Multi-wavelength Focusing with the Sun as Gravitational Lens

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Multi-wavelength Focusing with the Sun as Gravitational Lens

An old idea revisited

Focusing as a particular case of gravitational lensing

Geometrical caustics and amplification factor

Aberrations due to mass distribution in the solar system

Point Spread Function

Imaging

Astrophysical targets

Prospective mission

Old and recent work on gravitational focusing

Dyson, F.W., Eddington, A.S., and Davidson C.R., MNRAS 1919
A determination of the deflection of light by the sun's gravitational field from observations made at the total eclipse of May 29, 1919

Einstein, A. Science 84: 506, 1936
Lens-like Action of a Star by the Deviation of Light in the Gravitational Field

Zwicky, F. Phys. Rev. 51: 290&679, 1937
On the Probability of Detecting Nebulae Which Act as Gravitational Lenses

Fomalont, E. B. and Sramek, R. A. ApJ 199: 749, 1975

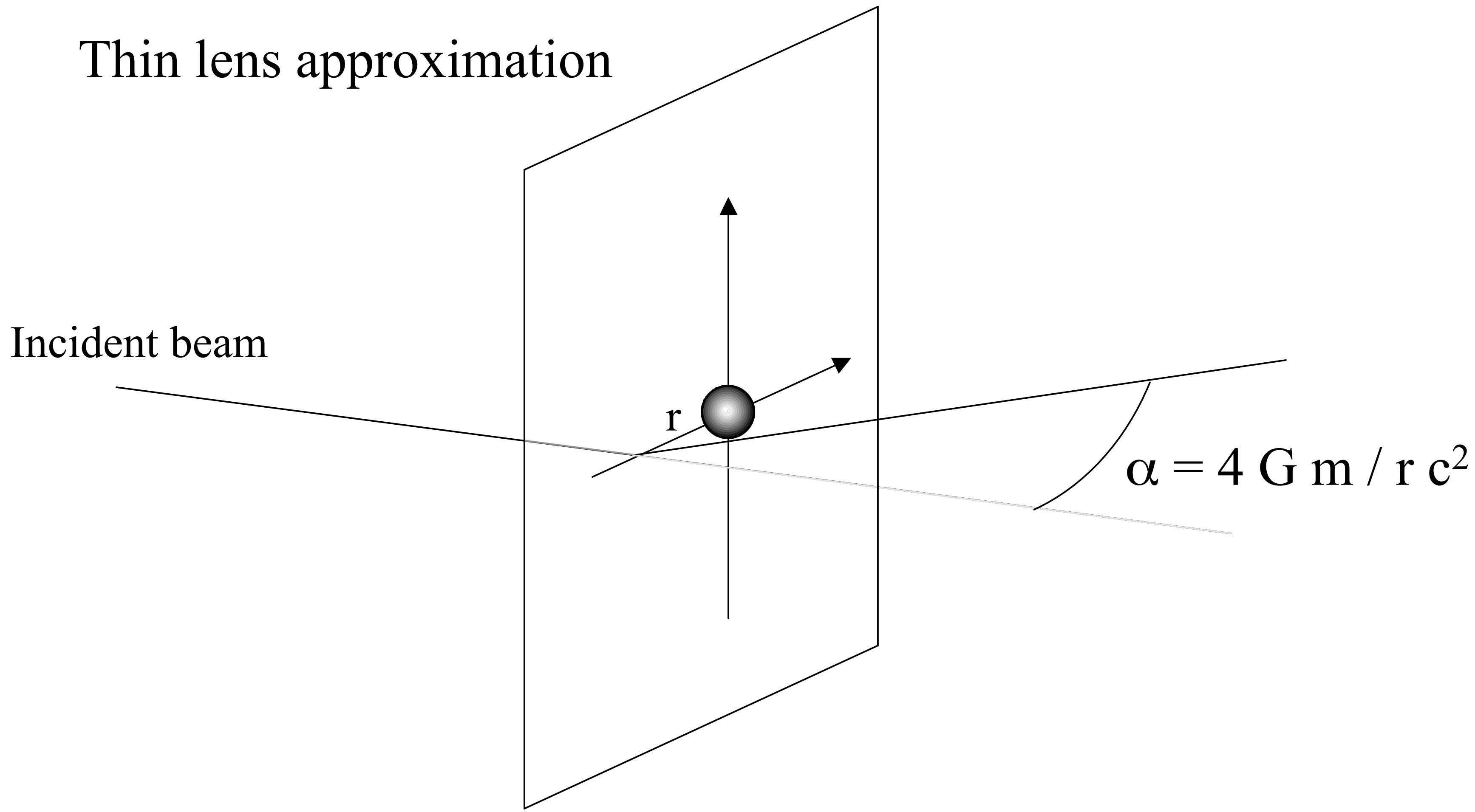
Nemiroff, R. J. ApJ 341: 579, 1989
Sun as gravitational lens

Macone C. IPI press 1999
The sun as gravitational lens, proposed space missions

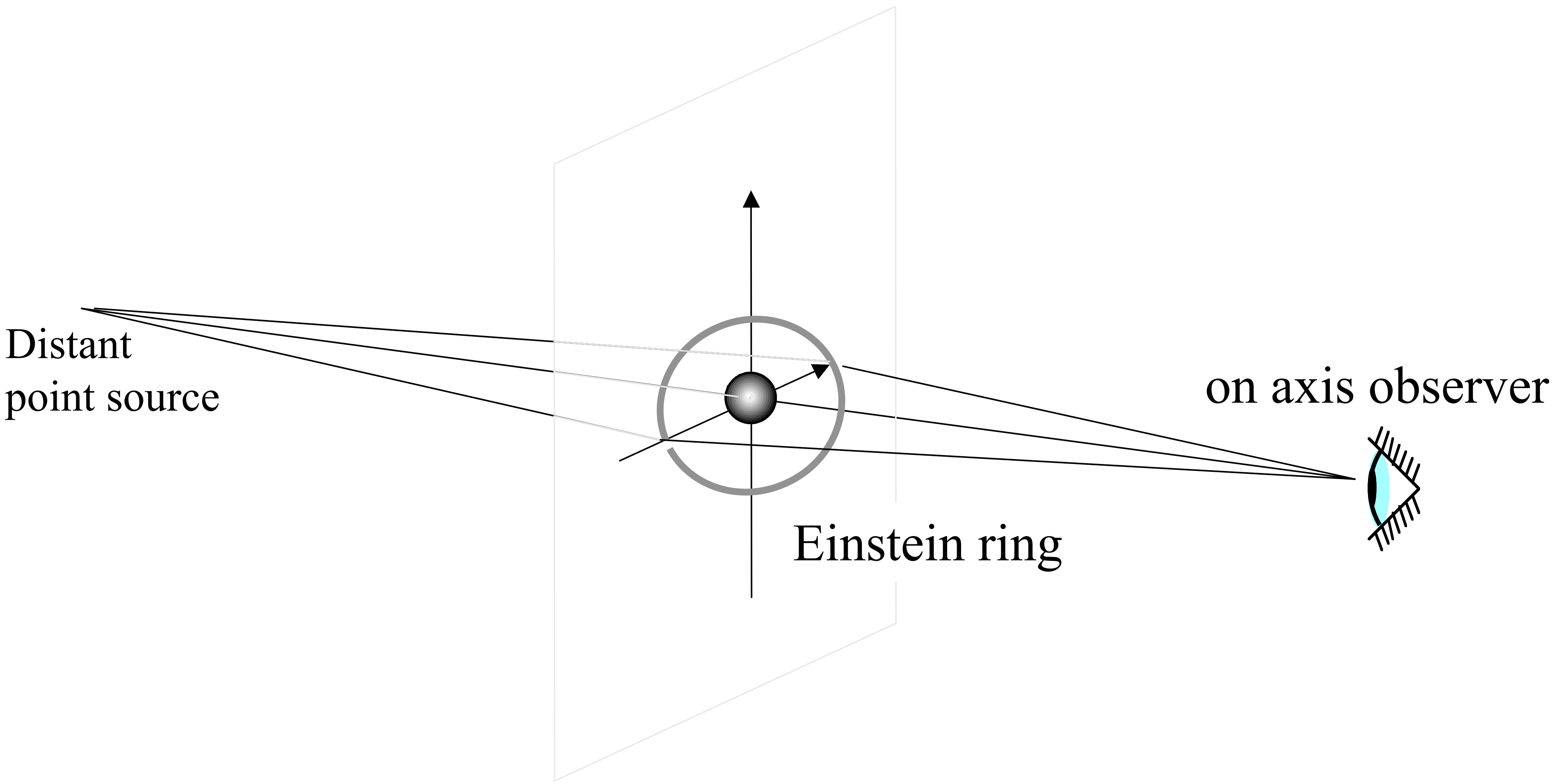
Paczynski, B. An. Rev. Astro. Ap. 34: 419, 1996.

Gravitational lens

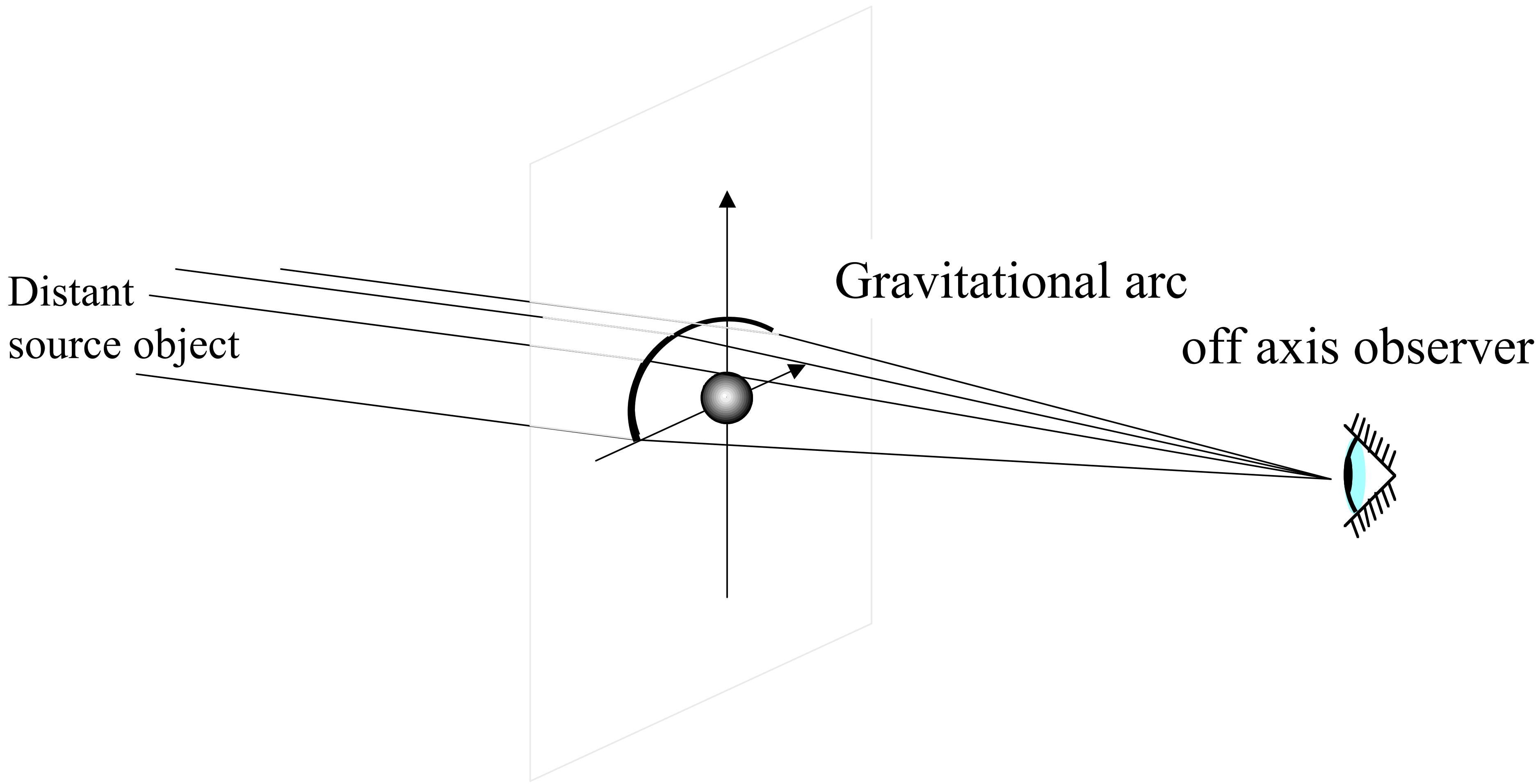
Thin lens approximation



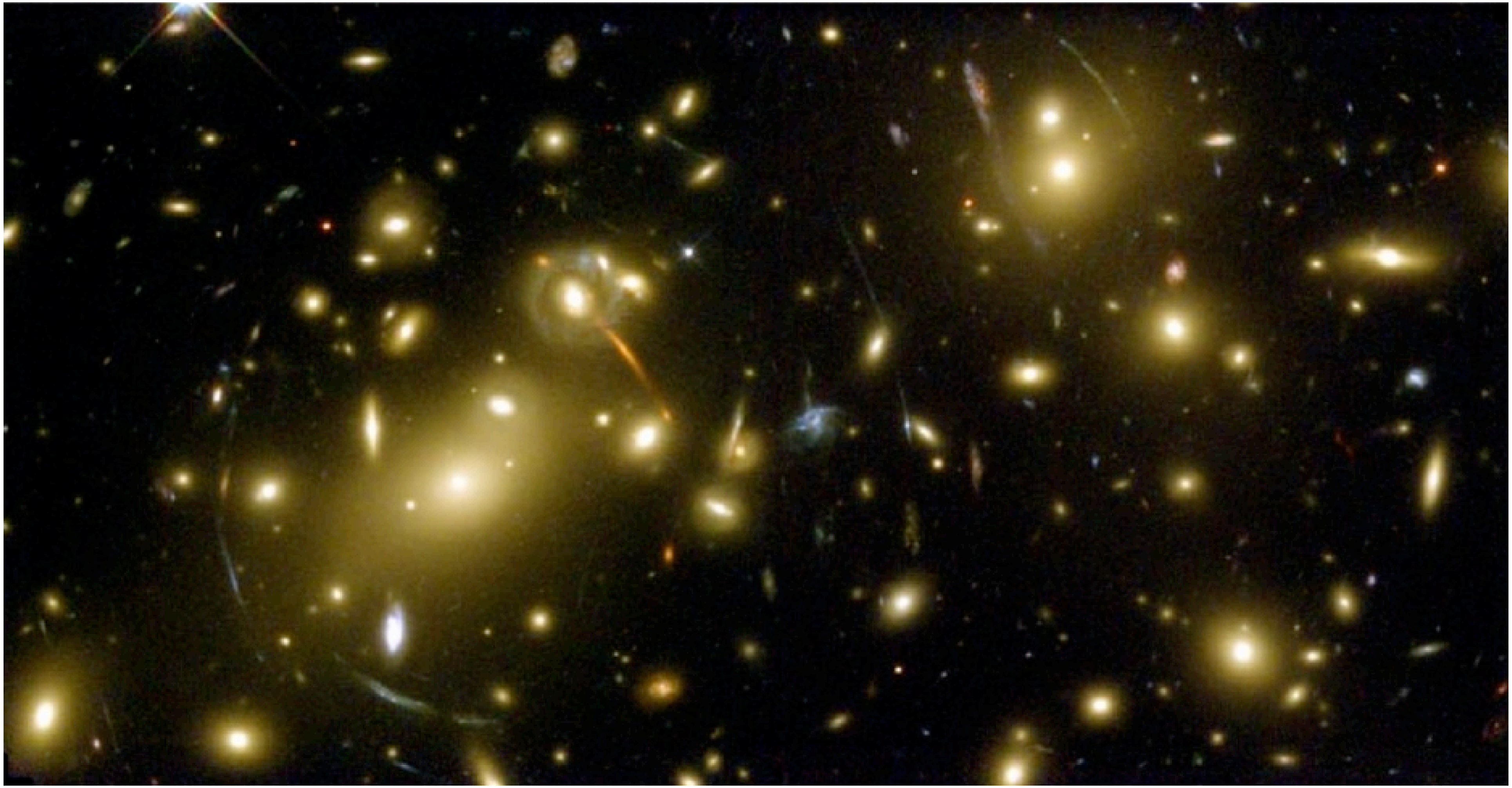
Gravitational ring



Gravitational arc

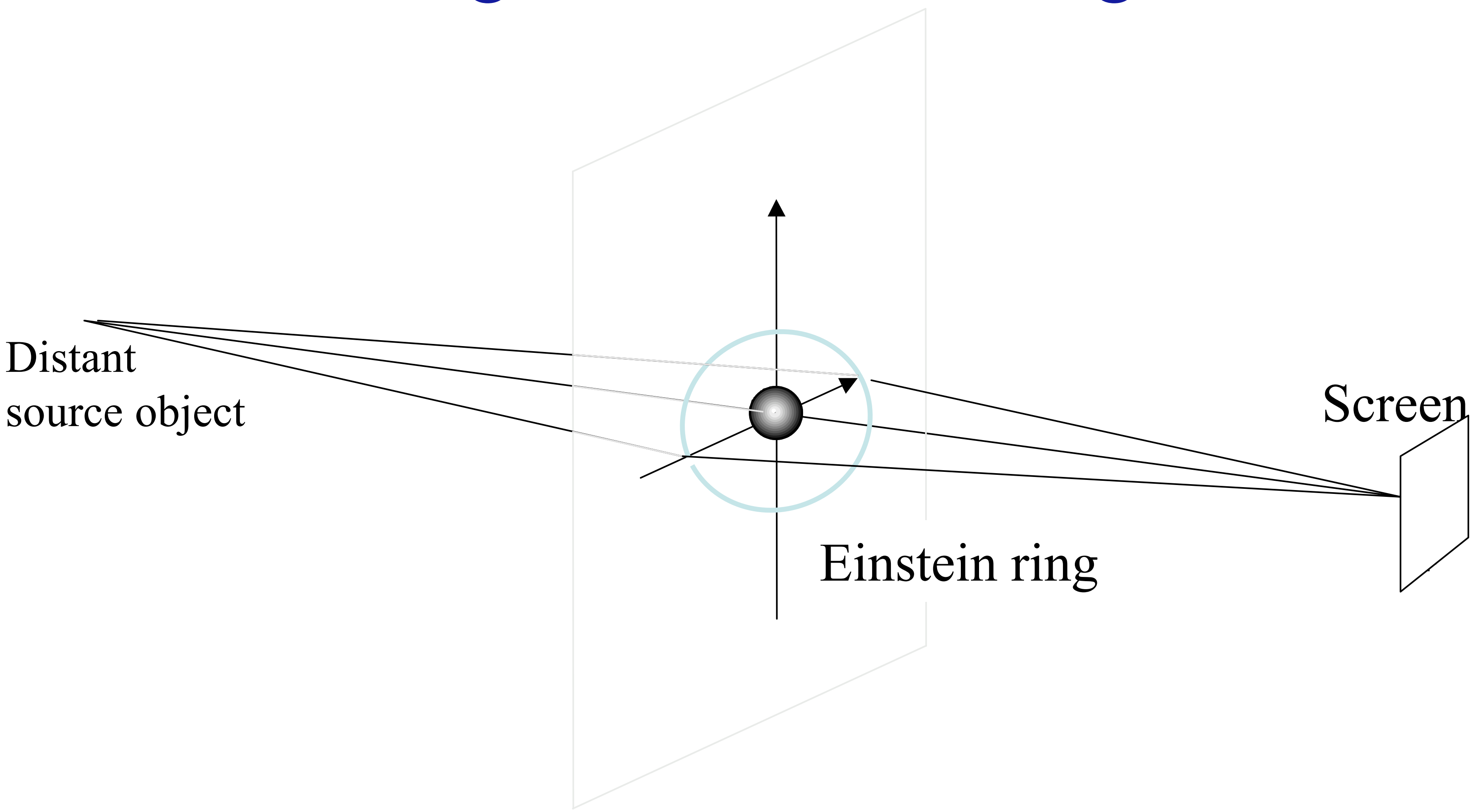


Gravitational arcs

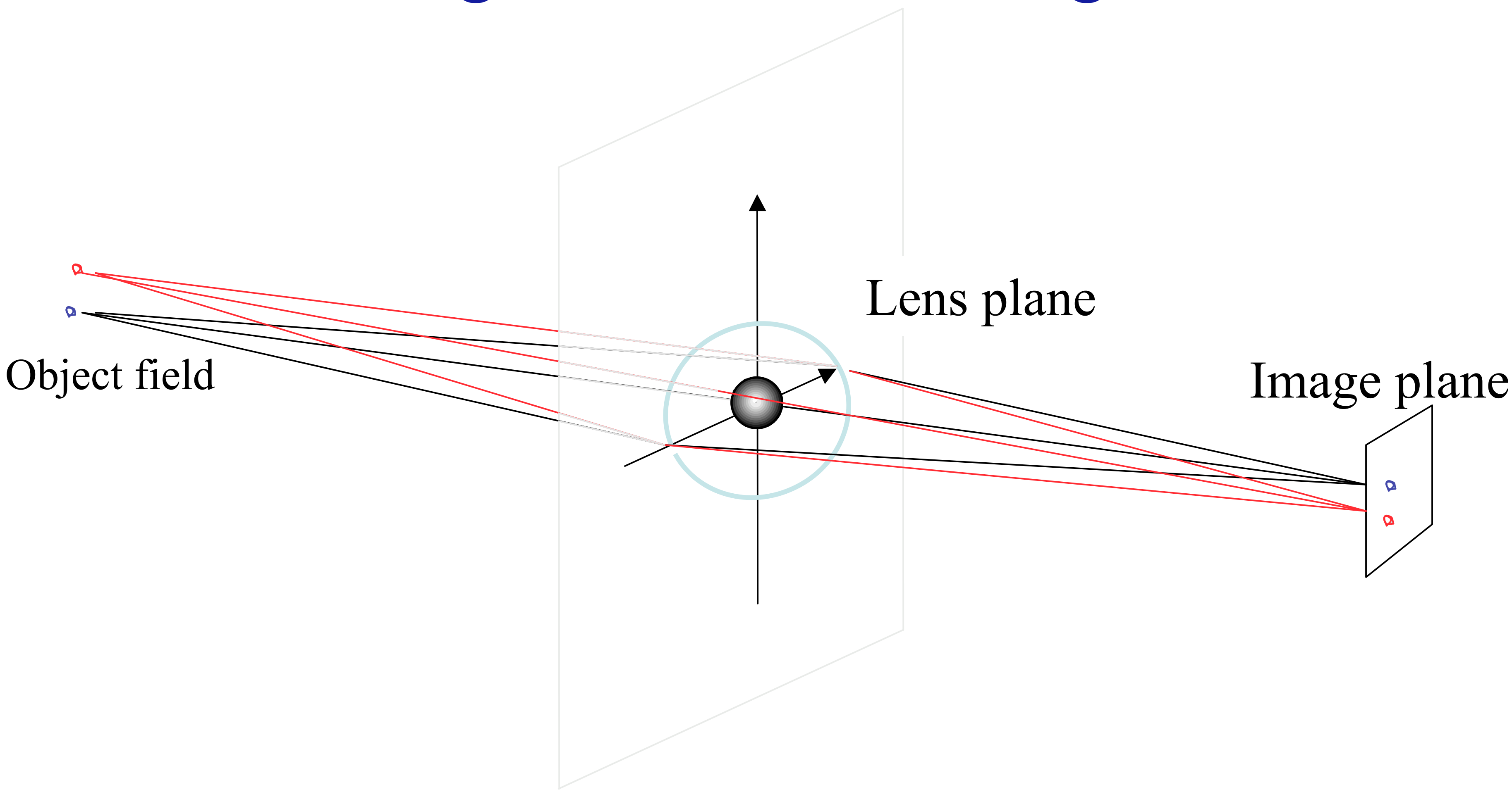


Abell 2218 cluster of galaxies HST picture

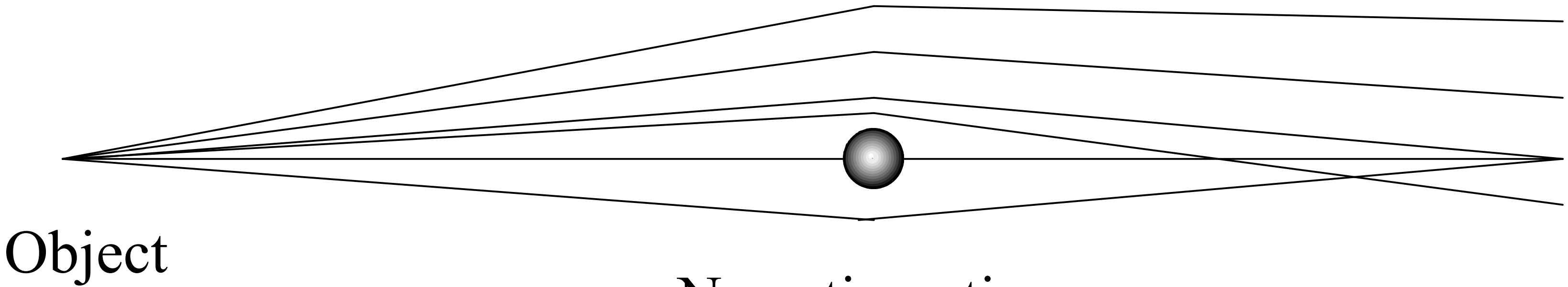
Focusing as a particular case of gravitational lensing



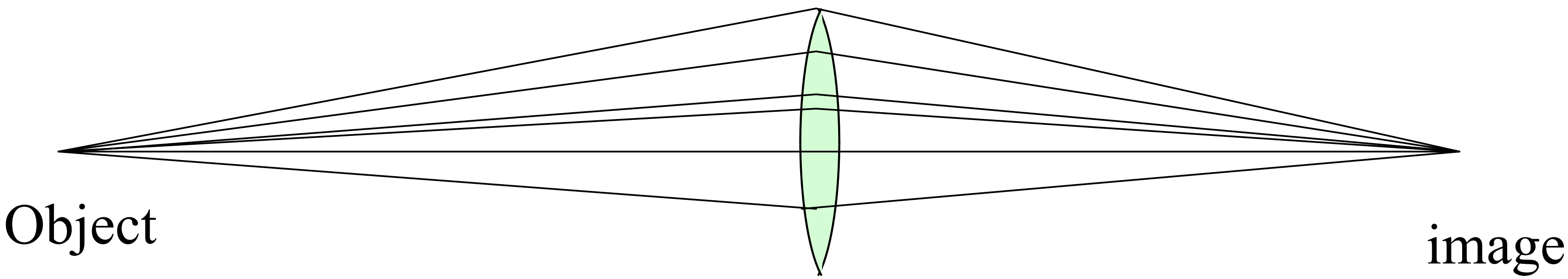
Focusing as a particular case of gravitational lensing



gravitational lens vs optical lens

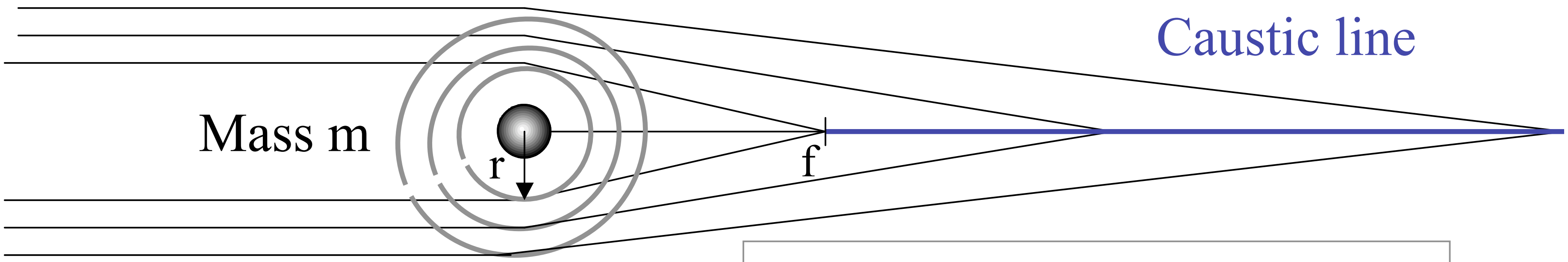


Non stigmatic



Stigmatic

Pseudo focal length and caustic line

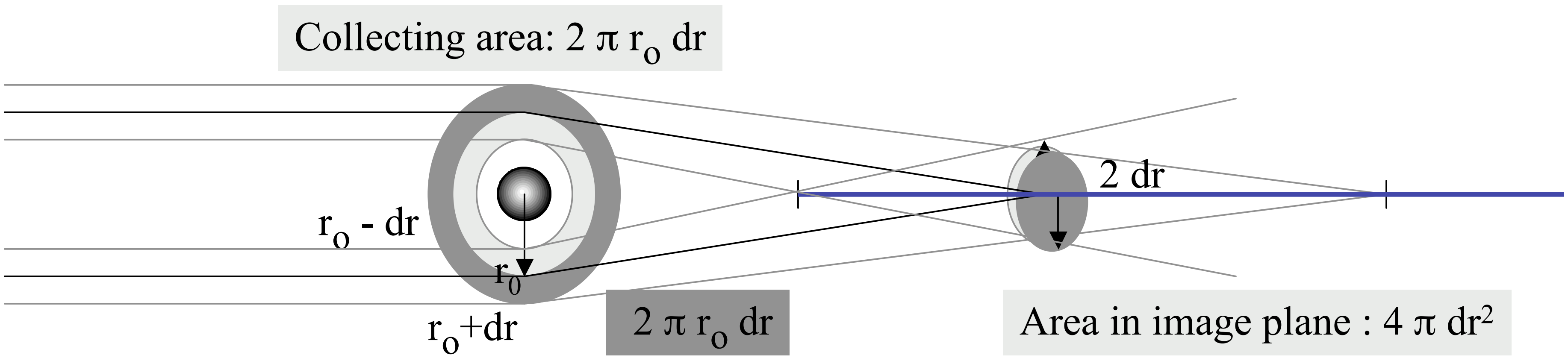


Pseudo focal: $f = r^2 c^2 / 4 G m$

for m = one solar mass,
and r = 1.2 solar radius:
$f = 1.18 \, 10^{14}$ m = 789 AU = 4.6 light days

f_{min} = 548 AU (r_{min}= 1 r_{sun}) for an opaque sun (photons)
f_{min} = 50 AU (r_{min}= 0.3 r_{sun}) for a transparent sun (neutrinos, GW)

Intensity amplification on the caustic

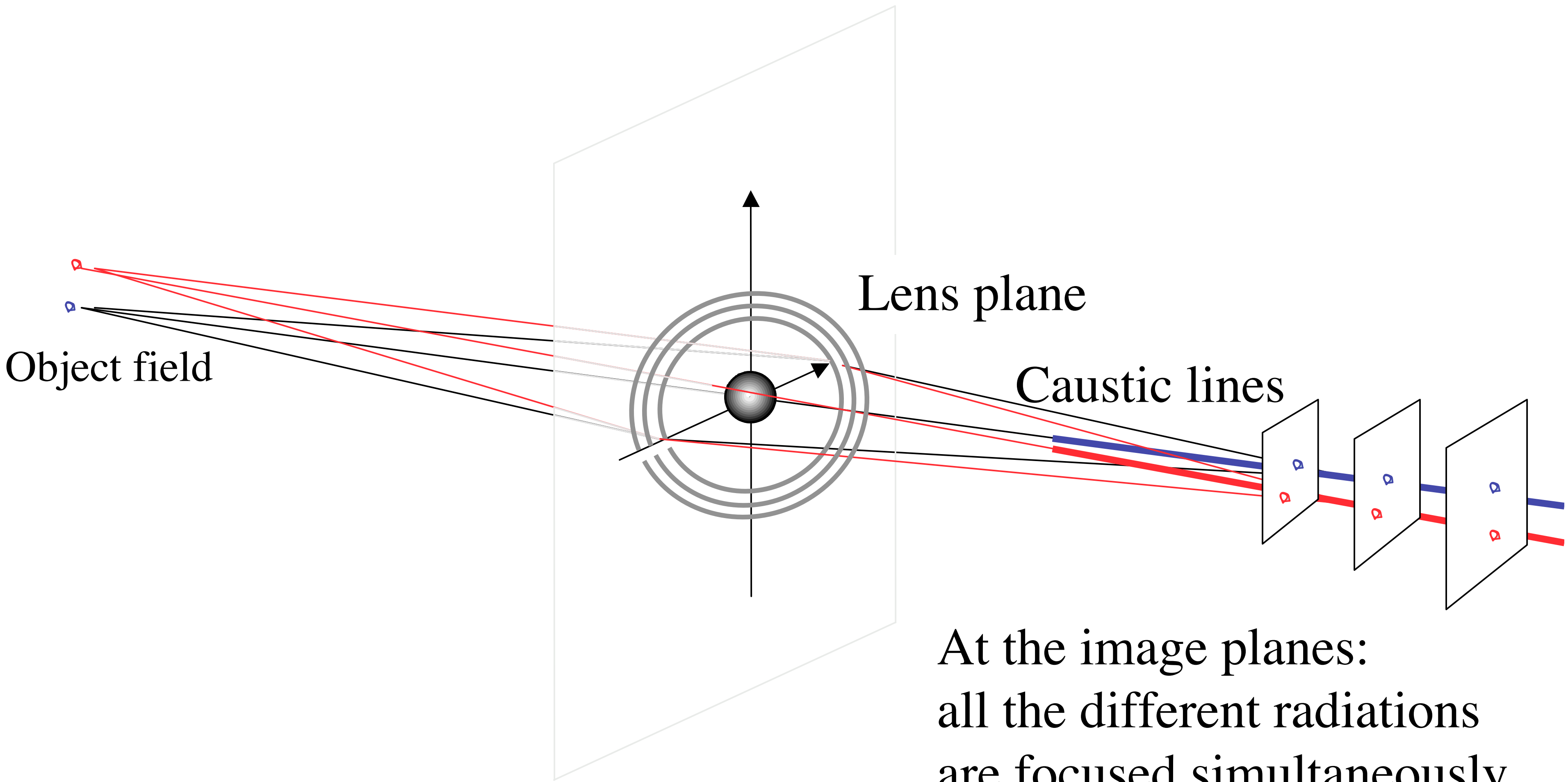


Effective collecting area: $4 \pi r_o dr$ => $I_{image} = I_o r_o / dr$

Example for detector of size $d = 2dr = 0{,}2$ m and $r_o = 1.2$ solar radius:

$$I_{image} = 8.4\ 10^8 I_o$$

images on the caustic

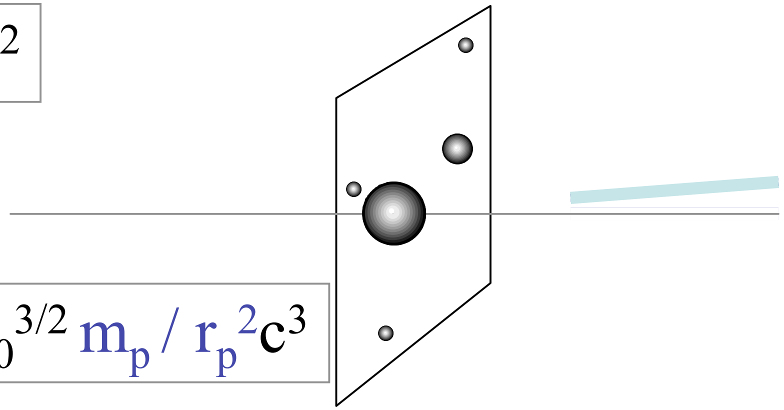


At the image planes:
all the different radiations
are focused simultaneously

Aberrations due to non-centrosymetric mass distribution

Other solar system masses cause caustic displacement

$$\Delta x = r_0^2 \, m_p / m_0 \, r_p = 4 \, f \, G \, m_p / r_p c^2$$



And aberrations (approx valid for $r_0 << r_p$)

$$\chi_{aberr} = 2 \, r_0^3 m_p / m_0 r_p^2 = 16 \, f^{3/2} G^{3/2} \, m_0^{3/2} \, m_p / r_p^2 c^3$$

Aberrations (and diffraction) limit the amplification factor on axis for a point source

Caustic displacement Δx (meters) at r_0 = 1.2 solar radius (f=789 AU) for different planets

Mercury	Vénus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
2,0	15,8	14,1	1,0	856,2	139,6	10,6	8,0

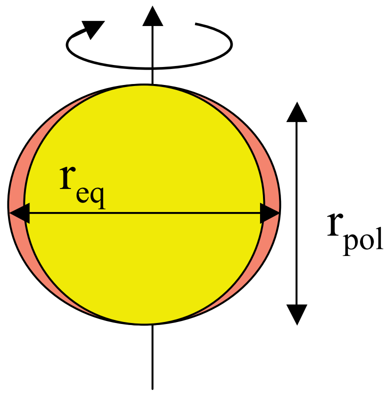
Aberration: χ_{aberr} (meters)

Mercury	Vénus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
0,058	0,245	0,157	0,007	1,837	0,163	0,006	0,003

Aberrations due to non-centrosymetric mass distribution

Estimate of an upper value of the aberration due to the non sphericity of the sun (solar rotation)

$$\chi_{solar\_rot} = 8\,(r_{eq} - r_{pol})^2 / r_0$$



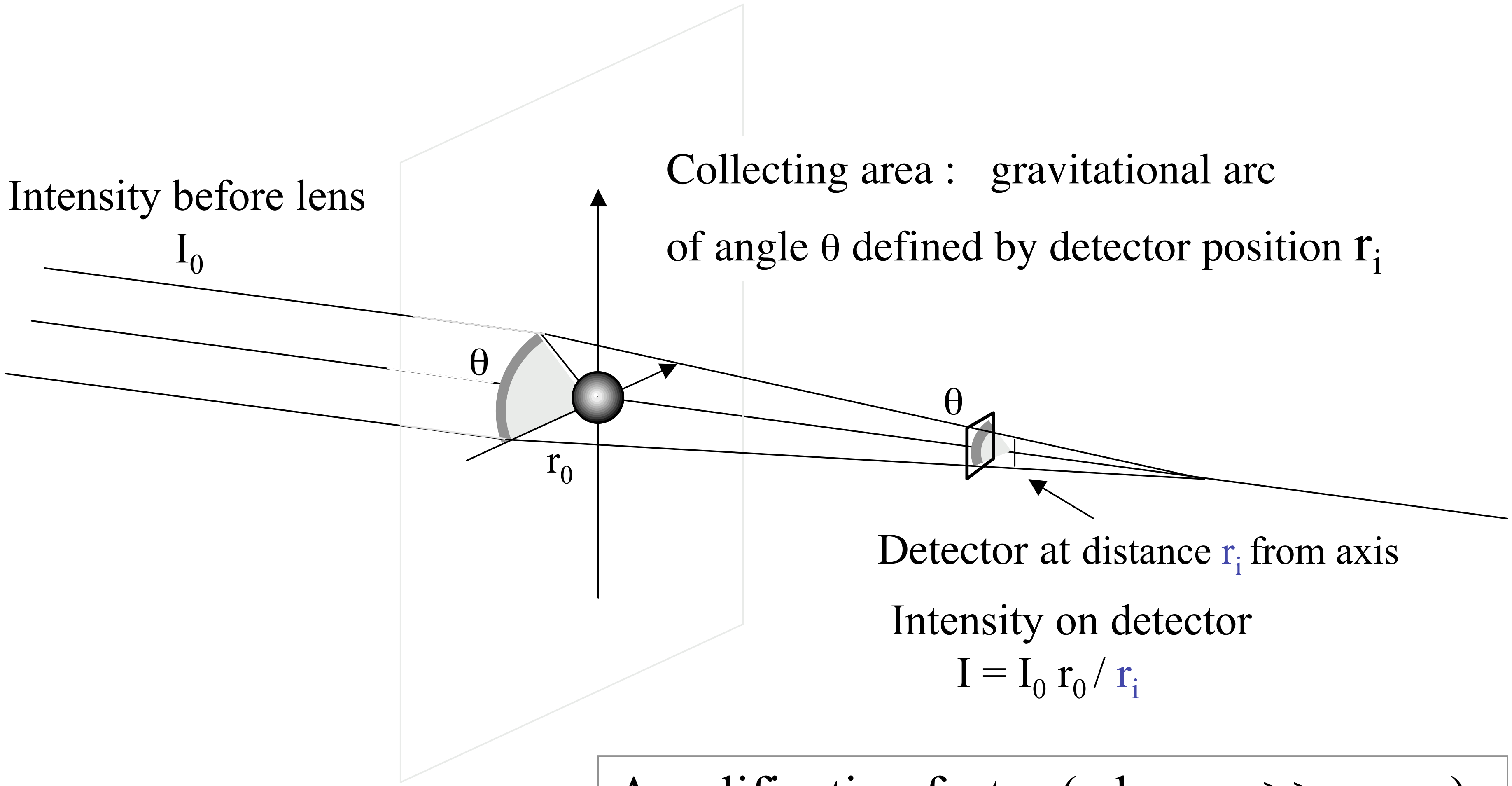
For a maximum value of $(r_{eq} - r_{pol}) = 7000$ km:

$$\chi_{solar\_rot} < 0.4 \text{ m} \quad \text{at } f = 789 \text{ AU}$$

This is an estimate giving an upper limit of that aberration

Other aberrations need to be investigated :
- non negligible mass of solar flares ?
- non negligible refractive index of corona column density for the γ domain ?

Point Spread Function and imaging



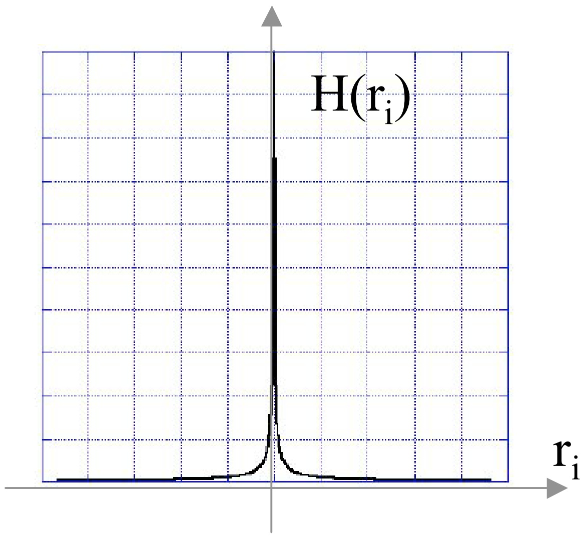
Amplification factor (when $r_i >> \chi_{aberr}$)

$$A = r_0 / r_i$$

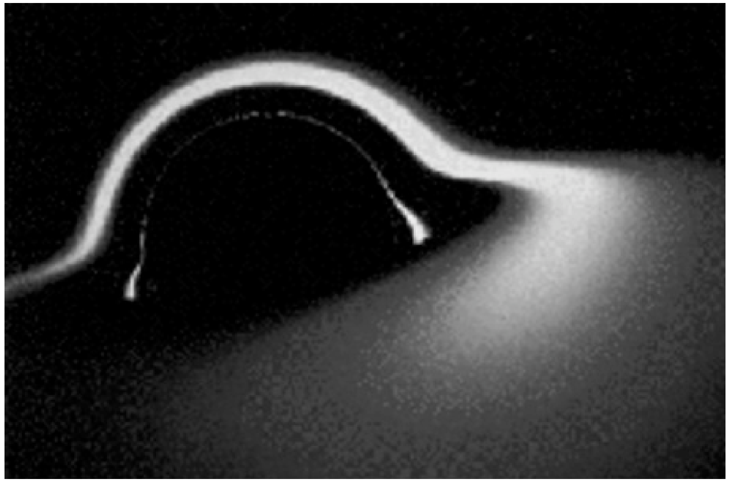
Example of image obtained with a gravitational lens

Point Spread Function

$$H(r_i) = r_0 / r_i$$

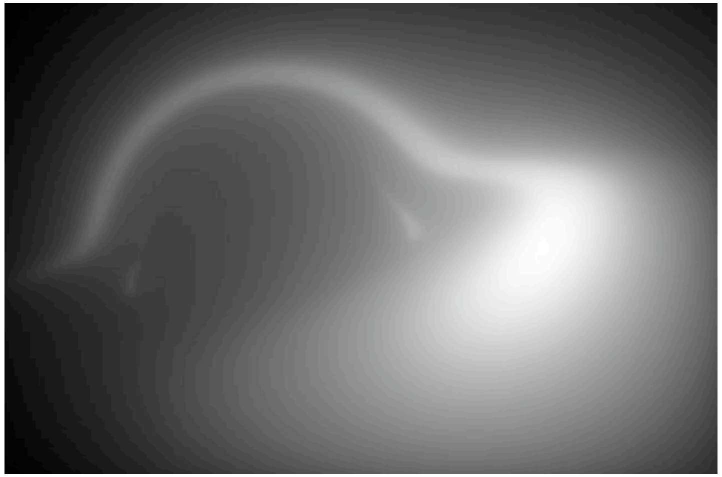


Angular resolution
at f = 789 AU:
3 nano arc seconds



Source object : $O(x, y)$

accretion disk simulation by J-P Luminet



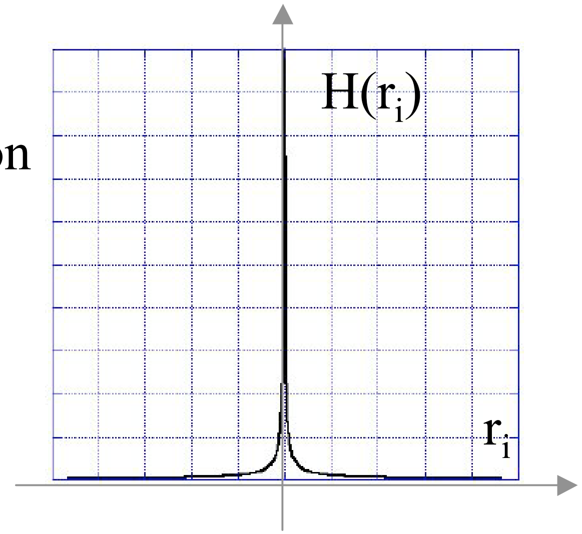
$$I(x_i, y_i) = \iint O(x, y)\, H(x_i - x, y_i - y)\, dx\, dy$$

response computed by D. Serre at OMP

Gravitational Lenses have a pathologic PSF

G.L. Point Spread Function

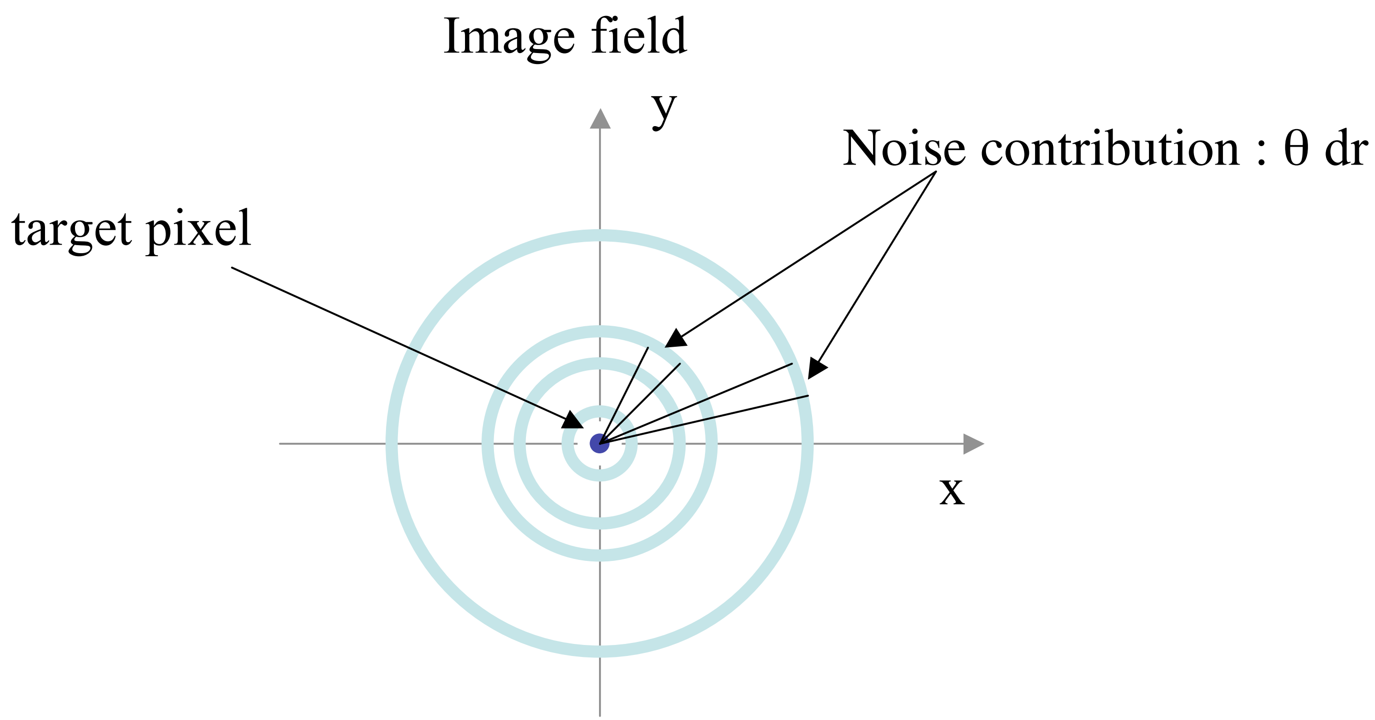
$H(r_i) = 1 / r_i$



A G.L PSF decreases in 1/r

Whereas a stigmatic lens PSF decreases in $1/r^2$

Gravitational Lenses have a pathologic PSF



$$\iint H(r, \theta)\, O(r, \theta)\, r\, dr\, d\theta \;=\; \iint O(r, \theta)\, dr\, d\theta$$

Possible large background caused by extended objects:
concentric rings contribute to a given pixel by the same amount.

The problem may be solved by limiting the detector angular field (collimation).

Gravitational Lenses have a pathologic PSF

But this is an advantage for source acquisition:

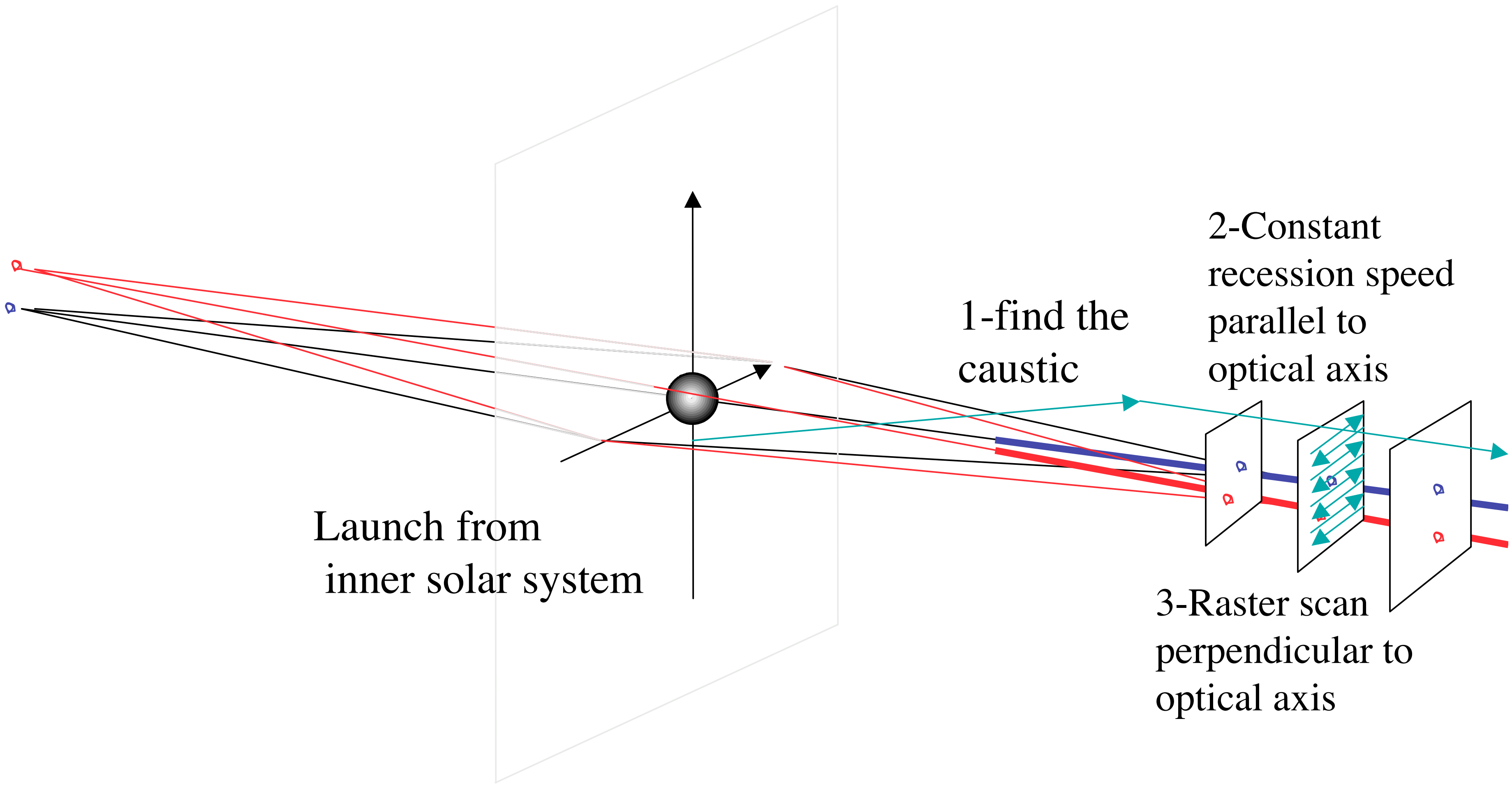
A given source sends signal very far in the image plane.

Astrophysical targets

Only one possible field for a given mission

Mission parameters	Galactic center	Stellar black hole	AGN
Accr disk inner radius	$2.2\ 10^{10}$ m	$1.6\ 10^{4}$ m	$6\ 10^{10}$ m
distance	8.5 k Pc	200 Pc	20 M Pc
Estimated raw ph s^{-1} m^{-2}	100	10^{5}	0.2
Image size at focal plane	20 km	0.63 m	23 m
Detector area	1 m^{2}	0,01 m^{2}	0,01 m^{2}
Photons / s on detector	11 000 ph s^{-1}	$3.1\ 10^{11}$ ph s^{-1}	$8.2\ 10^{8}$ ph s^{-1}
Image resolution elements	7000 x 7000	1	12 x 12

Example of observing procedure



Conclusion

Imaging with the solar gravitation seems possible:

Small geometrical aberrations caused by solar system bodies

Weird Point Spread Function, but image reconstruction possible

10^4 to 10^{11} photons s^{-1} per pixel (X or γ) in accretion disc images

10^{-9} second angular resolution, achromatic

A challenging space mission!