# GRAVITATIONAL LENSING BY GALAXY CLUSTERS

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*with inputs from*

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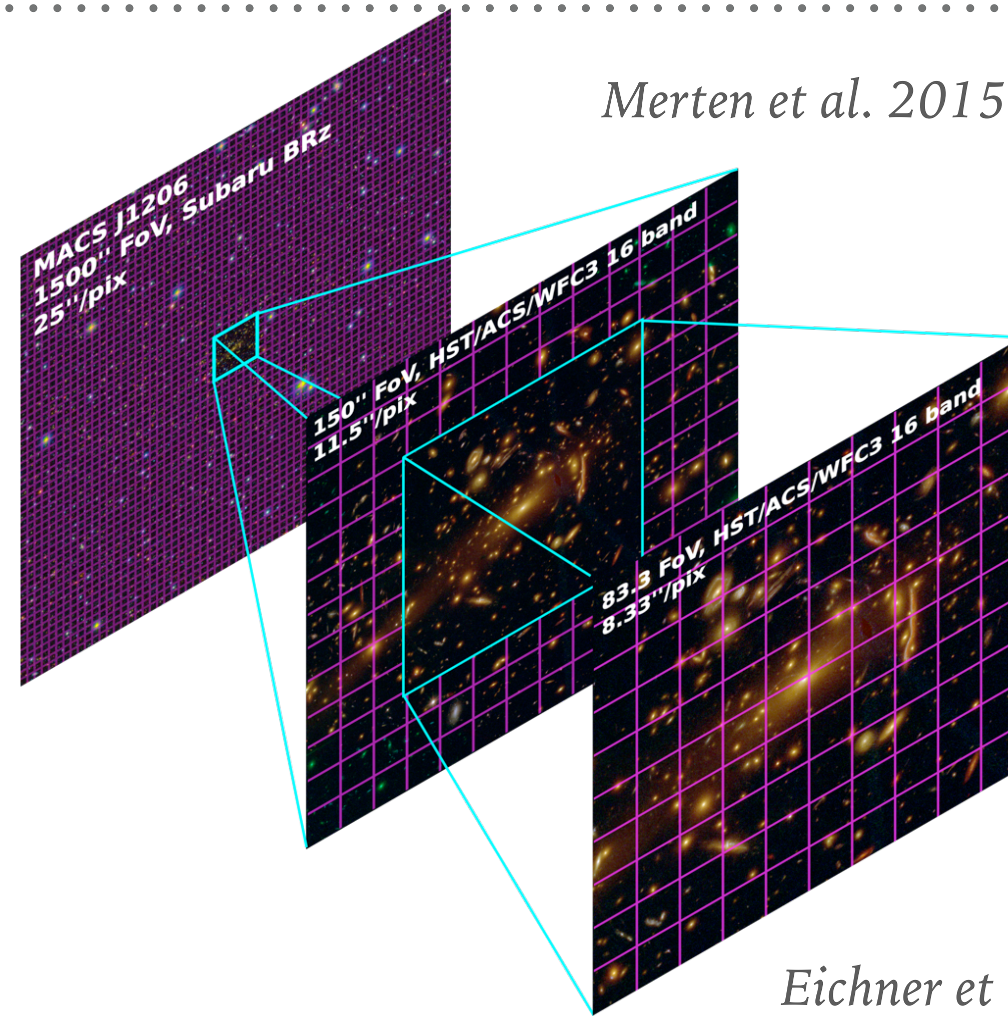
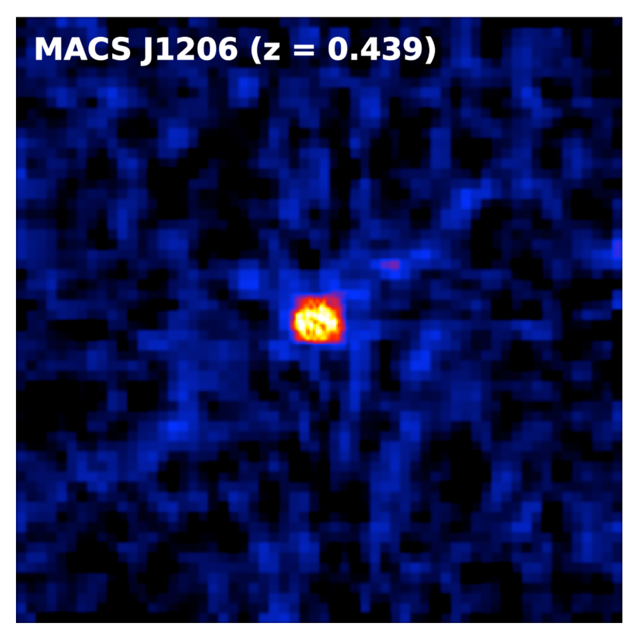
# GRAVITATIONAL LENSING BY CLUSTERS

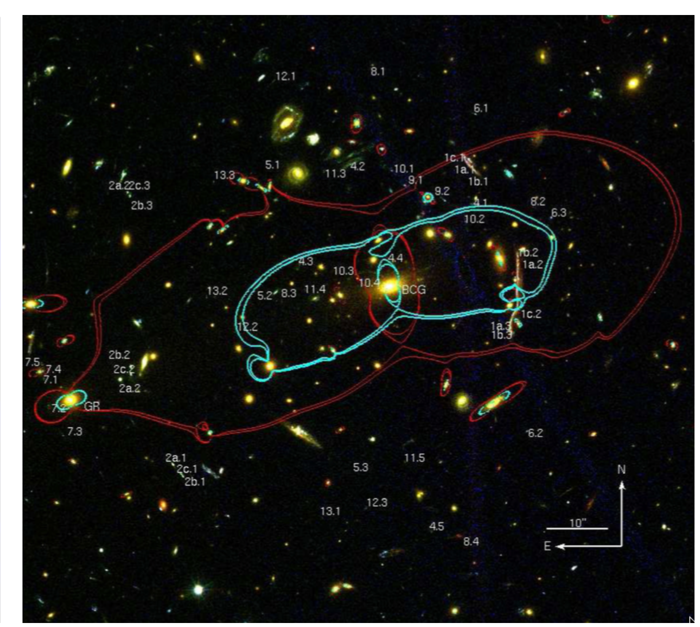
- Gravitational lensing is now recognized as a ***powerful, unbiased*** **tool for probing the mass distribution** of galaxy clusters, enabling a variety of science applications
- All lensing regimes are in action in massive systems like clusters: **from weak to strong lensing**
- The advantage of lensing is that **it does not require to make assumptions on the dynamical state of the cluster** to infer the mass distribution
- The disadvantage is that **it probes the projected mass distribution** and is sensitive to contaminations from line-of-sight structures

*Merten et al. 2015*




*Eichner et al. 2013*



# GROUPS ACTIVE IN CLUSTER LENSING


*Expertise in:*

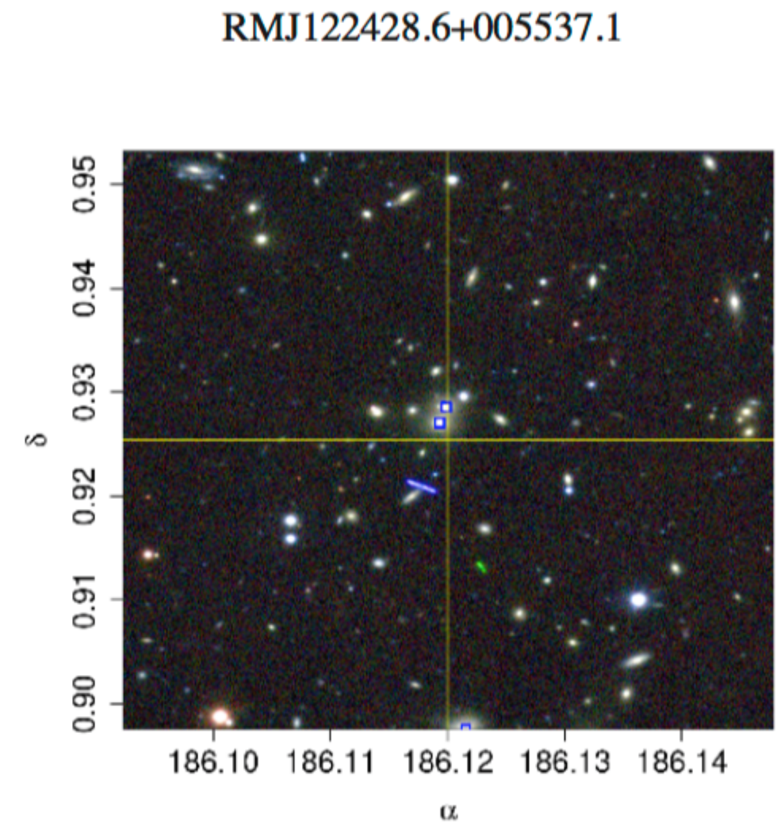
- *lens modeling*
- *theory*
- *simulations*

*Leadership in:*

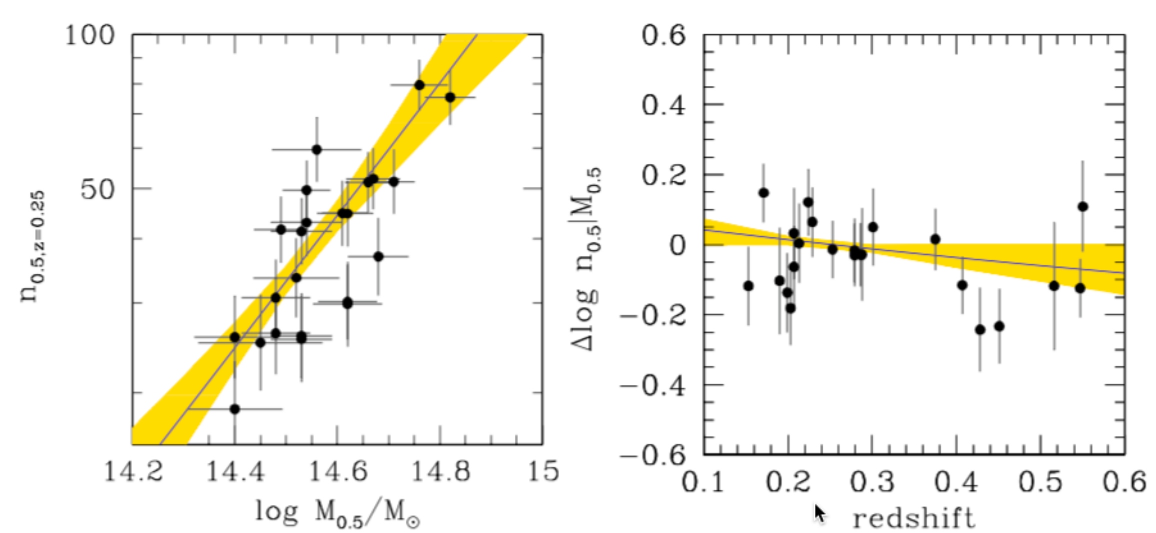
- *Euclid*
- *KiDS*
- *CLASH-VLT*

# CLUSTER COSMOLOGY: CALIBRATION OF SCALING RELATIONS

- **Euclid and Athena are ahead of us [+other large surveys like XXL, eROSITA…]**
- tens of thousands of clusters available for cosmology, provided we measure their masses
- not yet feasible to think to measure lensing masses for all of them, but we can use lensing to calibrate scaling relations, e.g. **Mass-Richness, M-(X-ray observables)** [e.g. Andreon & Congdon 2014; Sereno & Ettori] (see A. Biviano's talk)
- groups in **Padova, Bologna and Napoli** (*M. Radovich, L. Moscardini, F. Bellagamba, M. Roncarelli, G. Covone,…*) are working on efficient algorithms for detecting photometrically galaxy clusters
- algorithms being tested and used on **KiDS** data, being challenged by others for implementation in Euclid
- currently working on an area of ~**100 sq. deg.** from the KiDS survey
- shortly moving to **~450 sq. deg**. (including the GAMA areas). KiDS covers 1500 sq. deg. of sky
- **KiDS provides accurate imaging for the WL analysis:** ideal for measuring WL masses and calibrate scaling relations



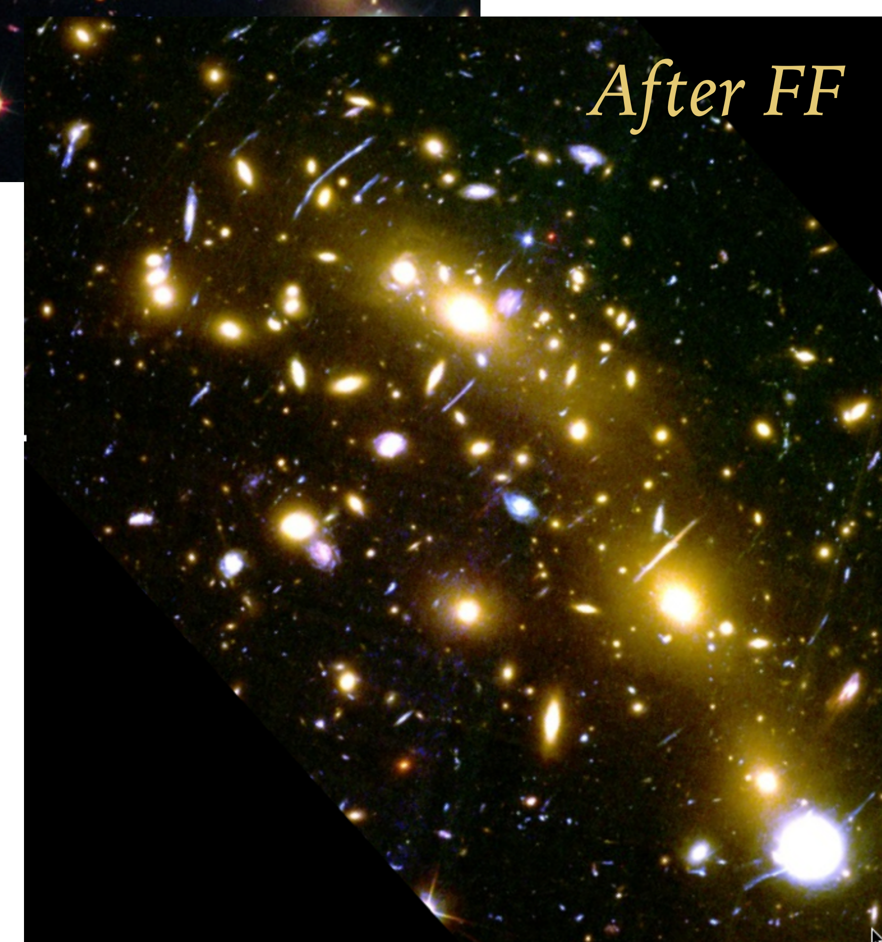

*Radovich et al. 2016*




*Andreon & Congdon, 2014*

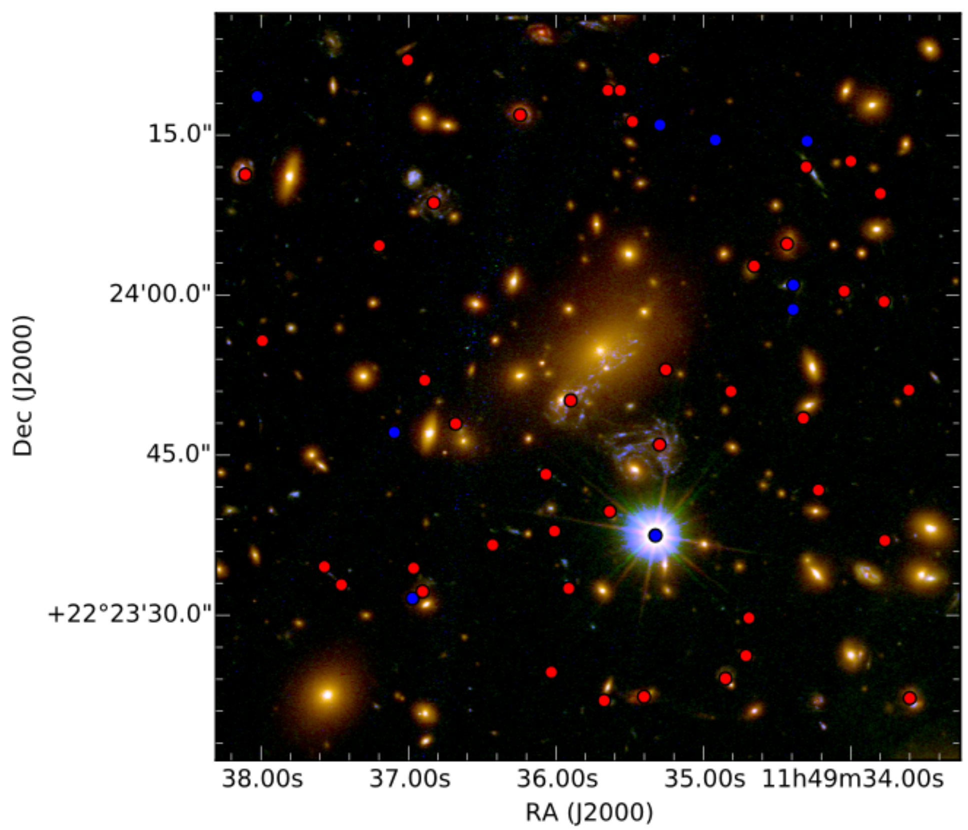
# MASS MODELING: THE IMPORTANCE OF SPECTROSCOPY

- **CLASH and the Frontier Fields** represent a huge investment of resources by the HST (524+800 orbits to observe 25+6 clusters) **producing the best dataset for cluster lensing ever**
- **to exploit these data at best we need robust mass models**
- spectroscopy is an overwhelmingly important complement to any lensing analysis
- key ingredients for modeling: **source redshifts, cluster membership, member masses** (in particular for SL)
- the **CLASH-VLT collaboration** (*Ferrara, Trieste, Milano, Napoli, Bologna,…*; **PI Rosati**) is producing redshift catalogs for the lensing (and dynamical — see A. Biviano's talk) analysis of the CLASH and of the FF data

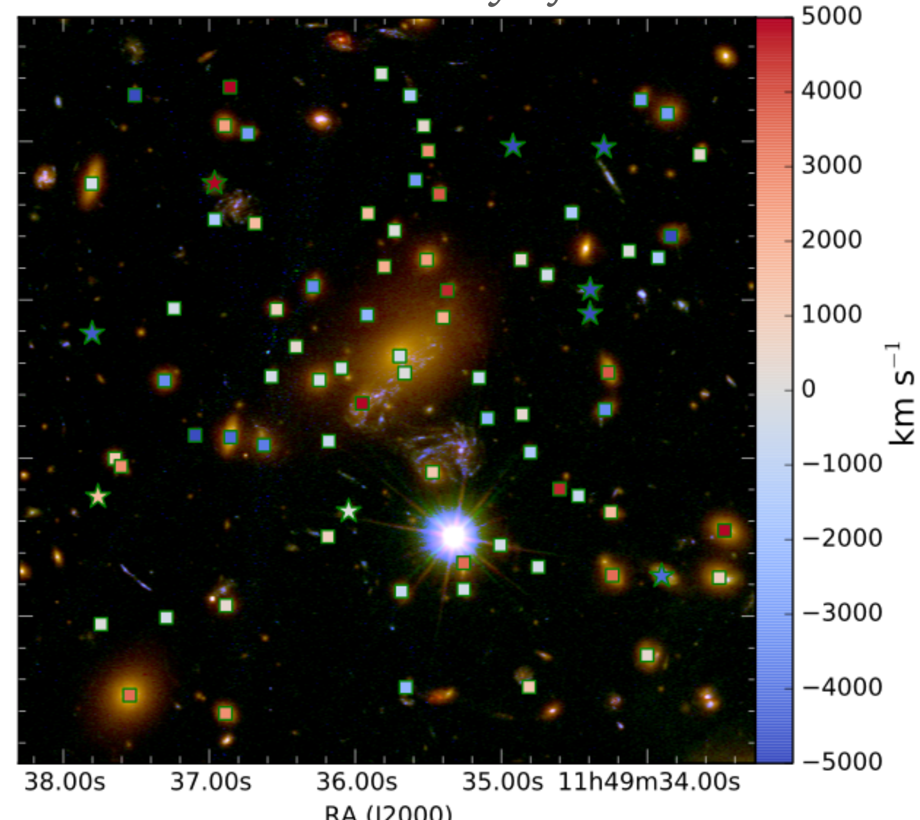



*Multi Unit Spectroscopic Explorer, 24 IFU, 1 arcmin$^2$, sp. res. 0.2”, R=3000, 4800-9300A*

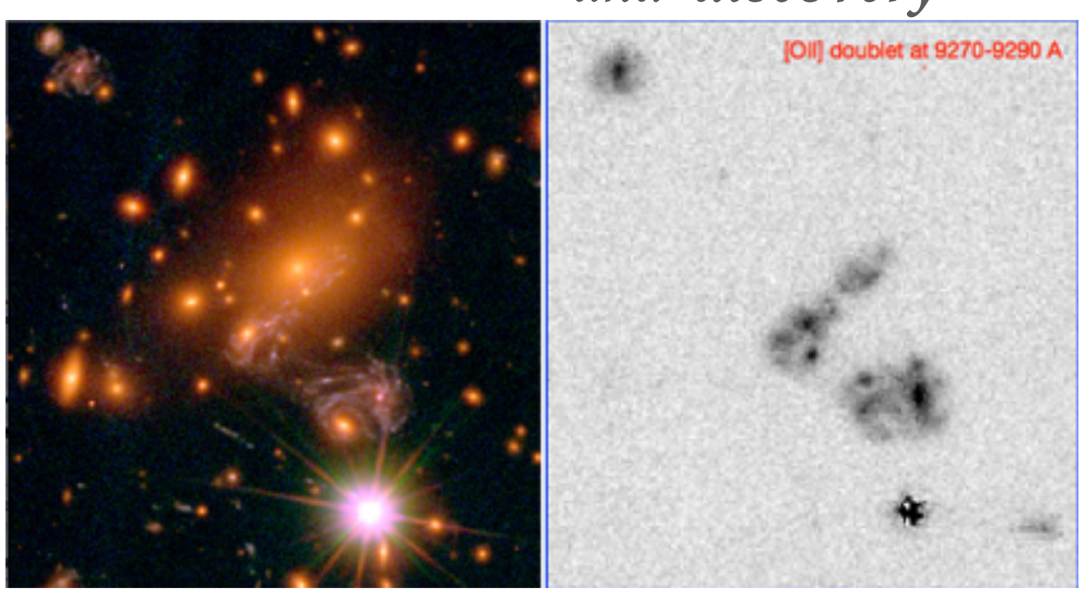
*Courtesy of C. Grillo*




*Lensed sources: confirmation and* ***discovery***




*Cluster membership, masses of cluster galaxies*

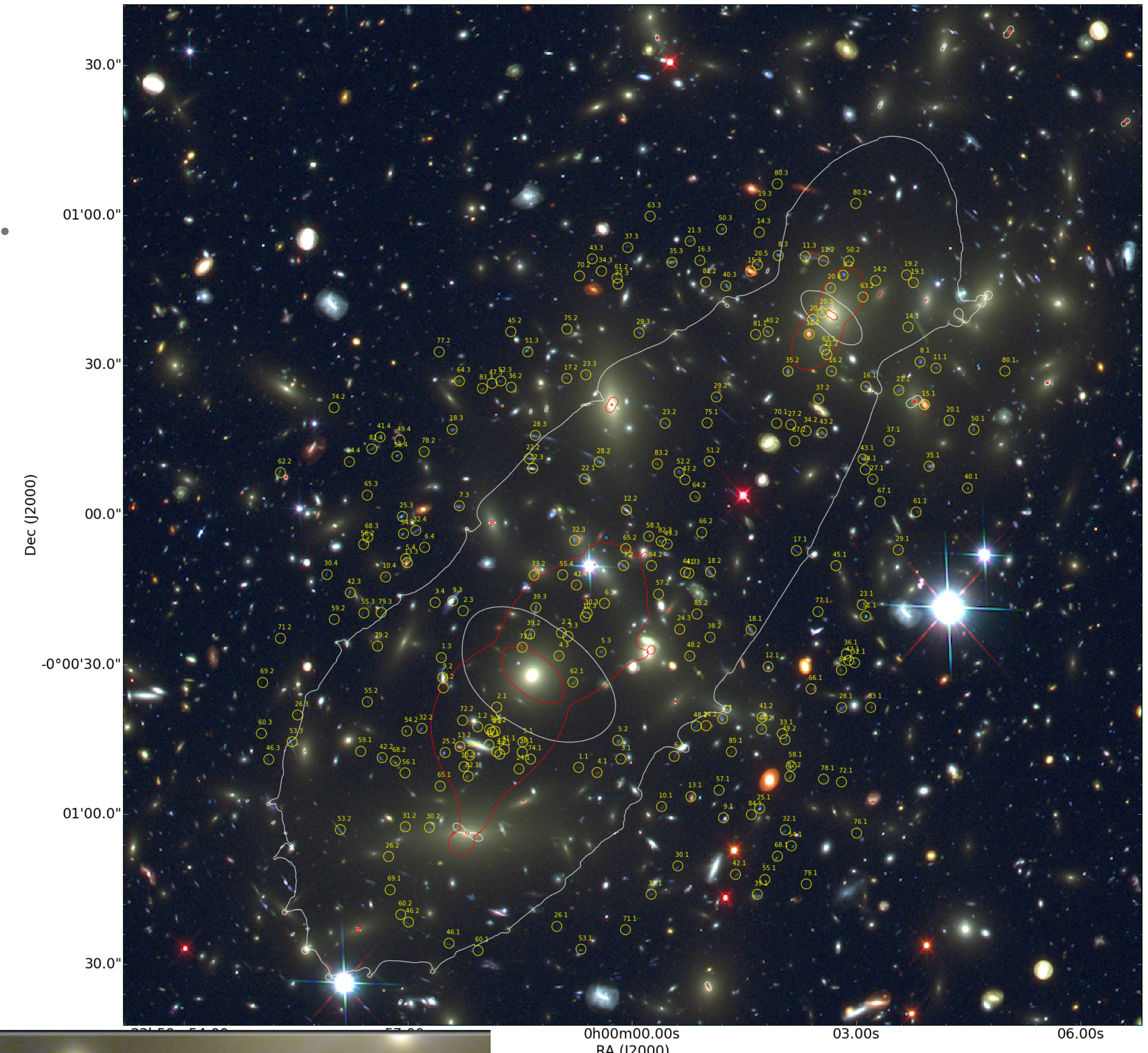


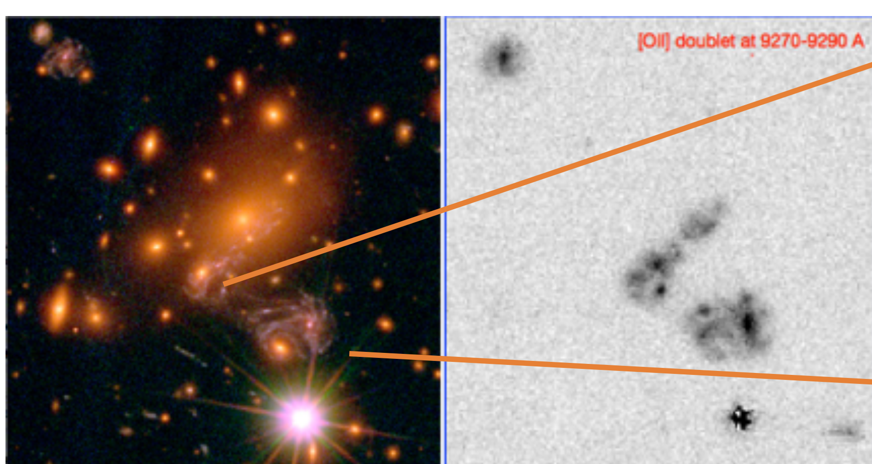

*in the case of line-emitters, MUSE allows to isolate single sources making very easy the identification of multiple images*

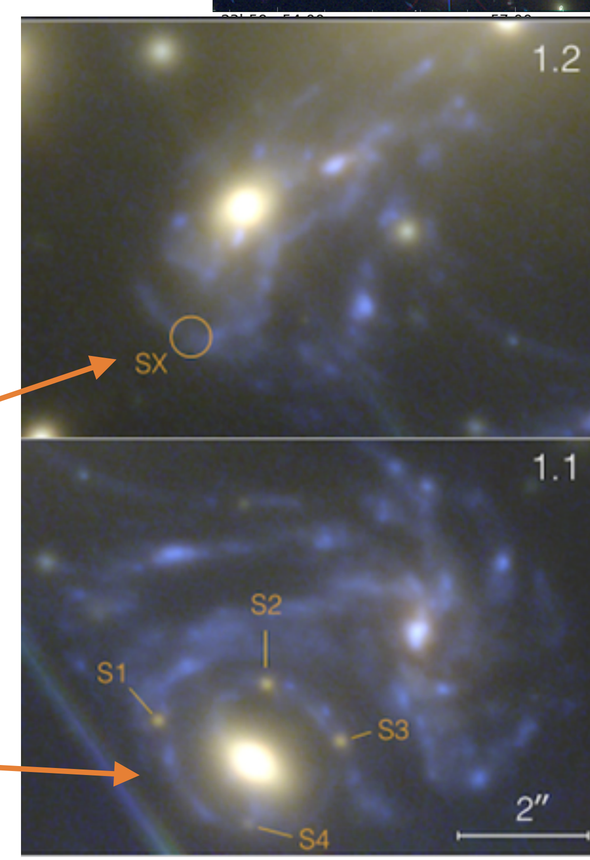
# ROBUST MASS MODELS

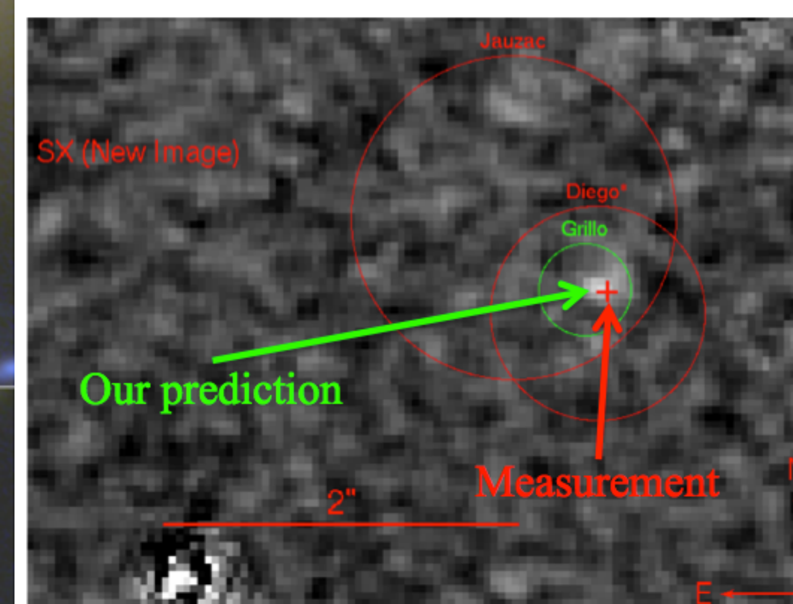
- with redshifts measured for >100 multiple images and accurate membership information, very robust mass models can be built
- tested with image simulations (Meneghetti et al. 2016)
- and also in nature thanks to the multiply lensed  SN “Refsdal” observed in MACS1149
- capable of predicting (~one year before) the re-appearance of the supernova “Refsdal” in one of the host multiple images within ~0.1”!!! (Grillo et al. 2016, Kelly et al. 2016)

*Meneghetti et al. 2016*




SX Position

*Kelly et al., 2016*

# SCIENCE ENABLED BY CLUSTER LENSING

- the combination of SL and WL (+stellar kinematics if possible) allows to measure **mass density profiles from few kpc to the viral radius**.
- SL models can be used to **trace the mass in substructures**. Improvements are expected if second order lensing effects are measured (group in Rome — V. Cardone)

*What is the nature of DM? Does CDM work on cluster scales?*

- Lensing magnification allows to detect faint and high redshift sources. The CLASH and the FF clusters, used as cosmic telescopes, have provided a catalog of ~300 candidates at $z>6$ and up to $z\sim10$. Most of them will be followed-up with JWST. Magnification also allow to spatially resolve sources at $1<z<2.5$. **Robust mass models allow to de-lens and thus *characterize* magnified sources**.

*Which sources re-ionized the universe? How did galaxy formation proceed?*

- the combination of lensing, X-ray, SZ observations can be used to **constrain the 3D shape of galaxy clusters**, further improving the precision of the mass measurements by mitigating projection effects (CLASH-3D, M. Sereno et al.)
- Robust mass models can be used for **lensing cosmography**: once the lens is known, lensing of sources at different redshifts can be used to probe ratios of angular diameter distances
- Other cosmological application of lensing by clusters include **arc and Einstein ring statistics**

*Which is the favored cosmological model? What is the nature of dark energy?*