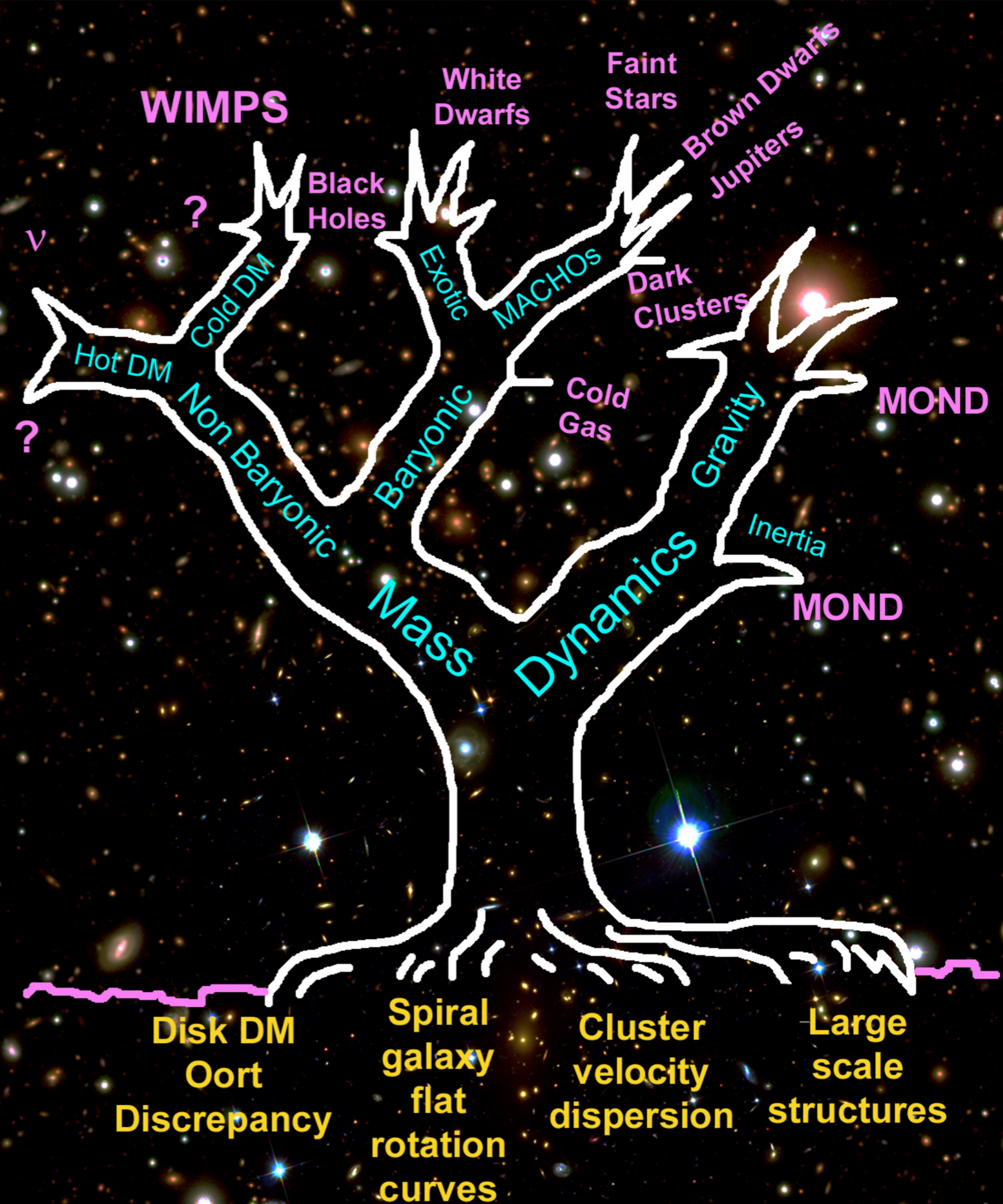


# DARK MATTER

ASTR 333/433

TODAY  
MICROLENSING  
MACHOs

Homework 3 on-line  
Due Thursday, April 9  
(one week from today)

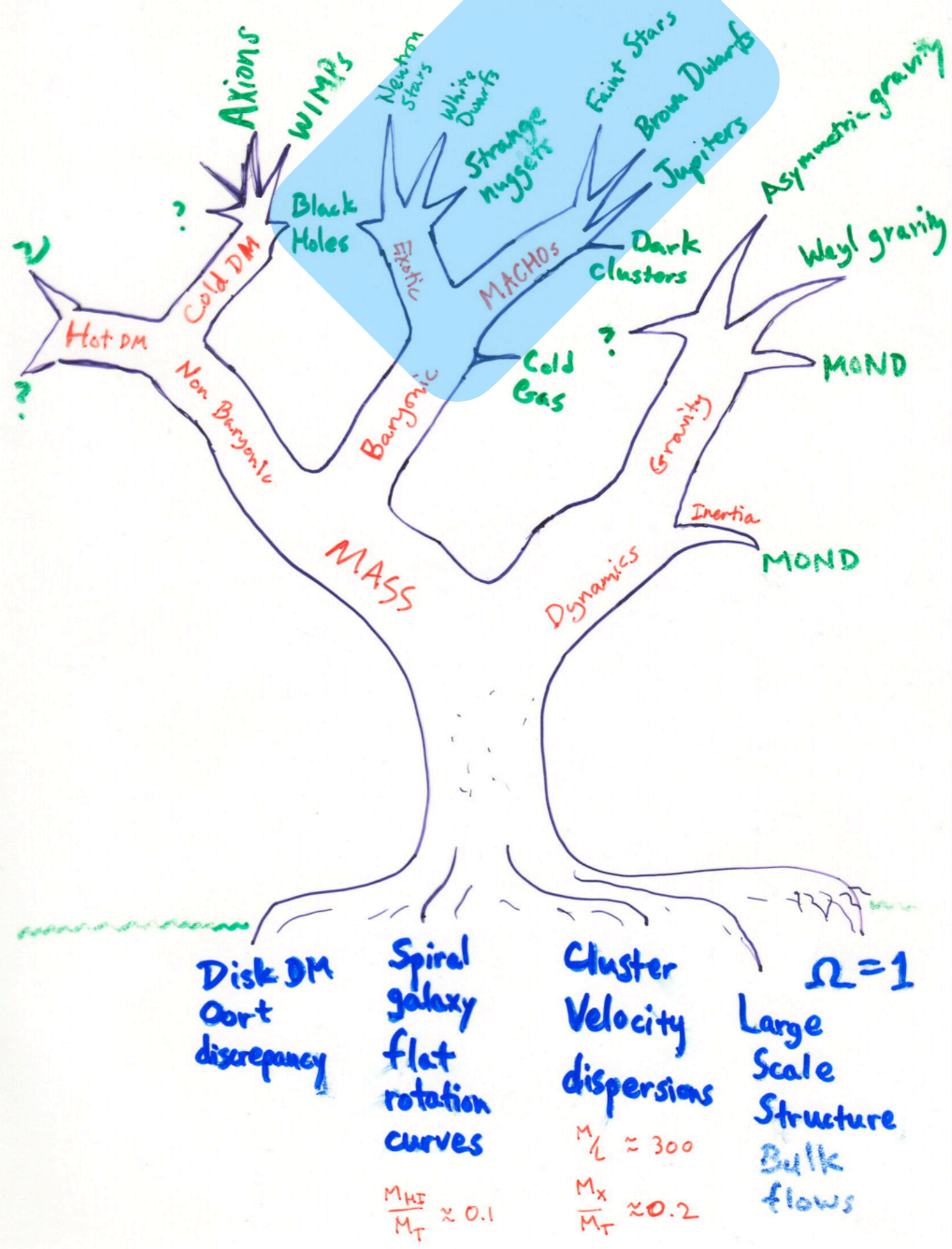


# MACHO

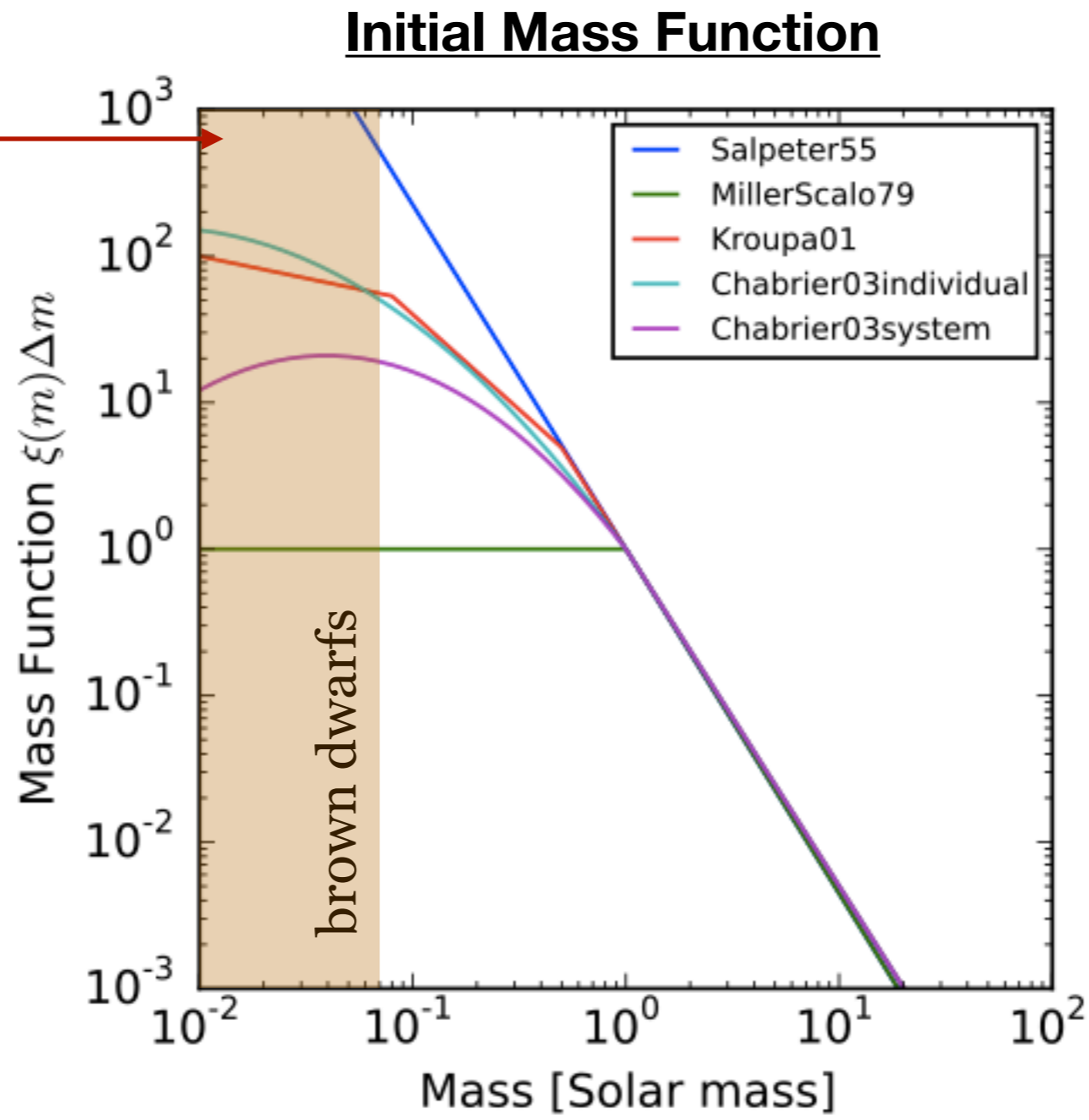
## MASSIVE COMPACT HALO OBJECT

e.g.,  
brown dwarfs  
white dwarfs  
neutron stars  
black holes  
planets  
very faint stars  
strange nuggets  
macros

Concentrated  
dark matter:  
two parts Plutonic Quarks,  
one part Cesium; add water



there could be a lot of mass in brown dwarfs, depending on the IMF



$$M_{BD} < 0.07 M_{\odot}$$

brown dwarfs are failed stars  
below the hydrogen burning limit

# Microensing surveys: MACHO, EROS, OGLE

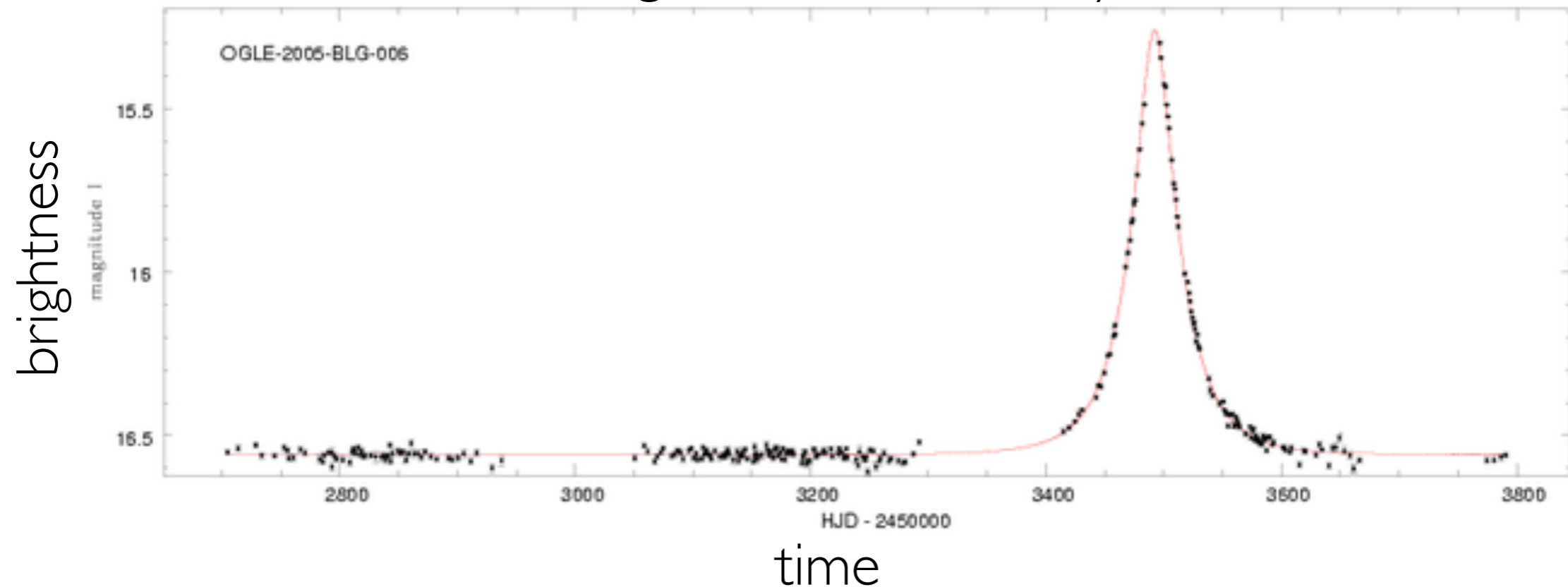
Monitor regions of dense star fields: LMC/SMC/Galactic Center

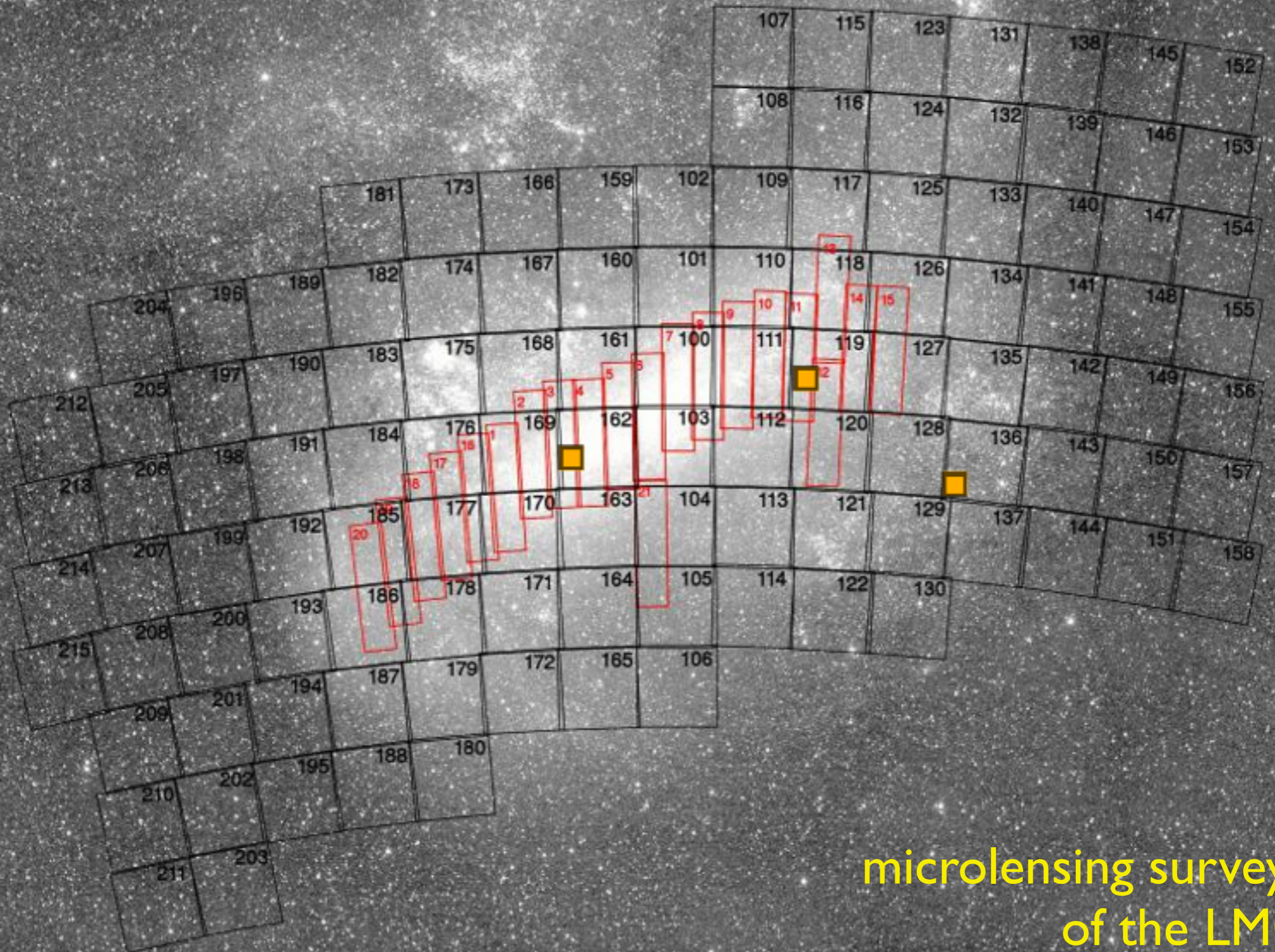
Watch for microlensing events due to intervening masses

Sensitive to brown dwarfs & stellar mass objects,  
including neutron stars and black holes.

Don't detect the object itself, but the light bending effect it causes on  
background stars

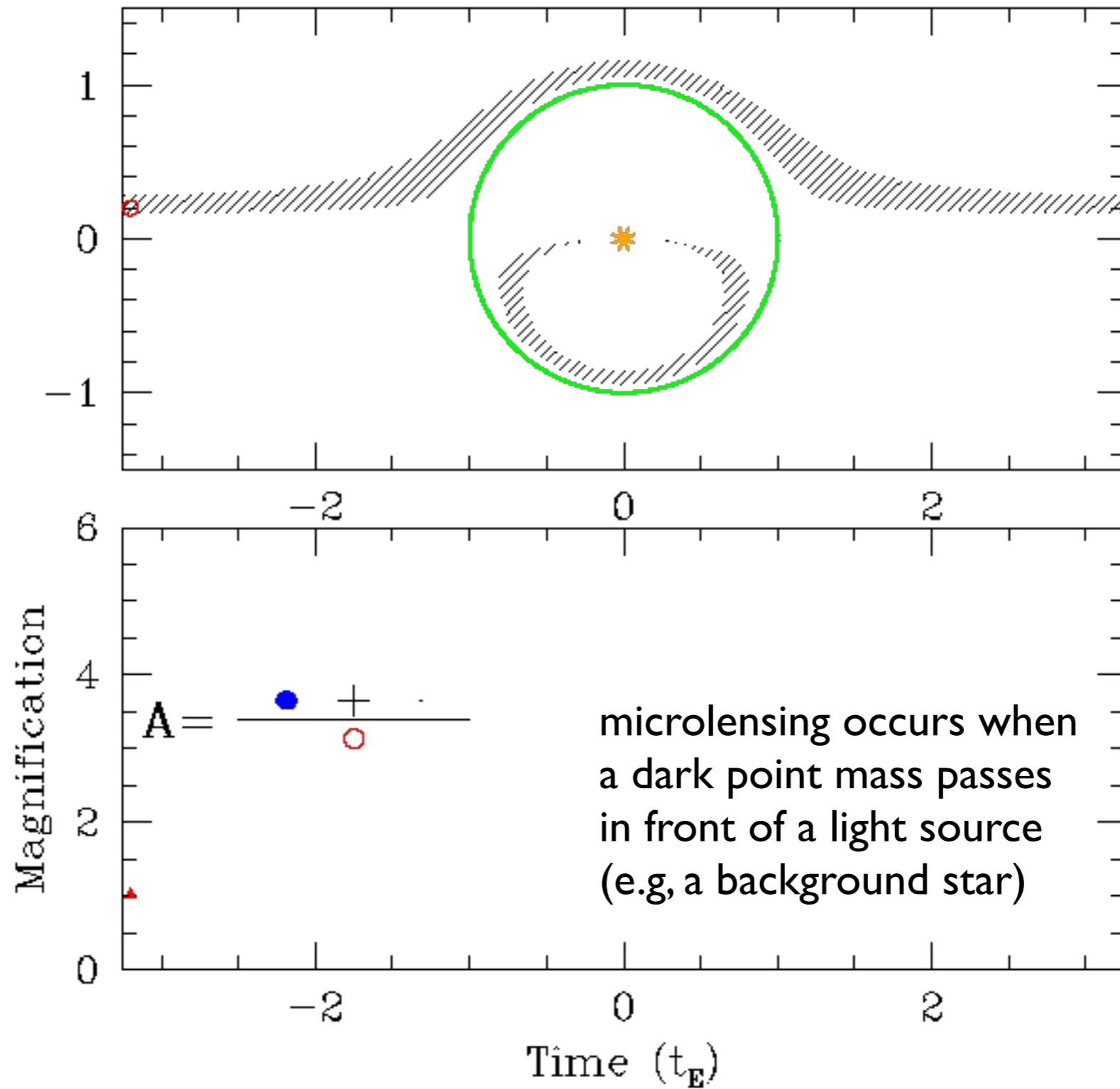
microlensing event observed by OGLE

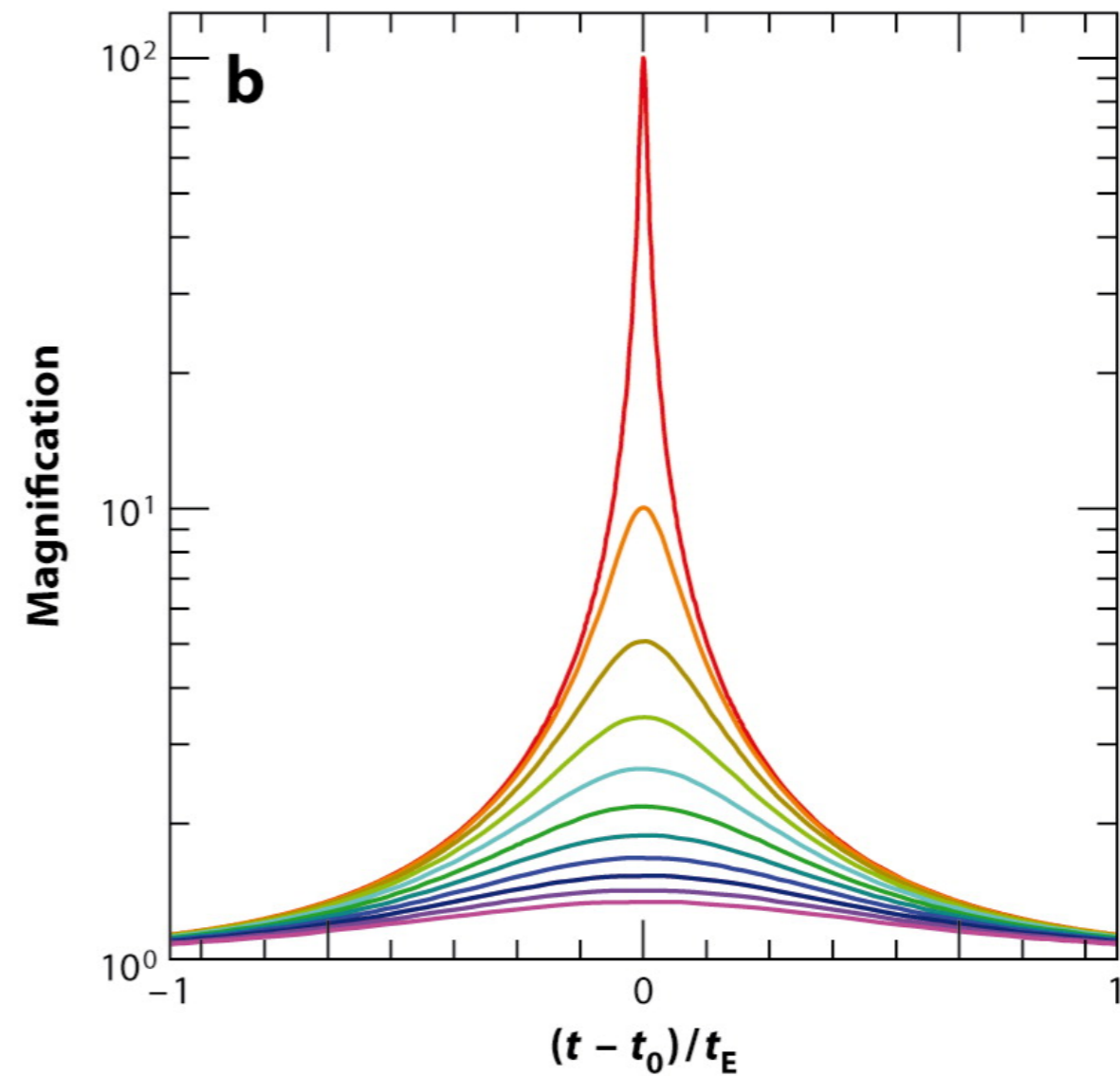
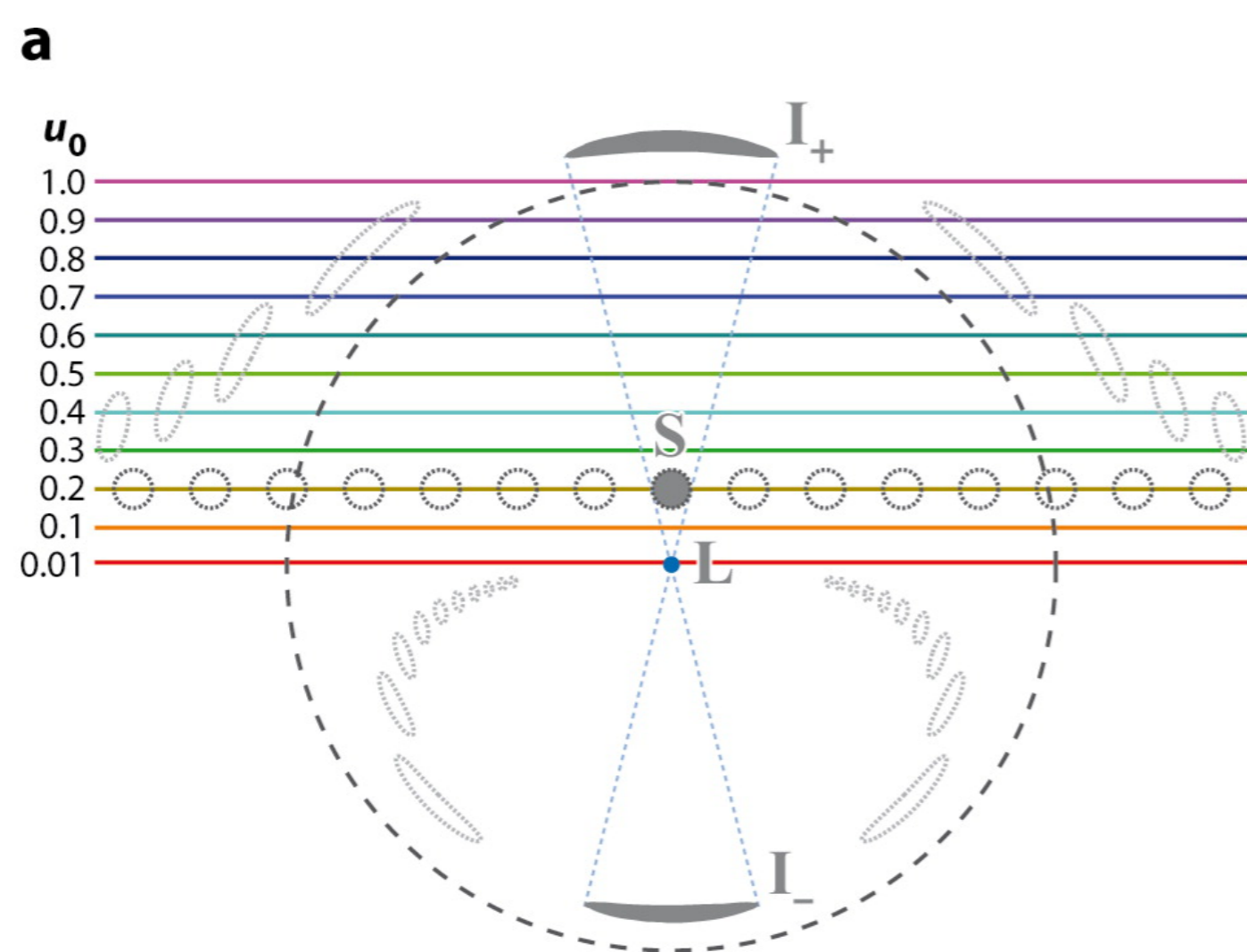




microlensing surveys  
of the LMC

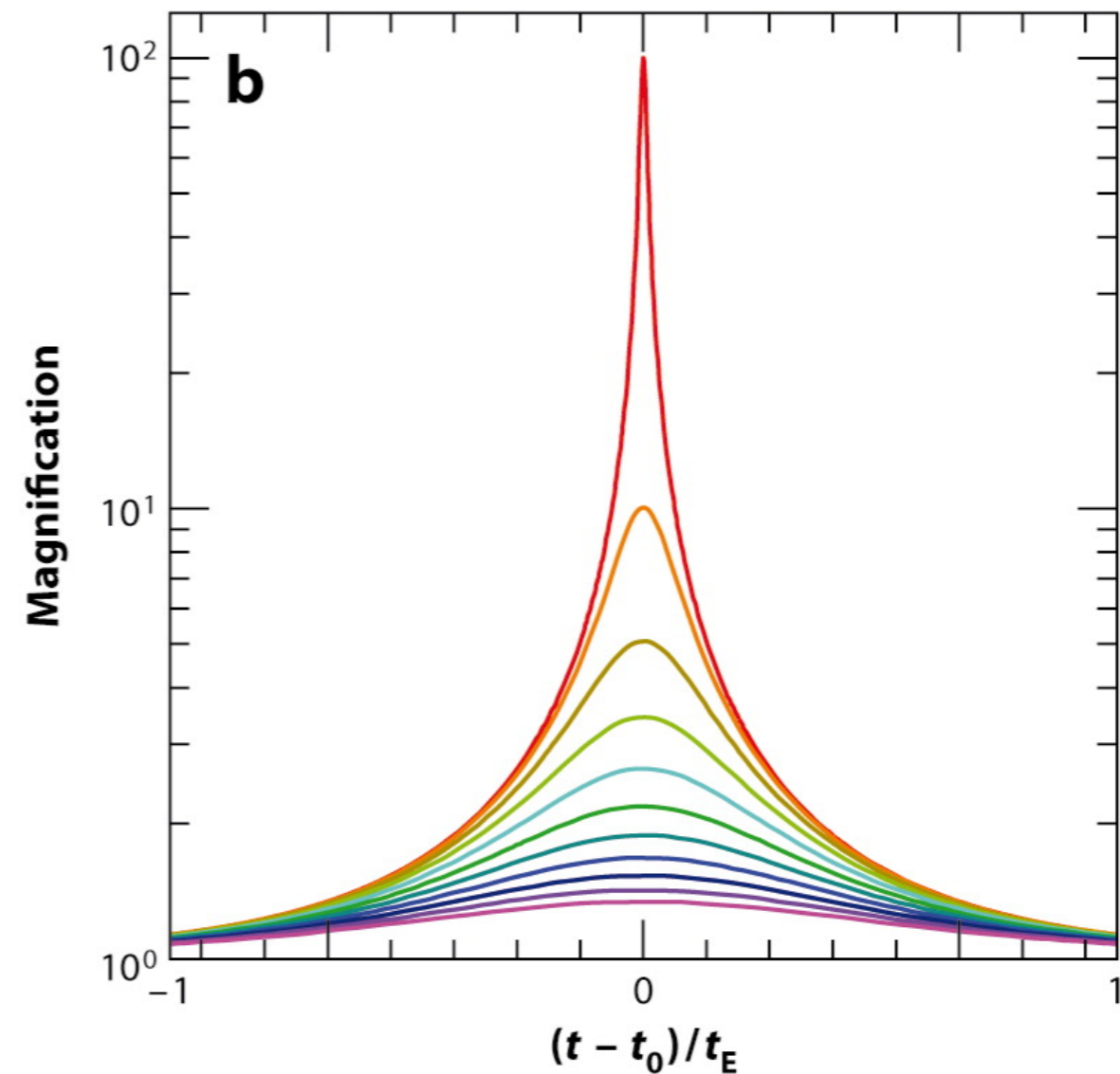
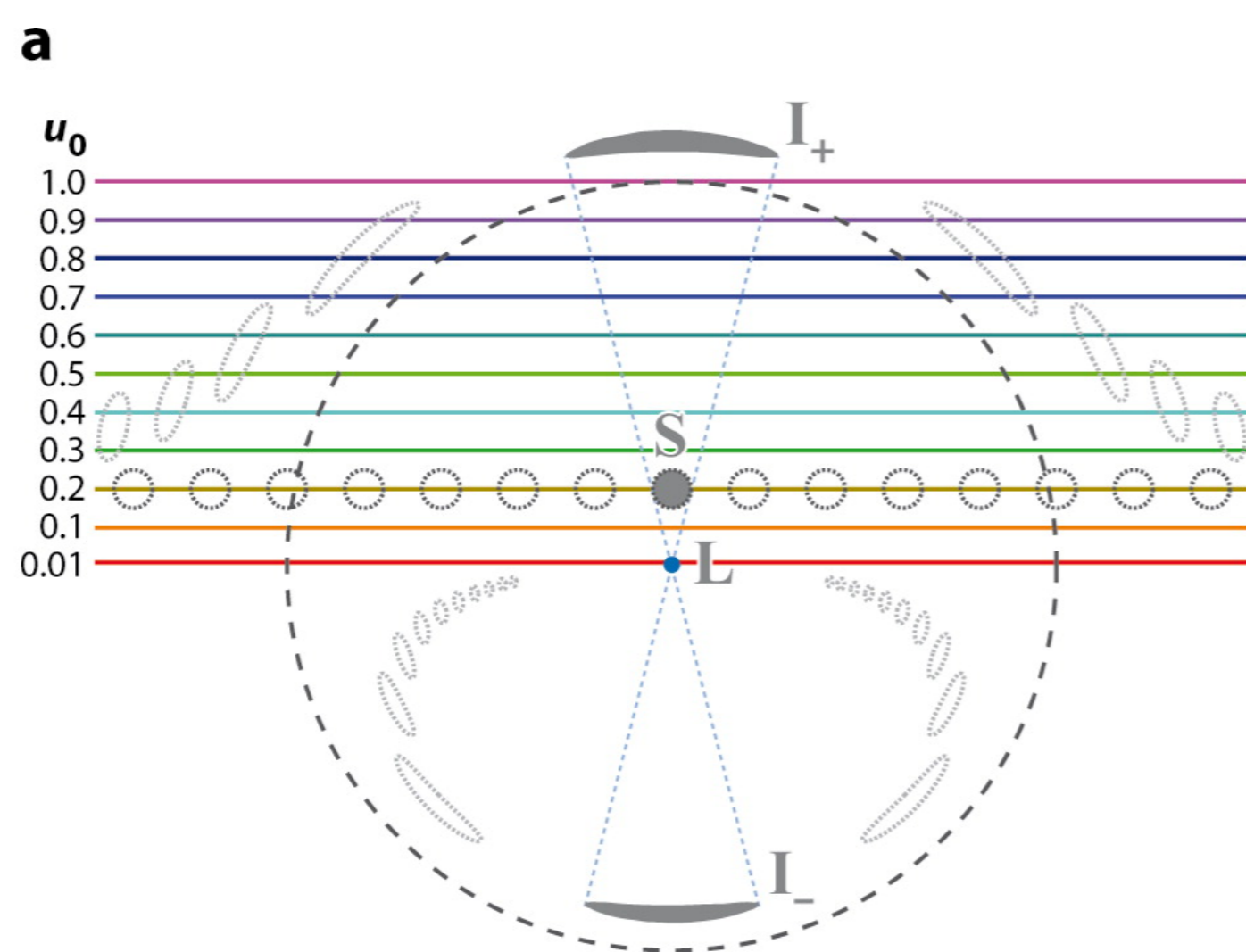
# microlensing





Amplification: 
$$A = \frac{2 + u^2}{u\sqrt{4 + u^2}} \quad u = \frac{\theta}{\theta_E}$$

Einstein ring radius: 
$$\theta_E = \sqrt{\frac{4GM}{c^2} \frac{D_{LS}}{D_L D_S}}$$



**AR** Gaudi BS. 2012.  
 Annu. Rev. Astron. Astrophys. 50:411–53

$$t_E = \frac{\theta_E}{\mu_{rel}} \quad \text{Einstein crossing time: time to cross Einstein ring.}$$

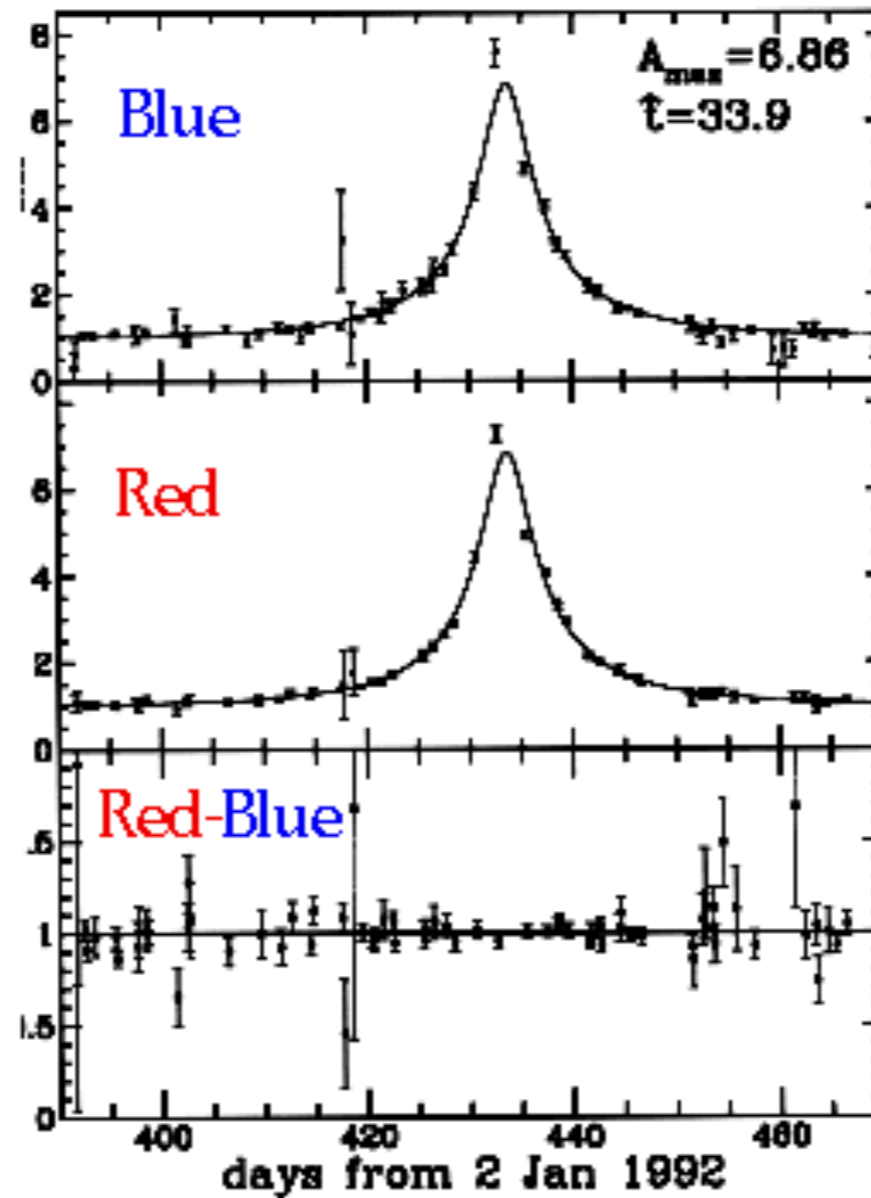
Einstein ring radius: 
$$\theta_E = \sqrt{\frac{4GM}{c^2} \frac{D_{LS}}{D_L D_S}} \quad \approx 10^{-4} \text{ arc seconds for a brown dwarf half way to the LMC}$$

$M = 0.06 M_\odot \quad D_L = D_{LS} = 25 \text{ kpc}$



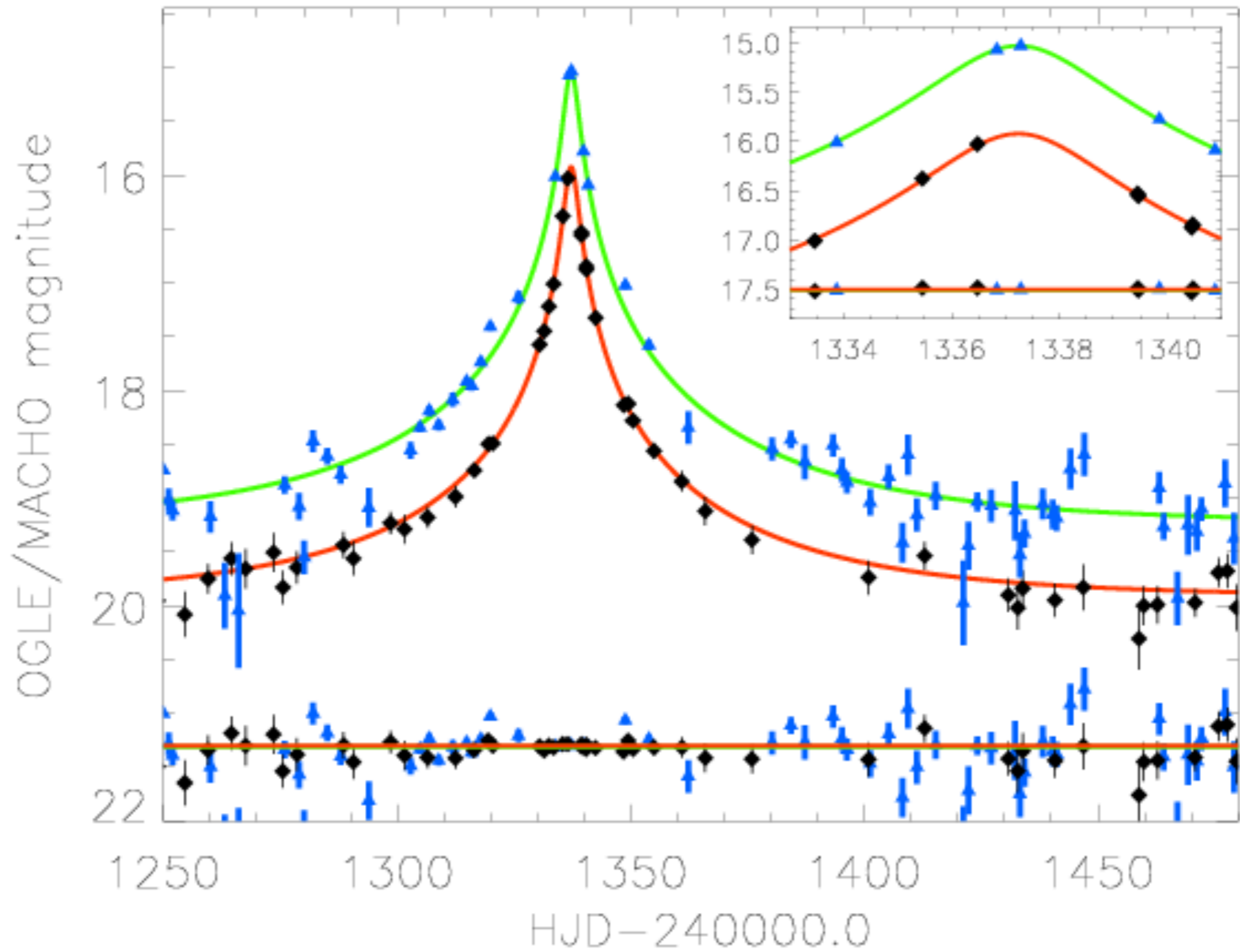


# microlensing events achromatic



should also be symmetric in time  
(unless there is a companion planet)

# OGLE-LMC-01



achromatic macho candidate event



Number of microlensing events

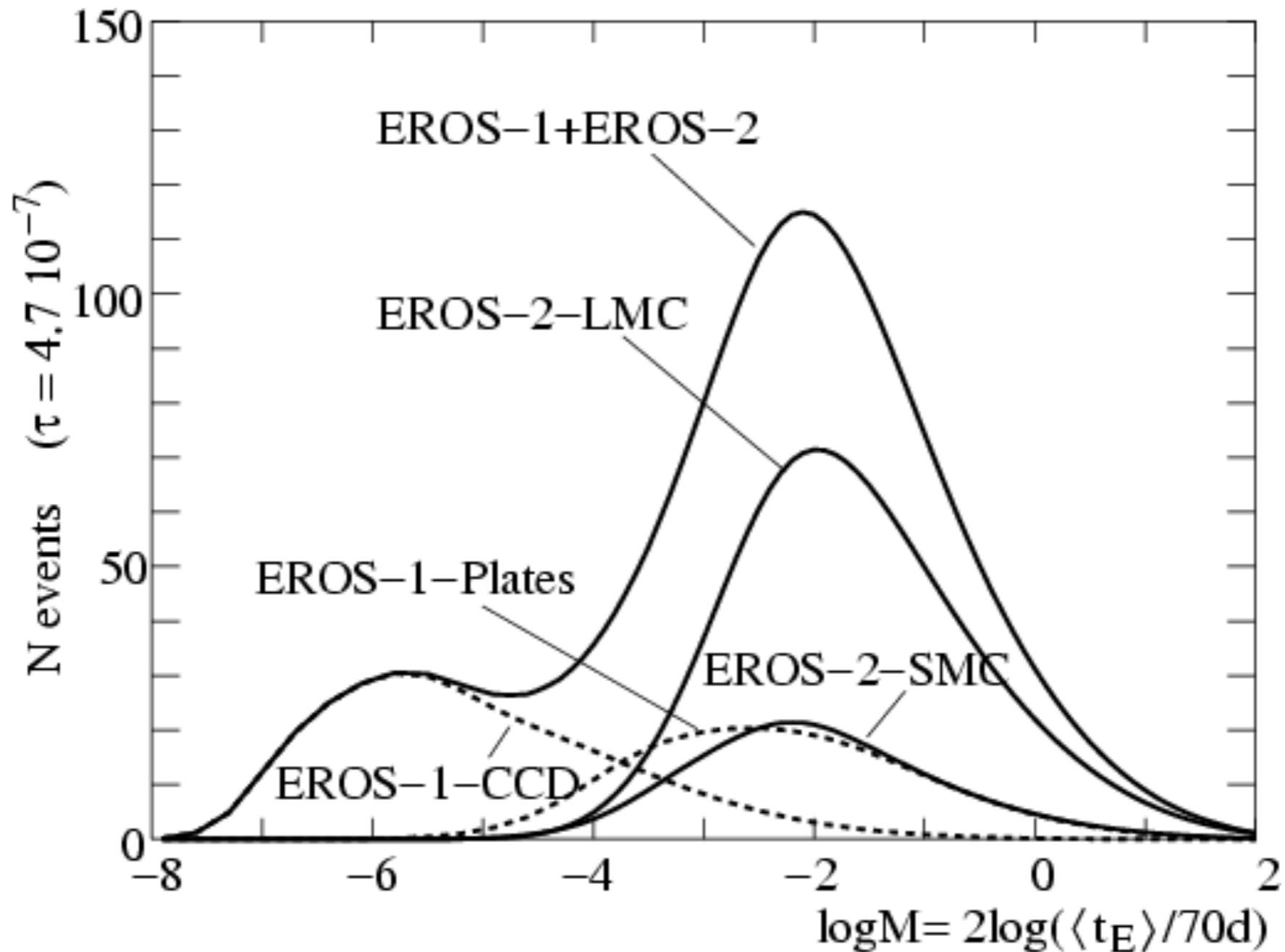
$$N(> A) = \frac{2\tau}{(A^2 - 1) + A\sqrt{A^2 - 1}}$$

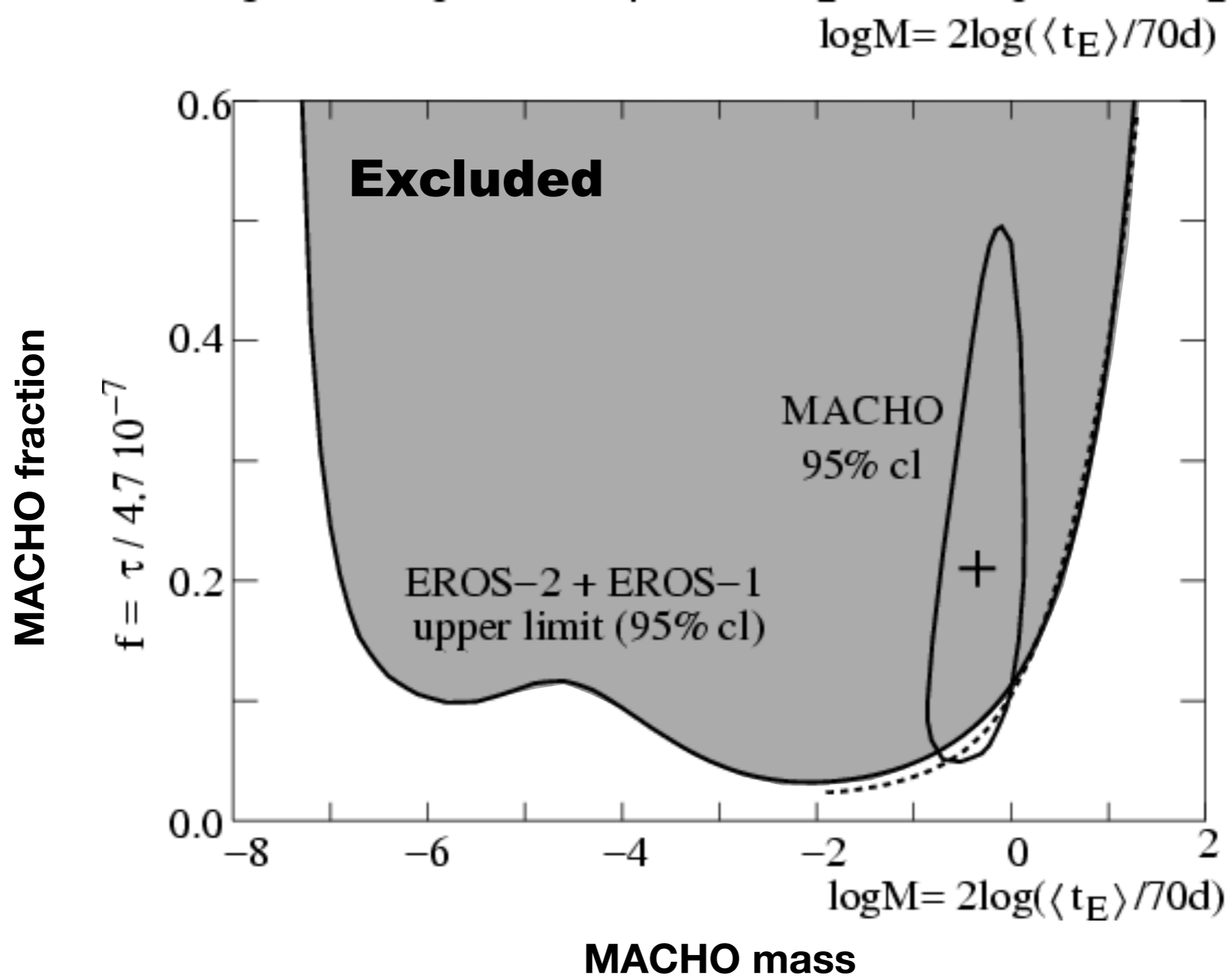
optical depth as a fcn of radius through an isothermal sphere

$$\tau = 2\pi \frac{\sigma_V^2}{c^2} \frac{D_L D_{LS}}{r D_s}$$

optical depth = fraction of the sky covered by Einstein rings

Number of microlensing events expected if all the halo mass is in MACHOs

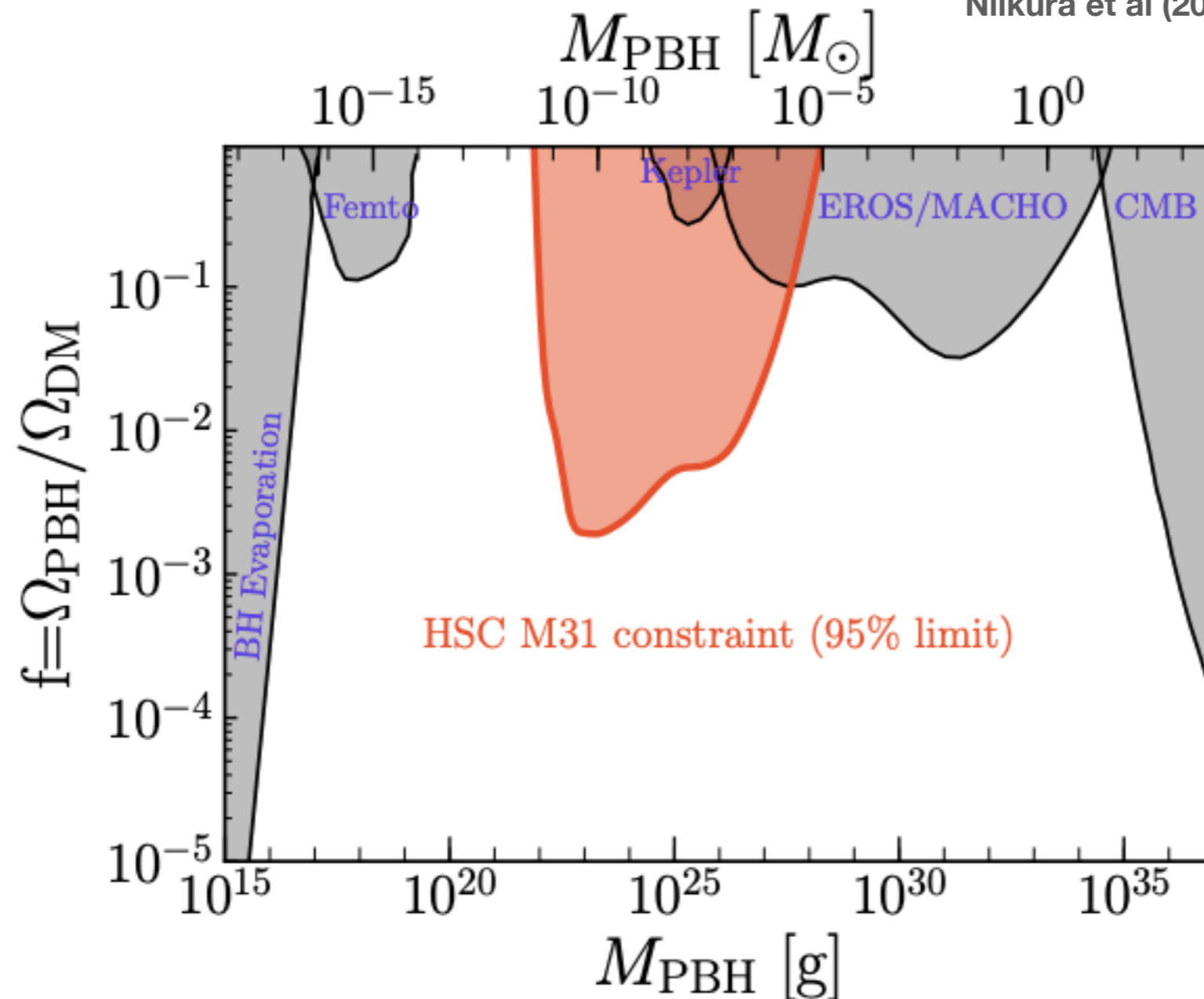




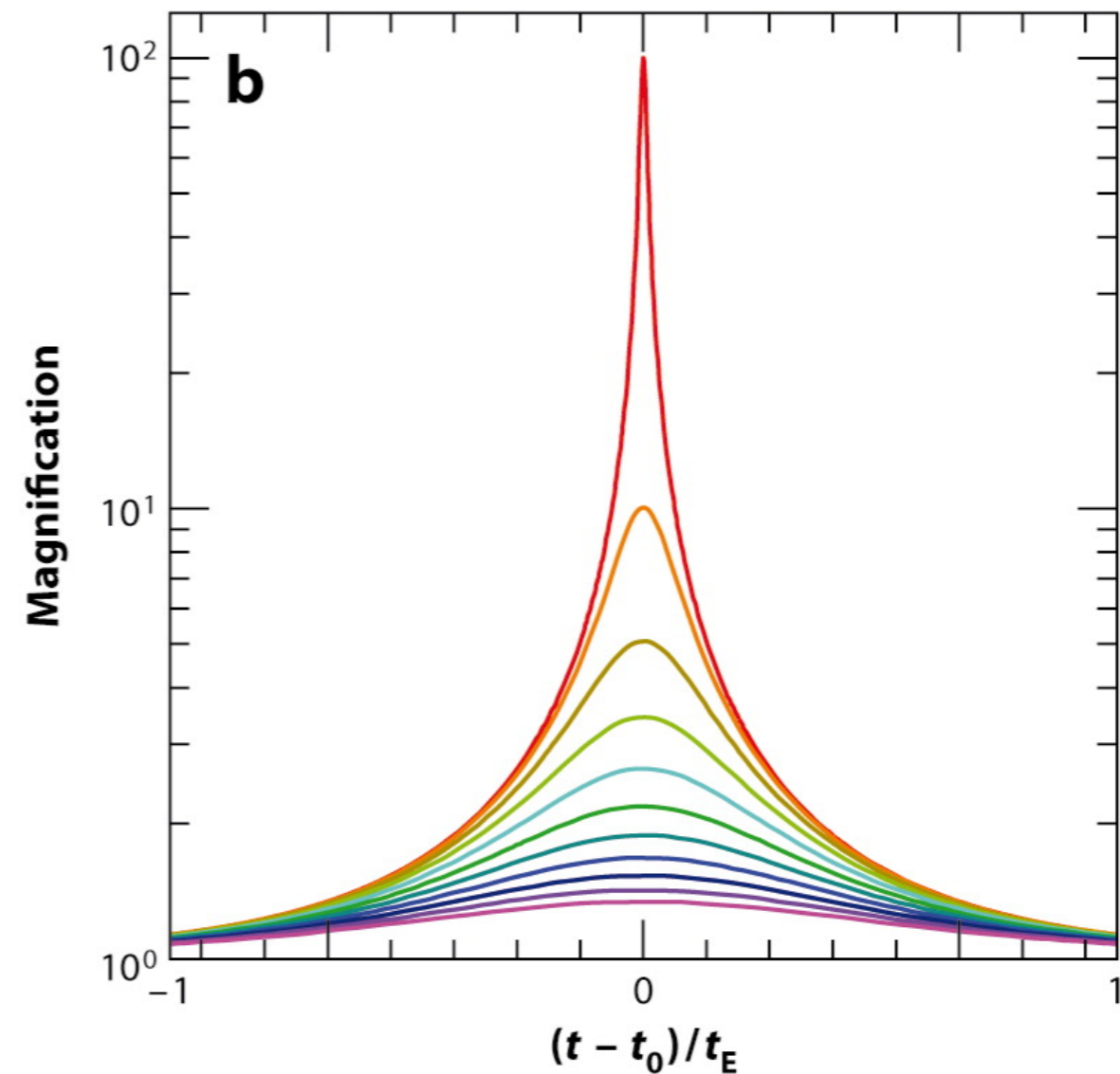
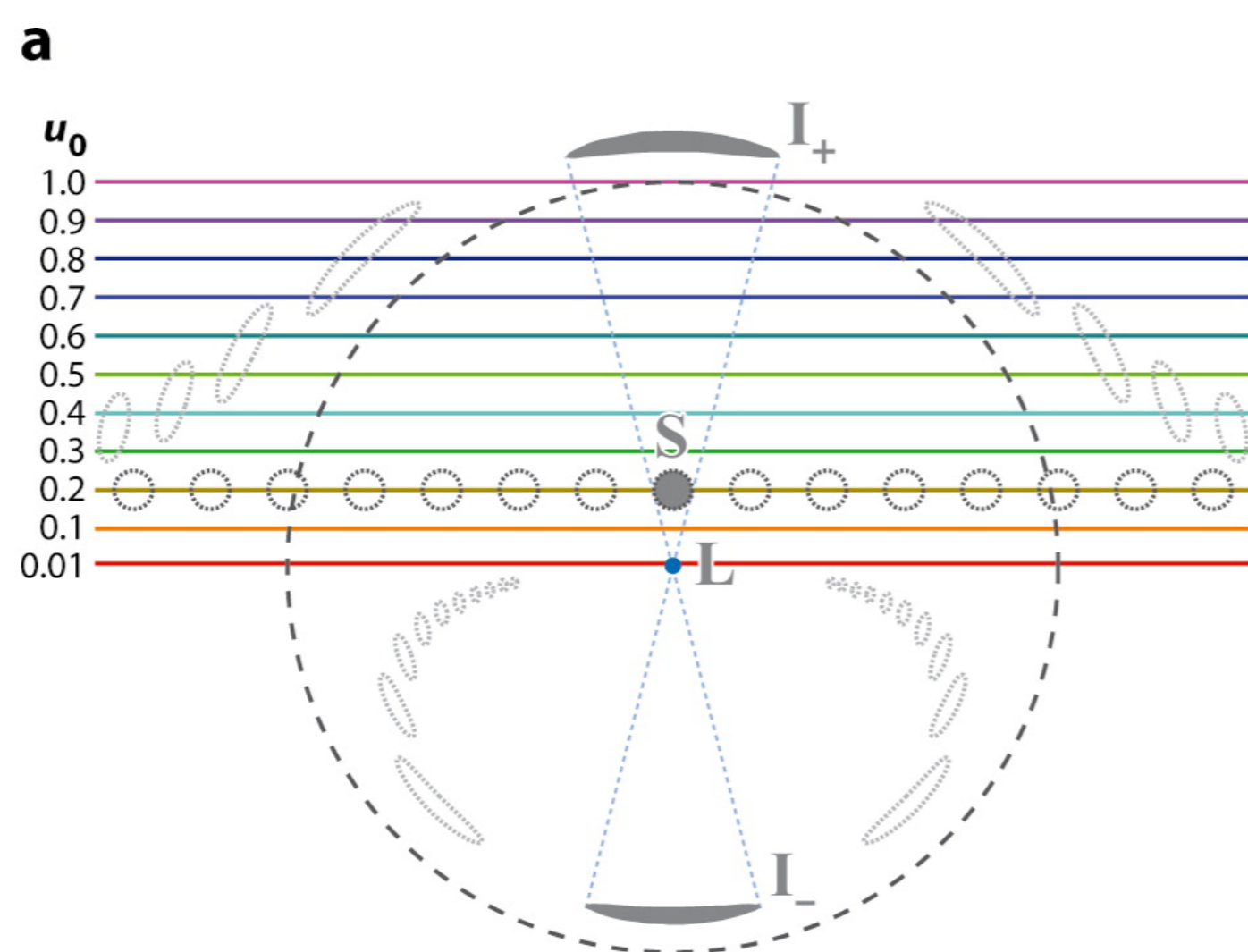
The observed rate of microlensing events leaves no room for the dark matter halo of the Milky Way to be composed of massive compact objects like brown dwarfs or black holes in the mass range  $10^{-7} < M < 10$  solar masses.

# Subaru study of microlensing towards M31

Niikura et al (2019) Nature Astronomy, 3, 524



The red shaded region corresponds to the 95% C.L. upper bound on the PBH mass fraction to DM in the halo regions of MW and M31, derived from our search for microlensing of M31 stars based on the “single-night” HSC/Subaru data and fills a large gap in the existing constraints by closing the PBH DM window around lunar mass scale. To derive this constraint, we took into account the effect of finite source size, assuming that all source stars in M31 have a solar radius, as well as the effect of wave optics in the HSC r-band filter on the microlensing event (see text for details). The effects weaken the upper bounds at  $M \lesssim 10^{-7} M_{\odot}$ , and give no constraint on PBH at  $M \lesssim 10^{-11} M_{\odot}$ . Our constraint can be compared with other observational constraints as shown by the gray shaded regions: extragalactic  $\gamma$ -rays from PBH evaporation [32], femtolensing of  $\gamma$ -ray burst (“Femto”) [33], microlensing search of stars from the satellite 2-years Kepler data (“Kepler”) [18], MACHO/EROS/OGLE microlensing of stars (“EROS/MACHO”) [15], and the accretion effects on the CMB observables (“CMB”) [34], updated from the earlier estimate [35].



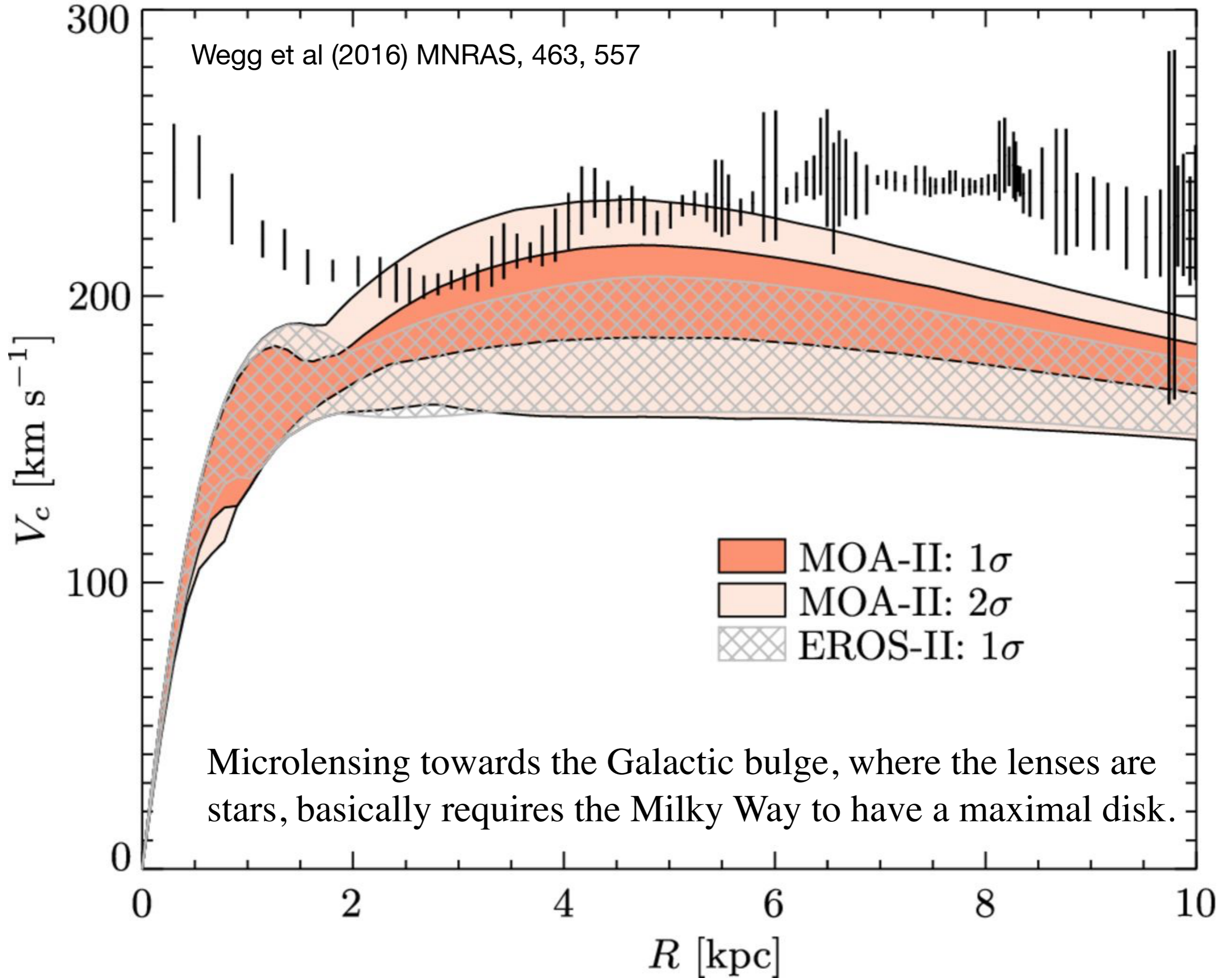
## Microlensing towards Galactic Center

$$t_E = \frac{\theta_E}{\mu_{rel}} \quad \text{Einstein crossing time: time to cross Einstein ring.}$$

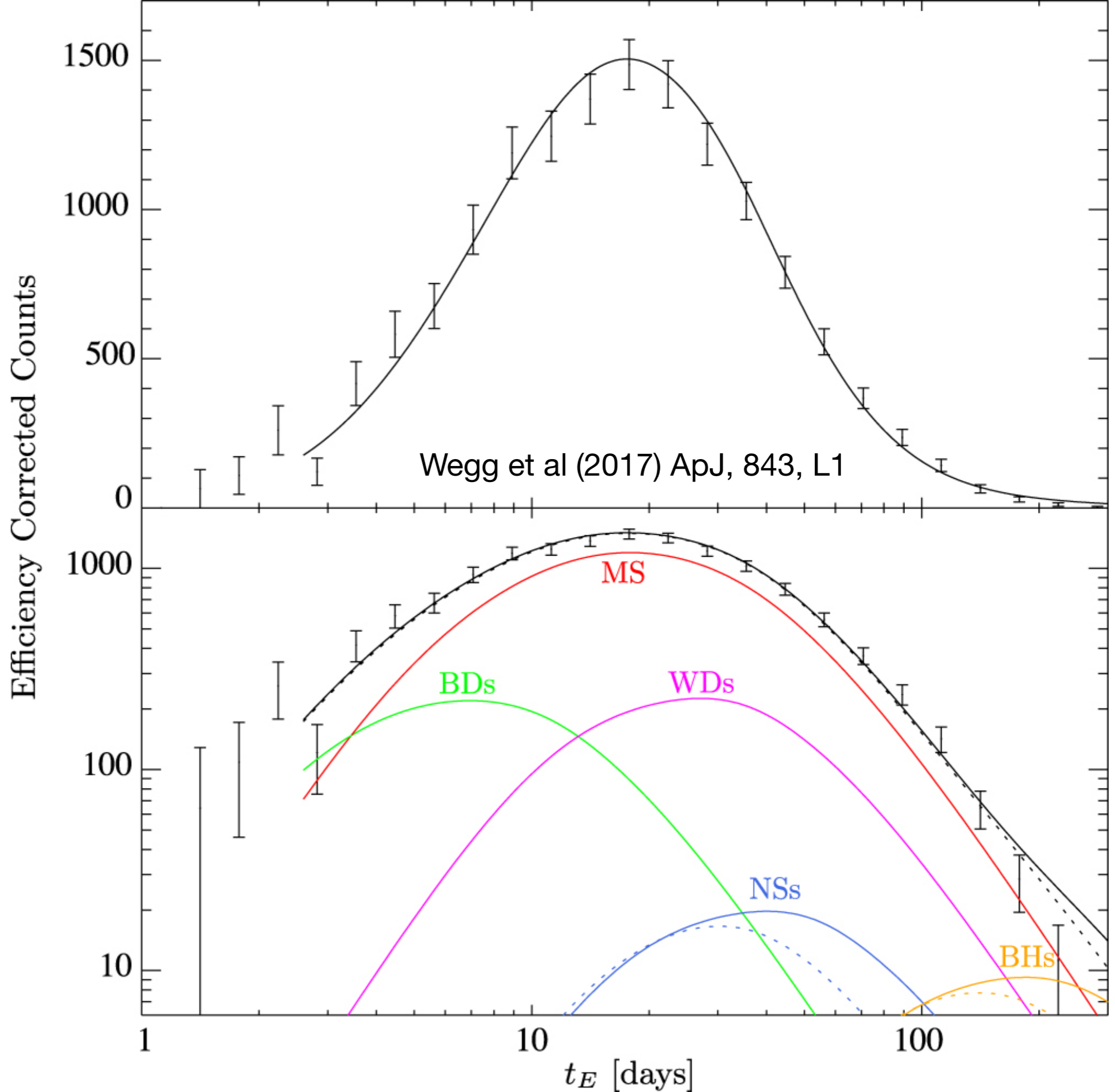
$$t_E \approx (24.8 \text{ days}) \left( \frac{M}{0.5 M_\odot} \right)^{1/2} \left( \frac{\pi_{rel}}{125 \mu\text{as}} \right)^{1/2} \left( \frac{\mu_{rel}}{10.5 \text{ mas yr}^{-1}} \right)^{-1}$$

for lensing events towards the Galactic bulge.





Also constrains the IMF to be basically the same as seen everywhere else.



# microlensing summary

- microlensing is rare but routinely detected
- optical depth consistent with known stars & stellar mass objects
- no positive evidence for MACHO type dark matter
- broad range of MACHO masses excluded:

$$10^{-7} < M_{\text{MACHO}} < 10 M_{\odot}$$

basically ruled out