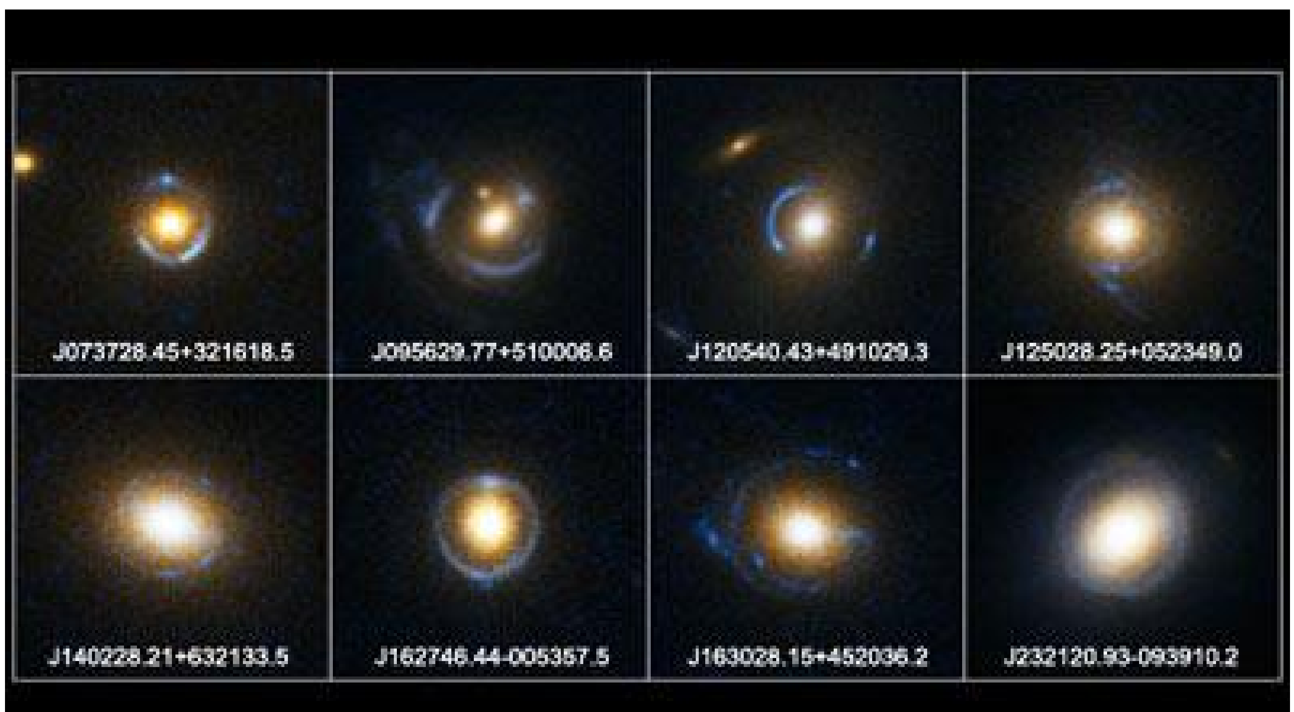
Weak lensing around SLACS strong lenses

Raphaël Gavazzi (UCSB)

& SLACS team: T. Treu, A. Bolton, S. Burles, L. Koopmans, L. Moustakas & J. Rhodes



Introduction

How do early-type galaxies (ETGs) form and evolve within hierarchical CDM scheme of structure growth?

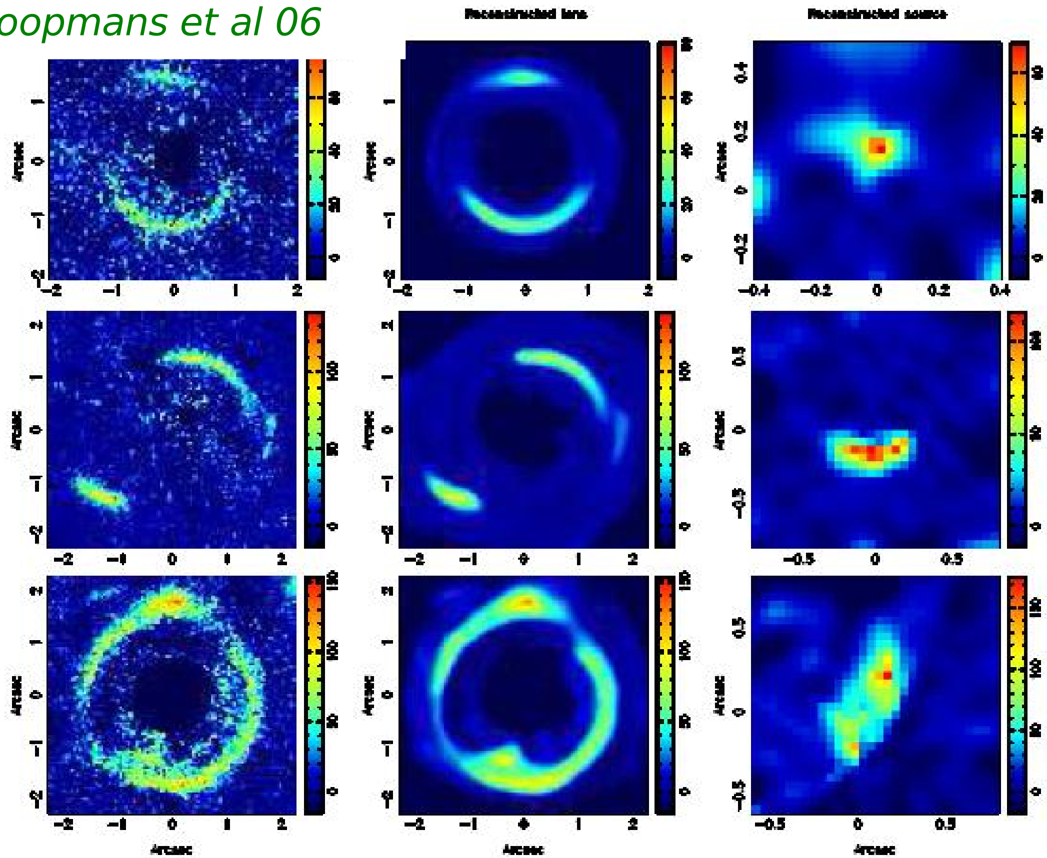
To link observations and theory we must learn about the mass distribution of ETGs (and time evolution!)

Especially, what are the relative contributions of Dark Matter and Stars?

To this end we have

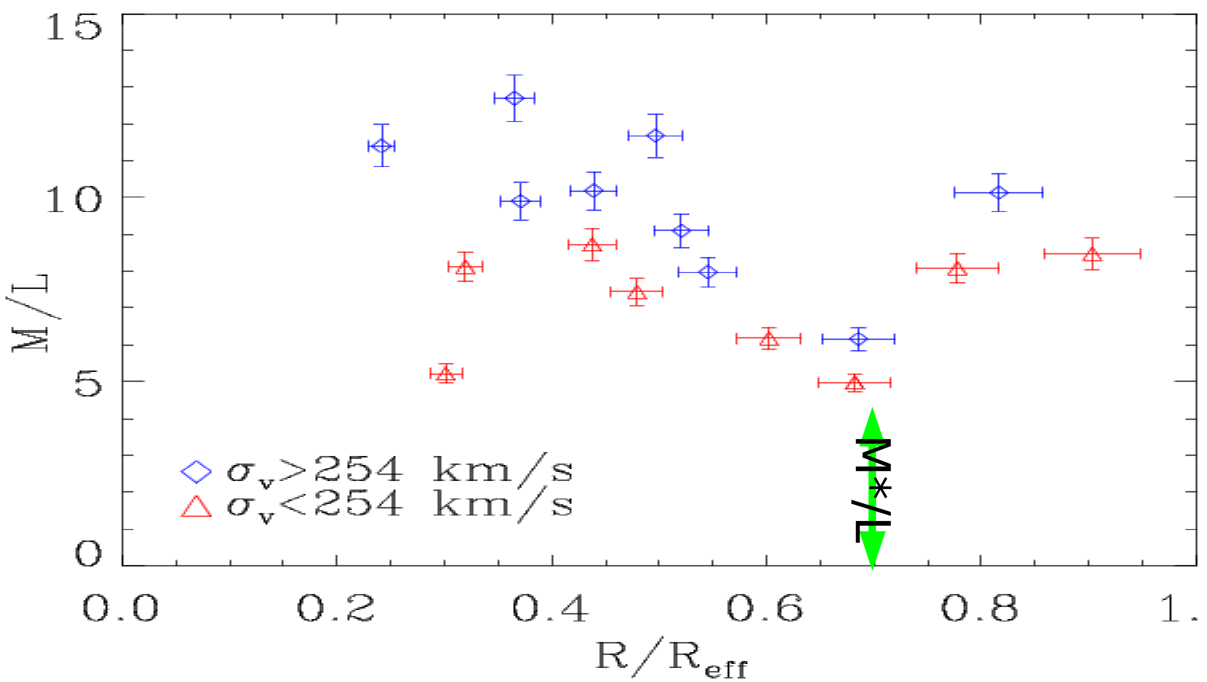
- strong lensing (R<5kpc ~ $R_{eff}/2$)
- stellar kinematics (R<10kpc~R_{eff})
- weak lensing (10<R<300.. kpc ~ $100R_{eff}$)

Koopmans et al 06



SLACS Einstein rings successfully modelled with SIE.

- Orientation and ellipticity consistent with lens light.
- But Strong Lensing essentially probes the mass within R_{Ein} .

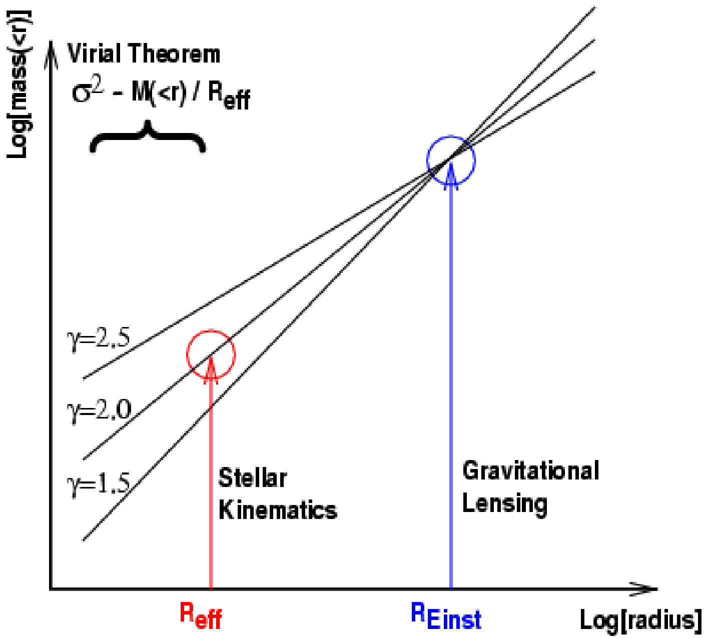


V band total (cylindric) mass-to-light ratio

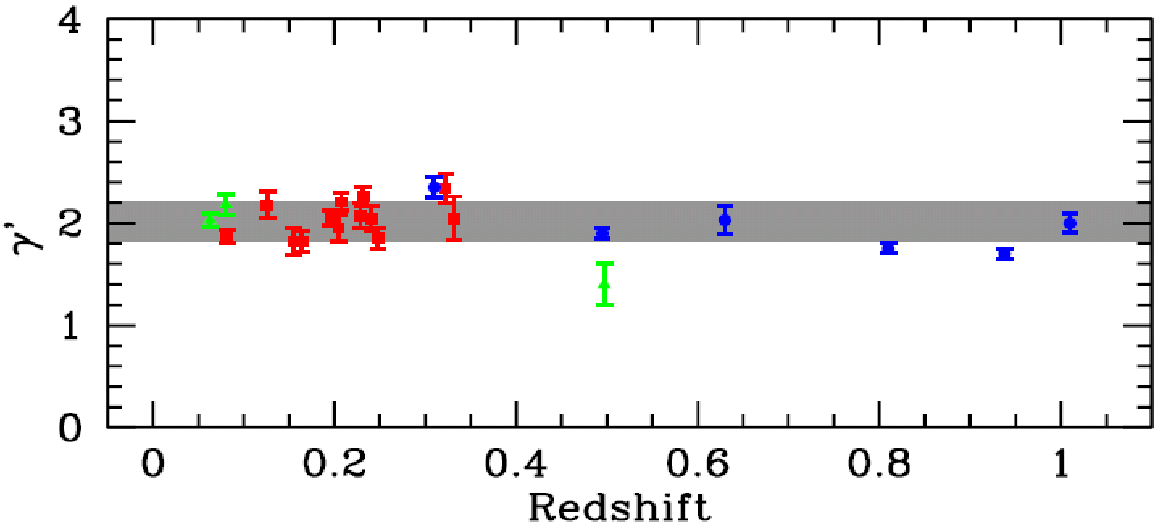
corrected for passive evolution to z=0.3

Need DM below Reff

Combining SL with stellar kinematics yields the mean total density slope within R_{Ein}. Very close to isothermal!!



Koopmans et al 06



What happens beyond a few kpc (*ie* R_{eff})?

Weak lensing can give the answer by stacking galaxies since WL signal is too noisy on a single lens galaxy *(and will ever!)*.

Weak gravitational lensing

$$\boldsymbol{\alpha} = -\frac{2}{c^2}\int_S^O \nabla_\perp \Phi \, dl \, .$$

- Lens equation

$$\vec{\eta} = \frac{D_{os}}{D_{ol}}\vec{\xi} - D_{ls}\vec{\alpha}\left(\vec{\xi}\right) \Longleftrightarrow \vec{\beta} = \vec{\theta} - \vec{\alpha}\left(\vec{\theta}\right)$$

- Effective potential

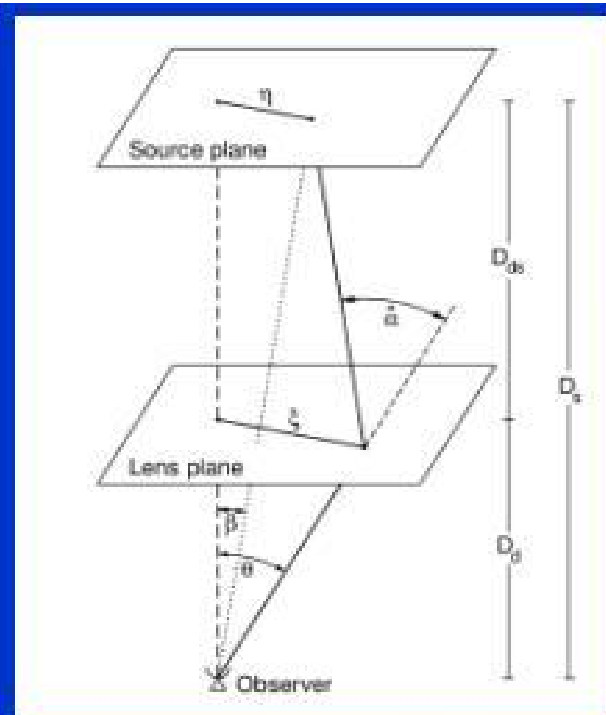
$$\psi(\vec{\alpha}) = \frac{1}{\pi}\int \kappa(\vec{\alpha}) \, \ln\left|\vec{\theta} - \vec{\theta}'\right| \, d^2\theta'$$

- Lens Mapping & Magnification Tensor M

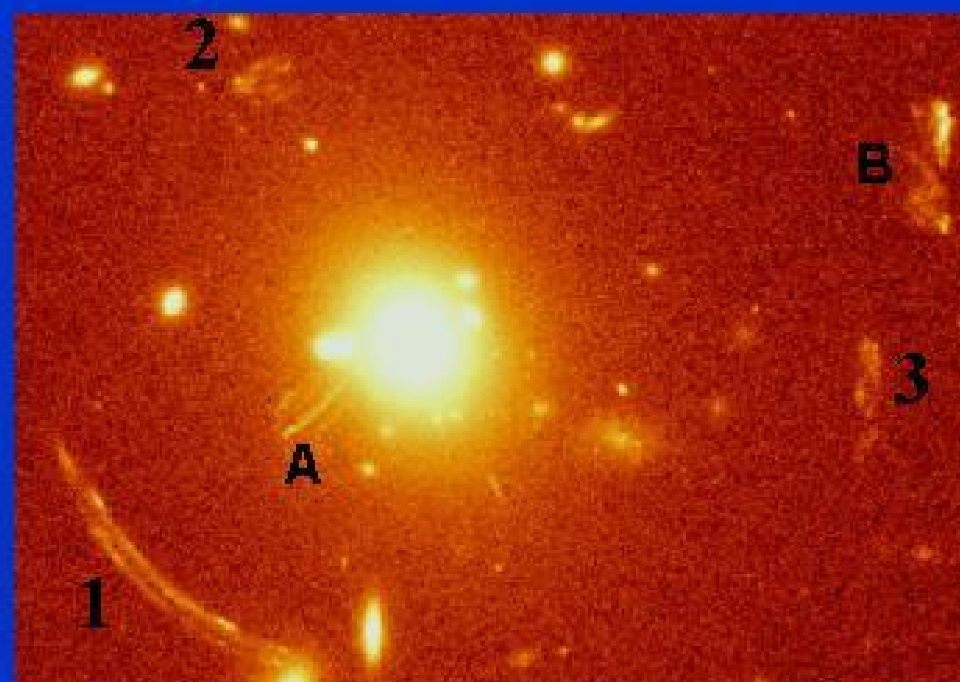
$$A = \frac{\partial\vec{\beta}}{\partial\vec{\theta}} = \left(\delta_{ij} - \frac{\partial^2\psi\left(\vec{\theta}\right)}{\partial\theta_i\partial\theta_j}\right) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix} = M^{-1}$$

- Convergence, Shear

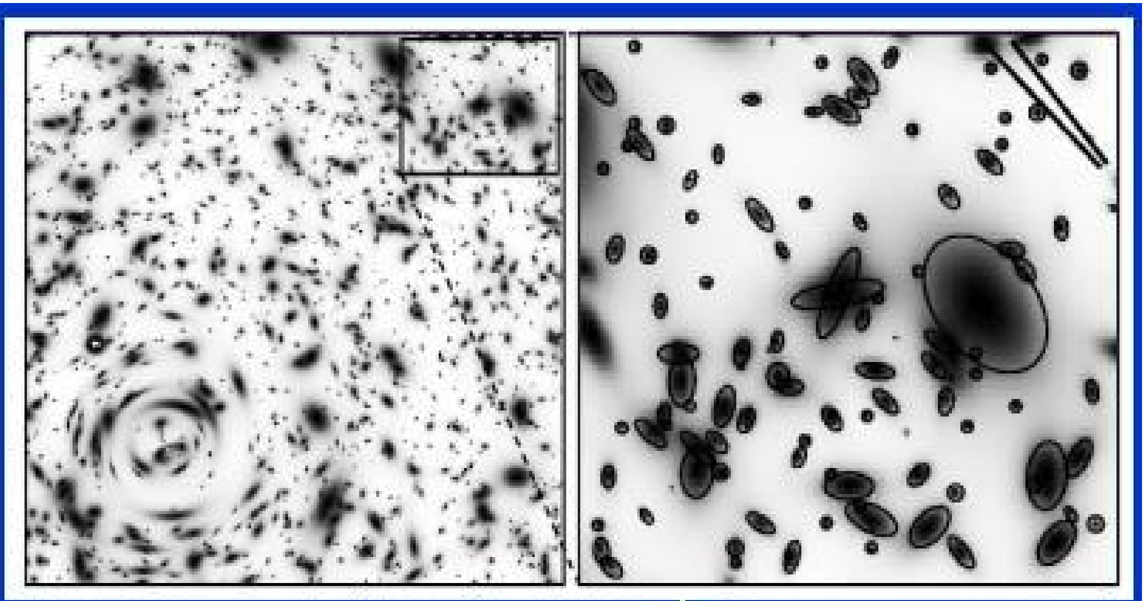
$$\begin{cases} \kappa = \frac{1}{2}(\psi_{11}+\psi_{22}) \\ \gamma_1\left(\vec{\theta}\right) = \frac{1}{2}(\psi_{11}-\psi_{22}) = \gamma\left(\vec{\theta}\right)\cos\left[2\Phi\left(\vec{\theta}\right)\right] \\ \gamma_2\left(\vec{\theta}\right) = \psi_{12} = \gamma\left(\vec{\theta}\right)\sin\left[2\Phi\left(\vec{\theta}\right)\right] \end{cases}$$



Gravitational lensing



From galaxy shape to shear signal



$$\hat{\boldsymbol{\alpha}} = \frac{2}{c^2} \int \nabla_\perp \Phi \; \mathrm{d}l$$

- $\kappa(\boldsymbol{\theta}) = 1/2\, [\Psi_{11} + \Psi_{22}] = \Sigma(\boldsymbol{\theta}) / \Sigma_c$
- $\gamma_1(\boldsymbol{\theta}) = 1/2\, [\Psi_{11} - \Psi_{22}] = \gamma(\boldsymbol{\theta})\, cos[2\Phi(\boldsymbol{\theta})]$
- $\gamma_2(\boldsymbol{\theta}) = \Psi_{12} = \gamma(\boldsymbol{\theta})\, sin[2\Phi(\boldsymbol{\theta})]$

$$\delta = \frac{2\gamma\,(1-\kappa)}{(1-\kappa)^2 + |\gamma|^2} = \frac{a^2 - b^2}{a^2 + b^2}$$

$$M_{ij} = \frac{\int I(\boldsymbol{\theta})\, \theta_i\, \theta_j\, \mathrm{d}^2\theta}{\int I(\boldsymbol{\theta})\, \mathrm{d}^2\theta}$$

$$\frac{a^2 - b^2}{a^2 + b^2}$$

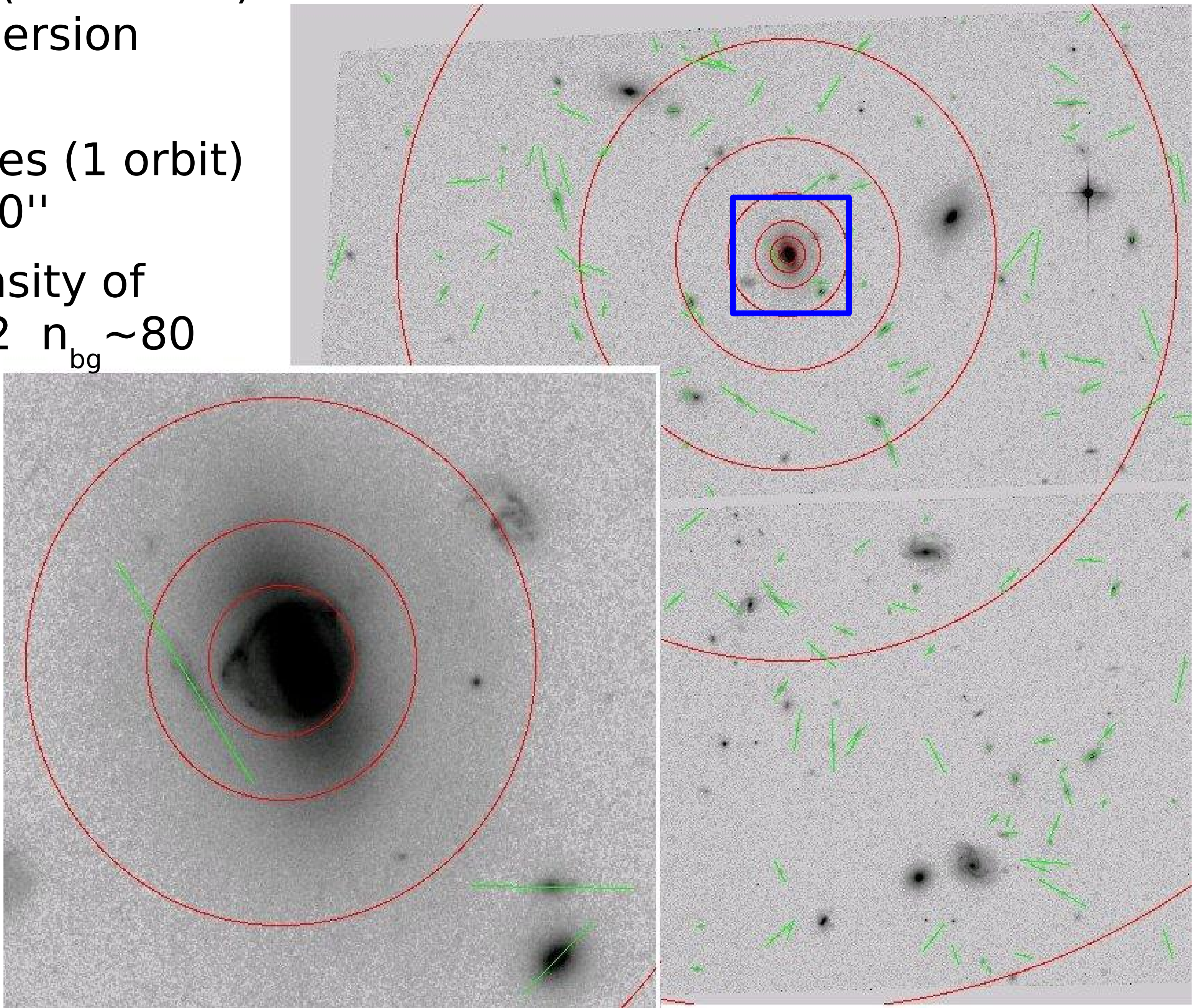
PSF anisotropy correction with stars

lensing + intrinsic ellipticity of each galaxy

$$\boldsymbol{\delta} \sim 2\gamma = \boldsymbol{\varepsilon}_s \; \ldots\ldots + \boldsymbol{\varepsilon}_i + \text{noise} + \text{systematics} \ldots.$$

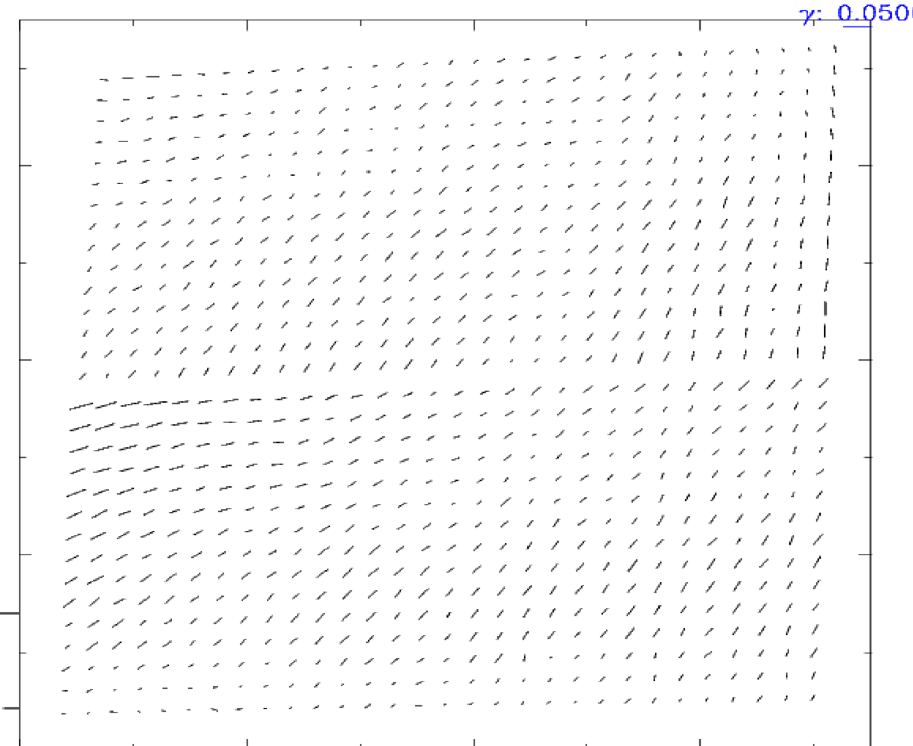
Weak lensing Data

- So far, 18 lenses ($z \sim 0.1$-0.3) with velocity dispersion $\sigma \sim 200$-330 km/s
- F814W/ACS images (1 orbit) with fov 200''x200''
- Huge surface density of sources $I_{AB} < 26.2$ $n_{bg} \sim 80$ arcmin^{-2}.

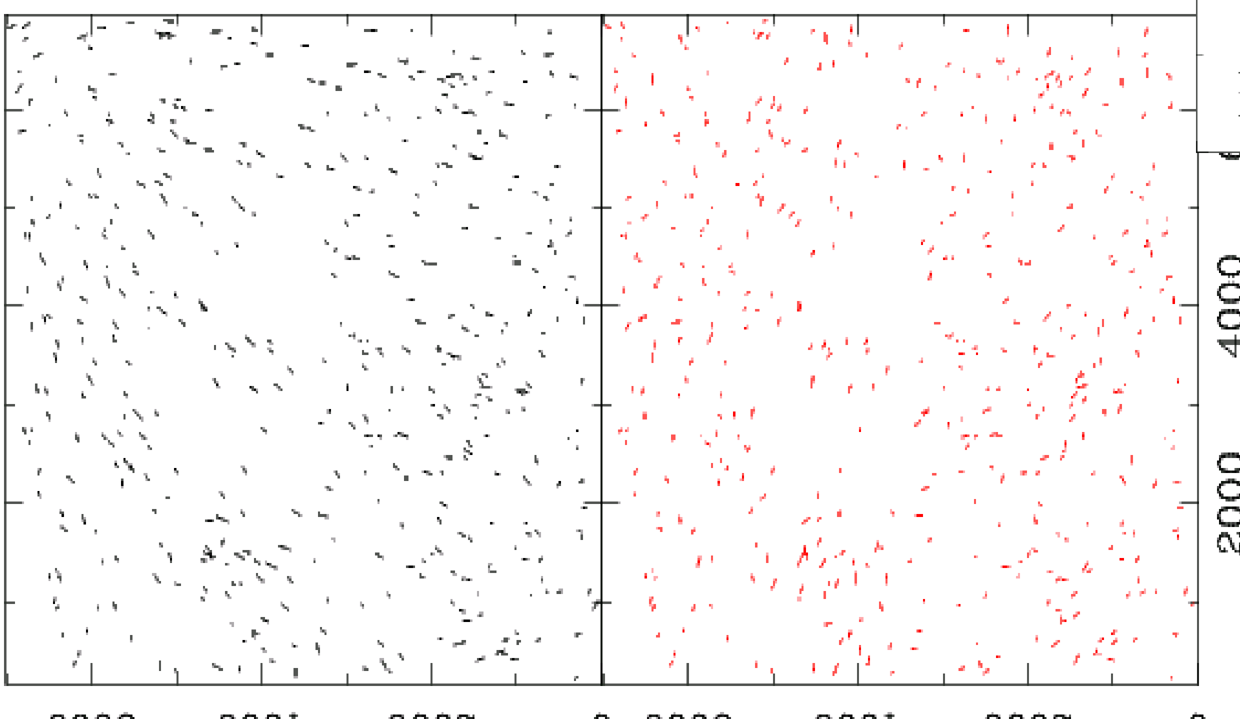


Correction of systematics: PSF

- Galaxies blurred by complex ACS PSF
- Difficult correction: time variations!
- Too few stars: need a model for PSF field. Stars and galaxies are corrected accordingly.
- Isotropic smearing also corrected (KSB method)



Mock TinyTim
(courtesy Rhodes & Massey)

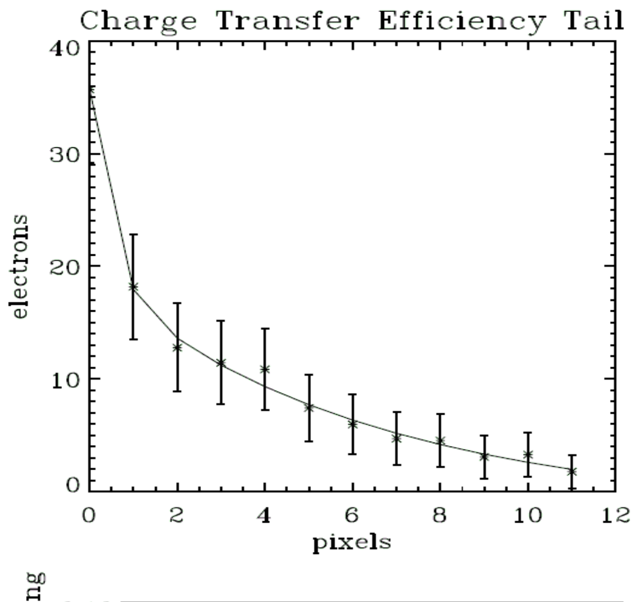


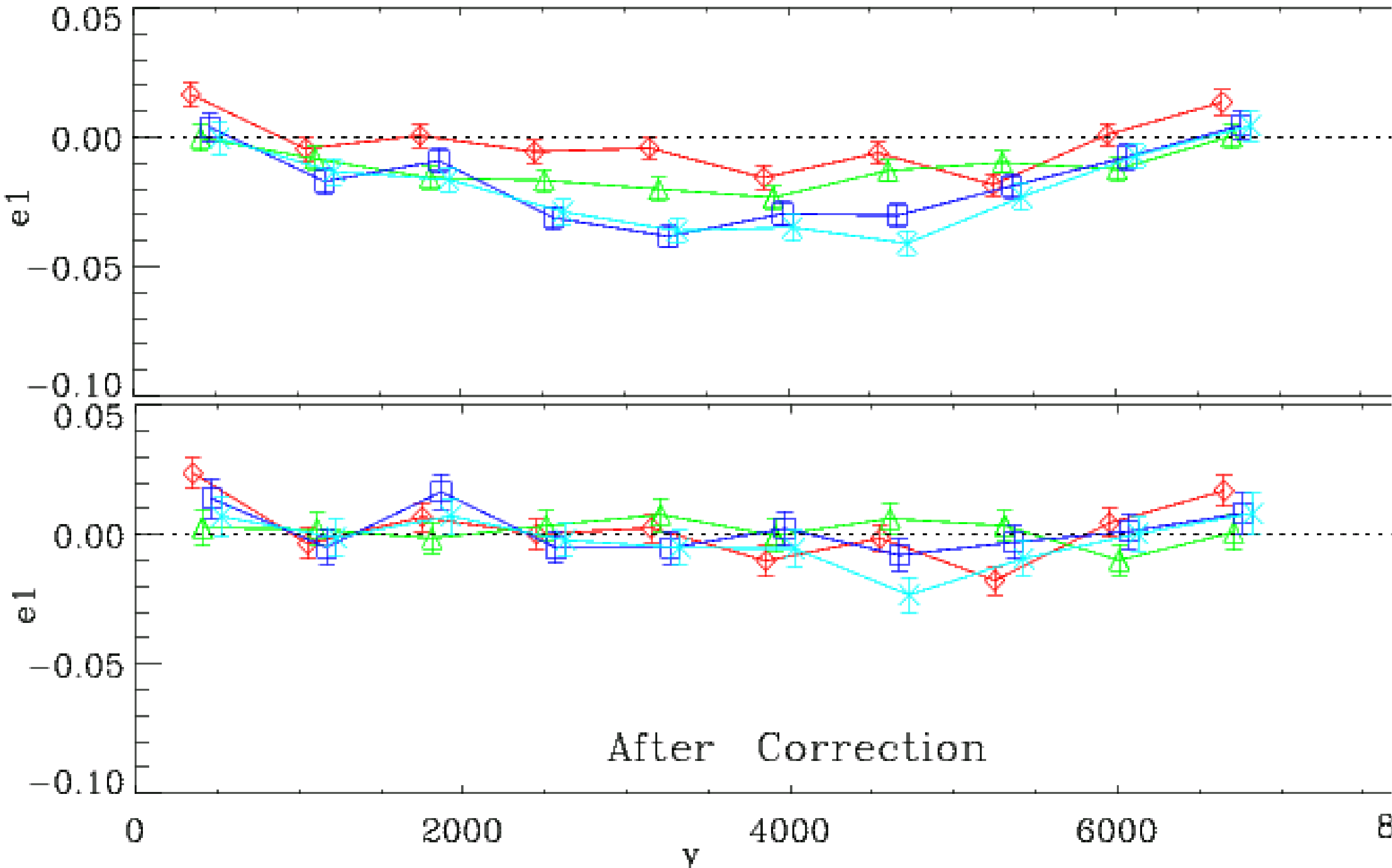
No patterns in residuals

<e>=0.000± 0.007

Correction of systematics: CTE

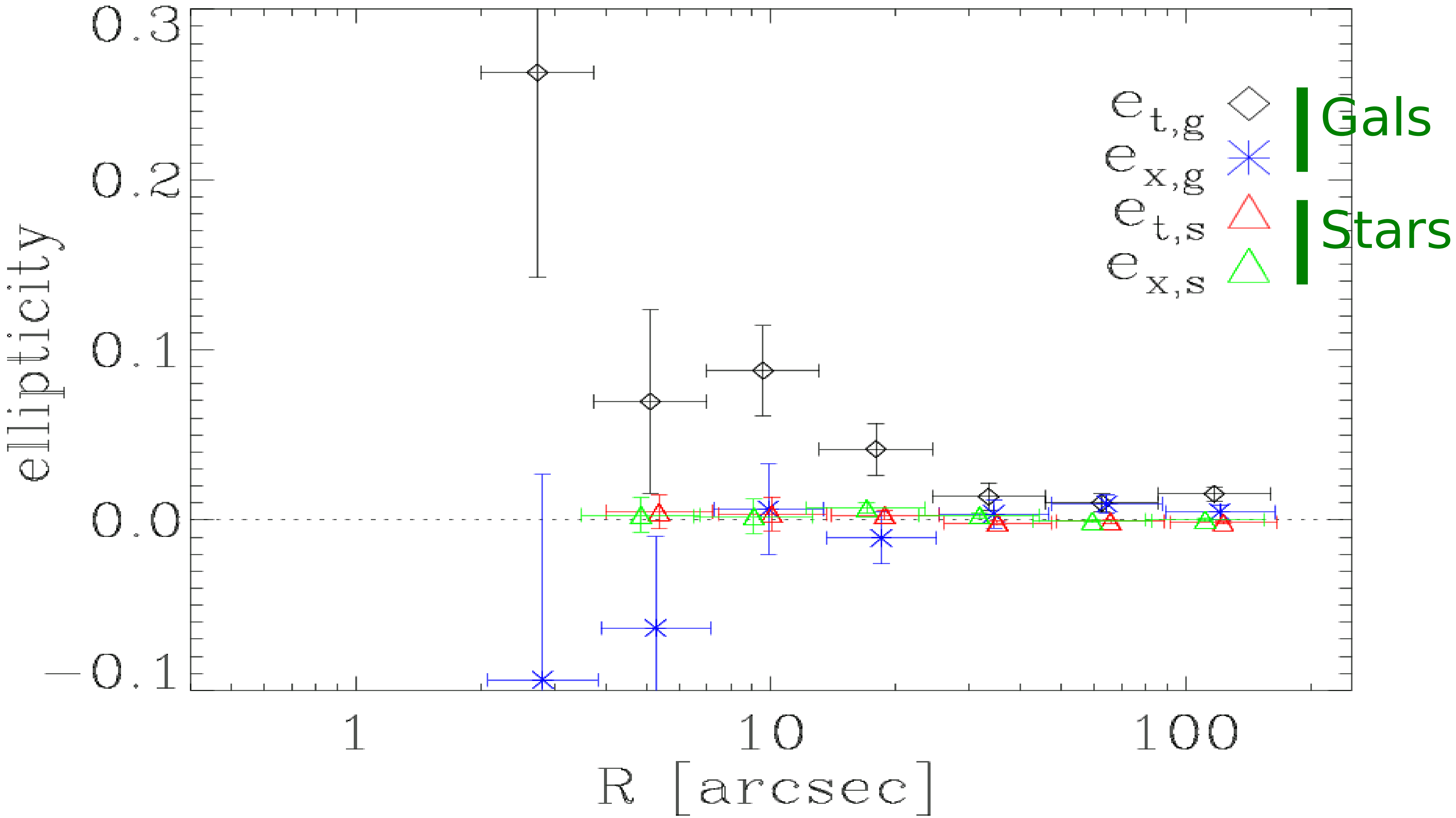
- During CCD readout, charges are delayed. Cosmic rays produce defects that retain e^- *producing a tails along y axis (i.e. negative e_1 'shear')*
- More pronounced close to gap between CCDs (far from readout)
- Severe for faint objects
- Calibrated in COSMOS survey (Rhodes et al.06)





Test for Residual Systematics

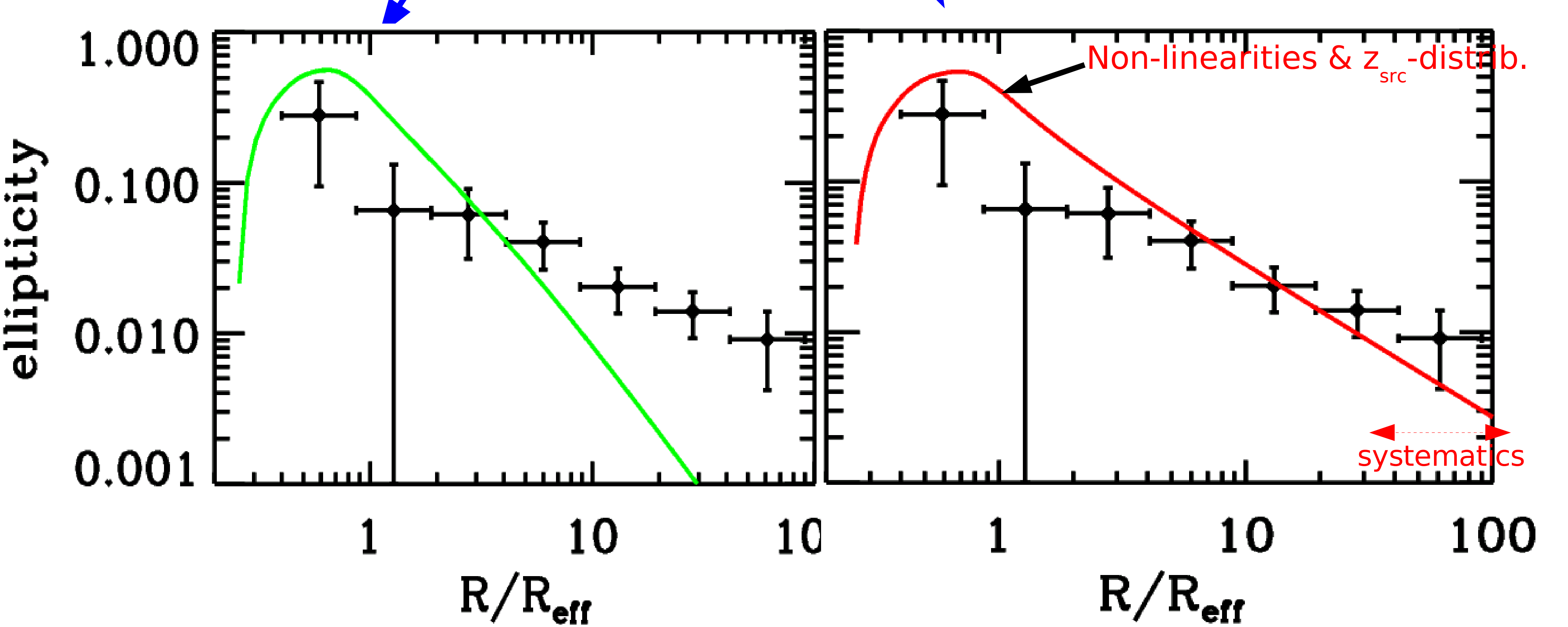
Shear split into tangential (+) and rotational (x) modes. For a circular lens, gravity only produces +.



Shear Profile

Mean tangential shear profile around the 18 lenses...

- Clear signal observed between 2 and 100'' *(No signal ruled out 7σ)*
- By construction, strong lensing is matched (using $\kappa(<R_{Ein})=1$) .
- Shear model rescaled by z-distrib of sources $(D_{ls}/D_s)_{WL} \neq (D_{ls}/D_s)_{SL}$
- Constant M/L ruled out whereas SIS OK.

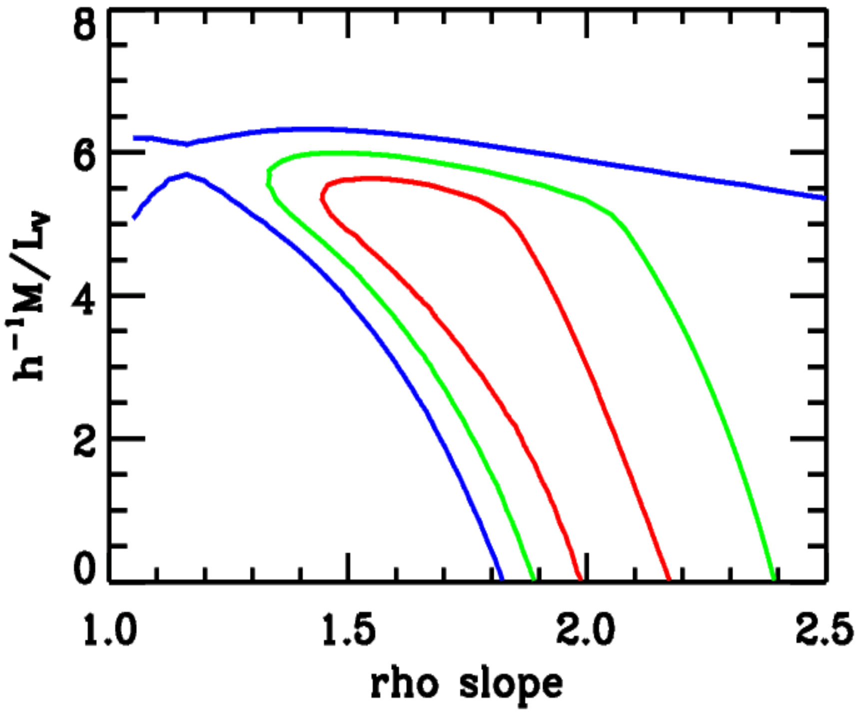


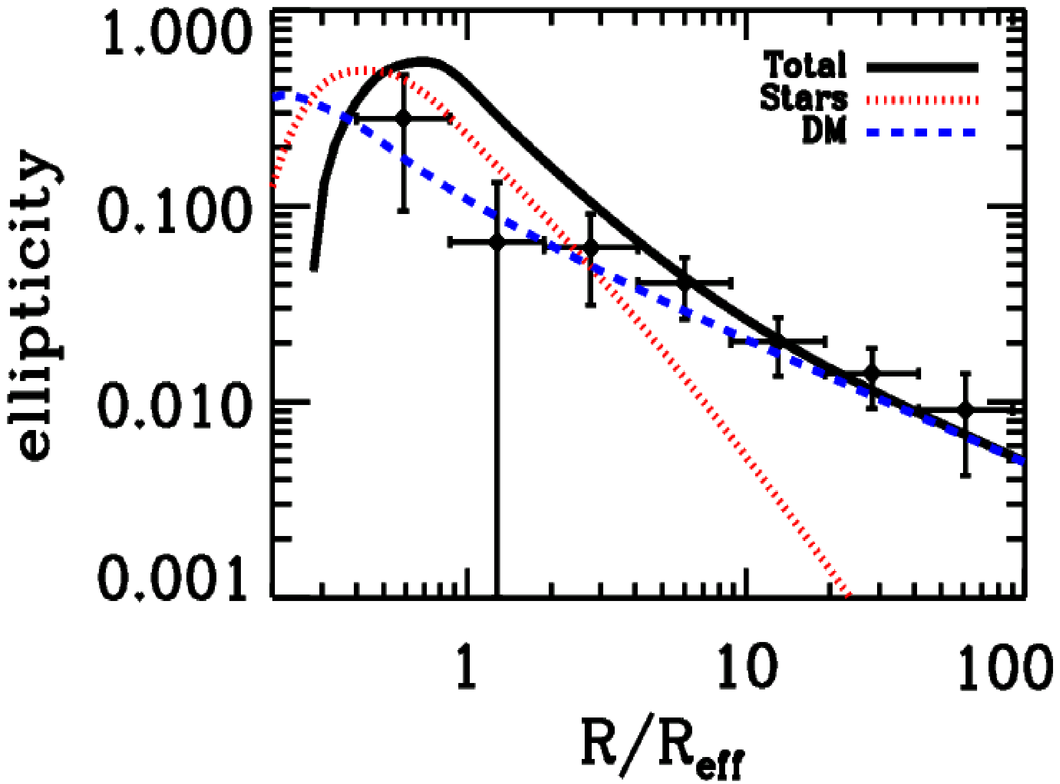
S+W lensing Modelling

Single power law for Dark Matter (free slope).

+ De Vaucouleur Stellar component (free M_*/L).

SL-consistent by construction.





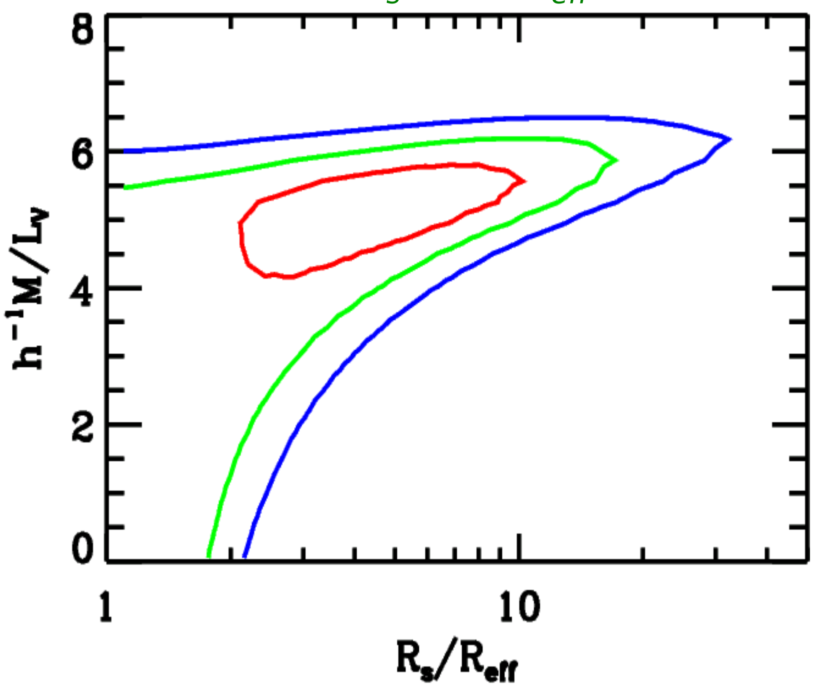
Slow decline at large scale (best fit slope $\rho \propto r^{-1.6+0.3-0.1}$):

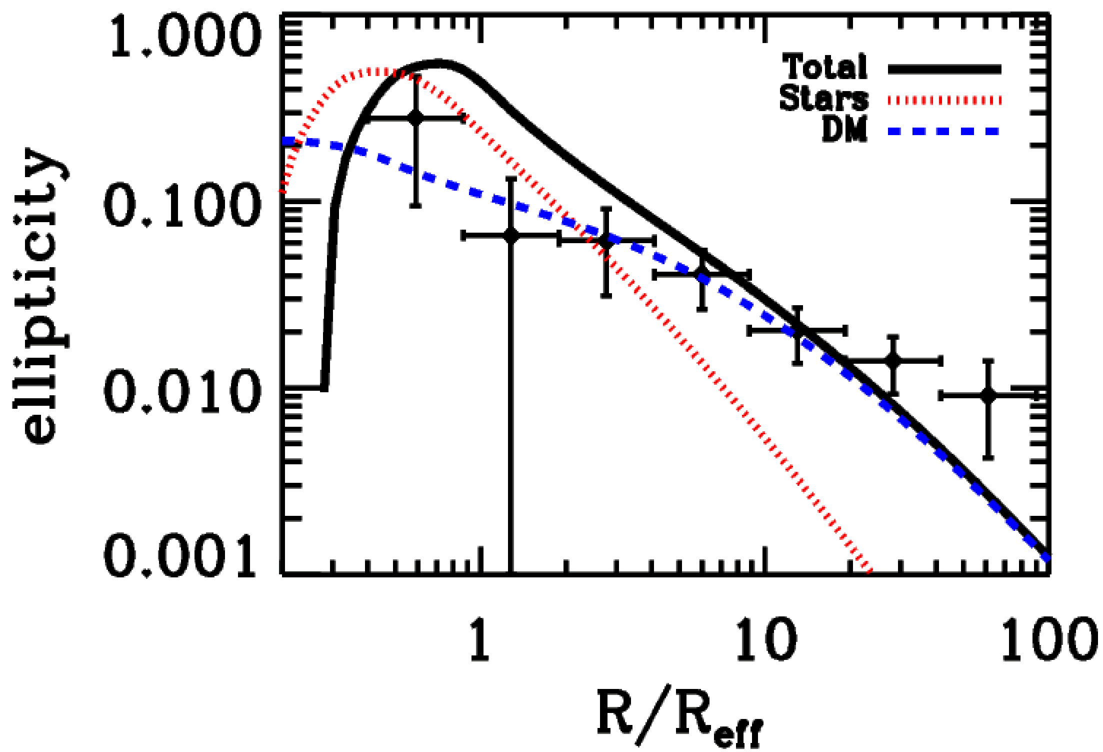
due to clustering (Sheldon et al 04 found $r^{-1.79\pm0.06}$) ?

NFW assuming scaling between R_s and R_{eff} (free R_s/R_{eff})

+ De Vaucouleur Stellar component (free M_*/L).

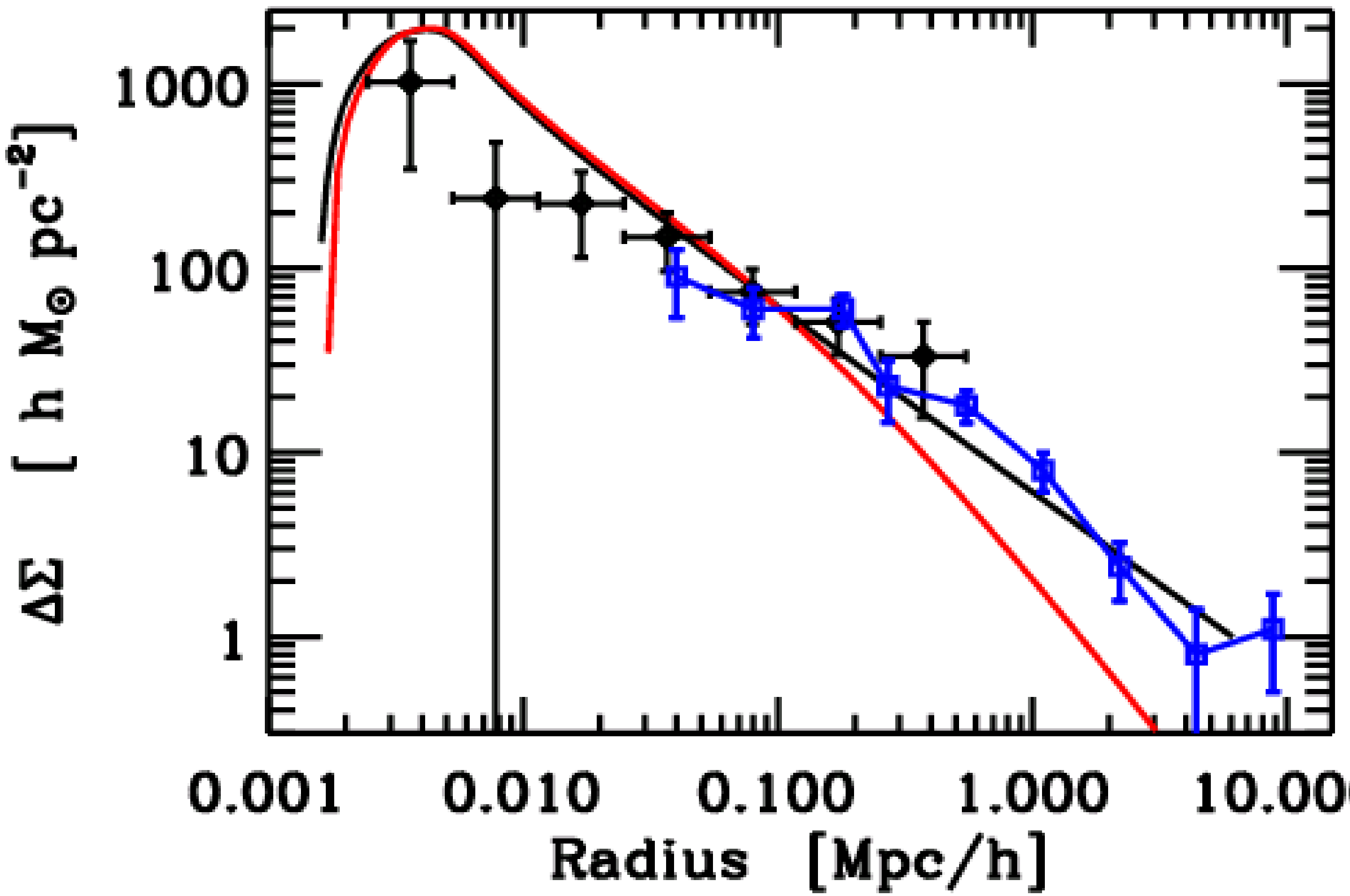
Best fit $R_s \sim 5\ R_{eff}$.





If constant Rs/Reff scaling applicable, we could infer concentration and M_{200} for each lens!

Consistent with Sheldon et al 2004 for σ_v>182 km/s
(and Mandelbaum et al. 2006)



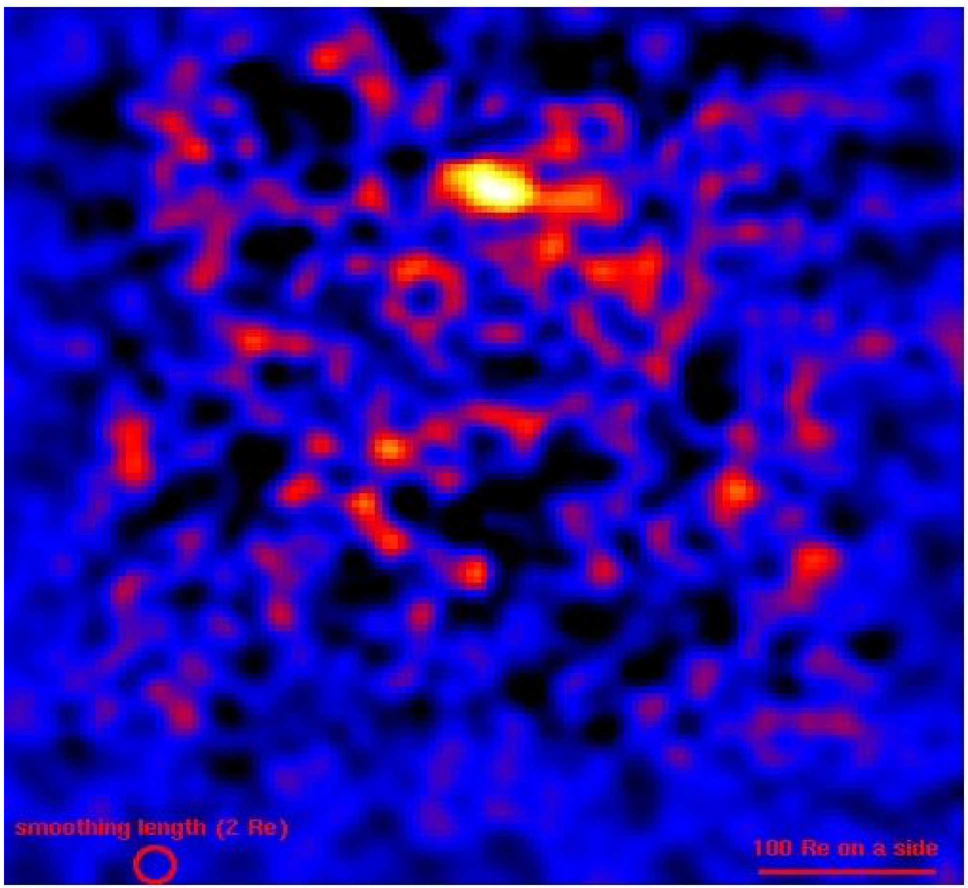
Large scale profile hopelessly isothermal. A new conspiracy!!

Non-NFW behaviour due to clustering (ξ_{gm}) ?

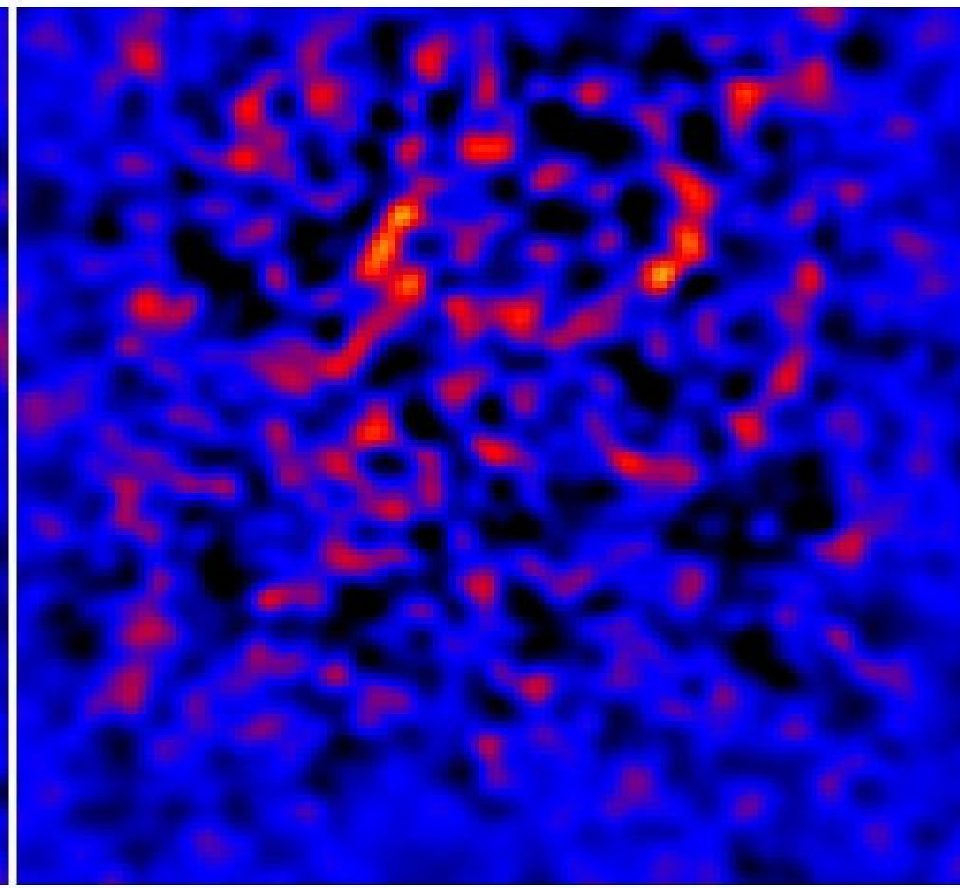
Mass reconstruction

From 2D shear field $\gamma(\theta)$ -> 2D convergence field $\kappa(\theta)$.

Convergence map (from 'E' modes)



Noise realization (from 'B' modes)



Are there evidences for DM halo ellipticity?

Conclusion & outlooks

- Preliminary results promising! Still working on a better control of systematics (lens envelope, dilution by satellites...)
- Improve the modelling (combine SL+WL+kinematics properly, adiabatic contraction?...)
- Total density profile still close to isothermal
- We do see where the dark matter begins and will see where it ends unless 2-halo term of gal-mass correlation function starts to dominate?
- Full sample (~80 lenses) shall then be split (low/mid z, low/high mass, environment...)
- Will we see the halo ellipticity?

Probing Dark Matter caustics with gravitational lensing.

Cols: R. Gavazzi, R. Mohayaee, S. Shandarin, B. Fort, S. Colombi, J. Touma

Gavazzi, Mohayaee, Fort 06
astro-ph/0506061

Introduction

The collisionless nature of Dark Matter implies a peculiar behaviour of the phase space distribution of DM particle *(governed by Vlasov+Poisson equations)*

$$\frac{\partial f(\vec{x},\vec{v})}{\partial t} + v_i \frac{\partial f(\vec{x},\vec{v})}{\partial x_i} - \frac{\partial \Phi}{\partial x_i} . \frac{\partial f(\vec{x},\vec{v})}{\partial v_i} = 0$$

$$\nabla^2 \Phi = 4\pi G \int f(\vec{x},\vec{v}) \mathrm{d}^3 v$$

From small cosmological perturbations, linear theory well suited but after shell crossing non linear effects are huge and funny things like 'caustics' occur!

We expect sharp *dark* density peaks if DM is COLD and COLLISIONLESS.

Like lensing, it is an exemple of mathematical catastrophes (eg. Arnold 86).

Dynamics of Collisionless fluids

In Lagrangian representation, a ''fluid'' element at q is displaced to x according to :

$$\vec{x} = \vec{q} + \vec{\nabla}_q \Phi(q) \delta t$$

Zeldovitch approx.

$$\rho(x) = \rho(q(x)) \left| \frac{\mathrm{d}x}{\mathrm{d}q} \right|^{-1}$$

We see caustics {x} coming from *closed* 'critical' manifolds {q}

Lowest order catastrophe (fold like!): $\rho \propto \delta x^{-1/2}$

Gravitational Lensing

The lens equation:

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

Magnification

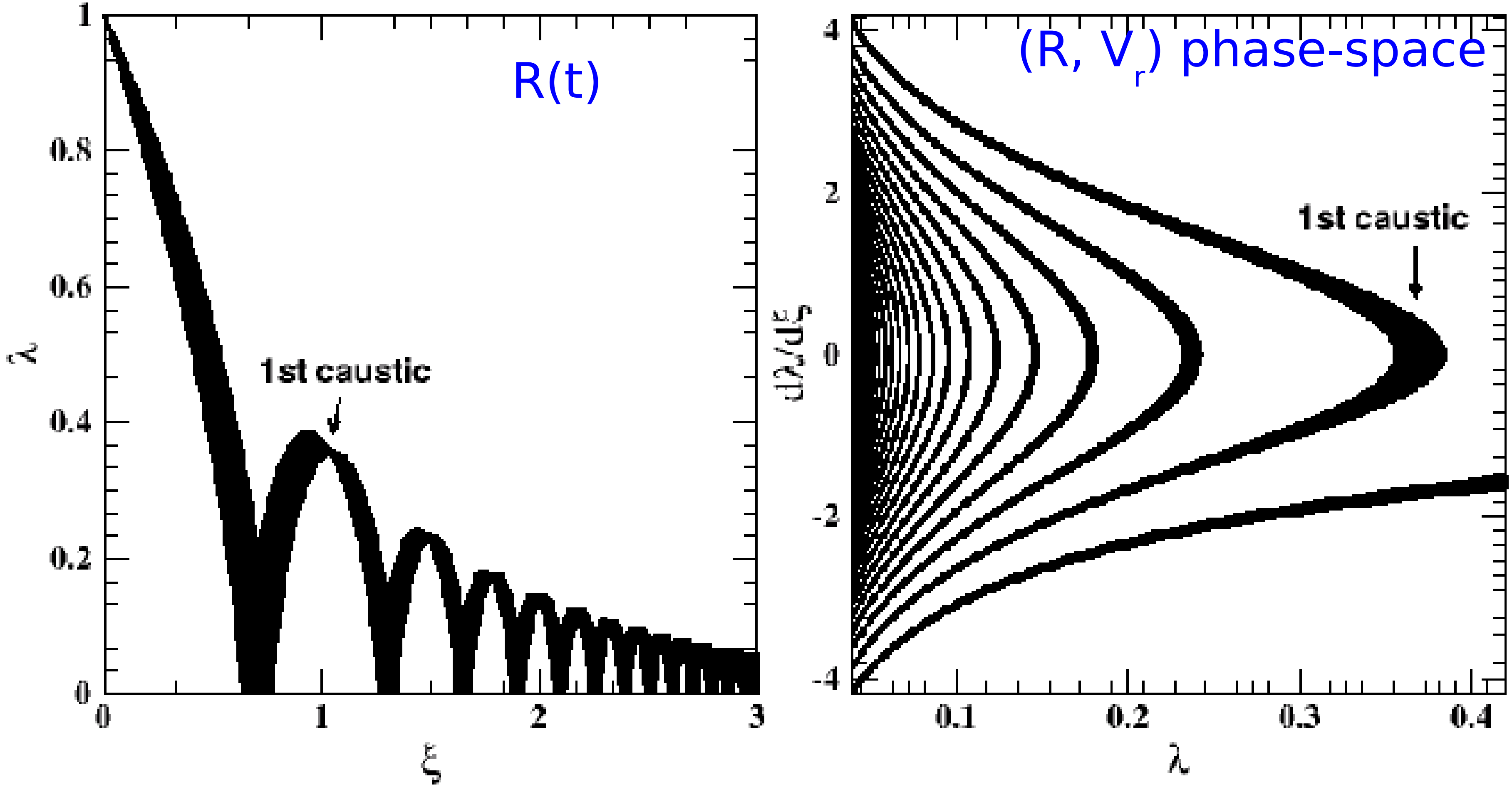
$$\mu(\theta) = \left| \frac{\mathrm{d}\beta}{\mathrm{d}\theta} \right|^{-1}$$

We see *closed* critical curves {θ} cast into caustics {β}

Close to fold caustics: $\mu \propto \delta\beta^{-1/2}$

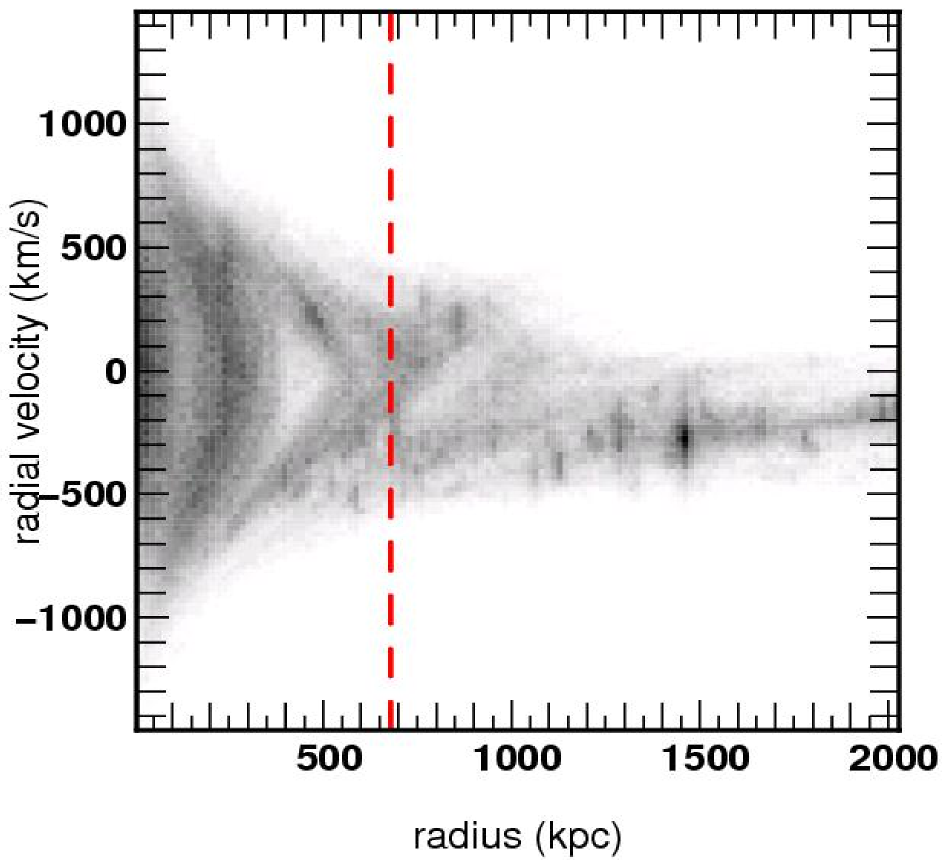
Spherical collapse

Secondary infall model (Bertschinger 85):



Thickness of ribbon: CDM temperature ($T \propto a^{-2}$, ~ few cm/s for axions, neutralinos)

Phase-space density in N-body simulations

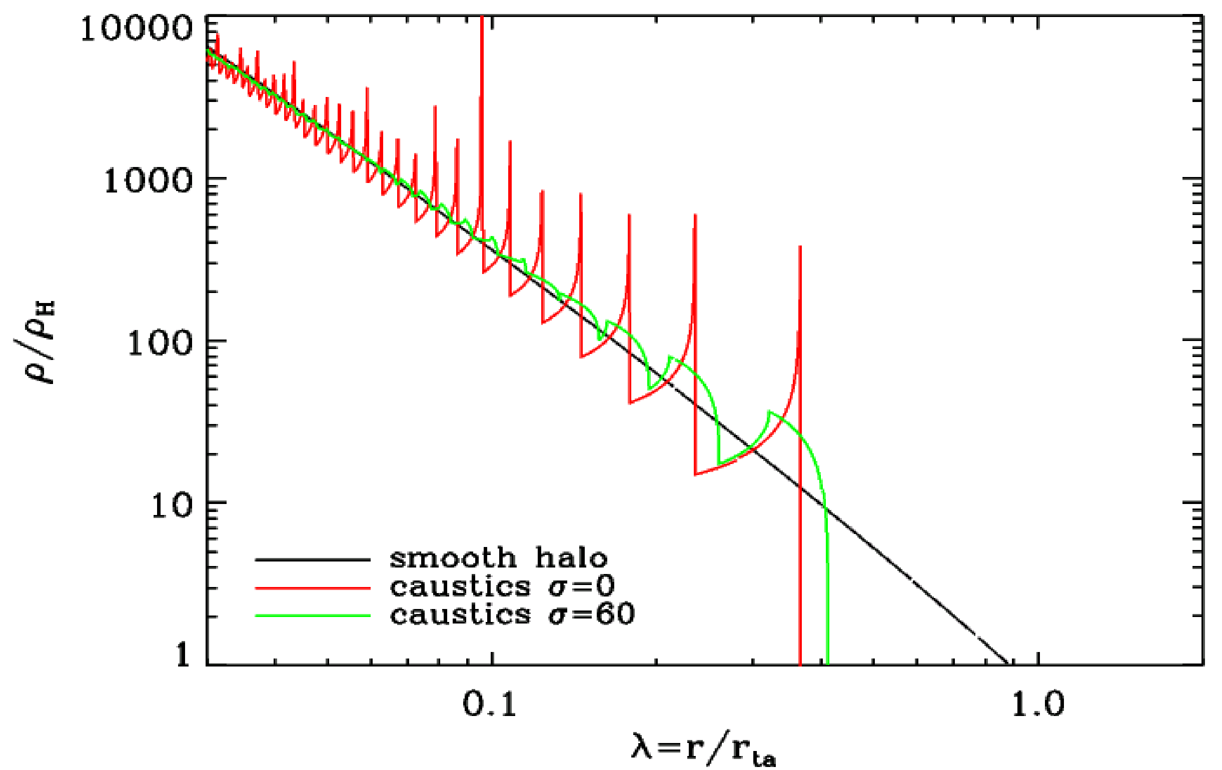


Courtesy S. Colombi, D. Aubert

Some movies!

Courtesy Ed Bertschinger

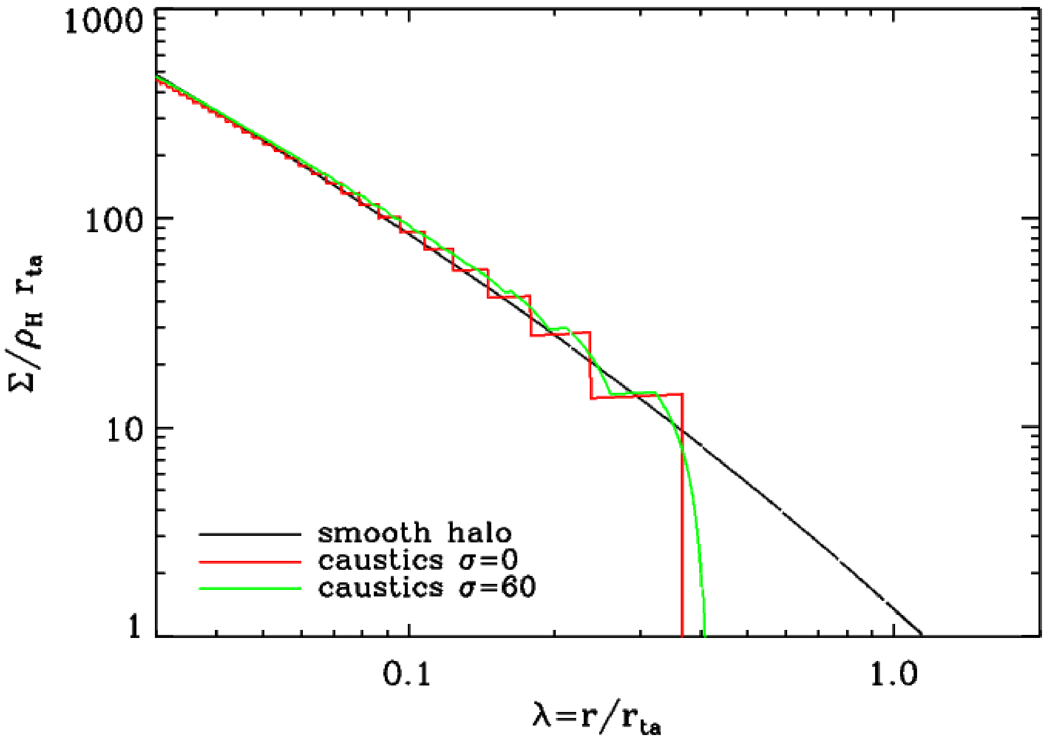
1. Simplified N-body (small scale power suppressed)
2. The phase space density
3. Spatial density (radial profile)

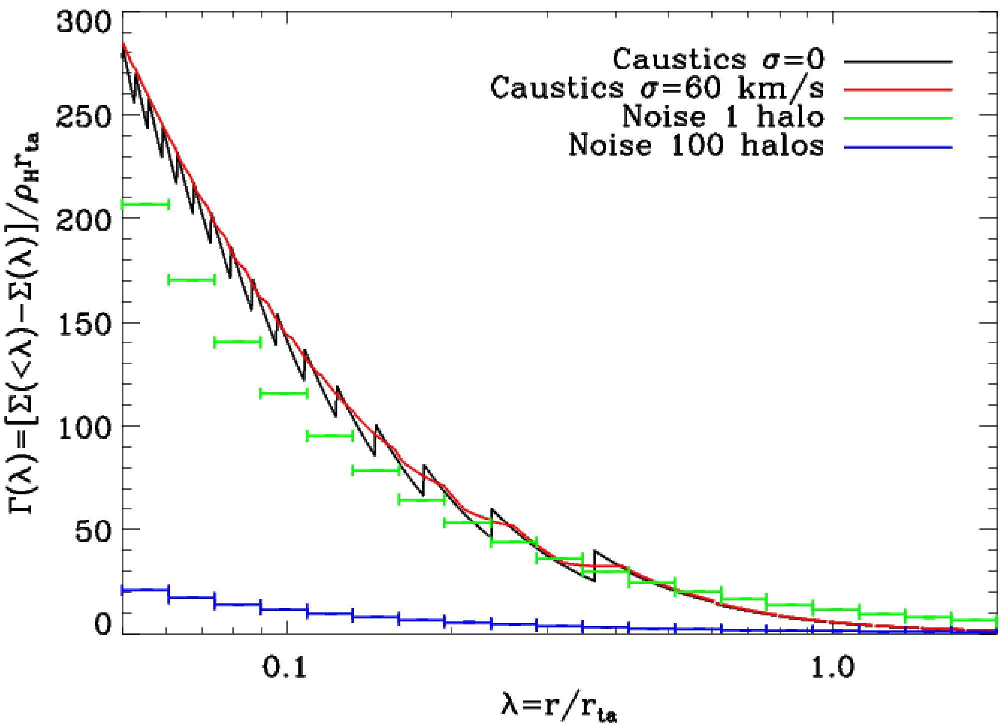


$\rho \propto \delta x^{-1/2}$

Turnaround radius ~ 2 r_{vir}

Could lensing probe them?





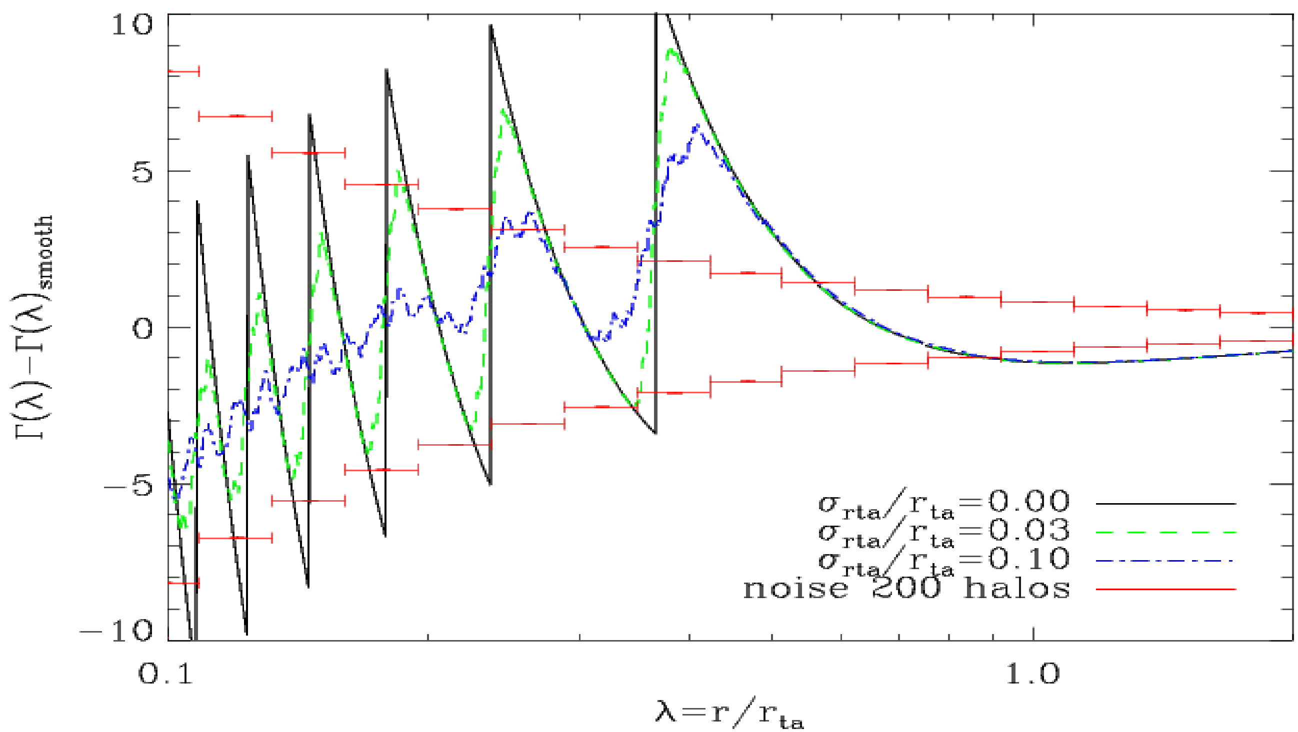
Projected density Σ not so sharp (because $\rho \propto r^{-1/2}$)

This kind of caustics won't produce strong lensing

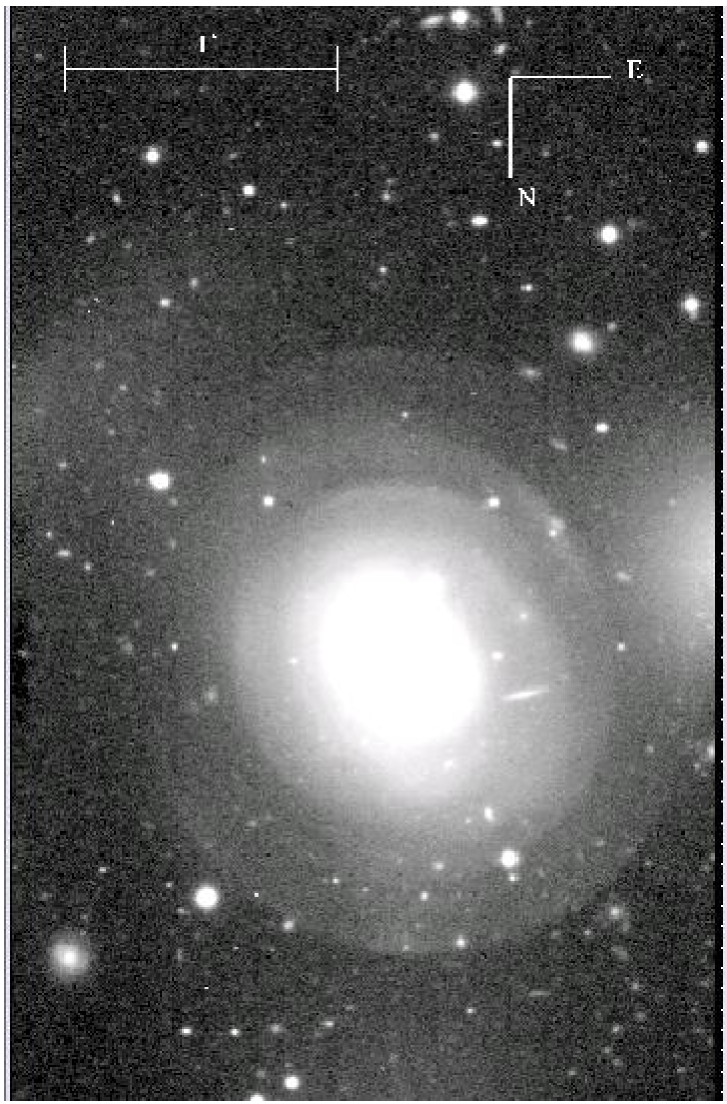
But weak lensing may see sawtooth patterns on shear profile...

By stacking cluster size halos!

- With about 200 z~0.3 clusters observed from ground (60 from space) with wide field images (to reach r_{vir}), could put constraints on existence and shape of caustics
- Test whether CDM temperature < 20 km/s (still quite far from constraints for DM candidates)
- We need a proper rescaling and know R_{vir} to a few % accuracy! (possible with weak lensing + X-rays data)



Conclusion



- Caustics are strong prediction of collisionless and coldness of CDM and should exist if we believe Liouville theorem. Modified gravity could not produce caustics!!!
- In shell galaxies (collisionless stellar systems) we see such features!
- Lensing is among the best ways to detect them (gas has nothing to do in caustics)!
- We are also looking at γ-ray annihilation (ρ^2 makes caustics emissivity highly singular!!)
- Simulations help addressing more realistic situations! Go beyond N-body with continuous Vlasov solvers (Alard&Colombi 05)