

PHY-765 SS18 Gravitational Lensing Week 8

Microlensing

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Last week

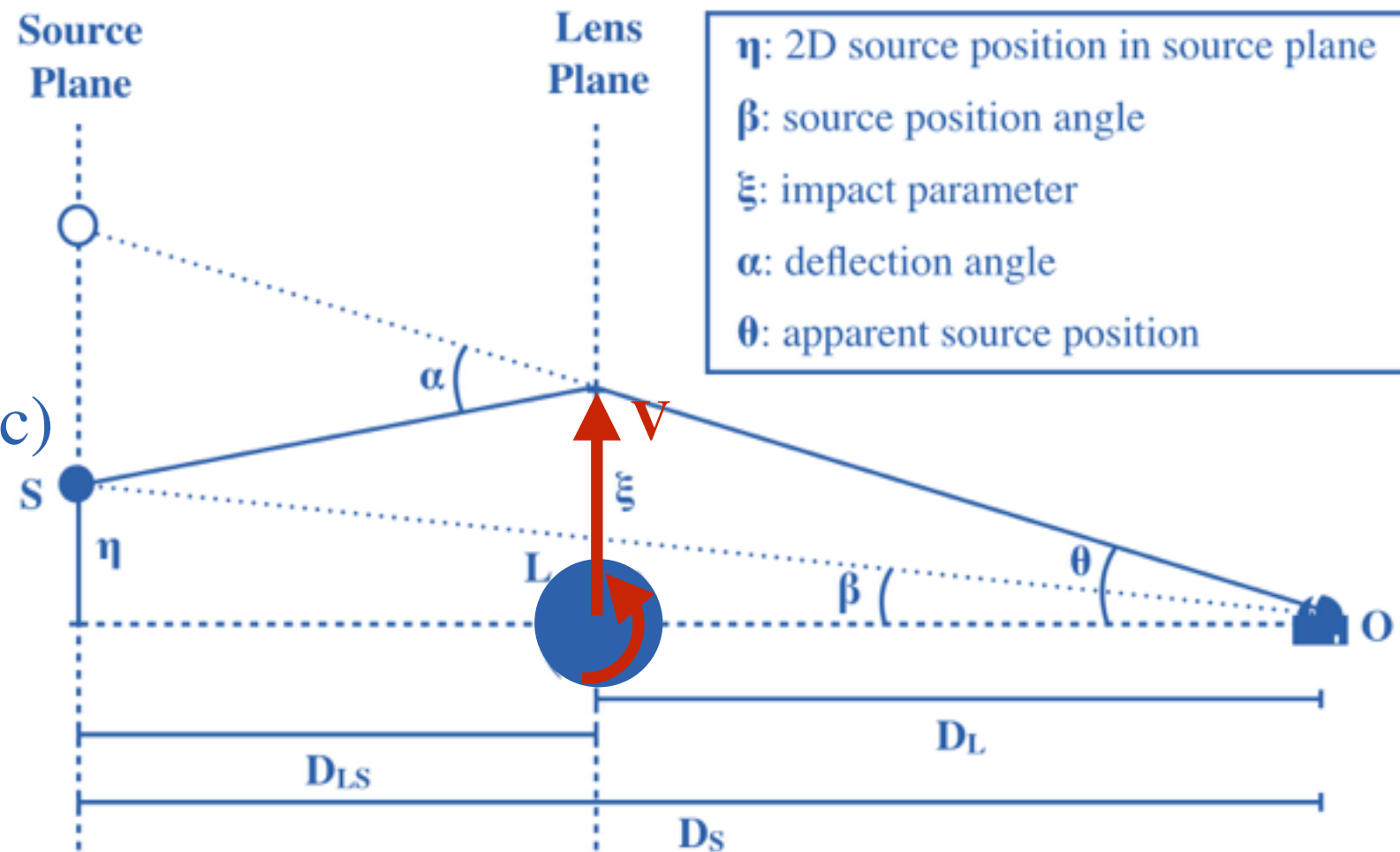
- Topic was how to find (strong) gravitational lenses in data
- Put together a “shopping list” for confirming gravitational lenses
- Multiple examples where similar lists lead to discovery of lenses, incl.
 - Multiple imaged AGN radio lenses
 - Multiple imaged QSO in SDSS, Gaia and the DES
 - Galaxy-Galaxy lenses in SDSS
 - Cluster lenses
- Lens numbers for current and future surveys (Oguri & Marshall 2010)
 - >1000 QSO lenses expected from DES
 - $\sim 10^4$ 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)
 - Of the lens (Galactic)
- ML can be thought of as “Strong lensing with unresolved image positions”



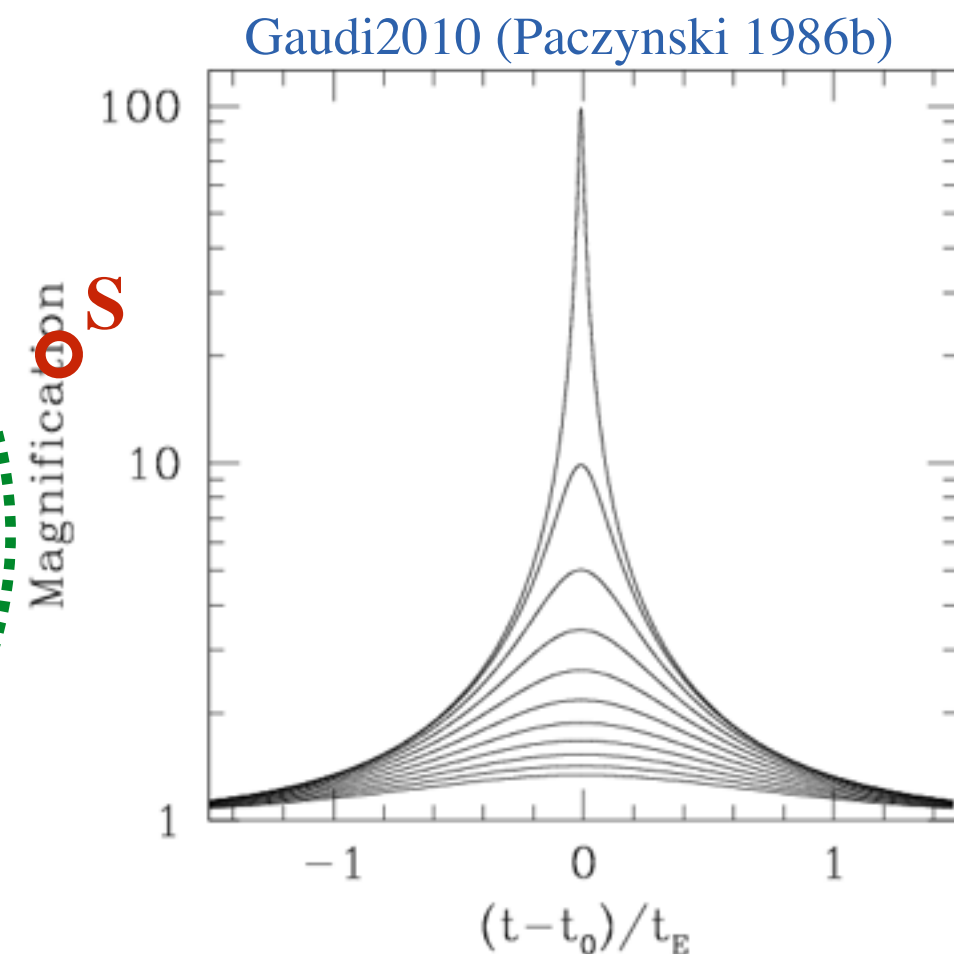
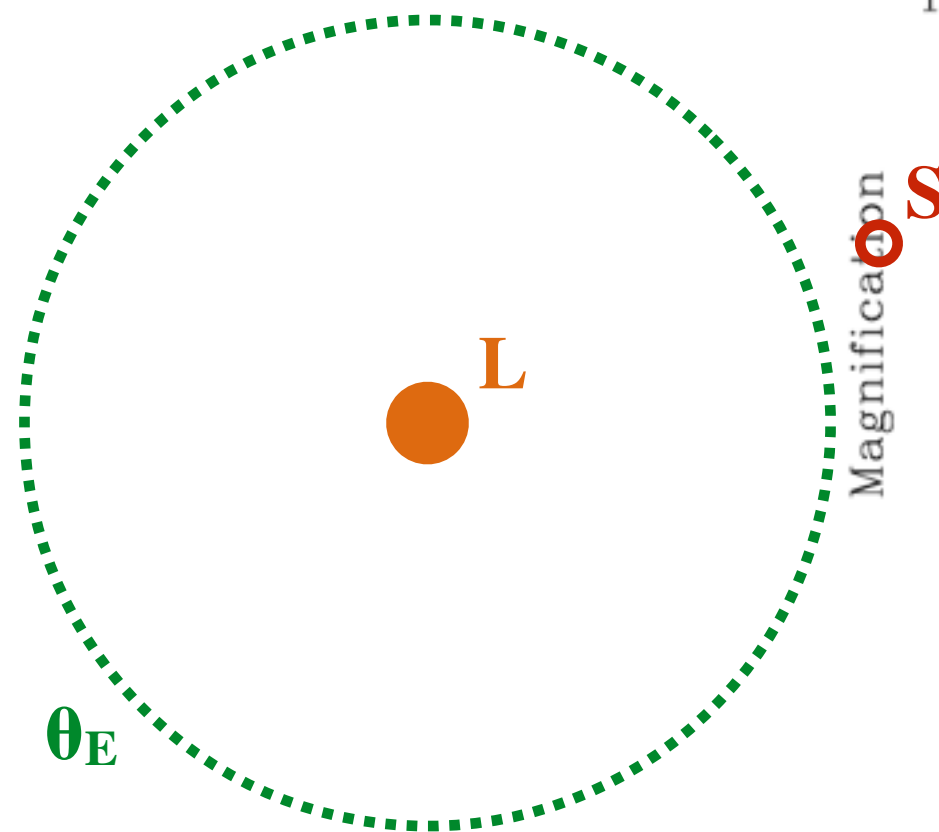
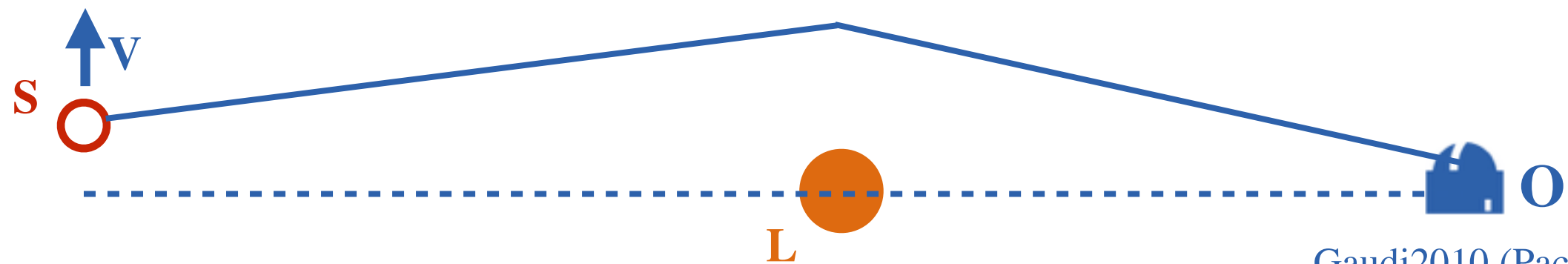
- The term “microlensing” was coined by Paczynski (1986a):
 - “Gravitational deflections due to individual solar mass stars placed at cosmological distances are of the order of 1 micro-arcsec”

- So if $D_L \sim 1 \text{ Gpc}$ and $M = 1 M_\odot$ then $\alpha \sim 10^{-6} \text{ arcsec}$ from
$$\alpha(\theta) = \frac{4MG}{c^2} \frac{D_{LS}}{D_S D_L} \frac{\theta}{|\theta|^2}$$

- 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
- 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

$$\mu_{\pm} = \frac{1}{1 - (\theta_E/\theta_{\pm})^4} \quad (\text{week 6})$$

- 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

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

- 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

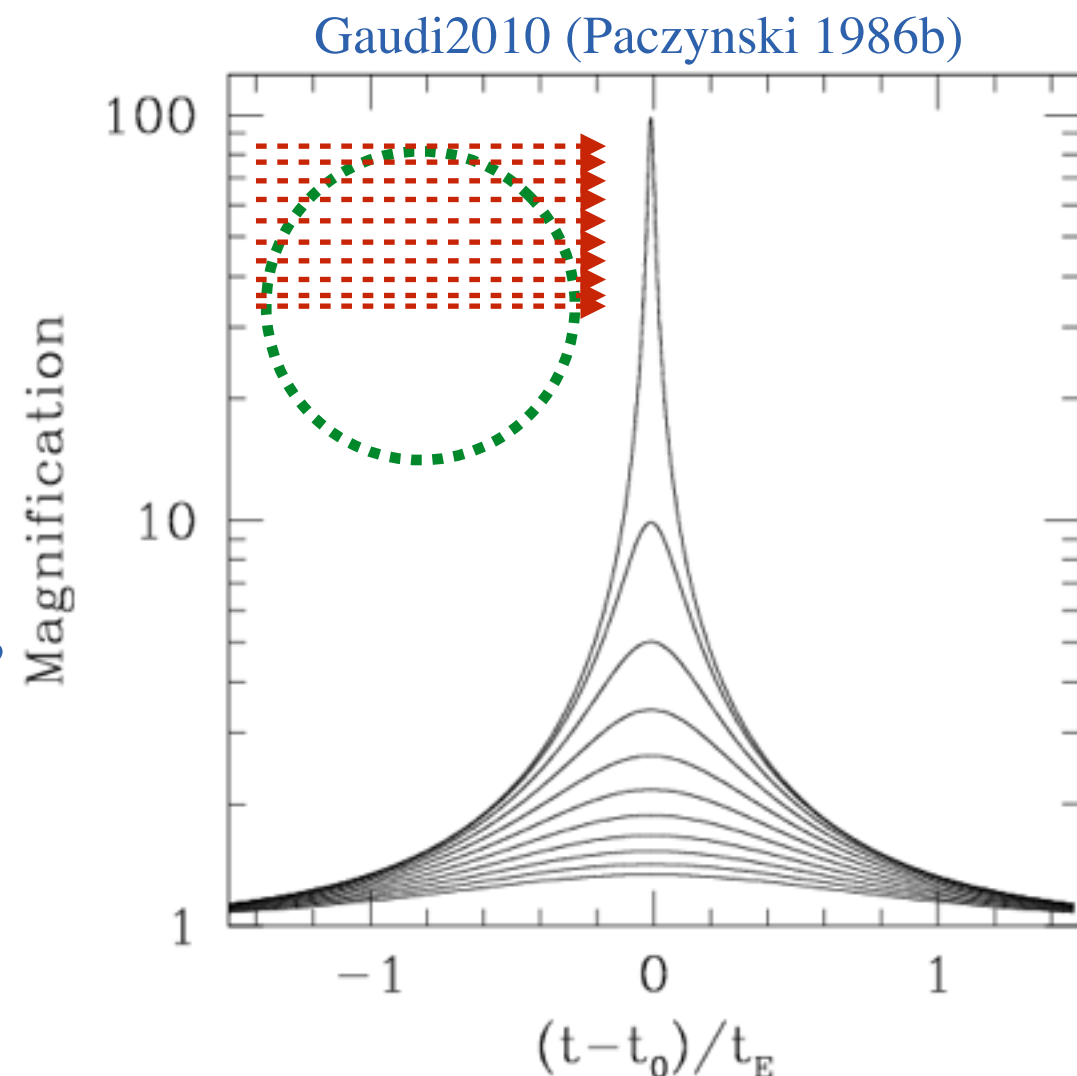
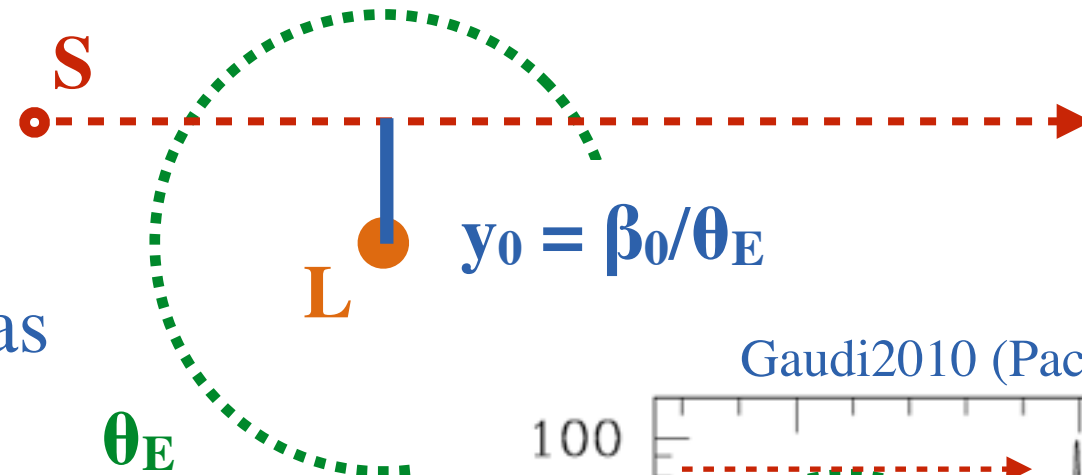
- Note that in the the expression for μ , y is a function of time, i.e., $y(t)$
- It depends on β_0 , v_\perp and D_L . Actually one can define the Einstein time

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

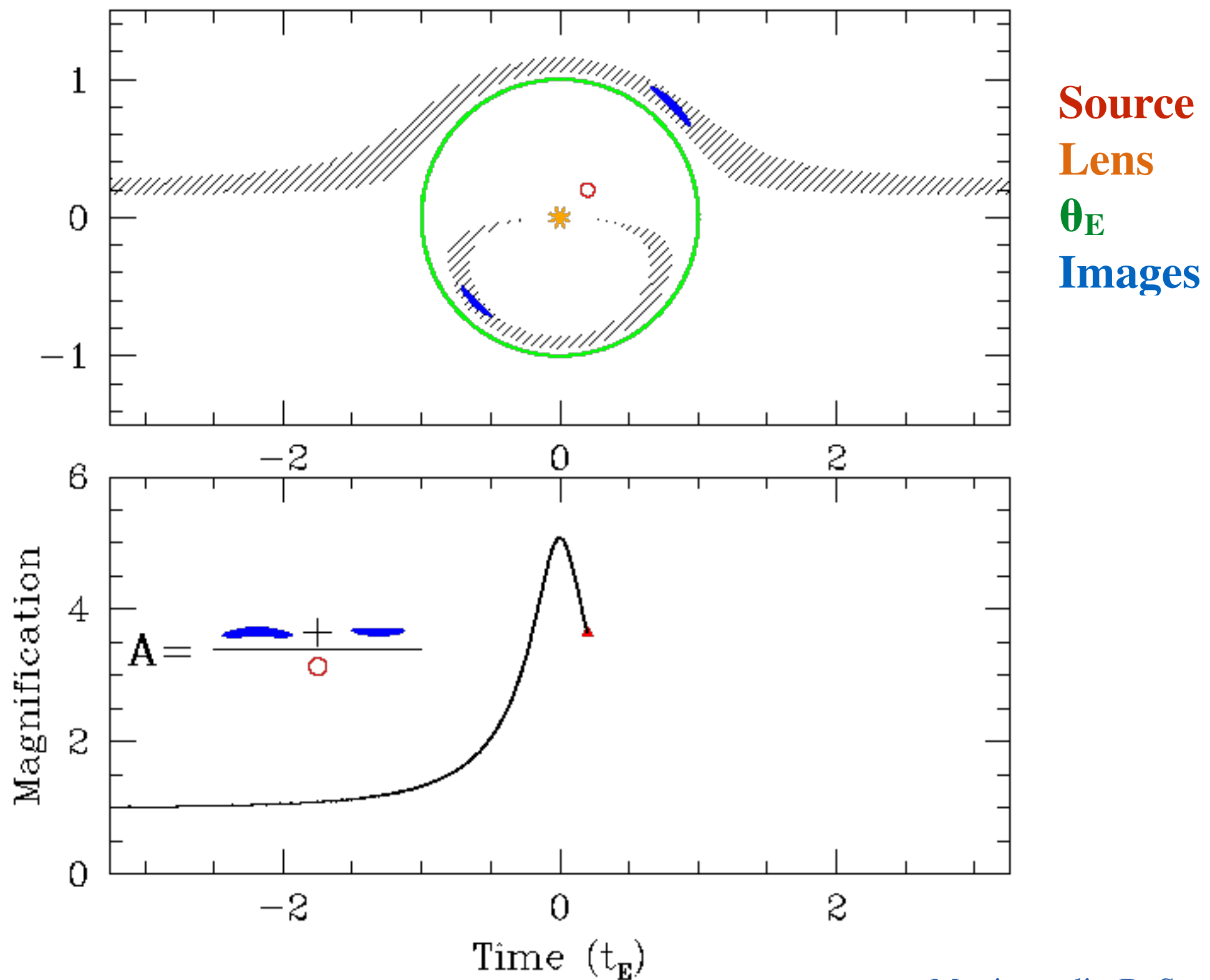
- This enables us to express $y(t)$ as

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

- 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 $y_0 = 0.01, 0.1, 0.2 \dots 1.0$



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 later)

OGLE

- Alcock+1993 (MACHO project)

- Aubourg+1993 (EROS project)

EROS

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

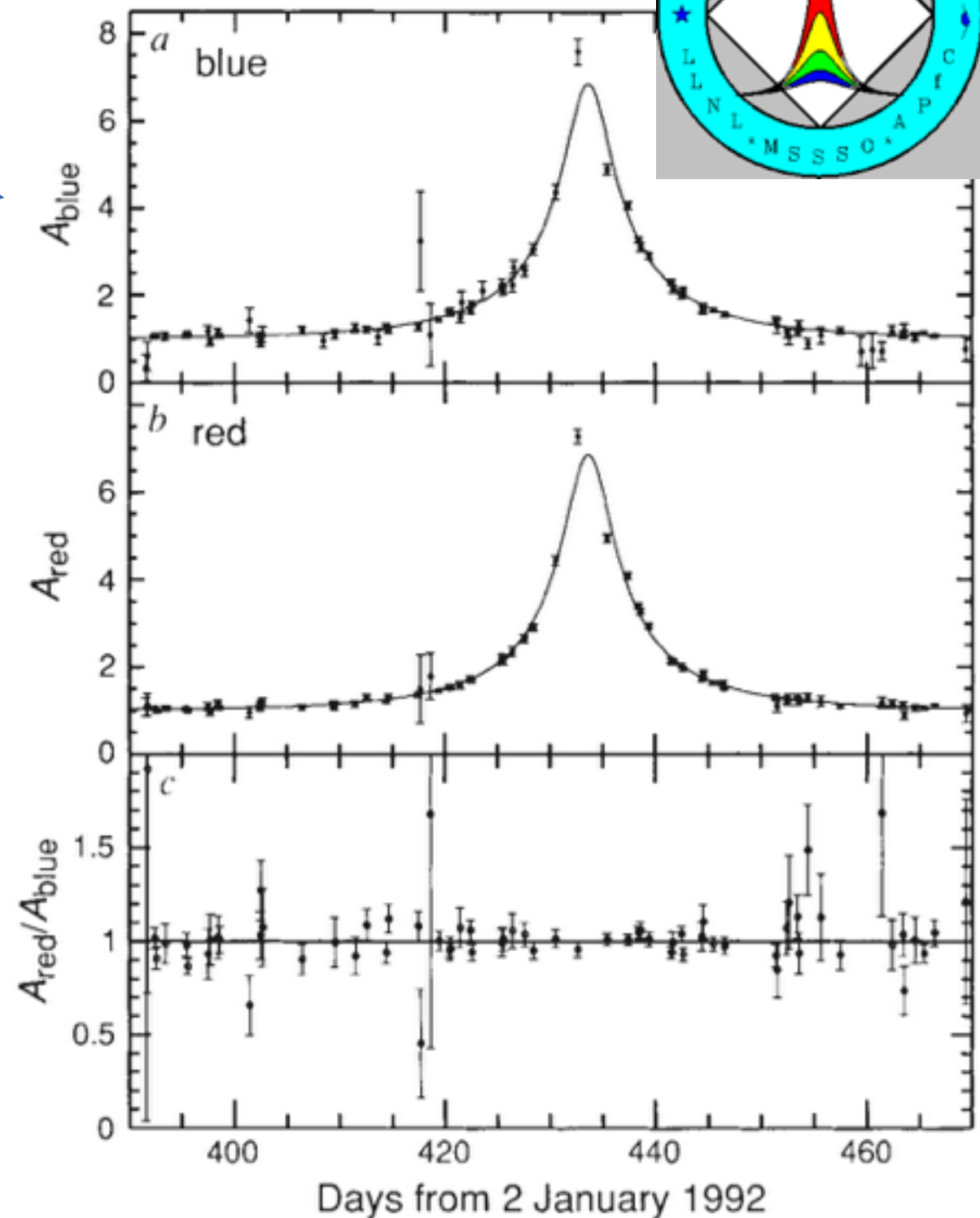
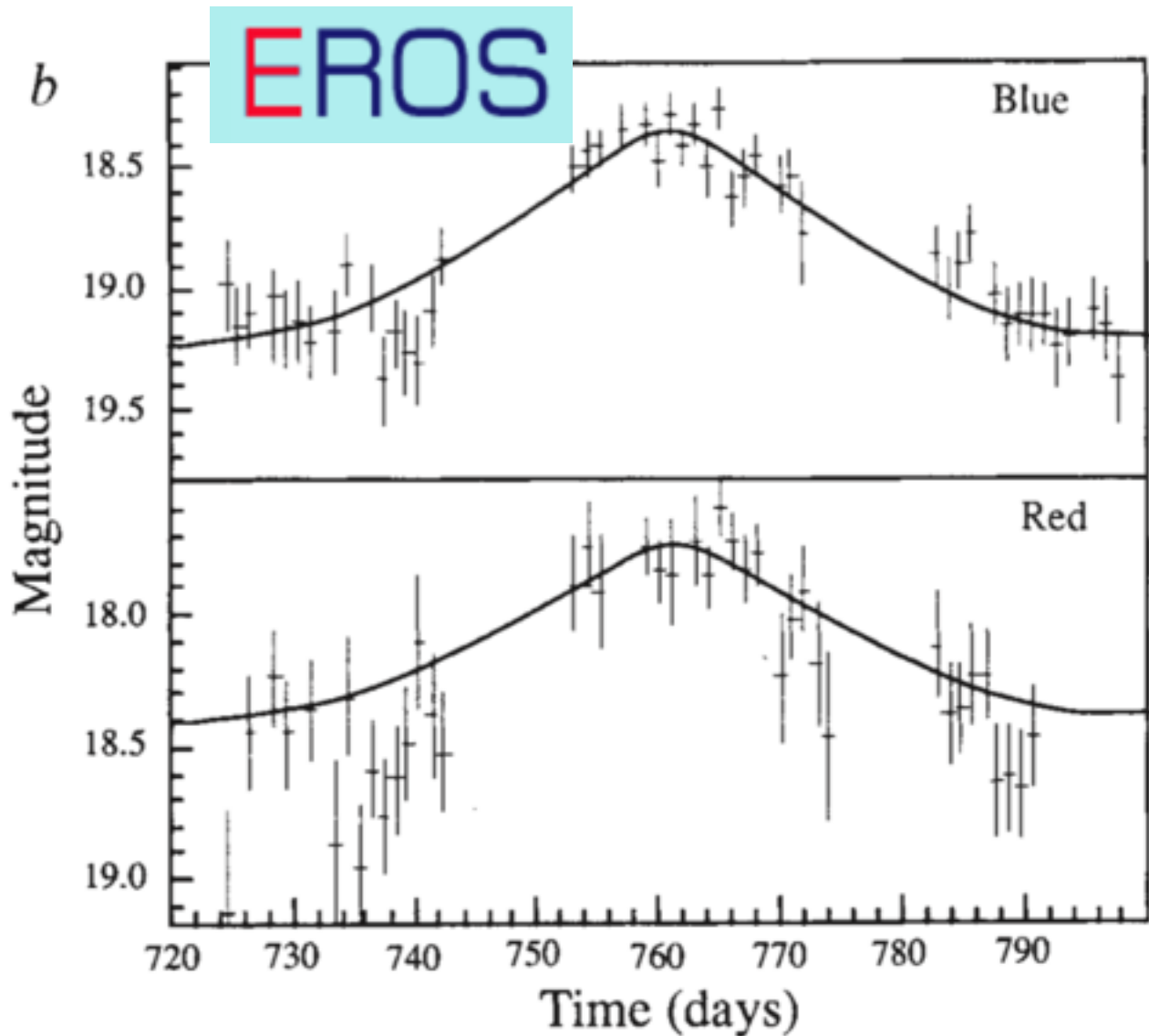
The EROS project

- <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



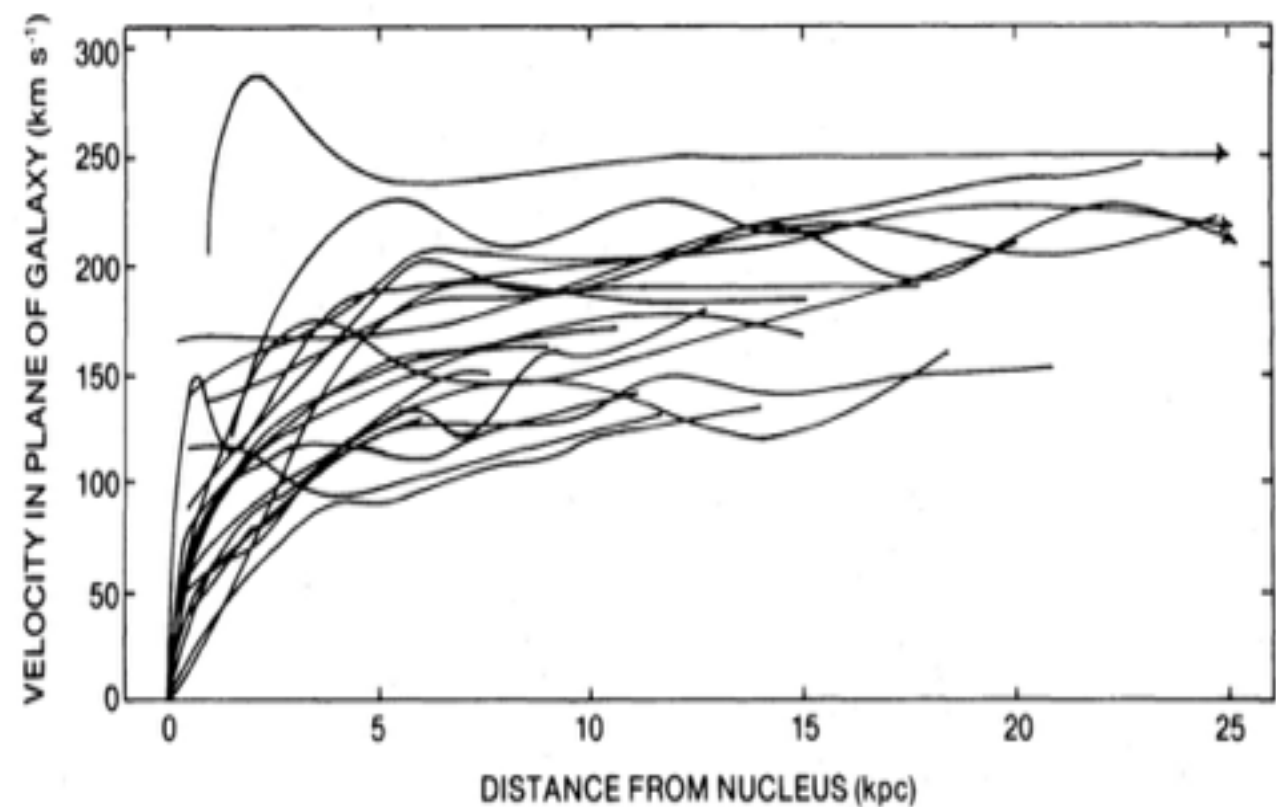
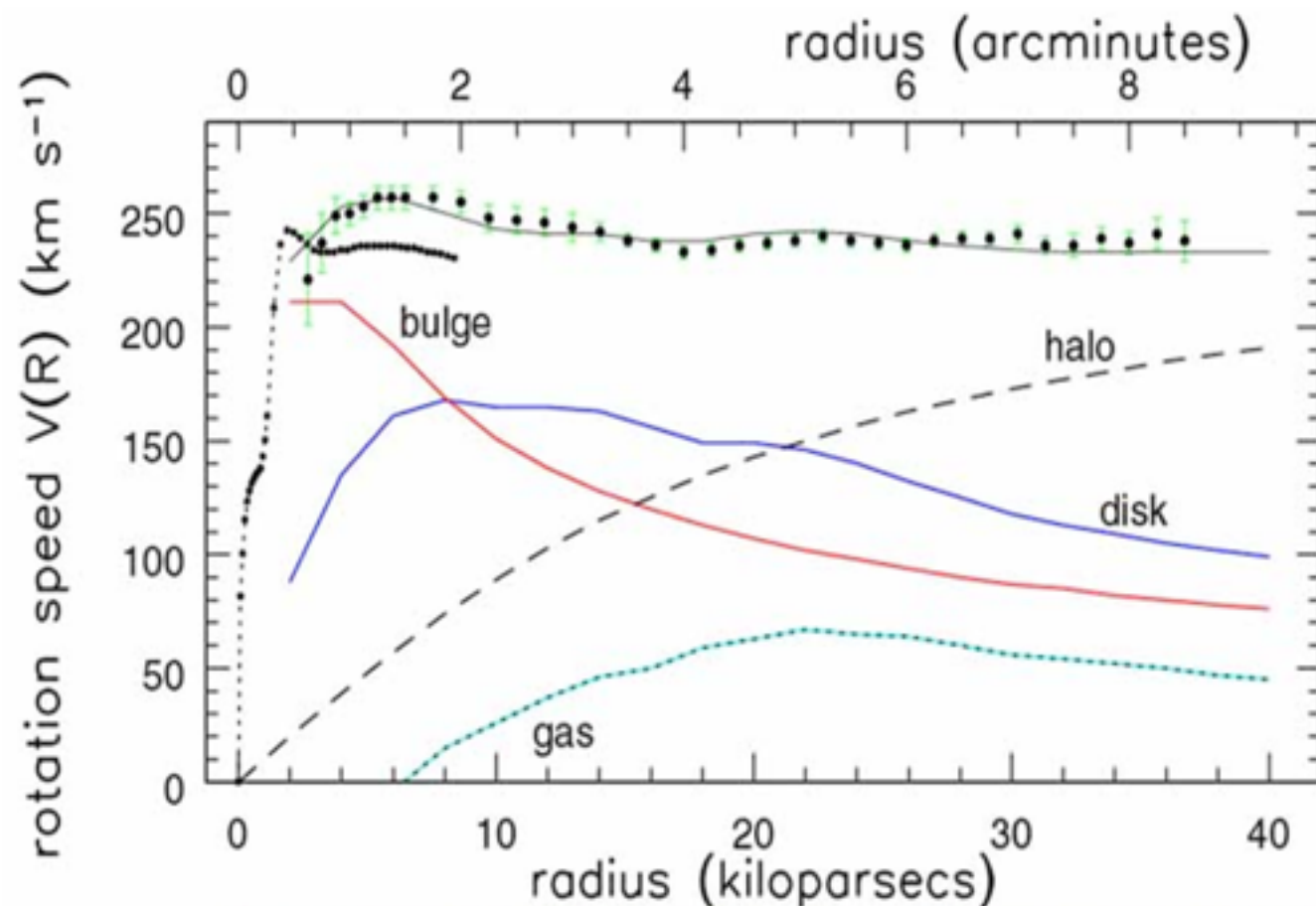
First Galactic Microlenses

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- Alcock+1993 (MACHO project)
- Aubourg+1993 (EROS project)



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 has been induced 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...



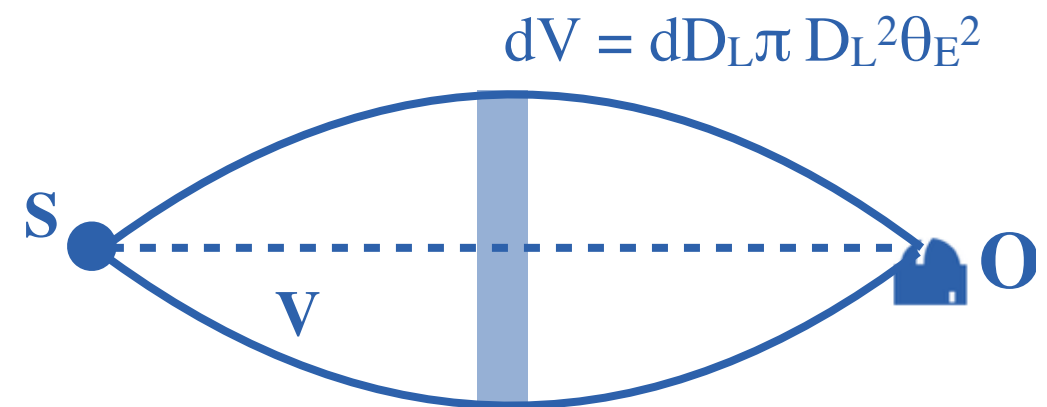
Sparke & Gallagher (2000)

Rubin+1980

MACHOs

- Search for Massive Compact Halo Objects (MACHOs) in the MW
- If $10^{-6} < M_{\text{MACHO}} / M_{\odot} < 10^2$:
 - 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*

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

- 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.

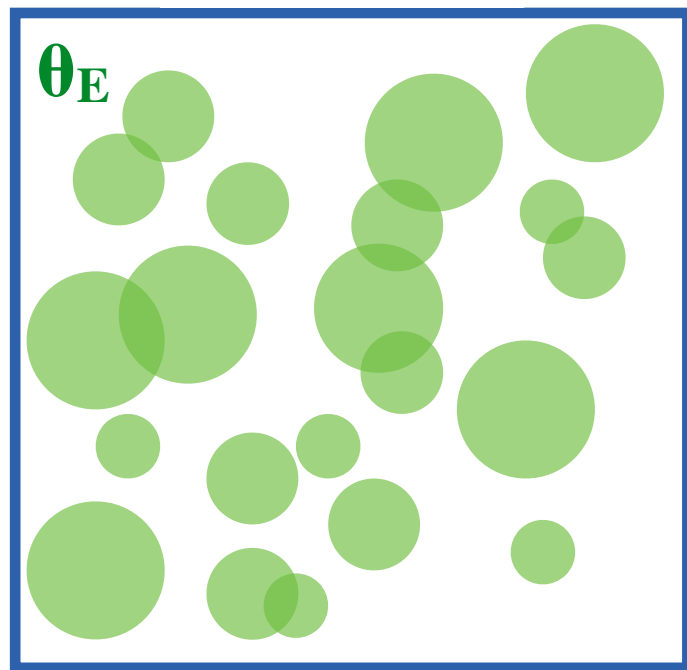
Microlensing (MACHO) optical depth

- 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 $b=2.5^\circ$):

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

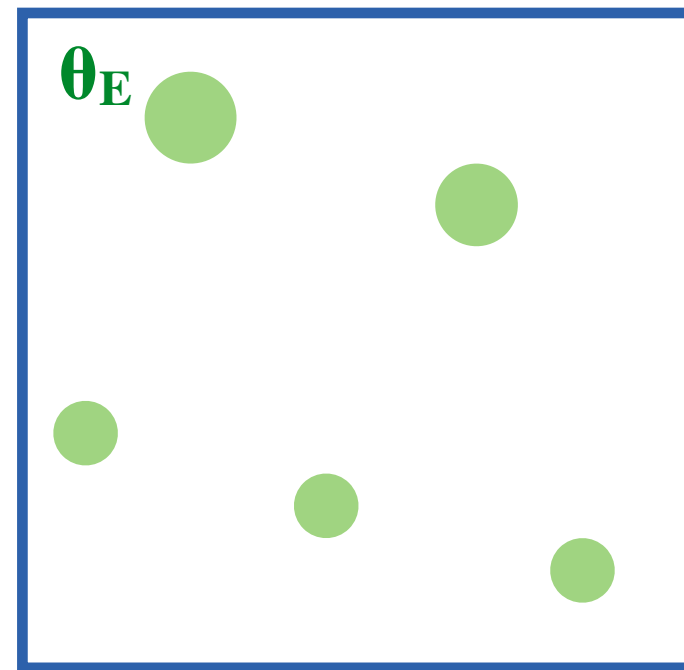
- The optical depth corresponds to area covered by Einstein radii on the sky

$$\tau \sim 0.4$$



~3 sight lines and you
will have microlensing

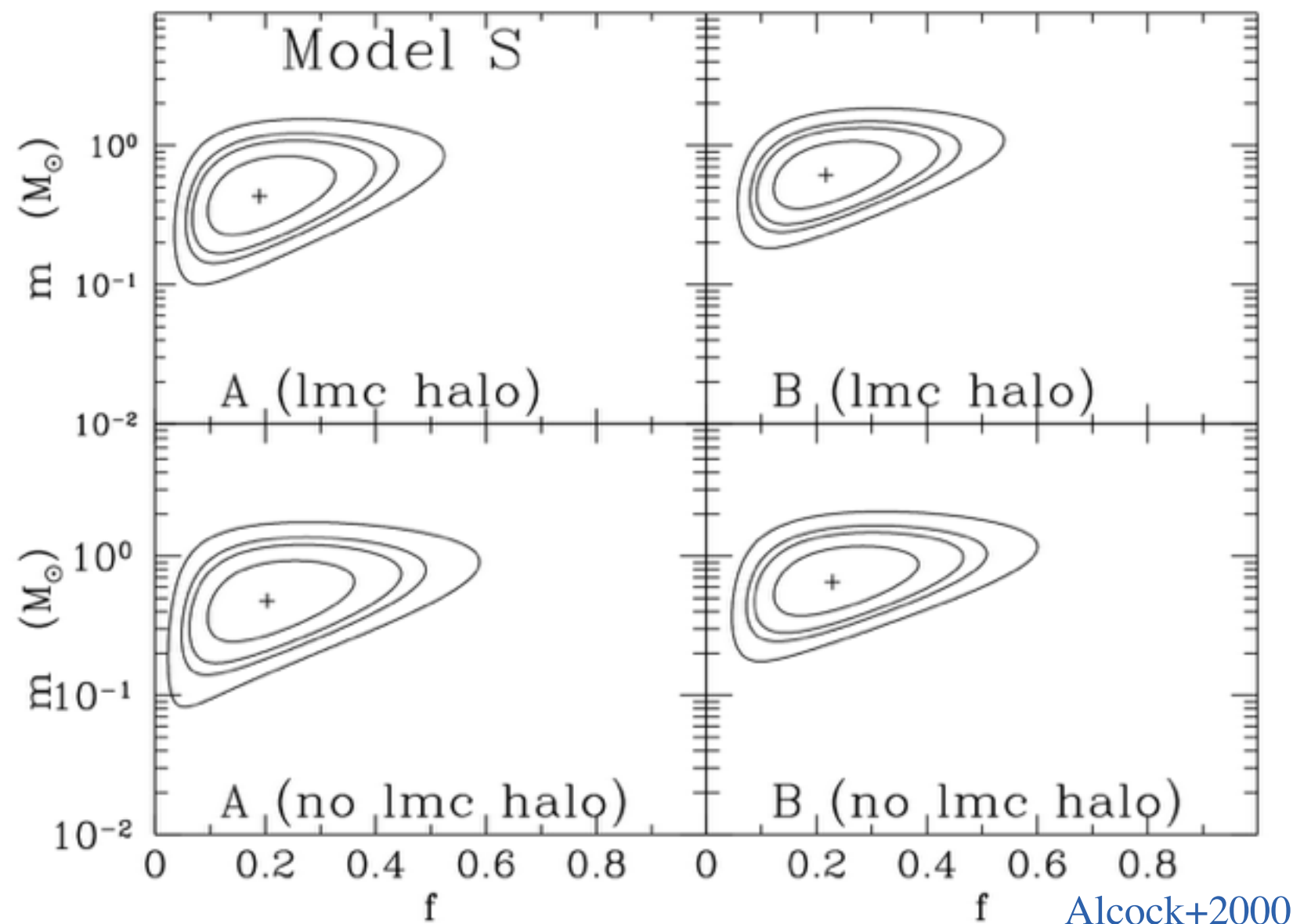
$$\tau \sim 0.01$$



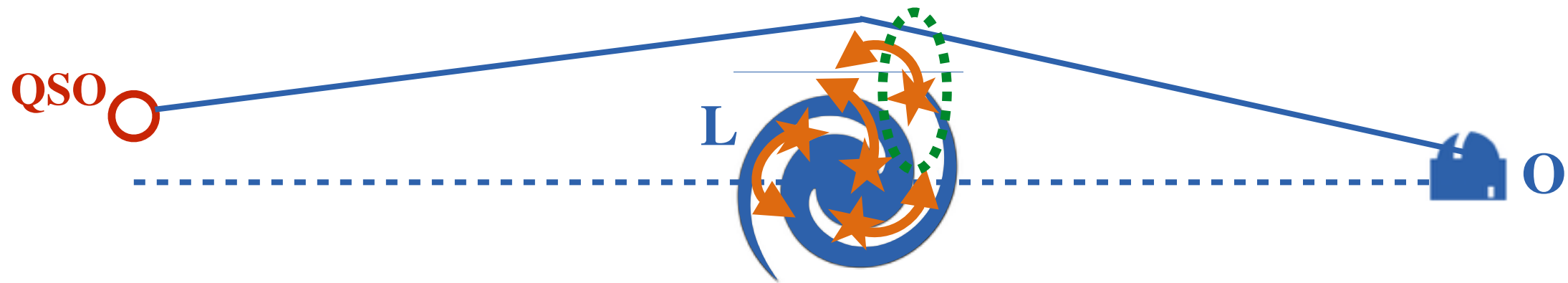
~100 sight lines and you
will have microlensing

Estimating MACHO fraction in MW halo

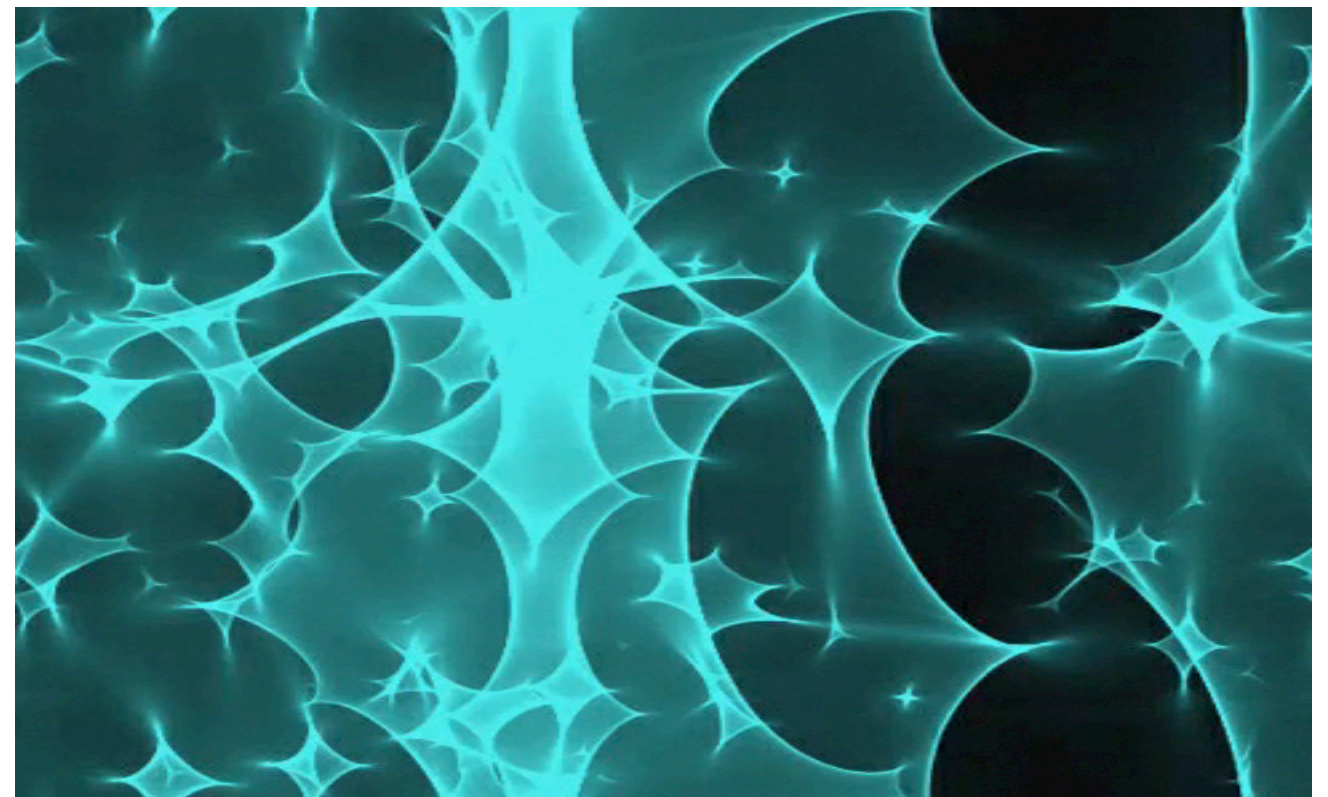
- Estimating microlensing events monitoring millions of stars can be used to estimate the fraction of matter in the MW halo from MACHOs
- Monitoring 12 million stars in the LMC detecting 15 events the MACHO project estimated the fraction f of MACHO mass in the MW halo.



Extra-Galactic Microlensing

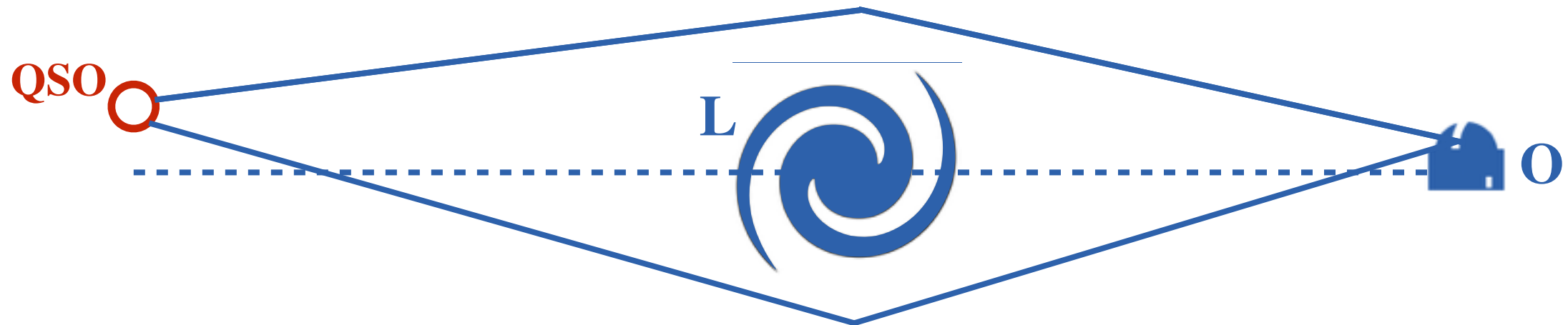


- Movement of individual stars within main lens.
- If relative motion (v_{\perp}) puts **source** within star θ_E , microlensing happens
- There are many stars in the main lens galaxy that can cause microlensing
- Mapping the magnification of the relative motions of all these stars gives varying magnification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

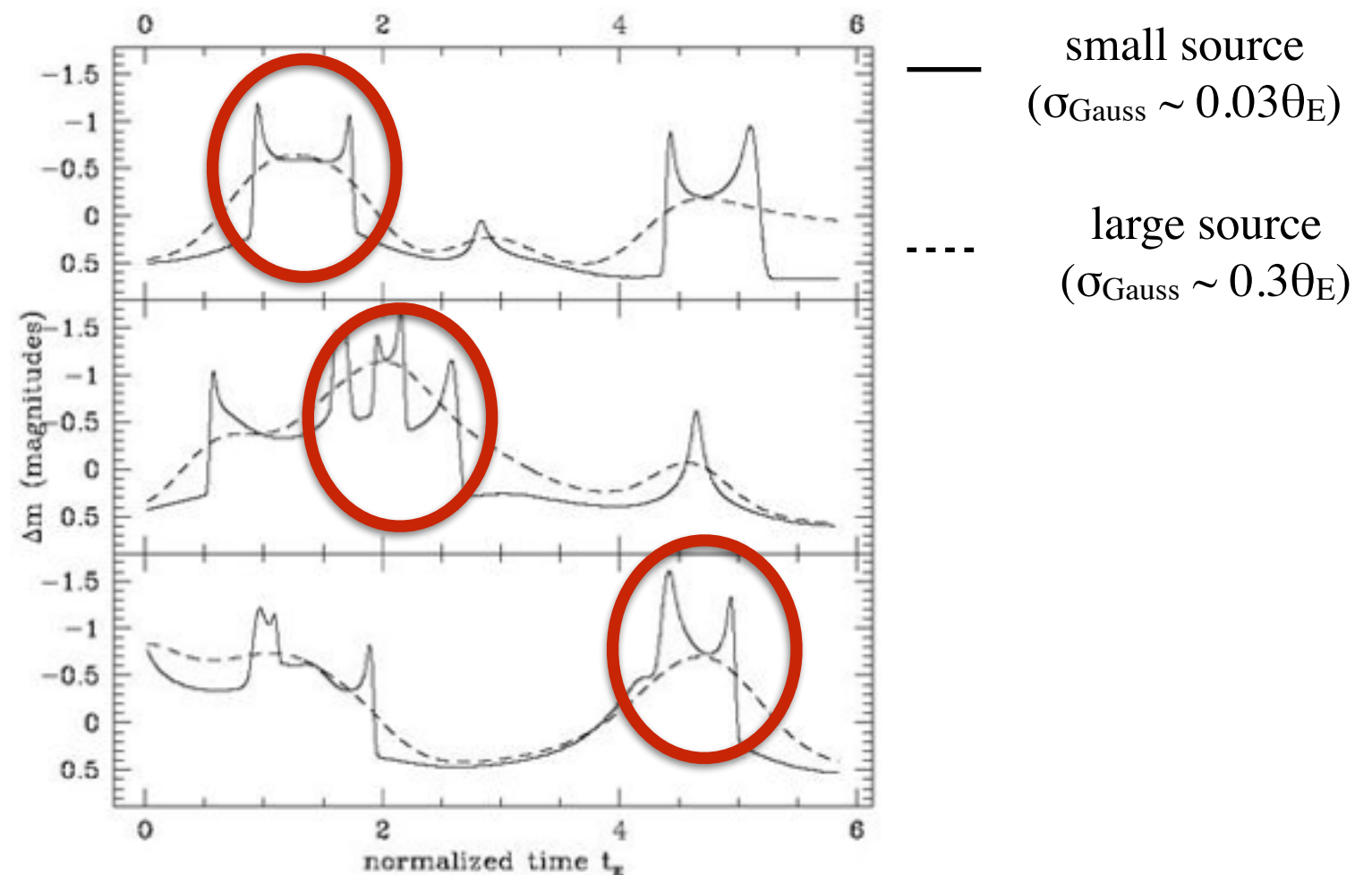
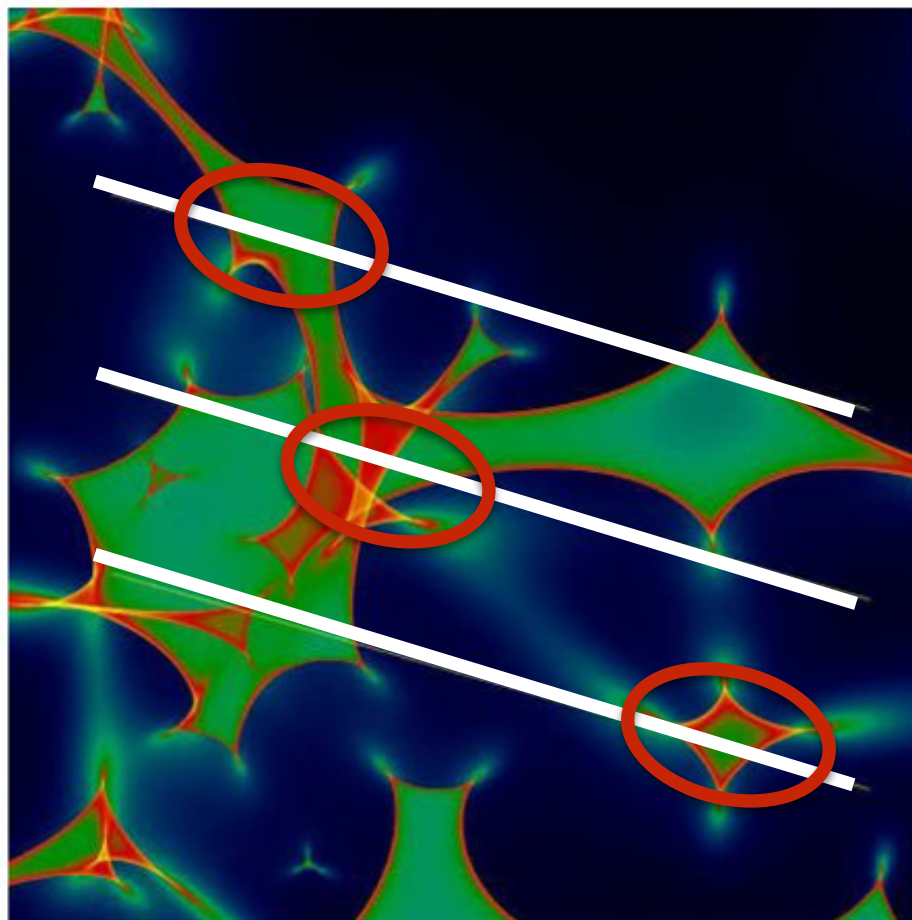


S. Poindexter (OSU Astronomy)

QSO Caustic/Magnification maps



- Multiple images will encounter different magnification patterns



Schneider, Kochanek & Wambsganss (2006)

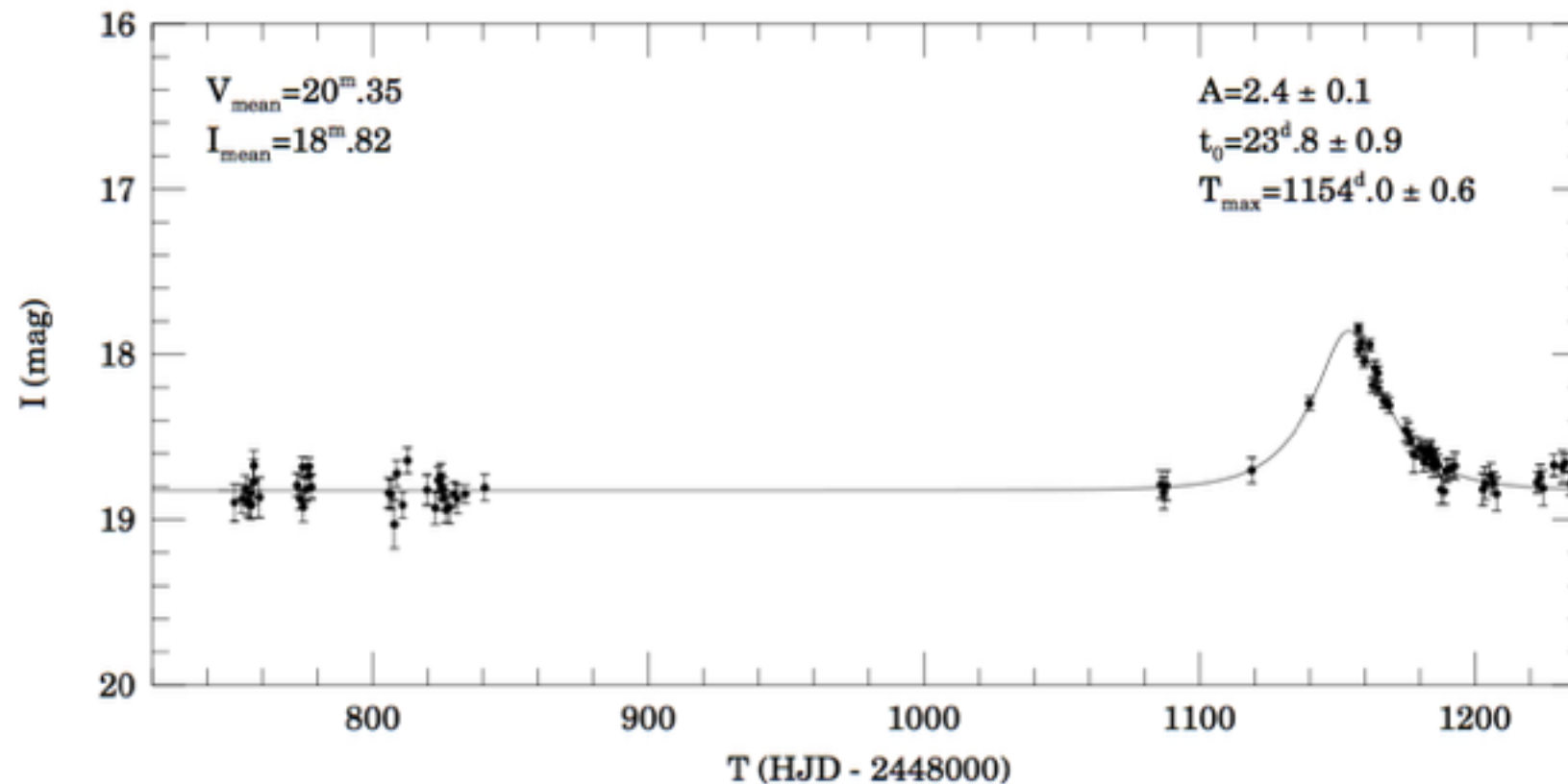
First Extra-Galactic Microlens

- QSO 0957+561 (Vanderriest+89) and QSO2237+0305 (Irwin+89)
- Wozniak and the OGLE team have monitored the Einstein Cross further
- Detour...

The Optical Gravitational Lensing Experiment



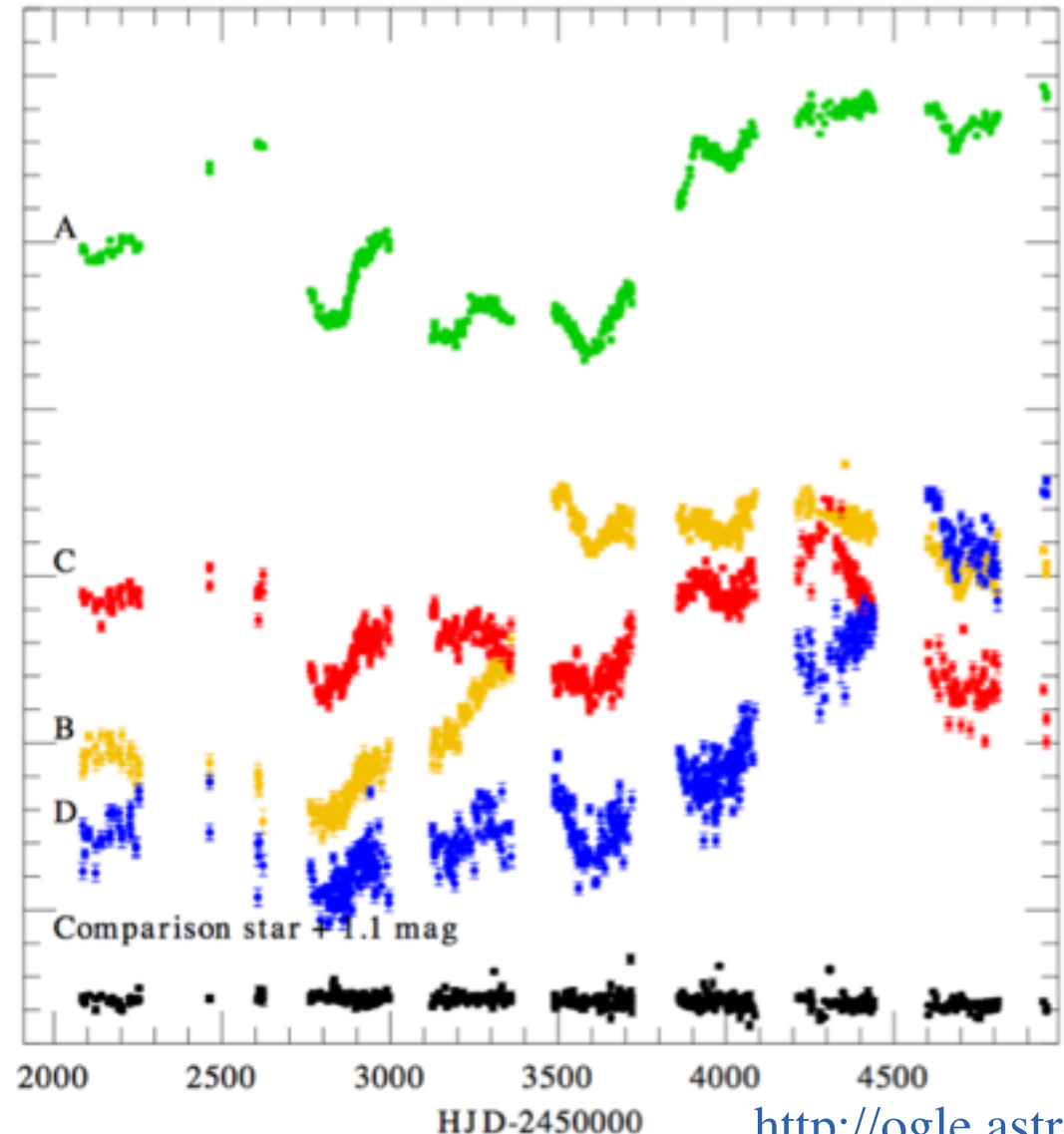
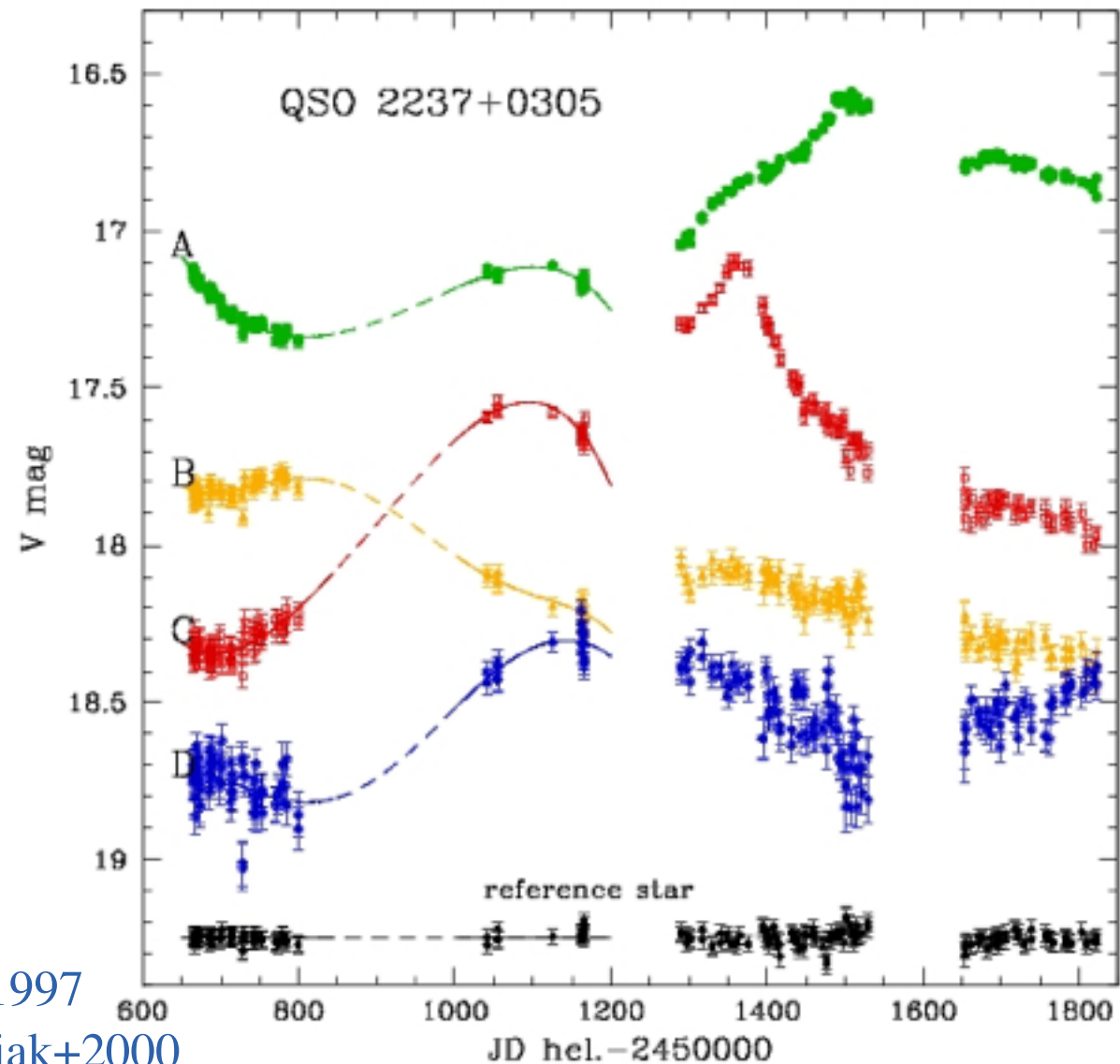
- OGLE - 25 years (1992-2017) photometric monitoring
 - <http://ogle.astrouw.edu.pl>
- OGLE campaigns: I (92-95), II (98-00), III (02-09), IV (11-16)
- The Udalski+93 first galactic microlens is from OGLE



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

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.

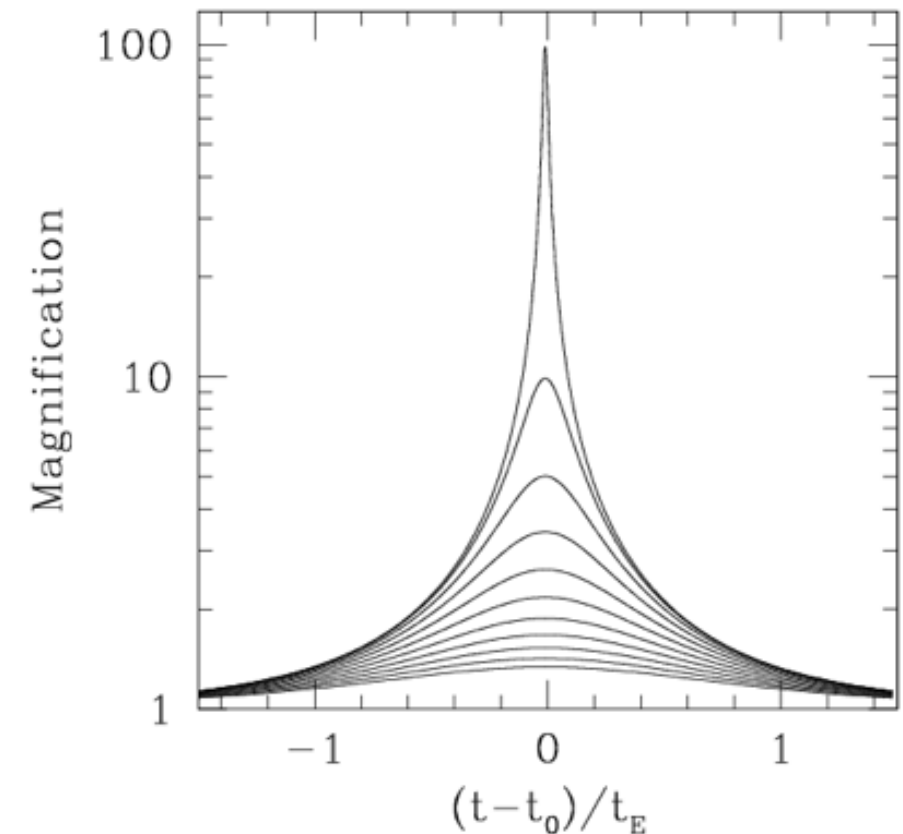


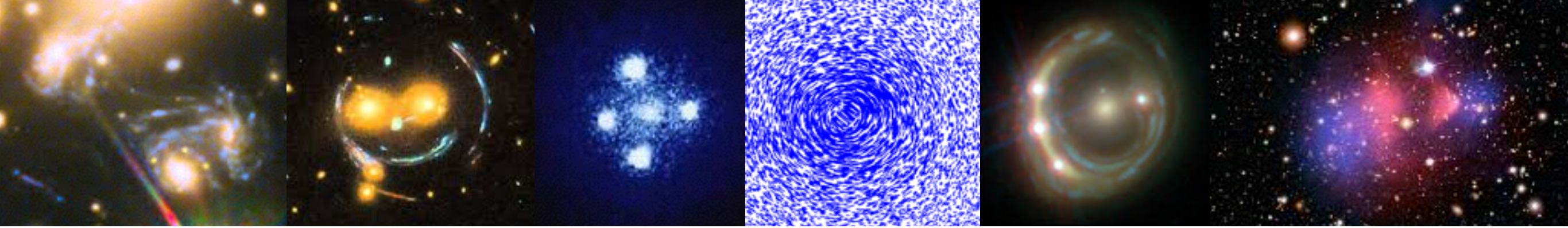
So in summary...

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

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

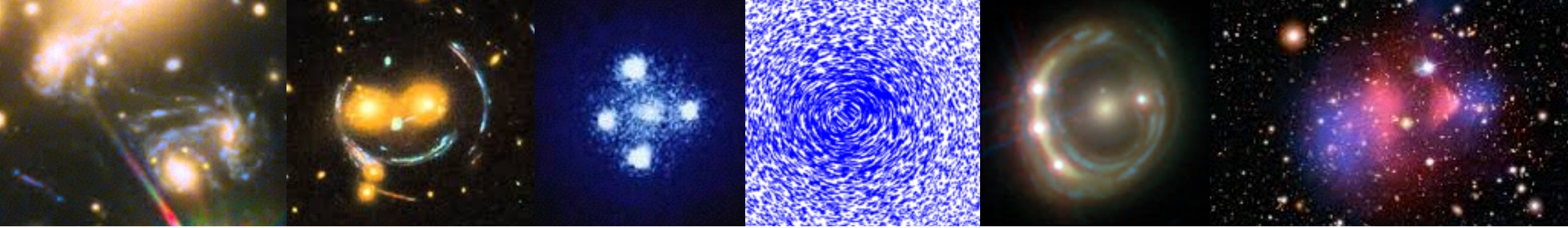
- This results in the ‘Paczynski Curve’
- Microlensing for MACHO detections
- Monitoring of stars have show:
 - MW halo is mainly non-MACHOs
- Extra-galactic microlensing of multiple images of strongly lensed QSOs
- In a similar manner, such measurements provides information about stars in lens galaxies





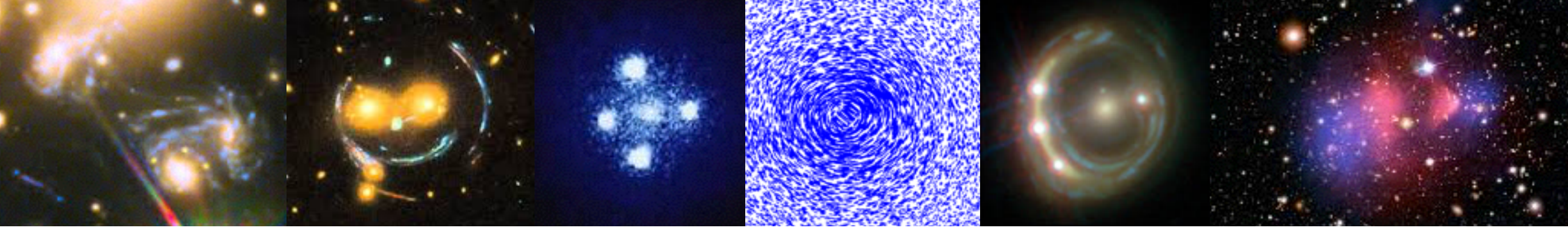
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Questions?



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Last Week's Worksheet



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This Week's Worksheet