Kavli IPMU, 19th November 2014

# The total mass reconstruction and the inner subhalo population of the galaxy cluster MACS J0416.1-2403

Grillo C., Suyu S., Rosati P., et al., arXiv: 1407.7866

Frontier Fields Cluster MACS J0416.1-2403
Hubble Space Telescope
ACS/WFC F435W + F606W
ACS/WFC F814W + WFC3/IR F105W
WFC3/IR F125W + F140W + F160W

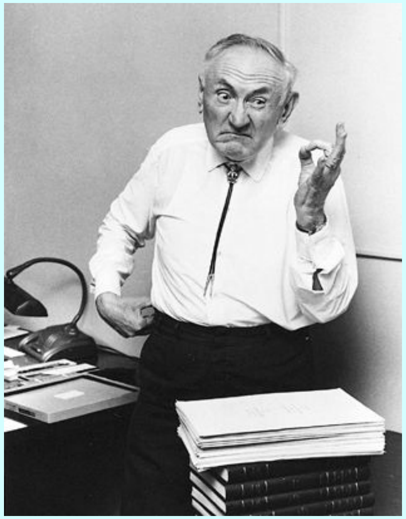
Image: Frontier Fields Science Data Products Team
(A. Koekemoer, J. Mack, J. Anderson, R. Avila, E. Barker, D. Hammer, B. Hilbert, R. Lucas, S. Ogaz, M. Robberto, and the Frontier Fields Implementation Team)

Claudio Grillo

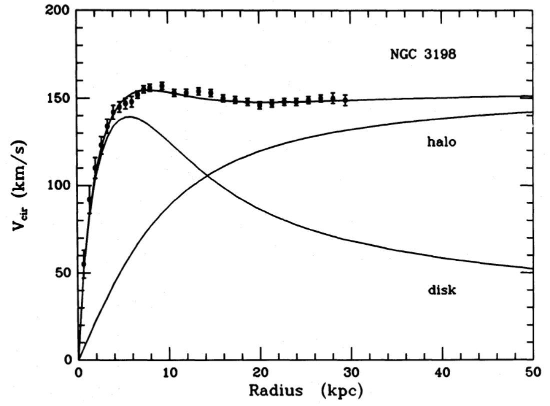
Dark Cosmology Centre

CLASH

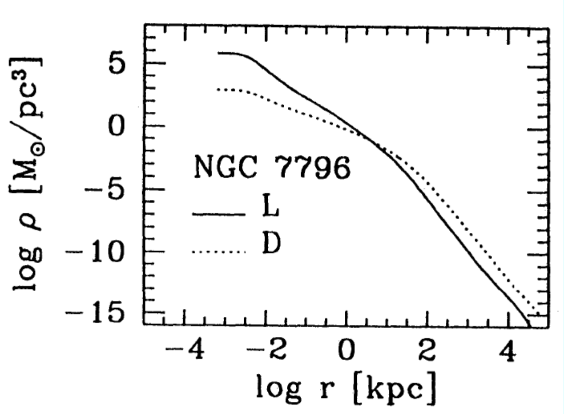
# The "problem" of Dark Matter



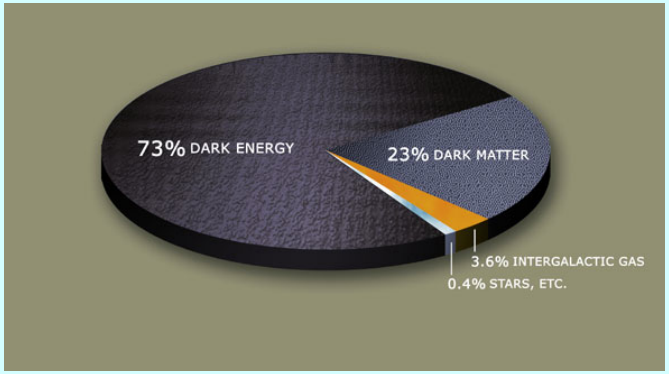
- In 1933, Fritz Zwicky finds evidence of a "dark" mass component



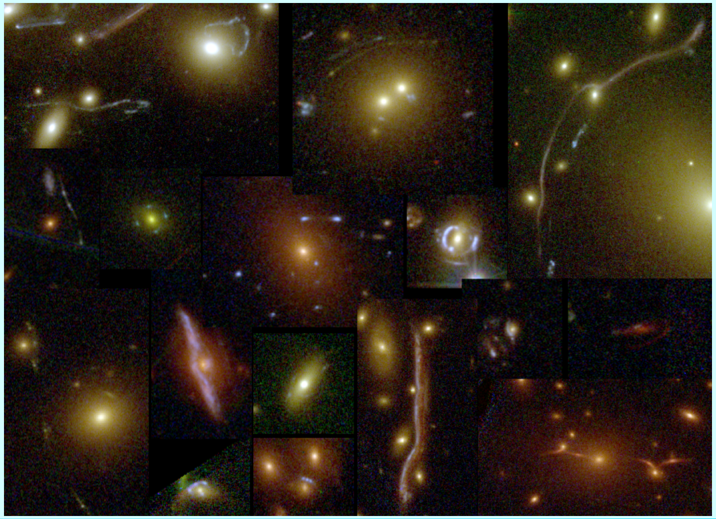

van Albada T. S. et al. 1985, ApJ, 295, 305



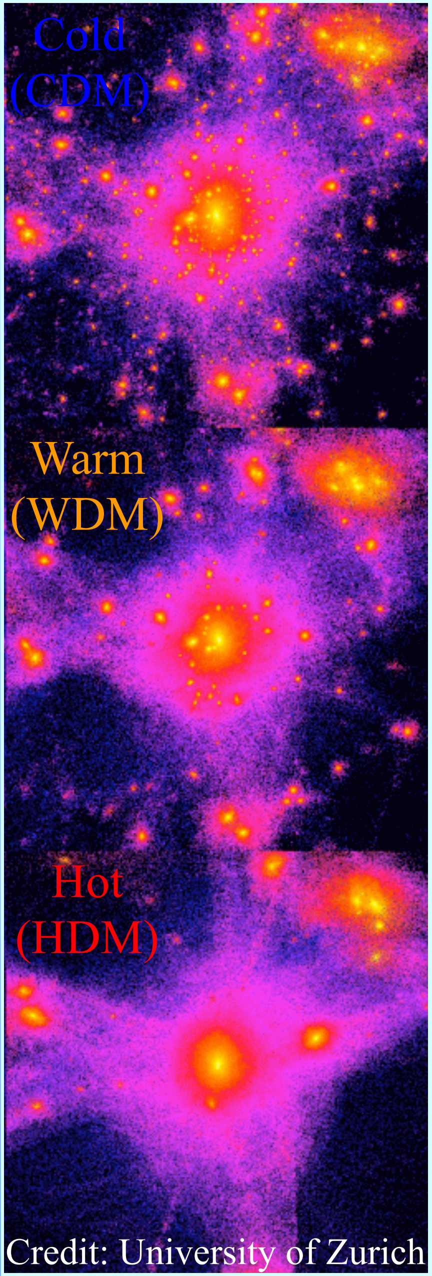

Bertin G. et al. 1994, A&A, 292, 381




- Further evidence from the rotation curves of spirals and velocity dispersion profiles of ellipticals

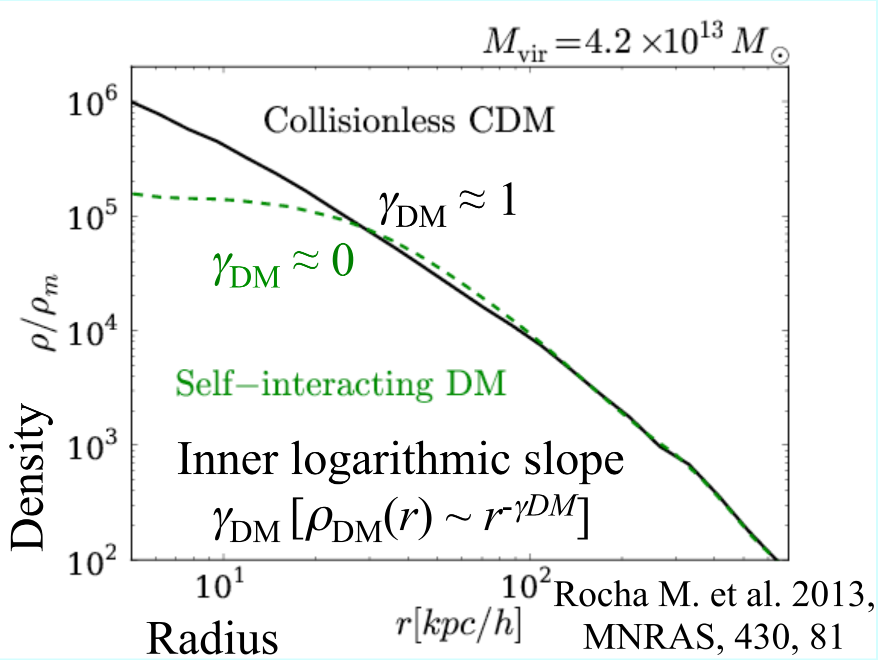


- After 80 years, the nature of the DM is still unknown
- Today, gravitational lensing is a unique tool to study DM




# Simulations vs Observations

- ✓ Cosmological simulations provide valuable information about the structure of galaxies and galaxy clusters
- ✓ CDM predicts more substructure than WDM and HDM
- ✓ Self-interacting CDM predicts rounder and less dense (in the core) haloes than collisionless CDM
- ✓ We can test these models with good observations!




Rocha M. et al. 2013, MNRAS, 430, 81

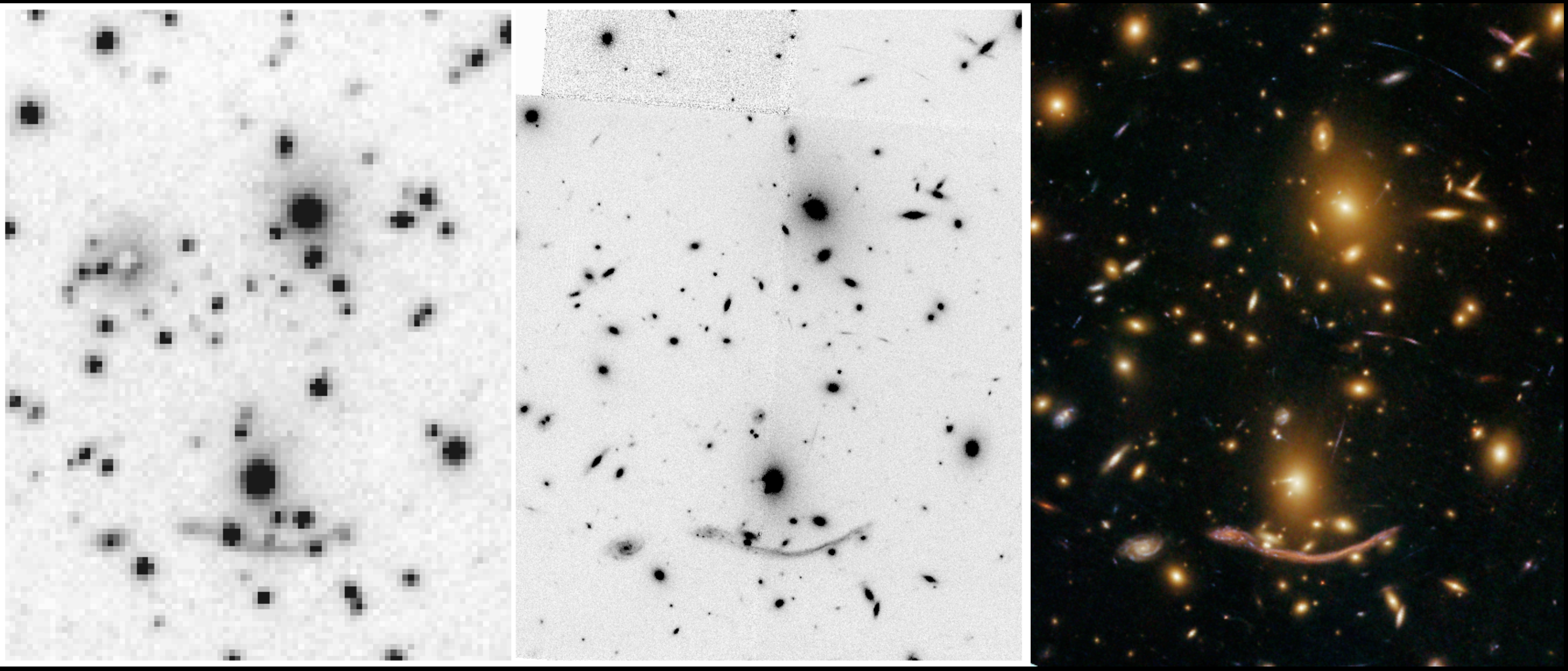
# The right time for these tests is now!

- Cosmological simulations have reached the resolution to distinguish among various DM models

- Present observations contain exquisite details to perform accurate strong lensing modelling

Abell 370

CFHT in 1985 | HST in 1995 | HST in 2009



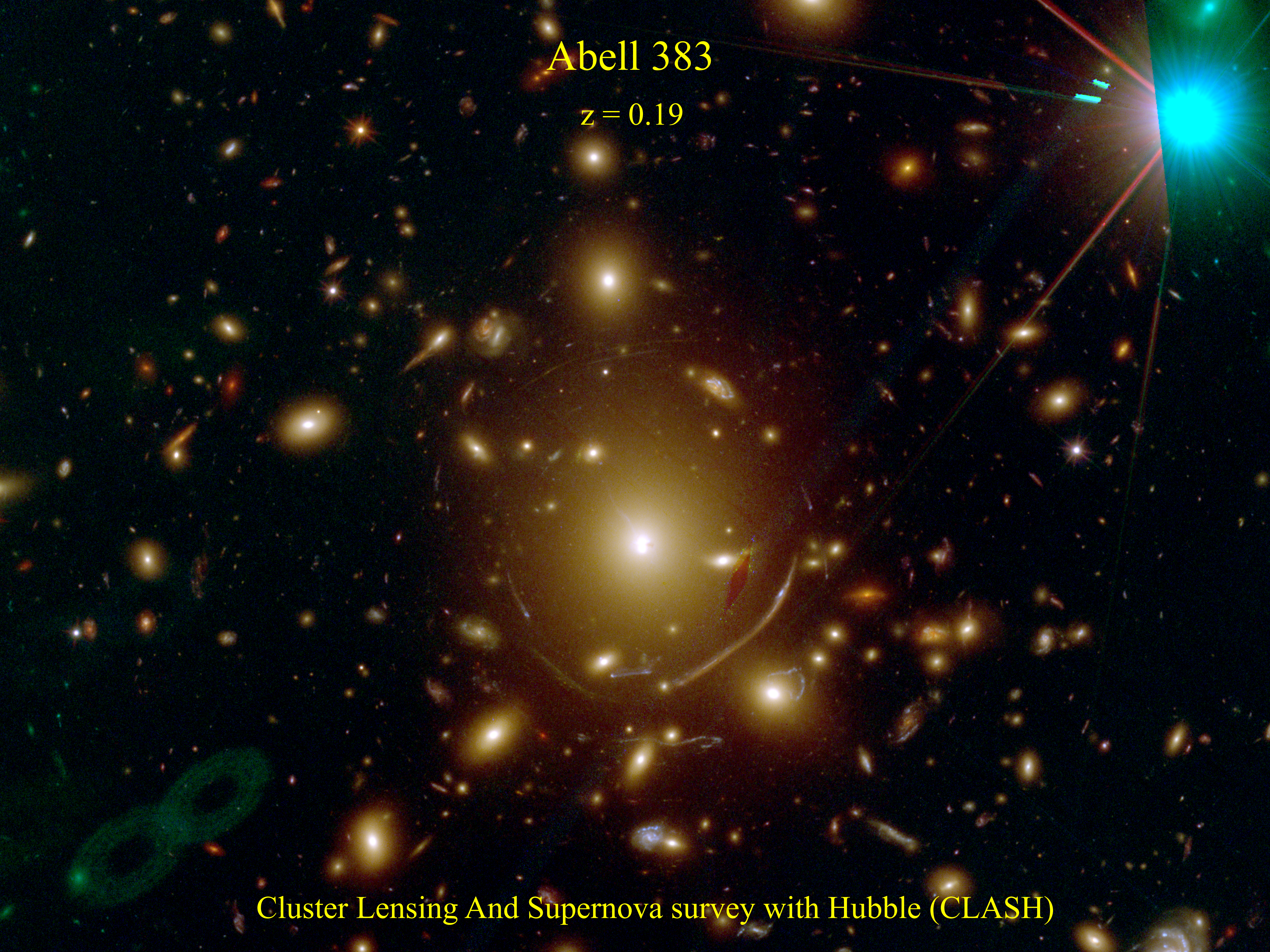
# CLASH and CLASH-VLT

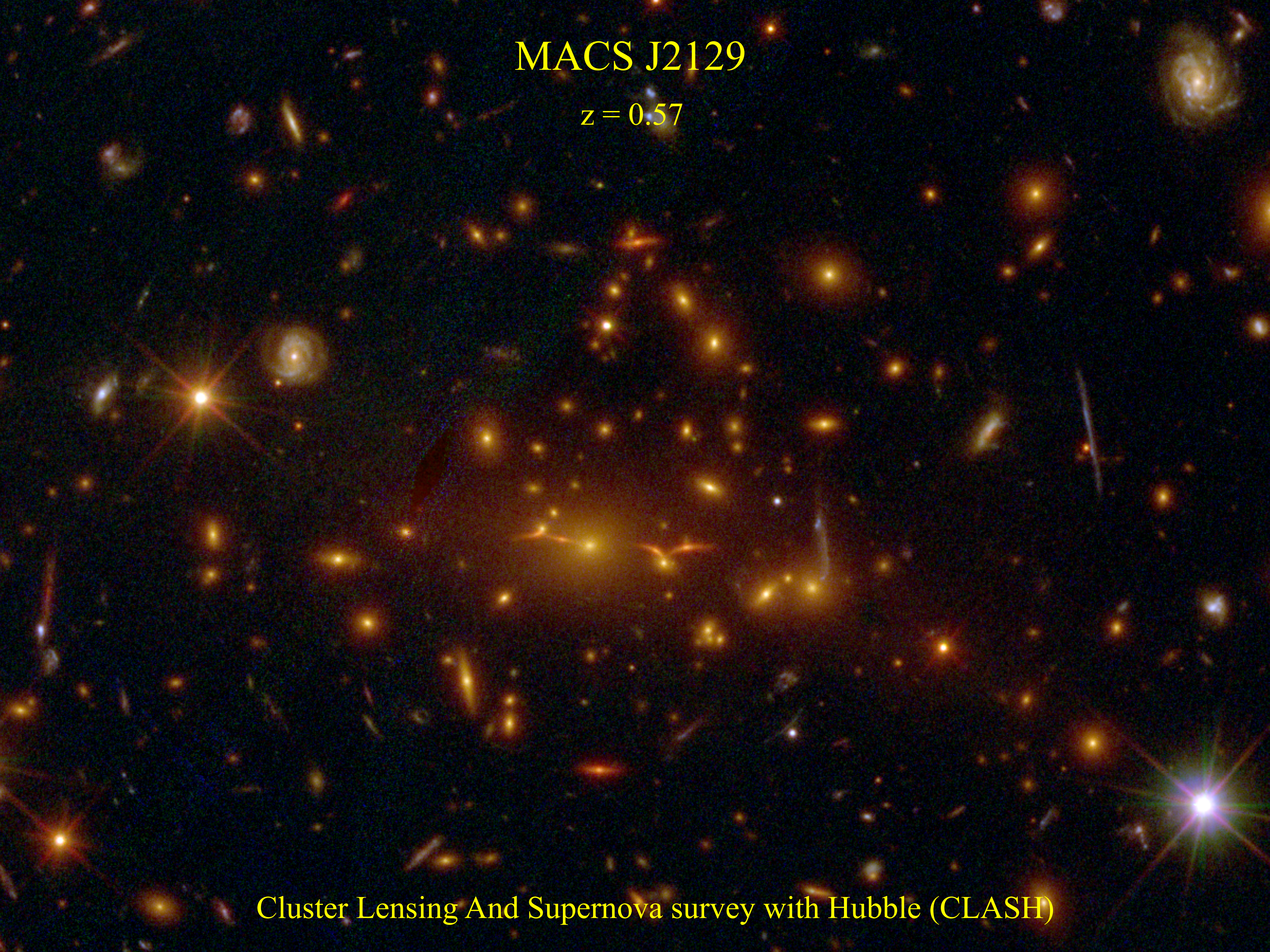
Cluster Lensing And Supernova survey with Hubble

- ✧ 524-orbit HST Multi-Cycle Treasury Program – PI: M. Postman
- ✧ 25 massive intermediate-z galaxy clusters observed with 16 (ACS+WFC3) broadband filters
- ✧ Study DM mass profiles and substructures with unprecedented precision and resolution
- ✧ Detect some of the most distant (z>7) galaxies through the gravitational telescope effect
- ✧ Find in parallel fields new Type Ia supernovae out to redshift z~2.5

- ✧ 200-hr (95% completed to date) VLT/VIMOS Large Program – PI: P. Rosati

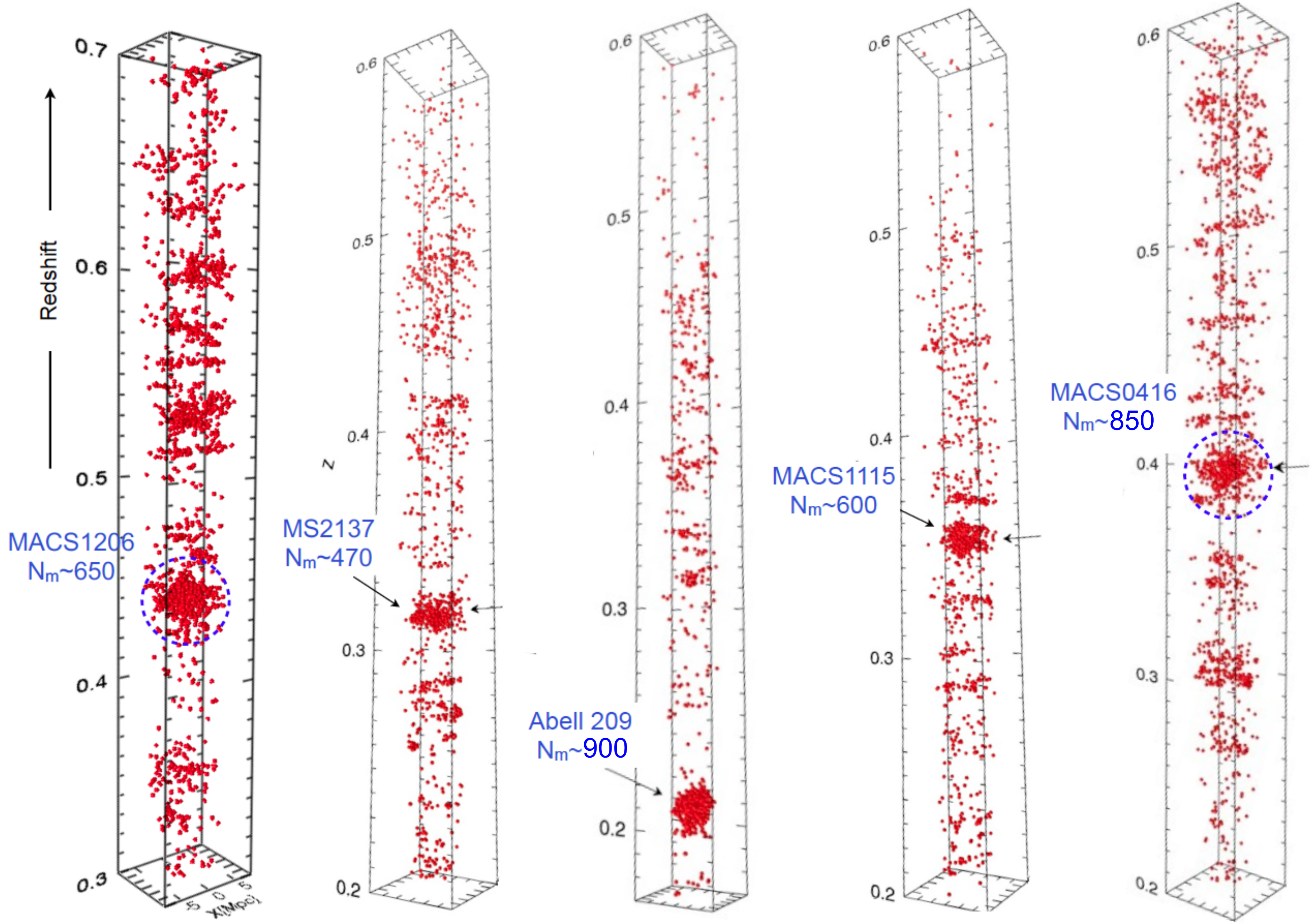
- ✧ Spectroscopic follow-up of the 14 southern CLASH galaxy clusters
- ✧ Spectroscopic confirmation of the multiple-image systems
- ✧ Dynamical study beyond $R_{vir}$ with ~ 500 members per cluster
- ✧ Galaxy formation and evolution analyses of lens and lensed galaxies


Abell 383
z = 0.19
Cluster Lensing And Supernova survey with Hubble (CLASH)

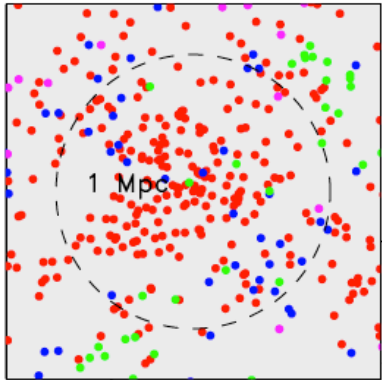

MACS J2129
z = 0.57
Cluster Lensing And Supernova survey with Hubble (CLASH)

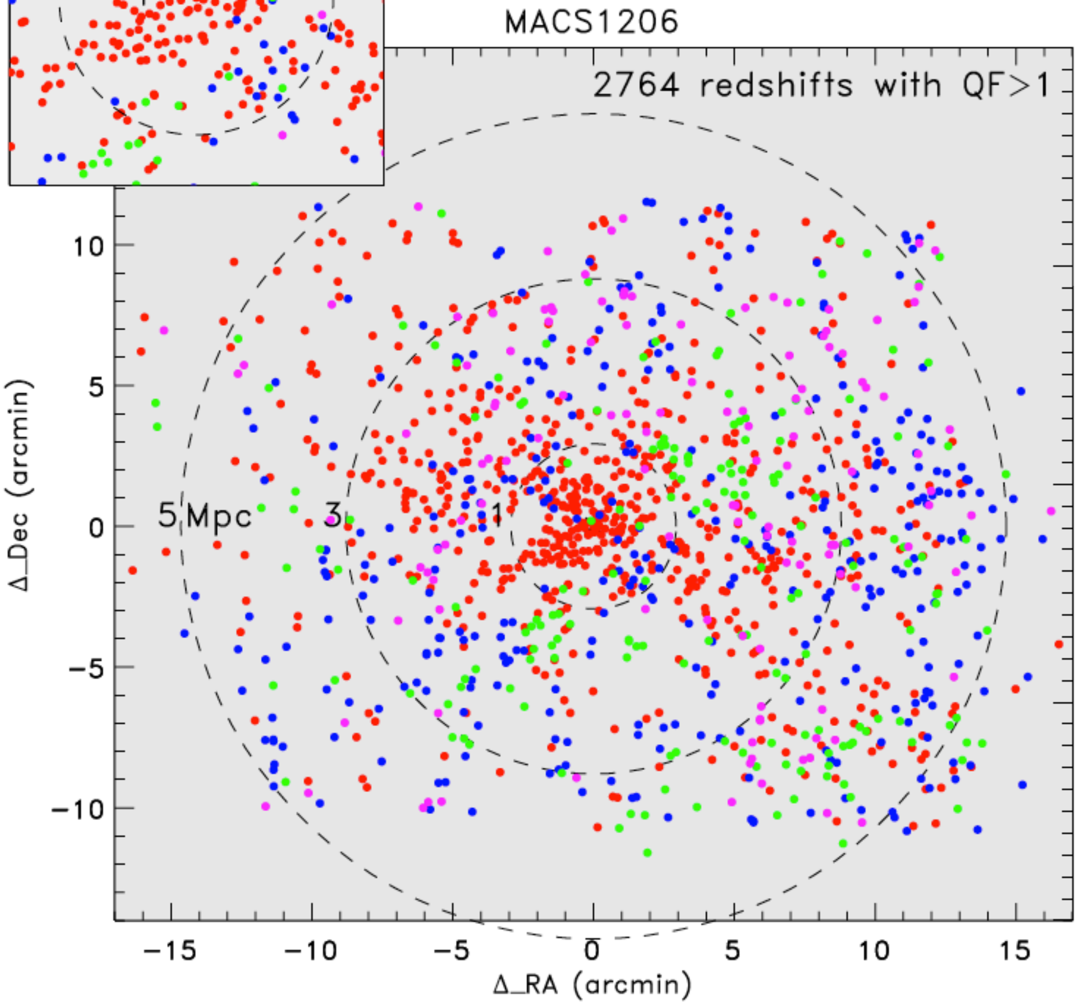

MACS J1206
z = 0.44
Cluster Lensing And Supernova survey with Hubble (CLASH)

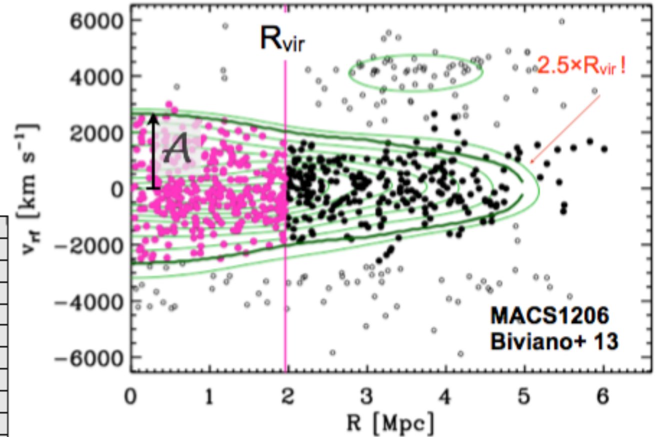
# CLASH-VLT will deliver ~30000 redshifts
# (≳6000 of which cluster members, ~300 lensed galaxies to z~7)

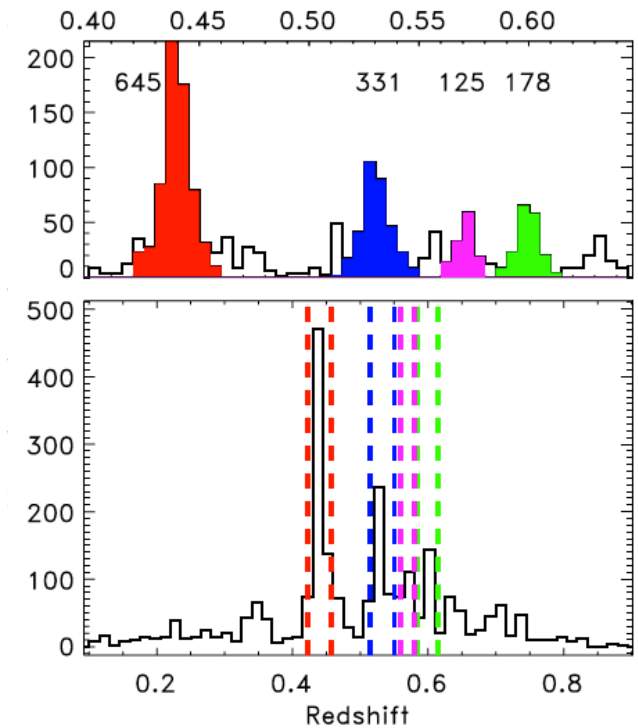


# MACS J1206.2-0847



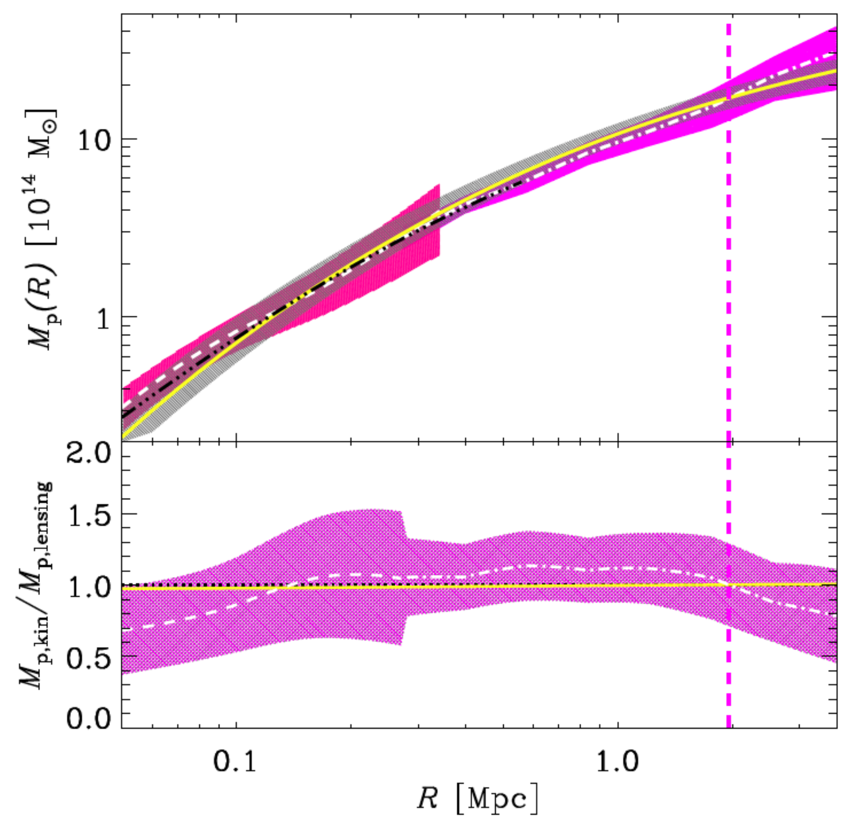




with P. Rosati, M. Nonino, I. Balestra, A. Mercurio,…

# The dynamical analysis of MACS J1206.2-0847




Biviano A. et al. 2013, A&A, 558, 1

✧ Study of the mass, velocity-anisotropy, and pseudo-phase-space density profiles

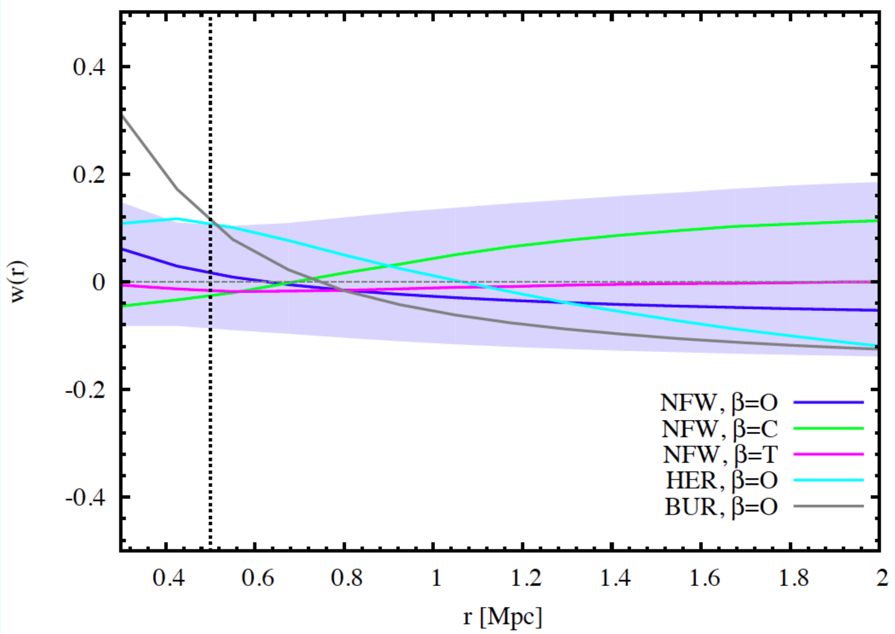
✧ $M_{200} = (1.4\pm0.2) \times 10^{15}\ M_\odot$

✧ $c_{200} = 6\pm1$

✧ Kinematics and lensing total mass determinations in excellent agreement

✧ The comparison of different total mass diagnostics allows the determination of the EoS parameter of the cluster fluid

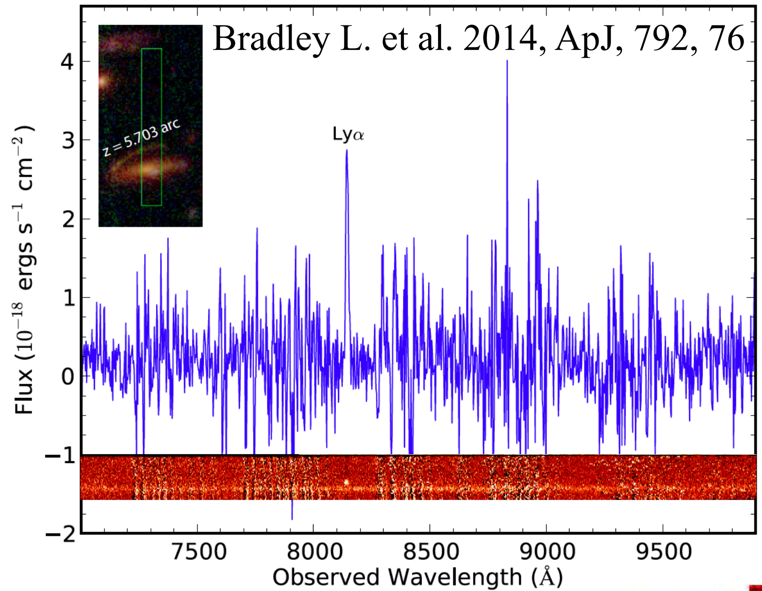
✧ $w = (p_r + 2p_t) / (3\ c^2\ \rho) =$
$0.00 \pm 0.15$ (stat.) $\pm 0.08$ (syst.)

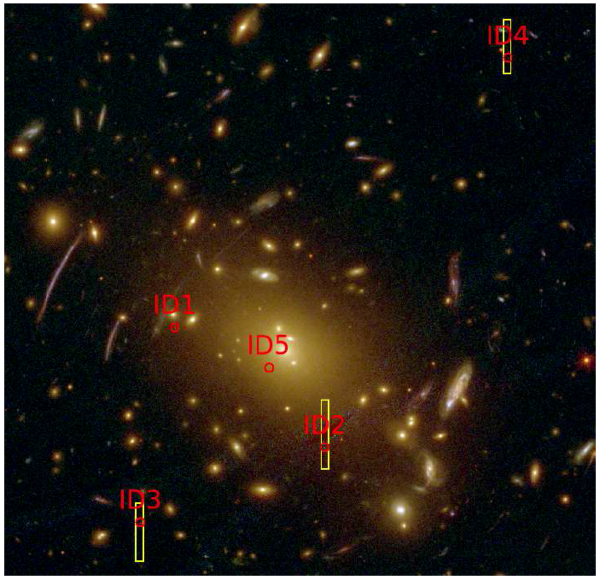



Sartoris B. et al. 2014, ApJ, 783, 11

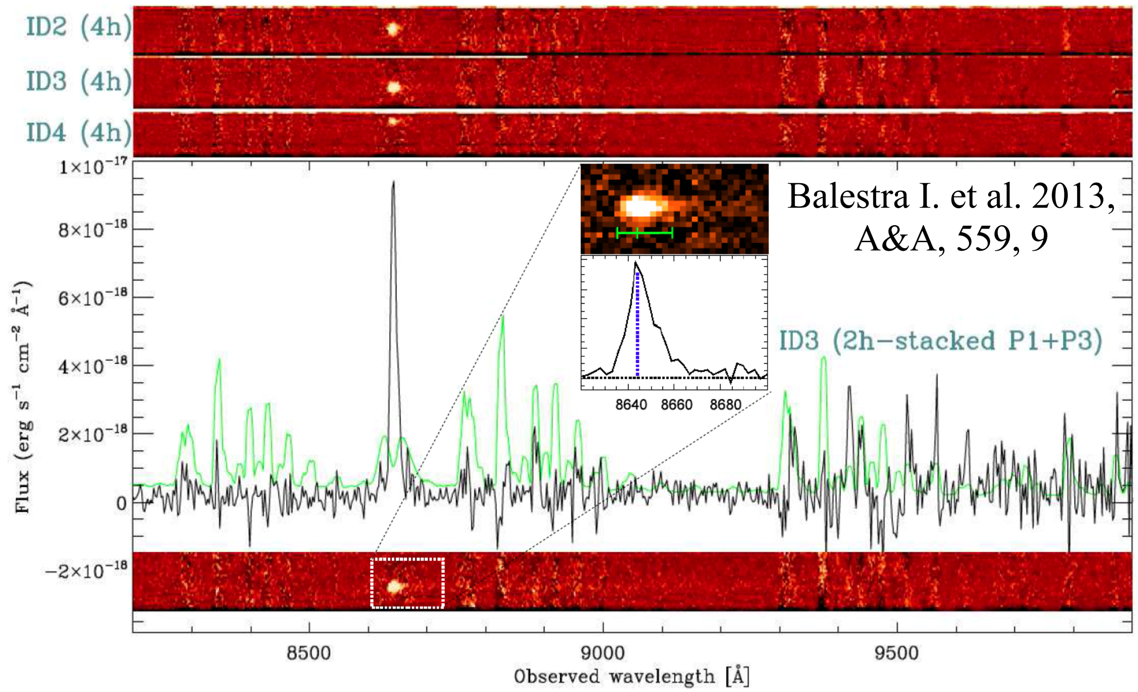
# Spectroscopic high-z sources

- A young, compact, sub-L* galaxy at z=6.11 ($T_U$=1 Gyr) imaged 5 times
- UV continuum detection of an unlensed ~27$^{th}$ mag galaxy in only 1 hr!
- $L_{1600} \approx 0.4\ L^*_{1600}$
- EW(Ly$\alpha$) = 79±10 Å
- SFR(Ly$\alpha$) = 11 $M_\odot$/yr
- $R_e < 0.4$ kpc
- $M_* \approx 10^8\ M_\odot$
- age < 300 Myr

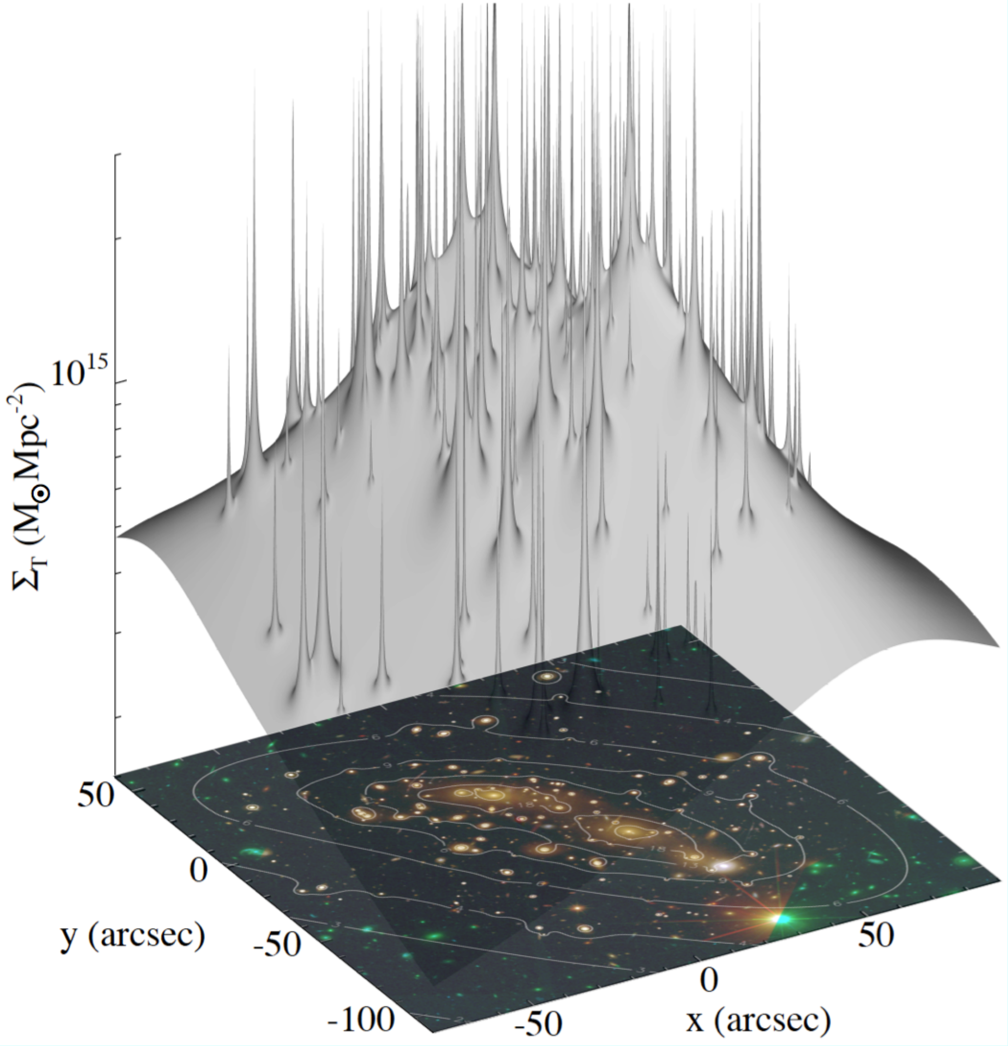



Monna A. et al. 2014, MNRAS, 438, 1417

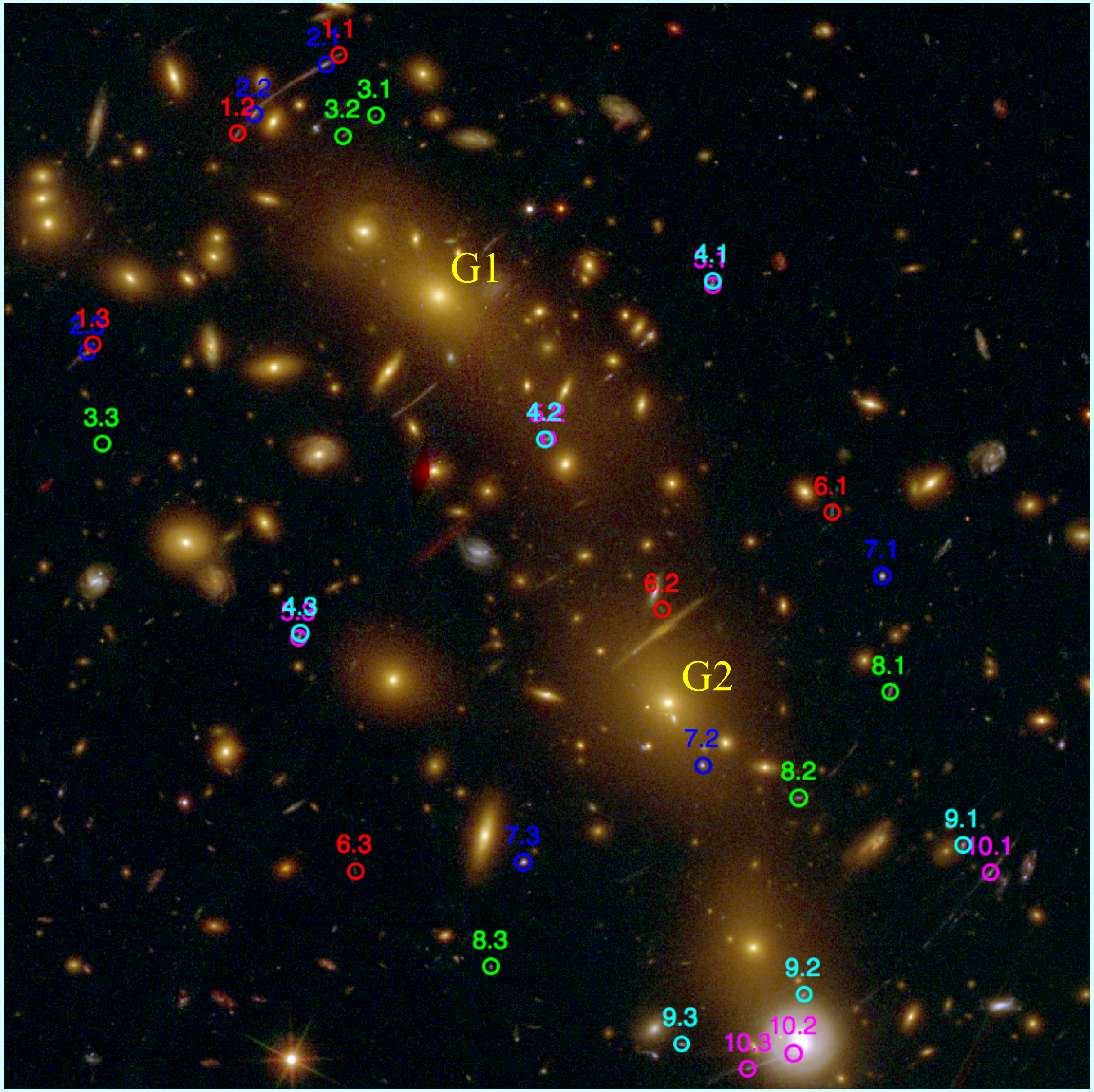


# Refined strong lensing studies in the CLASH galaxy clusters




(Grillo, Suyu, Rosati, et al., arXiv: 1407.7866)

# The multiple image systems of MACS 0416

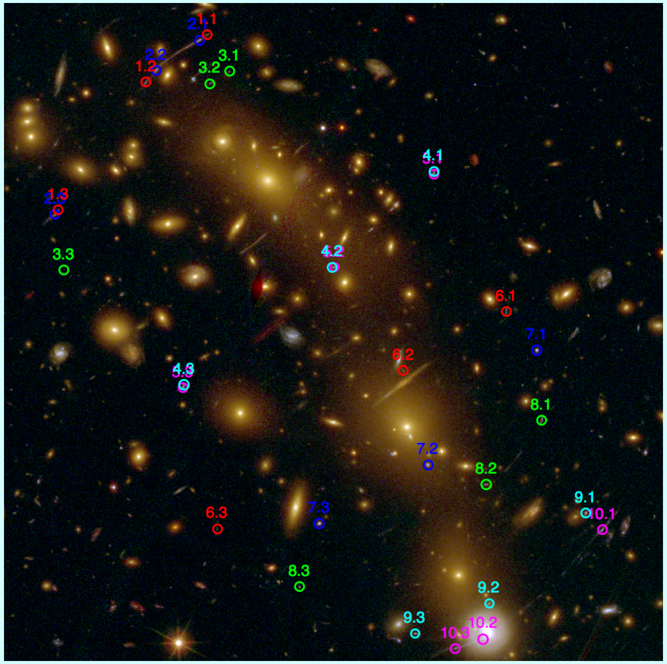


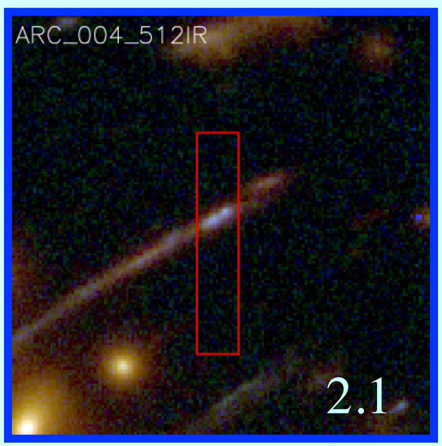

- We use 10 multiple image systems, each composed of 3 images
- All the systems are spectroscopically confirmed
- Systems well distributed around the 2 BCGs, G1 and G2

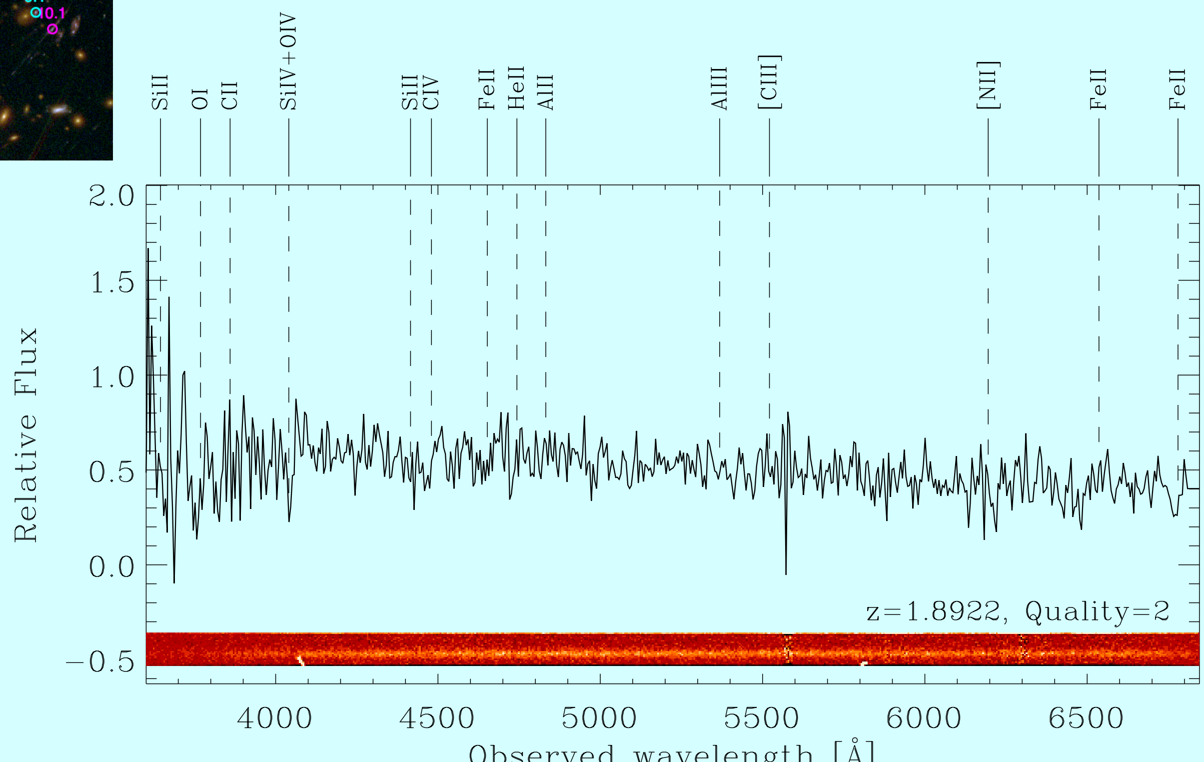
Grillo C., Suyu S., Rosati P., et al., arXiv: 1407.7866

# The multiple image spectra

- For each system, at least 1 image has an either 'SECURE' or 'VERY LIKELY' redshift
- If we have 1 'SECURE' and 1 'VERY LIKELY', we take the 'SECURE'
- If we have 2 'SECURE', we take the mean value



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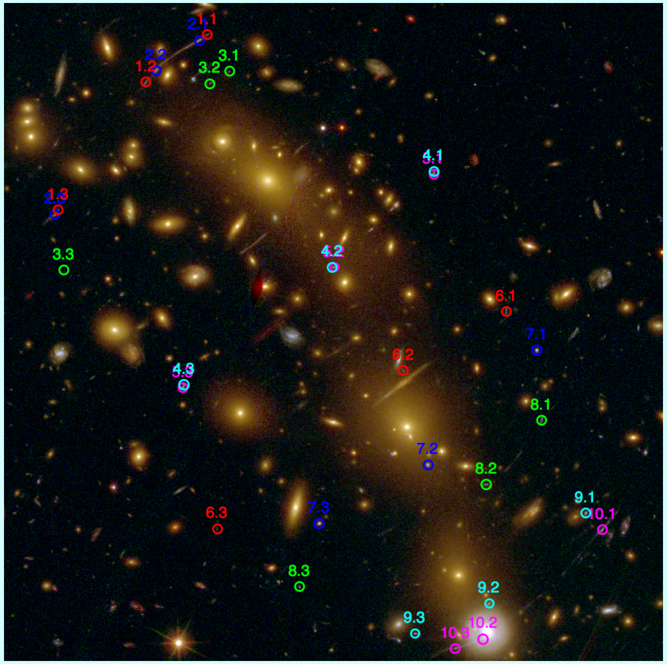


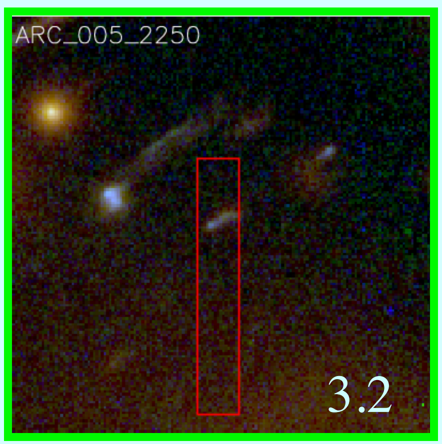


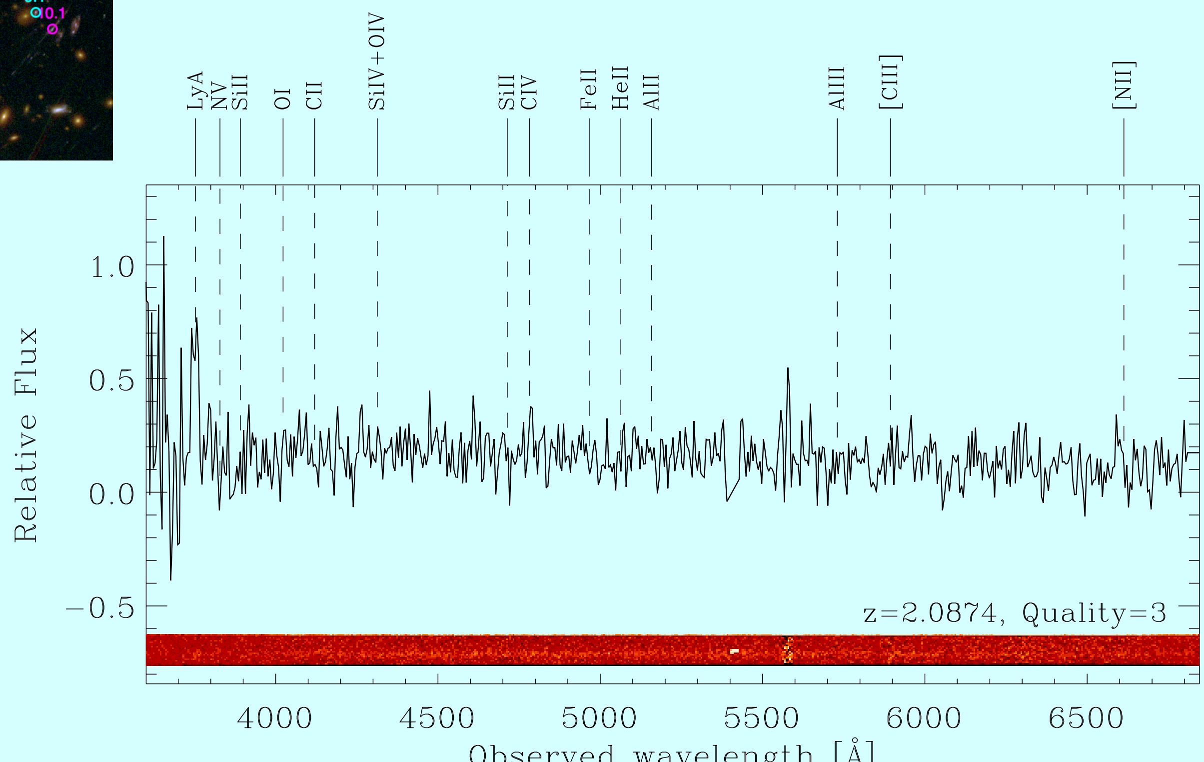

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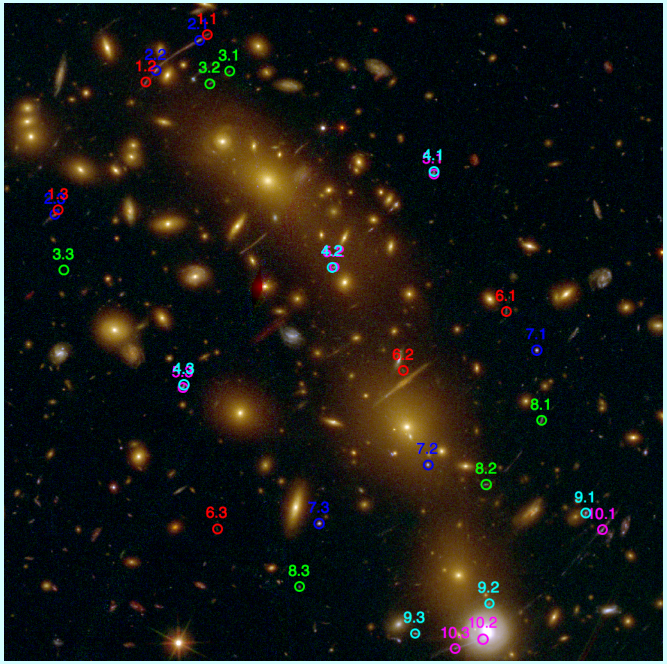


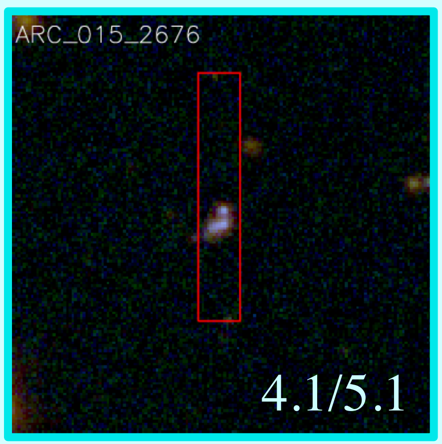


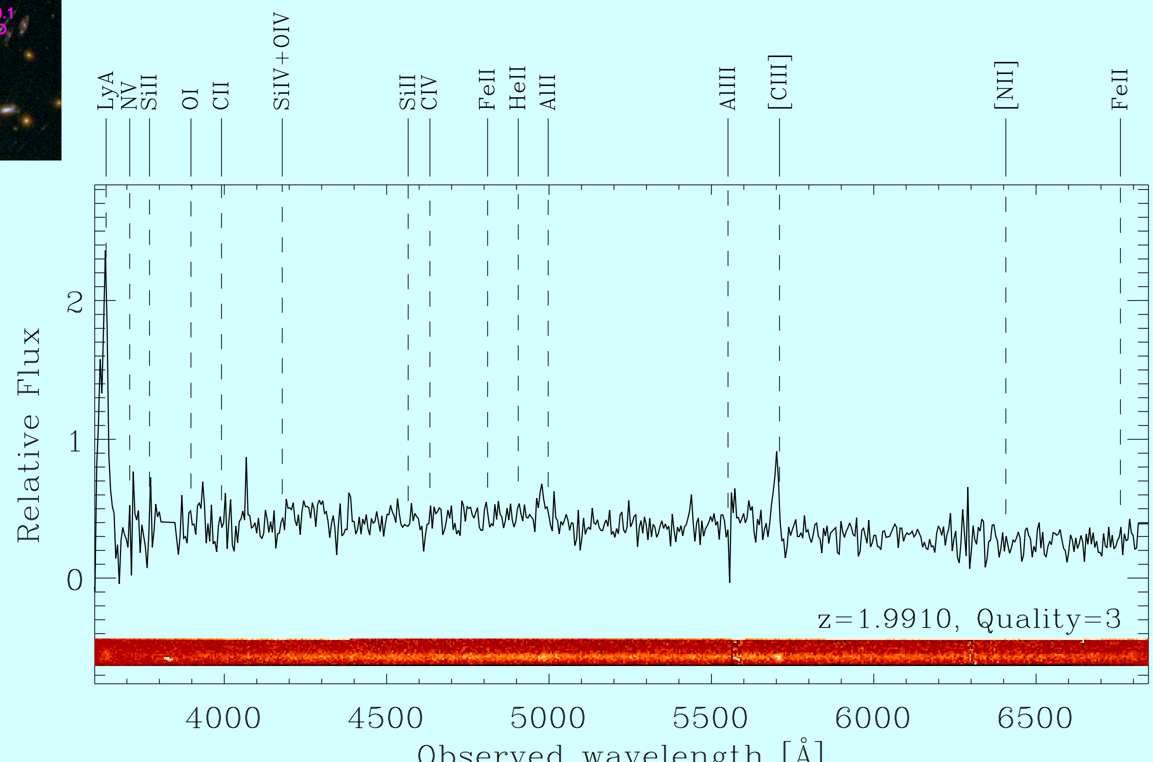

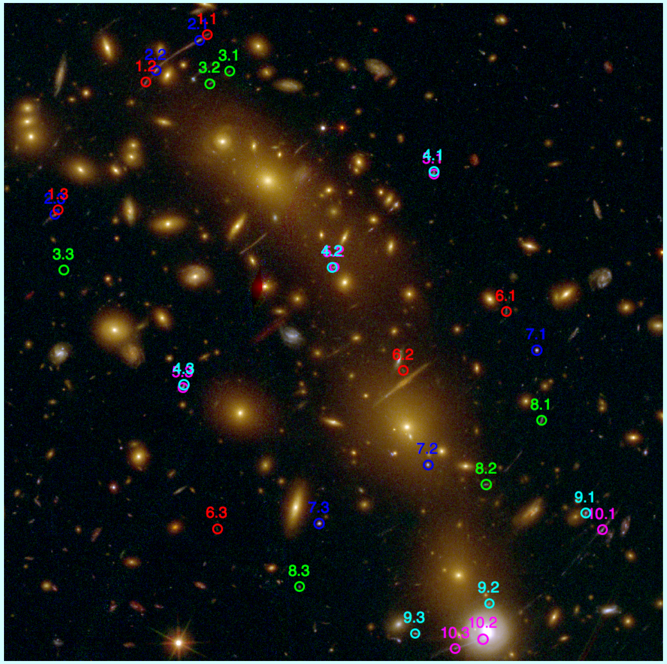


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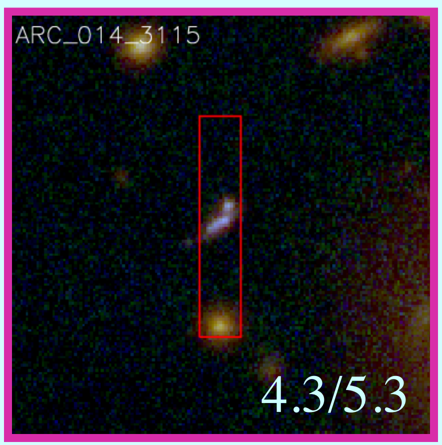


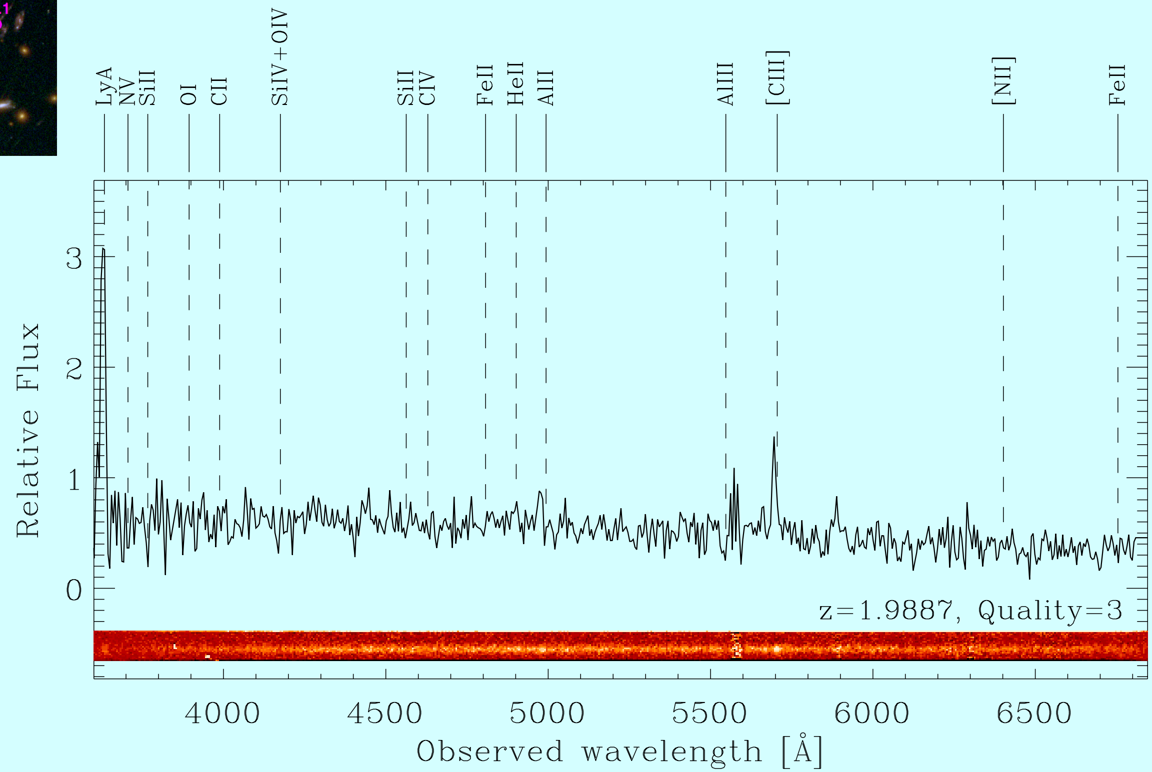

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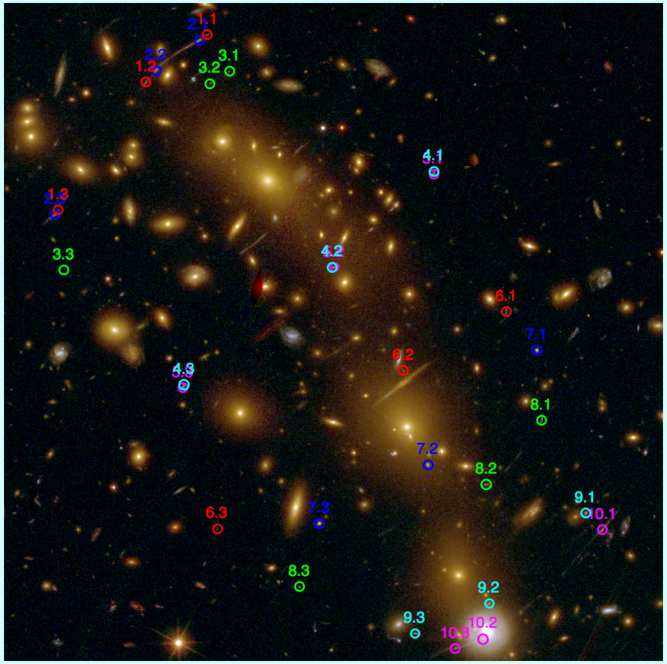

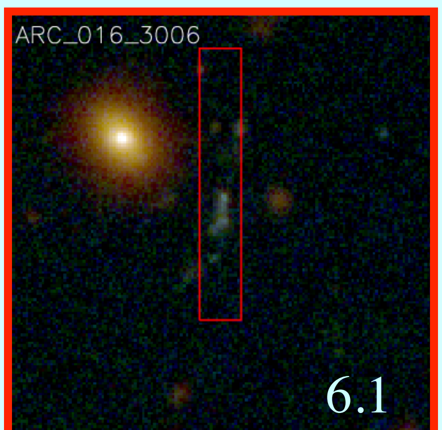


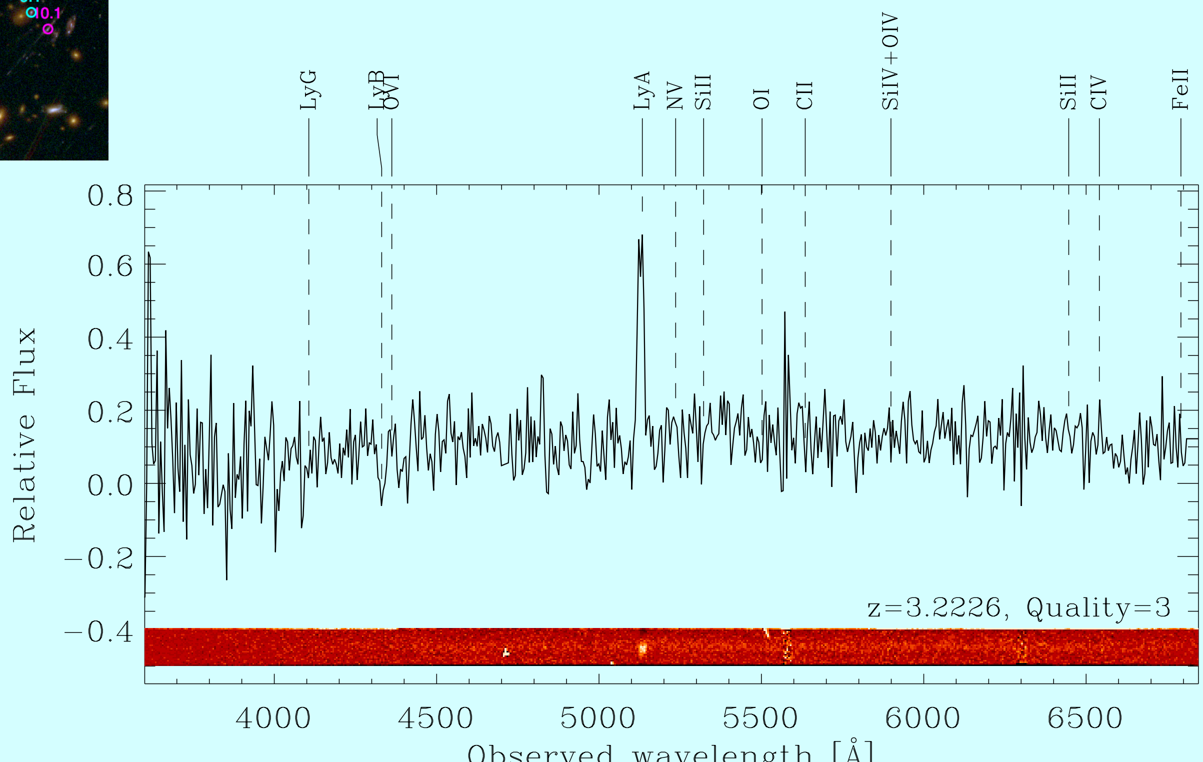

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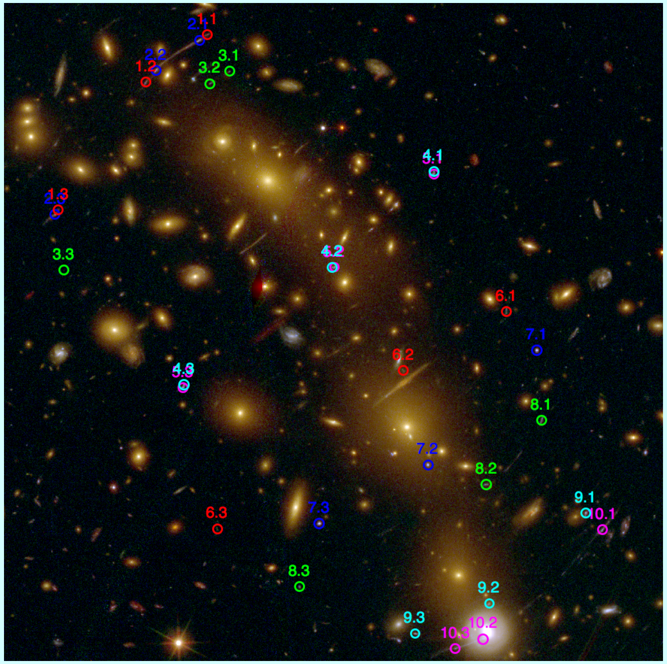

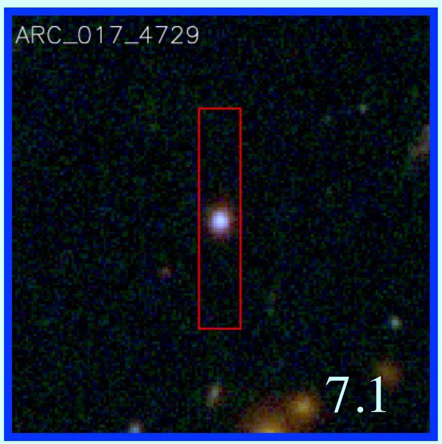


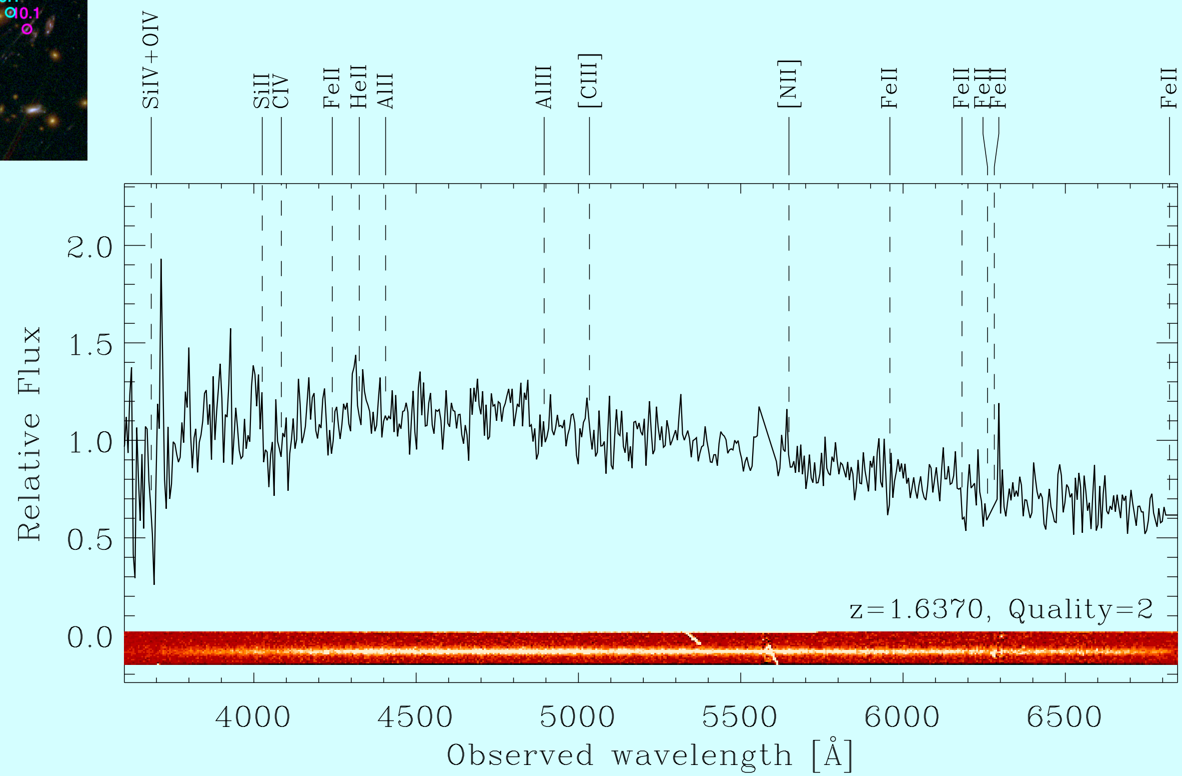

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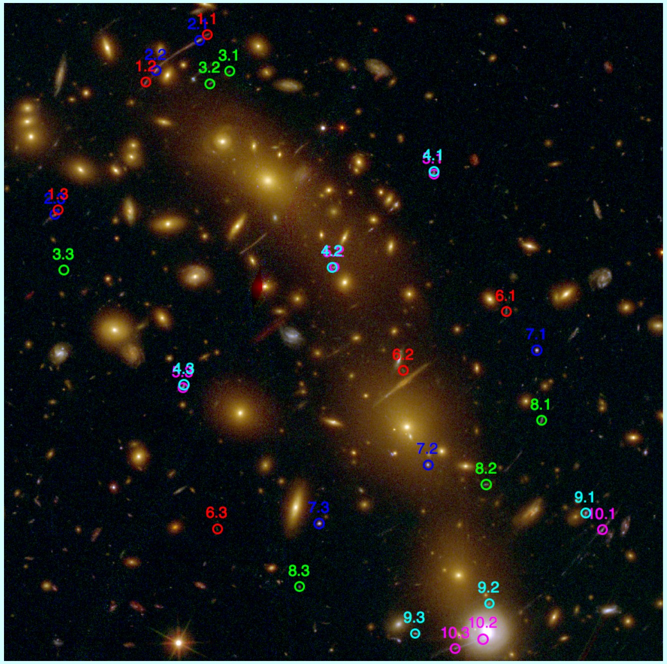


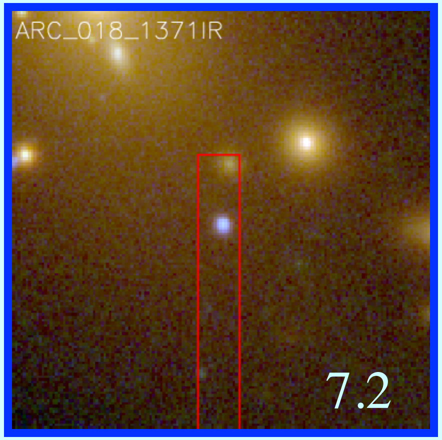


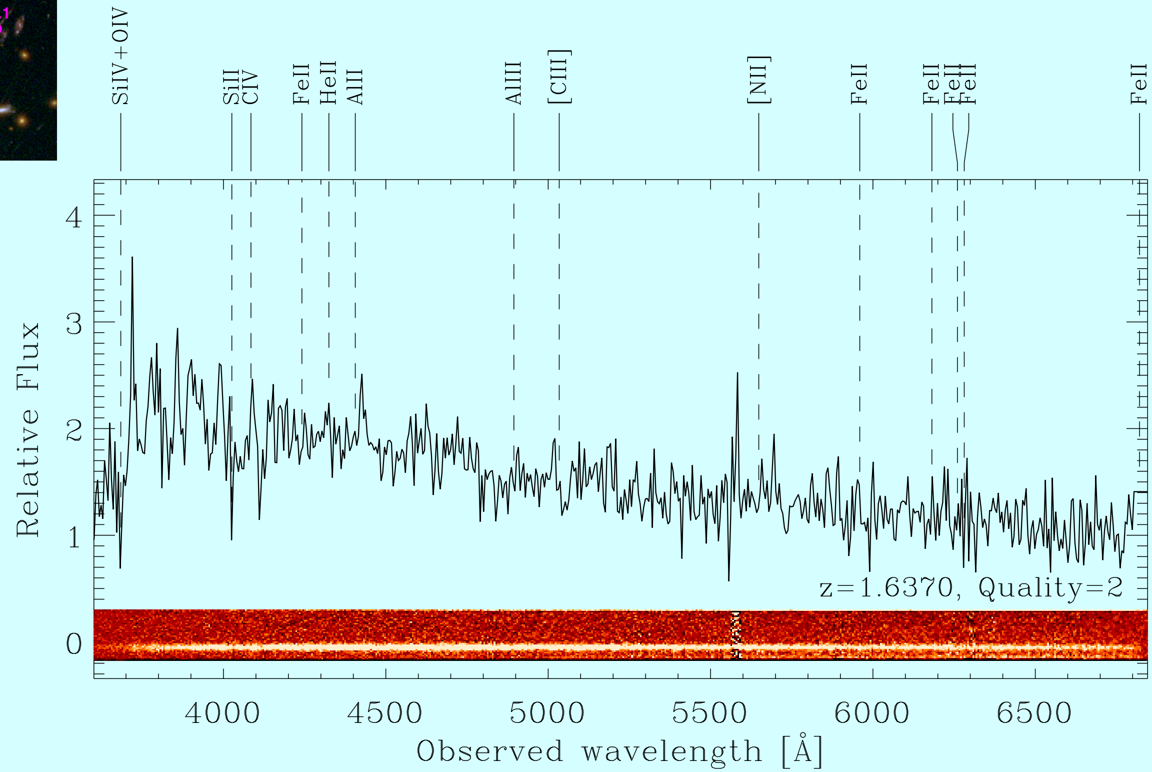

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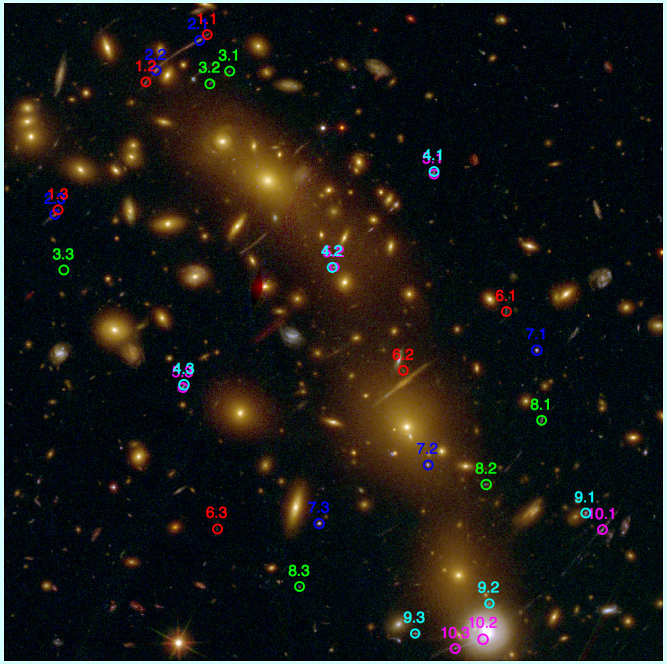


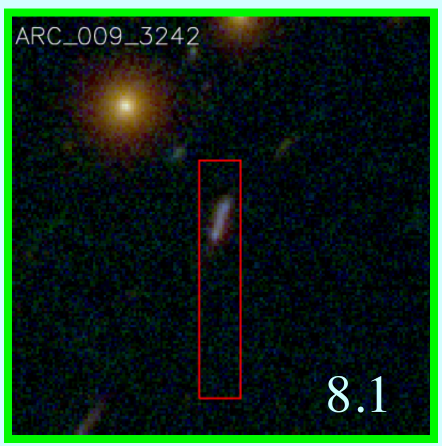


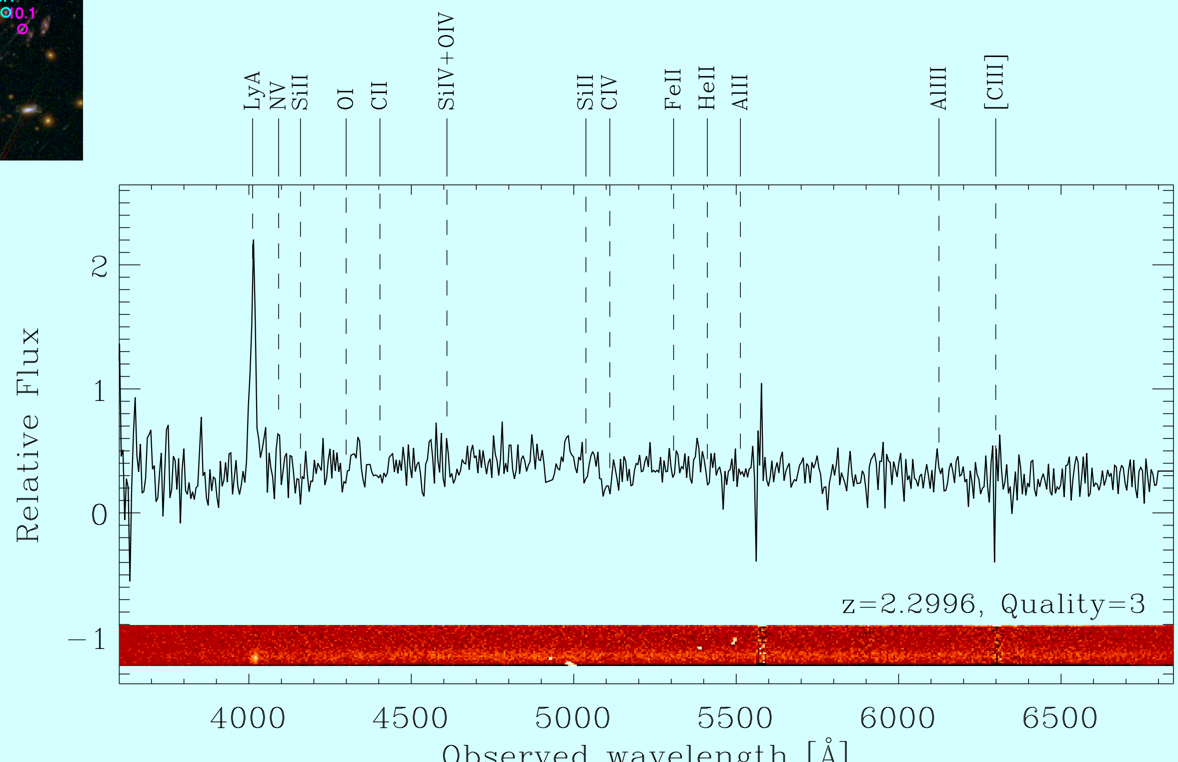

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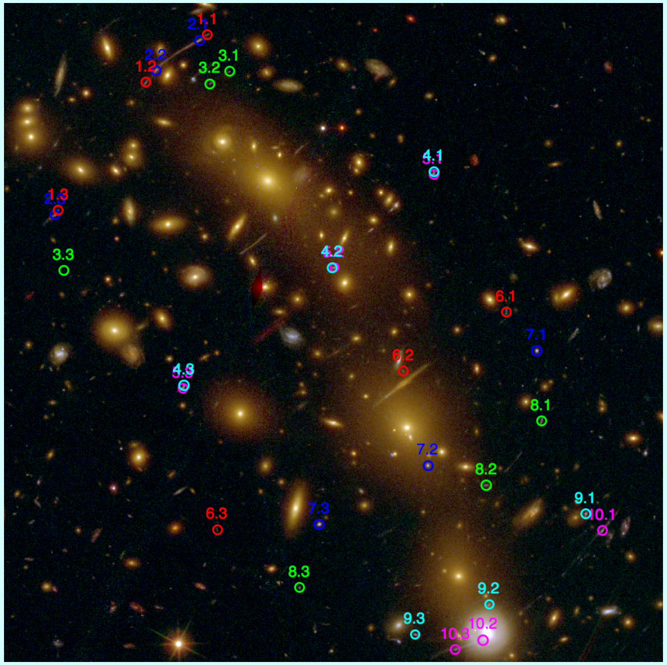


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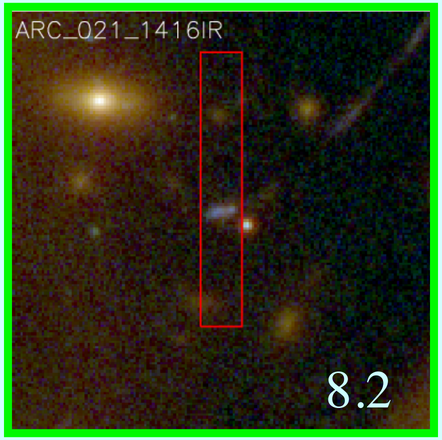


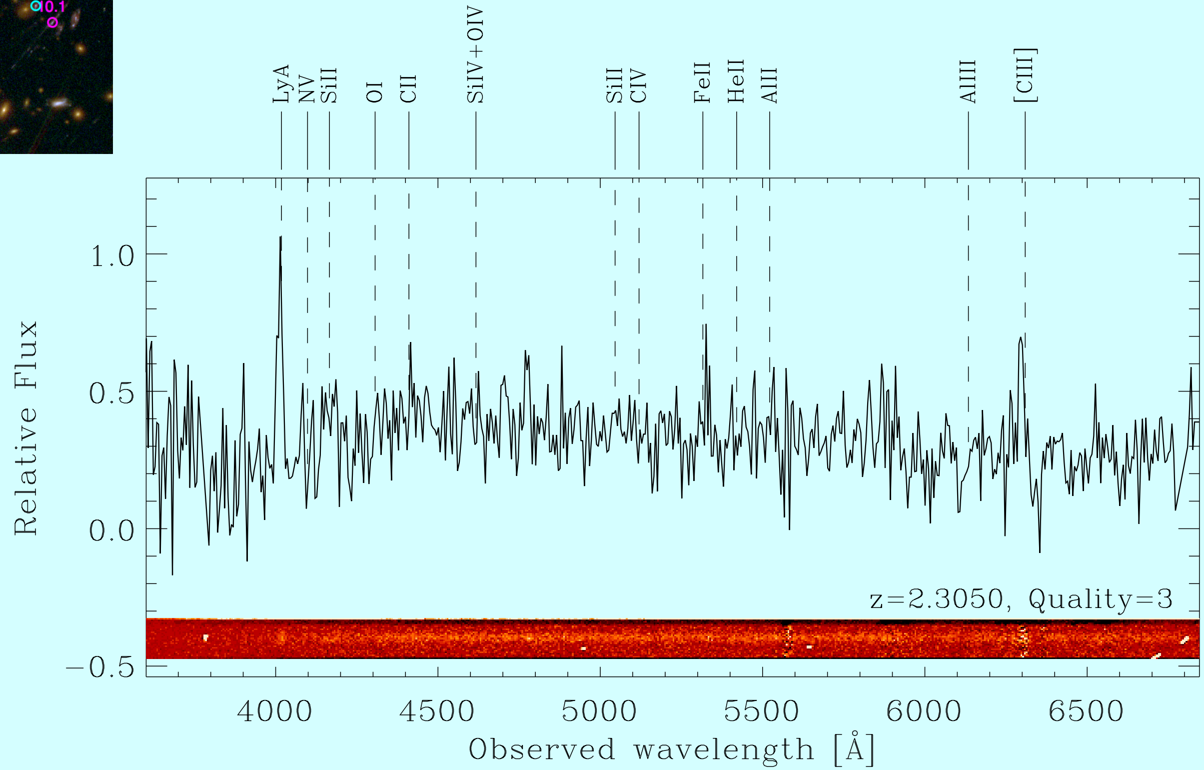

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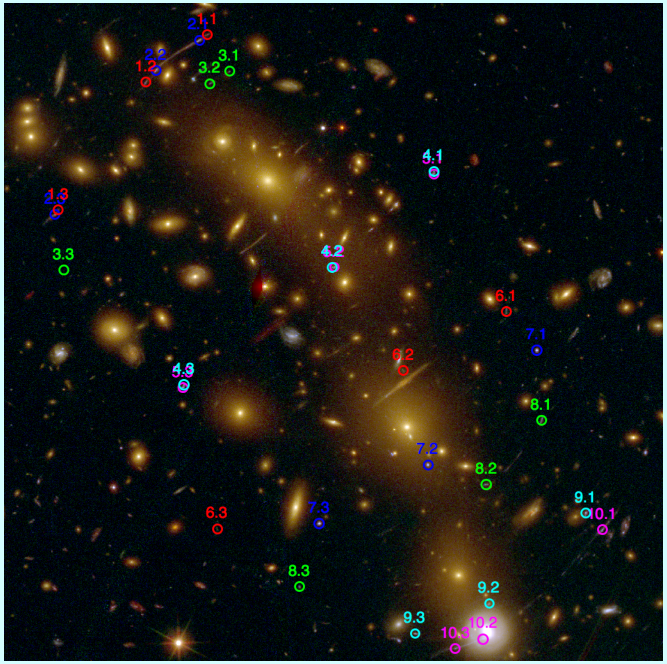


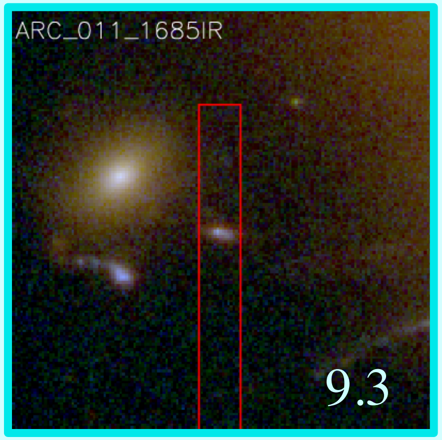


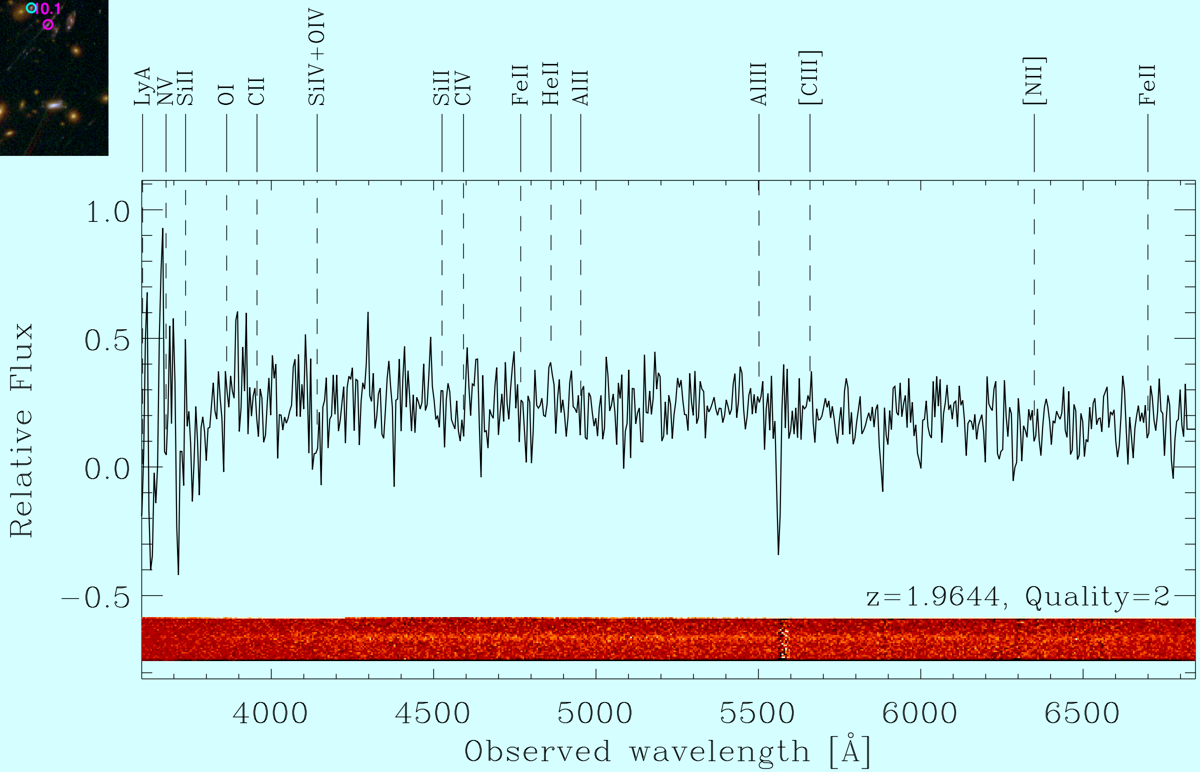

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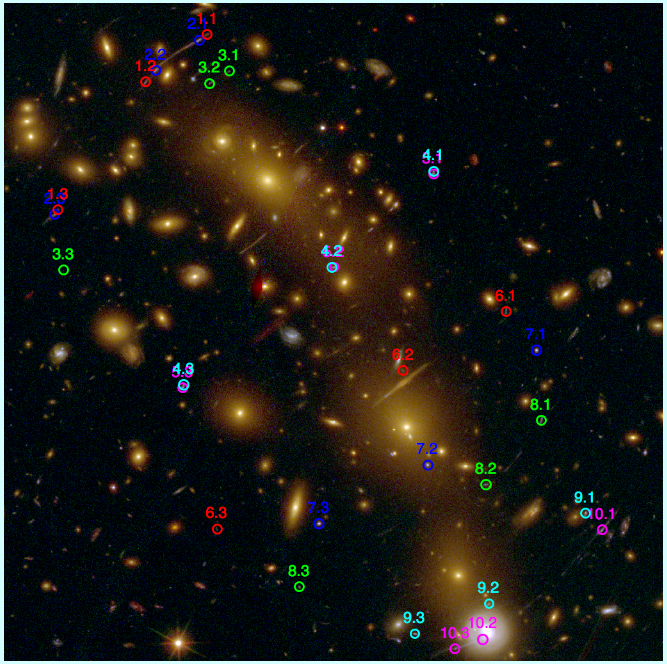
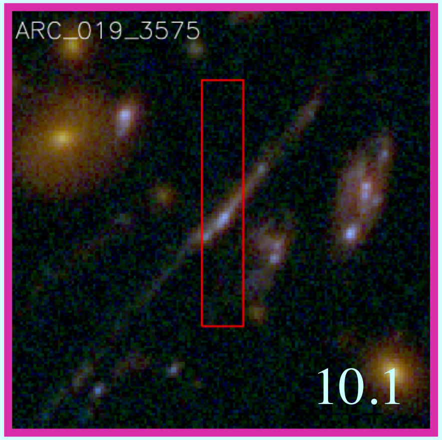
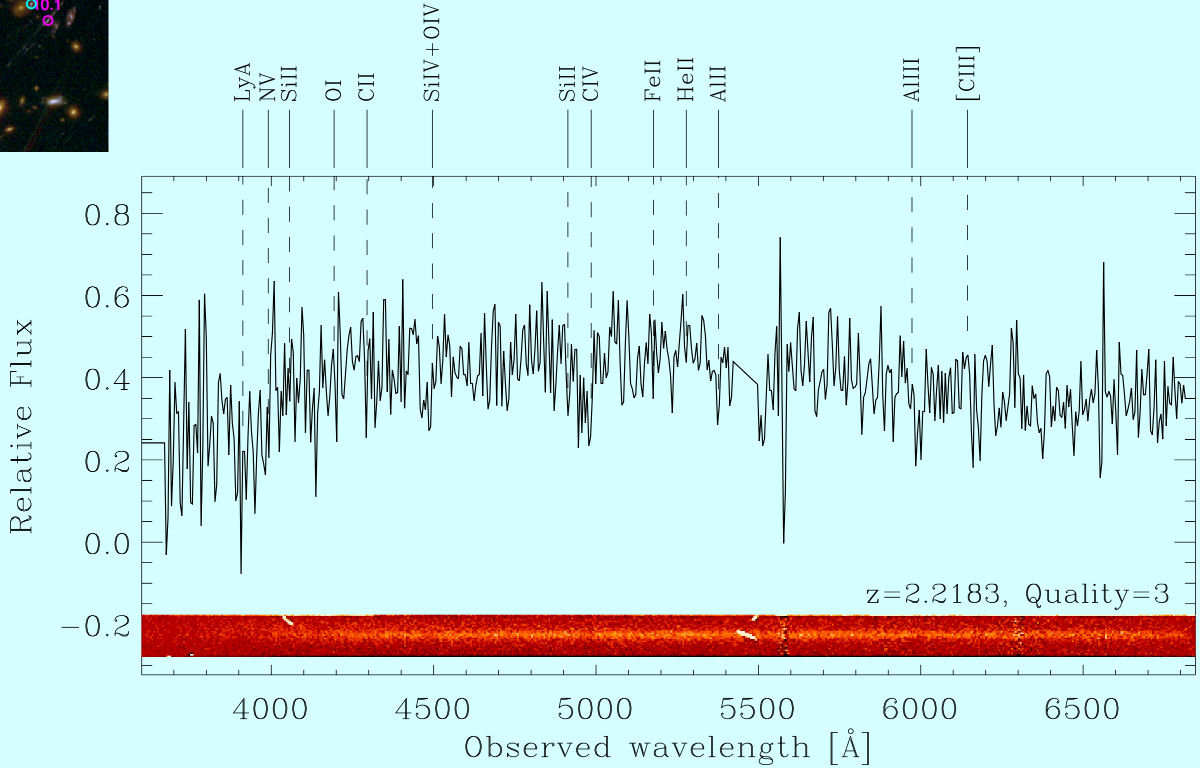
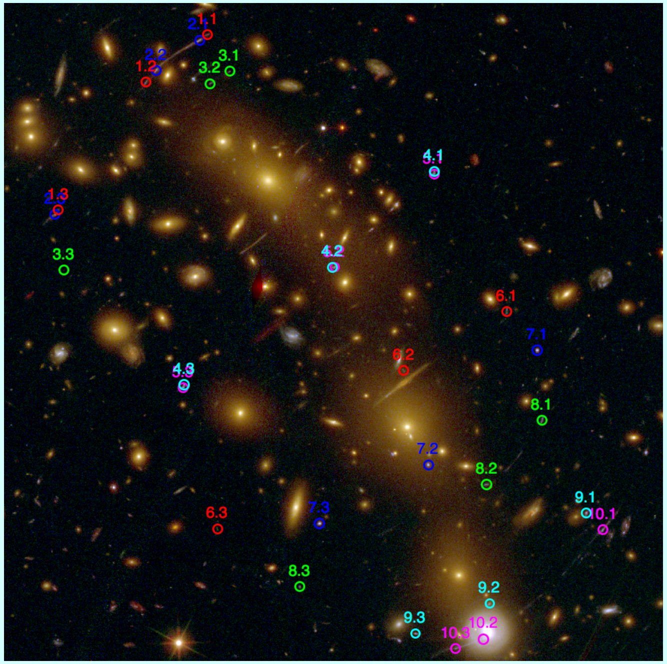


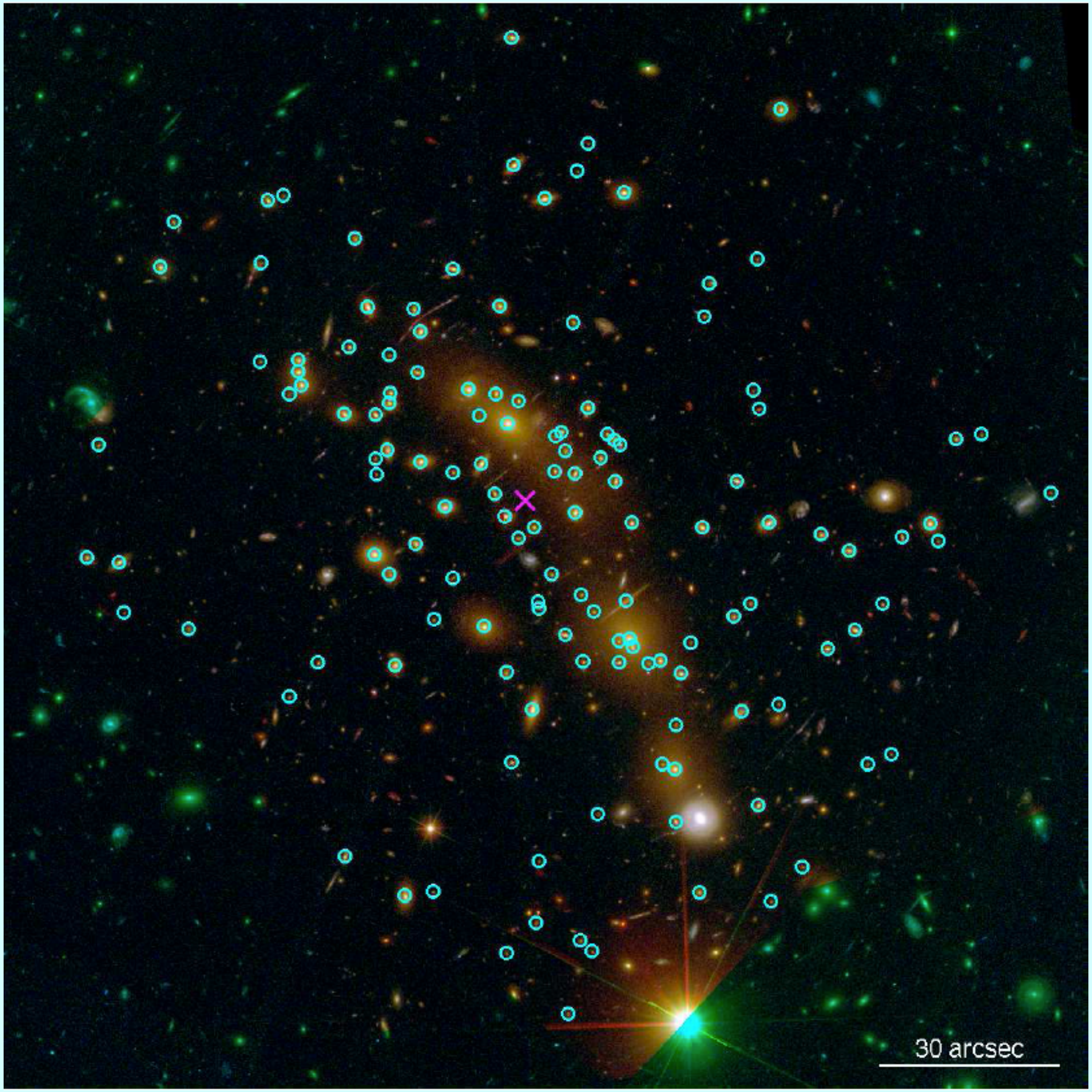



# The strong lensing observables

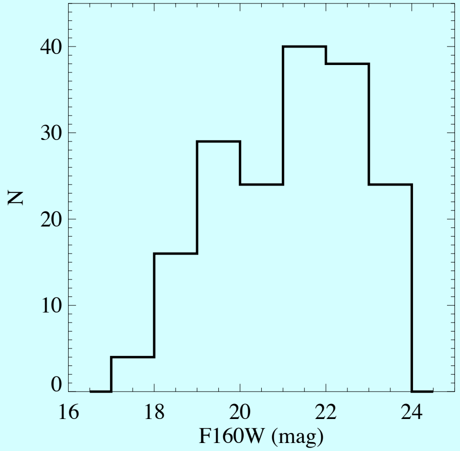
| ID | R.A. (J2000) | Decl. (J2000) | $x^{a}$ ($''$) | $y^{a}$ ($''$) | $z_{sp}$ | $\delta_{x,y}$ ($''$) | ID Z13[b] |
|---|---|---|---|---|---|---|---|
| 1.1 | 04:16:09.784 | −24:03:41.76 | −8.805 | 21.184 | 1.892 | 0.065 | 1.1 |
| 1.2 | 04:16:10.435 | −24:03:48.69 | −17.727 | 14.261 | 1.892 | 0.065 | 1.2 |
| 1.3 | 04:16:11.365 | −24:04:07.21 | −30.463 | −4.265 | 1.892 | 0.065 | 1.3 |
| 2.1 | 04:16:09.871 | −24:03:42.59 | −10.002 | 20.356 | 1.892 | 0.065 | 2.1 |
| 2.2 | 04:16:10.329 | −24:03:46.96 | −16.279 | 15.984 | 1.892 | 0.065 | 2.2 |
| 2.3 | 04:16:11.395 | −24:04:07.86 | −30.876 | −4.915 | 1.892 | 0.065 | 2.3 |
| 3.1 | 04:16:09.549 | −24:03:47.08 | −5.597 | 15.866 | 2.087 | 0.065 | c7.1 |
| 3.2 | 04:16:09.758 | −24:03:48.90 | −8.460 | 14.048 | 2.087 | 0.065 | c7.2 |
| 3.3 | 04:16:11.304 | −24:04:15.94 | −29.630 | −12.993 | 2.087 | 0.065 | c7.3 |
| 4.1 | 04:16:07.385 | −24:04:01.62 | 24.042 | 1.327 | 1.990 | 0.065 | 3.1 |
| 4.2 | 04:16:08.461 | −24:04:15.53 | 9.314 | −12.583 | 1.990 | 0.065 | 3.2 |
| 4.3 | 04:16:10.031 | −24:04:32.62 | −12.197 | −29.672 | 1.990 | 0.065 | 3.3 |
| 5.1 | 04:16:07.390 | −24:04:02.01 | 23.979 | 0.937 | 1.990 | 0.065 | 4.1 |
| 5.2 | 04:16:08.440 | −24:04:15.57 | 9.598 | −12.623 | 1.990 | 0.065 | 4.2 |
| 5.3 | 04:16:10.045 | −24:04:33.03 | −12.384 | −30.087 | 1.990 | 0.065 | 4.3 |
| 6.1 | 04:16:06.618 | −24:04:21.99 | 34.553 | −19.039 | 3.223 | 0.065 | 13.1 |
| 6.2 | 04:16:07.709 | −24:04:30.56 | 19.610 | −27.614 | 3.223 | 0.065 | 13.2 |
| 6.3 | 04:16:09.681 | −24:04:53.53 | −7.397 | −50.585 | 3.223 | 0.065 | 13.3 |
| 7.1 | 04:16:06.297 | −24:04:27.60 | 38.952 | −24.652 | 1.637 | 0.065 | 14.1 |
| 7.2 | 04:16:07.450 | −24:04:44.23 | 23.156 | −41.287 | 1.637 | 0.065 | 14.2 |
| 7.3 | 04:16:08.600 | −24:04:52.76 | 7.401 | −49.813 | 1.637 | 0.065 | 14.3 |
| 8.1 | 04:16:06.246 | −24:04:37.76 | 39.639 | −34.814 | 2.302 | 0.065 | 10.1 |
| 8.2 | 04:16:06.832 | −24:04:47.10 | 31.621 | −44.157 | 2.302 | 0.065 | 10.2 |
| 8.3 | 04:16:08.810 | −24:05:01.93 | 4.529 | −58.981 | 2.302 | 0.065 | c10.3 |
| 9.1 | 04:16:05.779 | −24:04:51.22 | 46.039 | −48.273 | 1.964 | 0.065 | 16.1 |
| 9.2 | 04:16:06.799 | −24:05:04.35 | 32.070 | −61.404 | 1.964 | 0.065 | 16.2 |
| 9.3 | 04:16:07.586 | −24:05:08.72 | 21.286 | −65.775 | 1.964 | 0.065 | 16.3 |
| 10.1 | 04:16:05.603 | −24:04:53.70 | 48.447 | −50.751 | 2.218 | 0.065 | c17.3 |
| 10.2 | 04:16:06.866 | −24:05:09.50 | 31.153 | −66.551 | 2.218 | 0.065 | c17.2 |
| 10.3 | 04:16:07.157 | −24:05:10.91 | 27.166 | −67.963 | 2.218 | 0.065 | c17.1 |

- ✧ We use the observed positions of 30 multiple images from 10 different sources, distributed in redshift between 1.64 and 3.22
- ✧ We assume a positional uncertainty of 0.065” (1 pixel)
- ✧ All images are main or candidate images in Zitrin et al. 2013, ApJ, 762, 30
- ✧ GLEE is our strong lensing code (Suyu & Halkola 2010; Suyu et al. 2012)

# The cluster member selection




- We take the 63 spectroscopic cluster members (CMs) in the HST/WFC3 field of view
- We estimate the region where they reside in the multi-colour space using all the HST bands
- We measure the distance of each source to the previous region and decide whether it is a CM or not
- We select 175 CMs with F160W < 24 mag



# The best-fitting models

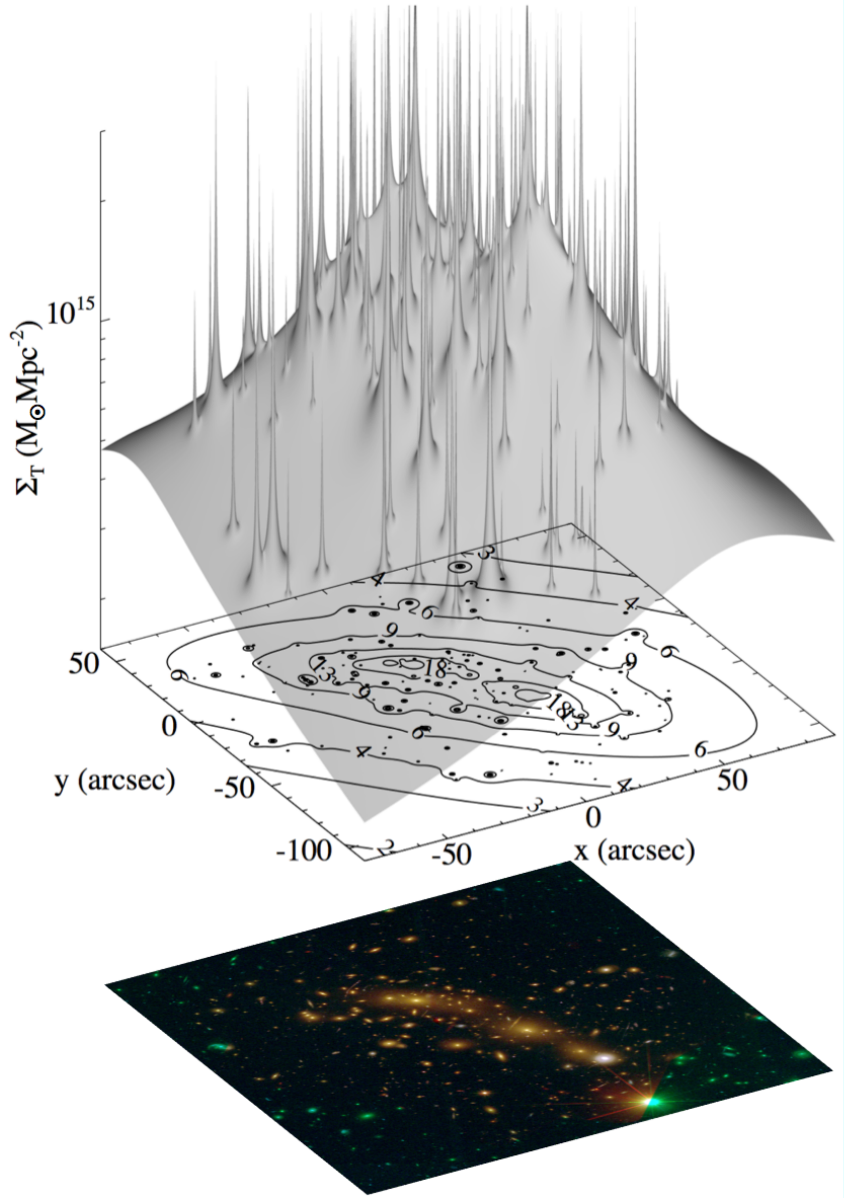
- We adopt truncated isothermal profiles for the CMs and 2 cored isothermal or prolate NFW profiles for the cluster haloes
- We scale the CM profiles in different ways:

✓ $\sigma_0 \sim L^{0.25}$ & $r_t \sim L^{0.5}$ ➔ $M_T \sim \sigma_0^2 r_t \sim L^{0.5} L^{0.5} = L$
Faber-Jackson relation; constant $M_T/L$

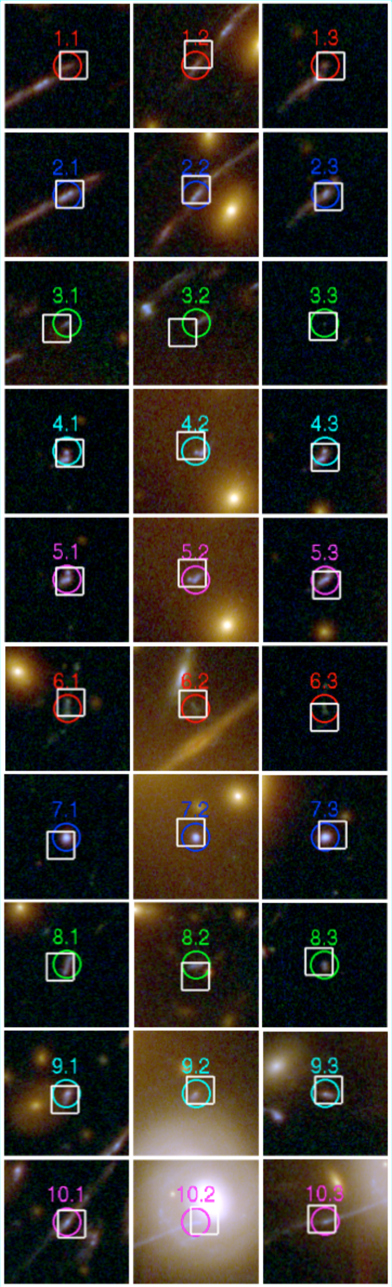
✓ $\sigma_0 \sim L^{0.35}$ & $r_t \sim L^{0.5}$ ➔ $M_T \sim \sigma_0^2 r_t \sim L^{0.7} L^{0.5} = L^{1.2}$
Mimic the Fundamental Plane $M_T/L$ relation

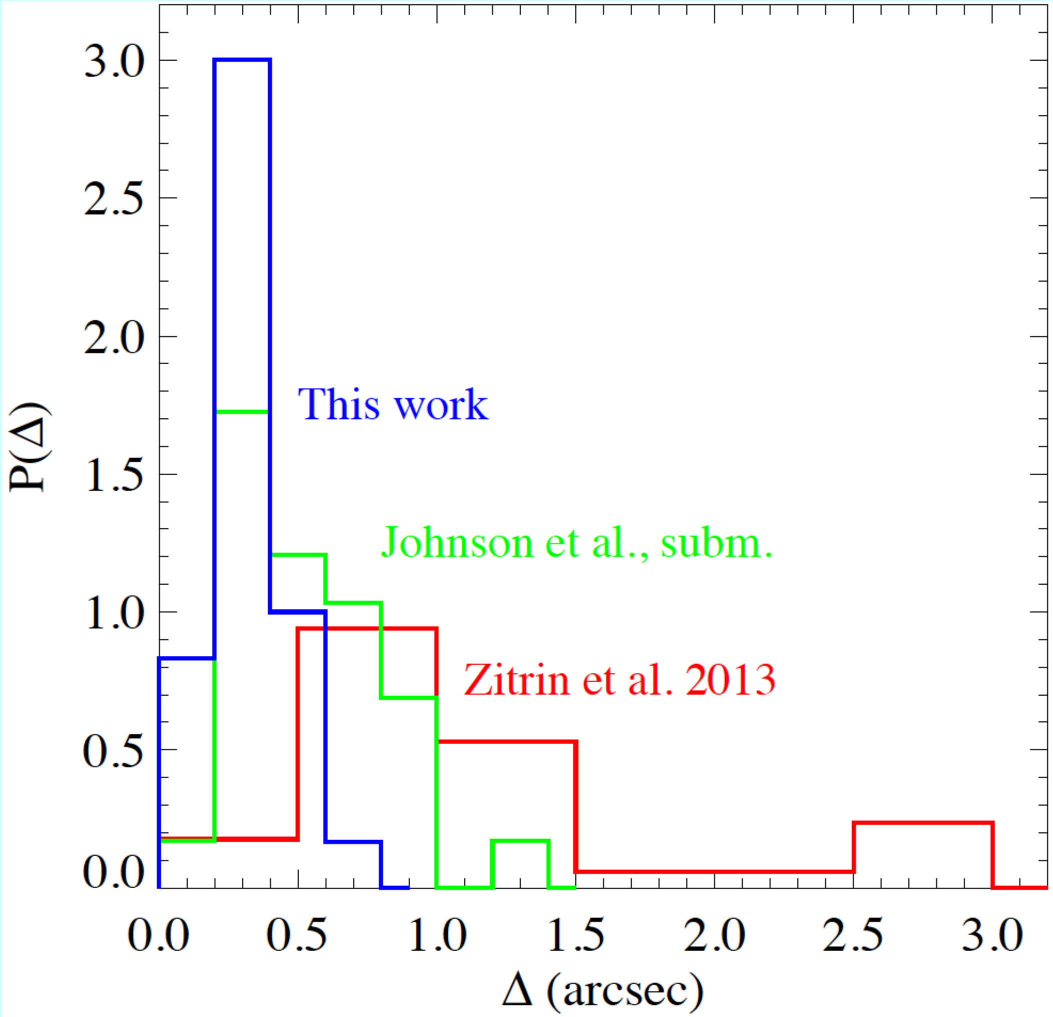
✓ $\sigma_0 \sim L^{0.25}$ & $r_t \sim L^{0.25}$
Faber-Jackson relation & tidal halo stripping

| Model | Min. $\chi^2$ |
|---|---|
| 2 NIE | 6032 |
| 2 NIE + 175(+1) TIS ($M_T/L=k$) | 1169 |
| 2 NIE + 175(+1) TIS ($M_T/L=L^{0.2}$) | 915 |
| 2 NIE + 175(+1) TIS ($r_t \sim L^{0.25}$) | 1262 |
| 2 PNFW | 6973 |
| 2 PNFW + 175(+1) TIS ($M_T/L=k$) | 1767 |
| 2 PNFW + 175(+1) TIS ($M_T/L=L^{0.2}$) | 1529 |
| 2 PNF + 175(+1) TIS ($r_t \sim L^{0.25}$) | 1901 |



# The best-fitting model I

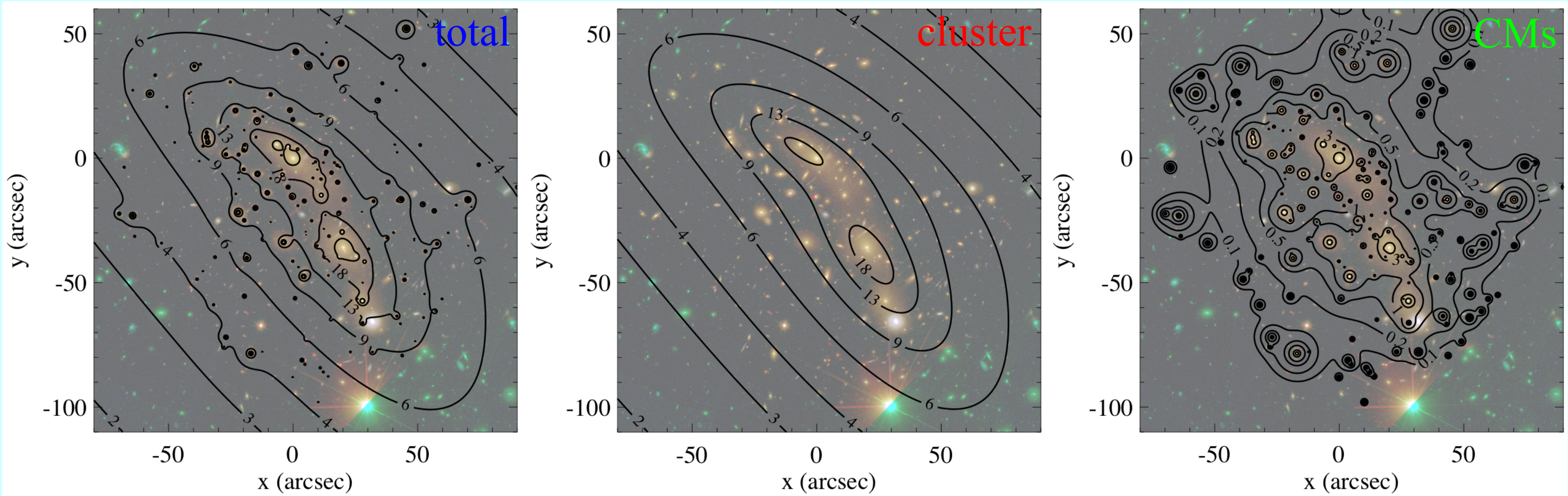


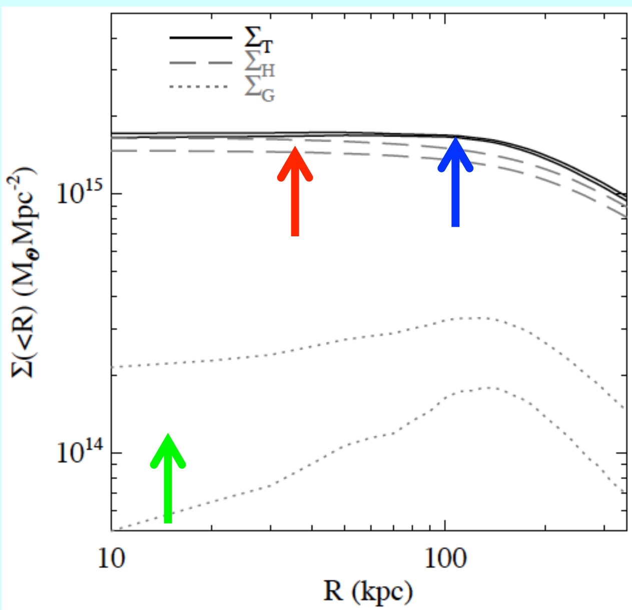




- We reproduce the multiple image positions with a median observed-predicted distance of 0.31” (<5 pixels)!

  The RMS is 0.36”

# The best-fitting model II

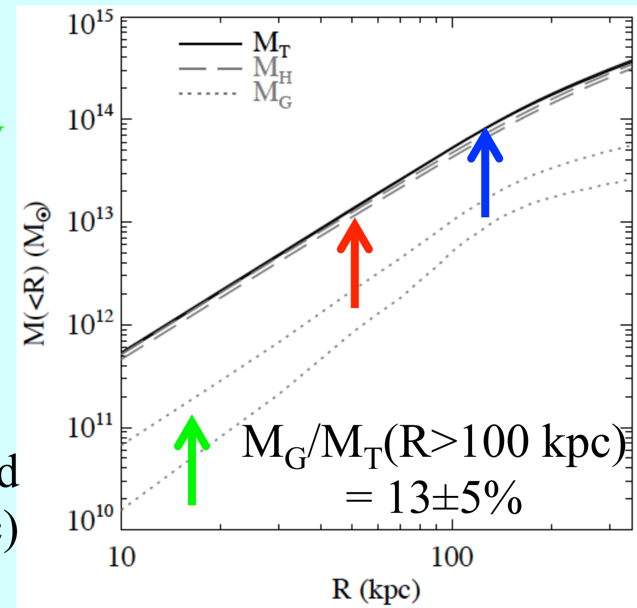


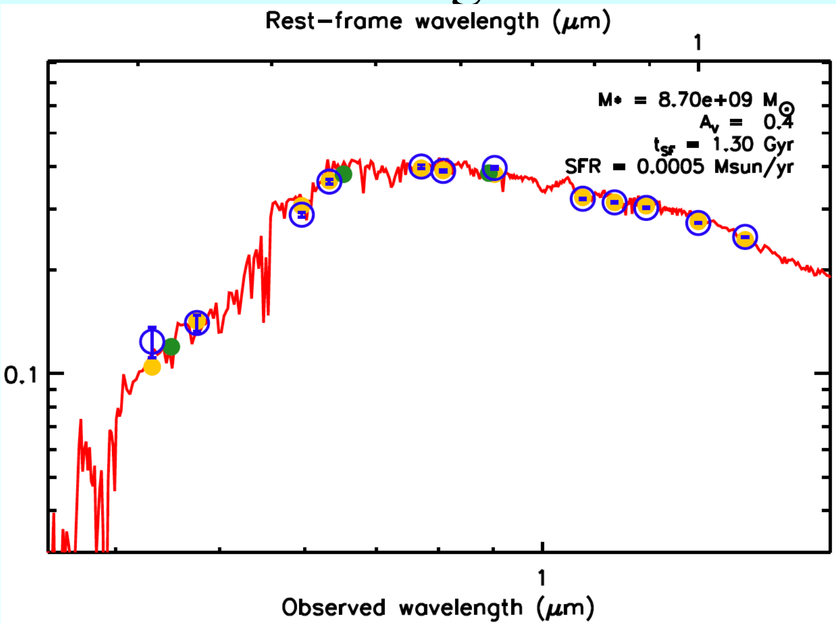

❖ We decompose the projected total mass into cluster and cluster galaxy dark matter haloes

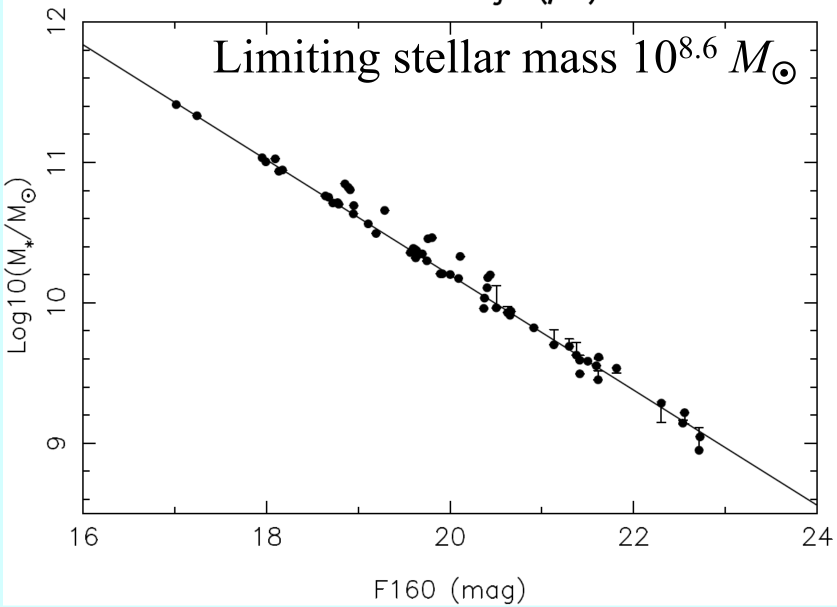
❖ We find an extended core for the projected total mass

❖ We measure a projected total mass $M_T(R<140\text{ kpc}) = 9.8\ 10^{13}\ M_\odot$

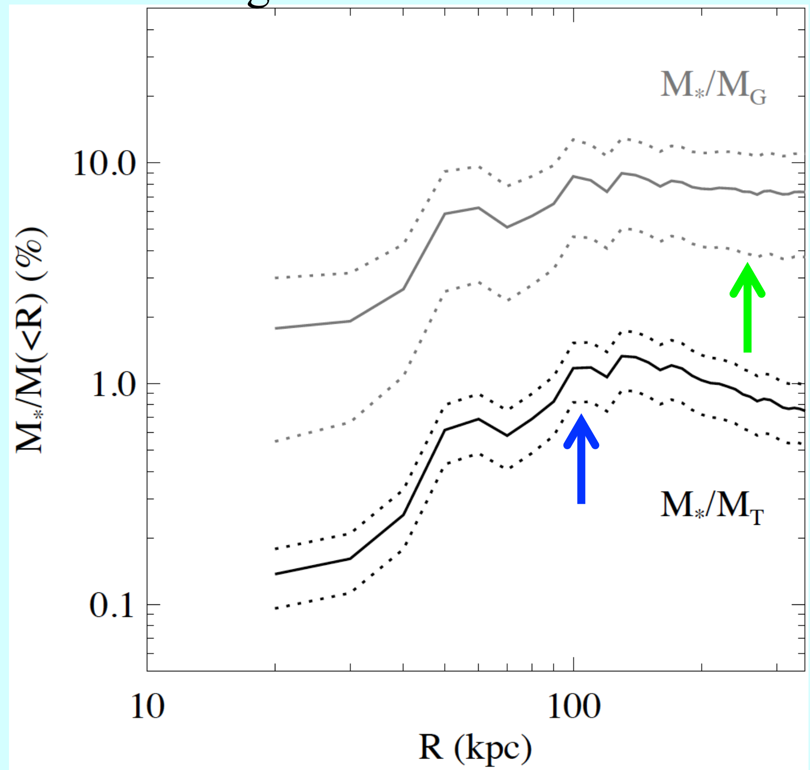


# The best-fitting model III



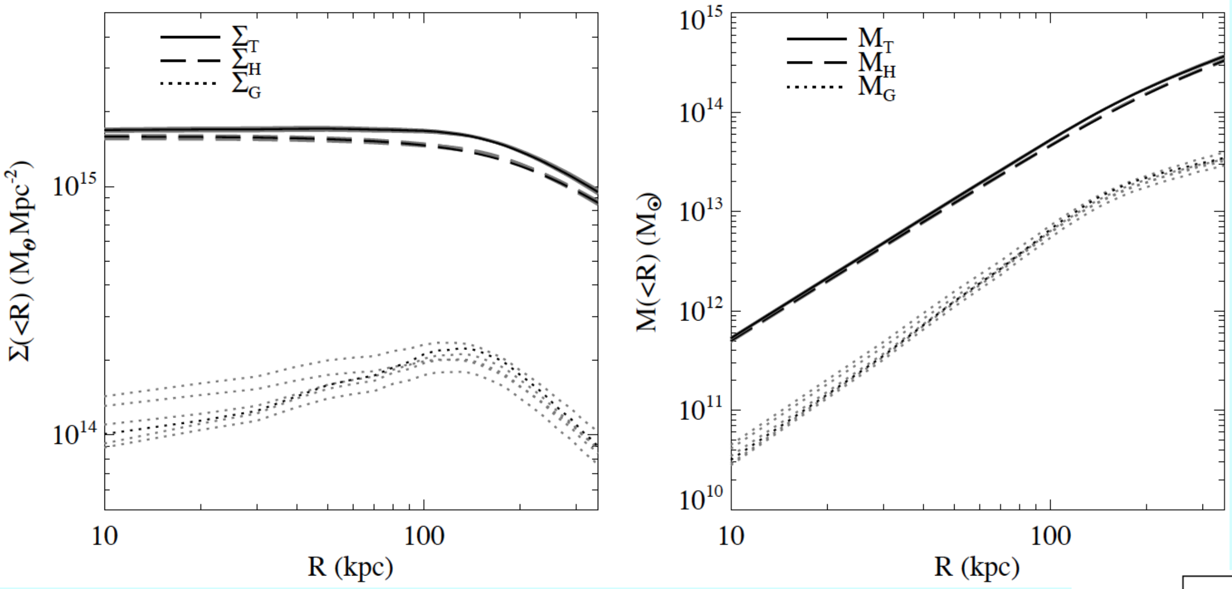




- SED fitting: Bruzual&Charlot (2003) templates, solar metallicity, dust, Salpeter IMF, delayed exponential SFHs
- For spectroscopic galaxy cluster members, tight correlation between F160W magnitudes and stellar masses

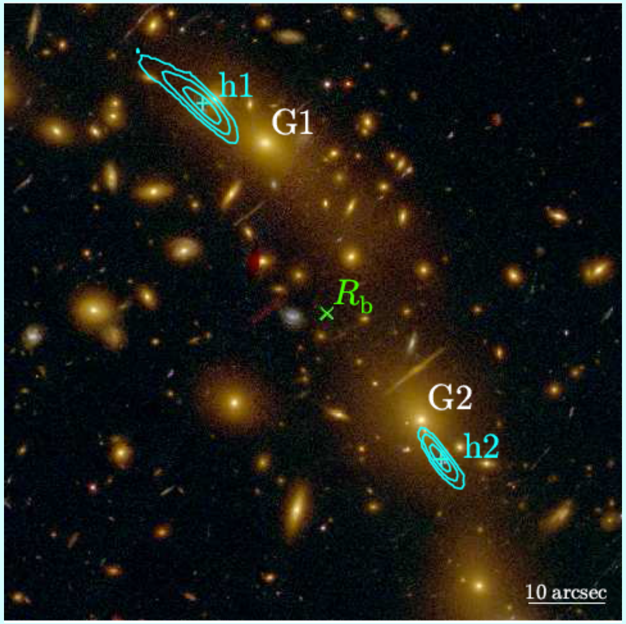



- Stellar over cluster galaxy halo mass ratio ~8% at R > 100 kpc
- Stellar over cluster total mass ratio ~1% at R > 100 kpc

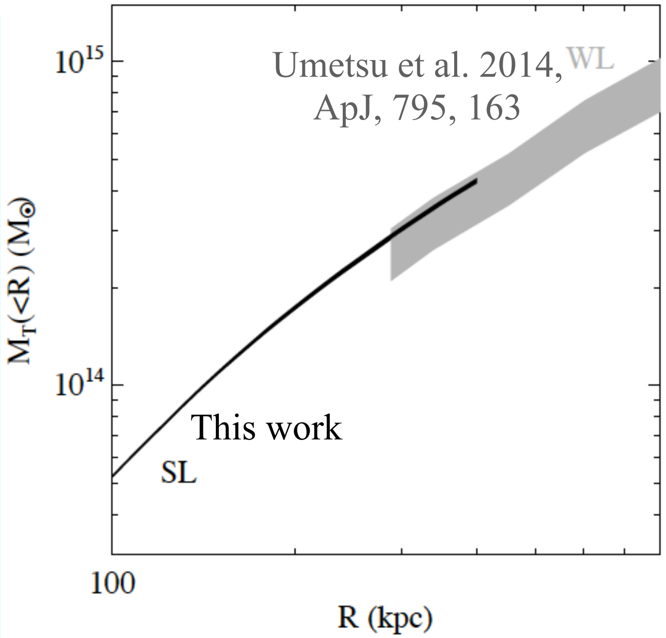
# The best-fitting model IV



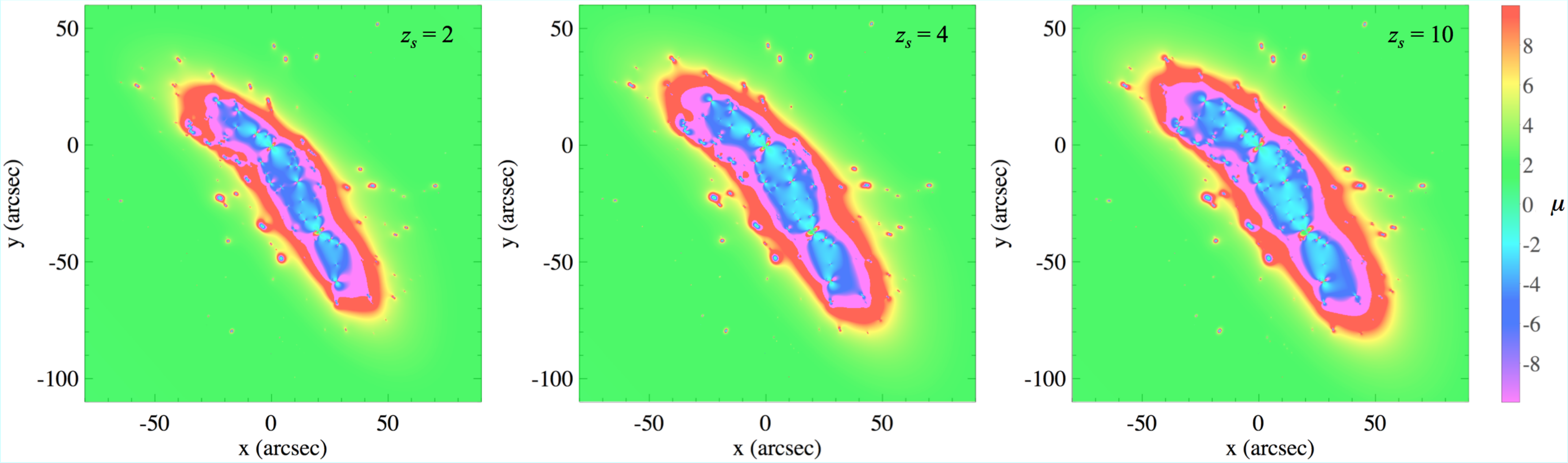

- ✧ Negligible variations in the cluster total mass profile for the different mass parameterizations
- ✧ In the outer regions (R > 300 kpc), very good agreement with the weak lensing results

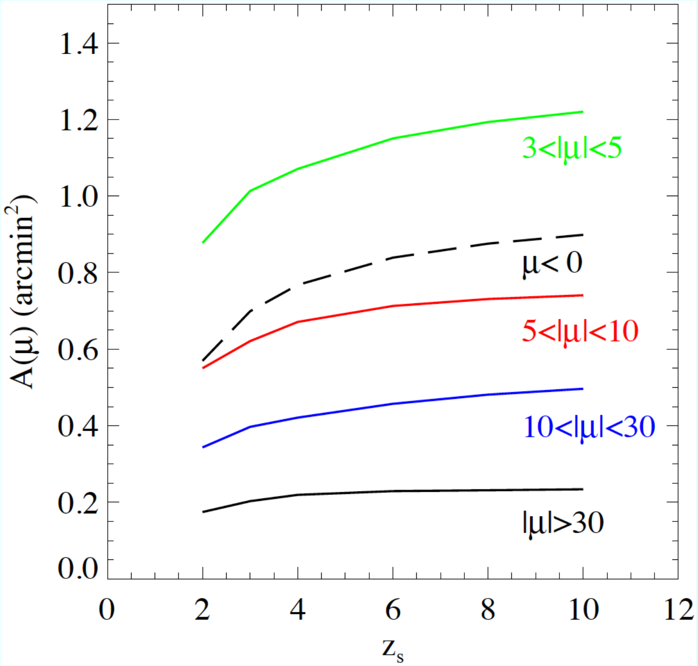



- ✧ Statistical significant offset between the DM halo centres and the BCG luminosity centres. Hints of self-interacting DM?



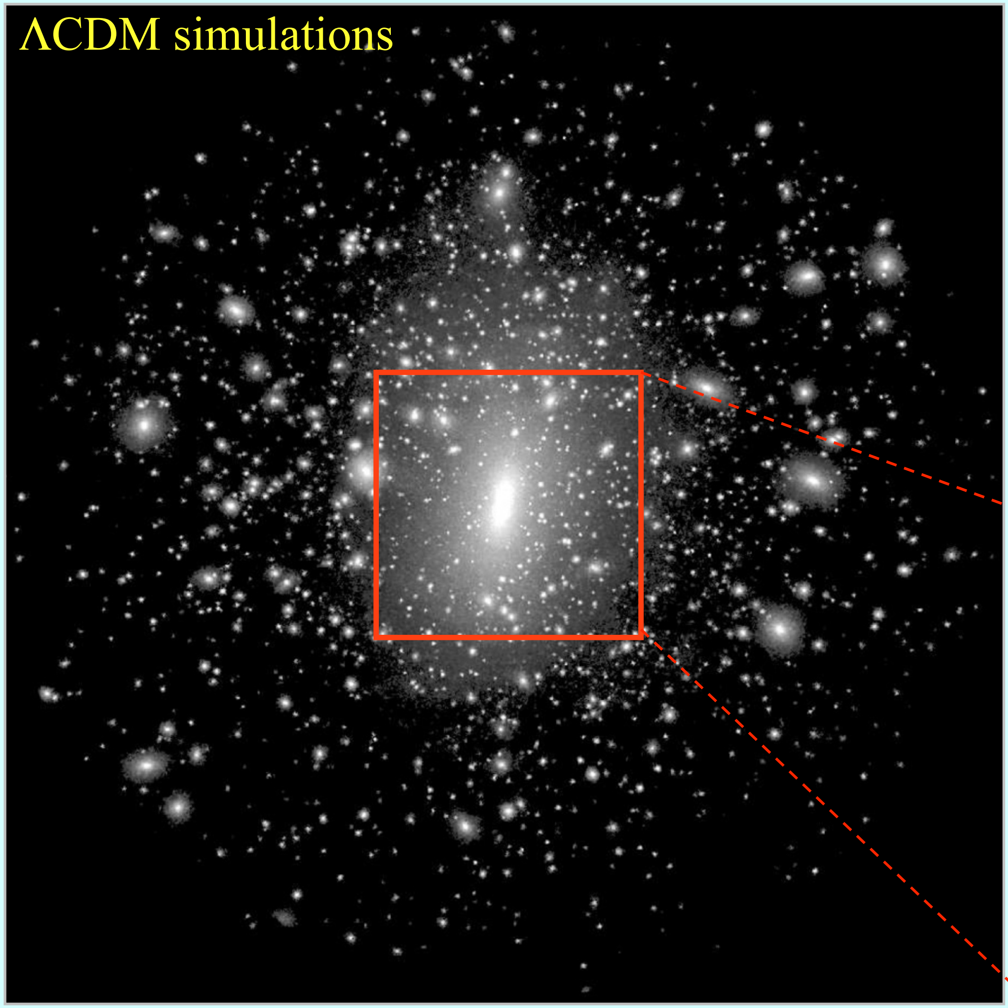
# The best-fitting model V

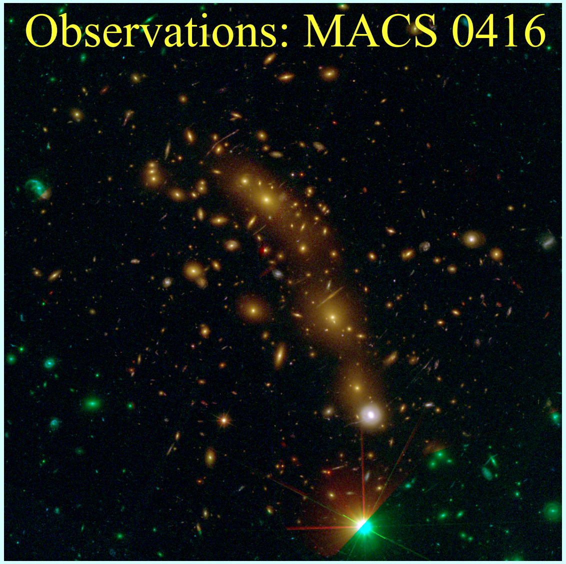


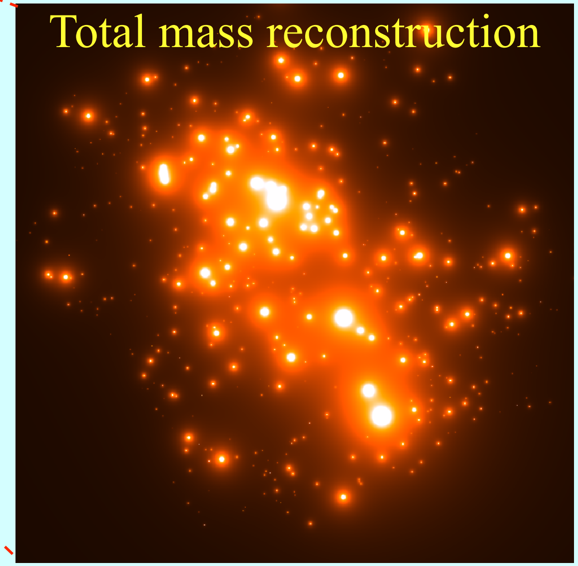




- ✓ We create magnification maps, useful for the FF initiative
- ✓ Extended areas on the lens plane with large magnification factors

# The galaxy cluster subhalo population I

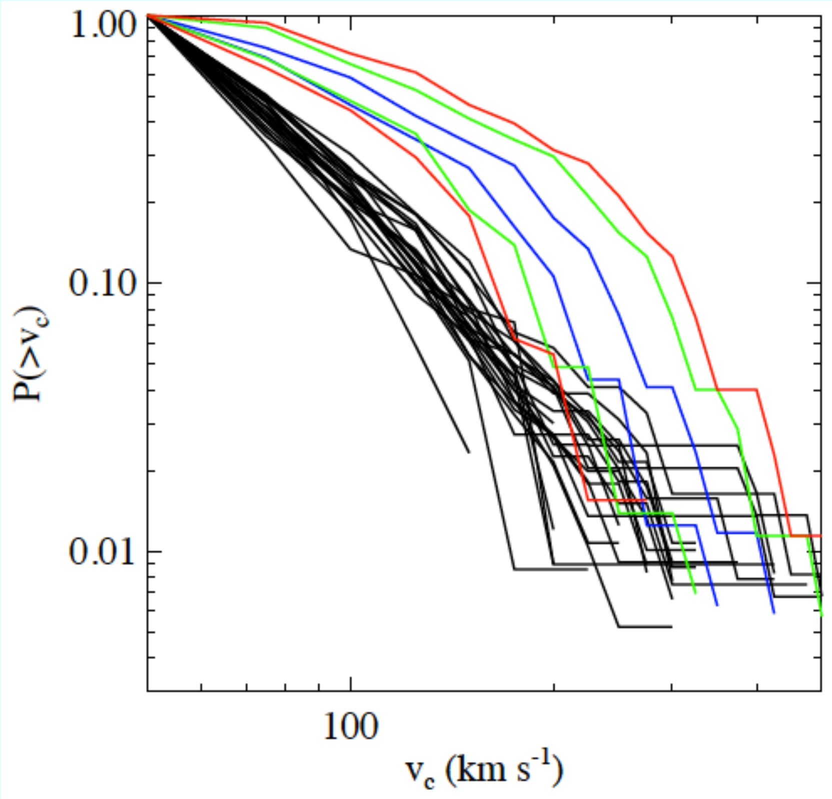


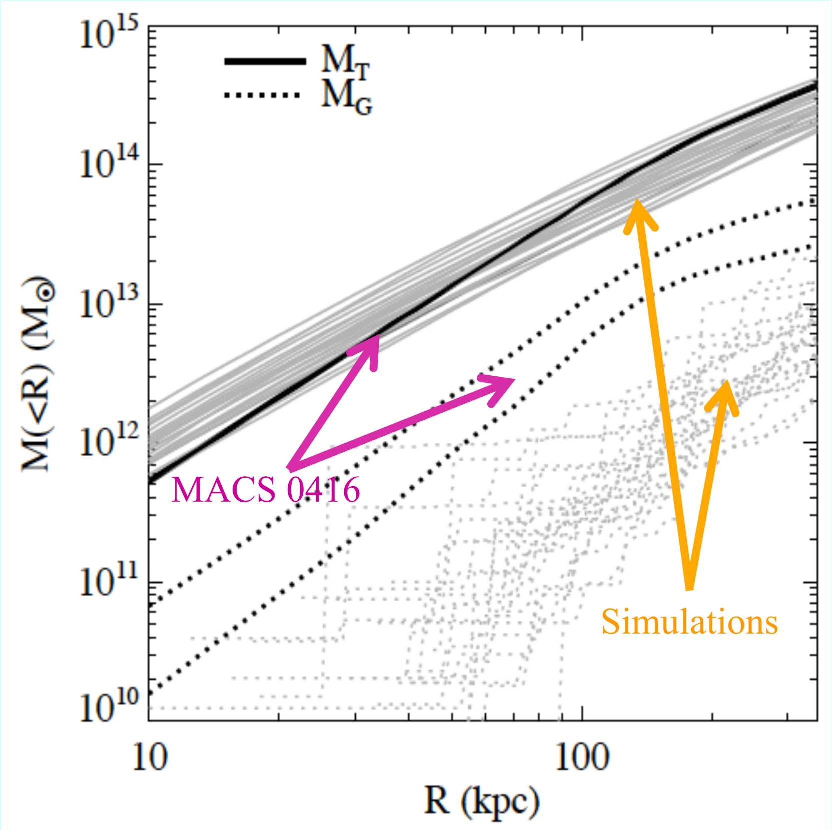




Dark matter density distribution from a high resolution simulation of a massive cluster to the virial radius 1.7 Mpc (e.g. Diemand et al. 2005)

# The galaxy cluster subhalo population II

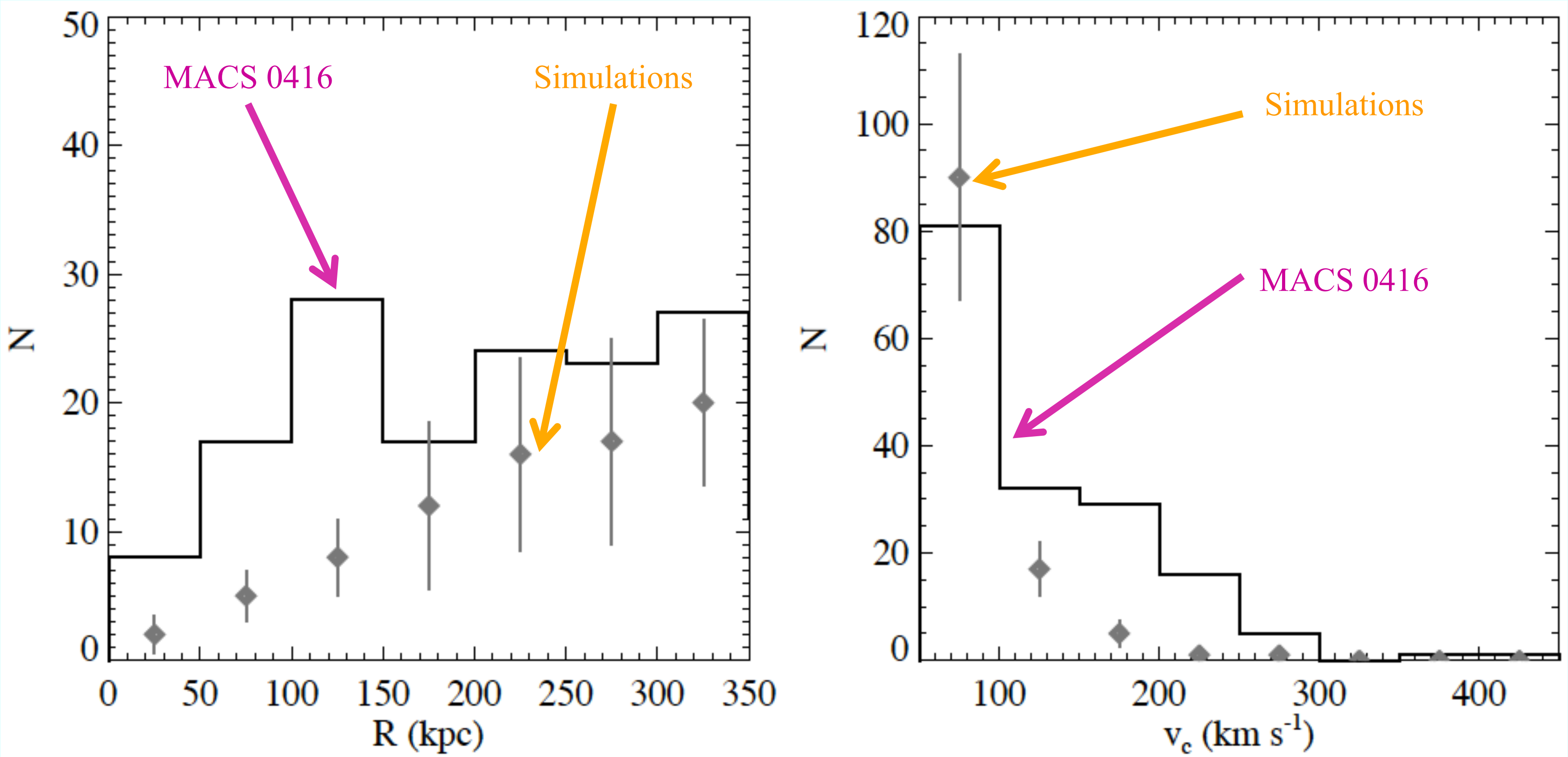



- The reconstructed velocity function of substructure in MACS 0416 from strong lensing at 1σ, 2σ, and 3σ
- Observed velocity function higher and with different shape than for 24 simulated clusters with total mass similar to that of MACS 0416




- Simulated galaxy clusters have less mass in substructure in the inner regions
- Possible explanation in terms of dynamical friction and tidal stripping effects in DM-only cosmological simulations

# The galaxy cluster subhalo population III




- Simulated halos consistently underpredict the number of subhalos on all radial scales (particularly in the inner 150 kpc)
- Simulated clusters have fewer substructures with $v_c$ within ~100-300 km/s (observational results robust here)
- Massive subhalos not formed or accreted so fast into the simulated clusters?
- Tidal stripping of massive subhalos more efficient than observed?

# Conclusions

Most interesting results from this study in the Frontier Fields MACS J0416.1-2403:

- Meticulous galaxy cluster and cluster member mass models can reproduce very accurately the observed multiple image positions

- A detailed reconstruction of the cluster substructure is possible

- A 2D cored total mass profile is preferred to a NFW profile and the cluster DM halos are not centered on the two BCGs

- Careful strong lensing analyses of galaxy clusters and cluster members can lead to new exciting results on their dark matter halos and subhalo population (studies on the dark-matter physics and on the cosmological parameter values)

- HST angular resolution and multiband coverage + VLT spectroscopic redshifts are essential

- Near-IR observations are very useful to select cluster members and trace their total mass distribution