Dark Matter

ASTR 333/433
Spring 2024
TR 11:30am–12:45pm
Sears 552

http://astroweb.case.edu/ssm/ASTR333/

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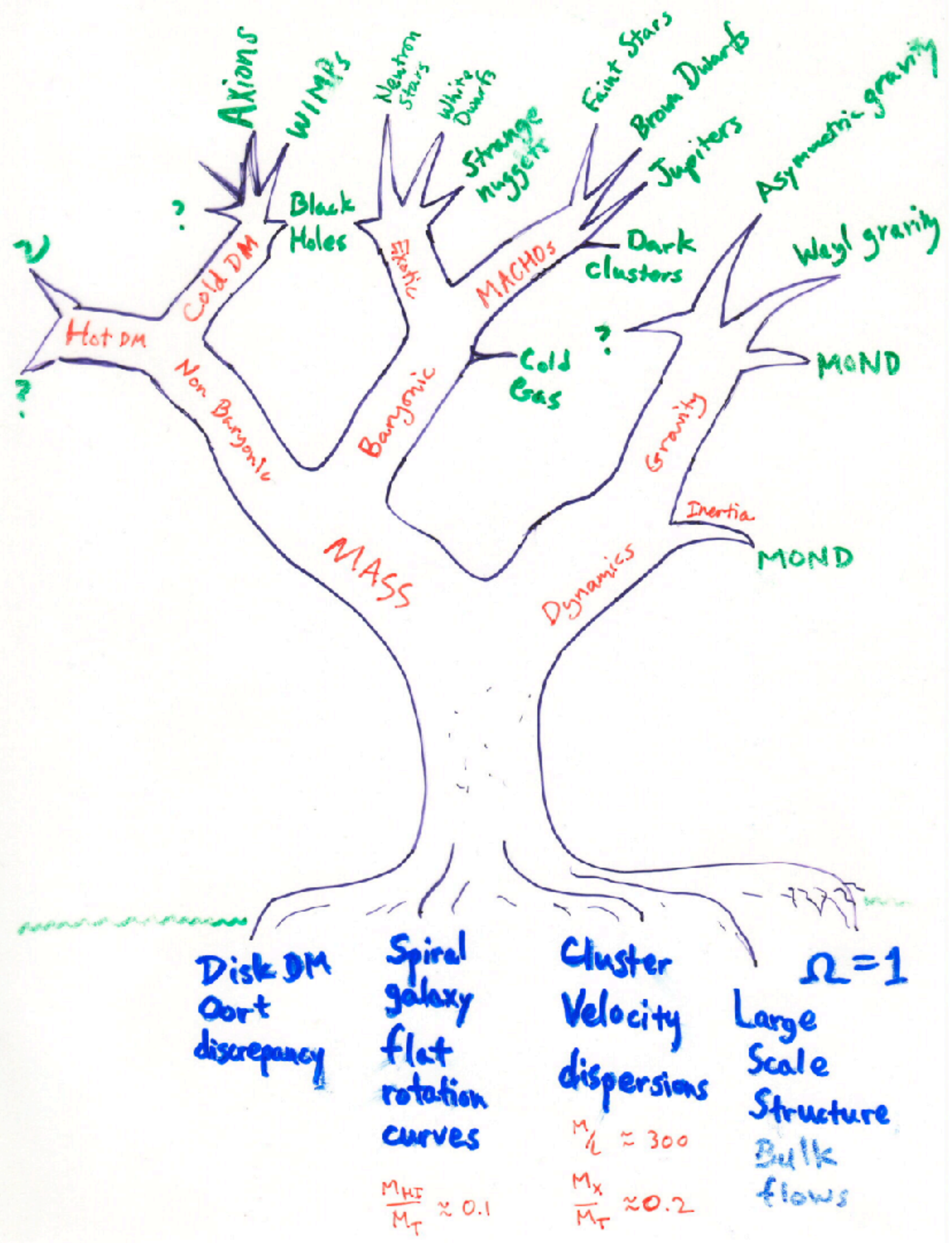


Gravitational Lensing

Flavors of gravitational lensing:

— weak lensing
mild distortion of lensed image

— strong lensing
multiple images, strong distortion

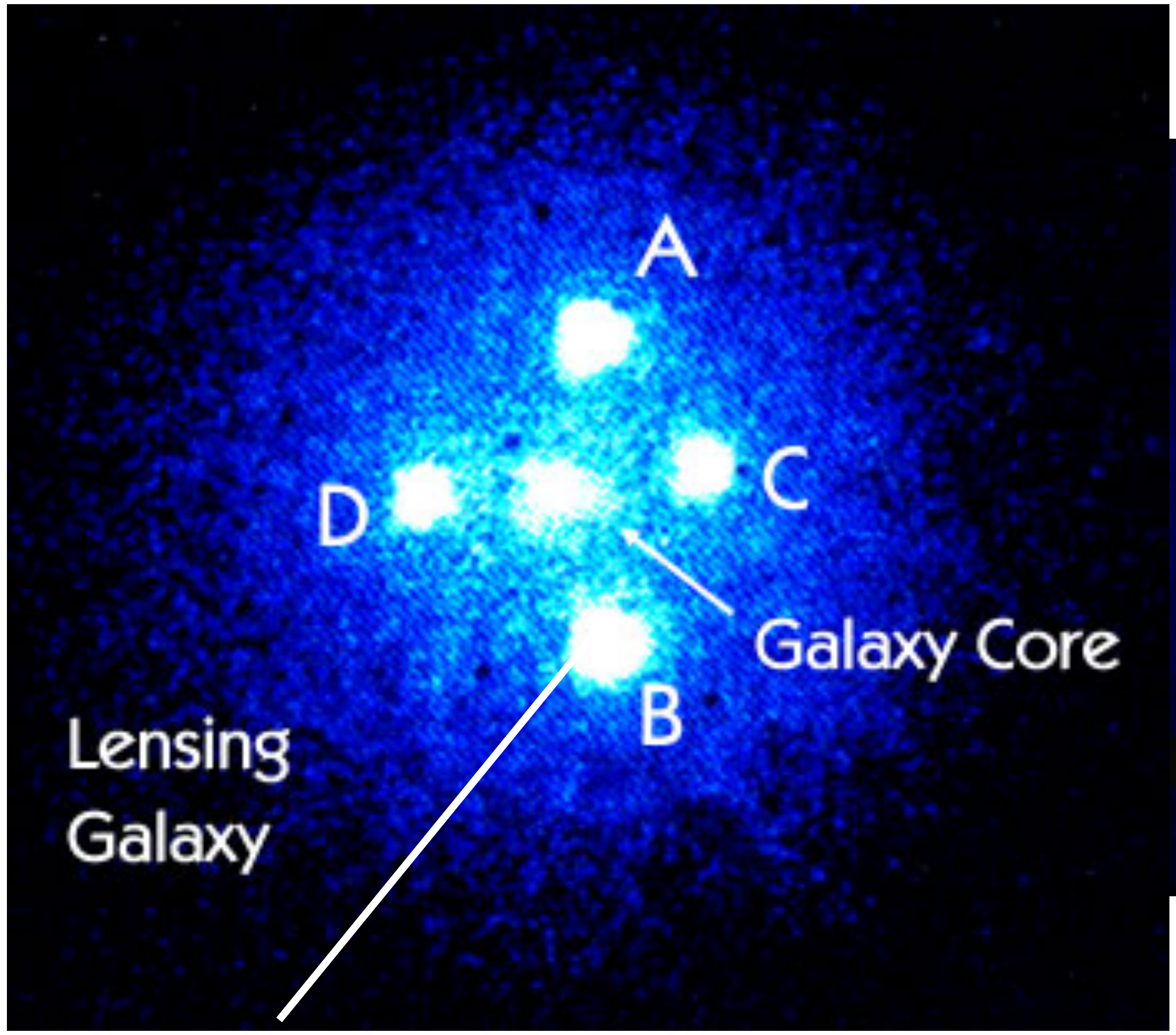
} separated by the critical surface density

$$\Sigma_{\rm crit} = \frac{c^2}{4\pi G}\frac{D_S}{D_L D_{LS}}$$

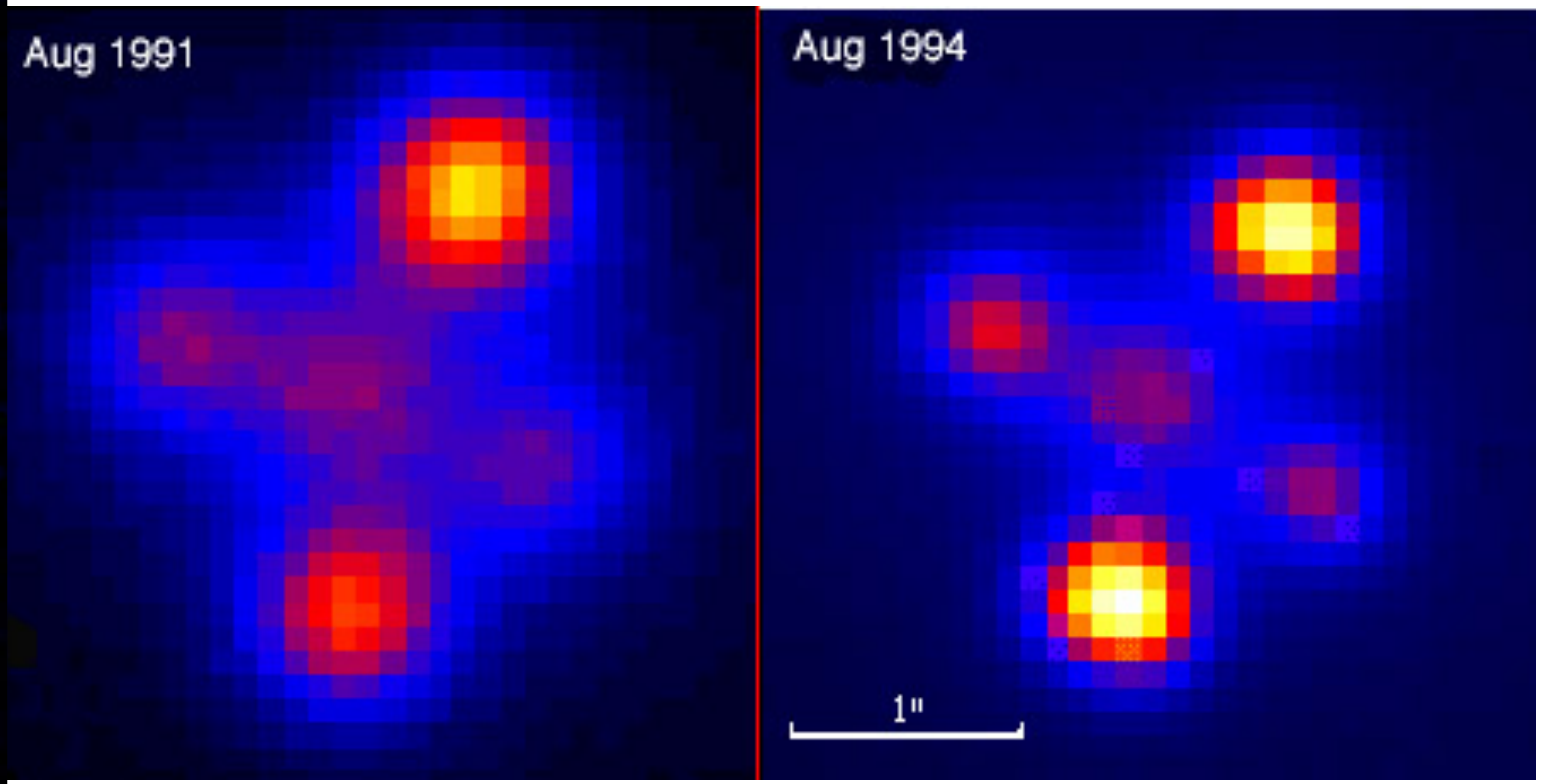
— microlensing
temporary brightening due to unresolved lensing

Multiple images from **strong lensing**

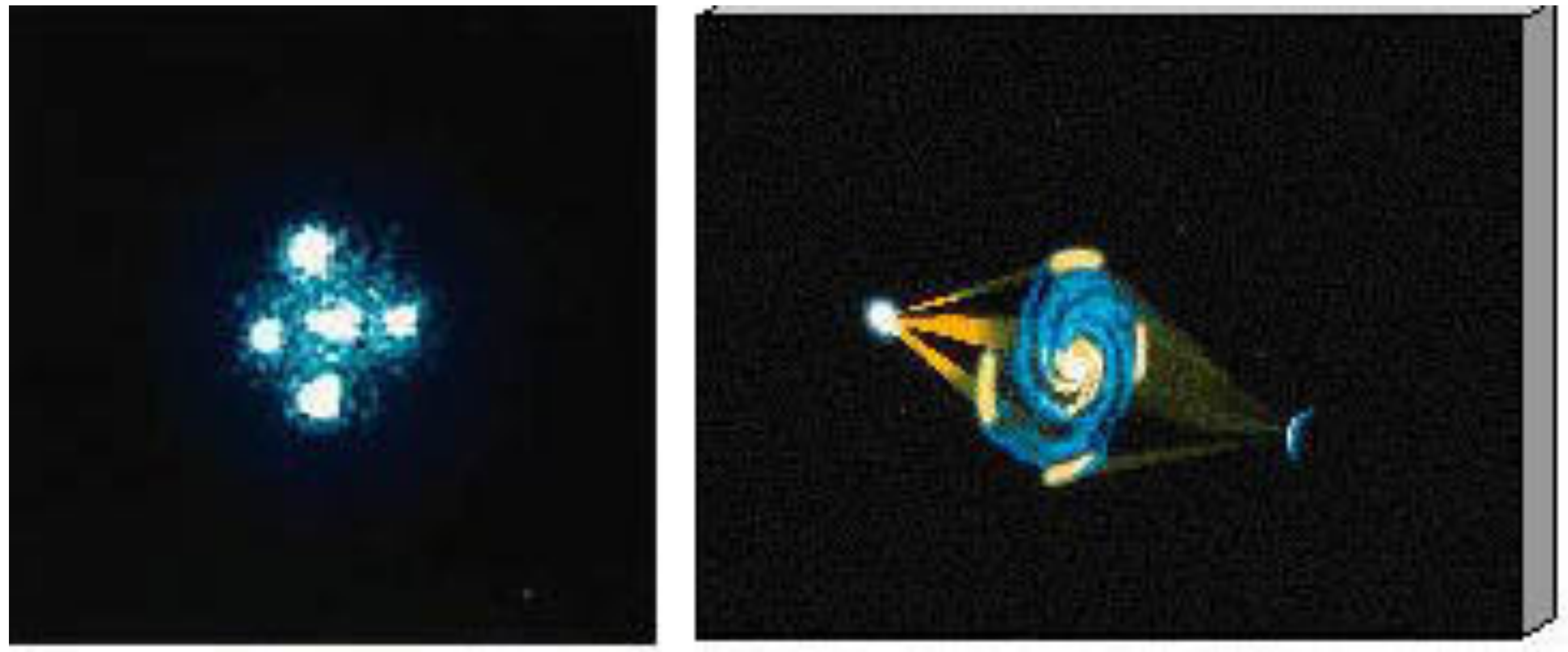
The Einstein Cross



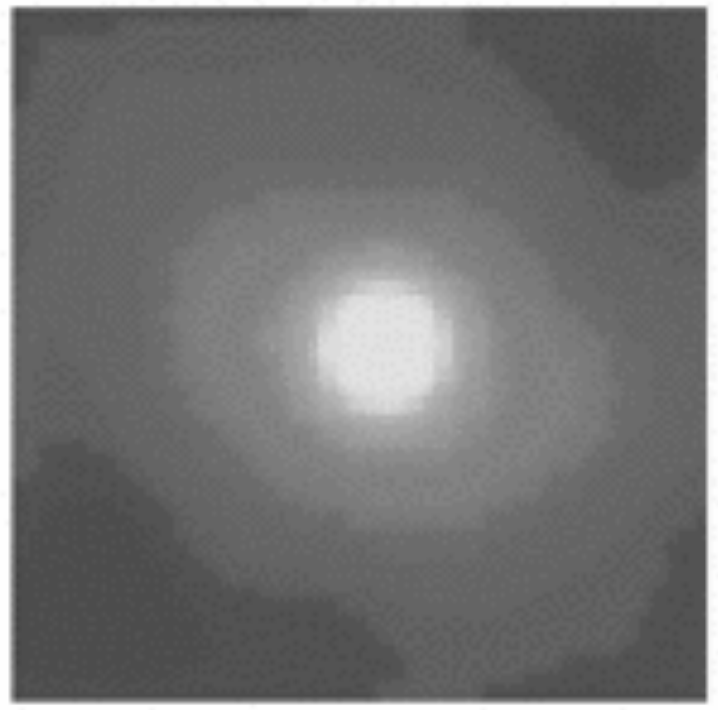
ABCD: same QSO seen 4 times



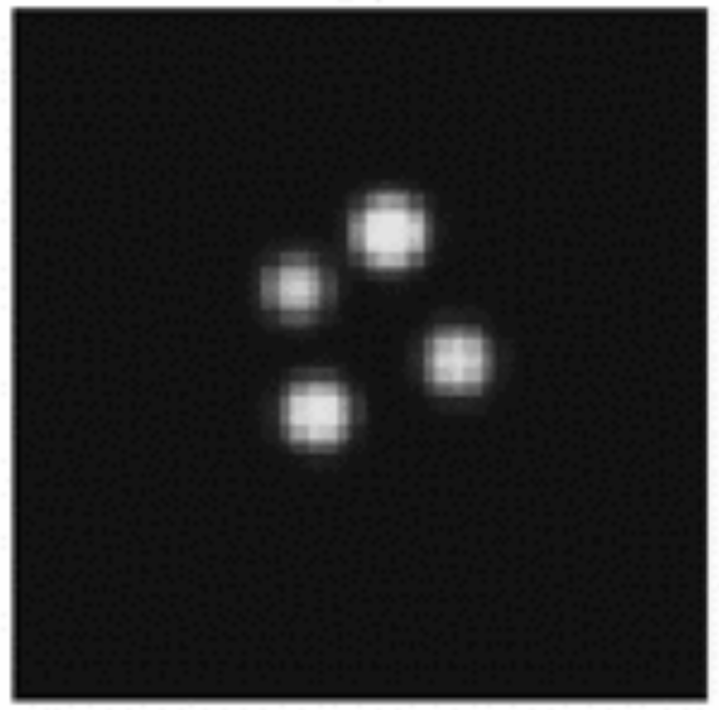
time variable multiple QSO image



(a) (b)



lensing galaxy



lensed QSO

Gravitational Lensing

θ_I observed angle between image and lens

θ_S true separation angle between image and lens

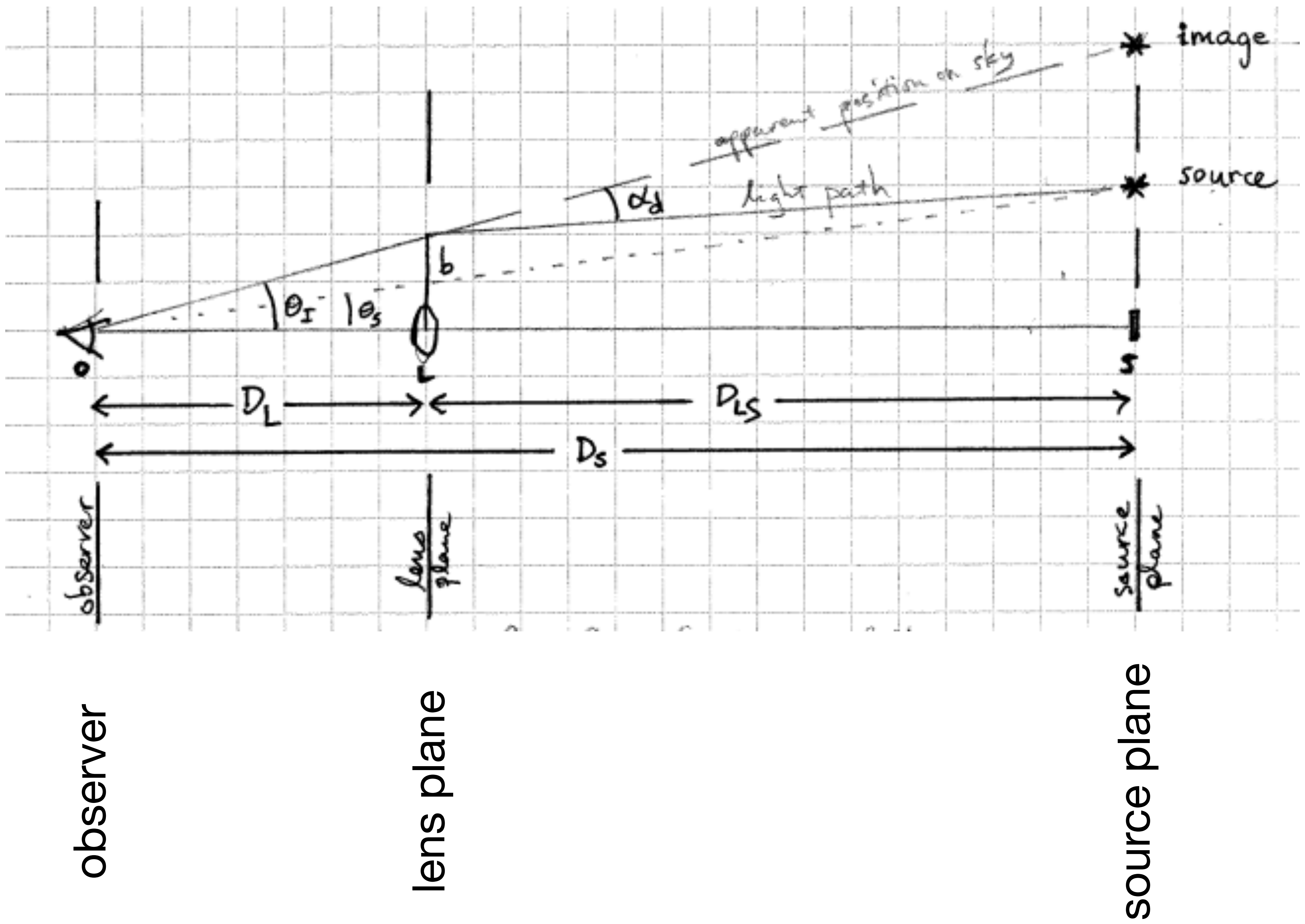
α_d bend angle

b impact parameter

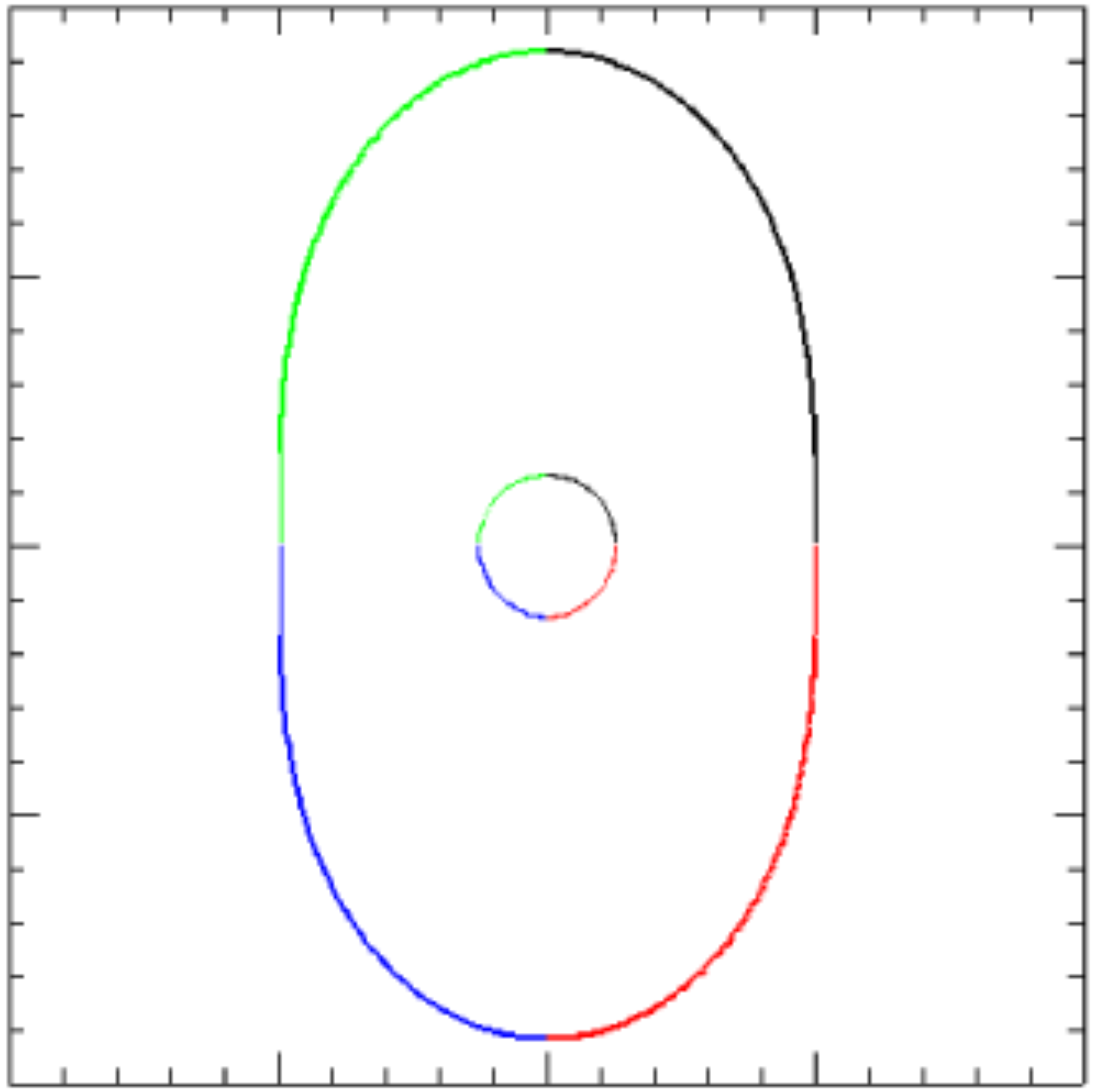
D_L lens distance

D_S source distance

D_{LS} lens-source separation



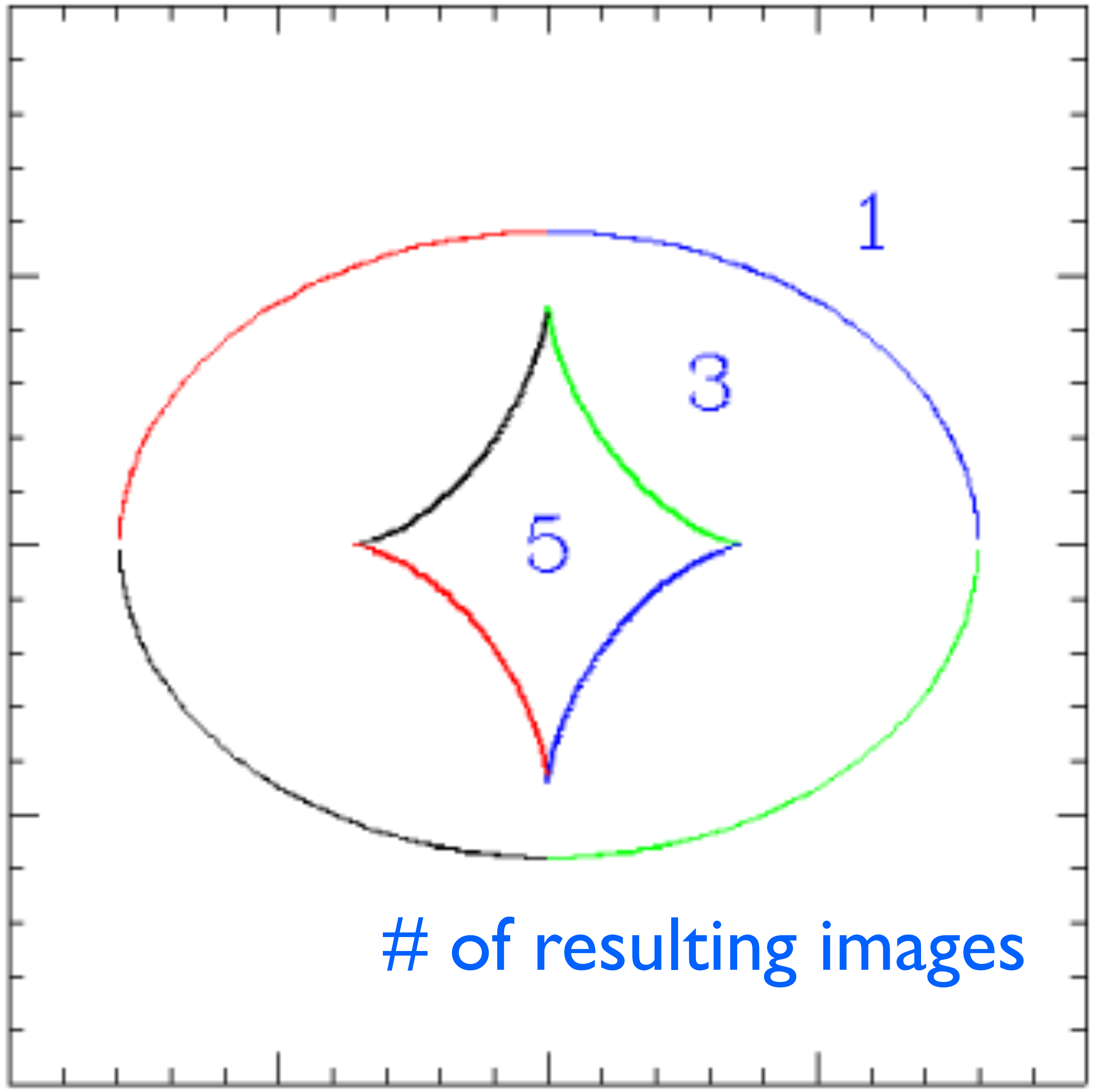
Lens plane



critical curves

Critical curves are the lines in the lens plane where the magnification diverges towards infinity.

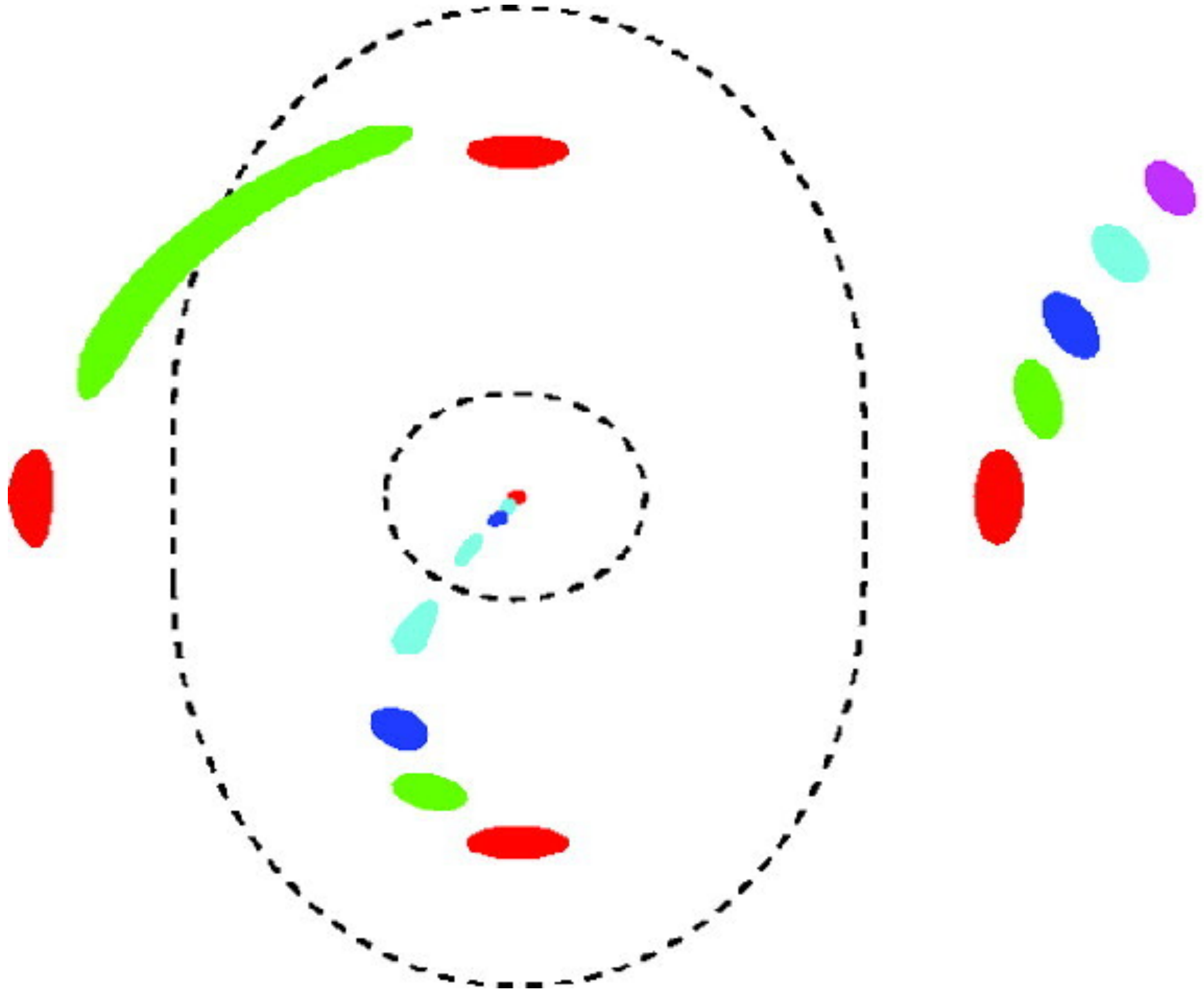
Source plane



caustics

Caustics are the corresponding lines in the source plane where the critical surface density Σ_{crit} is reached. Traced back from the observer, multiple light rays bunch up, causing high magnification.

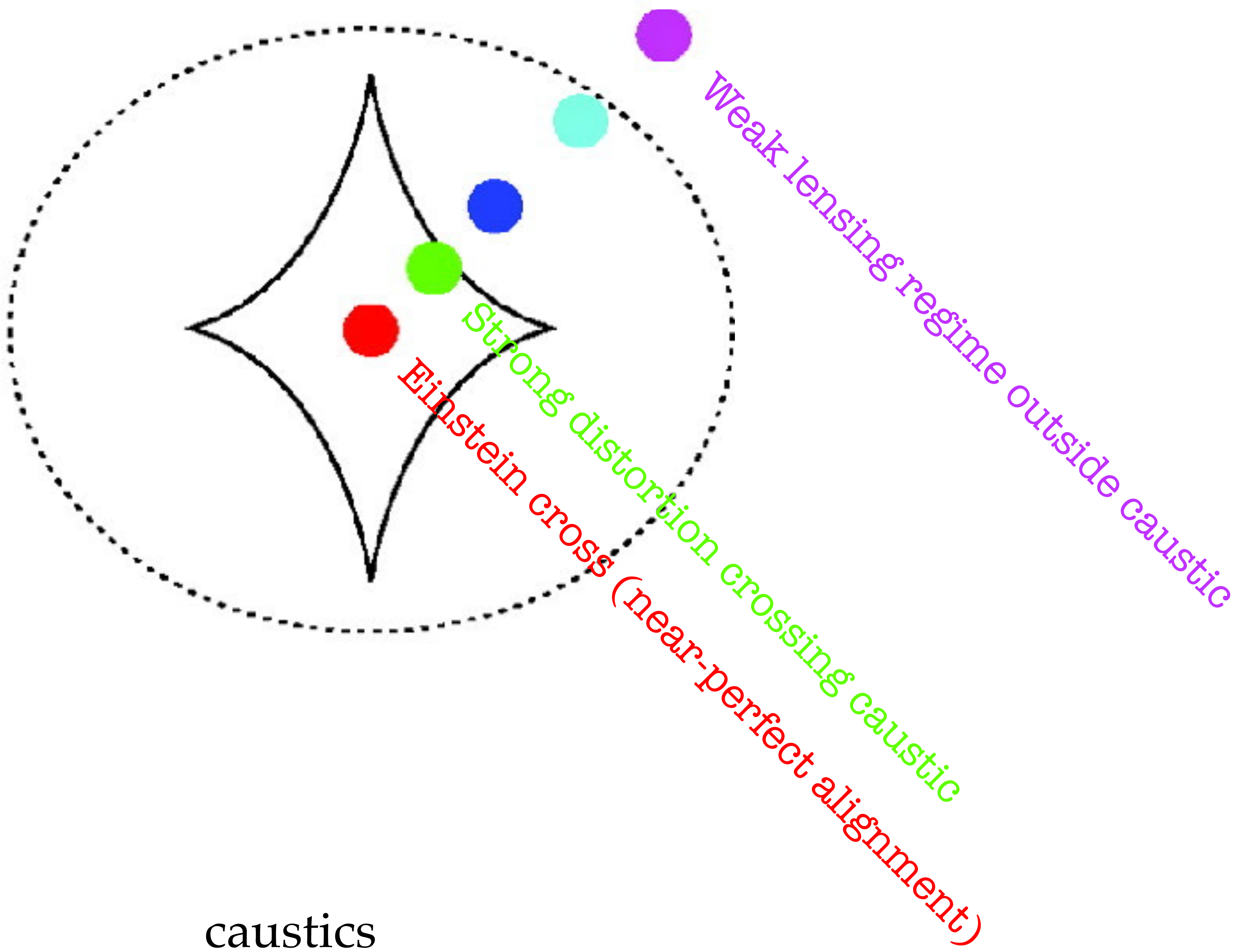
Lens plane



critical curves

Critical curves are the lines in the lens plane where the magnification diverges towards infinity.

Source plane



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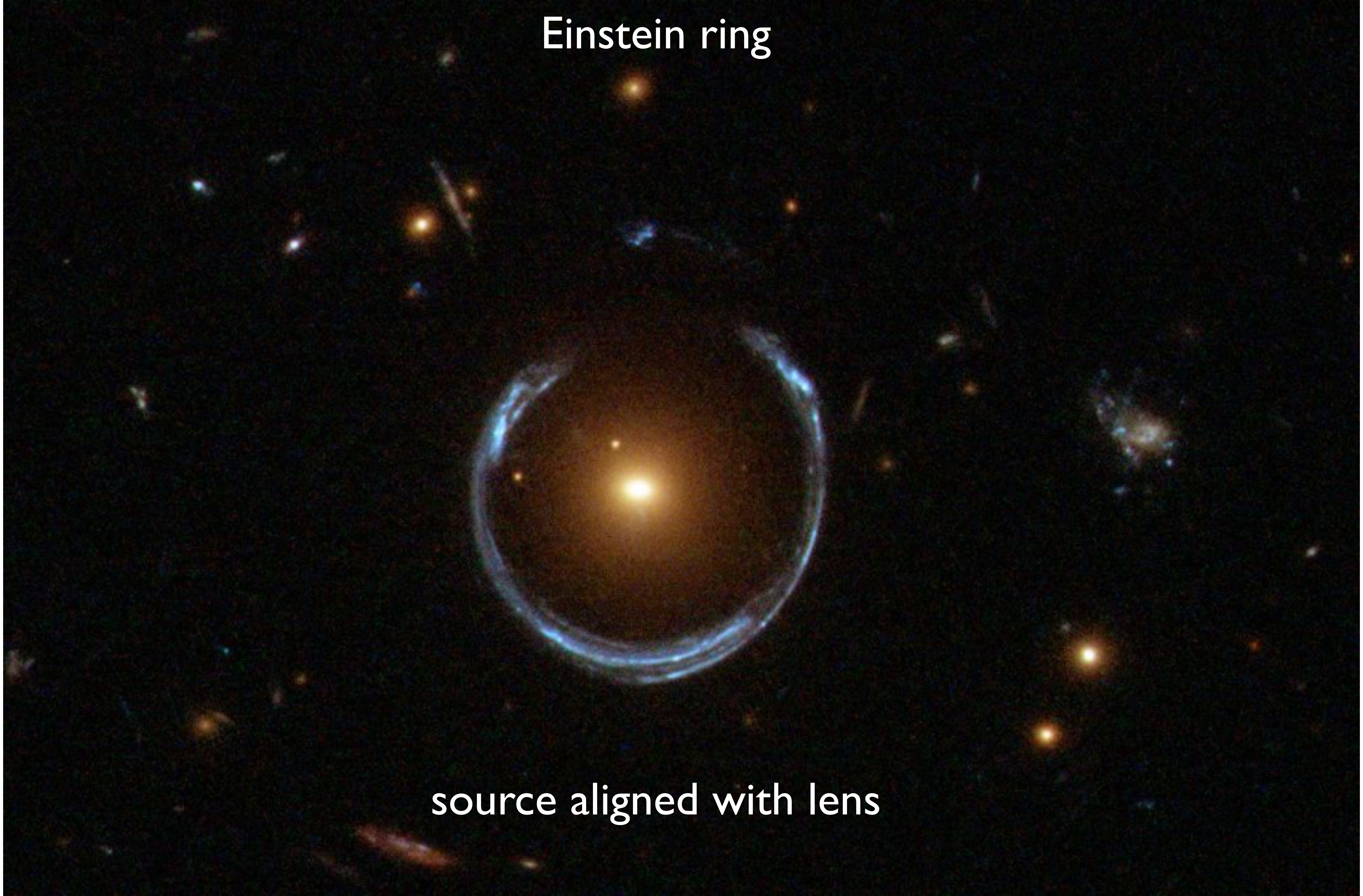
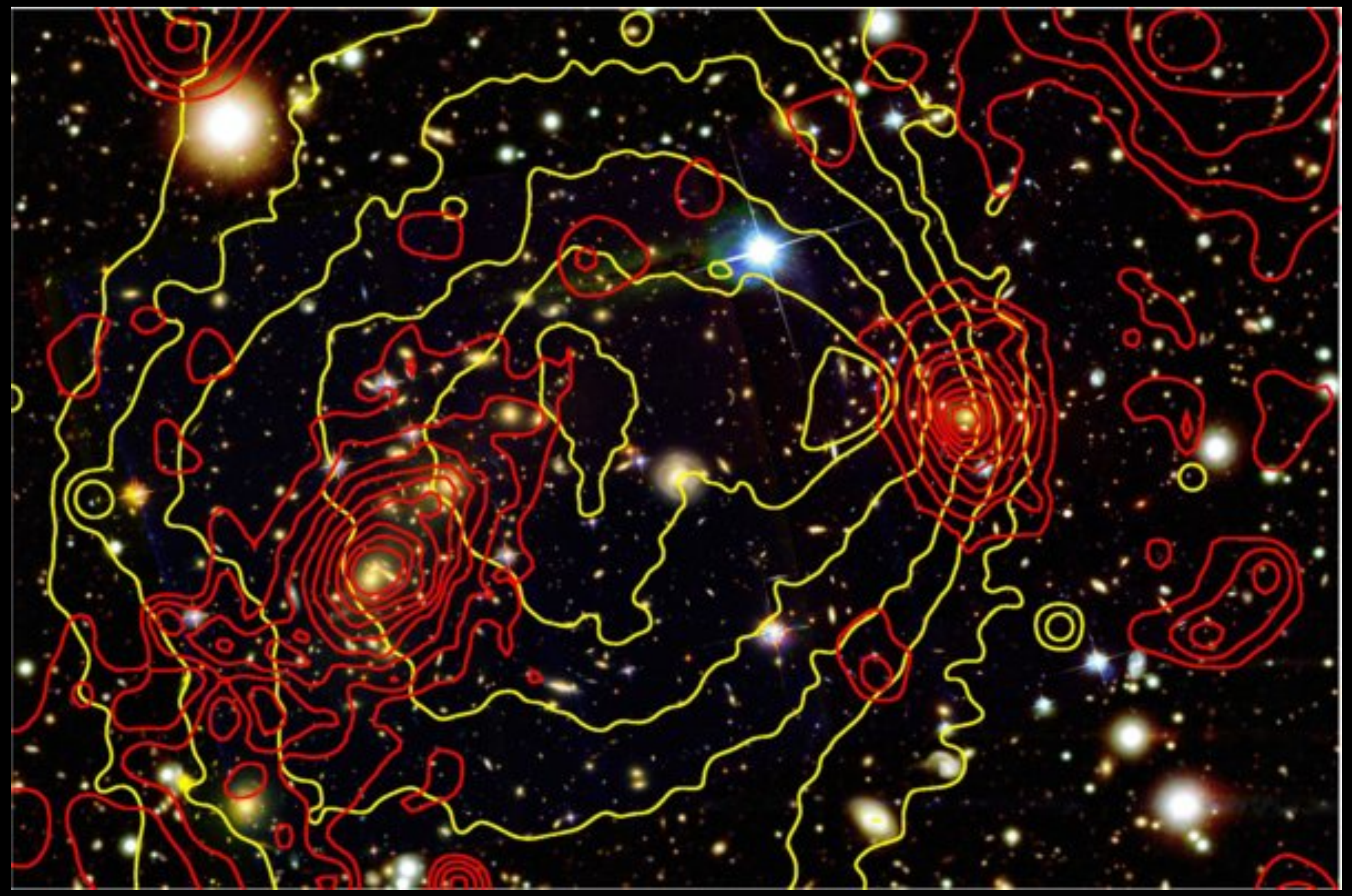

Einstein ring
source aligned with lens

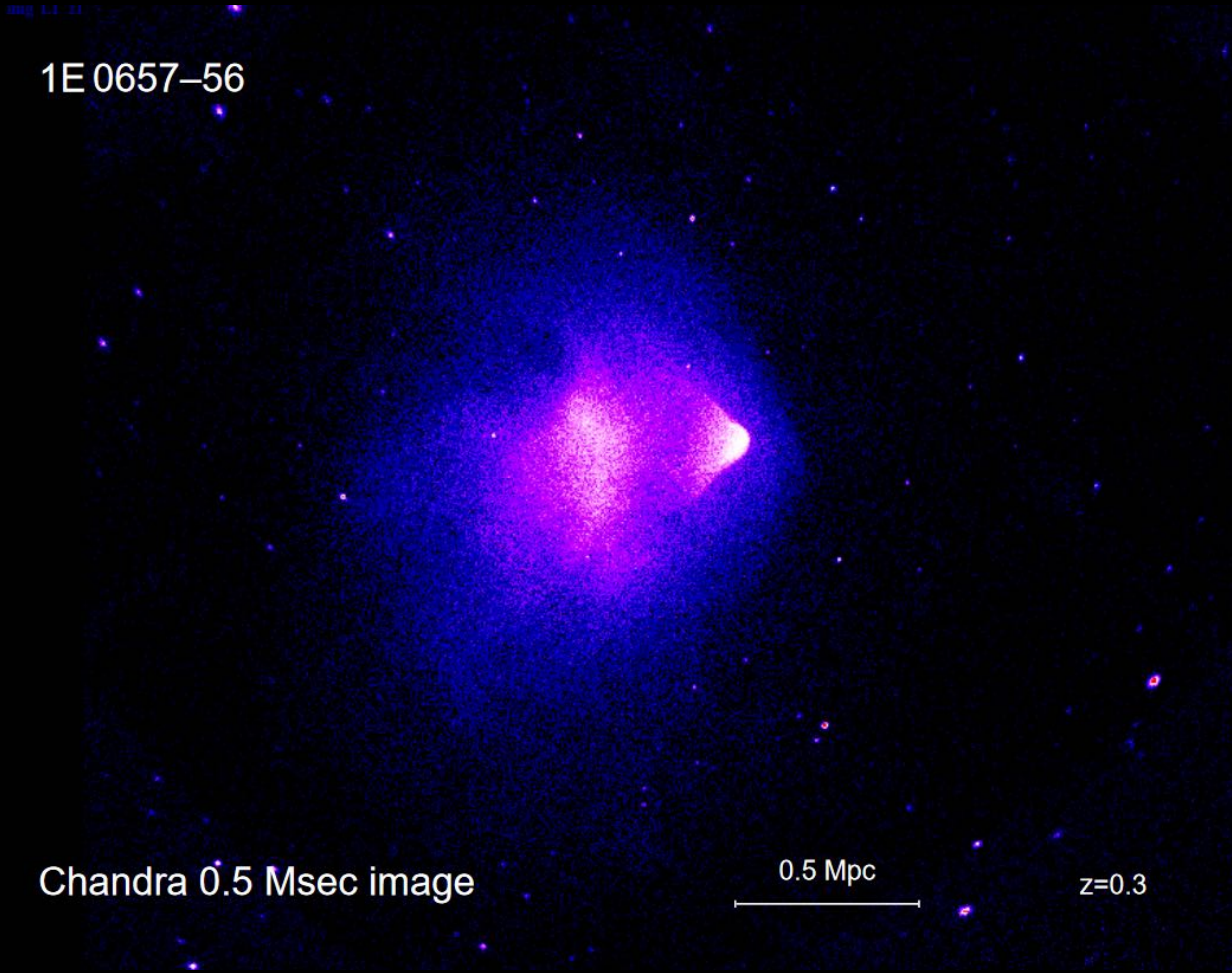
Bullet cluster (press release version)

Bullet cluster (data: Bradac et al. 2009)

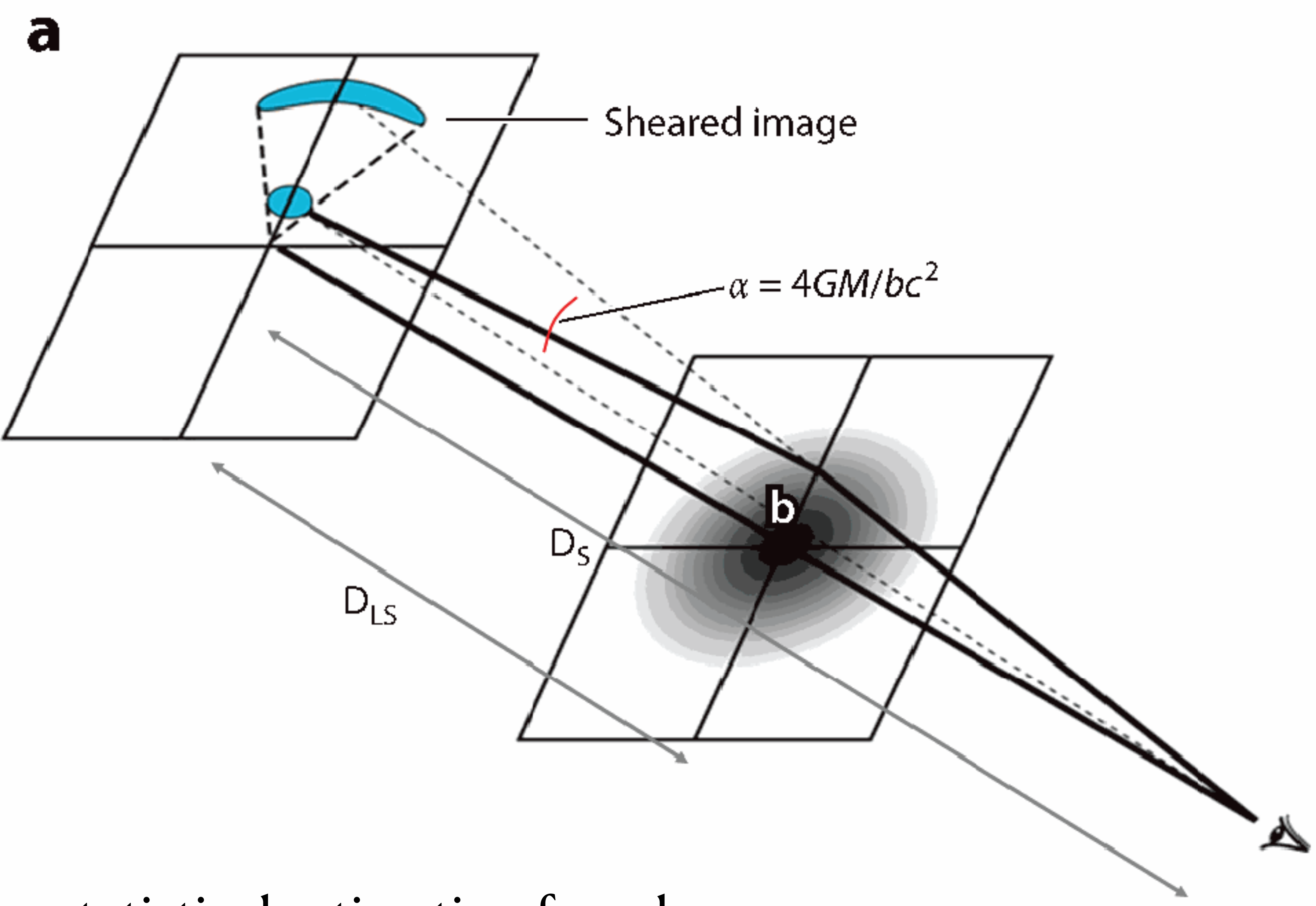
X-ray: yellow contours

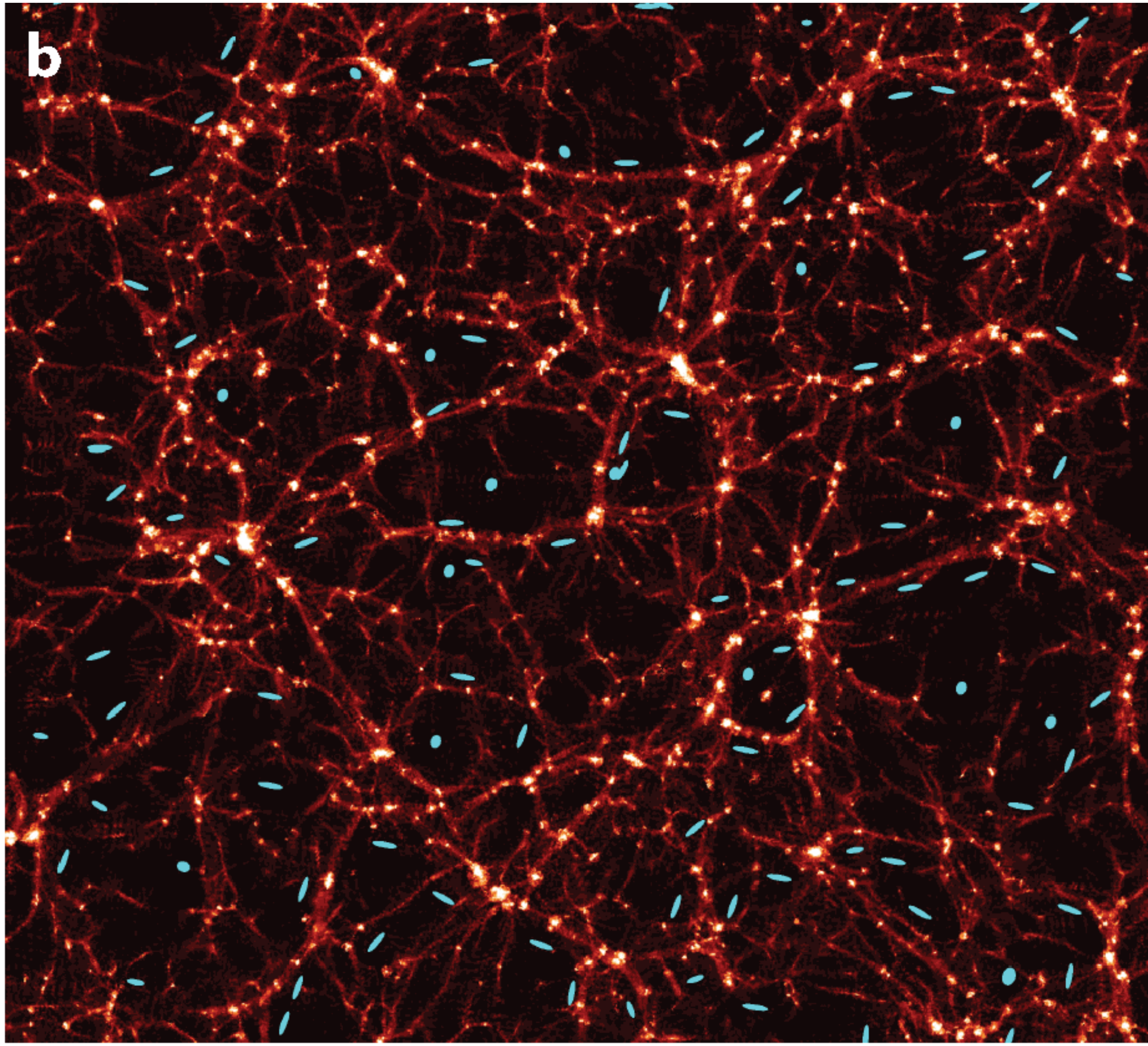


gravitational (strong+weak) lensing: red contours



weak gravitational lensing



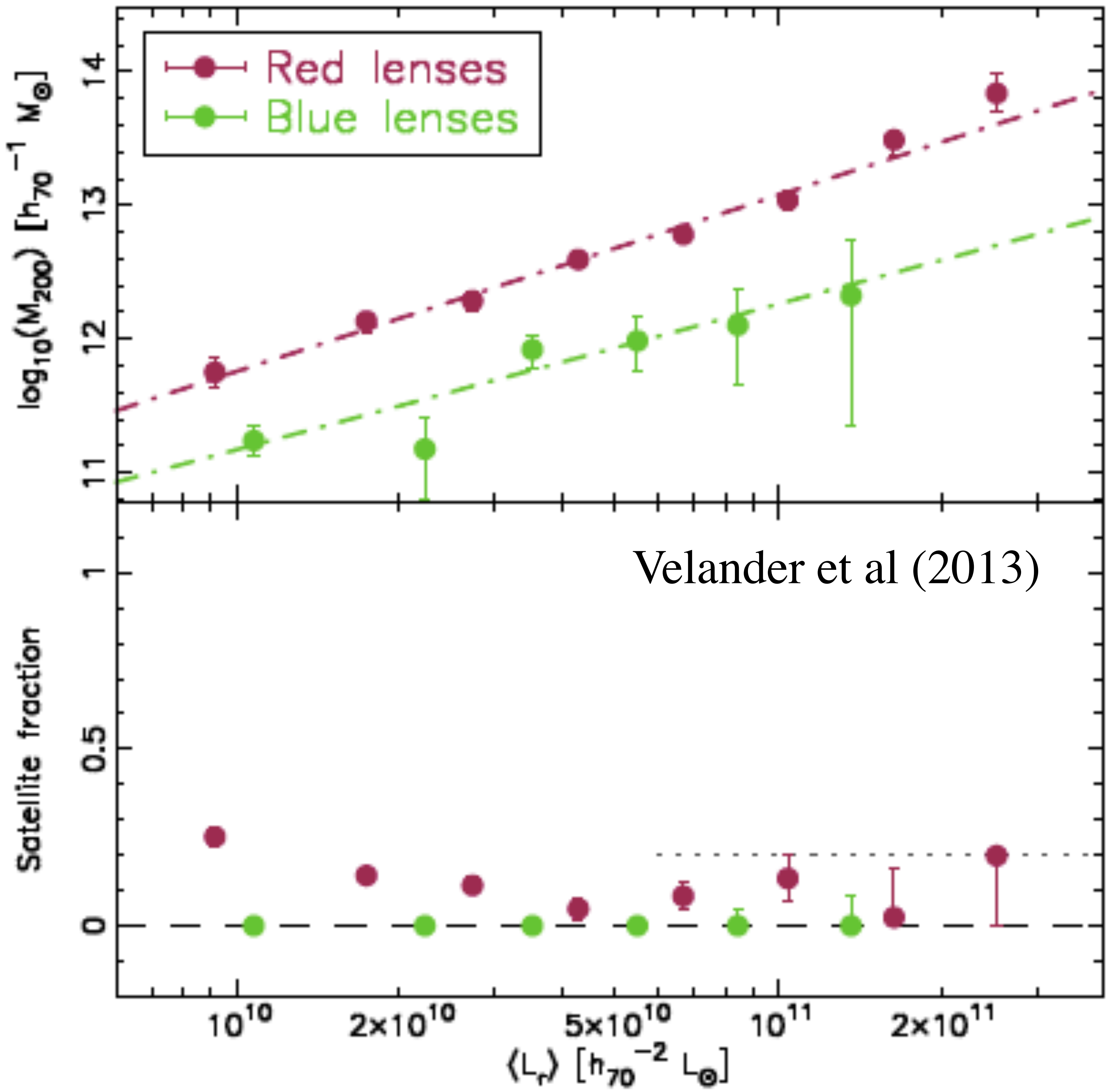


statistical estimation from large surveys
constrain the shear across the sky
which is related to the excess
surface density of lensing

Mandelbaum R, et al. 2018.
Annu. Rev. Astron. Astrophys. 56:393–433

BIG SCALES

average shear across the universe



Weak lensing provides a statistical constraint on the total halo mass

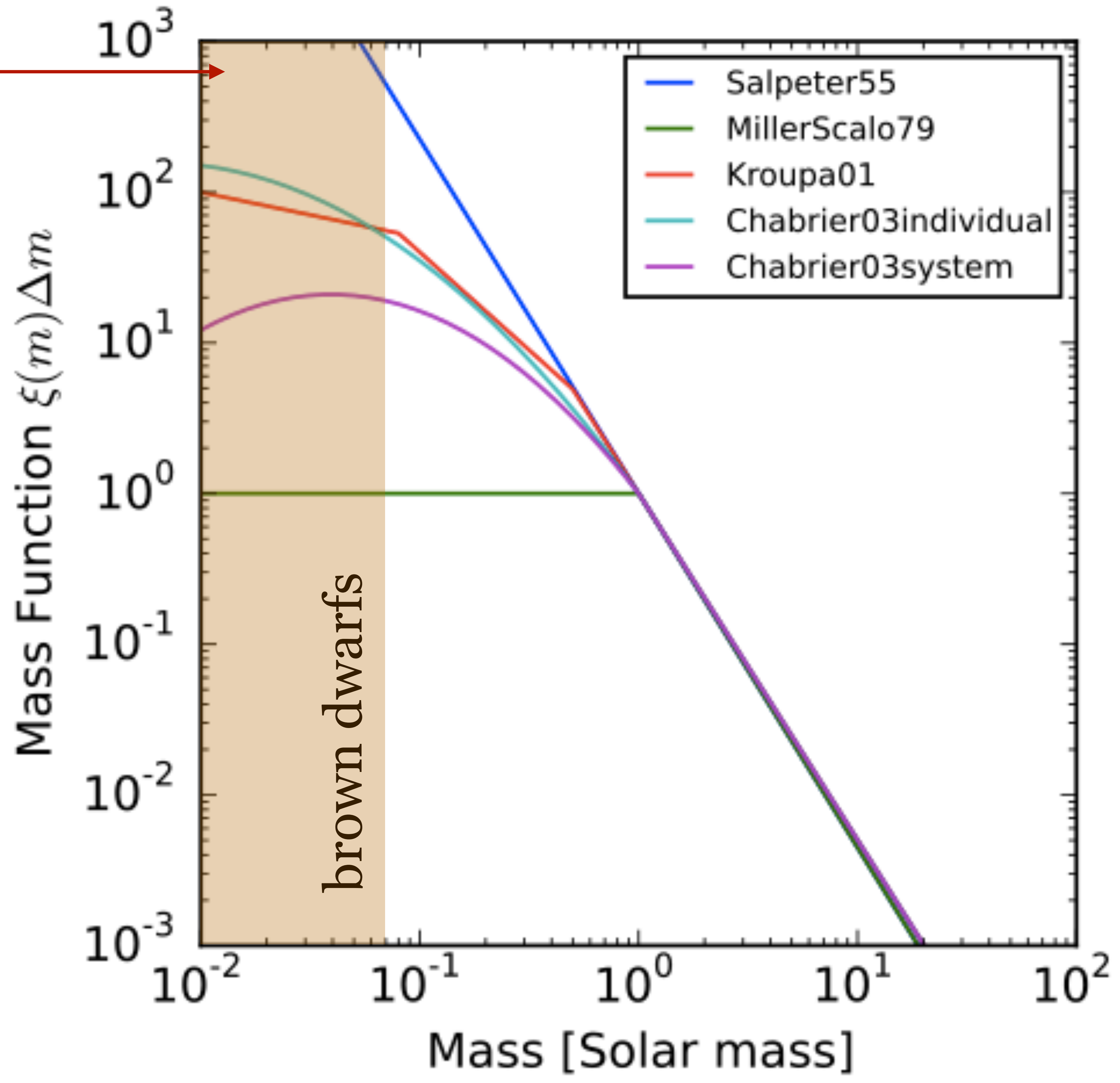
see also
Brimioulle et al (2013)

$$M_{200} = 119 L_r^{1.32}$$ for red galaxies

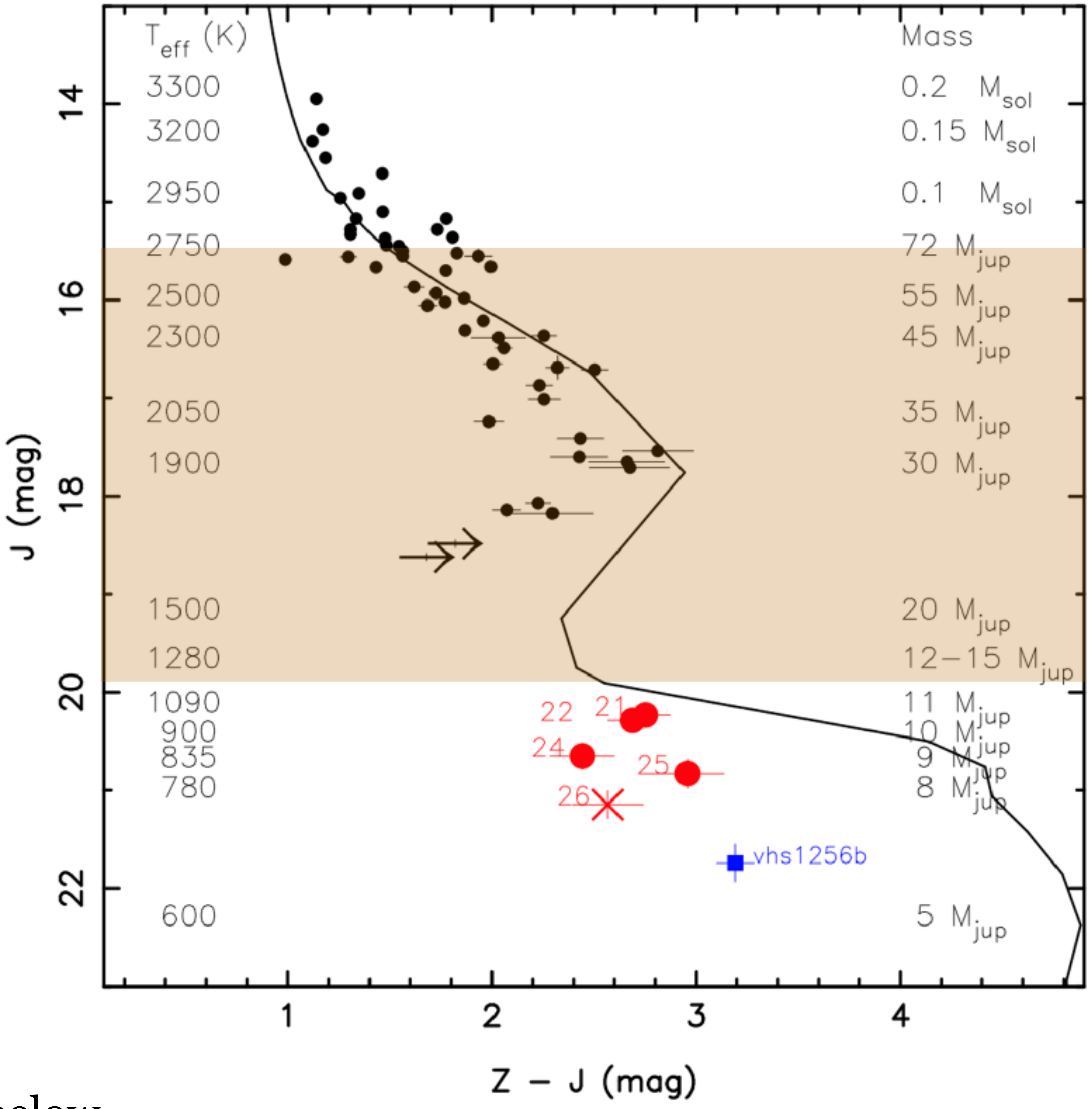
Microlensing searches for dark matter

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

Initial Mass Function



Geosciences **2018**, *8*(10), 362; https://doi.org/10.3390/geosciences8100362



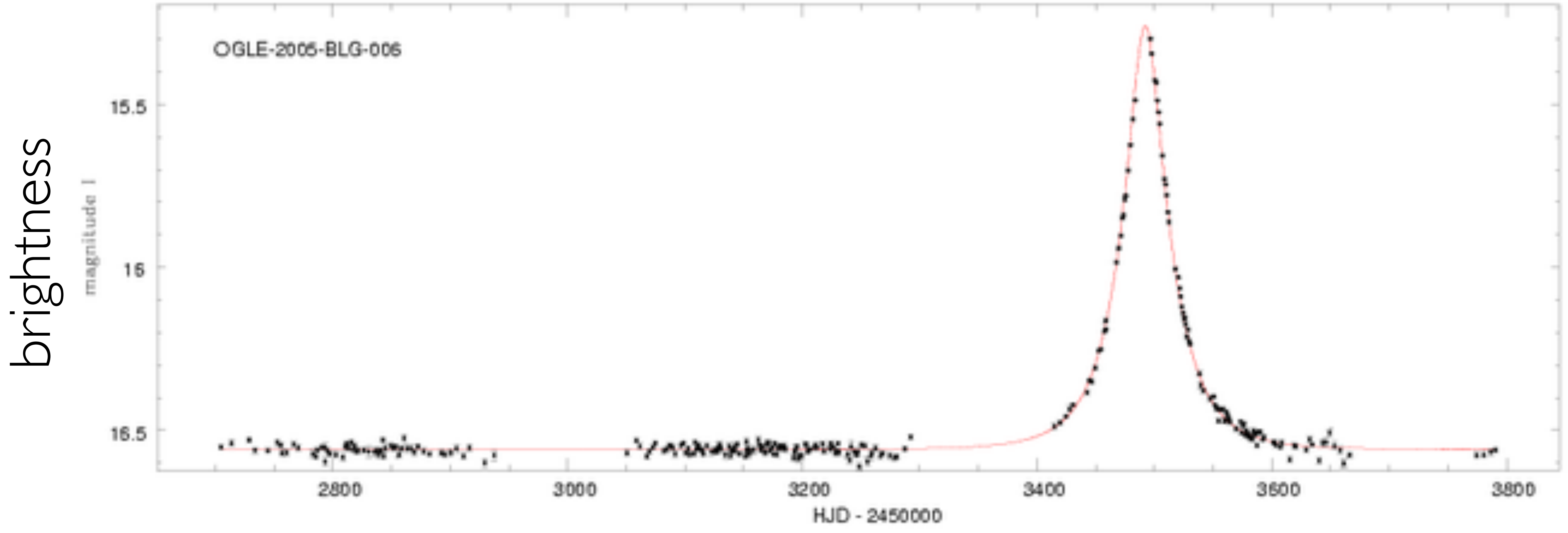
$M_{BD} < 0.07\ M_{\odot}$

brown dwarfs are failed stars below the hydrogen burning limit

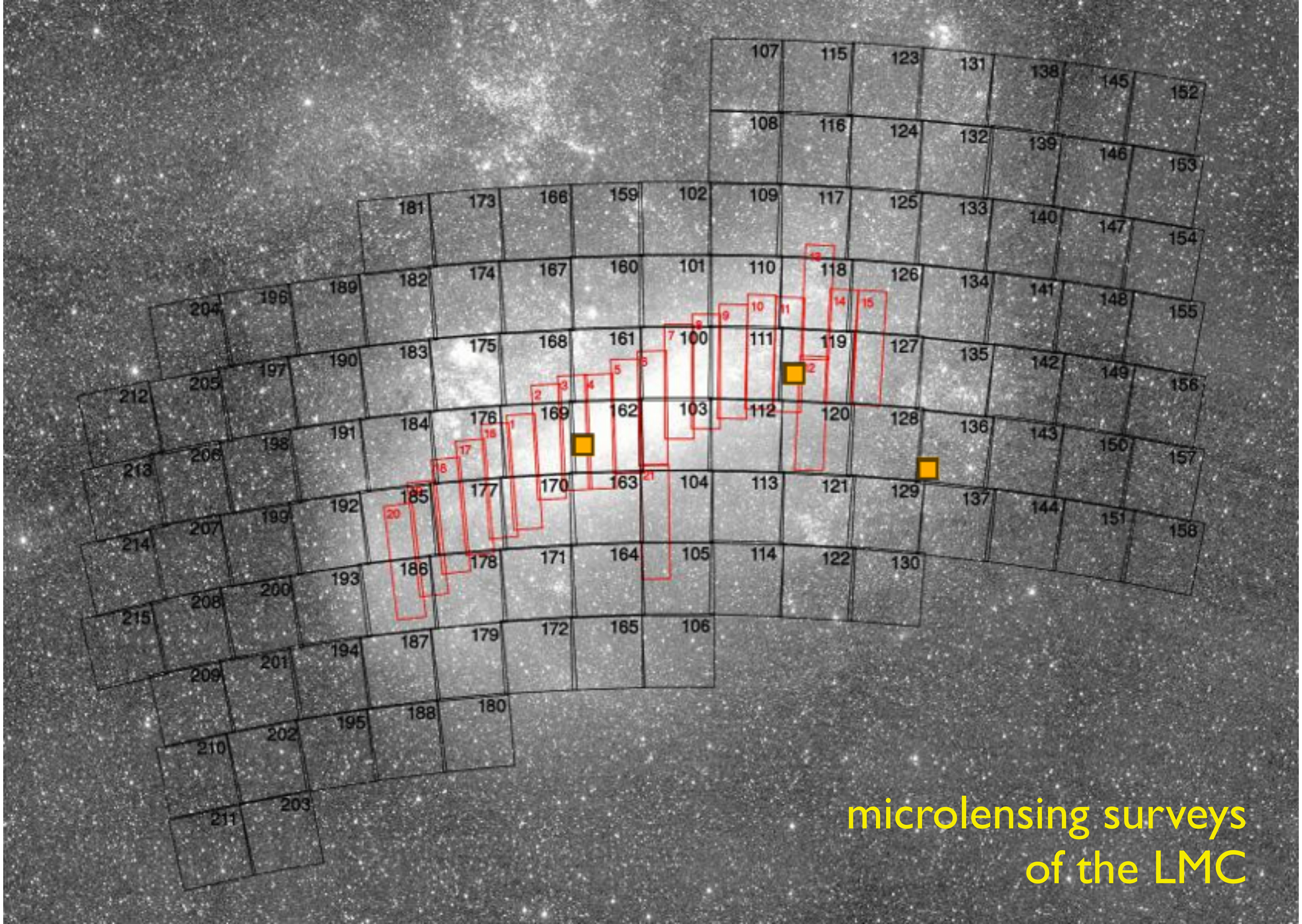
Microlensing surveys:
MACHO, EROS,OGLE

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

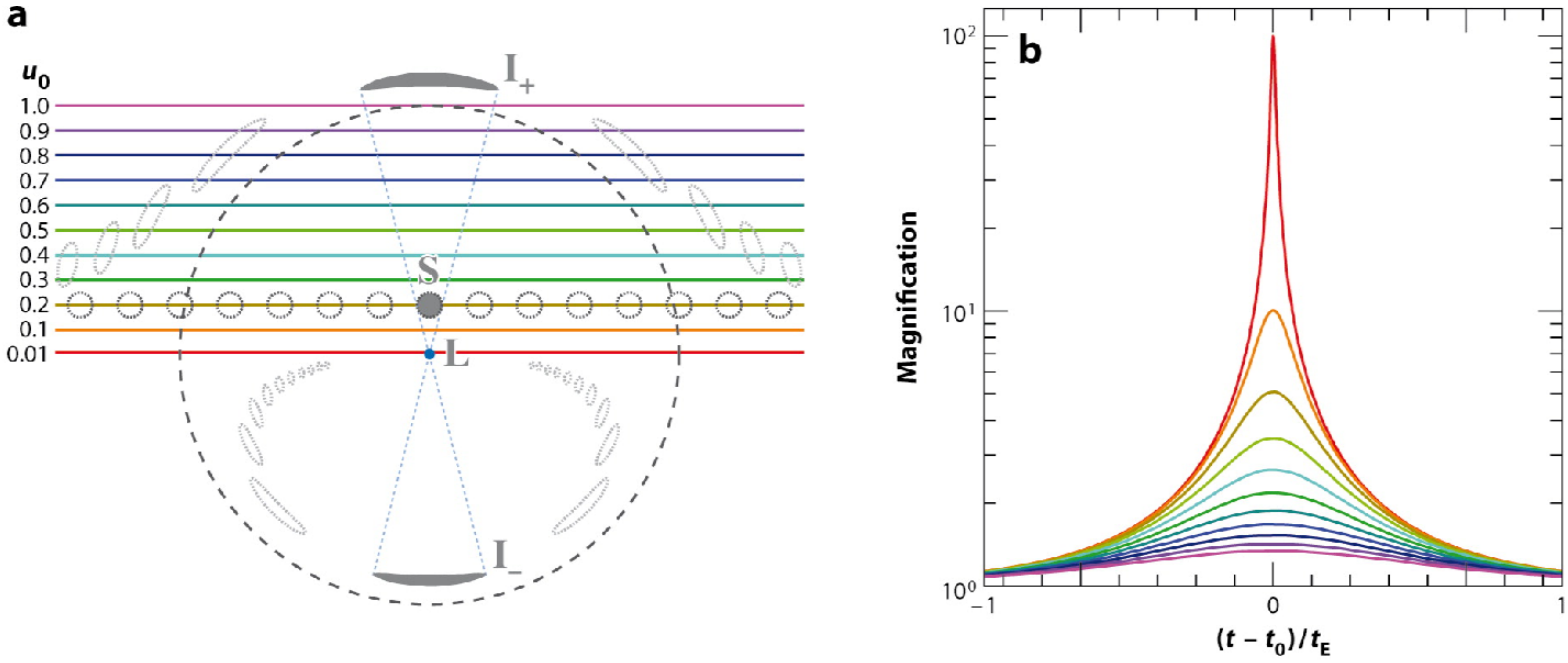
microlensing event observed by OGLE



time


microlensing surveys
of the LMC

$$u = \frac{\theta}{\theta_E}$$



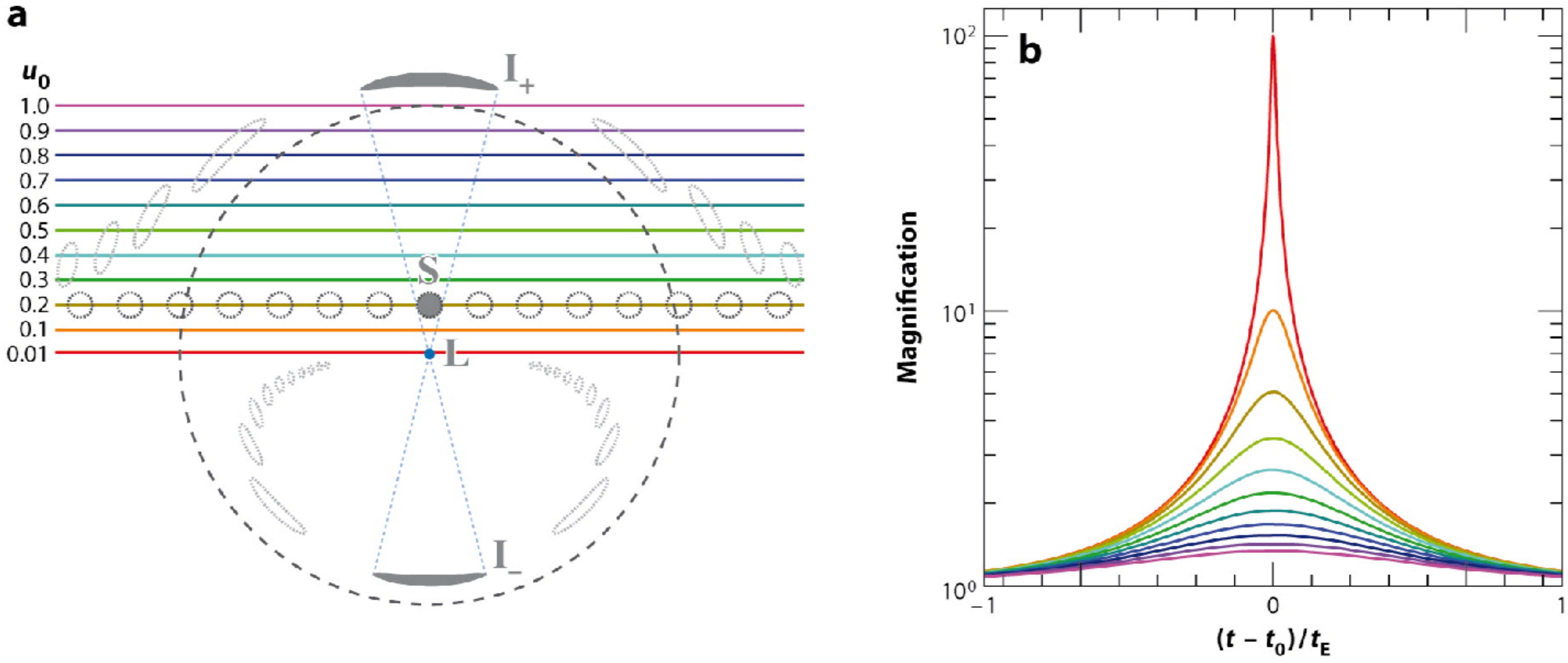
Gaudi BS. 2012.
Annu. Rev. Astron. Astrophys. 50:411–53

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

$$t_E = \frac{\theta_E}{\mu_{rel}}$$ 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

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



Lensing optical depth:

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

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

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

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

Number of microlensing events

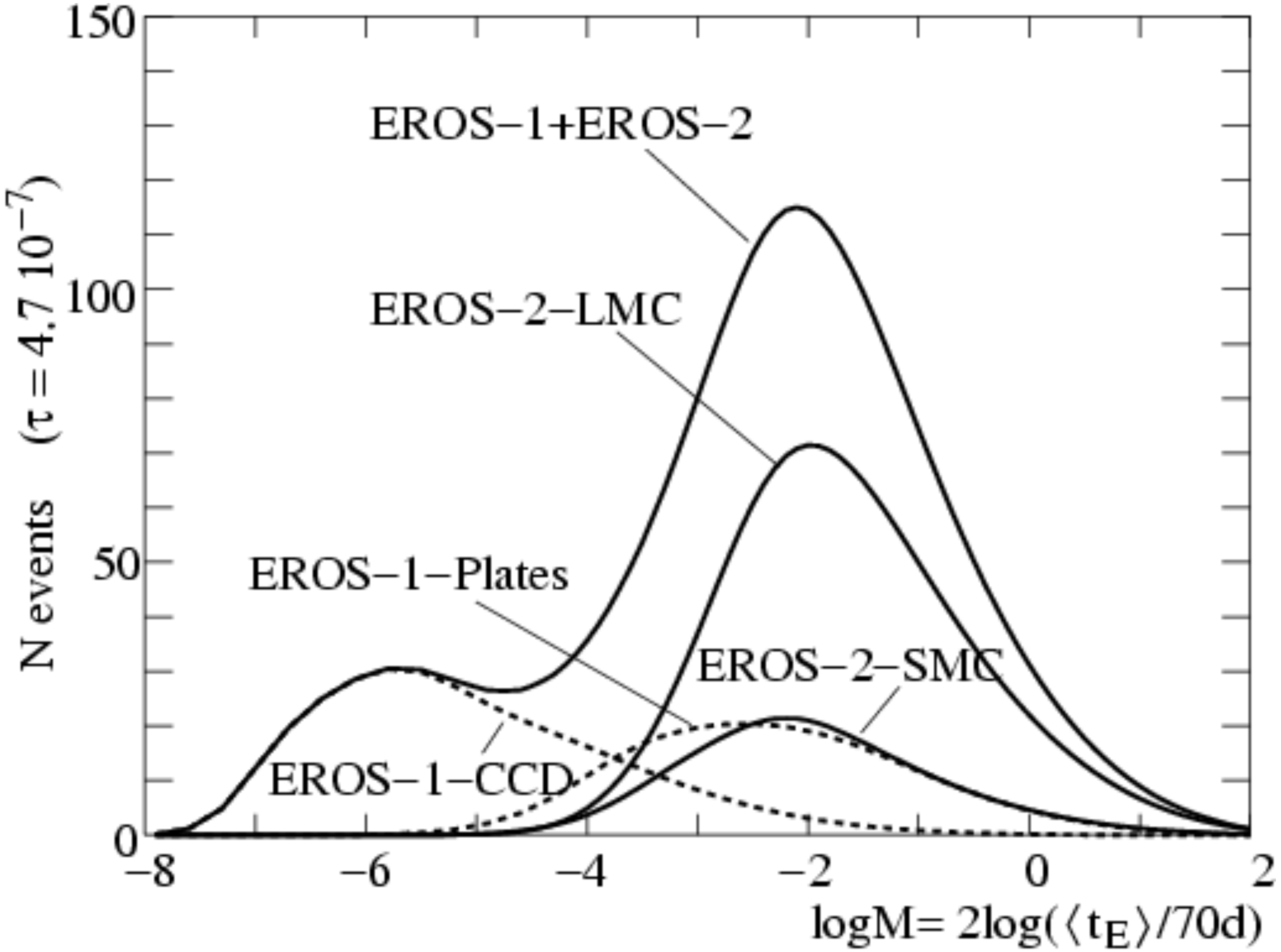
$$N(>A) = \frac{2\tau}{(A^2-1)+A\sqrt{A^2-1}}$$

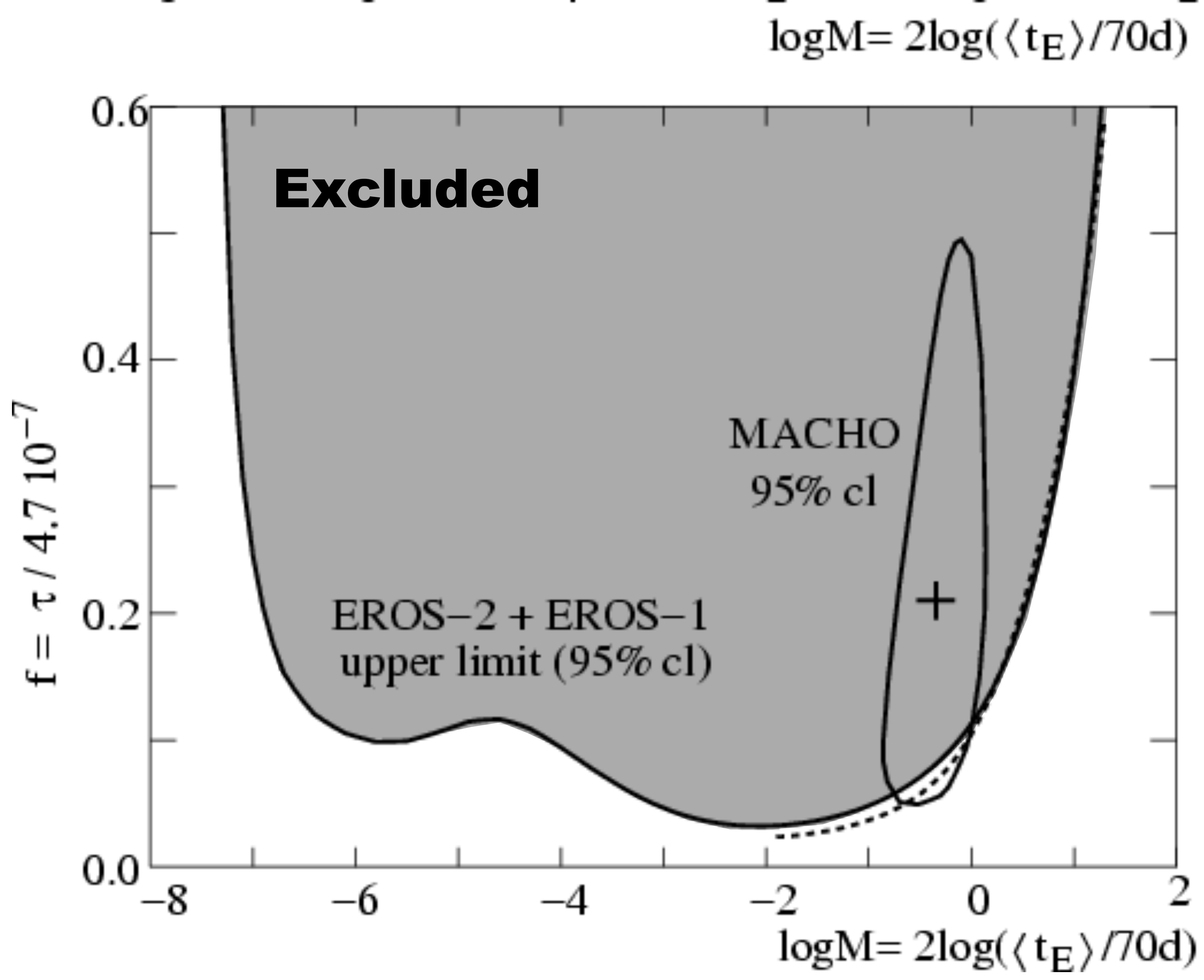
optical depth as a fcn of radius through an isothermal sphere

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

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.