Lecture 15

The shapes of faint galaxies: A window unto mass in the universe

Intensity weighted second moments

Optimal filtering

Weak gravitational lensing

Shear components

Shear detection

Inverse problem: from shear to mass

Low surface brightness: Looking deeper

- **Light pollution**
  - residual PSF structure near bright stars
  - Scattered light in telescope/camera

    cure: chop by dithering the telescope between images
- **Unresolved galaxies**
  - There are a million galaxies per square degree
  - Differential galaxy counts:

    N(mag) = 17500 dex (B – 24) /mag /sq.deg

    B = blue magnitude
- **Sky nonuniformity**
  - PSF wings and large numbers of faint galaxies merge to create bumpy pseudo-sky

Recursively cleaning the sky

Bayesian method:

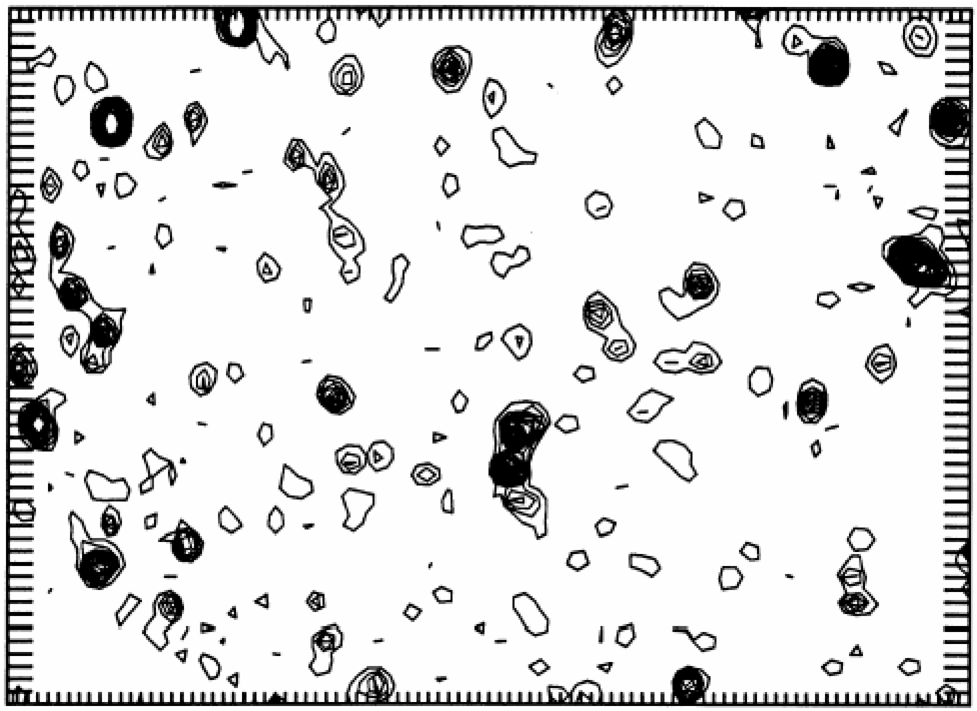
- Find PSF vs position and galaxy shape parameters for each object
- Model and subtract all detected galaxies and stars
- Start with brightest objects
- *ITERATE*

Unbiased method:

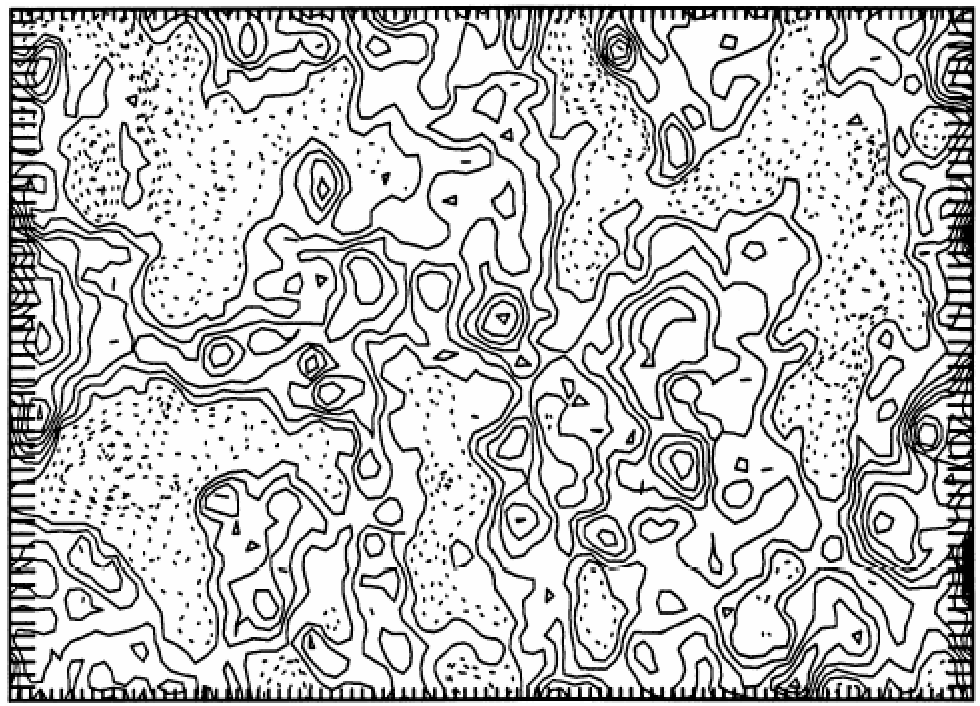
- Use FOCAS or Sextractor detection isophotes to subtract flux of detected "objects"
- No priors
- Noisier but useful for finding the unexpected

Recursive image cleaning: no priors

Collect data by shift-and-stare method: chop. De-fringe and flat-field each of these many sky-limited exposures using a super sky flat formed from hundreds of images in that band. Register the images and co-add via median averaging. Only objects common to all exposures survive. Detect all objects down to 5 sigma of sky noise with FOCAS and then subtract their smoothed flux. Smooth image on several pixel scale and repeat detection and subtraction.

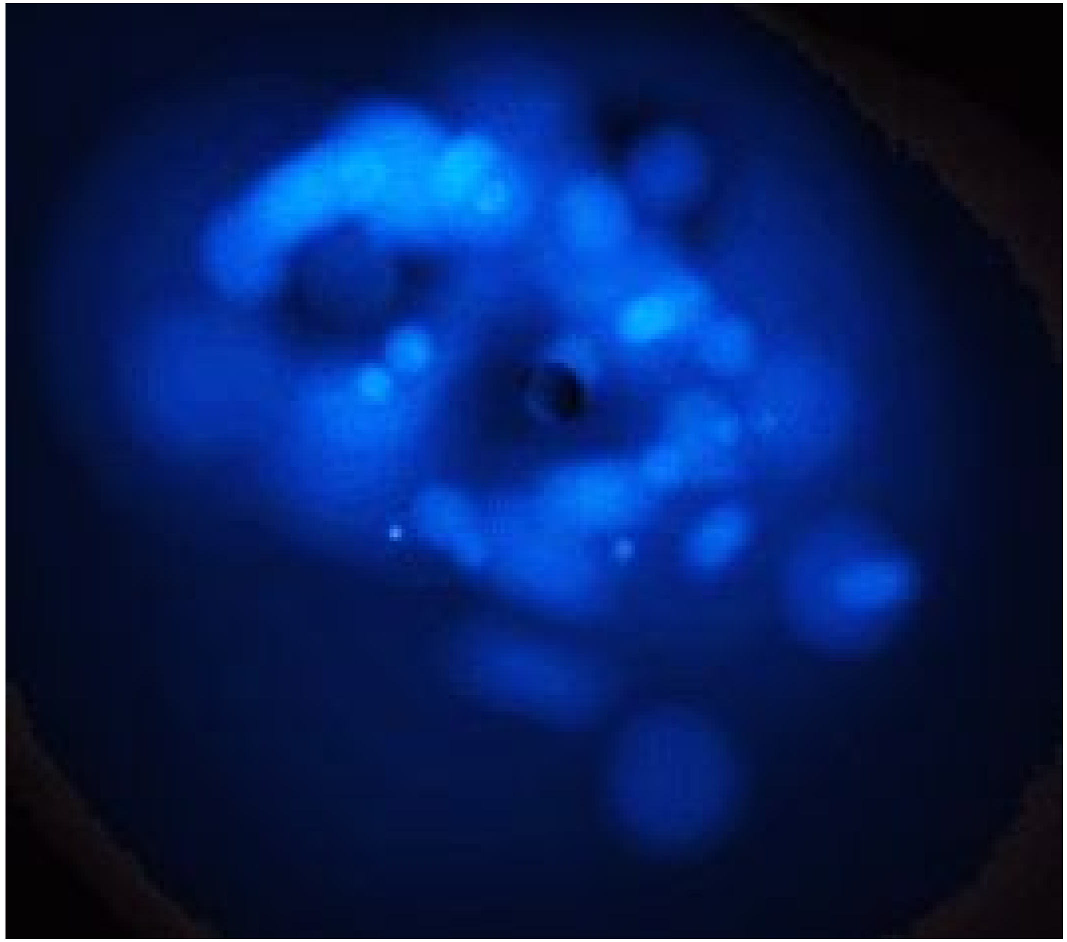


CCD field 0427 20,000 sec

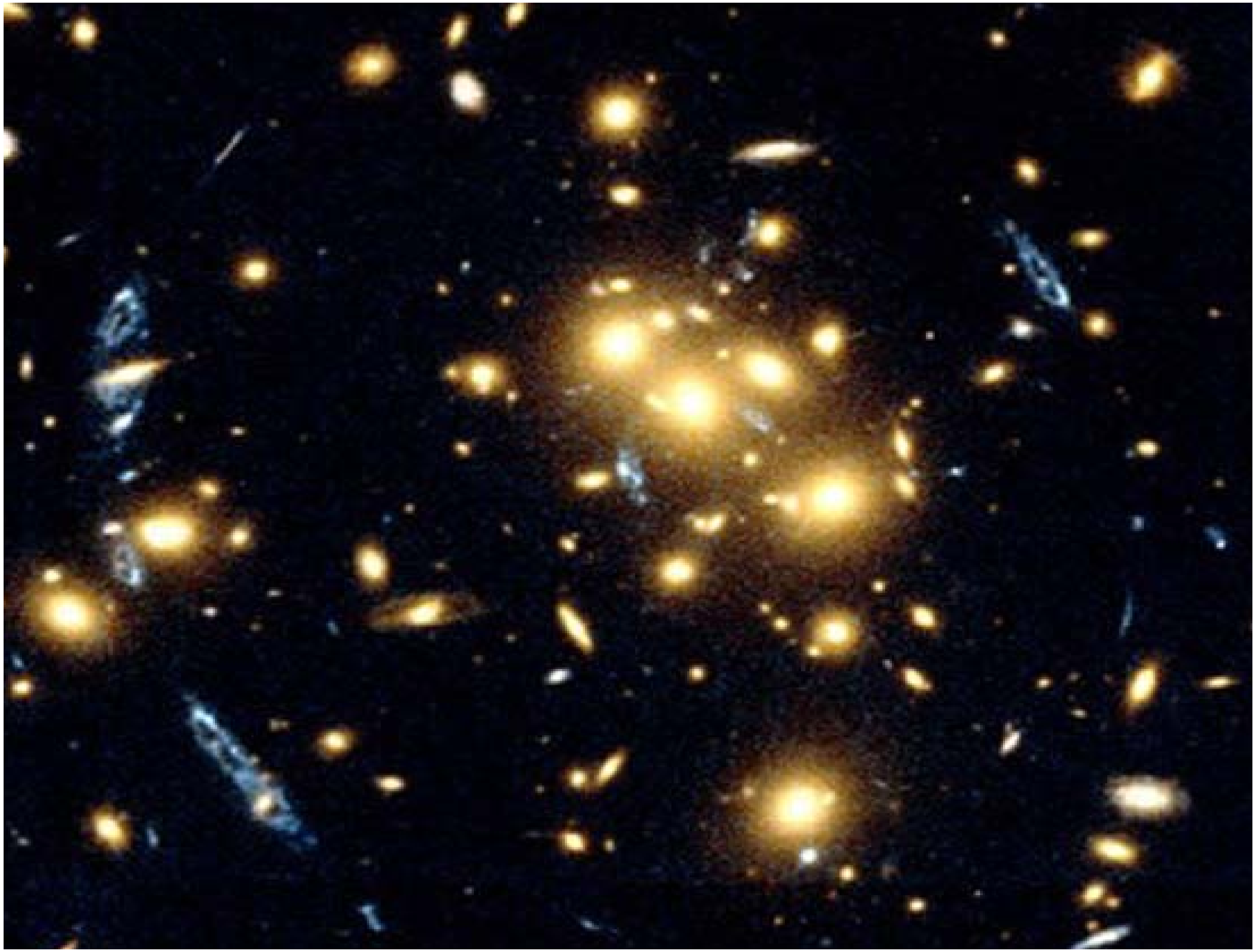


Cleaned to 32 mag/sq.arcsec

Galaxy 12 billion light-years distant

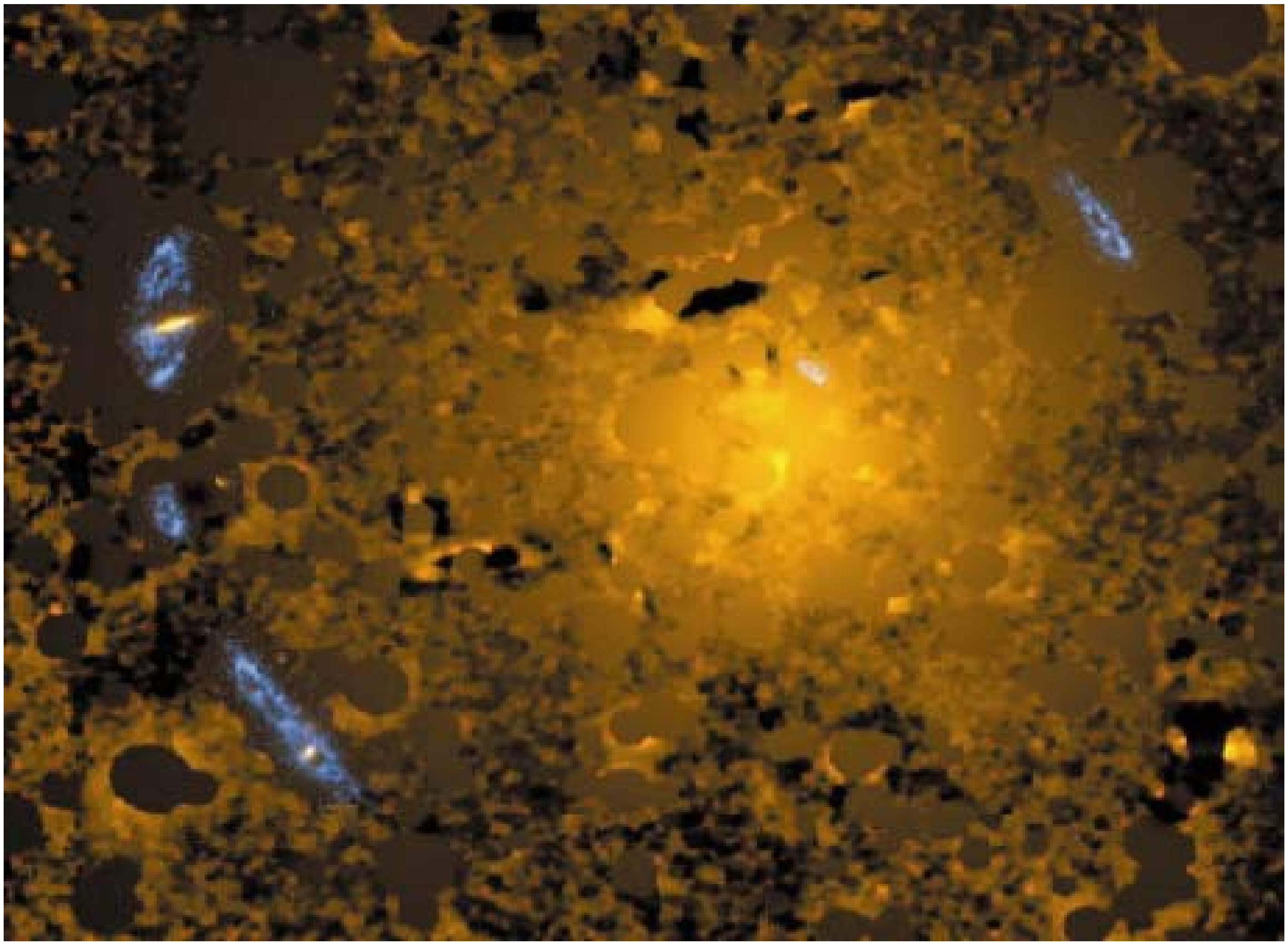


30-orbit HST image of cluster at z=0.4



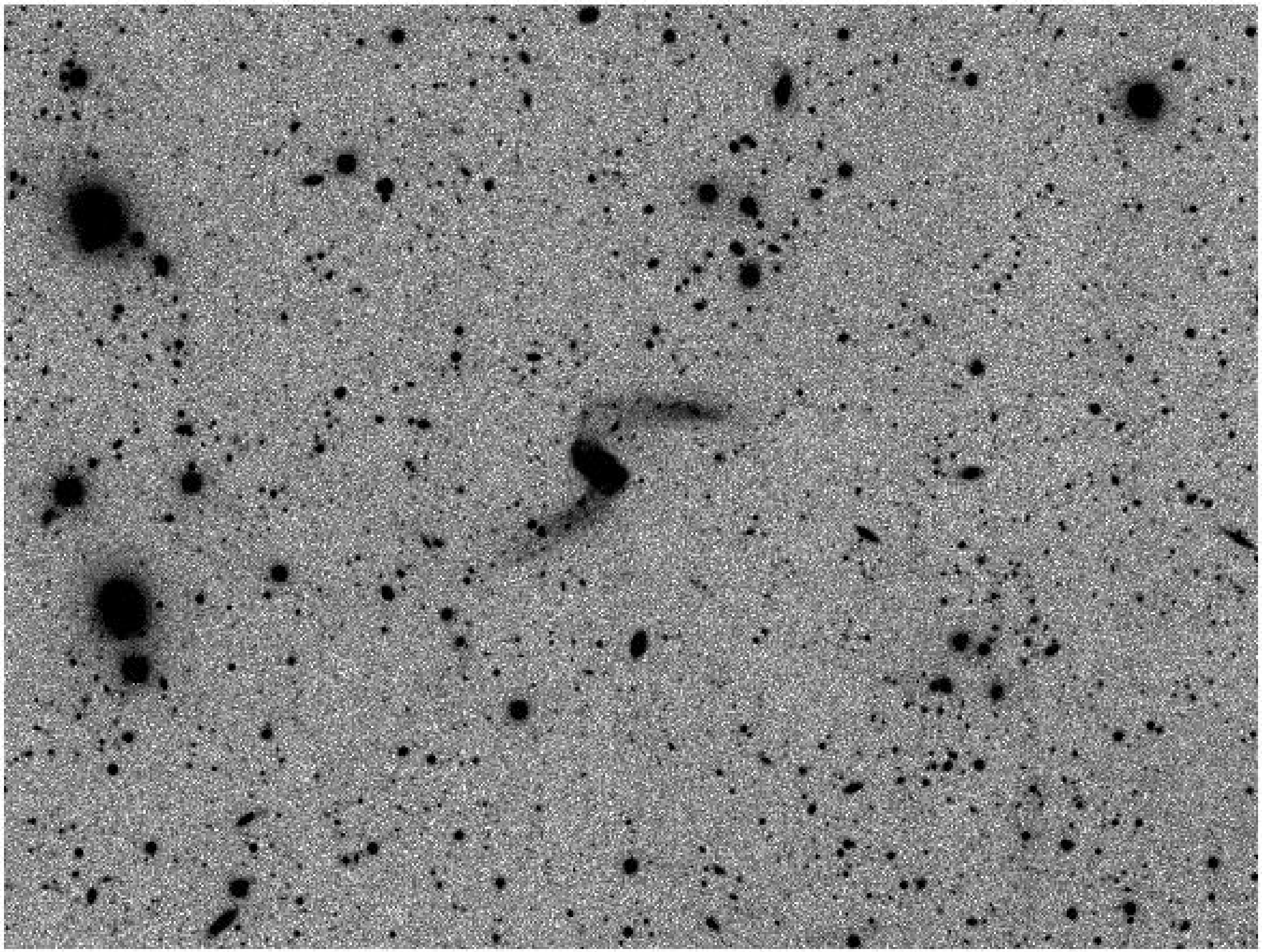
Yellow: residual light after cleaning galaxies

Recursive image cleaning <u>with</u> priors: galaxy morphology templates



Discovery:
12% of the optical light in the cluster is in a diffuse distribution similar to the dark matter!

Ultradeep optical imaging



DLS image stack from 20 shift-and-stare 900 sec exposures

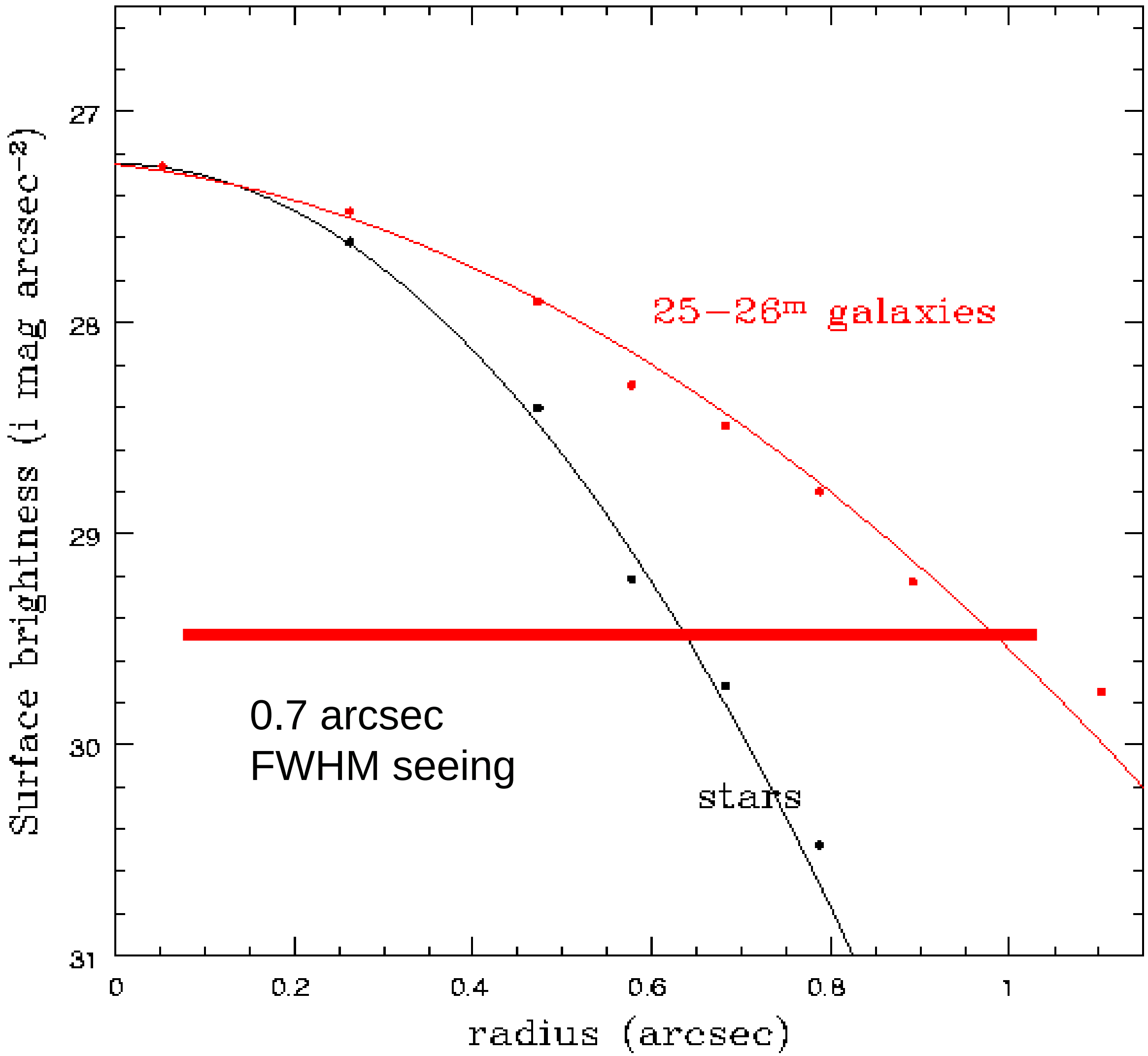
Goal: increase the number density of faint galaxies used for weak lens shear.

We cannot do photometry on objects we cannot detect!

First step: clean the sky. Sky artifacts + detected galaxies.

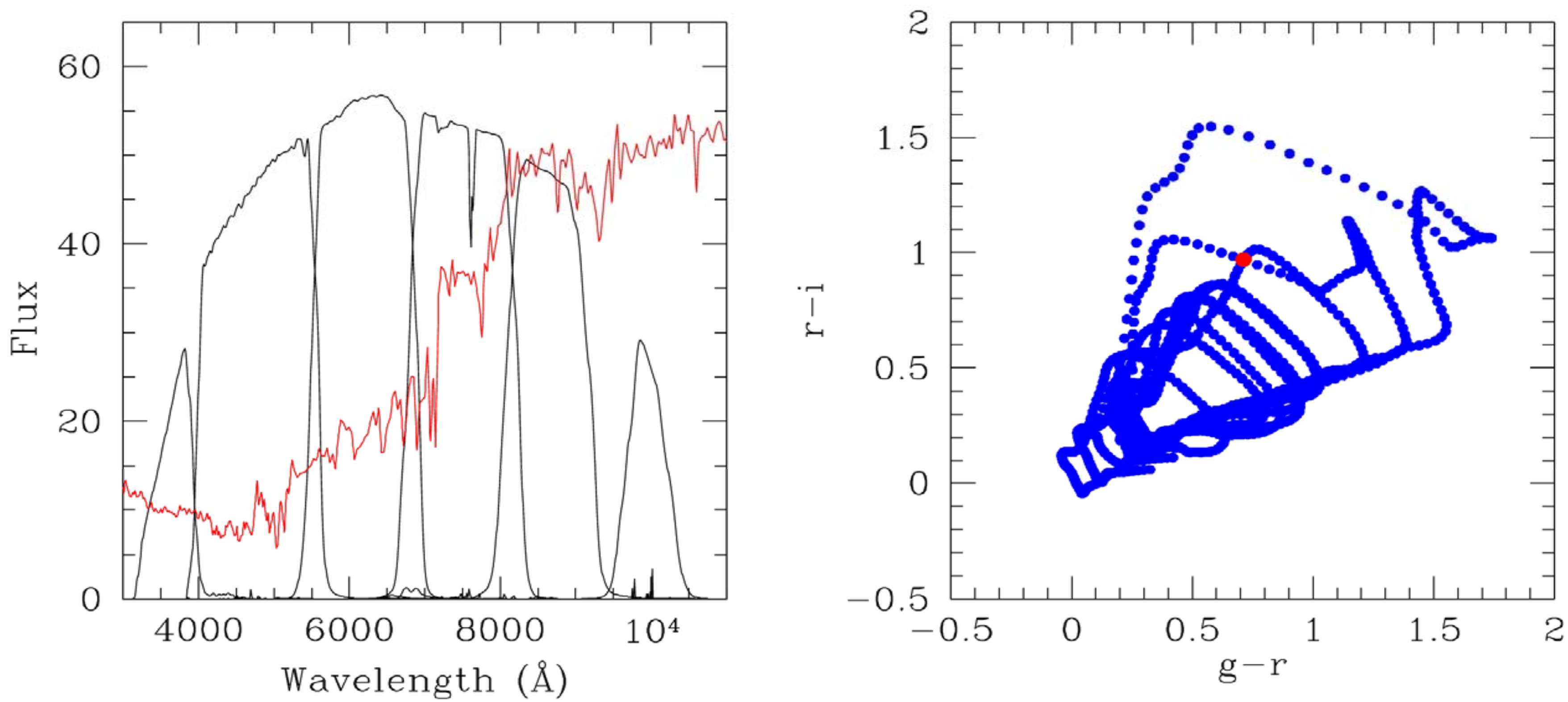
Second step:
What priors on the undetected faint lensed background galaxies can we use to increase the S/N ratio in weak lens shear maps?

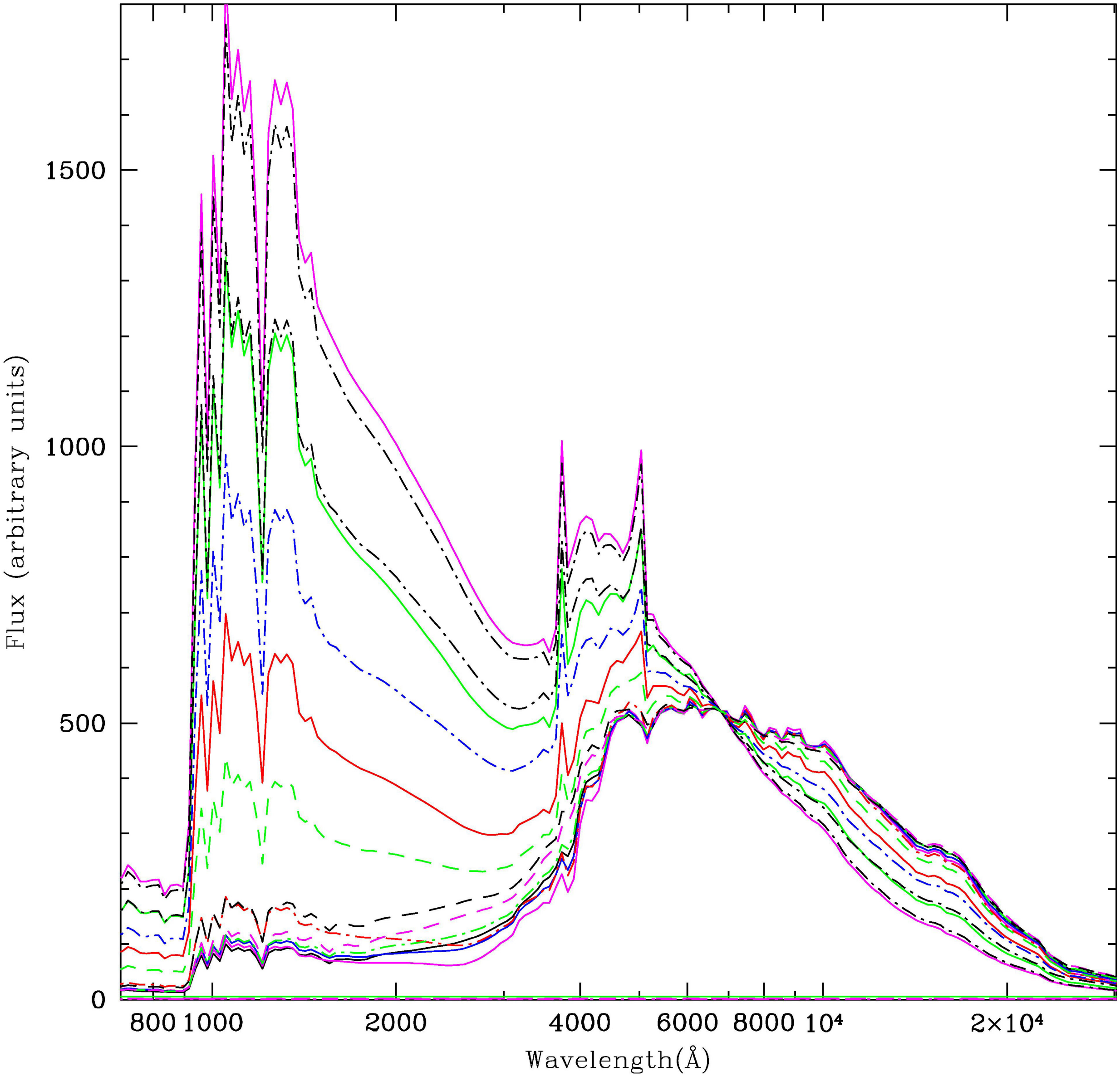
Surface brightness profile of galaxies used for weak lensing with LSST



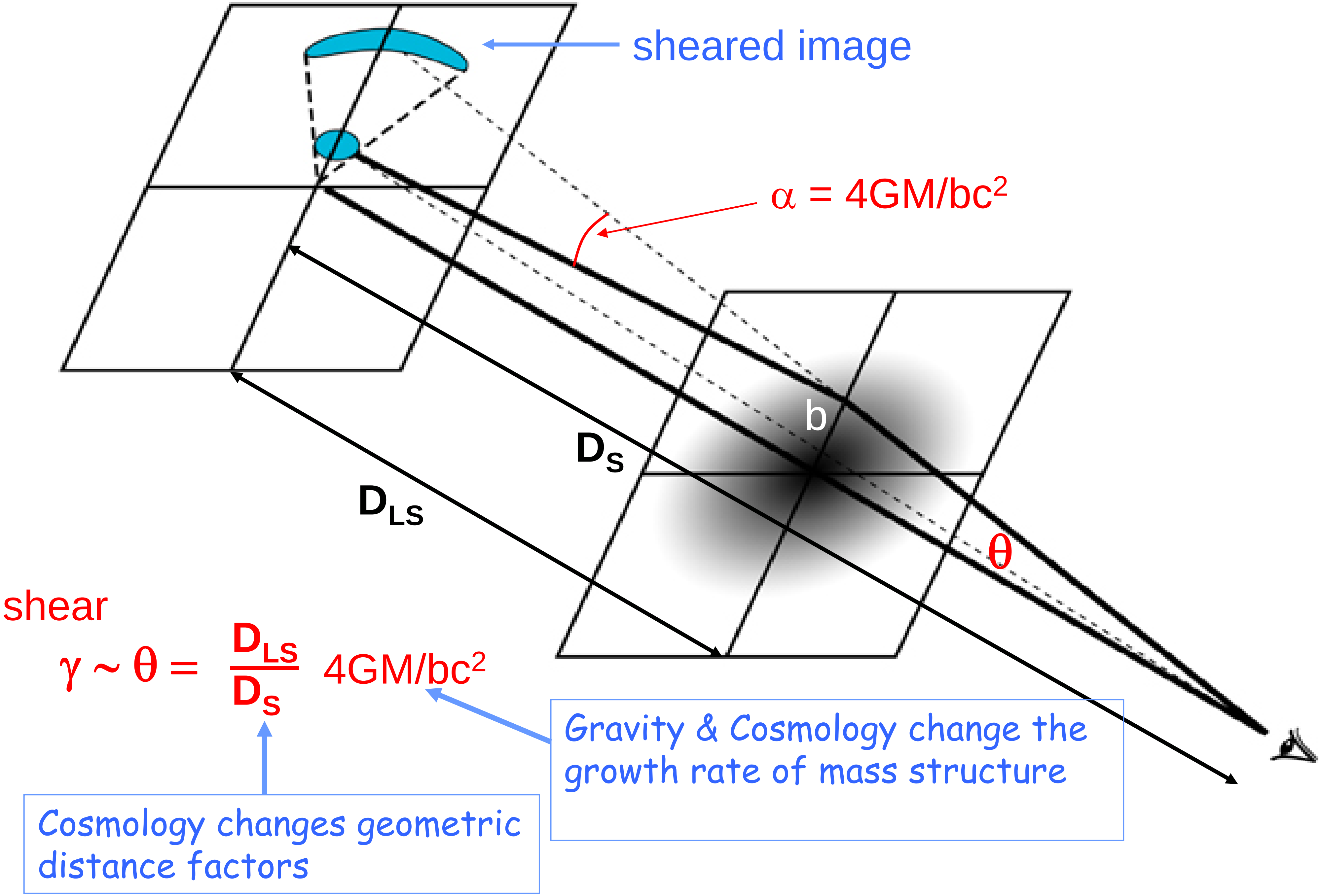
From HST ACS data

Photometric Redshifts

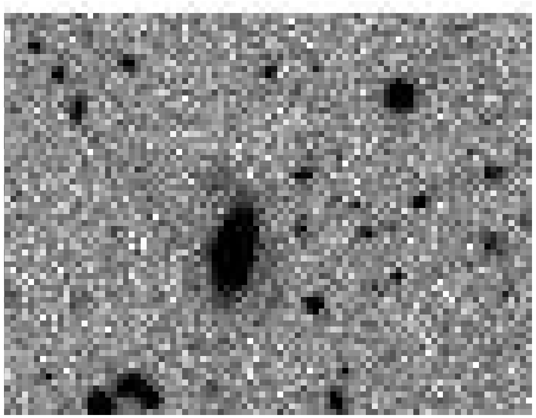




Flux (arbitrary units)
1500
1000
500
0
800
1000
2000
4000
6000
8000
10^4
2×10^4
Wavelength(Å)


sheared image
α = 4GM/bc²
b
θ
D_S
D_{LS}
shear
$\gamma \sim \theta = \frac{D_{LS}}{D_S}\, 4GM/bc^2$
Gravity & Cosmology change the growth rate of mass structure
Cosmology changes geometric distance factors

Galaxy shape parameters: filtered second moments of intensity



$$\sigma_x^2 \sim \sum_{x,y} (D_{xy} - \mathrm{sky})(x - x_0)^2 g(x,y)$$

$$\sigma_y^2 \sim \sum_{x,y} (D_{xy} - \mathrm{sky})(y - y_0)^2 g(x,y)$$

$$\sigma_{xy} \sim \sum_{x,y} (D_{xy} - \mathrm{sky})(x - x_0)(y - y_0) g(x,y)$$

Signal-matched filter:

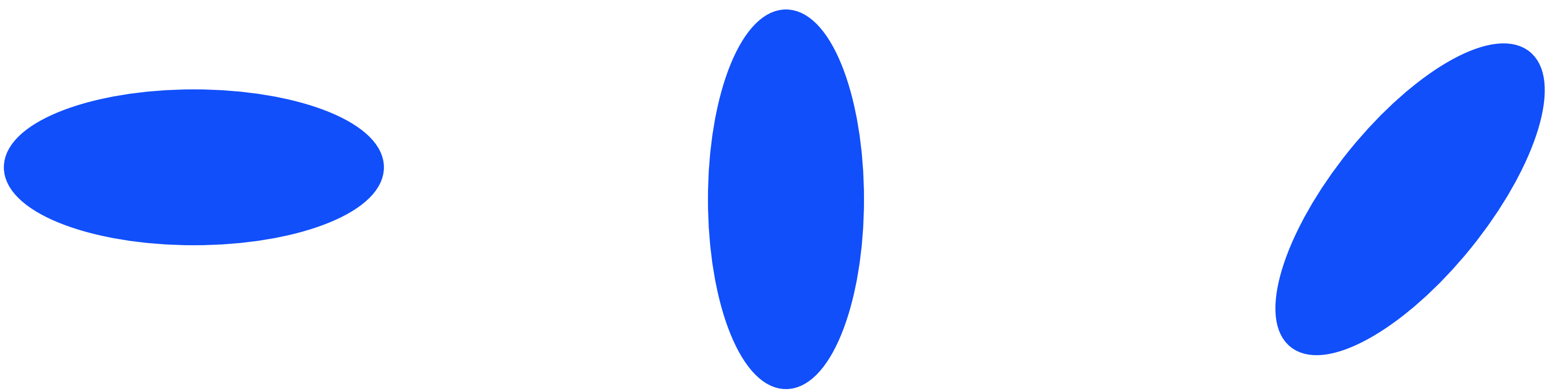
g(x,y) = galaxy profile

Galaxy shape parameters: normalized filtered second moments of intensity

$$I_{xx} = [\sum_{x,y} (D_{xy} - sky)(x - x_0)^2 g(x,y)] \;/\; [\sum_{x,y} (D_{xy} - sky)\; g(x,y)]$$

$$I_{yy} = [\sum_{x,y} (D_{xy} - sky)(y - y_0)^2 g(x,y)] \;/\; [\sum_{x,y} (D_{xy} - sky)\; g(x,y)]$$

$$I_{xy} = [\sum_{x,y} (D_{xy} - sky)(x - x_0)(y - y_0) g(x,y)] \;/\; [\sum_{x,y} (D_{xy} - sky)\; g(x,y)]$$



Ellipticity components:

e_1 = Ixx-Iyy / Ixx+Iyy $\qquad$ e_2 = 2Ixy / Ixx+Iyy

Gravitational lens mapping

$$(x_S, y_S) = (x_I, y_I) - \nabla\phi(x_I, y_I) \qquad \nabla^2\phi = 2(\Sigma/\Sigma_{crit}) = 2\,\kappa$$

Magnification: $$A^{-1} \equiv \frac{\partial(x_S, y_S)}{\partial(x_I, y_I)} \equiv \begin{pmatrix} 1-\kappa-\lambda & -\mu \\ -\mu & 1-\kappa+\lambda \end{pmatrix}$$

$$\lambda = \frac{1}{2}\left(\frac{\partial^2\phi}{\partial^2 x_I} - \frac{\partial^2\phi}{\partial^2 y_I}\right), \qquad \mu = \frac{\partial^2\phi}{\partial x_I \,\partial y_I}$$

Principle axis rotation:

$$A^{-1} = \begin{pmatrix} 1-\kappa-\gamma & 0 \\ 0 & 1-\kappa+\gamma \end{pmatrix} \qquad \lambda = \gamma\cos(2\beta), \text{ and } \mu = \gamma\sin(2\beta)$$

"Stretching factor" is the ratio of the two eigenvalues:

$$(1-g)/(1+g), \quad g = \gamma/(1-\kappa).$$

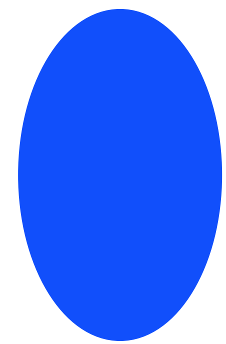
Shear γ from source ellipticity

"Stretching factor" is the ratio of the two eigenvalues:

$$(1-g)/(1+g), \qquad g = \gamma/(1-\kappa).$$

ellipticity: $\varepsilon = 1 - (1-g)/(1+g),$

$$\varepsilon / 2 = \gamma/(1-\kappa)$$



$\varepsilon > 0$

Weak Lens limit: $\varepsilon = 2\gamma$

Center on lens mass and then look at radial and tangential shear components: x,y to r,θ principal axis transform

$$I_{\theta\theta} - I_{rr} \;/\; I_{\theta\theta} + I_{rr} = 2\gamma / (1-\kappa)$$

κ = normalized projected 2-d mass density

Consider the average tangential component of the shear around circle C:

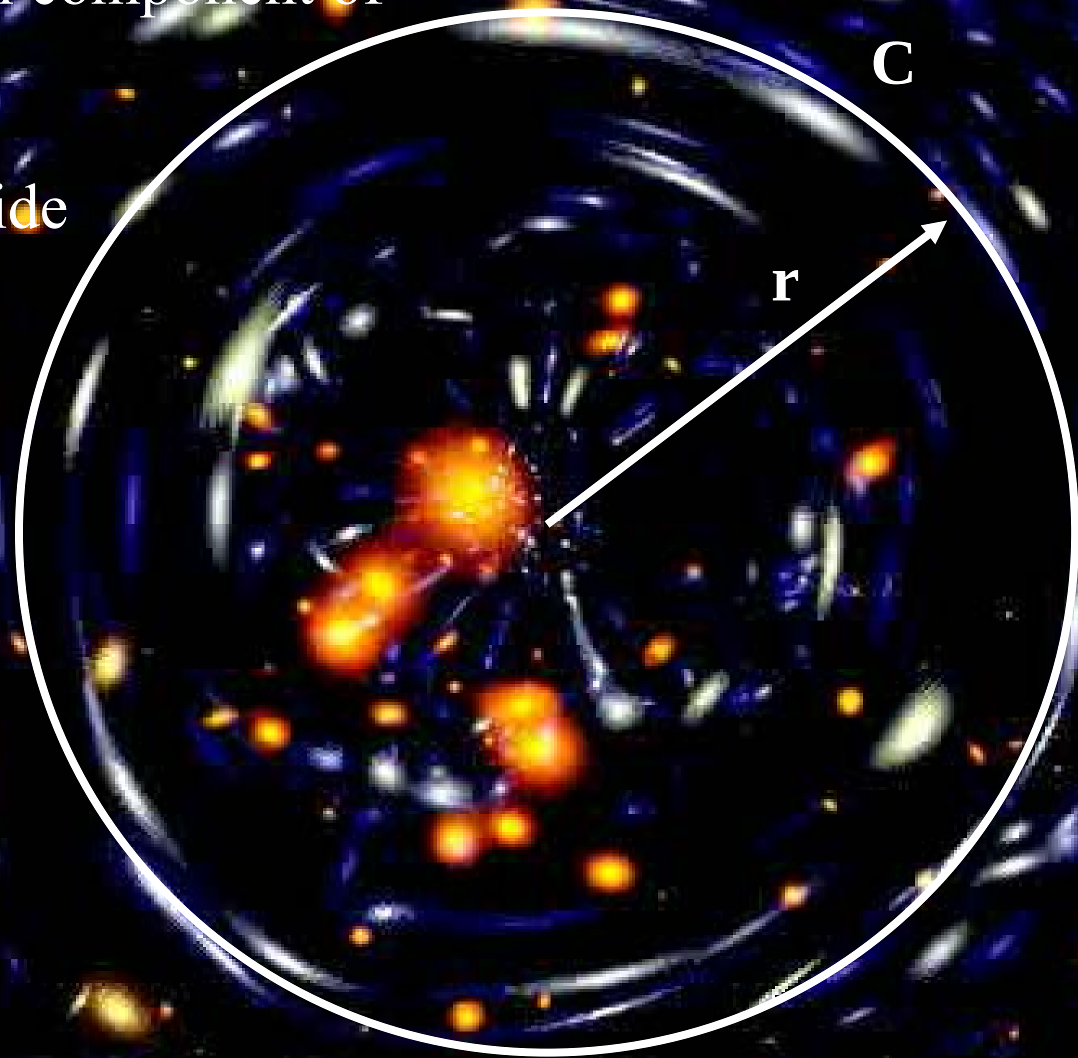
Contribution due to mass inside the circle:

$$\lambda_t^C = \bar{\kappa}$$

But shear from a uniform sheet is zero, so:

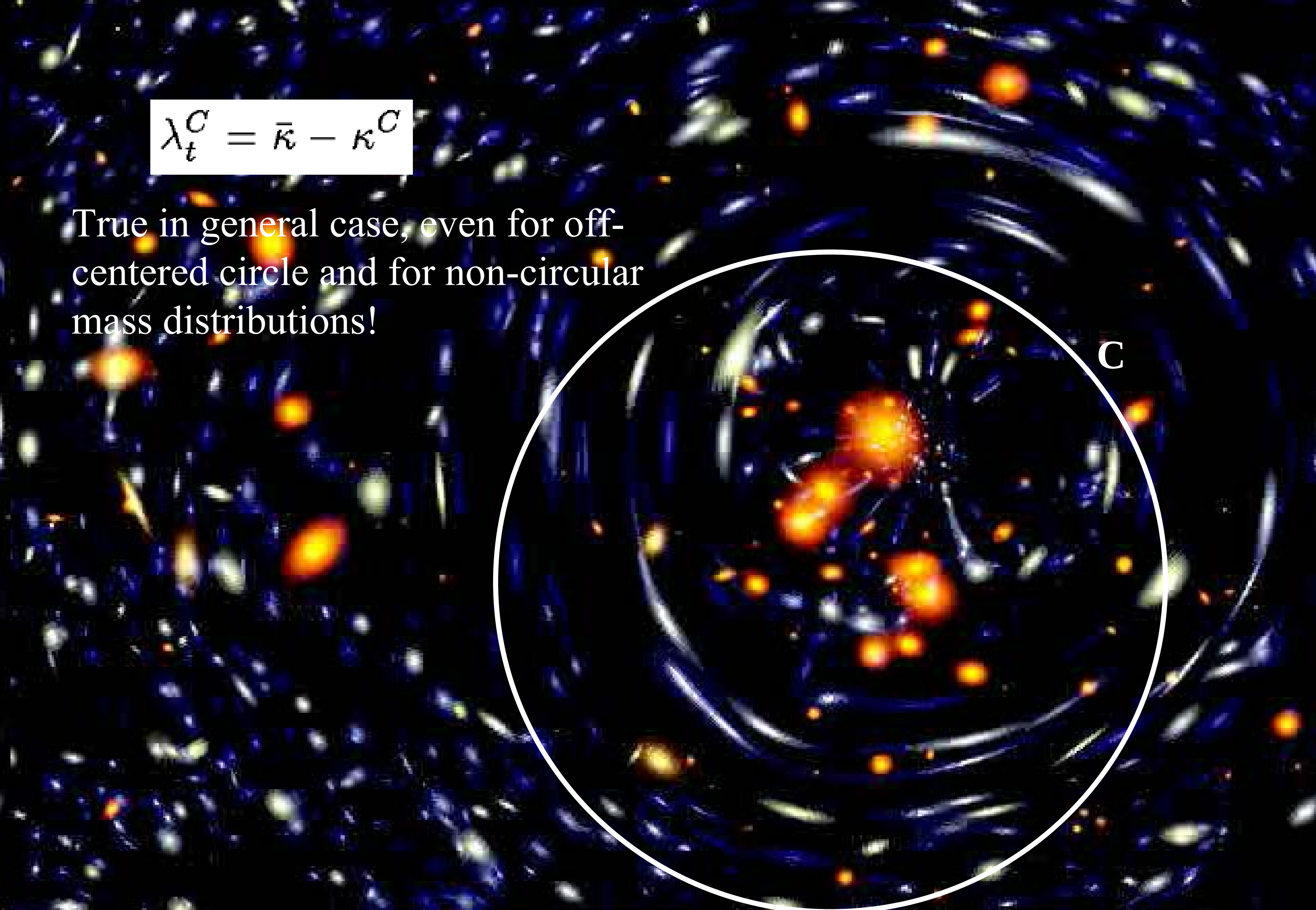
$$\lambda_t^C = \bar{\kappa} - \kappa^C$$

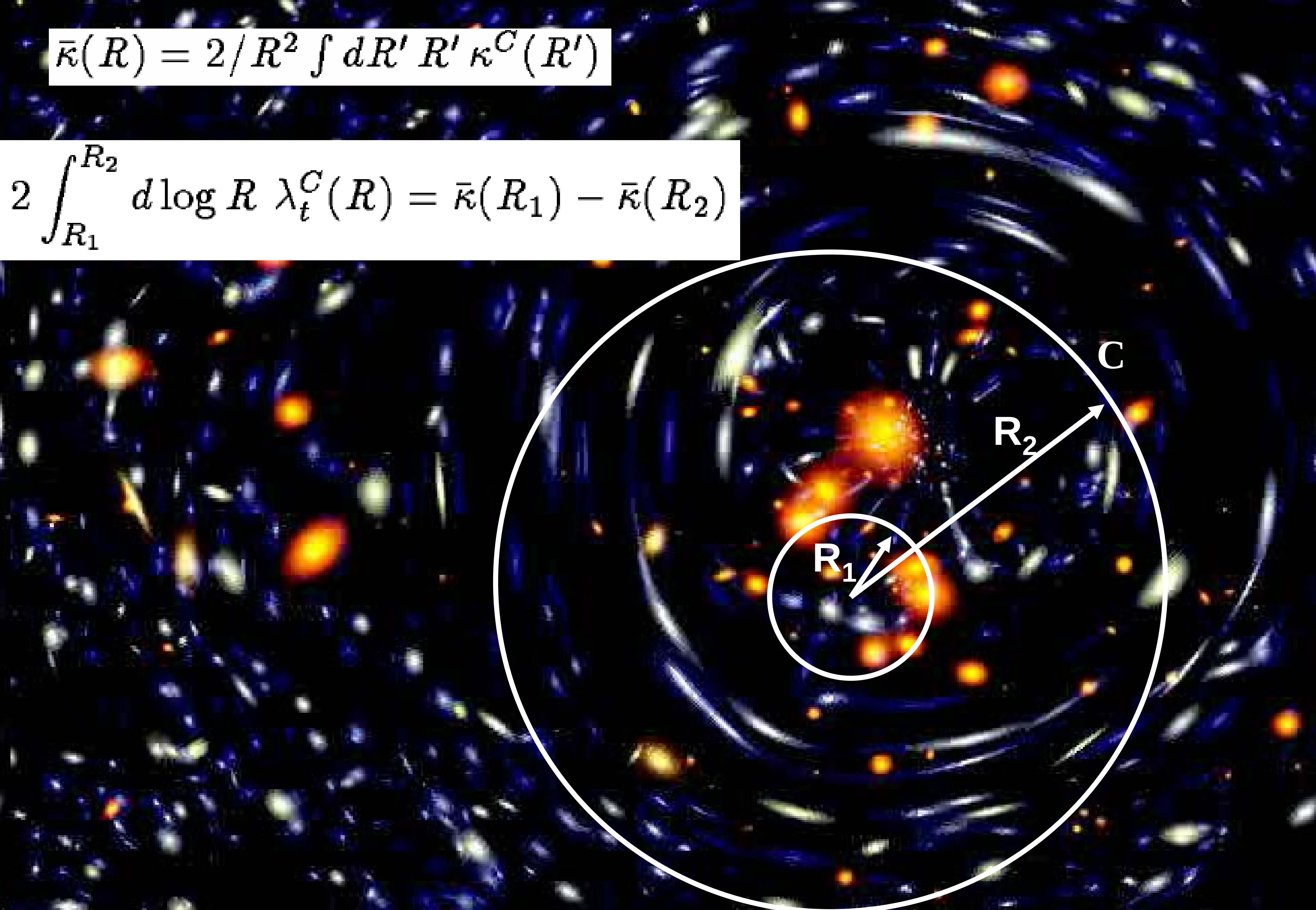
Where: $\lambda_t^C = \gamma(r)$



$$\lambda_t^C = \bar{\kappa} - \kappa^C$$

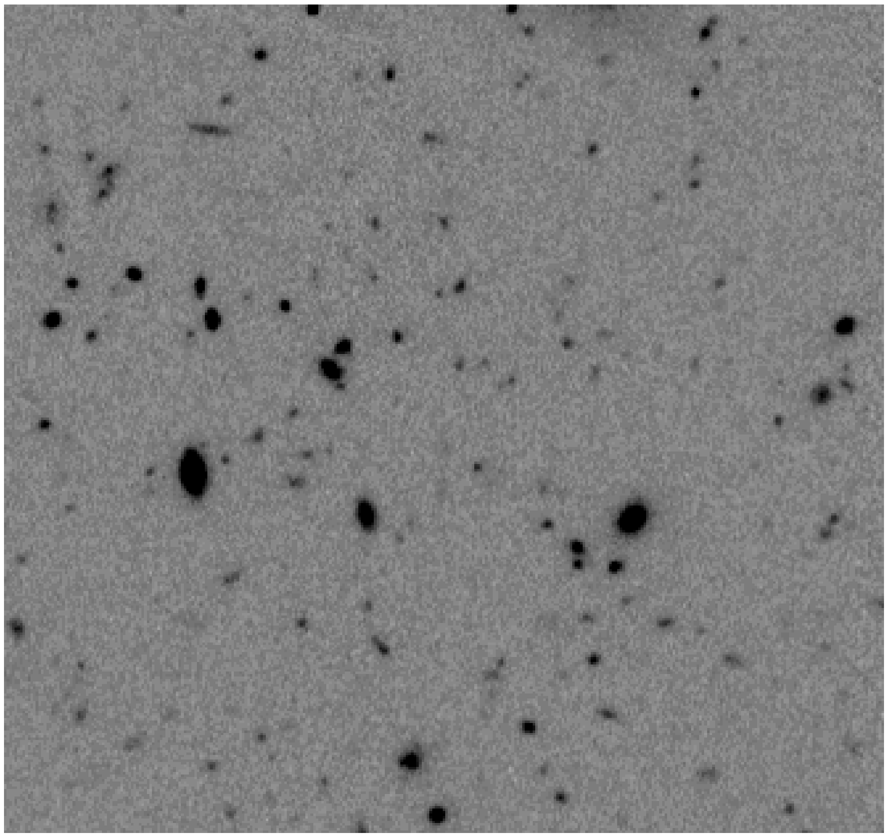
True in general case, even for off-centered circle and for non-circular mass distributions!





$\bar{\kappa}(R) = 2/R^2 \int dR' \, R' \, \kappa^C(R')$
$2 \int_{R_1}^{R_2} d \log R \; \lambda_t^C(R) = \bar{\kappa}(R_1) - \bar{\kappa}(R_2)$
C
R_2
R_1

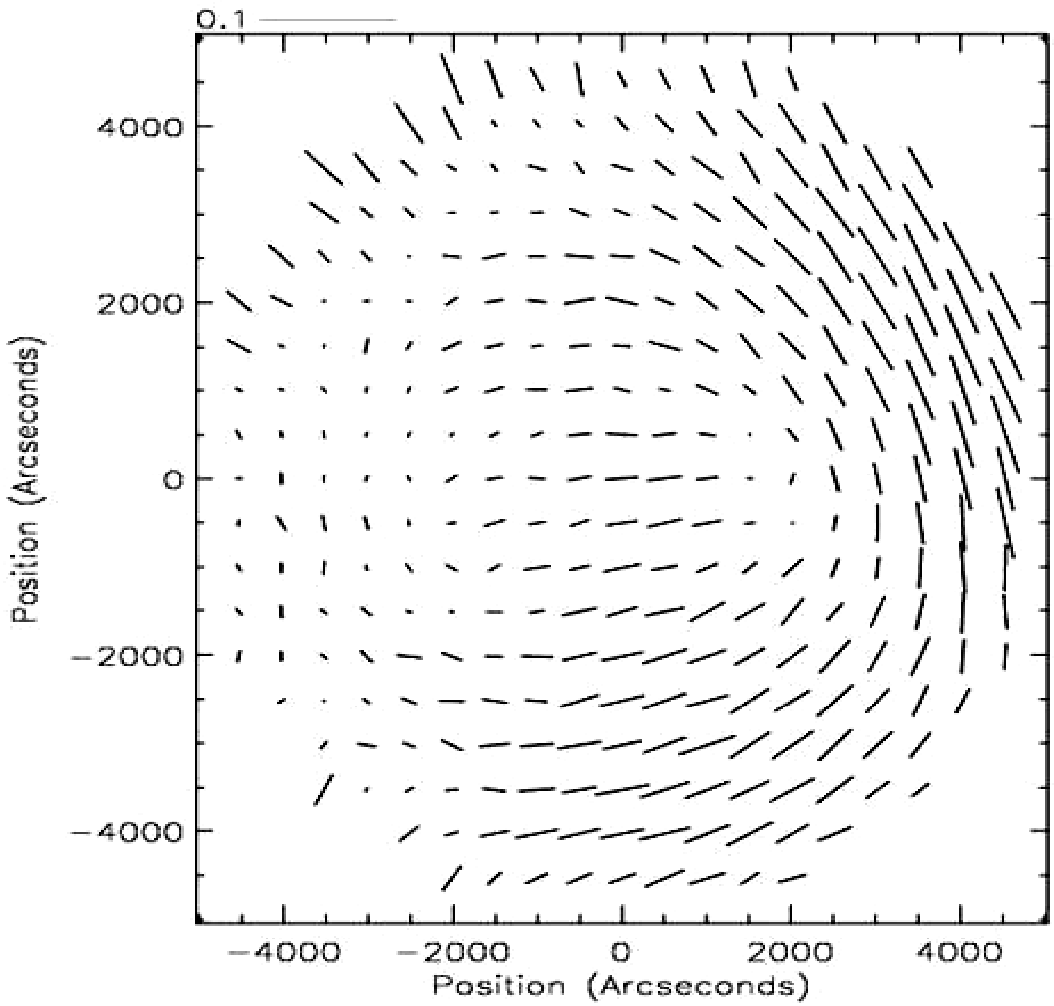
Statistical Weak Lensing: overcoming galaxy shape shot noise



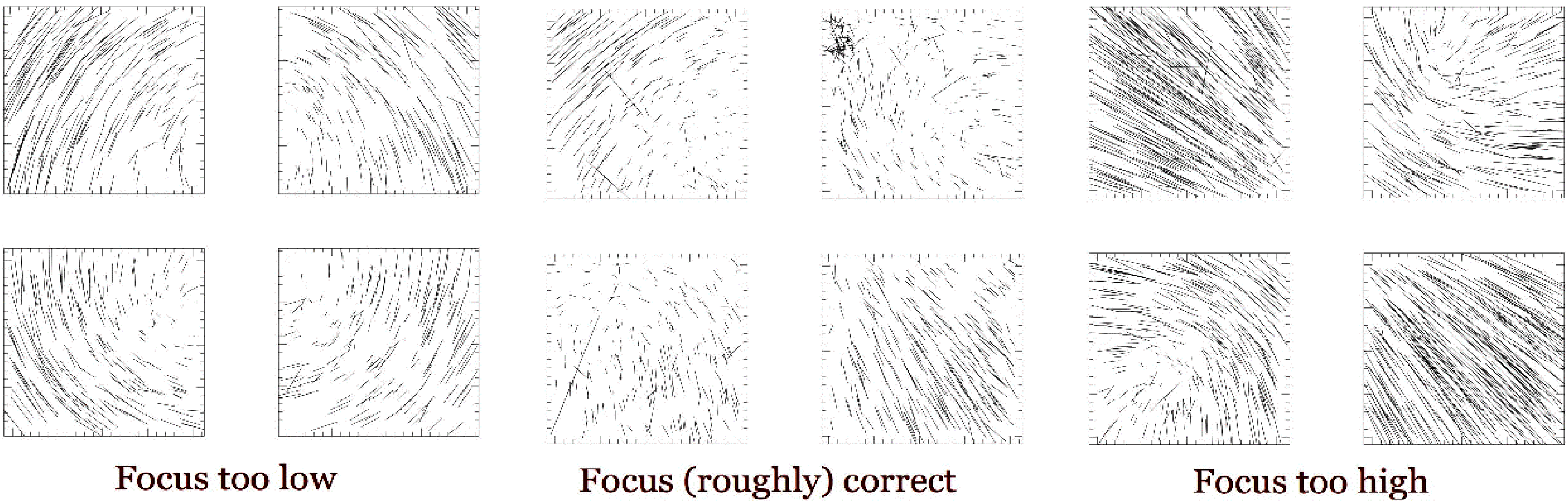
Each source galaxy is prepared differently and has its own intrinsic ellipticity, before its image is lens distorted! So the source galaxy population has an intrinsic ellipticity distribution but averages out to zero over large areas. Rms ellipticity = 0.3

But we need to get ellipticity noise down to 0.003 on ten arcminute angular scales. -> average 10,000 galaxies.

Optics distortion



PSF orientation vs focus

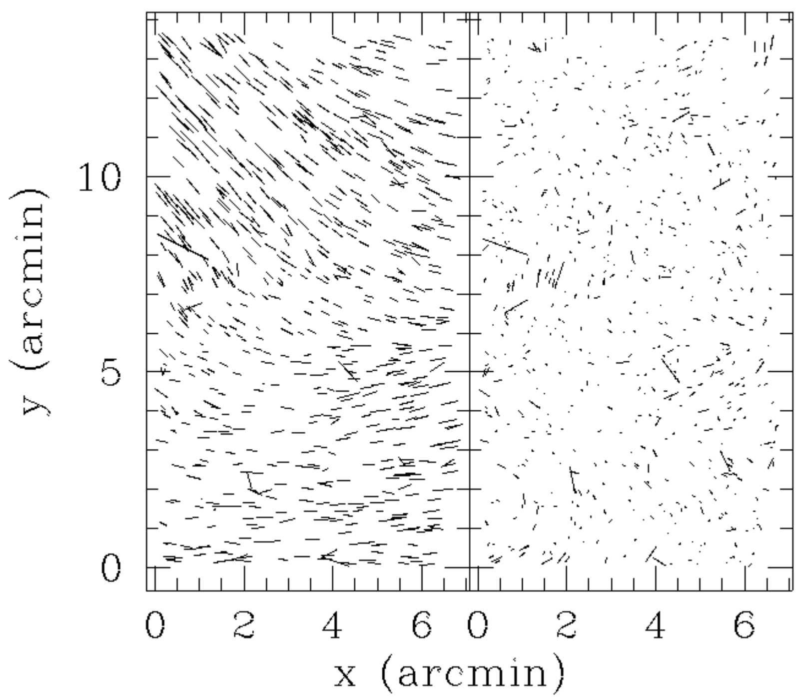


Systematic error #1: PSF ellipticity

Use foreground stars to define the PSF everywhere in the image. Then form the inverse transform (as a function of position in the image) which makes the stars round. i.e. convolve the image with this "rounding" matrix. Need enough unsaturated stars per square arcminute to fit a good PSF model.

Star shapes before

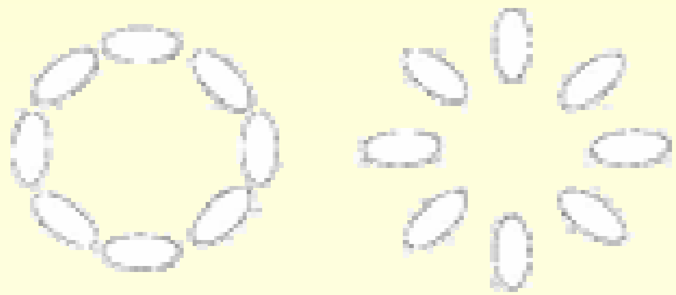
Convolution with rounding filter



E and B modes

The shear is a spin-2 field and consequently we can measure two independent ellipticity correlation functions. The lensing signal is caused by a gravitational potential and therefore should be curl-free. We can project the correlation functions into one that measures the divergence and one that measures the curl: E-B mode decomposition.

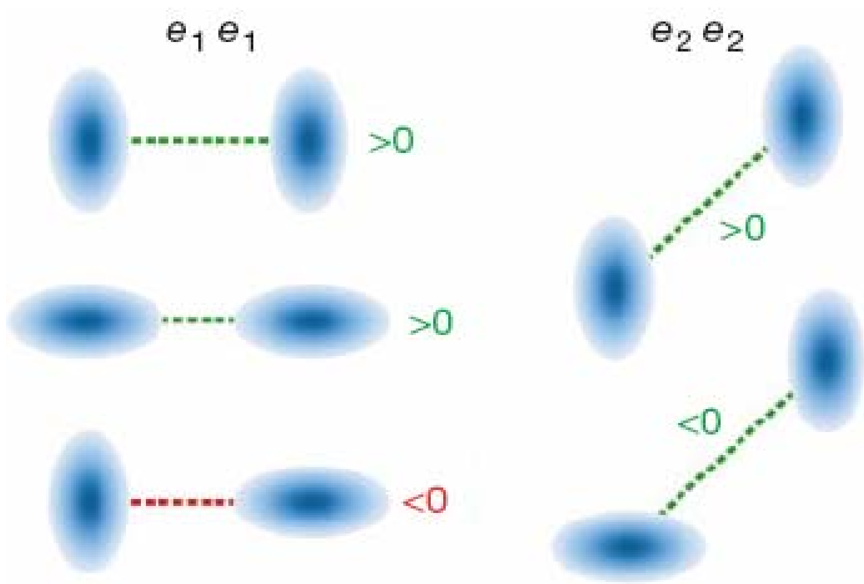
E-mode (curl-free)



B-mode (curl)

Ellipticity correlations between galaxies

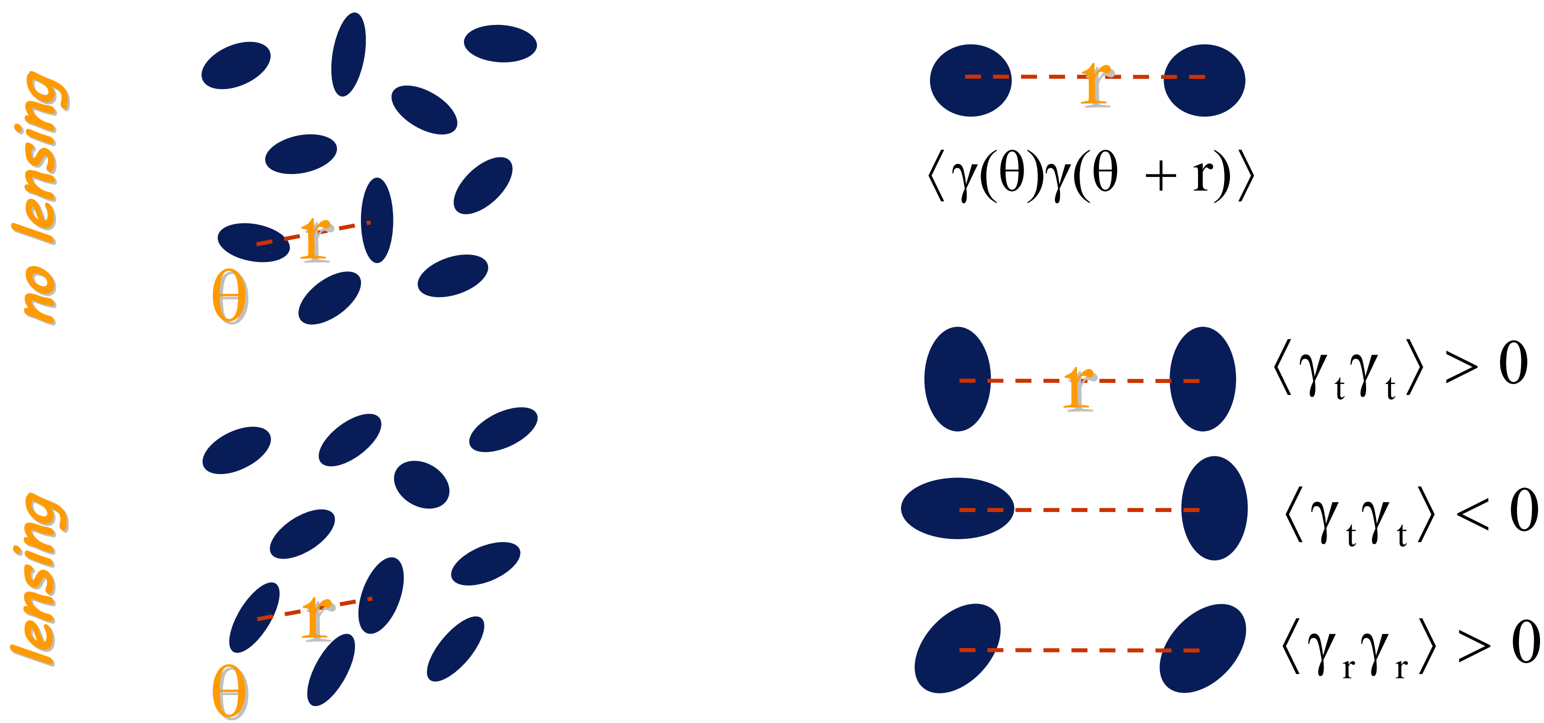
The shape of a star or galaxy can be described by its second central moments, $I_{xx} = \Sigma I w x^2$, $I_{yy} = \Sigma I w y^2$ and $I_{xy} = \Sigma I w xy$, where $I(x,y)$ is the intensity distribution above the night sky level, $w(x,y)$ is a weight function, the sum is over a contiguous set of pixels defined as belonging to the galaxy, and the coordinate system has been translated so that the first moments vanish. The second moments can be combined to form a size, $I_{xx} + I_{yy}$, and two components of a pseudo-vector ellipticity, $e_1 = (I_{xx} - I_{yy})/(I_{xx} + I_{yy})$ and $e_2 = 2I_{xy}/(I_{xx} + I_{yy})$, which vary in the range $[-1,1]$ (ellipticity in its colloquial sense is the amplitude of this pseudo-vector, $\epsilon = (e_1^2 + e_2^2)^{1/2}$ with its range $[0,1]$). Traditional intensity-weighted moments are calculated with $w = 1$, but this produces ellipticity measurements with noise properties that are far from optimal—or even divergent. In cases of white noise, the formal optimal weight for an elliptical source is a noise-free image of that elliptical source



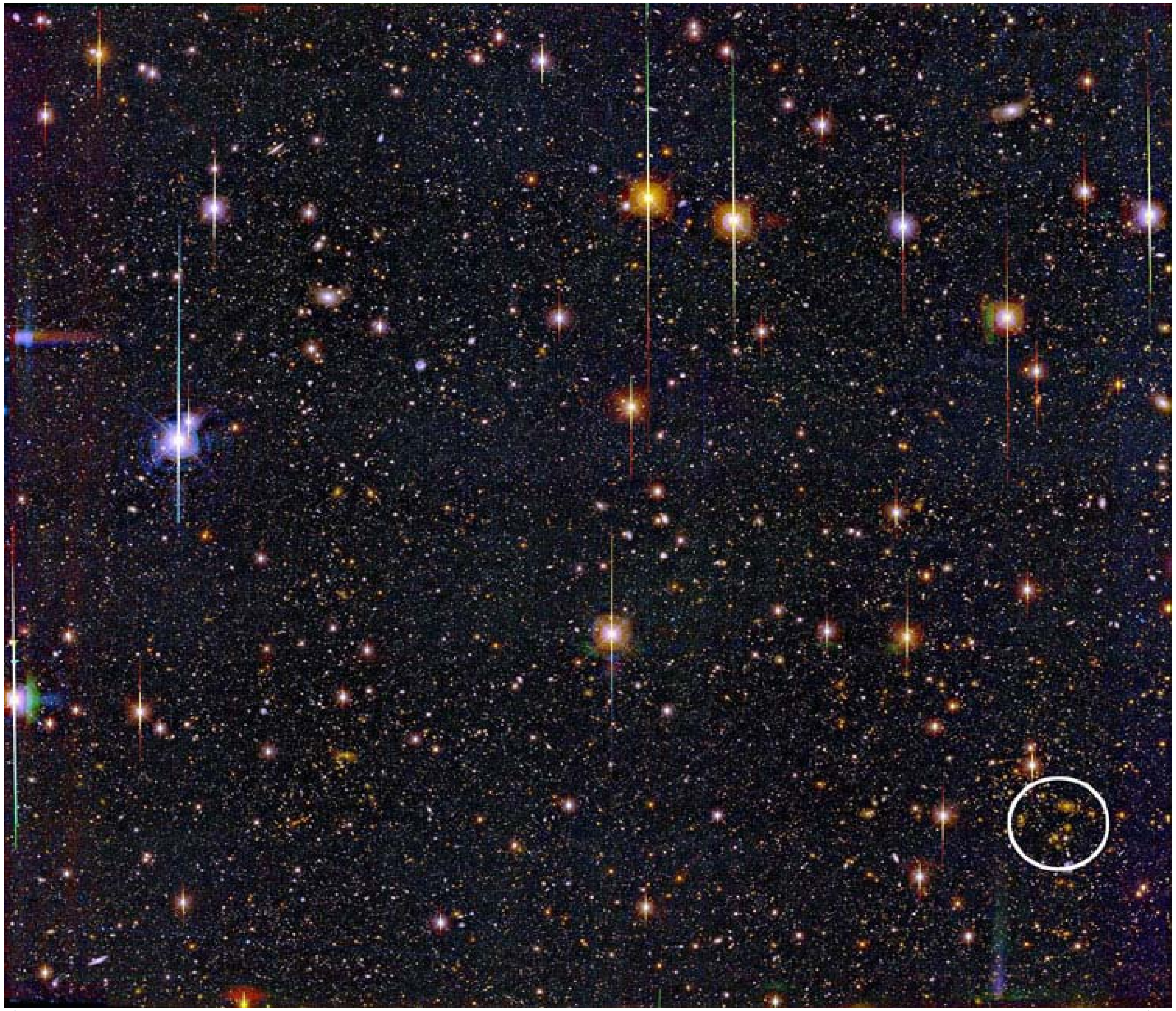
Use signal-matched optimal filter. For each galaxy angular size (in discrete bins) there is an approximate matched filter given by an elliptical Gaussian at the best-fit angle.

What do we measure from the data?

To quantify the cosmic shear signal we use the shear-shear correlation functions:



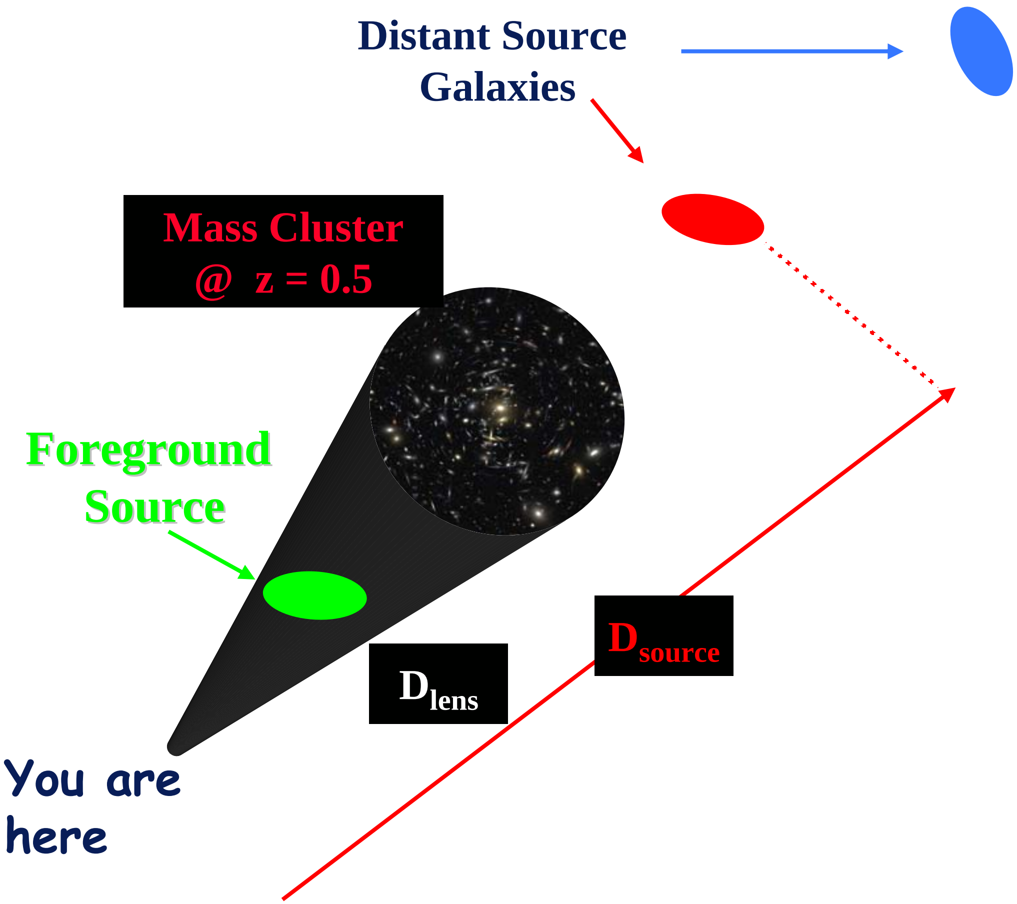
Cluster of dark matter discovered by weak gravitational lensing



Size of moon

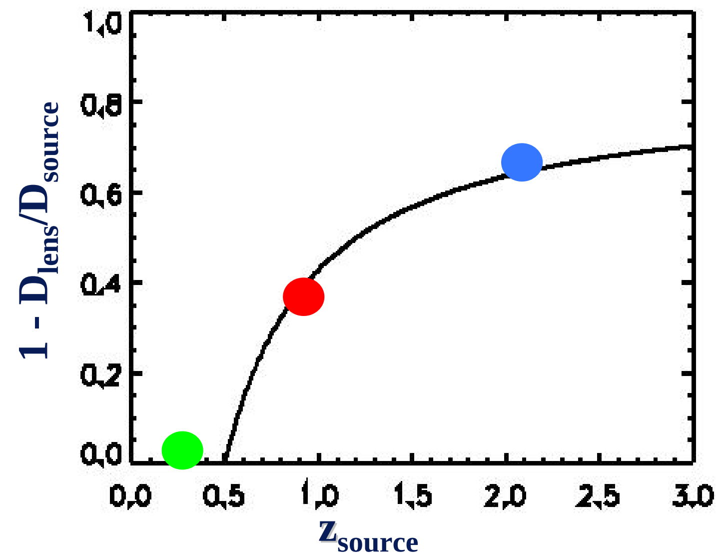
- First cluster of galaxies discovered through its gravitational lensing effect rather than radiation!

3-D Mass Tomography



Lens Strength

$$\gamma \propto \frac{\Sigma}{\Sigma_{crit}} \propto 1 - \frac{D_{lens}}{D_{source}}$$



The blue galaxy is sheared more than the red galaxy.

The green galaxy is not sheared.

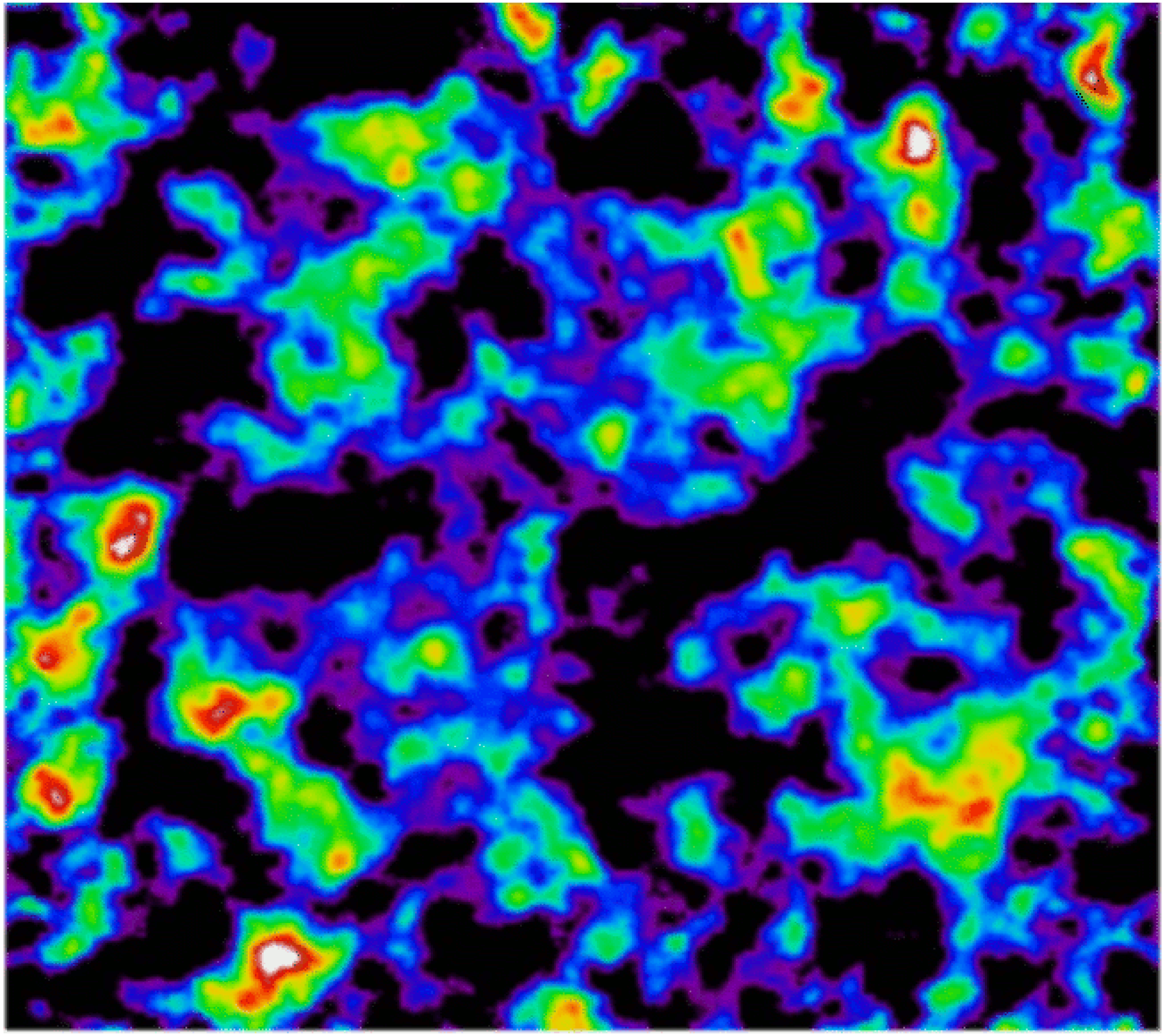
Deep Lens Survey

- 5-yr NOAO Survey Program
- Deep multicolor imaging of 20 deg^2 at NOAO 4-meter telescopes
- Catalogue of 10 million galaxies
- Detect foreground dark matter via gravitational mirage of background galaxies
- Directly measure the history of the expansion of the Universe
- Detect transient objects/events (timescales of hours to months)

First mass-selected survey

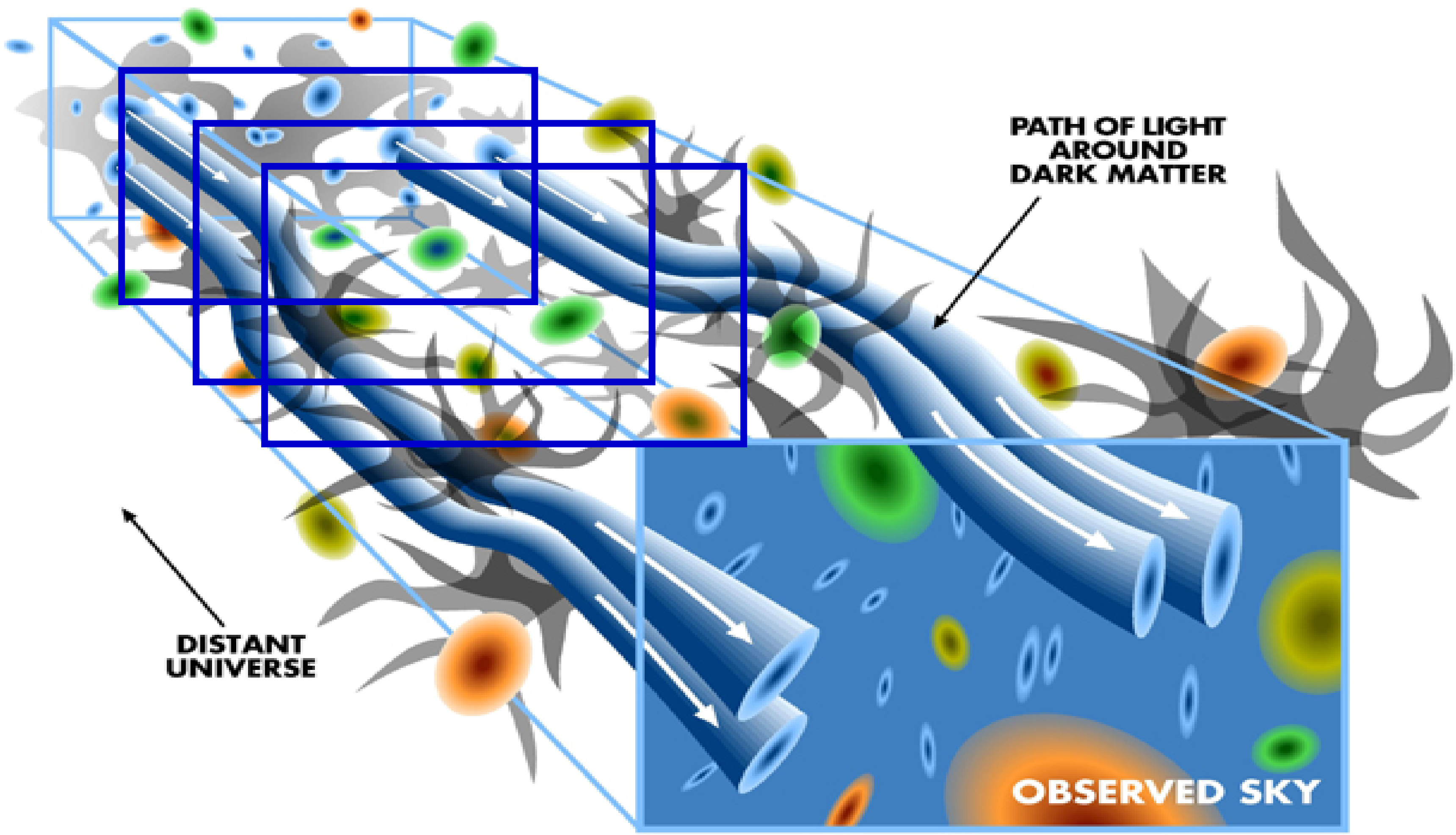
http://dls.physics.ucdavis.edu

3-D Mass Tomography

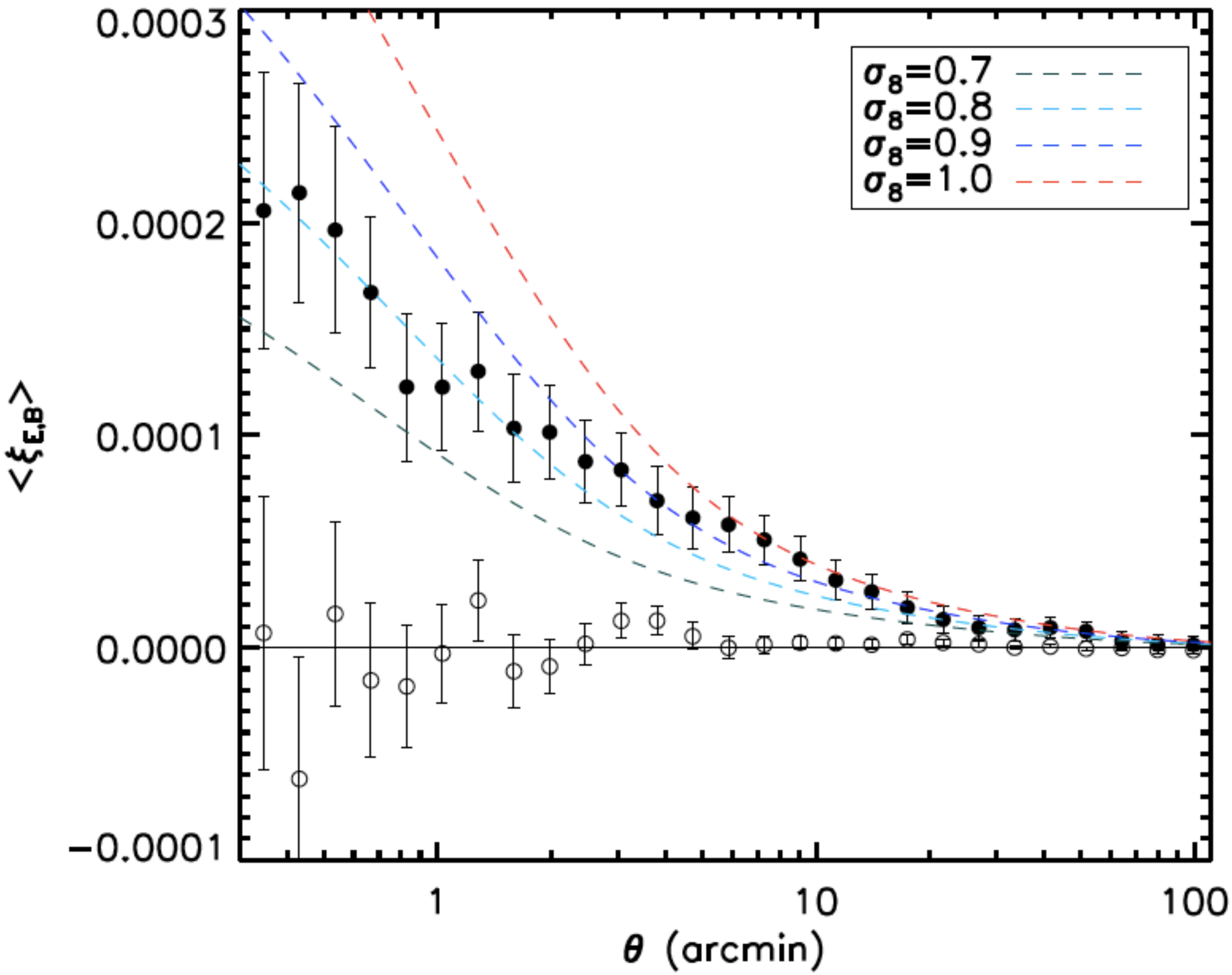


2x2 degree mass map from Deep Lens Survey

Cosmic shear vs redshift

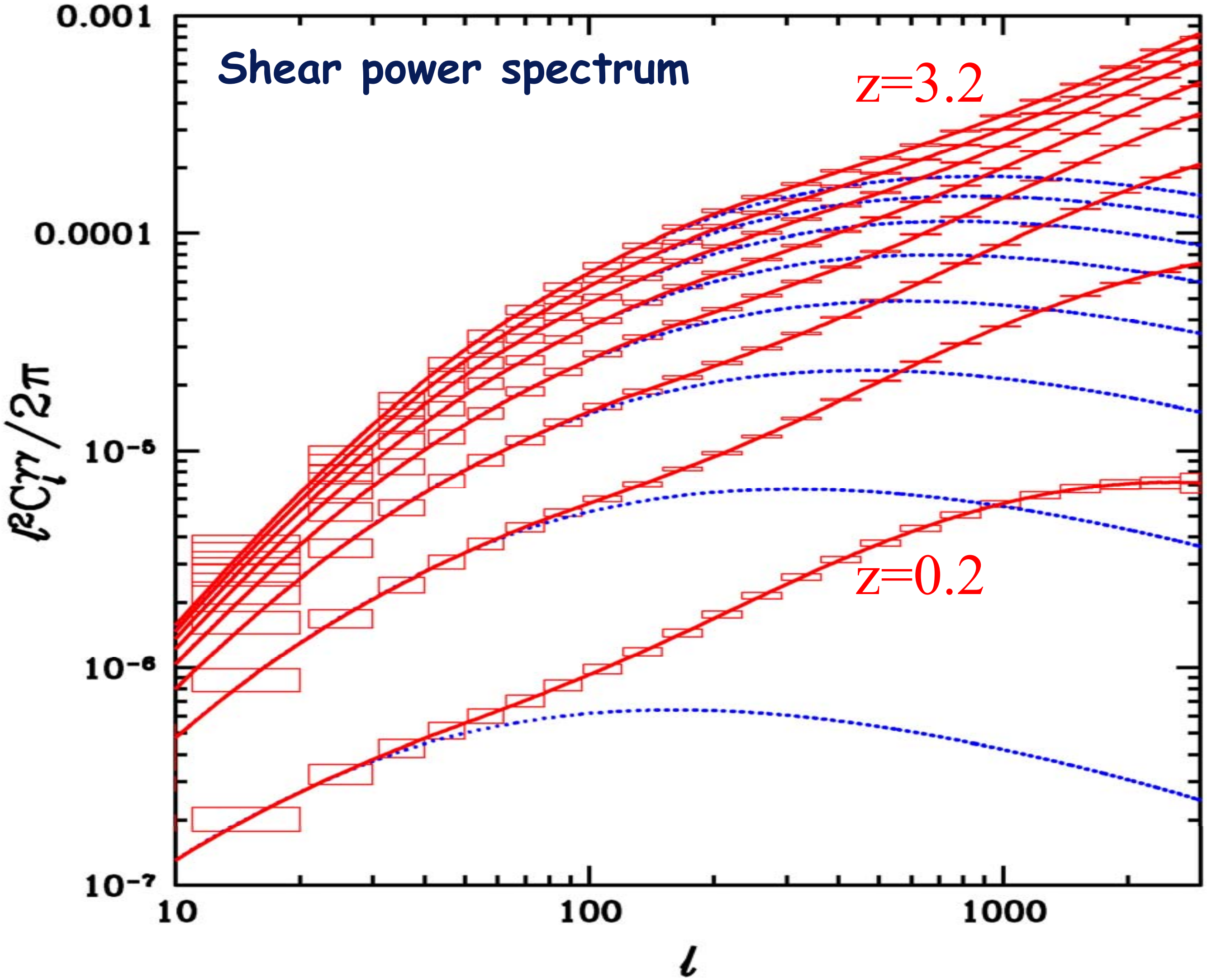


Cosmic shear in Deep Lens Survey



Compared with 4 cosmologies with differing dark matter fluctuations.
Open circles are a null test, and should be consistent with zero.

Fourier transform of shear-shear correlation function: LSST 20000 sq.deg WL survey shear power spectra



0.01 shear

0.001 shear