = \text{Lens} \ (H \approx 17.2)$$

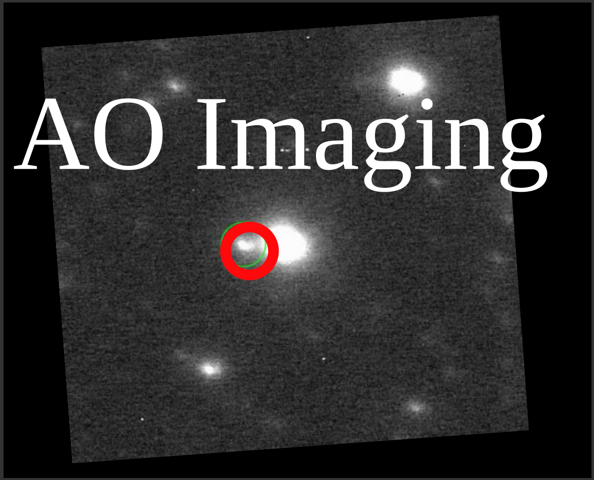
A ~0.5$M_\odot$ late K-dwarf at ~1.5 kpc

Finite Source

$\theta_E \simeq 1.48\ \text{mas}$

Parallax

$\tilde{r}_E \simeq 2.76\ \text{AU}$


AO Imaging

$D_l \simeq 1.49 \pm 0.13\ \text{kpc}$

$M = 0.50 \pm 0.05 M_\odot$

The OGLE-2006-BLG-109L Planetary System

Planet b:

Mass = $0.71 \pm 0.08\ M_{Jup}$

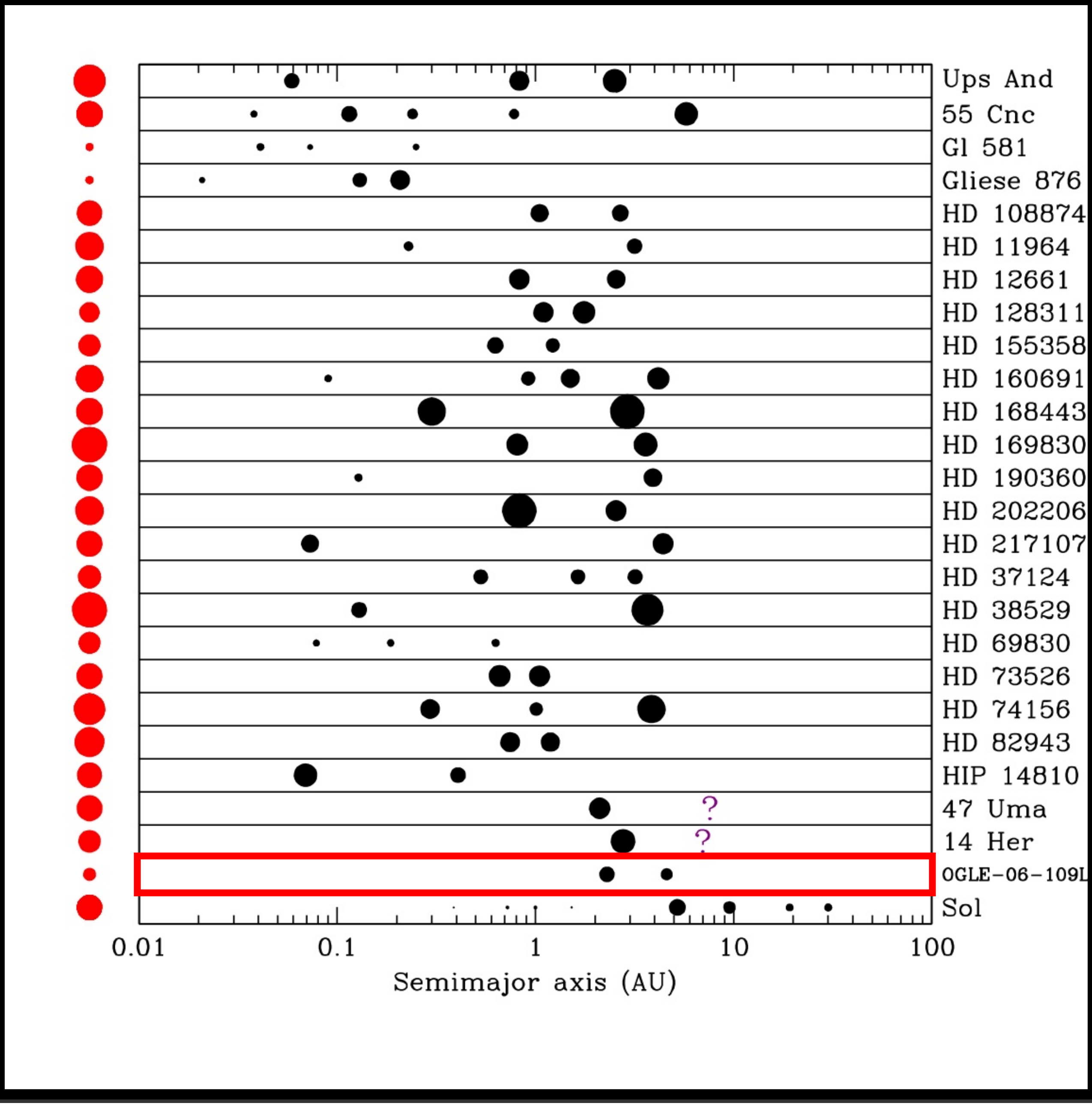
Semimajor Axis = 2.3 ± 0.2 AU

Planet c:

Mass = $0.27 \pm 0.03\ M_{Jup} = 0.90\ M_{Sat}$

Semimajor Axis = 4.6 ± 0.5 AU

Comparison to Other Systems



Equilibrium Temperatures

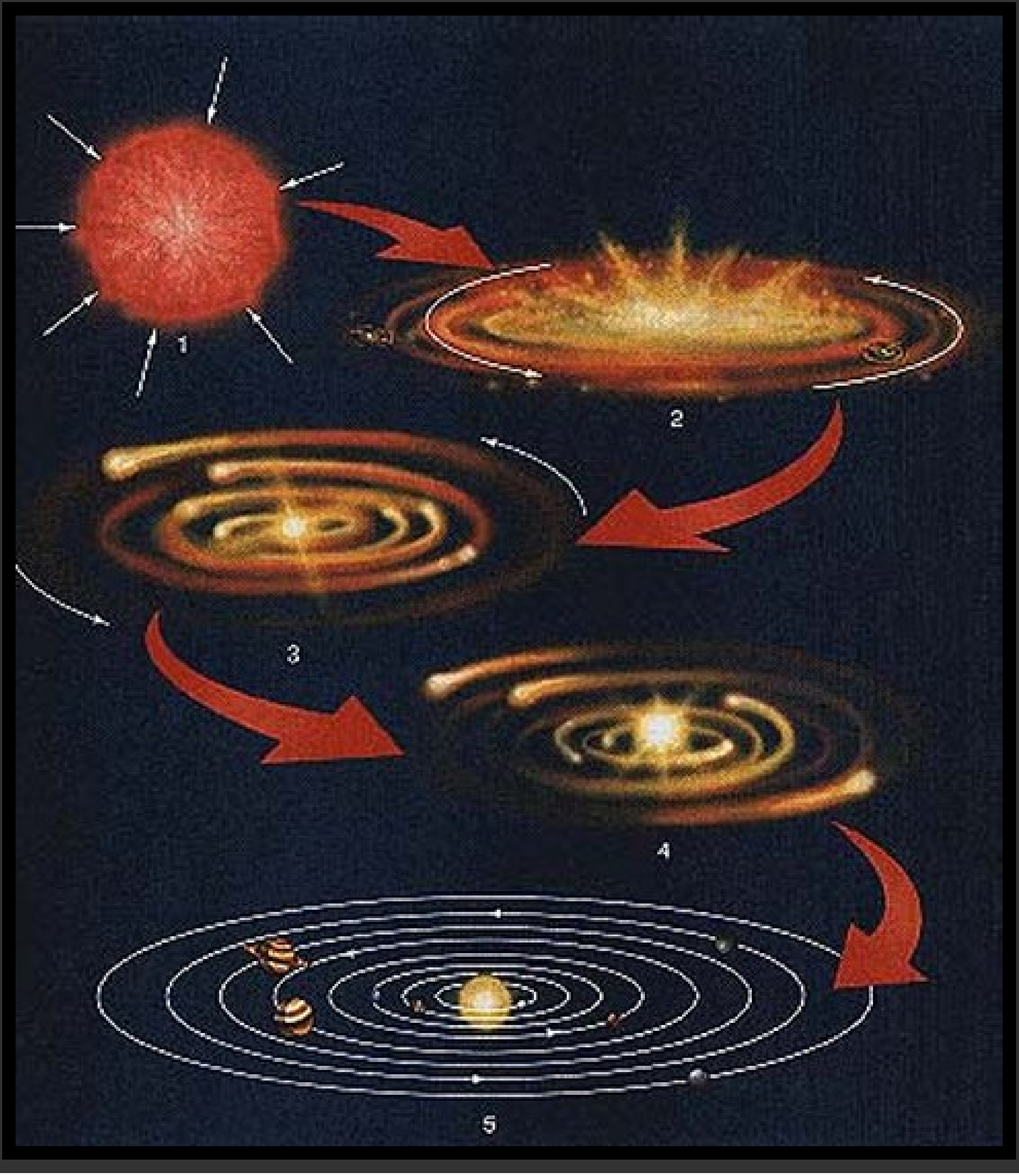
$$T_{eq} = \left(\frac{L_*}{16\pi a^2} \right)^{1/4} \cong 278\text{K} \left(\frac{L_*}{L_\circ} \right)^{1/4} \left(\frac{a}{\text{AU}} \right)^{-1/2}$$

Planet b:

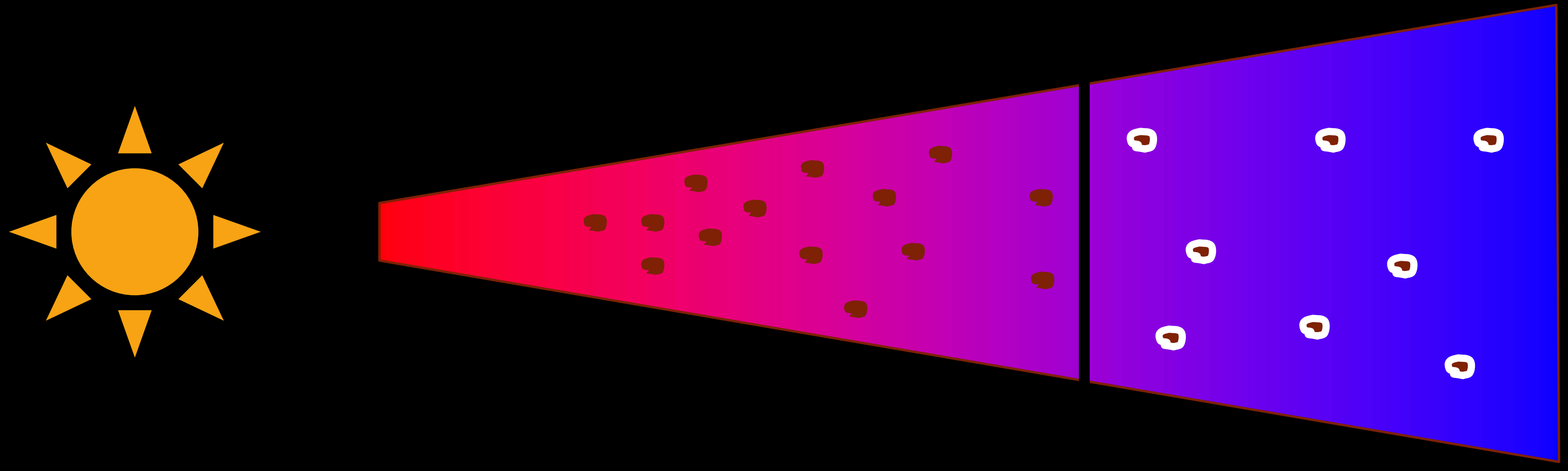
$$T_{eq} = (82 \pm 12)\ \text{K}$$

Planet c:

$$T_{eq} = (59 \pm 7)\ \text{K}$$

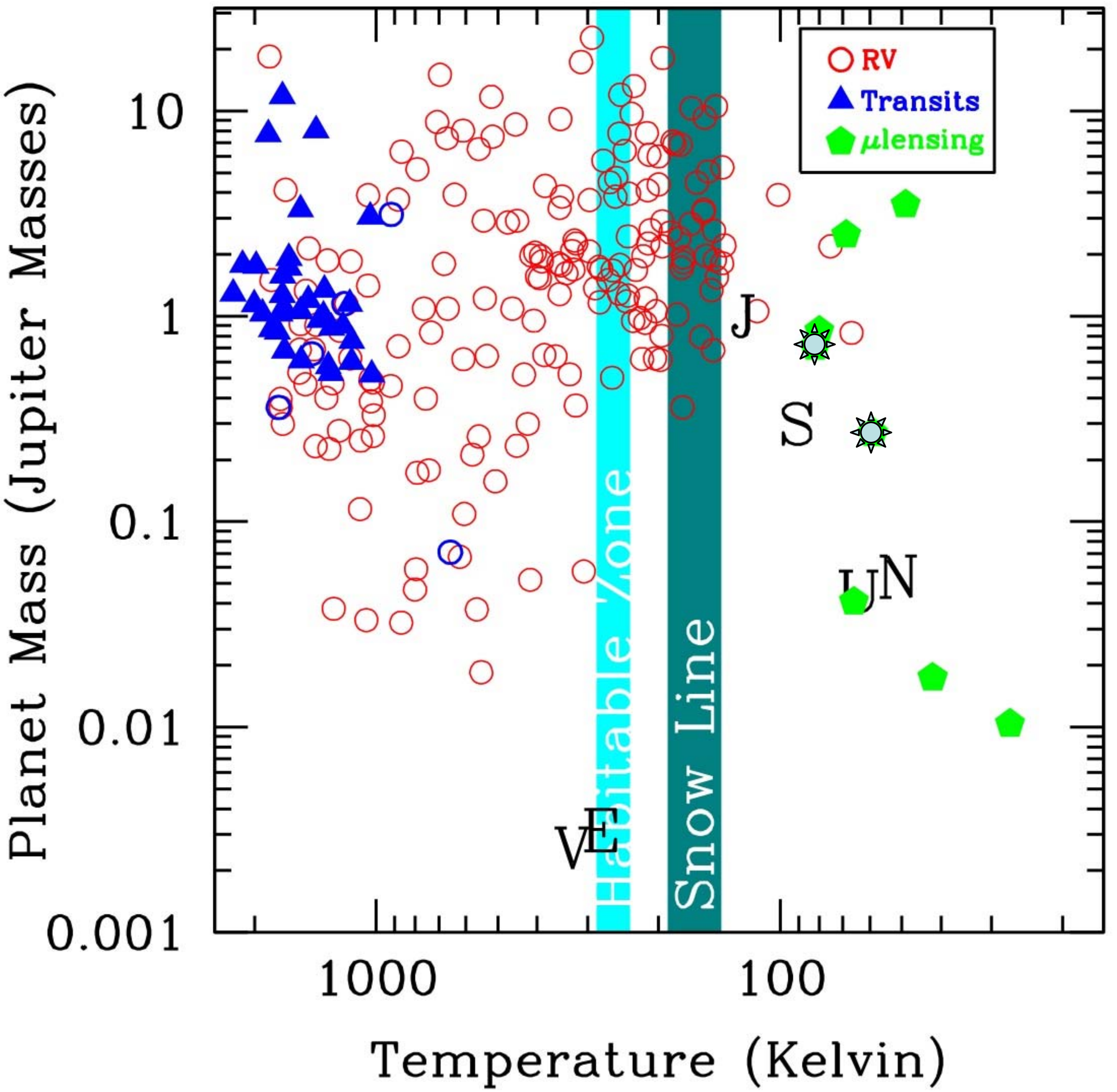

1
2
3
4
5

The Snow Line.

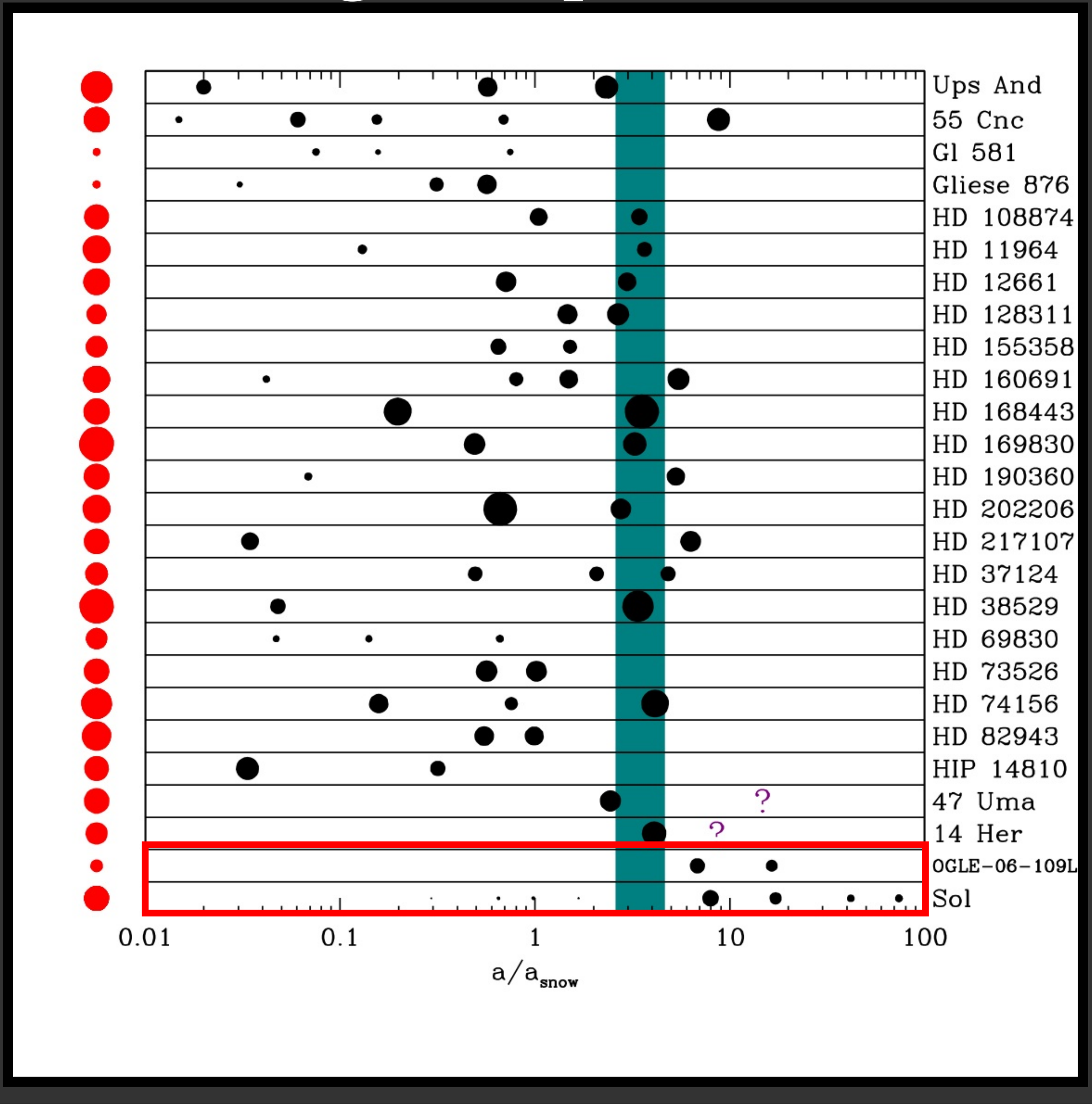


Too Hot for Ice

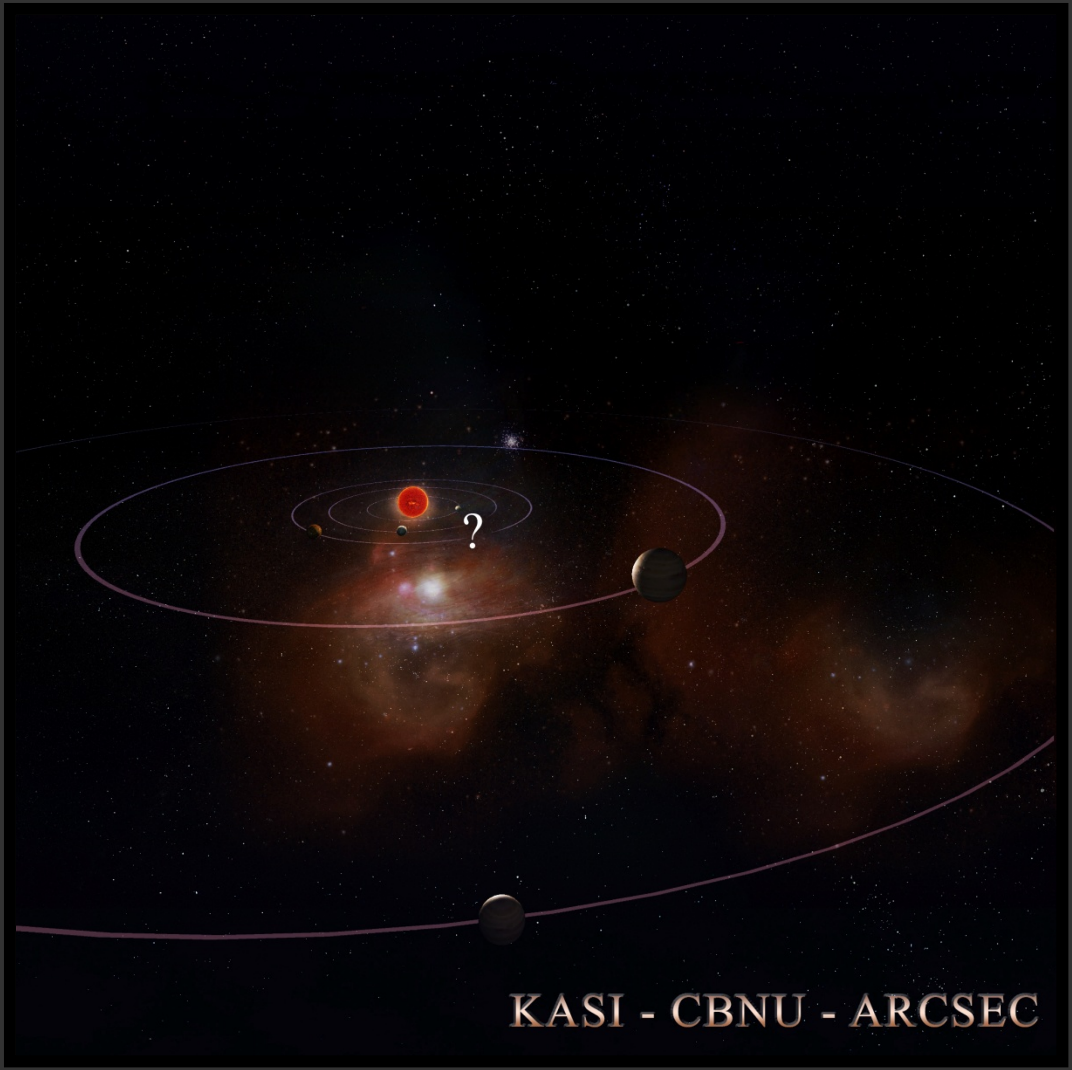
Cool enough for Ice


Planet Mass (Jupiter Masses)
10
1
0.1
0.01
0.001
1000
100
Temperature (Kelvin)
RV
Transits
μlensing
Habitable Zone
Snow Line
J
S
U
N
V
E

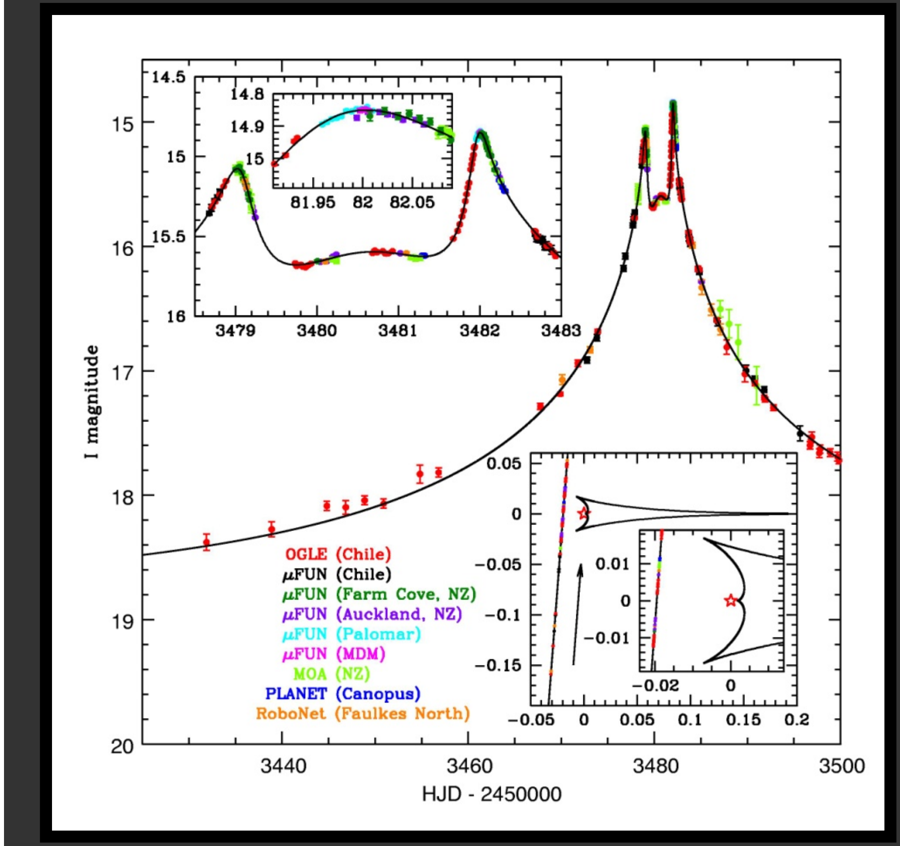
Analog to Jupiter/Saturn



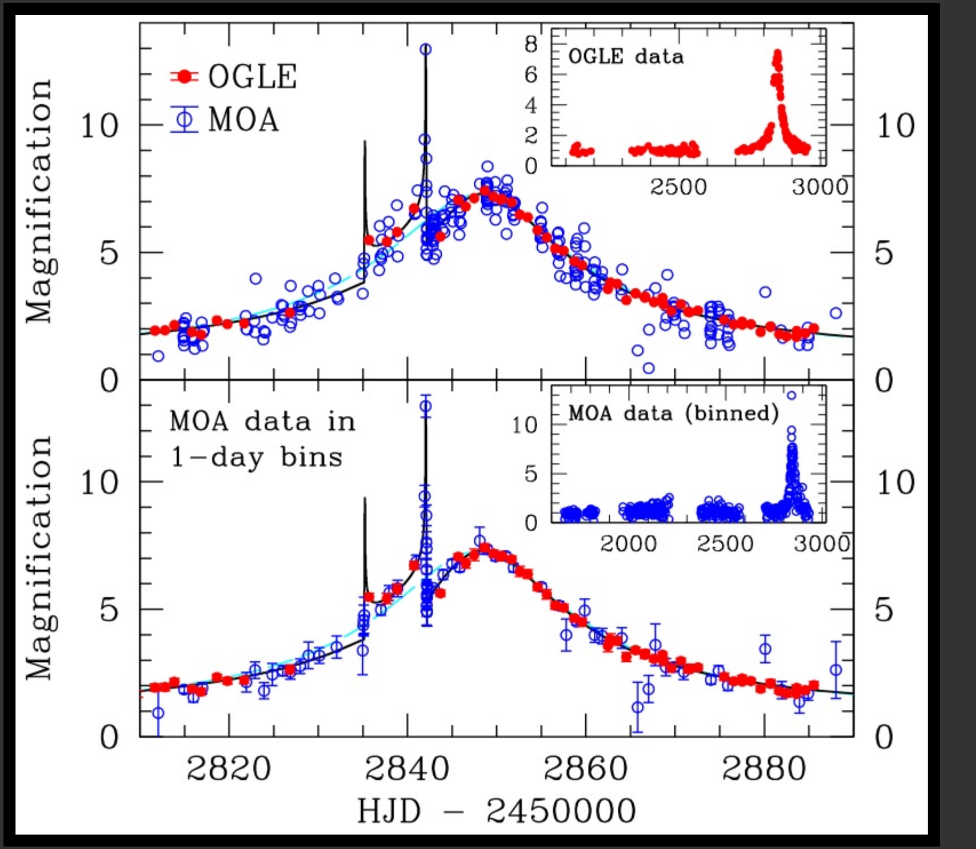
A Solar System Analog?



Implications for Frequency of Systems



(Udalski et al. 2005)



(Bond et al. 2004)