# The Cult of Microlensing

**cult *n.***

**1. a religion or religious sect generally considered extremist or false, with its followers often living in an unconventional manner under the guidance of an authoritarian, charismatic leader.**

**2. A system or community of religious worship and ritual.**

**3. The formal means of expressing religious reverence; religious ceremony and ritual.**

**4. A usually non-scientific method or regimen claimed by its originator to have exclusive or exceptional power in curing a particular disease.**

**5. Obsessive, especially faddish, devotion to or veneration for a person, principle, or thing.**

**6. An exclusive group of persons sharing an esoteric, usually artistic or intellectual interest.**

# What is microlensing?

**• Time variable gravitational lensing of a distant source by an intervening mass where multiple images are created but not resolved.**

# Why is it so great?

**•No flux needed from lens.**
**•Sensitive to mass.**
**•Magnifies the flux from the source.**
**•Very high angular resolution**

# Proposed applications of microlensing:

**•*Dark matter***
**•*Stellar atmospheres***
**•*Gamma-ray burst afterglows***

**•Binary frequencies**
**•*Mass functions***
**•Stellar rotation speeds**

**•Quasar central engines**
**•Abundances of stars**
**•*Extrasolar planets***

# Fellow Cult Members

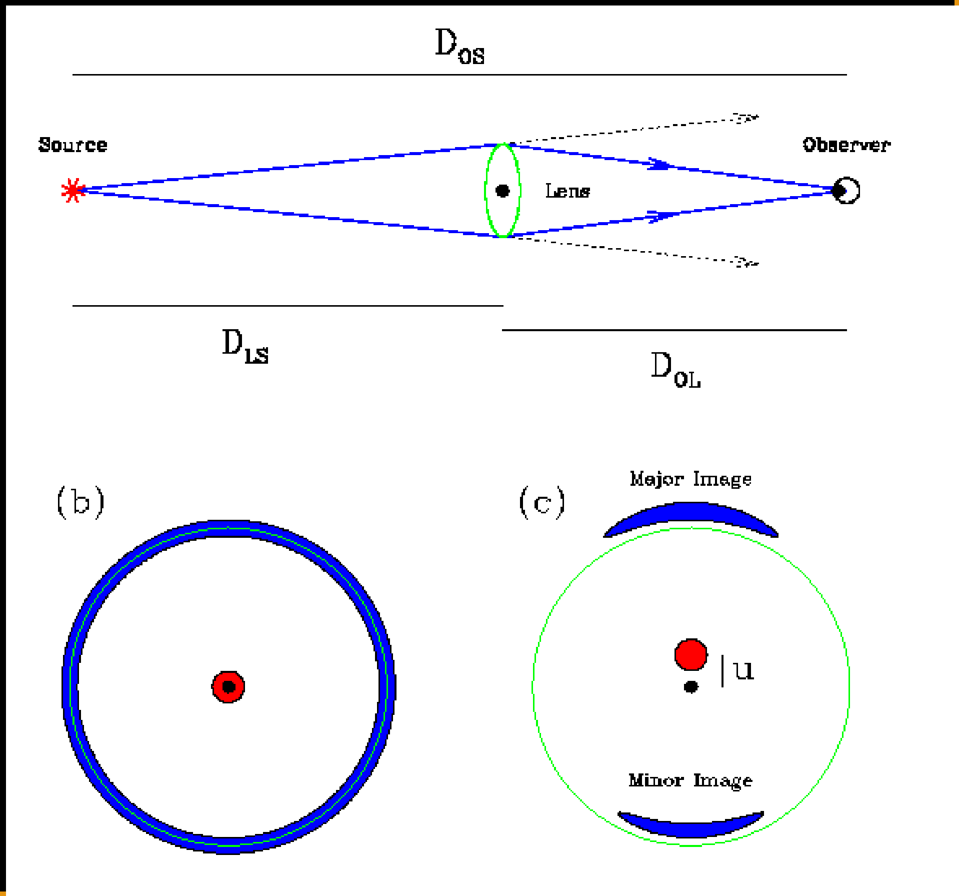
- Jin An (OSU)
- Andrew Gould (OSU)
- David Graff (OSU)
- Jonathan Granot (IAS)
- Cheongho Han (Chungbuk)
- Avi Loeb (Harvard)
- Arlie Petters (Duke)

**The PLANET Collaboration**

**SIM Microlensing Key Project Team**

- Andrew Gould
- Dave  Bennett
- Andy Boden
- Neal Dalal
- Darren DePoy
- Kim Griest
- Cheongho Han
- Bohdan Paczynksi
- Neill Reid
- Sun Hong Rhie

# Simple Microlensing




Time Delay

$$\tau = \frac{1}{2}(\vec{\theta} - \vec{\beta})^2 - \psi(\vec{\theta})$$

$$\psi(\vec{\theta}) = \frac{1}{\pi}\int \kappa(\vec{\theta}')\ln|\vec{\theta} - \vec{\theta}'|d^2\vec{\theta}'$$

$$= \theta_E^2 \ln \theta$$

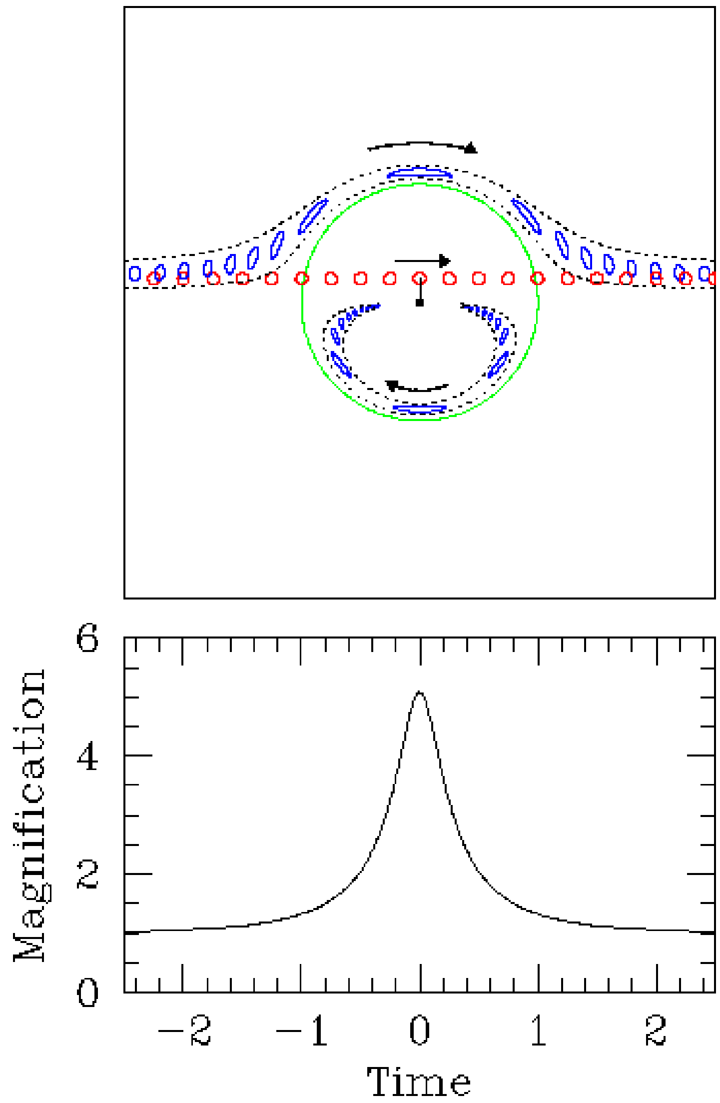
Lens Equation

$$\beta = \theta - \theta_E^2/\theta$$

Angular Einstein Ring Radius

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_{OL}D_{OS}}} = 570\mu as \left(\frac{M}{0.5M_\odot}\right)^{1/2}\left(\frac{D_{rel}}{12.5kpc}\right)^{-1/2}$$

# Dark Matter




## Microlensing Lightcurves:

- Symmetric.
- Non-repeating.
- ~Achromatic

## Single Lens Parameters:

- Impact parameter
- Time of Maximum Mag.
- Timescale

$$t_E = \frac{\theta_E}{\mu} \simeq 45\text{days}\left(\frac{M}{0.5M_\odot}\right)^{1/2}$$

# Dark Matter

**Optical Depth:** $\tau = 1.2^{+0.4}_{-0.3} \times 10^{-7}$ **(Alcock et al. 2000)**

- **Four times smaller than standard dark halo.**
- **Considerably larger than "known" background (disk, LMC, spheroid).**

**Where/what are the lenses?**

$$t_E = 45\text{d}\left(\frac{0.5M}{M_\odot}\right)^{1/2}\left(\frac{v}{220kms^{-1}}\right)^{-1}\left(\frac{D_{rel}}{12.5\text{kpc}}\right)^{-1}$$

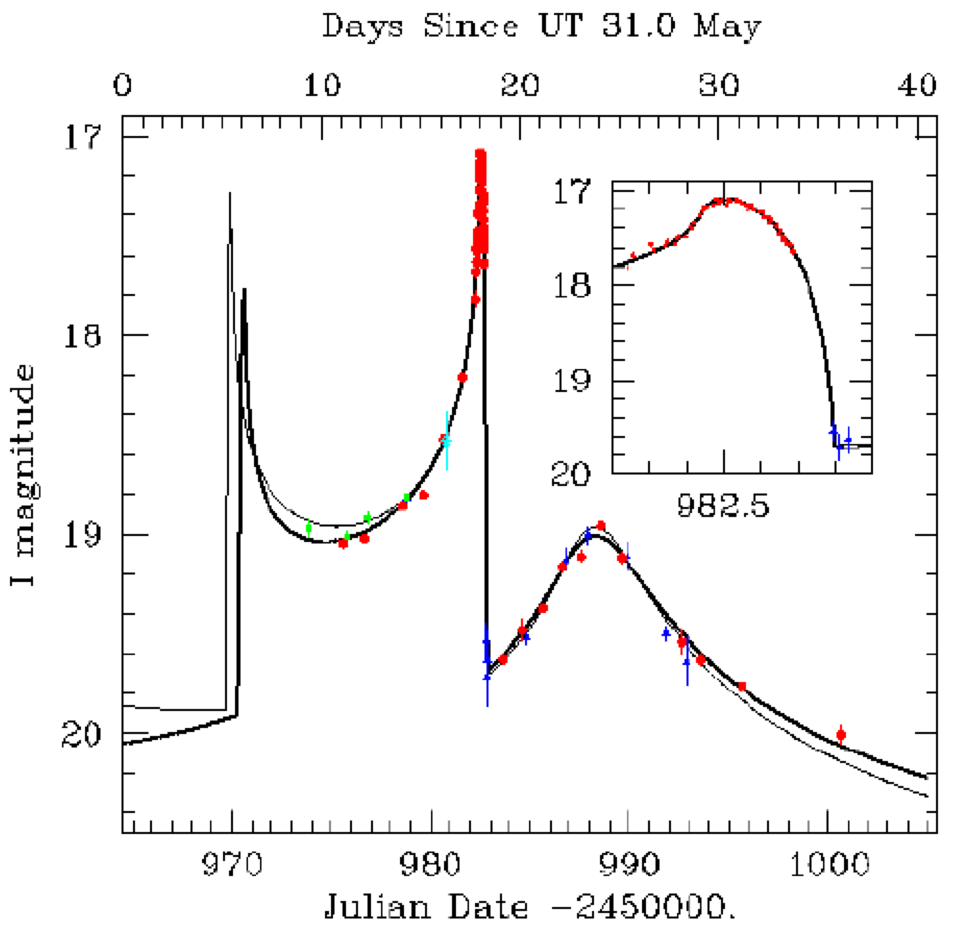
$$t_E = 45\text{d}\left(\frac{0.2M}{M_\odot}\right)^{1/2}\left(\frac{v}{30kms^{-1}}\right)^{-1}\left(\frac{D_{rel}}{6200\text{kpc}}\right)^{-1}$$

- **Impossible to tell from timescale alone.**

**Halo White Dwarfs?**

**Extended LMC Stellar Halo?**

# Dark Matter




Proper Motion:

- Halo: $\mu \sim 20 \;\; \mathrm{km} \;\; \mathrm{s}^{-1} \;\; \mathrm{kpc}^{-1}$
- MCs: $\mu \sim 0.5 \;\; \mathrm{km} \;\; \mathrm{s}^{-1} \;\; \mathrm{kpc}^{-1}$

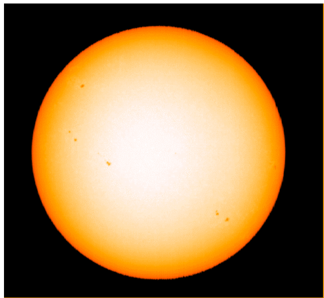
Resolved Source:

$$\mu = \theta_* / t_*$$

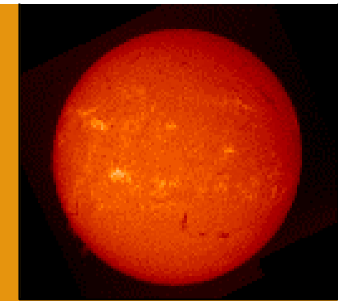
- MACHO-1998-SMC-1

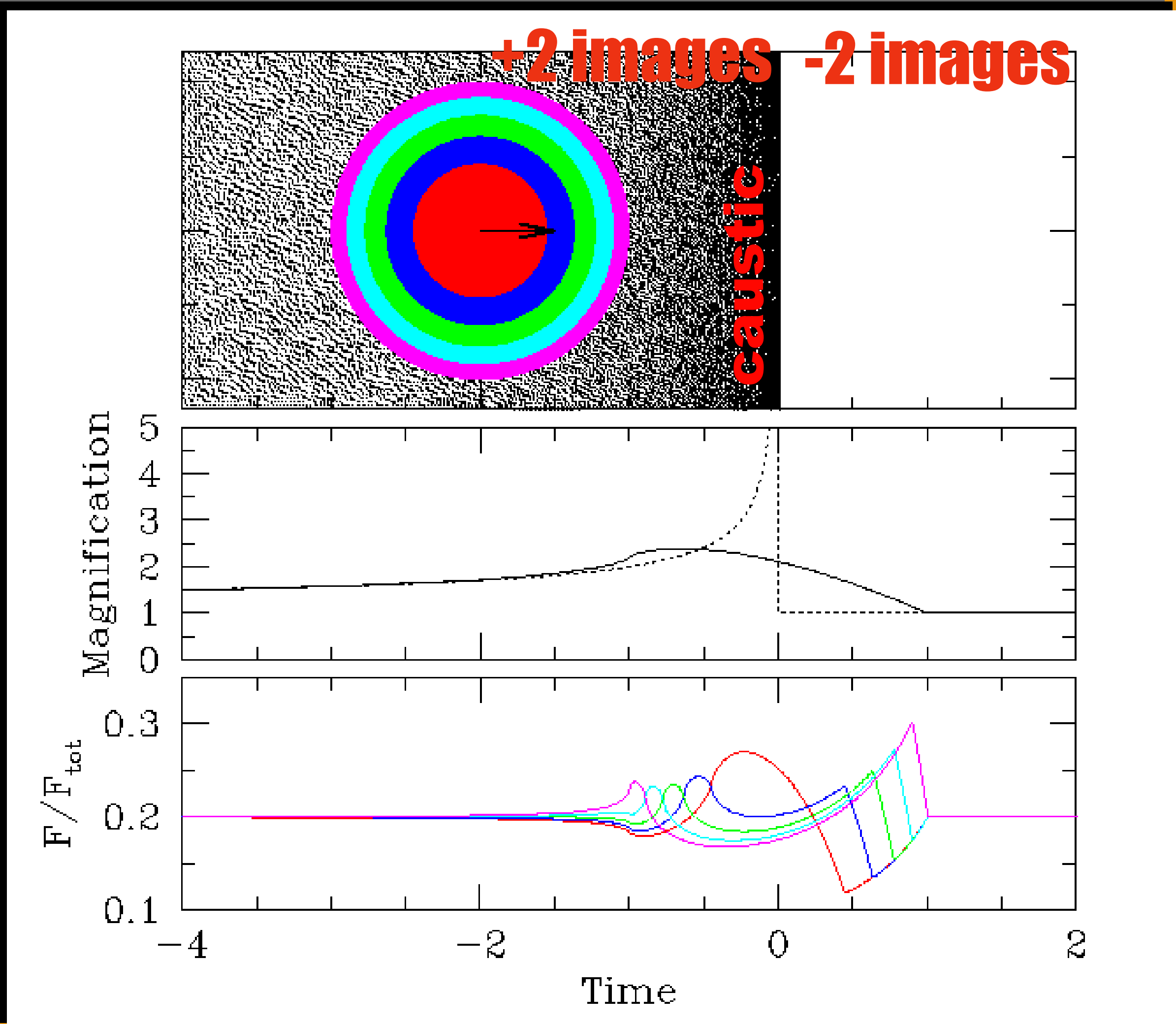
$$\mu \simeq 1 \;\; \mathrm{km} \;\; \mathrm{s}^{-1} \mathrm{kpc}^{-1}$$

**In the SMC!**



# *Stellar Atmospheres*






**Caustic**: locus of formally infinite magnification.

**Inside caustic**: Extra pair of images.

**Magnification**: $\propto \text{distance}^{-1/2}$

## Time Resolution
## =
## Spatial Resolution

(Loeb & Sasselov 1995,
Valls-Gabaud 1995,
Gaudi & Gould 1999)

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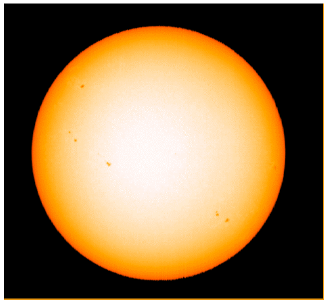

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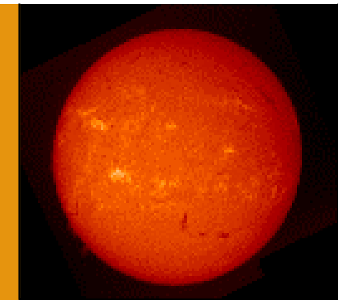
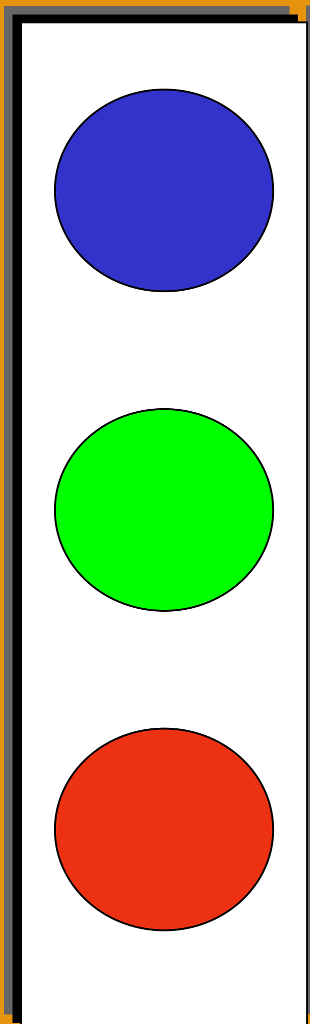
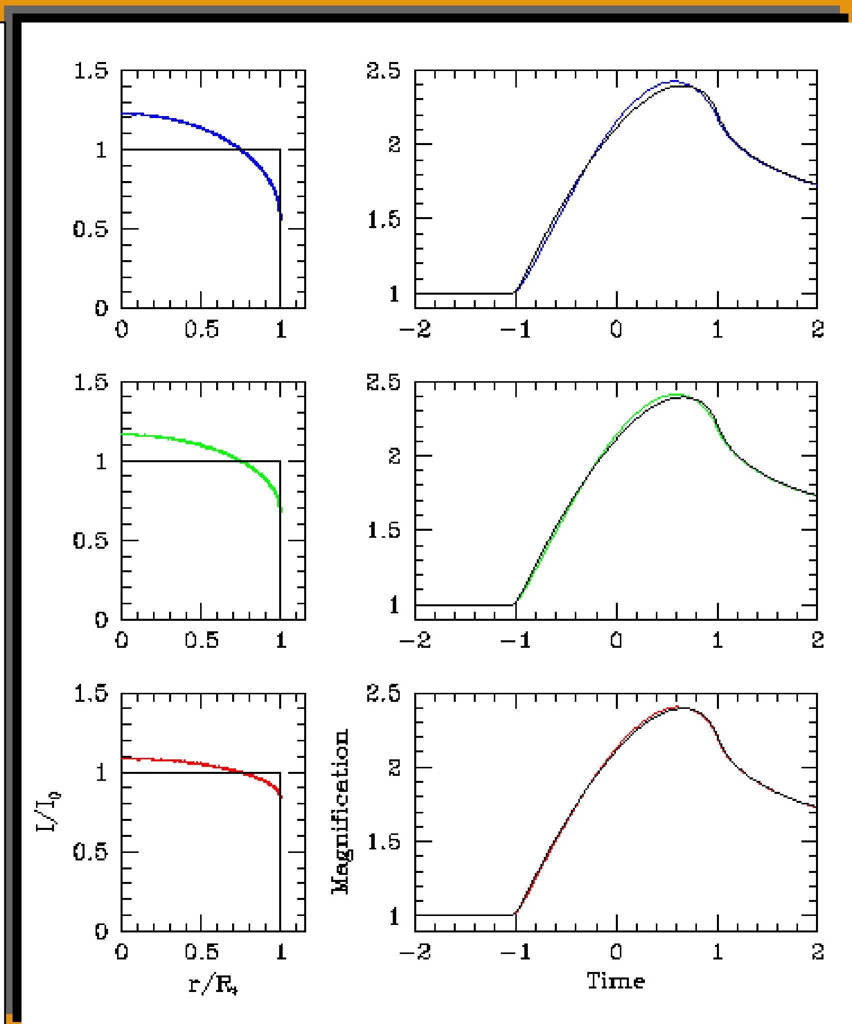


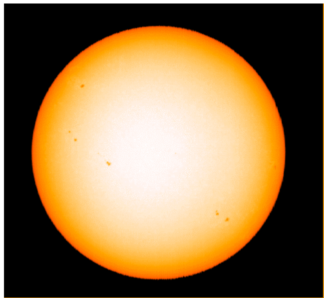





550 nm

620 nm

800 nm



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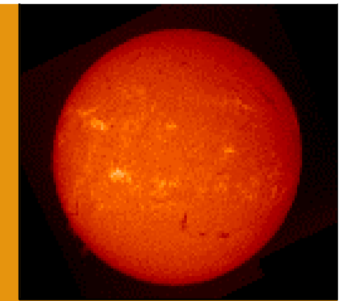
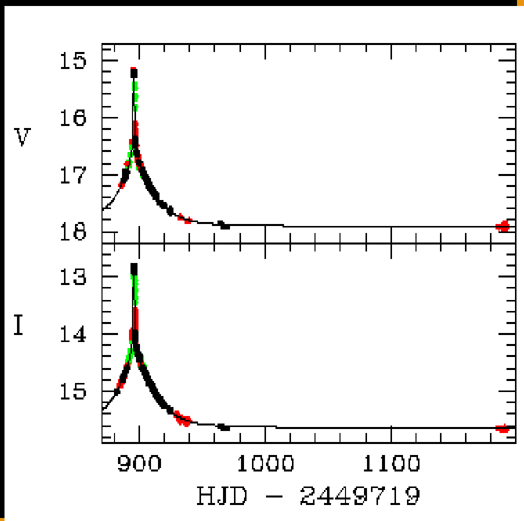
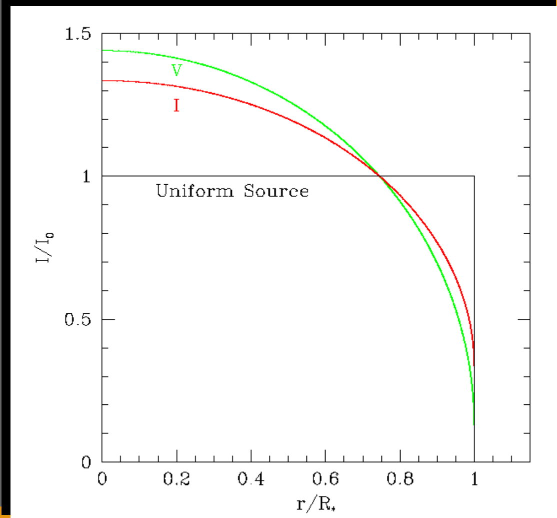


Albrow et al 1999

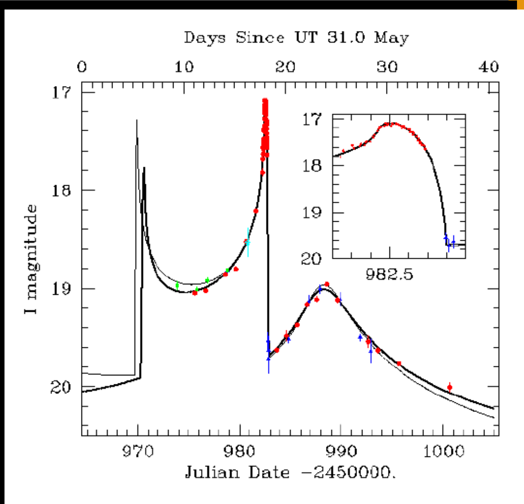


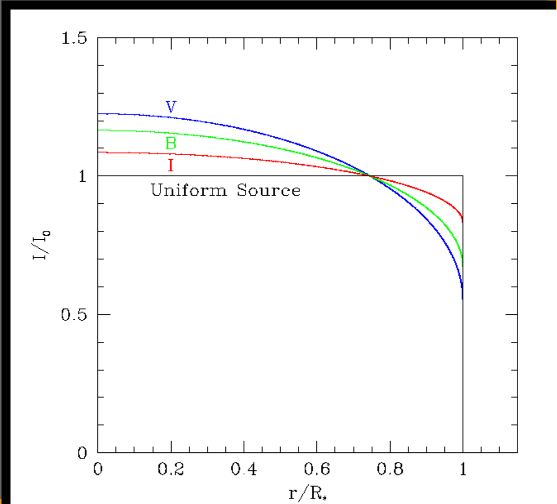




MACHO-1997-BUL-28

- K giant in bulge
- Cusp-crossing event
- $\theta_* = 9\mu as$
- V & I measurements

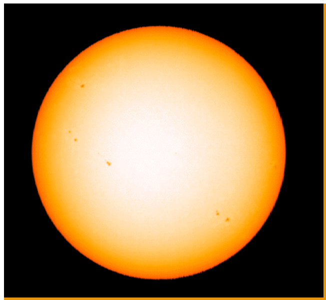
Alfonso et al 2000



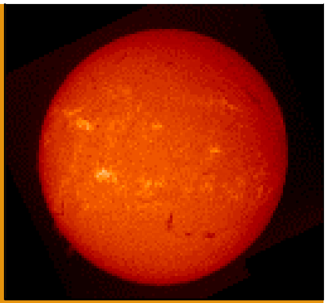




MACHO-1998-SMC-1

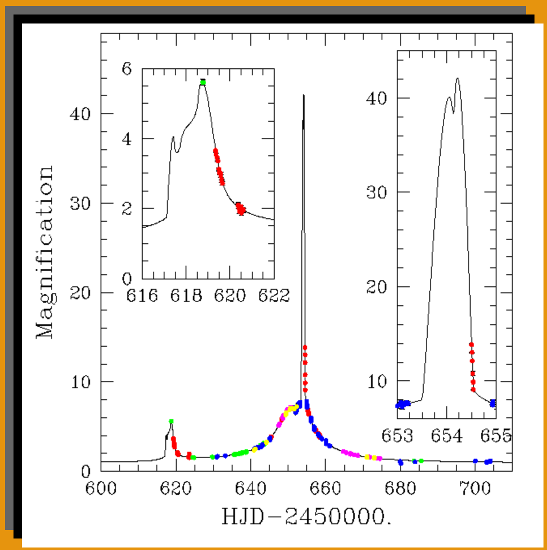
- Metal-poor A star in SMC
- Fold-crossing event
- $\theta_* = 79$nas
- V, Eros B, & I meas.

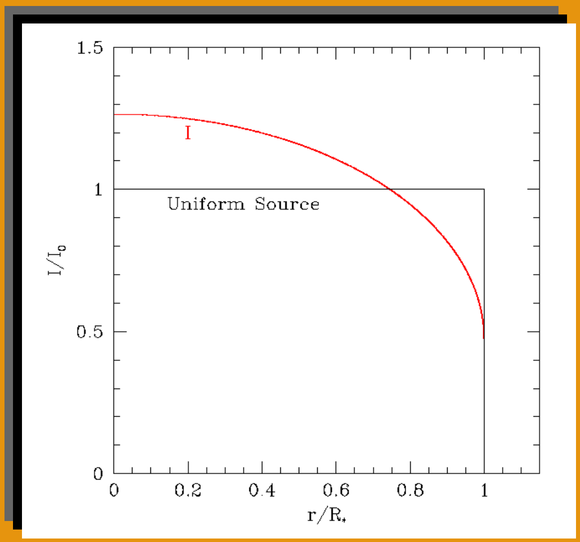


# Stellar Atmospheres



Albrow et al 2000

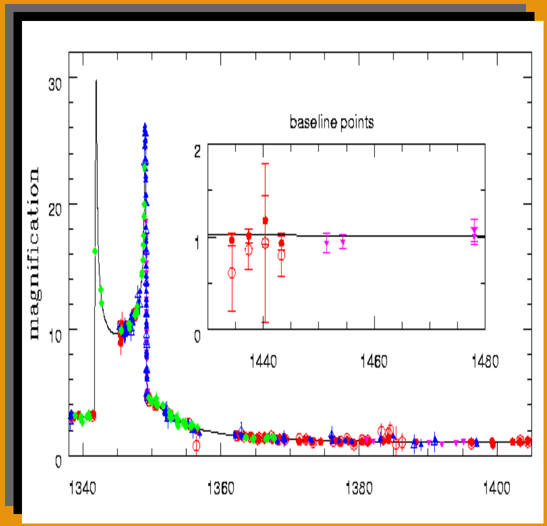


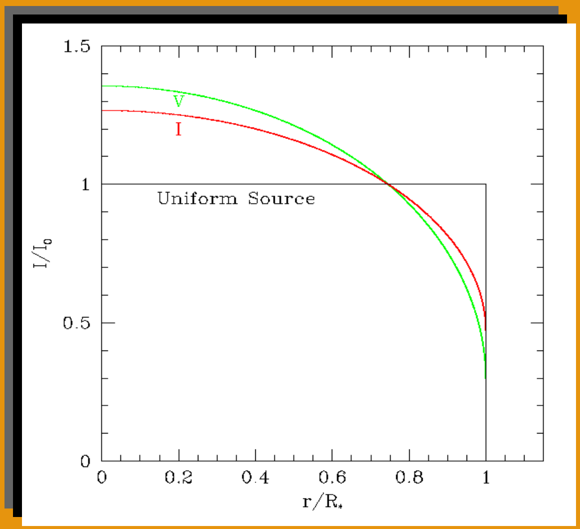




MACHO-1997-BUL-41

- K giant in bulge
- Cusp- & Fold-crossing
- $\theta_* = 5.6\mu$as
- I measurement

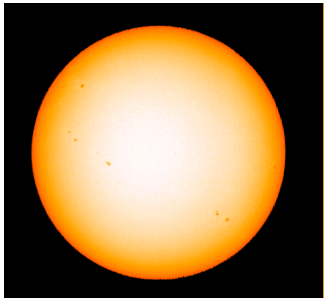
Albrow et al 2001



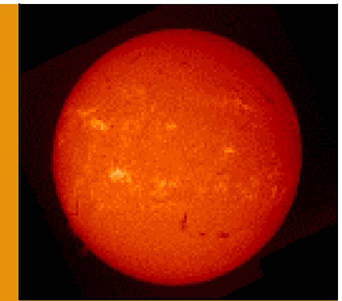




OGLE-1999-BUL-23

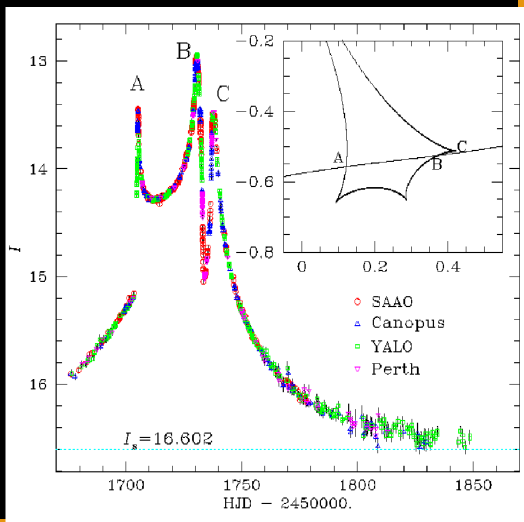
- G/K subgiant in bulge
- Fold-crossing event
- $\theta_* = 1.8\mu$as
- V & I measurements

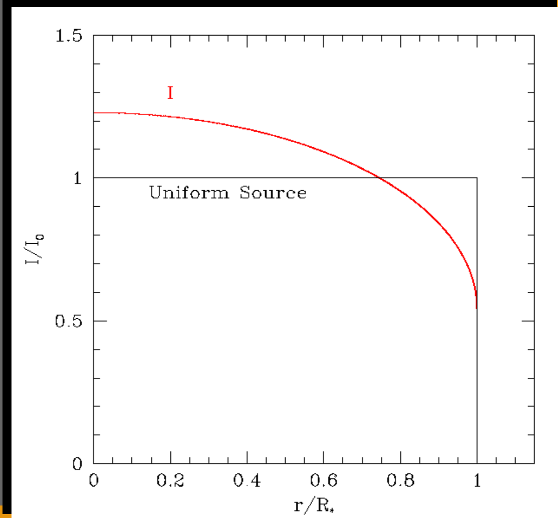


# Stellar Atmospheres



An et al 2002

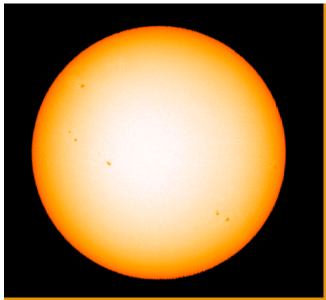


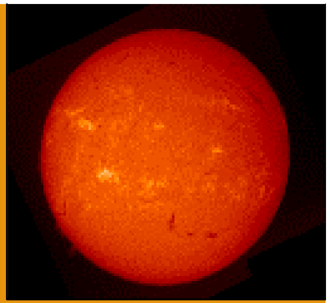

EROS BLG-2000-5
- K3 giant in bulge
- **Long** Fold-crossing
- $\theta_* = 6.6\mu$as
- 2-parameter
  I measurement
- More to come!

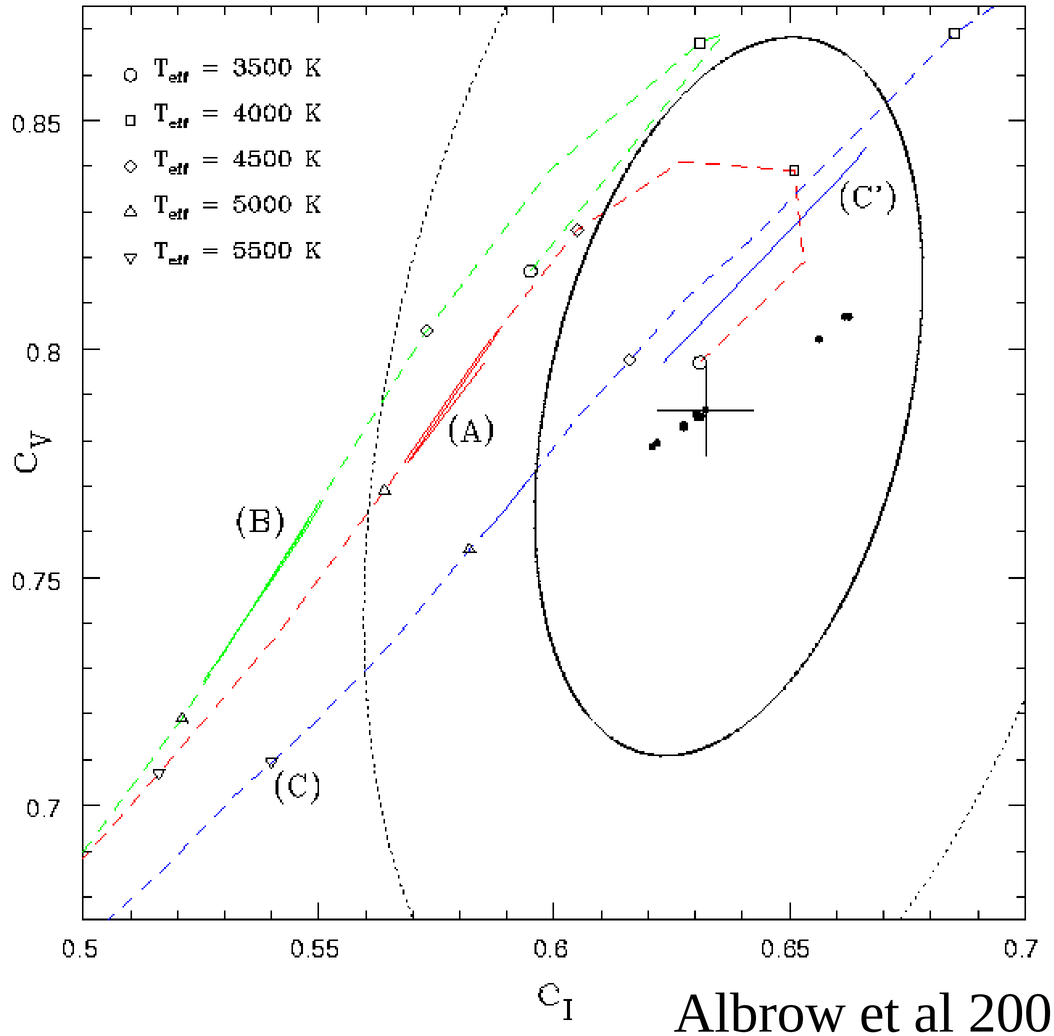
**Five LD Measurements using microlensing.**

→ Can expect ~ few per year.



# Stellar Atmospheres

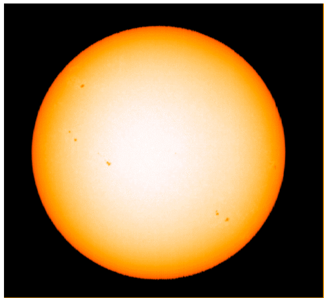




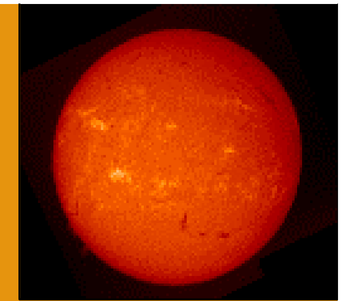

Albrow et al 2001

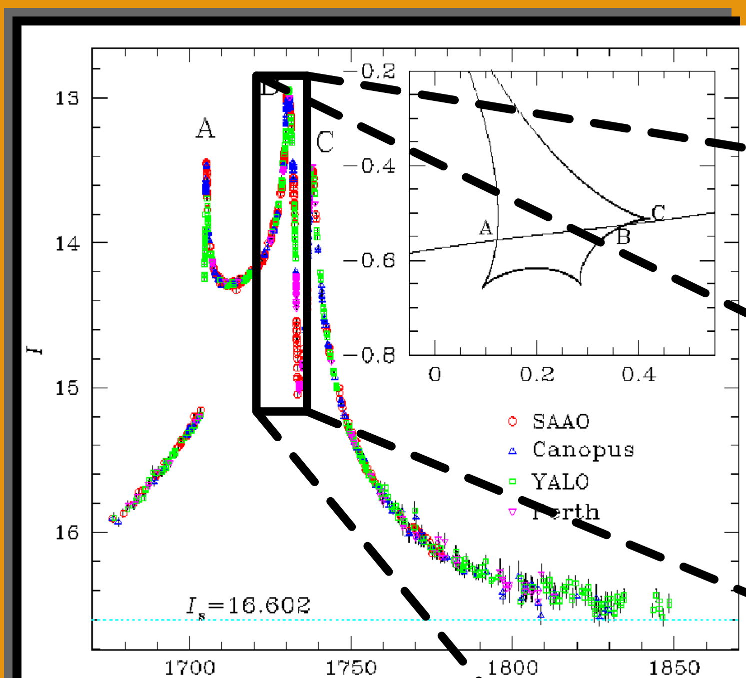
Theory vs. Measurement

Close to being able to distinguish between models.



# Stellar Atmospheres

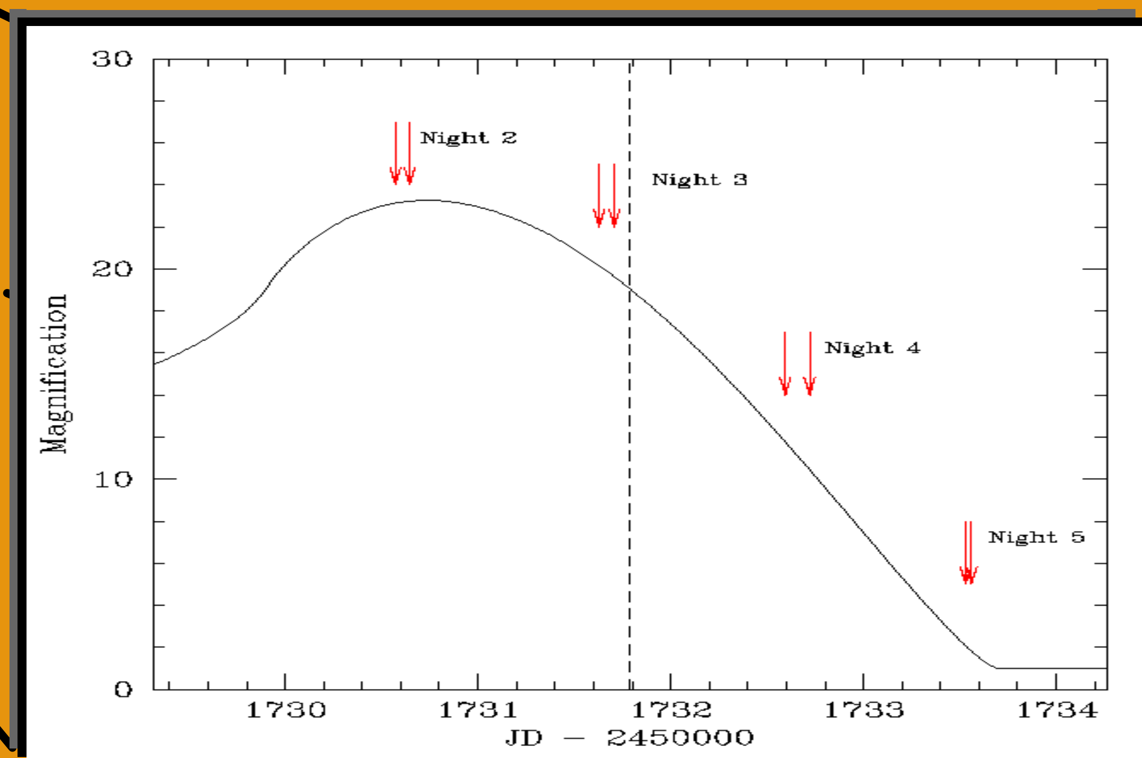





An et al 2002

Spectral Resolution:
EROS BLG-2000-5

Long timescale 2$^{nd}$ crossing

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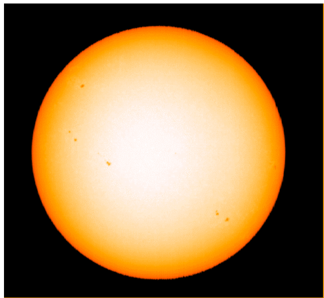

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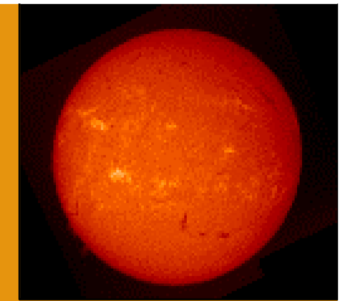
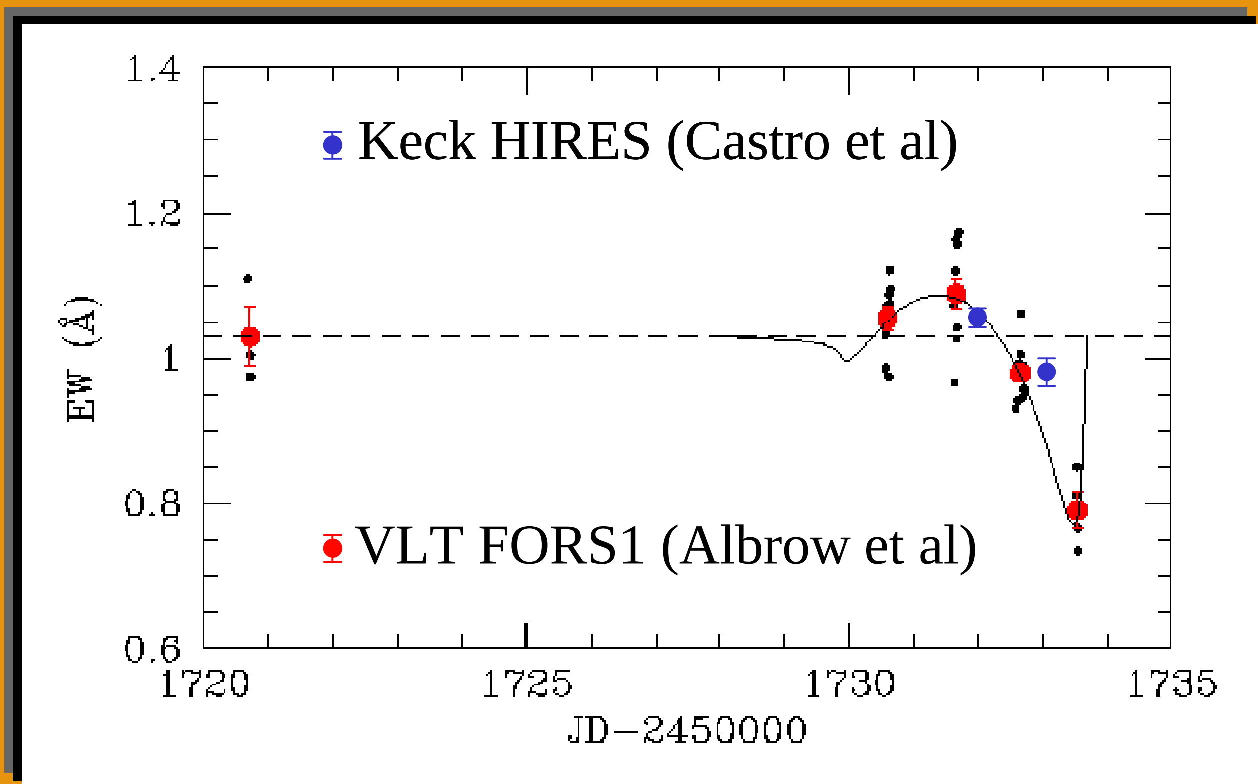





Castro et al 2001, Albrow et al 2001

**Two Groups:**

- Keck HIRES (high-res)
- VLT FORS1 (low-res)

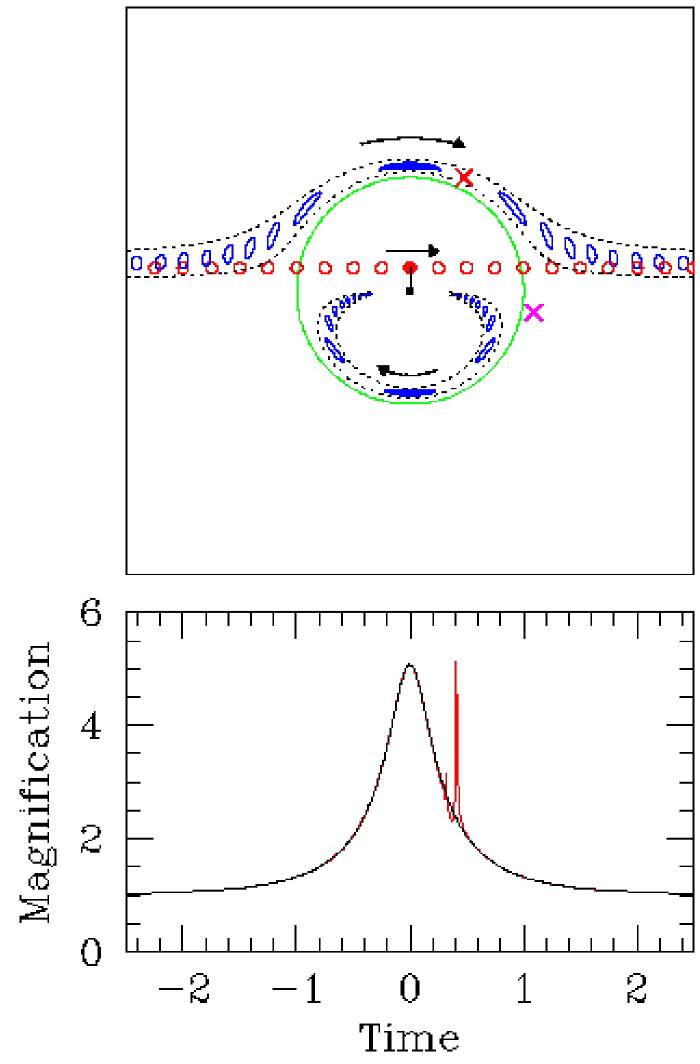
⇒ **Both saw variations in EW of Ha.**

**VLT measurements imply:**

- outer 4% of the source in emission in Hα.
- in conflict with models.

(Afonso et al 2001)

# EXTRASOLAR PLANETS




## Planet Parameters:

- Angle wrt Binary Axis
- Projected Separation
- Mass Ratio - q

$$t_p \simeq \sqrt{q}\, t_E \simeq 1\text{day} \left(\frac{M_p}{M_J}\right)^{1/2}$$

## Detection Efficiency:

$$\sim A\frac{\theta_p}{\theta_E} \simeq 15\% \left(\frac{q}{10^{-3}}\right)^{1/2}$$

High-Magnification Events

→ Higher Efficiencies

Maximized at $a \sim \theta_E$

(Mao & Paczynski 1991,
Gould & Loeb 1992,
Griest & Safizadeh 1998)

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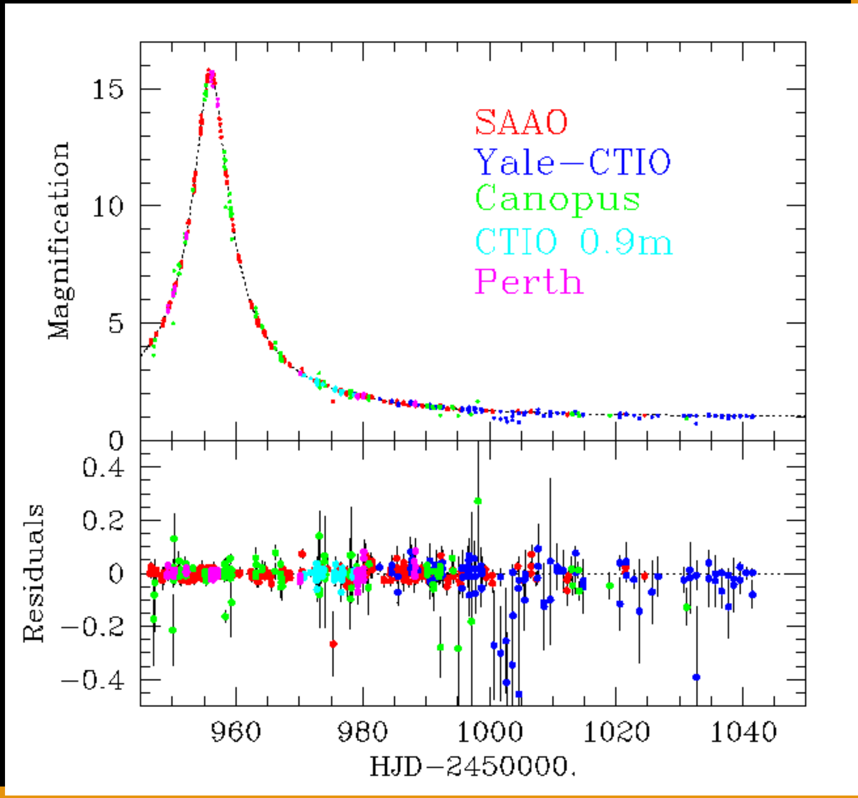
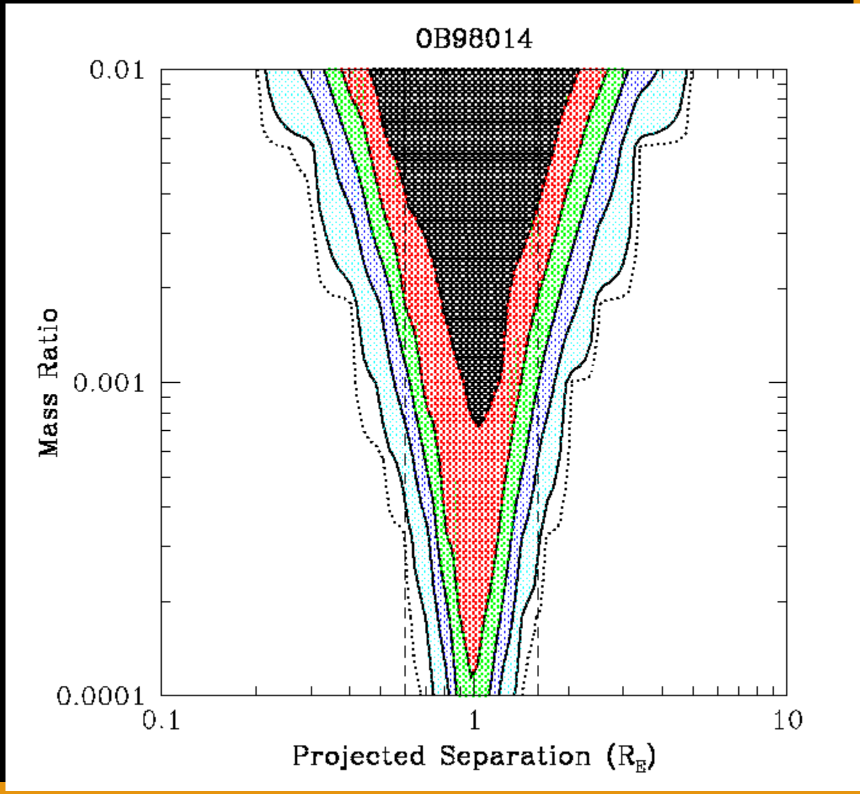
# EXTRASOLAR PLANETS

(Albrow et al 2000)




Dense, Accurate Photometry → High Detection Efficiency

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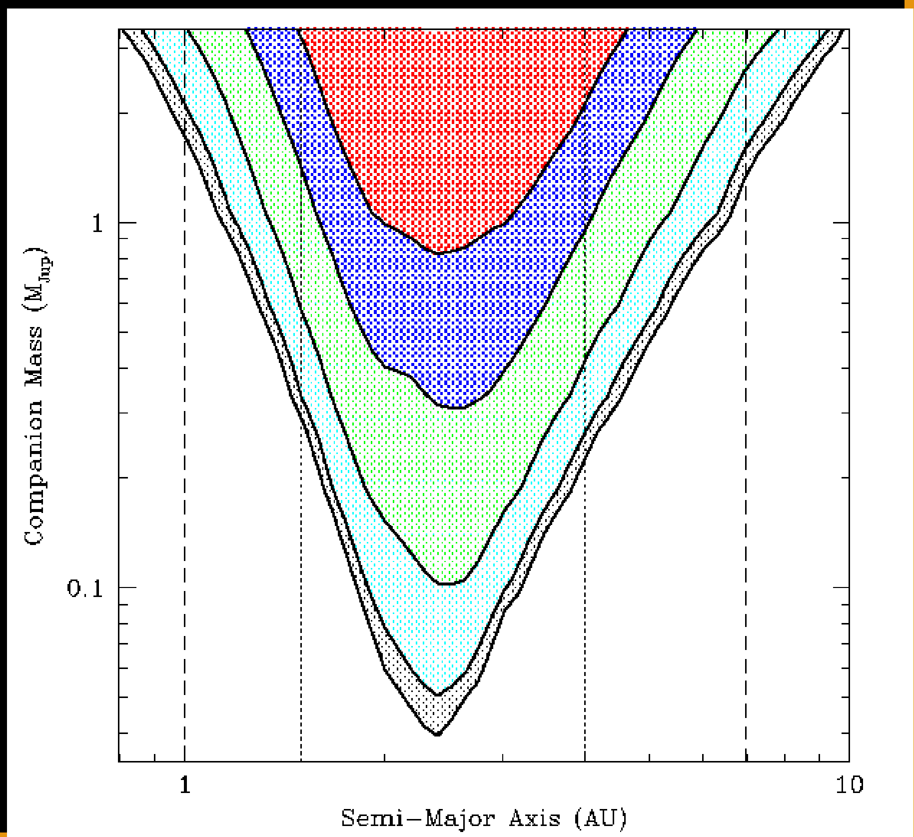
# EXTRASOLAR PLANETS




## But no detections!

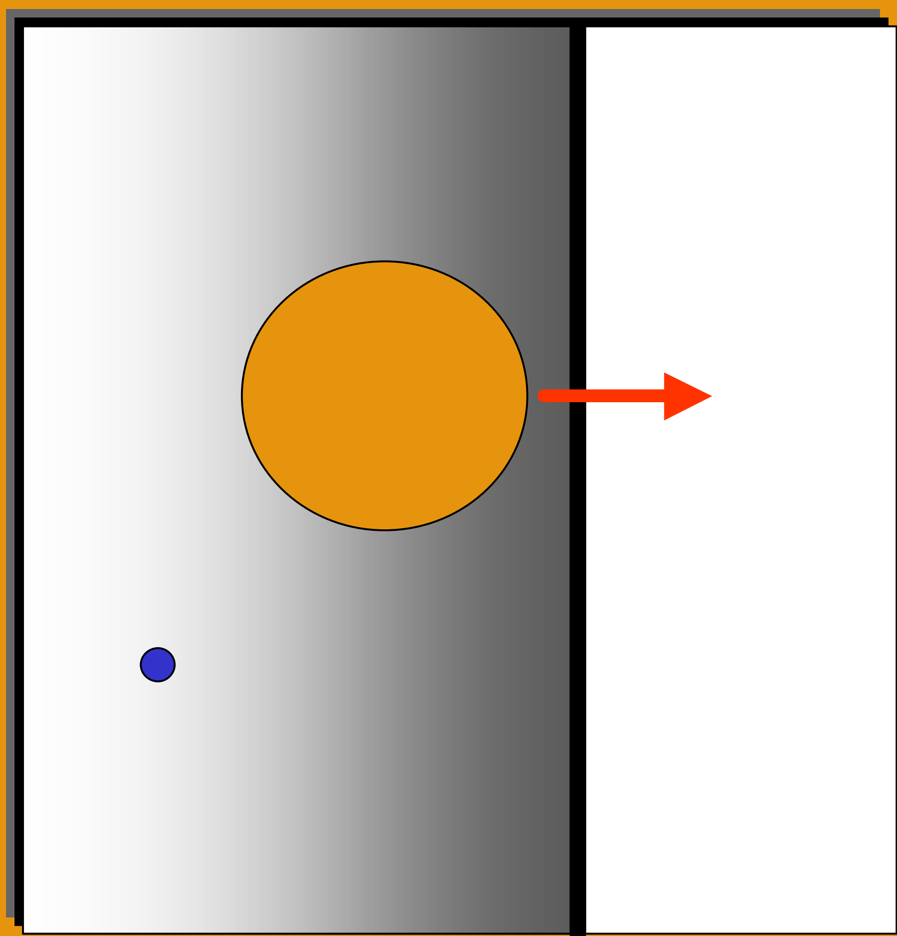
(43 events in PLANET 95-99 Dataset)

(Albrow et al. 2001, Gaudi et al. 2002)

<33% Have Jupiter-mass companions between 1.5-4 AU
<45% Have 3 x Jupiter-mass companions between 1-7 AU

# EXTRASOLAR PLANETS

## Direct Detection: Companions to the Source



### Caustic-crossing Binary Events

•Flux Ratio

$\epsilon \sim p\phi 10^{-4}(R/R_J)^2(a/0.05\mathrm{AU})^{-2}$

•Magnification

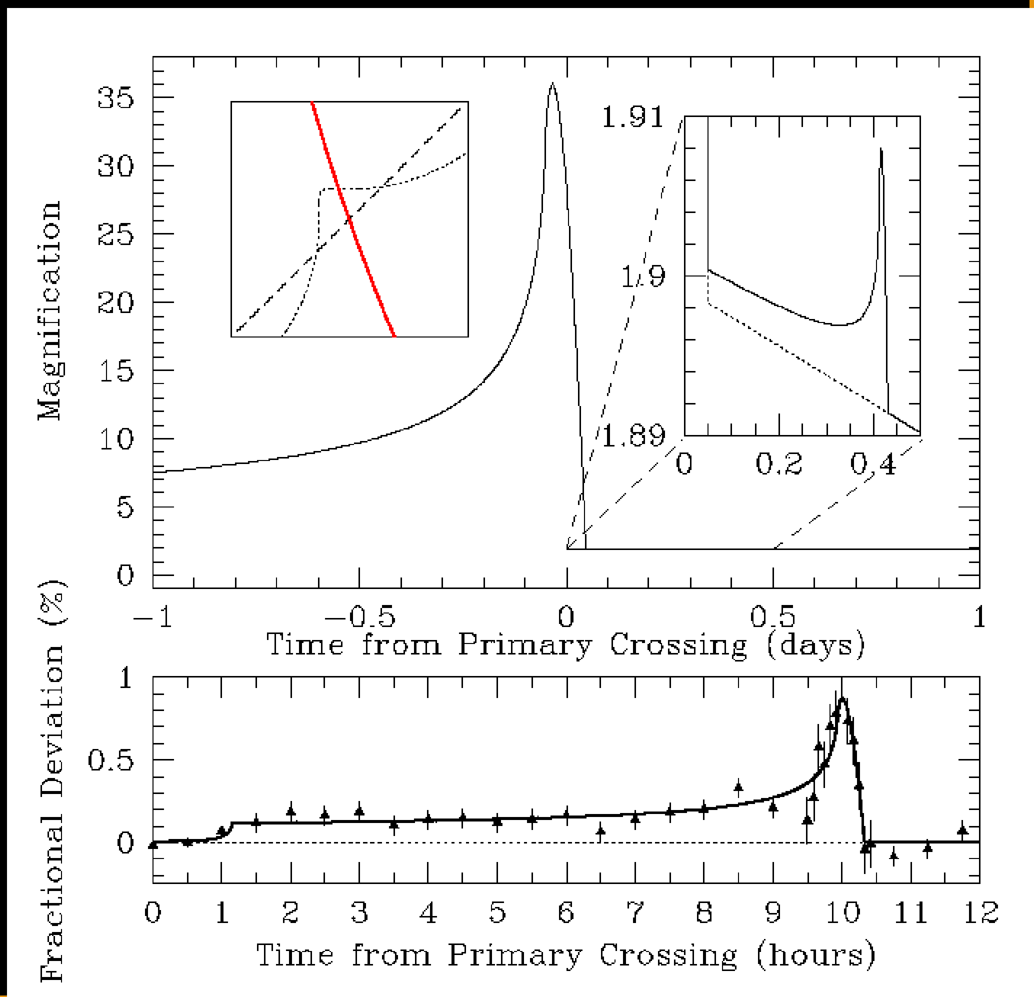
$A \sim 10^2(R/R_J)^{-1/2}(M/M_\odot)^{1/2}$

•Deviation

$\delta \simeq A\epsilon \sim 1\%$

(Graff & Gaudi 2000, Lewis & Ibata 2000)

# EXTRASOLAR PLANETS




(Graff & Gaudi 2000)

## How Many Events?

- Number of Alerts ~ 200-500
- Fraction of C.C. Events ~7%
- Fraction of Stars w/ Planets ~1-5%
- Total number of Events ~0.1-1

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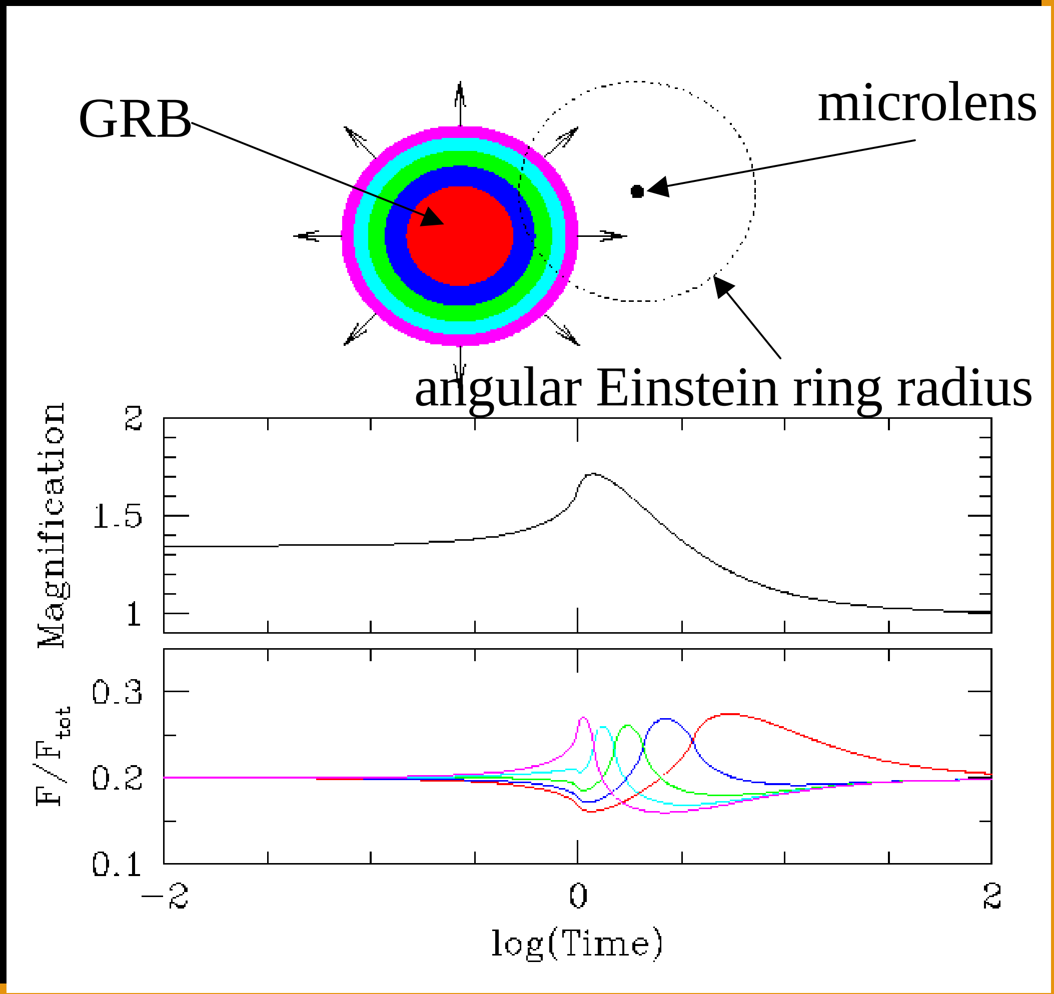
# Gamma-ray Bursts




GRB afterglow angular radius:

$$\theta_{ag} \simeq 1\mu\text{as}(t/\text{day})^{5/8}$$

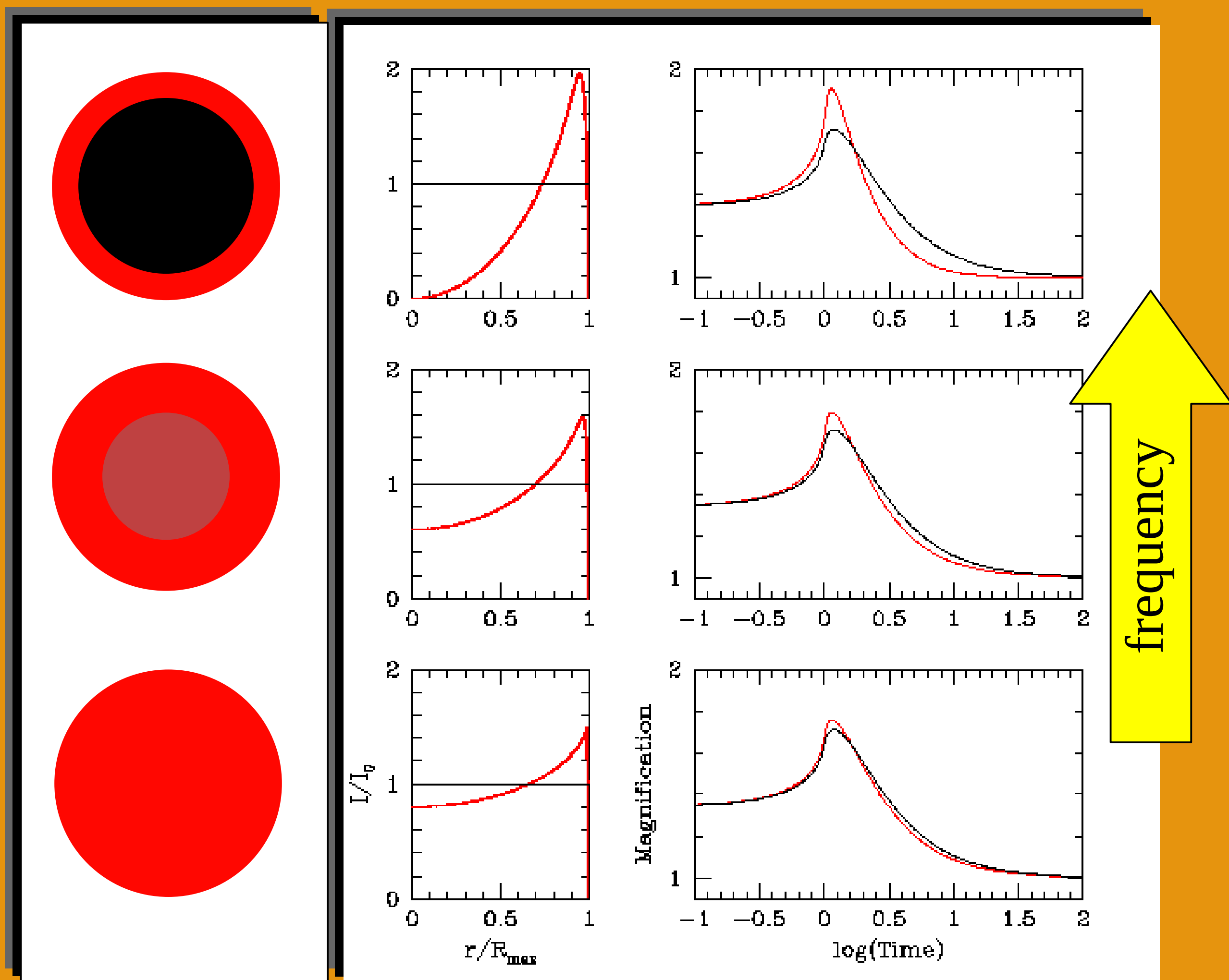
Angular Einstein ring radius of lens at cosmological distances:

$$\theta_E \simeq 1\mu\text{as}(M/M_\odot)^{1/2}$$

- Detectable deviation.
- Convenient duration.

(Loeb & Perna 1998, Mao & Loeb 2001, Granot & Loeb 2001, Gaudi & Loeb 2001)

# Gamma-ray Bursts




- Dense photometry
- 4m-class telescopes

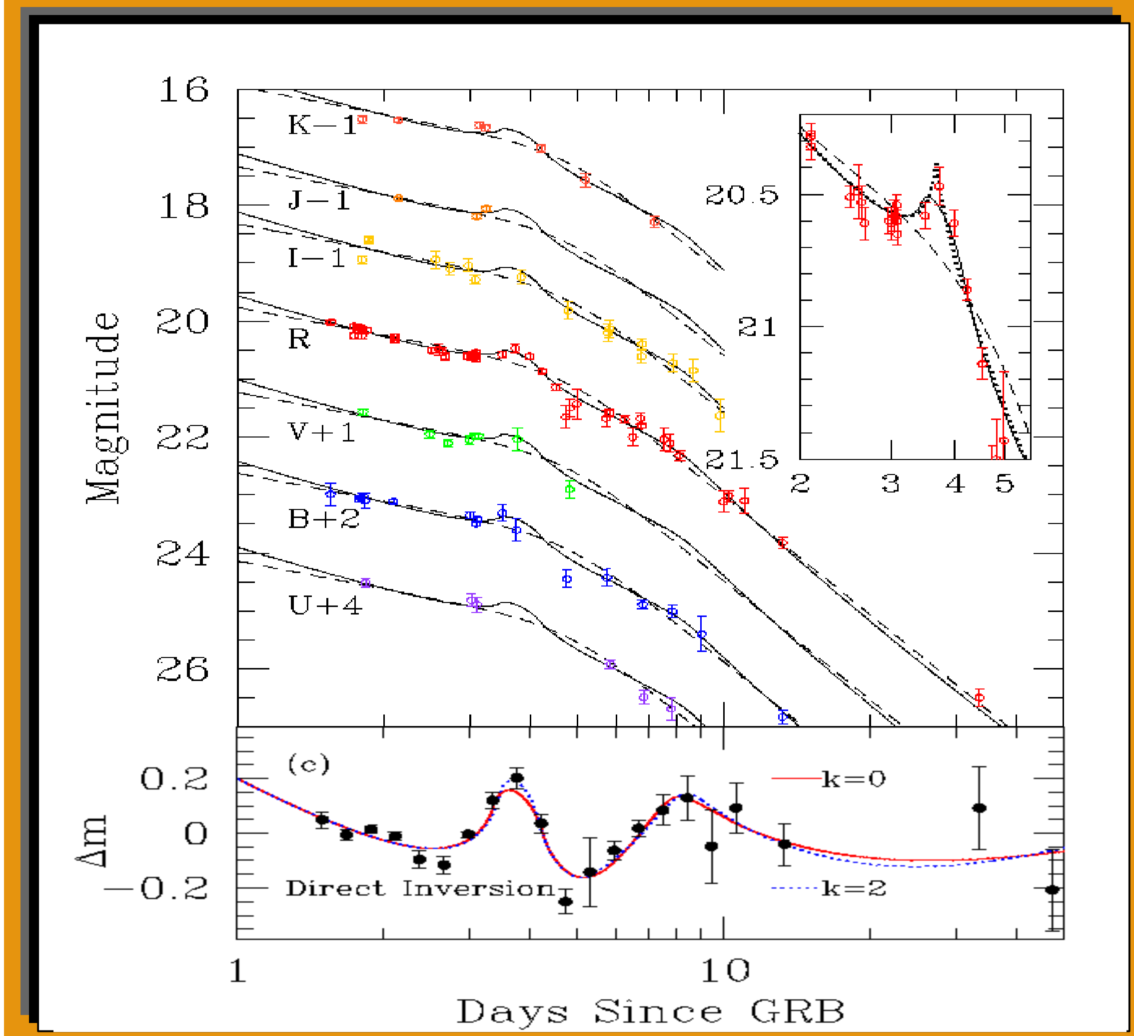
⇨ resolve SBP ~few %
(Gaudi & Loeb 2001)

- Models predict different SBP

(Granot & Loeb 2001)

**Microlensing can provide additional constraints on afterglow models.**

# Gamma-ray Bursts




## GRB 000301C

- Short, achromatic 'bump'
- Microlensing?
  (Garnavich, Loeb, Stanek 2000)

## Can realistic profiles fit data?

- Fit models of Granot & Loeb

## What does data imply for SBP?

- "Direct Inversion"

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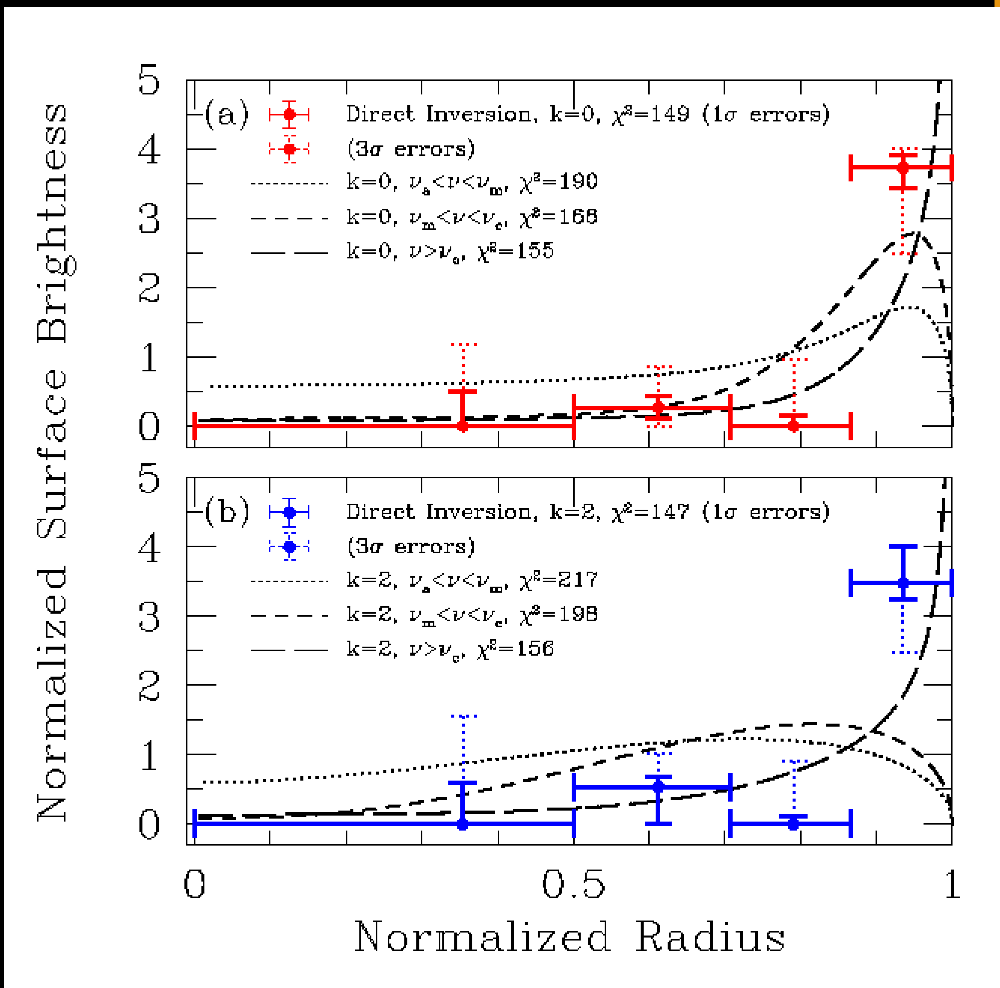
# Gamma-ray Bursts




(Gaudi, Granot & Loeb 2001)

## Direct Inversion

• > 60% of flux must come from outer 25% of the area of the afterglow.

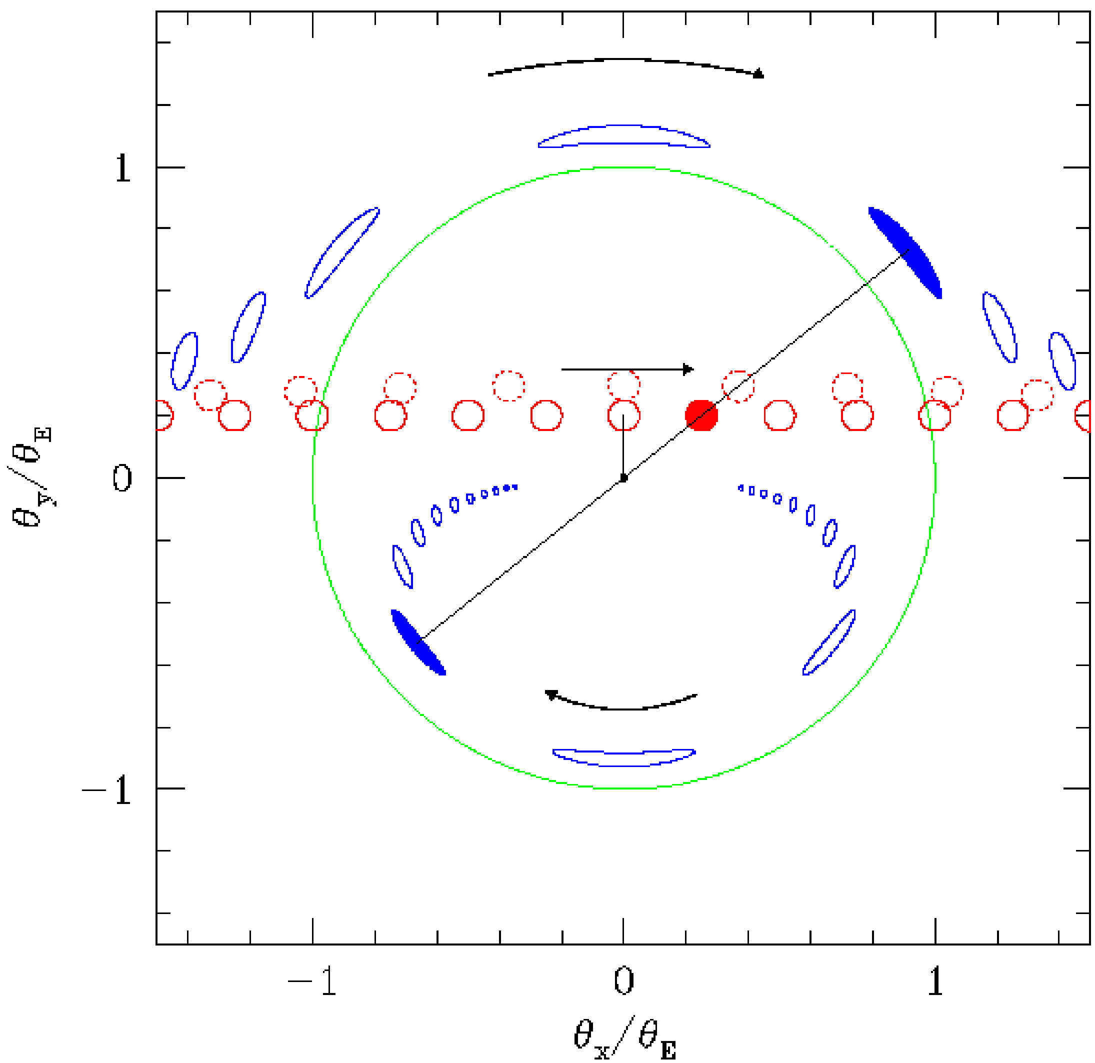
## Model Fits

•Realistic SBP fit, provided that $\nu > \nu_c$

Underlying light curve is consistent with a jet propagating into a uniform medium with $\nu > \nu_c$

## Caveats?

# Compact Object Masses

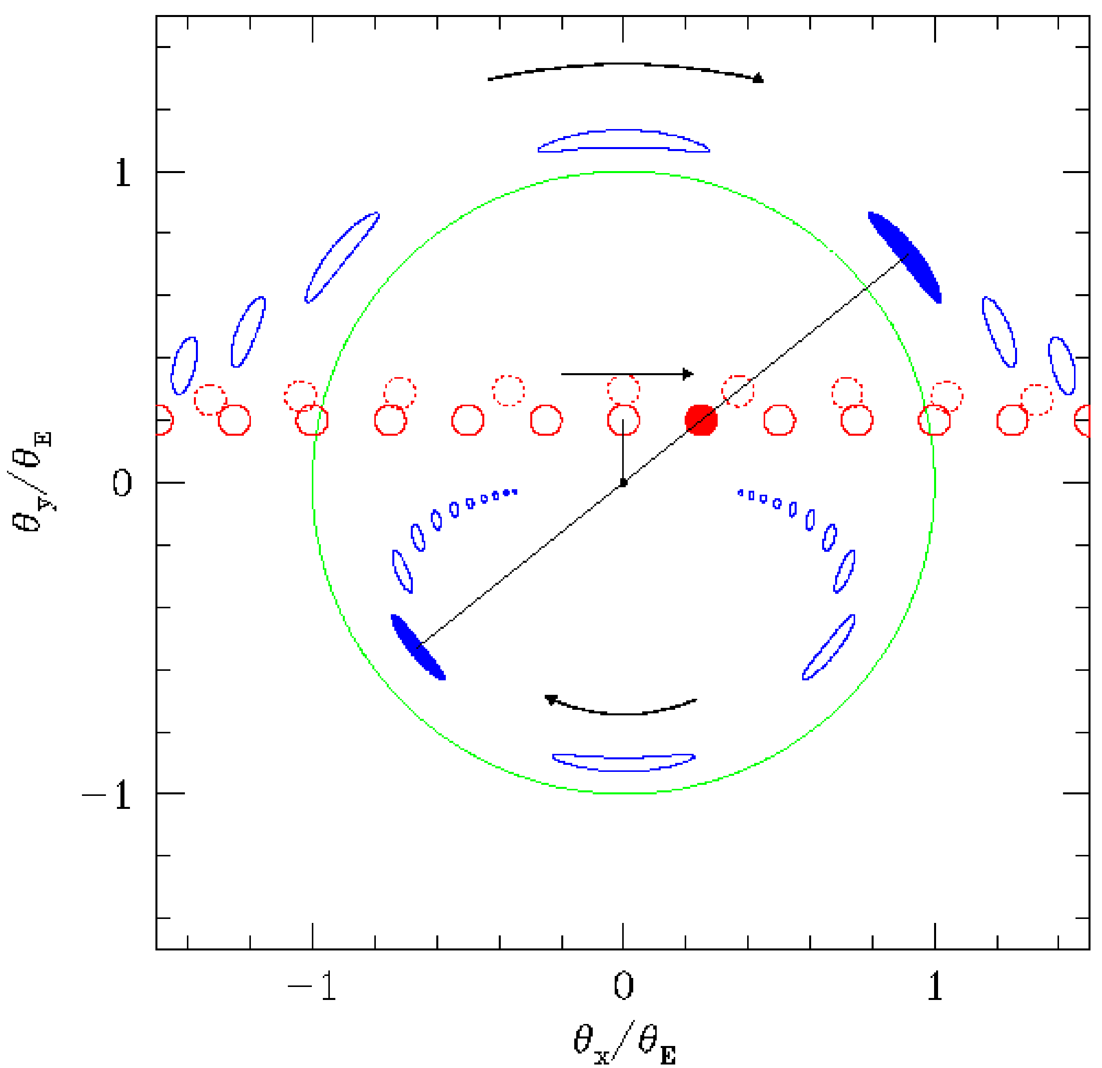



## $\theta_E$ -Measurement

- Images unresolved
- Generally easier to centroid than resolve
- Centroid moves a significant fraction of $\theta_E$
- For Bulge lenses:

$$\theta_E = 300\mu\text{as}(M/M_\odot)^{1/2}$$

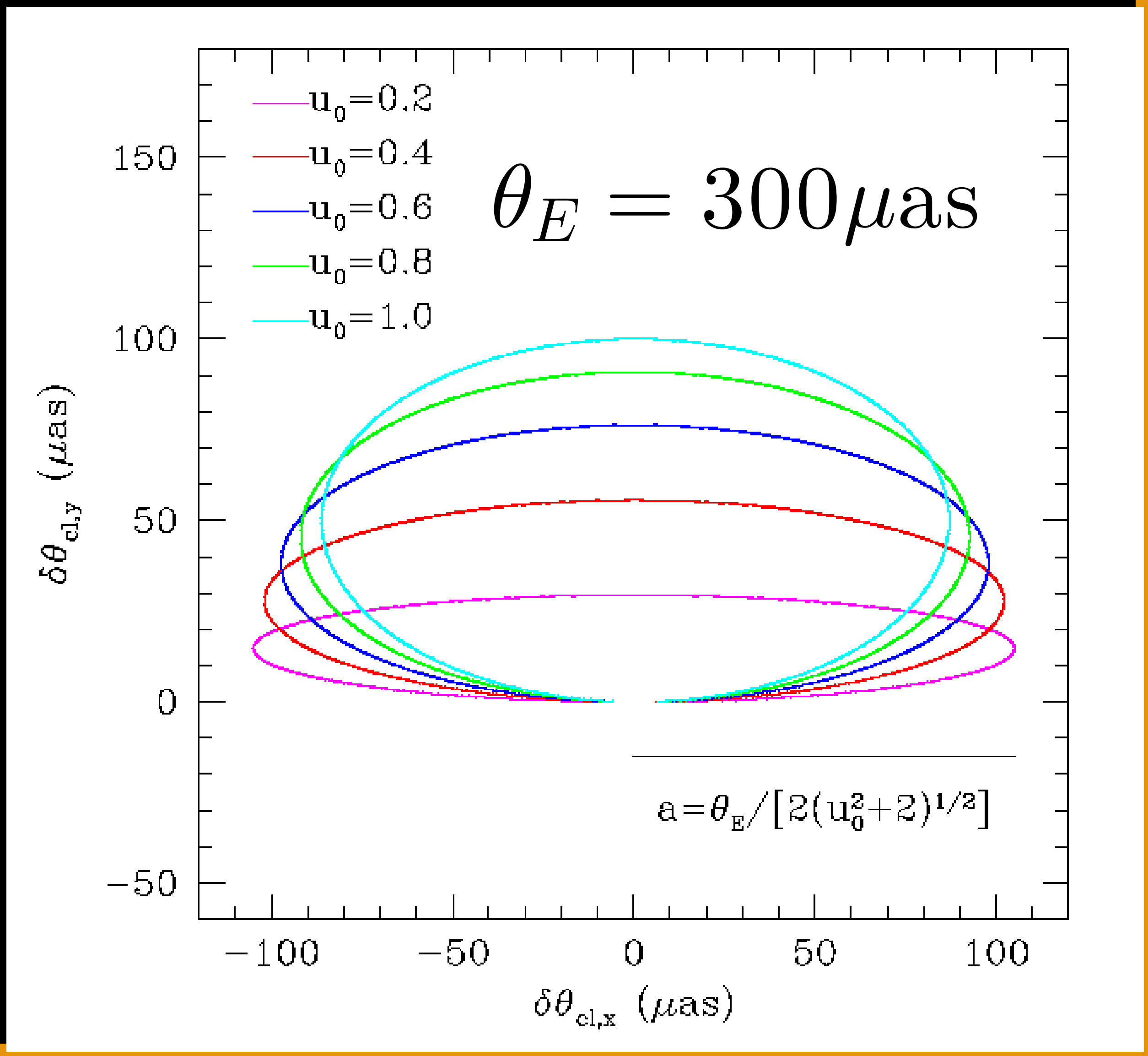
# Compact Object Masses




## $\theta_E$ -Measurement

- Typically faint lens
- Measurements made wrt unlensed source position.
- Traces an ellipse.

# Compact Object Masses




## $\theta_E$ -Measurement

- Two-parameter family

Impact Parameter → $u_0$

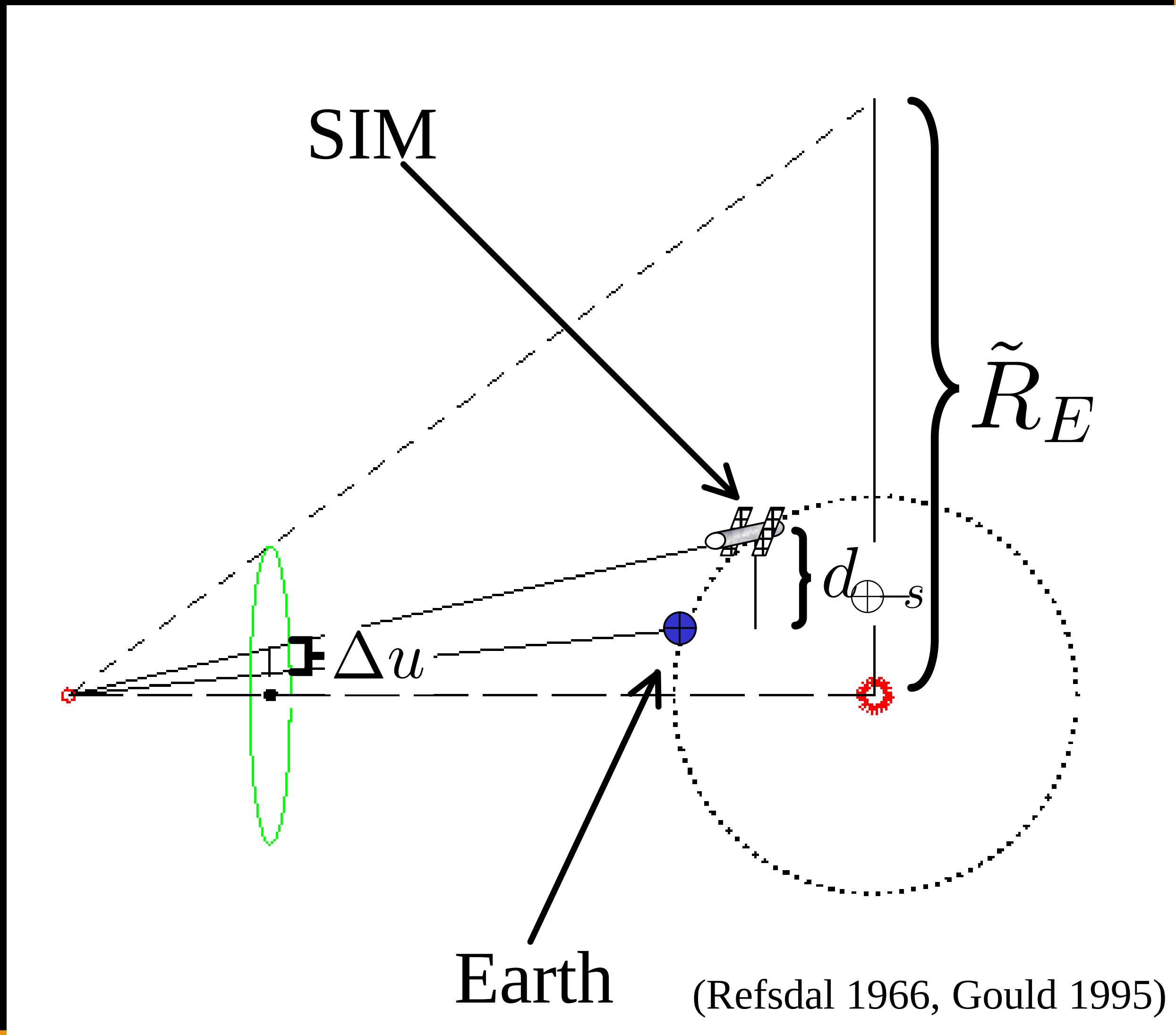
Angular Einstein Ring Radius → $\theta_E$

- Detectable with SIM

$$\sigma_{ast} \sim 10\mu\text{as}$$

[ Walker 1995,
Boden, Shao, Van Buren 1998,
Paczynski 1998 ]

# Compact Object Masses



(Refsdal 1966, Gould 1995)

## $\tilde{R}_E$-Measurement

- If two observers are significantly displaced, i.e.

$$\text{if} \;\; d_{\oplus - s} = \mathcal{O}(\tilde{R}_E)$$

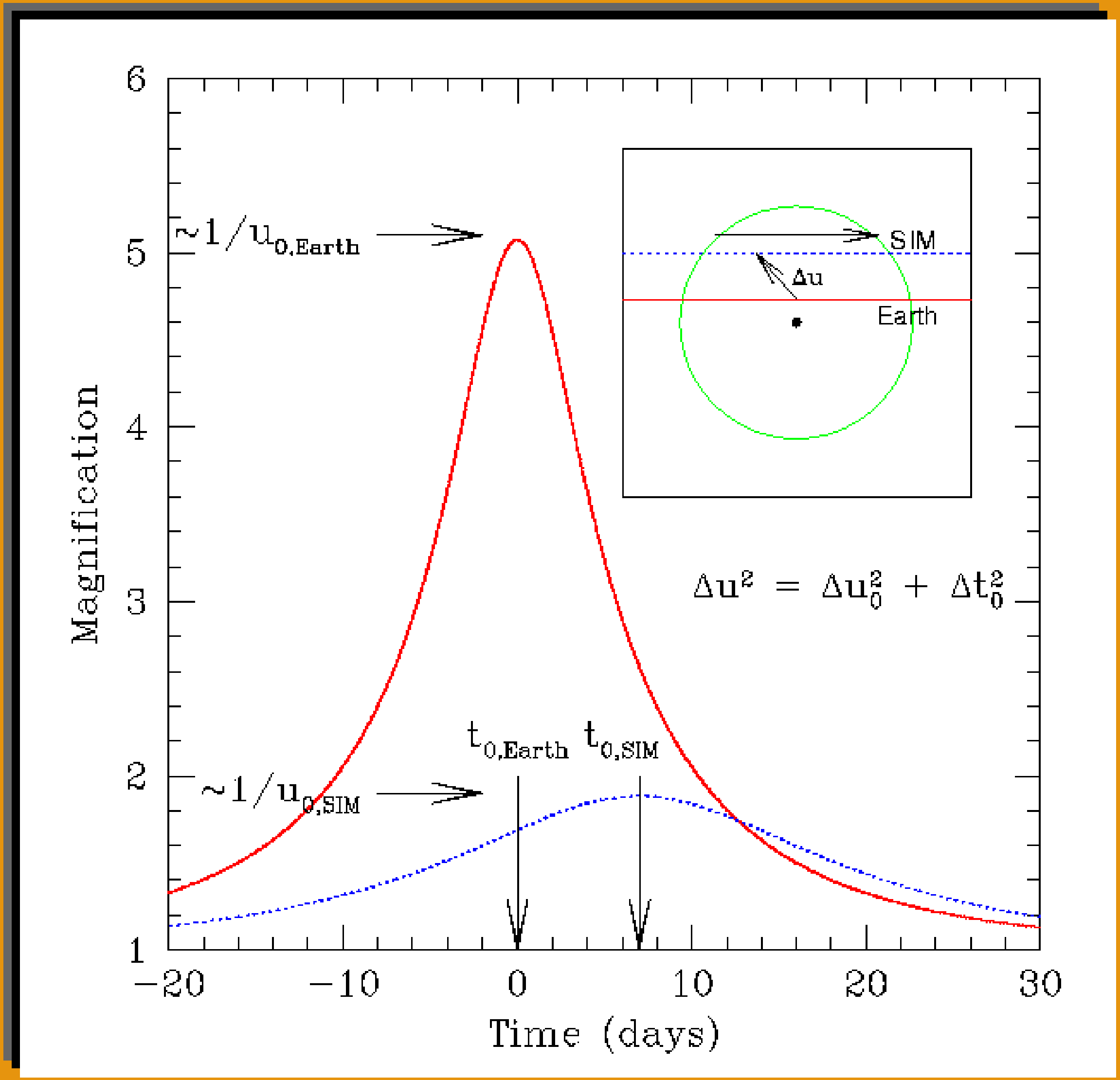
where

$$\tilde{R}_E \equiv D_{rel}\theta_E$$

- The event will appear different.
- Measure

$$\tilde{R}_E = d_{\oplus - s}/\Delta u$$

# Compact Object Masses




## $\tilde{R}_E$-Measurement

- Measuring $\Delta u$
- Difference in impact parameters:

$$\Delta u_0 = u_{0,\oplus} - u_{0,s}$$

- Difference in time of maximum magnifications:

$$\Delta t_0 = t_{0,\oplus} - t_{0,s}$$

- Yields:

$$\Delta u^2 = \Delta u_0^2 + \Delta t_0^2$$

(Gould 1994,1995, Boutreux & Gould 1996 Gaudi & Gould 1997)

# Compact Object Masses

$$M = \left(\frac{c^2}{4G}\right) \tilde{R}_{\mathrm{E}}\theta_{\mathrm{E}}$$

(Gould & Salim 1999)

# Compact Object Masses

## SIM Microlensing Key Project:

- Mass function in the Bulge for $M > 0.01 M_\odot$
  ⟹ *Including WD, NS, BH*
- Masses (to 1%) of nearby high proper motion objects.
- Mass, distance, and velocity for about 5 LMC microlenses.
- Masses of planets detected via microlensing.

## Also:

- Measure angular radii of stars in Bulge to ~few %.
- Determine binary frequency from 0.1 < a < 10 AU.

[ Paczynski 1998, Gould 2000a, 2000b, Han & Jeong 1999,
Han & Kim 2000,Graff & Gould 2002, Gaudi, Graff & Han 2002 ]

# Join the Cult of Microlensing!

**Act now, and you'll get to study:**

- Dark Matter
- Stellar Atmospheres
- EXTRASOLAR PLANETS
- Gamma-ray Bursts
- Compact Object Masses
- **and much, much, more!**