Hubble Frontier Fields:
"A New Era for Gravitational Lensing"

Galaxies & Cosmology in Light of Strong Lensing
19th November 2014

Durham University

Mathilde Jauzac

Richard Massey, Johan Richard, Eric Jullo, Jean-Paul Kneib, Hakim Atek, Marceau Limousin, Benjamin Clément, Dominique Eckert, Harald Ebeling & the CATS team

The CATS team — Lensing Workshop in Durban – South Africa
January 2014

lastro
EPFL - LABORATOIRE D'ASTROPHYSIQUE

Durham University

LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

Astrophysics & Cosmology Research Unit
ACRU

CRA Lyon

DEPARTMENT OF ASTRONOMY
YALE UNIVERSITY

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Institute for Astronomy
University of Hawaii

THE UNIVERSITY OF ARIZONA.

Frontier Fields community - Yale Workshop (last week)

Outlines

1. *The HST Frontier Fields Initiative*

2. Inner Core & Outskirts of MACSJ0416

3. Inner Core of Abell 2744

4. Other ‘on-going’ CATS works, Conclusions & Perspectives

WHAT ARE *HUBBLE FRONTIER FIELDS* ?

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

- 6 strong lenses & 6 blank fields
- 140 HST orbits (> 3days of observations) – ACS & WFC3
- mag ~28.7-29 in the optical and near-IR

THE DEEPEST DATA EVER OBTAINED FOR LENSING GALAXY CLUSTERS !!!

- **Highly-constrained Gravitational Lensing mass models :**
  - More strong lensing constraints
  - More weak lensing constraints

- **Highly-accurate magnification measurements**
  - Better constraints on high-redshift UV luminosity functions

BETTER KNOWLEDGE OF THE DISTANT UNIVERSE !

WHAT IS *HUBBLE FRONTIER FIELDS* MASS MAPPING INITIATIVE ?

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

- **Provide the community with mass maps of the 6 clusters using the existing HST data**

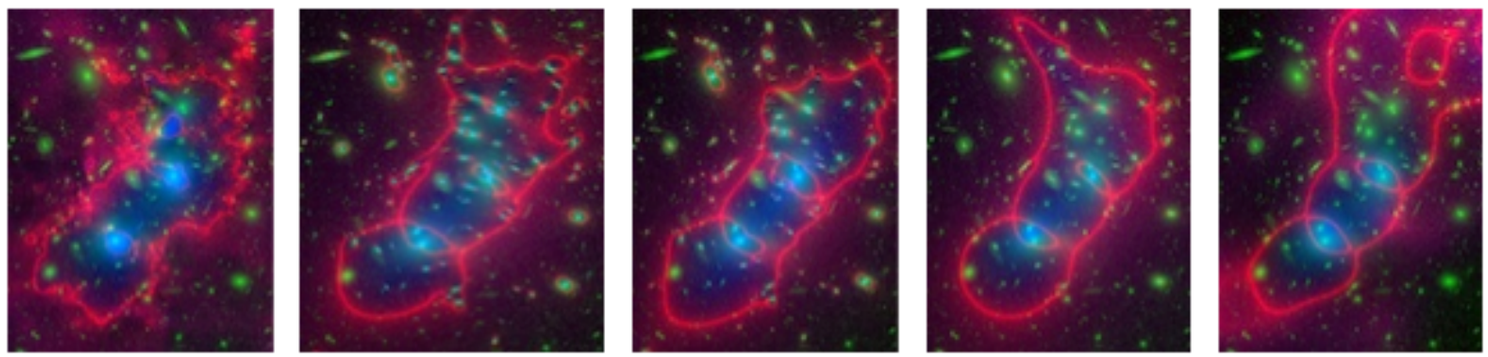
Johnson et al. 2014, arXiv 1405.0222 : **Sharon et al. TEAM**

Coe et al. 2014, arXiv 1405.0011 : **Merten, Zitrin et al. TEAM**

Richard, Jauzac et al. 2014, MNRAS, 444, 268 : **CATS TEAM**

The Frontier Fields Lens Models

Abell 2744: Overlay of magnification (red) and mass models (blue) on the full-band HST imaging (green)



Bradac et al. | CATS Team | Merten, Zitrin et al. | Sharon et al. | Williams et al.

The Frontier Fields (FF) are selected to be among the strongest lensing clusters on the sky. In order to interpret many of the properties of background lensed galaxies, reliable models of the lensing maps for each cluster are required. Preliminary models for each of the six Frontier Fields clusters have been provided by five independent groups prior to the HST Frontier Fields observing campaign in order to facilitate rapid analysis of the FF data by all members of the community. These models are based upon a common set of input data, including pre-FF archival HST imaging and a common set of lensed galaxies.

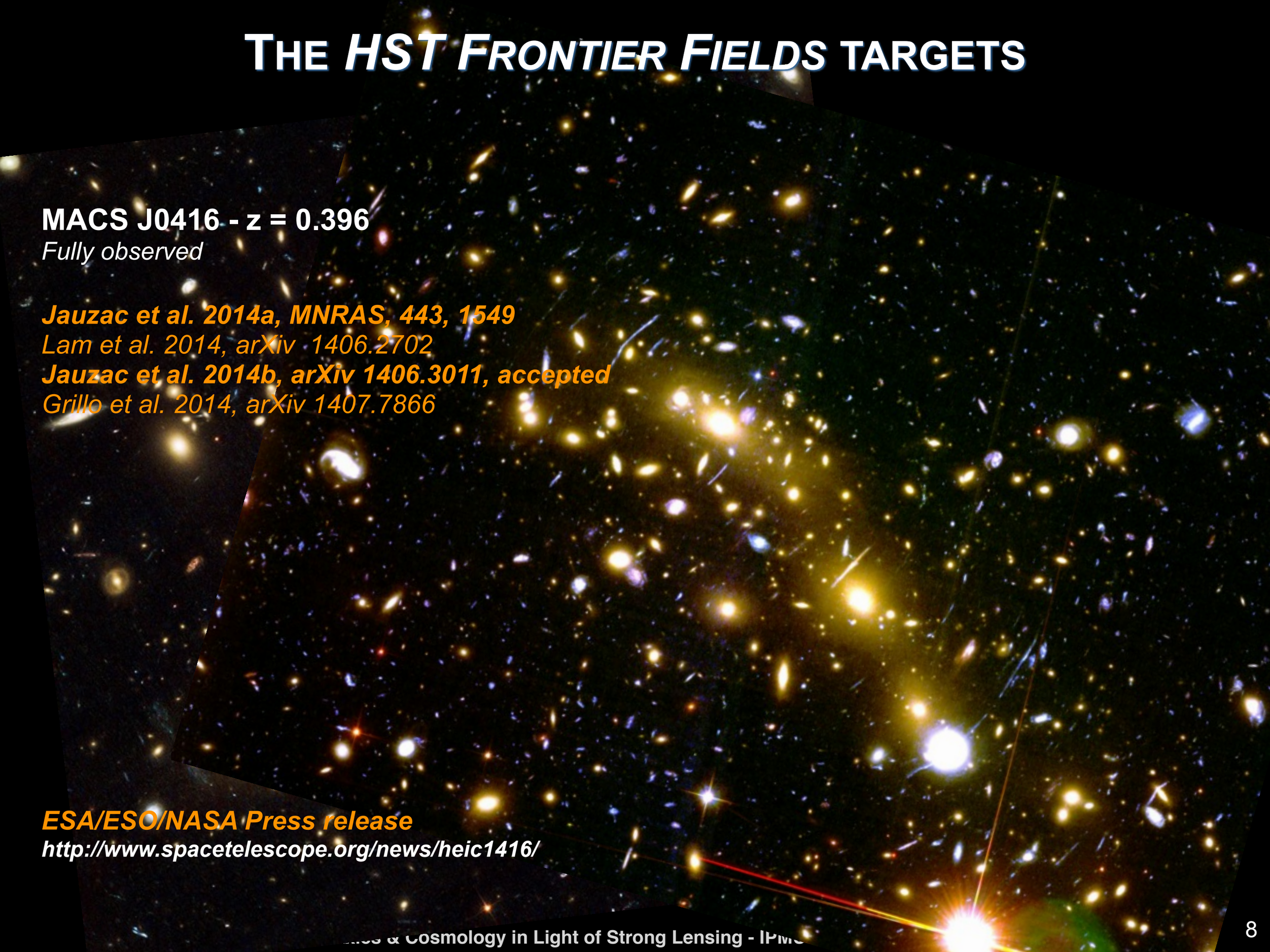
THE *HST FRONTIER FIELDS* TARGETS

Abell 2744 - z = 0.308
Fully Observed

Atek et al. 2014a, ApJ, 786, 60
Laporte et al. 2014, A&A, 562, 8
Zitrin et al. 2014, arXiv 1407.3769
Ishigaki et al. 2014, arXiv 1408.6903
Atek et al. 2014d, arXiv 1409.0512
Jauzac et al. 2014c, arXiv 1409.8663

ESA/ESO/NASA Press Release
http://www.spacetelescope.org/news/heic1401/

THE *HST FRONTIER FIELDS* TARGETS

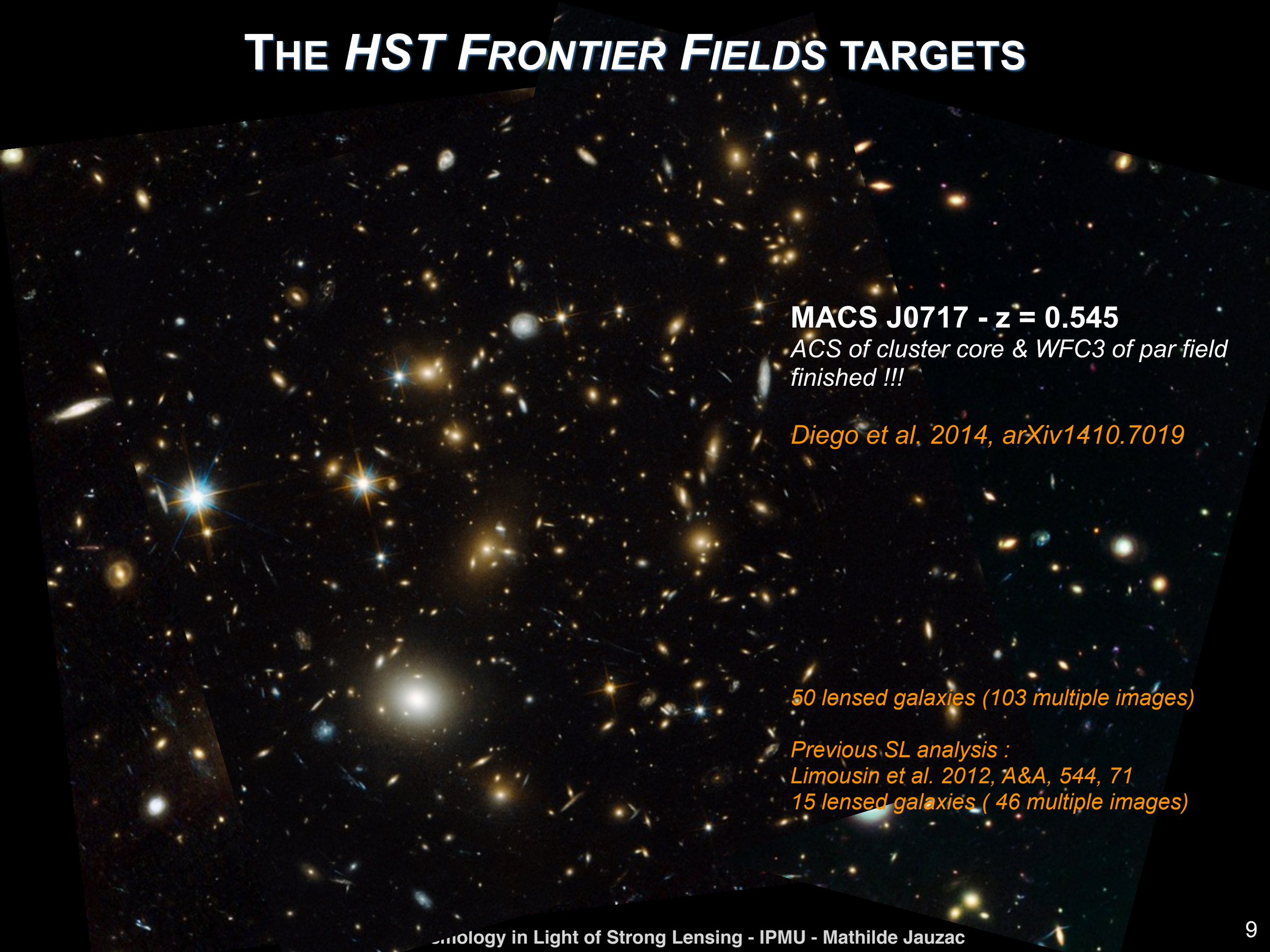


MACS J0416 - z = 0.396
Fully observed

Jauzac et al. 2014a, MNRAS, 443, 1549
Lam et al. 2014, arXiv 1406.2702
Jauzac et al. 2014b, arXiv 1406.3011, accepted
Grillo et al. 2014, arXiv 1407.7866

ESA/ESO/NASA Press release
http://www.spacetelescope.org/news/heic1416/

THE *HST FRONTIER FIELDS* TARGETS



MACS J0717 - z = 0.545

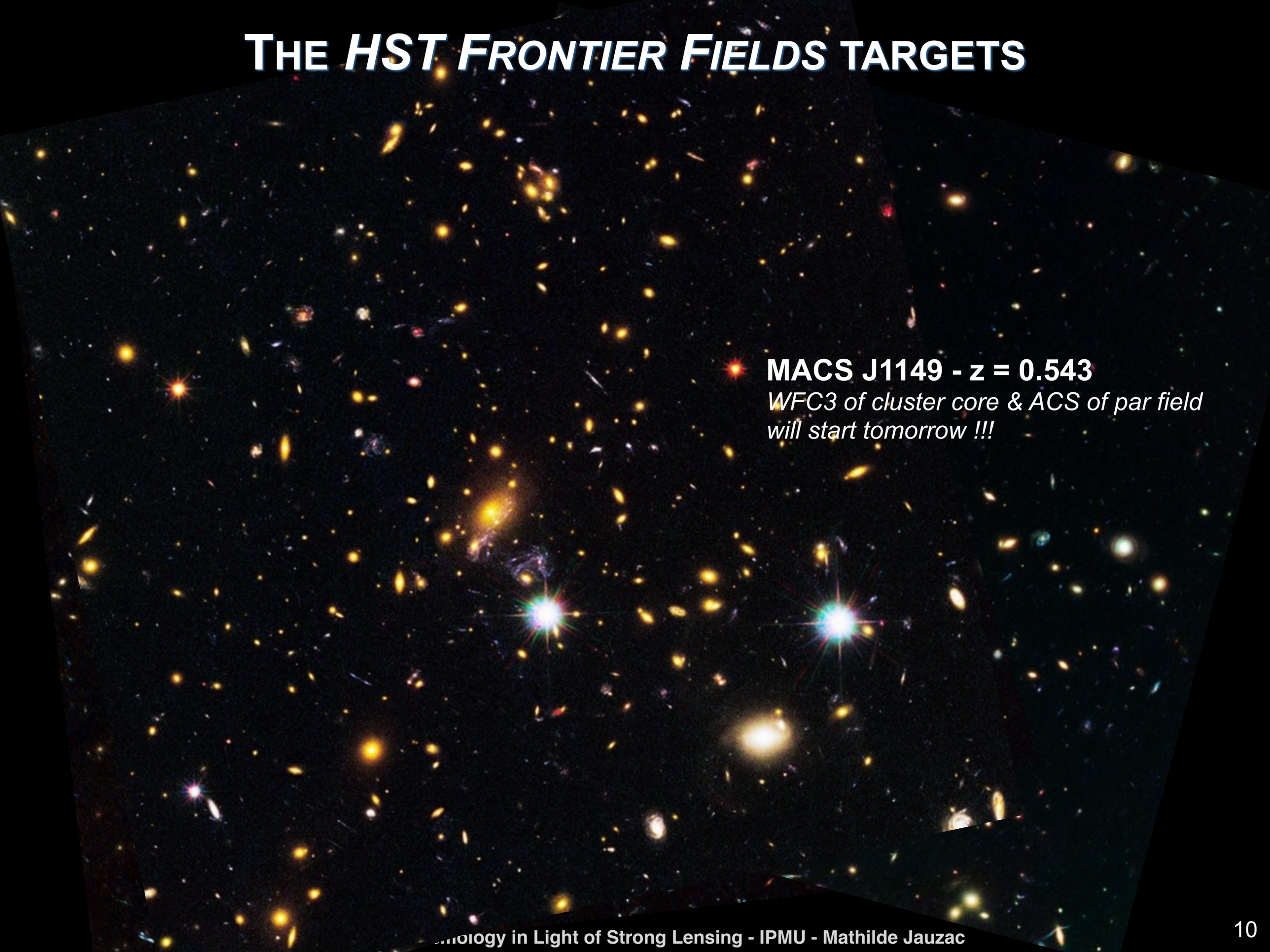
ACS of cluster core & WFC3 of par field finished !!!

Diego et al. 2014, arXiv1410.7019

50 lensed galaxies (103 multiple images)

Previous SL analysis :
Limousin et al. 2012, A&A, 544, 71
15 lensed galaxies (46 multiple images)

THE *HST FRONTIER FIELDS* TARGETS



MACS J1149 - z = 0.543

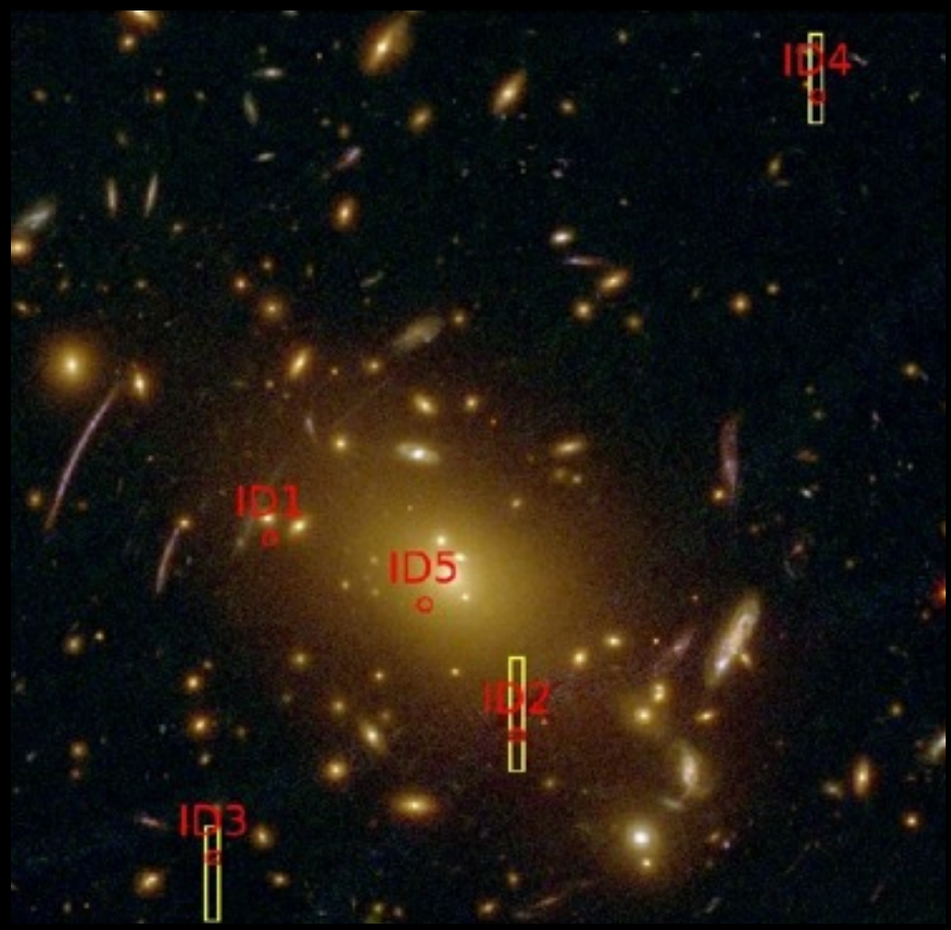
WFC3 of cluster core & ACS of par field will start tomorrow !!!

THE *HST FRONTIER FIELDS* TARGETS

The last 2 targets … Will they be observed ???

Abell 370
z = 0.375

Abell S1063
z = 0.348



Outlines

1. The HST Frontier Fields Initiative

2. *Inner Core & Outskirts of MACSJ0416*

3. Inner Core of Abell 2744

4. Other ‘on-going’ CATS works, Conclusions & Perspectives

1. 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}

1. … After HFF !!!

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

194 SL multiple images

~100 WL gal.arcmin^{-2}

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

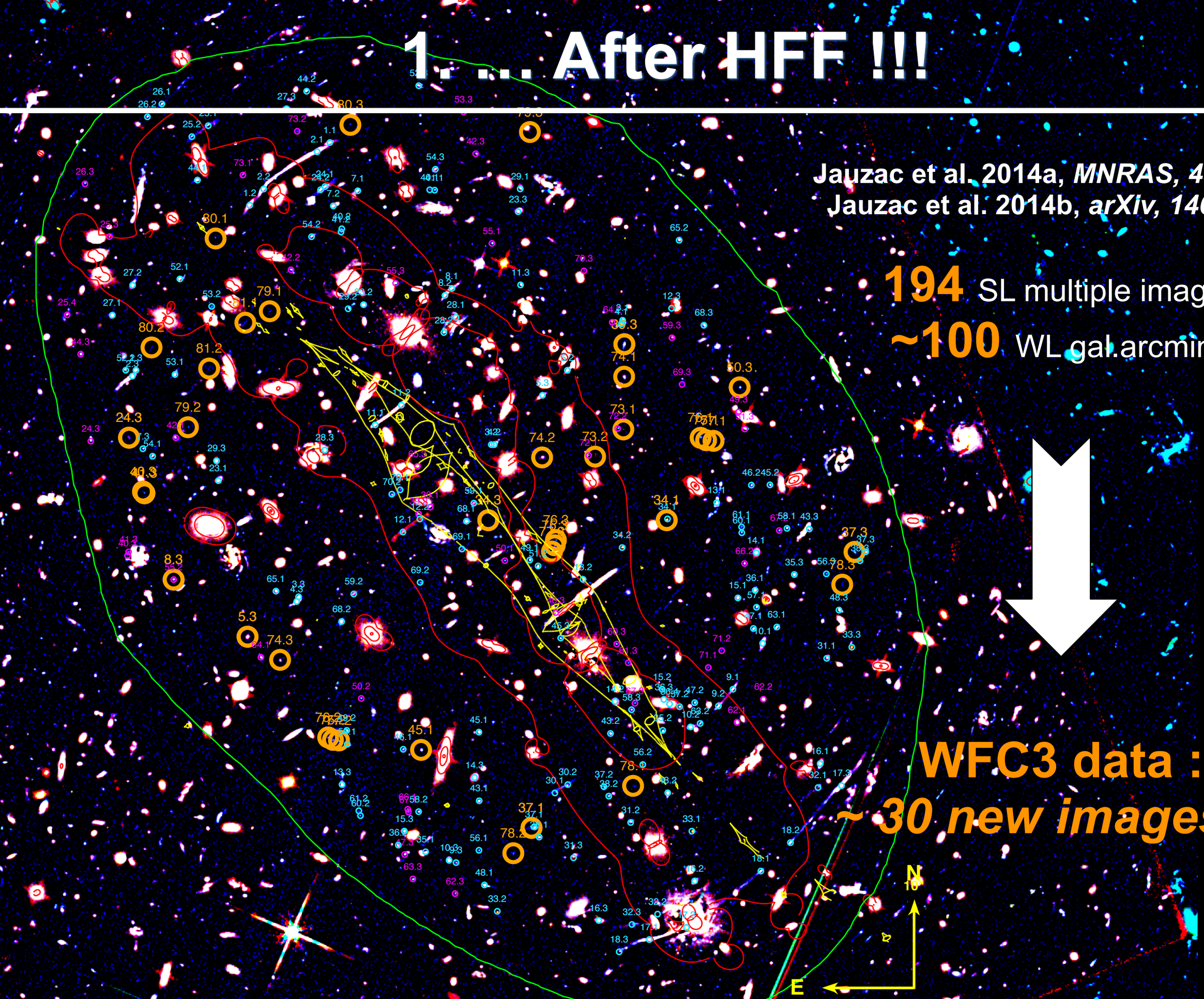
1. ... After HFF !!!

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

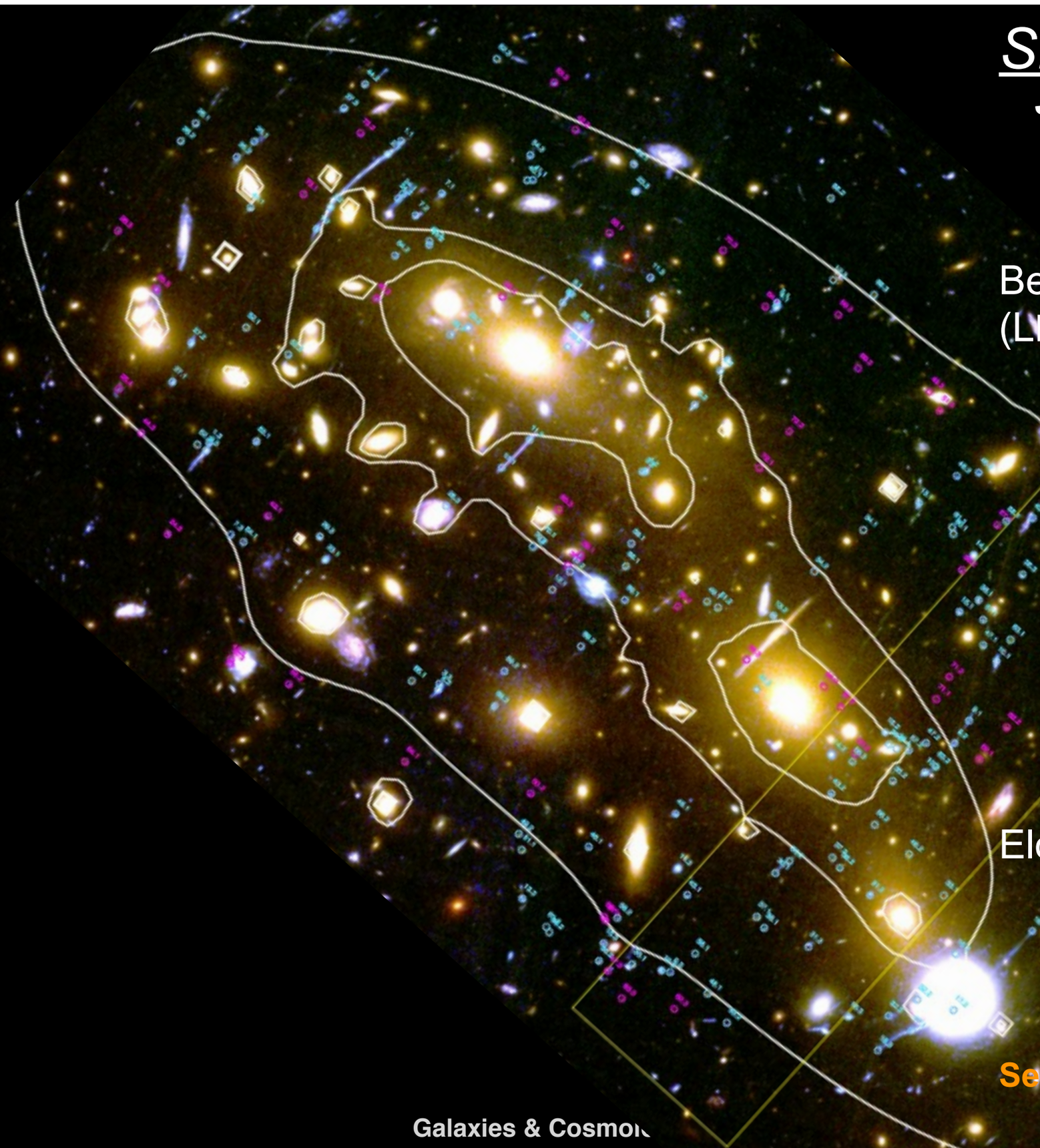
194 SL multiple images

~100 WL gal.arcmin^{-2}

WFC3 data :
~ 30 new images !!!



2. Inner Core Mass Distribution



SL-only analysis

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

Best-fit parametric mass model (LENSTOOL):

- 194 SL constraints
- 2 DM clumps
- 98 cluster galaxies

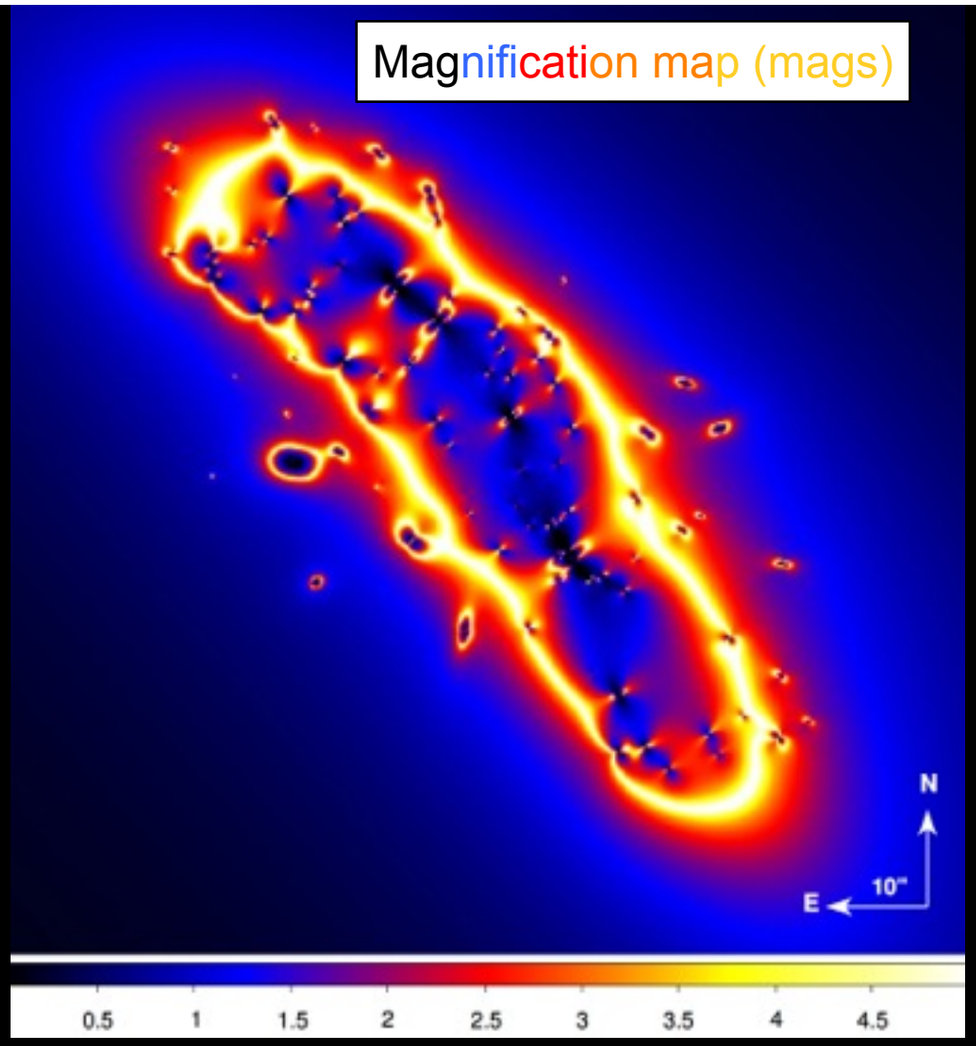
- RMS = 0.68”
- No 3rd clump needed

Elongated mass distribution NE-SW

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

See Claudio’s talk for inner core physics

3. Mass & Magnification measurements



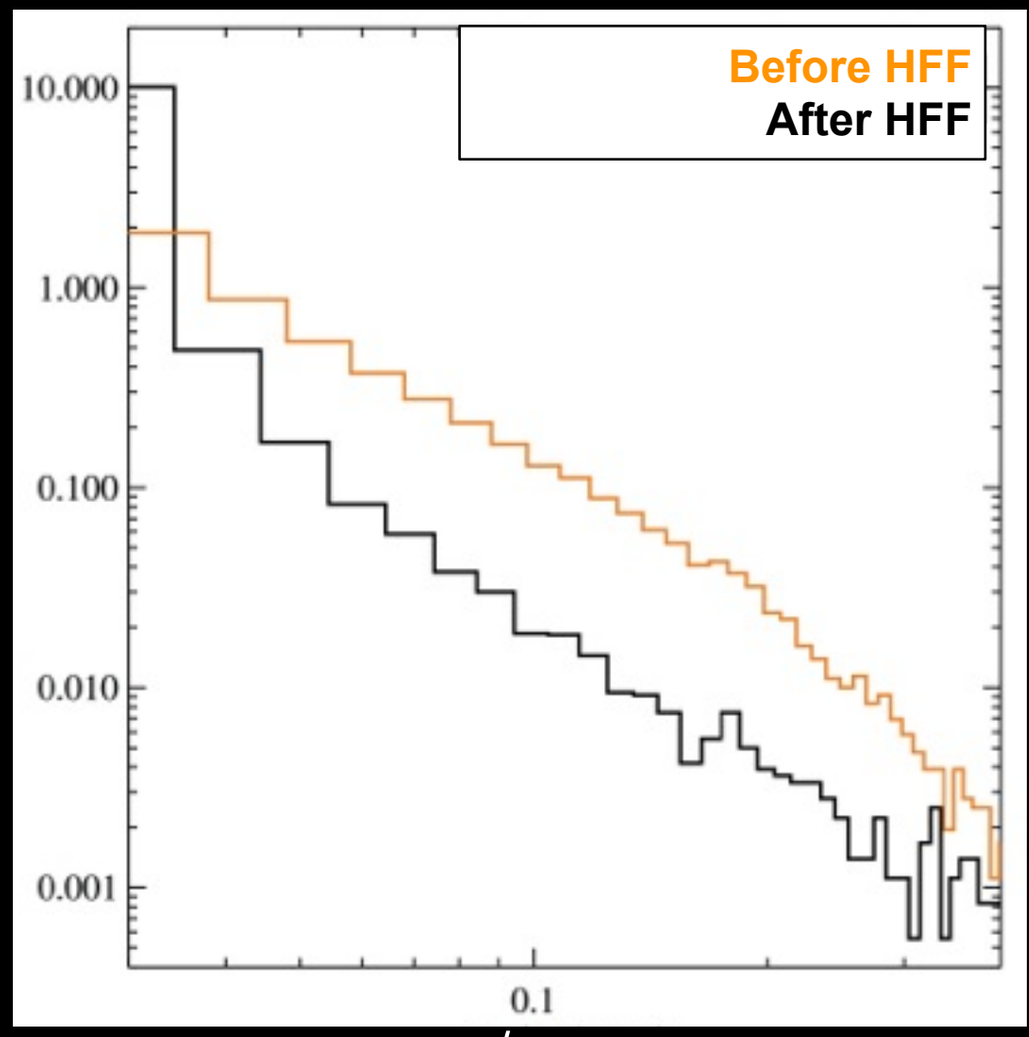
Mass estimation to the 1% level :

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

Magnification to the 4% level :

μ = 3.88 ± 0.15 (stat)

Highest precision ever obtained for mass & magnification measurements



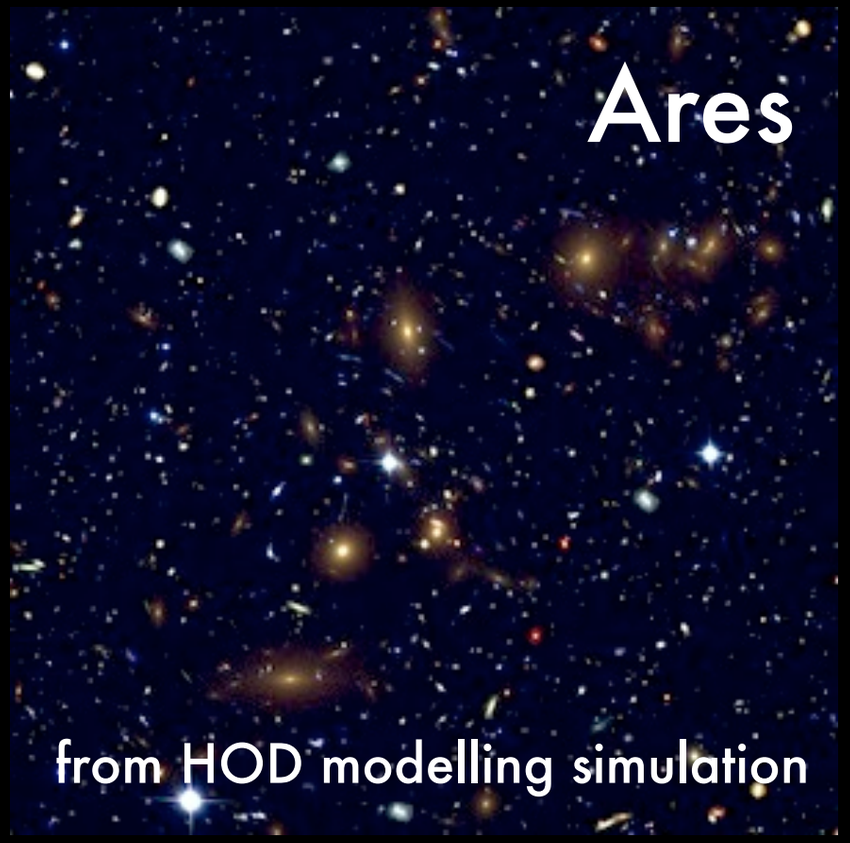
3. Mass & Magnification measurements

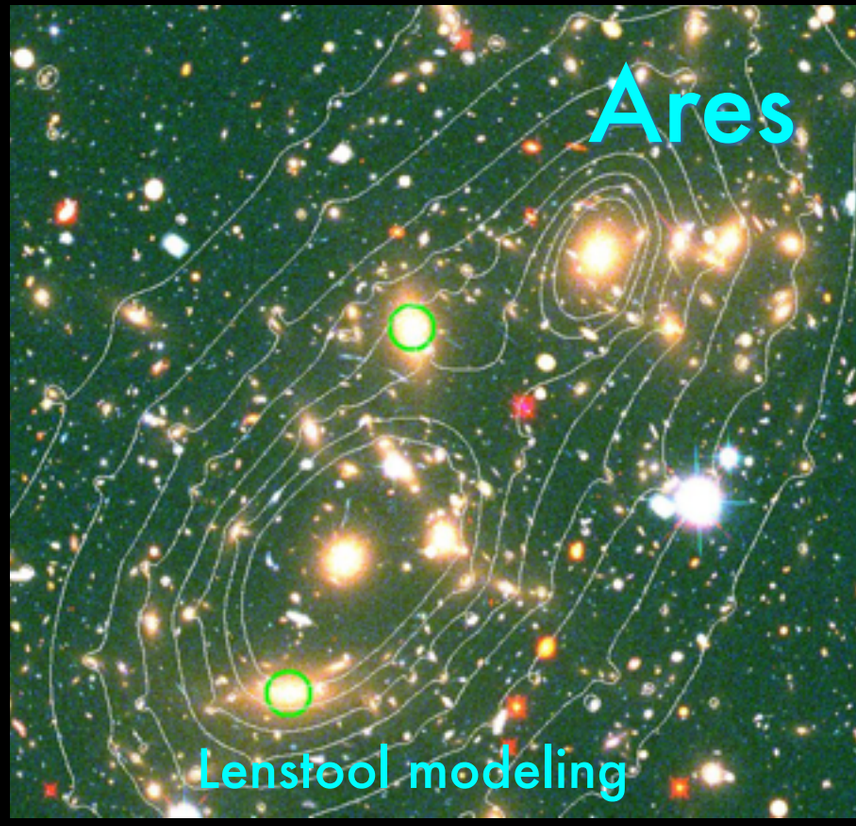
Simulated clusters to estimate systematics : http://pico.bo.astro.it/~massimo/Public/FF/ares.html [login: FFmodeler passwd:FFmagnify]

Color image: http://www.stsci.edu/~dcoe/FF/MAX/ares/

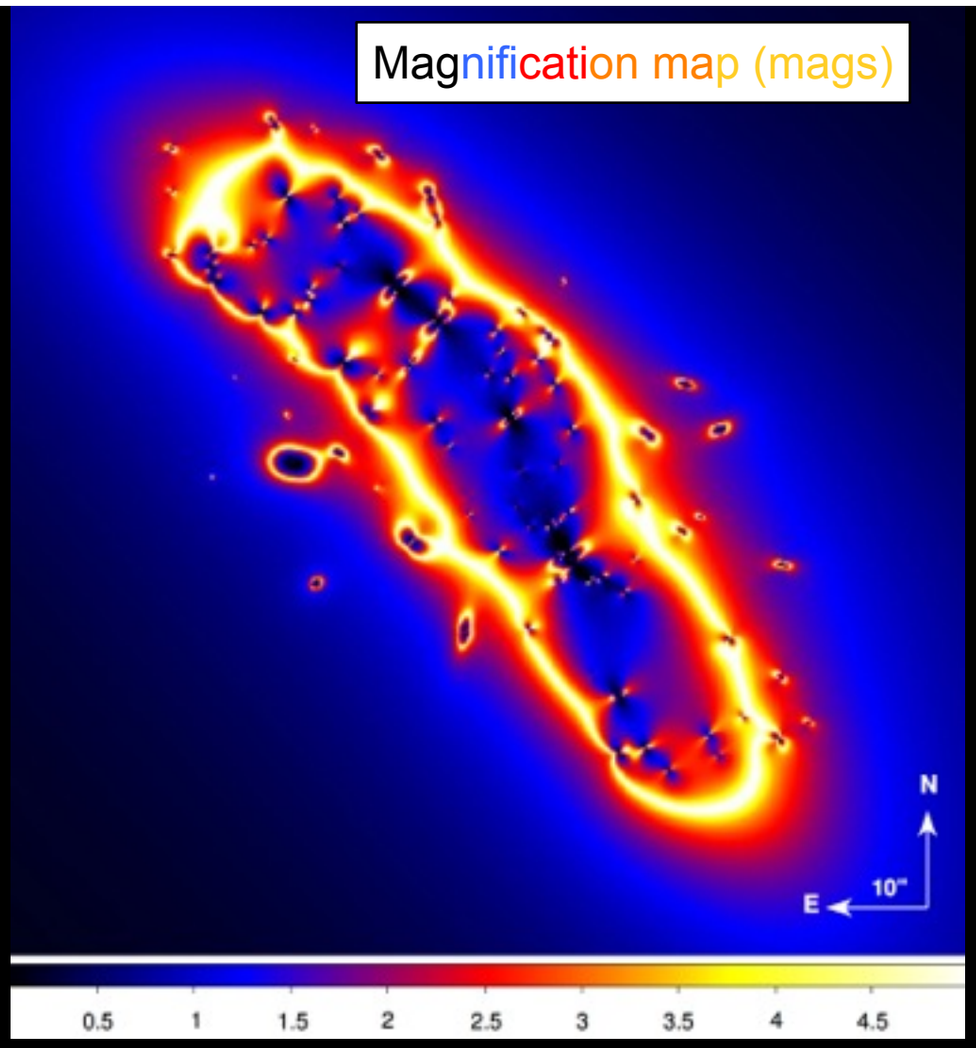
Comparison of the results provided by different modellers **= IMPROVE LENS MODELLING !!!!**

SEE Massimo's talk (next) for more details …





4. Quest for High-z Galaxies …



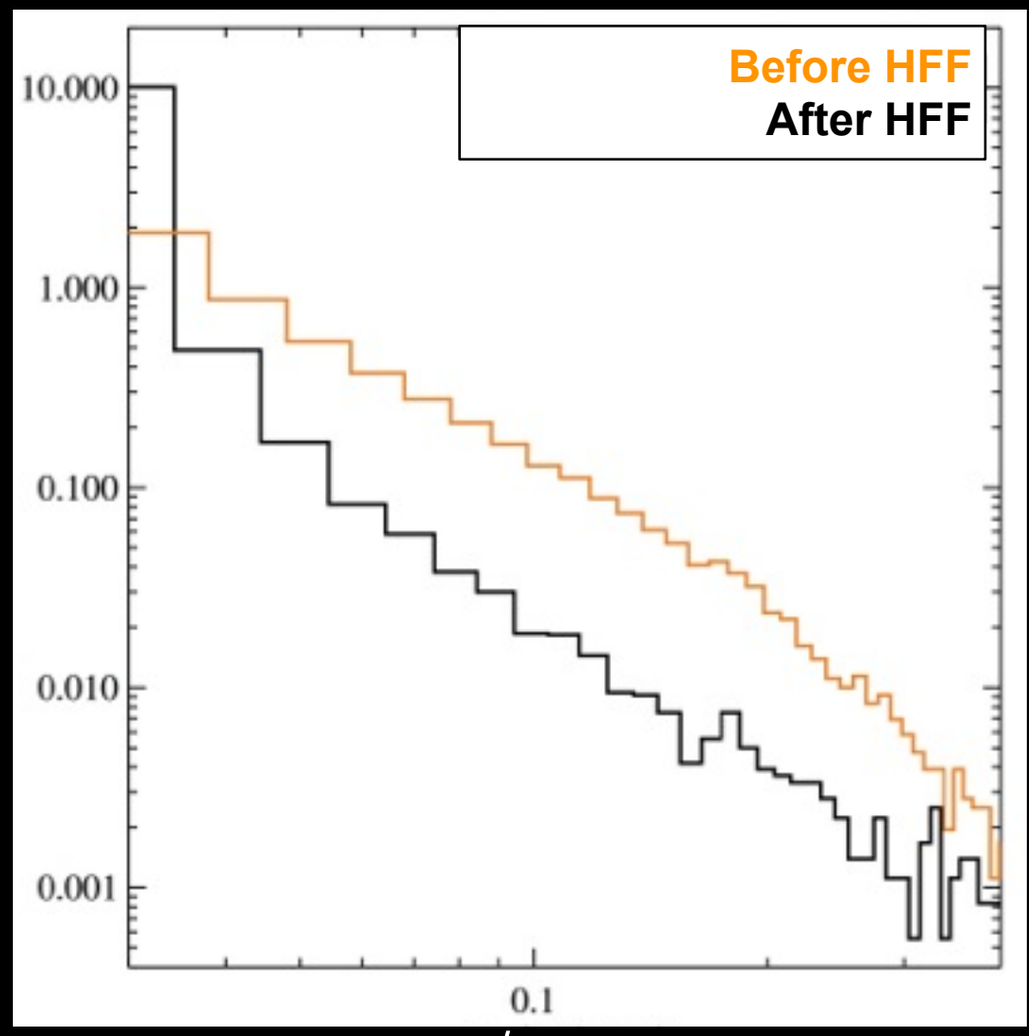
Highest precision ever obtained for mass & magnification measurements

=

Strong constraints on UV Luminosity function for high-redshift galaxies !!!!

Work in progress - *Atek et al. 2015, in prep*

z ~ 7 : 43 candidates
z ~ 8 : 8 candidates
z ~ 9 : 3 candidates



5. The Surroundings of MACSJ0416

SL + WL COMBINED ANALYSIS

Jauzac et al. 2014b, *arXiv, 1406.3011*

Grid-based mass model (**LENSTOOL**):

- 2 DM clumps
- 2741 grid potentials
- 146 cluster galaxies

5. The Surroundings of MACSJ0416

Really elongated mass distribution (NE-SW)

WL « WANTS » TO EXTEND THE MASS DISTRIBUTION !

S2
$M = 1.46 \pm 0.20\ 10^{13}\ M_{sun}$

Detection of sub-structures

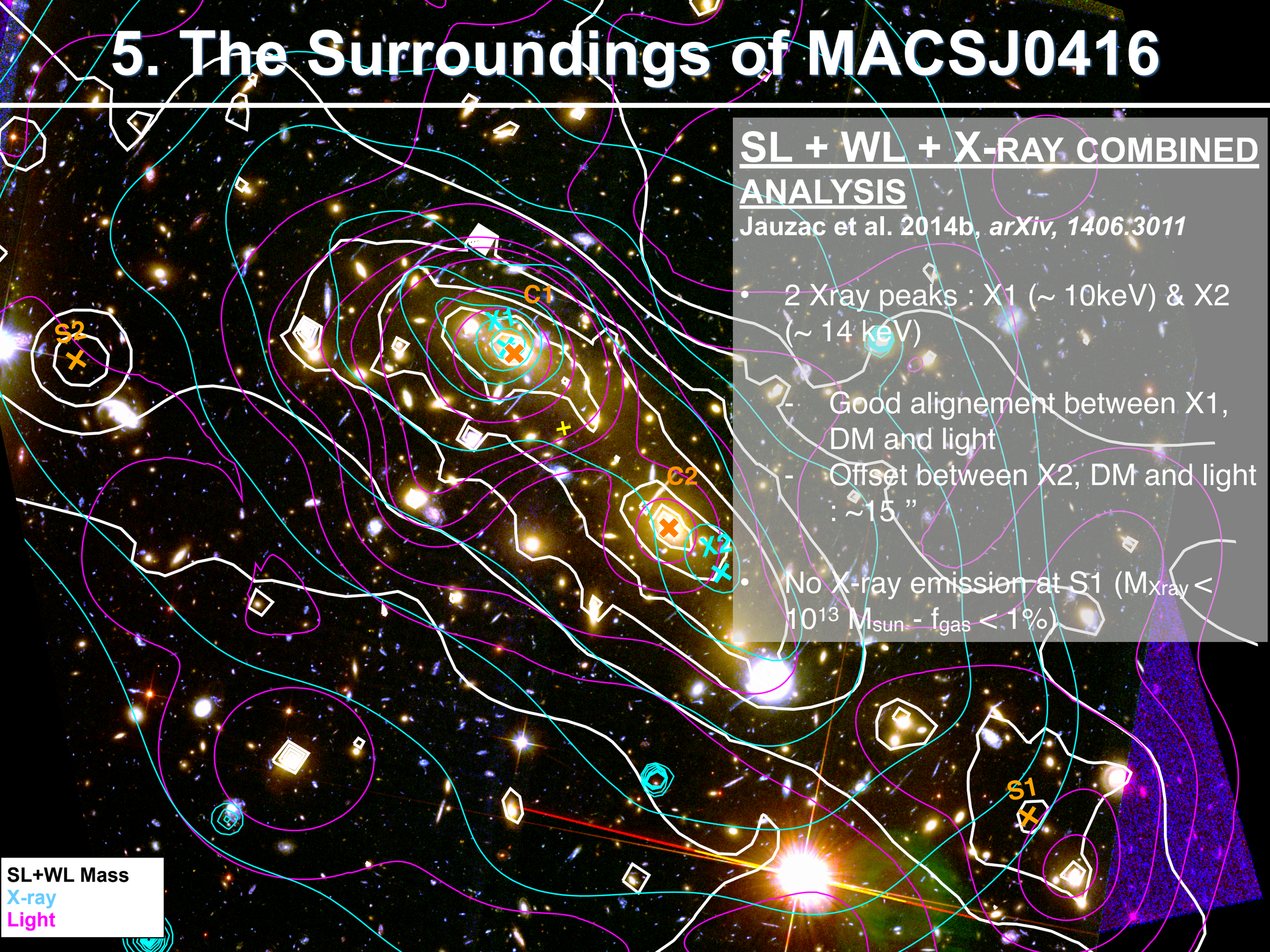
S1
$M = 4.22 \pm 0.56\ 10^{13}\ M_{sun}$

5. The Surroundings of MACSJ0416

SL + WL + X-RAY COMBINED ANALYSIS

Jauzac et al. 2014b, *arXiv, 1406.3011*

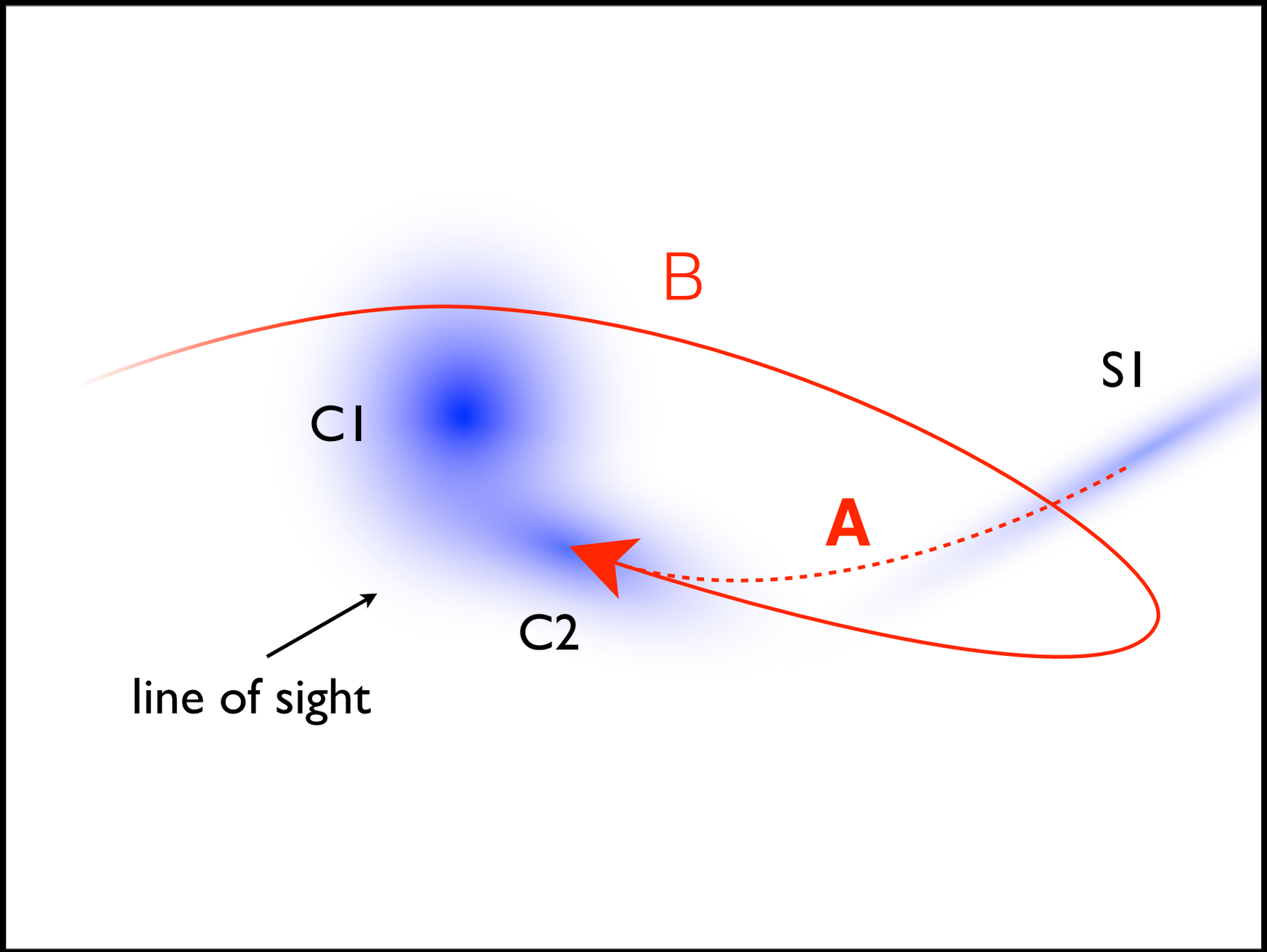
- 2 Xray peaks : X1 (~ 10keV) & X2 (~ 14 keV)
  - Good alignement between X1, DM and light
  - Offset between X2, DM and light : ~15 ”
- No X-ray emission at S1 ($M_{Xray} < 10^{13} M_{sun}$ - $f_{gas} < 1\%$)



6. Putative merger scenarios …

A. Merger C1-C2 = a ‘fly-by’ at the time of observation

B. Merger C1-C2 = on its way for a 2nd core passage



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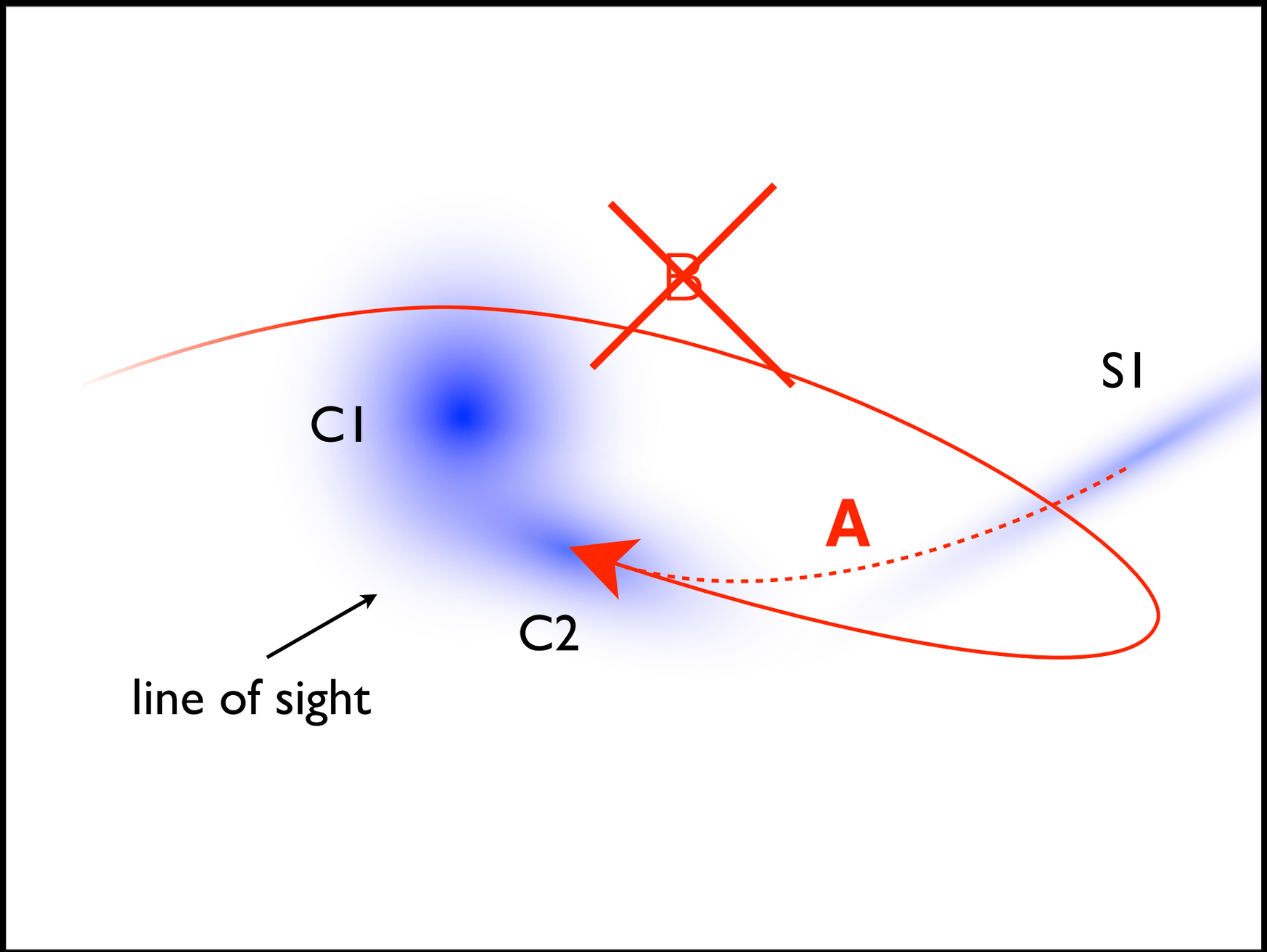
A. Merger C1-C2 = a ‘fly-by’ at the time of observation

Giorgiana Ogrean talk at the Yale HFF Workshop last week !!!

B. ~~Merger C1-C2 = on its way for a 2nd core passage~~



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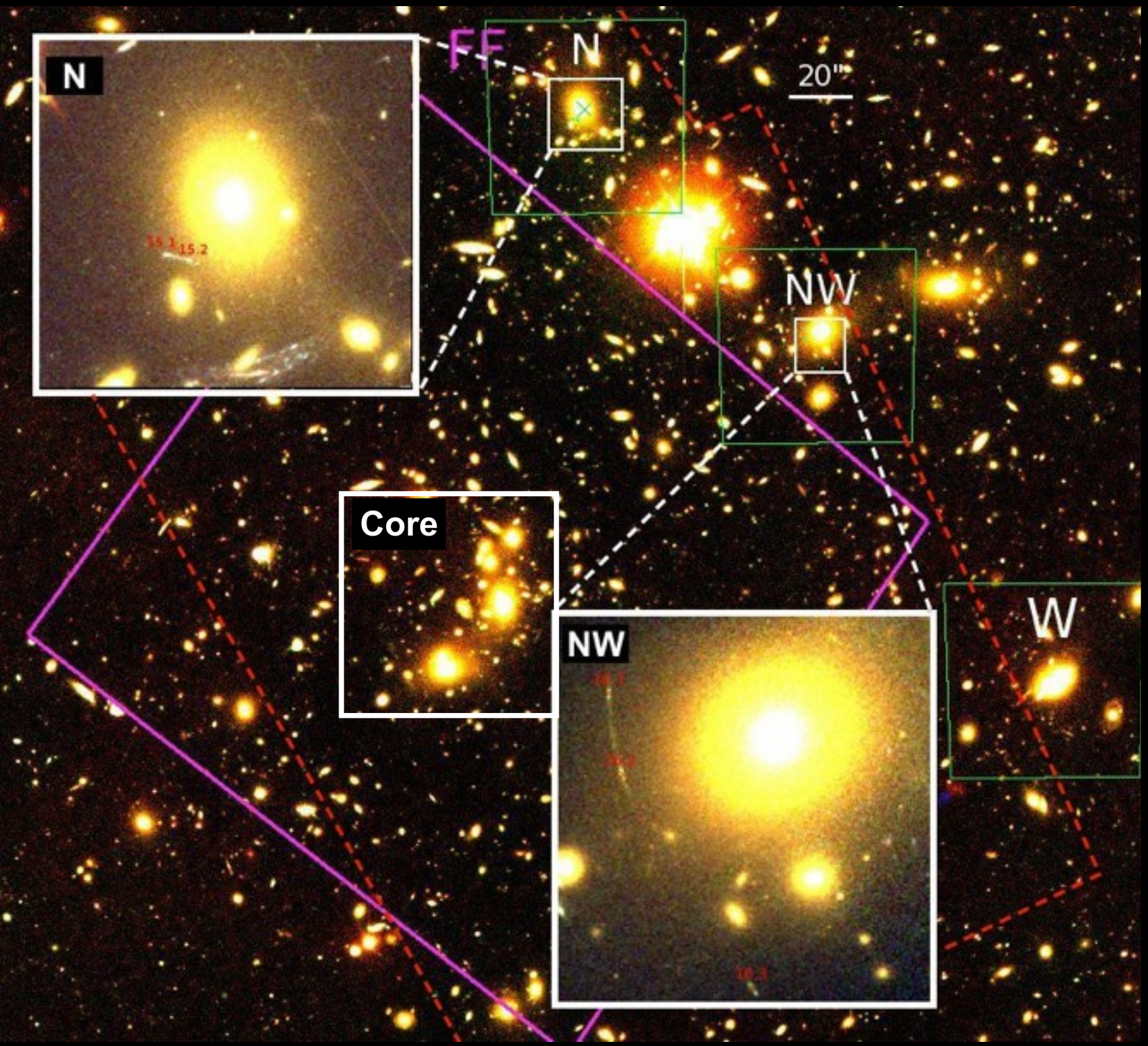


HST/ACS imaging - Merten et al. 2011

Previous GL analysis :

Smail et al. 1997, *APJ, 479, 70*
Allen 1998, *MNRAS, 296, 392*
Merten et al. 2011, *MNRAS, 417, 333*

- Lensing + X-ray
- SL constraints :

34 images of 11 galaxies

- Active merger with 4 cluster-mass components

PreHFF GL analysis :

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

- SL constraints :

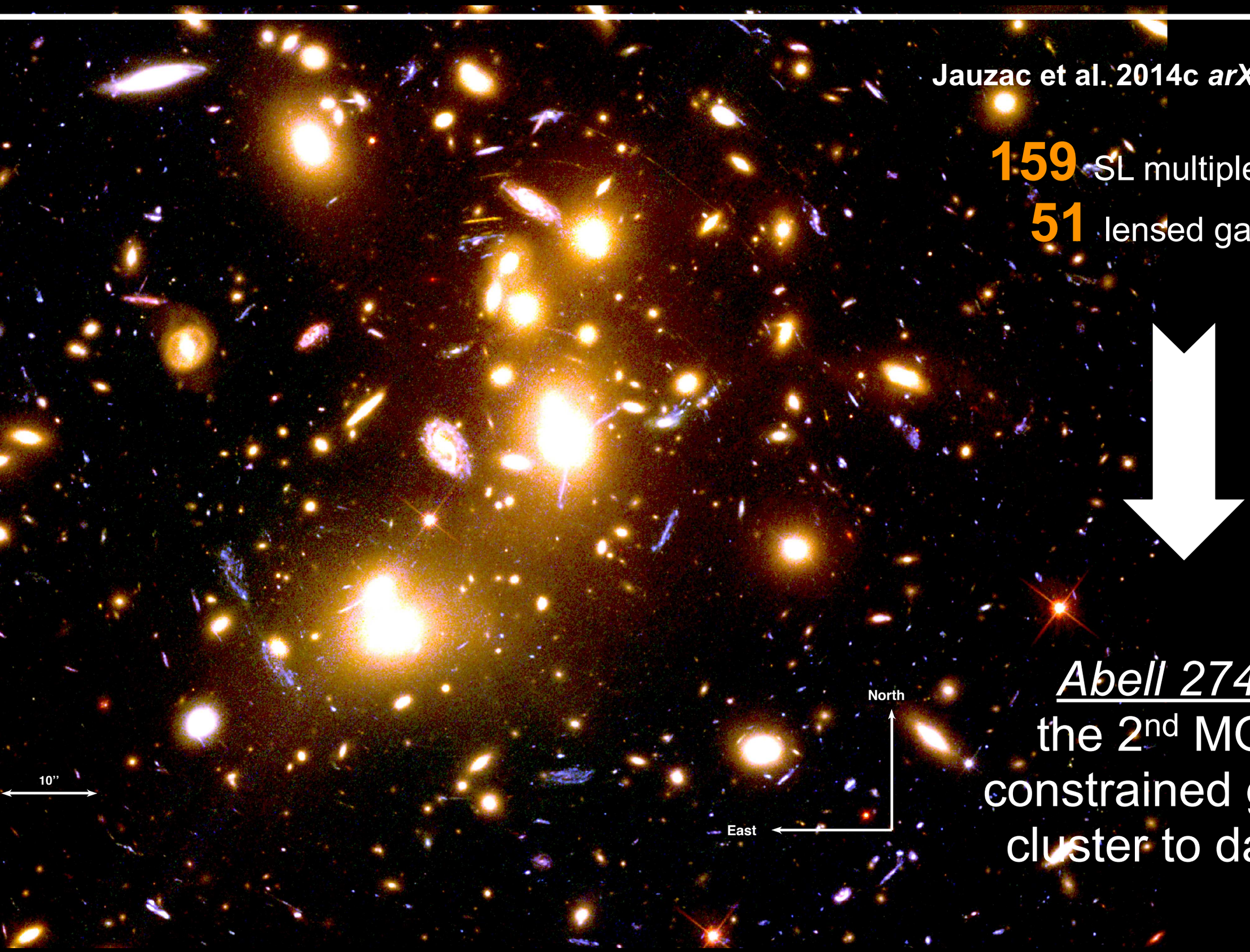
55 images of 18 galaxies
- 5 cluster-mass components

1. … After HFF !!!

Jauzac et al. 2014c *arXiv, 1409.8663*

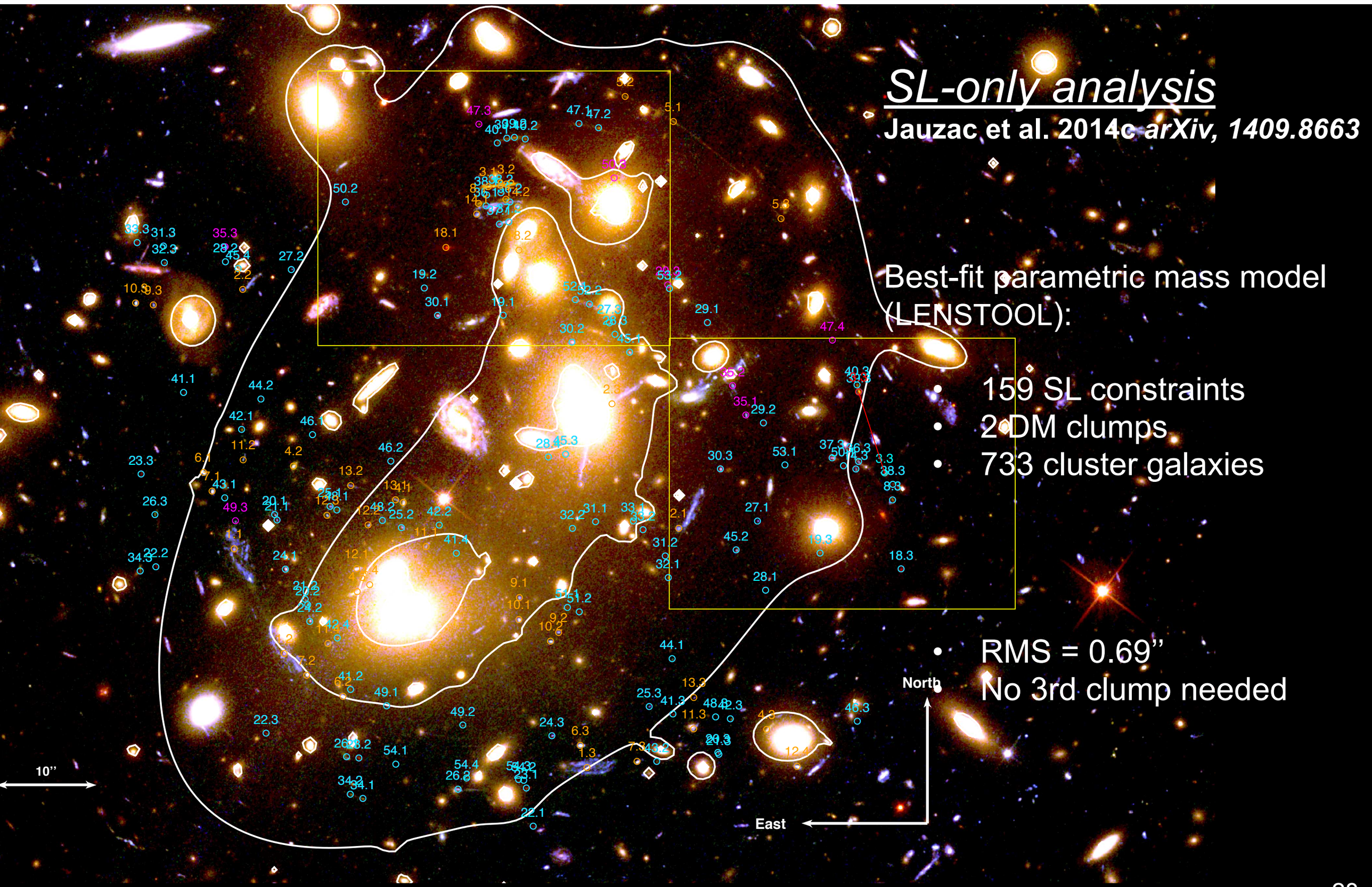
159 SL multiple images

51 lensed galaxies



Abell 2744 :
the 2nd MOST constrained galaxy cluster to date !!!

2. Inner Core Mass Distribution



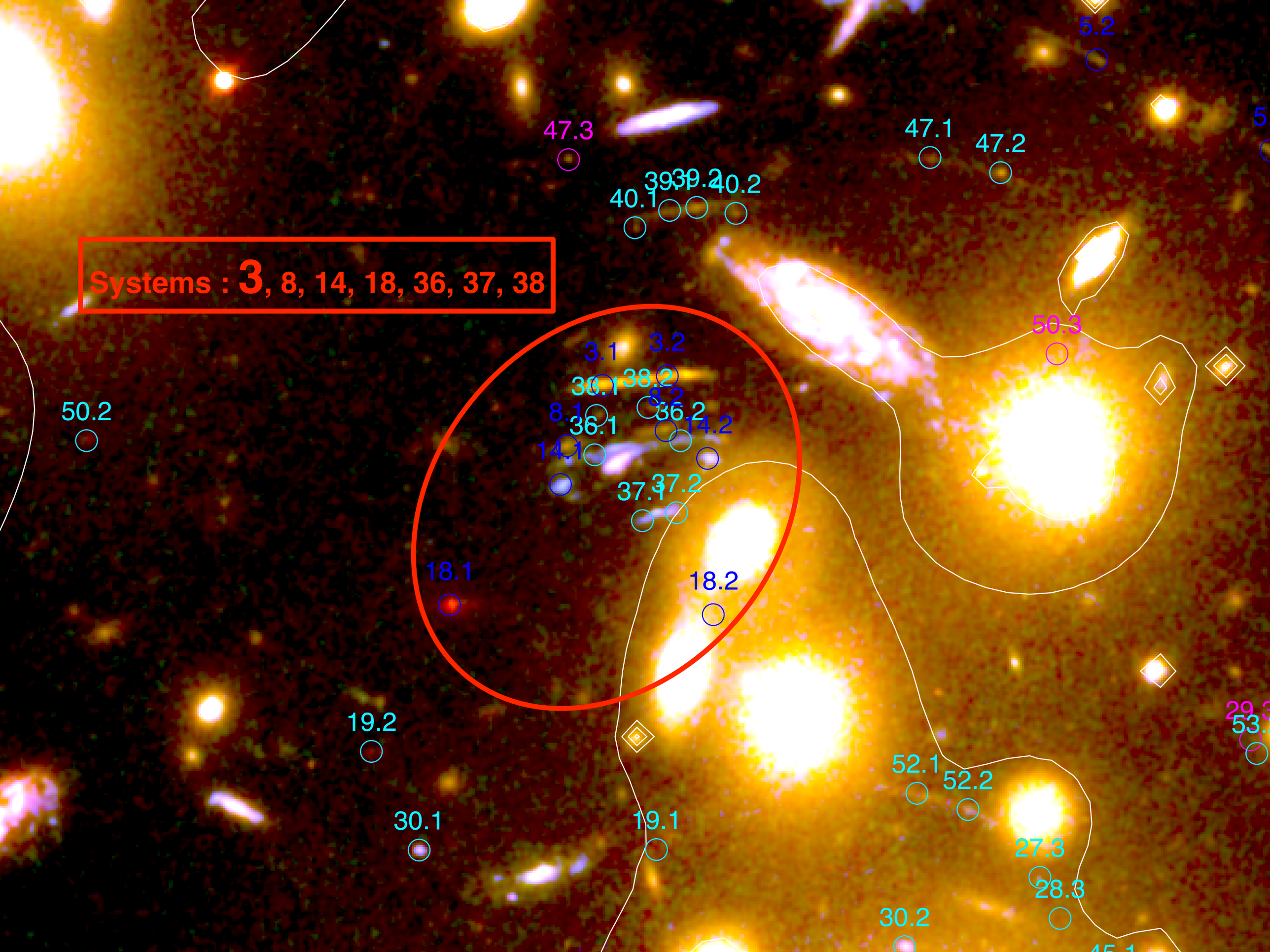
SL-only analysis

Jauzac et al. 2014c *arXiv, 1409.8663*

Best-fit parametric mass model (LENSTOOL):

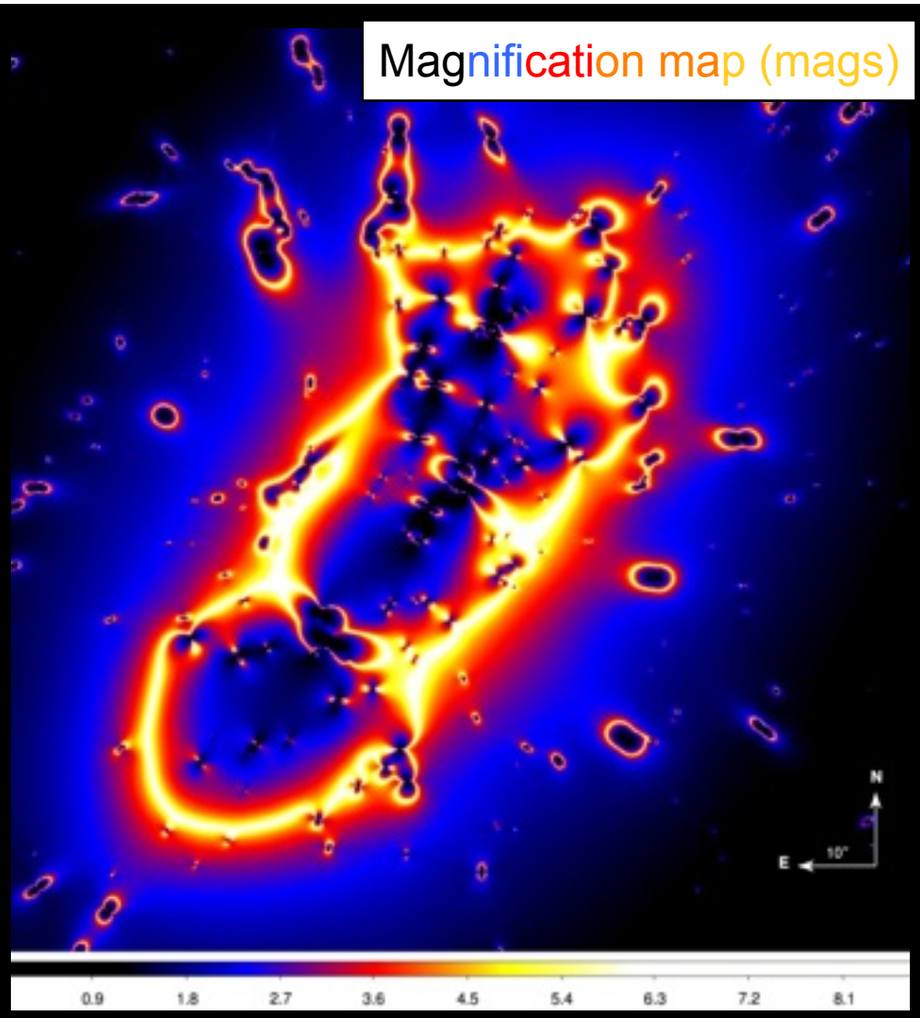
- 159 SL constraints
- 2 DM clumps
- 733 cluster galaxies

- RMS = 0.69''
- No 3rd clump needed


Systems : 3, 8, 14, 18, 36, 37, 38
47.3
47.1
47.2
5.2
40.1
39
39.2
40.2
50.3
3.1
3.2
38.2
36.1
36.2
14.2
37.1
37.2
50.2
18.1
18.2
19.2
30.1
19.1
52.1
52.2
27.3
28.3
30.2


~10” shift !!!!
3.3old rejected by 12σ
Systems : 3, 8, 14, 18, 36, 37, 38
see Daniel’s talk for multiples in A2744 also
35.2
35.1
29.2
40.3
39.3
3.3old
37.3
50.1
36.3
14.3
53.1
30.3
3.3
3.3new
38.3
8.3
27.1
2.1
45.2
19.3
18.3
28.1

3. Mass & Magnification Measurements



Mass estimation to the <1% level :

M(R<200kpc) = 2.156 ± 0.003 (stat) 10^{14} M_{sun}

Magnification to the 2% level :

μ = 6.75 ± 0.12 (stat)

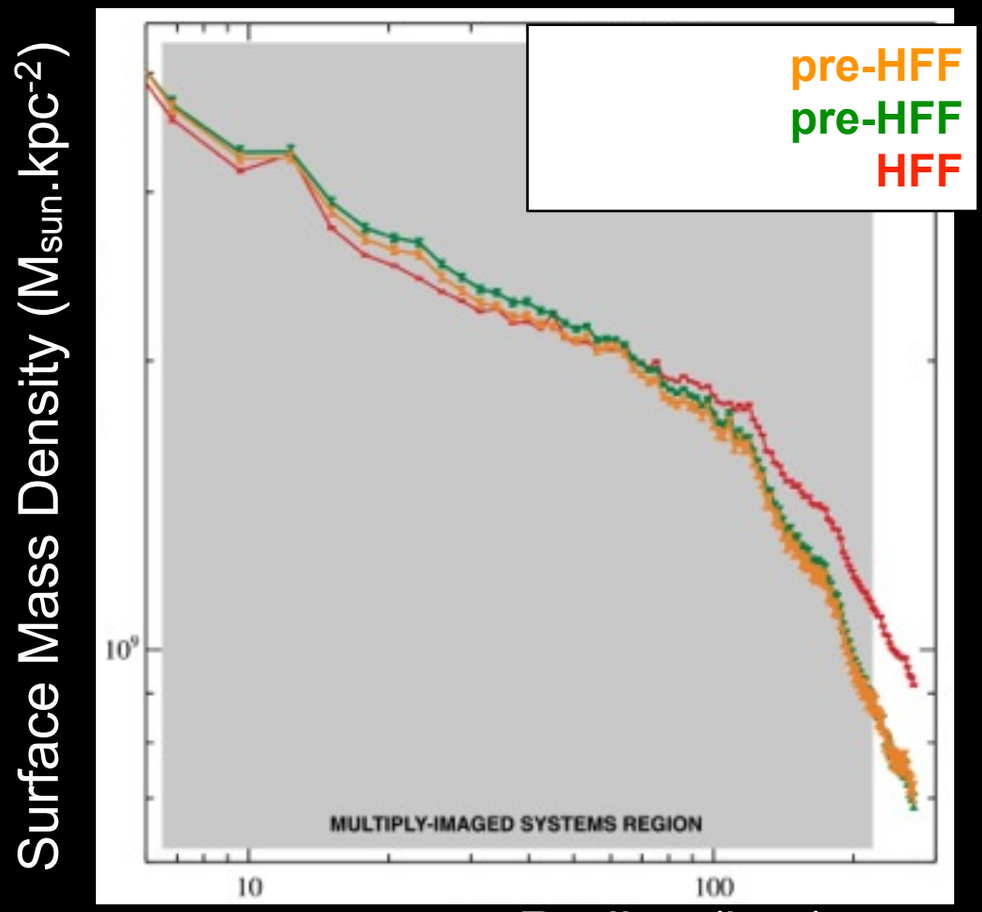
pre-HFF (Richard et al. 2014, MNRAS, 444, 268) :

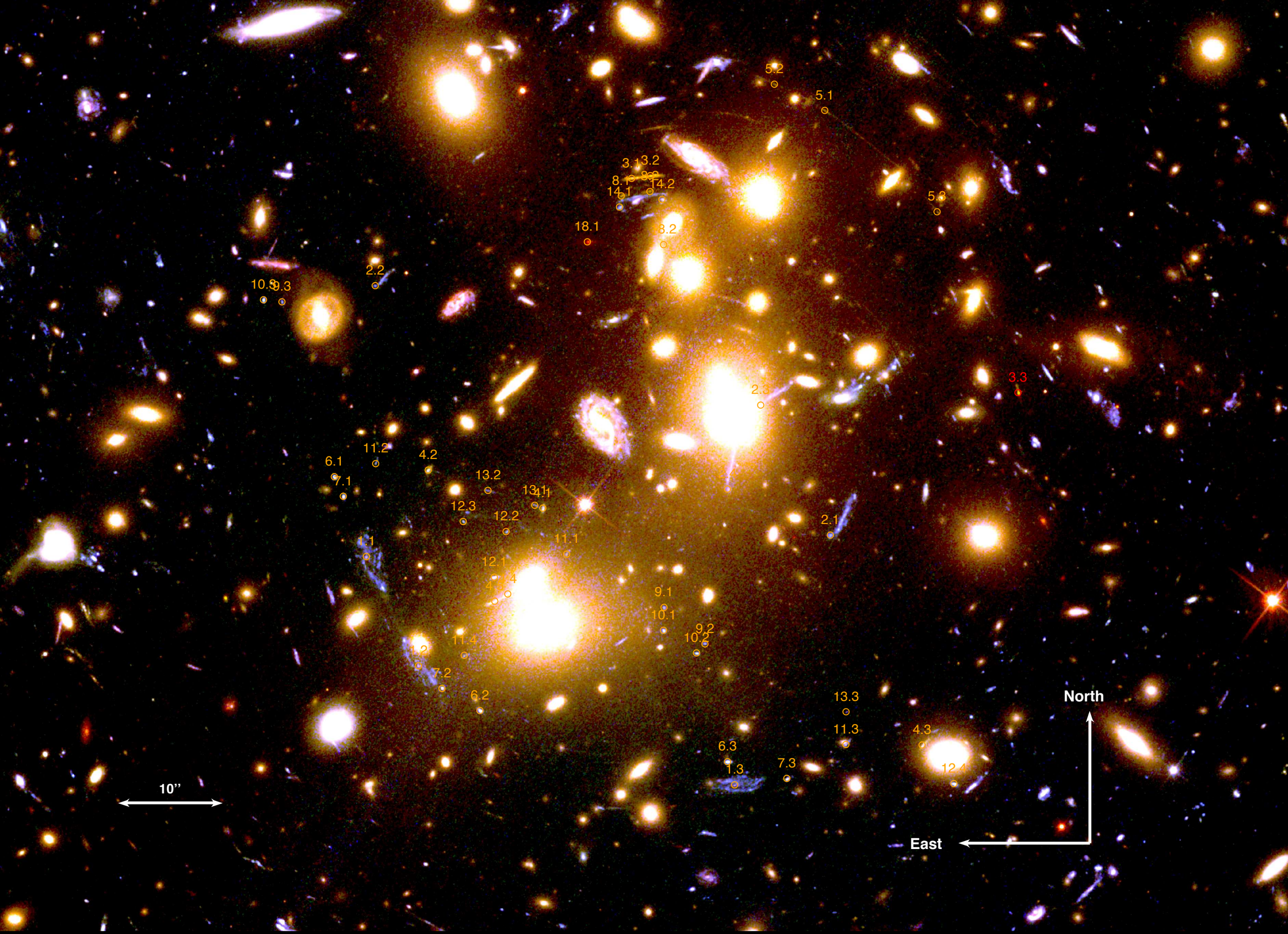
μ = 4.40 ± 0.18 (stat)

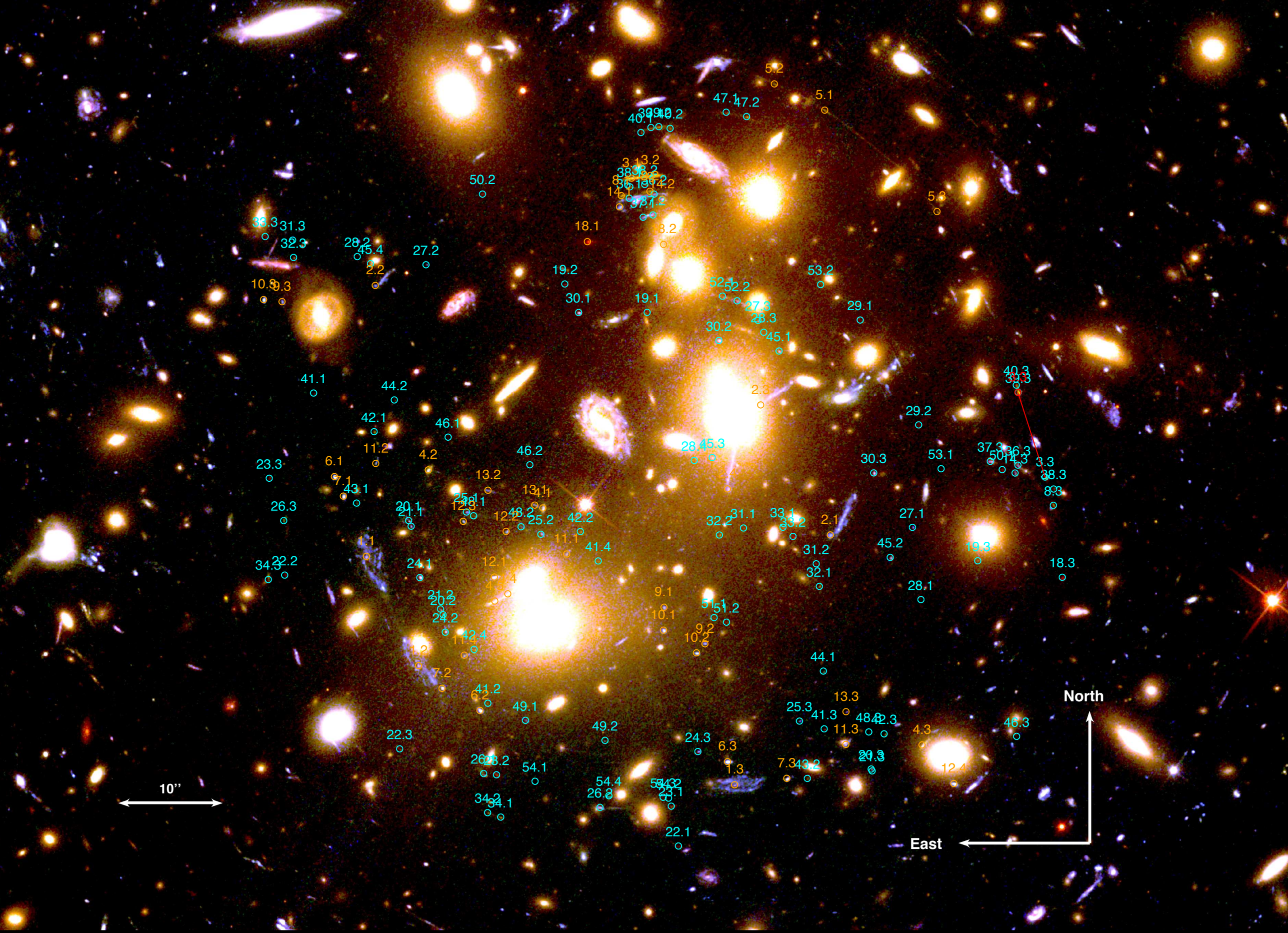
see Massimo's talk for estimation of systematics

More SL constraints for the whole core :

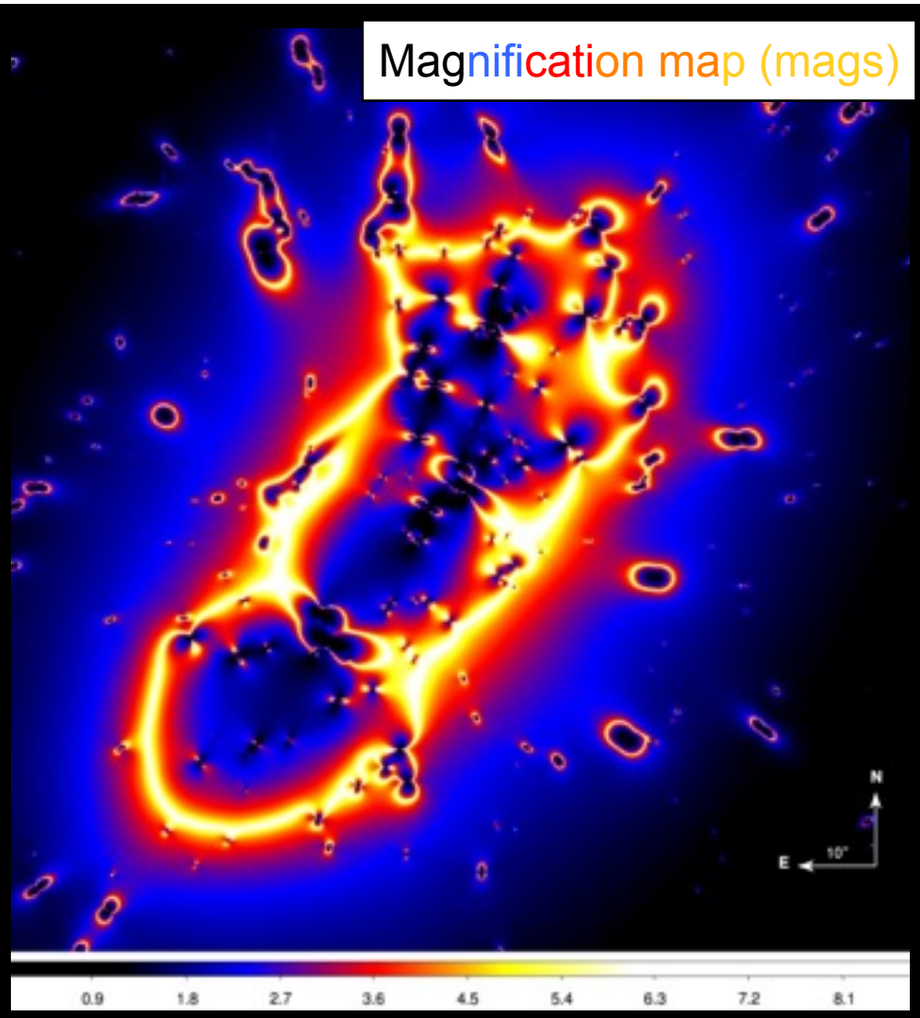
- **correction of pre-HFF model**
- **more reliable estimation of the magnification**
- **better constraints on high-redshift luminosity function (Zitrin et al. 2014,Atek et al. 2014d)**




5.2
5.1
3.1
3.2
8.1
14.1
14.2
5.3
18.1
8.2
2.2
10.3
9.3
3.3
2.3
11.2
4.2
6.1
7.1
13.2
13.1
4.1
12.3
12.2
2.1
11.1
12.1
4
9.1
10.1
9.2
10.2
11.4
7.2
6.2
13.3
11.3
4.3
6.3
7.3
1.3
12.4
10”
North
East


10''
North
East

3. Mass & Magnification Measurements



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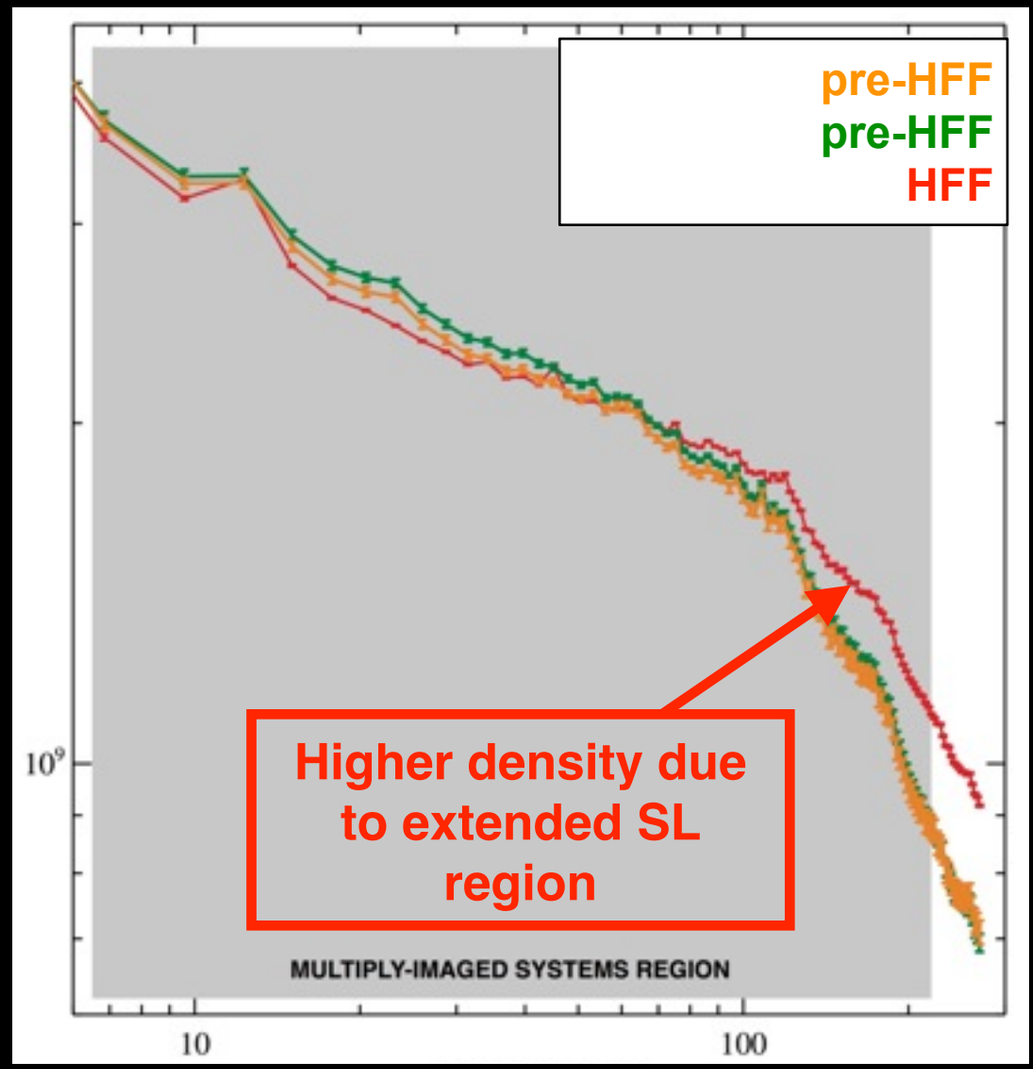
Zitrin et al. 2014, *arXiv 1407.3769,* Ishigaki et al. 2014, arXiv 1408.6903, Atek et al. 2014d, *arXiv 1409.0512*



3. Mass & Magnification Measurements

Why are the *Frontier Fields* so important/meaningful for our knowledge of the Early Universe ?

see Dan's talk (tomorrow) for more details on high-z Universe with Cluster Lensing & HFF

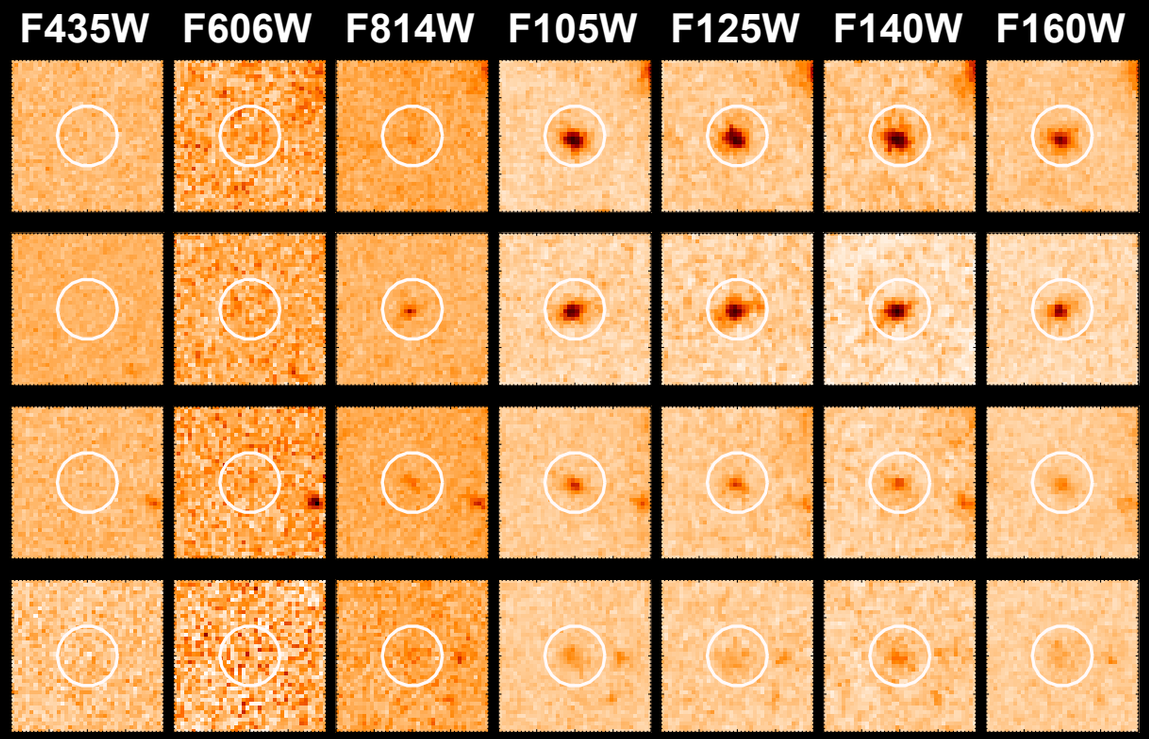
3. Mass & Magnification Measurements

Gravitational lensing helps reach the faint galaxies likely responsible for cosmic reionization !!!

see Dan's talk (tomorrow) for more details on high-z Universe with Cluster Lensing & HFF

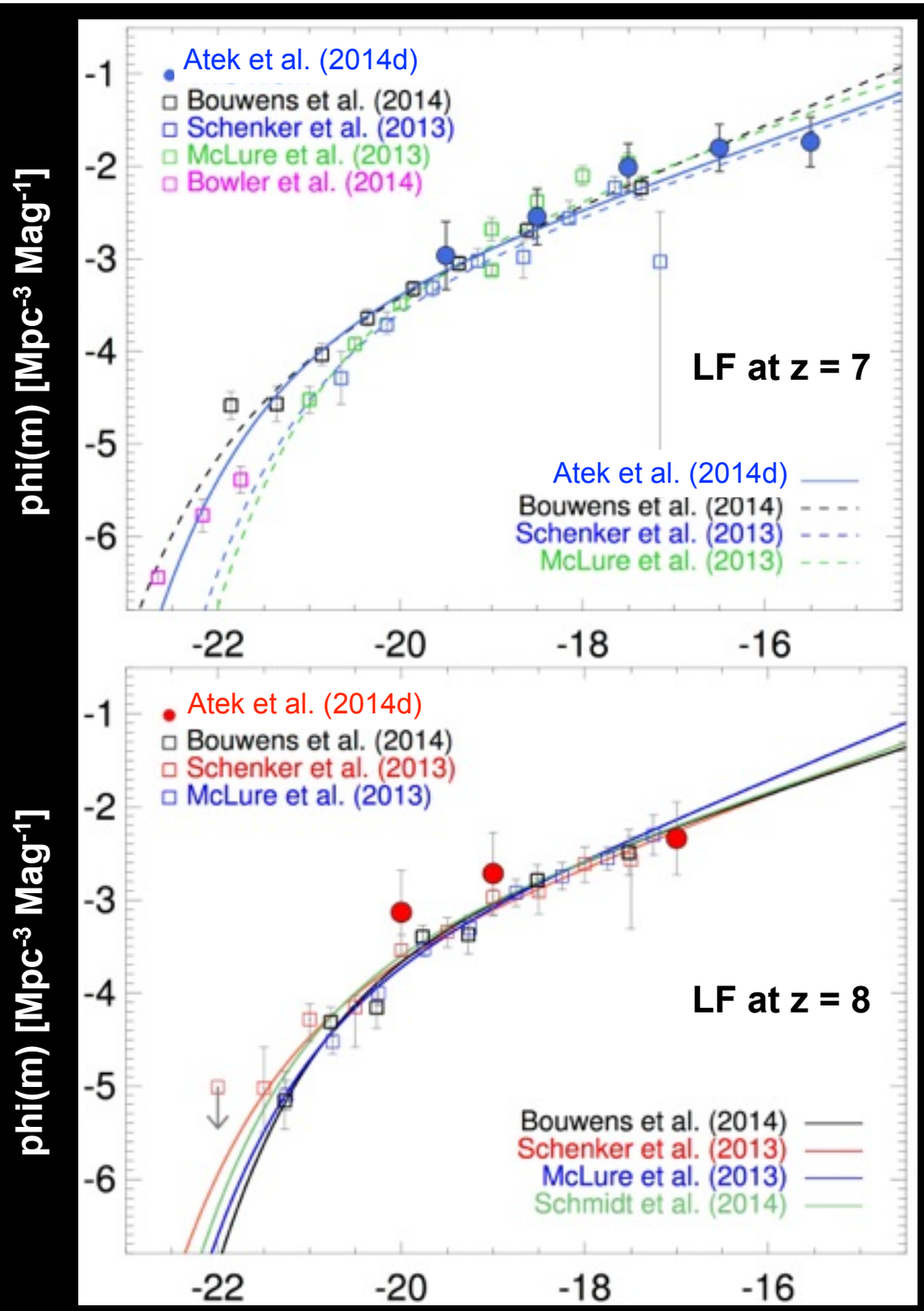
4. Quest for High-z Galaxies in Abell 2744

Atek et al. 2014d : z = 7



50 candidates at z ~ 7
8 candidates at z ~ 8

- **Detection of the faintest galaxies at z>6**
- **2 magnitudes deeper than deep blanck fields (z = 7 to M_{UV} ~ -15.5)**
- **Lensing is the best way to constrain the faint-end UV-LF**
- **Blanck fields better for the bright-end UV-LF**



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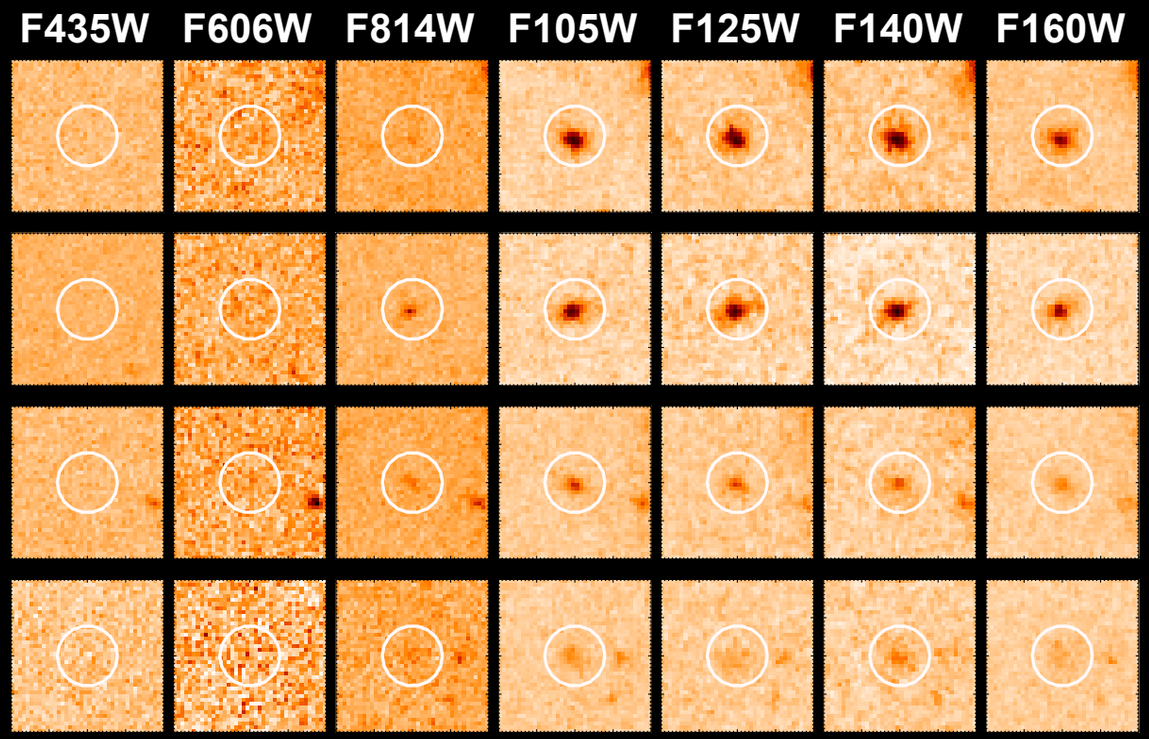
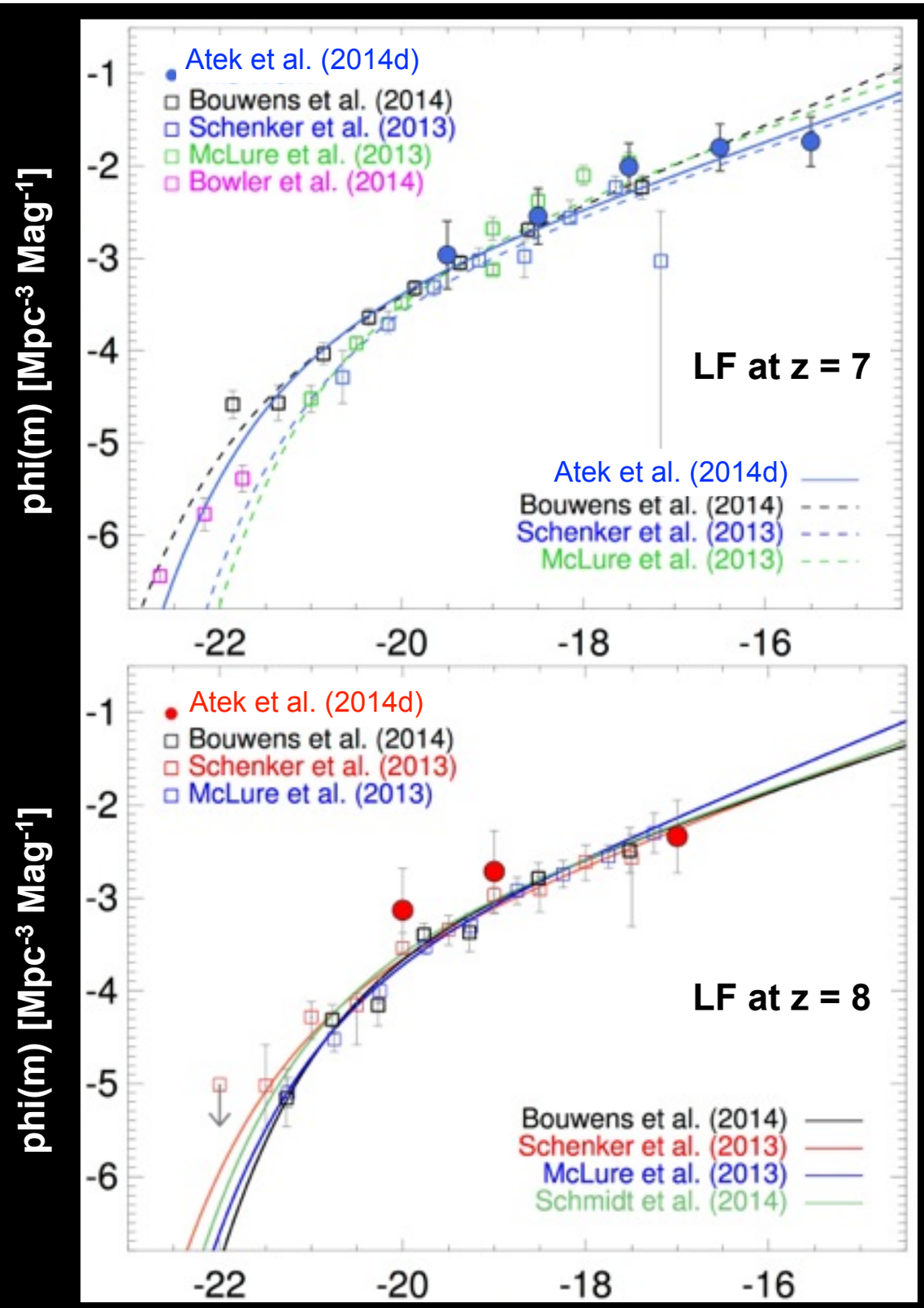


- Slope remains steep down to very faint luminosities, 0.01 L*
- z~8 UV LF confirms steep faint-end slope

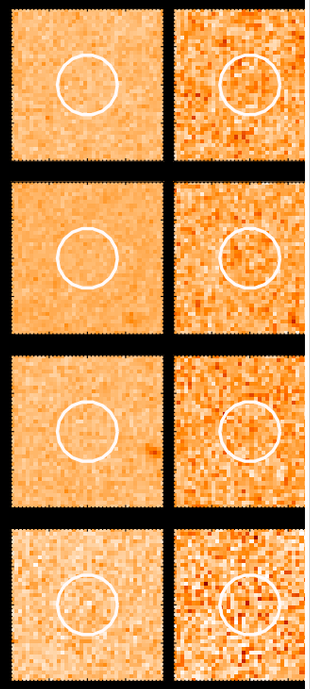
- **Comparison with mass function of DM halos to understand connection between galaxies & dark matter evolution**
- **Star formation density & evolution across cosmic time**



4. Que … l 2744

At …

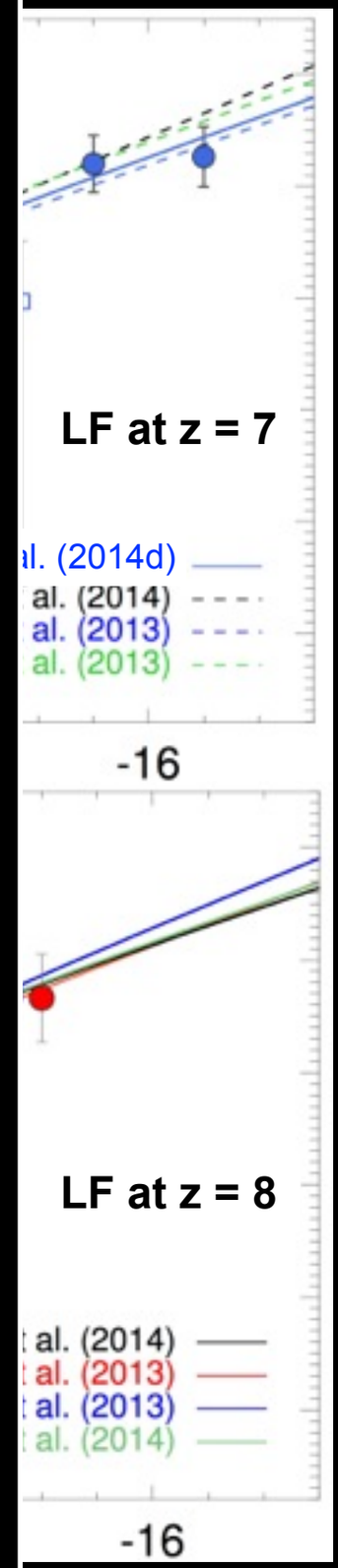
F435W F606W



- Slope remai… luminosities…
- z~8 UV LF c…

- Comparisc… halos to ur… galaxies &…
- Star forma… across cos…

More about this in Masafumi's talk (tomorrow) !!!



M_{AB}

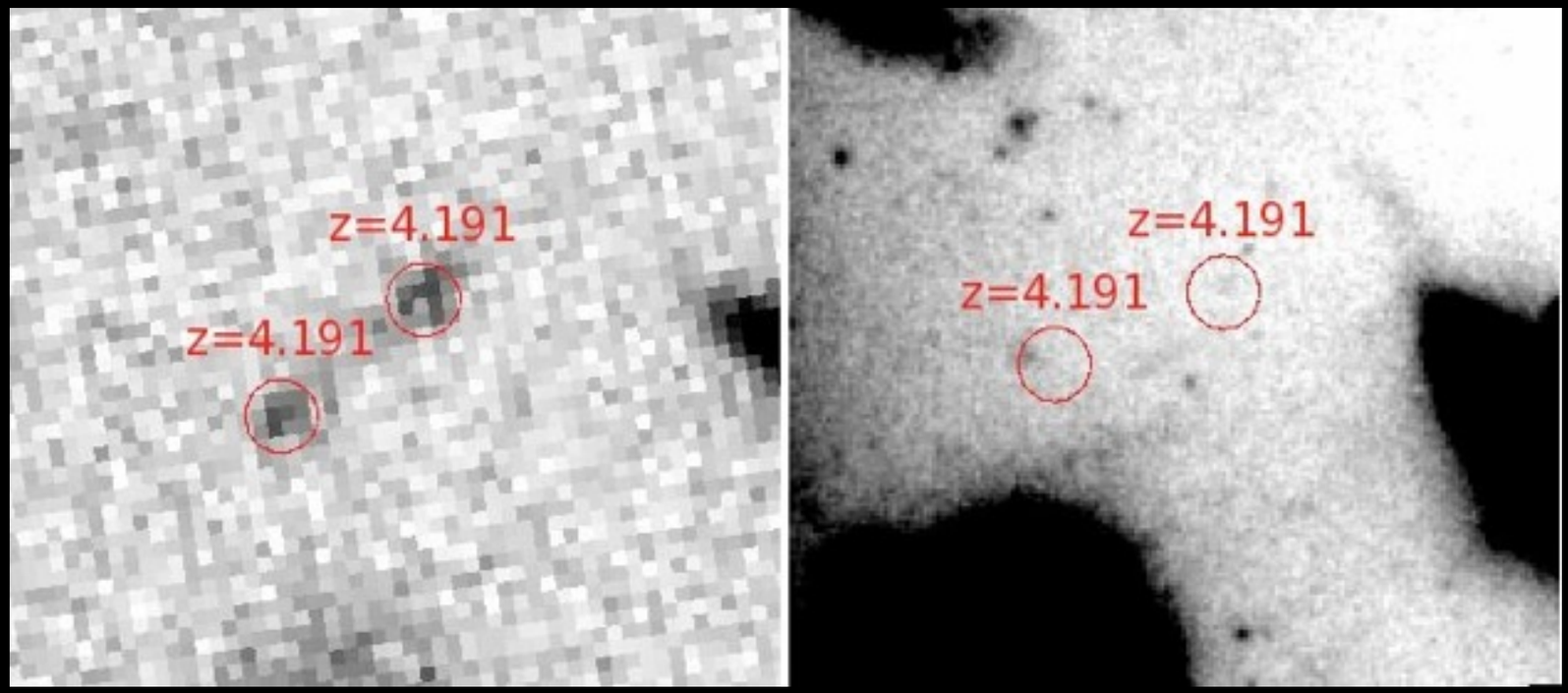
5. What's next for Abell 2744 ?

A2744 core GTO VLT/MUSE observations

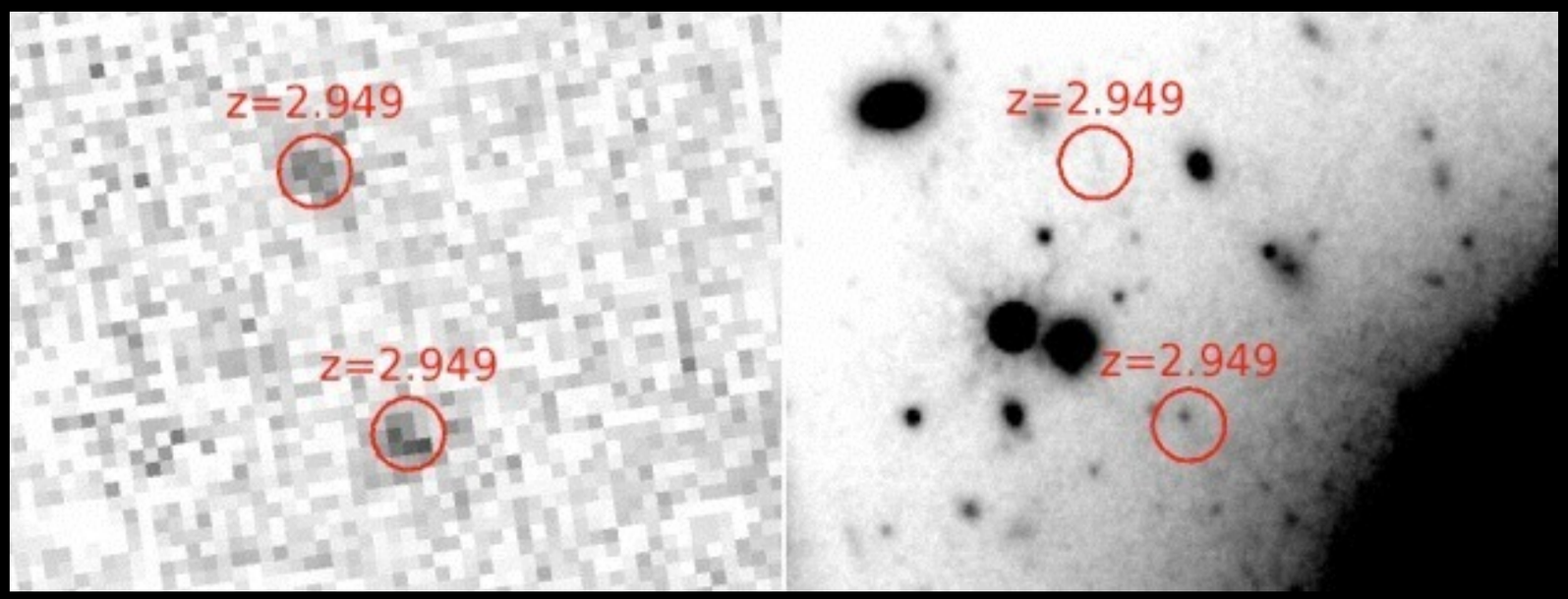
Courtesy : Johan Richard & the MUSE consortium

MUSE (GTO observations)

STACKED WFC3 (all bands)



Already new multiple images detected in the cluster core … And many more to come !



5. What's next for Abell 2744 ?

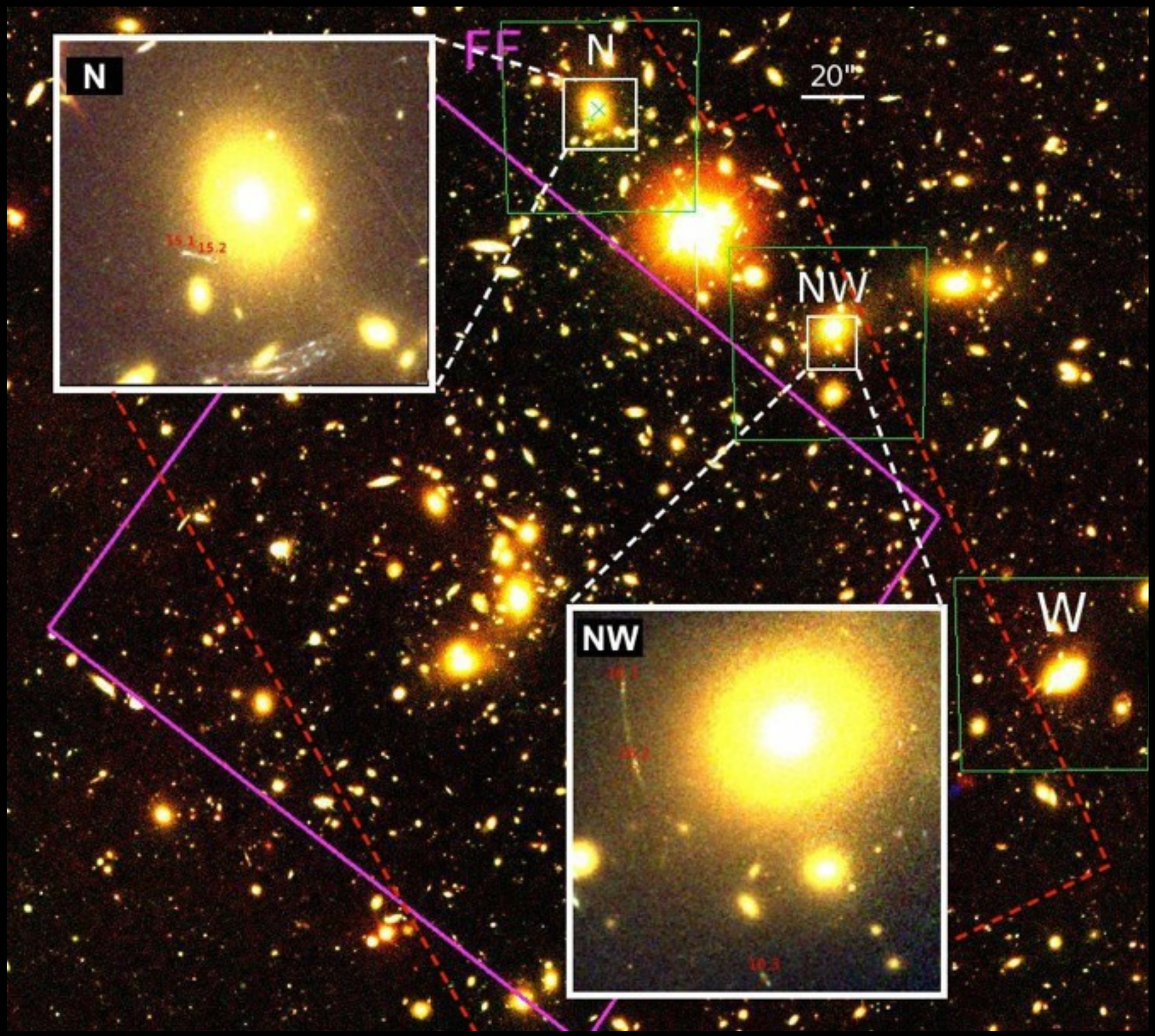
TO GO FURTHER ON A2744

VLT/MUSE observations
(J. Richard & W. Karman 's talks)

Image the *N*, *NW* and *W* components:

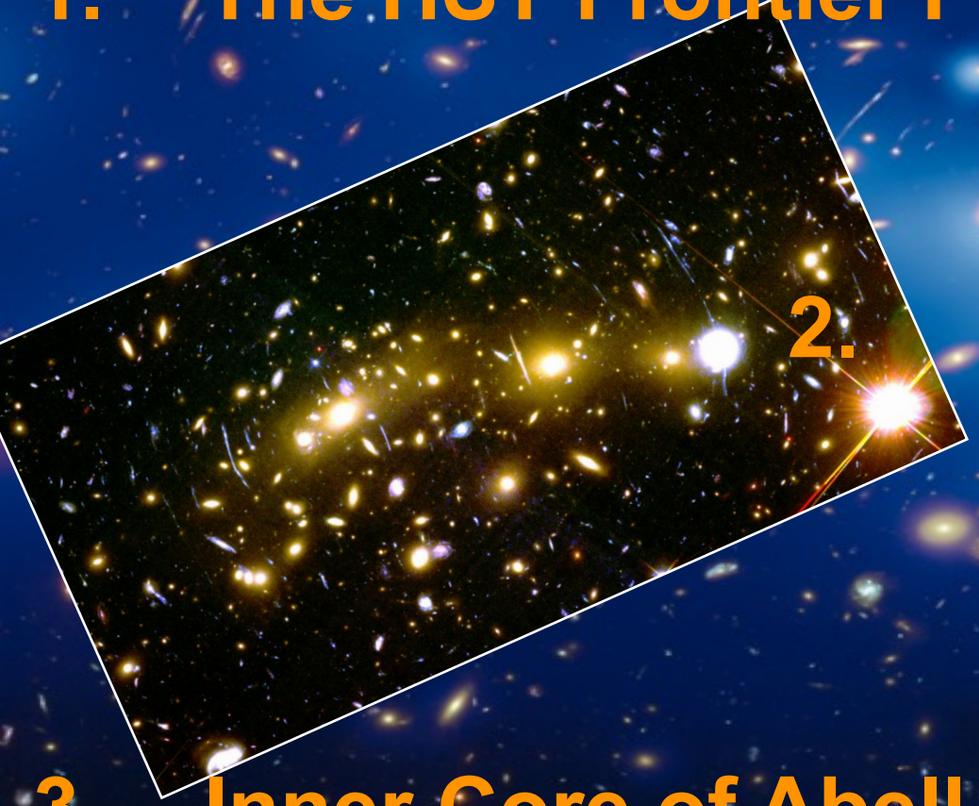
- To get spectroscopy for their known multiple images
- To **detect new multiply-imaged systems** (Richard et al. 2014b, **arXiv 1409.2488**) :
  ~ 20 multiply-imaged systems

More accurate mass distribution of the cluster = **MANDATORY FOR A GOOD ESTIMATION OF THE MAGNIFICATION !!!**



Outlines

1. The HST Frontier Fields Initiative

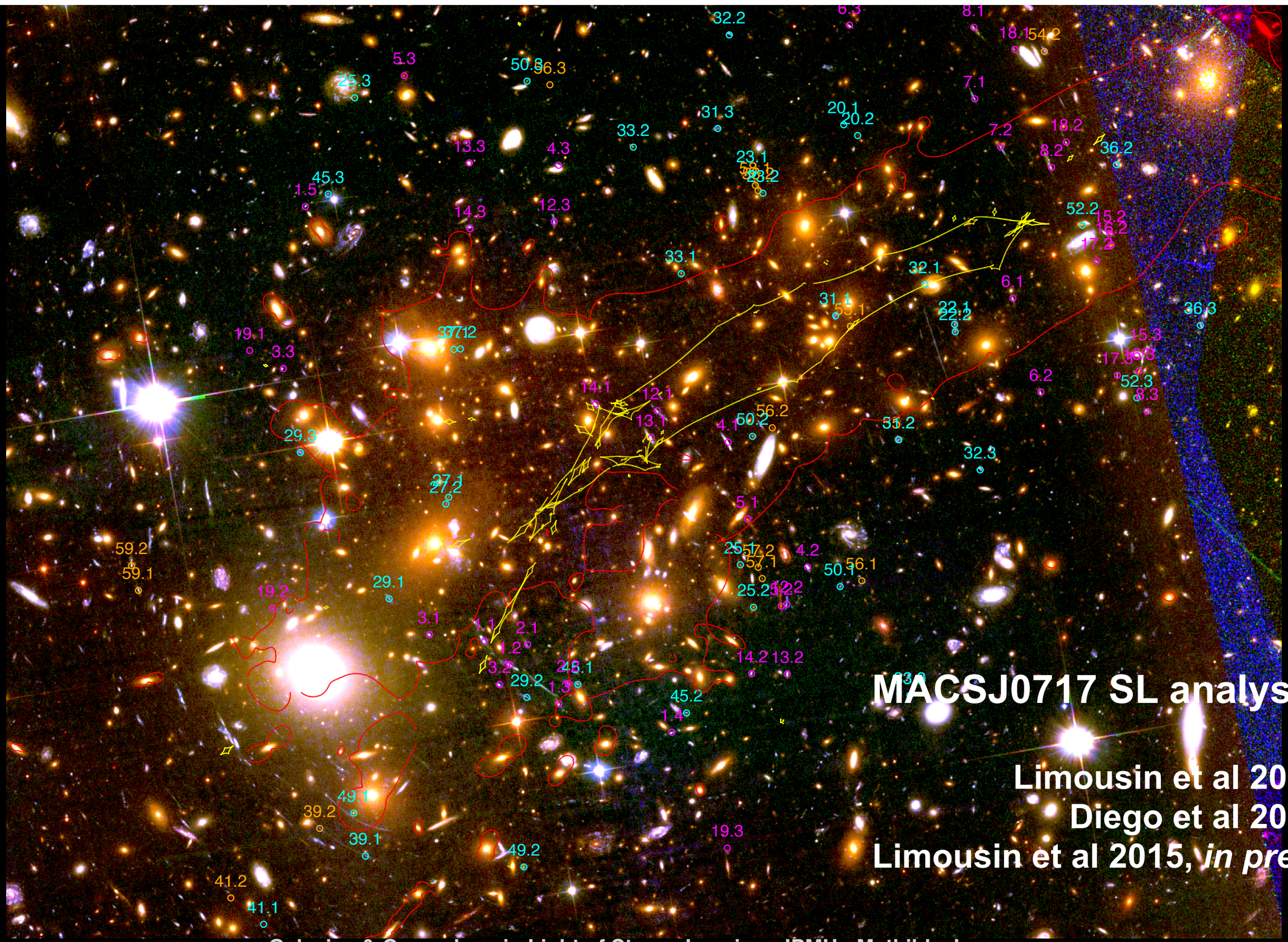


2. Inner Core & Outskirts of MACSJ0416

3. Inner Core of Abell 2744

4. *Other 'on-going' CATS works, Conclusions & Perspectives*

Other '*on-going*' CATS works ...

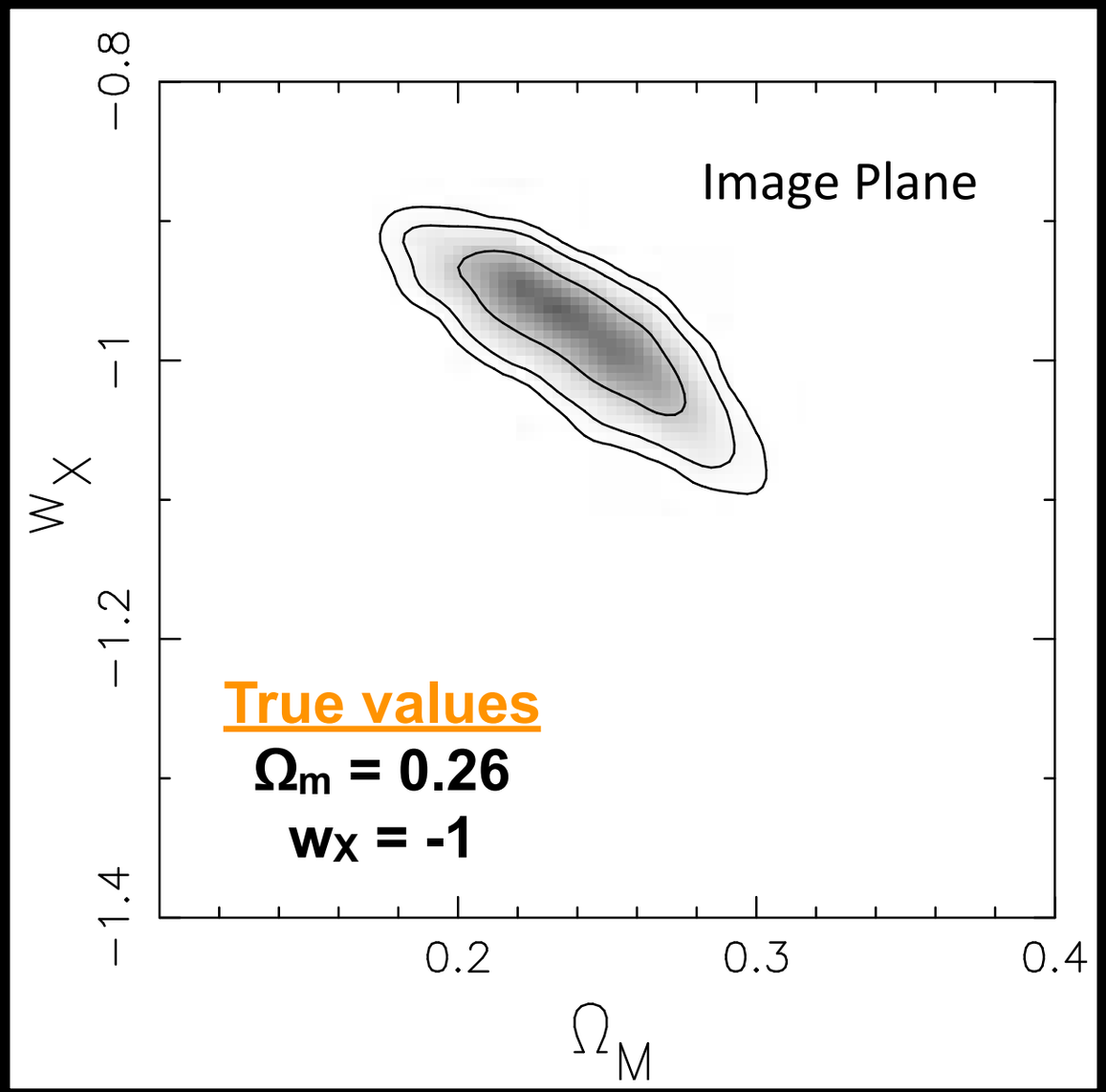


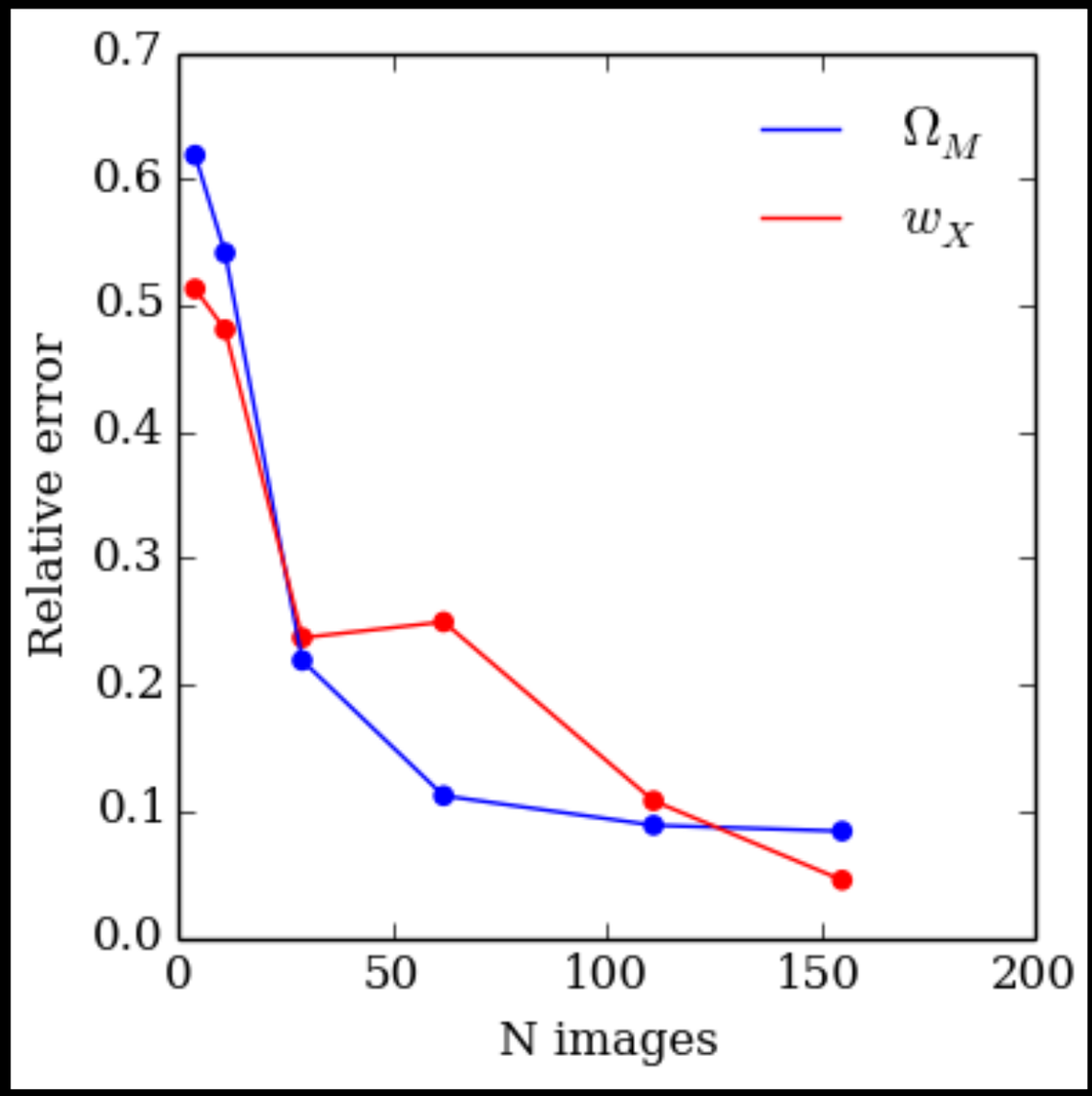
Other *'on-going'* CATS works …

Cosmography with the HFF clusters

Jullo et al. 2010, Jullo et al. 2015 *in prep.*

Tests on ARES : Better precision on cosmological parameters as you increase the number of multiple images





Conclusions & Perspectives

- ***Hubble Frontier Fields*** **reaching its goals : high precision mass & magnification measurements, detection of high-redshift galaxies, … !!!!!!**

- **If you combine it with other observational probes (X-ray & spectroscopy) then you can do some FANCY Science !!!**

High-redshift side …

- ***MACSJ0416 :*** **The MOST CONSTRAINED Lensing mass model ever built to date !**

(Jauzac et al. 2014a,b)

» **~ 200 strongly-lensed images + ~ 30 new ones !!!!!**

» **~ 100 background galaxies / arcmin^2**

» **high-z candidates : 43 at z ~ 7, 8 at z ~ 8, 3 at z ~ 9 - Work in Progress**

- ***Abell 2744*** **: The 2nd MOST CONSTRAINED Lensing mass model ever built to date !**

(Zitrin et al. 2014, Ishigaki et al. 2014, Atek et al. 2014d, Jauzac et al. 2014c)

» **~ 160 strongly-lensed images**

» **high-redshift galaxies : 43 + 18 (+ 17) at z ~ 7, 8 + 11 (+ 4) at z ~ 8, 3 (+ 3) at z ~ 9, 1 at z ~ 10**

- ***MACSJ0717 :*** **Will beat the the two previous ones !!!!!!!!**

(Diego et al. 2014d, Limousin et al. 2014 in prep.)

» **~ 100 strongly-lensed images with only 1/3 of the data !!!!!**

» **~ 200 now !!!!**

» **high-z candidates : TO COME !!!**

Conclusions & Perspectives

On the Cluster Physics side …

- ***MACSJ0416*** **: An active double-merger !!!**

(Jauzac et al. 2014b)

» **Deeper *Chandra*/ACIS-I observations confirmed our first putative scenarios (Georgiana Ogrean work)**

- ***Abell 2744*** **: An active four-component merger (at least !)**

(Jauzac et al. 2014d, *in prep.*)

» **New SL+WL analysis coming … helped by MUSE observations maybe ?**

More globally for the HFF clusters …

- **Highly-disturbed clusters : NODES of the Cosmic Web ???**

Jauzac et al. 2012, MNRAS, 426, 3369

» **Get HST time to map wider fields and detect filamentary structures using WL !!!**

» **But also DM substructures in the cluster outskirts, stripping of DM halos, galaxy evolution, …**

- **Mass models for MACSJ0717 & MACSJ1149, …**

- **More investigations on simulated clusters to improve our mass modeling techniques !!!**

The last CAT I pictured @ Kolkata, India - Nov 2014

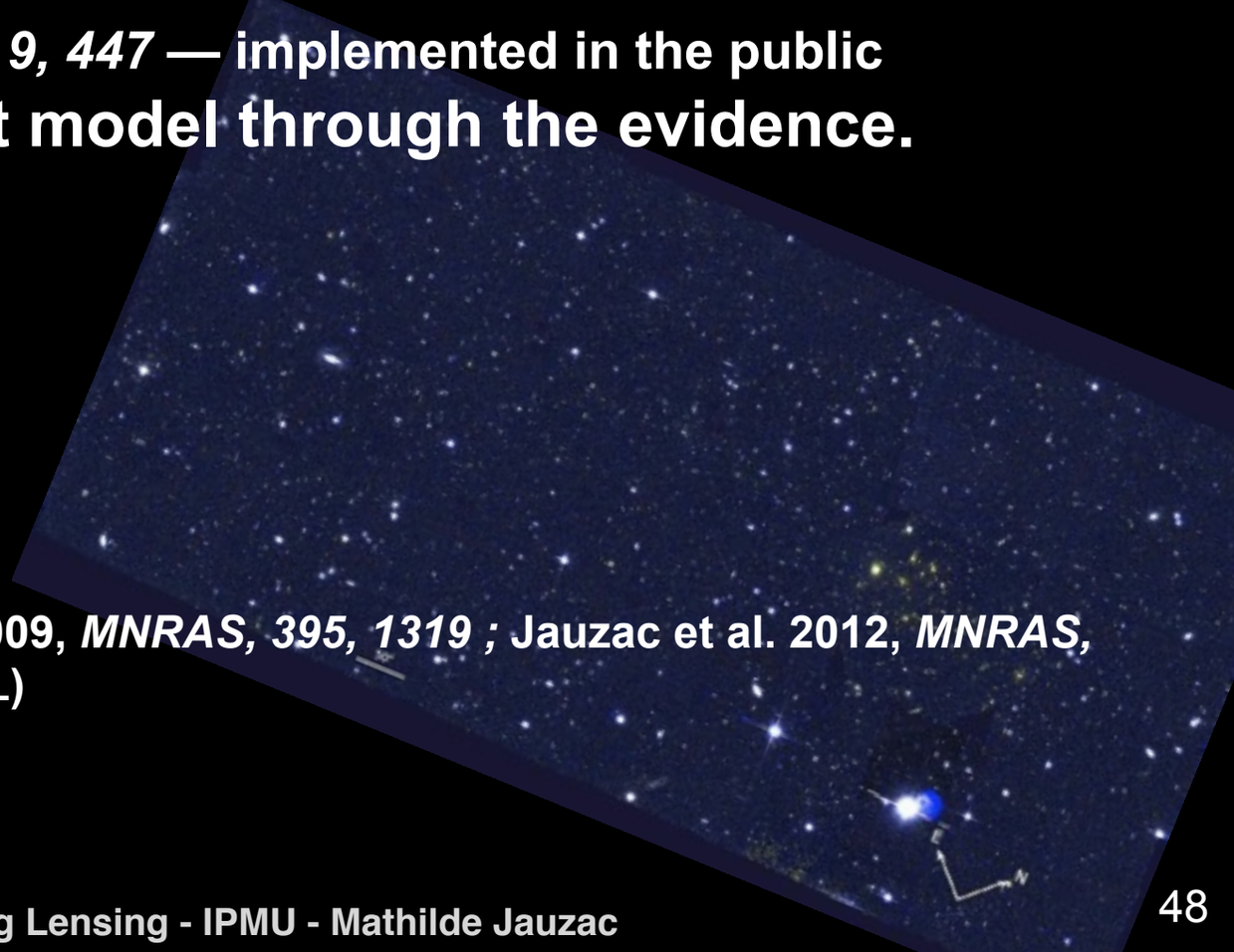
Thank you for your attention

Some basics on Mass Modeling I

Two main Mass Modeling Techniques :

1. Profile based (if few constraints)

- Simple, good with limited number of constraints
- Used for both strong and weak lensing
- Bayesian approach allows effective combination of SL+WL and other dataset (Jullo et al 2007, *NJoP, 9, 447* — implemented in the public Lenstool code) and can select best model through the evidence.

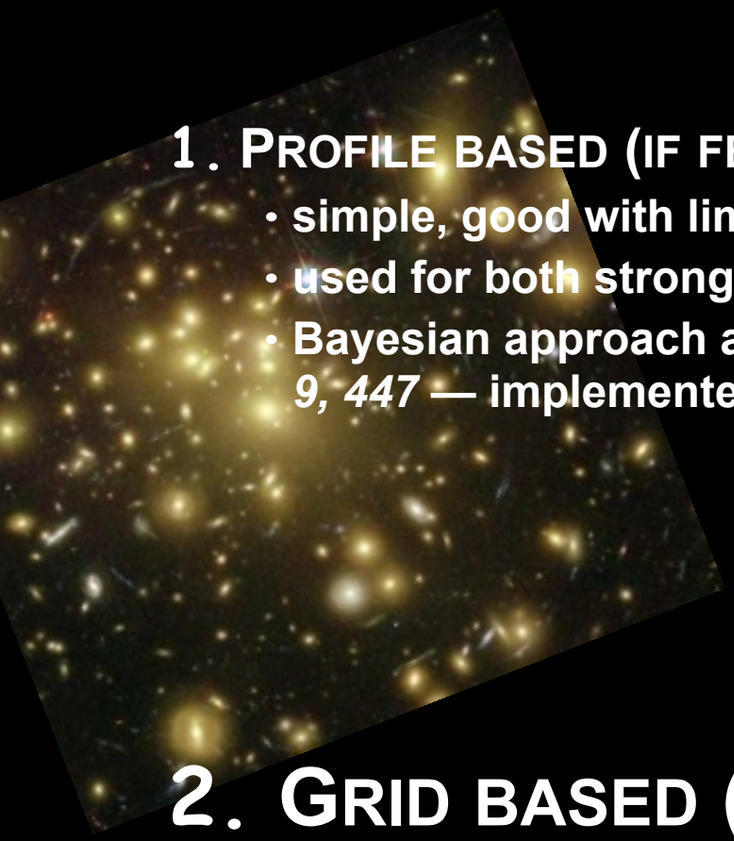


2. Grid based (if many constraints)

- Extensively used for 2D WL mass map
- Can probe the unexpected: bullet cluster
- Multi-resolution mass mapping (Jullo & Kneib 2009, *MNRAS, 395, 1319 ;* Jauzac et al. 2012, *MNRAS, 426, 3369* ; 2014b, *arXiv 1406.3011* — in Lenstool)

Some basics on Mass Modeling II

Two main Mass Modeling Techniques :



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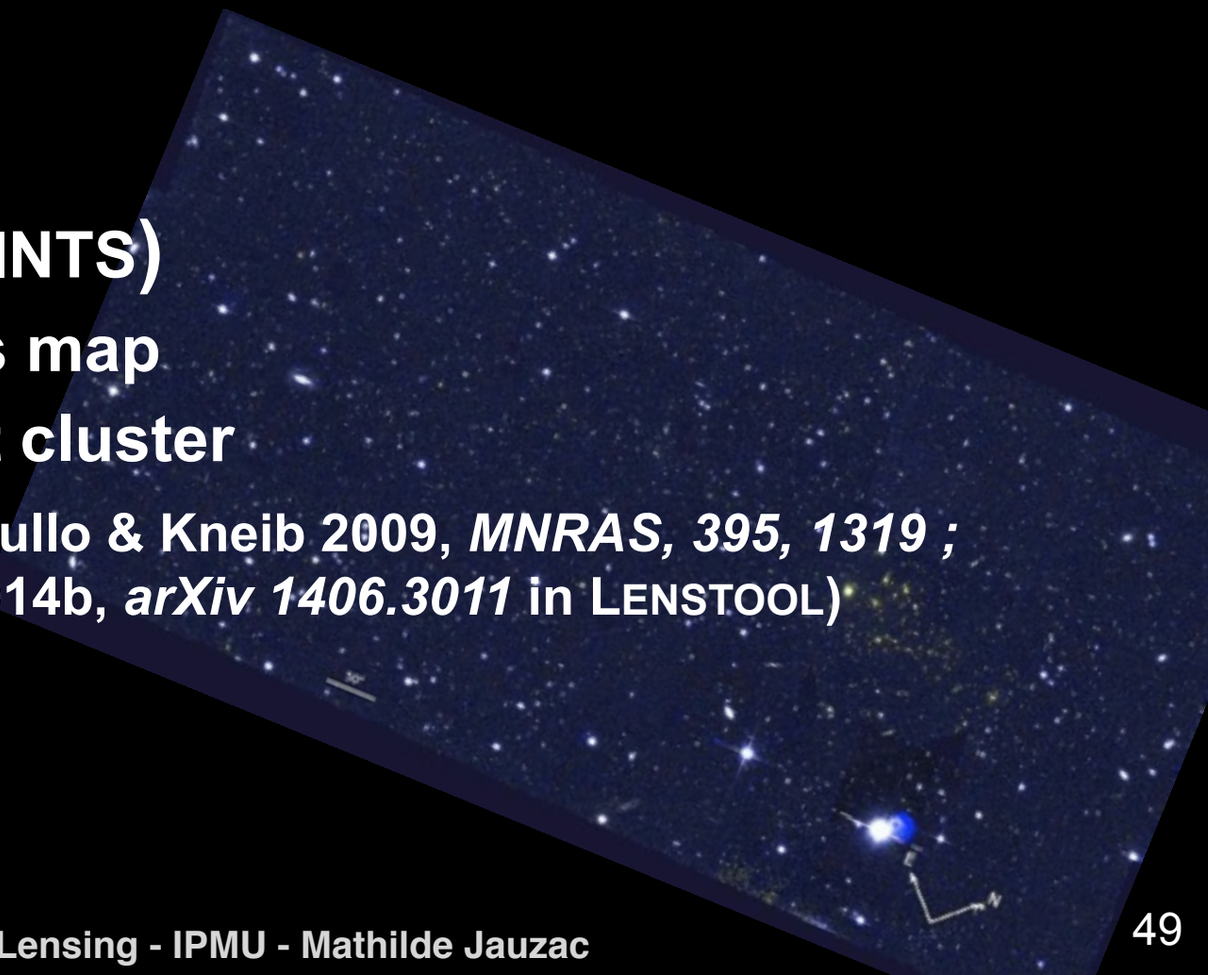

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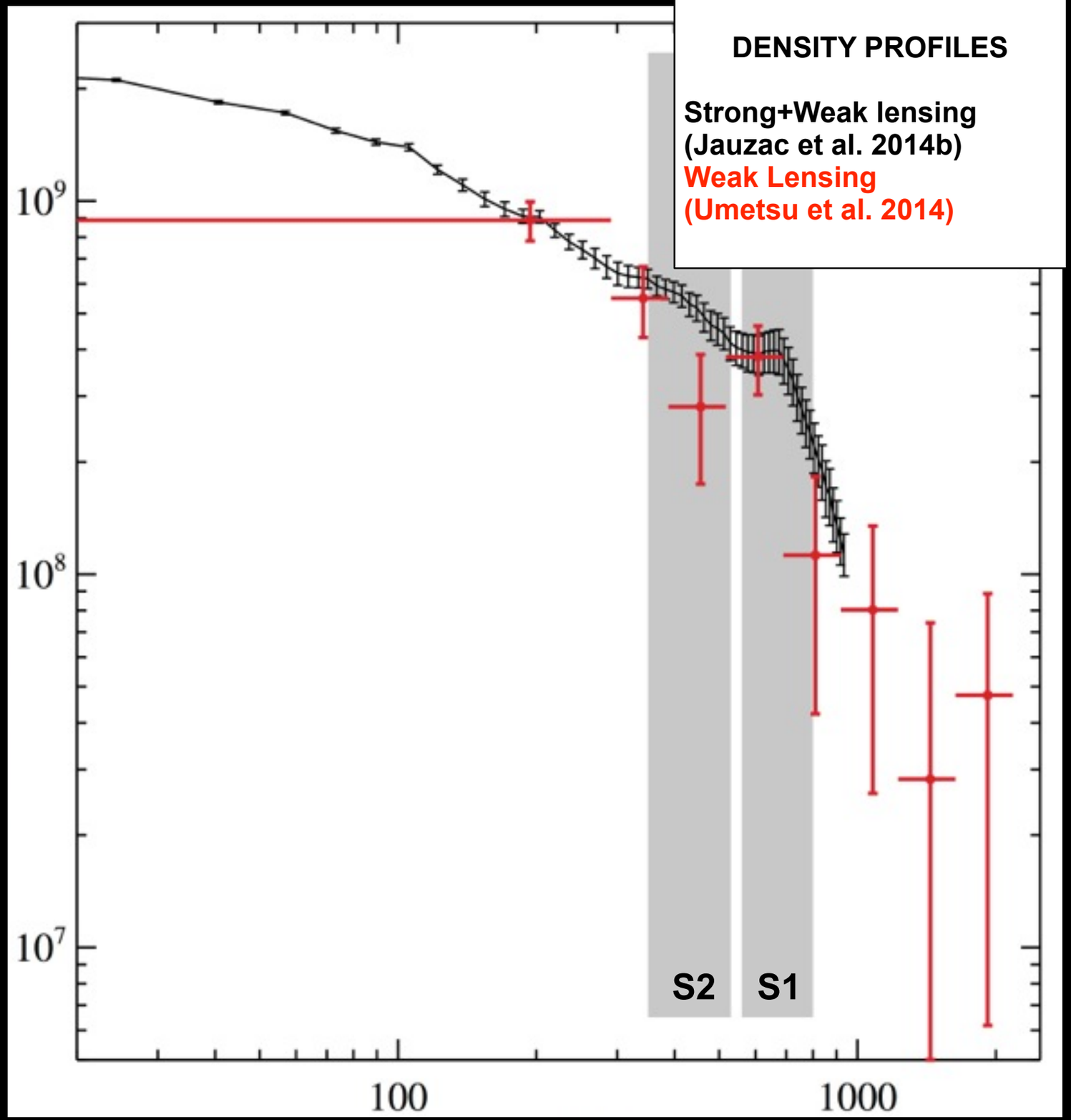
The Surroundings of MACSJ0416



COMPARISON WITH CLASH

Umetsu et al. 2014, *arXiv 1404.1375*

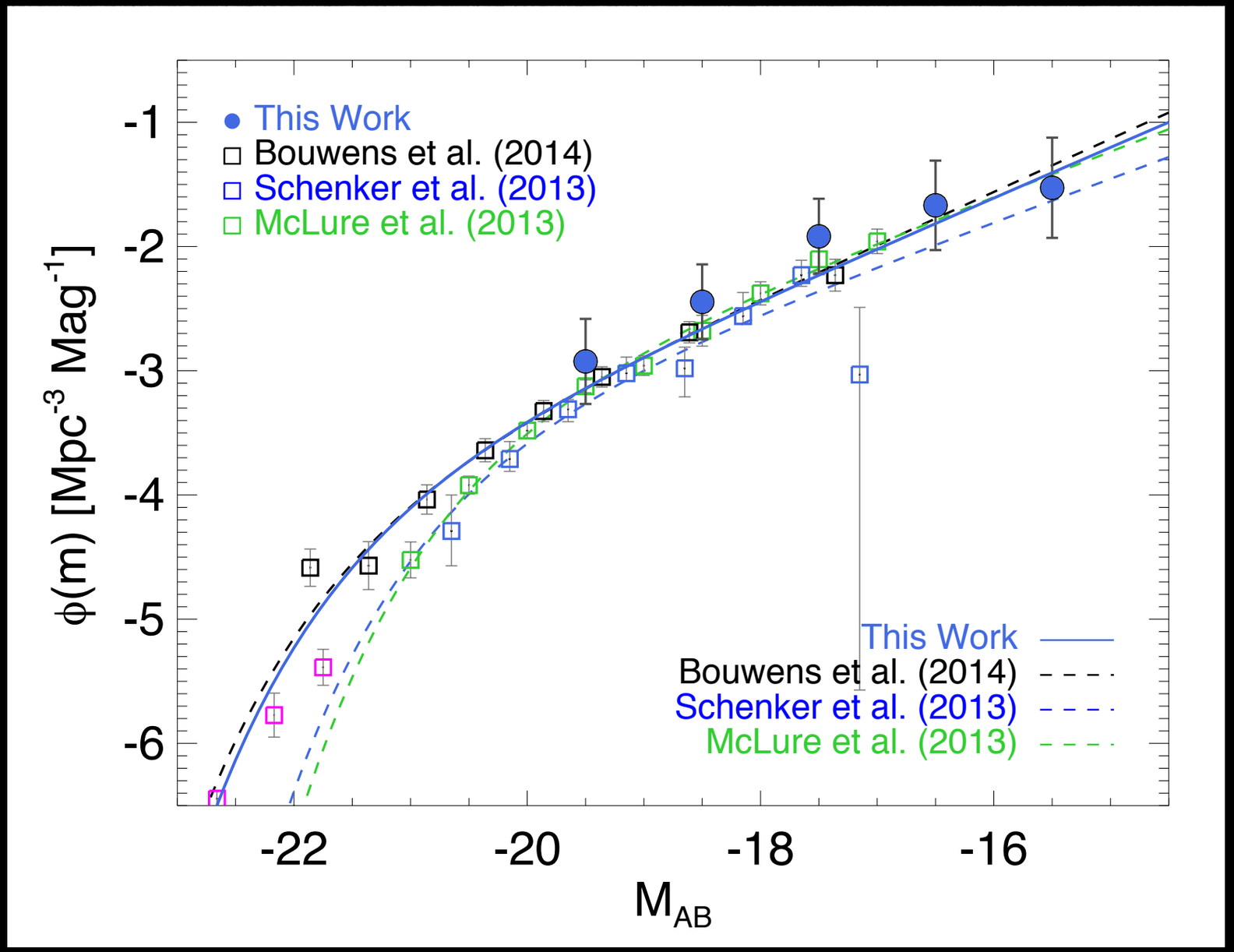
Really good agreement between ground-based WL-only & SL+WL

HFF DENSITY PROFILE

WL ‘’wants” to extend the mass distribution
&
Adds ‘’pertubators”

Quest for High-z Galaxies in Abell 2744

Impact of model uncertainties on the UV LF :
comparison between **pre-HFF** and **HFF** based model of A2744



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

Quest for High-z Galaxies in Abell 2744

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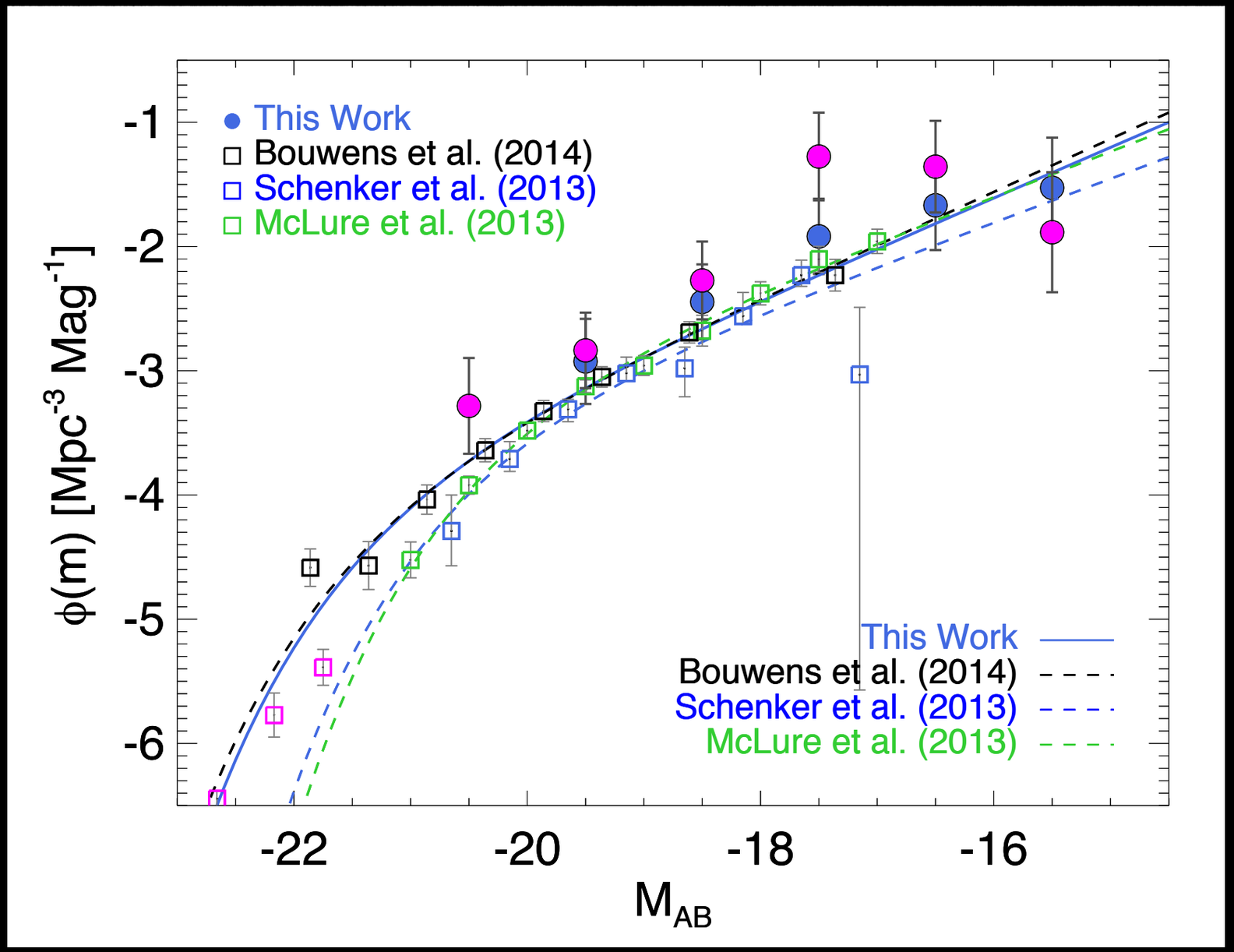

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