Mapping Dark Matter in the Universe

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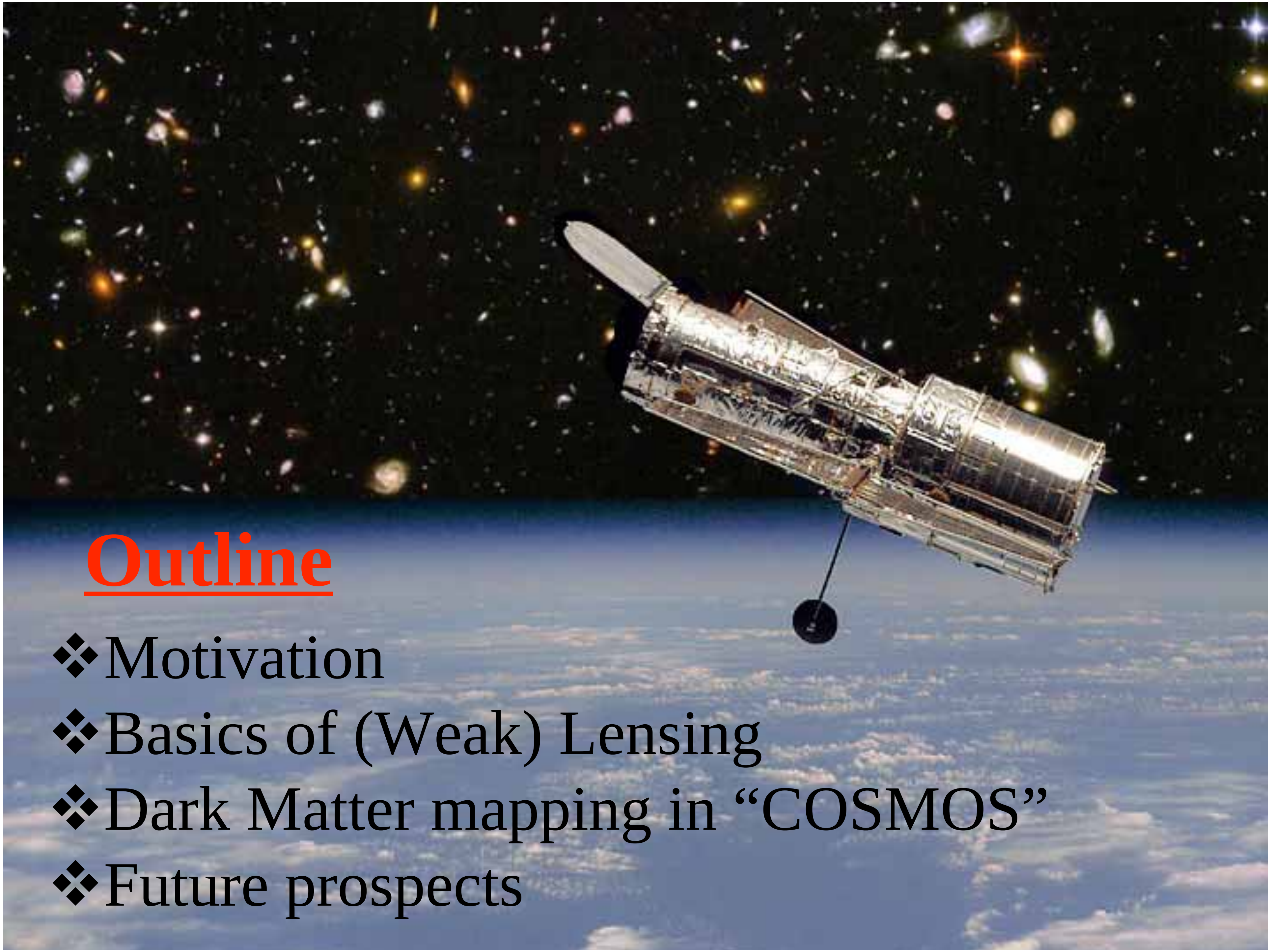
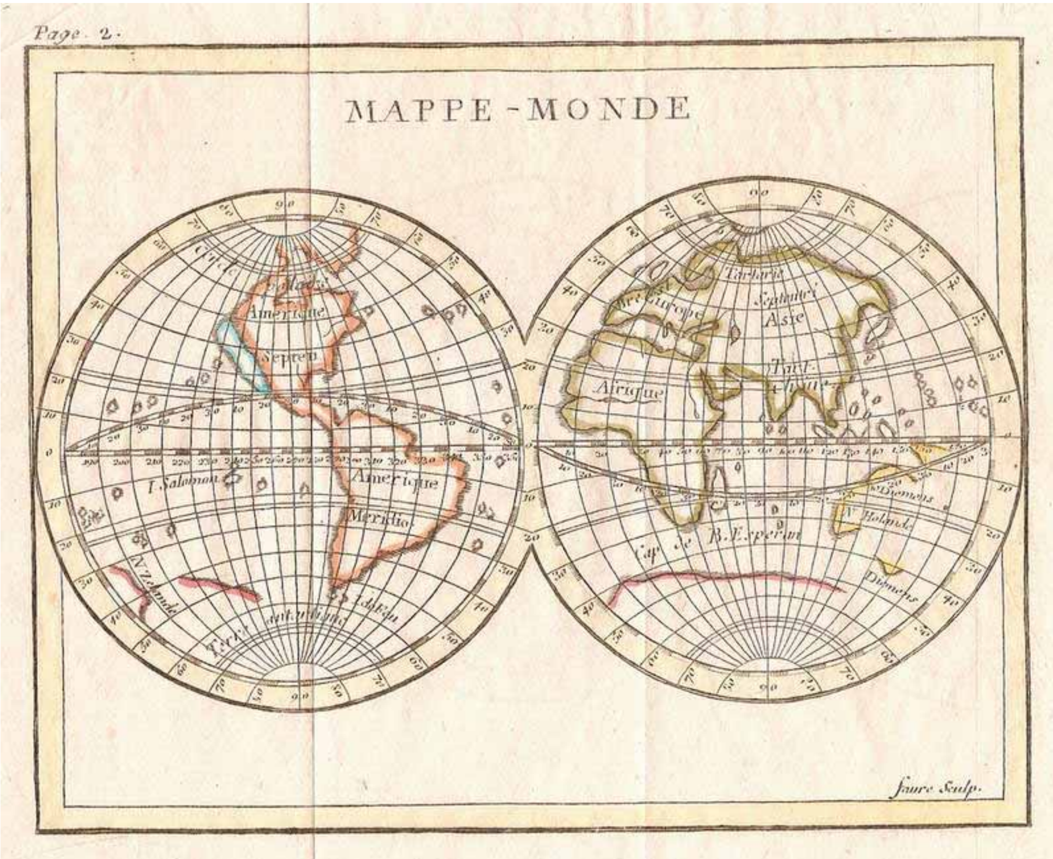
A. Leauthaud, R. Massey, J. Rhodes, the *COSMOS team*,

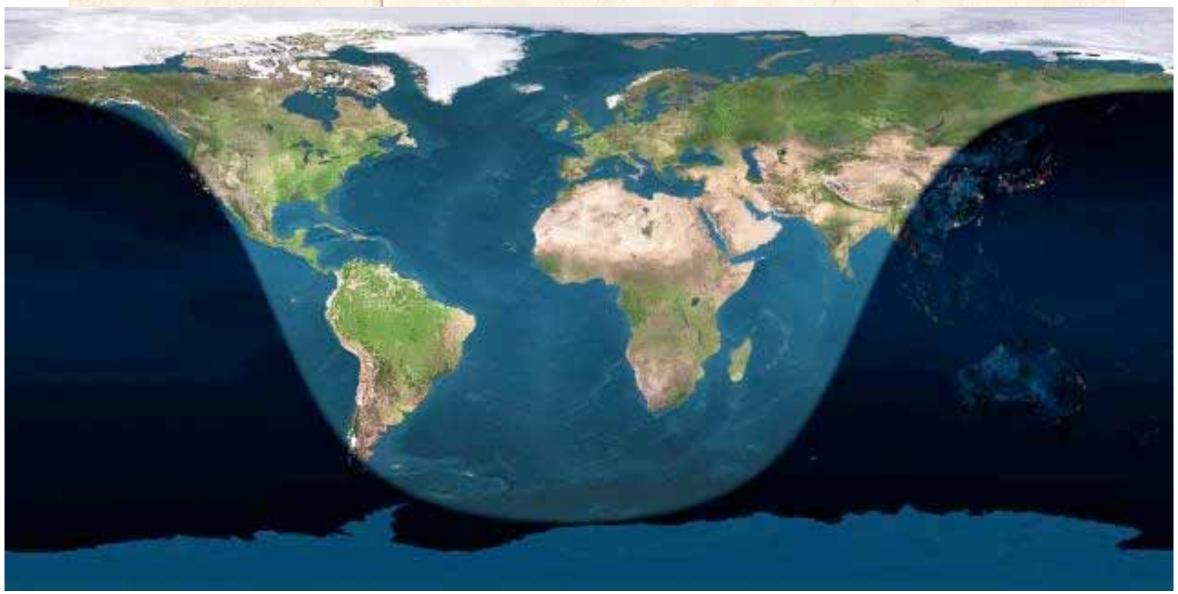
and many others



Outline

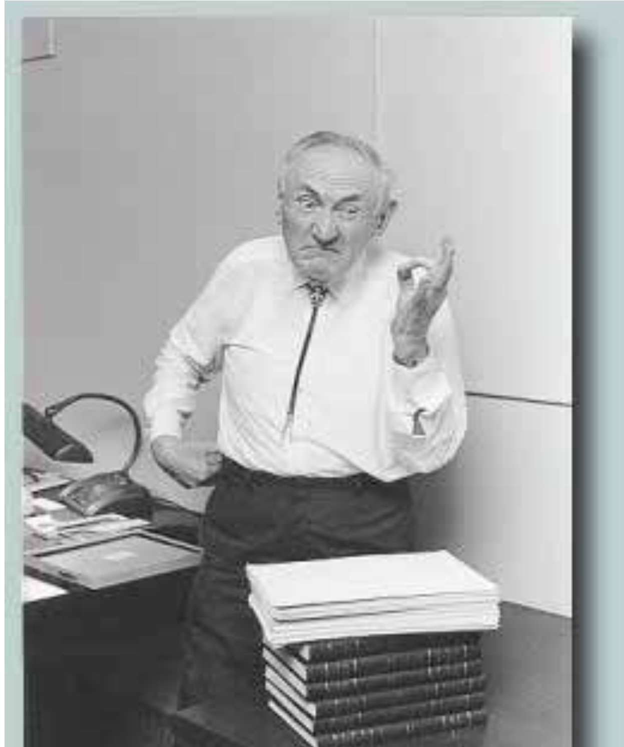
- Motivation
- Basics of (Weak) Lensing
- Dark Matter mapping in "COSMOS"
- Future prospects

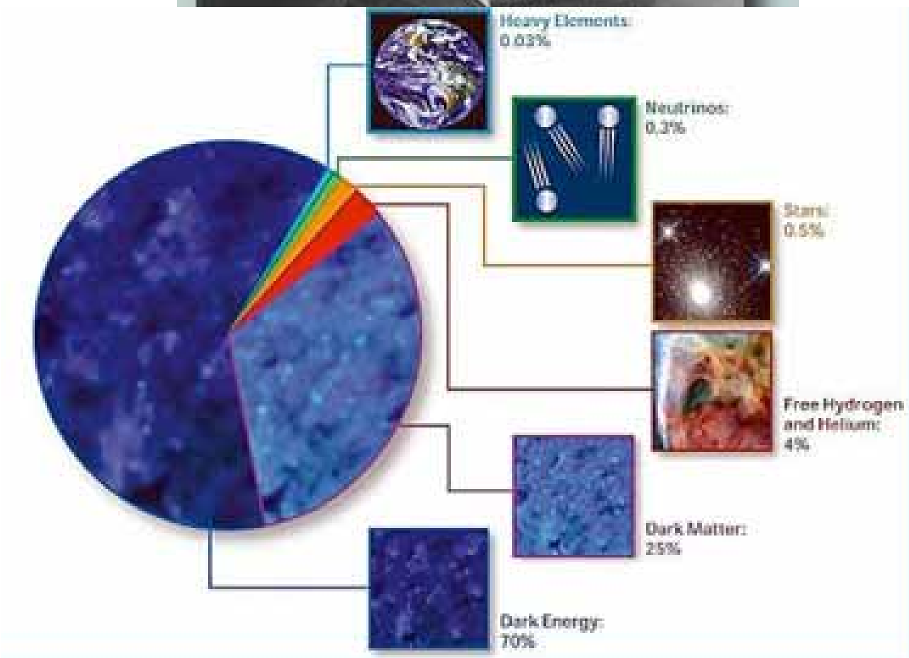




‘Geo-meter’

- First « good » world map in the XVIIIs century
- « Perfect » maps nowadays with space Earth observatories
- Deep understanding of our planet





What about our Universe ?

"Normal" matter:

in stars, galaxies, IGM …
traced by photons

Dark matter (~1930)

in clusters, galaxies …

traced by gravitational effects

Dark energy (~2000)

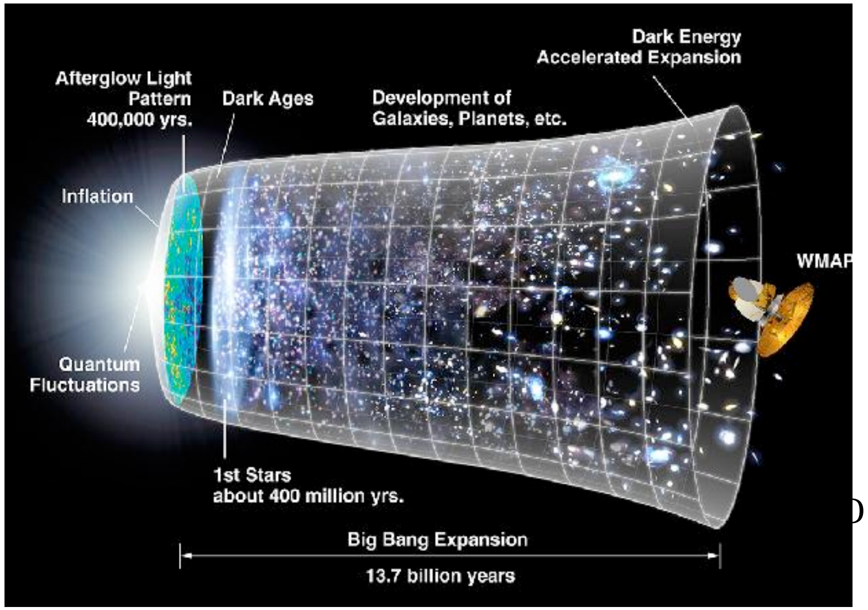
everywhere !

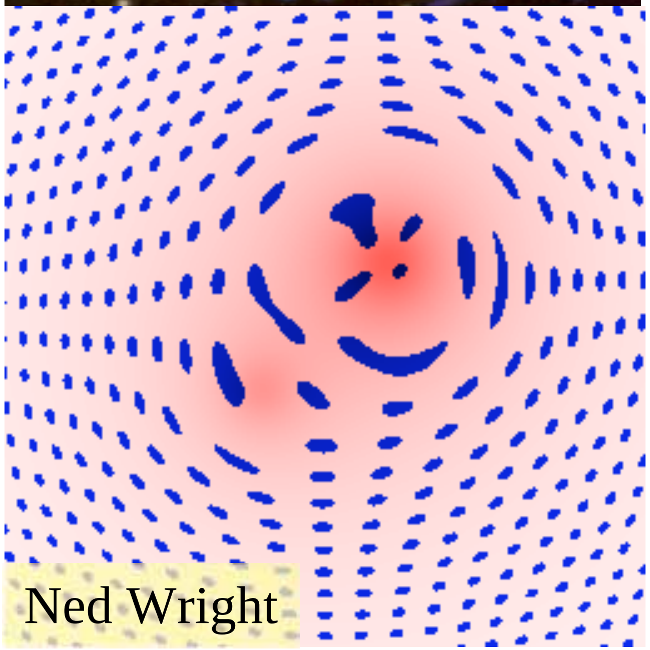
traced by Universe geometry,
& Dark Matter growth

Motivation for the ‘Cosmos-meter’

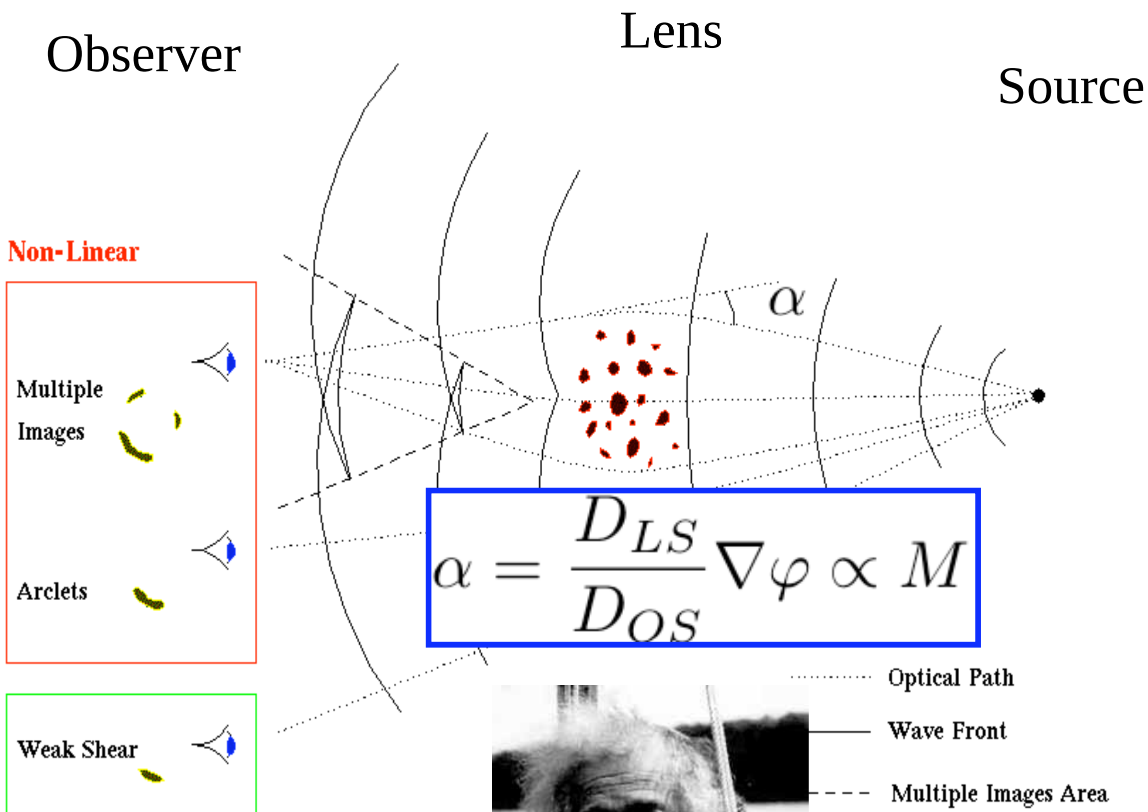
Mapping (Dark) matter:

- DM is a *necessary and essential ingredient* of the Universe
- Its distribution is shaping up galaxies (the visible bricks of our Universe): DM & baryons interactions
- Growth of DM is a tracer of Dark Energy: new physics?
- … should deeply impact Galaxy Evolution and our understanding of Physics

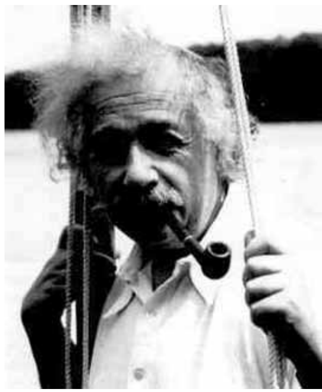


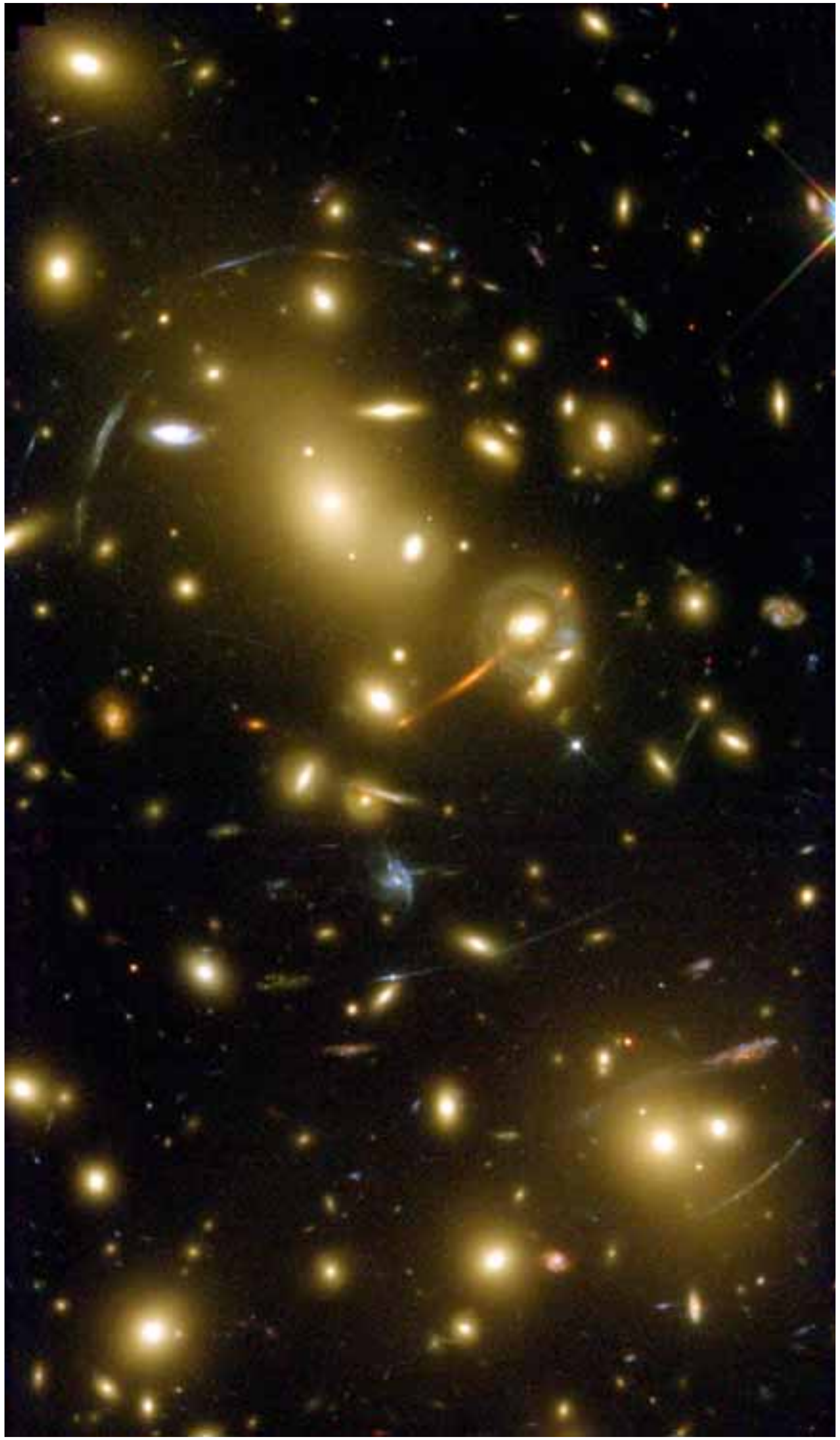


Gravitational Lensing the ‘Cosmos-meter’ tool



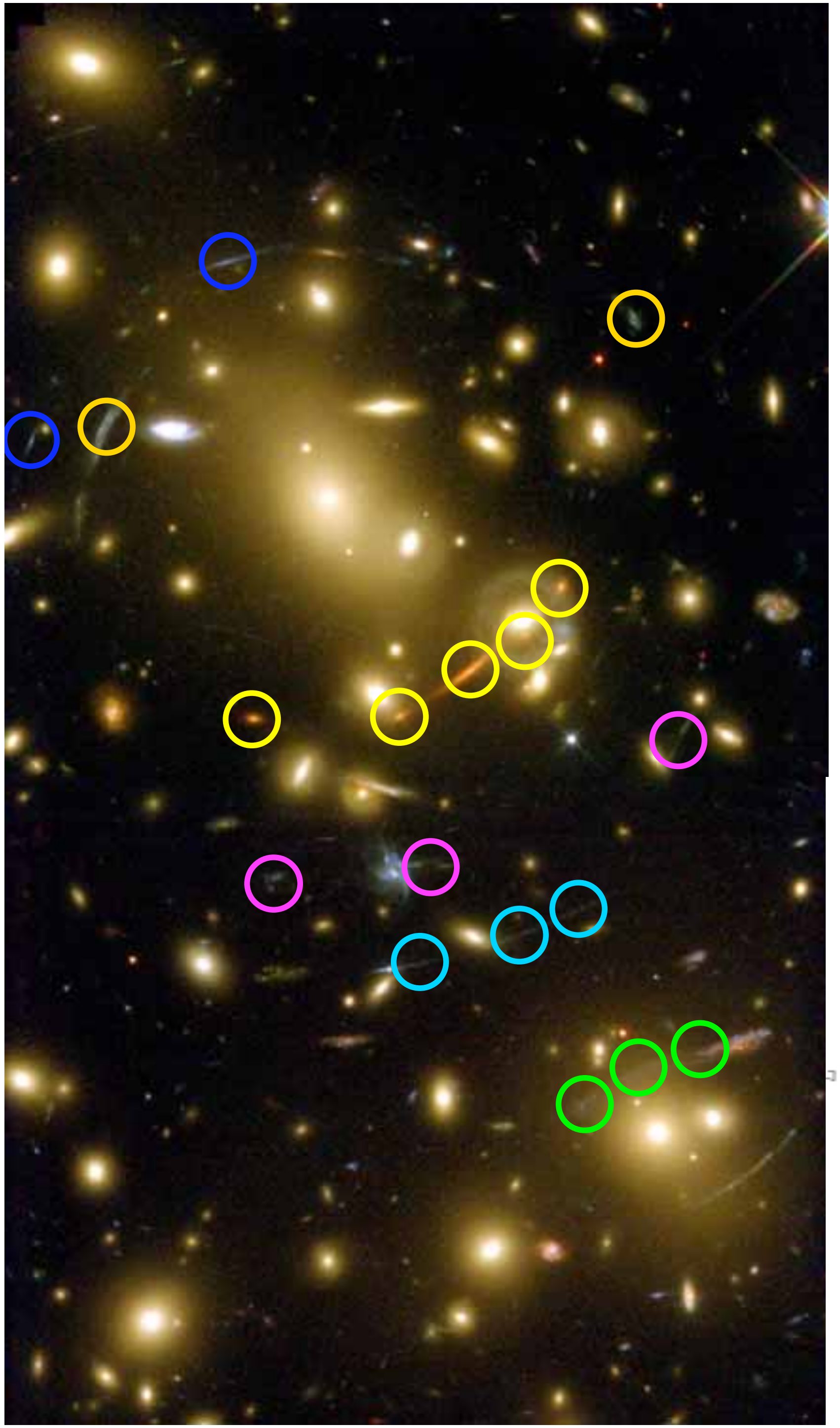
$$\boxed{\alpha = \frac{D_{LS}}{D_{OS}} \nabla \varphi \propto M}$$





Cluster of Galaxies

•Identify multiple images, measure their redshift



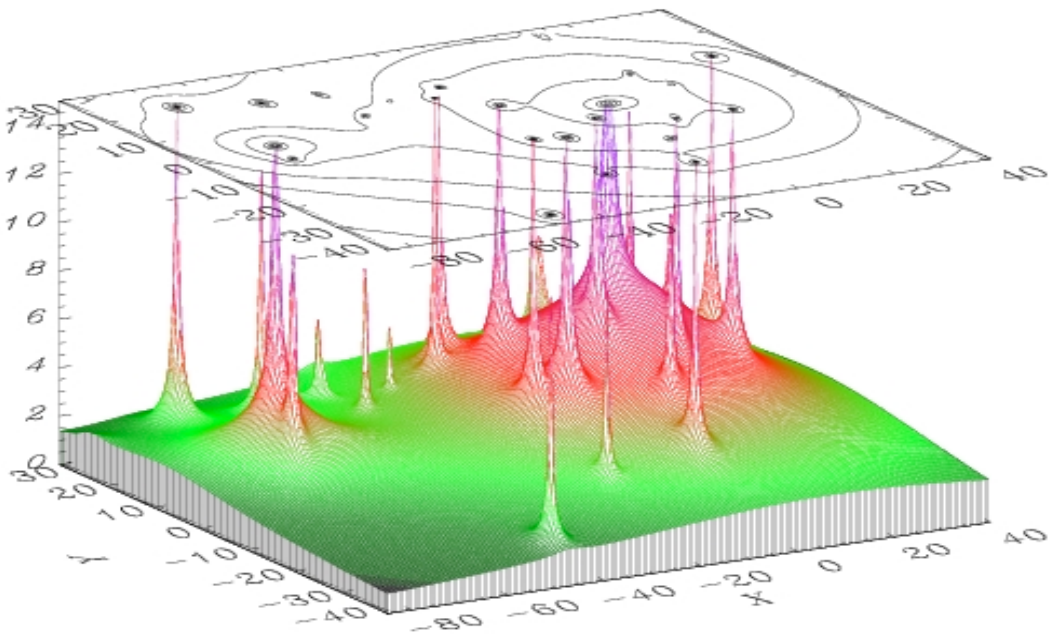
Cluster of Galaxies

•Identify multiple images, measure their redshift

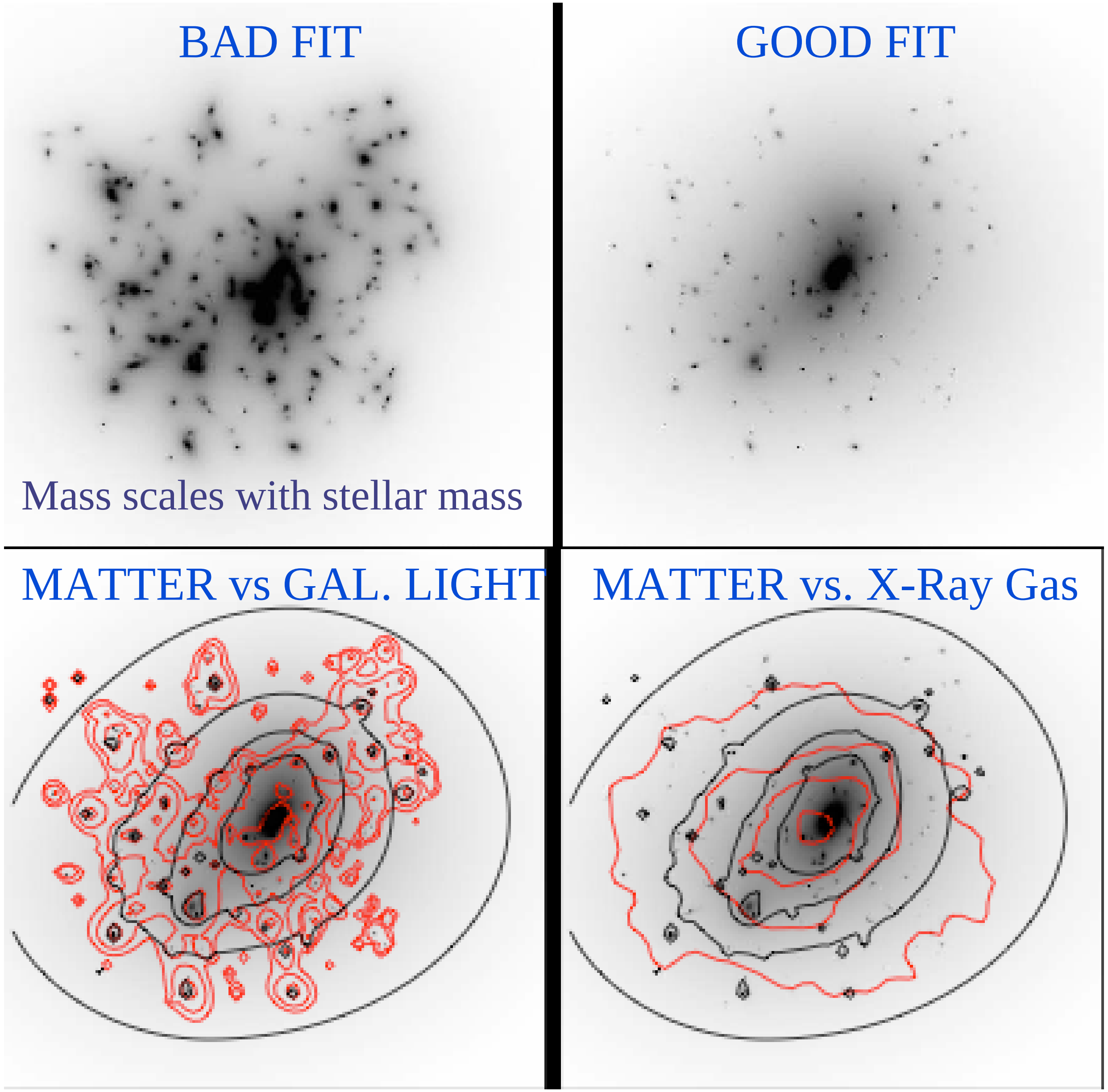
•Model the cluster by a sum of: cluster components and dark halos around galaxy clusters

•Galaxies halos contribute for ~10% of the total mass in cluster cores

• **Lenstool software, MCMC optimisation (Jullo et al 2007)**



Where is the Matter in A2218?

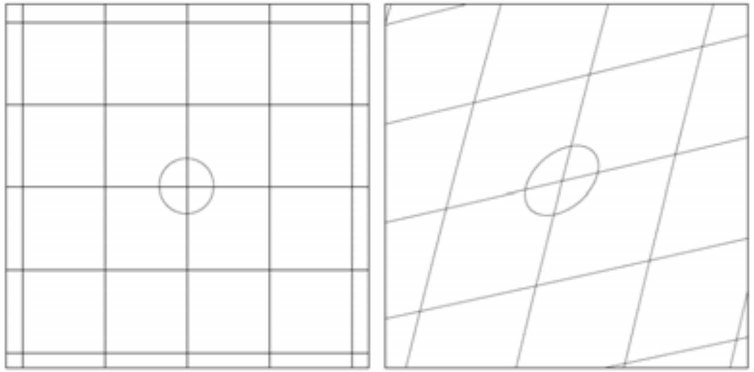


Strong Lensing constraints in Abell 2218:

- ➢ Mass distribution proportional to the stellar mass produce a BAD FIT to the lensing data
- ➢Require large scale mass distribution (cluster DM)
- ➢Important difference between DM , Galaxy distribution and X-ray gas (different physics)
- ➢But scaling relation should exists

Eliasdottir et al. 2008

Lens Mapping



source image

Amplification Matrix :

$$\mathcal{A}^{-1} = \begin{pmatrix} \boxed{1-\kappa} - \gamma_1 & -\gamma_2 \\ -\gamma_2 & \boxed{1-\kappa} + \gamma_1 \end{pmatrix}$$

κ: convergence

$$\boxed{\kappa = \Delta\varphi/2 = \Sigma/2\Sigma_{crit}}$$

$$\Sigma_{\rm cr} = \frac{c^2}{4\pi G}\frac{D_{\rm s}}{D_{\rm d}D_{\rm ds}} = 0.35\,{\rm g\,cm^{-2}}\left(\frac{D}{1\,{\rm Gpc}}\right)^{-1}$$

$\gamma(\gamma_1,\gamma_2)$: shear vector

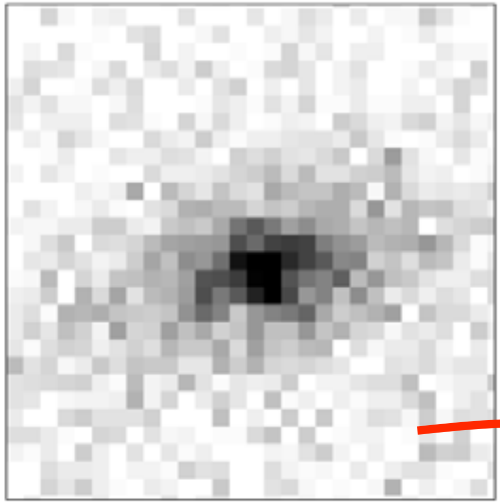
$$\boxed{\gamma_1 = (\partial_{yy}\varphi - \partial_{xx}\varphi)/2 \qquad \gamma_2 = \partial_{xy}\varphi}$$

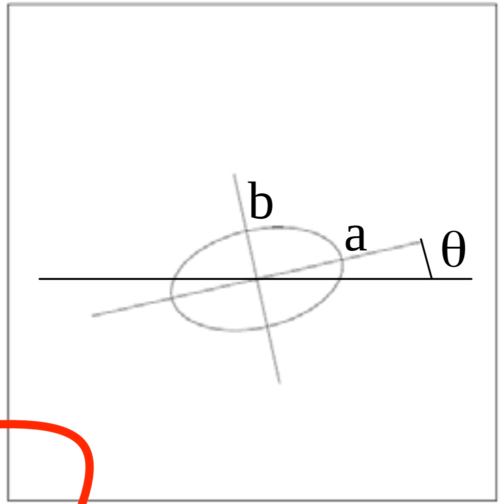
Reduced shear (what we can measure):

$$\boxed{g = \frac{\gamma}{1-\kappa}}$$

Weak Lensing

Morphometry and shear measurement





$$M_{ij} \propto \; R_\theta \begin{pmatrix} a^2 & 0 \\ 0 & b^2 \end{pmatrix} R_{-\theta}$$

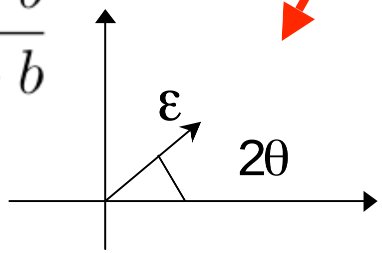
Lensing equation for image moments

$$M^S = \; A^{-1} \; M^I \; {}^t A^{-1}$$

Lensing equation for ellipticity vectors

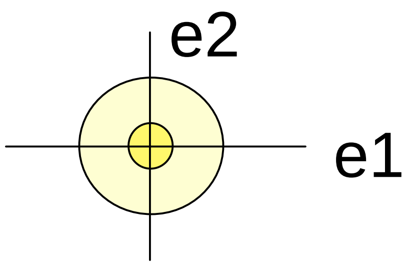
$$\boxed{\varepsilon_S = \frac{\varepsilon_I - g}{1 - g\varepsilon_I} \sim \varepsilon_I - \gamma}$$

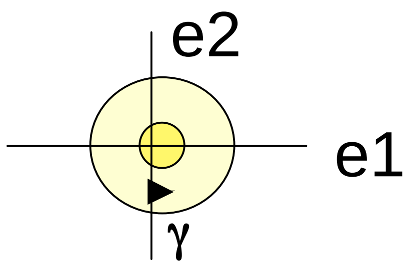
$$\varepsilon = \frac{a-b}{a+b}$$



Ellipticity vector 07

Ellipticity distribution





Measuring Weak Shear

- In the ***weak regime***,the shape of galaxies are linearly modified by the gravitational shear:

$$\varepsilon_I = \varepsilon_S + \gamma \qquad \boxed{\gamma(x,y) <=> \Sigma(x,y)}$$

- The average of galaxy shape is an unbiased estimator of the gravitational shear:

$$< \varepsilon_I > = < \cancel{\varepsilon_S} >_{=0} + < \gamma >$$

- Error on shear is a function of intrinsic shape, measurement error and number of galaxies

Galaxy Properties

$$\sigma^2(\varepsilon_I) = \sigma^2(\gamma) \propto \frac{\boxed{\sigma^2(\varepsilon_S)} + \boxed{\delta^2 \varepsilon_I}}{\boxed{N}}$$

PSF correction & method

Survey size & depth

Weak Lensing: recipe and results

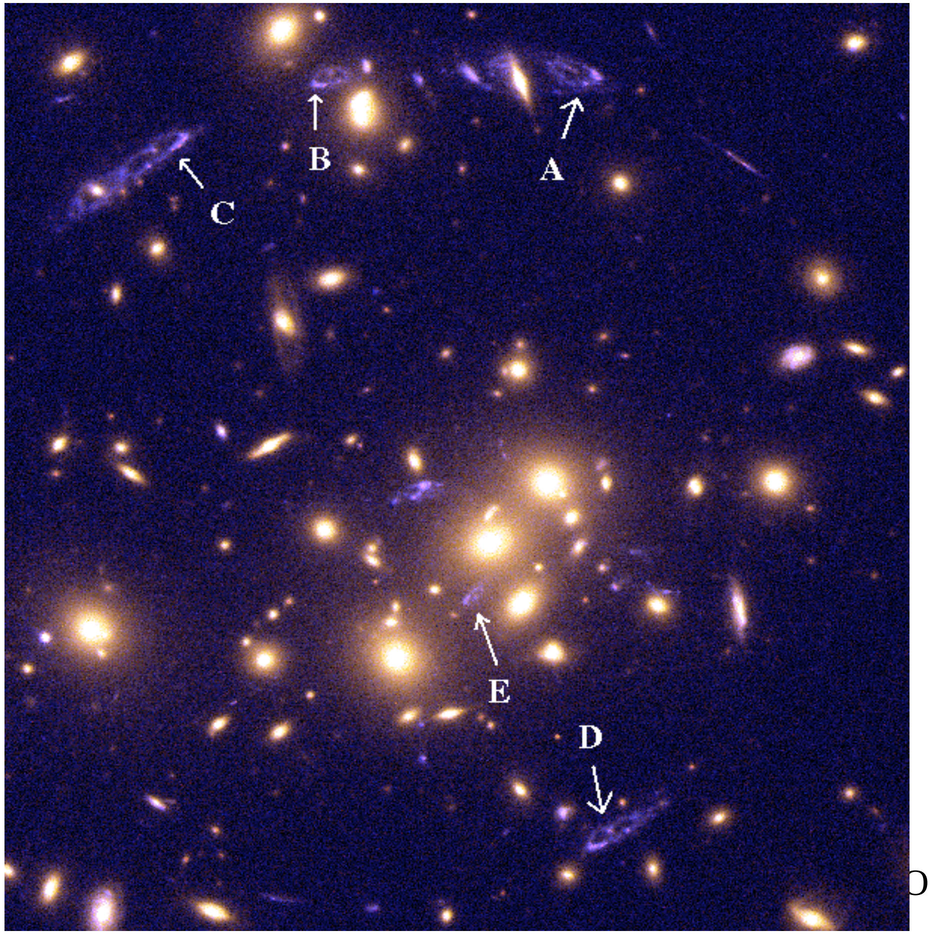
- start with detecting objects in the CCD frame
- select galaxies removing stars, defects, stellar spikes
- correct for PSF circularization and anisotropy
- estimate a redshift for each galaxy (using photometric redshift if color information is available)
- select galaxies to be used as the ‘background sample’

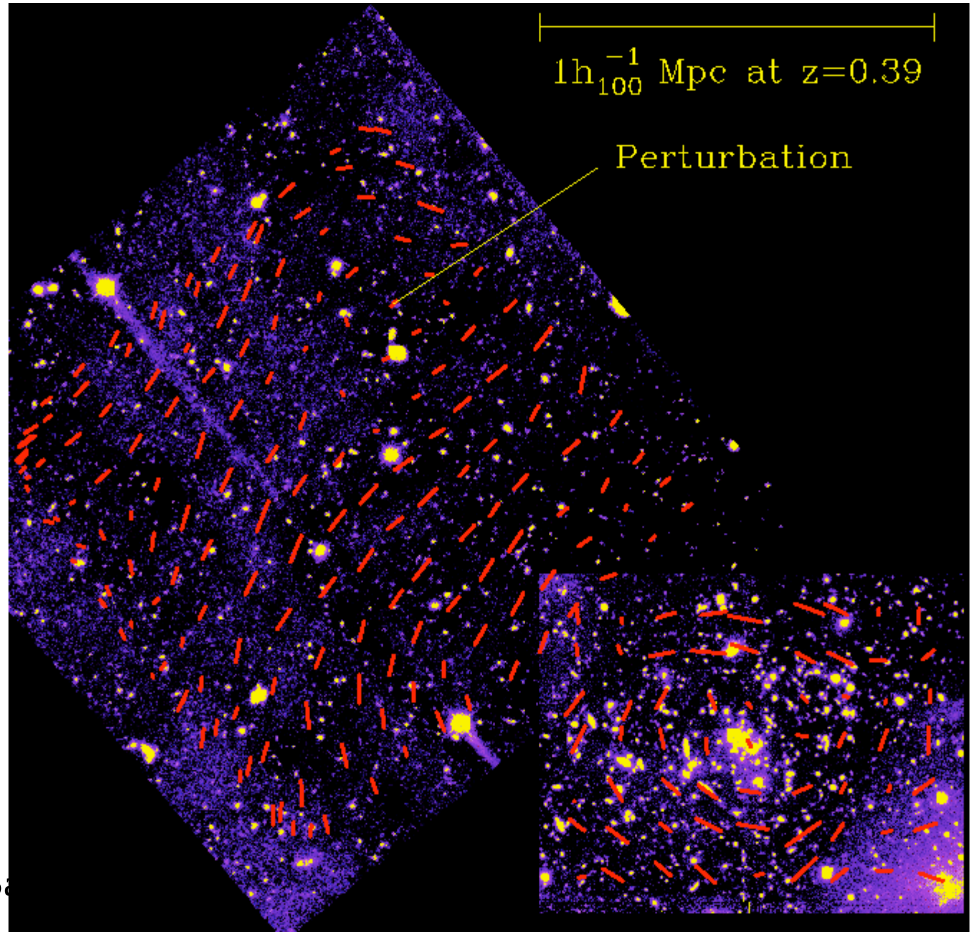
- Compute weak lensing statistics to constrain cosmology
- reconstruct the dark matter map
- probe the mass distribution of groups and galaxies
- **confirm the results** by comparing to other dataset

Coupling Strong and Weak Lensing

Absolute central mass

relative total mass and slope

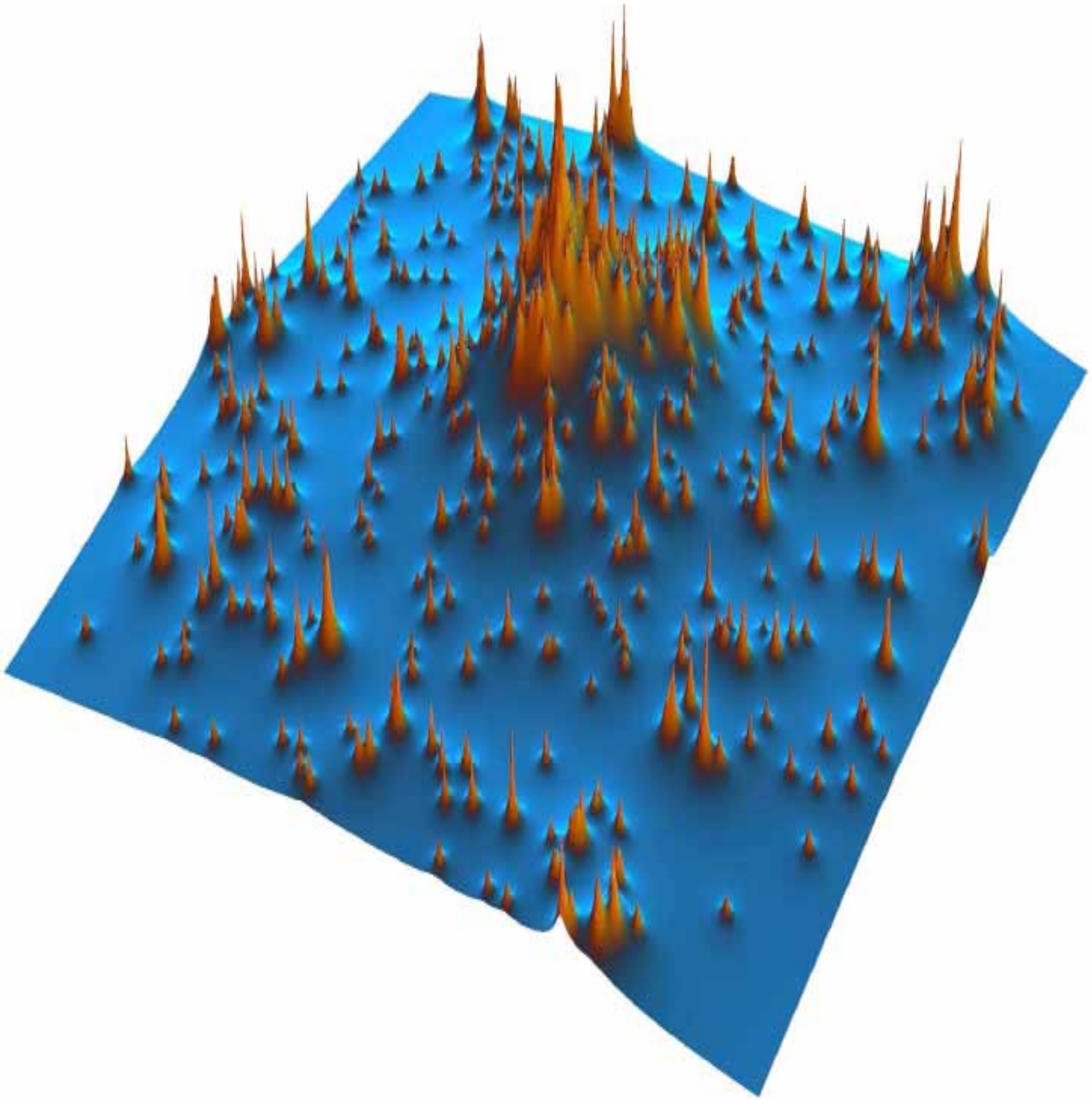




Cl0024+1654 HST wide field sparse mosaic

- **76 orbits, 38 pointings**
- **Probe regions up to ~5Mpc**

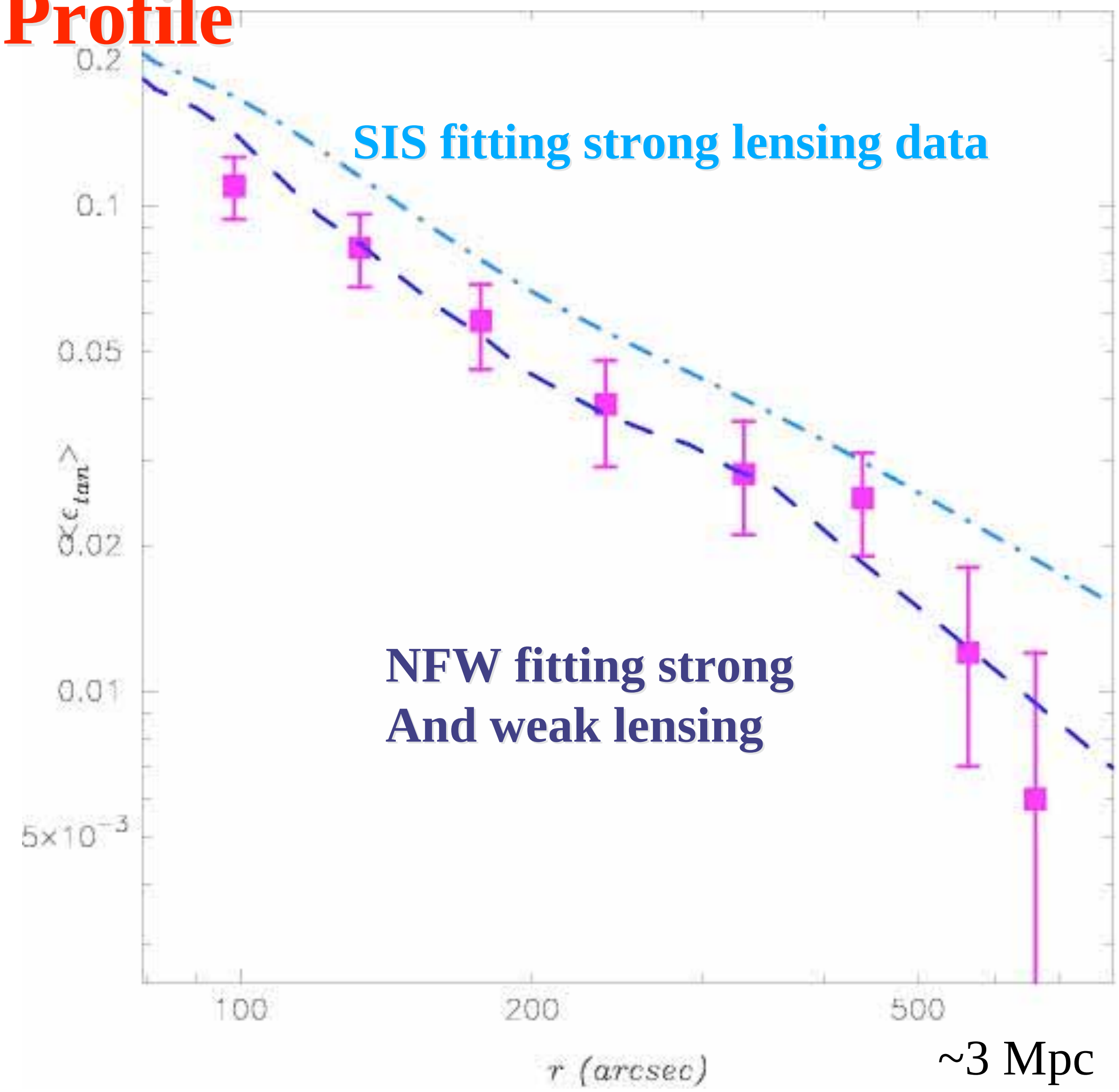
Aim: learn cluster physics of clusters by comparing with other mass estimates: X-ray, dynamics, learn on galaxy halo mass stripping



Treu et al 2003, Kneib et al 2003, Natarajan et al 2007

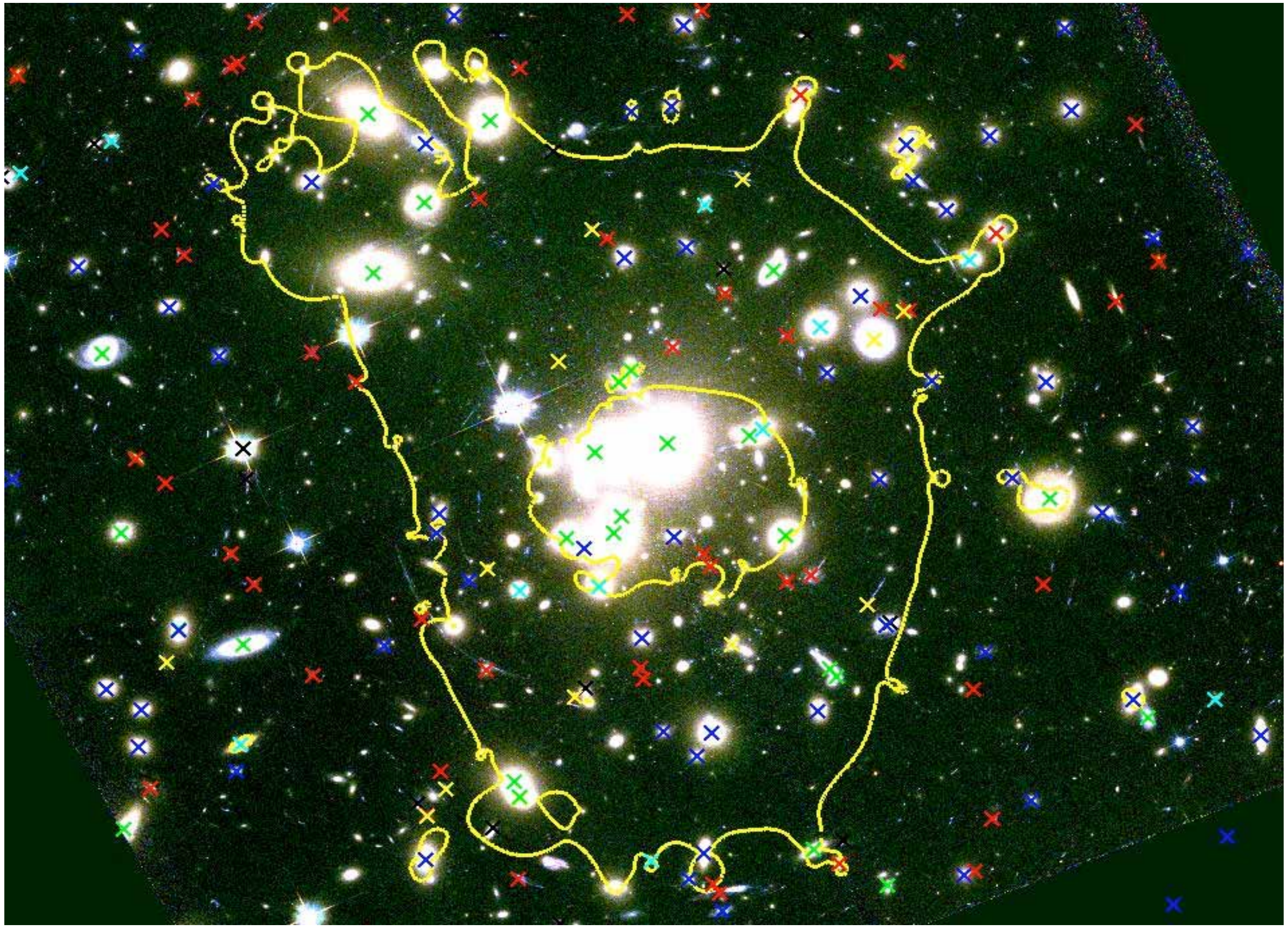
0024: Shear/Mass Profile

- Extrapolate strong lensing models at large scale by exploring various cluster mass profile.
- Rule out SIS model
- NFW (with large c~20) or Power-law profile give a good fit.
- Large ‘c’ is unexpected from CDM simulations!
  - ➢Line of sight alignment/merger?
  - ➢Very old structure?
  - ➢**Systematics (N(z), and others)?**



The most massive cluster: Abell 1689

- Mass models form different groups w. or w/o weak lensing
- Massive spectroscopic surveys (2003-2006)
- 41 multiple image systems, 24 with spectro-z with $1.1 < z < 4.9$



Broadhurst et al 2005
Halkola et al 2007
Limousin, et al. 2007
Richard et al. 2007
Frye et al 2007
Leonard et al 2007

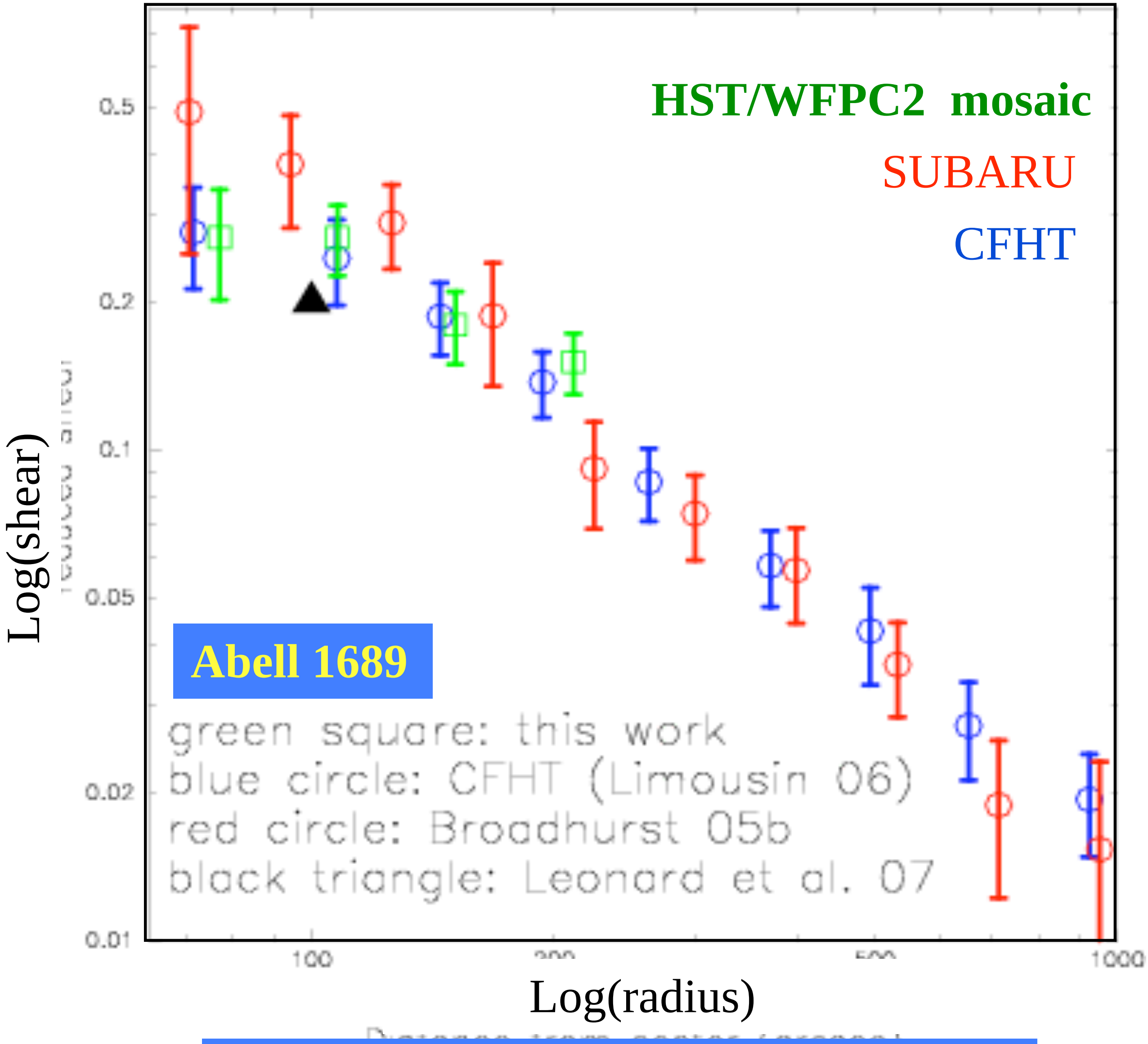
X KECK/LRIS
X VLT/FORS
X CFHT/MOS
X MAGELLAN /LDSS2
X Littérature

Mass Profile of Clusters (SL+WL)

- **background source selection is *critical* to accurately measure WL**

- **Improved lensing constraints, revised concentration from c~15 to c~8**

- **Better agreement with current understanding of structure formation**



Limousin, et al. 2007, Dahle et al 2007

The « Bullet Cluster »: Direct Proof of DM

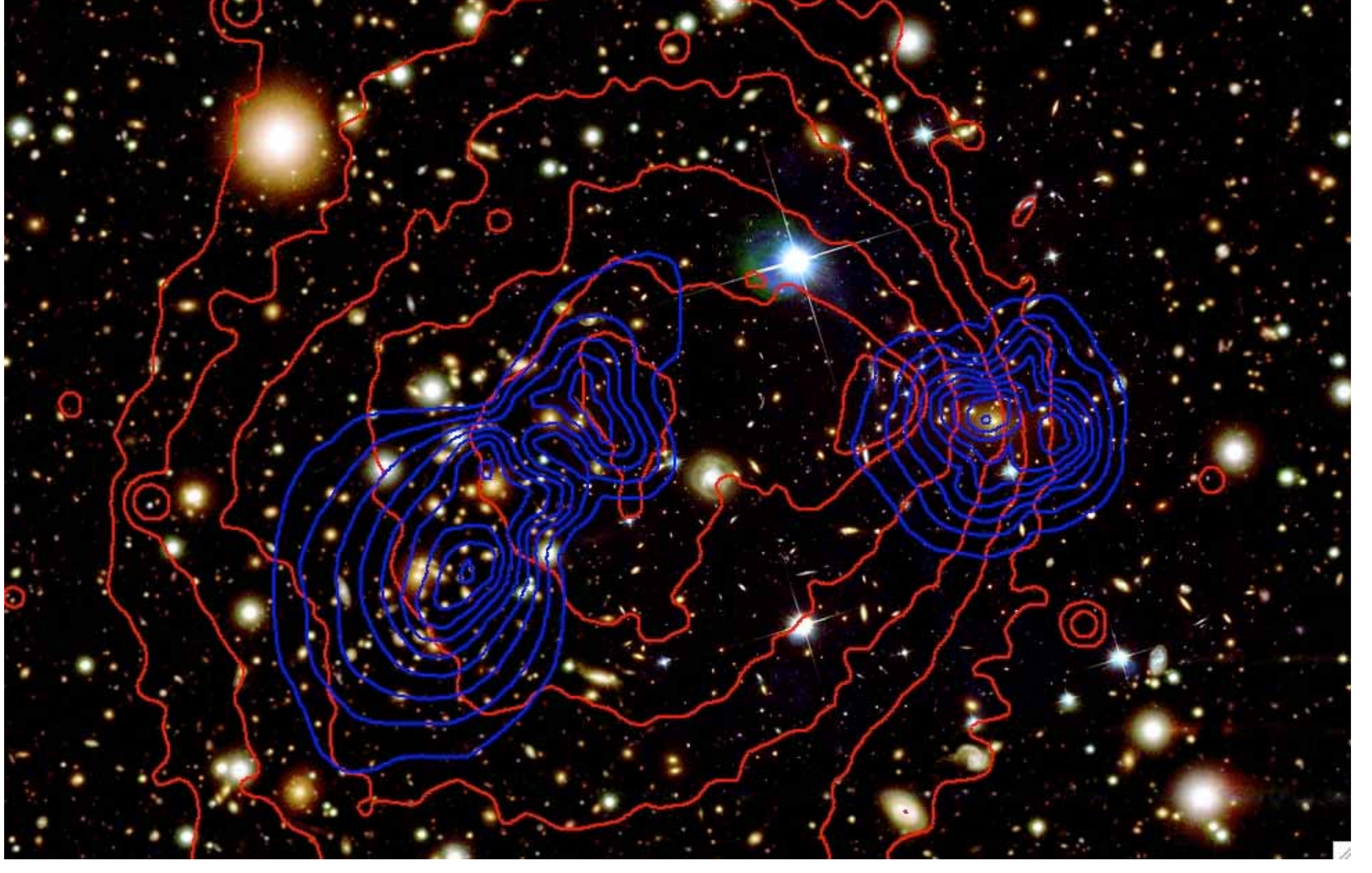
•Encounter of 2 massive clusters

•Significant offset between X-ray gas and lensing mass peaks

⇒ probably best evidence for « collisionless dark matter »

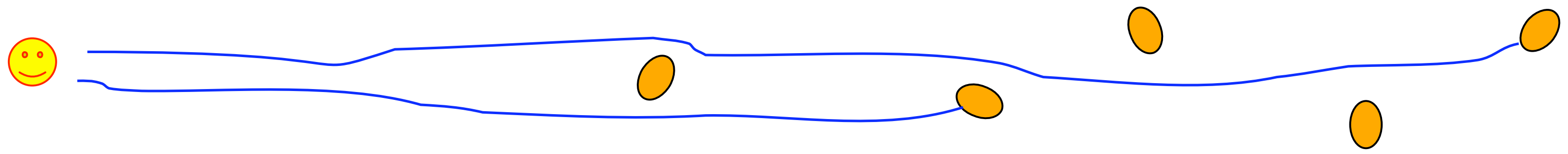
⇒ lensing better mass estimator for counting cluster?

1E0657



Clowe et al 2006,
Bradac et al 2006

Combining Lensing & Photo-z in wide field surveys



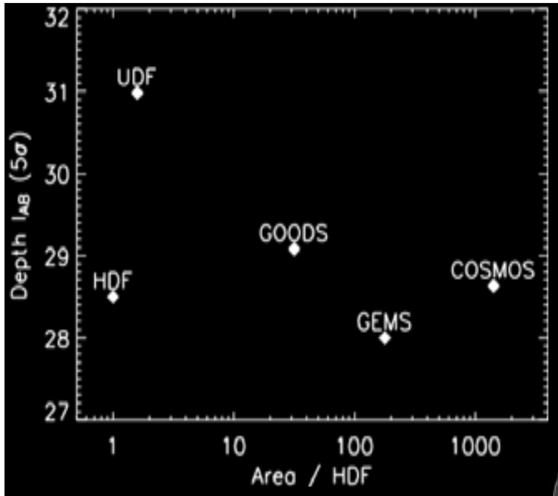
- Weak lensing distortion depends on the cumulative mass distribution along the line of sight.
- Knowledge of the galaxy redshift (photo-z) allows *tomography of the mass distribution* in the Universe at various scales and allow comparison to the galaxy distribution
- **Ultimate aim**: measure the growth of structures, which will impact our understanding of cosmology (dark energy)

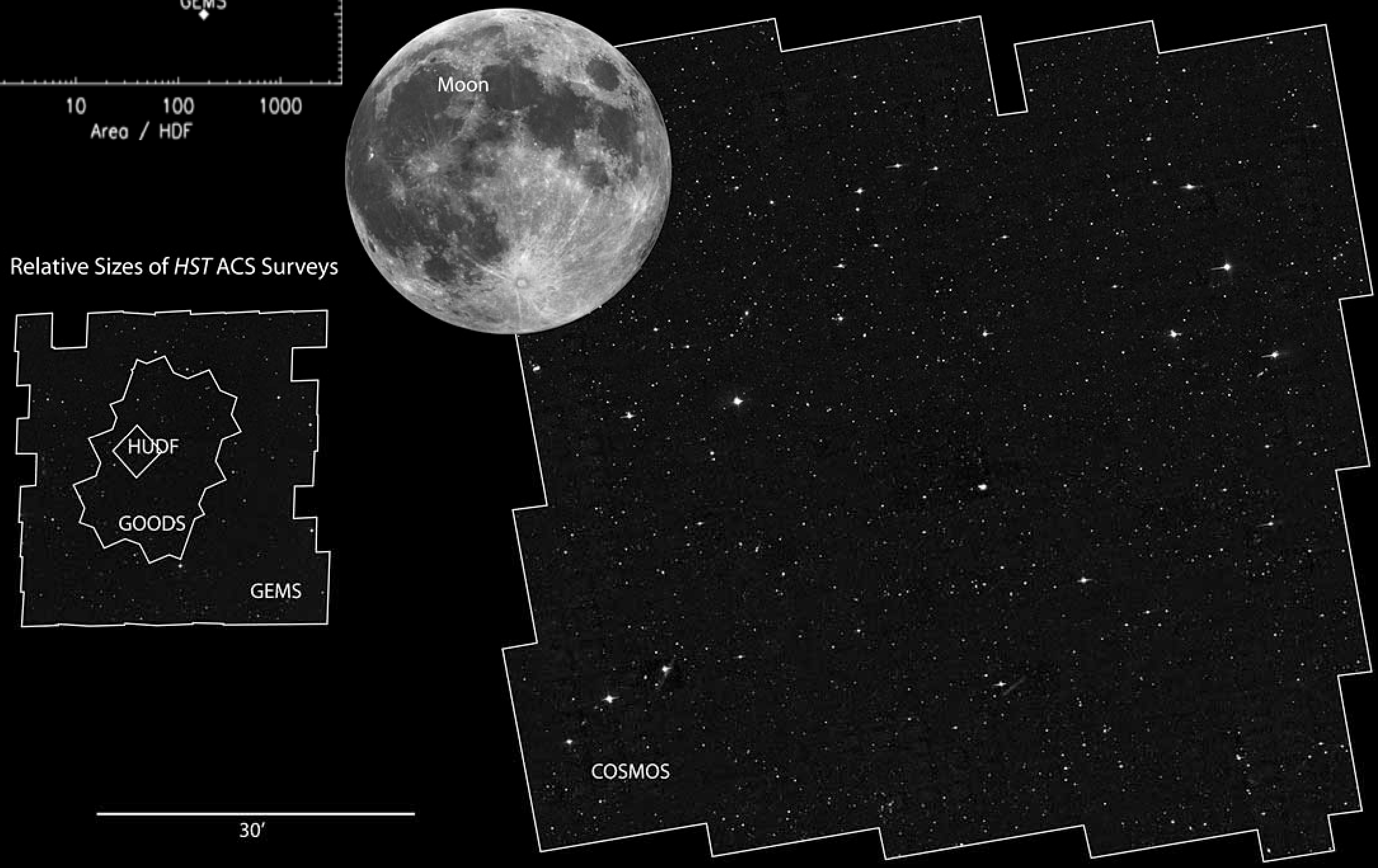
The COSMOS *Hubble* Survey

Largest ever HST program

- **10% of Hubble during 2 years**
- **575 contiguous ACS fields in F814W (~I band); ~50min int.time per pixel**
- **1.64 square degrees**
- **20 Giga pixel image (0.03”/pixel)**
- **0.12” image resolution**
- **1.2 millions of galaxies with I_{F814}<26.6 (at 5σ)**
- **0.4 millions galaxies useful for lensing**
- **~100 astronomers**

Comparison to other *Hubble* Surveys





COSMOS: Multi-wavelength follow-up

Optical/IR follow-up:

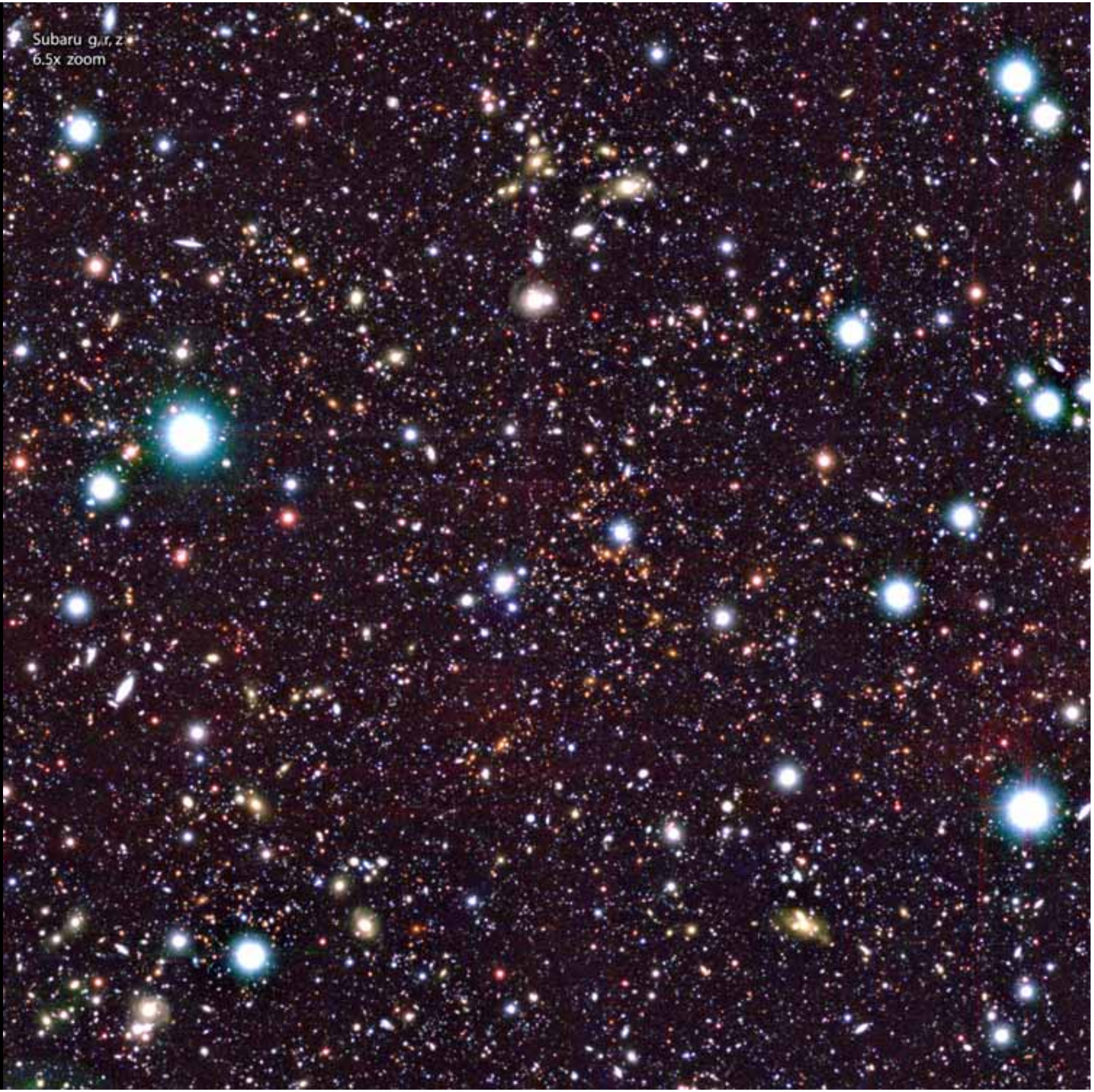
- **SUBARU:** (~5% time/year)
    - BgVriz+NB
    - **seeing 0.9-1.5”**
- **CFHT:** (~5% time/year)
    - U band
    - H-K-band
- UKIRT Y-J band
- Spitzer:
    - IRAC ~200h (3.6 to 8 μm)
    - MIPS ~400h (24 μm)
- GALEX
- VLA
- XMM, Chandra
- ….

Public data!

http://irsa.ipac.caltech.edu/Missions/cosmos.html

Subaru SuprimeCAM

g,r,z
6.5 x zoom



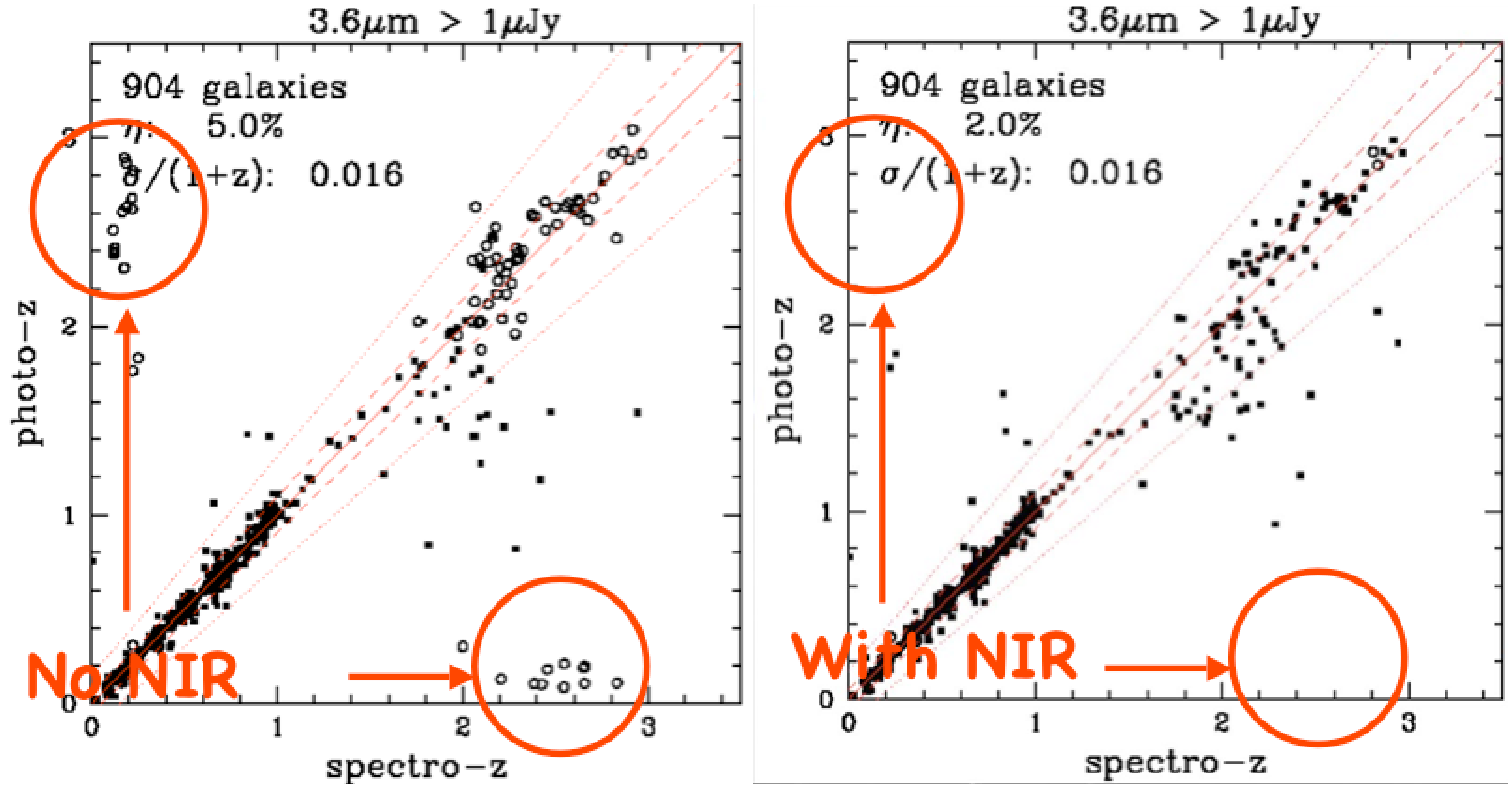
Photometric Redshift

Fitting SED templates with photometry from:

7 broad optical bands, 6 intermediate bands + K-band + IRAC 3.6&4.5 μm

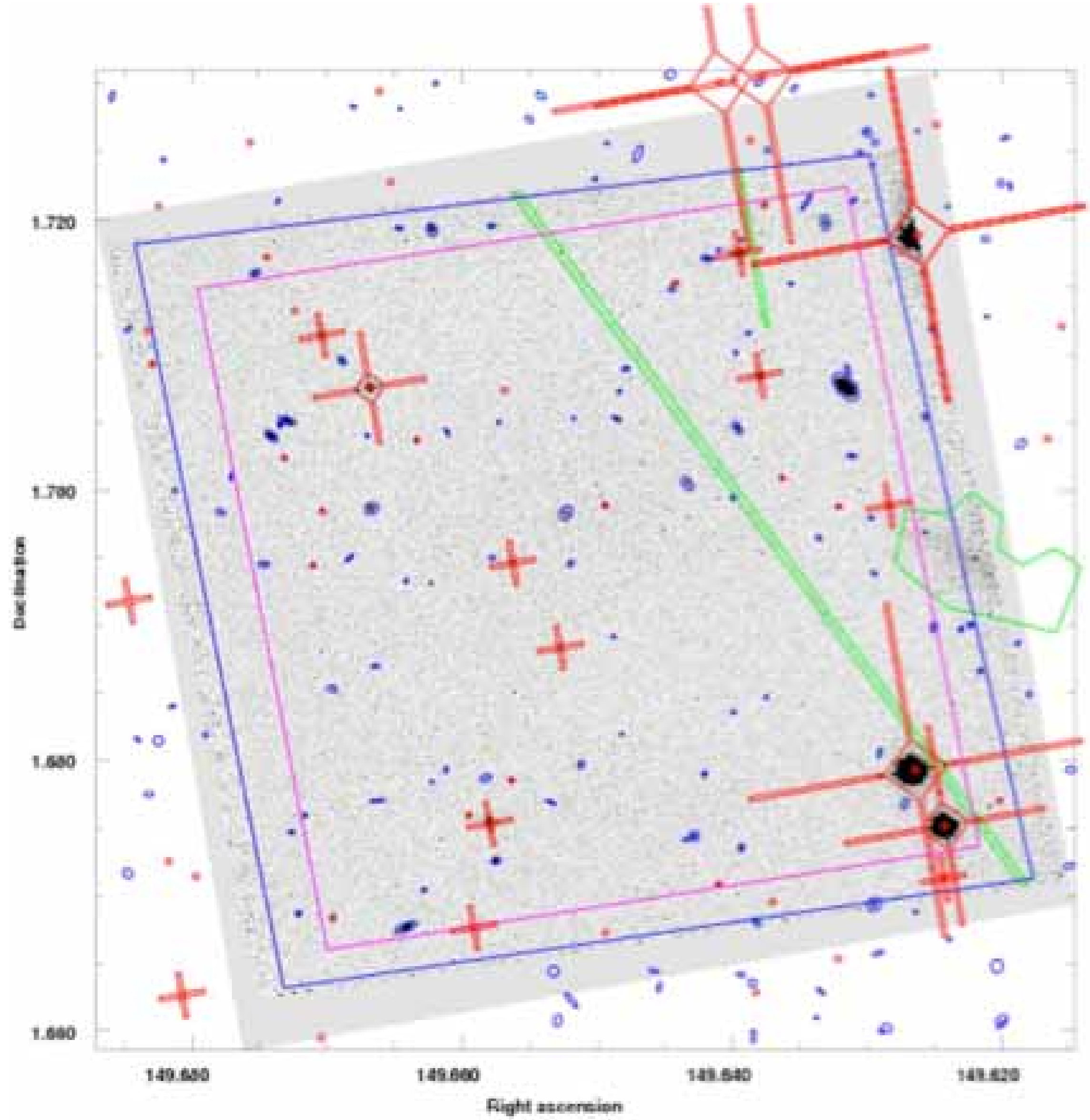
IR reduces catastrophic errors

intermediate bands reduce scatter for bright objects (Ilbert et al 2008)



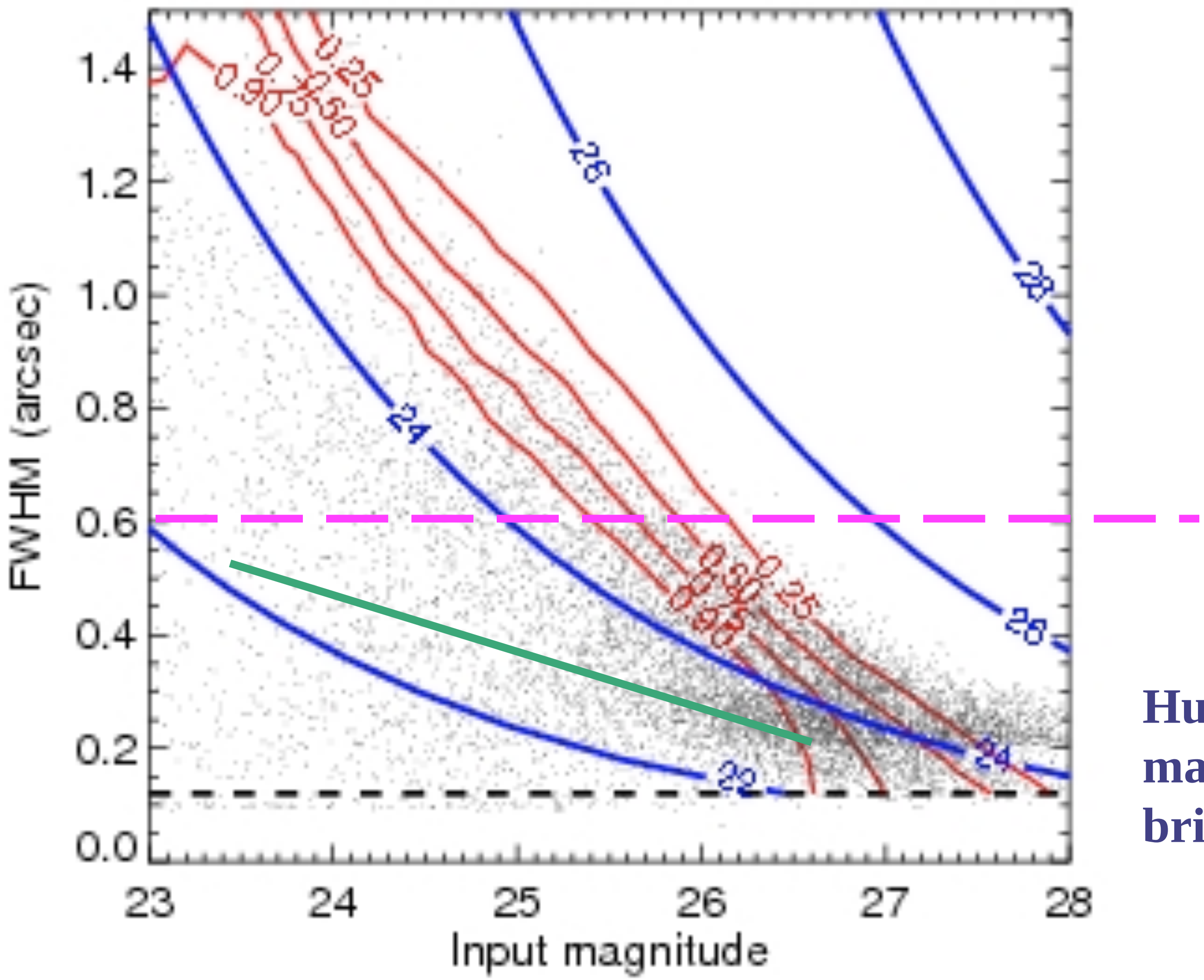
Making of the ACS lensing catalogue

- 575 tiles
- 1.5 million detections using « hot-cold » sextractor method
- 0.4 million galaxies surviving various cuts (**masking**, PSF correction, **photo-z**, weak lensing S/N …)
- With the better photo-z, more galaxies will be used for lensing



Leauthaud et al 2007

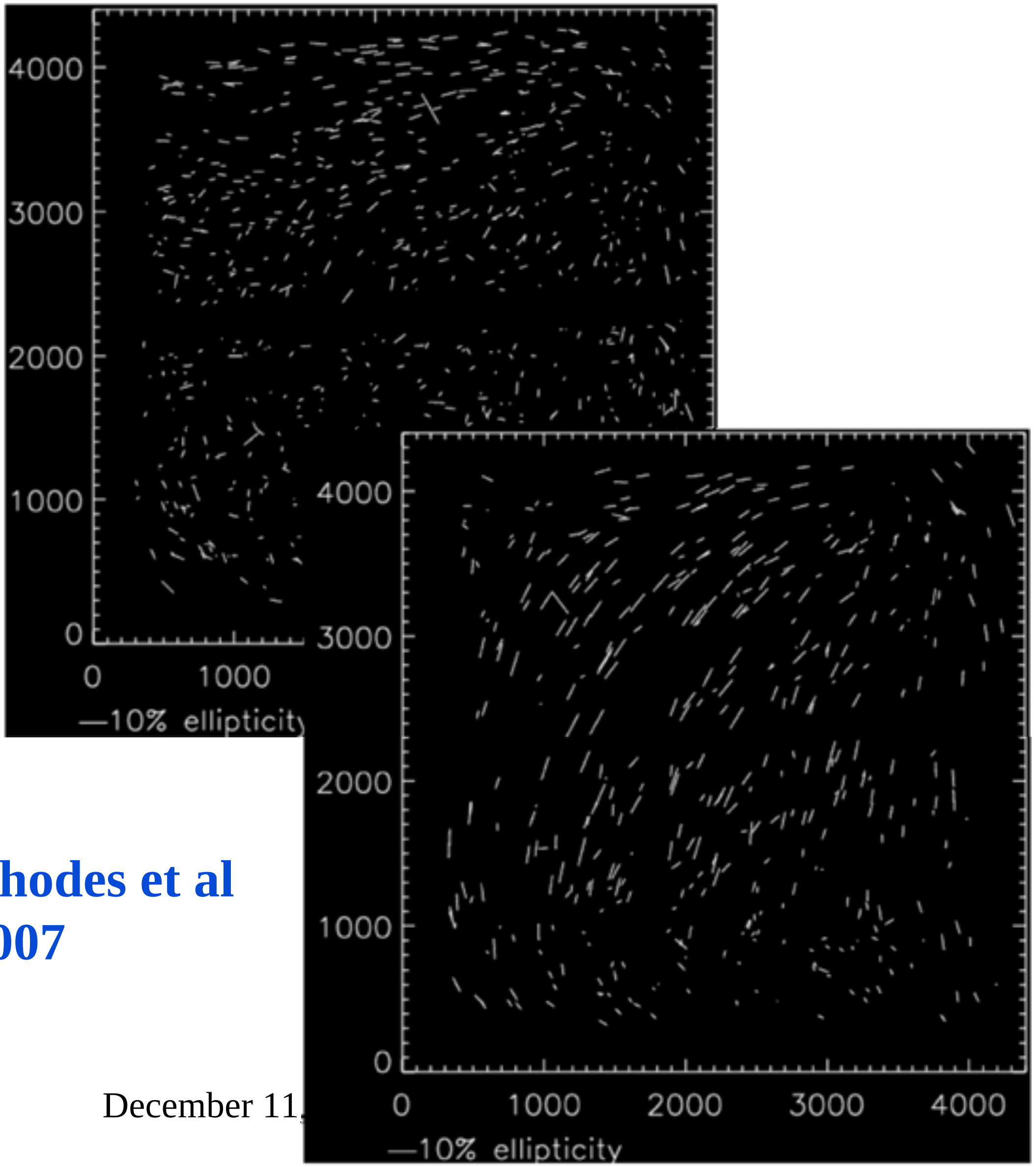
Size vs Magnitude & Completness



Ground based
Seeing limit

Hubble/ACS data
mainly surface
brightness limited

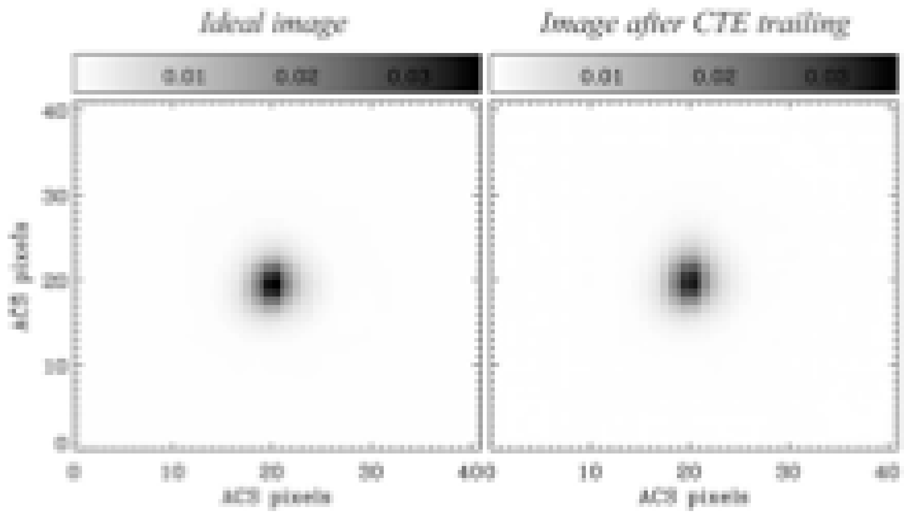
Lensing in COSMOS: PSF variation

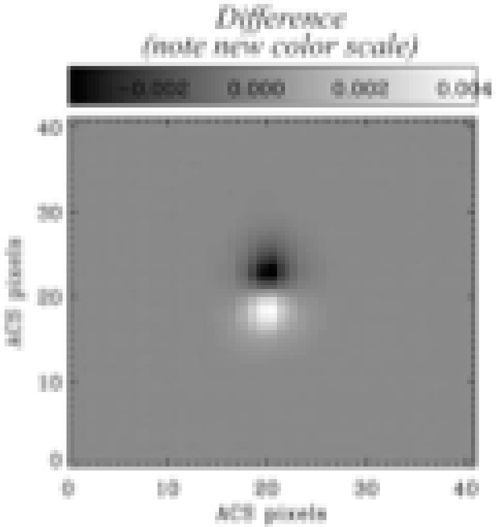


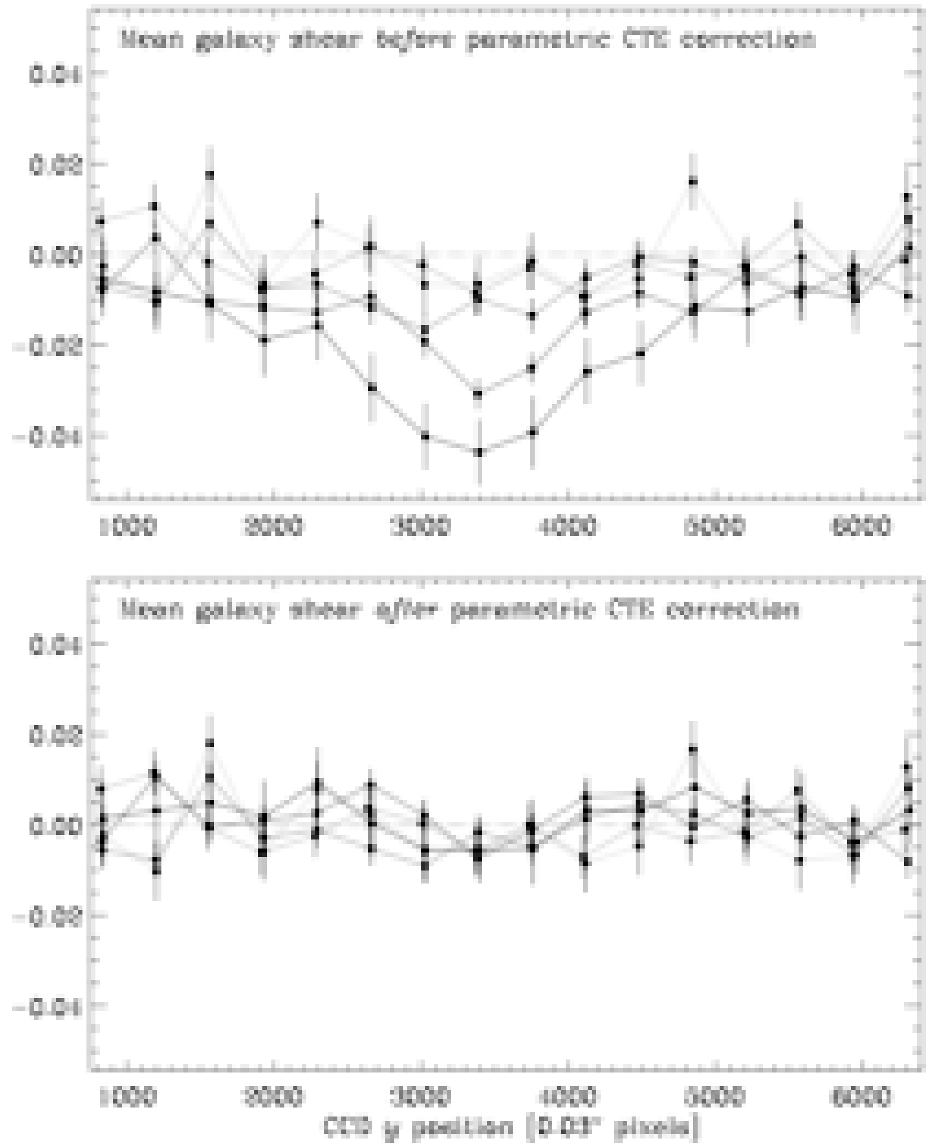
Rhodes et al 2007

- ACS PSF is varying with time (focus is changing with T variation)
- TinyTim PSF model adjusted by measuring the shape of stars (~20 per pointing)
- provide PSF correction for any position on ACS chips.
- CTE corrections

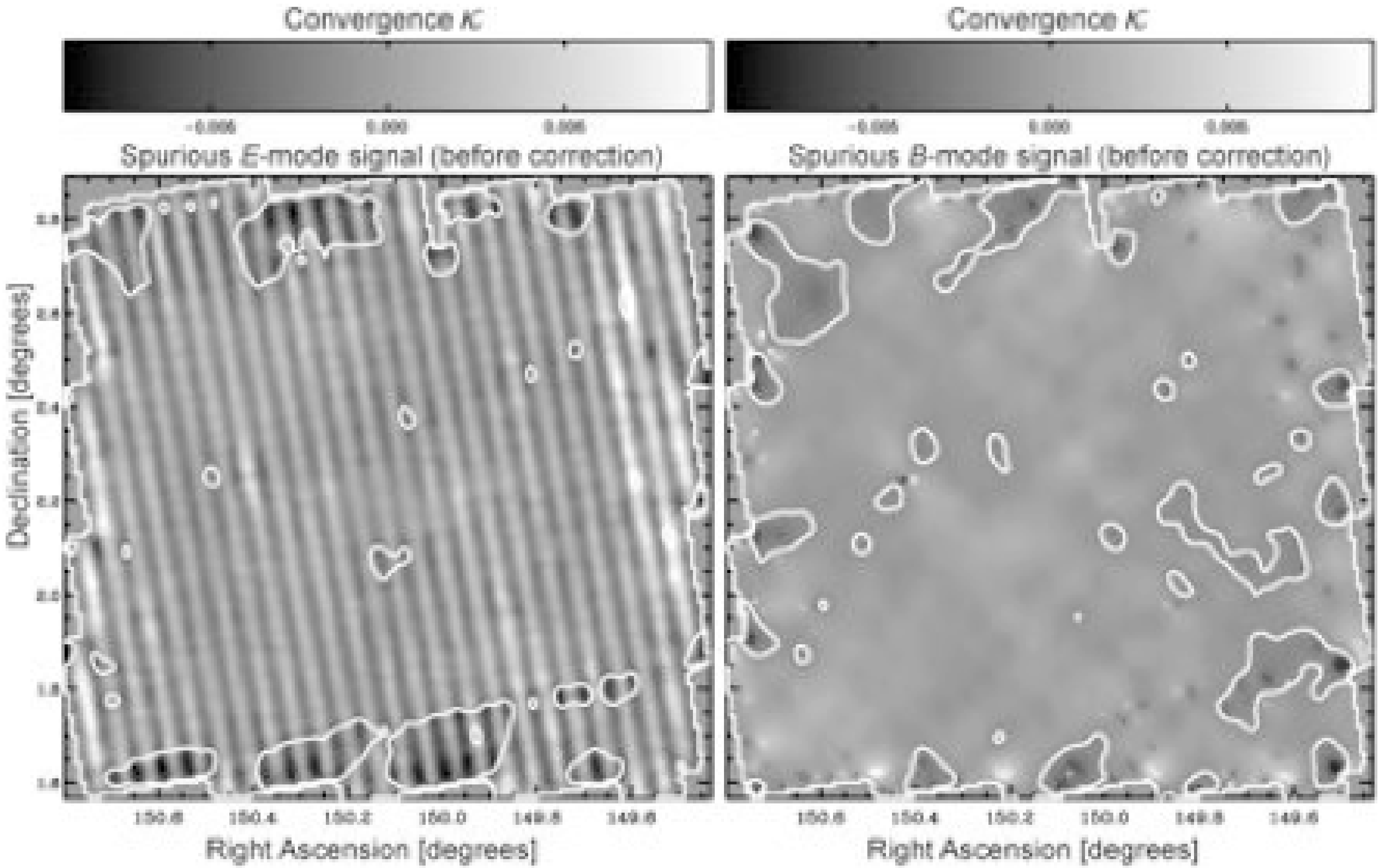
Analytic correction of the CTE







Charge Transfer Efficiency Correction Needed



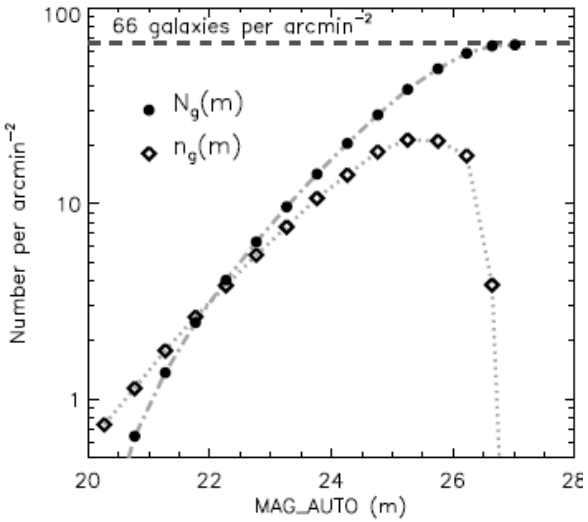
Galaxy Properties

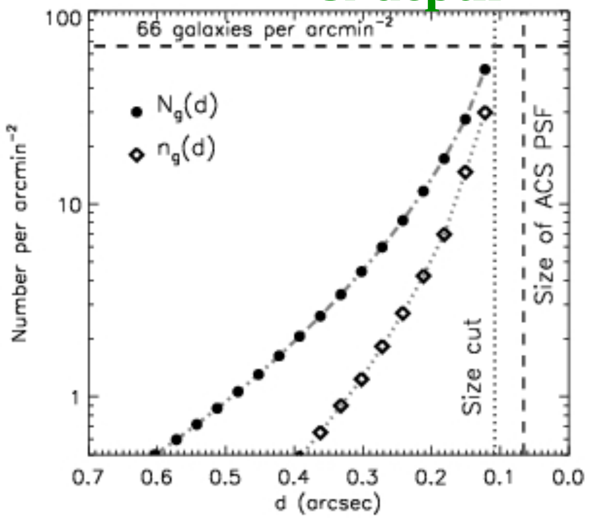
$$\sigma^2(\varepsilon_I) = \sigma^2(\gamma) \propto \frac{\boxed{\sigma^2(\varepsilon_S)} + \boxed{\delta^2 \varepsilon_I}}{\boxed{N}}$$

PSF correction & method

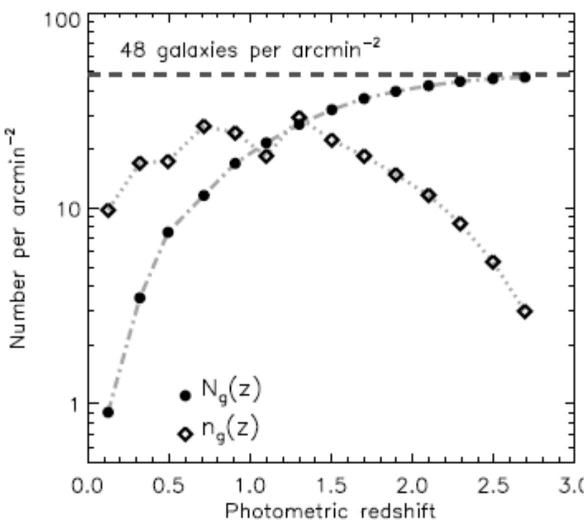
Survey size & depth

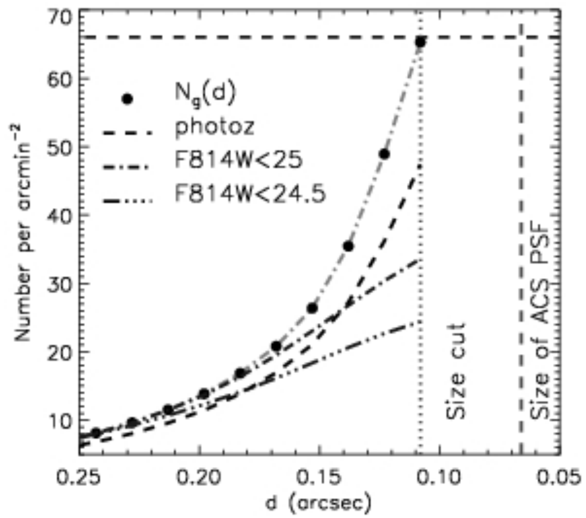
Number density of galaxies in the ACS catalogue





d Size= FWHM/2





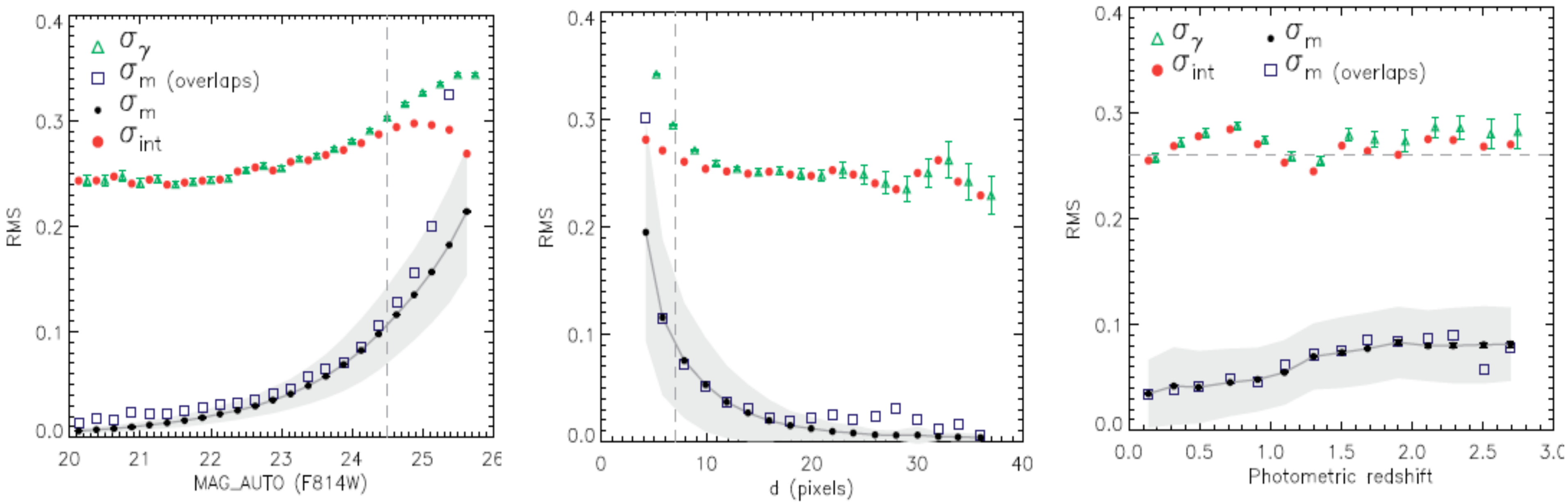
Shape Noise as a function of Mag, Size,Redshift

Galaxy Properties

PSF correction & method

$$\sigma^2(\varepsilon_I) = \sigma^2(\gamma) \propto \frac{\boxed{\sigma^2(\varepsilon_S)} + \boxed{\delta^2 \varepsilon_I}}{\boxed{N}}$$

Survey size & depth

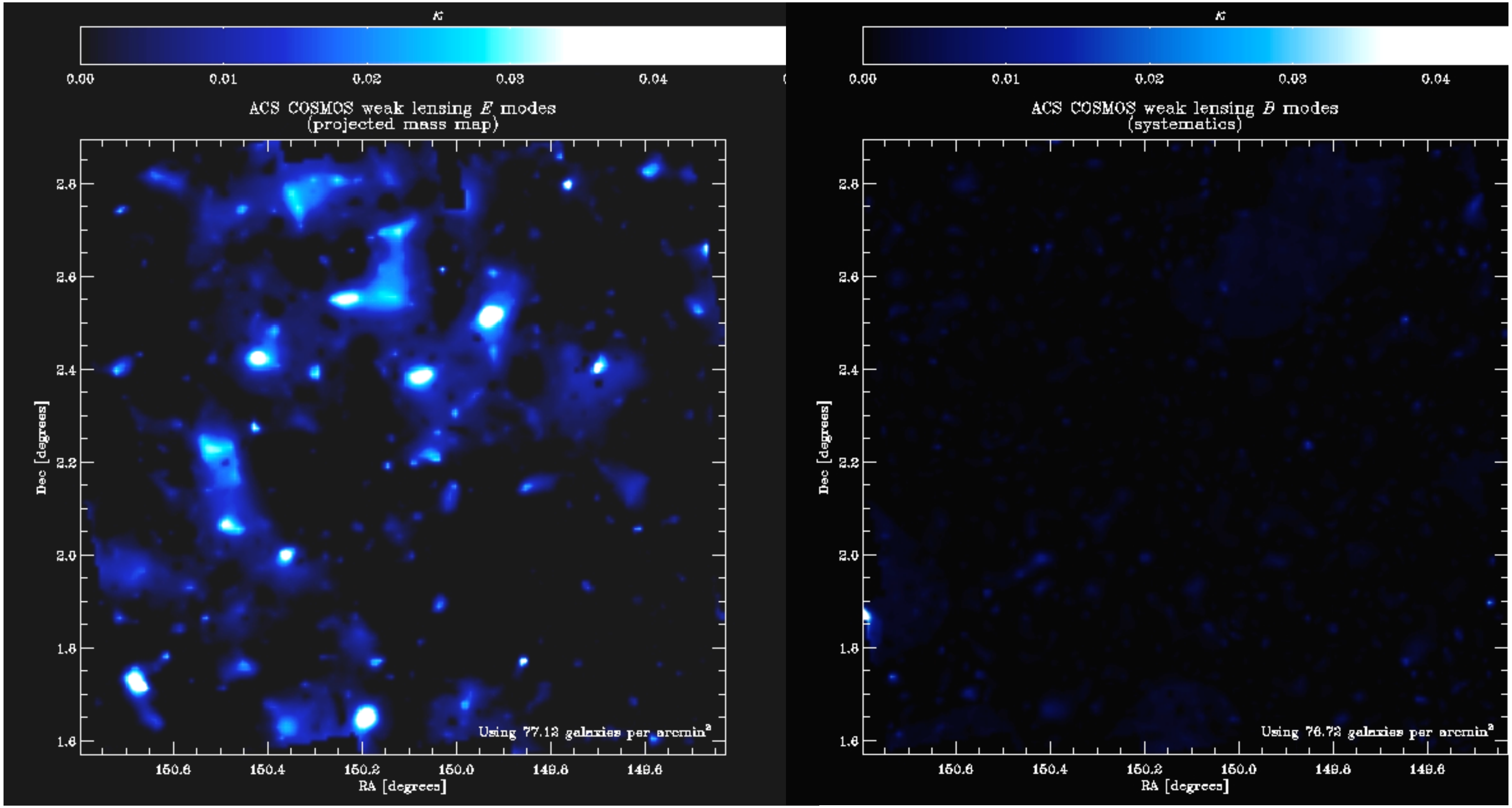


RMS ellipticity σ (ε_s)=0.26 is constant with magnitude,size, redshift

Mass map of COSMOS survey

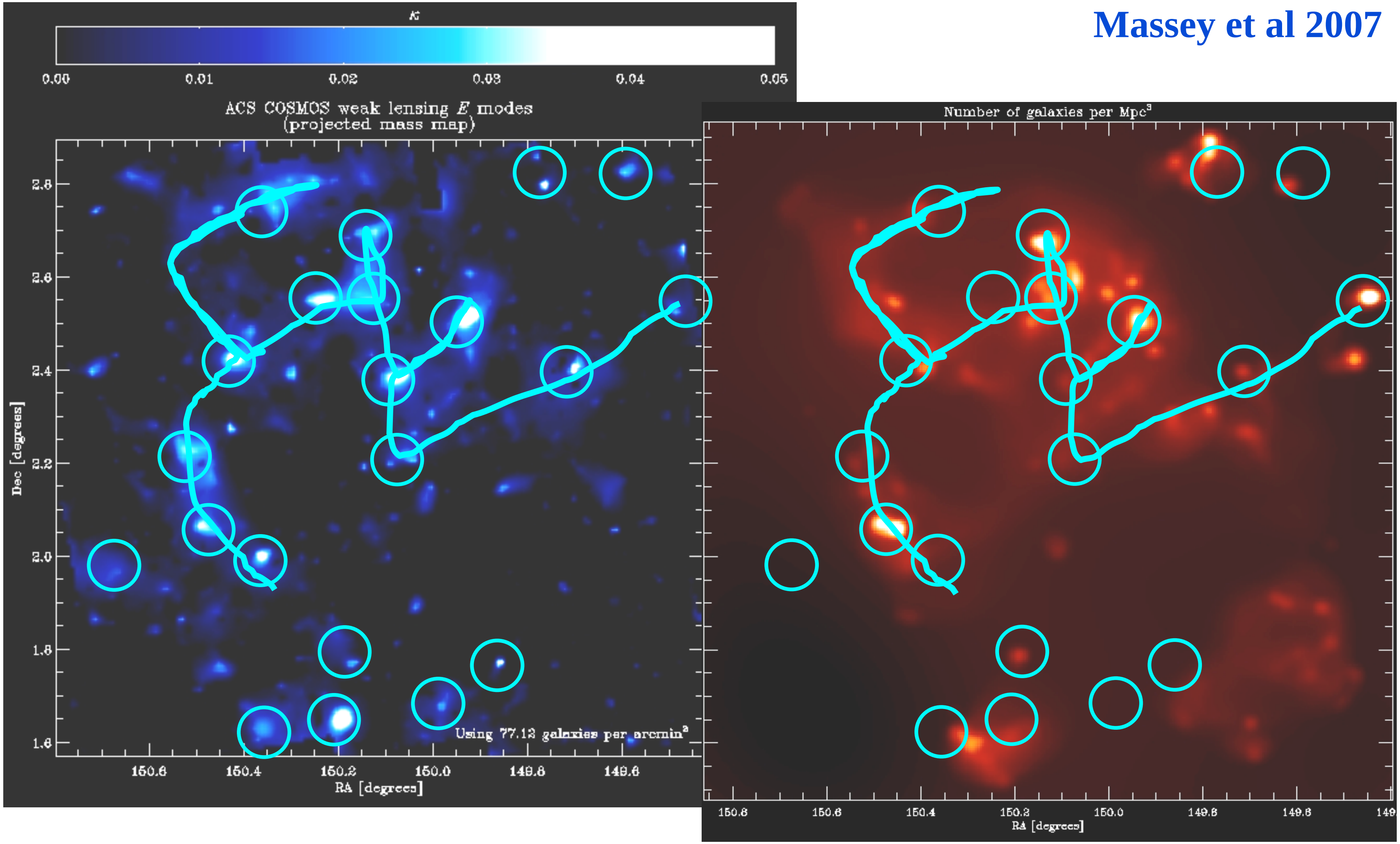
Massey et al 2007

Signal: E mode **Noise: B mode**



Mass vs light

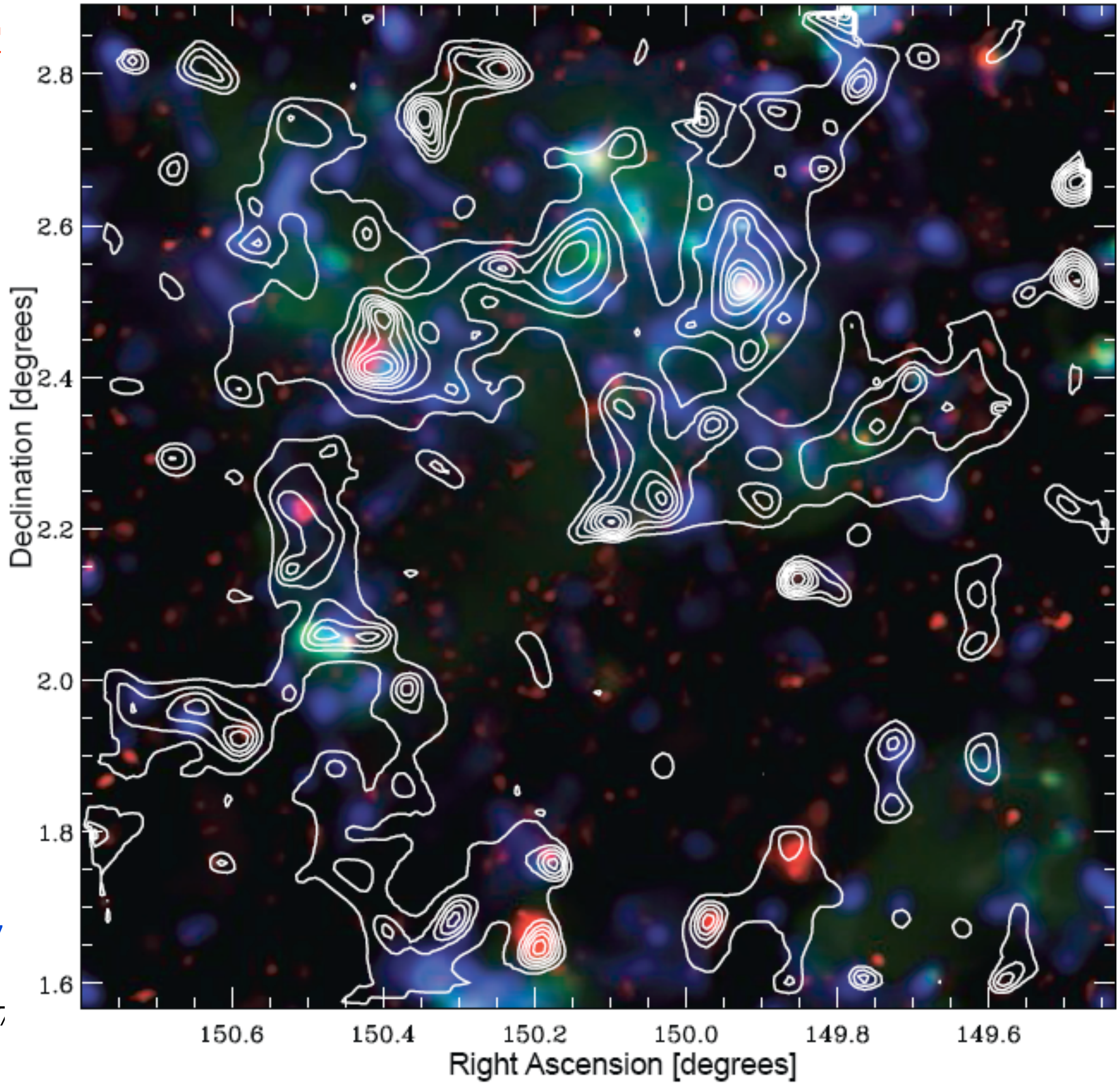
Massey et al 2007



Panchromatic view of COSMOS

- Contours: DM
- Blue: Stellar mass
- Green: gal. number density
- Red: hot gas (x-ray)

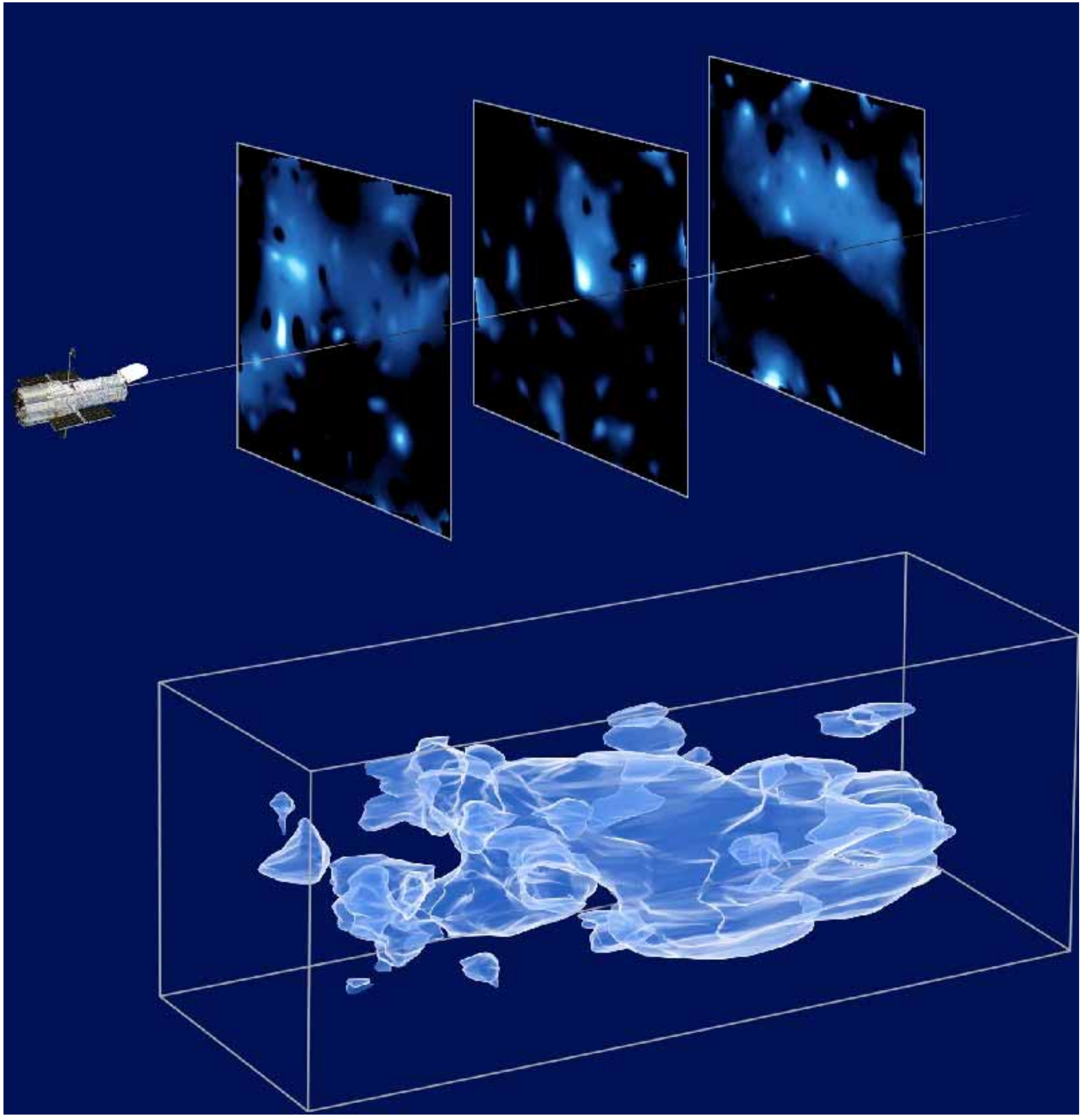
Massey et al 2007



Tomography Mapping

By isolating the faint background galaxies at different redshift, we are sensitive to the mass distribution in different redshift slices, and then can reconstruct the 3D map of the dark matter along the line of sight.

Massey et al 2007

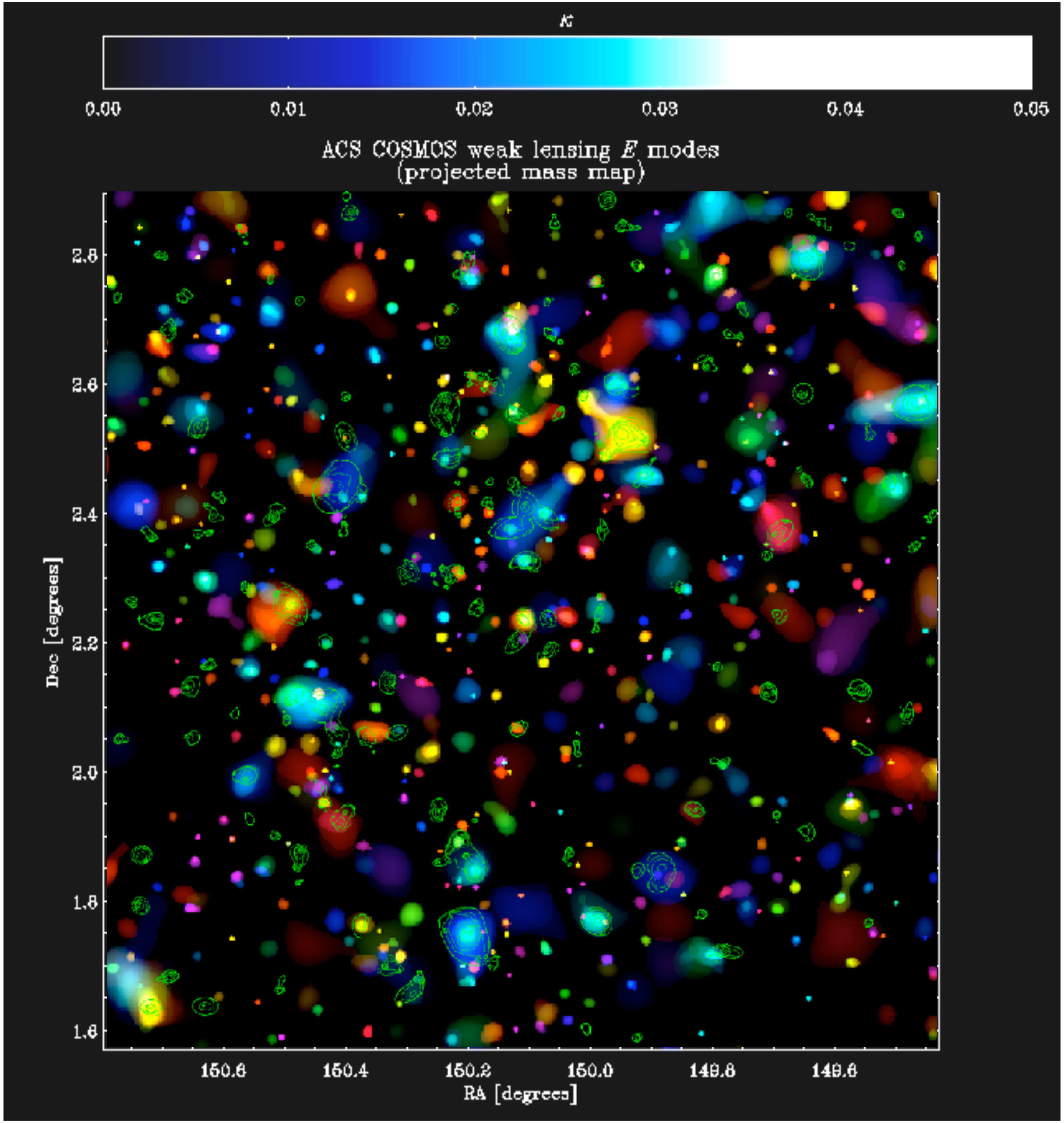


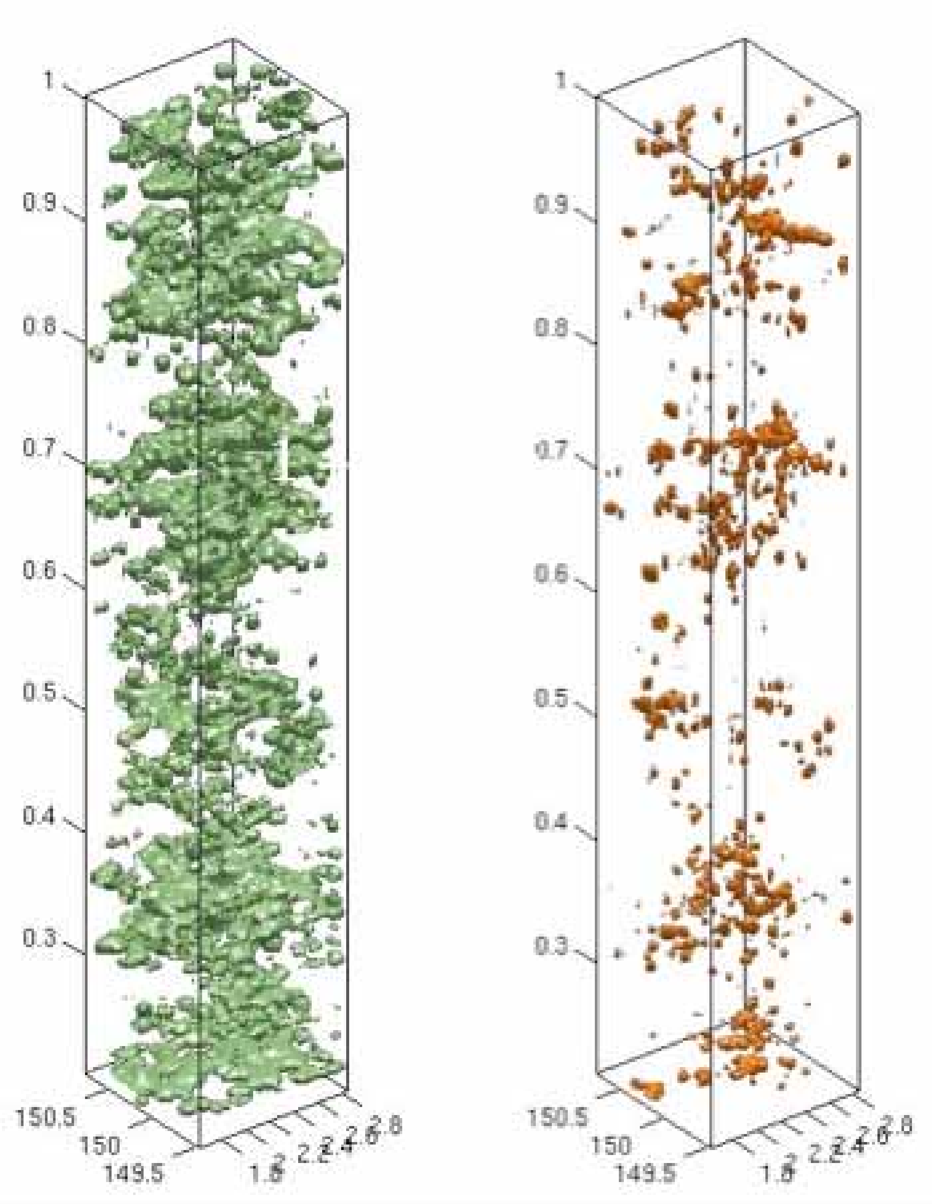
How to improve this first measurement?

- Add new information!
- Better redshift measurement (more spectro-z, better photometry), better lensing catalogue (improving PSF+CTE model)
- *Analysis of the mass of individual structures: groups/clusters and galaxies*

Lensing Mass Map vs. Optical and X-ray identified groups

December 11, 2007

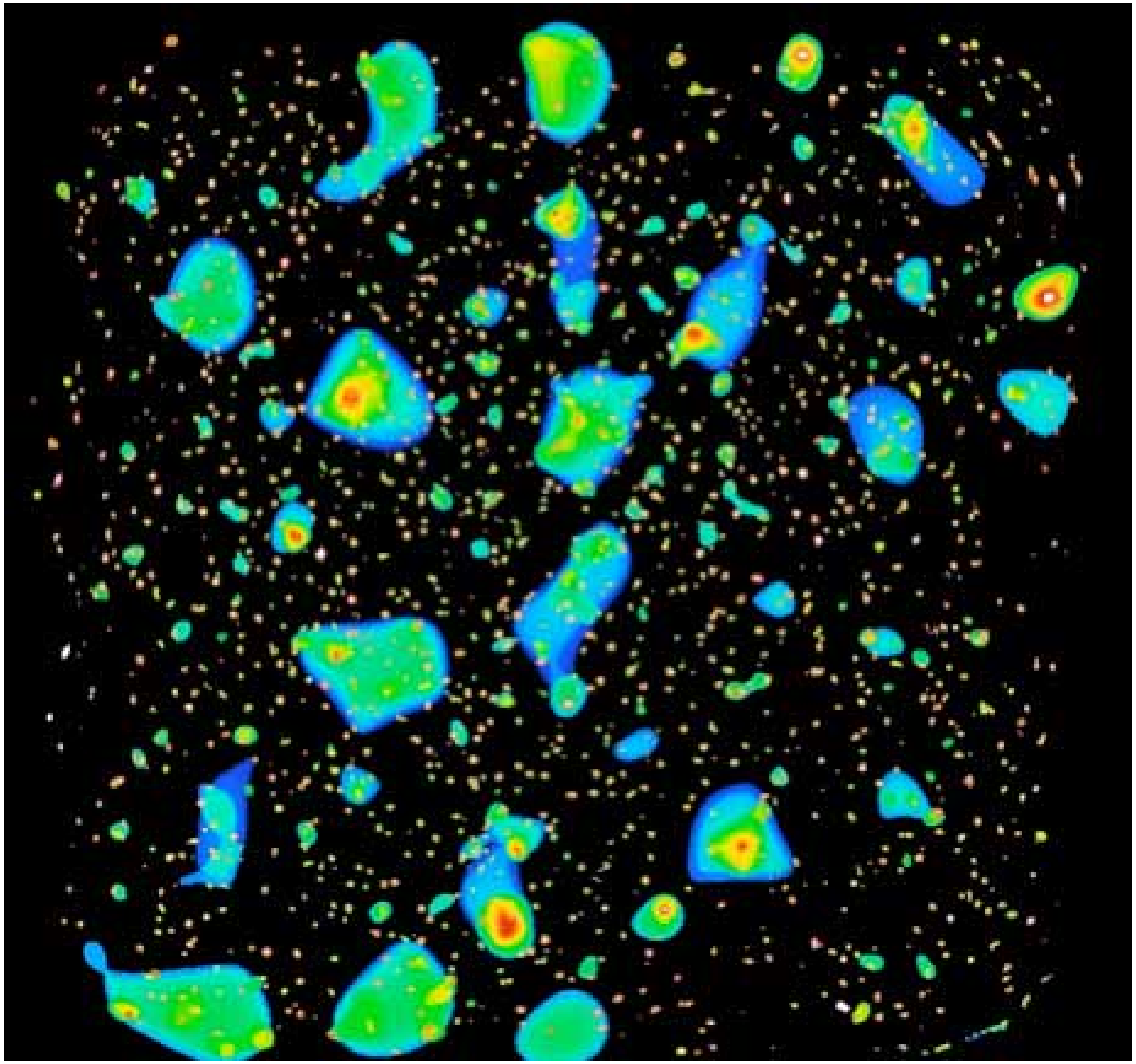




Kovac et al 2007

3D density field of galaxies

Combination of ~10k spectro-z and 200k photo-z



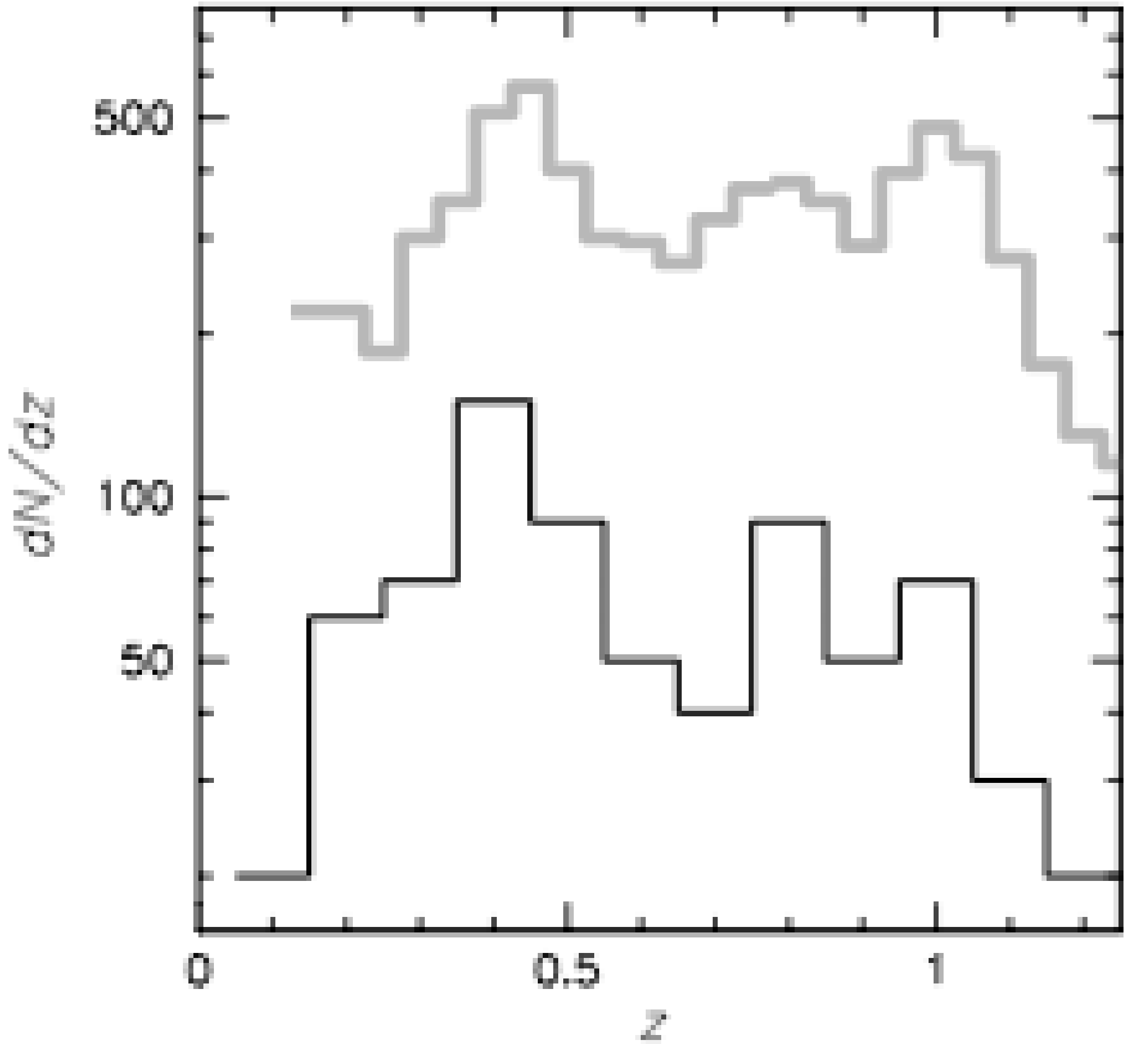
XMM COSMOS

142 XMM cluster candidates:
64 clusters: 0.5<z<1.0
23 clusters: z> 1

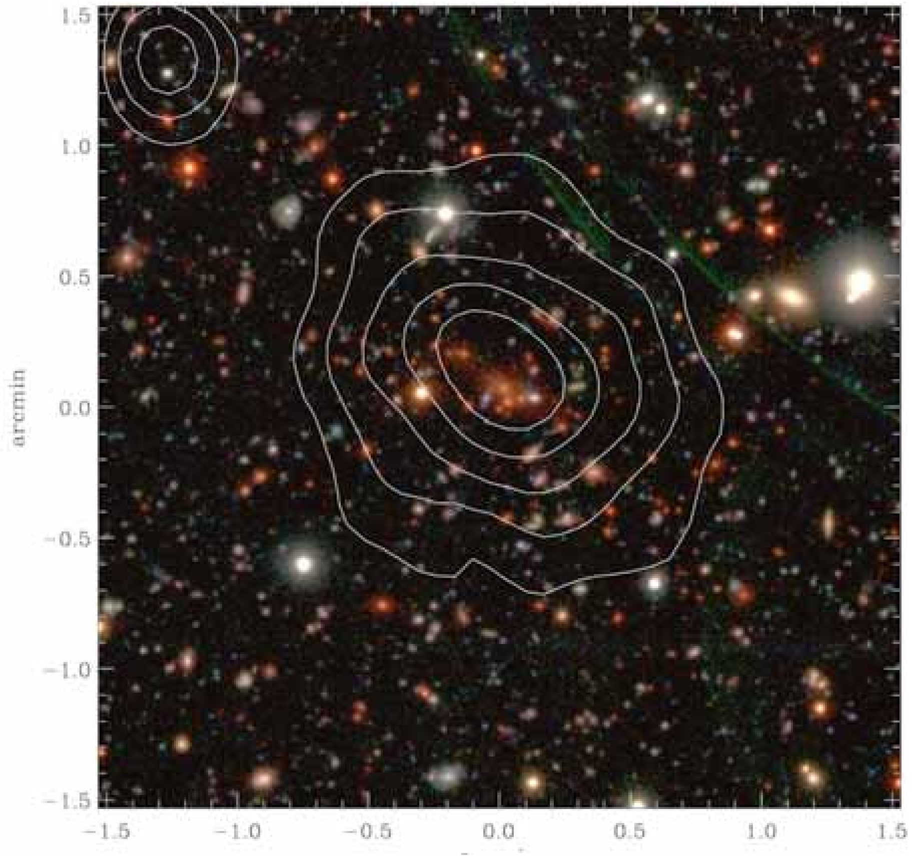
 Finoguenov et al 2007

Redshift distribution of structures

- **Grey:** photo-z concentration
- **Black:** extended X-ray sources



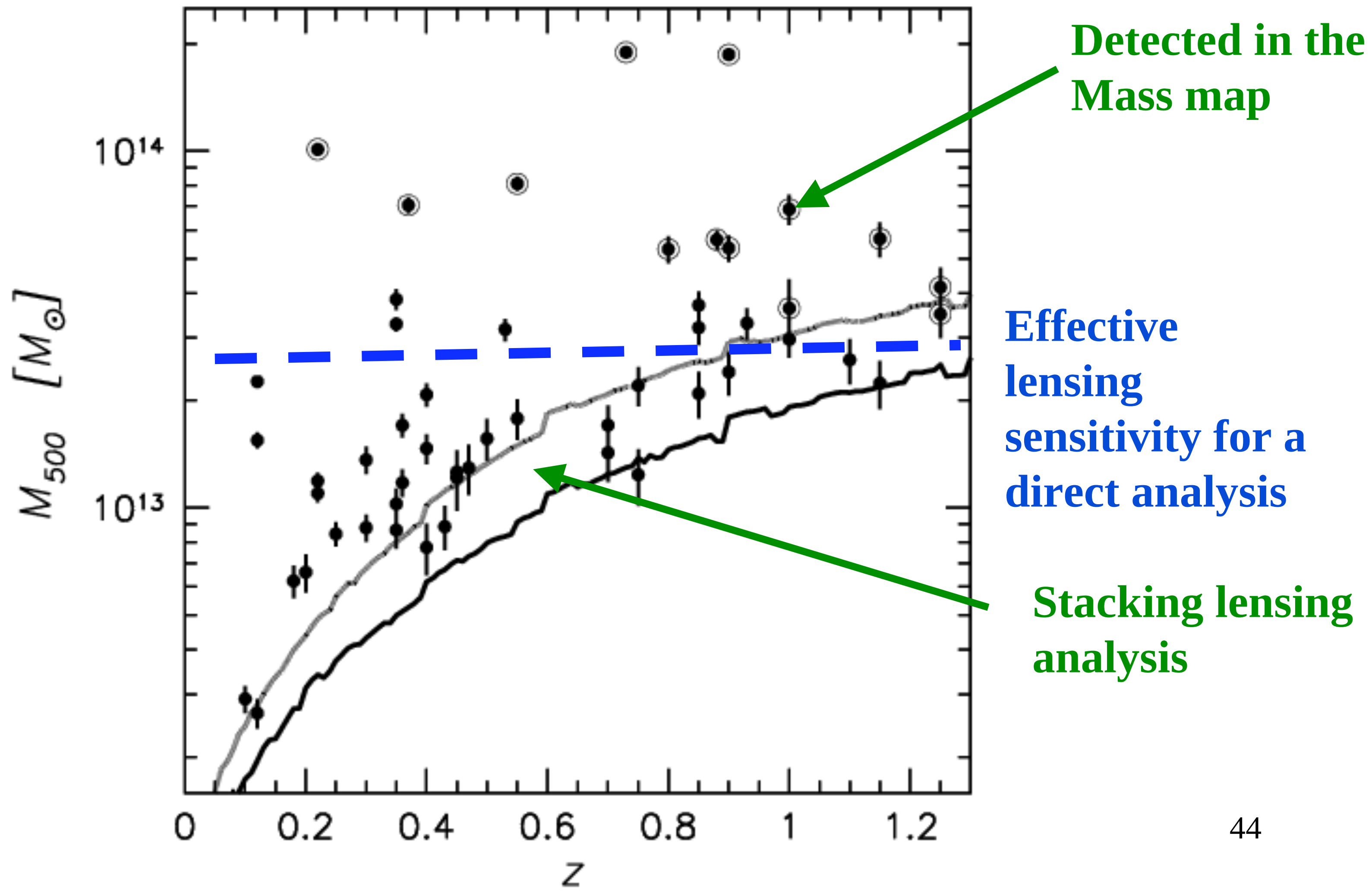
Group-Galaxy Lensing: 142 Groups Selected with XMM



Aim: calibration of the Mass-Temperature relation.

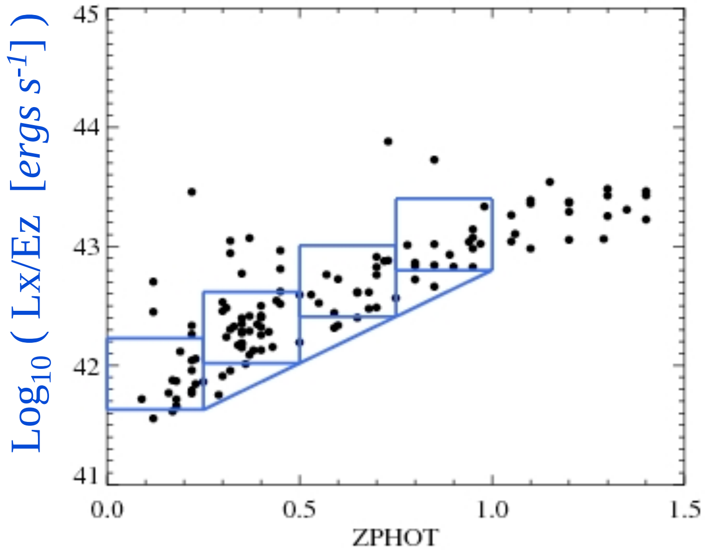
- How to center the stacked signal? Currently using the BCG.
- Need to understand the offset between X-ray/BCG/optical distribution? (*Chandra* data will help)
- Extend the groups sample to lower masses by stacking WL data

Comparing X-ray selected clusters with weak lensing detection



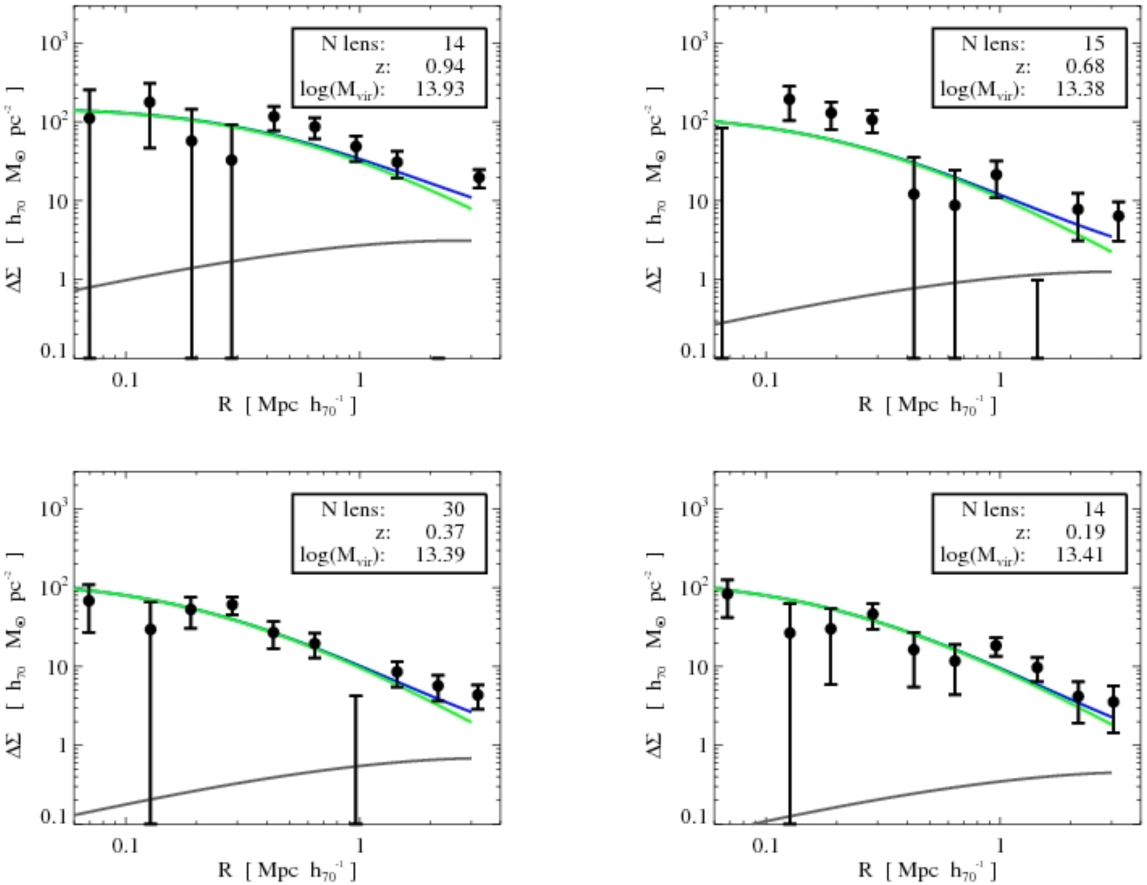
X-Ray selected group mass in COSMOS

- Measuring mass of X-ray selected groups in COSMOS
- Identify groups with similar properties in redshift and X-ray luminosity
- Stack weak lensing signal



X-Ray selected group mass in COSMOS

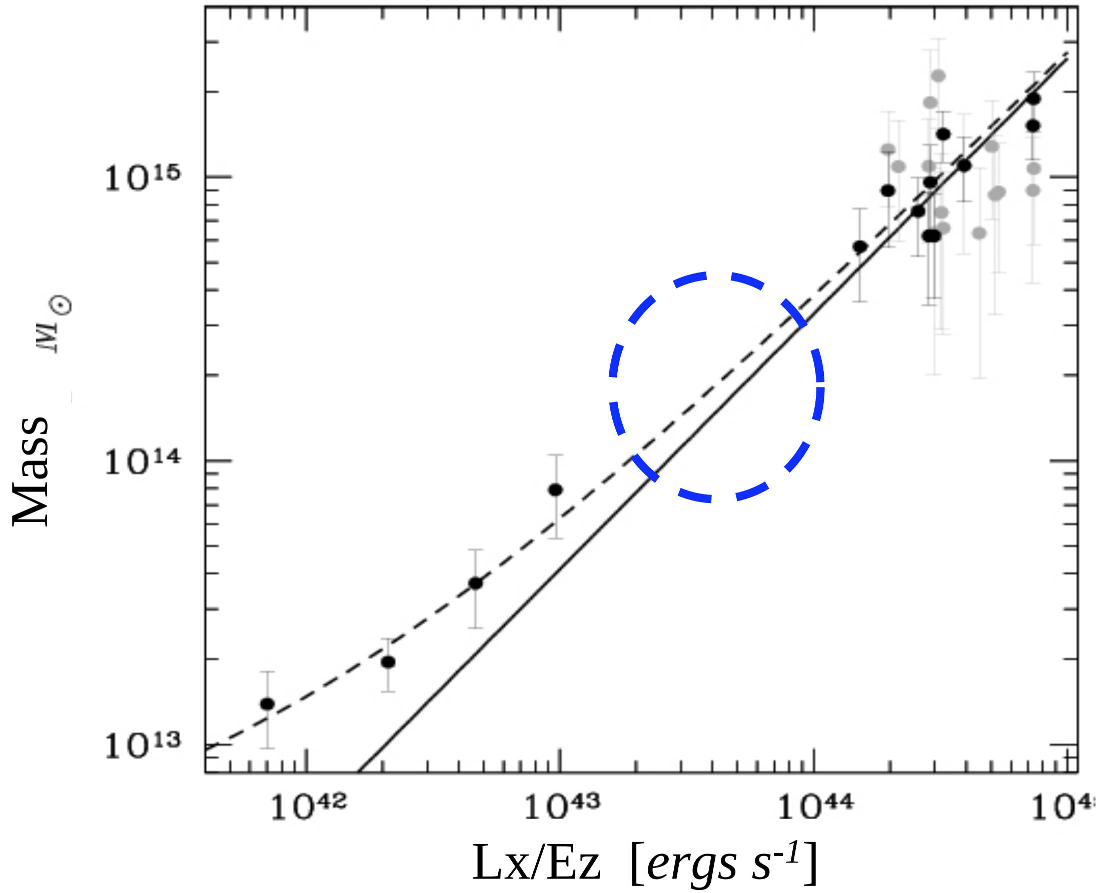
Surface Mass density



Radial distance Mpc

Leauthaud et al 2007 in prep

M(lensing)-L relation

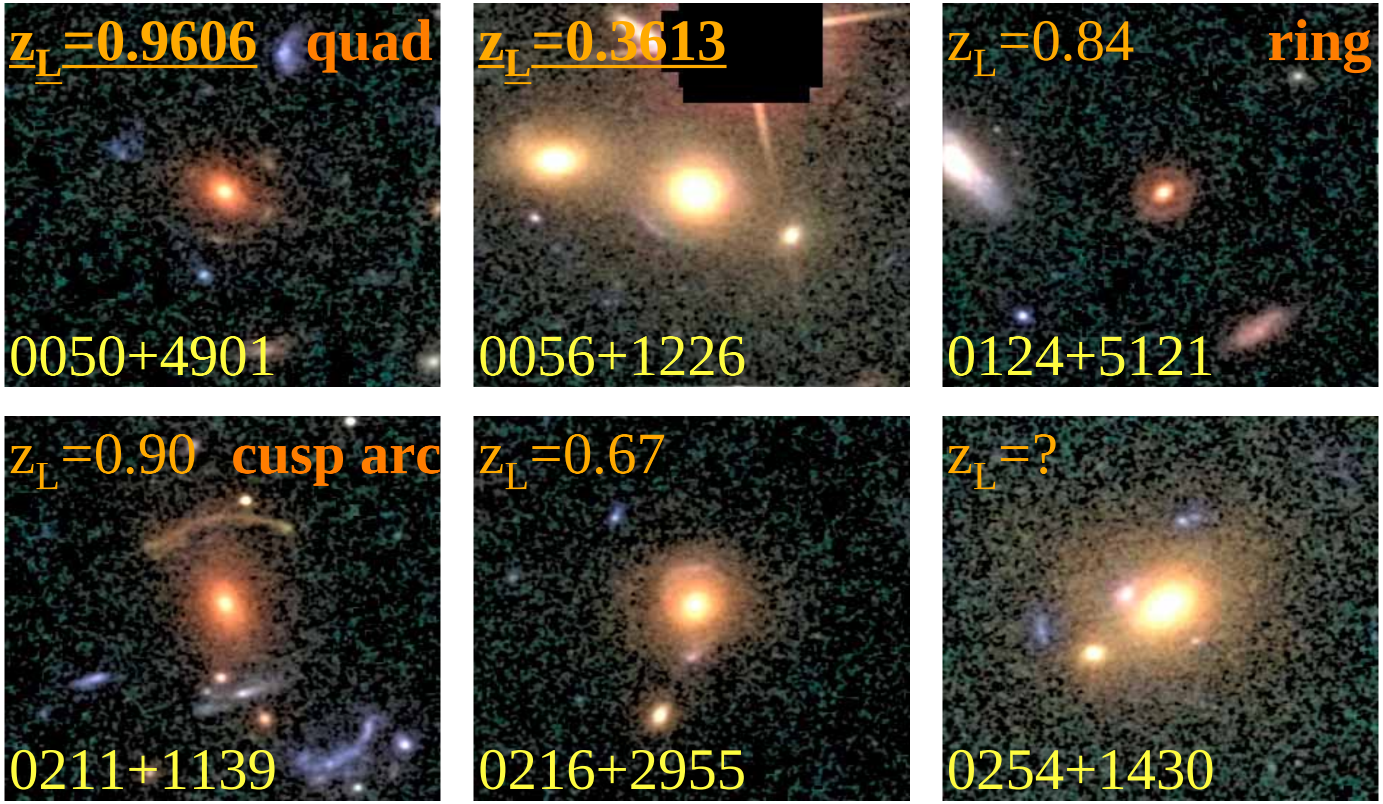


- Wrong behavior at lowest X-ray luminosity?

- Need to explore intermediate X-ray luminosity (new lensing surveys?)

Leauthaud et al 2008

Galaxy Lensing in COSMOS



Strong Lenses

Faure et al 2007

•16+(50) lens candidates identified (by eye) based on photometric selection of ~9000 Elliptical galaxies with: 0.3< Z_{phot} <1

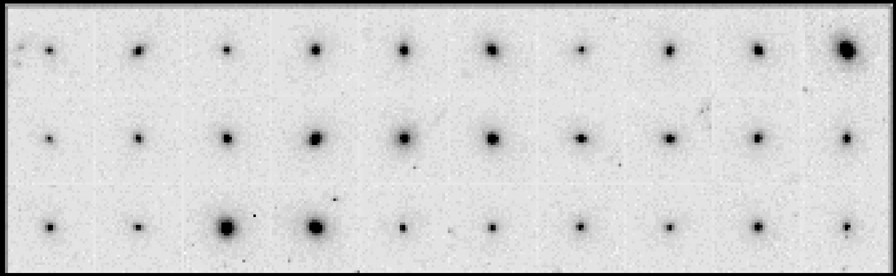
•**16 SL candidates in COSMOS => expect more than 200 000 strong lensing systems over the whole visible sky**

Galaxy morphology

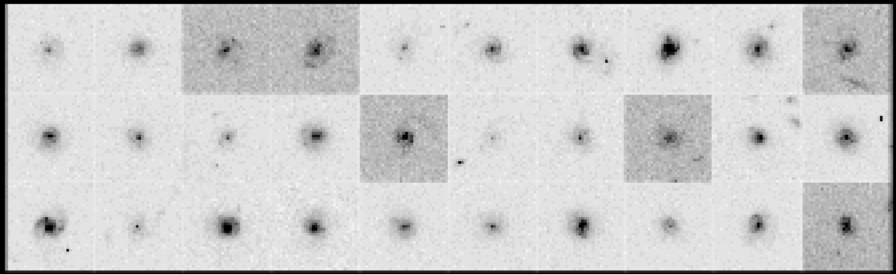
Principal component analysis
(A, C, G, M_{20}, e)

→ Three main PC's :
PC1, PC2, PC3

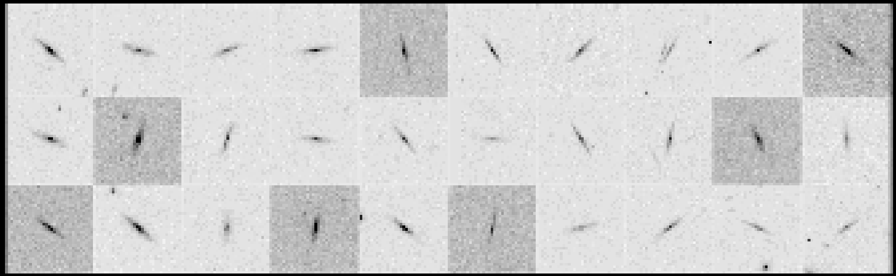
We show four separate unit cubes of PC1-PC2-PC3 space, centered around the values reported in the labels. In every unit cube, a few representative galaxies of the population are shown.



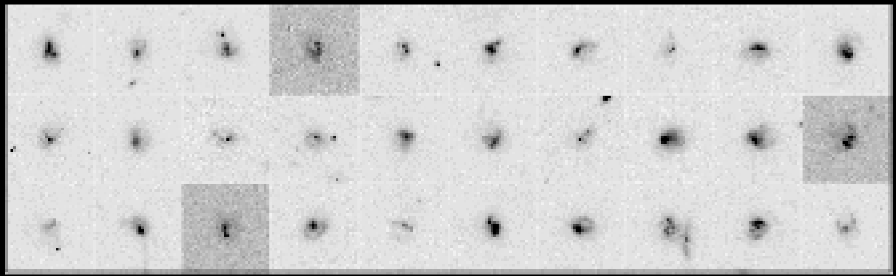
PC = -4,0,0
Early Type



PC = 0,-1,-1
Disk Galaxies
(face on)

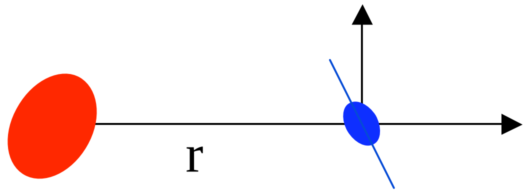


PC = 1,2,2
Disk Galaxies
(edge on)



PC = 1,-2,0
Irregular

The Galaxy-Mass Cross Correlation Function (GMCF)

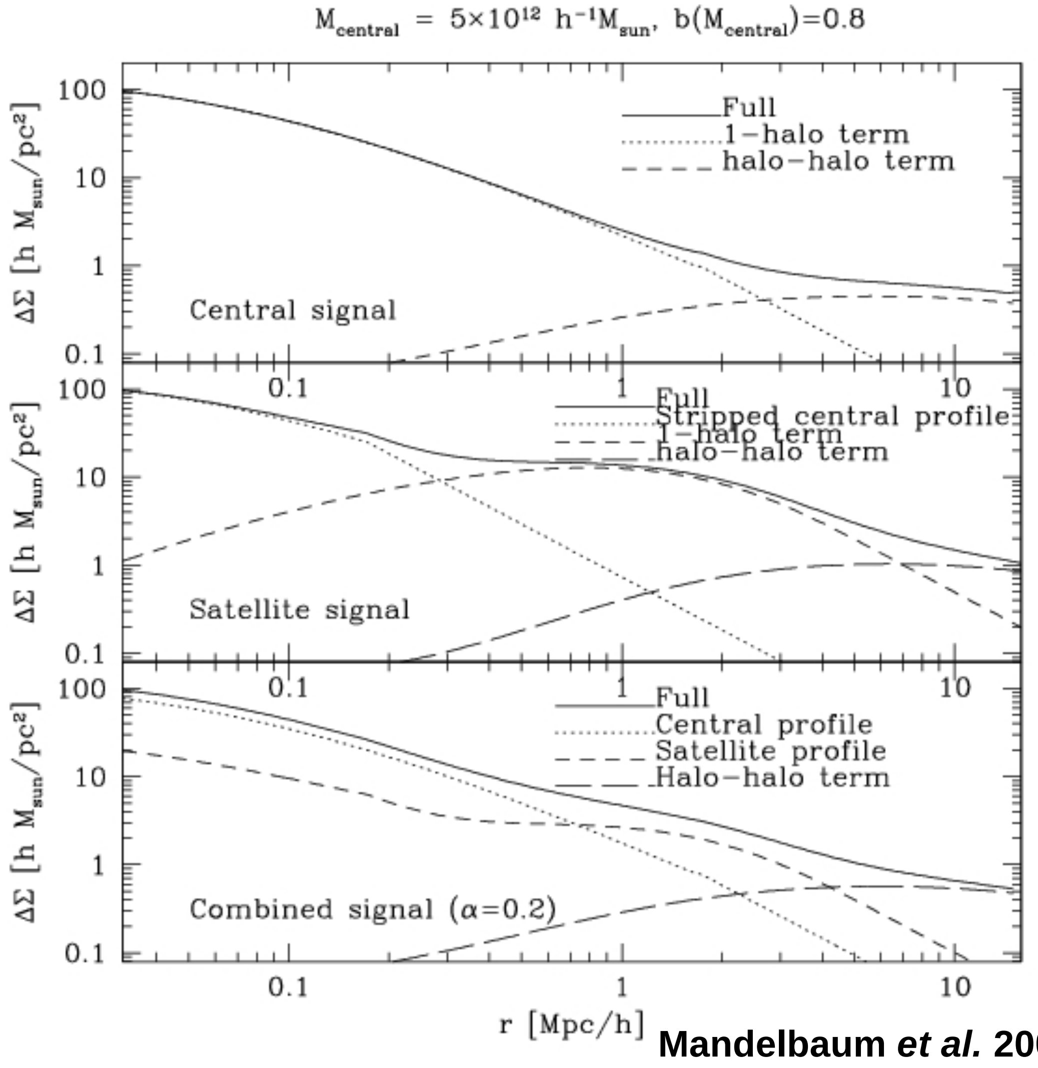


Shapes of galaxies

GMCF

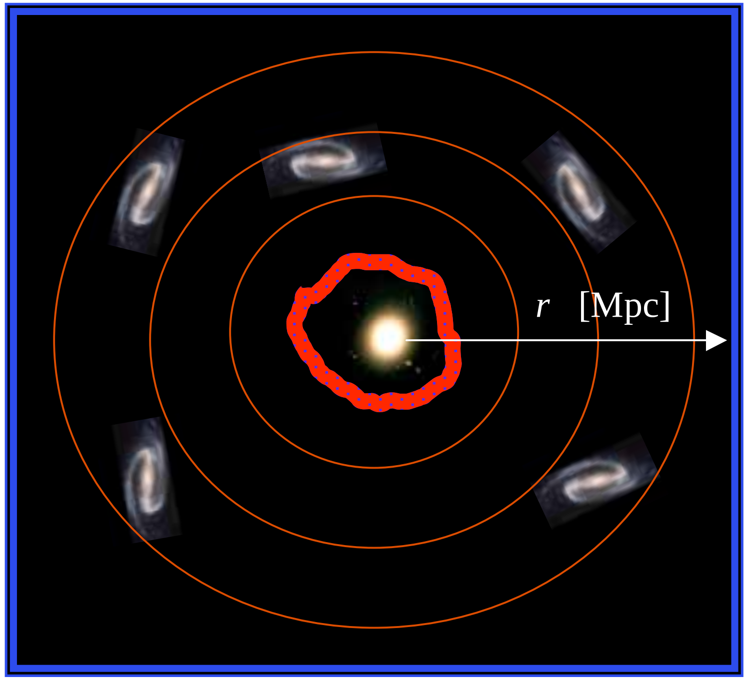
$$\boxed{\Sigma_{crit} \times \gamma = \Delta\Sigma(r)}$$

Redshifts are essential!



Mandelbaum *et al.* 2005

Galaxy-galaxy Weak Lensing technique



The idea is to measure the tangential shear rescaled by the distance scaling (Critical Sigma) to measure *Delta Sigma* :

$$\boxed{\Delta\Sigma(r) \equiv \overline{\Sigma}(< r) - \overline{\Sigma}(r) = \Sigma_{crit} \times \gamma_t(r)}$$

Delta Sigma is the relative surface mass density. To compute *Delta Sigma*, Critical *Sigma should be computed for each lens and sources.*

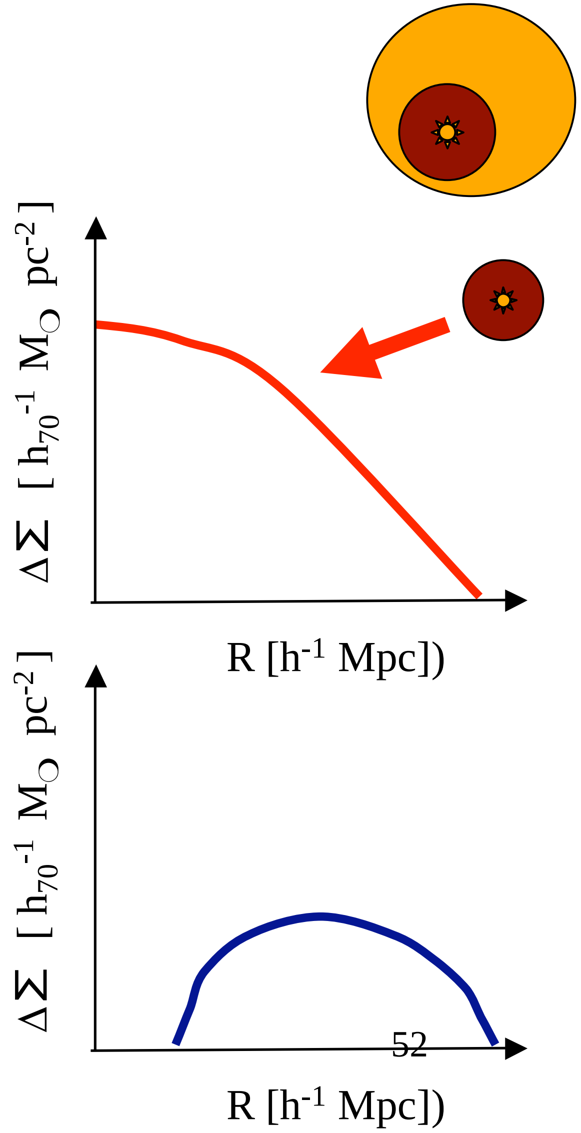
$$\boxed{\Sigma_{crit} = \frac{c^2}{4\pi G}\frac{D_{OS}}{D_{OL}D_{LS}}} \longrightarrow \textit{Photo-Z}$$

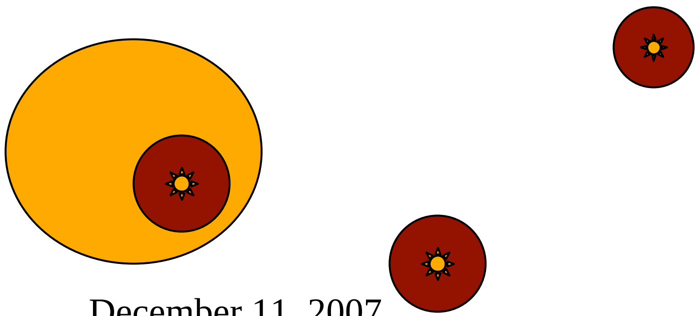
Need the redshift of both the lens and the source. Spectro-z are more important for the lens than the source.

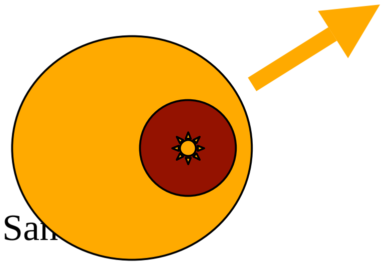
Baryons, DM halo and the 'BUMP'…

$$\Delta\Sigma = \Delta\Sigma_b + \Delta\Sigma_{NFW} + \alpha.\Sigma_{NC}$$

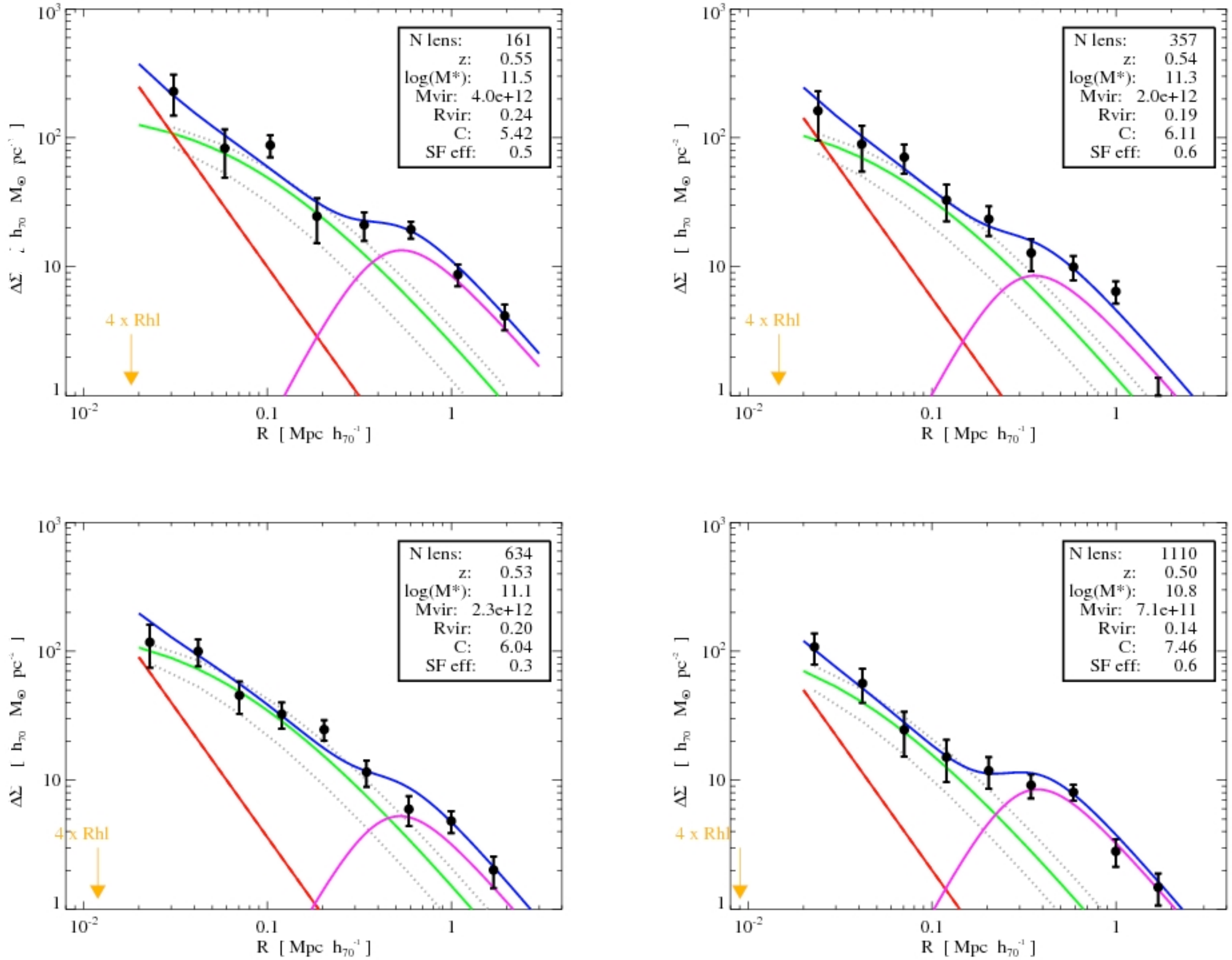
1) The Baryonic contribution is determined by the stellar mass
2) A NFW profile is assumed for dark matter halos.
3) α is the fraction of galaxies in sub-halos.
4) $\Delta\Sigma_{NC}$ is the off centered 'group' contribution.





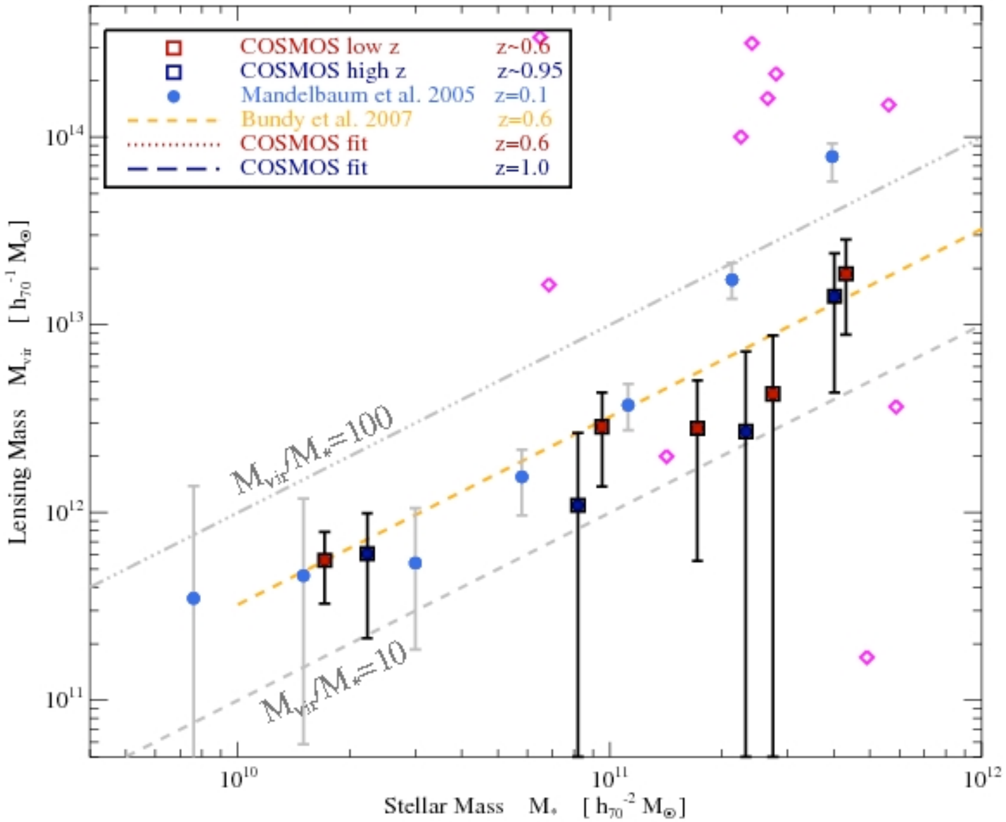


The Dark Matter Profiles of Elliptical Galaxies



- **Stellar Component**
- **DM halo**
- **The ‘bump’ or the ‘two-one halo’ term (cluster/group)**

Stellar mass vs. virial mass



Strong lensing, too dependent of zs and nearby substructure, more data needed

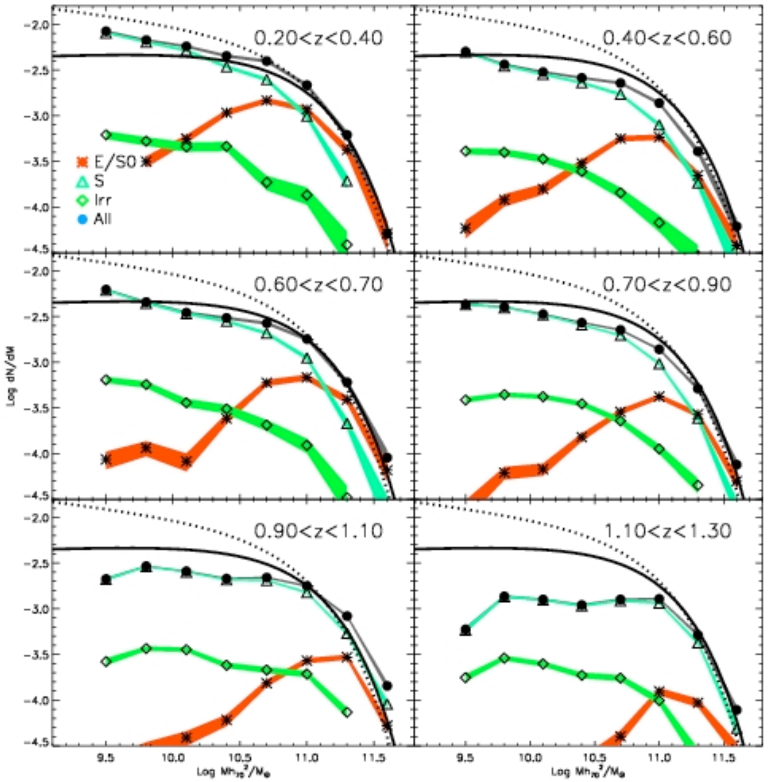
Virial and stellar mass are well corelated !

- *The relation is linear in between $M_\star = 10^{10} M_{sun}$ and $M_\star = 10^{12} M_{sun}$*
- *No strong variation with redshift between Z = 0.2 and Z = 1.2*
- *Fitted relation:*

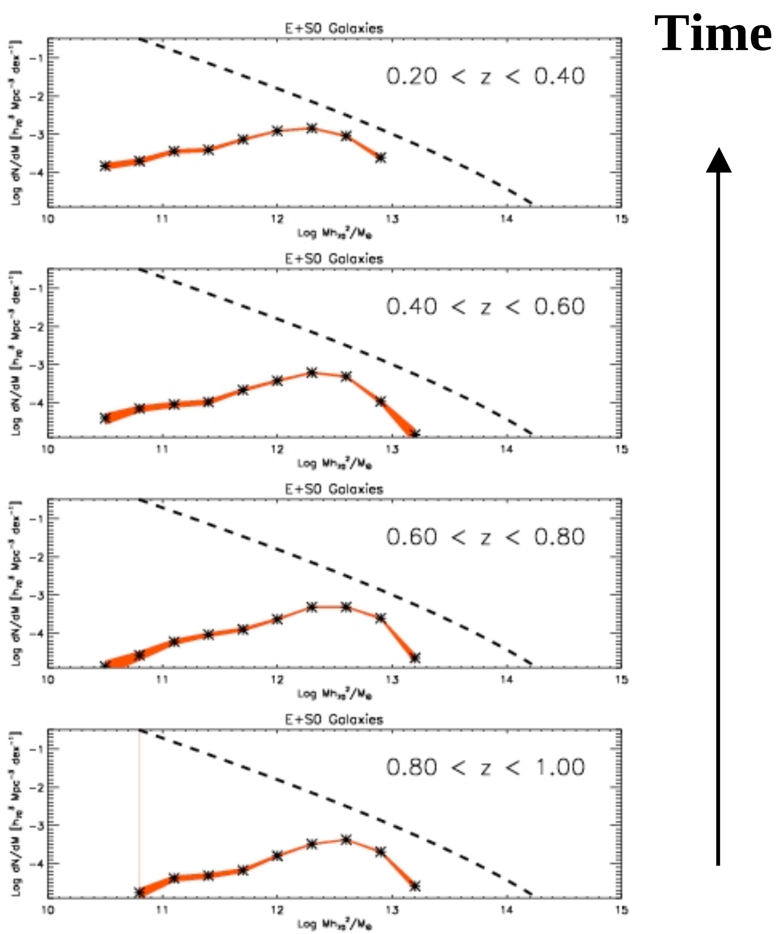
$$\log(M_{\rm vir}) = A \log(M_*) + B + C(1+z)$$

With A=1.02±0.19
B=12.41±0.78
C=0.04±0.47

The Rise of The Red Galaxies



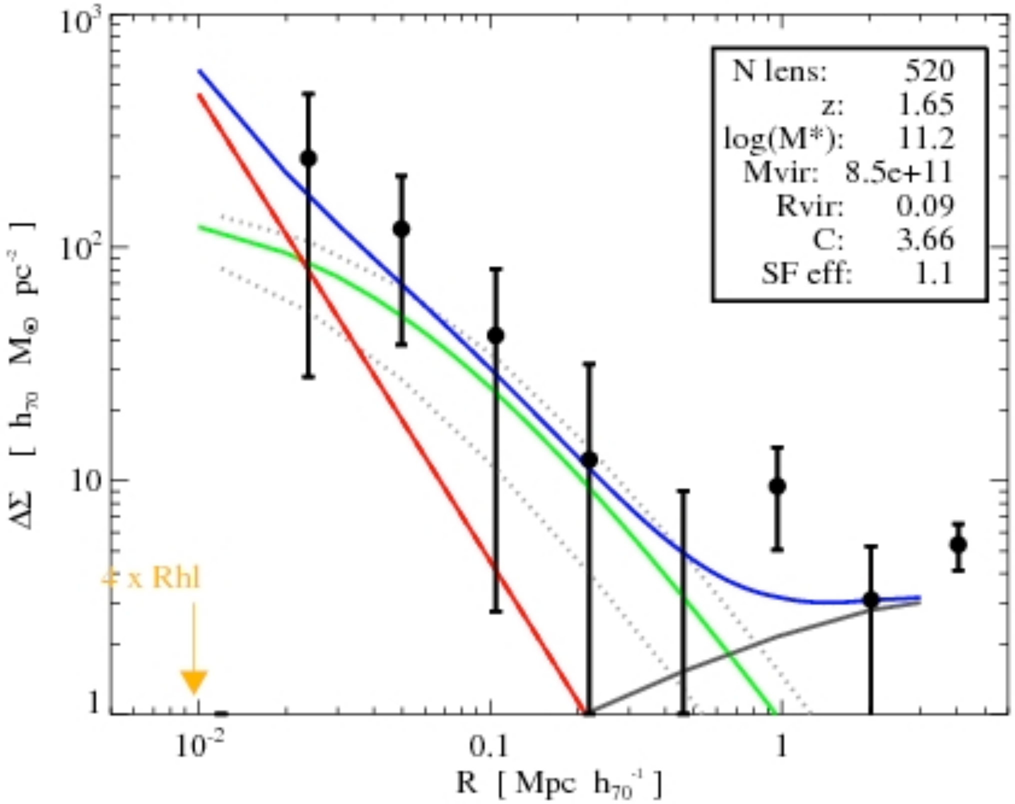
COSMOS Stellar Mass Functions



Dark Matter Mass Function of Elliptical galaxy halo

WORK in progress

- preliminary analysis of Galaxies selected by the BzK technique (passive red galaxies at z~1.5)
- … can probably extend this to LBG galaxies selected with GALEX



Likely the highest redshift gg-lensing measurement

More work in progress

- Measure galaxy mass for all galaxy types with lensing, and check evolution
- Investigate mass of optically selected groups
- Refine COSMOS mass map including the mass distribution found at different scales => direct probe of filamentary structure

Conclusions & Perspective

Lensing is a unique tool to probe DM in the Universe

• (Weak) Lensing provide constraints on DM profiles from <100 Mpc scales down to few kpc (baryon/DM physics)

•Combined with photometric redshift information Weak Lensing can map dark matter in 3D for the LSS, and trace galaxy mass evolution

•**Future cosmology surveys (particularly those in space) will allow to fully map the 3D structure of the Universe and understand the growth of structures which is a way to probe dark energy.**

•**Like the 'geo-meter', the 'cosmos-meter' will not only learn the cosmology (a few numbers) but gain an in-depth knowledge of the physics of DM in the Universe, and the formation and evolution of galaxies.**