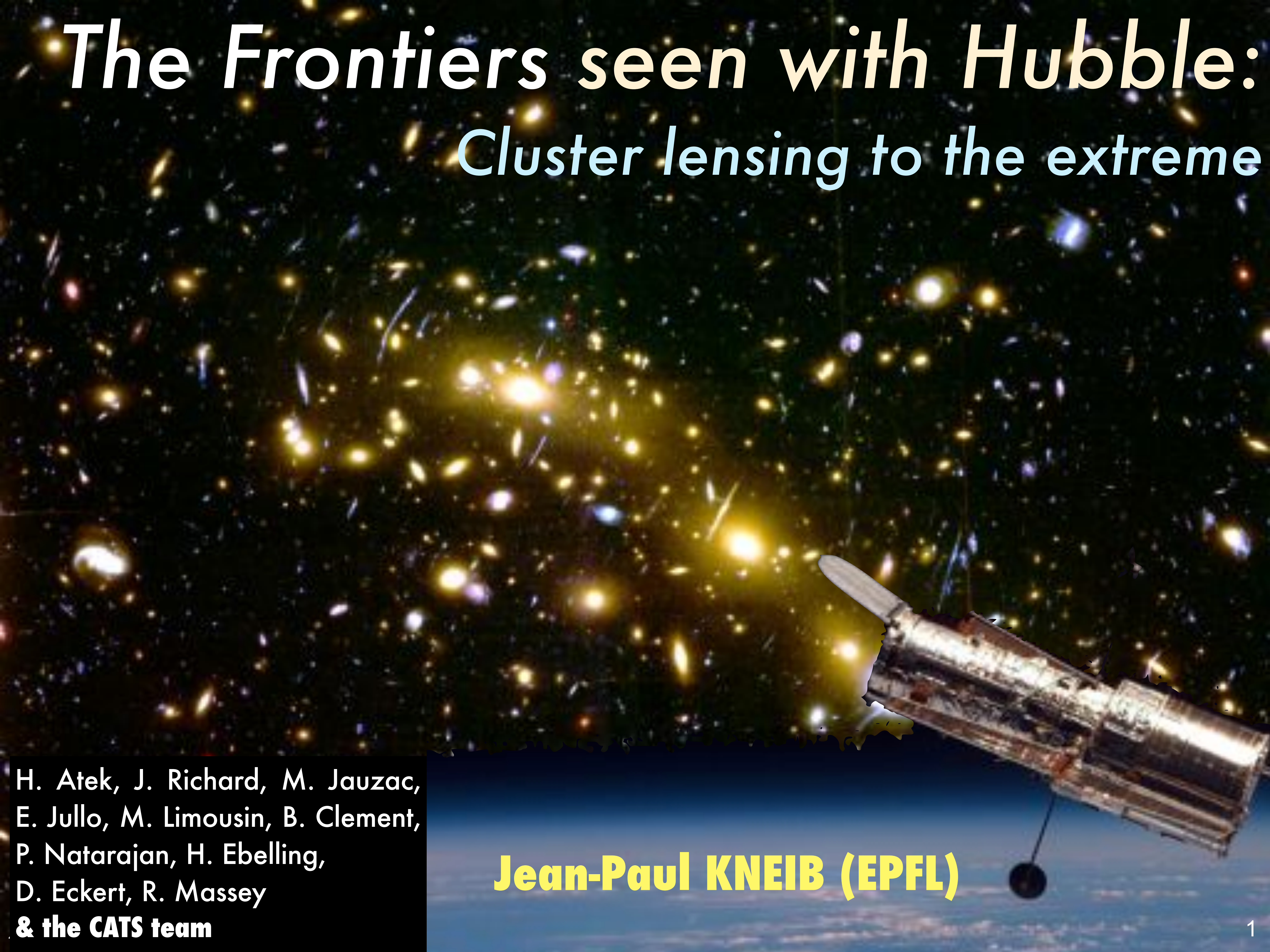
The Frontiers seen with Hubble:
Cluster lensing to the extreme



H. Atek, J. Richard, M. Jauzac,
E. Jullo, M. Limousin, B. Clement,
P. Natarajan, H. Ebelling,
D. Eckert, R. Massey
& the CATS team

Jean-Paul KNEIB (EPFL)

Experimenting New Physics in (Air) Space

Thanks
to the organisers
with
a special thanks to
Ioav Waga !

Outline

- Motivation
- Basics of Lensing
- Mass distribution
- Distant Galaxies
- Lensed Supernovae
- Next steps
- Conclusion

Motivation

- **Cosmology:** *theoretically driven to* *<u>observationally driven</u>* science,
- Explore and put constraints on the **nature of Dark Matter and Dark Energy**, as well as exploring the **Dark Ages**

Matter

✶ What is the distribution of DM compared to Baryons?

✶Can we put constraints on possible DM/baryons interactions? self-interaction of DM?

Energy

✶How to explain the accelerated expansion? How accurate can it be measured?

✶Expansion as a function of time? Equation of state of Dark Energy?

Ages

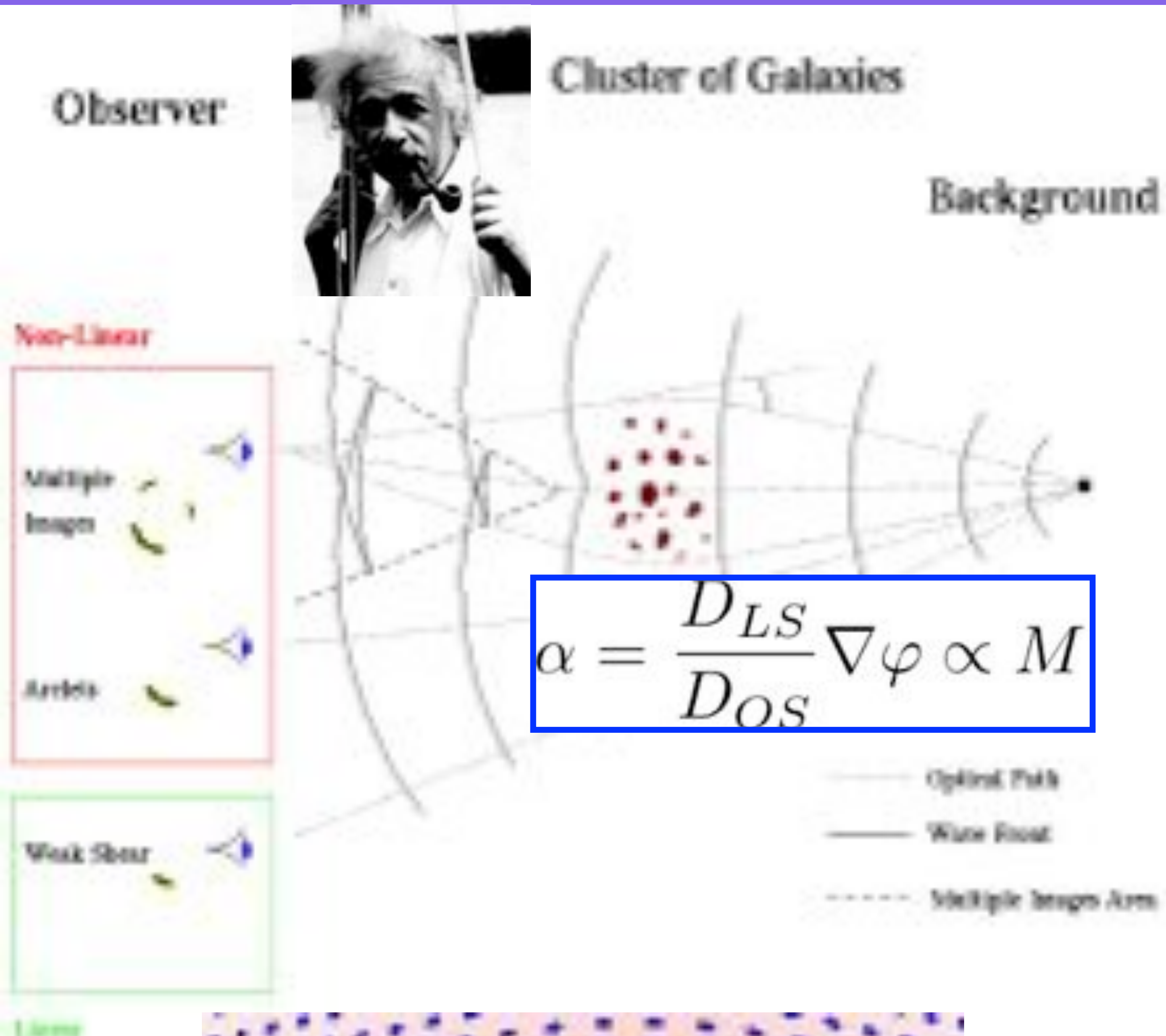
✶What are the sources that re-ionize the Universe?

Motivation

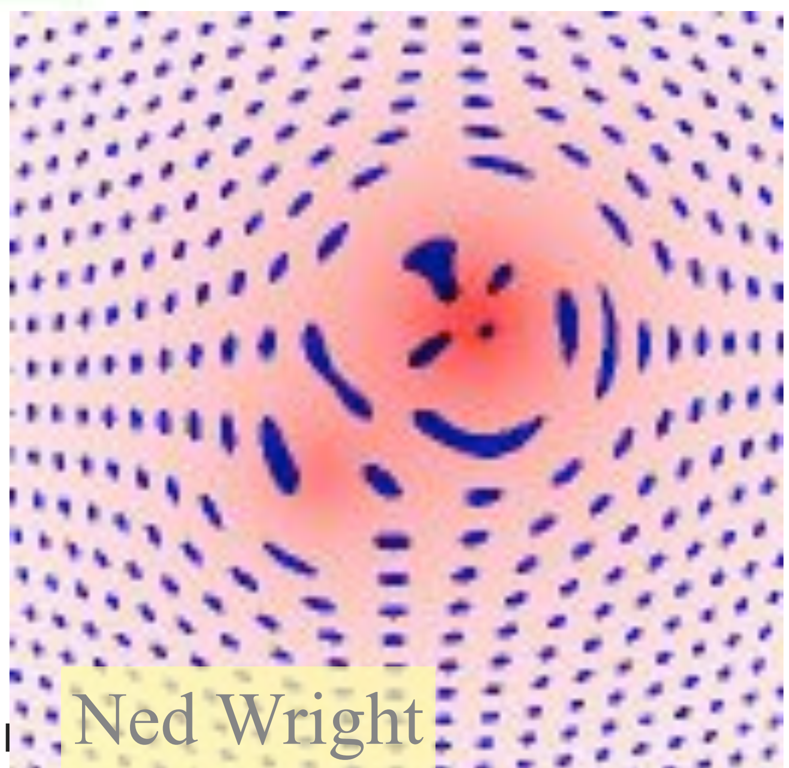
- PRECISION Cosmology:
  - **strong gravitational lensing:** simple physics !
  - no systematic (at least as little as possible)
  - strong predictive power (multiple-image position, redshift)
    - **Hubble Frontier Fields [2013-2016] a STScI Director initiative**

Yale Frontier Fields Workshop - Nov 2014

Cluster Lensing - Basics



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

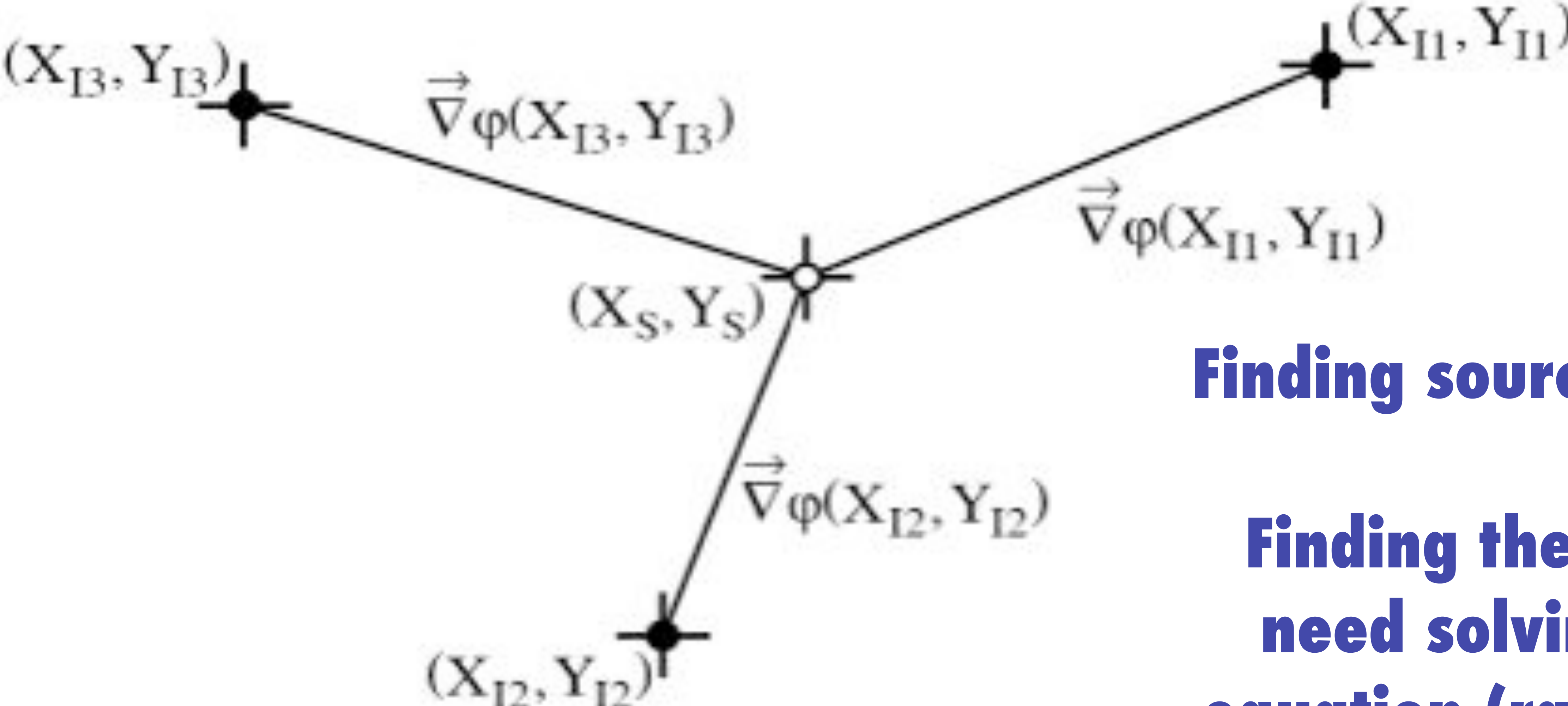


- **Basics of lensing:**
  - Large mass over-densities locally deform the Space-Time
  - *A pure geometrical effect, no dependence with photon energy - depends on TOTAL MASS*
- **Lensing by (massive) clusters**
  - Deflection of ~10-50 arcsec
  - *strongly lens many background sources => allow detailed mass reconstruction at different scales: cluster core, substructures, large scales*
  - *~1 SL cluster-lens per ~10 sq. deg: potentially ~2000 to study, Probably only ~200 identified today, nearly 20 with "a good" (SL) mass model*

Strong Lensing

Lensing equation have multiple solution (Strong lensing):

$$\theta_s = \theta_I - \nabla\varphi(\theta_I)$$

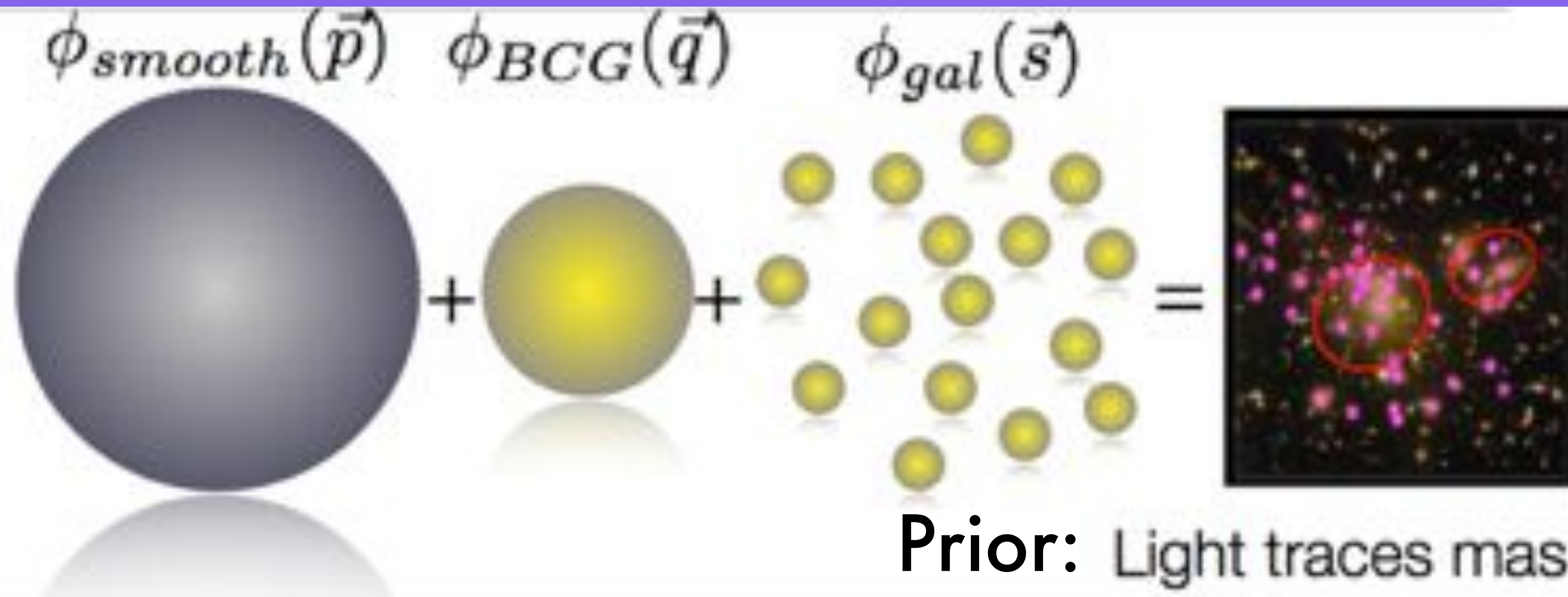


Finding source is easy!

Finding the images need solving a 2D equation (ray tracing)

Modelling Approaches

parametric



Prior: Light traces mass

free-form
(non-parametric)

No assumption that light traces mass or on the shape of the density profiles

Decomposition into pixels or RBFs

Work better with many constraints

Prior: 'pixel' geometry and/or regularisation

The “Bullet Cluster”: Direct Proof of existence of DM

- **Encounter of 2 massive clusters**
- **Significant offset between X-ray gas and lensing mass peaks**

⇒ probably best evidence for « collisionless dark matter »

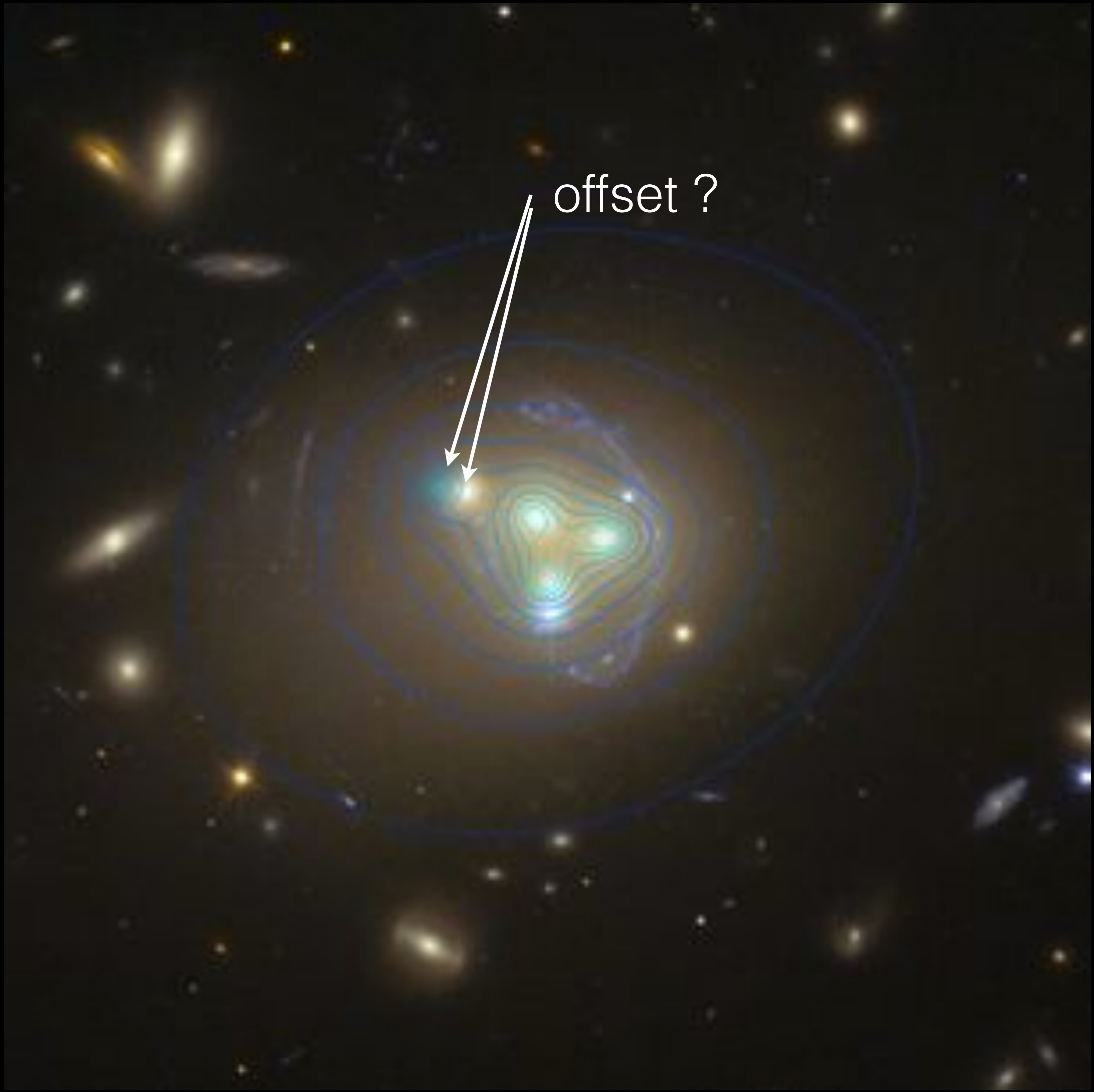
⇒ provide upper limit on DM self-interaction, and DM/Baryon cross-section

Clowe et al 2006,
Bradac et al 2006

Is Dark Matter interacting with baryonic matter?

Measurement of the offset between Dark and Baryonic Matter can inform us on their possible interaction.

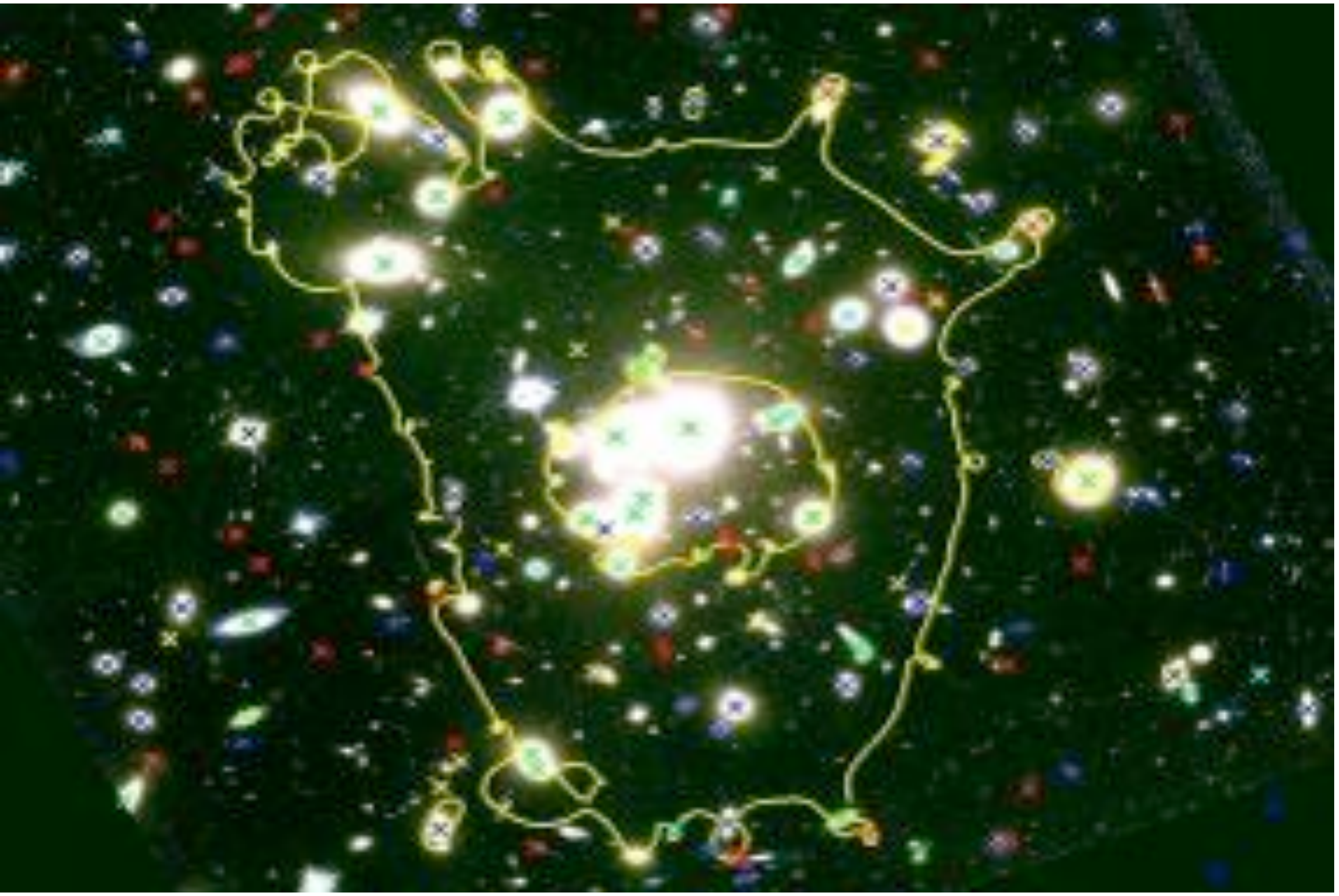
Example of a galaxy infalling in the cluster A3827.
Offset of DM and light => sign of DM self interaction? or limited by modelling priors?

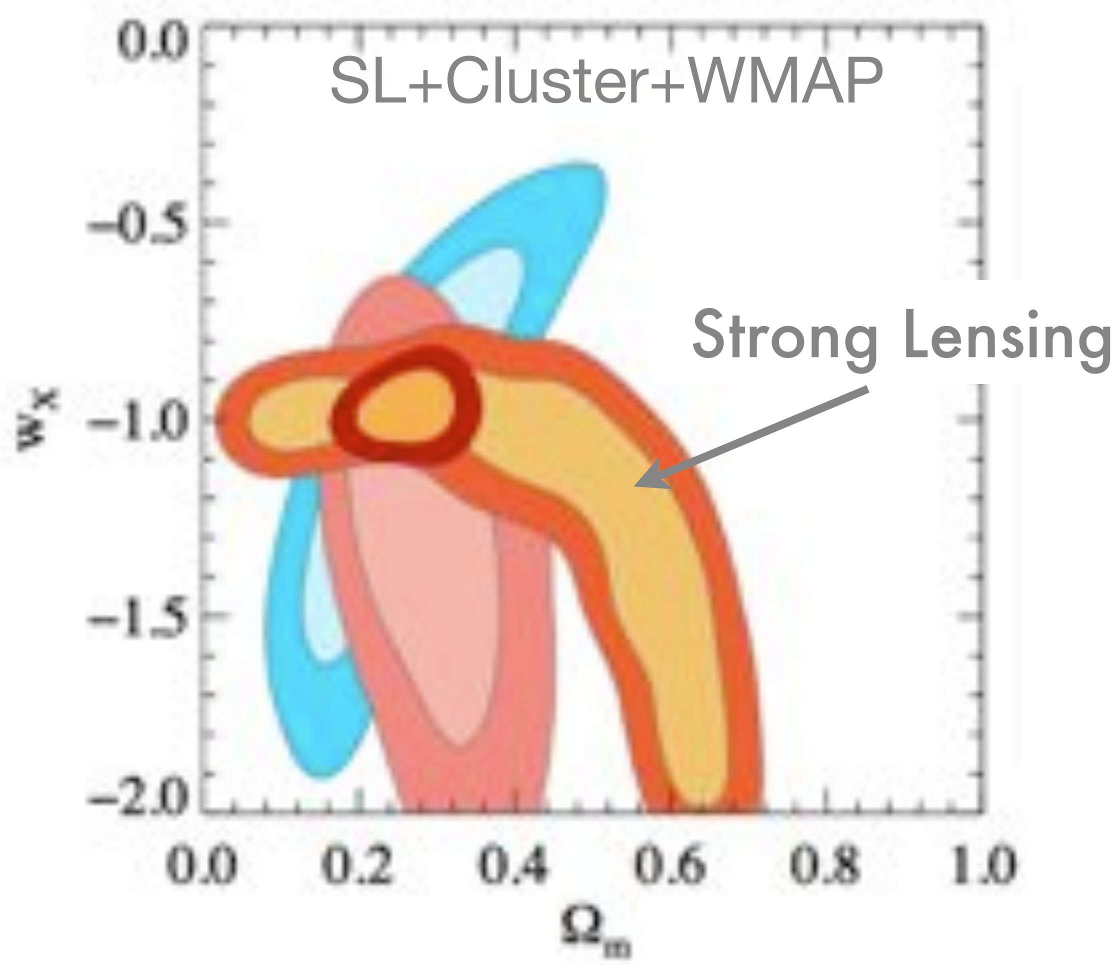


Massey et al 2015

Cosmography with Strong Lensing

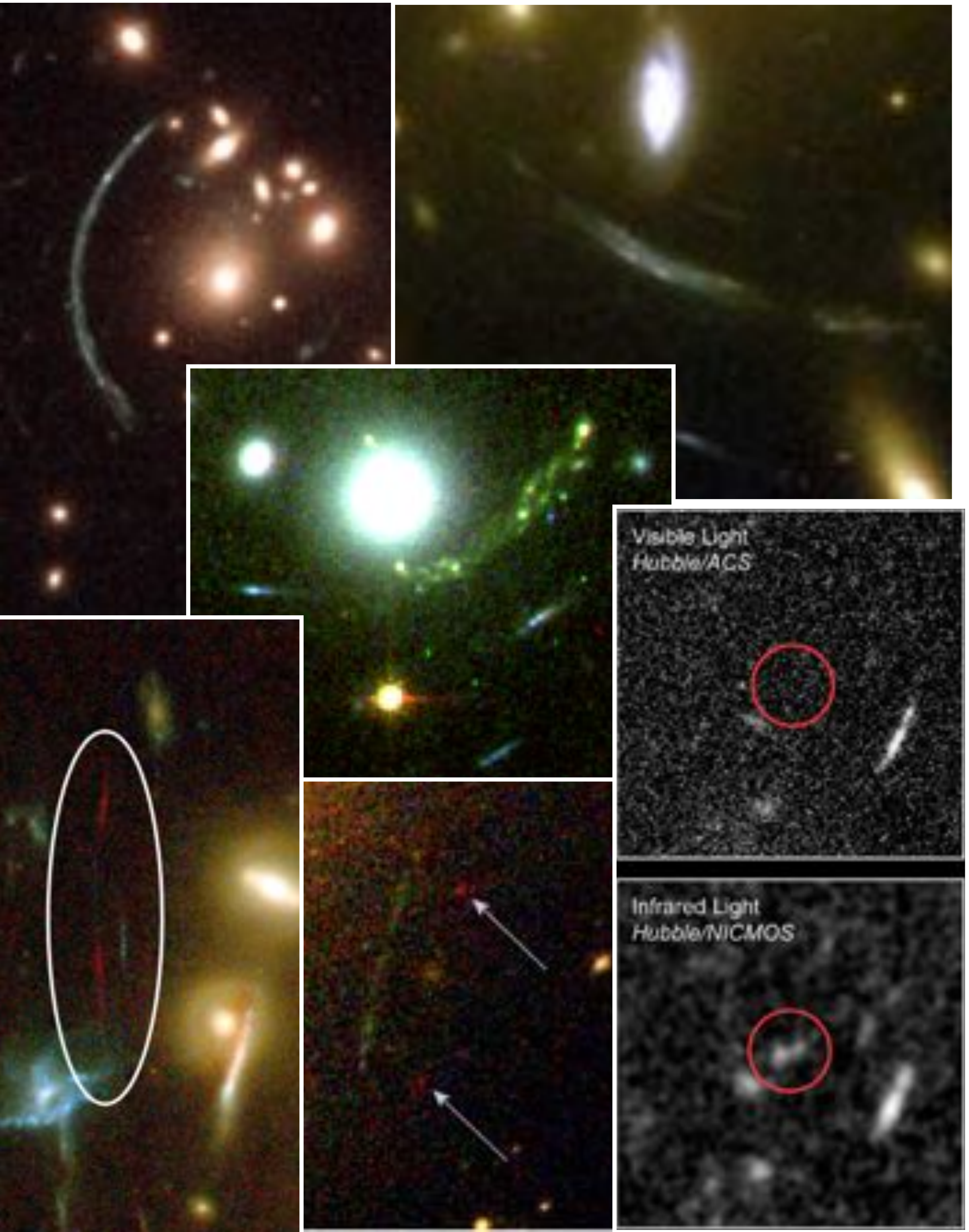
Cosmography test, based on ratio of distances of multiple images.
Mass model with 3 PIEMD potentials; 58 cluster galaxies
Bayesian optimization: 32 constraints, 21 free parameters;
RMS = 0.6 arcsec; 28 multiple images from 12 sources with spec z, flat Universe prior





D'Aloisio & Natarajan 10; Jullo & Kneib 09: Jullo+ 10

Cluster as Cosmic Telescopes

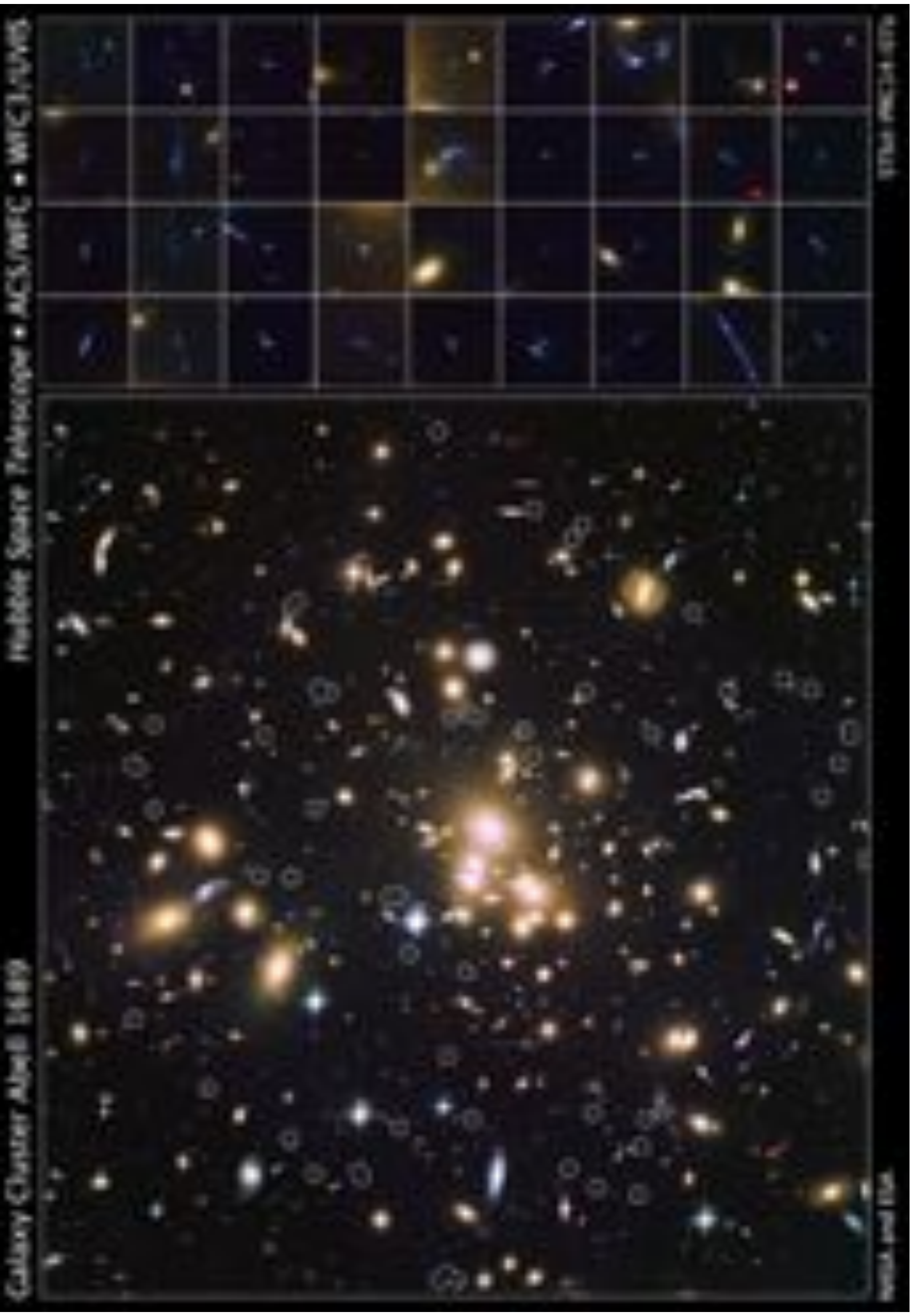


- **1987**: Cl2244 one of the first gravitational arc, latter recognized as a z=2.2 galaxy
  - Ebbels et al **1996**: a z=2.5 LBG in a2218
  - cB58 z=2.7 recognized as a strongly lensed source (Seitz et al **1998**)
  - Franx et al **1997**: a LAE at z=4.9
  - Ellis et al **2001**: LAE at z=5.6
  - Kneib et al **2004**, Egami et al **2005**: LBG at z~6.8
  - Bradley et al **2009**: LBG at z~7.6
  - … and more …

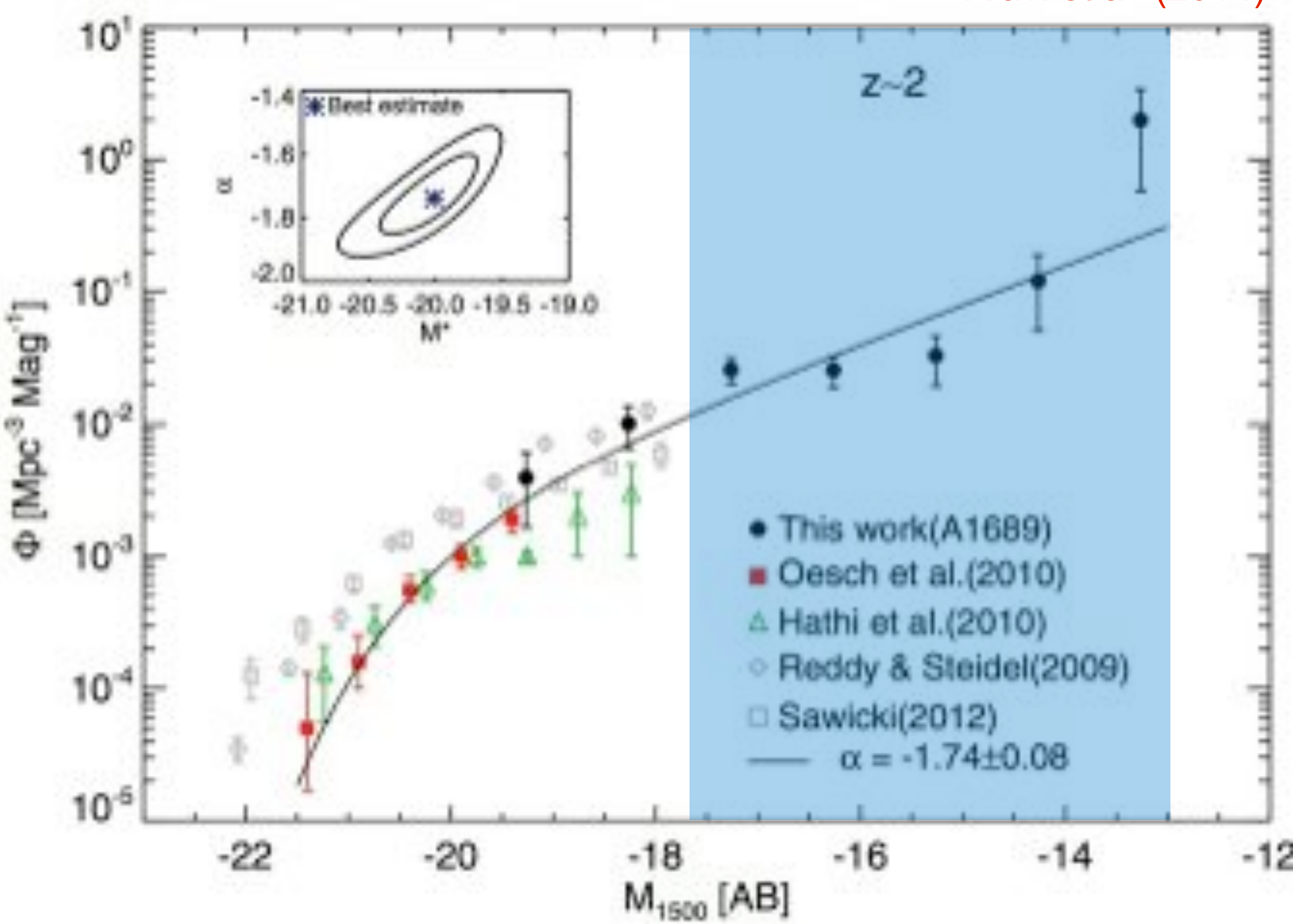
The Faintest Galaxy Population through "Gravitational Telescopes"

UV LF at z~2 down to Muv=-13 thanks to A1689 magnification

No sign of turnover in the UV LF



Alavi et al. (2014)



Ionized | Neutral | Ionized

z=1100	z~30	z=10	z=6	z=2	z=0
Age = 0.3Myr	100 Myr	500 Myr	1 Gyr	5Gyr	13.7Gyr

CMB **Dark Ages** **Epoch of Reionization**

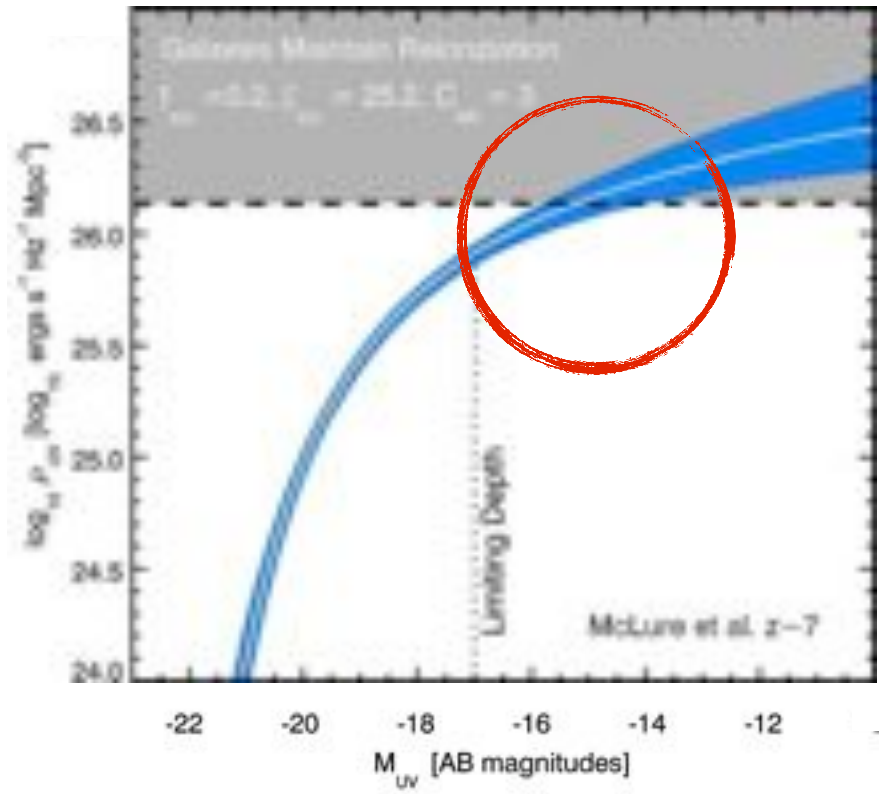
Hubble Frontier Fields Focus

Star-forming Galaxies and Cosmic Re-ionisation

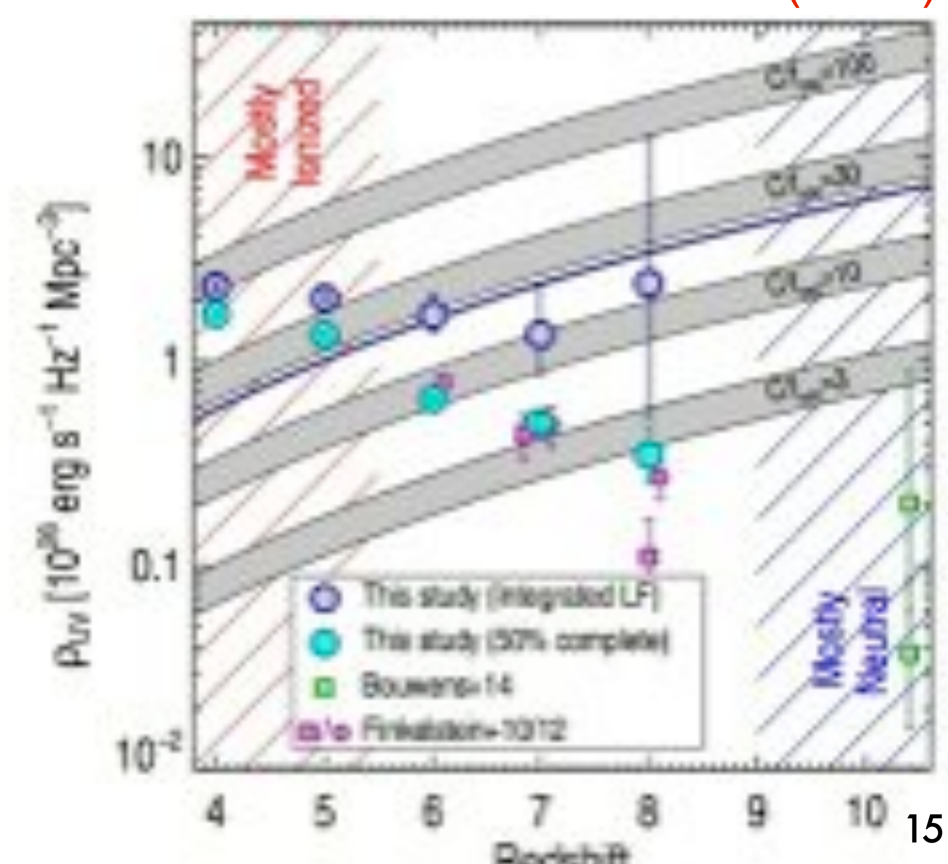
- Star-forming galaxies are thought to be the responsible of the ionising background Universe mostly (90%) ionised at z~6
- The exact contribution and the underlying physics (C, f_{esc} ...) depends on the faint end slope of the luminosity function.
- **Use cluster lenses as natural telescopes to probe deeper in the Universe:**

The Hubble Frontier Fields Clusters

Robertson et al. (2013)



Finkelstein et al. (2014)



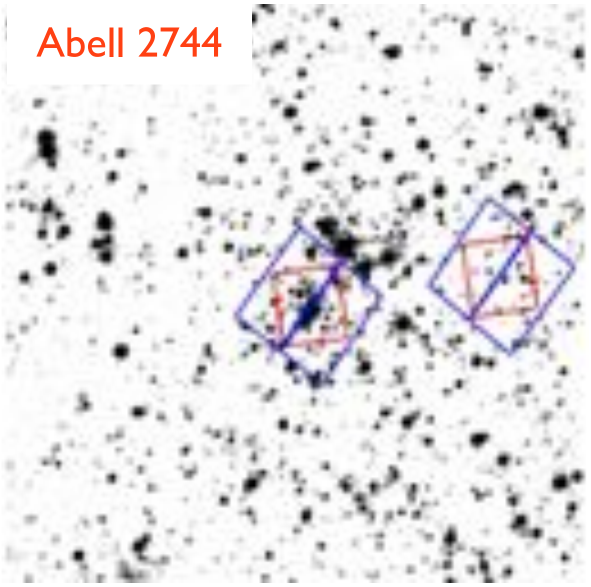
Hubble Frontier Fields Goals

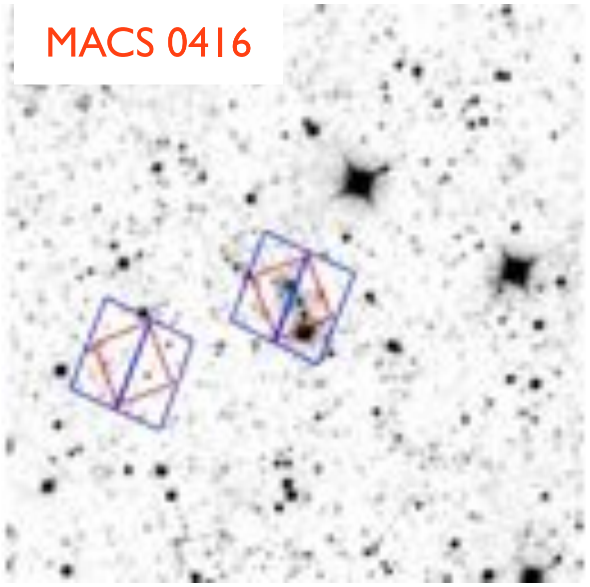
- **Main Focus: First galaxies/Re-ionisation**
  - intrinsically faint galaxies (fainter than UDF)
  - early star formation history ($z>7$)
  - high magnification sources (mag>50x)
- *Enabling science:*
  - **DM mapping**, *DM-Baryon interaction, DM self-interaction, nature of DM*
- *Other science:*
  - Lensed Transients (H_0 measurement)
  - Cosmography (Dark Energy constraints)

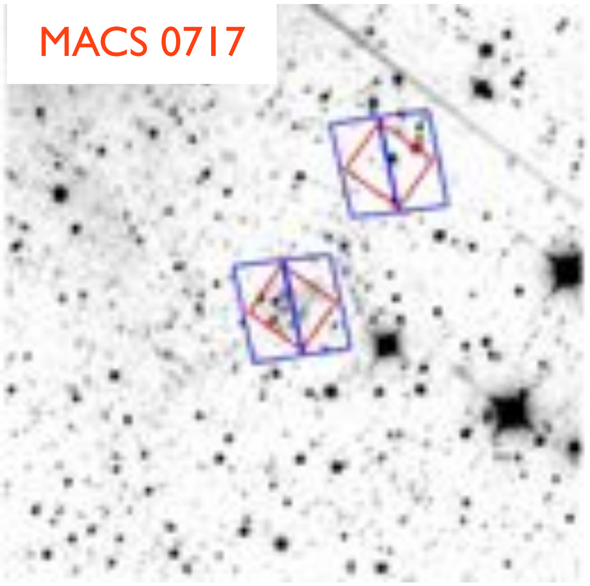
Hubble Frontier Fields

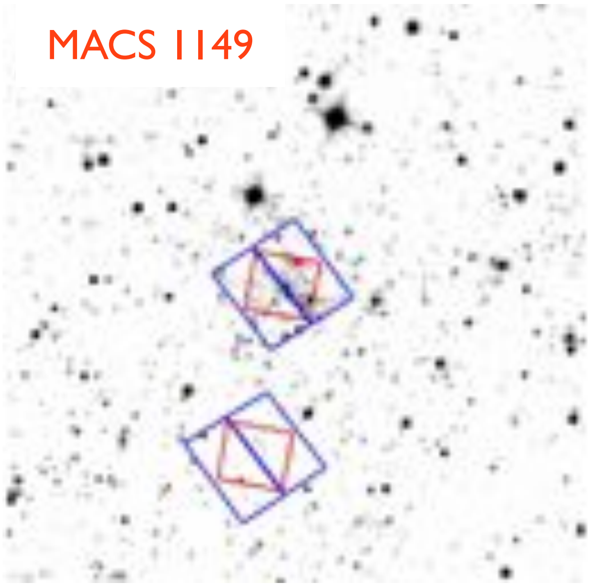
Combining the power of gravitational lensing with the unique HST observing capabilities

- **Ultra-deep Hubble imaging** of 6 clusters+parallel fields
- 140 orbits per cluster, 7 filters (ACS+WFC3)
- X-ray selected clusters with 0.3<z<0.55
- All have already been observed with HST
- Low-sky targets with ancillary dataset (Spitzer, Chandra)









http://www.stsci.edu/hst/campaigns/frontier-fields/

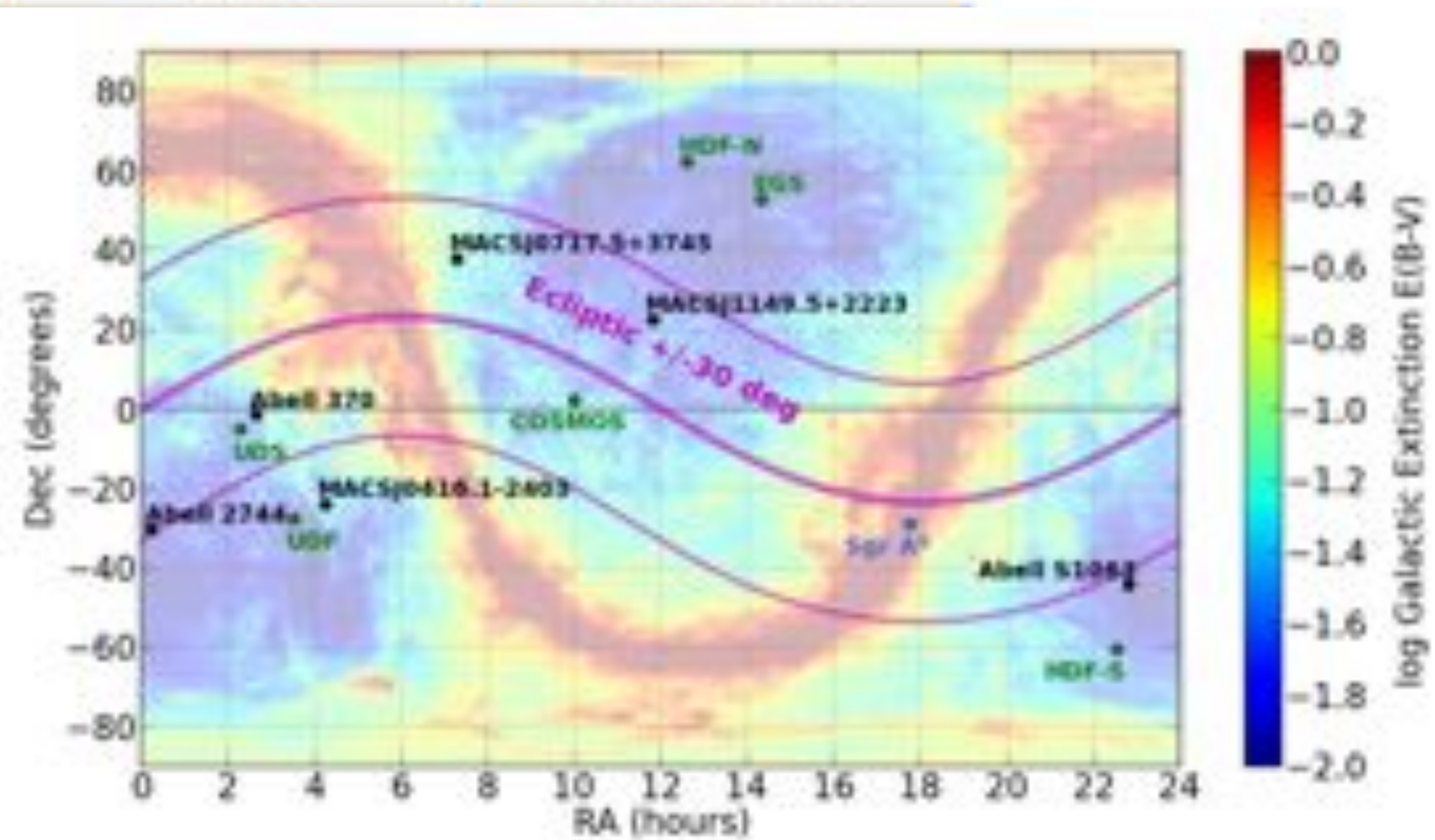
Frontier Fields Cluster Selected

• All X-ray Massive clusters (mostly from MACS sample) with 0.3<z<0.55, some overlap with CLASH clusters

•Non lensing selection Criteria:

- Ecliptic latitude and zodiacal foregrounds
- Galactic latitude, extinction, and foreground emission
- Declination and visibility from ground-based facilities
- Spitzer IRAC follow-up; Herschel, XMM, Chandra data availability

Cluster Name	z
Year 1:	
Abell 2744	0.308
MACSJ0416.1-2403	0.396
Year 2:	
MACSJ0717.5+3745	0.545
MACSJ1149.5+2223	0.543
Year 3:	
Abell S1063 (RXCJ2248.7-4431)	0.348
Abell 370	0.375



Observing Plan & Where to get data

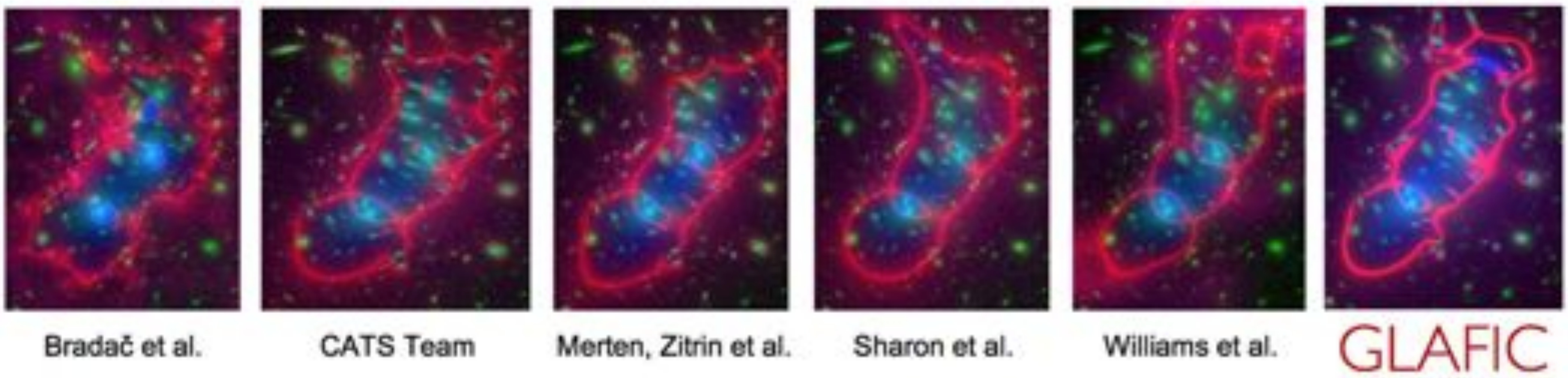
4 clusters fully observed - 2 more to be done

- Observation Status: http://archive.stsci.edu/prepds/frontier/obs-status/
- MAST webpage: http://archive.stsci.edu/prepds/frontier/
- Data repository: http://archive.stsci.edu/pub/hlsp/frontier/
  - where one can find: catalogue, images and models

HFF Requirements

- ✓ Deep *Hubble* data (DD projects: 840 orbits)
- ✓ Accessible data (Immediate STScI data releases)
- ✓ Accurate and Precise Mass models (Modelling plan)
  - ✓ large number of multiple images (ID in progress)
  - ✓ redshift of multiple images (just starting)
  - ✓ other multi-wavelength imaging (Many follow-up!)
  - ✓ other mass contraints: WL, X-ray, SZ?, galaxy dynamics (in progress)

Pre-HFF Mass Modelling



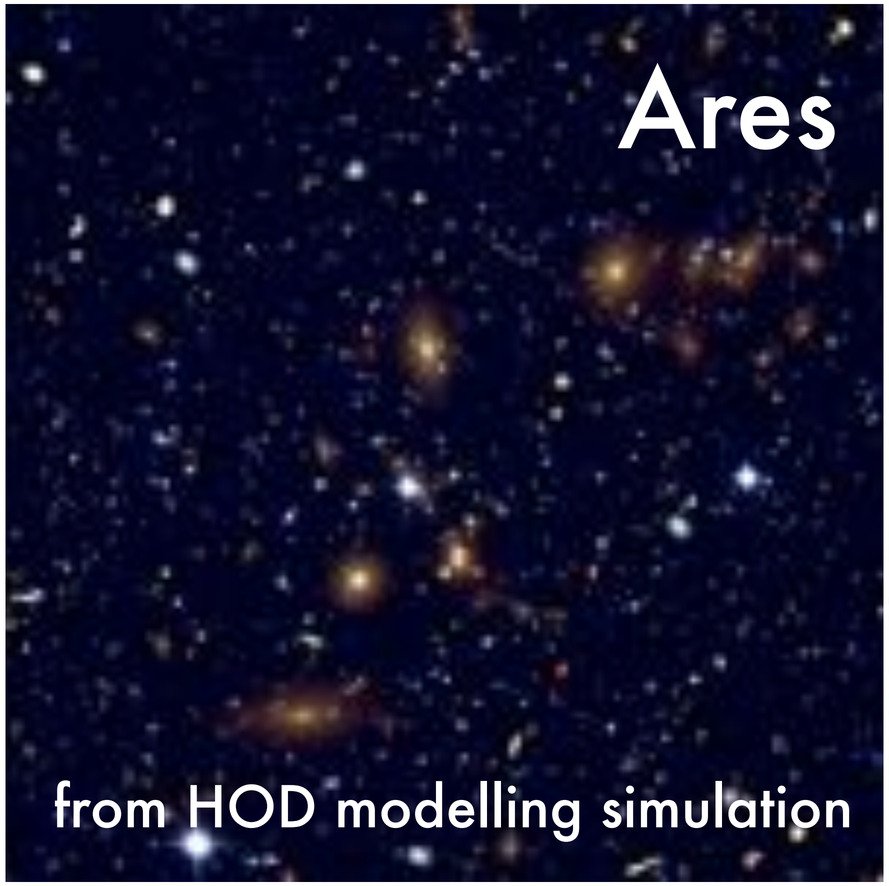
- Model access can be found here:
  - http://archive.stsci.edu/prepds/frontier/lensmodels/

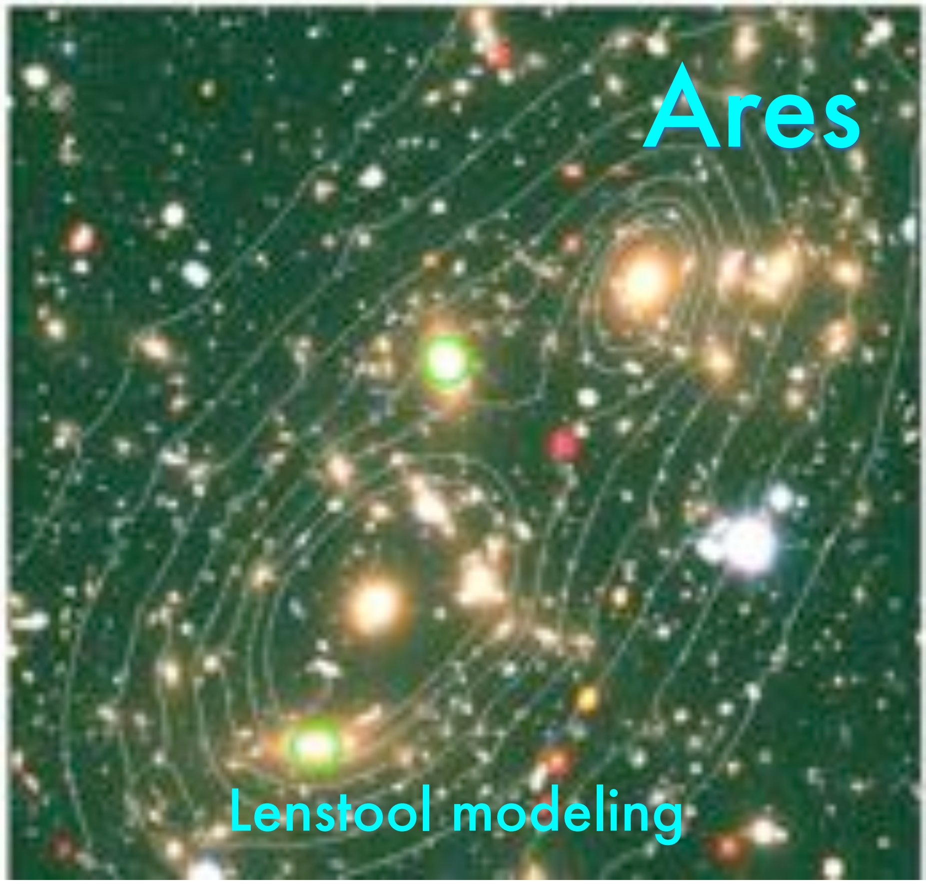
Pre-HFF Mass Modelling

- Model access can be found here:
  - http://archive.stsci.edu/prepds/frontier/lensmodels/
- Model Evaluation: Need to define the FOM of the models!
  - **Must give the image RMS a well define set of secure multiple images**
  - Make sure that model does not predict extra images that are not seen
  - When comparing models - should ask question, where the constraints the same, the priors the same (number of clumps)?
- New HFF model from the different teams to be made public September 15, 2015 for the two first cluster A2744 and MACS0416

Simulated cluster modelling challenge

- Simulated clusters can be found here: http://pico.bo.astro.it/~massimo/Public/FF/ares.html [login: FFmodeler passwd:FFmagnify]
- Color image: http://www.stsci.edu/~dcoe/FF/MAX/ares/
- Natarajan, Meneghetti & Coe compared the results provided by different modellers => ultimate goal: improve lens modelling !
- A new simulated cluster challenge planned in the next months.



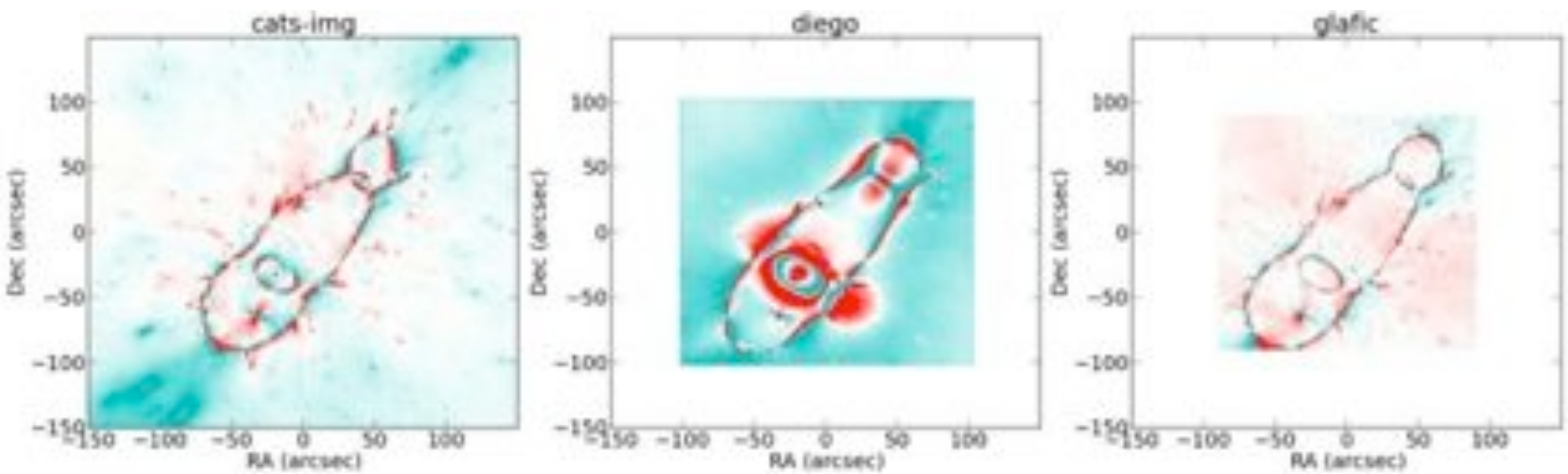



Test case #1:
Ares, z=0.5

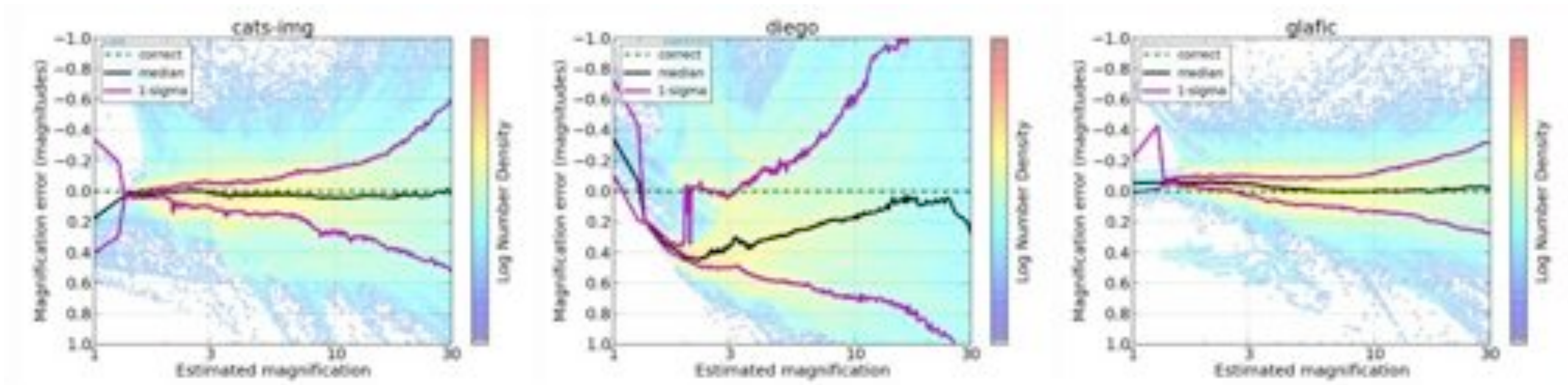
Testing Lensing Models

Reconstruction of the mass distribution
of simulated galaxy clusters

Example: magnification maps

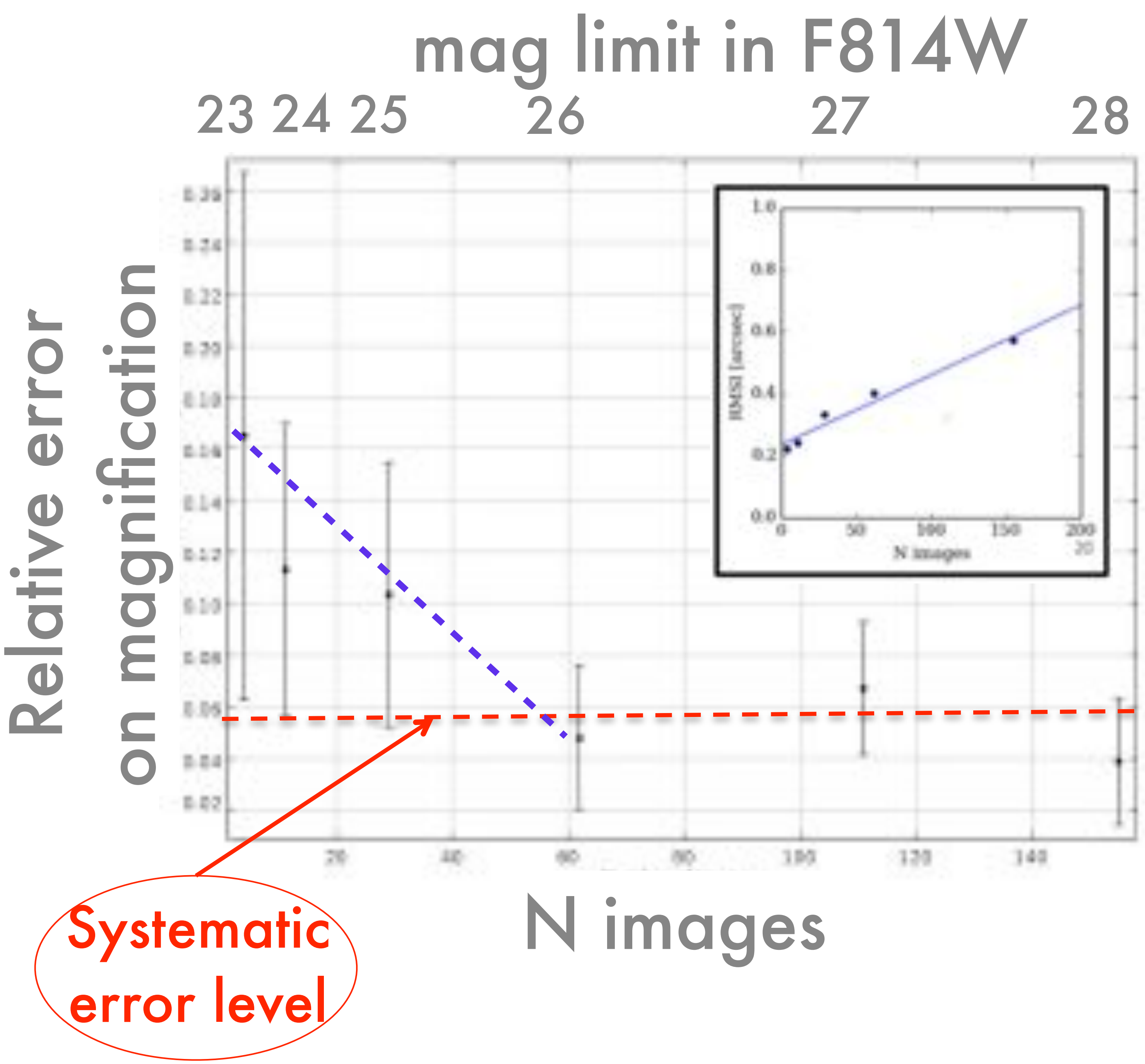


Meneghetti, Natarajan, Coe et al 2015 in prep



The FF lens modelling comparison project

Errors on magnification



- In our ARES model, we improve on statistical errors until $N_{image} < 60$
- **Modelling systematic errors** dominate at $N_{image} > 60$
- Same behaviour for the errors as for (Ω_m, w_X)

Jullo et al 2015 in prep

MACSJ0416 : Before HFF …

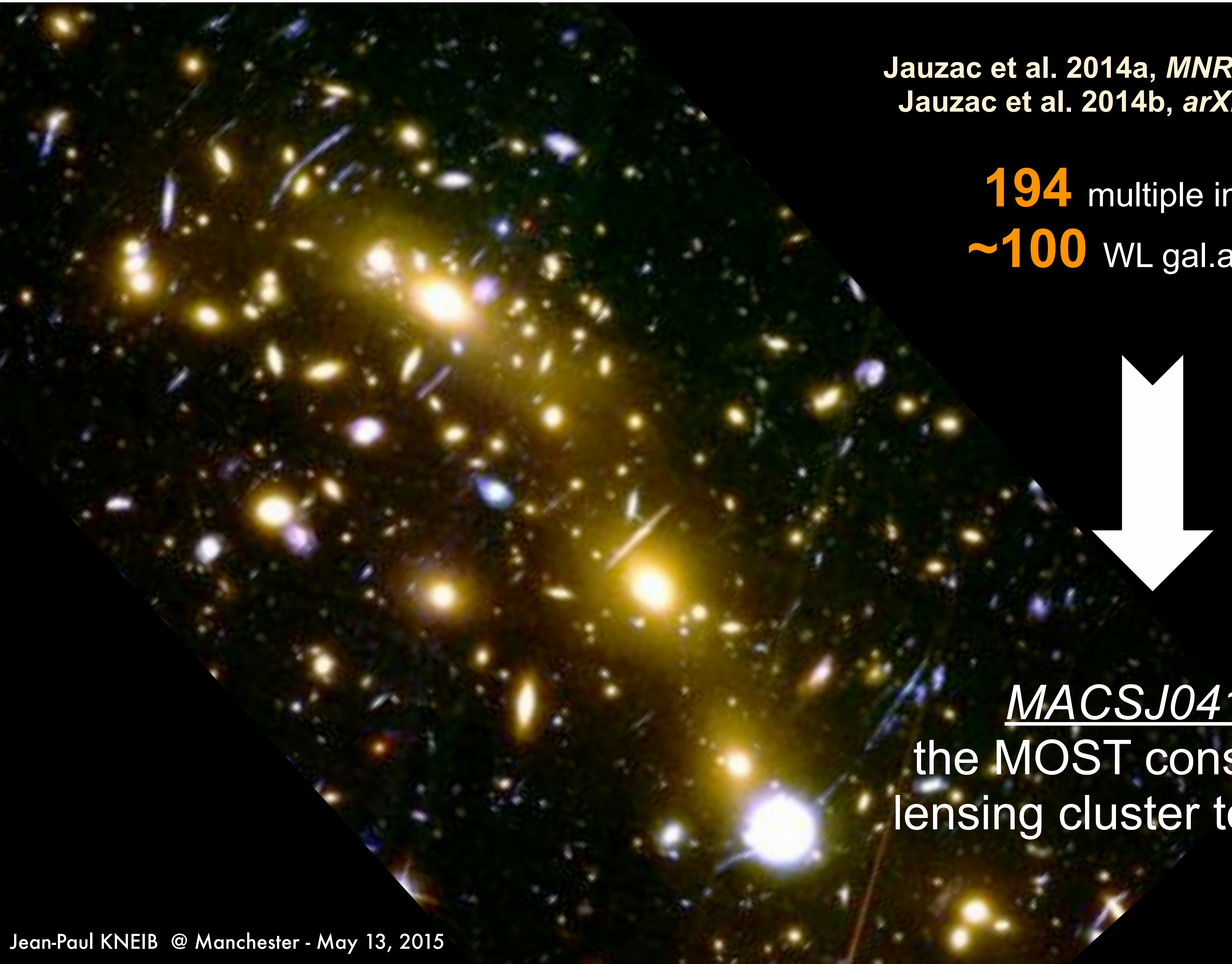
<u>Previous GL Analysis :</u>
Zitrin et al. 2013, *ApJ, 762, 30*

- 34 SL multiple images
- no WL data

<u>PreHFF GL analysis :</u>
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}

MACSJ0416 : … After HFF !!!

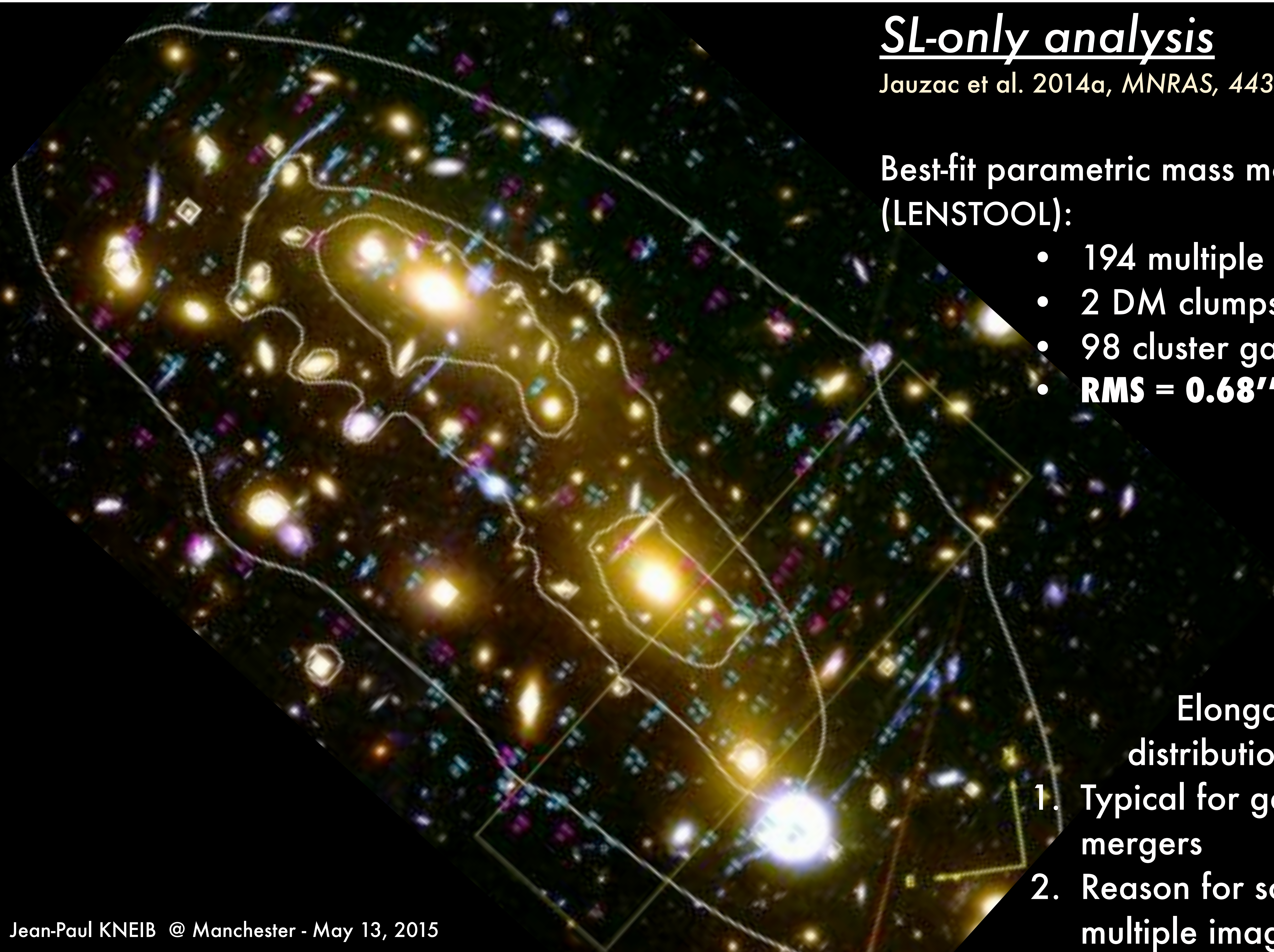


Jauzac et al. 2014a, *MNRAS, 443, 1549*
Jauzac et al. 2014b, *arXiv, 1406.3011*

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

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

Multiple Images in MACSJ0416



SL-only analysis

Jauzac et al. 2014a, *MNRAS, 443, 1549*

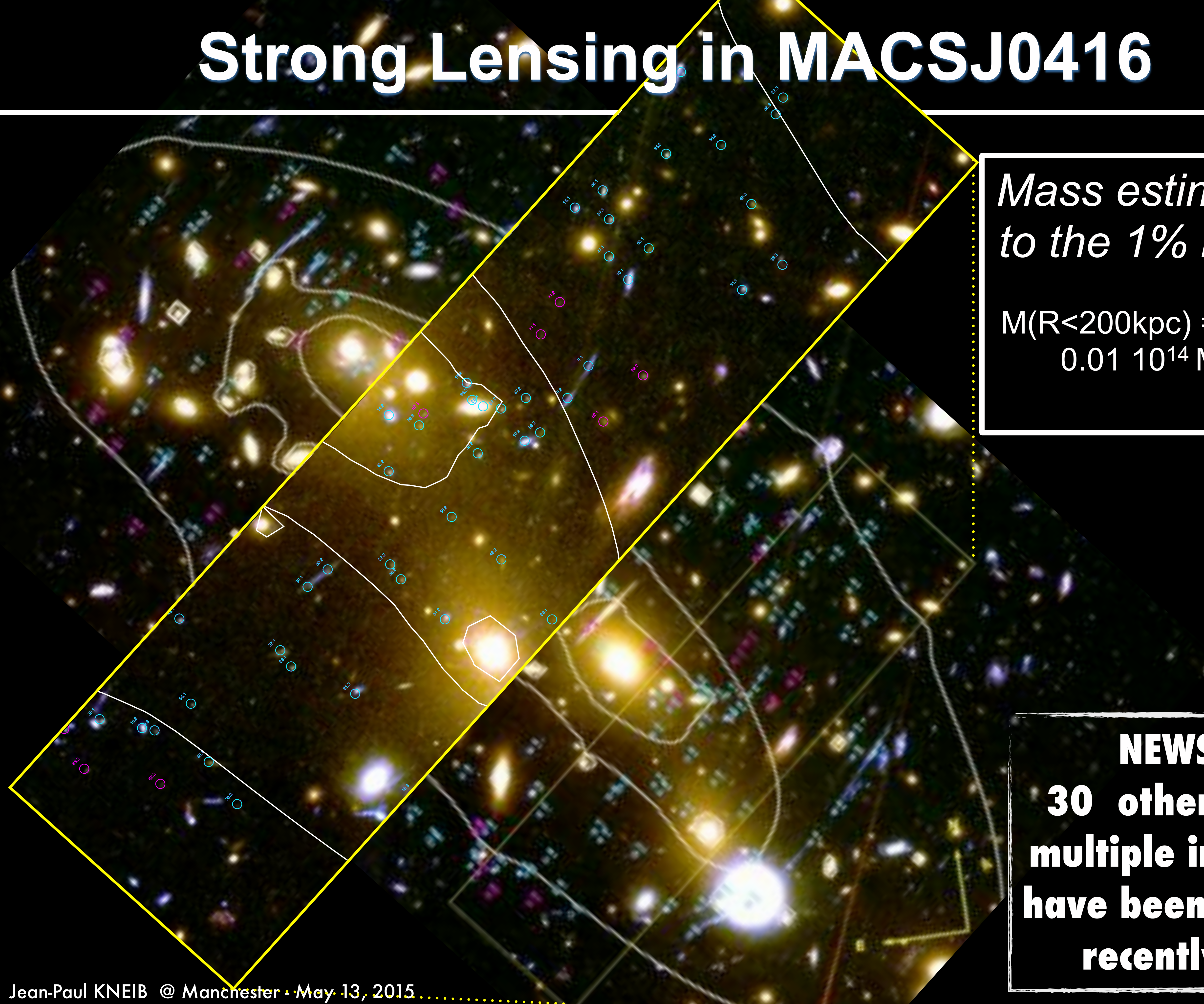
Best-fit parametric mass model (LENSTOOL):

- 194 multiple images
- 2 DM clumps
- 98 cluster galaxies
- **RMS = 0.68''**

Elongated mass distribution NE-SW

1. Typical for galaxy mergers
2. Reason for so many multiple images

Strong Lensing in MACSJ0416



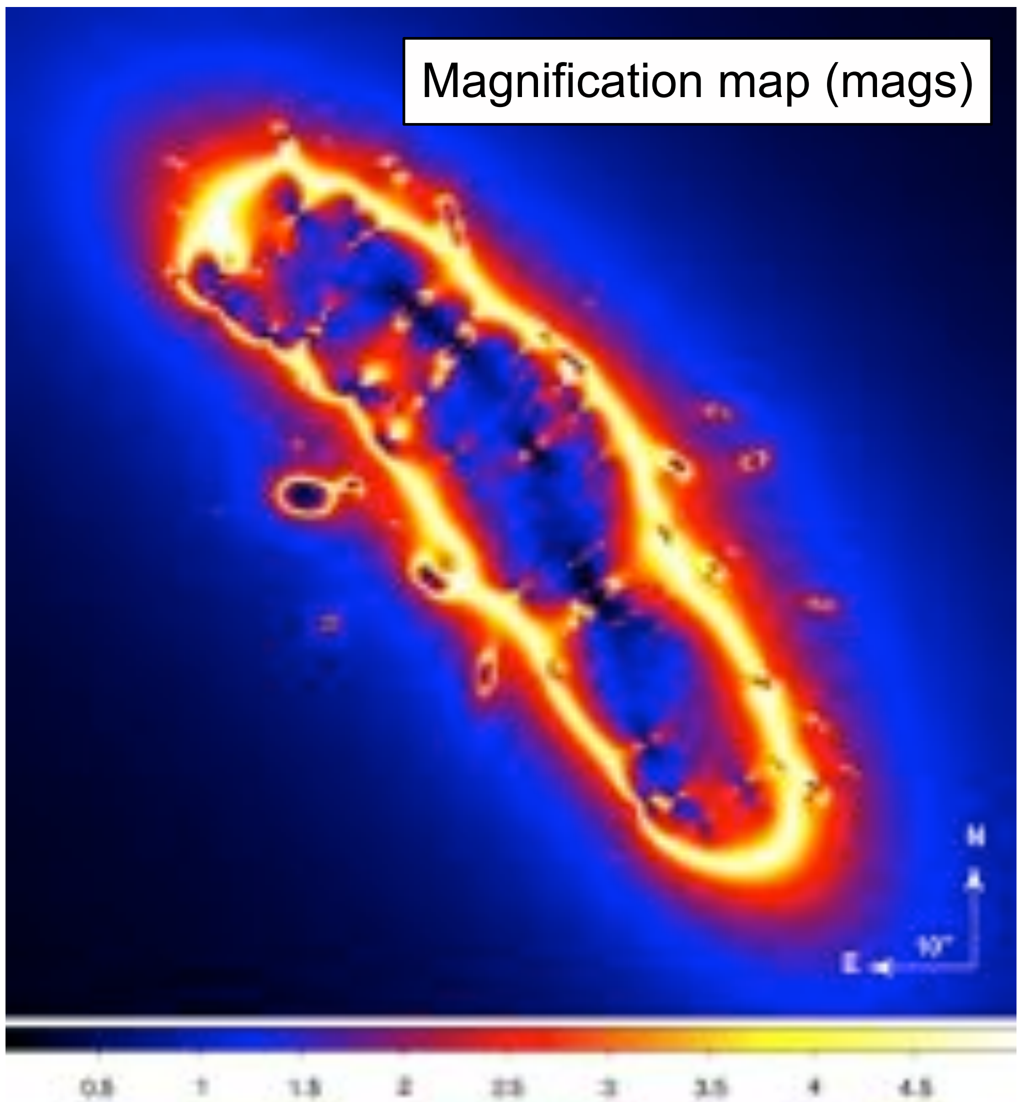
Mass estimation to the 1% level :

M(R<200kpc) = 1.60 ± 0.01 10^{14} M_{sun}

NEWS:
30 other new multiple images have been found recently !!

MACS0416 Results

Jauzac et al 2014

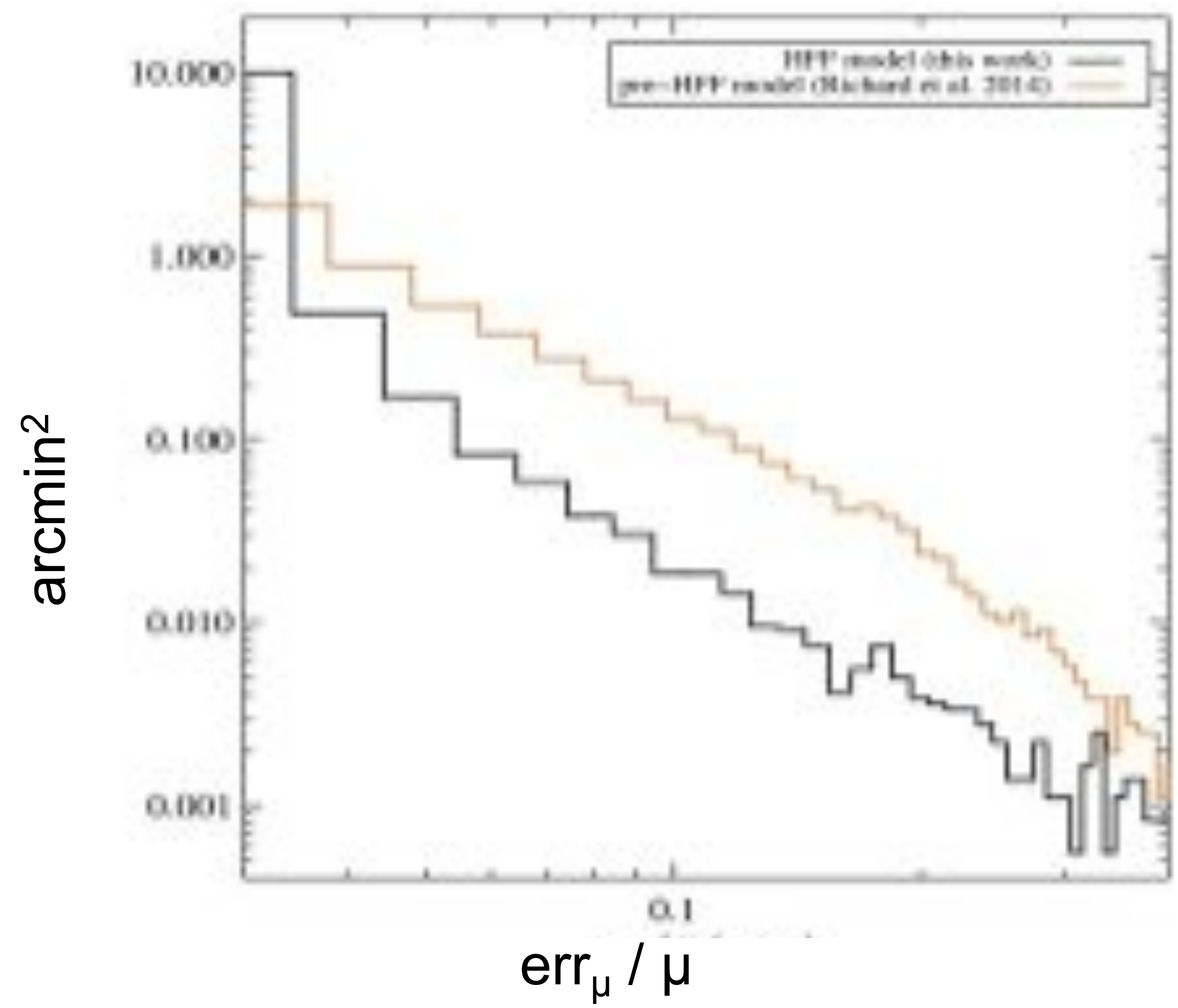


Mass estimation to the 1% level :

$M(R<200kpc) = 1.60 \pm 0.01\ 10^{14}\ M_{sun}$

Magnification to the 4% level :

$\mu\ = 3.88 \pm 0.15$

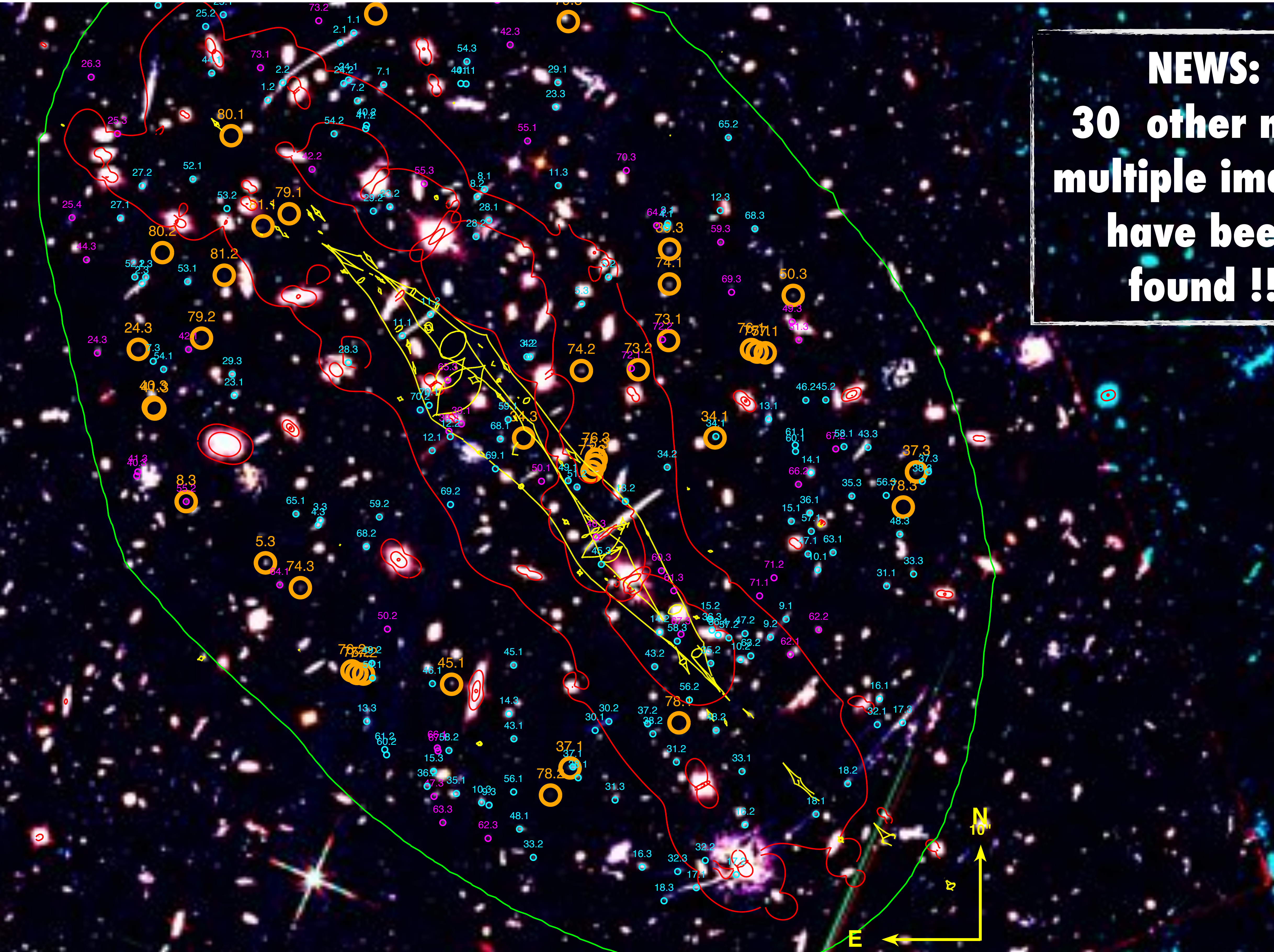


Highest precision ever obtained for mass & magnification measurements

Finding More Multiple Images

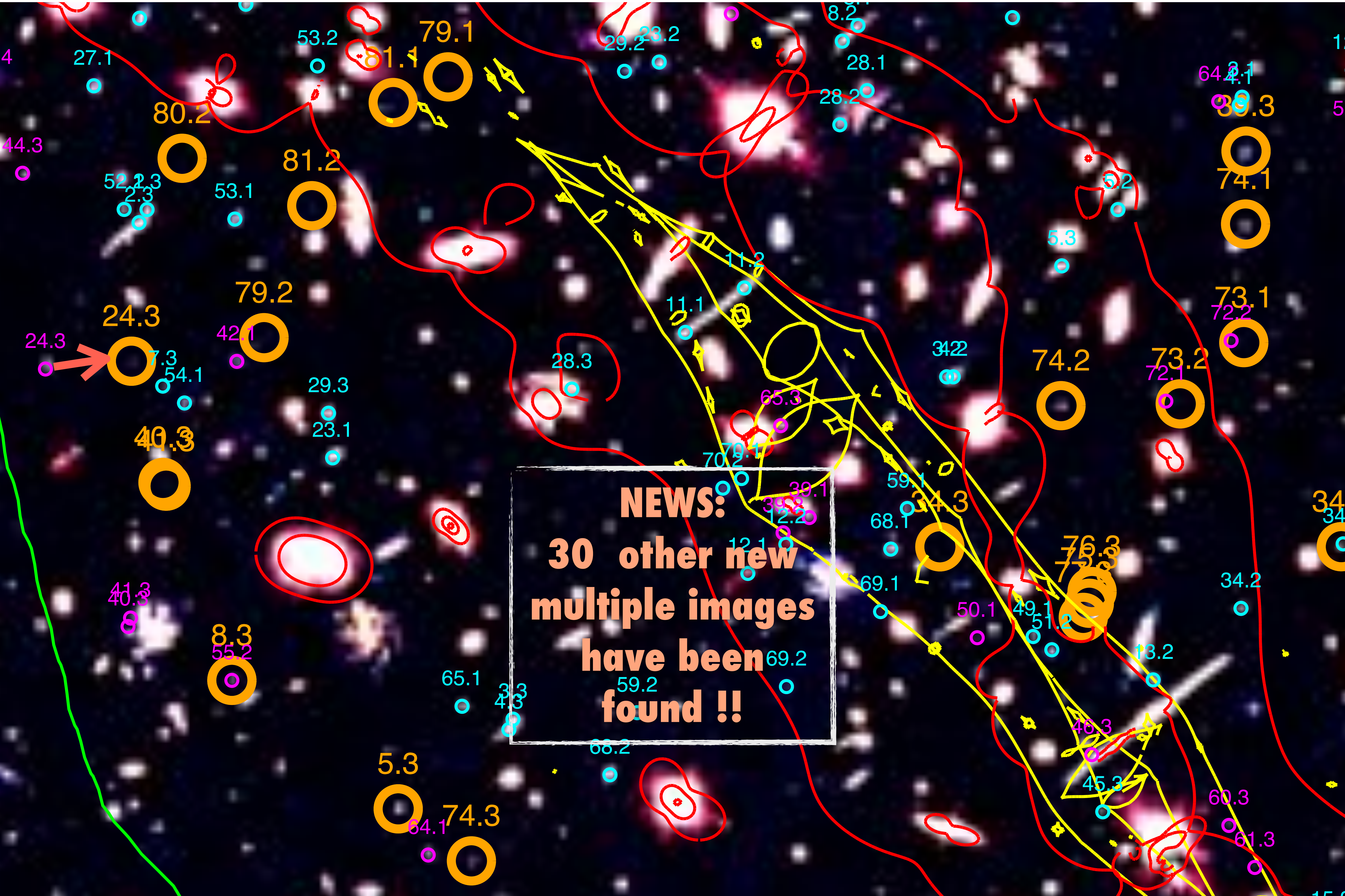
- Multiple images have:
  - ➡ same redshift, color, morphology
  - ➡ but when one image is an arc (only part of the source can be multiply imaged+high magnification reveals unresolved structure in counter image)
- Remove Cluster Light to find them better
  - ✓ Wavelet method (Livermore et al 2014)
  - ✓ Subtracting medianed image (CATS team)
- Multiple images are found by iterative process along the mass modelling of the cluster
- Automated multiple image finders in development

Multiple Images in MACSJ0416



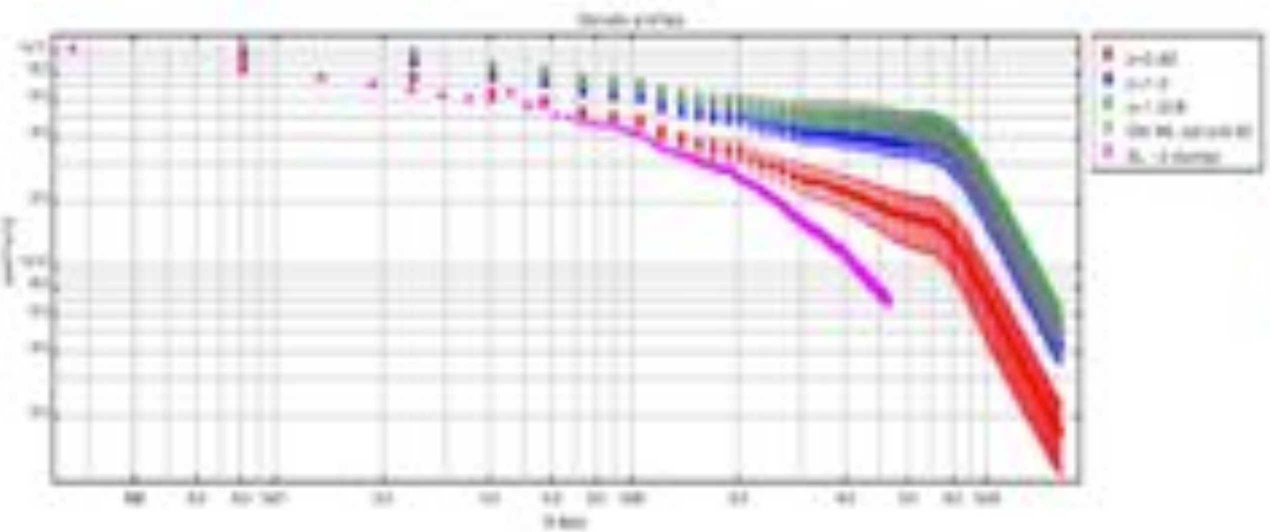
NEWS:
30 other new multiple images have been found !!

Multiple Images in MACSJ0416



Mixed parametric and free-form reconstruction to detect substructures

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

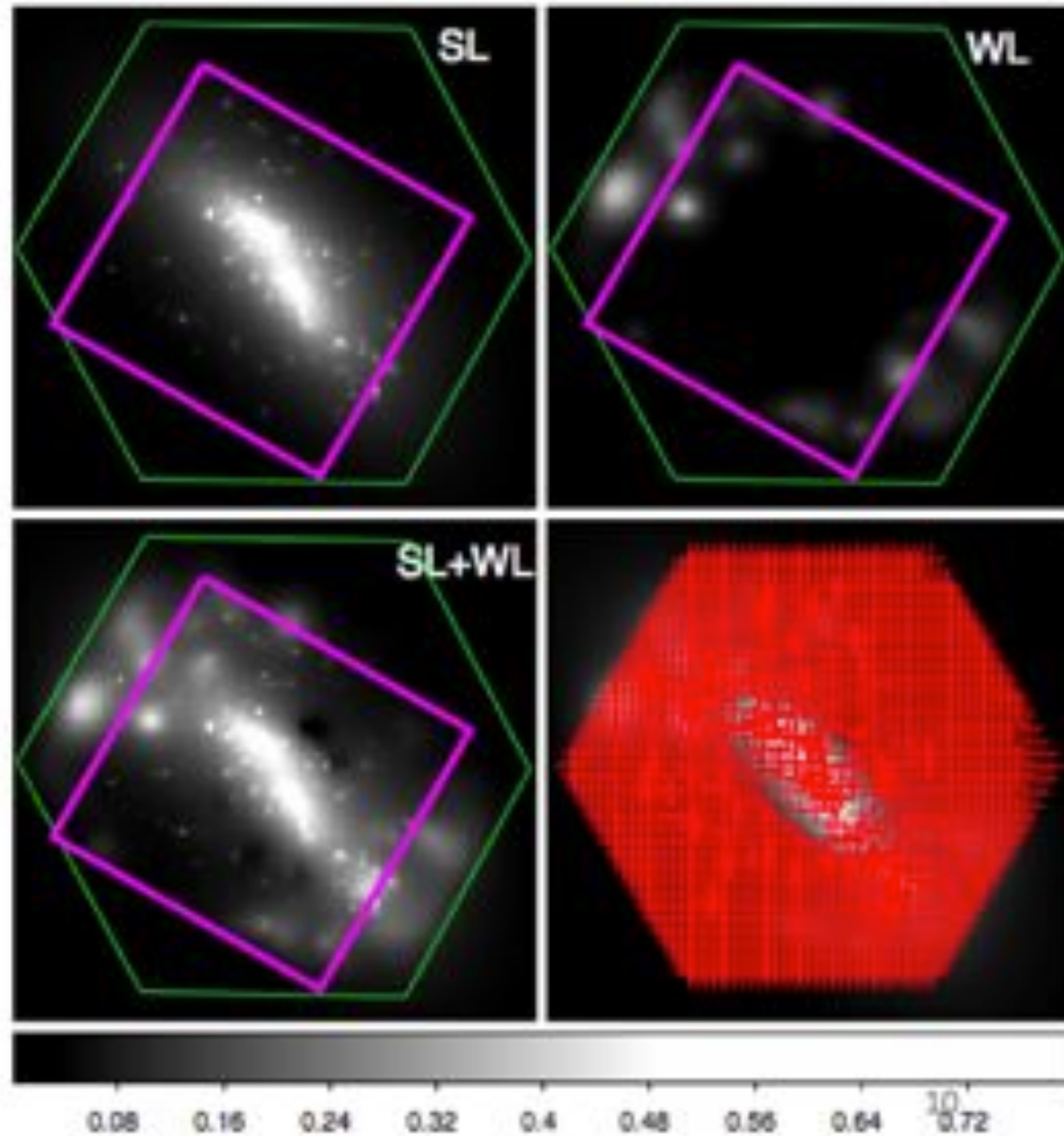


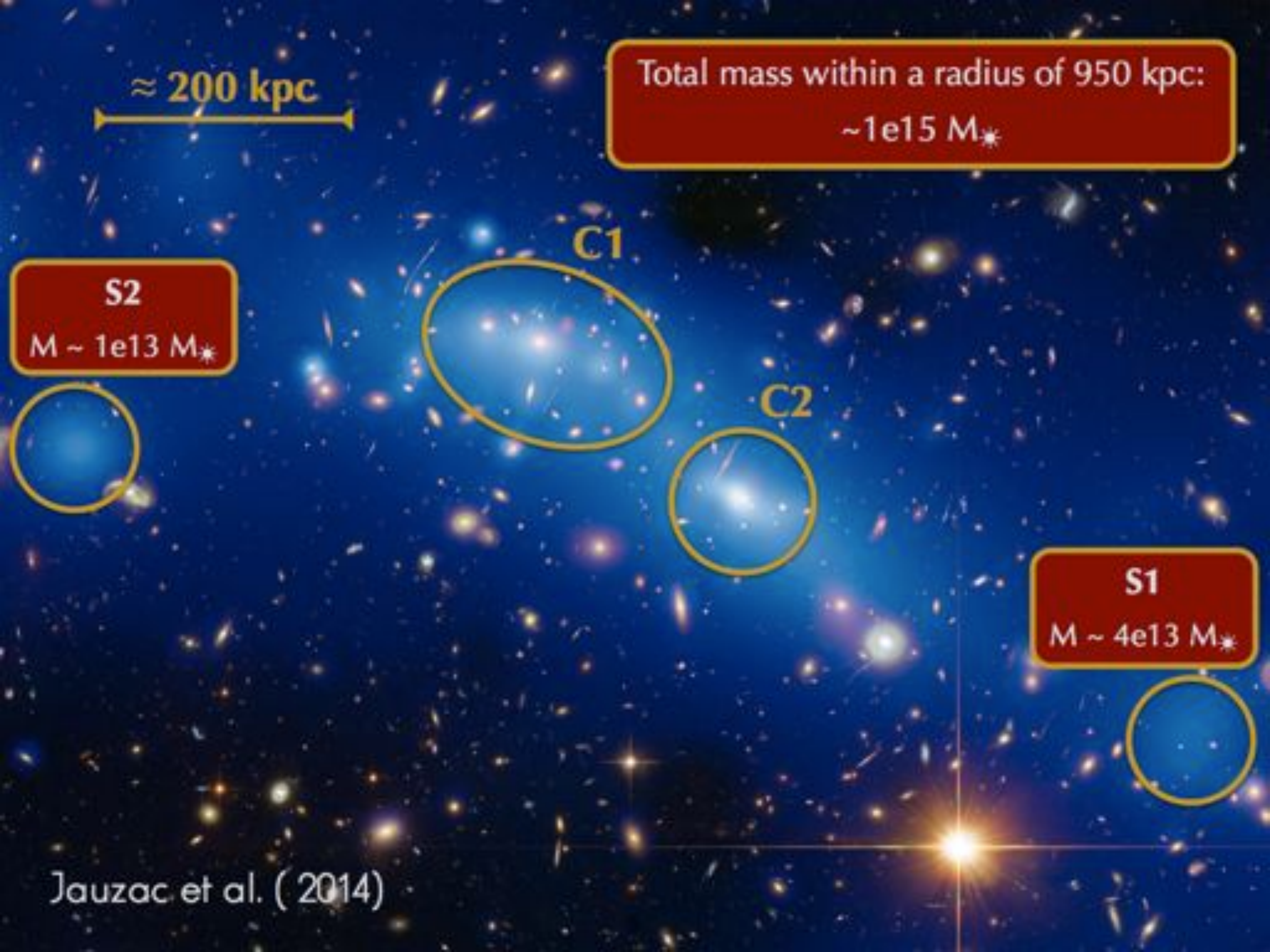
➔ Need to figure out SL and WL relative weights

Alternative, 2 step optimization

– Reconstruction with SL data

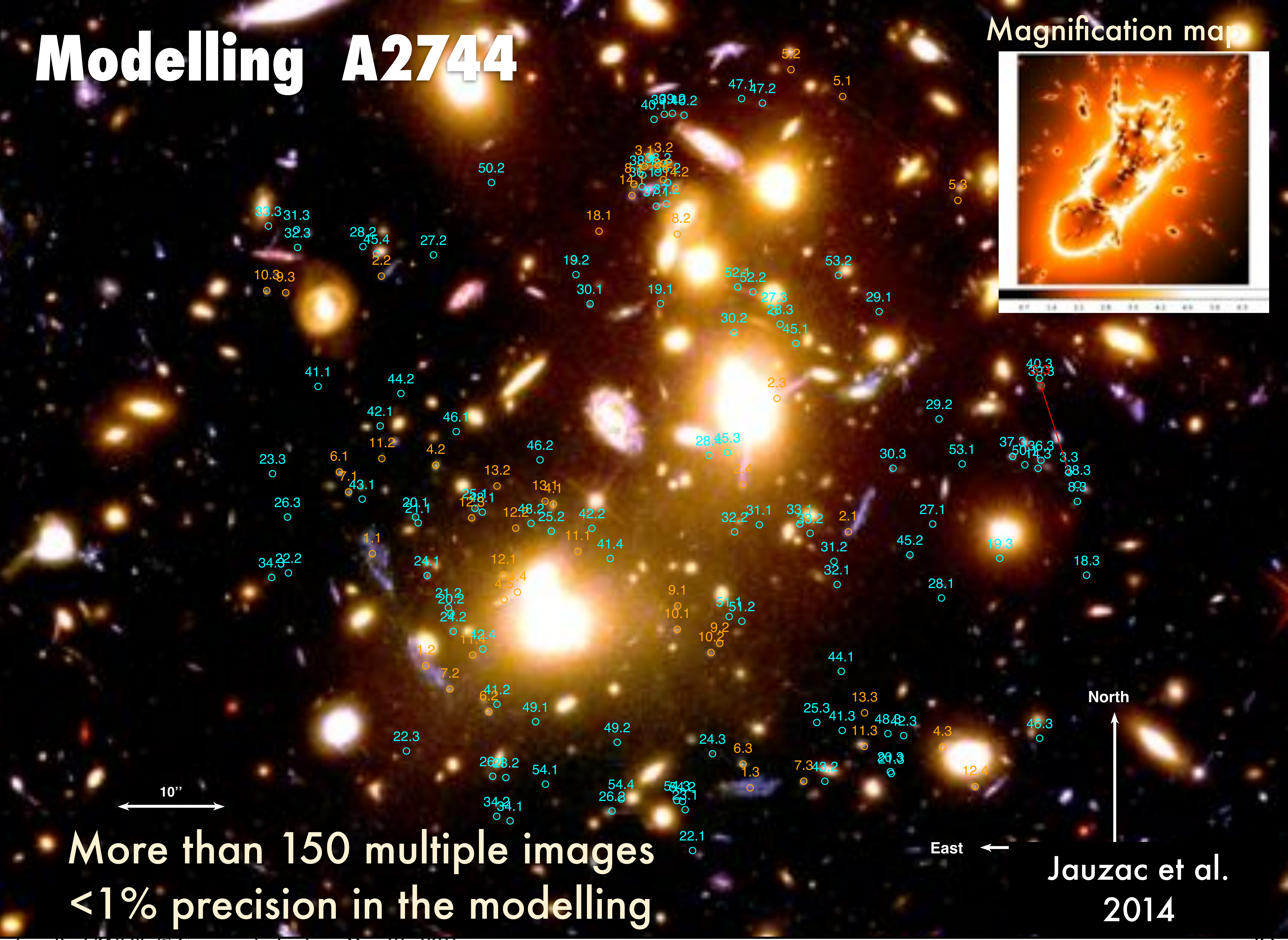
– WL reconstruction with prior parametric model





≈ 200 kpc
Total mass within a radius of 950 kpc:
~1e15 M☀
C1
C2
S2
M ~ 1e13 M☀
S1
M ~ 4e13 M☀
Jauzac et al. (2014)

Modelling A2744

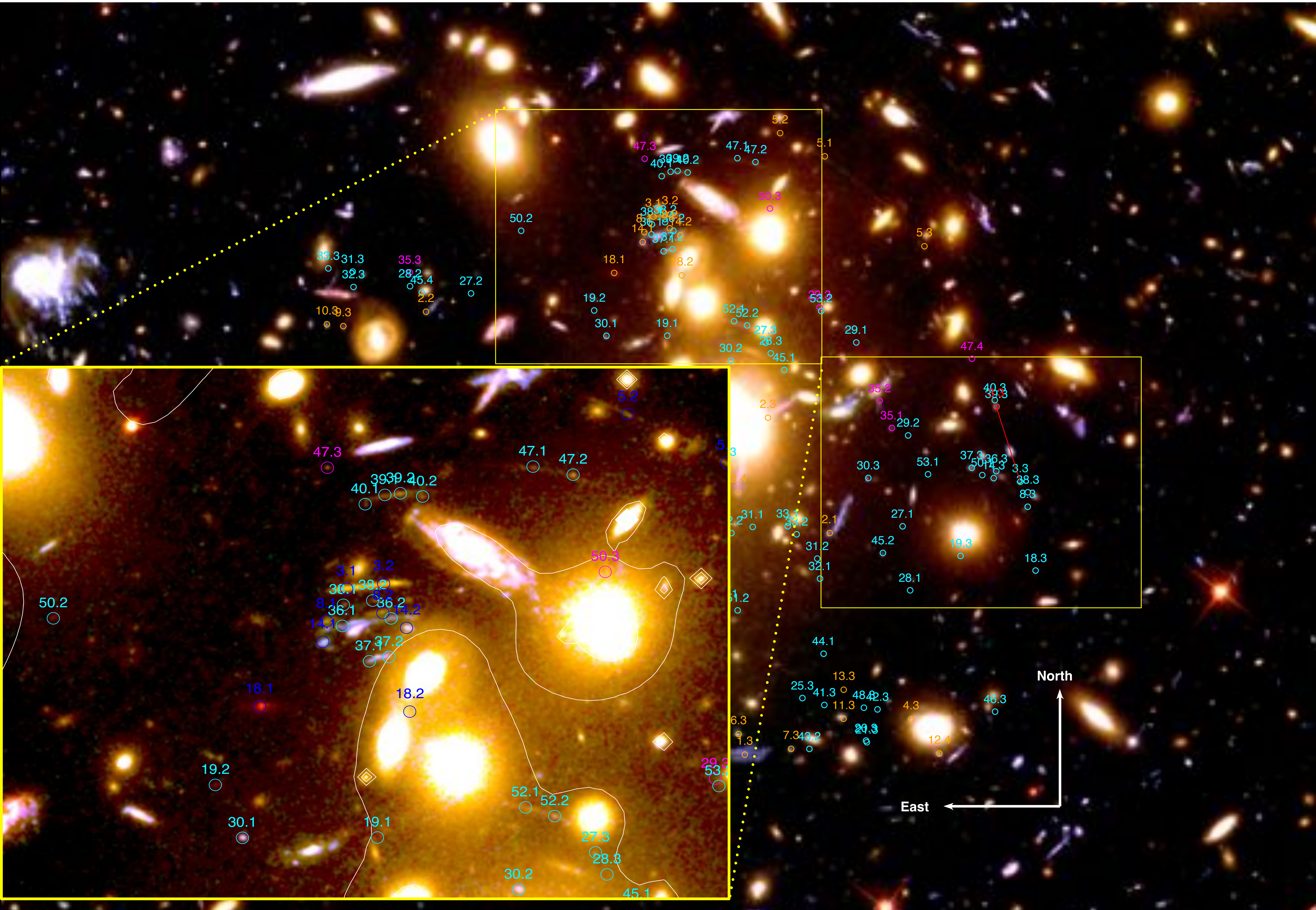


More than 150 multiple images

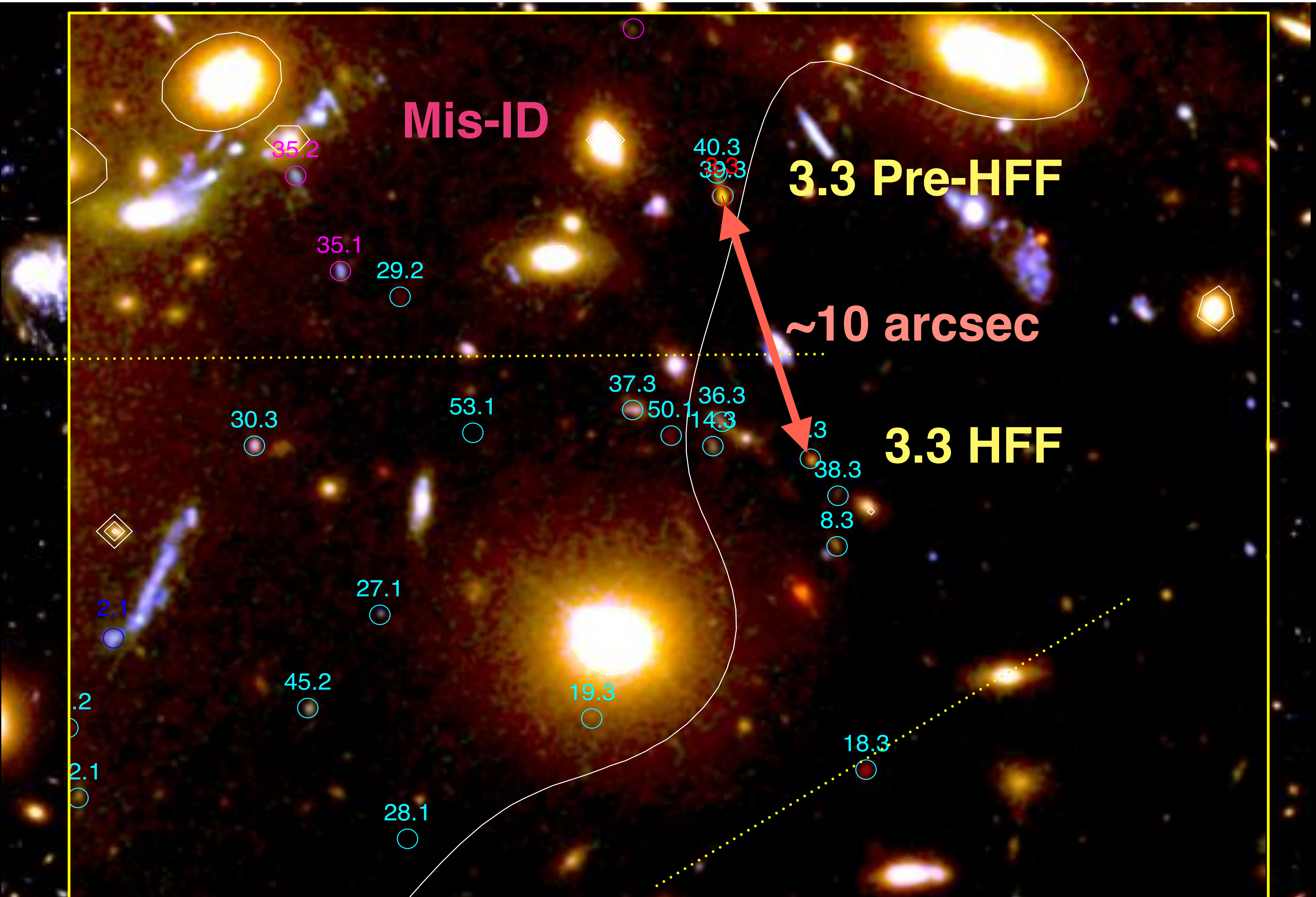
<1% precision in the modelling

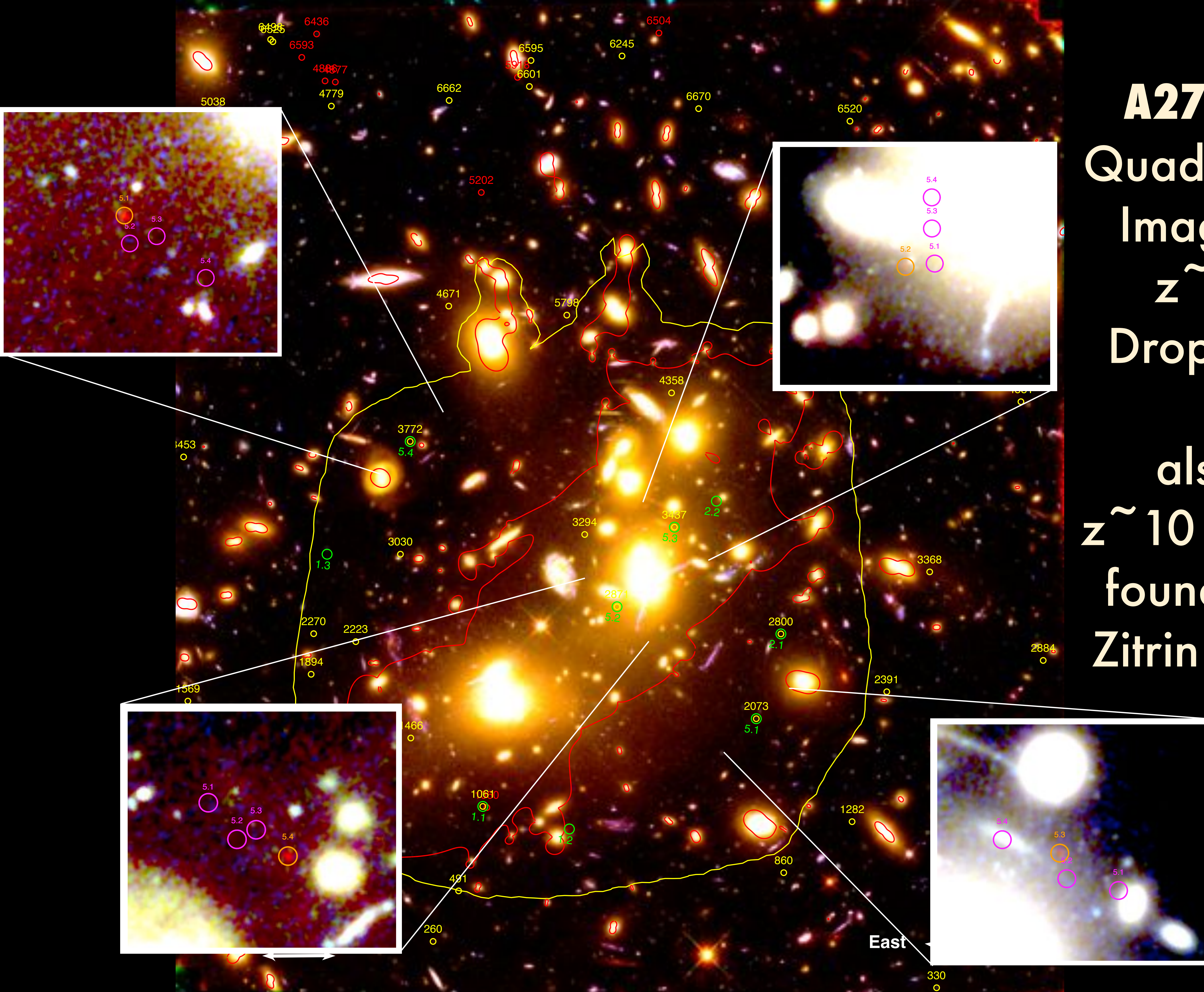
Jauzac et al. 2014

The Core of Abell 2744



Correct multiple image Identification



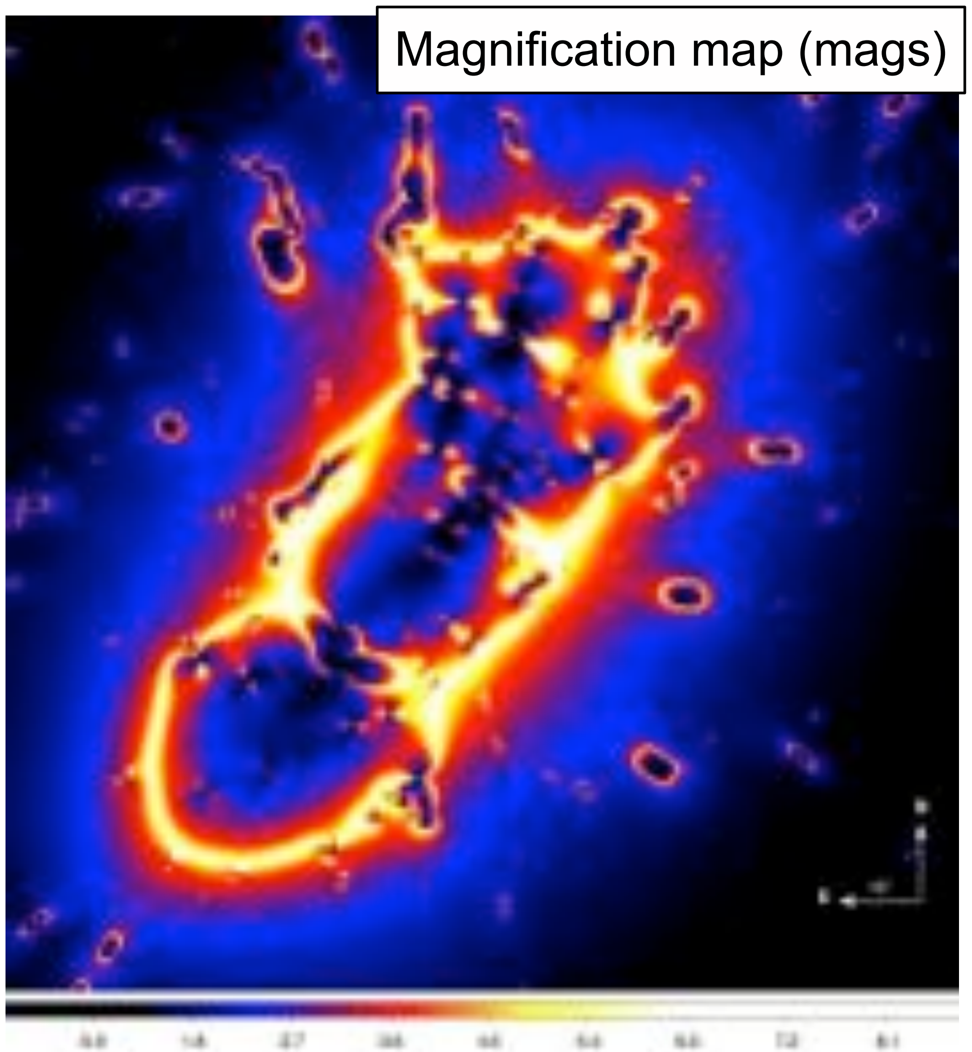


A2744:

Quadruply Imaged z~7 Drop-out

also z~10 triple found by Zitrin et al

Abell 2744 Results



Mass estimation to the <1% level :

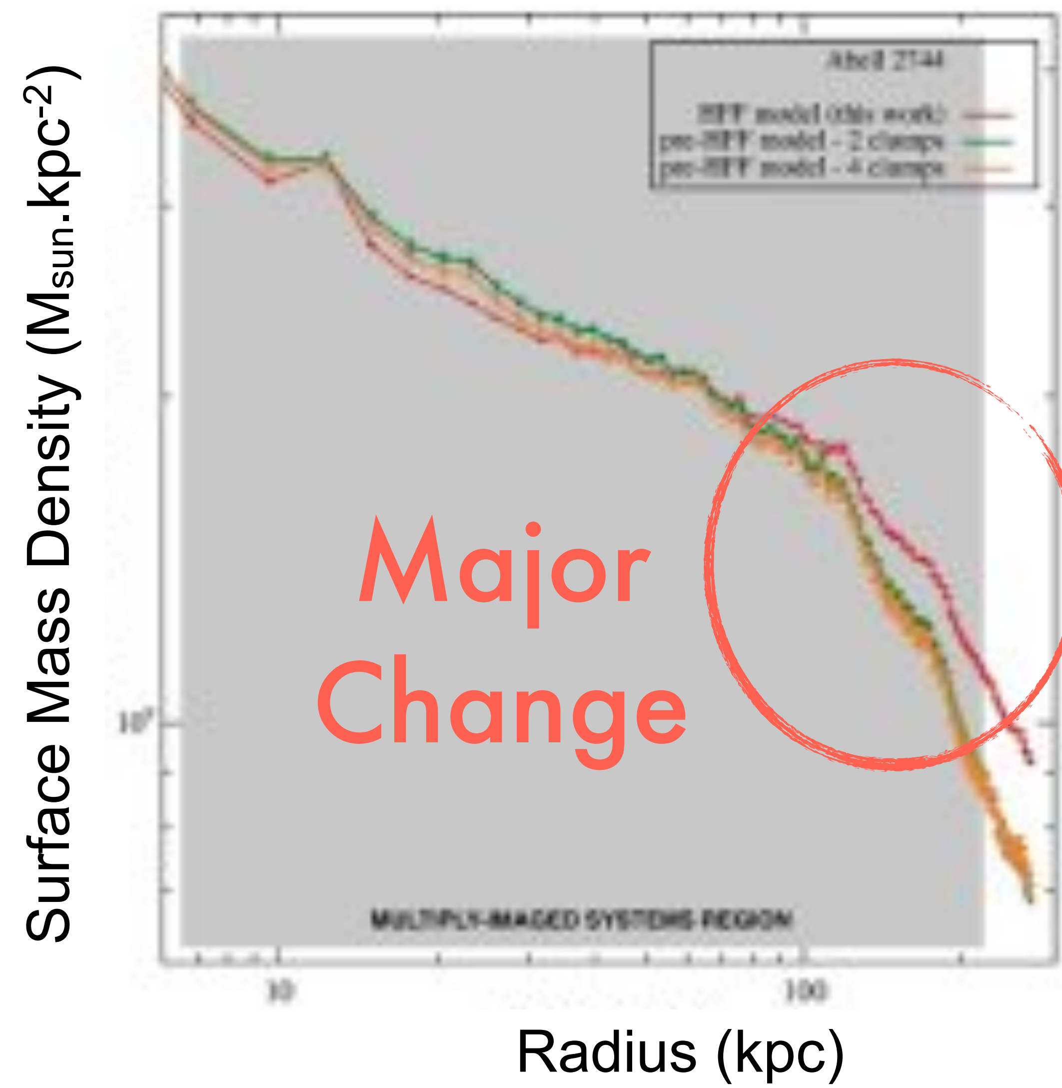
M(R<200kpc) = $2.156 \pm 0.003\ 10^{14}\ M_{sun}$

Magnification to the 2% level :

$\mu = 6.75 \pm 0.12$

pre-HFF (Richard et al. 2014, MNRAS, 444, 268) :

$\mu = 4.40 \pm 0.18$



- **multiple image ID correction compared to pre-HFF models**
- **more reliable estimation of the magnification**
- **better constraints on high-redshift LF (Atek et al. 2014)**

Distant Galaxies in Abell 2744

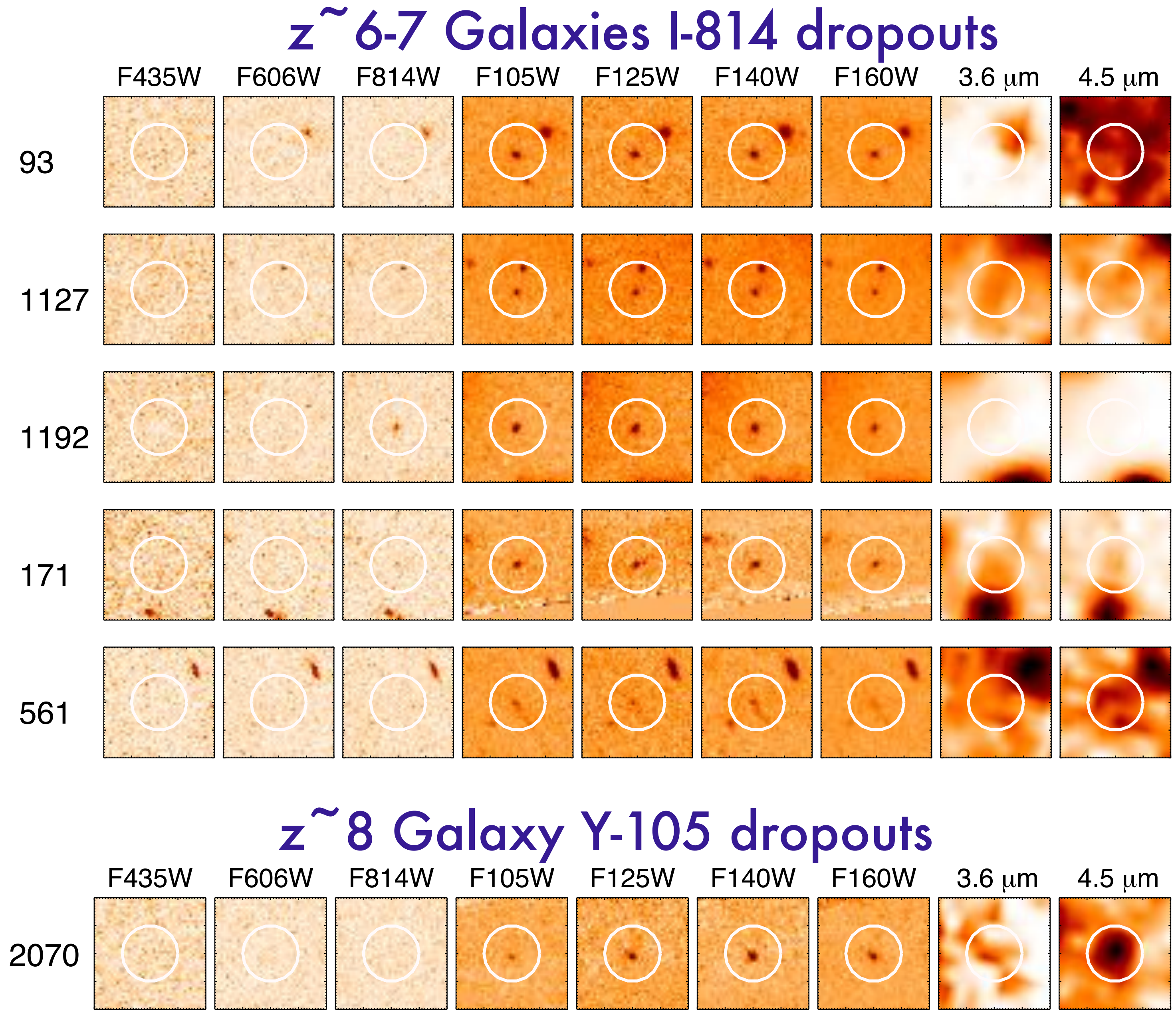
Observations

– HFF ACS & WFC3:

- A total of 140 orbits down to 29 AB mag.

- The UDF reaches a depth of 30 AB mag.

	ACS			WFC3			
Filter	F435W	F606W	F814W	F105W	F125W	F140W	F160W
Depth	28.8	29.4	29.4	28.6	28.6	29.1	28.3



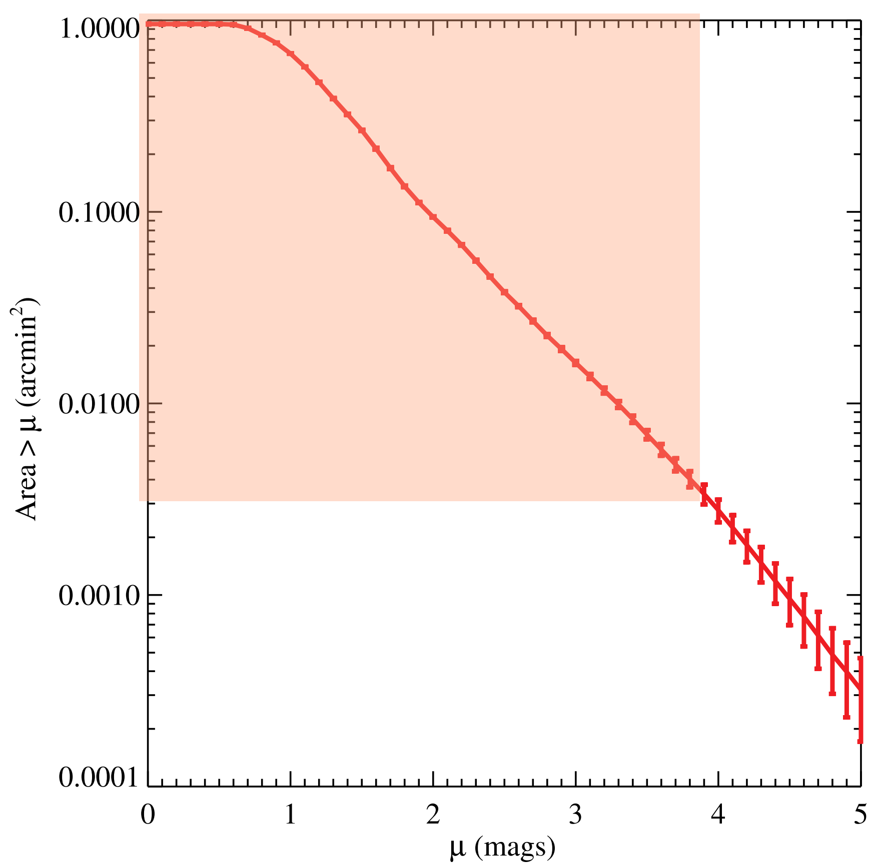
The UV Luminosity Function at z>6

Luminosity distribution of the sources:

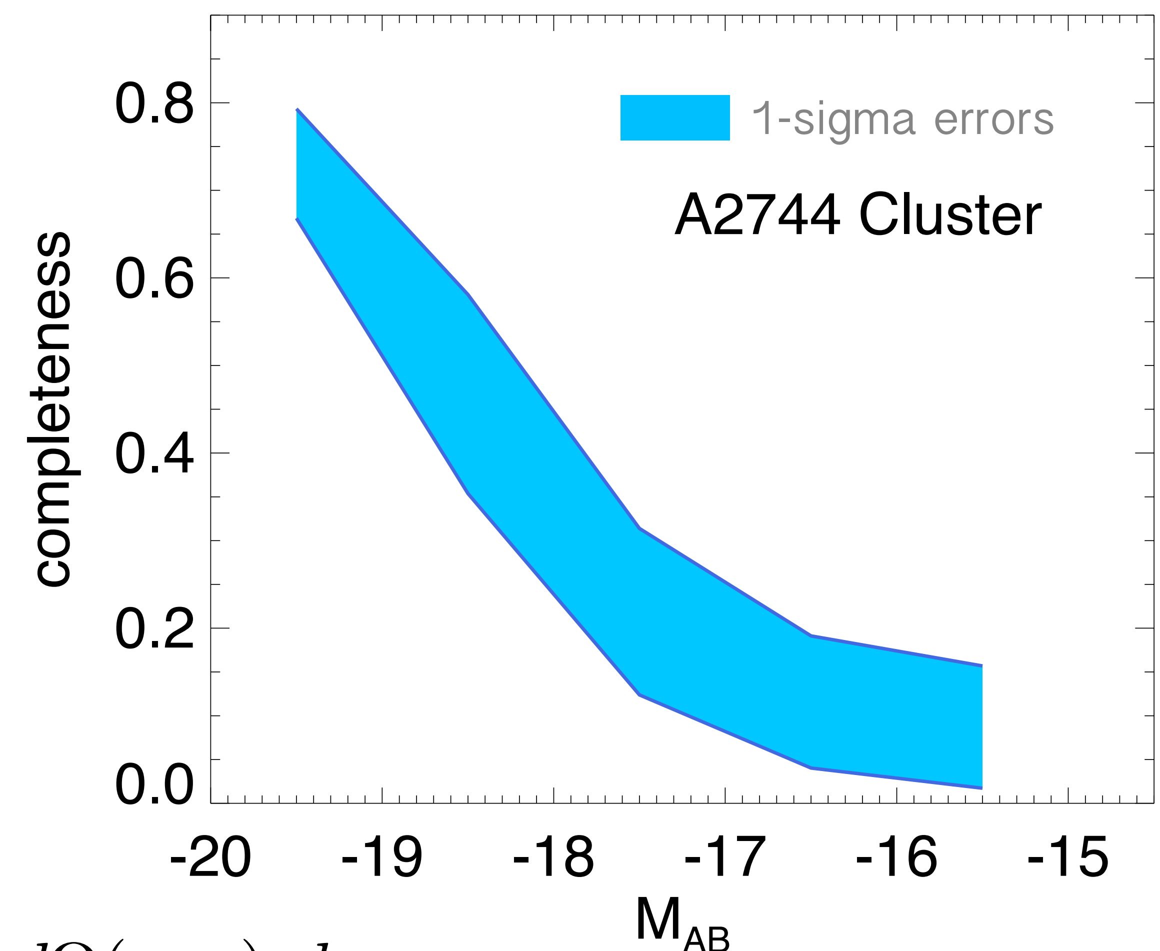
$$\phi(M)dM = \frac{N_i}{V_{eff}(M_i)}$$

- Completeness is a function of magnification e.g., source area reduction, sky position …

and **lensing distortion**



Jauzac et al. (2014)



Effective survey volume

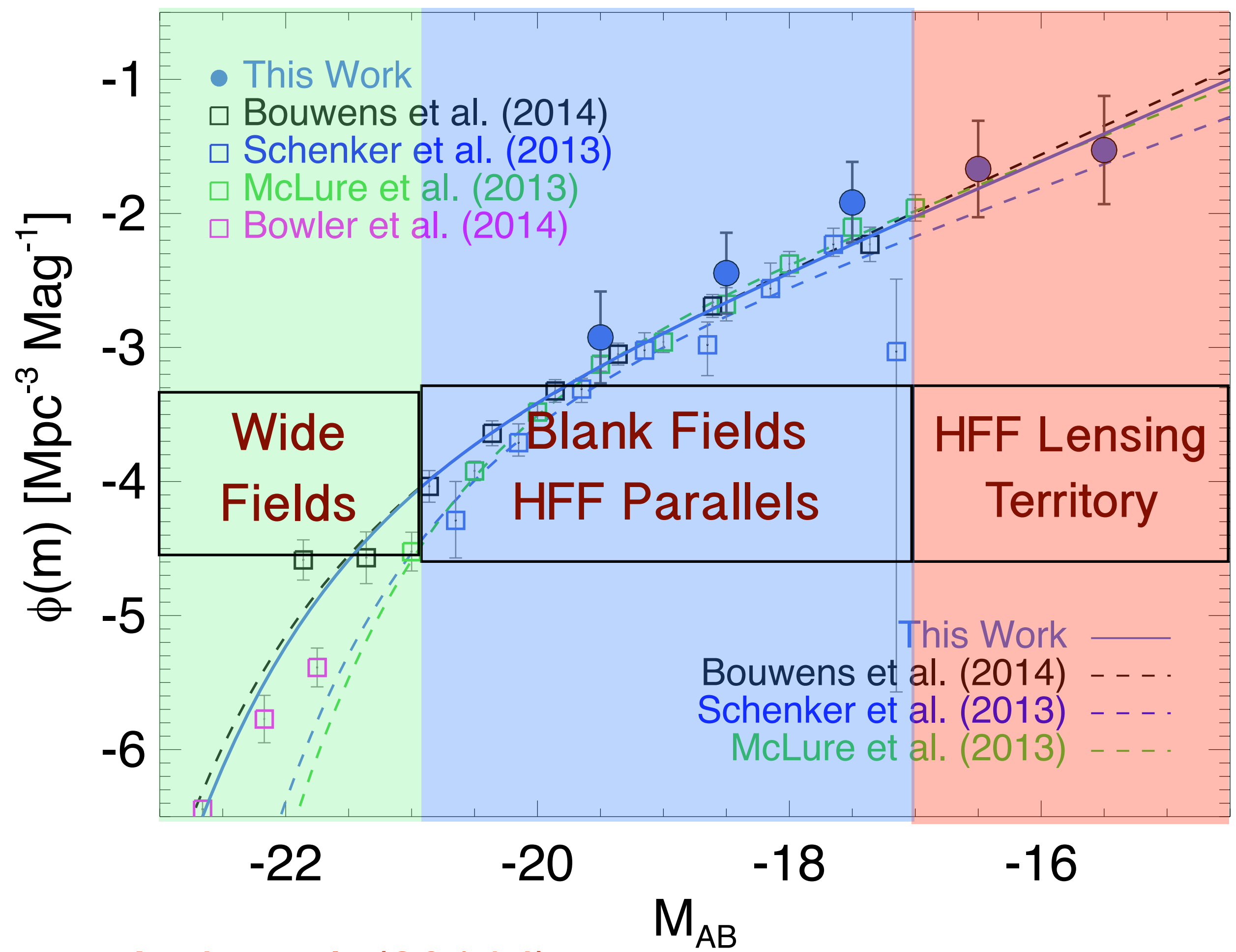
$$V_{eff} = \int_0^{\infty} \int_{\Omega > \Omega_{min}} \frac{dV_{com}}{dz} f(z, m, \mu)\, d\Omega(\mu, z)\, dz$$

The Faint-end of the UV LF at z>6

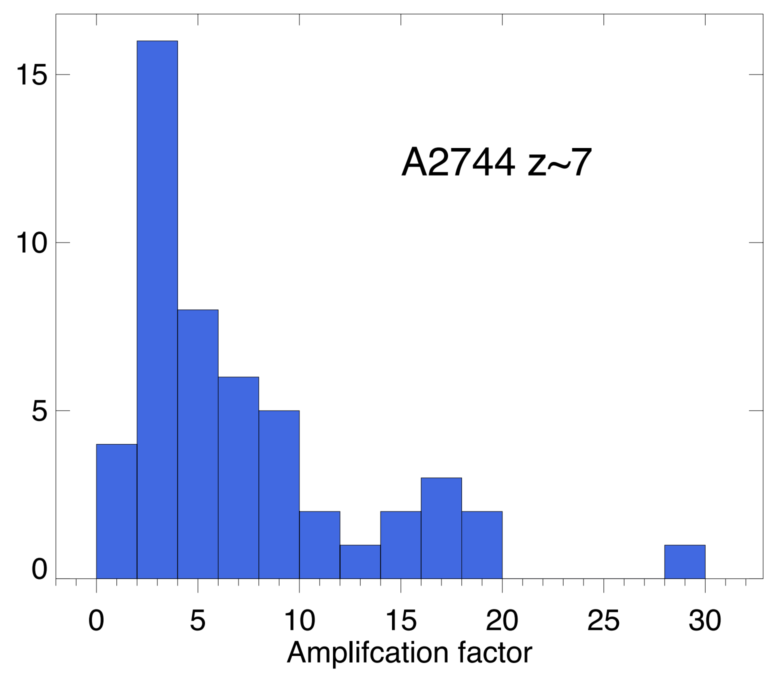
- Results in general agreement with blank fields
- Reaching down to $M_{abs,UV}$ ~ -15.5

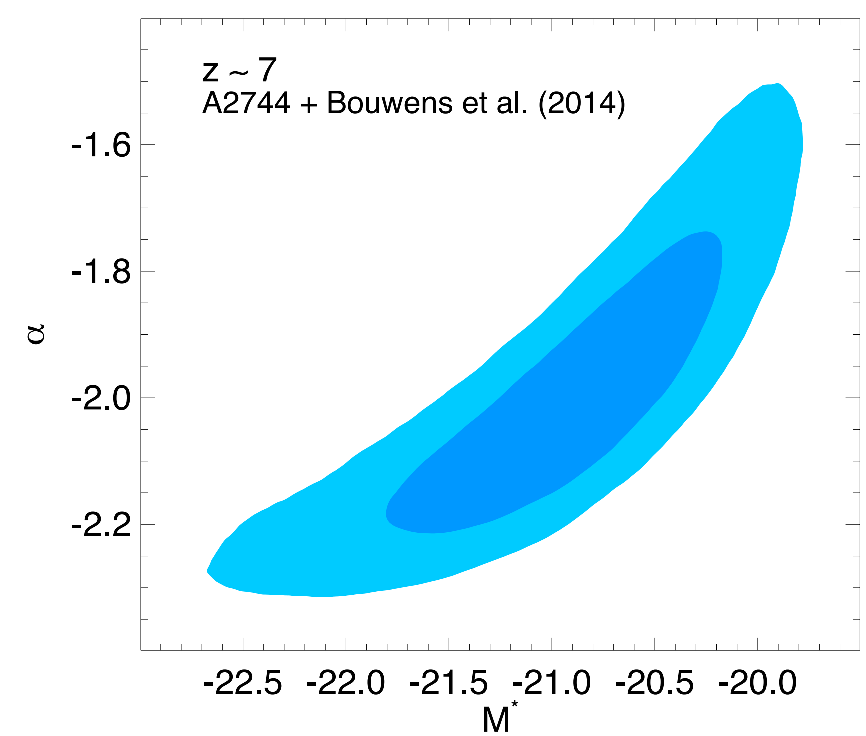
this is 0.01L* at z=7

- Faint-end slope alpha=-2.01. The steep faint-end slope holds to very faint magnitudes
- **No sign of turnover in faint-end slope**



Atek et al. (2014d)



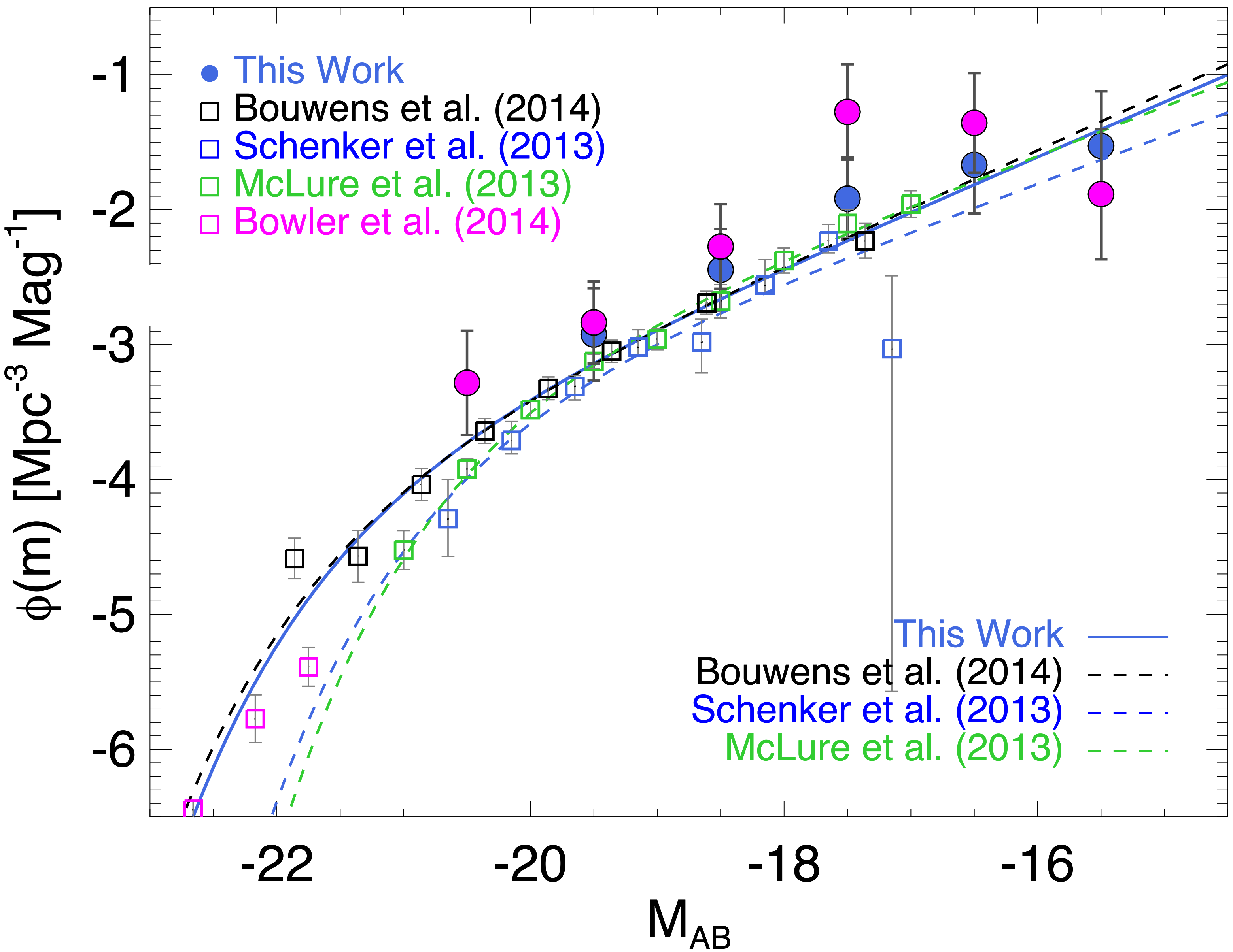


ref	This work	Bouwens et al. (2014)	Schenker et al. (2013)	Ishigaki et al. (2014)
∝	**-2.01 (-0.28,+0.20)**	-2.0 ±0.14	-1.87 ±0.18	-2.10 (-0.15,+0.3)

Lensing Model Uncertainties

- impact of model uncertainties on the UV LF
comparison between pre-HFF and HFF based model of A2744
=> complex interplay between magnification, survey area, completeness

Atek et al. (2014b,d)
Jauzac et al. 2014c
Richard et al. 2014a

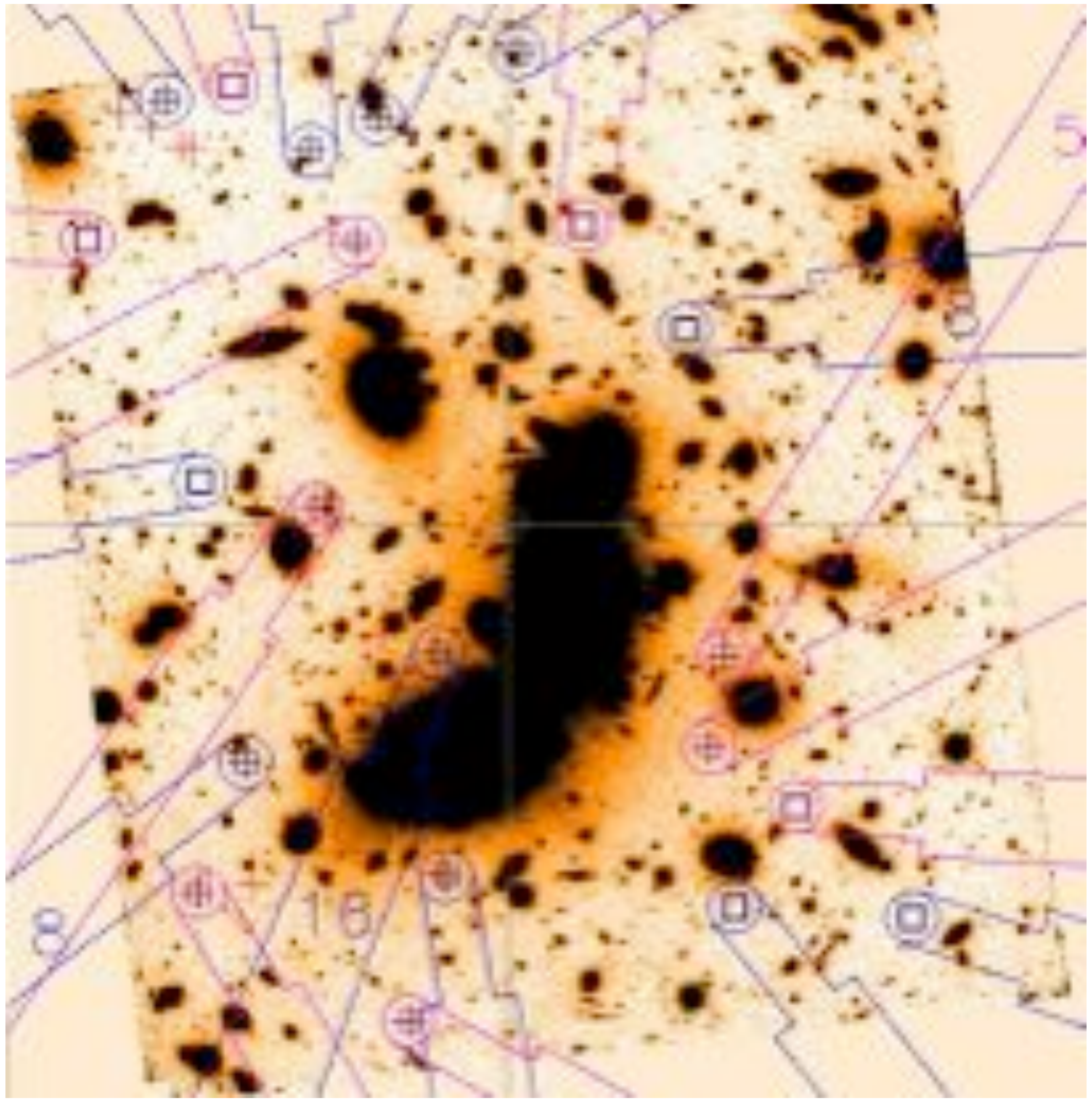


Importance of validating the lens model further:
improve modelling technique and lensing information (redshift)

Need For Spectroscopy

VLT KMOS IN PROGRESS
SPECTROSCOPY OF A2744, A1689, AS1063

Richard et al., Atek et al. in prep



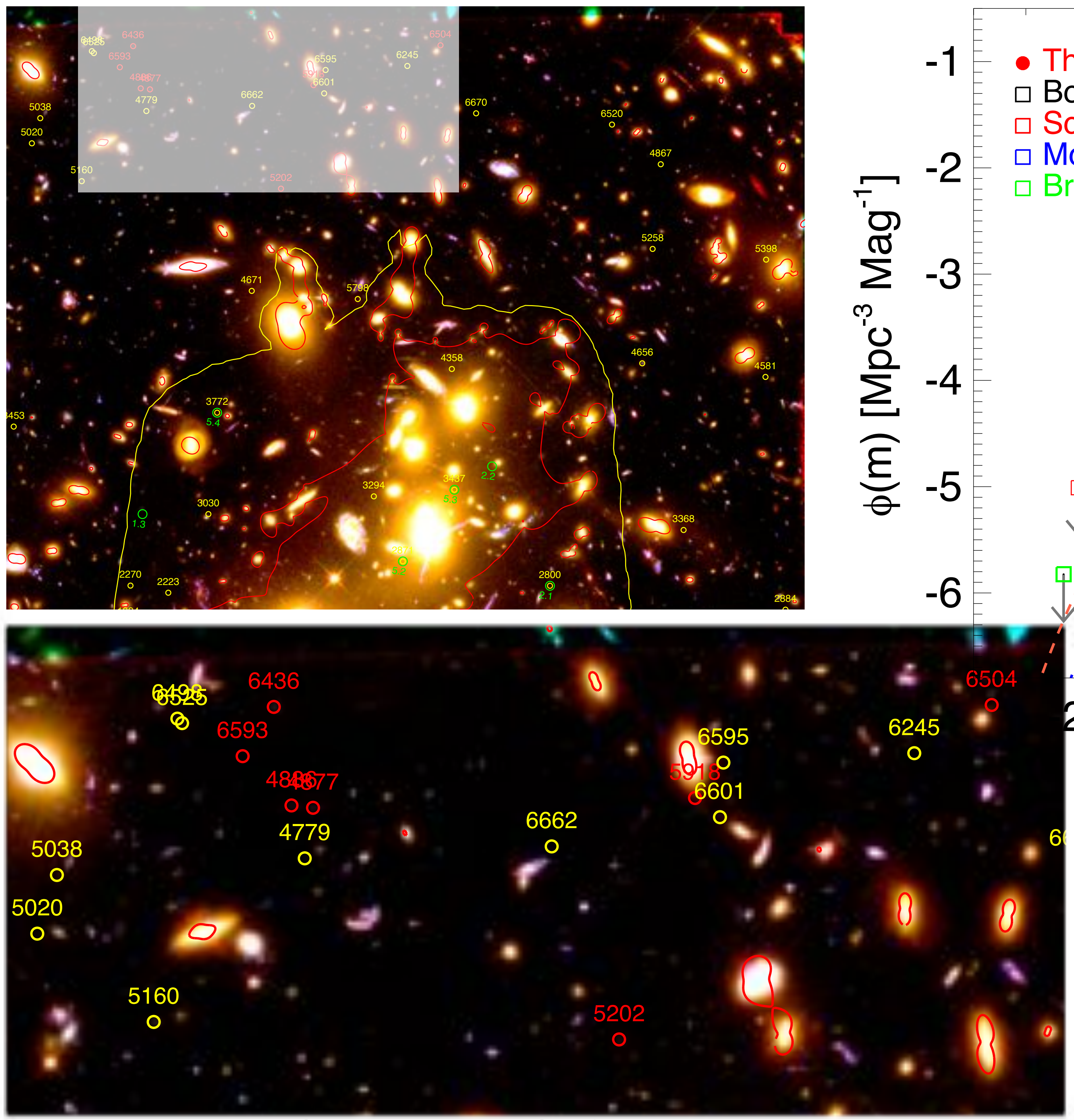
- Redshift confirmation of High-z dropout galaxies at z>6

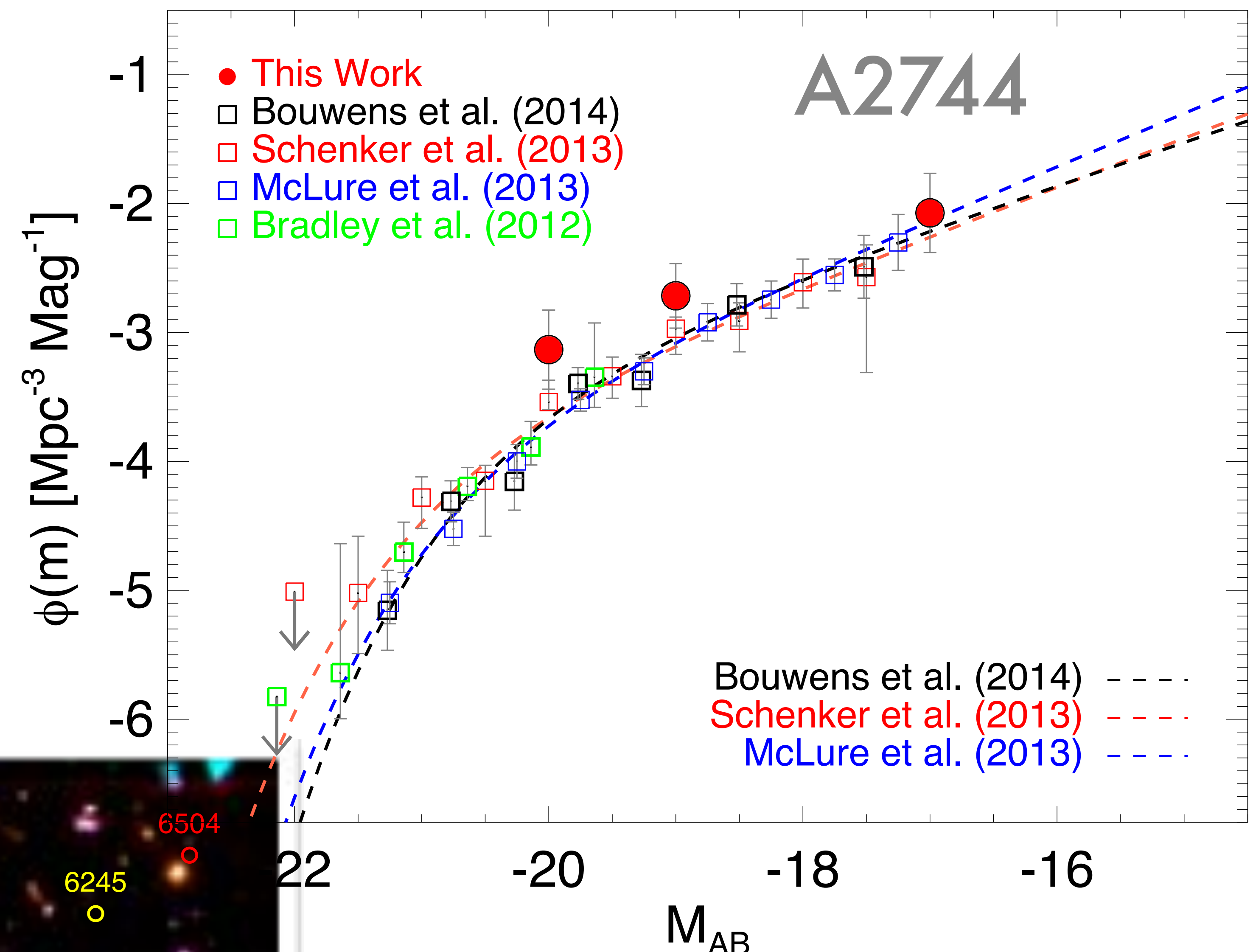
- Emission line measurements of multiple-image systems at z=1-3

- Spatially-resolved studies of star formation in lensed galaxies

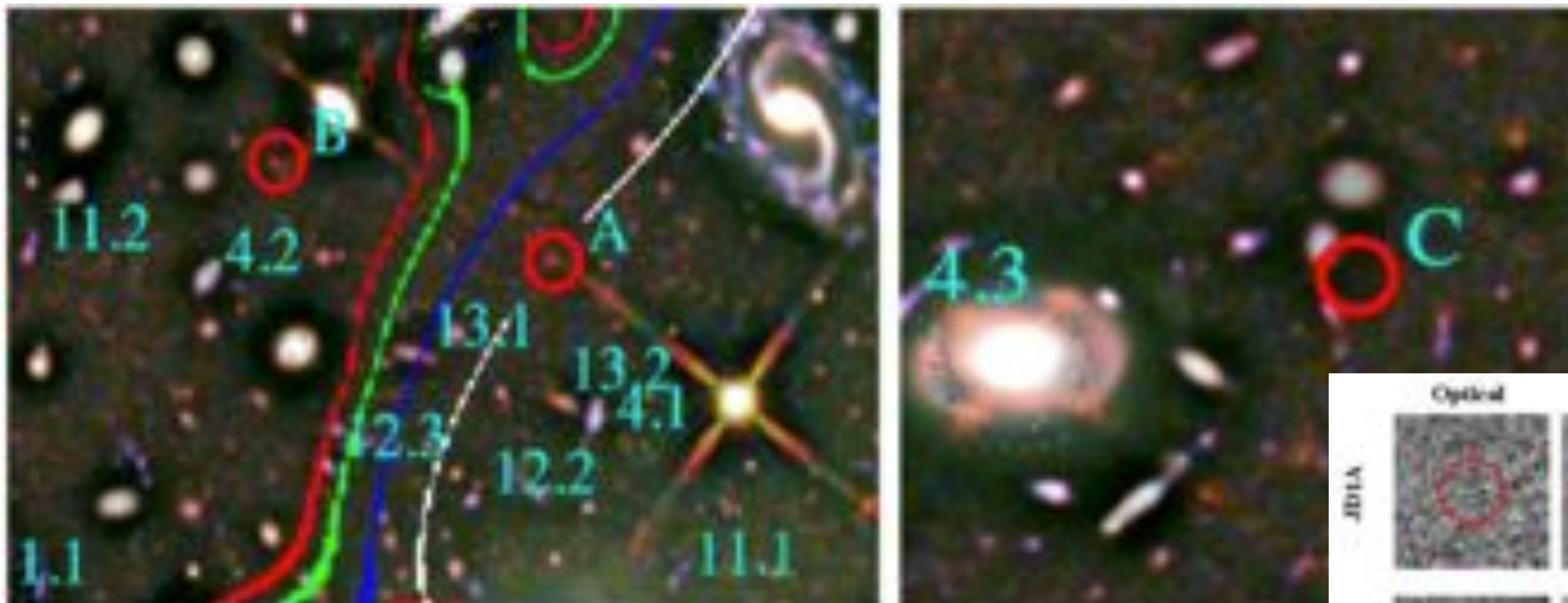
The Faint-end of the UV LF at z>8

Work in progress - using the first 4 HFF clusters ...

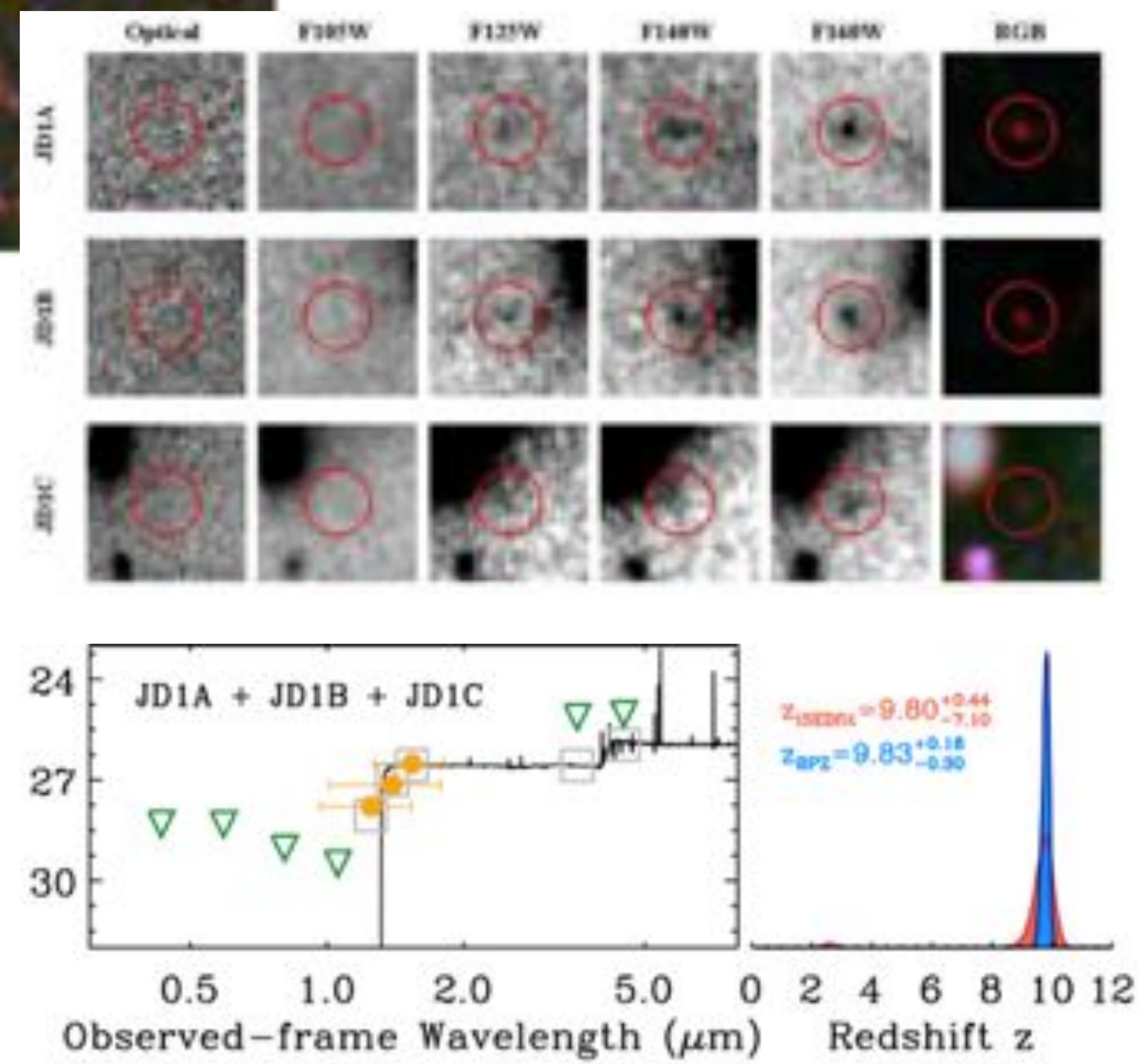




z~9.8 multiple image in A2744

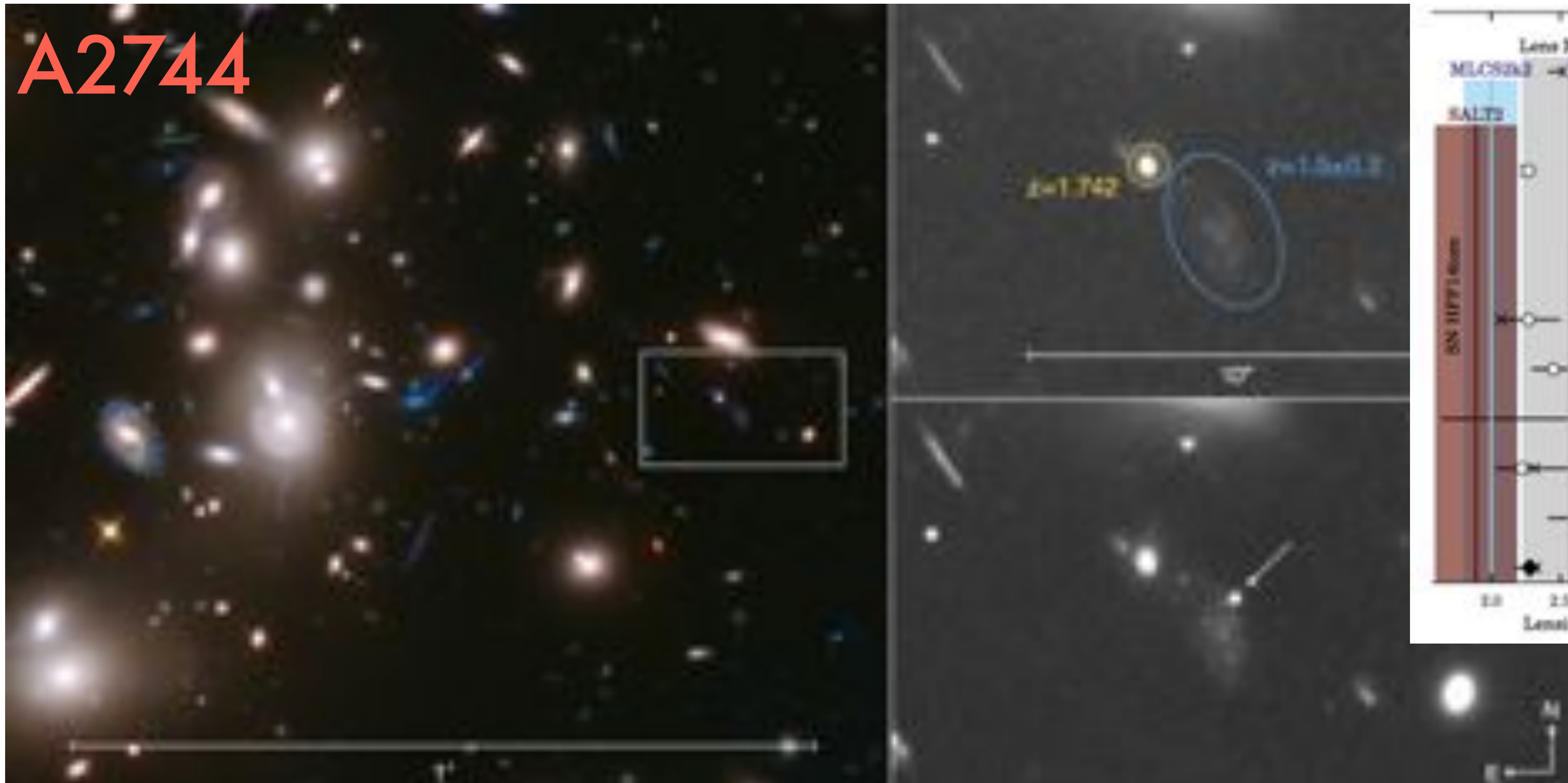


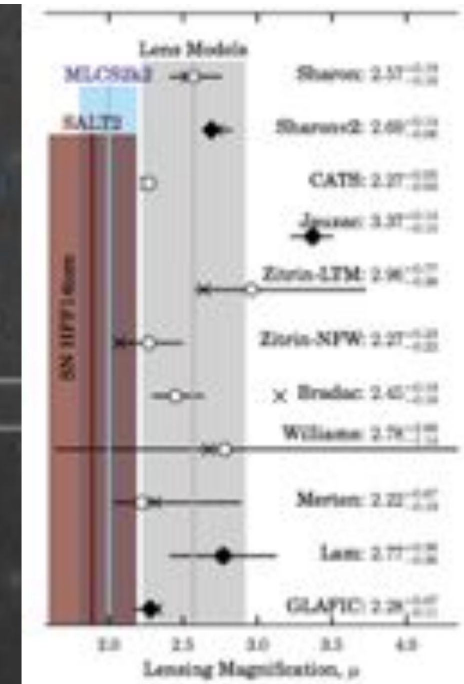
Zitrin et al. 2014

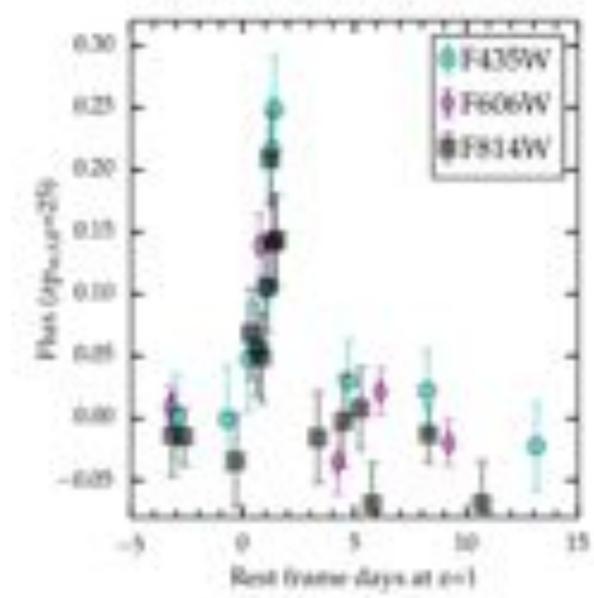


- Most distant galaxy yet found is in A2744
- confirmed by strong lensing models
- z~9.8, age of <220 Myr, SFR of 0.3 M_sol/year
- m(F160W)=29.9 => 0.2 L*

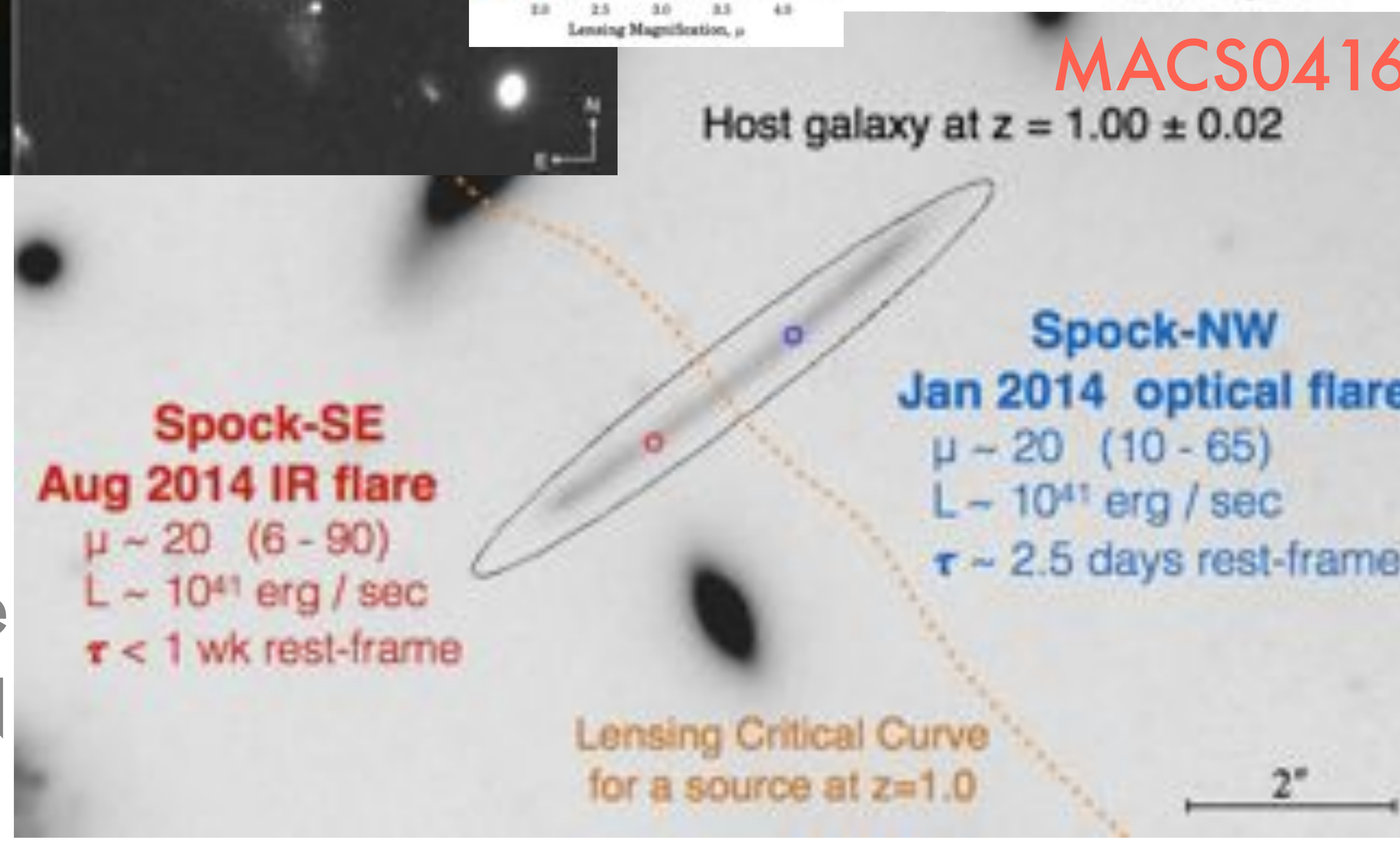
Supernovae Discoveries







Tom: Single image Type Ia



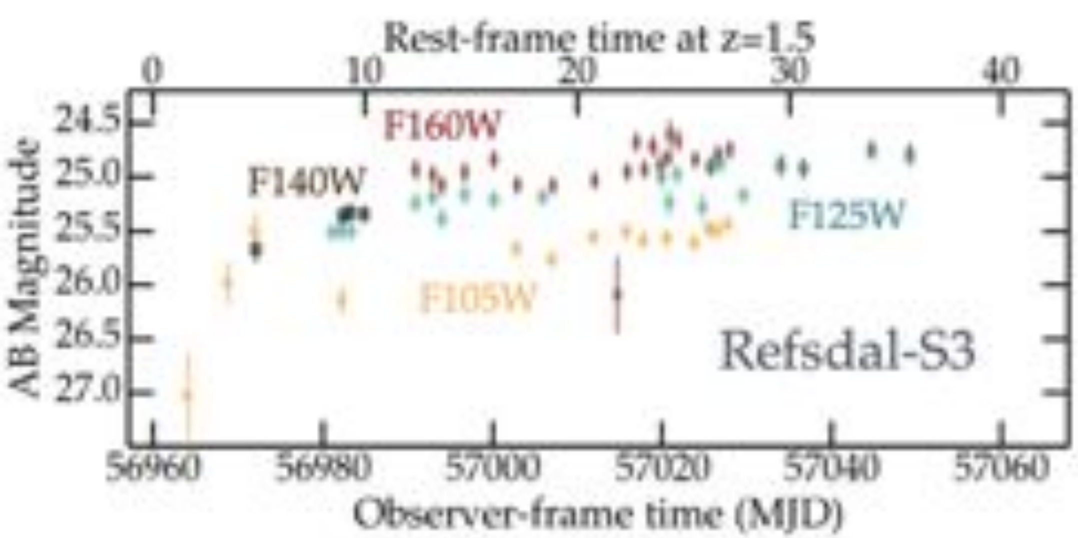
Spock: Double image Peculiar SN

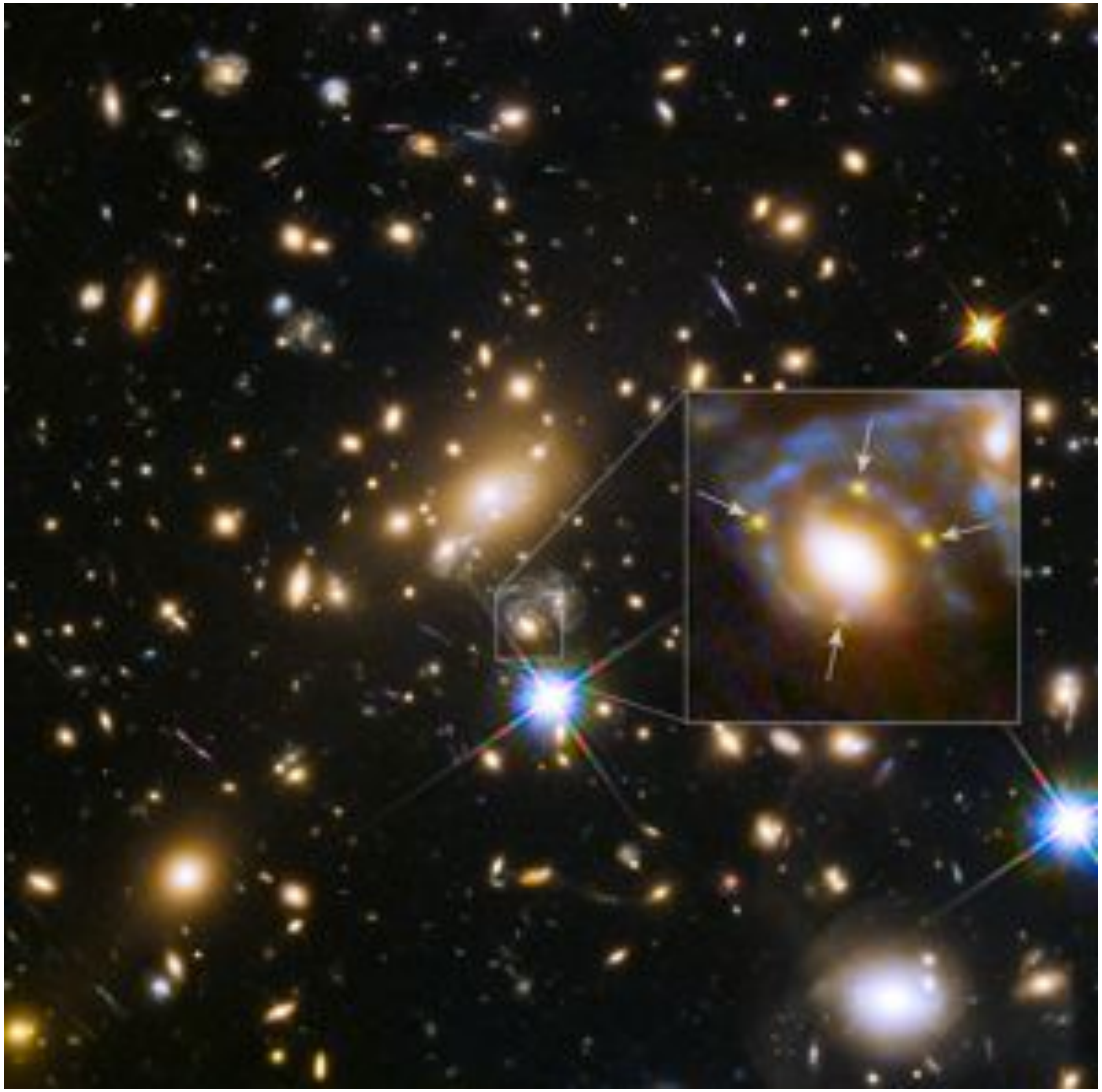
Supernovae Discoveries

Multiple images: "**Refsdal**"
Supernova - not a SNIa

Both cluster and galaxy scale lensing.

Prediction of a new image in couple of months. Important for H_0 measurement.





Rodney et al 2015

Can we do better?

- Frontier Field is a rich dataset, most of it is publicly available
=> lot of scientific activities! High-value science!

- **Current Modelling reach below the 1% level in mass precision with identification of 150-200 multiple images per cluster !**

- **Can we do better?**
    - image RMS uncertainty on reconstructed image position is currently 0.5-0.8" while HST observation have precision better than 0.1"
    - **this means a huge step of improvement possible: a factor of 5-10 betters in the image RMS => would allow new science**

How to Improve Mass Models ?

Stunning results but we can do better!

- **Improve modelling techniques**
  - ➡More Cluster Strong Lens Challenge

- **What to improve?**
  - Cluster substructure (galaxy halos)
  - Line of sight substructure (3D lensing)
  - More flexible component for the cluster DM (grid-based)
  - Include more constraints:
    - Identify more multiple images
    - Include Spectroscopic redshift (MUSE, WFC3 grism)
    - Include Weak Lensing (need Hubble data => proposal)
    - Include Flexion (Rexroth PhD thesis)
  - *Faster modelling: parallelisation of codes*

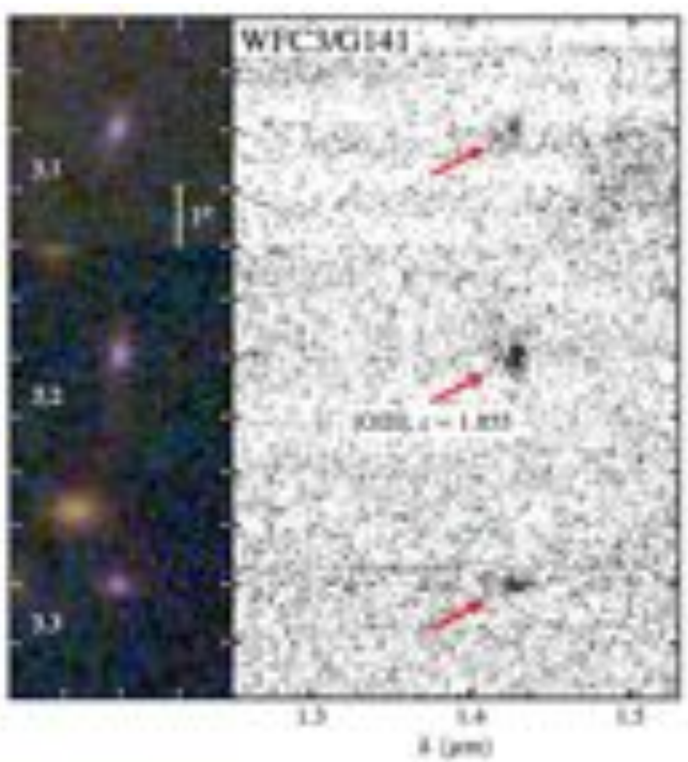
Measuring the redshift of multiple images

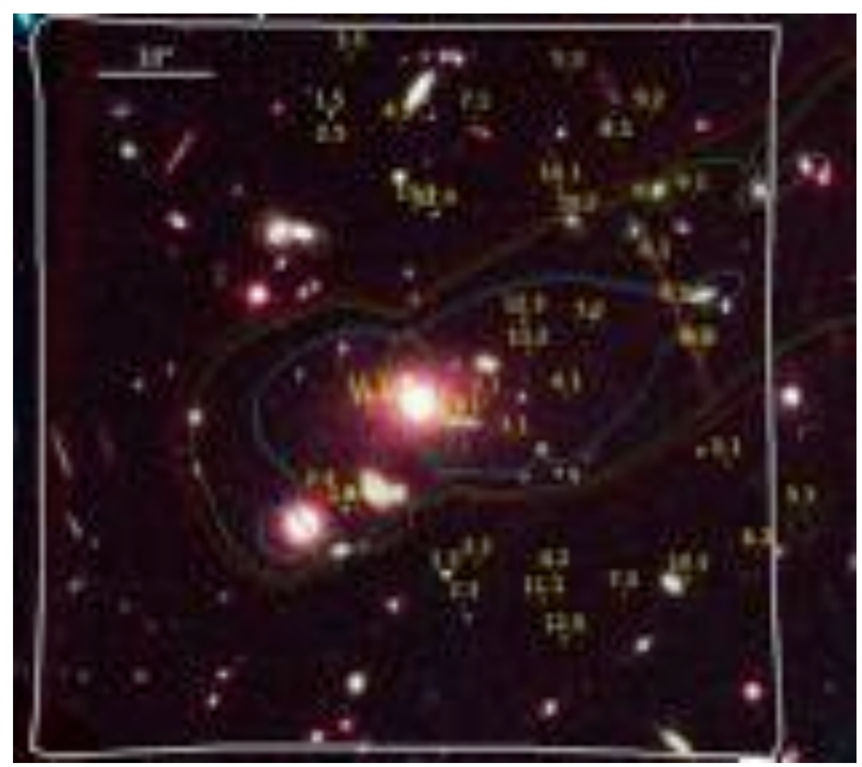
- Standard MOS instruments (LRIS, FORS) are inefficient for multiple images redshift measurement

✓WFC3 grism works but require long integration!

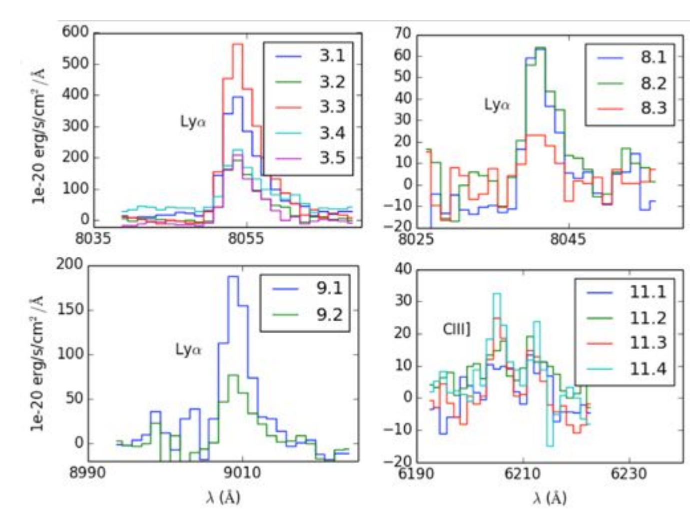
  ✴ but crowding issues & GLASS not a deep survey

✓MUSE @ VLT is a Revolution: IFU over 1 arcmin^2





SMAC J2031.8-4036
Richard et al. 2014b,
arXiv 1409.2488
11 new multiple images with redshift



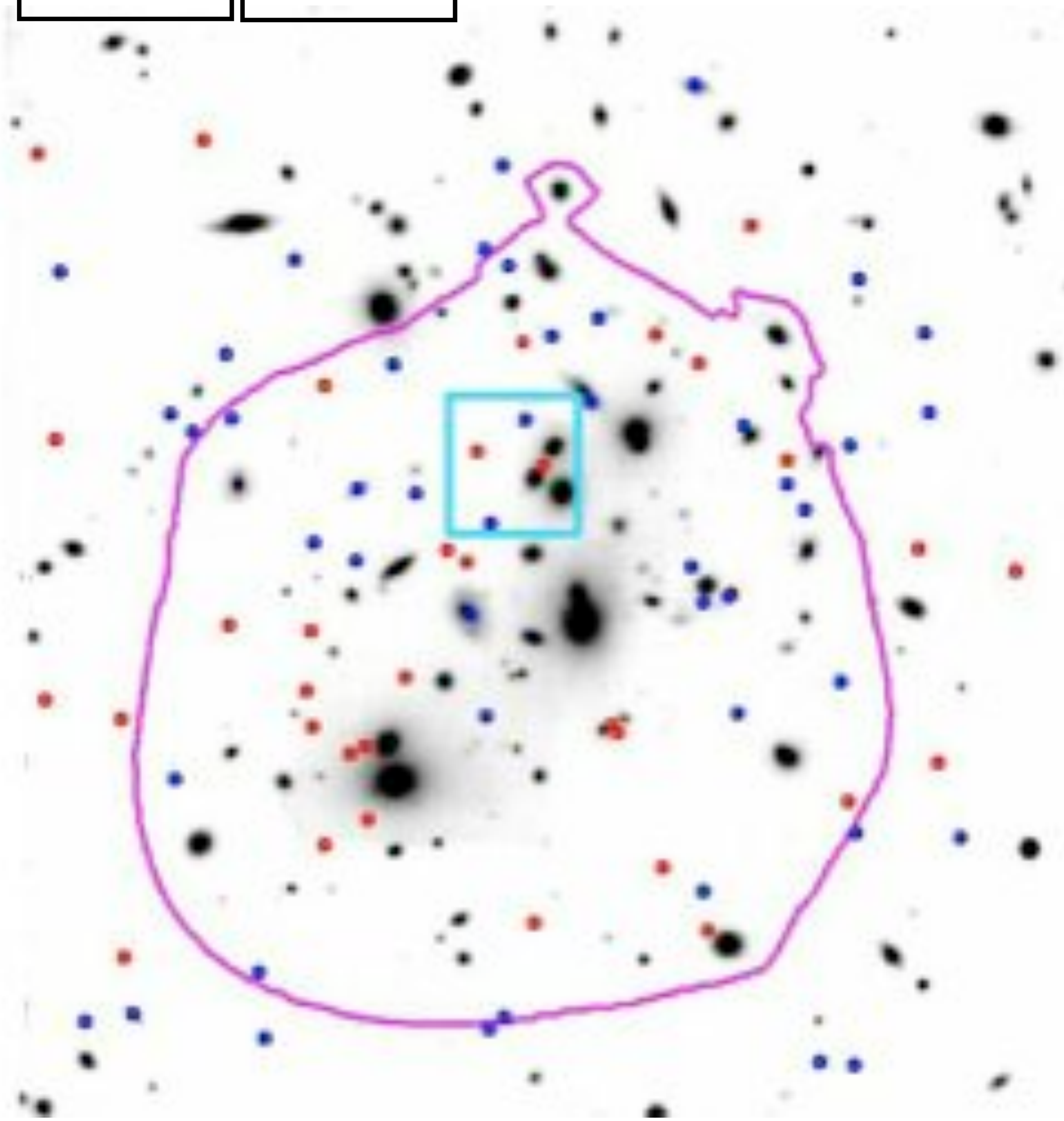
Need For Spectroscopy (hi-z confirmation)

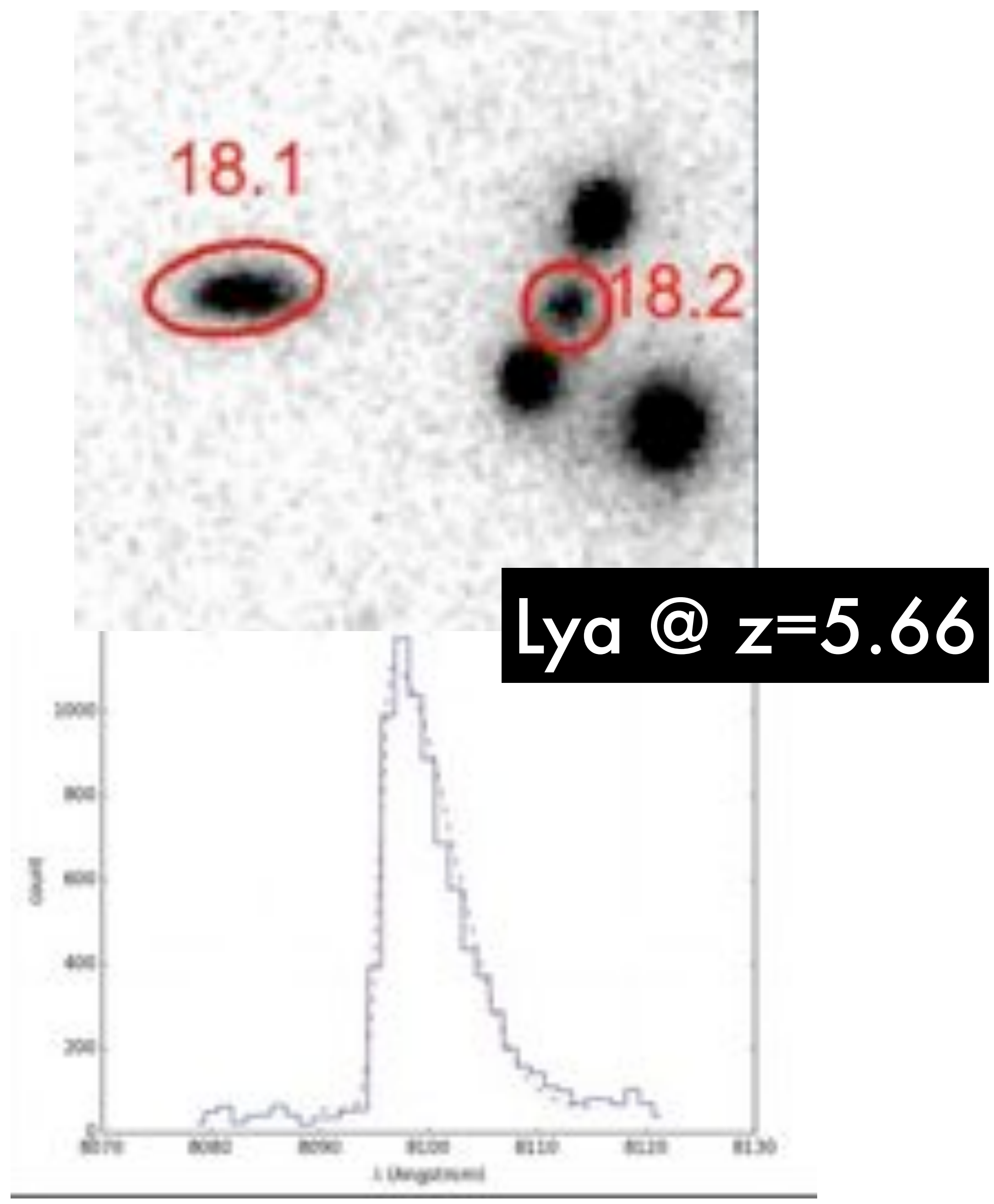
A2744 first analysis (Richard et al. in prep)

VLT/MUSE

z<1.5 z>1.5

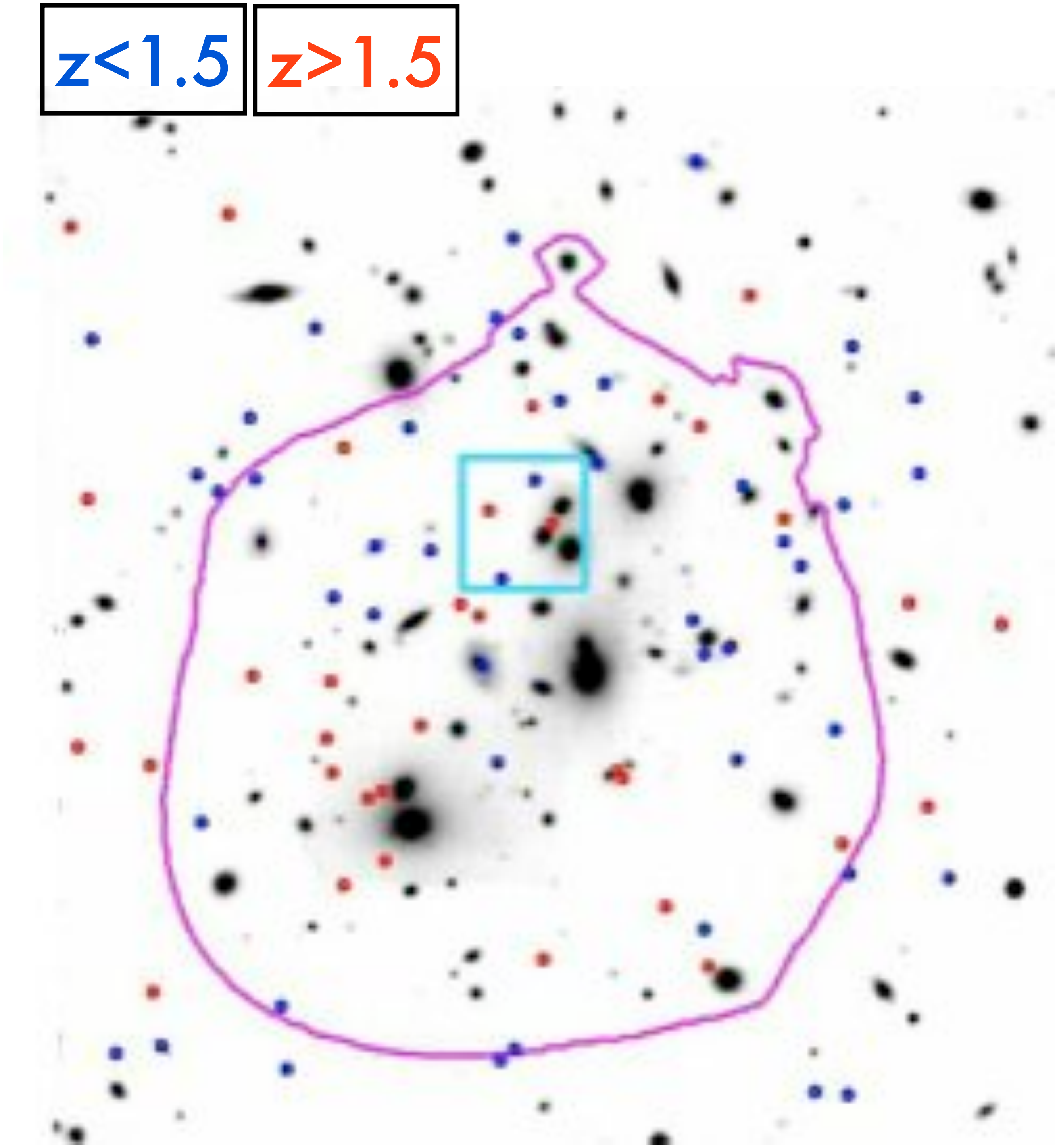
83 spectroscopic redshifts

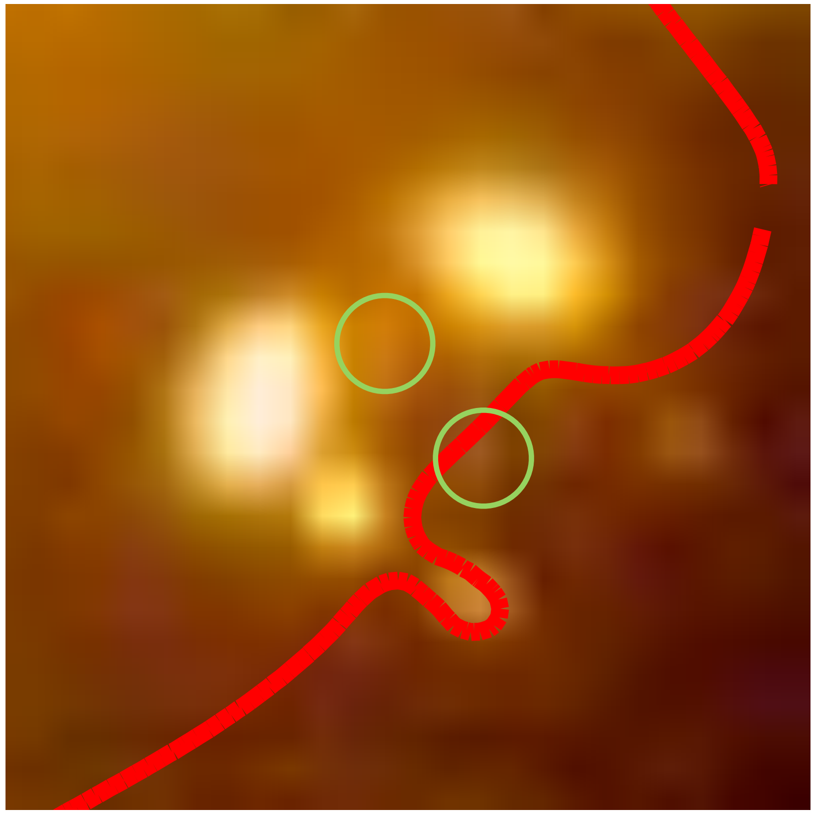




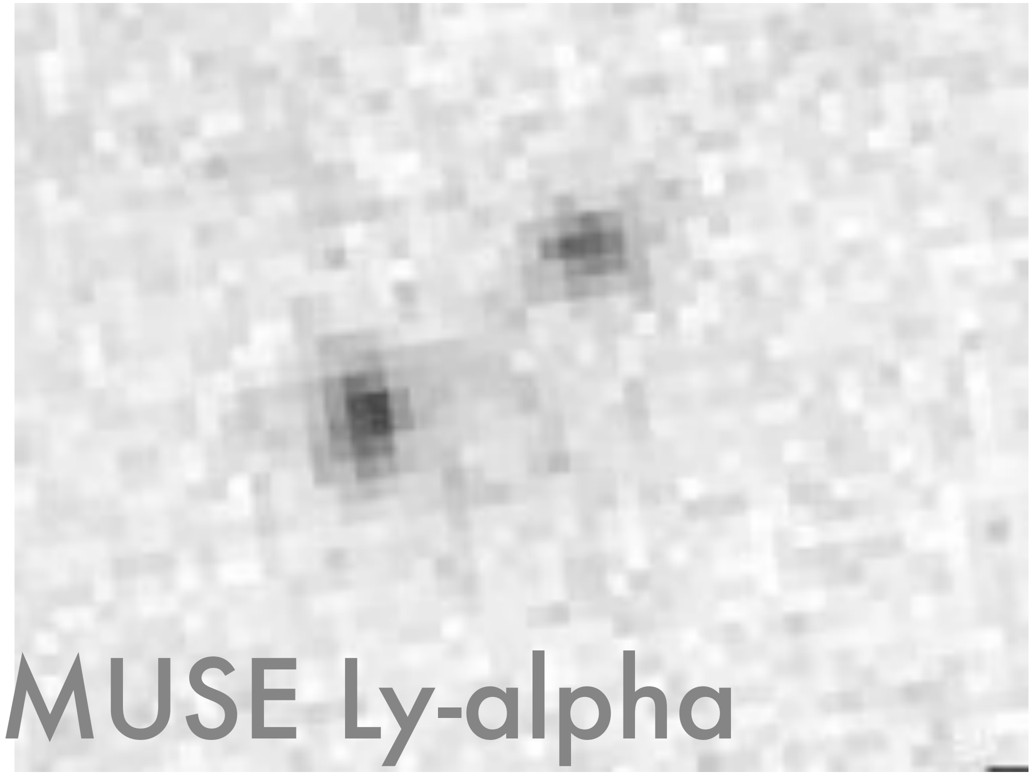
Need For Spectroscopy (hi-z confirmation)

A2744 first analysis (Richard et al. in prep)

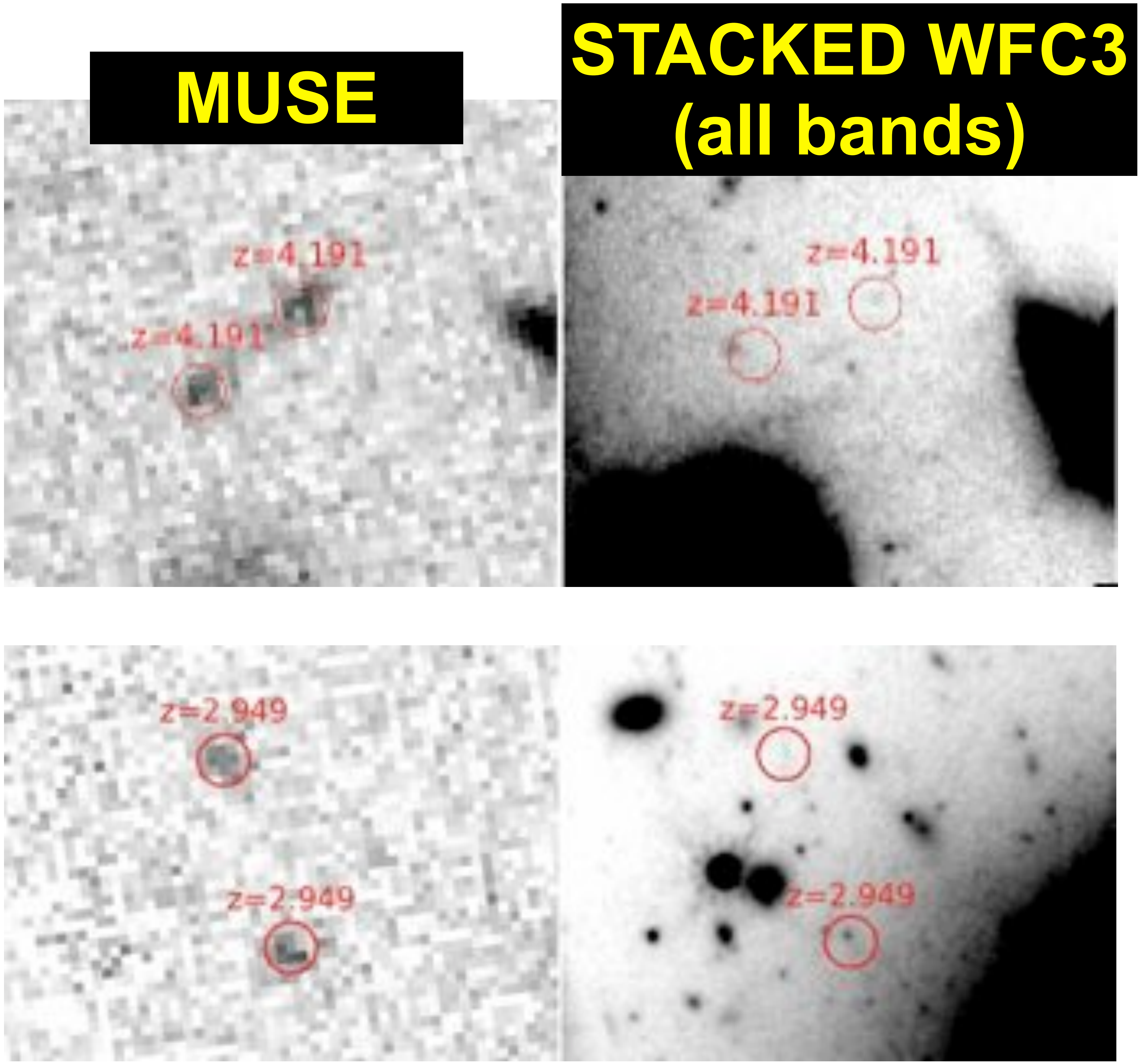




z~6 dropout with μ~30

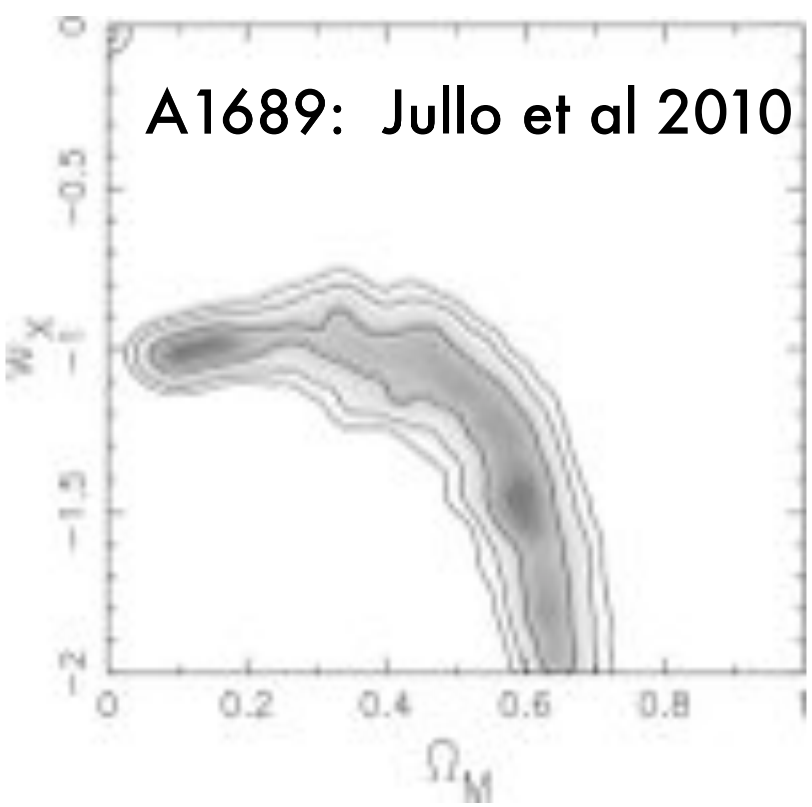


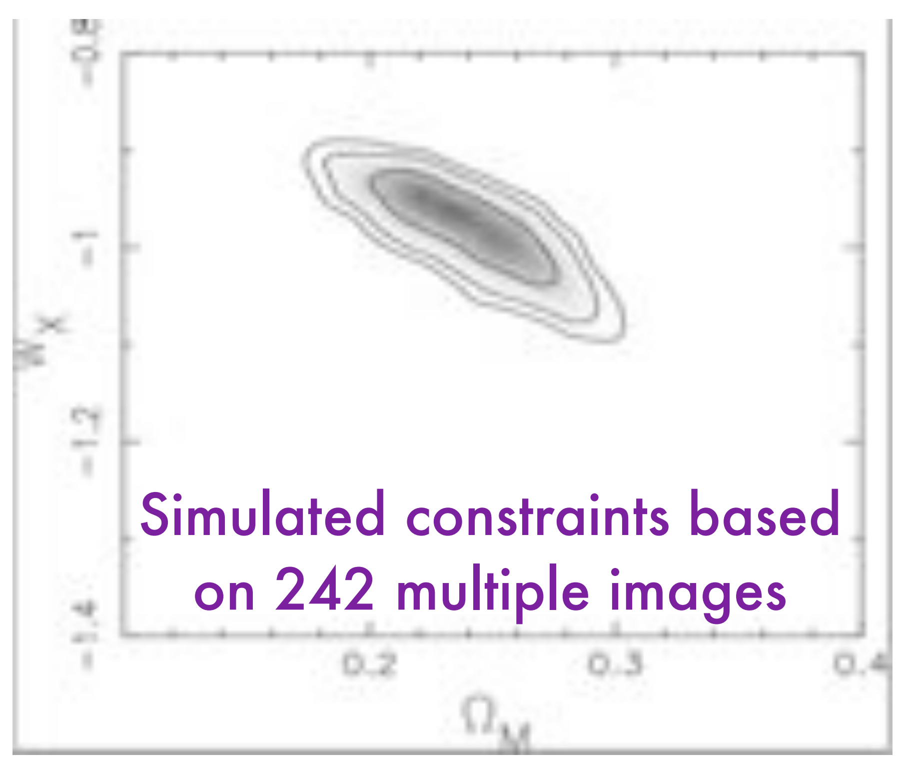
New MUSE multiply-imaged systems

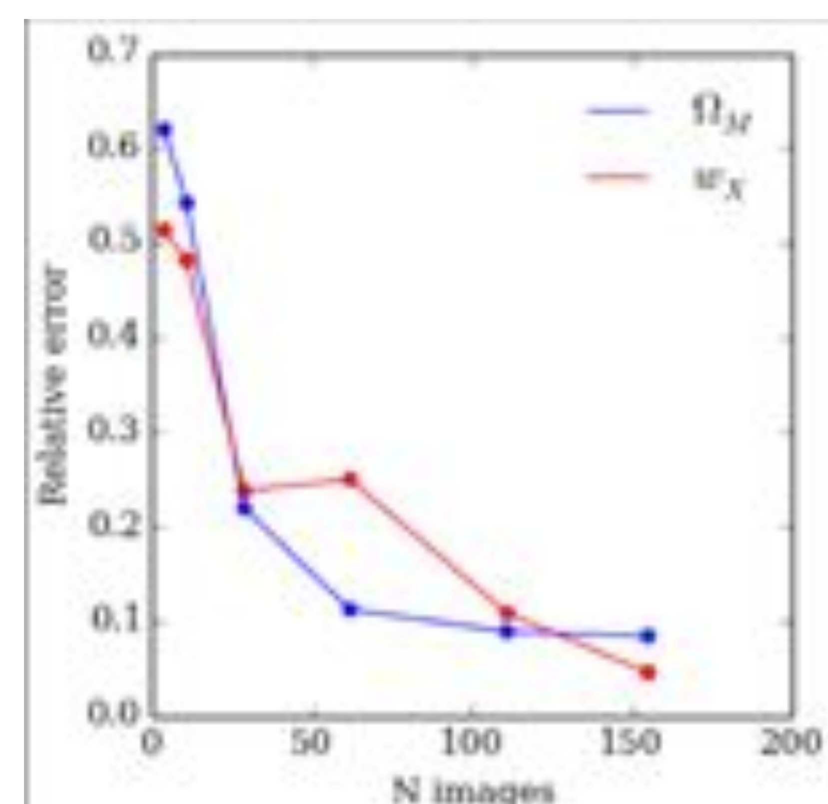


Cosmography forecast

- This will allow precision cosmology constraints (see Jullo et al 2010)
- First results likely mid/end 2015?: possibly percent precision of distance-redshift relation over $0.3<z<5$ in redshift







from E. Jullo

Conclusion

- *Hubble Frontier Fields* is the start of a **Revolution in cluster lensing** (JWST standard quality)
- We have a large amount of **challenges and improvements** in the modelling and analysis of the FF data to go below the percent level precision & accuracy … this will lead to even more discoveries!
- Stay tuned !
- *If interested to help let me know!*

THANKS