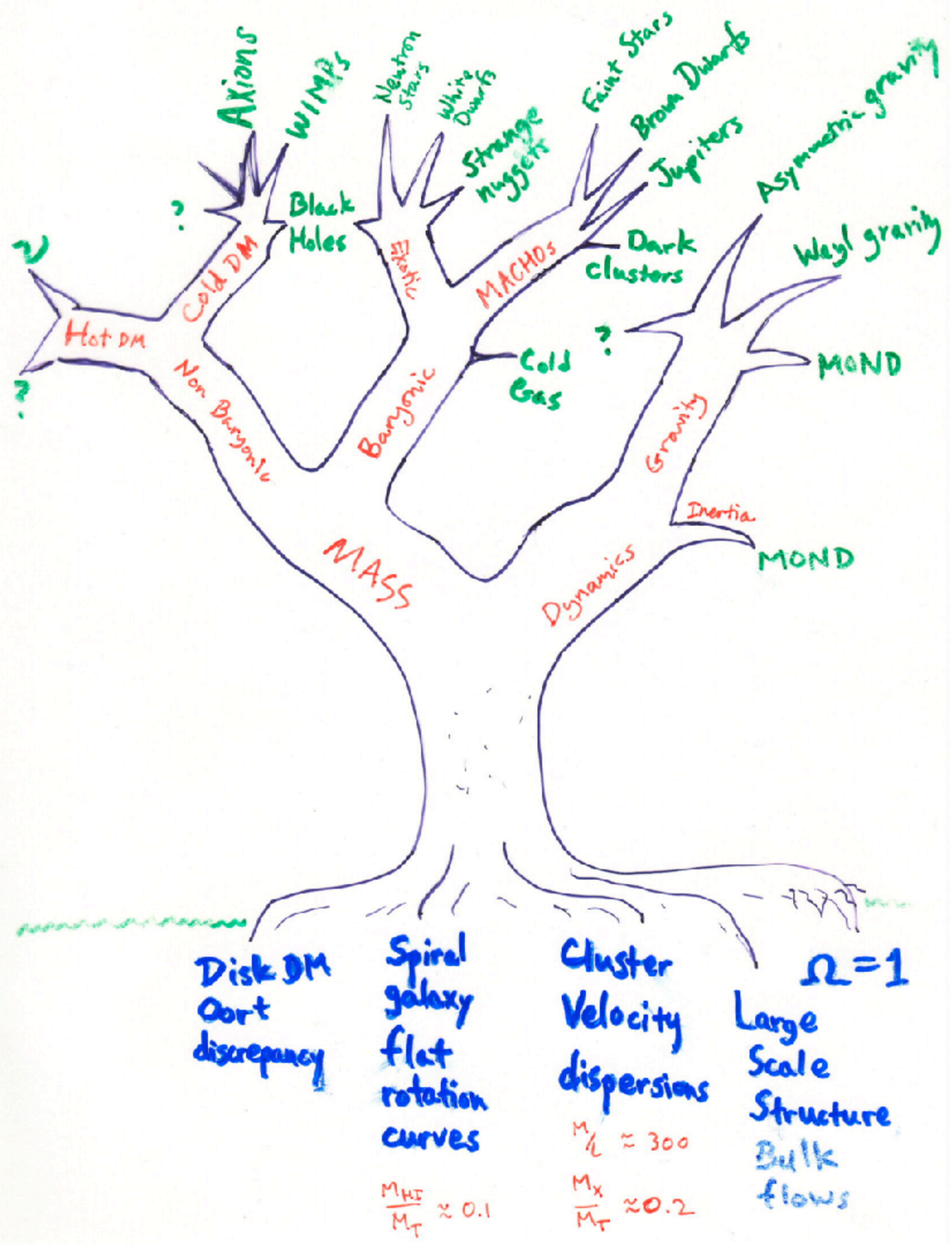
Dark Matter

ASTR 333/433
Spring 2026
TR 11:30am-12:45pm
Sears 552

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

Prof. Stacy McGaugh
Sears 558
368-1808
stacy.mcgaugh@case.edu



Case Western Reserve University Est. 1826

JWST First Release image

Gravitational lensing in
Cluster SMACS 0723

Four distinct measures:
velocity dispersion, hydrostatic equilibrium of X-ray gas, the Sunyaev-Zel'dovich effect, and gravitational lensing

Gravitational Lensing

Flavors of gravitational lensing:

— weak lensing
mild distortion of lensed image

— strong lensing
multiple images, strong distortion

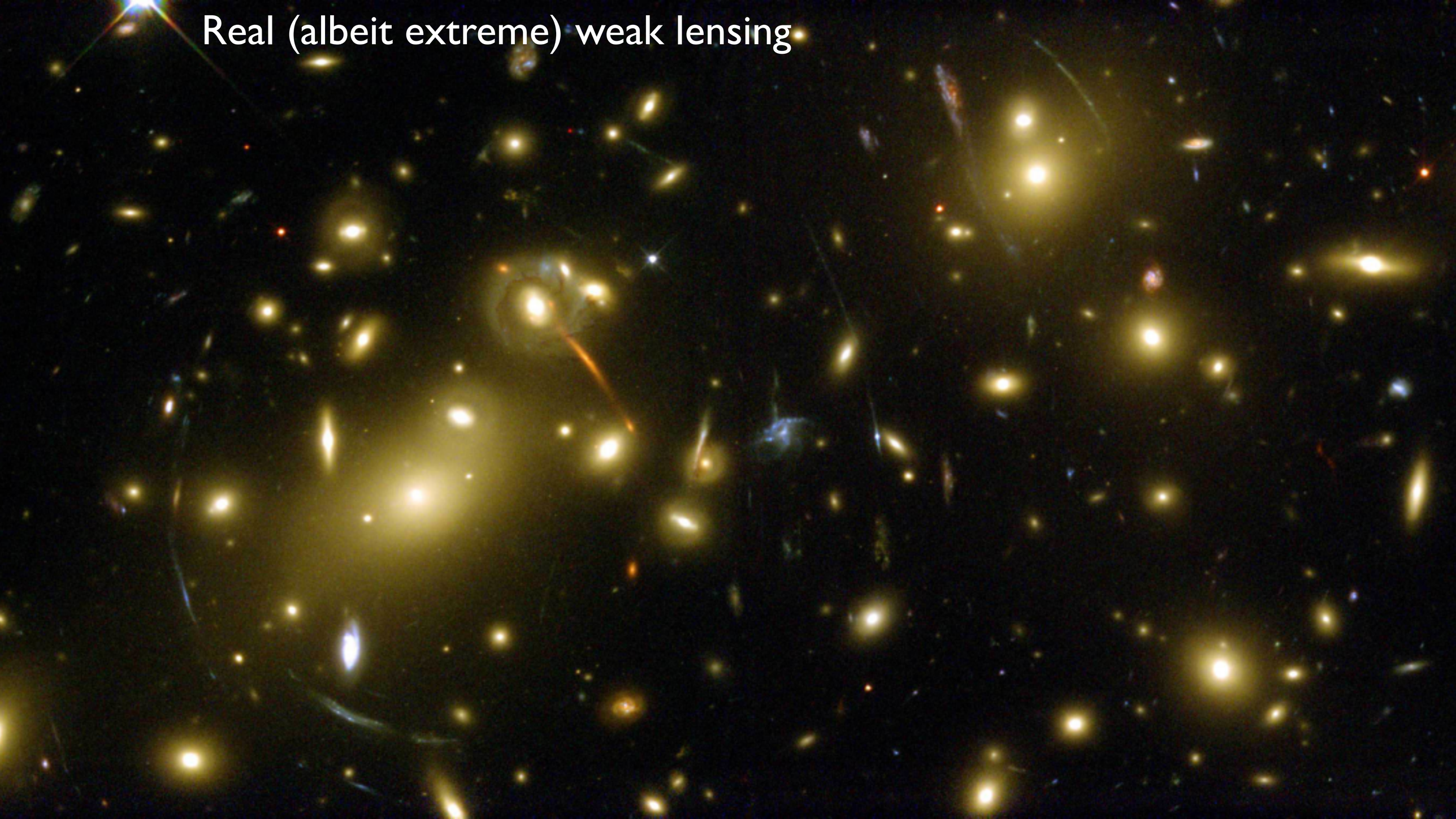
} separated by the critical surface density

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

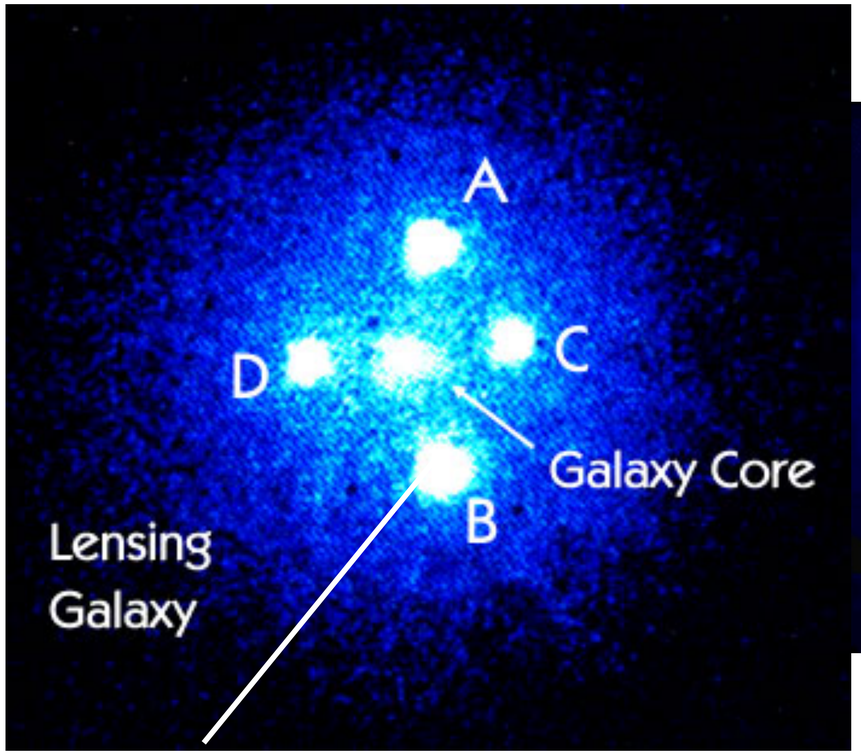
— microlensing
temporary brightening due to unresolved lensing

Fake illustration of weak lensing

Real (albeit extreme) weak lensing

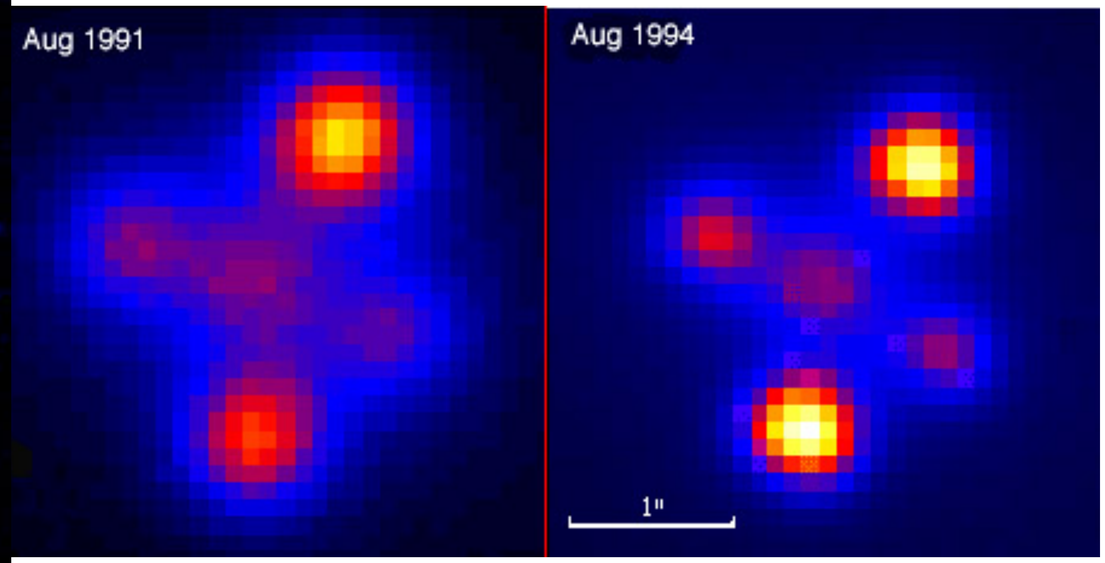


The Einstein Cross



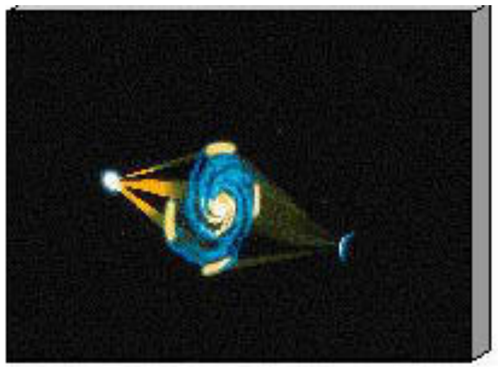
ABCD: same QSO seen 4 times

Multiple images from **strong lensing**

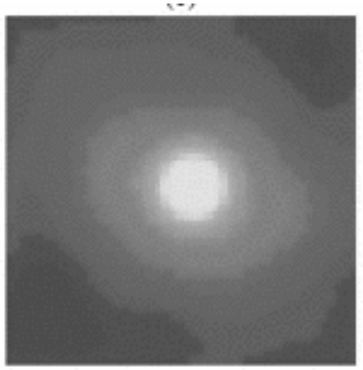


time variable multiple QSO image

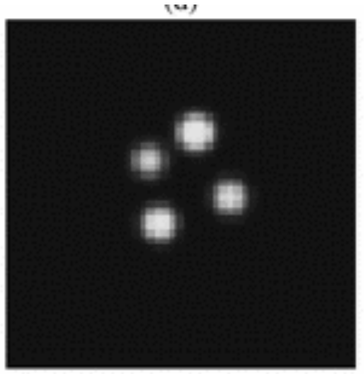
(a)



(b)



lensing galaxy



lensed QSO

Gravitational Lensing

θ_I observed angle between image and lens

θ_S true separation angle between image and lens

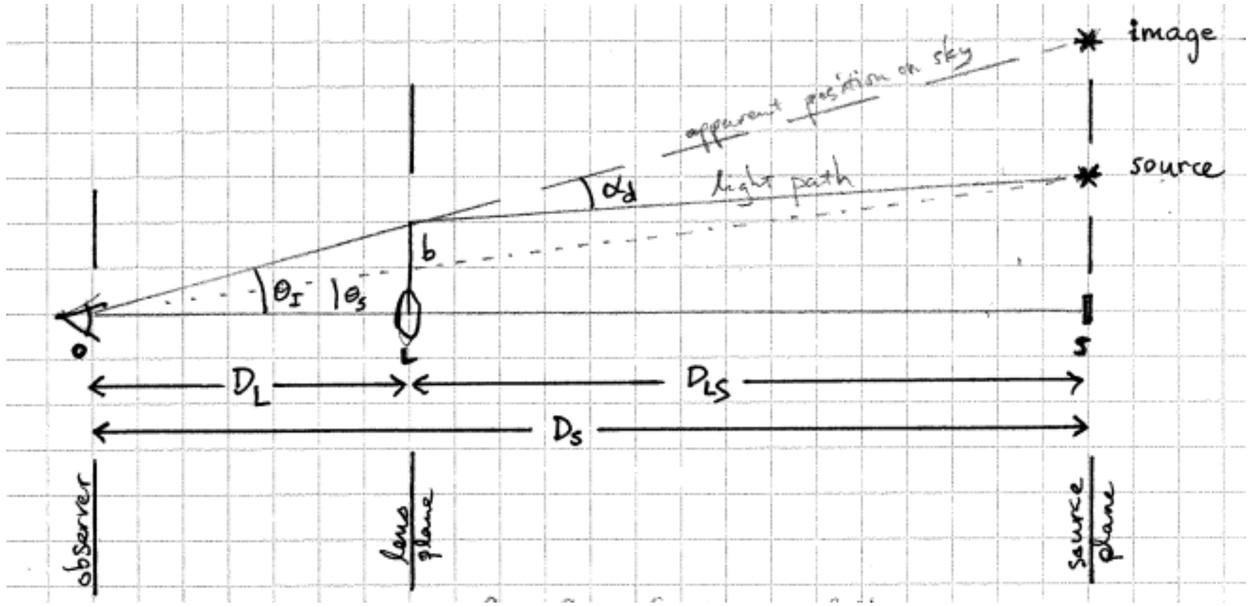
α_d bend angle

b impact parameter

D_L lens distance

D_S source distance

D_{LS} lens-source separation

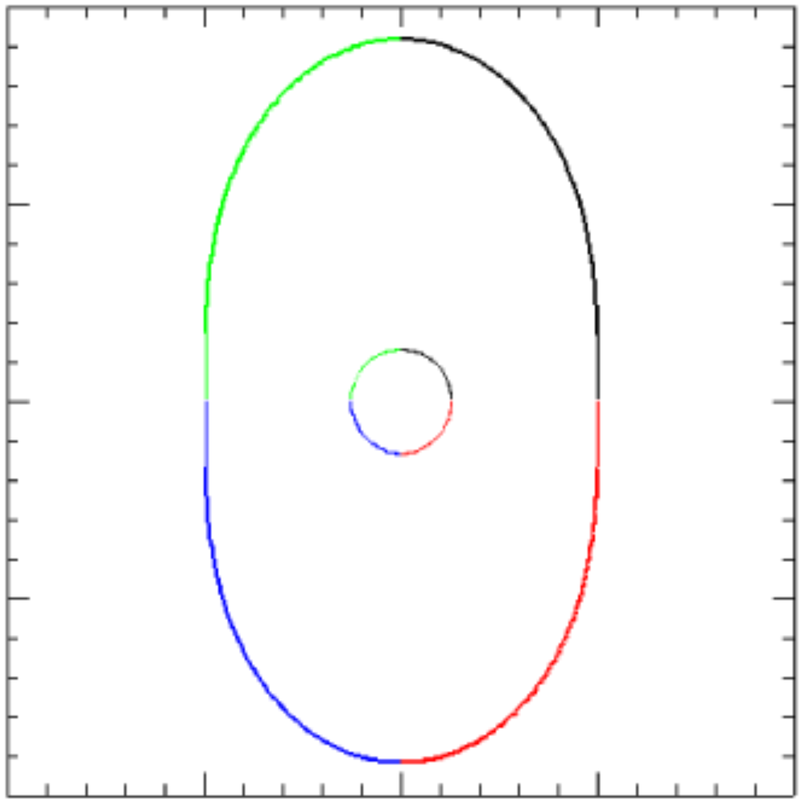


observer

lens plane

source plane

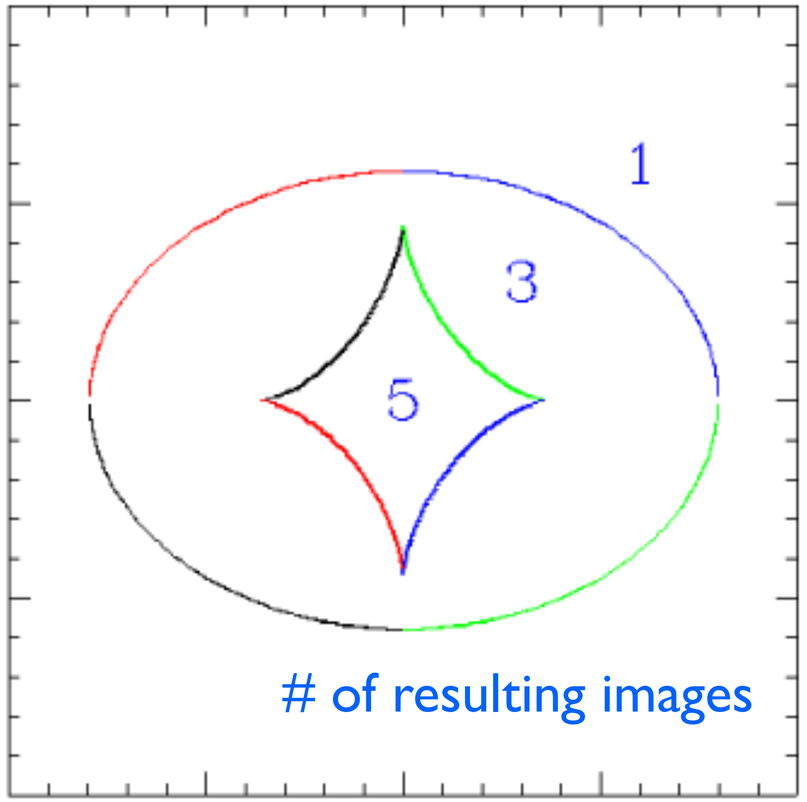
Lens plane



critical curves

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

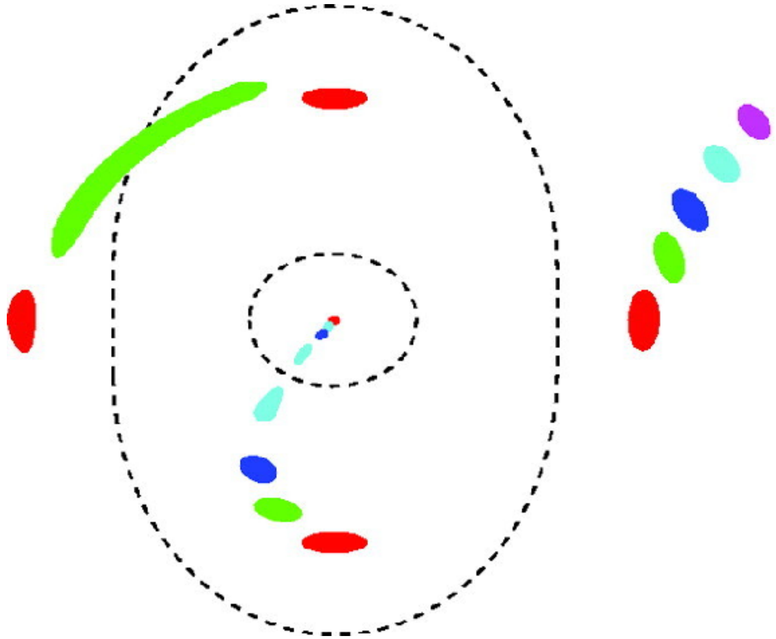
Source plane



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



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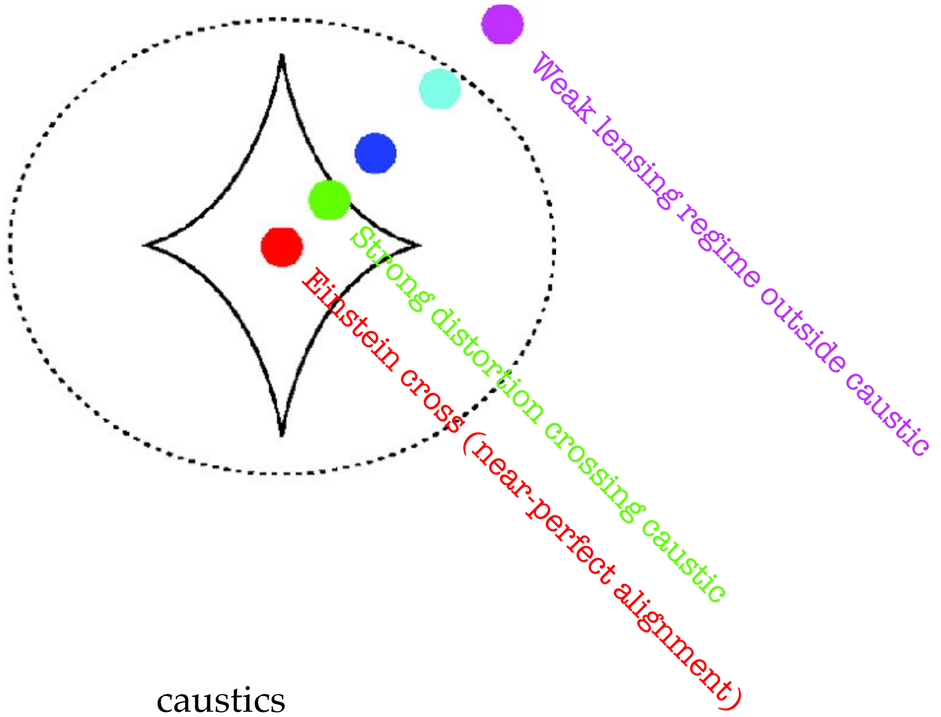

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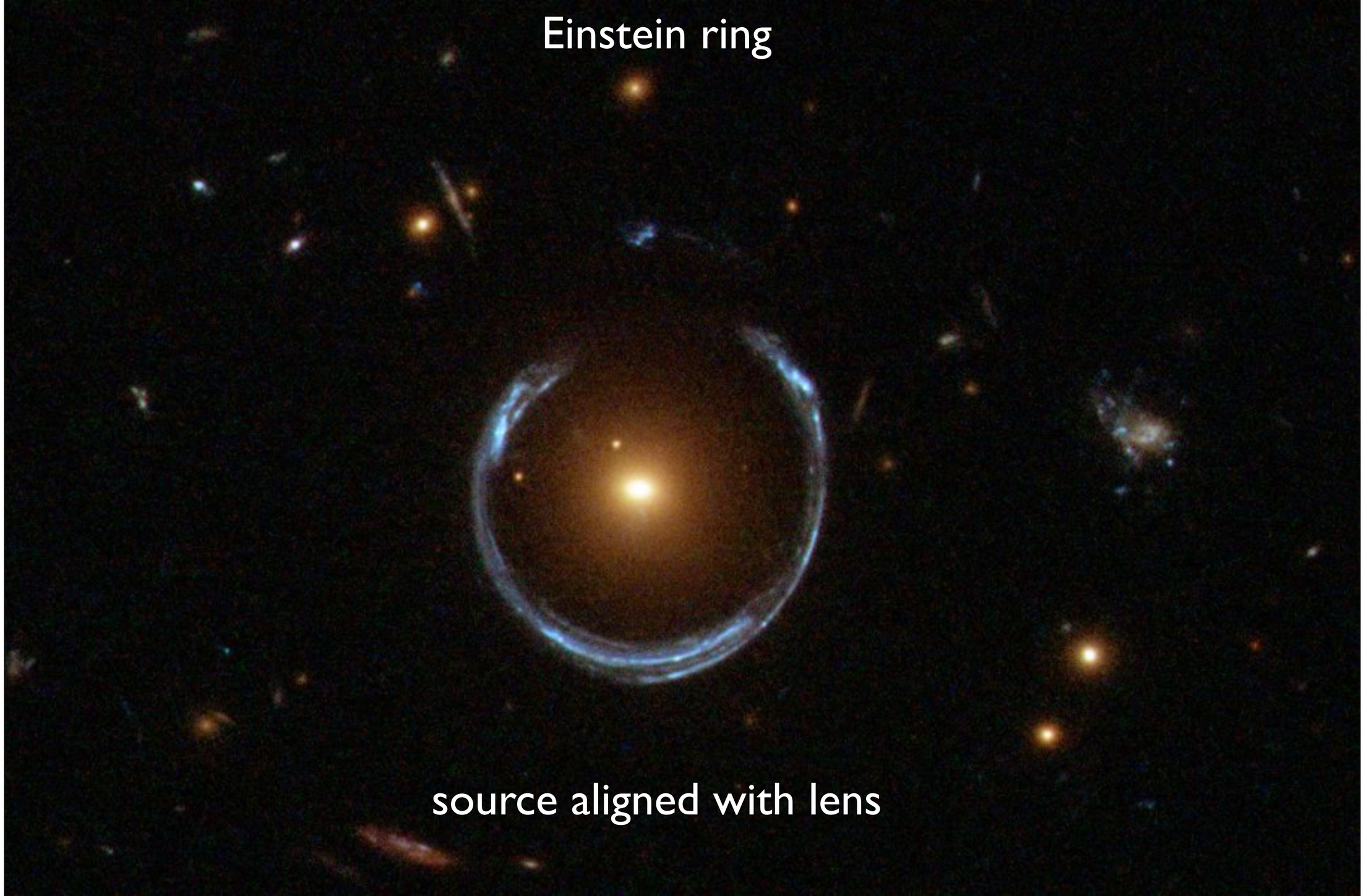
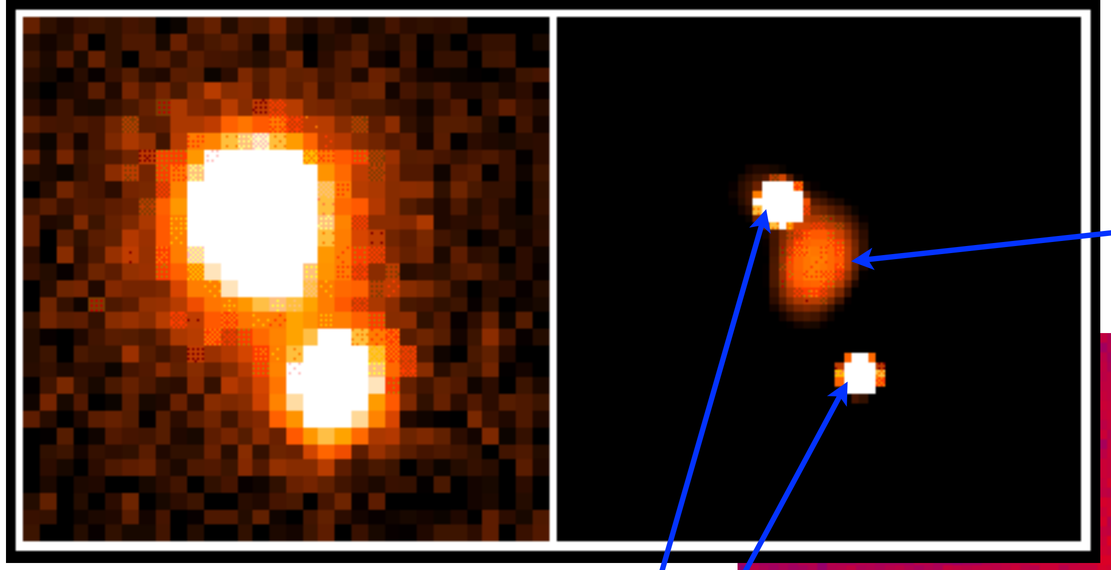
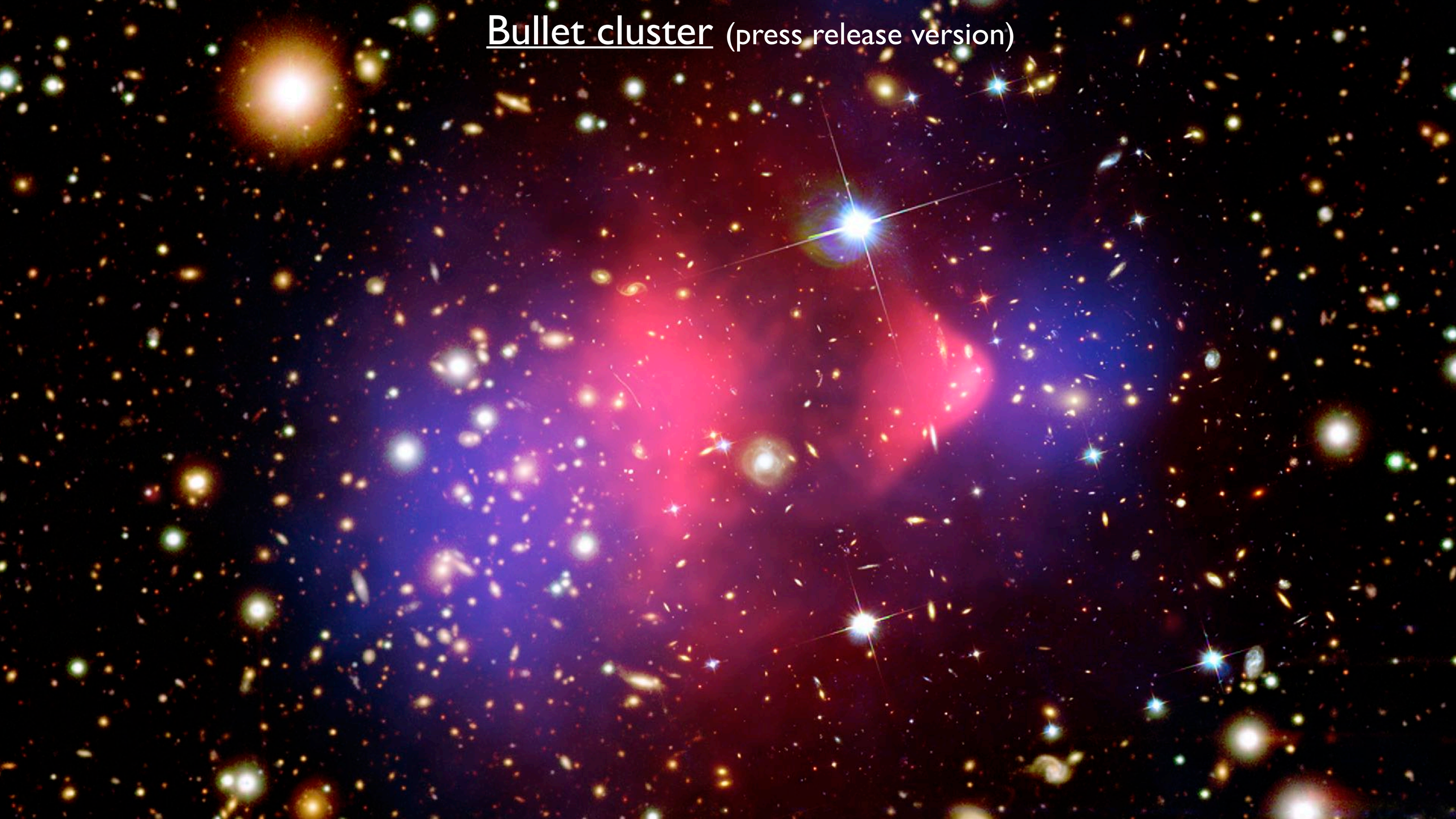

Einstein ring
source aligned with lens



Lensing galaxy

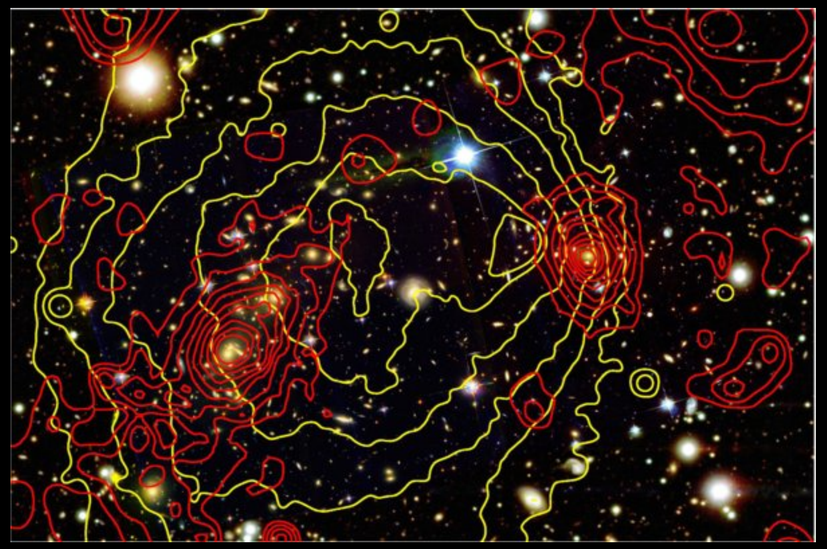
Lensed images

Bullet cluster (press release version)



Bullet cluster (data: Bradac et al. 2009)

X-ray: yellow contours

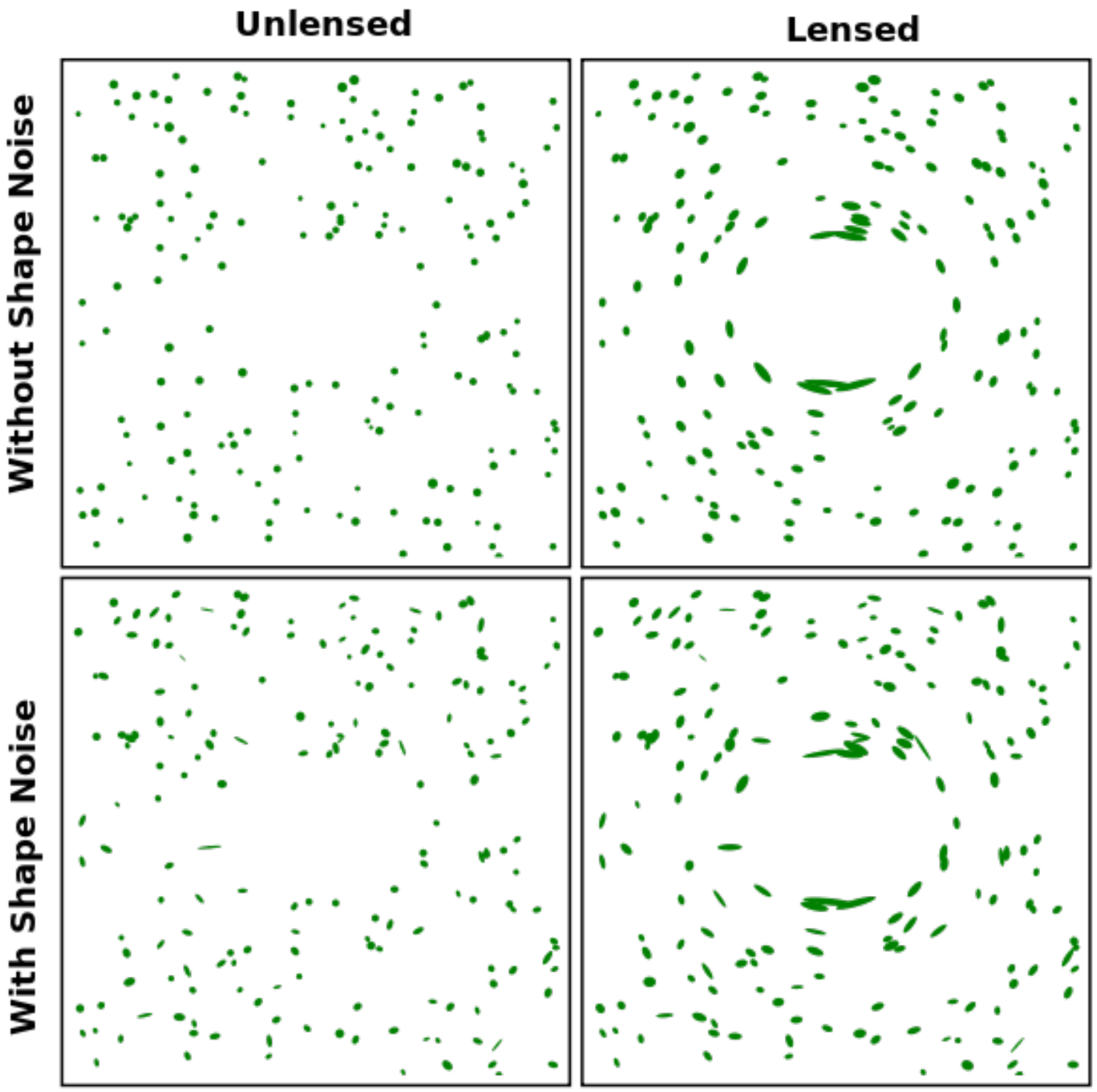


gravitational (strong+weak) lensing: red contours

weak gravitational lensing

statistical estimation from large surveys

constrain the shear across the sky
which is related to the excess
surface density of lensing



Gravitational Lensing

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D_L lens distance

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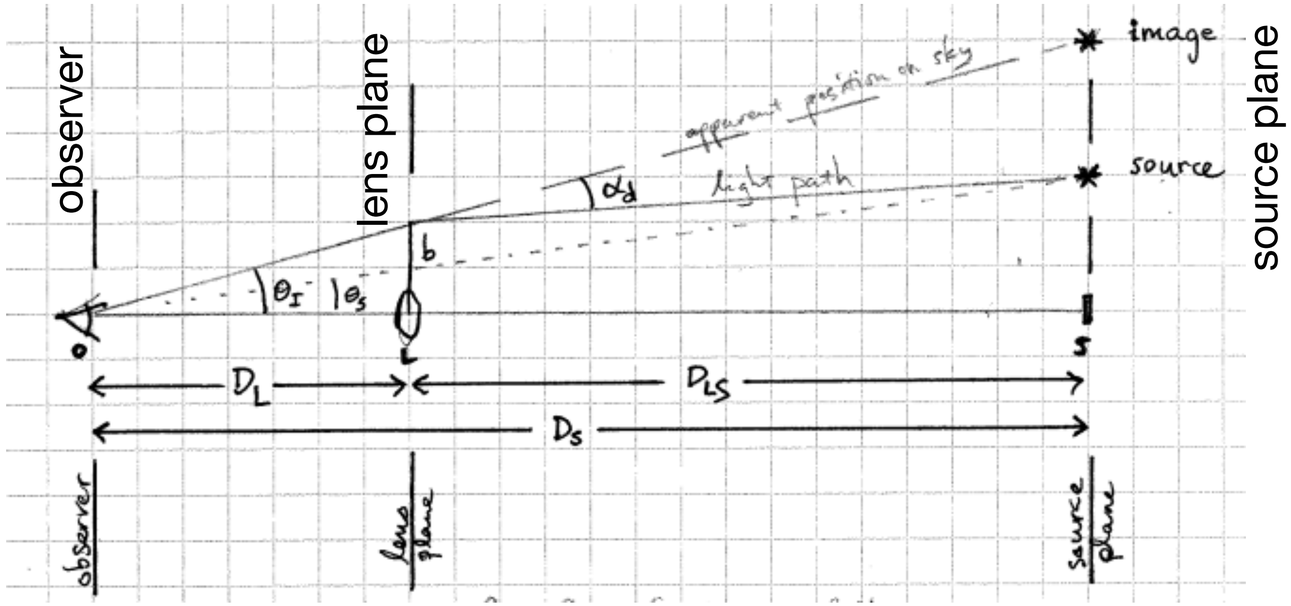
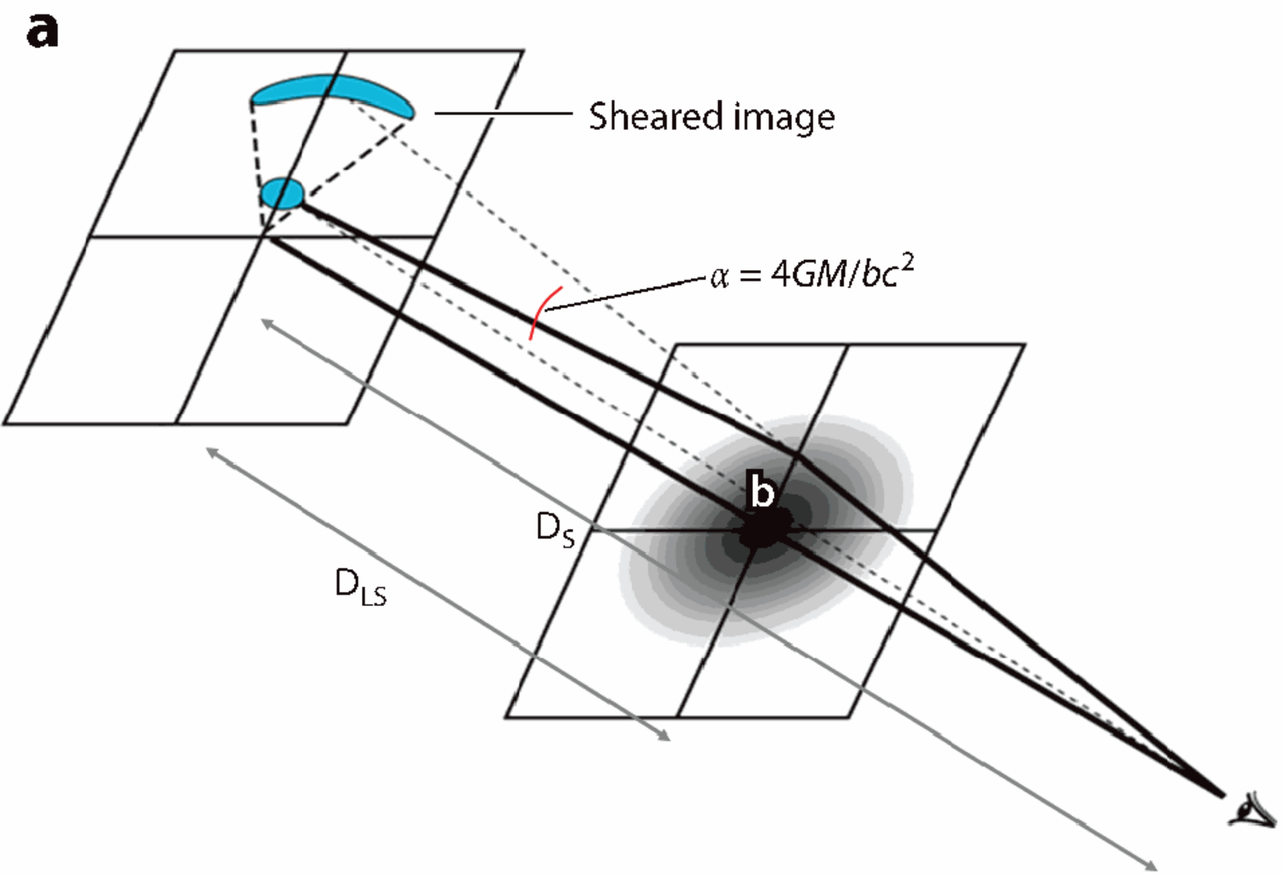
D_{LS} lens-source separation

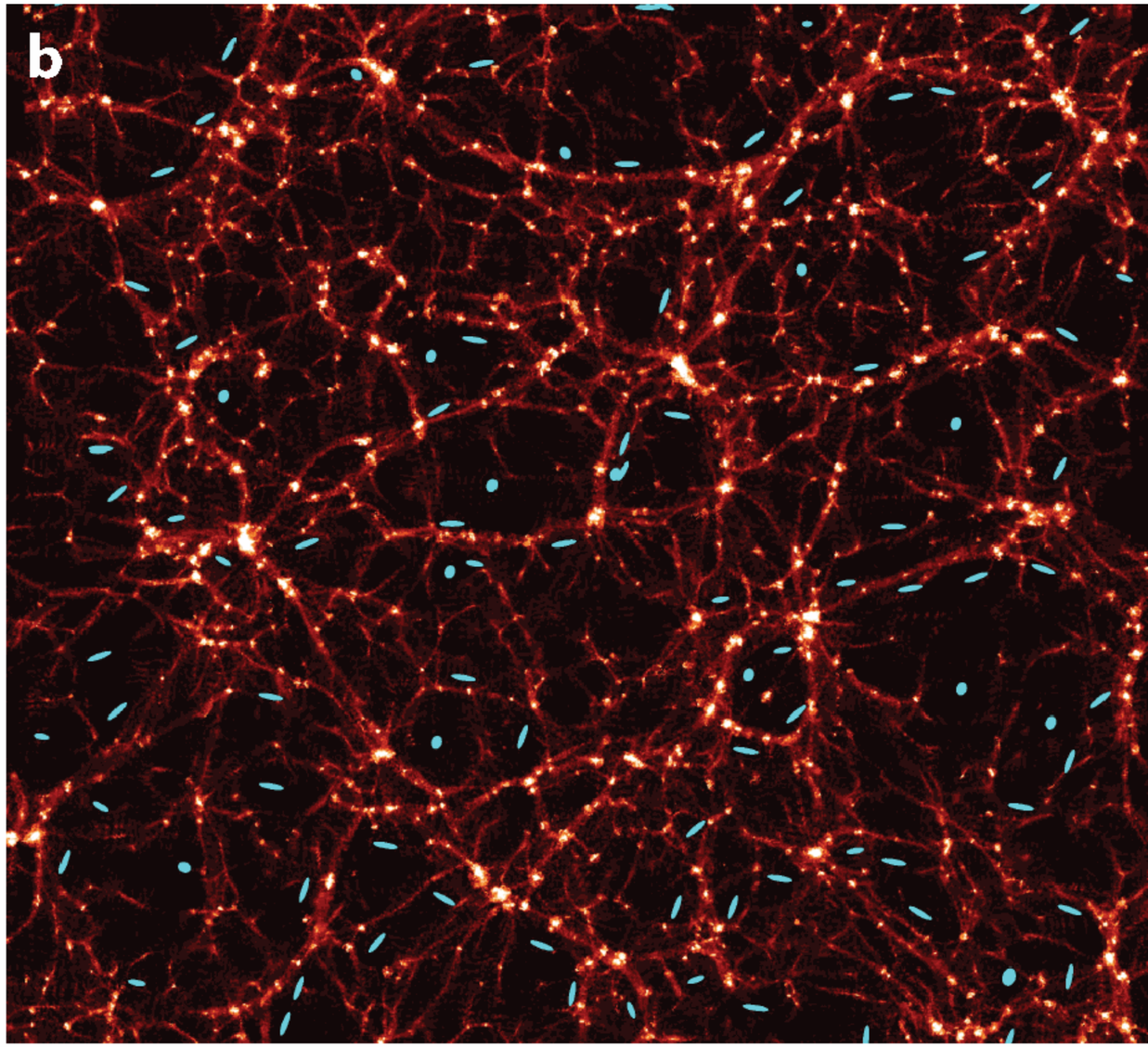


weak lensing

mass enclosed by angle Θ_I: $M(<\Theta_I) = (1.1\times10^{14}\ \mathrm{M}_\odot)\left(\frac{\Theta_I}{30''}\right)^2\left(\frac{D_L}{D_S}\right)\left(\frac{D_{LS}}{1\ \mathrm{Gpc}}\right)$ scaled for clusters of galaxies

weak gravitational lensing





statistical estimation from large surveys

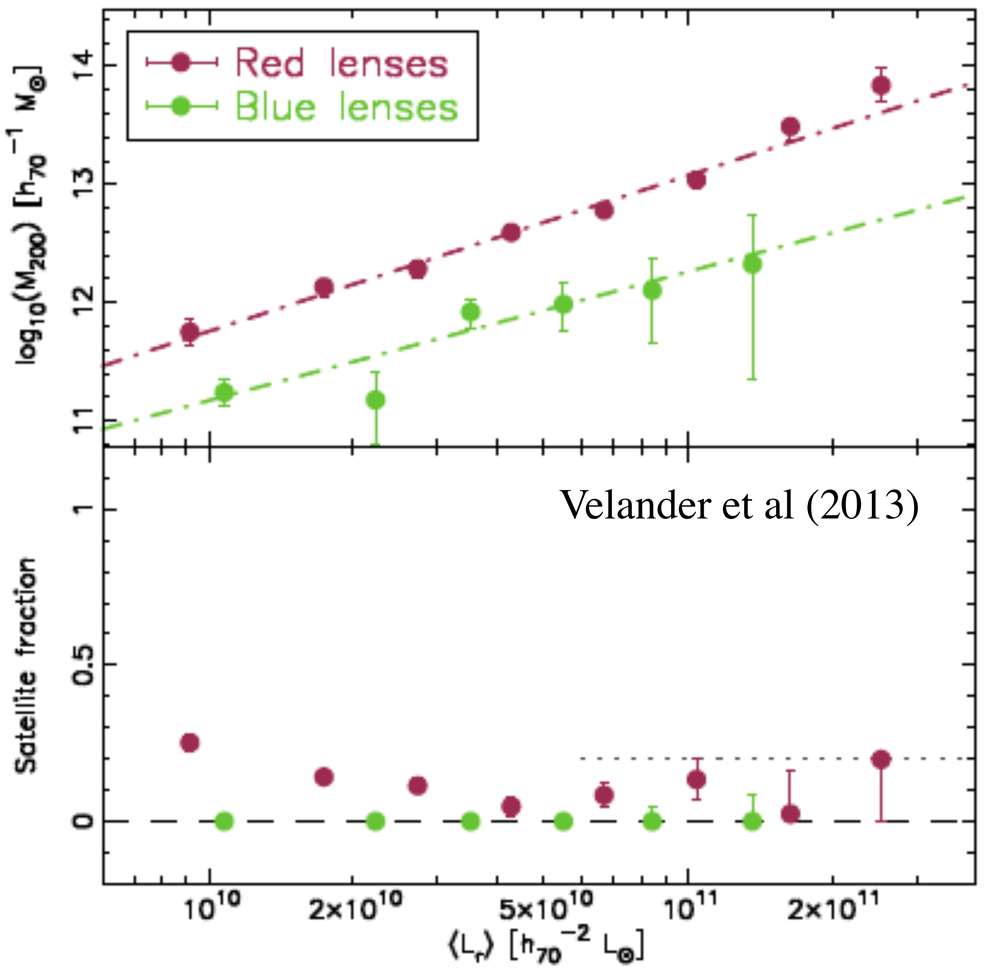
e.g., EUCLID

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

weak gravitational lensing

statistical estimation from large surveys

BIG SCALES
average shear across the universe



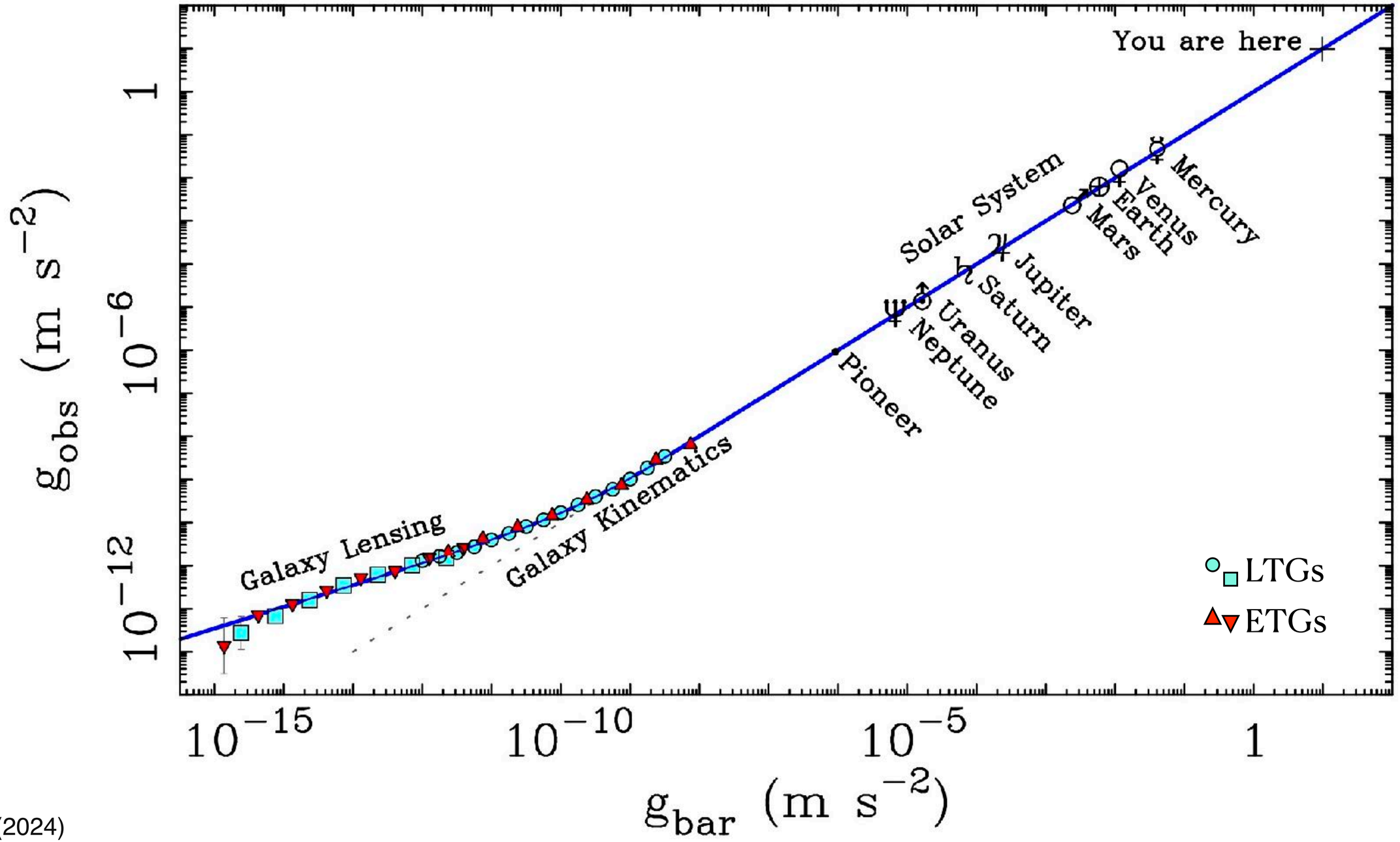
Weak lensing provides a statistical constraint on the total halo mass

see also
Brimioulle et al (2013)

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

weak gravitational lensing

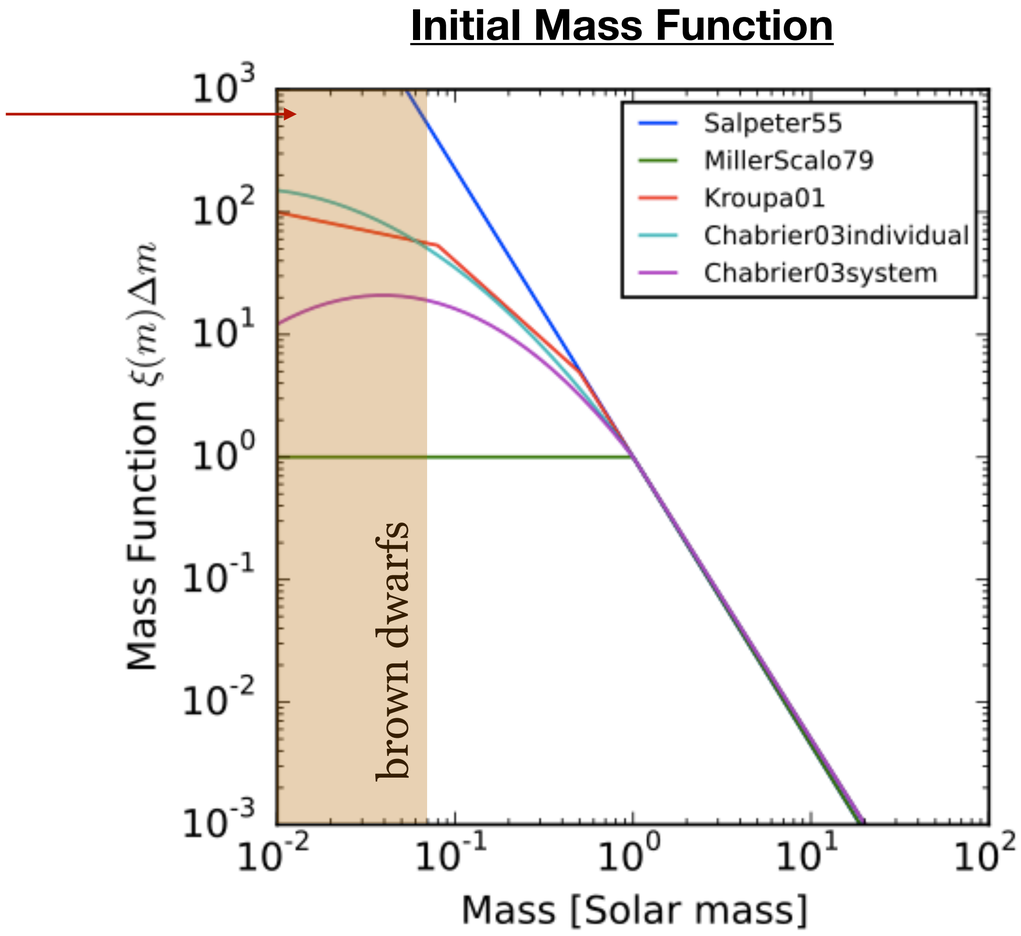
Weak Lensing extends the RAR to very low accelerations



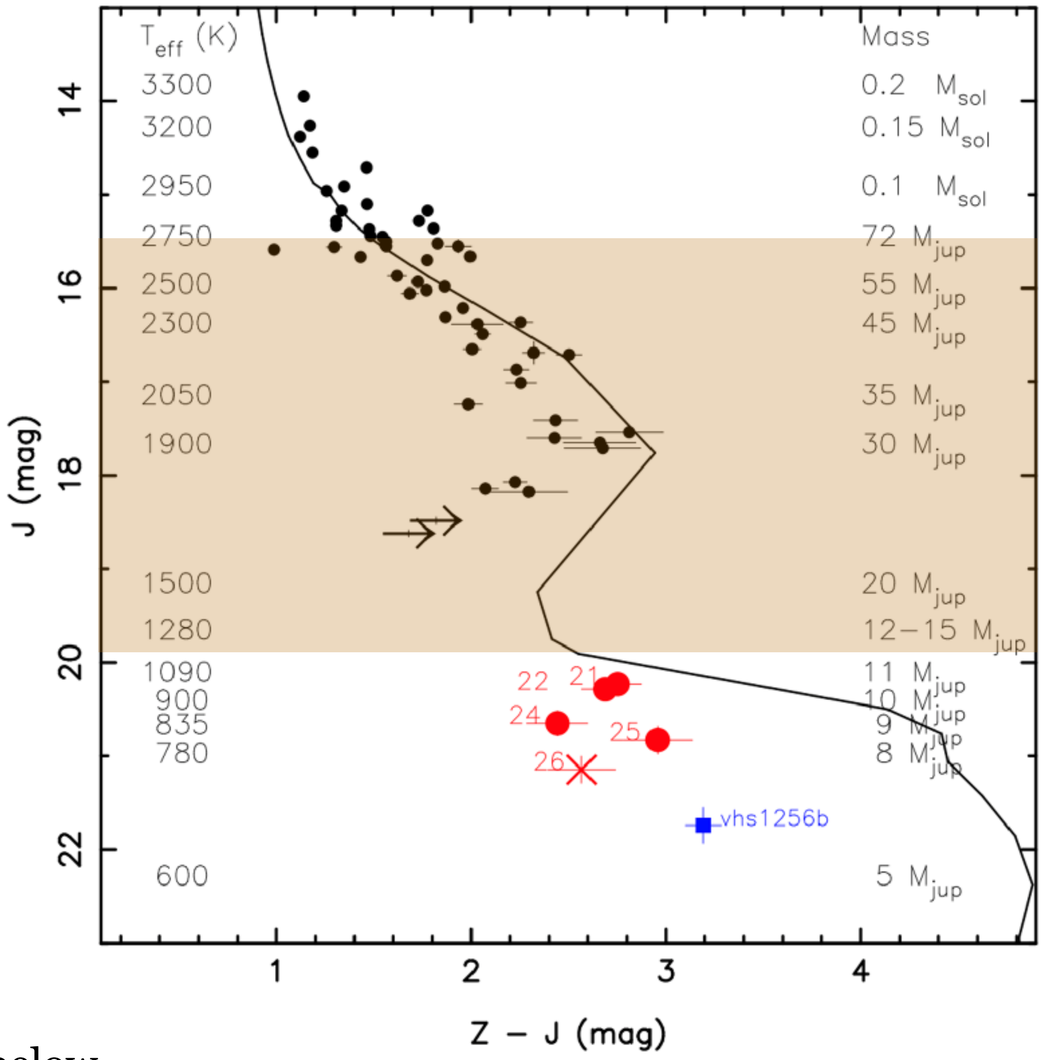
Mistele+ (2024)

Microlensing searches for dark matter

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



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

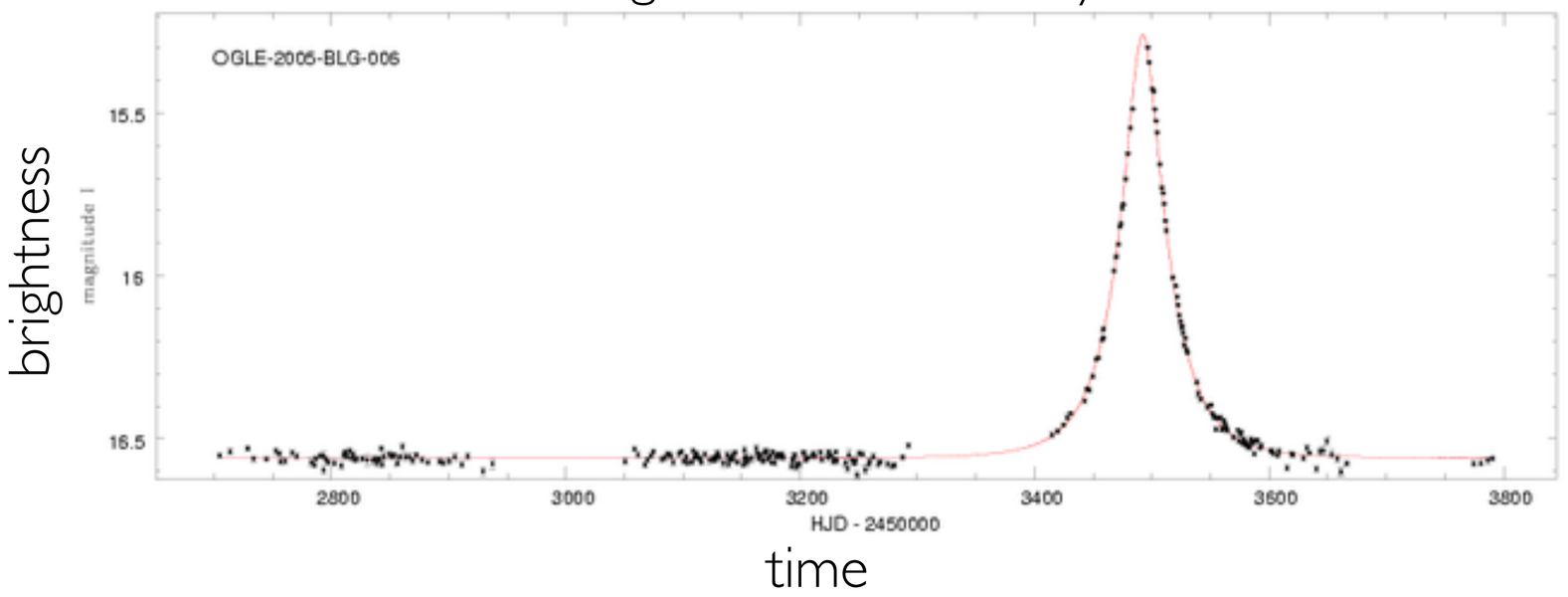


$M_{BD} < 0.07\ M_{\odot}$ brown dwarfs are failed stars below the hydrogen burning limit

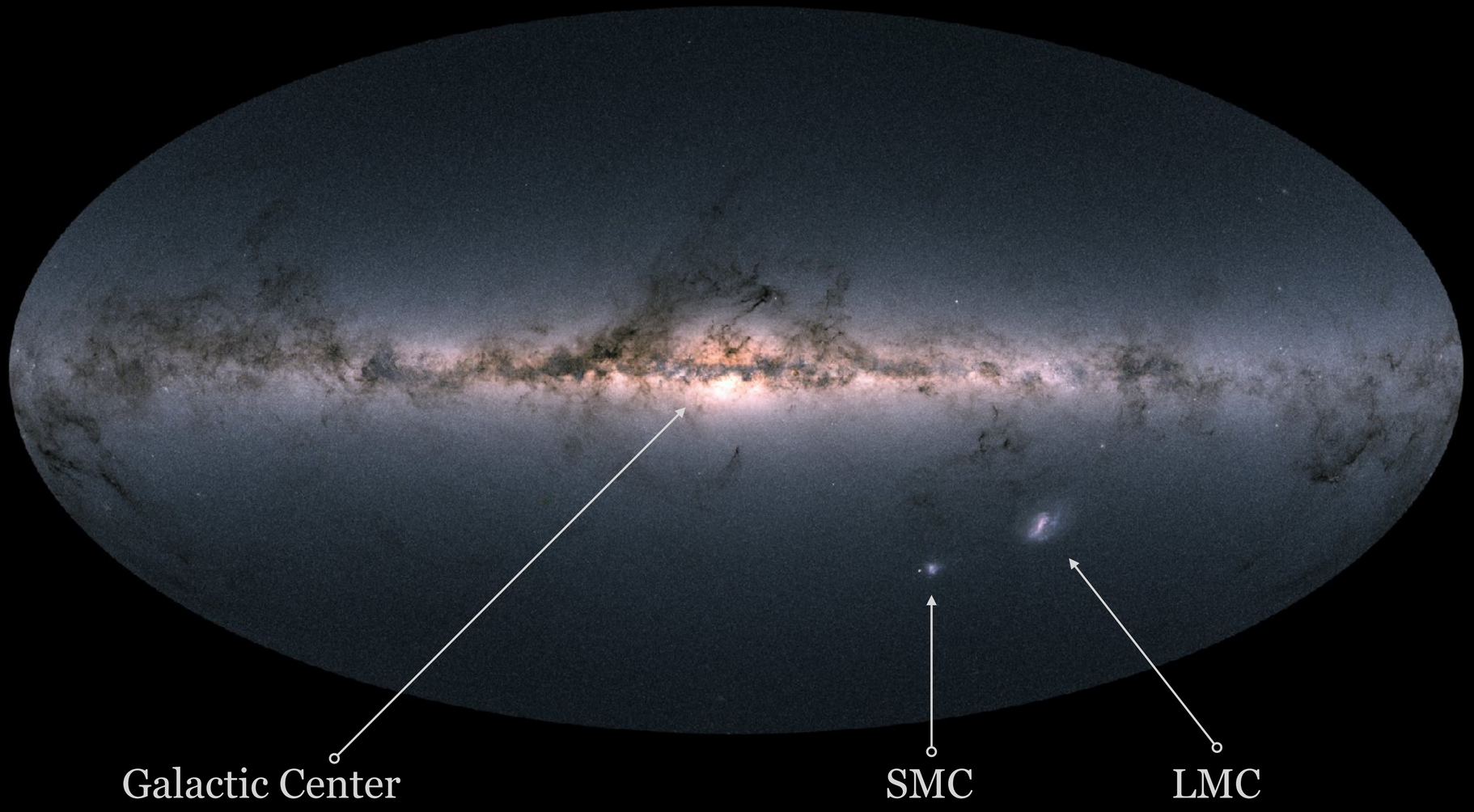
Microlensing surveys:
MACHO, EROS,OGLE

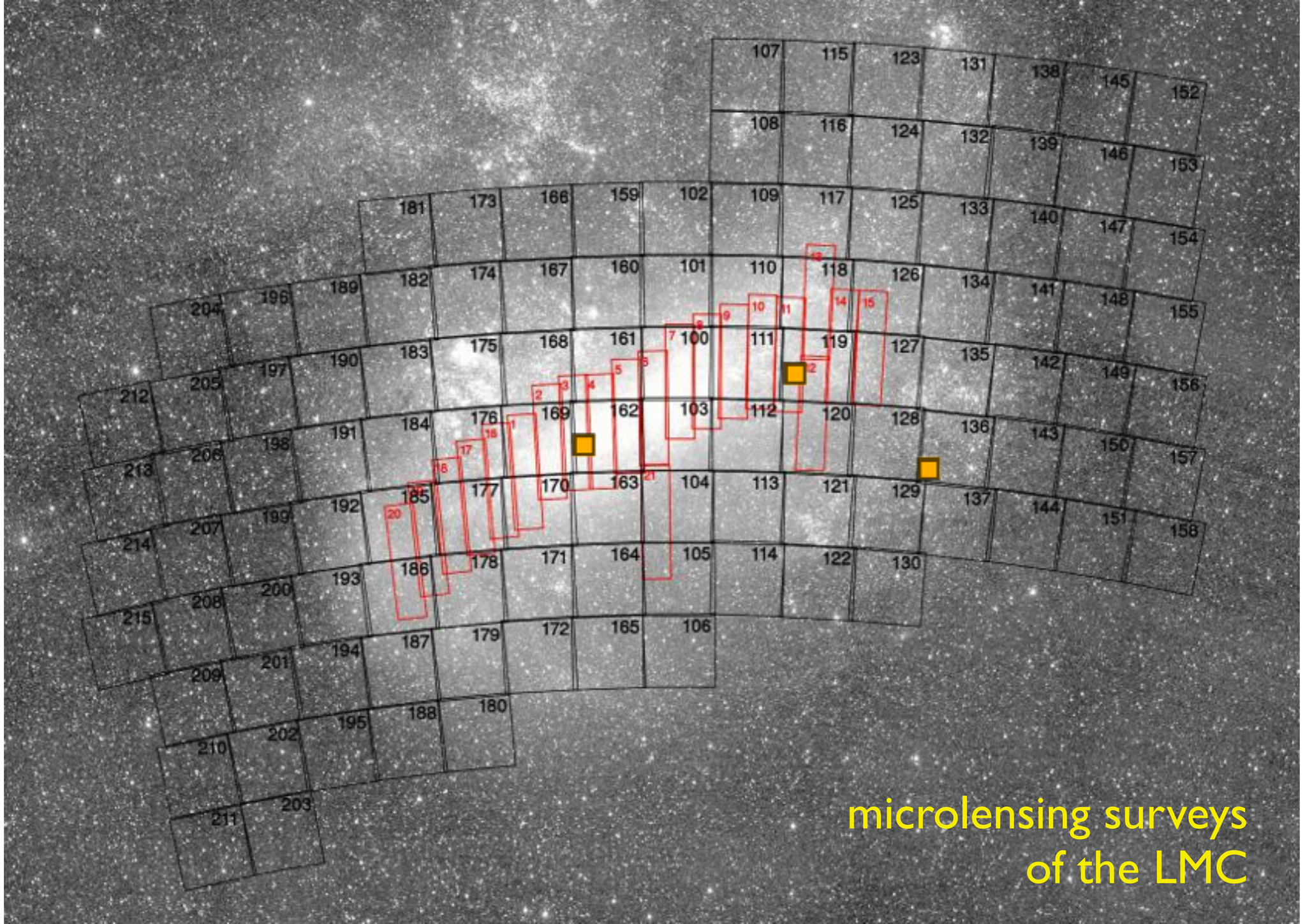
Monitor regions of dense star fields: LMC/SMC/Galactic Center
Watch for microlensing events due to intervening masses
Sensitive to brown dwarfs & stellar mass objects,
including neutron stars and black holes.
Don't detect the object itself, but the light bending effect it causes on background stars

microlensing event observed by OGLE

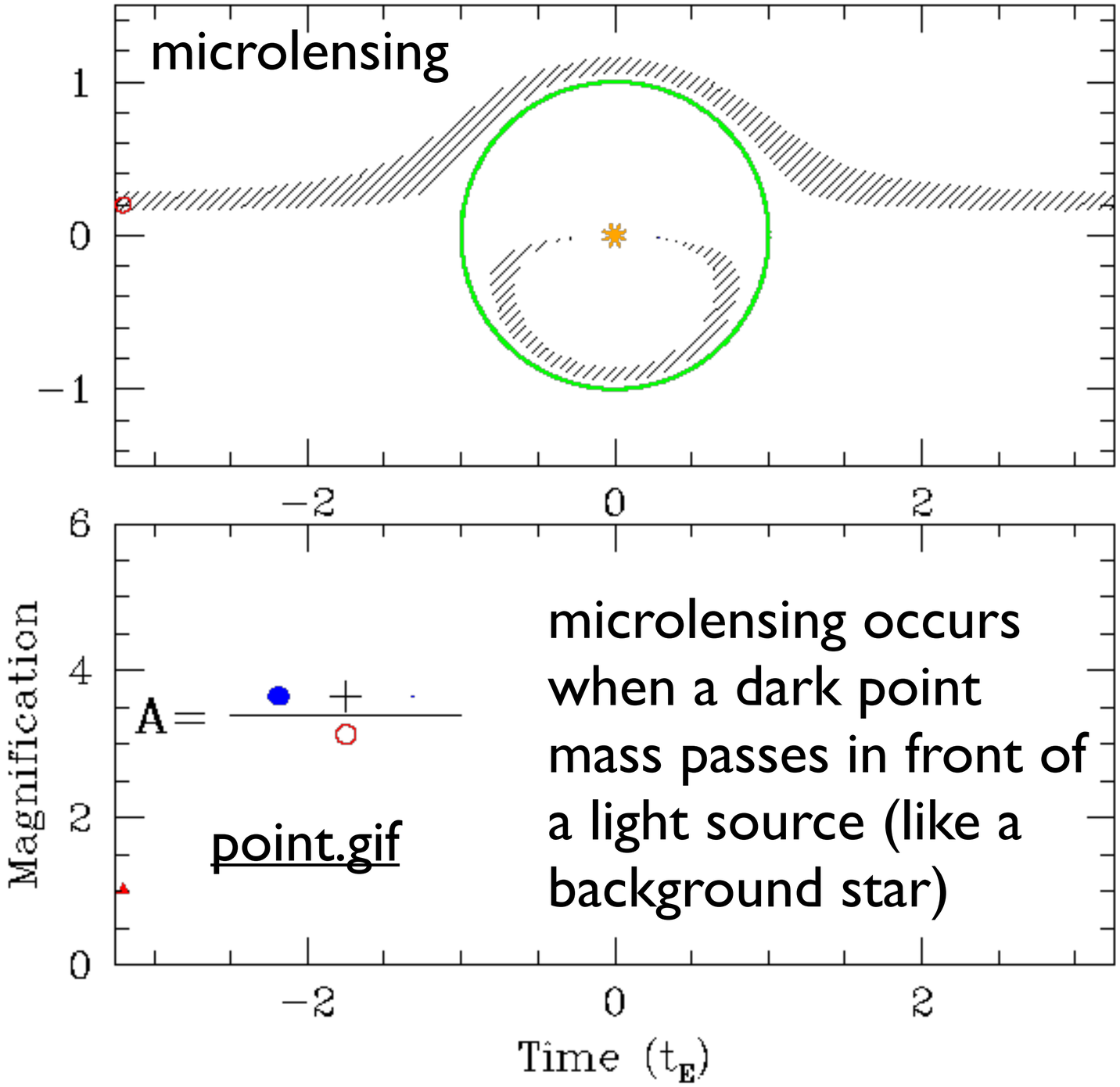


Milky Way in the optical (all sky Gaia data)

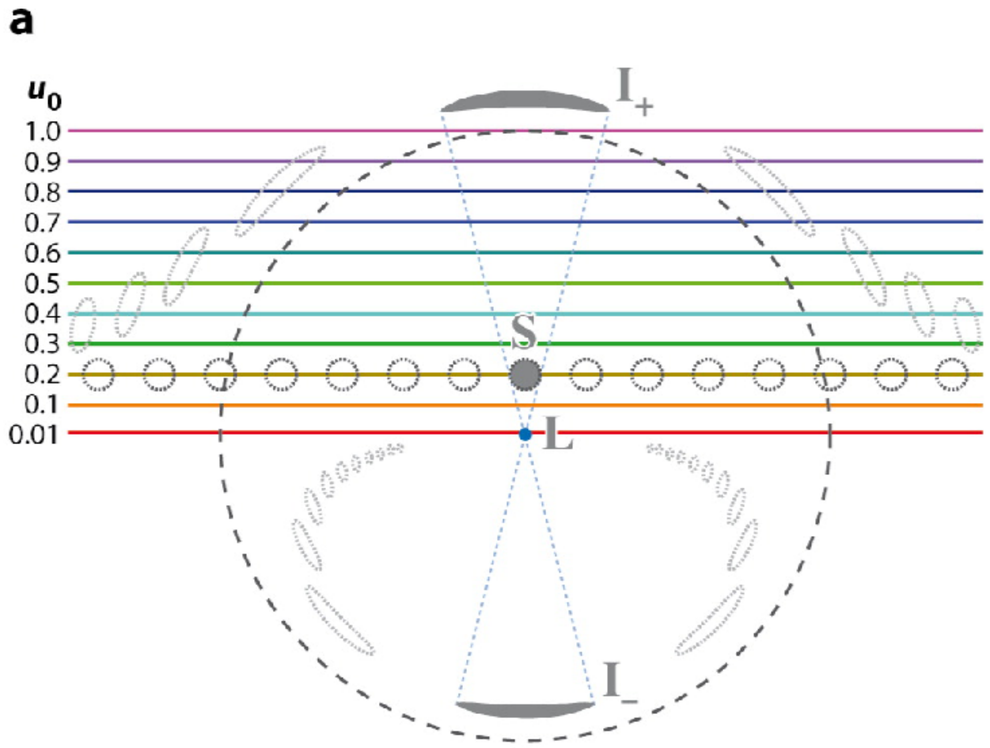


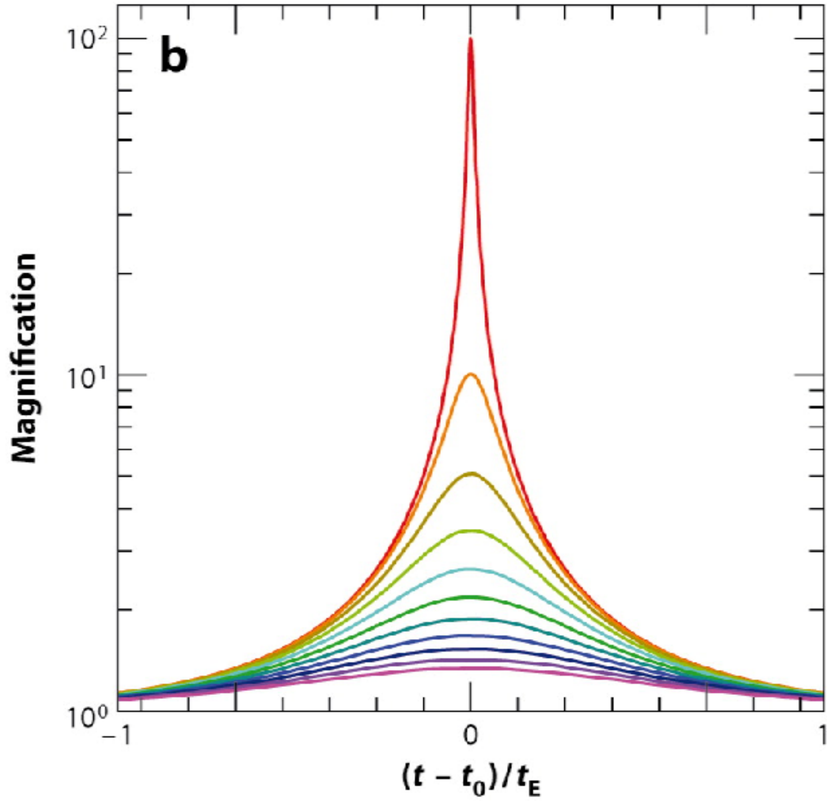

107 115 123 131 138 145 152
108 116 124 132 139 146 153
181 173 166 159 102 109 117 125 133 140 147 154
204 196 189 182 174 167 160 101 110 118 126 134 141 148 155
212 205 197 190 183 175 168 161 100 111 119 127 135 142 149 156
213 206 198 191 184 176 169 162 103 112 120 128 136 143 150 157
214 207 199 192 185 177 170 163 104 113 121 129 137 144 151 158
215 208 200 193 186 178 171 164 105 114 122 130
209 201 194 187 179 172 165 106
210 202 195 188 180
211 203
microlensing surveys
of the LMC

SMALL SCALES



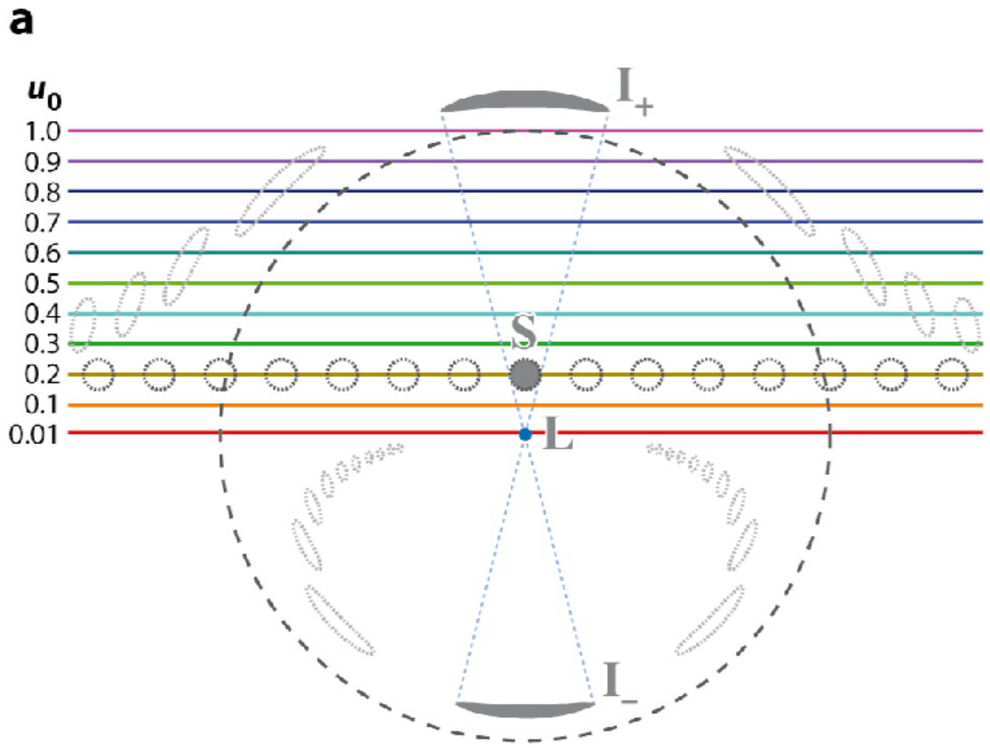
microlensing occurs when a dark point mass passes in front of a light source (like a background star)

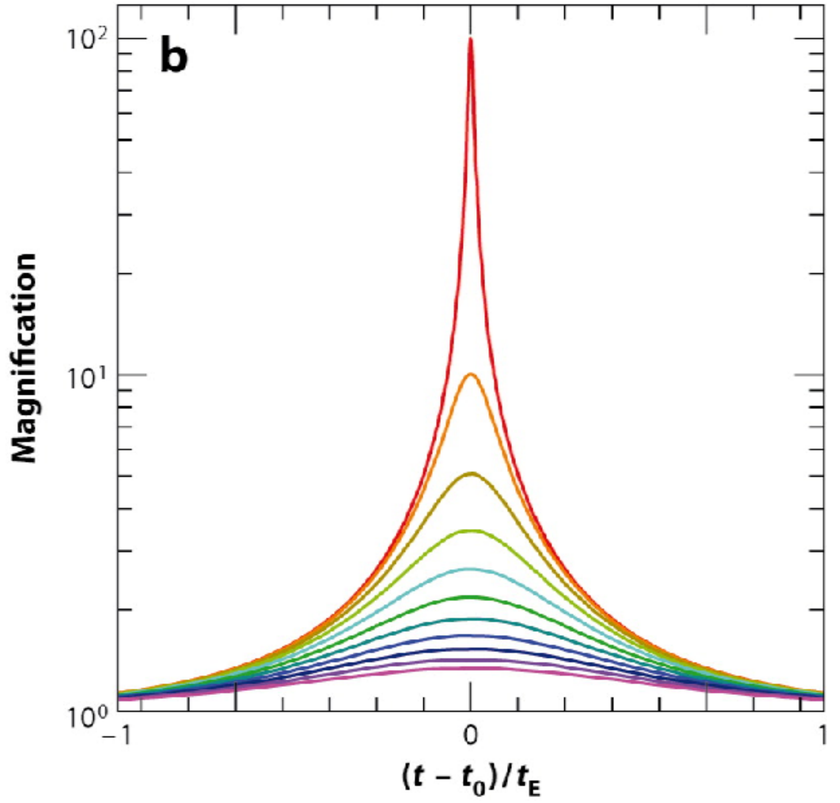




Amplification: $A = \dfrac{2 + u^2}{u\sqrt{4 + u^2}}$ $\qquad u = \dfrac{\theta}{\theta_E}$

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



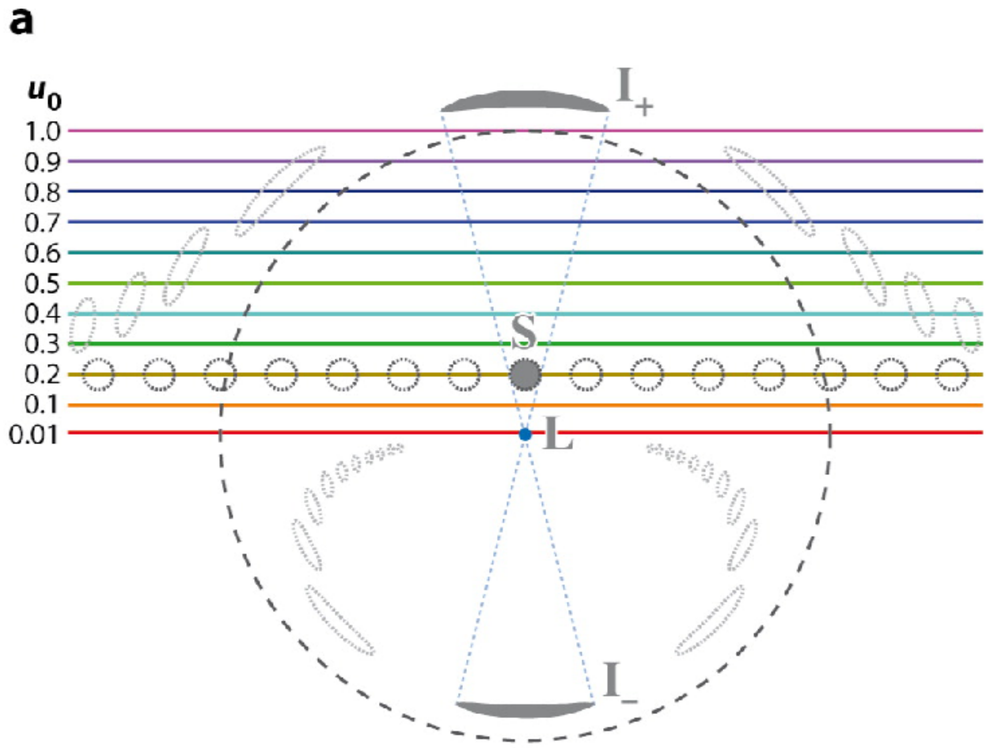


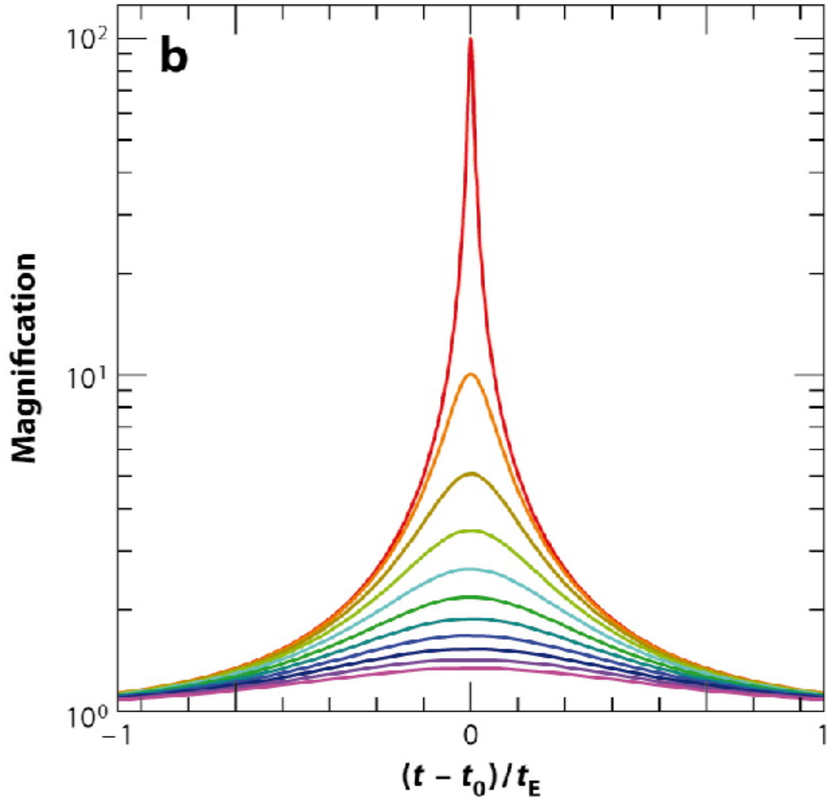
Gaudi BS. 2012.
Annu. Rev. Astron. Astrophys. 50:411–53

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

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





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

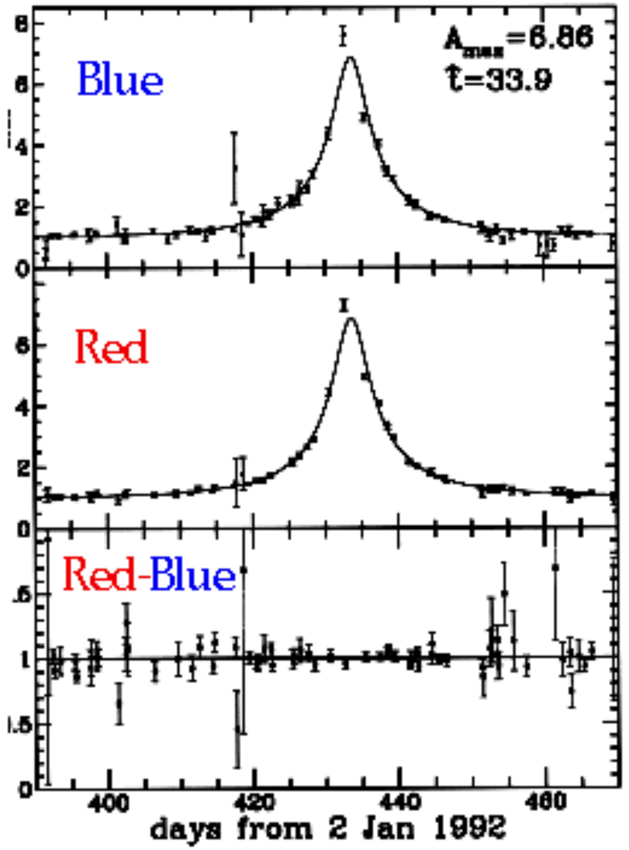
$$\tau = 2\pi \left(\frac{\sigma}{c}\right)^2 \frac{D_L D_{LS}}{R_0 D_S}$$

to the LMC

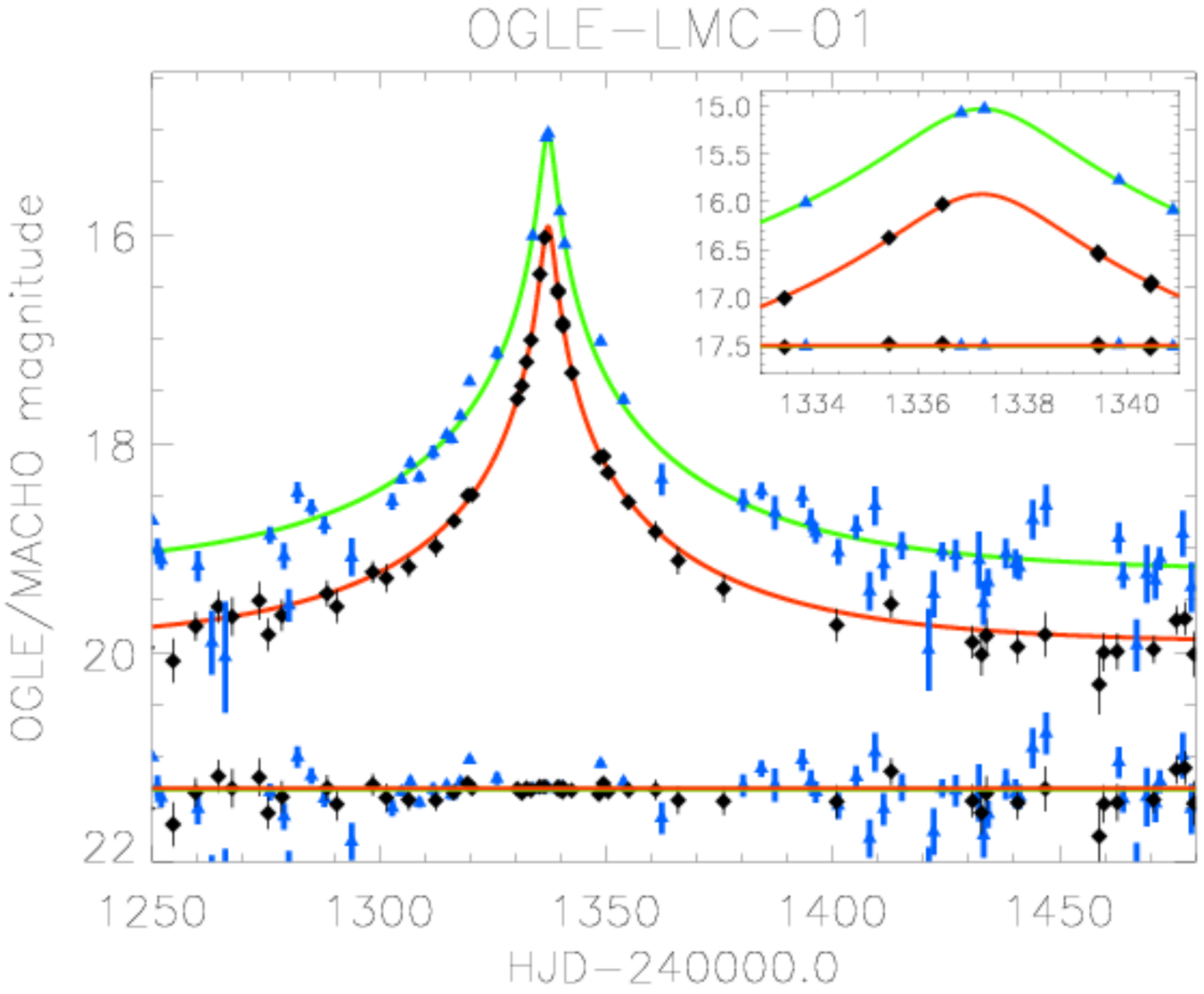
$$D_L \approx D_{LS} \approx D_S/2$$

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

microlensing events achromatic

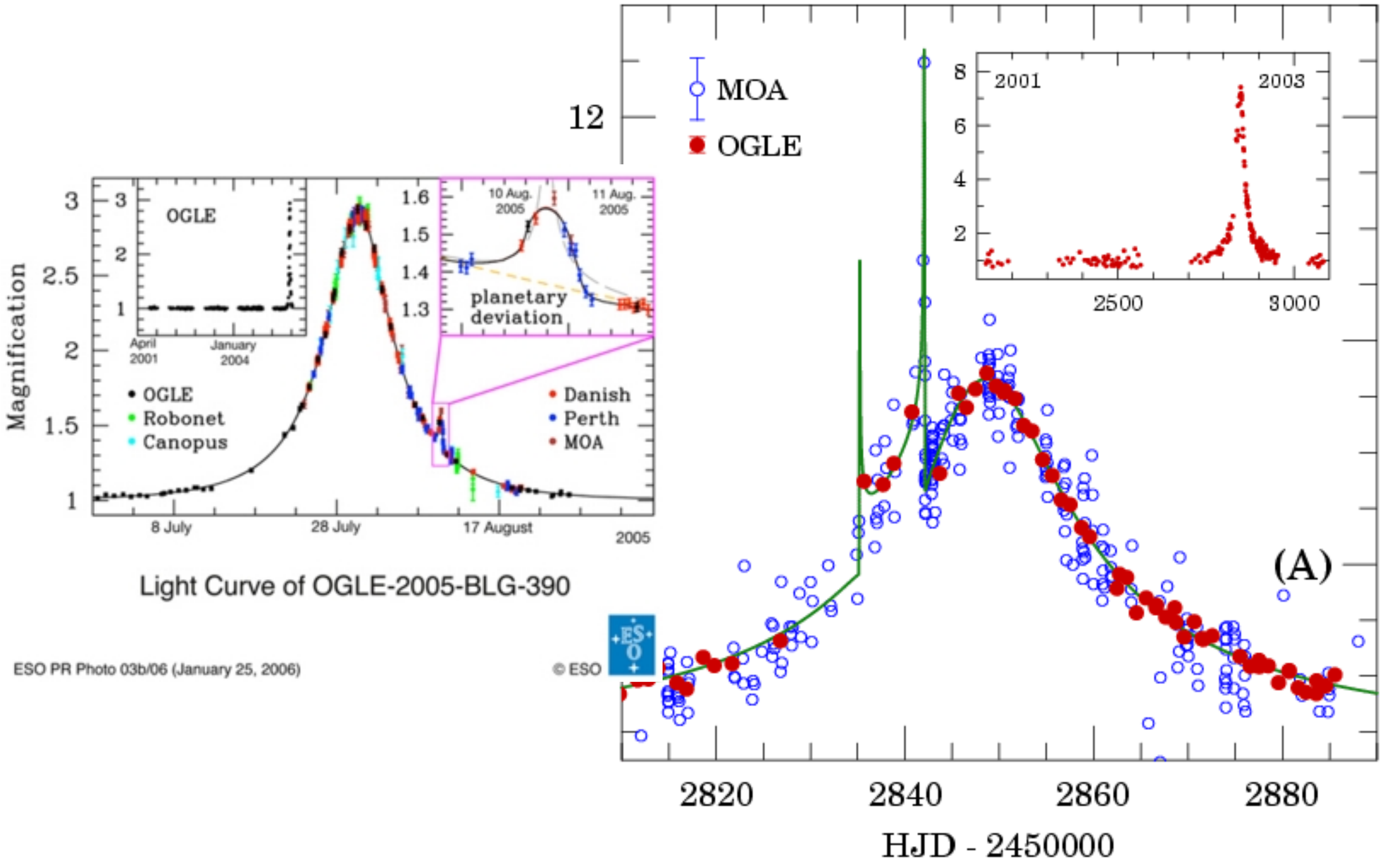


should also be symmetric in time
(unless there is a companion planet)



achromatic macho candidate event

Planet detections by microlensing



Number of microlensing events

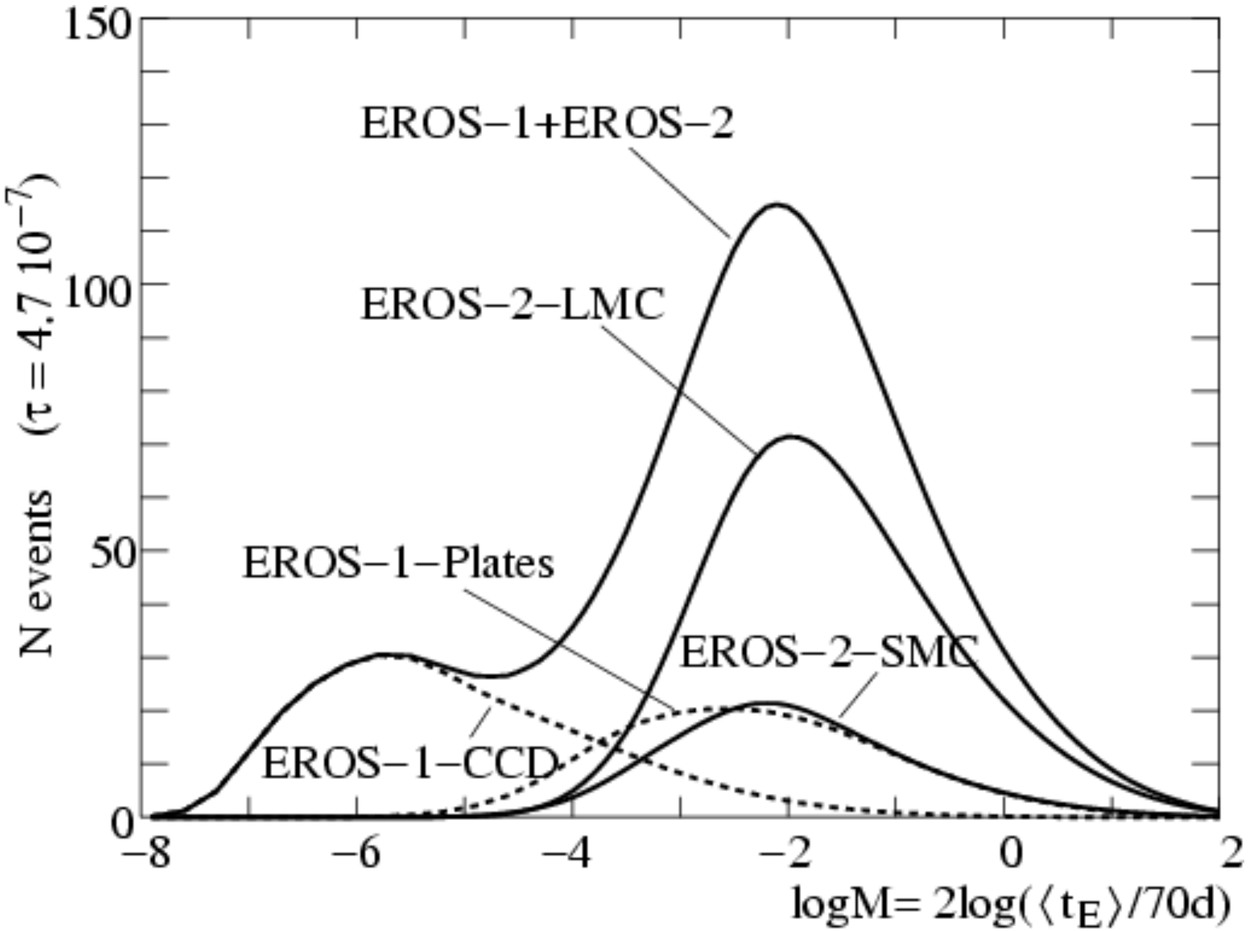
$$N(>A) = \frac{2\tau}{(A^2-1) + A\sqrt{A^2-1}}$$

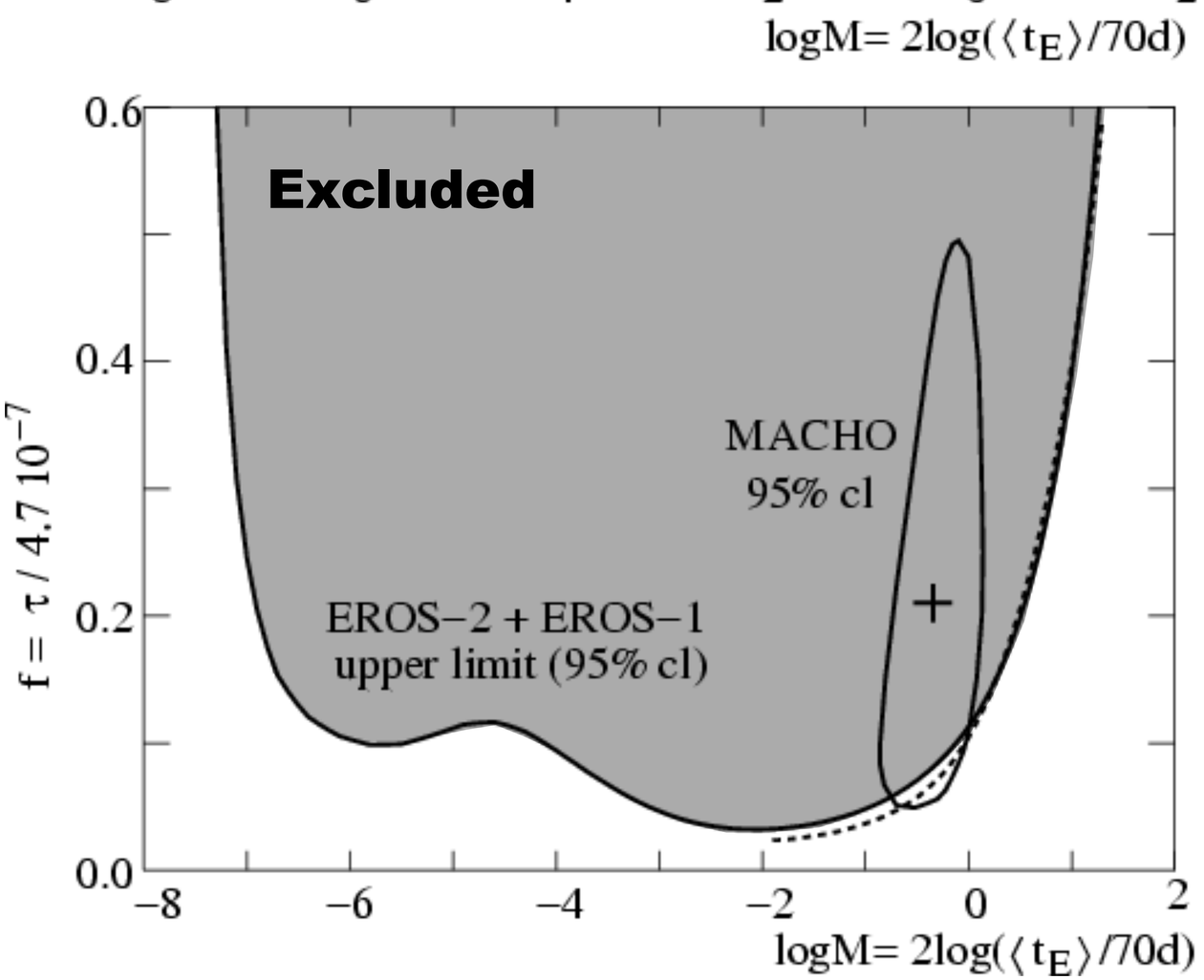
optical depth as a fcn of radius through an isothermal sphere

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

optical depth = fraction of the sky covered by Einstein rings

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

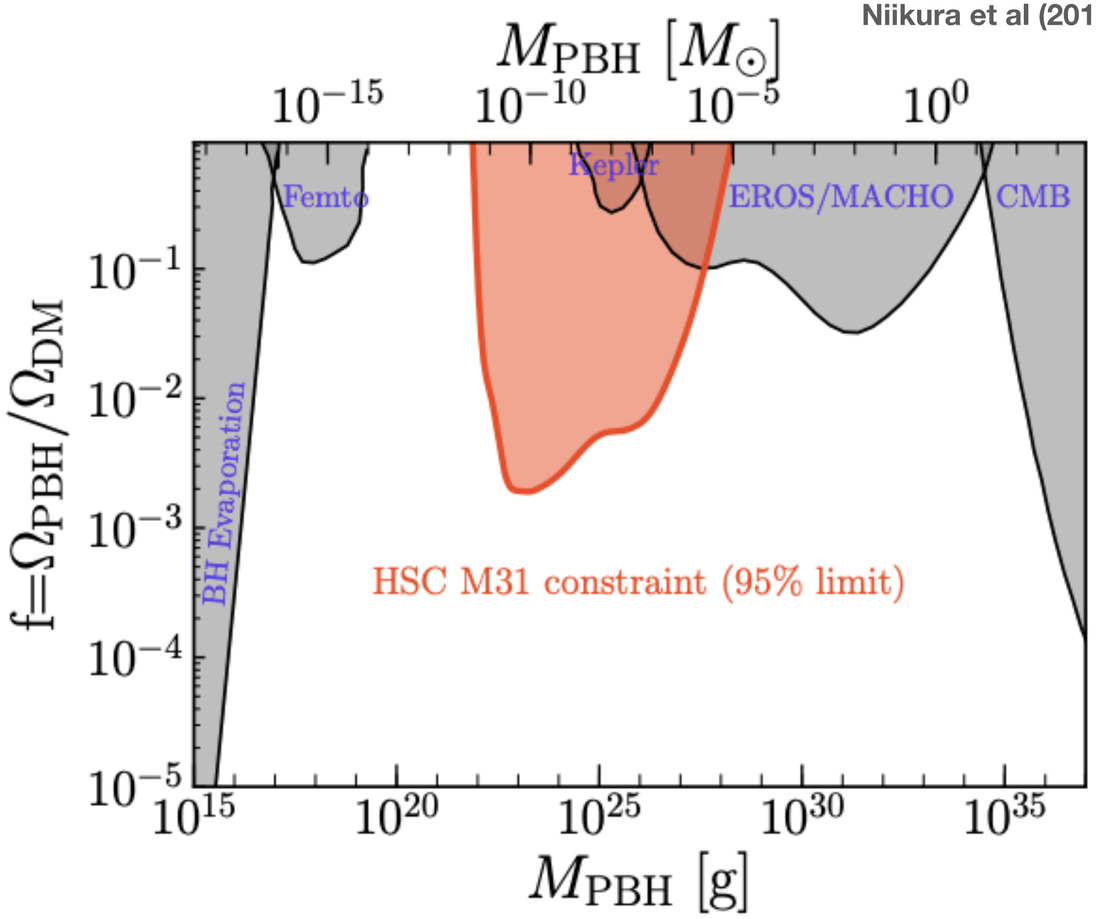




The observed rate of microlensing events leaves no room for the dark matter halo of the Milky Way to be composed of massive compact objects like brown dwarfs or black holes in the mass range $10^{-7} < M < 10$ solar masses.

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].

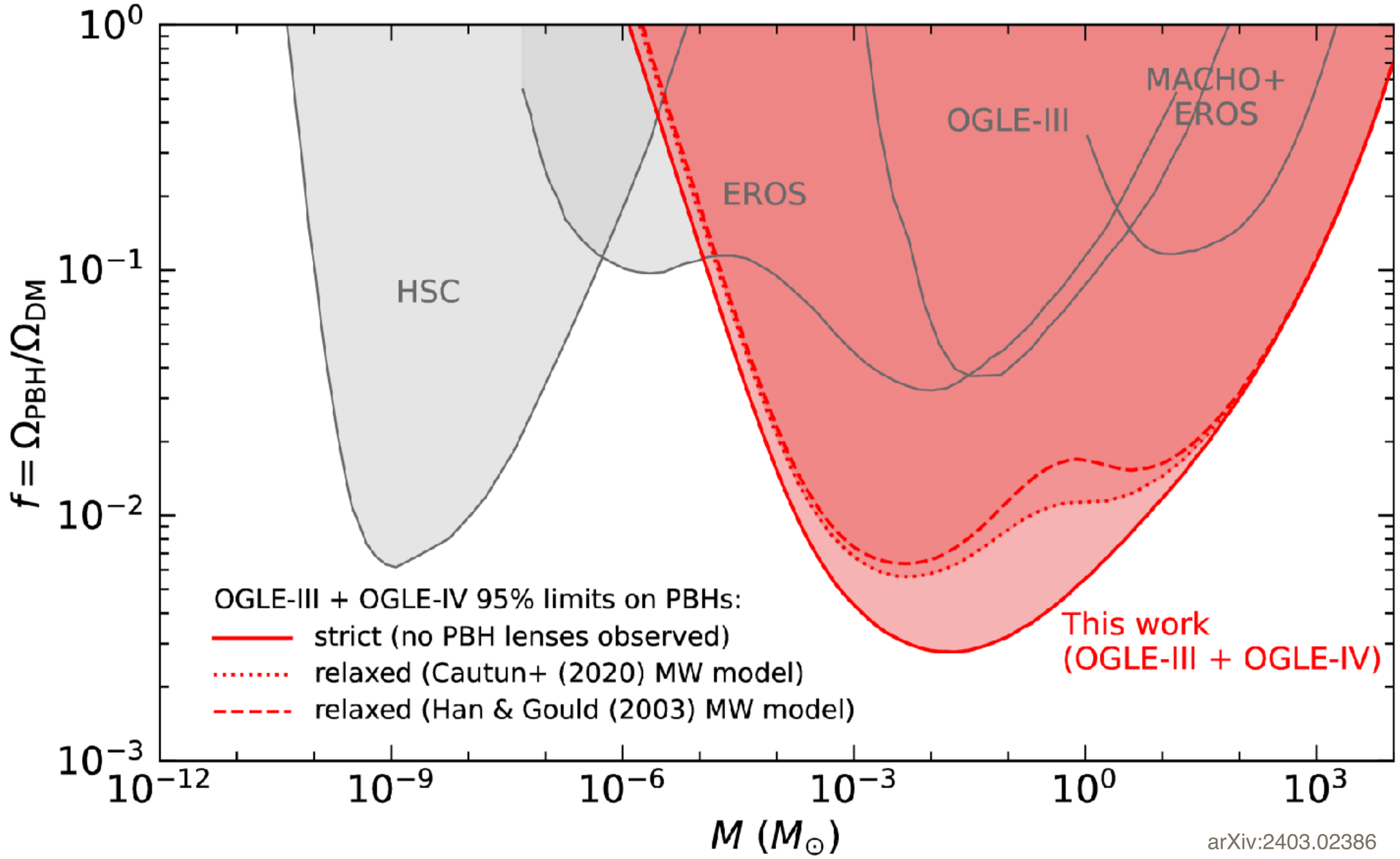
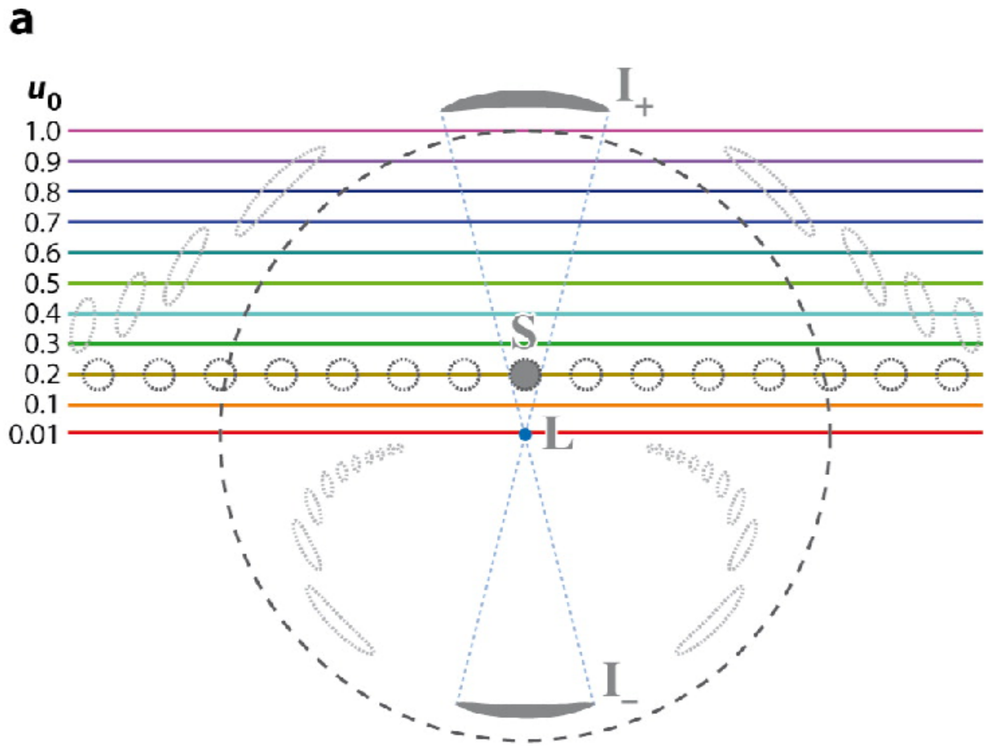
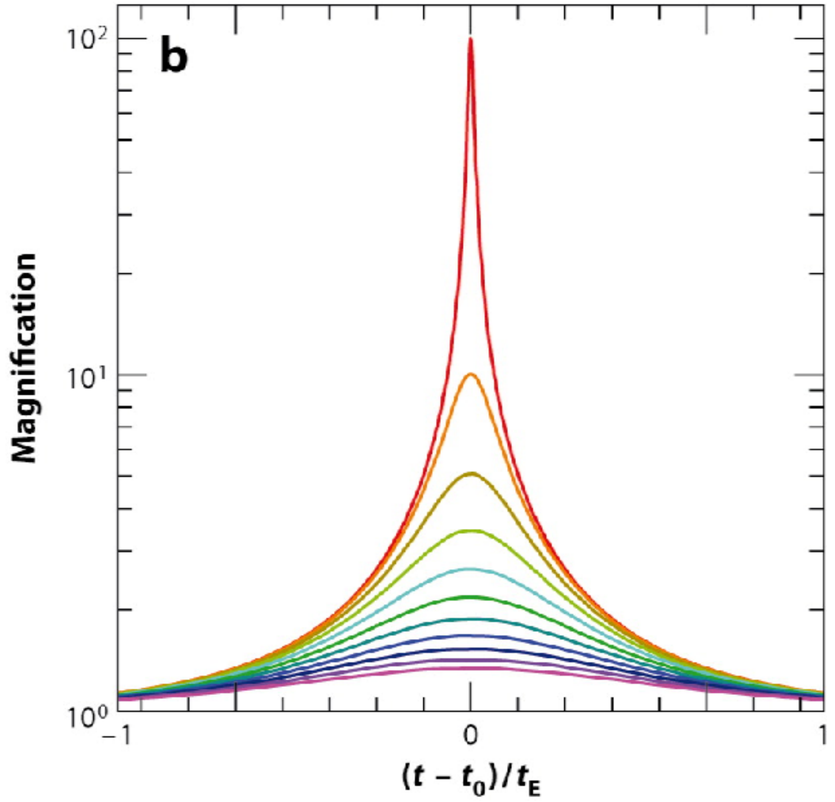


Figure 1: 95% upper limits on PBHs (and other compact objects) as constituents of dark matter. The solid red line marks the limits derived in this paper under the assumpt microlensing events detected by OGLE in the direction of the LMC are due to objects in the LMC itself or the Milky Way disk. If this assumption is relaxed, the limits (d depend on the choice of the Milky Way disk model ([23] or [24], respectively). The gray lines mark the limits determined by the following surveys: EROS [16], OGLE-III [1 (HSC) [25], and MACHO+EROS [18]. The new limits are publicly available online at https://www.astrouw.edu.pl/ogle/ogle4/LMC_OPTICAL_DEPTH/.





Microlensing towards Galactic Center

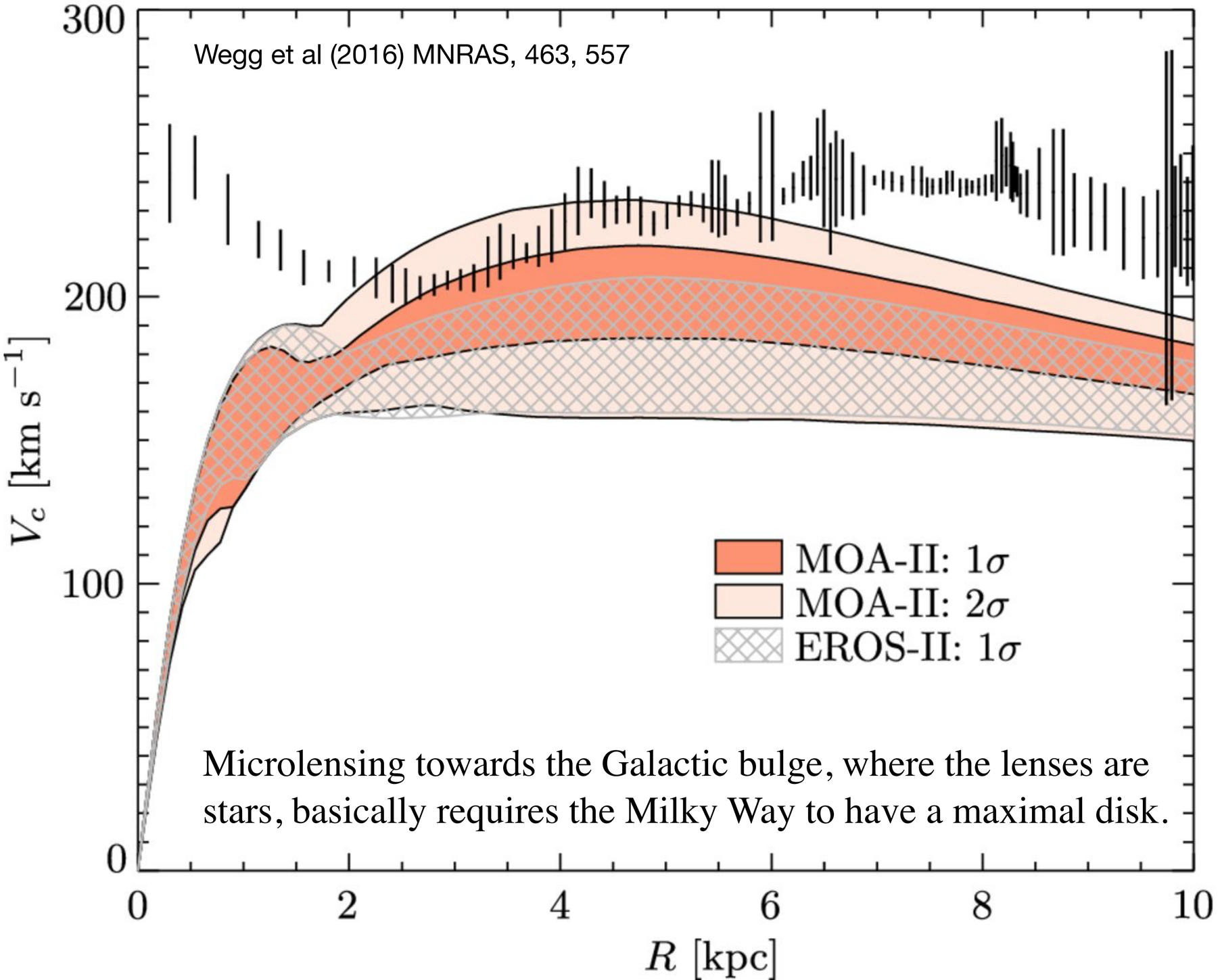
$$t_E = \frac{\theta_E}{\mu_{rel}}$$

Einstein crossing time: time to cross Einstein ring.

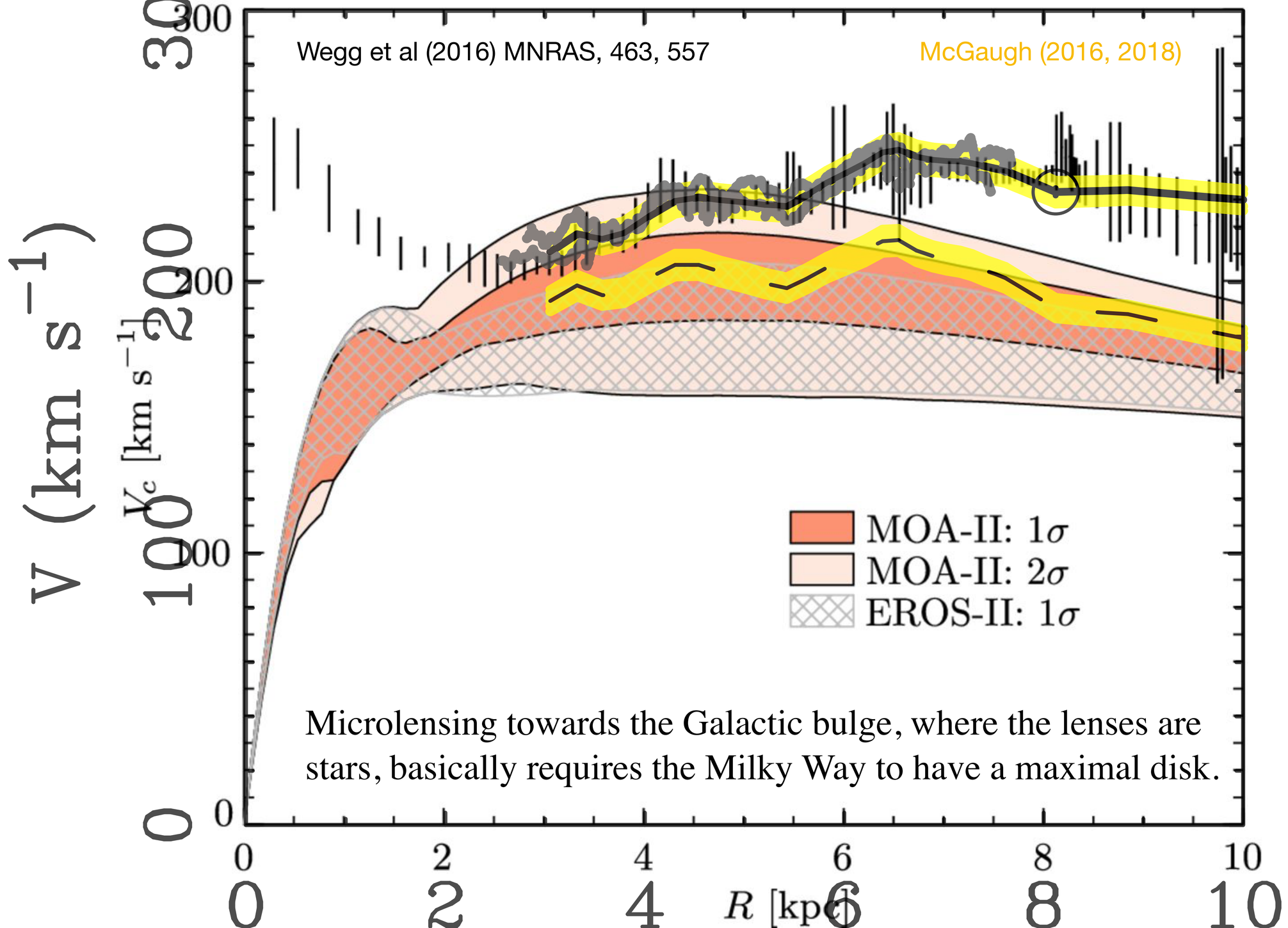
$$t_E \approx (24.8 \text{ days}) \left(\frac{M}{0.5\ \mathrm{M}_\odot}\right)^{1/2} \left(\frac{\pi_{rel}}{125\ \mu\mathrm{as}}\right)^{1/2} \left(\frac{\mu_{rel}}{10.5\ \mathrm{mas\,yr}^{-1}}\right)^{-1}$$

lens mass *parallax* *proper motion*

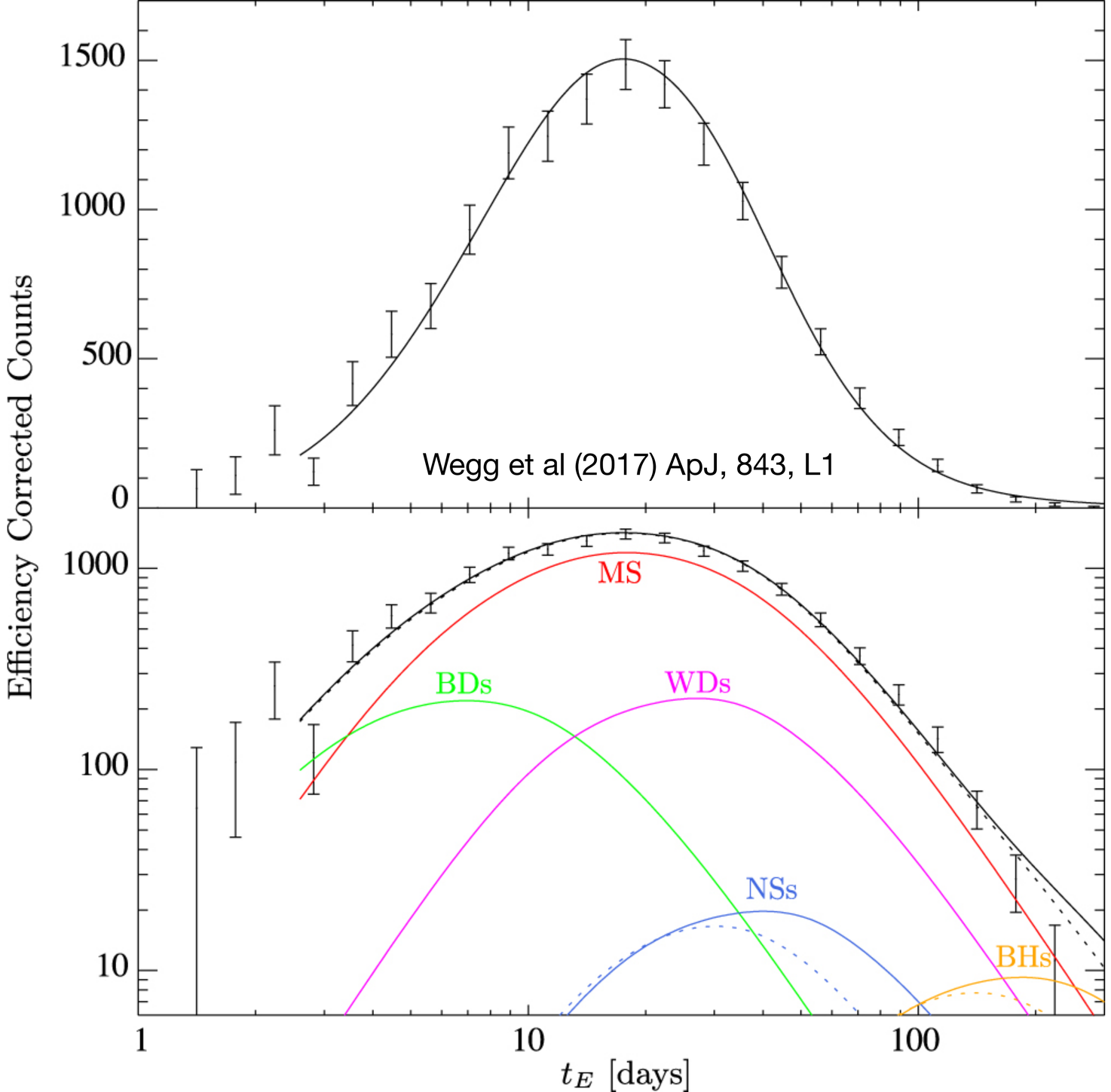
for lensing events towards the Galactic bulge.



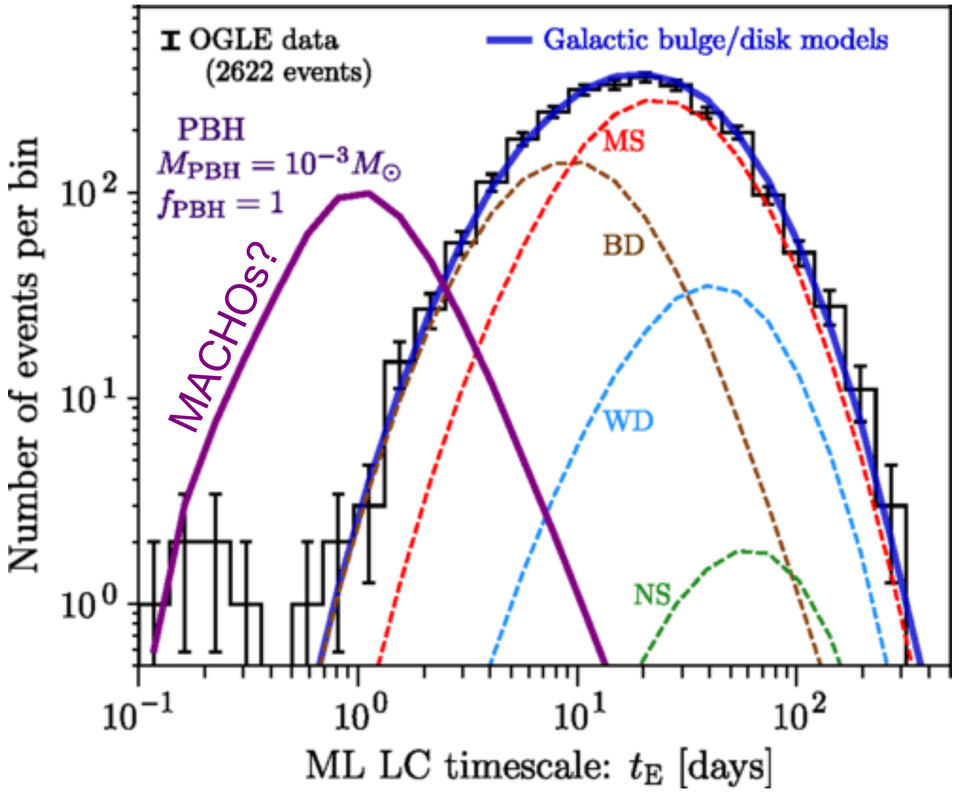
Microlensing towards the Galactic bulge, where the lenses are stars, basically requires the Milky Way to have a maximal disk.


Wegg et al (2016) MNRAS, 463, 557
McGaugh (2016, 2018)
V (km s^{-1})
V_c [km s^{-1}]
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 events towards the Galactic Center



well explained by known stars and stellar remnants
without room for extra MACHOs

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