Structure Formation and Cosmology with high-z Clusters

Lecture Plan

Piero Rosati (ESO)

L1 : Introduction, observational techniques
- Observational definition, observable physical properties
- Methods for cluster searches - Cluster surveys
- Multi-wavelength observations of distant clusters

L2: Clusters as Cosmological Tools
- Constraining cosmological parameters with clusters
- The new population of high-z clusters

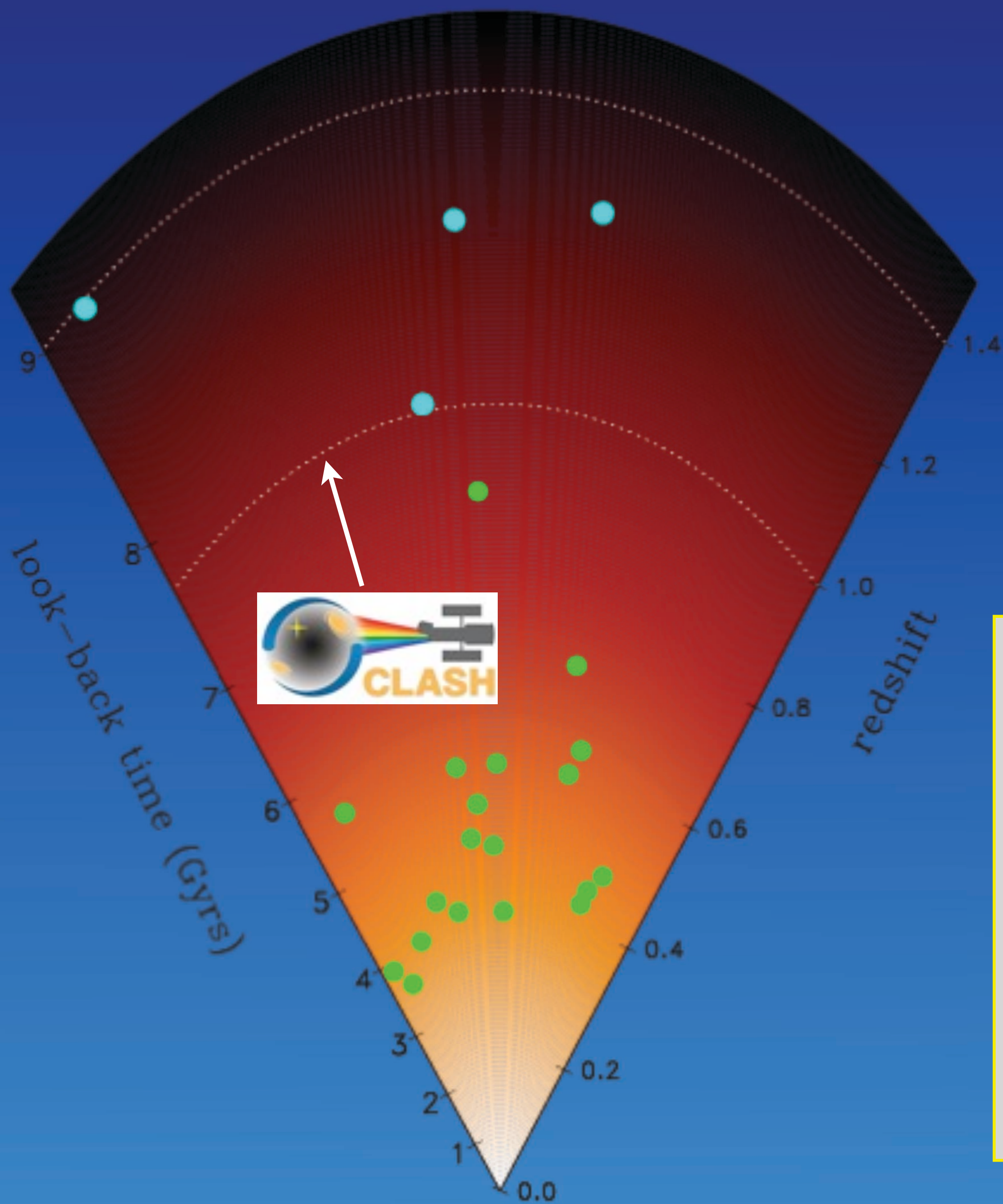
L3: Probing Dark Matter in Clusters
- Basics of gravitational lensing (strong and weak)
- Constraining DM density profiles in cores - ΛCDM predictions
- Clusters as gravitational telescopes

L4: Galaxy populations and evolution in distant clusters
- Star formation history of cluster galaxies
- Evolution as a function of environments
- (Proto-clusters)

XVI IAG/USP Advanced School on Astrophysics,
Itatiba, Brazil - Nov 5-9 2012

Can we extend this work beyond redshift one ?

[...continues from Lecture 3]



- 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
  - ➡test ΛCDM with most massive clusters $N(>10^{15}M_{\odot},z>1)$

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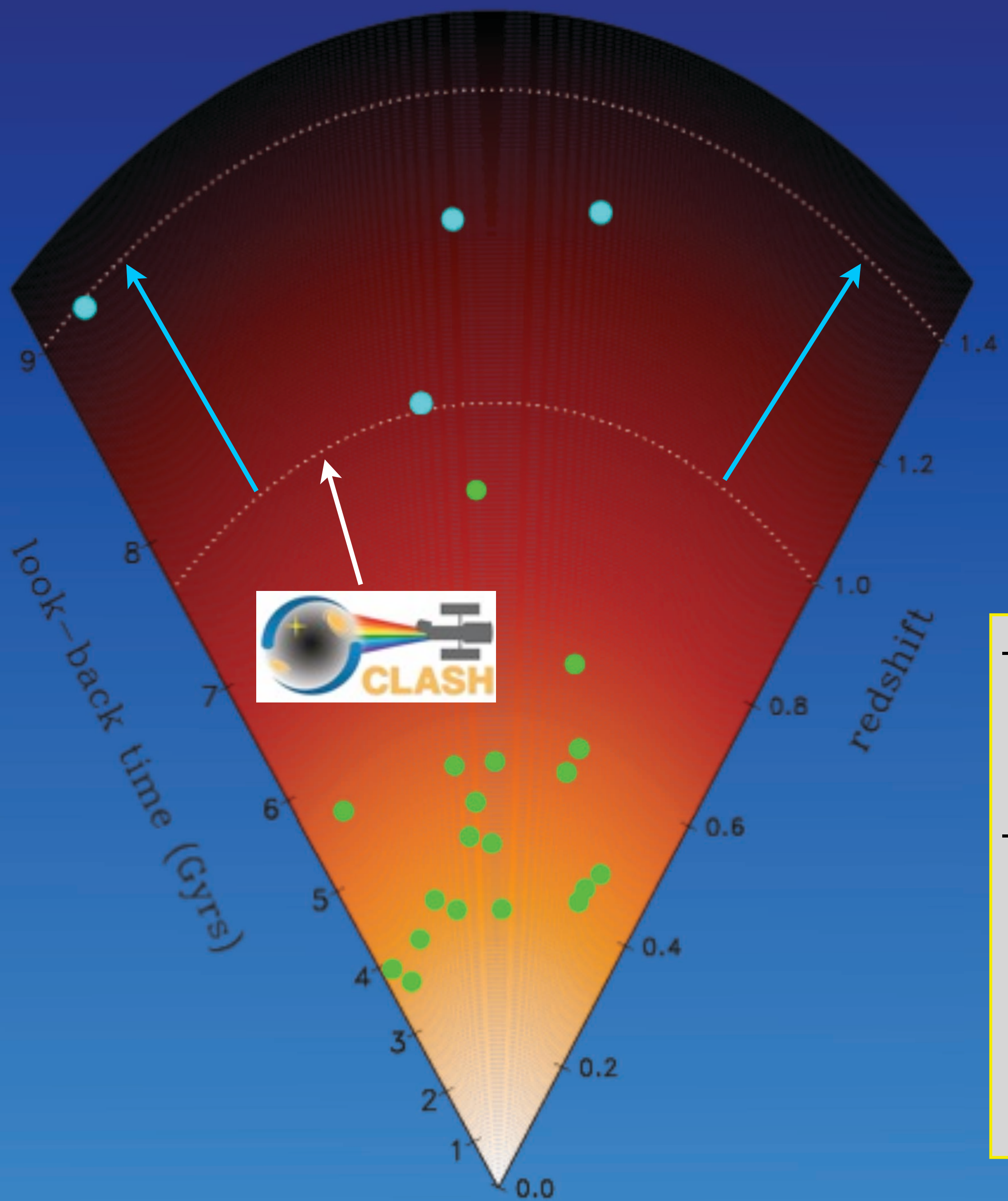

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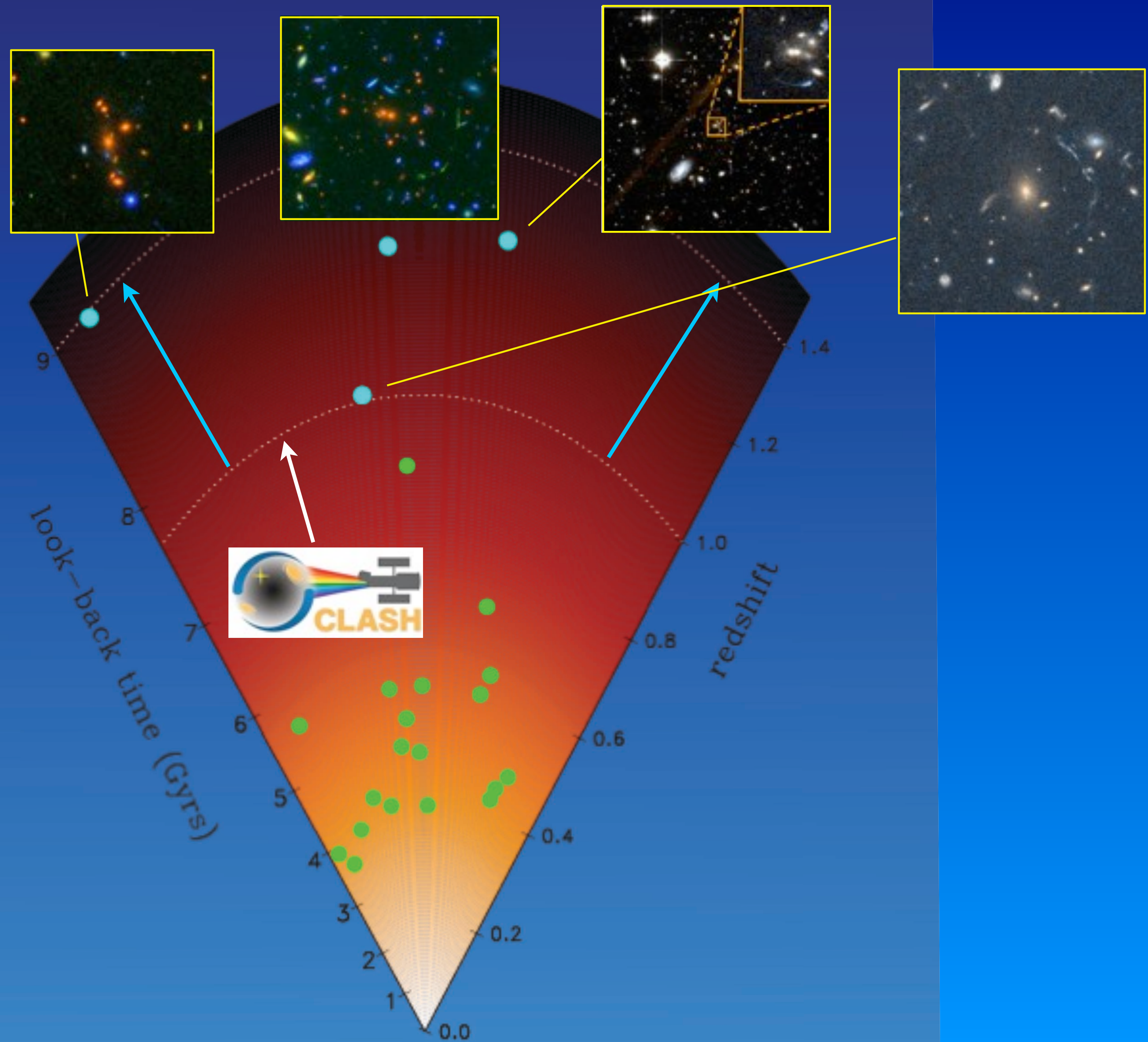
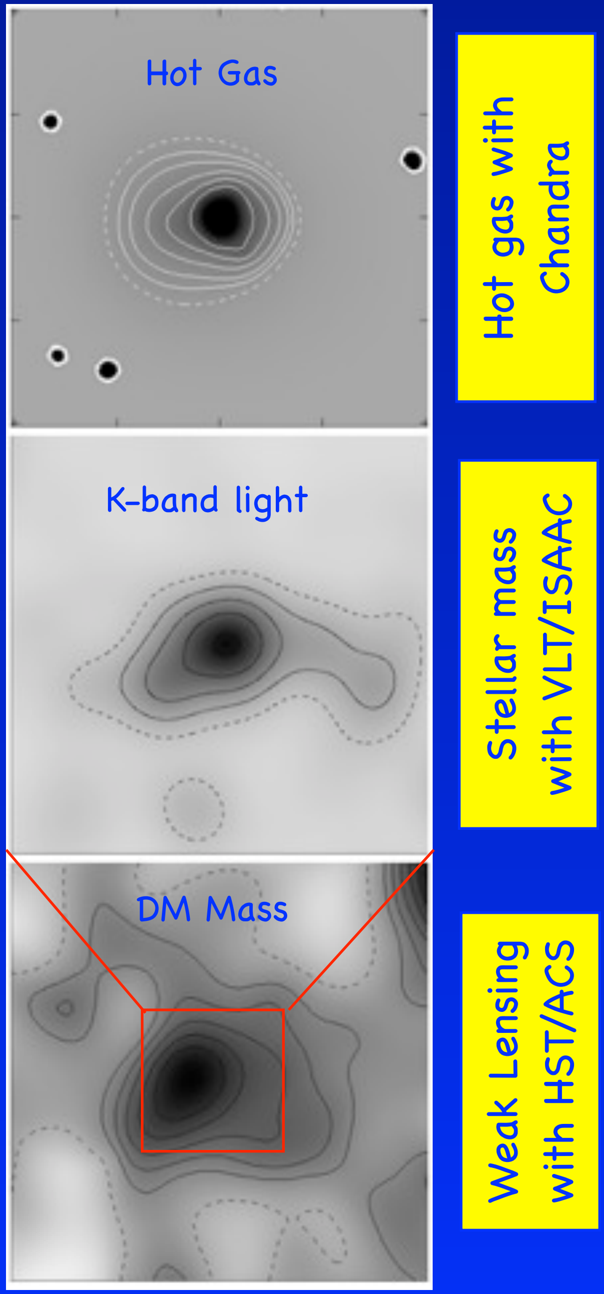


Distribution of baryons and DM in a distant cluster (z=1.24)



Lombardi et al. 05

➔ Weak lensing feasible with HST: good news for mass calibration of distant clusters

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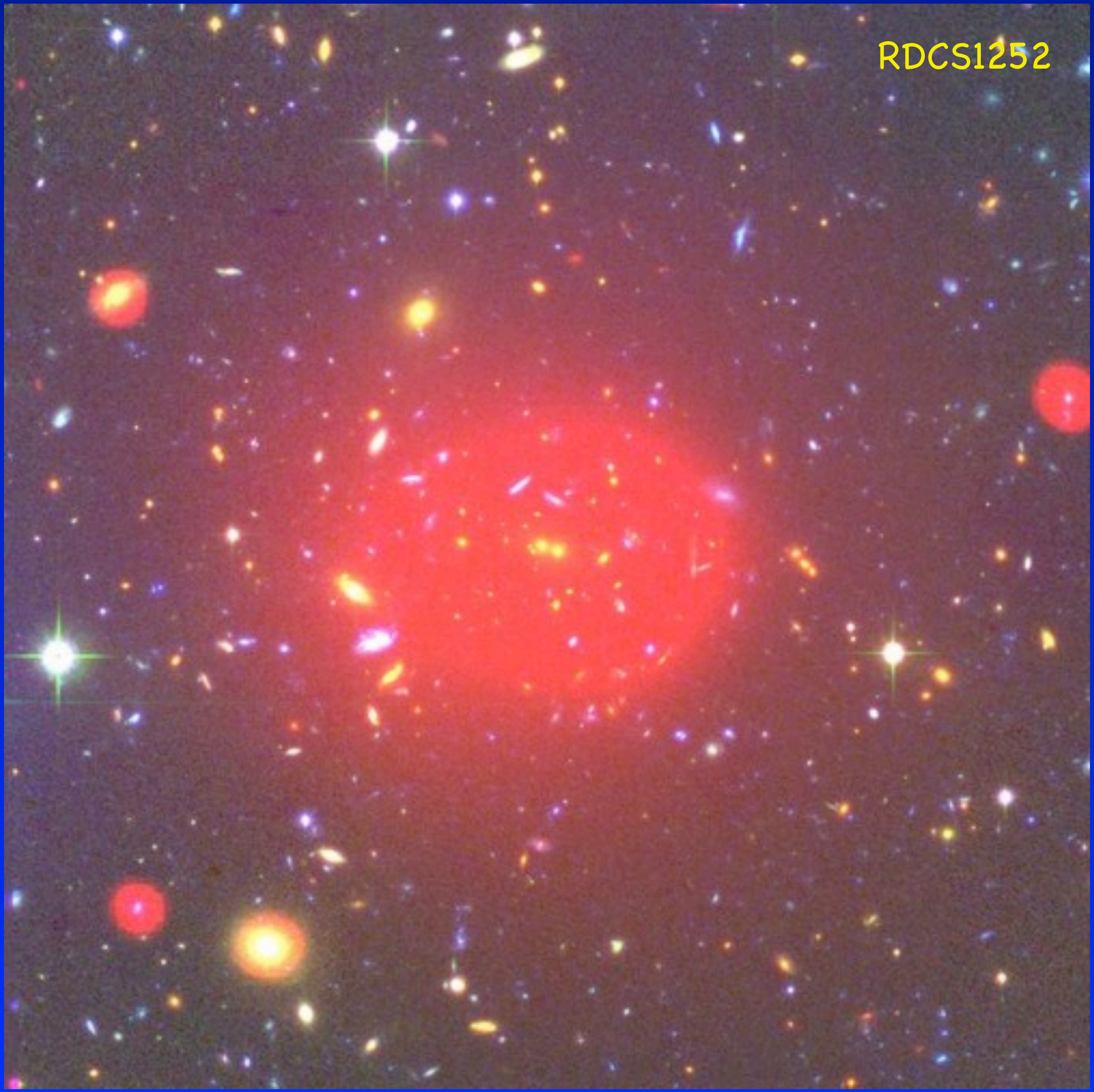
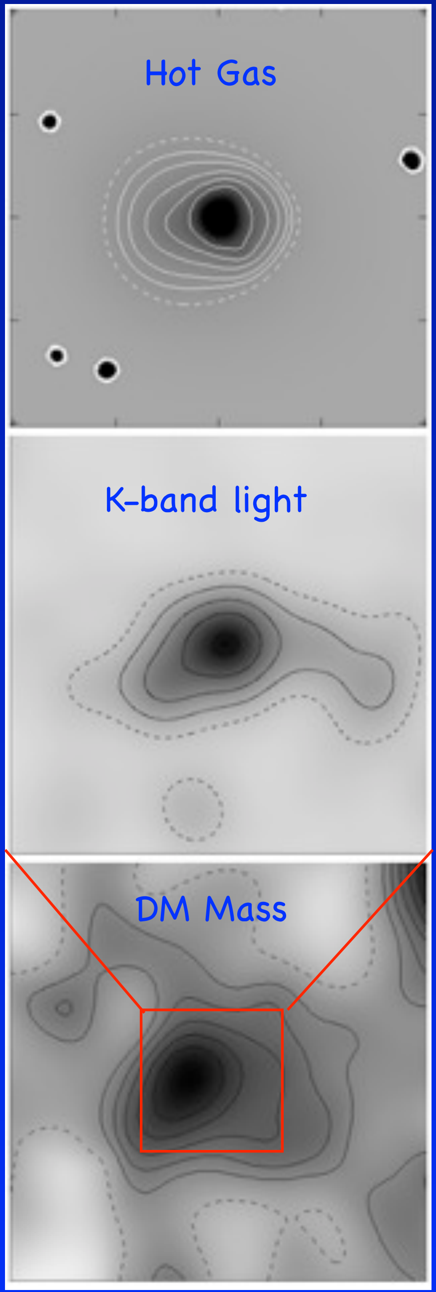




Hot gas with Chandra

Stellar mass with VLT/ISAAC

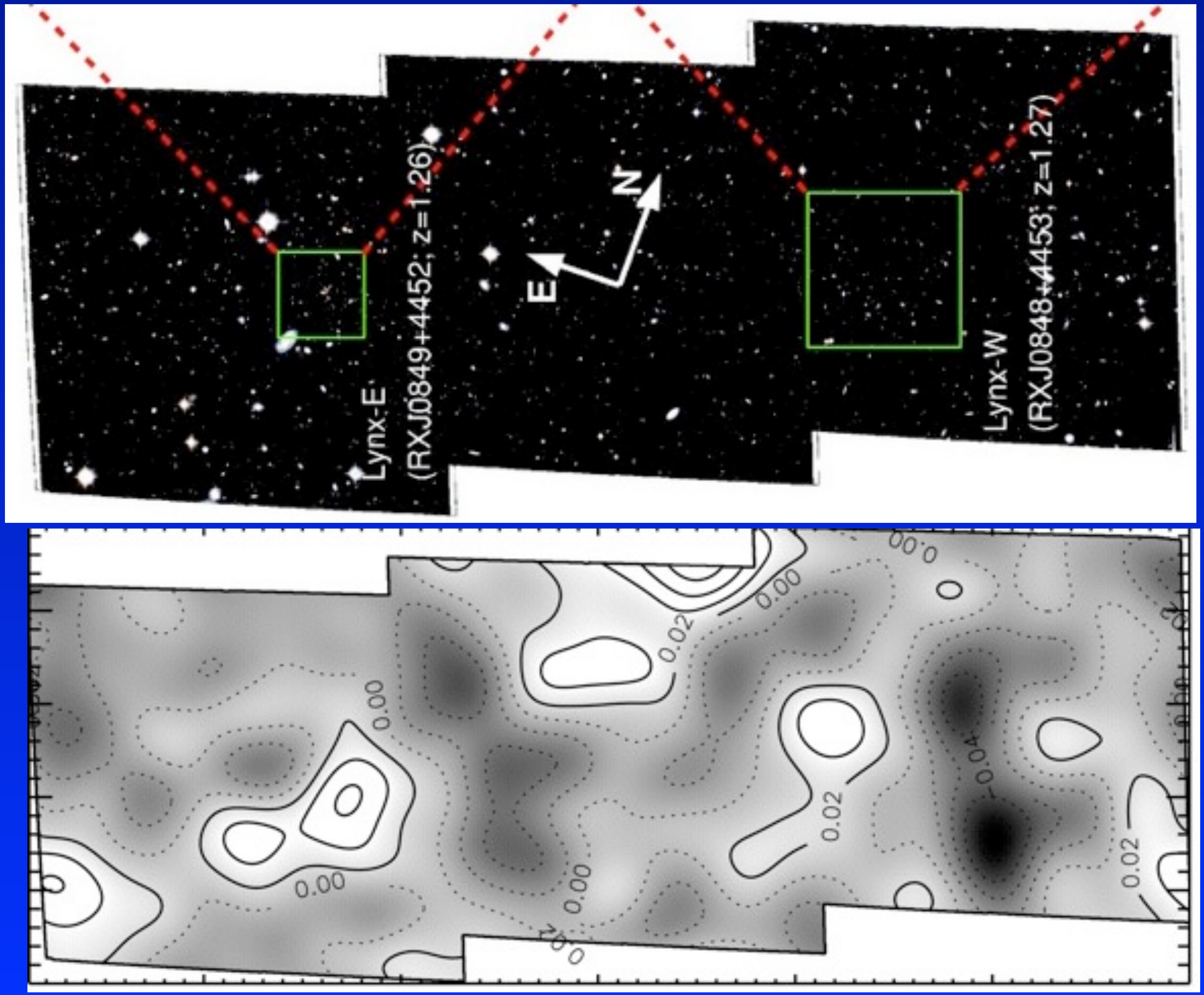
Weak Lensing with HST/ACS

Lombardi et al. 05

➔ Weak lensing feasible with HST: good news for mass calibration of distant clusters

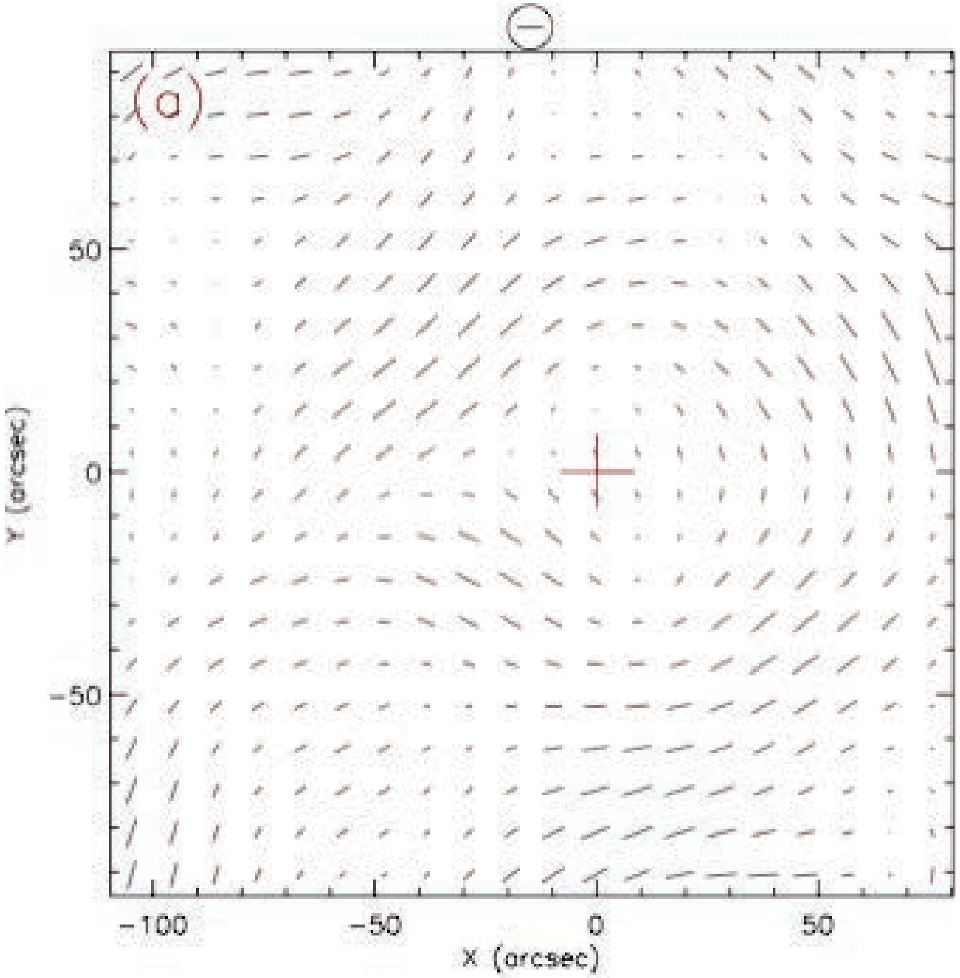
Probing the DM mass distribution of most distant systems:

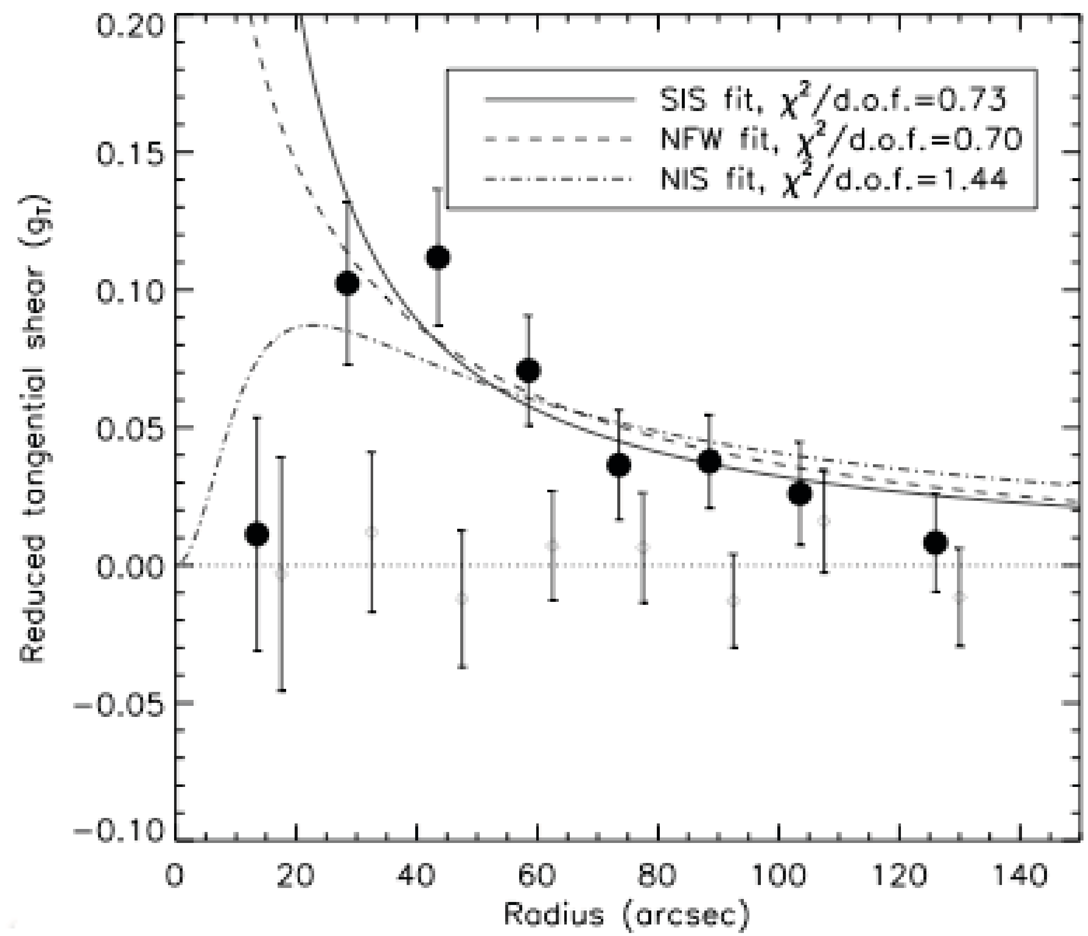
Lynx clusters (RDCS0848,49) at $z=1.27$, $M=(1\text{-}2)\times10^{14}\ M_\odot$ (Jee et al. 04)



Weak-lensing analysis from HST/ACS of XMM2235 at z=1.39

(Jee, PR et al. 09)





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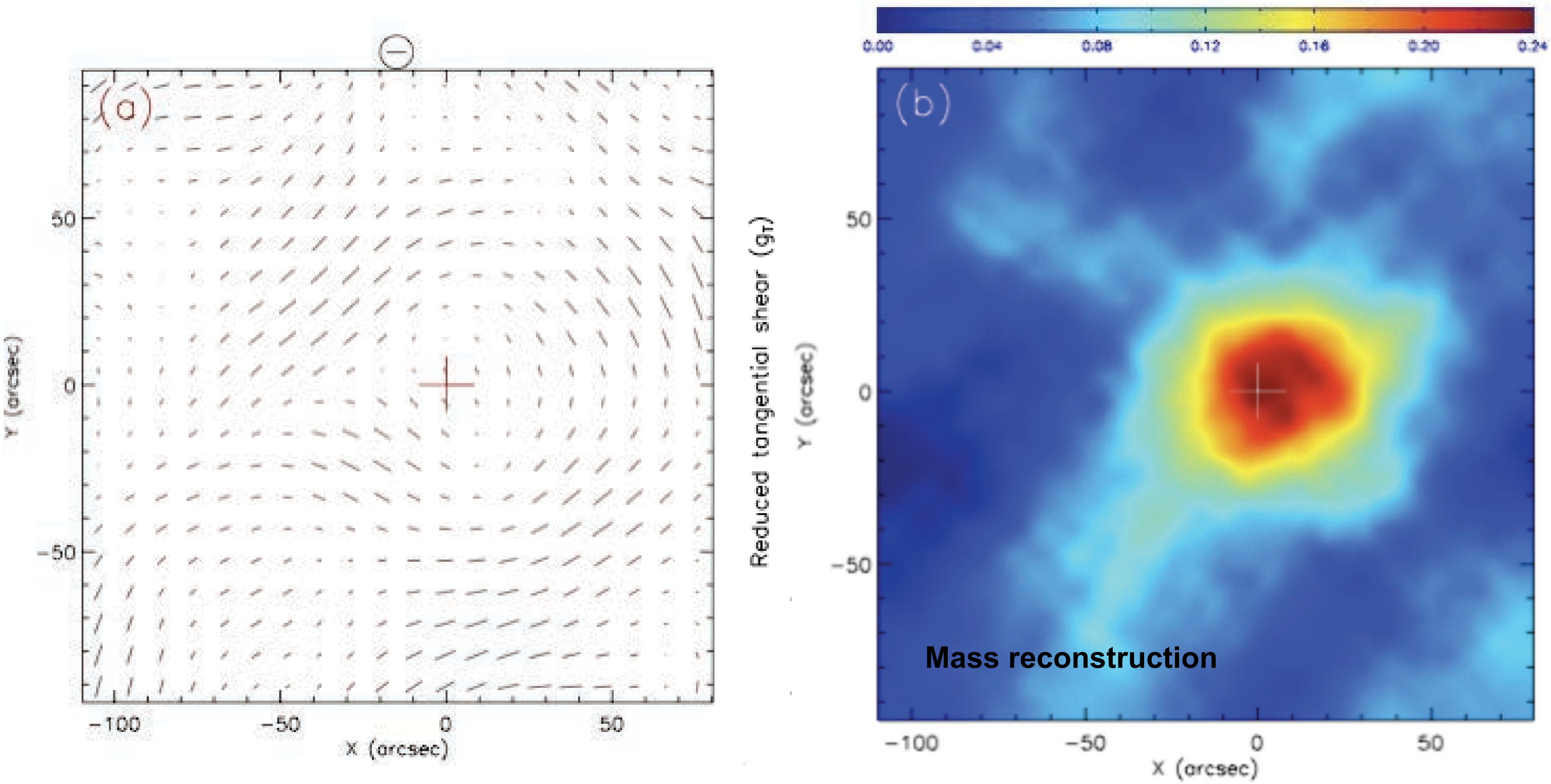

- Shear signal detected out to ~1 Mpc (max >8σ), beyond Chandra, with 8150s exp. (i_{775} band)
- X-ray and Weak Lensing based masses at r=1 Mpc agree within 5% !

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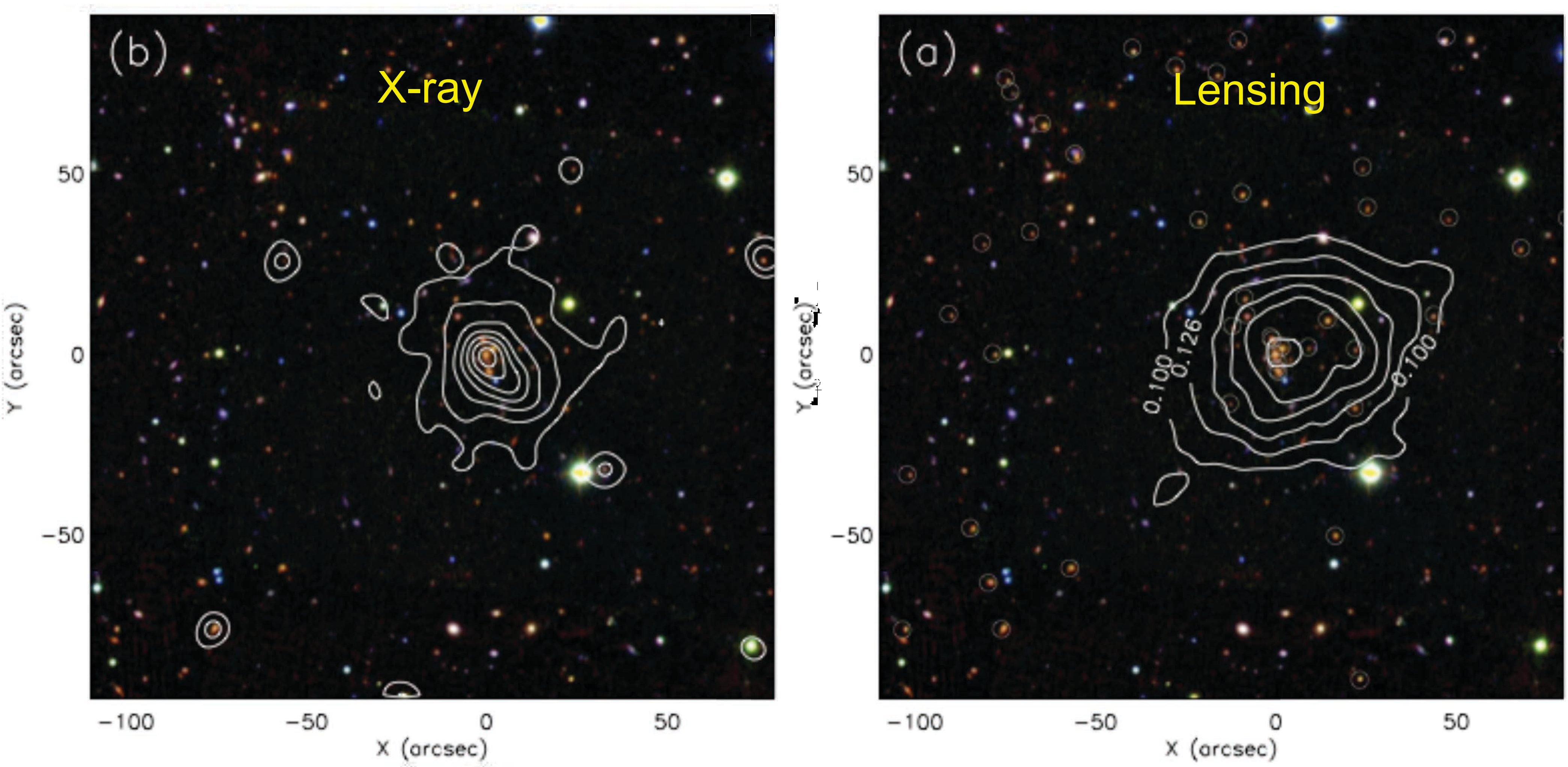

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Multiple image system in most distant lens

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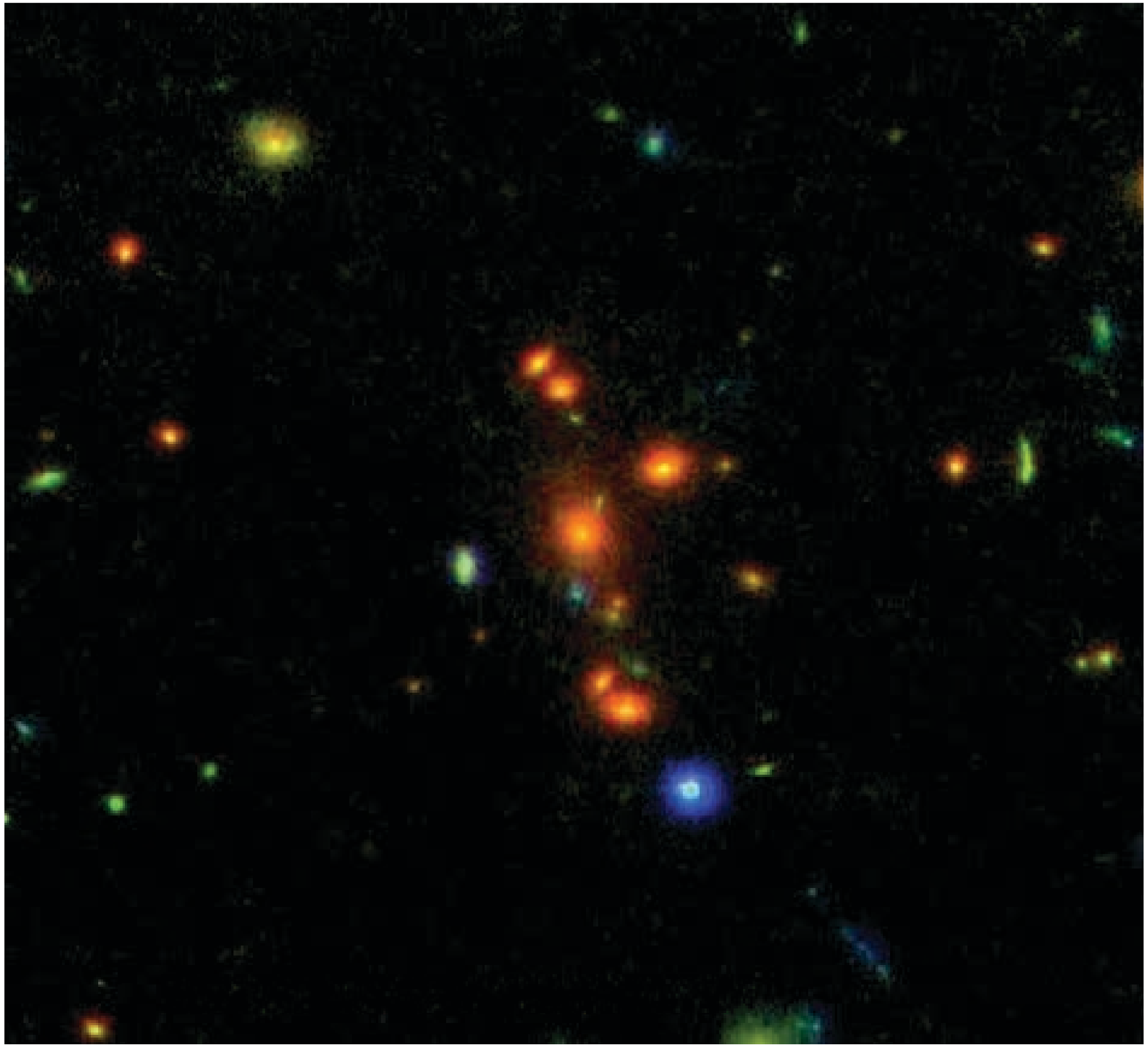
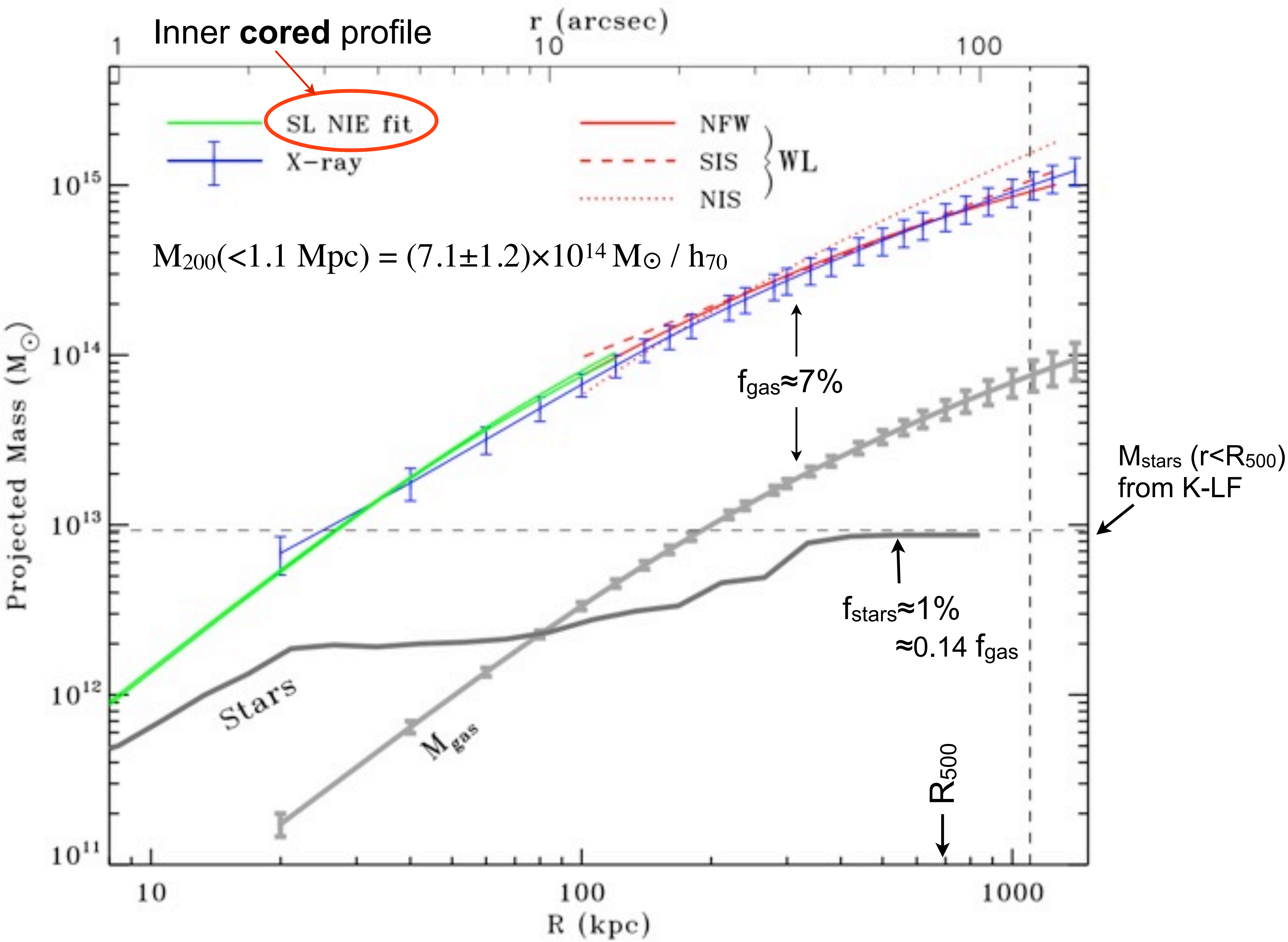


Mass components of XMM2235 (at z=1.4!)



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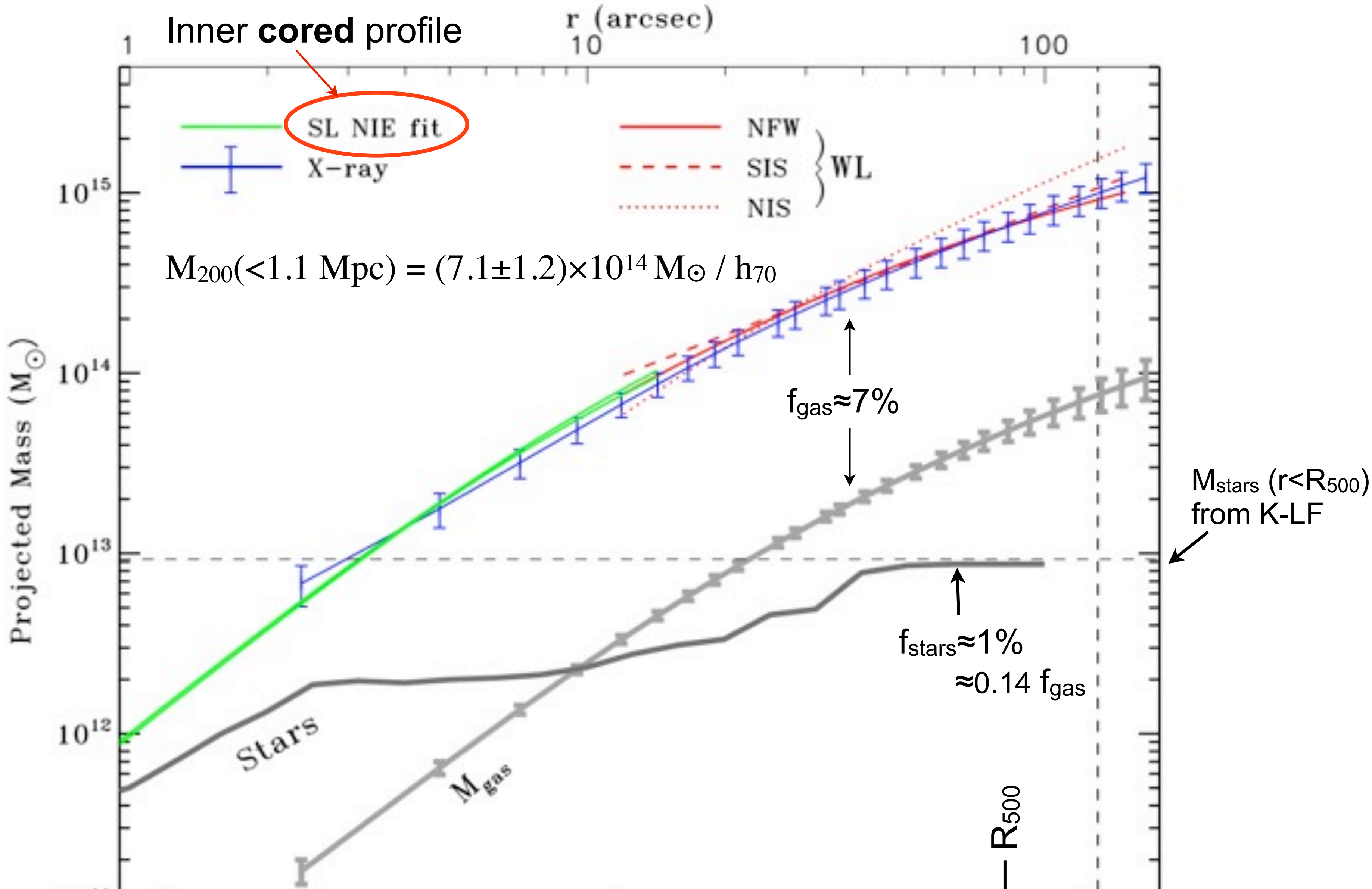
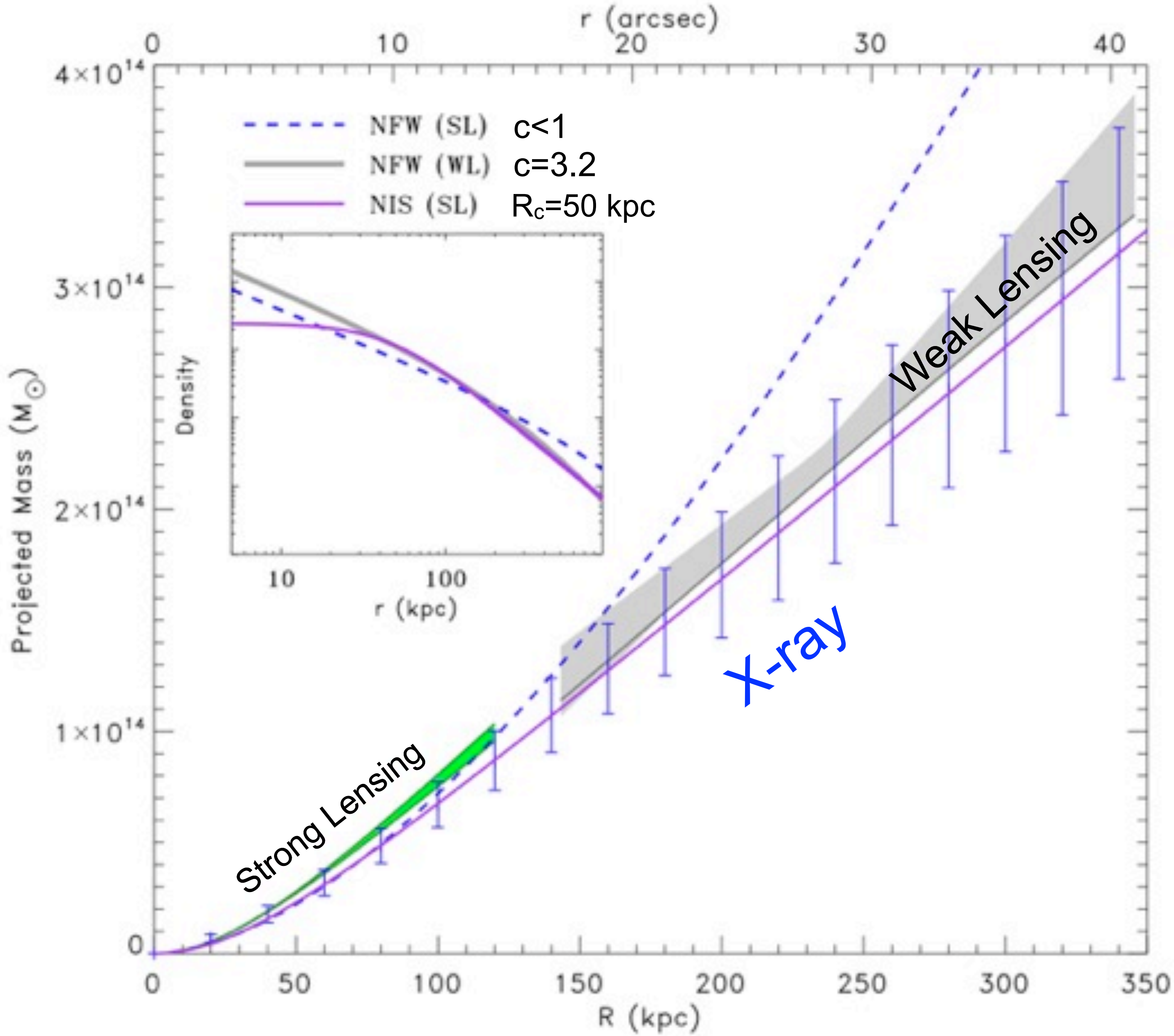


➡ Masses can be accurately estimated also at z>1:
good news for mass calibration of future cluster surveys

The core mass distribution



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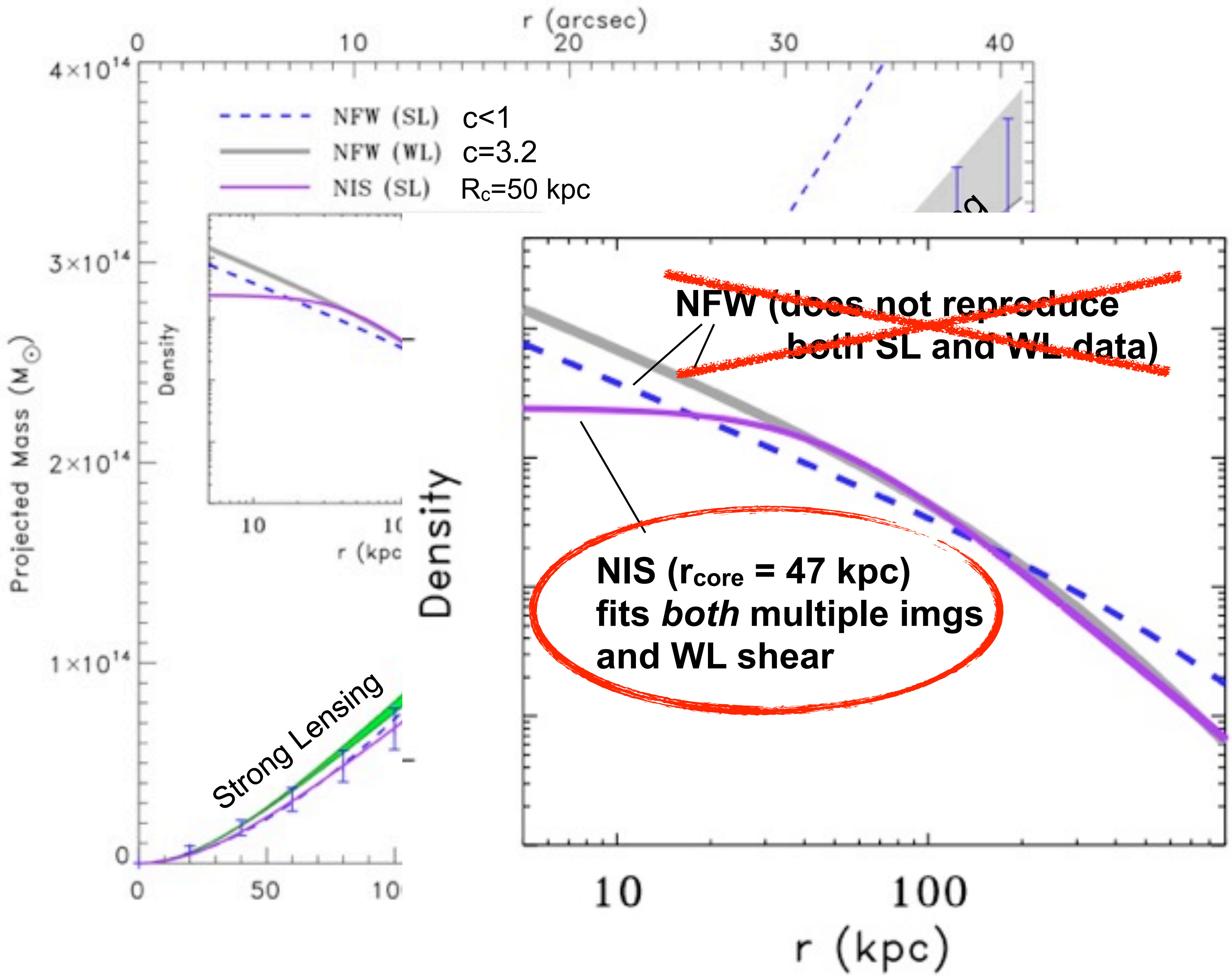

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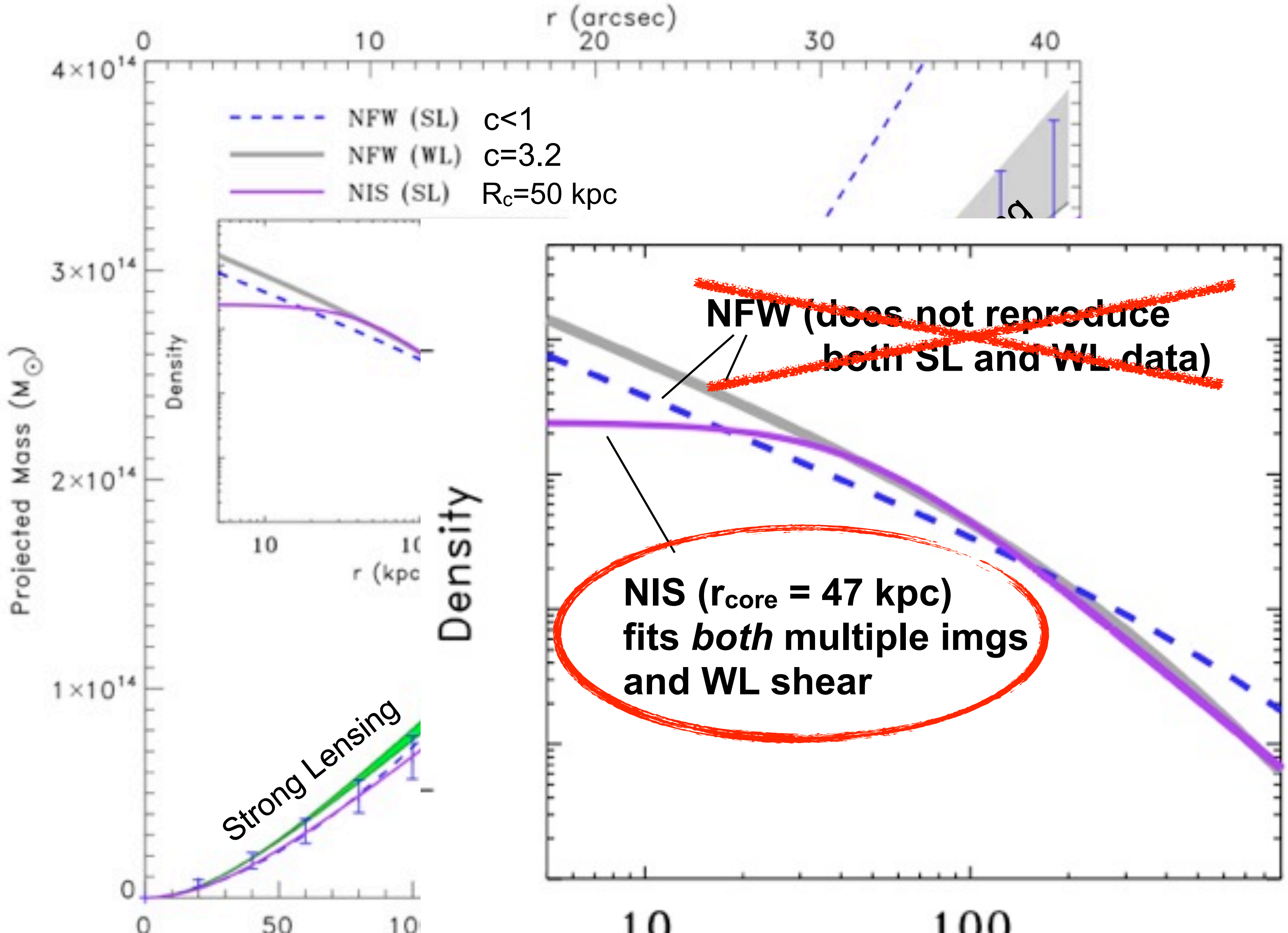
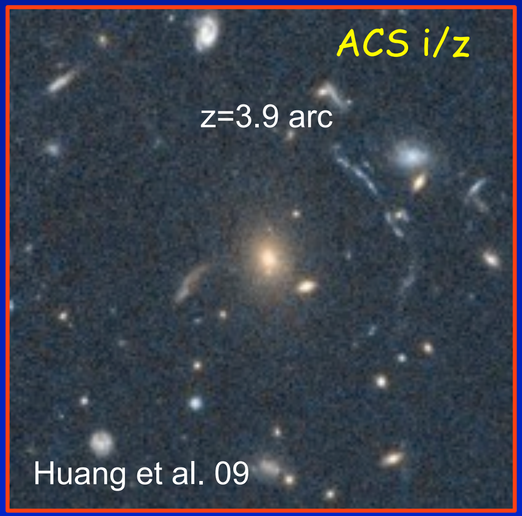
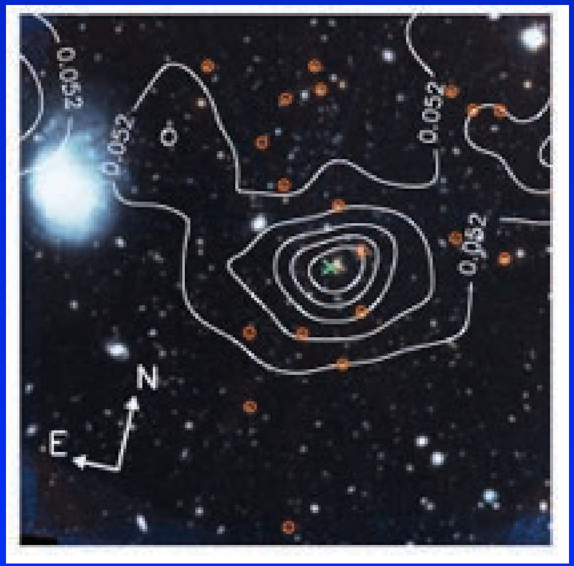


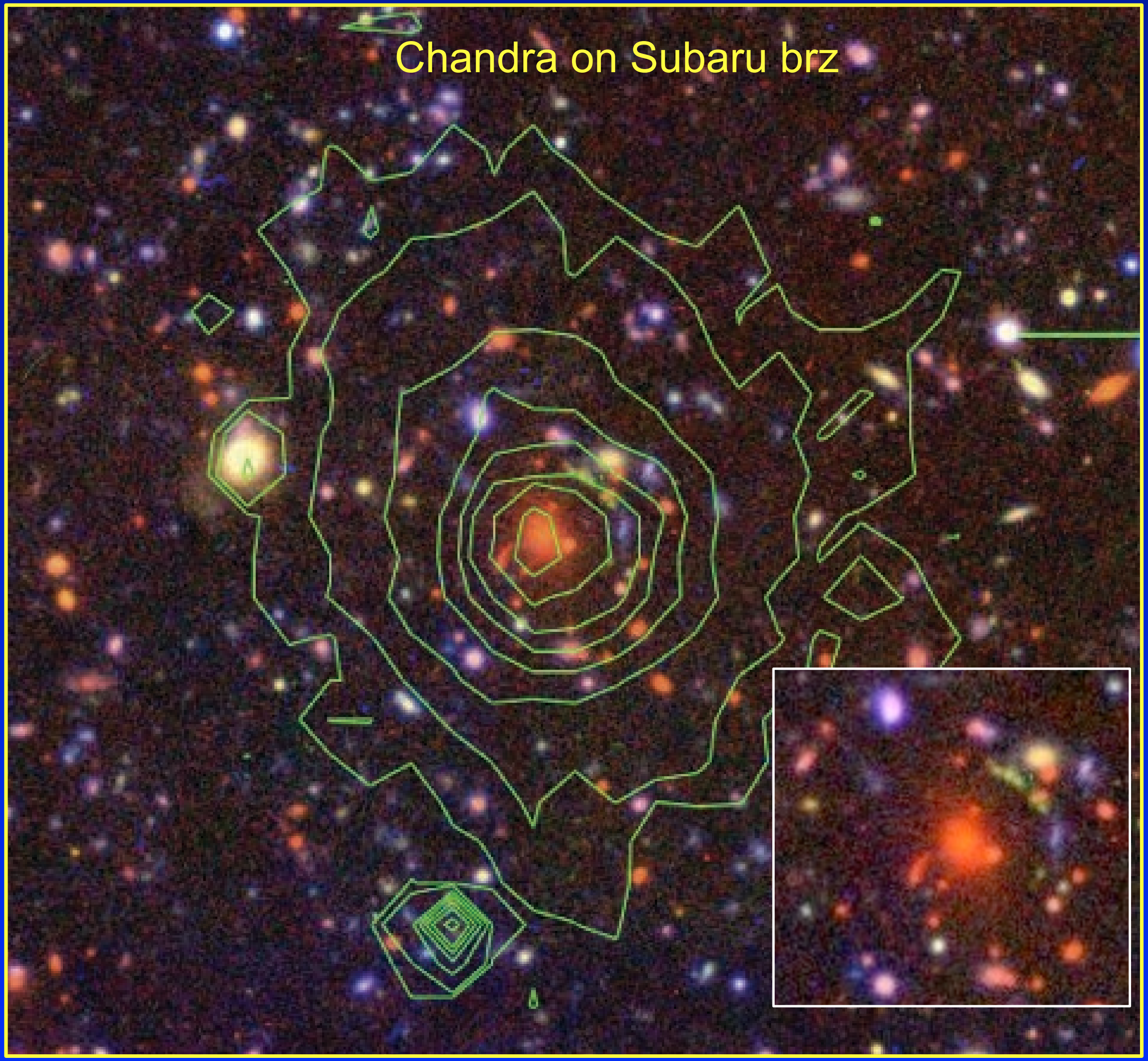
➡ SL+WL mass profiles imply very flat inner DM density profile (β <<1, similarly to several low-z clusters) in contrast with NFW predictions

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





Weak Lensing mass map
(Jee et al. 2011)



Santos al. 2011

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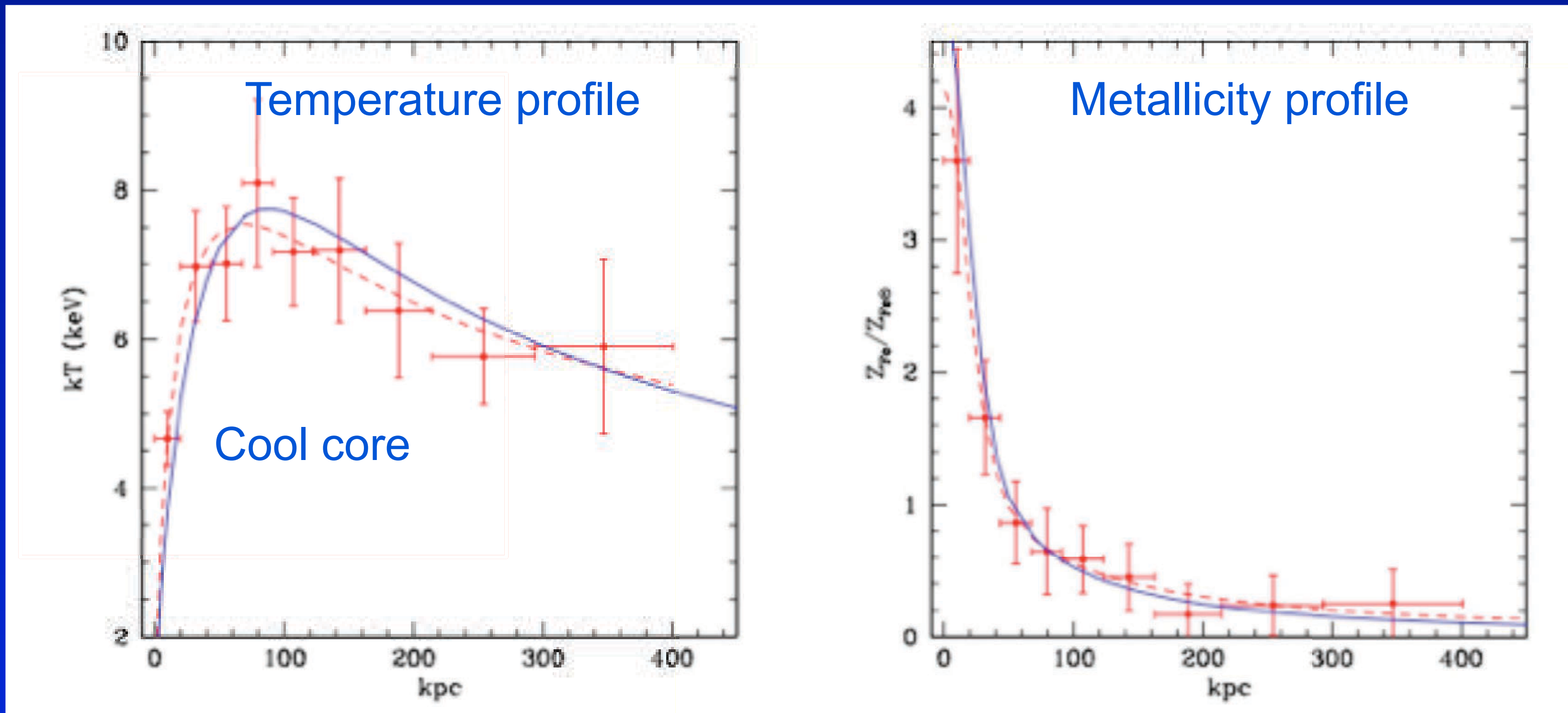

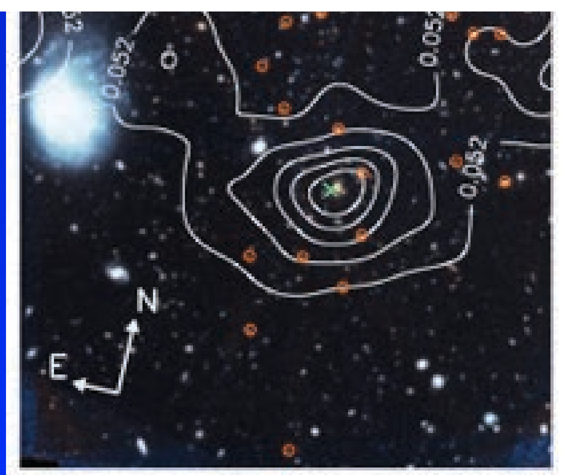

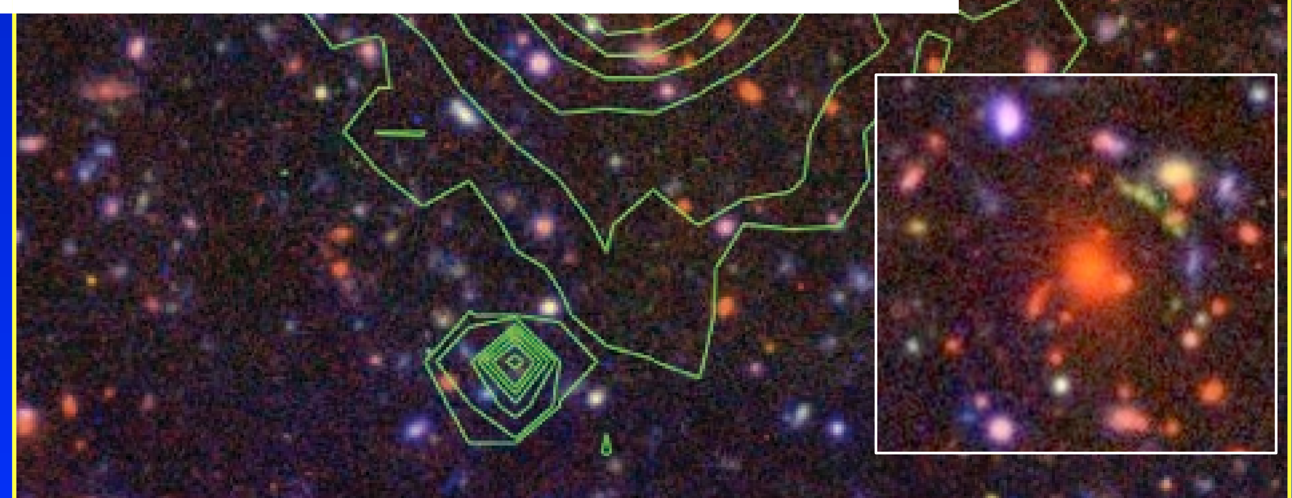

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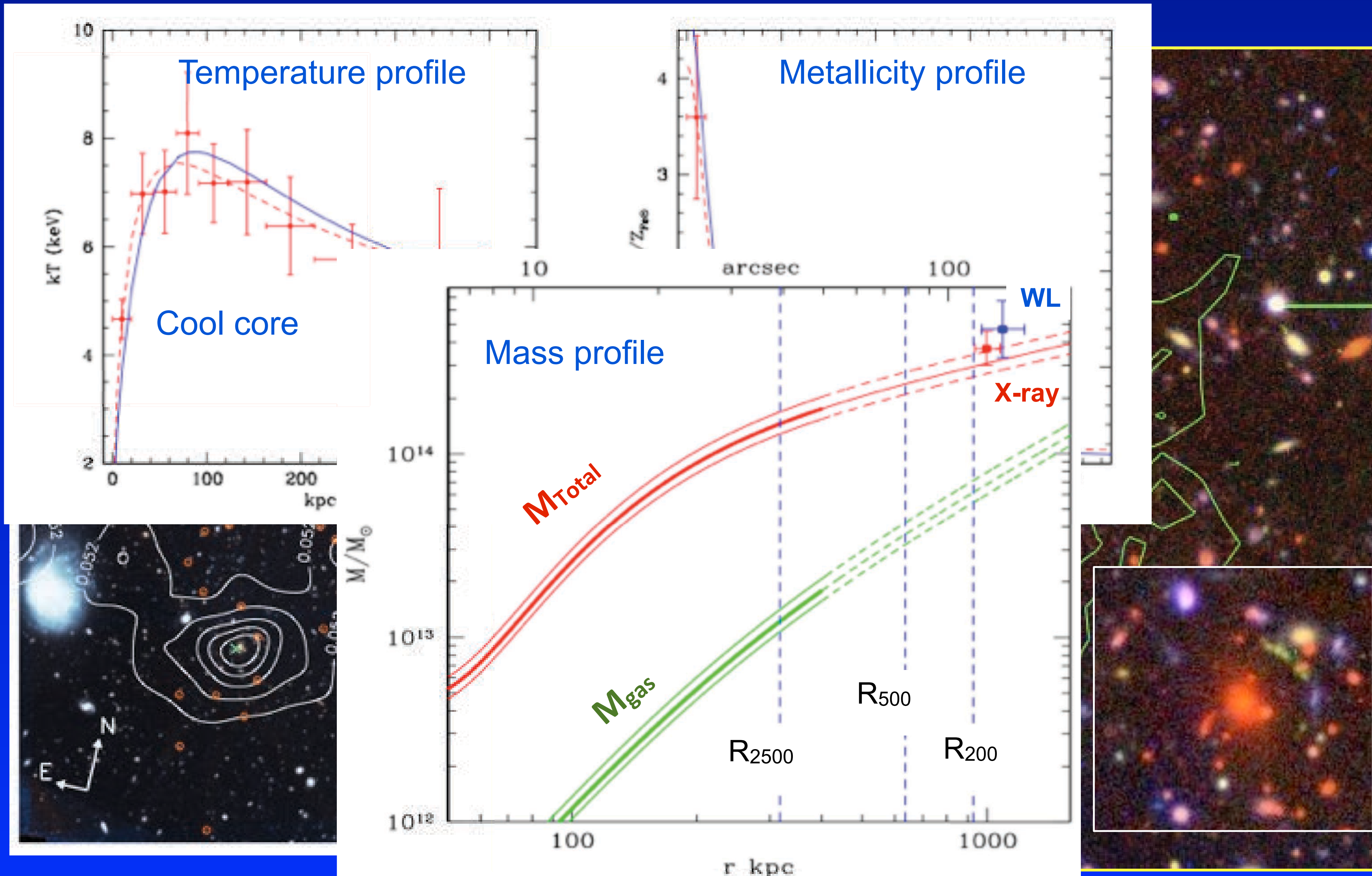

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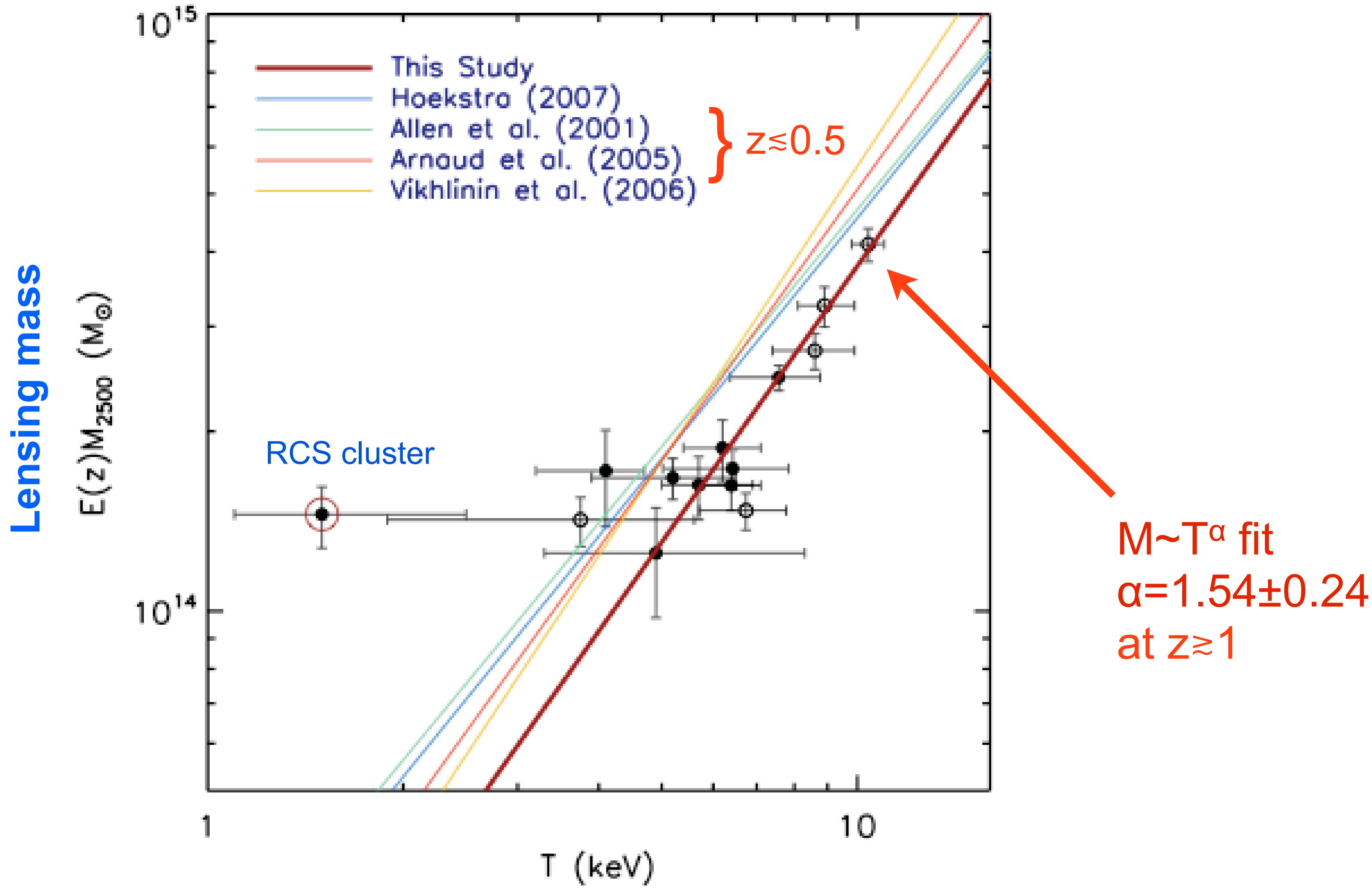
Santos al. 2011

Scaling relations at high-z with WL and X-ray studies

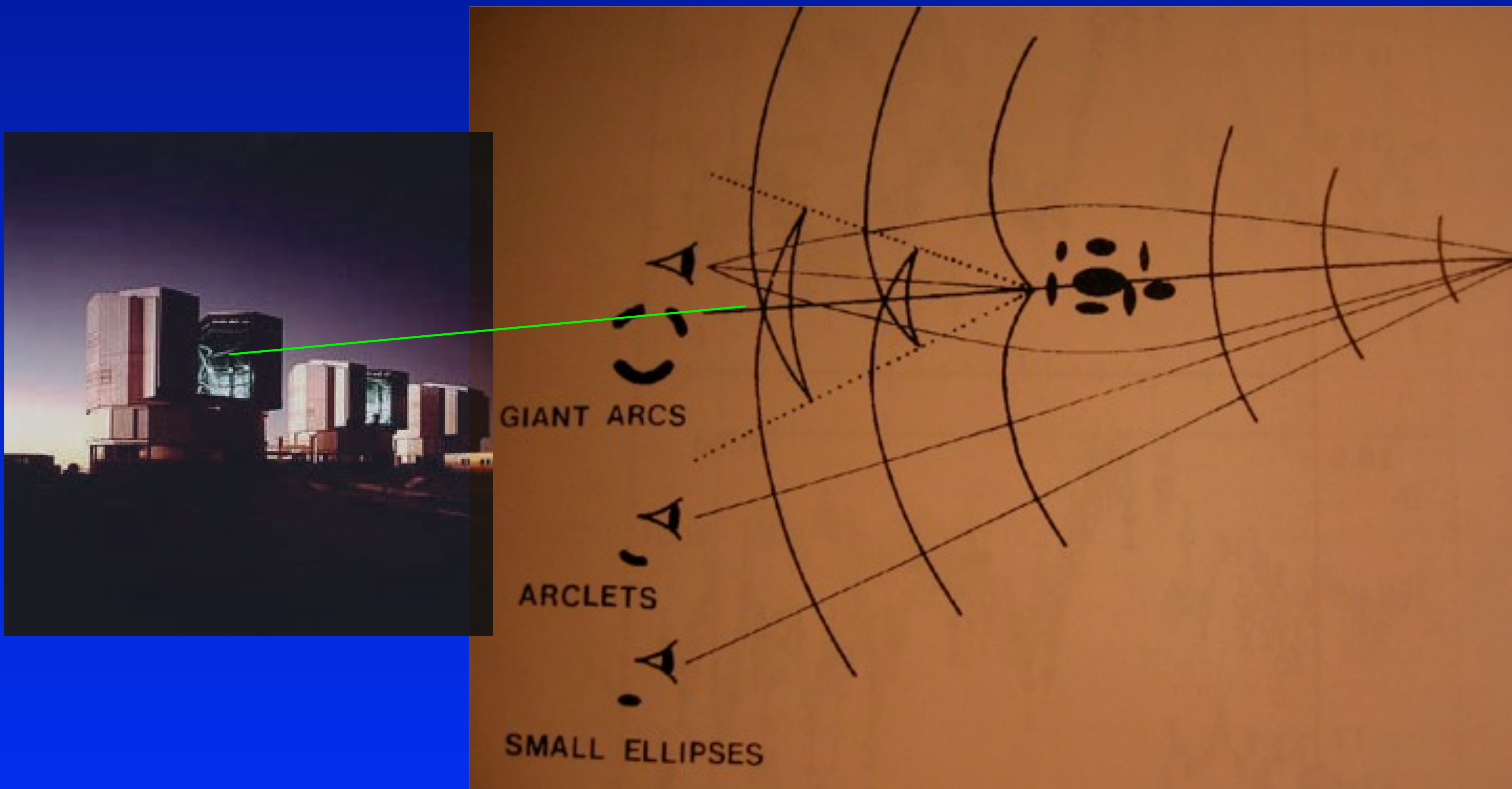
Sample of 22 clusters with *HST* and *Chandra* data at z=0.95 -1.46

JEE ET AL. 2011



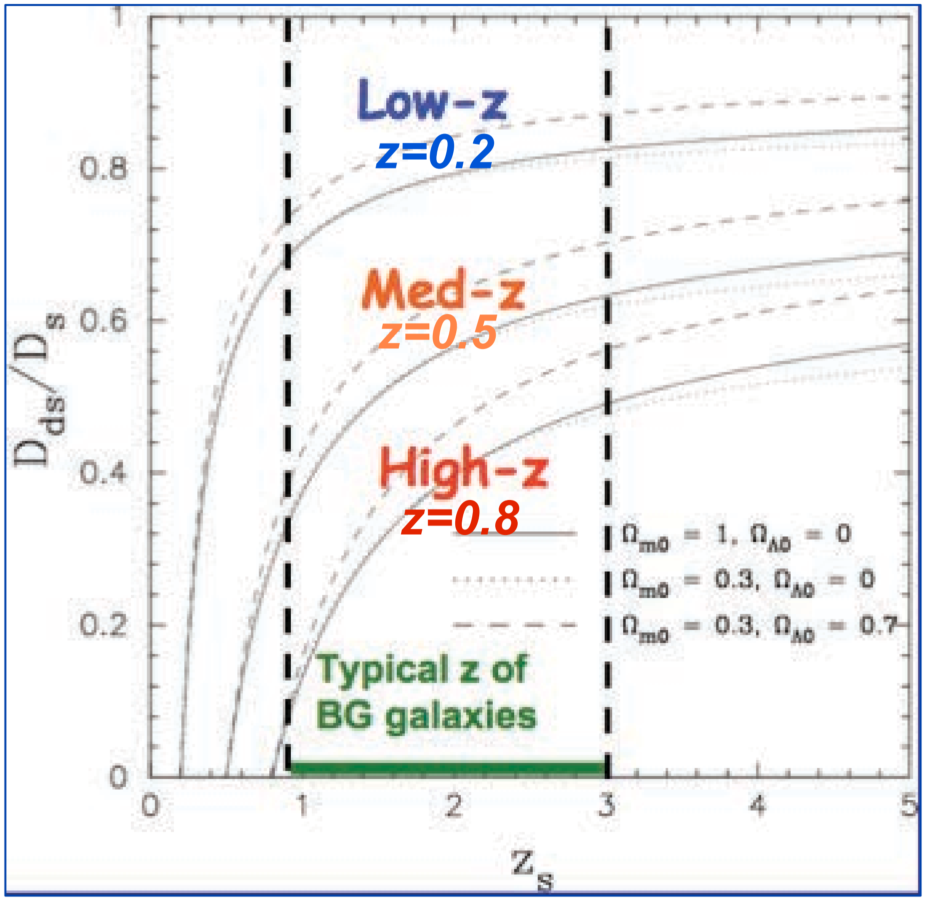
$\alpha \simeq 3/2$ (self-similar), but lower (20-30%) normalization at high-z ?

Clusters as Gravitational Telescopes



Geometric scaling of Lensing Signal

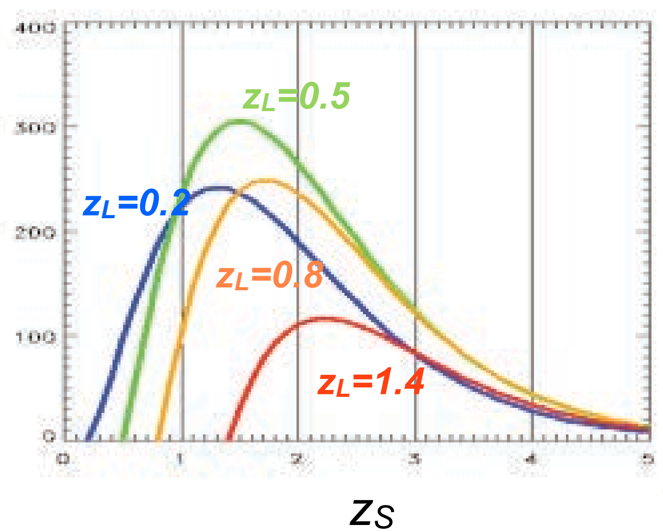
- Geometrically, strong lensing is maximized at low-to-intermediate redshifts, where, *for a given mass,* Σ_{crit} is minimal



For a given mass distribution at $z=z_L$

$$\Sigma_{\rm crit}^{-1} \propto D_L \frac{D_{LS}}{D_S}$$

$$p(z_S) \propto \Sigma_{\rm crit} \times dN(z)/dz$$

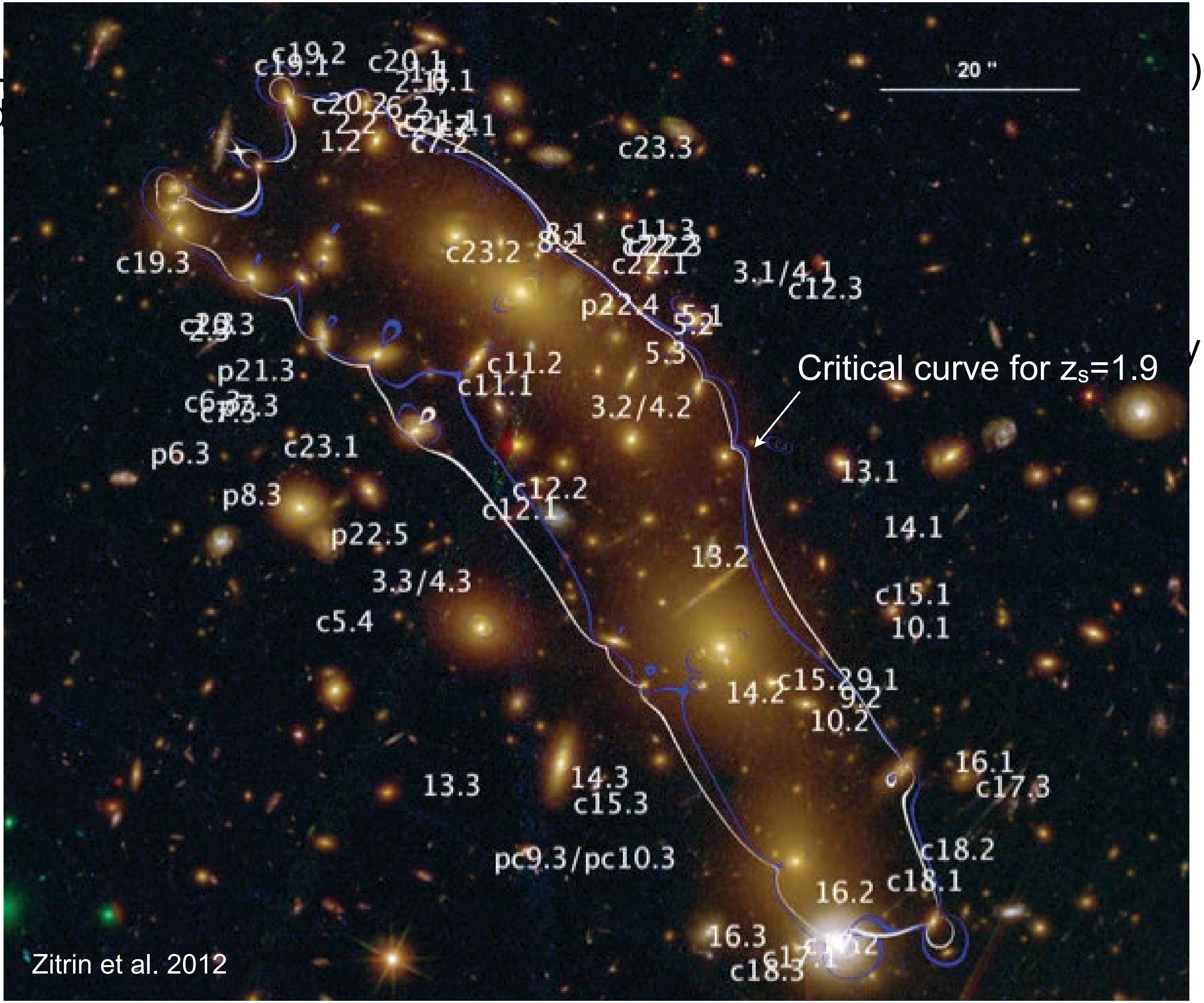


What makes a cluster an efficient gravitational telescope (besides geometrical considerations, D_L,D_S,DL_S) ?

- Lensing efficiency (e.g. measured from the number of multiple images) depends from factors which lead to increase the critical area:
  - ellipticity
  - degree of merging
  - degree of substructure
  - cluster concentration (the higher *c*, the higher the lensing efficiency

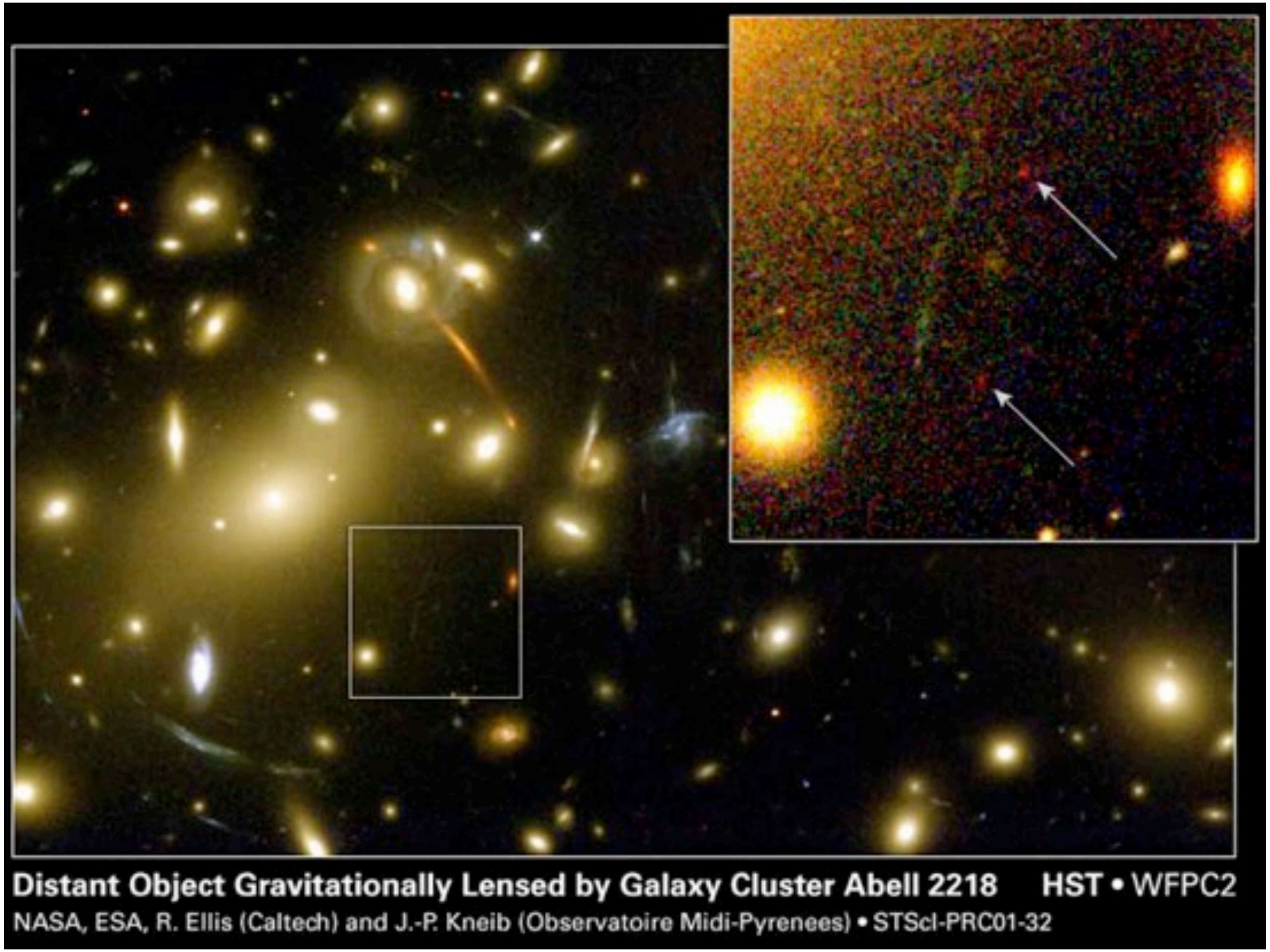
What makes a cluster an efficient gravitational telescope (besides geometrical considerations, D_L,D_S,D_{LS}) ?

- L …)
  d … y



Discovery a highly magnified galaxy at z=5.576 (Ellis et al. 01)

Magnification=3.8 mag !
I_{mag}(unlensed)=29.7 !



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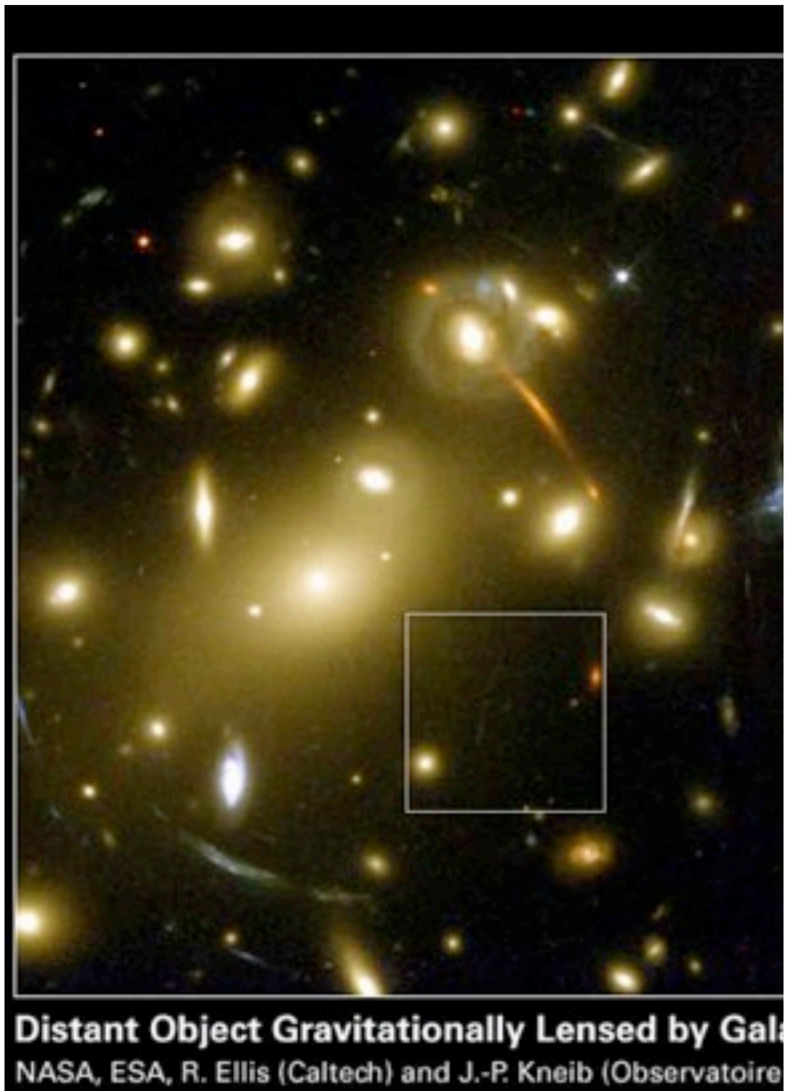
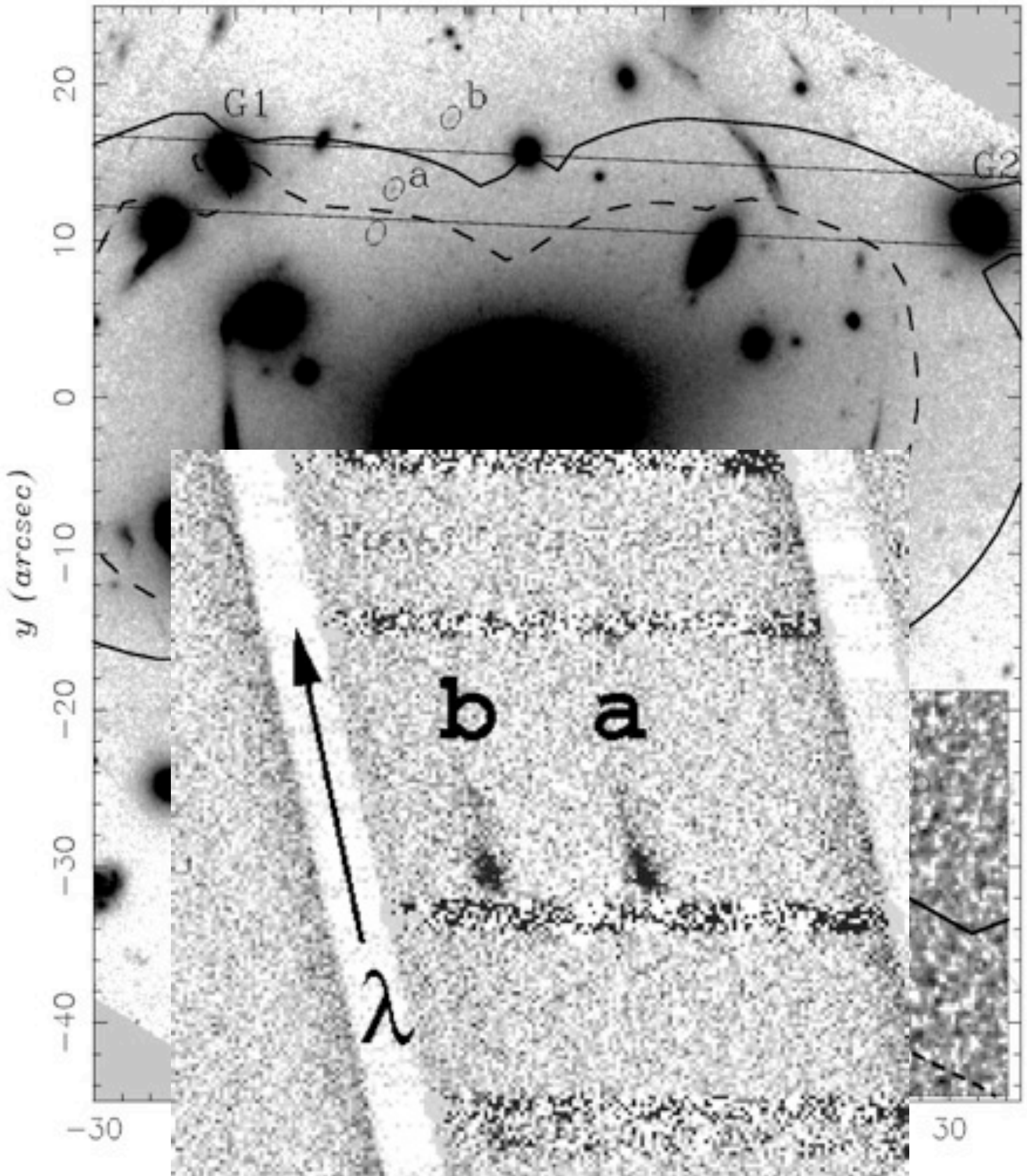
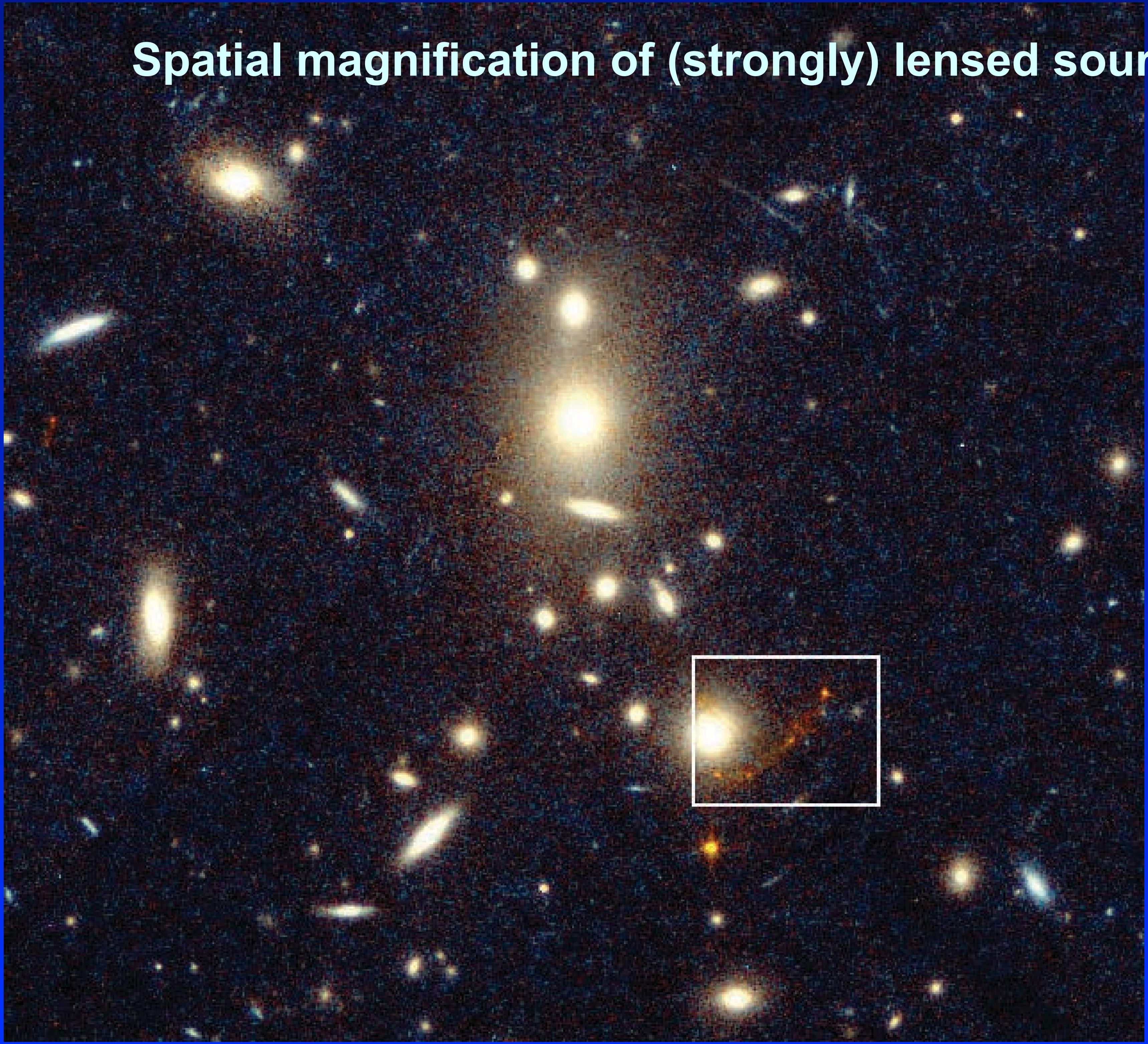




Spatial magnification of (strongly) lensed sources

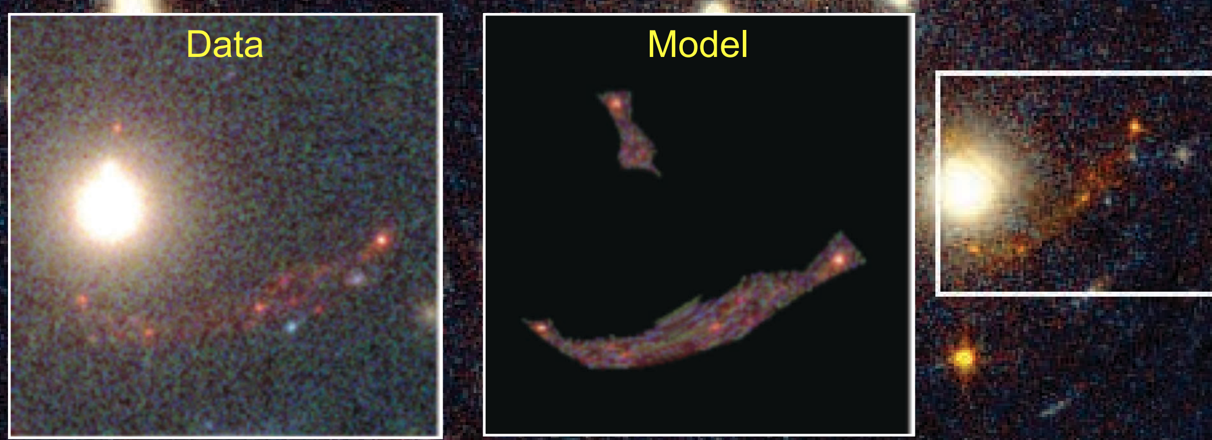


Spatial magnification of (strongly) lensed sources

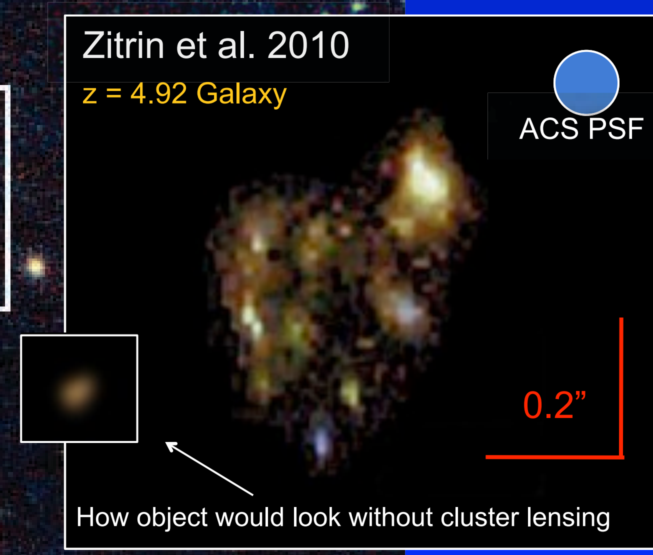
Example (Zitrin et al. 2010):

- Reconstruction of a z = 4.92 source lensed by the z = 0.33 cluster MS1358+62.
- Best resolved high-z object: μ≈100, spatial resolution of ~50 pc ! (rest-frame UV)
- *Equivalent to 20-m space telescope resolution of a non-lensed z=5 galaxy!*
- *Typical (or better) resolution of ELTs*

Lens plane

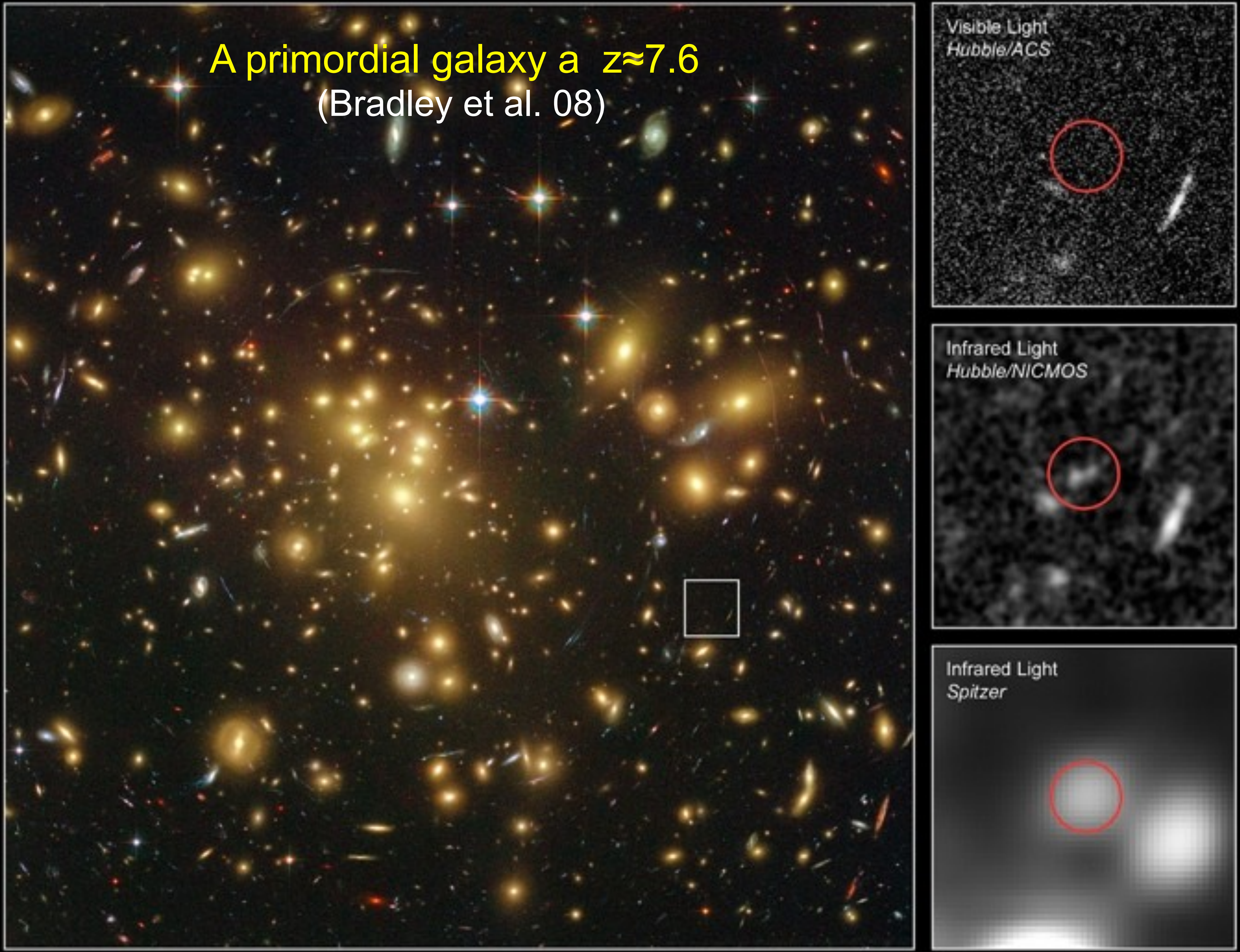


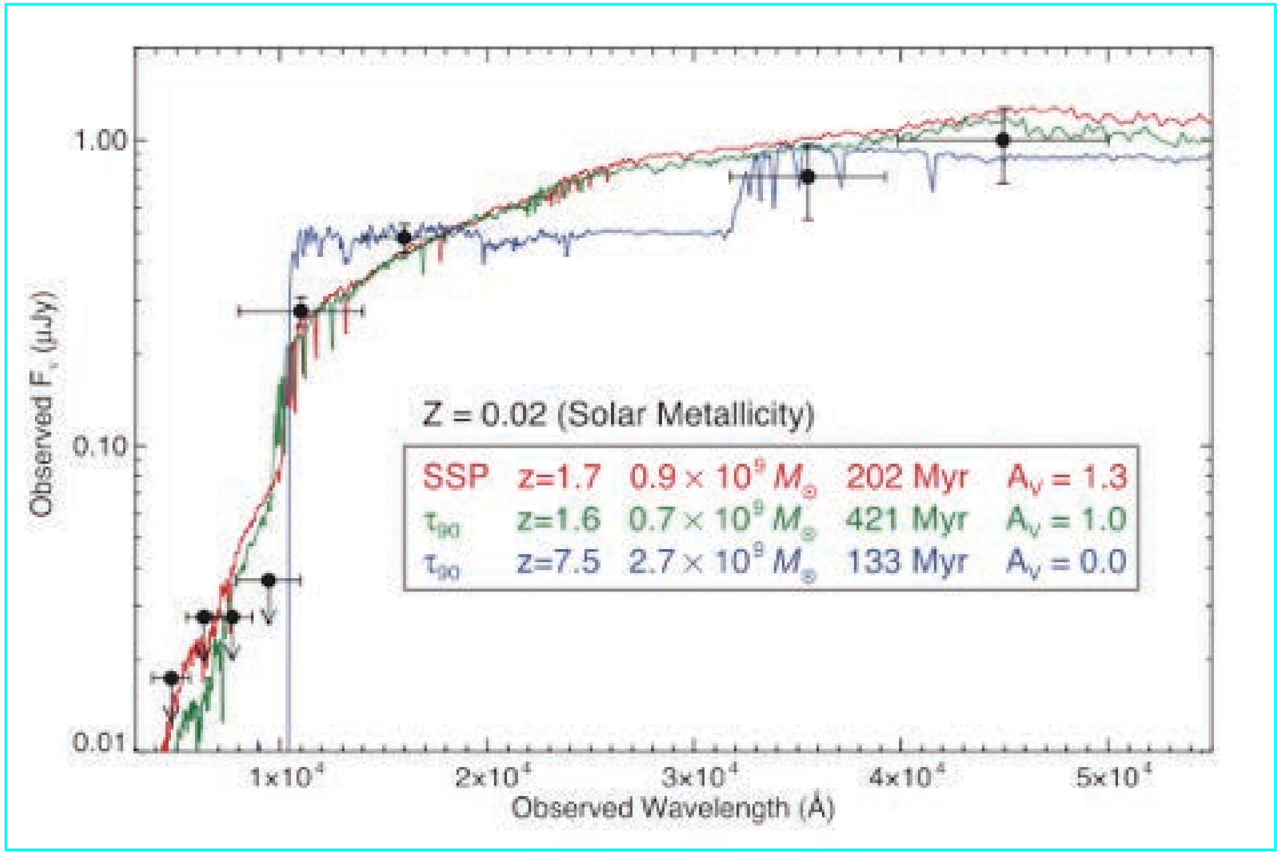
Source plane

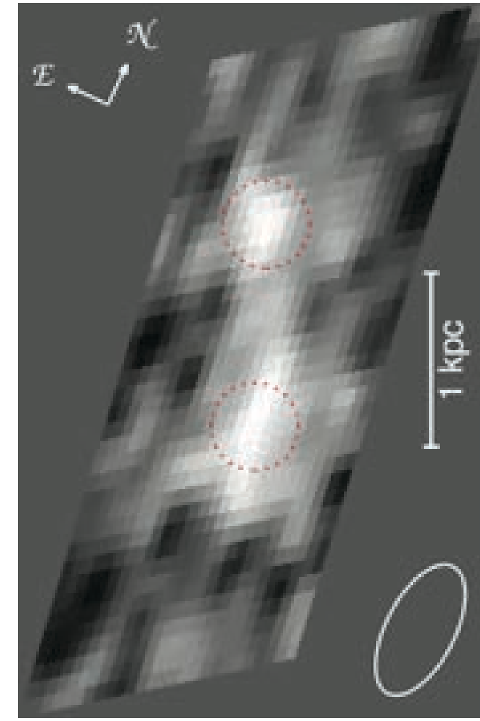


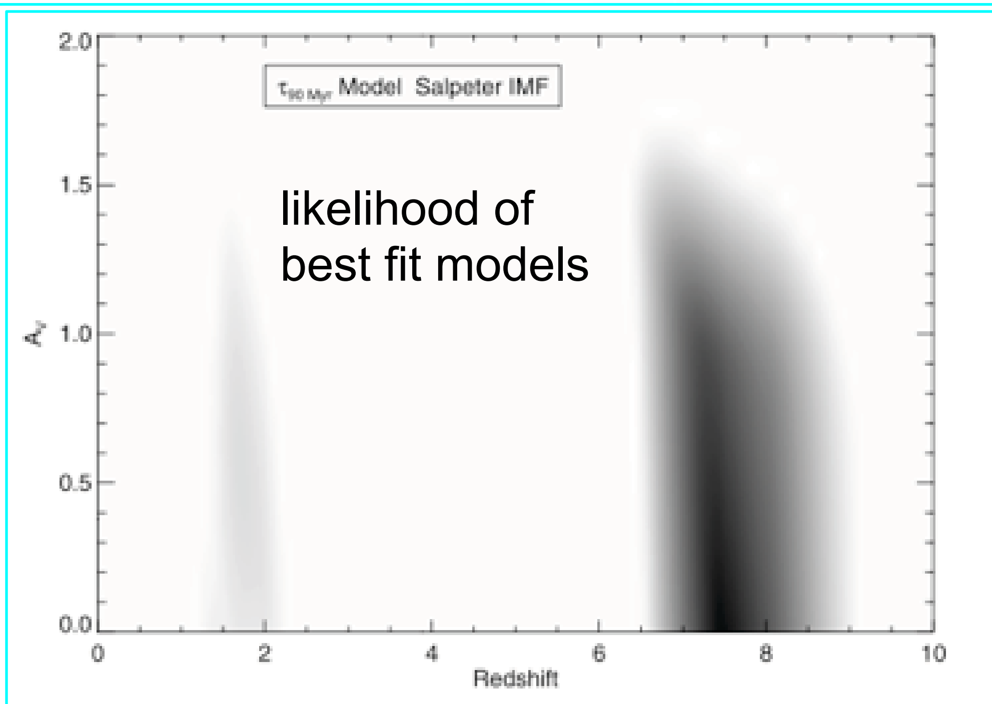
A primordial galaxy a z≈7.6

(Bradley et al. 08)







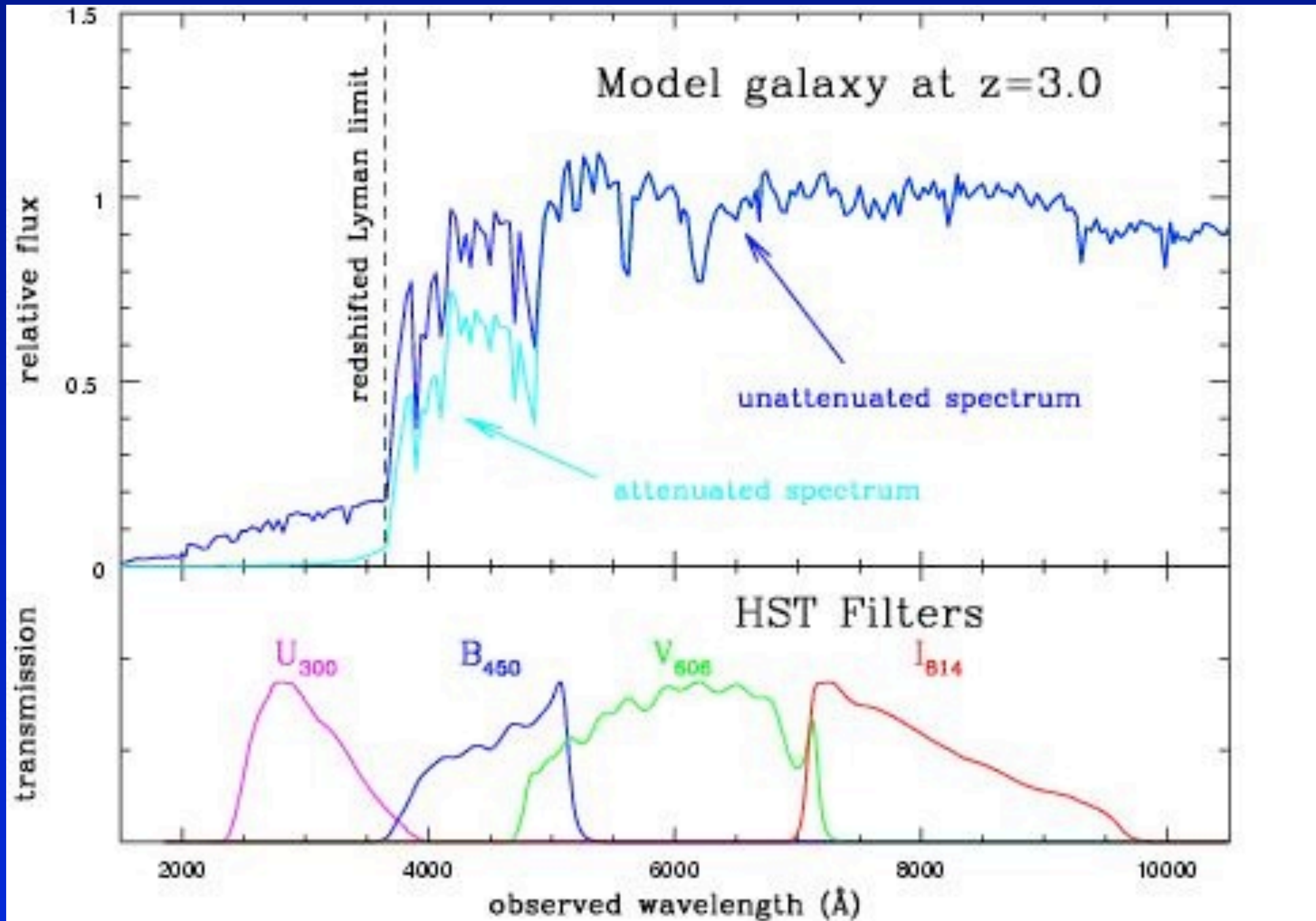


(1 kpc = 0.2” at z=7.6)

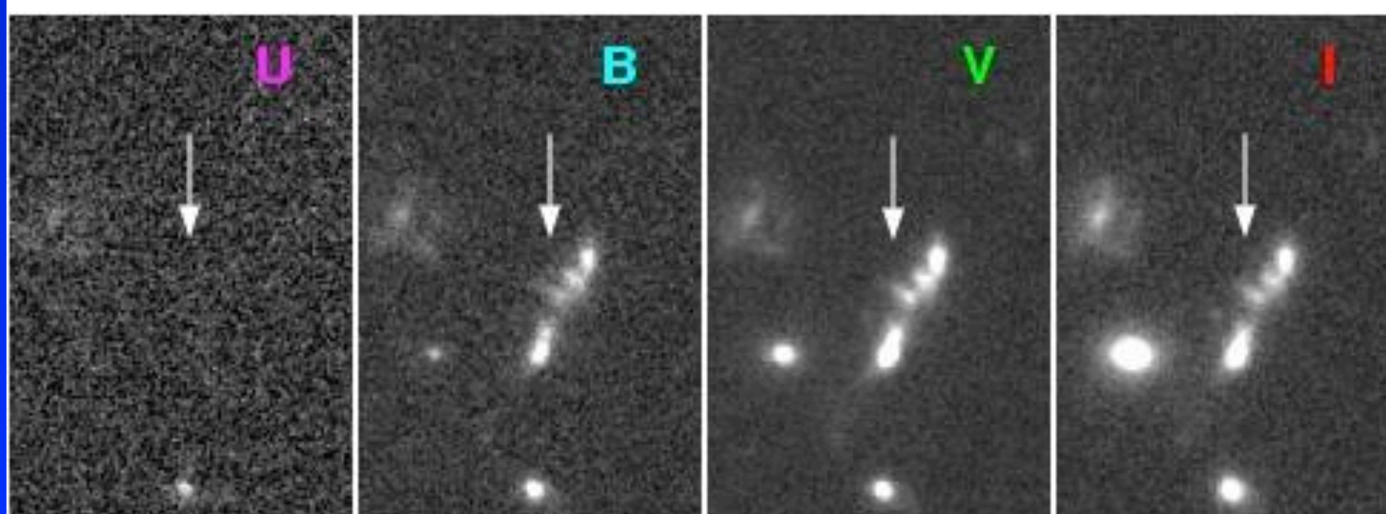
H_{160}=24.7AB (observed)
=27.1AB when corrected for ~9.3x magn.

M_S=(1-4)x10^9 $M_\odot$
Age=(40-300) Myr
z_F~8-10

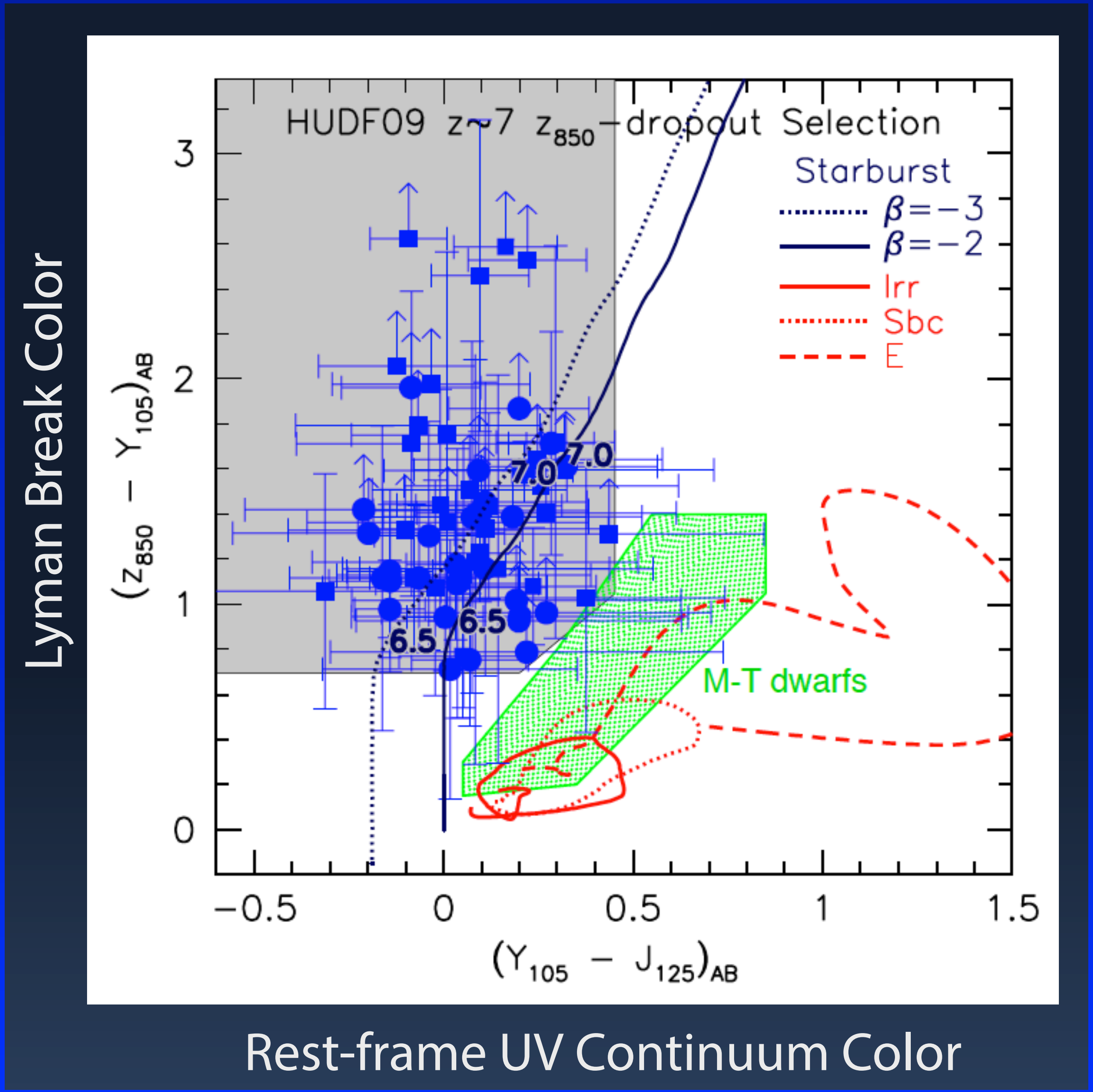
Lyman-break galaxy detection



Dickinson 1998



LBG Candidate Selection

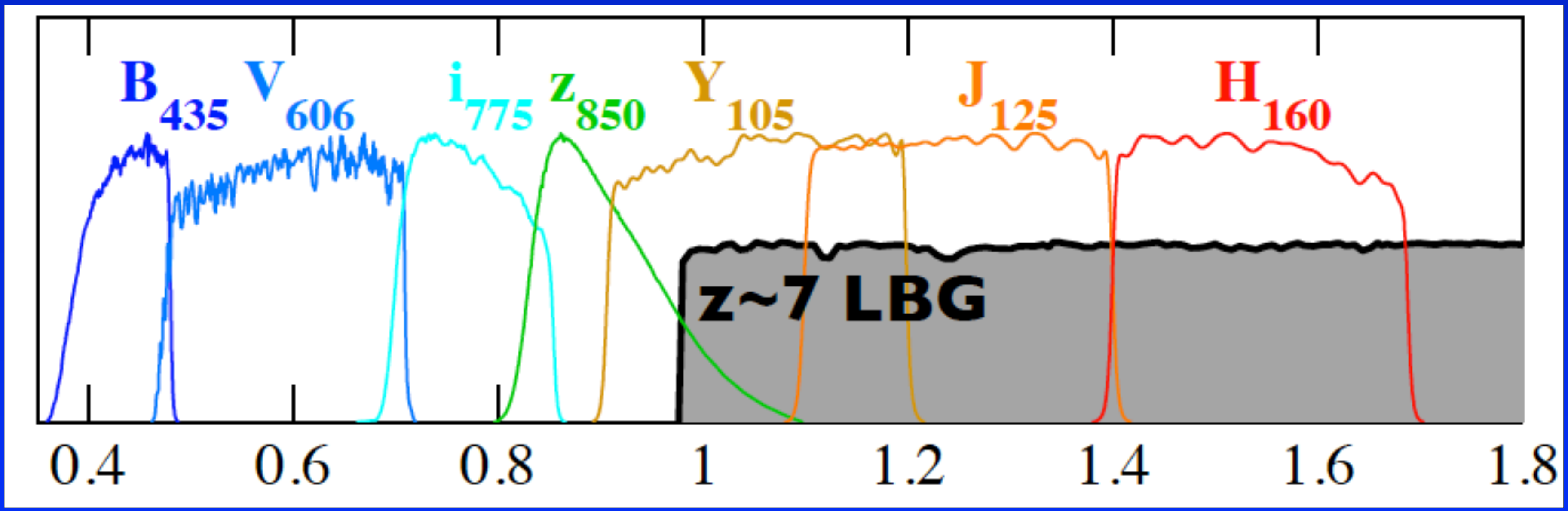


- "Drop-out galaxies" selected in color-color diagram
- Require non-detection in (deep) optical band
- Potential contaminants: SNe, cool stars, photometric scatter, spurious detections

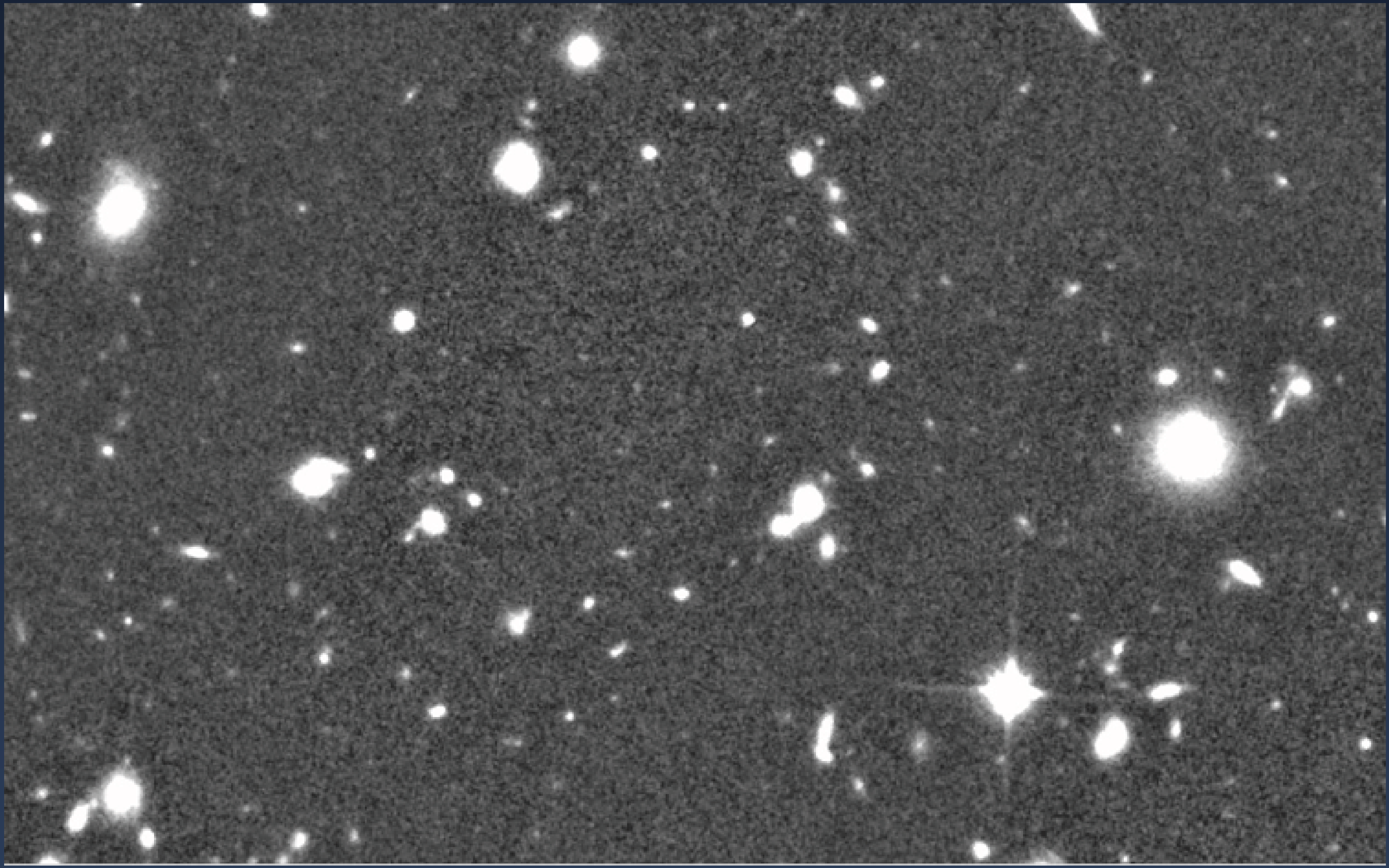
Bowens et al. 2011

Searching for galaxies beyond z≈6

- Near-IR wavelengths are needed, as well as deep optical imaging to exclude very dusty lower z objects
- Landmark progress in recent years thanks to WFC3 on HST:
  - 9 yr of NICMOS: ~10 galaxies at z>6.5
  - WFC3/IR: 40x more efficient (FOV, sensitivity, resolution) then NICMOS at very high-z ➜ 2 yr of WFC3 produced ~150 at z~7--9
    [only a few spec. confirmed at z=7-7.5]

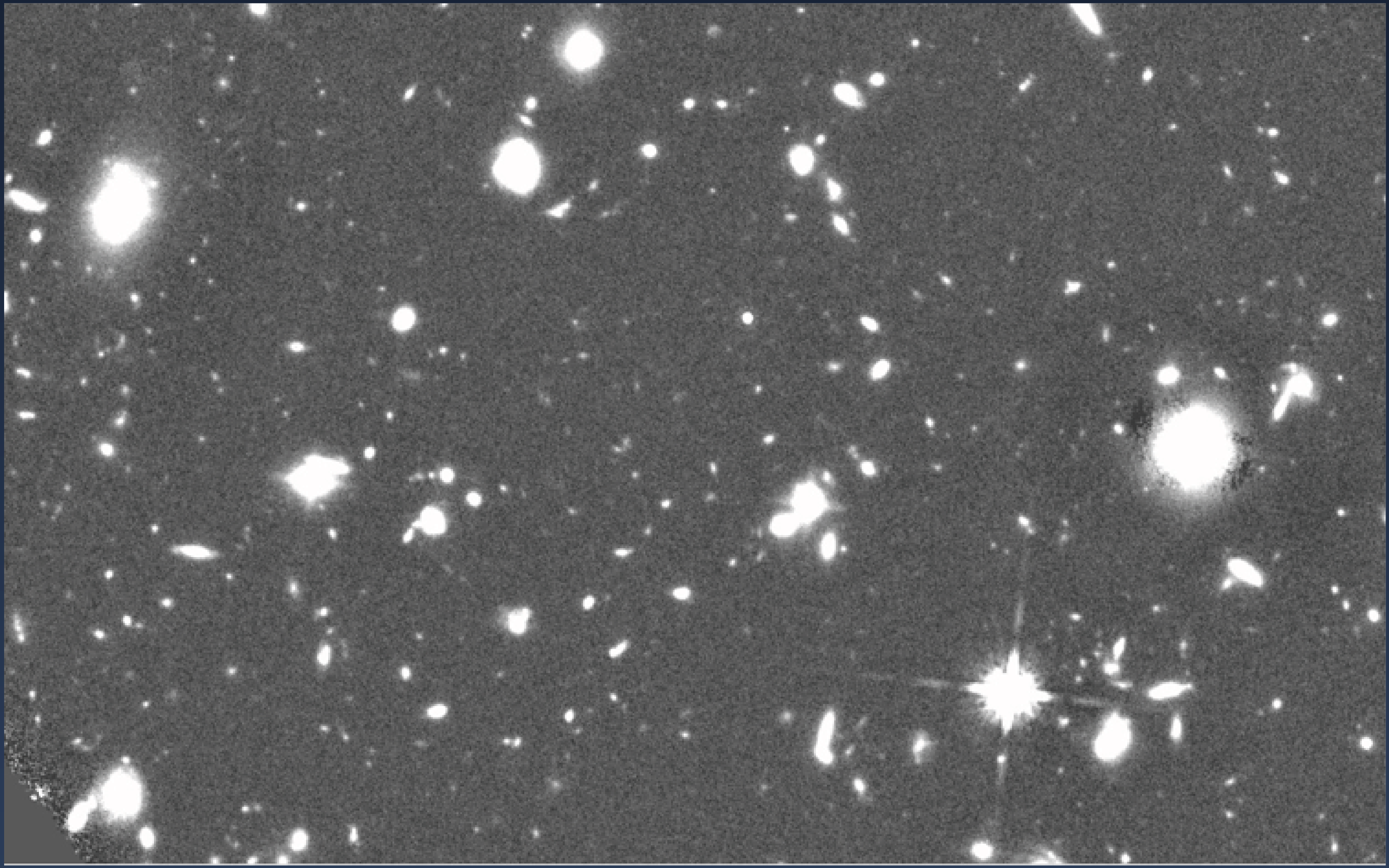


Old HST NIR Camera – NICMOS – 72 orbits



Slide credit: Garth Illingworth, UCSC, Lick Observatory

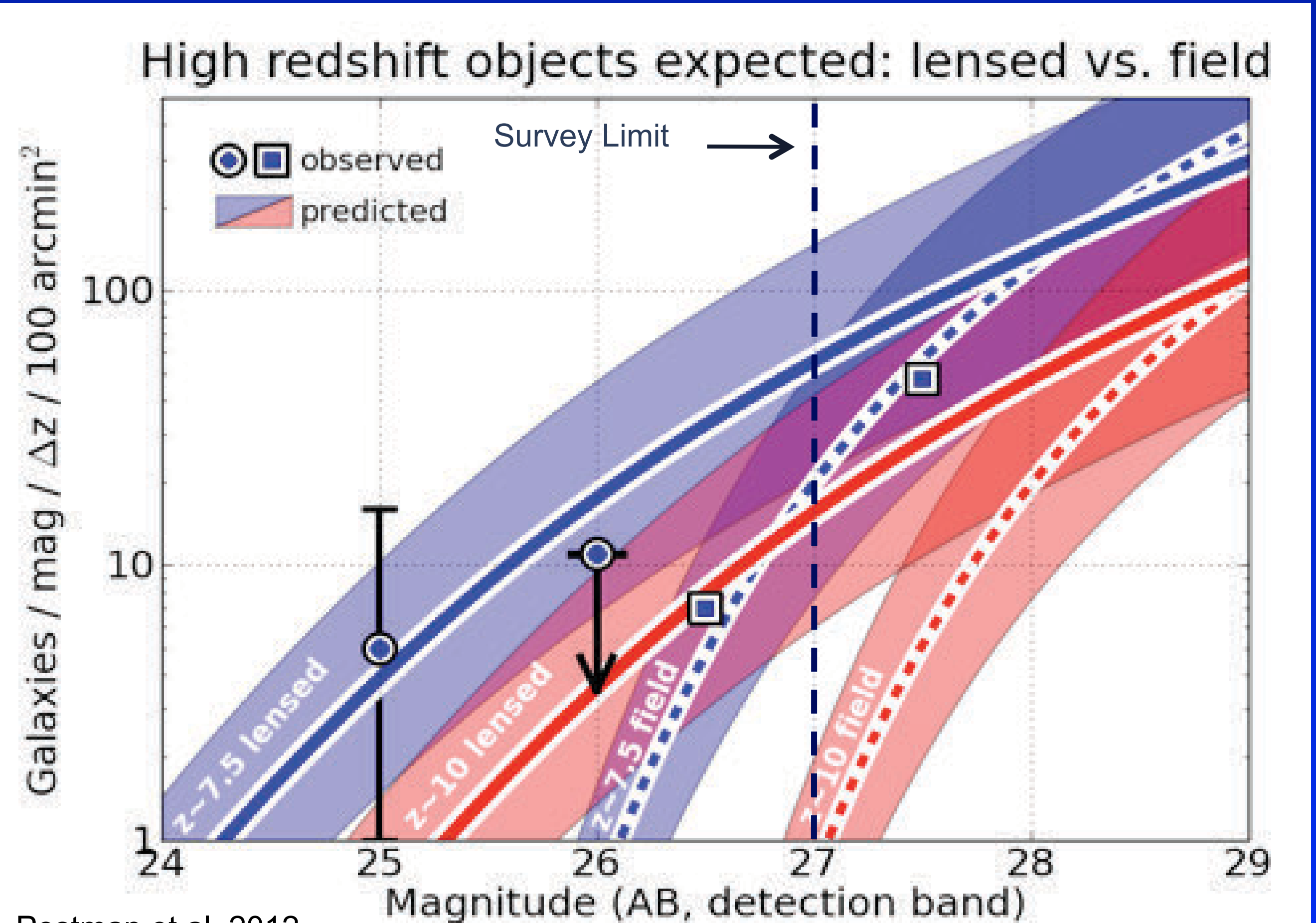
New HST NIR Camera – WFC3 – 16 orbits



Slide credit: Garth Illingworth, UCSC, Lick Observatory

The advantage of using gravitational telescopes to search for z>7 galaxies

Cluster vs Field strategy



Postman et al. 2012

Lensing greatly enhances the ability to detect distant galaxies

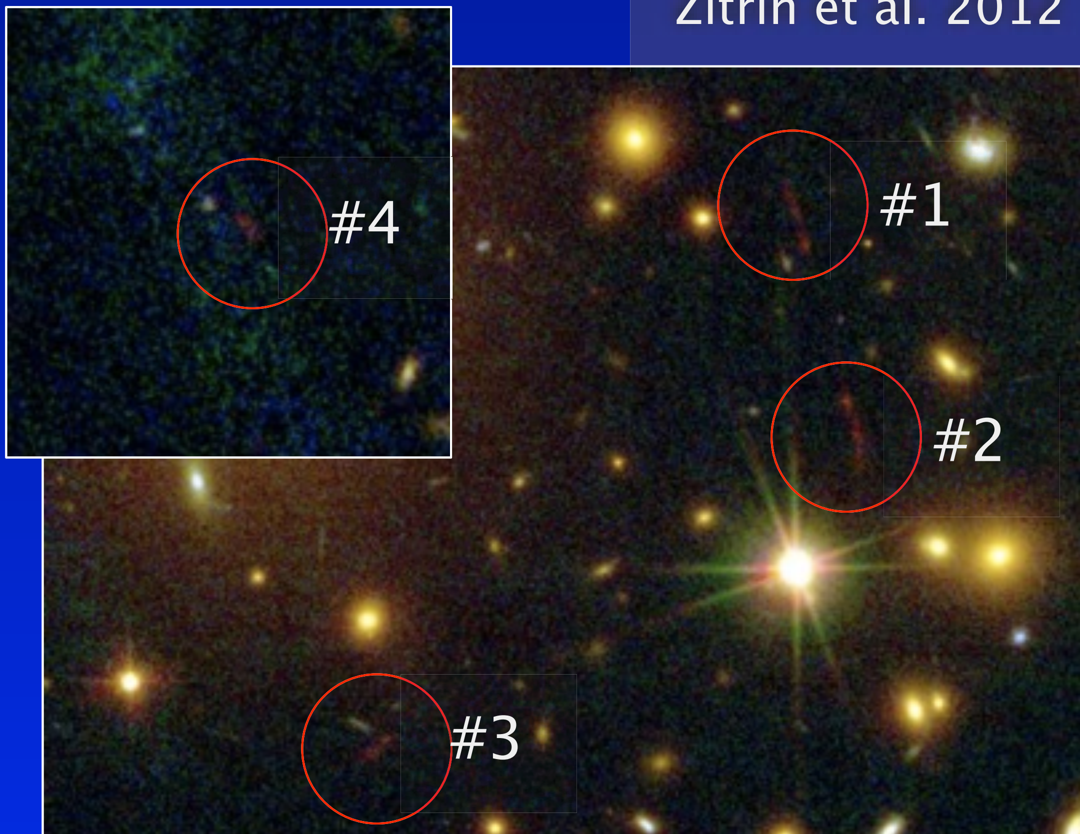
The blue and red solid curves show the expected number of z=8 and z=10 galaxies, respectively, to be discovered behind our 25 clusters as a function of magnitude in the detection band (F110W at z=8 and F140W at z=10).

A significant advantage of searching for high-z objects behind strongly lensing clusters is that the lens model can also be used to discriminate between highly-reddened objects and truly distant, high-z objects as the projected position of the lensed image is a strong function of the source redshift.

Uncertainties on the magnification are not found to be a serious problem for the derivation of the SFR density at very high-z

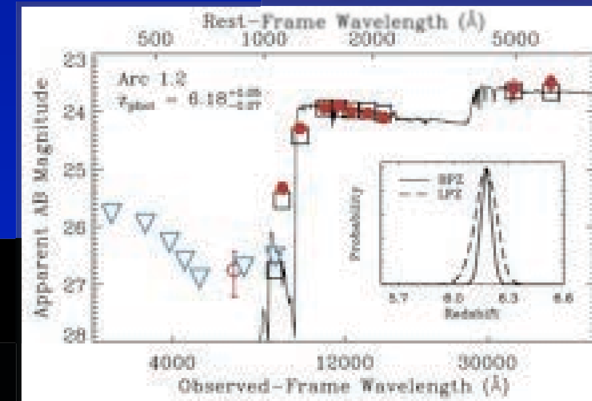
MACS J0329-02: Quadruply-lensed Galaxy at $z_{ph} = 6.15$

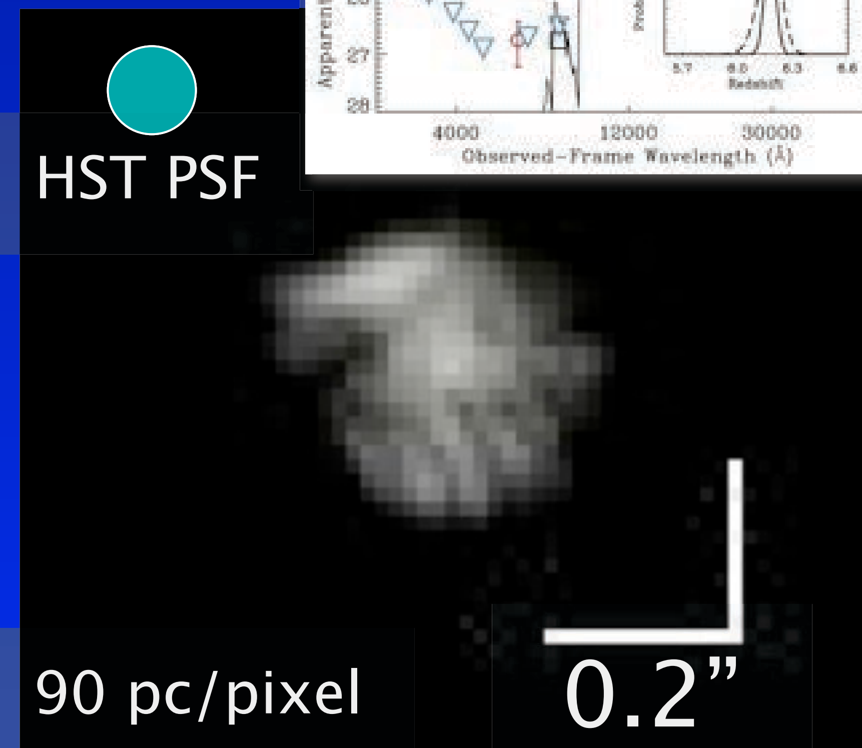
Zitrin et al. 2012



Magnifications: #1 = 11.6, #2 = 17.6, #3 = 3.9, #4 = 3.7

Age <400 Myr



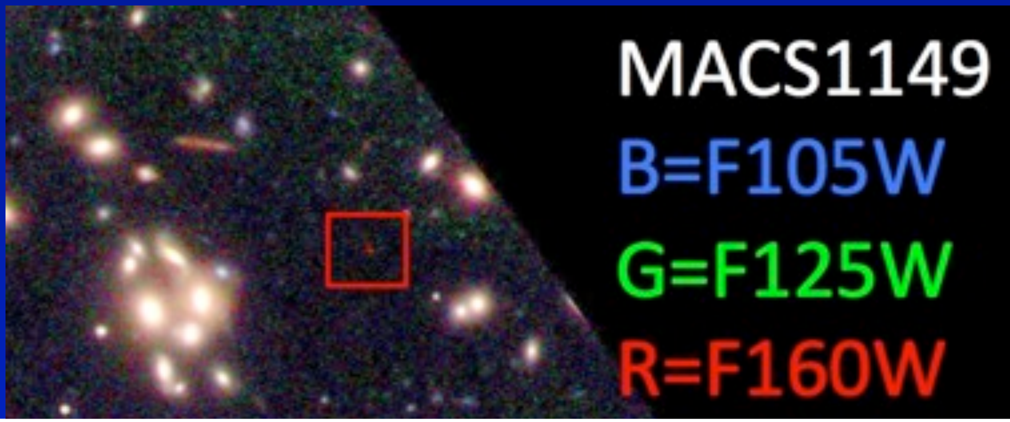


Delensed view (source plane)

- VIMOS spectroscopy 2 hrs (~1” seeing): ➔ no continuum, no Ly-α …

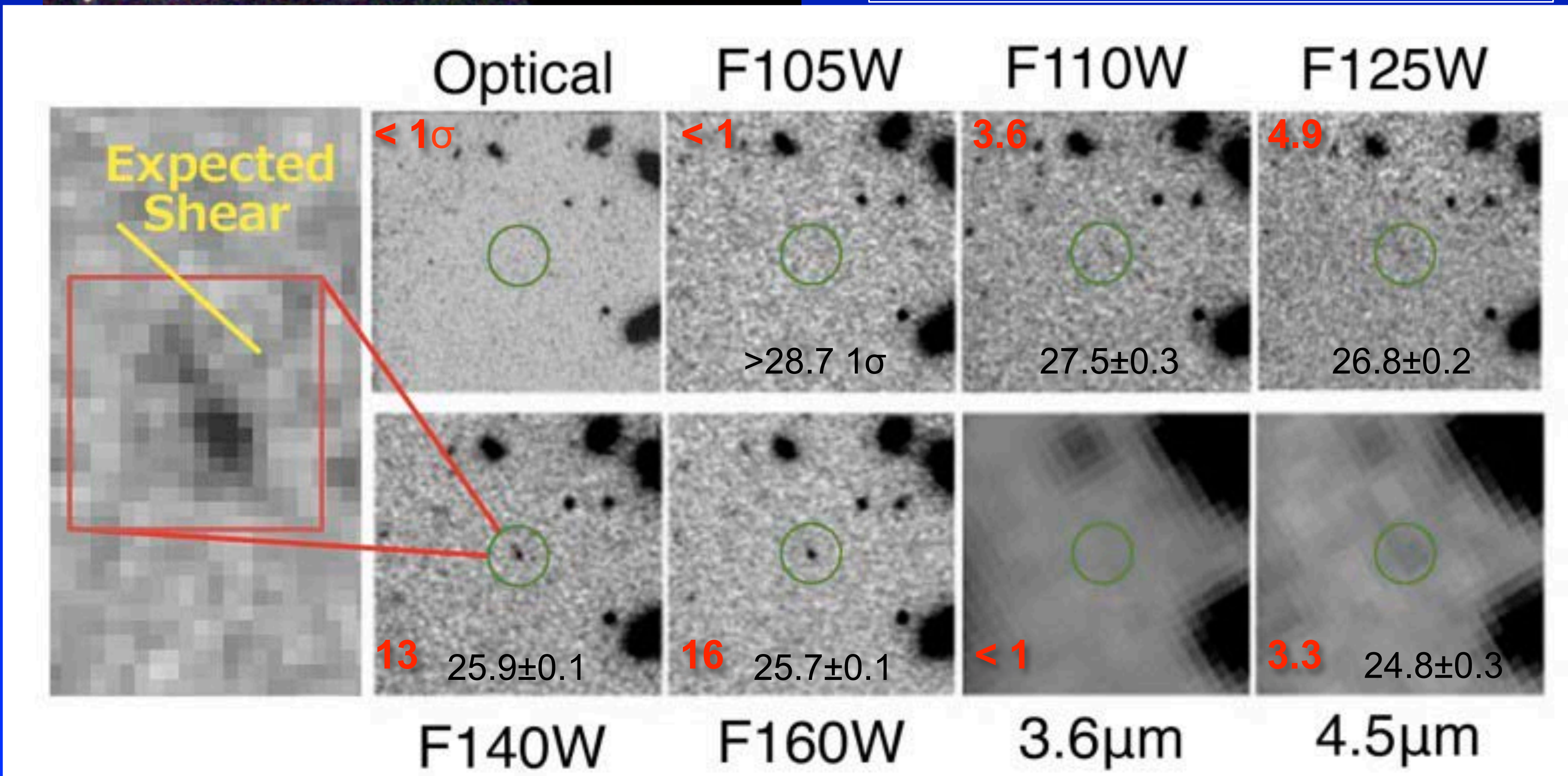
MACS1149-JD1: $z_{ph} = 9.6 \pm 0.2$

Zheng et al. 2012, Nature, Sept.



MACS1149 (z=0.54): high-magnification

J-band dropout criteria:
F110W – F140W > 1.3
F140W – F160W < 0.5
<2σ detection in F105W
<1σ detection in optical detection image



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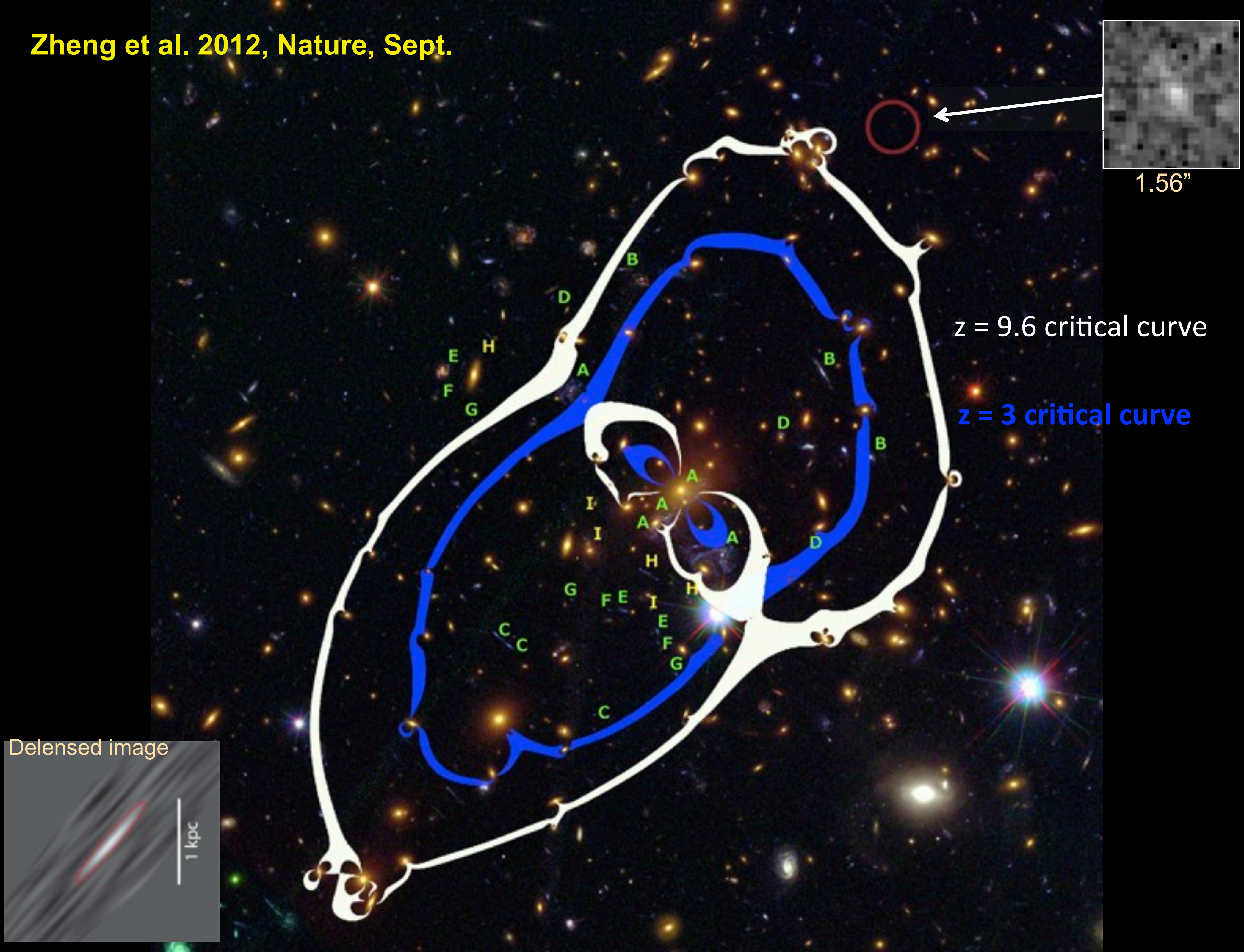
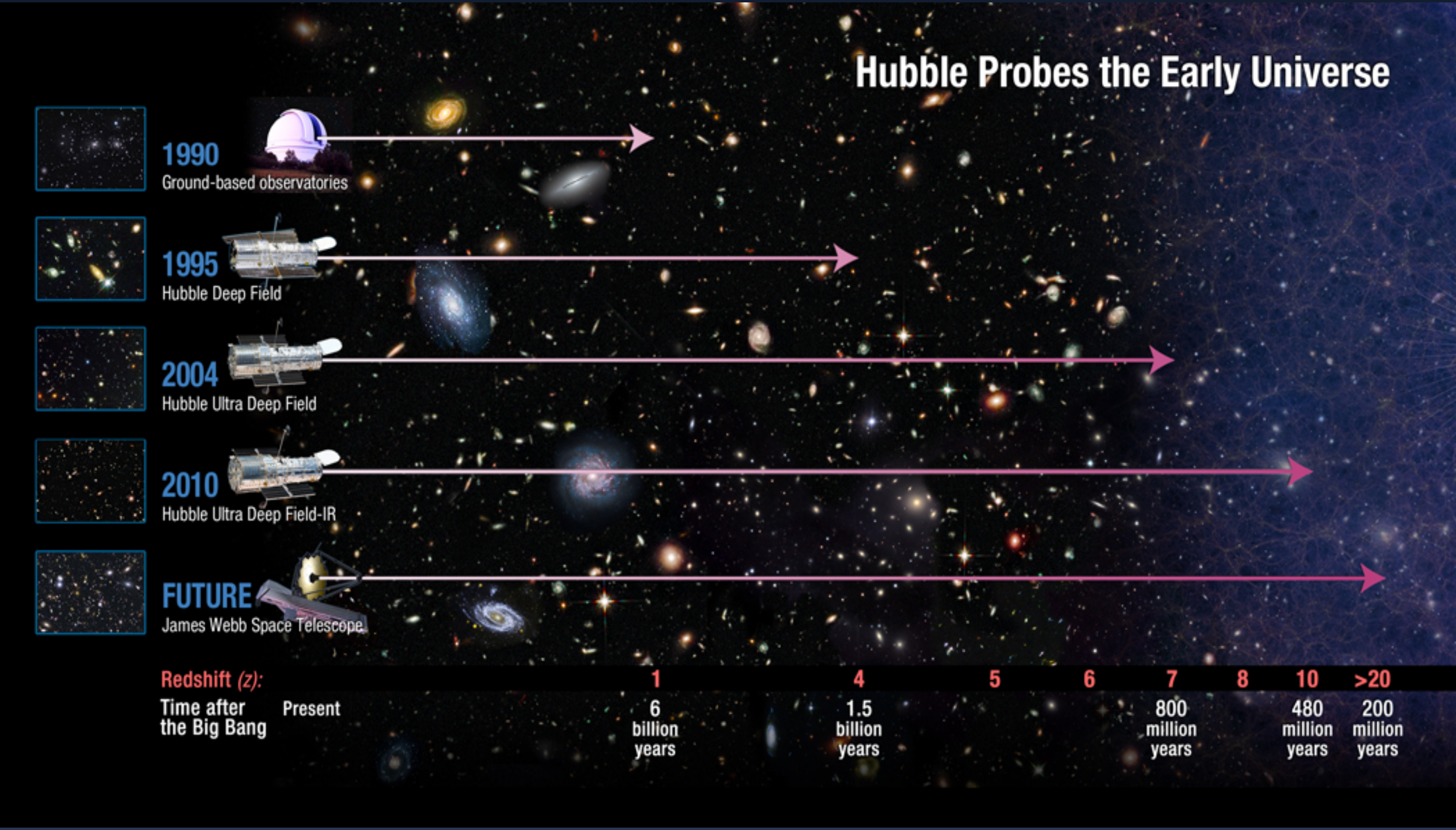
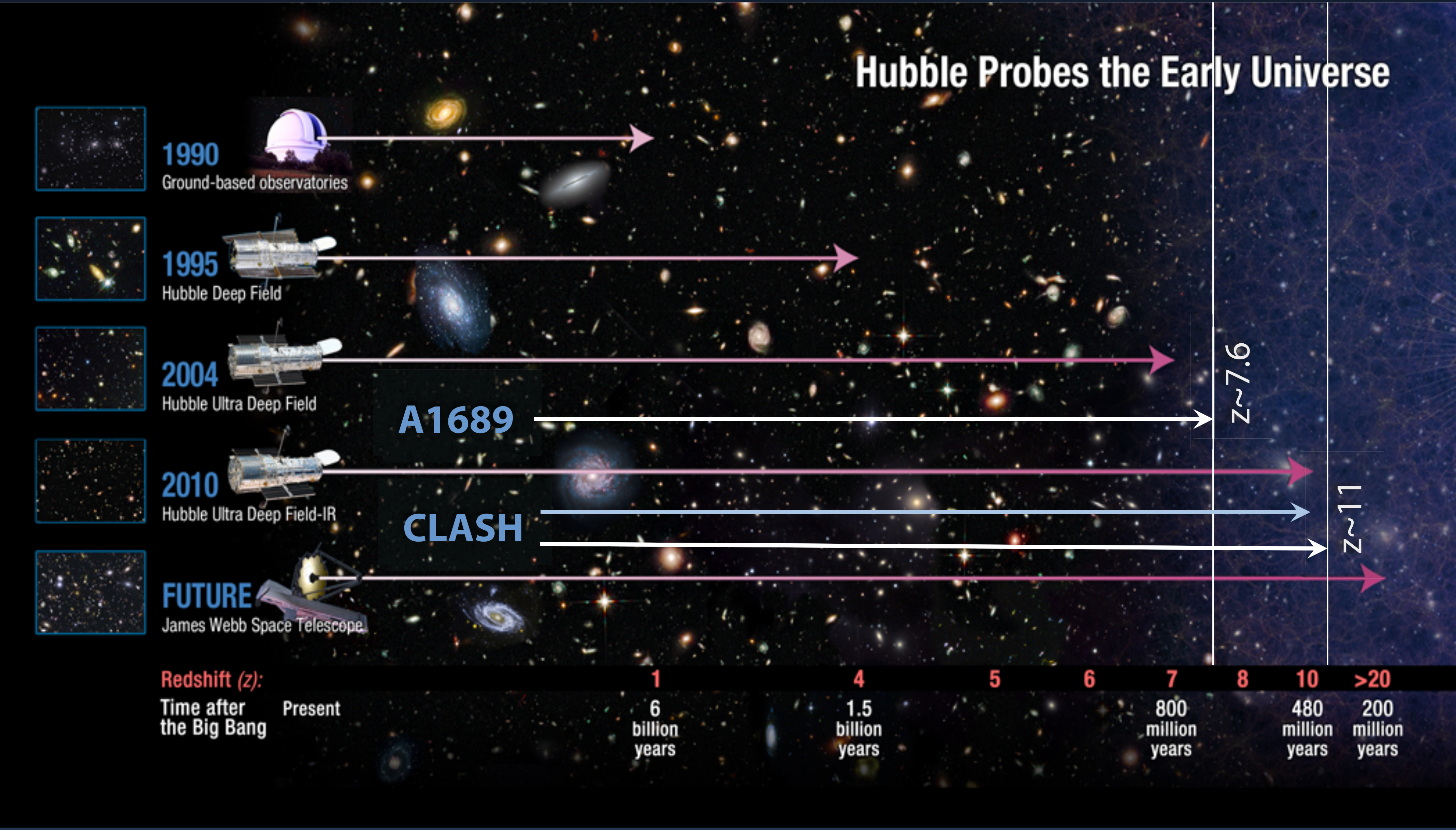


The Reionization Epoch with HST



Courtesy of L. Bradley

The Impact of Lensing Clusters



Courtesy of L. Bradley

Observational Probes of Cluster Formation & Evolution

Cluster Mass (DM)

- Mass Function (e.g. from X-ray) ⇔ N-body simulations, Extended PS
- Mass Distribution (inner cores from Lensing) ⇔ CDM simulations

Intra-Cluster Medium (ICM)

- Cluster Scaling Relations (L_x-T, M-T, Entropy, f_{gas})
- Gas Metallicity

⇔ hydro cosmo simulations + SAMs + chemical evolution

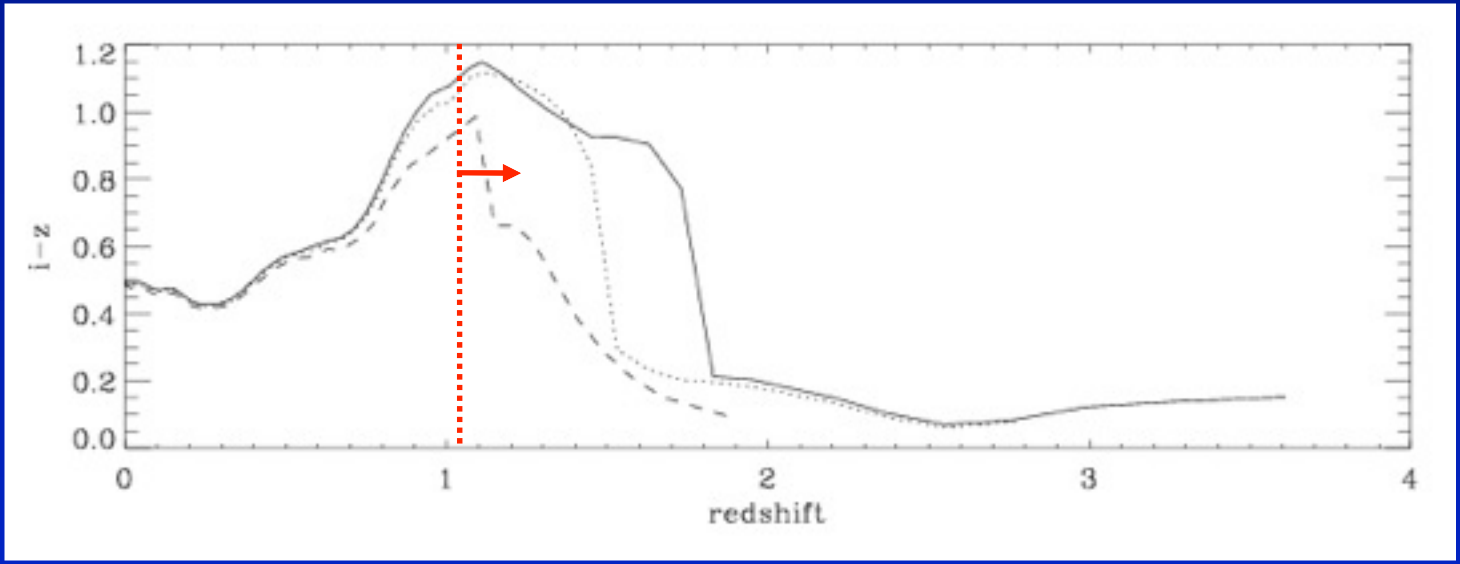
baryons

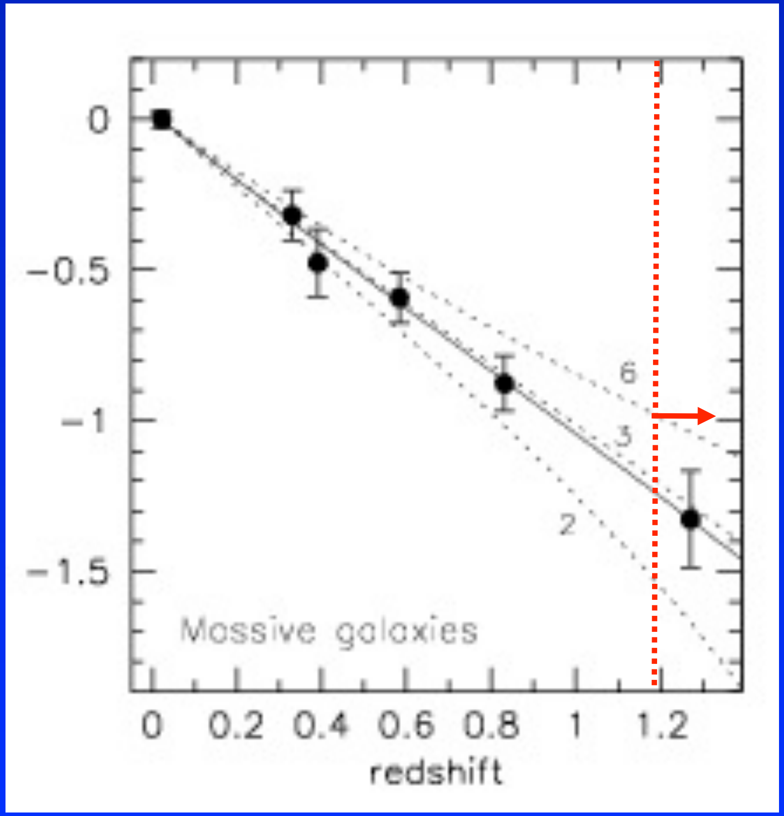
Galaxies/Stellar Mass Assembly

- Spectrophotometry, line diagnostics
- Red Sequence of Early types: normalization, scatter, slope
- Luminosity Function of cluster galaxies
- M/L (fundamental plane), Stellar Mass Function

⇔ stellar synthesis + semi-analytical models (SAM) + hydro simulations

Large look-back times ⇒ stronger leverage on models
(fractional age differences among galaxies are greater, ΔT/T ↗ with z)





Color Sequence Evolution: stellar population models for a 2 Gyr burst and z_F = 4,3,2

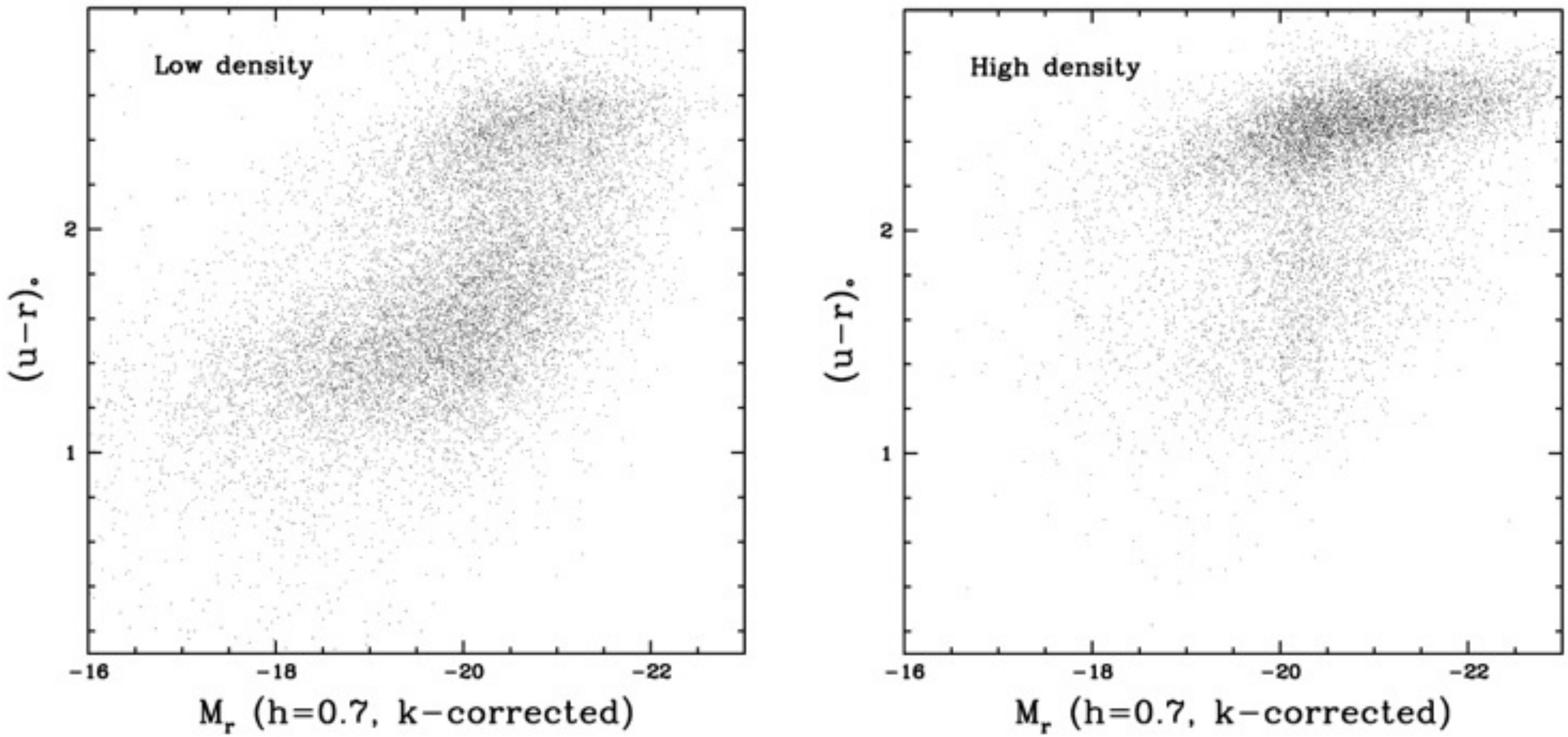
Evolution of M/L of cluster early-types: observations and models (van Dokkum et al .02)

$\Delta \ln(M/L_B) \propto (1.0 \pm 0.2)\, z$ = f(τ, IMF, Z)

derived from the Fundamental Plane:

$$\log r_e = \alpha \log \sigma + \beta \log < I_e > + \gamma$$

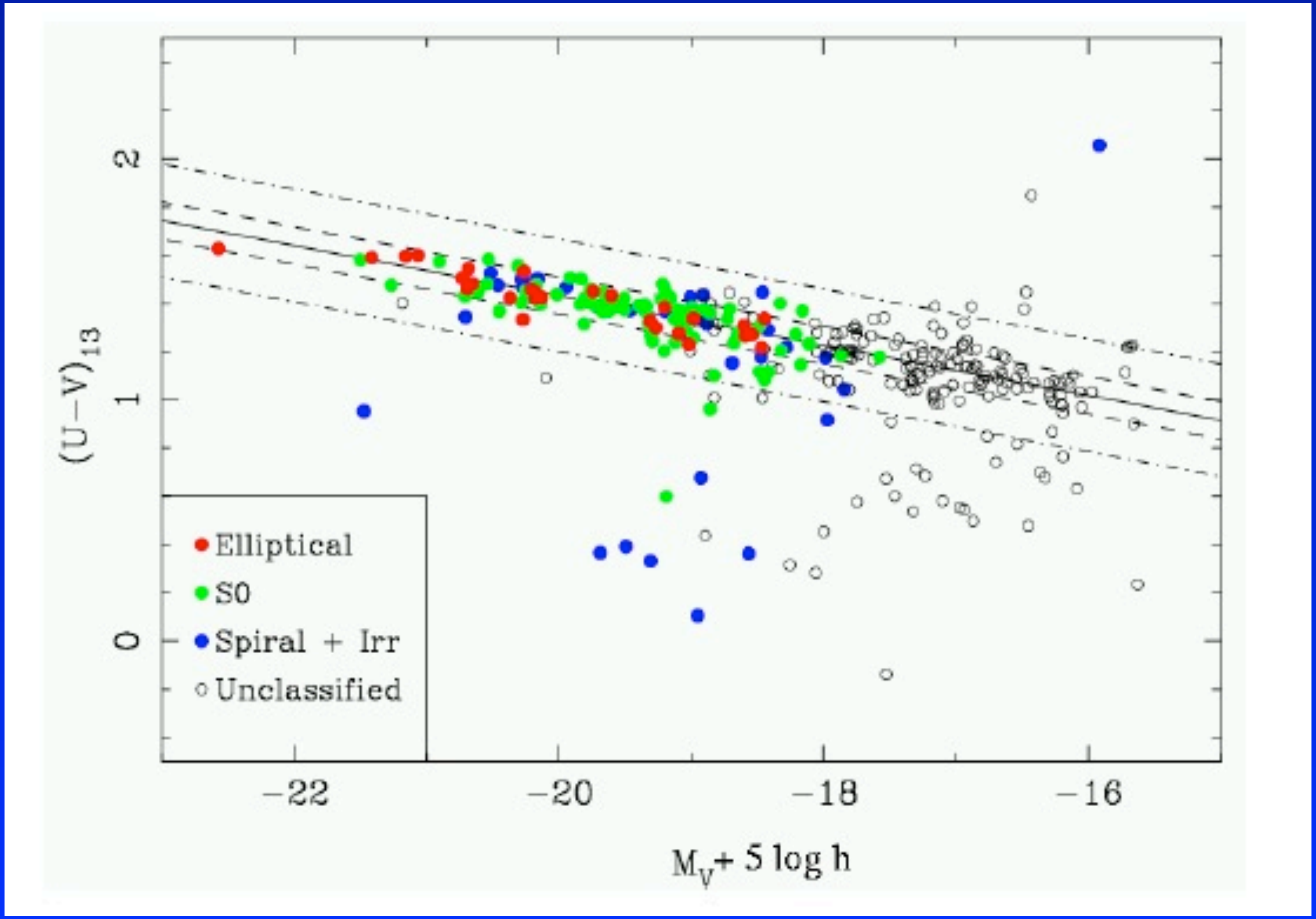
The colour-magnitude diagram in different environments



Baldry et al. 2003

The Color-Magnitude relation in clusters

CMD in the Coma cluster (Terlevich A. et al. 99)



The Color-Magnitude relation in clusters

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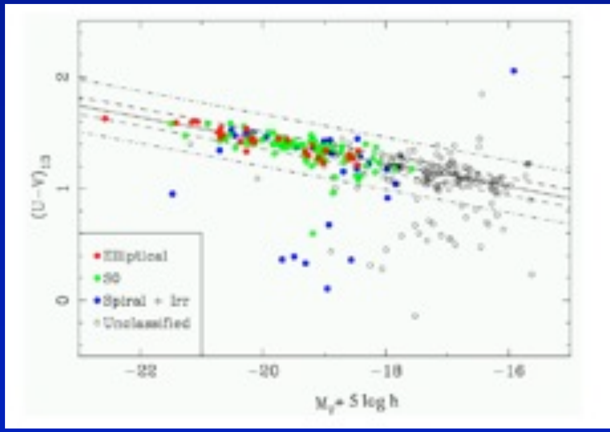

- The red sequence becomes extremely narrow (<0.05 mag) in the densest environments (clusters)
- Cluster galaxies (in contrast with the field) have a very well defined color- magnitude relation, which appears the same in all clusters (at least out to z<~1)
- Scatter (as small as 0.03 mag) sets strong constraints on age spread for the bulk of stars and challenges all semi-analytical models.
- The stars must be old to have such uniform colors, or formed in well coordinated single event: cluster galaxies are old passively evolved systems
- C-M slope&scatter set limits on degree of merging (number of galaxy mergers after the formation of its stars: reduces slope, increases scatter)
- The CM relations is likely a metallicity sequence, as opposed to an age sequence (given the lack of evolution of the slope and scatter)
- The higher is the redshift at which a tight CM relation is found the stronger the constraints on the age and formation syncronicity of the stellar populations

RDCS1252 (z = 1.24) C-M Relation with HST/ACS and VLT/ISAAC

(Blakeslee et al. 03; Lidman et al. 03)

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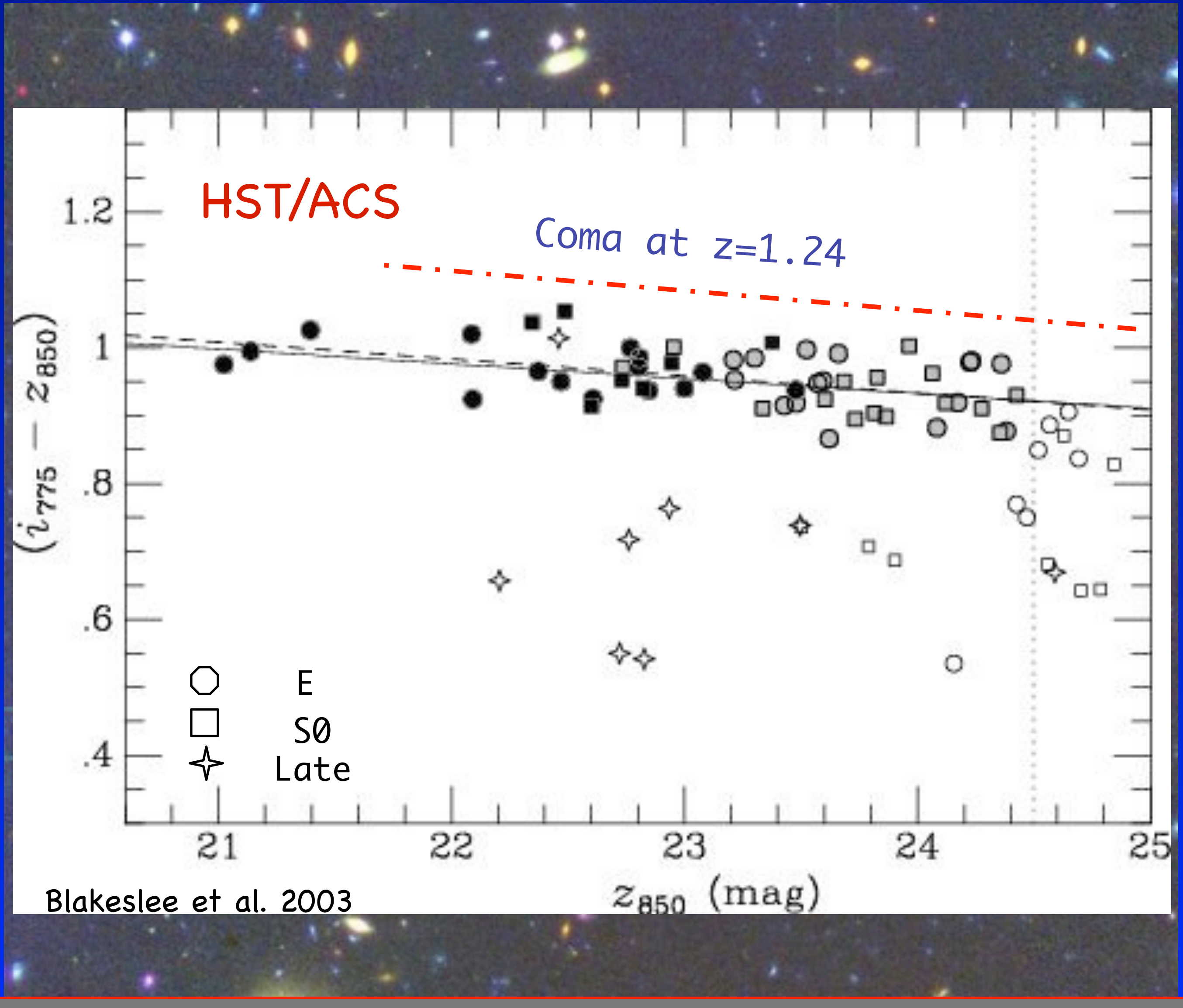
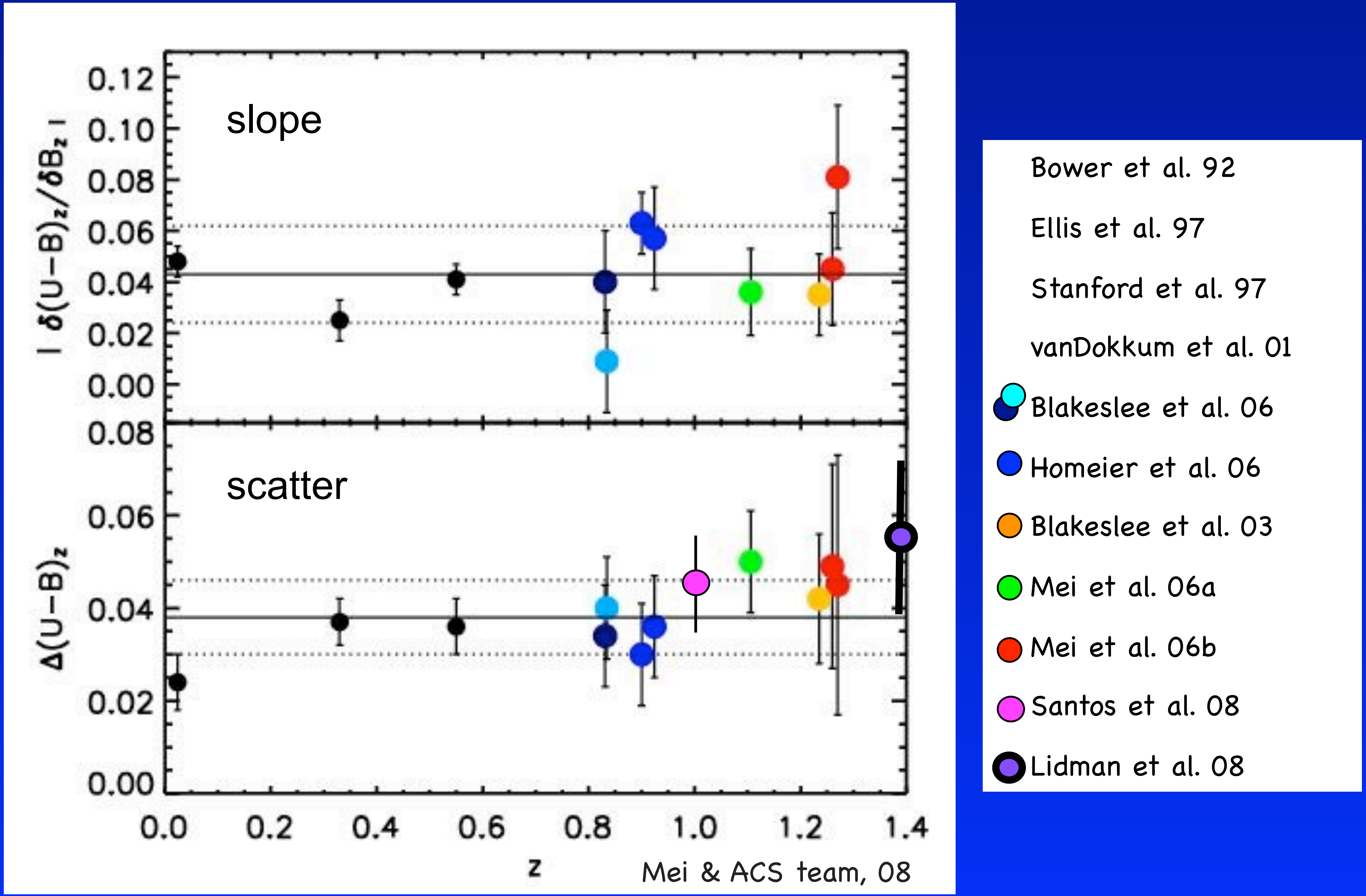


The scatter (0.042±0.015 mag in i-z, 0.06 in J-K) and slope of the red sequence are very similar to low-z clusters (e.g. Coma)

Using the color sequence to constrain the formation history of ETGs

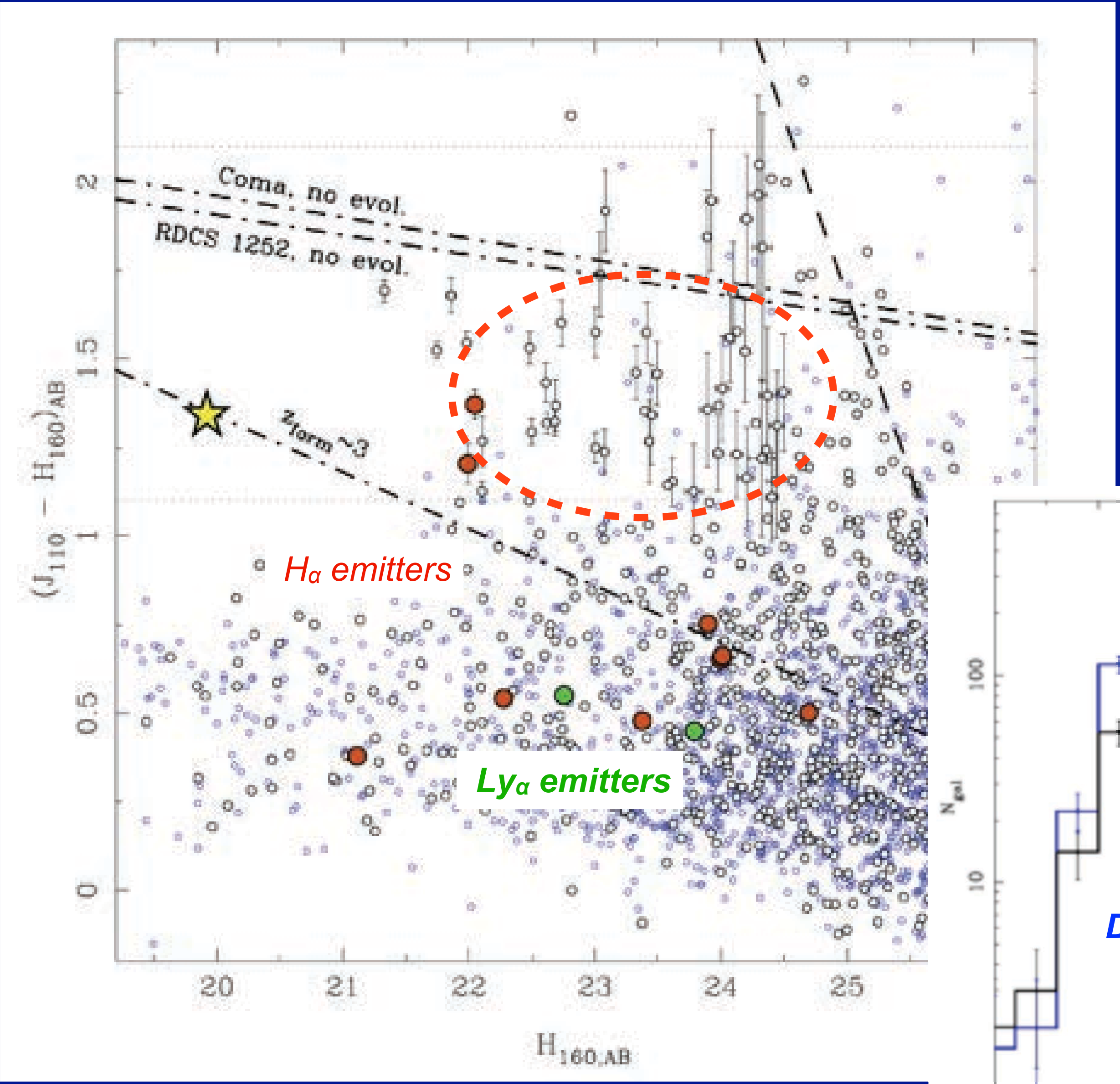


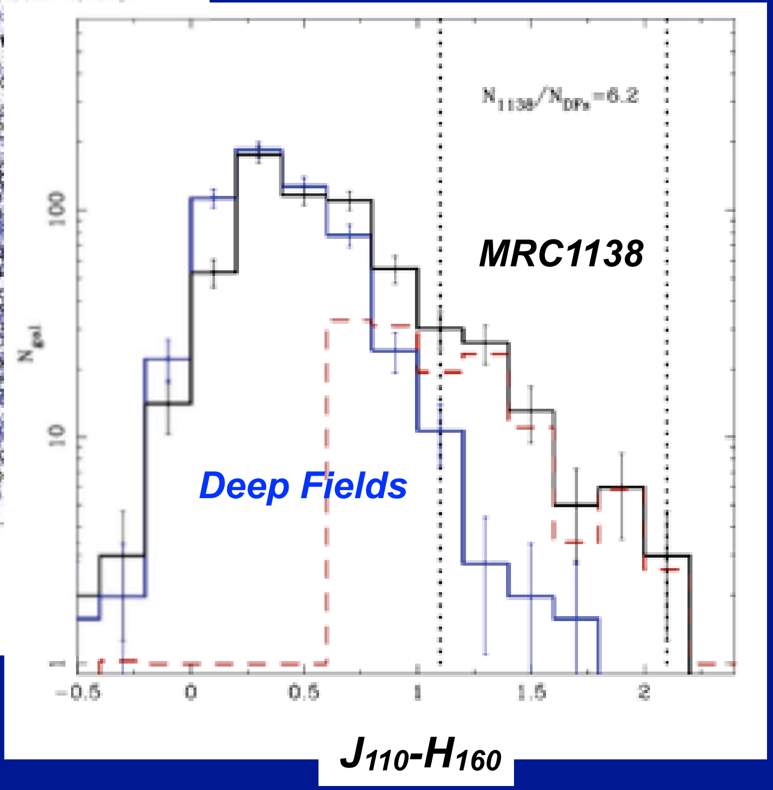
No (or little) evolution of the CMD slope and scatter out to z=1.4

→ The Cluster RS frozen over ~9 Gyr, well within 0.1 mag!

A Nascent Red Sequence at z~2

MRC1138-262 (z=2.16) *(Zirm et al. 2008)*

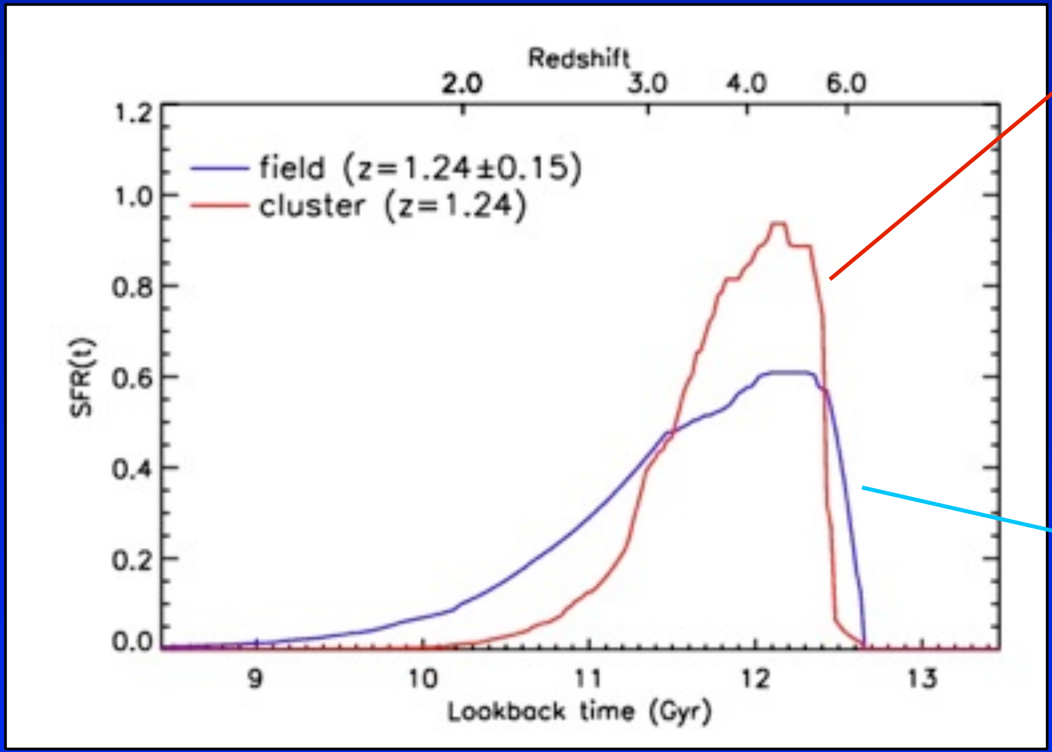


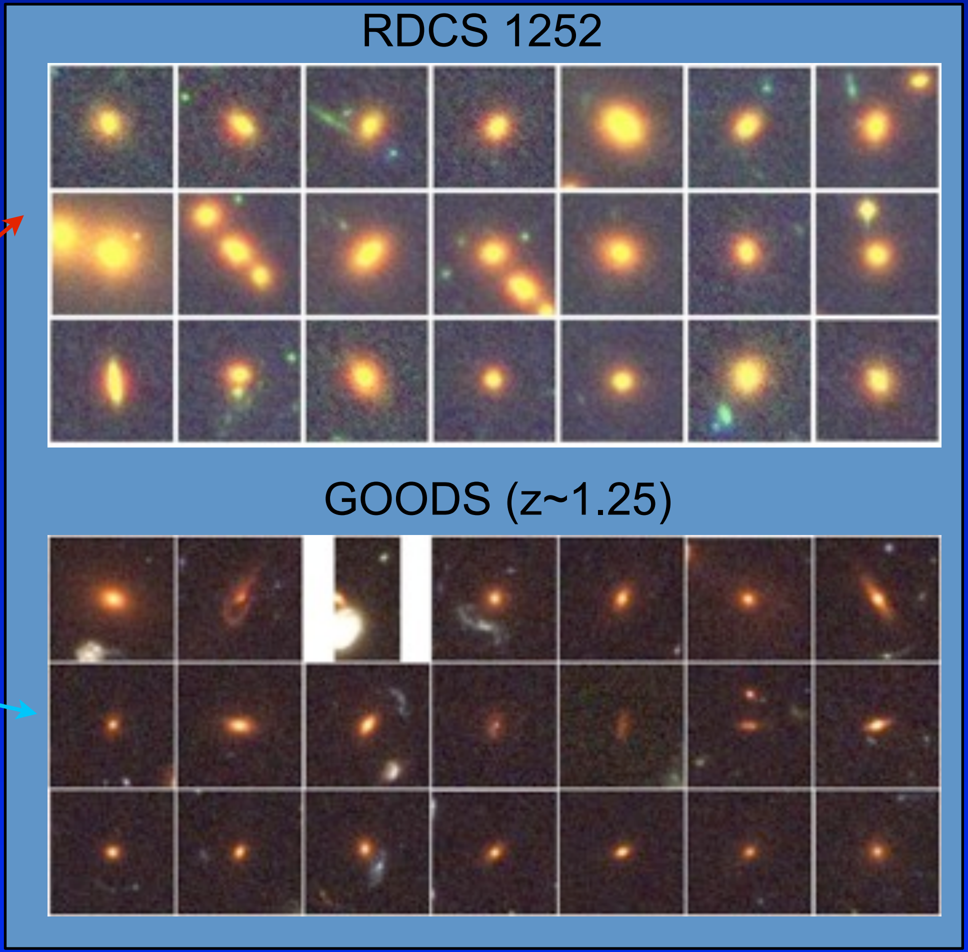


SF histories of ETGs in clusters (and field) at z~1.2

A long-standing prediction of hierarchical models is that early-type galaxies in the field are younger and less massive than those in cluster cores, since galaxy formation is accelerated in dense environments…

(Gobat al. 2008; Rettura et al. 08,11, Tanaka et al. 11)





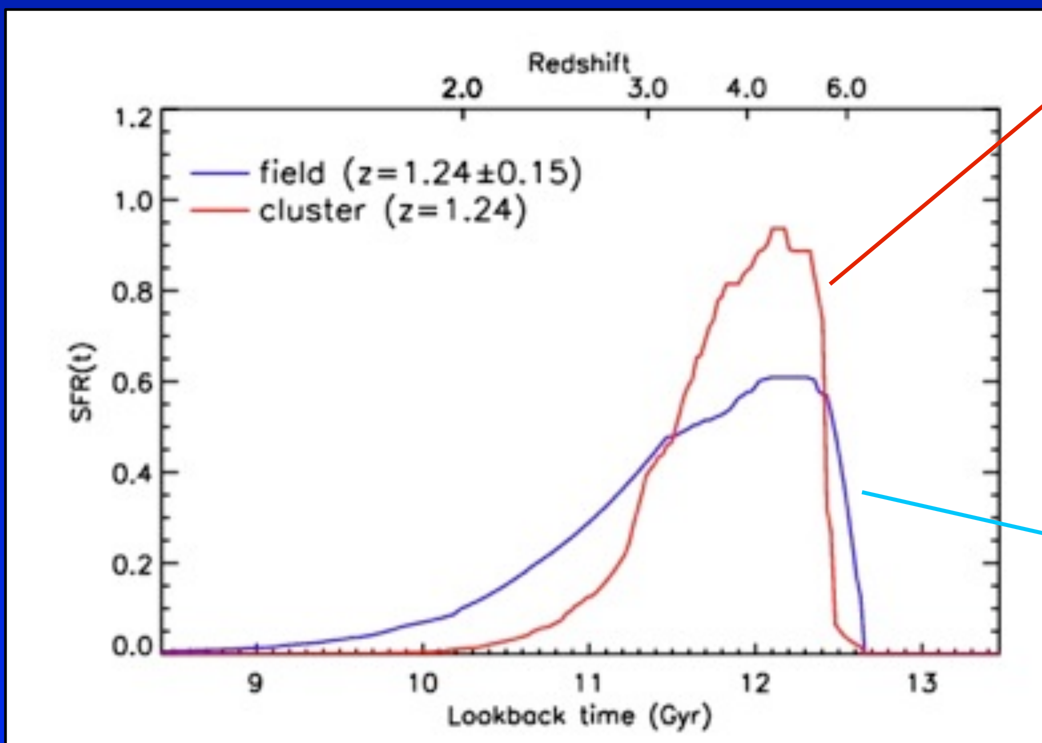
- Star formation in clusters is **accelerated**, rather than significantly delayed
- *Galaxy mass* regulates the *timing of galaxy formation*, the *environment* regulates the *time scale* of SFH

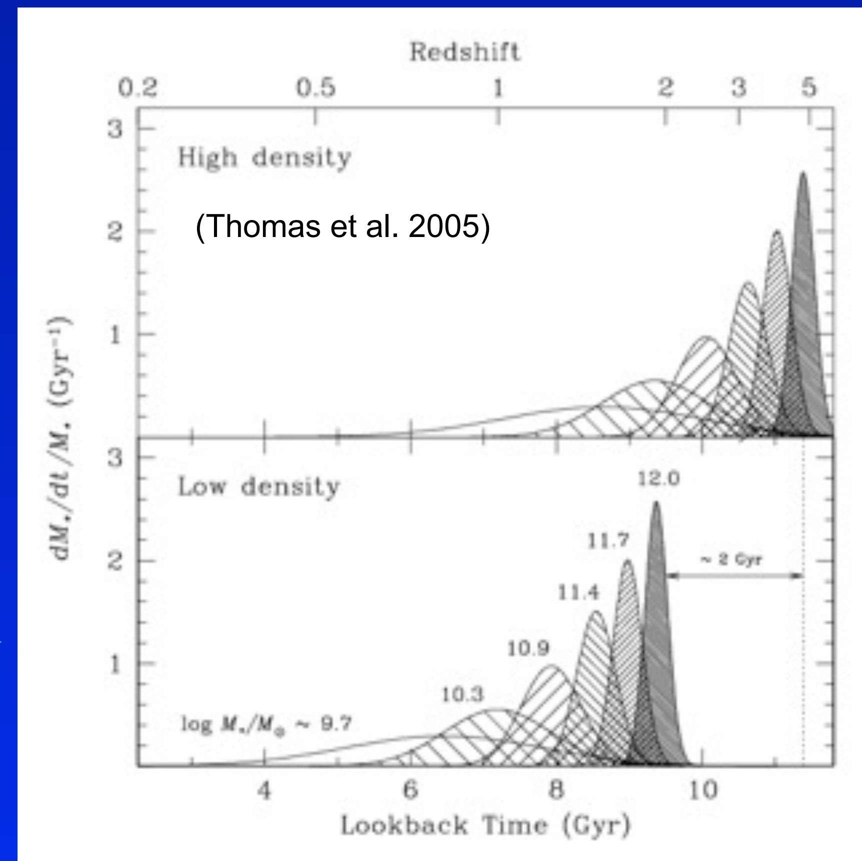
SF histories of ETGs in clusters (and field) at z~1.2

A long-standing prediction of hierarchical models is that early-type galaxies in the field are younger and less massive than those in cluster cores, since galaxy formation is accelerated in dense environments…

z~0 (fossil record)

(Gobat al. 2008; Rettura et al. 08,11, Tanaka et al. 11)

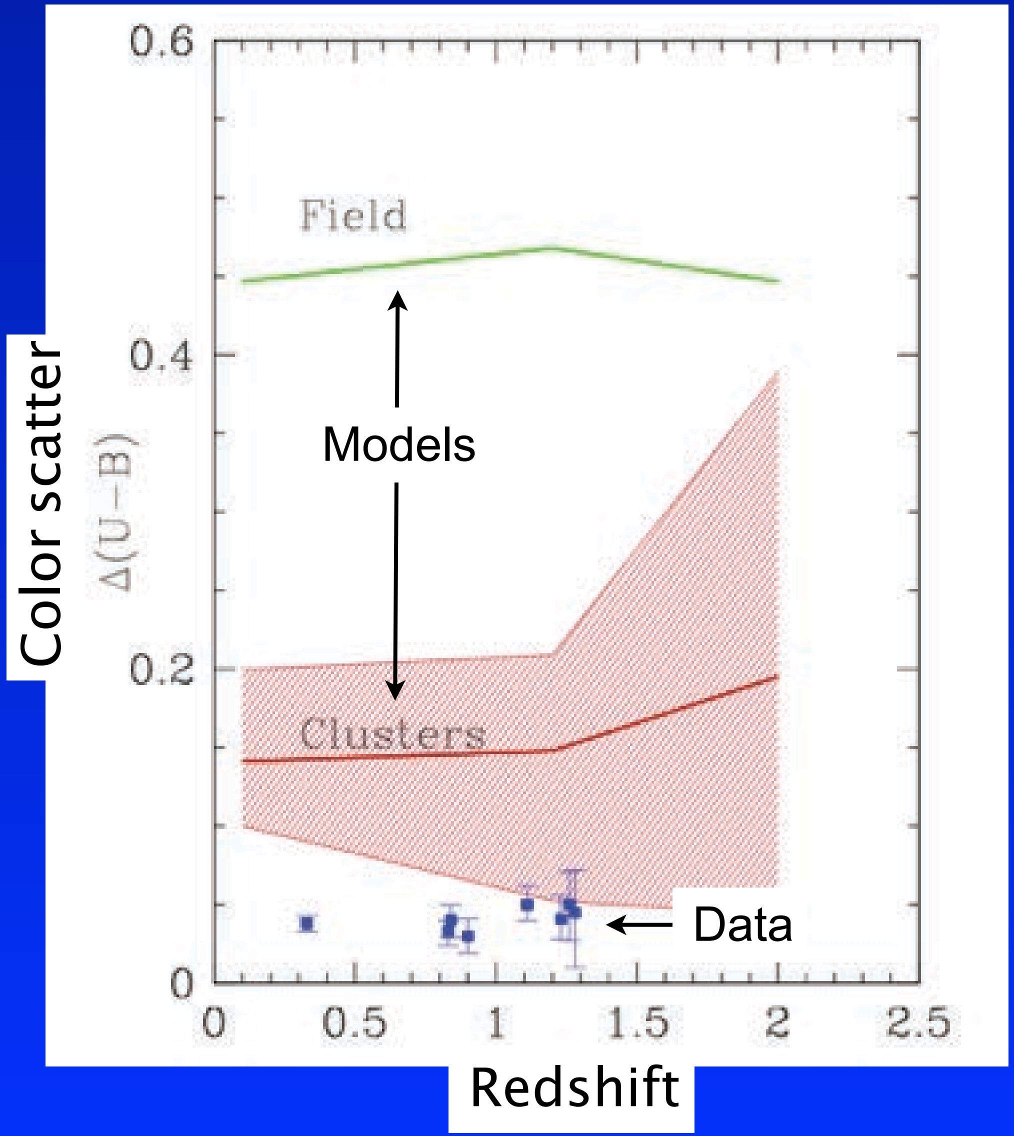




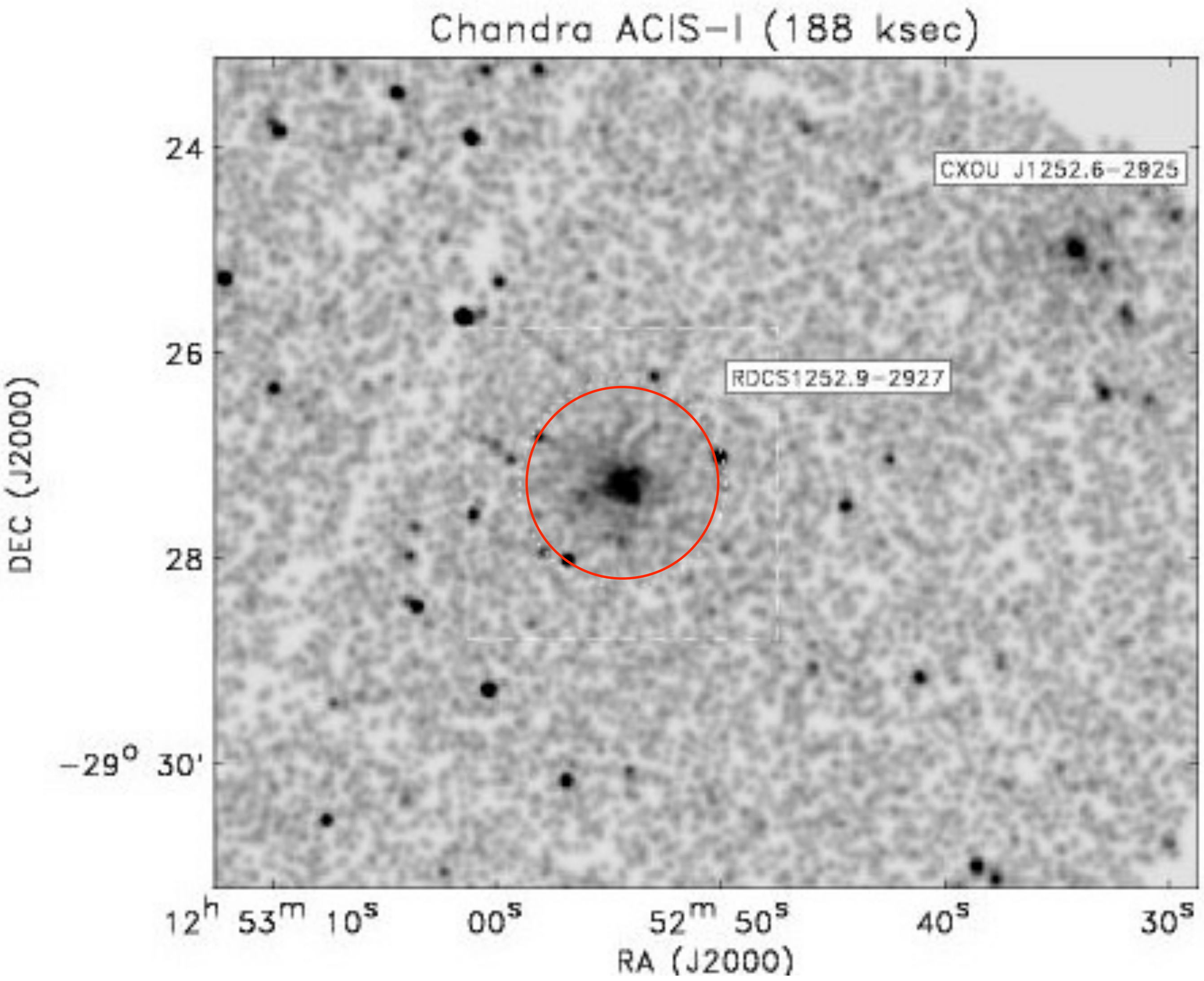
- Star formation in clusters is **accelerated**, rather than significantly delayed
- *Galaxy mass* regulates the *timing of galaxy formation*, the *environment* regulates the *time scale* of SFH
- Fossil record data in the local Universe show an increased lag between SFHs

SF histories of ETGs in clusters vs field at z~1.2

- General agreement with semi-analytical models (e.g. De Lucia+ 06, Menci+ 08)
- Models however cannot reproduce the very tight relation in clusters (Menci+ 08)



Measuring metallicity of the ICM at z>1



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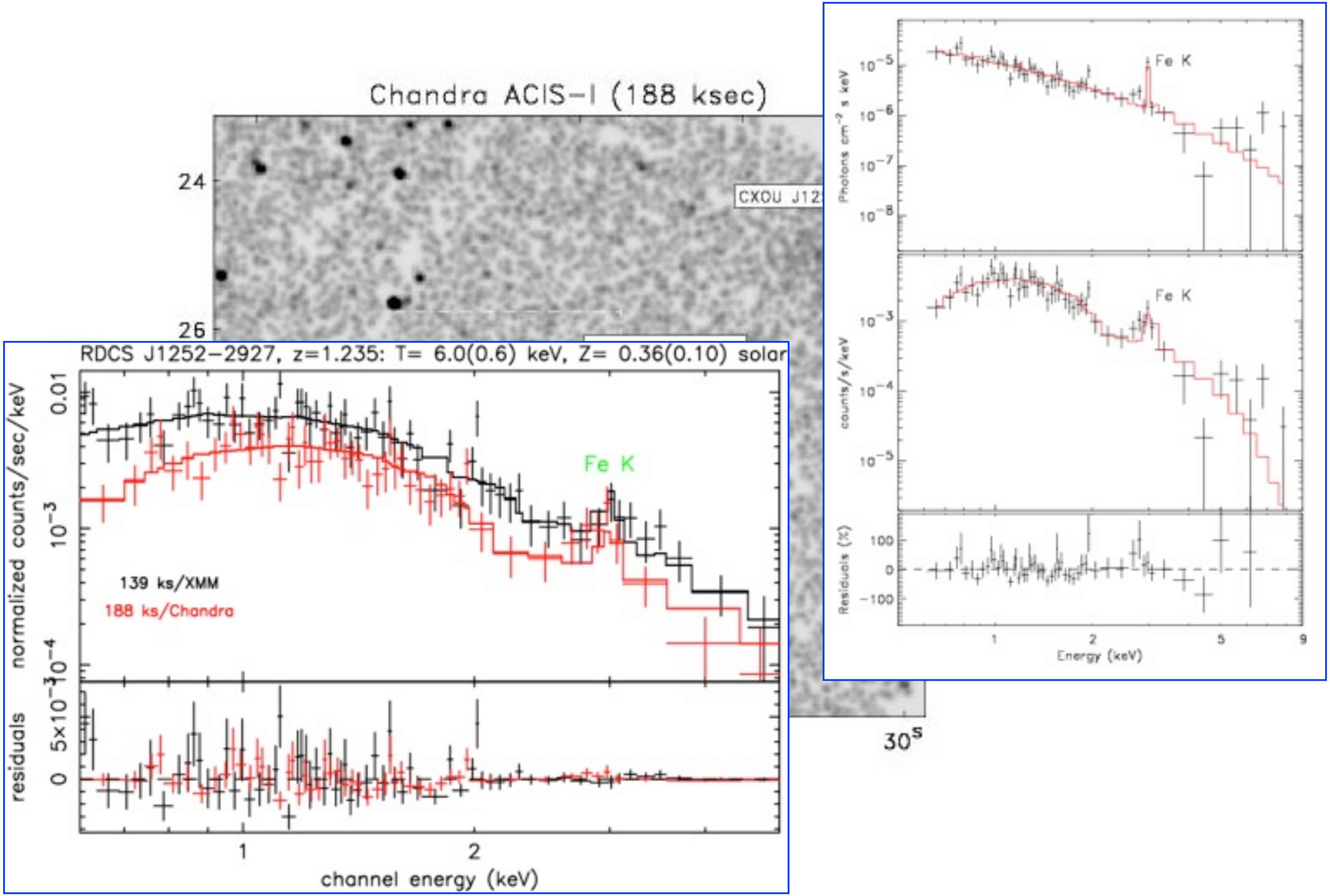
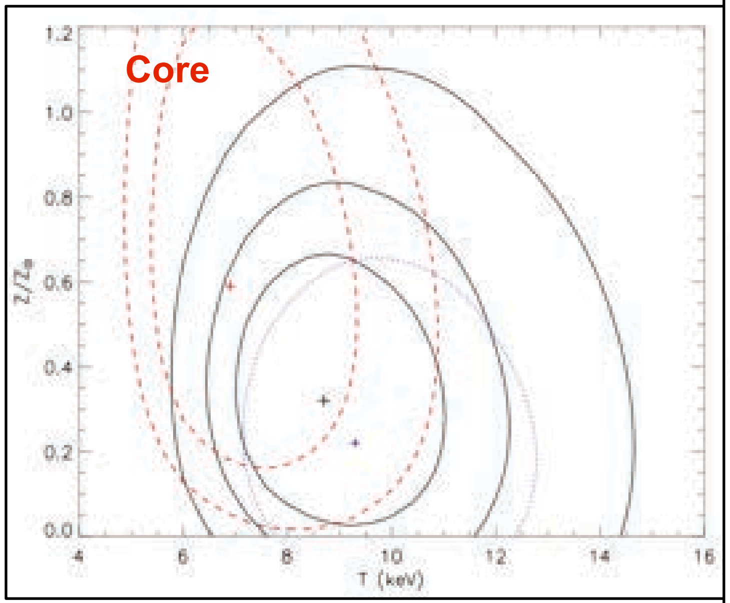
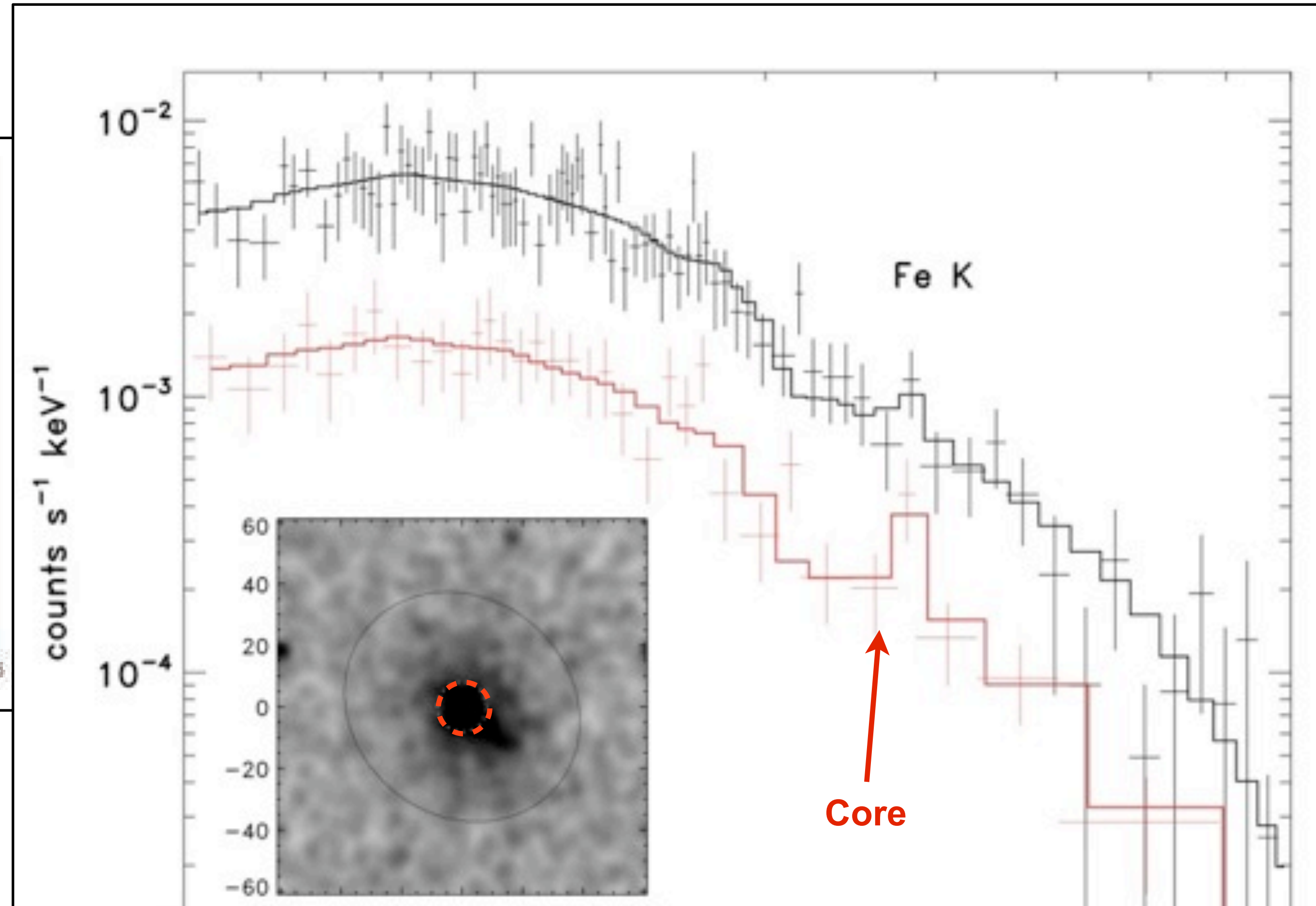


Out to z=1.4: Chandra Observations of XMM2235



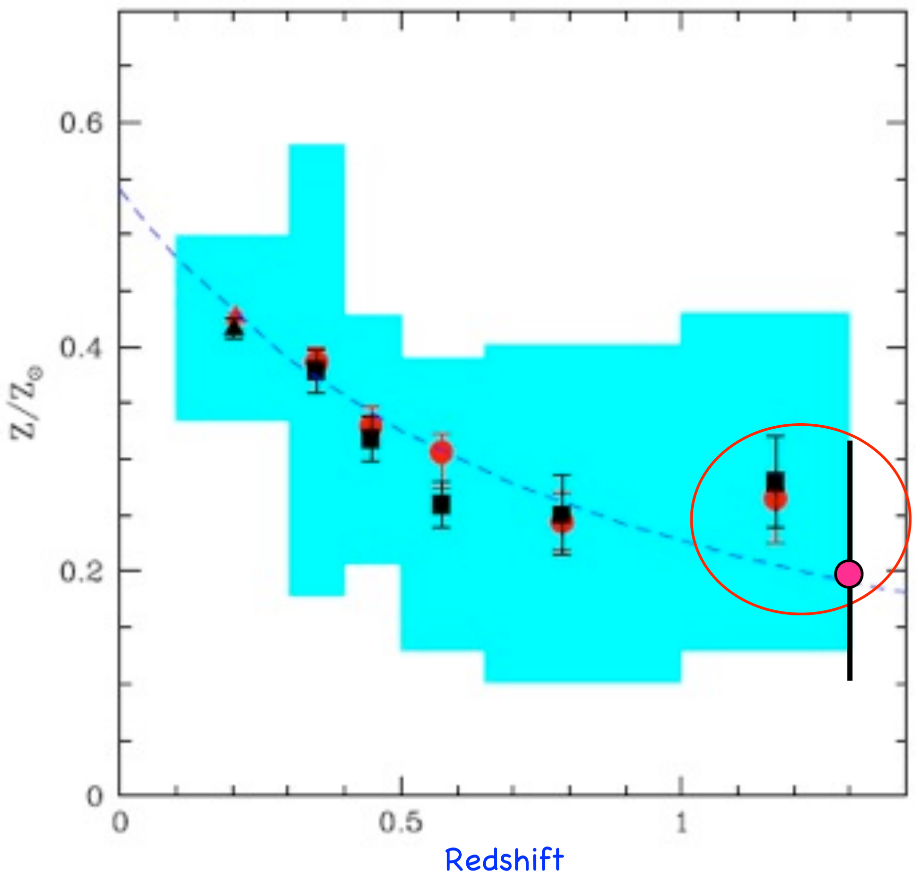
Rosati et al. 09



➡ The ICM is already enriched at local values at z=1.4 (metal enrichment must be completed by z~ 2.5)

- Global fit: $kT = 8.7^{+1.4}_{-1.2}$ keV, and $Z = 0.32^{+0.19}_{-0.22}\,Z_\odot$
- Core fit (r=7.5"=60 kpc): $kT = 6.9^{+1.5}_{-1.1}$ keV, and $Z = 0.59^{+0.29}_{-0.37}\,Z_\odot$

Evolution of ICM metallicity from Chandra Observations of distant clusters

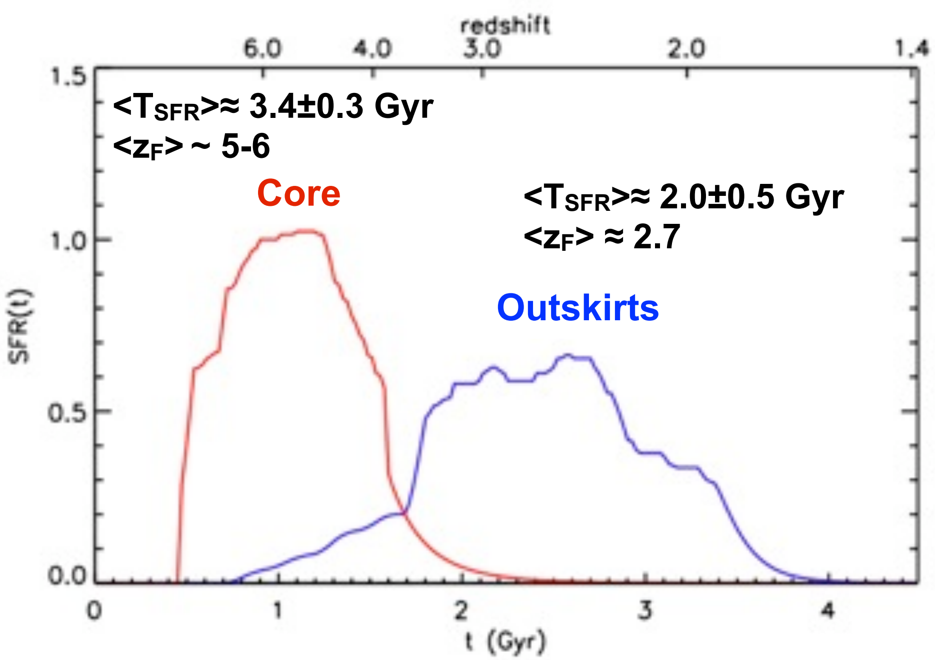


Method:
stacking spectral analysis of a sample of 20 high-z clusters (0.3<z<1.2)

(**Balestra et al. 06, Maugh et al. 07**)

➡ **Fe abundance at z~1.4 is already 0.2-0.3 solar**

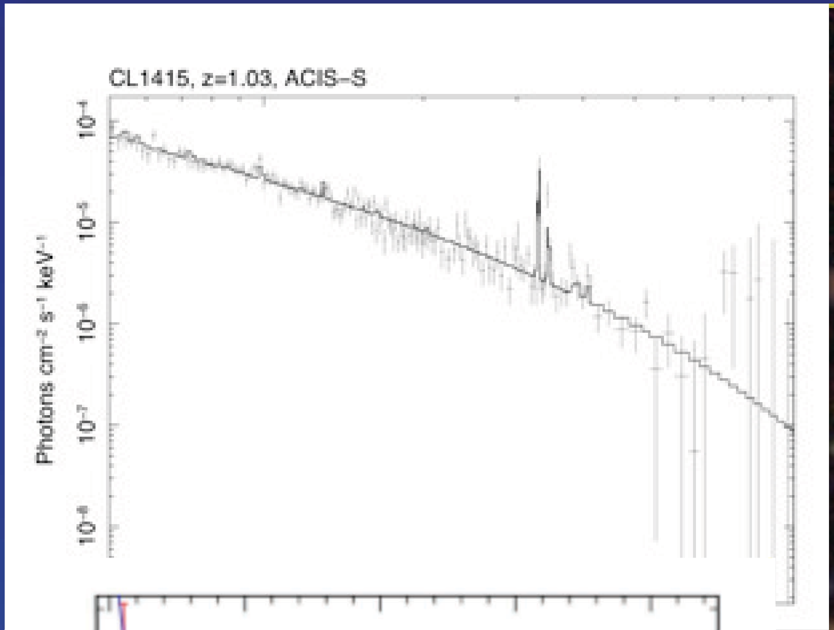
SF history of cluster ETGs at z=1.4

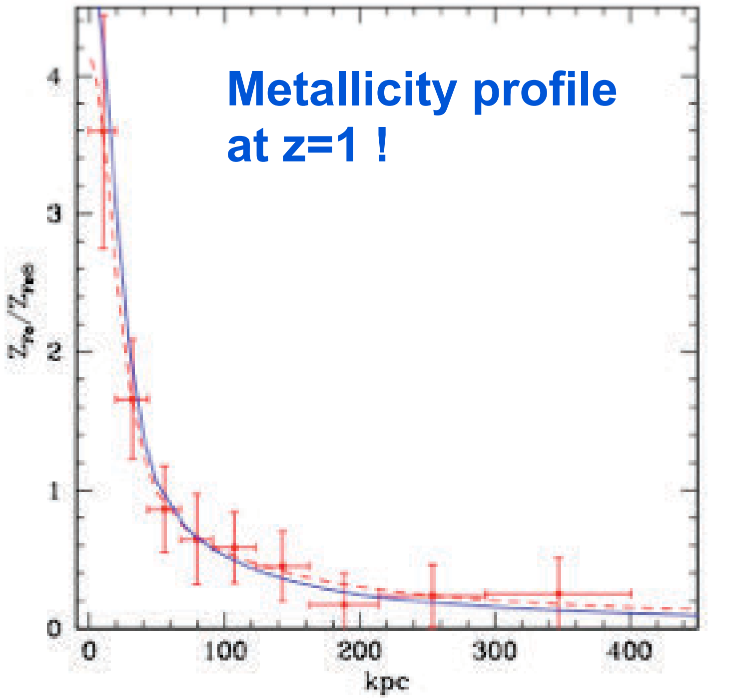


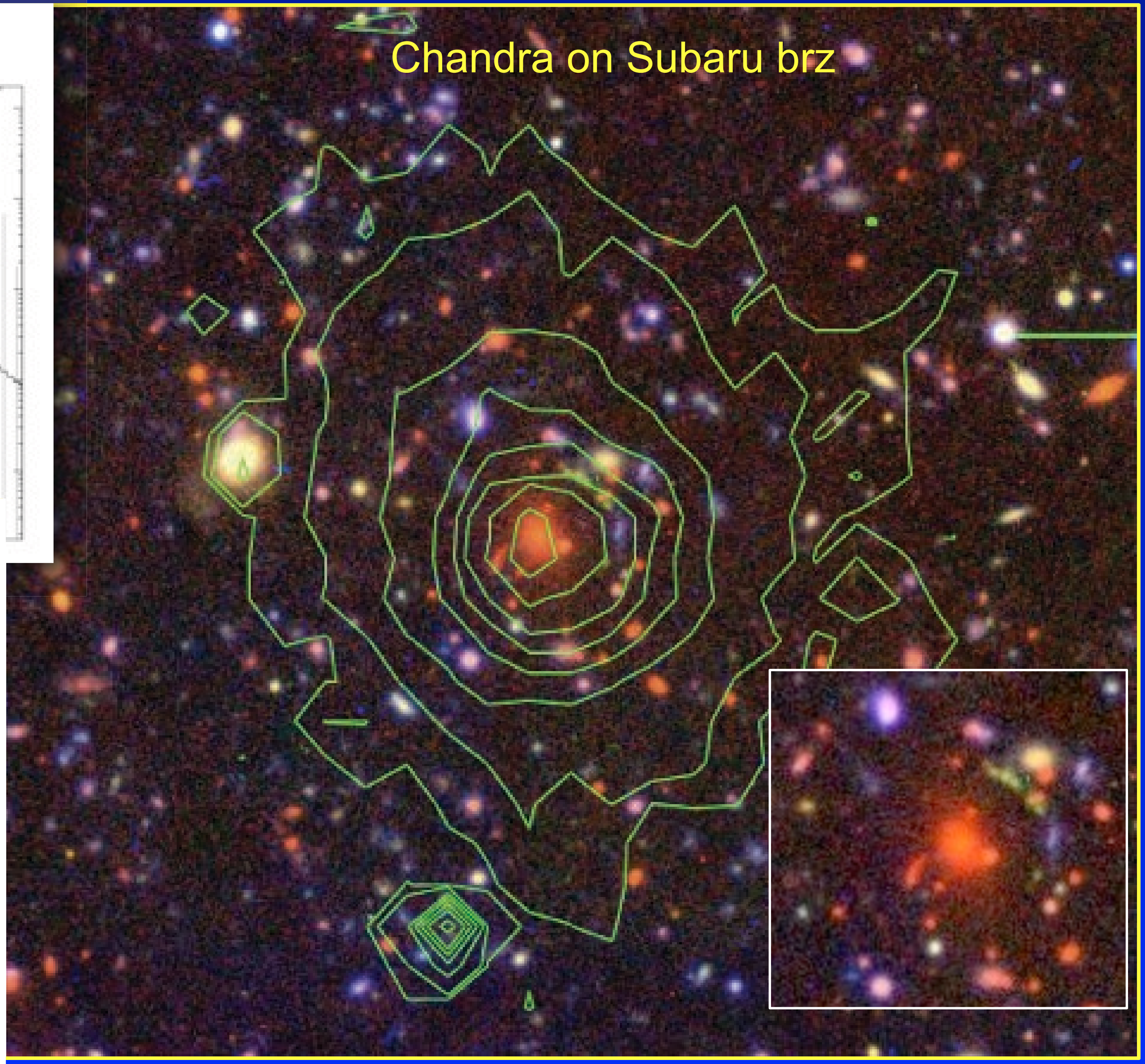
- ICM enrichment complete by $T_{z=1.4}+T_{cross}$ i.e. $z\approx2.5$
- Consistent with derived SFH of ETGs

WARPSJ1415 at z=1.01 - $M_{200} \approx 5 \times 10^{14}\ M_{\odot}$

The deepest (370 ksec) Chandra observations of a z=1 cluster



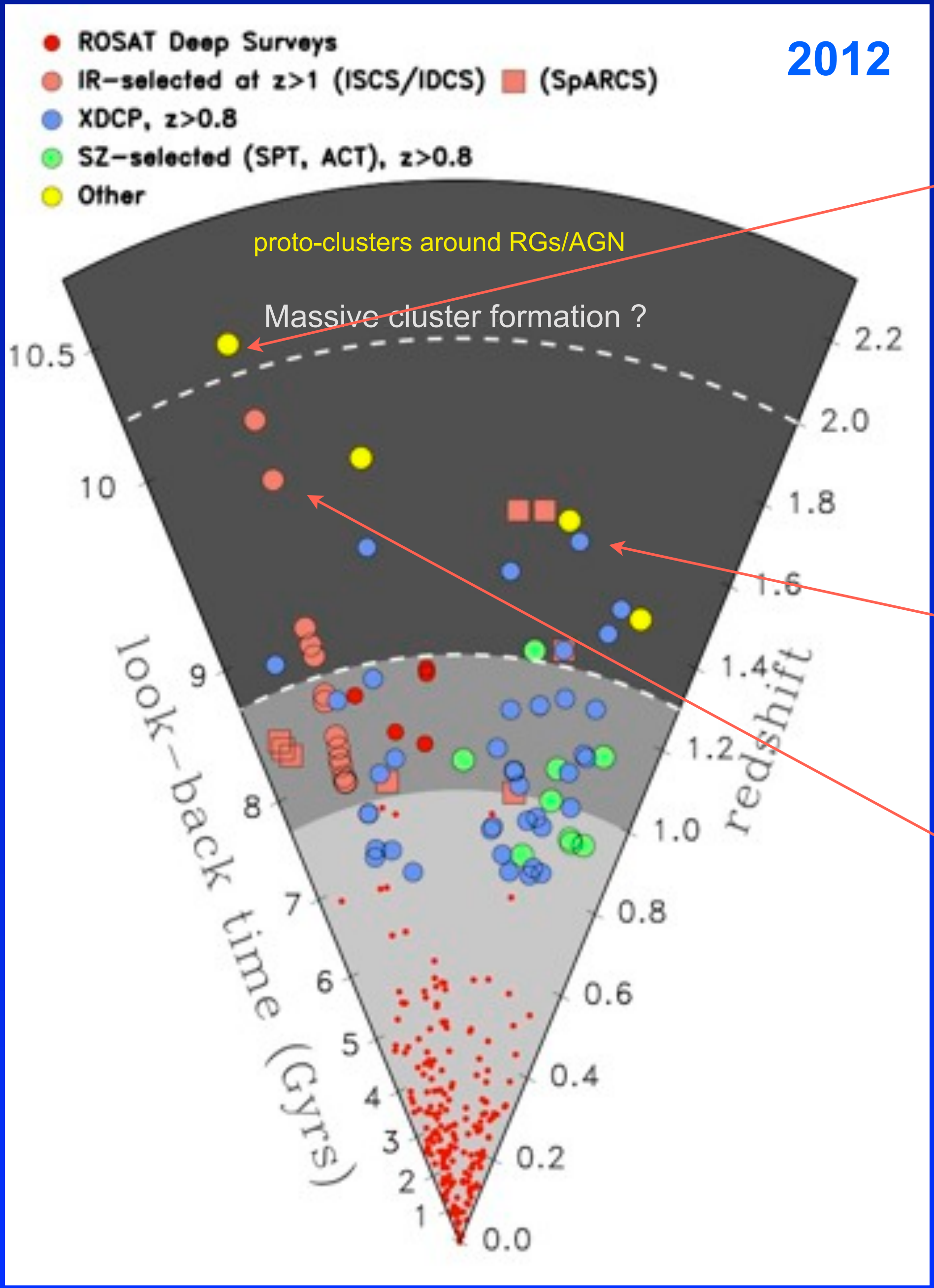


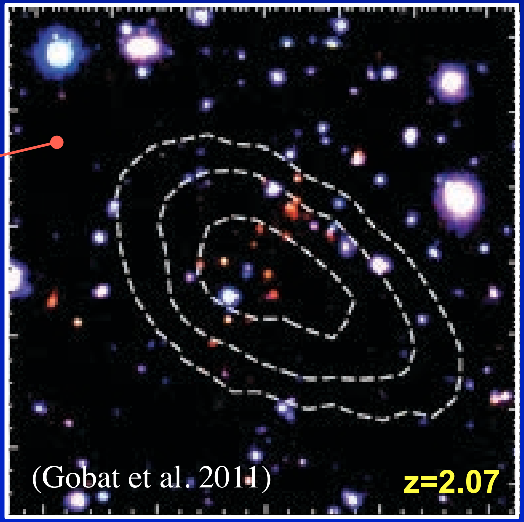


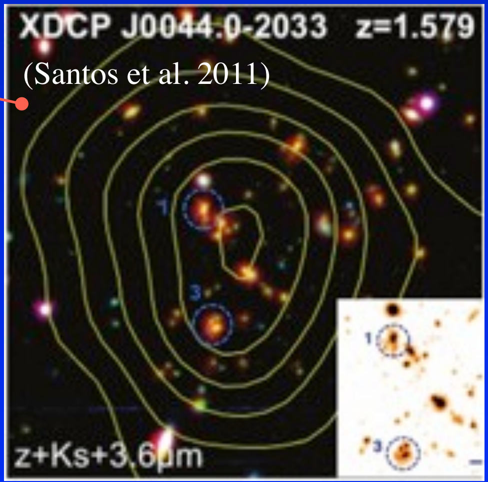
Santos al. 2011

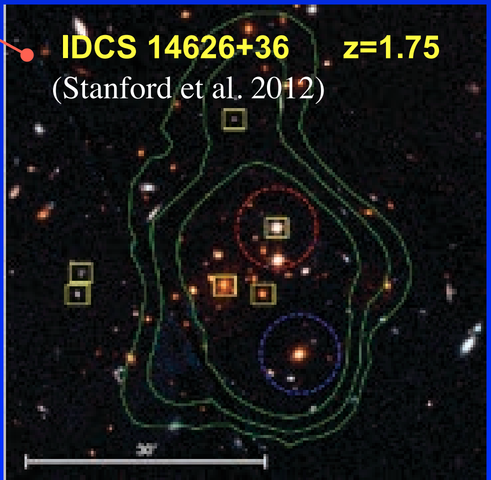
Galaxy populations in distant clusters

Clear signs (from spectro-photometry and morphology) of evolution of ETGs in high-densities at z~1.5−2 and (perhaps) enhanced AGN activity









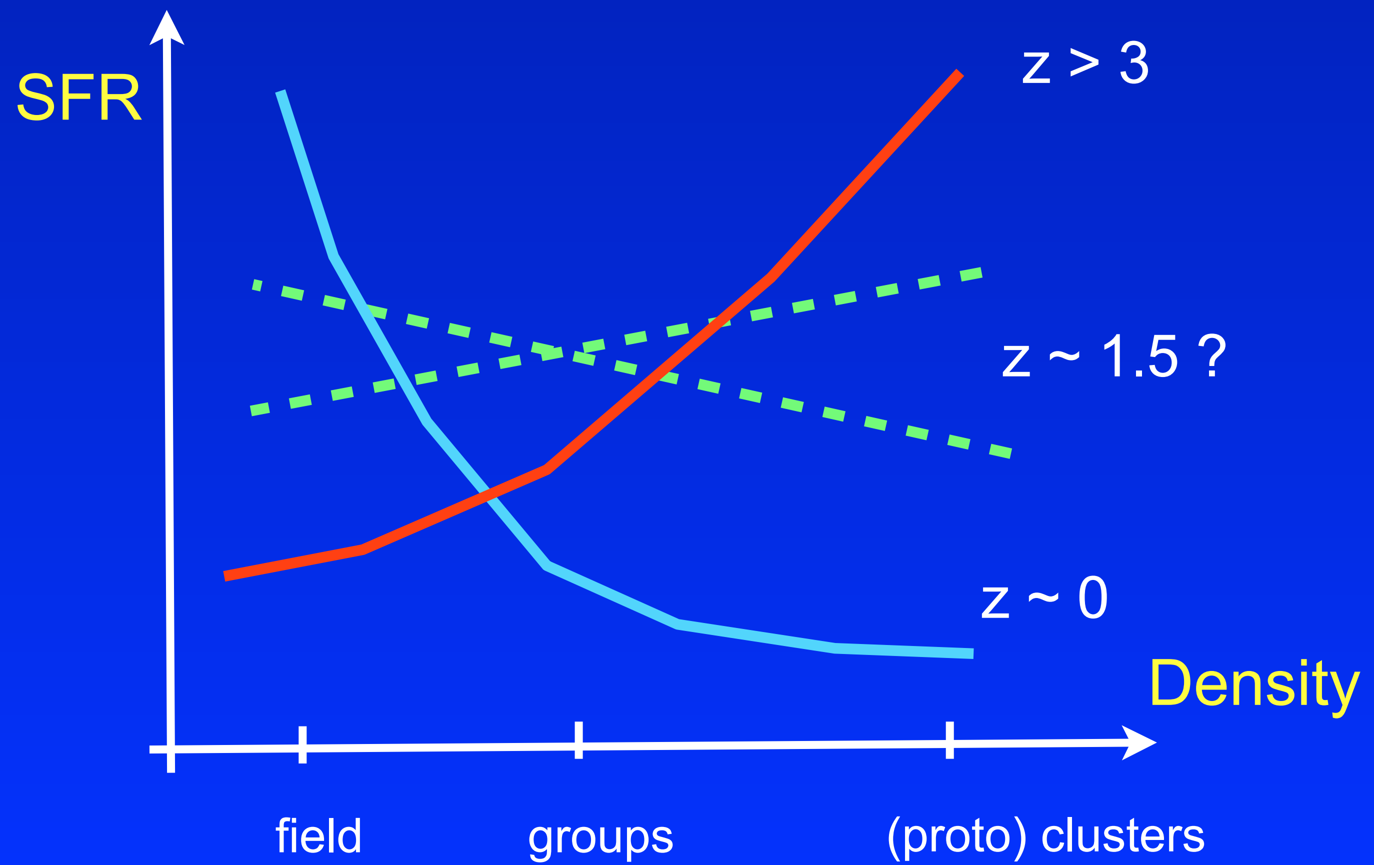
Galaxy populations in distant clusters

Identification of the epoch when massive galaxies showed the first signs of SF as a function of galaxy mass, environmental density and cluster halo mass can set tight constraints on galaxy formation models

Intermediate mass clusters at 1.5<z<2 show <u>in their cores</u> increasing (unobscured) SF, merging, disturbed morphologies

➔ solid evidence of increasing SF in high density environments at high-z

Inversion of the SFR-density relation



Elbaz et al. 2007
Saintonge et al. 2008
Hilton et al. 2010
Tran et al. 2010
Fassbender et al. 2011
Gobat et al. 2012
Brodwin et al. 2012
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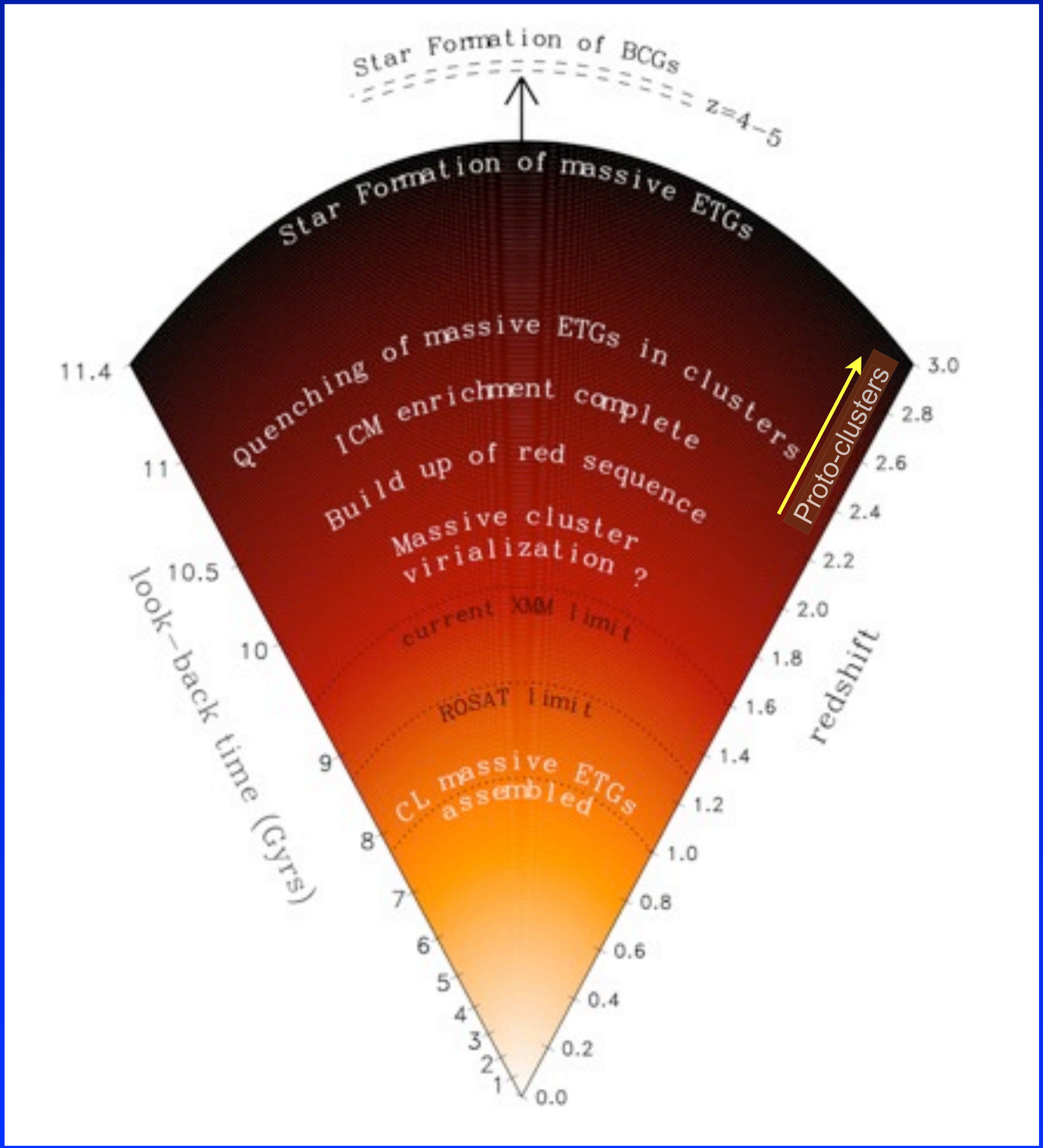
Approaching the epoch of cluster formation

Cluster baryon formation history



- **Probing Hot and Cold baryons at 1.5<z<2.5 is critical**
  - The global SF rate and the BH mass accretion rate peak at z~2
  - ≲50% of the stellar mass is assembled
  - Proto-cluster regions accrete large amount of gas and start radiating in X-ray
  - The first massive (~10^{14} $M_\odot$) virialized structures form (?)
  - The morphology-density relation and the red sequence emerge
  - Hubble morphological sequence emerged

THANKS!

THANKS!

Message to the students...

- Feel free to email me (prosati@eso.org) for questions, mistakes, references or..
  if you have a good idea about a project with the material I have shown!
- If they tell you that the "golden age of Astronomy is over", don't believe them!
  They haven't seen anything yet !
- Vast territory ahead for new discoveries: as technology is getting ahead with data volume and quality, intellectual exploitation of this goldmine will remain the main challenge