Lensing by galaxy clusters

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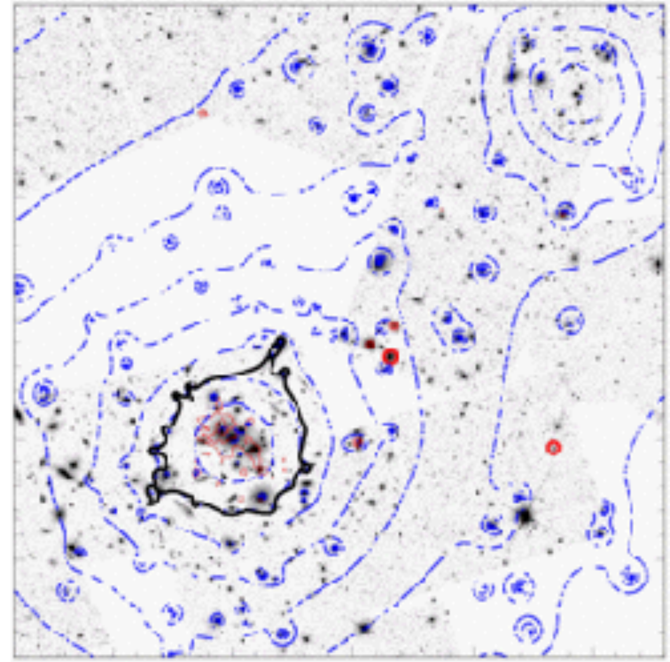
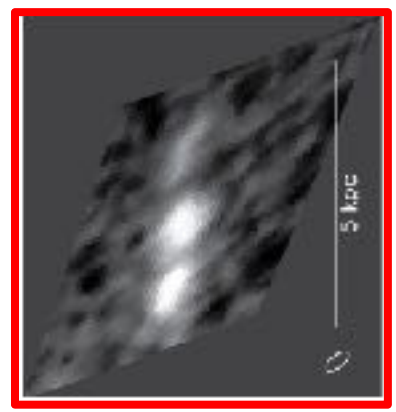
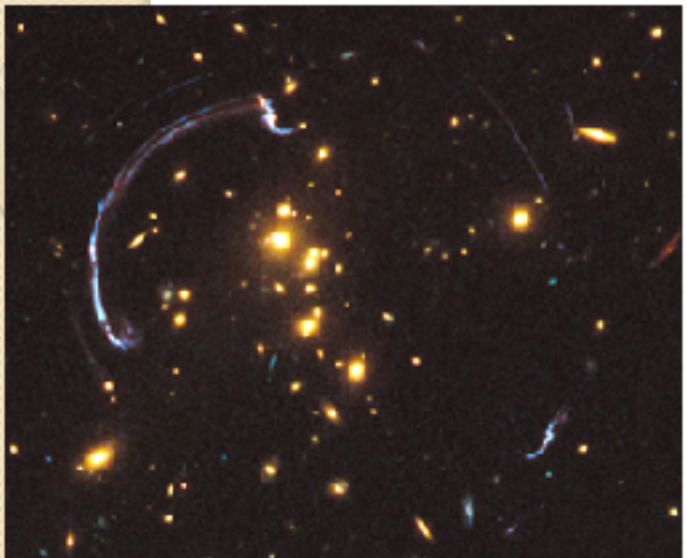
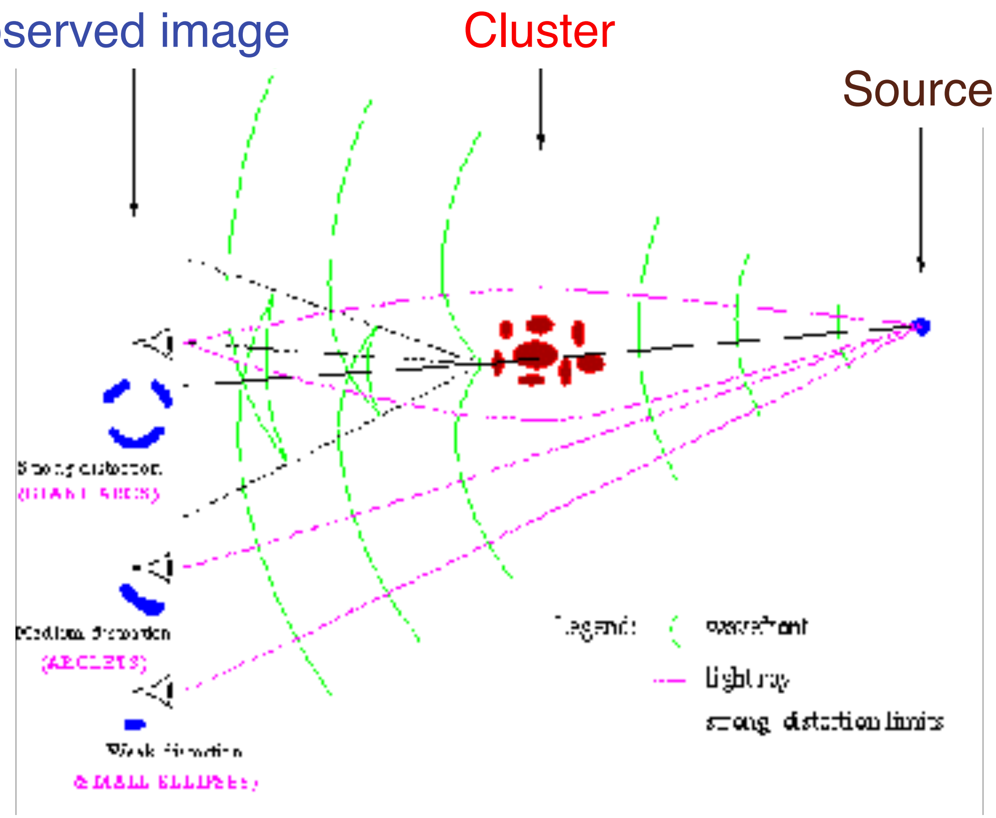
Outline

- Generalities on cluster lensing
- Lensing as a probe of the cluster mass distribution
- Clusters as Gravitational Telescopes
- Cosmology with strong lensing by clusters







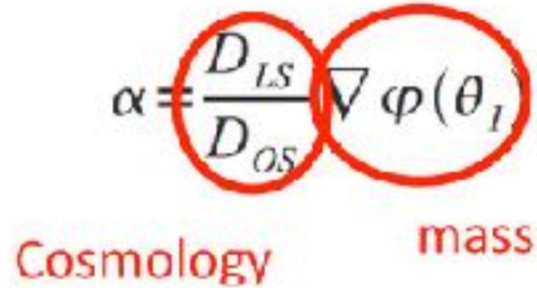


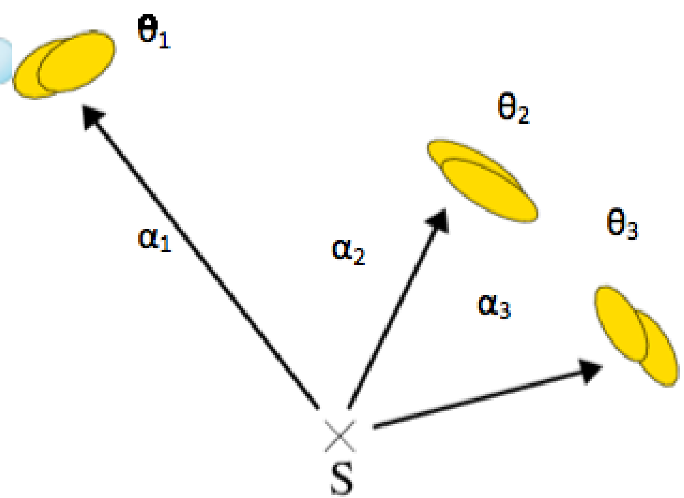
- Cluster cores produce a large area of strong lensing effect: many multiply-imaged systems, giant arcs and arclets

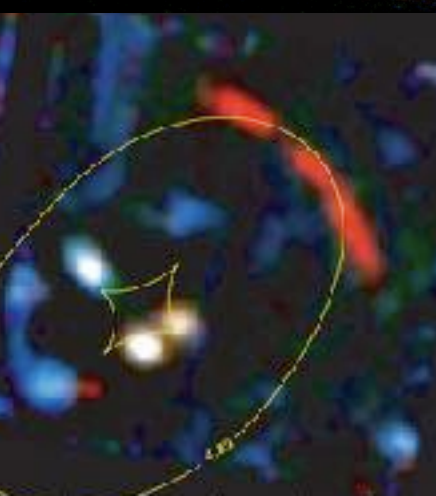
- Weak-lensing regime: massive clusters can be detected out to their virial radius

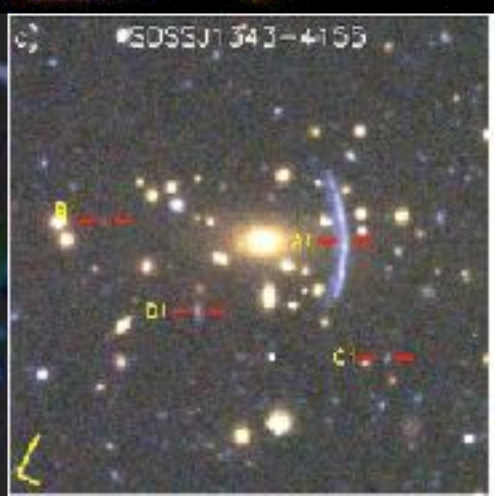
- Flexion: higher order effects to probe substructure

Strong lensing









Precise constraints from the location, shape and flux of multiple images.

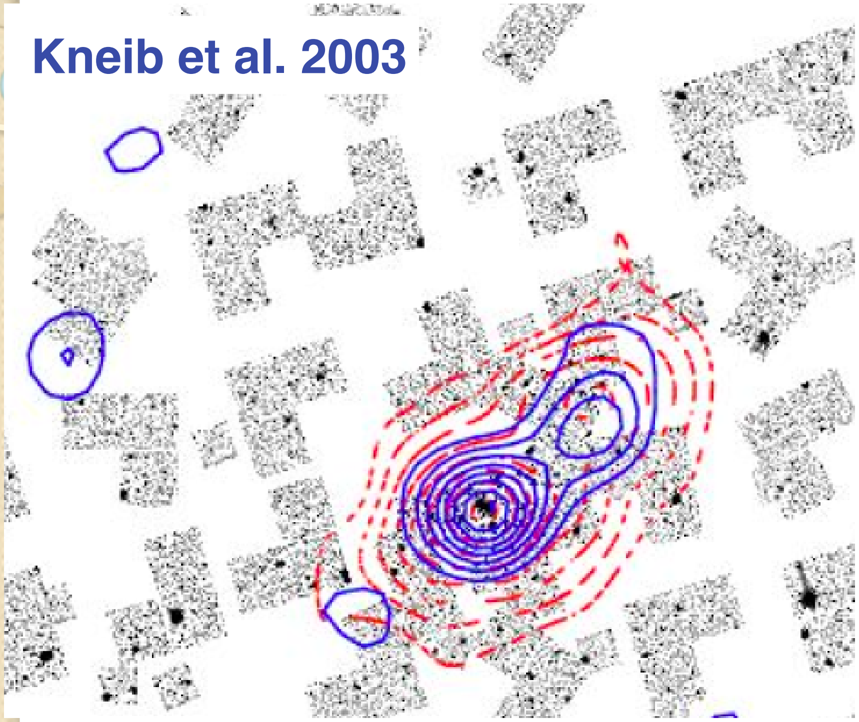
Regime of very high magnification (μ>~ 1 mag): use as gravitational telescopes

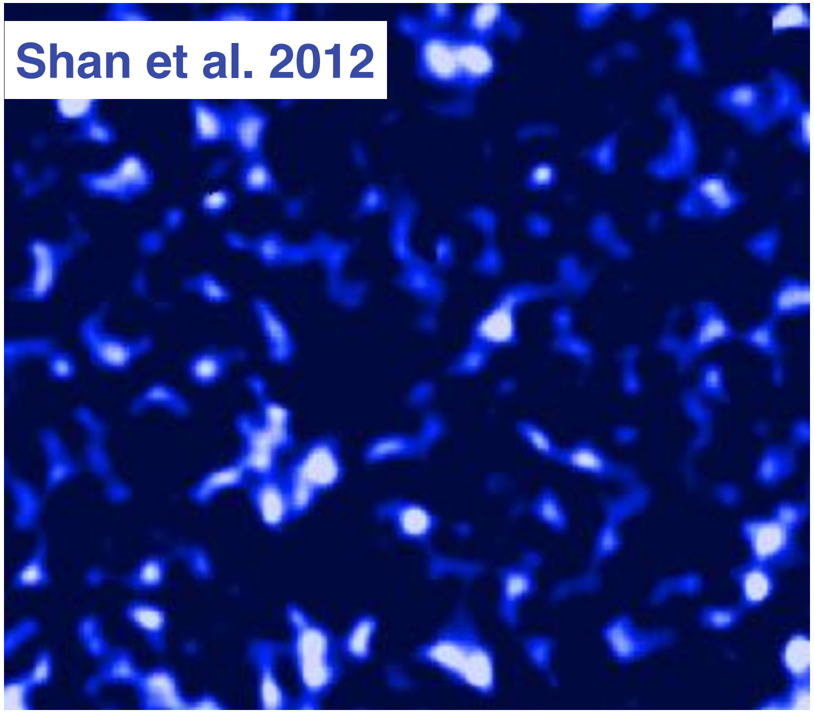
Spectroscopy of multiple images is necessary to calibrate the clusters.

Current cluster samples with strong lensing:

- **LoCuSS (PI: Smith) Richard et al. 10**
- **MACS (PI: Ebeling) Ebeling et al. 07,09**
- **SDSS/RCS: Bayliss et al. 11**

Weak lensing


Kneib et al. 2003


Shan et al. 2012

Cluster weak-lensing signal is detectable up to a few Mpc

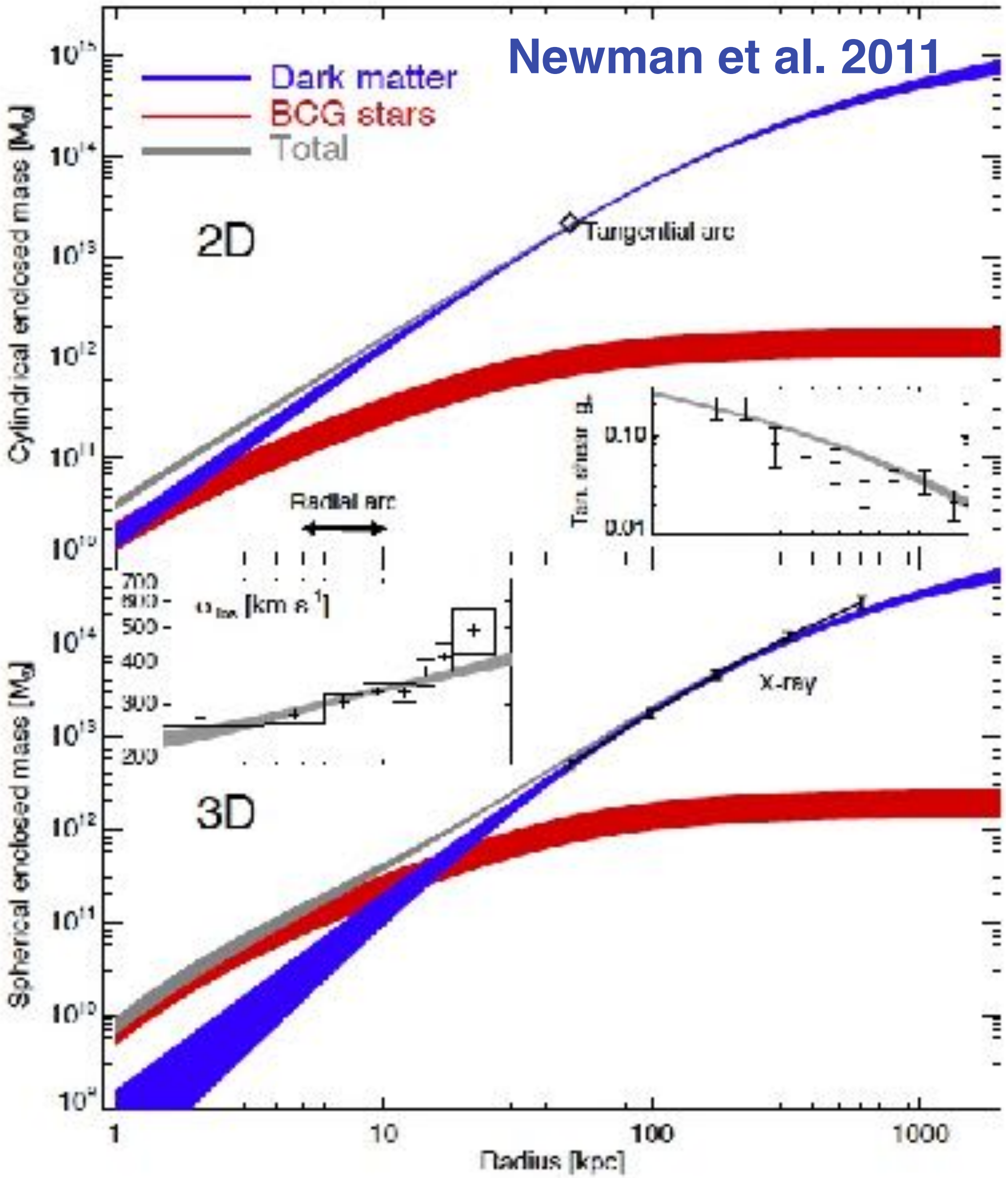
Gives accurate measurement of virial mass and concentration

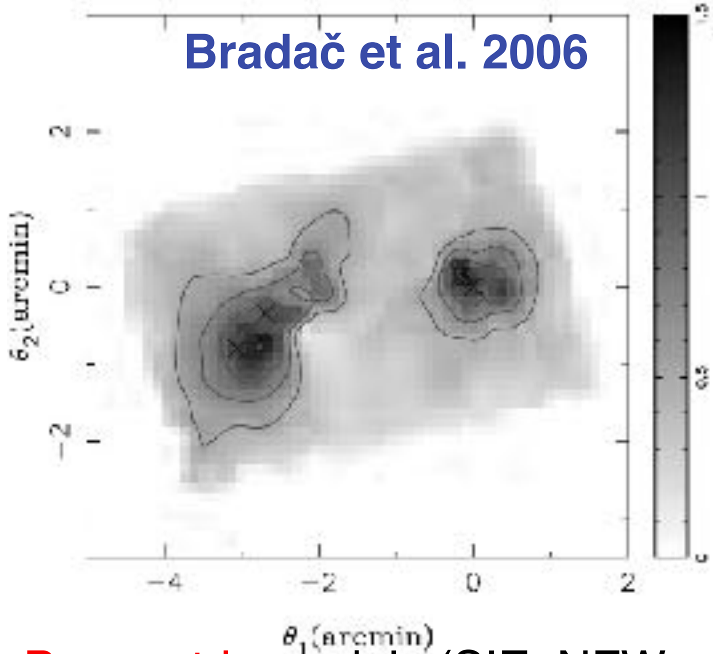
WL is also efficient to detect clusters a mass peaks in wide field imaging:

• CFHTLS (**Gavazzi & Soucail 2007**, **Bergé et al. 2008**, **Shan et al. 2012**)

• COSMOS (**Léauthaud et al. 2009**)

Cluster mass distribution





Parametric models (SIE, NFW, …):

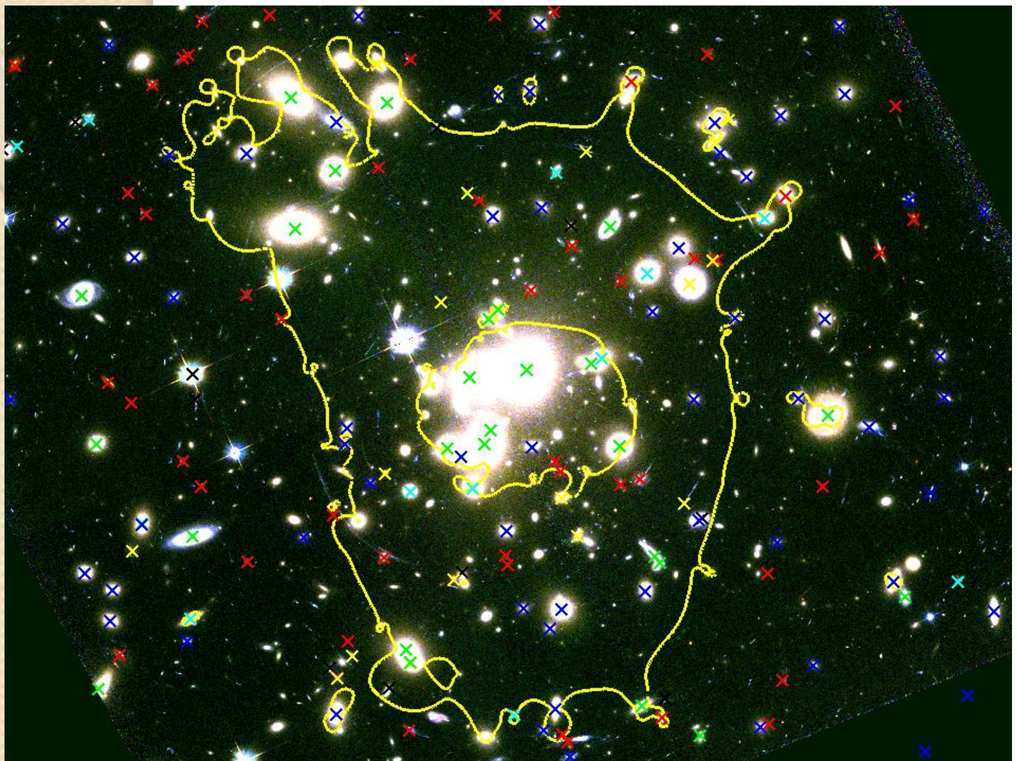
• 1 or several large-scale components DM or X-ray gas

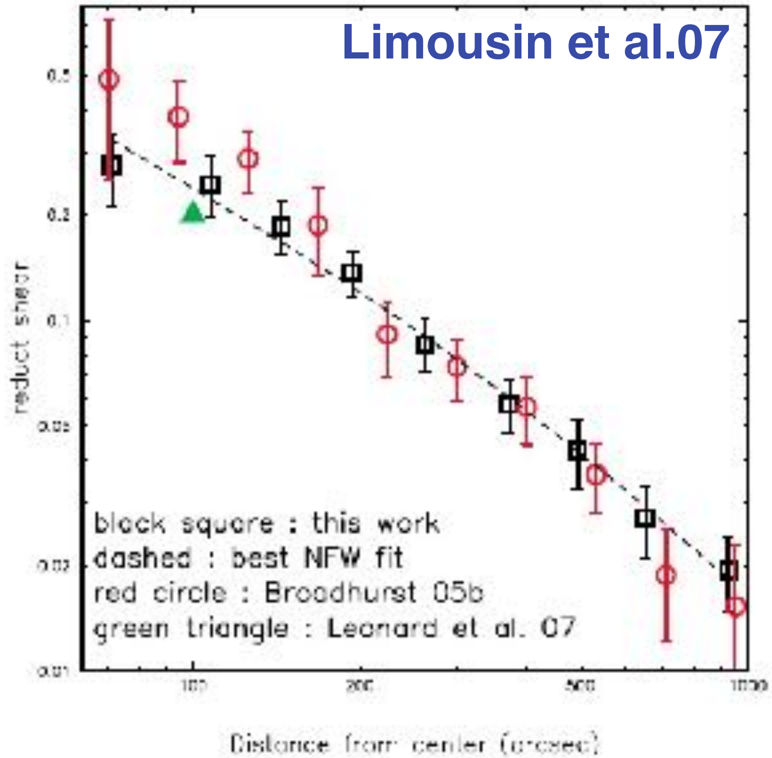
• Galaxy-scale components : substructure

Non-parametric models:

• Reconstruction on a regular or adaptive grid

Abell 1689





Cluster with the largest number of multiple images / constraints:

• 40 multiple systems with 25 having confirmed spectroscopic redshifts

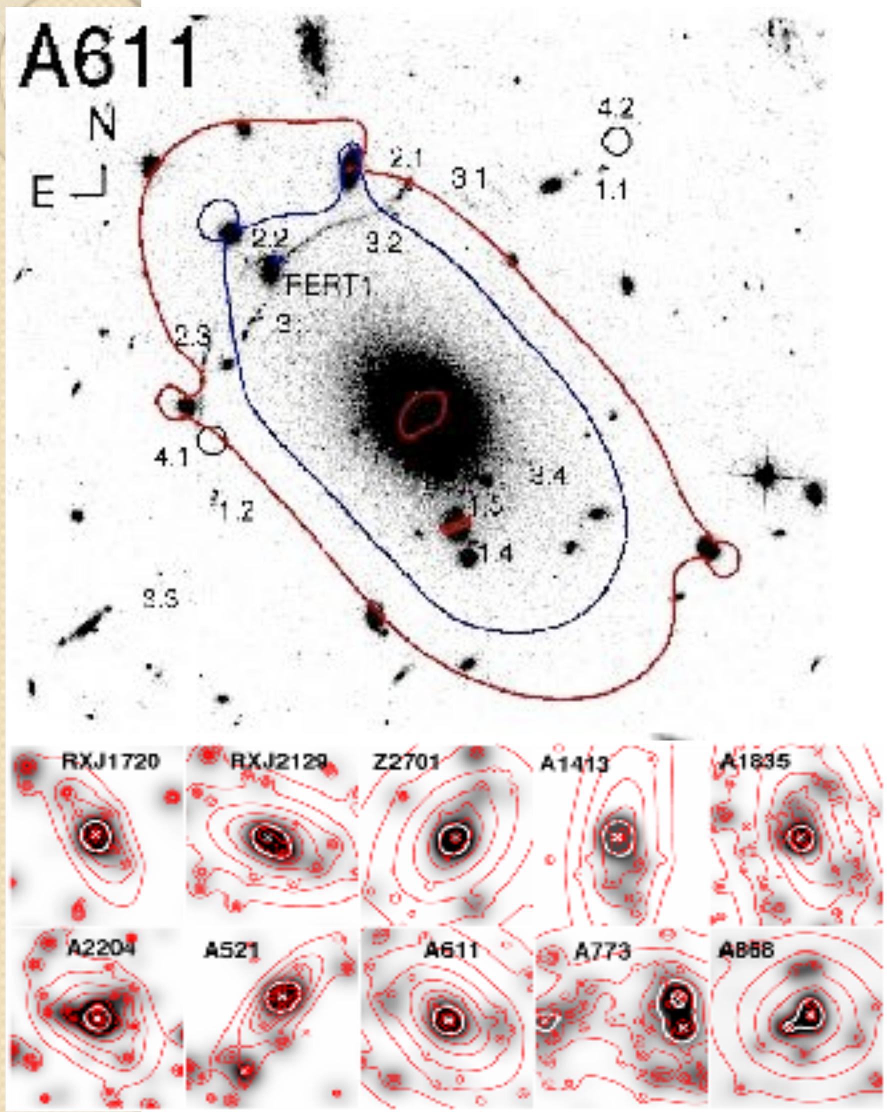
• SL reconstructions: Parametric (**Limousin et al. 2007**), non-parametric (**Coe et al. 2010**), hybrid (multi-scale, **Jullo & Kneib 2019**)

• Weak-lensing constraints from CFHT and Subaru images, agreement with SL

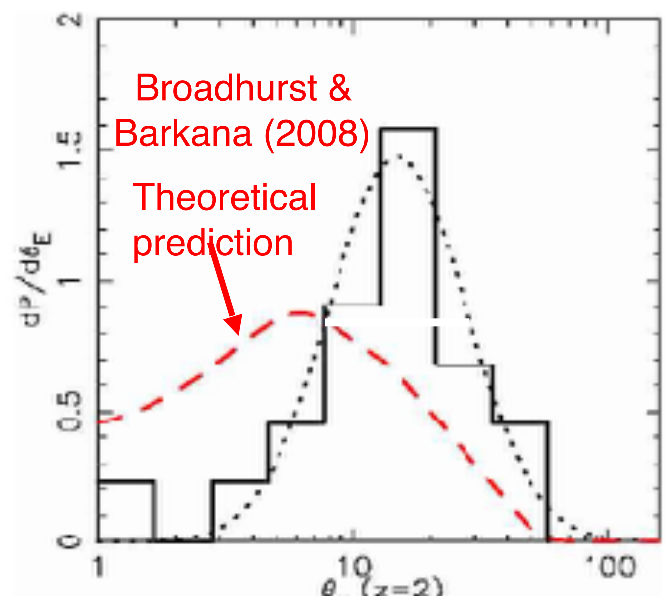
LoCuSS sample: SL

Richard et al. 2010

LoCuSS



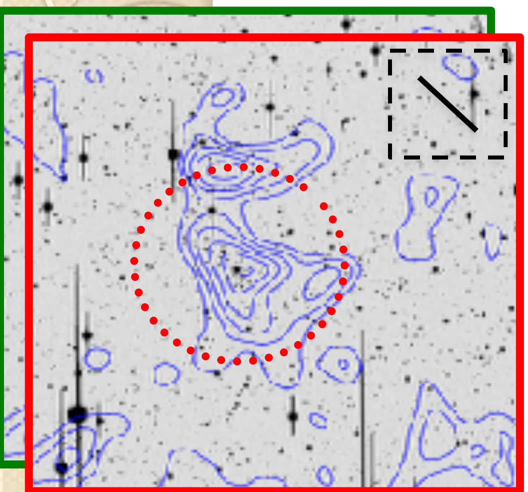
- 20 Northern/equatorial clusters
- HST + Keck/LRIS + Chandra + Palomar Near-IR
- Detailed structural study at Δ>5000 (sub-250kpc)
  - Distribution of Einstein radii
  - X-ray/lensing mass comparison
  - Cool core strength vs cluster substructure

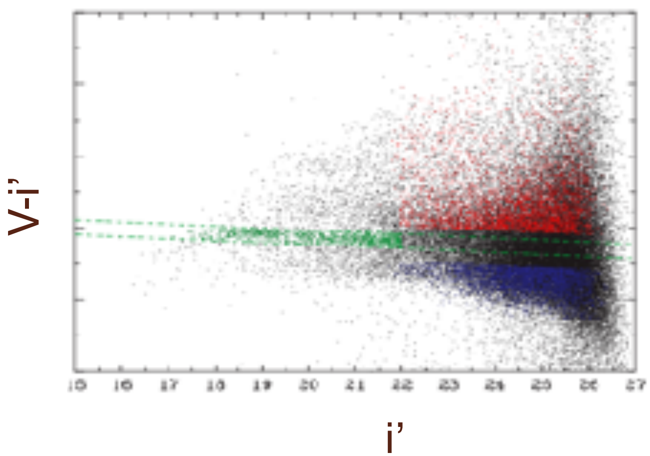


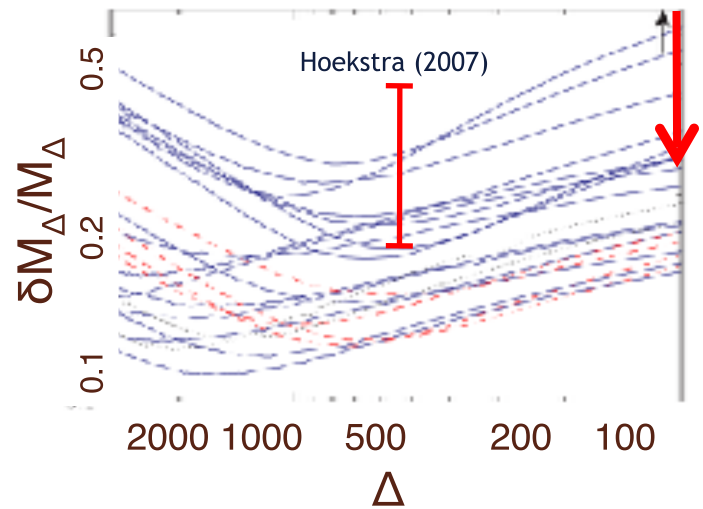
Subaru weak-lensing

Okabe et al. 2010, 2011

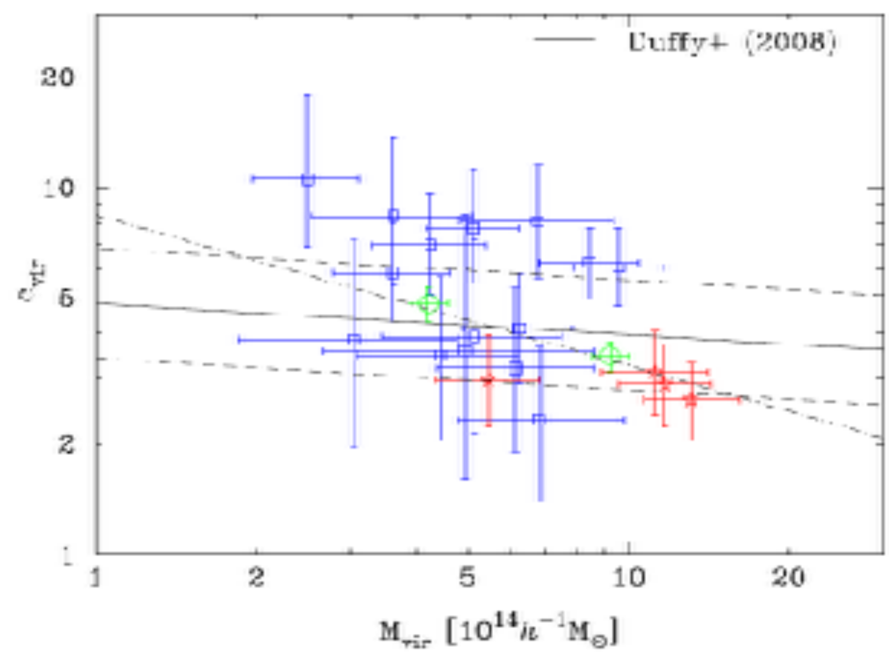
LoCuSS







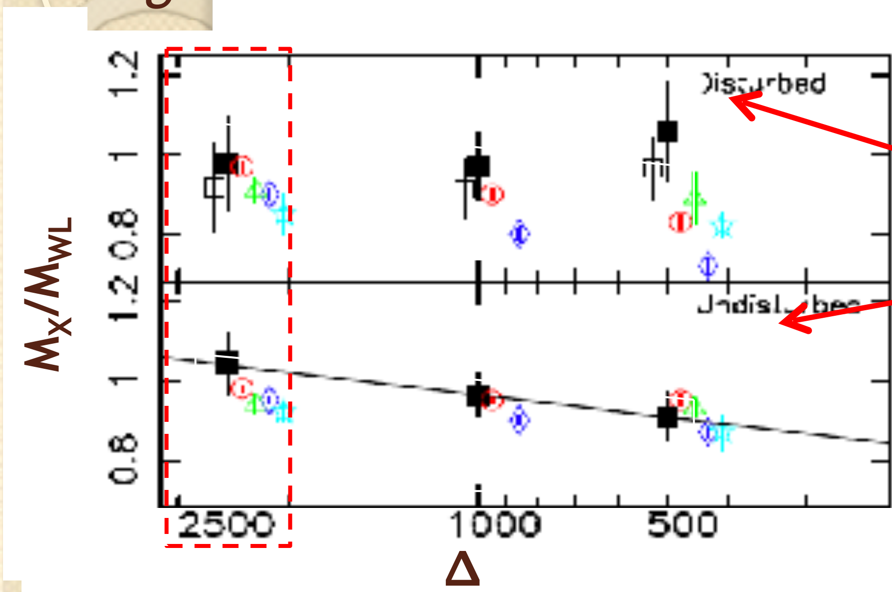
- 30 z~0.2 clusters with Suprime-cam
- Best accuracy at Δ ~ 1000
- NFW parameters show steeper cvir-Mvir slope than N-body simulations



Mass comparisons

LoCuSS

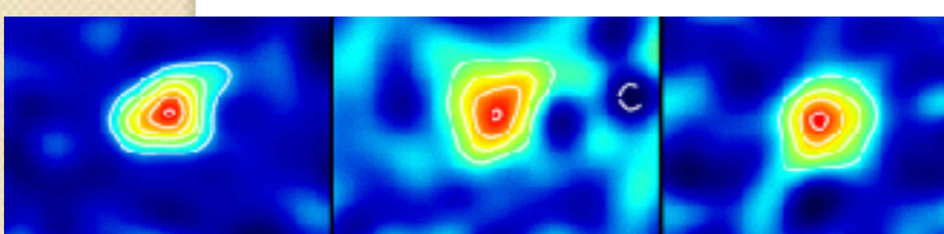
Zhang et al. 2010



- All **12**: $M_X/M_{WL}(\Delta=500) = 0.99\pm0.07$
- Disturbed: $M_X/M_{WL}(\Delta=500) = 1.06\pm0.12$
  Exc. A1914: $= 0.97\pm0.08$
- Undisturbed: $M_X/M_{WL}(\Delta=500) = 0.91\pm0.06$
- Previously: $M_X/M_{WL}(\Delta=500) = 0.9\pm0.1$
  - Madhavi et al. 2007; Zhang et al., 2008
  - Samples ~2-3x larger

SZA

Marrone et al. 2011



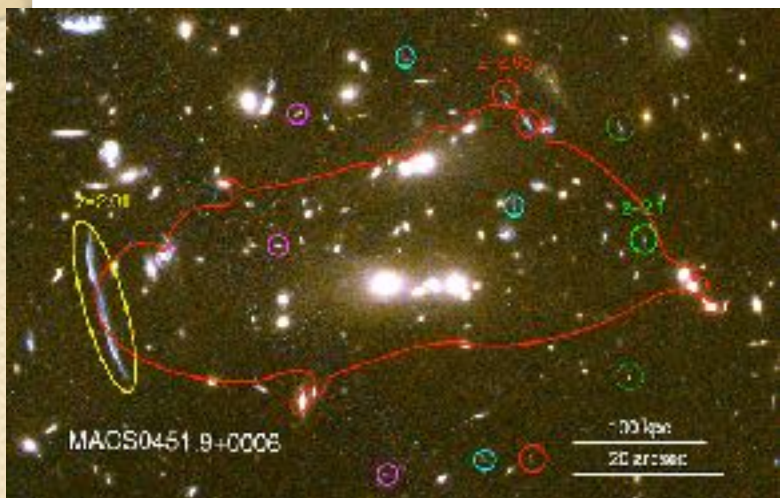
- Measurement of SZ effect in 18 clusters
- First calibration of the WL-SZ relation at Δ= 500, 1000, 2500

MAssive Cluster Survey

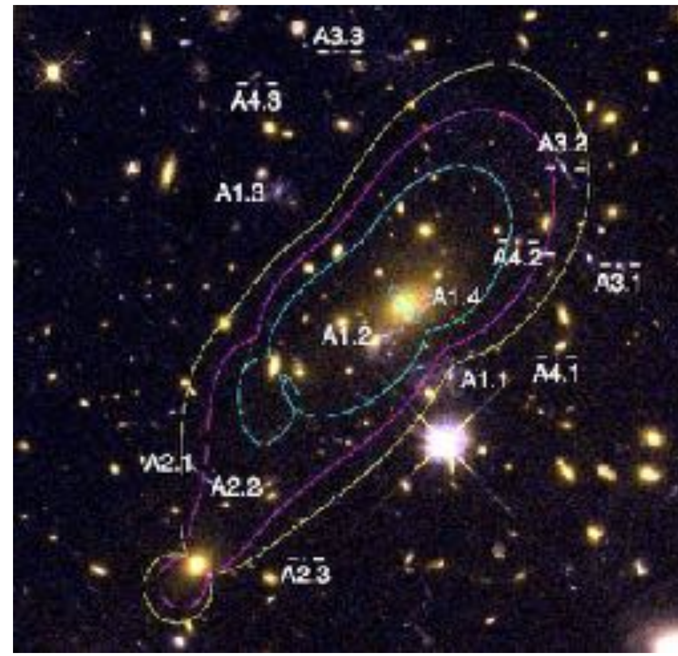
MAssive Cluster Survey: **Ebeling et al. 2010**,

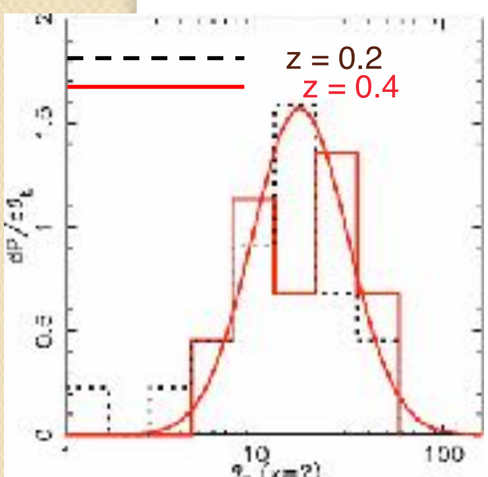
Selection: Lx > 7e44 erg/s @ [0.1-2.4] keV

150 clusters @ 0.3 < z < 0.5



12 clusters @ 0.5 < z < 0.7





- 45 clusters with strong-lensing models
- No significant change in distribution of Re
- Evolution towards less relaxed clusters at z=0.4

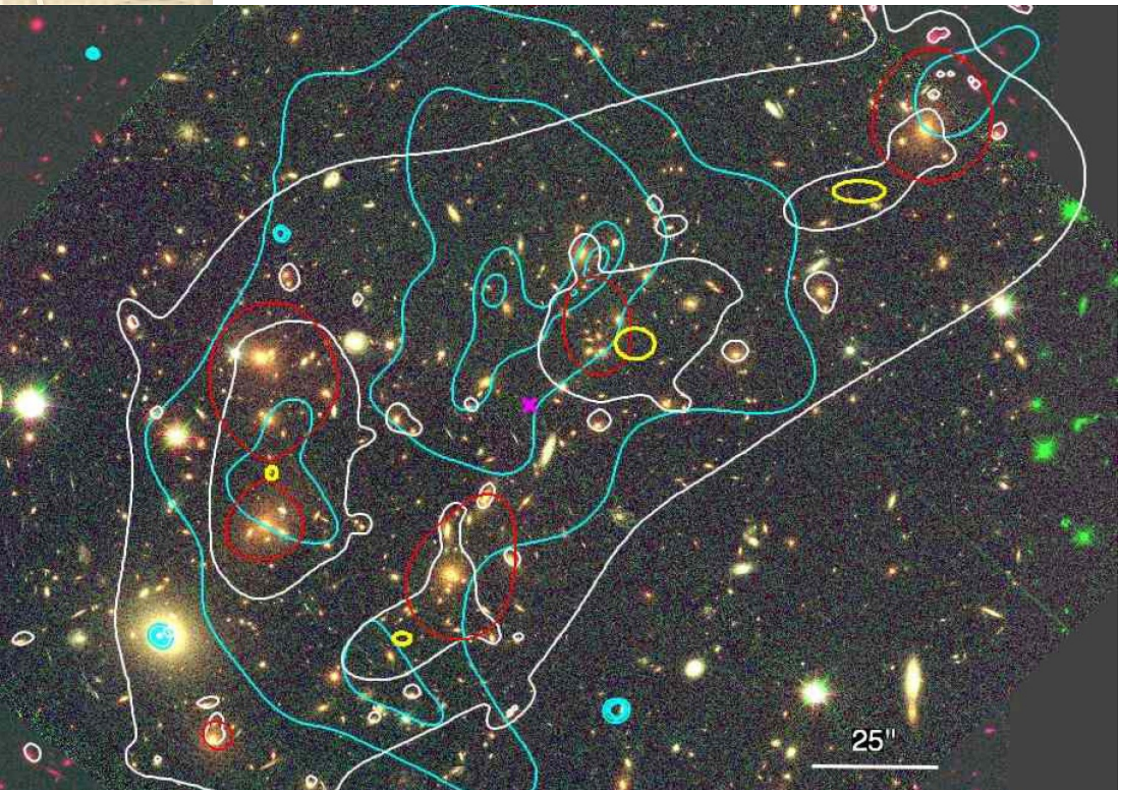
All very massive, show SL

Zitrin et al. 2009a,b: all 12

Limousin et al.2009: MACS1423

Smith et al.2010: MACS1149

MACS0717 (z=0.55)

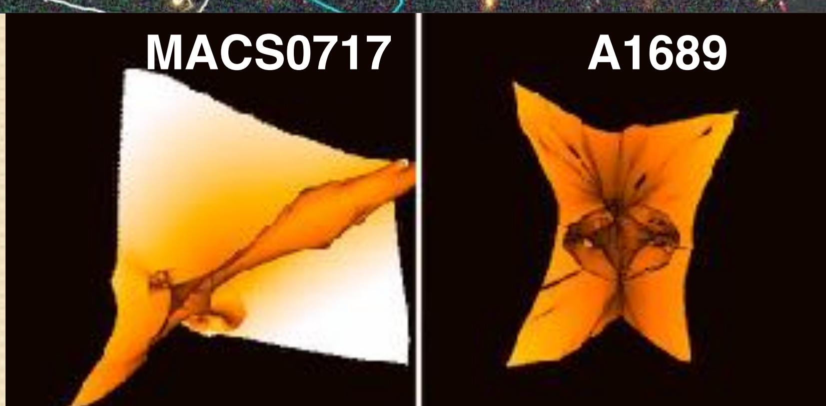


Limousin et al. 2012 (sub.)

- 15 systems, covering ACS fov LRIS spec-z
- SL features need 5 halo model
- Halo centres generally agree with light peaks (not Xray)

Jauzac et al. 2011

WL analysis with ACS of the associated filamentary structure



Projected mass within ACS: 2×10^{15} Msol

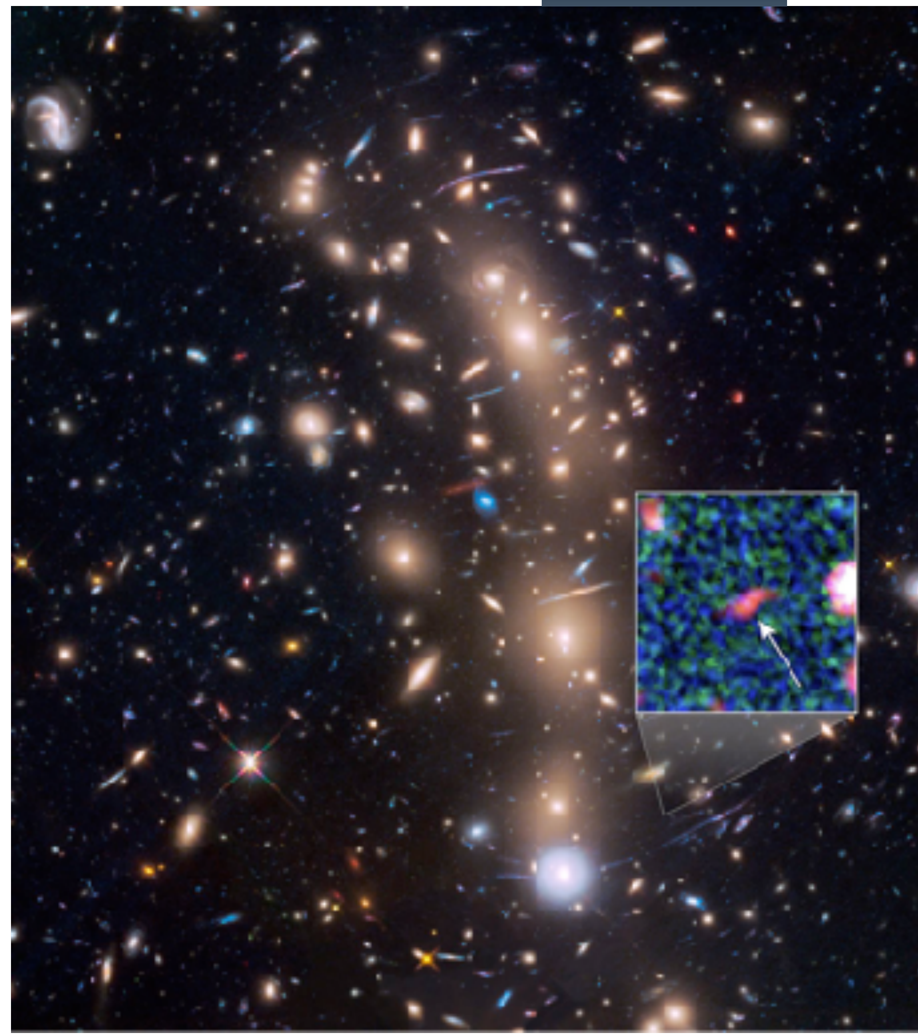
But MACS0717 still not as powerful GT as A1689

Frontier Fields

- Very deep Hubble observations of 6 massive lensing clusters (29 AB)
- Highly-constrained Gravitational Lensing mass models

1. The Distant Universe
2. Cluster Physics
3. Galaxy Evolution

…

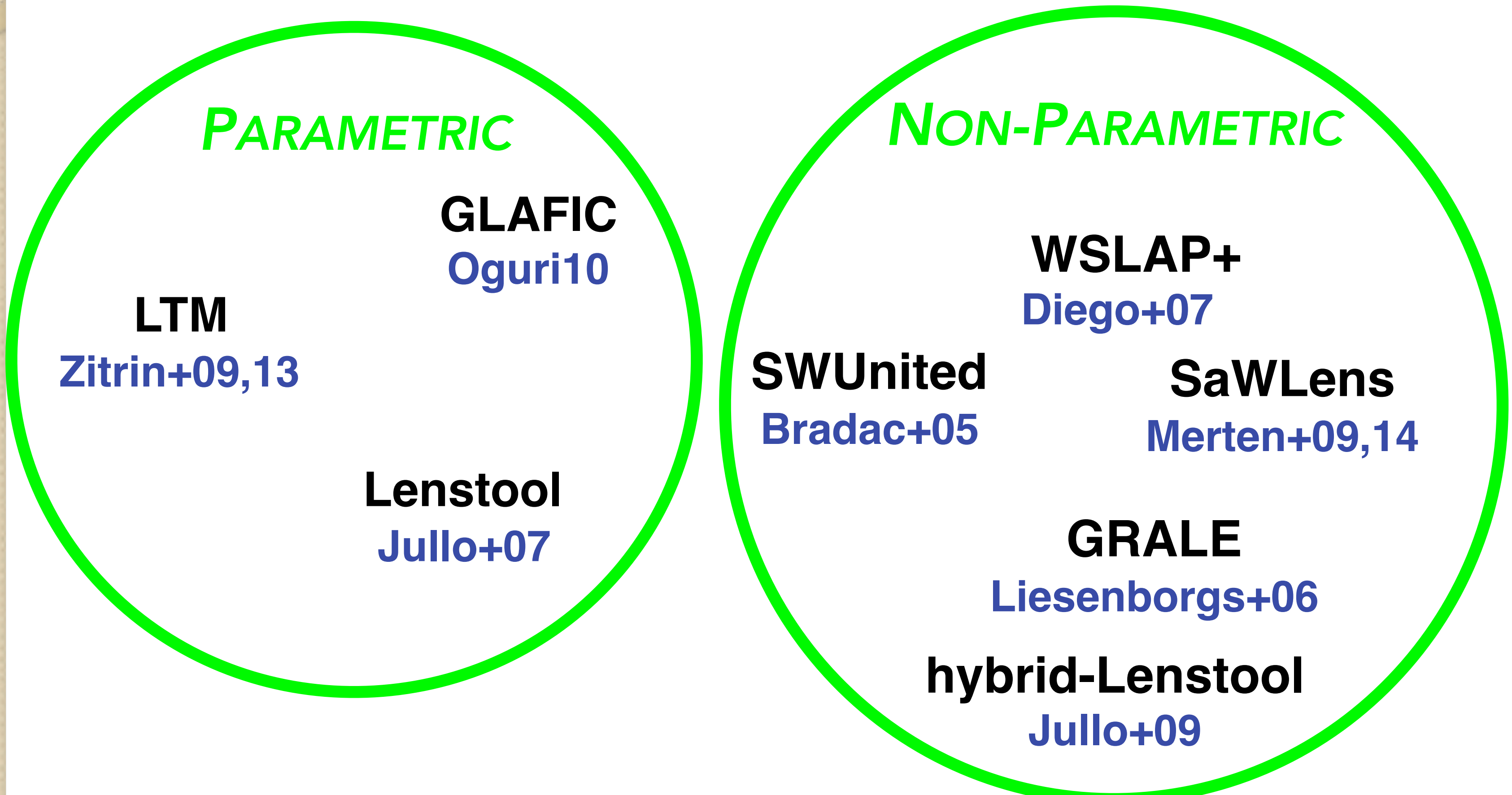


Infante, Zheng, Laporte et al. 2015 (z>9)

PRE-HFF & HFF MASS INITIATIVES

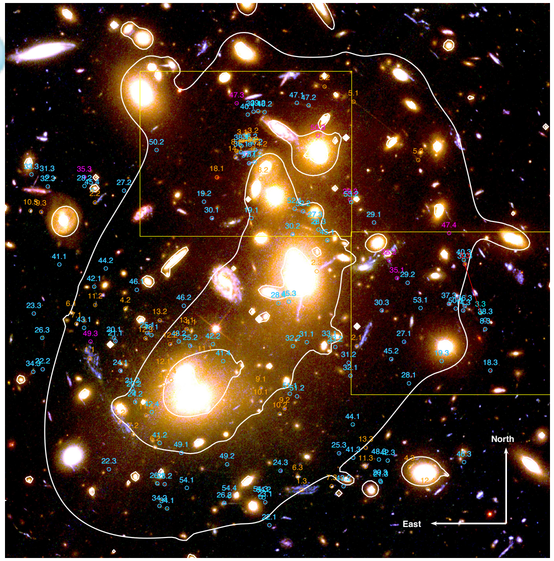
Public mass models

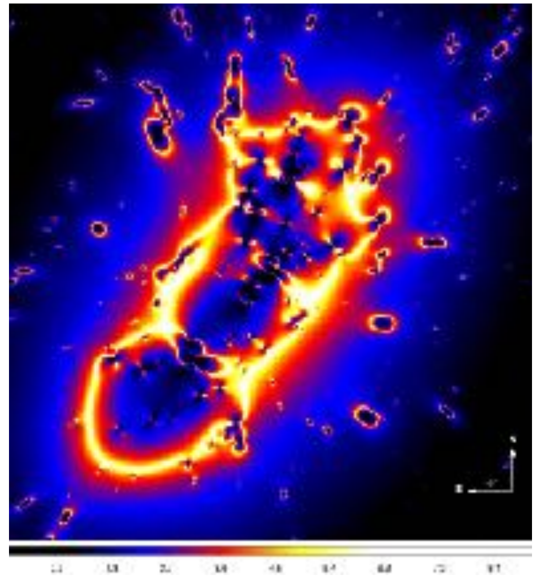
http://archive.stsci.edu/prepds/frontier/lensmodels/

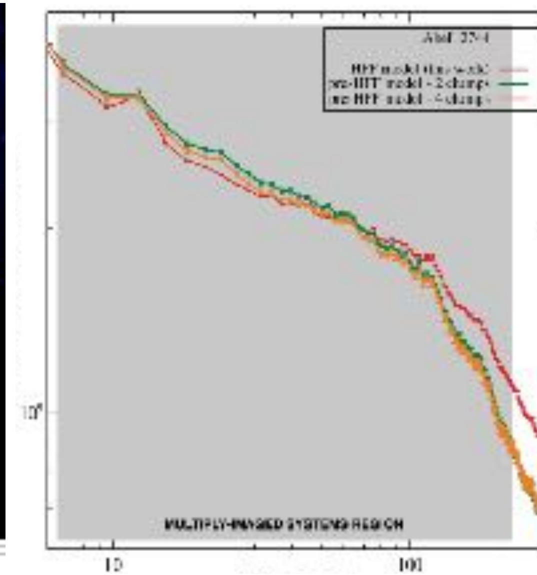


- Up to 8 lensing teams contributing with public mass models for the Frontier F clusters, continuously improving based on discussions and new data

Frontier Fields







More SL constraints for the whole core :

- correction of pre-HFF model
- more reliable estimation of the magnification

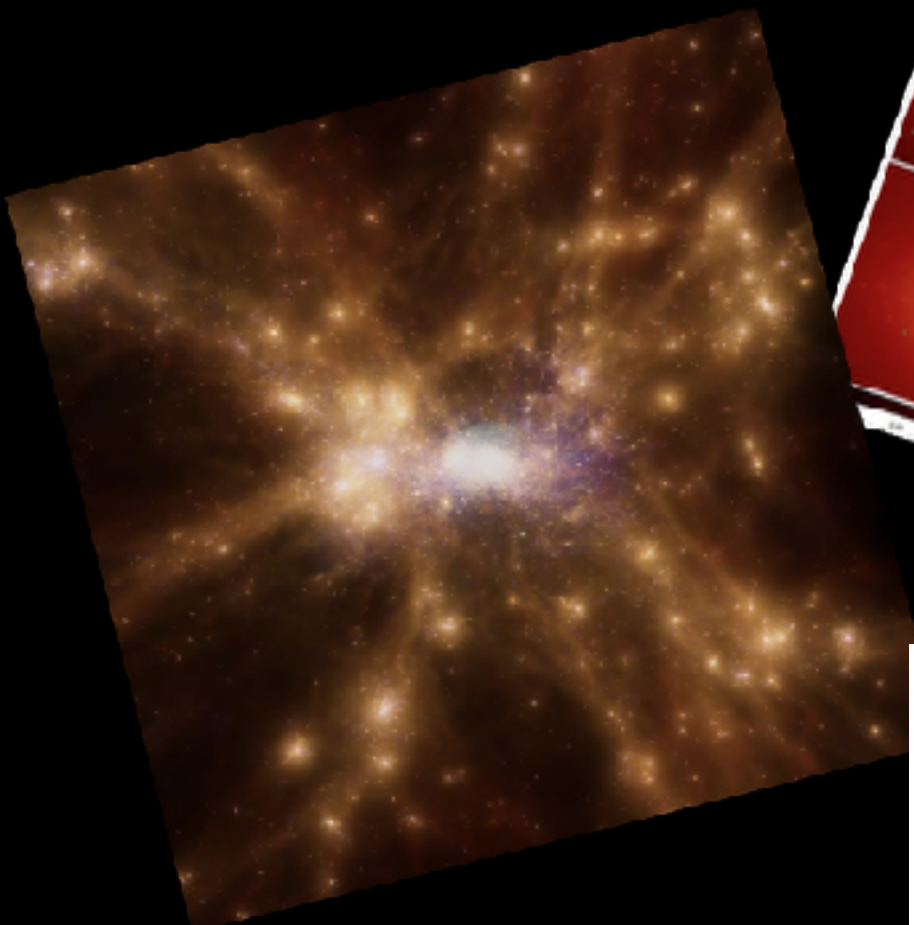
Mass estimation to ***the <1% level*** :
$M(R<250kpc) = 2.765 \pm 0.008$ (stat) $10^{14} M_s$

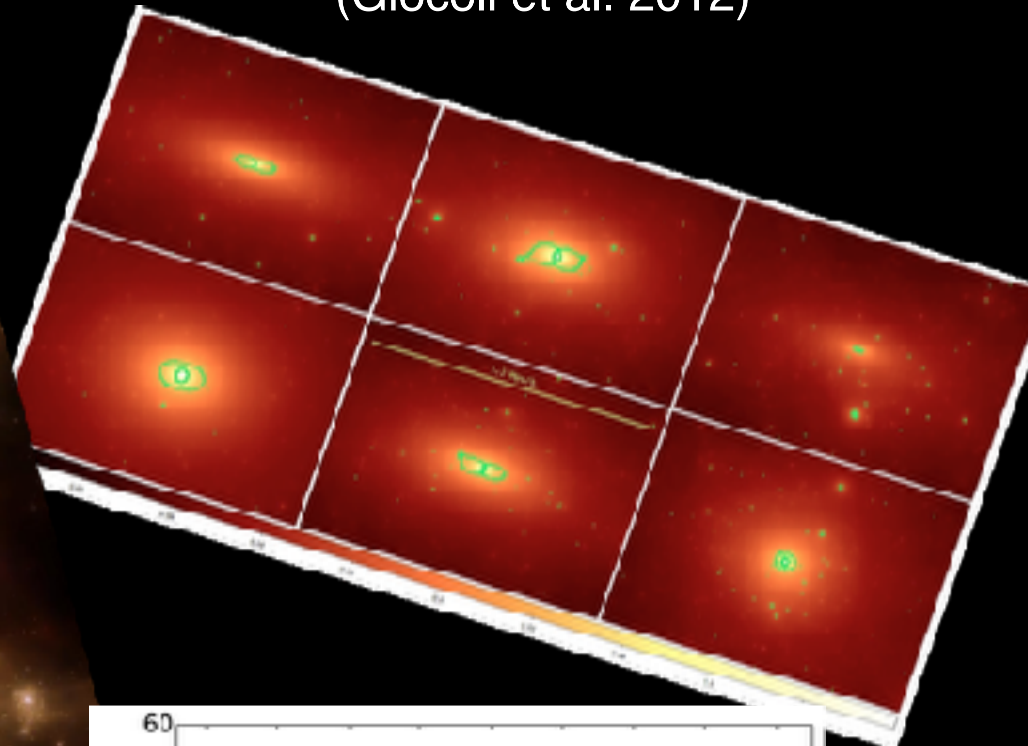
Magnification to ***the 2% level*** :
$\mu = 5.61 \pm 0.10$ (stat) ± 0.57 (sys)

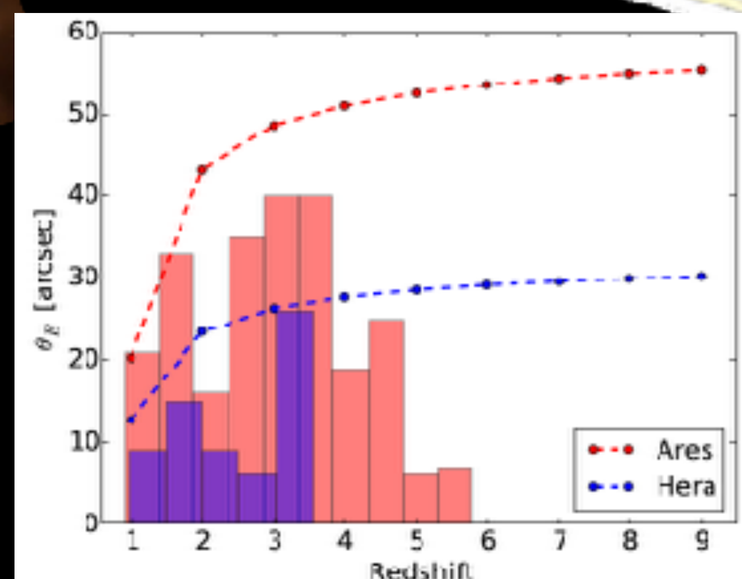
pre-HFF (Richard et al. 2014) :
$\mu = 4.69 \pm 0.32$ (stat)

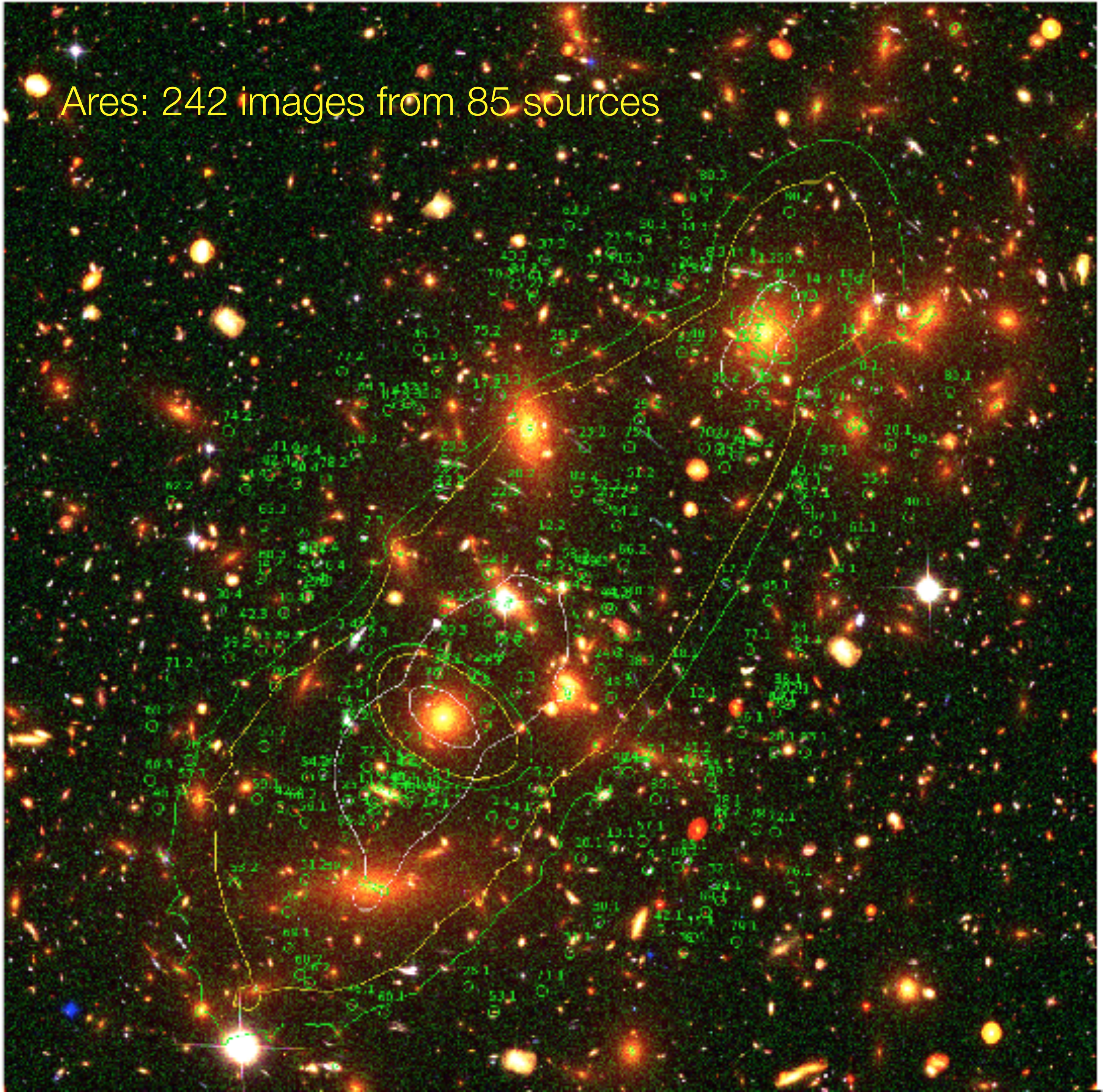
Hera: N-Body+Semi-analytical model (Meneghetti et al. 2016)

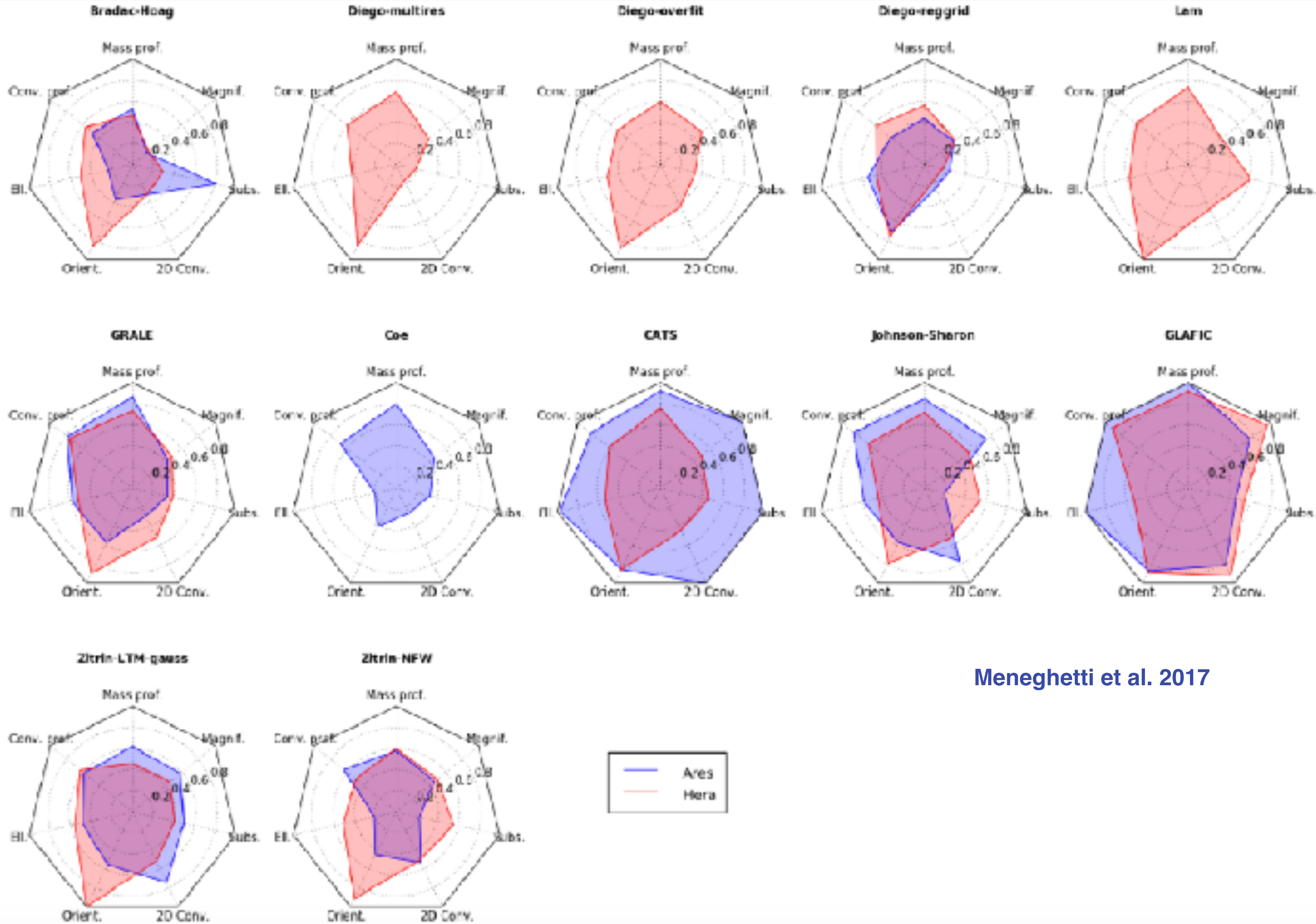
Ares: analytical MOKA library (Giocoli et al. 2012)





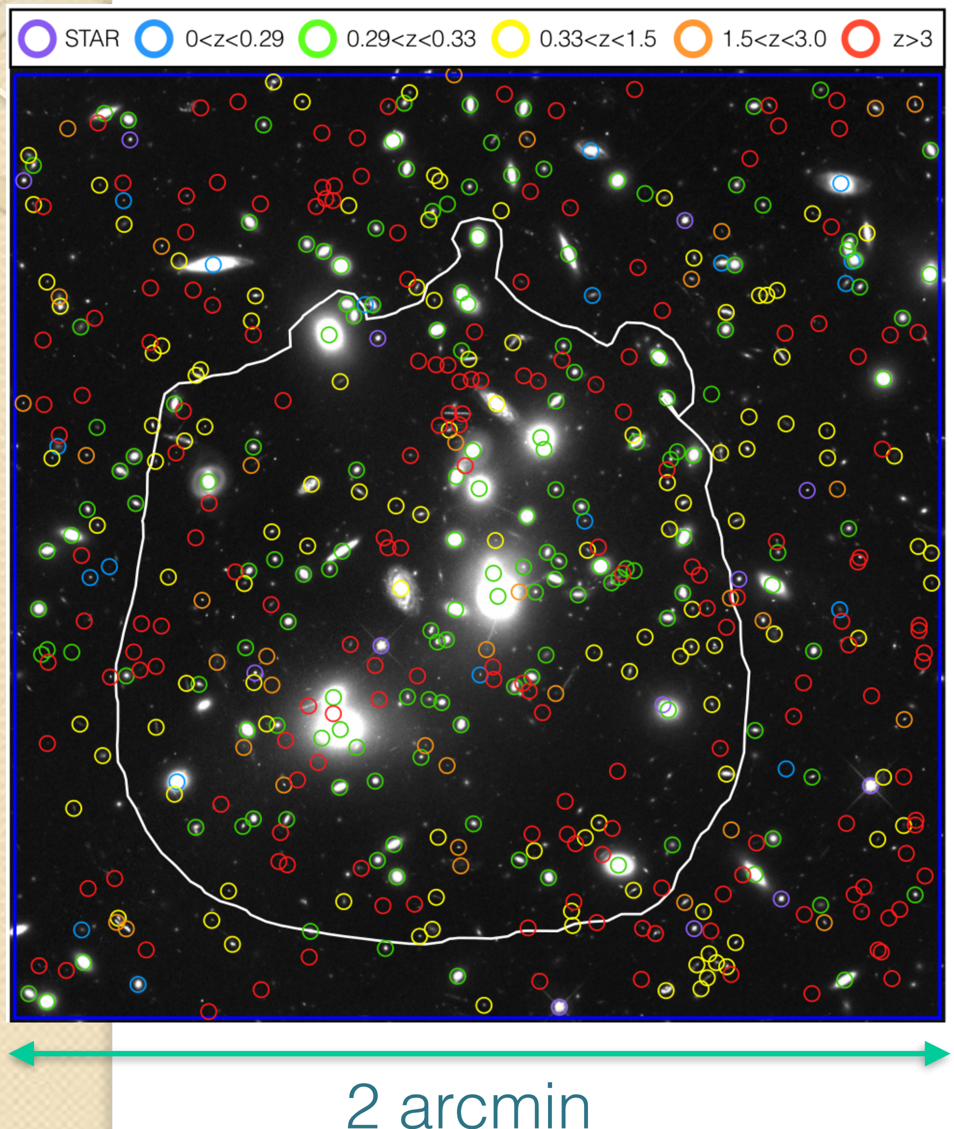



Ares: 242 images from 85 sources



Meneghetti et al. 2017

Frontier Fields + MUSE



Abell 2744: 2x2 mosaic
Mahler et al. MNRAS 2018

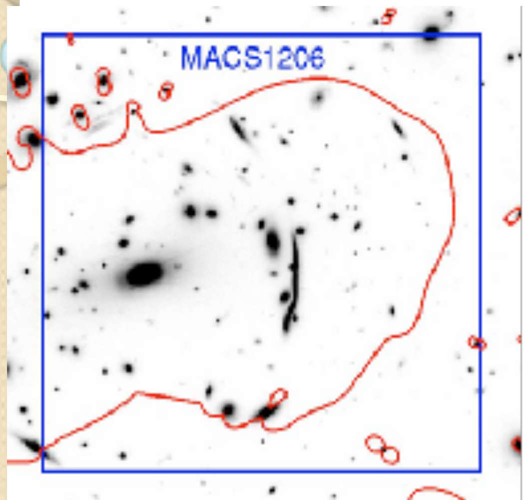
MACS0416: 2 pointings
Caminha et al. 2017 A&A 600, 90

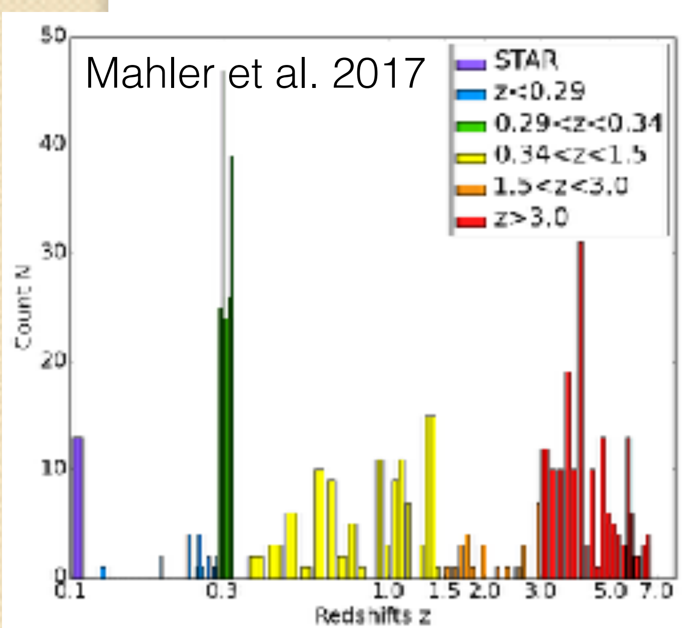
AS1063: 2 pointings
Caminha et al. 2016 A&A 587, 80
Karman et al. 2017 A&A 589, 28

Abell 370: 1 pointing
Lagattuta et al. 2017 MNRAS 469, 3946
+ 2x2 mosaic

MACS1149 : 1 pointing
Jauzac et al. 2016 MNRAS, 457, 2029
Grillo et al. 2016, ApJ 822, 278

Frontier Fields + MUSE

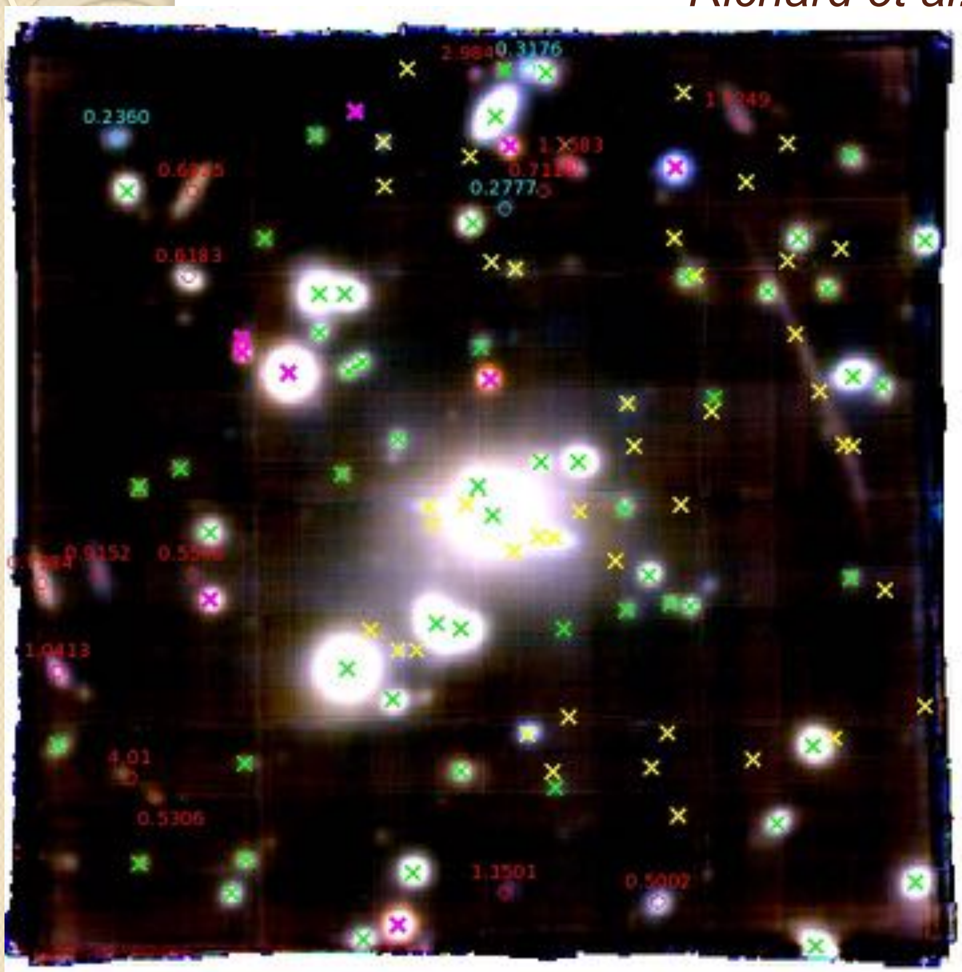




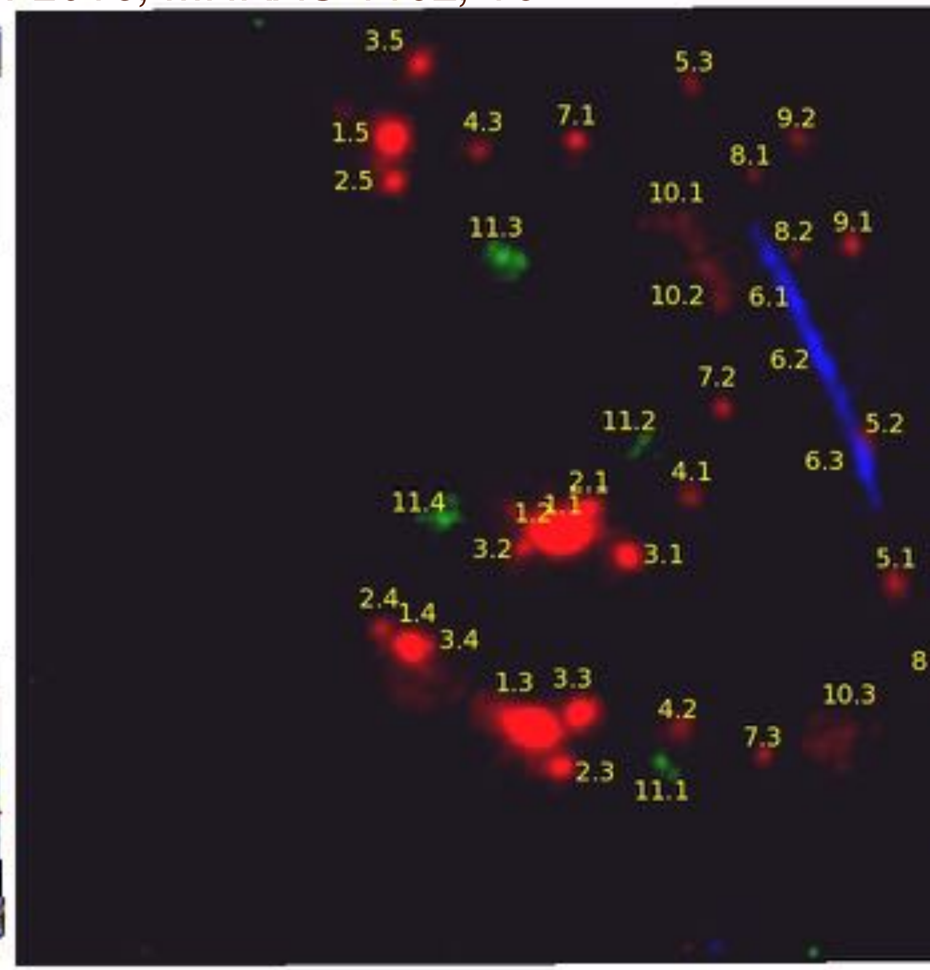
- Confirm the identification of multiple images
- Pinpoint the source redshift to improve mass modelling (also necessary for cosmography !)
- Large number of LAEs
- Large number of confirmed cluster members: dynamics of the cluster core
- Intermediate redshift background galaxies (0.5<z<1.5): resolved properties.

Mass modelling improvement

Richard et al. 2015, MNRAS 446L, 16



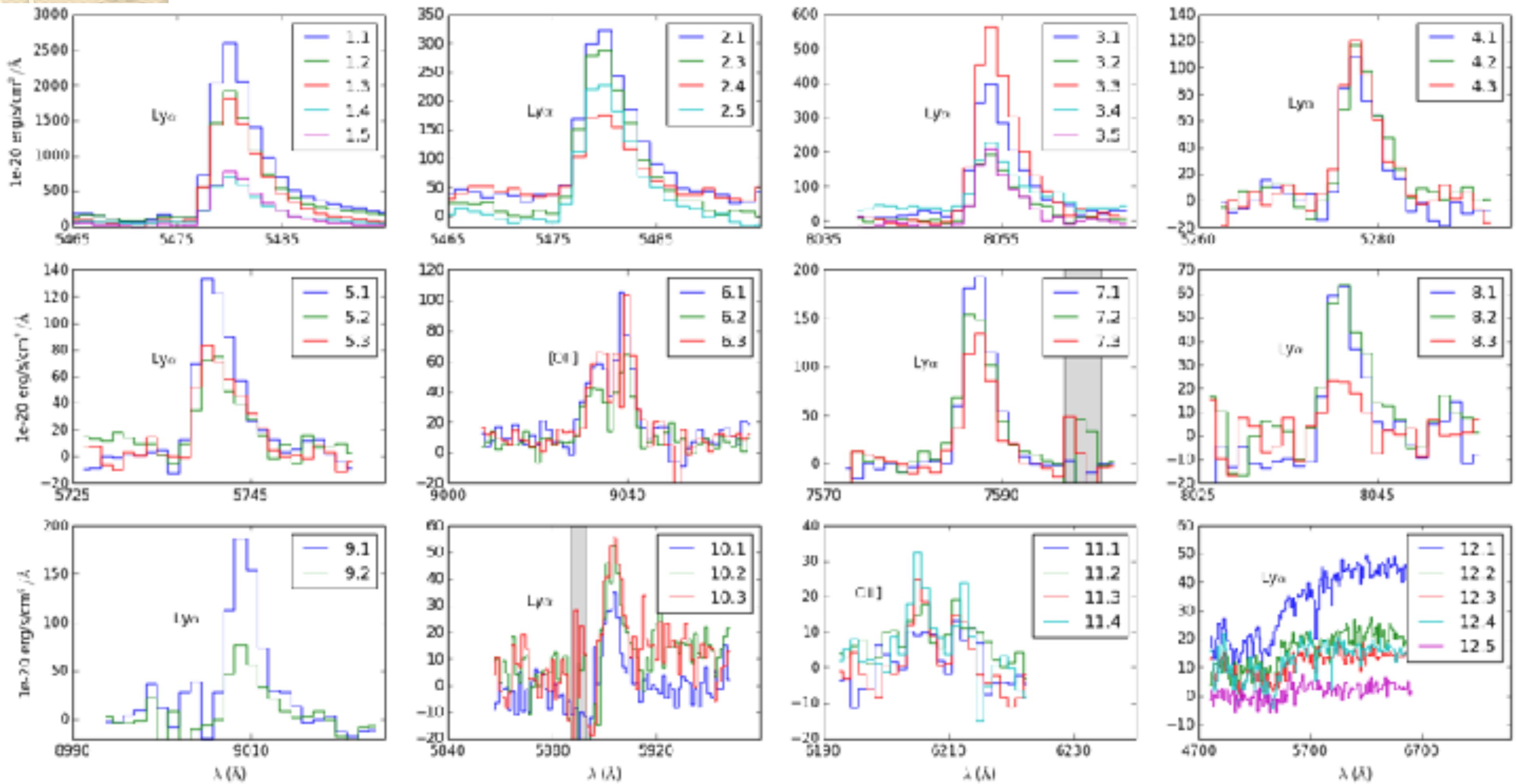
Continuum color image



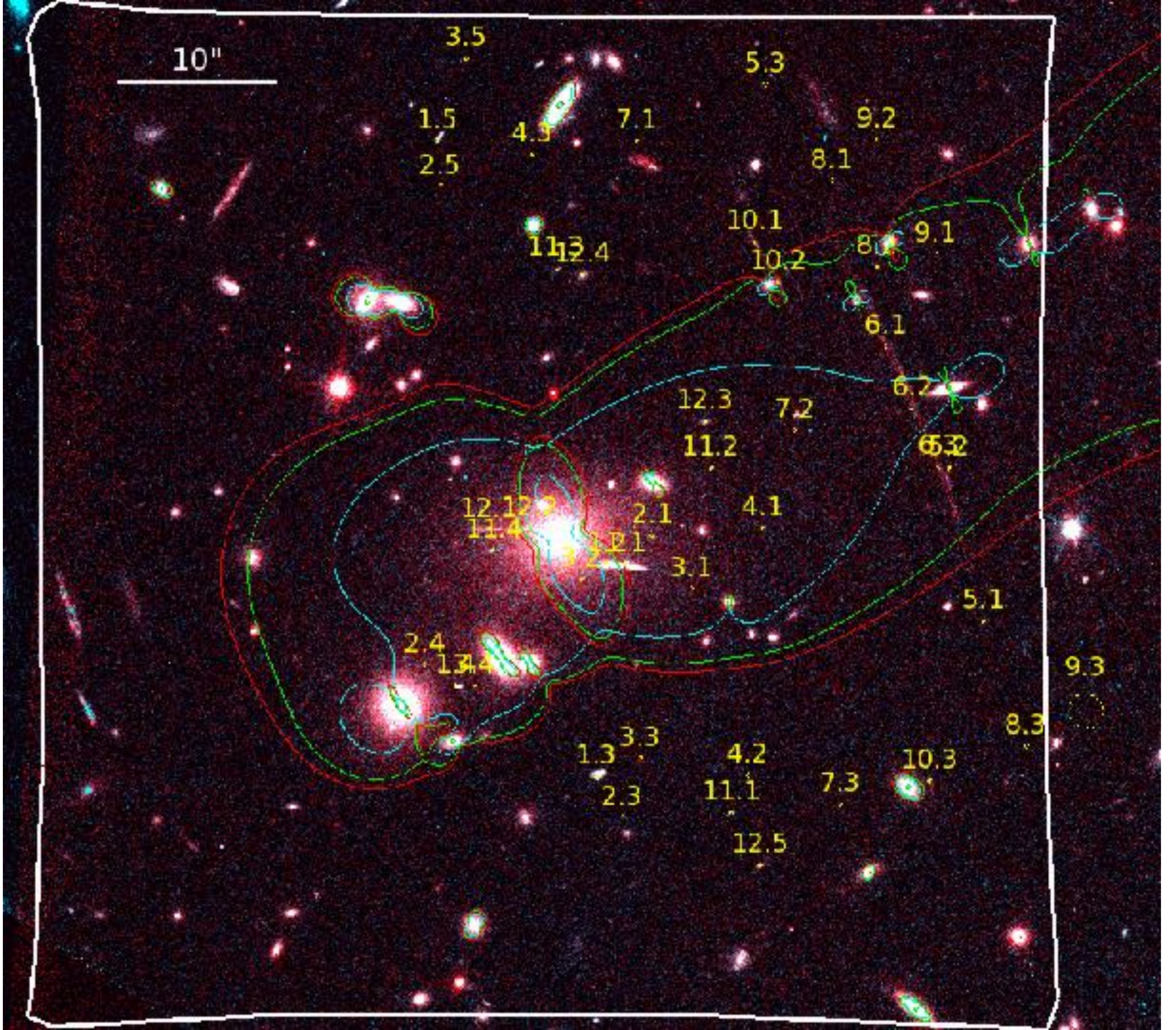
Composite narrow-band image

Lyα CIII] [OII]

Mass modelling improvement



Confirmation and spectroscopic redshifts for 11 new systems


10"
3.5
5.3
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4.3
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9.2
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8.1
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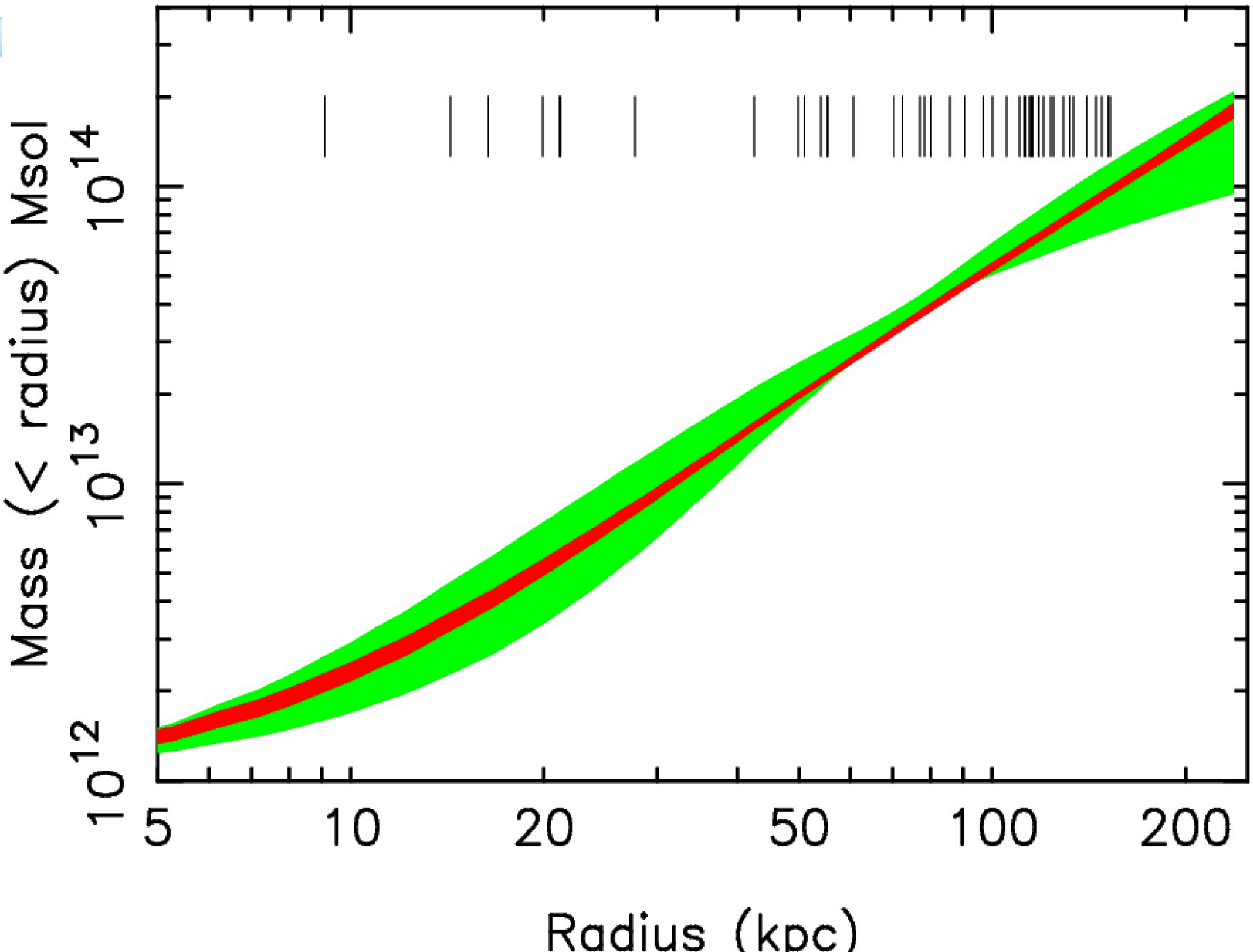
12.5

Mass modelling improvement



Frontier Fields + MUSE

◦ What do we learn with spectroscopic redshifts for ~ 100 images ?

- Reach the rms limit (typically 0.5") in reproducing the multiple images
  (Johnson et al. 2016)

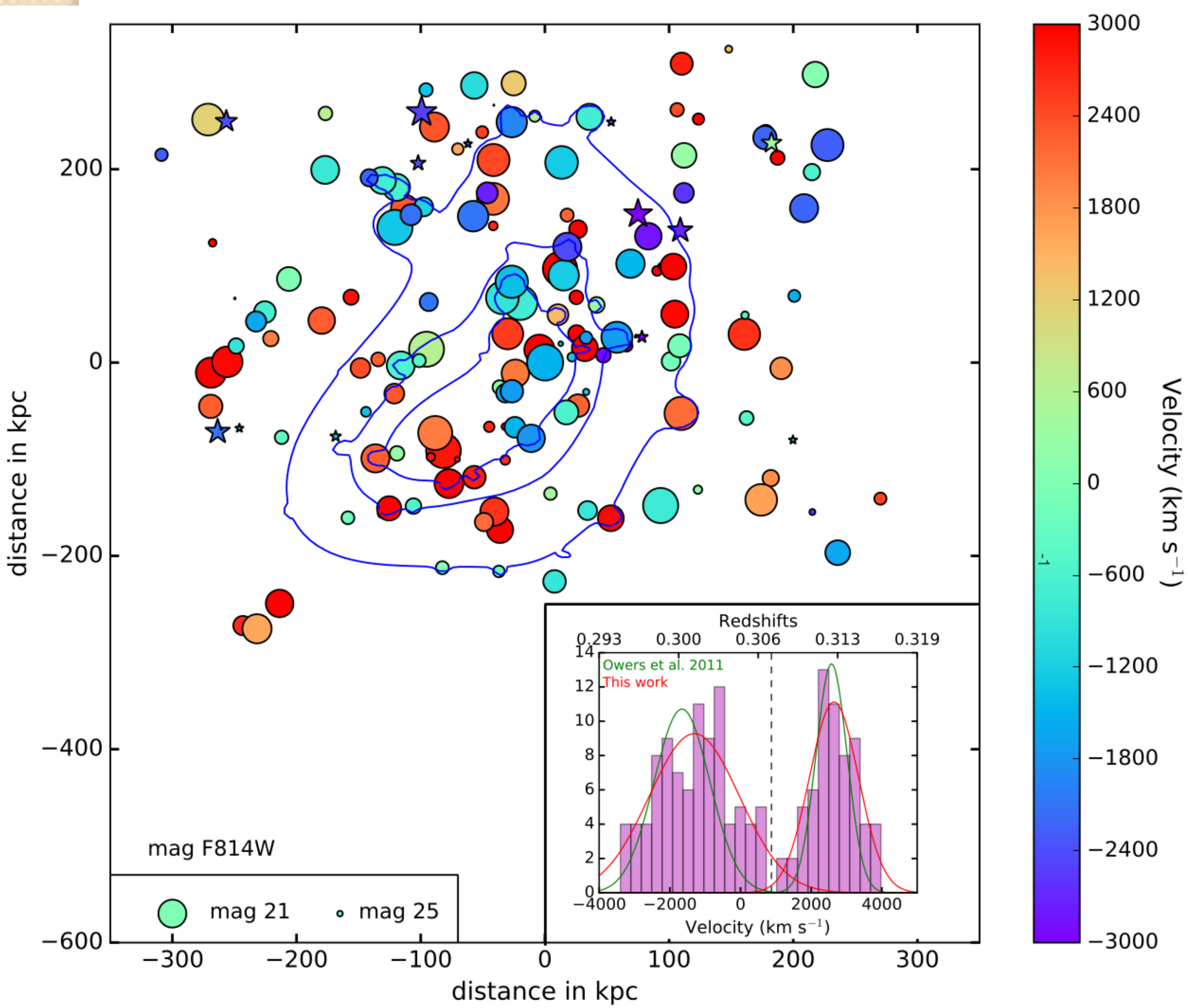
- Systematics on the mass and magnification
- Bias when knowing or not knowing the spec-z

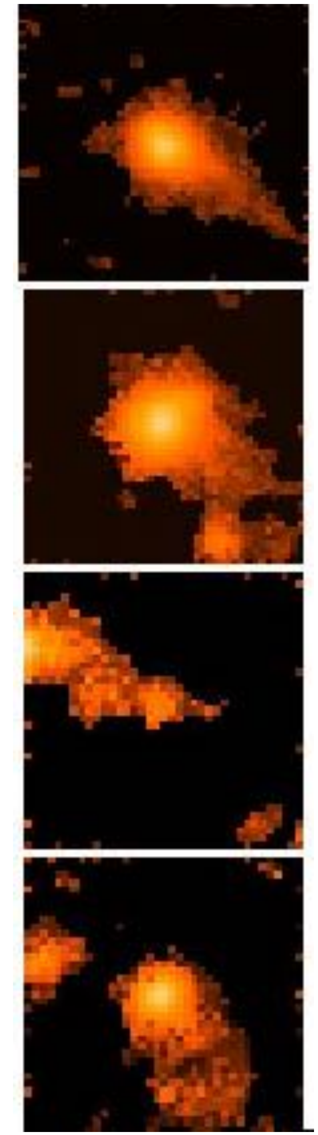
] **Mahler et al. 2018**

- Cosmography from strong lensing
Caminha et al. 2016

- Effect of line-of-sight substructure with multi-plane lens models
  (Chirivì et al. , 1706.07815)

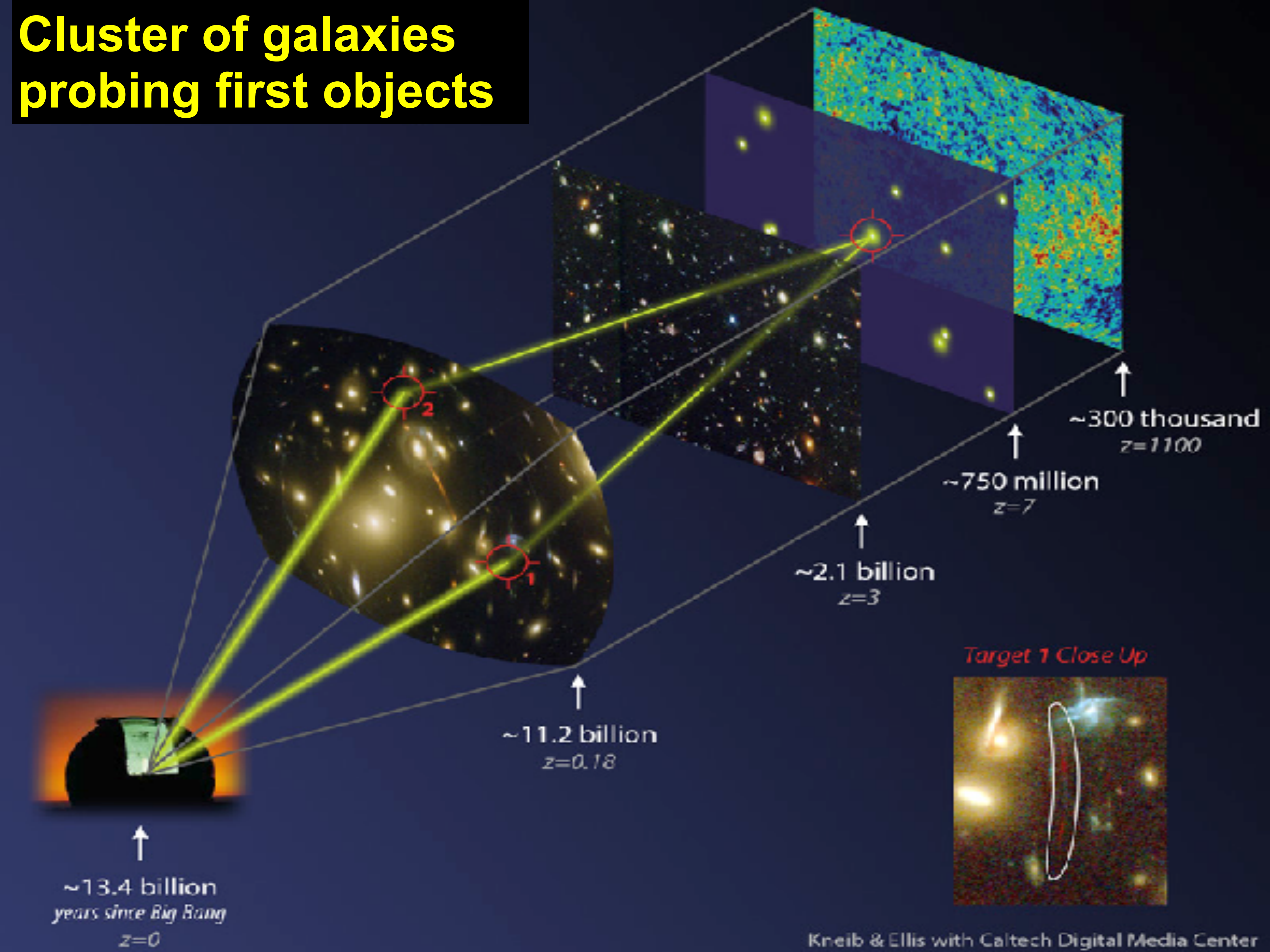
Cluster spectroscopy





Hamer et al. 2018, in prep.

Cluster of galaxies probing first objects



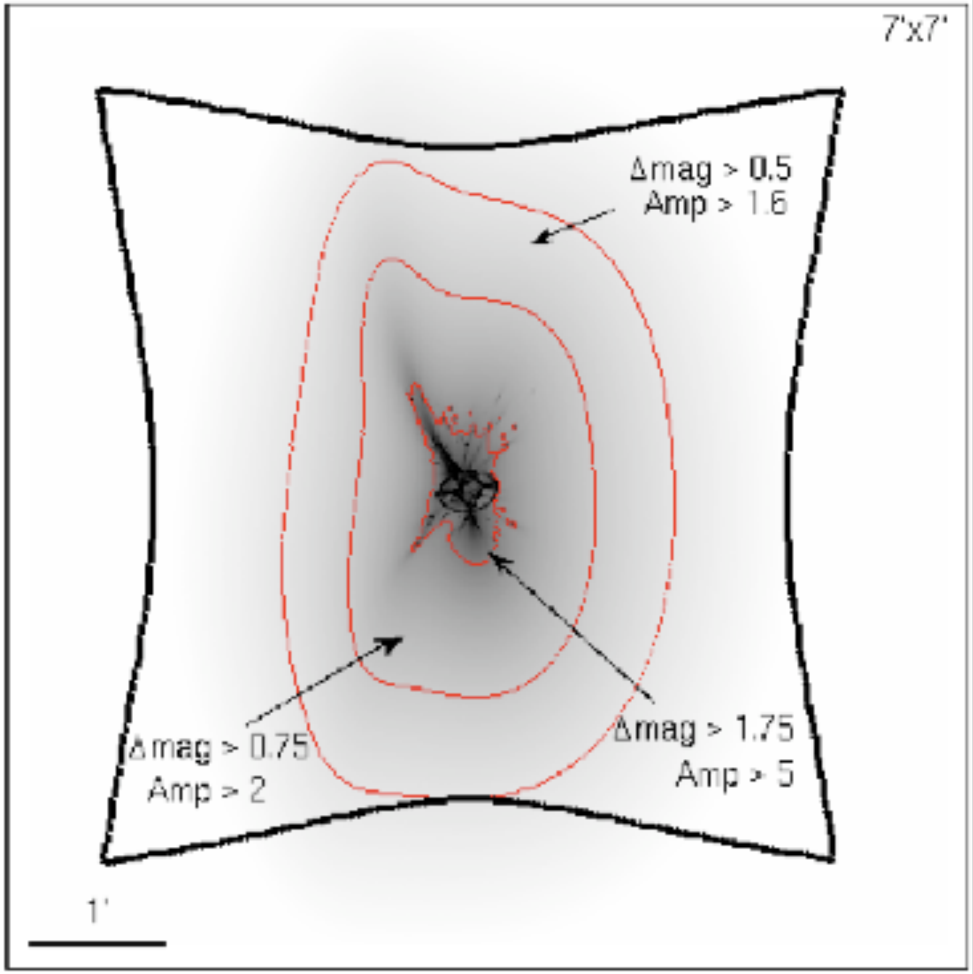
Gravitational telescopes:

• Advantages:

- boosts the total flux by increasing the observed size of background sources (constant surface brightness)
- efficient for unresolved sources
- multiple images configuration gives a hint on z

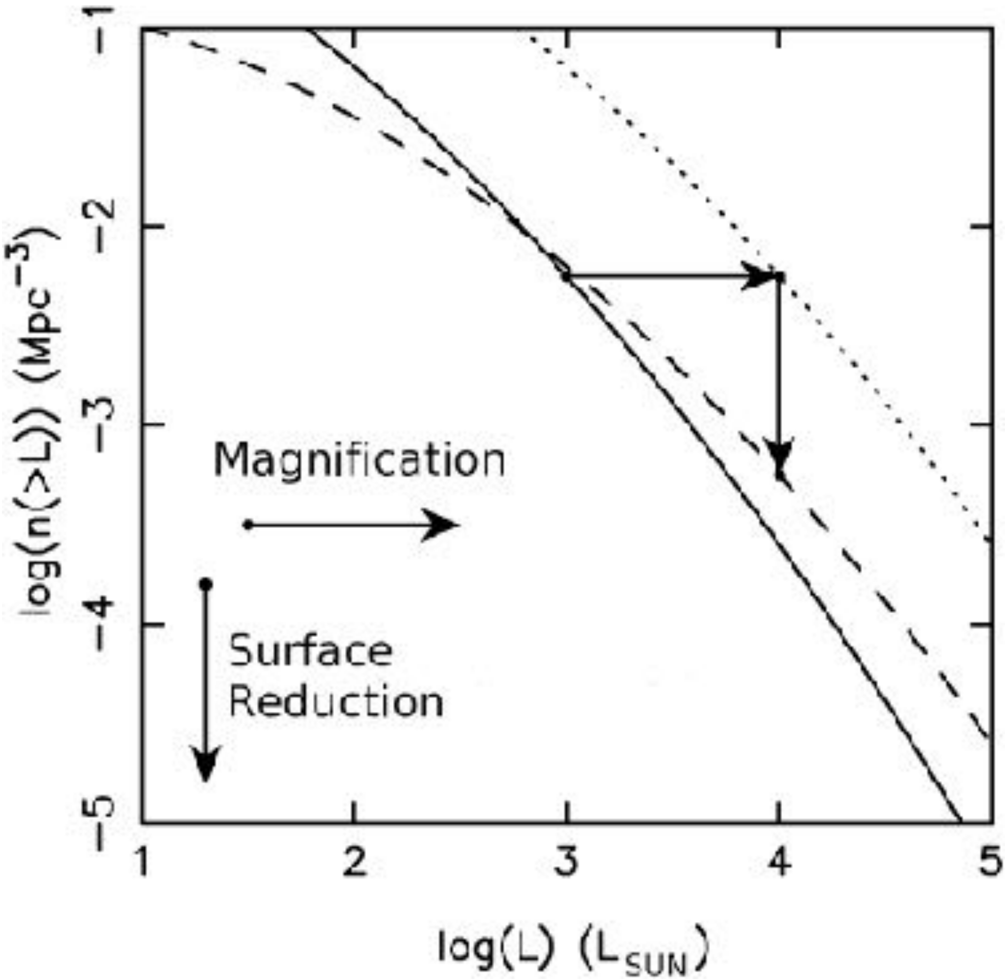
• Drawbacks:

- Effective area smaller in the source plane
- Need to estimate the magnification to correct it



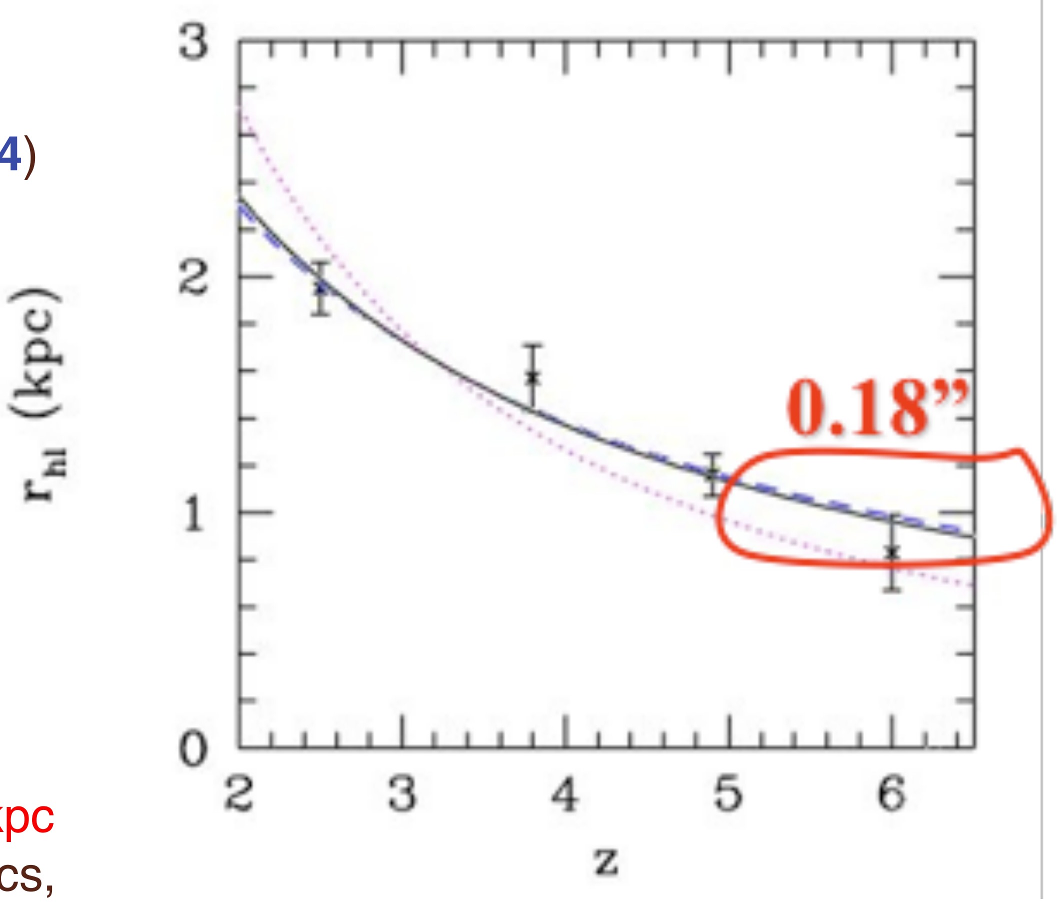
Magnification bias

- The observed LF is offseted, with more or less objects than a blank field depending on the luminosity range (**Broadhurst 95**)
- Current LF fits at z > 6 suggest a positive magnification bias for unresolved sources down to ~ 27_{AB} (**Maizy et al. 10**)
- Lensing cluster fields are complementary to blank fields to probe the LF

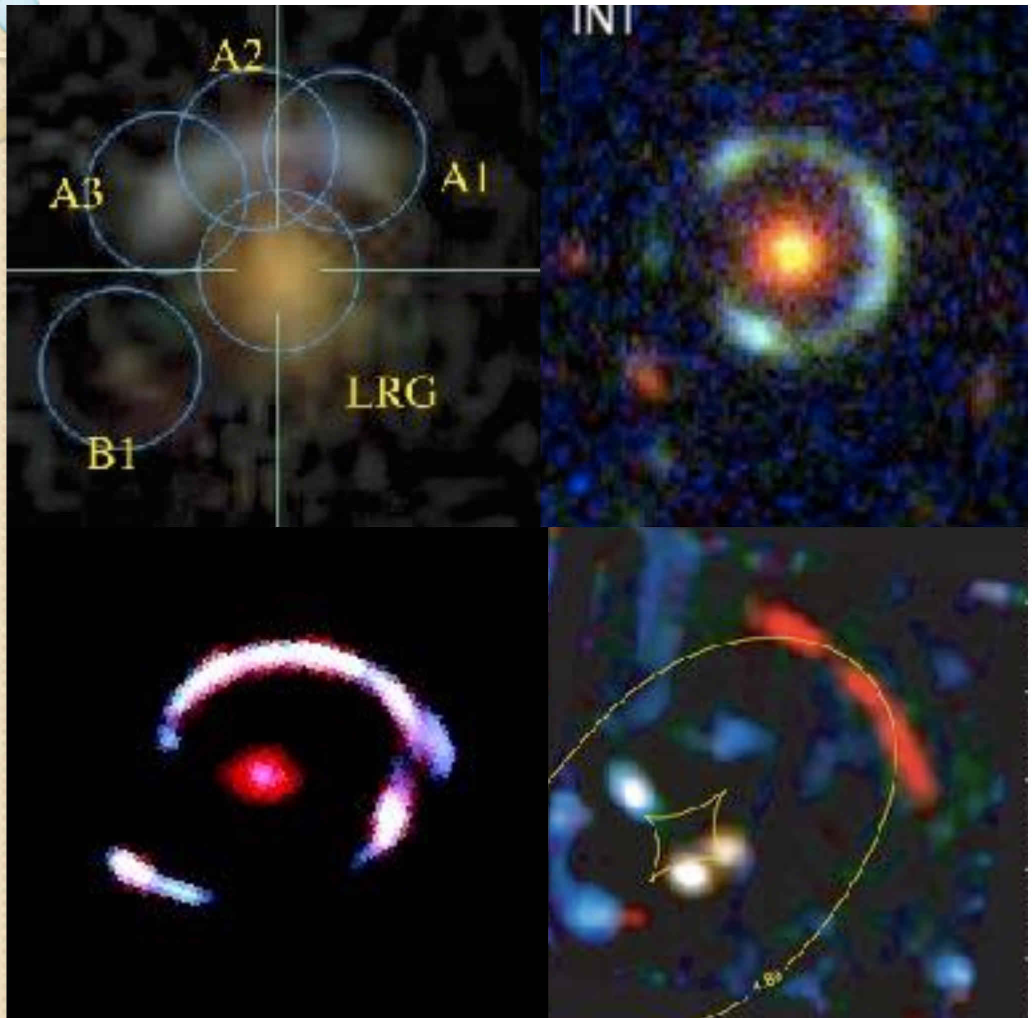


Resolved studies at z > 3

- Average size of 0.3 – 1 L* dropouts (**Bouwens et al. 04**)
- At z > ~ 5 only 1-2 resolution elements, even with HST
- Lensing as a gravitational microscope: stretches the apparent size of distant sources
- Unique way to reach sub-kpc scales: morphology, dynamics, gradients



Strongly lensed sources at high z



- Cb58 (**Seitz et al 98**): brightest LBG known until 2007

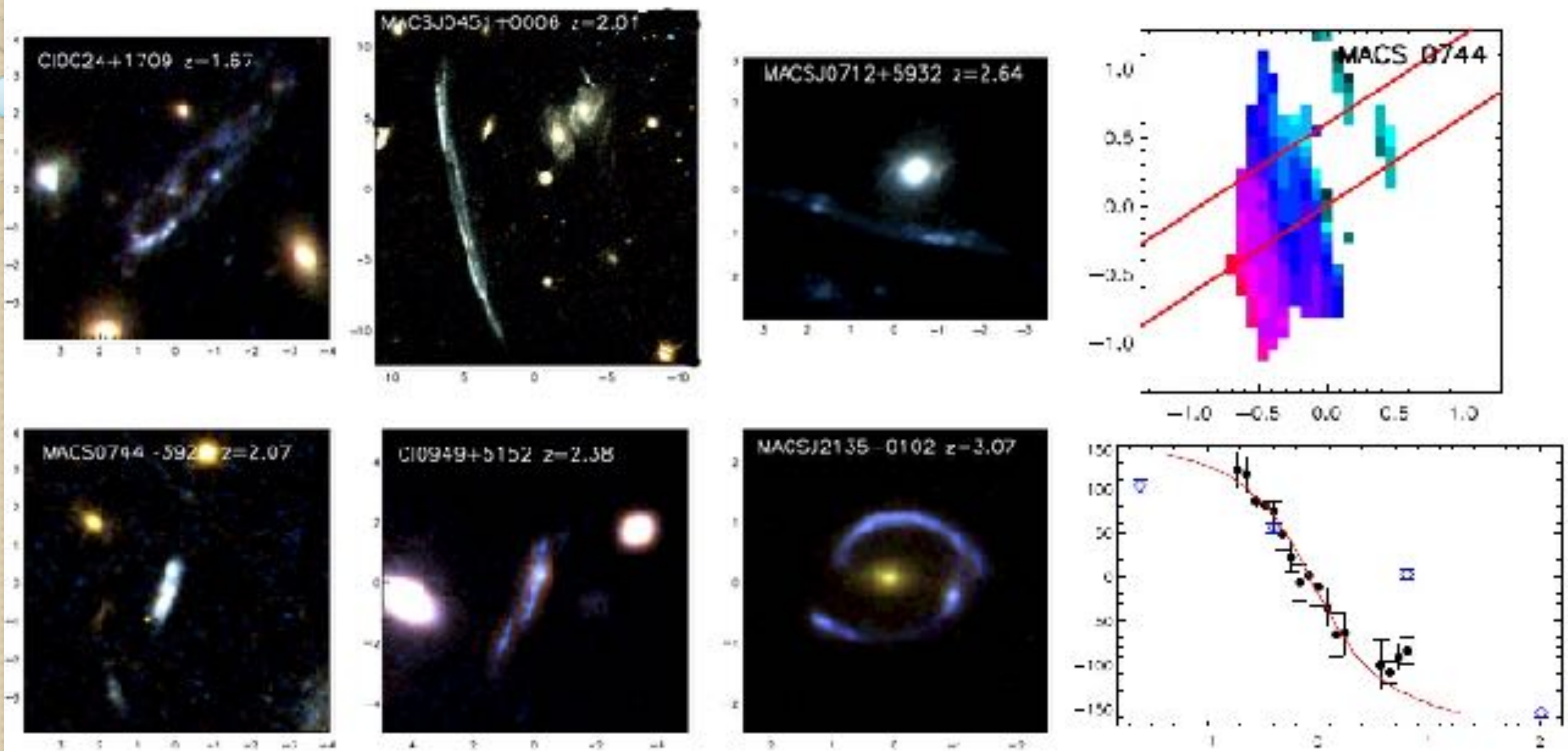
- The 8 o'clock arc (**Allam et al 07**)
- The Cosmic Eye (**Smail et al 07**)
- The Horseshoe (**Belokurov 07**)
- RCS0224 z ~ 5 (**Swinbank et al 07**)

Etc….

-Typically 20-21 AB

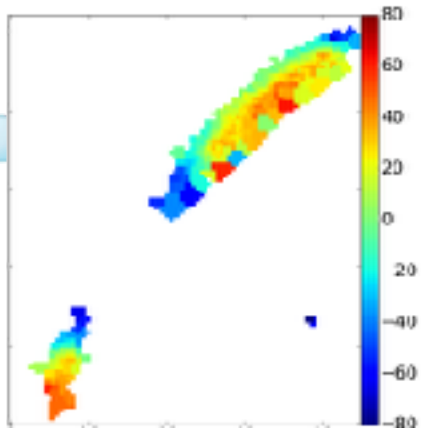
- Extended by 5-10"

Resolved studies with IFU

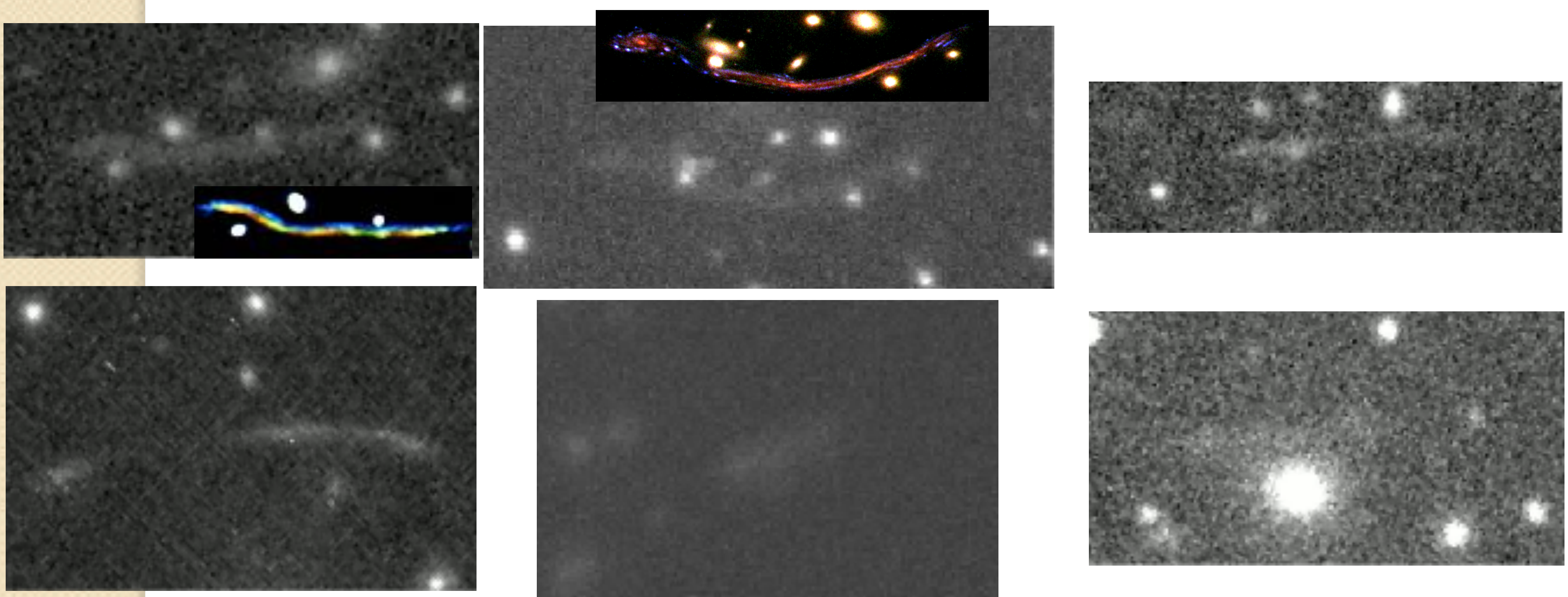


- NIR emission lines “screening” to select brightest sources (**Richard et al. 11**)
- Keck/OSIRIS follow-up: dynamics and SFR in H-II regions at z ~2-3 (**Jones et al. 2011**)
- At z=2-4 possibility to search for metallicity gradients with [OII]+Hβ+[OIII] or [NII] + Hα

Resolved studies with IFU

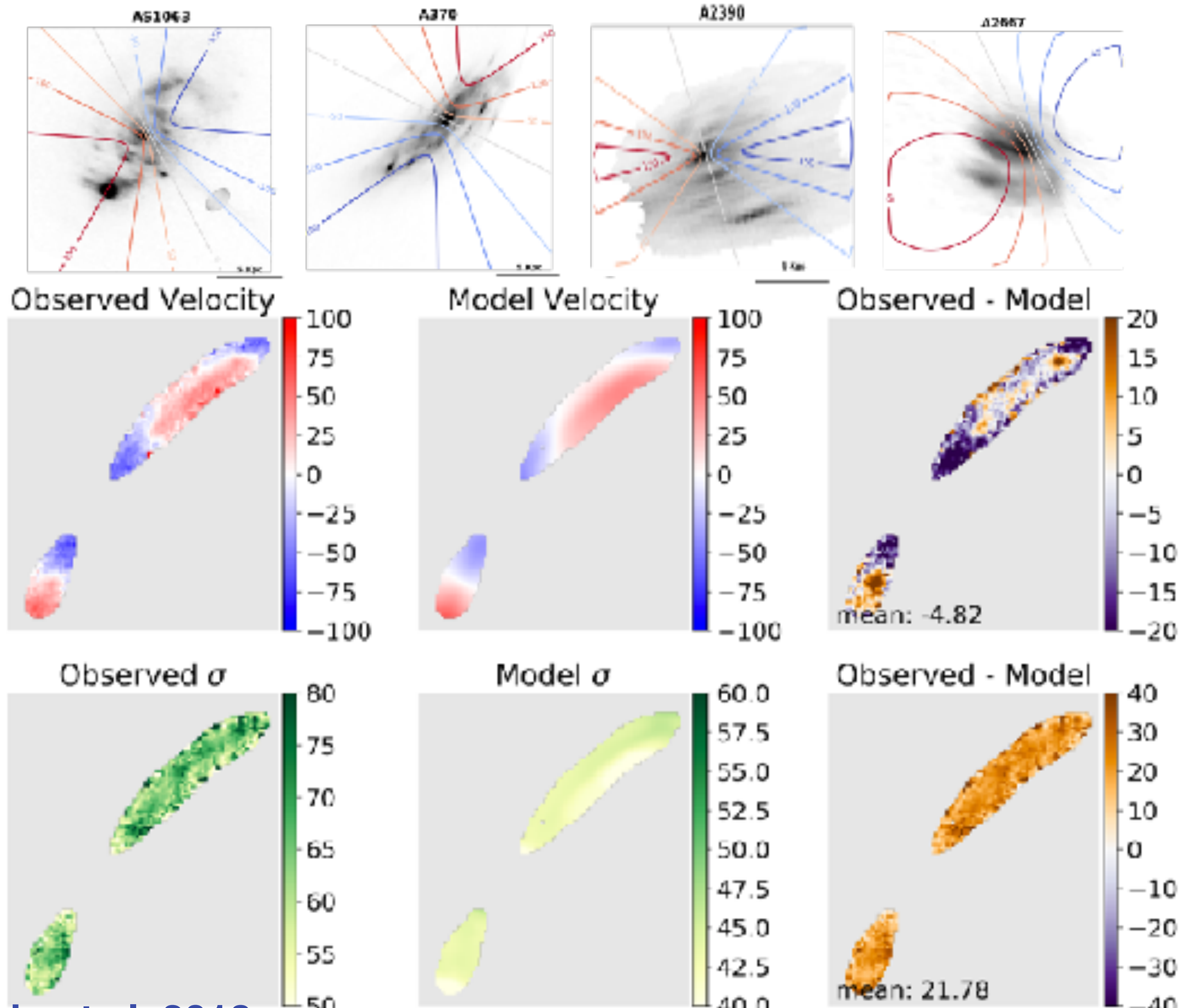


- SFR map from [OII] (+Hβ), gas kinematics
- Resolved stellar populations (MUSE + HST)
- Stellar kinematics from absorption lines
- Resolved abundances
- AGN signatures
- Size / σ of bright star-forming regions



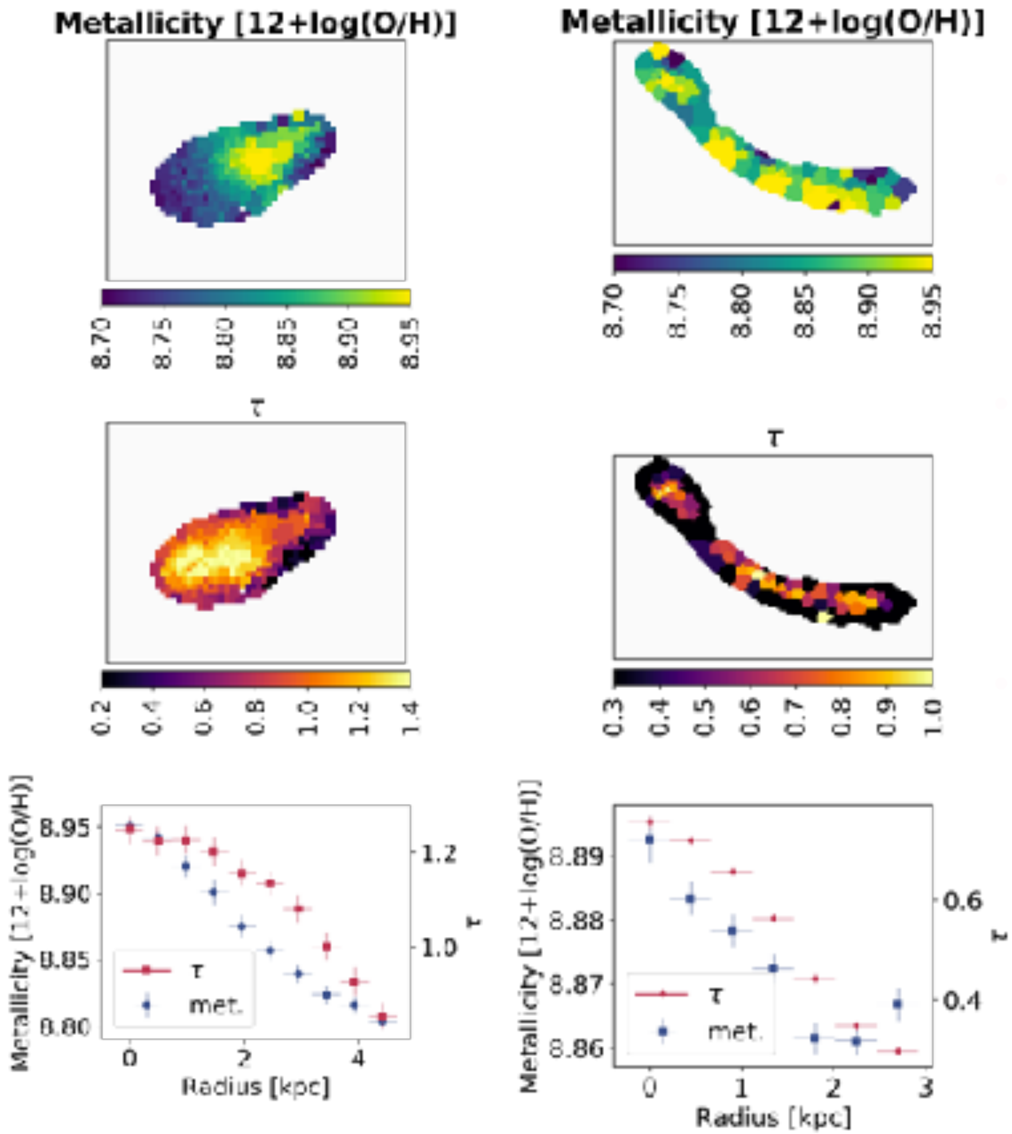
Patrício et al. 2018

Resolved studies with IFU



Patrício et al. 2018

Resolved studies with IFU



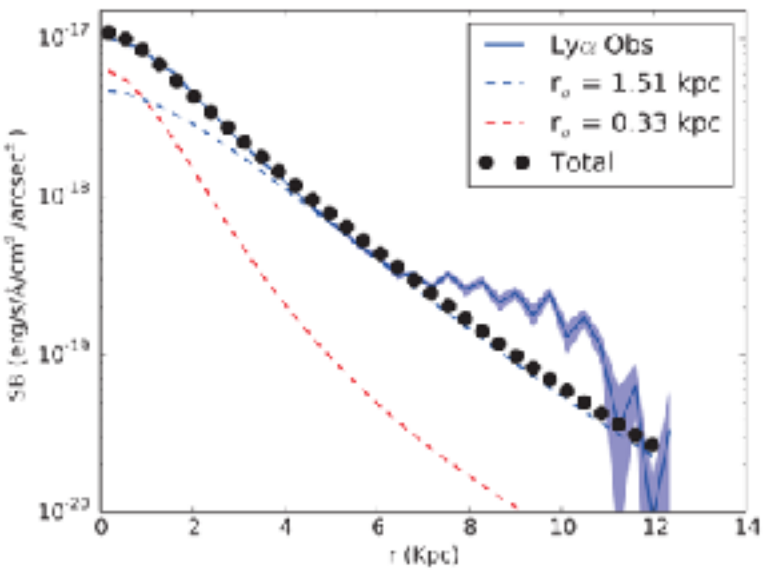
- Resolved maps of kinematics, metallicity, SFR and extinction
- Kinematics compatible with both exp. disk and isothermal sphere models
- Well-resolved negative metallicity gradient (0.6 < z<0.8)

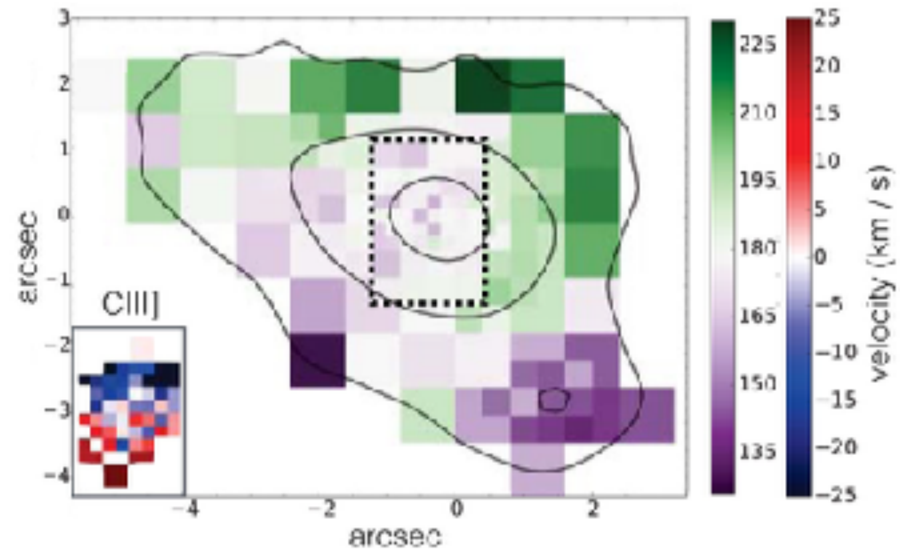
Patrício et al. 2018

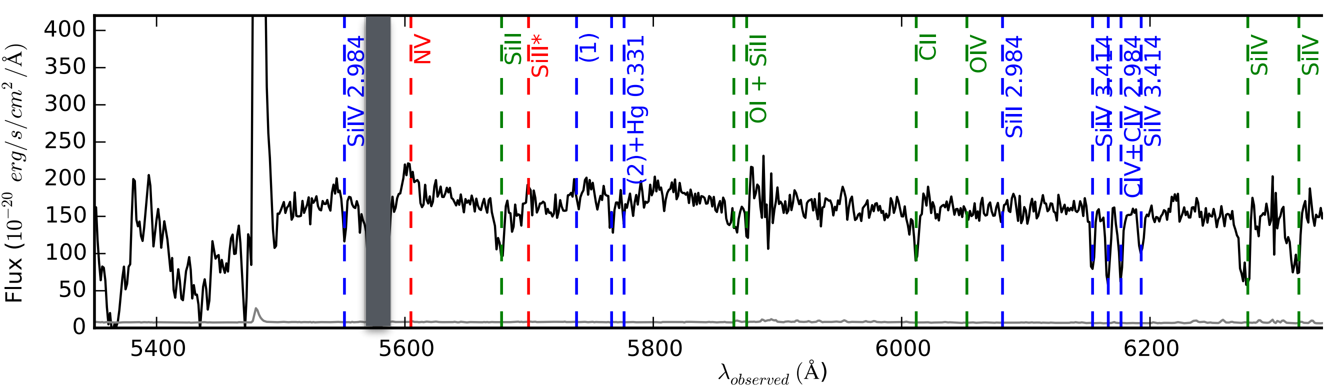
Resolved studies with IFU

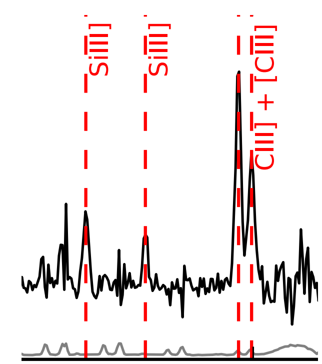
z=3.5 extended arc

Patrício et al. 2016, MNRAS 446L, 16



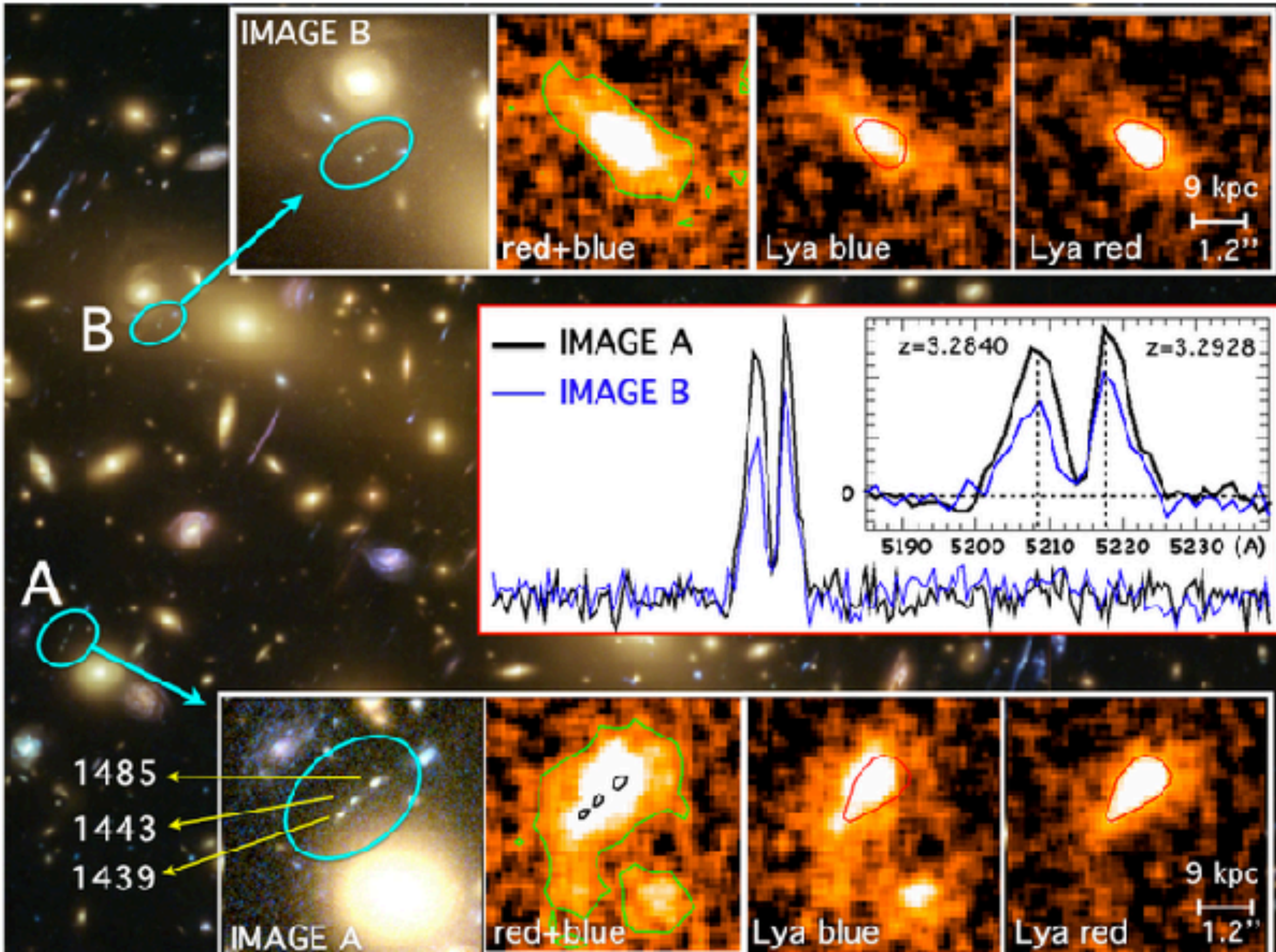




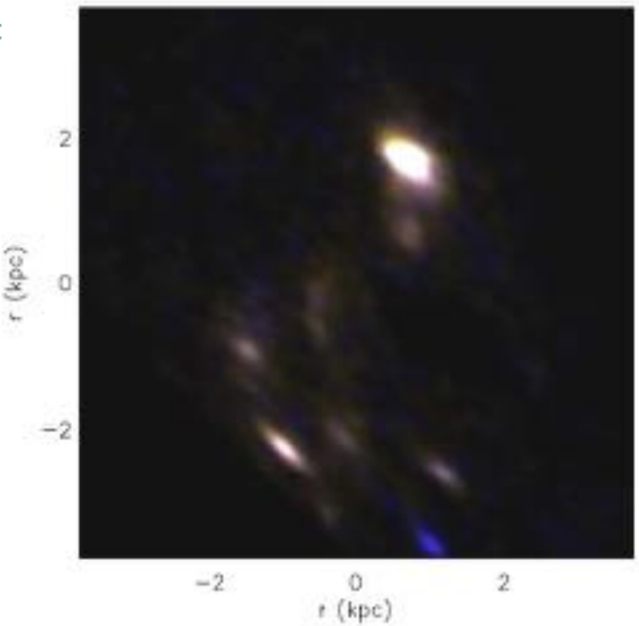


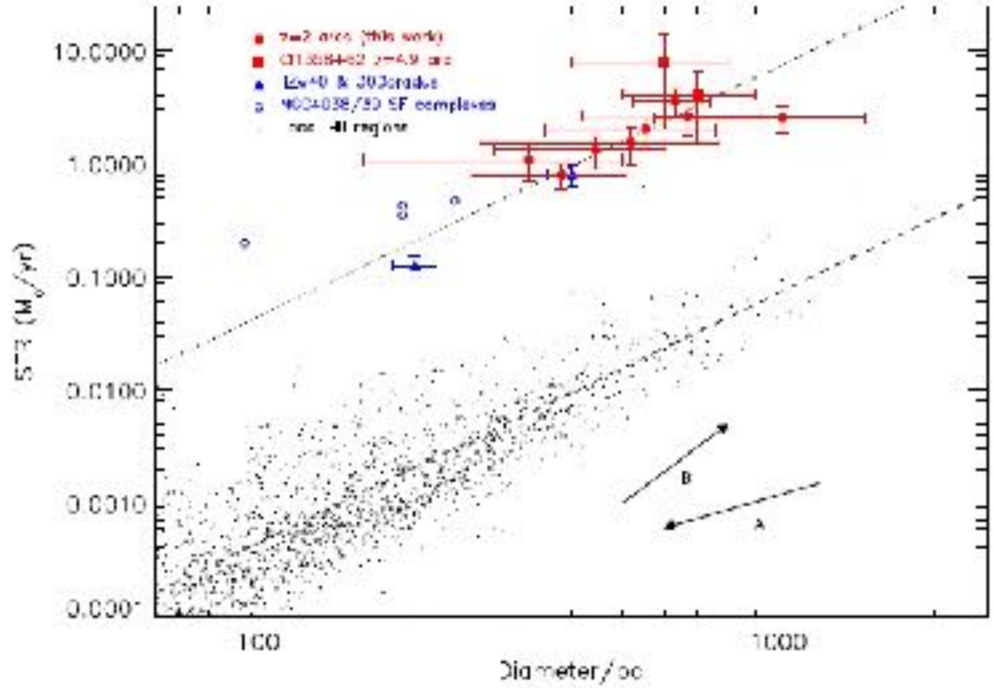
Resolved studies with IFU

Vanzella et al. 2017, MNRAS 465, 3803



MS1358: pushing to z ~ 5

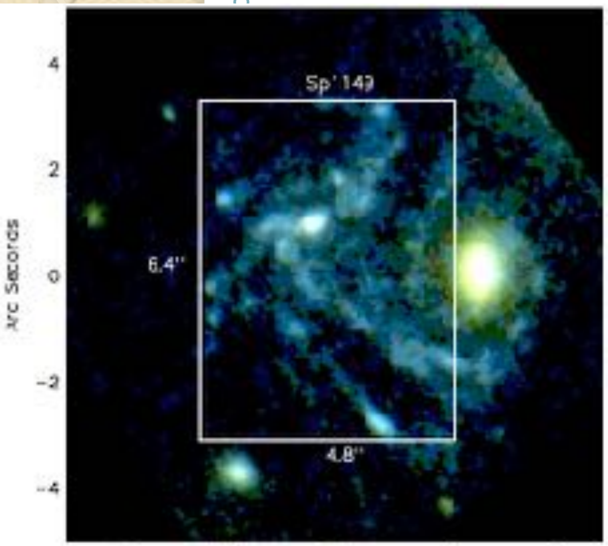


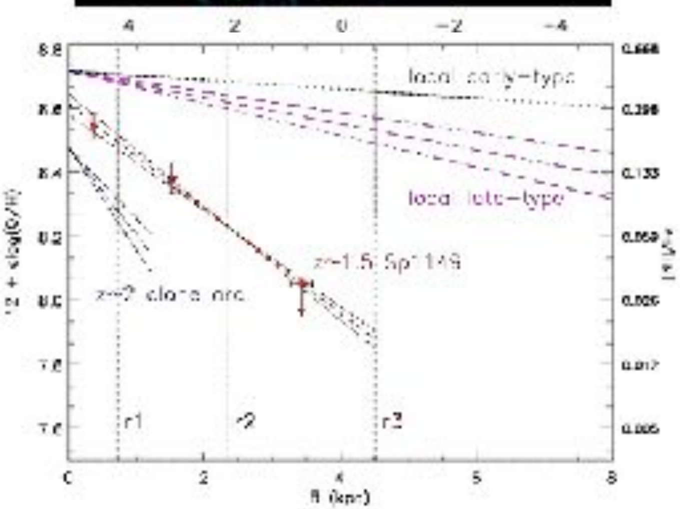


- Bright z ~ 5 strongly lensed source behind MS1358 (**Franx et al. 97**)
- NIFS spectroscopy: resolved [OII] emission in star-forming regions (**Swinbank et al. 09**)
- Star forming regions appear more concentrated compared to their local equivalents.
- New narrow-band program with HST (**Livermore et al. 2012**) to probe z ~ 1-1.5 sources

Metallicity gradients

Jones et al. 2011, Yuan et al. 2011

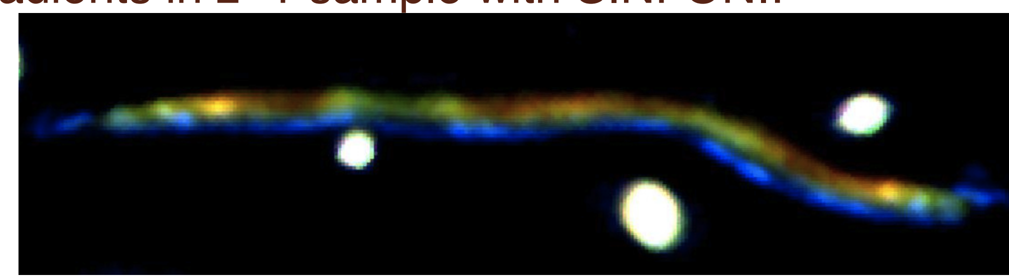


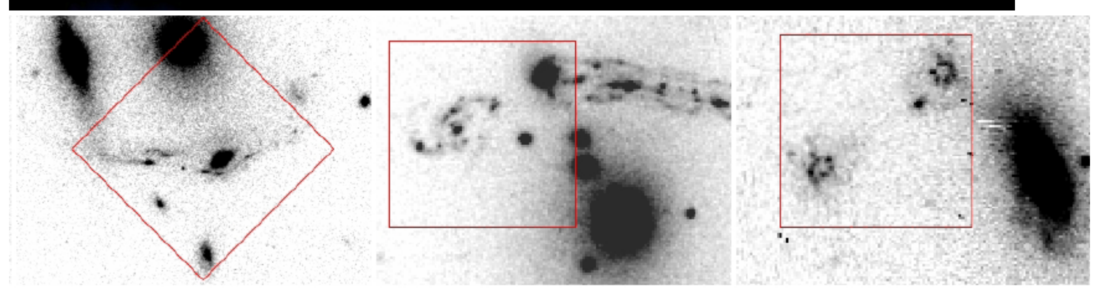


Observations of Hα and [NII] in the ``clone'' z=2 and MACS1149 z=1.5 with OSIRIS

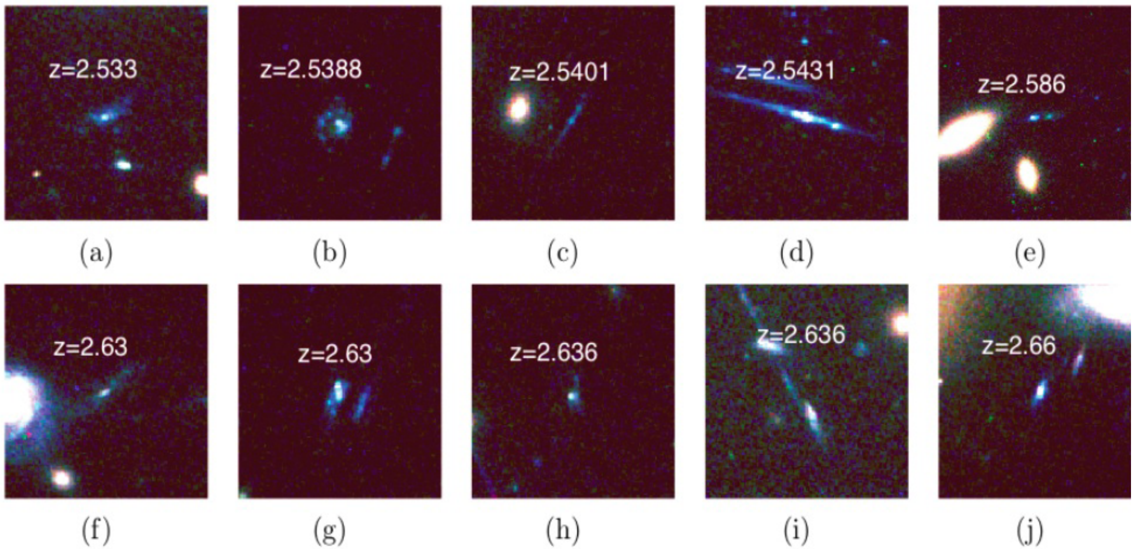
Measurement of a gradient of decreasing metallicity from the center

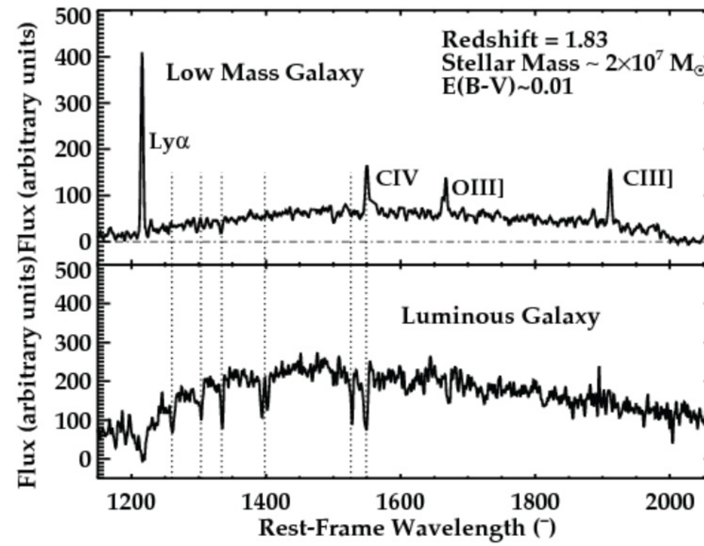
Results limited to 2 objects: now VLT program to probe gradients in z~1 sample with SINFONI:

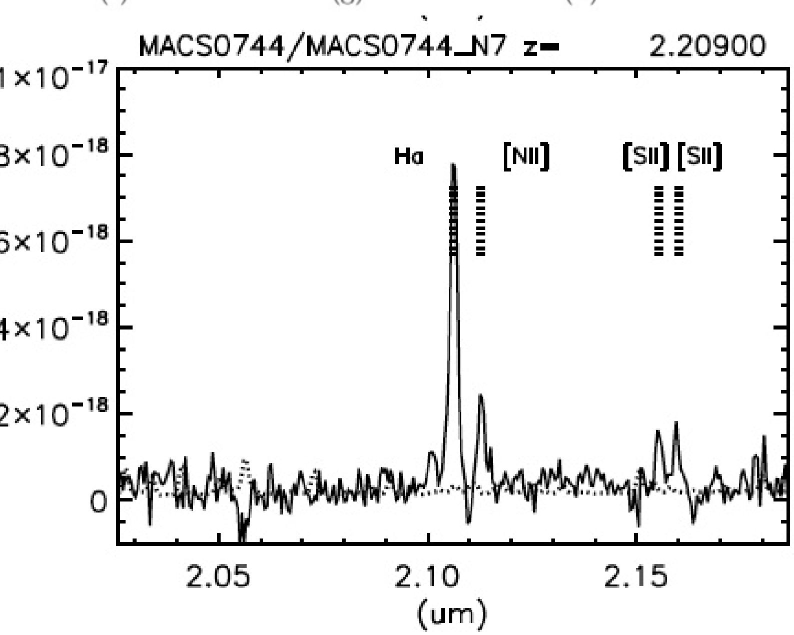


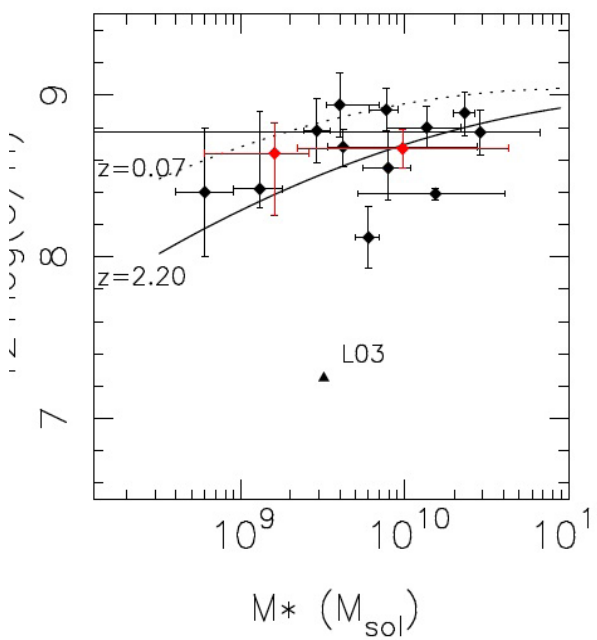


"Unresolved" studies







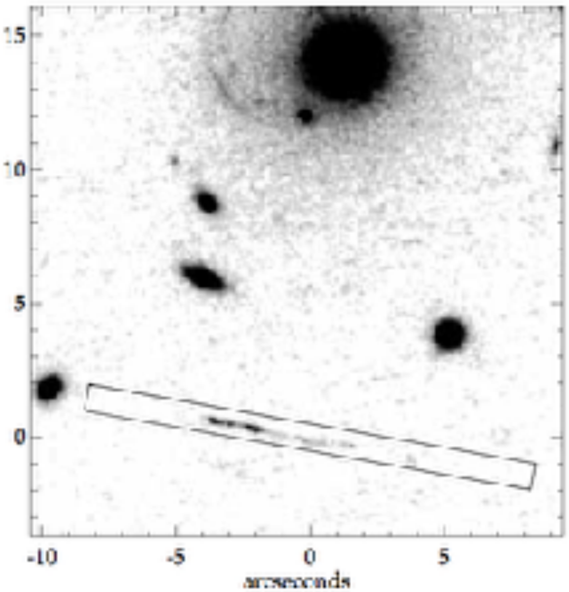


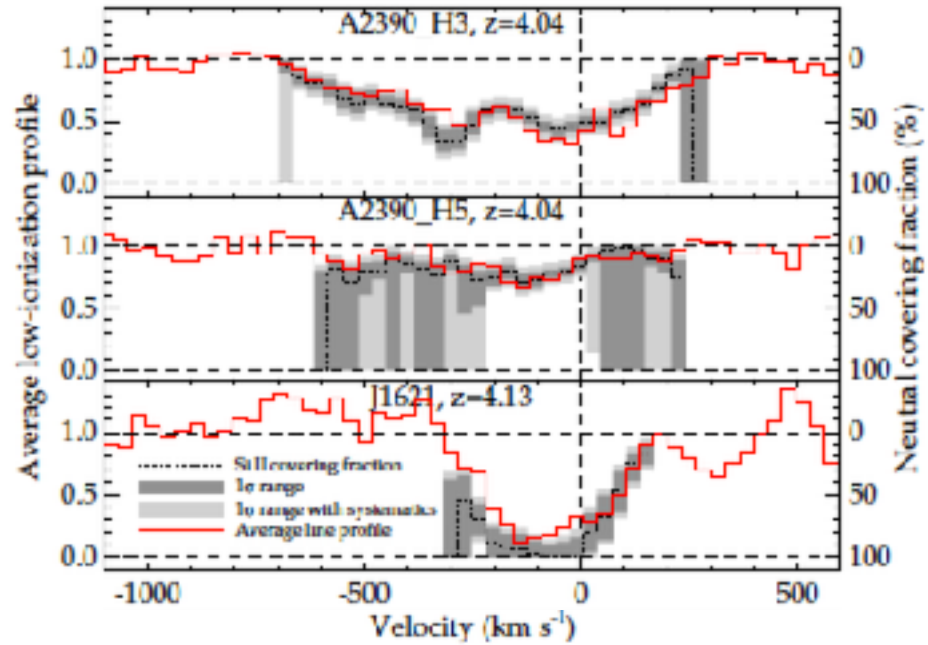
SNR boost in the integrated spectra (rest-UV or optical)

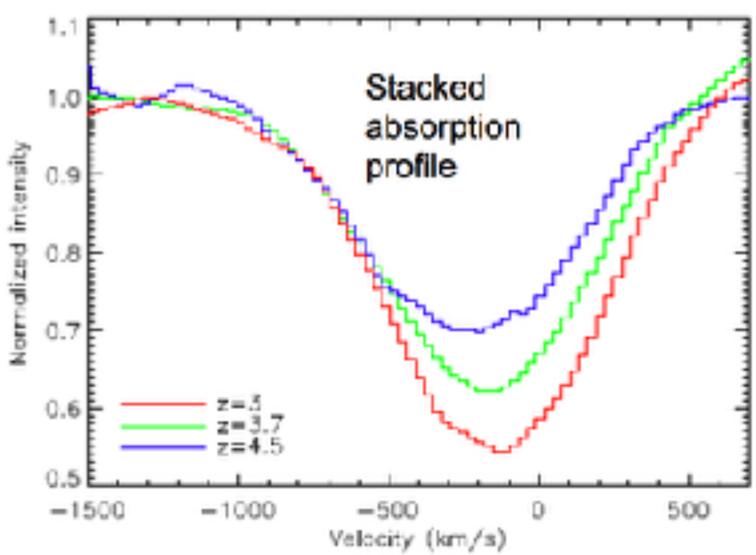
Richard et al. 2011: mass-metallicity relation for 12 sources at z~2.

=> **Wuyts et al. 2012**

"Unresolved" studies



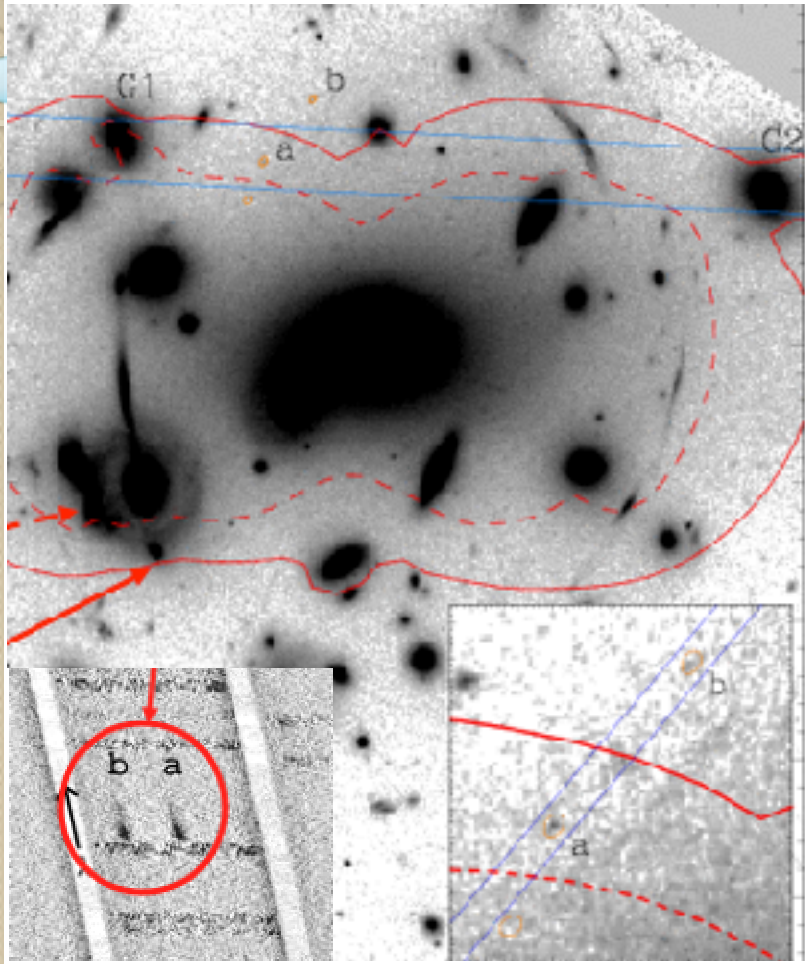




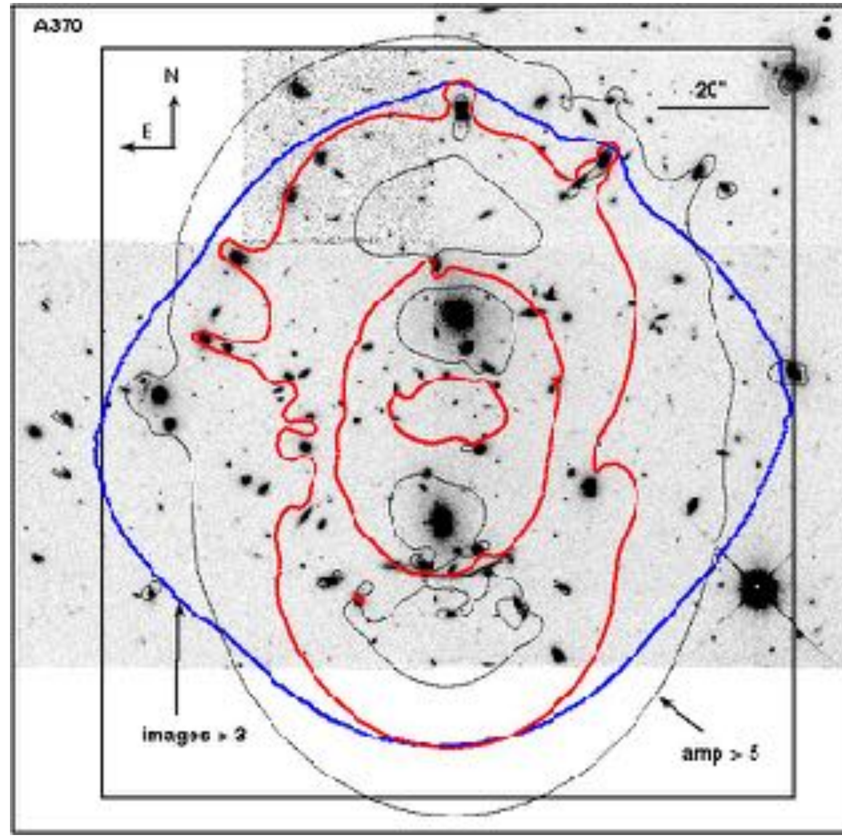
Jones et al. 2012, ApJ 751, 51
Jones et al. 2013, ApJ 779, 52

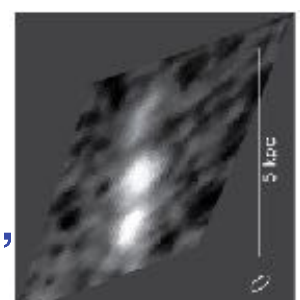
- Large variations of covering fractions (and therefore inferred escape fraction) seen in individual lensed galaxies.
- Small average increase of f_esc with redshift at z > 3?

High z searches



Critical line searches to search for LAEs: **Ellis et al. 01, Santos et al. 04, Stark et al. 07**

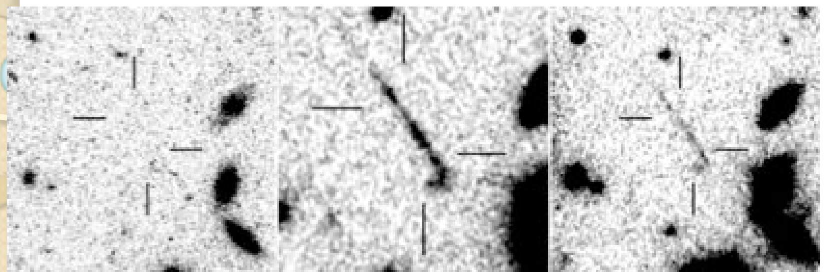




Hall et al. 11: 10 z ~7 behin bullet cluster

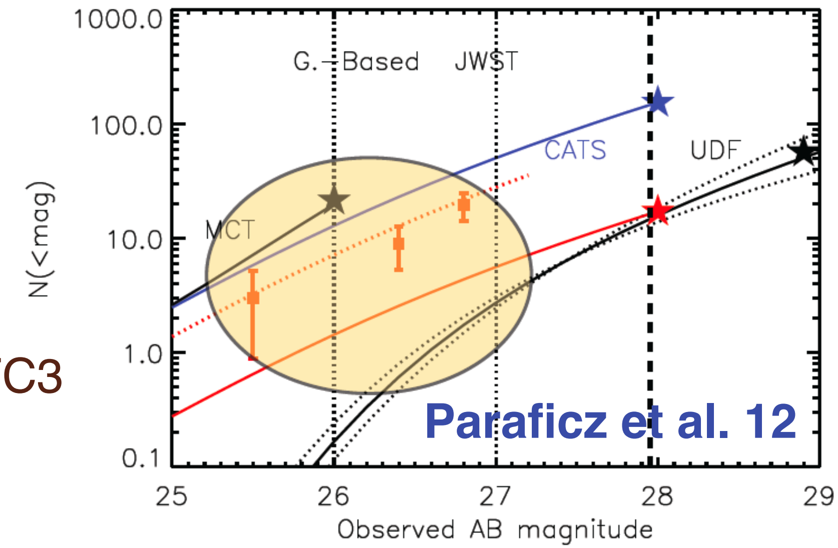
Bradley et al. 11: 8 z ~ 7 candidates behind A1703, maybe multiple images

High z searches (2)



Cycle 17 search for dropouts with WFC3

(PI: Kneib)



Paraficz et al. 12

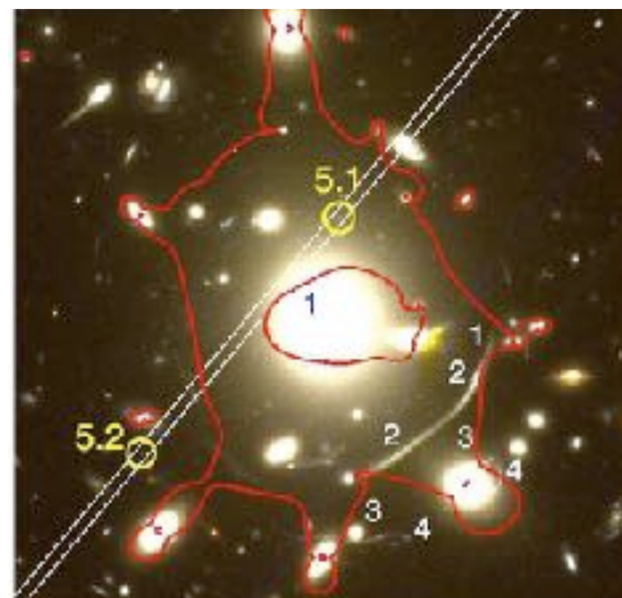
CLASH

Postman et al. 11

~ 500 orbits with HST/ACS and HST/WFC3, 25 clusters from MACS / LoCuSS

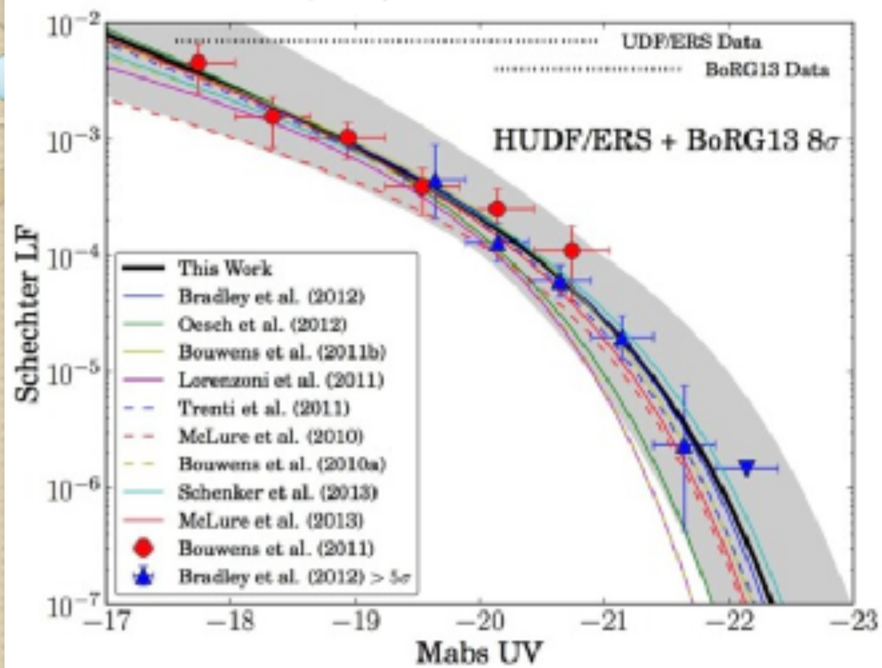
Accurate photo-z and mass modelling.

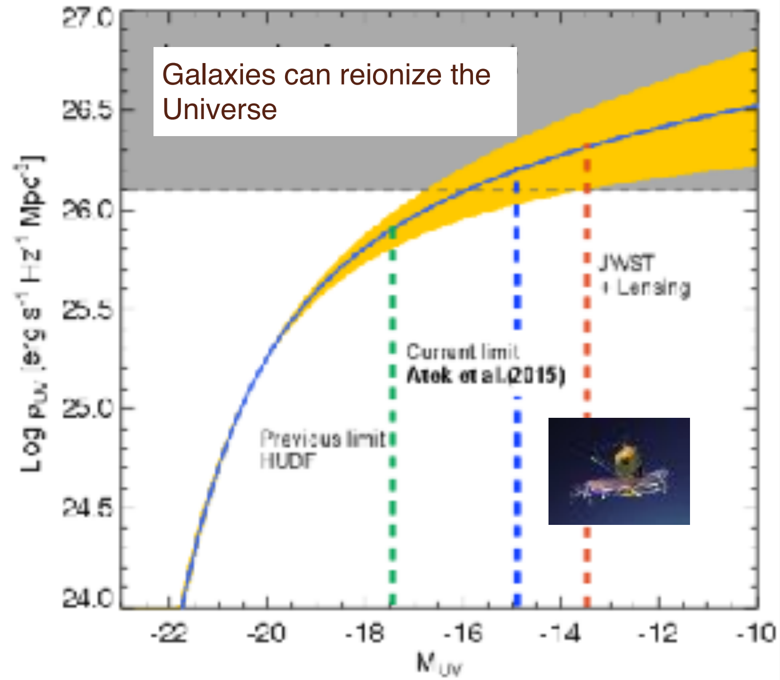
Richard et al. 11, Zitrin et al. 11abcd, Coe et al. 12



High z searches (3)

Schmidt et al. (2014)

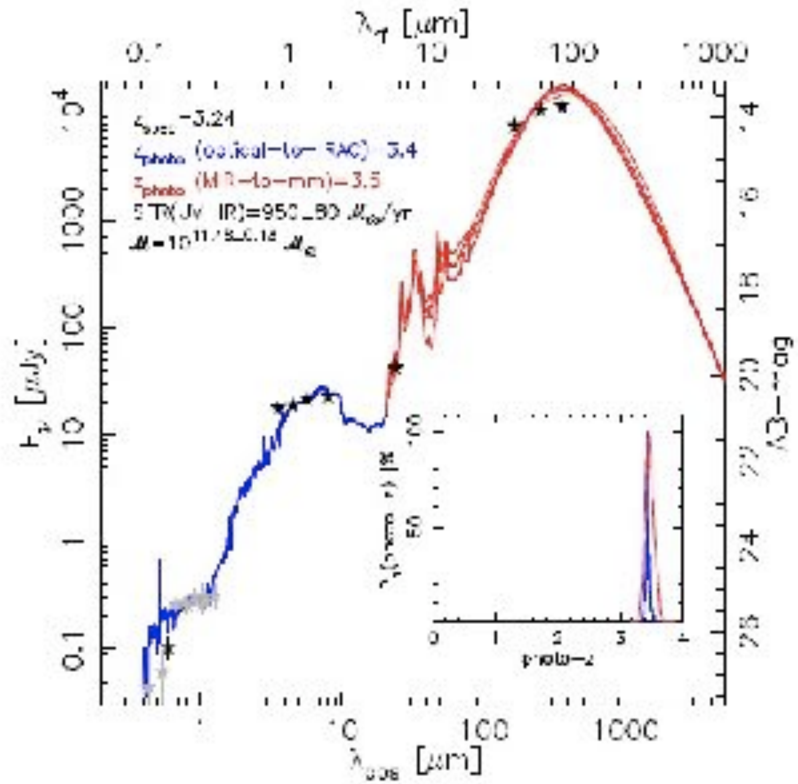


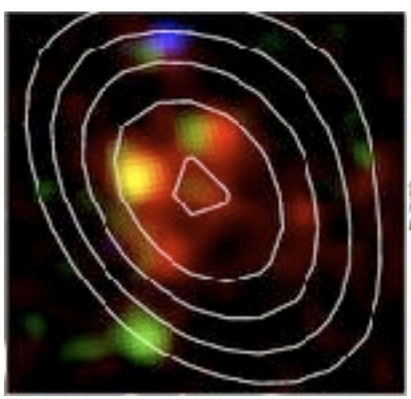


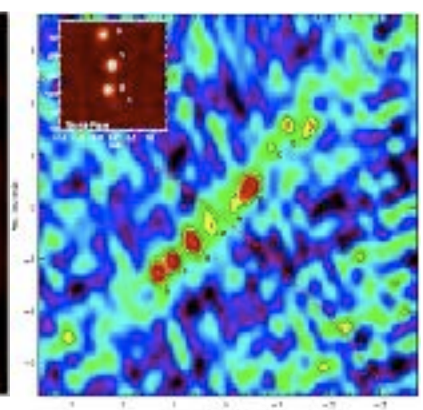
Current limits on the luminosity function:

- knowledge of the redshift evolution at $z > 7$, limited by statistics
- extrapolation to the faint end (sources dominating reionisation)

Multiwavelength studies







In the Rayleigh-Jeans tail of the dust blackbody spectrum, distant galaxies get ***brighter***

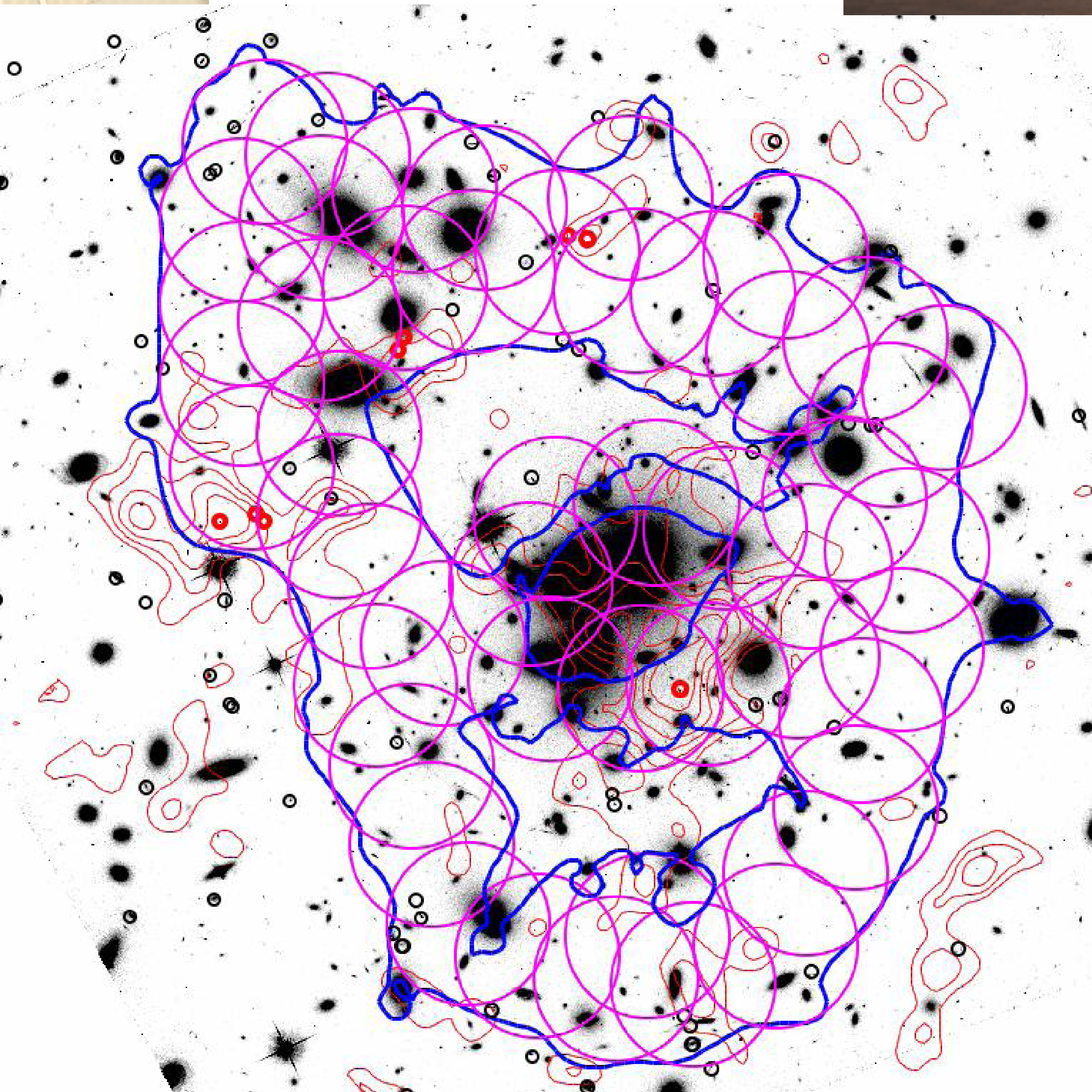
Submm surveys with SCUBA/ LABOCA/Herschel detect sources out to z ~ 5

Lensing+Submm:

- **Knudsen et al. 09** (A2218)
- **Swinbank et al. 10**
- **Gonzalez et al. 10**

Herschel **L**ensing **S**urvey (**Egami et al. 10**, **Rex et al.10, Combes et al. 12**)

ALMA

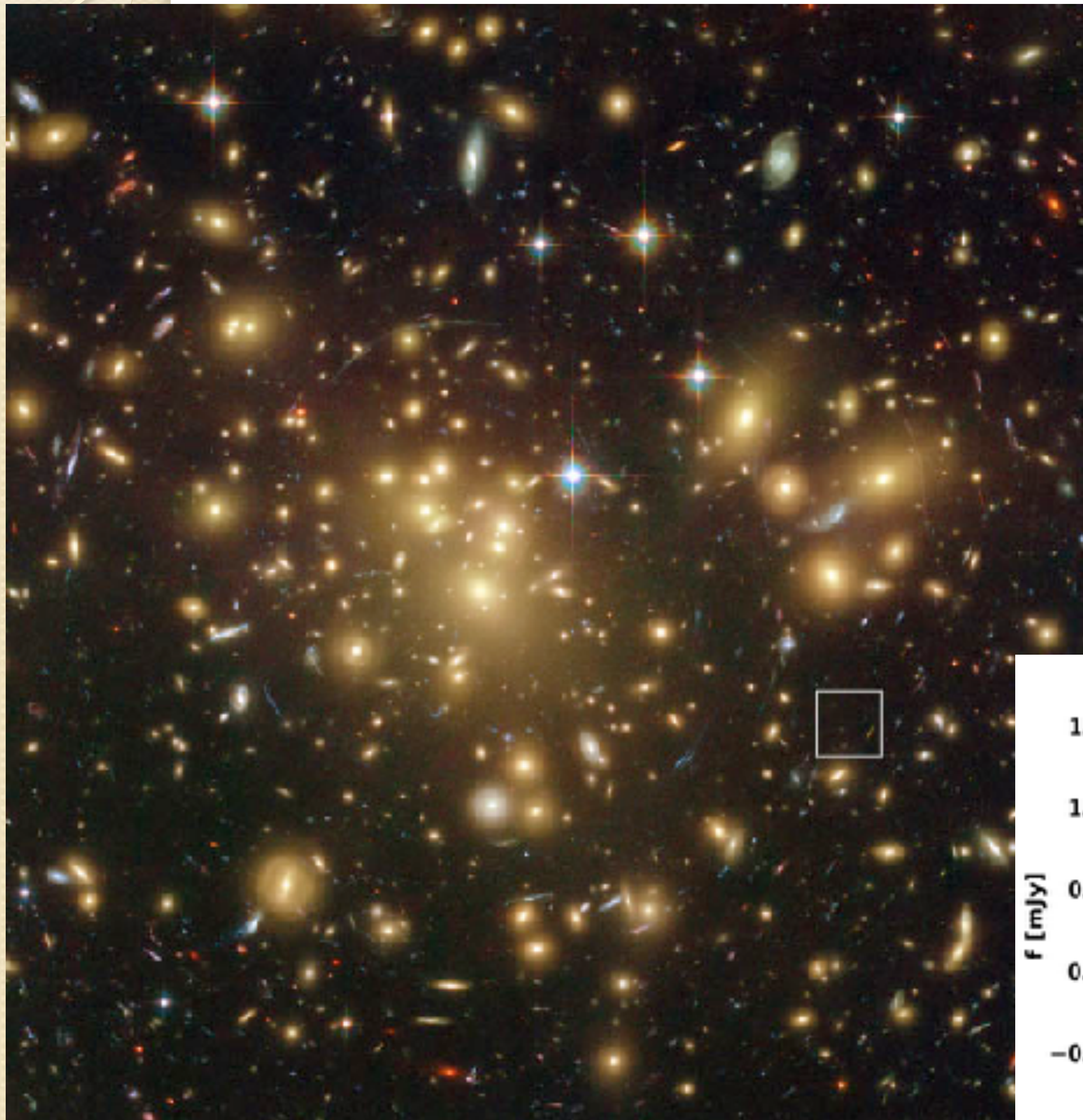


Abell 1689 Early-Science:
50 pointings covering the high magnification region, 7hrs

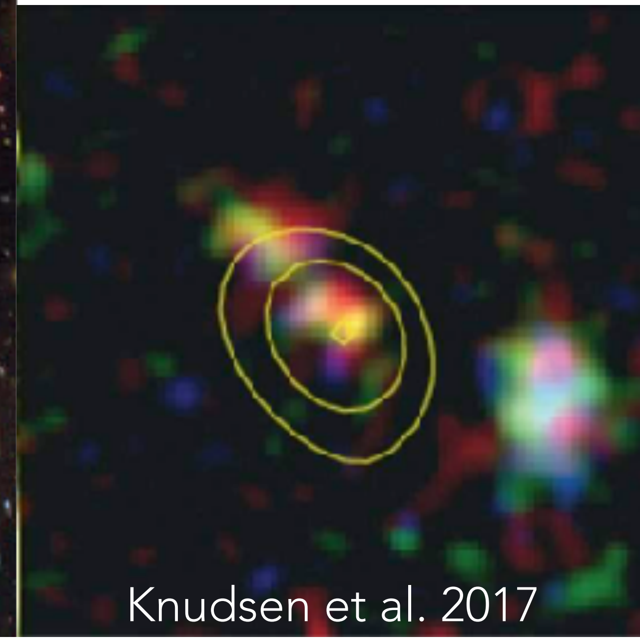
- 50 μJy limit in the continuum @1.3 mm (4sig)

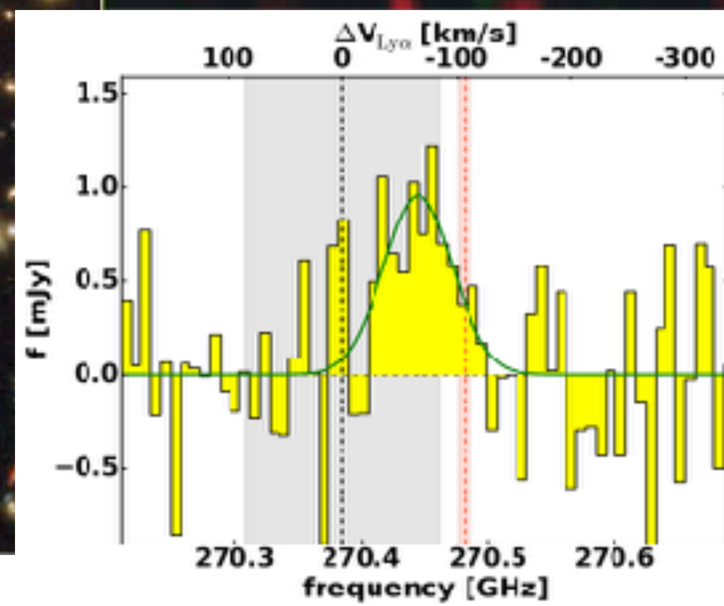
CO lines for known submm galaxies (Knudsen et al., SCUBA map)

- Stacked CO lines for 30 low-luminosity galaxies at known $1.5 < z < 3.0$

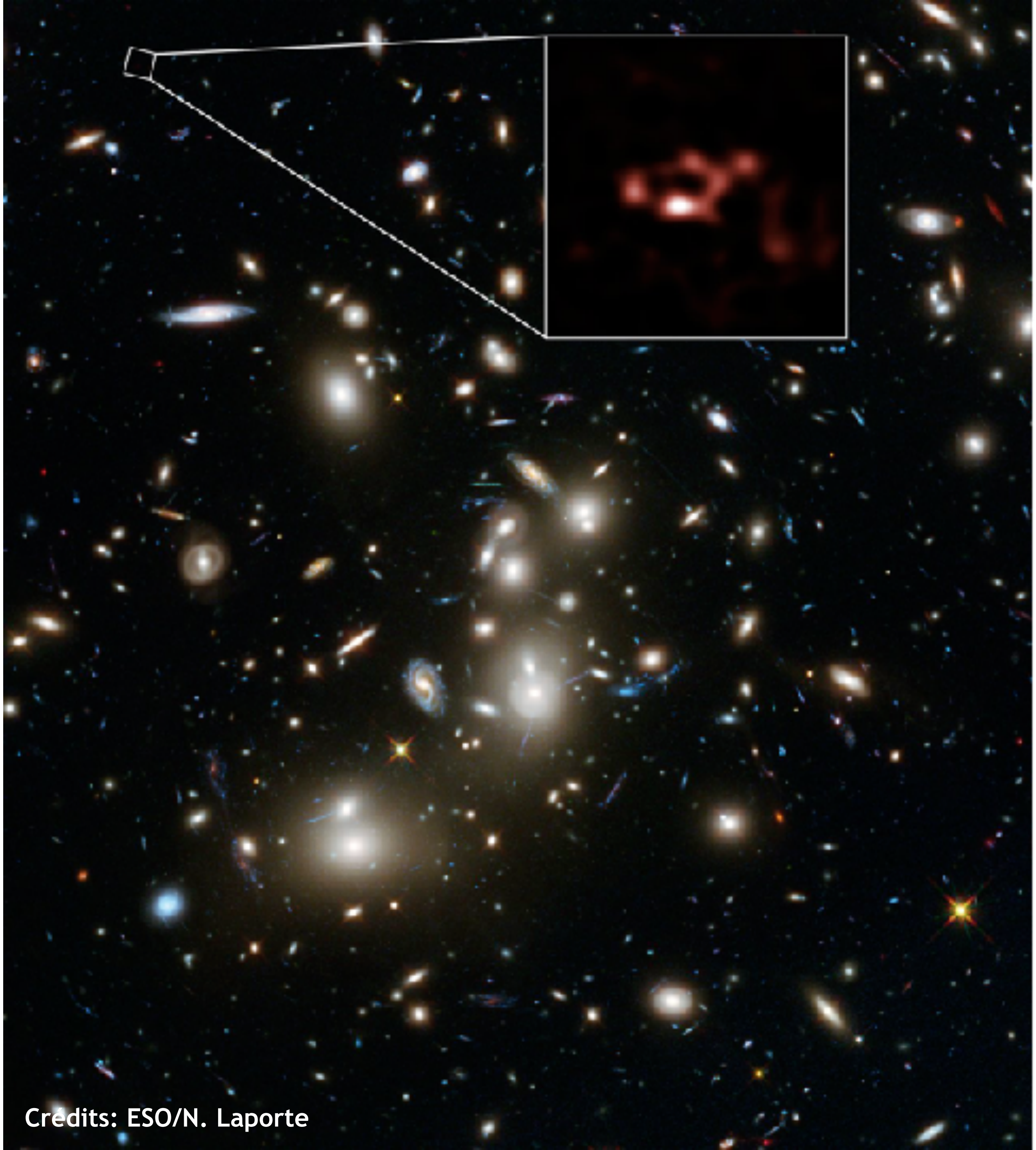


Watson et al. 2015





Crédits: ESO/J.Richard

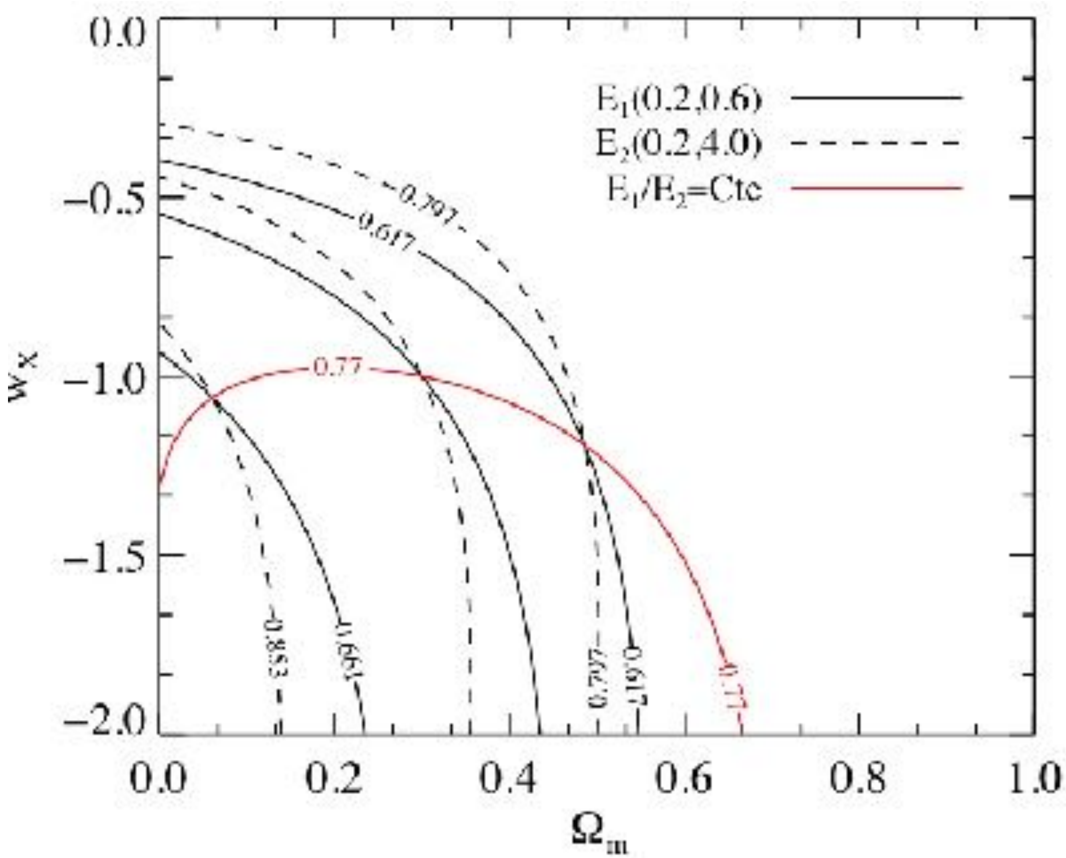

Credits: ESO/N. Laporte

Cosmology with strong lensing

$$R_{E_1} = \frac{4\pi\sigma^2}{c^2}\frac{D_{LS_1}}{D_{OS_1}}$$

$$R_{E_2} = \frac{4\pi\sigma^2}{c^2}\frac{D_{LS_2}}{D_{OS_2}}$$

$$\frac{R_{E_1}}{R_{E_2}} = \frac{D_{LS_1}}{D_{OS_1}}\frac{D_{OS_2}}{D_{LS_2}}$$



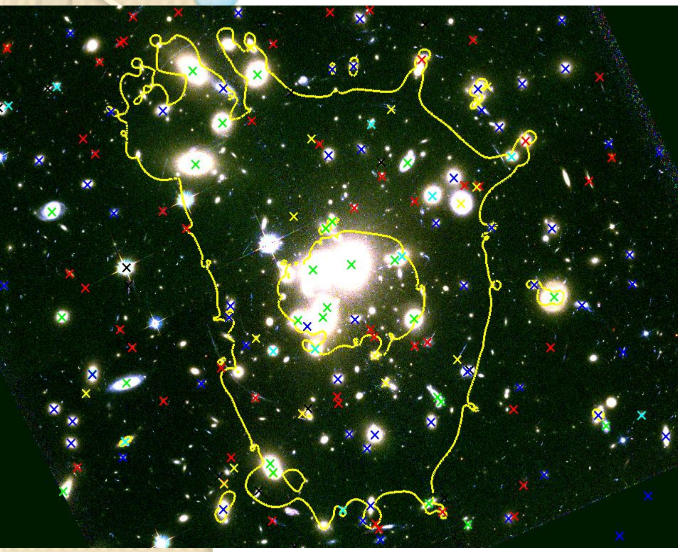
Geometric test:

Ratio of efficiencies for 2 systems at redshift z1 ≠ z2 constrains cosmological parameters Ωm and wx

Needs: accurate spectroscopic redshifts for many systems behind a given cluster

Cosmology with A1689

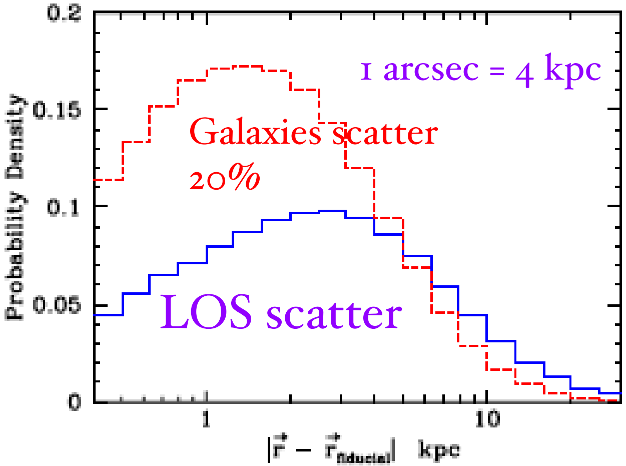
Jullo et al. 2010, Science

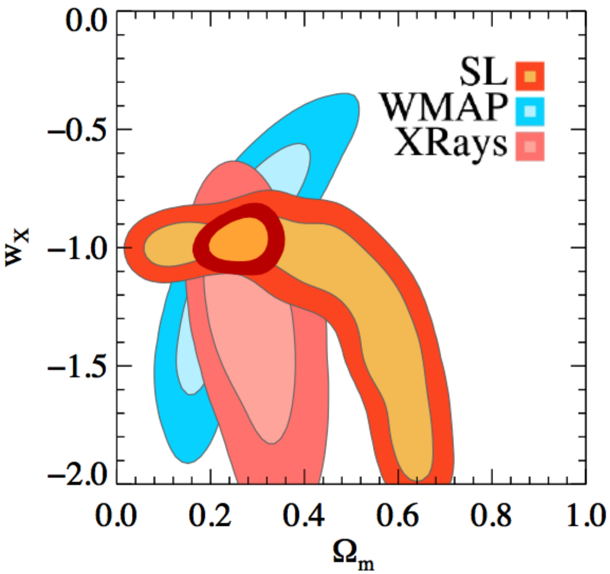


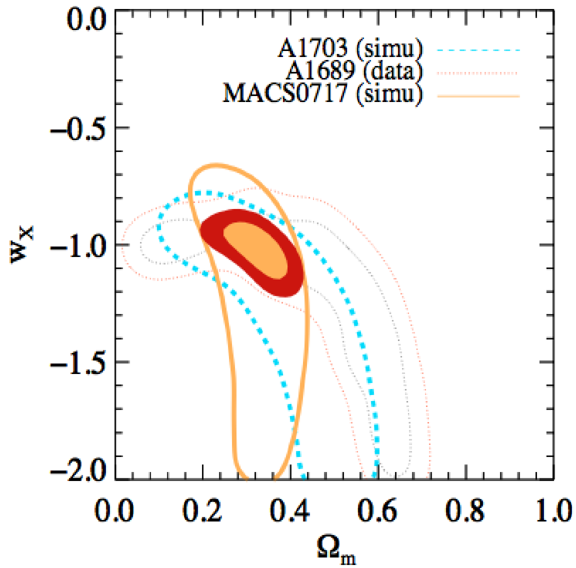
Mass model with 3 large-scale potentials, 58 cluster galaxies

Bayesian optimization: 32 constraints, 21 free parameters
28 multiple images from 12 sources with spec z
Accounting for errors due to galaxies scatter and LOS scatter (estimated from simulation)

RMS = 0.6 arcsec







Conclusions

- A large sample of strong lensing clusters has been assembled and modeled, with enough accuracy to use them as Gravitational Telescopes. They have a wide multiwavelength coverage, with HST, IRAC, Herschel
- Combination of WL and SL probe different ranges in the cluster mass profile and allow us to calibrate X-ray and SZ measurements.
- Lensing is the only way to resolve the inner morphology, dynamics and metallicity gradients in typical sources at $z > 3$
- SL is an independent (and promising)geometrical test for Ωm and wx
- Future: need for optimized reconstruction techniques for resolved sources observed with IFU