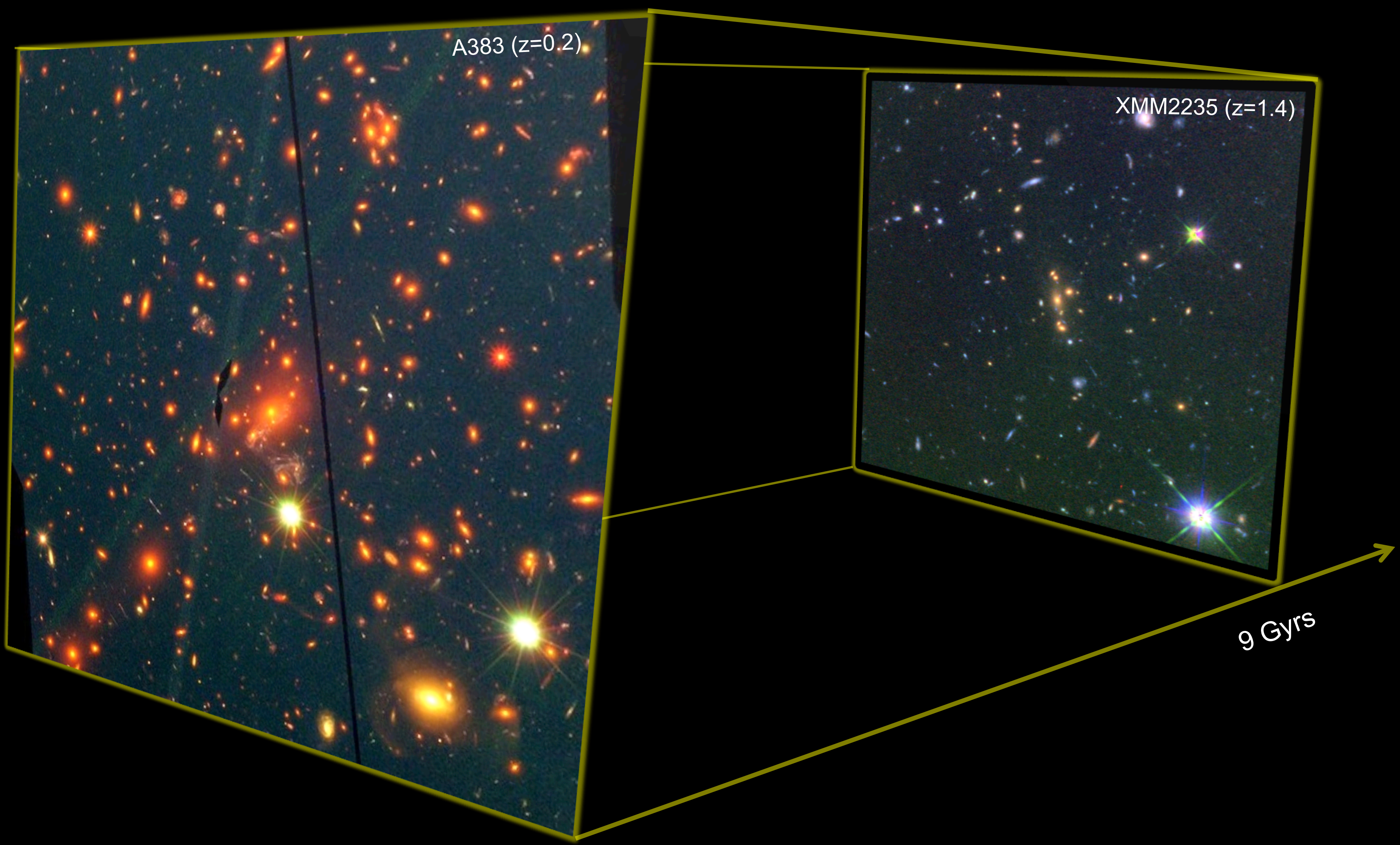
Testing the ΛCDM Paradigm with the Mass Distribution of Massive Clusters out to z=1.4

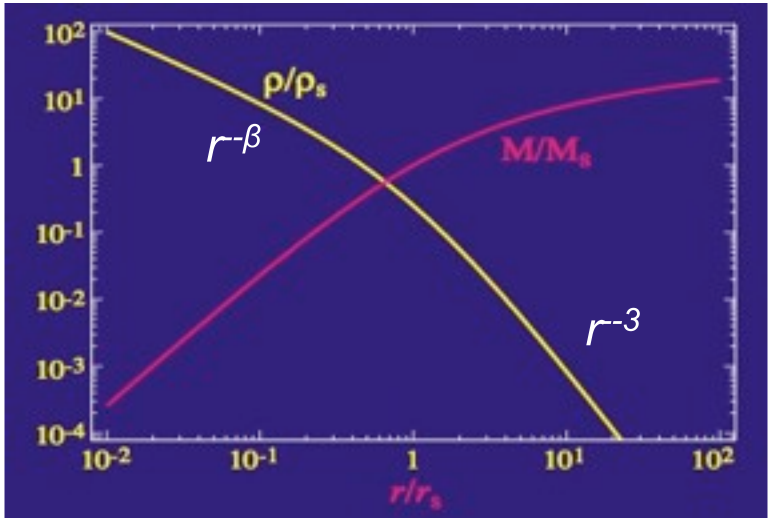
Piero Rosati
(ESO)



Monsters, Inc. - Santa Barbara, 18 March 2011

ΛCDM Predictions for the structure of DM Halos (dependence on Mass and Redshift on cluster scale)

- Accurate DM mass density profiles of massive clusters, over ~10-1000 kpc scale, can directly test the ΛCDM scenario



Generalized NFW profile:

$$\rho(r) = \frac{\rho_S}{(r/r_S)^\beta (1 + r/r_S)^{(3-\beta)}} \qquad c \equiv \frac{r_{200}}{r_S}$$

β ≈ 1-1.3 , c ≈ 3-5 from N-body simulations

$$M(r) = 3M_S[ln(1+x) - \frac{x}{1+x}], \quad x = r/r_S$$

- Even if gravity is scale free, the halo concentration c_{vir} will depend on mass&redshift via the formation epoch of DM halos (env density of the Universe), which depends on the structure formation scenario

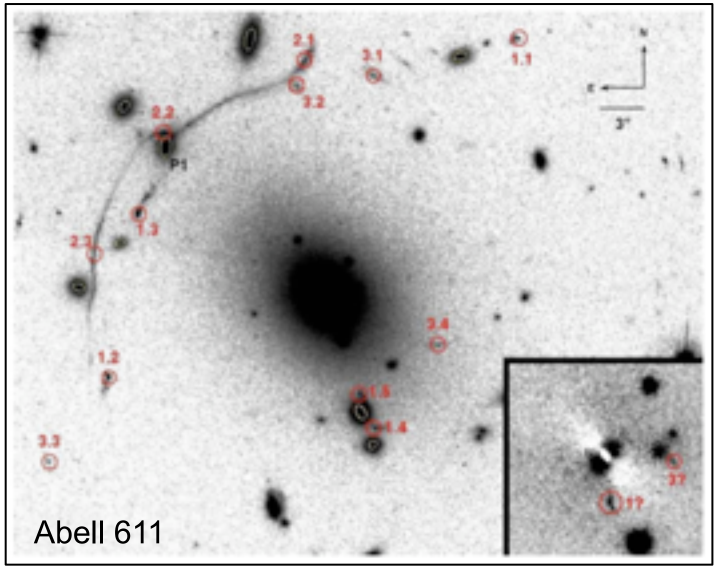
$$c_{vir} \equiv r_{vir}(M_{vir},z)/r_s(z_{vir}) \qquad \bar{c}_{vir} \approx c_0(1+z)^{-A}\left(\frac{M_{vir}}{10^{15}M_{sun}/h}\right)^{-B}$$

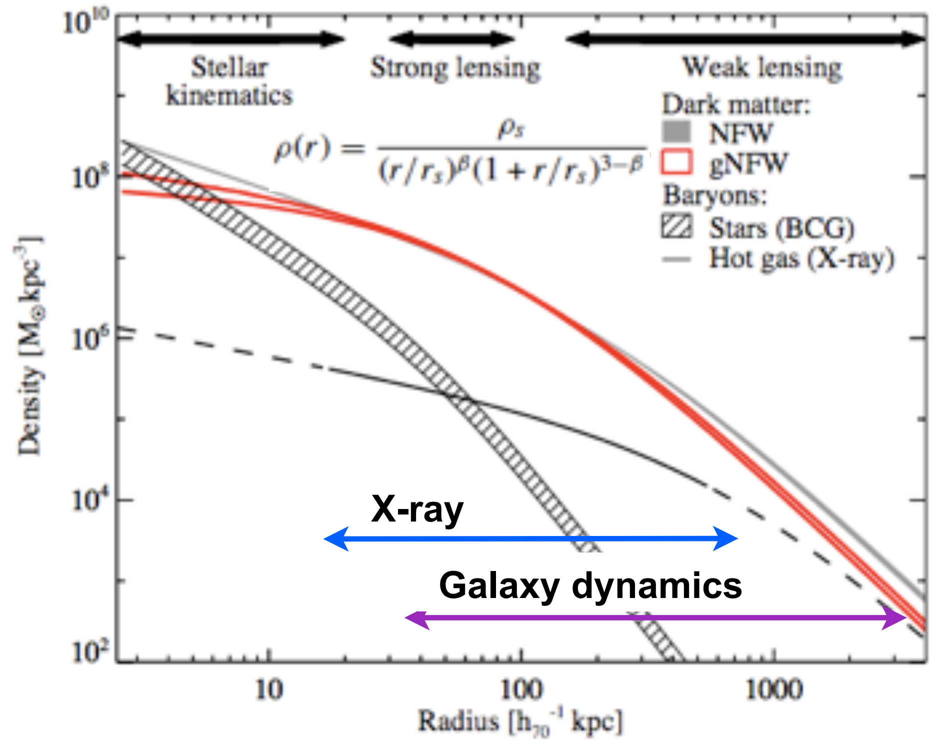
Duffy et al. 08

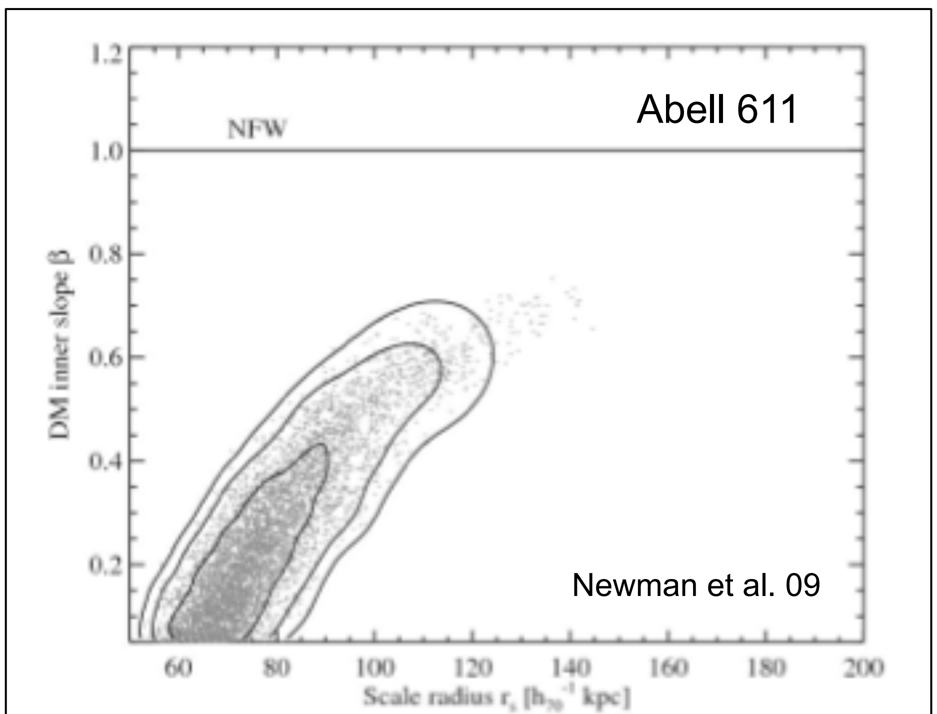
Simulations suggest A ≈ 0.1, B ≈ 0.7-1, c ≈ 5 (Log M=14-15)

➡ Test NFW predictions on DM concentration and inner slopes as a fnct of Mass and Redshifts

DM and Baryon mass distribution in clusters

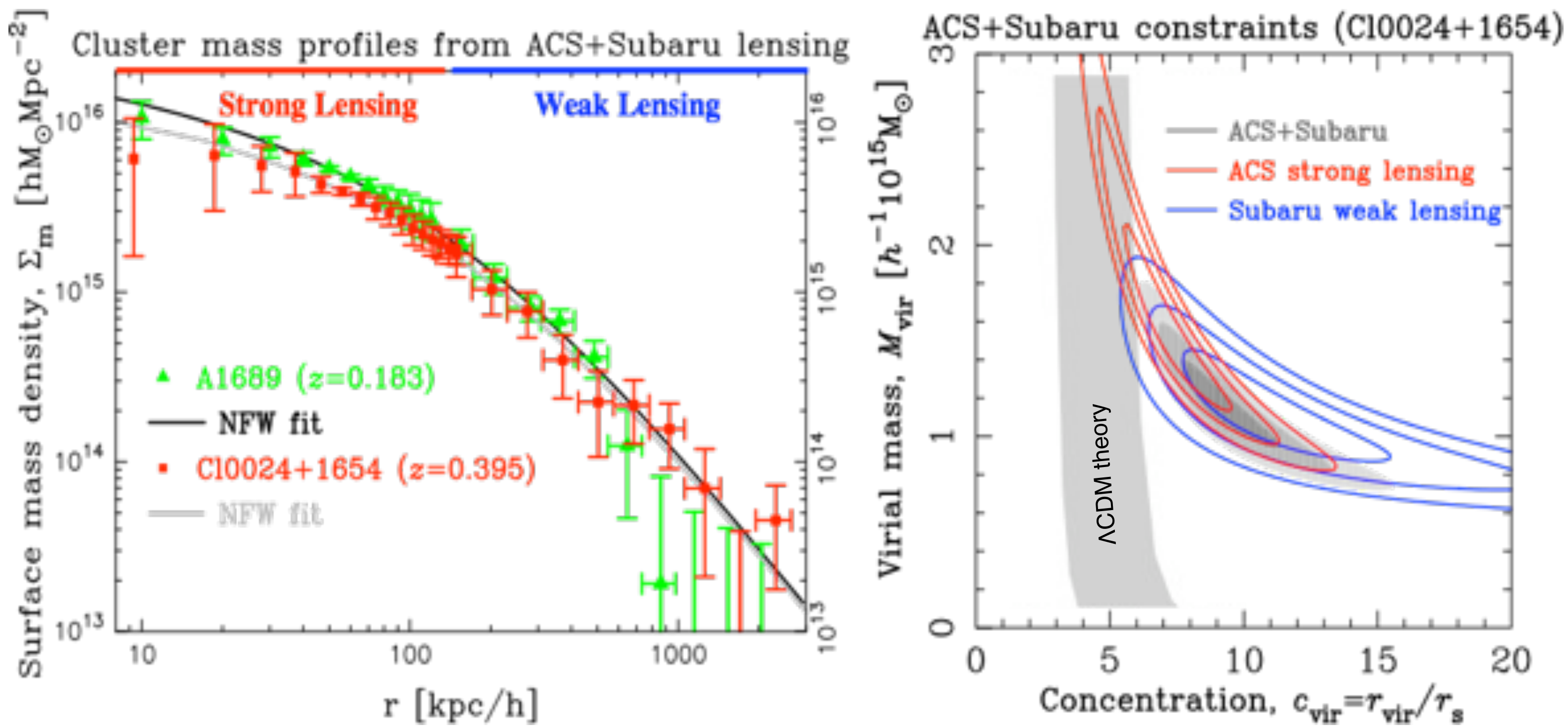






- *Key*: use a variety of complementary probes covering 2-3 decades in scale, degeneracies (inner slope, concentration and M*/L) are mitigated, systematics controlled

DM and Baryon mass distribution in clusters



Umetsu&Broadhurst 2008

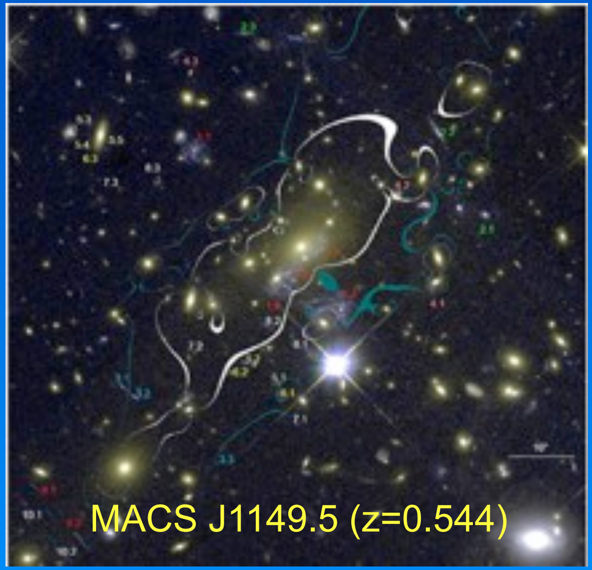
- Early results point to a clash with ΛCDM: large mass concentrations, shallow inner slopes, large Einstein radii:
  - Formation of clusters at earlier times than expected ? non-gauss. fluctuations ? EDE ?
  - Does ΛCDM have problems on small scales despite the success on large scales ?
  - How baryonic physics shapes the inner DM potential ?
- *But this is based on a handful of clusters..* small (biased?) samples ? triaxiality ? cl-cl variance ?

Through a Lens, Darkly:
An Innovative Hubble Survey to Study
the Dark Universe

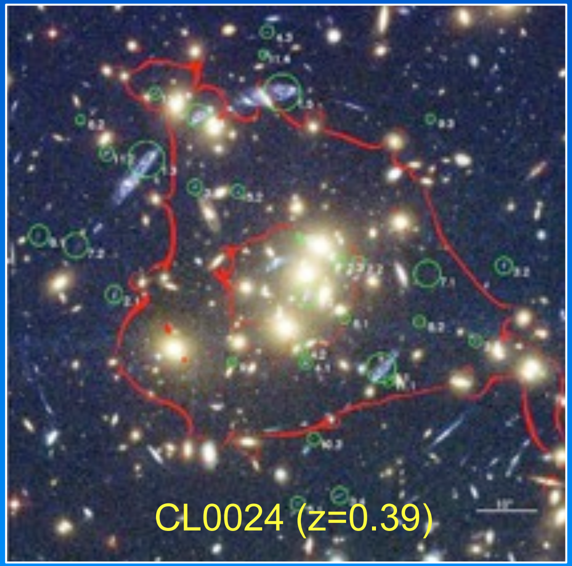
Cluster Lensing And Supernova survey with Hubble

HST multi-cycle Treasury Program (530 orbits) - PI: M.Postman

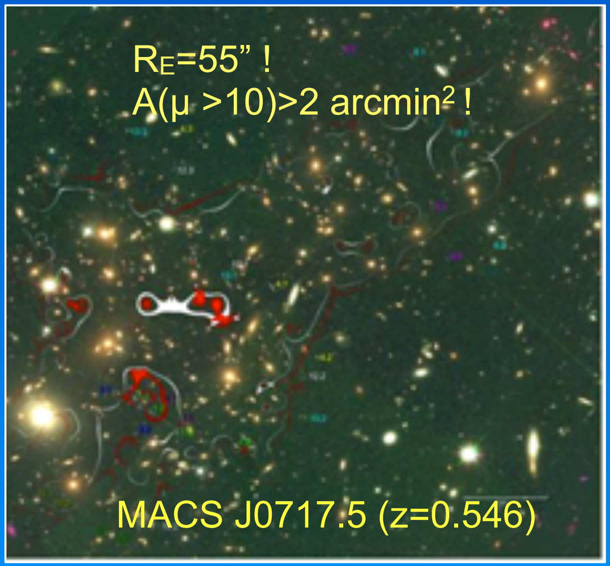
- Panchromatic (ACS+WFC3 16 filters) imaging of 25 massive intermediate-z galaxy clusters
- Measure DM mass profiles over 10-3000 kpc with unprecedented precision
- "Wide-field" gravitational telescopes on the very high-z Universe
- SNe Ia search at 1<z<2 from parallel fields (doubling SNe at z>1.2)



MACS J1149.5 (z=0.544)



CL0024 (z=0.39)



MACS J0717.5 (z=0.546)

Zitrim, Broadhurst et al. 09

http://www.stsci.edu/~postman/CLASH

The CLASH Science Team: 34 researchers, 18 institutions, 10 countries

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Thomas Broadhurst	University of the Basque Country
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Megan Donahue	Michigan State University
Holland Ford, Dep-P.I.	The Johns Hopkins University (JHU)
Or Graur	Tel Aviv University (TAU)
Genevieve Graves	University of California, Berkeley
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Dan Maoz	TAU
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Julian Merten	Universität Heidelberg
Alberto Molino	IAA
Leonidas Moustakas	JPL/Caltech
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Adam Riess	STScI / JHU
Piero Rosati	European Southern Observatory
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Keiichi Umetsu	Academia Sinica, Institute of Astronomy & Astrophysics
Arjen van der Wel	Max Planck Institüt für Astronomie
Wei Zheng	JHU
Adi Zitrin	TAU

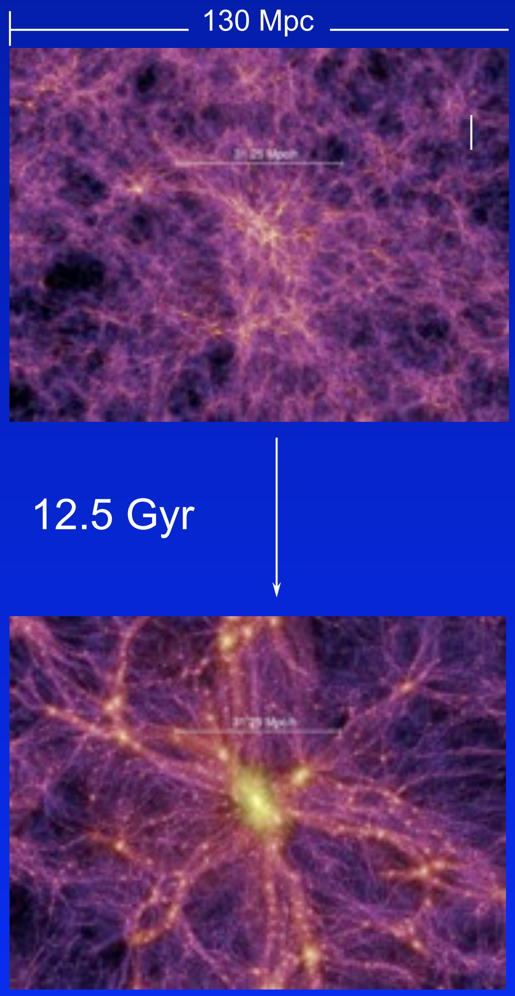
Chile
Germany
Israel
Italy
Netherlands
Spain
Switzerland
Taiwan
U.S.A.
U.K.

CLASH

Post-doctoral fellow
Graduate student

Fundamental Questions to be addressed with CLASH that Remain Unanswered or Unverified

- How is dark matter distributed in cluster & galaxy halos?
  - How centrally concentrated is the DM? Implications for epoch of formation.
  - What degree of substructure exists? and on what scales?
  - How does the DM distribution evolve with time?
  - What correlations exist between the distribution of baryonic matter and DM?
  - Is the DM mass profile universal?



“Millennium” simulation of DM (Springel et al. 2005)

Cluster Sample Selection

- Most clusters (20 out 25) were selected to be an unbiased sample of regular/relaxed massive clusters as indicated by *Chandra* observations
- All have T>5 keV and span a mass range: $(0.5 - 3)\times10^{15}$ $M_\odot$
- Extra five clusters were selected to have very large Einstein radius (not necessarily relaxed) to increase the chances to magnify ultra high-z galaxies
- Clusters drawn from the MACS (Ebeling et al. 10) and Abell catalogs (mostly Steve Allen's sample)
- The sample should be large enough to measure the intrinsic scatter of the mean mass concentration (10% accuracy)

Cluster Sample Size Justification

Why 25 clusters ?

Observational

- Want to measure mean "concentration" of DM profile to ~10% accuracy:

$$N_{CL} \approx (\sigma_{tot} / f)^2$$

$$f = 0.10$$

$$\sigma_{tot}^2 = \sigma_{LSS}^2 + \sigma_{int}^2 + \sigma_{Meas}^2$$

σ_{LSS} = 0.13 (e.g., Hoekstra et al. 2003)

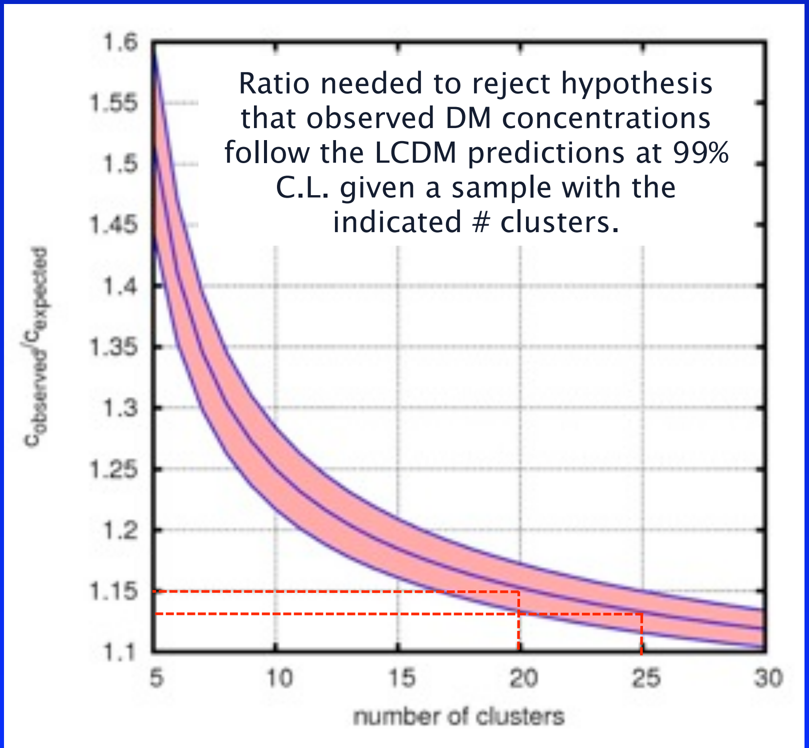
σ_{int} = 0.30 (e.g., Neto et al. 2007)

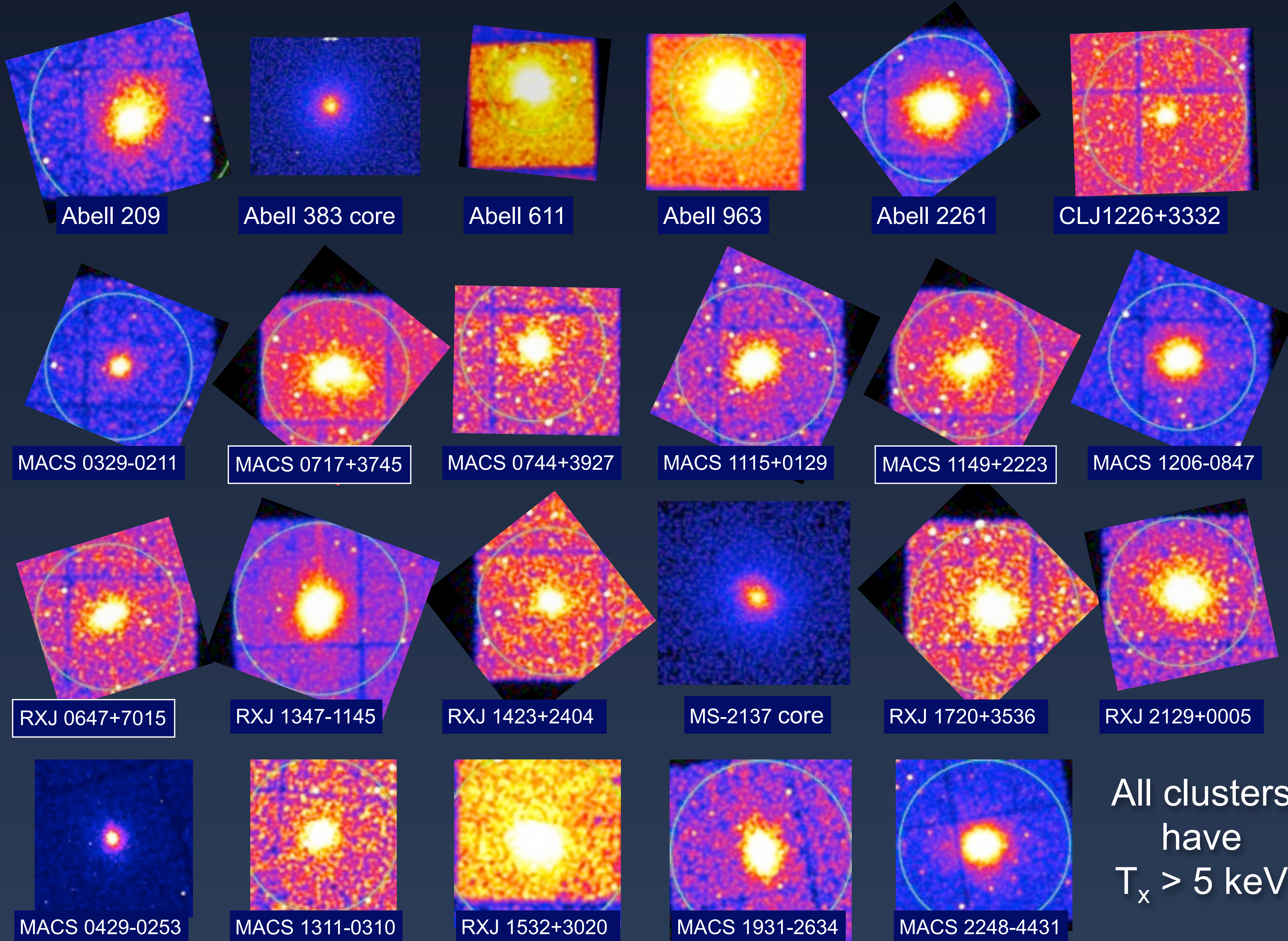
$\sigma_{Meas} = 0.22 (N_{arc,\ CL0024} / N_{arc})^{1/2}$ (Umetsu et al. 2010)

$$N_{CL} = 24$$

Theoretical

- N-body simulations show DM profile concentration distns are log-normal with σ~ 0.25±0.03 (e.g., Jing 2000; Meneghetti et al. 2009).





All clusters have $T_x > 5$ keV

Cutouts of Chandra images of 23 of the 25 CLASH clusters

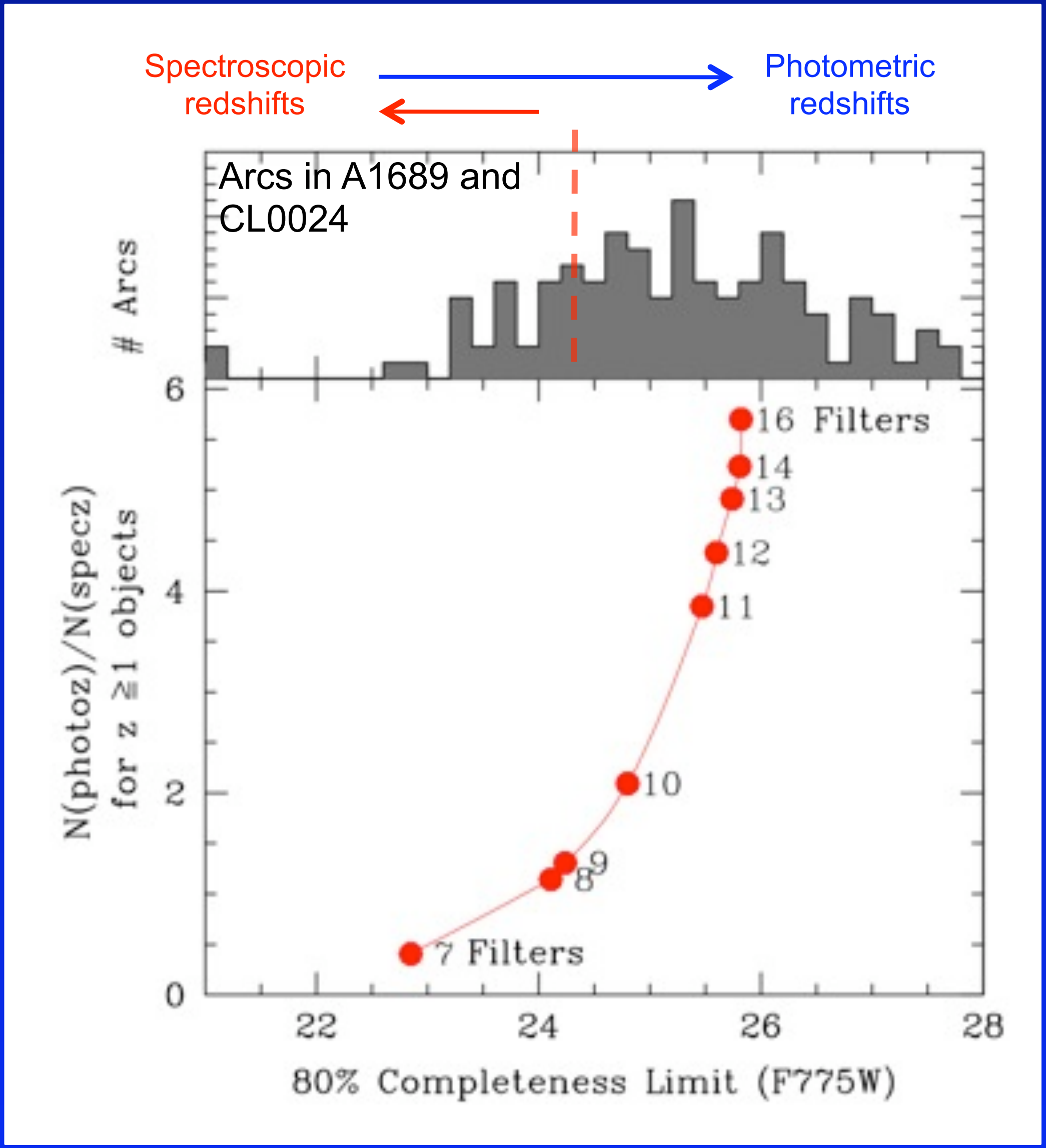
CLASH: An HST Multi-Cycle Treasury Program

Why 16 filters?

F225W … 1.5 orbits WFC3/UVIS
F275W … 1.5 orbits WFC3/UVIS
F336W … 1.0 orbit WFC3/UVIS
F390W … 1.0 orbit WFC3/UVIS

F435W … 1.0 orbit ACS/WFC
F475W … 1.0 orbit ACS/WFC
F606W … 1.0 orbit ACS/WFC
F625W … 1.0 orbit ACS/WFC
F775W … 1.0 orbit ACS/WFC
F814W … 2.0 orbits ACS/WFC
F850LP … 2.0 orbits ACS/WFC

F105W … 1.0 orbit WFC3/IR
F110W … 1.0 orbit WFC3/IR
F125W … 1.0 orbit WFC3/IR
F140W … 1.0 orbit WFC3/IR
F160W … 2.0 orbits WFC3/IR



Will yield photometric redshifts with rms error of ~2% x (1 + z) for sources down to ~26 AB mag.

CLASH multiple facilities: DM & Baryonic Mass Distribution from independent probes over the 10 kpc ~ 3 Mpc range

PI: M. Donahue

Baryon mass distribution
X-ray masses
ICM physics & metallicity

PI: S.Ettori

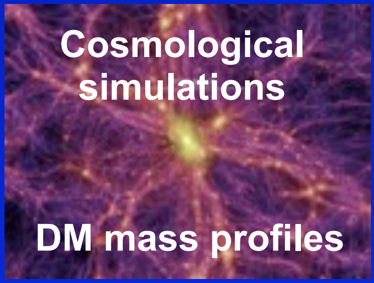
VLT

VIMOS Large Prog (230 hr)
~500 members per cluster
+ arcs redshifts

PI: P. Rosati

High-z gals
Dynamical analysis
Stellar masses

DM and Baryons in Clusters



AMiBA

ICM physics
DM&Baryon masses
SZ observations

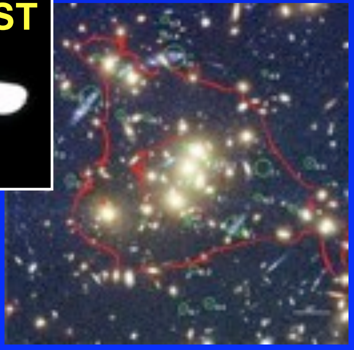
PI: K. Umetsu

Subaru (+ ESO-WFI)

WL masses profile
Stellar masses

PI: K. Umetsu

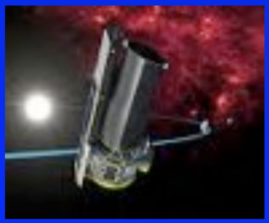
Strong Lensing
Mass profile in the core



Treasury Program
(530 orbits)
PI: M. Postman

High-z galaxies
Stellar masses

Spitzer

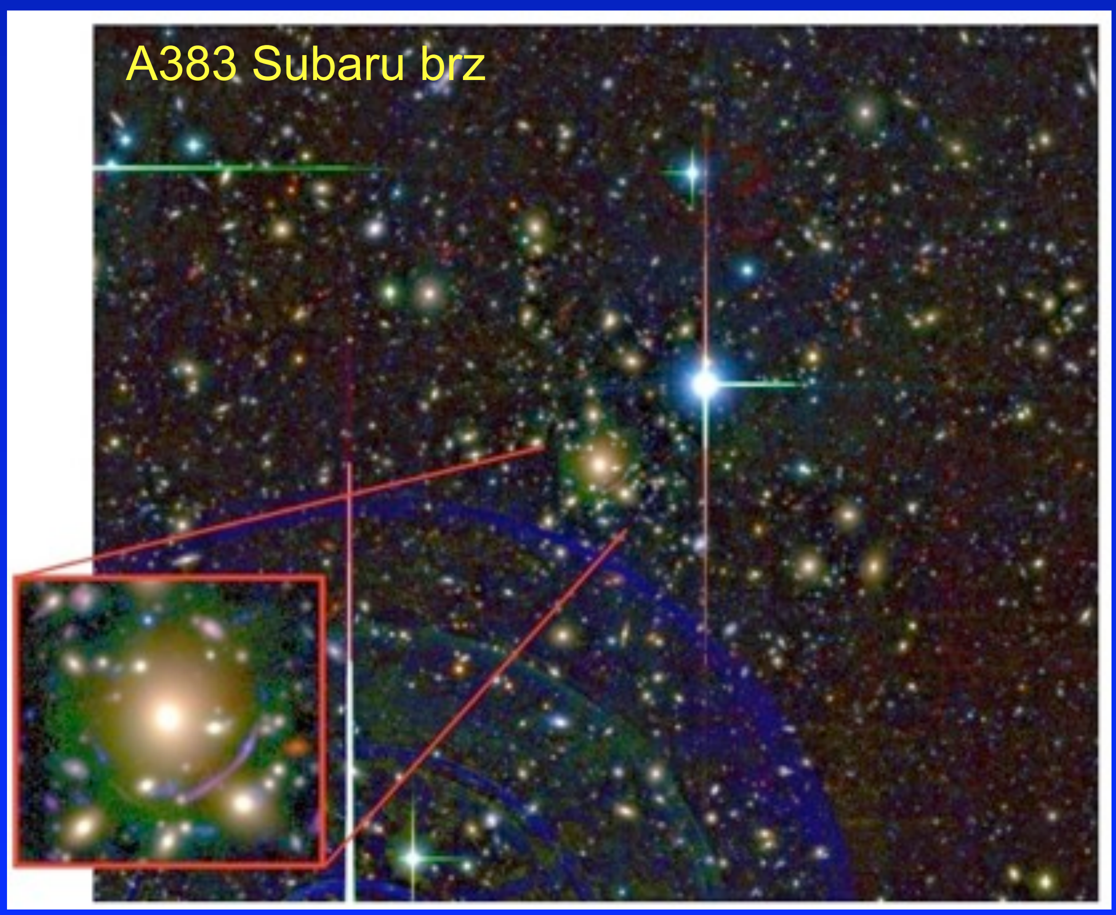


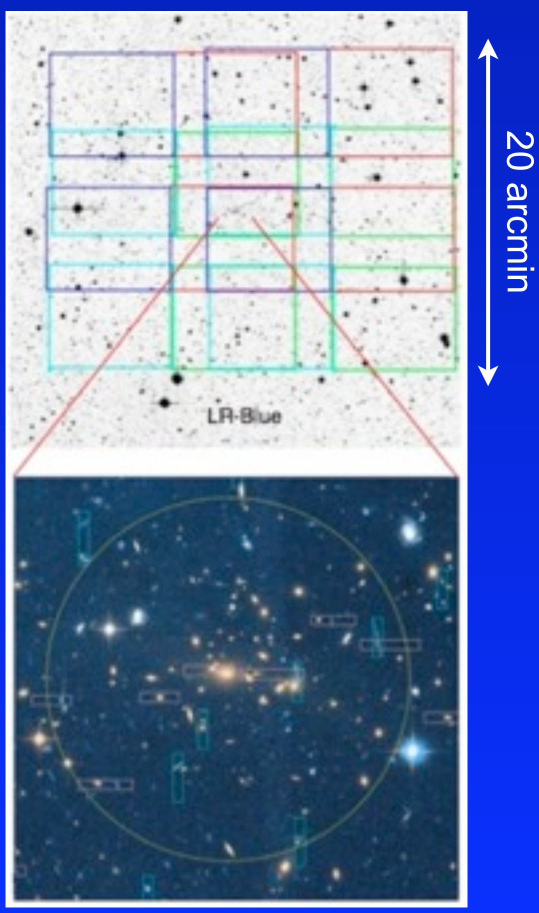
PI: W. Zheng

CLASH-VLT

VIMOS Large Programme (225 hr over 2 years)

- Panoramic (r≳3 Mpc) spectroscopic survey of 14 southern CLASH clusters at z=0.3-0.6
  Multi-band Subaru SupCam + HST data used for target selection



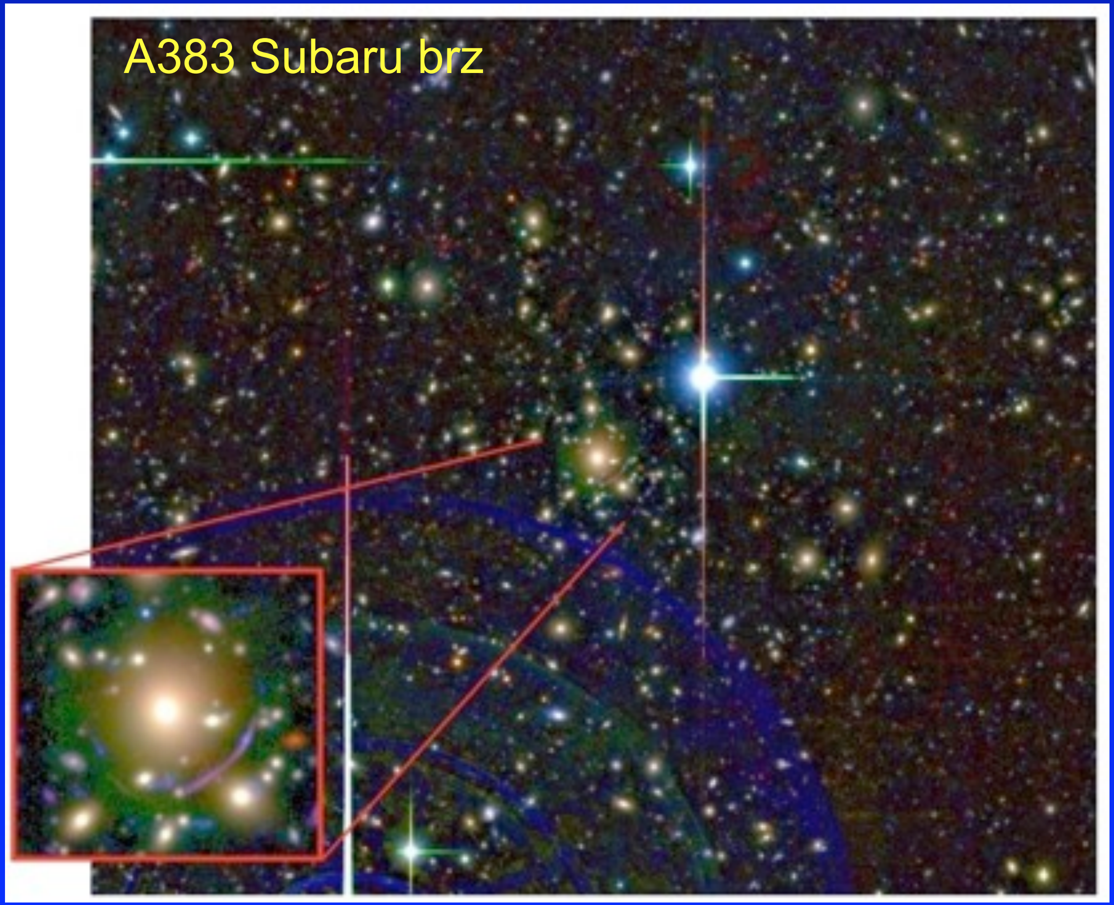


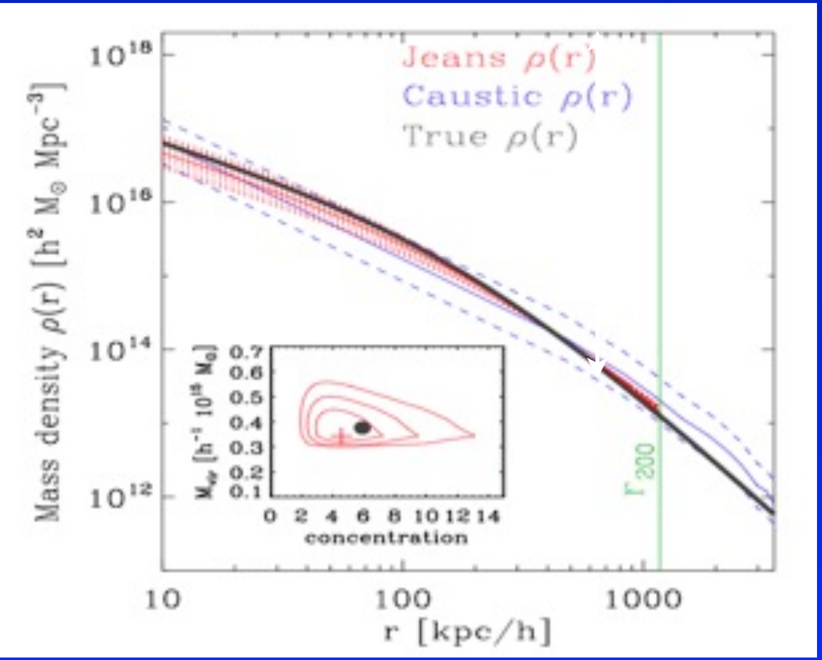
CLASH-VLT

VIMOS Large Programme (225 hr over 2 years)

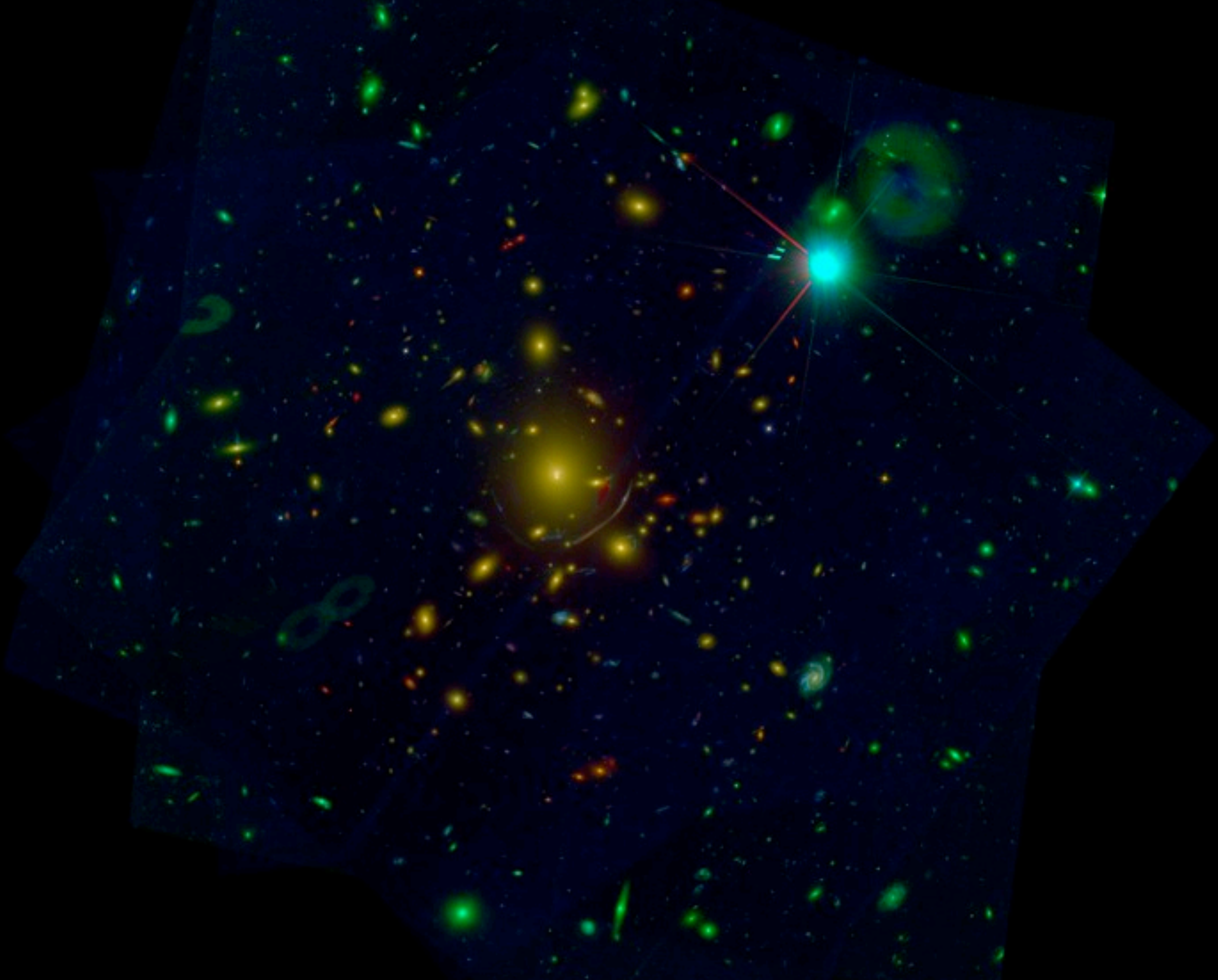
All data products will go public in the ESO Archive

- Panoramic (r≳3 Mpc) spectroscopic survey of 14 southern CLASH clusters at z=0.3-0.6 Multi-band Subaru SupCam + HST data used for target selection
- Dynamical analysis out to R_{vir} and beyond (r>3 Mpc) with ~500 members per cluster
- Highly magnified galaxies out to z~7
- Galaxy structure and stellar pop properties from high to low density environments





First CLASH observing campaign of A383 completed



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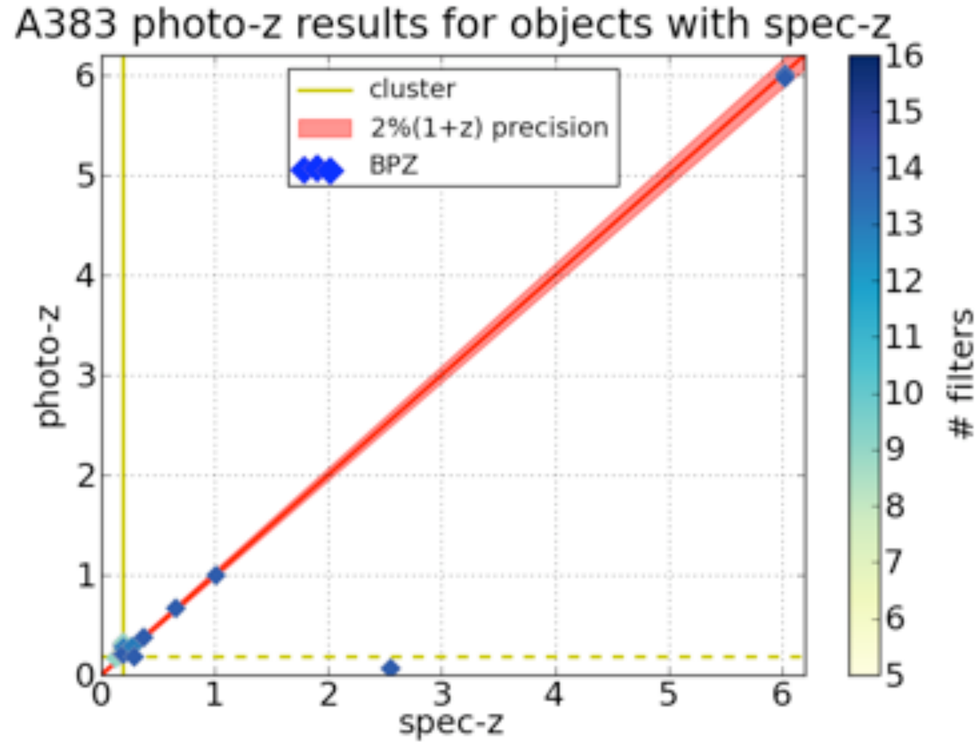
Validation of the 16 filter photo-z's methodology
[preliminary analysis by Dan Coe]



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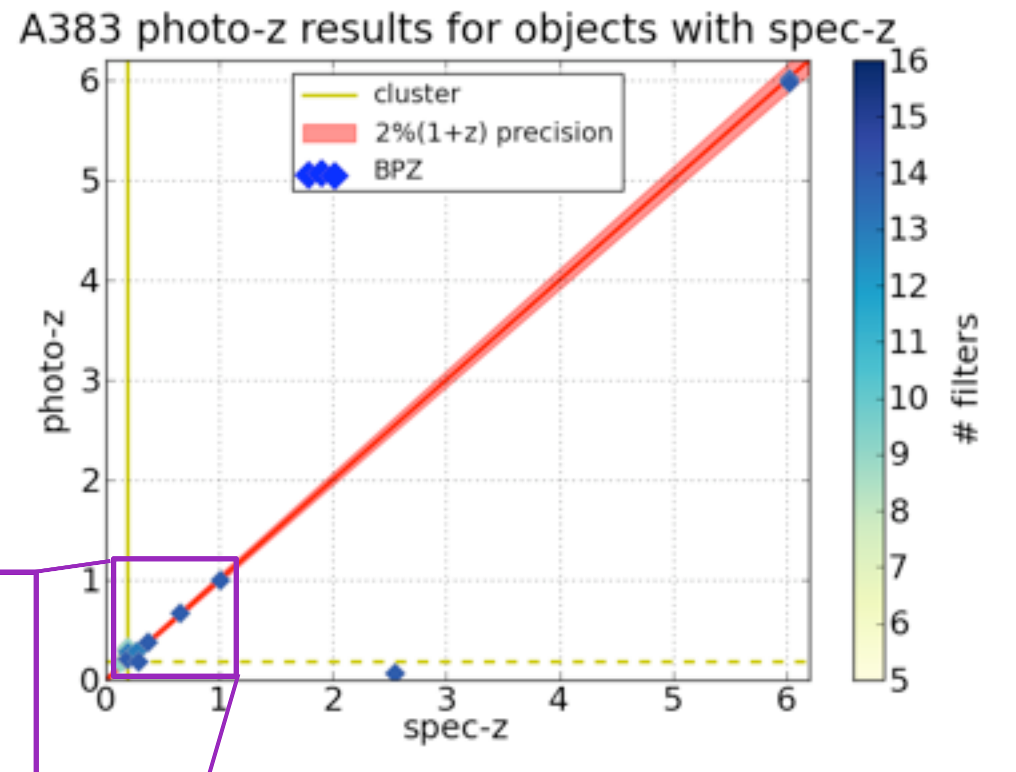

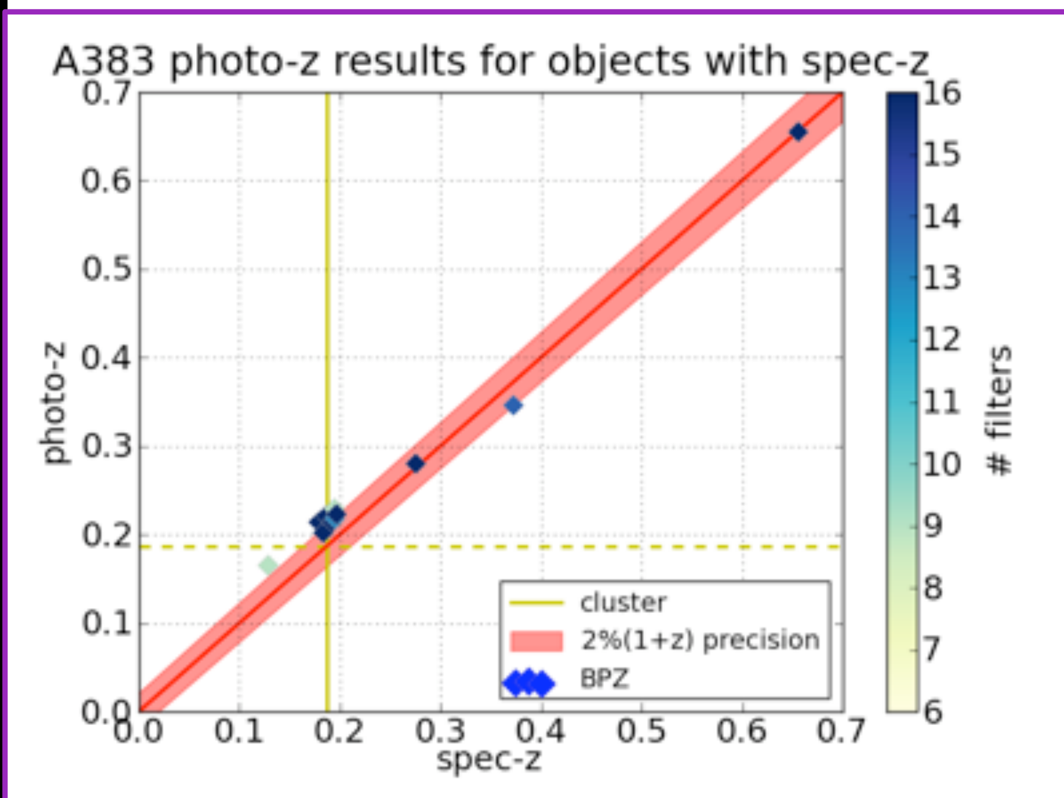

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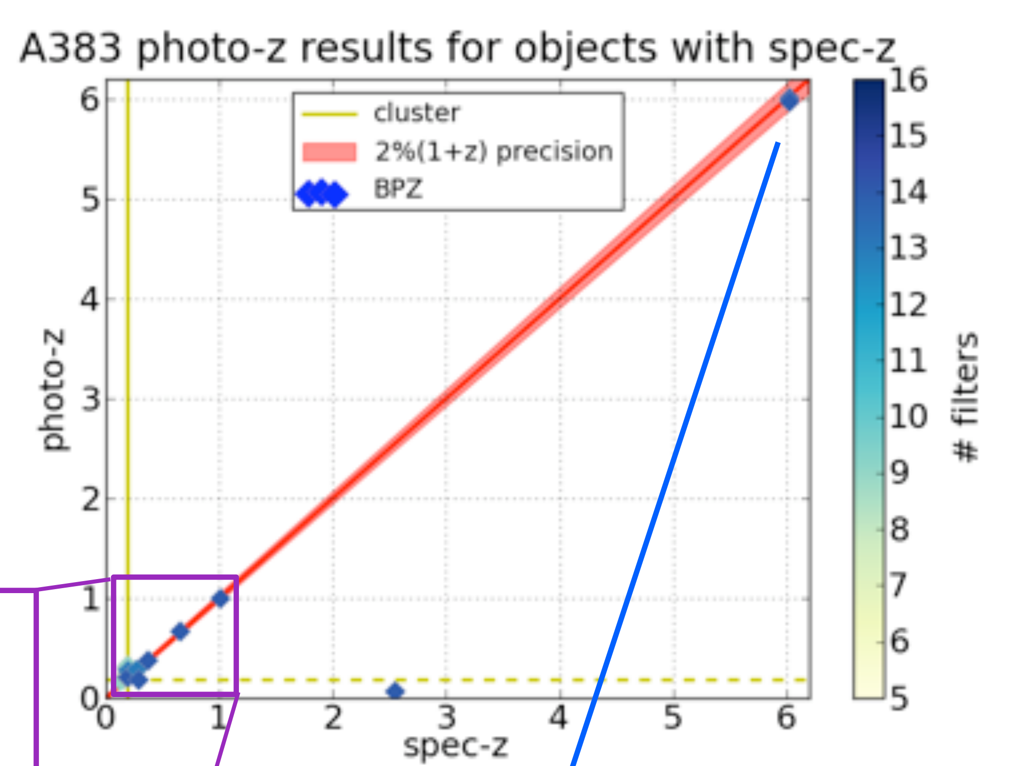
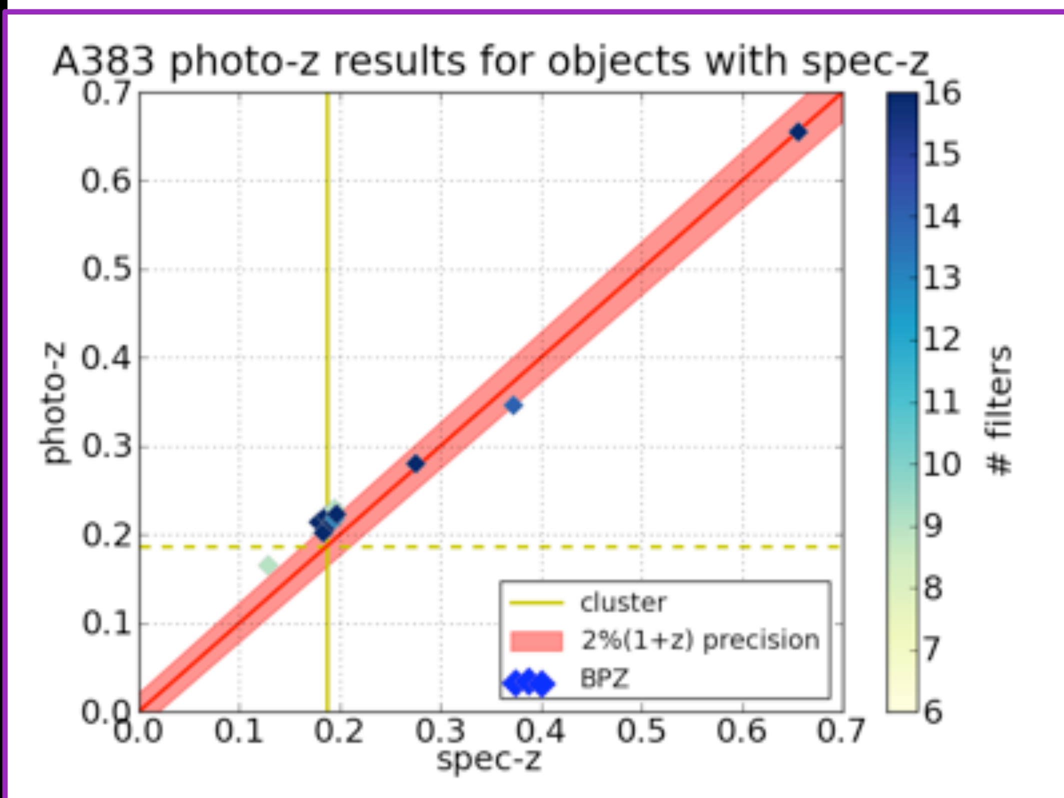
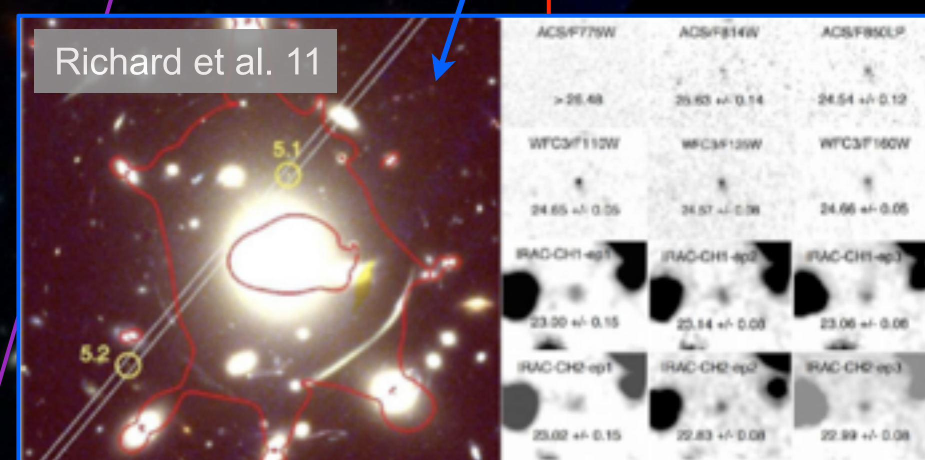
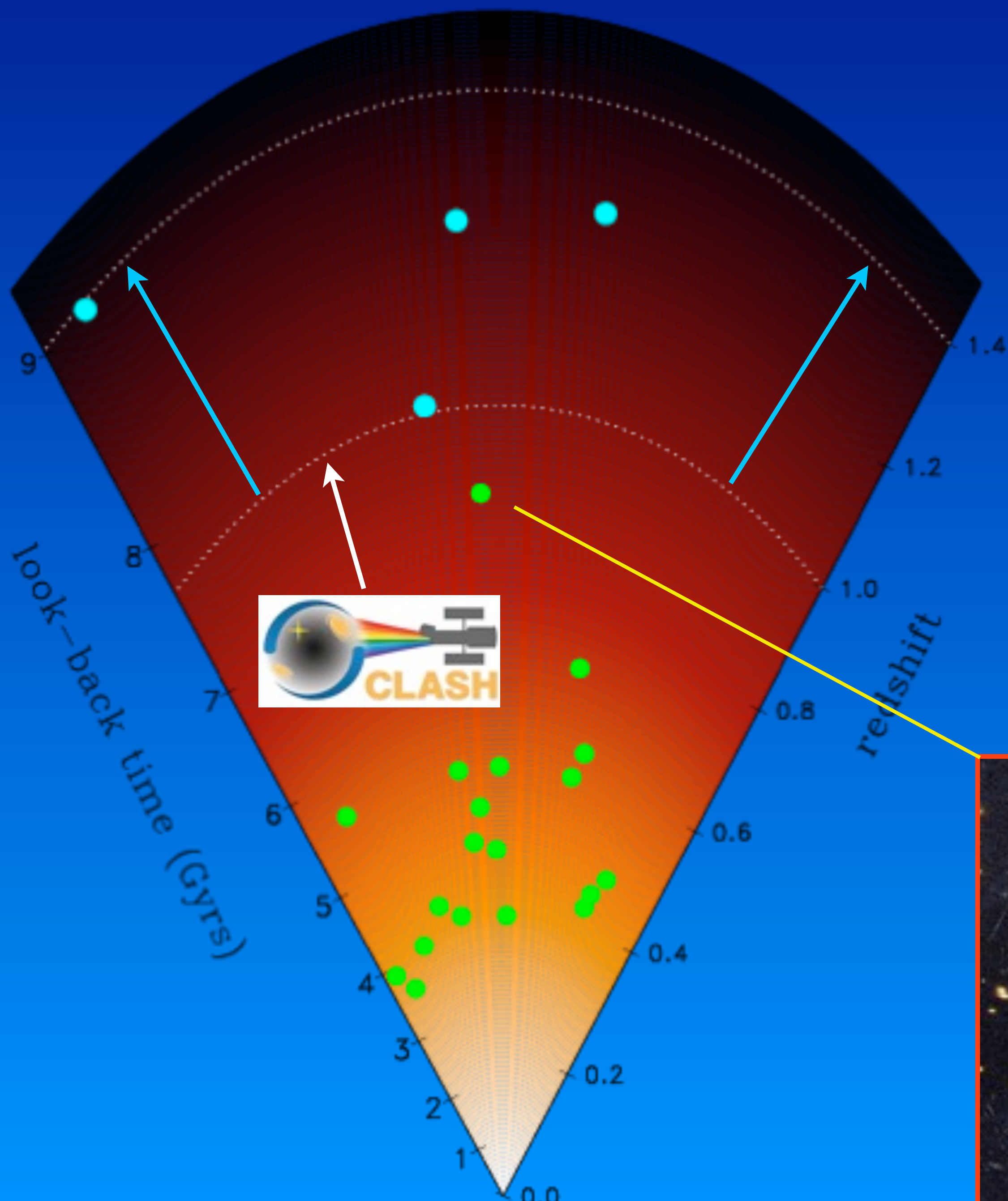




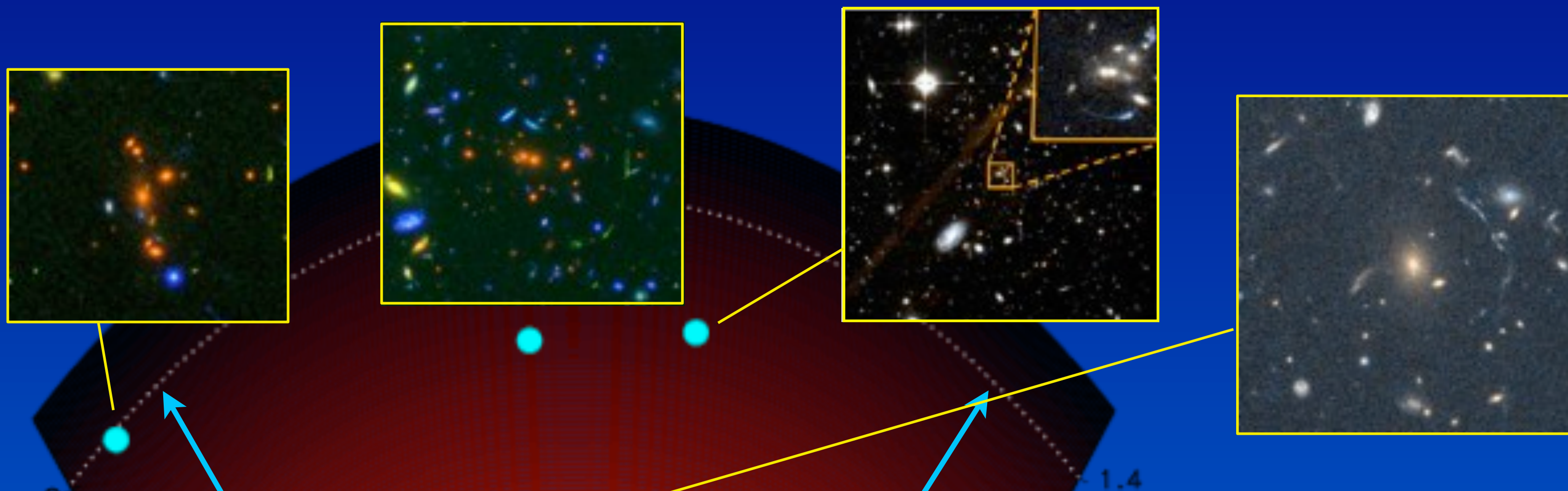


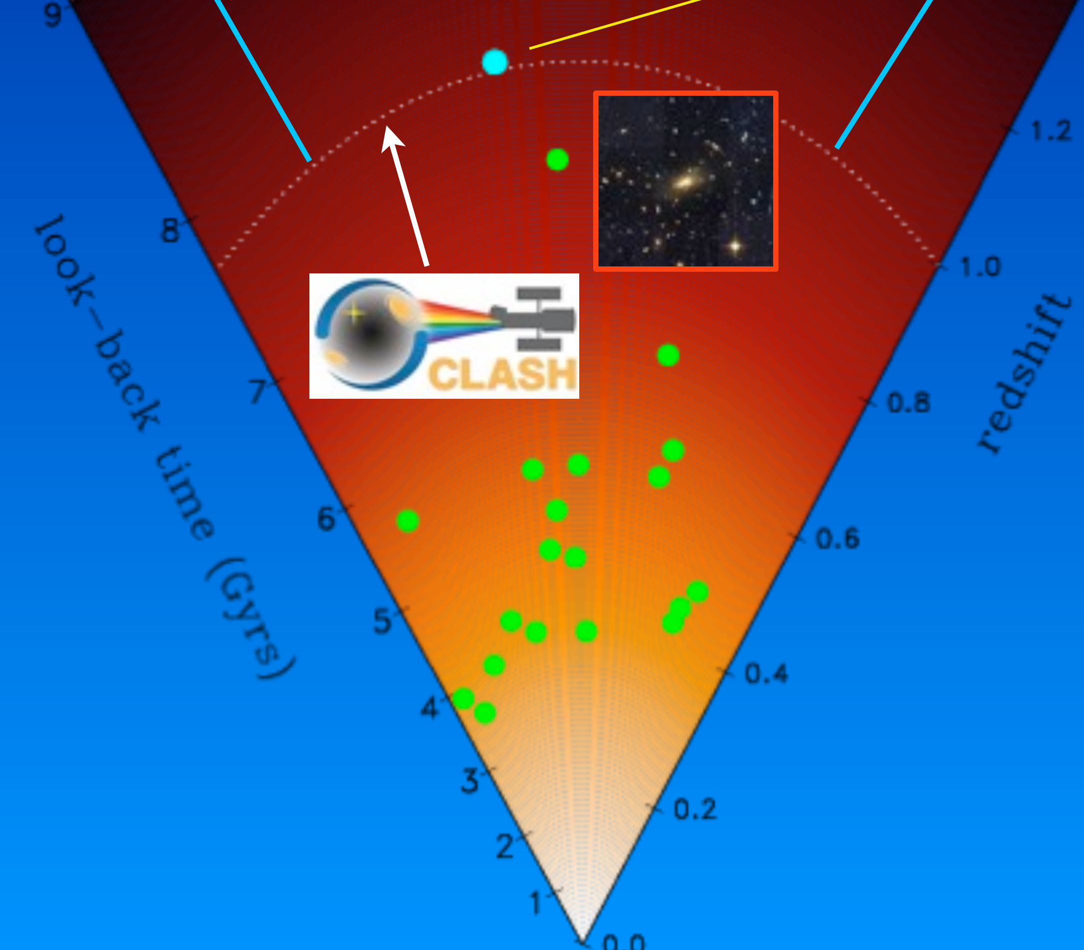
Extending the CLASH work beyond redshift one



– Can we measure the DM distribution in z>1 clusters with sufficient accuracy ?
    ➡ evolution of DM distribution
– Can we then measure M_{200} of most distant clusters with sufficient accuracy ?
    ➡ mass calibration of future surveys

Extending the CLASH work beyond redshift one

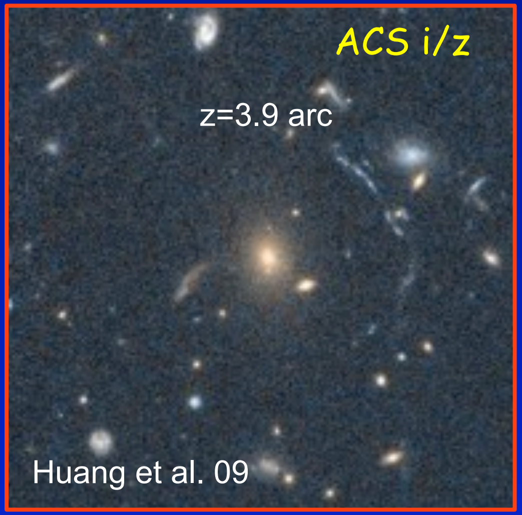


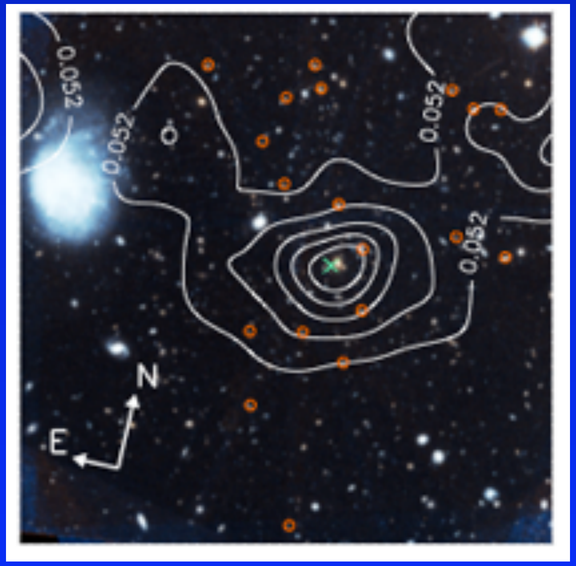


Sample and methodology

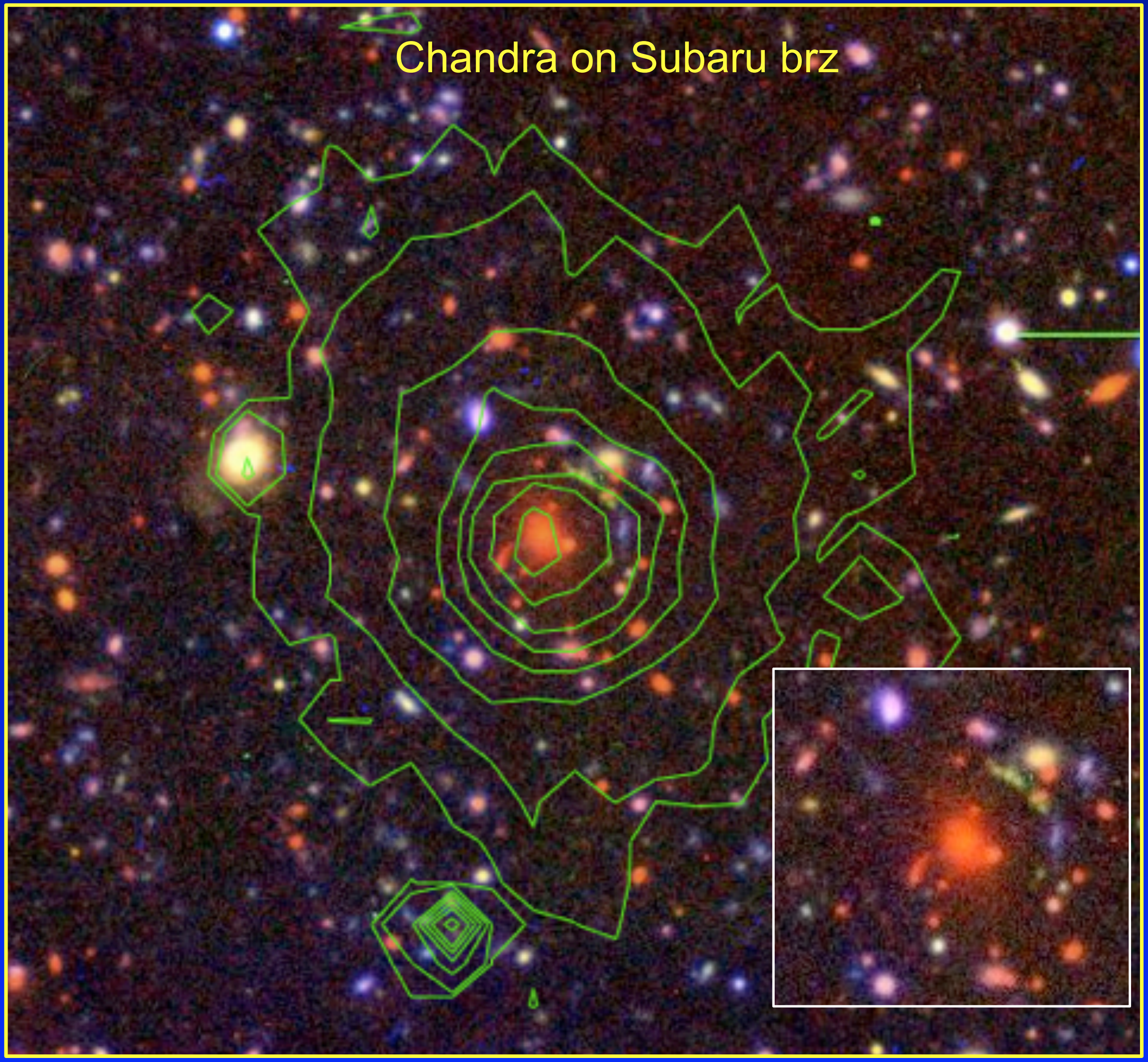
– X-ray selected clusters at $z>1$ with $M_{200}=[1\text{-}8]\times10^{14}M_{\odot}$
  - with SL features
  - WL shear detection (from ACS)
  - deep *Chandra* observations
  - multi-color imaging, esp. deep U-band (VLT)

WARPSJ1415 at z=1.01 - $M_{200} \approx 5 \times 10^{14}\ M_{\odot}$ (J.Santos' talk)
The deepest (370 ksec) Chandra observations of a z=1 cluster



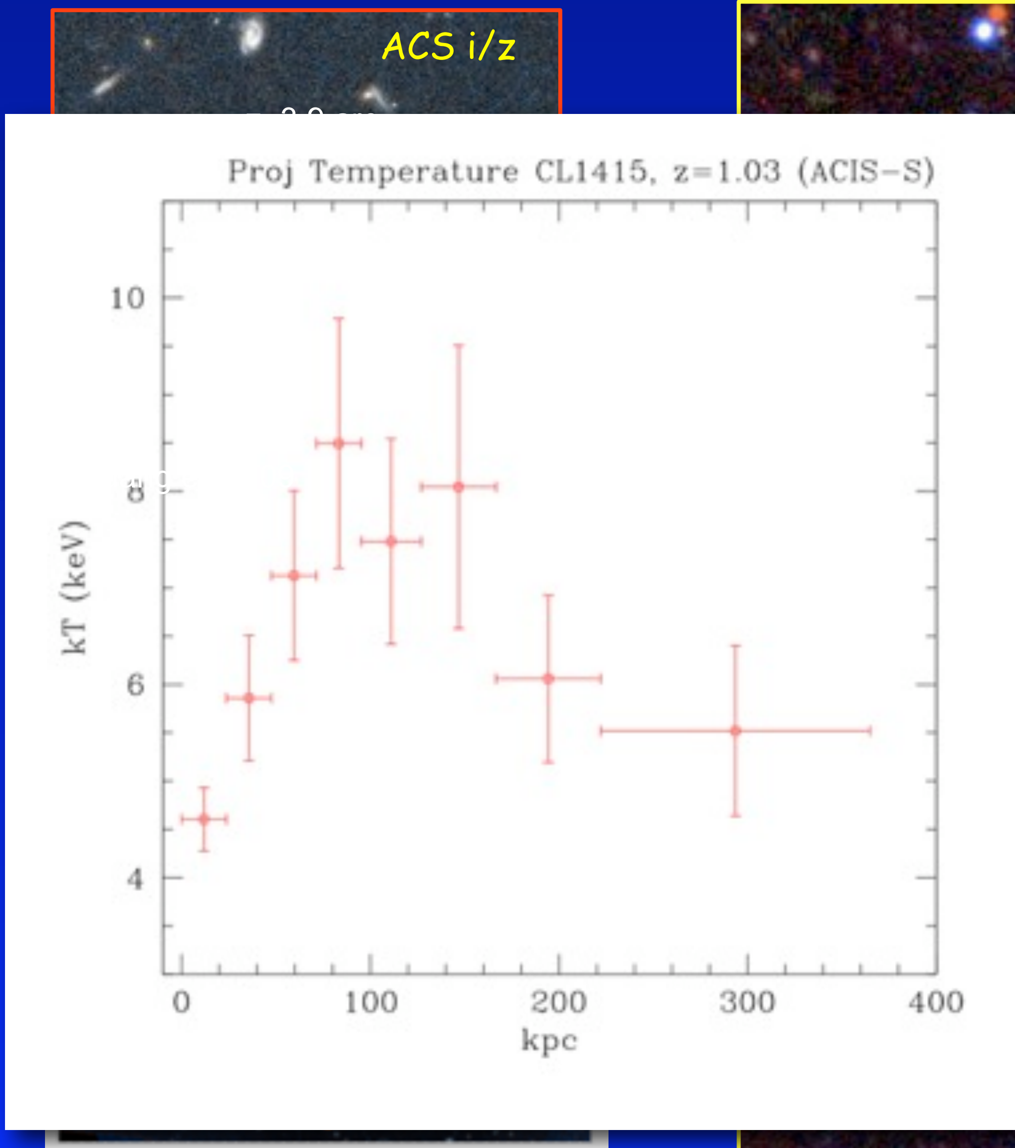


Weak Lensing mass map
(Jee et al. 2011)



Santos, Tozzi, Rosati et al. 2011 (in prep)

WARPSJ1415 at z=1.01 - $M_{200} \approx 5\times10^{14}\ M_{\odot}$ (J.Santos' talk)
The deepest (370 ksec) Chandra observations of a z=1 cluster



Weak Lensing mass map
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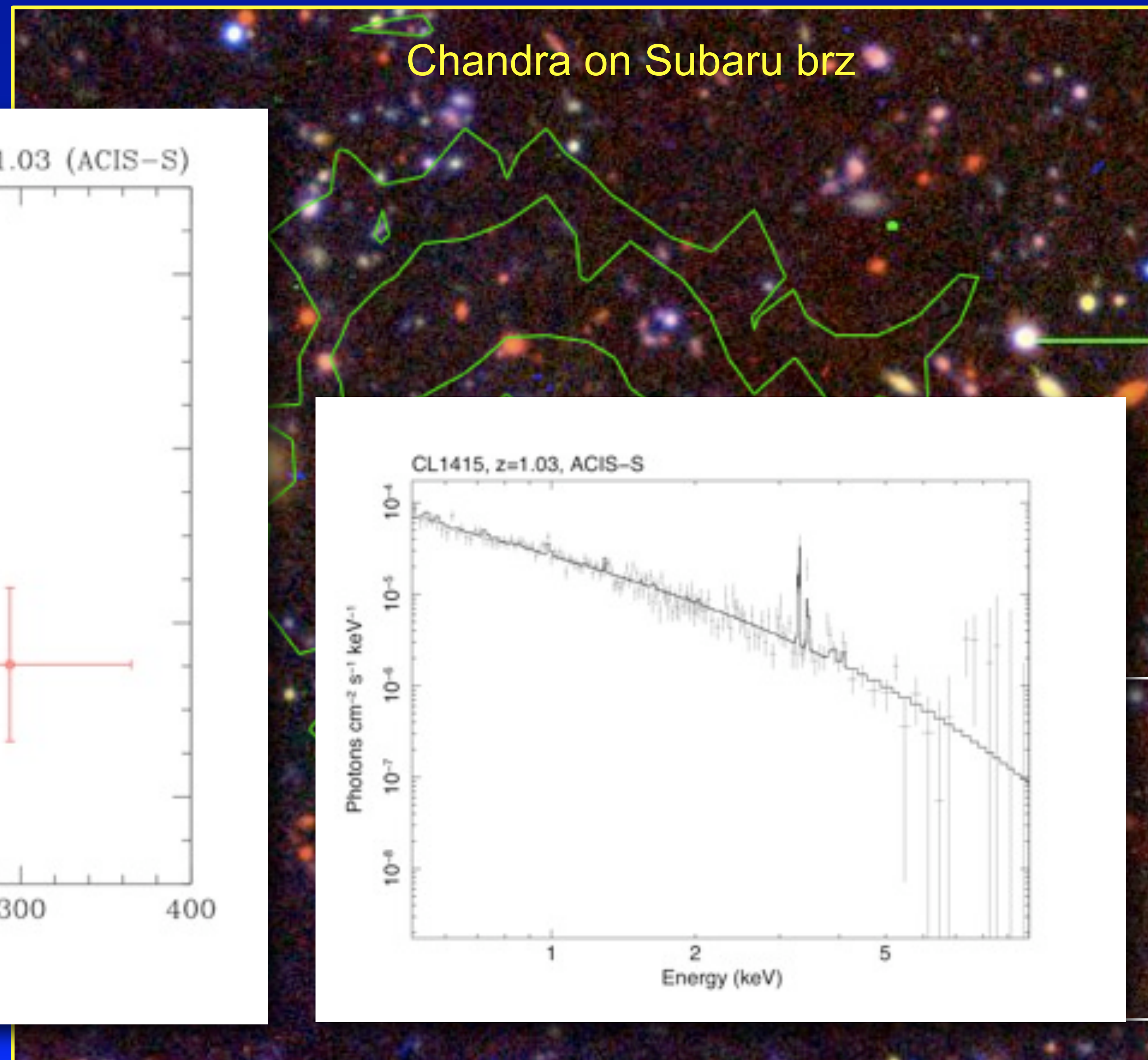
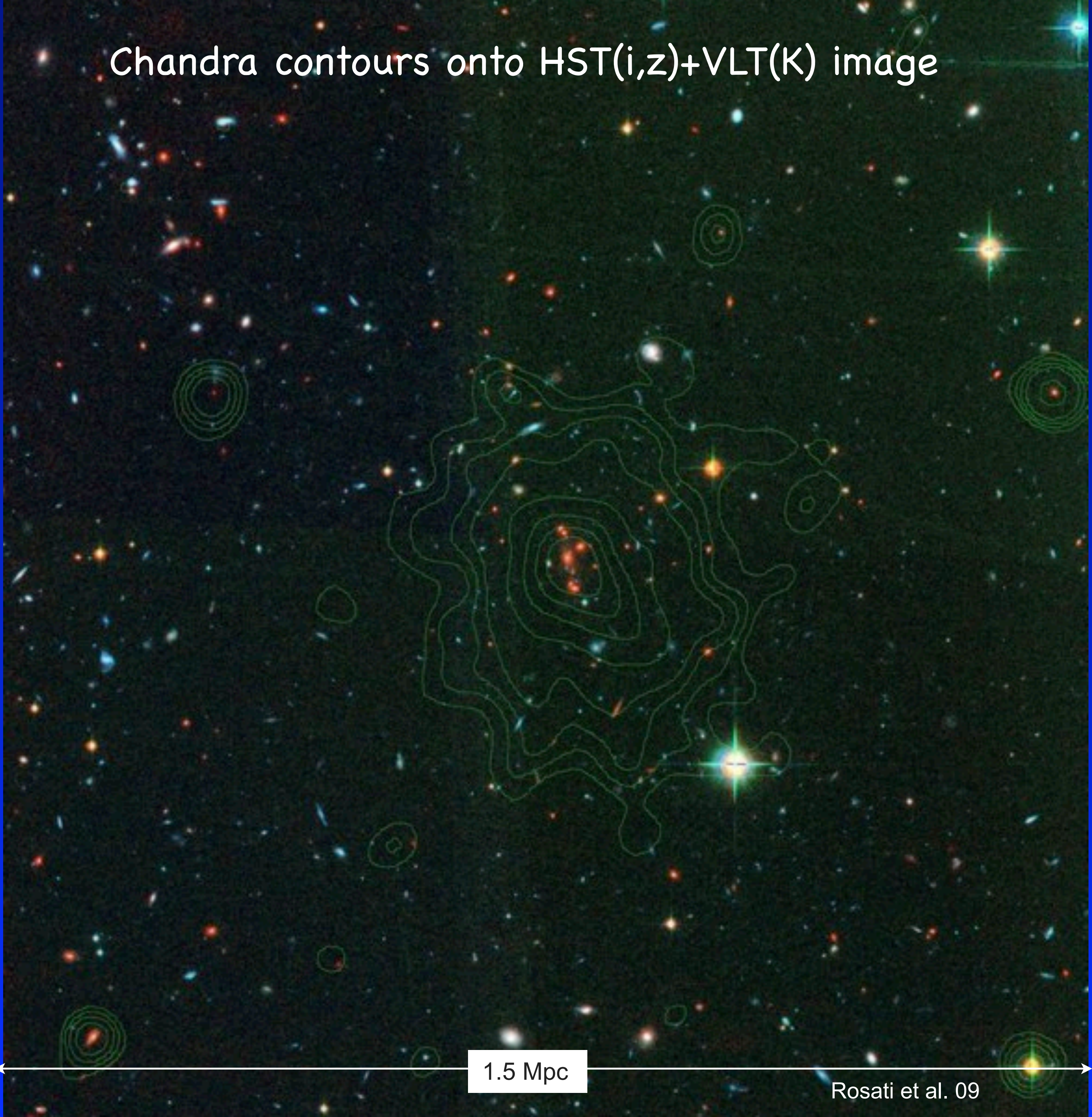


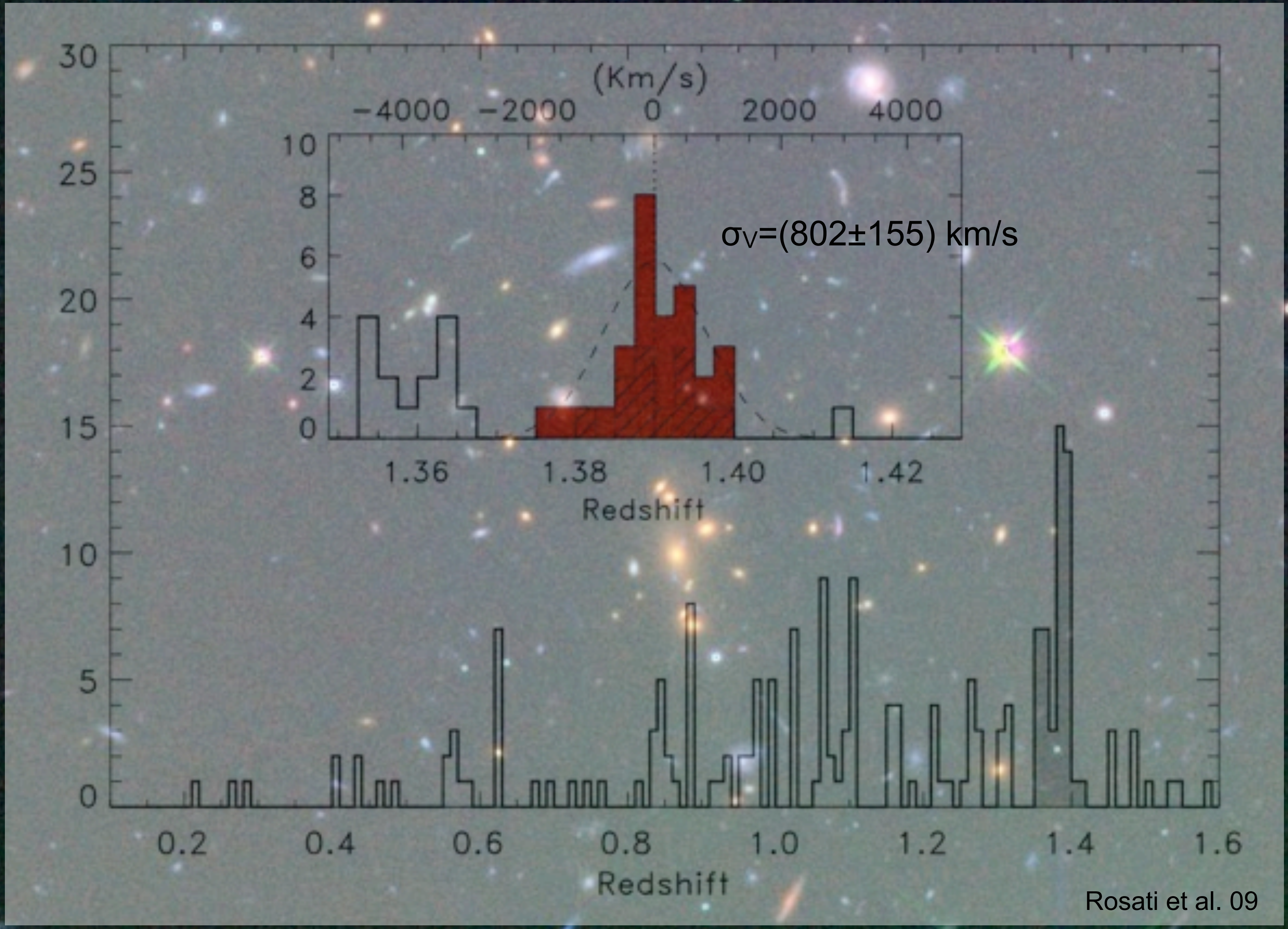
Santos, Tozzi, Rosati et al. 2011 (in prep)

XMMJ2235 at z=1.39 (Mullis+ 05, Rosati+ 09)
from the XDCP survey



Multi-λ photometry: URizJHK$F_{105}F_{110}F_{125}F_{160}$

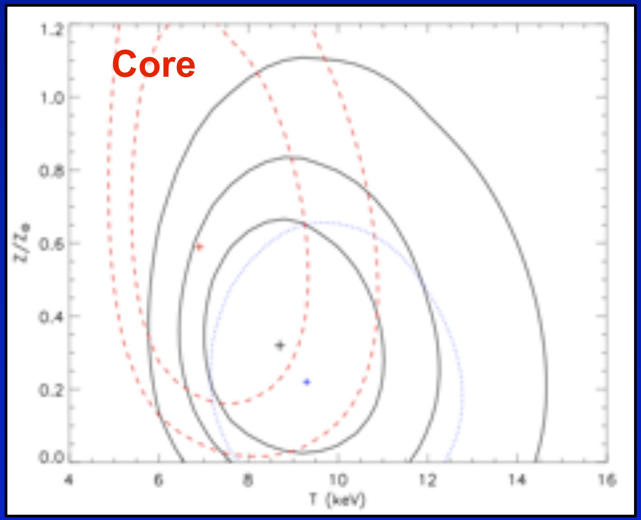
VLT Spectroscopic Campaign on XMM2235

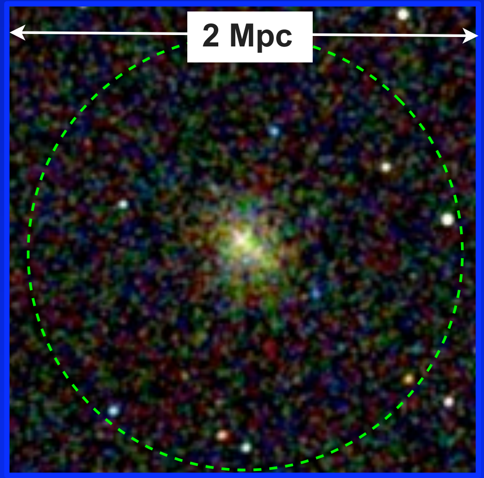


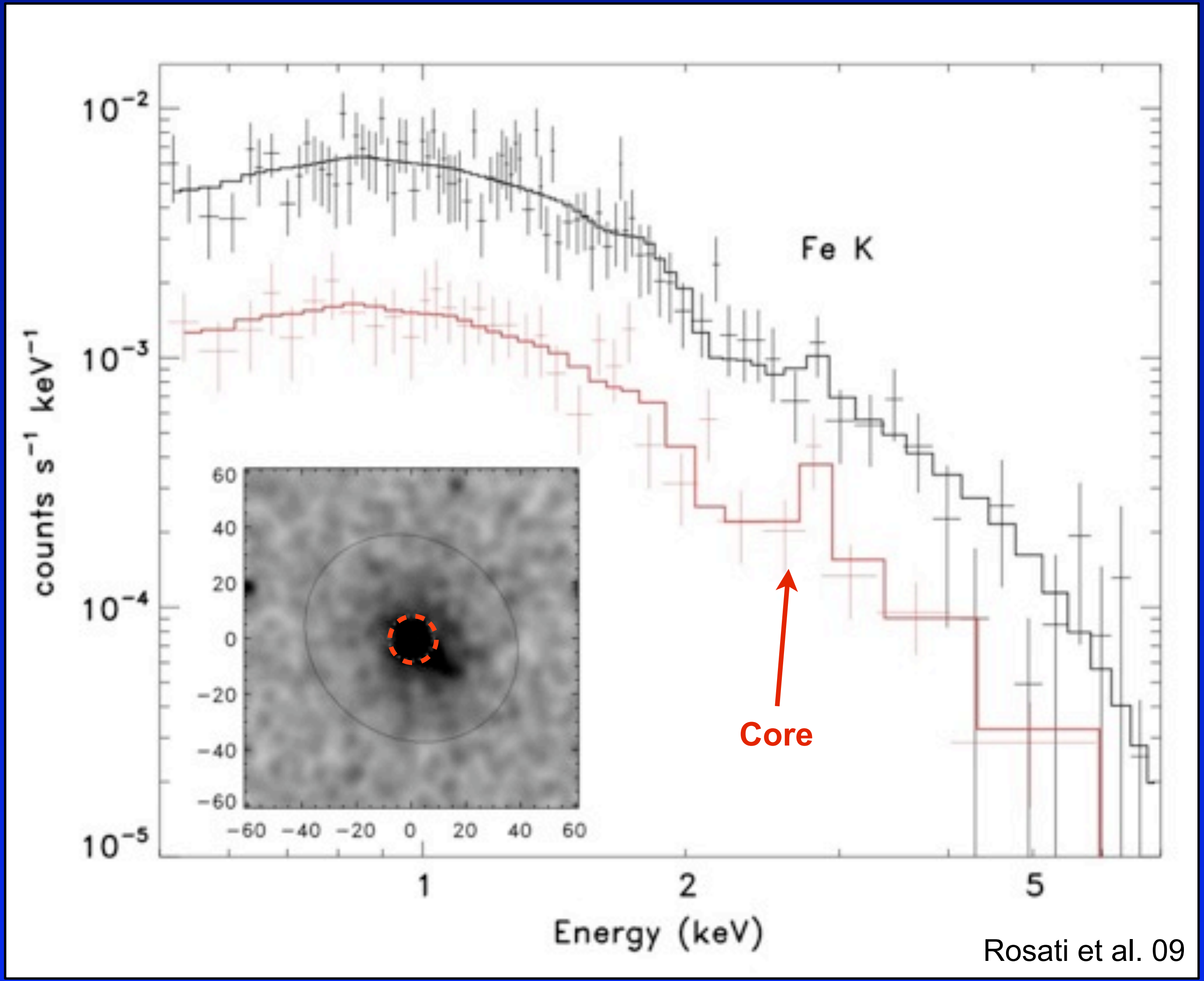
- Spectroscopic members (over 3 Mpc): 34 (22 passive, 12 star forming)
- >150 redshifts in the field

ACS(i+z) - WFC3(J+H) - HAWKI-K_s color composite (Rosati+ 09, Strazzullo+ 10, Nunez+ 11)

Chandra Observations of XMM2235 (190 ksec)







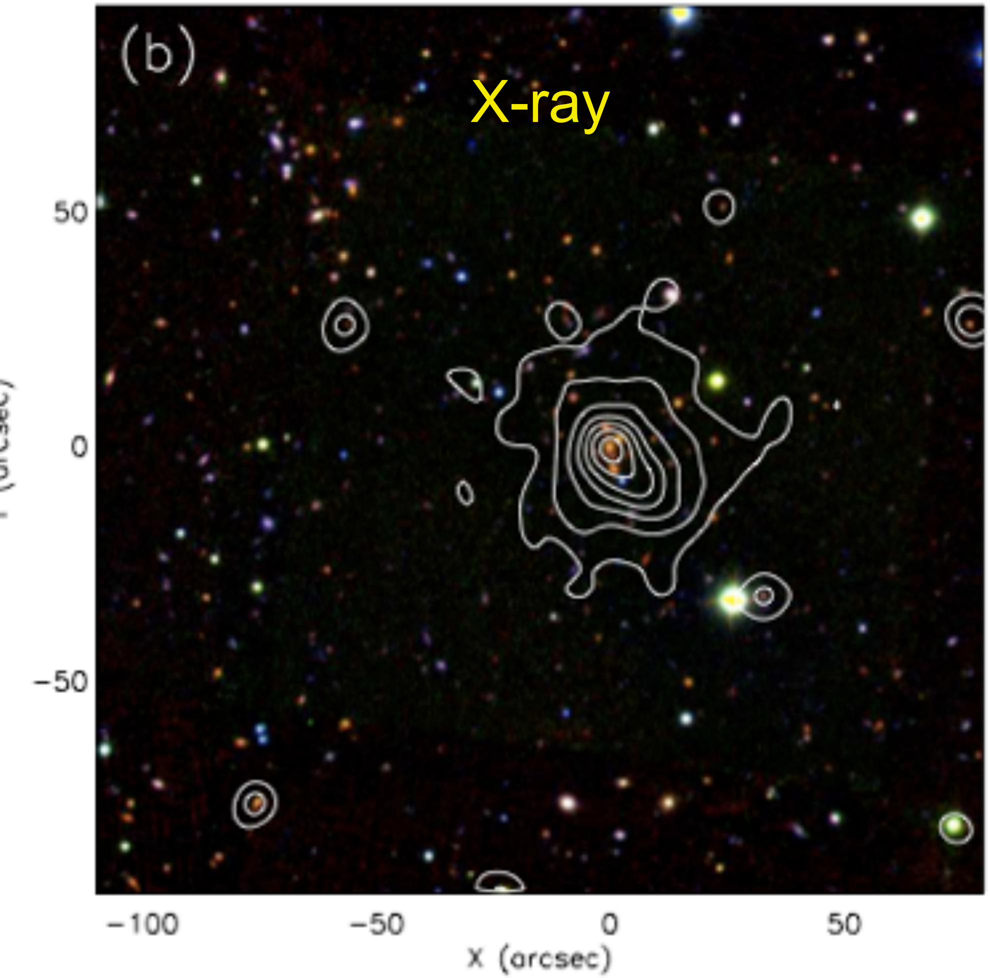
➡ Hottest most distant cluster to date with a prominent cool core:

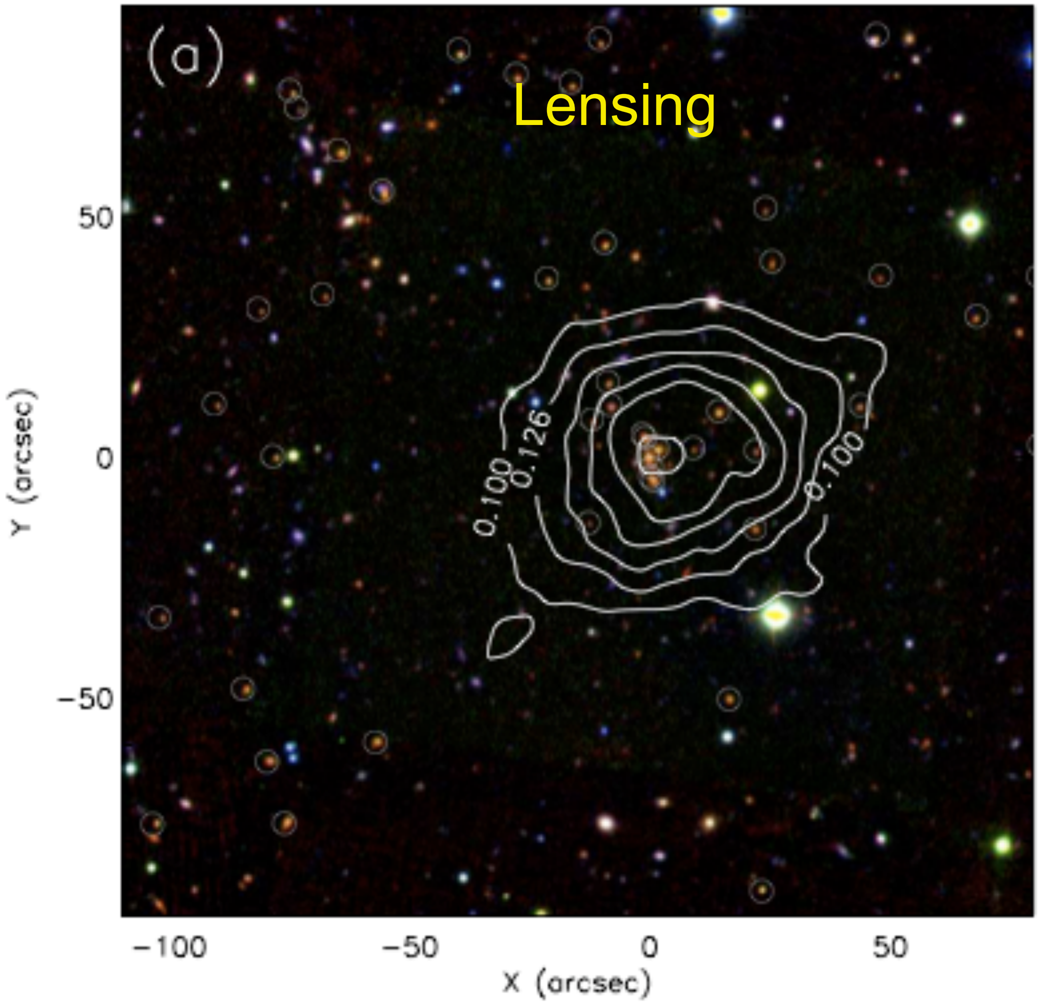
$M_{200}(<1.1\ \mathrm{Mpc}) = (7.1\pm1.3)\times10^{14}\ M_{\odot} / h_{70}$ (hydrostatic eq. assuming T(r))

➡ The ICM is already enriched at local values at z=1.4

Weak-lensing analysis from HST/ACS

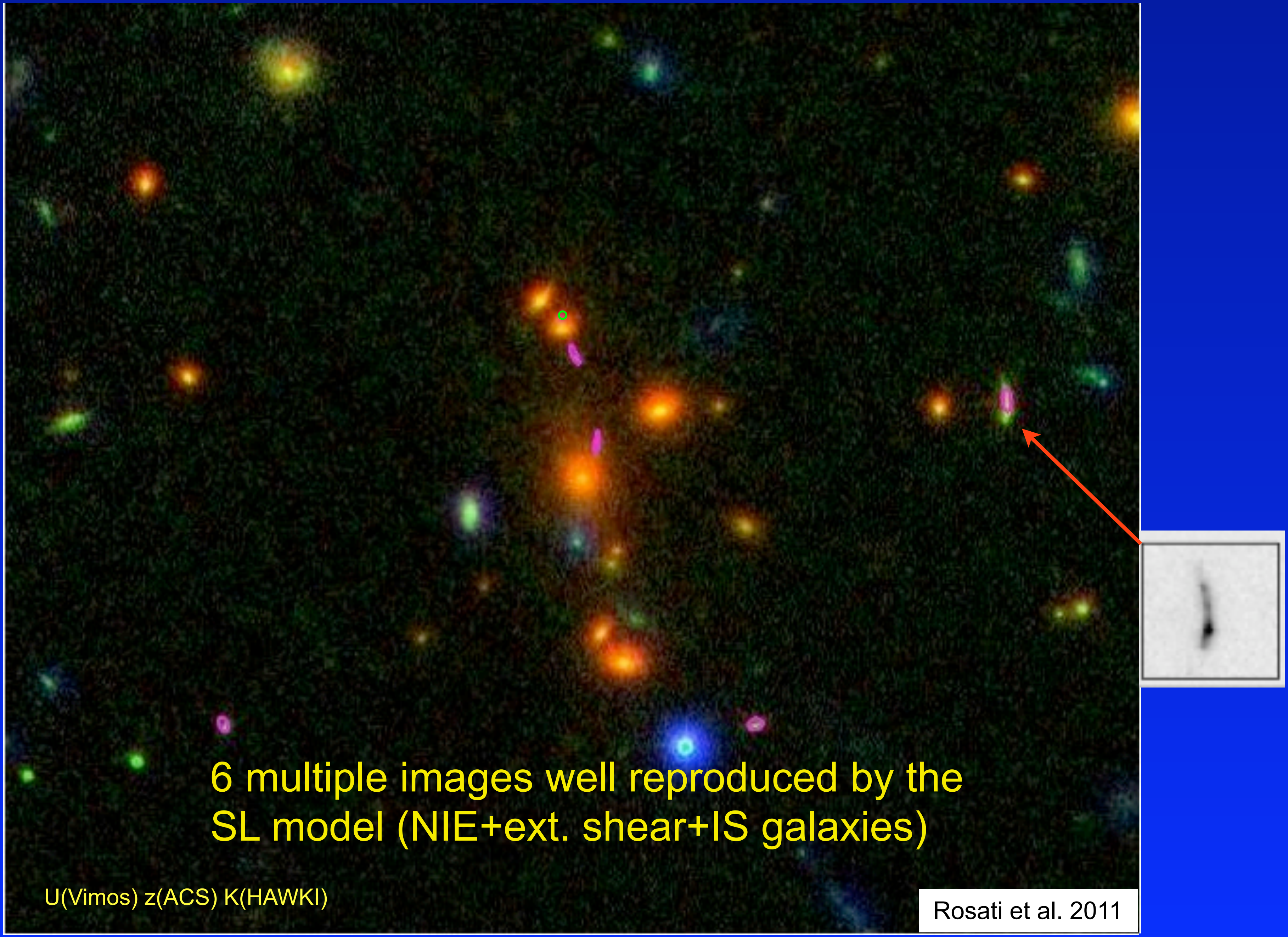
(Jee et al. 09)



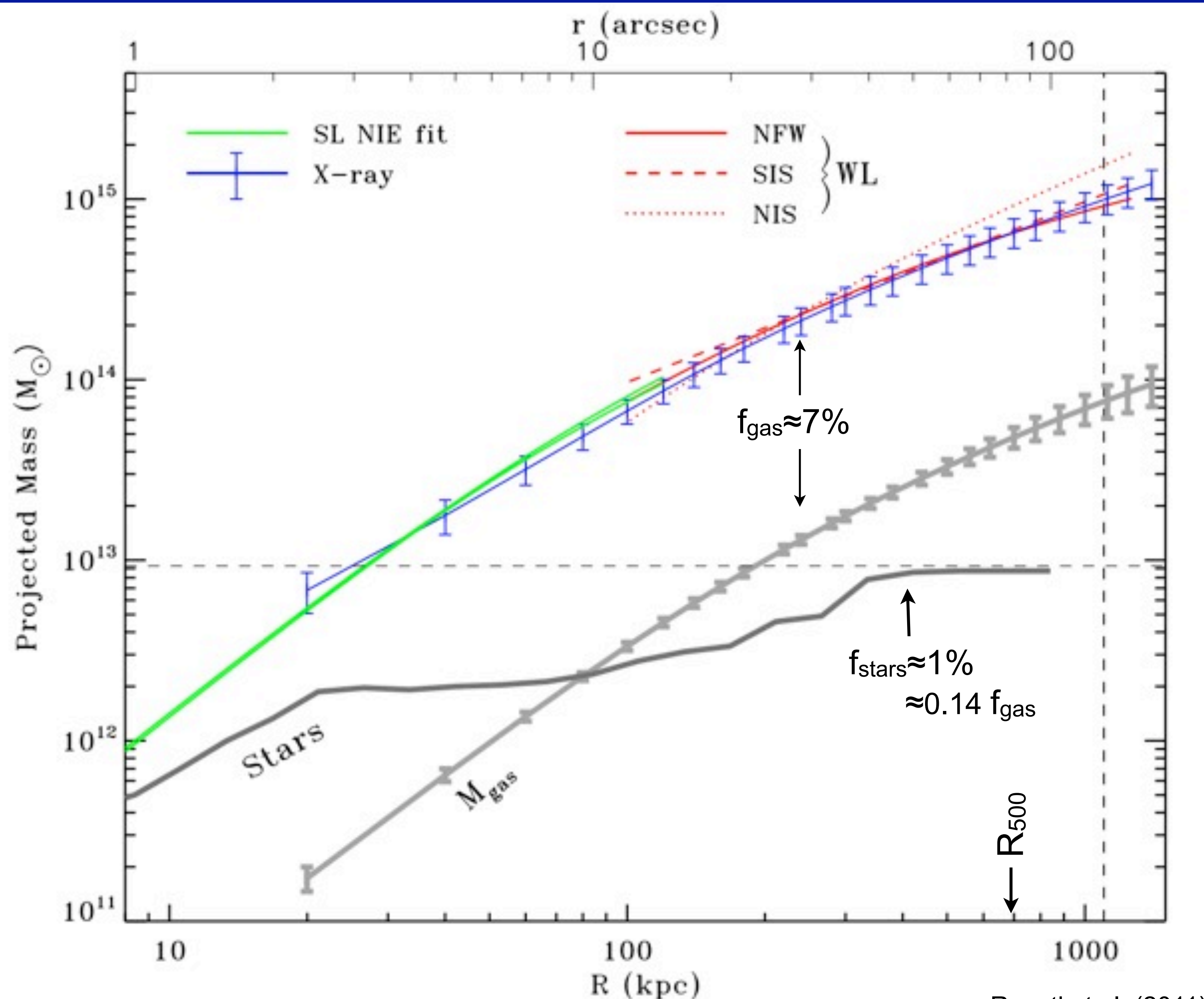


- Shear signal detected out to ~1 Mpc (max >8σ), beyond Chandra (8150s exp, i_{775} band)
- X-ray and Weak Lensing based masses at r=1 Mpc agree within 10%
- Systematics in WL can be further reduced with SL features

Modeling the core mass distribution (with the most distant lens)

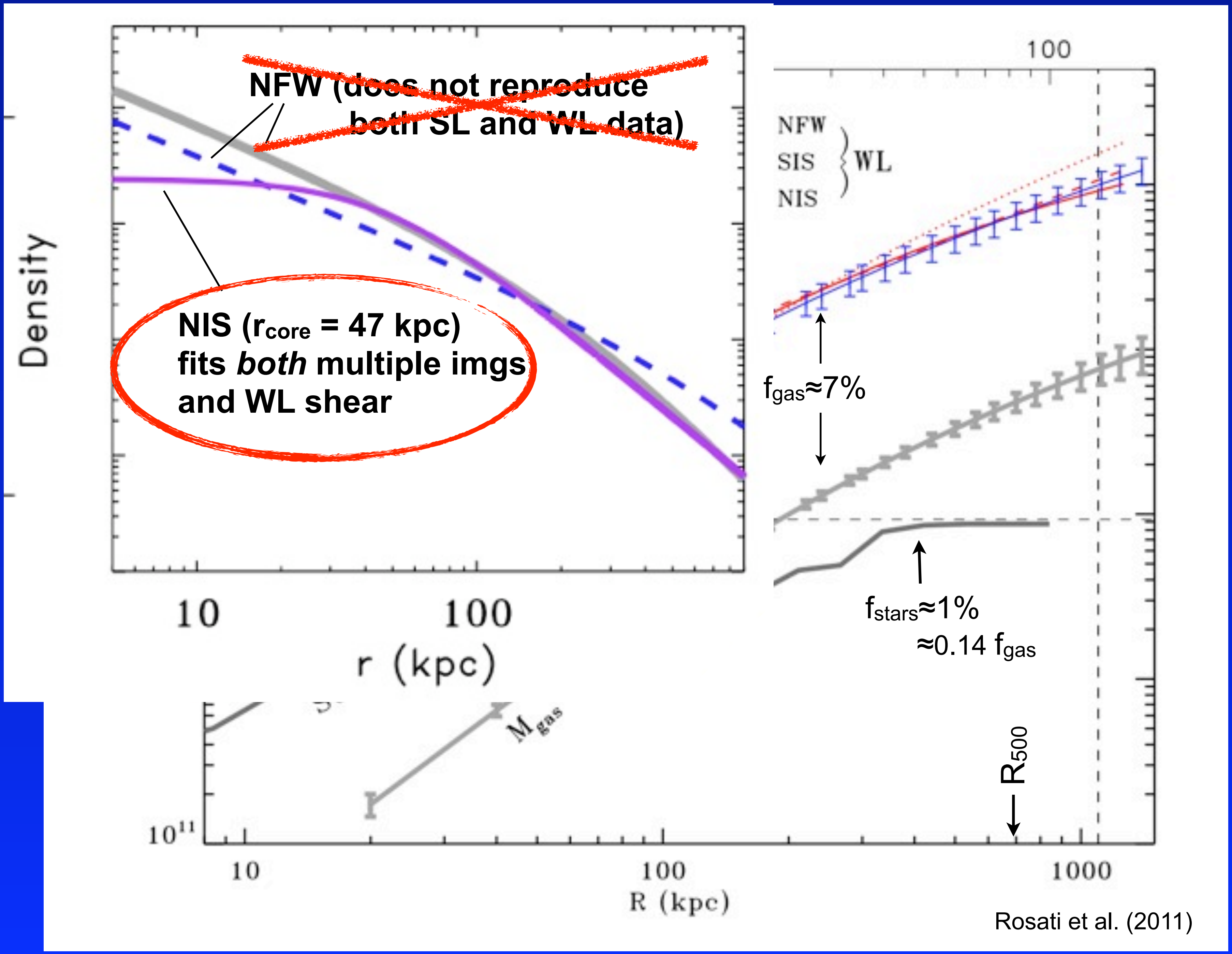


Mass components of XMM2235 (at z=1.4)



Rosati et al. (2011)

Mass components of XMM2235 (at z=1.4)



Rosati et al. (2011)

Anatomy of a massive cluster at z=1.4
Too big ? too early ?

See also J.Jee's talk

- XMM2235 is in a surprisingly advanced evolutionary state at 2/3 T_U:
  - Old stellar pops, almost complete stellar mass assembly, early ICM metal enrichment, prominent cool core

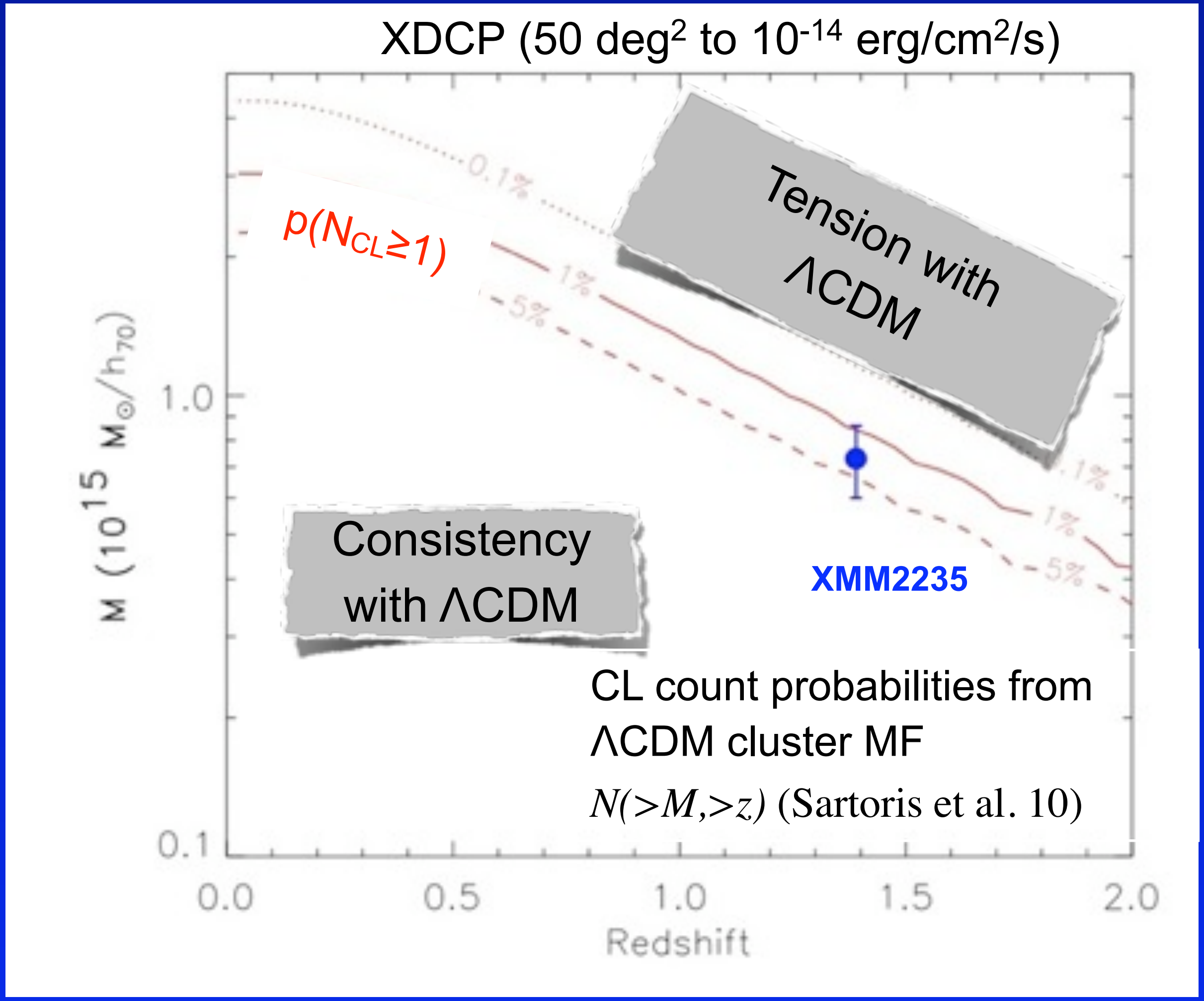
- Accurate mass profile, very robust mass determination (multiple mass probes):
  - Such massive cluster not expected ($p \approx 1$ %) in the X-ray survey volume ("3σ discrepancy with ΛCDM")

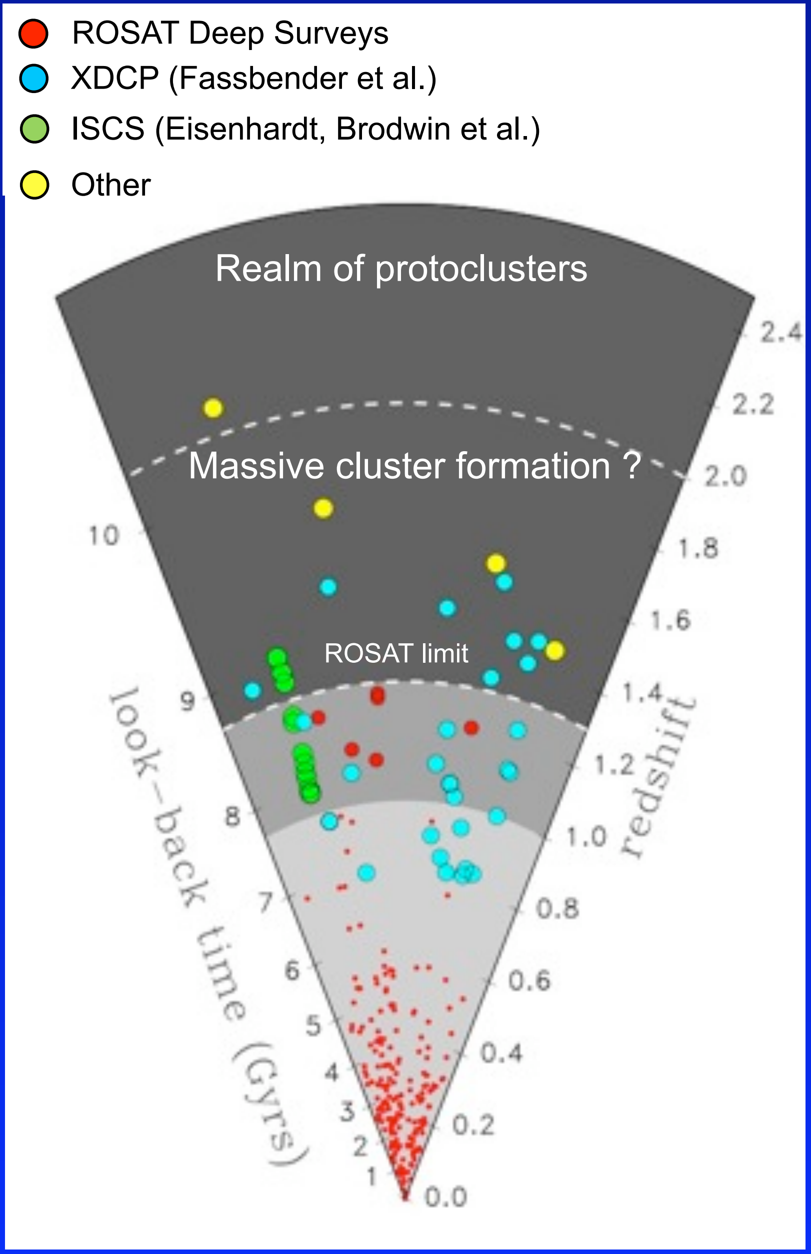
  ➔ this stimulated a number of papers exploring also "exotic solutions"

  - *non-gaussian fluctuations* (Jimenez&Verde 09, Sartoris et al. 10, Hoyle et al. 10)
  - *interacting dark energy (*Baldi & Pettorino 10, Mortonson et al. 10)
  - Holz&Perlmuter 10: *the cosmological leverage of massive high-z clusters*

The most massive distant clusters in the Universe and their impact on Cosmology

See J.Jee's talk





- selection function and completeness not critical
- weak and strong lensing very effective
- all mass probes available

☛ Accurate (<10% errors) M_{200} measurements needed !

The most massive distant clusters in the Universe and their impact on Cosmology

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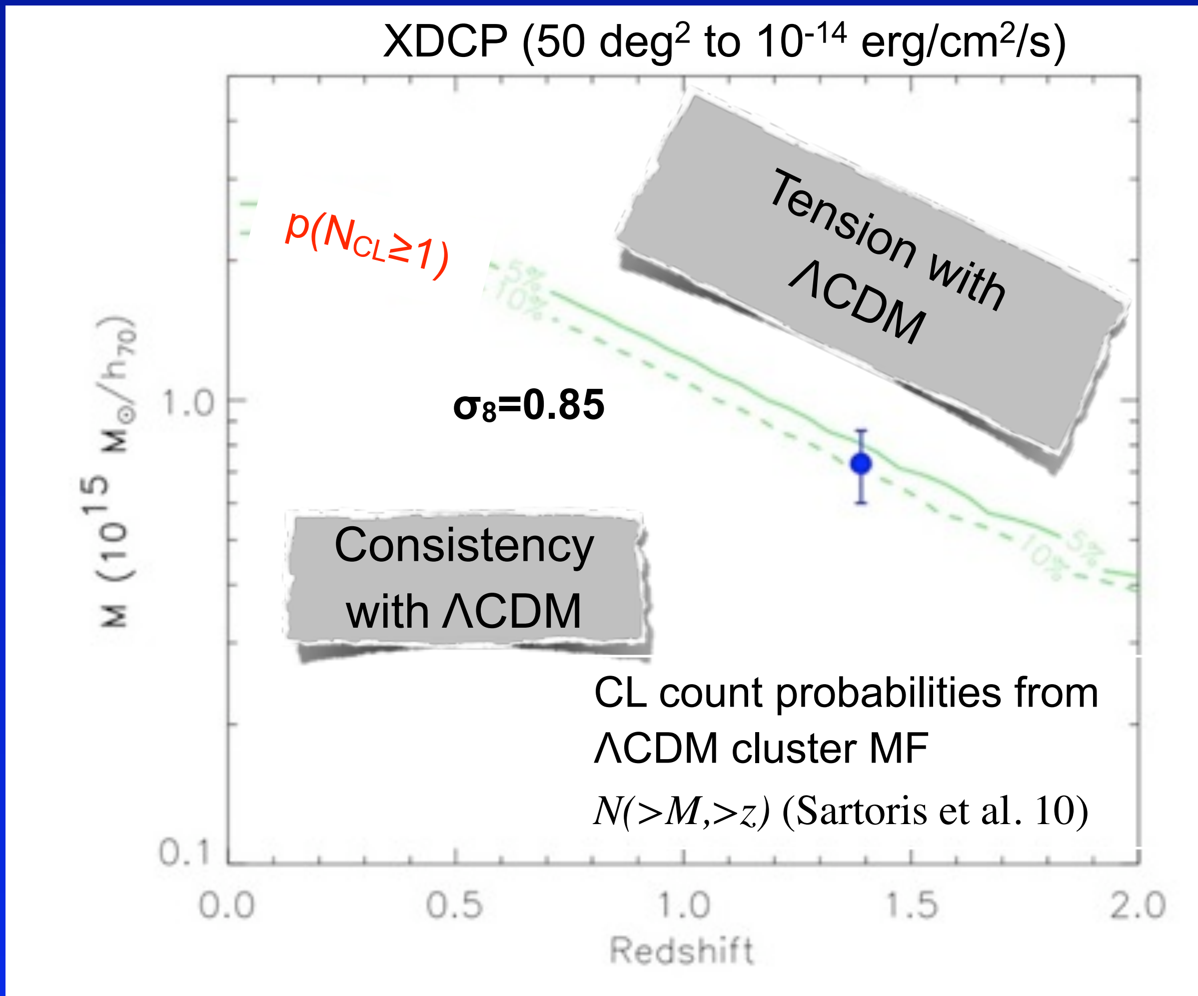

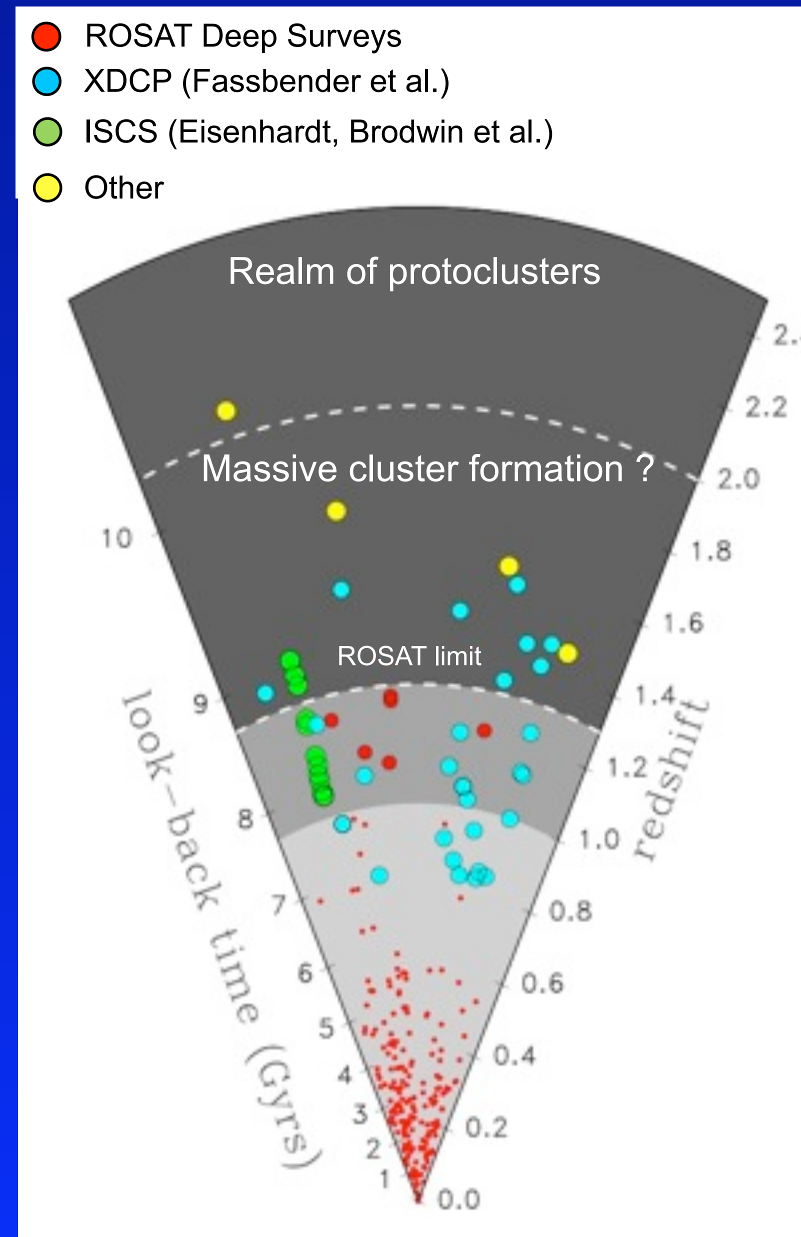

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Conclusions

- The CLASH MCT program with multi-wavelength, multi-observatory supporting data will dramatically improve our understanding on the DM (and baryonic) structure of massive clusters
- CLASH will be a public data set with a vast range of astrophysical applications
- With very good data the CLASH work can be extended beyond z=1
- The best data available to date, *with multiple mass probes,* show flat inner slopes *in contrast with ΛCDM predictions all the way to z=1.4* (ignorance on baryonic physics or fundamental failure of ΛCDM on small scales? small number statistics to date)
- The ability of measuring DM and Baryonic masses and mass distributions to high-z is good news for calibration programs of future cluster surveys and for cosmological applications (most massive cluster tests)

Thanks to collaborators

- CLASH Team

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- XDCP Collaboration