Astronomical observation through the earth atmosphere

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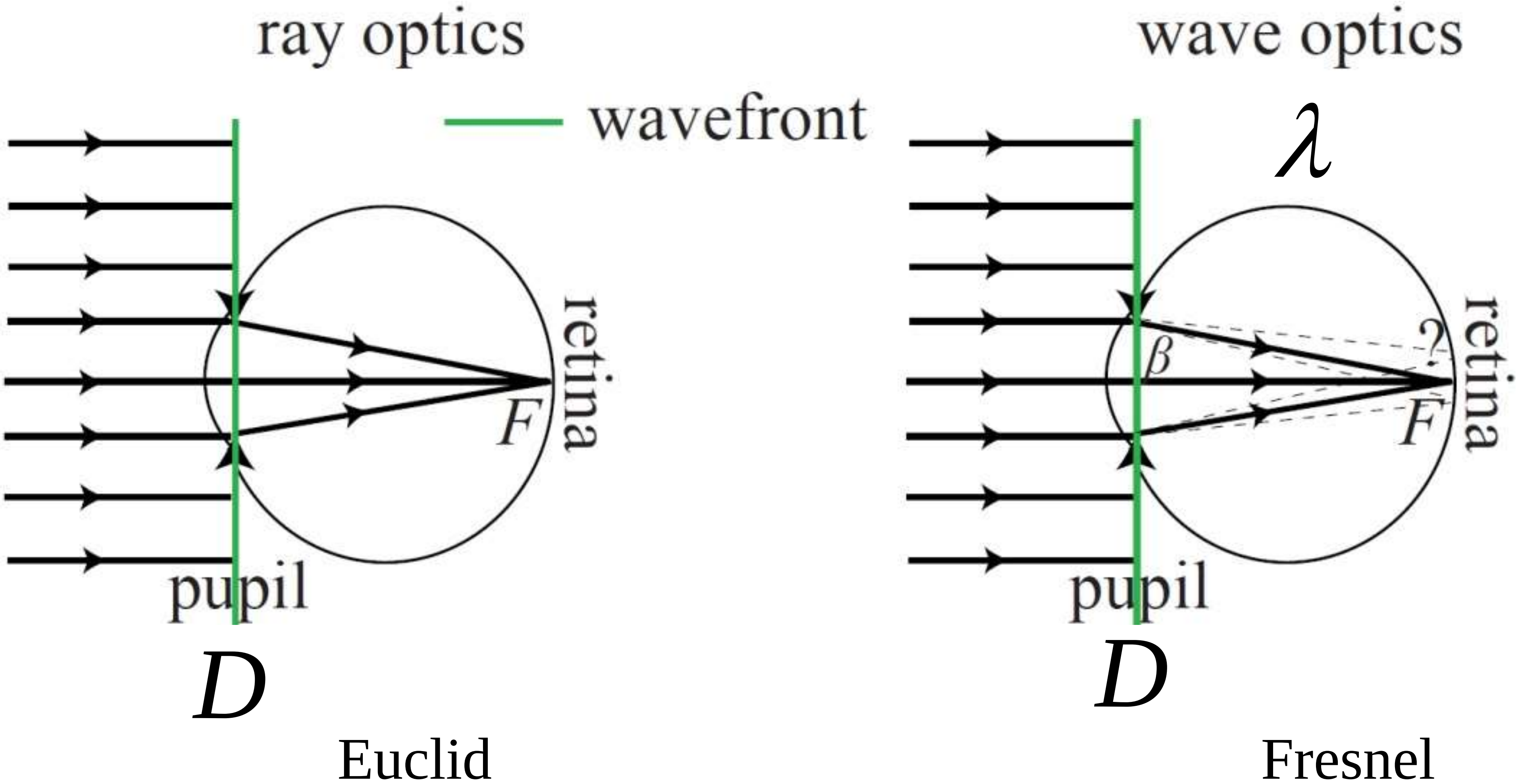
1) Limit to angular resolution

2) Observation with the aid of a telescope;
   - telescope types
   - image field
   - influence of telescope aberration

3) Influence of the earth atmosphere;
   - effect on resolution
   - E-ELT and the ‘resolution solution’

Intensity distribution on the retina

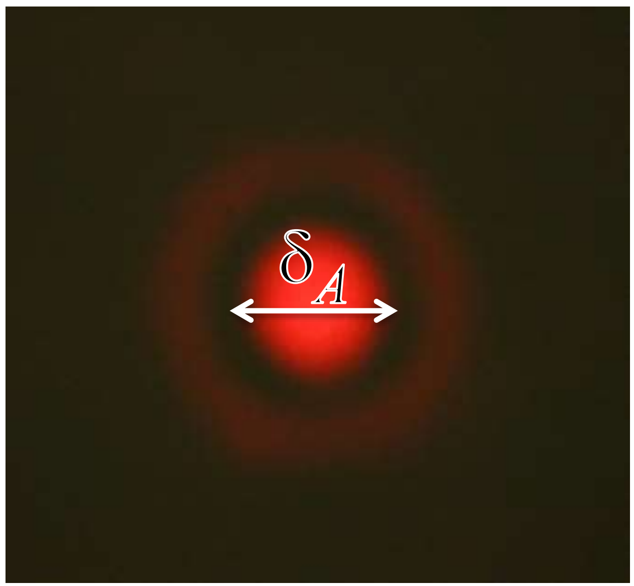


Intensity distribution in focus

George B. Airy (1801-1892), Astronomer Royal 1835-1881

Publication:
"On the diffraction of an object glass",
Transactions of the Philosophical Society of Cambridge,
Vol. 5, page 283 - 291 (1835).

n	$\phi(n)$
0,0	+ 1,0000
0,2	+ ,9950
0,4	+ ,9801
0,6	+ ,9557
0,8	+ ,9221
1,0	+ ,8801
1,2	+ ,8305
1,4	+ ,7742
1,6	+ ,7124
1,8	+ ,6461
2,0	+ ,5767
2,2	+ ,5054
2,4	+ ,4335
2,6	+ ,3622
2,8	+ ,2927
3,0	+ ,2261
3,2	+ ,1633
3,4	+ ,1054
3,6	+ ,0530
3,8	+ ,0067
4,0	− ,0330
4,2	− ,0660
4,4	− ,0922

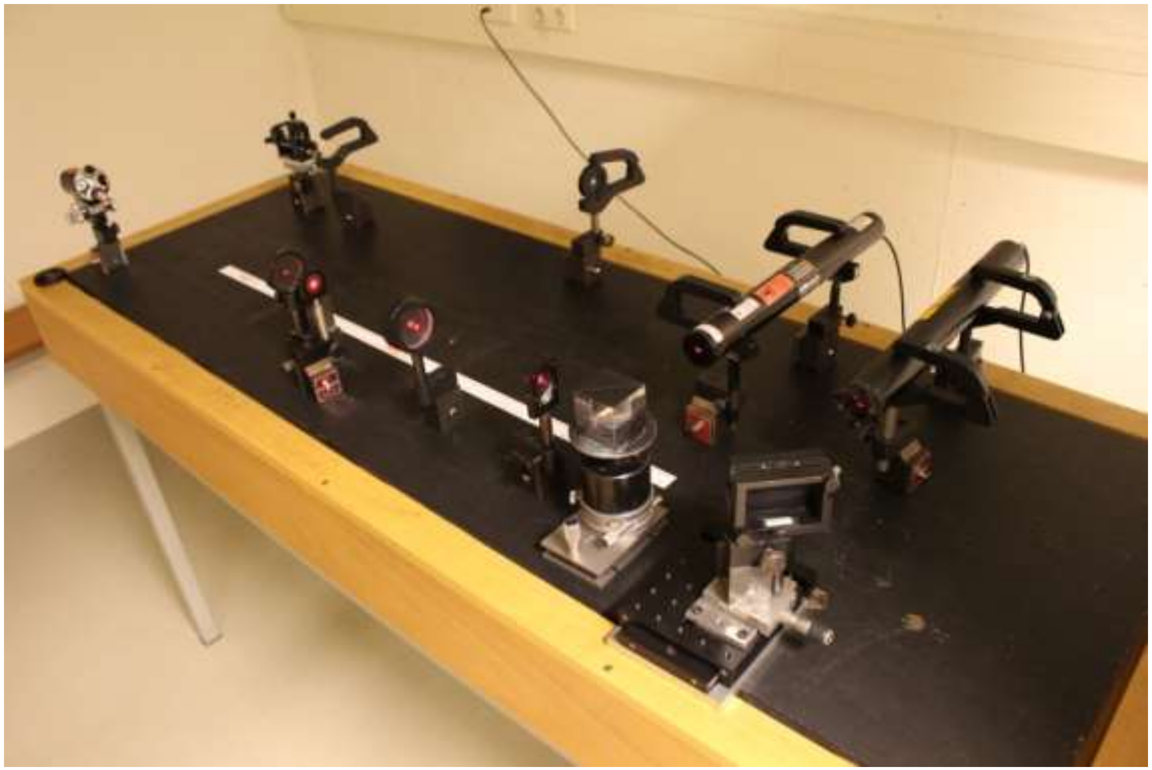


$$\delta_A = \left(2.4\frac{\lambda}{D}\right) f$$
$$= 2\,\alpha_A\, f$$

Eye:

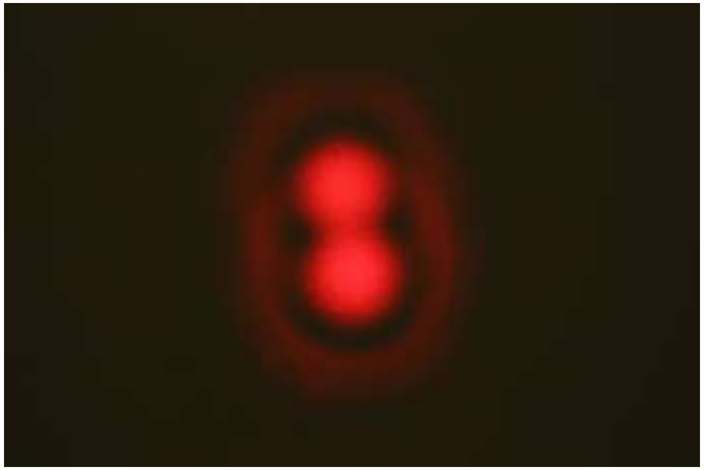
$$\alpha_A = 0.0002$$
$$\approx 1'$$

Illustration of two-star resolution



Testing of two-star resolution

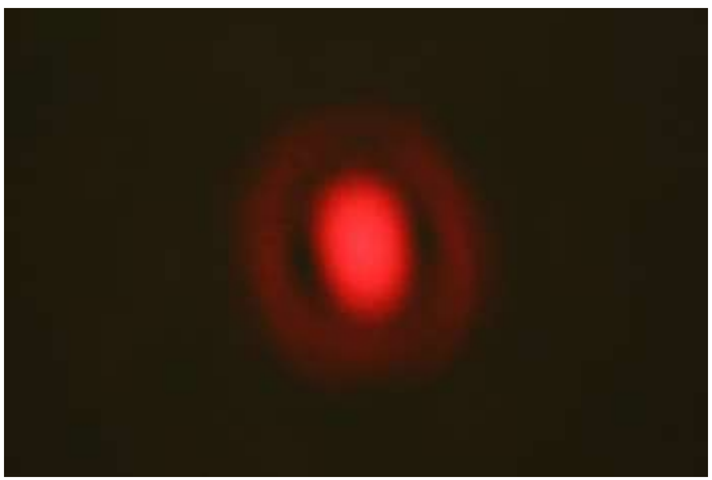
A $s = 1.2\,\delta_A$



B $s = 0.6\,\delta_A$

Rayleigh criterion

C $s = 0.3\,\delta_A$



D $s = 0$

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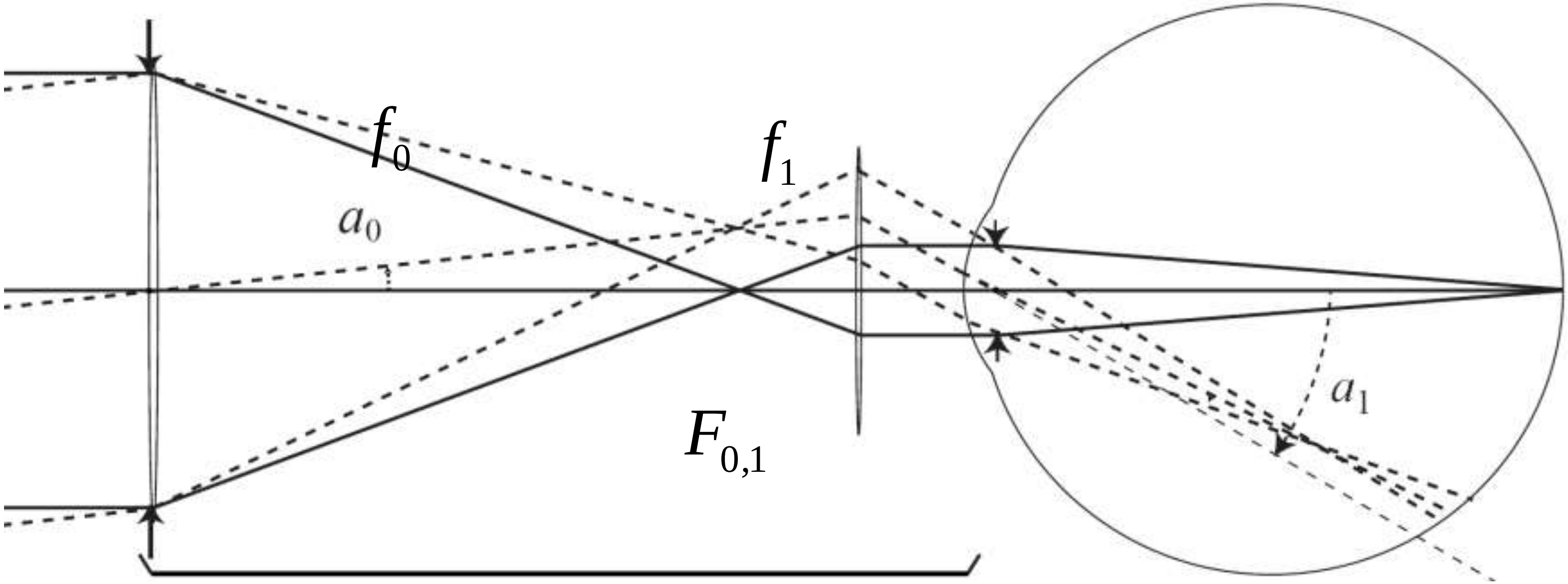
Lens telescope and (angular) magnification



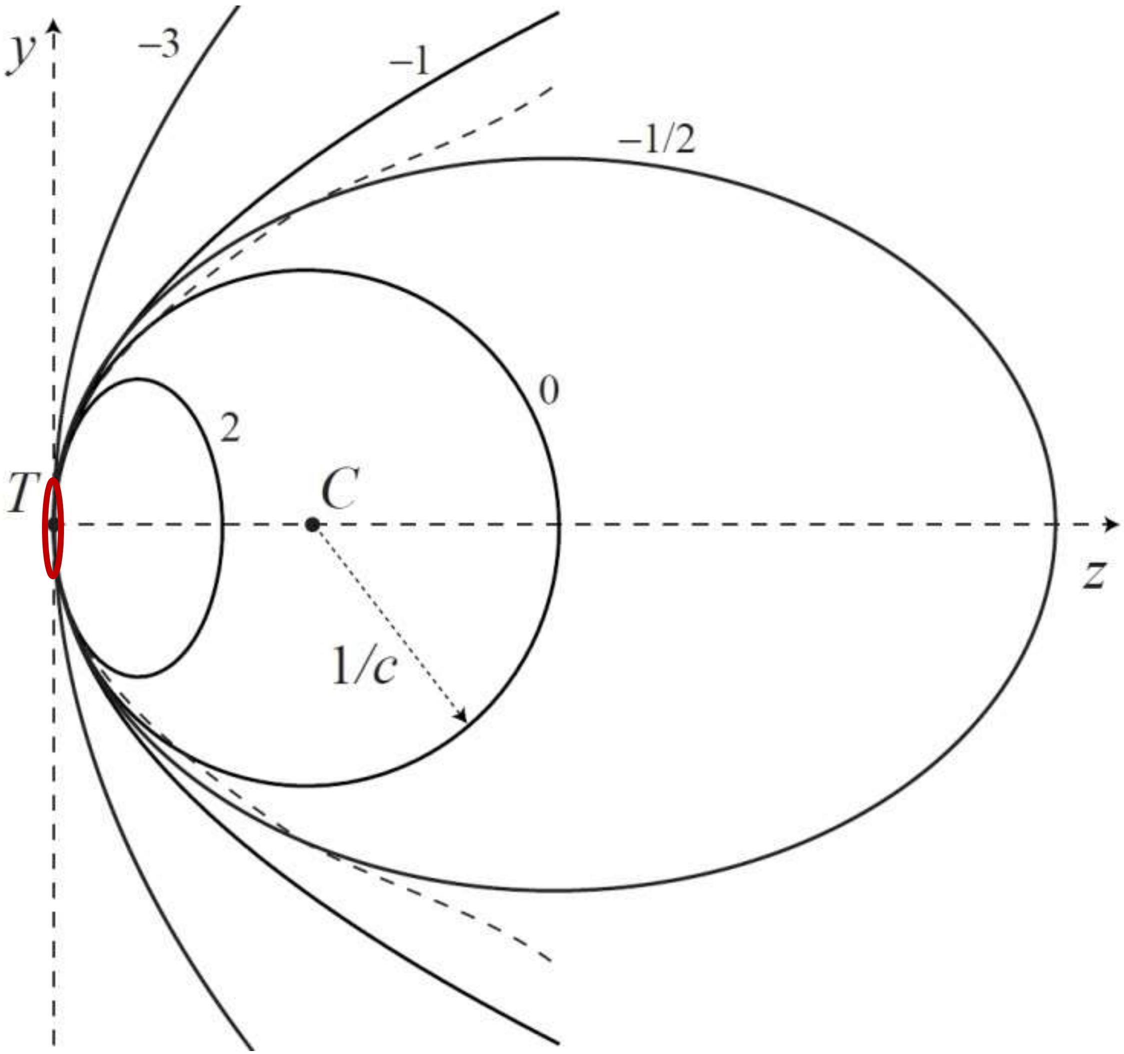
Telescope: $m_A = \dfrac{a_1}{a_0} = \dfrac{f_0}{f_1}$ $\qquad m_T = \dfrac{a_0}{a_1} = \dfrac{f_1}{f_0}$

Irradiance of a star image on the retina is m_A^2 LARGER

First observations with lens telescope by G. Galilei

Mirror telescope and aspheric surfaces

(conic sections and general aspheres)



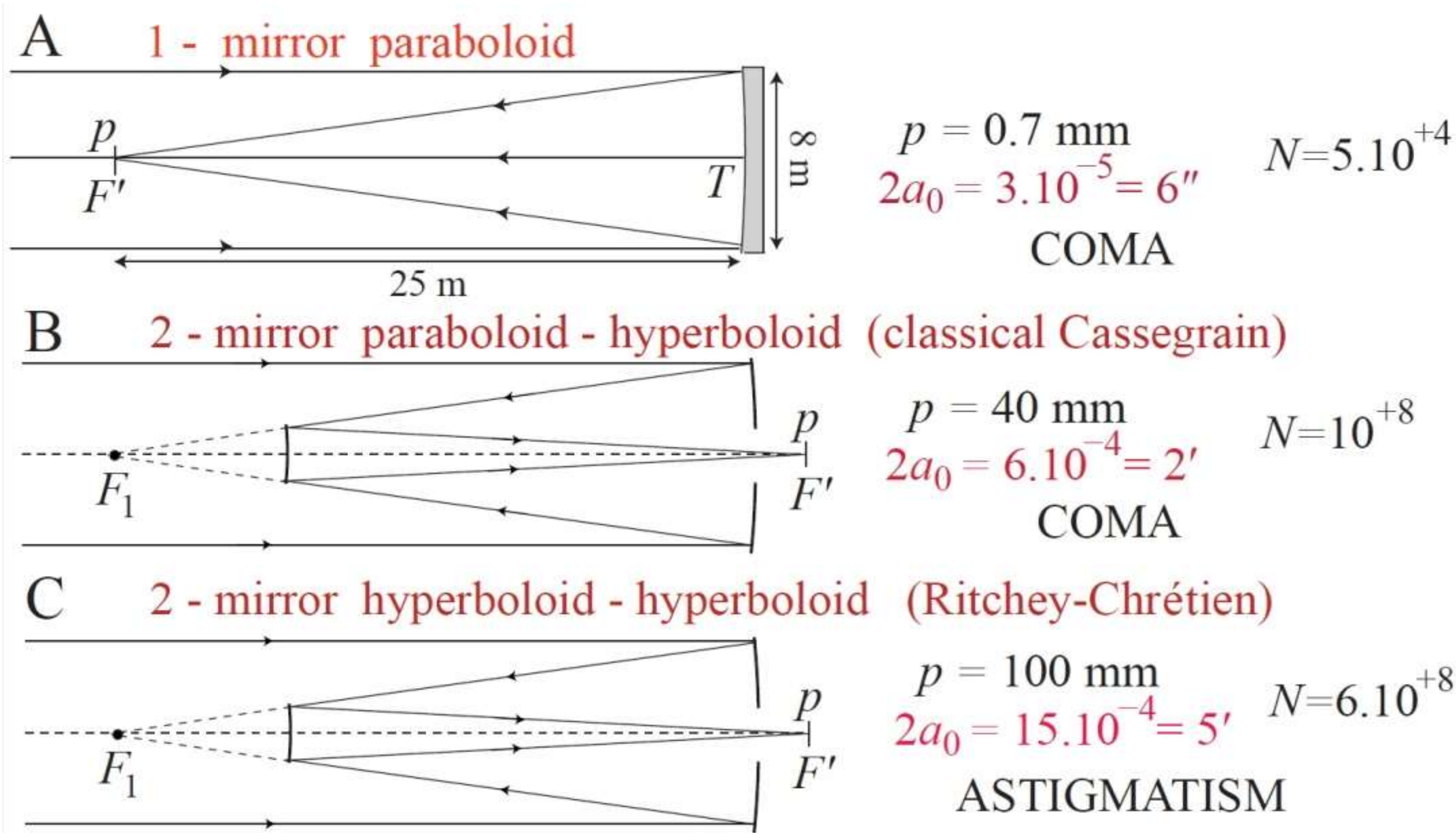
Conic constant κ

$\kappa < -1$	hyperbola
$\kappa = -1$	parabola
$-1 < \kappa < 0$	prolate ellipse
$\kappa = 0$	sphere
$\kappa > 0$	oblate ellipse

- - - - General Asphere

Mirror telescopes (8 m primary)

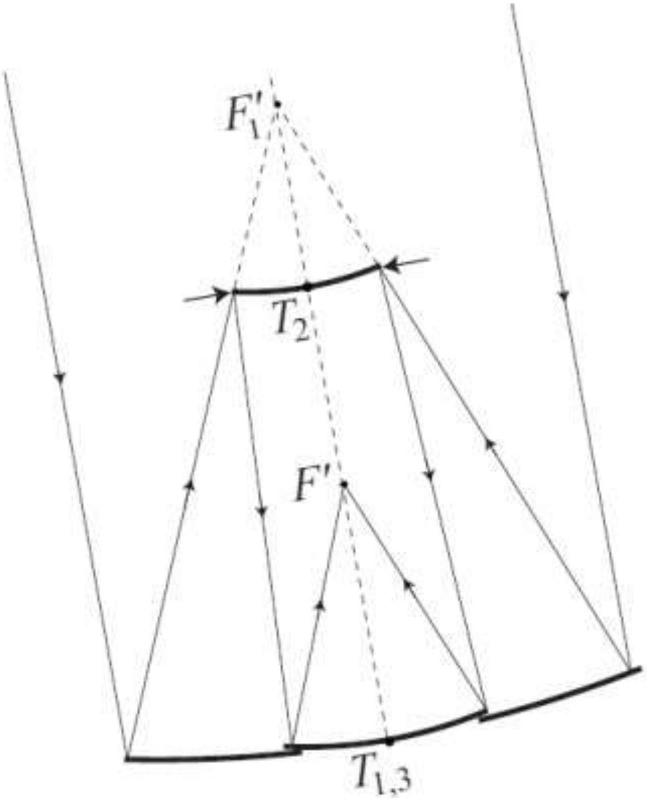
Theoretical resolution:
16 milli-arcsec = 8×10^{-8}



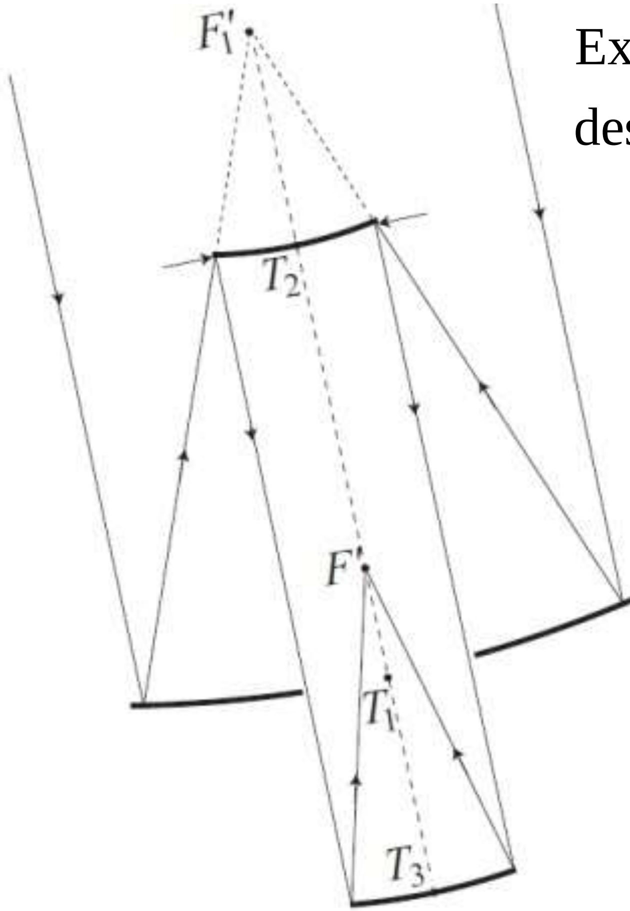
Three-mirror telescopes

Theoretical resolution ELT
3.4 milli-arcsec = 1.7 x 10^{-8}
(5 meter on the moon)

M. Paul (1935)



Paul - Baker (1969)



Example of a classical Paul-Baker design (primary mirror 39 m diameter)

NO COMA

NO ASTIGMATISM

NO FIELD CURVATURE

$f\,' = 75$ m

$p = 500$ mm (sensor size)

$2a_0 = 6.4 \text{ x } 10^{-3} = 23' = 0.38^{\text{O}}$

$N \approx 10^{+11}$

Three-mirror Paul-Baker telescope

Classical layout with general aspheres (39 meter primary)

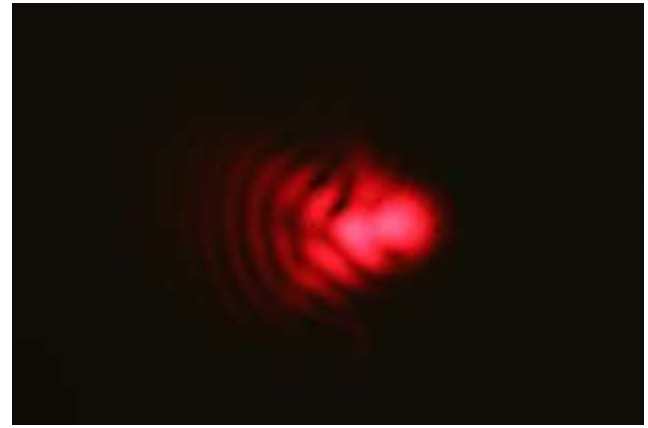
Paul-Baker-anastigmat, $f' = 75$ m, $\lambda = 550$ nm.				
$d_1 = \infty$	c_1	-0.0100136102		
	$a_{2,1}$	$-0.50068051 \cdot 10^{-02}$	$a_{4,1}$	$-0.29095457 \cdot 10^{-09}$
	$a_{6,1}$	$-0.63862737 \cdot 10^{-12}$	$a_{8,1}$	$-0.45324414 \cdot 10^{-16}$
$d_2 = -33.3333$	c_2	-0.030177320		
	$a_{2,2}$	$-0.15088660 \cdot 10^{-01}$	$a_{4,2}$	$-0.10647662 \cdot 10^{-05}$
	$a_{6,2}$	$-0.20207273 \cdot 10^{-08}$	$a_{8,2}$	$-0.15802737 \cdot 10^{-11}$
	$a_{10,2}$	$-0.23585205 \cdot 10^{-14}$		
$d_3 = +50.0000$	c_3	-0.020000000		
	$a_{2,3}$	$-0.10000000 \cdot 10^{-01}$	$a_{4,3}$	$-0.10052010 \cdot 10^{-05}$
	$a_{6,3}$	$-0.20202048 \cdot 10^{-09}$	$a_{8,3}$	$-0.52424597 \cdot 10^{-13}$
$d_4 = -25.06799900$				
Image quality	field angle γ		OPD_{rms} (units of λ)	
	$0.0'$		0.038	
	$3.7'$		0.030	
	$7.3'$		0.014	
	$10.3'$		0.040	
	$11.0'$		0.051	

general aspheres

Telescope aberrations: coma and astigmatism

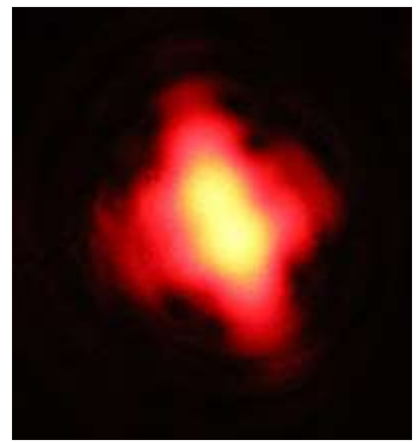
one star | two stars

Coma



Airy disc

Astigmatism



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   - angular resolution

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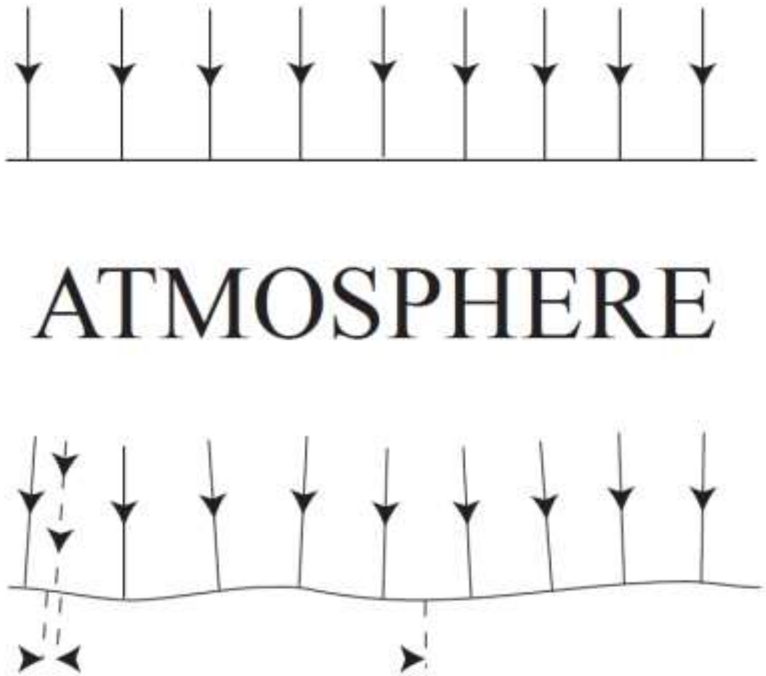
Atmospheric turbulence ('seeing')

Star light



wavefront

ATMOSPHERE

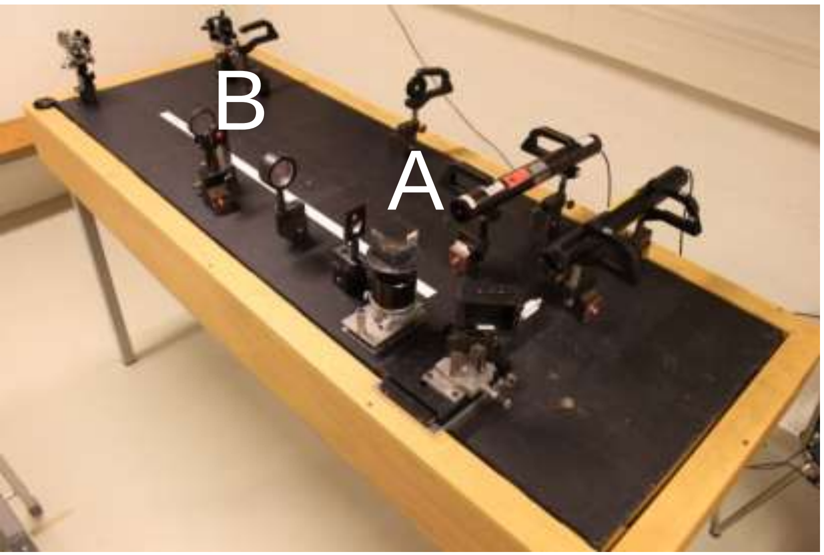
angular spread rays: 0.8 to 1.2 arcsec

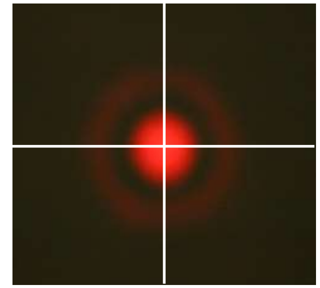
wavefront deviation: several micrometers

eye pupil
(4 mm)
NO BLUR,
ONLY TILT

E-ELT primary
(39000 mm)
SEVERE BLURRING
AND TILT

Atmospheric turbulence ('seeing')



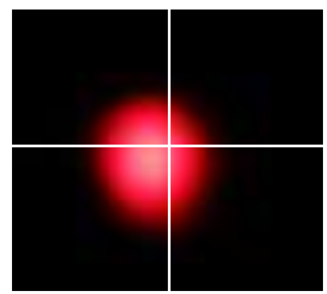


↓

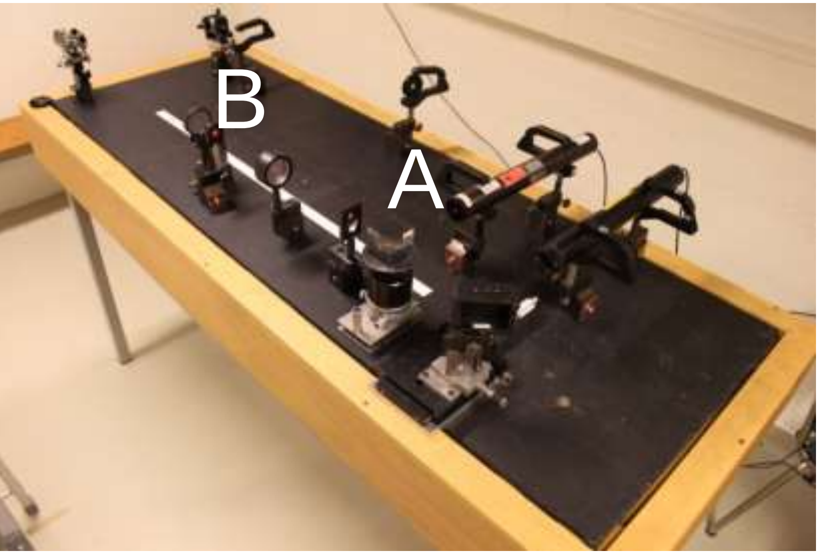
small-sized beam, 'weak turbulence'

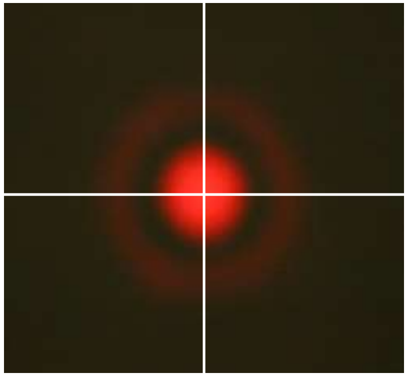
⟶ time –dependent shift of star mage

A



Atmospheric turbulence ('seeing')





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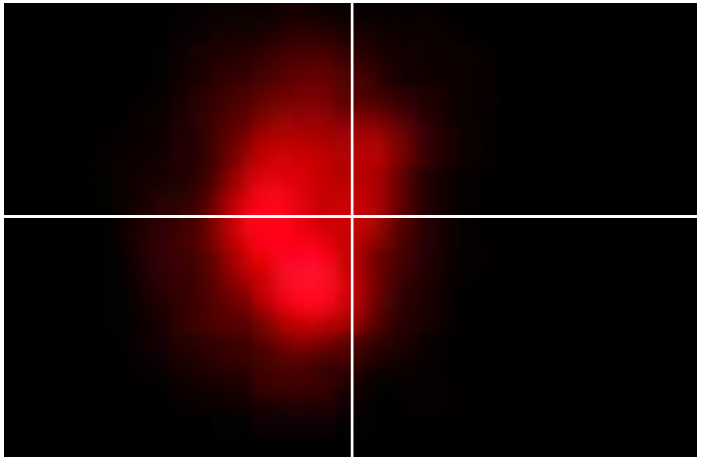
5x larger beam, 'stronger turbulence'

⟶ blur AND shift of star mage shift

B



Conclusions

- a (passive) 39 meter telescope is unique with respect to light collection

- all mirror surfaces should be individually measured and adjusted down to a fraction (50 nanometer) of the wavelength of visible light (λ=550 nanometer)

- `seeing' at E-ELT-site is of the order of 0.8 arcsec (0.3 arcsec record low value)
  → enormous gap with the theoretical resolution of E-ELT: 0.0034 arcsec

- full imaging capability of the 39-meter telescope requires

  - mechanical deformations add up to optical aberrations smaller than 100 nm

  - seeing effects should be cancelled over an area of 1100 square meters

HERCULEAN TASK for the E-ELT team of the European Southern Observatory