Elliptical galaxies as gravitational lenses

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Outline

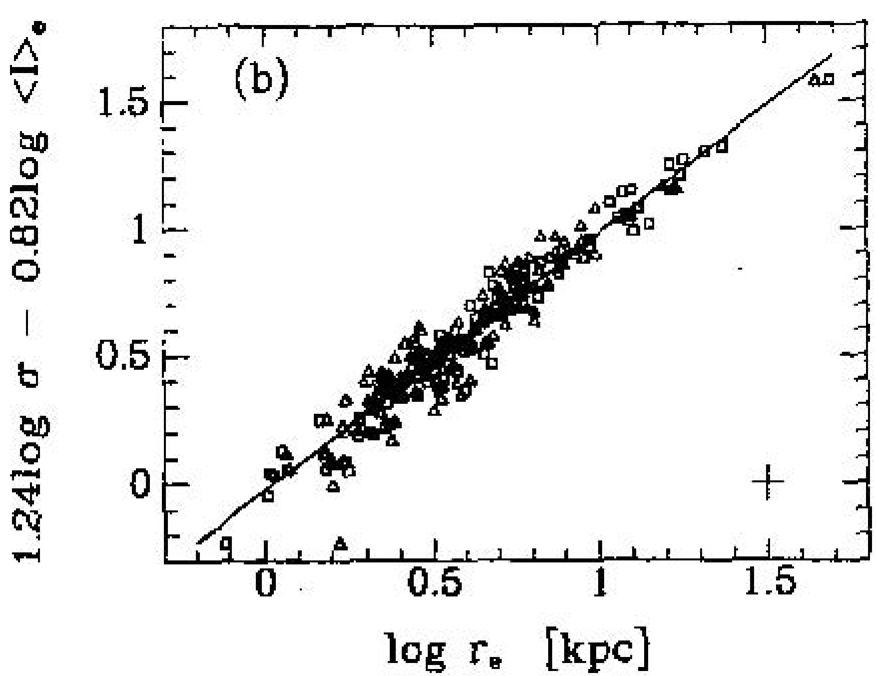
- Issues on Early-Type Galaxies (ETGs)
- Gravitational lensing, the basics
- SLACS: presentation & main results, *Weak Lensing*
- How to go beyond SLACS with the SL2S
- Conclusion

(Cosmology with lens ETGs ?)

Introduction

Properties of Ellipticals (~ETG~spheroids):

- Massive and Old stellar populations
- Tight correlations (velocity dispersion, luminosity, color, size, metallicity, SMBH mass): *eg* Fundamental Plane



Dressler et al. 1987; Djorgovski & Davis 1987; Bender Burstein & Faber 1992; Jorgensen et al. 1996

– Gives "effective M/L" at "effective mass" ($M_* = 5\sigma^2 R_e / G$),

– the FP reads $M_*/L \sim M_*^{0.25}$ *(tilt)*

– Partial explanations:

- Stellar population trends ('downsizing')
- Dynamical trends. More dark matter

How come the scaling relations? And why are they so tight?

Many sources of scatter (stellar pop. effects, DM content, environment) but somehow, baryons and DM *"conspire"* to preserve correlation.

Not 'scale free': Star formation history, mass build-up depend on final mass. *Stellar and DM density profiles of ETGs act as tests of the formation process.*

Most studies of high-z ETGs measure their star formation history or demographics

What about dynamical properties? Relation halo/bulge over cosmic time?

What can lensing do for us?

- Allows us to accurately weigh $0.01<z<1$ lens ETGs.
- Combination with stellar kinematics very powerful

Gravitational lensing (1)

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

- Lens equation

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

- Effective potential

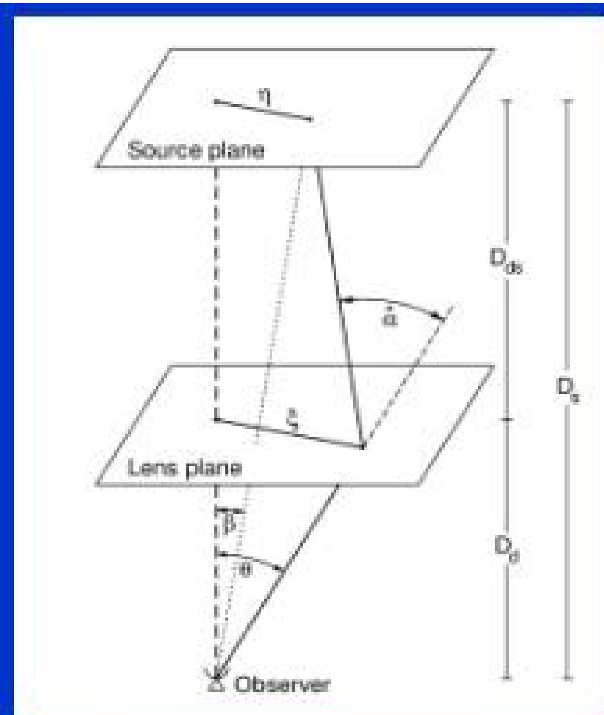
$$\psi(\vec{\alpha}) = \frac{1}{\pi}\int \kappa(\vec{\alpha}) \; \ln\left|\vec{\theta} - \vec{\theta}'\right| \; d^2\theta'$$

- Lens Mapping & Magnification Tensor M

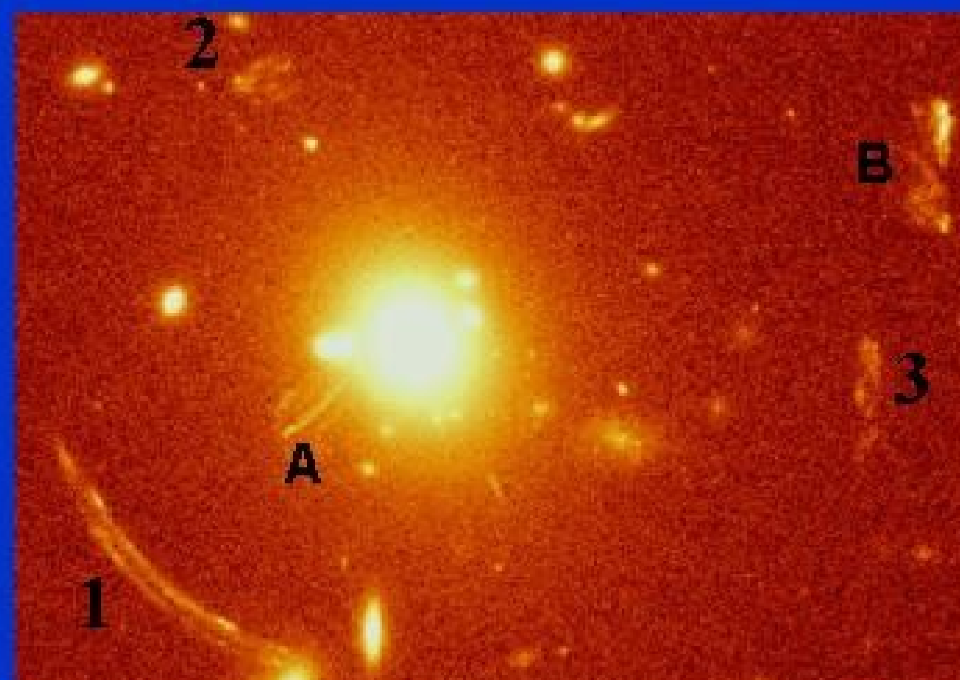
$$A = \frac{\partial\vec{\beta}}{\partial\vec{\theta}} = \left(\delta_{ij} - \frac{\partial^2\psi(\vec{\theta})}{\partial\theta_i\partial\theta_j}\right) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix} = M^{-1}$$

- Convergence, Shear

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

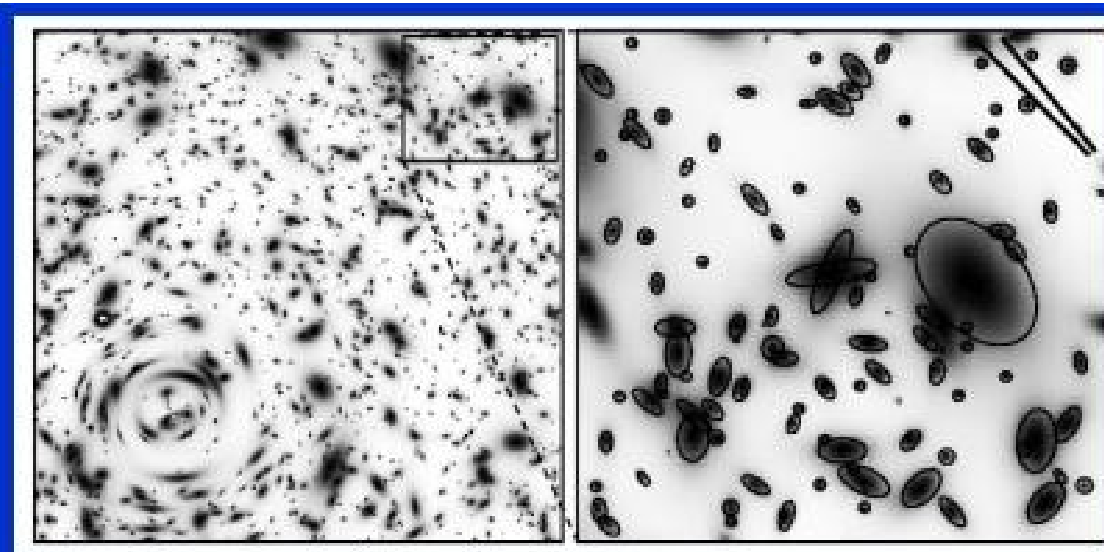


Gravitational lensing



Gravitational lensing (2)

From galaxy shape to shear signal



$$\hat{\alpha} = \frac{2}{c^2} \int \nabla_\perp \Phi \; dl$$

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

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

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

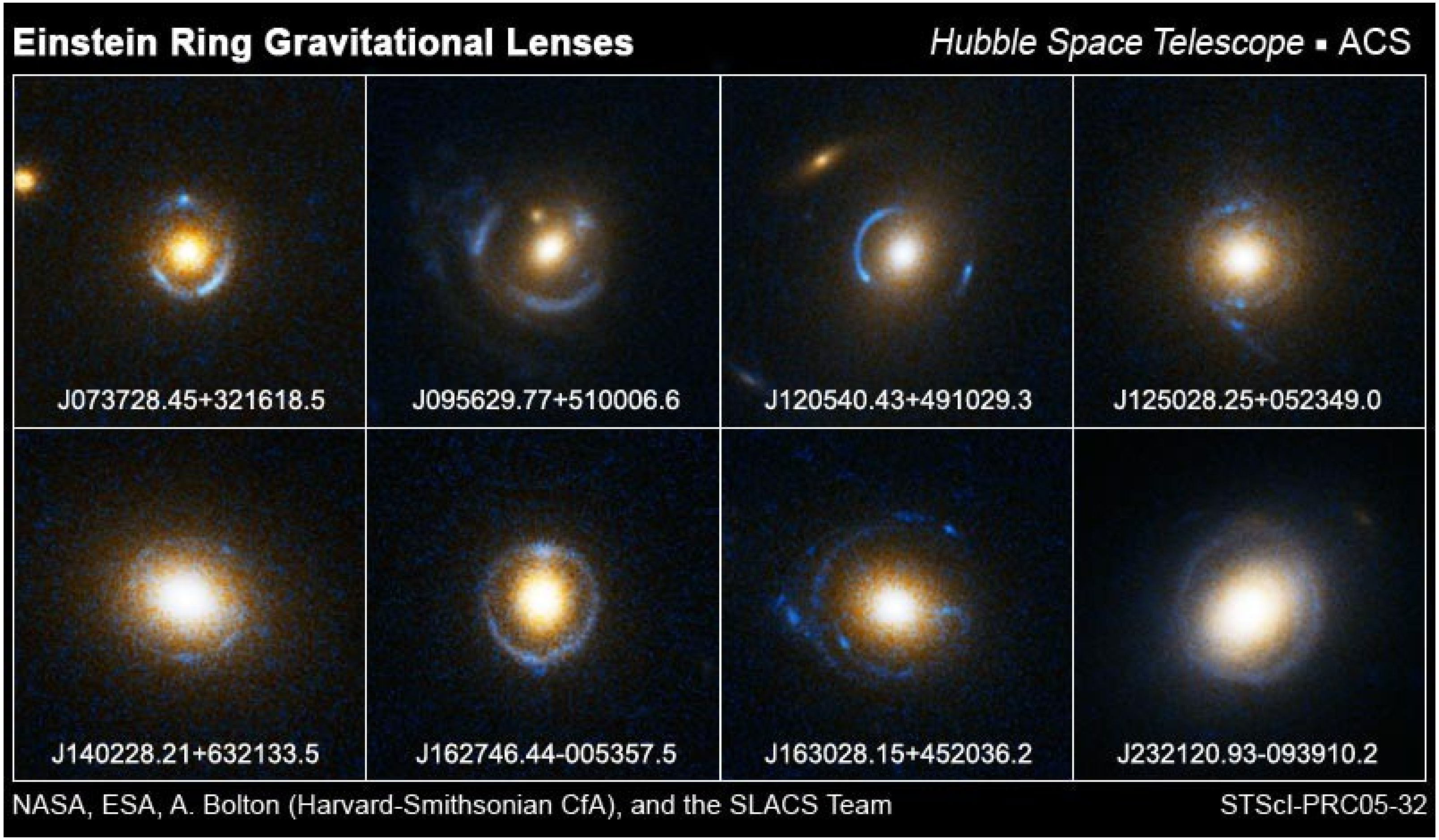
$$\frac{a^2 - b^2}{a^2 + b^2}$$

PSF anisotropy correction with stars

lensing + intrinsinc ellipticity of each galaxy

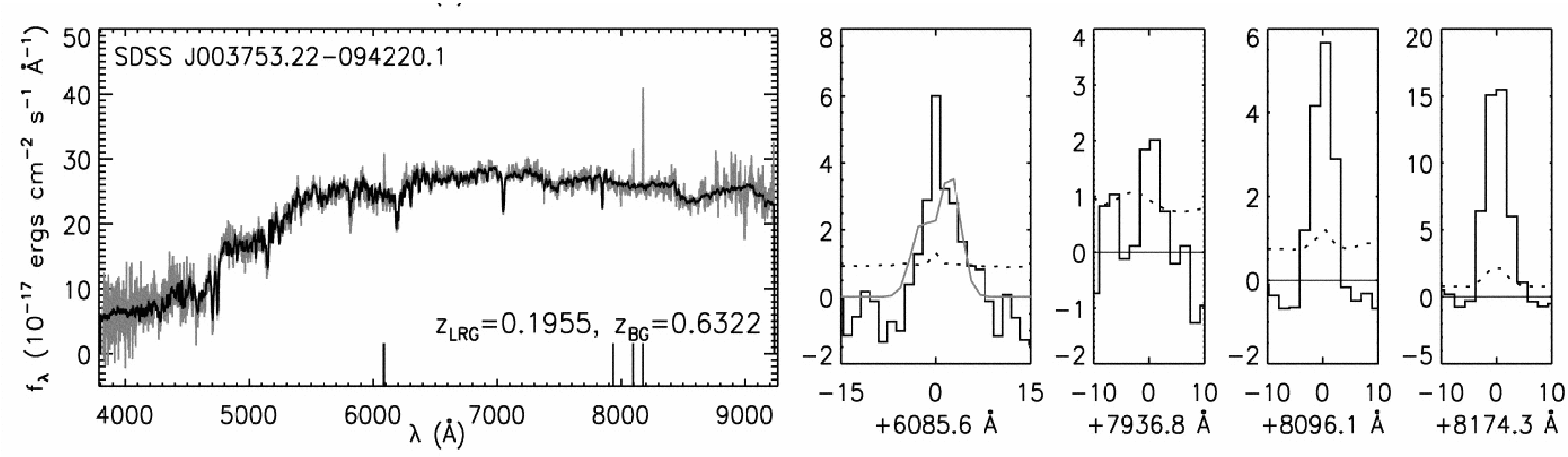
$\delta \sim 2\gamma = \varepsilon_s \;\ldots\ldots + \varepsilon_i$ + noise +systematics....

The Sloan Lens ACS Survey (SLACS)



Cols: T. Treu (UCSB), L. Koopmans (Kaptein), A. Bolton (CfA), S. Burles (MIT), L. Moustakas (JPL)

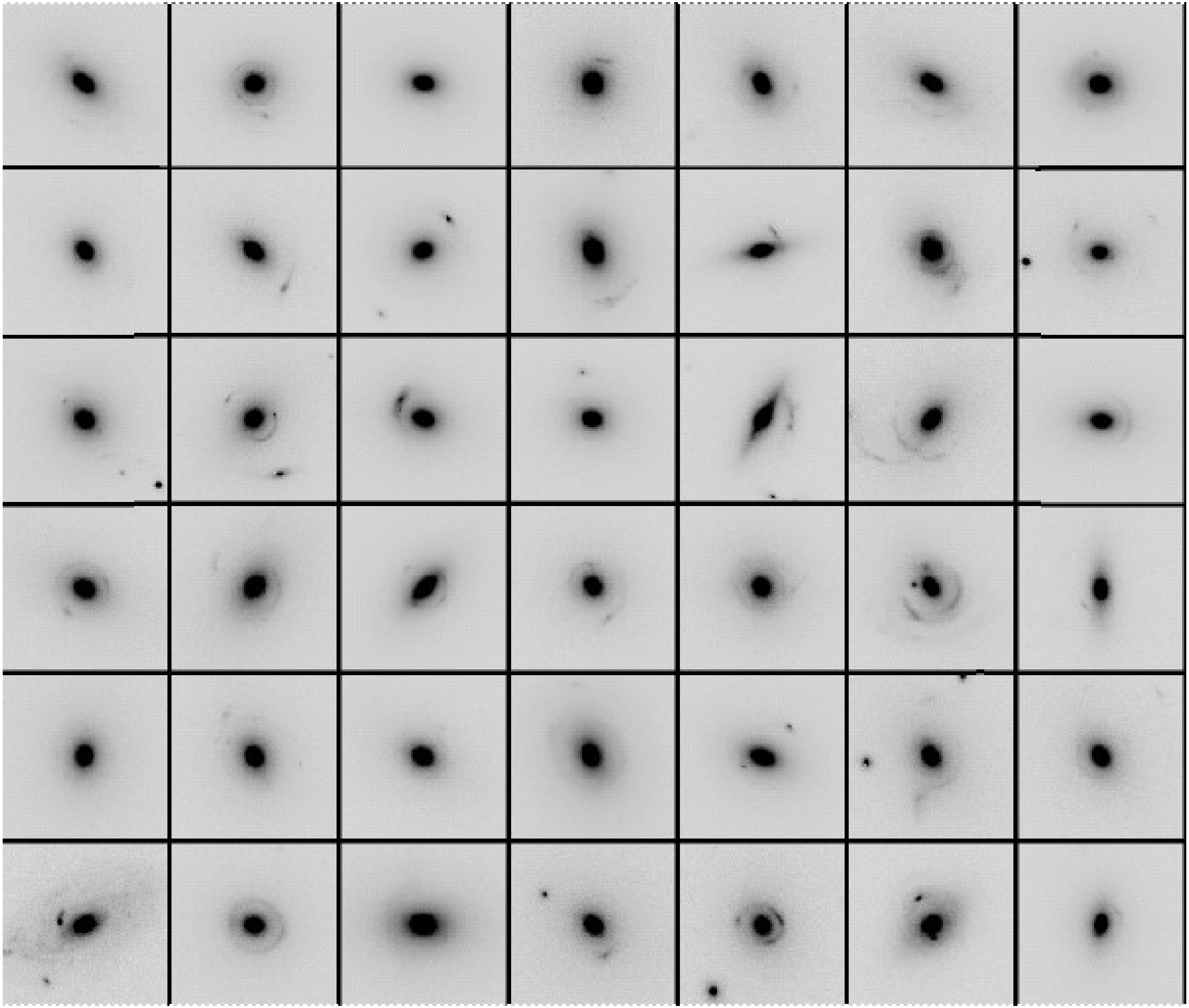
Spectroscopic selection

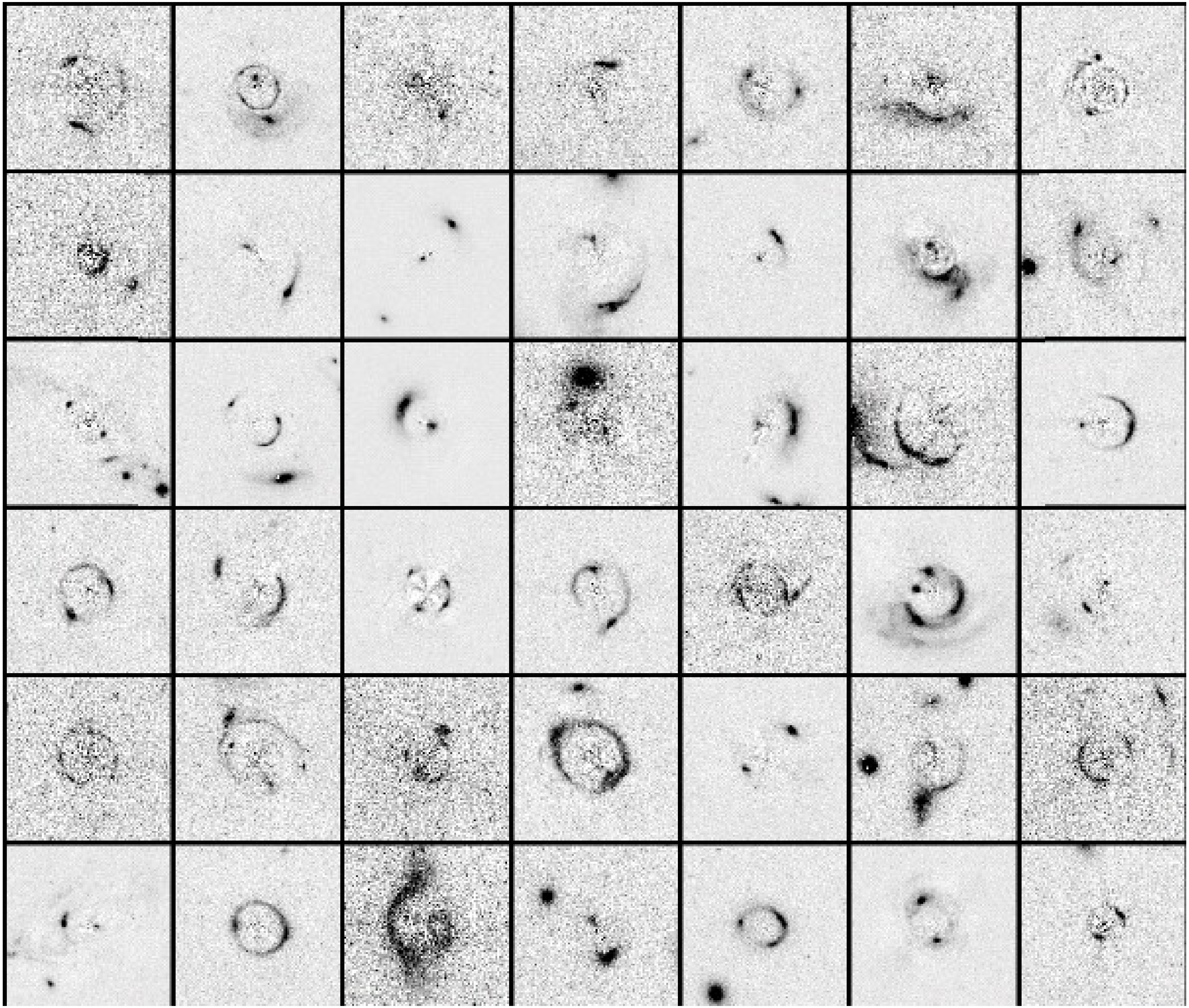


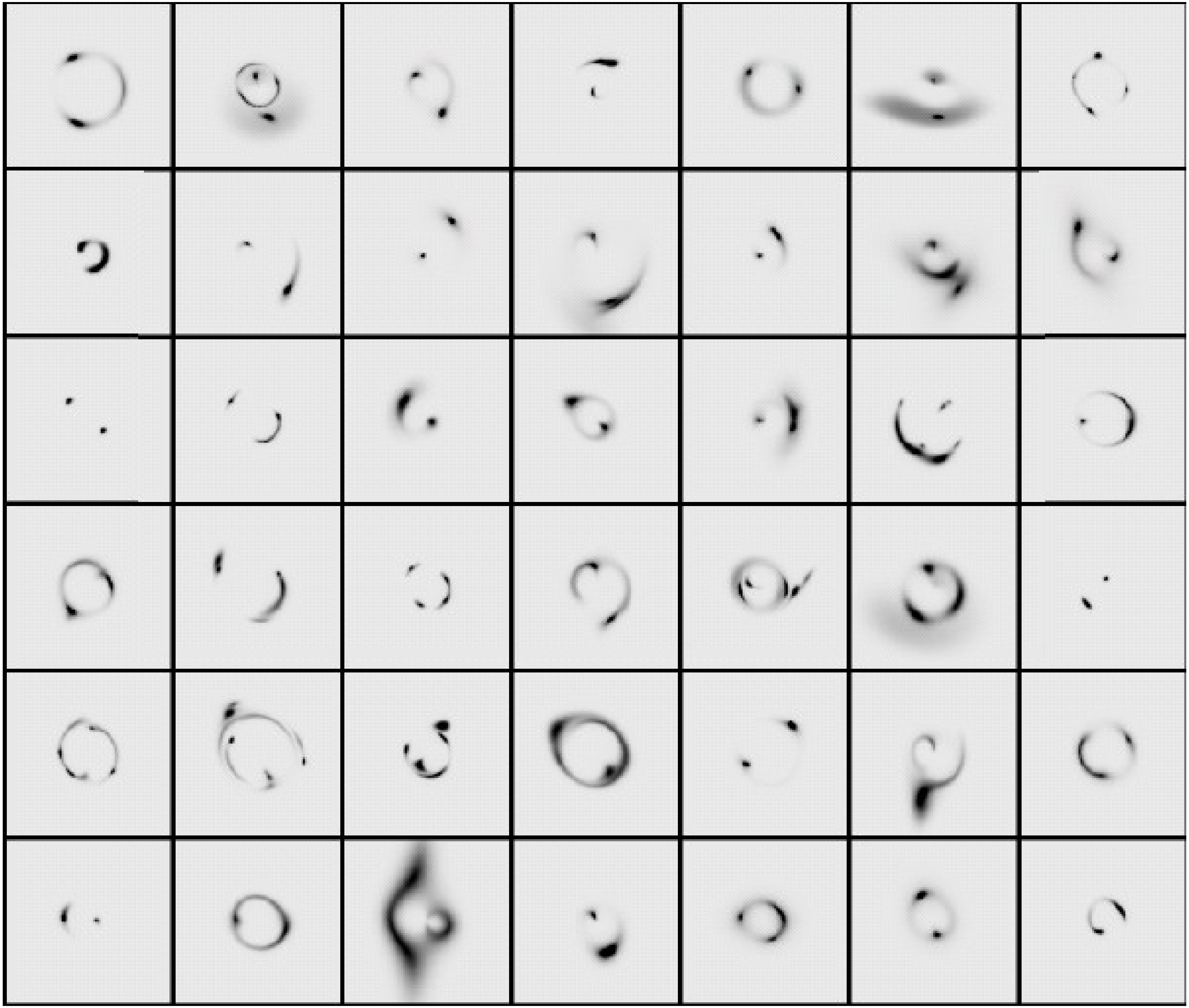
- Candidate lenses selected from SDSS as red galaxies with "spurious" emission lines (Bolton et al. 2004,2005,2006)
- **SDSS velocity dispersion can be used to pre-select masses and estimate success rate**

Then HST follow-up imaging for confirmation and to allow accurate lens modeling

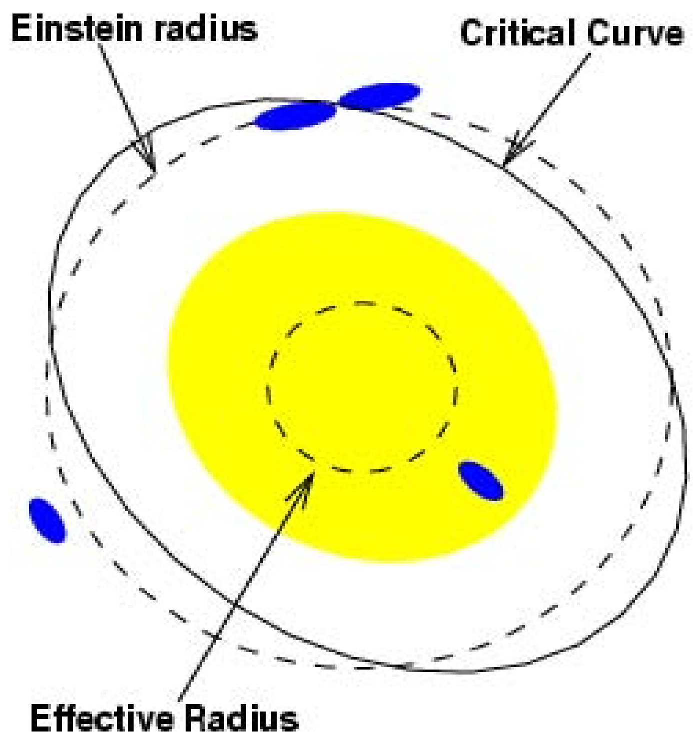
– 167 snapshot targets approved for HST imaging in Cycles 13-14
– 155 GO orbits approved in Cycle 14-15

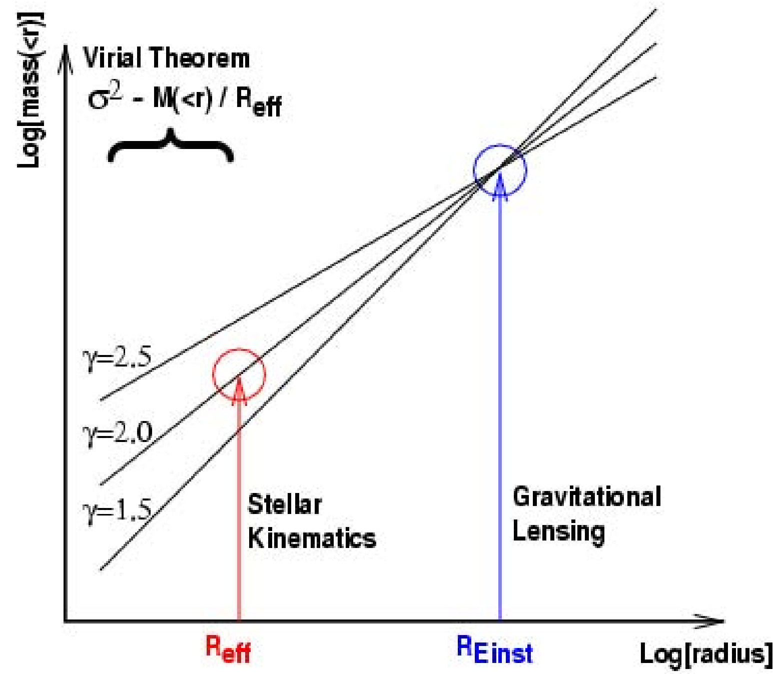






Coupling SL – internal kinematics (a)





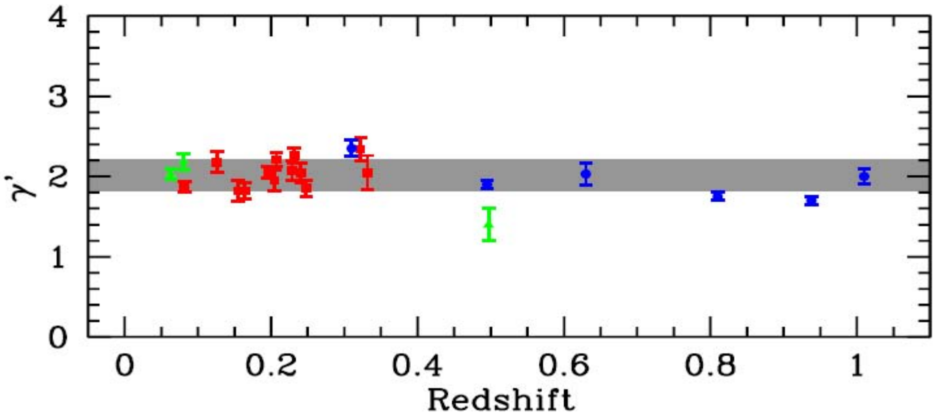
Einstein Radius = one point on mass profile

Internal kinematics within SDSS fiber aperture = another point on mass profile

Both methods only based on gravity (~few gas physics).

Breaks degeneracies: Mass-anisotropy (kinem.), Mass-sheet (lens)

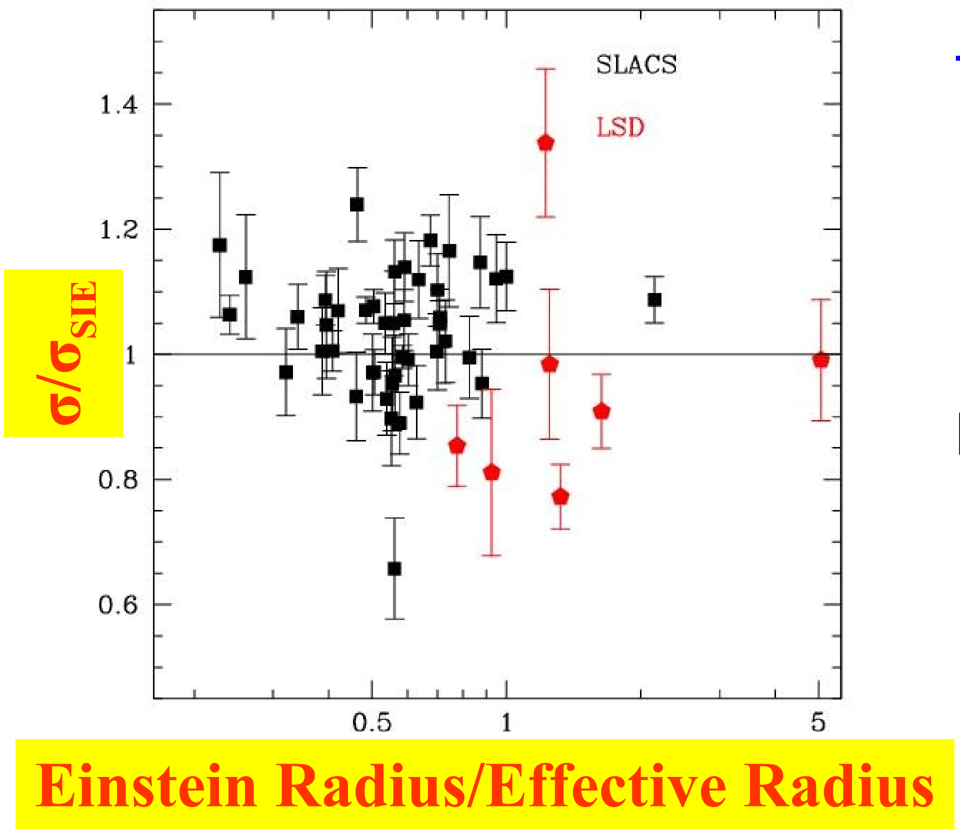
Coupling SL – internal kinematics (b)



Koopmans et al 06

Mass profile is close to isothermal: $\rho \sim r^{-2}$

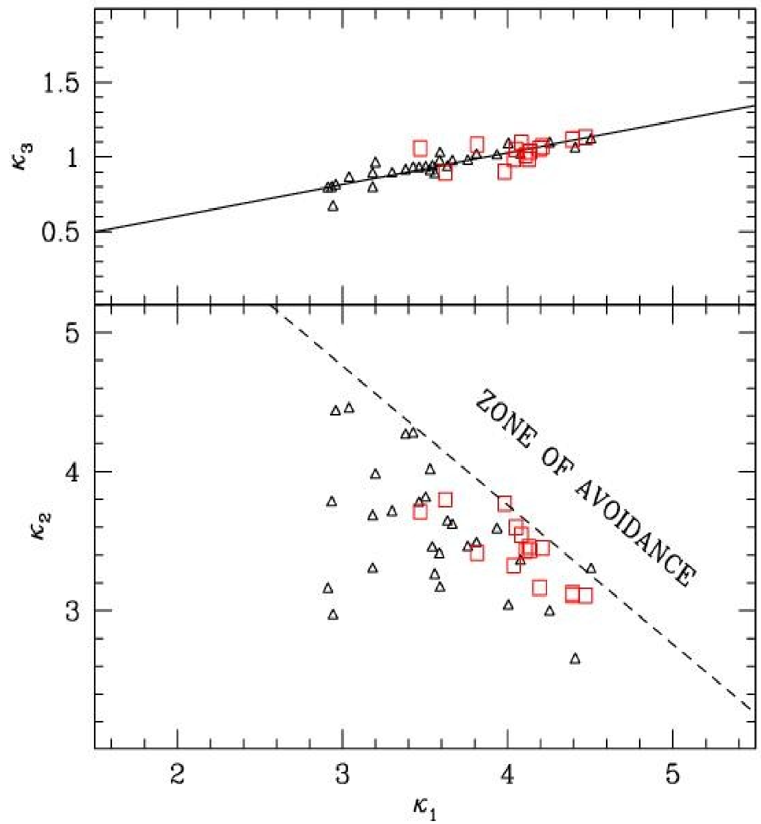
The shape (ellipticity,orientation) of light and mass also match



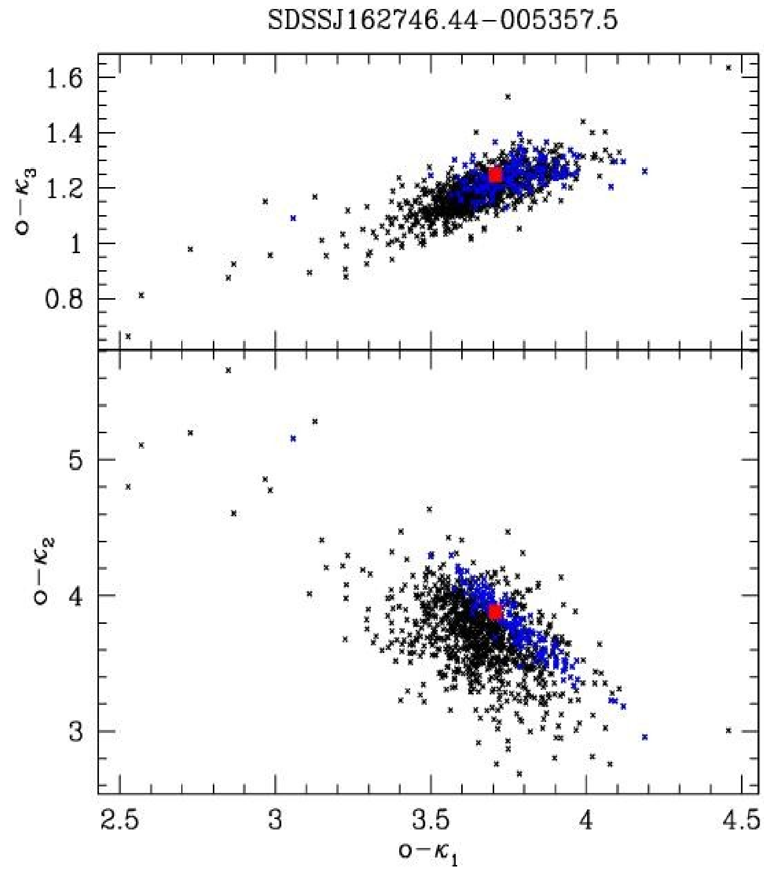
The ratio of the stellar velocity dispersion to that of the best fitting lens model is very close to unity. $R_{Ein}=4\pi\,(\sigma_{SIE}/c)^2$

How do stars and dark matter know "where to go"?

Coupling SL – internal kinematics (c)



Treu et al 06



Galaxies selected to have high velocity dispersion

Otherwise lenses live on the same FP as normal spheroids...

Coupling SL – internal kinematics (d)

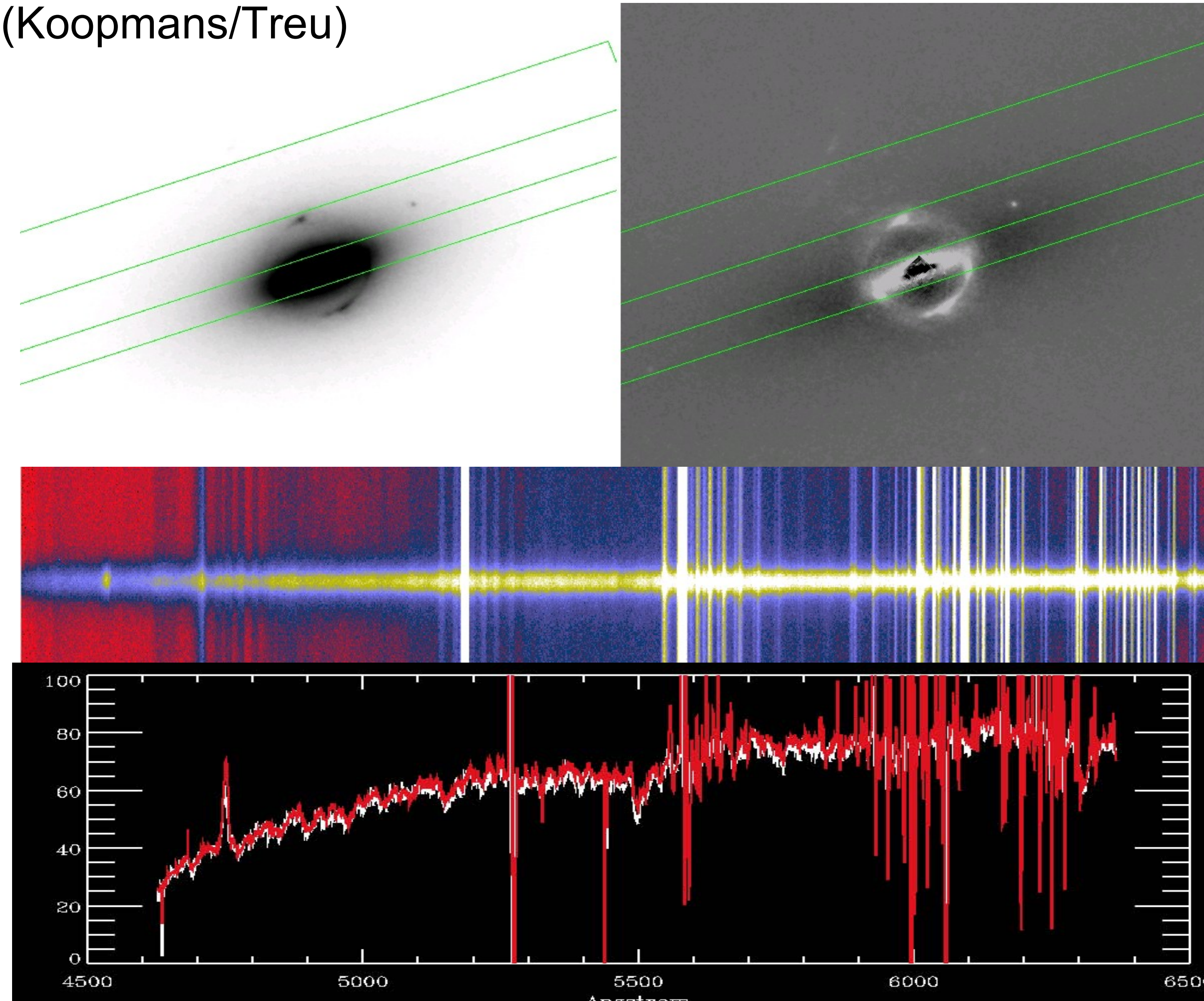
Complementary resolved long slit spectro. LRIS@Keck: (Treu/Gavazzi)

2D IFU @VLT (Koopmans/Treu)

0.5,1,3 hrs per split position

more complex dynamical models can be investigated

(M. Barnabé thesis at Kaptein)



Coupling SL – weak lensing

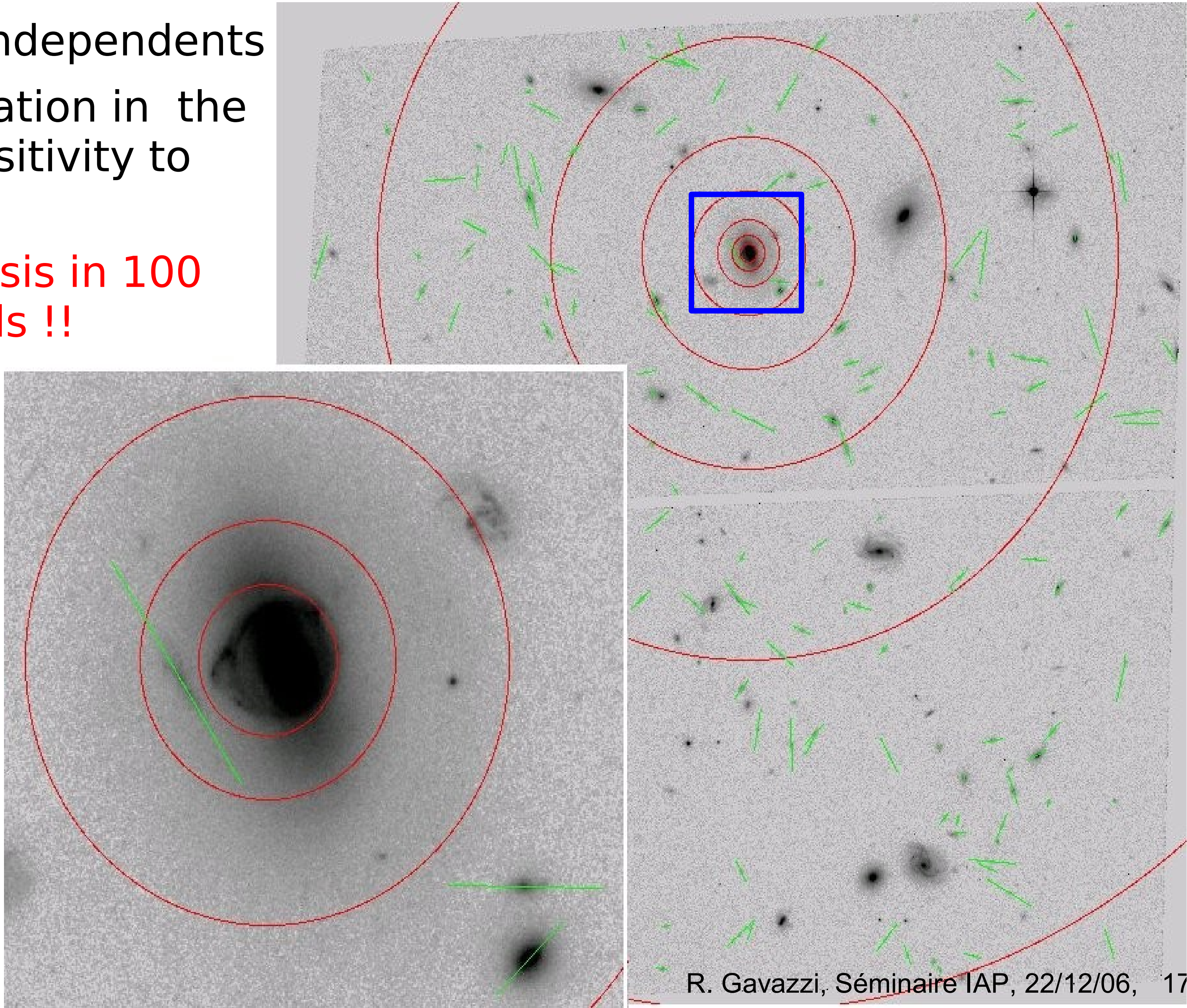
Cols: SLACS + J. Rhodes (JPL)

Gavazzi et al 07,
in preparation

- 80 lenses with deep ACS imaging (F814W~27)
- Weak lensing allows to extend constraints on the density profile beyond the few kpc ($\sim R_{eff}$) probed by SL.
- SNR too low on a single object : stacking... 'mean' lens!
- So far, 22 lenses ($z\sim0.2$) velocity disp. $\sigma\sim180$ - 330 km/s
- F814W/ACS images (1 orbit) 200''x200'' fov : $R < 300$ kpc/h
- Huge surface density of sources $I_{AB}<26.2$, $n_{bg}\sim80$ arcmin^{-2}.

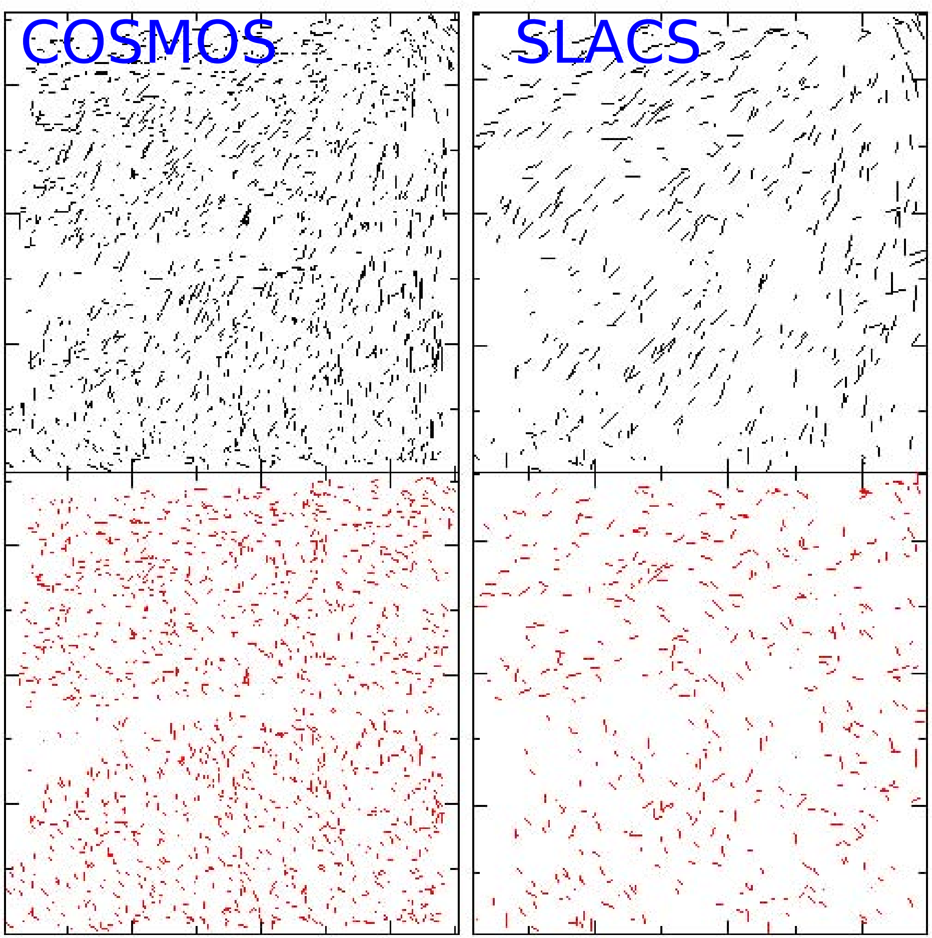
Coupling SL – Weak lensing

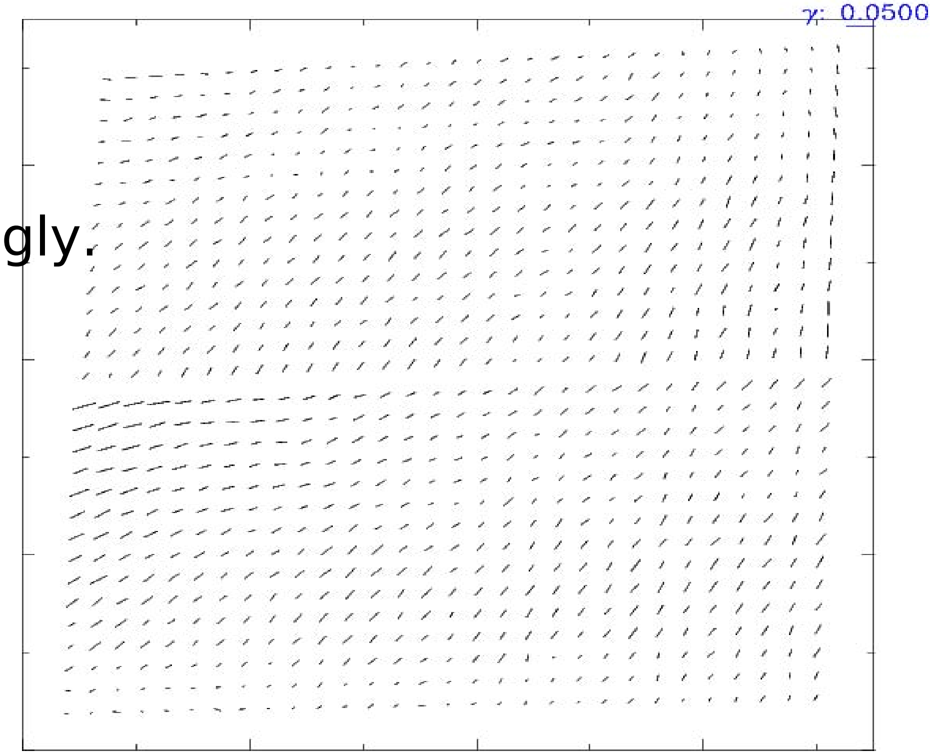
- Statistically independents
- But same location in the fov: High sensitivity to systematics
- Parallel analysis in 100 COSMOS fields !!



Correction of systematics: (a) PSF

- Galaxies blurred by complex ACS PSF
- Difficult correction: focus 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)

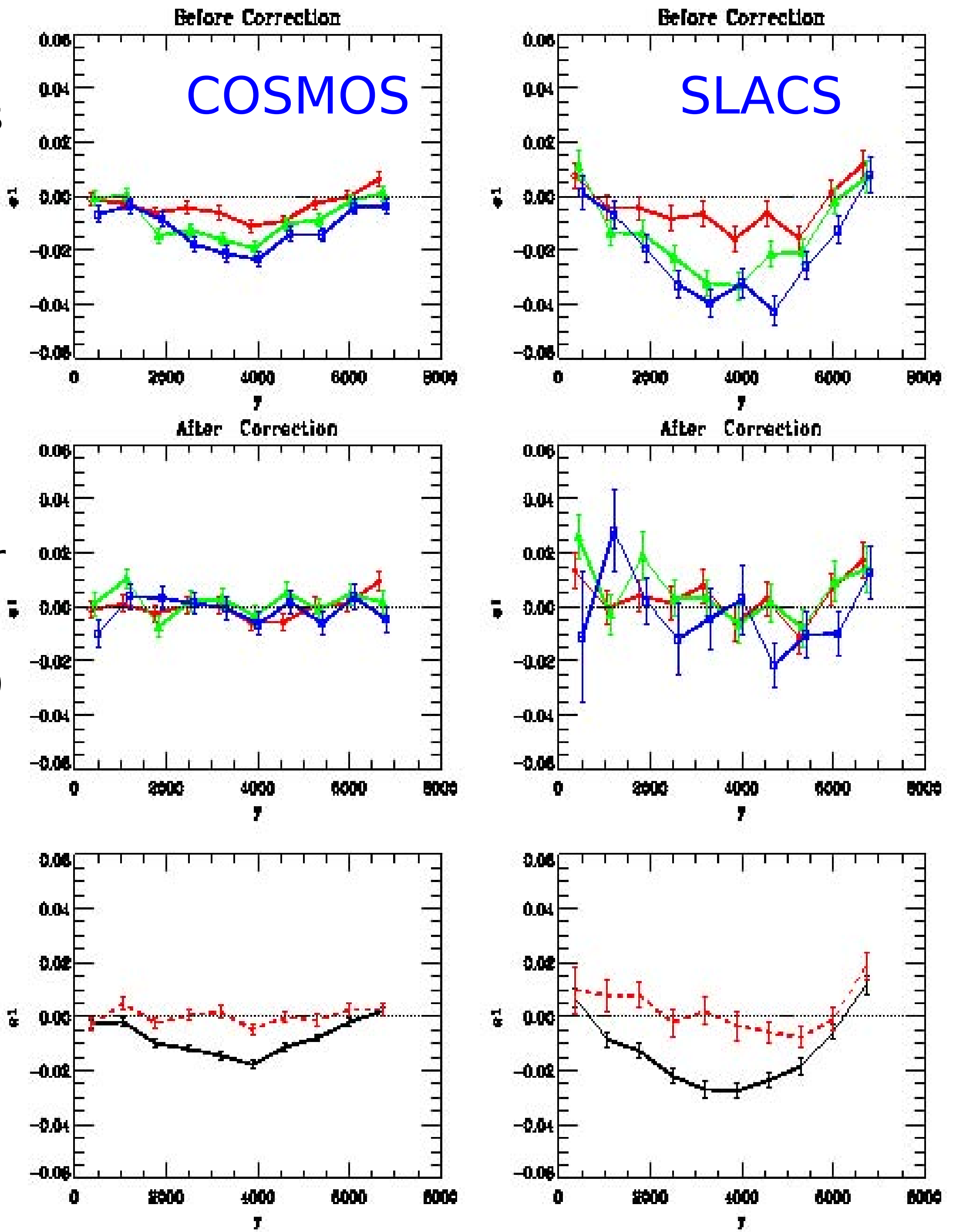
No patterns in residuals but
$\langle e_{residual} \rangle \sim 0.003$

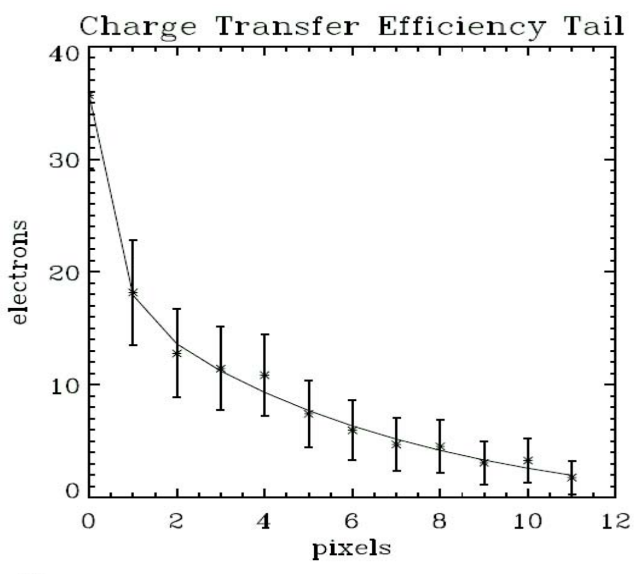
(before correction: 0.006)

much smaller than scatter ~0.08 !

(b) Charge Transfer Efficiency CTE

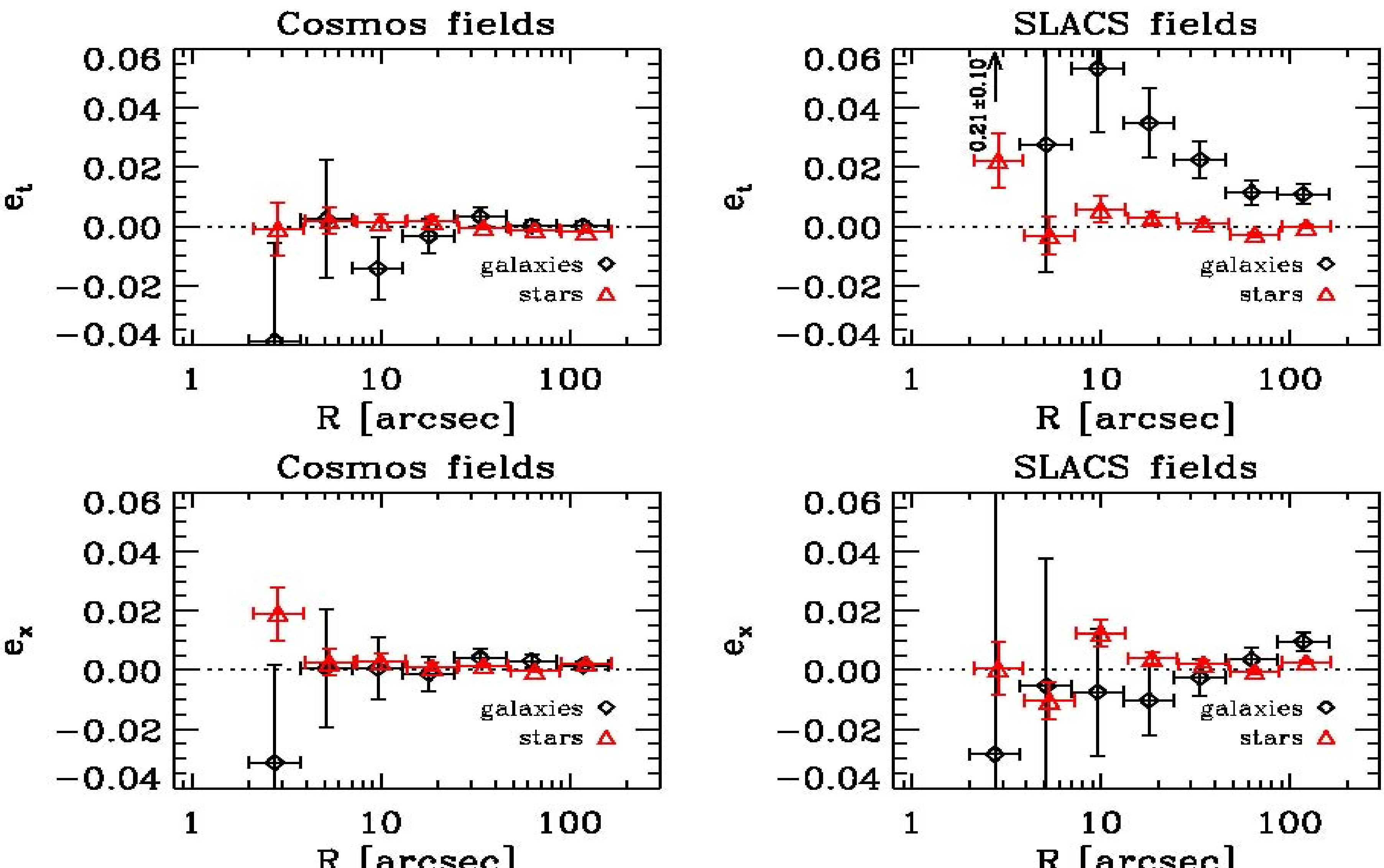
- During CCD readout, charges are delayed. Cosmic rays produce defects that retain e^- *producing a tail along y axis (negative e_1 'shear')*
- More pronounced close to gap between CCDs (far from readout)
- Severe for faint objects
- Calibrated in COSMOS survey (Rhodes et al.06) but tuned for proper KSB pipeline
- Increases with time (x2 in 2.3 years!!)





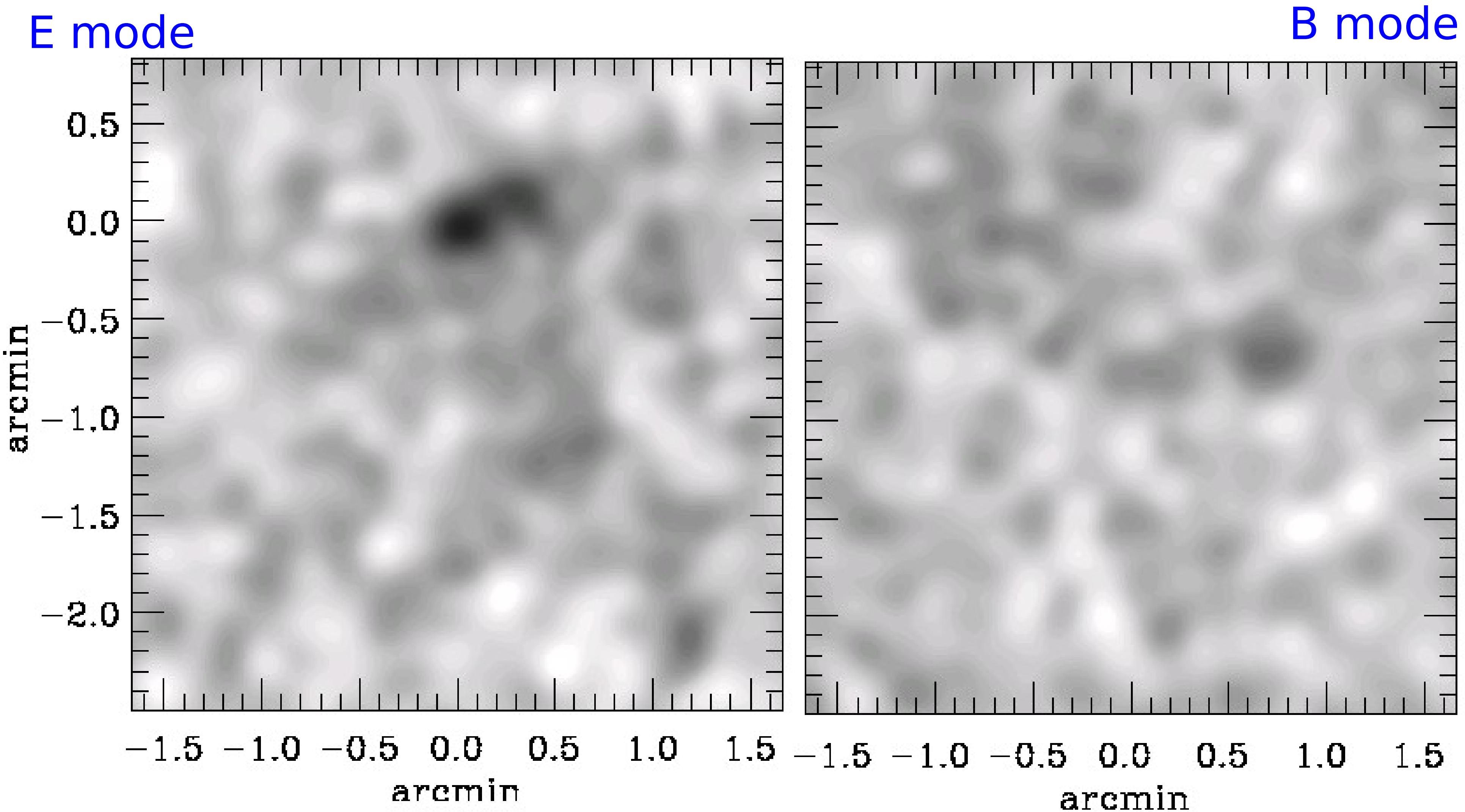
Any residual system. on shear profile?

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



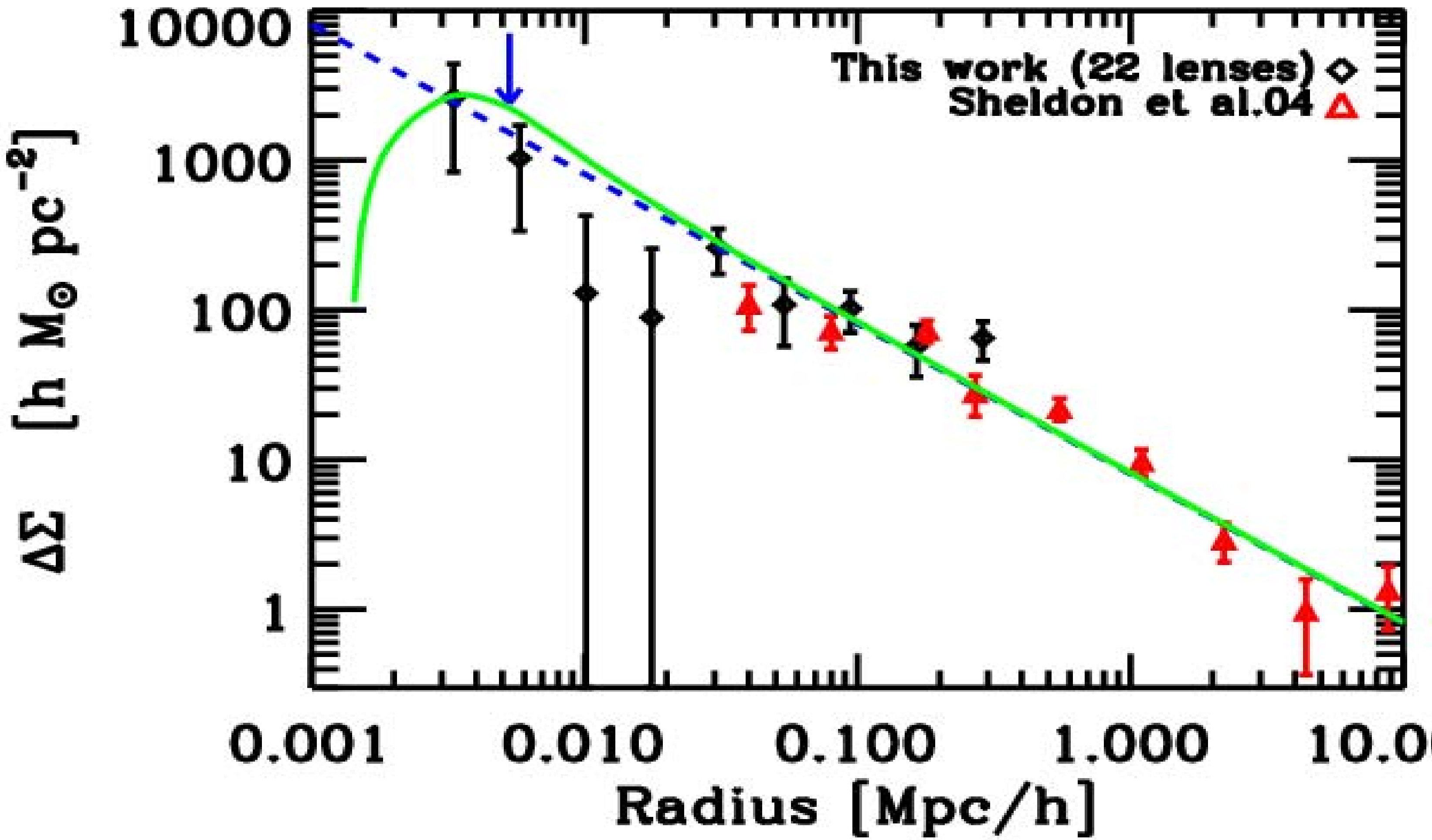
2D mass map

- Non-parametric shear γ -> convergence κ inversion
- Highest resolution convergence map   (8" FWHM)
- No non-circular patterns (either in detector frame or along lens PA)
- No B modes

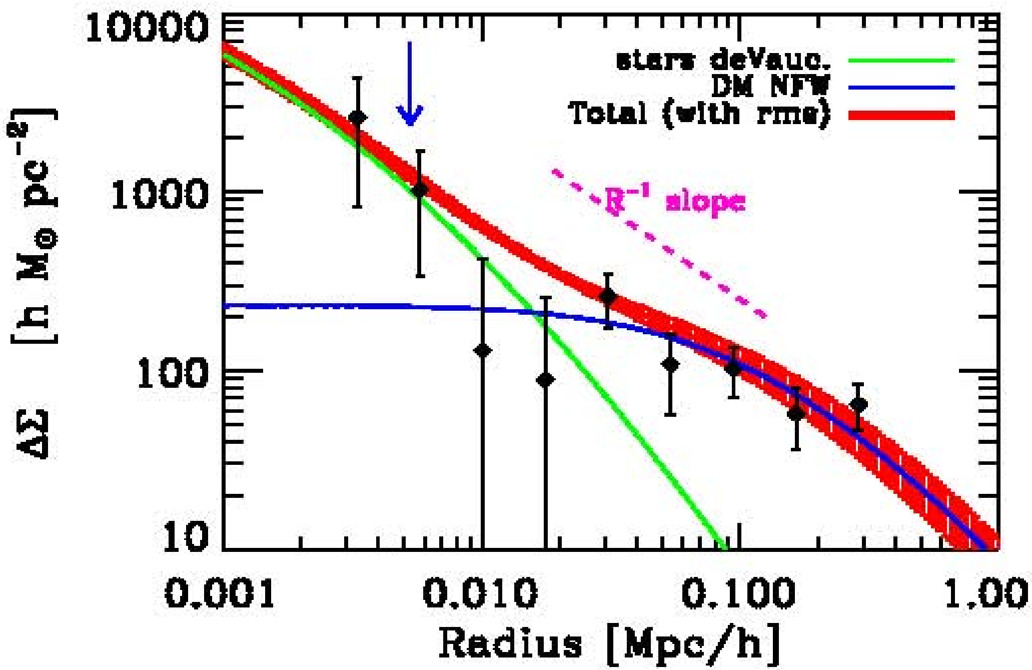


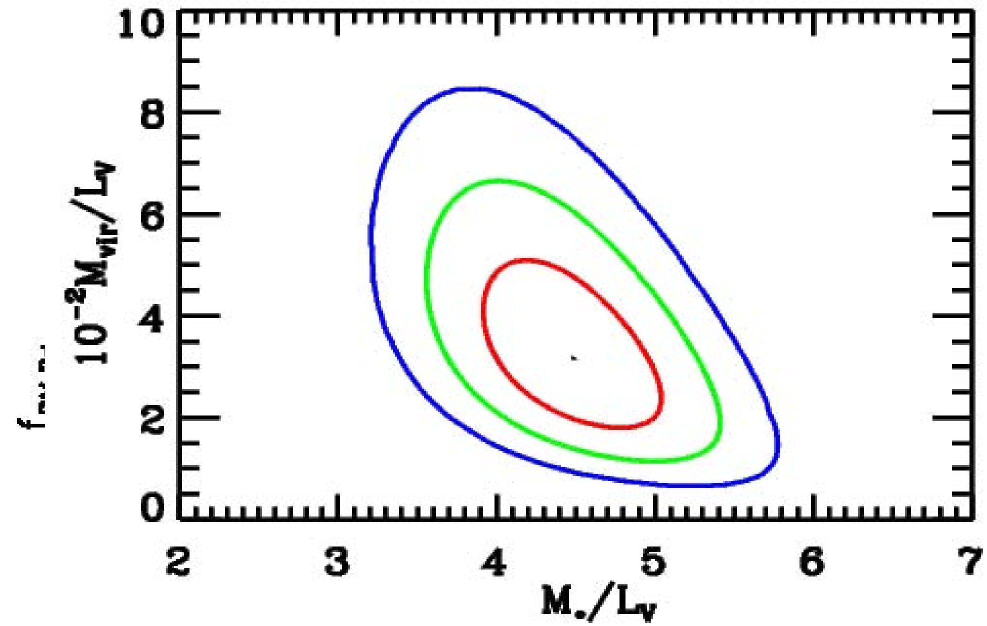
Radial Shear profile

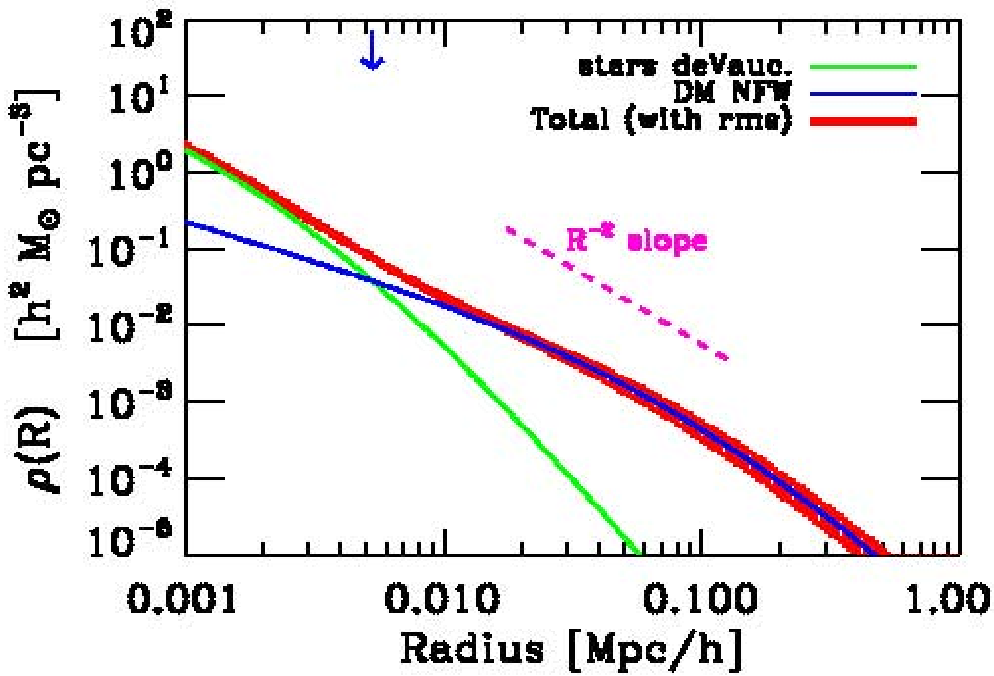
- $\Delta\Sigma(R) = \Sigma_{crit}\,\gamma(r)$
- Well consistent with SDSS analyses (Sheldon et al 04, Mandelbaum et al 06)
- Strong lensing Isothermal profile matches data (not a fit)



Radial Shear profile







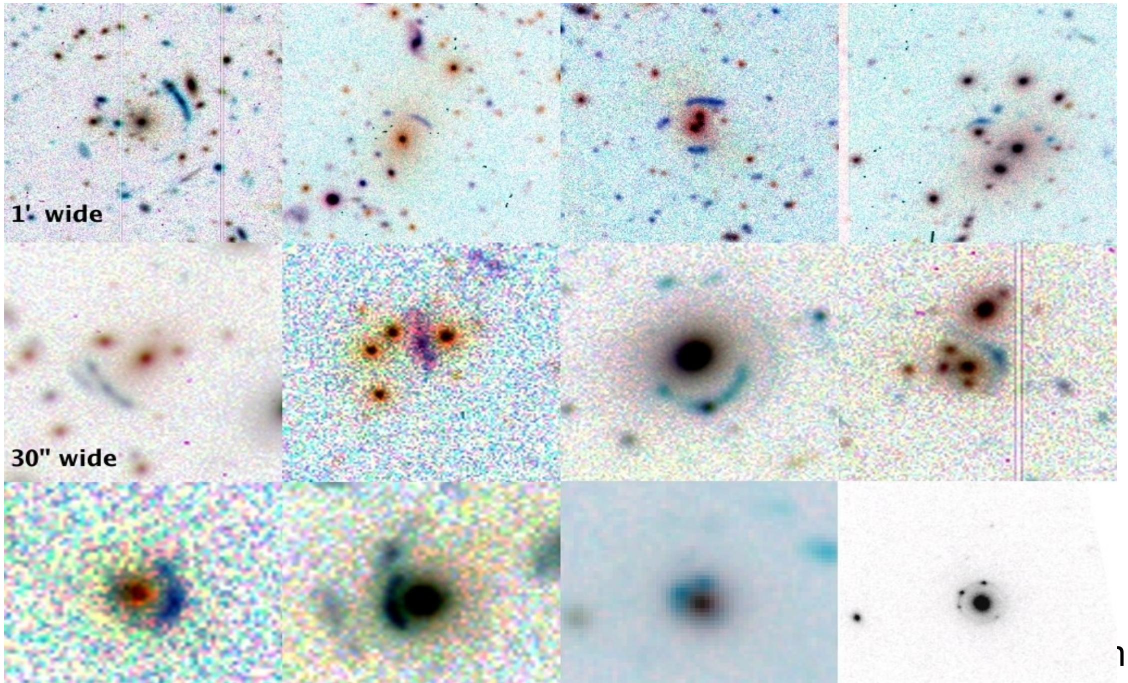
- **Shear profile AND Strong lensing** well fit with 2 components :
  - DM with NFW profile
  - Stellar mass with $R^{1/4}$ law.
- $M_*/L_V = 4.42 \pm 0.43h$
- $M_{vir}/L_V \sim 354 \pm 140\ h$
- Concentration assumed to match N-body simulations

$$c = \frac{9}{1+z}\left(\frac{M_{\rm vir}}{8.12\times10^{12}\,hM_\odot}\right)^{-0.14}$$

Next step: Einstein Rings in the SL2S

- Collab. France (@IAP Alard, Fort, Mellier, Sygnet, @OBSPM Dantel, @LAM Kneib, @OMP Cabanac,Pello,Soucail), Canada, USA, UK
- Find various strong lensing events in CFHTLS ugriz imaging with automated procedures.
- *Search for arcs around clusters, groups scale: ARC (C. Alard)*
- *Search for rings around ETGs: ring_finder (R. Gavazzi)*
- HST Follow-up (ongoing cycle15, 50 snapshot targets) for confirmation and accurate lens modeling
- Follow-up spectroscopy for lens/source redshift (and velocity dispersion).

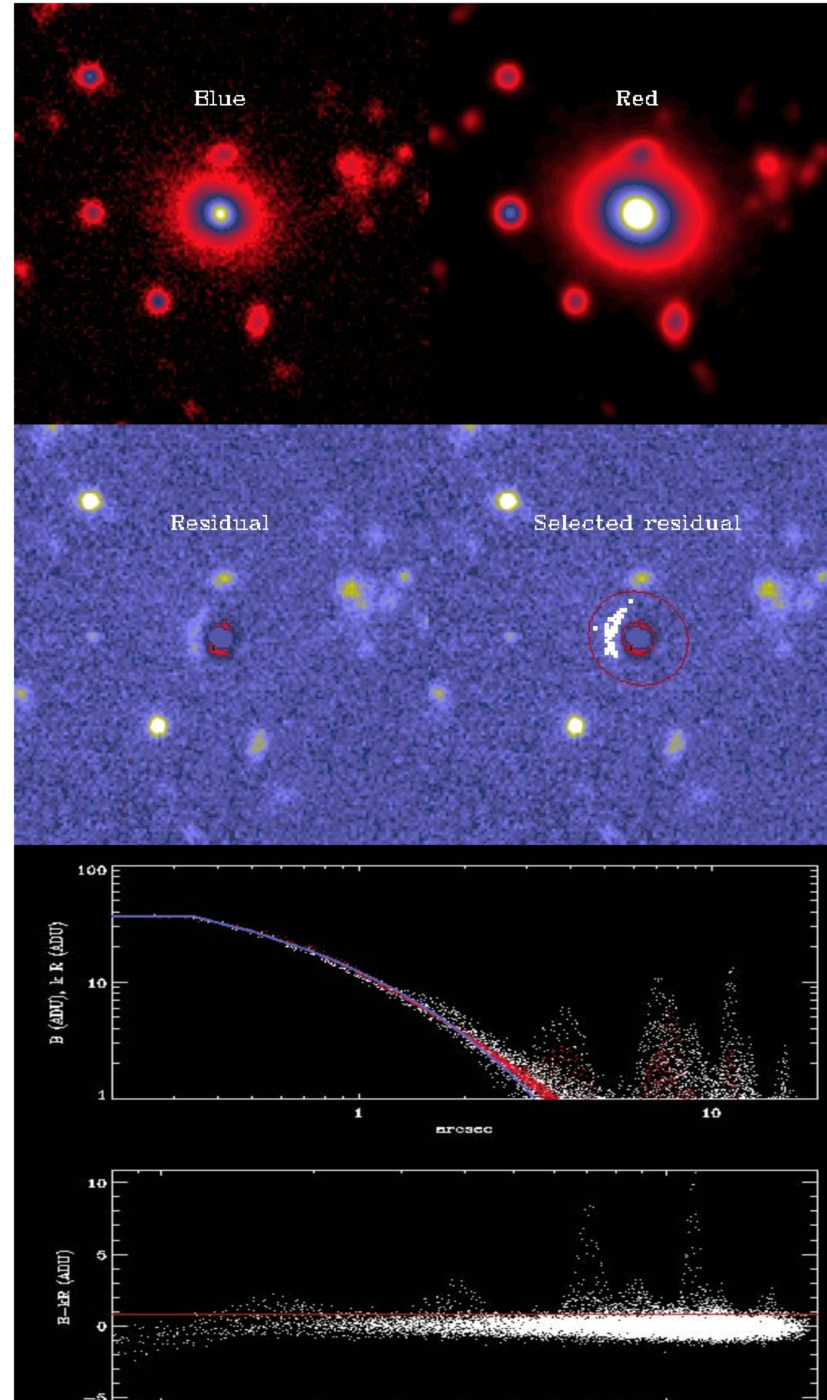
Cabanac etal 06



Next step: Einstein Rings in the SL2S

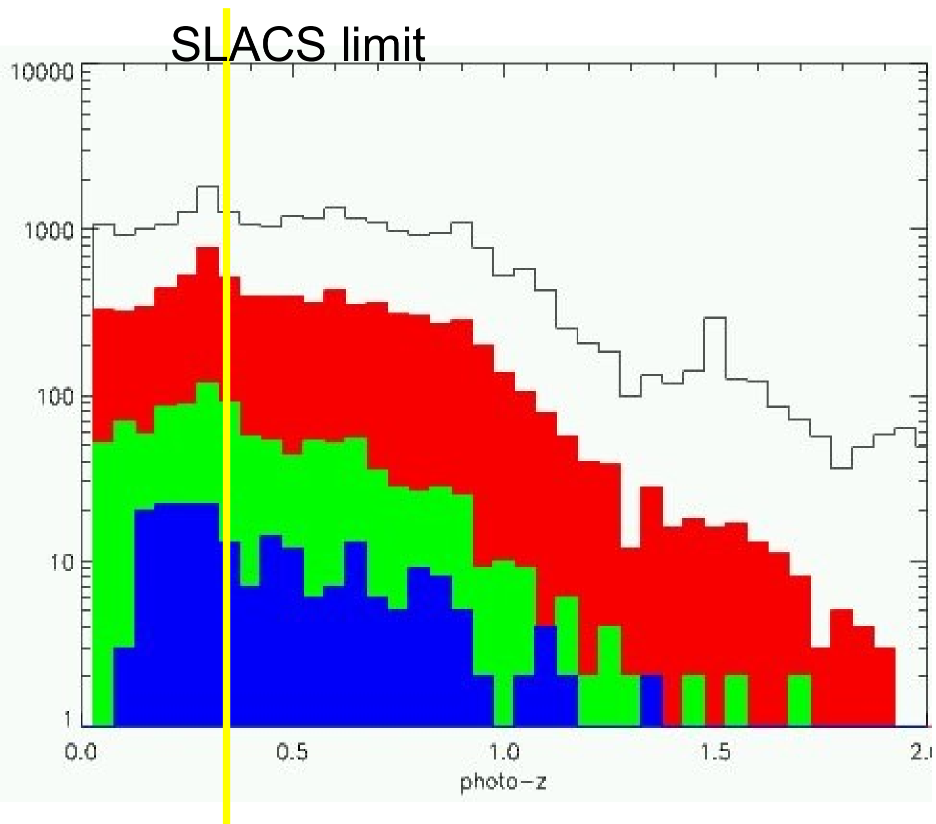
ring_finger:

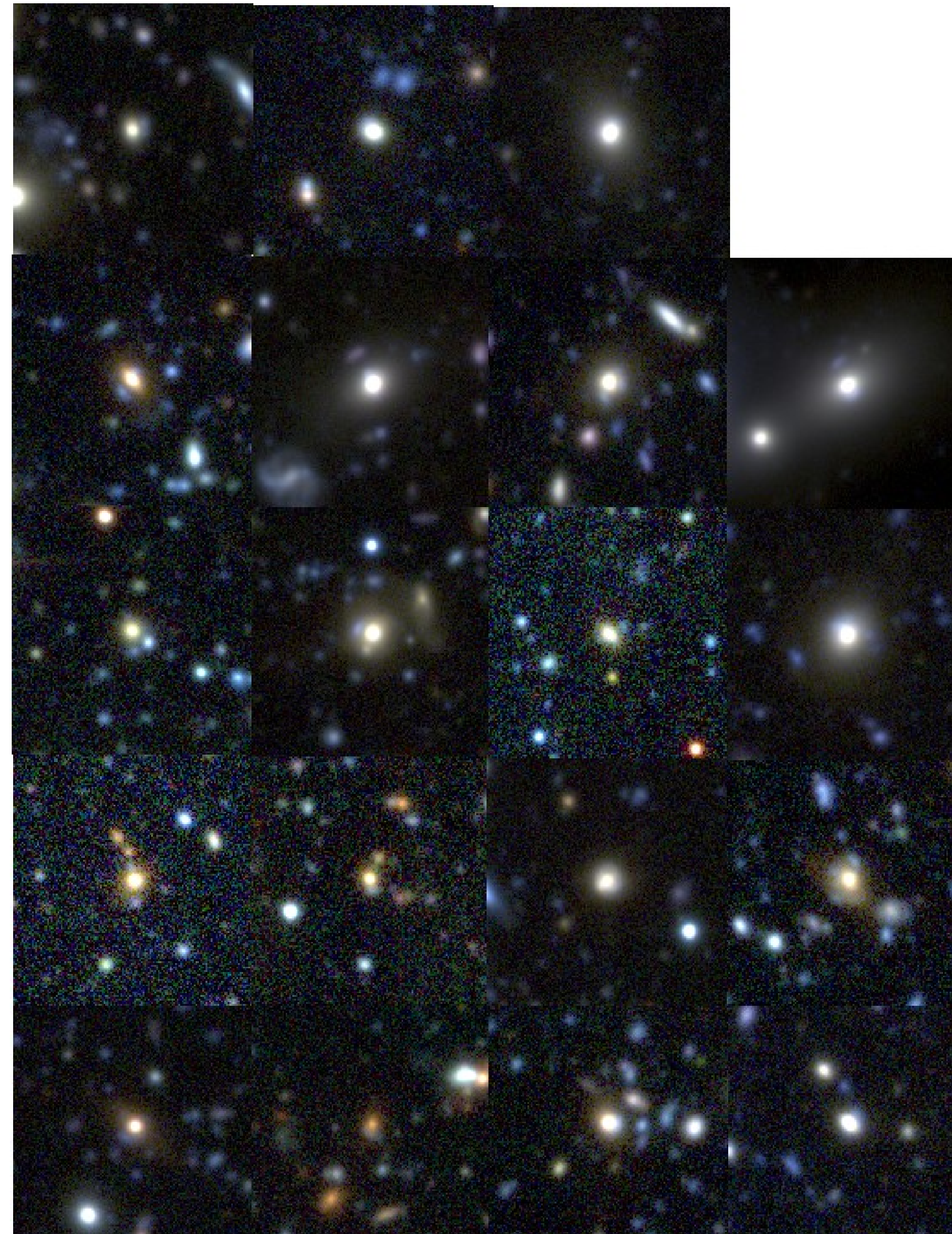
- define catalog of ETGs (from photo-z or 2 bands photometry)
- Study blue and red surface brightnesses and find best α such that $I_B = \alpha\, I_R$.
- Measure lenght, width, flux, distance... of any bluish residual.
- Automated alert if consistent with being a lensed object (*eg.* tangential elongation), then eyeball validation/rejection.



Next step: Einstein Rings in the SL2S

- Photo-z distribution, we will go beyond SLACS limit down to z~1.
- Wait spectro/HST confirmation (just awarded VIMOS@VLT time)





Conclusion

- Gravitational lensing and kinematics provide a powerful probe into the inner (<15kpc SL,kin or <500kpc WL) structure of ETGs to z=1.
- Inner parts of lens ETGs are isothermal. Lenses lie on same Fundamental Plane as normal ETG.
- DM only dominates beyond Reff but detected down to ~50 Reff with 22 systems through weak lensing ! Outer parts of lenses have similar mass properties. Work in progress...
- Bulge/halo Conspiracy: combine themselves to form an Isothermal profile.
- Early in place (z~1). Progenitors must have acquired this profile early on (when gas physics mattered) and then preserved through collisionless hierarchical merging.
- Promising cosmological tests possible. More calibration work required (with spectroscopy)
- Need to find many more high redshift lenses to reconstruct dynamical past assembly history of ETGs. And to lower mass systems
- Possible with SL2S@CFHTLS and future experiments (SNAP, DUNE, LSST)

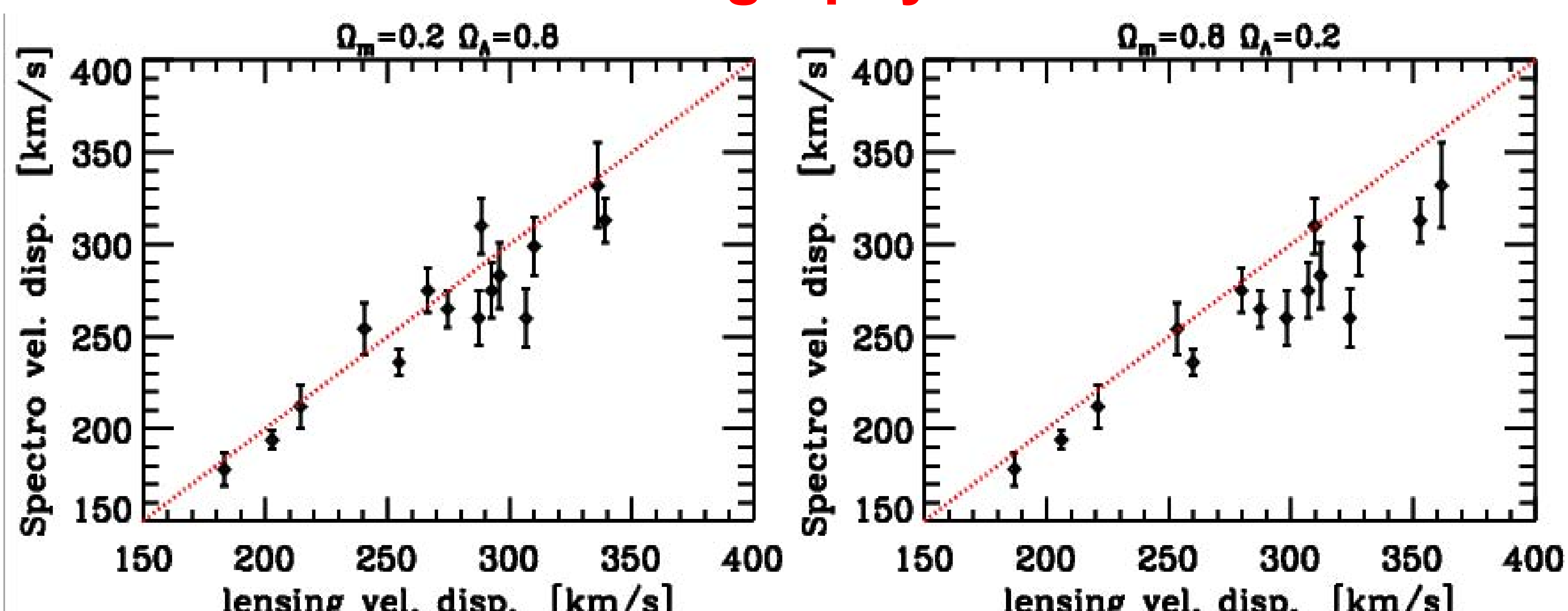
Cosmology with strong lensing galaxies and kinematics ?

$$\psi(\vec{\theta}) = \frac{4G}{c^2}\frac{D_{\mathrm{ol}}D_{\mathrm{ls}}}{D_{\mathrm{os}}}\int \mathrm{d}^2\theta' \Sigma(\vec{\theta}')\ln|\vec{\theta} - \vec{\theta}'|$$

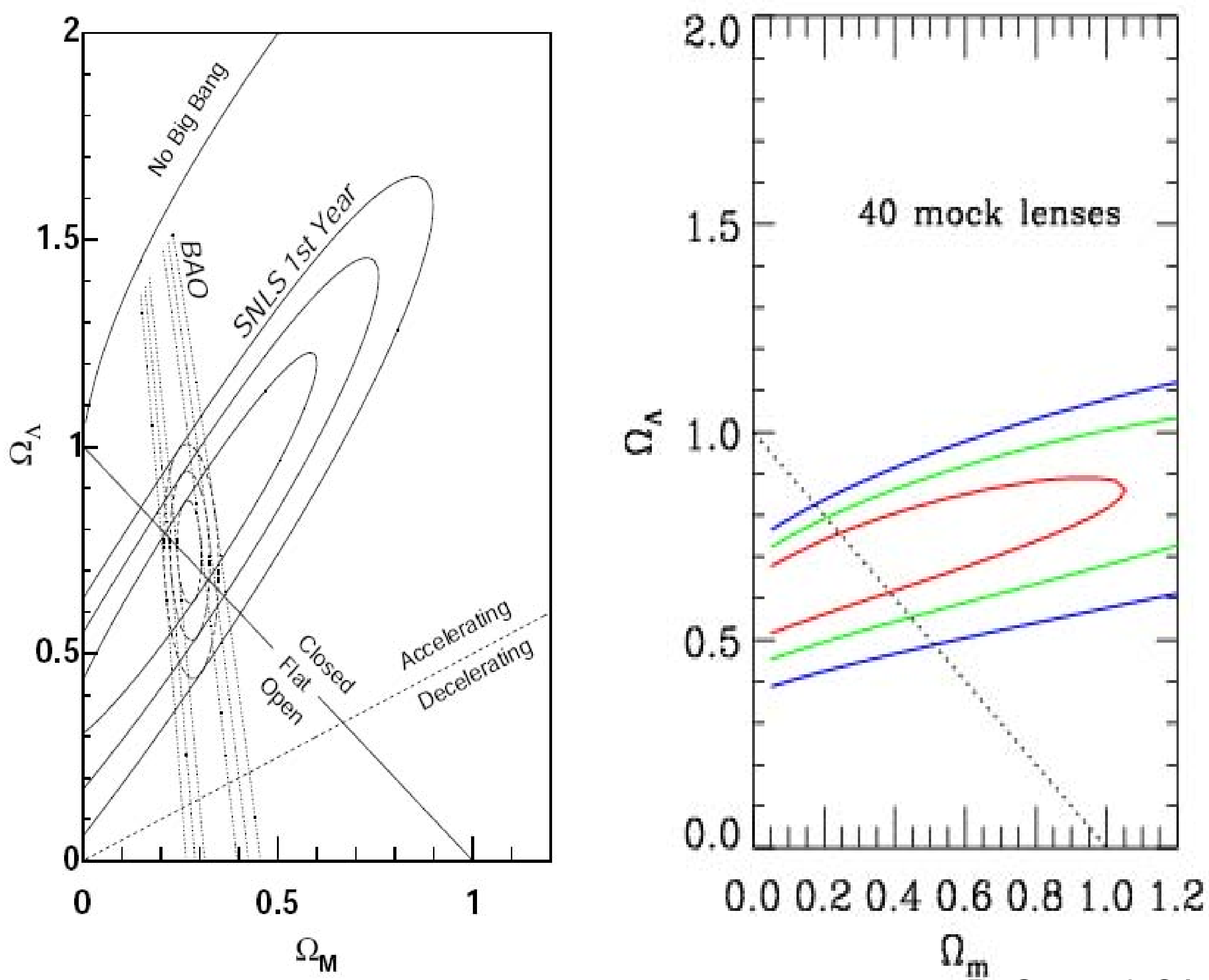
Einstein Radius
(SL in general)

Distance ratio:
Cosmography

Stellar kinematics
(with well resolved LSS)



Possible results with **SLACS** *(short term forecast)*



Dark Energy Equation of state w

Forecast for SNAP (2016?) *Courtesy P. Marshall*