

LENTES GRAVITACIONALES EN ASTROFÍSICA Y COSMOLOGÍA

SEMANA - 11

PARTE II: LENTES POR GALÁXIAS Y CÚMULOS DE GALÁXIAS

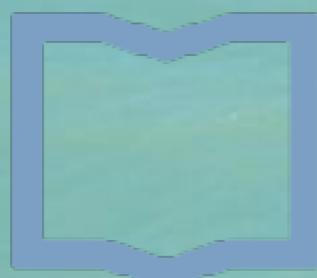
MARTÍN MAKLER

ICAS/IFI/CONICET & UNSAM Y CBPF

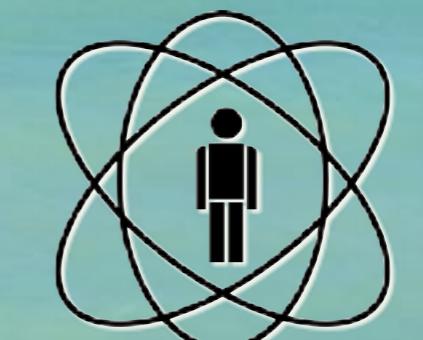
ICAS



CONICET



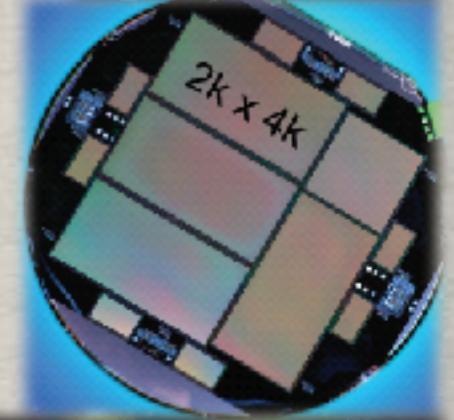
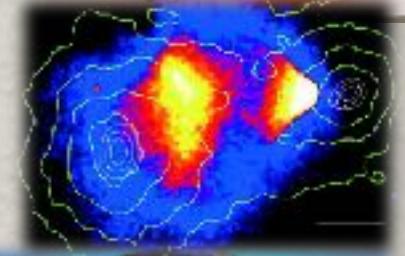
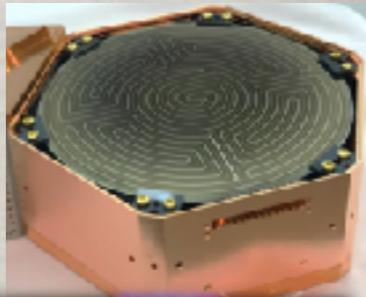
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CBPF

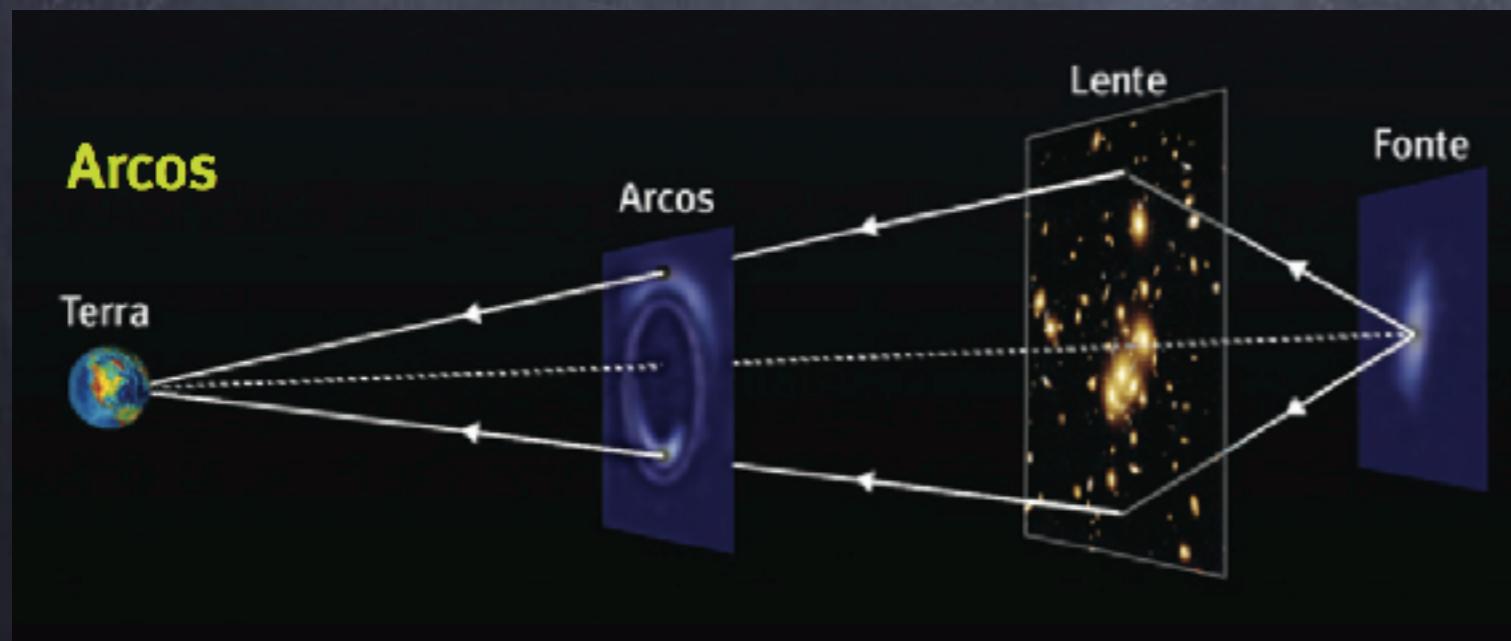
PLAN DE LA PARTE II

- Redshift y expansión del Universo
- Dinámica y parámetros cosmológicos
- Métrica y distancias
- Energía oscura
- Propagación de la luz y ecuación de la lente
- Lentes extendidas
- Jacobiana de la transformación:
cáusticas y curvas críticas
- Modelos de lentes extendidas y aplicaciones
- Retraso temporal y aplicaciones
- Efecto débil de lentes



Efecto fuerte de lentes

- Imágenes múltiples, grandes deformaciones, magnificación, retraso temporal
 - Imágenes múltiples permiten reconstruir la distribución de masa de la lente y la forma de las fuentes!
 - Trayectoria de la luz en el espacio curvo
 - brillo superficial conservado
 - acromático
 - estrutura de galaxias y cúmulos → materia oscura y bariones
 - informaciones complementares sobre la cosmología y tests de la gravedad
- } **Telescópios gravitacionales**



efecto fuerte de lentes, **gravedad débil**



MACRO LENTEAMENTO: DOIS REGIMES

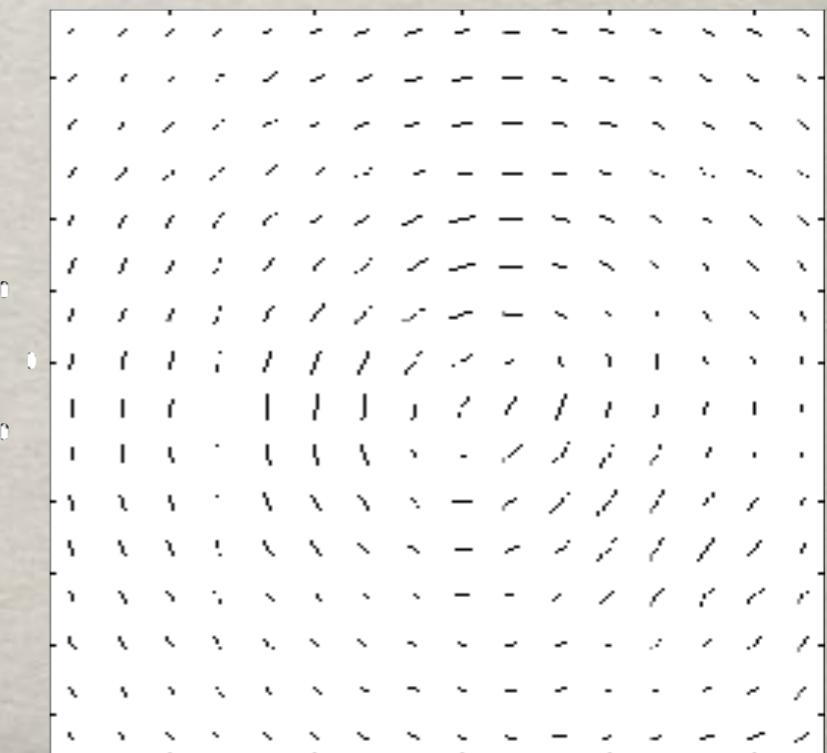
● Lenteamento forte:

- Grandes magnificações
- Imagens múltiplas
- Grandes distorções (arcos, anéis)
- Defasagem temporal
- $\Sigma > \Sigma_c$
- Regiões centrais de galáxias e aglomerados



● Weak Lensing:

- Mudança na “orientação” (+magnificação)
- Regiões não centrais/de baixa massa de galáxias e aglomerados
- Estrutura em grande escala



Efecto débil y fuerte de lente

observador

Non-Linear

Multiple Images

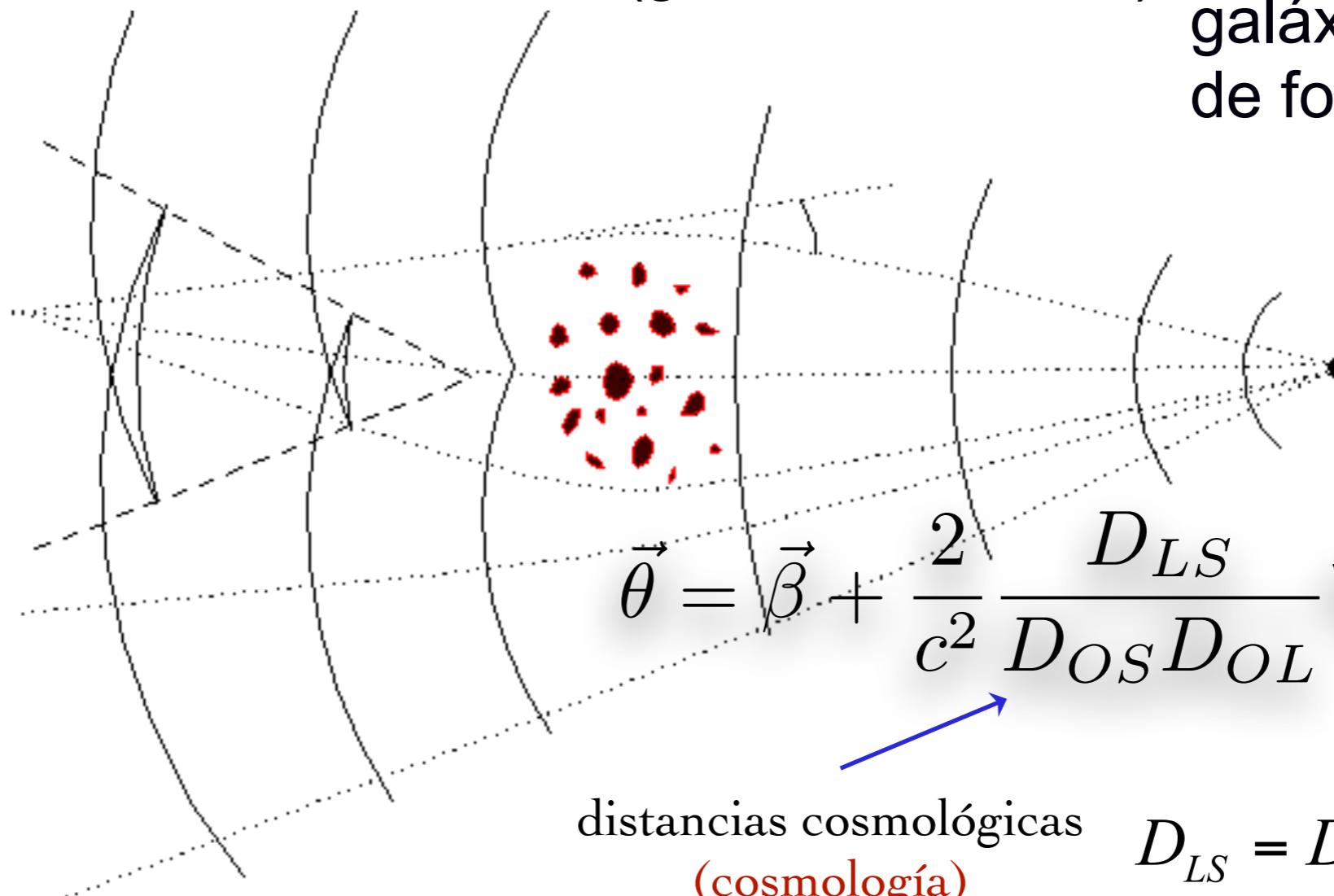
Arclets

Weak Shear

Linear

Lente (galáxia o cúmulo)

galáxia
de fondo



$$\vec{\theta} = \vec{\beta} + \frac{2}{c^2} \frac{D_{LS}}{D_{OS} D_{OL}} \nabla_{\theta} \psi(\vec{\theta})$$

distancias cosmológicas
(cosmología)

$$D_{LS} = D_A(z_L, z_S) \dots$$

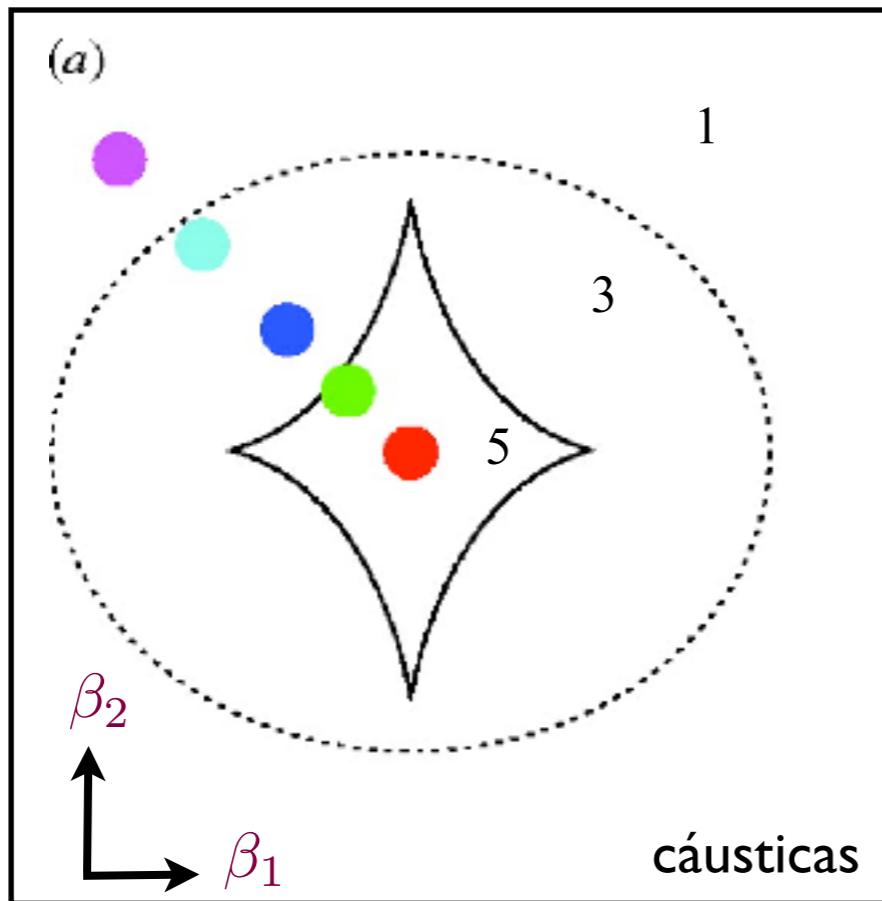
$$\psi = \int_0^{r_{\text{source}}} \phi(\xi, r) dr$$

potencial gravitacional
(astrofísica)

Efecto fuerte: el domínio de las cáusticas y curvas críticas

► mapeo imagen → fuente

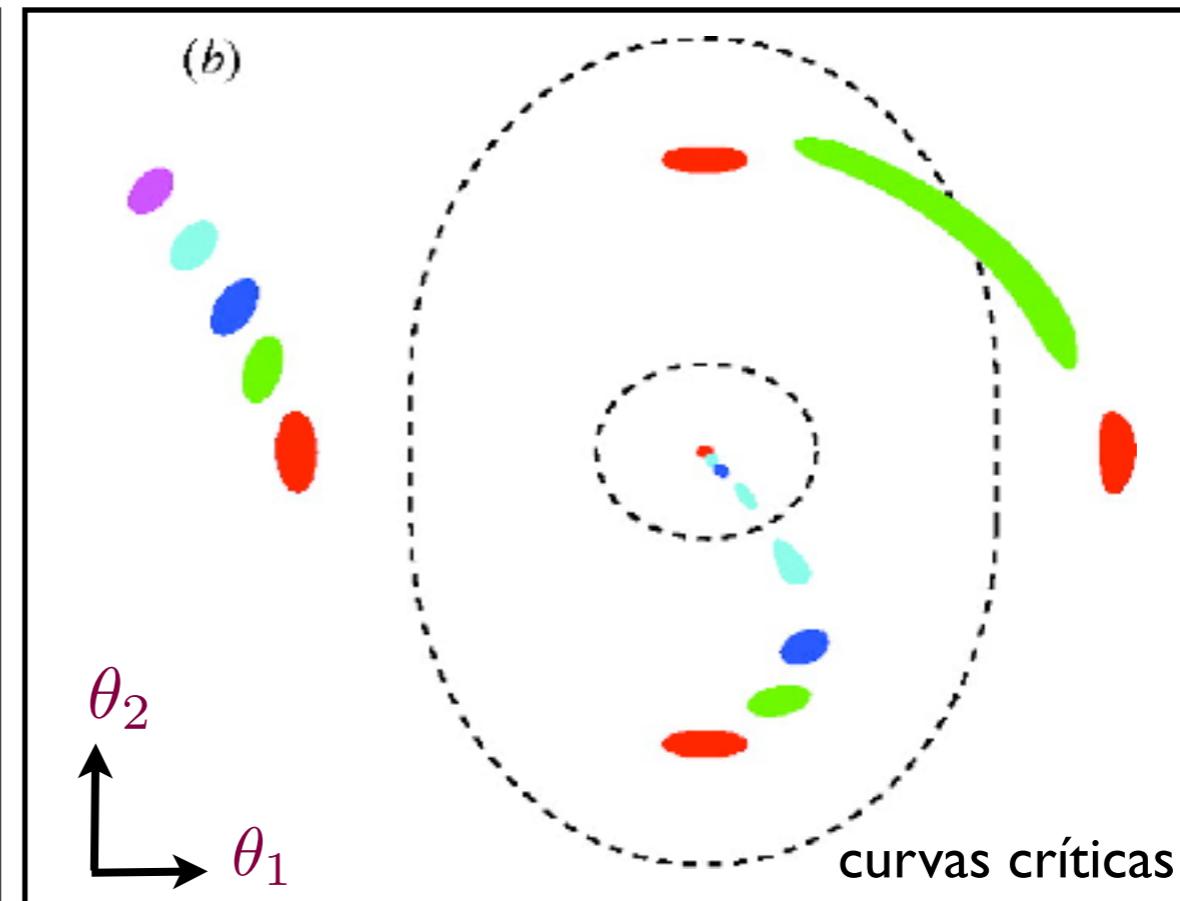
$$\frac{\partial \beta_i}{\partial \theta_j} = \delta_{ij} - \frac{\partial^2 \Psi(\vec{\theta})}{\partial \theta_i \partial \theta_j}$$



Plano de las fuentes

► autovalores:

$$\mu_1 = \frac{1}{1-\kappa+\gamma}, \mu_2 = \frac{1}{1-\kappa-\gamma}$$



Lente/imágenes

Los números en el plano de las fuentes indican la multiplicidad de las imágenes

Jacobiana de la transformación

$$\vec{\beta} = \vec{\theta} - \vec{\nabla}_{\theta} \Psi(\vec{\theta})$$

$$J_{ij} = \left(\frac{\partial \vec{\beta}}{\partial \vec{\theta}} \right)_{ij} = \delta_{ij} - \frac{\partial^2 \Psi}{\partial \theta_i \partial \theta_j}, \quad \text{definiendo } \Psi_{ij} = \frac{\partial^2 \Psi}{\partial \theta_i \partial \theta_j}$$

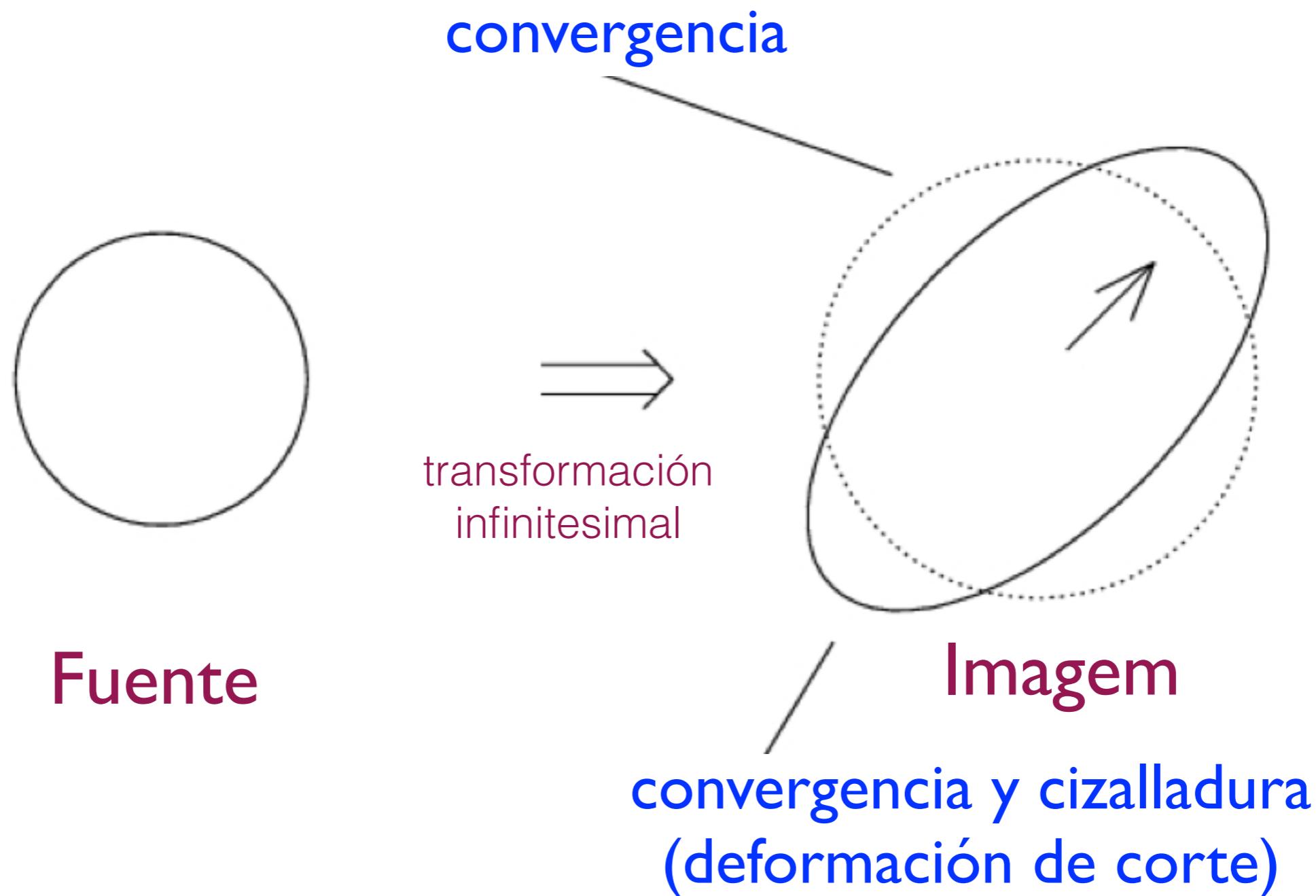
tenemos $\mathbf{J} = \begin{pmatrix} 1 - \Psi_{11} & -\Psi_{12} \\ -\Psi_{21} & 1 - \Psi_{22} \end{pmatrix}$

como $\nabla_{\theta}^2 \Psi = \Psi_{11} + \Psi_{22} = 2\kappa$

$$\mathbf{J} = (1 - \kappa)\mathbf{I} - \begin{pmatrix} \frac{1}{2}(\Psi_{11} - \Psi_{22}) & \Psi_{12} \\ \Psi_{21} & -\frac{1}{2}(\Psi_{11} - \Psi_{22}) \end{pmatrix}$$

Jacobiana de la transformación

$$\mathbf{J} = (1 - \kappa)\mathbf{I} - \begin{pmatrix} \frac{1}{2}(\Psi_{11} - \Psi_{22}) & \Psi_{12} \\ \Psi_{21} & -\frac{1}{2}(\Psi_{11} - \Psi_{22}) \end{pmatrix}$$



Convergencia

Ecuación de Poisson

$$\nabla_{\vec{\theta}}^2 \Psi = \frac{2}{c^2} \frac{D_{\text{LS}}}{D_{\text{OS}} D_{\text{OL}}} D_{\text{OL}}^2 4\pi G \Sigma(\vec{\theta}) = 2 \frac{\Sigma(\vec{\theta})}{\Sigma_{\text{crit}}}$$

Densidad superficial crítica

$$\Sigma_{\text{crit}} = \frac{c^2}{4\pi G} \frac{D_{\text{OS}}}{D_{\text{OL}} D_{\text{LS}}}$$

Convergencia

$$\kappa(\vec{\theta}) = \frac{\Sigma(\vec{\theta})}{\Sigma_{\text{crit}}}$$

Ecuación de Poisson

$$\nabla_{\vec{\theta}}^2 \Psi = 2\kappa(\vec{\theta})$$

Cizalladura

$$\mathbf{J} = (1 - \kappa)\mathbf{I} - \begin{pmatrix} \frac{1}{2}(\Psi_{11} - \Psi_{22}) & \Psi_{12} \\ \Psi_{21} & -\frac{1}{2}(\Psi_{11} - \Psi_{22}) \end{pmatrix}$$

Cizalladura:

$$\gamma_1(\vec{\theta}) = \frac{1}{2}(\Psi_{11} - \Psi_{22}) \quad \gamma = \sqrt{\gamma_1^2 + \gamma_2^2}$$
$$\gamma_2(\vec{\theta}) = \Psi_{12} = \Psi_{21}$$

En términos de la cizalladura y la convergencia tenemos

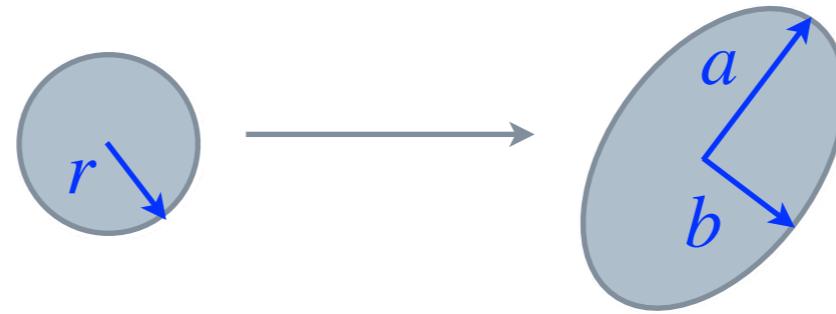
$$\mathbf{J} = (1 - \kappa)\mathbf{I} + \begin{pmatrix} -\gamma_1 & -\gamma_2 \\ -\gamma_2 & \gamma_1 \end{pmatrix}$$

Autovalores de \mathbf{J}^{-1}

$$\mu_1 = \frac{1}{1 - \kappa - \gamma}, \quad \mu_2 = \frac{1}{1 - \kappa + \gamma}$$

Mapeo Lineal

Fuente circular



$$a = \left(\frac{1}{1 - \kappa - \gamma} \right) r$$
$$b = \left(\frac{1}{1 - \kappa + \gamma} \right) r$$

● Magnificación

$$\mu = \frac{A_{\text{imagem}}}{A_{\text{fonte}}} = \left[(1 - \kappa)^2 - \gamma^2 \right]^{-1}$$

● Elipticidad

$$\epsilon := \frac{a - b}{a + b} = \frac{\gamma}{1 - \kappa} =: g$$

¿Qué es la elipticidad para una fuente real?

MAPEO LINEAL

- ➊ Efectos:
 - ➊ Distorsión (más usual): variación en la orientación
 - ➊ Magnificación: cambio en el área y en la densidad de objetos
 - ➊ Análogamente a la cizalladura γ , la elipticidad tiene 2 componentes: matriz, pseudo-vector o número complejo

$$\epsilon = \epsilon_1 + i\epsilon_2 = |\epsilon|e^{2i\varphi}$$

- ➊ La cizalladura también se suele escribir como un número complejo

$$\gamma = \gamma_1 + i\gamma_2$$

- ➊ En *weak lensing*, tenemos $\kappa \ll 1$ y $|\gamma| \ll 1$

REAL SOURCES

- Center of the object (image)

$$\bar{\theta}_i = \frac{\int d^2\theta q_I [I(\theta)] \theta_i}{\int d^2\theta q_I [I(\theta)]}$$

- Second order momenta

$$Q_{ij} = \frac{\int d^2\theta q_I [I(\theta)] (\theta_i - \bar{\theta}_i)(\theta_j - \bar{\theta}_j)}{\int d^2\theta q_I [I(\theta)]}$$

- Area

$$\Omega = (Q_{11}Q_{22} - Q_{12}^2)^{1/2}$$

- Ellipticity

$$\epsilon := \frac{Q_{11} - Q_{22} + 2i Q_{12}}{Q_{11} + Q_{22} + 2(Q_{11}Q_{22} - Q_{12}^2)^{1/2}}$$

REAL SOURCES

Second order momenta

$$Q_{ij} = \frac{\int d^2\theta q_I[I(\theta)](\theta_i - \bar{\theta}_i)(\theta_j - \bar{\theta}_j)}{\int d^2\theta q_I[I(\theta)]}$$

Area

$$\Omega = (Q_{11}Q_{22} - Q_{12}^2)^{1/2}$$

Ellipticity

$$\epsilon := \frac{Q_{11} - Q_{22} + 2iQ_{12}}{Q_{11} + Q_{22} + 2(Q_{11}Q_{22} - Q_{12}^2)^{1/2}}$$

Linear distortion

$$\epsilon_S = \frac{\epsilon_I - g}{1 - g^* \epsilon_I} \quad g_i := \frac{\gamma_i(\theta)}{1 - \kappa(\theta)} \quad |g| \leq 1$$

reduced shear o cizalladura o distorsión reducida

WEAK LENSING

- ➊ Slight shear in background galaxies (change in axis + size)
- ➋ Weak lensing regime

$$\epsilon = \epsilon_I = \epsilon_S + g$$

- ➌ “weak lensing fundamental theorem”:

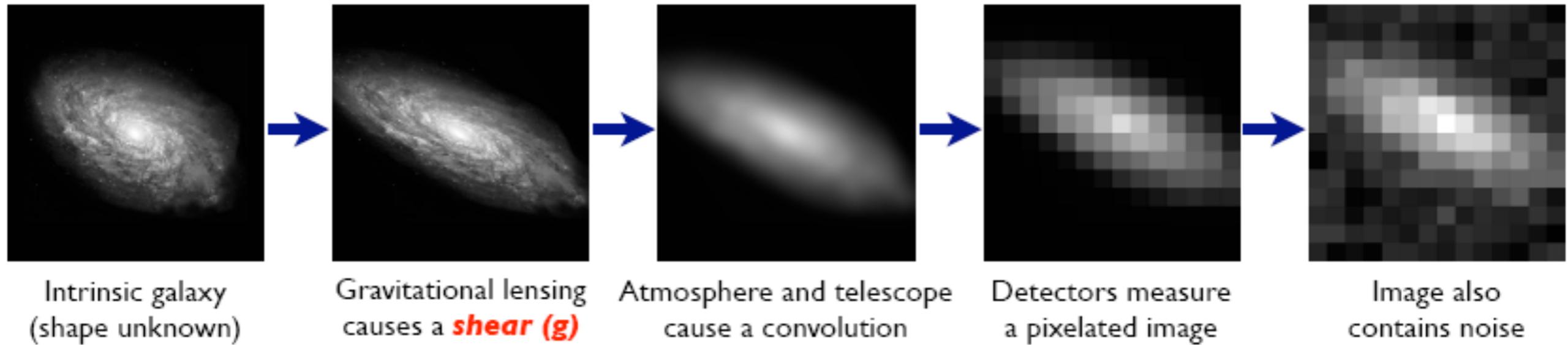
$$\langle \epsilon \rangle = g$$

- ➍ but

$$|g| \ll |\epsilon|$$

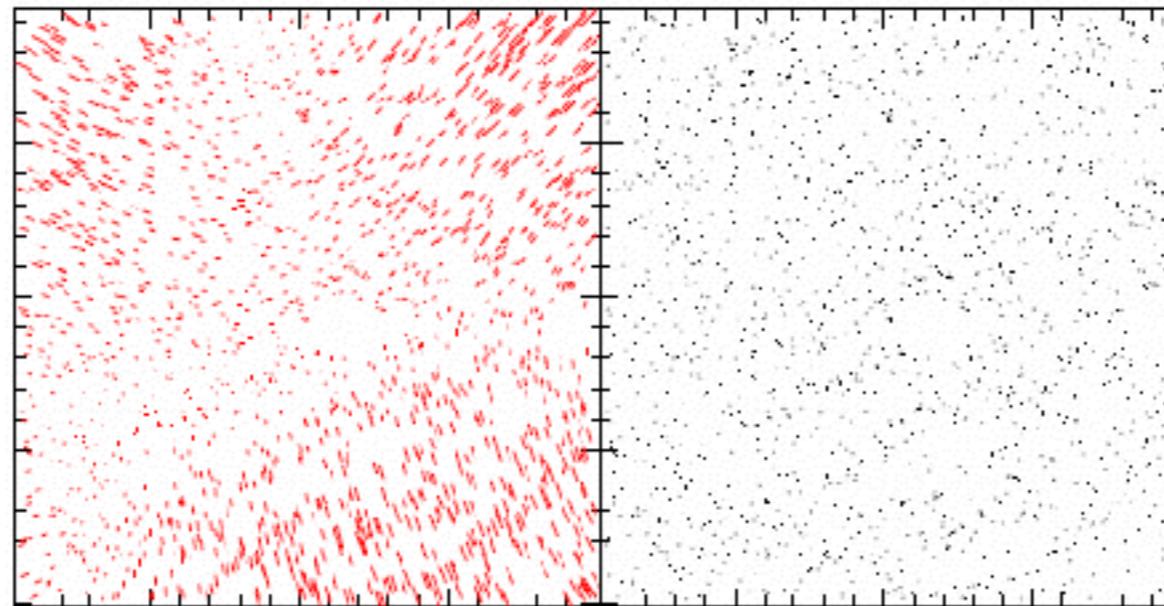
- ➎ observational, instrumental, computational and theoretical challenges!

Technical challenges



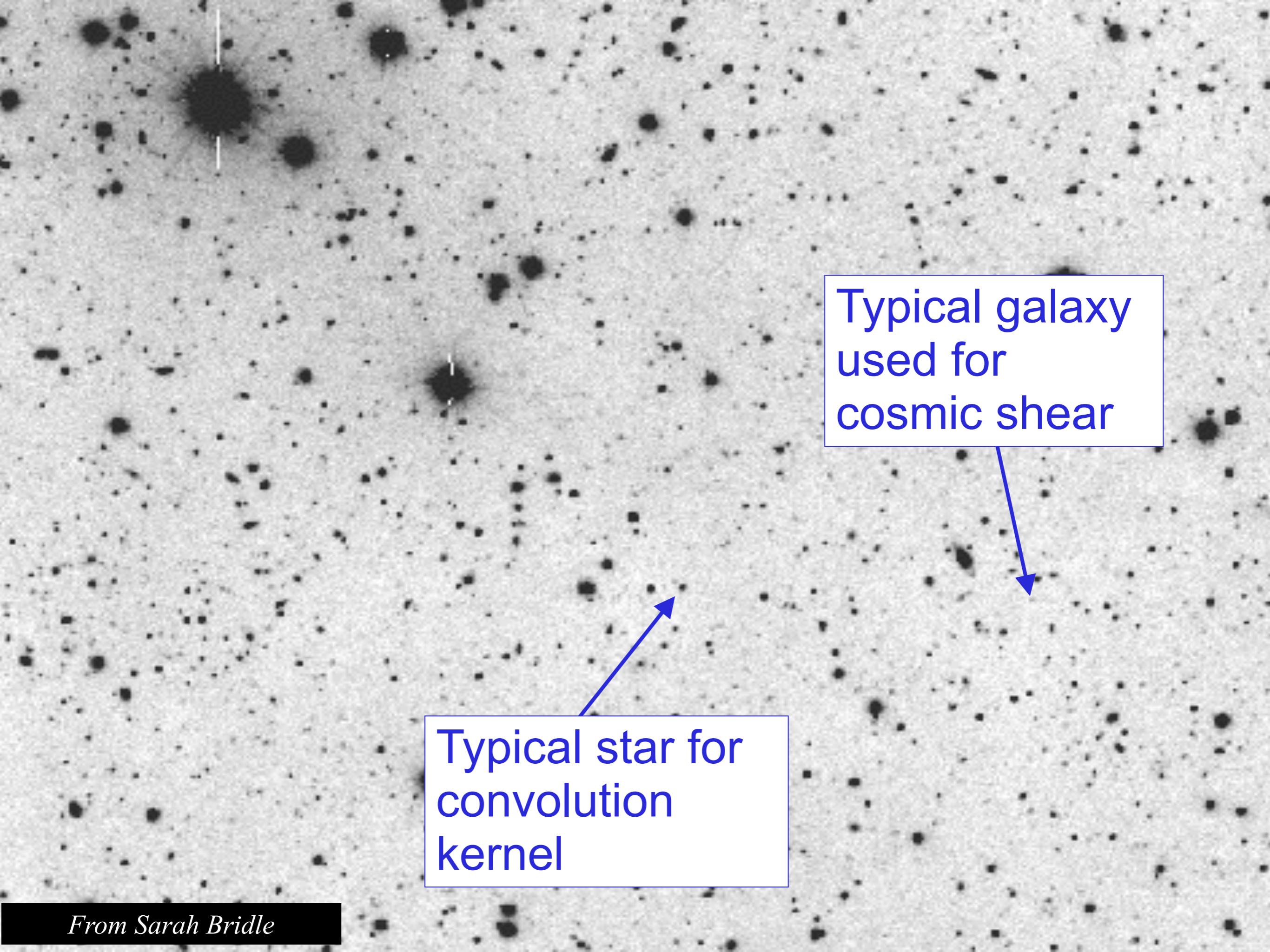
Sarah Bridle

- Model the PSF distortion (many sources)
 - measure a large number of stars in the field



CFHTLS Deep 1
Gavazzi, Soucail 2006

- Difficulties: saturated stars, charge transfer efficiency, halos, tracking...



Typical galaxy
used for
cosmic shear

Typical star for
convolution
kernel

Measuring weak lensing

- Signal $\langle \varepsilon_I \rangle = \gamma$ ($\varepsilon_I = \varepsilon_S + \gamma$)
- Noise $\sigma_\varepsilon = \sqrt{\langle |\varepsilon_S|^2 \rangle} \sim 0.3 \gg \gamma$
- Win over the noise by averaging over a large number of galaxies

Regime	γ	$\gamma/\sigma_\varepsilon$	N_{gal} for S/N ~ 1
weak lensing by clusters	0.03	0.1	10^2
galaxy-galaxy lensing	0.003	0.01	10^4
cosmic shear	0.001	0.003	10^5

Much more galaxies for precision measurements needed.

(de Kilbinger)

El camino...

I) Obtener las medidas de forma de las galaxias

- Modelar las distorsiones de la PSF (muchas fuentes)
- Medir la forma de las galaxias
- Aplicar la PSF a las medidas de forma de las galaxias
- Seleccionar las galaxias (z , S/N, tamaño/magnitud, etc.)

2) Realizar las mediciones de las cantidades relevantes

- Una miríada de observables y de estimadores estadísticos
- Obtener estimadores óptimos, teniendo en cuenta efectos instrumentales y observacionales
- Determinar las incertidumbres

El camino...

I) Obtener las medidas de forma de las galaxias

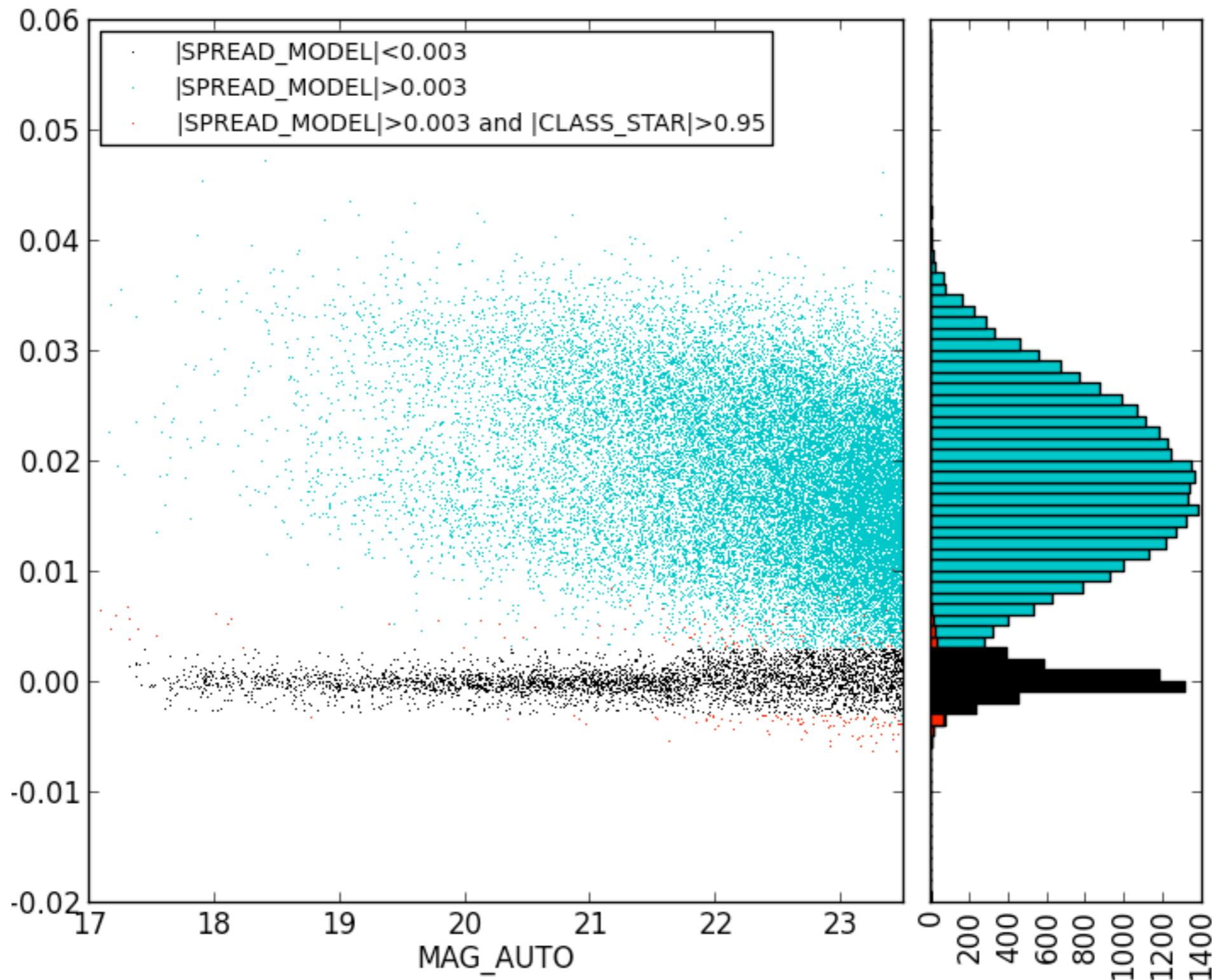
- Modelar las distorsiones de la PSF (muchas fuentes)
- Medir la forma de las galaxias
- Aplicar la PSF a las galaxias
- Seleccionar una muestra relevante (magnitud, etc.)

2) Realizar las medidas

- Una miríada de estadísticos
- Obtener estimadores óptimos, teniendo en cuenta efectos instrumentales y observacionales
- Determinar las incertidumbres

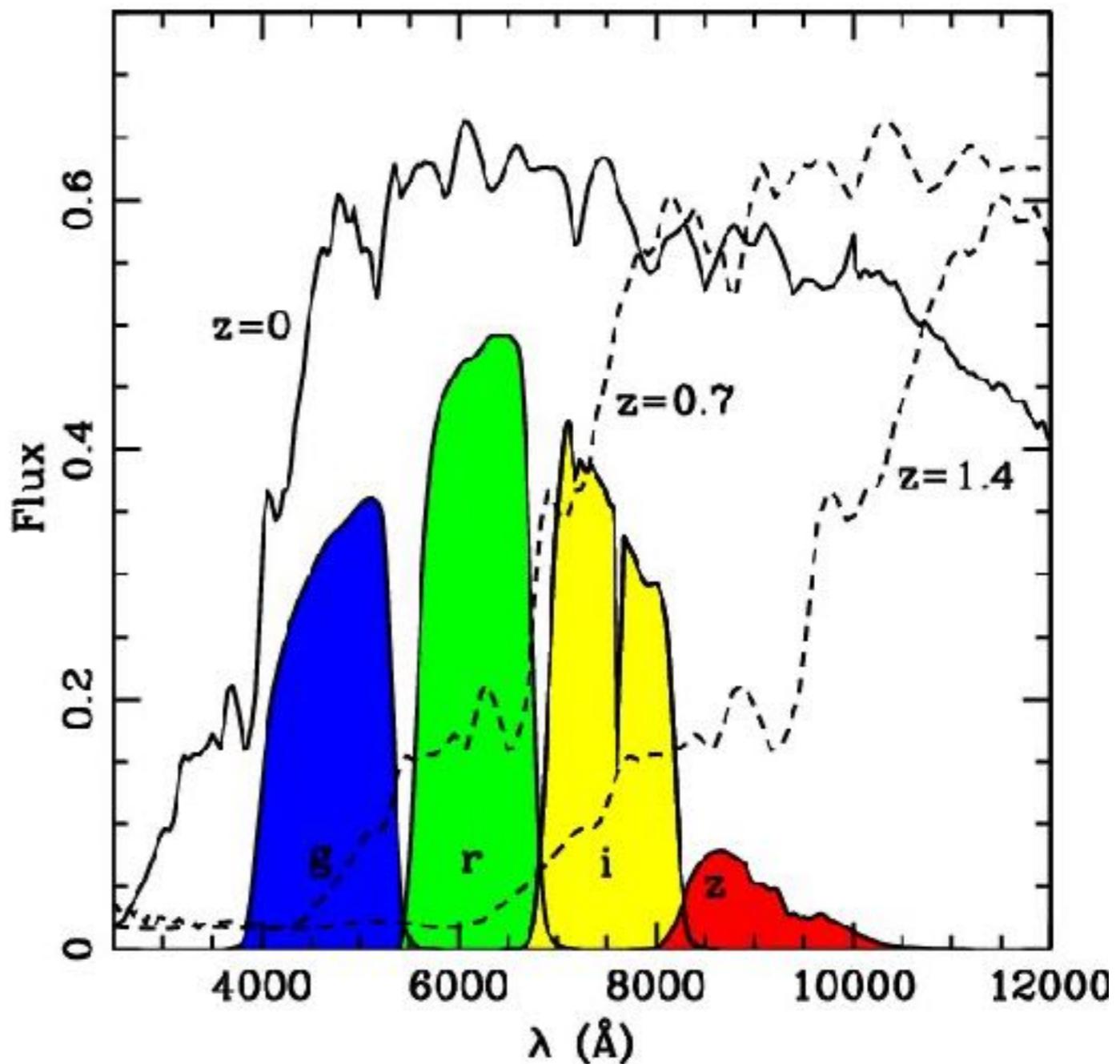
El dominio
de la
estadística

Ejemplo: separación estrella-galaxia



Desvios para o vermelho fotométricos

- Características marcantes do espectro (quebra de 4000 Å)
- Diferença no fluxo através dos filtros quando a galáxia é desviada para o vermelho



2 Regimes and Methods

Lensing by galaxies and clusters

- Larger signal
- Center of reference
- Model/profile fitting
- Individual objects or *Stacking* of the signal

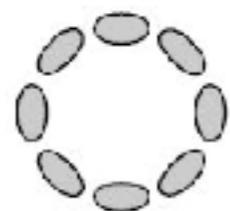
Large-scale structure

- Convergence maps (also in clusters)
- Correlations:
 - power spectrum, correlation function
 - among different probes, z-bins, CMB, etc.

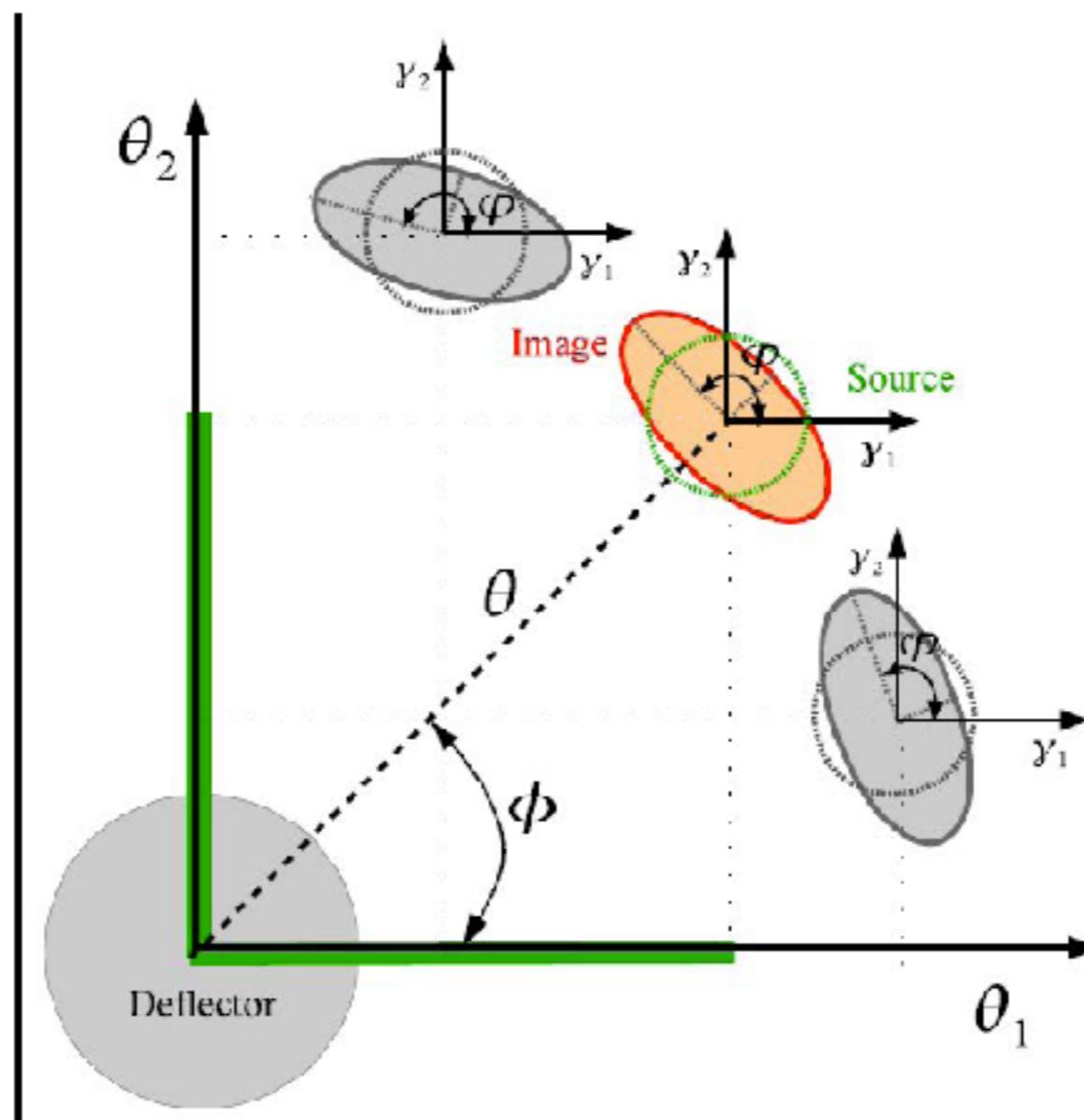
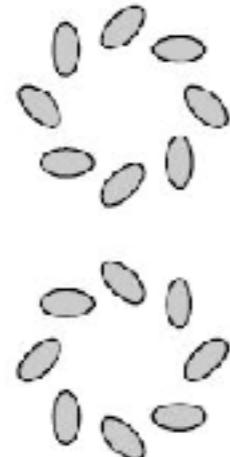
Components of the Shear

Figueiró 2011

Tangential alignment



Cross alignment



Mean shear in circles

$$\langle \gamma_t(\theta) \rangle = \bar{\kappa}(\theta) - \langle k(\theta) \rangle$$

Mean shear and radial profiles

It is possible to show that

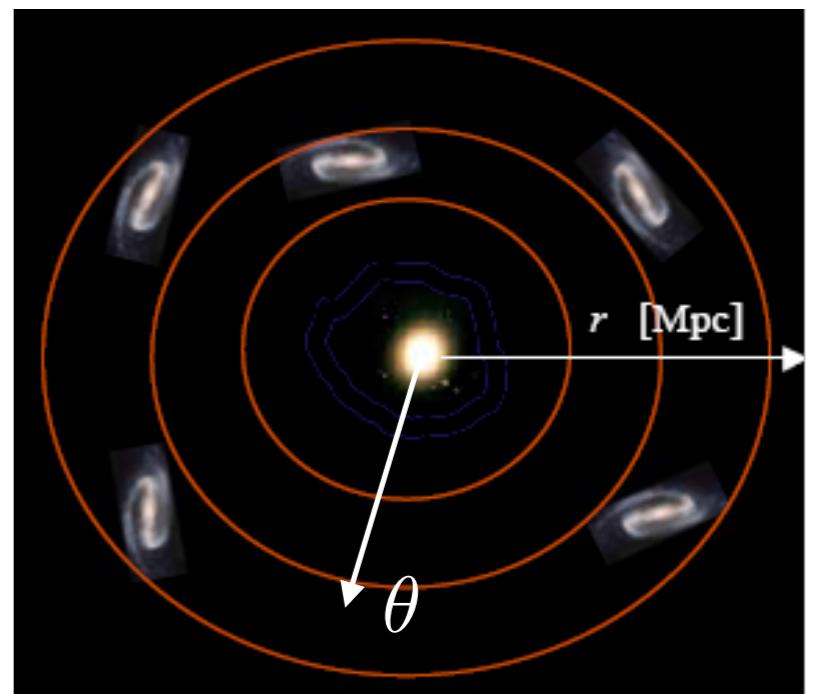
$$\langle \gamma_t(\theta) \rangle = \bar{\kappa}(\theta) - \langle k(\theta) \rangle$$

mean along a circle of the tangential component of the shear

mean within a disk of radius θ

mean on the circle

In practice: mean on annuli
(radial bins)



Stacking of the signal

Need (and possibility) to increase the S/N

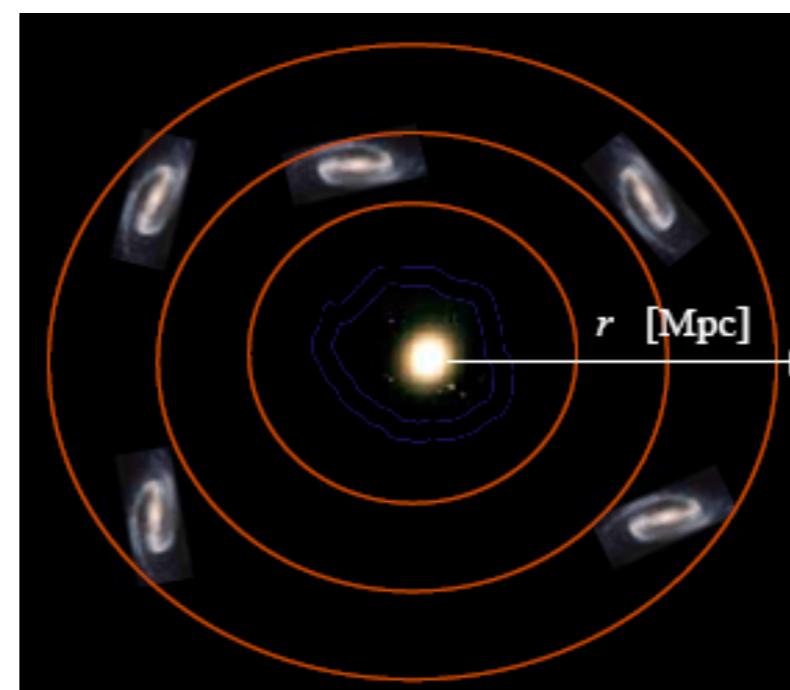
Combine data on many galaxies or clusters: mean signal

Physical signal and models: $\Sigma(r) \rightarrow$ multiply by Σ_{crit}

$$\Sigma_{\text{crit}} \times \langle \gamma_t(\theta) \rangle = (\bar{\kappa}(\theta) - \langle k(\theta) \rangle) \times \Sigma_{\text{crit}}$$

$$\Sigma_{\text{crit}} \times \langle \gamma_t(r) \rangle = \bar{\Sigma}(r) - \langle \Sigma(r) \rangle := \Delta\Sigma(r)$$

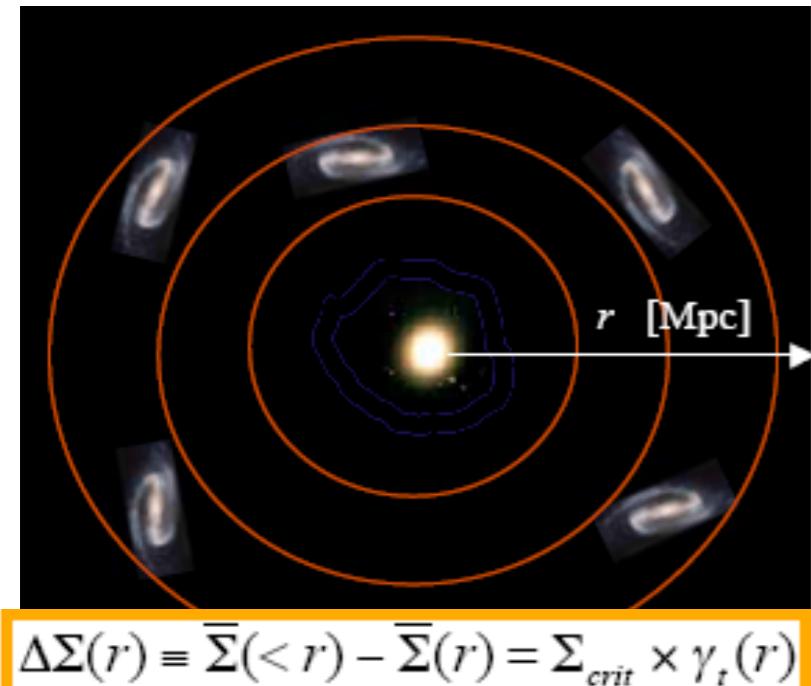
↓
redshifts ↓
shapes



↓
model

Mass reconstruction in clusters (radial profile)

- Measure the tangential shear to get $\Delta\Sigma$

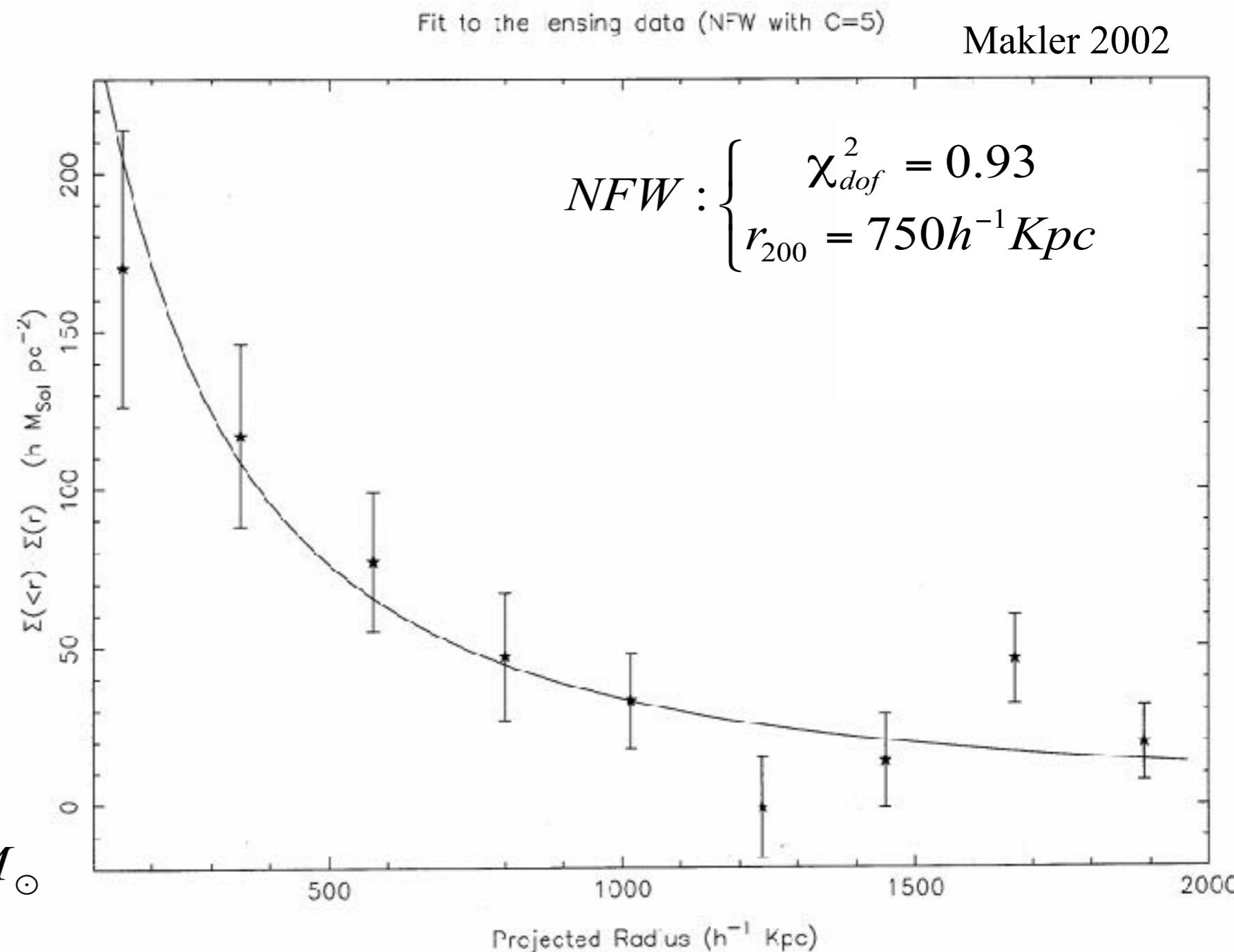


$$\Sigma_{crit} = \frac{c^2}{4\pi G} \frac{D_{OS}}{D_{OL} D_{LS}}$$

- Masses:

$$\bar{M}_{NFW} = (1.0 \pm 0.2) 10^{14} h^{-1} M_\odot$$

$$\frac{\Delta M_{200}}{M_{200}} \simeq 2.5\%$$



42 clusters (RASS/SDSS), Sheldon, et al., ApJ 554, 88 (2001)