Unveiling the First Galaxies through E-ELT and Cosmic Lenses

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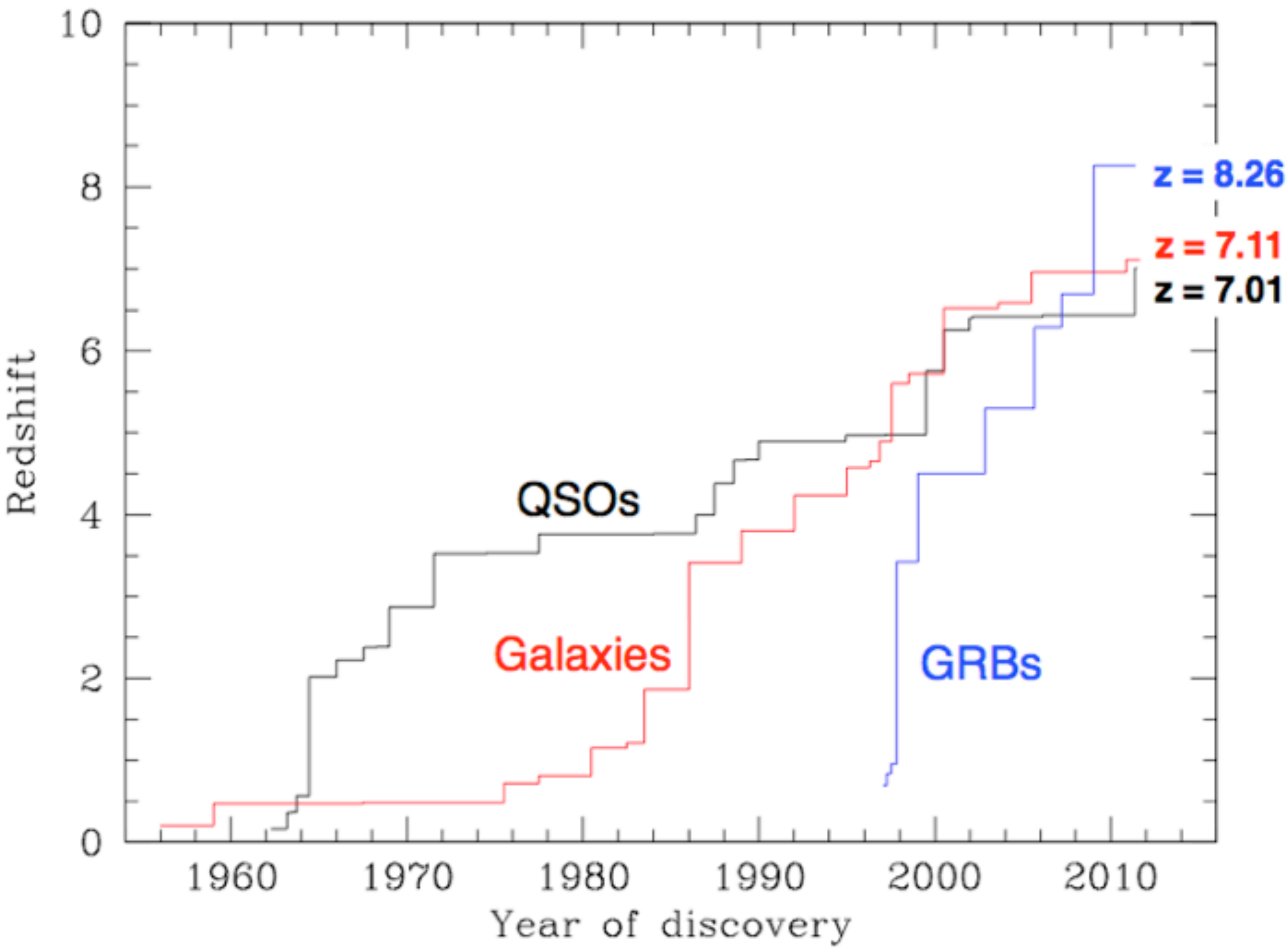
Outline

- Distant Galaxies Science (see Jim Dunlop talks)
- Basics on Cluster Strong Lensing
- Using Clusters as Cosmic Telescopes
- E-ELT Spectrograph for Cosmic Telescopes

The most distant objects:

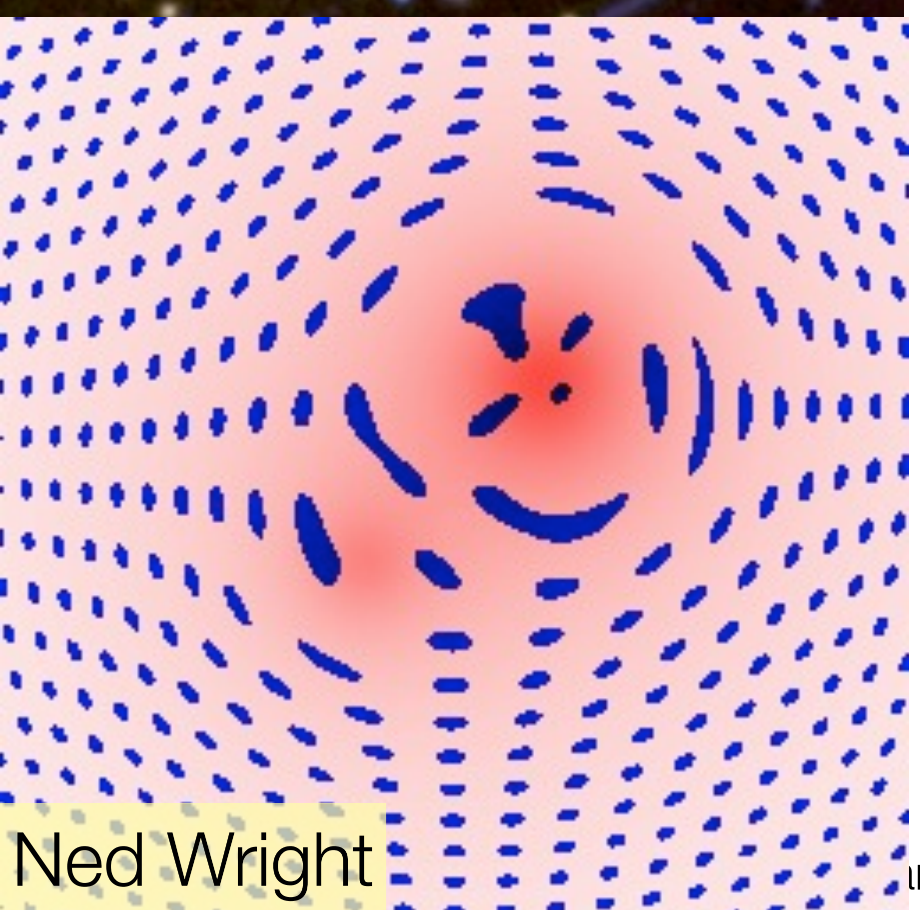


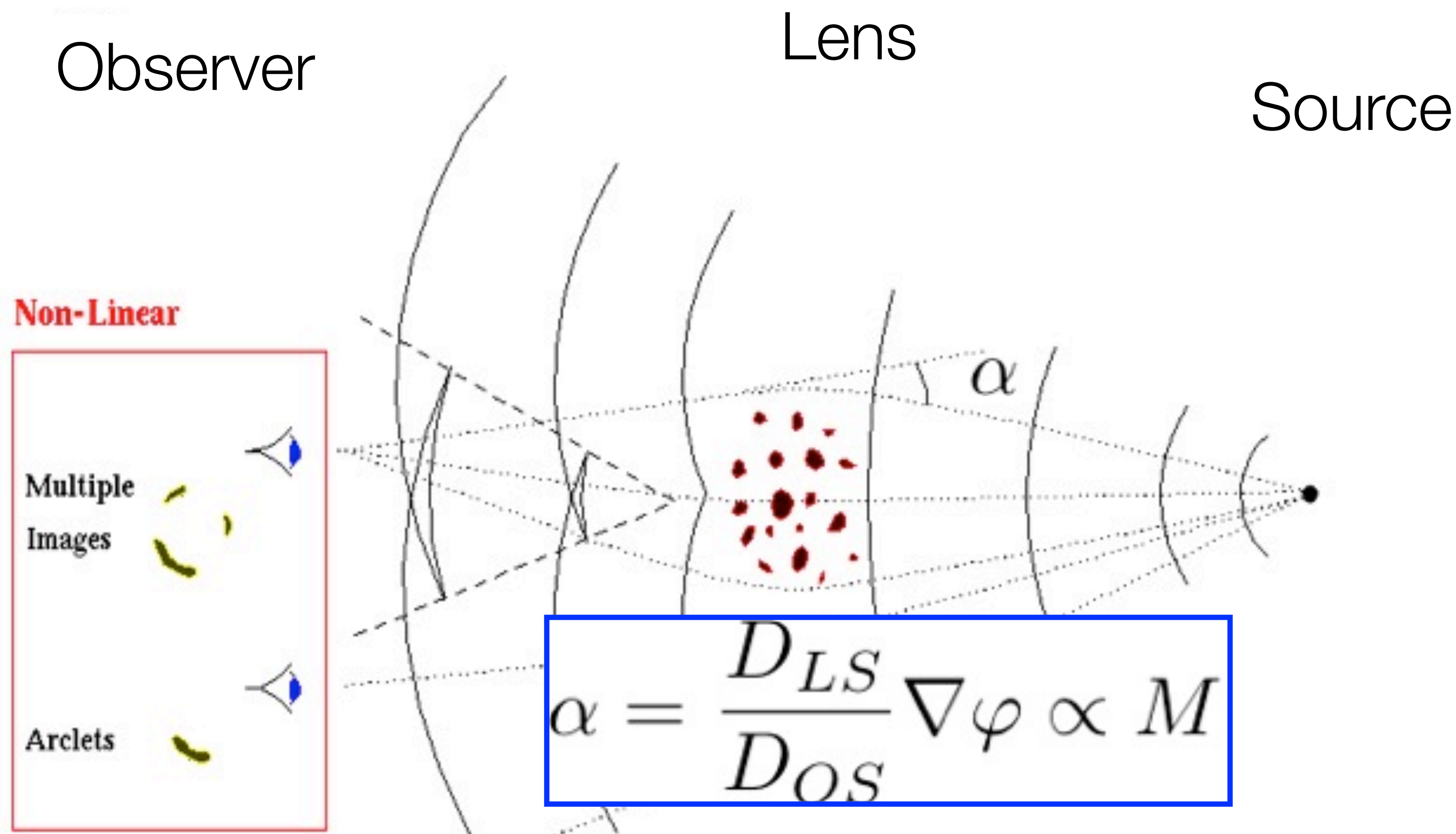
Steady redshift increase of the most distant objects! (spectro-z)

Recent rate is: $dz/dt=0.3\ yr^{-1}$ for galaxies.

In 10 years we will hit z~12 ! Really? (JWST? **E-ELT**?)

Boosting the E-ELT with Gravitational Lensing in Massive Clusters

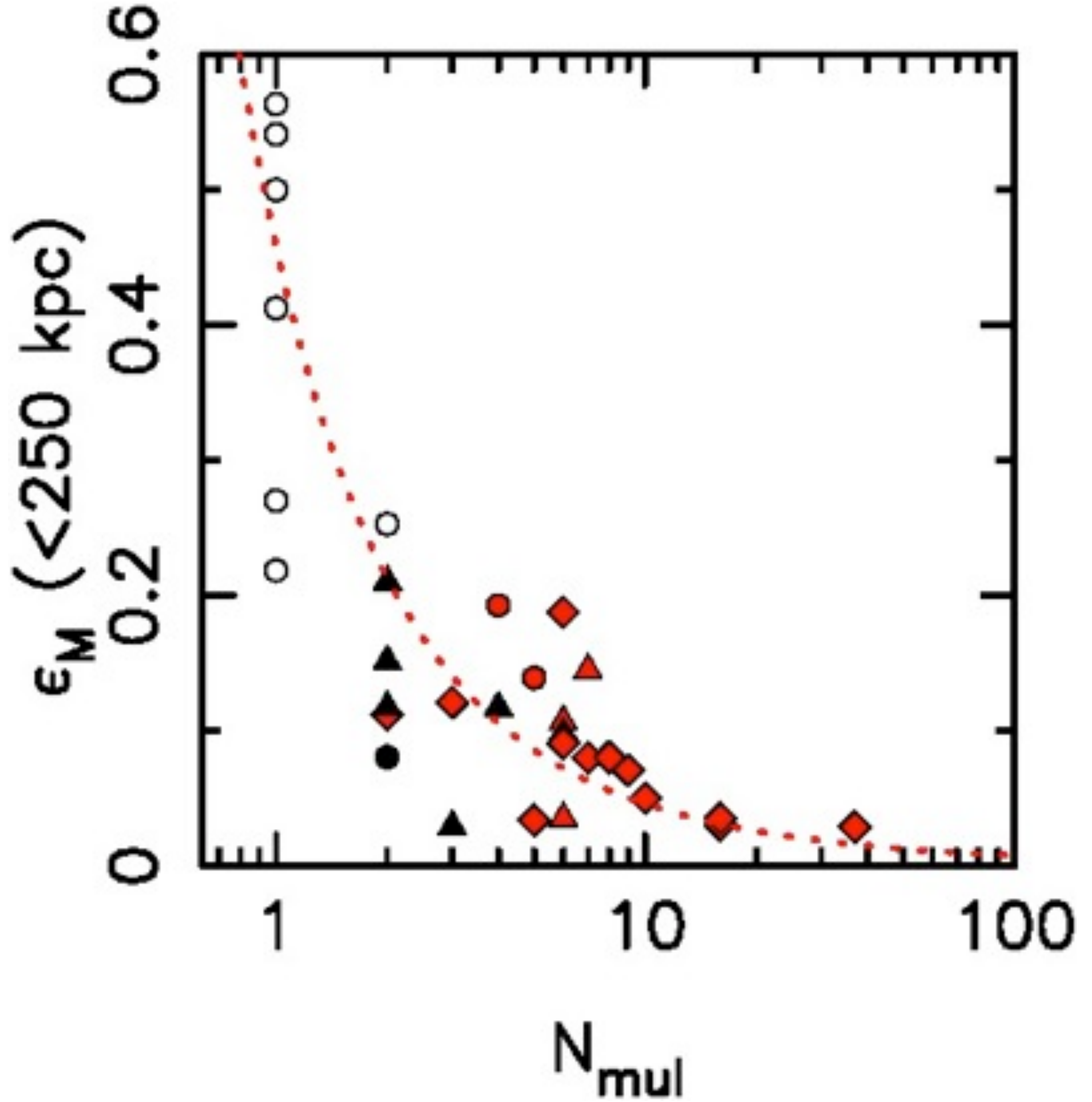


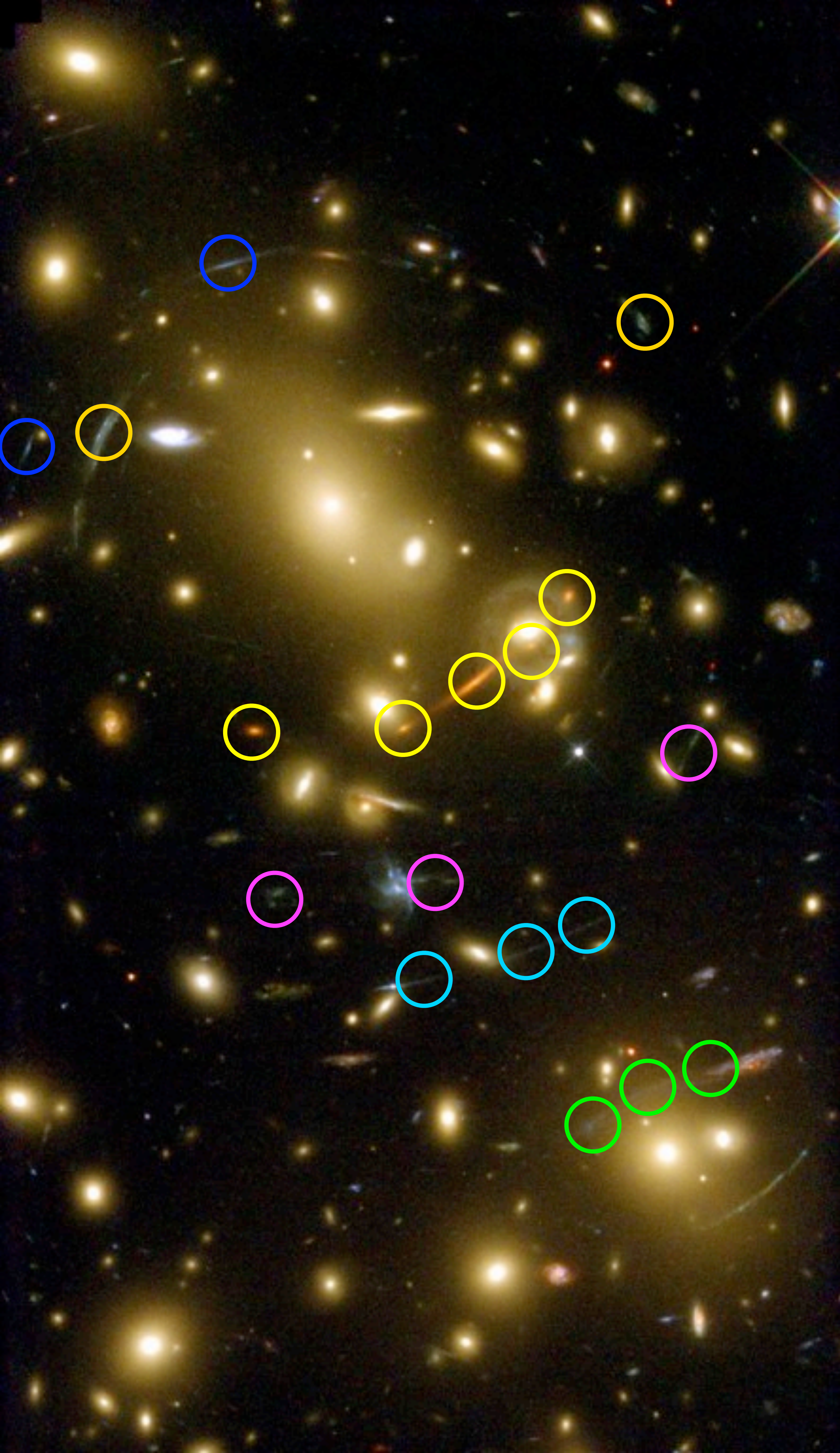


$$\alpha = \frac{D_{LS}}{D_{OS}} \nabla \varphi \propto M$$

Typical Cosmic Telescope

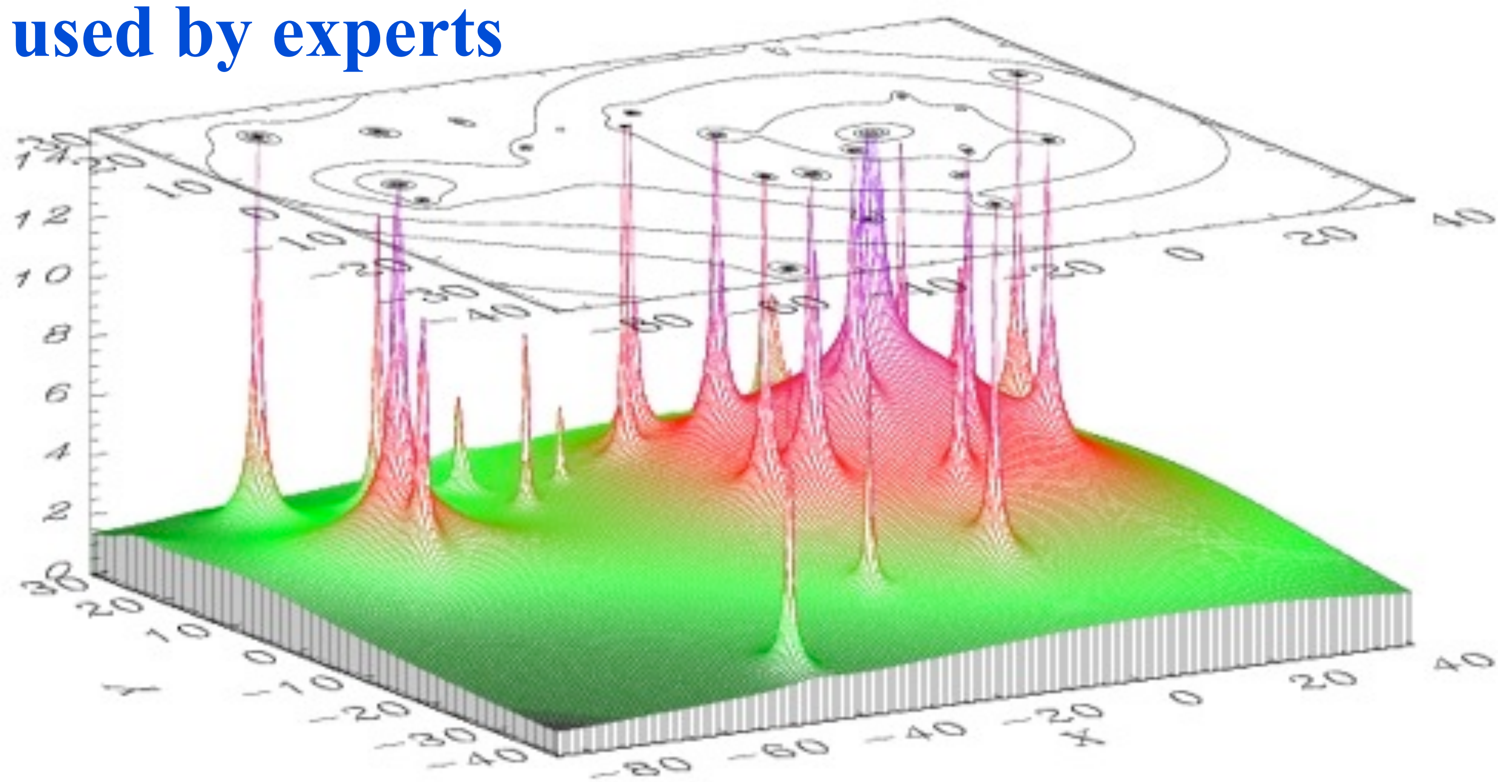
- Einstein radius 20-40”
- 100’s of sources strongly amplified to AB~27
- ~1 massive cluster per 10 deg^2
- Thousands massive clusters - *hundreds known and modeled*
- Mass Model accuracy directly linked to image depth - reaching ~1-3% level (current best observations)





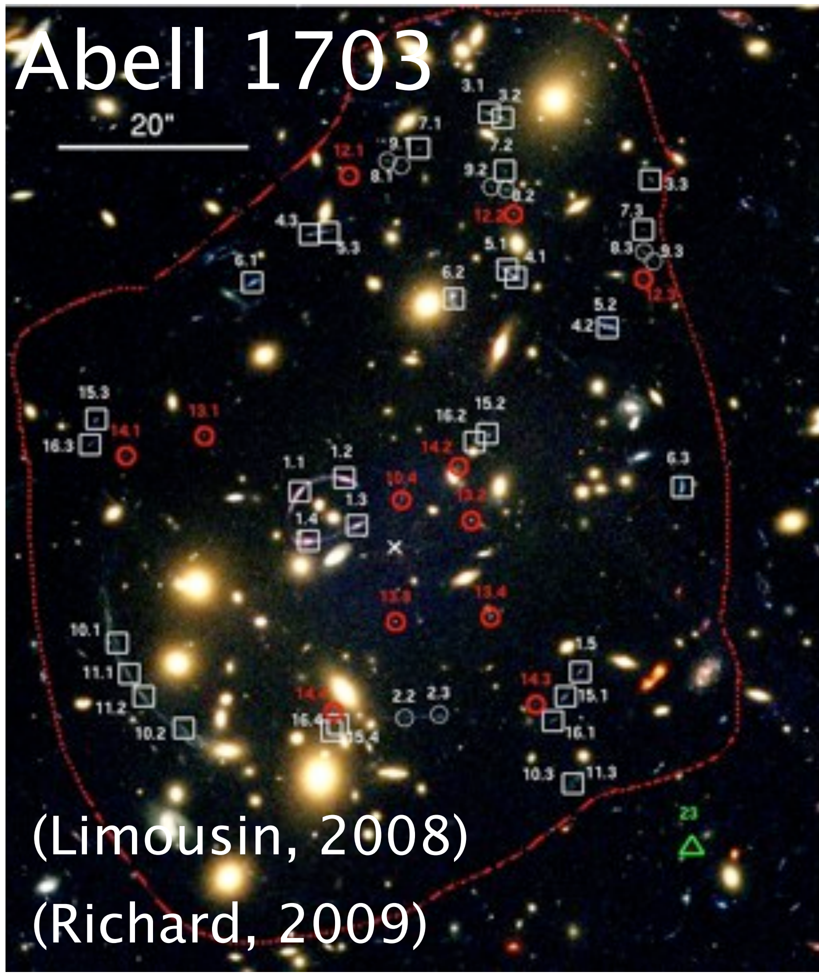
Modeling Cluster Mass Distribution

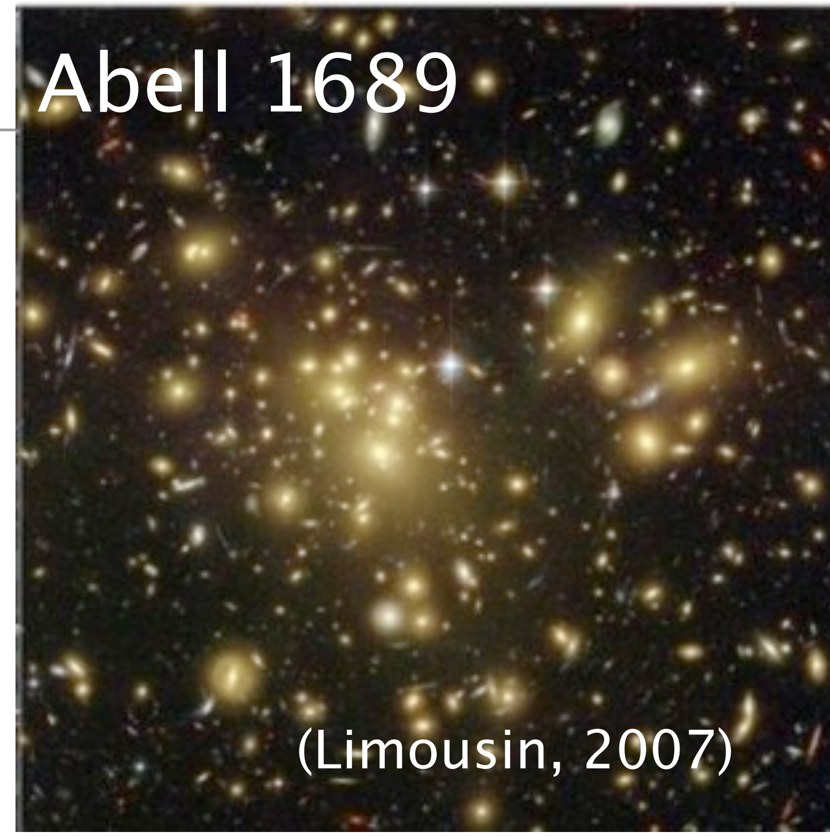
- **Identify multiple images, measure their redshift**
- Model the cluster by a sum of: *cluster components (**DM+X-ray gaz**) and dark halos around galaxy clusters* (**galaxy dynamics**)
- Galaxies halos contribute for ~10% of the total mass budget in cluster cores
- **Lenstool software, MCMC optimisation (Jullo et al 2007, Jullo & Kneib 2009), widely used by experts**

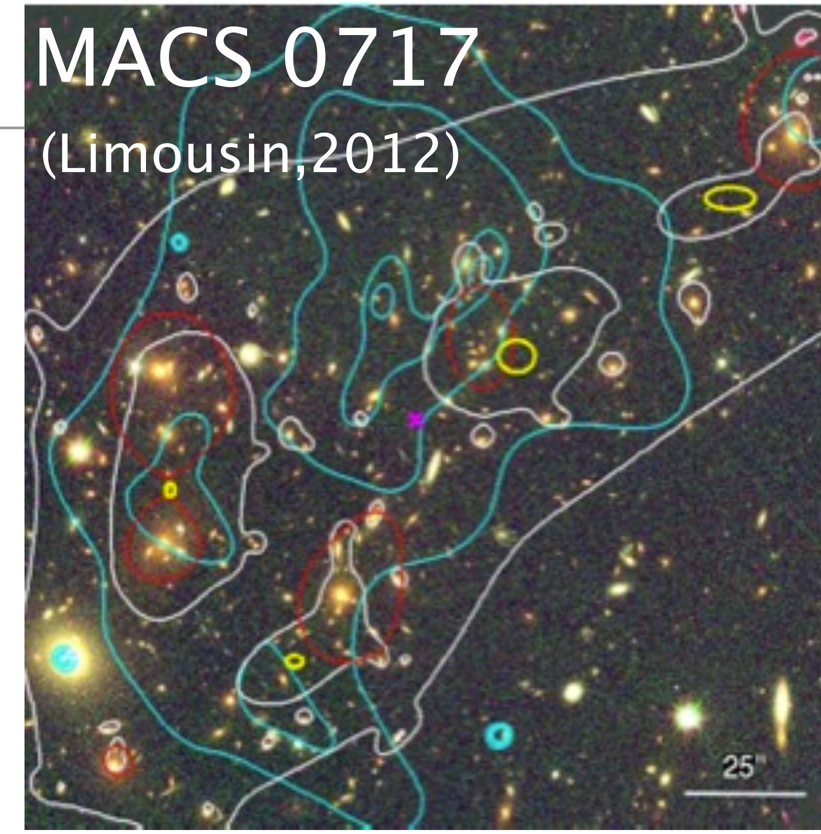


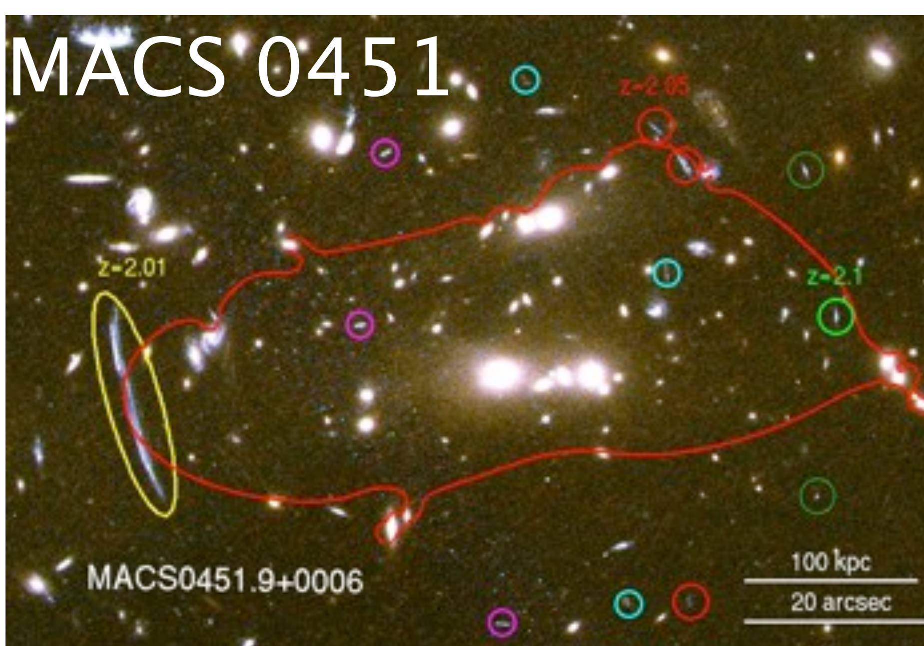
Many cluster lens mass models !

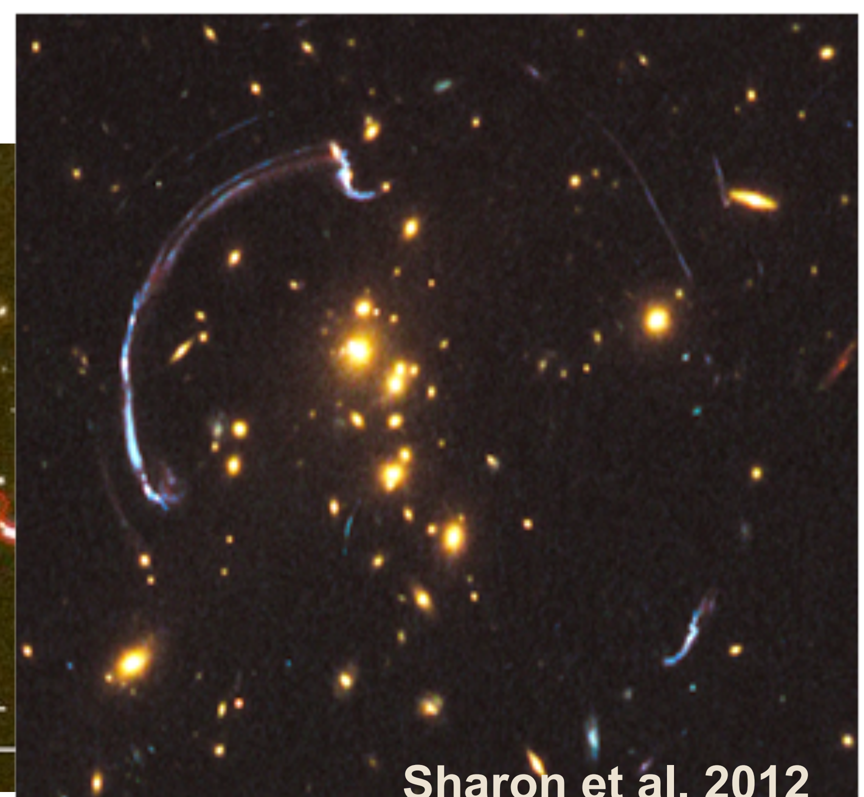
~100 massive clusters modeled ... and number is growing!

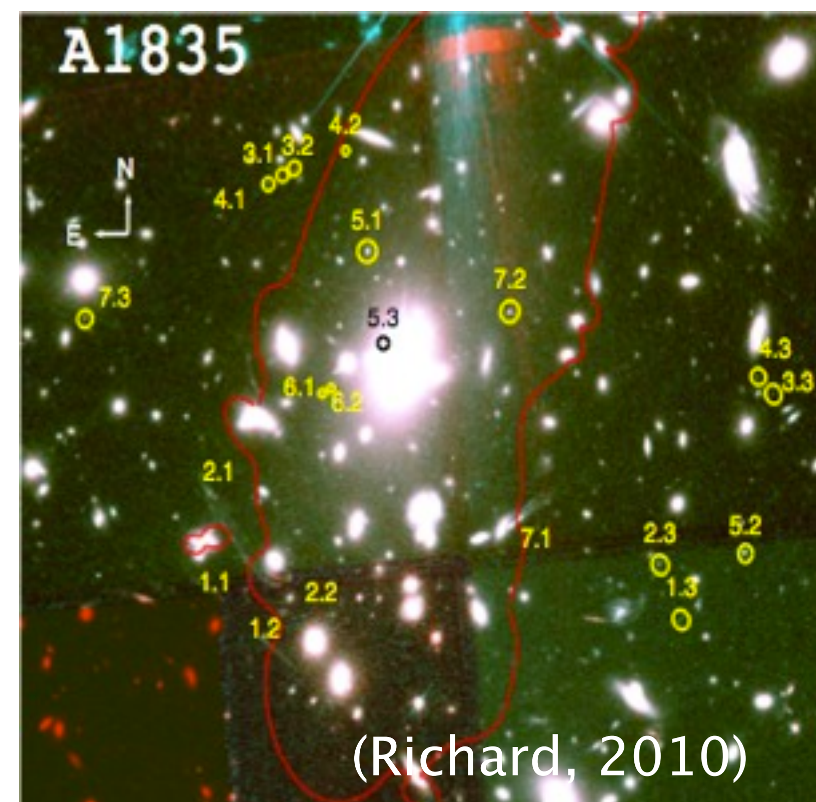




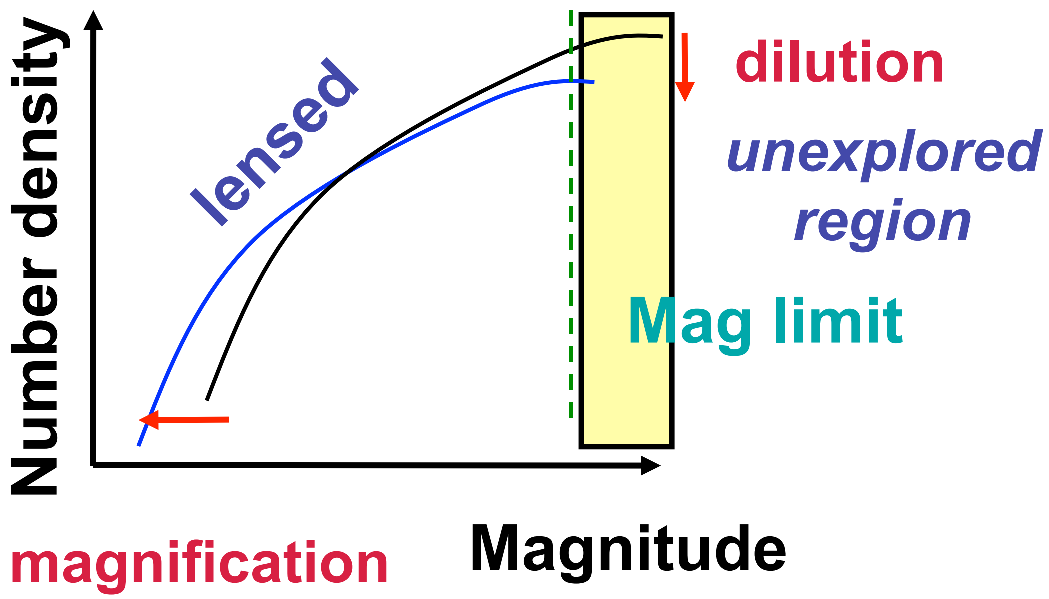




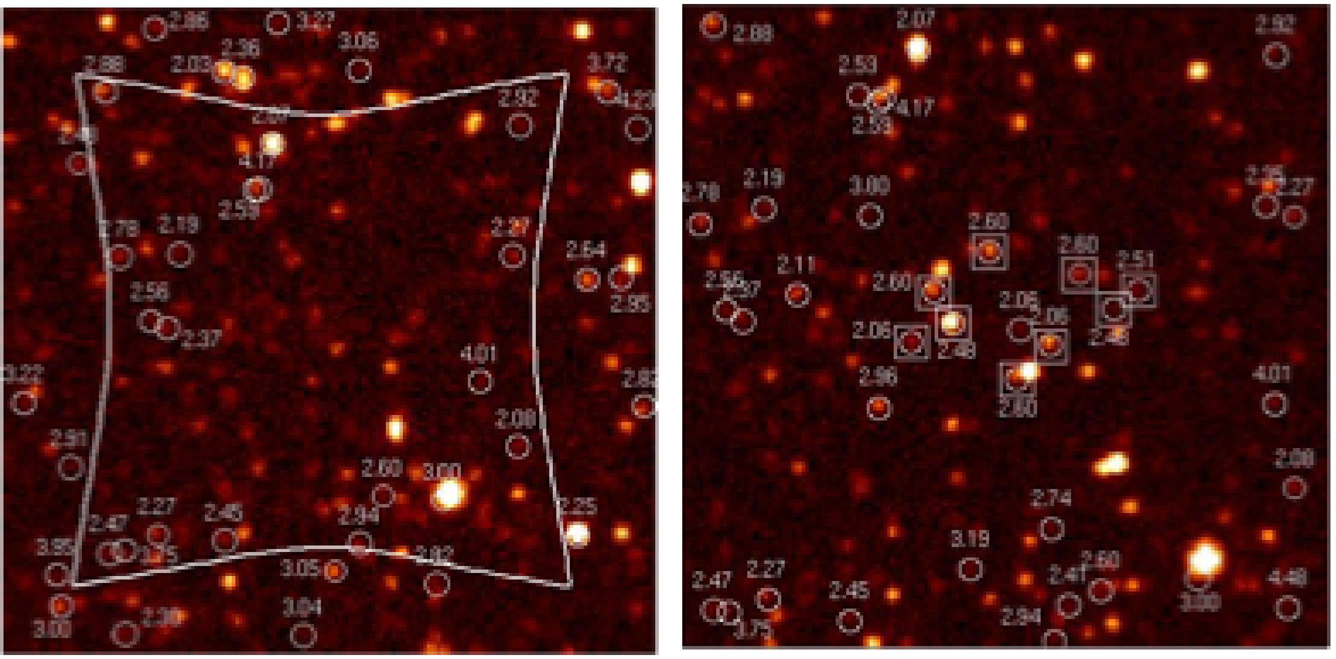




Clusters as a Cosmic Telescope



7x7 arcmin^2 Herschel simulation



Unlensed field Lensed field

- Source plane, Image plane transformation

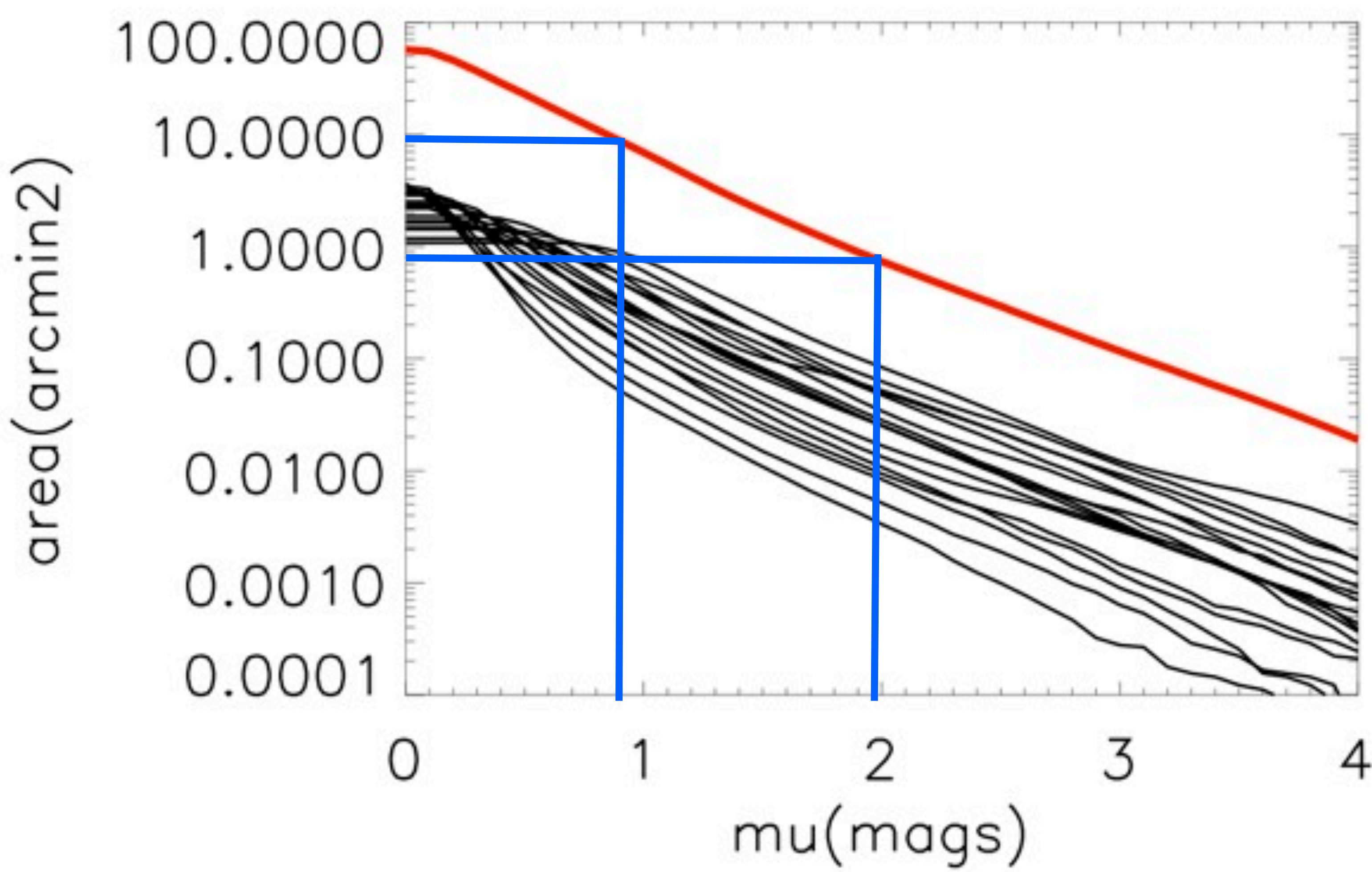
  $$N_L(f)=N_0(f/A)/A$$

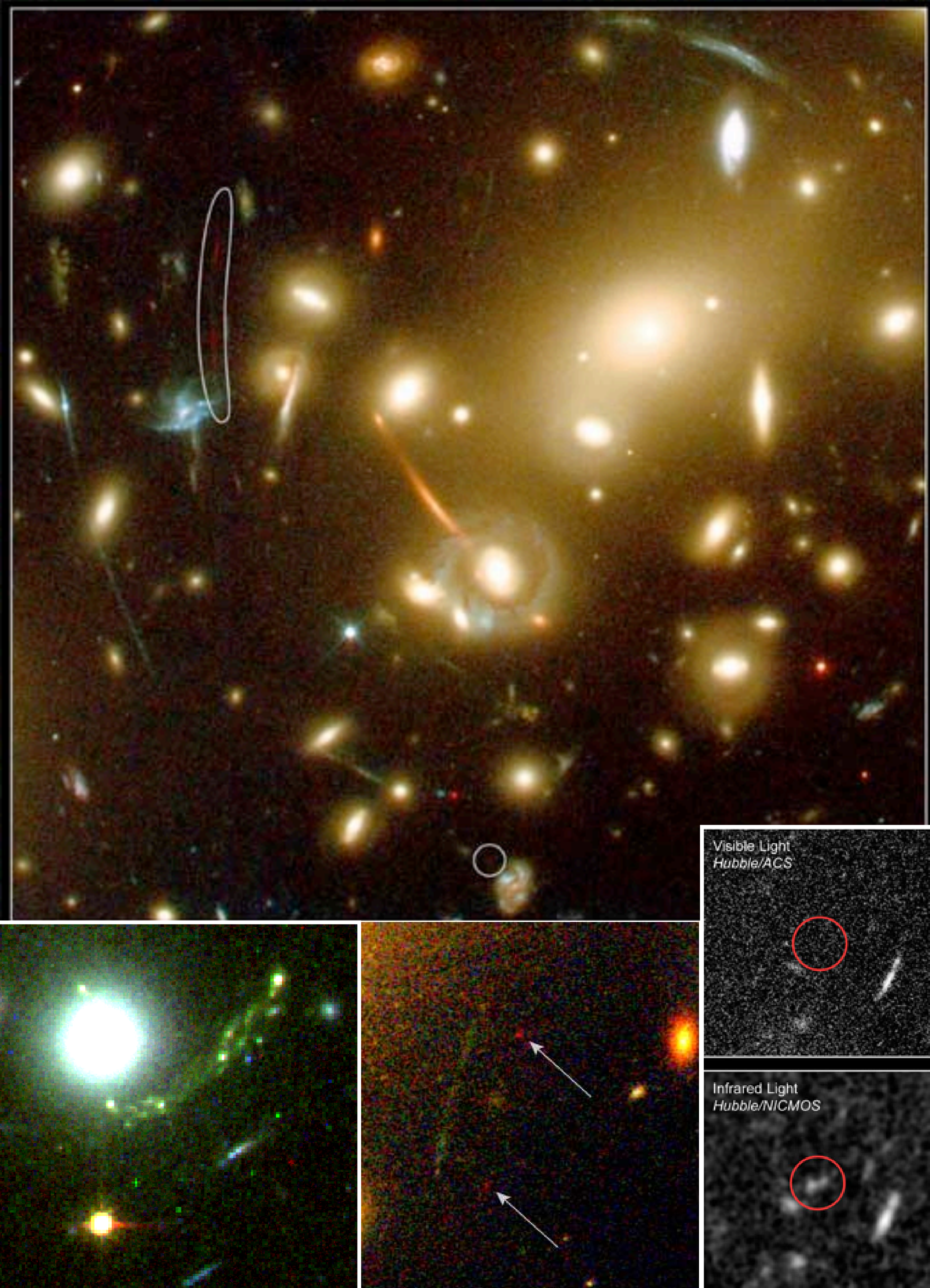
  - Magnification of sources
  - Dilution of area

- Benefits of cluster-lens obs:
  1. **Magnification**, makes spectroscopic follow-up/size measurement possible for most amplified sources
  2. Observe below the usual detection limit (faint luminosity)
  3. Multiple images confirmation of strongly lensed sources
  4. Avoid confusion (important in FIR/Submm)

High Magnification vs. Area Surveyed

- Cosmic Lenses provide higher magnification over smaller area
- Need to probe many cluster lenses
- For 25 clusters observed with a 5 arcmin^2 field of view
- we have typically:
  - 2 mag of magnification over 1 arcmin^2 (in source plane)
  - 0.9 mag of magnification over 10 arcmin^2 (in source plane)
- Importance of surveying many clusters to probe the rare highly-magnified sources

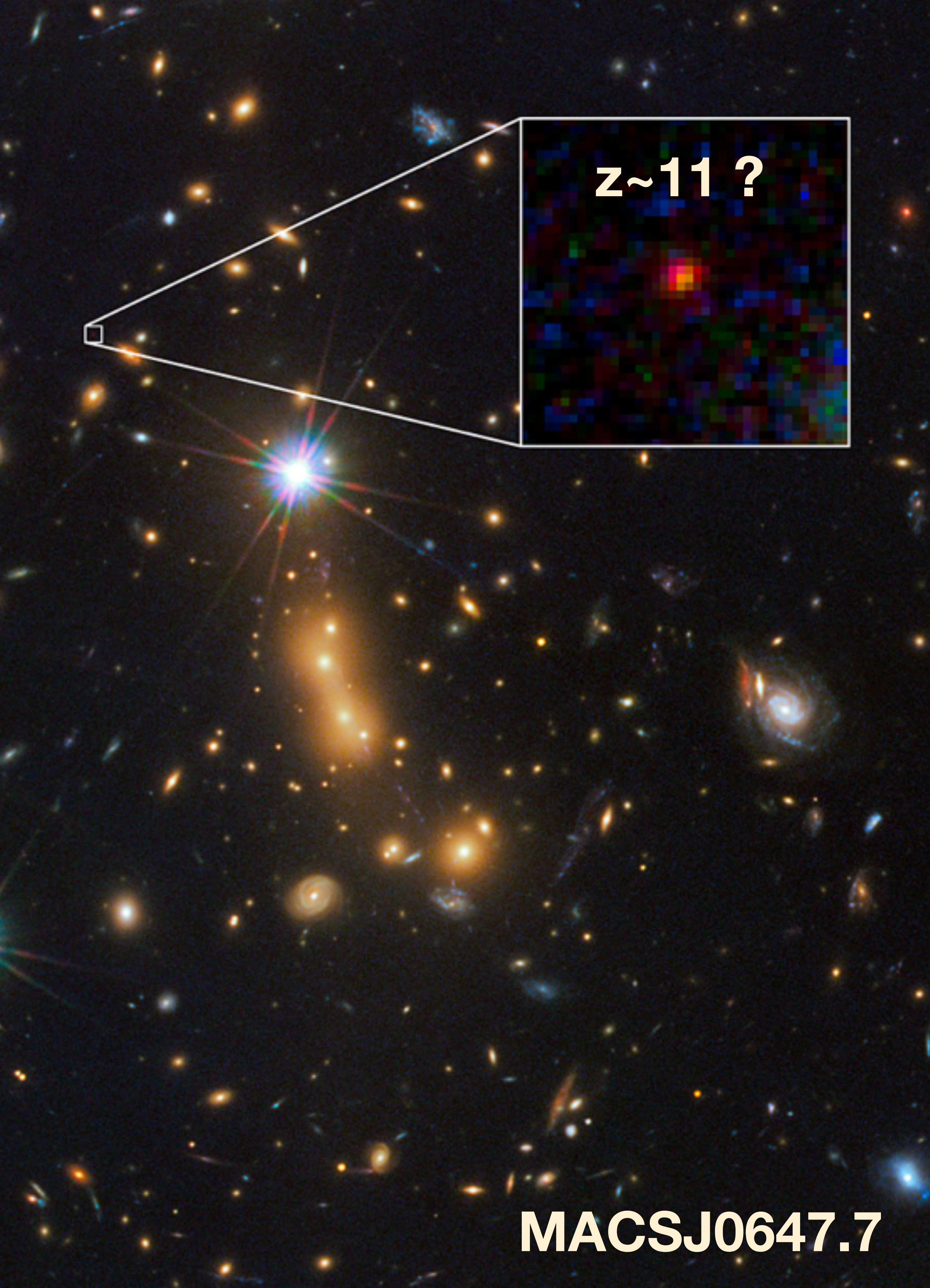




Cluster Lenses as Cosmic Telescopes

High redshift galaxy search:

- **Franx** (1998): z=4.91 [MS1358]
- **Ellis**(2001): z=5.578 [A2218]
- Hu(2002): z=6.56 [A370]
- **Kneib**(2004): z~6.8 [A2218]
- Pello(2004): z=10.0 ??? [A1835]
- Stark(2007): z~9.5 ??? [survey]
- **Bradley**(2008): z~7.6 [A1689]
- Richard (2009): z=5.827 [a1703]
- Richard(2011): z=6.027 [A383]
- Bradley(2012): z~7 [A1703]
- Bradac(2012): z=6.74 [Bullet]
- **Zheng**(2012): z~9.6 ! [MACS1149]
- **Coe (2012): z~11 ! [MACS0647]**



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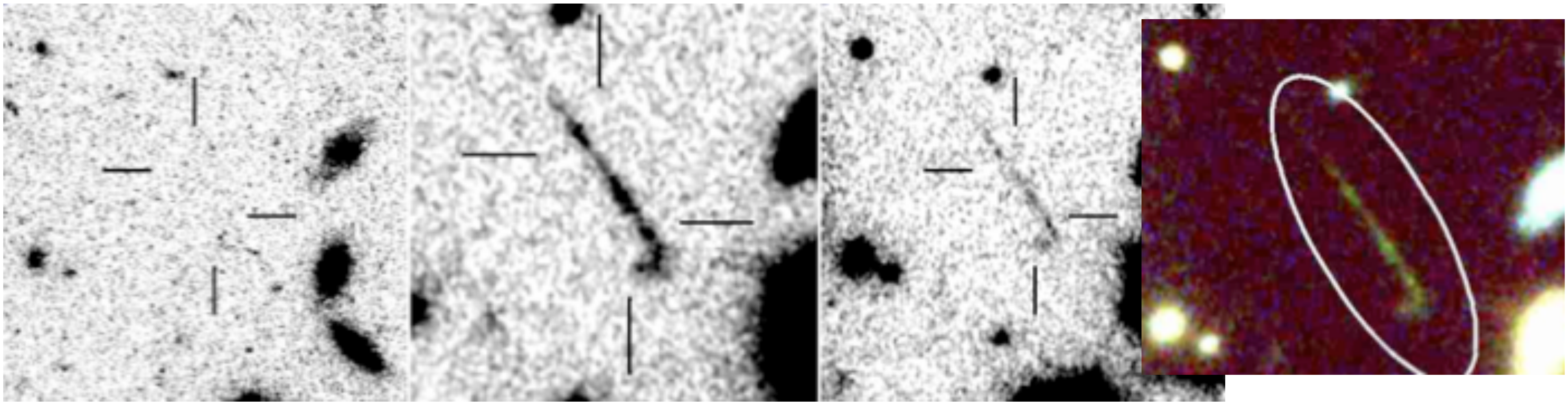
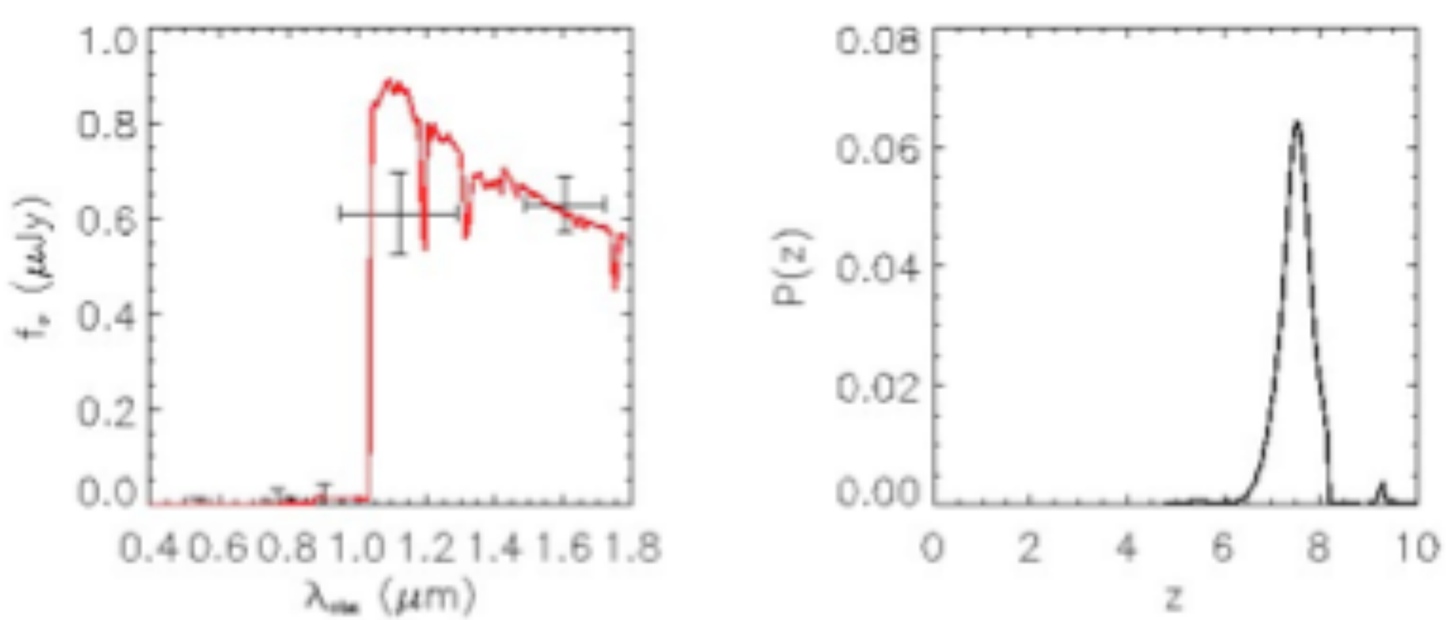
WFC3 z~7 search in massive clusters
Best candidate !



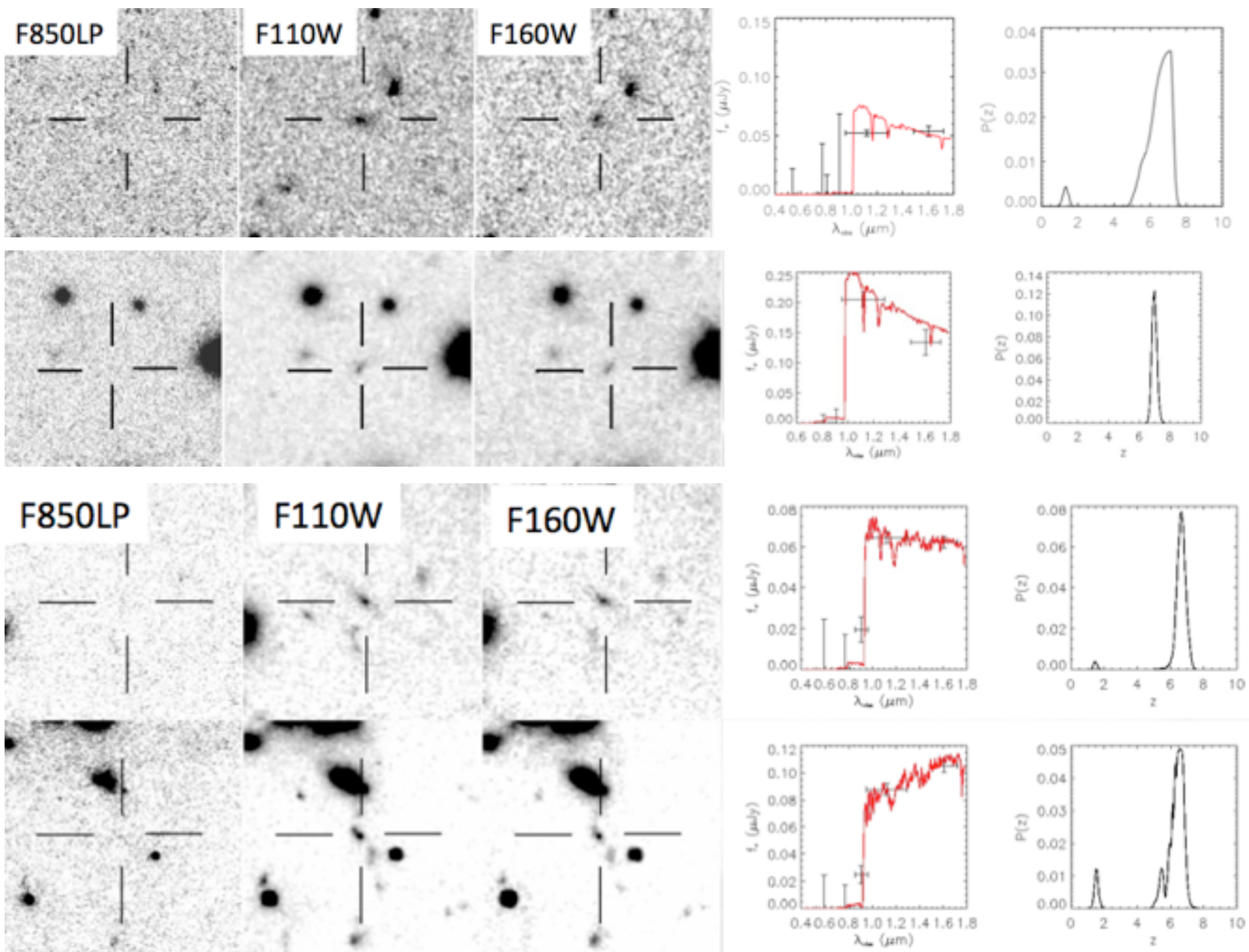


Observed=F110W=24.6 AB
Magnified by 2.1
Intrinsic=26.7 AB
X-shooter spectra
No lines !!!

Kneib et al 2013

WFC3 z~7 search in massive clusters
Hi-z candidates

Paraficz et al 2013

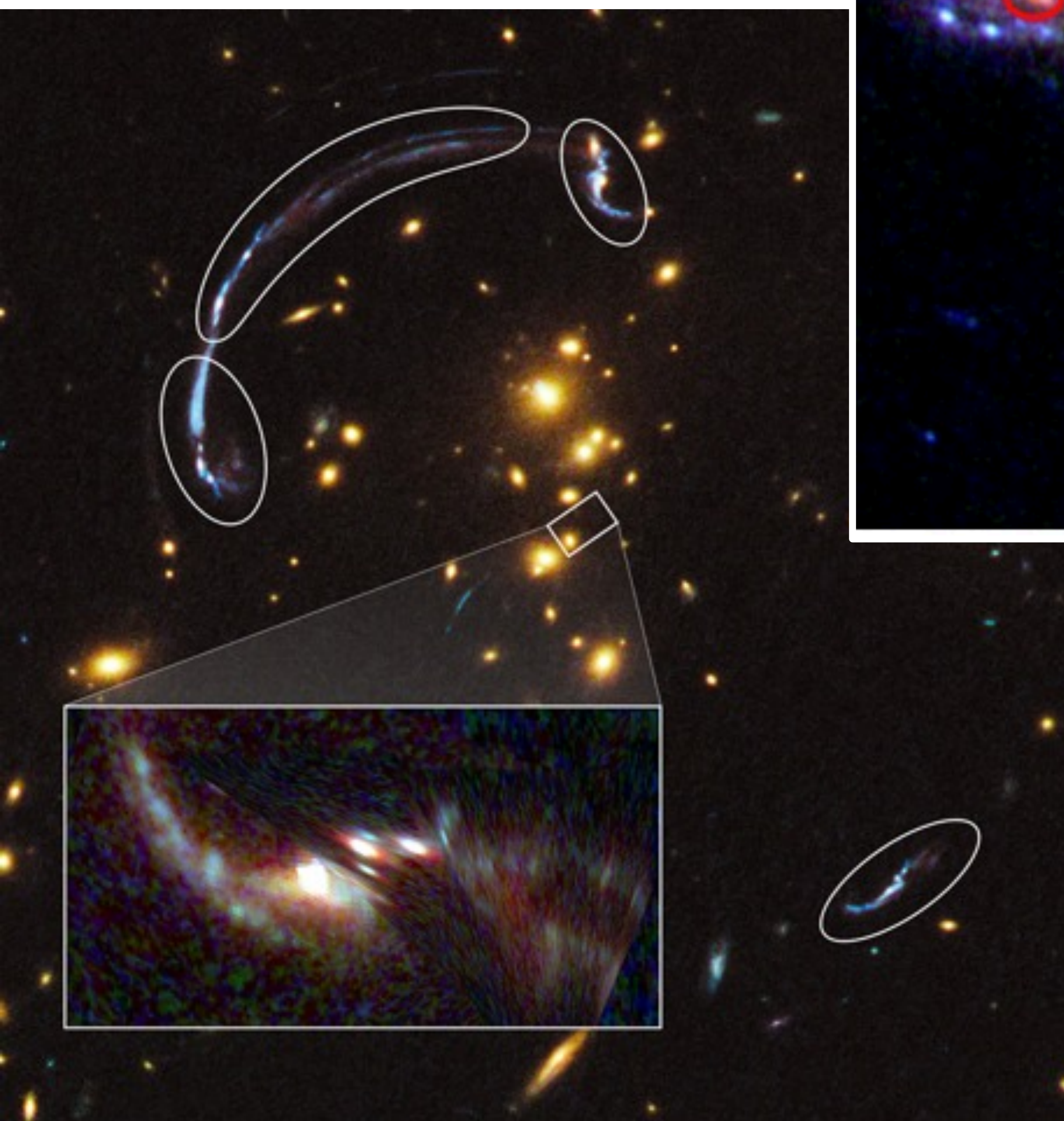


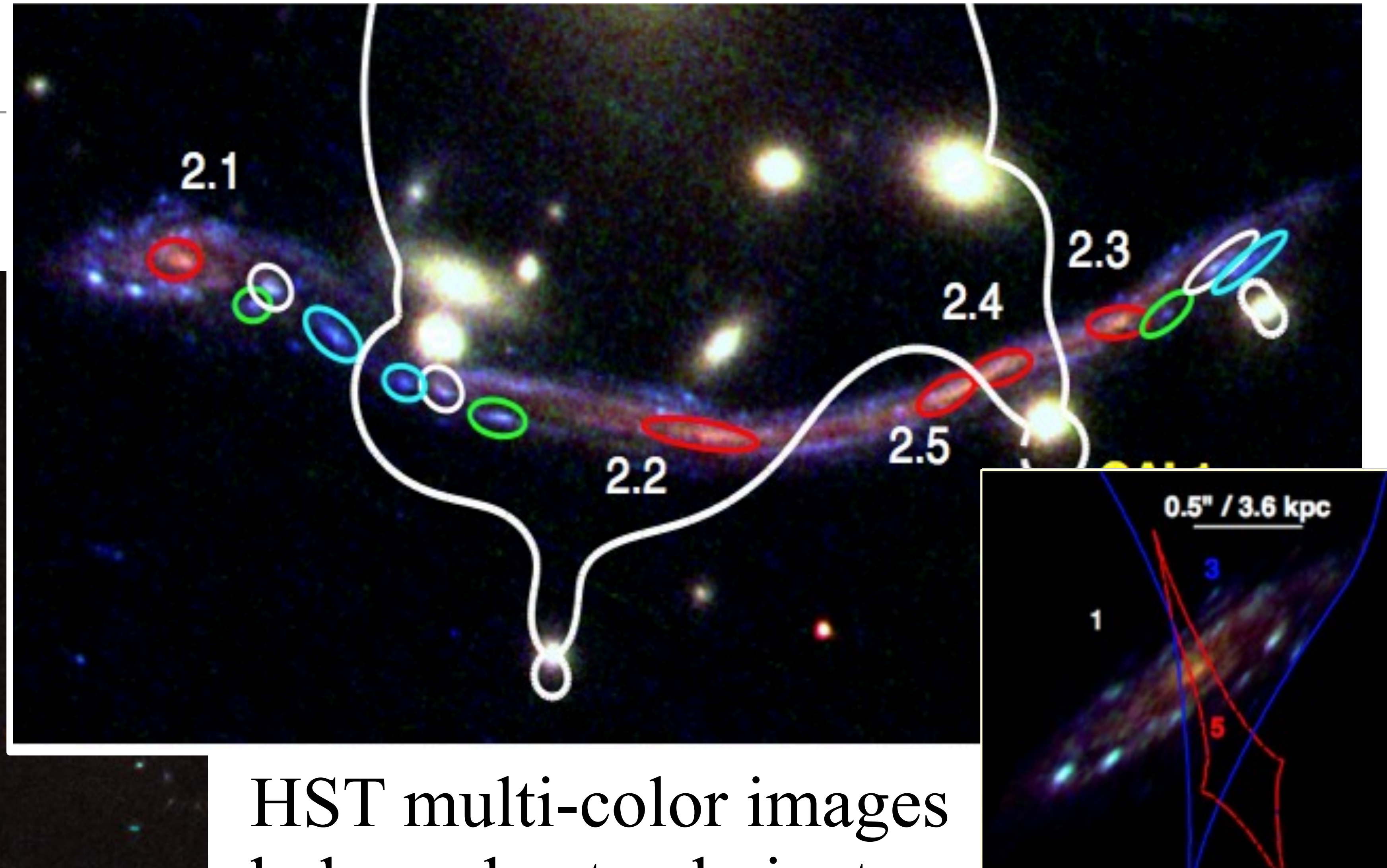
iz/J/H imaging of 4 massive clusters

Dropout candidates:

~40 i-dropout (z~6)
~10 z-dropout (z~7)
(J~27.5 AB limit)
no J-dropout (z~8.5)

Giant Gravitational Arcs



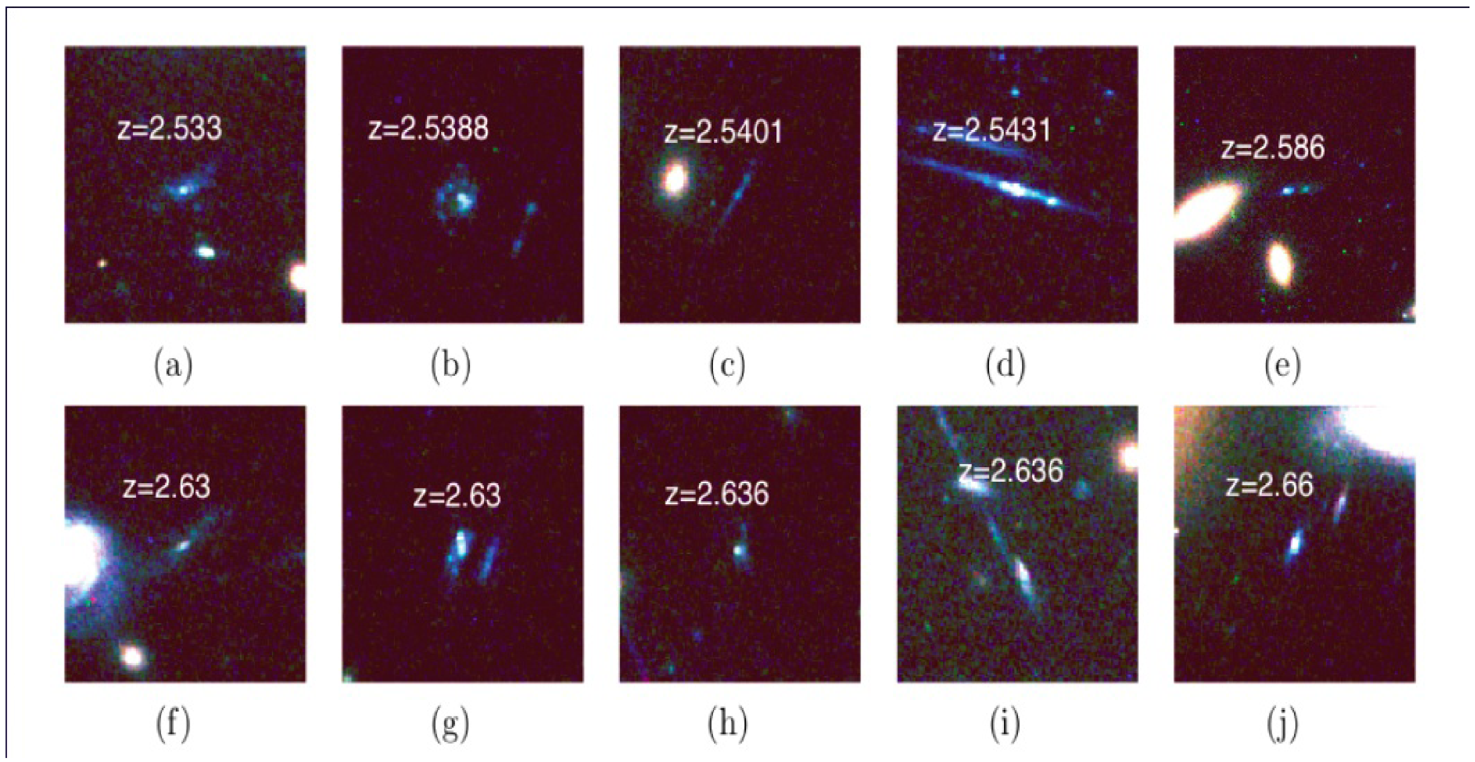


HST multi-color images help understand giant arc morphologies…

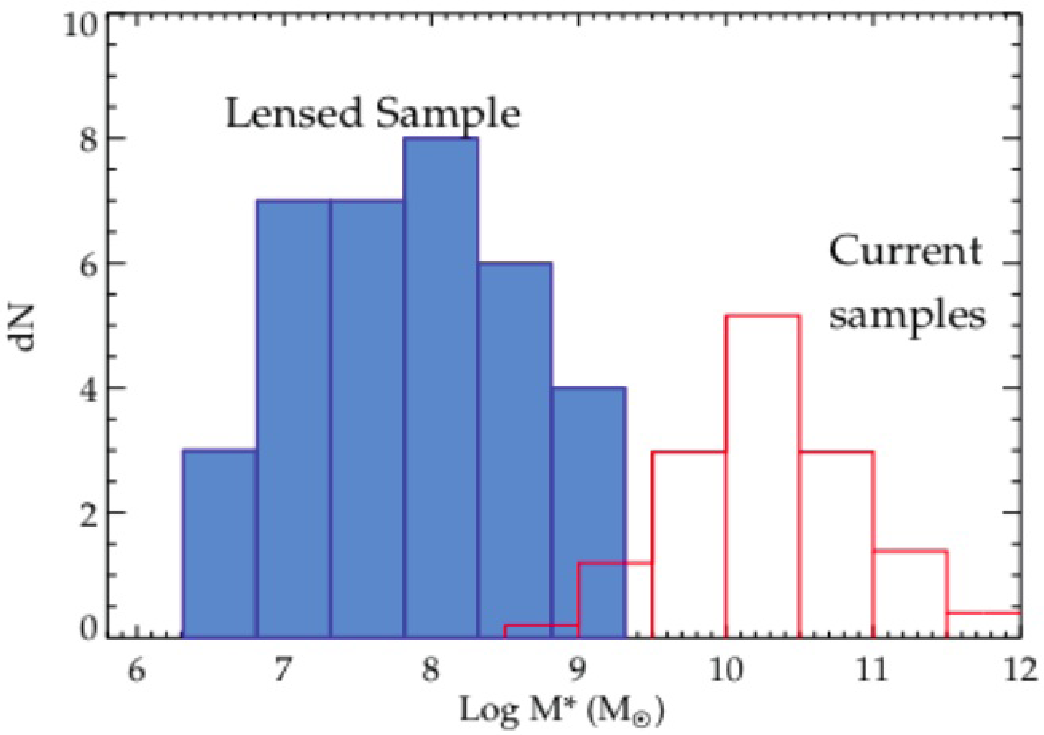
… and allow unlensed source reconstruction!

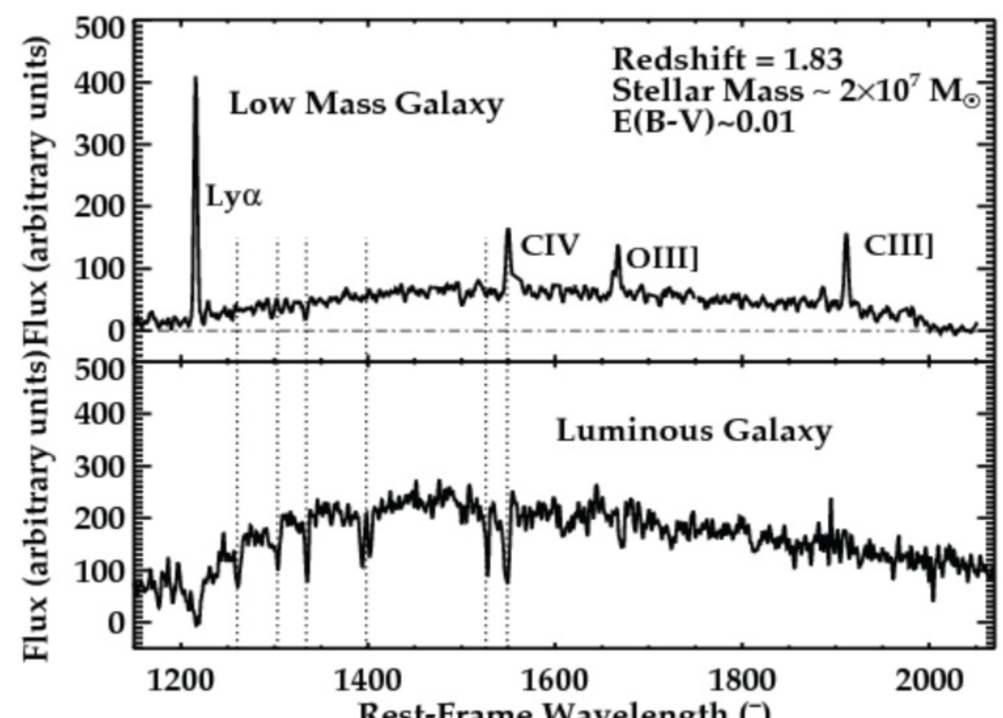
=> and velocity field measurement.

Cluster Lenses as Cosmic Telescopes



Richard et al 2013

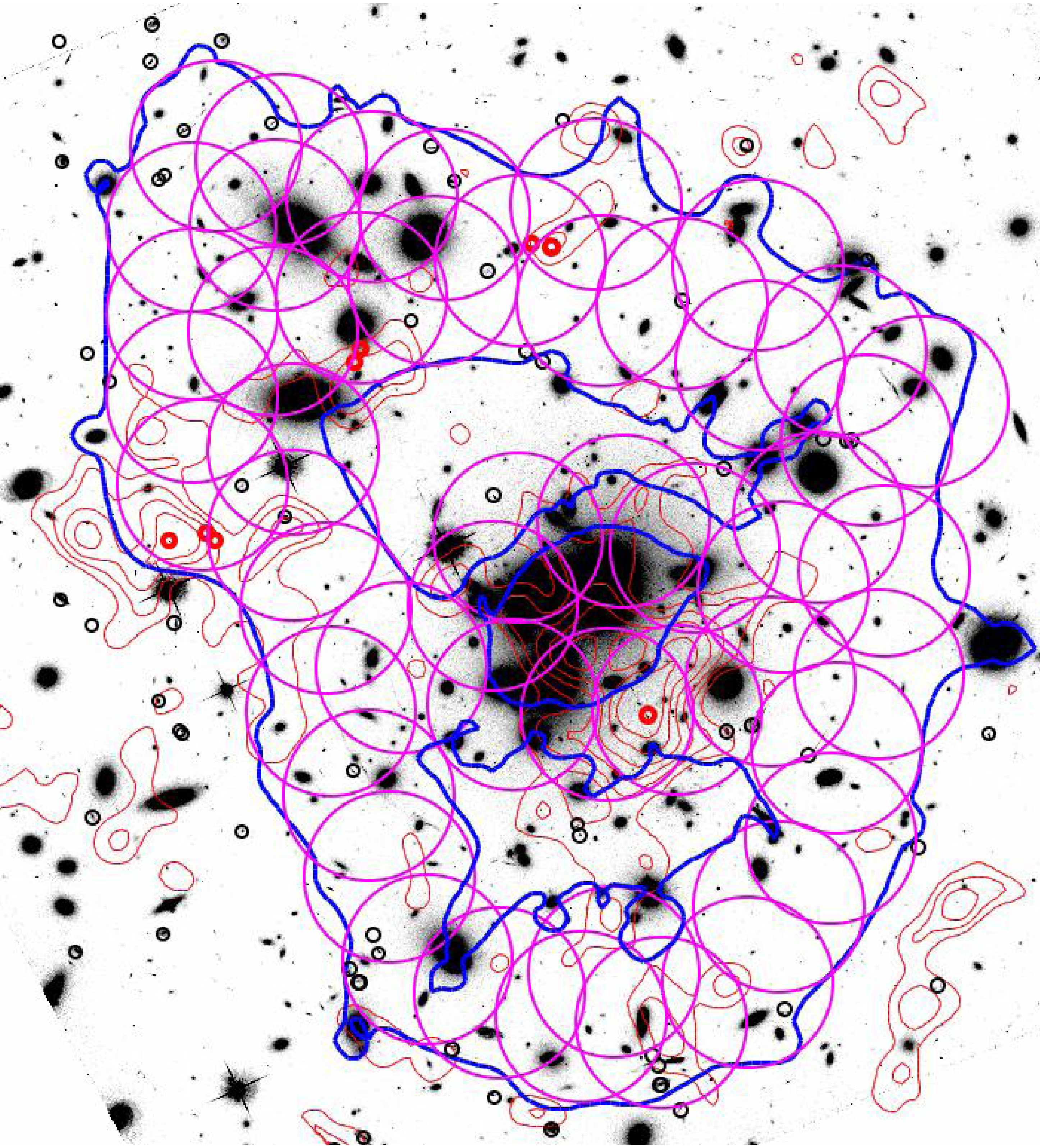




Magnifying cosmic telescope:

- allow to view morphology of sub-arcsec galaxy size
- probe deeper in the low luminosity/mass properties at high-z (1<z<5)

Critical Line Mapping with ALMA



Search of continuum sources (~1-3mm) and CO/[CII] lines.

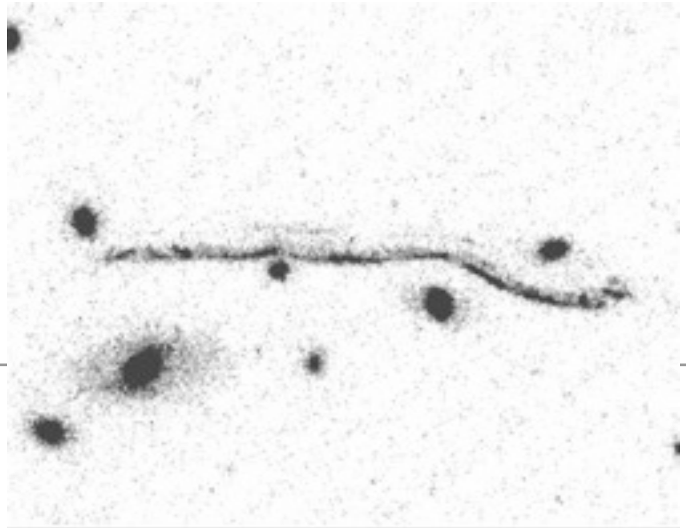
Abell 1689 Early-Science project (cycle 0): 50 pointing with high magnification: $\mu>10$,

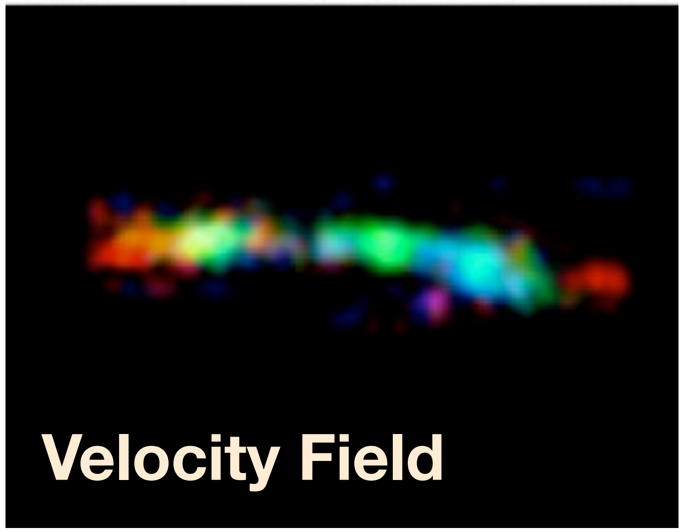
~7h integration to reach 50 μJy in the continuum at 1.3 mm (4σ)

-probe of CO lines for known SMM sources (**Knudsen et al. 2008**, SCUBA & SCUBA2)

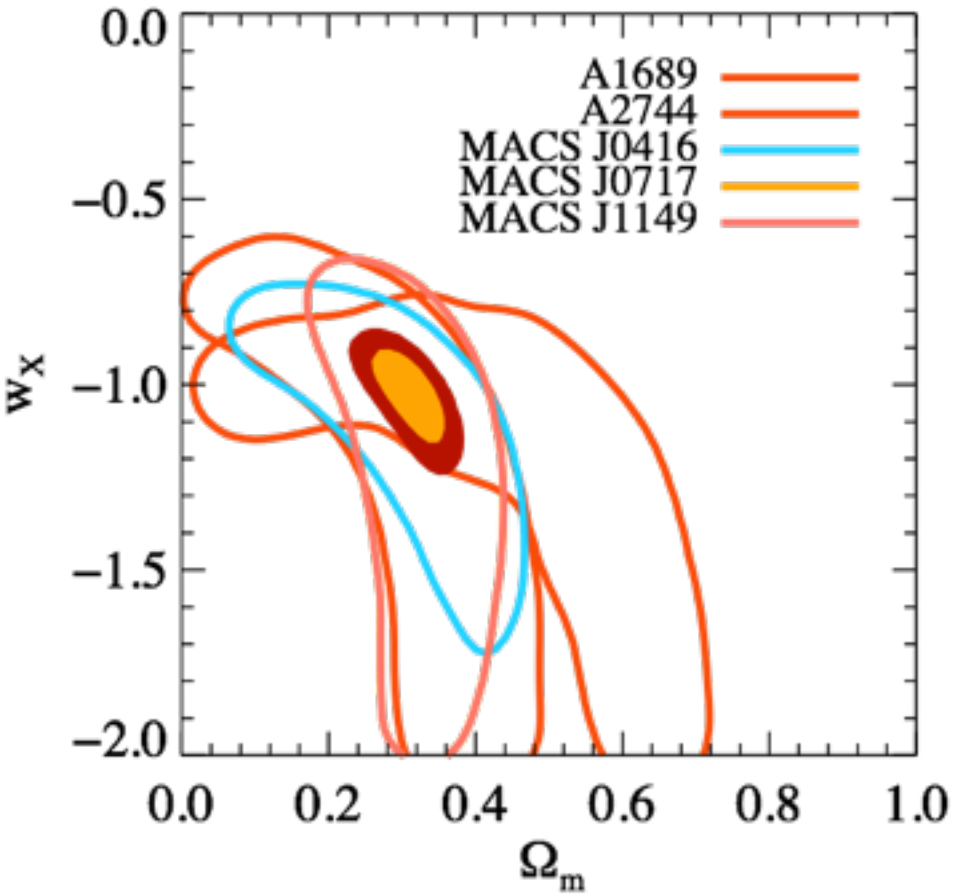
- stacked CO lines for ~30 galaxies of the spectroscopic samples with $1.5 < z < 3.0$

Cosmic Telescope Science

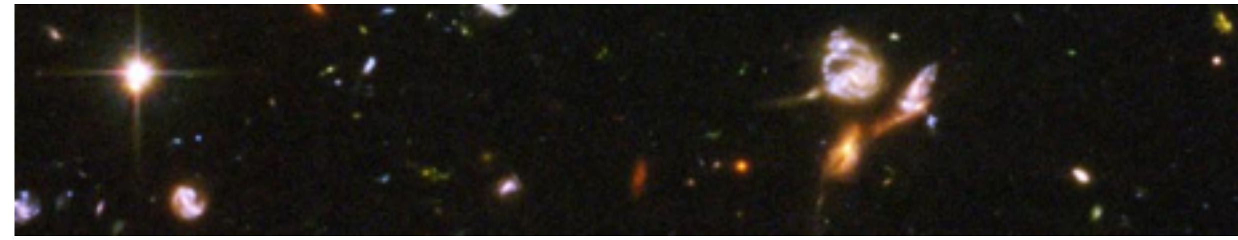




- Hi-z galaxies/Epoch of Reionization
- Spatially resolved spectroscopy of distant galaxies (z>1)
- Critical line mapping (focus on high magnification region: ALMA, MUSE)
- DM distribution in cluster cores (e.g. Bullet Cluster)
- Cosmographic constraints (through multiple images, Jullo et al 2010)



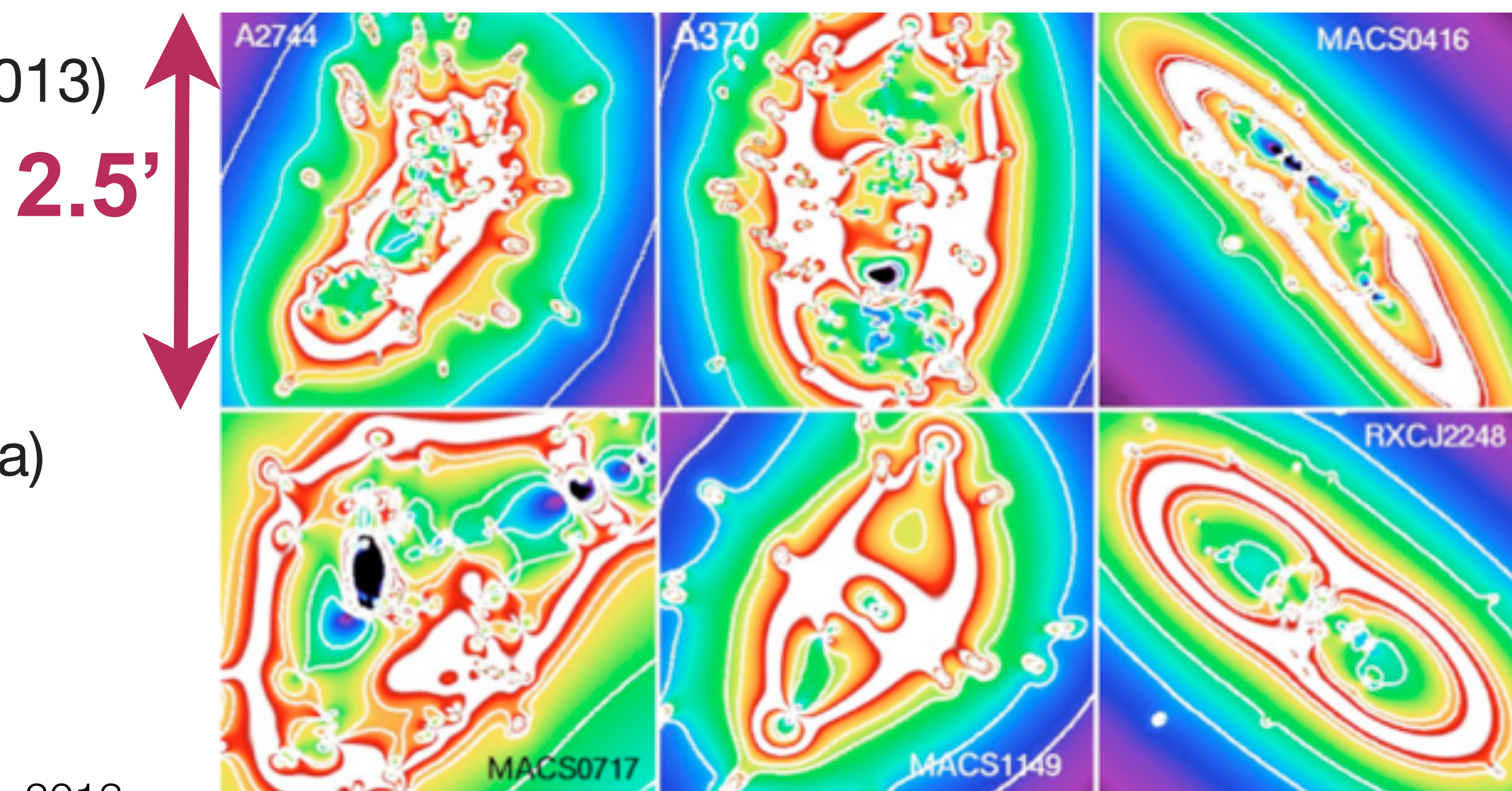
Frontier Fields Initiative



- In the spirit of the HDF and UDF projects - the STScI director has dedicated hundreds of orbits to conduct a multi-band survey of 4 (possibly 6) massive clusters. http://www.stsci.edu/hst/campaigns/frontier-fields/

- ***This Frontier Field project is recognizing the strength of massive clusters as cosmic telescopes!***

- 2 clusters per cycle (starting 2013)
- 7 wide filters ACS+WFC3
- Depth 28.5-29 AB mag (3sigma)
- Cluster Core + 1 Parallel Field



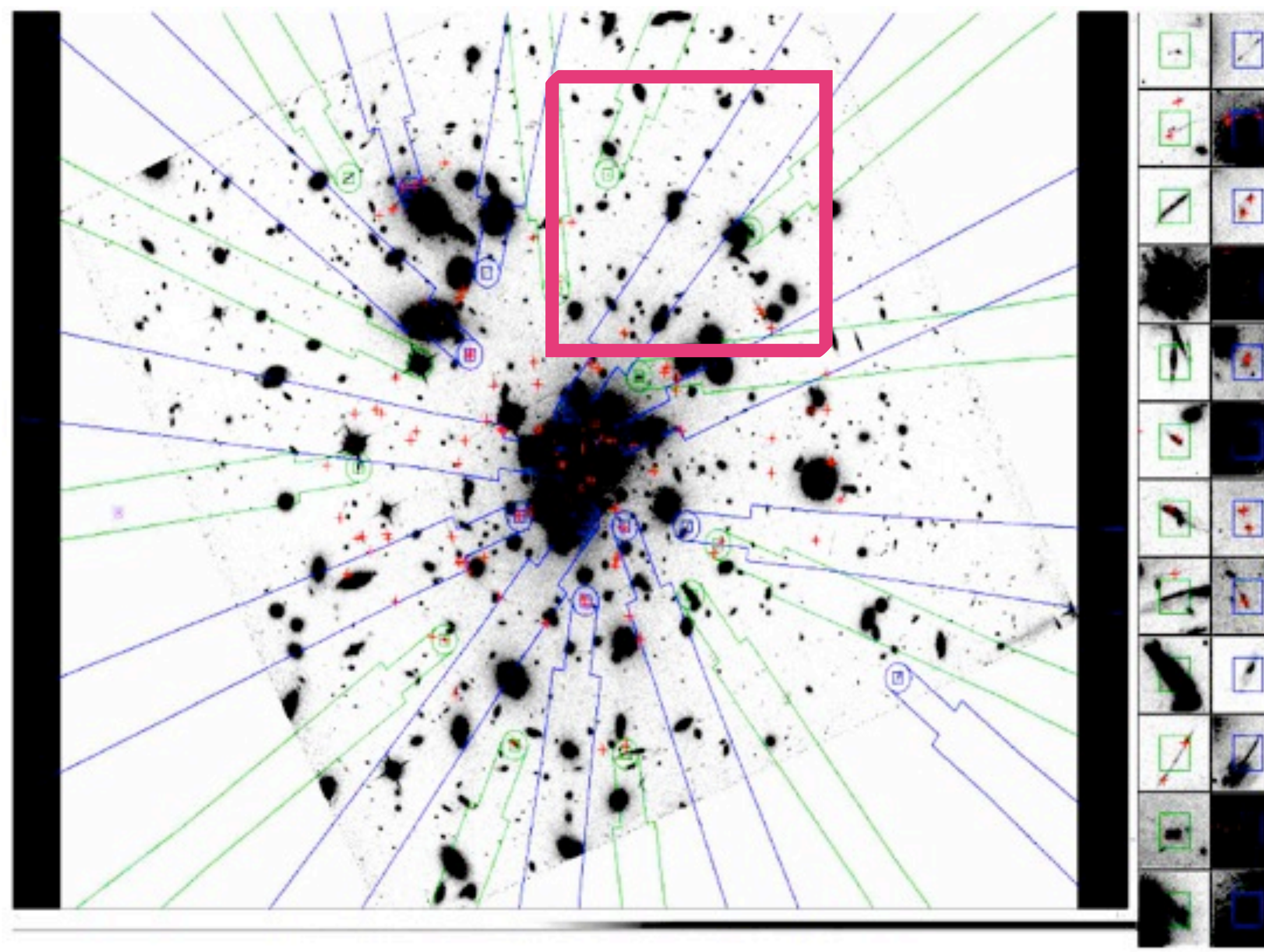
ELT Observations of Cosmic Lenses ?

- ELT field of view matches well the cluster critical line regions (a few $arcmin^2$)
- ELT infrared capabilities fits well with high redshift work
- ELT light collection bucket +AO will enable search and study of very distant/faint sources (Continuum ~26AB, Line ~28AB for ~1h integration time)
- Cosmic Telescopes+ELT will achieve the deepest spectroscopic look in the Universe !
- CT+ELT+3D spectrograph would allow a complete census of the Universe in the L.o.S. of Cosmic Telescope achieving high-accuracy mass modeling, & deepest (ever?) NIR galaxy surveys !

What is the ideal E-ELT instrument for Cosmic Telescopes?

- 3D spectroscopy is the ultimate as it allow spatially resolved spectroscopy
- KMOS concept vs MUSE concept ?
- *Blind search is important to detect emission line galaxies => total sum of field of views is important (ideally a few arcmin^2 to match the critical line regions) => MUSE like better but more challenging in building it!*
- Resolution: R~5000 (sky lines)
- Wavelength 9000-16000 [from Halpha(z=0.4) to Ly-alpha(z=12)]
- AO to match the compact size of distant galaxies ~0.1"

MUSE



E-ELT Cosmic Telescopes Survey: an Example for a MUSE like survey

- Survey two hundreds of the best cluster lenses (2.5 $arcmin^2$ FoV)
  - with ~1 hour reach AB=26 in the continuum, AB~28 in line emission (assuming typical line width) => 200 hours project
  - with ~6 hours (~1night) reach AB=27 in the continuum, AB~29 in line emission => 200 nights projects
- Benefit of ~1 magnitude magnification over 40 $arcmin^2$
- Benefit of 2 magnitude magnification over 4 $arcmin^2$ [20 at z=8, a few at z=9 - Jim Dunlop number - continuum]
- Benefit of 3 magnitude magnification over ~0.5 $arcmin^2$
- Beat cosmic variance by looking at different line of sight

Conclusion

- Cosmic Lenses together with the E-ELT offer the best combination to target the distant Universe
- Complementarity with HST/JWST and ALMA Cosmic Telescope mapping
- Need an instrument that matches the size of typical cluster lenses
- 3D spectrograph (MUSE-like) with a large field of view (~arcmin^2 scale) and a broad wavelength range (0.9-1.6 micron ?) should allow to conduct a complete redshift survey in the LOS of cluster cores - addressing DM distribution and galaxy formation and evolution science
- Such an E-ELT instrument in concert with Cosmic Telescopes would provide the deepest spectroscopic view of the distant universe before long ... AB=30 limit !?