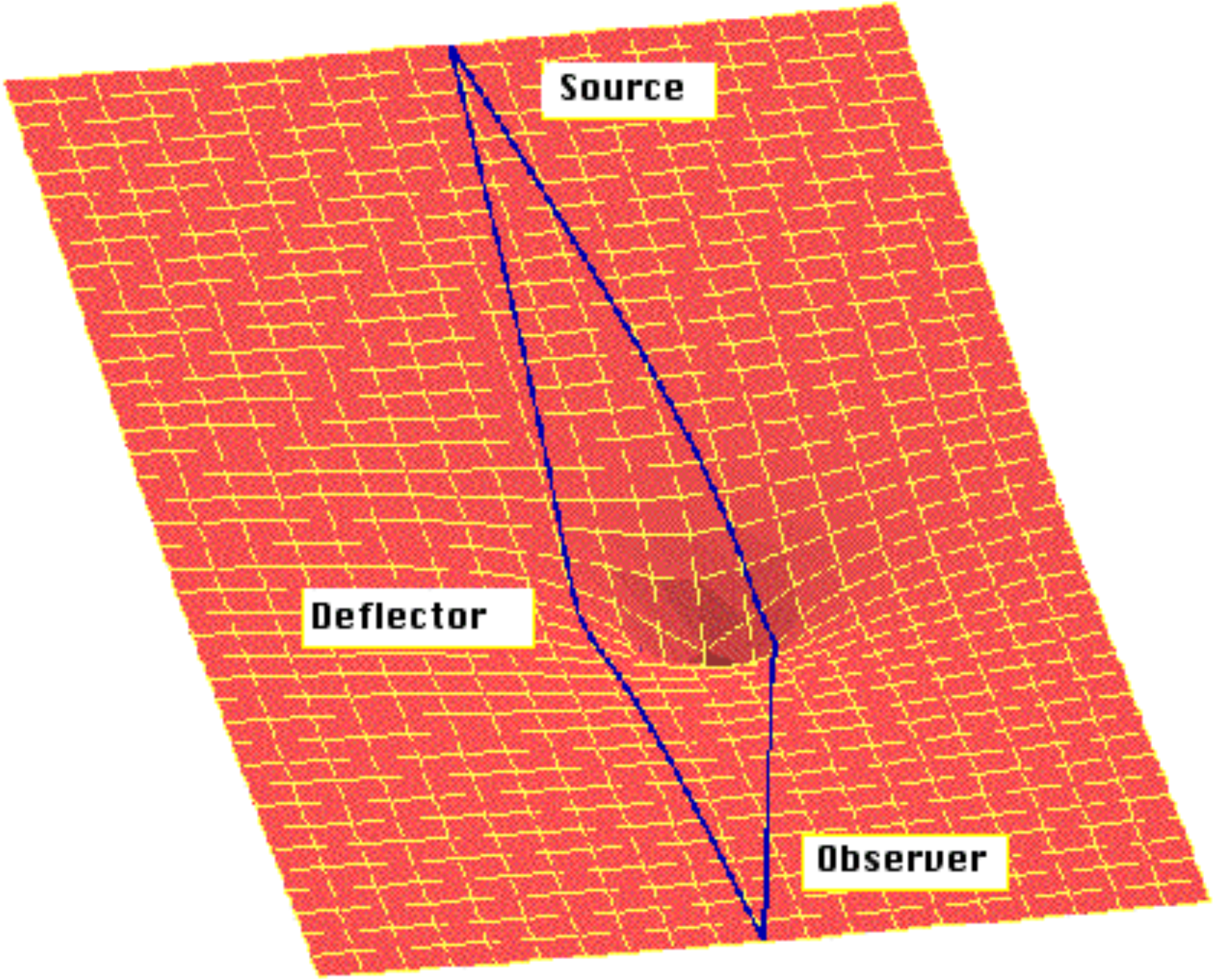
Galaxies and Extragalactic Astronomy

8. Gravitational Lensing

8 Gravitational Lensing

8.1 Introduction

- According to GR matter distorts spacetime and therefore light paths are changed: gravitational lensing
- Gravitational lensing effects depend on the matter distribution and the geometry


Source
Deflector
Observer

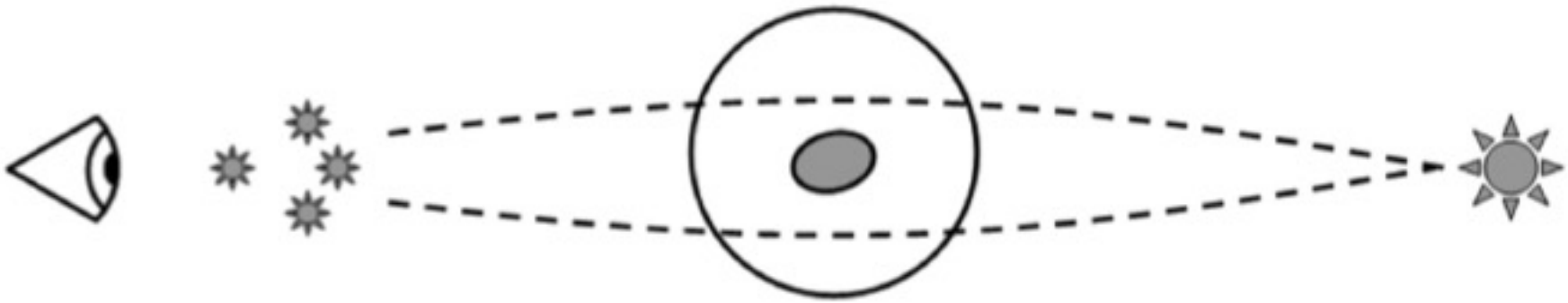
8 Gravitational Lensing

8.1 Introduction

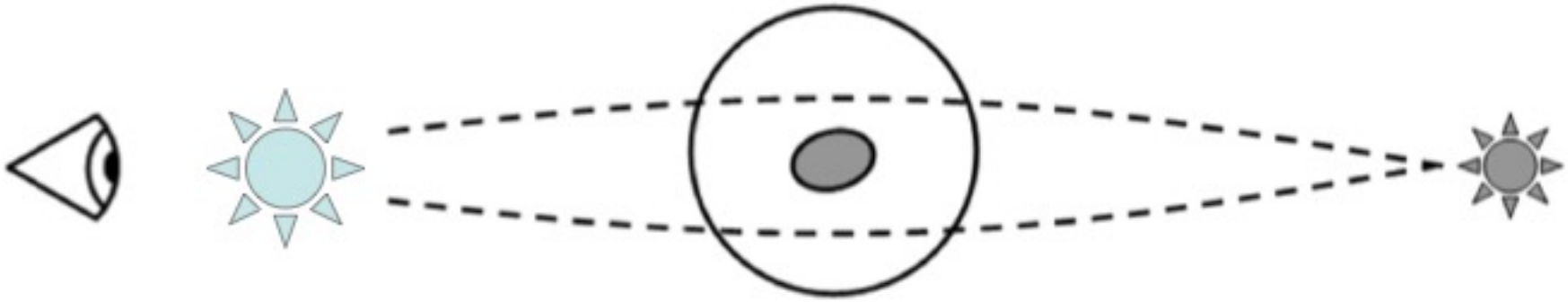
- According to GR matter distorts spacetime and therefore light paths are changed: gravitational lensing
- Gravitational lensing effects depend on the matter distribution and the geometry
- Two regimes: strong and weak lensing
- achromatic

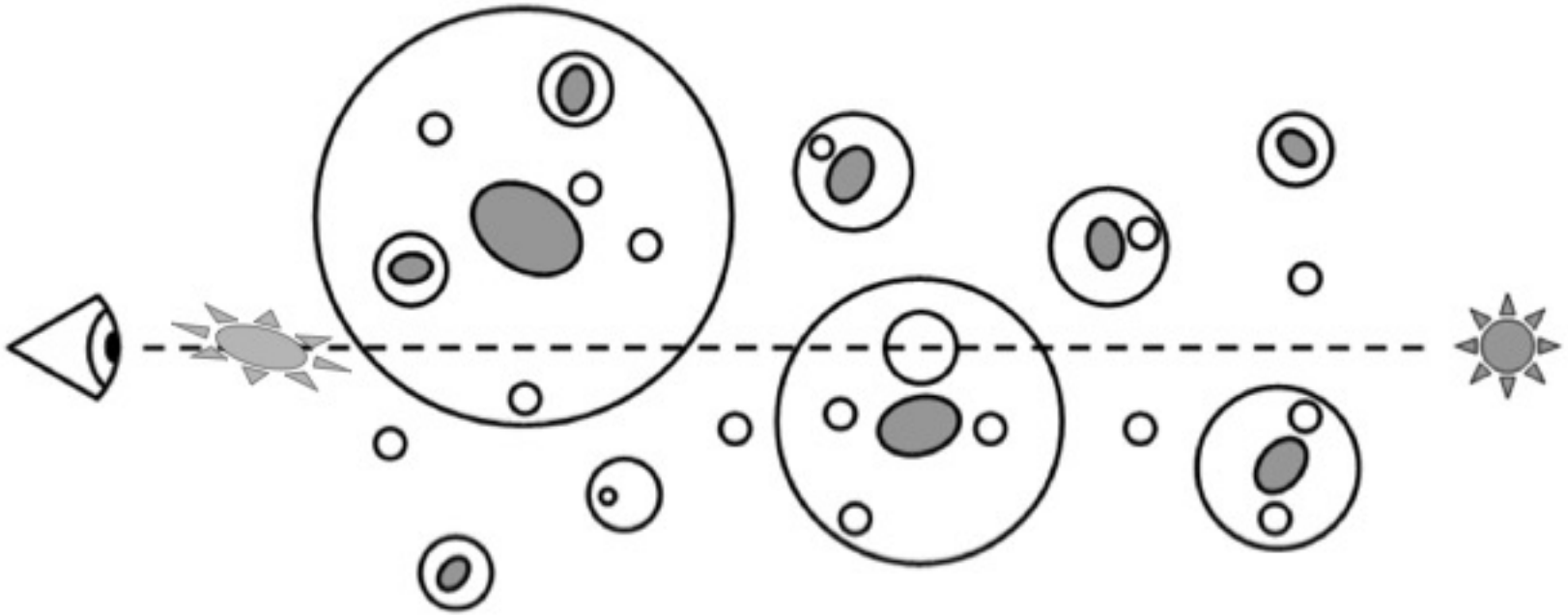
- strong lensing
  - lensing of background sources by foreground galaxies, clusters, …

    (→ strong distortion, magnification, and multiple images)



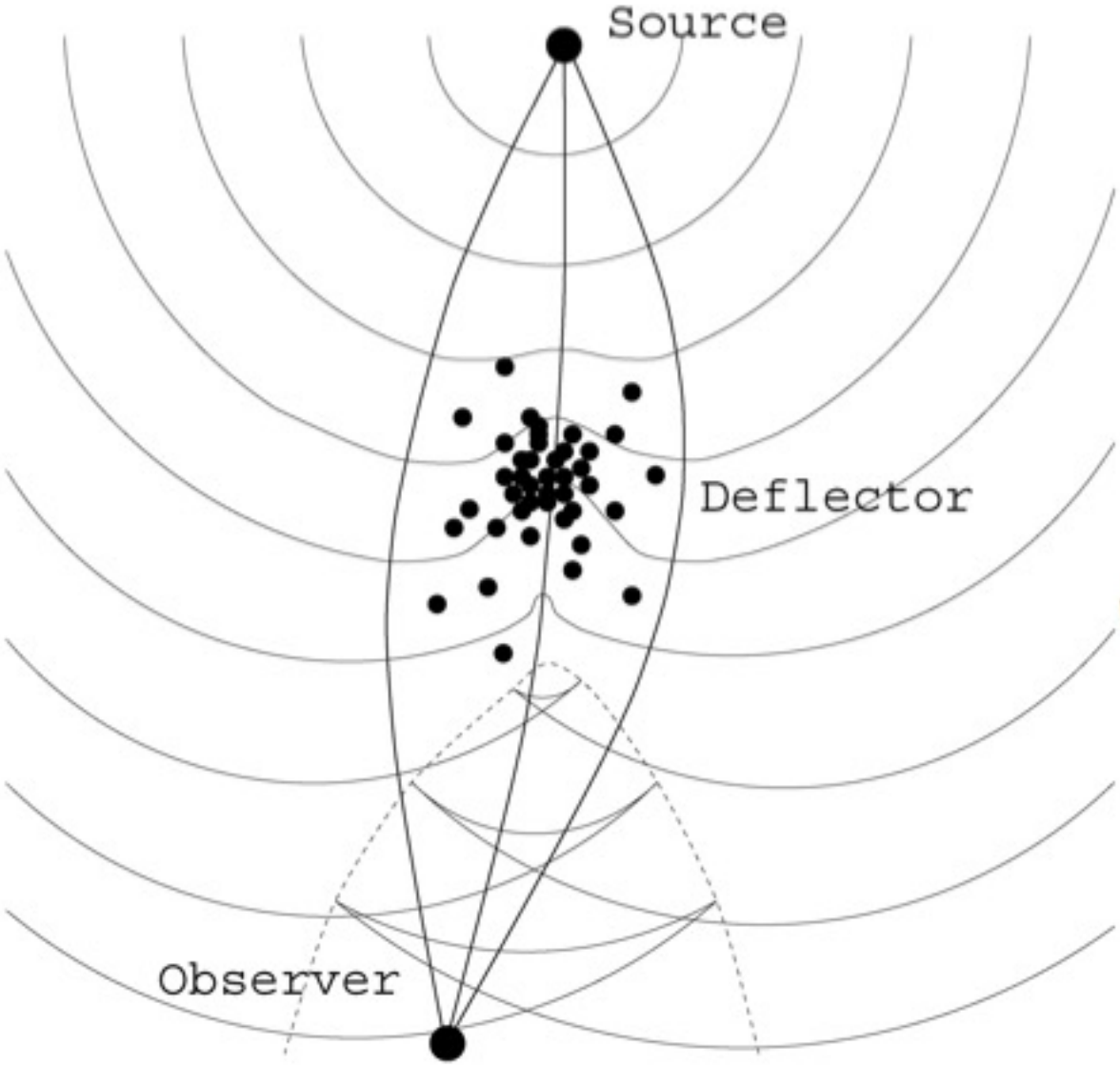
- microlensing
  - mainly referred to as lensing by objects of stellar (point) masses
    (→ no distortion, mainly magnification)





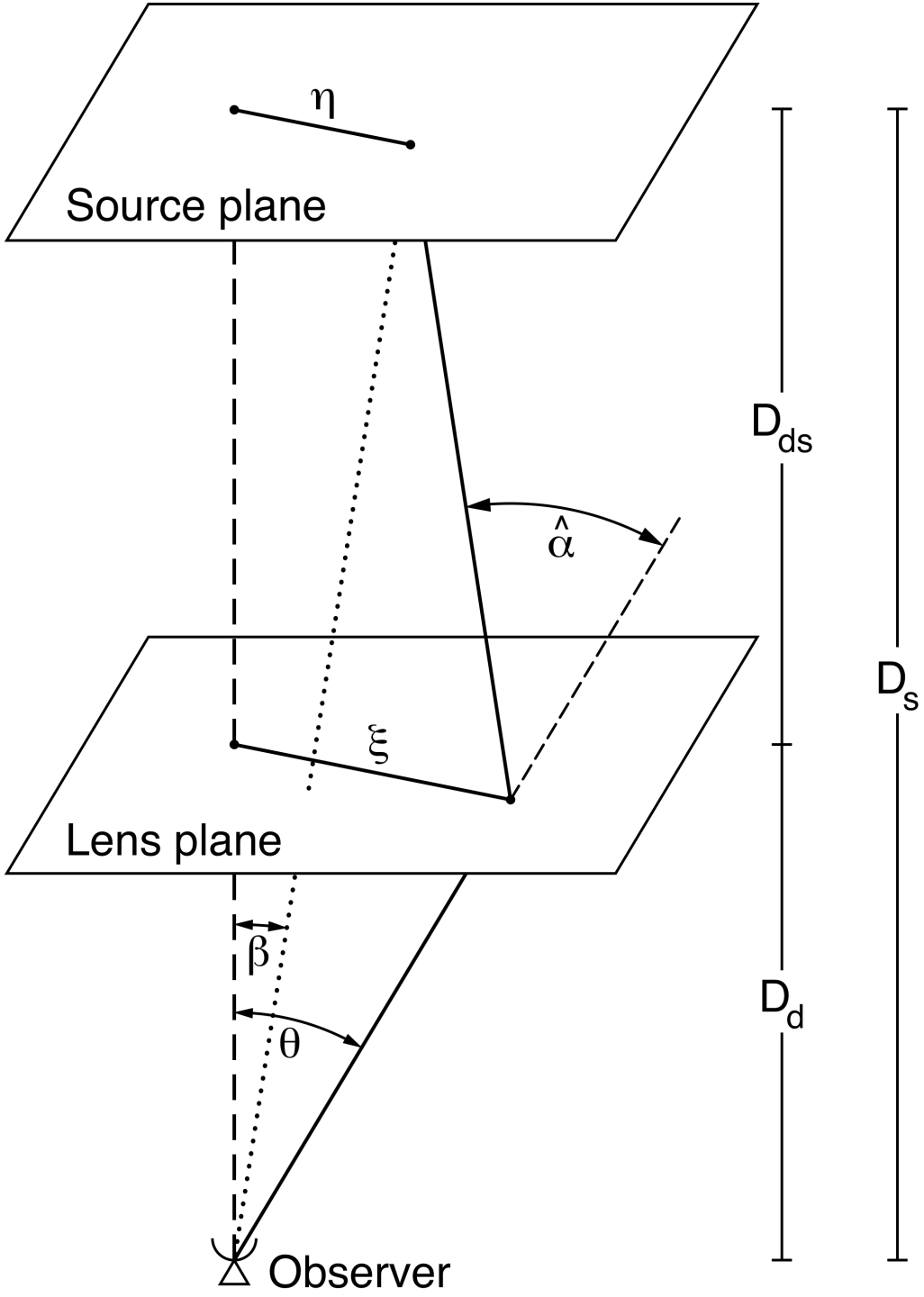
- **weak lensing**
  - lensing via large-scale structure
    (→ weak distortion and magnification)

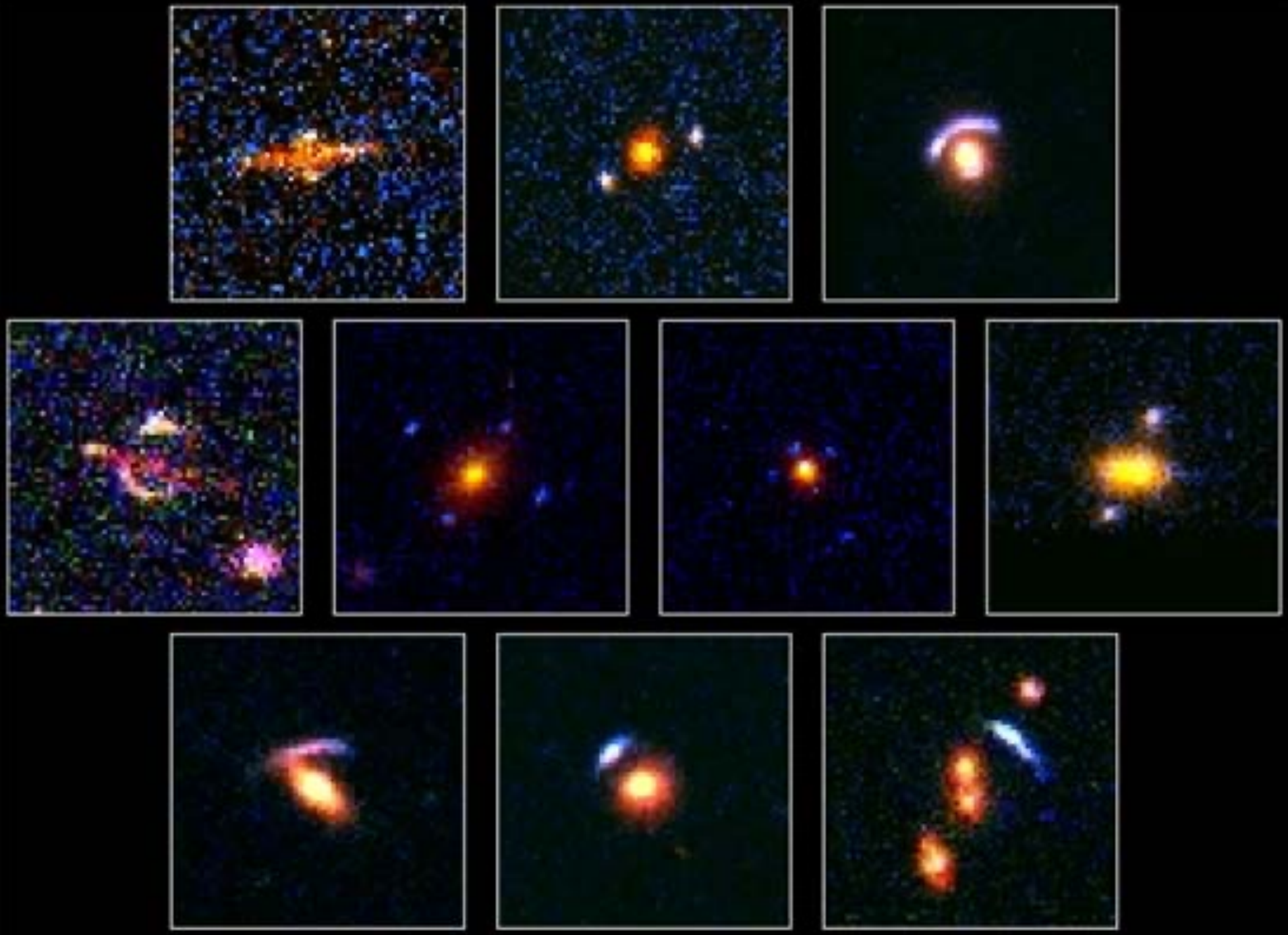
wave picture

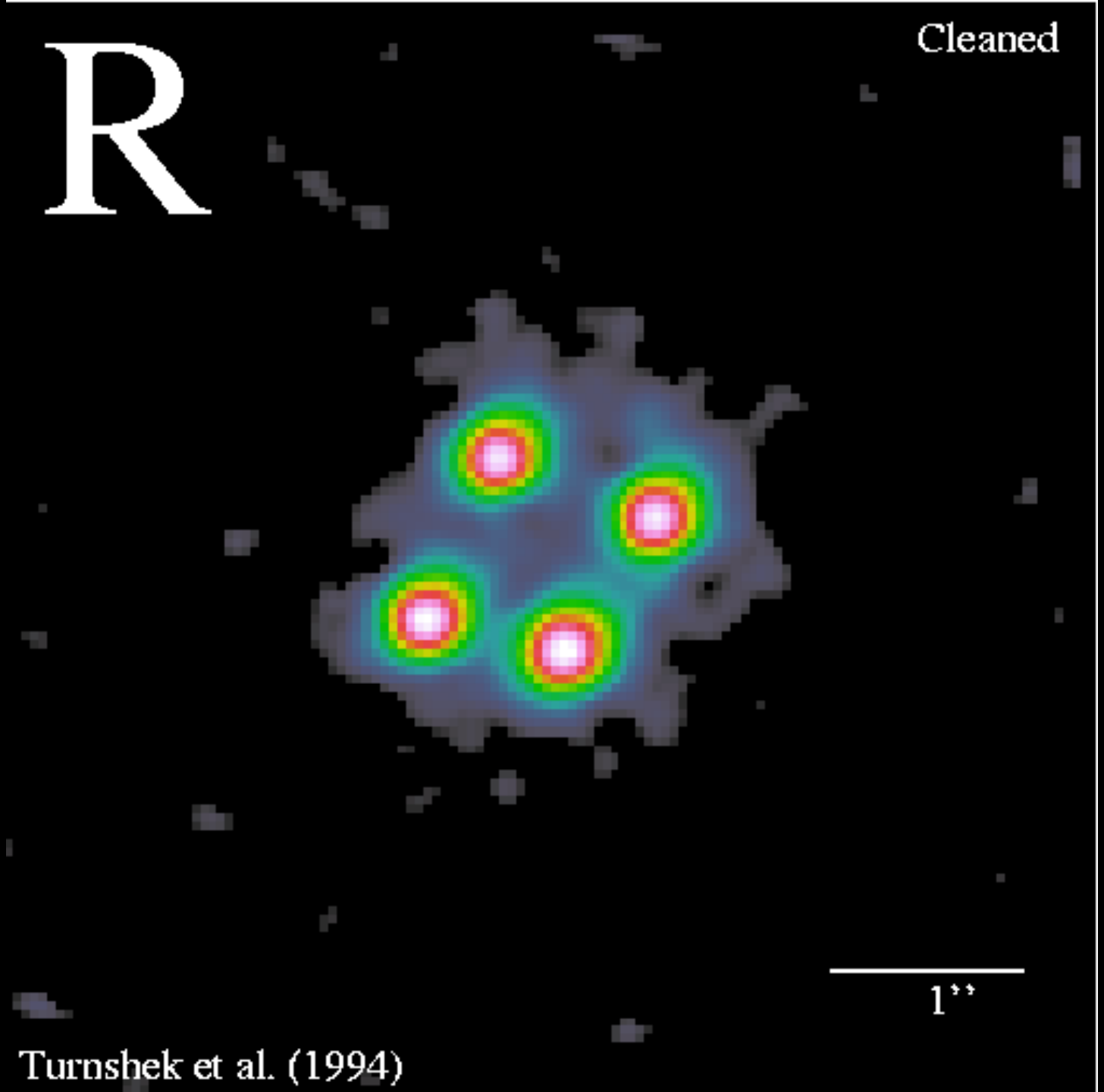


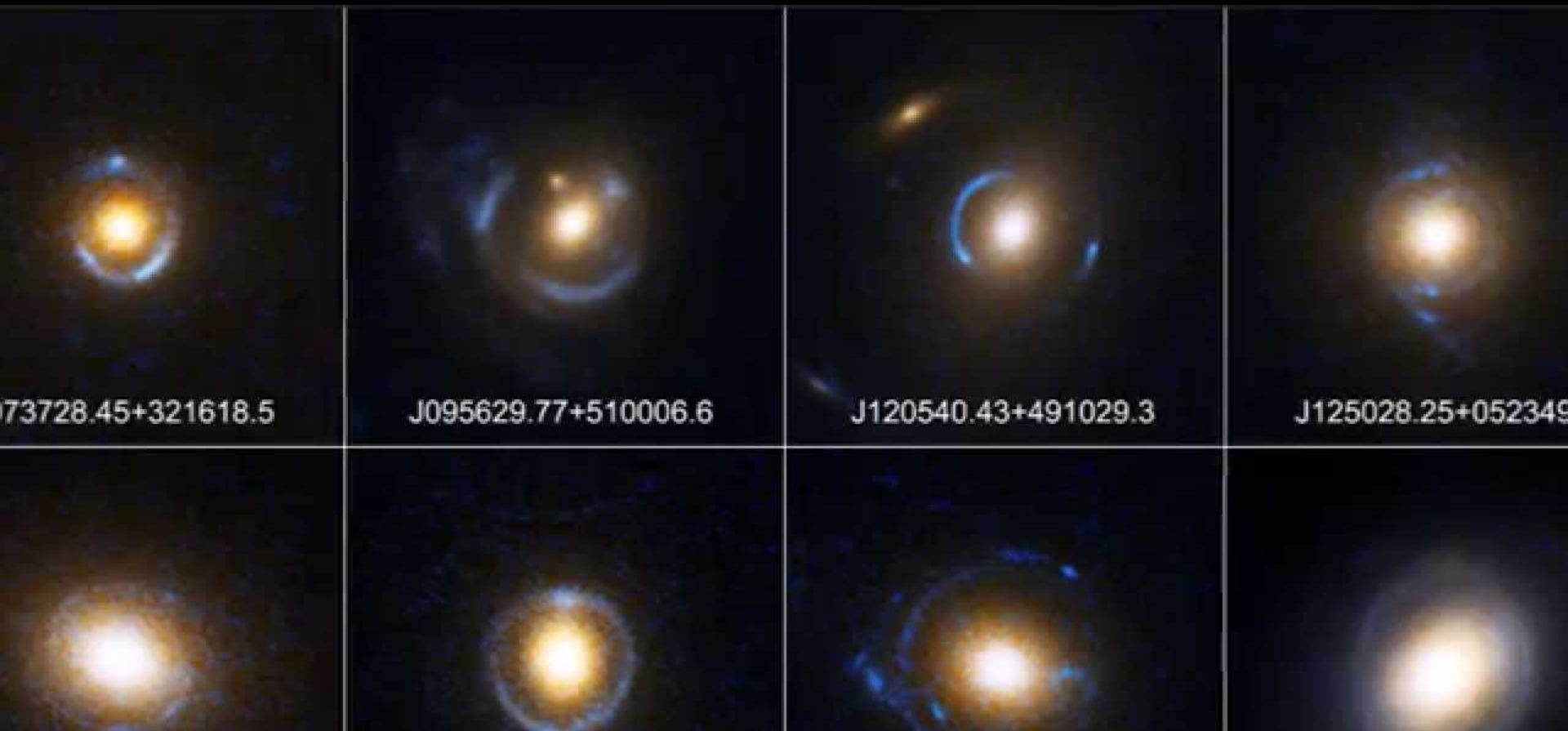
weak lensing regime

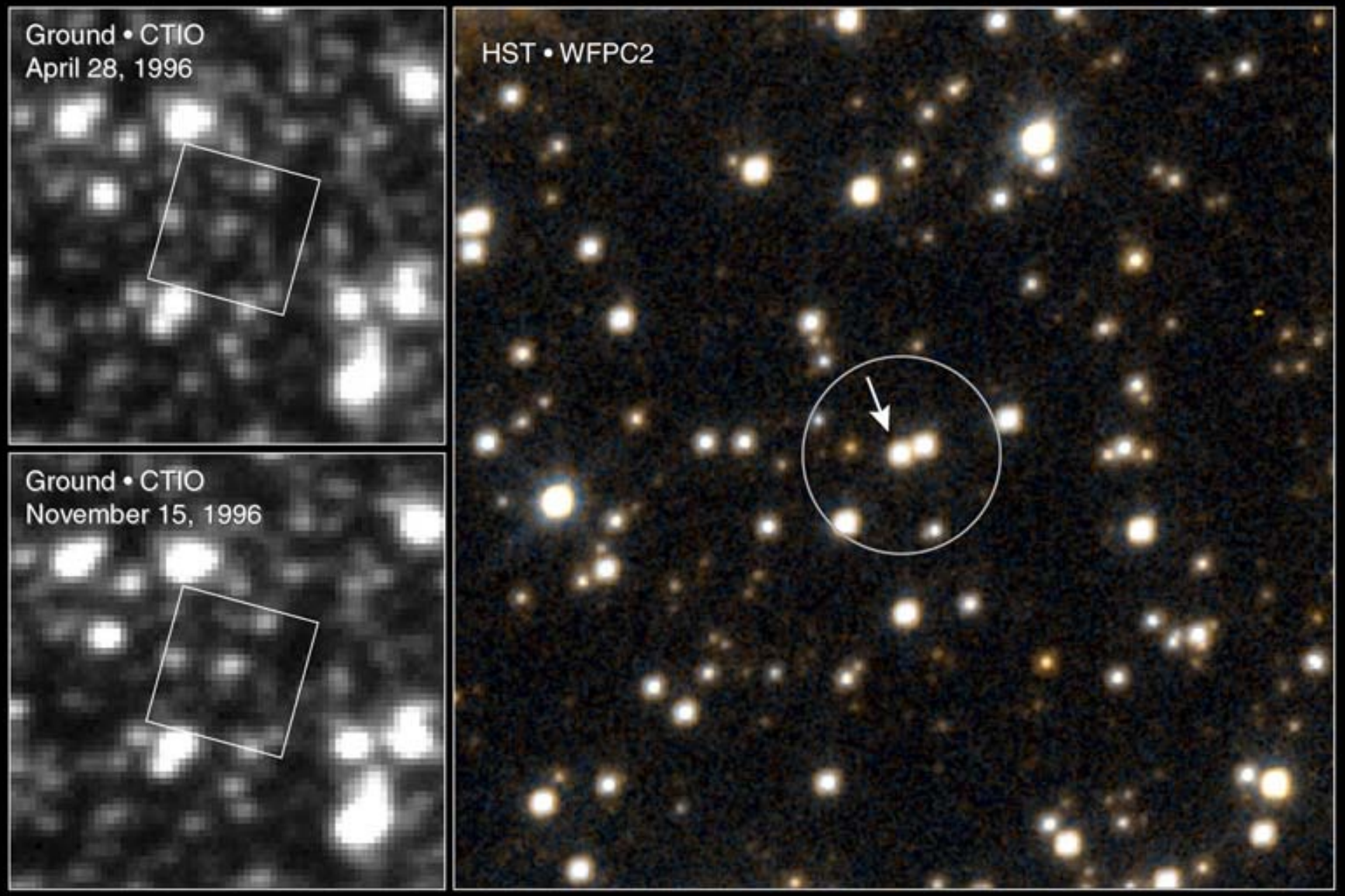
strong/micro lensing regime


η
Source plane
$\hat{\alpha}$
ξ
Lens plane
β
θ
Observer
D_{ds}
D_s
D_d



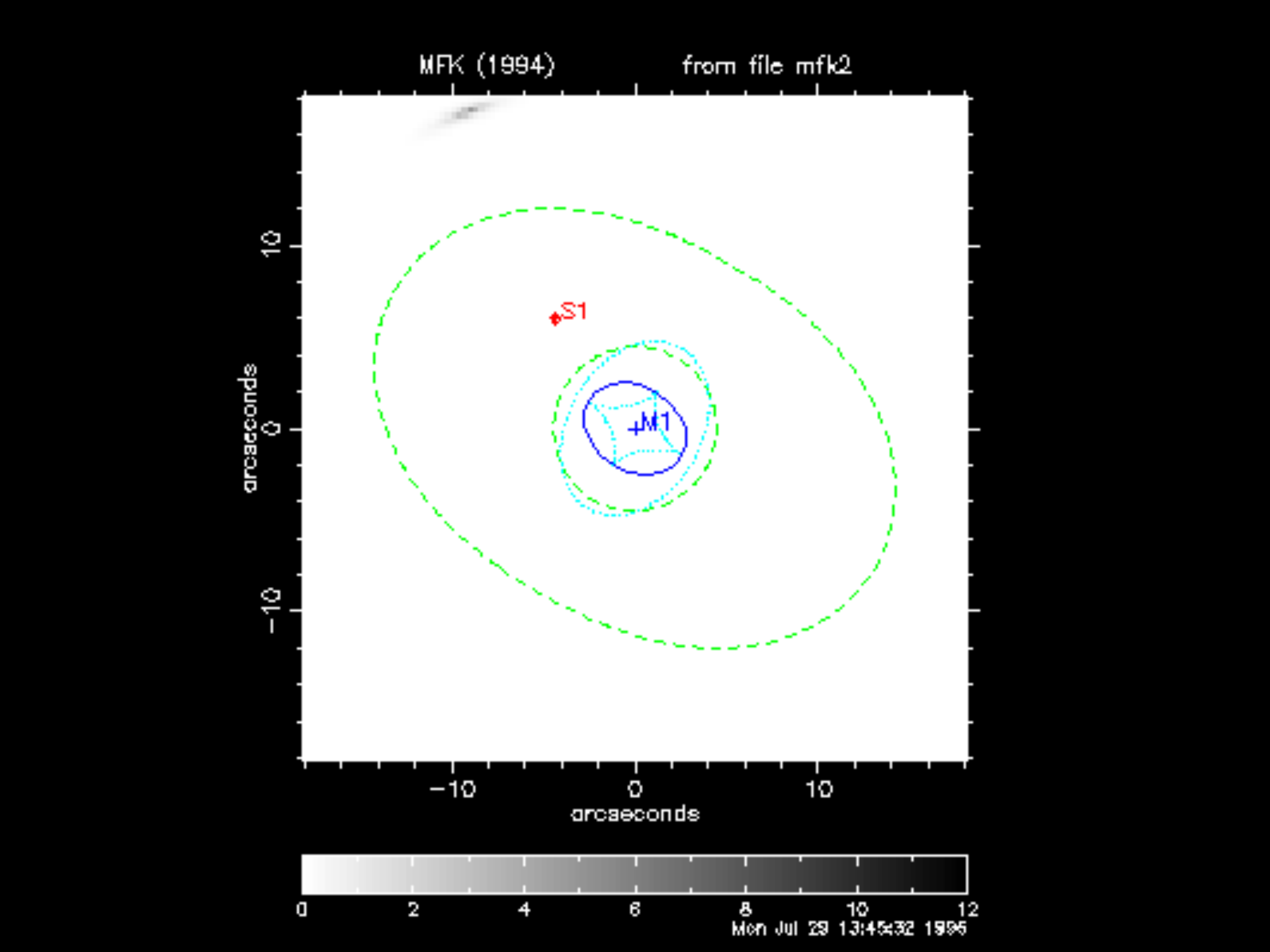

R
Cleaned
1''
Turnshek et al. (1994)


073728.45+321618.5
J095629.77+510006.6
J120540.43+491029.3
J125028.25+052349
040228.21+632133.5
J162746.44-005357.5
J163028.15+452036.2
J232120.93-093910.
WIZSCIENCE.COM

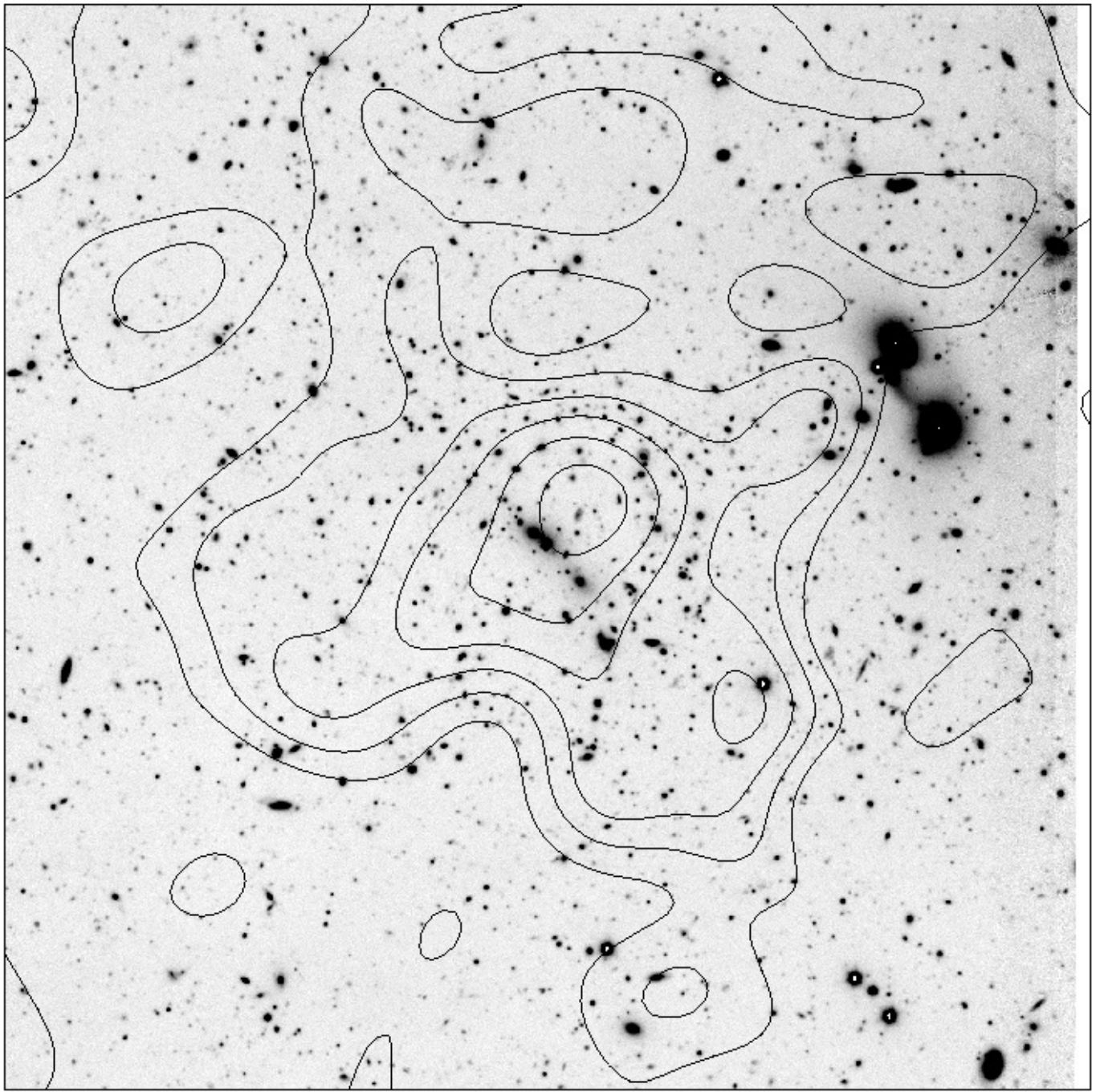


Microlens Event MACHO-96-BLG-5
Hubble Space Telescope • WFPC2

NASA and D. Bennett (University of Notre Dame) • STScI-PRC00-03


MFK (1994)
from file mfk2
S1
M1
10
0
−10
arcseconds
−10
0
10
arcseconds
0
2
4
6
8
10
12
Mon Jul 29 13:45:32 1996

MS0016+16

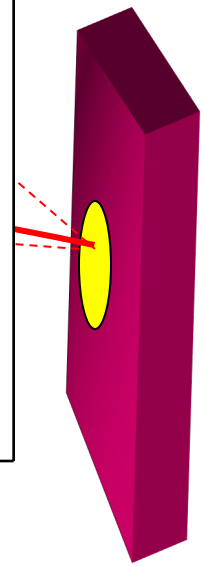


The picture can't be displayed.

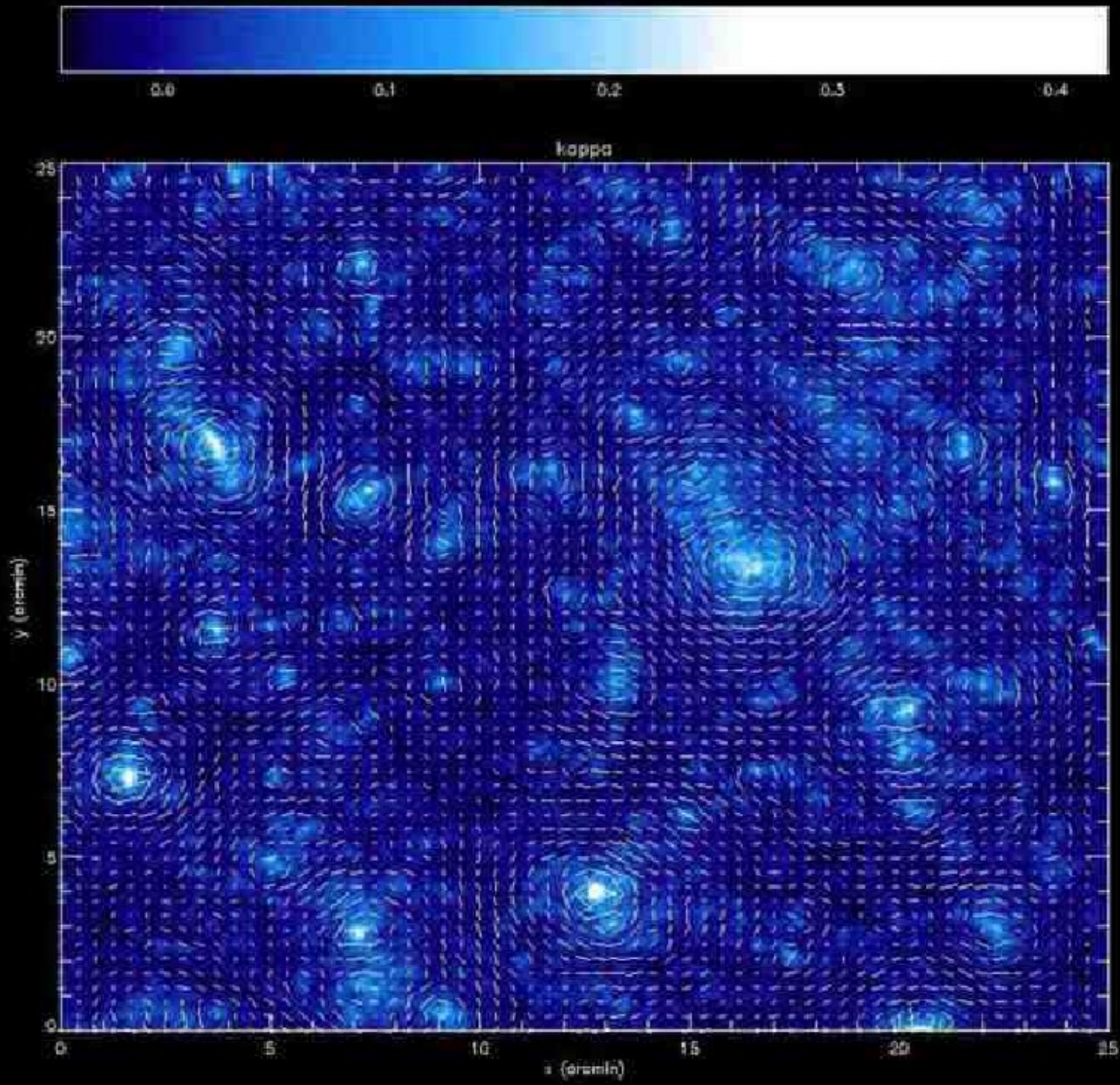
The picture can't be displayed.

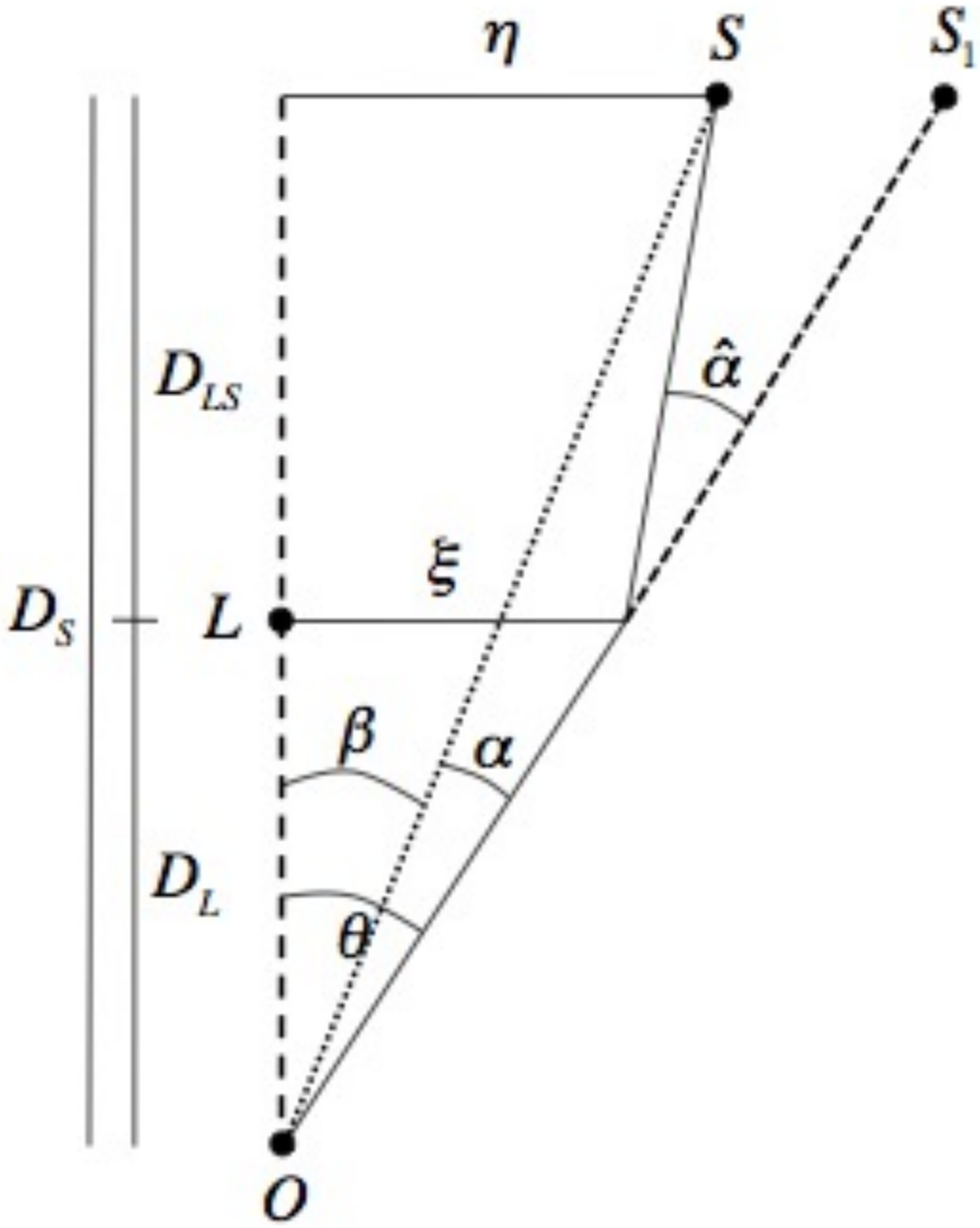
kground
ources

Obs

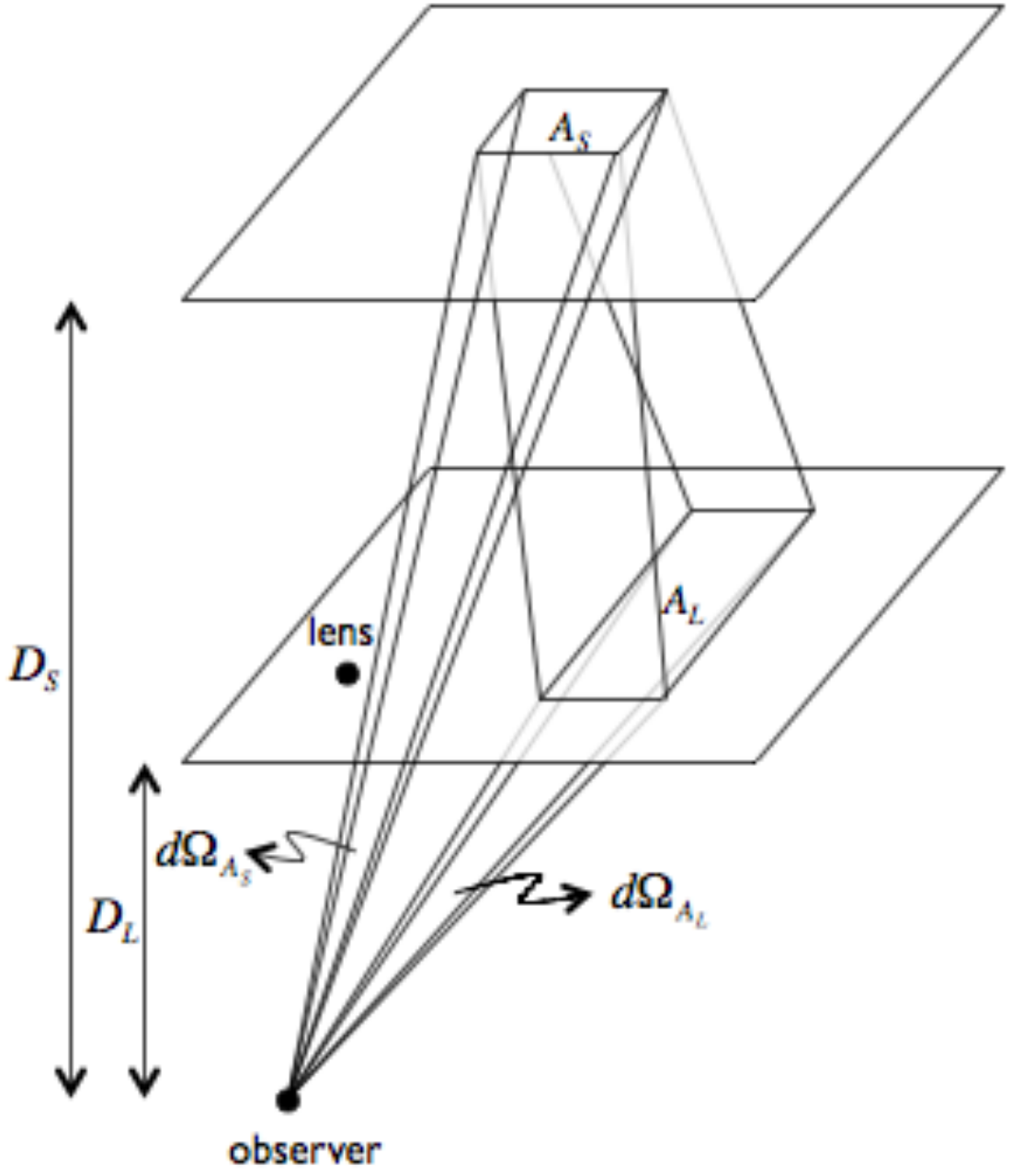


- Statistical measure of shear pattern, ~1% distortion
- Radial distances depend on *geometry* of Universe
- Foreground mass distribution depends on *growth* of structure

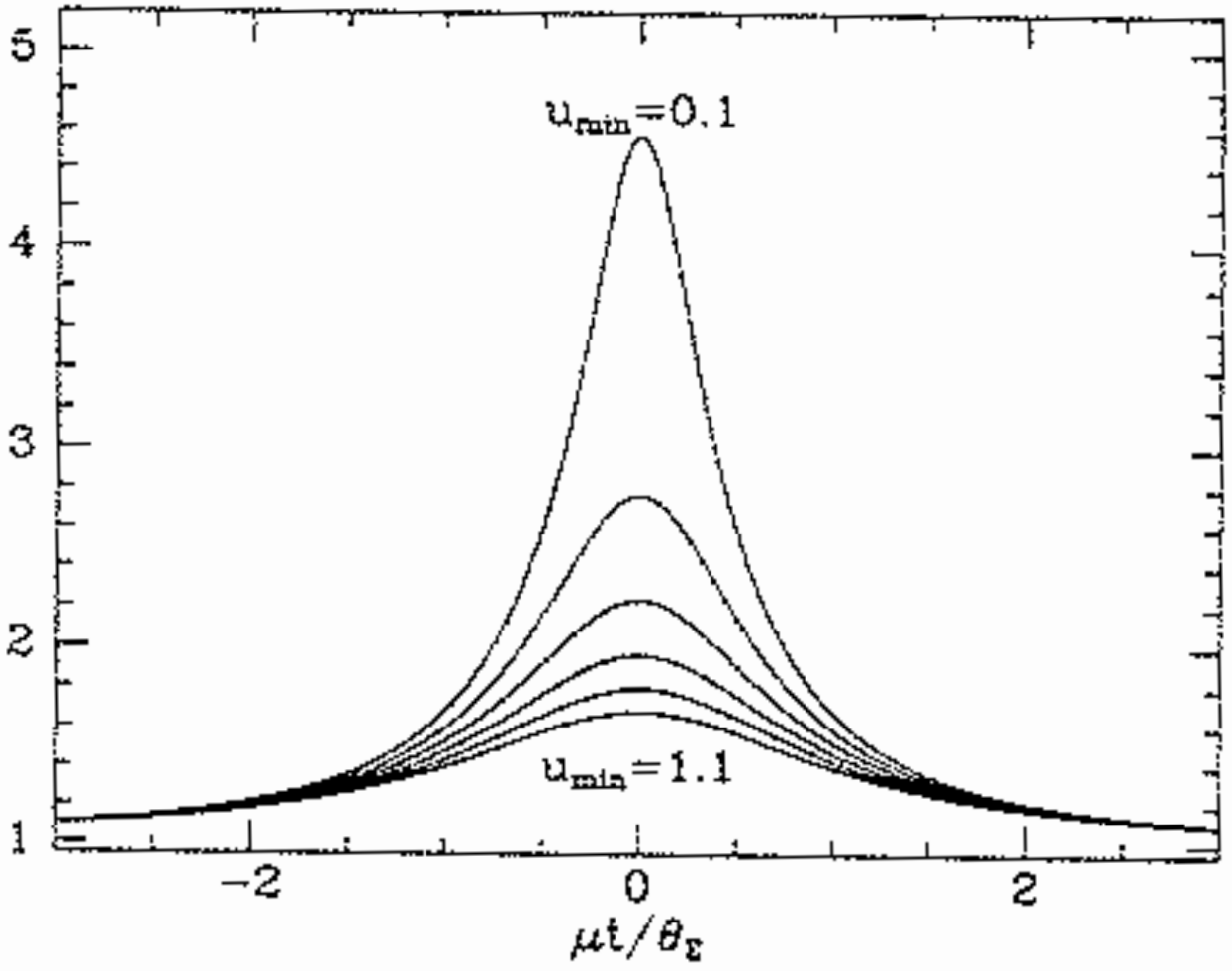

0.0
0.1
0.2
0.3
0.4
kappa
25
20
15
10
5
0
y (arcmin)
0
5
10
15
20
25
x (arcmin)


η
S
S1
D_LS
α̂
ξ
D_S
L
β
α
D_L
θ
O

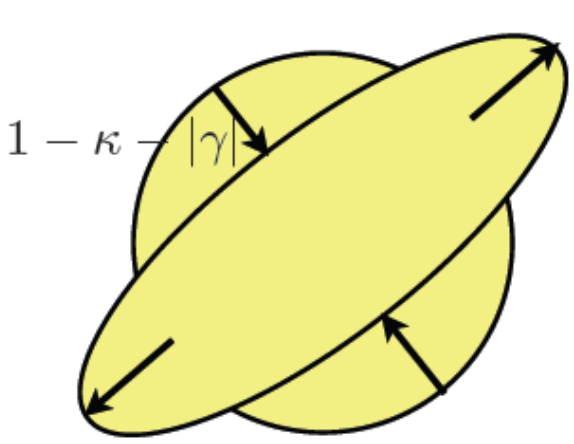
lensing preserves surface brightness



a



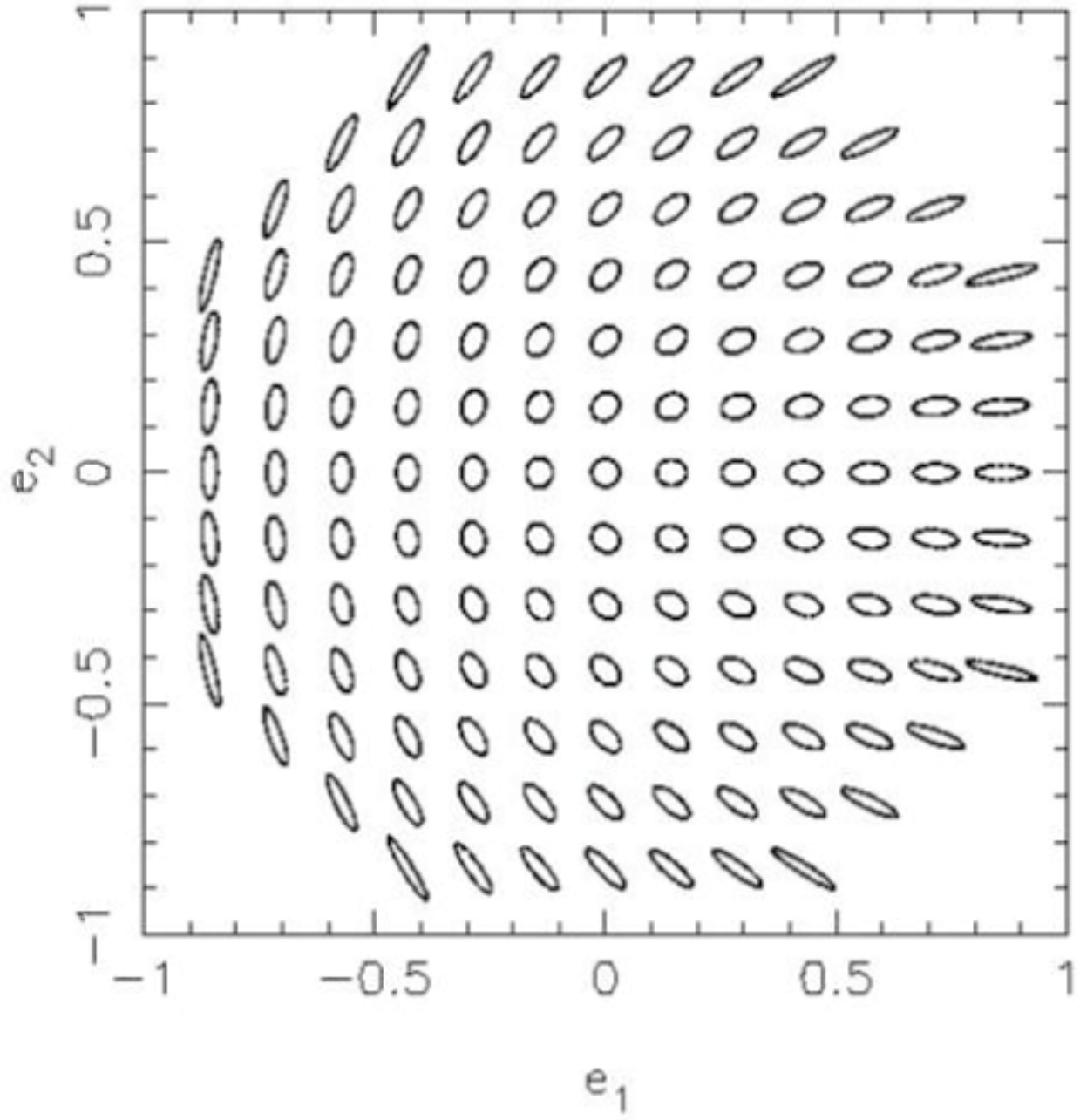
$$I(\vec{\theta}) = I^{(s)}\left[\vec{\beta}_0 + \mathcal{A}(\vec{\theta}_0)\cdot(\vec{\theta}-\vec{\theta}_0)\right]$$

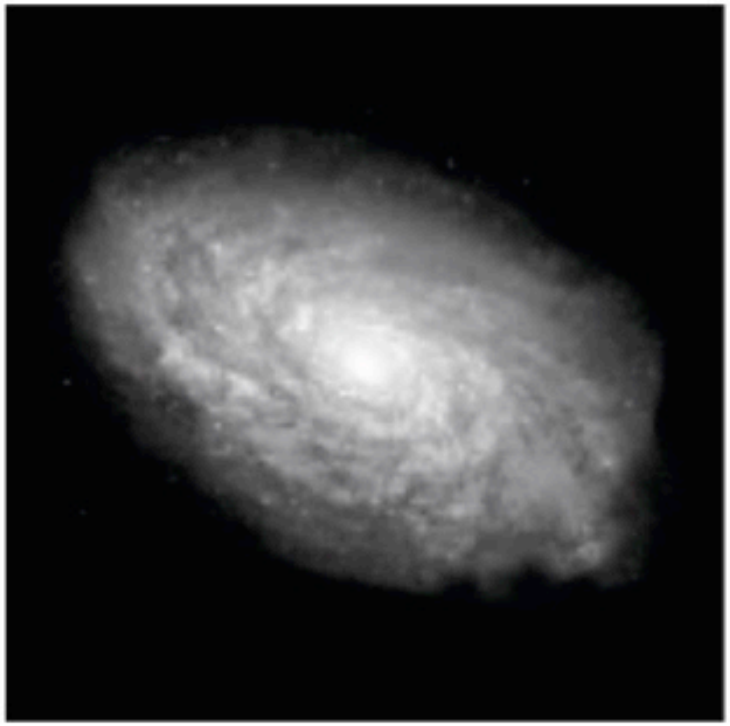


A circle becomes an ellipse.

The minor and major axes given by the inverse of the eigenvalues of A.

The orientation is given by the eigenvectors of A

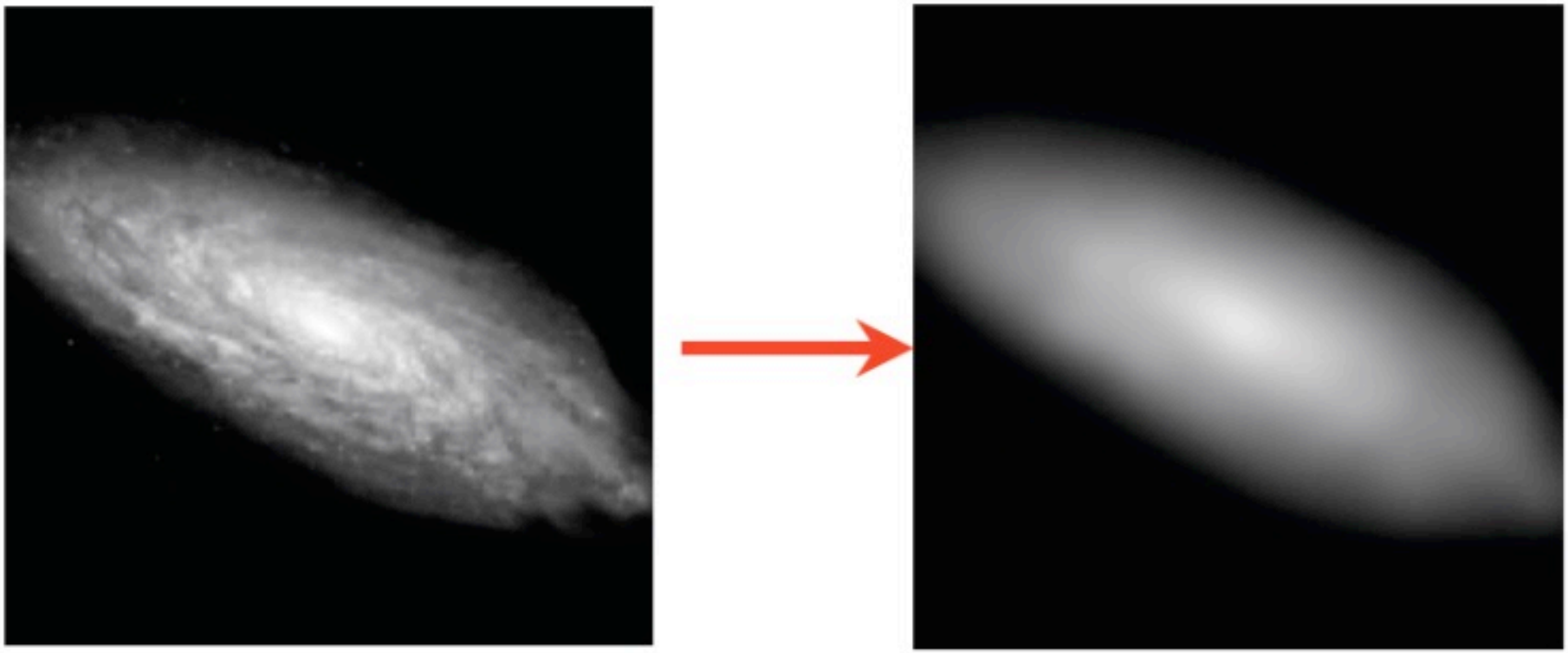

1
0.5
0
−0.5
−1
e_2
−1
−0.5
0
0.5
1
e_1



$g_i \sim 0.2$

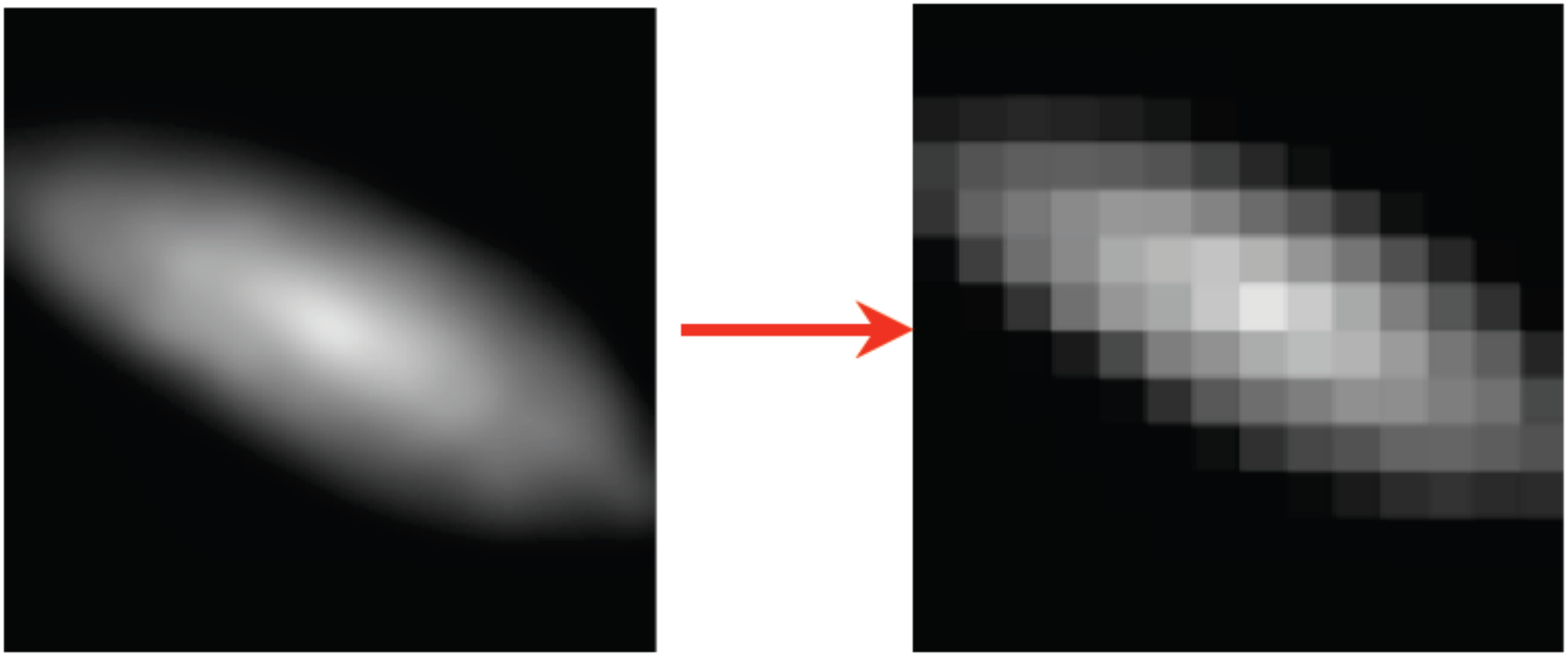
$$\begin{pmatrix} x_u \\ y_u \end{pmatrix} = \begin{pmatrix} 1-g_1 & -g_2 \\ -g_2 & 1+g_1 \end{pmatrix} \begin{pmatrix} x_l \\ y_l \end{pmatrix}$$

Real data:
$g_i \sim 0.03$



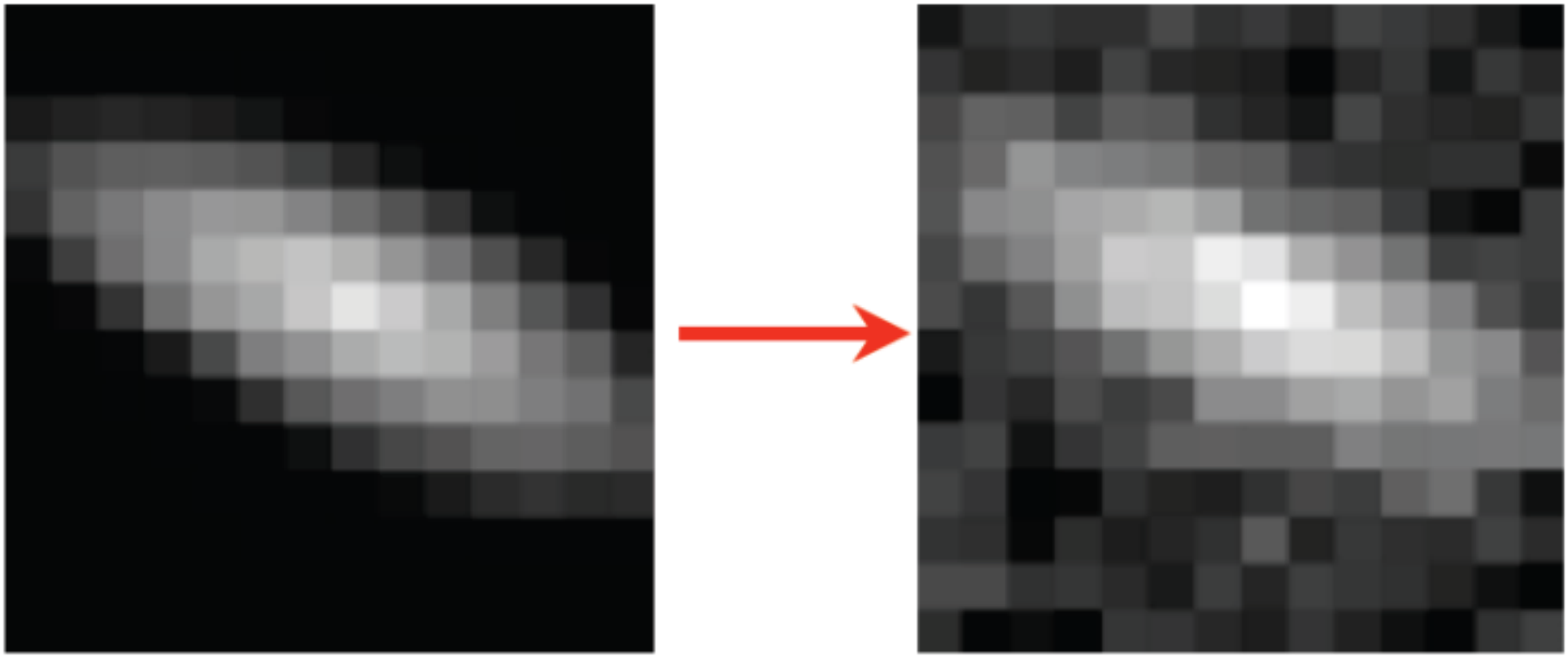
Atmospheric Seeing and telescope PSF

Real data: seeing disk ~ Galaxy size



Sum light in each square

Real data: Pixel size ~ seeing size /3



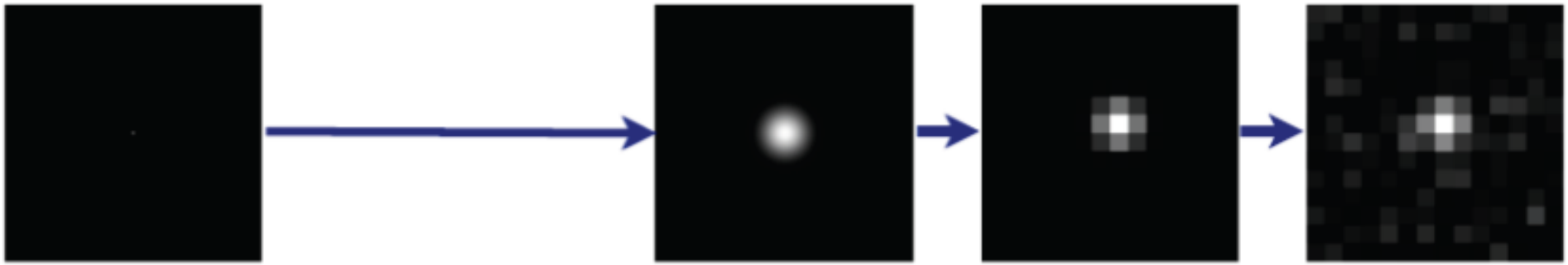
Mostly Poisson. Some Gaussian and bad pixels.
Uncertainty on total light ~ 5 per cent

The Forward Process.

Galaxies: Intrinsic galaxy shapes to measured image:

Intrinsic galaxy (shape unknown) | Gravitational lensing causes a ***shear (g)*** | Atmosphere and telescope cause a convolution | Detectors measure a pixelated image | Image also contains noise

Stars: Point sources to star images:

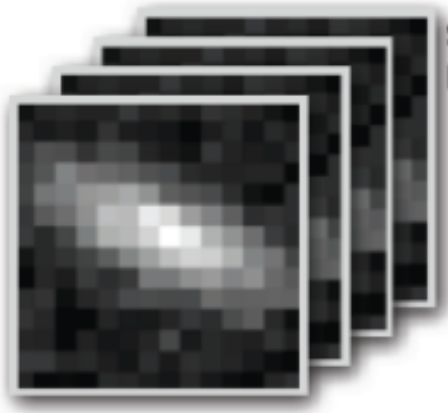


Intrinsic star (point source) | Atmosphere and telescope cause a convolution | Detectors measure a pixelated image | Image also contains noise

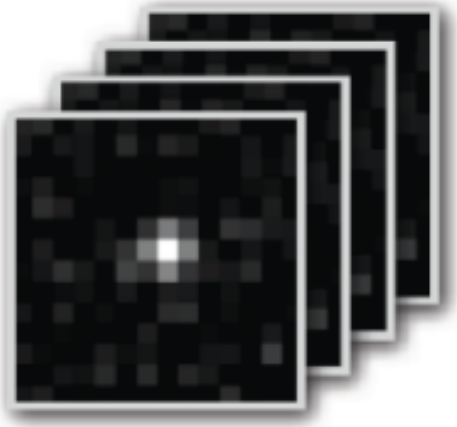
The Inverse Problem:
Measured images to *shear*

Intrinsic galaxy shapes can be inferred, but are not used beyond shear estimation

Shear Field

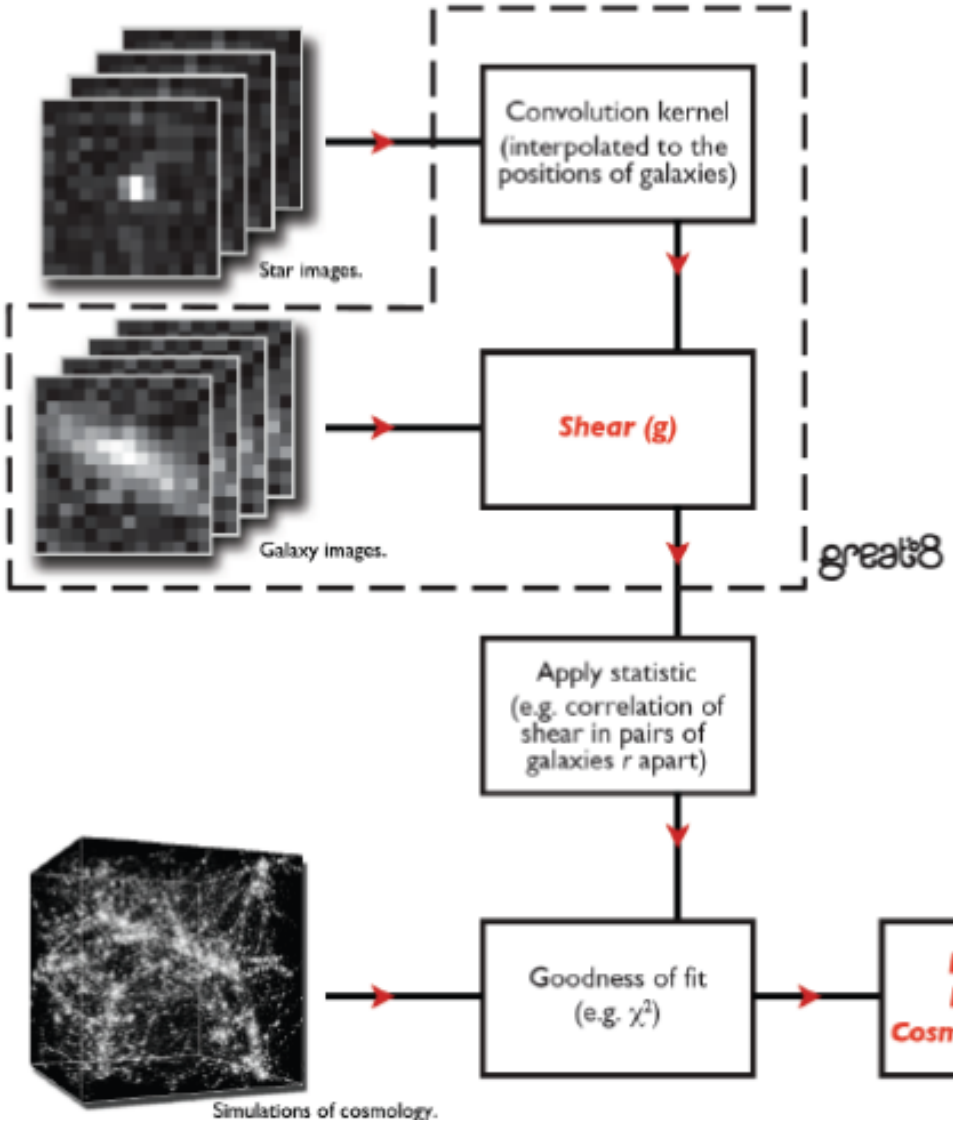


Set of galaxy images.
Each contains:
- noise
- pixelisation
- convolution
- ***shear***
- intrinsic shape



Set of star images.
Each contains:
- noise
- pixelisation
- convolution

A full weak lensing pipeline:
The broader context typical for cosmological measurements



But there are many different methods that were found to give very different results!

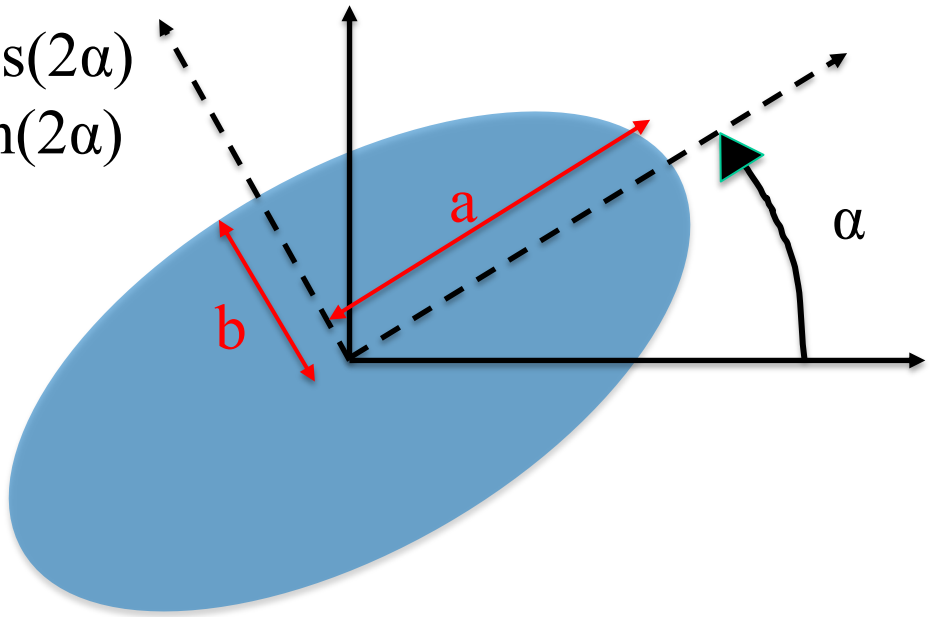
Weak gravitational lensing

Measure galaxy sizes and shapes

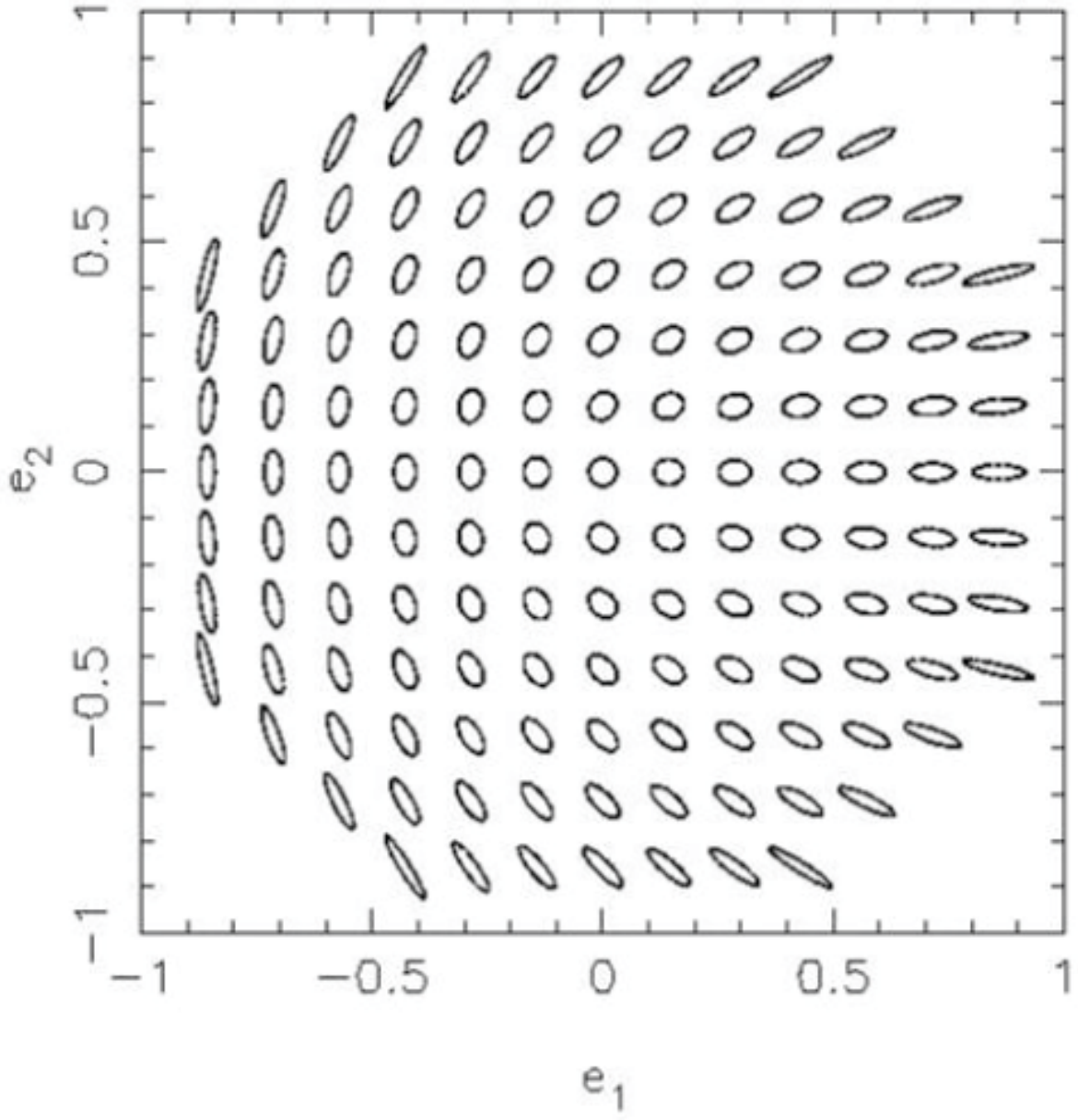
$e1 = (a-b) / (a+b) \cos(2\alpha)$
$e2 = (a-b) / (a+b) \sin(2\alpha)$

$a = 2$
$b = 1$
$\alpha = 30^o$
$\cos(2\alpha) = 0.5$
$\sin(2\alpha) = 0.866$

$e1 = 0.167$
$e2 = 0.289$

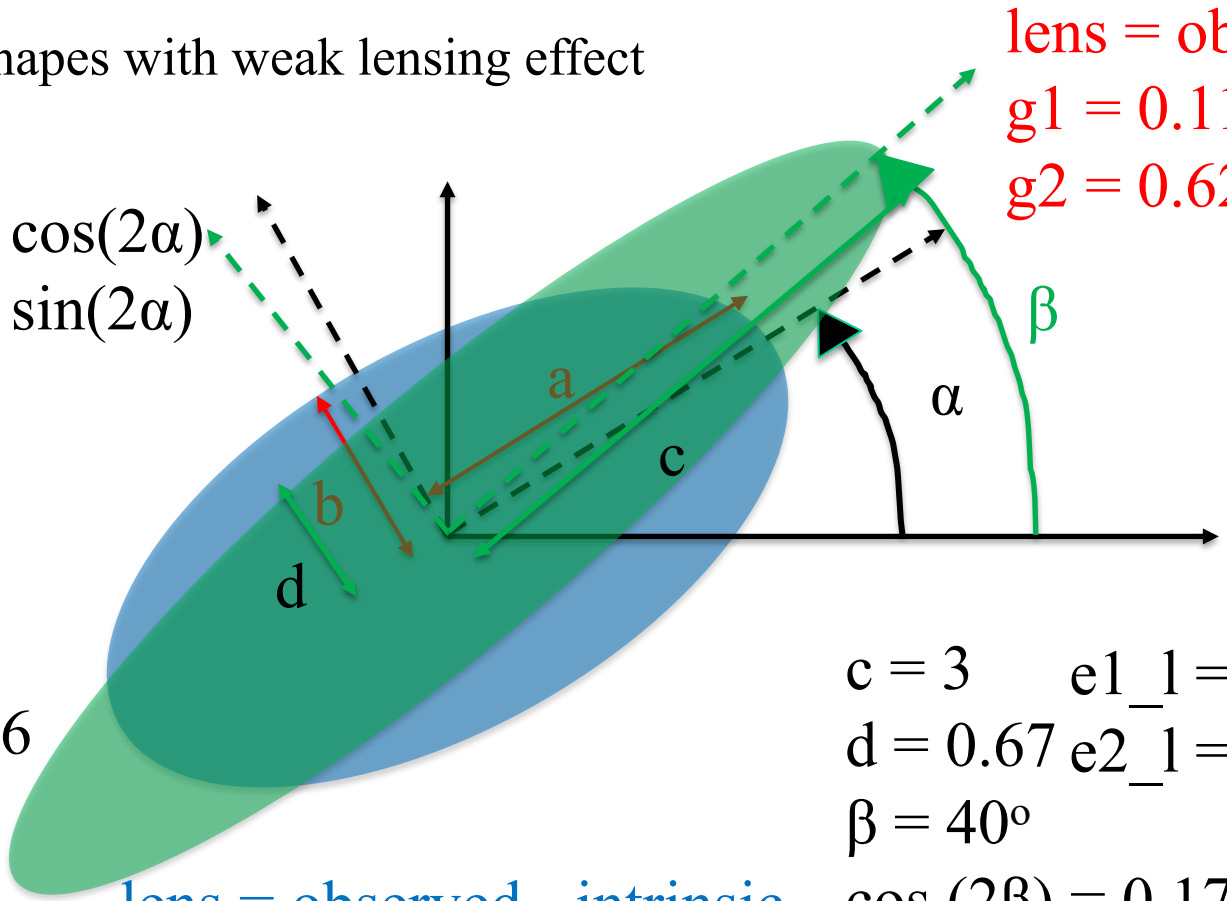


Weak gravitational lensing



Weak gravitational lensing

Galaxy sizes and shapes with weak lensing effect



$e1 = (a-b) / (a+b) \cos(2\alpha)$

$e2 = (a-b) / (a+b) \sin(2\alpha)$

$a = 2$

$b = 1$

$\alpha = 30^o$

$\cos(2\alpha) = 0.5$

$\sin(2\alpha) = 0.866$

$e1 = 0.167$

$e2 = 0.289$

lens = observed

g1 = 0.111

g2 = 0.627

$c = 3$ $e1\_1 = 0.111$

$d = 0.67$ $e2\_1 = 0.627$

$\beta = 40^o$

$\cos(2\beta) = 0.174$

$\sin(2\beta) = 0.985$

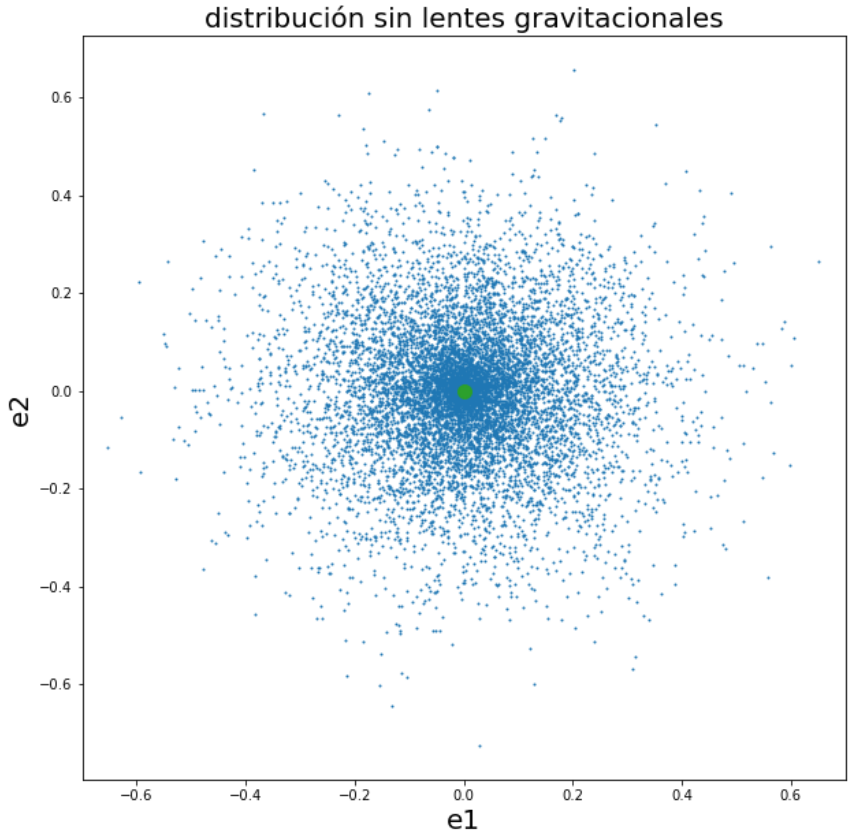
lens = observed - intrinsic

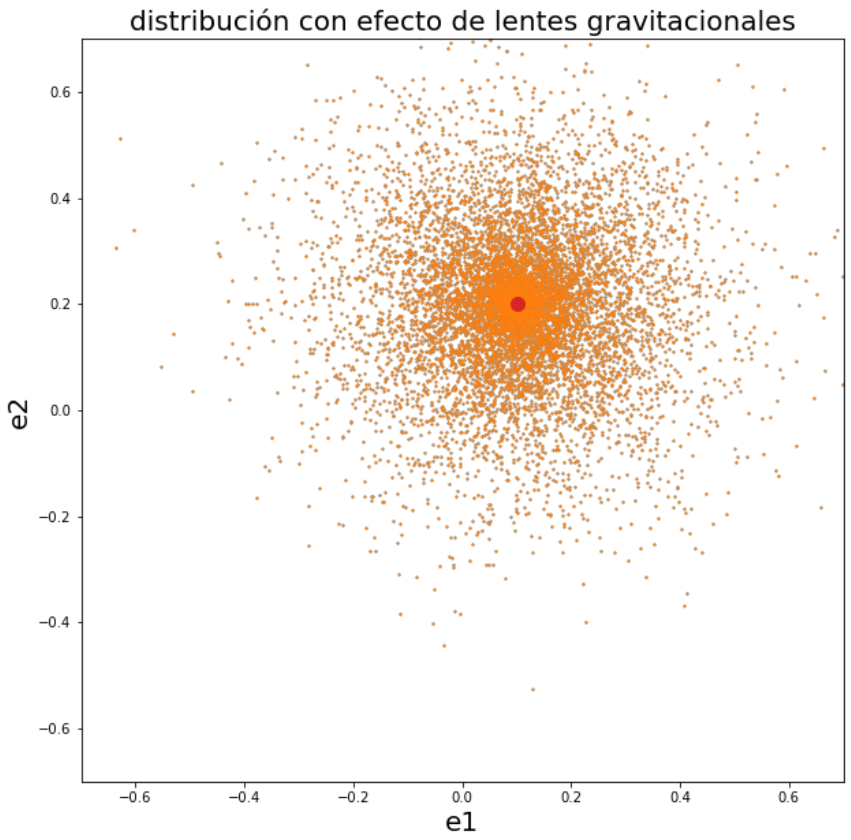
g1 = -0.056

g2 = 0.338

Weak gravitational lensing

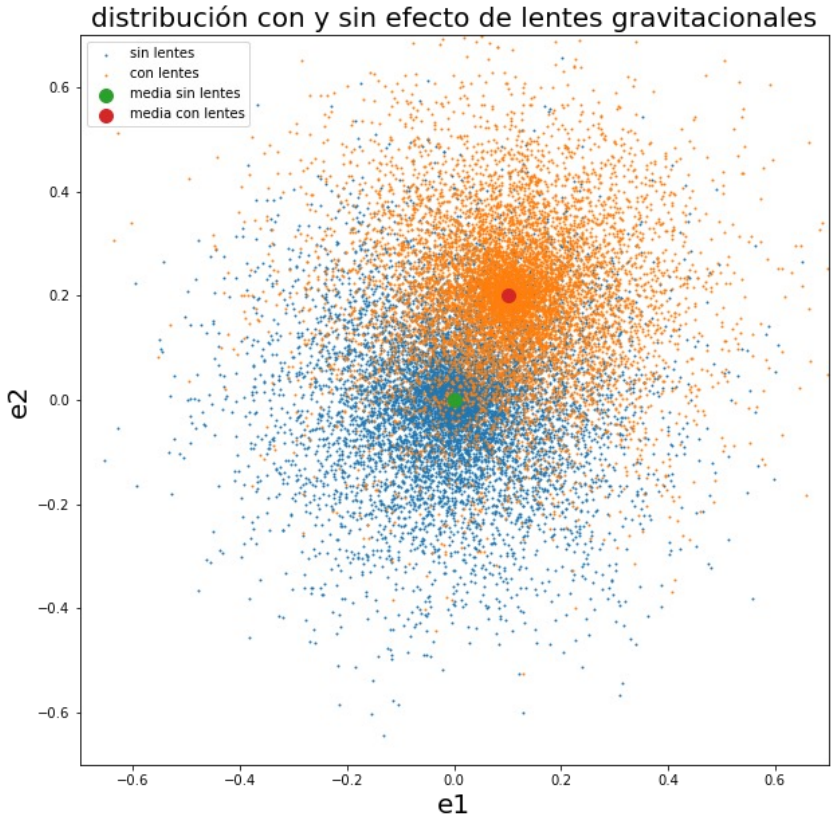
Example 10000 galaxies





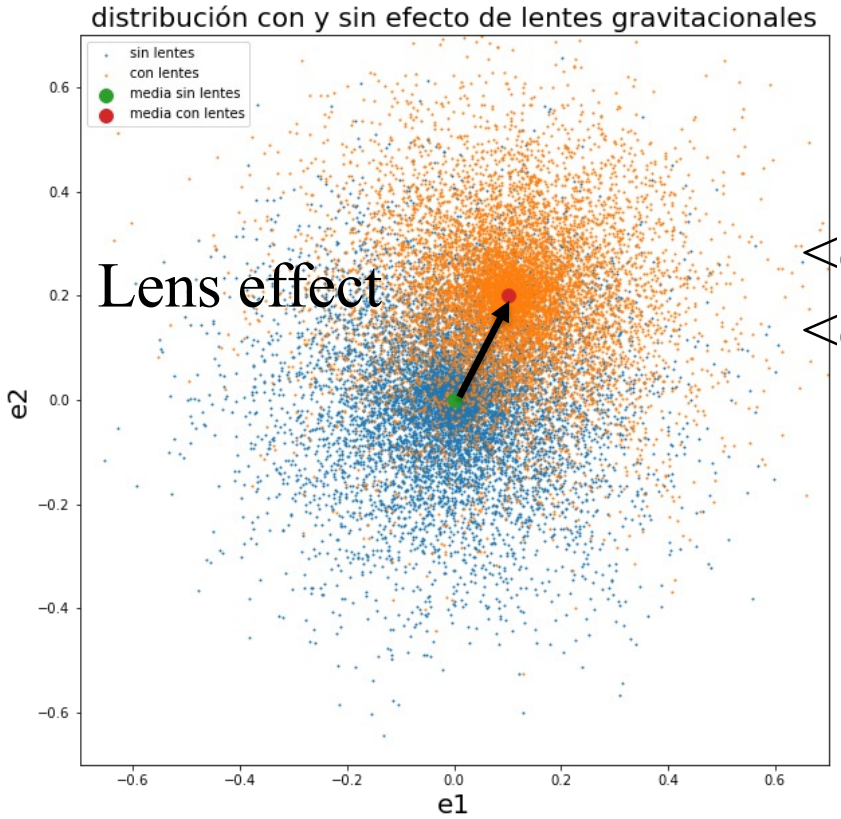
Weak gravitational lensing

Example 10000 galaxies



Weak gravitational lensing

Example 10000 galaxies



$e1 = e1\_s + g1$

$e2 = e2\_s + g2$

$\langle e1 \rangle = \langle e1\_s \rangle + \langle g1 \rangle$

$\langle e2 \rangle = \langle e2\_s \rangle + \langle g2 \rangle$

$\langle e1\_s \rangle = 0$

$\langle e2\_s \rangle = 0$

$\langle e1 \rangle = \langle g1 \rangle$

$\langle e2 \rangle = \langle g2 \rangle$