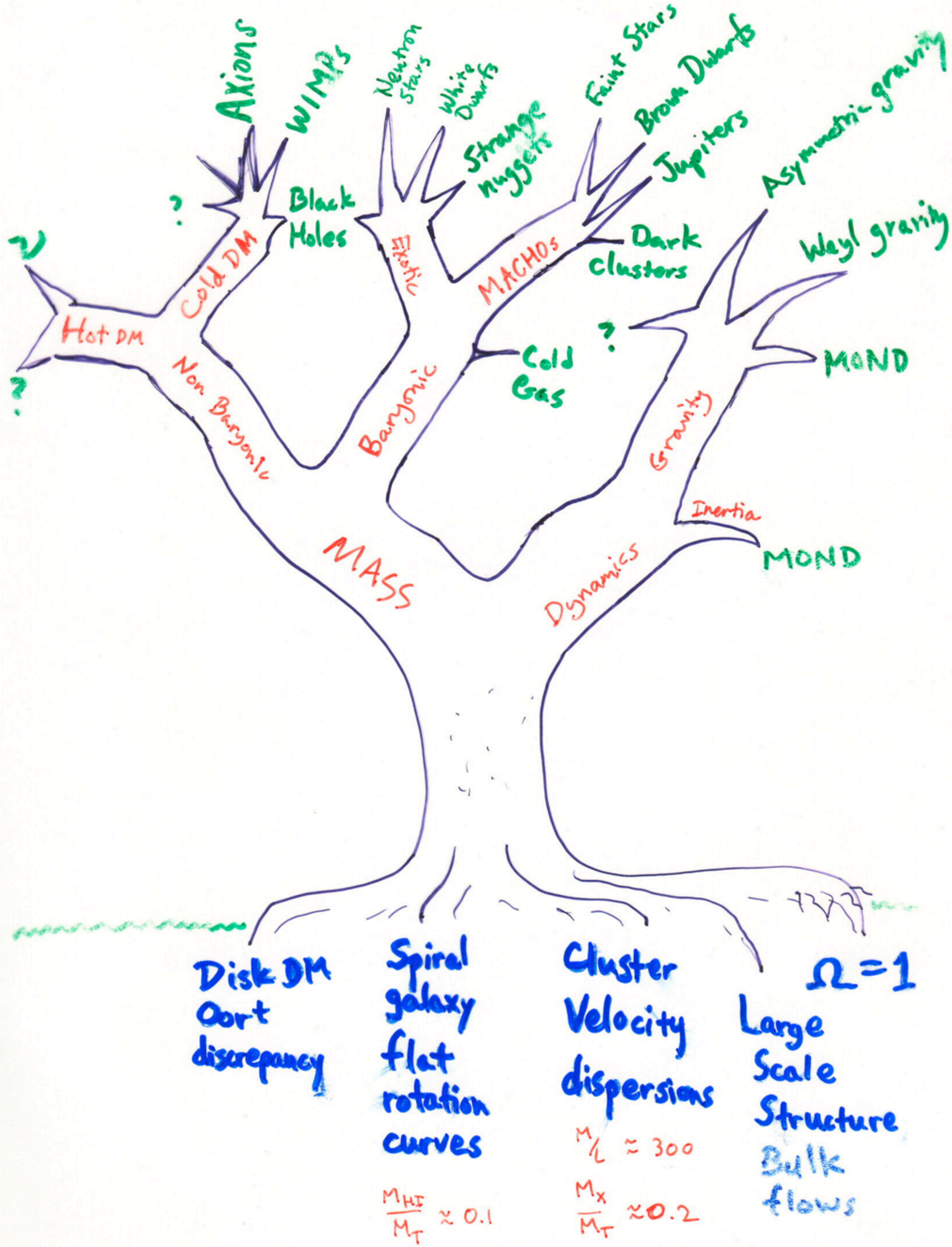
Dark Matter

ASTR 333/433

TODAY

Microlensing

experiments to detect dark matter

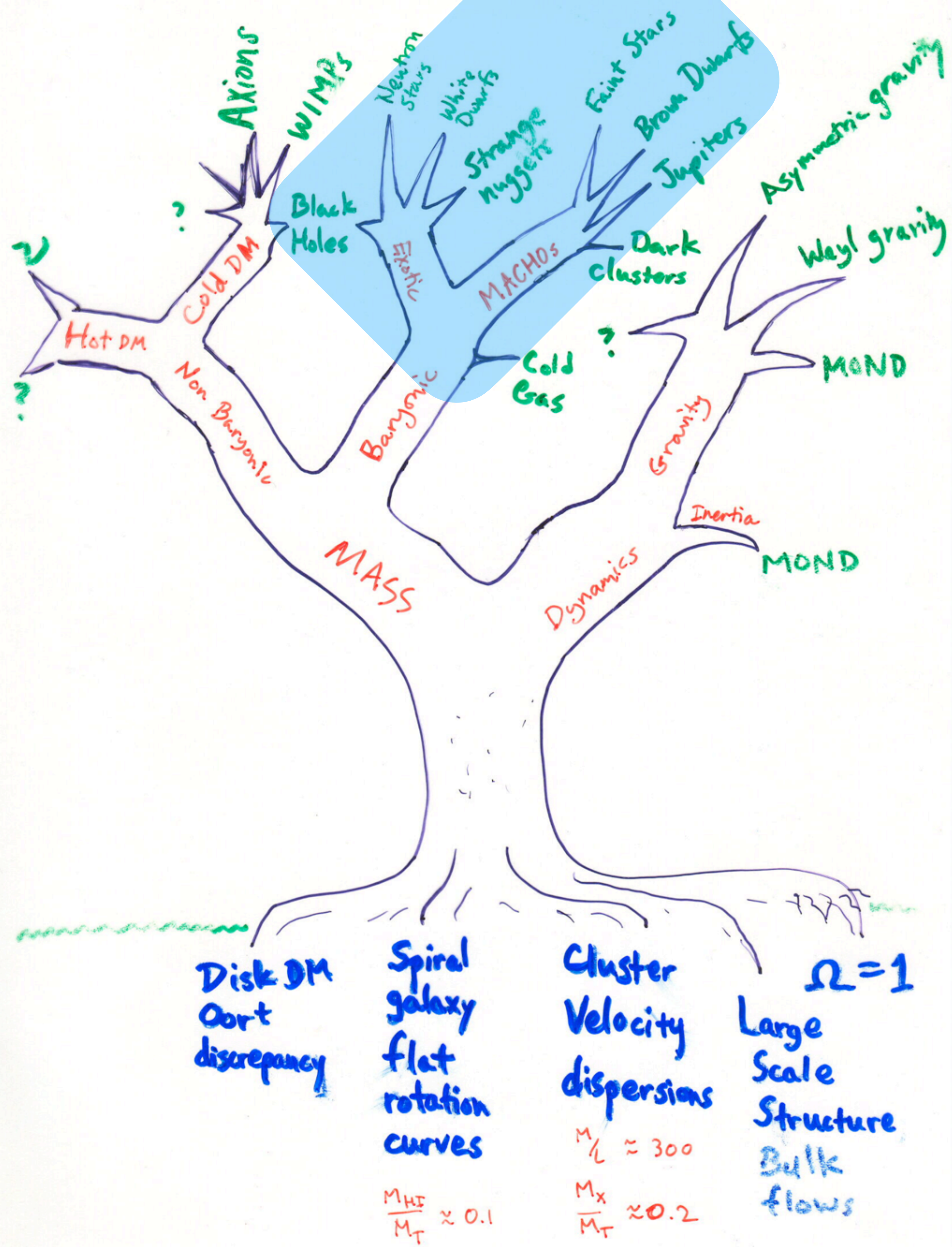


MACHOs

MASSIVE
COMPACT
HALO
OBJECTS

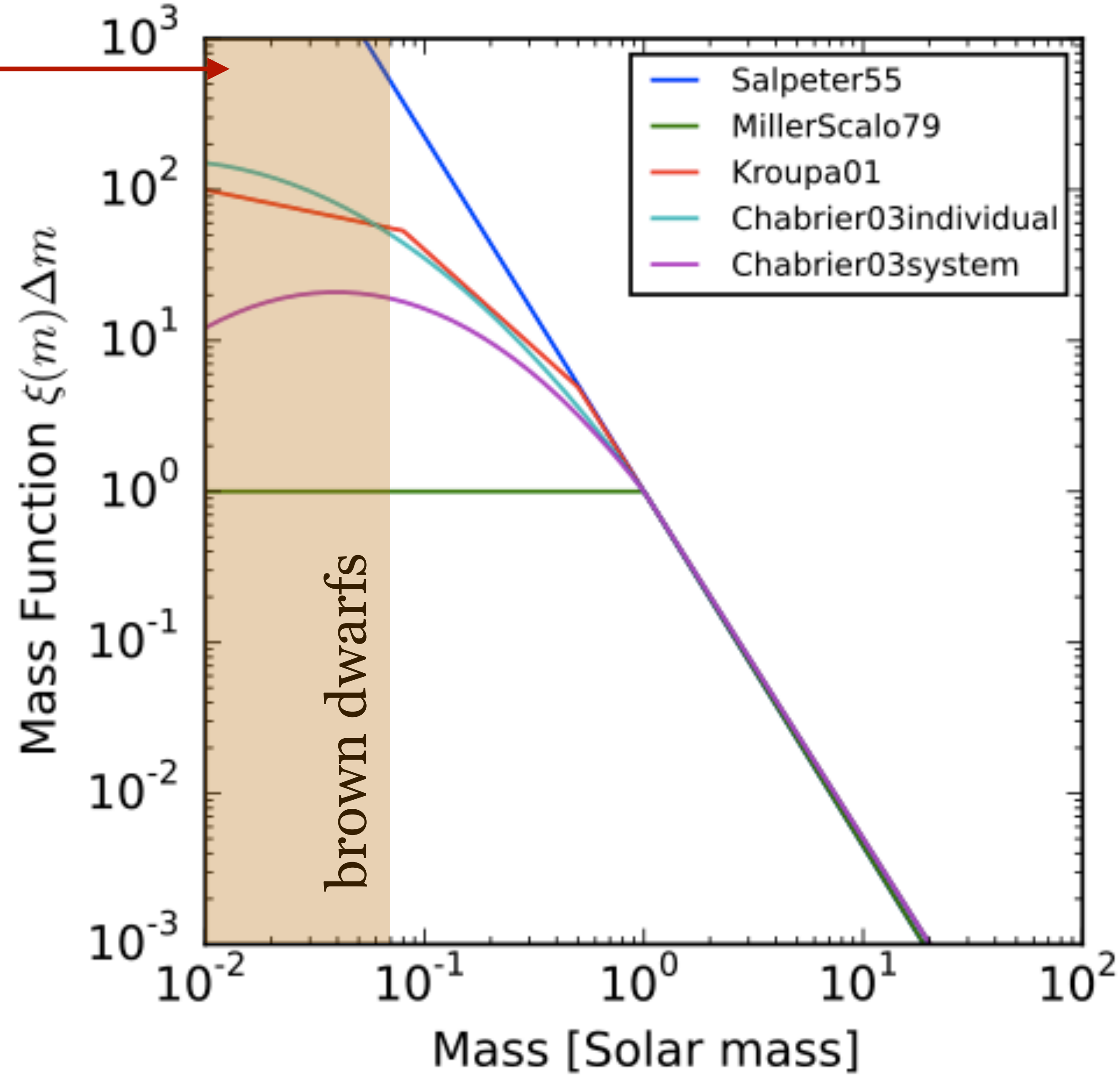
e.g.,

- brown dwarfs
- white dwarfs
- neutron stars
- black holes
- planets
- very faint stars
- strange nuggets
- macros



Initial Mass Function

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



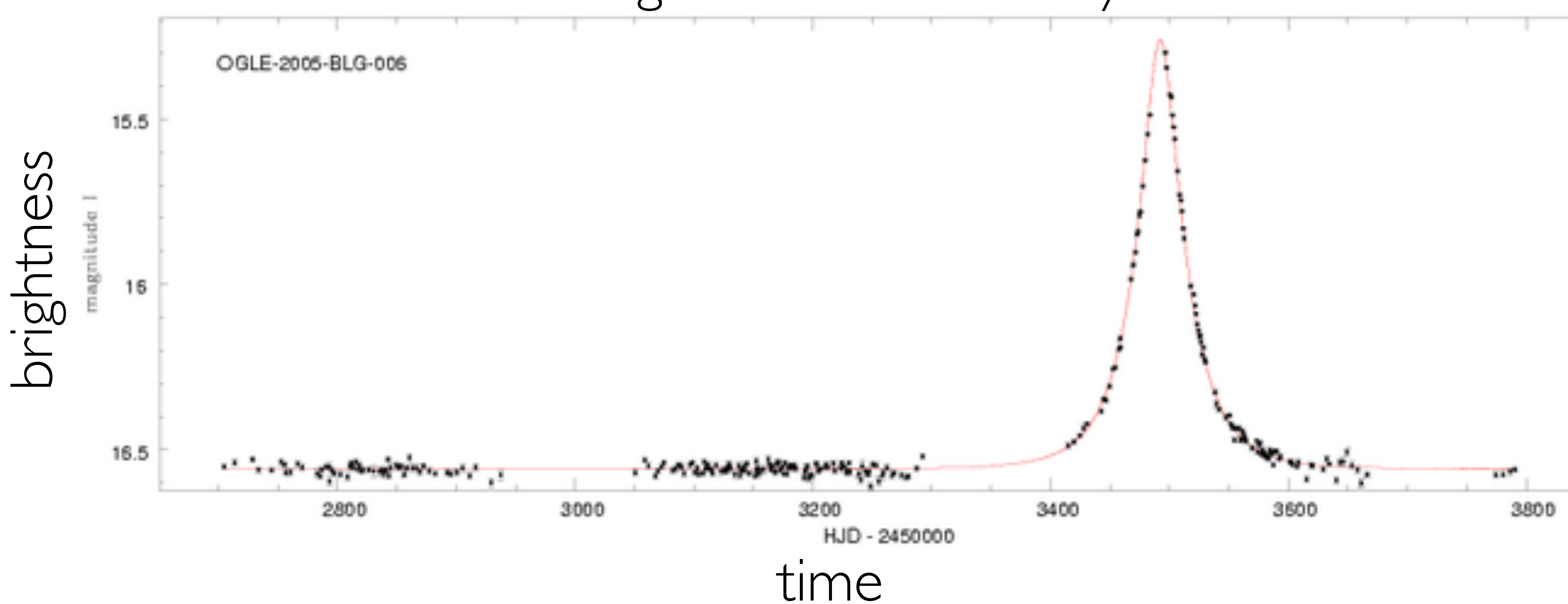
$M_{BD} < 0.07\ M_\odot$

brown dwarfs are failed stars below the hydrogen burning limit

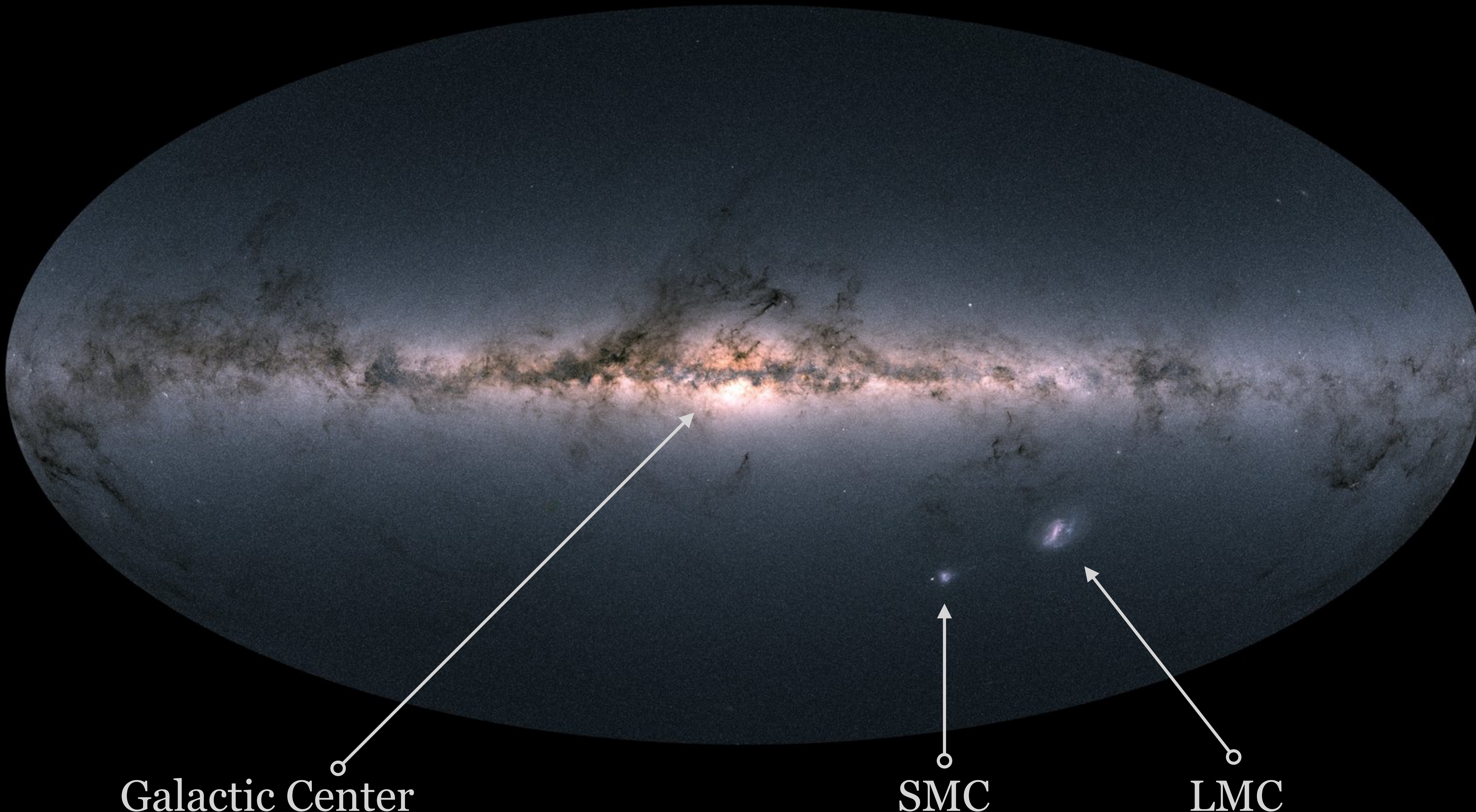
Microlensing surveys:
MACHO, EROS, OGLE

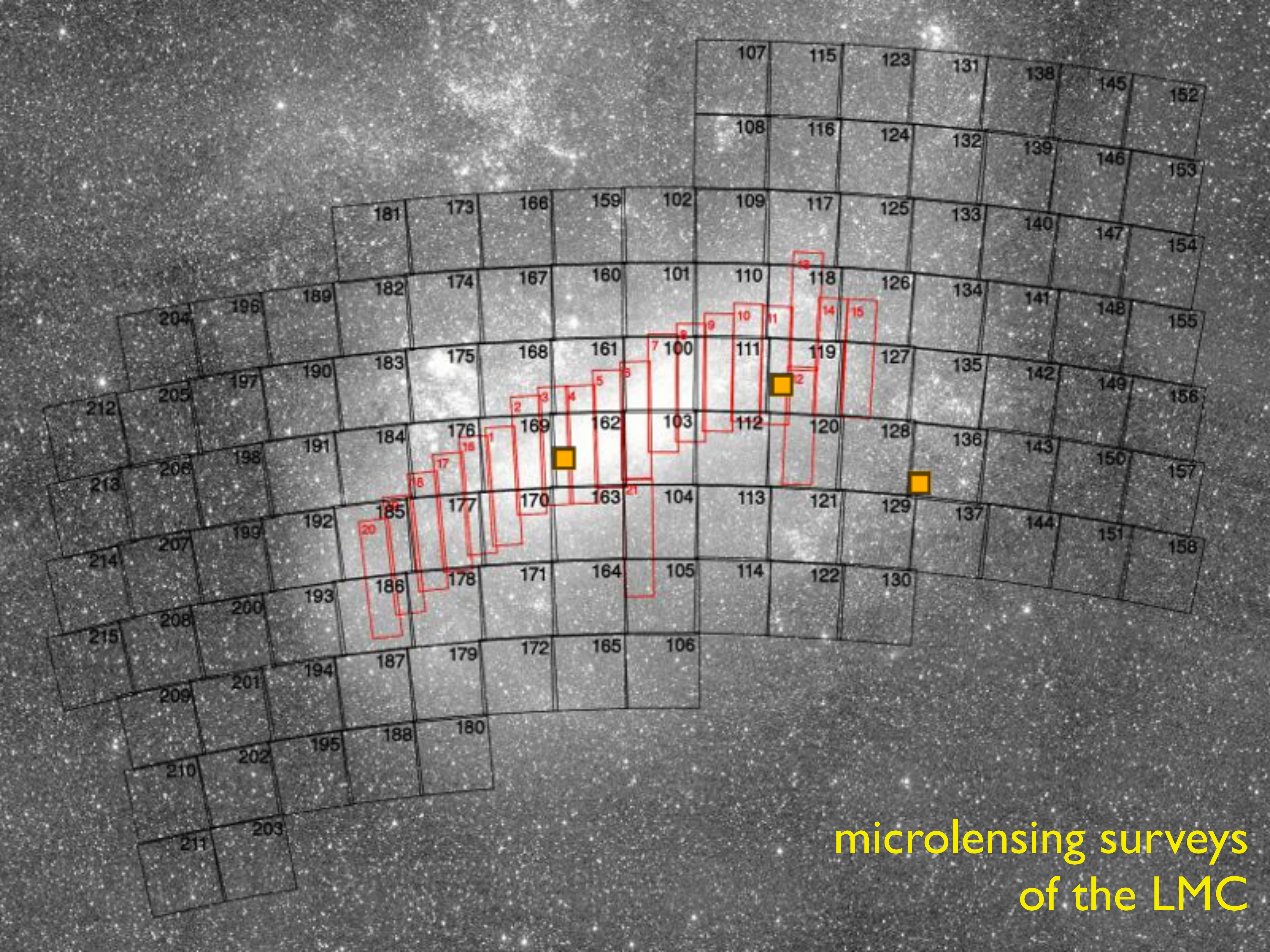
Monitor regions of dense star fields: LMC/SMC/Galactic Center
Watch for microlensing events due to intervening masses
- Sensitive to brown dwarfs & stellar mass objects,
  - including neutron stars and black holes.
- Don't detect the object itself, but the light bending effect it causes on background stars

microlensing event observed by OGLE



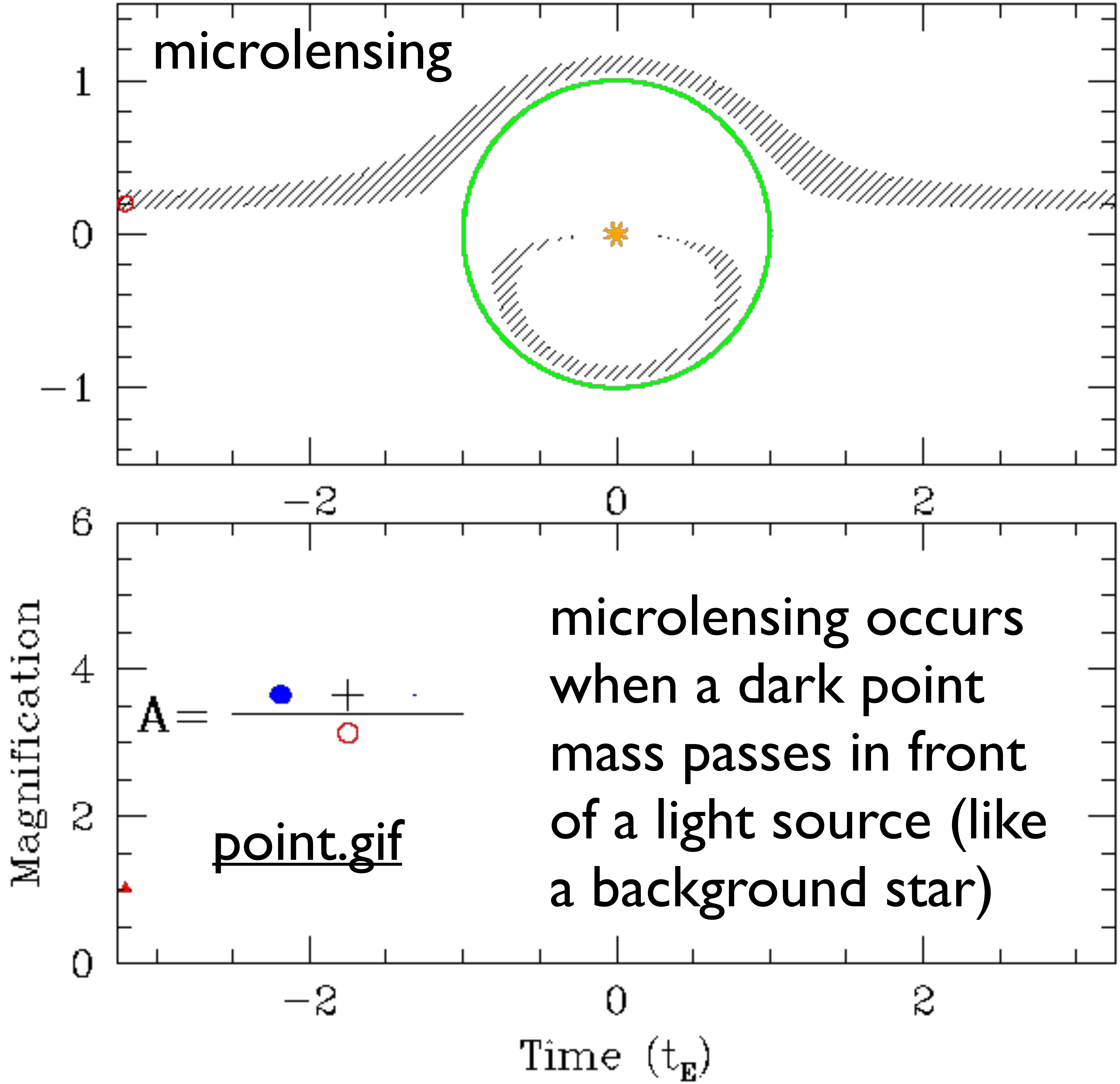
Milky Way in the optical (all sky Gaia data)



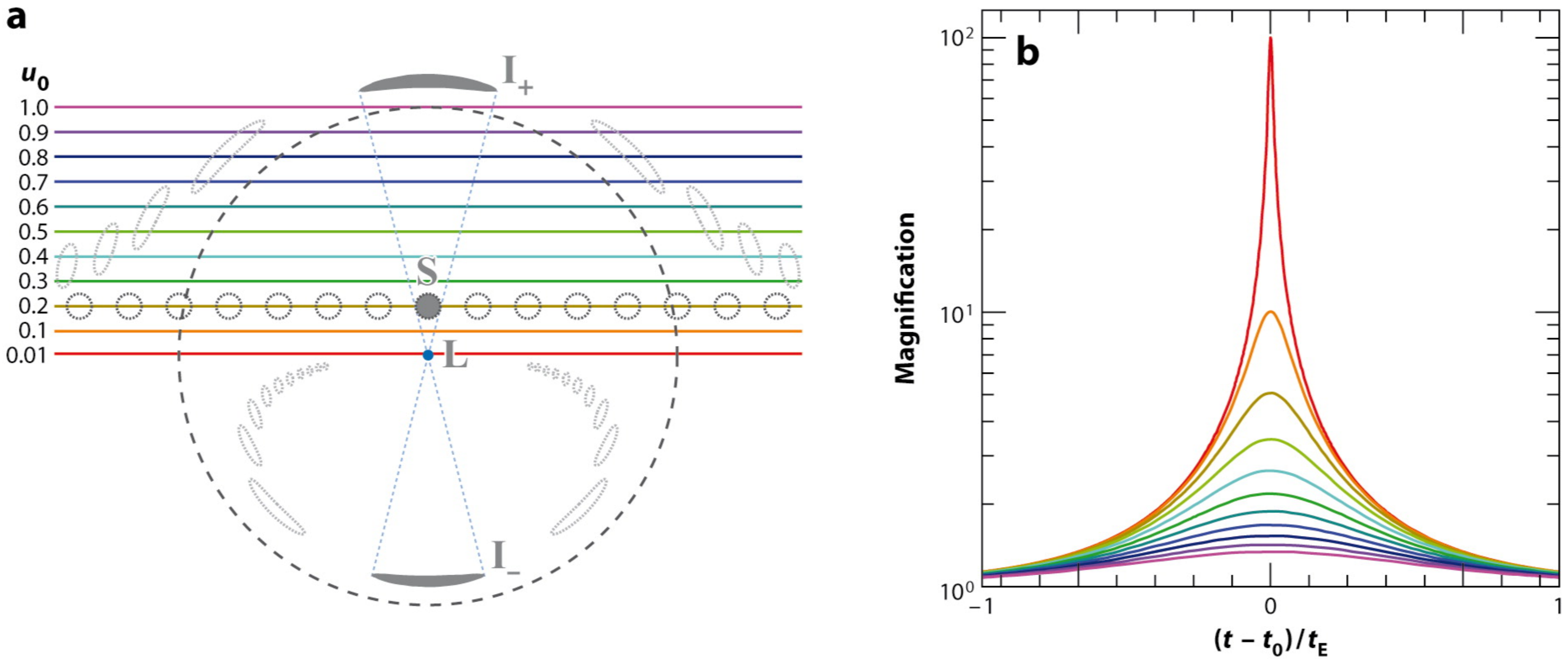


microlensing surveys
of the LMC

SMALL SCALES

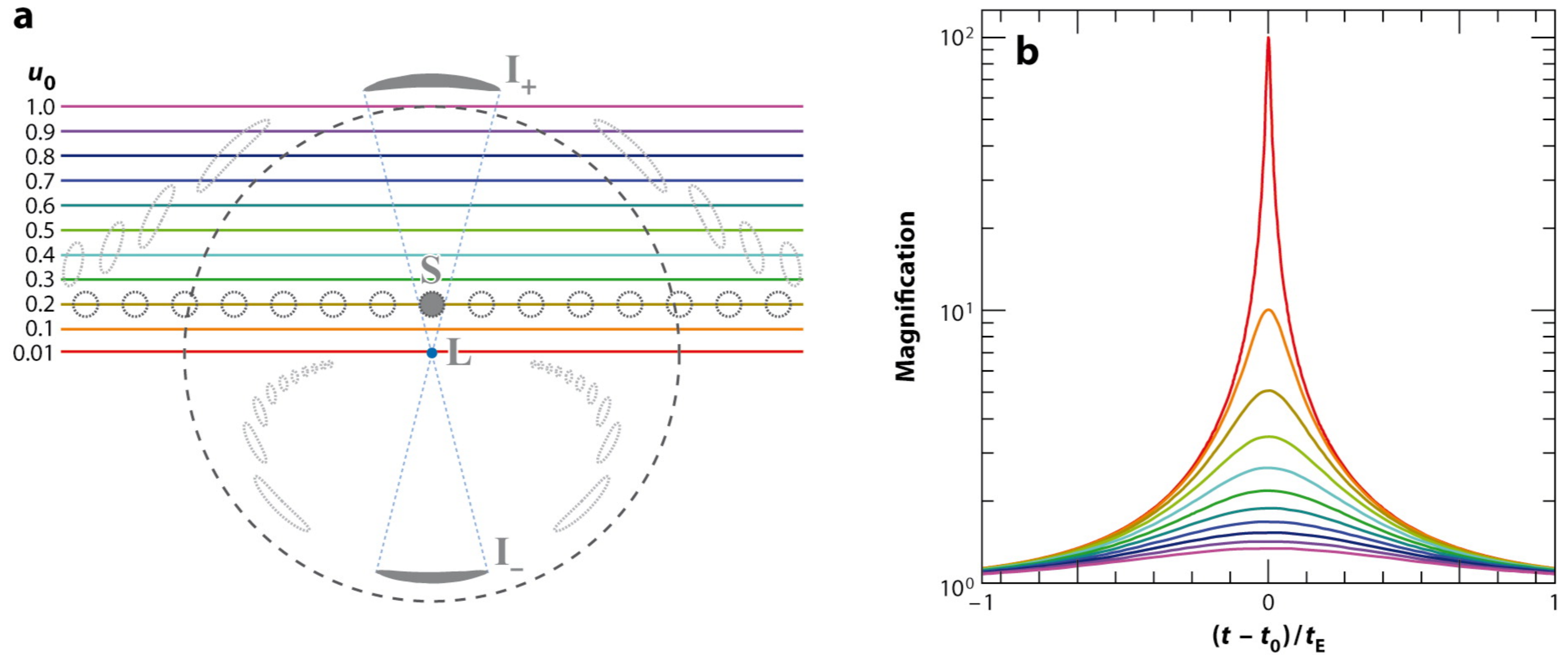


microlensing occurs when a dark point mass passes in front of a light source (like a background star)



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

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

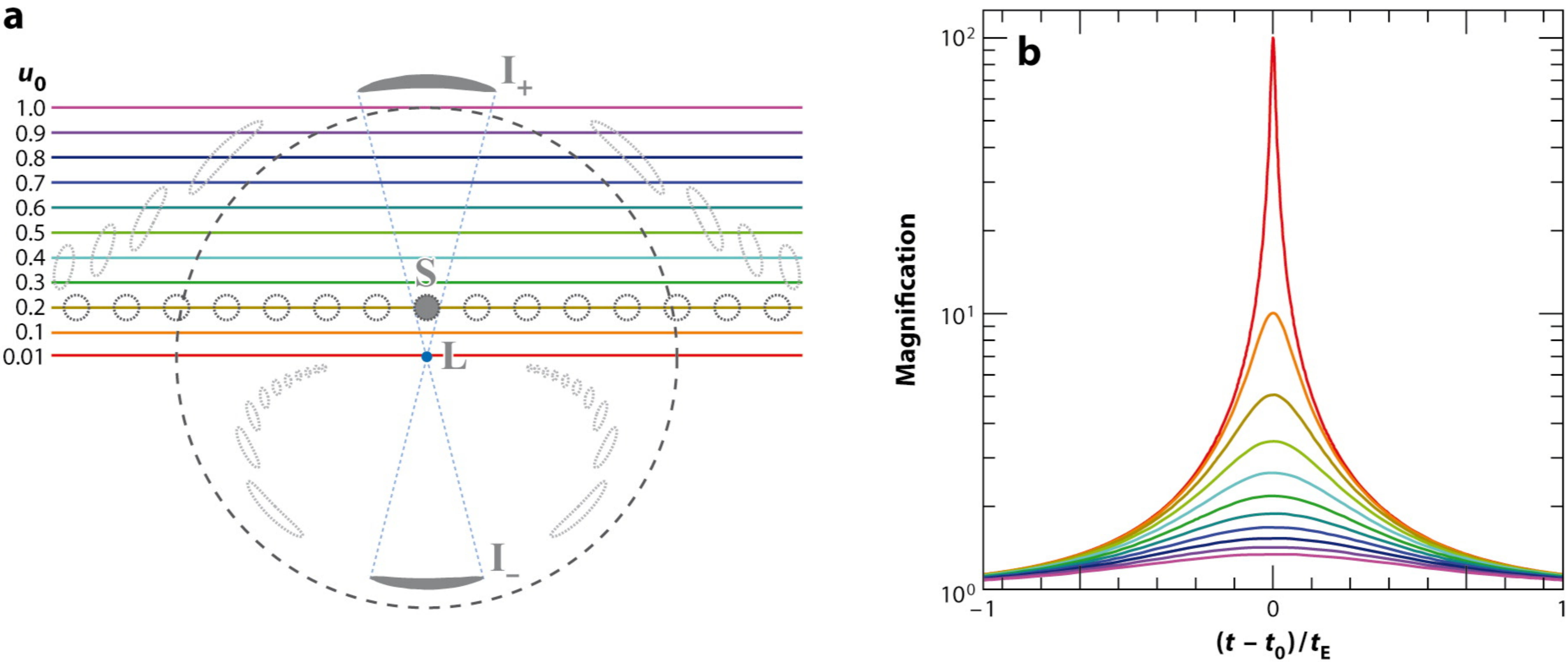


Gaudi BS. 2012.
Annu. Rev. Astron. Astrophys. 50:411–53

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

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

$M = 0.06\ \mathrm{M}_\odot$ $D_L = D_{LS} = 25$ kpc



Lensing optical depth:

$$\tau = \frac{4\pi G}{c^2} D_S^2 \int_0^{D_S} \rho(x) x(1-x) dx \quad \text{where} \quad x = \frac{D_L}{D_S} \quad \text{for density of lenses} \quad \rho(x)$$

for constant density

$$\tau = \frac{2\pi G \rho}{3c^2} D_S^2$$

for Milky Way dark matter halo

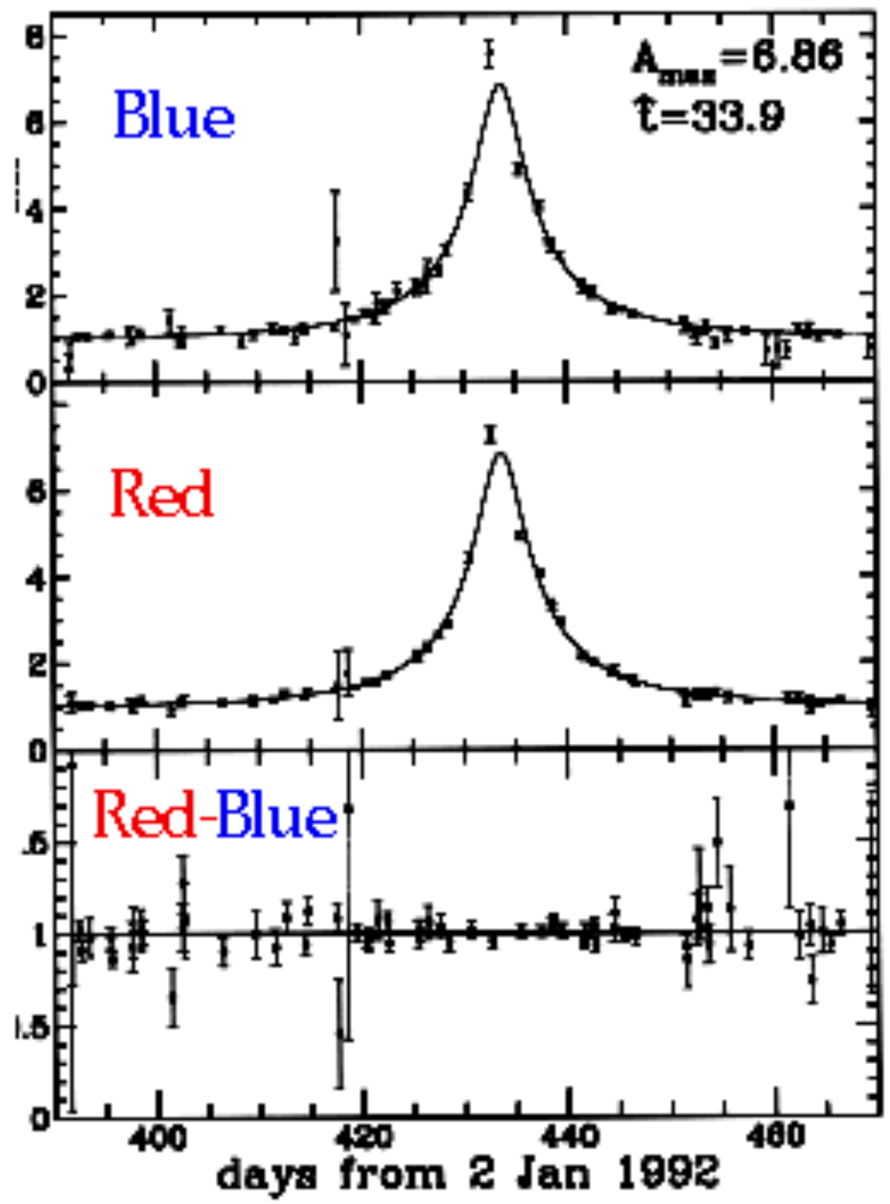
$$\tau = 2\pi \left(\frac{\sigma}{c}\right)^2 \frac{D_L D_{LS}}{R_0 D_S}$$

to the LMC

$$D_L \approx D_{LS} \approx D_S/2$$

$$D_S = 50 \text{ kpc}$$

microlensing events achromatic



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

Number of microlensing events

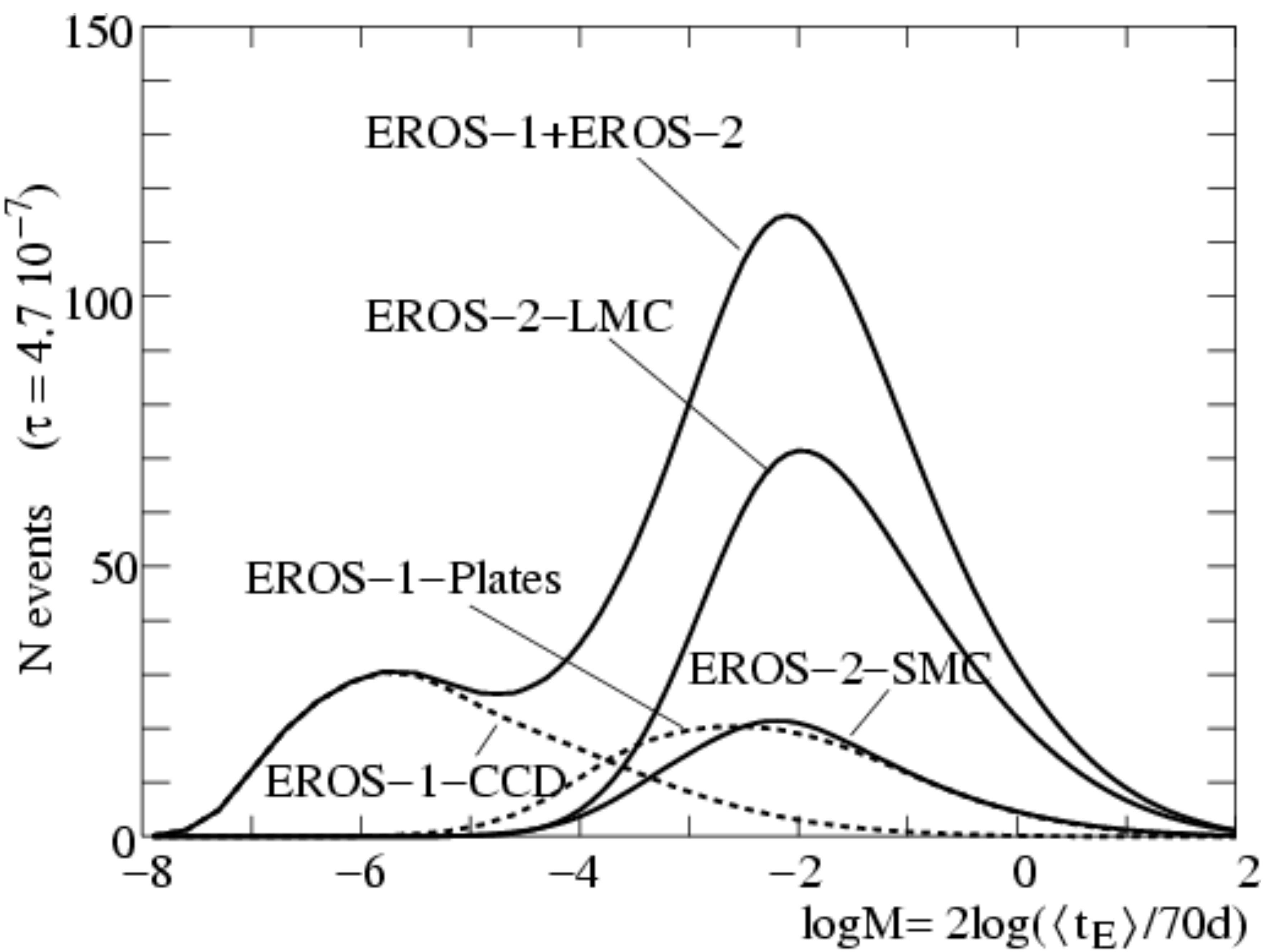
$$N(>A) = \frac{2\tau}{(A^2-1) + A\sqrt{A^2-1}}$$

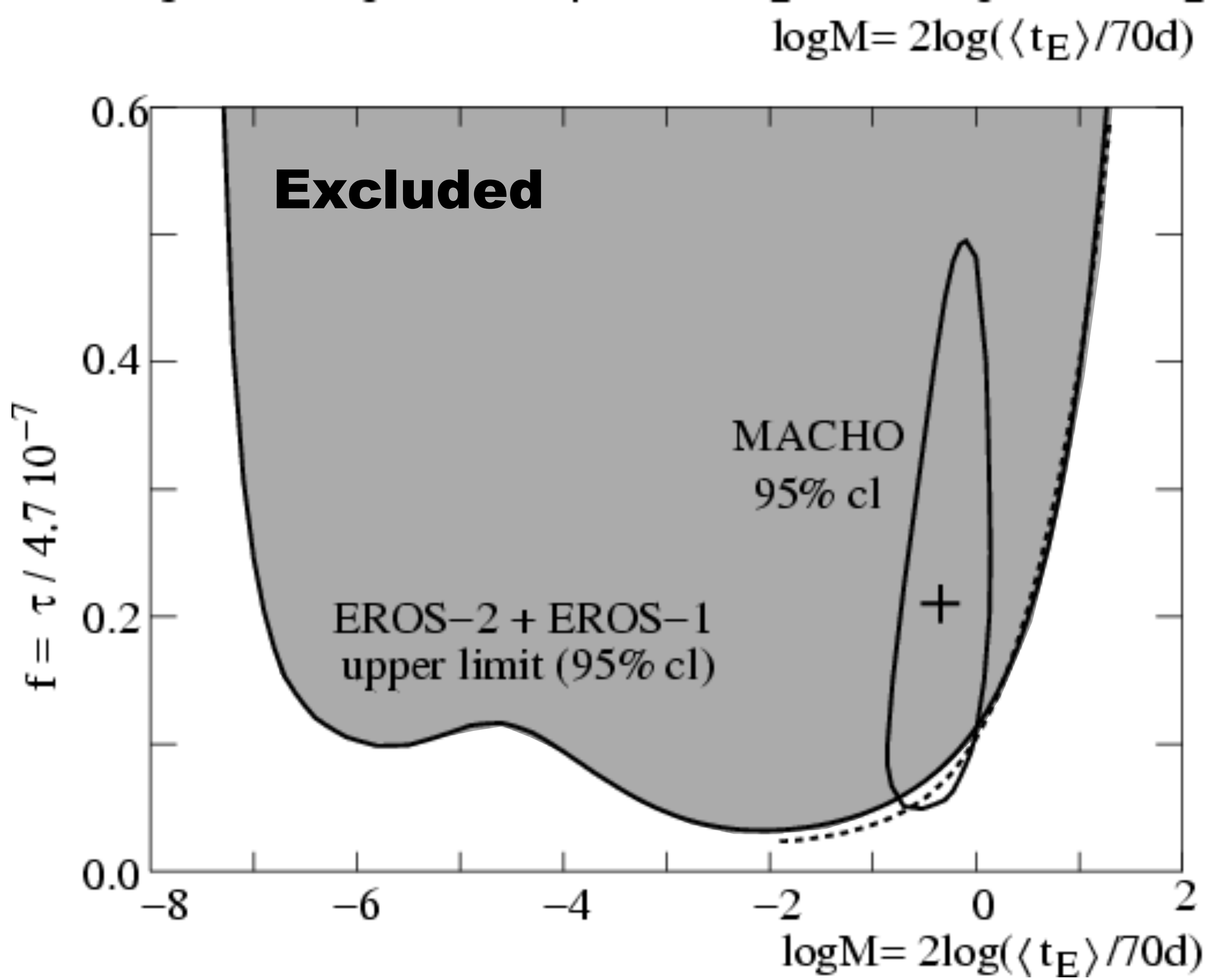
optical depth as a fcn of radius through an isothermal sphere

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

optical depth = fraction of the sky covered by Einstein rings

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

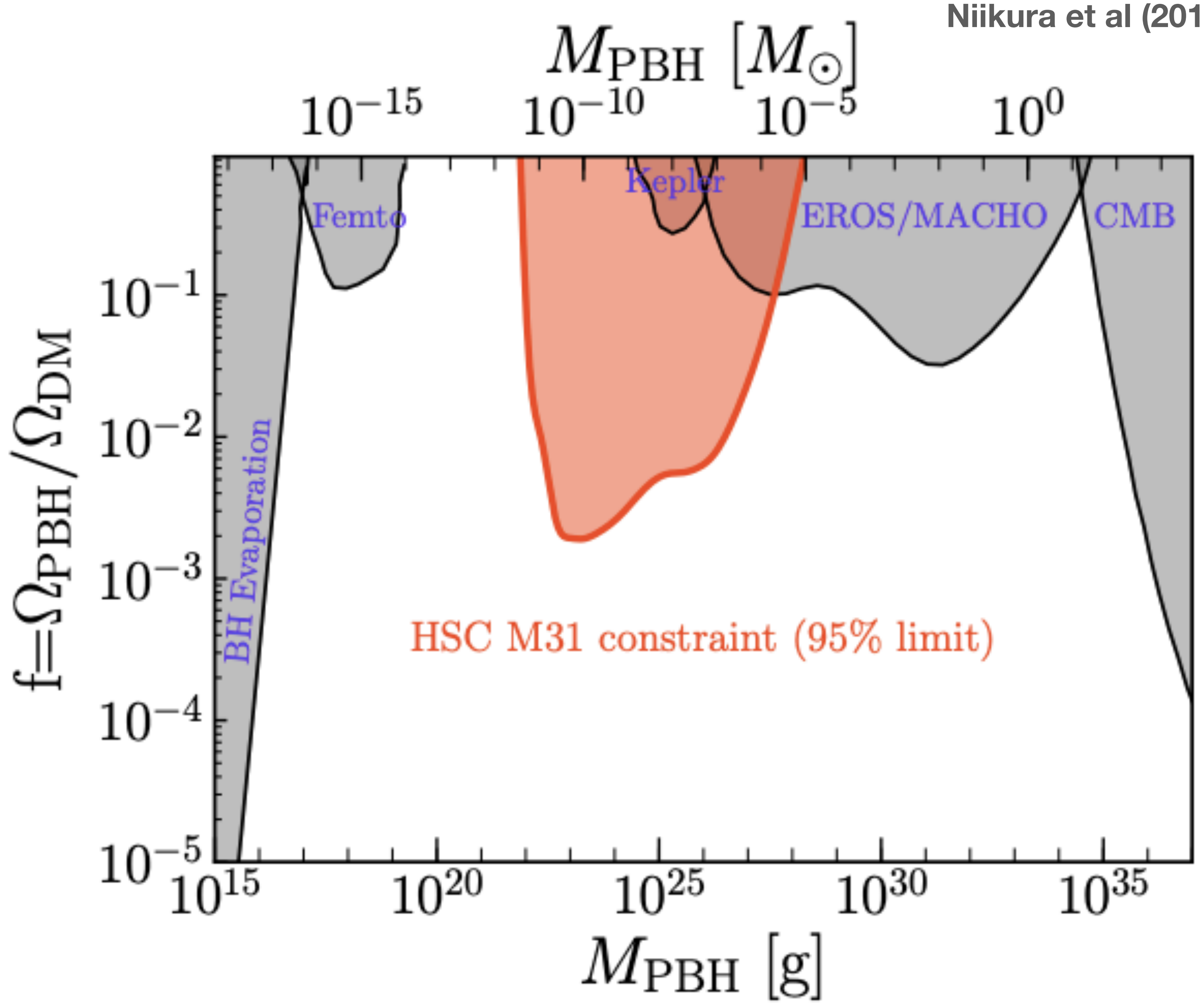




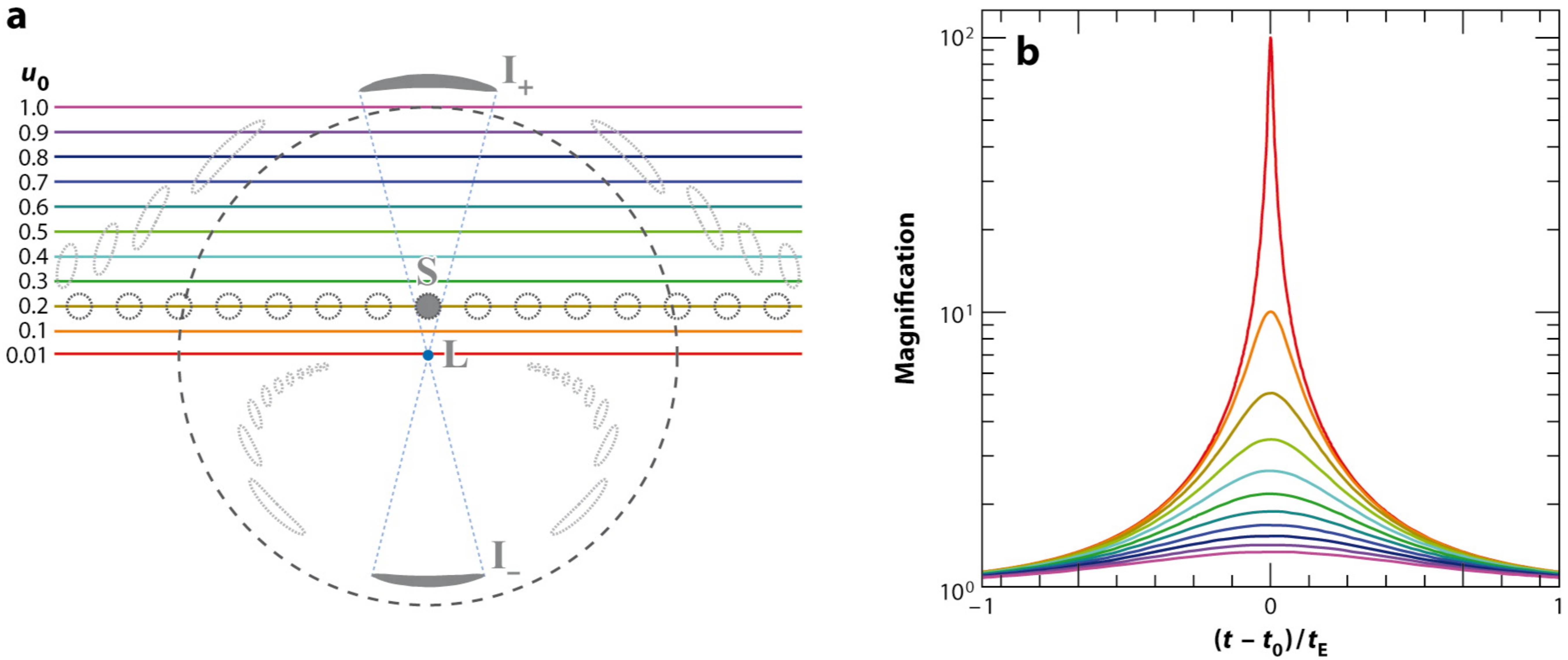
The observed rate of microlensing events leaves no room for the dark matter halo of the Milky Way to be composed of massive compact objects like brown dwarfs or black holes in the mass range $10^{-7} < M < 10$ solar masses.

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 <~ 10−7M , and give no constraint on PBH at M <~ 10−11M . Our constraint can be compared with other observational constraints as shown by the gray shaded regions: extragalactic γ-rays from PBH evaporation [32], femtolensing of γ-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].



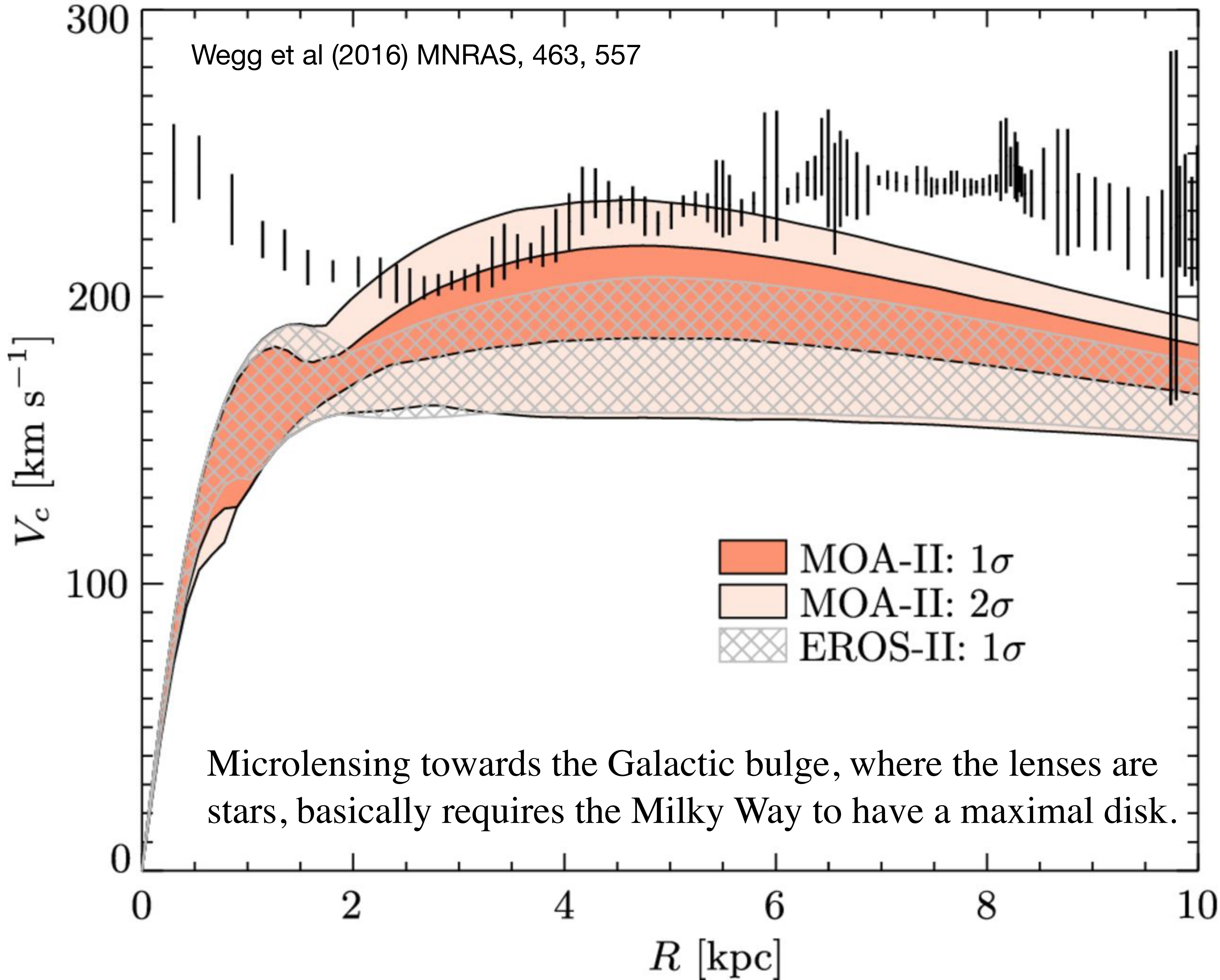
Microlensing towards Galactic Center

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

lens mass — *parallax* — *proper motion*

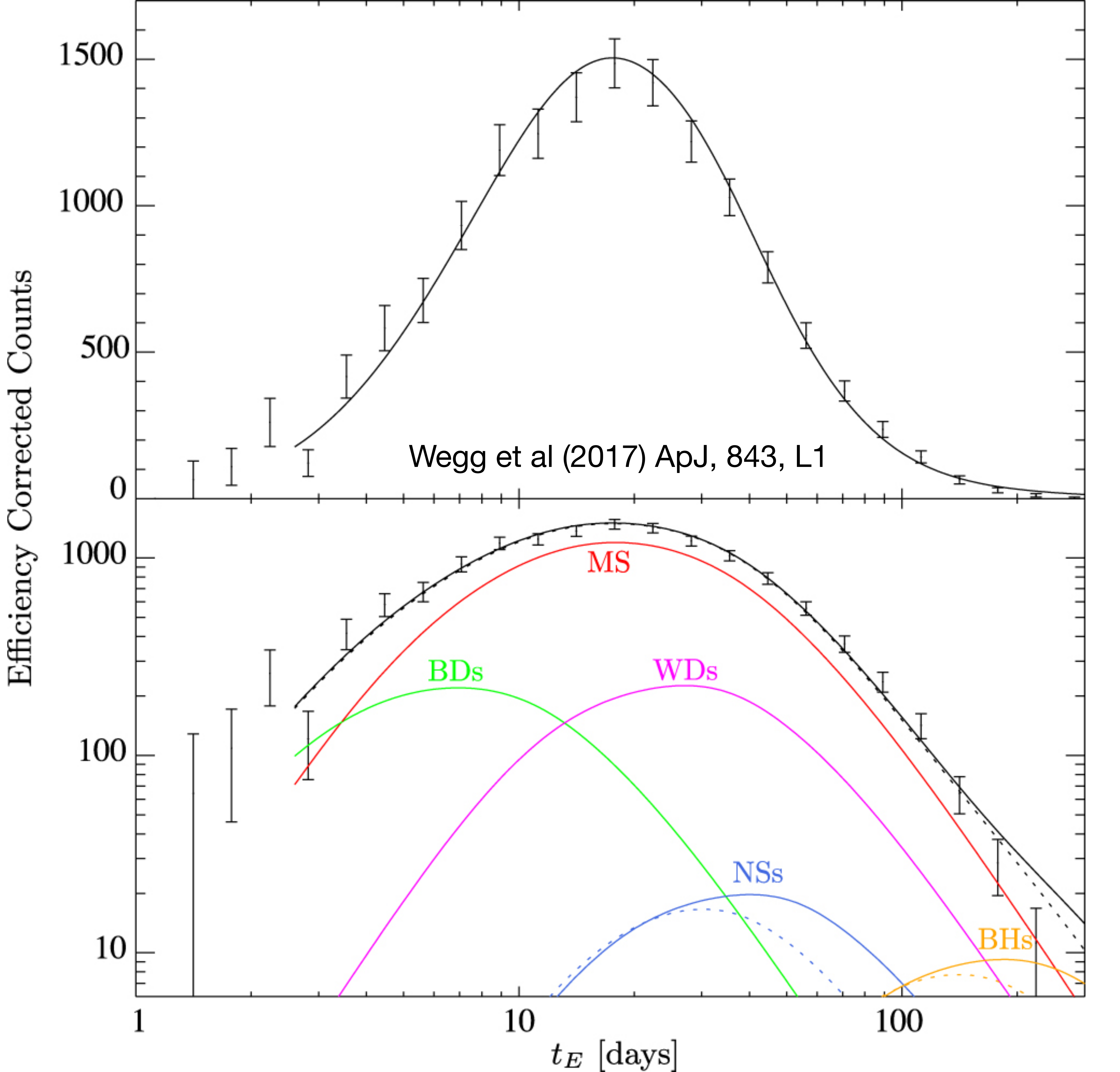
$$t_E \approx (24.8\ \text{days}) \left(\frac{M}{0.5\ \mathrm{M}_\odot}\right)^{1/2} \left(\frac{\pi_{rel}}{125\ \mu\text{as}}\right)^{1/2} \left(\frac{\mu_{rel}}{10.5\ \text{mas}\,\text{yr}^{-1}}\right)^{-1}$$

for lensing events towards the Galactic bulge.



Wegg et al (2016) MNRAS, 463, 557
300
200
100
0
V_c [km s^{-1}]
0
2
4
6
8
10
R [kpc]
MOA-II: 1σ
MOA-II: 2σ
EROS-II: 1σ
Microlensing towards the Galactic bulge, where the lenses are stars, basically requires the Milky Way to have a maximal disk.

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:

$$10^{-7} < M_{\mathrm{MACHO}} < 10\ \mathrm{M}_{\odot}$$

basically ruled out