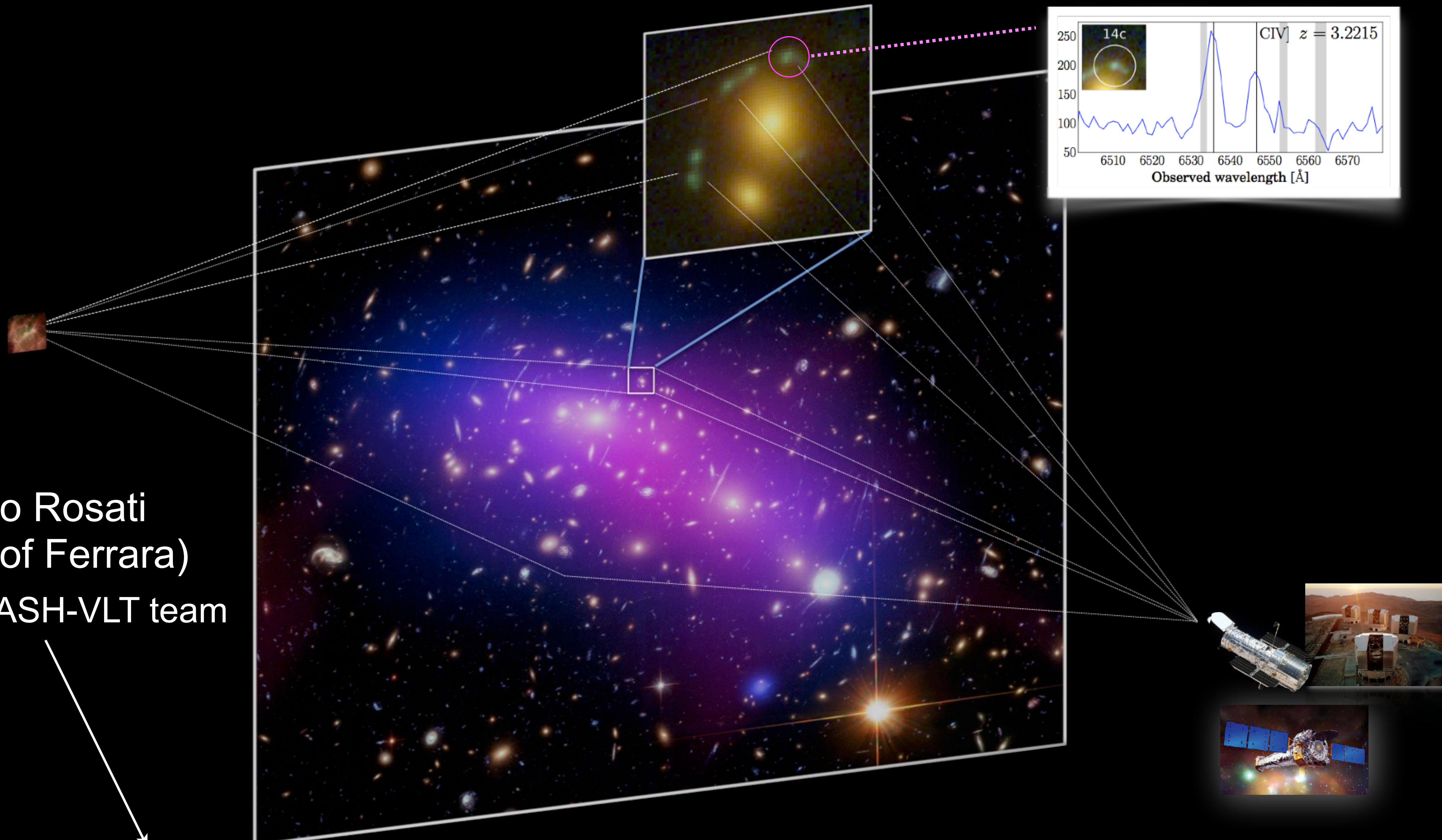
Towards high-precision cluster lensing models: illuminating dark matter and dark ages



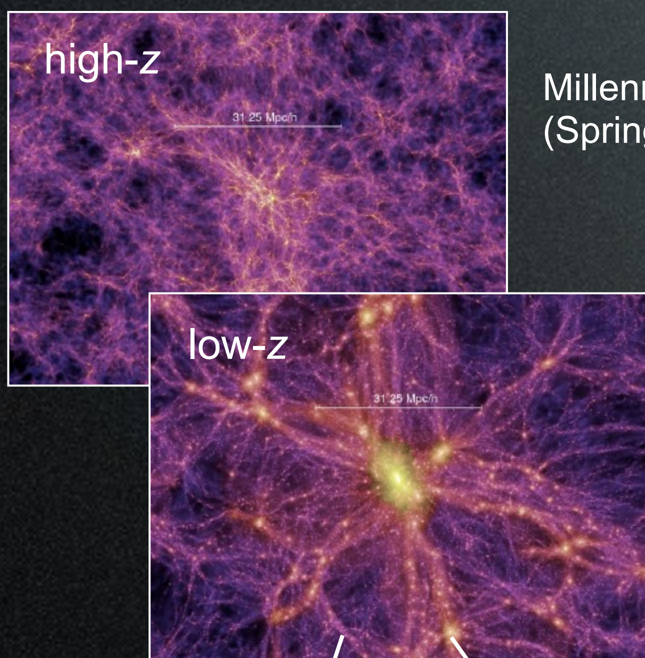
Piero Rosati
(Univ. of Ferrara)
& the CLASH-VLT team

I.Balestra (USM), G.B.Caminha (Groningen), C.Grillo (UniMI/Dark), A.Mercurio (INAF-NA), M.Nonino, A.Biviano, B.Sartoris (INAF-TS), E. Vanzella, M. Meneghetti (INAF-BO)

ICTP-Trieste, 5 July 2018

Clusters inner mass distribution to test LCDM paradigm and the nature of DM

Structure of DM halos
(≲5 Mpc scale)

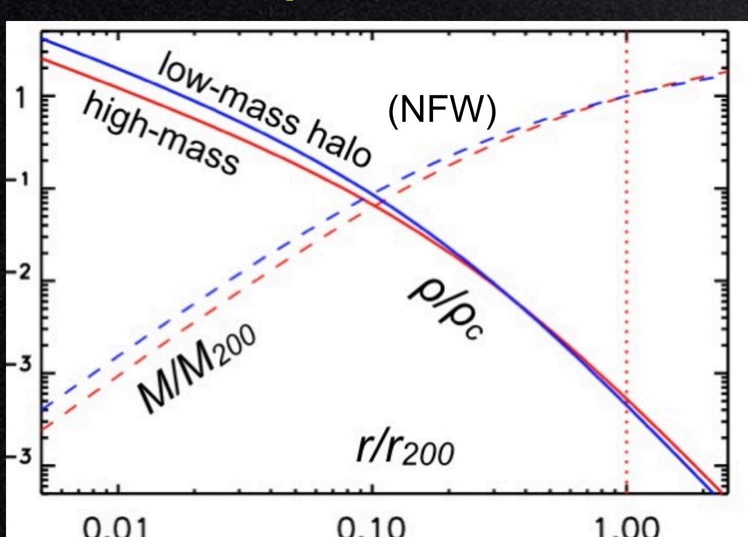


Millennium simulations
(Springel et al. 2005)

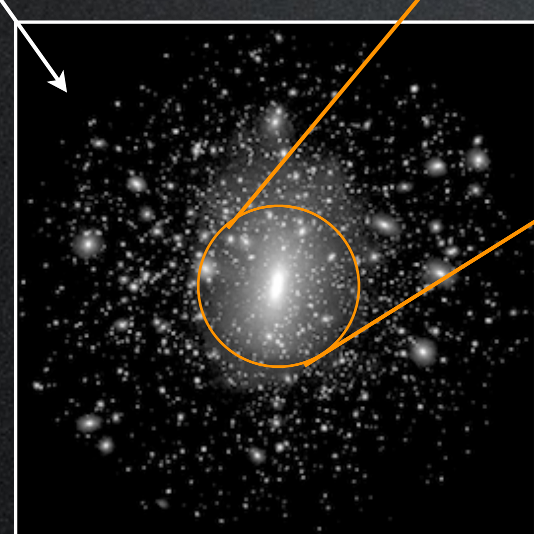
Structure of the largest DM halos to test:

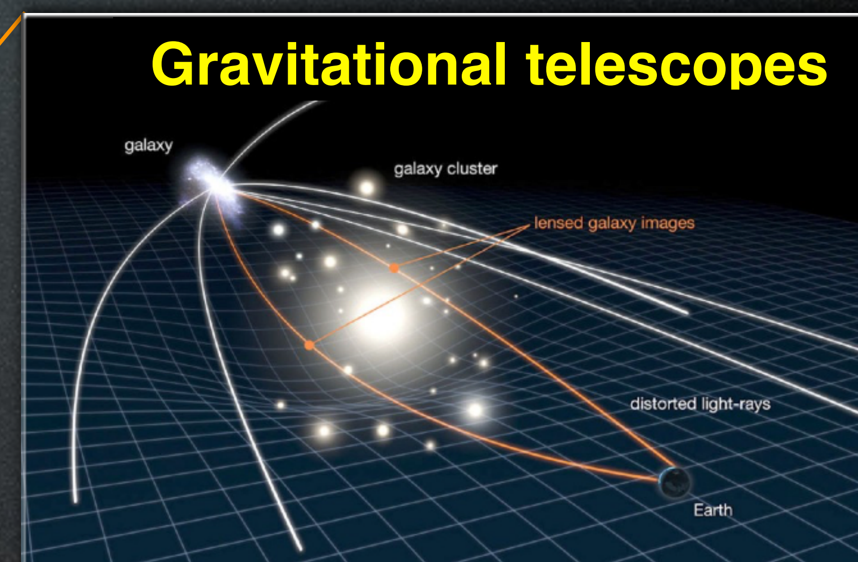
- ΛCDM predictions on:
  - DM density profiles
  - Inner structure of Mpc scale halos
- Collision-less nature of DM?
  (inner core, merging systems)

Profile shapes



Inner structure





High-precision strong lensing

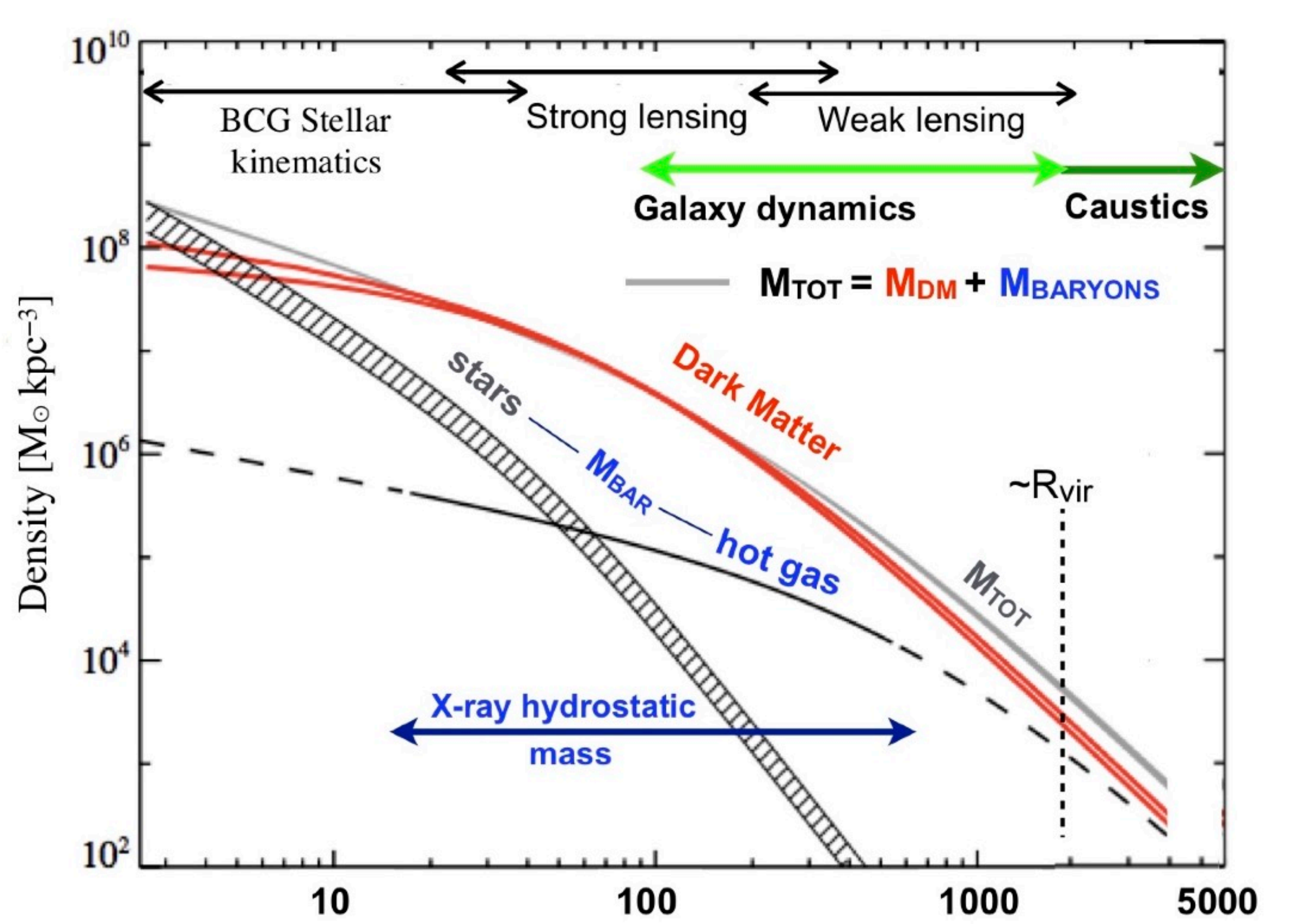
High-z/low-M "proto-galaxies"
Cosmography

Multi-probe mass distribution of galaxy clusters

- Dynamics: using stars, galaxies, gas as test particles to probe gravitational potential
- Gravitational lensing: using photon trajectories to probe gravitational potential

Requirements → **Methodologies, mass probes**

- Probe wide radial range of mass profile (Kpc…Mpc)
- Understand systematics (different for each method)
- Trace both DM and baryons (gas and stars): $M_{DM} = M_{TOT} - M_{BARYONS}$
- Mass maps with high-angular resolution in the core (strong lensing)



(Adapted from Newman et al. 13)

Tensions with LCDM…?

- flat cores (galaxy to cluster scales)
- amount of sub-structure

CLASH-VLT survey

CLASH HST Treasury Program (530 orbits) - PI: M.Postman (2010-13)

\+

VIMOS Large Programme (230 hr over 5 years) - PI: P.Rosati

Common goals

- New constraints on DM & Baryons distribution in clusters
- Discover primordial galaxies exploiting magnification

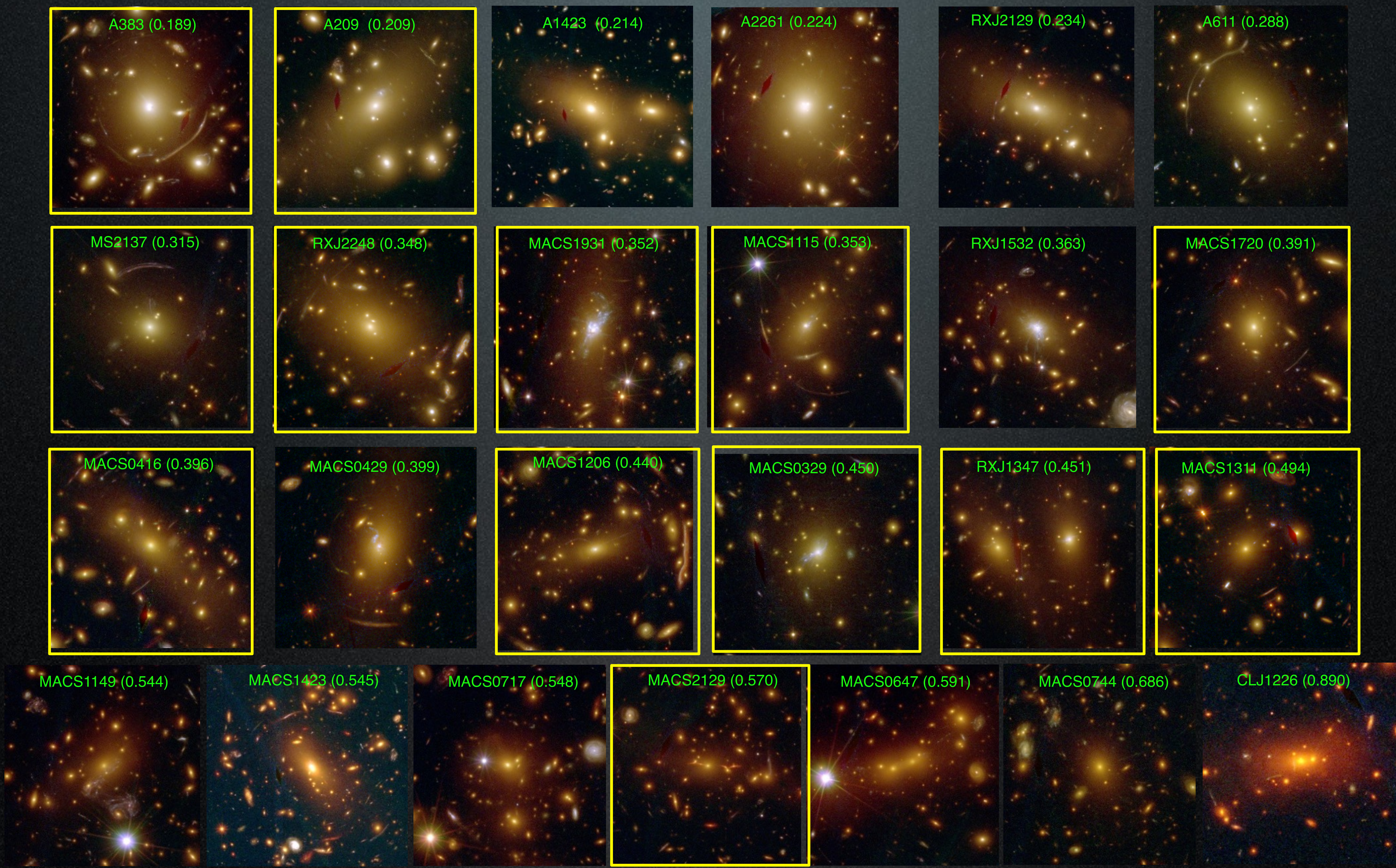
- Panoramic spectroscopic survey of 13 southern CLASH clusters at z=0.3-0.6
- Dynamical mass profiles out to 2-3 R_{vir} with at least ~500 members per cluster
- Background and highly magnified galaxies out to z~7 (AB_{mag}<26) ➔ lens models
- Cluster assembly history from stellar pops, kinematics, morphologies of cluster galaxies

Augmenting VIMOS spectroscopy with VLT/MUSE IFU

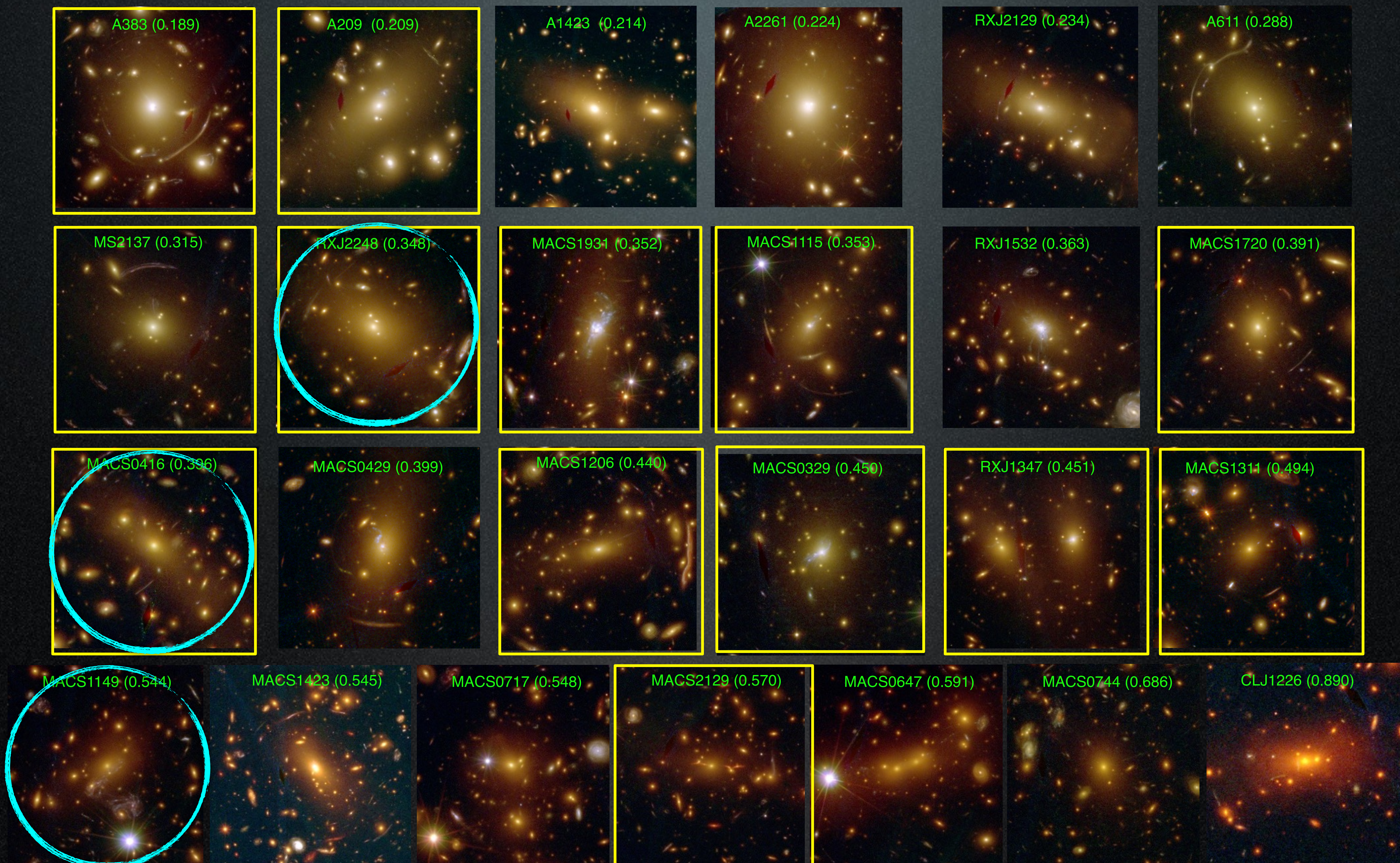
- Full spectroscopic coverage of the core (~1 $arcmin^2$ ~ 300-400 kpc)

➔ game changer for strong lensing models

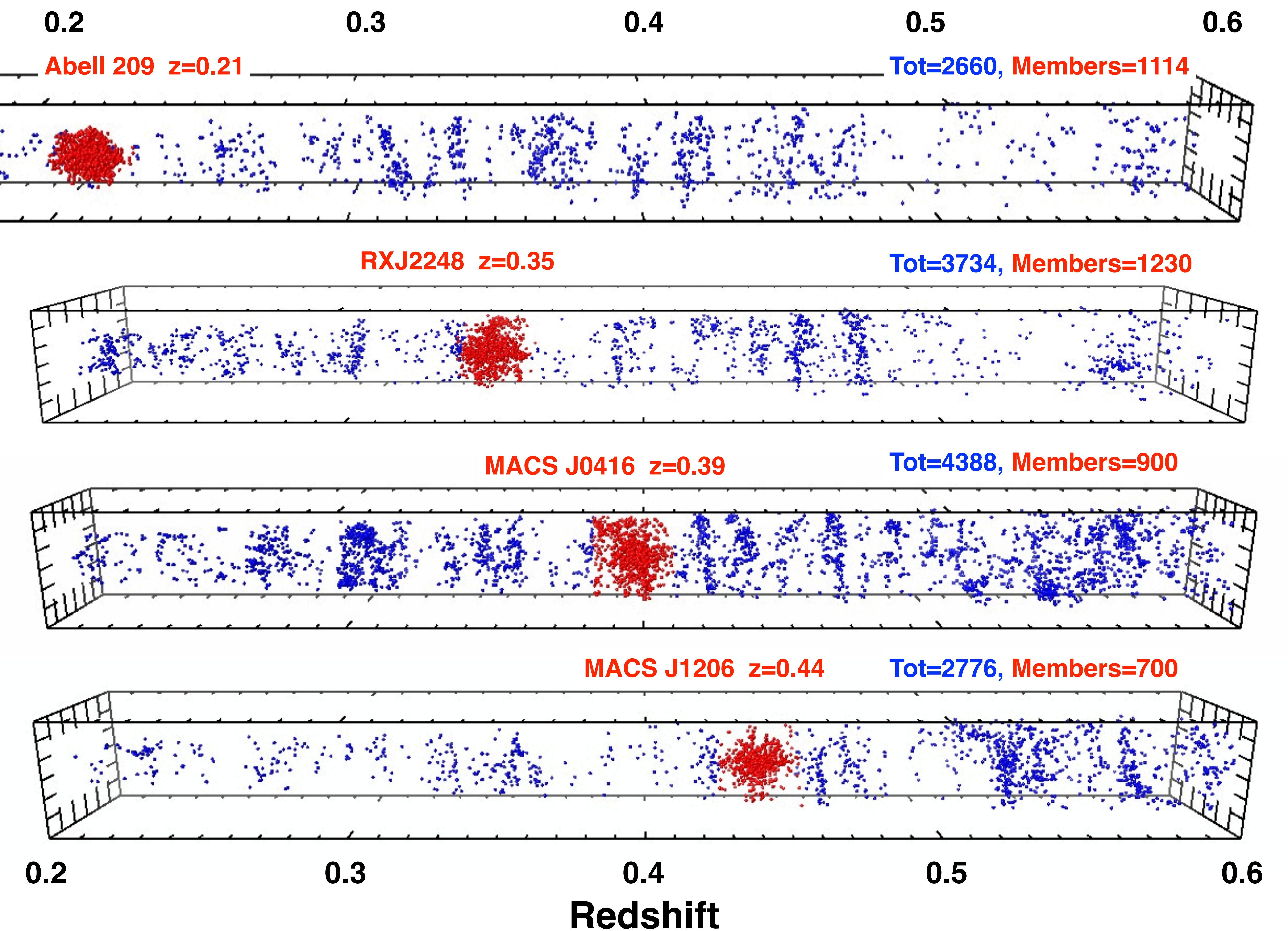
CLASH Gallery: 25 Clusters (13 CLASH-VLT)

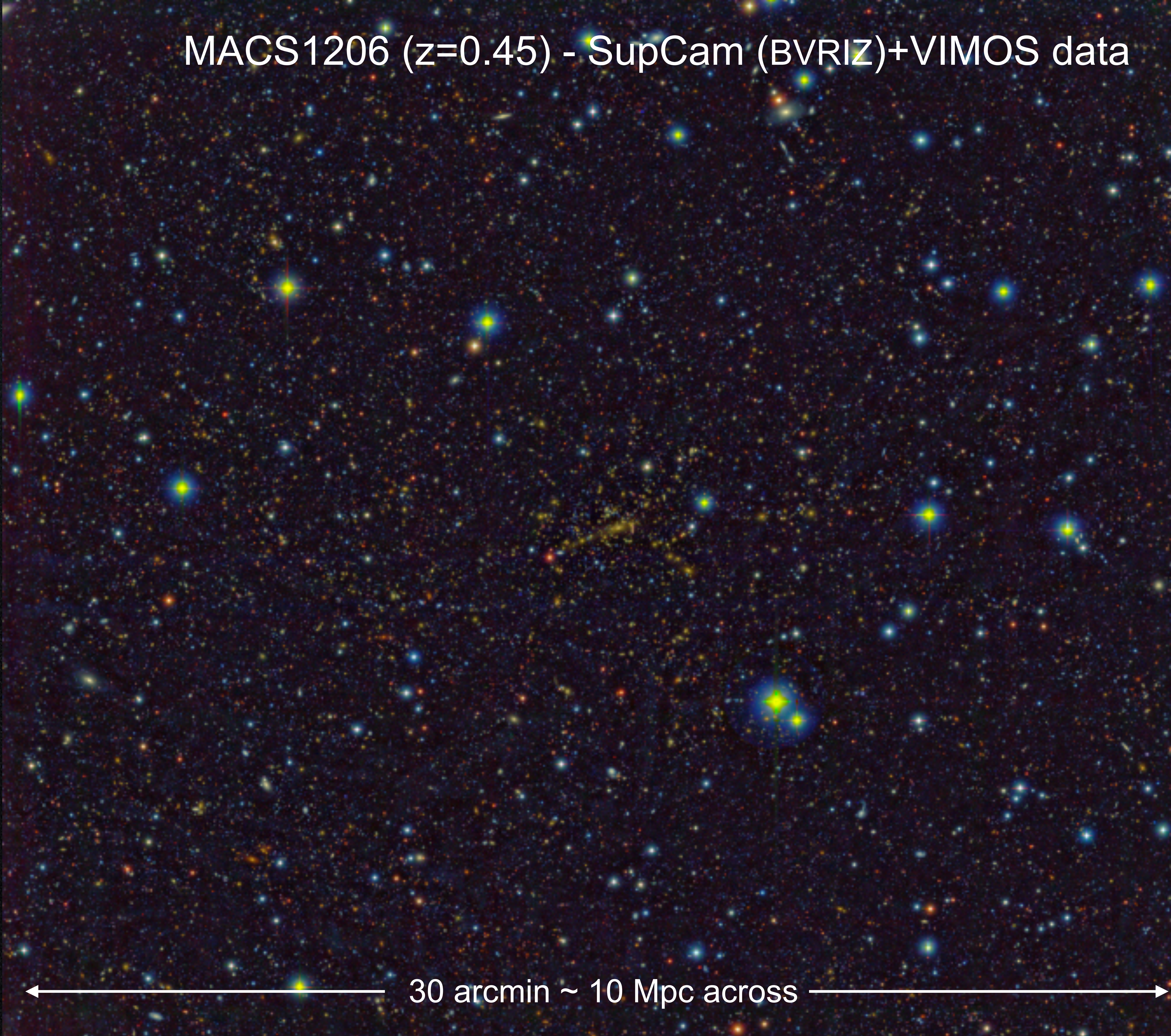


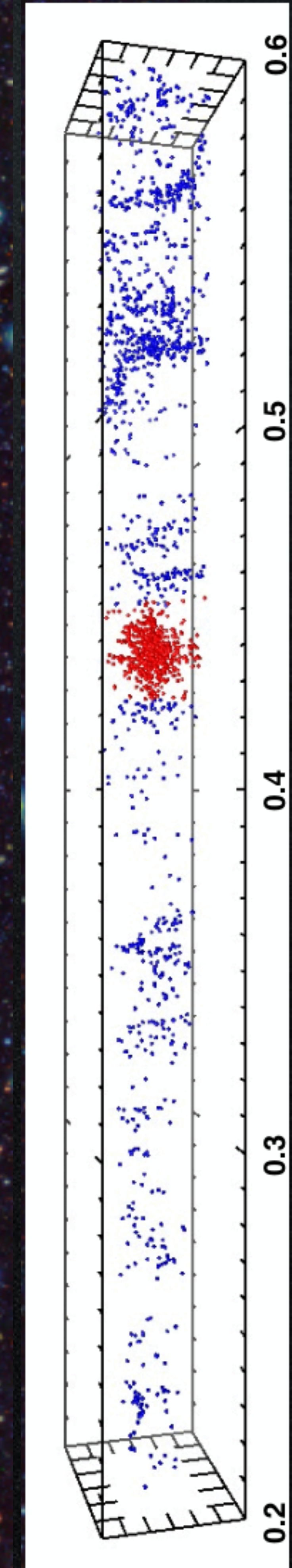
CLASH Gallery: 25 Clusters (13 CLASH-VLT)



Frontier Fields program


0.2
0.3
0.4
0.5
0.6
Abell 209 z=0.21
Tot=2660, Members=1114
RXJ2248 z=0.35
Tot=3734, Members=1230
MACS J0416 z=0.39
Tot=4388, Members=900
MACS J1206 z=0.44
Tot=2776, Members=700
0.2
0.3
0.4
0.5
0.6
Redshift


MACS1206 (z=0.45) - SupCam (BVRIZ)+VIMOS data
30 arcmin ~ 10 Mpc across


0.6
0.5
0.4
0.3
0.2

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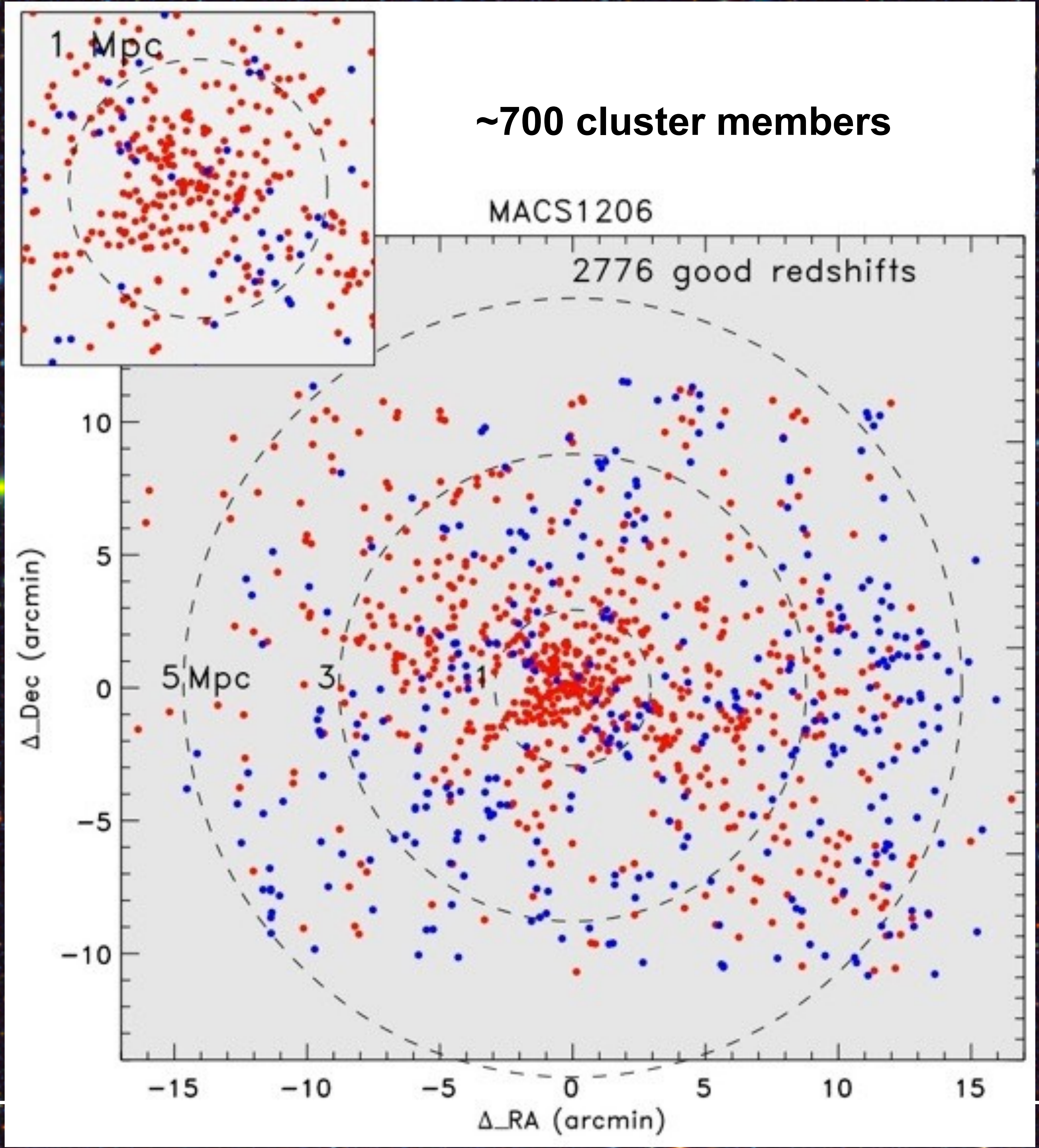
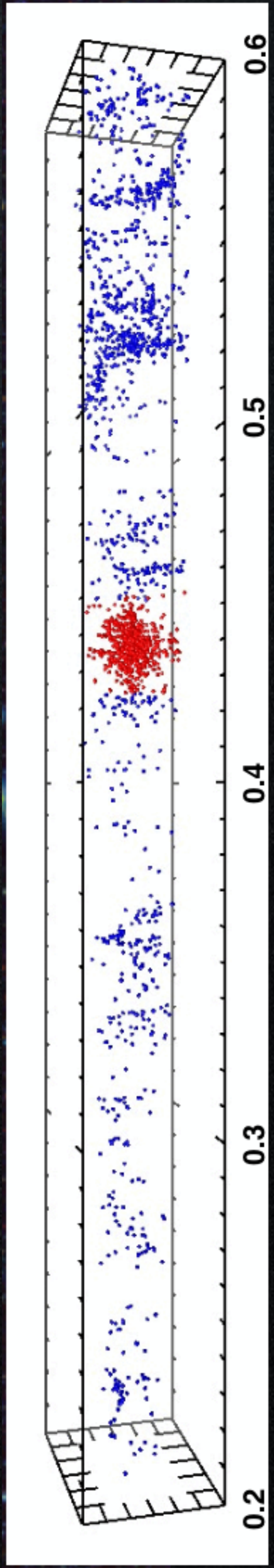
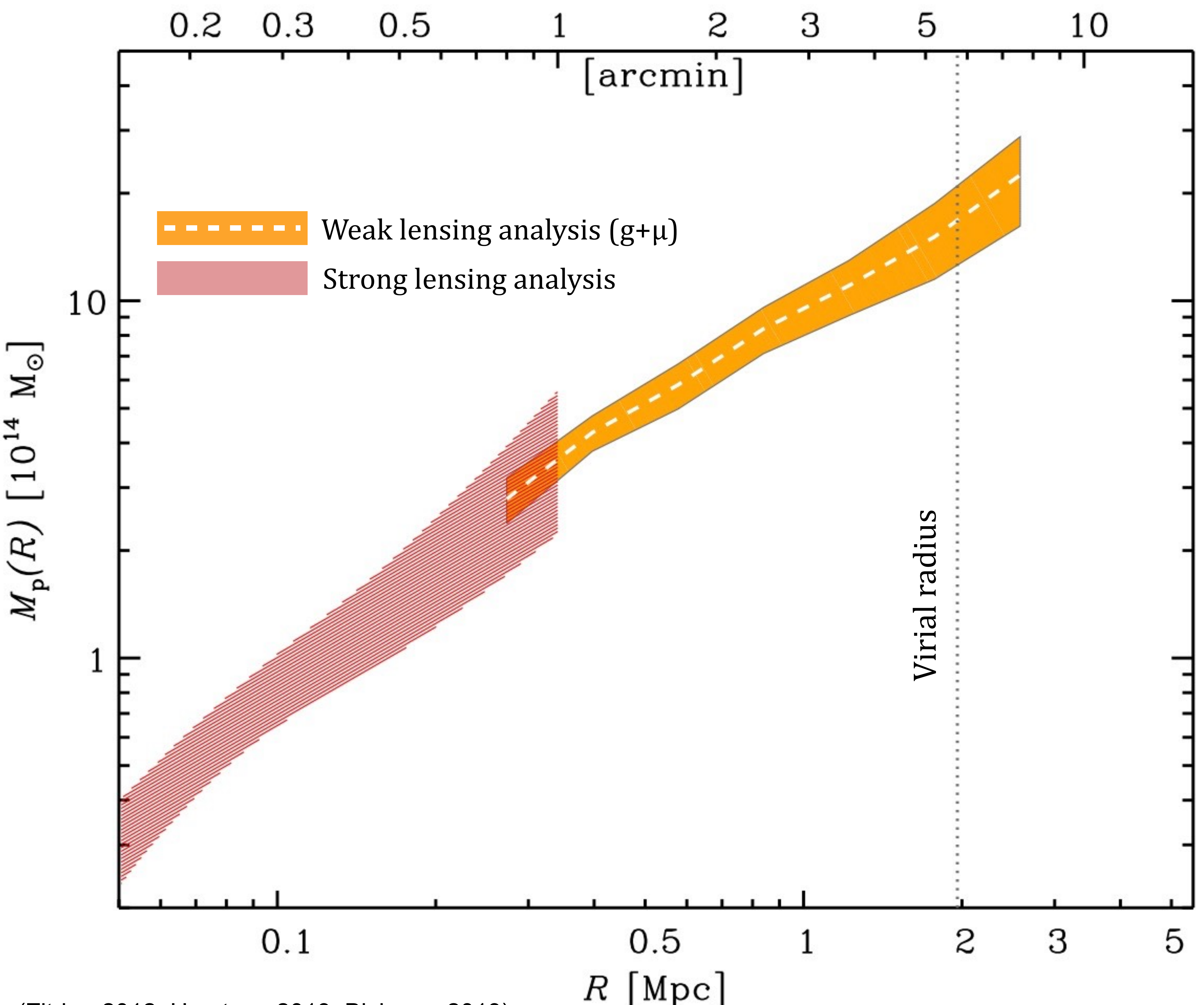
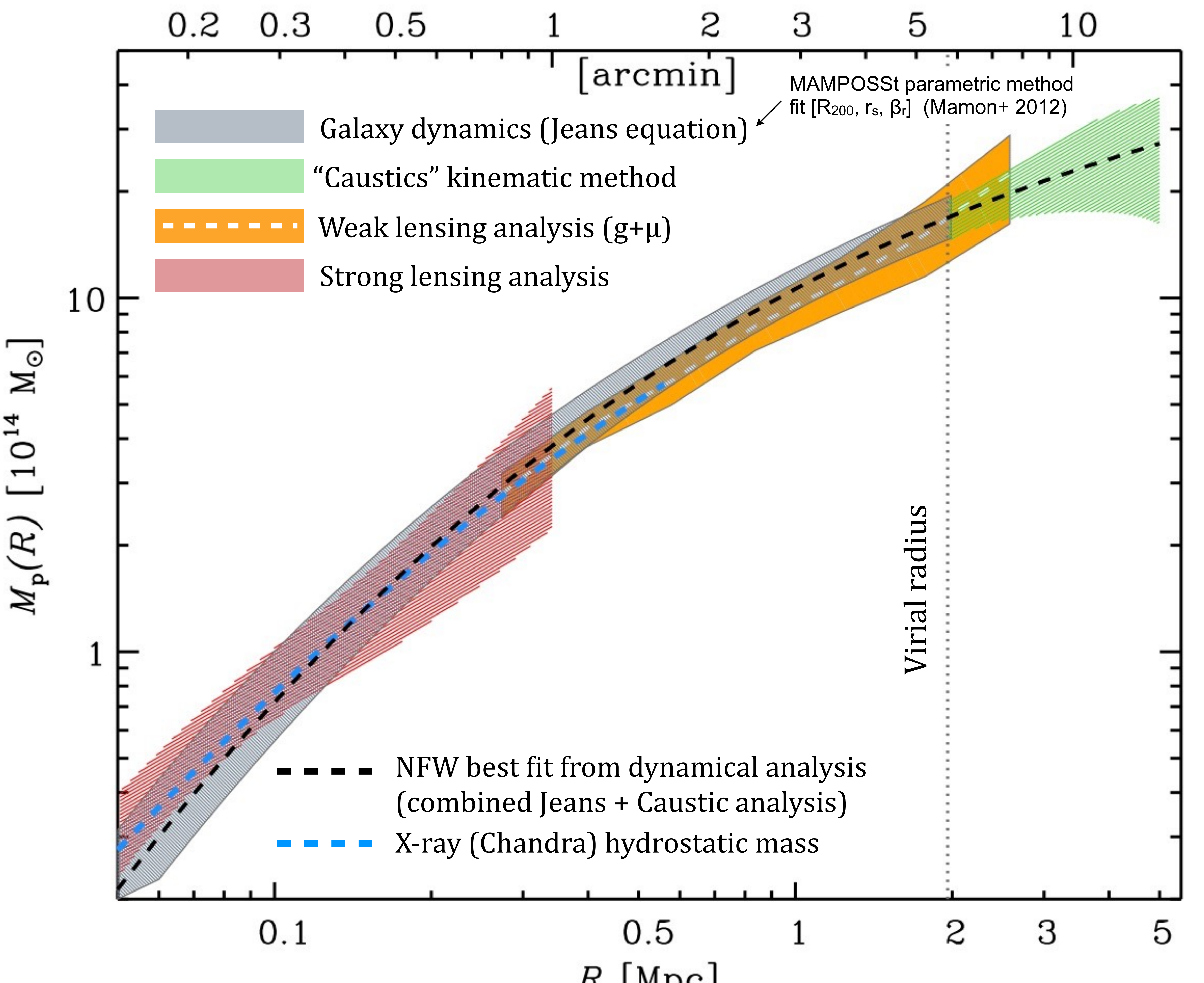






(Zitrin+ 2012, Umetsu+ 2013, Biviano+ 2013)



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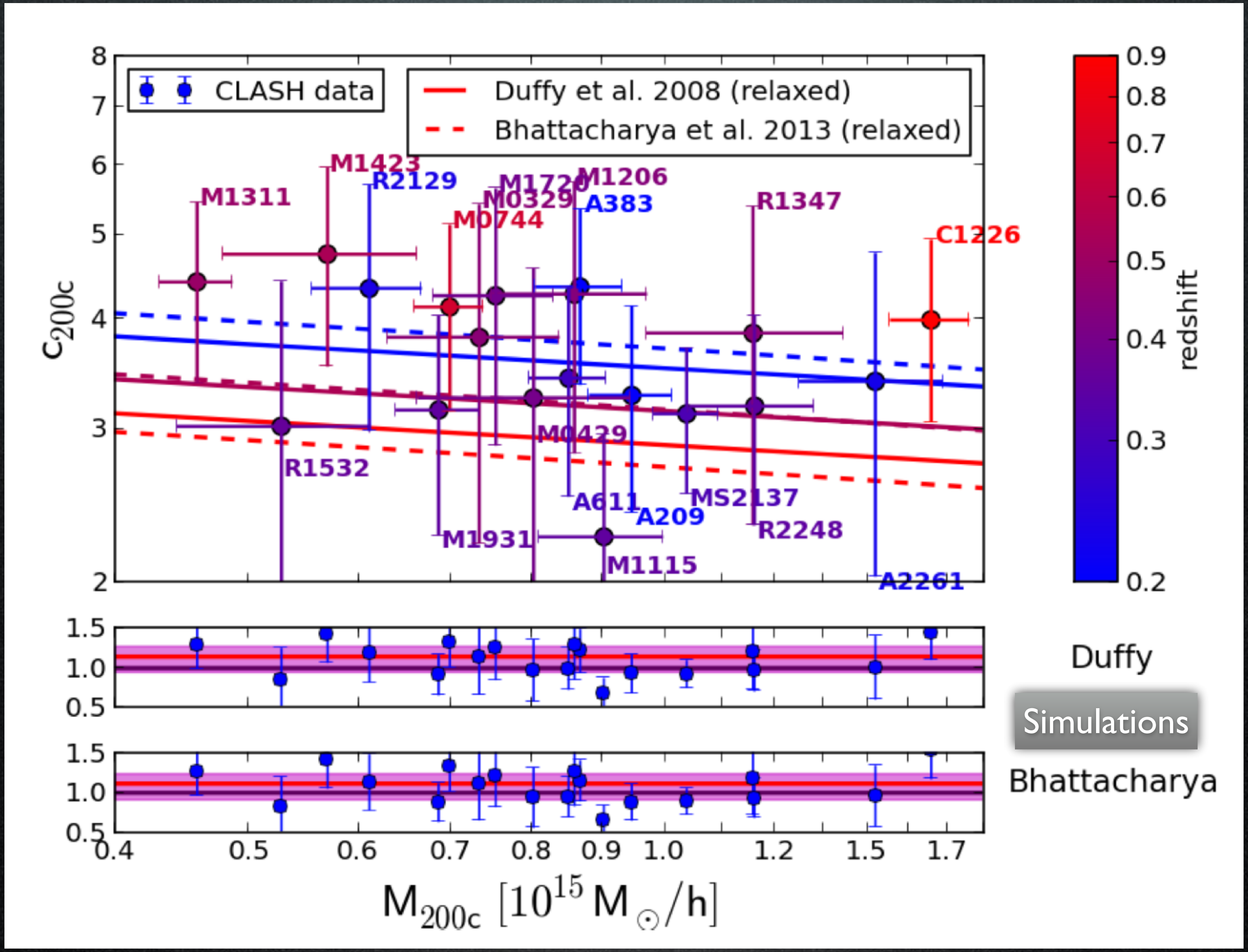
Concentration – Total Mass Relationship from CLASH

J.Merten & CLASH team, 2015, (also Umetsu et al. 2015)

NFW fits of weak & strong lensing profiles from 19 CLASH X-ray selected clusters (sample selection and projection effects evaluated with mock lensing clusters)

$$c = \frac{r_{200}}{r_s}$$



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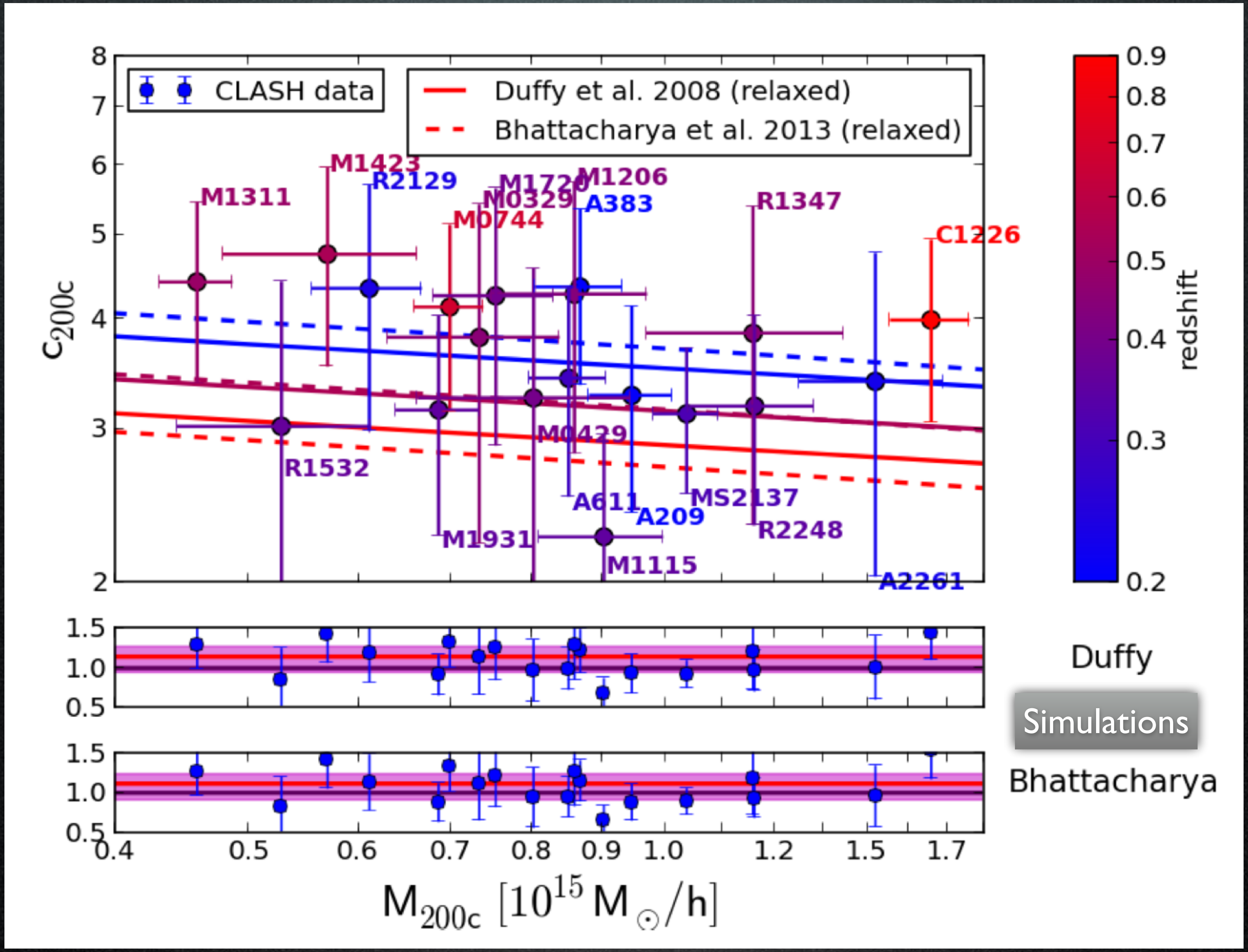
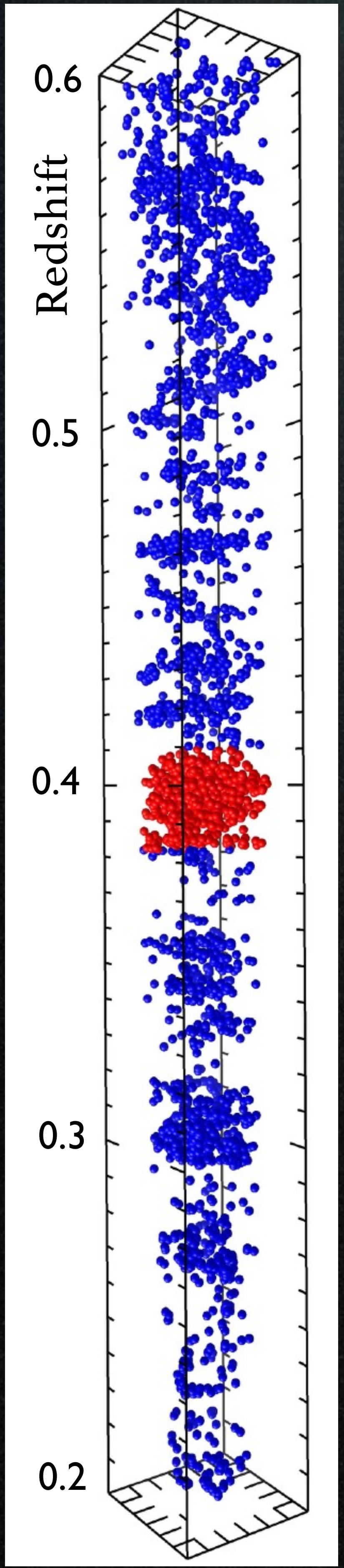
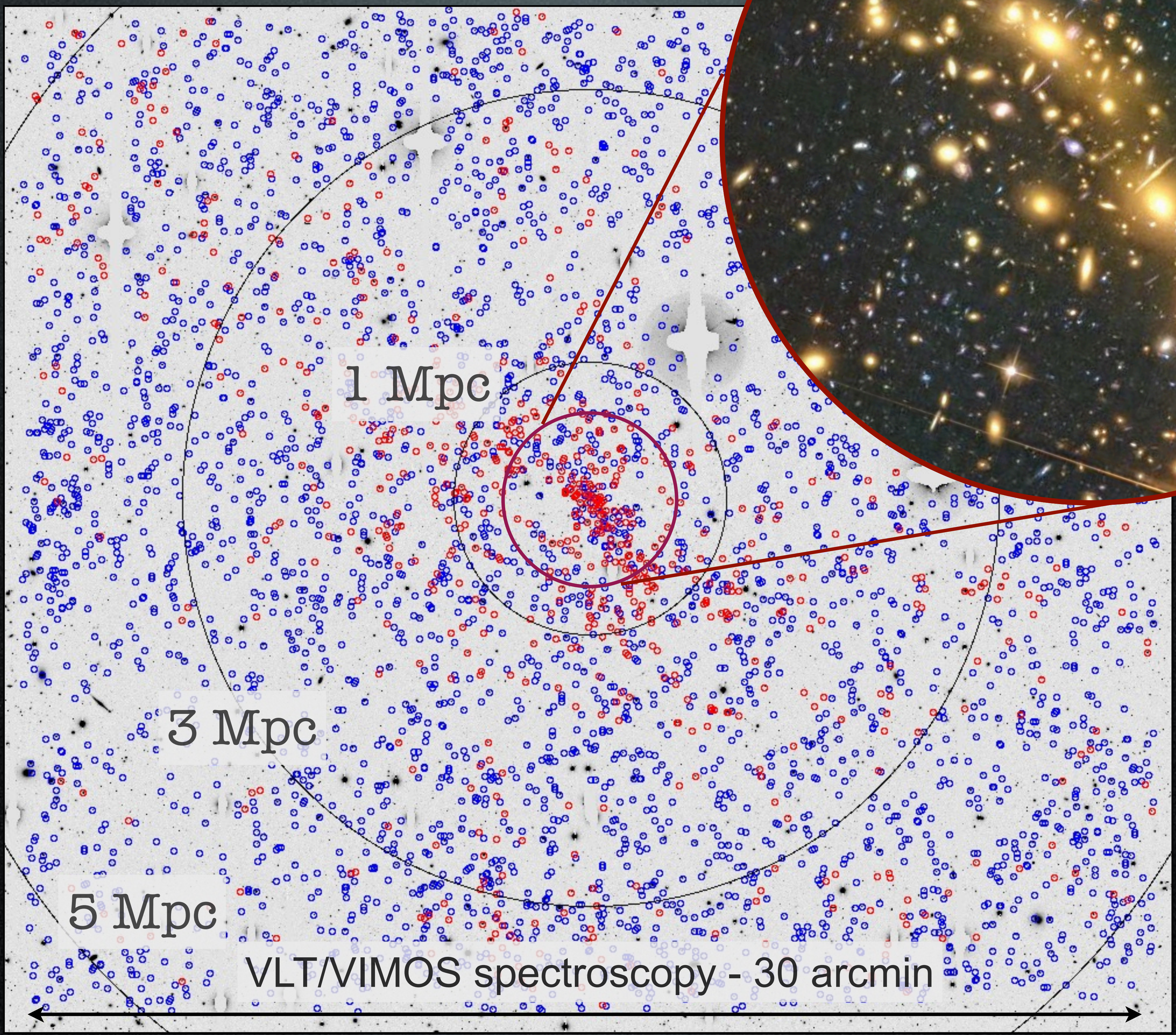


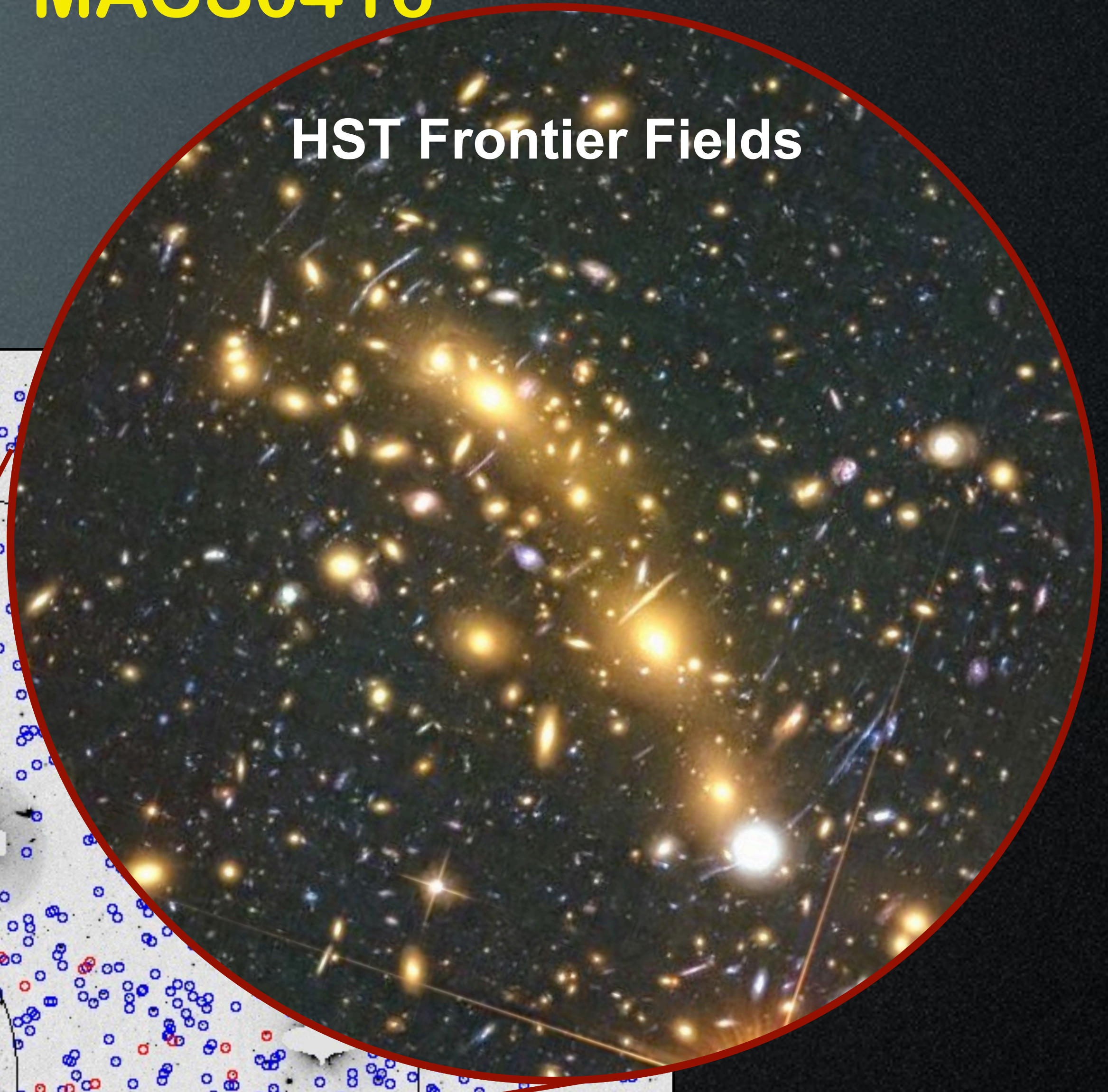
➔ Overall cluster mass profile: No significant tension with predicted c-M relation in ΛCDM

CLASH-VLT spectroscopic campaign of MACS0416

(Grillo+ 2015, Balestra+ 2016 + data release, Caminha+ 2017, Bonamigo+ 2018)



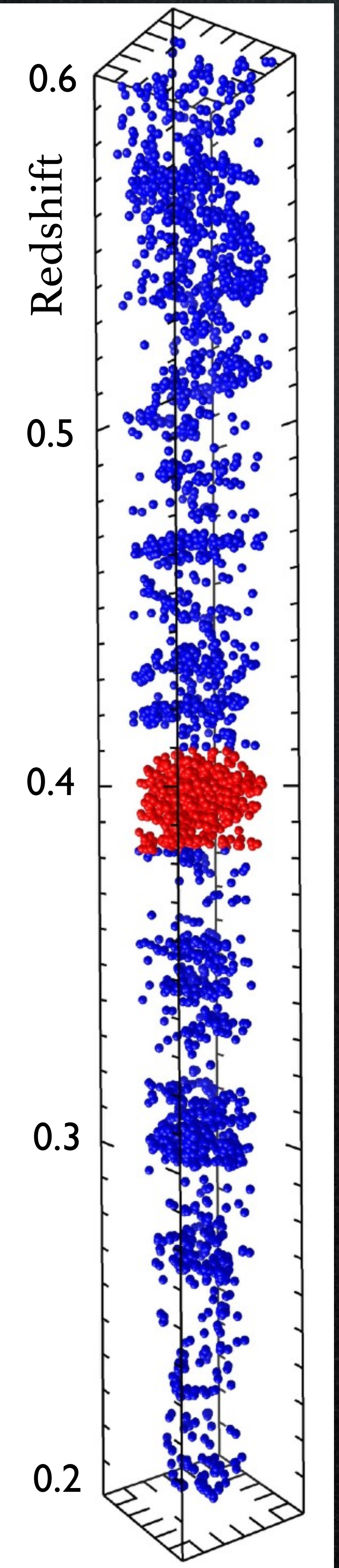


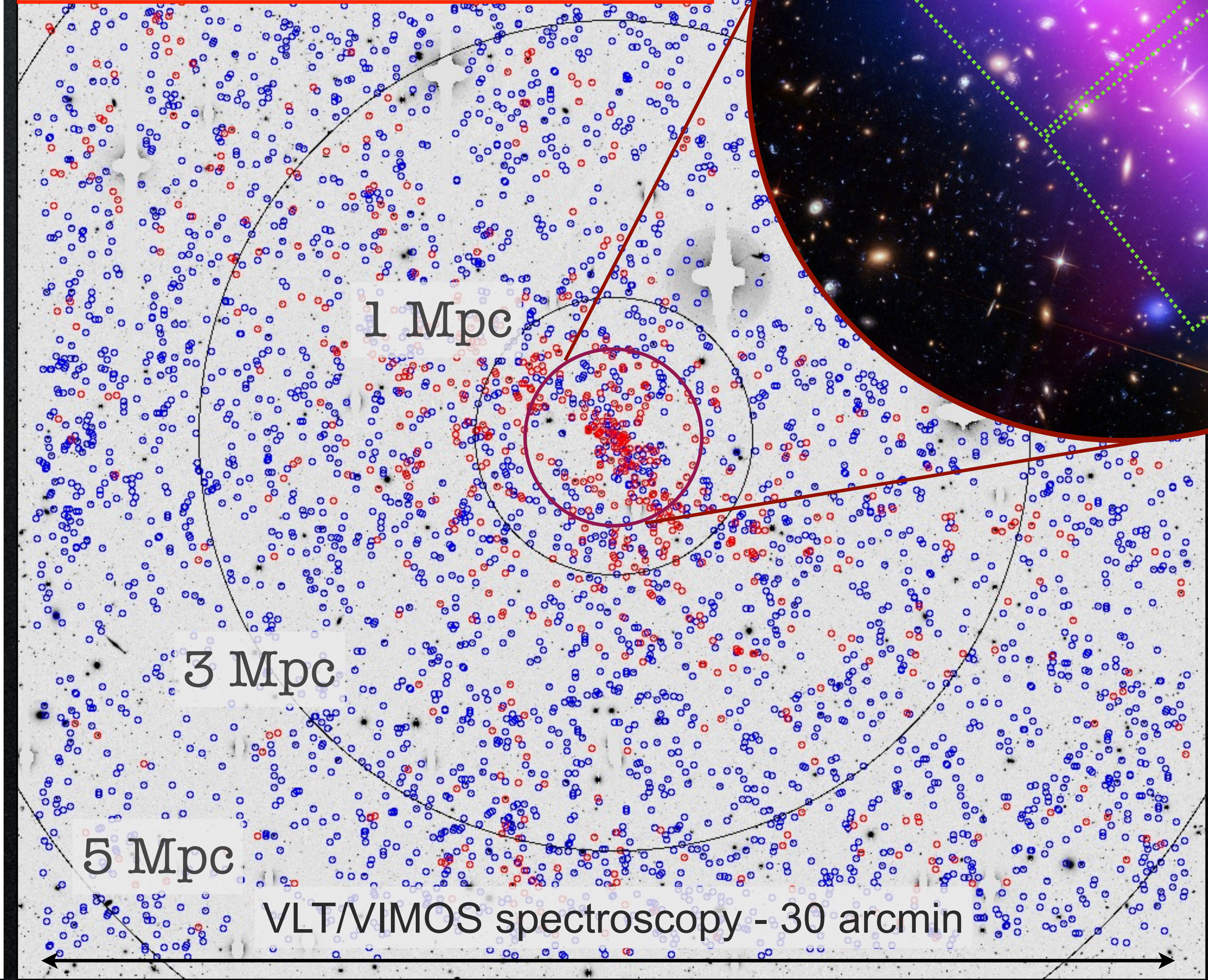


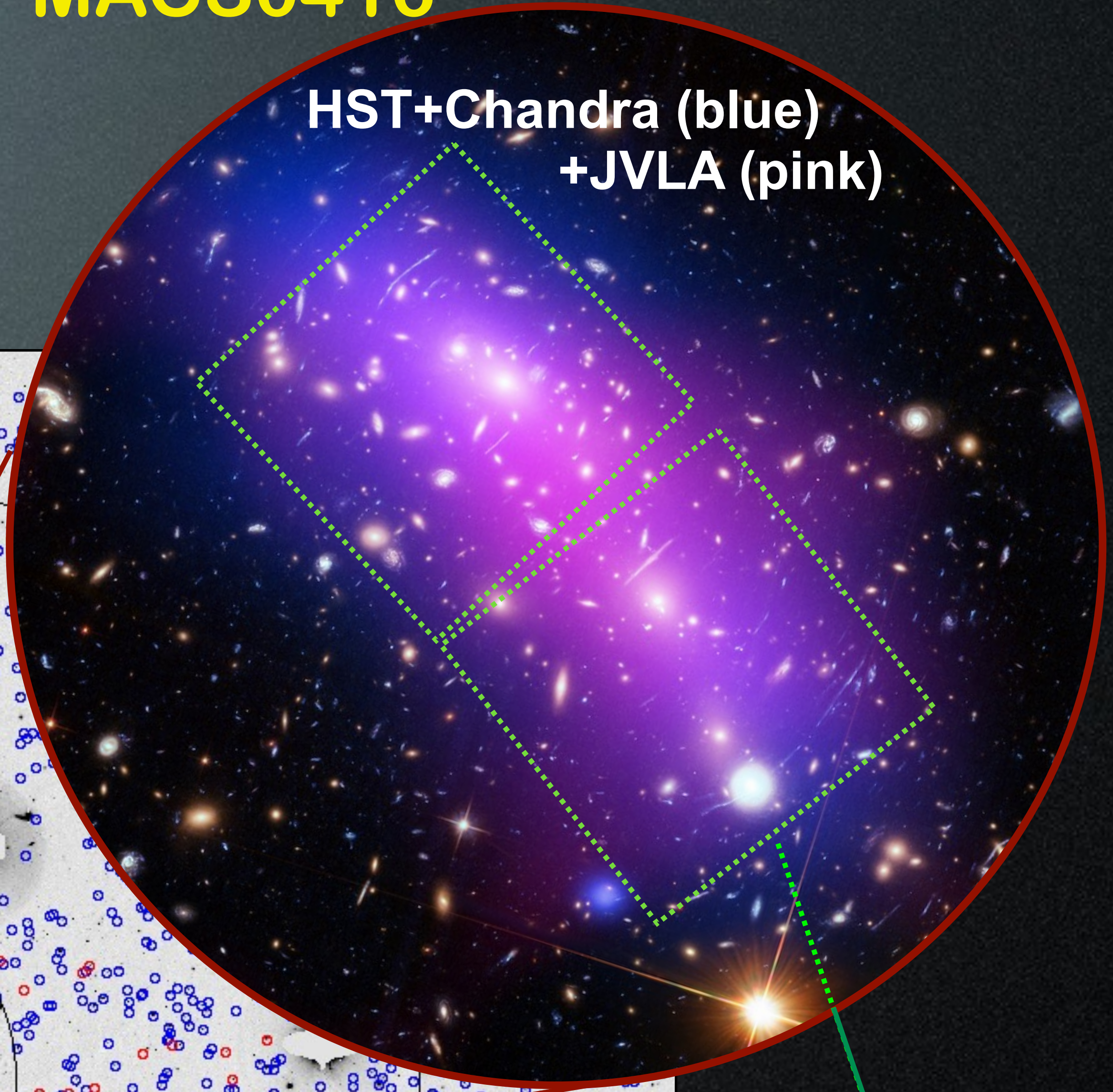
CLASH-VLT spectroscopic campaign of MACS0416

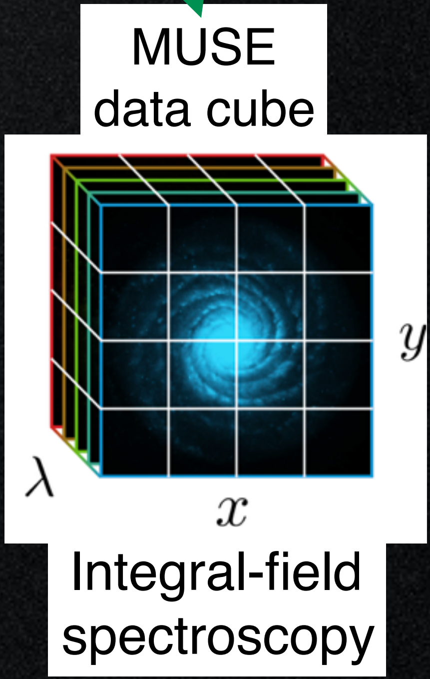
(Grillo+ 2015, Balestra+ 2016 + data release, Caminha+ 2017, Bonamigo+ 2018)

- 4200 redshifts in the field
- + ~200 in the core from VLT/MUSE
- ~900 spec members



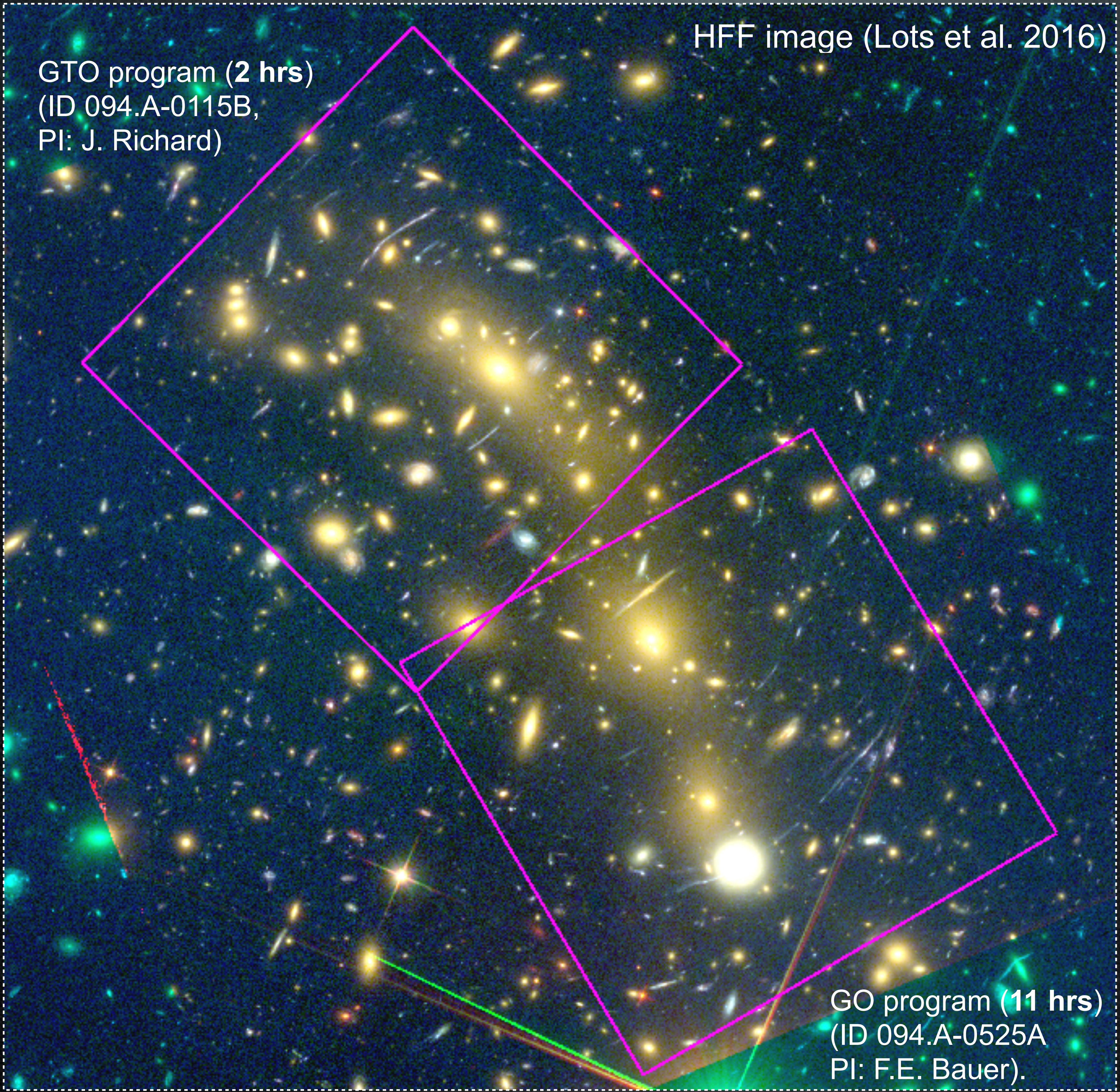






Another leap forward with VLT/MUSE spectroscopy combined with deeper Frontier Field data

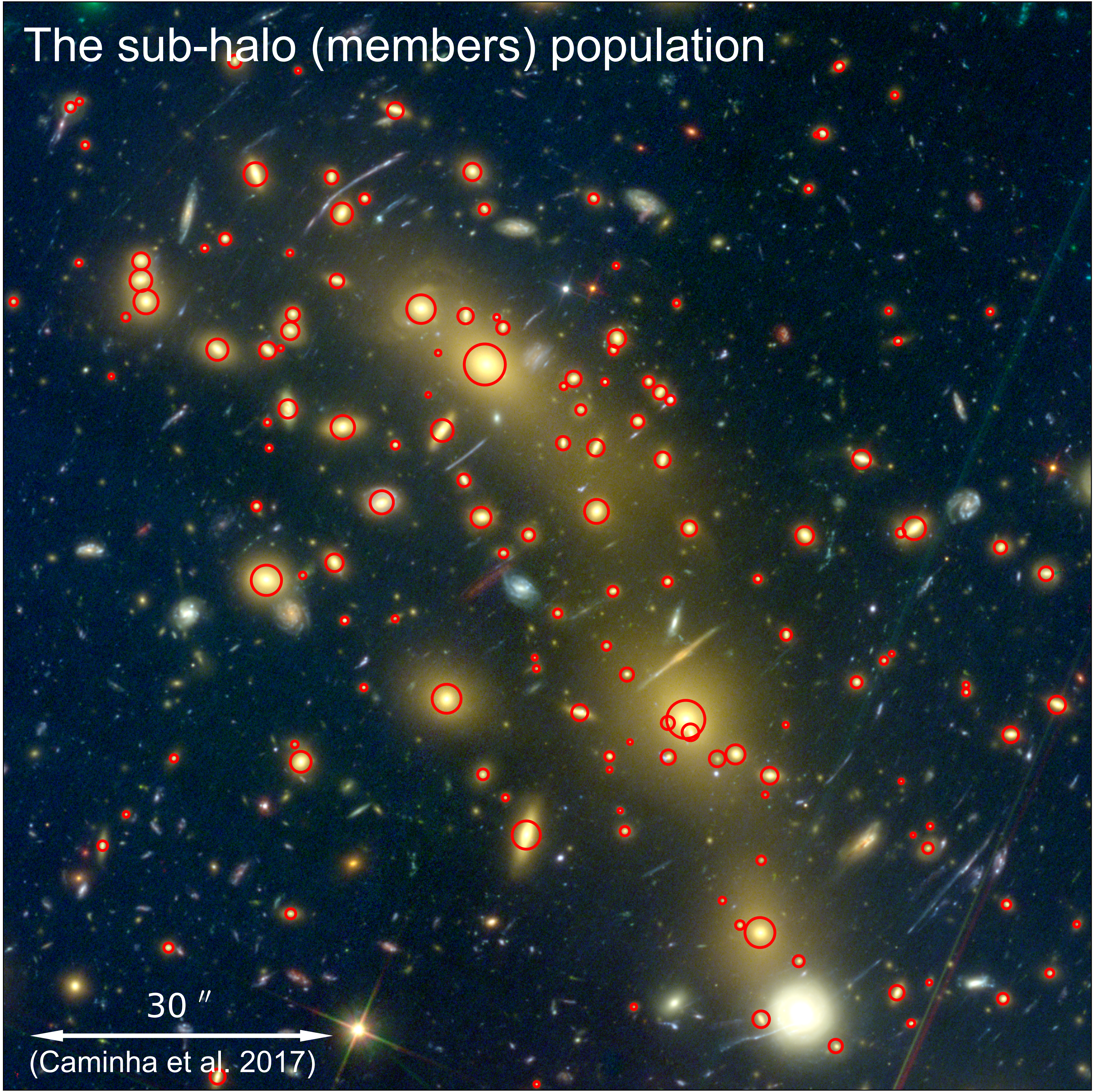
(Caminha et al. 2017)



CLASH-VLT
+
MUSE campaign

1 arcmin^2 FoV
2.6 Å resolution
4750-9350 Å
0.2 arcsec/pxl
90,000 spectra !
(Exp. = 2-11 hrs)

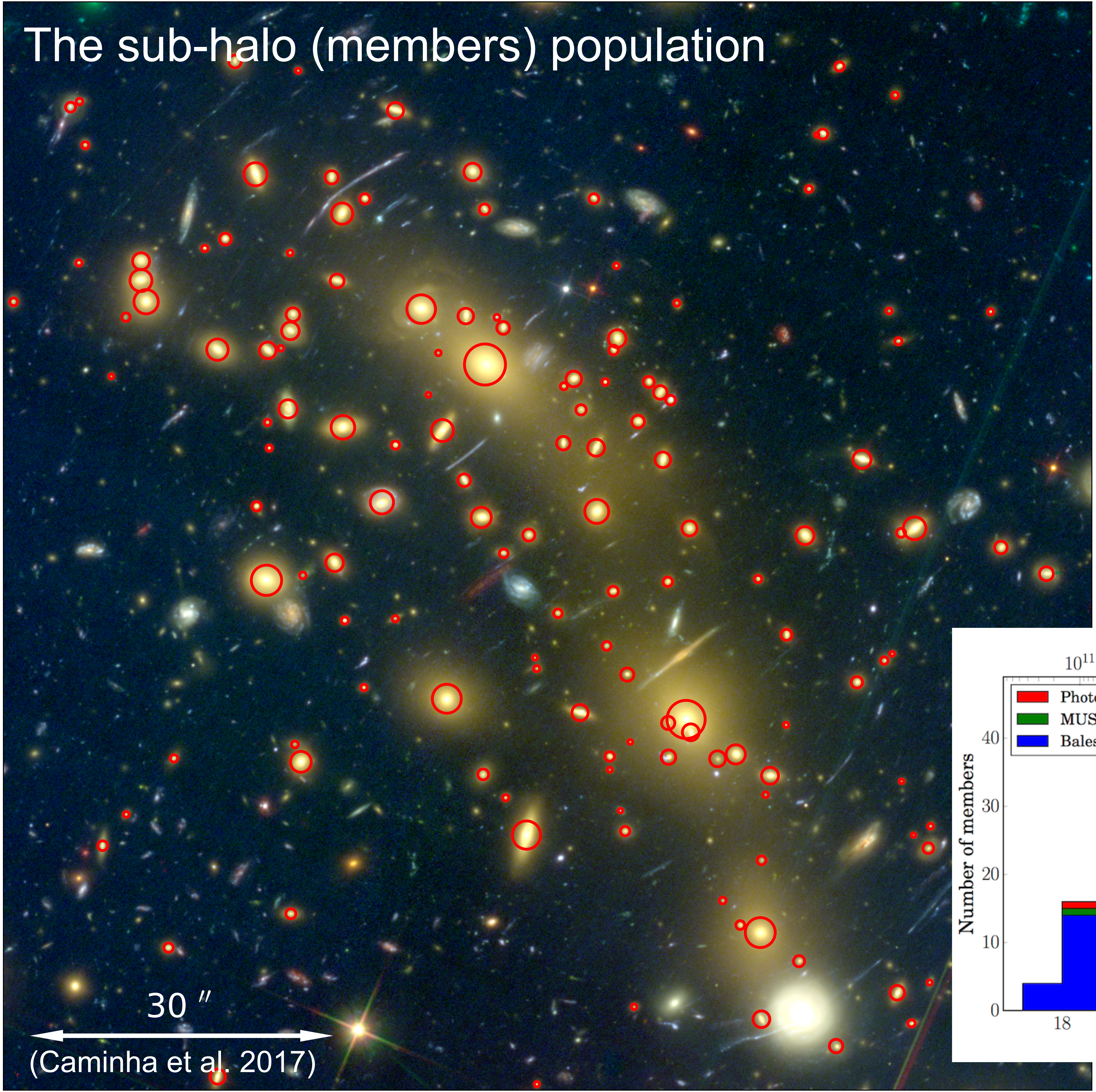
The sub-halo (members) population



CLASH-VLT
+
MUSE campaign

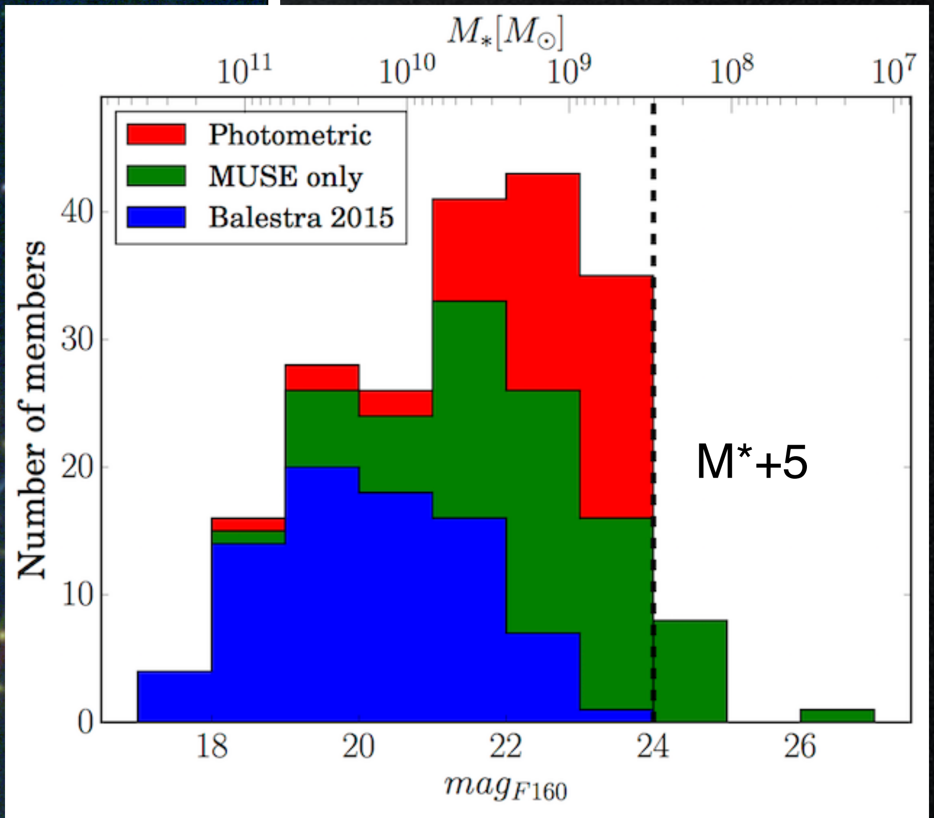
M*+5

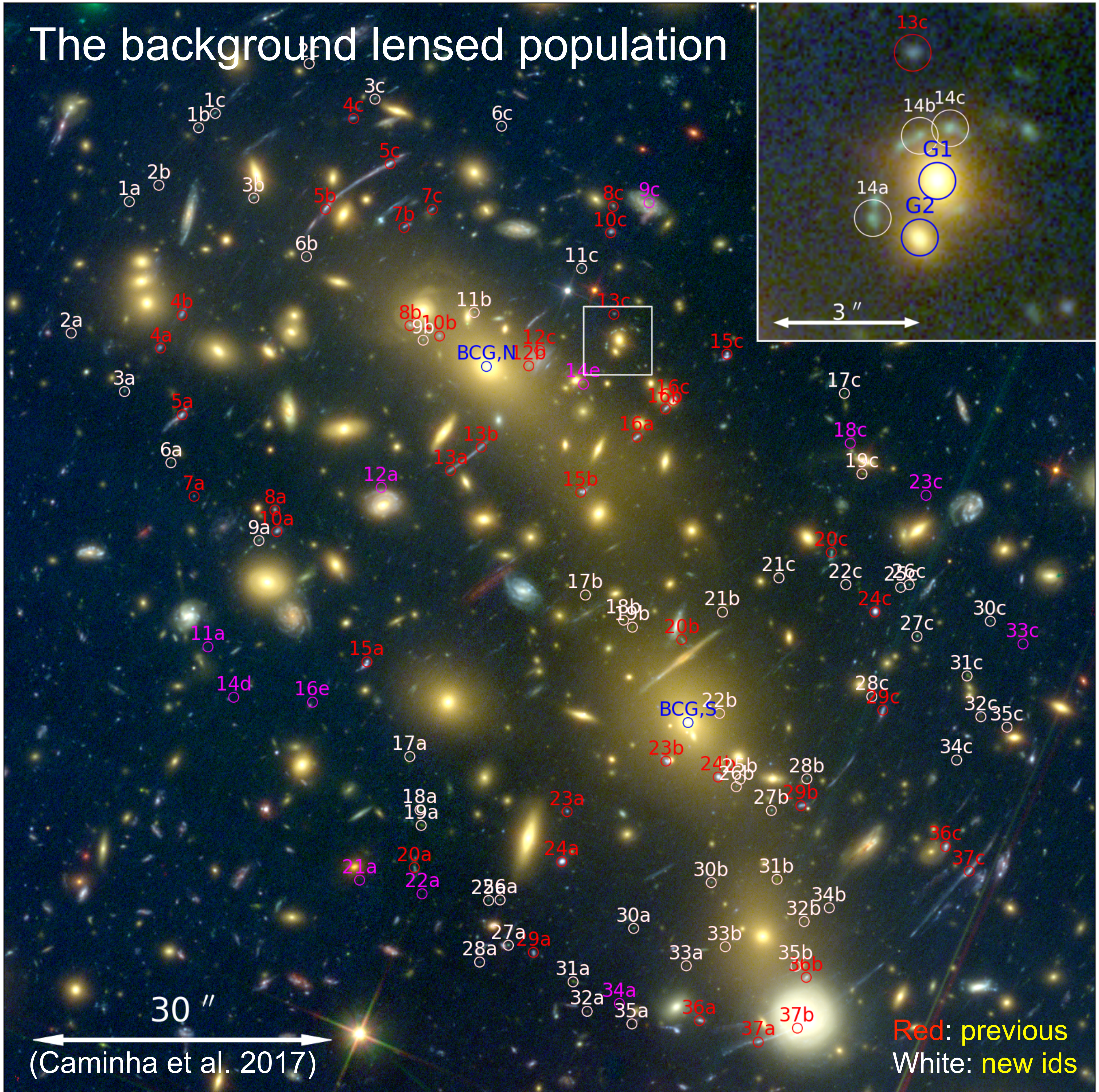
The sub-halo (members) population



CLASH-VLT
+
MUSE campaign

Complete and pure sample of 193 cluster galaxies (75% spec confirmed)





Largest sample of multiply lensed galaxies to date:

- **22 new multiple systems (from 15)**
- 102 images with redshift as constraints
- z=0.94–6.15
- Mostly faint LAEs
- Lensed LAB @z=3.3 (Vanzella et al. 2017a)

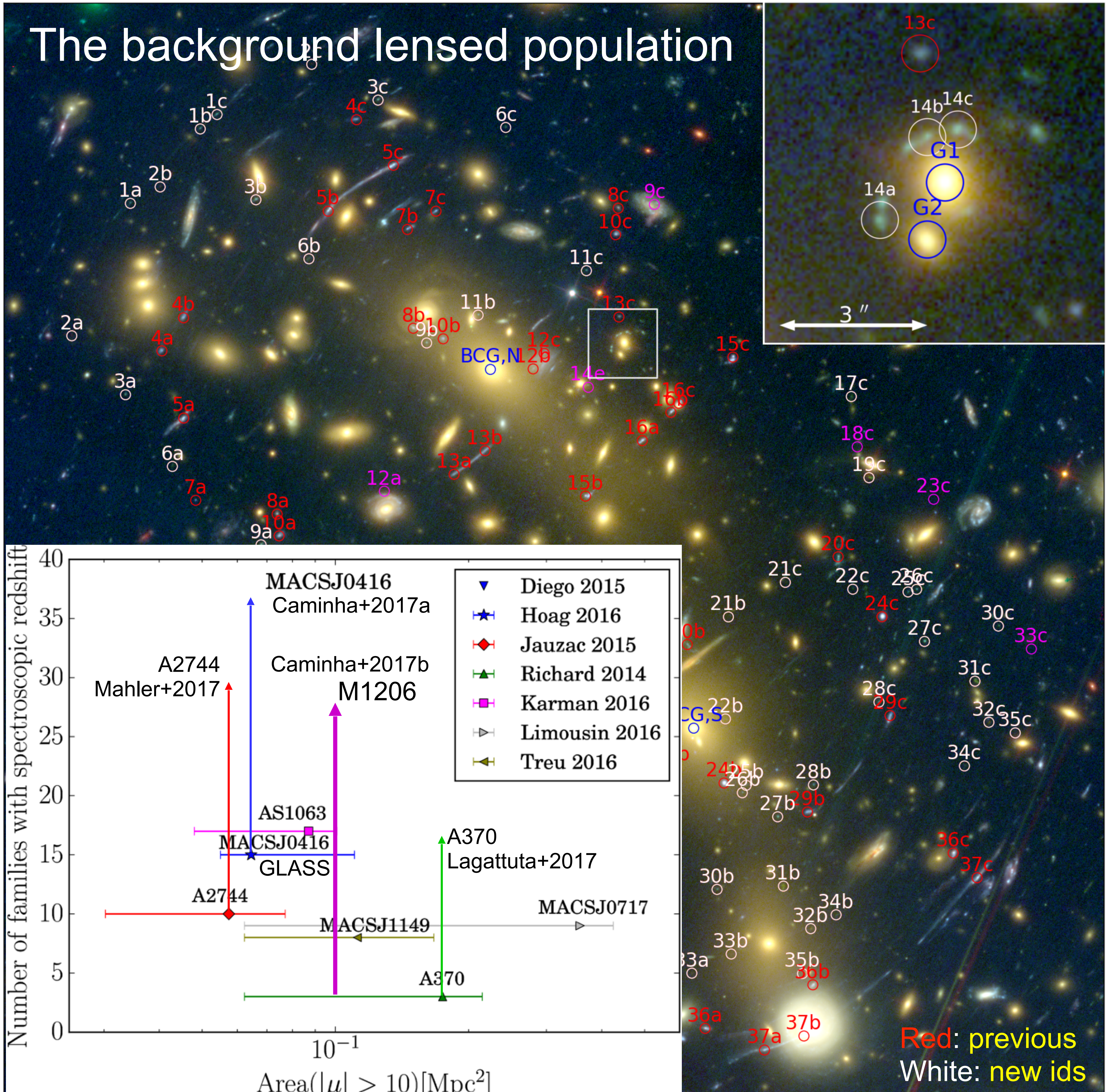
No. of multiple image systems:

37 MUSE (Caminha 17)

15 GLASS (Hoag 16)

8 CLASH-VLT (Grillo 15)

The background lensed population



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No. of multiple image systems:

37 — MUSE (Caminha 17)

15 — GLASS (Hoag 16)

8 — CLASH-VLT (Grillo 15)

Transition to high-precision strong lensing models

- Original CLASH studies based on photo-zs of multiple image sources
  ➔ suitable for aperture mass measurements, circularised mass profiles
  ➔ prone to systematics when probing inner substructure
  ➔ μ-maps prone to systematics in the high-μ regime

- Deep integral-field spectroscopy critical for high-precision strong lensing models i.e. subarcsec positional residuals

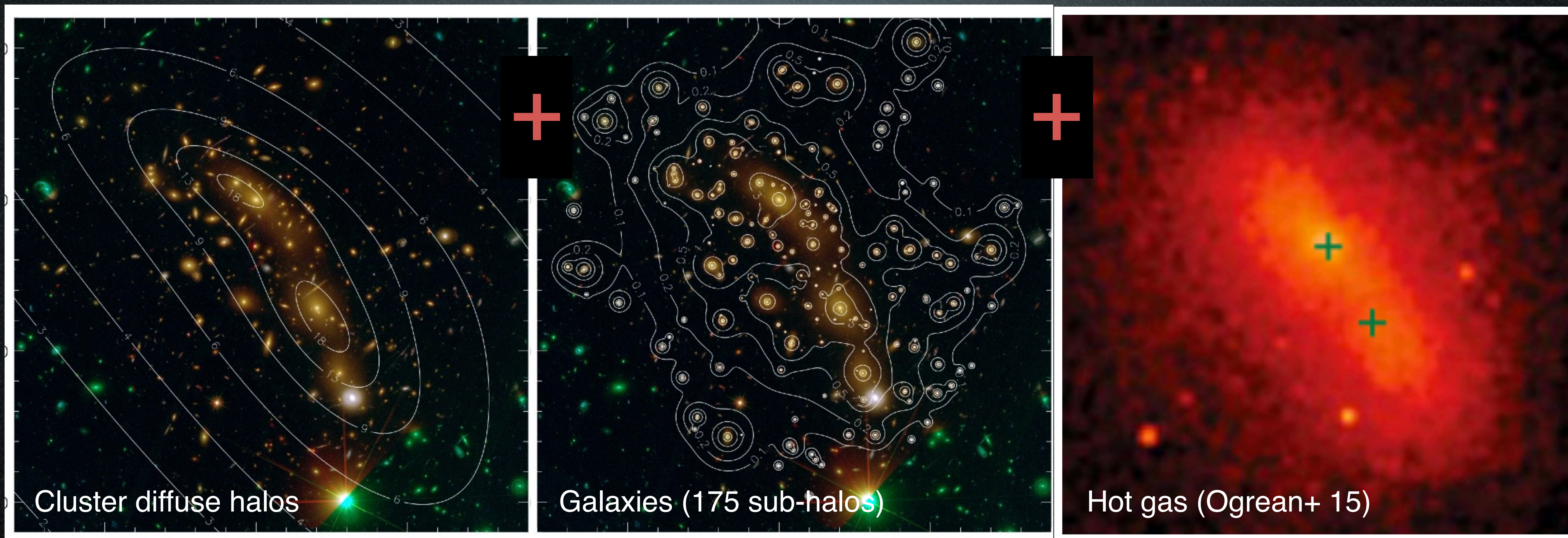
$$\Delta_{\rm rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} |\theta_I^{obs} - \theta_I^{pred}|} \approx 0.3 - 0.5''$$

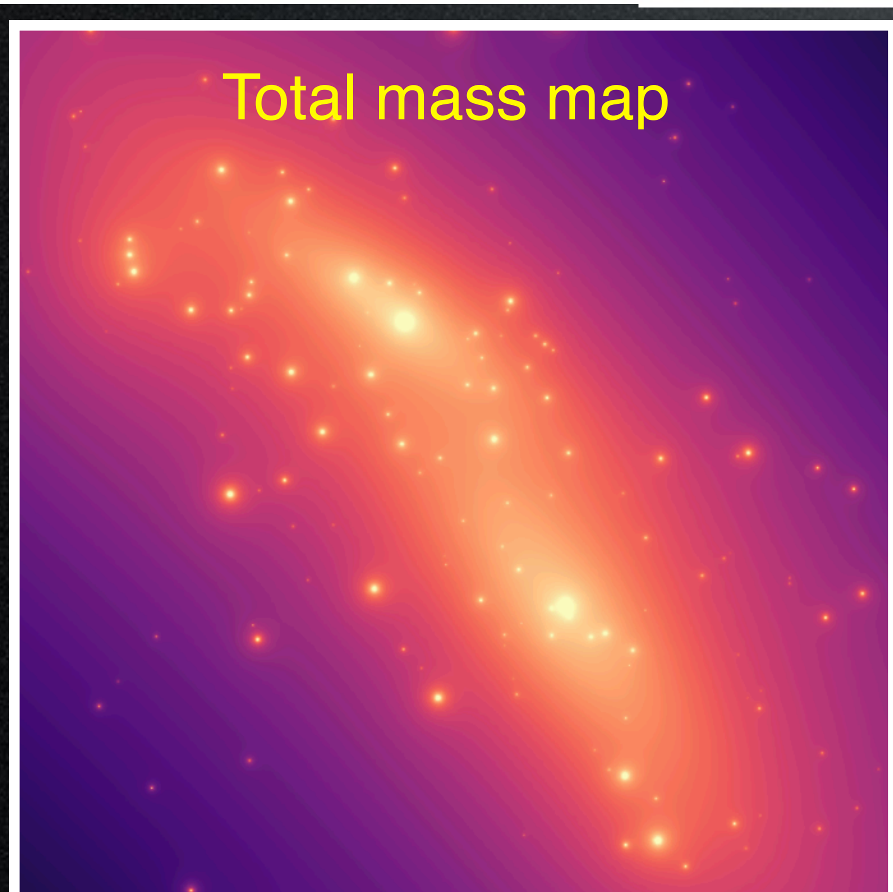
  ➔ use only (or mostly) spectroscopically confirmed multiple images
  ➔ avoid mass-distance degeneracies and identification biases
  ➔ pure/complete samples of cluster galaxies (sub-halo pop)
  ➔ LOS effects ($\Delta_{\rm rms,LOS}$ ~0.3") can be modelled with multi-plane methods

- High precision SL models
  ➡ essential to glean (delensed) physical parameters from magnified high-z galaxies (luminosity, SFR, $M_{\rm stellar}$, sizes, LF)
  ➡ open the way to cluster lensing cosmography

Detailed inner halo structure of MACS0416

(Grillo et al. 2015, Caminha et al. 2017, Bonamigo et al. 2017)

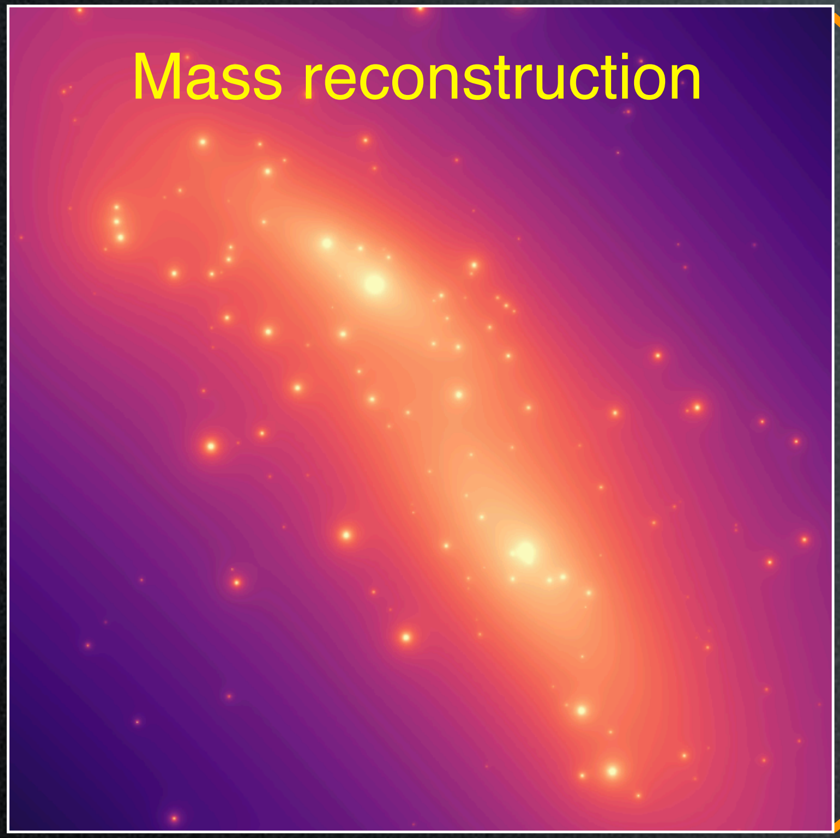


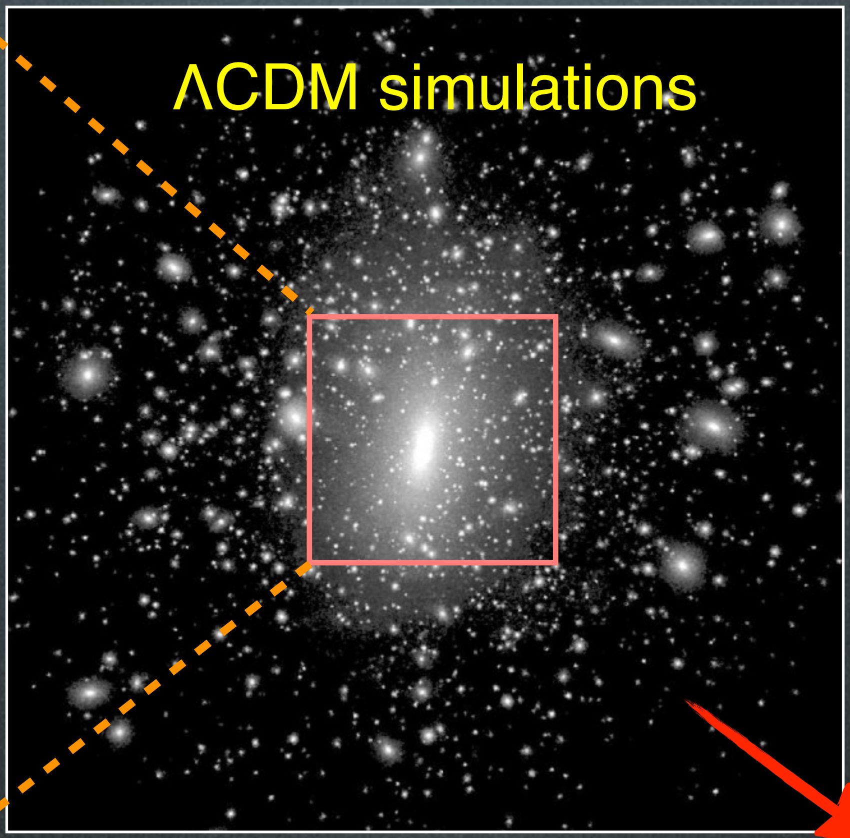


- Accurate SL model: 130 constraints, 26 parameters (3 DM halos, M_T/L of sub-halos, M_{GAS} given)
- Multiple images can be reproduced with ~0.5” rms positional accuracy
- **No significant offsets between DM and stars: negligible self-interaction cross-section**

DM halo structure: mass function of sub-halos

observations vs simulations

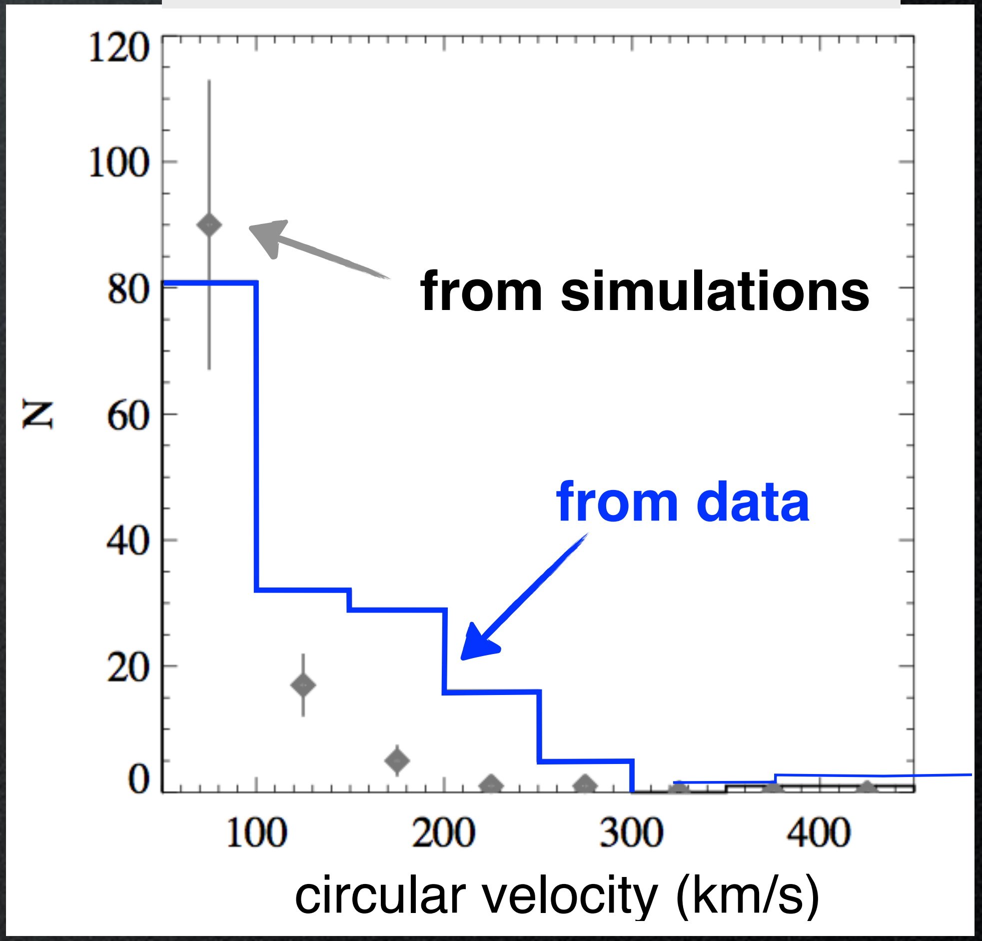




24 simulated clusters with similar masses (DM only) (Trieste group)

(Grillo et al. 2015, Caminha et al. 2017, Bonamigo et al. 2018)

Sub-halo mass function



Findings:

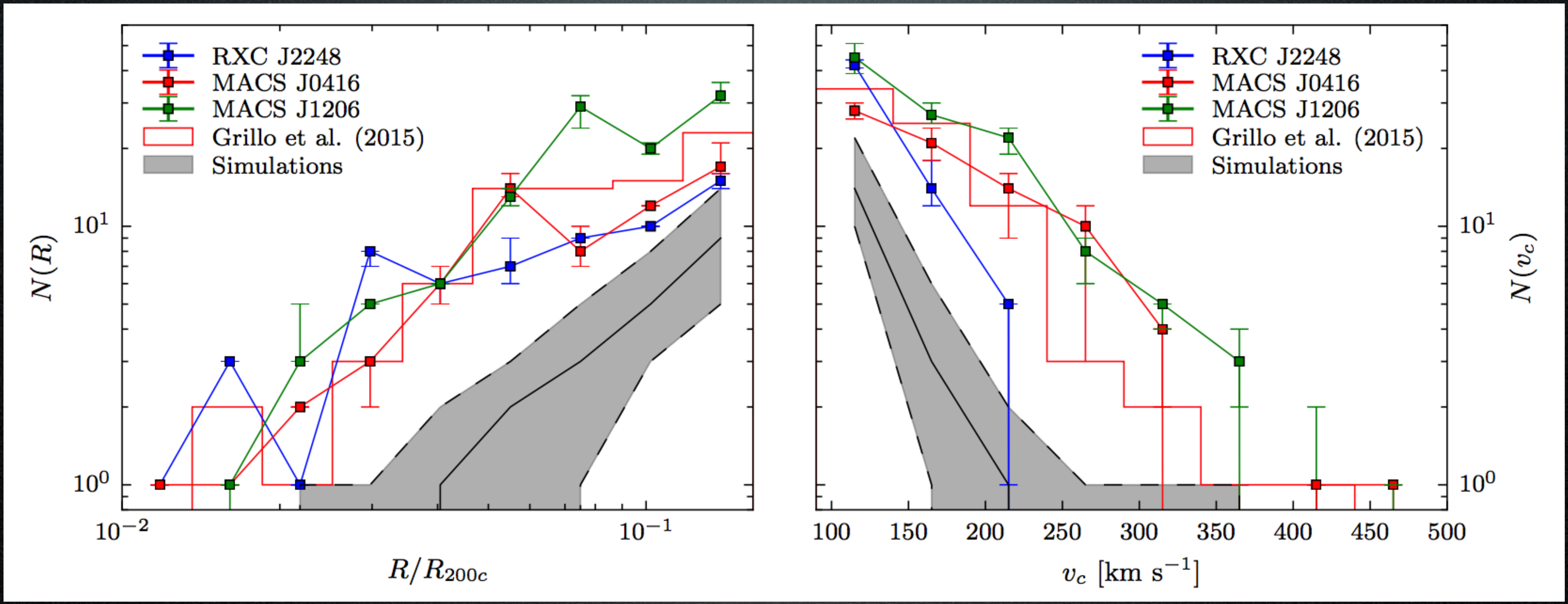
lack of massive sub-halos in N-body DM only simulations, mostly located in the central regions

- why didn't they form in simulations ?
- tidal stripping of massive sub-halos ?
- Also found in Munari+ 2016 (A2142 with SDSS): baryonic physics does not seem to fix the problem

Sub-halo mass function (“substructure”)

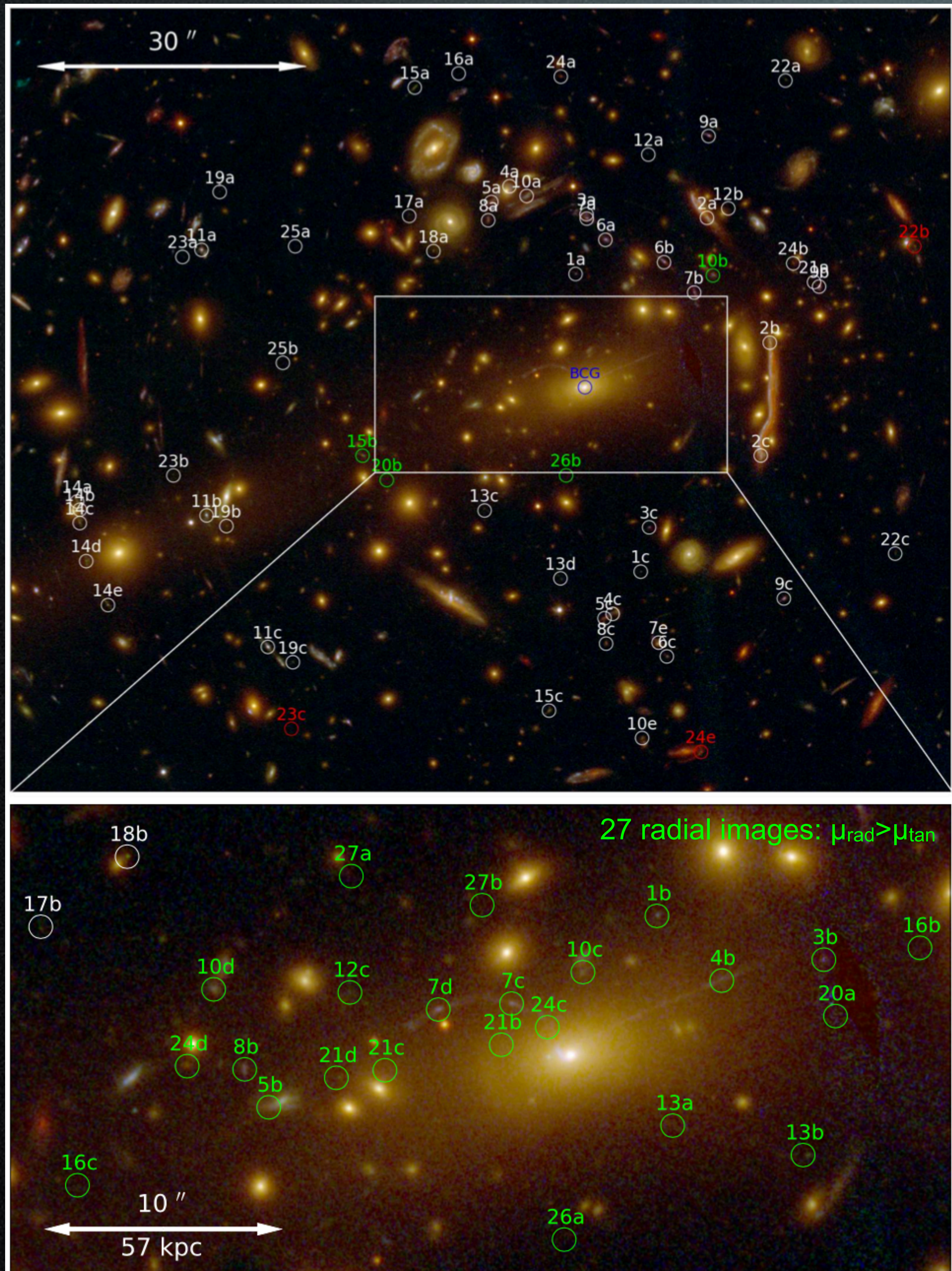
Results confirmed for other two CLASH/FF clusters

(Bonamigo et al. 2018, submitted)



- Problems with simulations in treating DM halo stripping ?
  (van den Bosch 2017: disruption of DM sub halos is an artefact ?)
- Lack of understanding of baryonic effects ?
- Problems with the strong lens model (normalization of sub-halo masses) ?

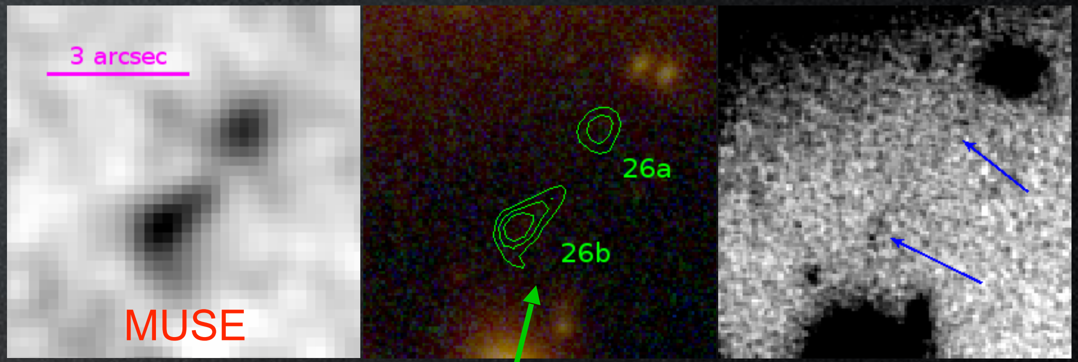
The core of MACS1206 with MUSE



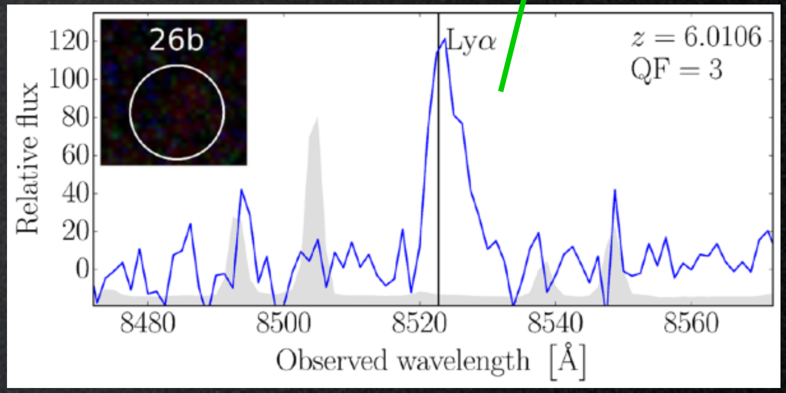
(Caminha et al. 2017)

- 27 multiple systems
- 85 multiple images
- 11 multiple images within 50 kpc!
- Accurate lens model (Δ_{rms}=0.4”)

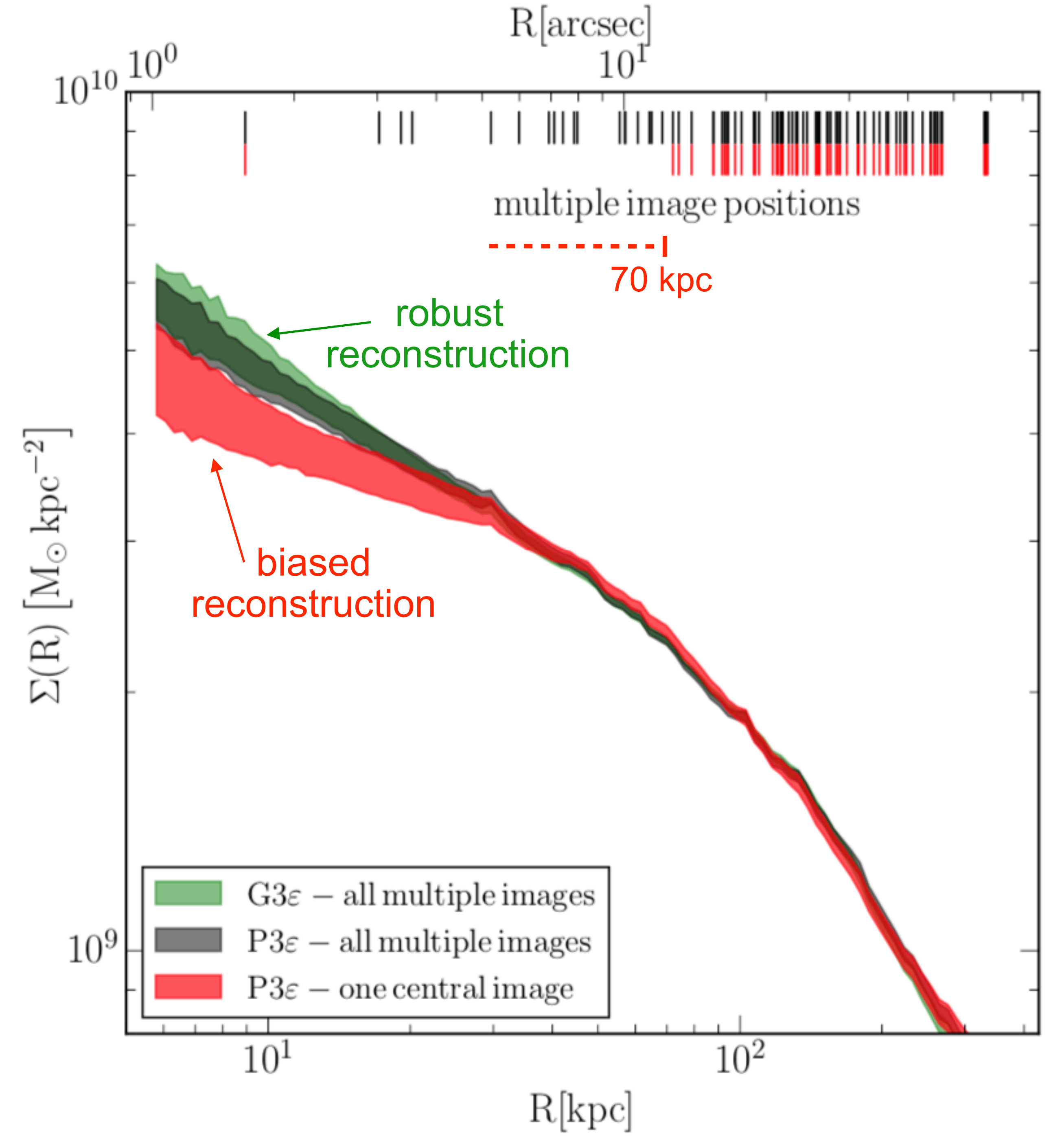
z=6 Lya emitter

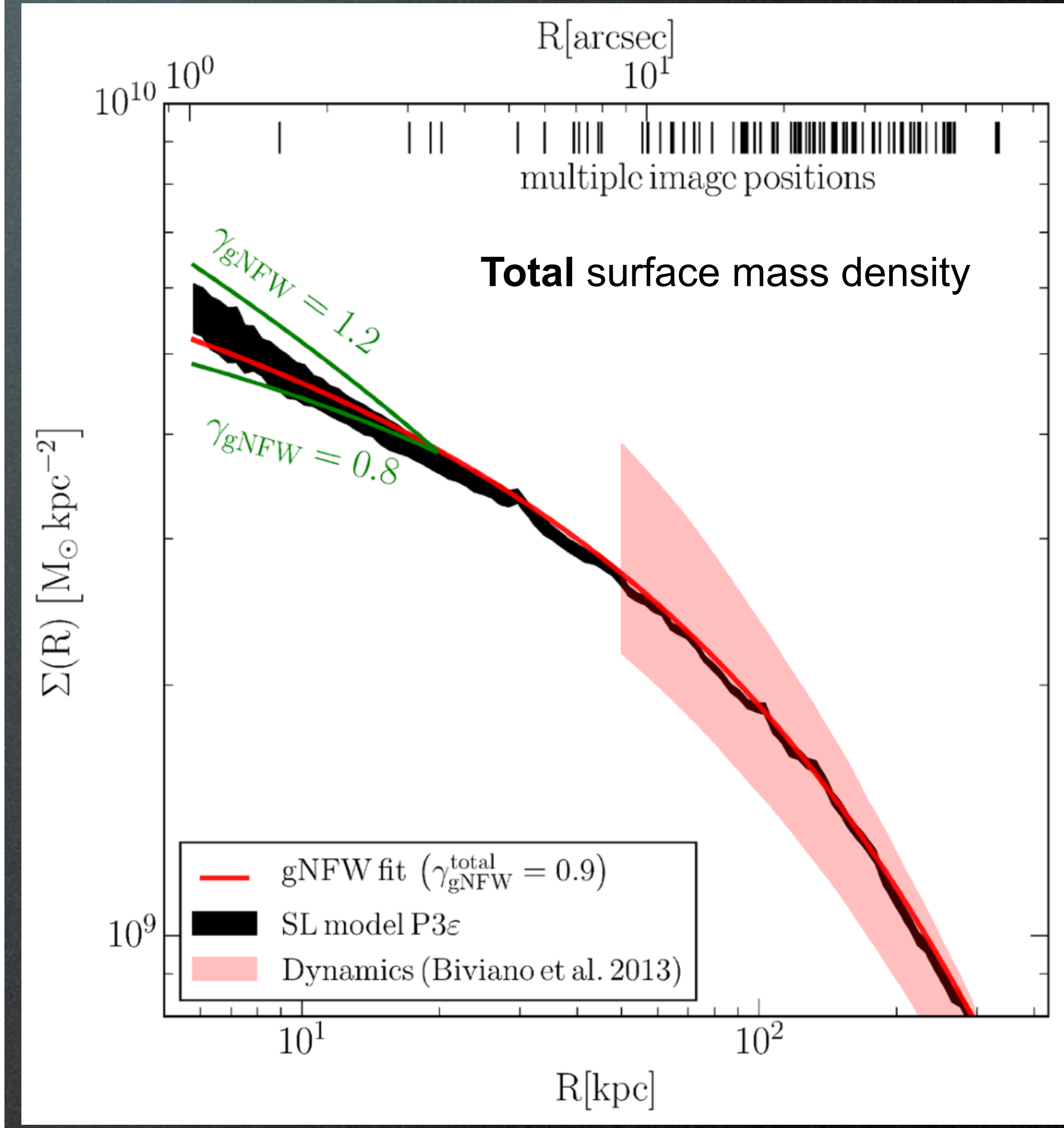


Limiting F160W = 27.5



The mass density profile in the inner core of MACS1206





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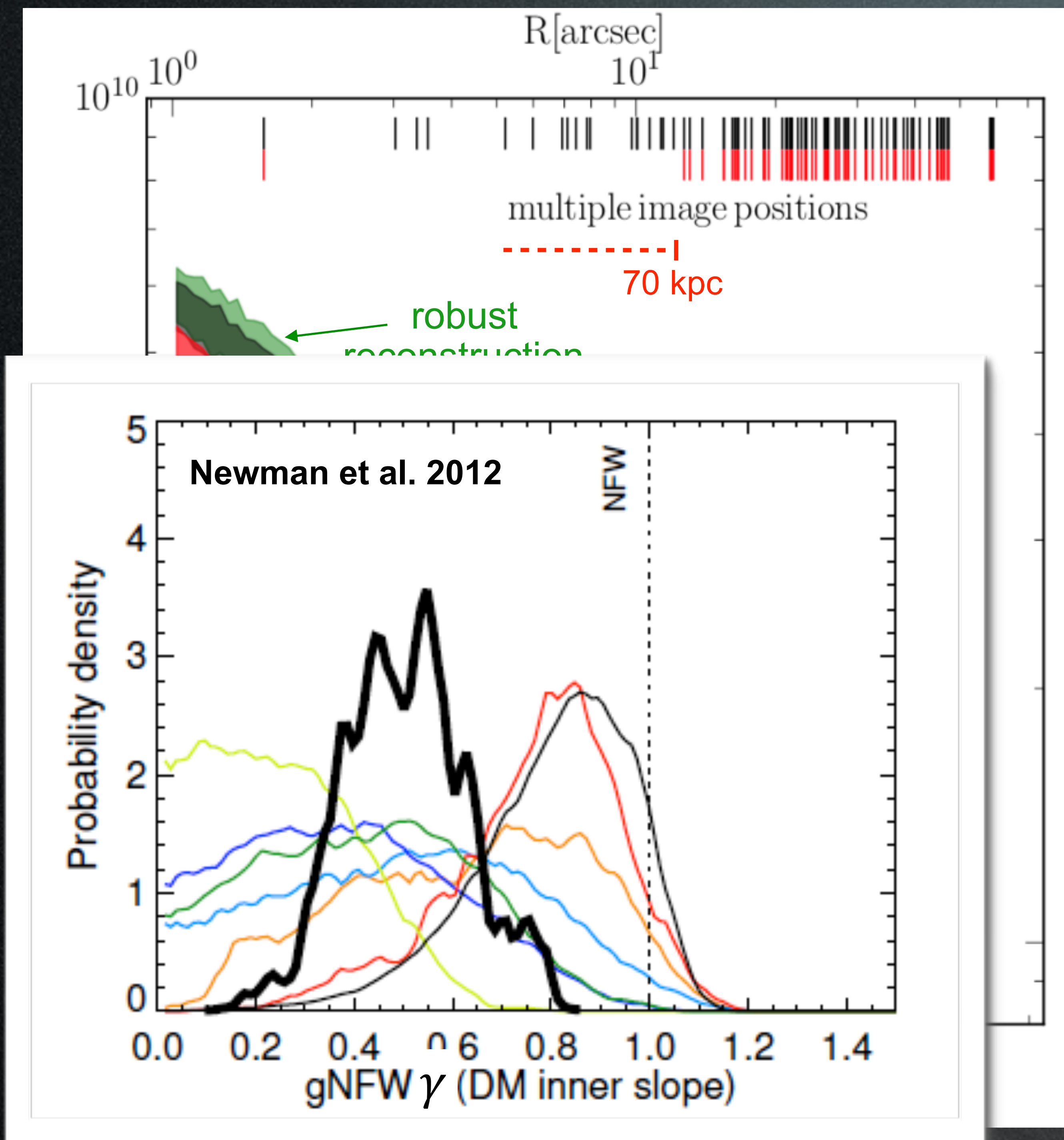
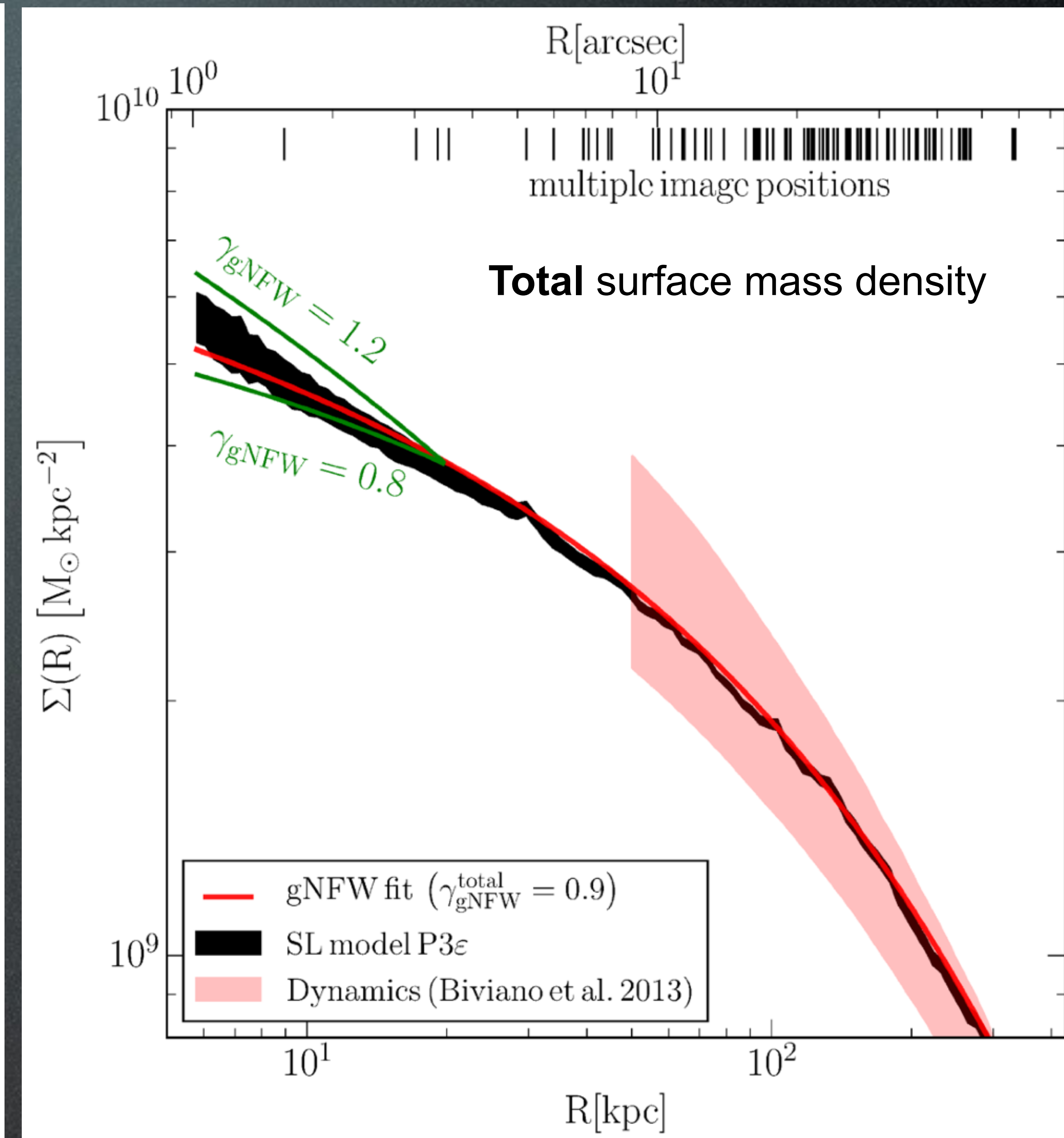




- The DM density profile appears shallower than NFW ($\gamma_{DM} \approx$ 0.6-0.7)
- Cluster-cluster variance in the inner core slope may reflect heterogeneous data quality
- See B. Sartoris' talk on the inner γ_{DM} with resolved BCG kinematics+galaxy dynamics

Cosmography with cluster strong lensing

ON THE POSSIBILITY OF DETERMINING HUBBLE'S PARAMETER AND THE MASSES OF GALAXIES FROM THE GRAVITATIONAL LENS EFFECT*

Sjur Refsdal

(Communicated by H. Bondi)

(Received 1964 January 27)

Summary

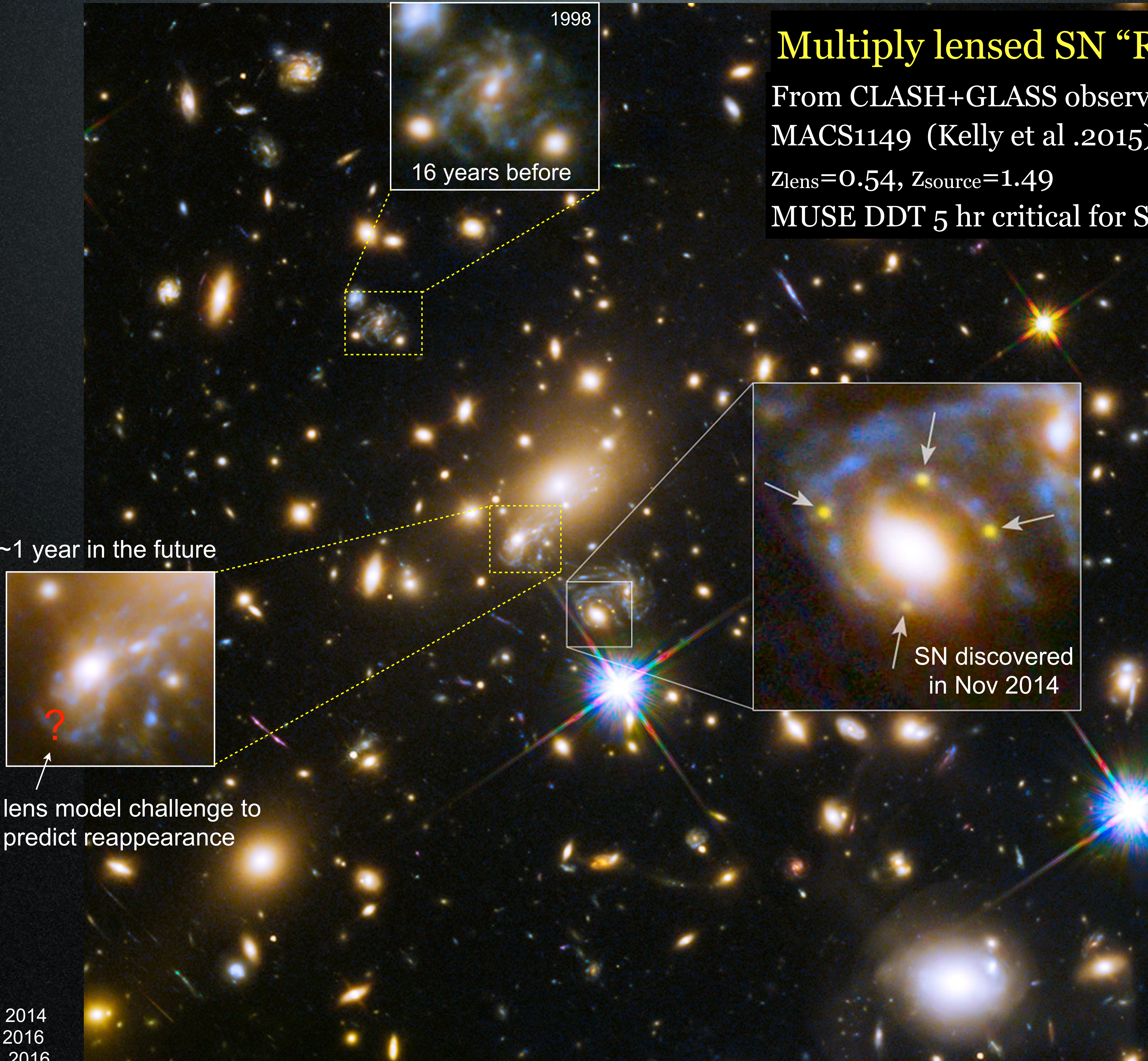
The gravitational lens effect is applied to a supernova lying far behind and close to the line of sight through a distant galaxy. The light from the supernova may follow two different paths to the observer, and the difference Δt in the time of light travel for these two paths can amount to a couple of months or more, and may be measurable. It is shown that Hubble's parameter and the mass of the galaxy can be expressed by Δt, the red-shifts of the supernova and the galaxy, the luminosities of the supernova " images " and the angle between them. The possibility of observing the phenomenon is discussed.

Multiply lensed SN “Refsdal”

From CLASH+GLASS observations of MACS1149 (Kelly et al .2015)

$z_{lens}=0.54$, $z_{source}=1.49$

MUSE DDT 5 hr critical for SL model



Kelly et al. 2014
Treu et al. 2016
Grillo et al. 2016

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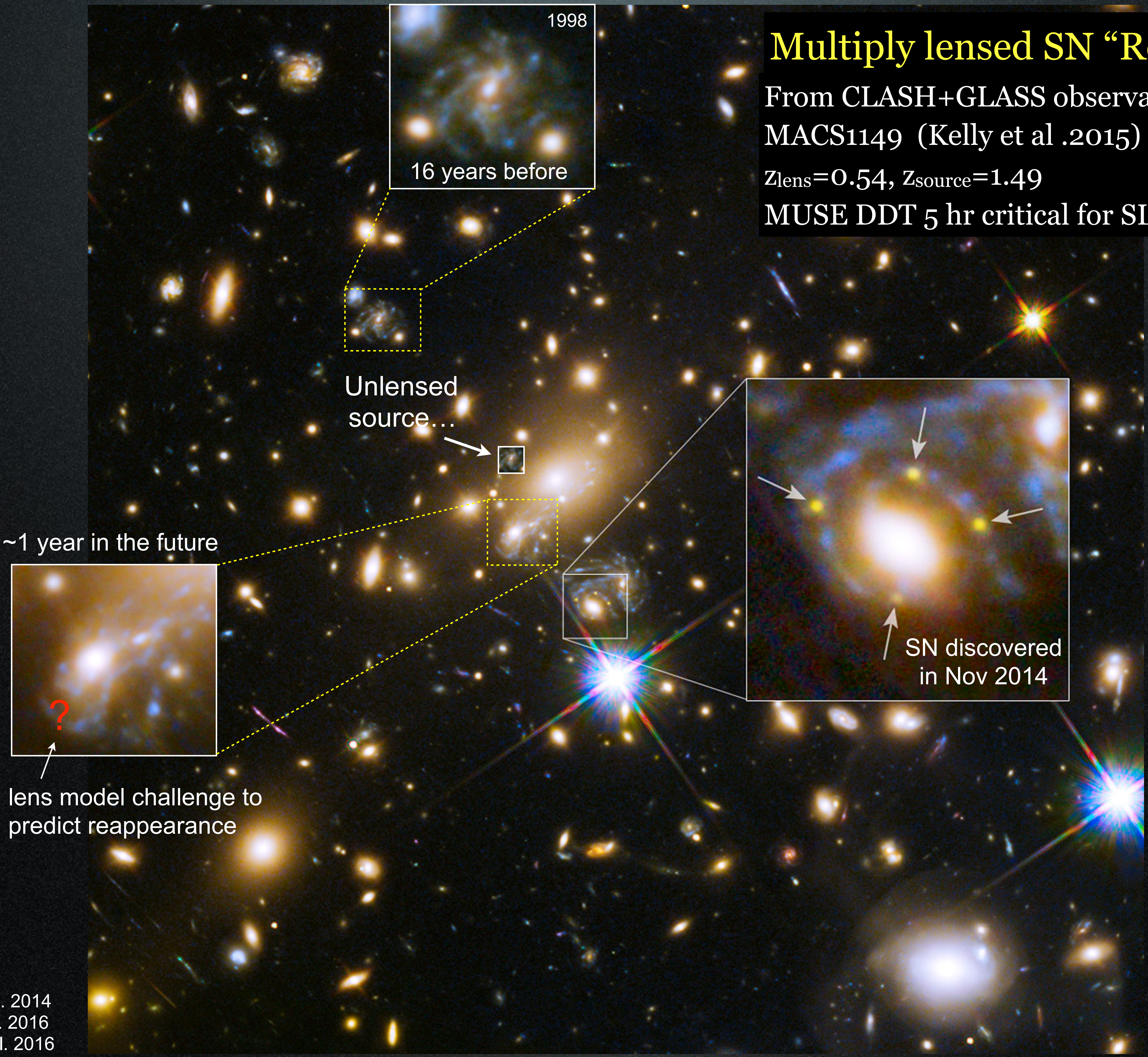
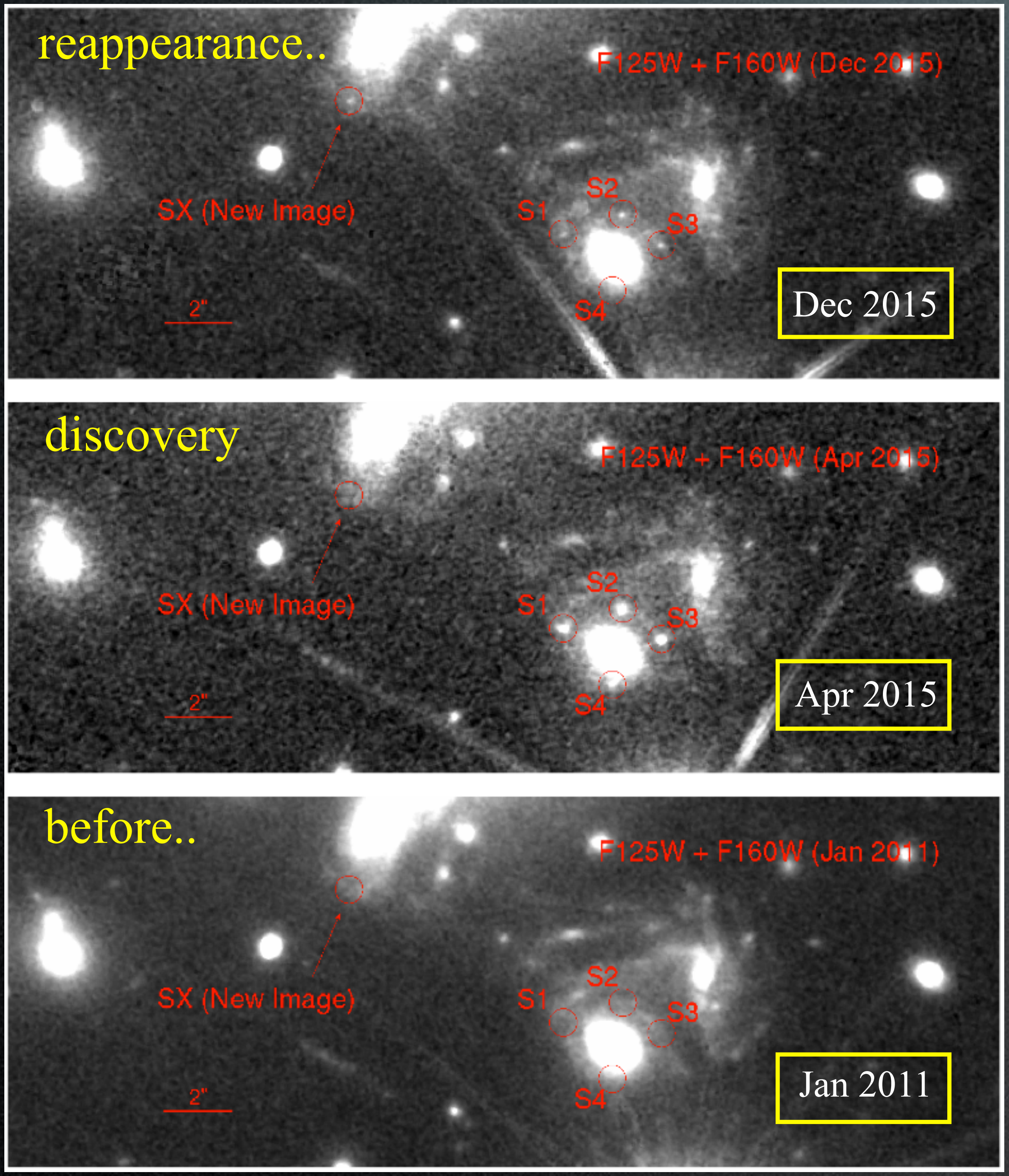


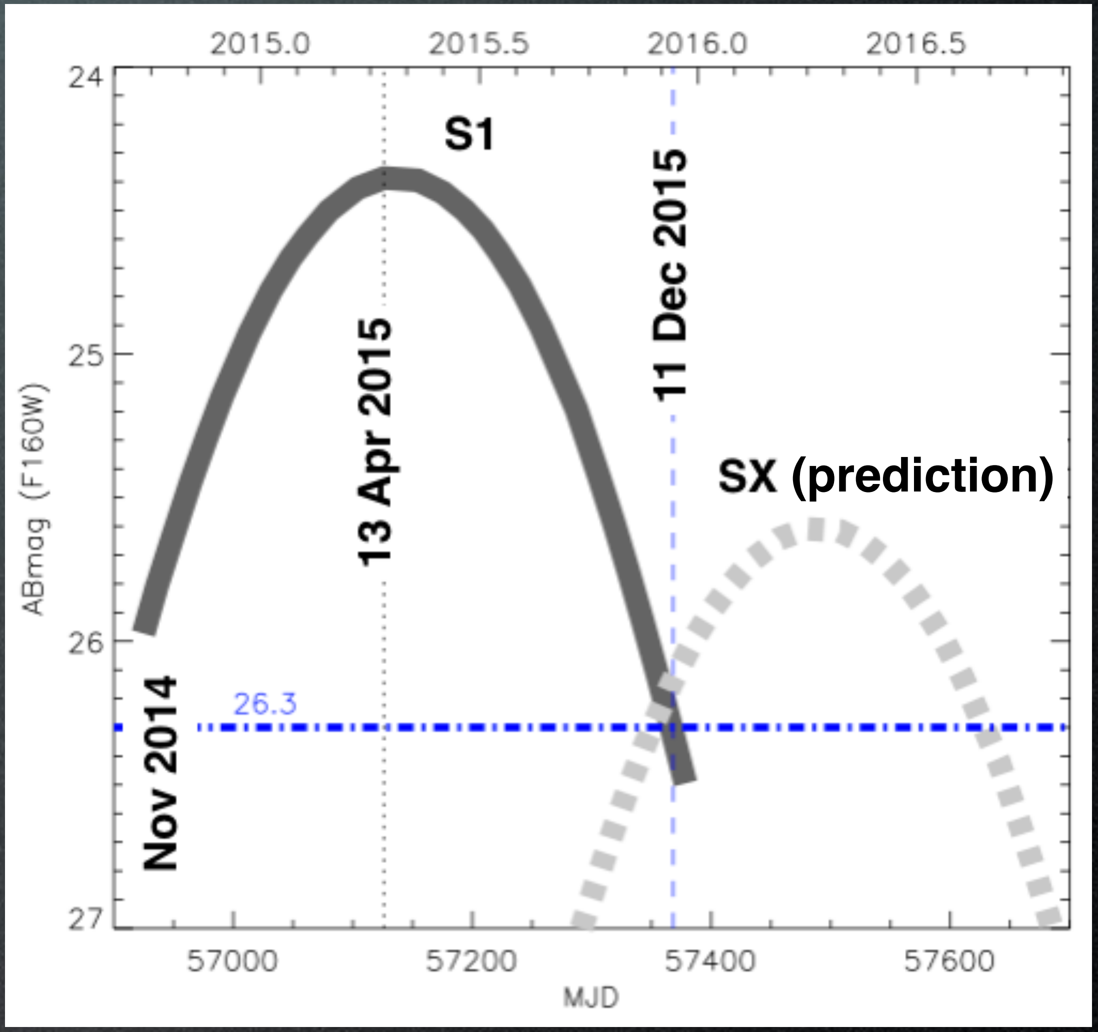
Kelly et al. 2014
Treu et al. 2016
Grillo et al. 2016

SN Refsdal: a true blind tests of model predictions

The reappearance of SN Refsdal

Kelly, Rodney et al. 2016





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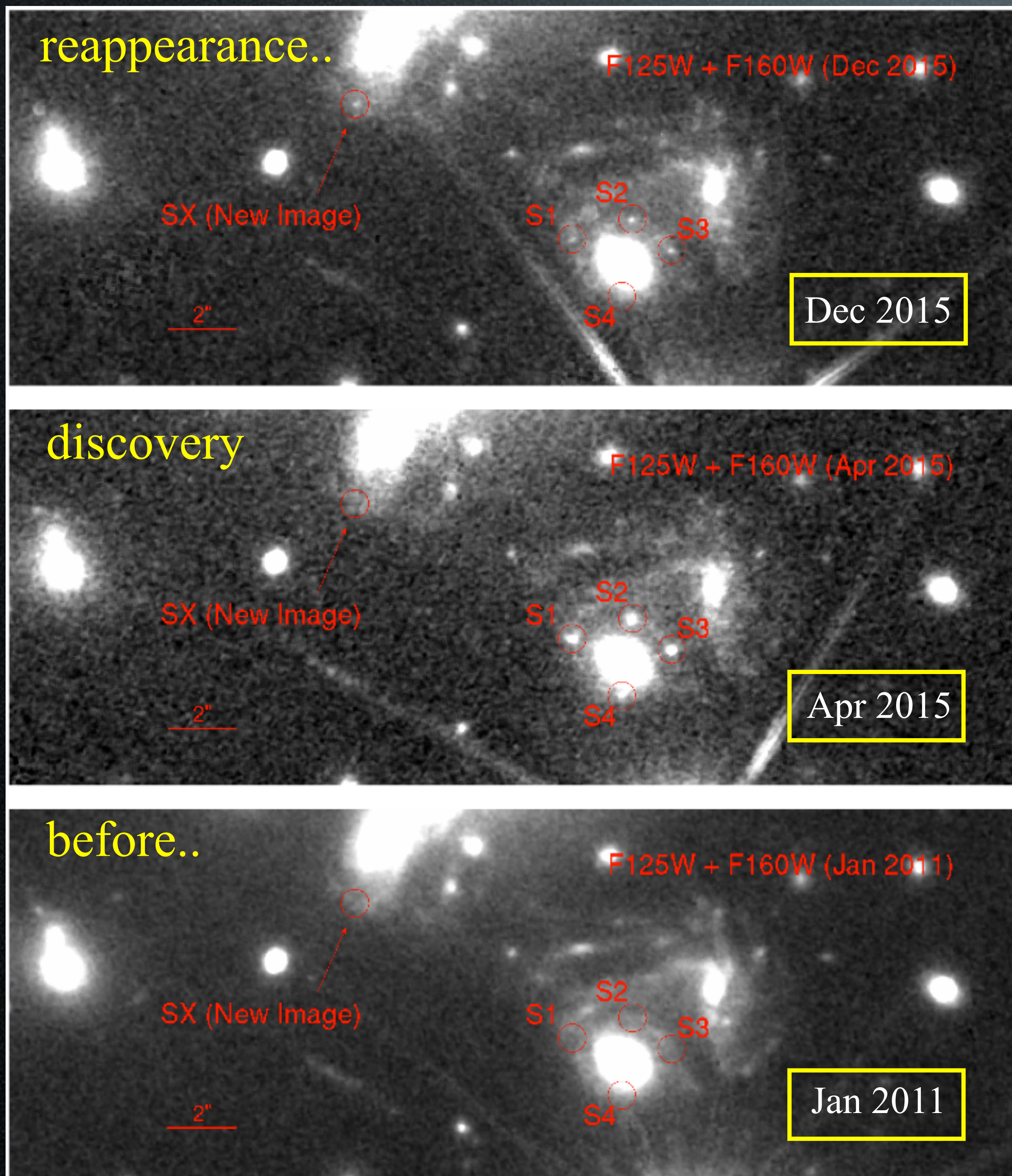
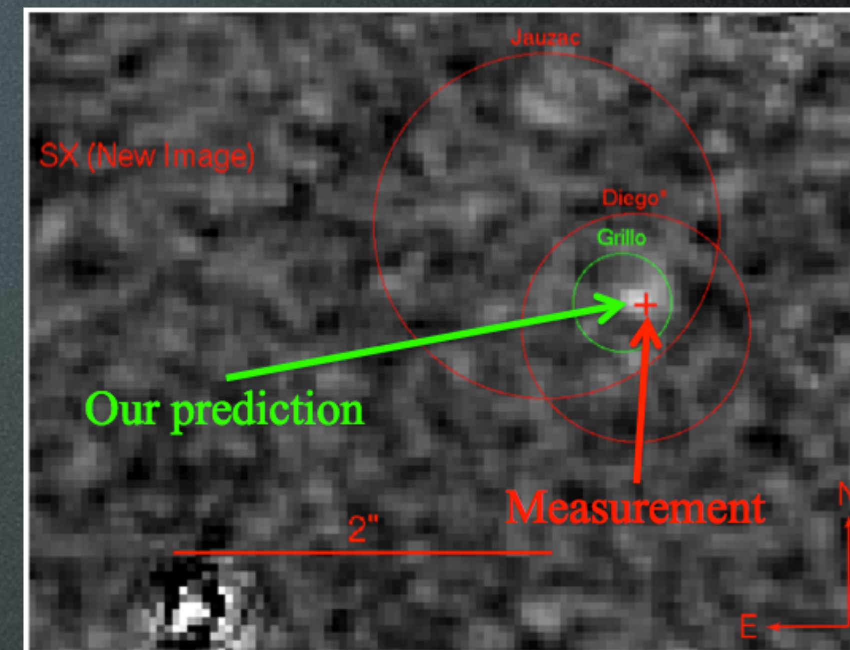
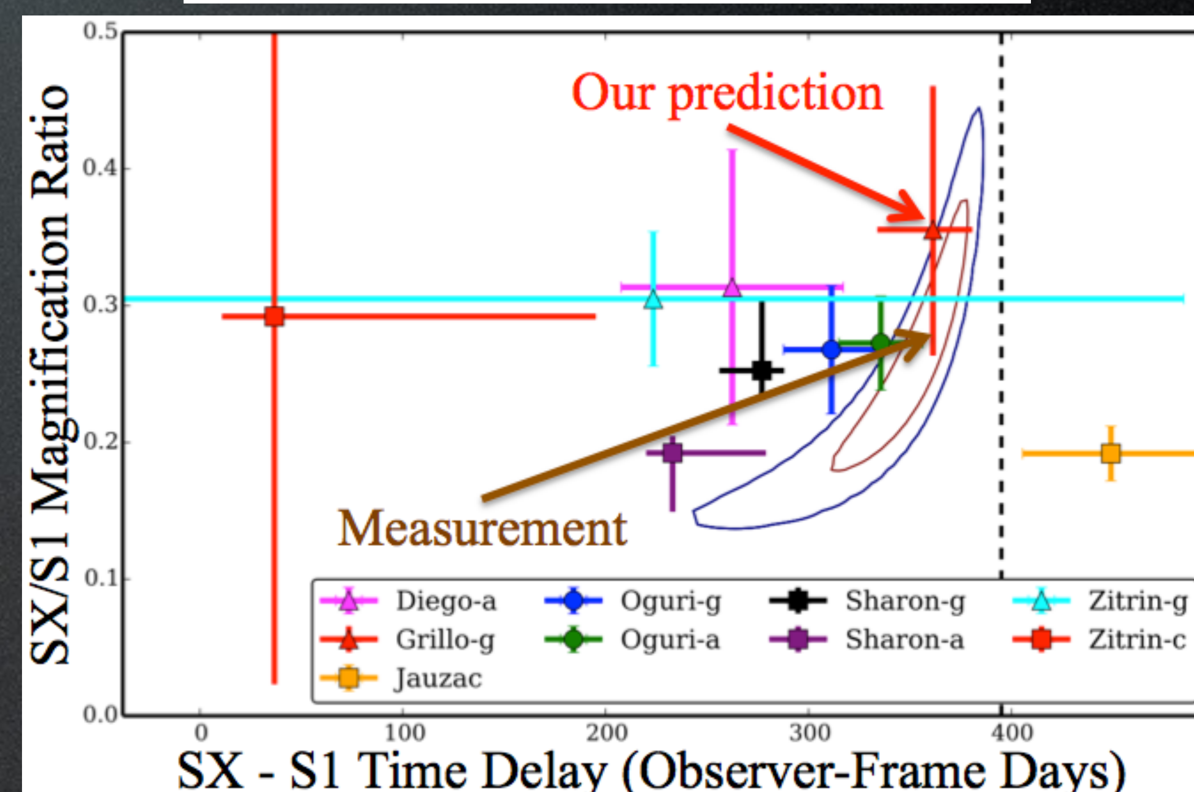




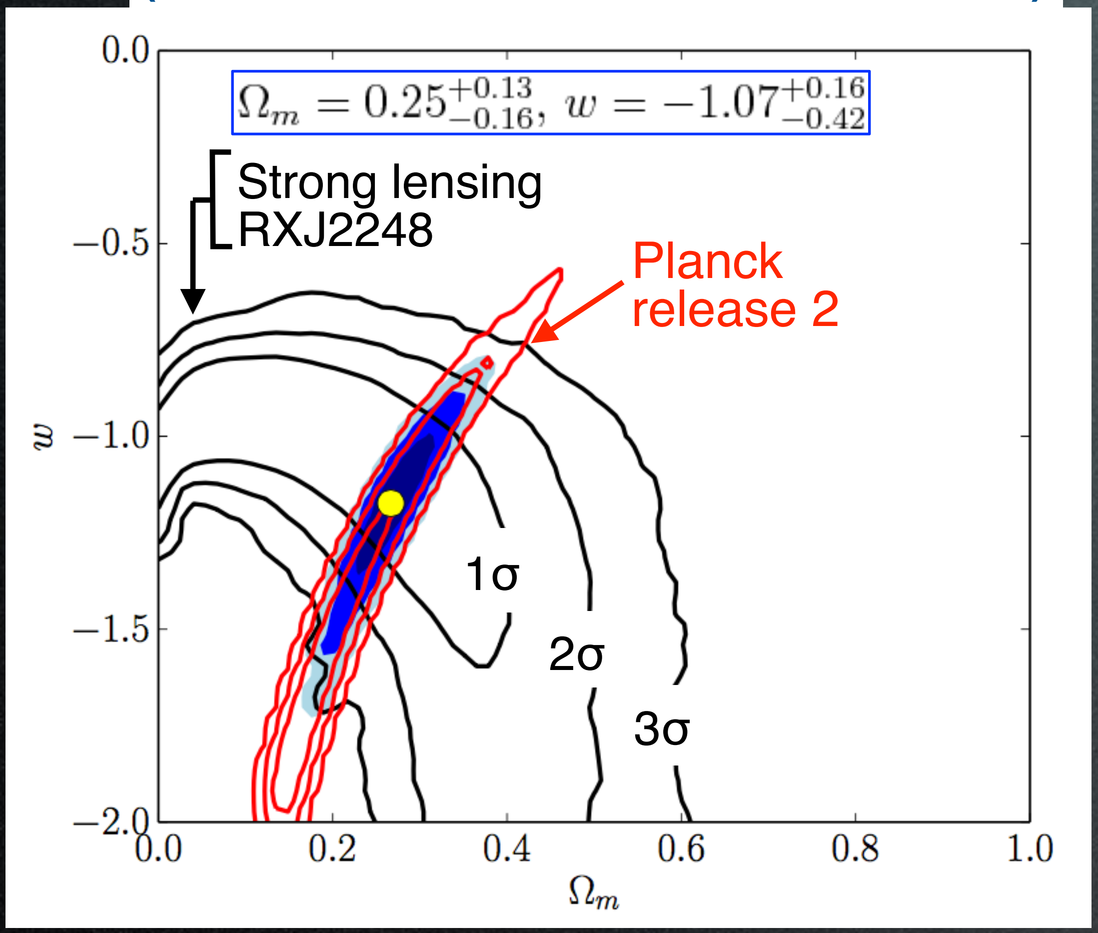
SX Position



⇒ High-precision prediction of SL models when adequate spectroscopic info is available, hence reliable reconstruction of ψ, ψ', ψ'' (cluster potential) and DM distribution

Cosmography with cluster strong lensing

(Caminha+ 2016 from FF cluster RXJ2248)

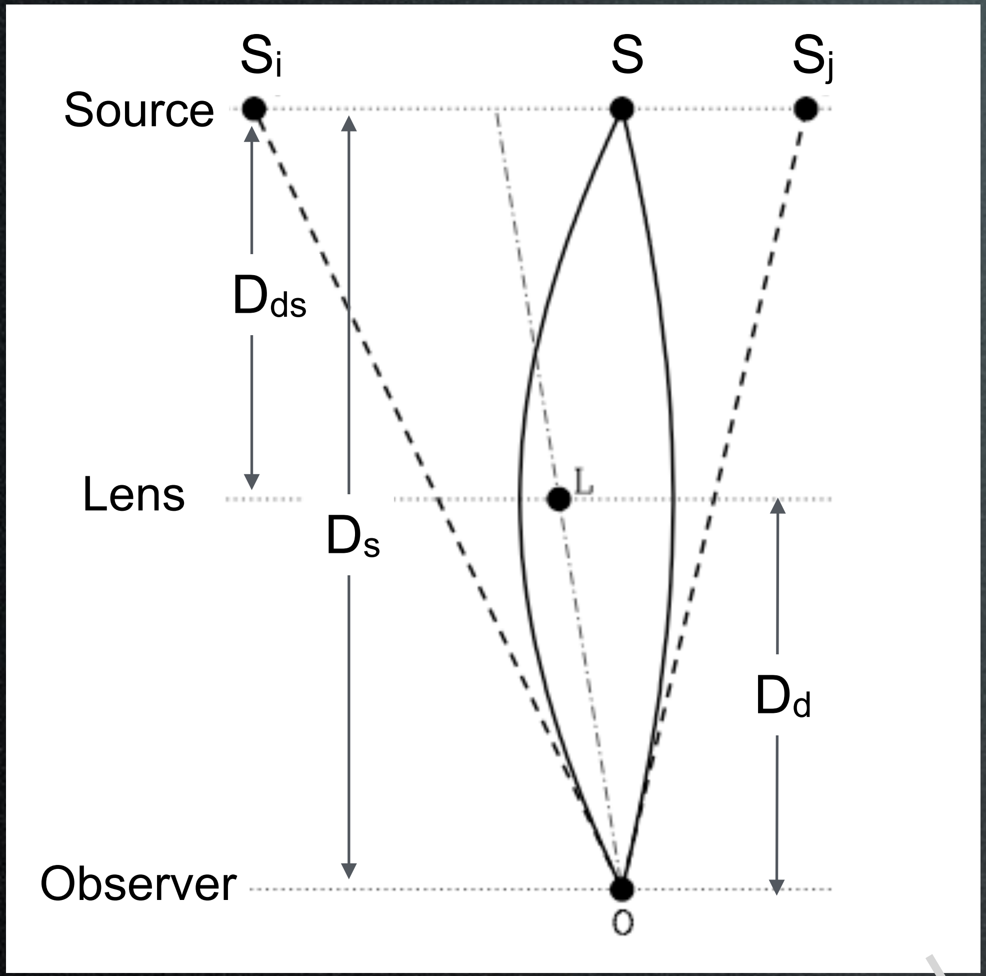


$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})\,, \quad \vec{\alpha}(\vec{\theta}) = \frac{D_d D_{ds}}{D_s} \int \Sigma(\vec{\theta}) \ldots$$

Using the ratio of angular diameter distances at different redshifts one can solve for mass and geometry (Soucail+ 2004, Jullo+ 2010, Caminha+ 2016):

$$\Xi(z_{\rm d}, z_{\rm s_1}, z_{\rm s_2}) = \frac{D_{\rm ds_1} D_{\rm s_2}}{D_{\rm s_1} D_{\rm ds_2}} = f\,(\Omega_M, \Omega_\Lambda, z_L, z_S)$$

Cosmography with cluster strong lensing



$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta}) \,, \quad \vec{\alpha}(\vec{\theta}) = \frac{D_d D_{ds}}{D_s} \int \Sigma(\vec{\theta}) \ldots$$

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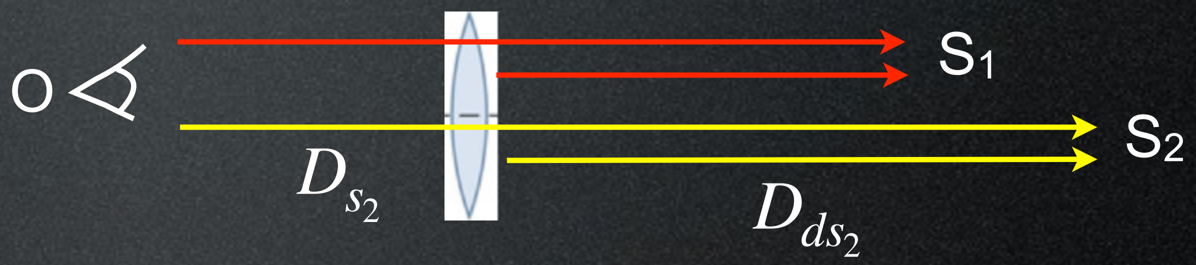


Refsdal original idea (1964)

If the source is variable, the time delay between image i and j is:

$$\Delta t_{ij} = \frac{D_{\Delta t}}{c} \left[\frac{(\boldsymbol{\theta}_i - \boldsymbol{\beta})^2}{2} - \psi(\boldsymbol{\theta}_i) - \frac{(\boldsymbol{\theta}_j - \boldsymbol{\beta})^2}{2} + \psi(\boldsymbol{\theta}_j) \right]$$

with the time-delay distance:

$$D_{\Delta t}(z_{\rm d}, z_{\rm s}) = (1 + z_{\rm d}) \frac{D_{\rm d} D_{\rm s}}{D_{\rm ds}} = (1/H_0)\, \tilde{f}\,(\Omega_M, \Omega_\Lambda, z_L, z_S)$$

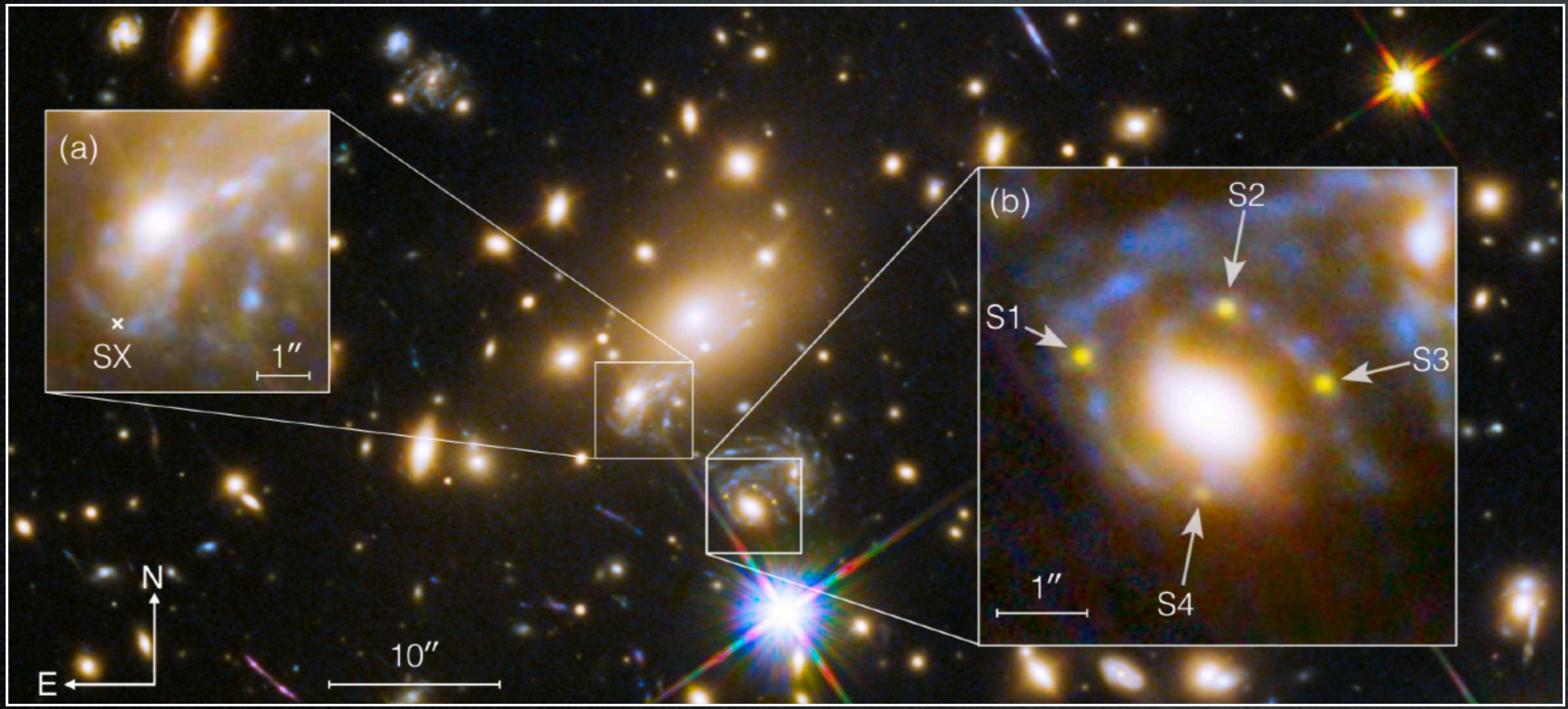
Cosmography with cluster strong lensing

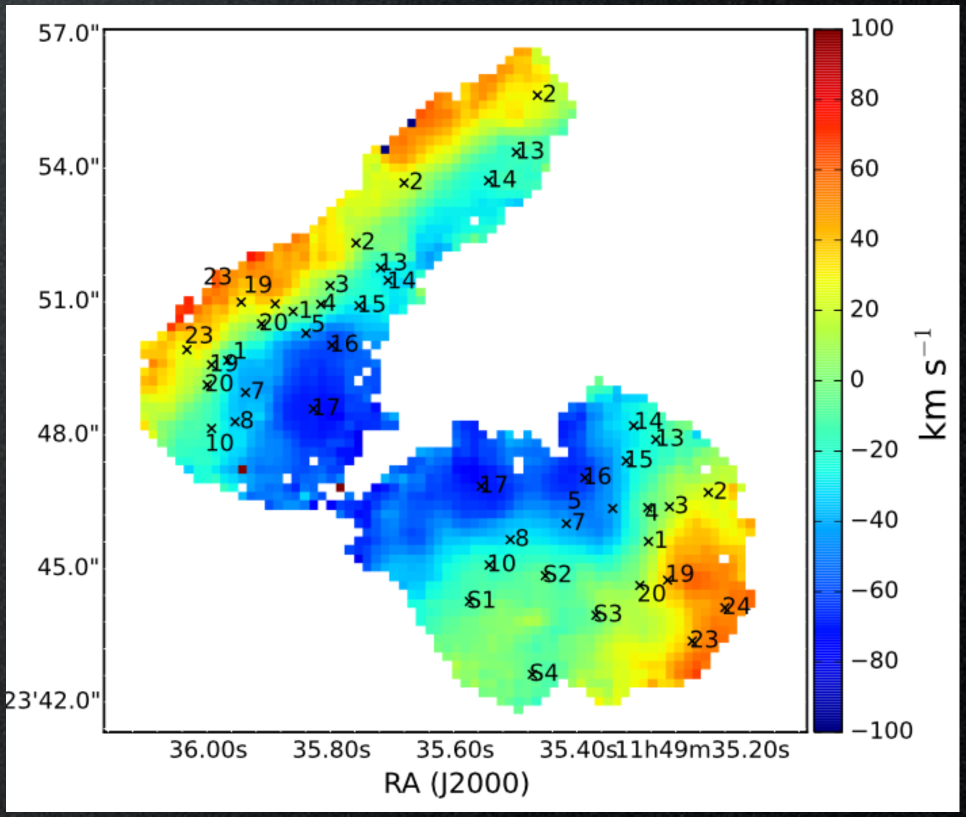
Constraining both expansion rate and geometry with SN Refsdal in MACS1149

(Grillo, Rosati, Suyu et al. 2018, ApJ, 860, 94)

Constraints: no priors from other cosmological experiments

- 89 multiple images (10 sources at z=1.2-3.7, 18 knots in Refsdal host at z=1.489)
- Time delays $S_1-S_{2,3,4}$, and S_1-S_{SX} =343±10 days (3%) (reference value, not measured yet!)
- SL model with GLEE reproduces multiple image positions with Δ_{rms} = 0.26"





MUSE kinematics map of SN host

Cosmography with cluster strong lensing

Constraining both expansion rate and geometry with SN Refsdal in MACS1149

(Grillo, Rosati, Suyu et al. 2018, ApJ, 860, 94)

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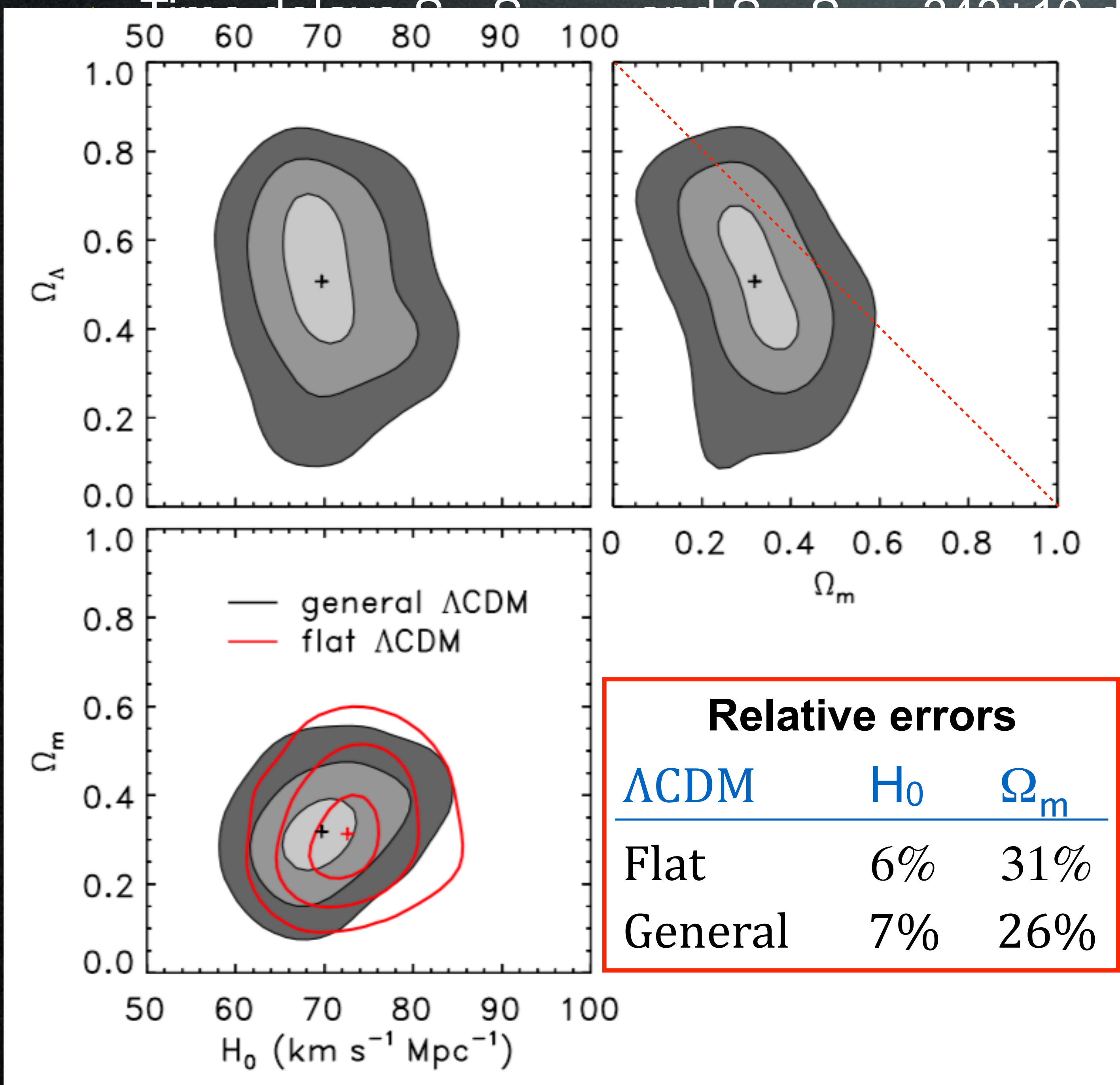
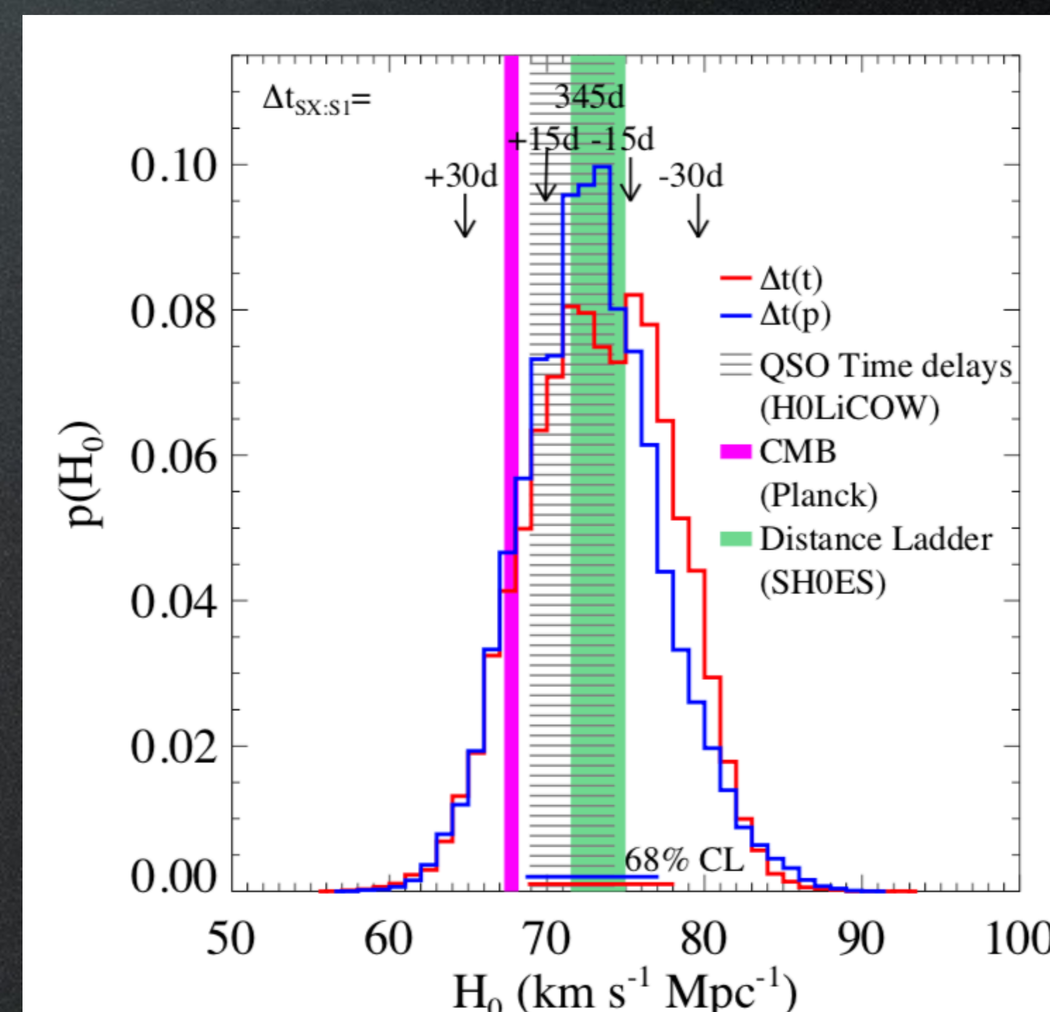


Relative errors

ΛCDM	H_0	Ω_m
Flat	6%	31%
General	7%	26%

Systematics (ρ slope, κ_{ext}): subdominant

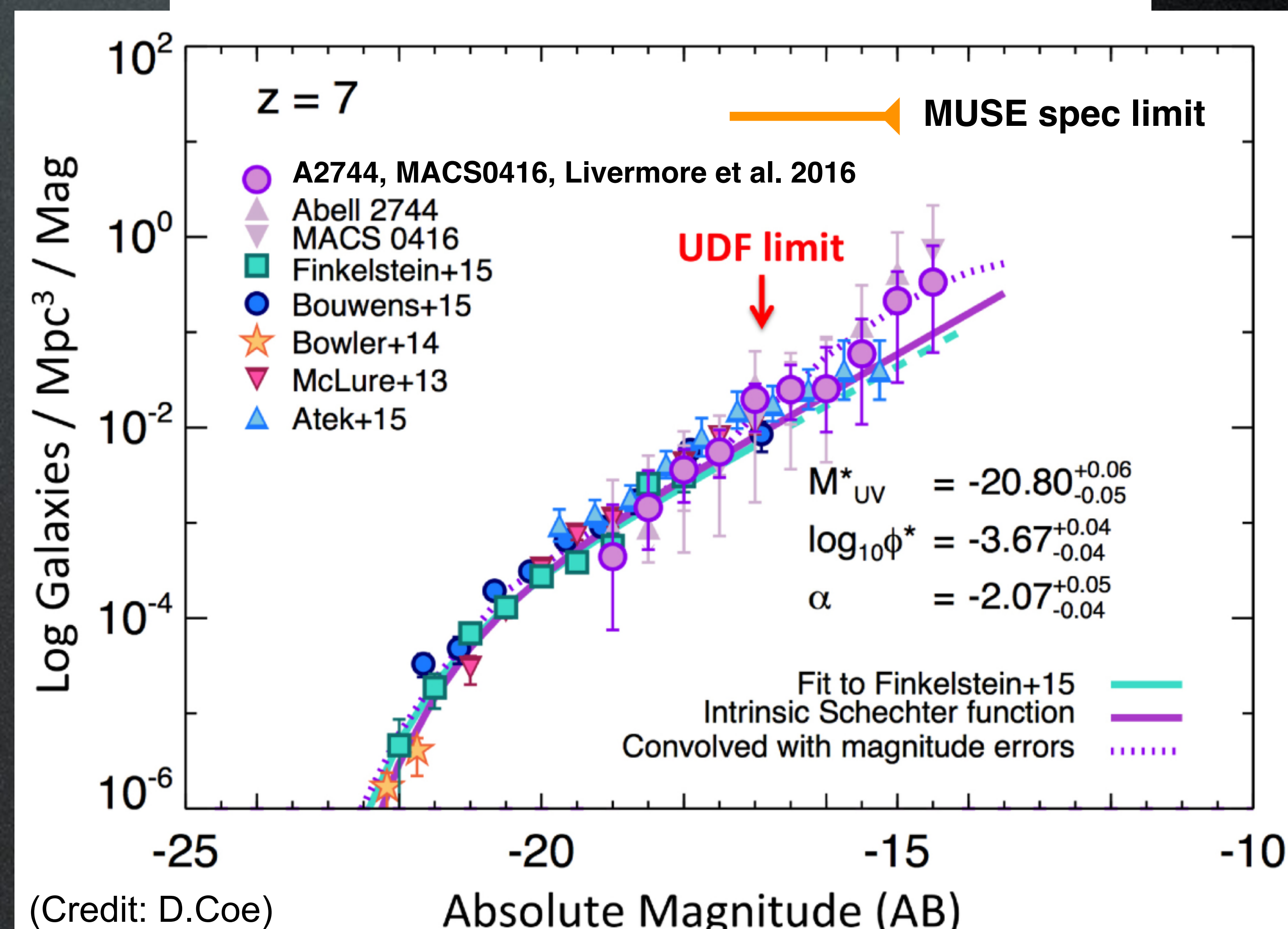


Galaxy Clusters as Cosmic Telescopes

A preview of E-ELT science

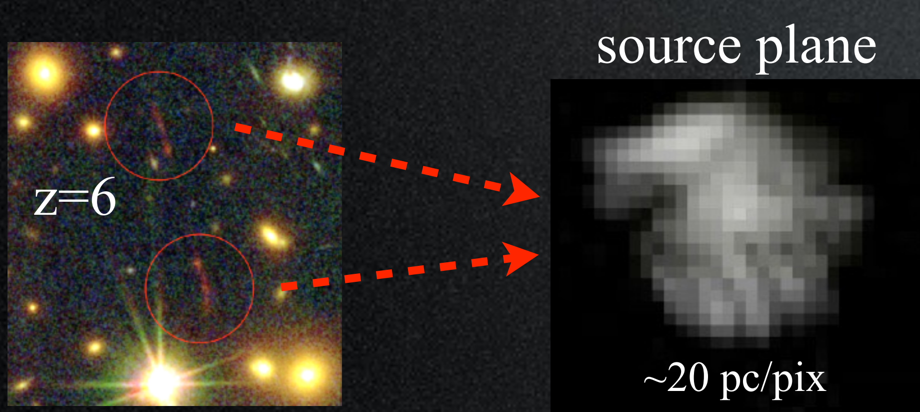
- Significant progress over last 10 years driven by coherent programs with HST
- Amplification (μ~3–100) boosts discovery efficiency for galaxies at fainter mags or/and higher redshifts, but also the volume shrinks by ~ 1/μ !
- Original skepticism on lens models…

UV Luminosity function from deep blank and lensed fields (photo-zs only)

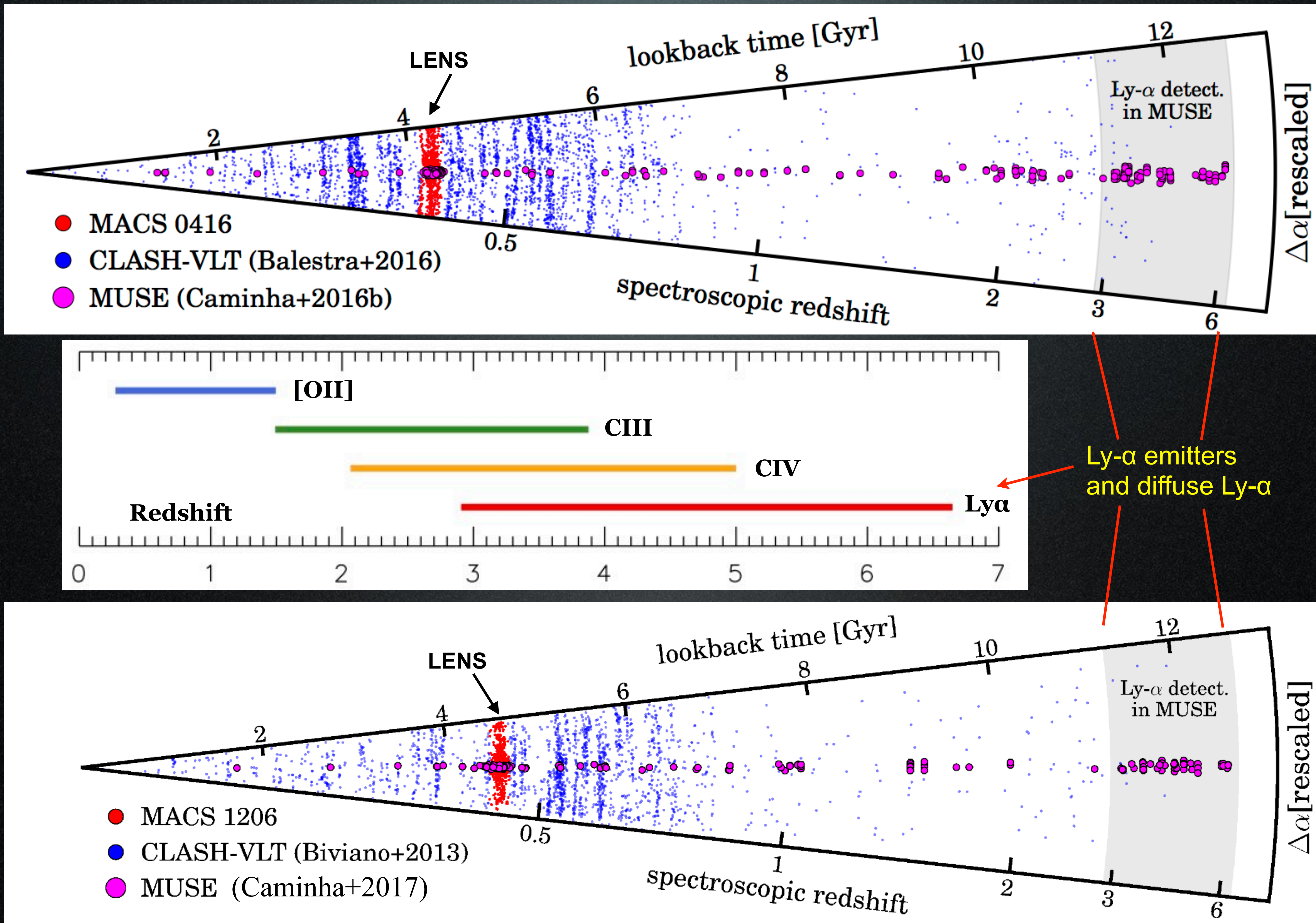


- But also magnification ! :

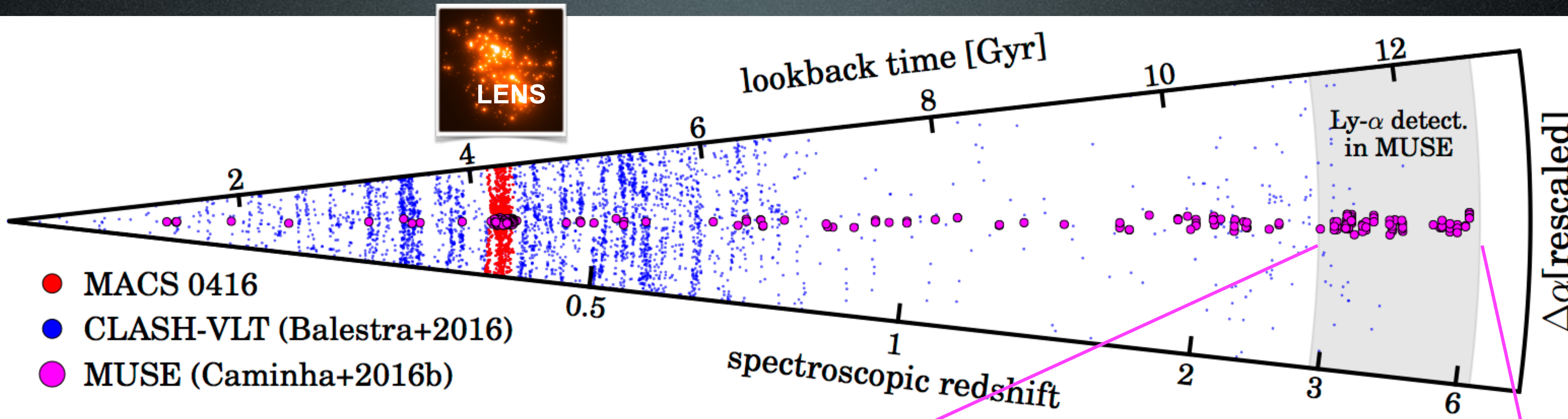
1 HST pixel (30 mas) =
17 pc (μ/10)$^{-1}$ @ z=6
23 pc (μ/10)$^{-1}$ @ z=3

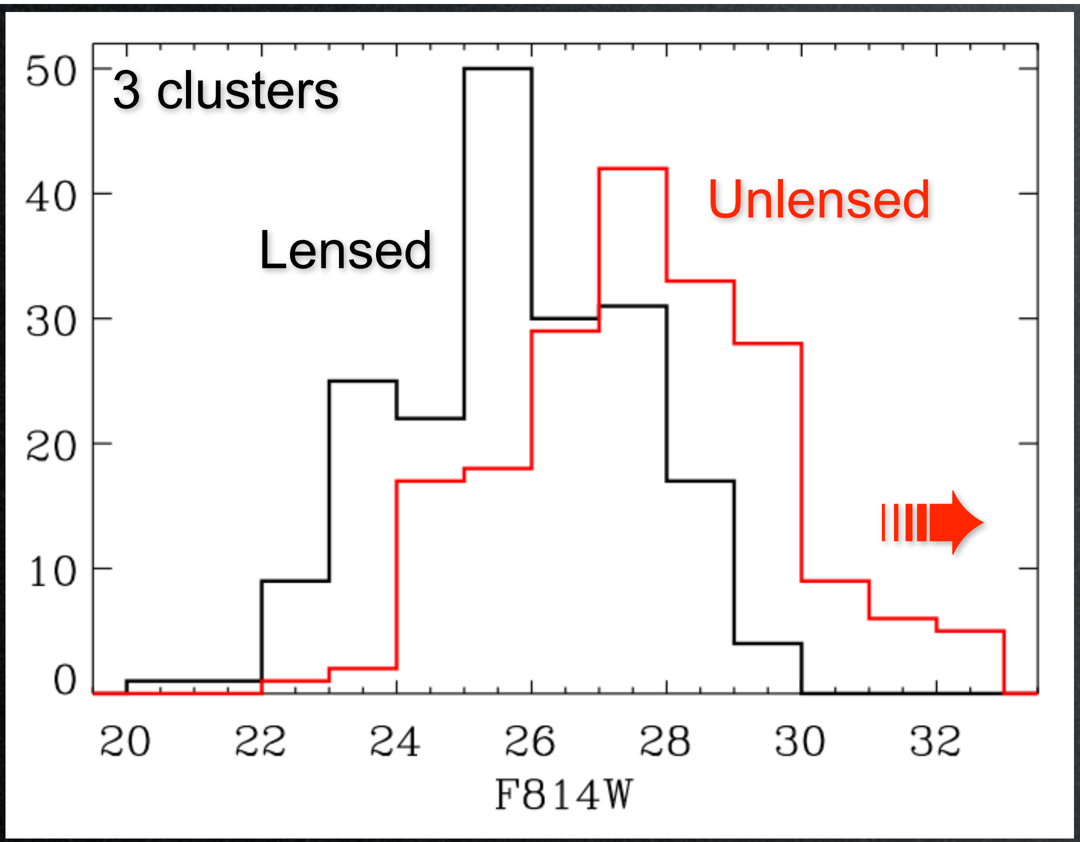


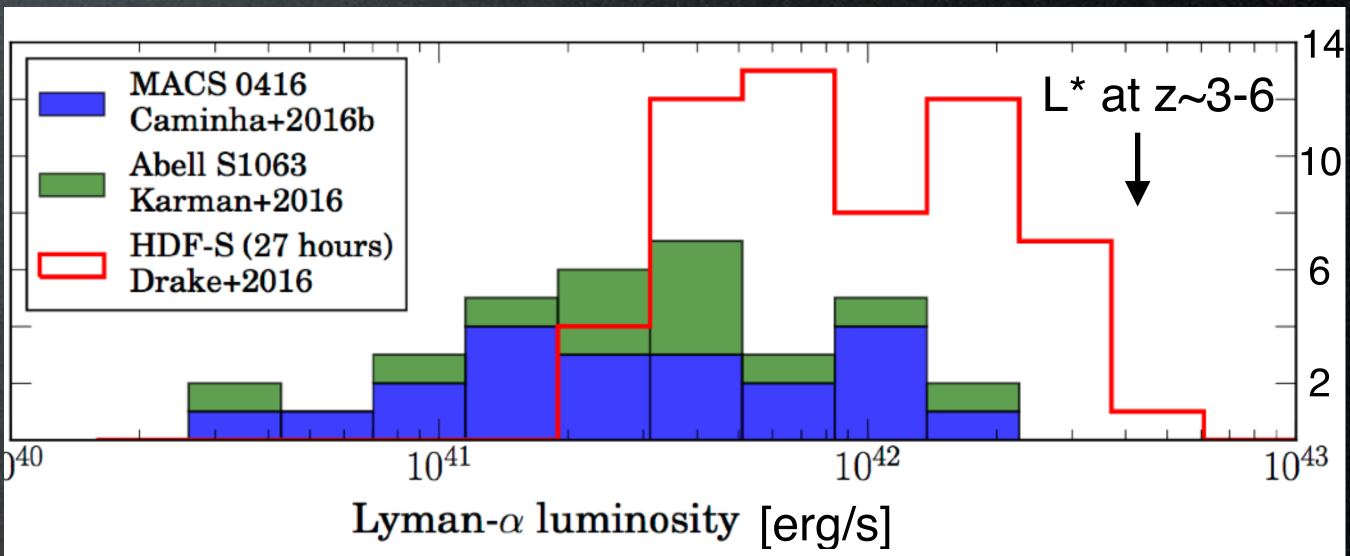
The background source population



A census of low-luminosity Ly-α emitters at z = 3–6.6 (first 2 Gyr)





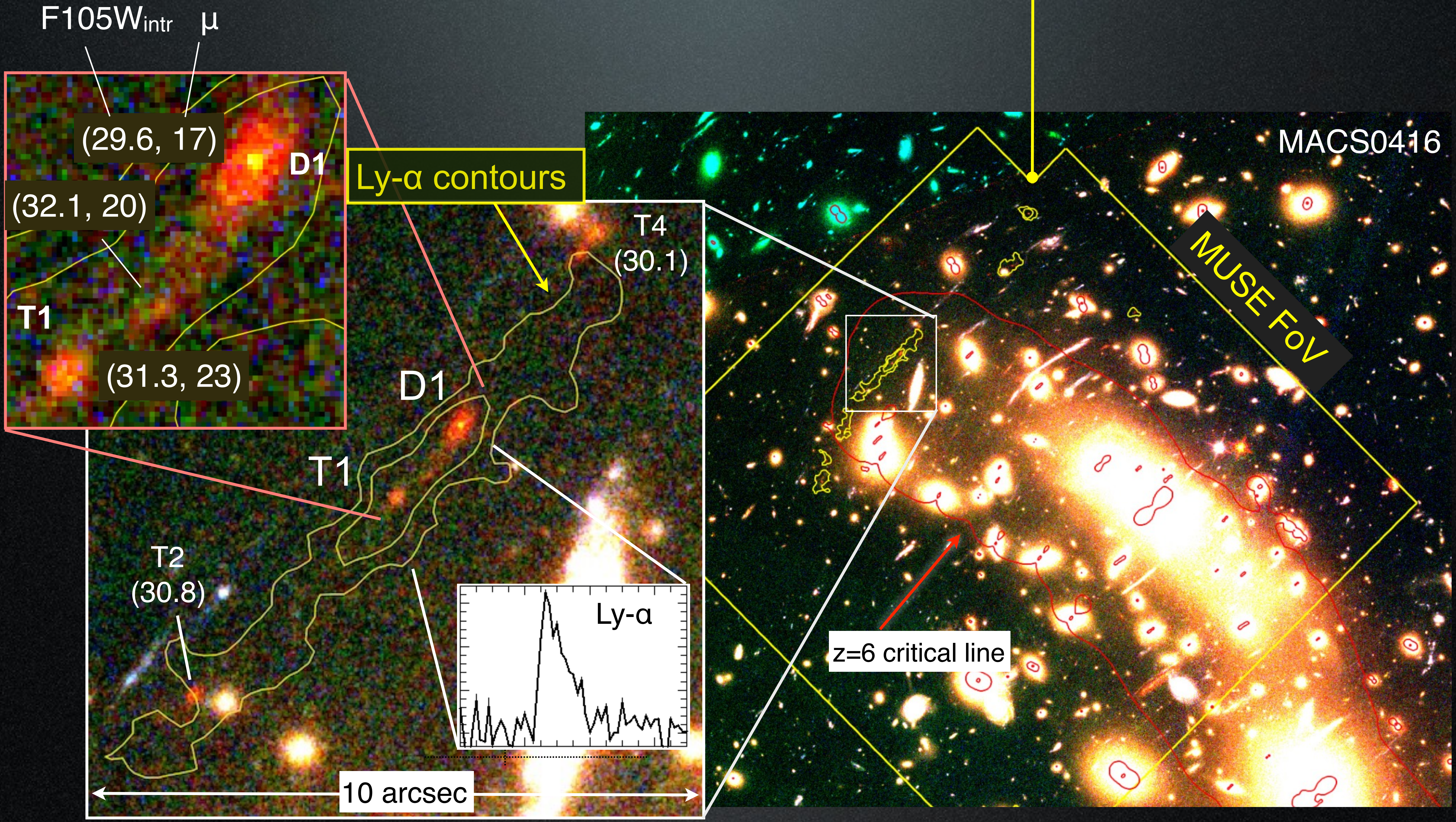


- 3 combined FF/CLASH clusters cover 6.3 arcmin² on the image plane
  ➔ ~1 arcmin² on the source plane at z~3-6 with 2 mag boost

Magnifying a star forming complex at z=6.14

(Vanzella et al. 2017b)

MUSE Deep Lensed Field (PI: Vanzella)
22 h integration, WFM-AO (only 4h to date, on-going)

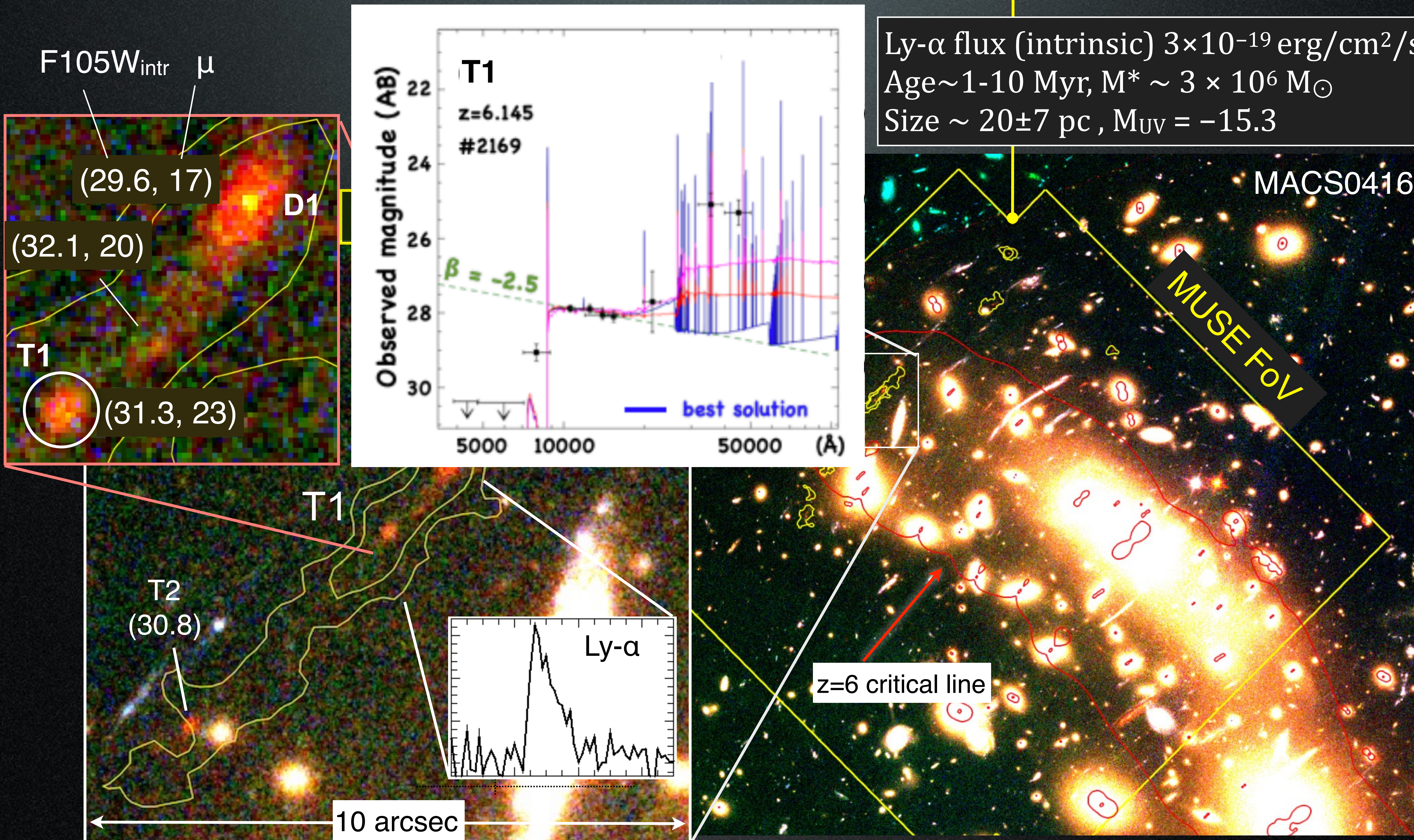


Magnifying a star forming complex at z=6.14

(Vanzella et al. 2017b)

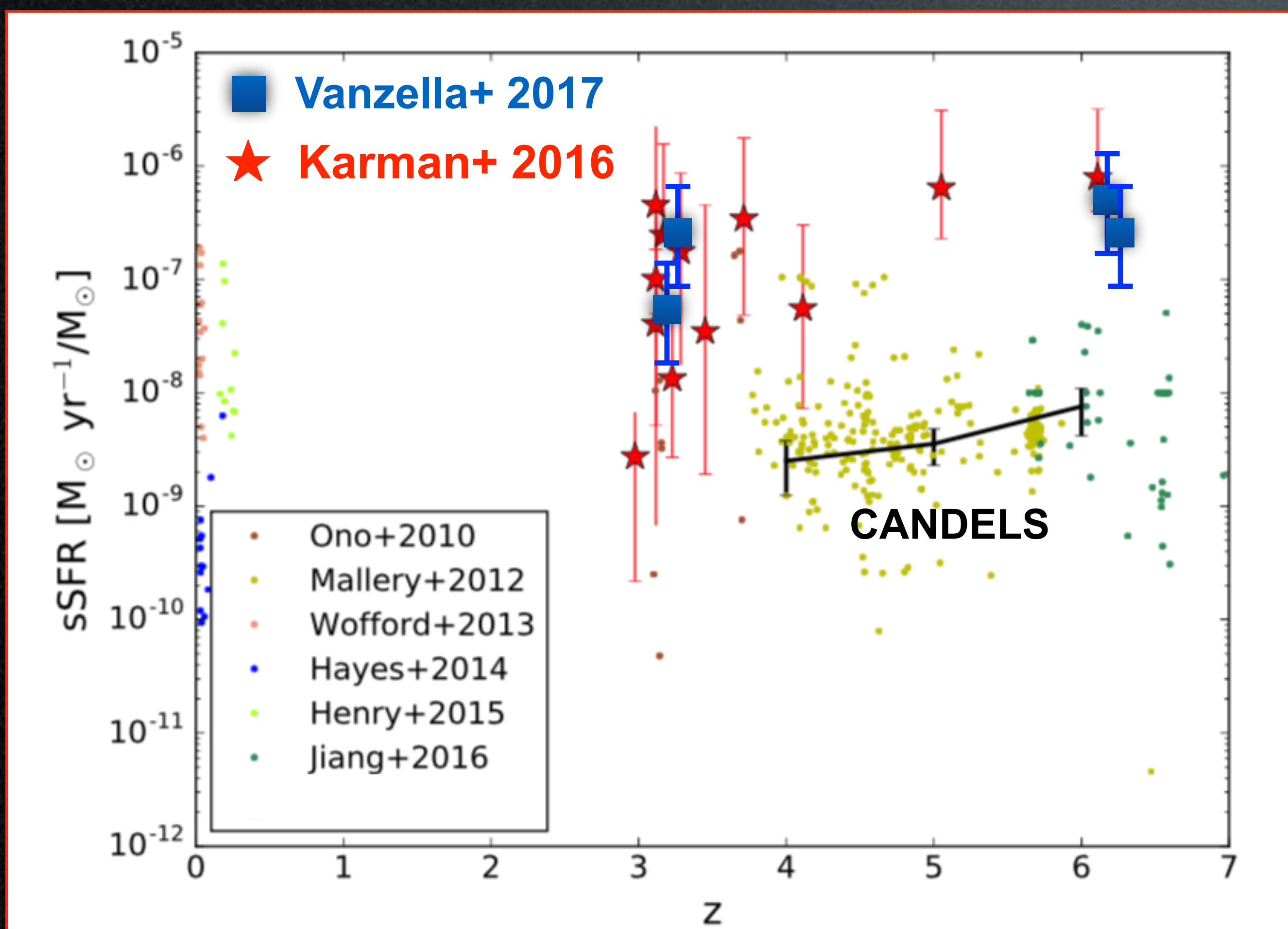
MUSE Deep Lensed Field (PI: Vanzella)
22 h integration, WFM-AO (only 4h to date, on-going)

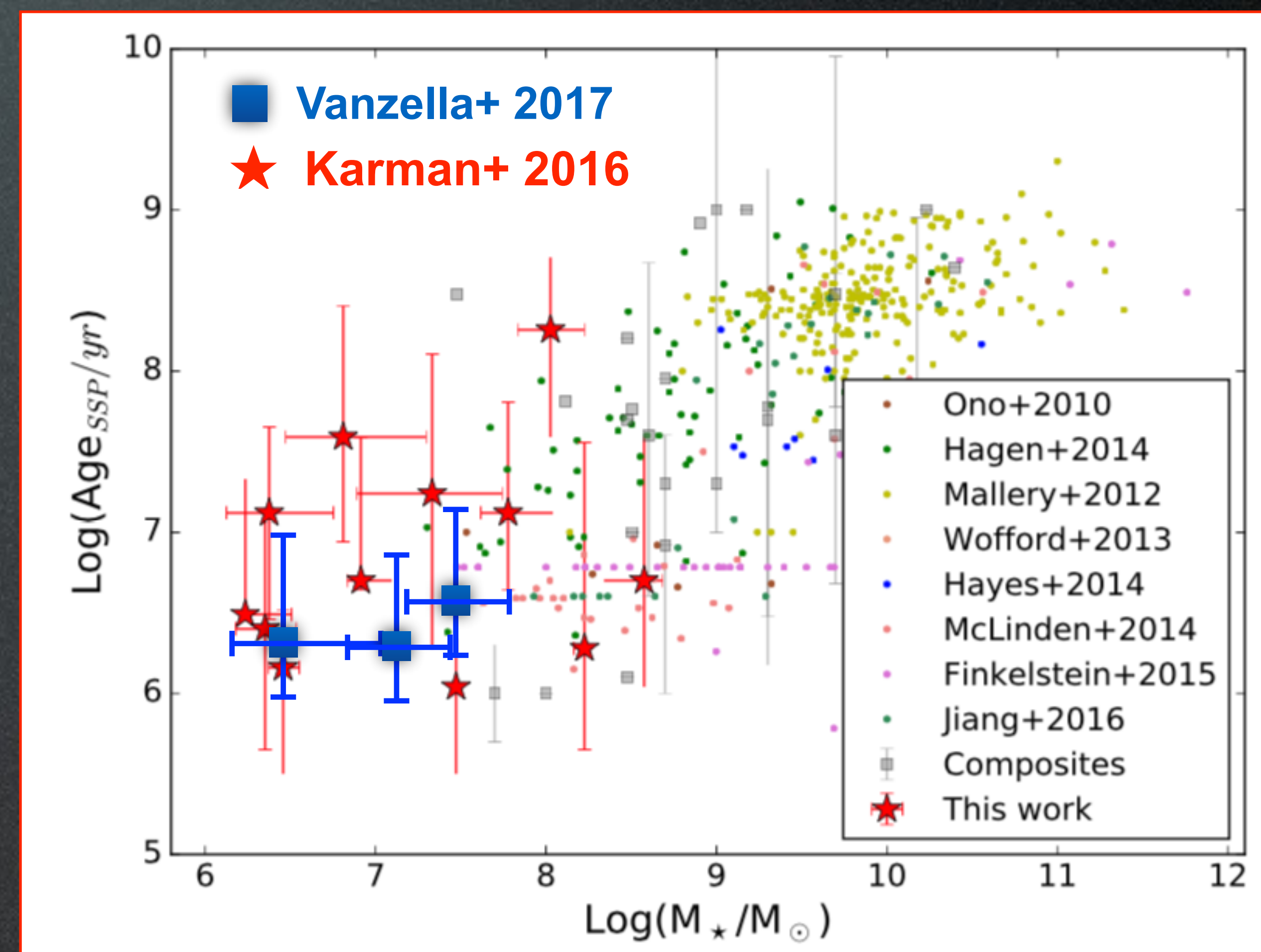
Ly-α flux (intrinsic) 3×10^{-19} erg/cm^2/s
Age~1-10 Myr, $M^* \sim 3 \times 10^6\ M_\odot$
Size ~ 20±7 pc , $M_{UV} = -15.3$



A new window on low-L, low-M "proto-galaxies" at z >3

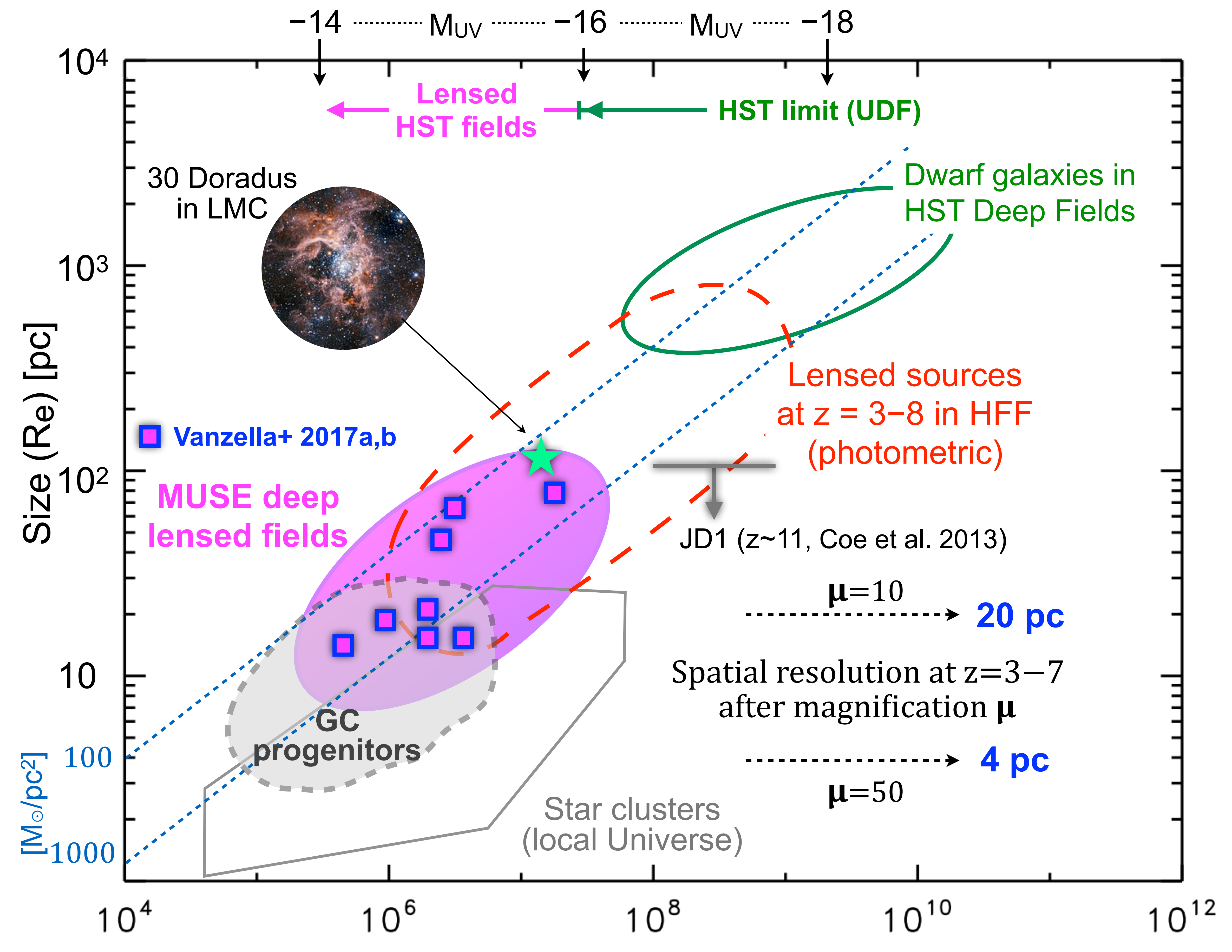
- Low-mass (10^{6-8} $M_\odot$), young galaxies (1-100 Myr), some extremely compact
- Actively star-forming (high sSFR, above the MS), i.e. rapidly increasing their mass
- low UV-continuum slopes ($\beta<-2$), low dust content
- Characterizing a population of low-mass galaxies which could be responsible for reionization (fraction of LAEs increases at lower stellar mass)



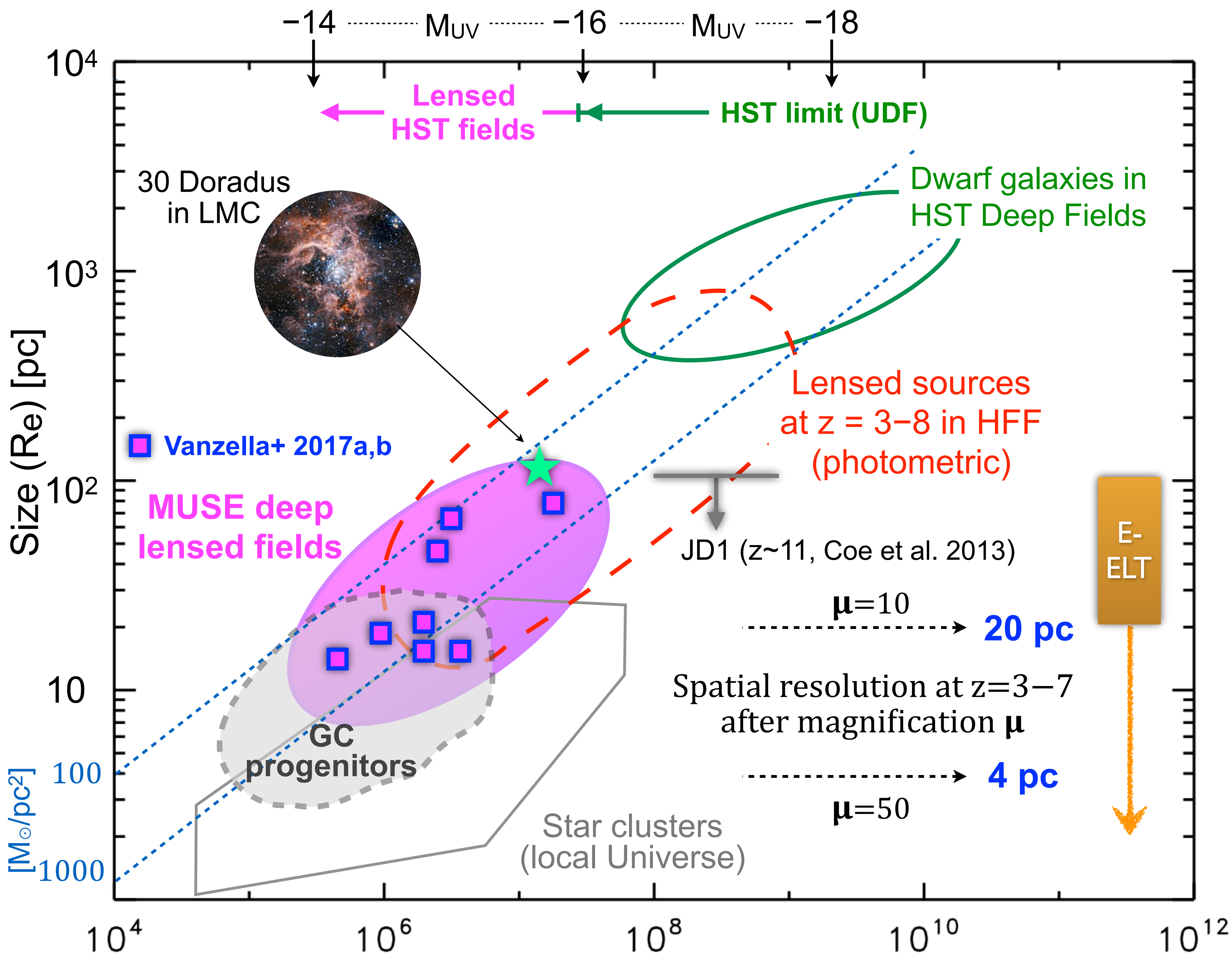


… but what's the real nature of these low-mass star forming systems ??

…consistent with physical properties of super-star clusters in local Universe, possibly globular cluster progenitors (Renzini 2017; Boylan-Kolchin 2017)



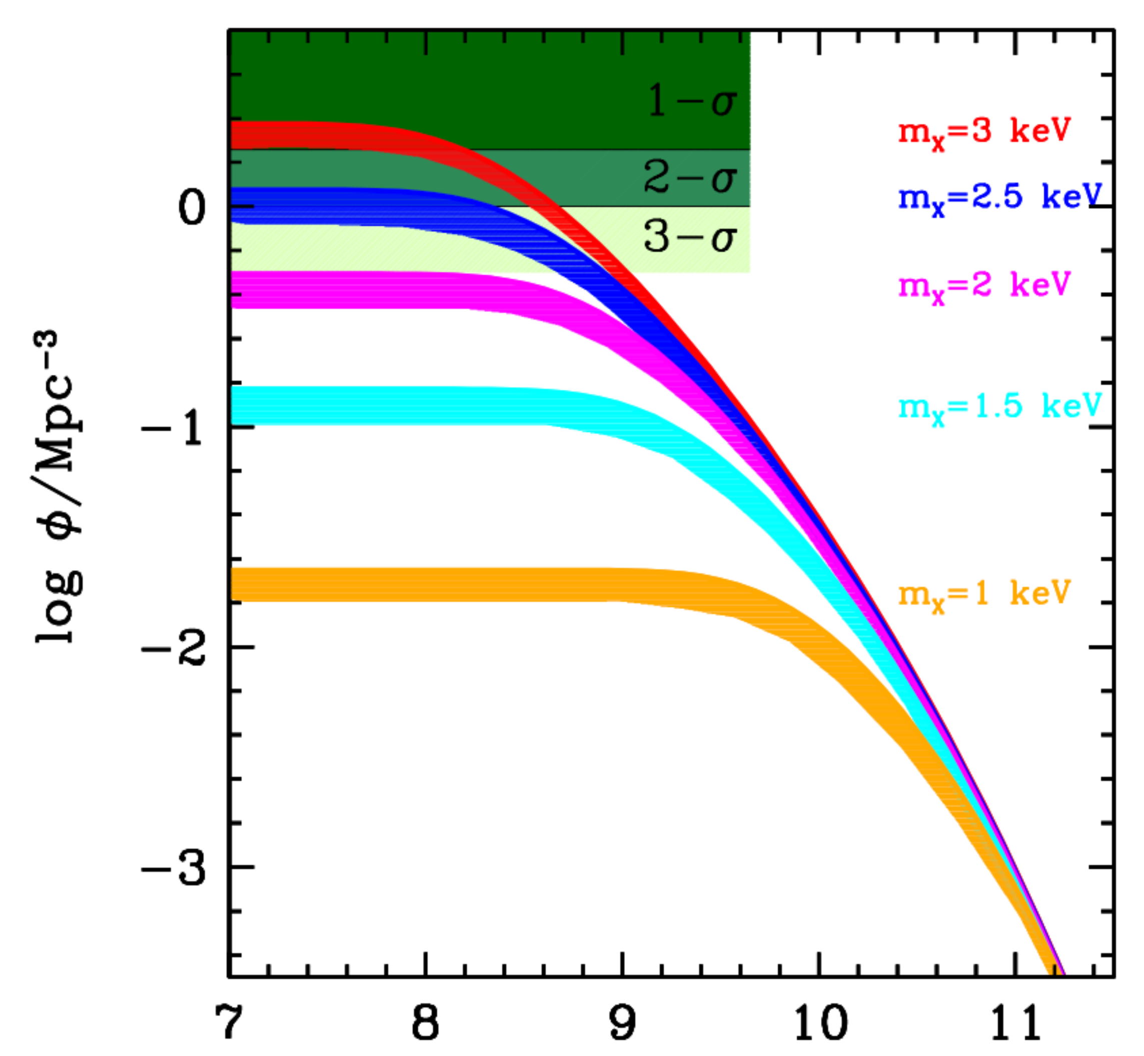
(adapted from Bouwens et al. 17)



(adapted from Bouwens et al. 17)

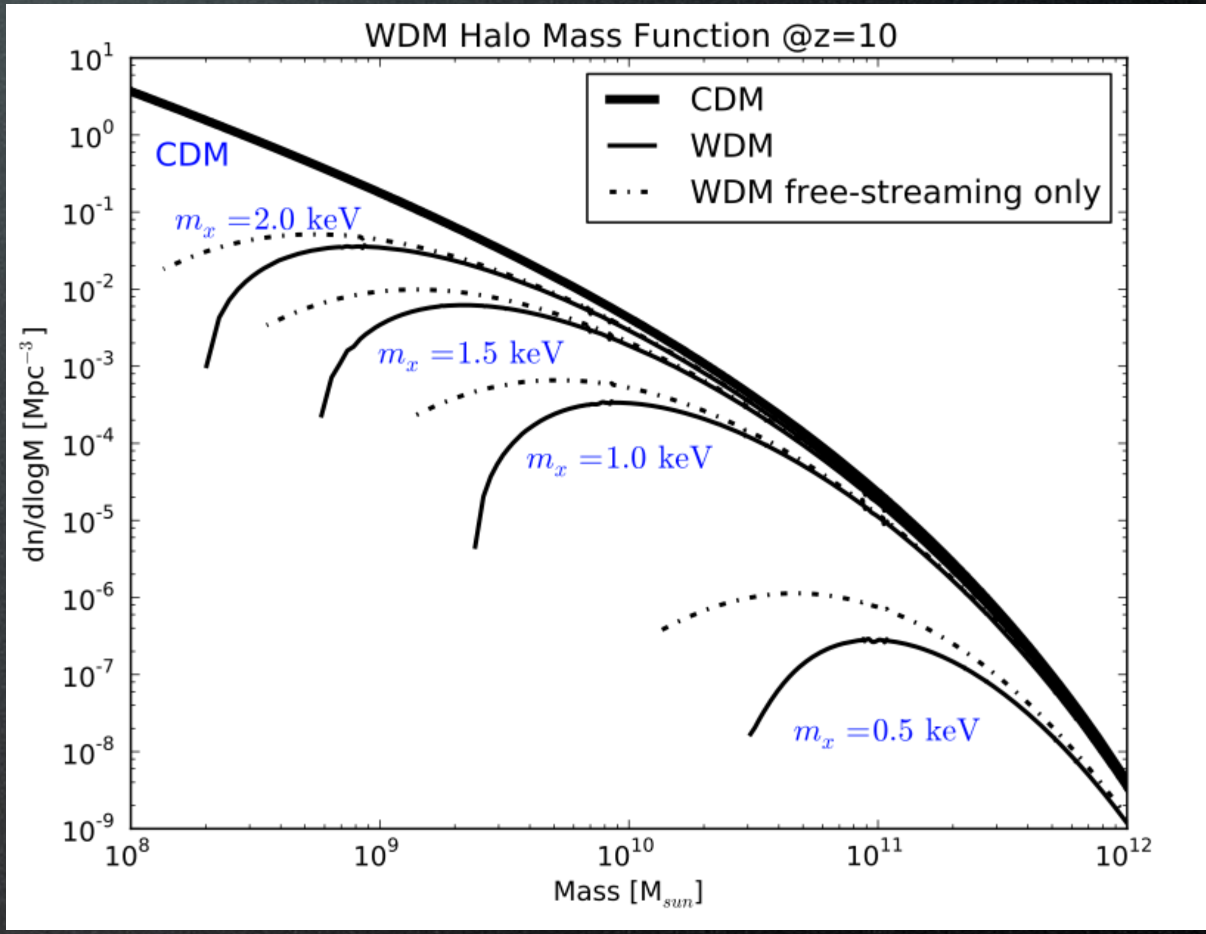
The faint end LF of high-z galaxies and WDM

- The faint end of the high-z LF gives constraints ⇒ lower limit to the number density of collapsed DM halos)
- Existence of galaxies at very high z implies ⇒ significant primordial power on small scales



Menci et al. (2016)

Pacucci et al. (2013)



➡ Mass of WDM particles > 2 keV

Summary

- HST+VLT (VIMOS+MUSE)+Chandra coordinated programs:
  ➔ detailed structure of cluster halos with independent mass probes

- Deep IFU spectroscopy critical for high-precision strong lensing models:
  ➡ overall mass density profile consistent with LCDM halo structure
  ➡ cores: tensions with LCDM predictions (flat cores? and sub-halo pop)

- Further advances will need to measure LOS effects and galaxy kinematics

- Deep IFU spectroscopy & high-precision μ-maps
  ➔ new exploration of (very) low mass/luminosity "proto-galaxies" at z=3-7
  ➔ physical parameters of 10^{6-7} $M_\odot$ SF systems on ~10 pc scales at z=3−6

- We are getting a first glimpse of the science in the era of JWST and ELTs (~500-1000 multiple images down to a few parsec scale within reach)

- New exciting prospects for cosmography with cluster lens time delay: H_0 with <5% error feasible with deep IFU spectroscopy