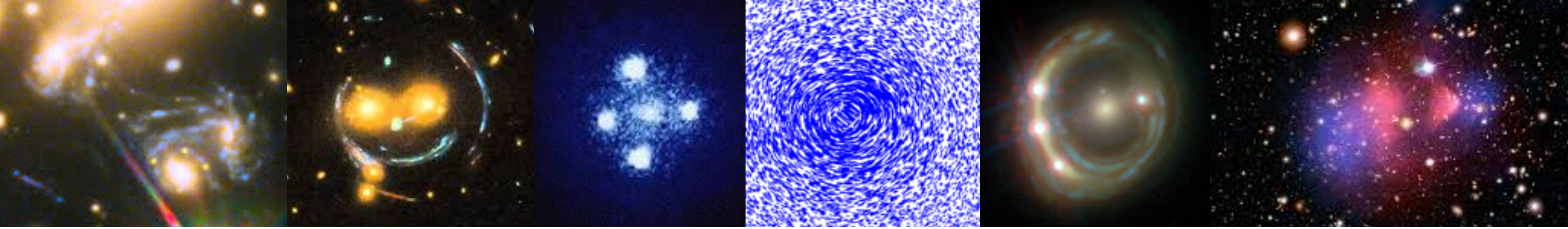

PHY-765 SS19 Gravitational Lensing Week 9

Microlensing

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Last week - what did we learn?

- Topic was how to find (strong) gravitational lenses in data

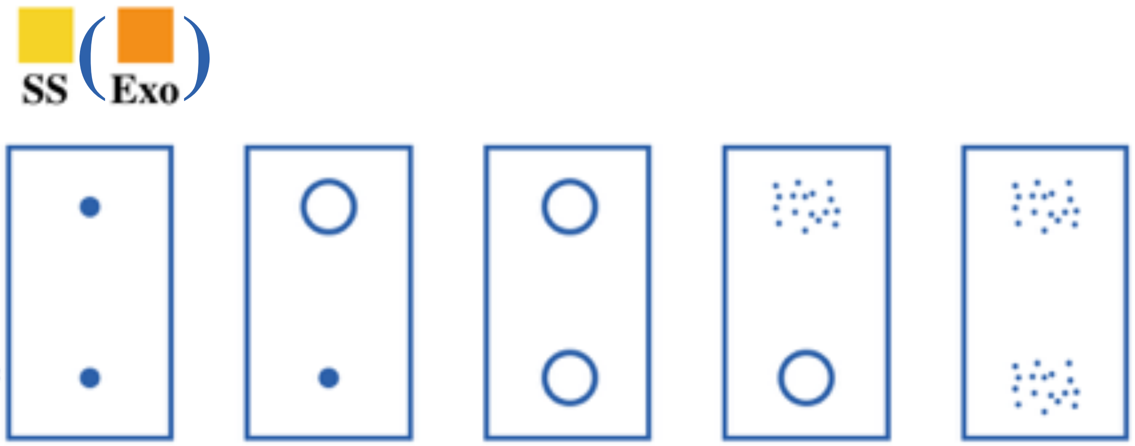
- Put together a "shopping list" for confirming gravitational lenses

- Multiple examples where similar lists lead to discovery of lenses, incl.
    - Multiple imaged AGN radio lenses
    - Multiple imaged QSO in SDSS, Gaia and the DES
    - Galaxy-Galaxy lenses in SDSS
    - Cluster lenses

- Lens numbers for current and future surveys (Oguri & Marshall 2010)
    - >1000 QSO lenses expected from DES
    - ~10^4 QSO lenses expected from LSST

The aim of today

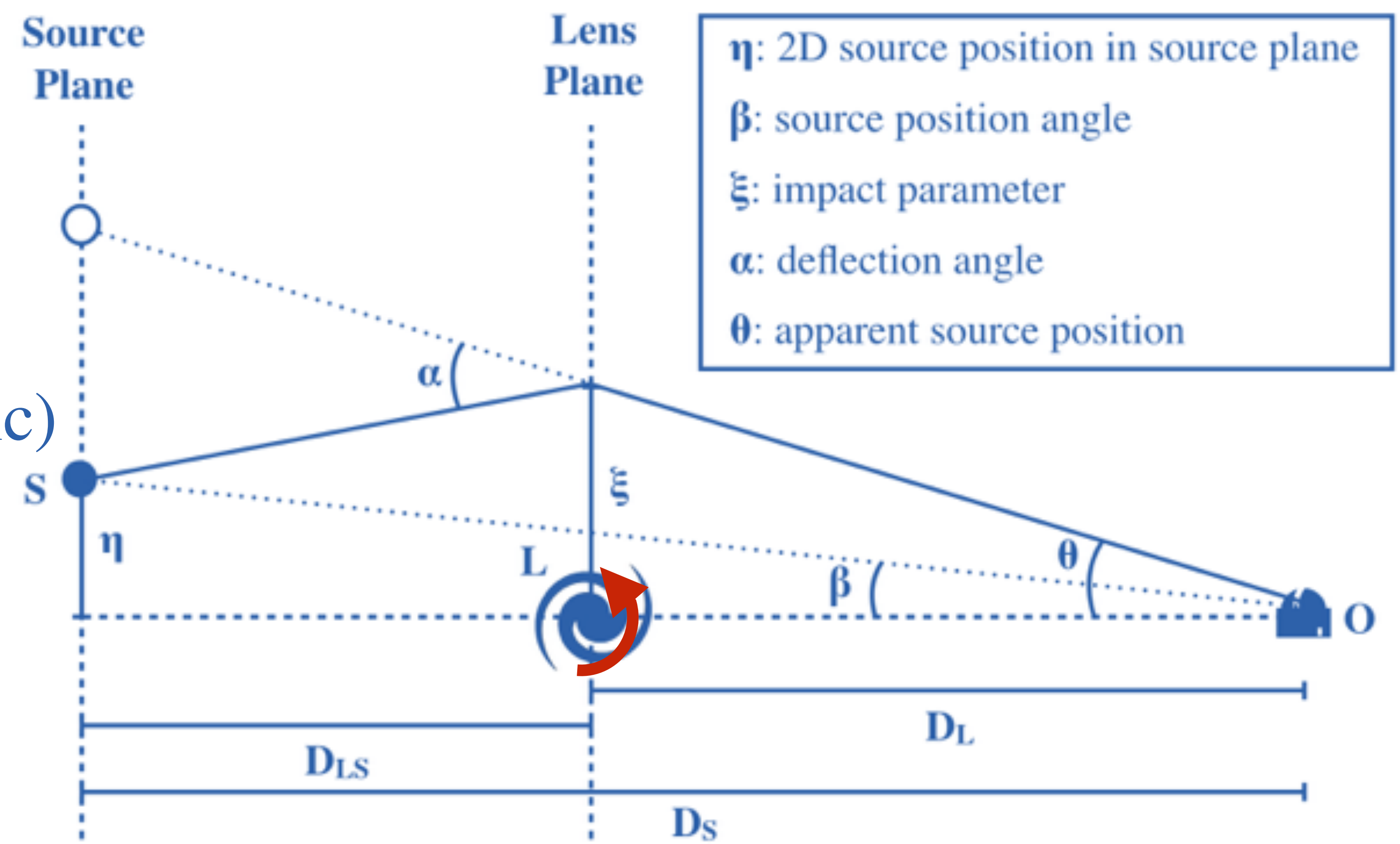
- Look at galactic and extra-galactic microlensing
- Consider the time-varying aspect of microlensing
- Describe the geometry of the microlensing setup
- Look at microlensing optical depth
- Using microlensing to probe the dark matter of galactic halos
- Prominent surveys enabling microlensing studies.



Microlensing - A Time-Variable Phenomenon

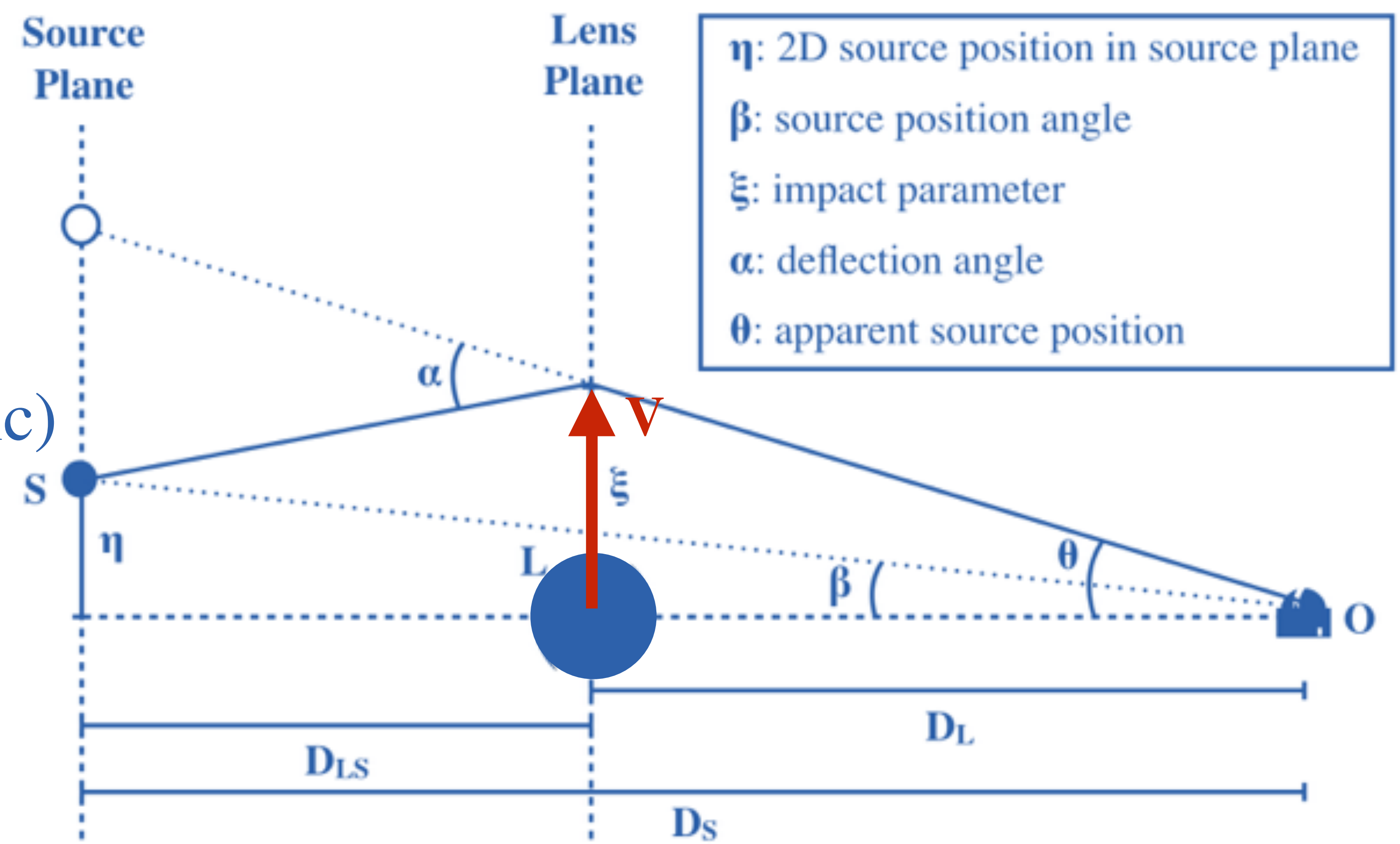
- Until today everything has been static

- ML introduces movement:
  - Within lens (extra-Galactic)



Microlensing - A Time-Variable Phenomenon

- Until today everything has been static
- ML introduces movement:
  - Within lens (extra-Galactic)
  - Of the lens (Galactic)
- ML can be thought of as "Strong lensing with unresolved image positions"



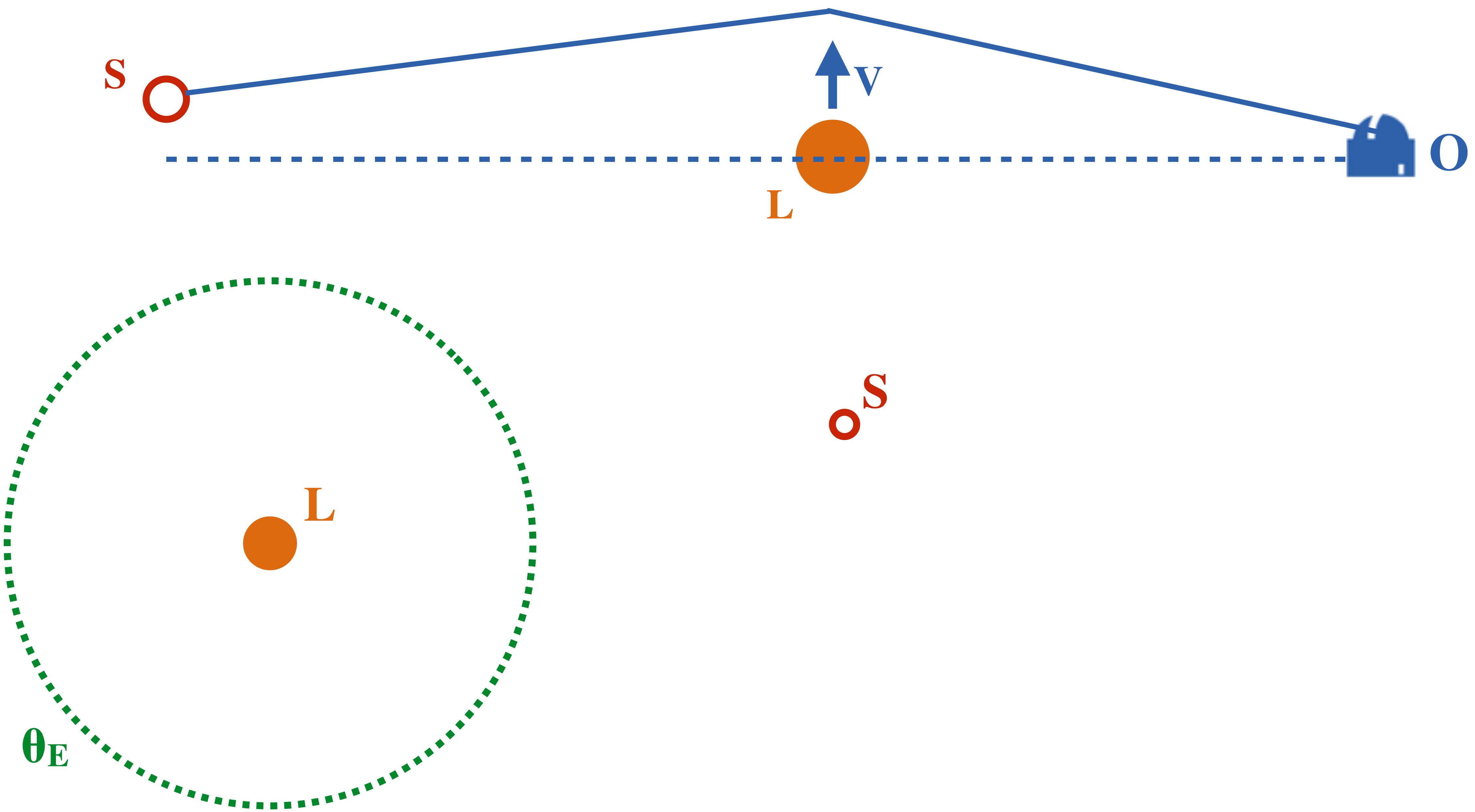
- The term "microlensing" was coined by Paczynski (1986a):
  - "*Gravitational deflections due to individual solar mass stars placed at cosmological distances are of the order of 1 micro-arcsec*"

(Week 3)

- So if D_L~1Gpc and $M = 1M_\odot$ then $\boldsymbol{\alpha} \sim 10^{-6}$ arcsec from $$\boldsymbol{\alpha}(\boldsymbol{\theta}) = \frac{4MG}{c^2}\frac{D_{\rm LS}}{D_{\rm S}D_{\rm L}}\frac{\boldsymbol{\theta}}{|\boldsymbol{\theta}|^2}$$
- Microlensing now used more generally for time-variable flux changes in lenses

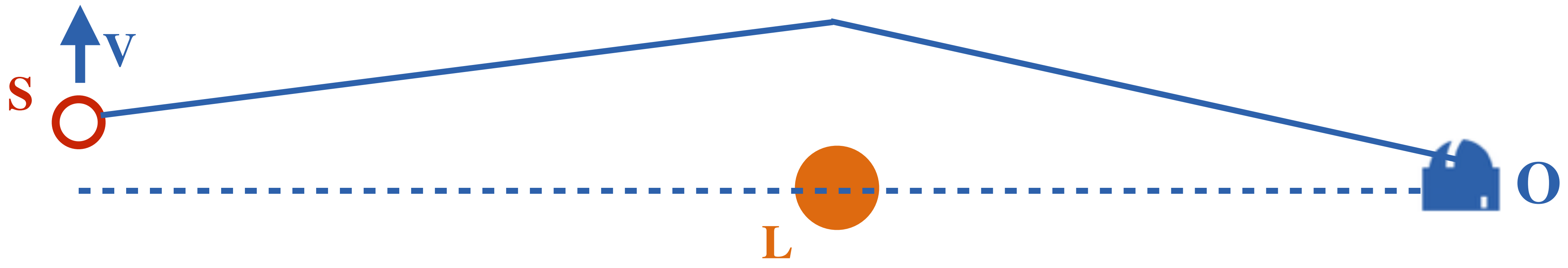
Microlensing Geometry

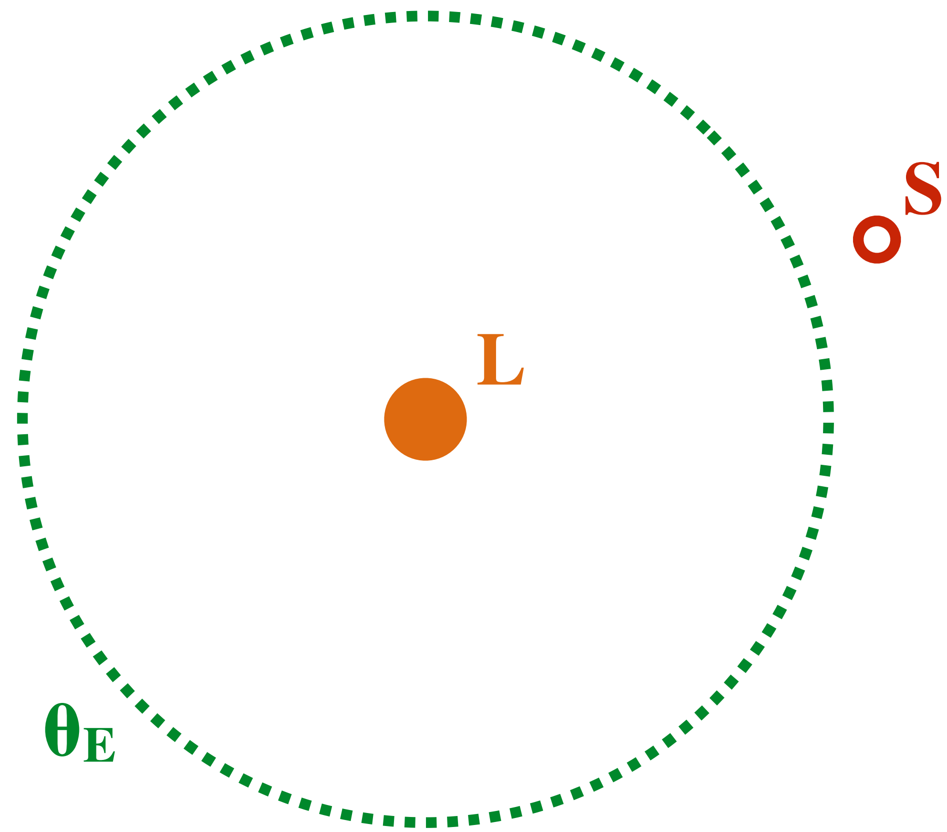
- The “light-curve” of a source is dictated by the *relative* movement of the lens
- Formally it is movement in/of the lens inducing time-variable flux



Microlensing Geometry

- The "light-curve" of a source is dictated by the *relative* movement of the lens
- Formally it is movement in/of the lens inducing time-variable flux
- But the movement is relative, so can also be seen as the source moving





The Point Mass Lens

- We know the magnification of the two images of the point mass lens

$$\mu_\pm = \frac{1}{1-(\theta_E/\theta_\pm)^4} \qquad \text{(week 7)}$$

- This can be expressed as

$$\mu_\pm = \pm\frac{1}{4}\left[\frac{y}{\sqrt{y^2+4}} + \frac{\sqrt{y^2+4}}{y} \pm 2\right] \quad \text{where} \quad y = \frac{\beta}{\theta_E}$$

- As the individual images are unresolved, the total source magnification is

$$\mu = \mu_+ + |\mu_-| = \mu_+ - \mu_- = \frac{y^2+2}{y\sqrt{y^2+4}} \qquad \text{(Exercise 2)}$$

- Furthermore

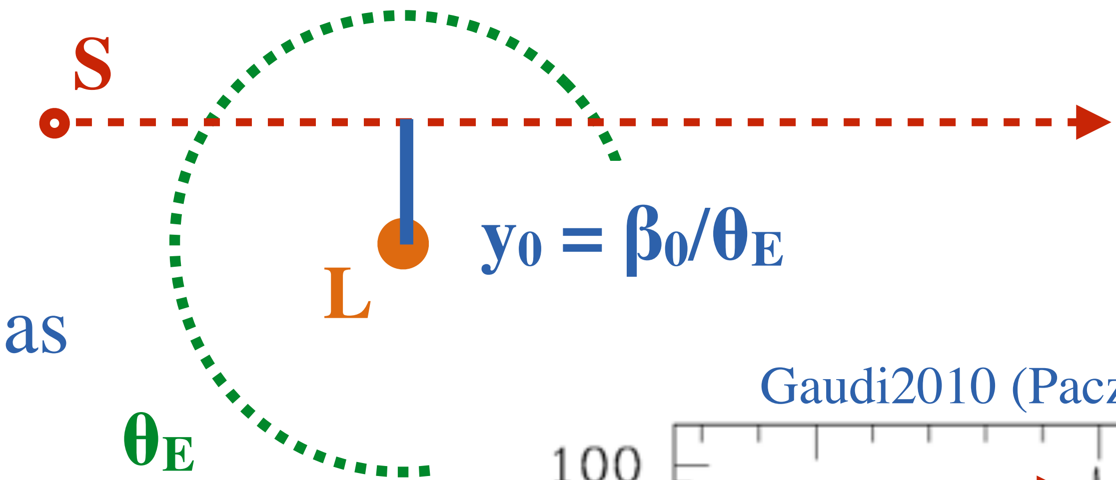
$$\mu_+ + \mu_- = 1 \quad \text{and} \quad \left|\frac{\mu_-}{\mu_+}\right| = \left(\frac{y-\sqrt{y^2+4}}{y+\sqrt{y^2+4}}\right)^2 = \left(\frac{x_-}{x_+}\right)^2 \quad \text{where} \quad x_\pm = \frac{\theta_\pm}{\theta_E}$$

- Natural extension - two point mass lenses… finding planets → next week

The Point Mass Lens

- Note that in the the expression for μ, $y = \beta/\theta_E$ is a function of time, i.e., *y(t)*
- It depends on β_0, $v_\perp$ and D_L. Actually one can define the Einstein time

$$t_E \equiv \frac{D_L \theta_E}{v_\perp}$$

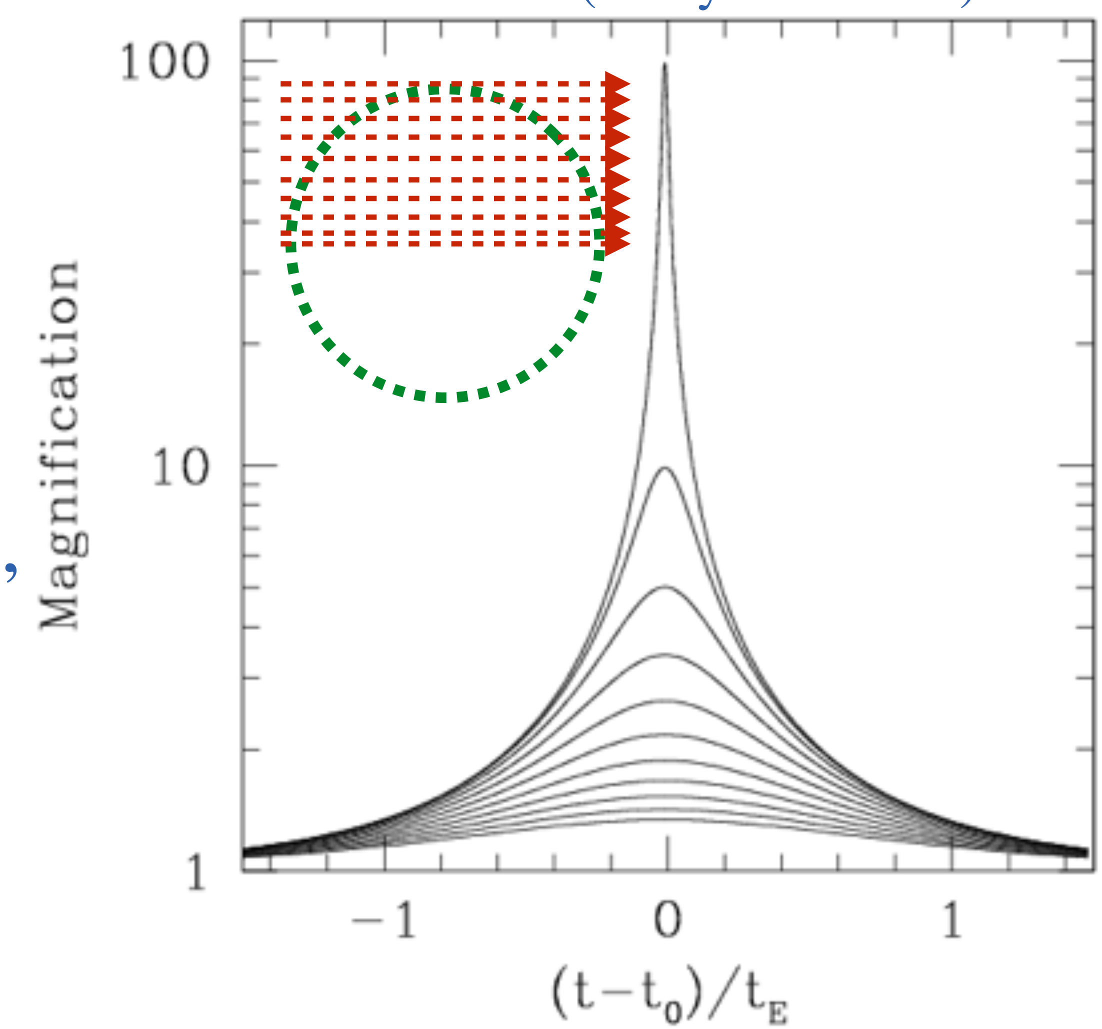


- This enables us to express *y(t)* as

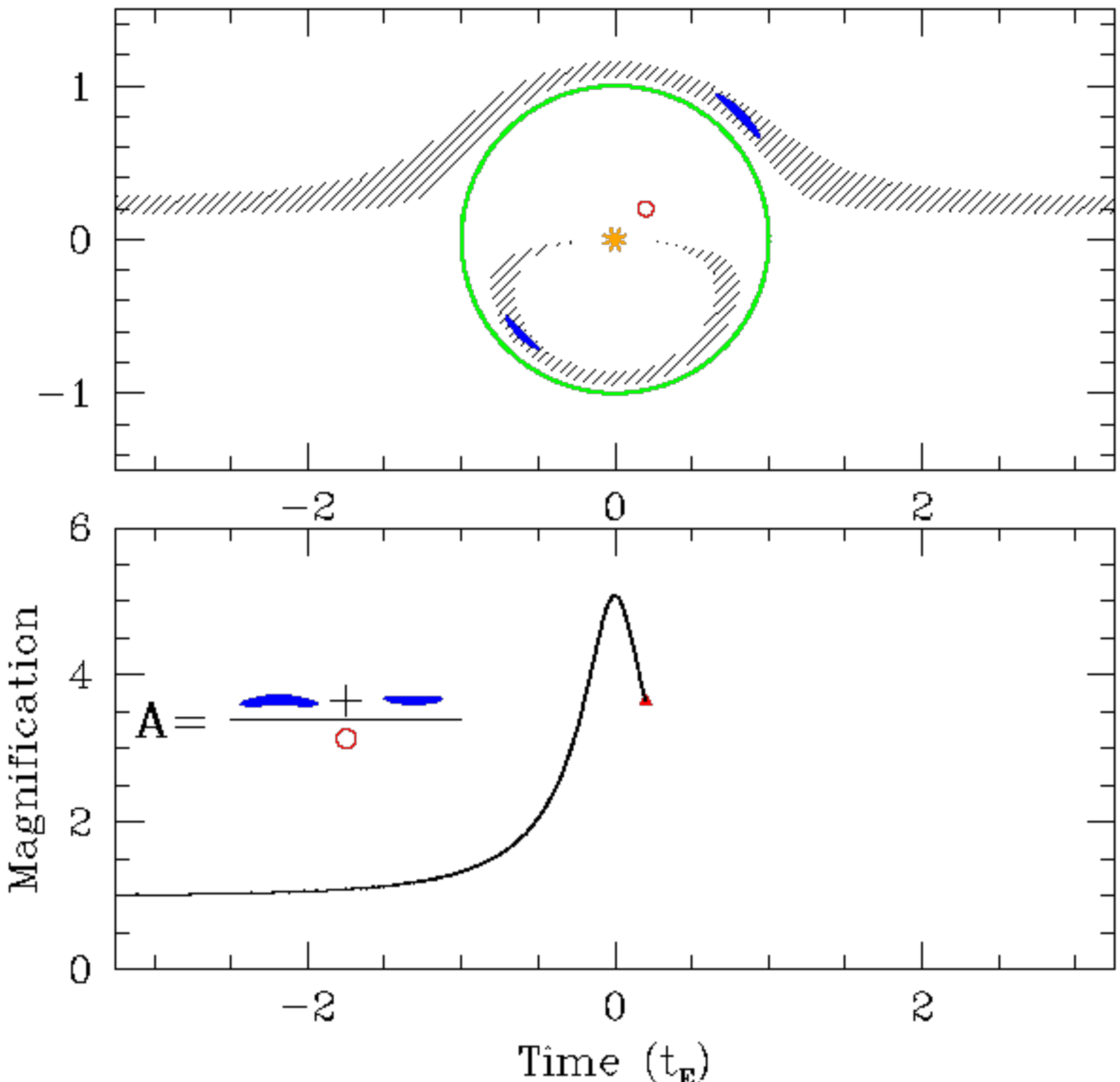
$$y(t) = \sqrt{y_0^2 + \left(\frac{t - t_0}{t_E}\right)^2}$$

- Here t_0 is time of closest approach y_0 and maximum magnification μ_0
- Plotting $\mu(t)$ results in the "Paczynski curve"
- Different curves correspond to $y_0 = 0.01, 0.1, 0.2 \ldots 1.0$

Gaudi2010 (Paczynski 1986b)



The Point Mass Lens



Movie credit: B. Scott Gaudi, OSU

First Galactic Microlenses

- Galactic microlensing observed first by multiple teams:
- Udalski+1993 (OGLE project; more in a bit)
- Alcock+1993 (MACHO project)
- Aubourg+1993 (EROS project)

EROS

The EROS project

- http://eros.in2p3.fr
- 1.5m @ La Silla, CH
- find MACHOs in MW halo
- EROS-1 (90-95) EROS-2 (96-03)
- Also monitoring stars and SN

The MACHO project

- www.macho.anu.edu.au
- 1.3m @ Mt. Stromolo, AU
- find MACHOs in MW halo
- Photometric monitoring:
  - ~6 years in the early 90s
  - millions of stars in LMC & SMC
  - Also monitoring stars and SN

First Galactic Microlenses

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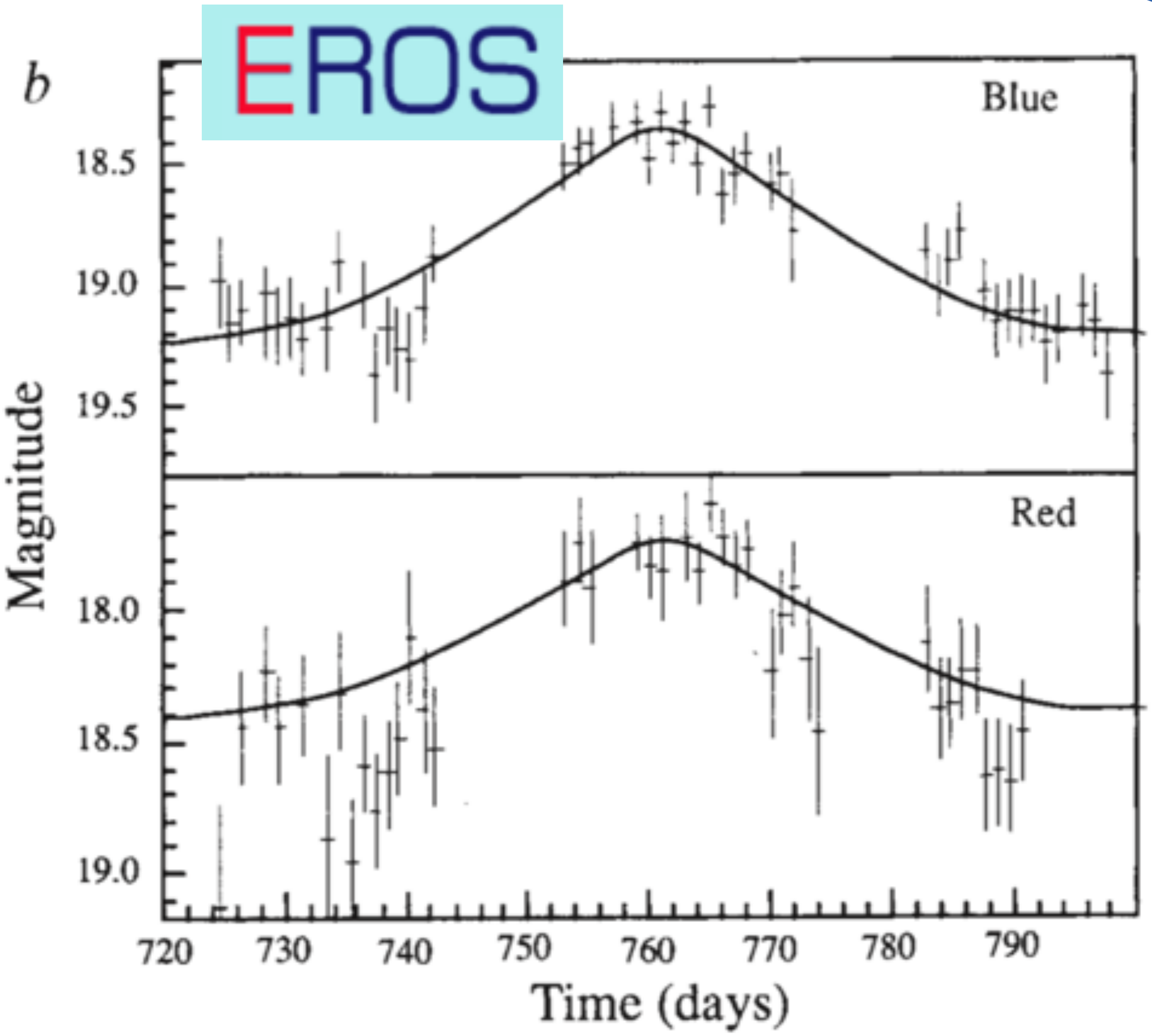
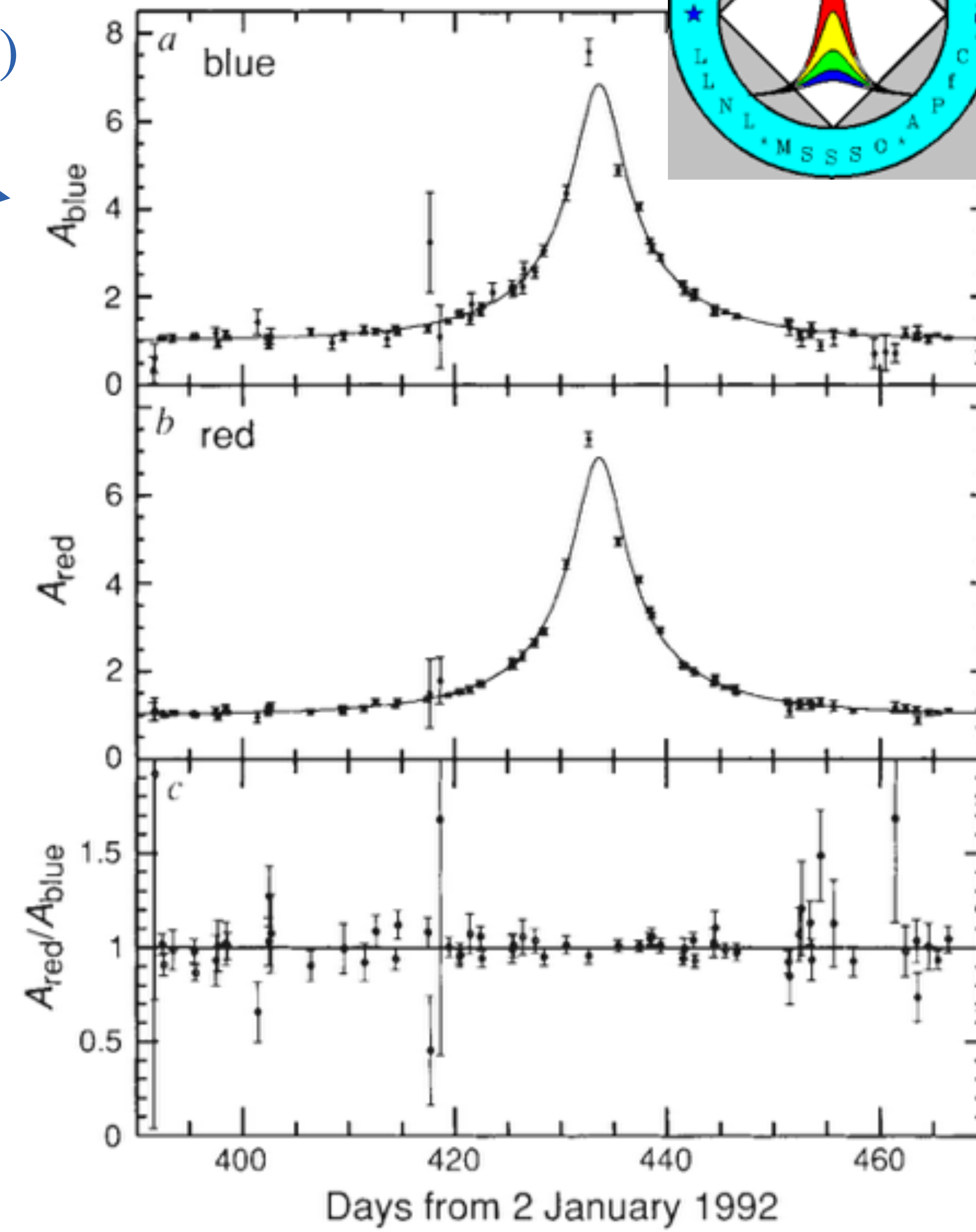
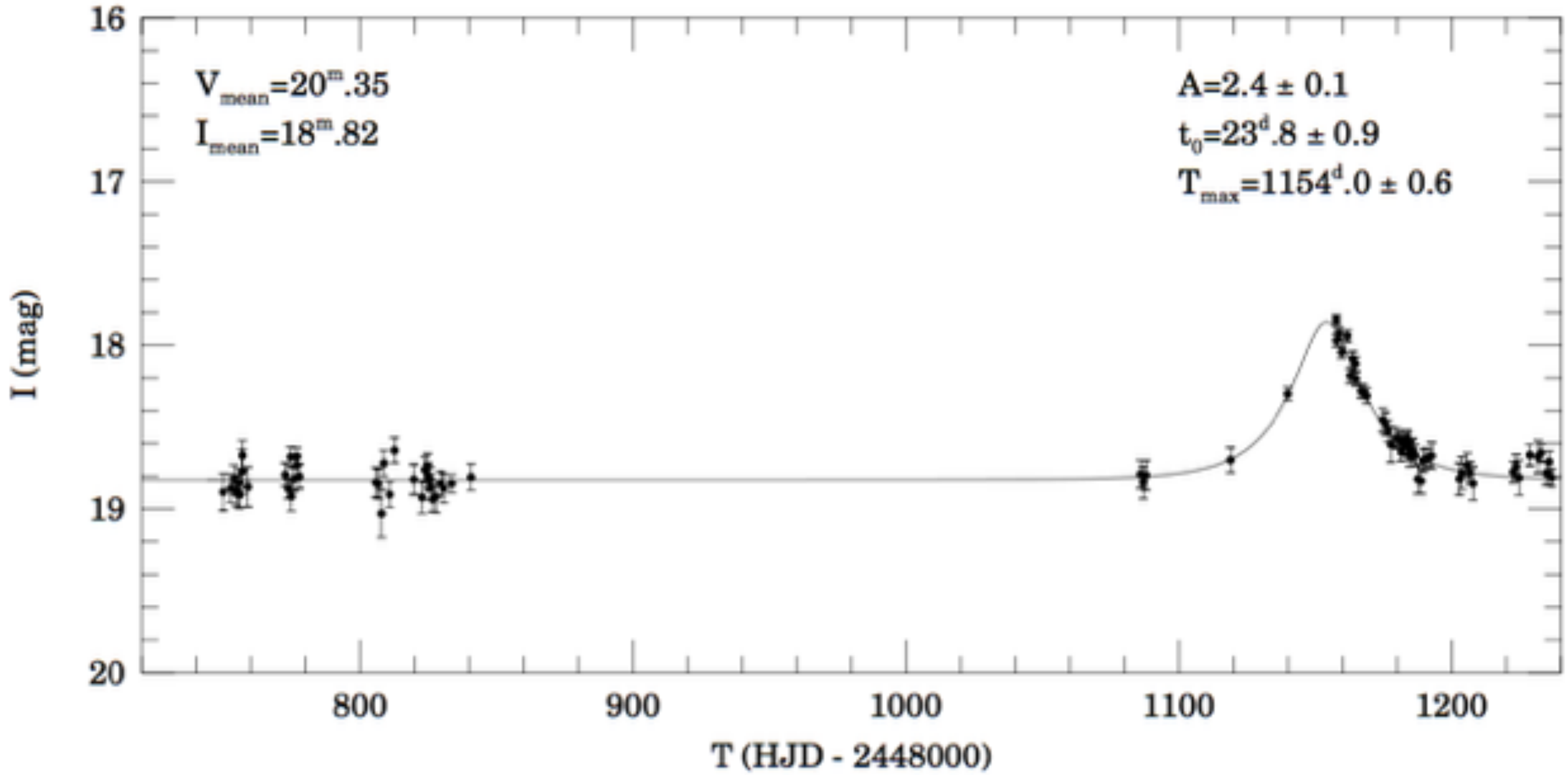




The Optical Gravitational Lensing Experiment

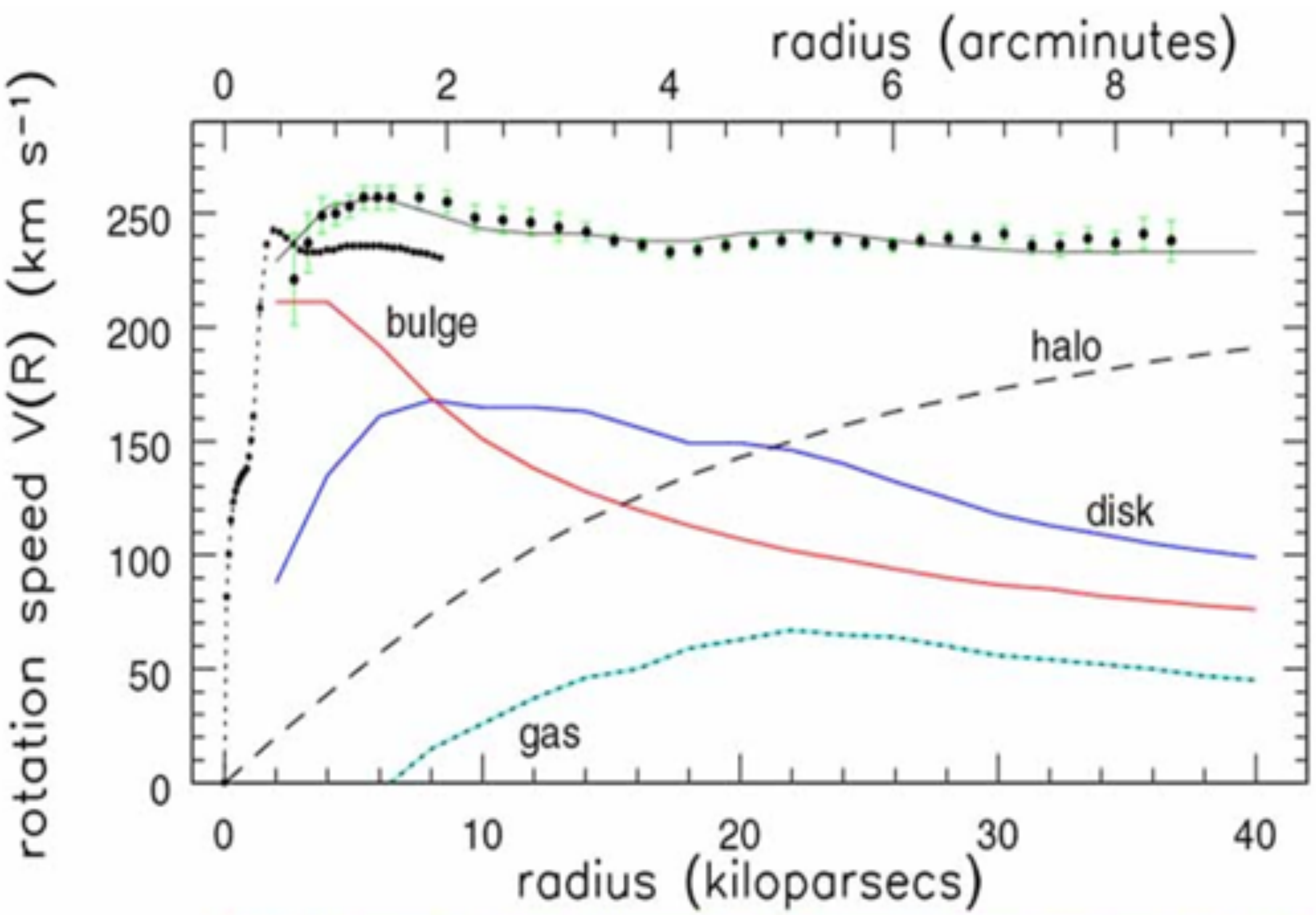
- OGLE: >25 years (1992-present) photometric monitoring
  - http://ogle.astrouw.edu.pl
- OGLE campaigns: I (92-95), II (98-00), III (02-09), IV (11-present)
- The Udalski+93 first galactic microlens is from OGLE



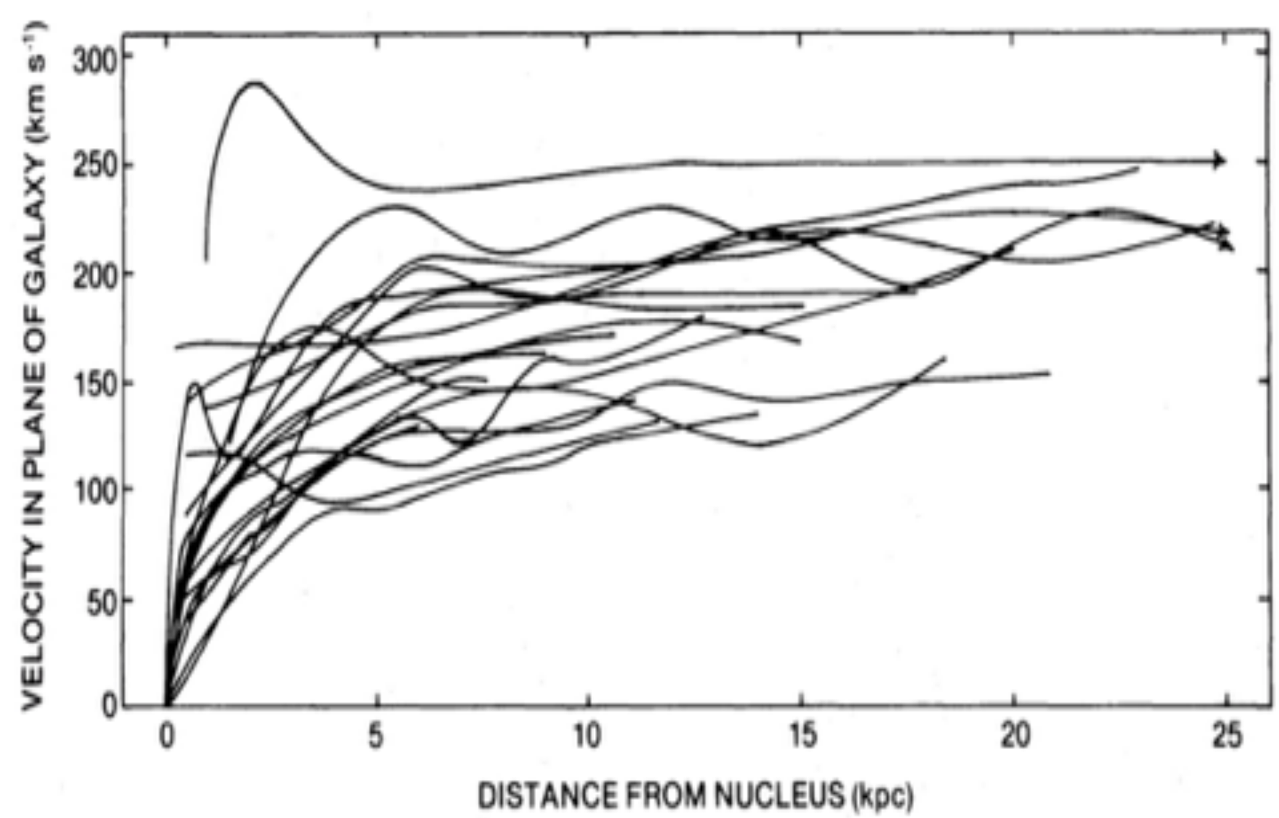
- Dark Matter searches were focused towards the LMC and SMC
- Also exoplanet discoveries have been a main driver of OGLE

Searching for Dark Matter

- One of two main applications of microlensing is searching for dark matter
  - the second is searching for exoplanets; topic of next week.
- Searching for dark matter was introduced by galaxy rotation curves
- Which have been known to deviate from Keplerian since at least the 80s
- We now know that halo DM is not massive obj. - In the 80s/90s we didn't…



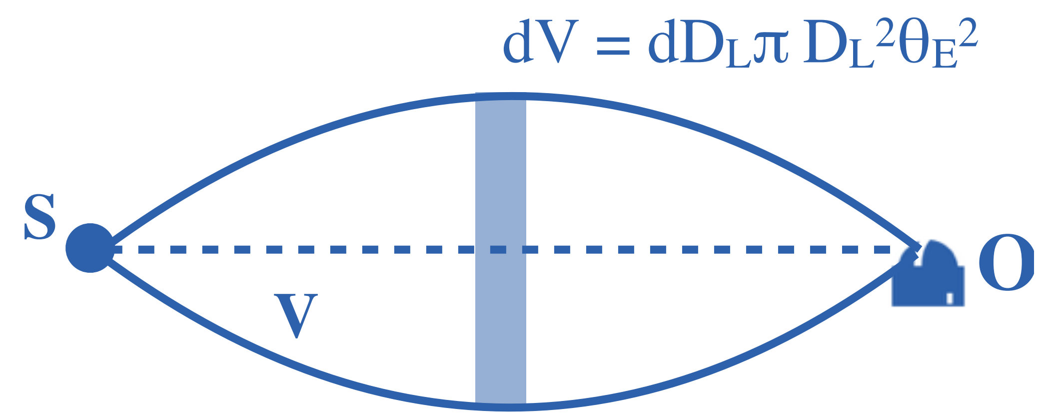
Sparke & Gallagher (2000)



Rubin+1980

MACHOs

- Search for Massive Compact Halo Objects (MACHOs) in the MW
- If $10^{-6} < M_{MACHO} / M_{\odot} < 10^{2}$:
  - MACHOs would leave microlensing imprint on stars in the LMC and SMC
- Any MACHO within the volume V can induce a microlensing "event"
- Simplifying the scenario, e.g.:
  - Spherical distribution of MACHOs
  - Fixed mass of MACHOs
  - μ-detectability of survey



- A number density $n(D_L)$ is obtained (mass and geometry dependent)
- Integrating $n(D_L)$ over dV results in the microlensing *optical depth*

$$\tau = 10^{-8}\mathrm{kpc}^{-3}\frac{M_{\odot}GR_0}{c^2}\int_0^{R_0} D_L \frac{R_0 - D_L}{R_0^2 + D_L^2 - 2R_0 D_L \cos(b)} dD_L$$

- R_0 is center of MACHO distribution and source is located at $(l=0,b)$ gal coord.
- The optical depth is independent of M_L and gives probability of observing event.

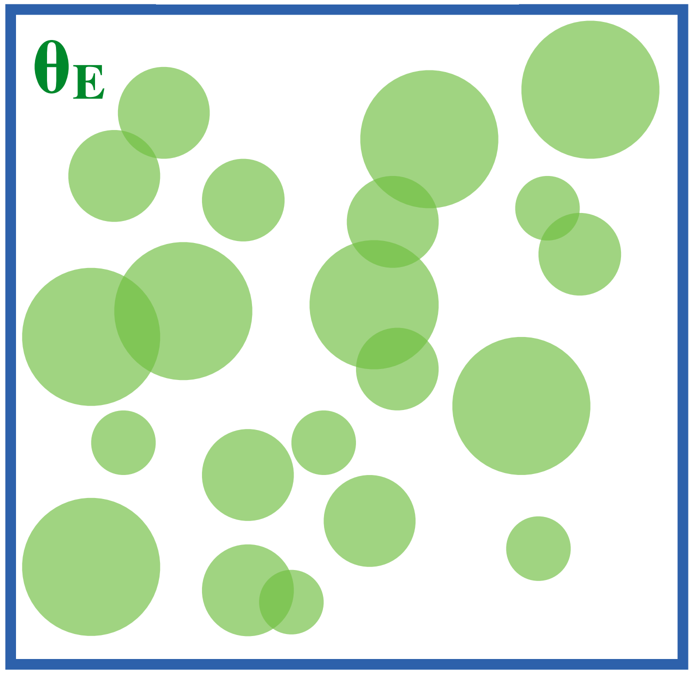
Microlensing (MACHO) optical depth

- The mass independence means that the observed frequency of (MACHO) microlensing events, directly relates to the number density of the lens(es)
- Evaluating optical depth integral towards the MW bulge (to b=2.5deg):

$$\tau_{\text{towards MW bulge}} \sim 6 \times 10^{-7}$$

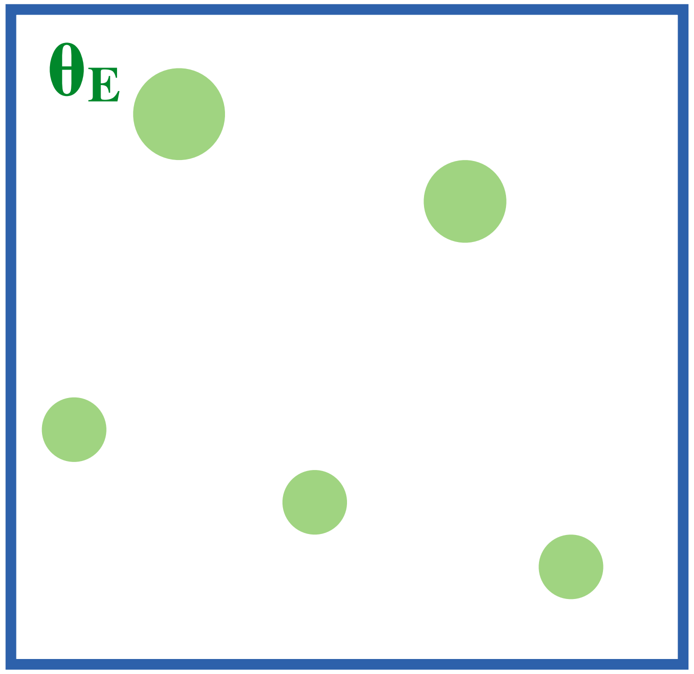
- The optical depth corresponds to area covered by Einstein radii on the sky

$\tau \sim 0.4$



~3 sight lines and you will have microlensing

$\tau \sim 0.01$

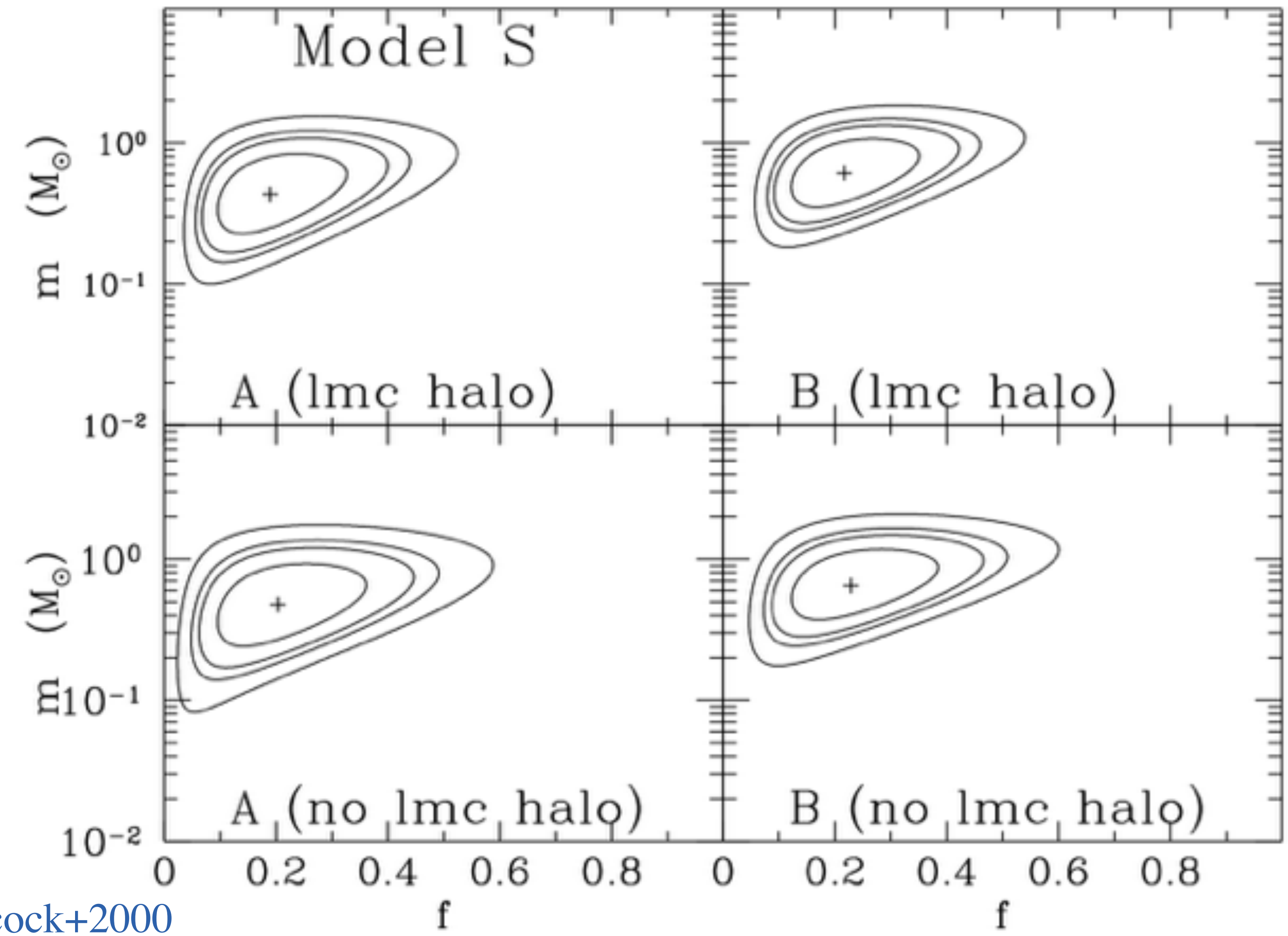


~100 sight lines and you will have microlensing

Estimating MACHO fraction in MW halo

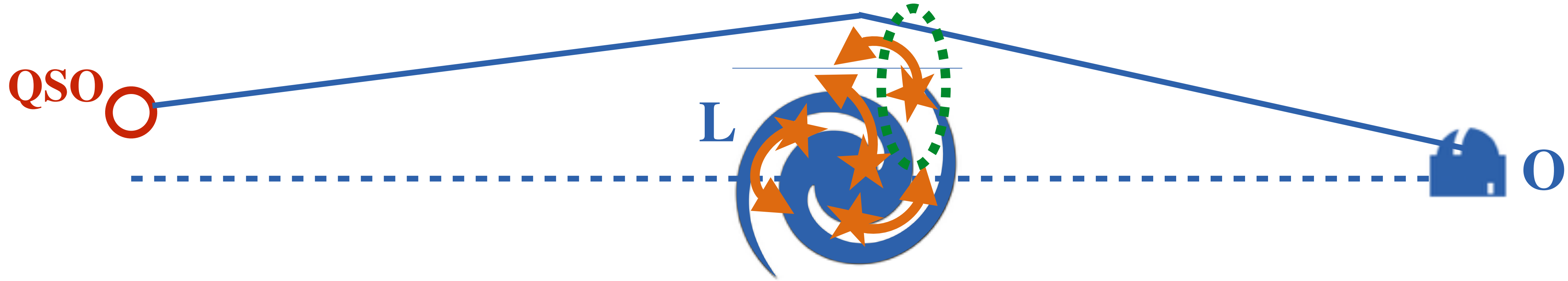
- Estimating microlensing events monitoring millions of stars can be used to estimate the fraction of matter in the MW halo from MACHOs

- Monitoring 12 million stars in the LMC detecting 15 events the MACHO project estimated the fraction f of MACHO mass in the MW halo.

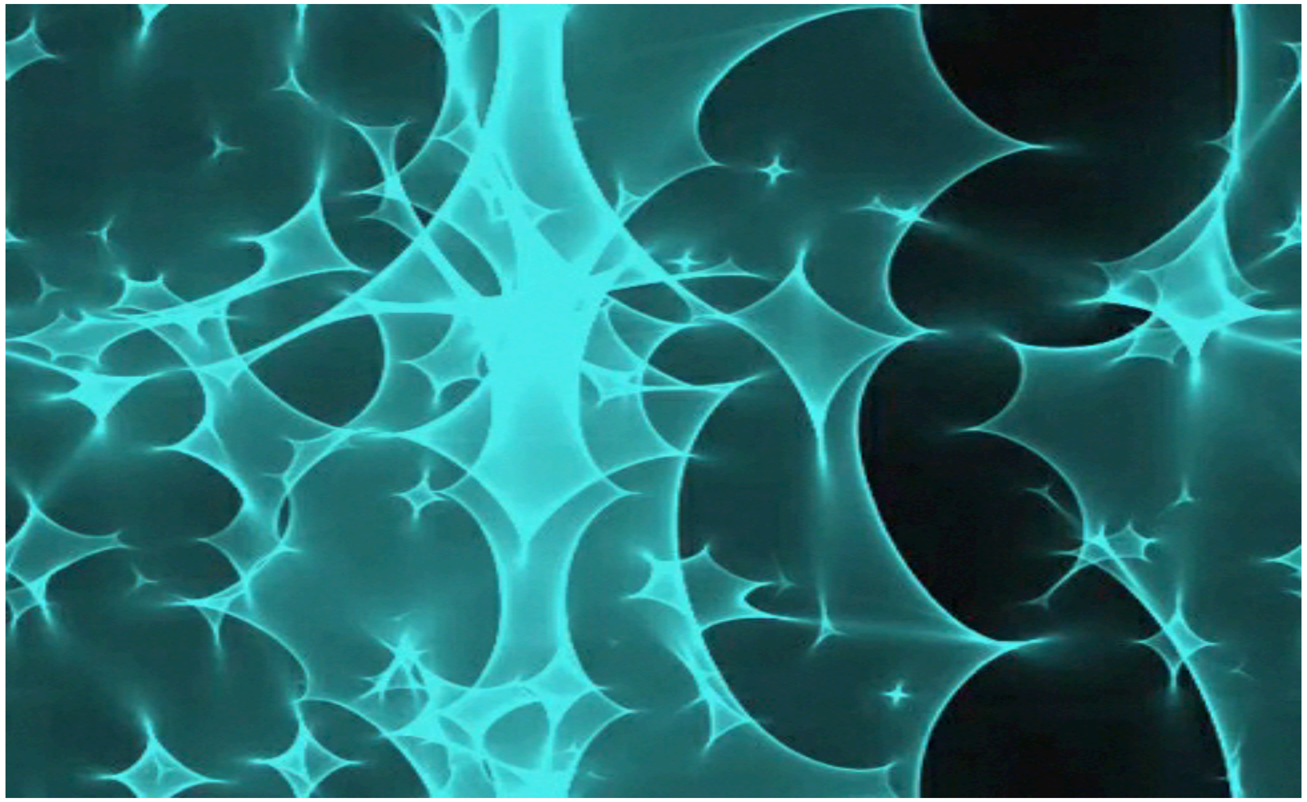


Alcock+2000

Extra-Galactic Microlensing

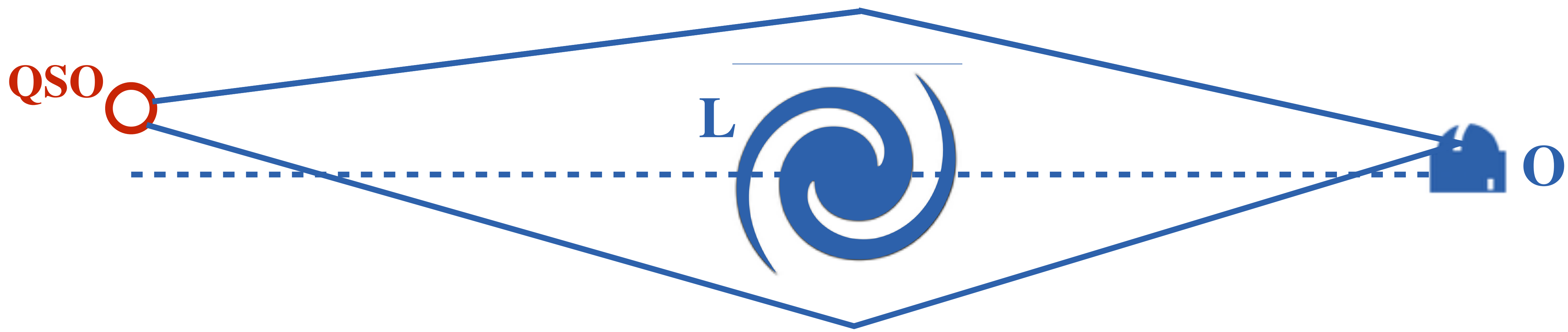


- Movement of individual stars within main lens.
- If relative motion ($v_\perp$) puts source within star θ_E, microlensing happens
- There are many stars in the main lens galaxy that can cause microlensing
- Mapping the magnification of the relative motions of all these stars gives varying magnification maps

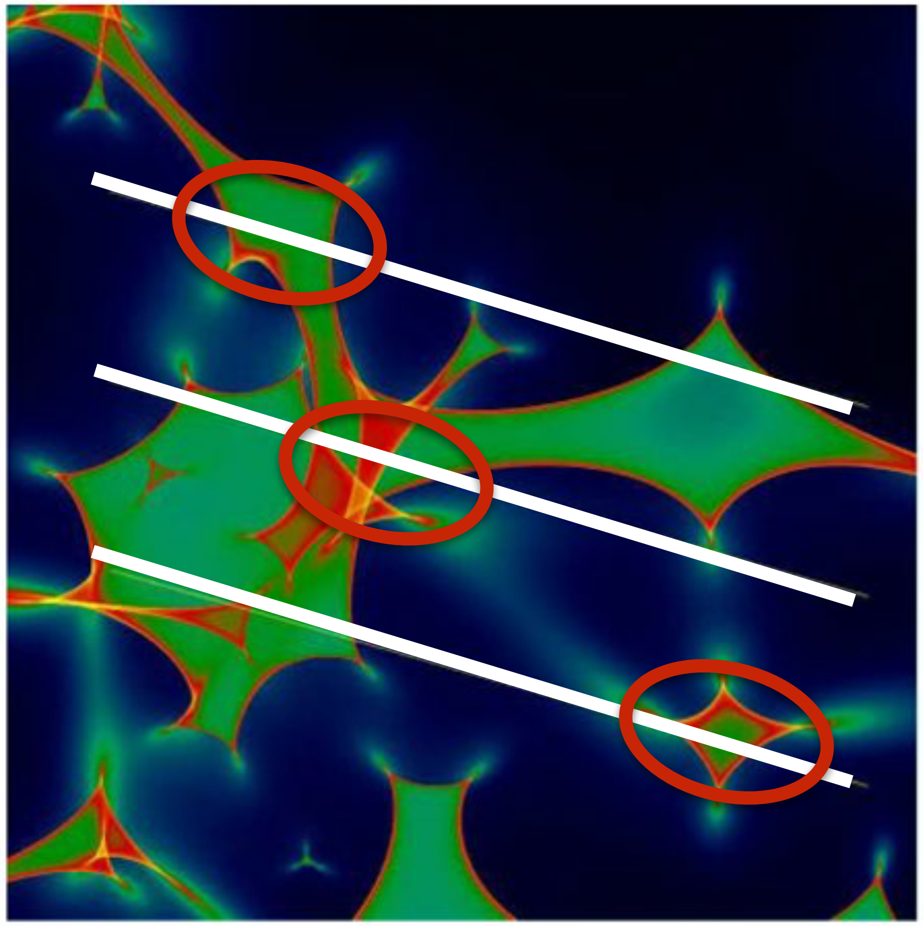


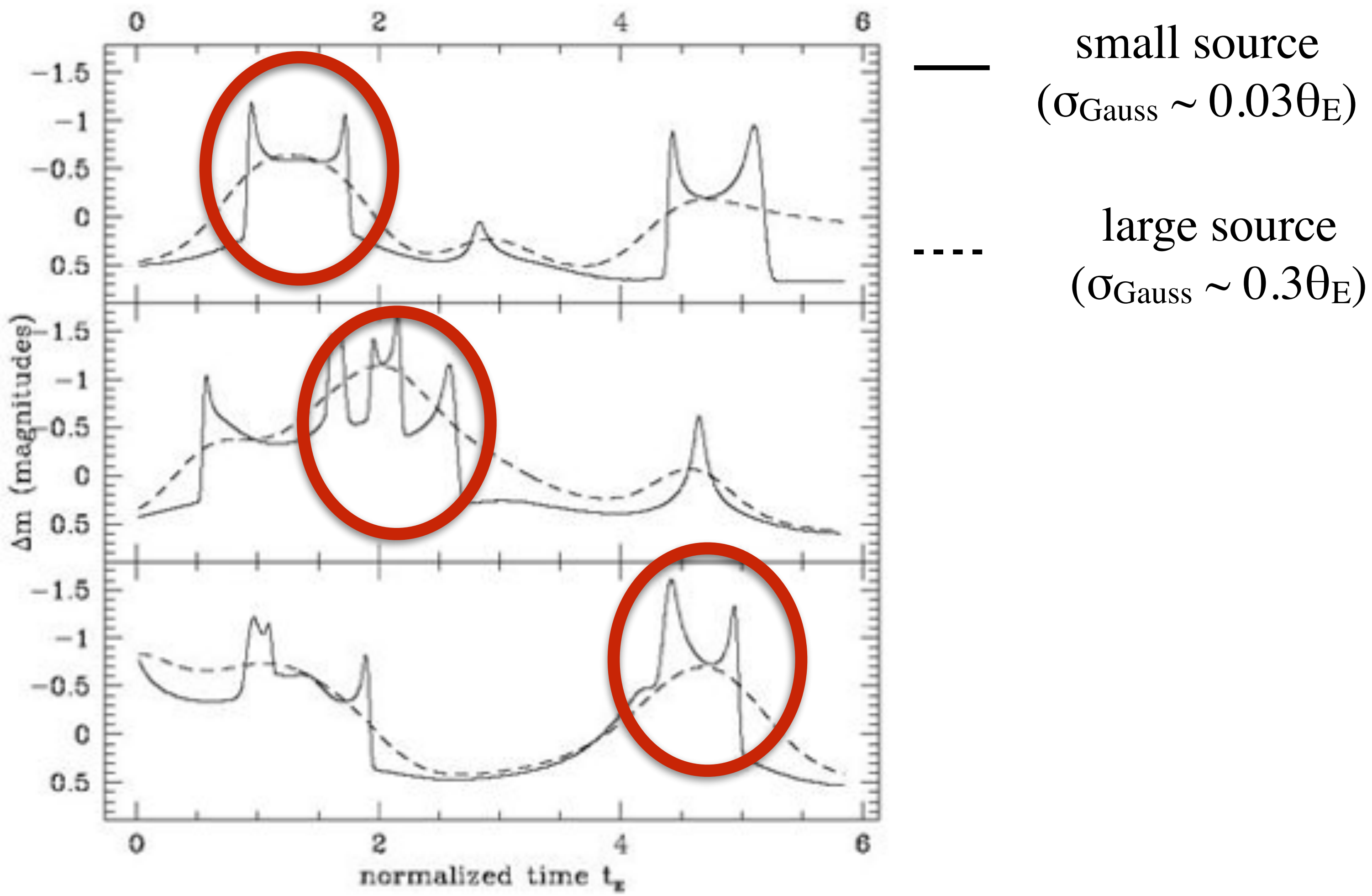
S. Poindexter (OSU Astronomy)

QSO Caustic/Magnification maps



- Multiple images will encounter different magnification patterns

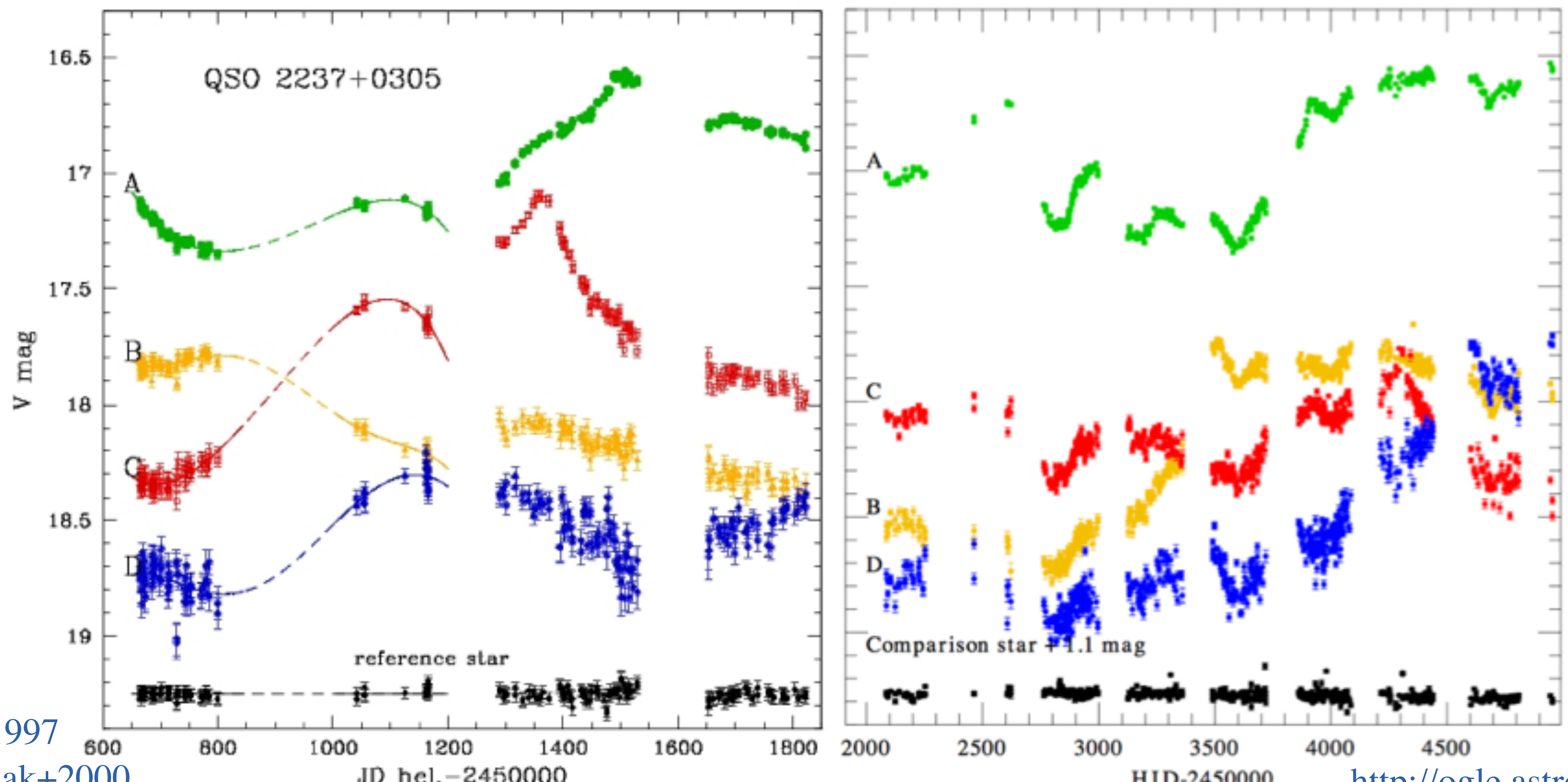




Schneider, Kochanke & Wambsganss (2006)

First Extra-Galactic Microlens

- QSO 0957+561 (Vanderriest+89) and QSO2237+0305 (Irwin+89)
- Wozniak and the OGLE team have monitored the Einstein Cross further
- Smooth (polynomial) variations best explained by microlensing
- Model comparison can reveal continuum size, exclude MACHO sizes, etc.



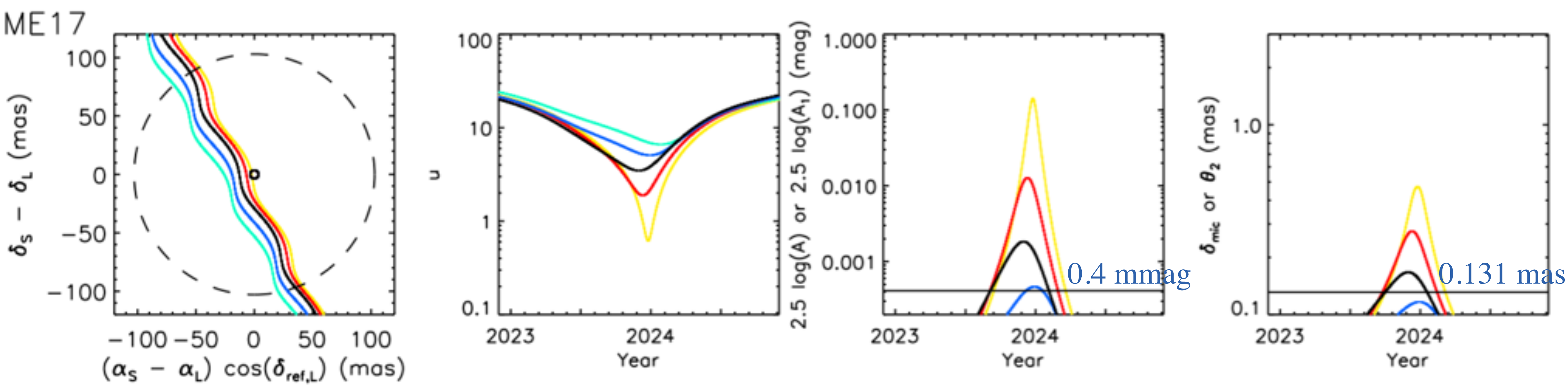
1997
Wozniak+2000

2010
http://ogle.astrouw.edu.pl

Predictions of ML events

- McGill et al. 2018 used Gaia DR1 to predict an ML event
- Bramich (2019) used positions and proper motion of Gaia DR2 stars to predict 76
  - 1.7×10^9 stars with astrometric solutions in Gaia DR2
- Using y(t) for individual stars can predict lensing effects

Source path relative to lens	Normalized source-lens seperation	Magnification in magnitudes	Astrometric signal

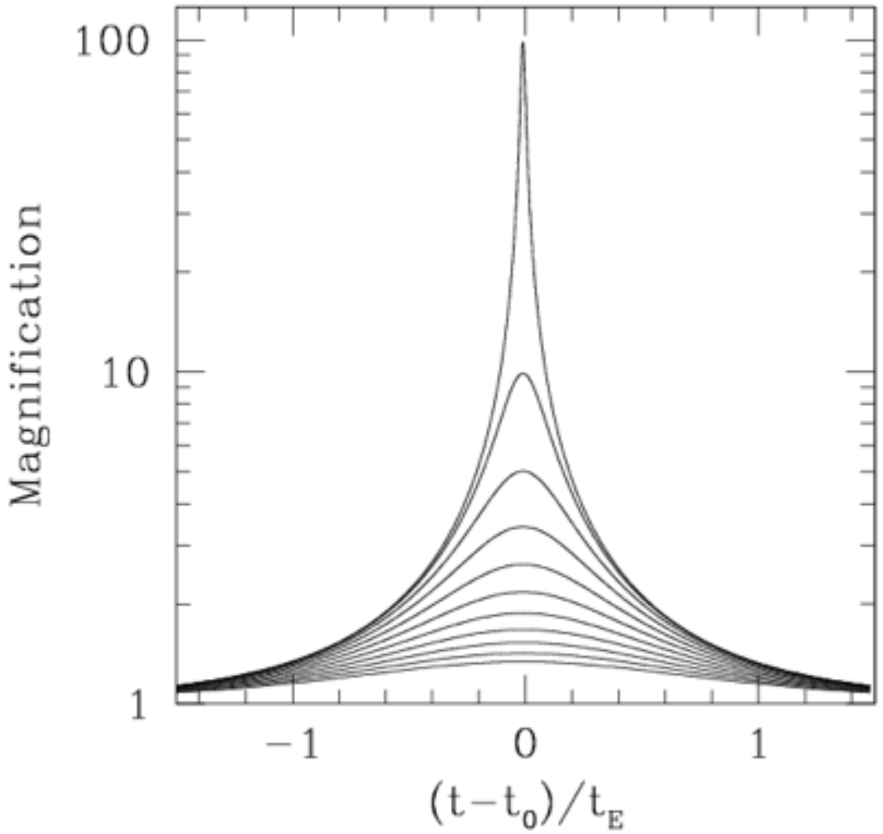


- Detecting ML events provide mass estimates independent of stellar models

So in summary…

- Micro lensing is the time variable unresolved ‘version’ of strong lensing
- Total magnification of unresolved images in point-lens case is

$$\mu = \frac{y^2+2}{y\sqrt{y^2+4}} \quad \text{where} \quad y = \frac{\beta}{\theta_E}$$



- This results in the ‘Paczynski Curve’
- Microlensing for MACHO detections
- Monitoring of stars have shown:
  - MW halo is mainly non-MACHOs
- Extra-galactic mircolensing of multiple images of strongly lensed QSOs
- In a similar manner, such measurements provides information about stars in lens galaxies