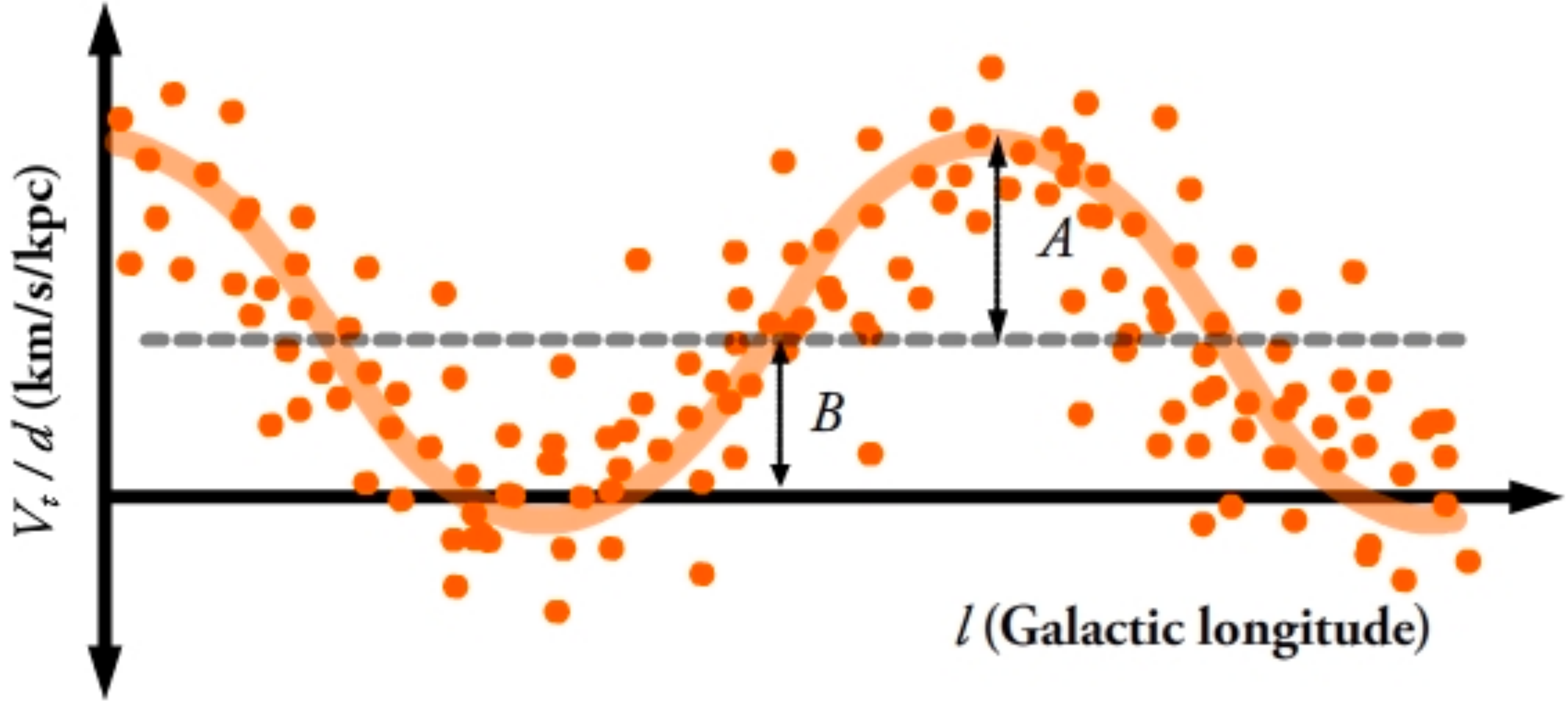
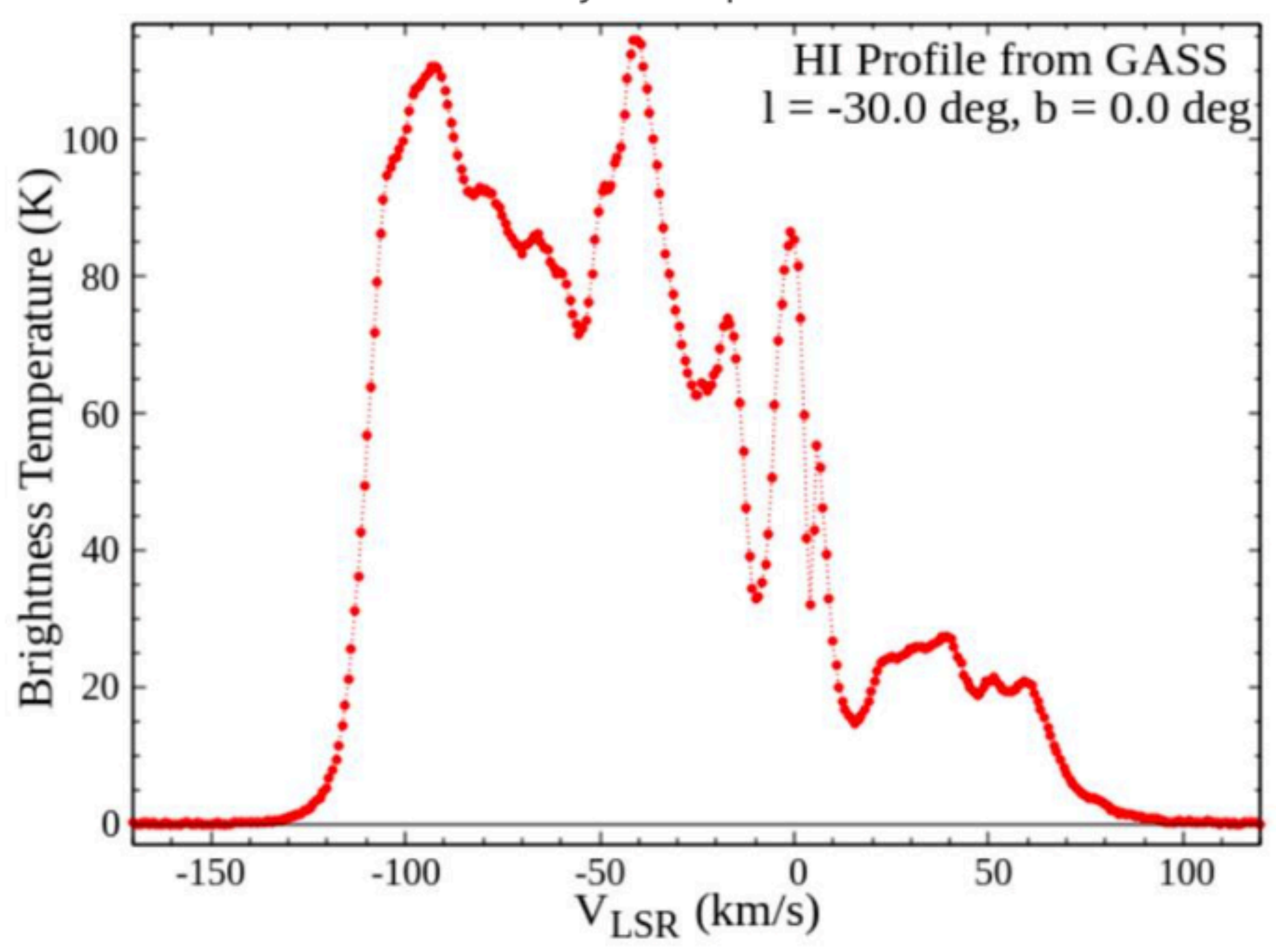
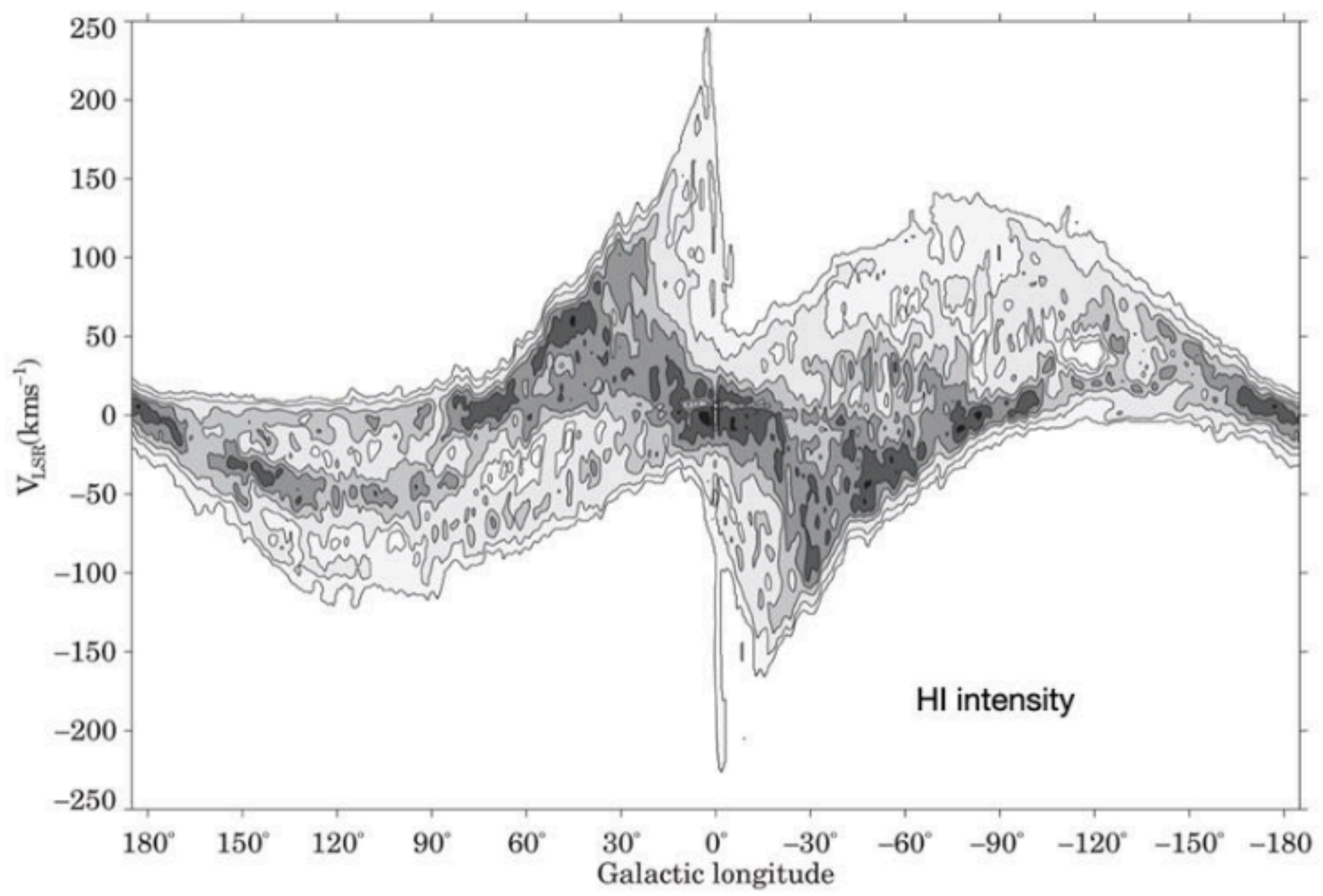
PH365: Lecture III

measuring Oort parameters from proper motion of stars in solar neighbourhood



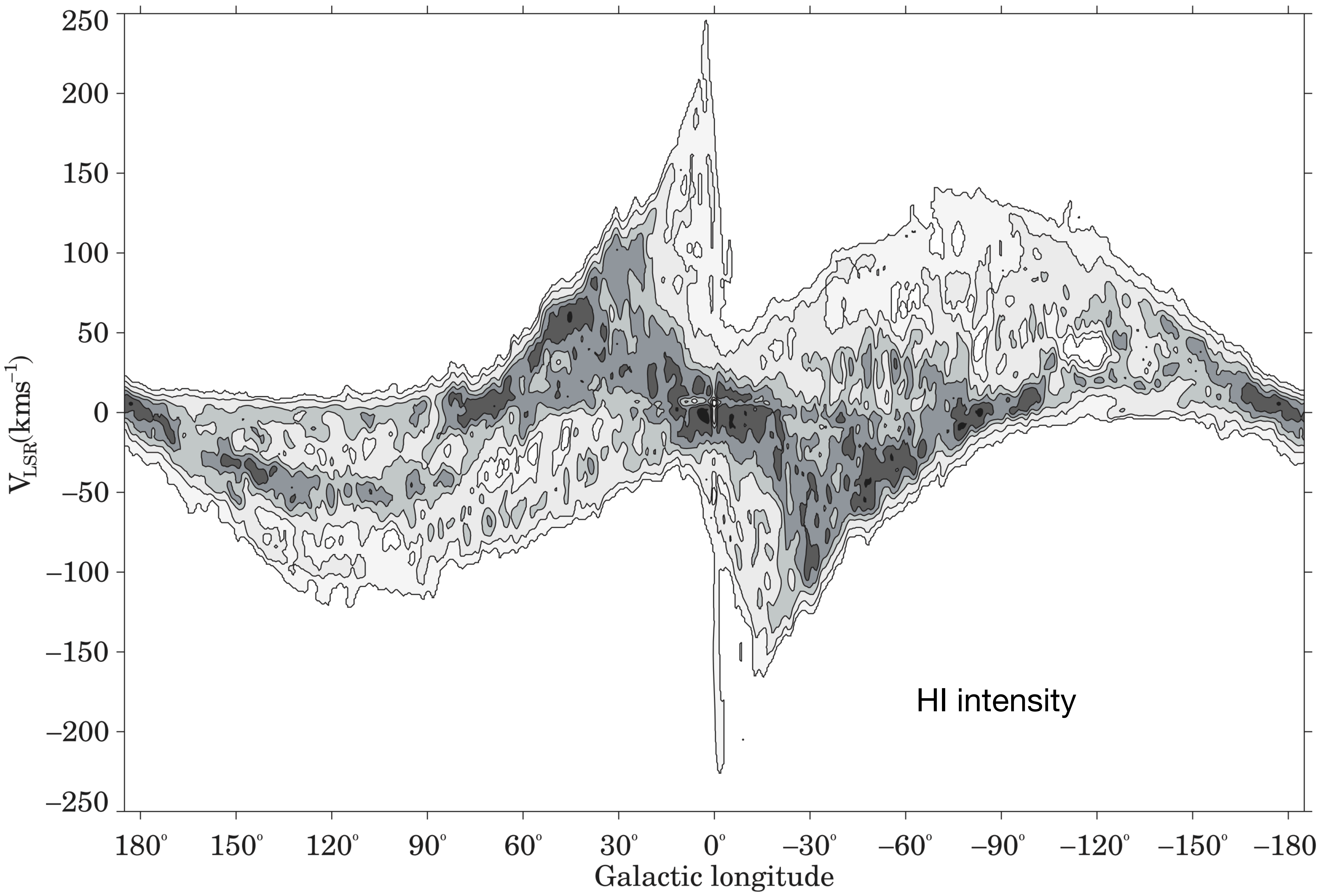


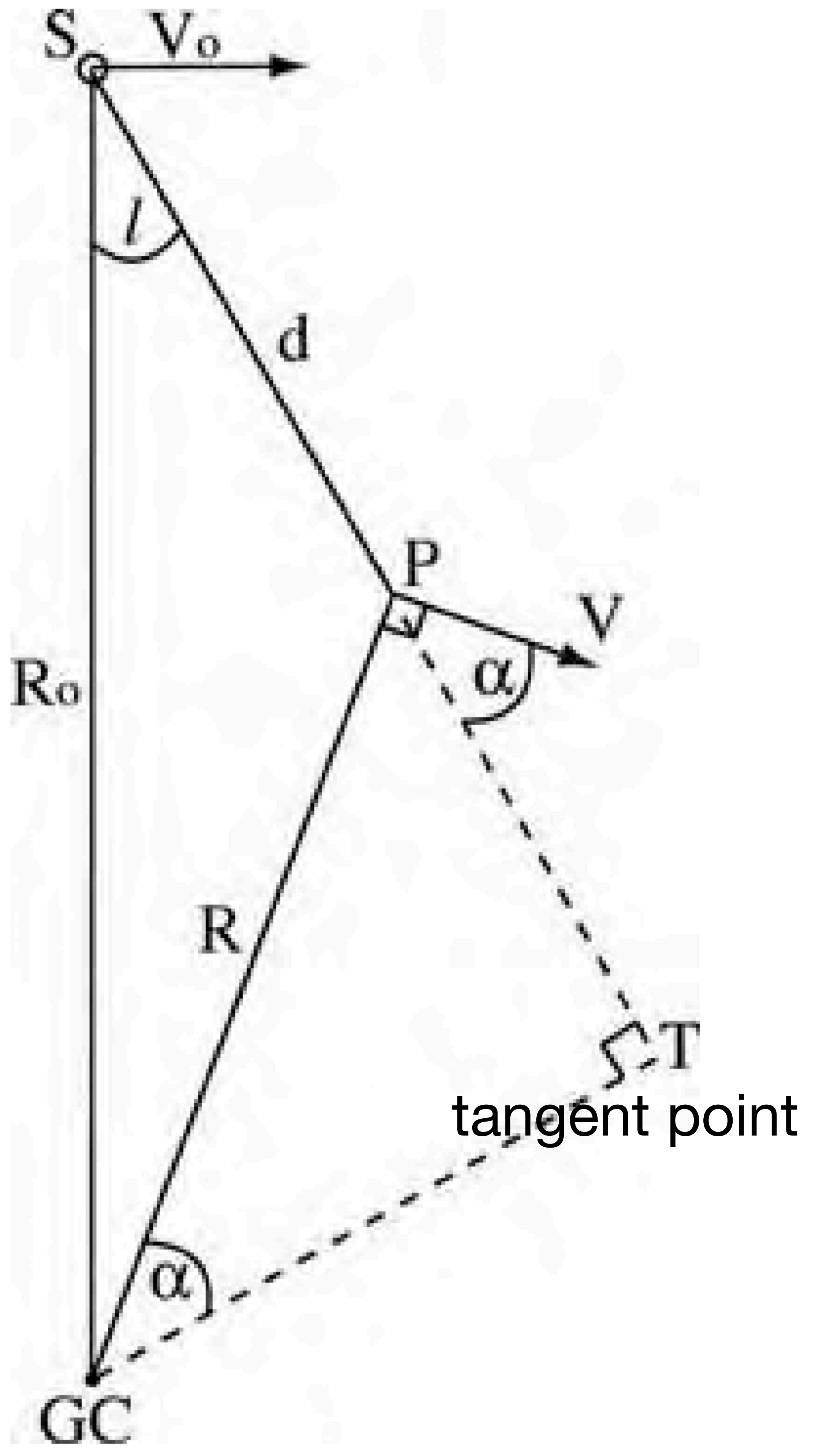
[General](#) this is an example of HI intensity spectrum as a function of the velocity relative to the local standard of rest (average velocity of stars in solar neighborhood) along l=-30 degrees. The velocity at the tangent point corresponds to the maximum radial velocity (~-110 km/s corresponds to a radius of R_t = |R_0 sin(l)|, so we calculate the circular velocity at R_0/2 to be ~ 220 km/s [be careful with signs! a value similar to solar velocity around Galactic center]; a negative value corresponds to blueshift). The maximum positive V_r at ~80 km/s comes from HI gas outside the solar circle but along l=-30 deg. V_r = 0 corresponds to the gas at the solar circle but on the other side of this line of sight (LOS). The peaks in HI intensity comes from dense HI (e.g., spiral arms) along this LOS. Such spectra along different l (Galactic longitudes) can be combined to form the HI intensity contour plots as a function of V_r versus longitude (below). Such a plot tells us a lot about the structure of HI in our Galaxy.



Here are some more details: https://physicsopenlab.org/2020/09/08/milky-way-structure-detected-with-the-21-cm-neutral-hydrogen-emission/

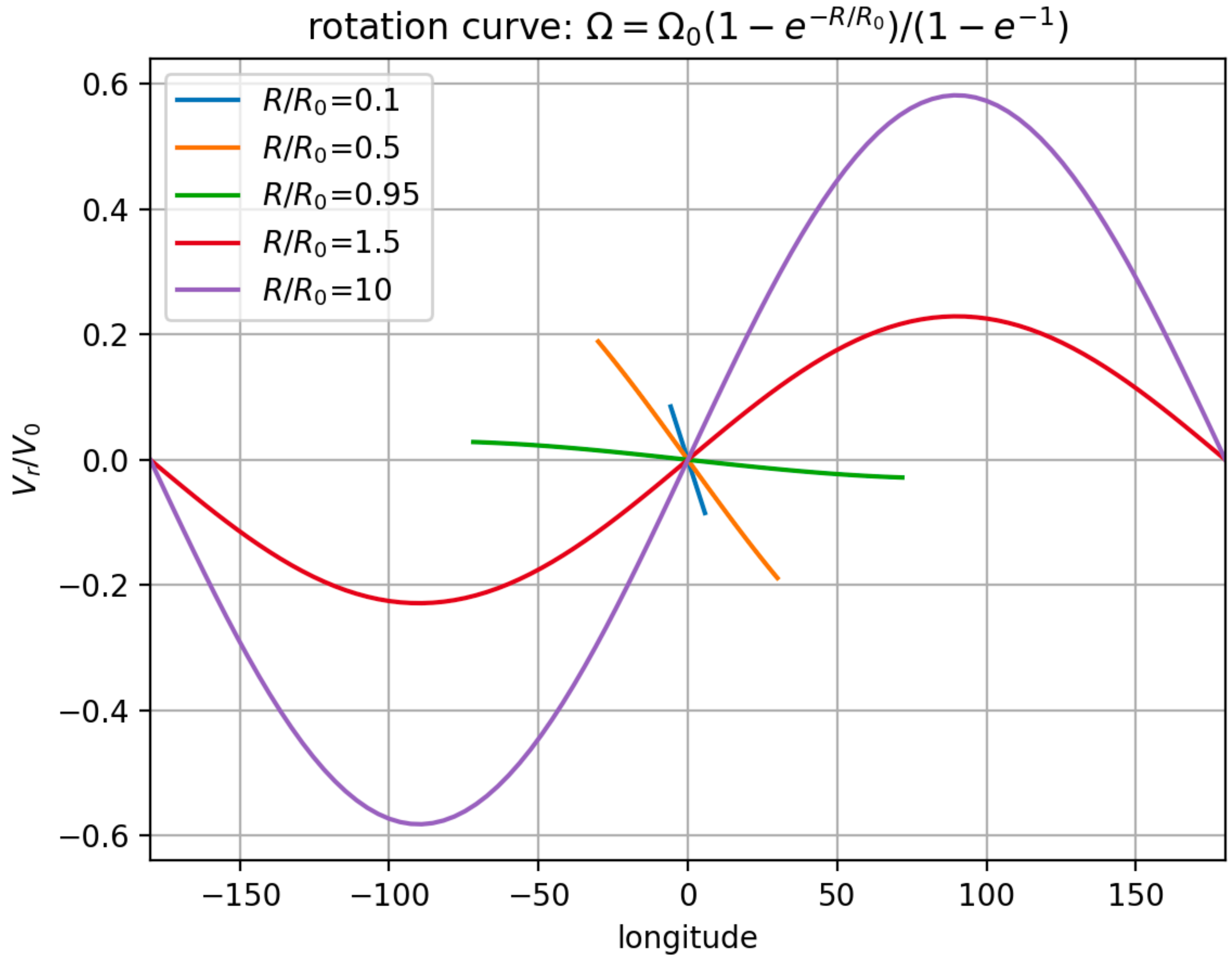
HI kinematics from 21 cm emission

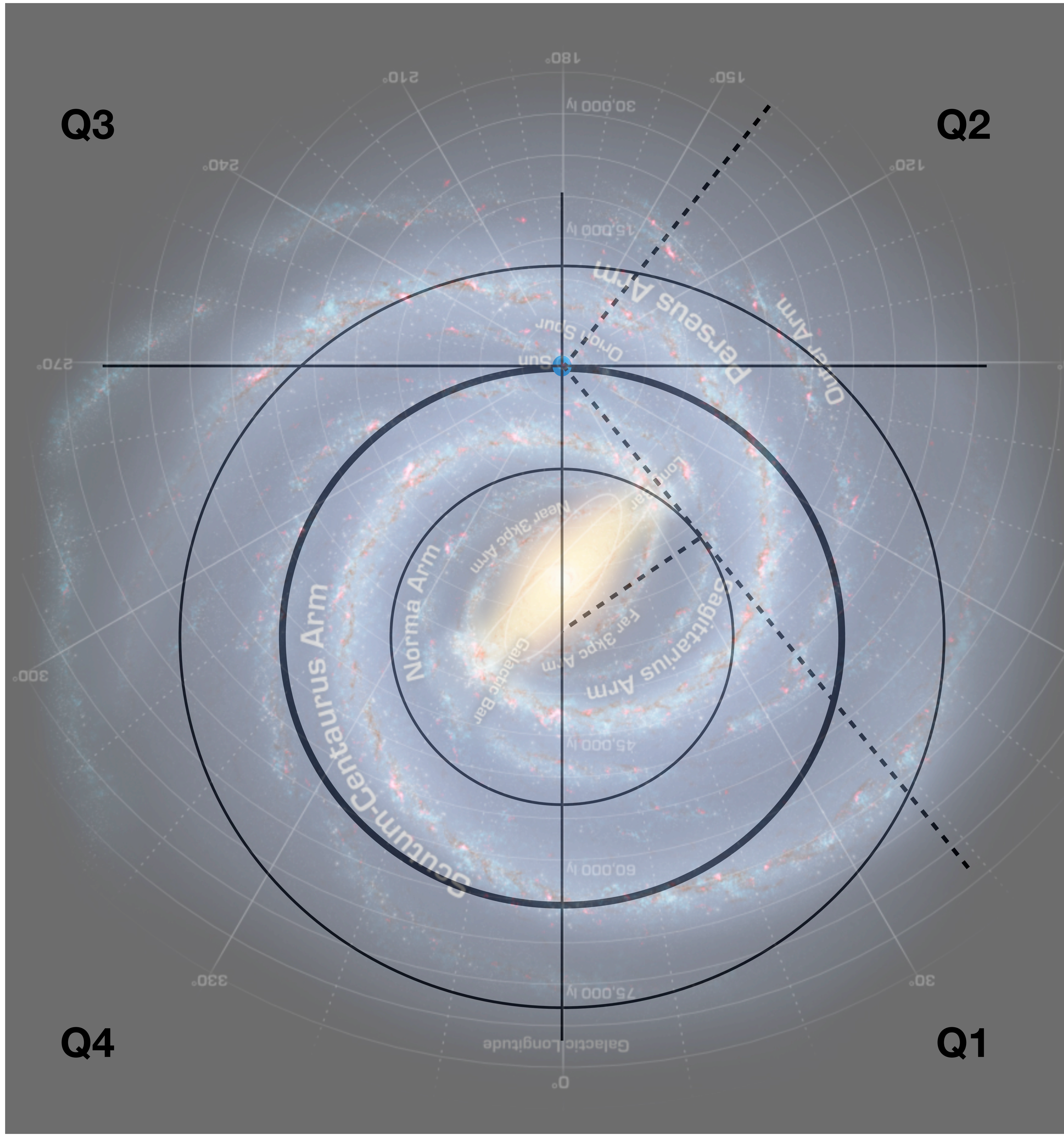




Interpreting the PV curve

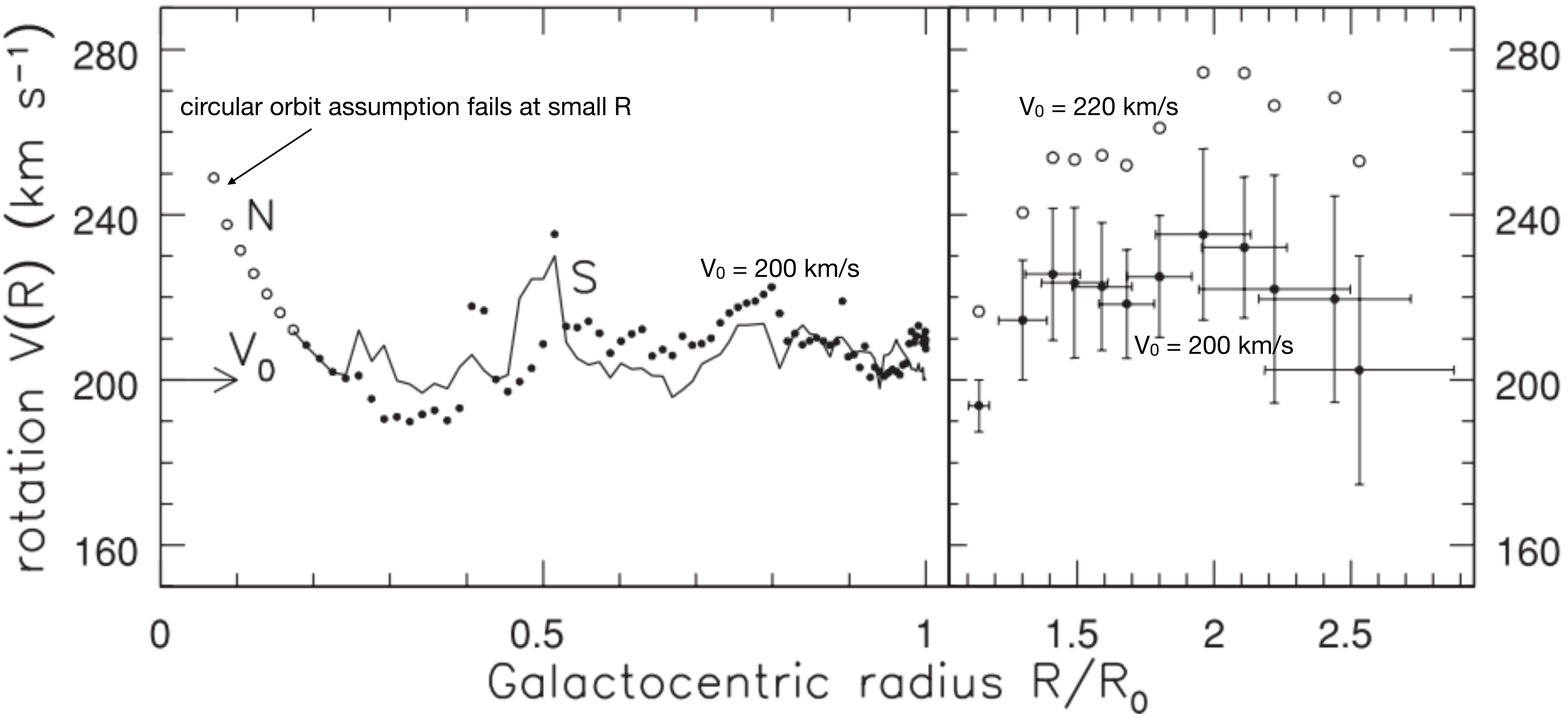
$$V_r = R_0 \sin l(\Omega(R) - \Omega_0)$$



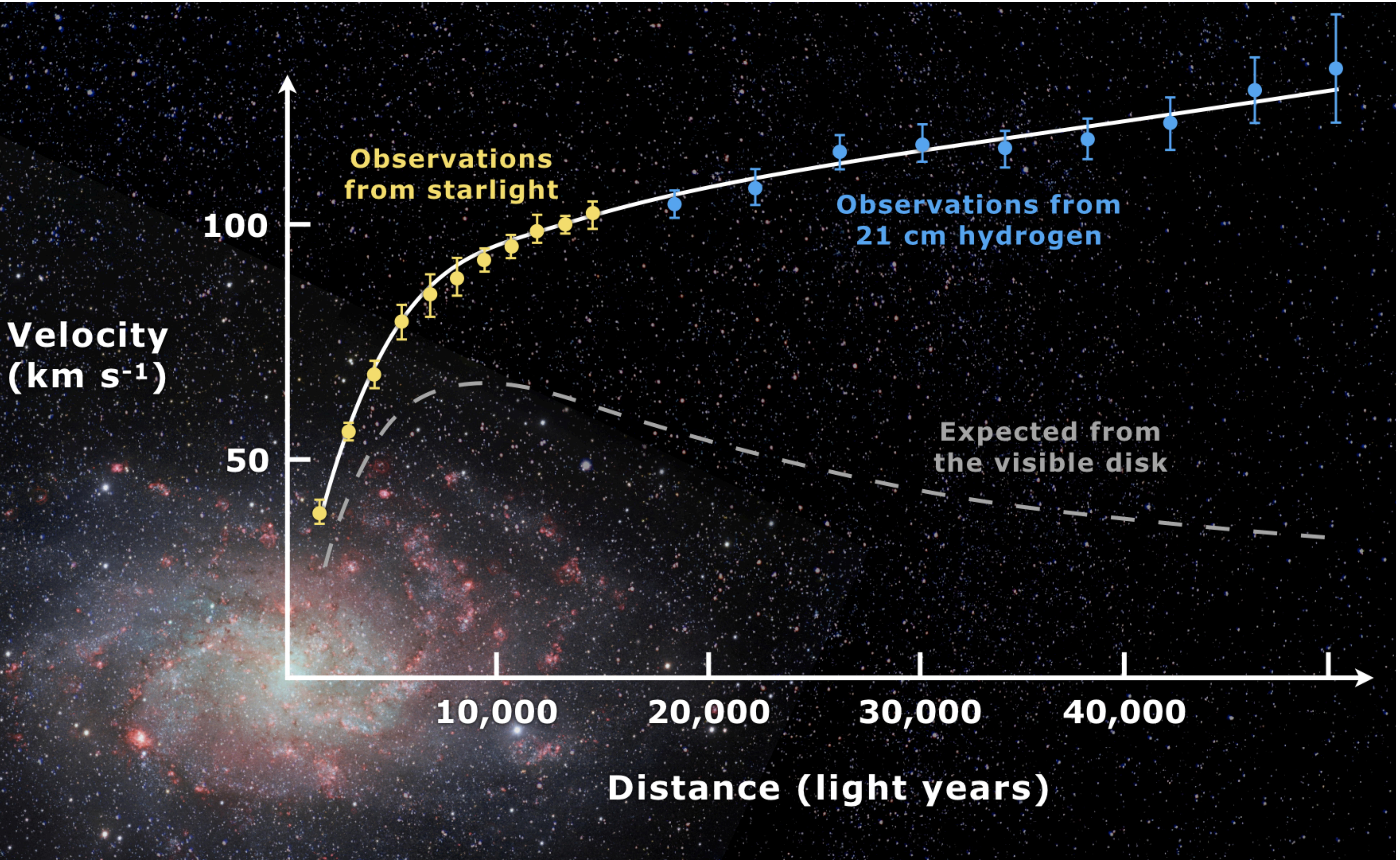


at each l, LOS crosses several overdensities that give higher intensity bands in PV plot

Rotation Curve of MW



Dark Matter



$$\frac{v_c^2}{r} = \frac{GM(r)}{r^2}$$

centripetal acceleration
=
gravitational force/m

if mass follows light,
expect $v_c \propto r^{-1/2}$ not flat!

=> invisible matter that exerts gravitational force

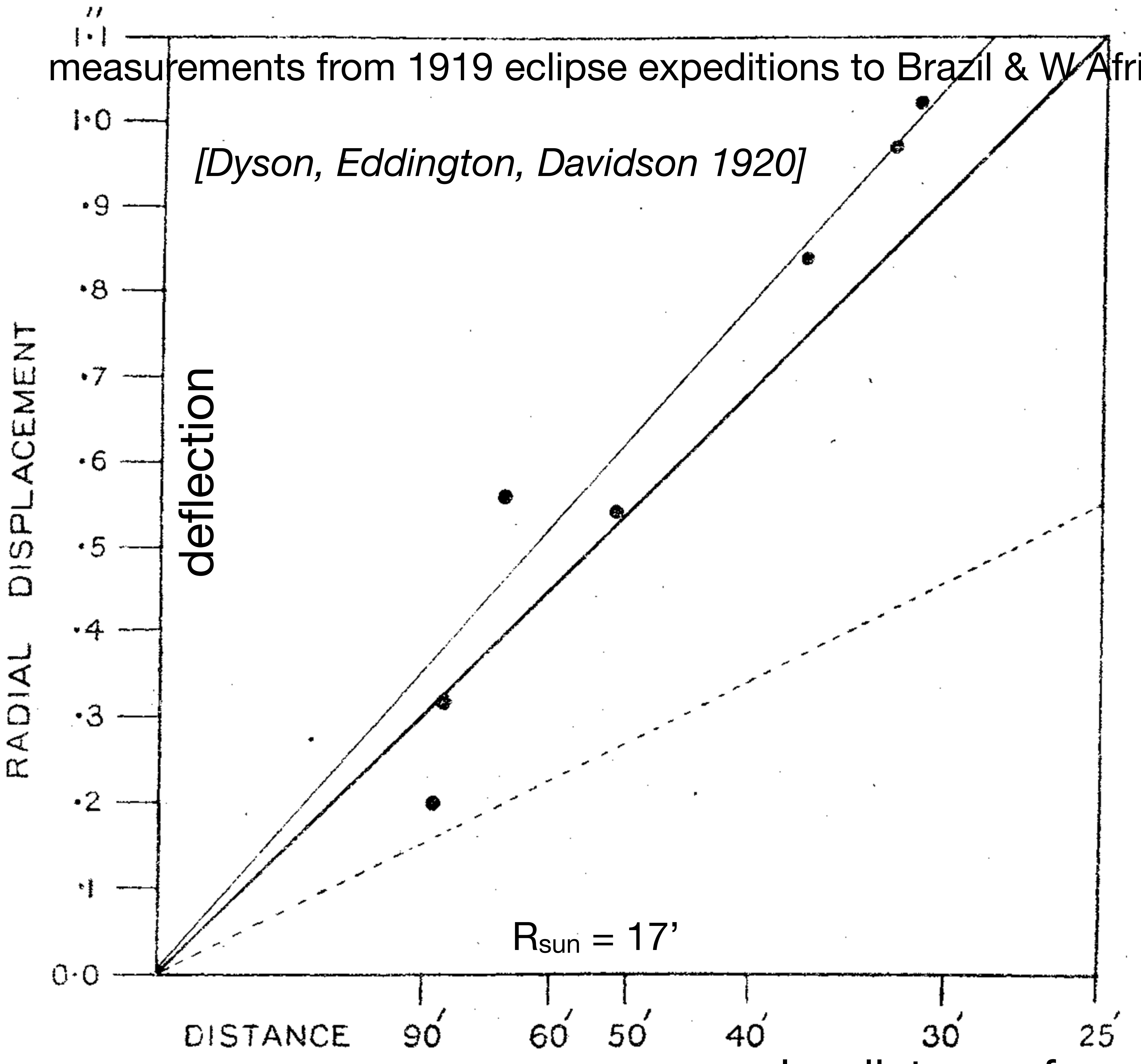
Dark Matter

Gravitational lensing

bending of light rays due to gravity

measurements from 1919 eclipse expeditions to Brazil & W Africa

[Dyson, Eddington, Davidson 1920]



deflection

R_{sun} = 17'

Diagram 2.

angular distance from centre of sun; R_{sun} = 16 arcsec

impact parameter

$$\hat{\alpha} = \frac{4GM}{c^2\,\xi}$$

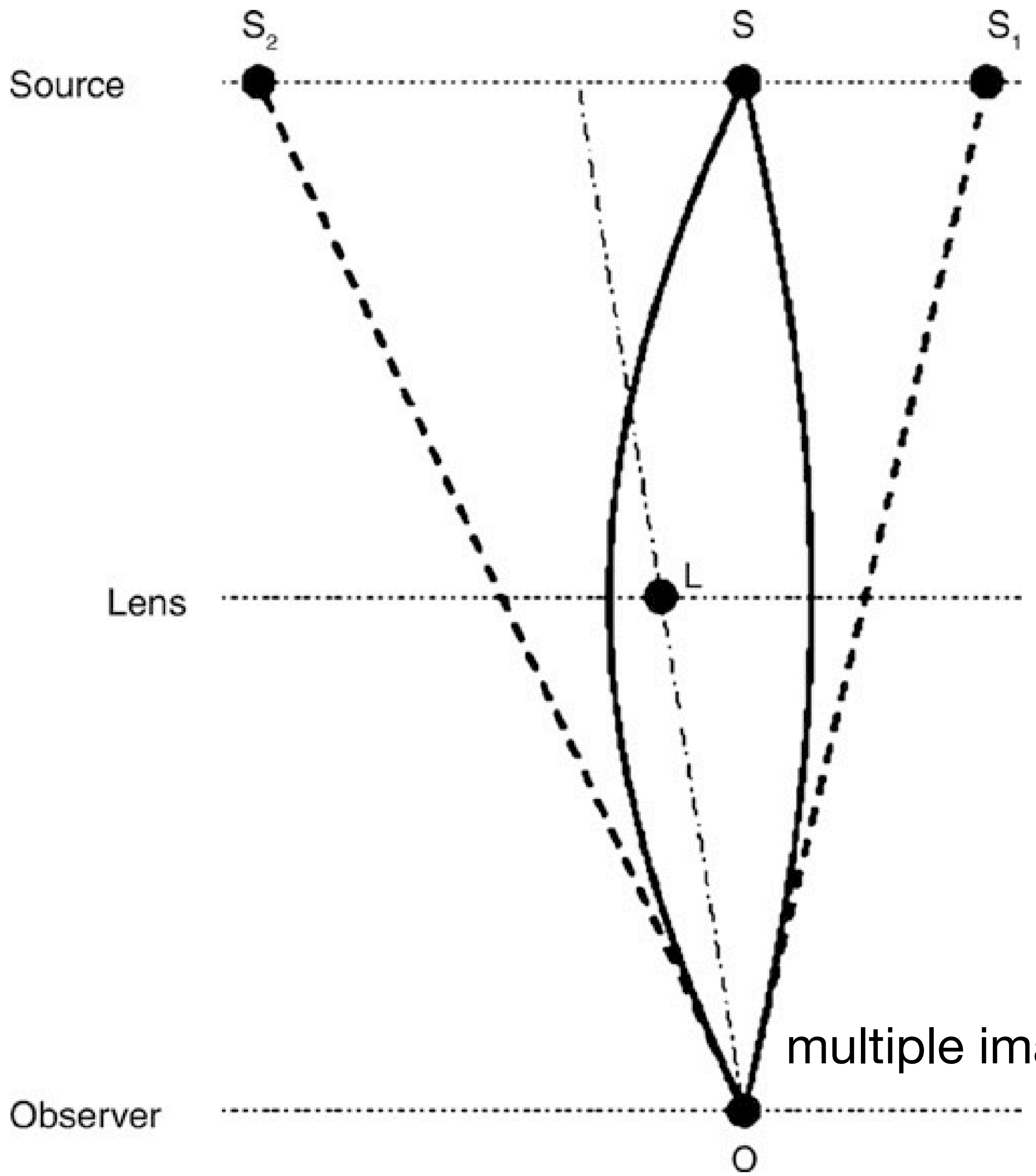
deflection angle for a point mass
(GR result is twice the Newtonian value)

$$= 1\overset{\prime\prime}{.}75 \left(\frac{M}{M_\odot}\right)\left(\frac{\xi}{R_\odot}\right)^{-1}$$

measurable during an eclipse

Gravitational lensing

$$\boldsymbol{\beta} = \frac{\boldsymbol{\eta}}{D_\mathrm{s}} \qquad \boldsymbol{\theta} = \frac{\boldsymbol{\xi}}{D_\mathrm{d}}$$



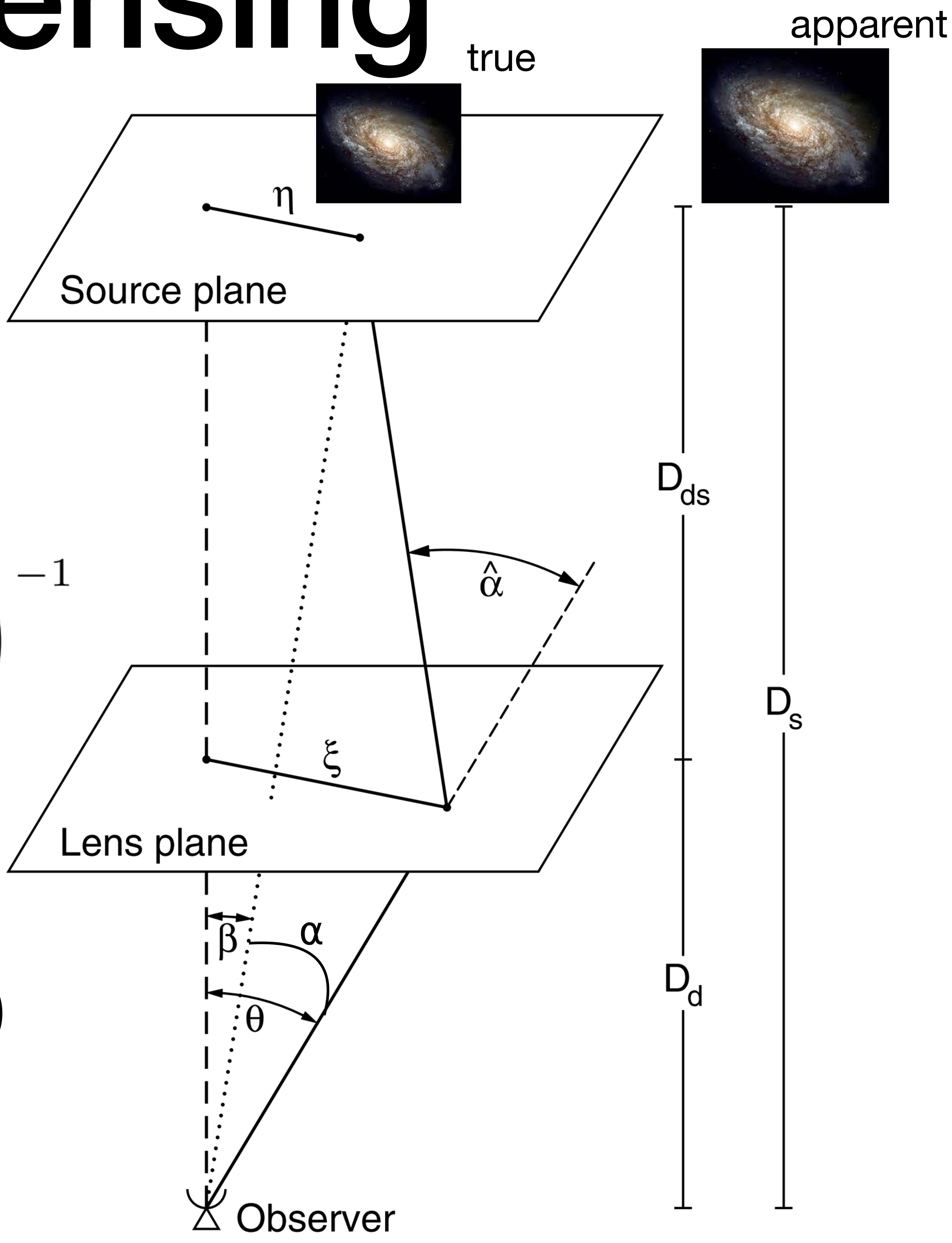
$$\hat{\alpha} = \frac{4GM}{c^2\,\xi}$$

$$= 1\rlap{.}''75 \left(\frac{M}{M_\odot}\right)\left(\frac{\xi}{R_\odot}\right)^{-1}$$

achromatic

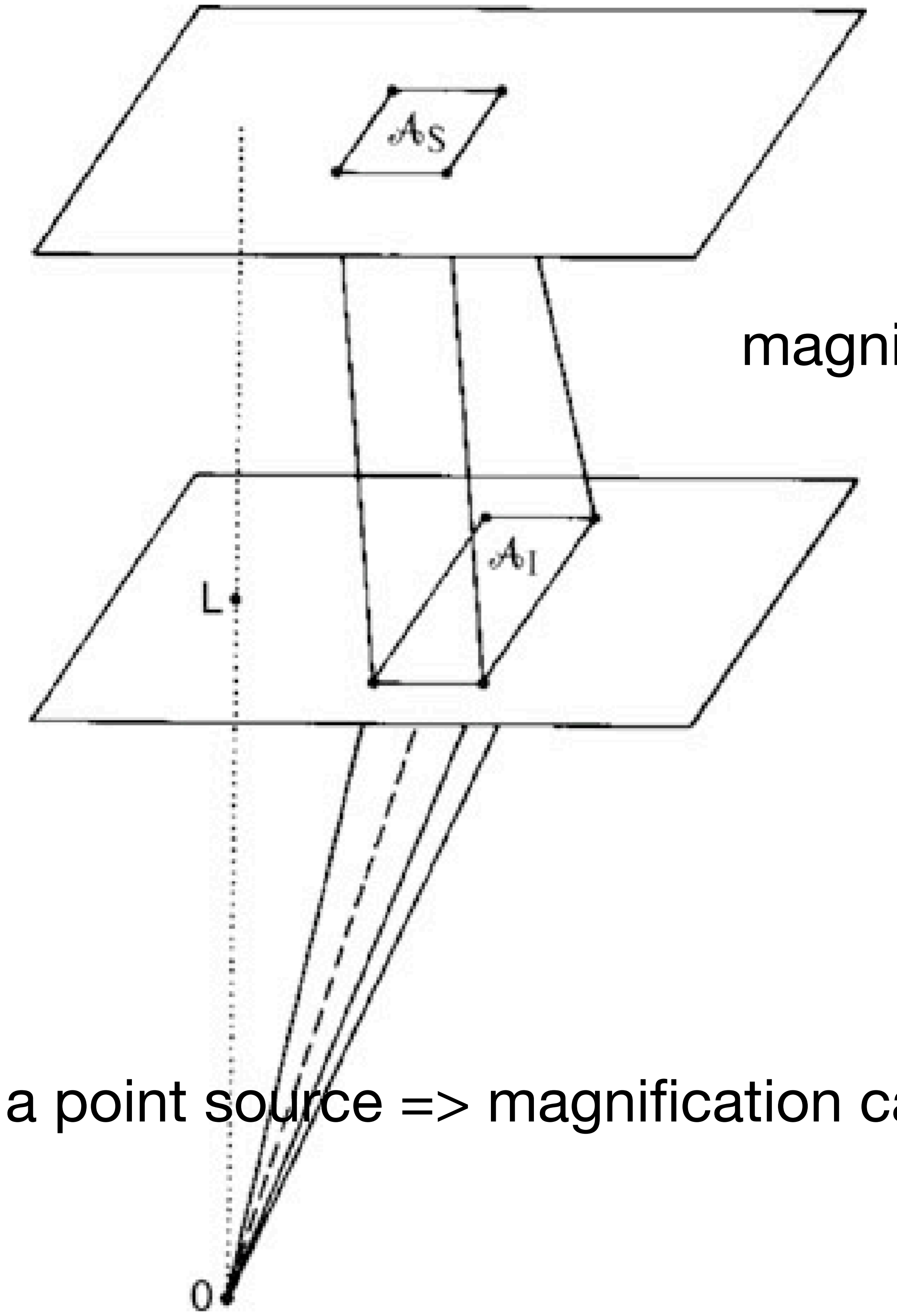
$$\theta = \beta - \alpha(D_d\theta)$$

multiple images are possible



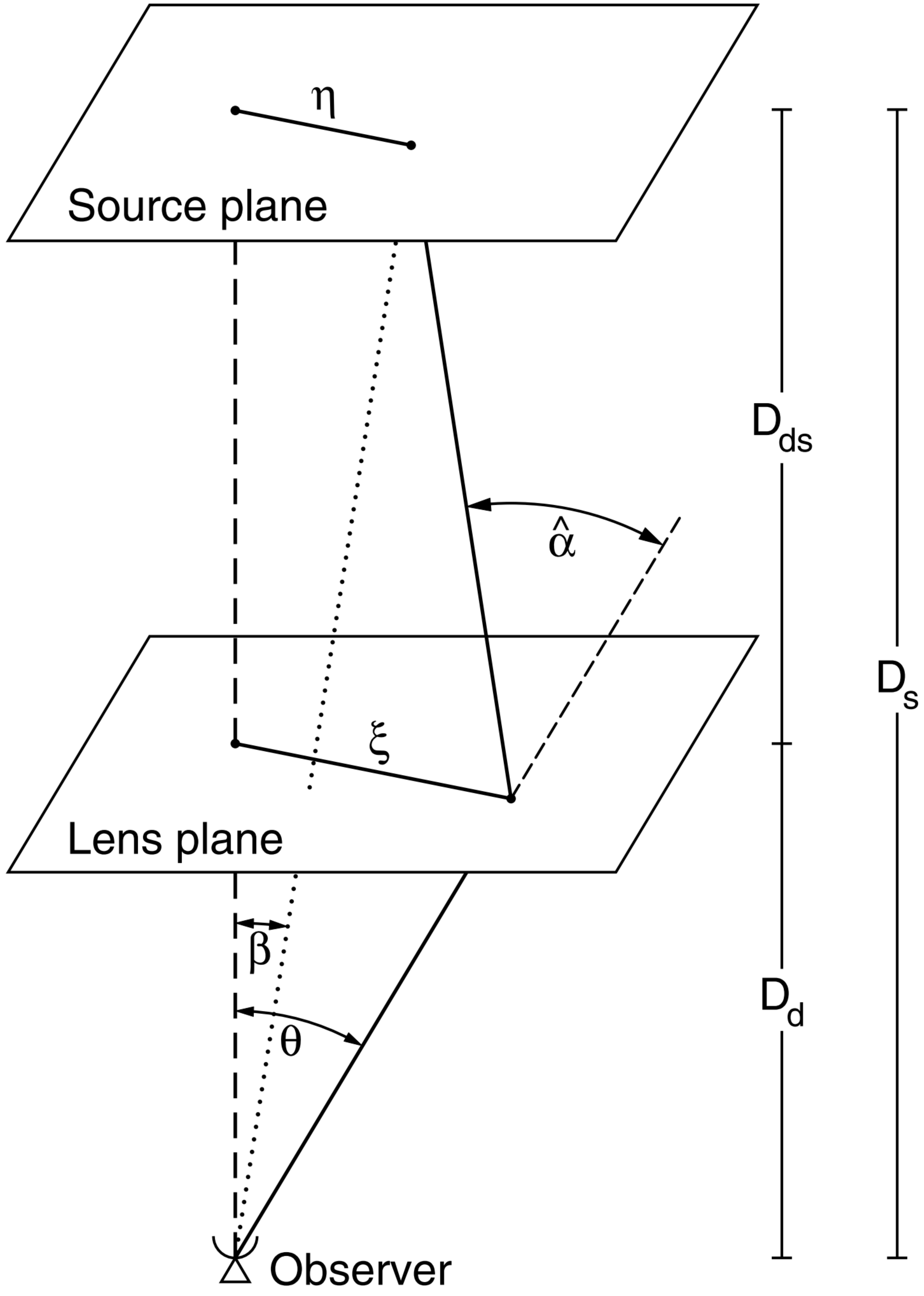
Lens geometry

multiple images
magnification
microlensing: temporal increase in flux without multiple images

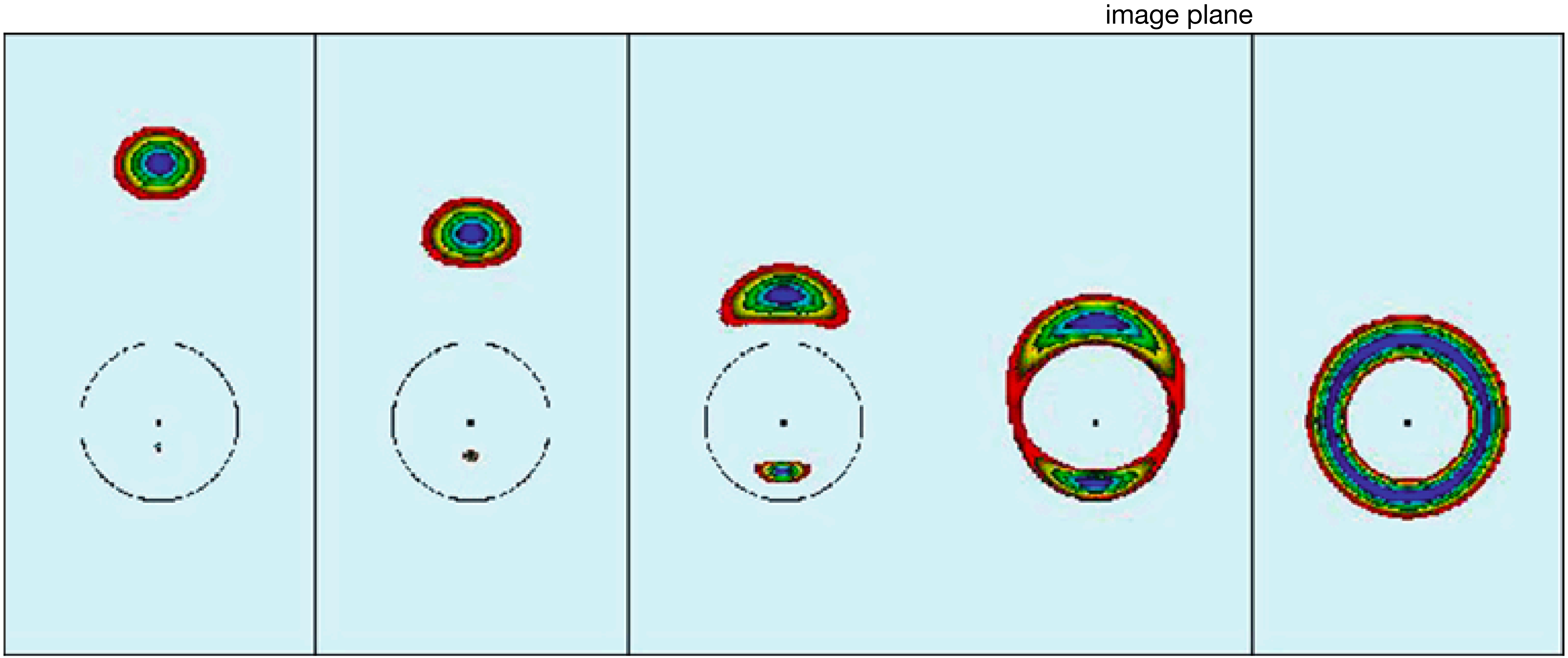


magnification: solid angle ratio, since SB preserved

for a point source => magnification can be large for $\theta<\theta_E$, source within Einstein angle



Cartoon



Microlensing

$$\boxed{\theta_{\rm E} = 0.902\,{\rm mas}\left(\frac{M}{M_\odot}\right)^{1/2}\left(\frac{D_{\rm d}}{10\,{\rm kpc}}\right)^{-1/2}\left(1-\frac{D_{\rm d}}{D_{\rm s}}\right)^{1/2}}$$

$$\dot\theta = \frac{v}{D_{\rm d}} = 4.22\,{\rm mas\,yr^{-1}}\left(\frac{v}{200\,{\rm km/s}}\right)\left(\frac{D_{\rm d}}{10\,{\rm kpc}}\right)^{-1}$$

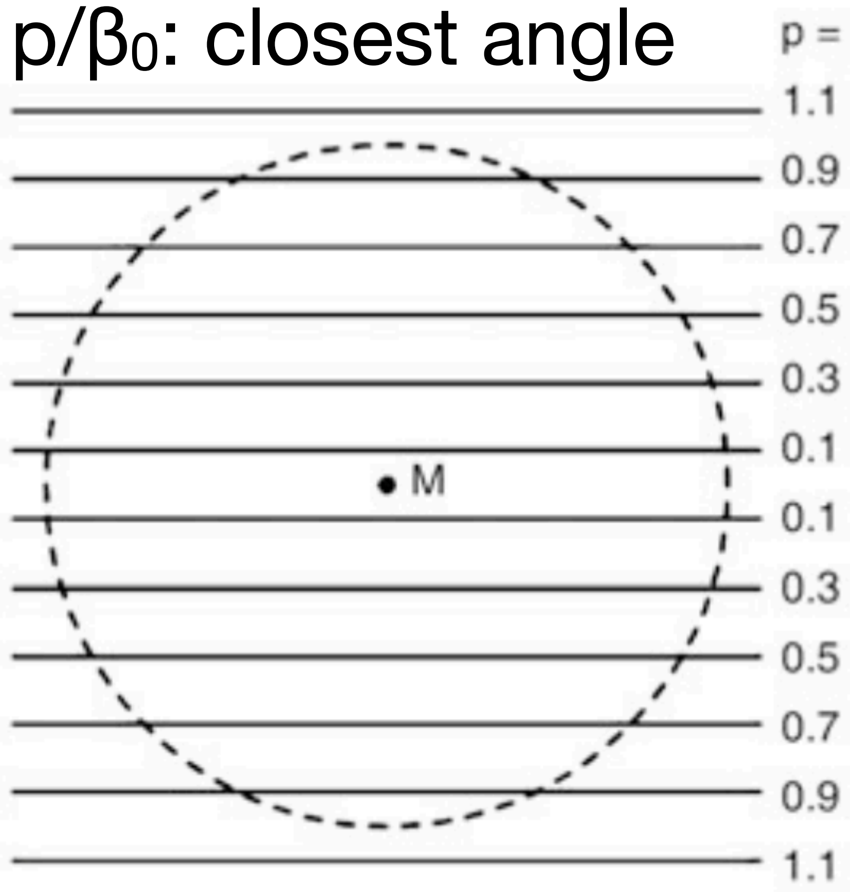
$$\boxed{\begin{aligned} t_{\rm E} := \frac{\theta_{\rm E}}{\dot\theta} &= 0.214\,{\rm yr}\left(\frac{M}{M_\odot}\right)^{1/2}\left(\frac{D_{\rm d}}{10\,{\rm kpc}}\right)^{1/2} \\ &\times\left(1-\frac{D_{\rm d}}{D_{\rm s}}\right)^{1/2}\left(\frac{v}{200\,{\rm km/s}}\right)^{-1}\,. \end{aligned}}$$

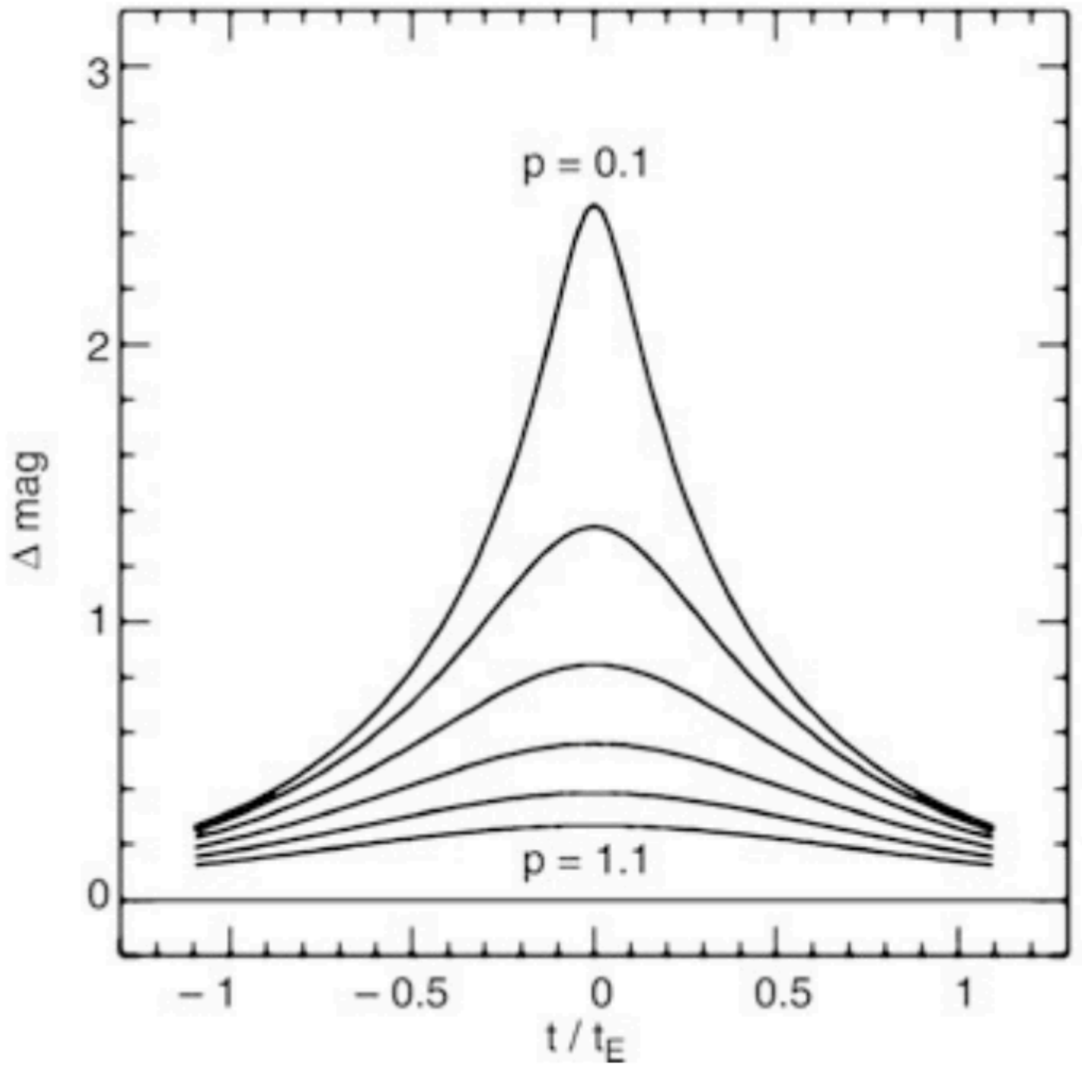
$$\mathcal{M} \approx \frac{\theta_E}{\beta_0} \approx \frac{\theta_E/\beta}{[1+(\mu t/\beta_0)^2]^{1/2}}$$

motion of lens star roughly straight line

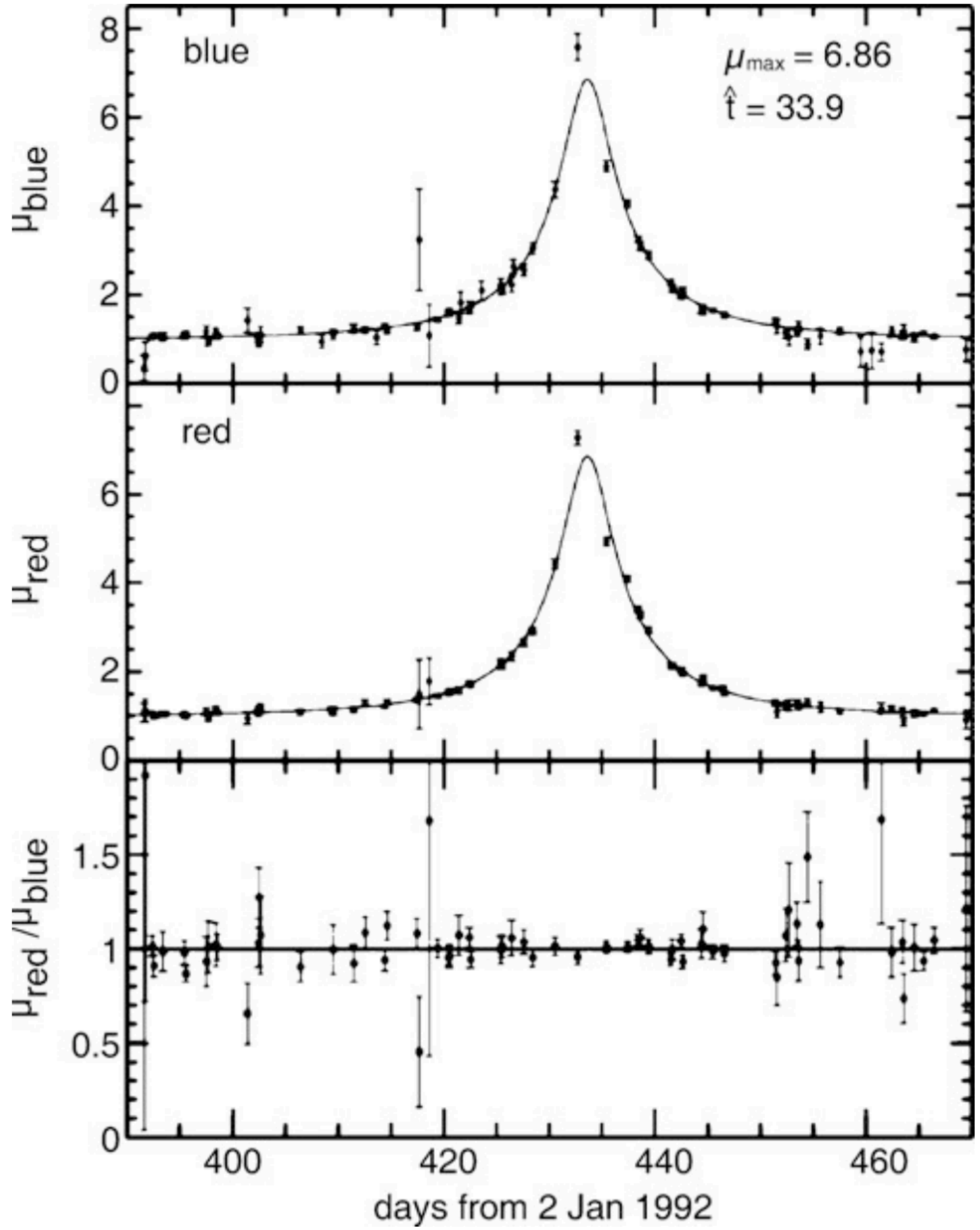
$$\boldsymbol{\beta} = \boldsymbol{\beta}_0 + \dot{\boldsymbol{\beta}}(t-t_0)$$

p/β_0: closest angle





Microlensing events

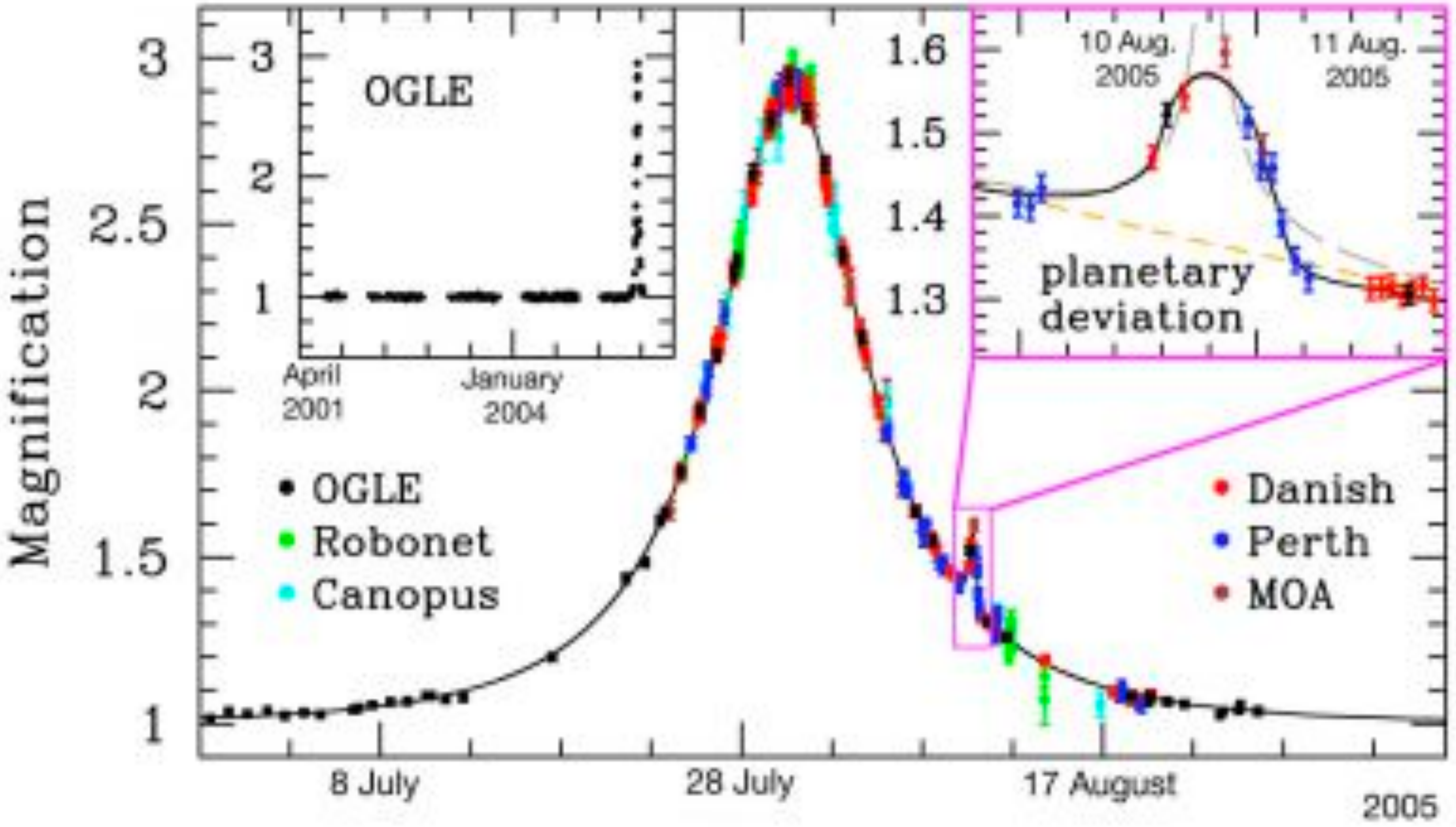


Probability of lens & source to come within θ_E if all DM in lenses ~ 10^{-6}
Need to monitor several millions of stars

EROS, OGLE, MACHO monitoring of large areas in sky

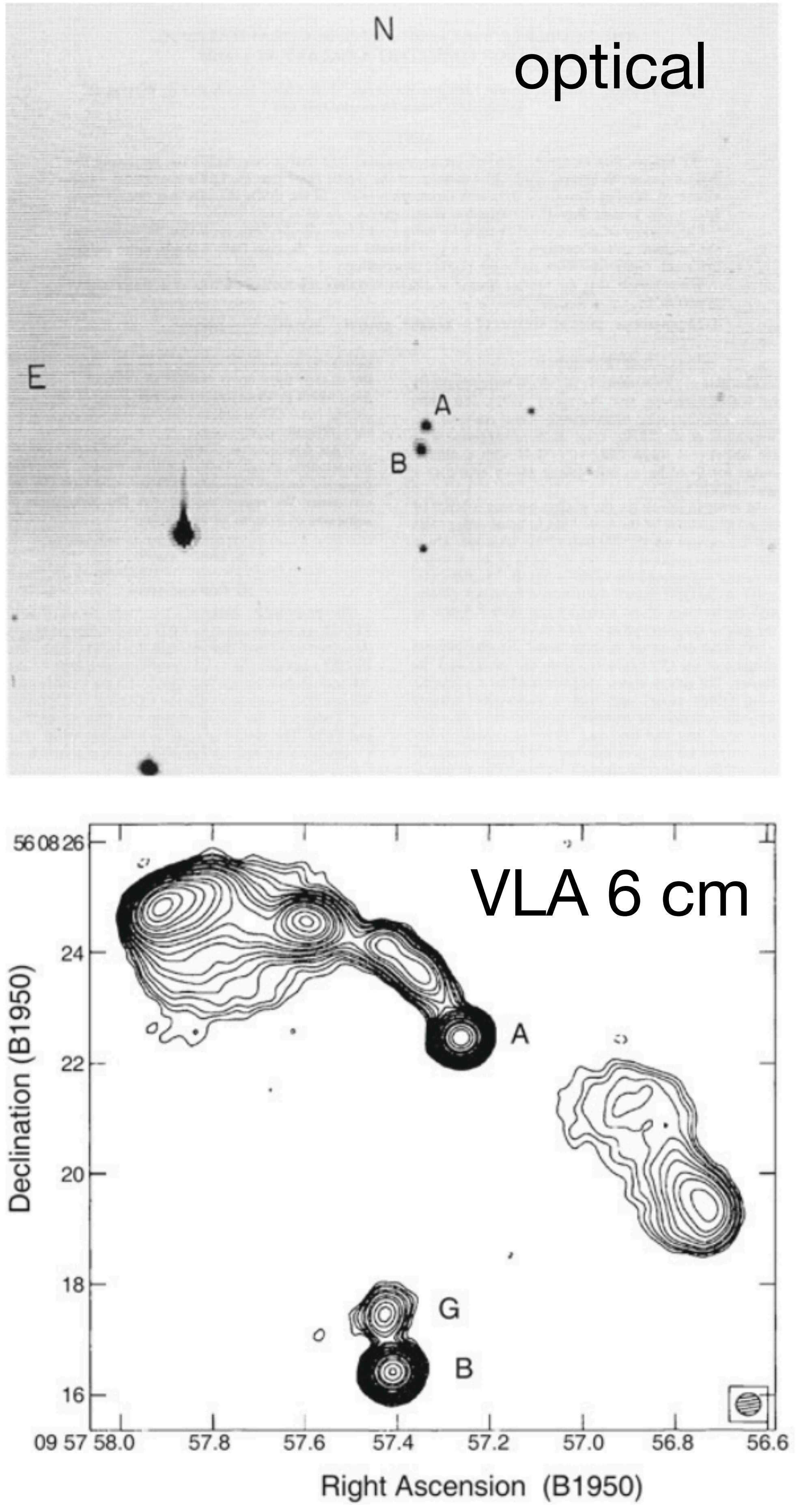
Monitoring halo stars in LMC as source, we can rule out MACHOs
MAssive Compact Halo Objects

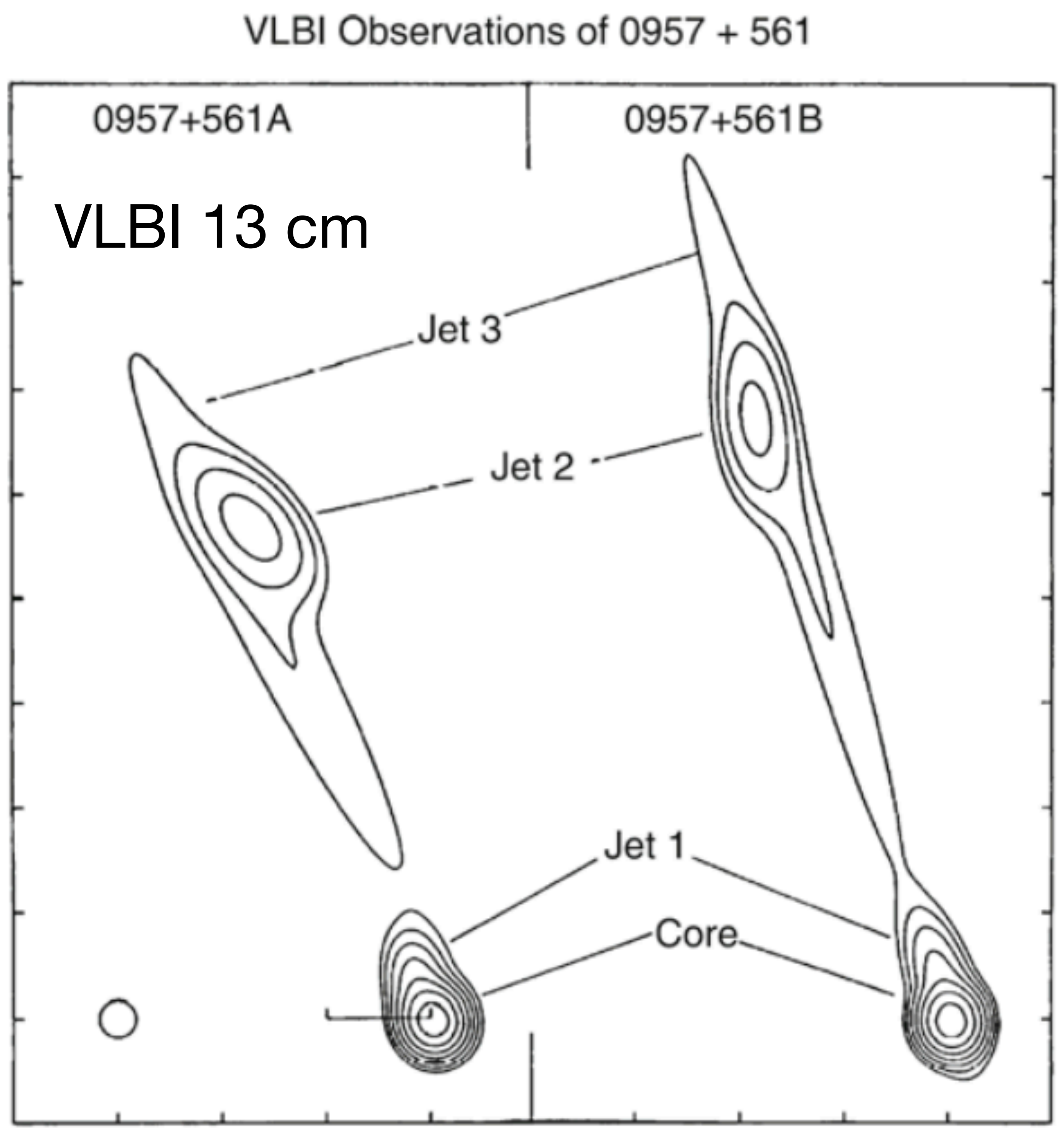
Microlensing events towards LMC smaller than expected
Maximum 20% of DM can be MACHOs with 0.5 M_{sun} (interpretation is tricky!)

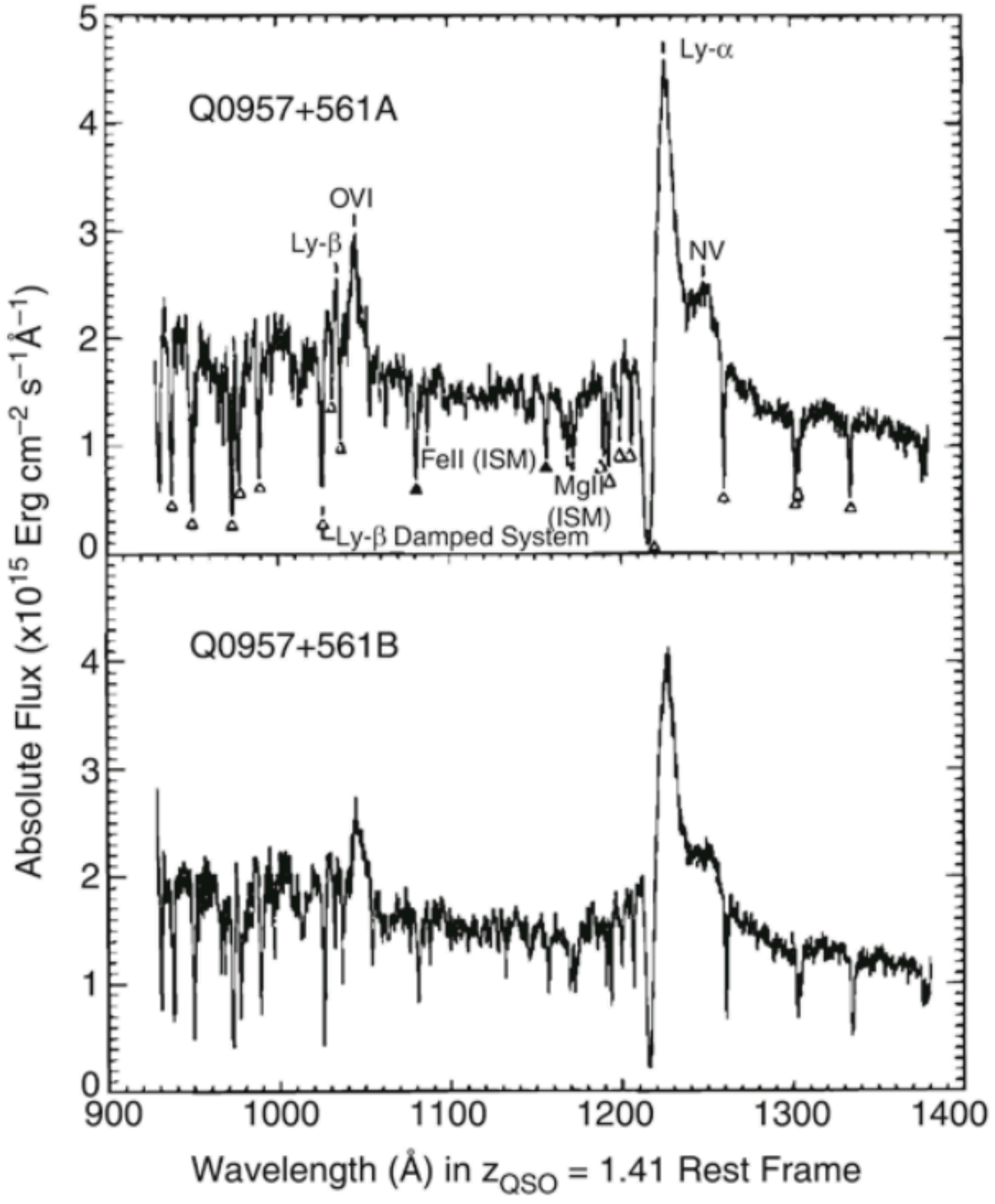


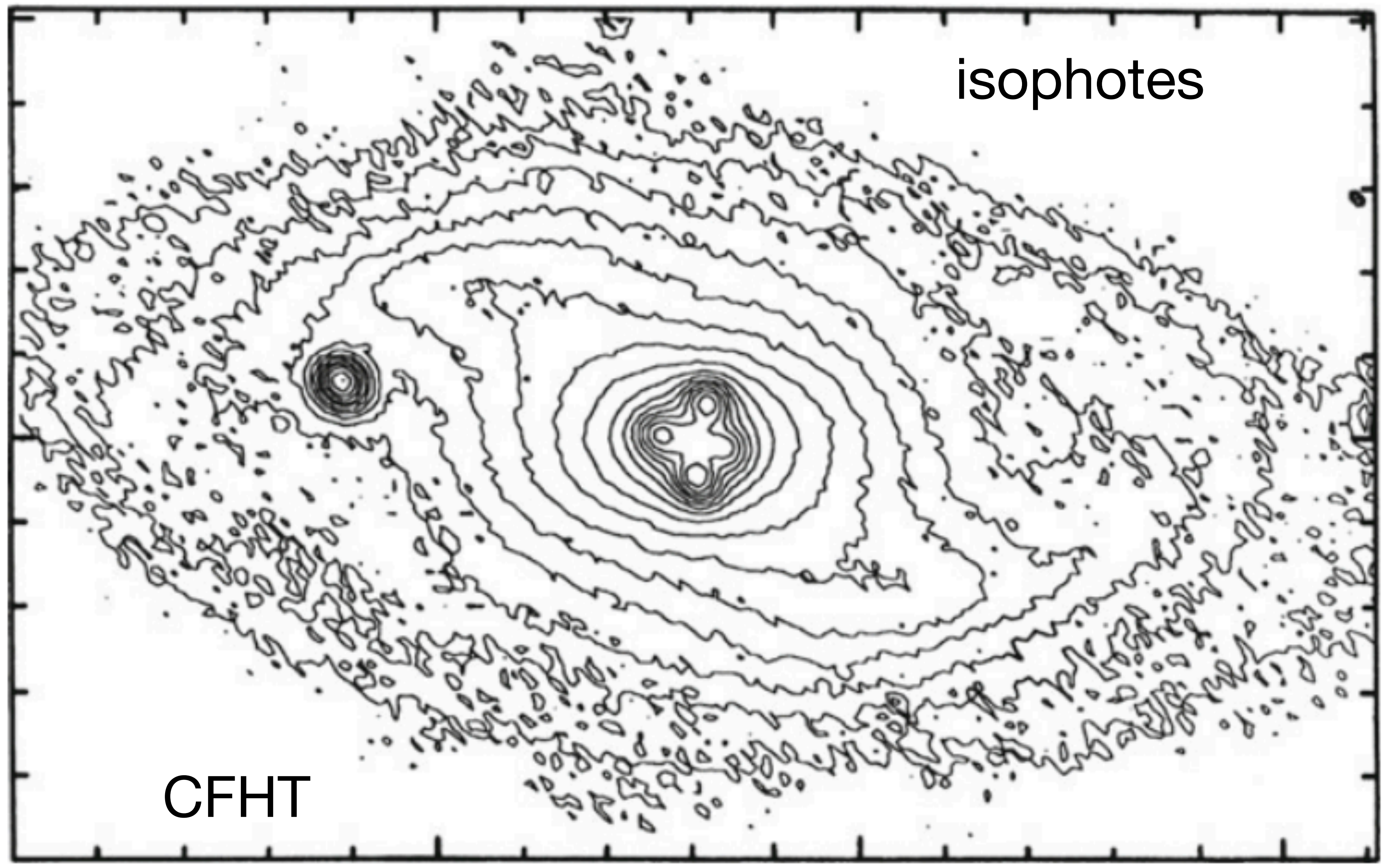
Example Applications

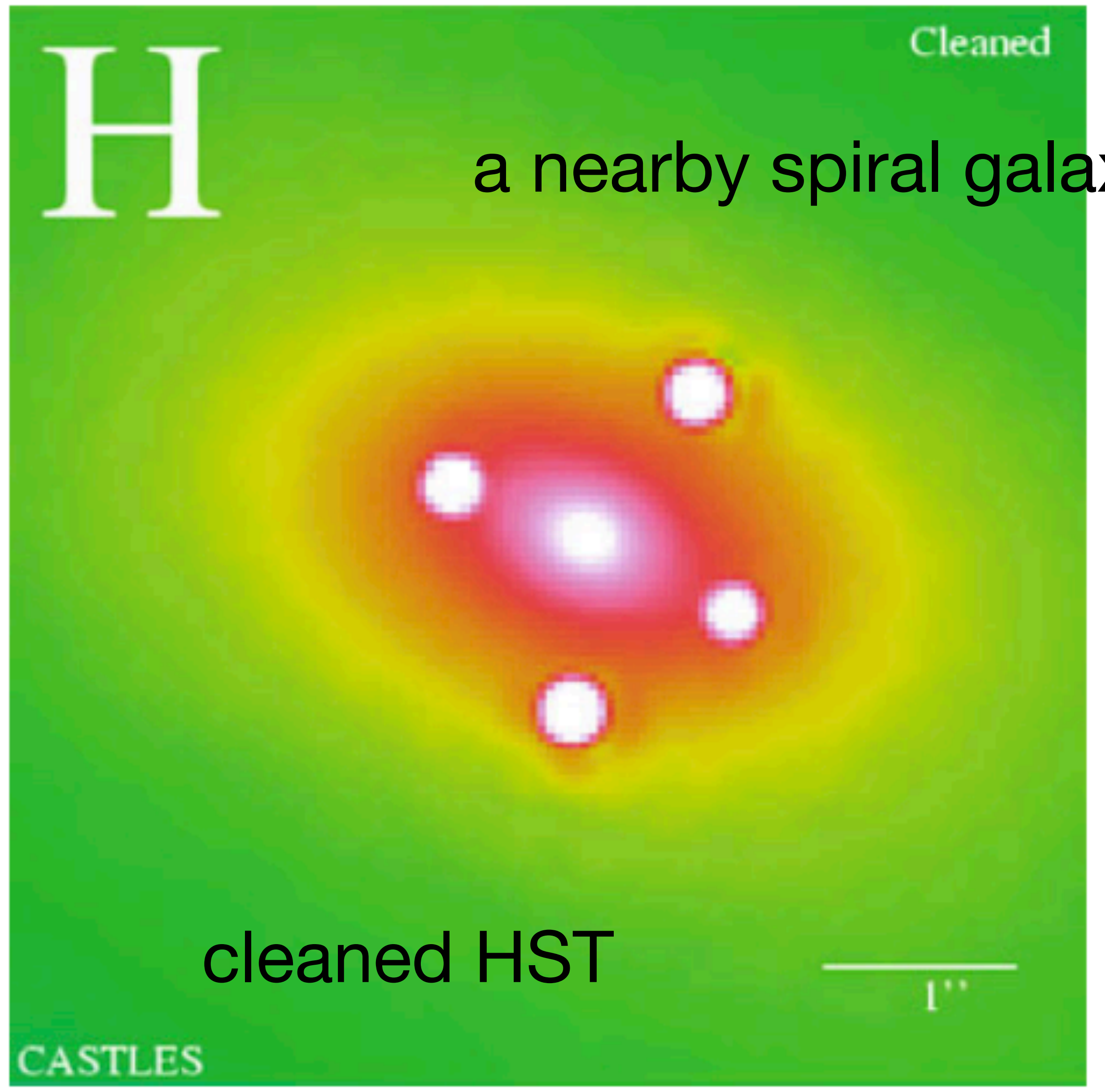
double quasar QSO 0957+561from Schneider’s book (figs. 3.56, 3.57)



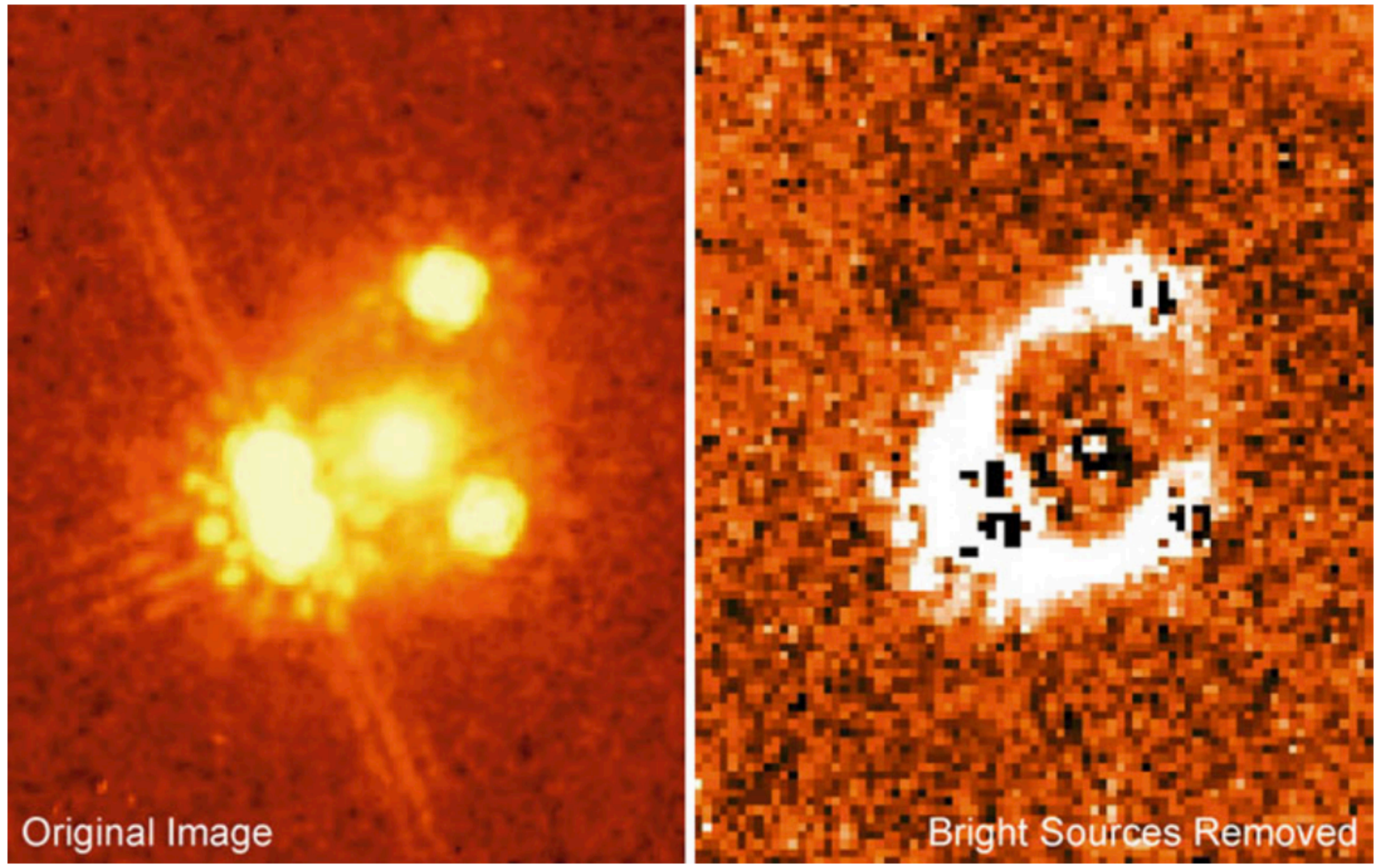




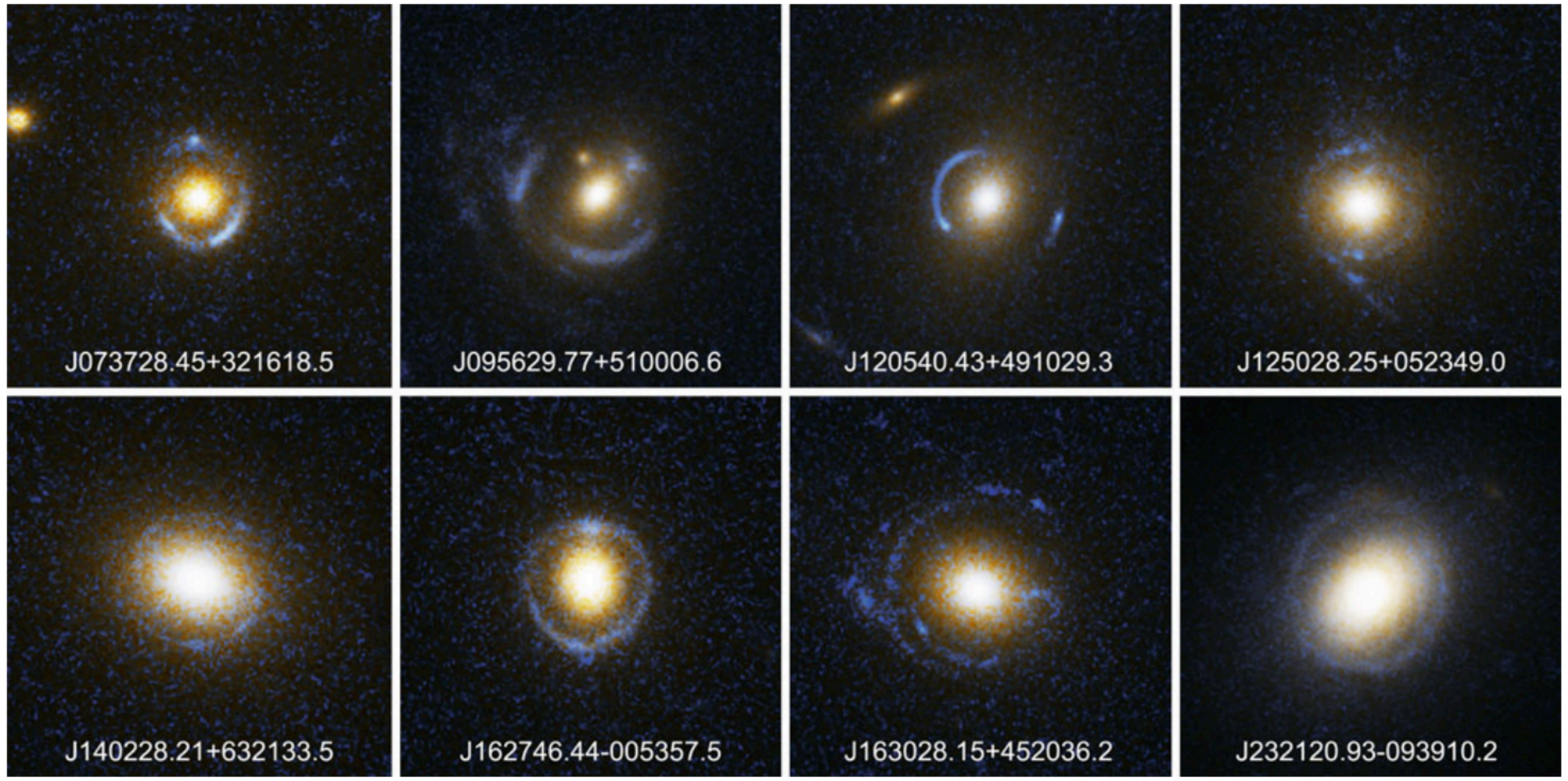




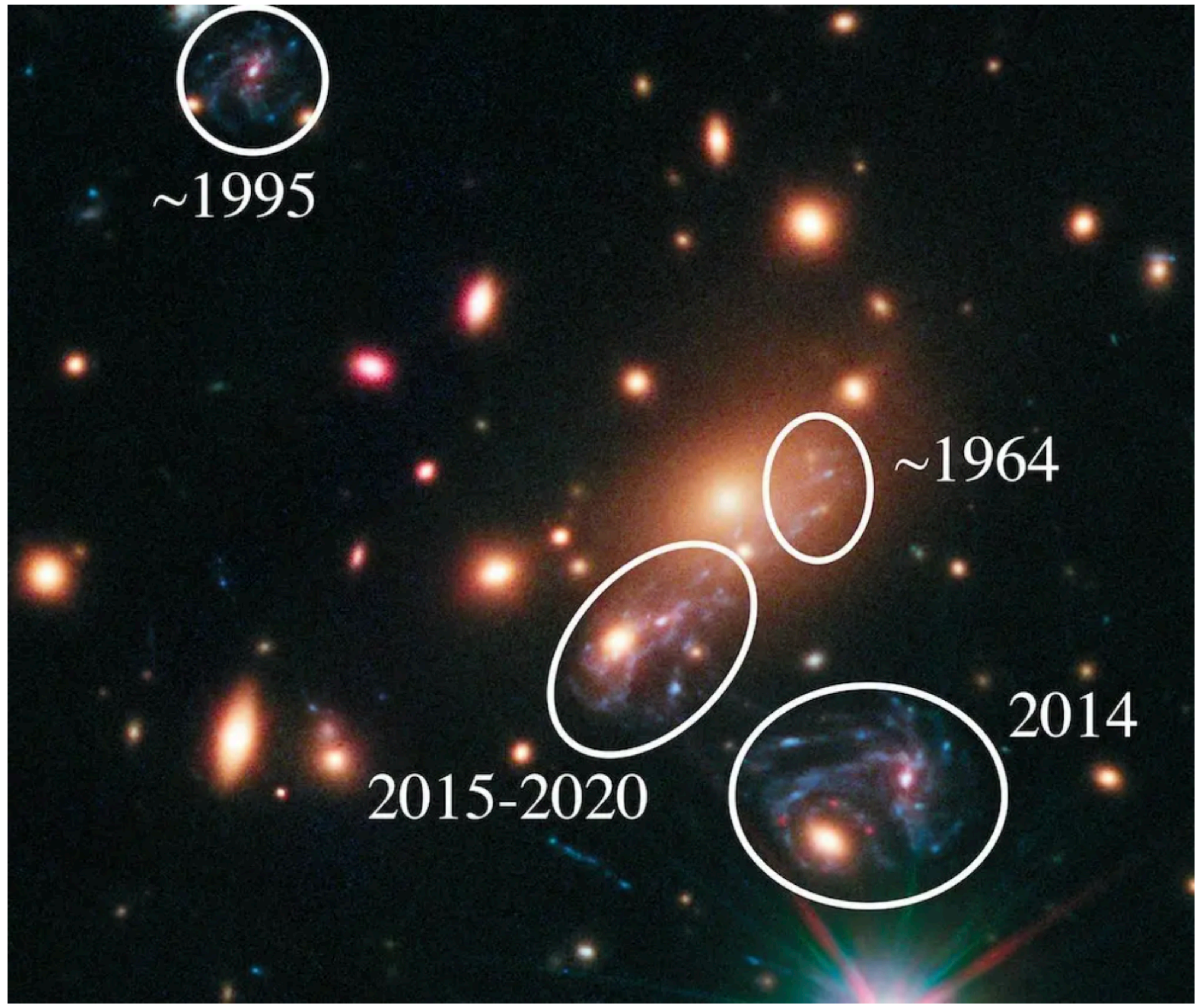
a nearby spiral galaxy with quadruply lensed background quasar



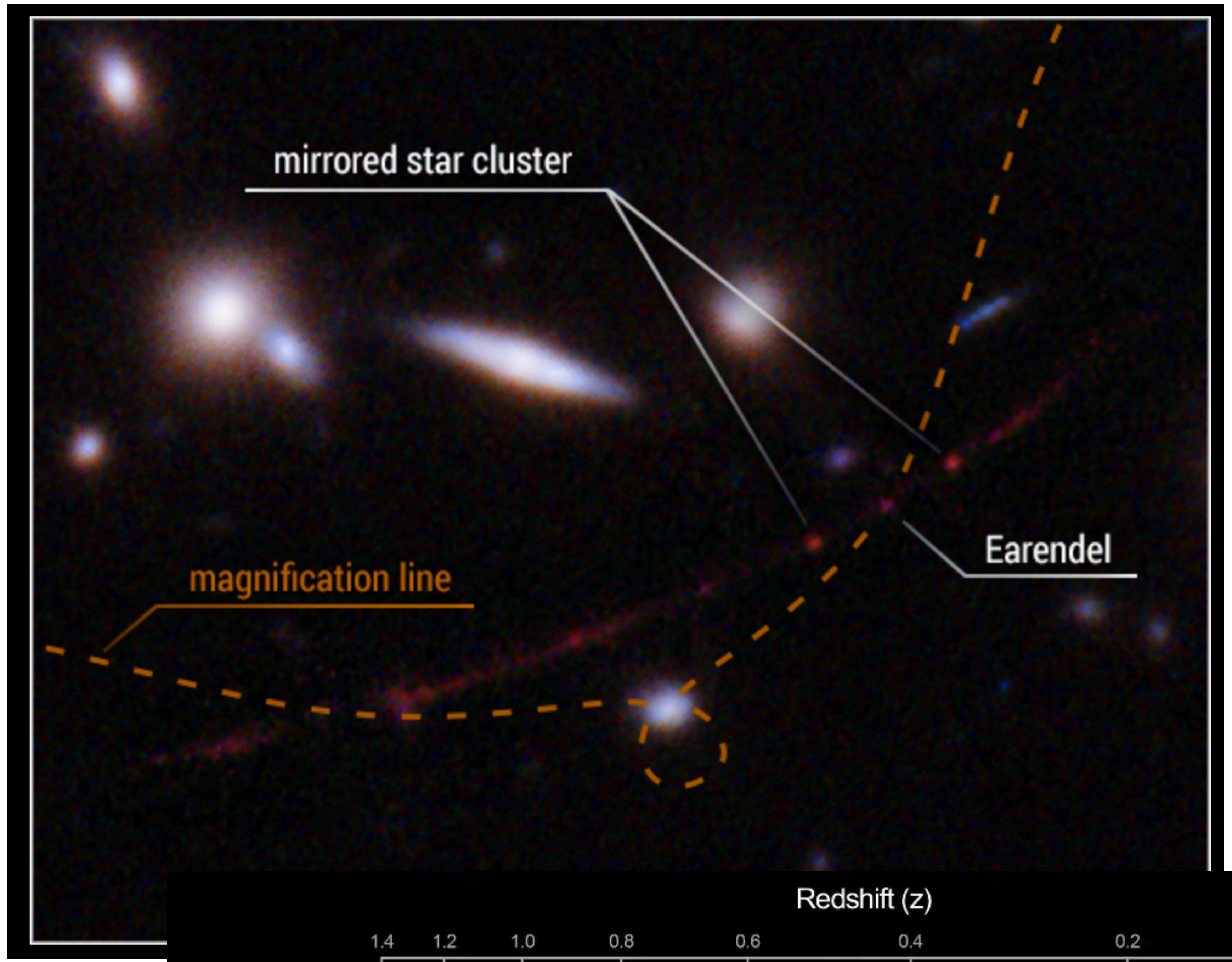
quadruply lensed background quasar and Einstein ring
from light of background galaxy



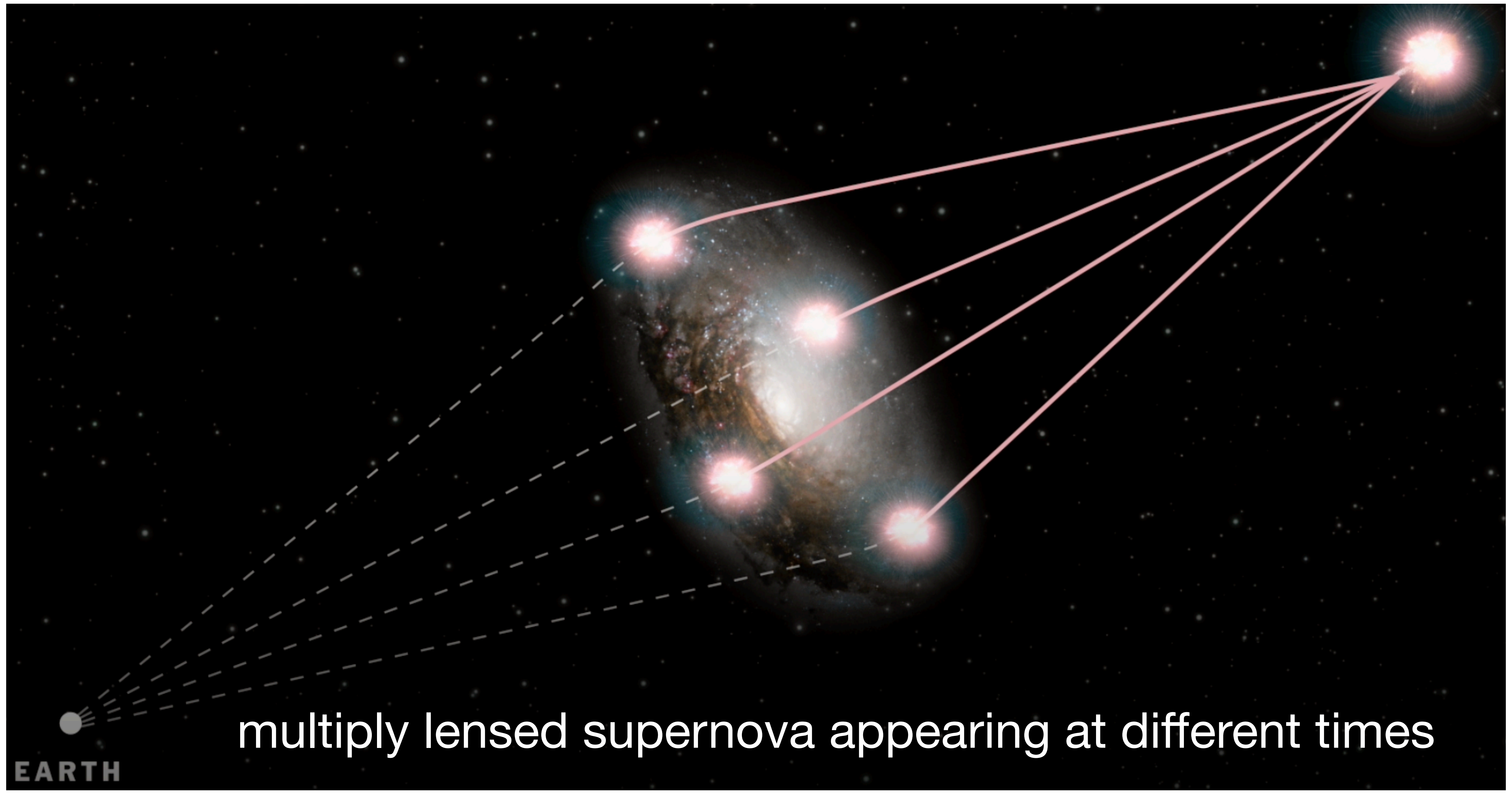
strong lensing of background galaxies by foreground cluster
one of the early observations fields by JWST was behind a cluster

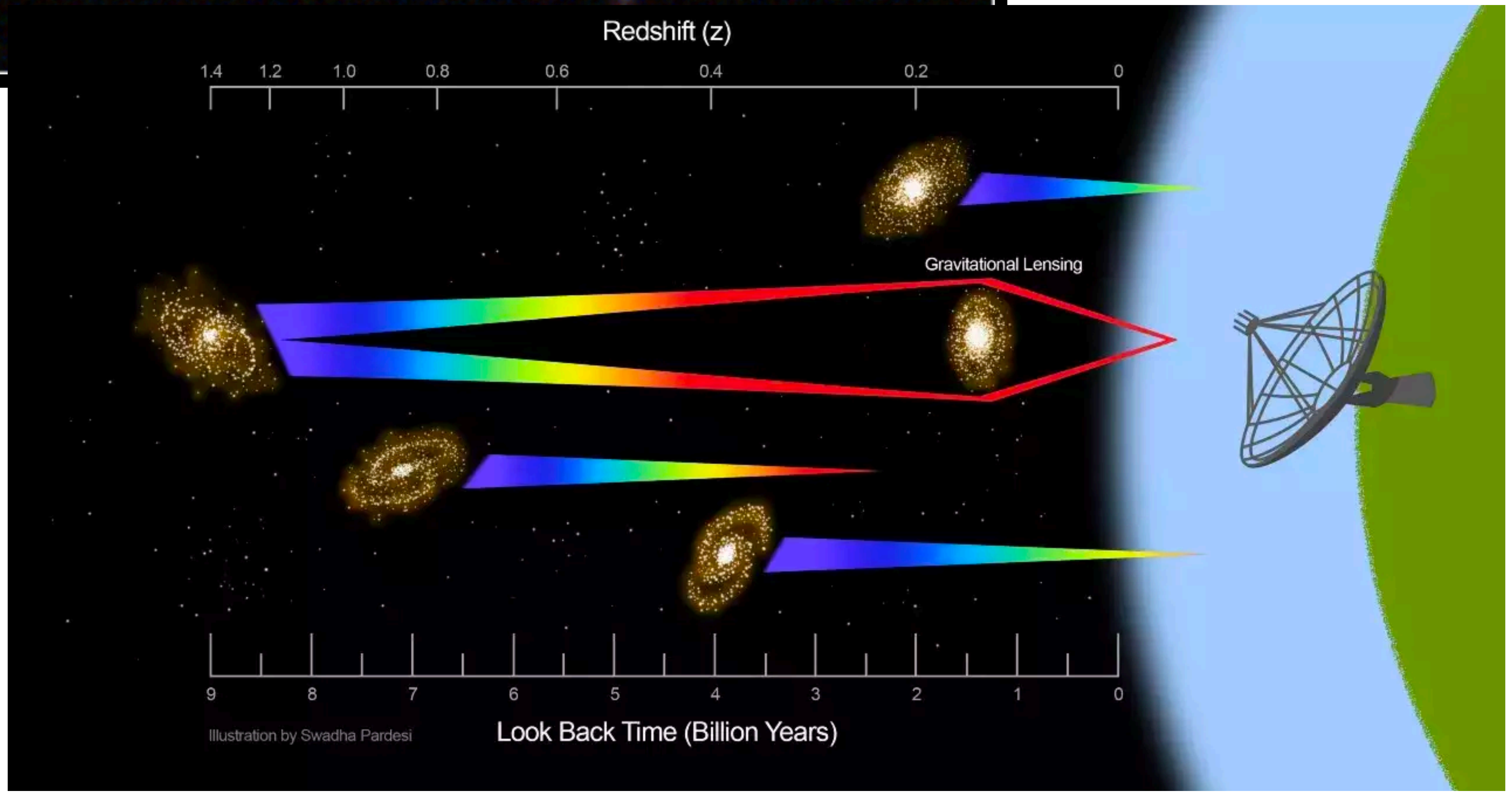


Multiple images of the Supernova Refsdal, appearing over time. NASA and European Space Agency



single star at z~6 magnified by ~10000x as it crosses large magnification line (critical curve)





Detection of H I 21 cm emission from a strongly lensed galaxy at $z \sim 1.3$

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