Cosmology with Cluster Lenses in HST and Wide Field Surveys

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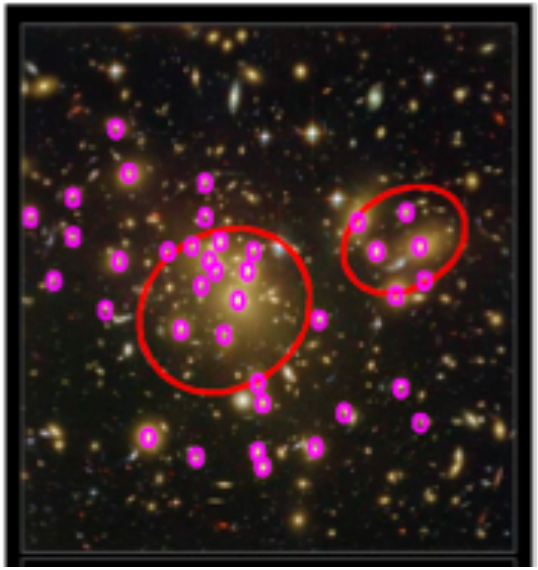
Cosmology with Maps

- In clusters, we use lensing maps to
  - Reconstruct the DM distribution, find and characterize DM structures (filaments, suhalos, DM particle detection, etc…)
  - Infer the lensing amplification and study the primordial Universe (z>10 galaxies, CIB, etc)
  - Estimate cosmological parameters with SL tomography
- We use wide field convergence maps to
  - count lensing peaks and estimate cosmological parameters

Lensing modeling strategies

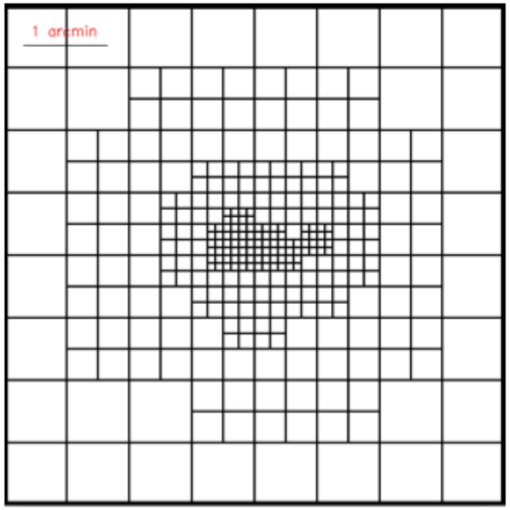
Observationally motivated models

- Decomposition into halos
- Simple clusters
- Few constraints
- Good fit with few constraints



Grid-based models

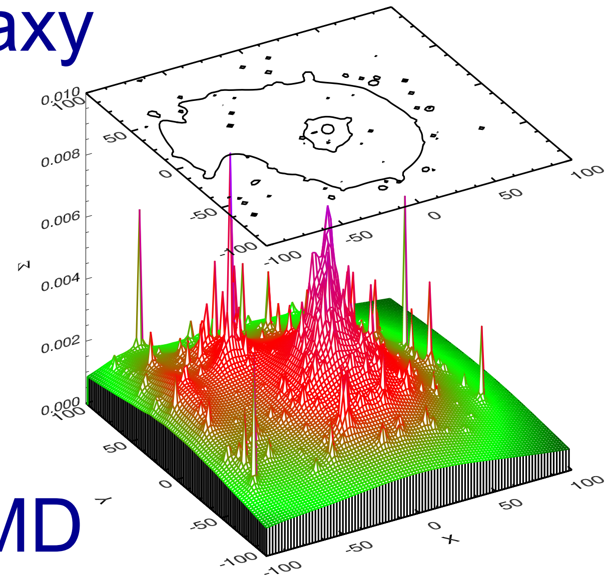
- Decomposition into pixels
- Complex clusters
- Lots of constraints
- Better fit with lots of constraints



Galaxy scale components model

Kneib et al 1996

- Large scale cluster component+galaxy halo components (stars+DM):



$$\phi_{tot} = \phi_{cluster} + \Sigma_i \phi^i_{halos}$$

- Need to scale the galaxy halo components, for example for a PIEMD mass distribution:

$$\sigma = \sigma_* \left(\frac{L}{L_*}\right)^{1/4} \quad r_{cut} = r^*_{cut} \left(\frac{L}{L_*}\right)^{\eta}$$

- Hence: $\frac{M}{L} \propto L^{\eta - 1/2}$

$\eta = 1/2$ Constant M/L

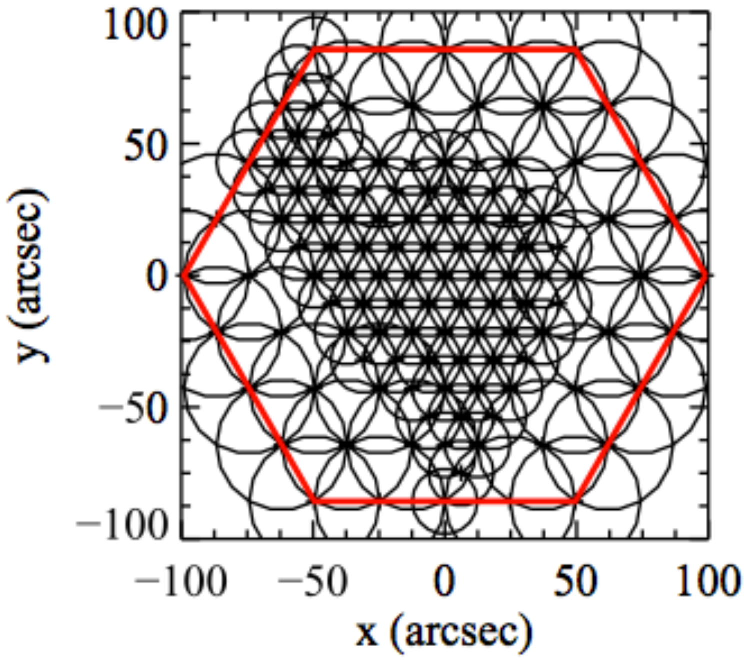
$\eta = 0.8$ FP scaling

Radial Basis Function Forward fitting

- No binning of the shear
- Multi-scale grid model of the potential with RBF instead of pixels

  Example in Jauzac et al. 2012:

  2741 RBF with s=5.5" for ~100 gal/arcmin2
- Optimization with Bayesian ML and Gibbs sampling
- WL+photz bayesian error propagation into the posterior pdf



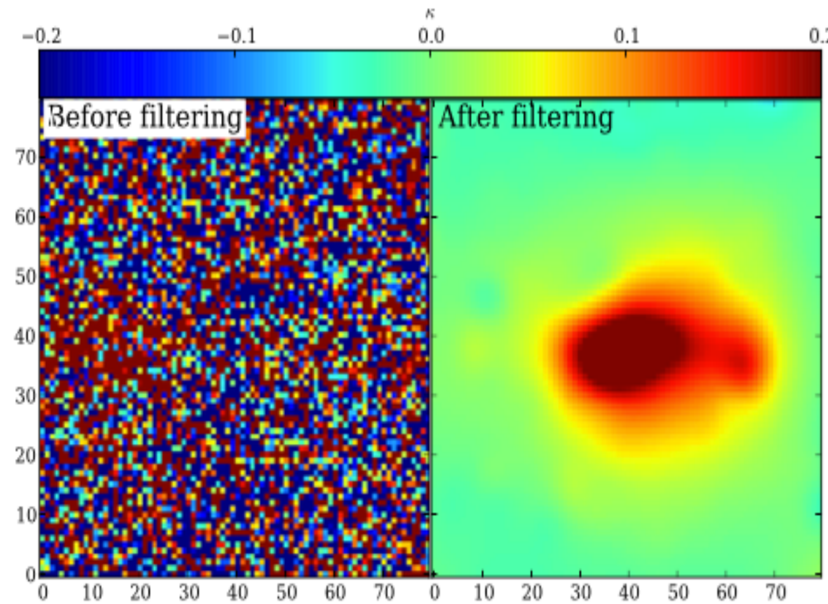
FLens

Pires et al. 2008

- Agressive binning with 1 gal/pixel
- Discrete cosine decomposition $D^T\kappa$ of the convergence κ map

$$\min_{\kappa} \|\mathcal{D}^T \kappa\|_0 \text{ subject to } \sum_i \| \gamma_i^{obs} - M(P_i * \kappa) \|^2 \leqslant \sigma$$

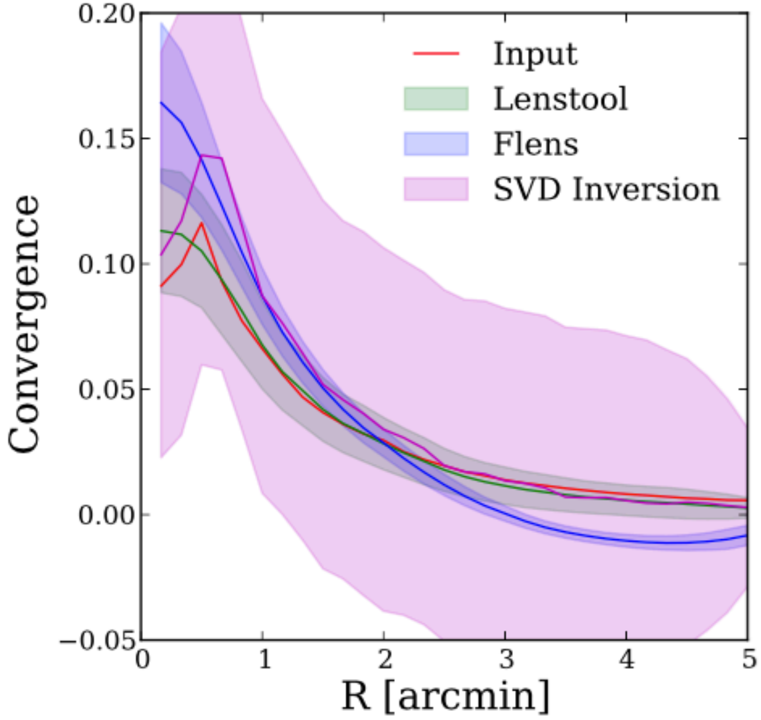
  - σ: measured error of the shear map
  - $M(.)$: Masking window function
  - P_i: K&S lensing kernel convergence to shear

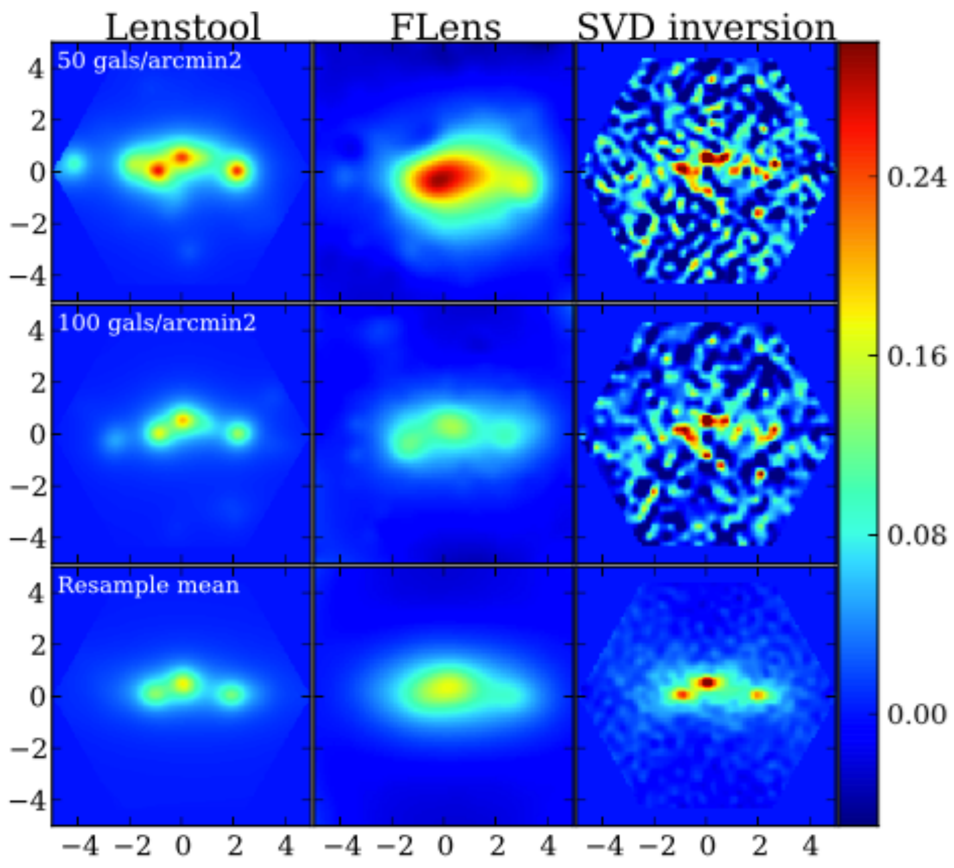


- Iterative inversion and minimization
- Wavelet-decomposition of κ maps and FDR denoising method (Miller et al. 2001)
- Underlying Hypothesis: The signal is sparsely distributed among noisy pixels

Challenge Comparison

Jullo et al. 2013





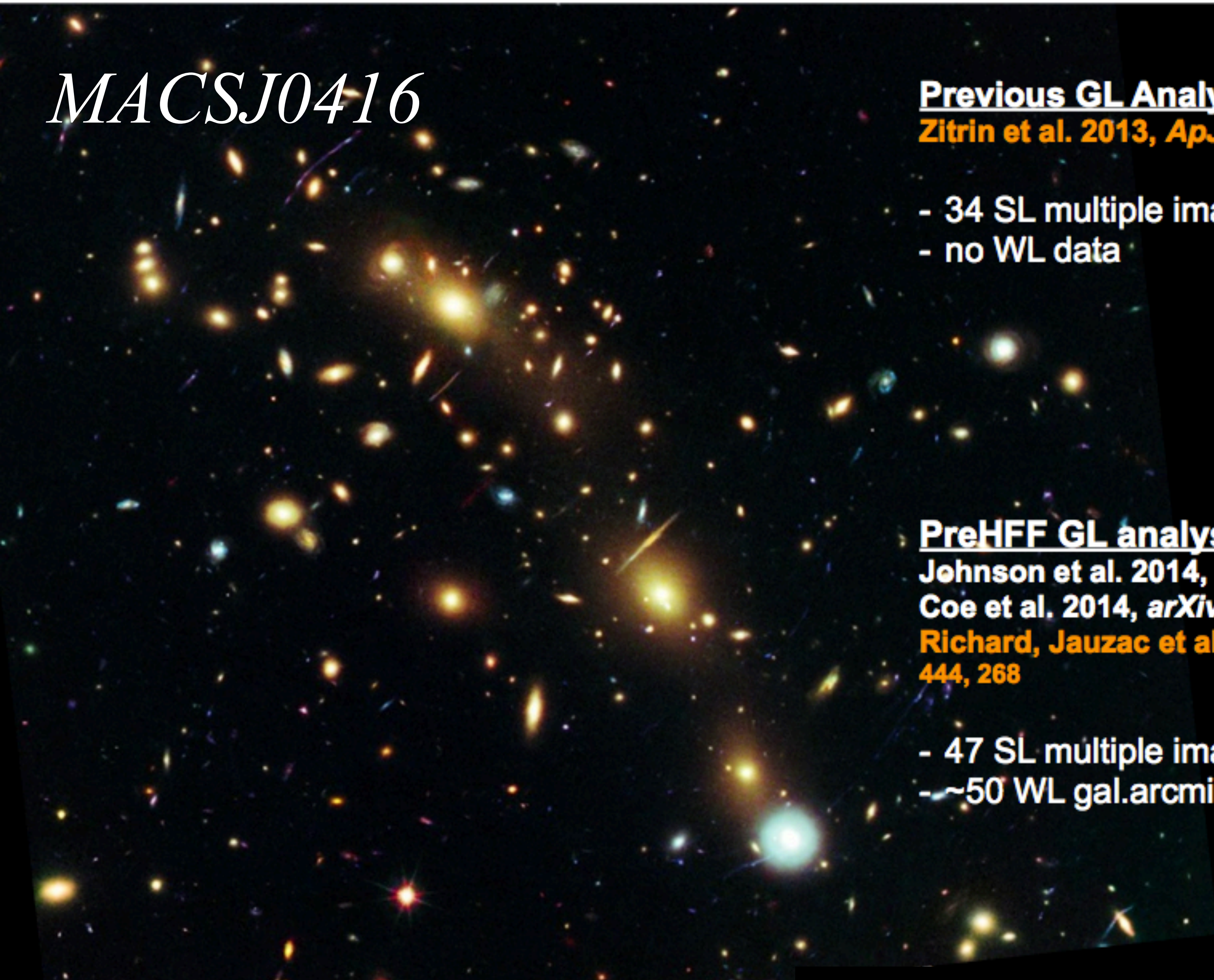
HST Frontier Fields

Cluster Name	z	Cluster		Parallel Field	
		RA	Dec	RA	Dec
Year 1:					
Abell 2744	0.308	00:14:21.2	-30:23:50.1	00:13:53.6	-30:22:54.3
MACSJ0416.1-2403	0.396	04:16:08.9	-24:04:28.7	04:16:33.1	-24:06:48.7
Year 2:					
MACSJ0717.5+3745	0.545	07:17:34.0	+37:44:49.0	07:17:17.0	+37:49:47.3
MACSJ1149.5+2223	0.543	11:49:36.3	+22:23:58.1	11:49:40.5	+22:18:02.3
Year 3:					
Abell S1063 (RXCJ2248.7-4431)	0.348	22:48:44.4	-44:31:48.5	22:49:17.7	-44:32:43.8
Abell 370	0.375	02:39:52.9	-01:34:36.5	02:40:13.4	-01:37:32.8

For each cluster:

- 70 orbits with ACS (F435W, F606W, F814W)
- 70 orbits with WFC3 (F105W, F125W, F140W, F160W)

Before HFF …



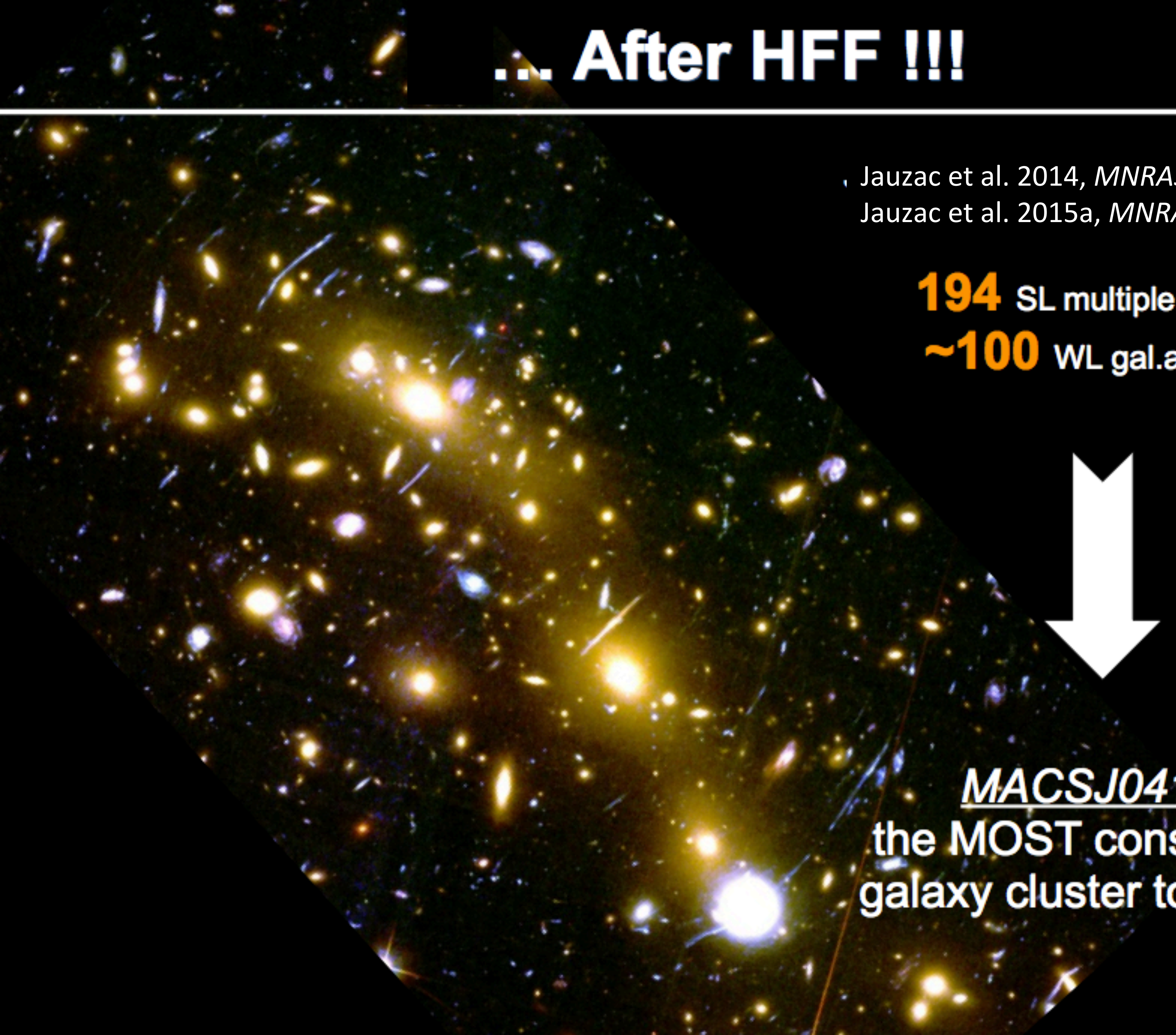
Previous GL Analysis :
Zitrin et al. 2013, *ApJ, 762, 30*

- 34 SL multiple images
- no WL data

PreHFF GL analysis :
Johnson et al. 2014, *arXiv 1405.0222*
Coe et al. 2014, *arXiv 1405.0011*
Richard, Jauzac et al. 2014, MNRAS, 444, 268

- 47 SL multiple images
- ~50 WL gal.arcmin^{-2}

... After HFF !!!



Jauzac et al. 2014, *MNRAS*, 443, 1549
Jauzac et al. 2015a, *MNRAS*, 446, 4132

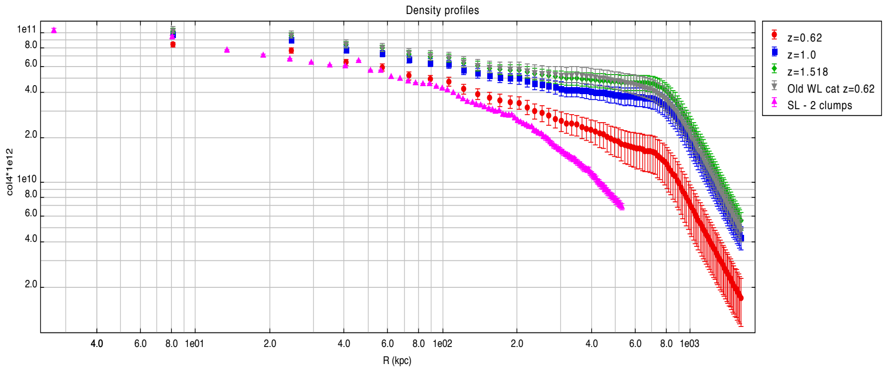
194 SL multiple images
~100 WL gal.arcmin^{-2}

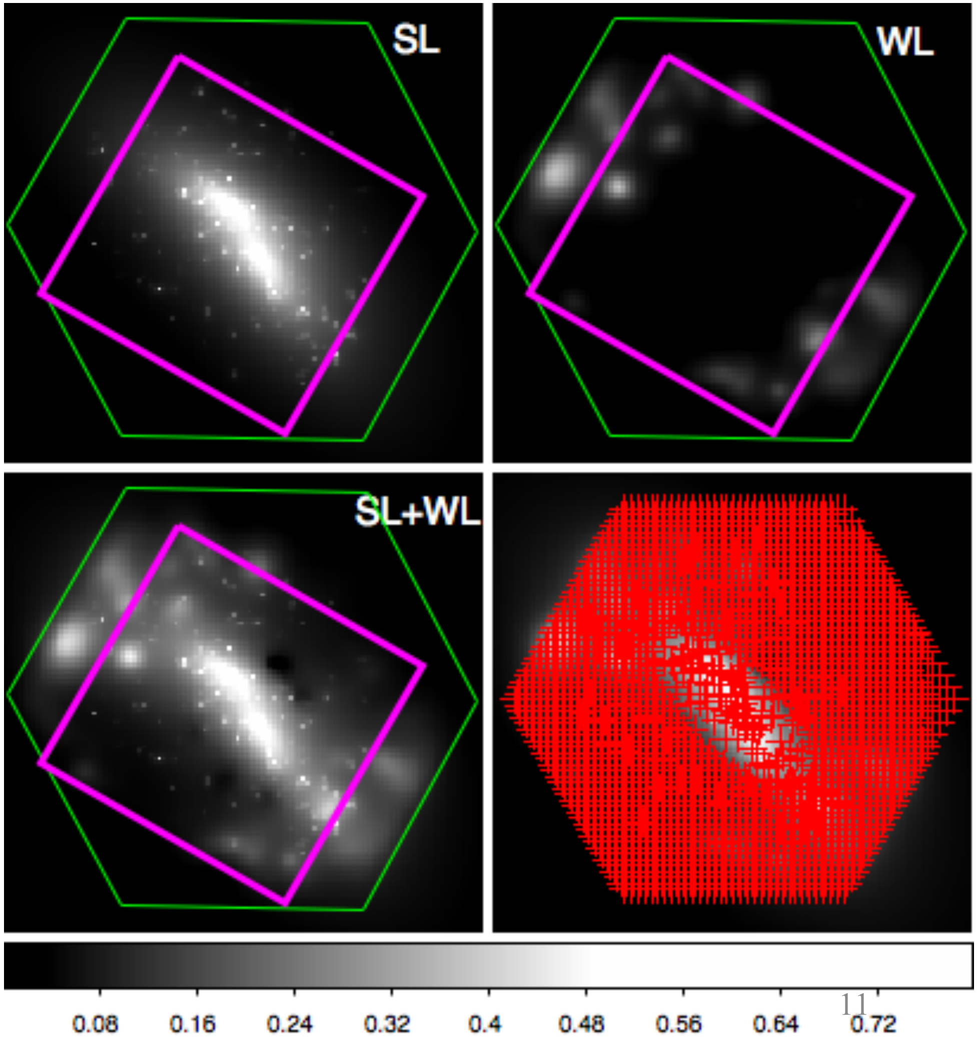
MACSJ0416 :
the MOST constrained
galaxy cluster to date !!!

Substructures Detection

A Mixed *parametric* and *free-form* model

Joint SL+WL fit for grid-based model doesn't work yet





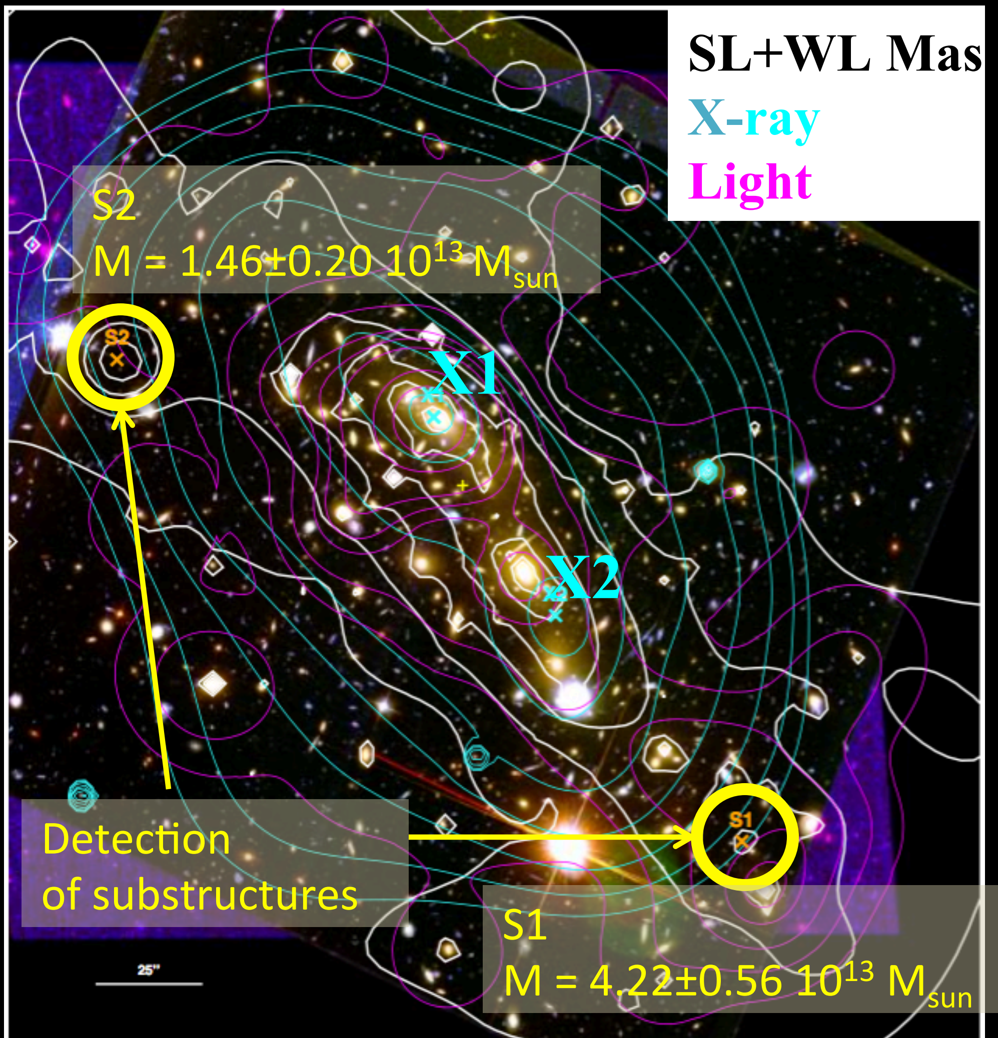
➔ Proposed 2 step solution

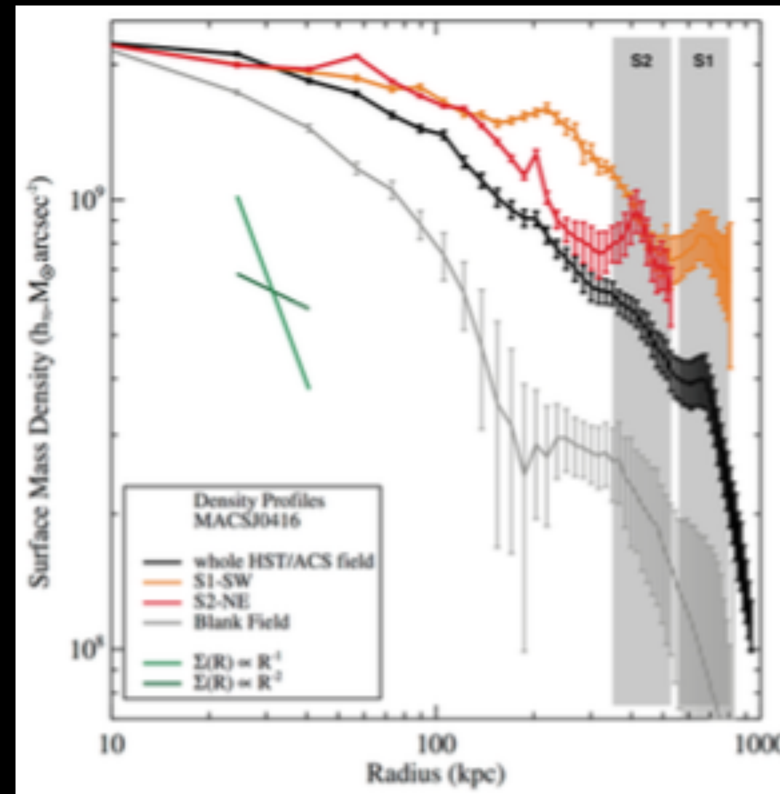
1. Reconstruction with SL data and *parametric* model

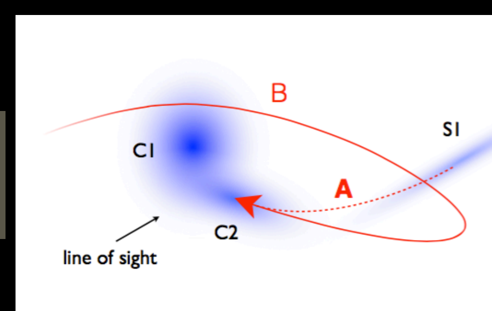
2. WL reconstruction with fixed parametric model and *free-form grid* model

Structure detections in MACS0416

Jauzac et al. 2015a







Evidence of pre-merger scenario A

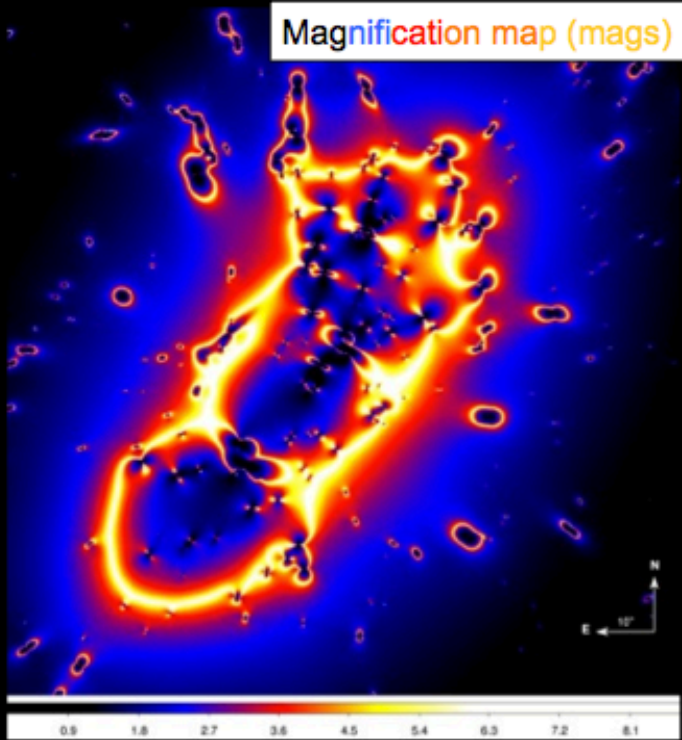
Abell 2744

Jauzac et al. 2015b

159 multiple images
51 lensed galaxies

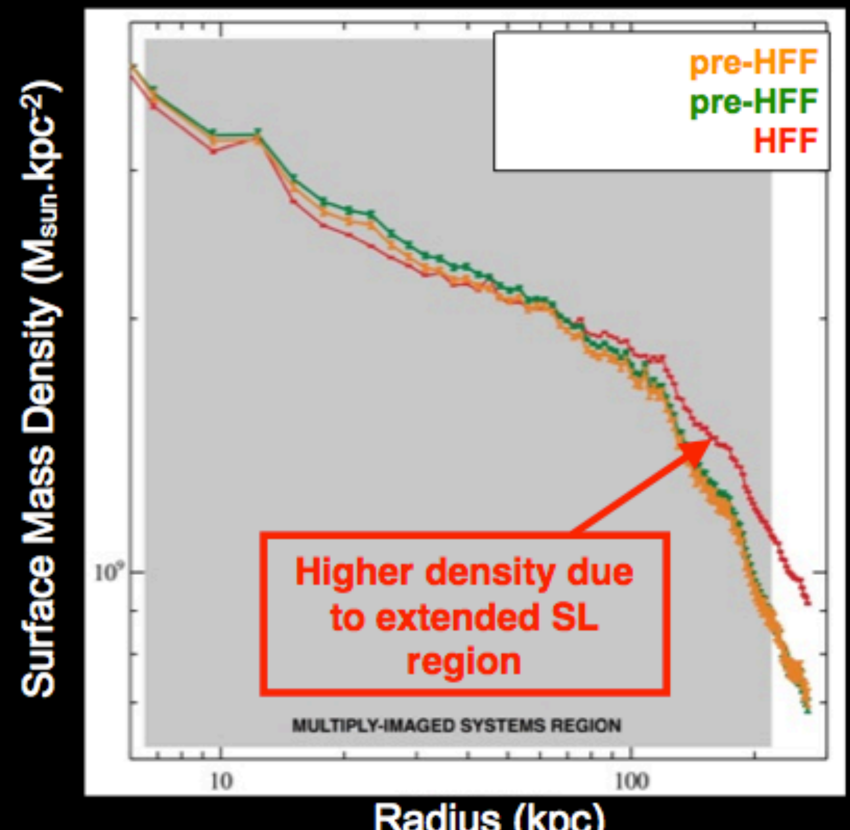
Abell 2744
The 2nd most constrained galaxy cluster to date

Mass & Magnification Measurements



Magnification to the 2% level :

μ = 6.75 ± 0.12



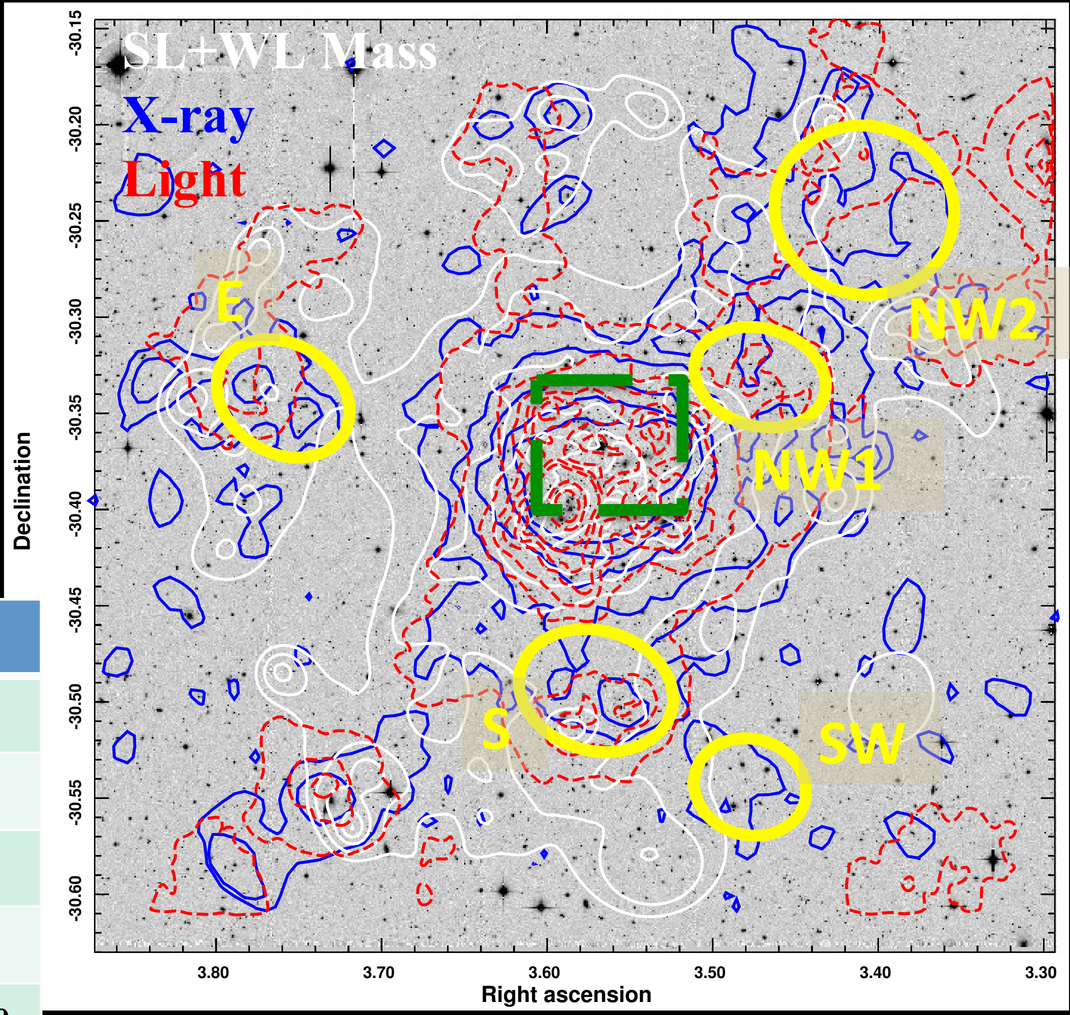
More SL constraints for the whole core :

- **correction of pre-HFF model**
- **more reliable estimation of the magnification**
- **better constraints on high-redshift luminosity function**
  Zitrin et al. 2014, *arXiv 1407.3769*, Ishigaki et al. 2014, arXiv 1408.6903, Atek et al. 2014d, *arXiv 1409.0512*

WH Filaments in Abell 2744

Eckert et al. 2015, Nature

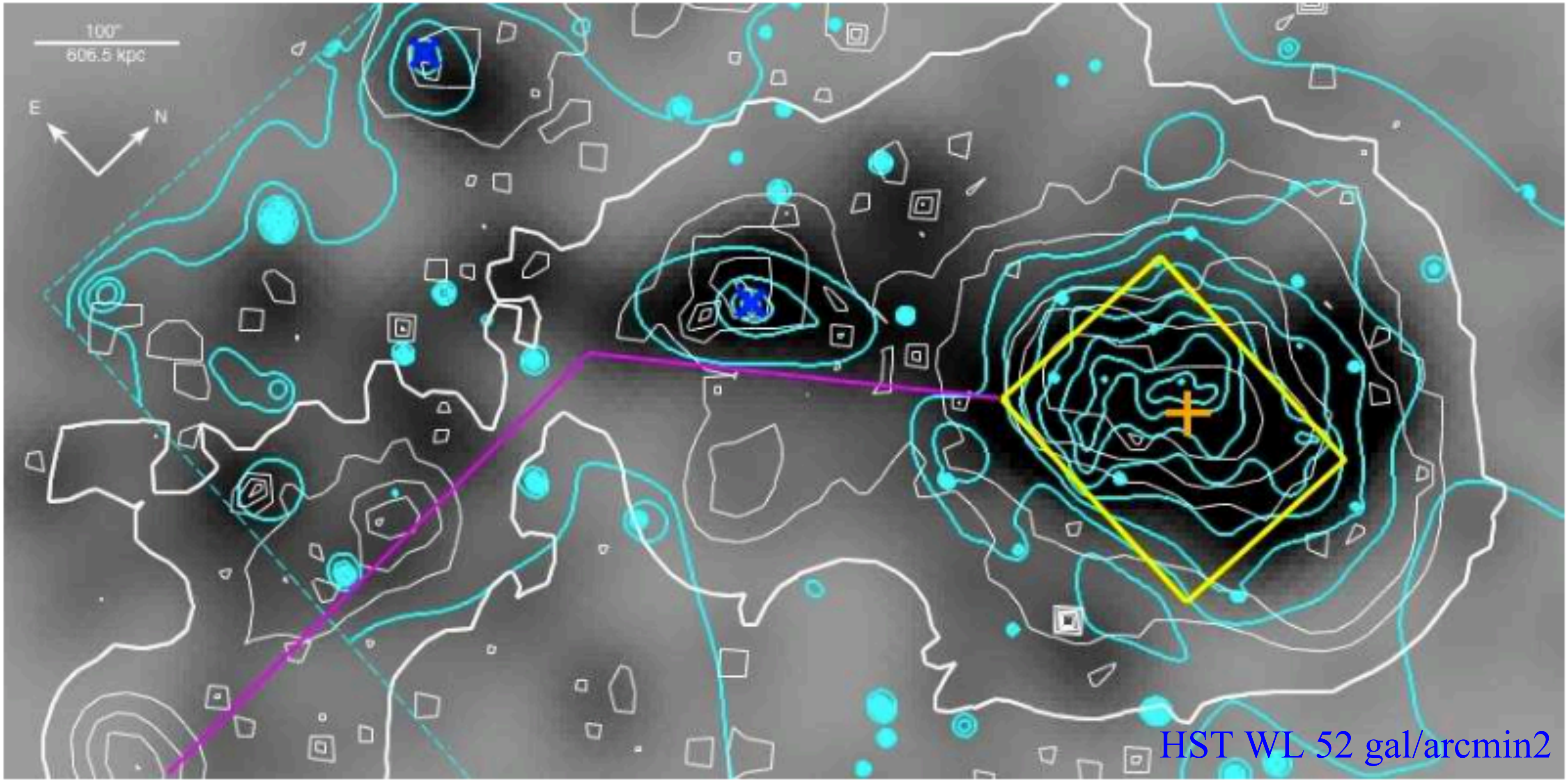
- 110 ksec XMM observations out to 4 Mpc/h_{70}
- Lensing observations:
  - WFI (BVR) 34’x34’
  - Megacam (*i’*) 60’x60’
    - ➔ 37gal/arcmin^2 total
  - ACS (F814W) 3’x3’
    - ➔SL + WL (Jauzac et al. in prep)



Region	*T [10⁶K]*	*Mgas**	*Mtot**
E	*15±2*	*3.8±0.6*	*79±28*
S	*16±2*	*7.1±0.8*	*95±24*
SW	*8±3*	*2.0±0.4*	*48±17*
NW1	*25±4*	*5.7±0.3*	*95±27*
NW2	*19±2*	*19±1*	*120±30*

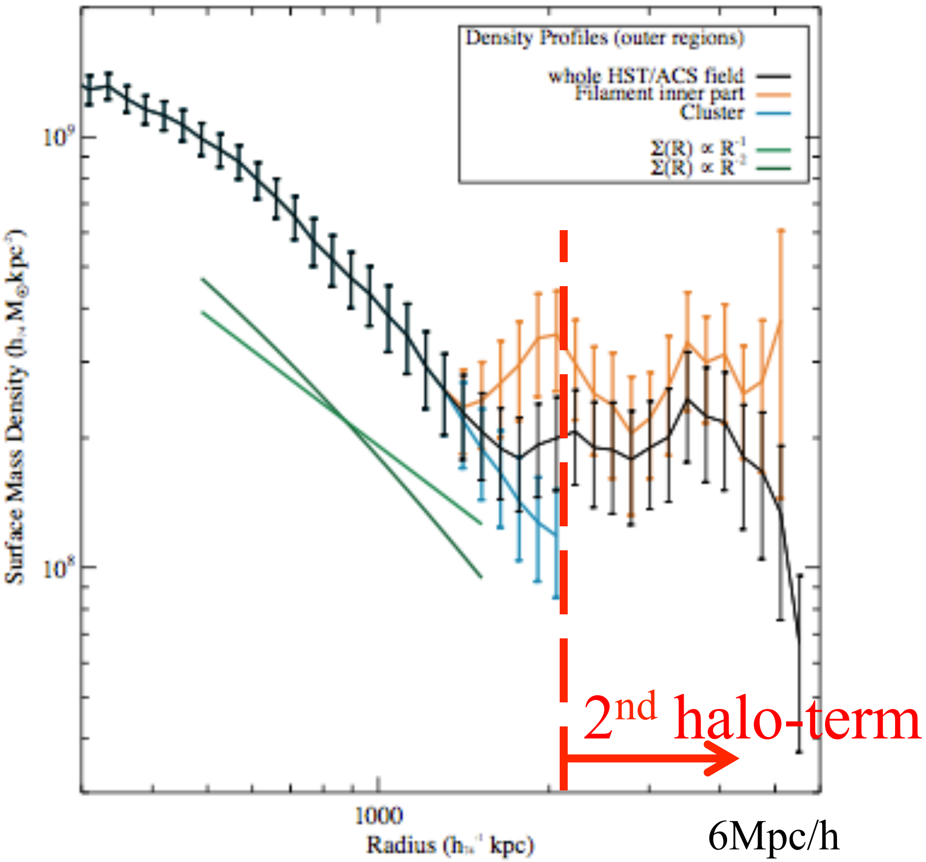
Filament detection in MACS0717

Jauzac et al. 2012



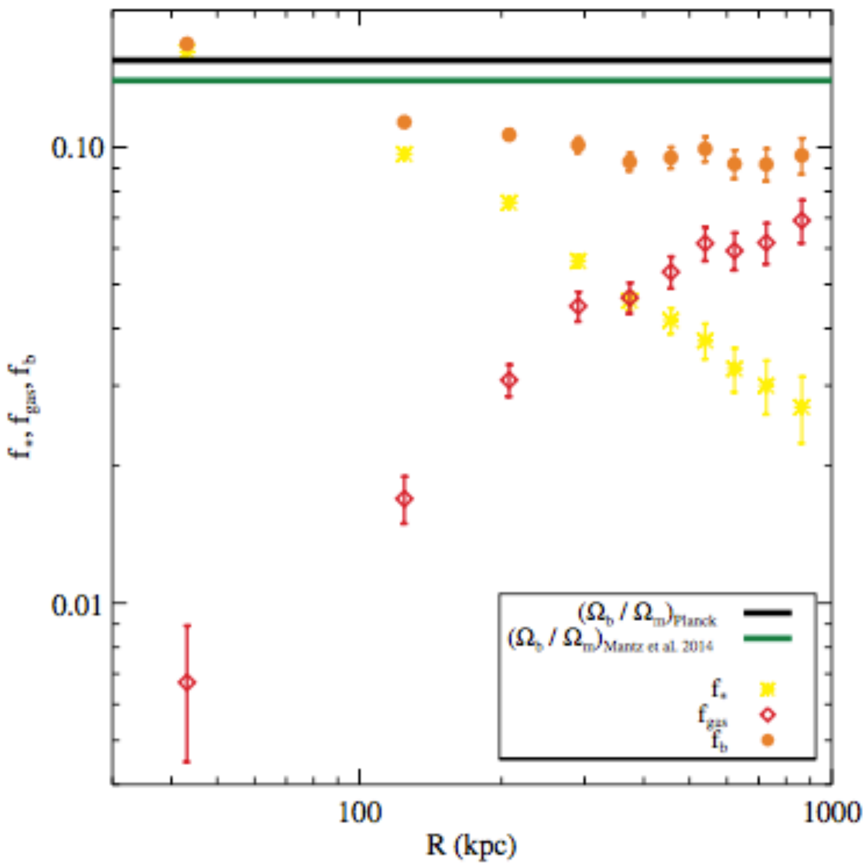
Filament analysis with maps

- Select regions of interest in MACS0717



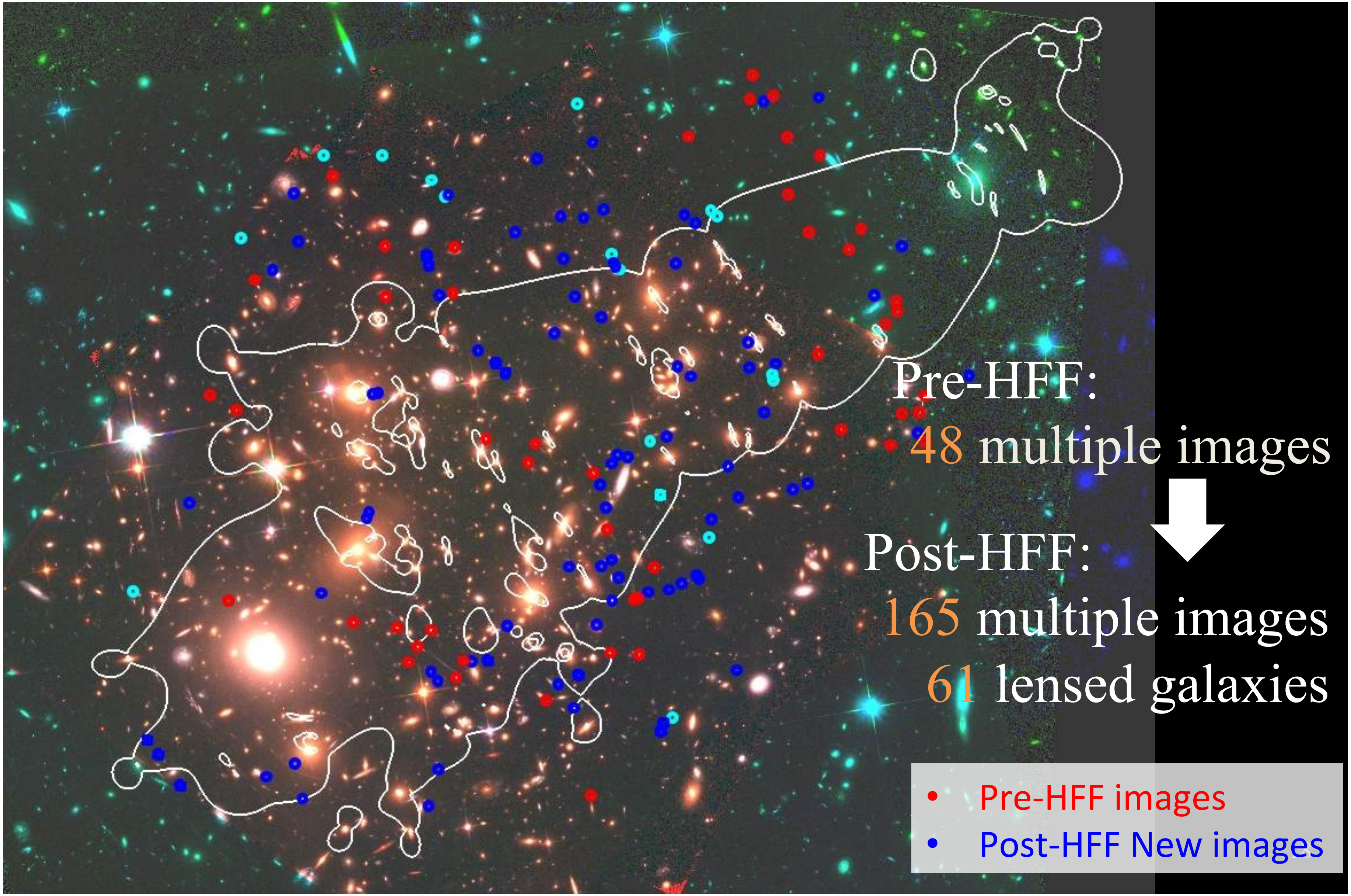
6Mpc/h
~ 20’@z=0.54

- Compare gaz and stellar fraction

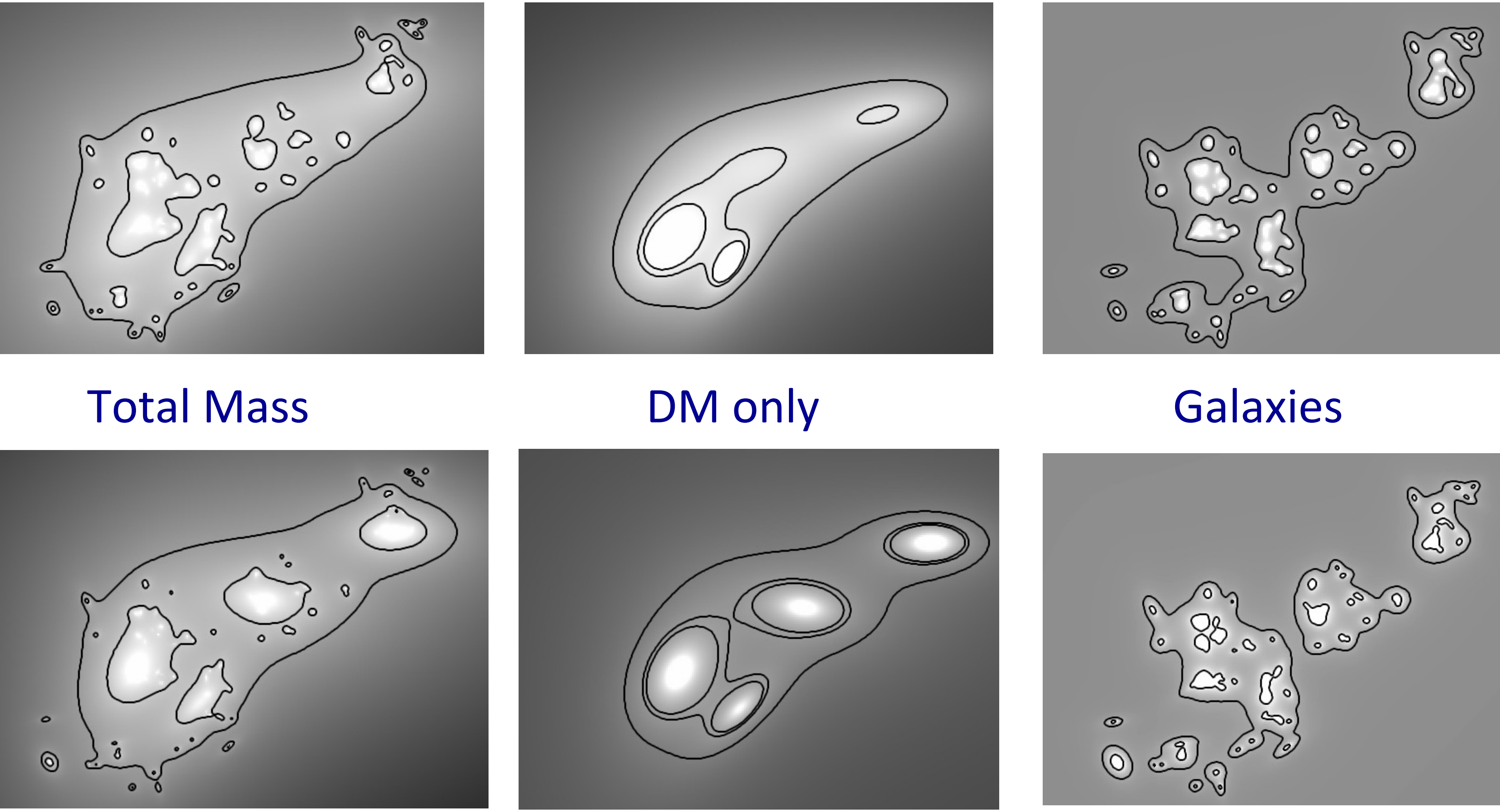


MACS 0717: How Well Can the Mass/Ampli be Constrained ?

Limousin et al. 2016



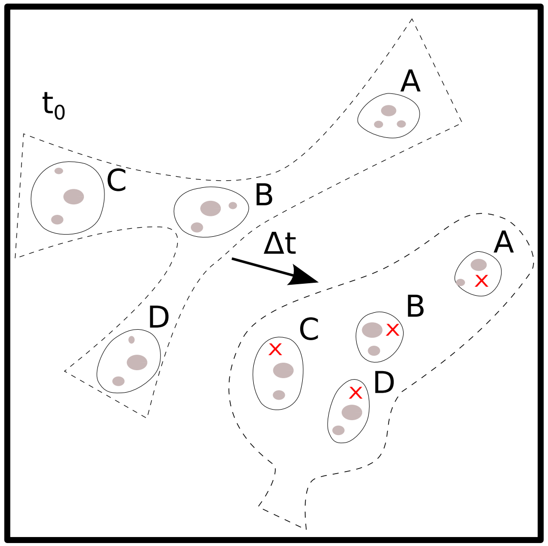
Dark Matter Distribution : Shallow or Peaked ?

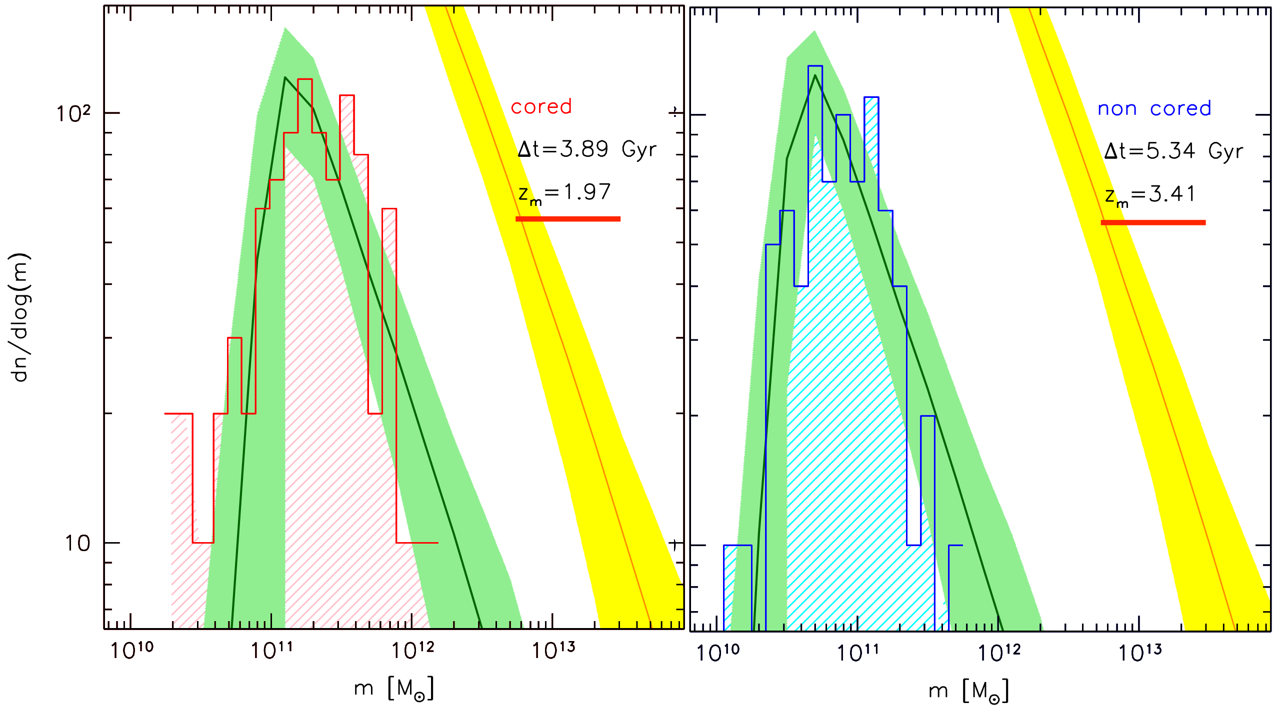


Additional Systematic Uncertainty:

➔ Reliable Area on the Amplification Map decreased by 50-70 %

MACS0717 initial merging redshift





- The mass function is derived from the cluster members lens modeling
- The time scale for mass loss is simulated with MOKA (Giocoli et al. 2012)

➔ The cored-model *initial collapse redshift* seems more realistic (z_m = 1.97)

Amplification maps for high-z galaxies

Atek et al. 2015

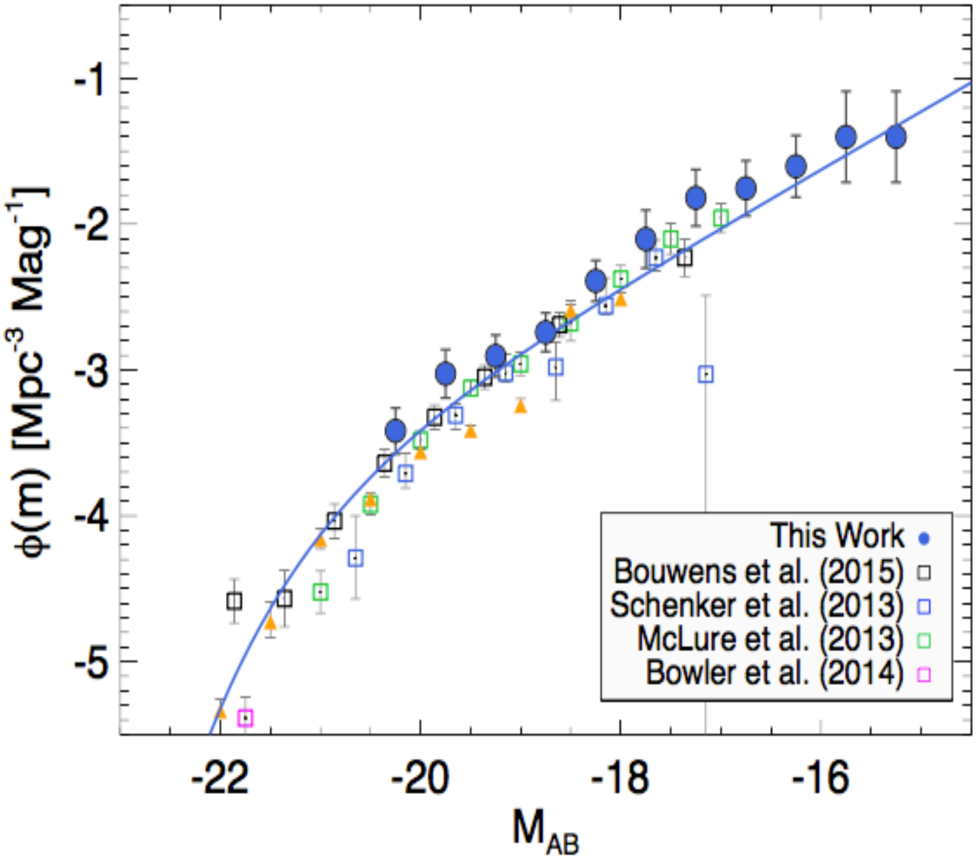
- Combination of 3 HST FF clusters and parallel fields
- Fluxes are corrected from local amplification obtained from maps

➔ While the survey area is smaller in cluster fields, the magnification bias allows the detection of fainter galaxies than in the parallel fields

Number of galaxy candidates in each field

Field	$z = 6-7$	$z = 8$
A2744	45	7
MACS0416	33	3
MACS0717	41	3
A2744 par	44	3
MACS0416 par	33	5
MACS0717 par	31	5

UV luminosity function at z ~ 7



CIB and amplification maps

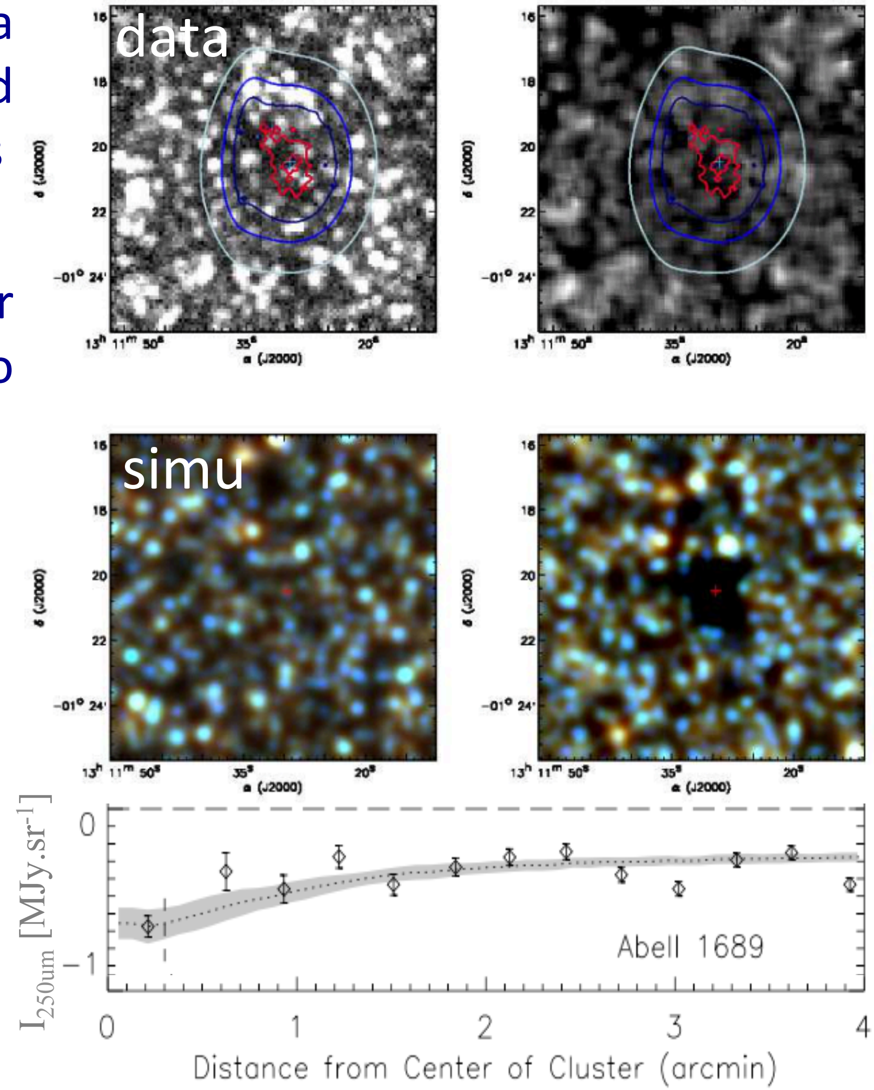
Zemcov et al. 2013

The amplitude of the central deficit is a strong function of the surface density and flux distribution of the background sources

Measurements with HERSCHEL/SPIRE over 4 cluster patches of 0.25 sq. deg. to characterize the CIB

➔ Total CIB at $I_{250um} > 0.69 \pm 0.14$ MJy.sr^{-1}

Cluster	$\sum \Omega$ (Ω_s)	CIB $I_{250\,\mu m}$ (MJy sr^{-1})
Abell 370	3.0	0.67
Abell 1689	7.5	0.68
Abell 2219	3.3	0.71
RX J1347−1145	11.3	0.71
Total	25.1	0.69



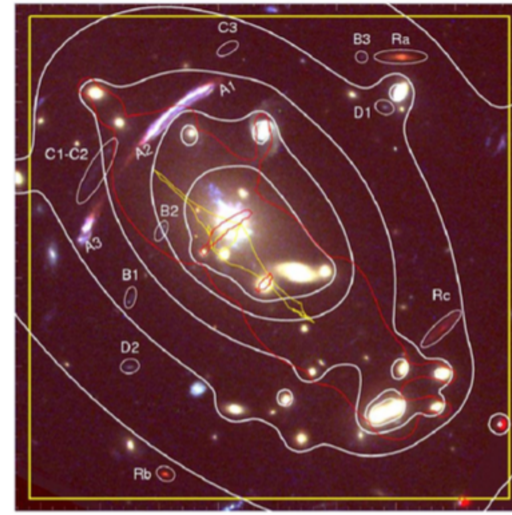
Axion search in galaxy clusters

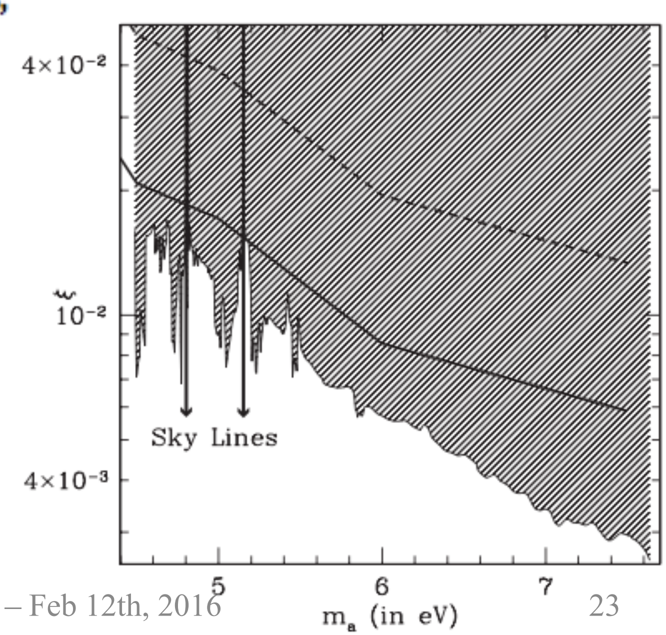
Grin et al. 2007

- Thermally produced axion can account for a fraction of the DM content
- The 2-photon coupling of axions can result in an emission line in galaxies and clusters (Ressell et al. 1991 and Bershady et al. 1991)

$$I_{\lambda_o} = 2.68 \times 10^{-18} \times \frac{m_{a,eV}^7 \xi^2 \Sigma_{12} \exp[-(\lambda_r - \lambda_a)^2 c^2/(2\lambda_a^2 \sigma^2)]}{\sigma_{1000}(1 + z_{cl})^4 S^2(z_{cl})} \text{ cgs},$$

- Search for axion emission lines in IFU data of 2 clusters Abell 2390 and Abell 2667
- Use strong lensing to reconstruct the mass distribution, and derive constraints on the 2-photon coupling of the axions





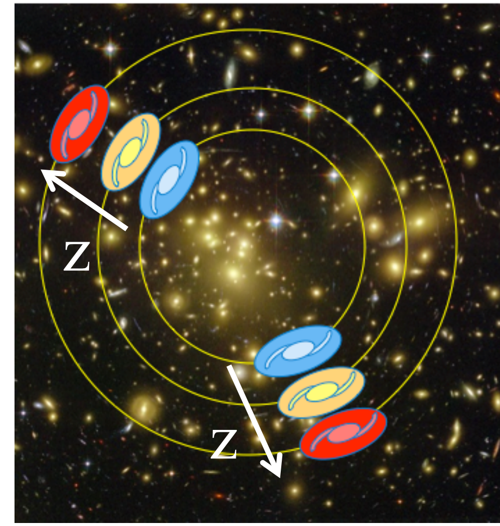
Cosmography with SL

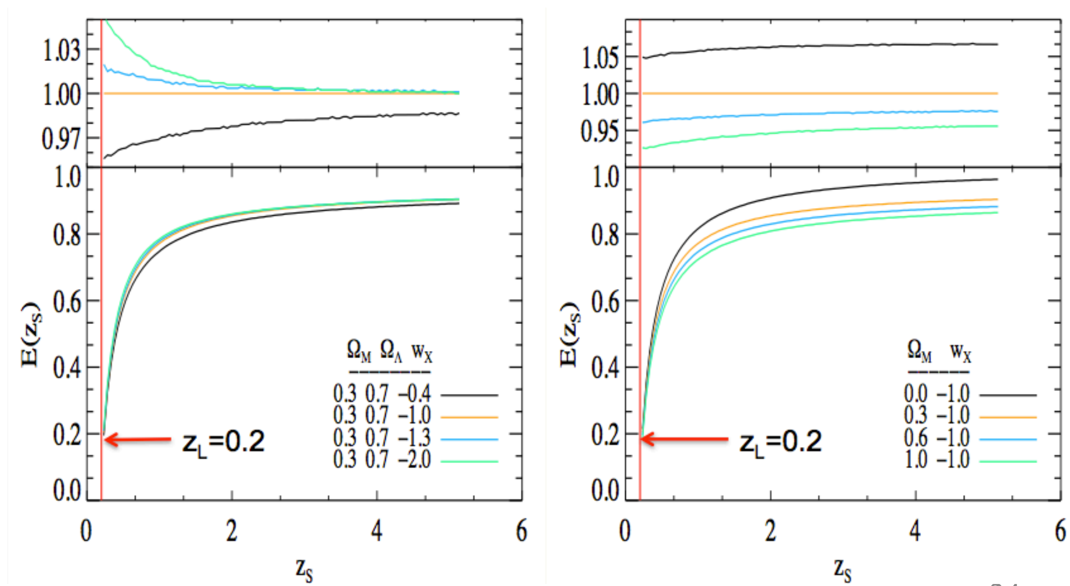
Strong lensing depends on both cluster mass and distances

$$\alpha = \frac{D_{LS}}{D_{OS}} \nabla \varphi(\theta_I)$$

Cosmology

mass





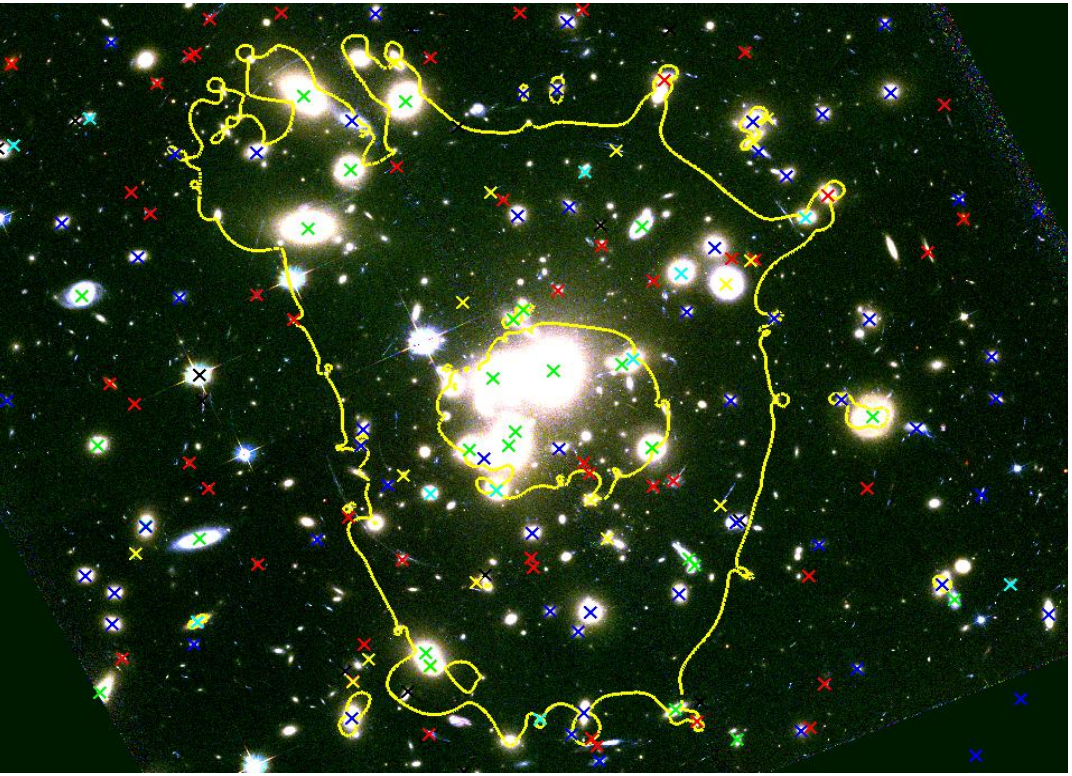
➔ The cosmological constraints depend on the redshift of the background sources

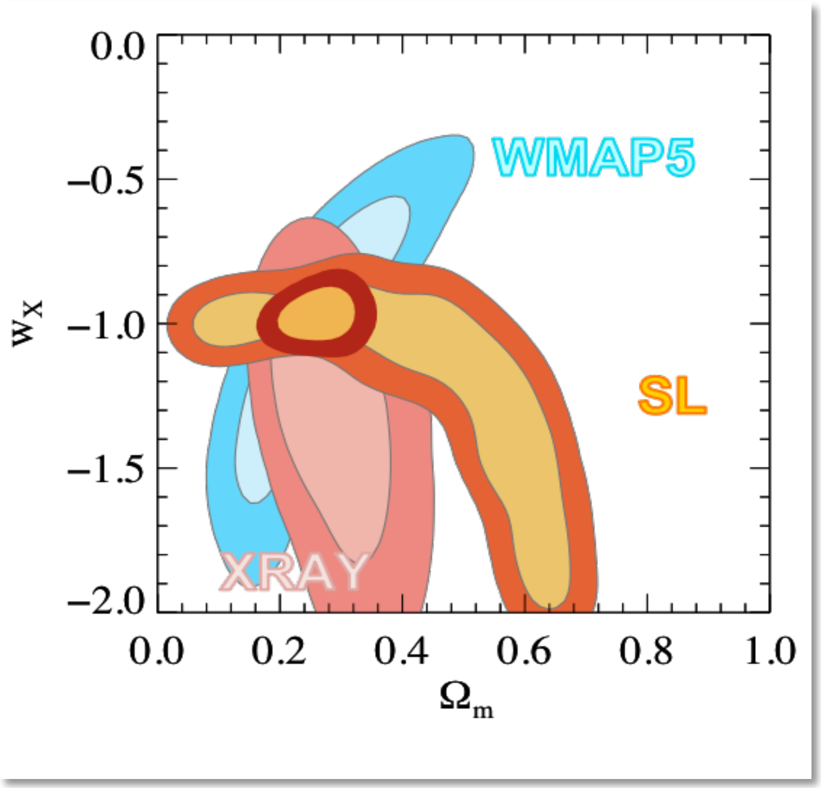
Cosmography with Abell 1689

Jullo et al. 2010, Science

- Mass model with 3 PIEMD potentials; 58 cluster galaxies; flat Universe
- 28 multiple images from 12 sources with spec z
- Bayesian optimization: 32 constraints, 21 free parameters
- **RMS = 0.6 arcsec**

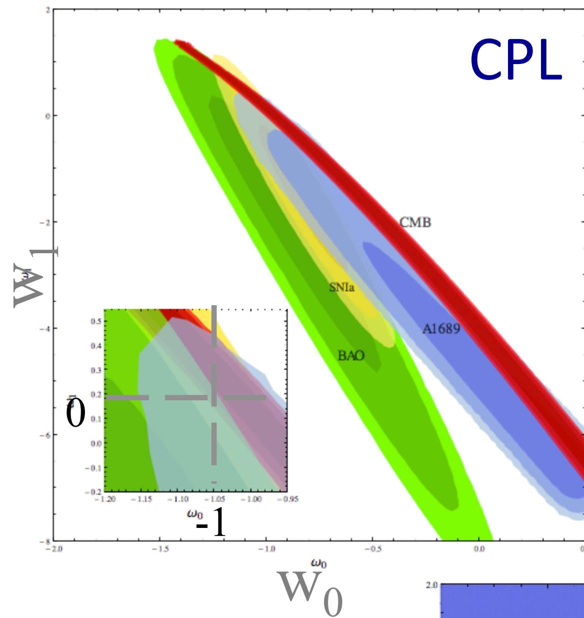
$$0.1 \leq \Omega_M \leq 0.58; -1.57 \leq w_X \leq -0.85$$





Alternative DE models

Magaña et al. 2015



1. CPL model

$$w(z) = w_0 + w_1 \frac{z}{1+z},$$

2. Interacting DE model

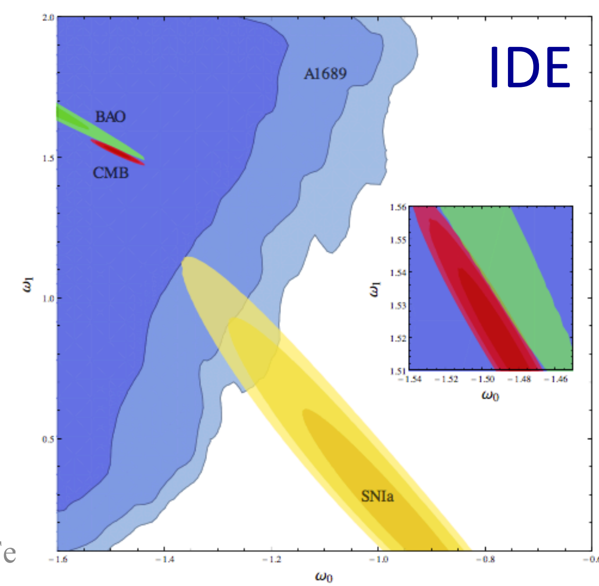
$$\dot{\rho_{DM}} + 3H\rho_{DM} = Q,$$
$$\dot{\rho_{DE}} + 3H\left(1+w_x\right)\rho_{DE} = -Q$$

3. Holographic DE model

$$L^3 \rho_{HDE} \leq M_p^2 L$$

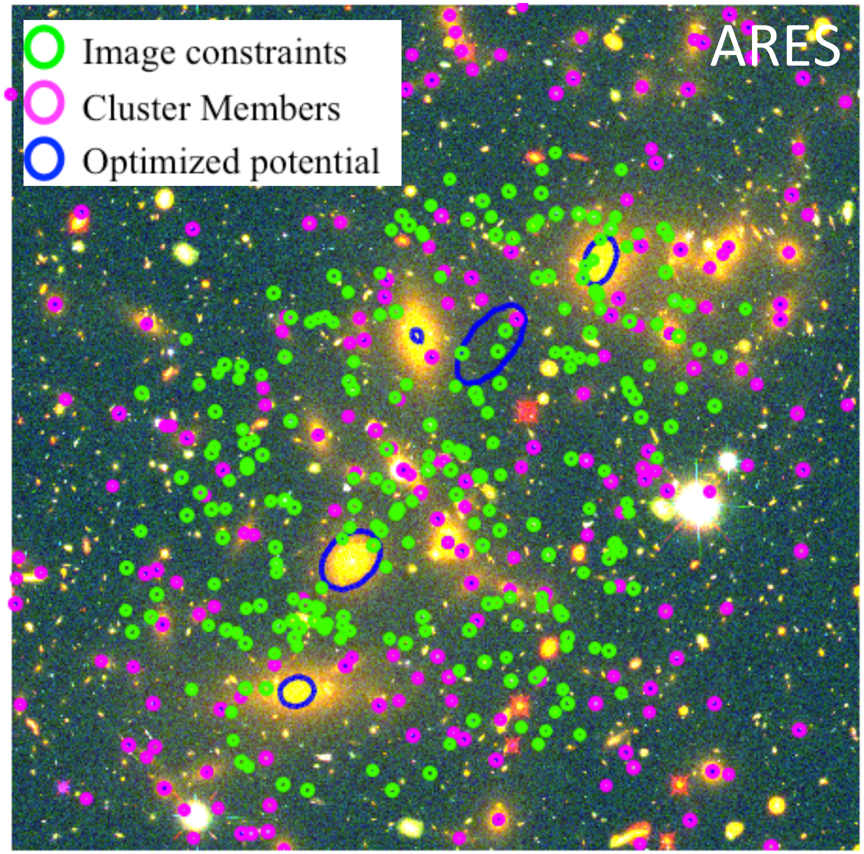
4. Polytropic Cardassian DE model

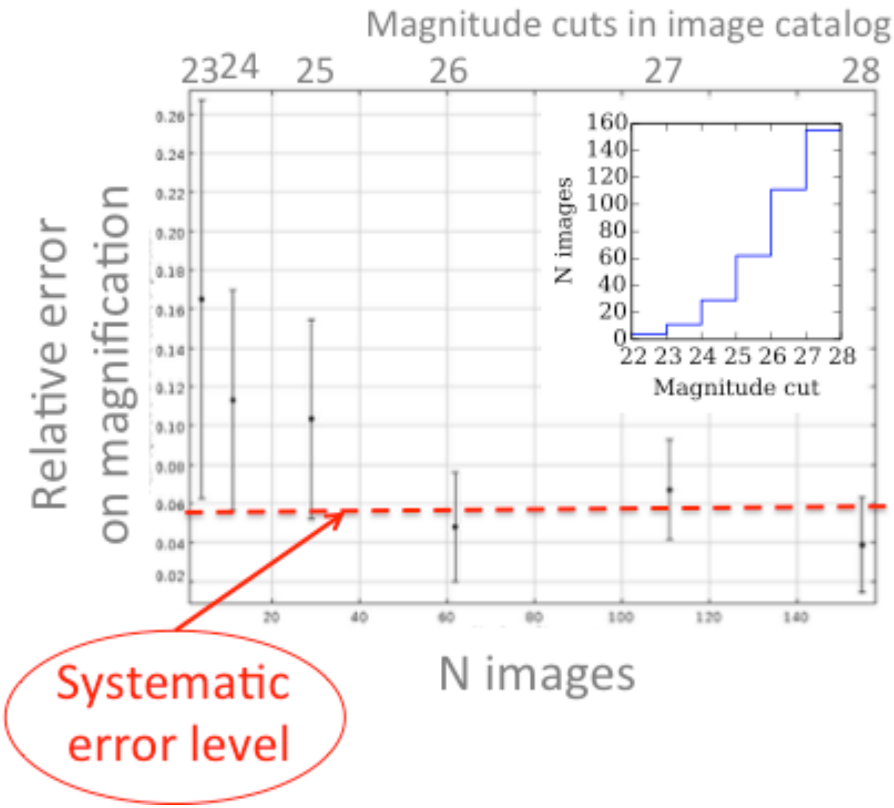
$$H^2 = 8\pi G\rho_m/3 + B\rho_m^n$$



Statistical vs Systematic errors

Acebron et al. in prep.

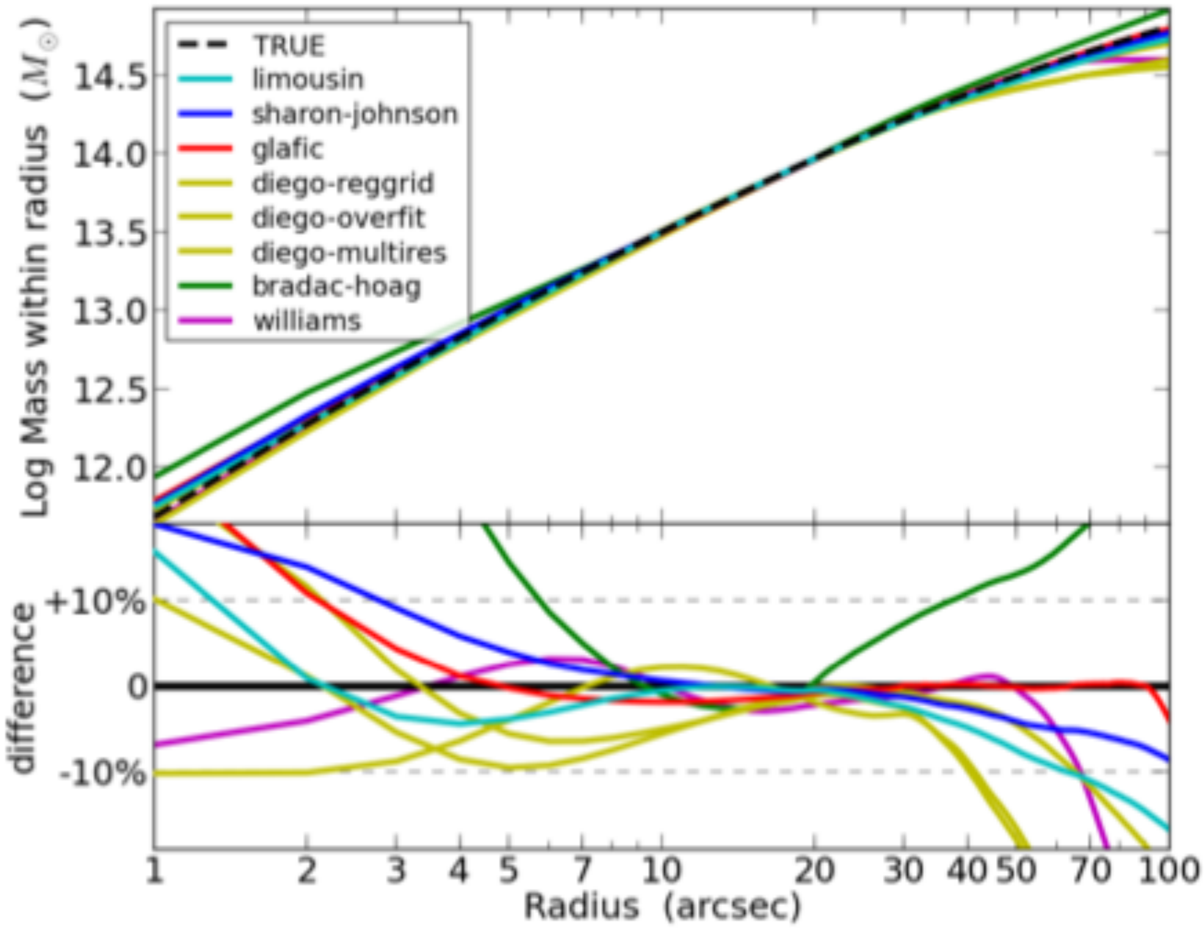




We use ARES STSci HFF simulation to investigate improvement on errors

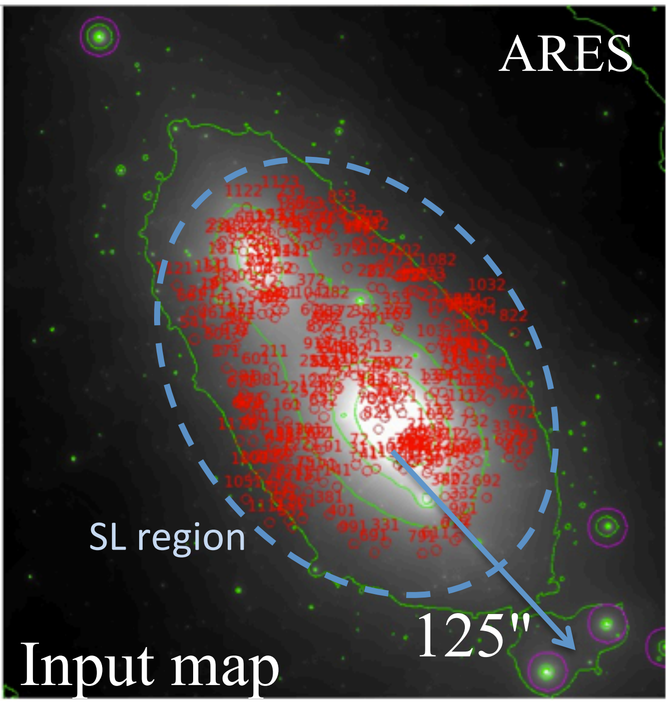
- Statistical errors decrease until $N_{images} < 50$
- Systematic errors dominate at $N_{images} > 50$

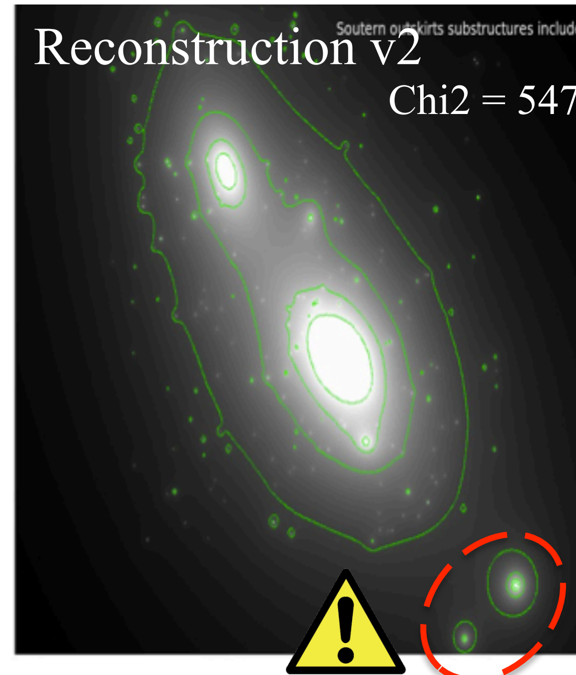
The FF Lens Modelling Comparison Project



Parametric methods perform well ! (***Meneghetti et al.***)

Impact of distance structures



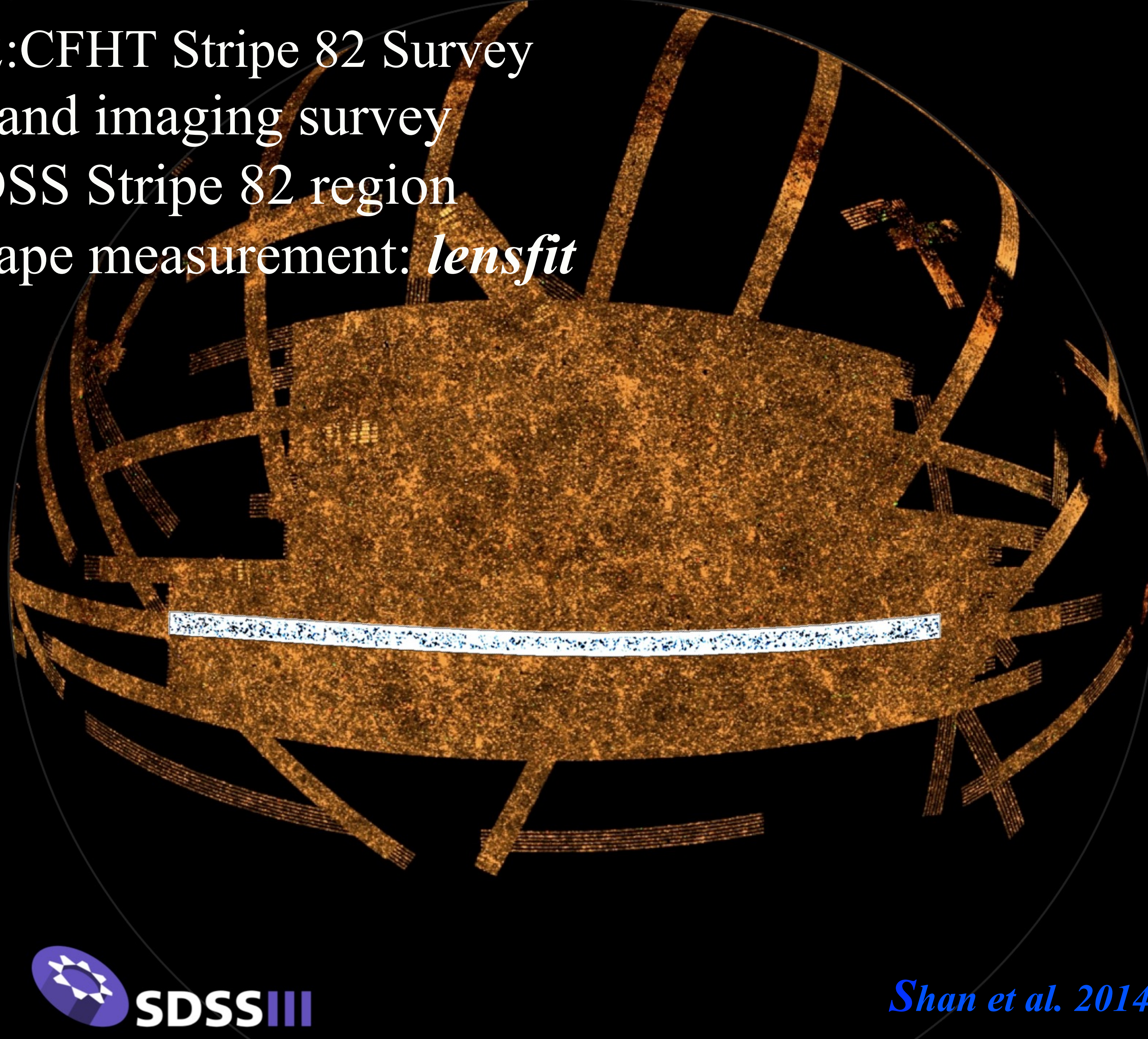


- ➔ Distance structures can significantly perturb the fit
- ➔ (see also previous analysis in Abell 1689, Tu et al. 2008)

Model (DM clumps – BCGs - galaxies)	Chi2	Chi2 (including outskirts substructures in the model)
PIEMD - no BCG - PIEMD	1906	
PIEMD - PIEMD - PIEMD	1840	} Reconstruction v1
NFW – no BCG - PIEMD	1312	
NFW – PIEMD - PIEMD	1015	547

CS82:CFHT Stripe 82 Survey

- *i*-band imaging survey
- SDSS Stripe 82 region
- Shape measurement: ***lensfit***

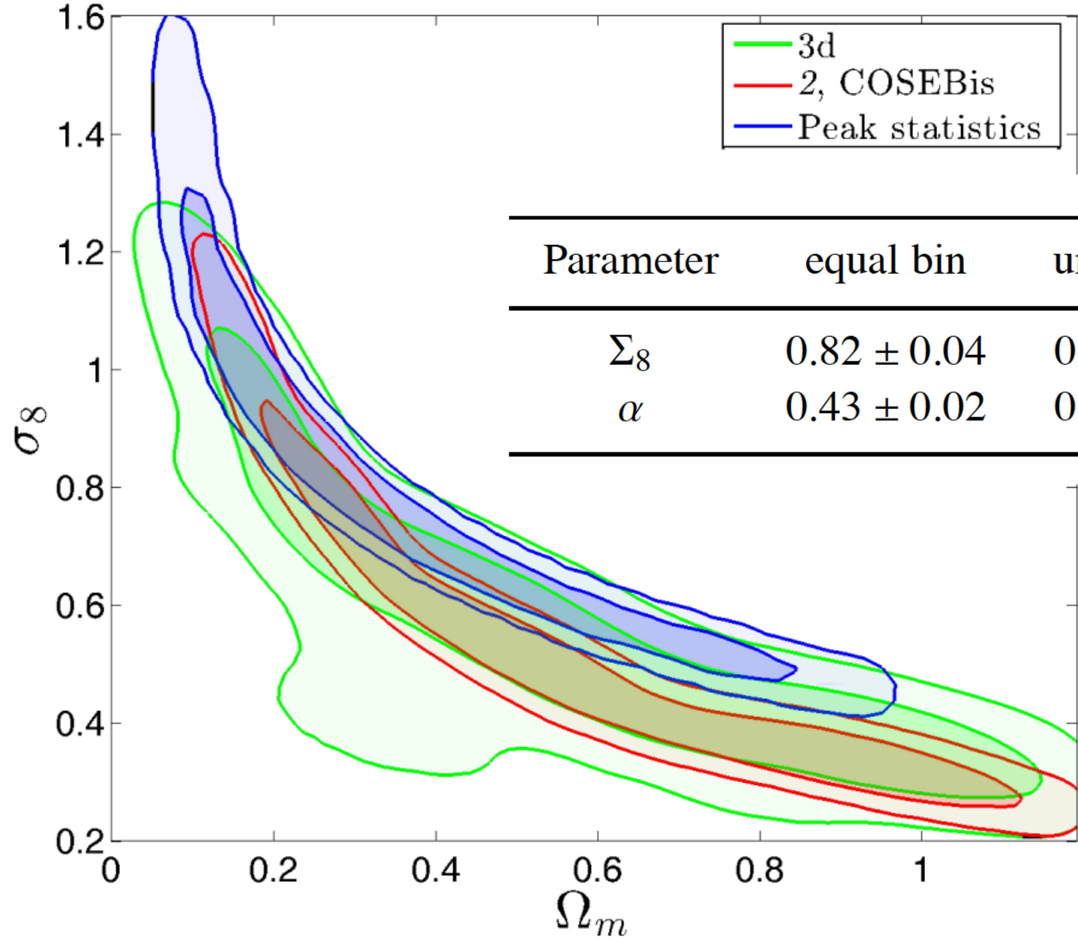


SDSSIII

Shan et al. 2014

CS82: Mass Mapping & Cosmology

Weak Lensing Peak Statistics

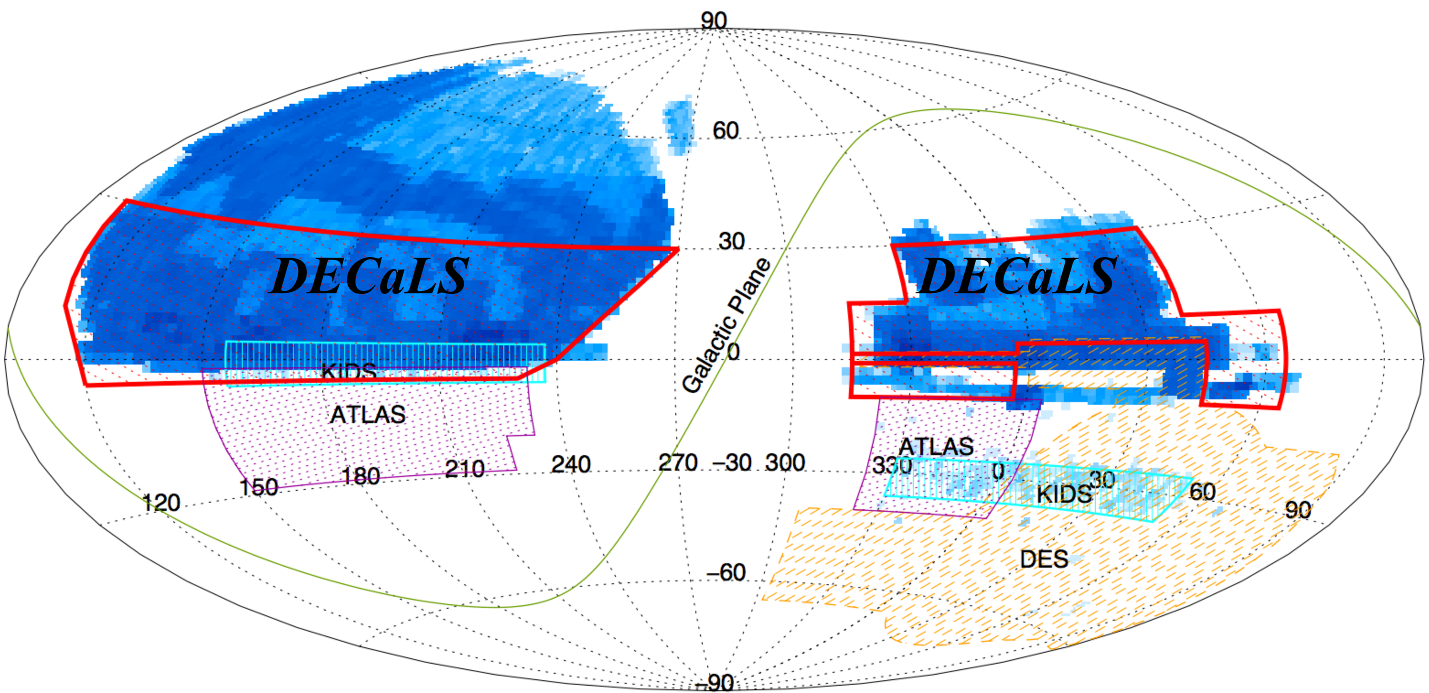


Parameter	equal bin	unequal bin	2-pt	3-pt
Σ_8	0.82 ± 0.04	0.82 ± 0.03	0.79 ± 0.06	$0.73^{+0.09}_{-0.19}$
α	0.43 ± 0.02	0.42 ± 0.02	0.70 ± 0.02	0.58 ± 0.02

Liu et al. 2015

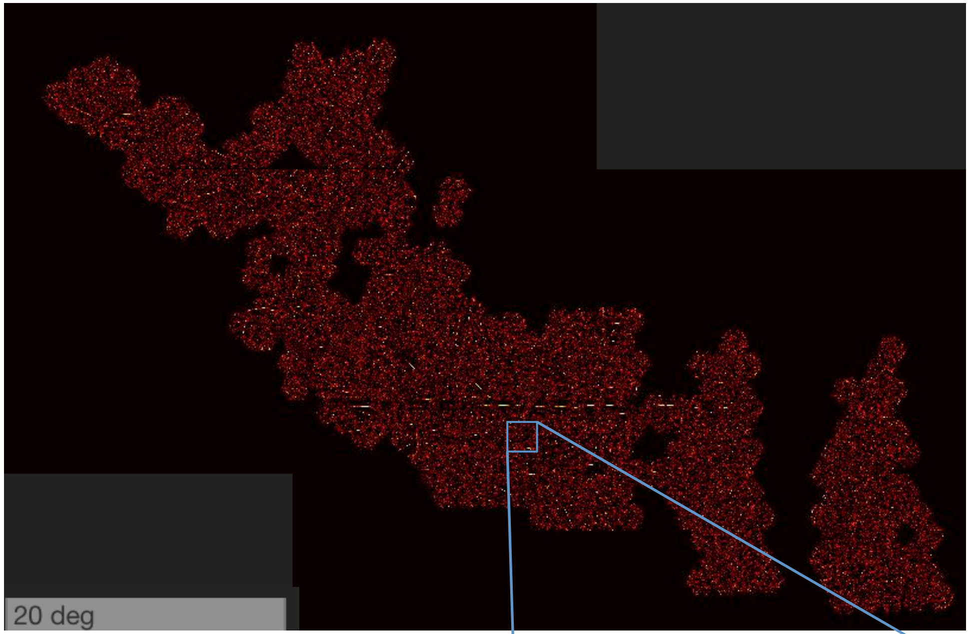
DECaLS: DECam Legacy Survey

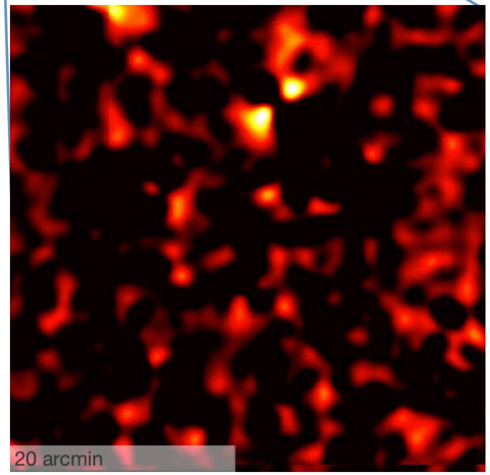
- ***DECaLS*** (PIs: Schlegel & Dey)
- Image ***SDSS*** footprint
  - Total area: ~**6700** sq. deg
  - 3 bands: *g, r, z*
  - ~1-2 mag deeper than ***SDSS*** (g~24.7, r~23.9, z~23.0)
  - Overlapping with the ***BOSS/eBOSS*** project



Preliminary Results

http://test.legacysurvey.org/decals-dr1j

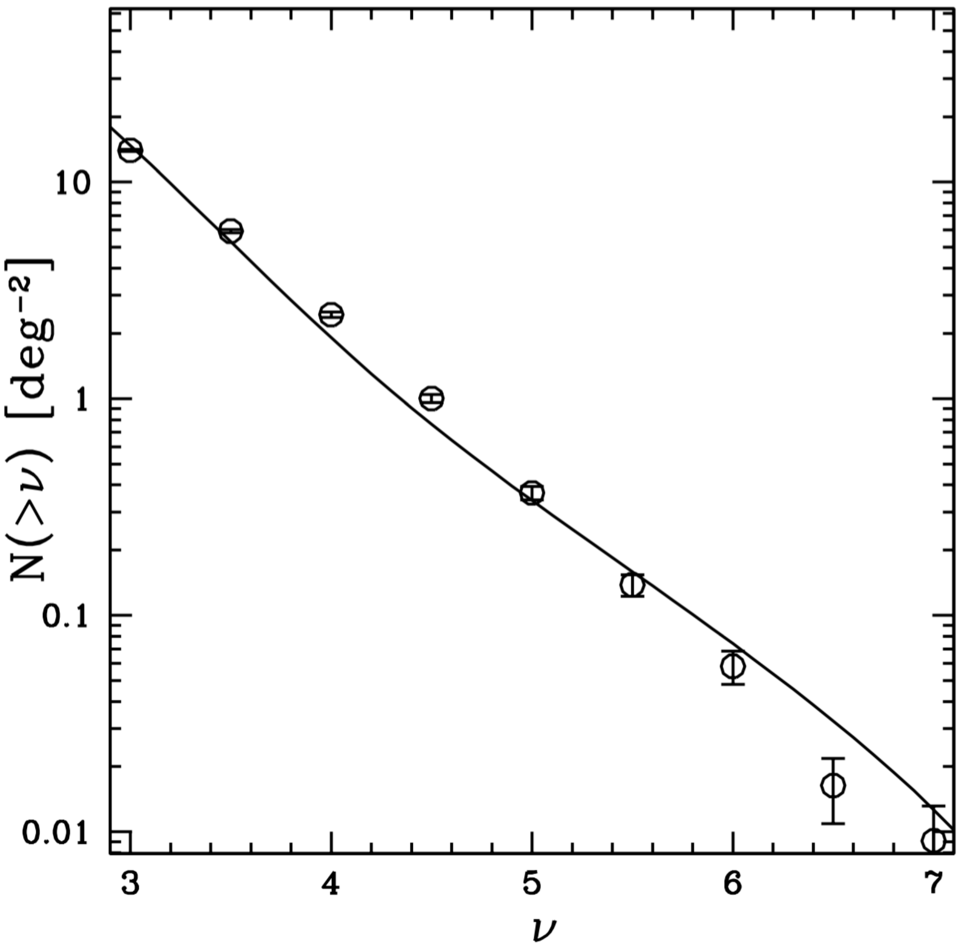




- **DECaLS DR1:**
  - WL maps: **550** sq. deg
  - About 10 gal/arcmin^2
  - mean redshift: **z~0.9-1.0**
  - **~7000** peaks with SNR>3.0
- Massive cluster candidates

Preliminary Results

Shan et al. in prep.



- **DECaLS DR1**:
  - WL maps: **550** sq. deg
  - About 10 gal/arcmin^2
  - mean redshift: **z~0.9-1.0**
  - **~7000** peaks with SNR>3.0

- Massive cluster candidates
- WL peak counts
- Estimation of the selection function with MultidarkLens simulations (Giocoli et al. 2015)

Conclusion

- So far, strong lensing only work with maps
- Maps are essential to correlate with other datasets, and perform multiwavelength studies

➔ Lensing maps are critical for astrophysics

- Maps also can mitigate the impact of systematic errors by properly taking care of the perturbers in the reconstruction

- On wide fields, peak counting and high order statistics from maps put stringent constraints on cosmological parameters