PROBING CLUSTER FORMATION FROM COSMIC NOON TO DAWN

an introductory review

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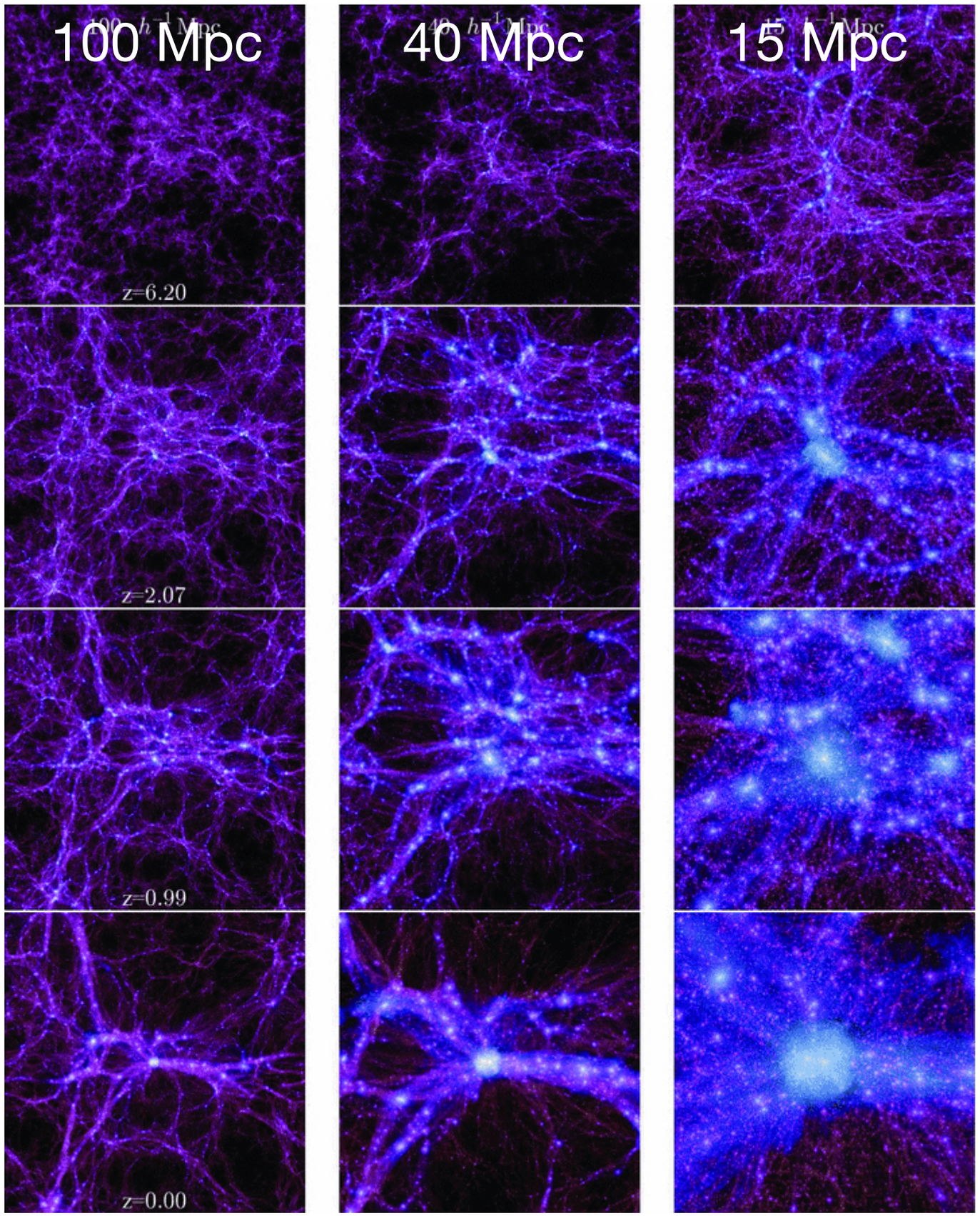
X-ray Astronomy 2019, Bologna

We are finally able to select statistical samples of galaxy clusters in their early stages of formation, extending classical research on clusters, their galaxies and SMBHs well into the epoch of reionization

Cluster formation in a ΛCDM universe



Boylan-Kolchin et al. (2012)

z > 6

- large-scale (~100 Mpc) dark matter overdensities present since before cosmic dawn

z ~ 2

- multiple centers, filamentary structure and elongated halos present at least down to z~2

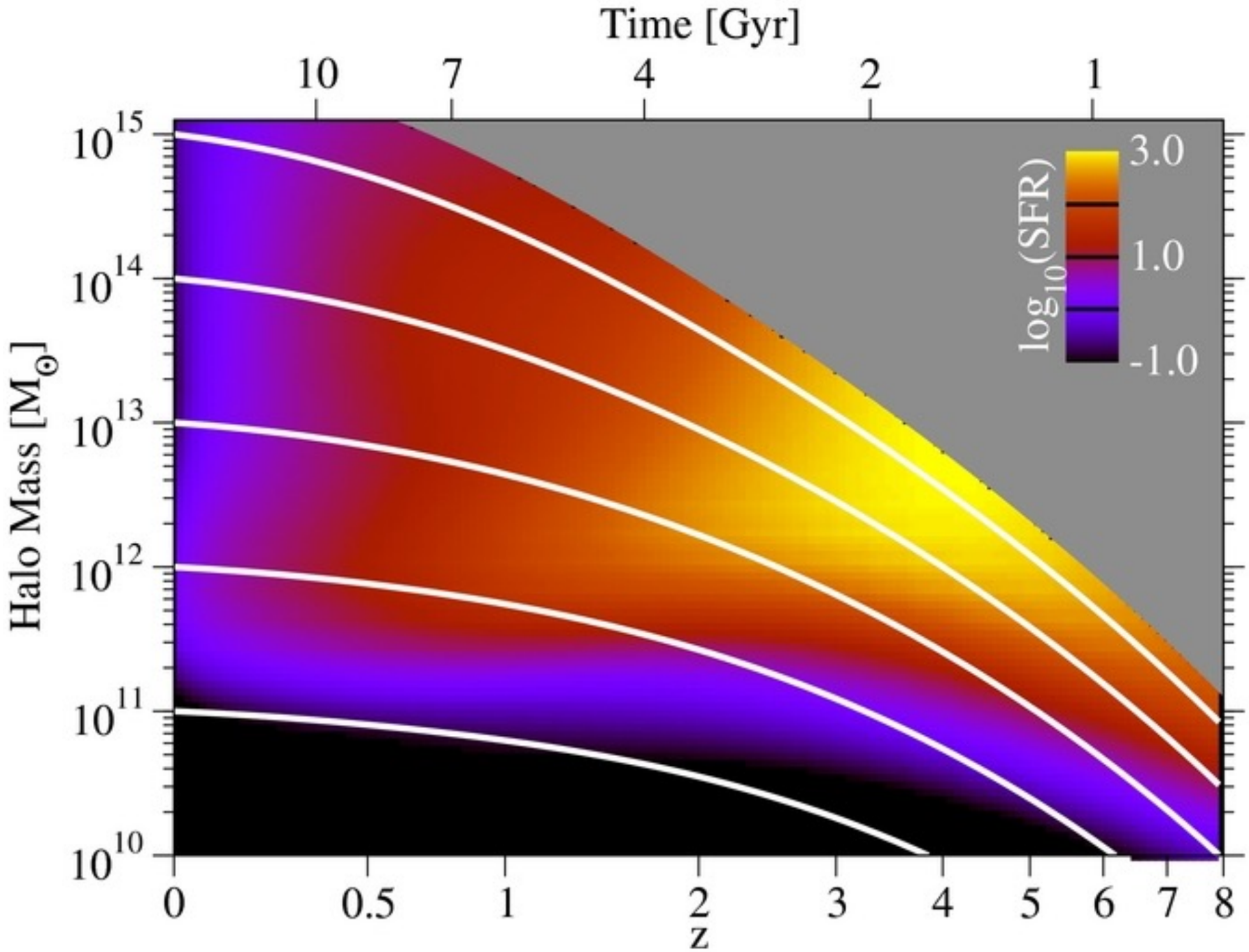
z ~ 1

- last epoch of major mergers

z ~ 0

- single cluster-sized halo surrounded by “frozen” large-scale structure at z~0

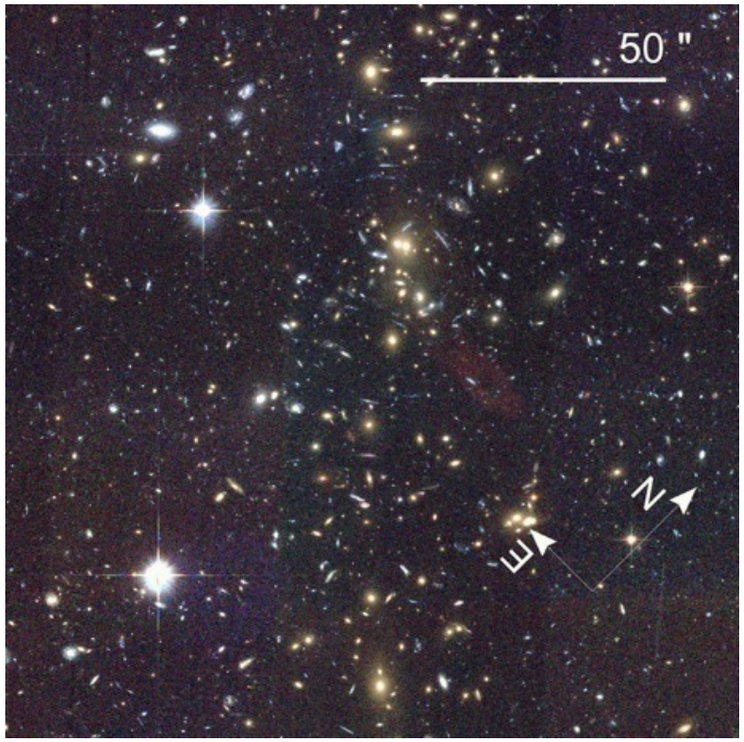
Most massive dark matter halos formed their stars *first*

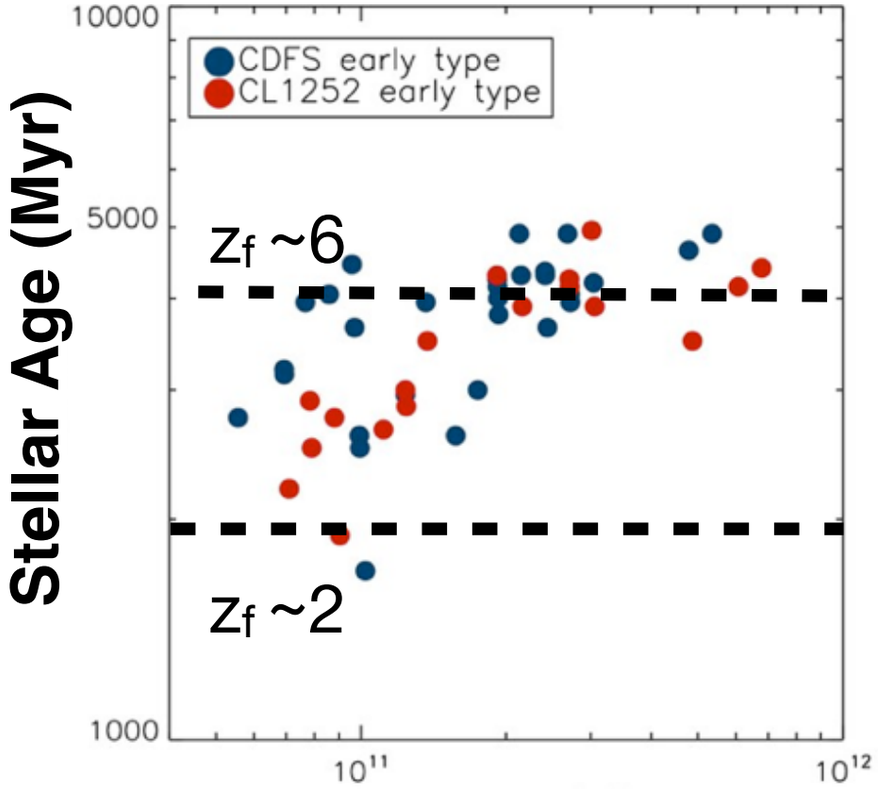


Behroozi et al. (2012)

- more massive dark matter halos formed their stars earlier
- most of the action is already over by z ~ 2 for massive clusters

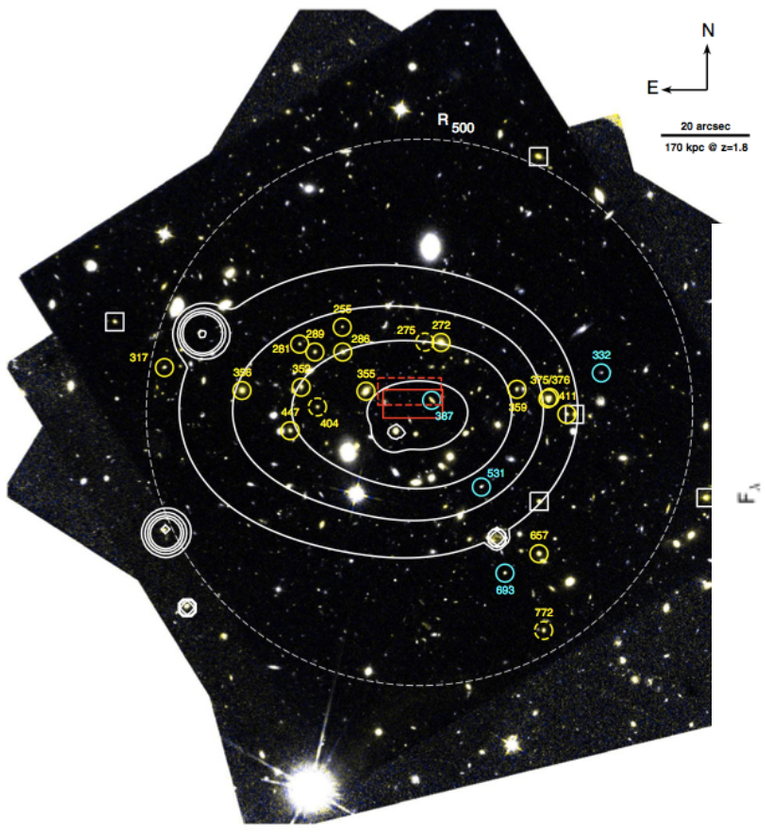
Massive dark matter halos formed their stars *first*

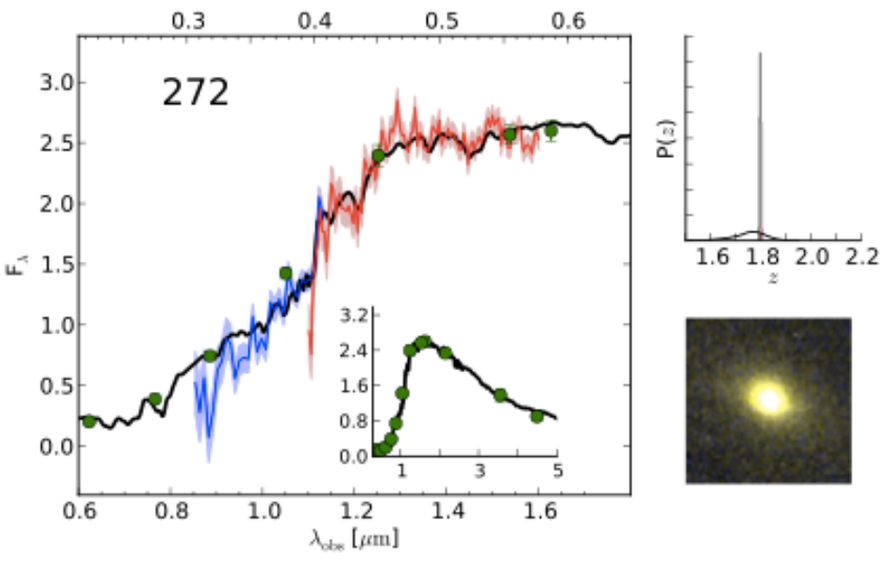


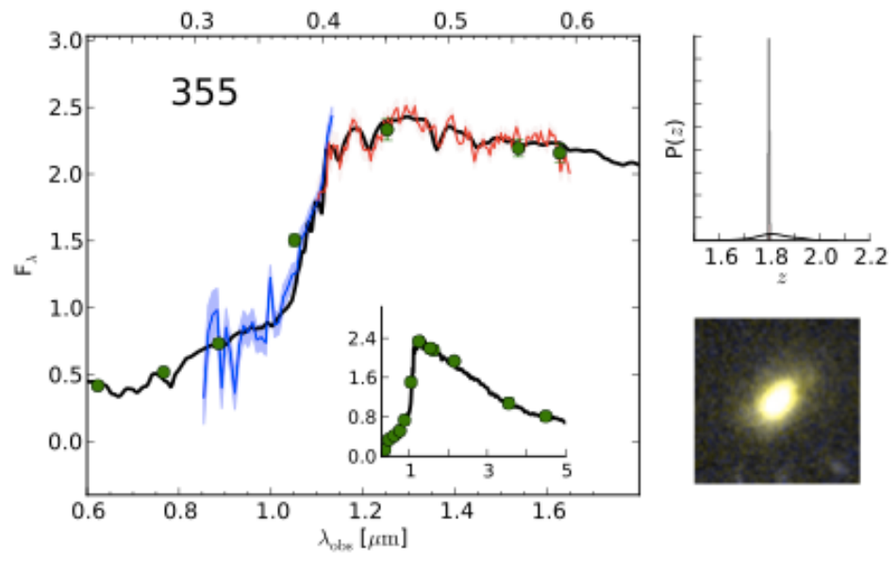


CL1252 at z = 1.24

Rettura et al. (2010)





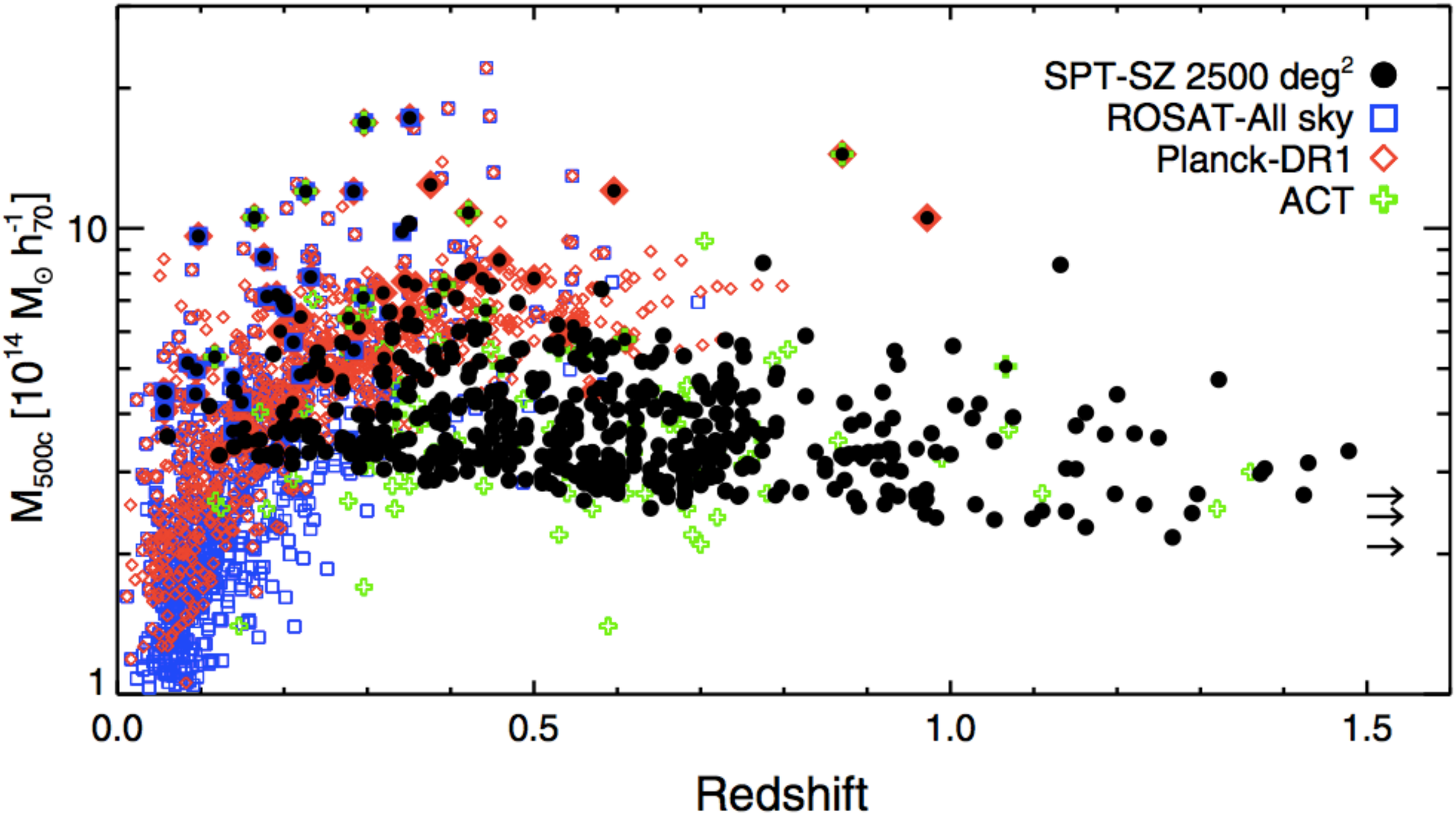


JKCS041 at z = 1.8

Newman et al. (2014)

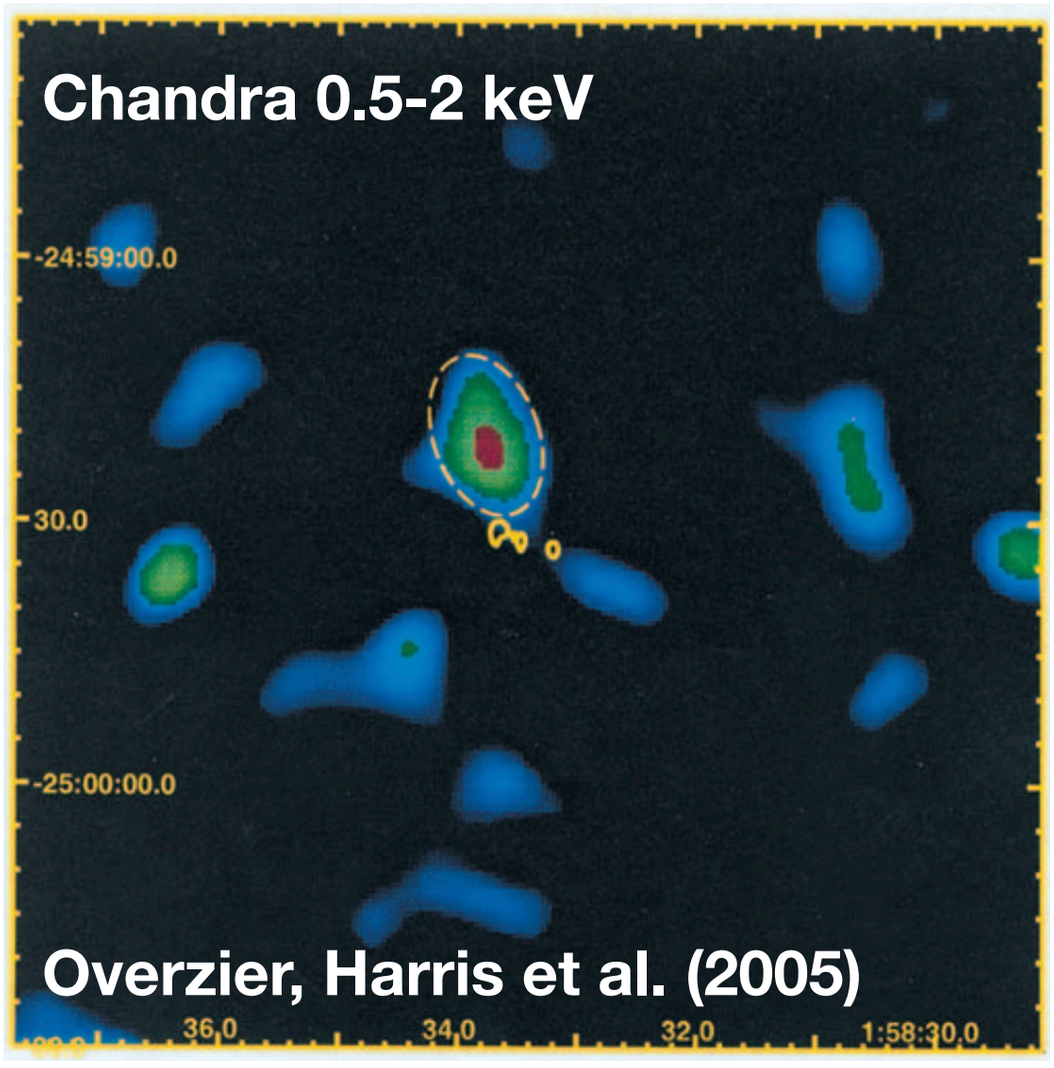
The limits of classical cluster searches

- **WL/X-ray/SZE/red sequence techniques run out of steam by z ~ 2**

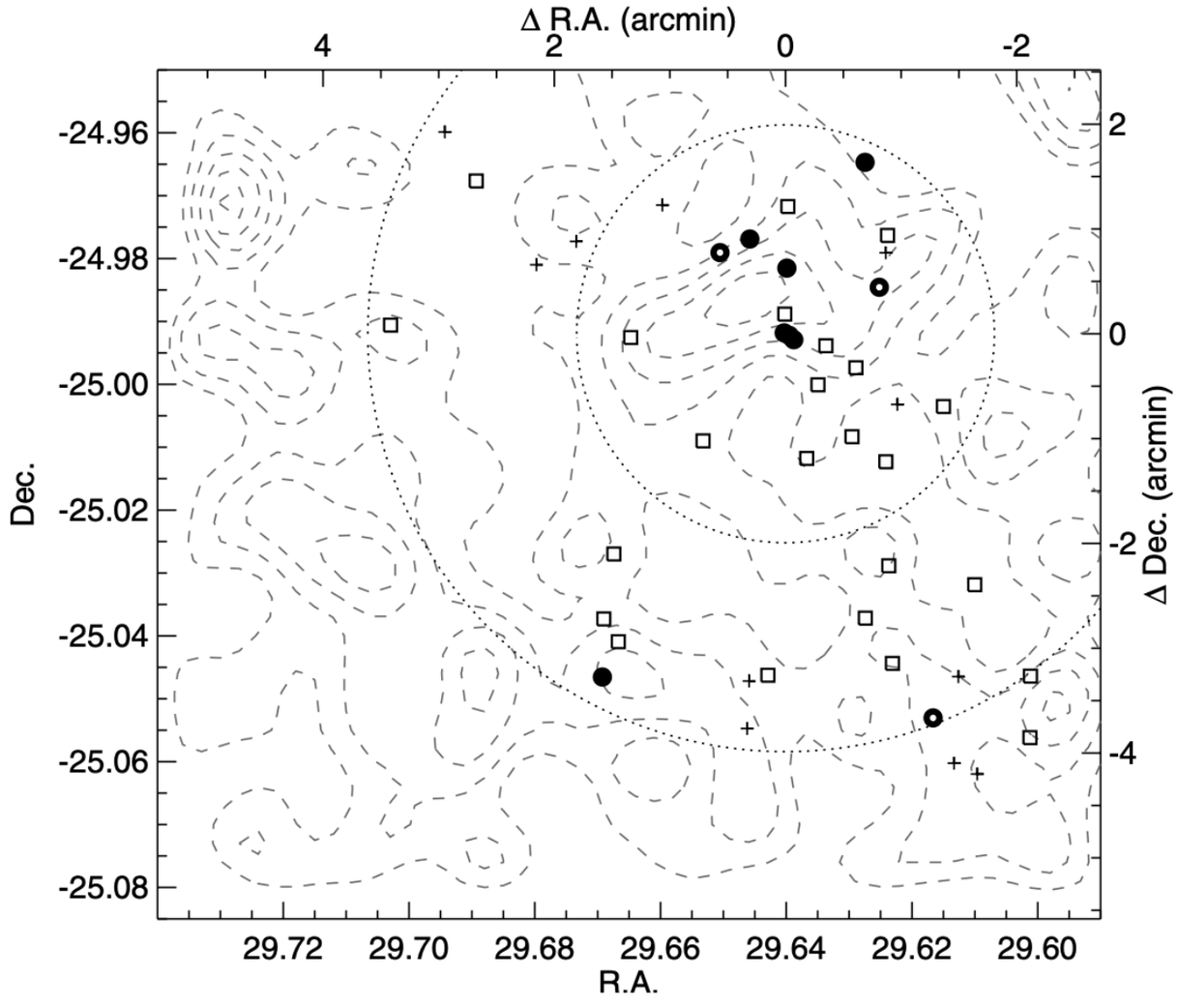


Bleem et al. (2015)

Detection of the proto-ICM in X-rays at z > 2 ?



Almost a decade later, a moderately rich (proto)-cluster was found at this approximate location:

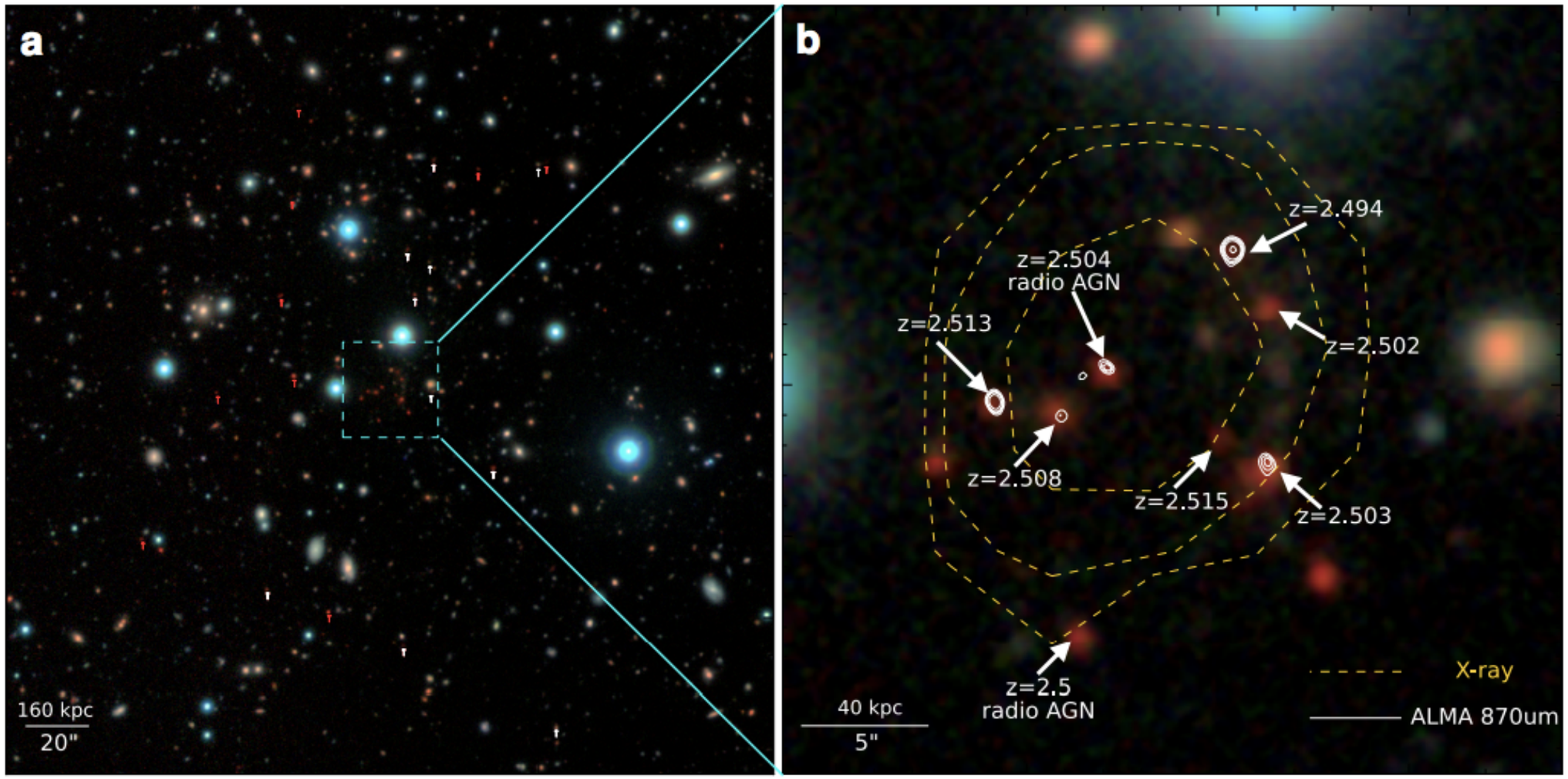


Galametz et al. (2013)

Dan Harris
(1934–2015)

80 × 140 kpc "egg" of ~7 × 10^{43} erg s^{-1} near radio galaxy MRC 0156–252 at z = 2.02

Most distant X-ray detected *cluster* at z = 2.506 ?



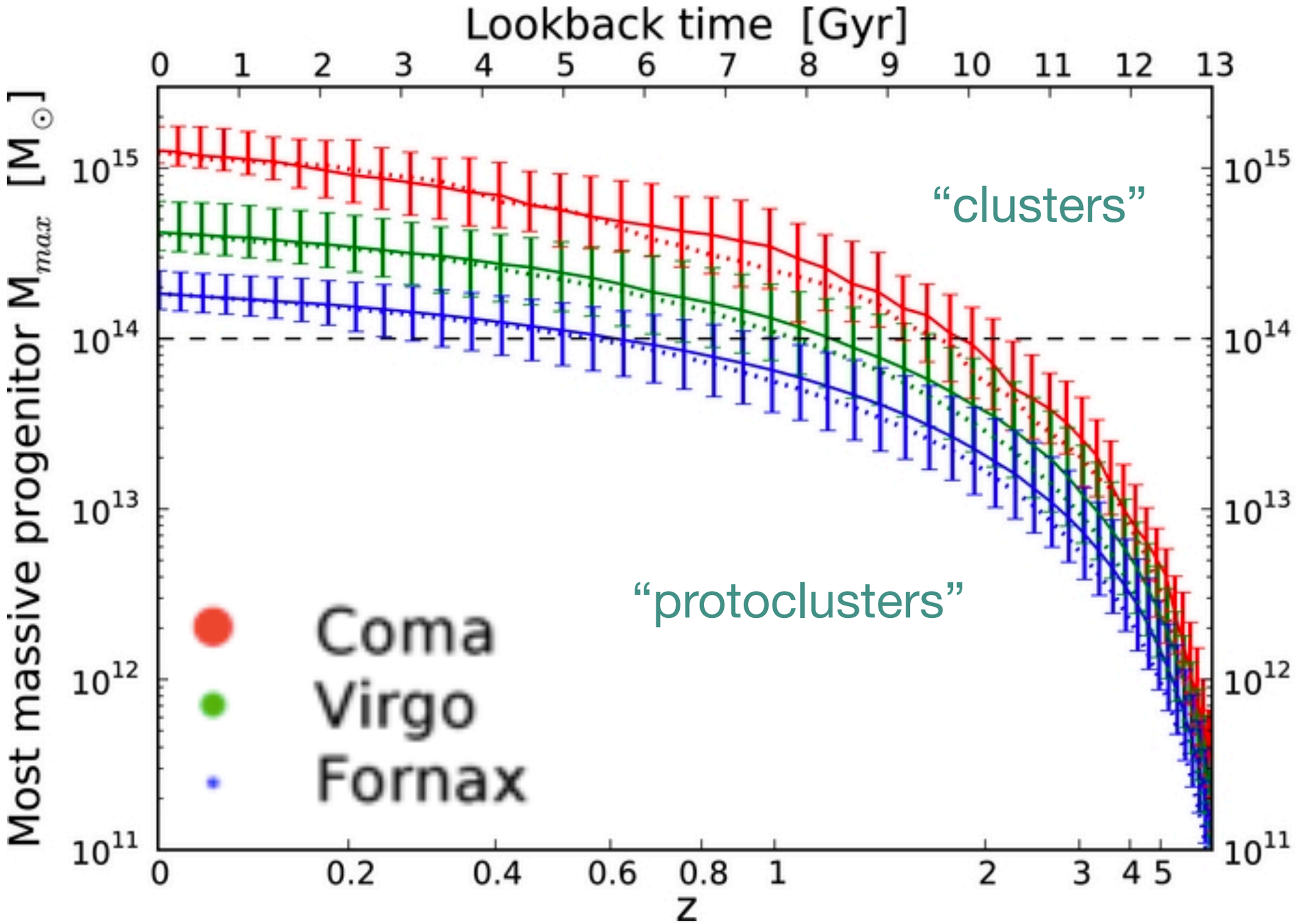
Chiang et al. (2014)

Wang et al. (2016)

- candidate in our photo-z sample of “Coma”-type protoclusters in COSMOS
- Chandra+XMM detection of $L_{0.1\text{-}2} \sim 9\times10^{43}$ erg s^{-1} ; $R_{500c} \sim 185$ kpc at z = 2.5
- velocity dispersion, L_X and stellar mass all point to log $M/M_\odot \approx 13.9 \pm 0.2$
- beware of the (radio) AGN

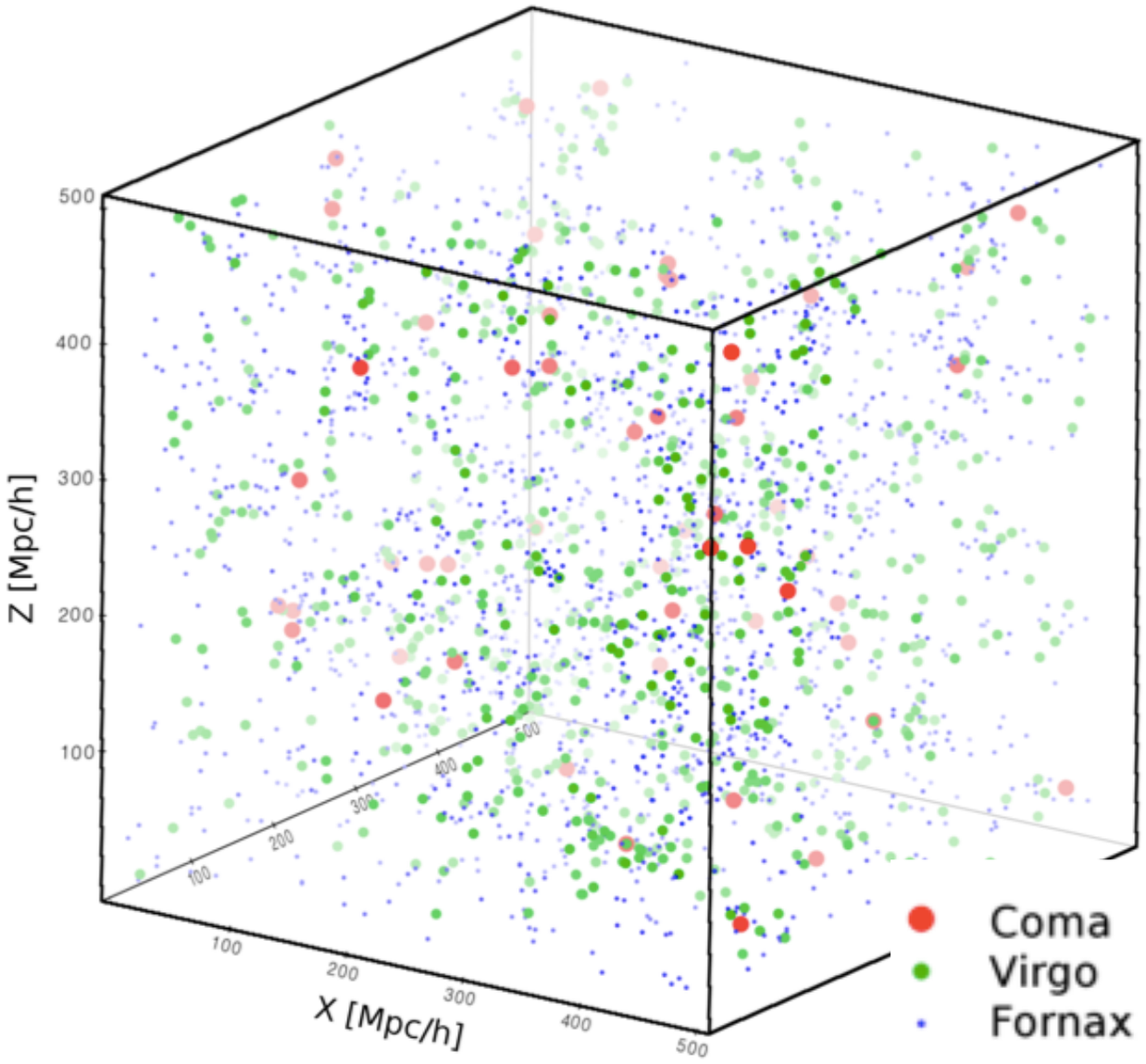
Appearance of the first virialized clusters by z ~ 2

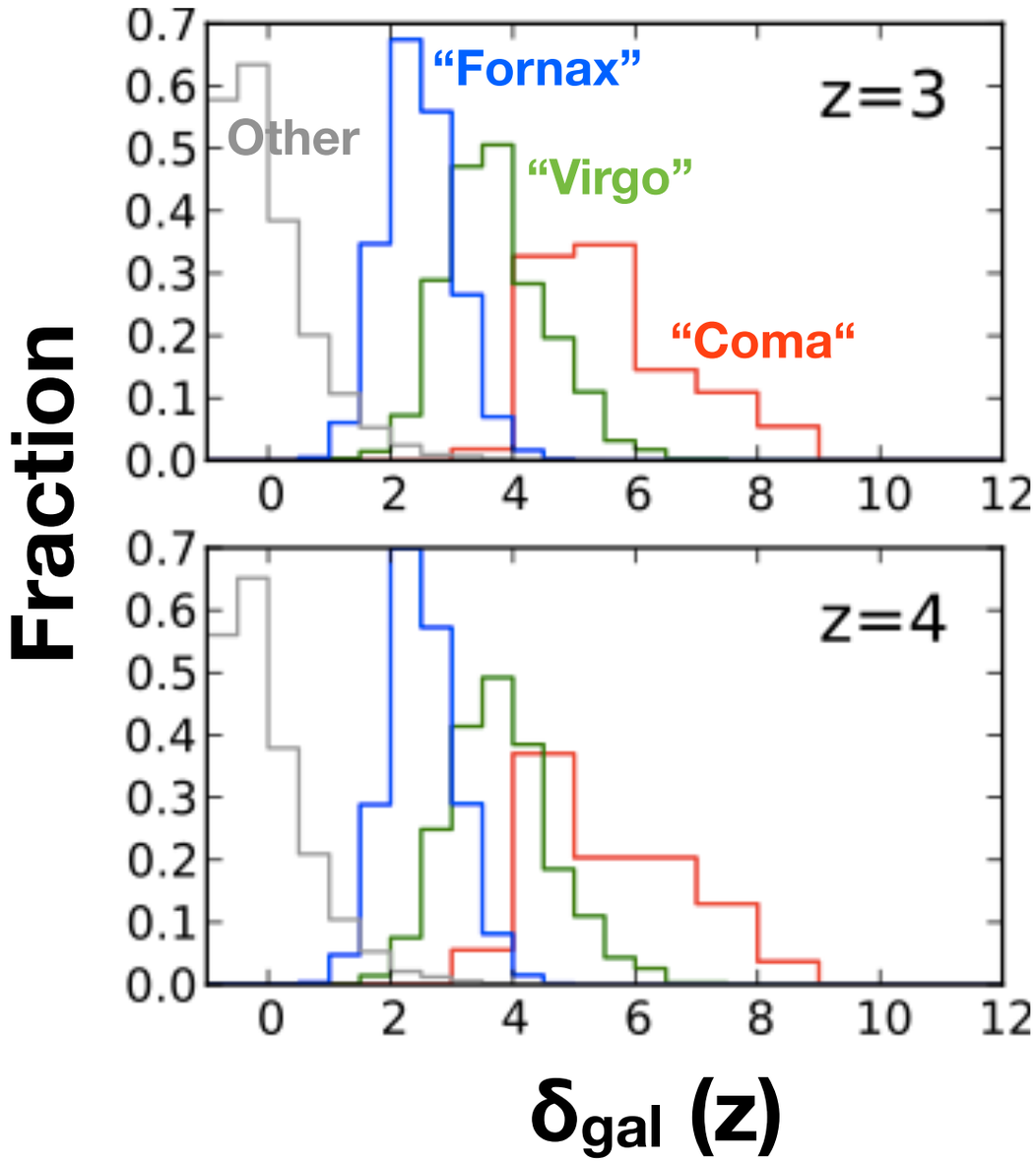
- **a typical "proto-Coma" first passes the ~10^{14} $M_\odot$ threshold at z ~ 2**



Chiang, Overzier & Gebhardt (2013)

Selection of collapsing clusters at z > 2 in ΛCDM simulations



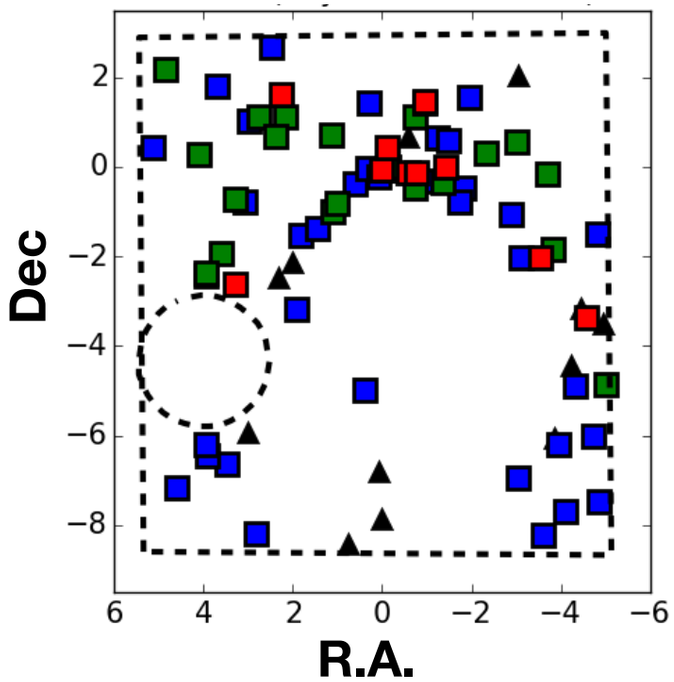


- higher mass clusters today generally came from larger overdensities
- larger overdensities have low contamination (but high incompleteness)
- we can even estimate present-day cluster mass from δ_{gal} at z ~ 2—6

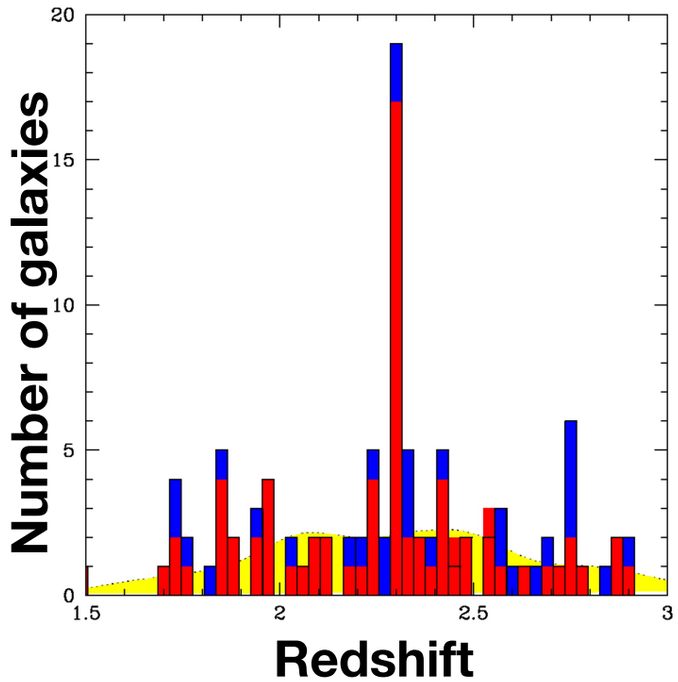
Chiang, Overzier & Gebhardt (2013)

1995—2016: about 30 of such “protoclusters” at z ≈ 2—6

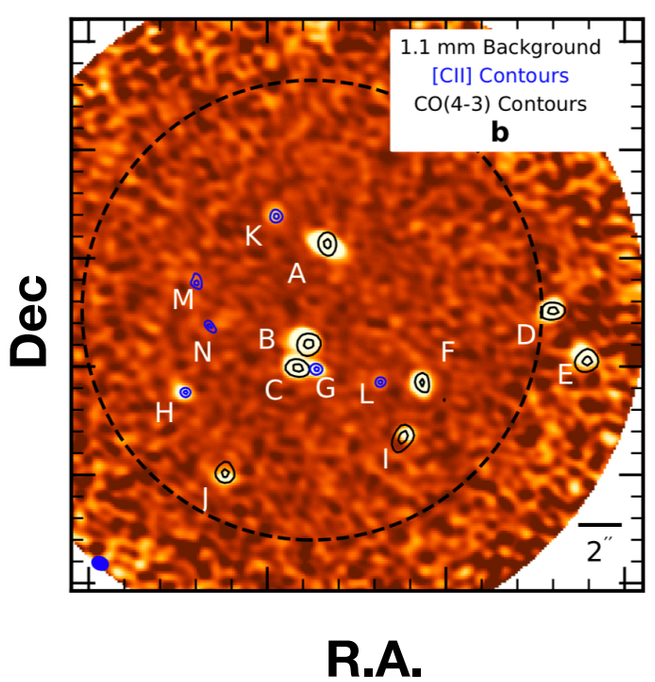
z = 2.16



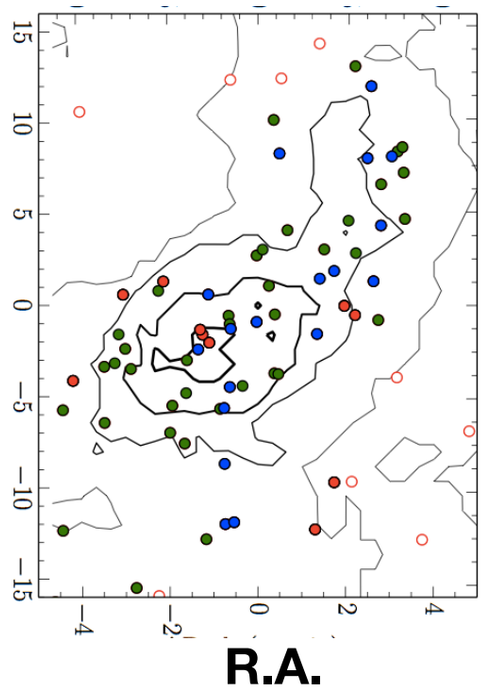
z = 2.30

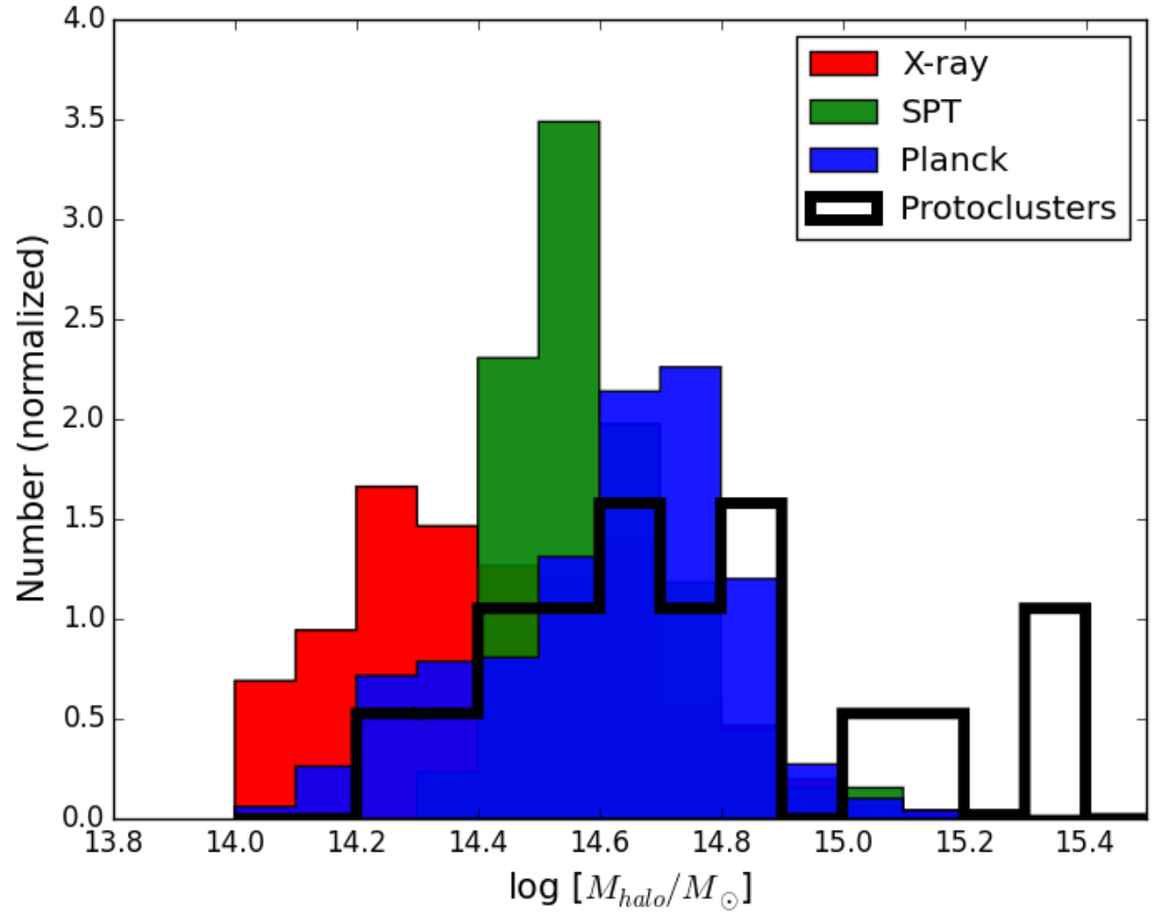


z = 4.3



z = 6.01





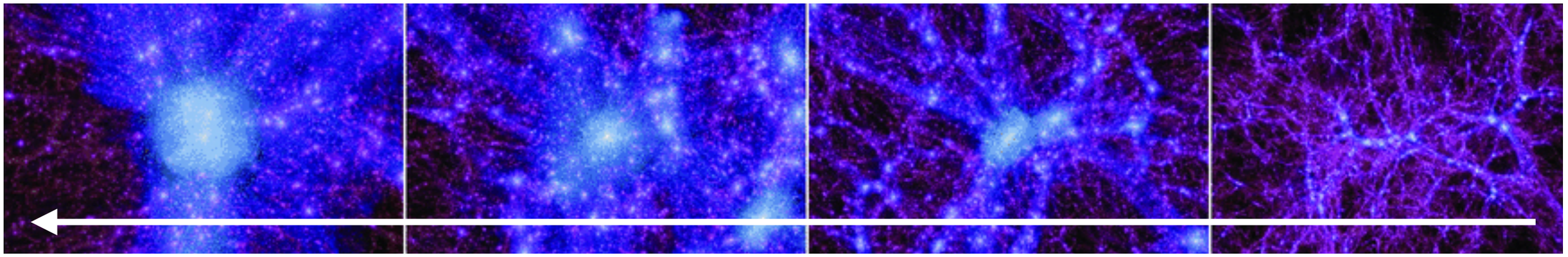
Koyama+13 Steidel+05 Miller+18 Toshikawa+14

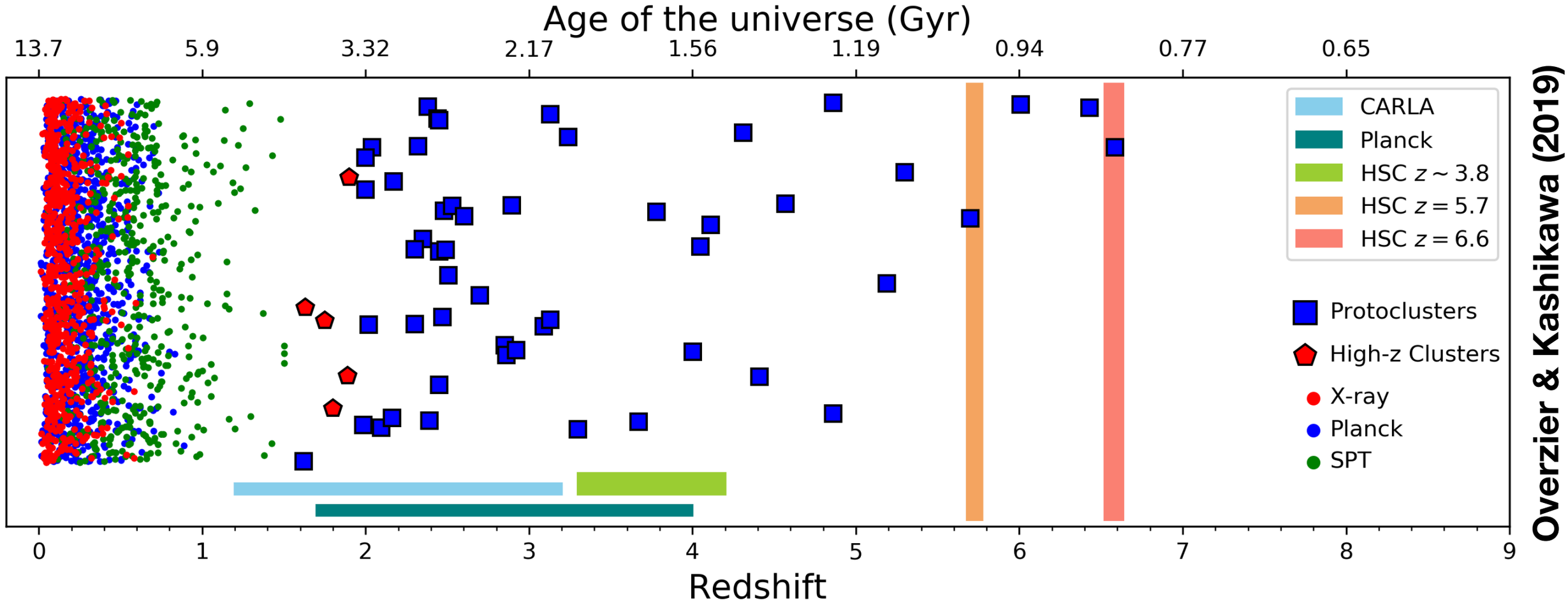
- satisfy the properties expected for the protocluster stage of the massive red-sequence/X-ray/SPT/Planck selected clusters found at z < 1.5

- but found in a multitude of ways, making comparisons very difficult

Overzier (2016)

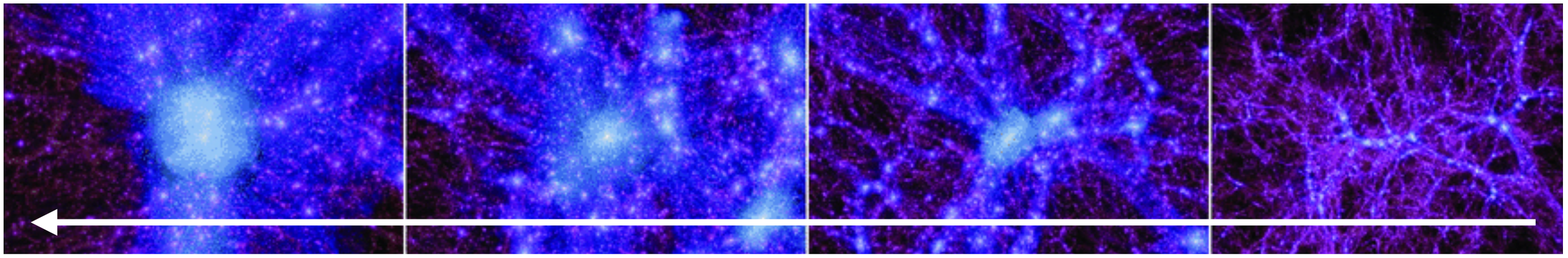
From *butterfly collecting* to *evolutionary biology*…

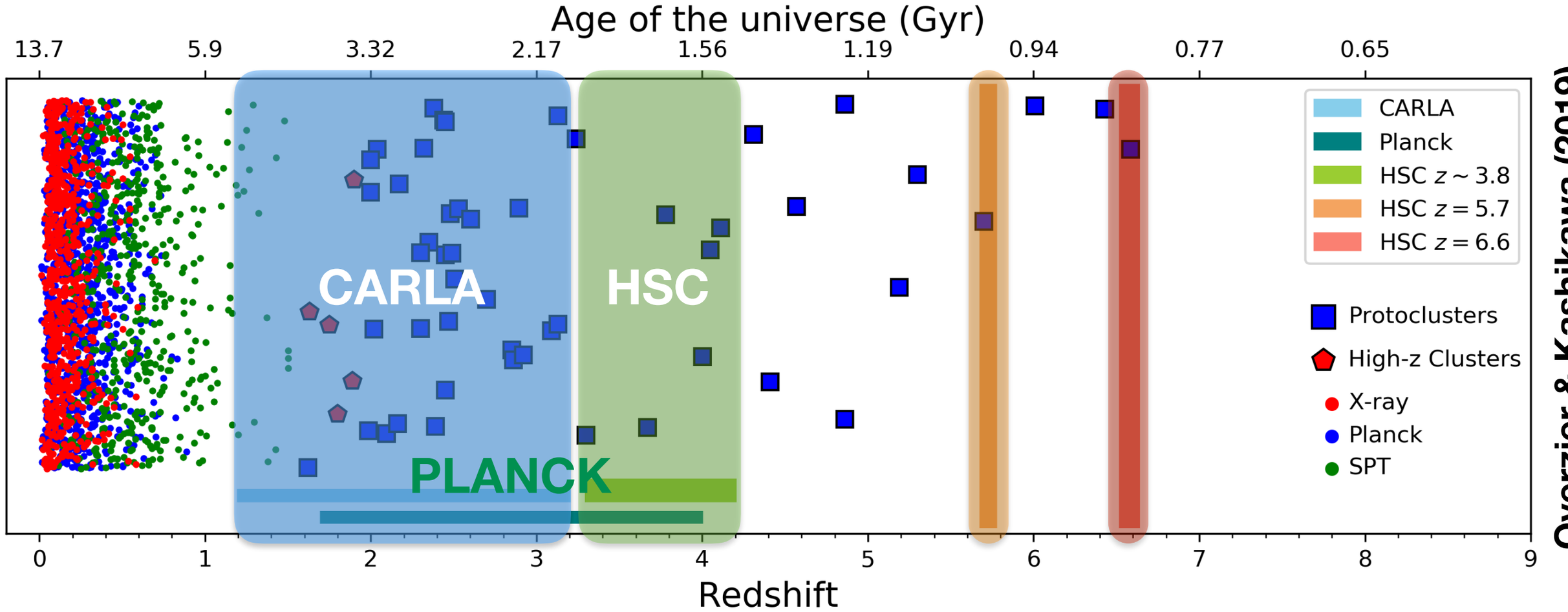




- now hundreds of systems owing to the large mapping speed on large telescopes
- classical field of galaxy clusters transitioning into “proto-clusters”

From *butterfly collecting* to *evolutionary biology*…

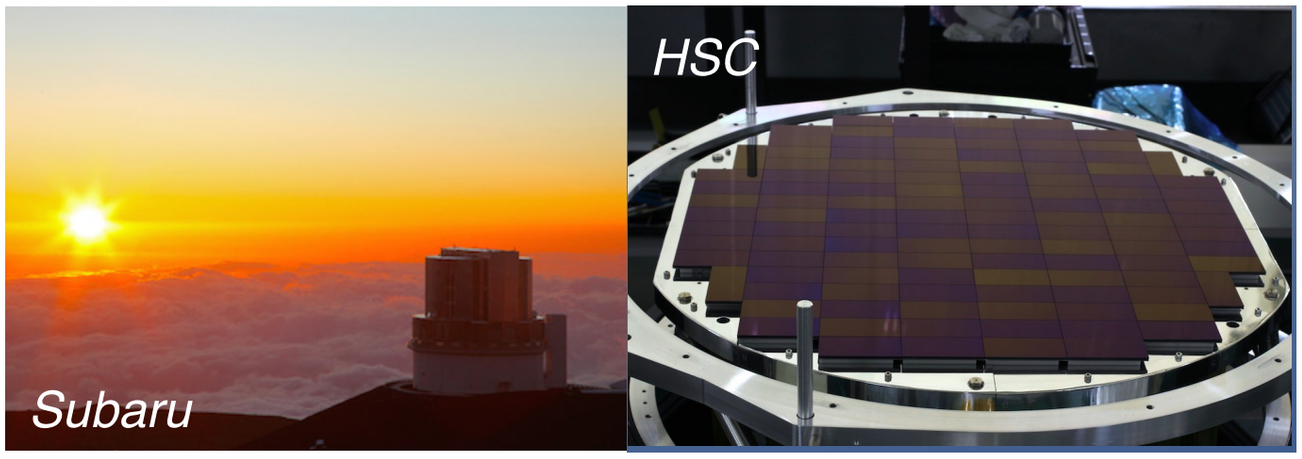




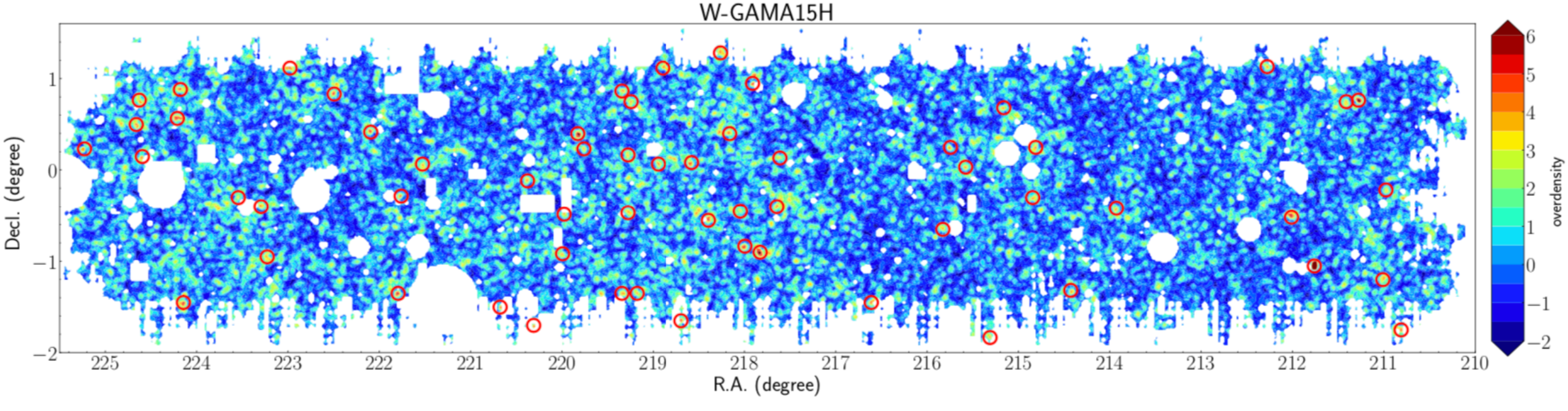
- now hundreds of systems owing to the large mapping speed on large telescopes
- classical field of galaxy clusters transitioning into “proto-clusters”

Subaru HyperSuprimeCam SSP: ~200 protoclusters at z~4

- first 10% of 1500 deg² Wide survey completed: **1 million z ~ 4 galaxies**
- ideal for rare density peaks (protoclusters)
- we already found **~200 reliable candidate proto-clusters**



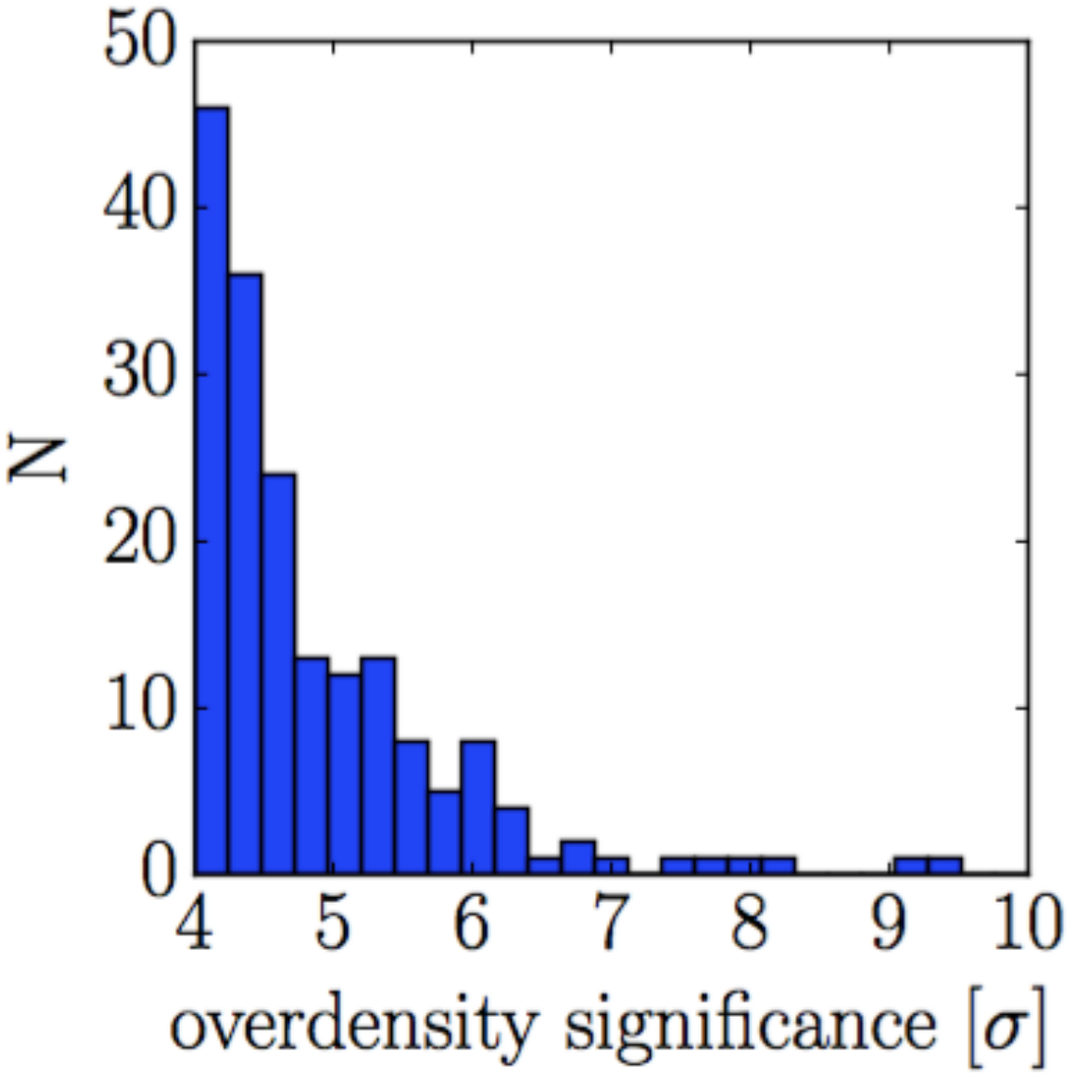
Uchiyama et al. (2018)
Toshikawa et al. (2018)
Onoue et al. (2017)
Higuchi et al. (2019)
Overzier & Kashikawa (2019)

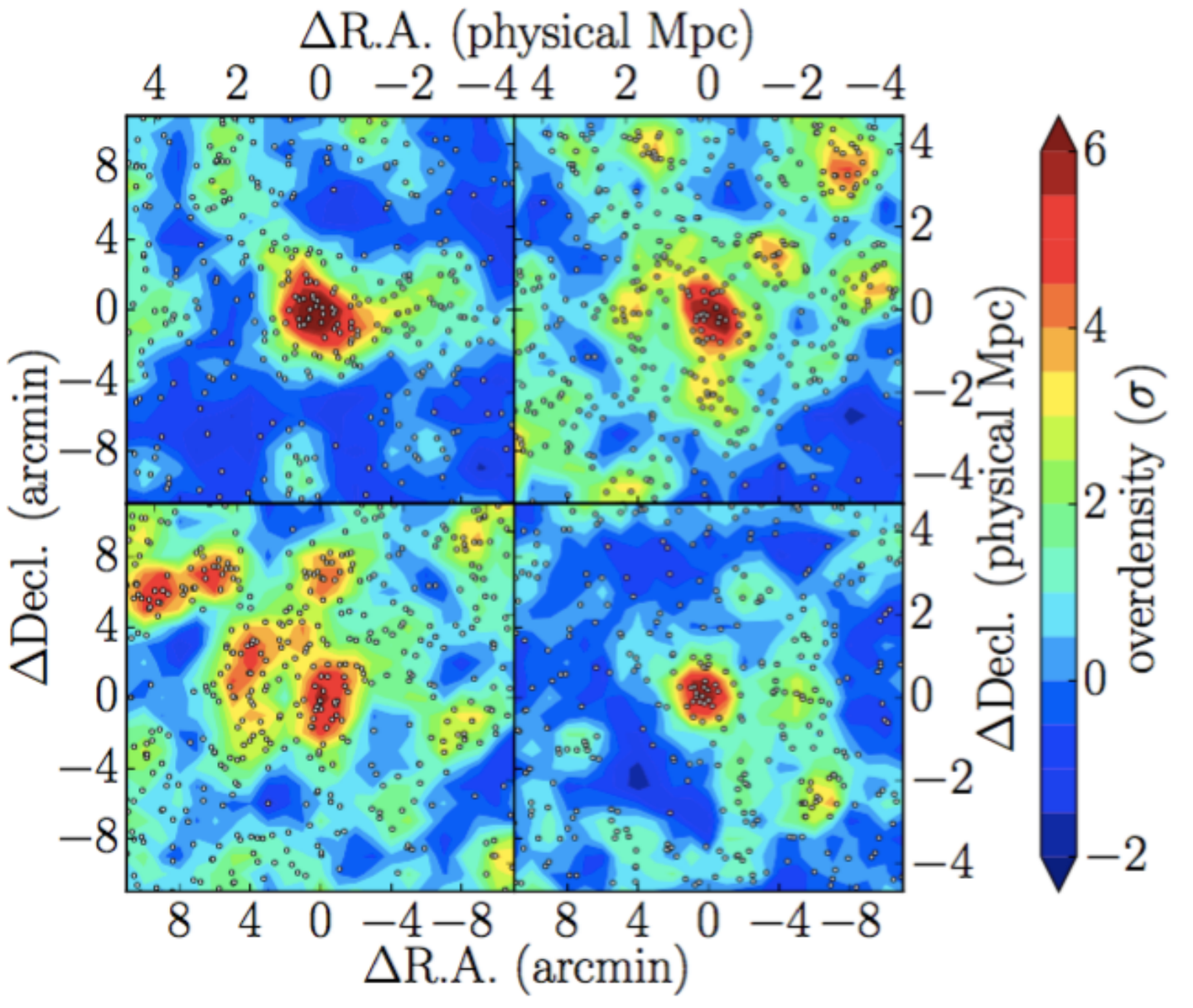


Subaru HyperSuprimeCam SSP: ~200 protoclusters at z~4

- **selection of all >4σ overdensities of z ~ 4 LBGs (g-dropouts)**
- ~80% of these will be **genuine "protoclusters" of $\langle M_h \rangle \sim 5\times10^{14}\ M_\odot$**

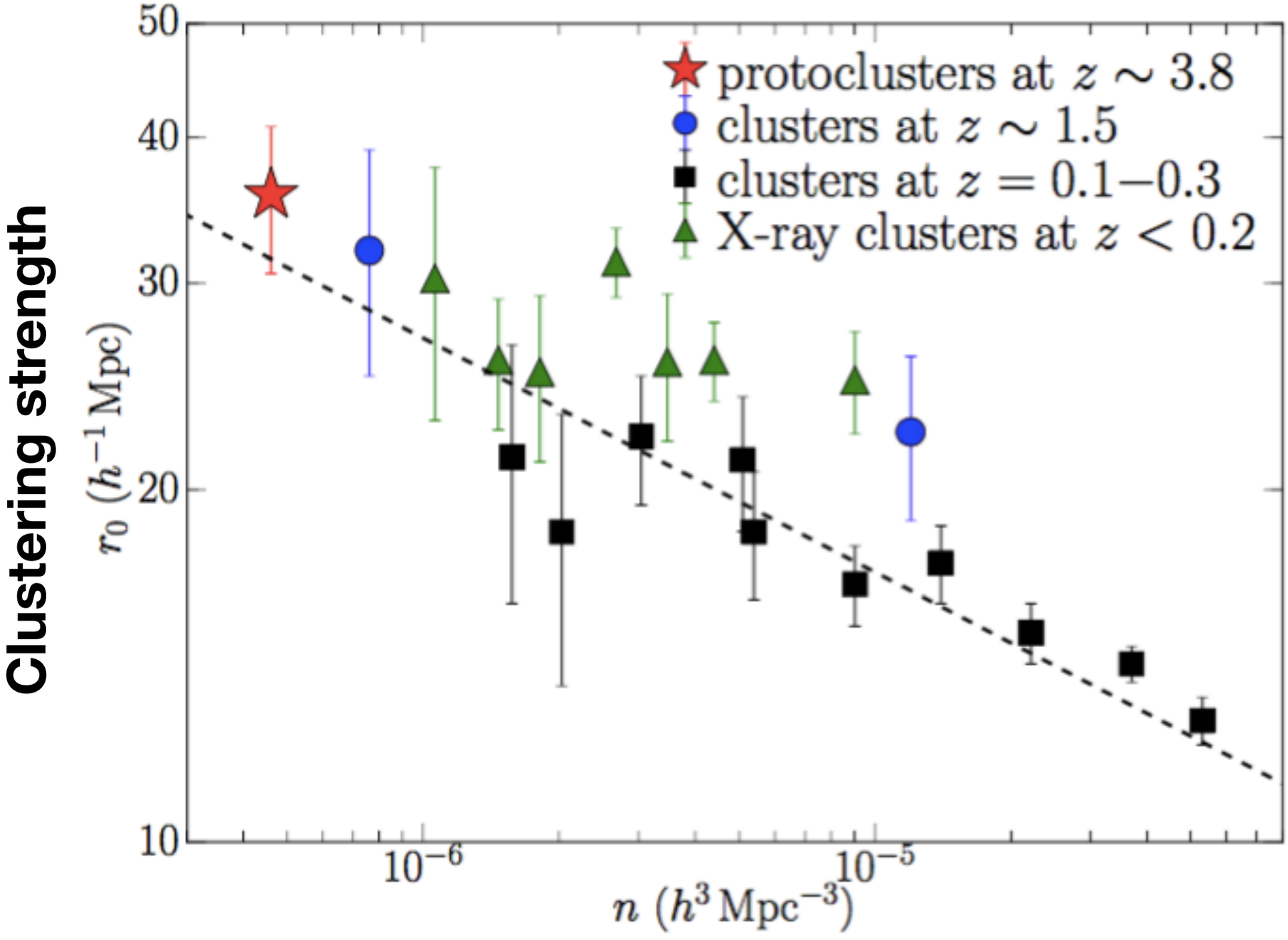
Toshikawa et al. (2018):





- spectroscopic follow-up **has become a huge problem** with 200 candidates, will require VLT/MOONS, Subaru/PFS, etc.

Subaru HyperSuprimeCam SSP: ~200 protoclusters at z~4

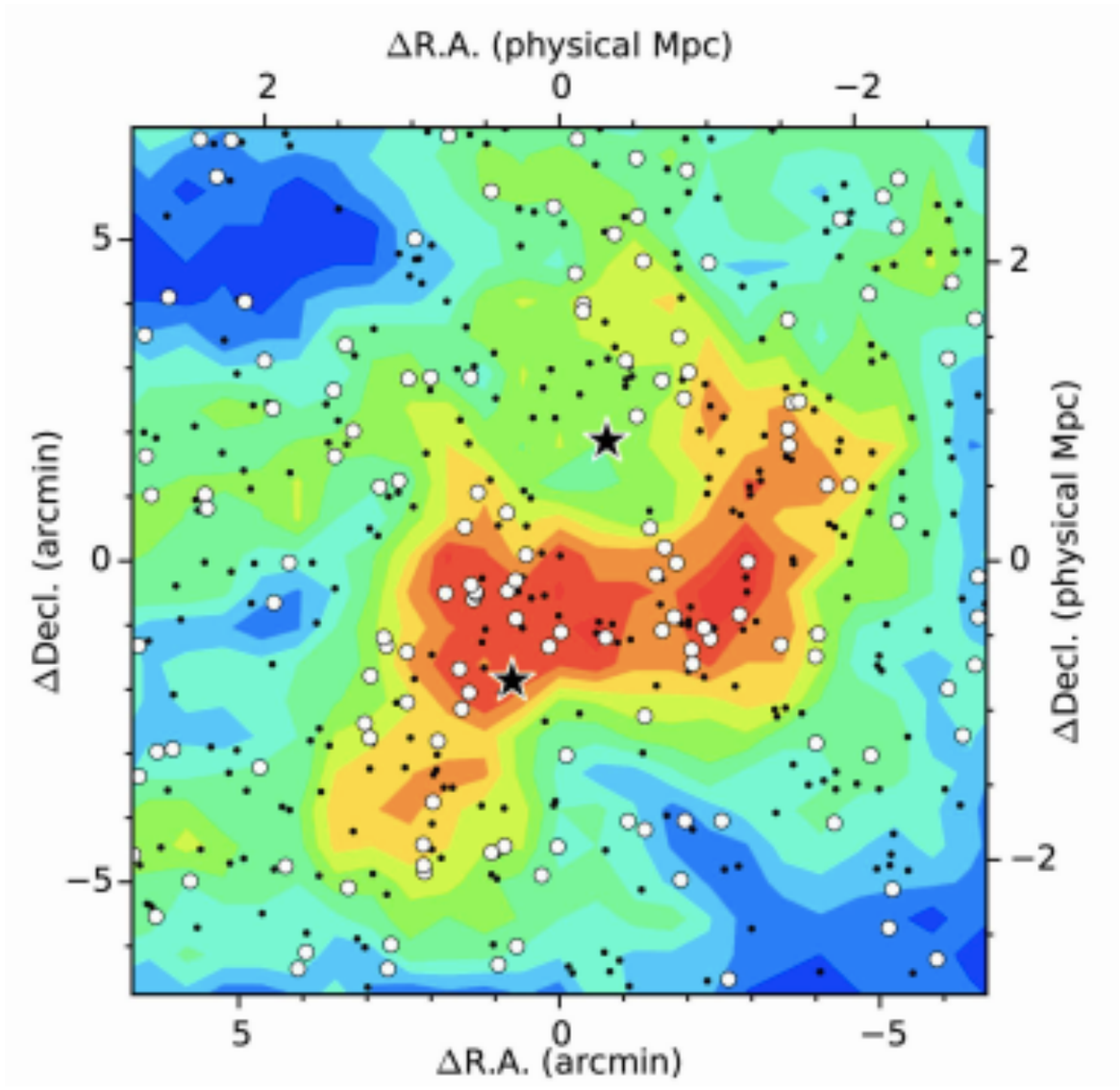


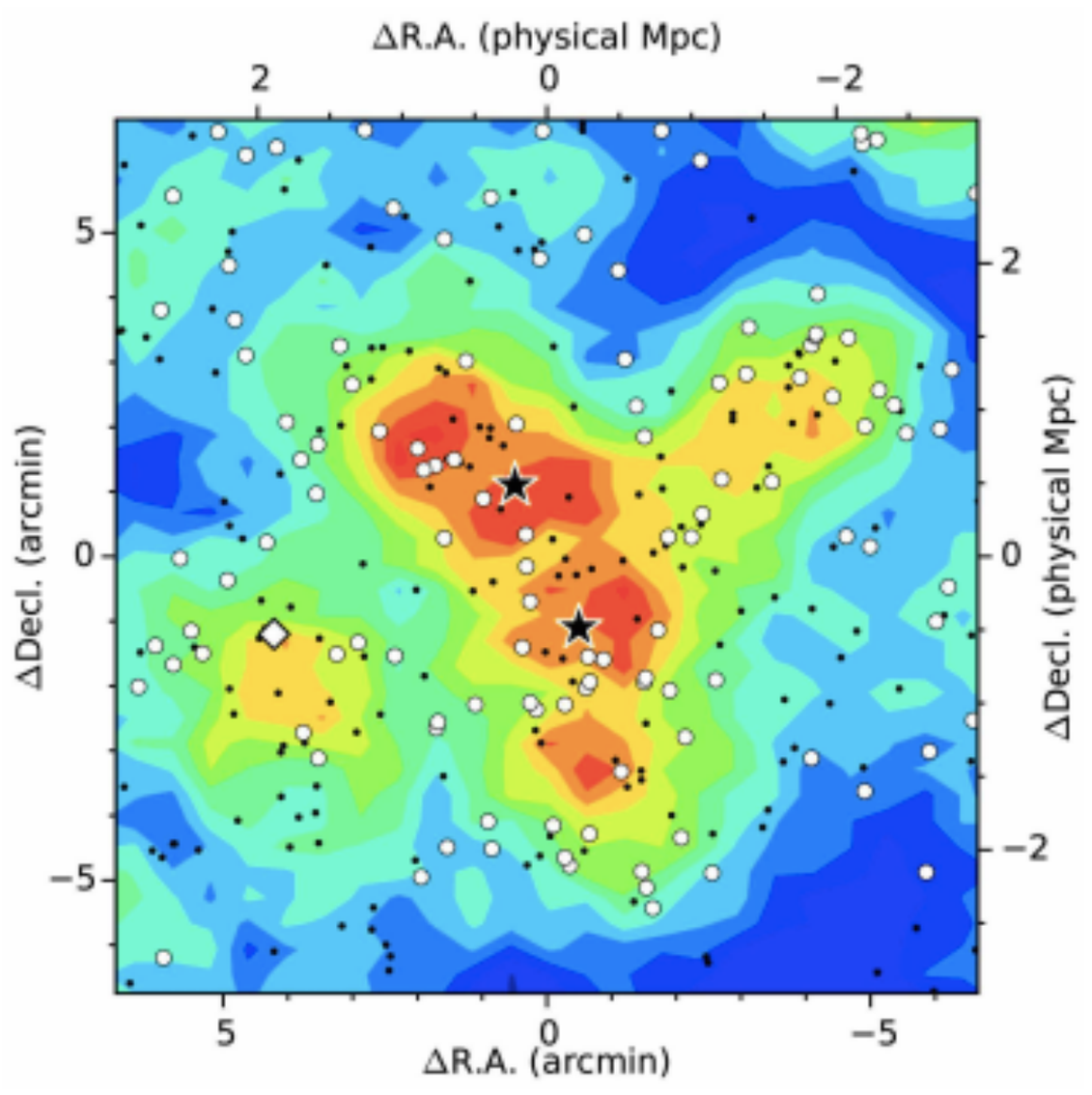
Toshikawa et al. (2018)

- correlation function of proto-clusters confirms that these must be progenitors of clusters with halo masses of $\langle M_h \rangle \sim 6.3 \times 10^{14}\ M_\odot$ today
- we are only selecting the (very massive) tip of the iceberg

Subaru HyperSuprimeCam SSP: ~200 protoclusters at z~4

- 151 luminous SDSS QSOs at z~4 versus the ~200 protoclusters in HSC-Wide
- first statistical *cross-match between protoclusters and SDSS quasars*
- at most a few % of protoclusters coincide with SDSS luminous quasars

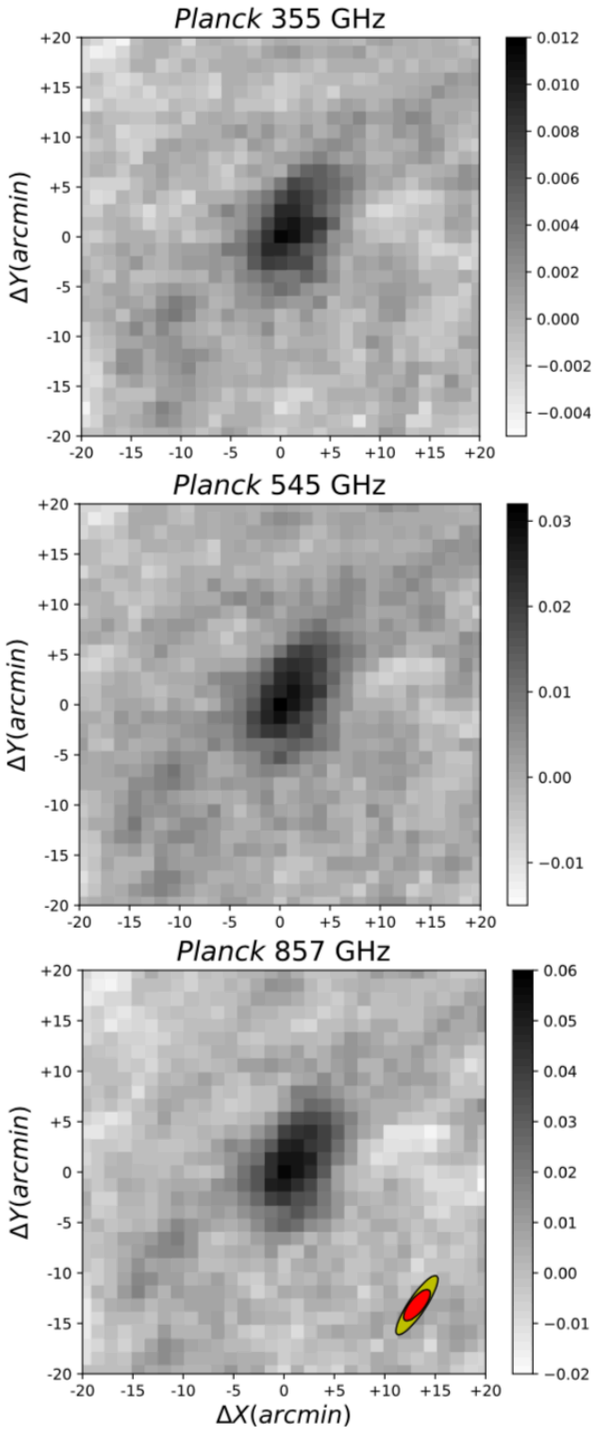


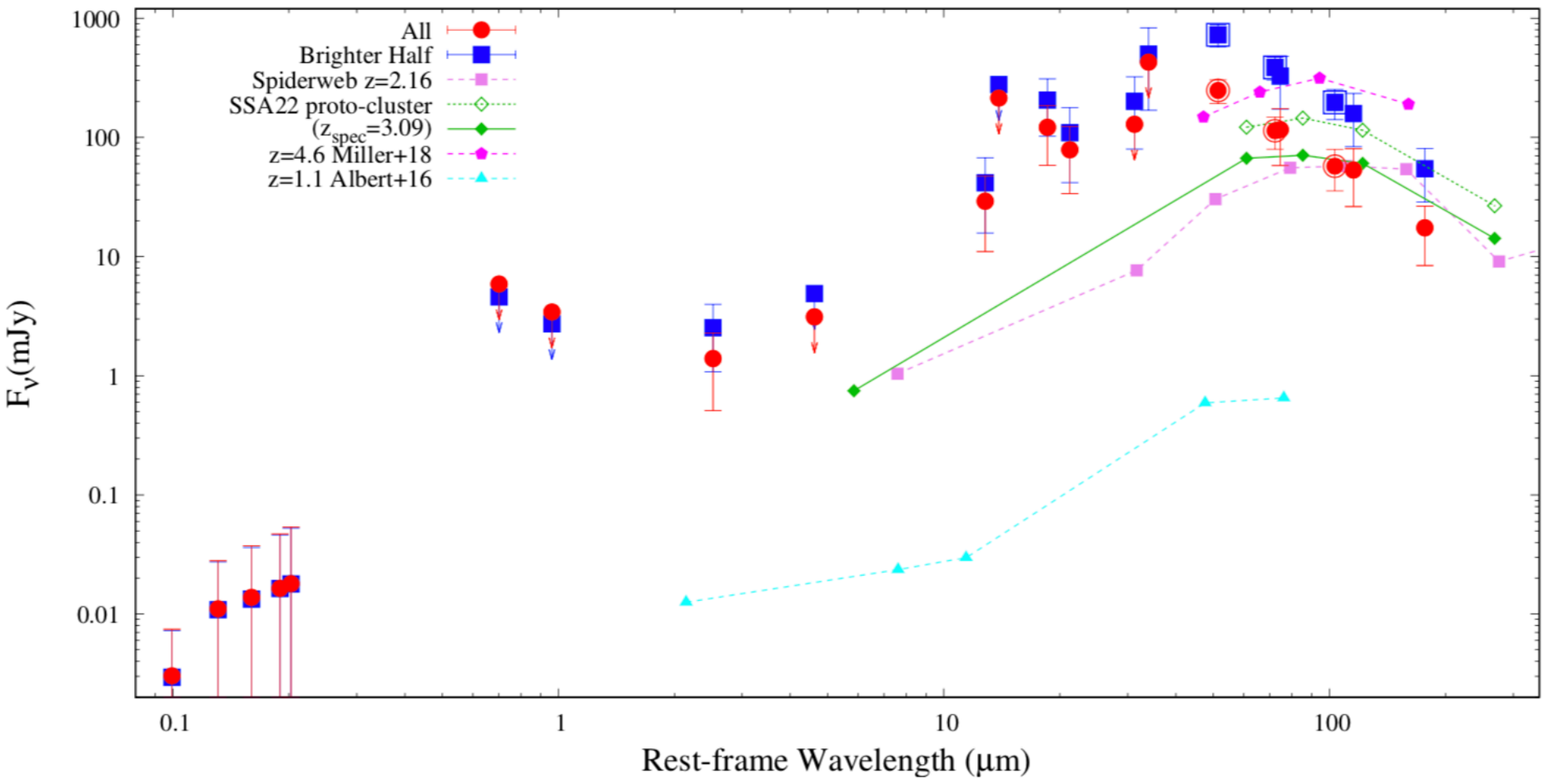


- the only 2 matches between protoclusters and quasars we find ***are binary quasars***

Uchiyama et al. (2018) and Onoue et al. (2017)

Planck detection of stacked Subaru/HSC protoclusters at z ~ 4





- highly significant detections at 355, 545 and 857 GHz
- total FIR star formation rates of ~10,000 $M_\odot$ yr^{-1}

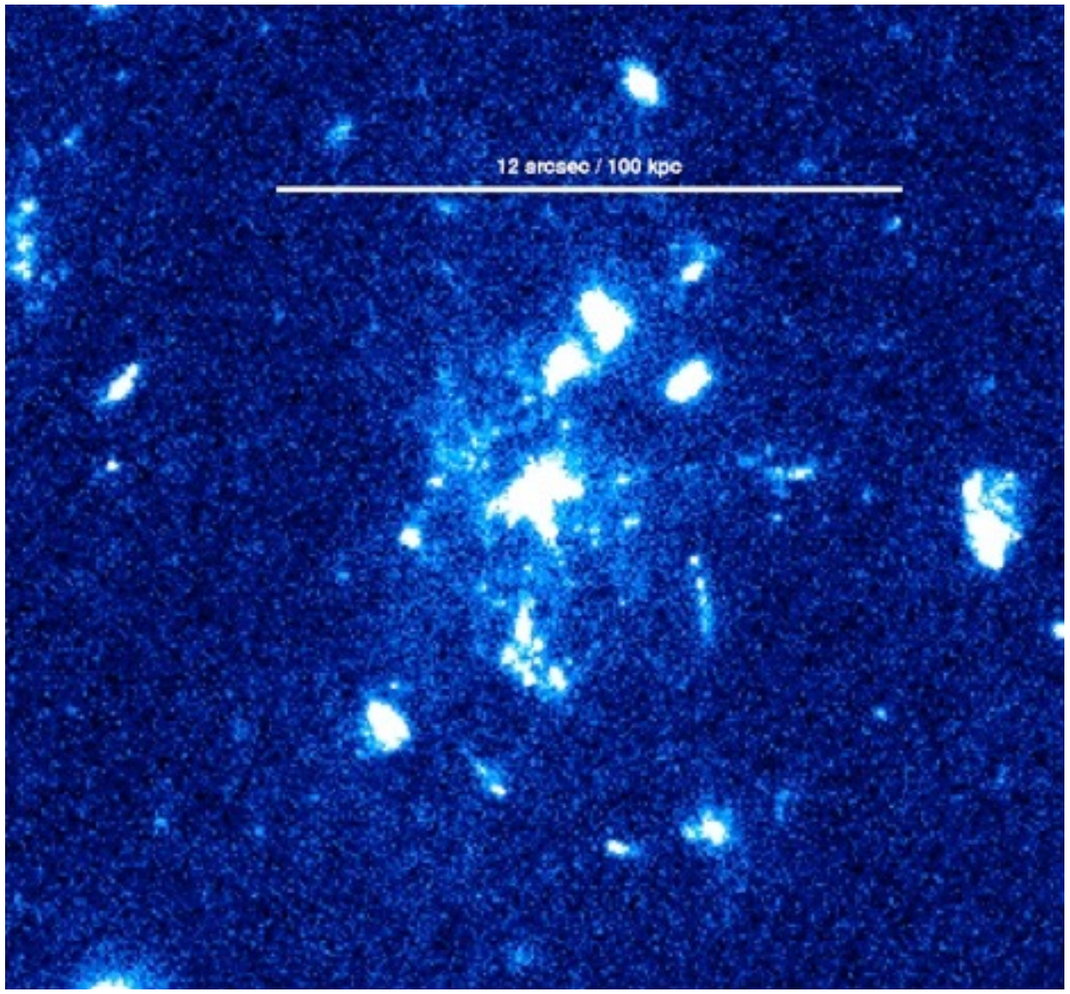
Mariko Kubo et al. (submitted)

Formation of Brightest Cluster Galaxies at z > 2

z = 2.2

"Spiderweb Galaxy"

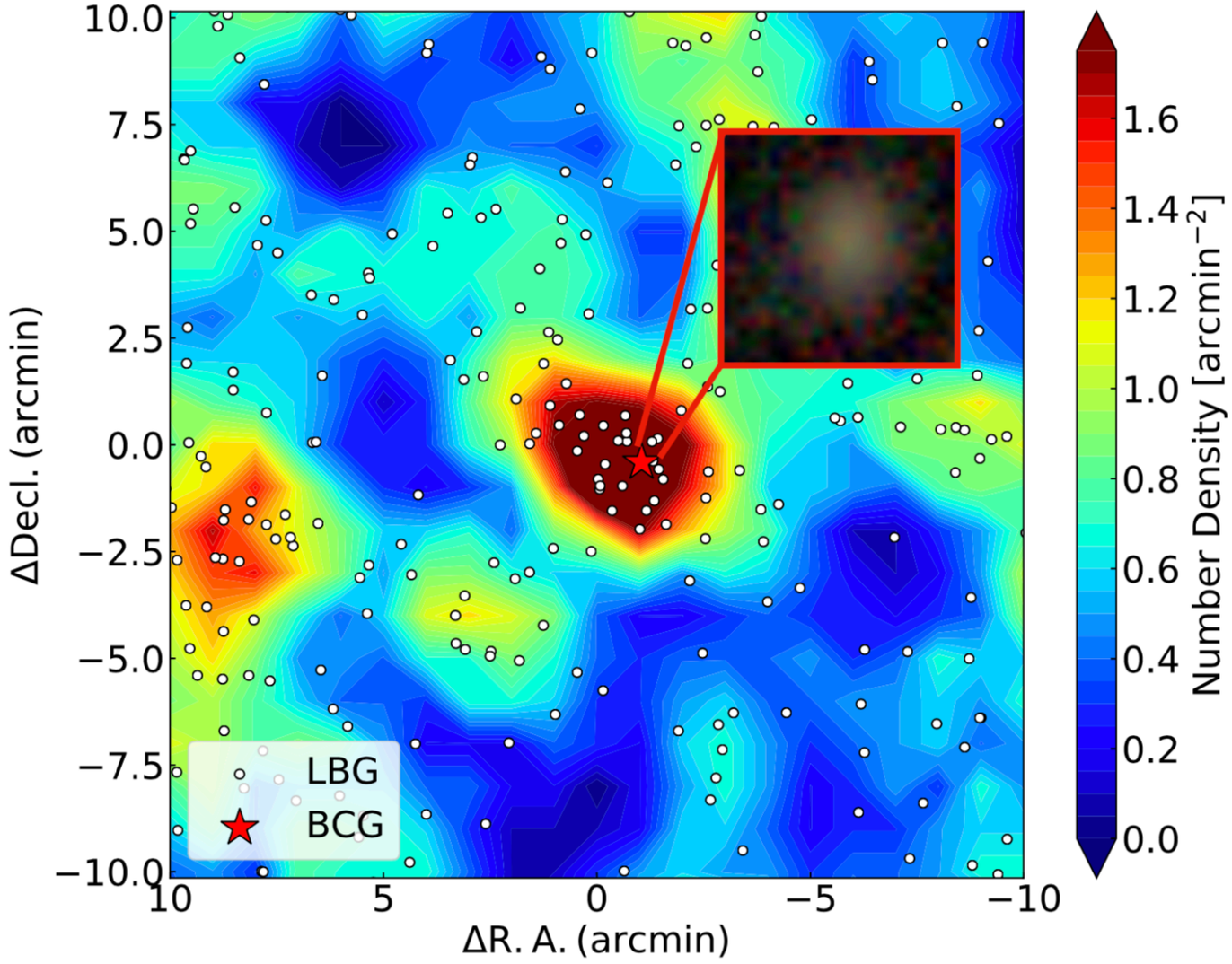
(**Overzier, Miley et al. 2007**)



z ~ 4

Subaru/HSC

(**Ito et al. 2019**)



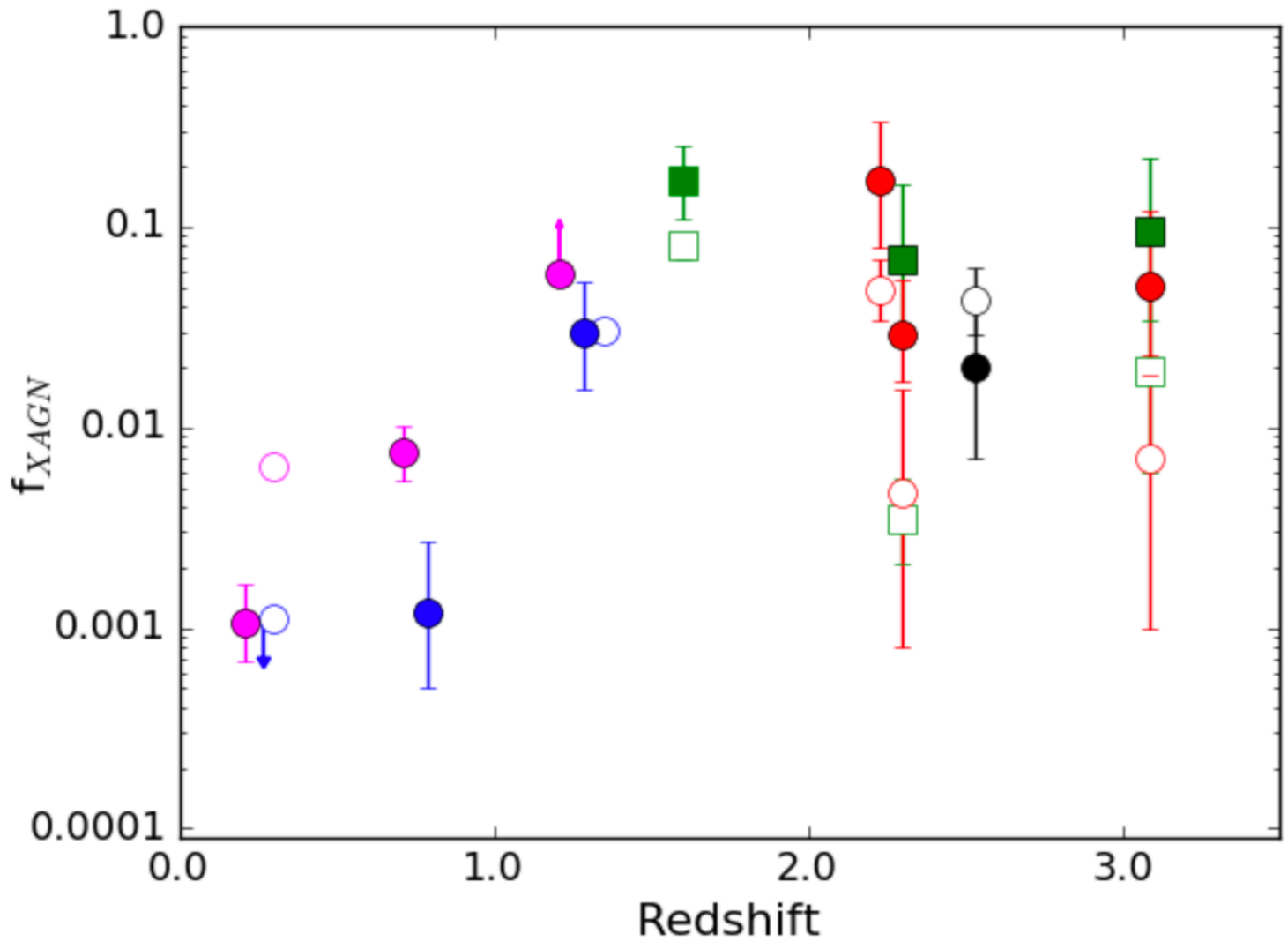
- large samples of protoclusters should finally allow us to start studying also the formation of brightest cluster galaxies systematically

Rising AGN fraction in forming cluster environments at z > 2?

AGN fraction in proto-clusters *may be expected to be* enhanced:

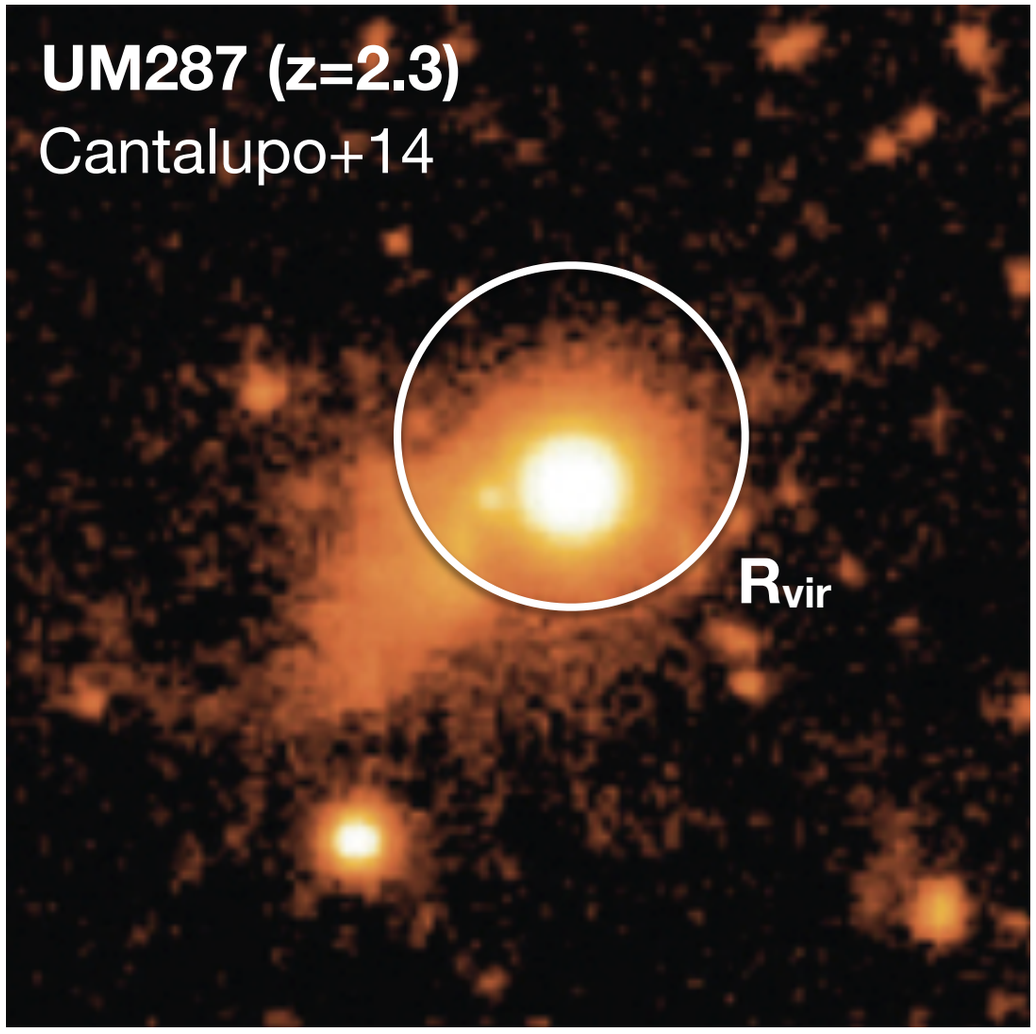
- faster galaxy growth leading to more massive galaxies ?
- more frequent mergers in overdense regions ?
- more efficient inflows of gas in overdense regions ?

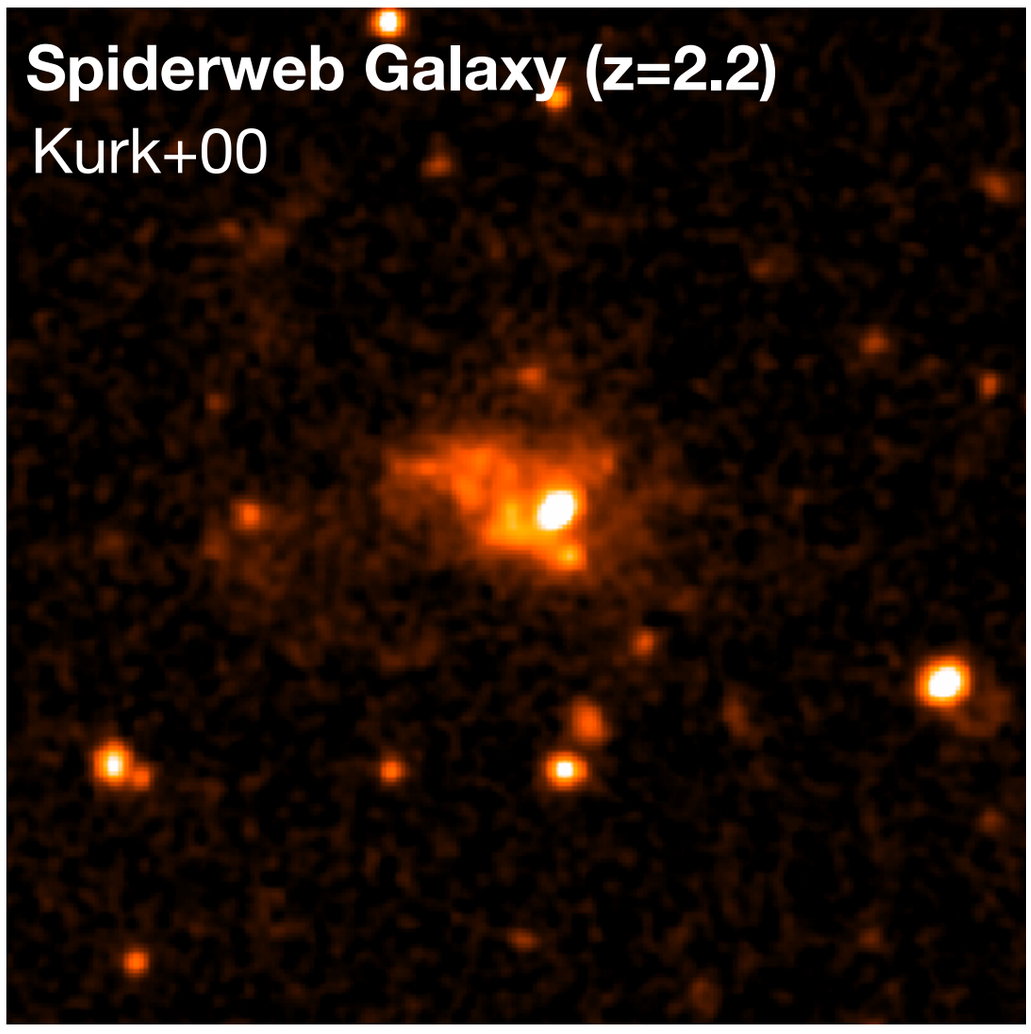
The data at z > 2 is not yet clear:



Pentericci et al. (2002)
Cappi et al. (2002)
Overzier et al. (2005)
Lehmer et al. (2009)
Martini et al. (2013)
Macuga et al. (2019)

Lyα blobs/halos: evidence for large-scale flows of cosmic gas





$L_{Ly\alpha} > 10^{44}$ erg/s; size > 100 kpc; mainly visible through AGN photoionization

- evidence for gas accretion from the large-scale cosmic web (?)
- gas produced in AGN-driven superwinds (?)
- metallicity measurements show some of the material has been enriched (?)

(e.g., Overzier et al. 2001, 2013; Cantalupo et al. 2014; Hennawi et al. 2015; Morais et al. 2016)

Galaxy gas-phase abundances in proto-clusters at z > 2

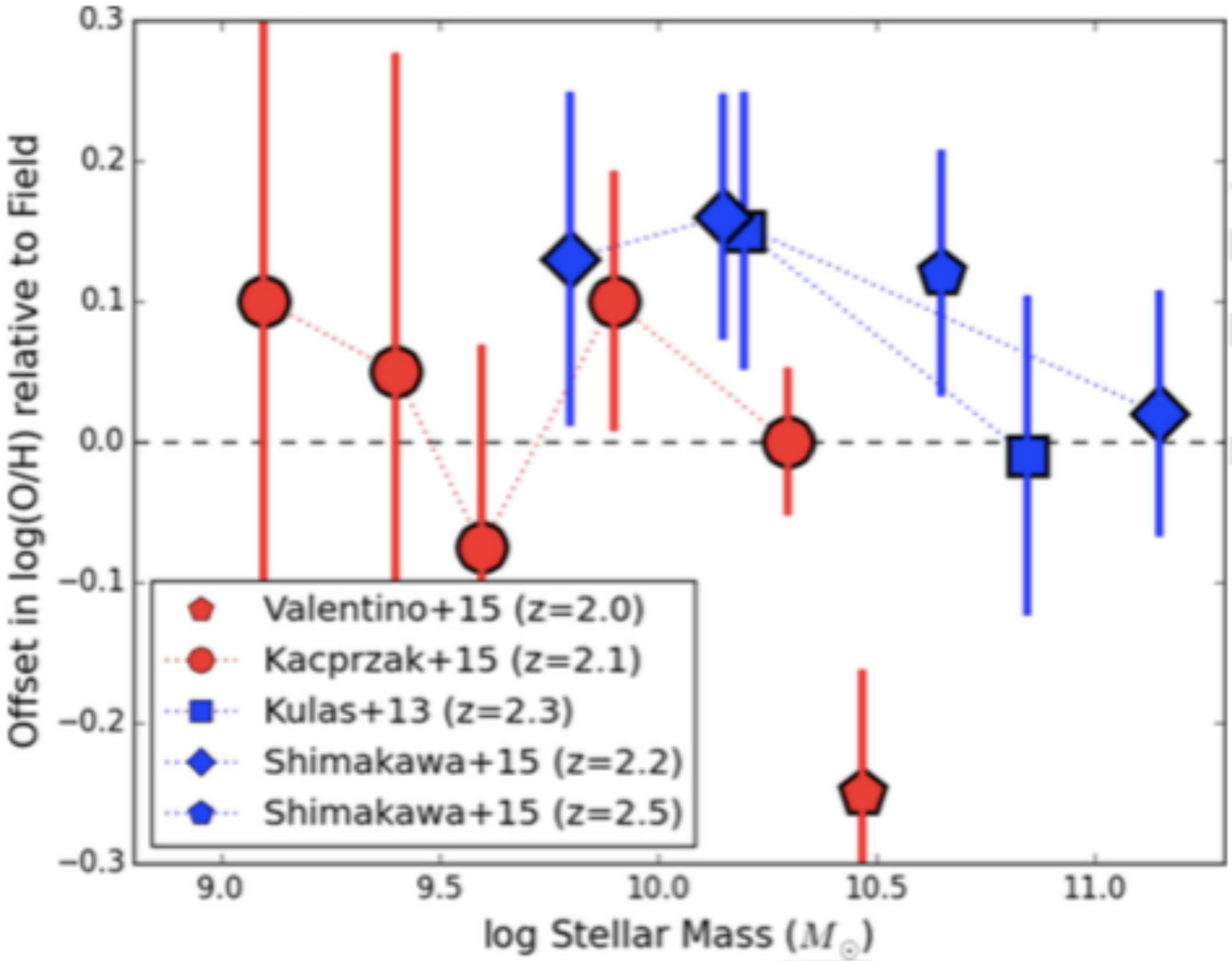
Hydro simulations of cluster formation show that the dense ***environment should play some role:***

- **extra enrichment** due to faster gas-recycling times in dense regions

(e.g., Oppenheimer & Davé 2008, Kacprzak et al. 2015)

- **but also dilution** due to the rapid inflows of pristine gas from the IGM

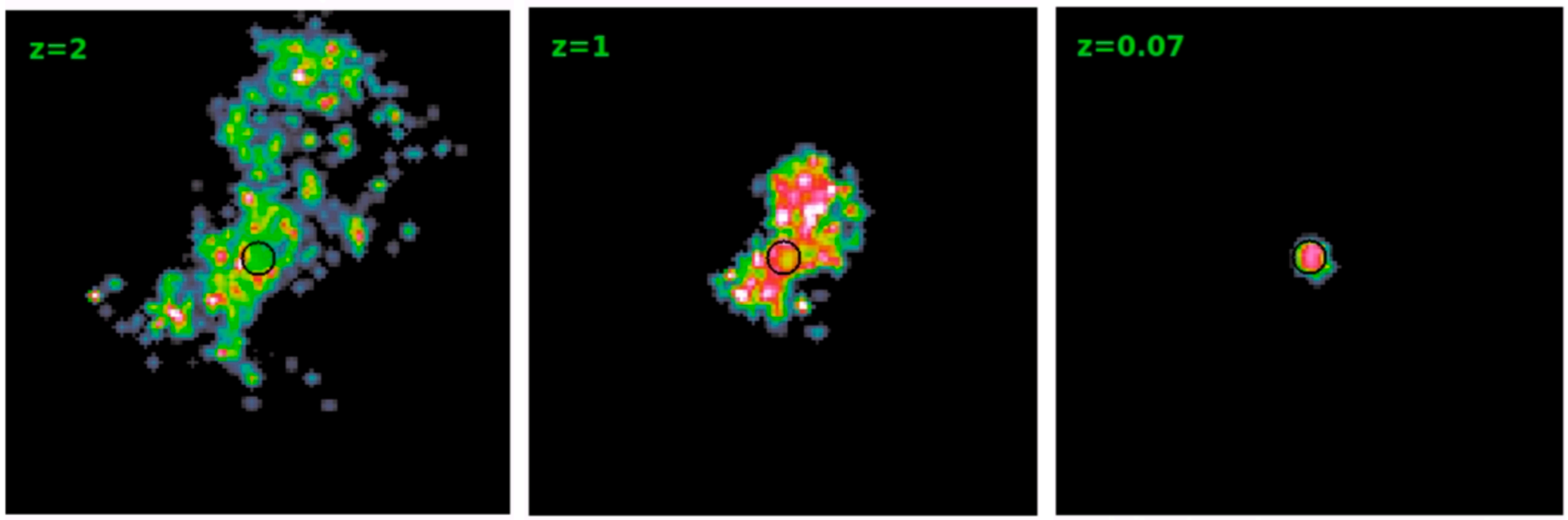
(e.g., Valentino et al. 2015)



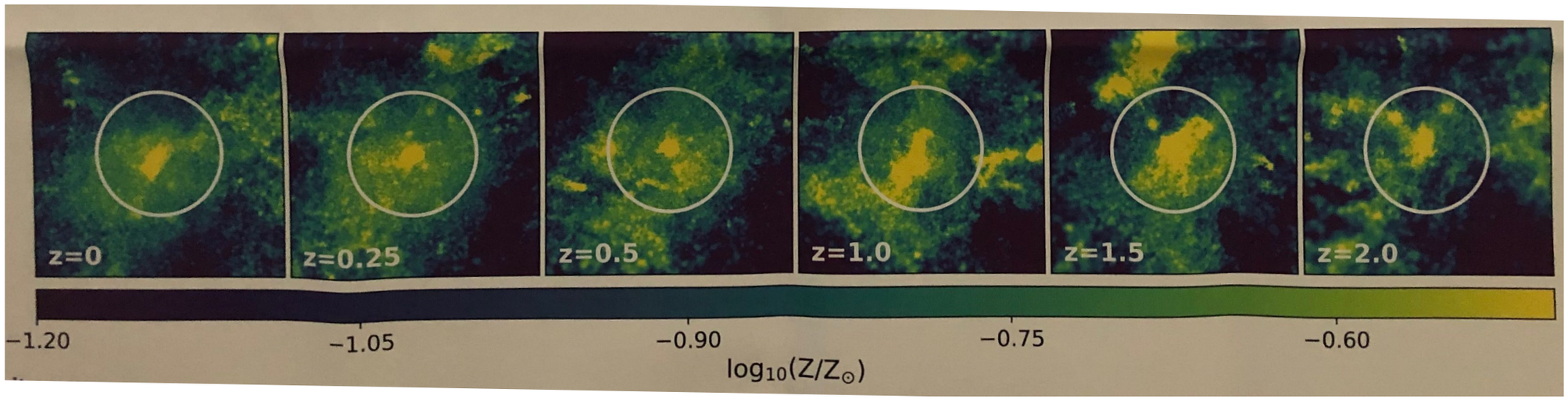
Overzier (2016)

First measurements on 4 (proto)clusters are inconclusive

ICM enrichment history of cluster outskirts at z = 0



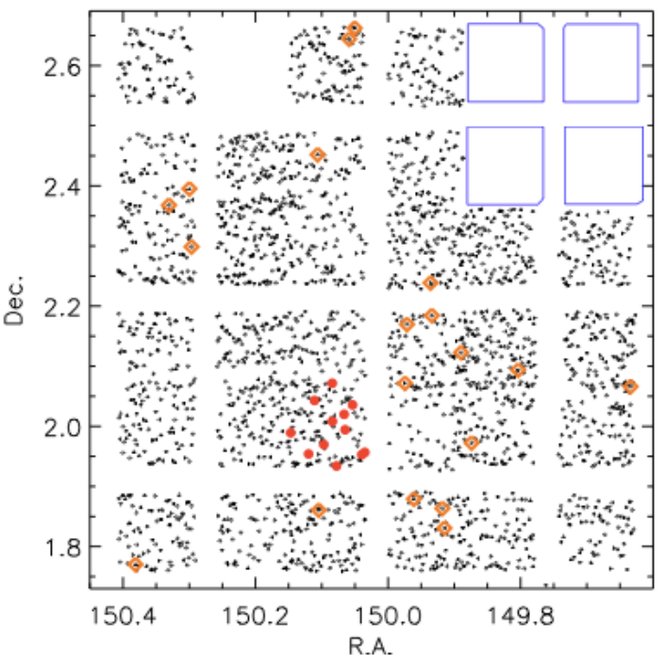
Biffi et al. (2017, 2018)

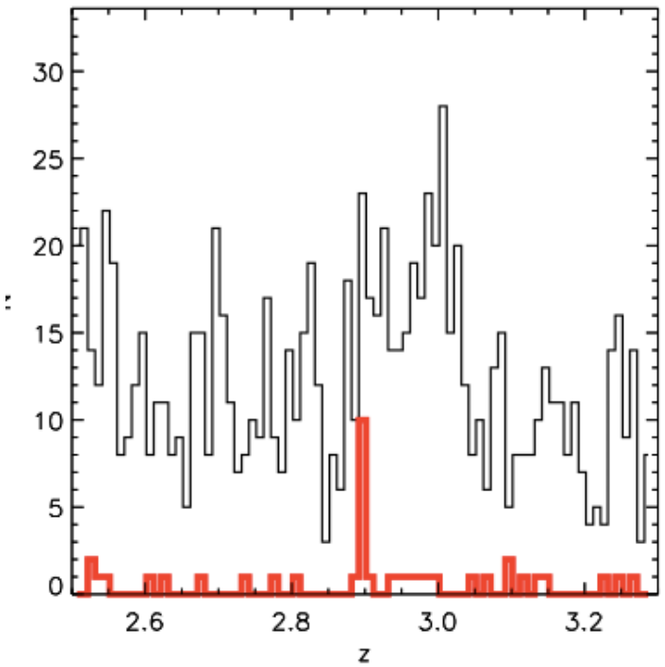


poster by Francesca Pearce (see also posters by **Ang Liu** and **François Mernier**)

- understanding the protocluster stage at z > 2 important for interpreting the ICM

New developments: large, blind spectroscopic surveys

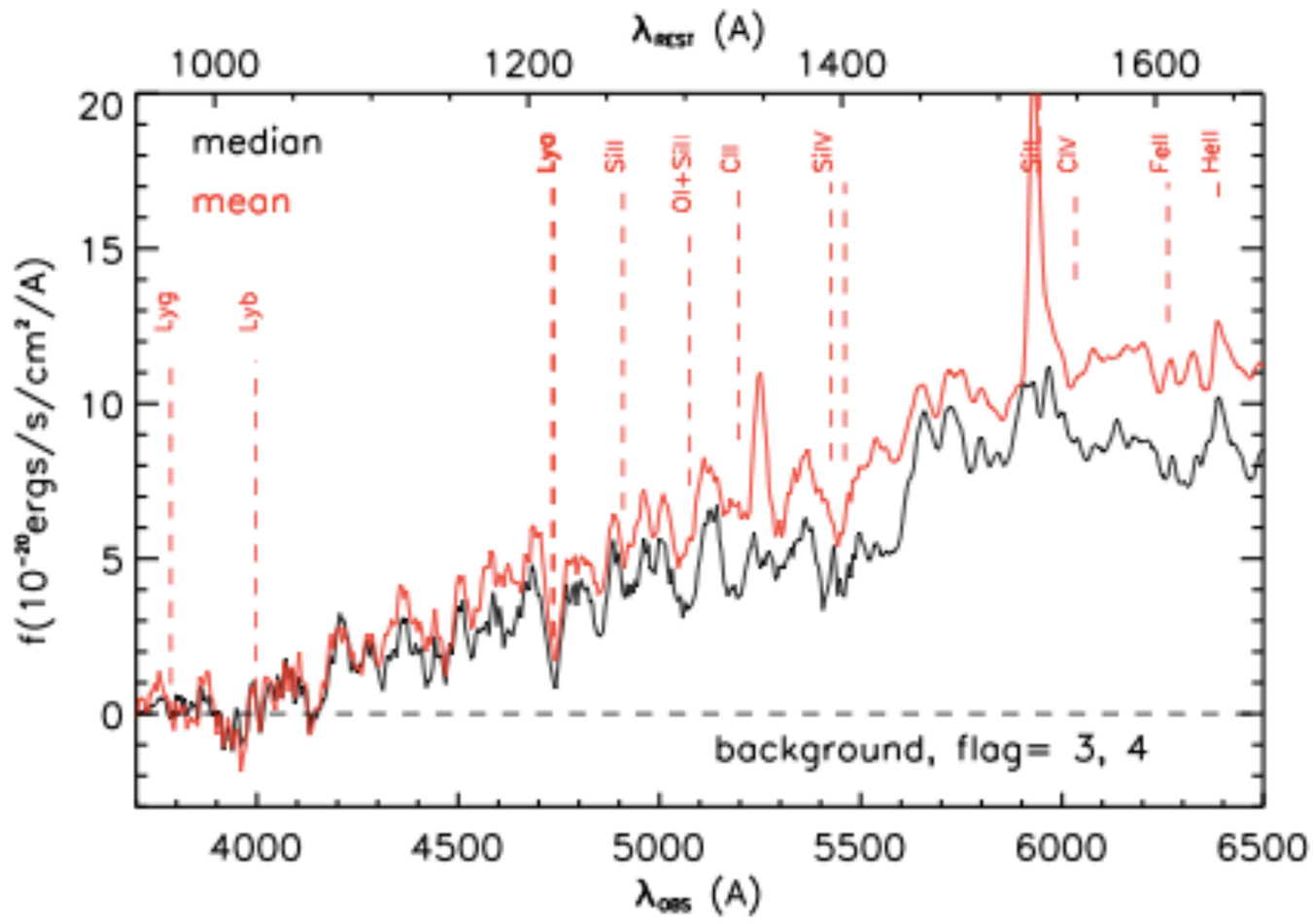




- VUDS: densely sampled survey over 1 deg^2 targeting z = 2-6 (LeFèvre et al. 2015)
- protoclusters at z = 2.9, 3.3 & 4.6
- 12 spec-z members with $\delta_{gal} \sim 12$
- $M_{z=0}$ of about 3 x 10^{15} M_o

associated cold gas seen in absorption in background galaxy spectra:

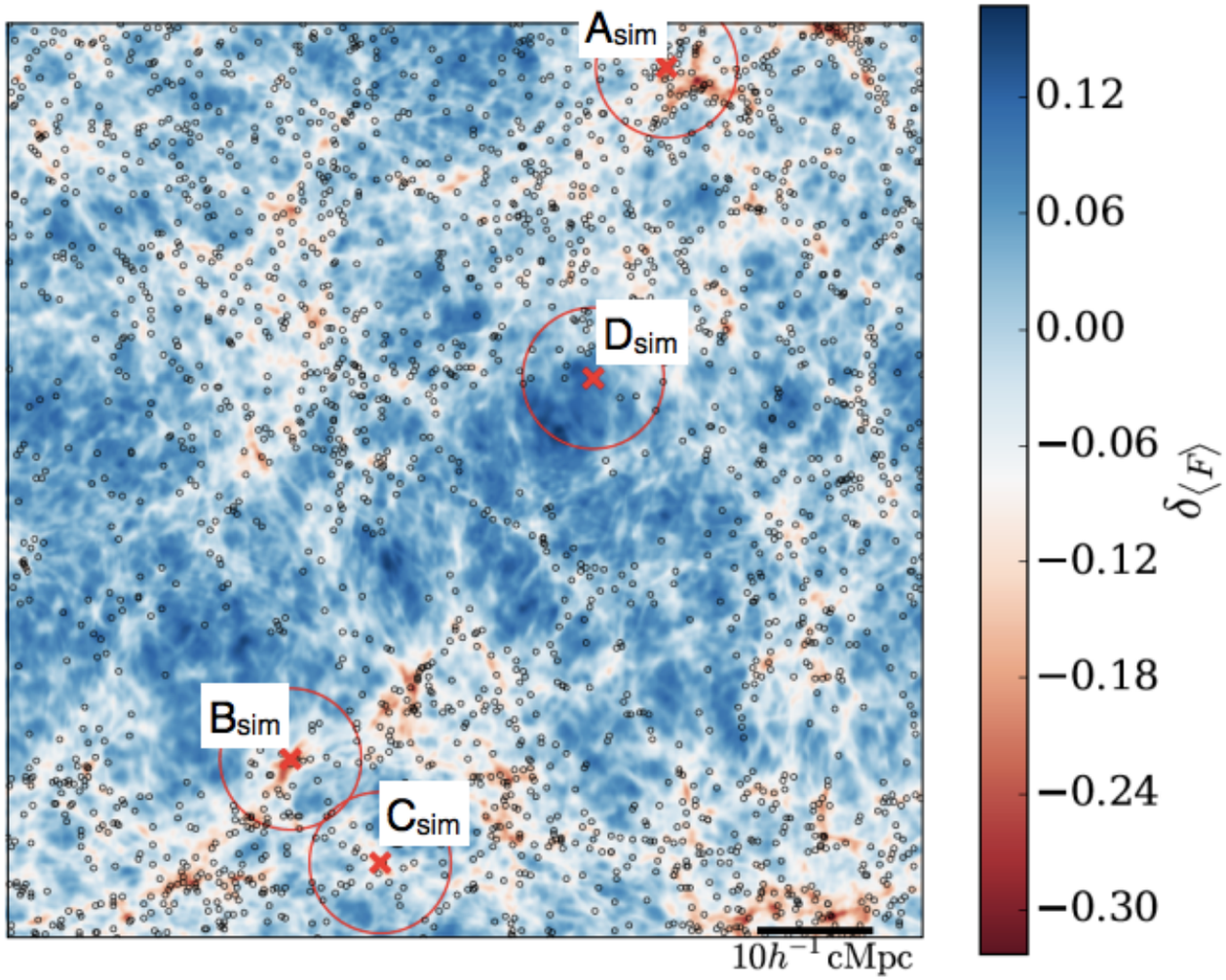
infalling gas from the cosmic web or **outflowing gas** blown out by the forming proto-cluster galaxies (?)



Cucciati et al. (2014), Lemaux et al. (2014, 2017)

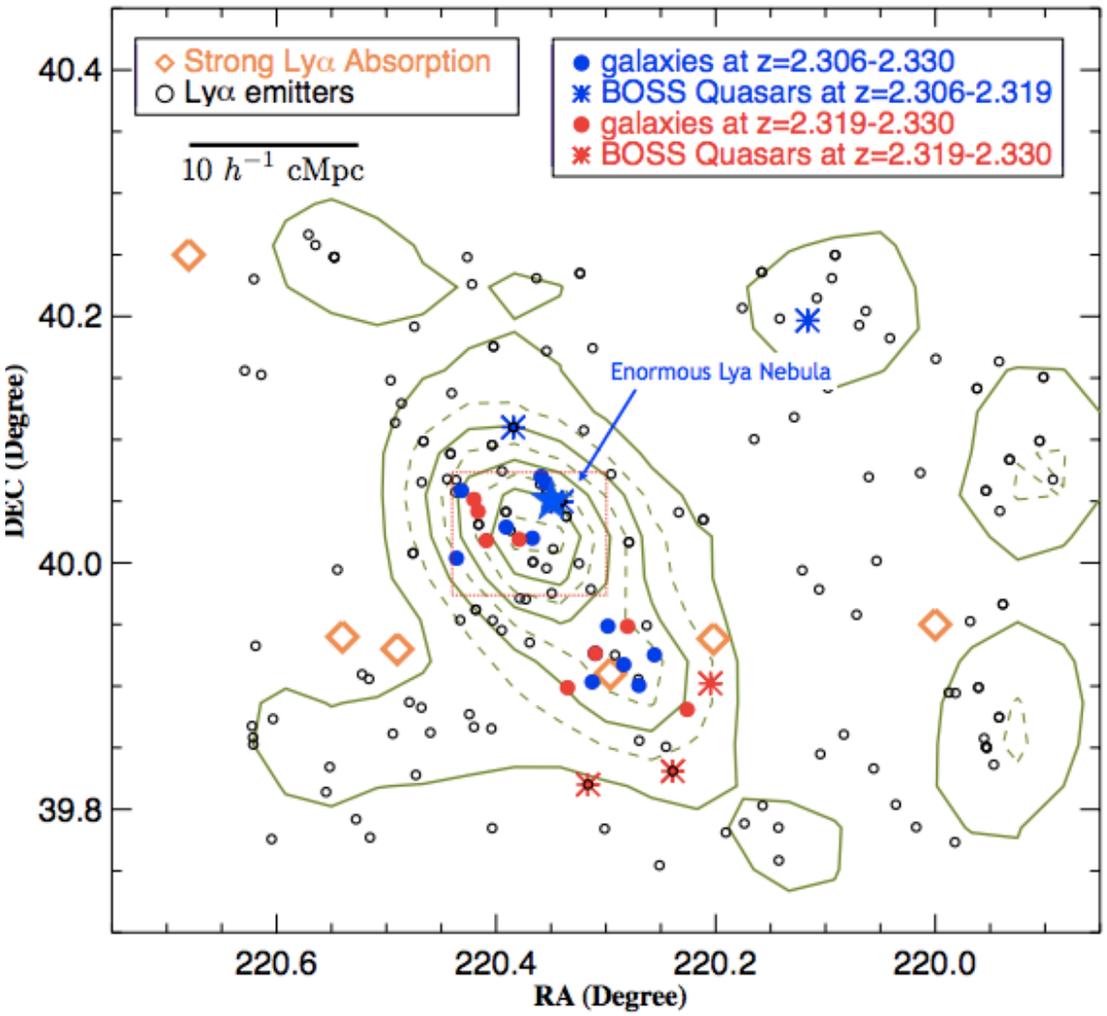
New developments: tomographic mapping of cosmic web

simulations



Mukae et al. (2016)

BOSS1441 at z = 2.32

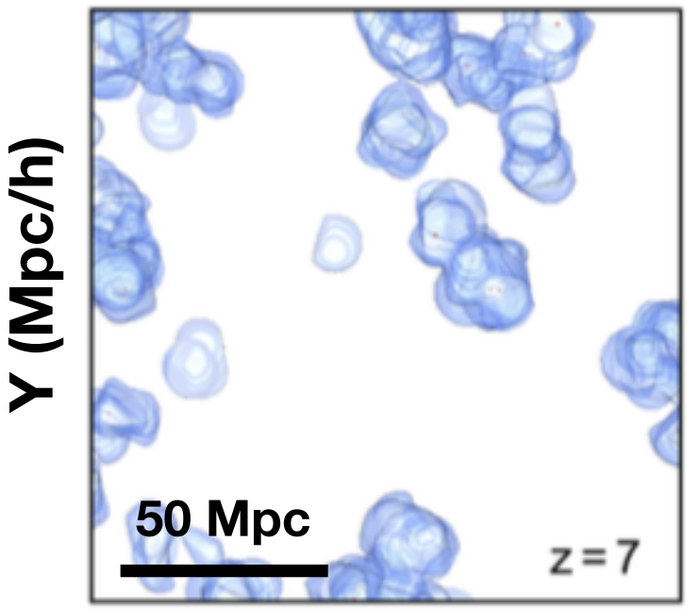


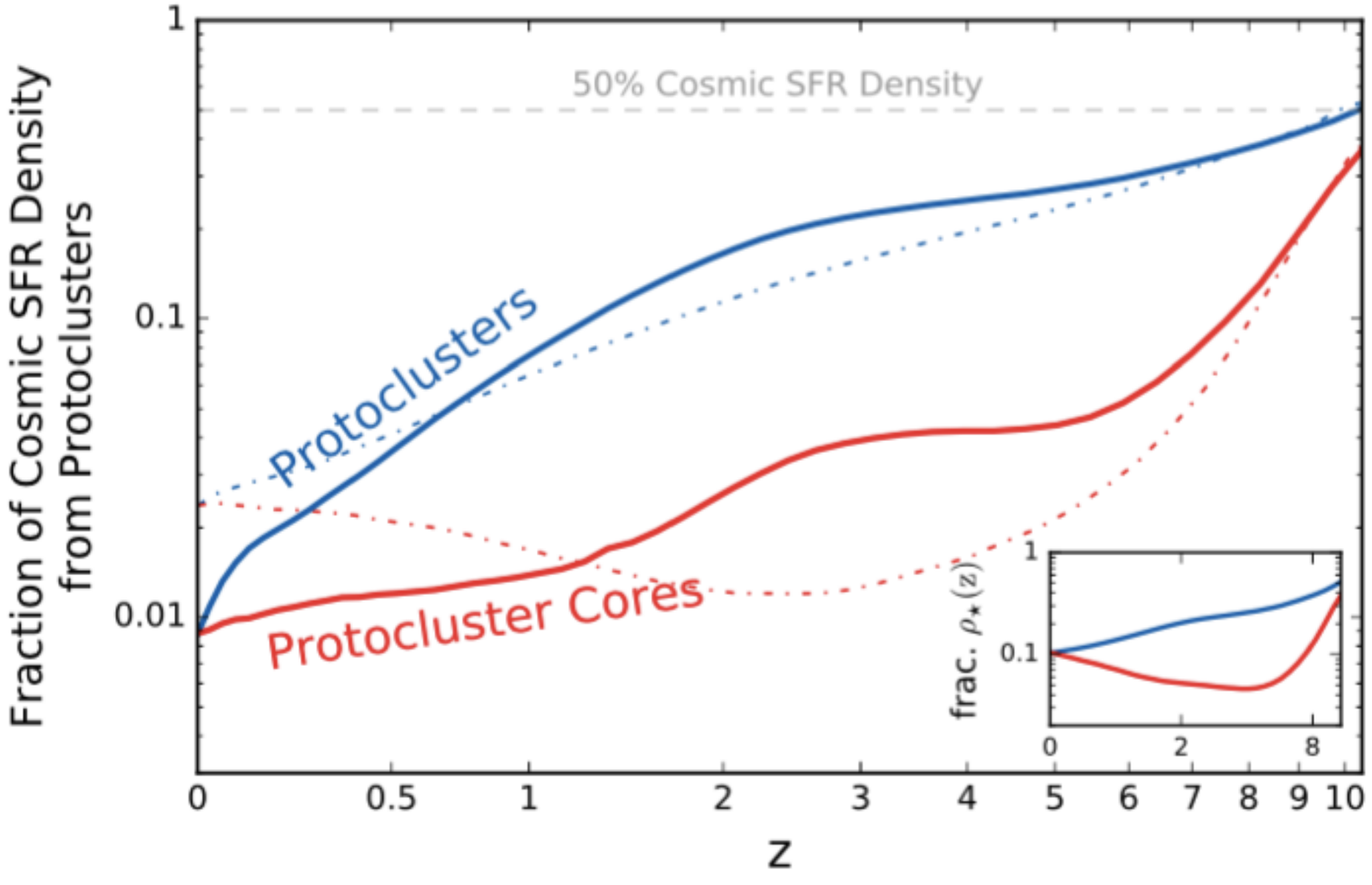
Cai et al. (2015, 2017)

- selection of dense regions through Lya tomography techniques has opened up a whole new path to discovery
- will be an essential “trick” of new surveys such as Subaru/PFS that will use background *galaxies* as the tomographic tracers

Observing the dawn of cluster formation at z = 6-7

- contribution from cluster progenitors to the cosmic SFRD increases with z
- by z ~ 3 (z~10) they represent ~20-30% (>50%) of all cosmic SF

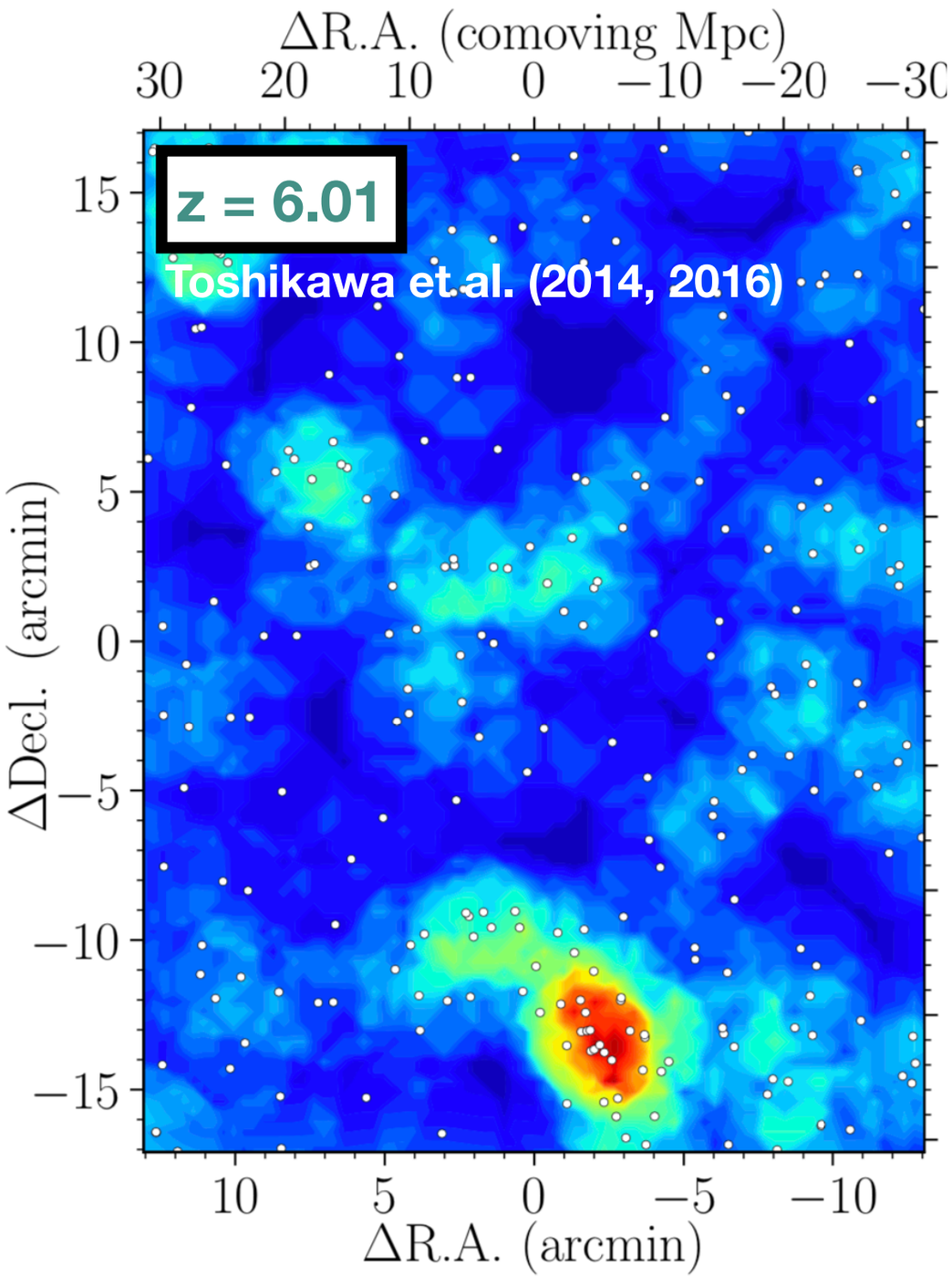


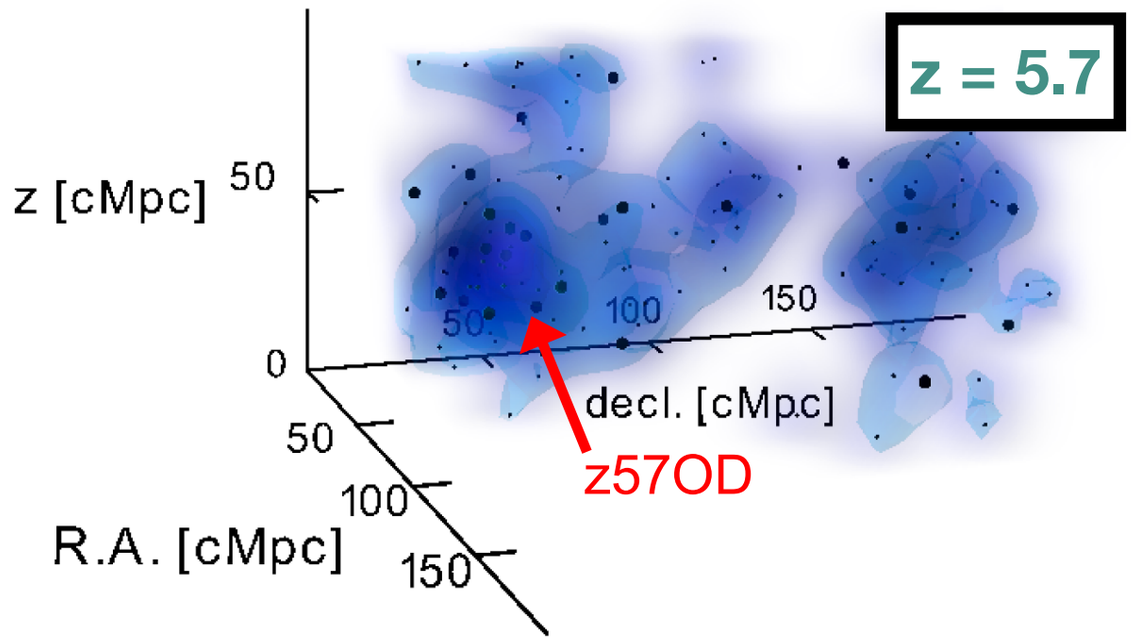


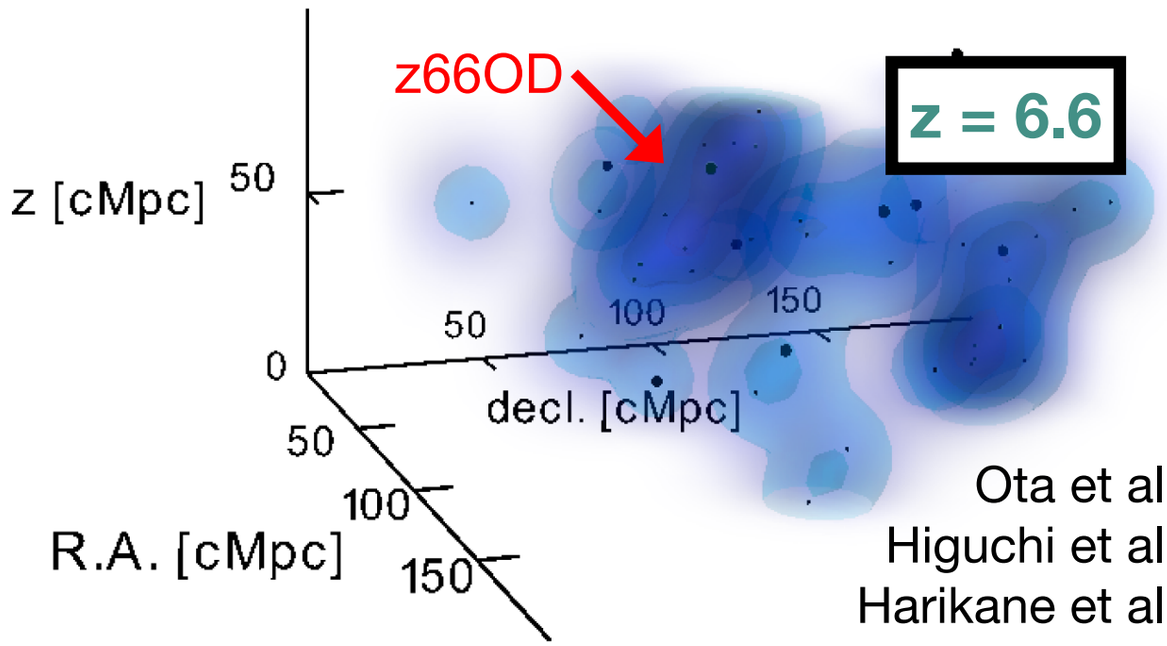
Chiang, Overzier et al. (2017)

Observing the dawn of cluster formation at z = 6-7

- we are now starting to find many examples at z ~ 6—7
- perhaps major sources of reionization due to high ionizing photon rate

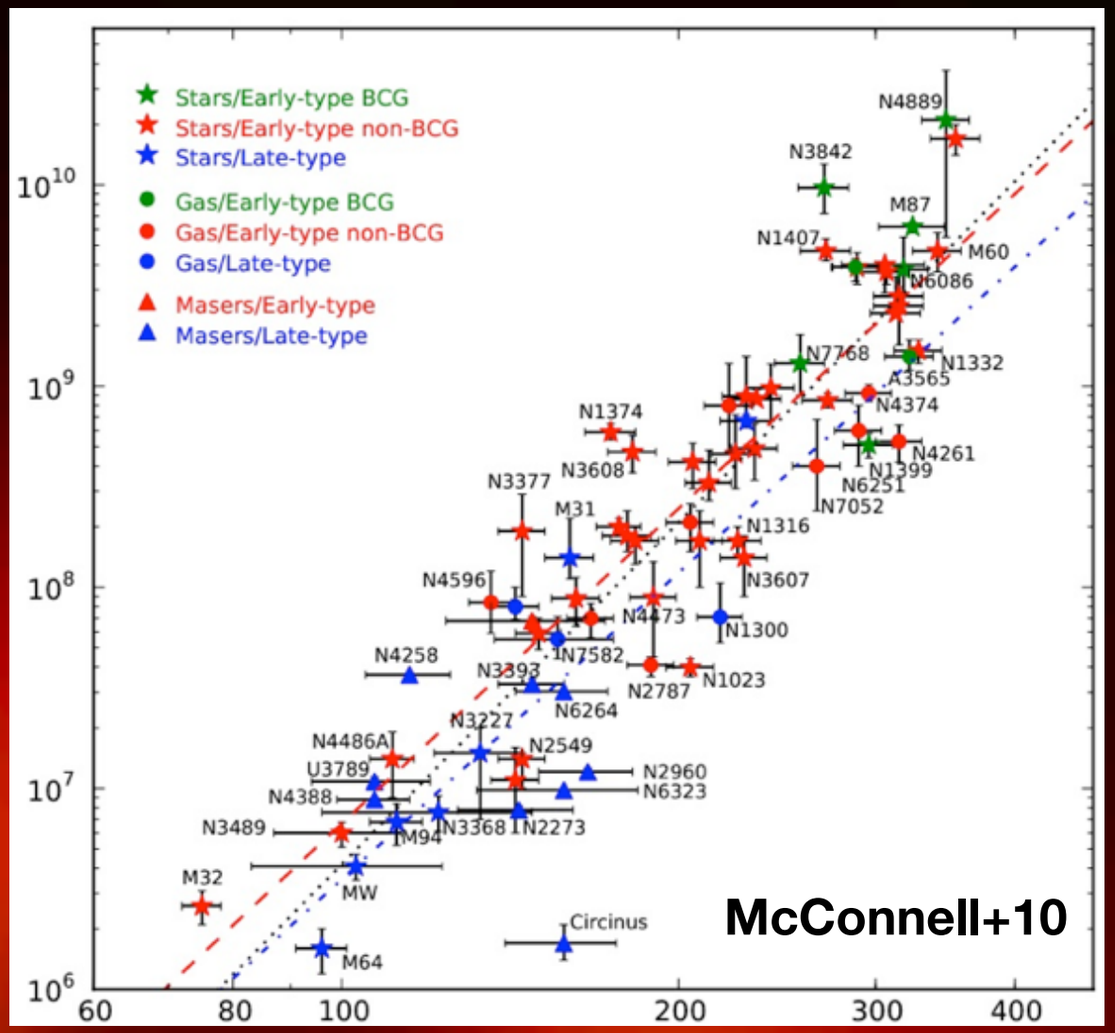




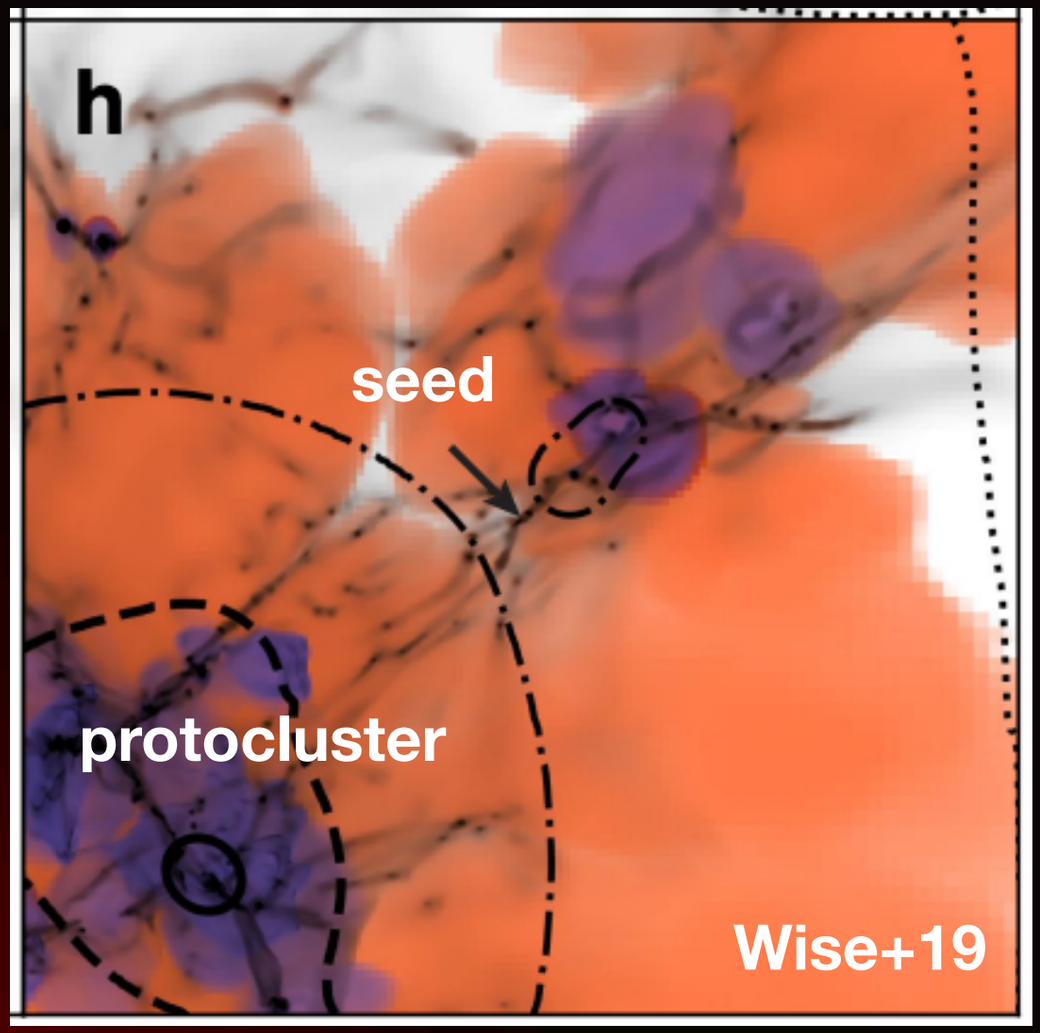


Ota et al. (2018)
Higuchi et al. (2019)
Harikane et al. (2019)

Did the first supermassive black holes form in protoclusters?



Bulge Velocity Dispersion (km/s)



the top of the M-sigma relation populated by massive SMBHs in galaxy clusters

protocluster regions produce large background of Lyman-Werner photons perhaps needed for the direct collapse of **massive SMBH seeds (JWST, Athena, …)**

M87; Event Horizon Telescope/NSF

The unexpectedly boring environments of QSOs at z ~ 6

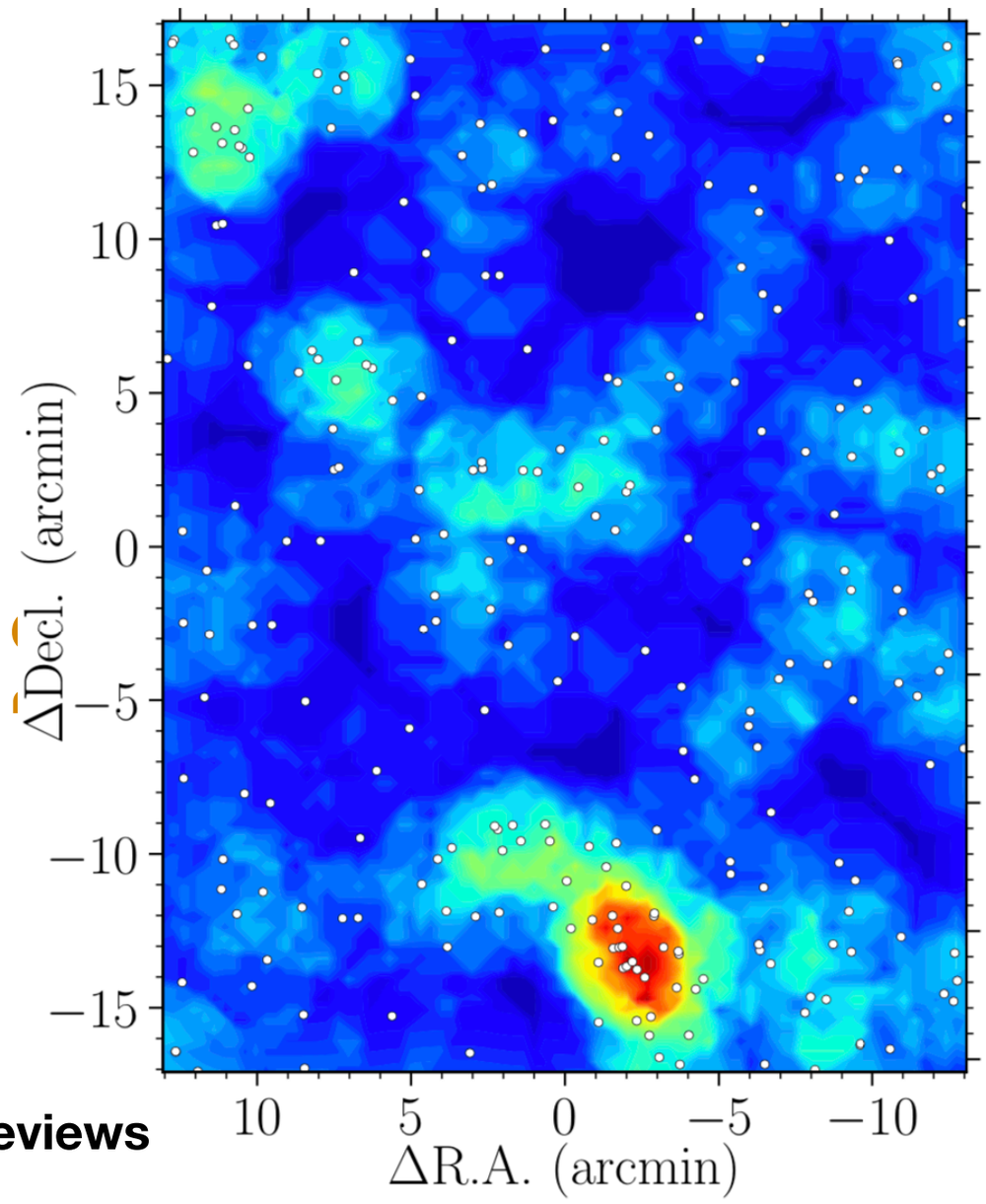
- at least some SMBHs with M87-like masses already existed at z ~ 6—8 (e.g. Bañados et al. 2018)

The rapid SMBH accretion needed to form these extreme objects could perhaps be explained *if the first quasars formed in large overdense regions*

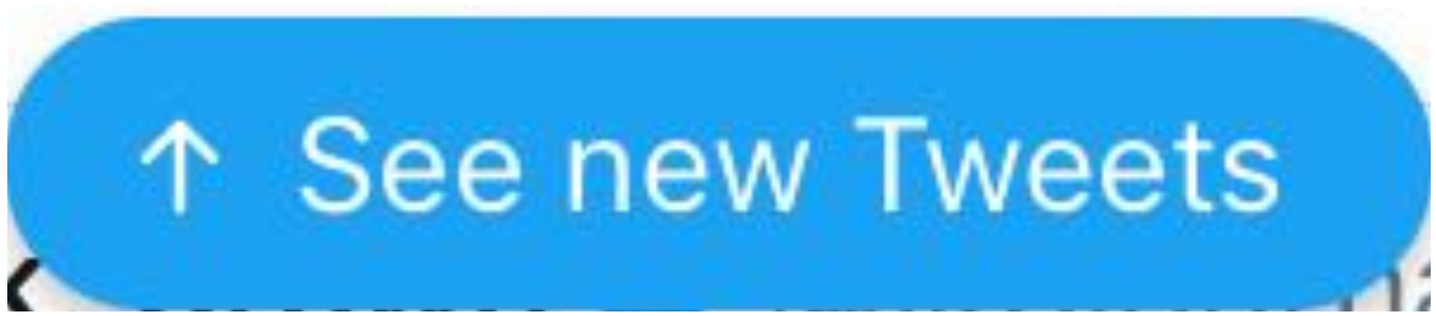
However,

Most observations of z~6 QSO fields to date have failed to produce any significant large-scale structure associated with these QSOs:

e.g. Stiavelli et al. 2005; Zheng et al. 2006; Overzier et al. 2009, Overzier 2016; Kim et al. 2009; Angulo & White 2012; Morselli et al. 2014; Bañados et al. 2016; Mazzucchelli et al. 2017; Goto et al. 2017; Decarli et al. 2017; Balmaverde et al. 2018



See Overzier (2016) and Mazzucchelli et al. (2017) for recent reviews


↑ See new Tweets

Donald J. Trump

@realDonaldTrump

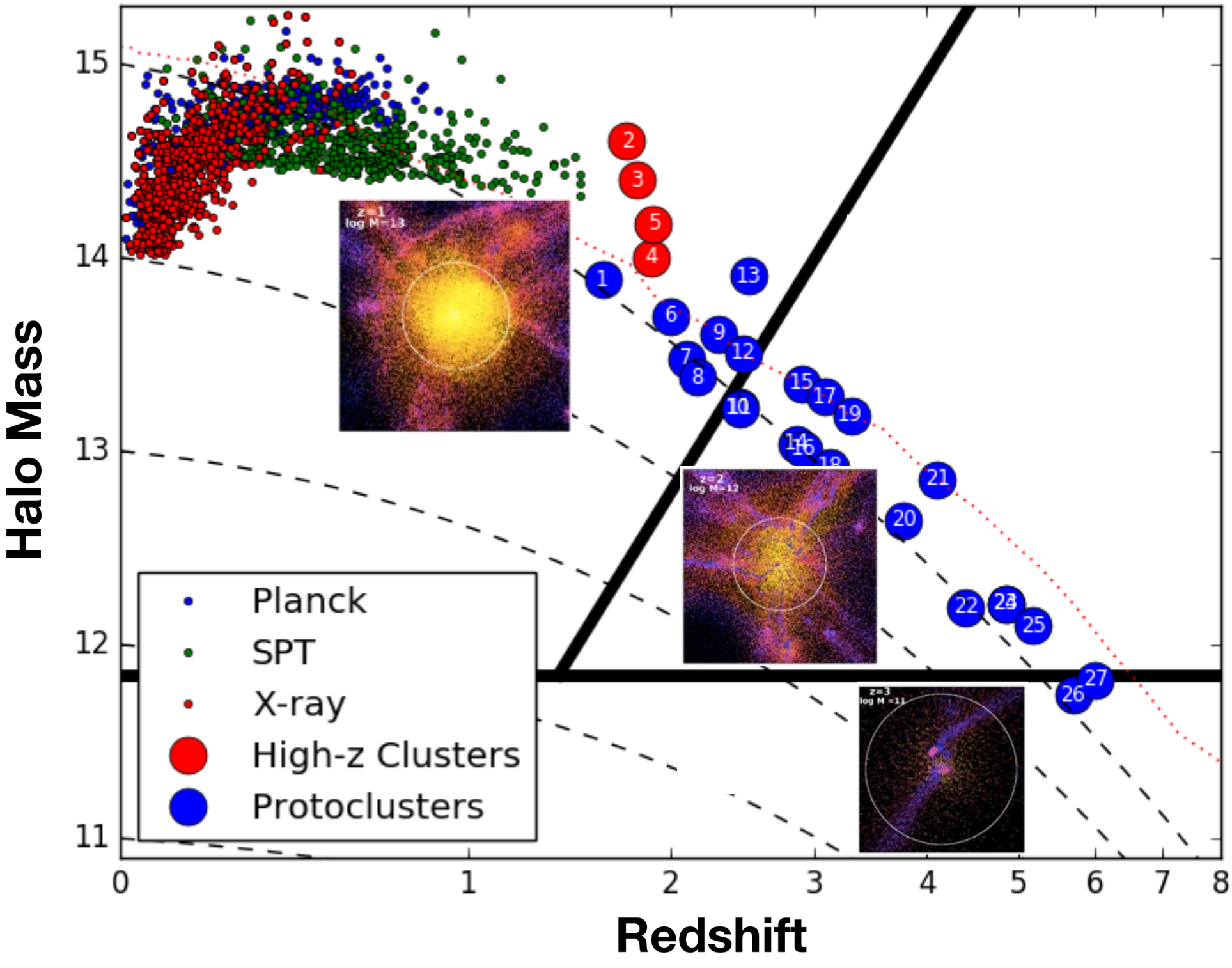
Follow

Quasars at z~6 do NOT trace the densest regions of the early Universe. Sad! #xrayastronomy19

17:20 PM - 10 September 2019

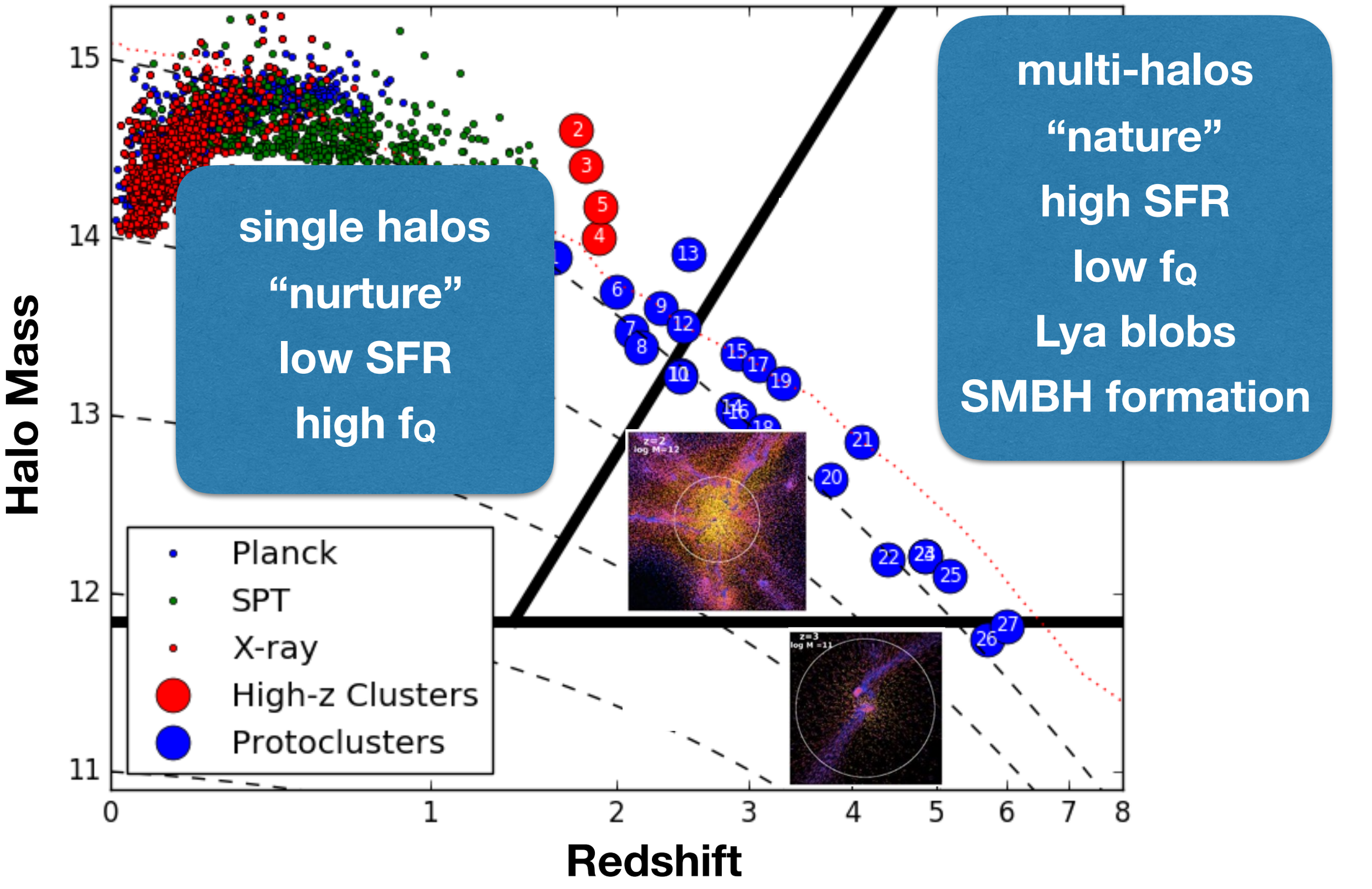
2,167 6,286

Evolutionary picture that needs to be tested



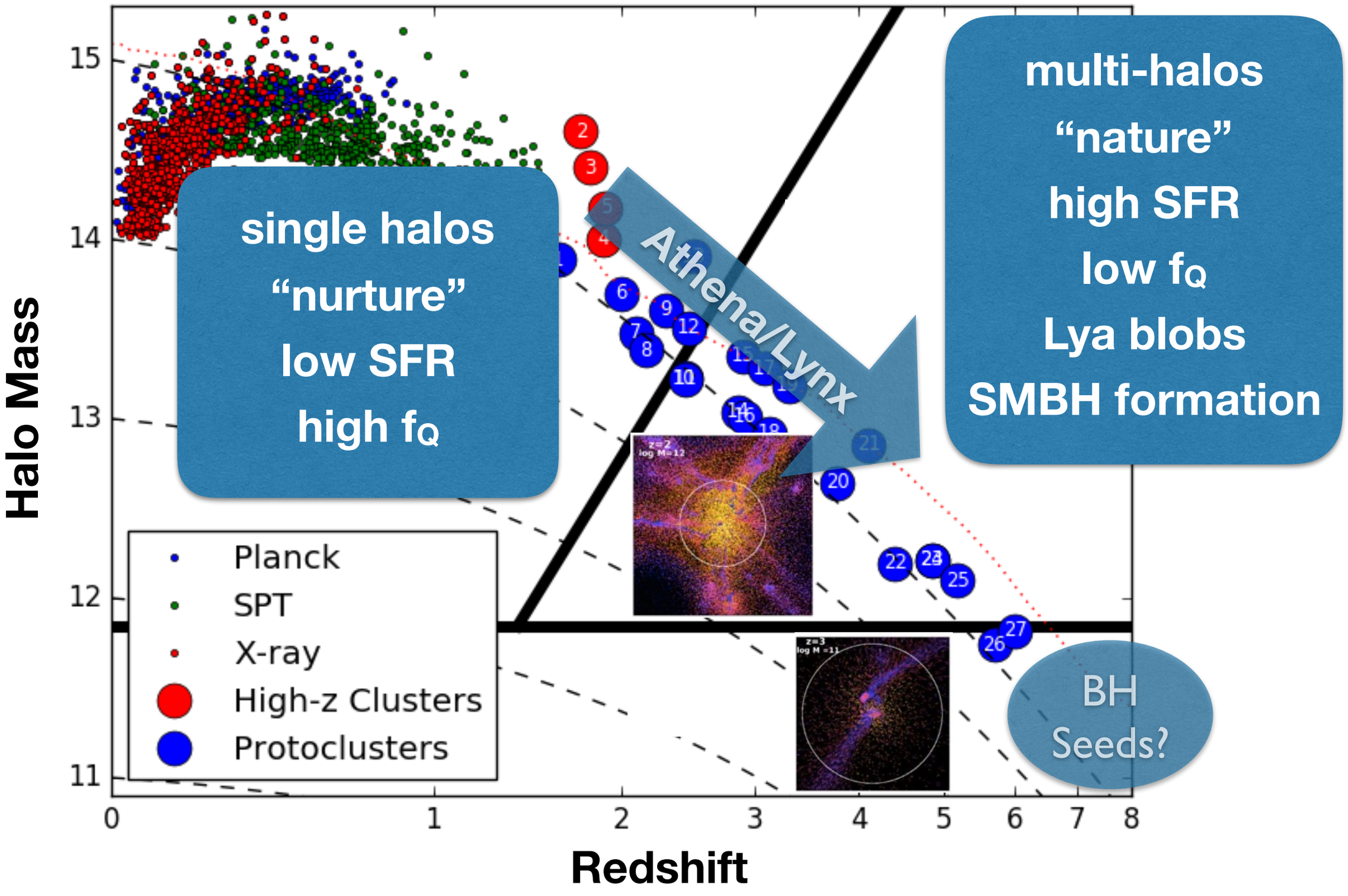
Overzier (2016)

Evolutionary picture that needs to be tested



Overzier (2016)

Evolutionary picture that needs to be tested



Overzier (2016)