The optical gravitational lens experiment and discovery of multiply imaged quasars with Gaia and the ILMT

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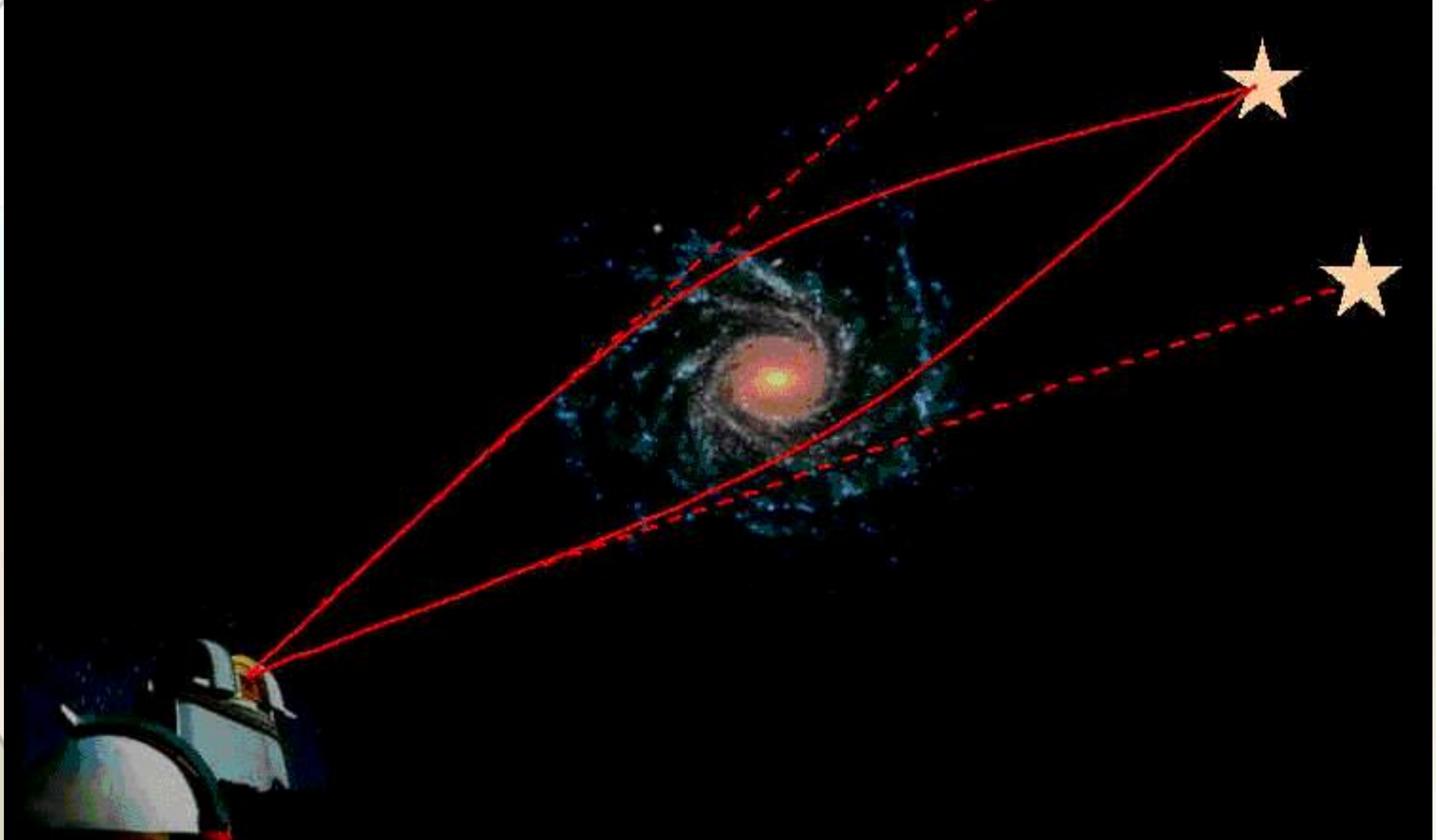
(Dharamshala, India)

Sjur Refsdal 1935-2009

Sjur Refsdal (1964)



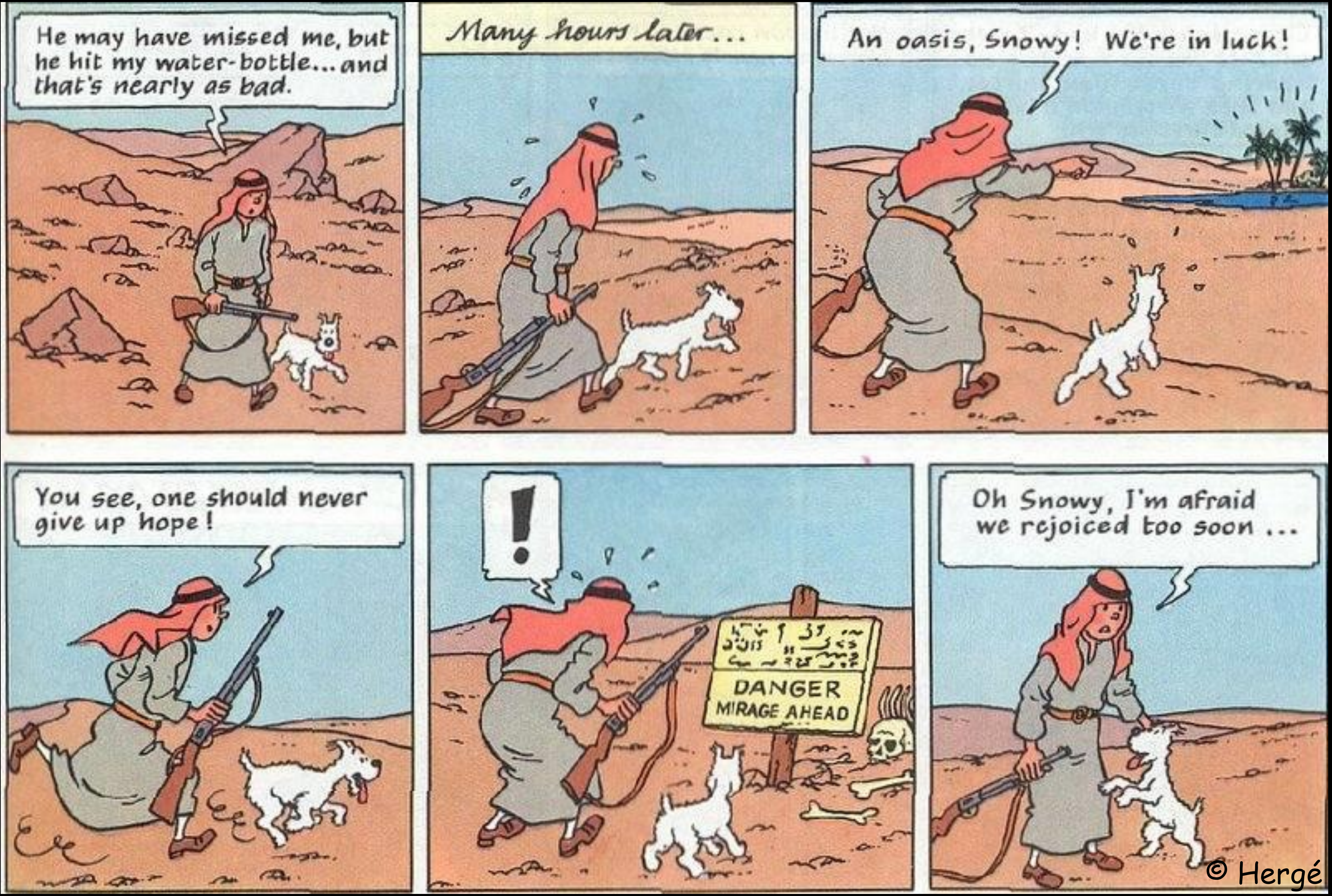
Atmospheric lensing

What is a mirage?

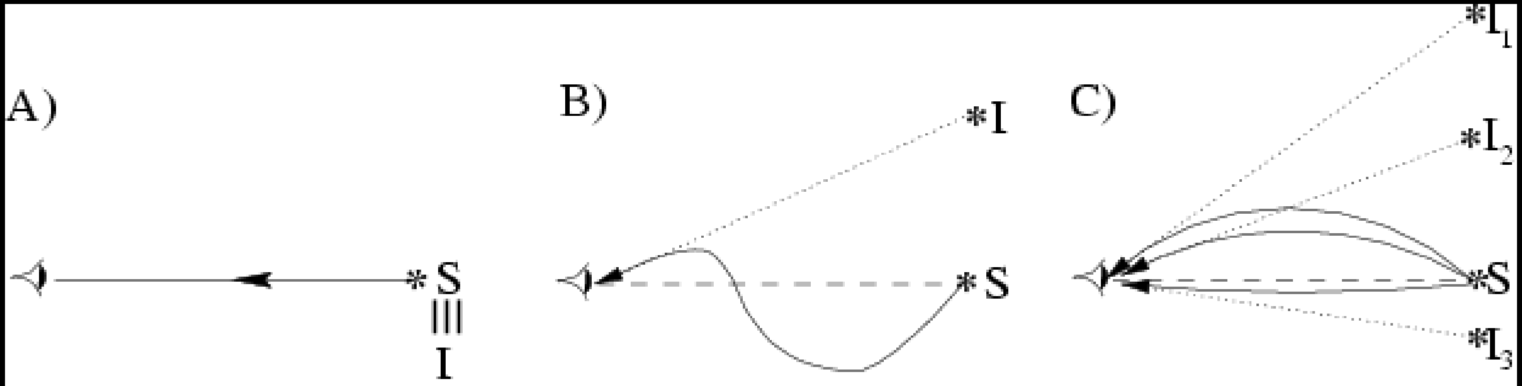
A mirage is an optical illusion …

… whose cause is real!

Next morning . . .
There ! All fixed now !
Off we go !
Look !
Ooh! . . . A lake!
Why don't we have a swim !
That's a smashing idea !
I bet I can dive farther than you !
Show-off !
Fiddlesticks!...Another mirage!
To be precise : yes.

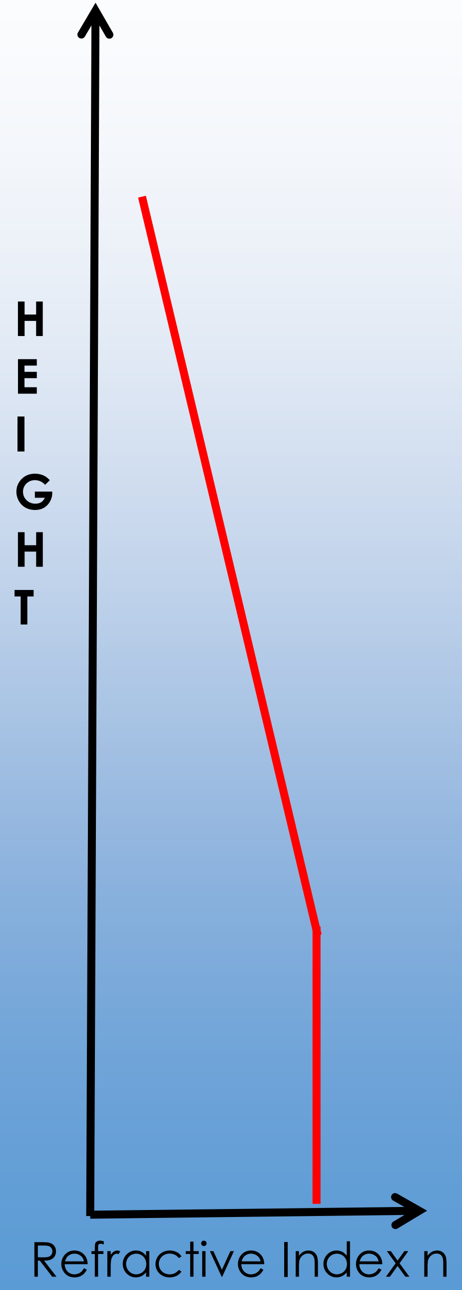

He may have missed me, but he hit my water-bottle... and that's nearly as bad.
Many hours later...
An oasis, Snowy! We're in luck!
You see, one should never give up hope!
!
DANGER
MIRAGE AHEAD
Oh Snowy, I'm afraid we rejoiced too soon ...

What is a mirage?

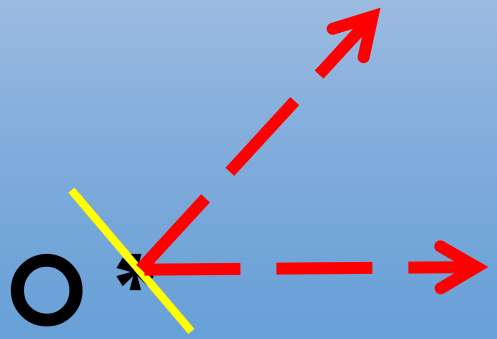


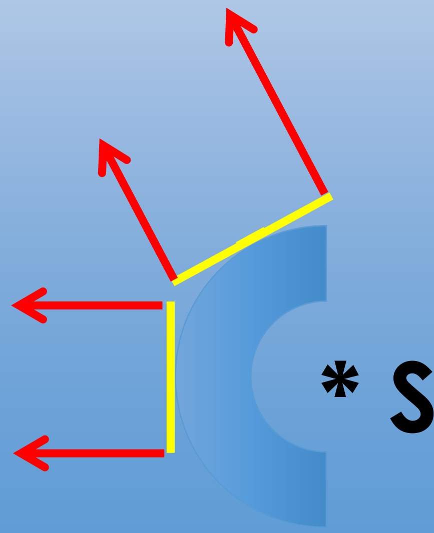
1. An image is always seen along the direction of the incoming light ray
2. A mirage is formed when the incoming light rays do not propagate along straight lines
3. Light may propagate along different trajectories with propagation times which are always extrema (Fermat Principe)

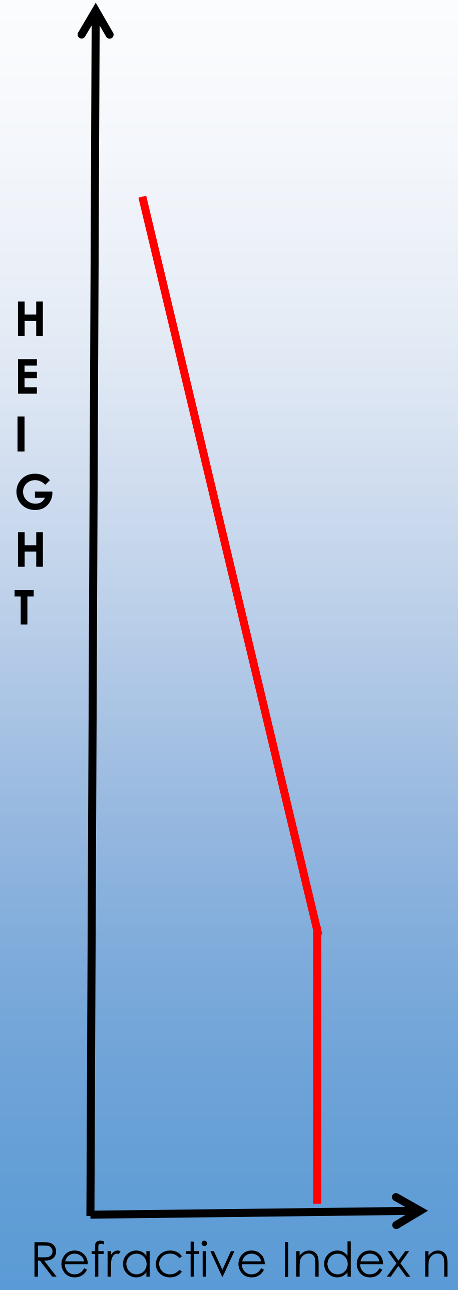
➔ possible formation of multiple images



$$v = \frac{c}{n}$$







$$n = 1 - \frac{2U}{c^2}$$

$$v = \frac{c}{n}$$

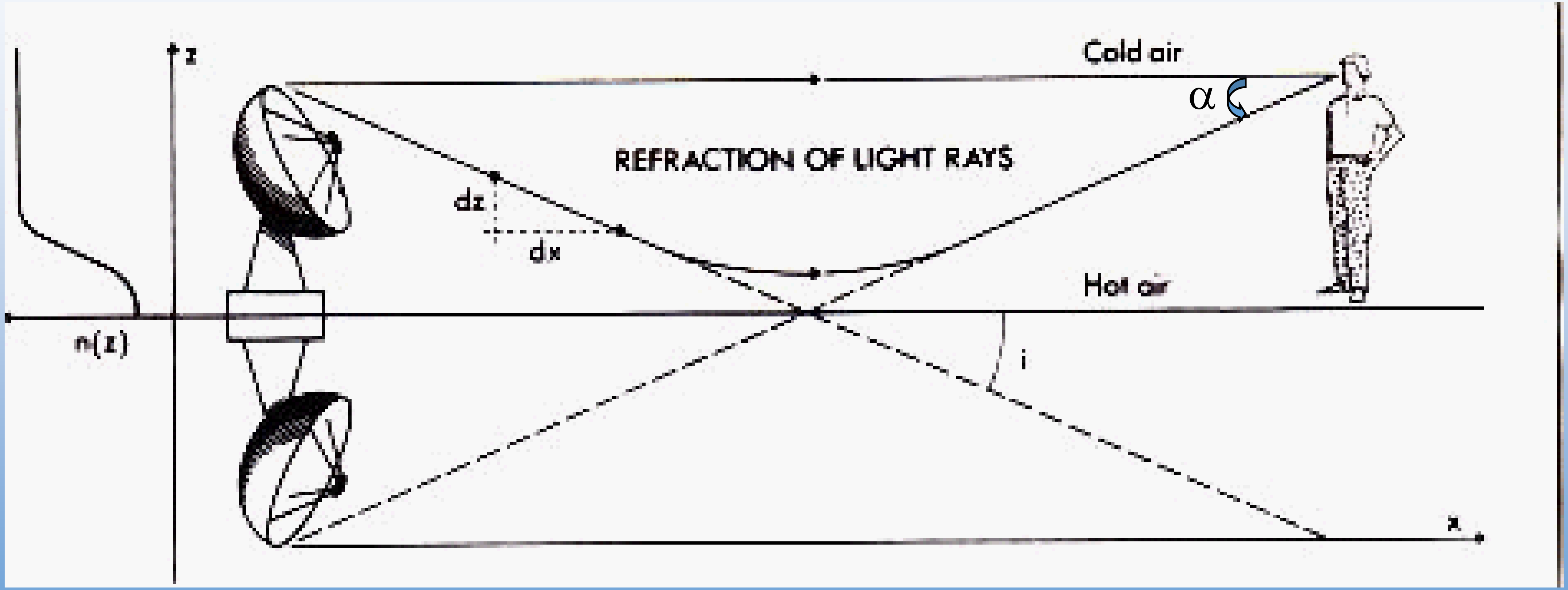
$$\delta\left(\int dt\right) = 0$$

$$n(z)\cos(i) = Cte$$

O *

* S

$$di = \frac{(dn/dz)dx}{n(z)} \quad and \quad \alpha = \int di = \int \frac{(dn/dz)dx}{n(z)} = \int \frac{d\ln(n(z))}{dz}dx$$



Formation of an atmospheric mirage across an atmosphere characterized by a refractive index distribution n(z), as shown along the left horizontal axis.

ATMOSPHERIC LENSING:

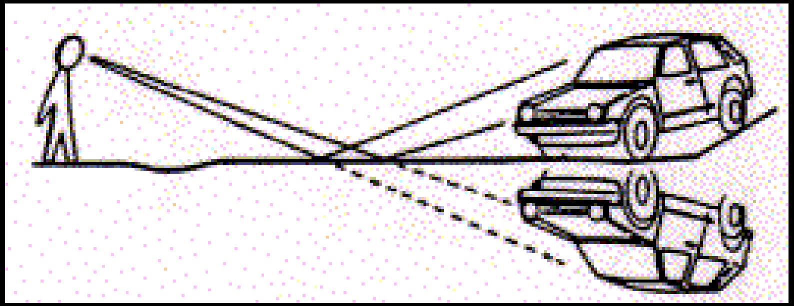
Paranal (ESO), Chile,
December 2008

ATMOSPHERIC LENSING:

(a)


(b)


(c)

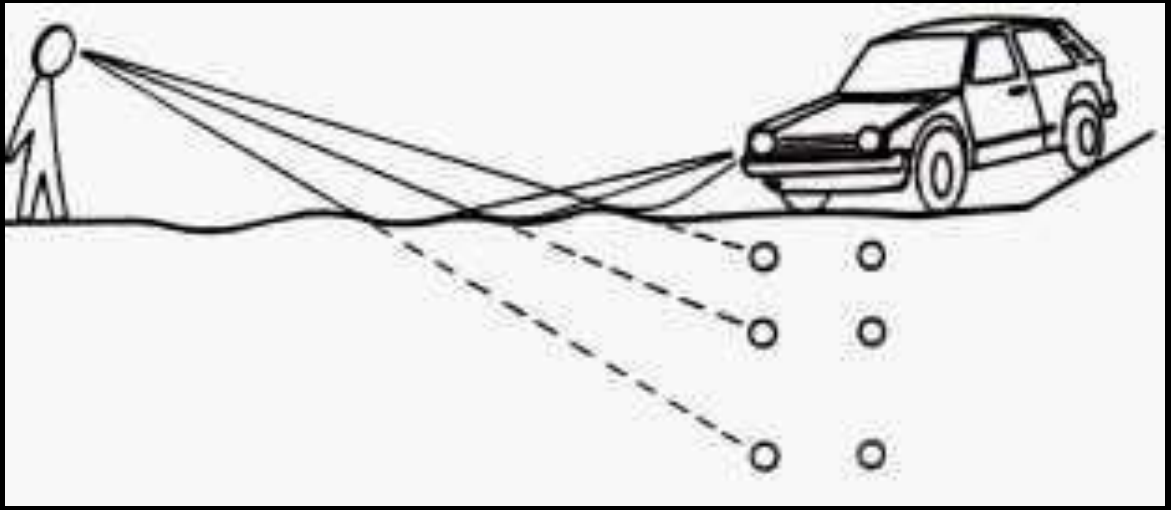

(d)


Atmospheric lensing: (a) and (b) illustrate double images of a distant, approaching, truck and (c) of a distant car along the North Panamericana highway between the towns of Pichidangui and La Serena (Chile, 2 December 1987). (d) gives a schematic view of double light rays for the case of an inferior atmospheric mirage.

ATMOSPHERIC LENSING:

(e)

(f)



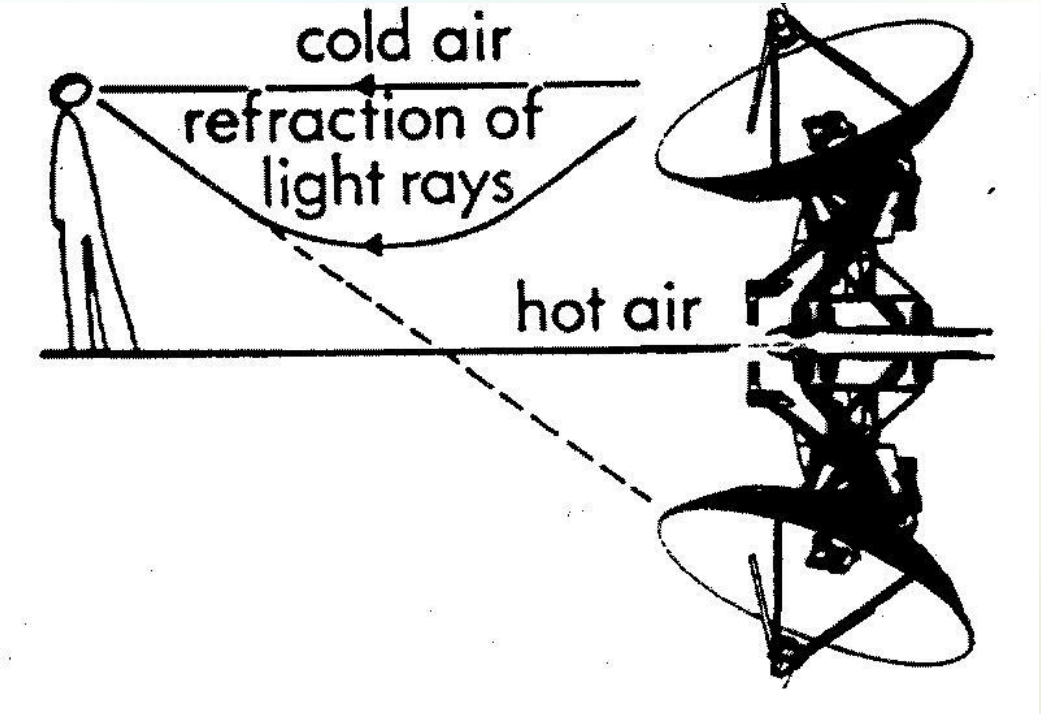
Atmospheric lensing: (e) represents the multiple car lights of a distant vehicle along the US 60 road between Magdalena and Datil in New Mexico on the night of 19 January 1989. The distance between the car and the observer was estimated to be 10 miles. (f) gives a schematic representation of the light rays from a distant car when the ground turns out to be somewhat hotter than the ambiant air. Because air refraction always leads to a bending of light rays towards regions of colder air, several lower and somewhat deformed images of a distant car may result.

Atmospheric lensing

Schematic view of the N-S arm of the Very Large Array (VLA) in Socorro (New Mexico), in the A configuration. The second last antenna, at an approximate distance of 10 km, is not resolved with the naked eye (January 1988).

Atmospheric lensing

PREAMBLE:

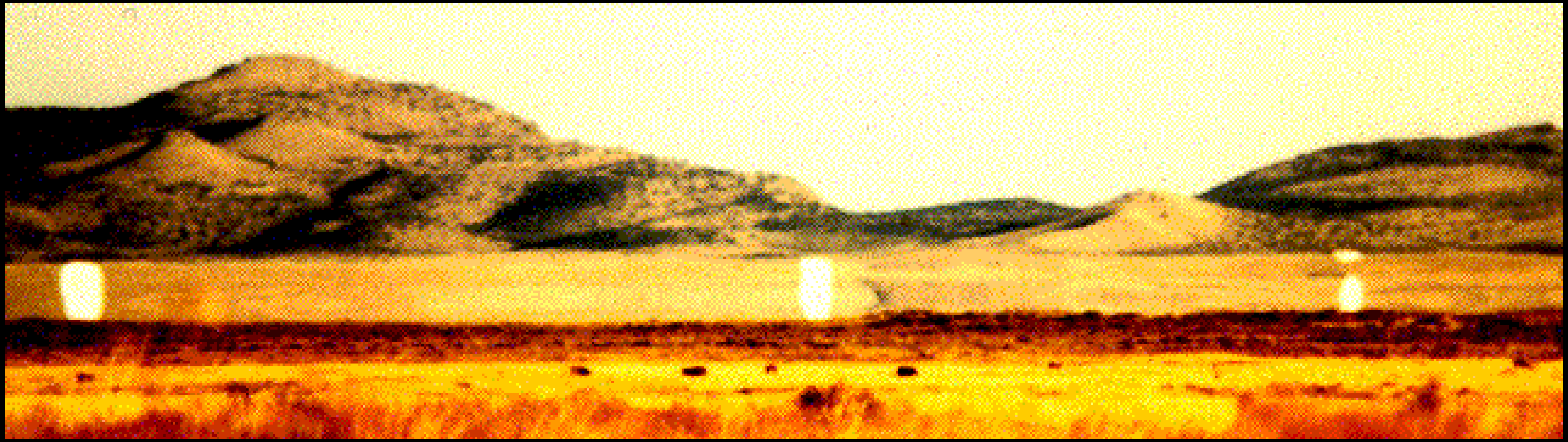


Due to atmospheric lensing, the second last antenna was doubly imaged and, while it was unresolved with the naked eye, it appeared brighter than the third and fourth last antenna.

ATMOSPHERIC LENSING:

(g)

(h)



Atmospheric lensing: (g-h) correspond to two different views of the north-south arm of the Very Large Array at the National Radio Astronomical Observatory (Socorro, New Mexico) as seen in the early morning of 17 January 1989.

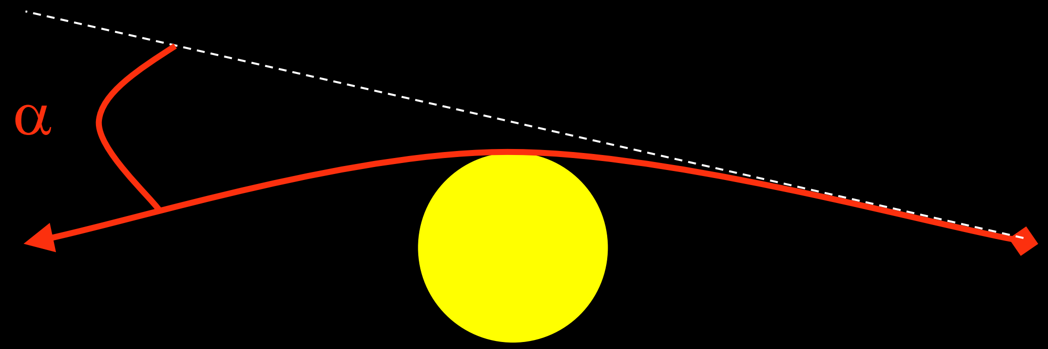
Gravitational Lensing

HISTORICAL BACKGROUND:

- "Do not Bodies act upon Light at a distance, and by their action bend its Rays; and is not this action strongest at the least distance?"

  Isaac Newton, 1704

- J. Soldner (1804): $\underline{\alpha} = 2GM_{\odot} / (c^2 R_{\odot}) \sim 0.875''$

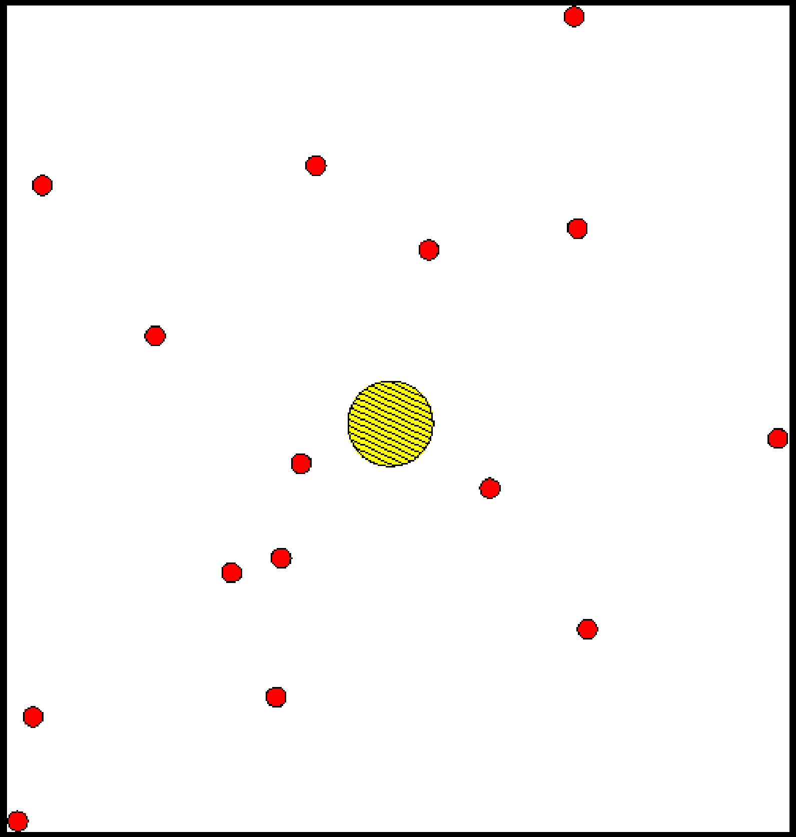


- XVIIIth and XIXth centuries

HISTORICAL BACKGROUND:

- Einstein (1912, 1915): $\underline{\alpha} = 4GM_{\odot} \;/\; (c^2 R_{\odot}) = 1.75''$, (2.1)

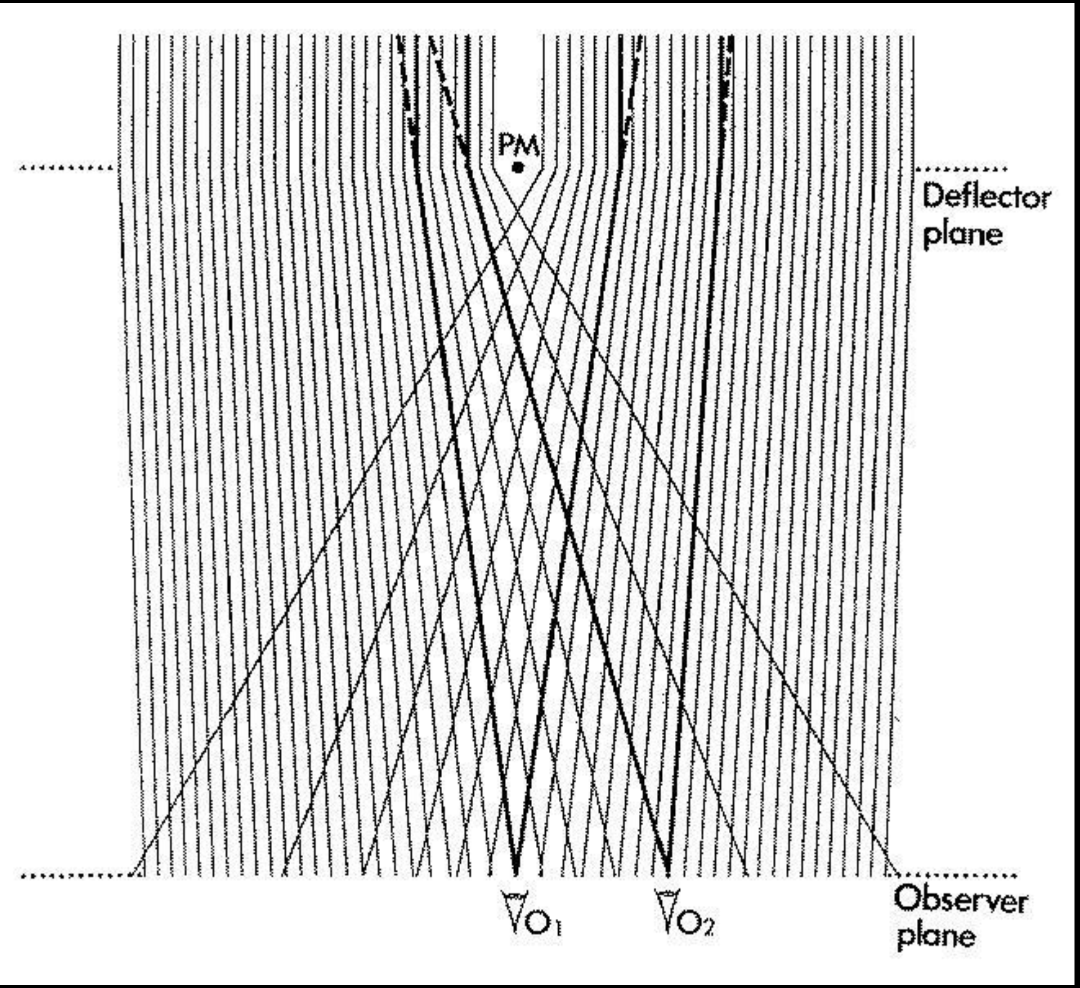
- Dyson et al. (1920): 20-30% uncertainty; Fomalont and Sramek (1975a, b), Robertson et al. (1991): << 1% uncertainty

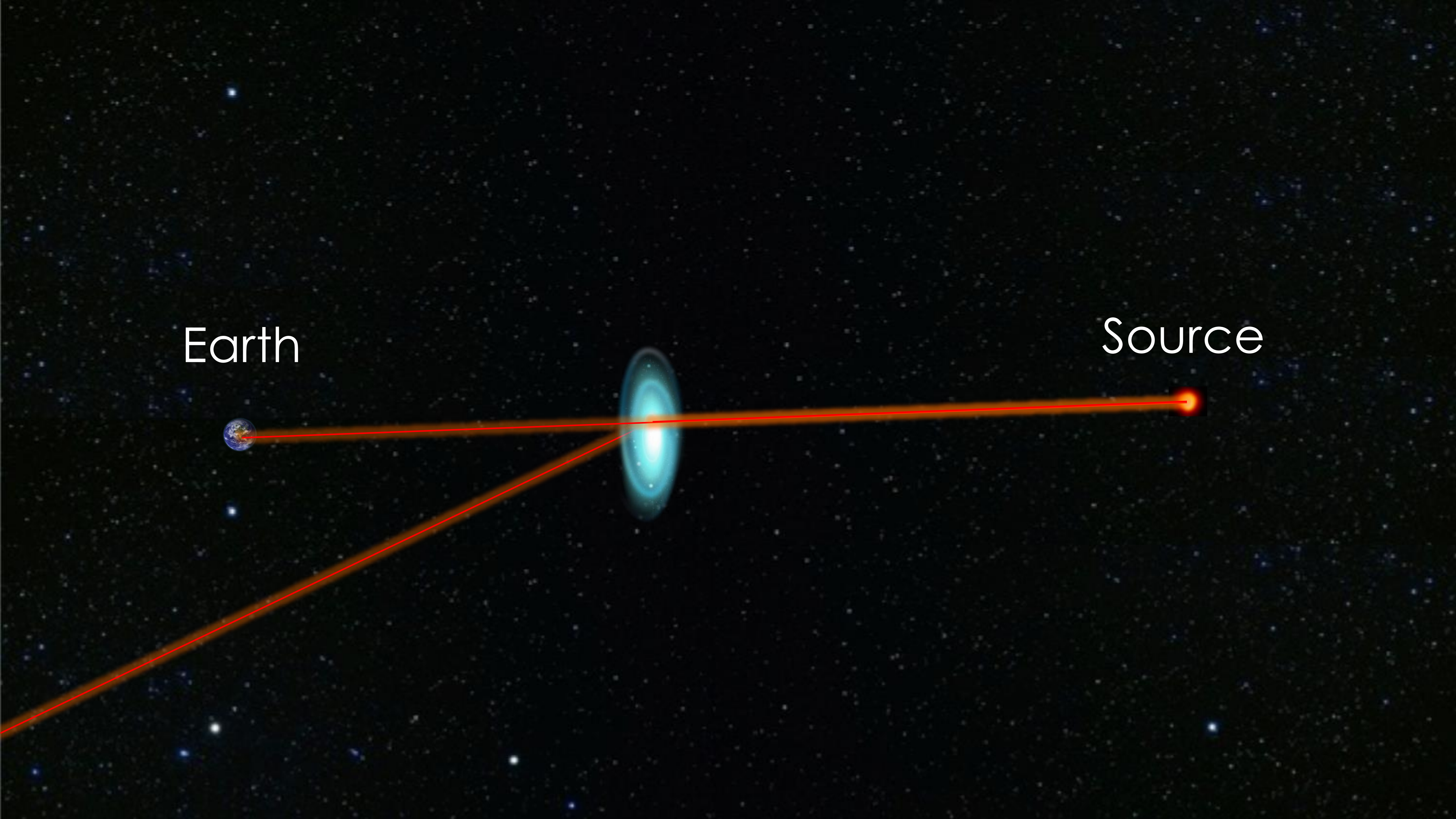


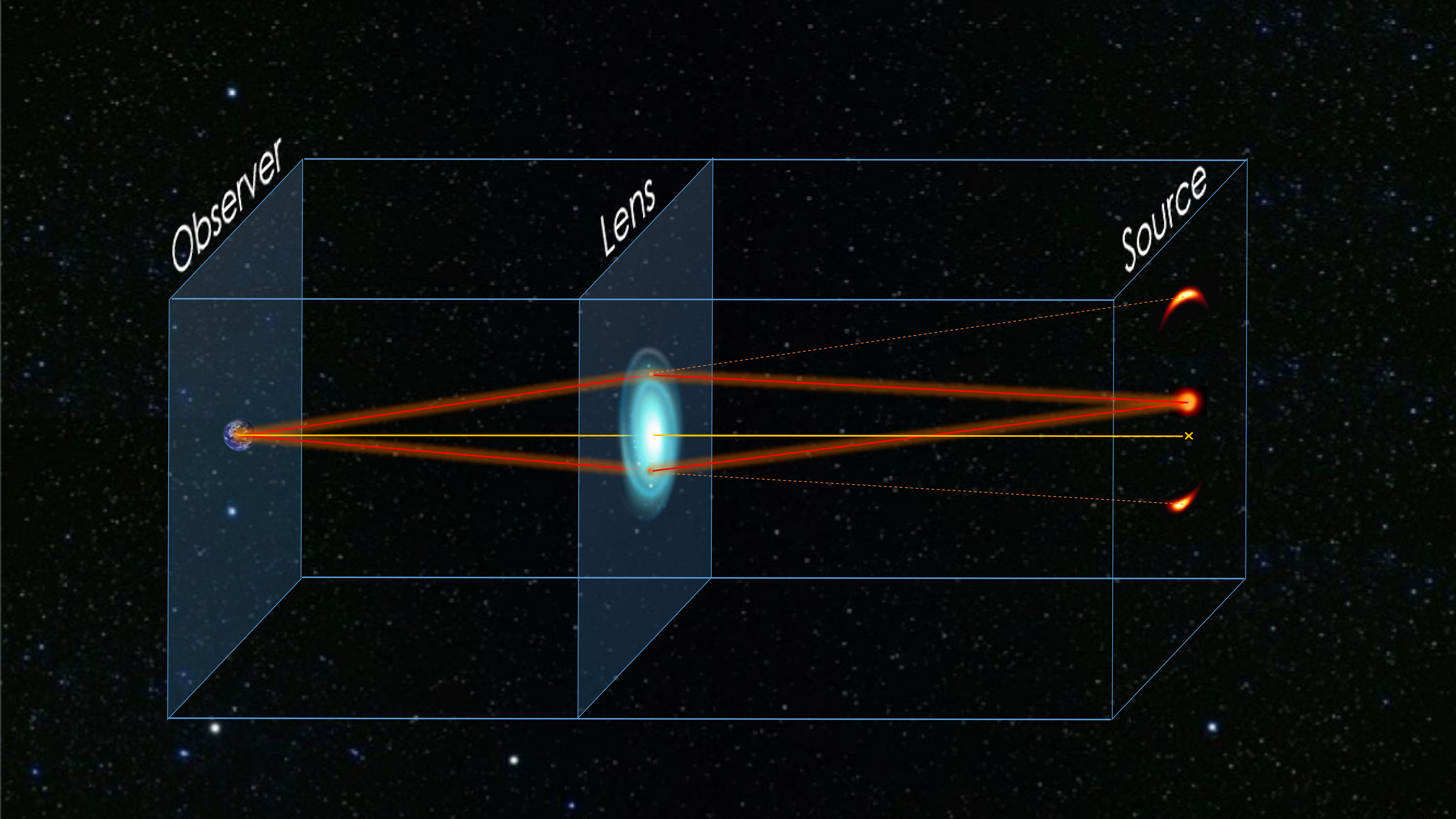
HISTORICAL BACKGROUND:

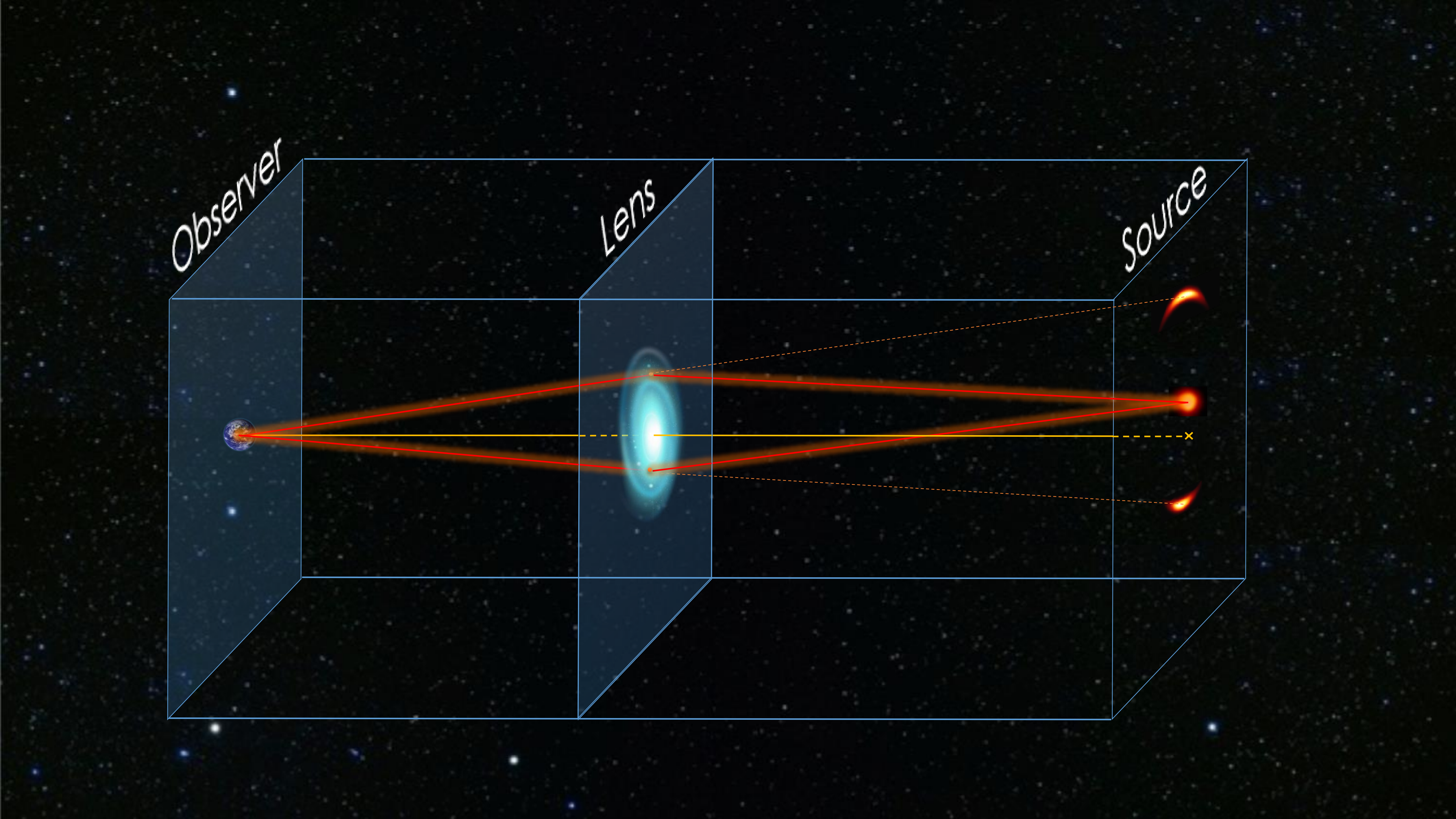
- Eddington (1920) … but see Einstein (1912)
- Sir Oliver Lodge (1919)
- E.B. Frost (1923)

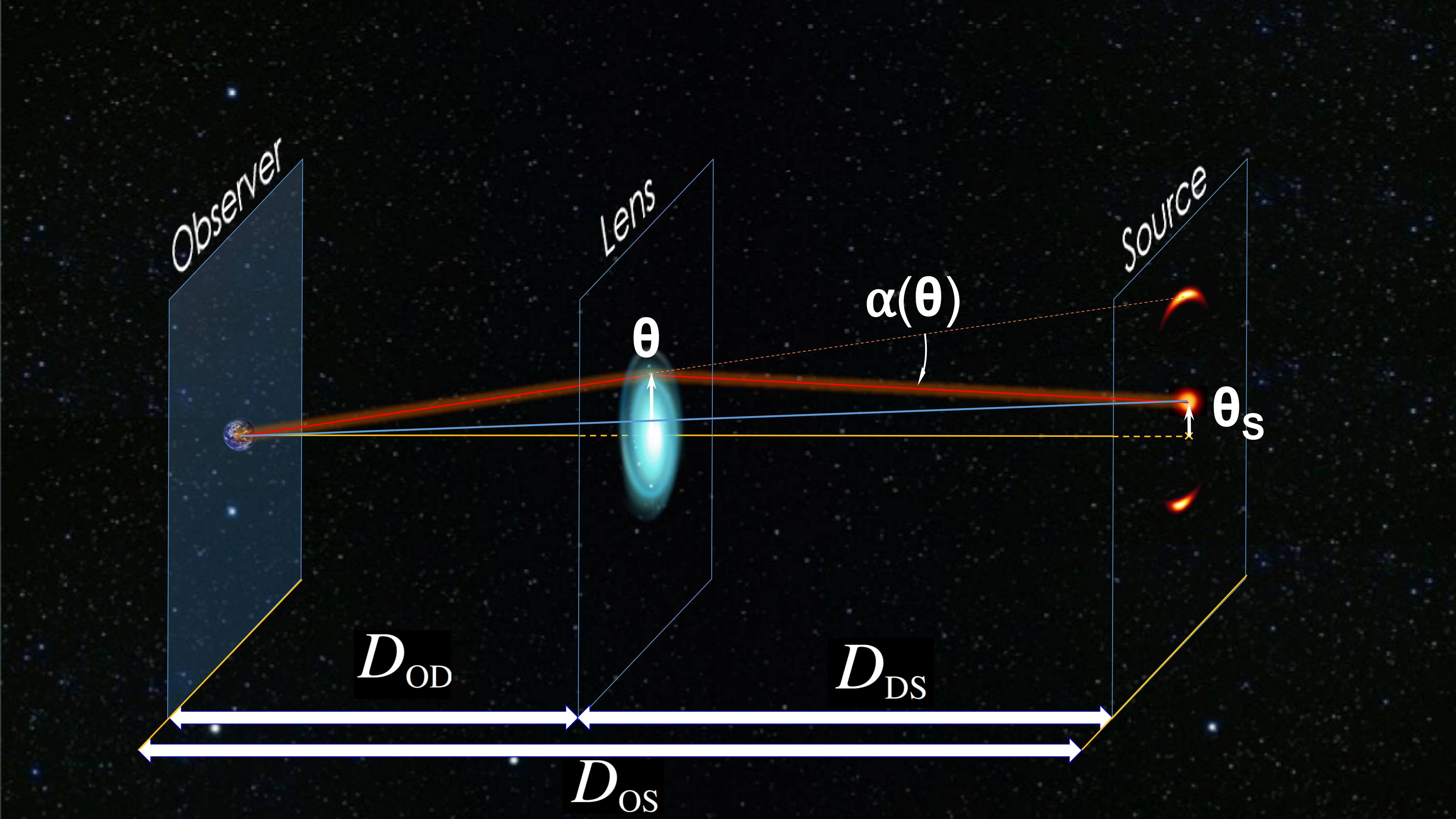
A point mass object consists of a very imperfect, although achromatic, lens!



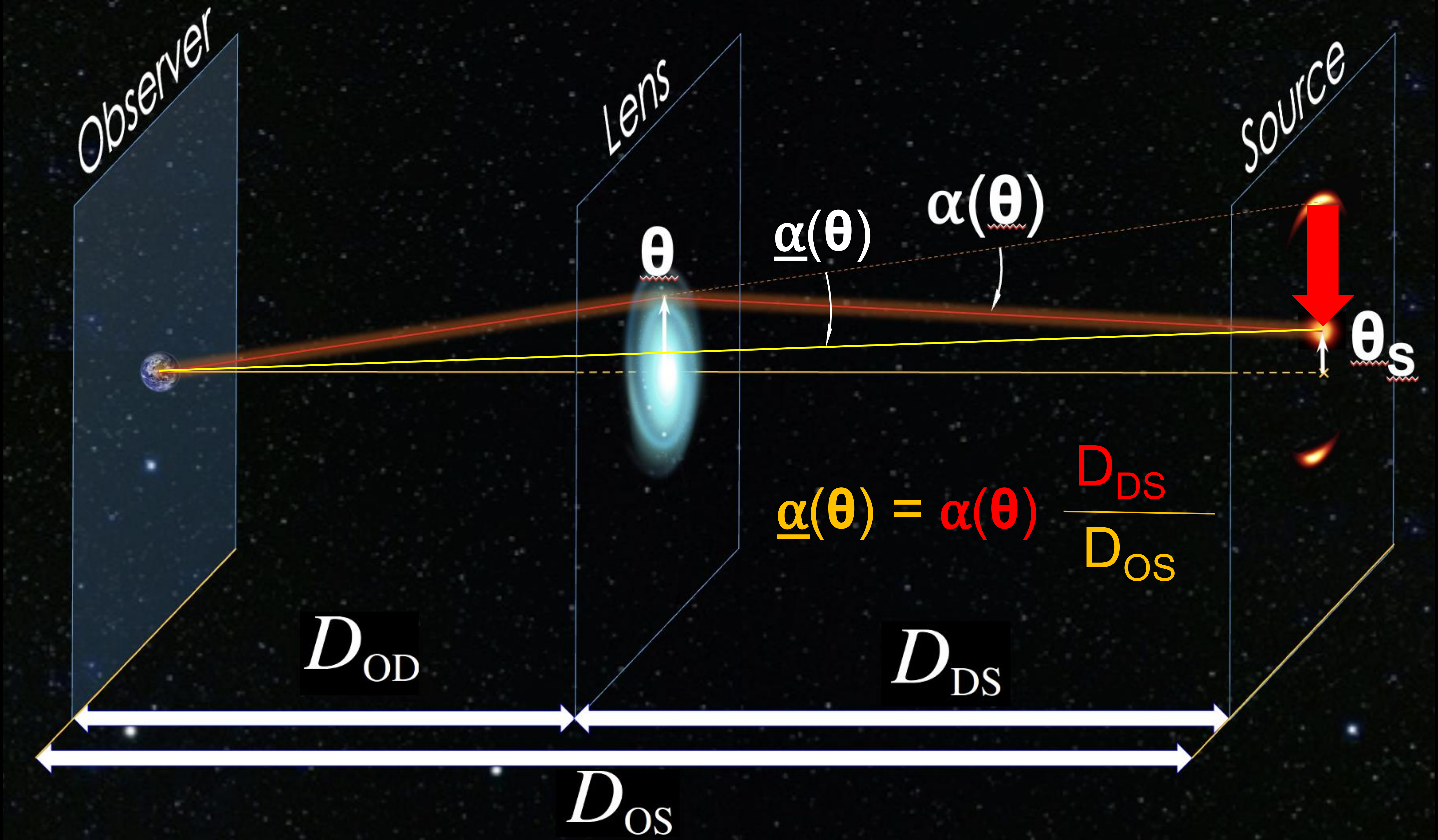

Earth
Source


Observer
Lens
Source


Observer
Lens
Source



Observer
Lens
Source
α(θ)
θ
θs
DOD
DDS
DOS



Observer
Lens
Source
θ
α(θ)
α(θ)
θs
α(θ) = α(θ) DDS / DOS
DOD
DDS
DOS

The angular lens equation

$$\boldsymbol{\theta}_S = \boldsymbol{\theta} + \underline{\alpha}(\boldsymbol{\theta}) \qquad \underline{\alpha}(\boldsymbol{\theta}) = \alpha(\boldsymbol{\theta}) \frac{D_{DS}}{D_{OS}}$$

PML: $$\alpha(\boldsymbol{\theta}) = - \frac{4G}{c^2} \frac{M}{\theta\, D_{OD}} \frac{\boldsymbol{\theta}}{\theta}$$

$$\alpha(\boldsymbol{\theta}) = - \frac{4G}{c^2} \iint \frac{\Sigma(\boldsymbol{\theta})\,(\boldsymbol{\theta} - \boldsymbol{\theta}')}{(\boldsymbol{\theta} - \boldsymbol{\theta}')^2} \frac{d\theta'_x\, d\theta'_y}{D_{OD}}$$

The angular lens equation

$$\boldsymbol{\theta}_S = \boldsymbol{\theta} + \underline{\alpha}(\boldsymbol{\theta}) \qquad \underline{\alpha}(\boldsymbol{\theta}) = \alpha(\boldsymbol{\theta}) \frac{D_{DS}}{D_{OS}}$$

PML: $$\alpha(\boldsymbol{\theta}) = - \frac{4G}{c^2} \frac{M}{\theta \, D_{OD}} \frac{\boldsymbol{\theta}}{\theta}$$

$$\theta_S = \theta + \alpha(\theta) \frac{D_{DS}}{D_{OS}} = \theta - \frac{4G}{c^2} \frac{M}{\theta \, D_{OD}} \frac{D_{DS}}{D_{OS}}$$

The angular lens equation

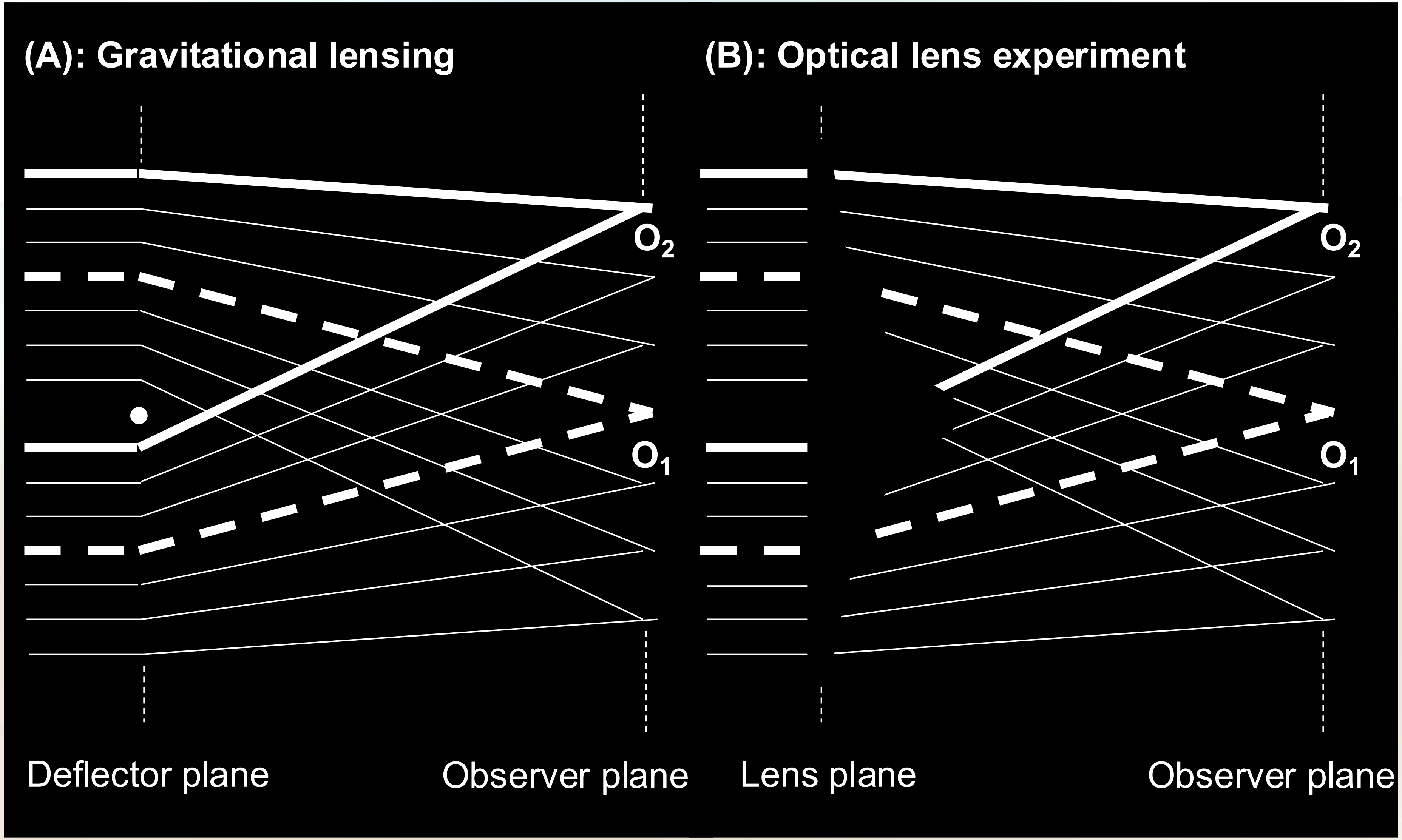
$$\theta_S = \theta + \alpha(\theta)\frac{D_{DS}}{D_{OS}} = \theta - \frac{4G}{c^2}\frac{M}{\theta\, D_{OD}}\frac{D_{DS}}{D_{OS}}$$

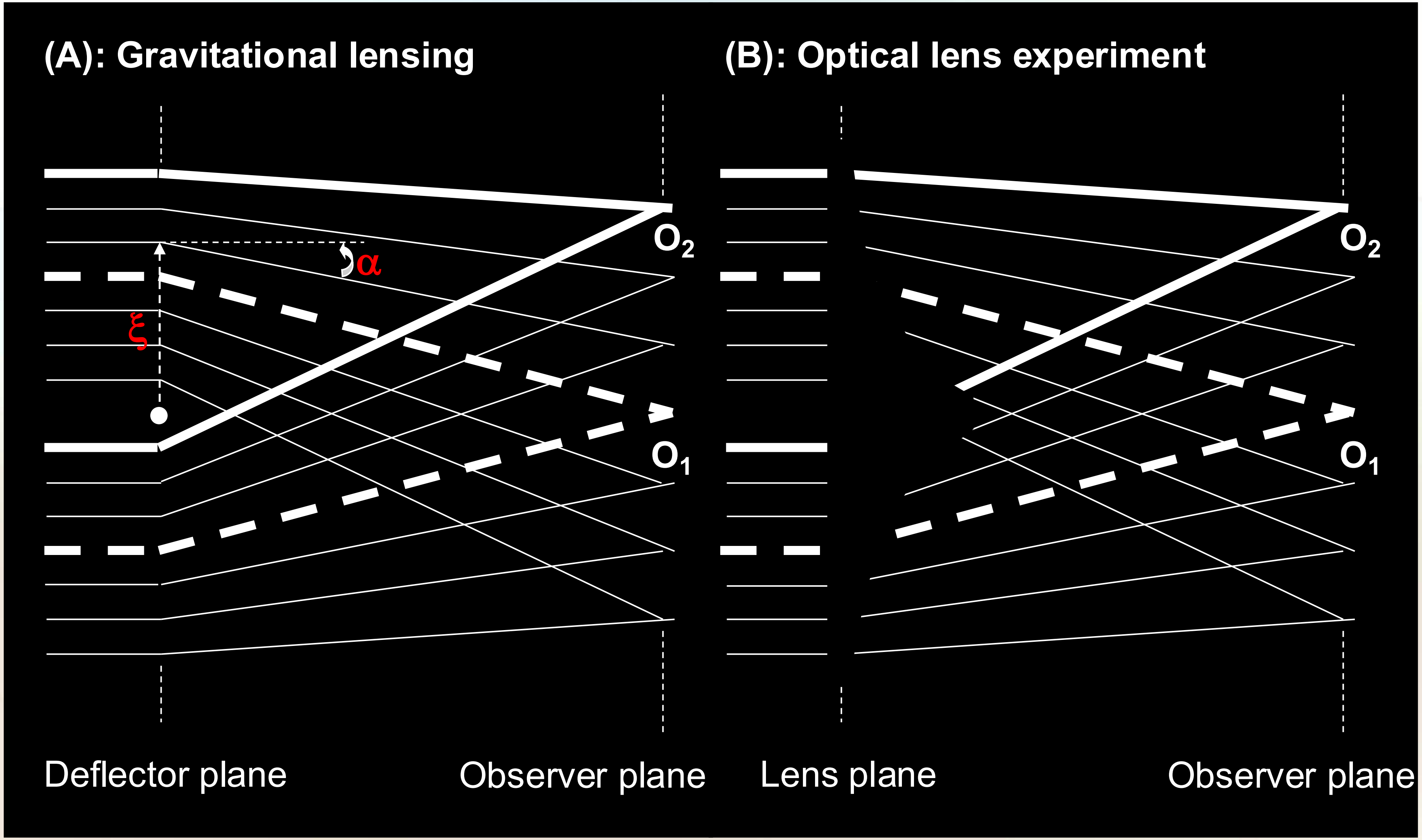
If $\theta_S = 0 \rightarrow \theta_E = \mathrm{sqrt}\left[\frac{4G}{c^2}\frac{M}{D_{OD}}\frac{D_{DS}}{D_{OS}}\right]$

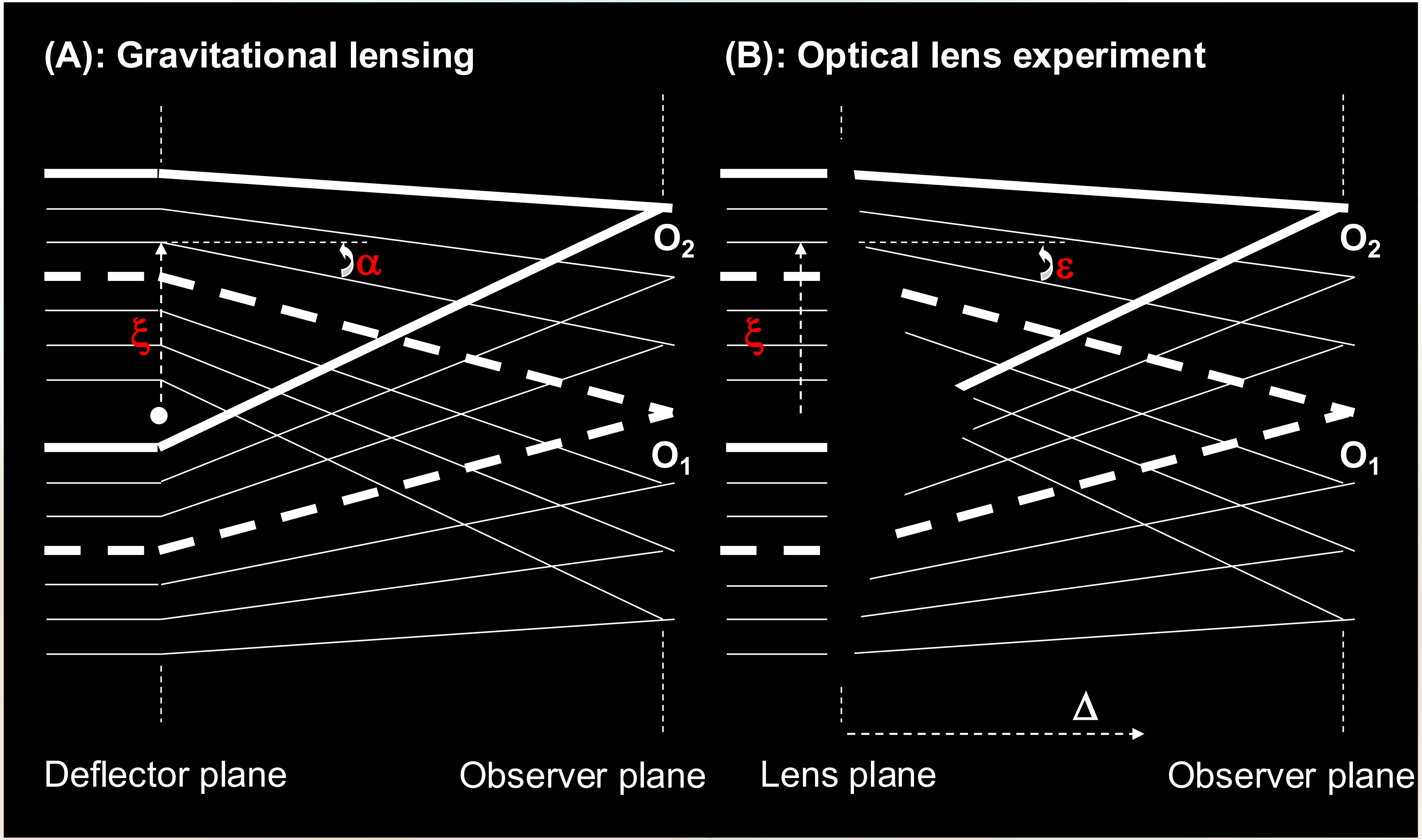
If $\theta_S \neq 0 \rightarrow \theta^2 - \theta_S\,\theta - \theta^2{}_E = 0$

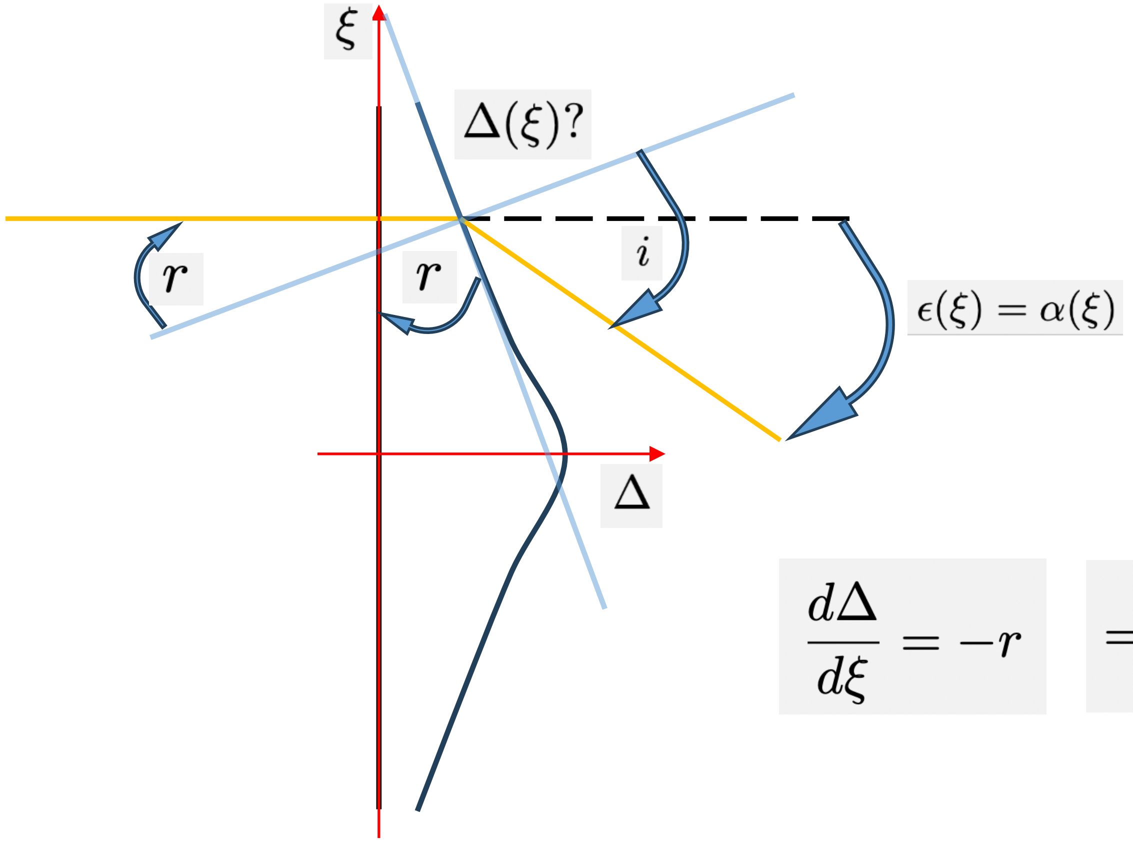
$$\theta_{1,2} = \frac{\theta_S \pm \sqrt{\theta^2{}_S + 4\,\theta^2{}_E}}{2}$$

THE OPTICAL GRAVITATIONAL LENS (GL)




(A): Gravitational lensing
(B): Optical lens experiment
ξ
α
O2
O1
O2
O1
Deflector plane
Observer plane
Lens plane
Observer plane


(A): Gravitational lensing
(B): Optical lens experiment
α
ξ
O2
O1
ε
ξ
O2
O1
Δ
Deflector plane
Observer plane
Lens plane
Observer plane



$$\frac{\sin(i)}{\sin(r)} \simeq \frac{i}{r} = n \qquad \Rightarrow i = n\, r$$

$$i = \epsilon + r \Rightarrow r = \frac{\epsilon}{n-1}$$

$$\frac{d\Delta}{d\xi} = -r$$

$$\Rightarrow \frac{d\Delta}{d\xi} = -\frac{\epsilon}{n-1} = -\frac{\alpha}{n-1} = \frac{-4G}{c^2(n-1)} \frac{M(\xi)}{\xi}$$

If $M(\xi) = M$

$$\frac{d\Delta}{d\xi} = \frac{-K}{\xi} \quad \text{where} \quad K = \frac{4GM}{c^2(n-1)}$$

$$d\Delta = \frac{-K d\xi}{\xi}$$

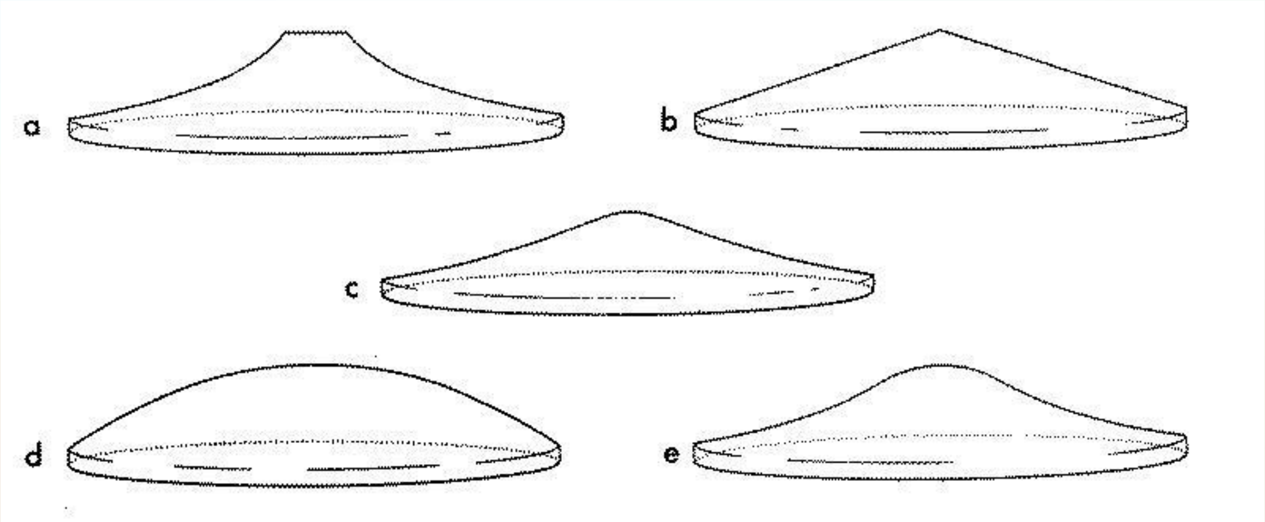
$$\int_{\xi_0}^{\xi} d\Delta = \int_{\xi_0}^{\xi} \frac{-K d\xi'}{\xi'}$$

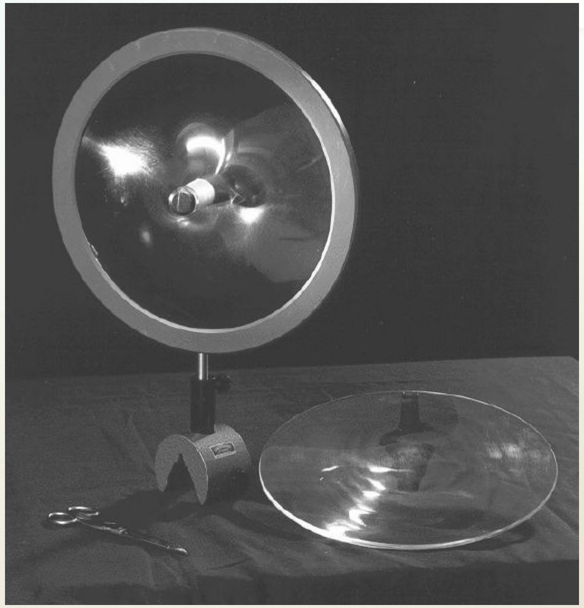
$$\Delta(\xi) = \Delta(\xi_0) + K \ln(\frac{\xi_0}{\xi})$$

THE OPTICAL GL EXPERIMENT:

Shapes of axially symmetric optical lenses:

Below: several examples of axially symmetric optical lenses simulating the light deflection properties due to a point mass (a), a SIS galaxy (b), a spiral galaxy (c), a uniform disk (d) and a truncated uniform disk of matter (e).



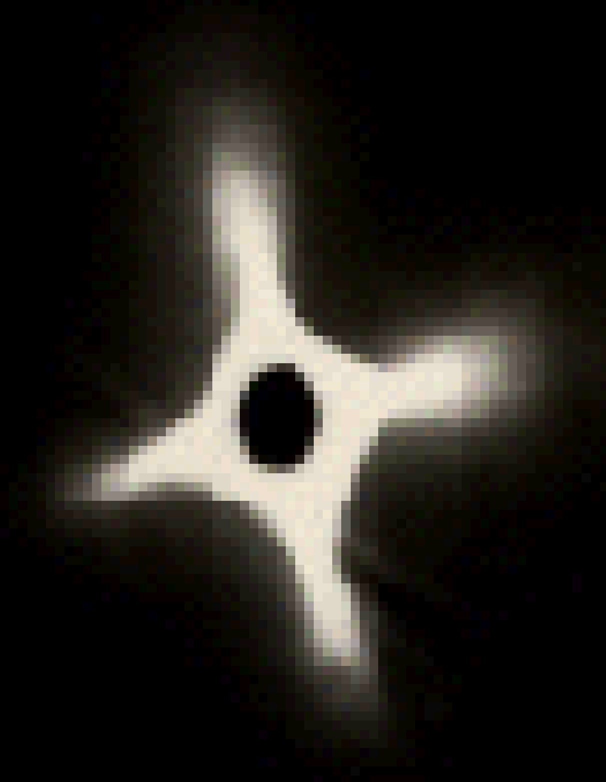


Right: examples of (upper left) a 'point mass' lens (28 cm in diameter) manufactured at the Hamburg Observatory and of (lower right) a 'spiral galaxy' optical lens (30 cm in diameter) produced by the authors at the European Southern Observatory (Garching bei München).

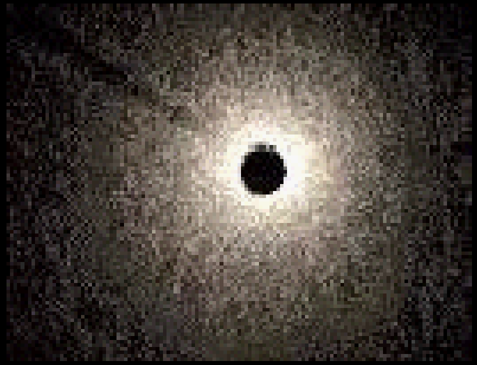

Dark Matter Exposed!
Background
To Do and Notice
Each of the two plastic disks represents a galaxy cluster, one with dark matter and one without.
Look through each of the disks at the picture of the galaxy behind them and compare views.
What Happens and Why

The GL experiment

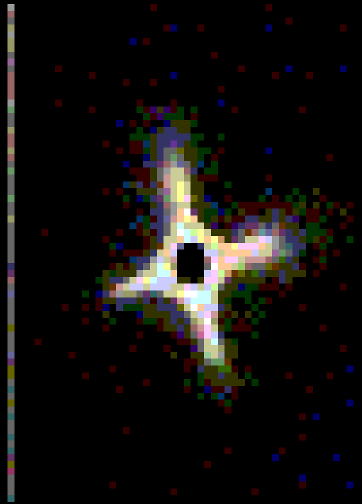
Setup of the optical gravitatio-nal lens experiment.



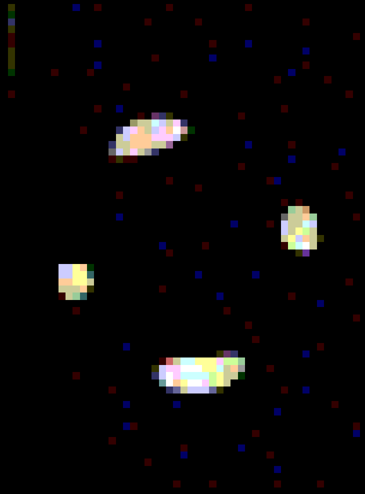
GL MODELS; Asymmetric lenses:



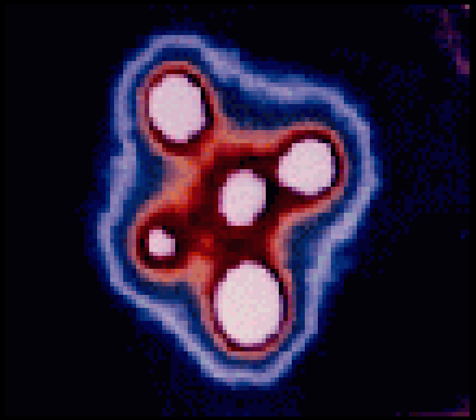
(z)



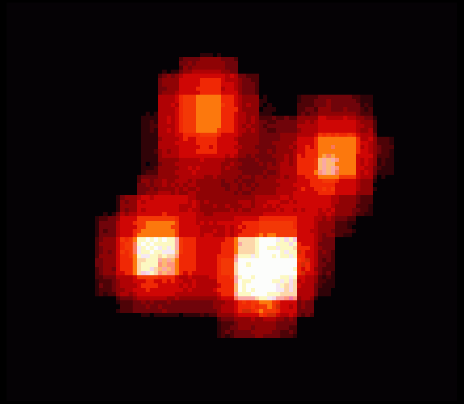
(a)



(b)

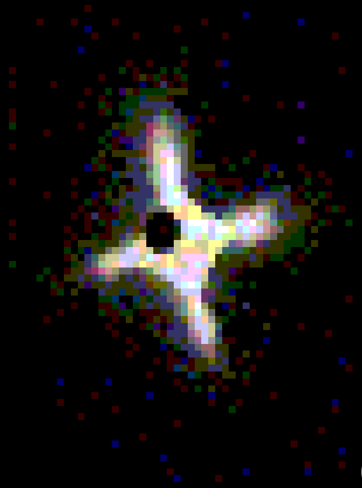


2237+0305, Δθ ~ 1.5”,
z_q = 1.69, z_d = 0.04

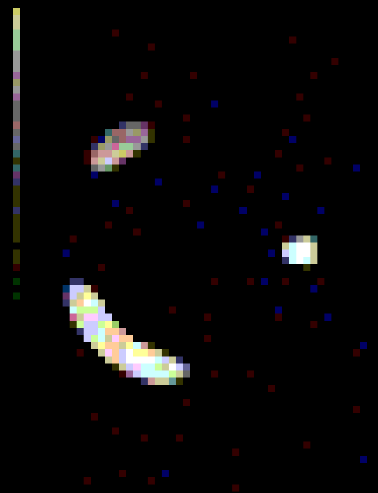


H1414+117, Δθ ~ 1”,
z_q = 2.55, z_d = ?

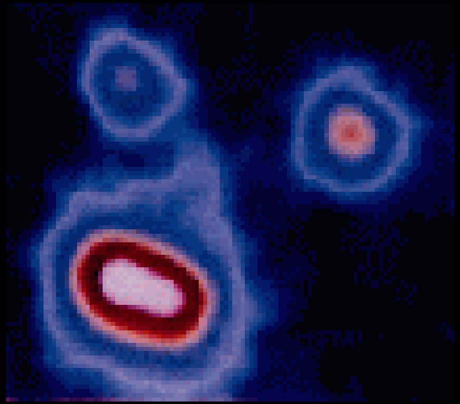
GL MODELS; Asymmetric lenses:



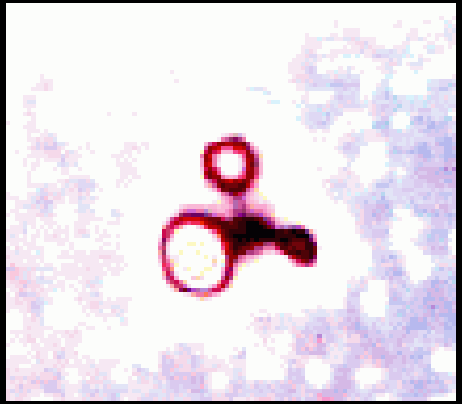
(c)



(d)

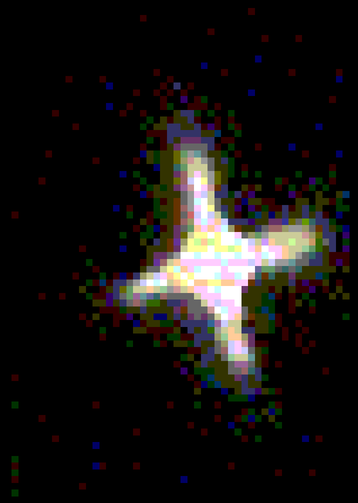


PG1115+080, Δθ ~ 2”,
$z_q = 1.72$, $z_d = 0.29$

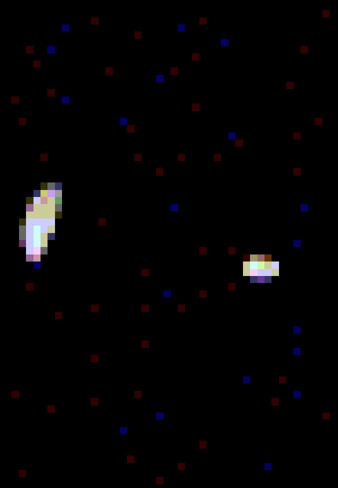


0414+0534, Δθ ~ 3”,
$z_q = 2.63$, $z_d = 0.96$

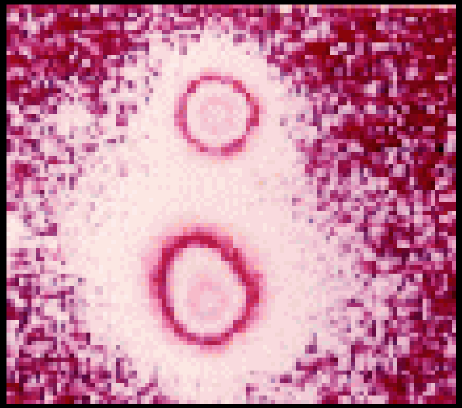
GL MODELS; Asymmetric lenses:



(e)

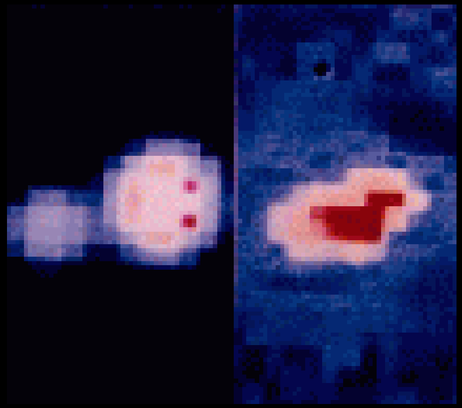


(f)



Q0957+561, $\Delta\theta \sim 6''$,
$z_q = 1.41$, $z_d = 0.36, 0.5$

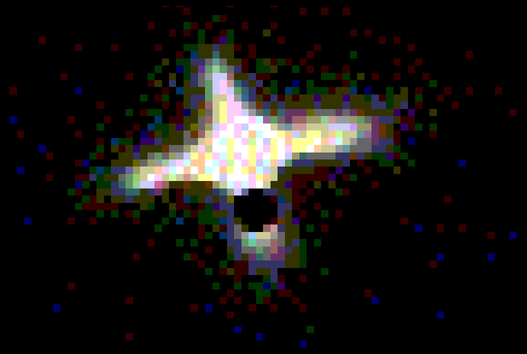
Lensed Quasar



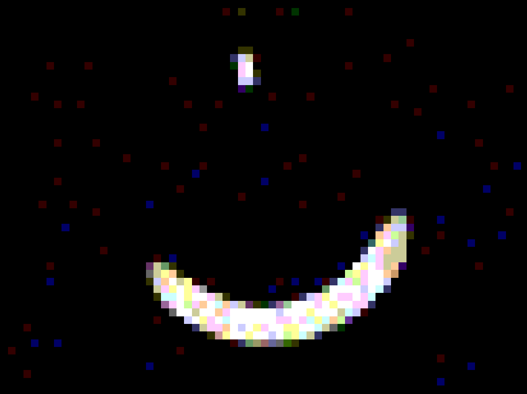
Lens

UM673, $\Delta\theta \sim 2''$,
$z_q = 2.72$, $z_d = 0.49$

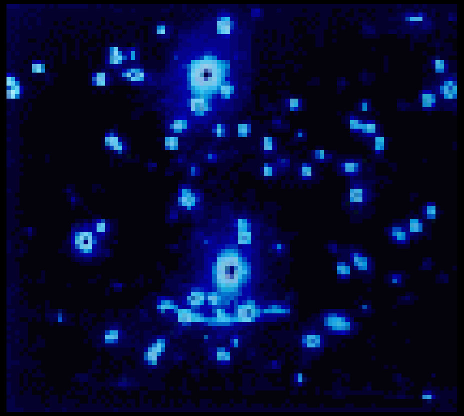
GL MODELS; Asymmetric lenses:



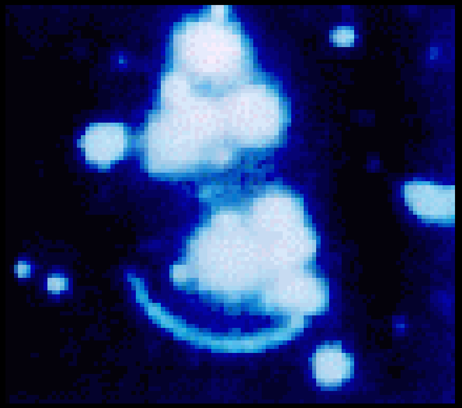
(g)



(h)



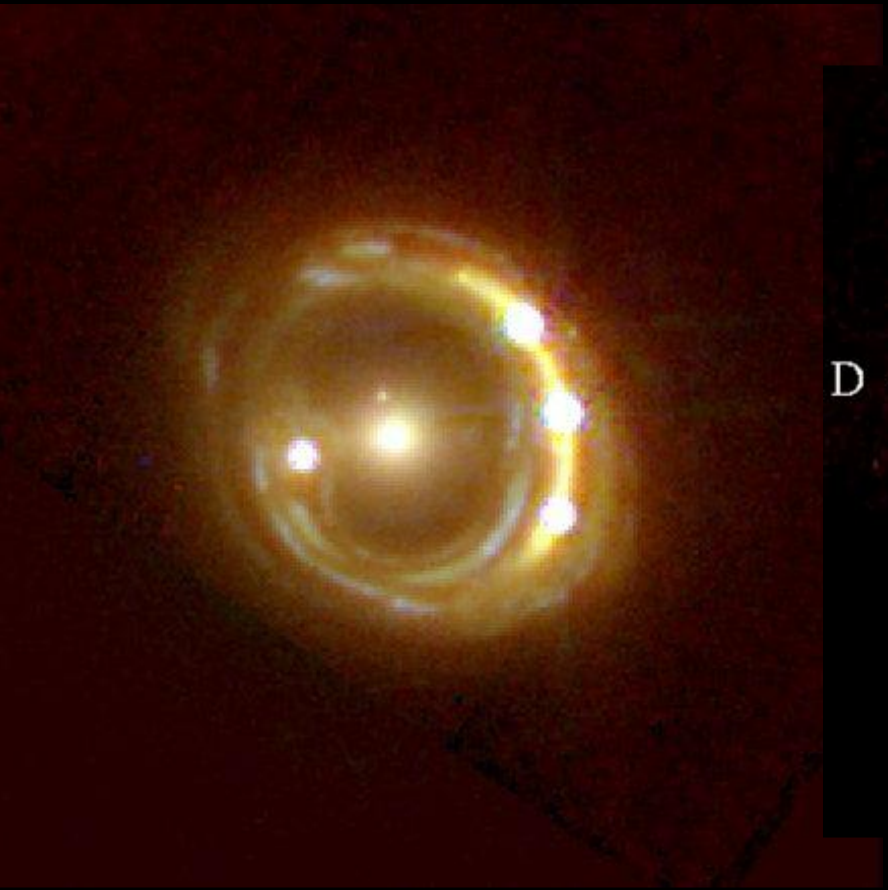
Abell370, $\Delta\theta \sim 20''$, $z_s = 0.725$, $z_d = 0.37$

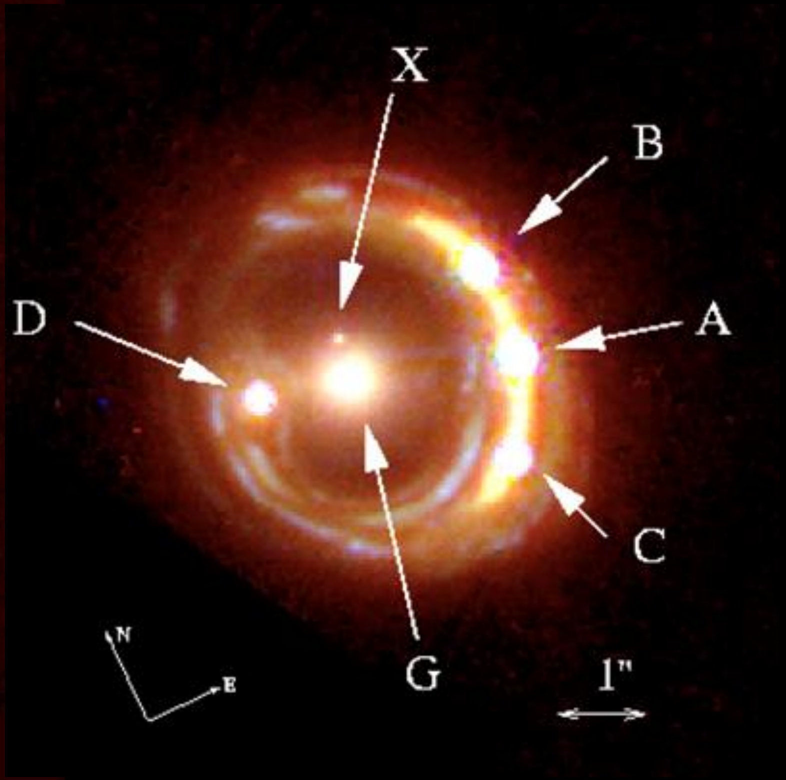


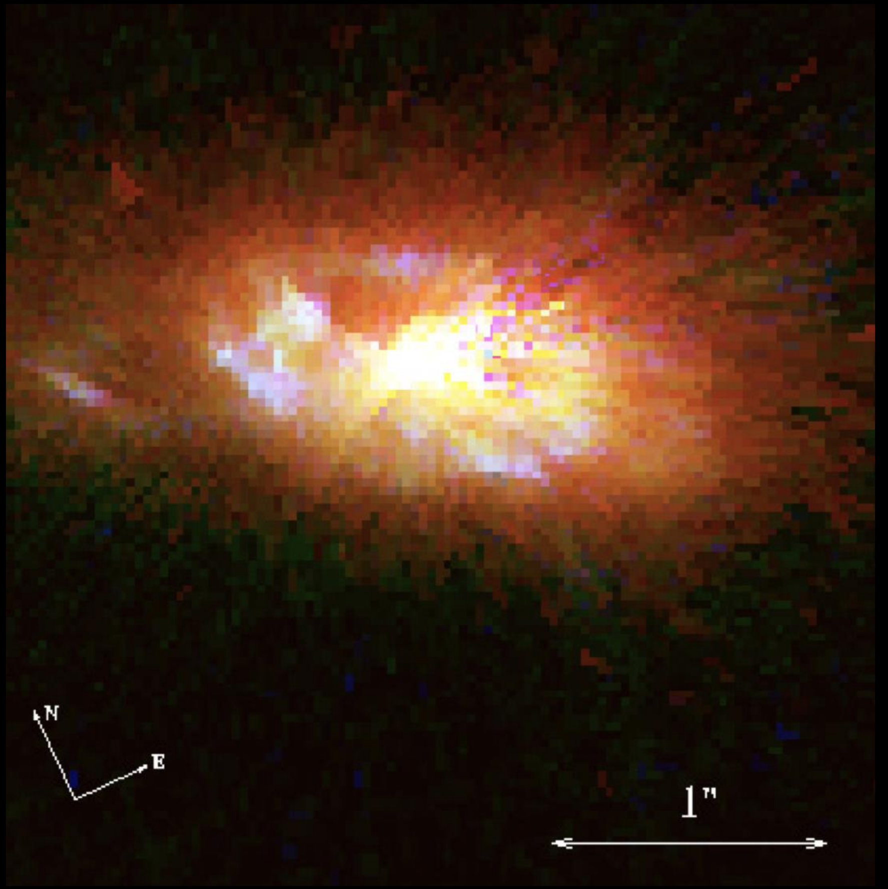
Cl2244-02, $\Delta\theta \sim 20''$, $z_q = 2.237$, $z_d = 0.34$

OBSERVATIONS

RXS J11331-1231 (Sluse et al. 2003, 2005, Claeskens et al. 2006) : z_s=0.658, z_l=0.295

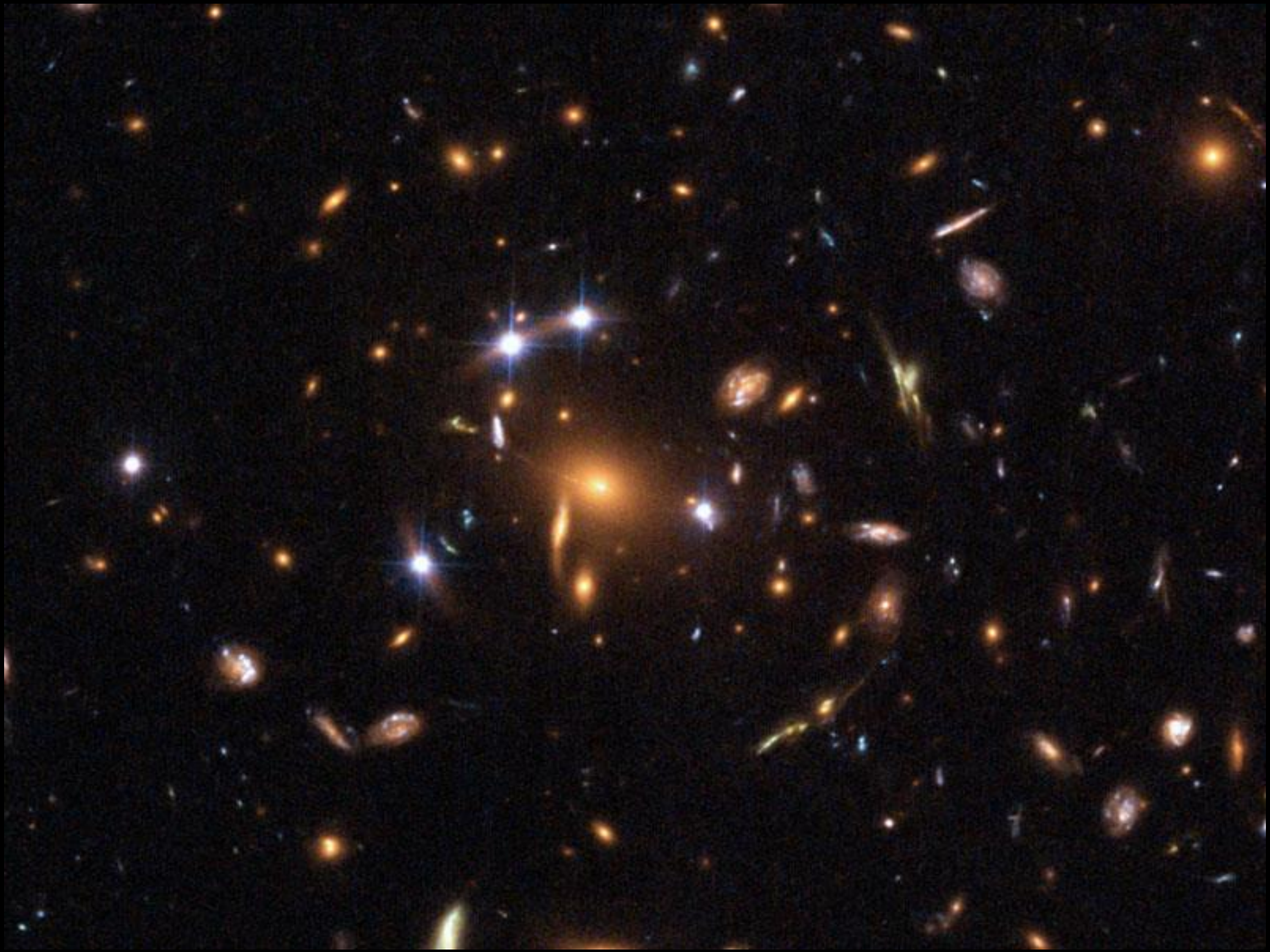






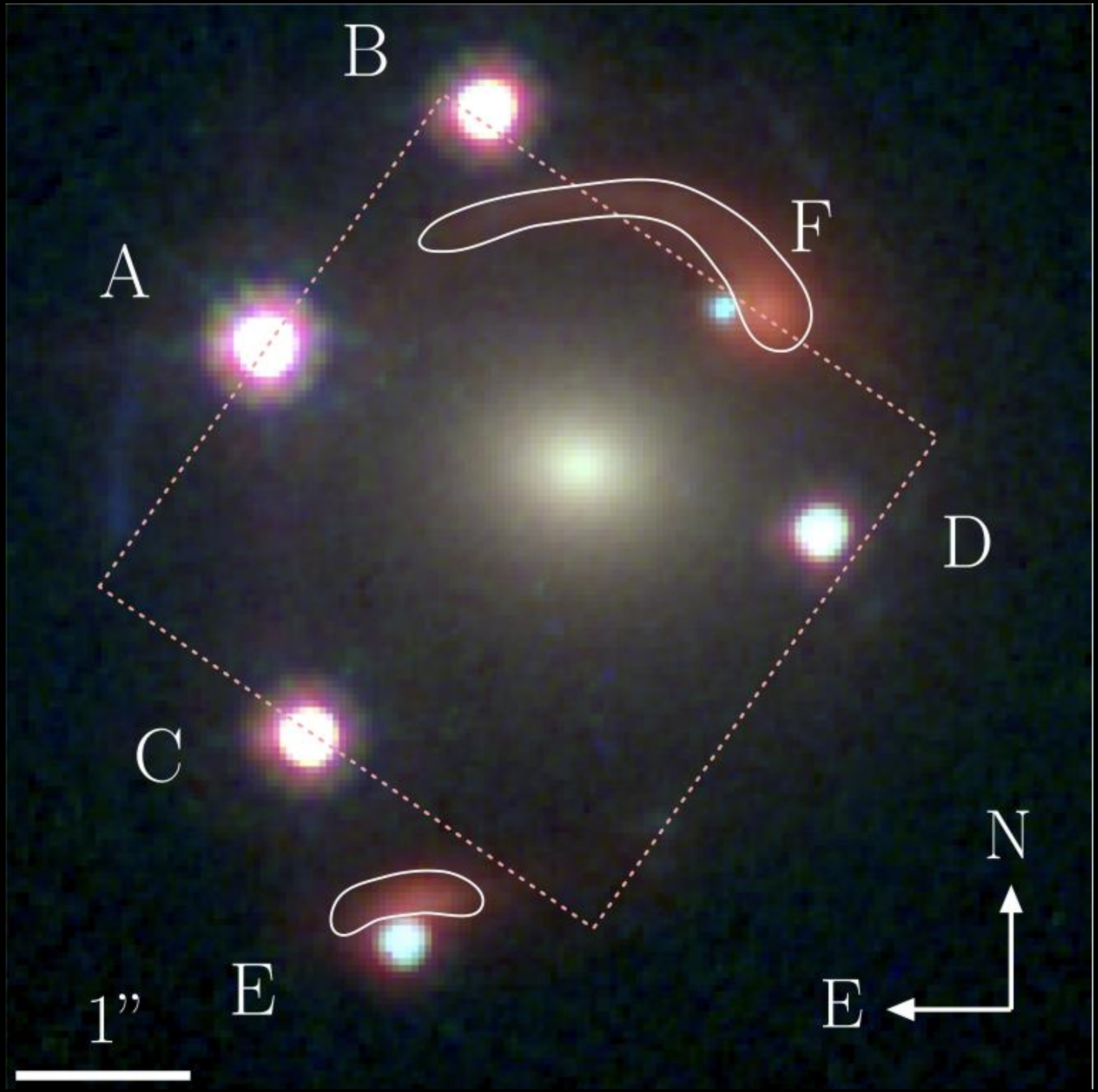
CL 0024+1654, Colley et al 1996; HST WFPC2

QSO: z=1.74, Cluster: z=0.68



SDSS J1004+4112; Sharon et al. 2005; © HST

J1721+8842: The first Einstein zig-zag lens



Dux et al. (2024)

A&A 590, A42 (2016)
DOI: 10.1051/0004-6361/201425411

Astronomy & Astrophysics

Multiply imaged quasi-stellar objects in the *Gaia* survey

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Results. Out of the 6.64×10^5 QSOs brighter than $G = 20$ to be detected, we expect the discovery of about 2886 multiply imaged sources, 450 of these being produced by a late-type galaxy . We only expect $\sim$ 1600 of these multiply imaged quasars to have an angular separation between their images large enough to be resolved from seeing limited observations, $\sim$ 80 of them having more than 2 lensed images.

A&A 622, A165 (2019)
https://doi.org/10.1051/0004-6361/201833802

Astronomy & Astrophysics

Gaia GraL: *Gaia* DR2 Gravitational Lens Systems

III. A systematic blind search for new lensed systems*

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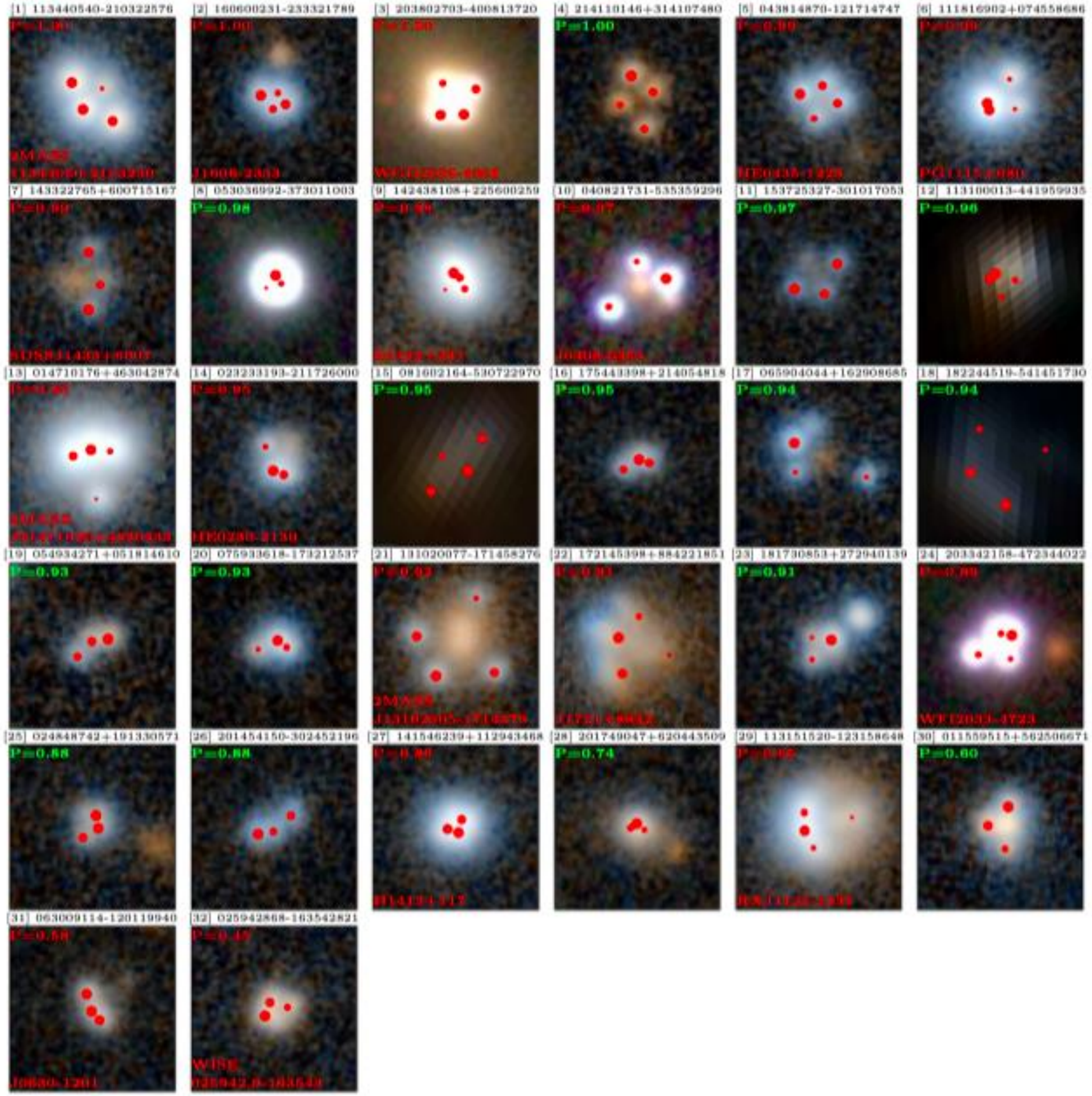

Fig. 4. Finding charts of the 17 known GLs and 15 GL candidates contained in our catalogue of clusters (Appendix B). They are ordered according to their ERT probabilities (upper left corner of each subplot). The common name of the known lenses is labelled in red in the lower left corner of each subplot, while the candidates we propose have their probabilities written in green fonts. Images [1], [2], [4–7], [9], [11], [13], [14], [16], [17], [19–23], [25–32] come from the Pan-STARRS survey (Chambers et al. 2016); images [12], [15], [18] come from the Digitized Sky Survey II (Lasker et al. 1996); and images [3], [8], [10], [24] come from the DES (Dark Energy Survey Collaboration et al. 2016). All images were collected from the ALADIN sky atlas (Bonnarel et al. 2000) in a field of view of $10.8'' \times 10.8''$ centred around the mean coordinates of the GL where east is to the left and north is up. Points are scaled according to the relative flux of the components with respect to the brightest image of each configuration.


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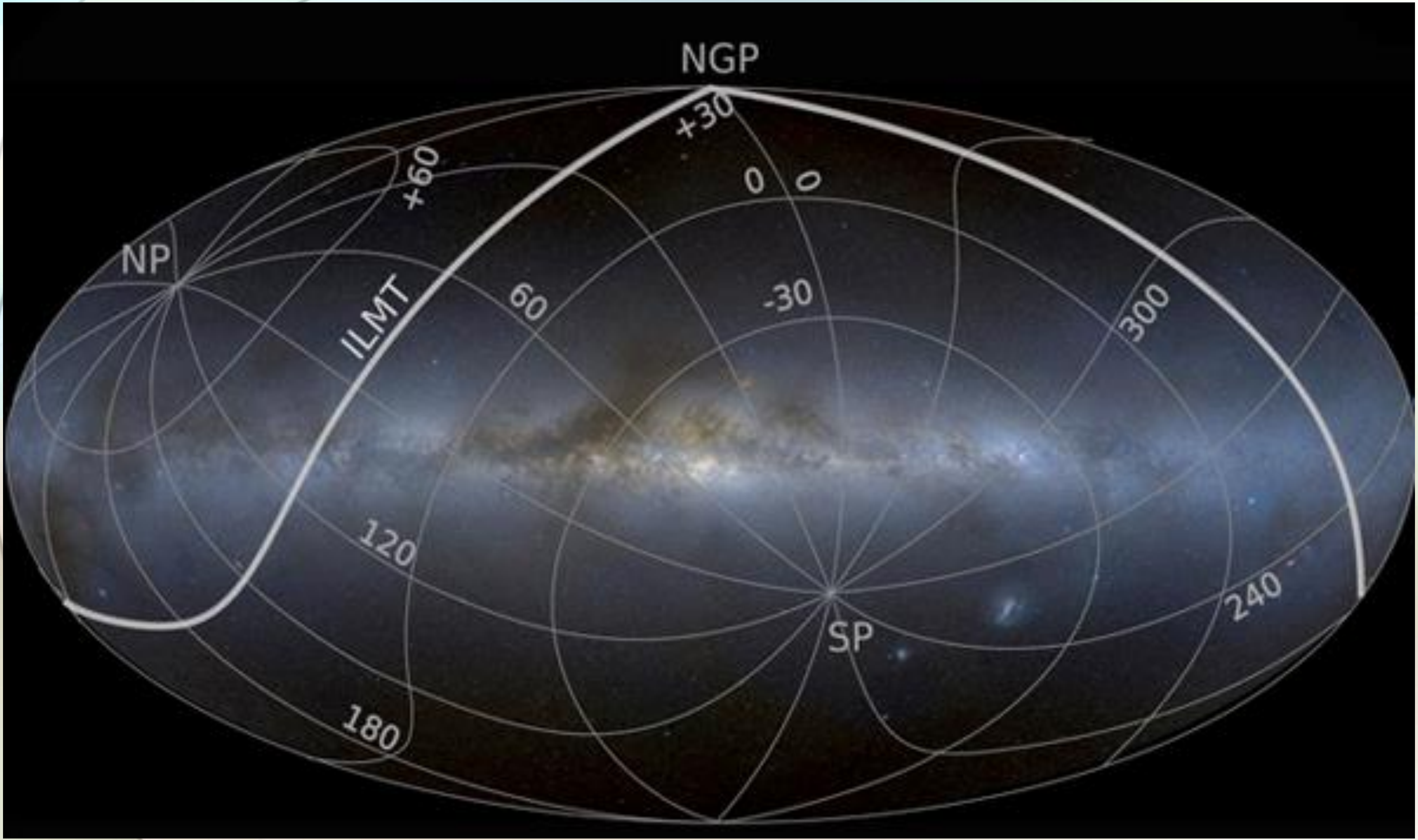
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