THE REALM OF THE GALAXY PROTO-CLUSTERS

an introductory review

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Galaxy Clusters 2017, Santander

Why care about Galaxy Clusters?

Structure Formation Models

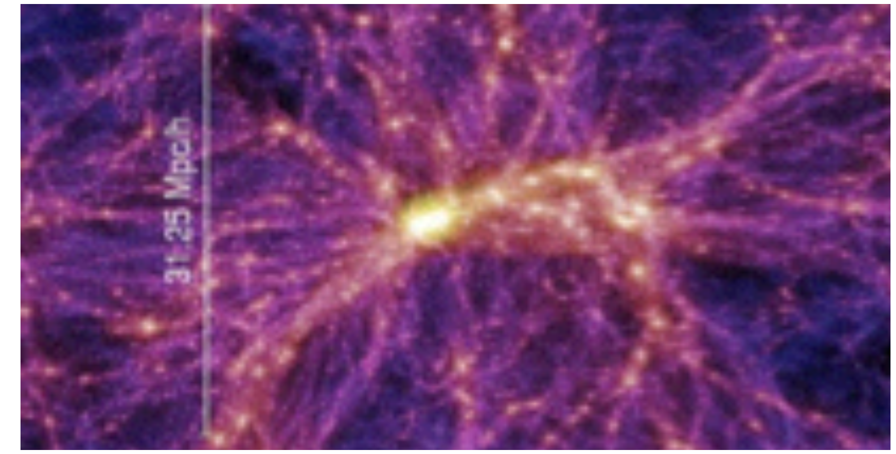
- Assembly history of largest halos, galaxies, gas
- Cosmology

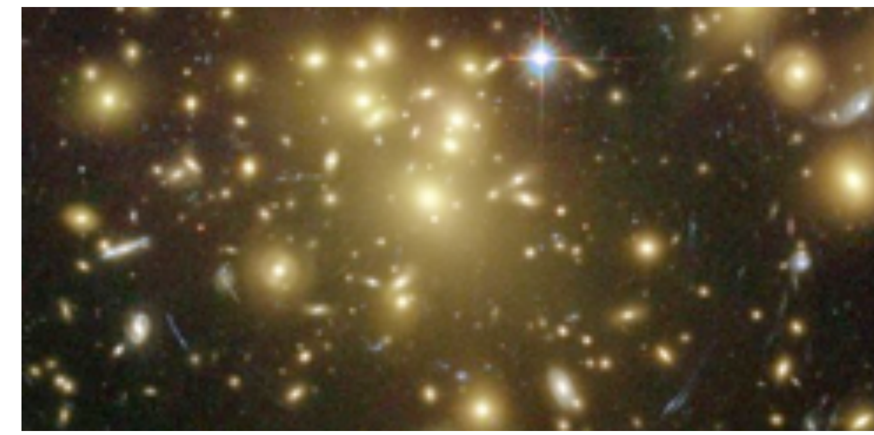
Galaxy Formation

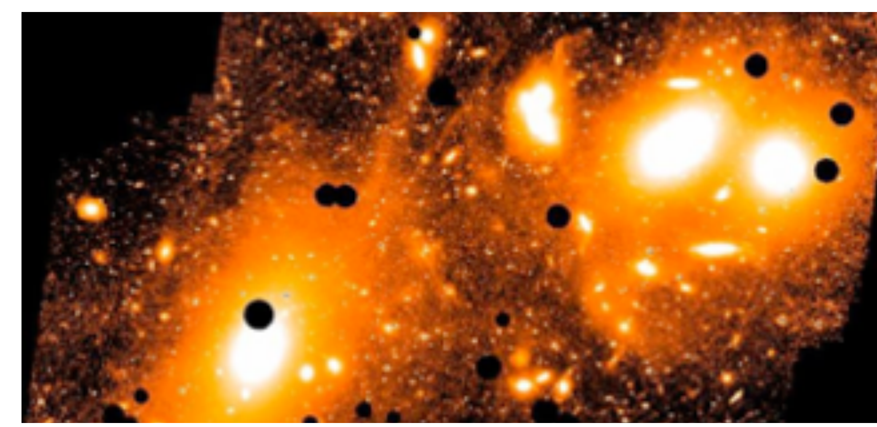
- Clusters contain large numbers of galaxies
- Pre-processing at the group stage?
- Assembly bias
- Reionization

Lots of astrophysics unique to clusters

- Galaxy evolution in dense environments
- Brightest Cluster Galaxies
- Thermal ICM and Intra-Cluster Light
- Supermassive Black Holes & AGN Feedback







A lot of the "action" happened at redshifts well before these clusters were actual "clusters" (i.e. $z > 2$, for massive clusters)

Some definitions: Clusters versus “proto-clusters”

- **Cluster: virialized object (halo) with mass $M \gtrsim 10^{14}\ M_\odot$**

- **“Protocluster”: (Langrangian) volume that will collapse to form a $M \gtrsim 10^{14}\ M_\odot$ halo before or at $z = 0$**

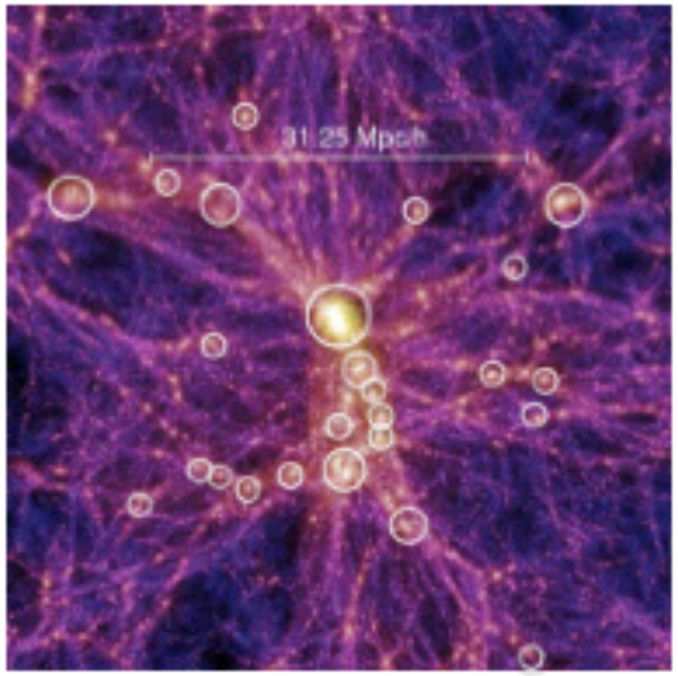
Some observations:

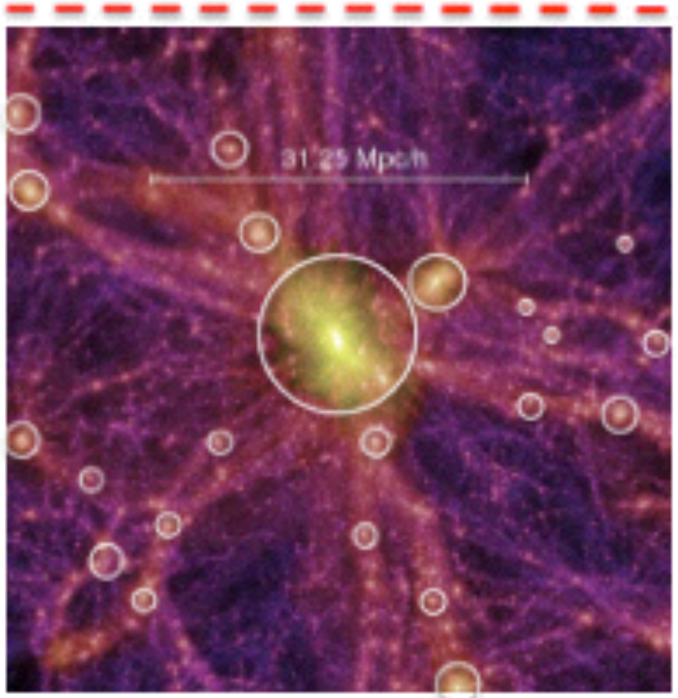
1) the distinction is clear only in theory/simulations, less clear in observations
2) the $10^{14}\ M_\odot$ threshold is somewhat arbitrary, but follows the convention
3) a $10^{14}\ M_\odot$ object at z~2 is *also* a proto-cluster of a $10^{15}\ M_\odot$ cluster at z~0
4) other useful definitions exist: Thermalized X-ray ICM ? Well-defined red-sequence ? Strong environmental effects ?

The total number density of clusters and protoclusters at any redshift is equal to the cluster abundance today:

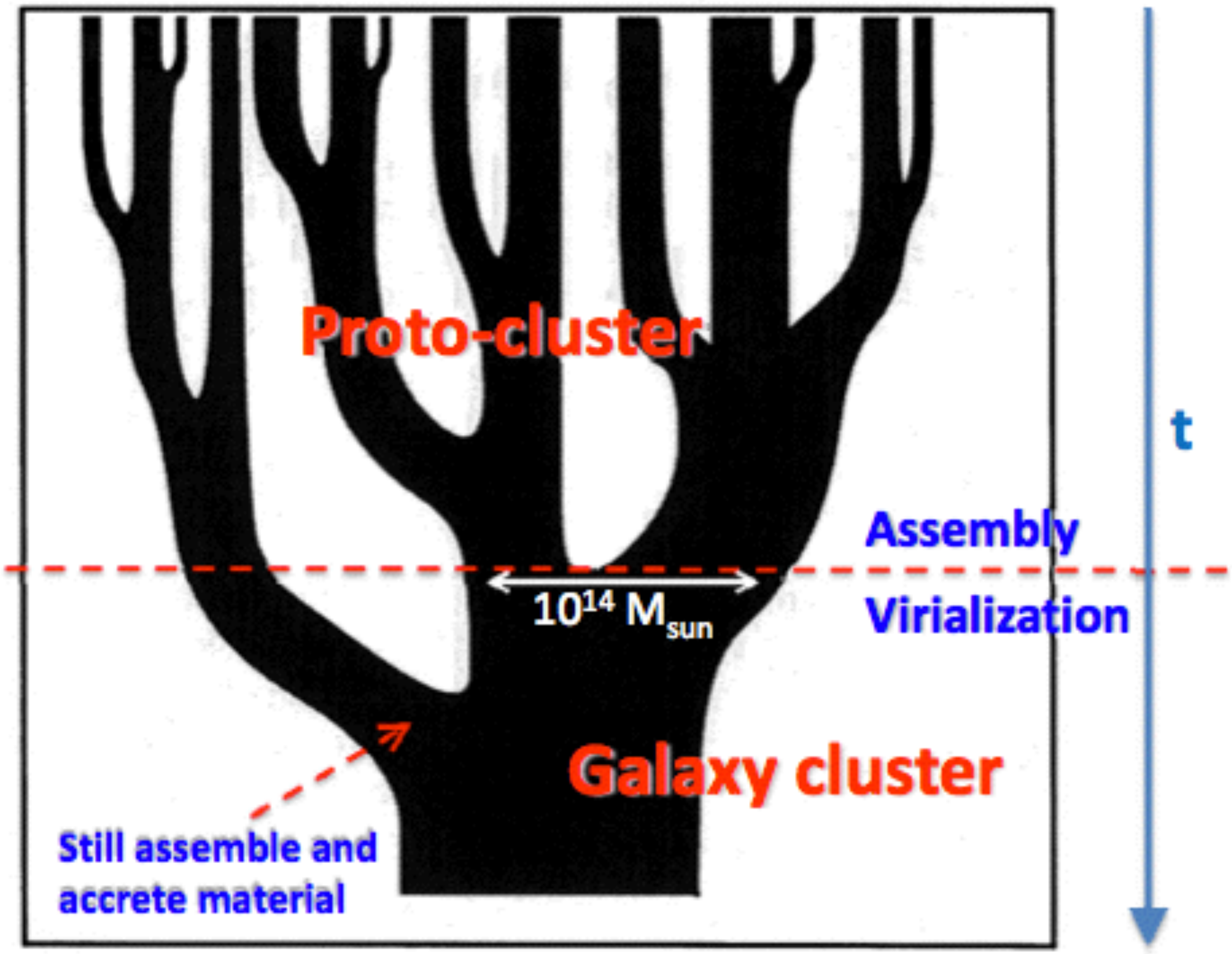
$$n_{clusters}(M_{z=0},z) + n_{protoclusters}(M_{z=0},z) = n_{clusters}(M_{z=0},z=0)$$

Some definitions: Clusters versus “proto-clusters”





Dark matter halo merger tree



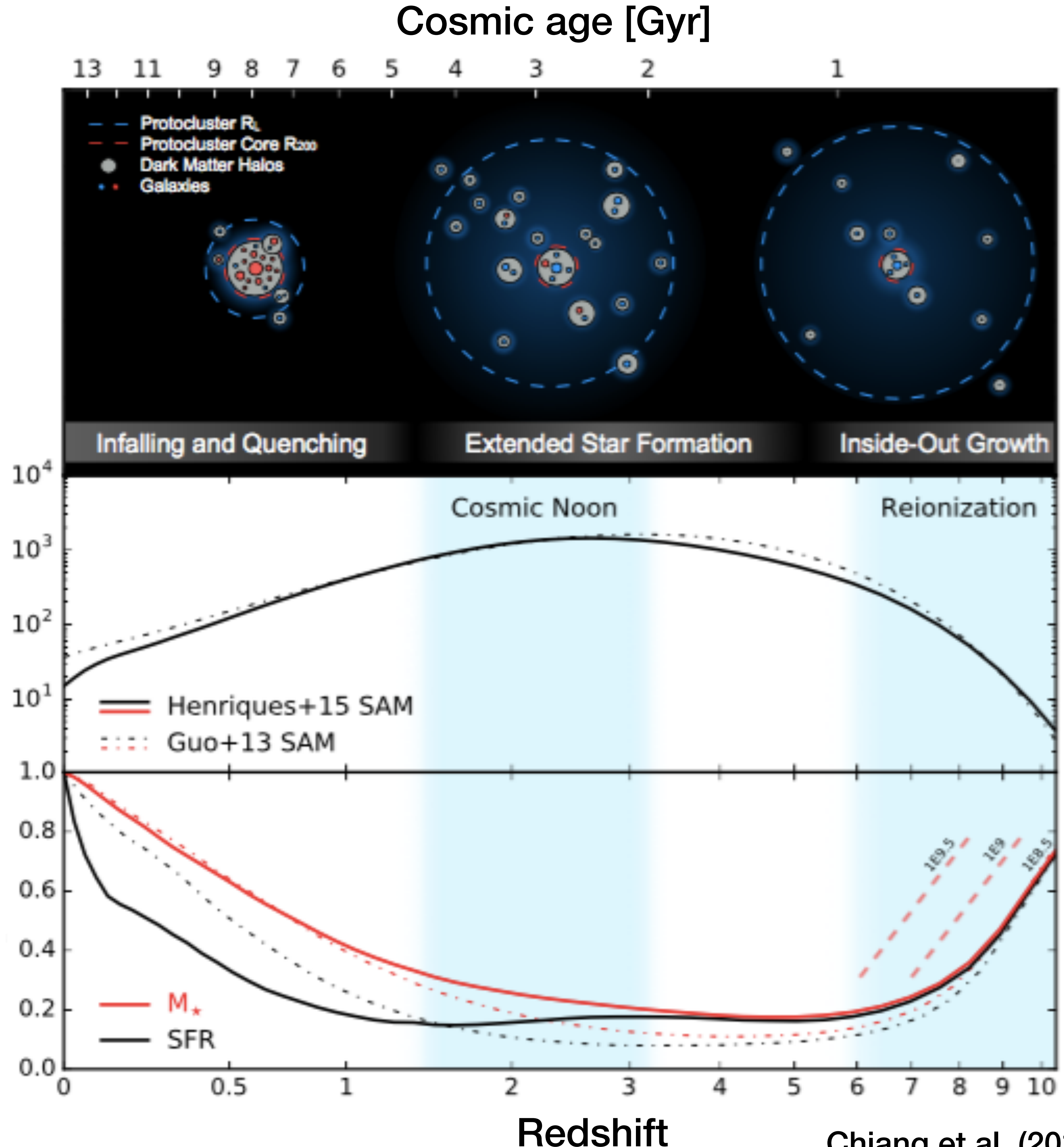
Lacey and Cole 1993

- formation of most halos and their galaxies happens in large overdense regions of star-forming galaxies at high redshift *long before virialization*

Most of galaxy and halo formation happens during the proto-cluster phase of the collapse:

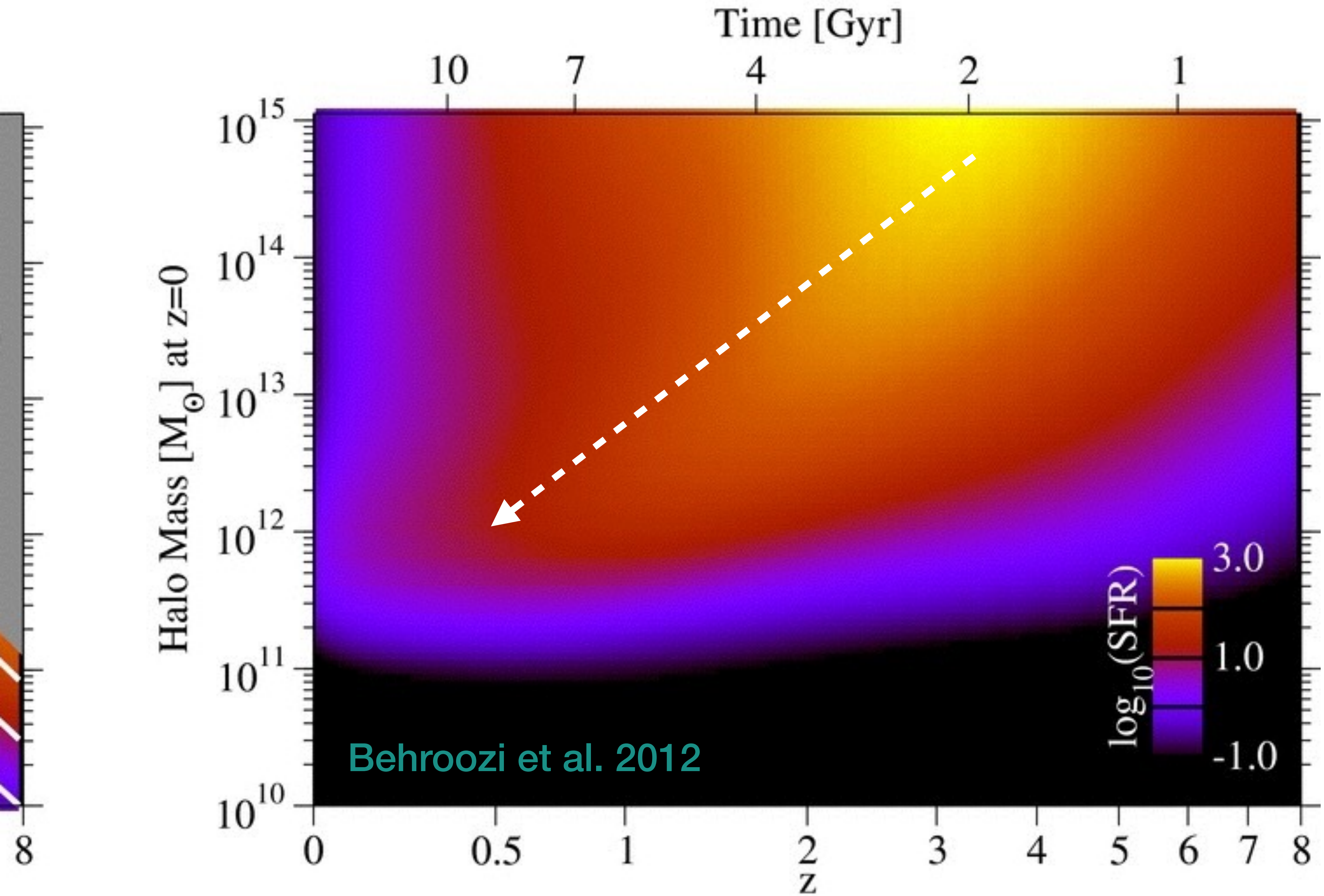
Total SFR

Fraction of SFR (mass) in cluster "core"



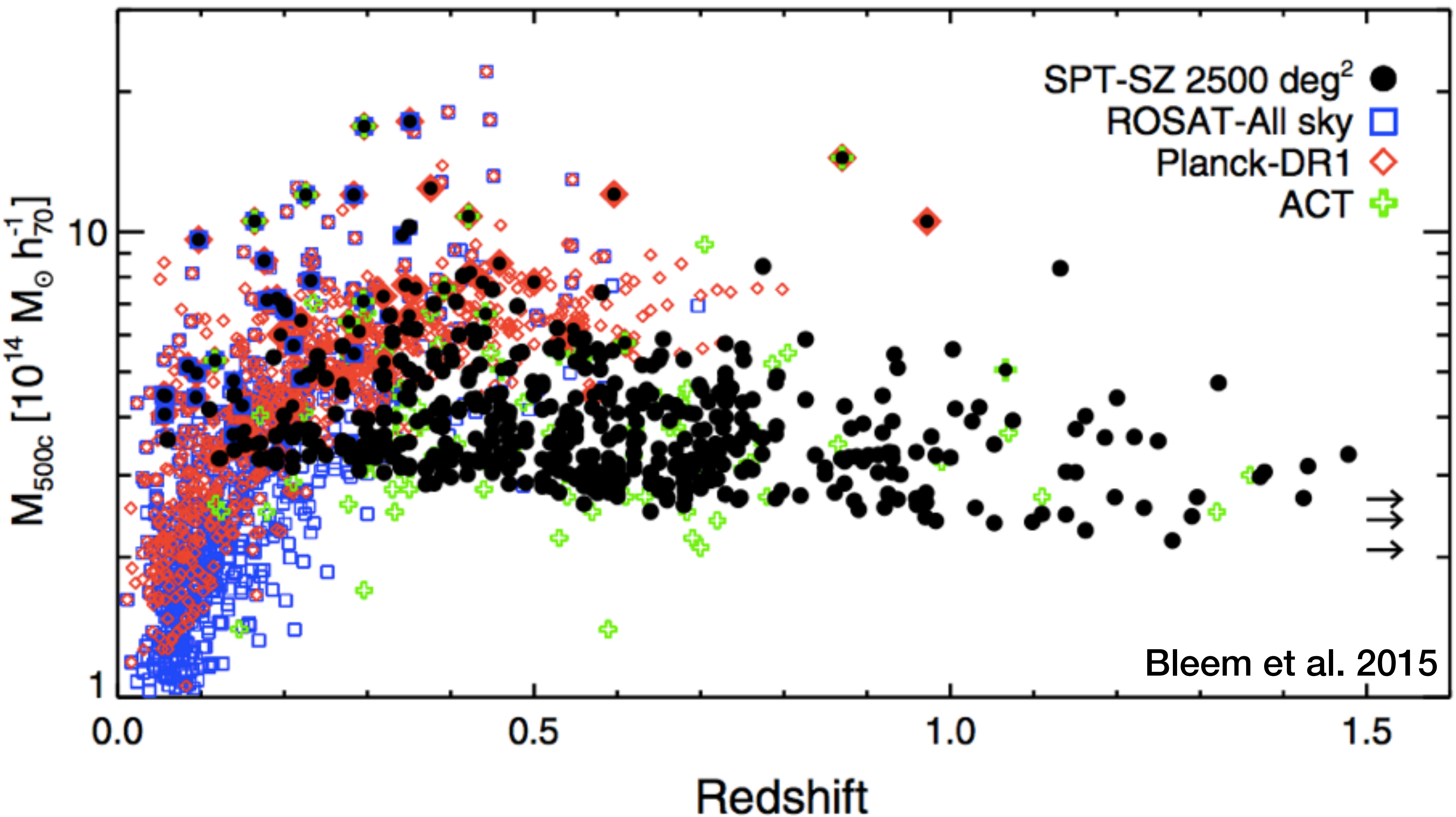
Chiang et al. (2017)

Evolution of star formation rate as function of halo mass



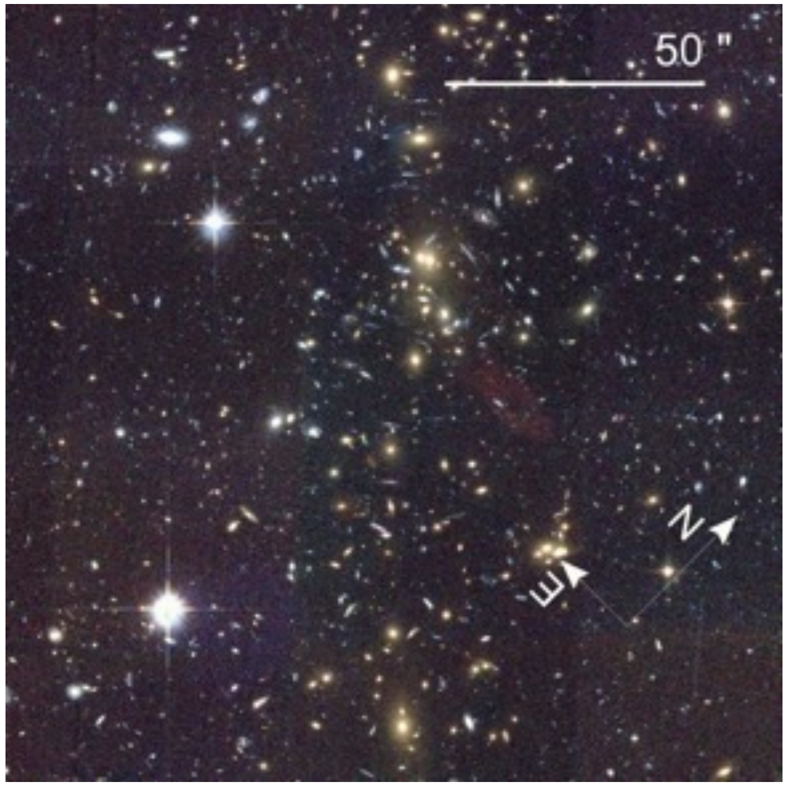
- more massive dark matter halos formed their stars earlier
- for massive clusters and their galaxies, even z ~ 2 is too nearby

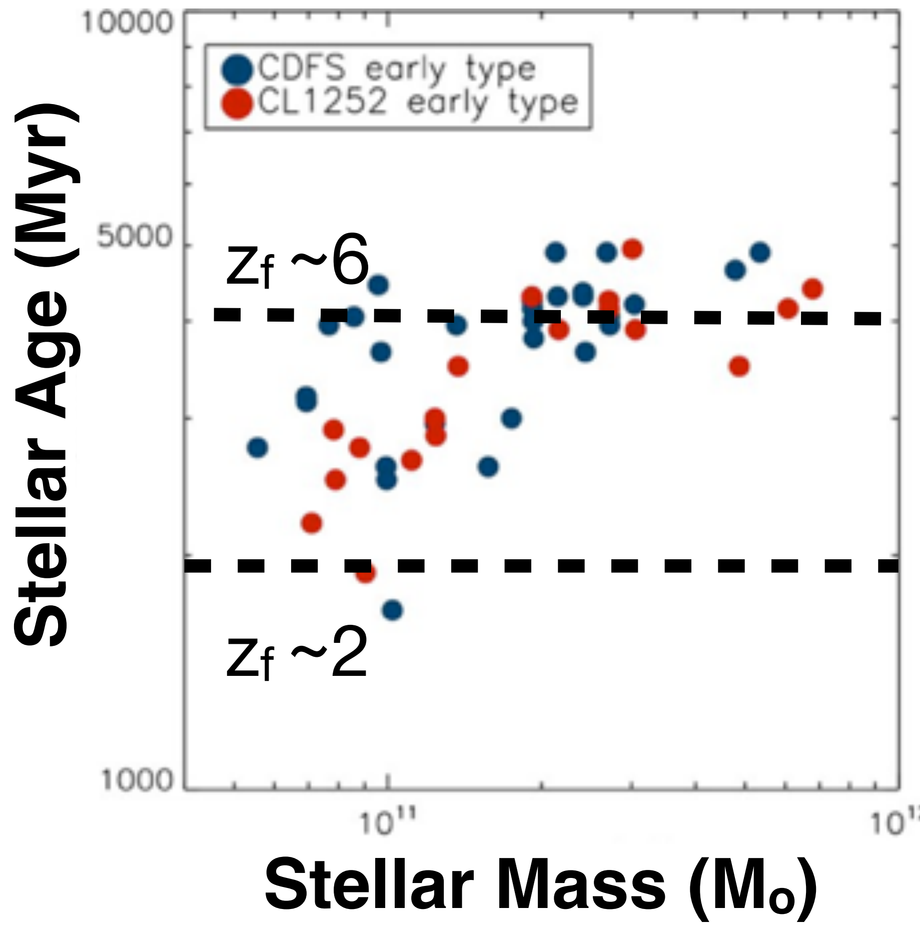
Recent compilation of X-ray and SZ-selected clusters



- WL, X-ray, SZE, red sequence techniques impractical by z ~ 2

Higher redshift clusters not necessarily yield younger systems!



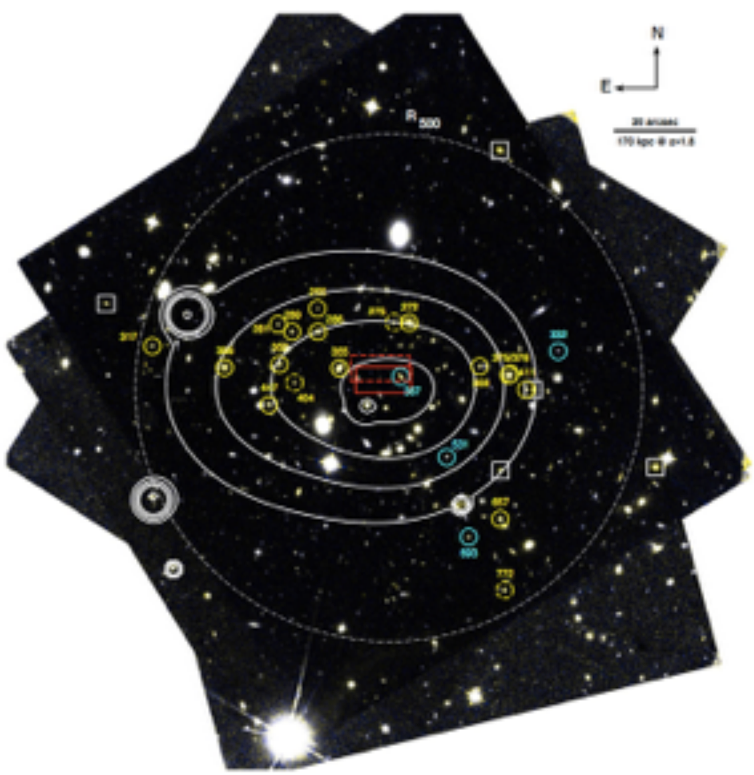


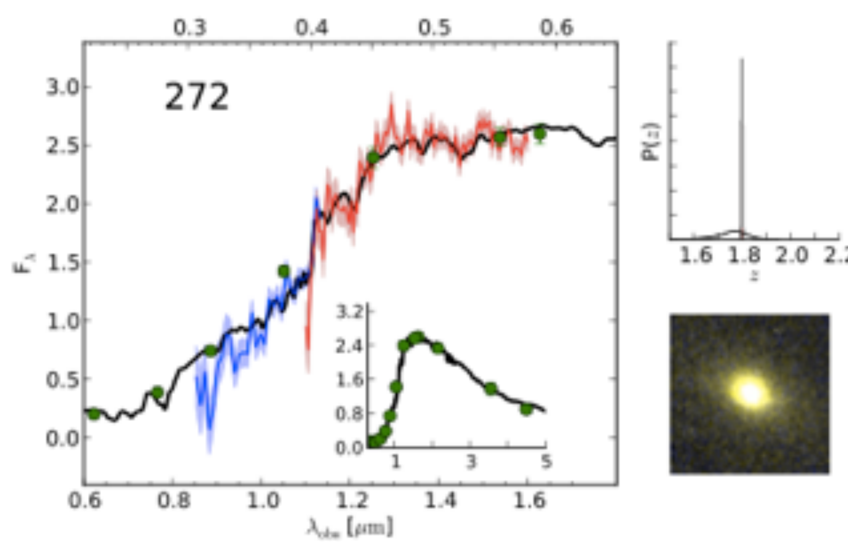
CL1252 at z = 1.24

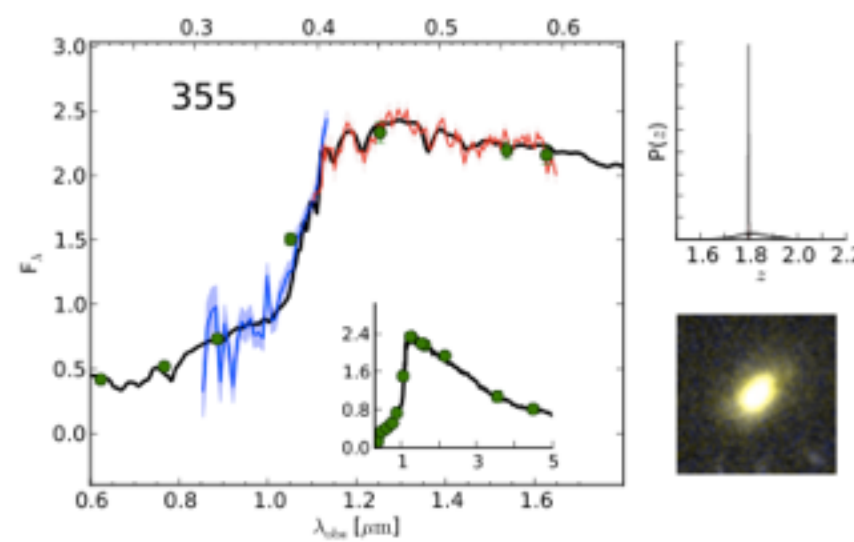
Rettura et al. (2010)

JKCS041 at z = 1.8

Newman et al. (2014)







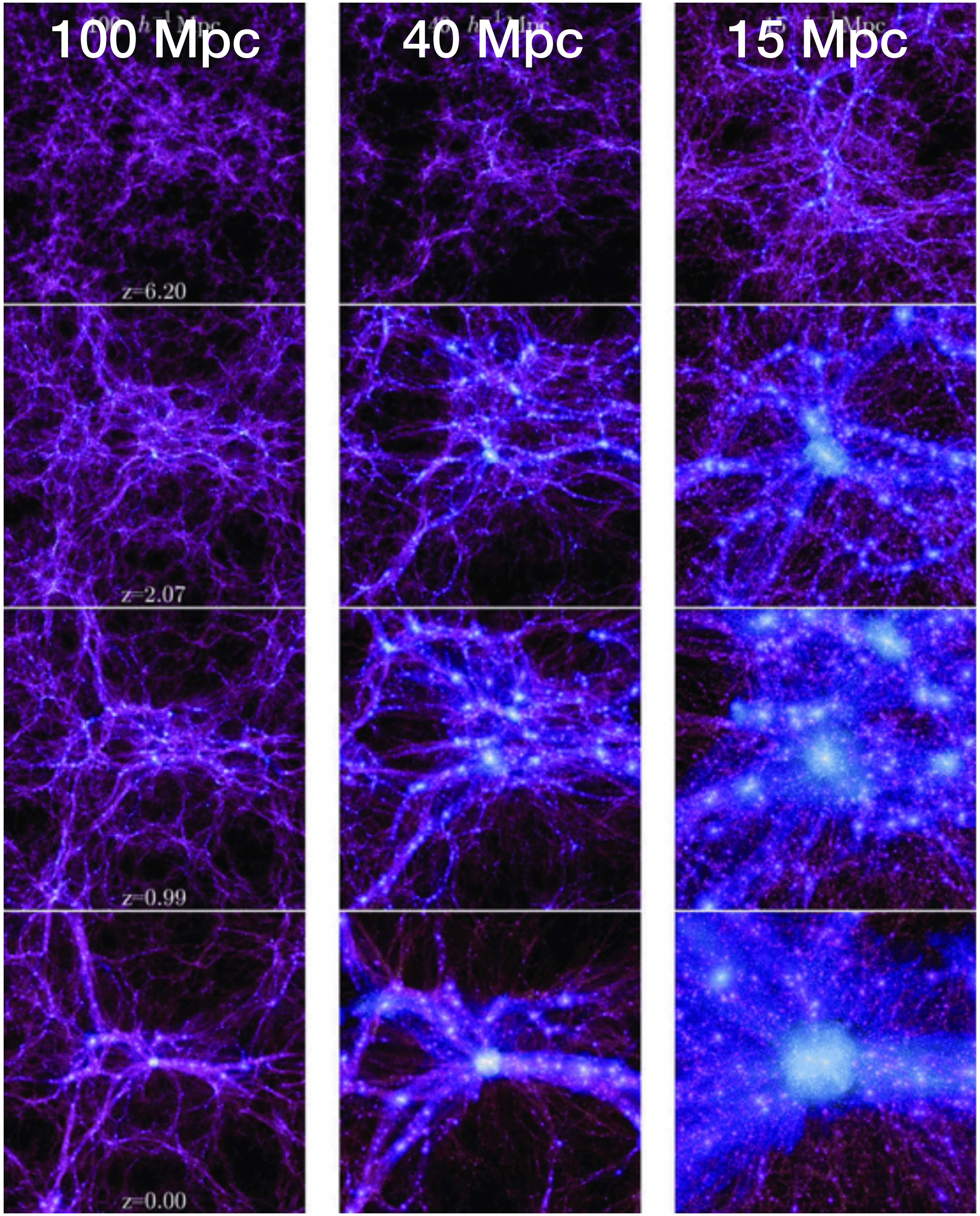
Cluster formation in a hierarchical universe

z = 6

z = 2

z = 1

z = 0



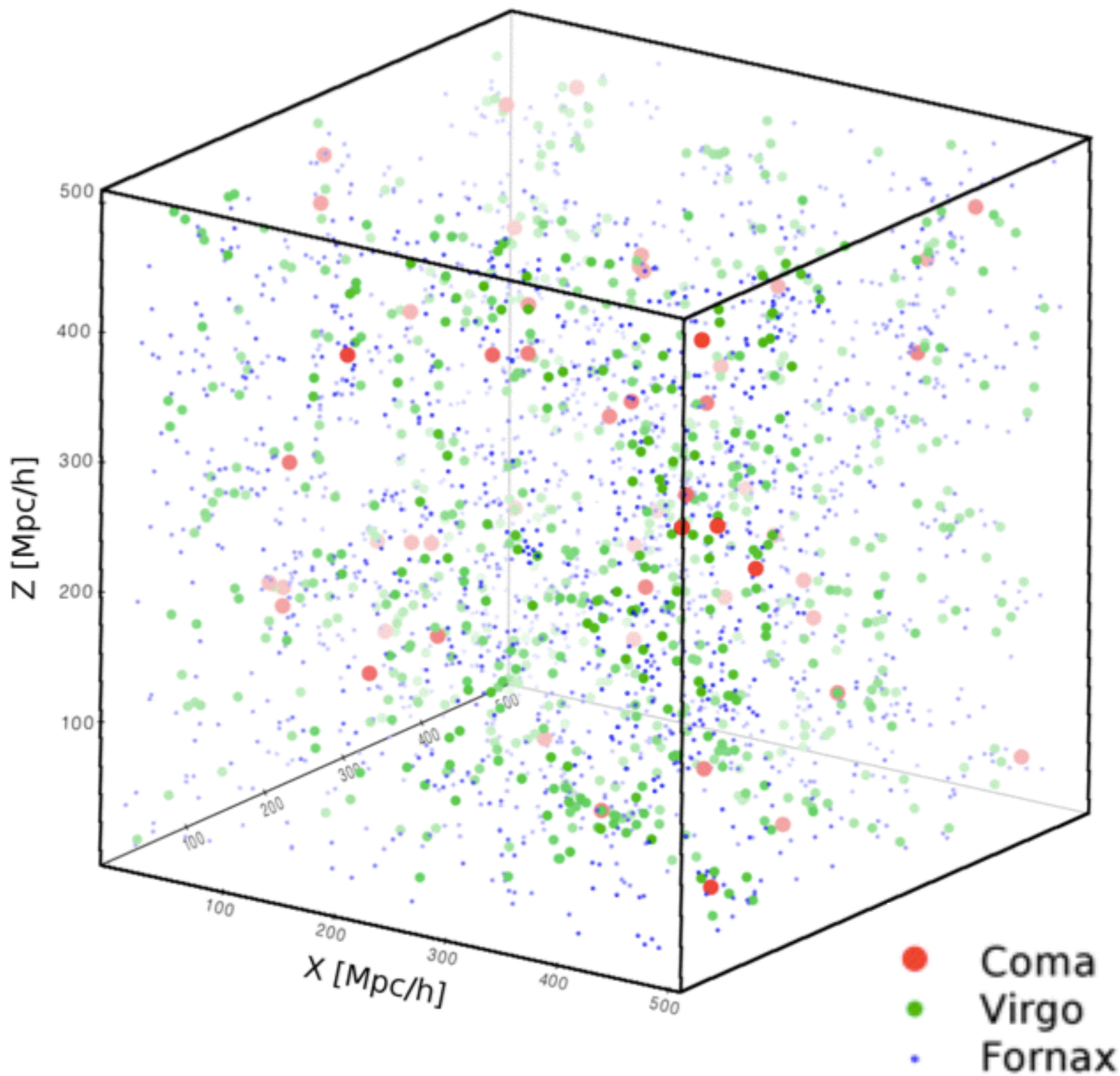
- large-scale (~100 Mpc) dark matter overdensities present from very early on (z>6)
- multiple centers, filamentary structure and elongated halos present at least down to z~2
- last major mergers at z~1
- single cluster-sized halo surrounded by “frozen” large-scale structure at z~0

Boylan-Kolchin et al. (2012)

Cluster growth in cosmological simulations

Chiang, Overzier & Gebhardt (2013, 2014, 2015, 2017)

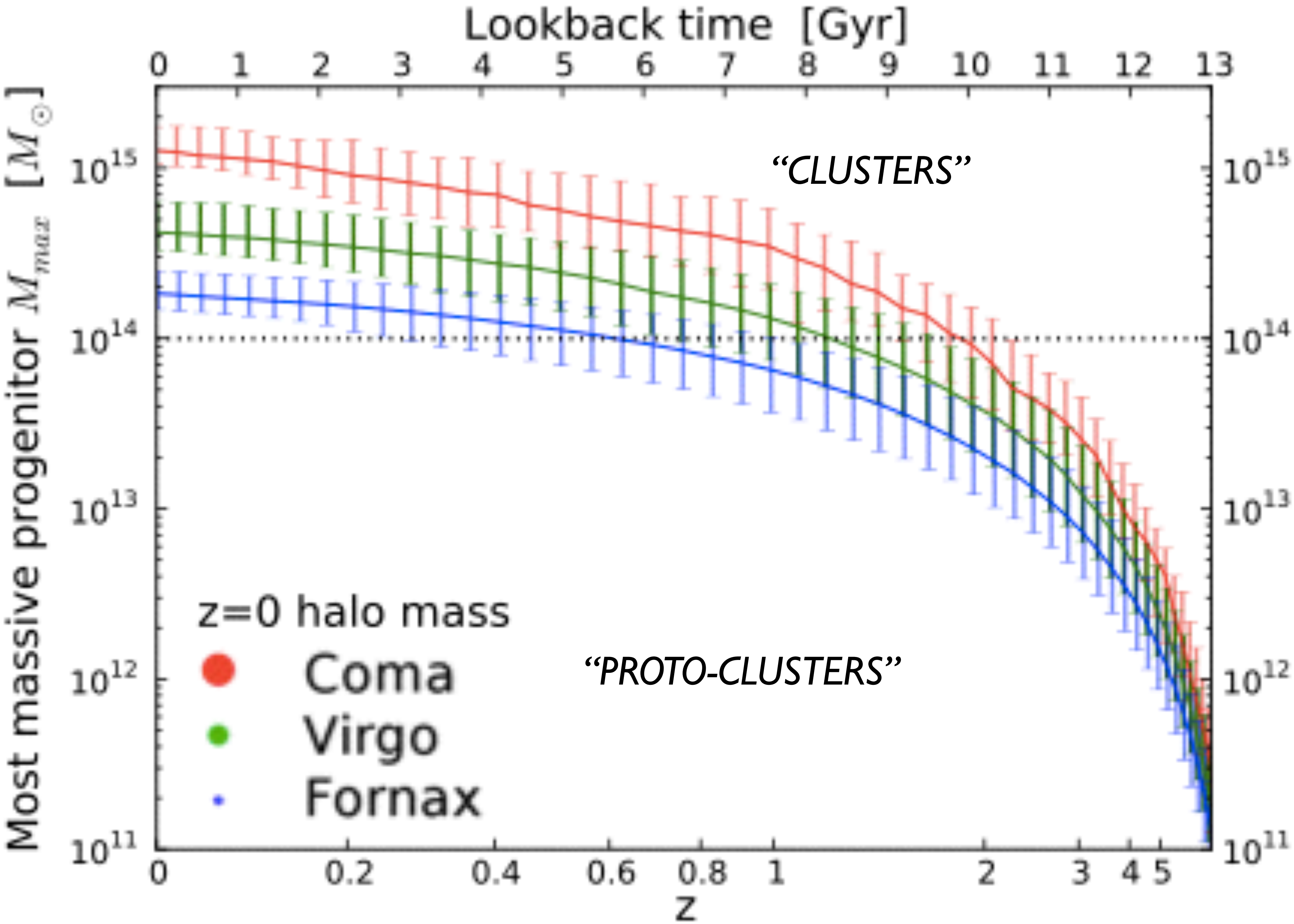
see also Suwa+06, Overzier+09, Sembolini+14, Muldrew+15, Contini+15

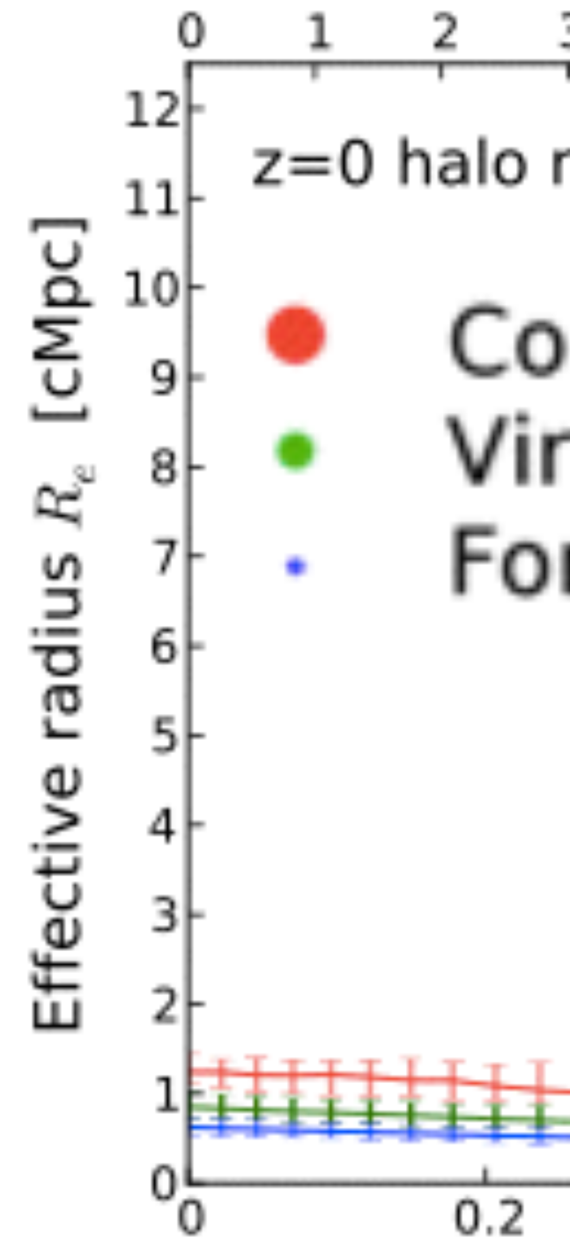


Millennium Run DM simulations + SAM galaxies

- GOALS: **understand current data** and **prepare for large surveys** of high redshift (proto-)clusters (e.g., VUDS, HSC, HETDEX, PFS)
- ~3,000 clusters from z~10 to z=0
- derive **sizes**, **masses** and **overdensity statistics** of cluster progenitors as function of (M,z)
- results relatively insensitive to either cosmology or semi-analytics

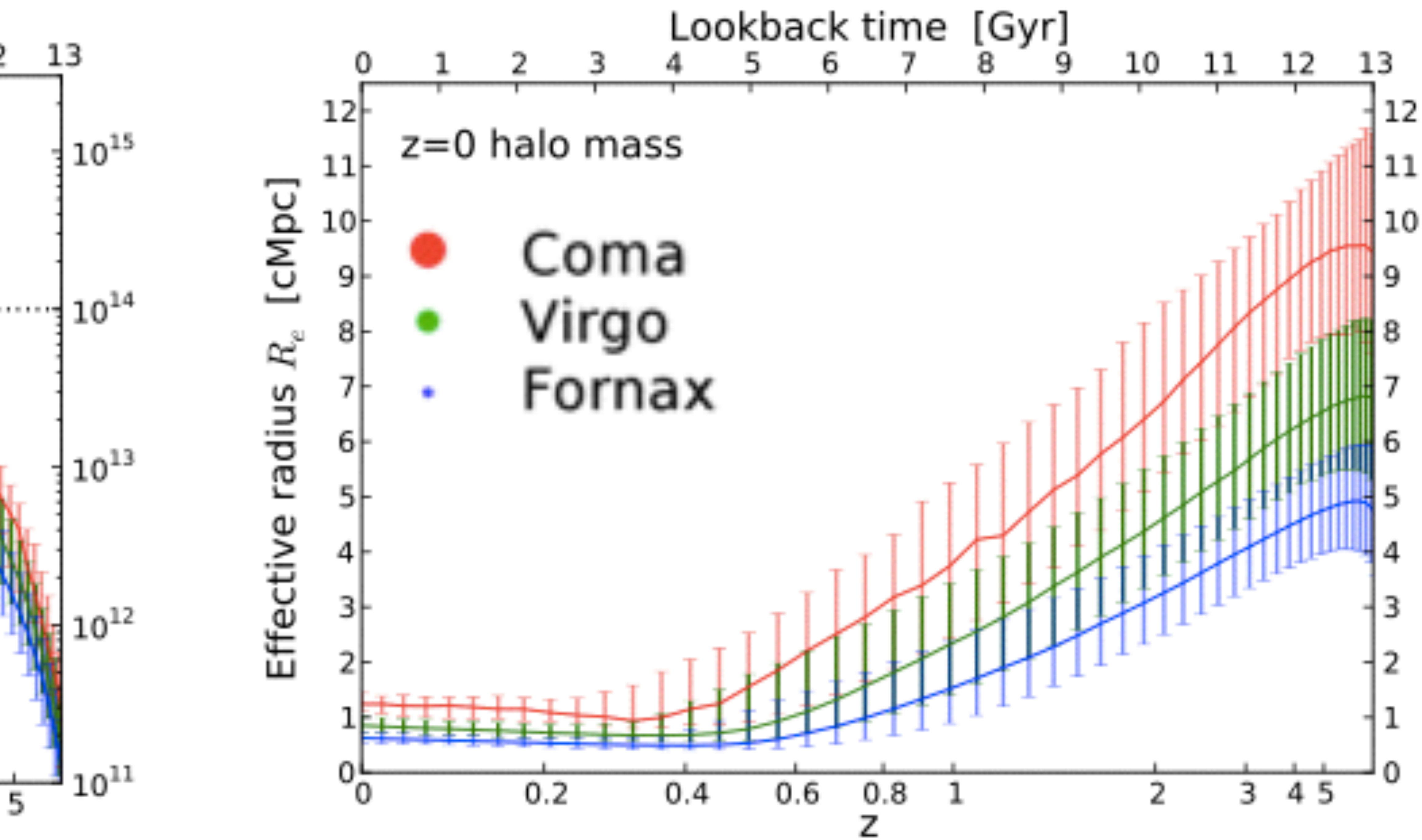
Mass evolution of clusters (central halos only)





Chiang, Overzier & Gebhardt (2013)

Size evolution of (proto-)clusters

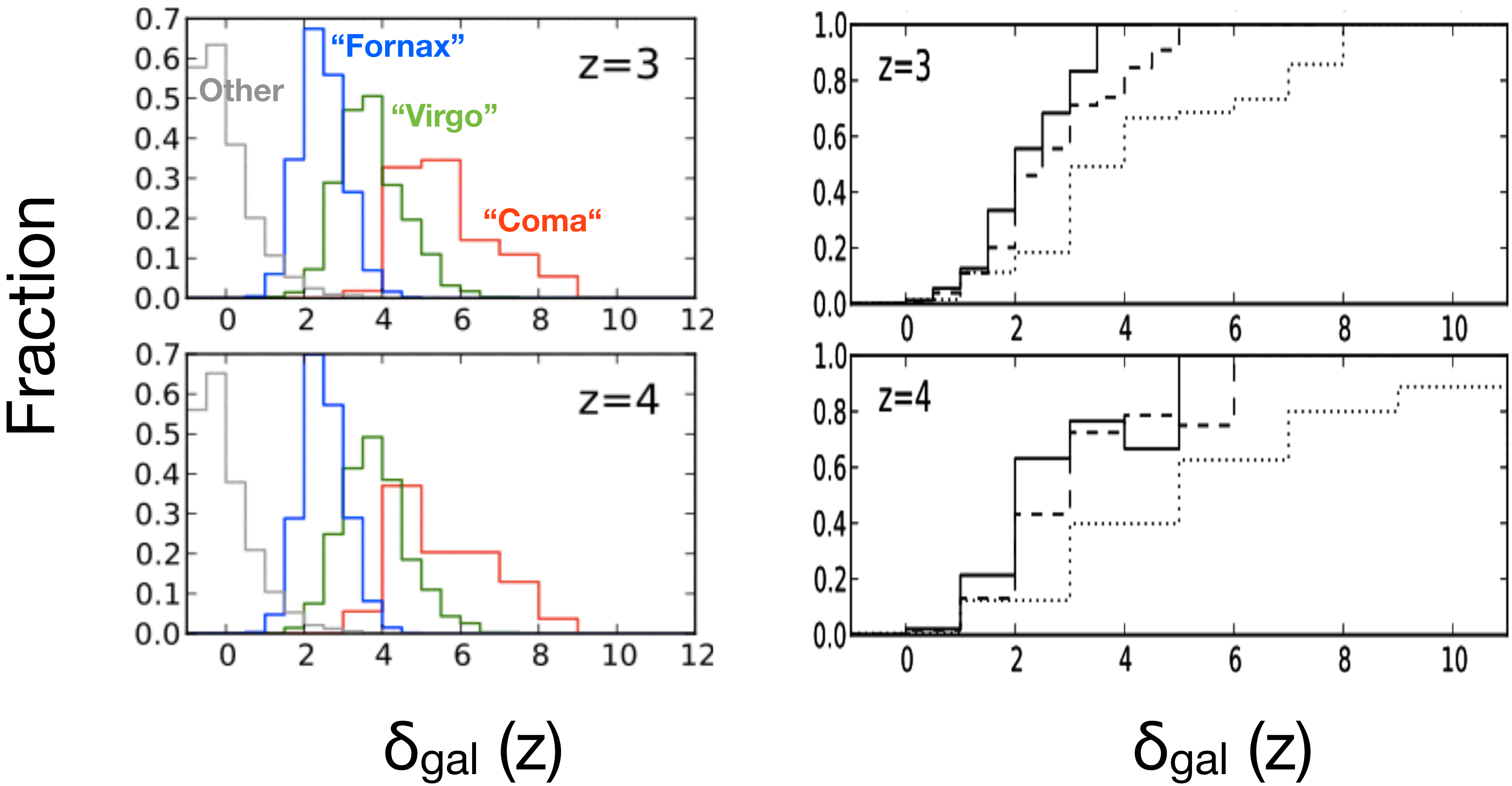


(Rₑ is the second order moment of the mass distribution)

Chiang, Overzier & Gebhardt (2013)

Galaxy overdensities derived from the simulated clusters

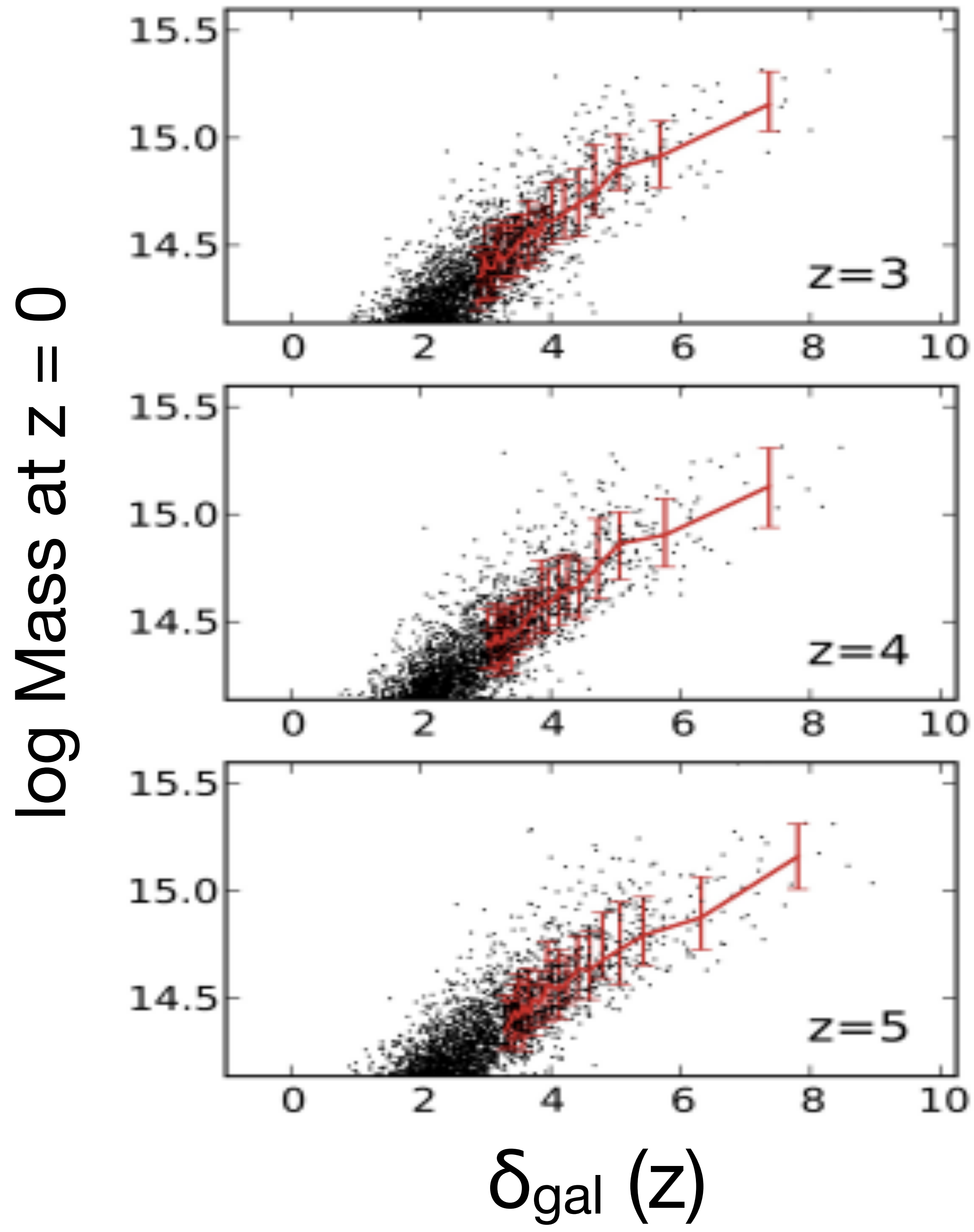
Galaxy overdensity | Success rate



- **higher mass clusters today generally came from higher overdensities**
- **higher overdensities have lower contamination (but higher incompleteness)**

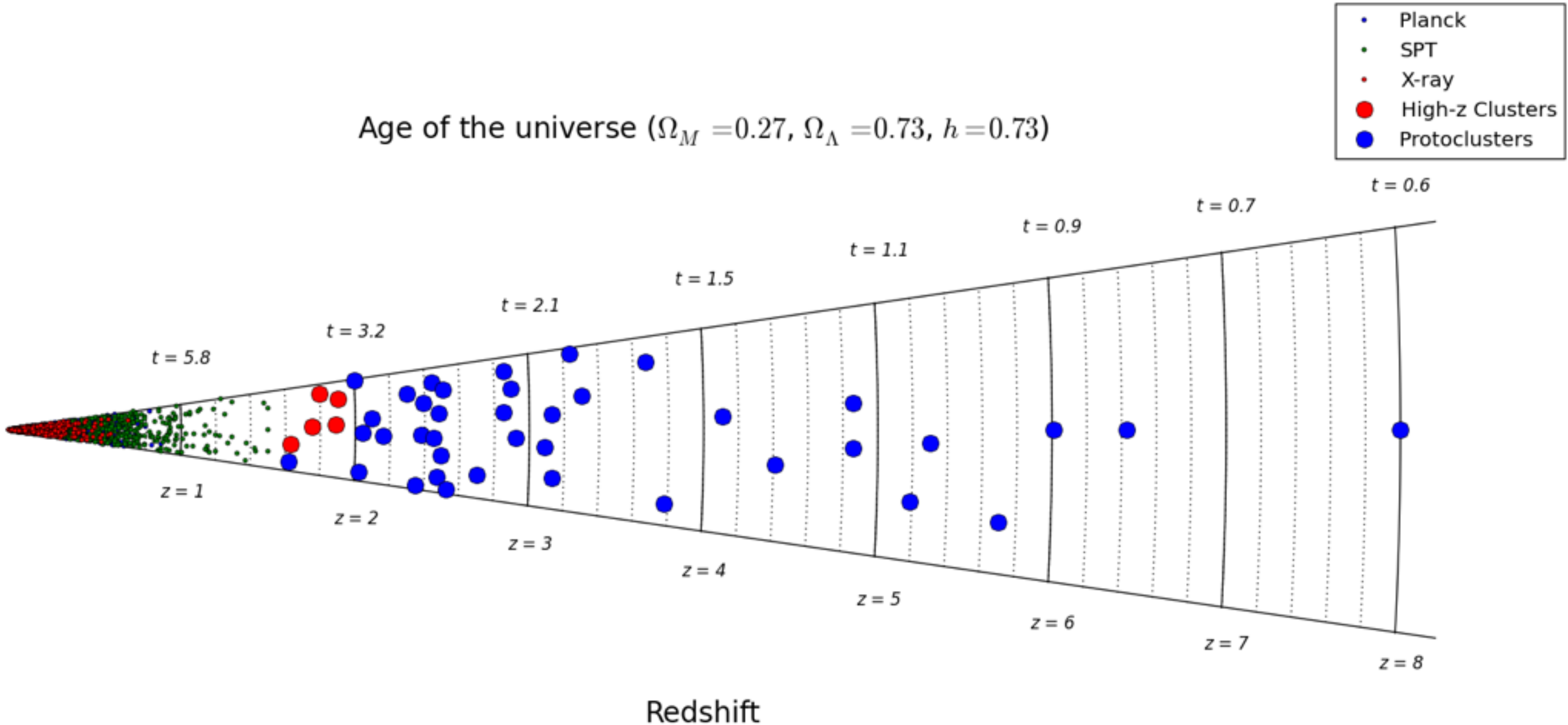
Galaxy overdensities derived from the simulated clusters

Estimating the present-day mass estimate of high redshift overdensities



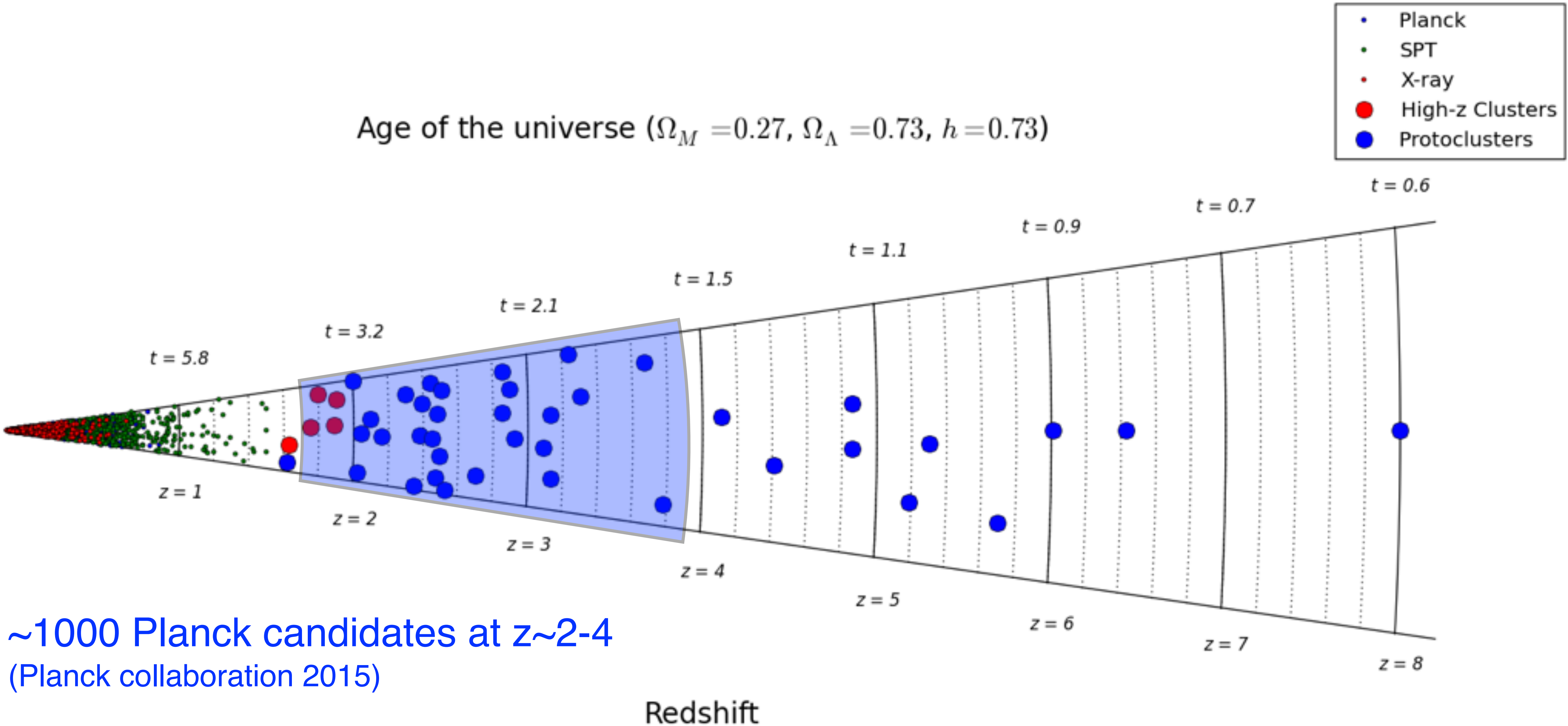
- **high-z overdensities reasonably accurate proxies for z = 0 cluster mass**
- **this should allow us to track cluster evolution all the way back to z > 2**

Overview of galaxy protoclusters discovered to date



Overzier (2016)

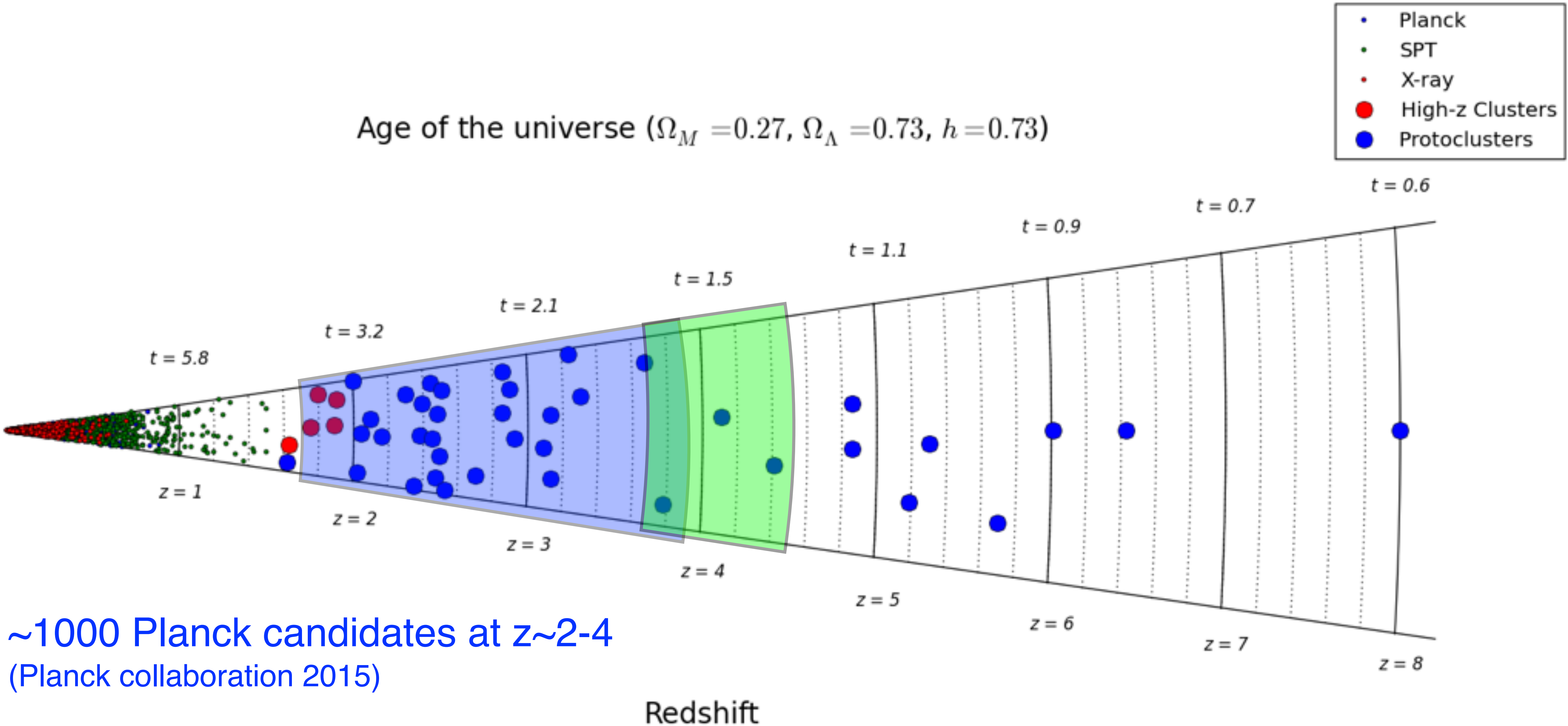
Overview of galaxy protoclusters discovered to date



~1000 Planck candidates at z~2-4
(Planck collaboration 2015)

Overzier (2016)

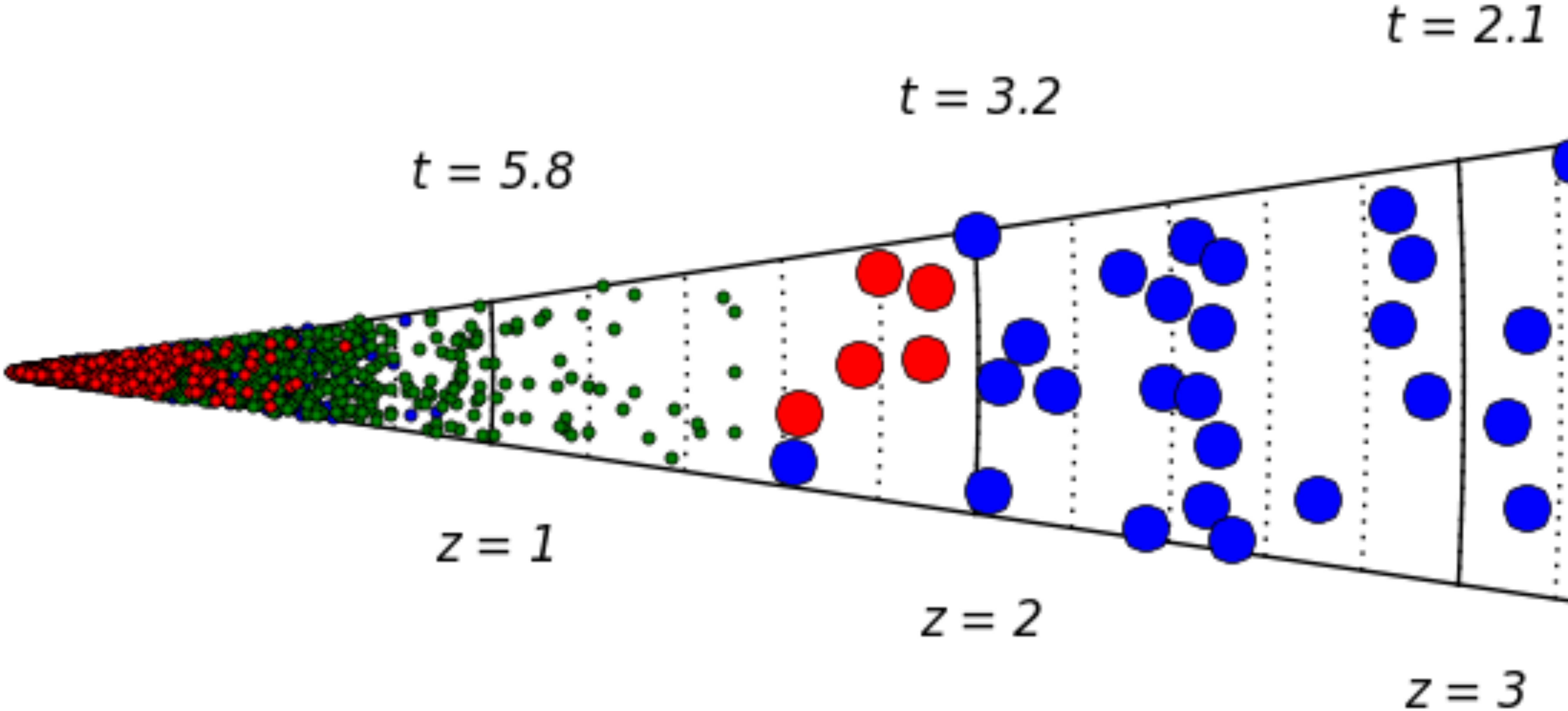
Overview of galaxy protoclusters discovered to date

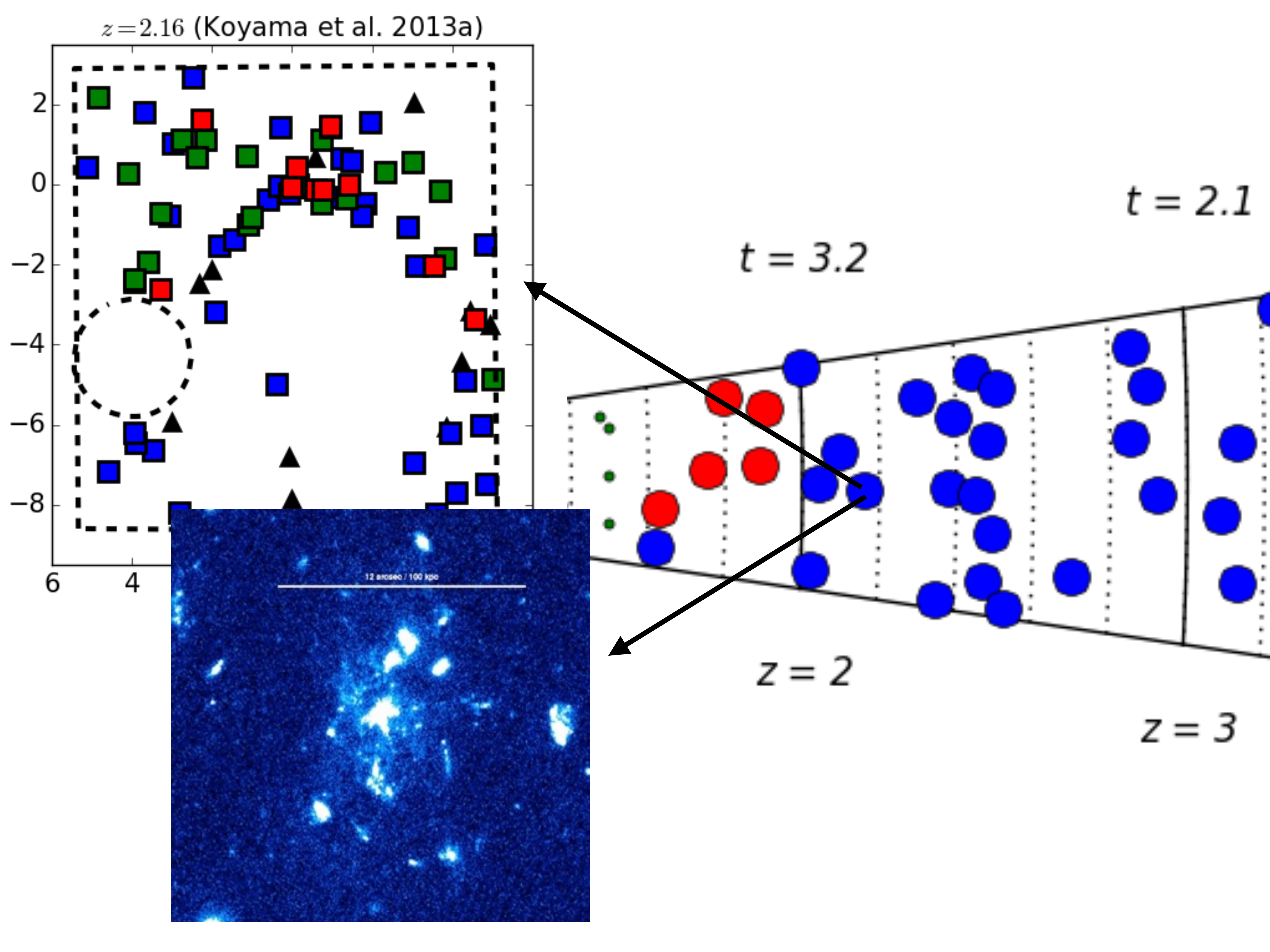


~1000 Planck candidates at z~2-4
(Planck collaboration 2015)

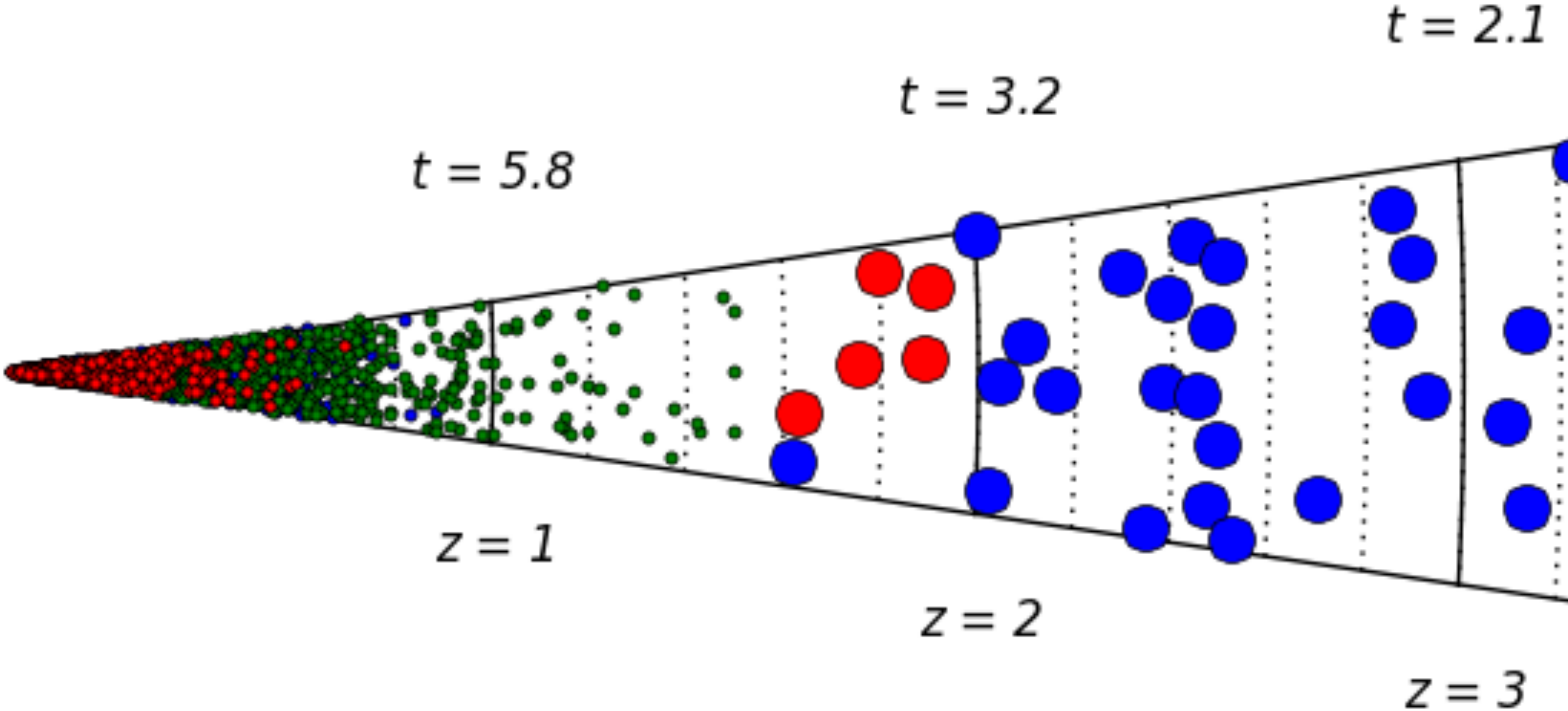
~200 Subaru HyperSuprimeCam candidates at z~4
(Uchiyama et al. 2017; Toshikawa et al. 2017)

Overzier (2016)


t = 2.1
t = 3.2
t = 5.8
z = 1
z = 2
z = 3



$z = 2.16$ (Koyama et al. 2013a)
2
0
−2
−4
−6
−8
6
4
t = 3.2
t = 2.1
z = 2
z = 3


t = 2.1
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z = 1
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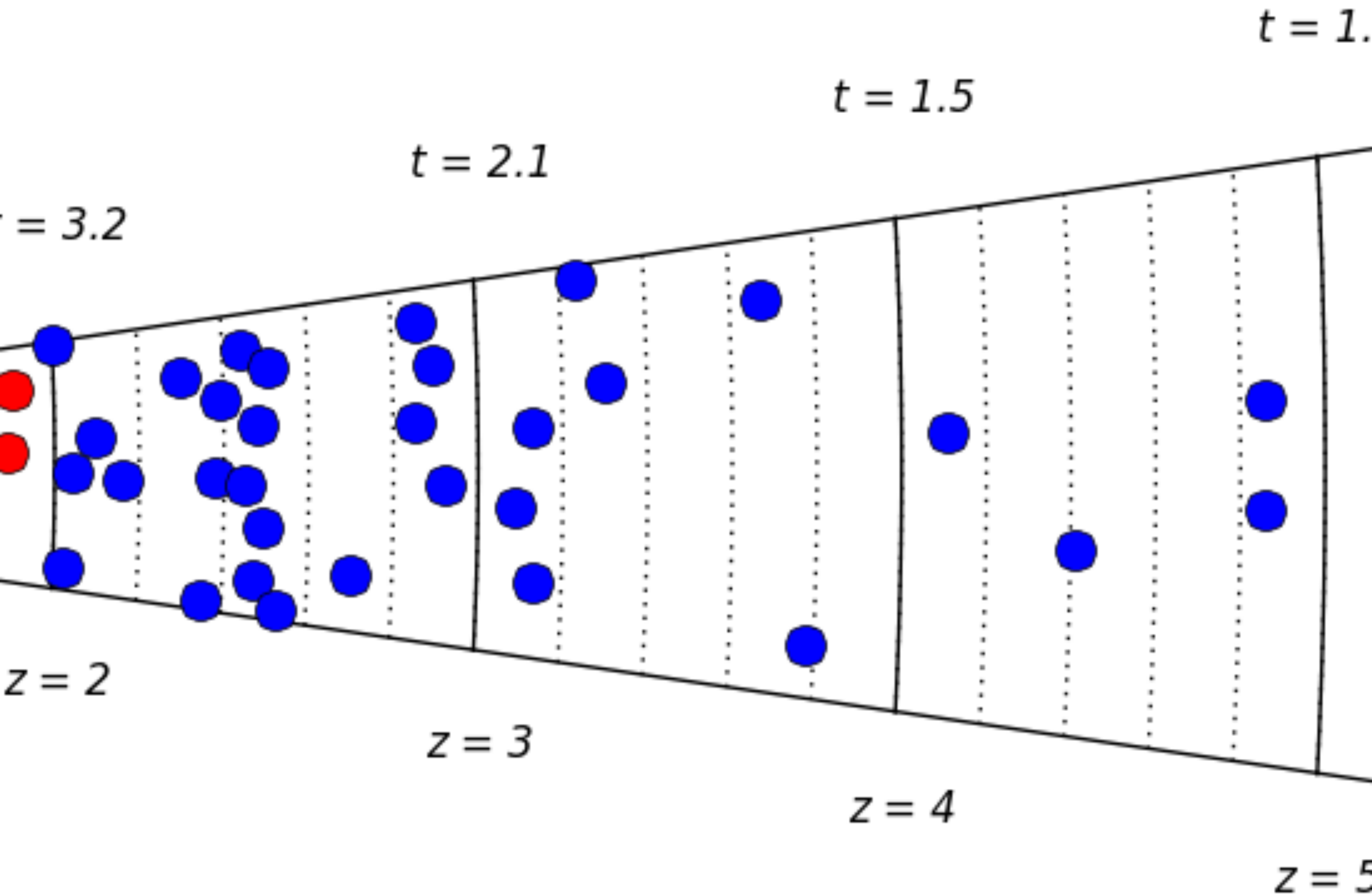
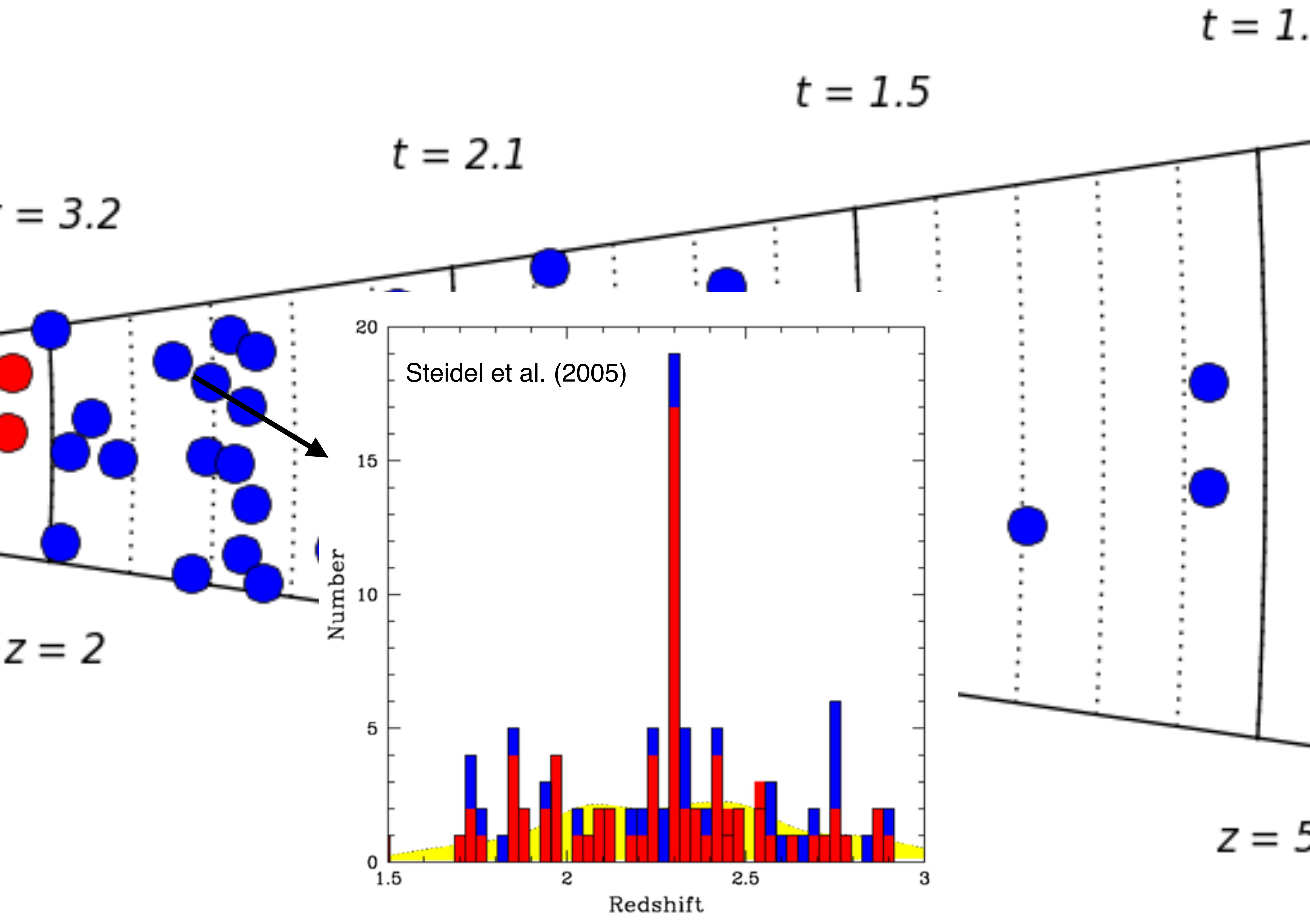
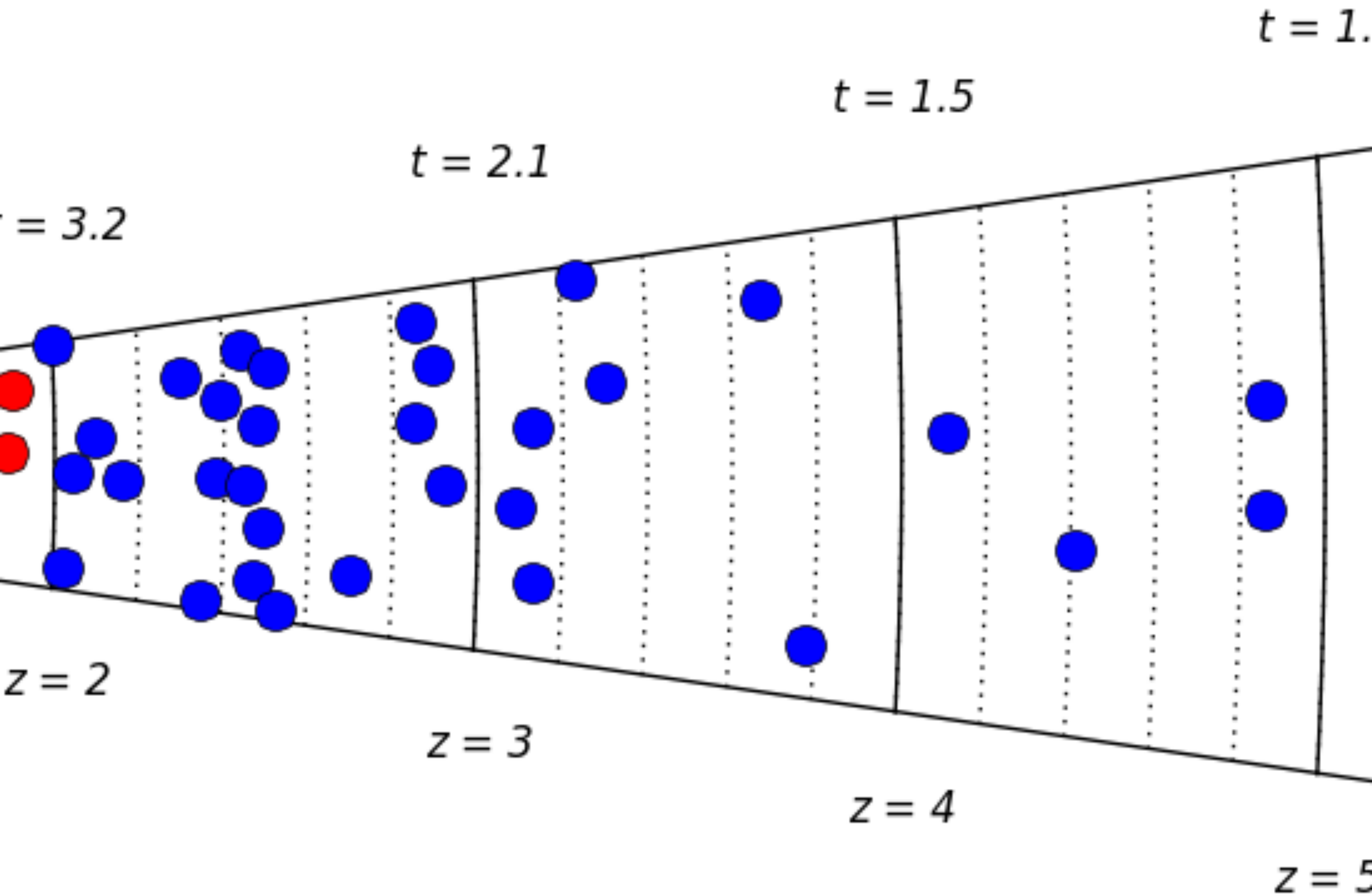
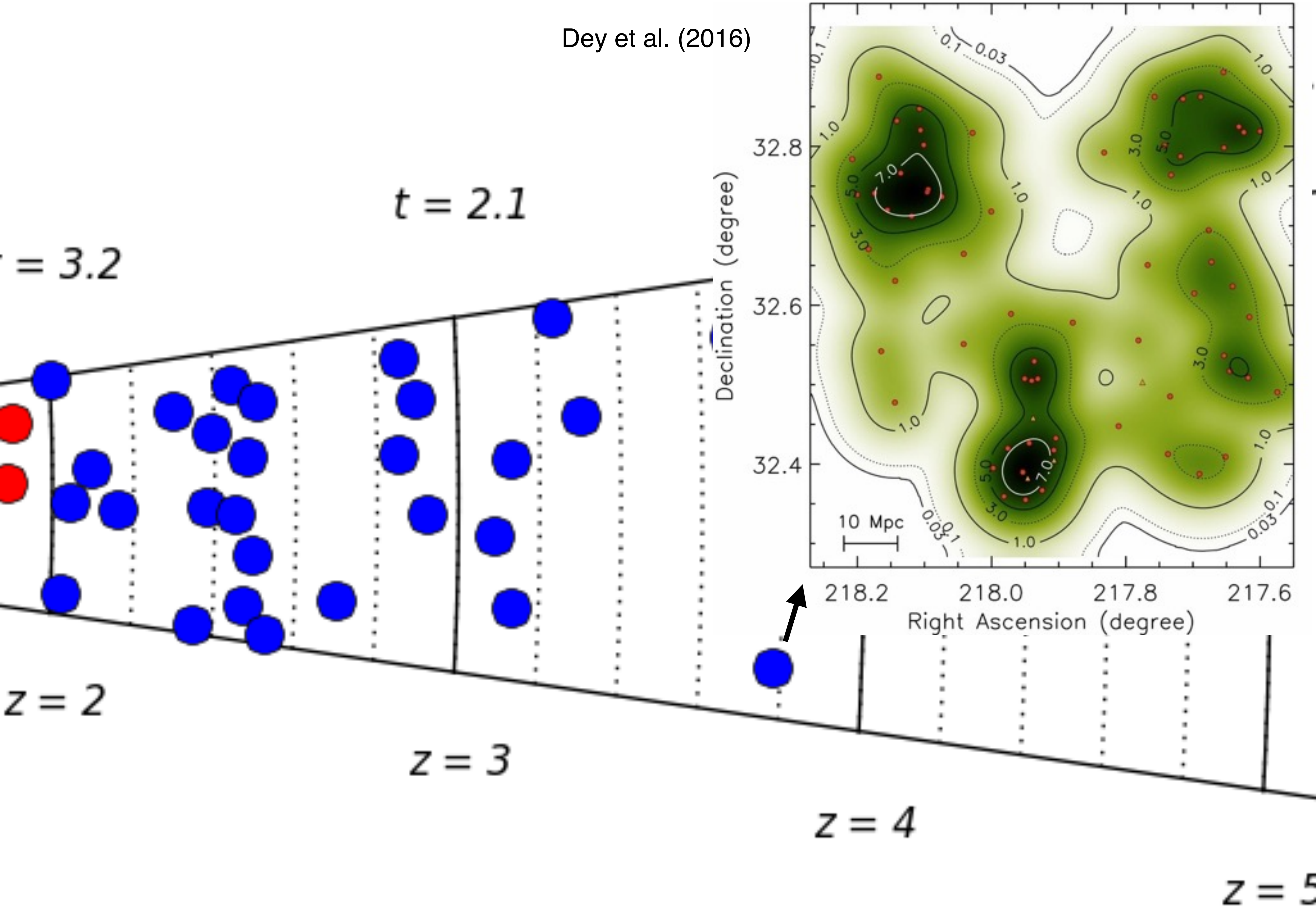
z = 3


t = 1.
t = 1.5
t = 2.1
= 3.2
z = 2
z = 3
z = 4
z = 5

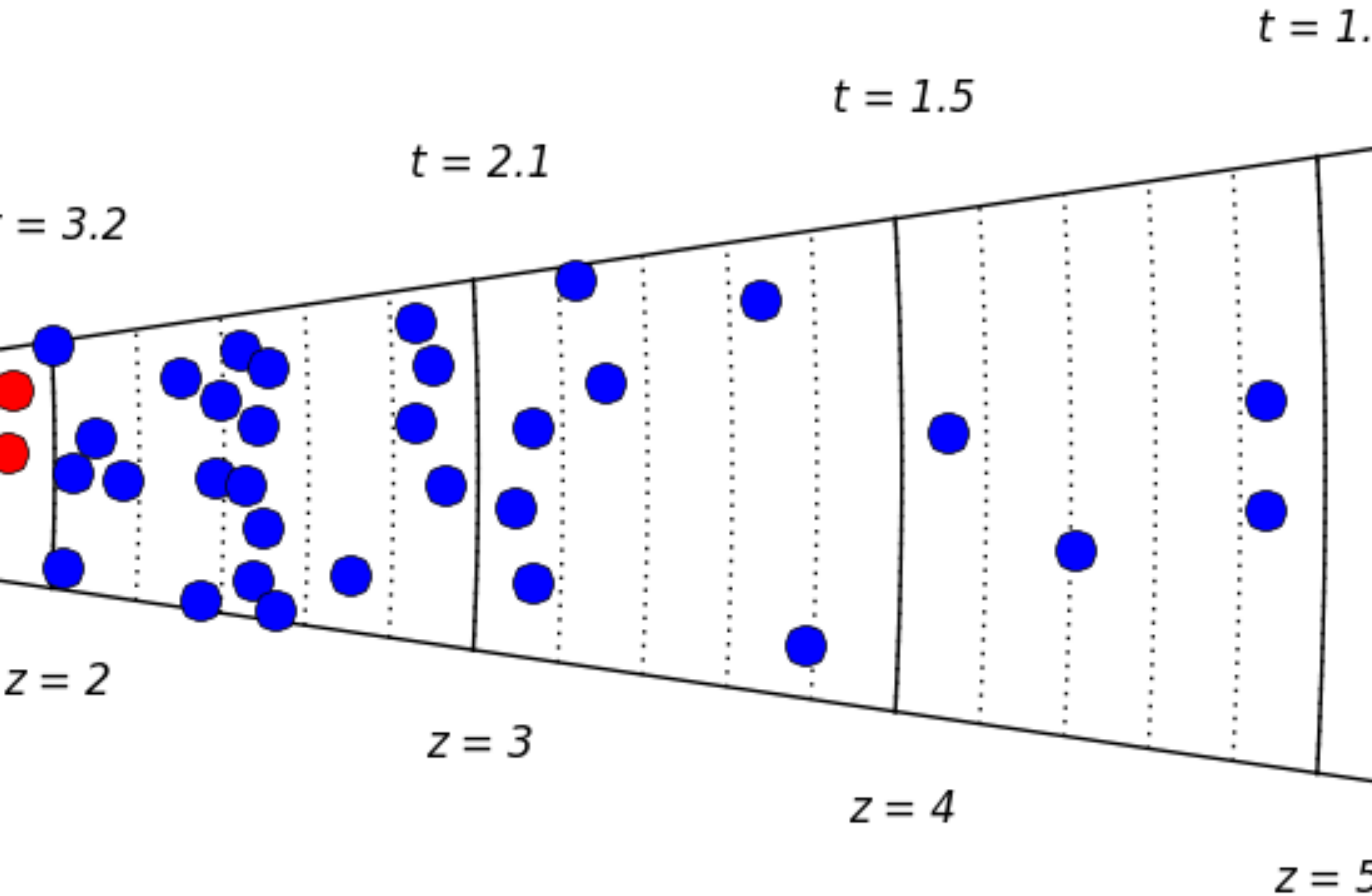

t = 1.
t = 1.5
t = 2.1
= 3.2
z = 2
z = 5
Steidel et al. (2005)
Number
Redshift
20
15
10
5
0
1.5
2
2.5
3



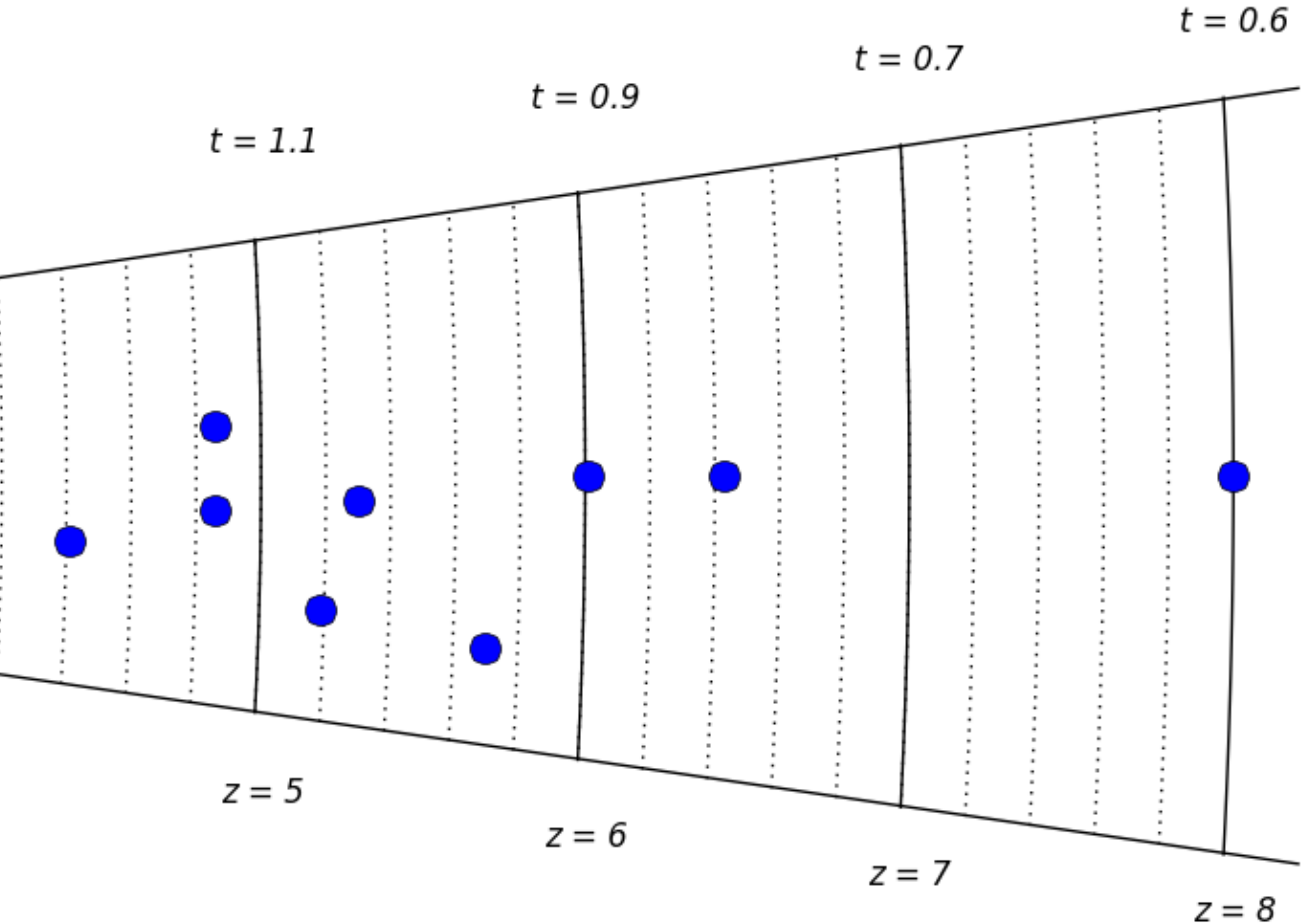
= 3.2
t = 2.1
t = 1.5
t = 1.
z = 2
z = 3
z = 4
z = 5

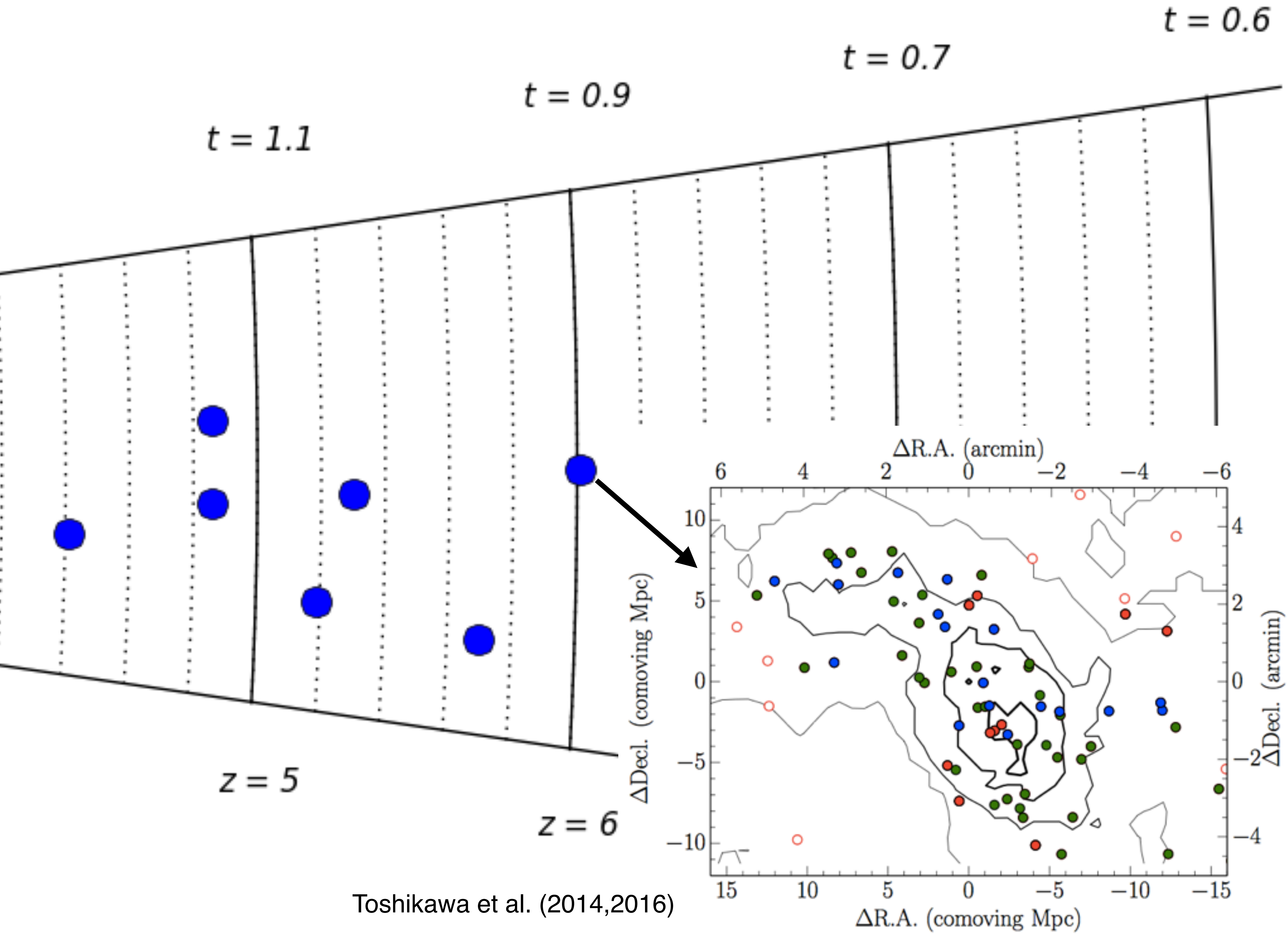


Dey et al. (2016)
t = 2.1
= 3.2
z = 2
z = 3
z = 4
z = 5
10 Mpc
Declination (degree)
Right Ascension (degree)
32.8
32.6
32.4
218.2
218.0
217.8
217.6

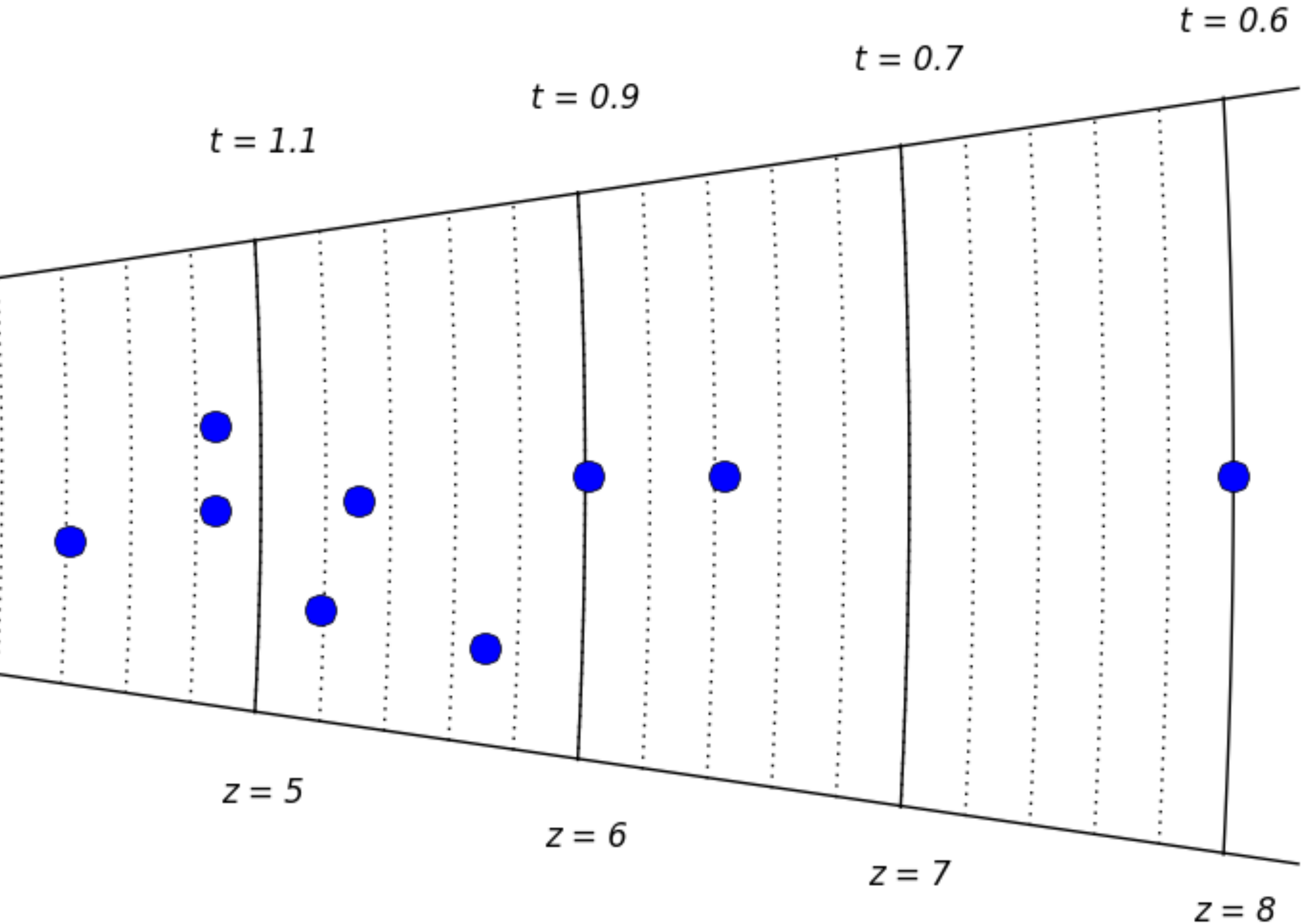


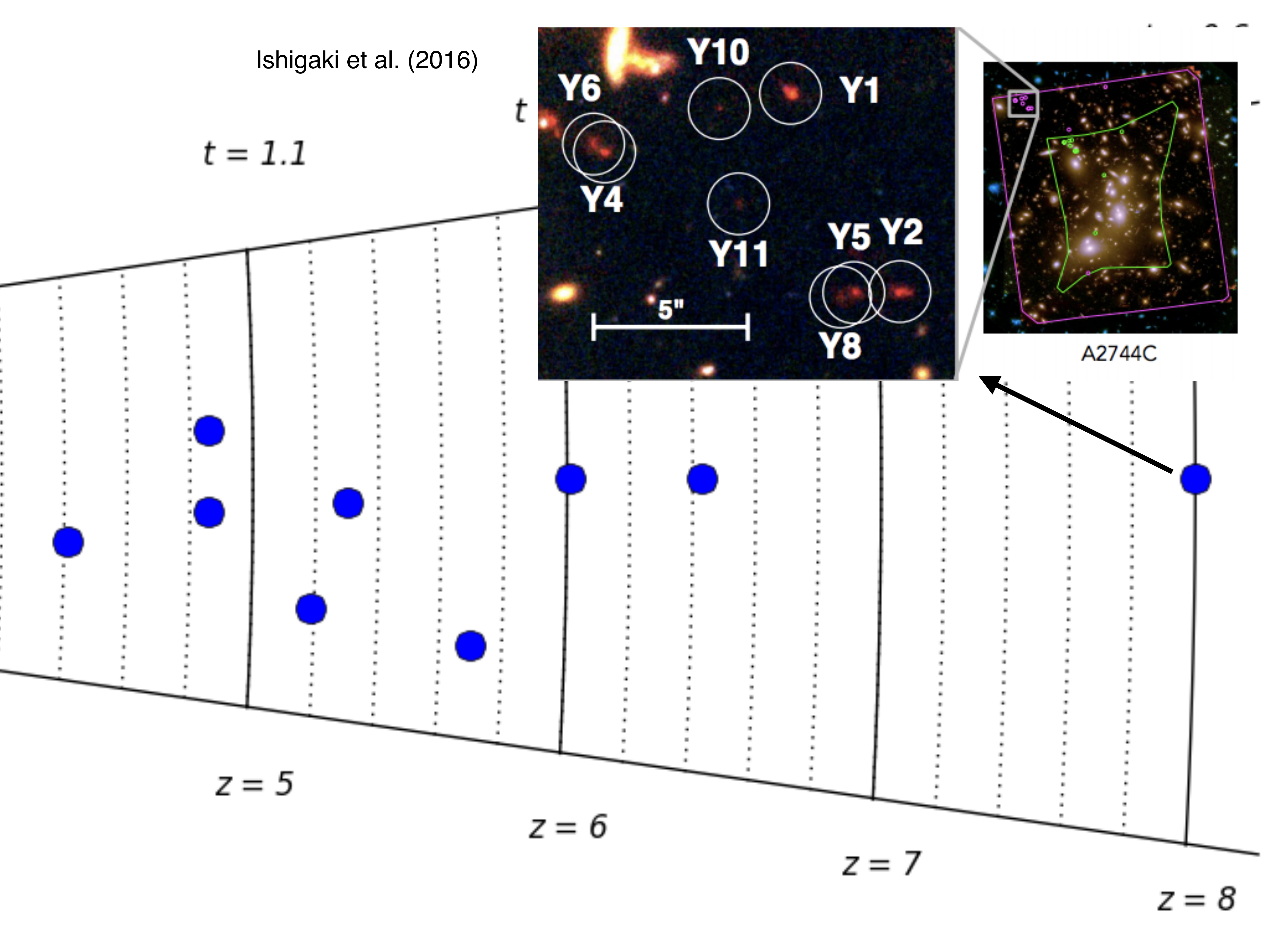
t = 1.
t = 1.5
t = 2.1
= 3.2
z = 2
z = 3
z = 4
z = 5


t = 1.1
t = 0.9
t = 0.7
t = 0.6
z = 5
z = 6
z = 7
z = 8



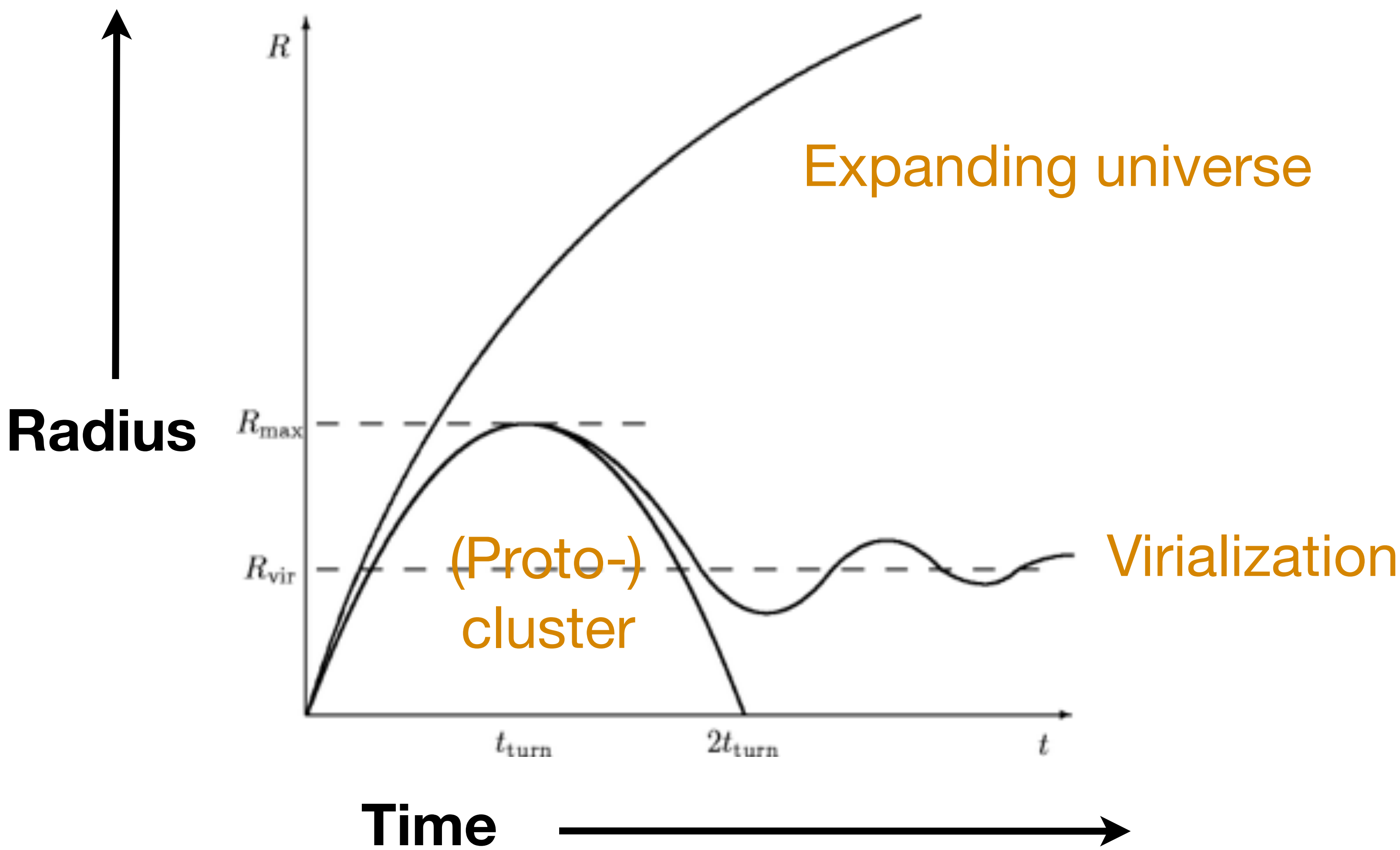
Toshikawa et al. (2014,2016)

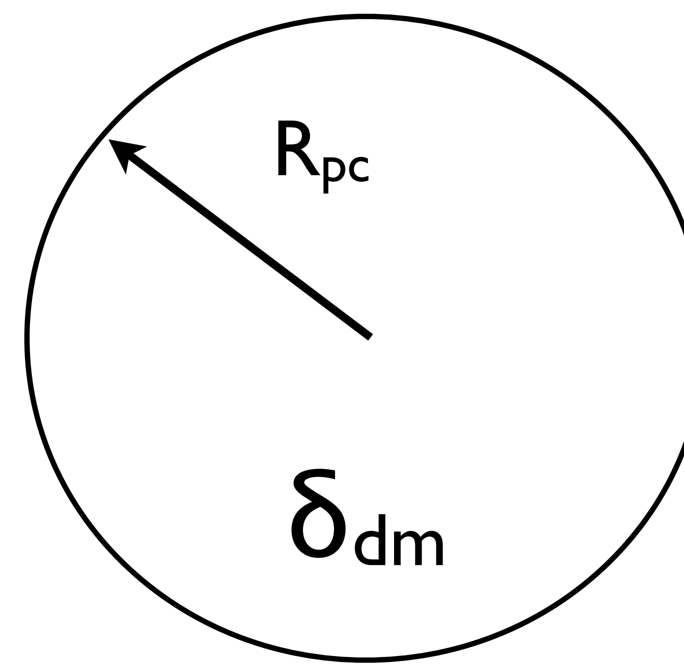

t = 0.6
t = 0.7
t = 0.9
t = 1.1
z = 5
z = 6
z = 7
z = 8


Ishigaki et al. (2016)
t = 1.1
Y10
Y6
Y1
Y4
Y11
Y5
Y2
5"
Y8
A2744C
z = 5
z = 6
z = 7
z = 8

Derivation of present-day masses (based on dodgy high-z data)

- MASS METHOD 1: assume spherical collapse model:





1. DM overdensity

$\delta_{gal,obs}(z) = n_{gal} / \langle n \rangle - 1$

$\delta_{dm}(z) \simeq \delta_{gal,obs} / b_g$

2. Mass at z=0

$V_{pc} \sim 4\pi \cdot R_{pc}^3 / 3$

$M_{z=0} \simeq (1 + \delta_{dm}(z)) \cdot \rho_{dm} \cdot V_{pc}$

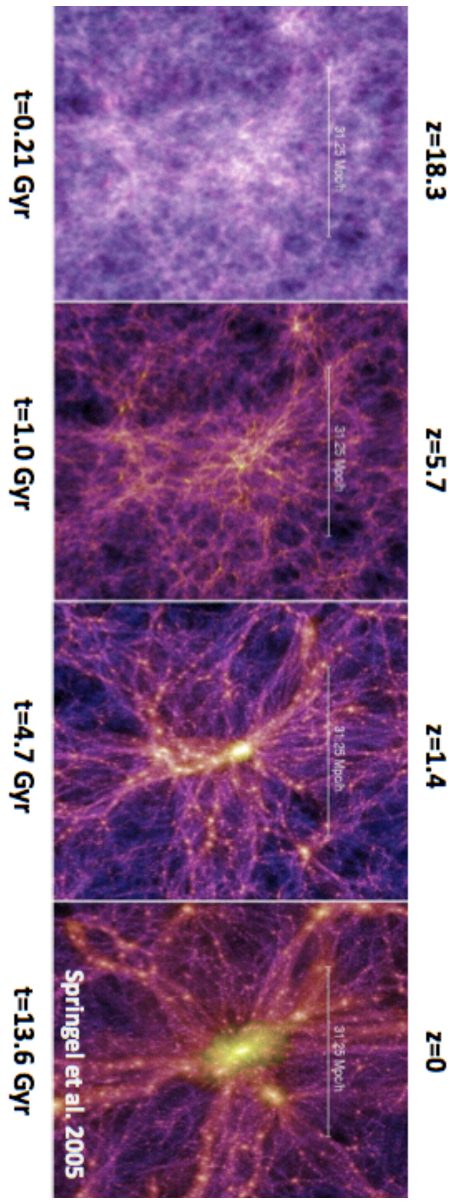
3. Collapse redshift

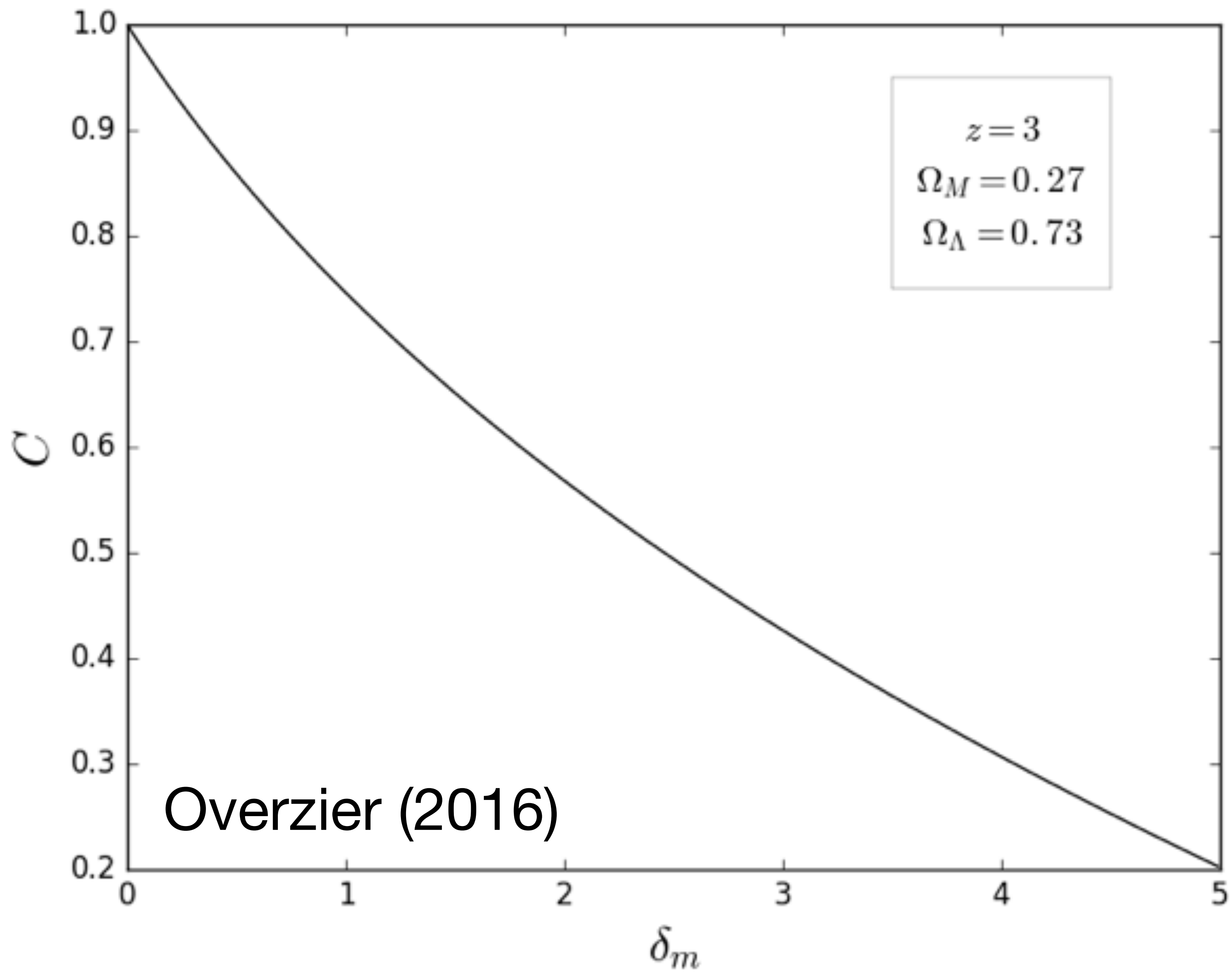
$\delta_L(z) = \delta_L \cdot D'(z)$

assumed collapsed as long as $\delta_L > 1.69$ by z=0

Important: Redshift Space Distortions

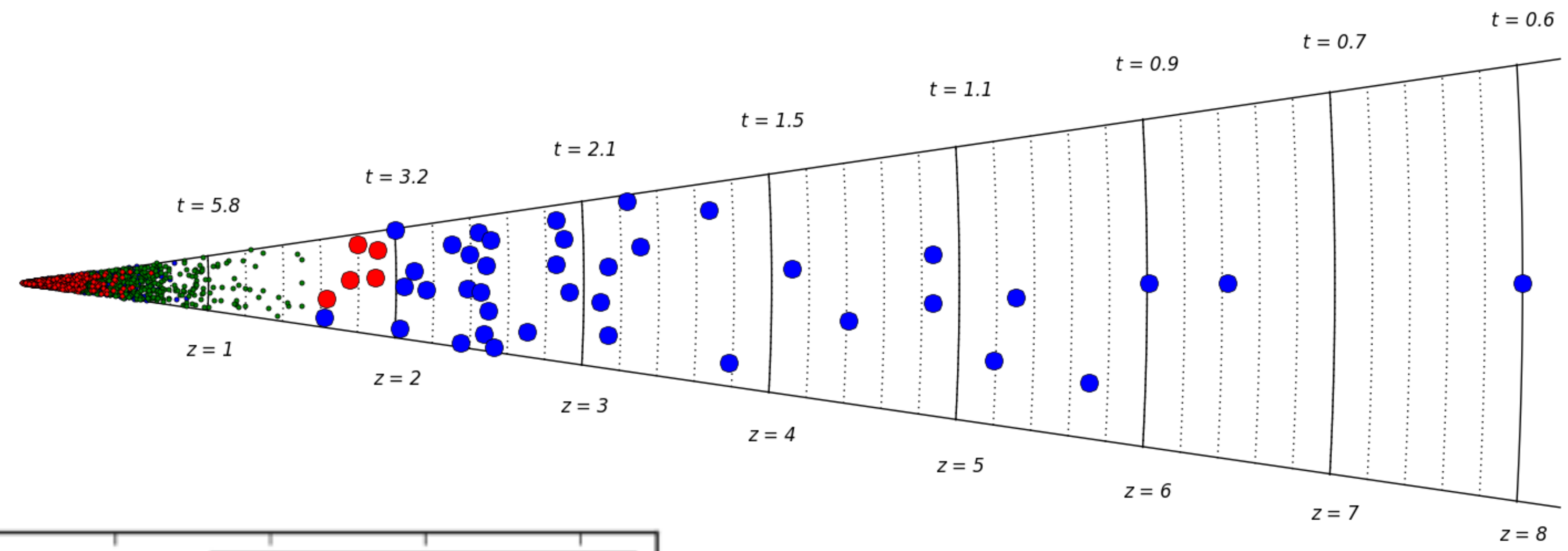
A collapsing structure will appear compressed along the redshift direction, and the density of galaxies will appear enhanced:

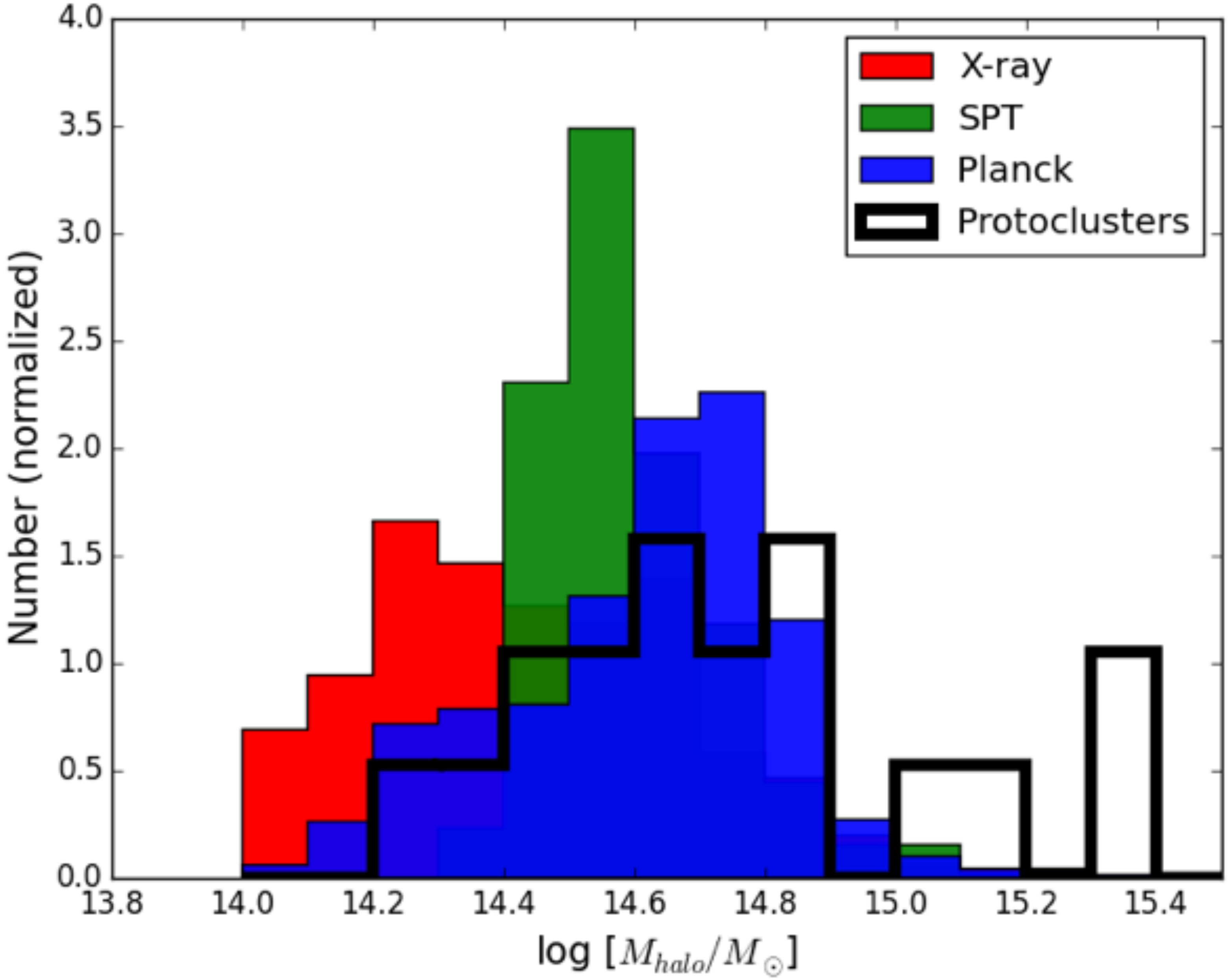




- The larger the overdensity, the larger the distortion (C)
- C virtually does not depend on redshift or cosmology!
- **MASS METHOD 2: Directly compare δ_{gal} with cosmological simulations**

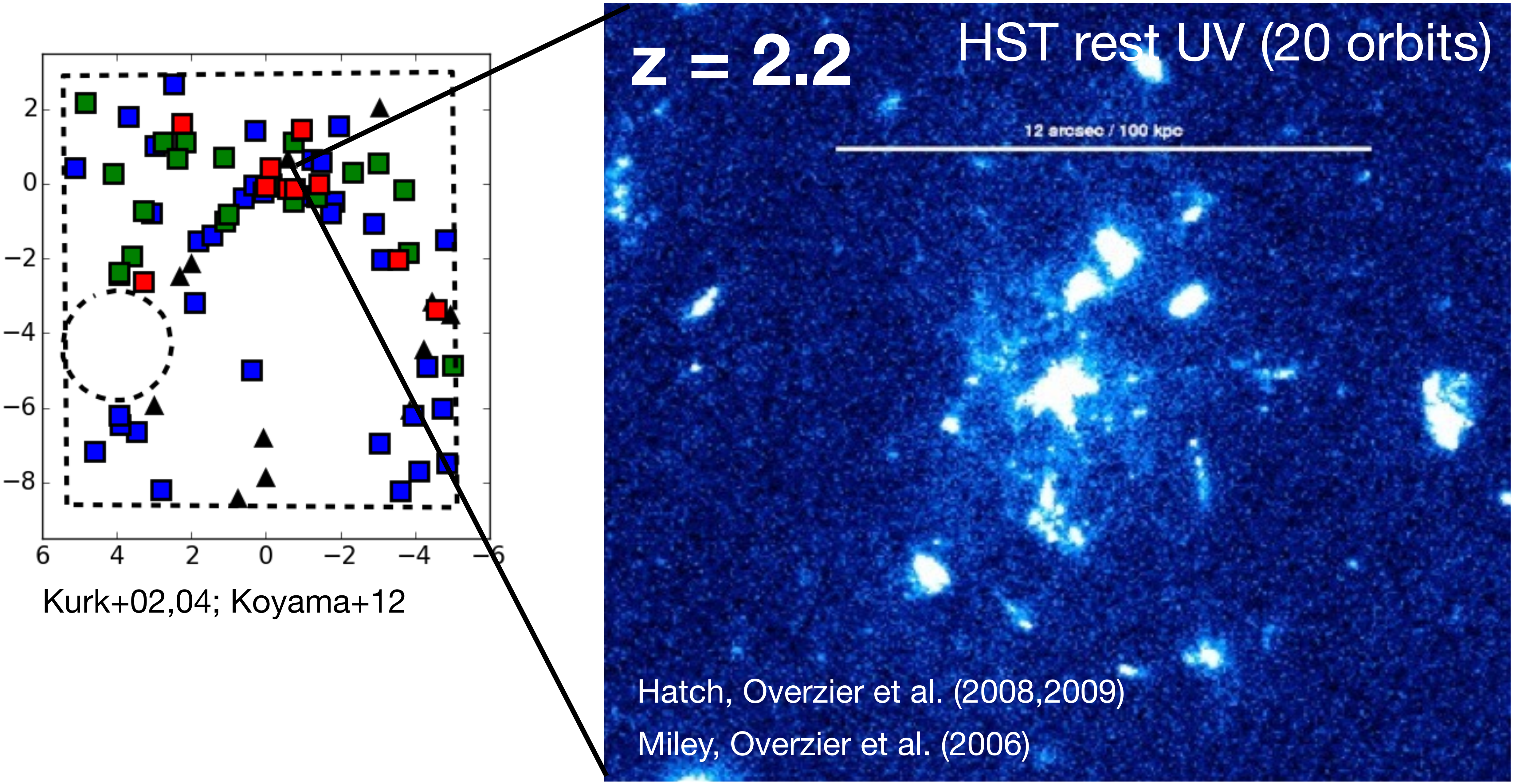
These “protoclusters” trace today’s (massive) cluster population





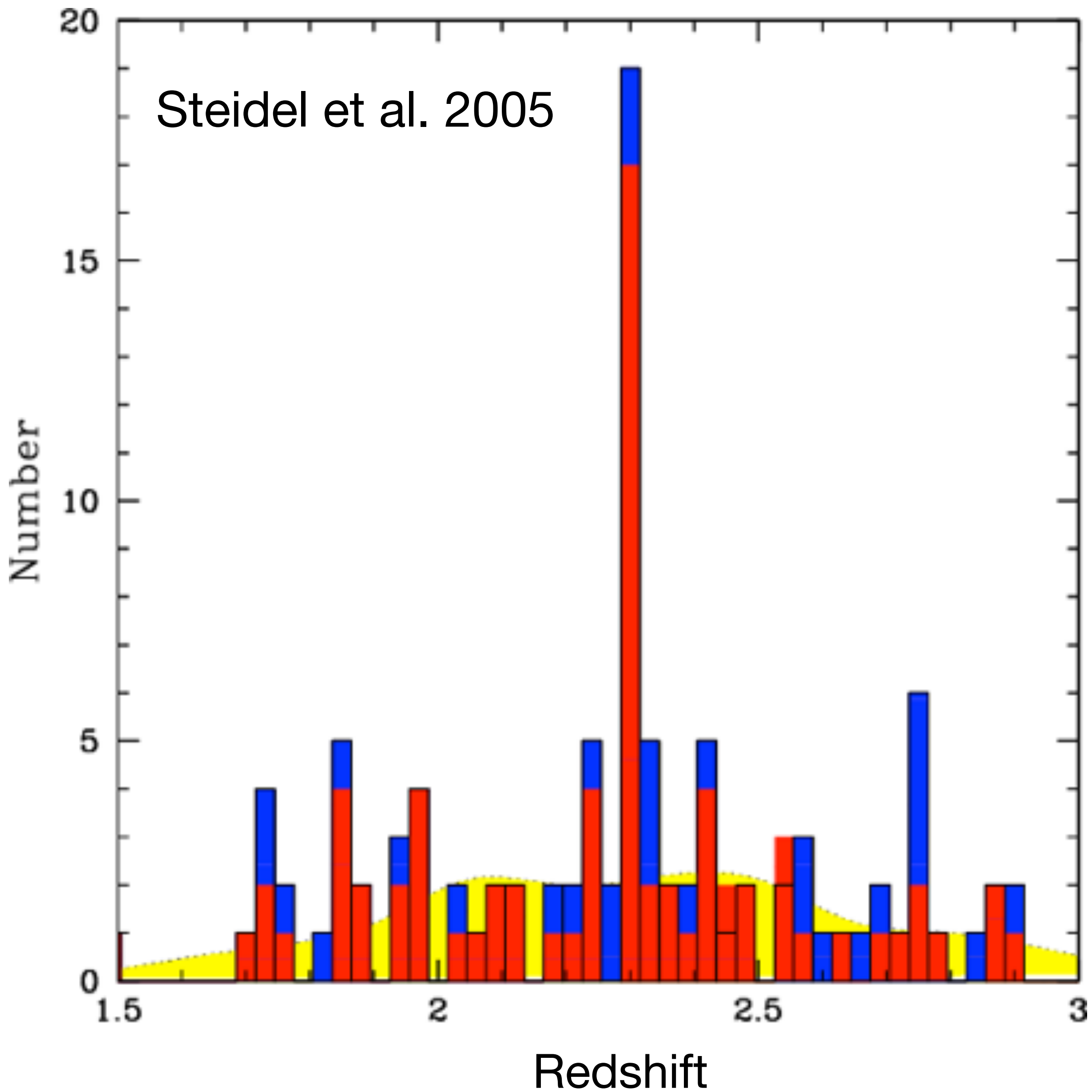
Overzier (2016)

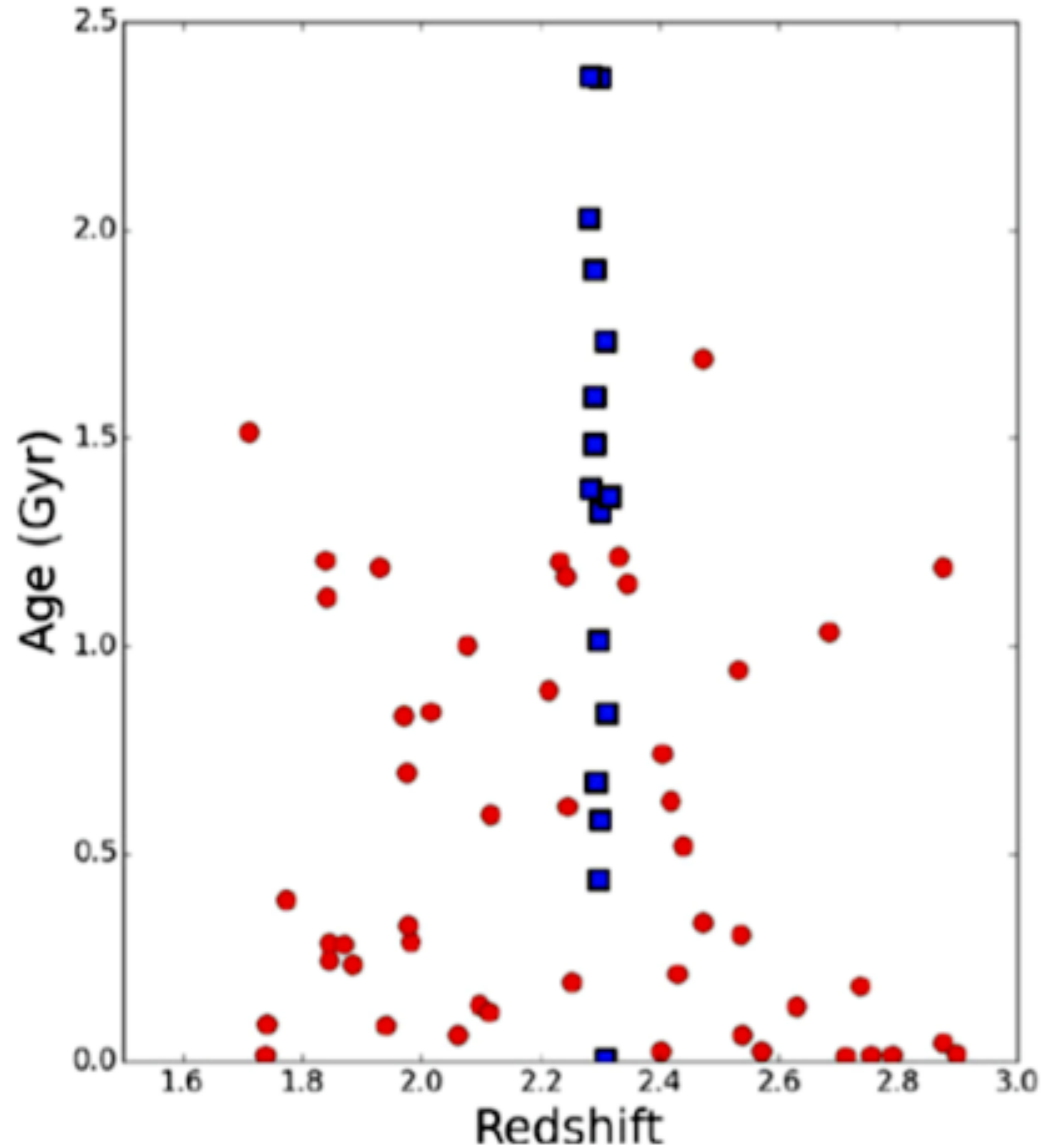
First glimpse of BCG formation (?)



- **most massive and most complex z > 2 galaxy known**
- **powerul radio galaxy with SMBH of ~10^{10} M$_\odot$**
- **star formation in a ~100 kpc diffuse halo (intra-cluster light?)**
- **faint thermal X-ray emission (maybe ICM but likely radio AGN)**
- **NB: not typical of central galaxies in protoclusters !**

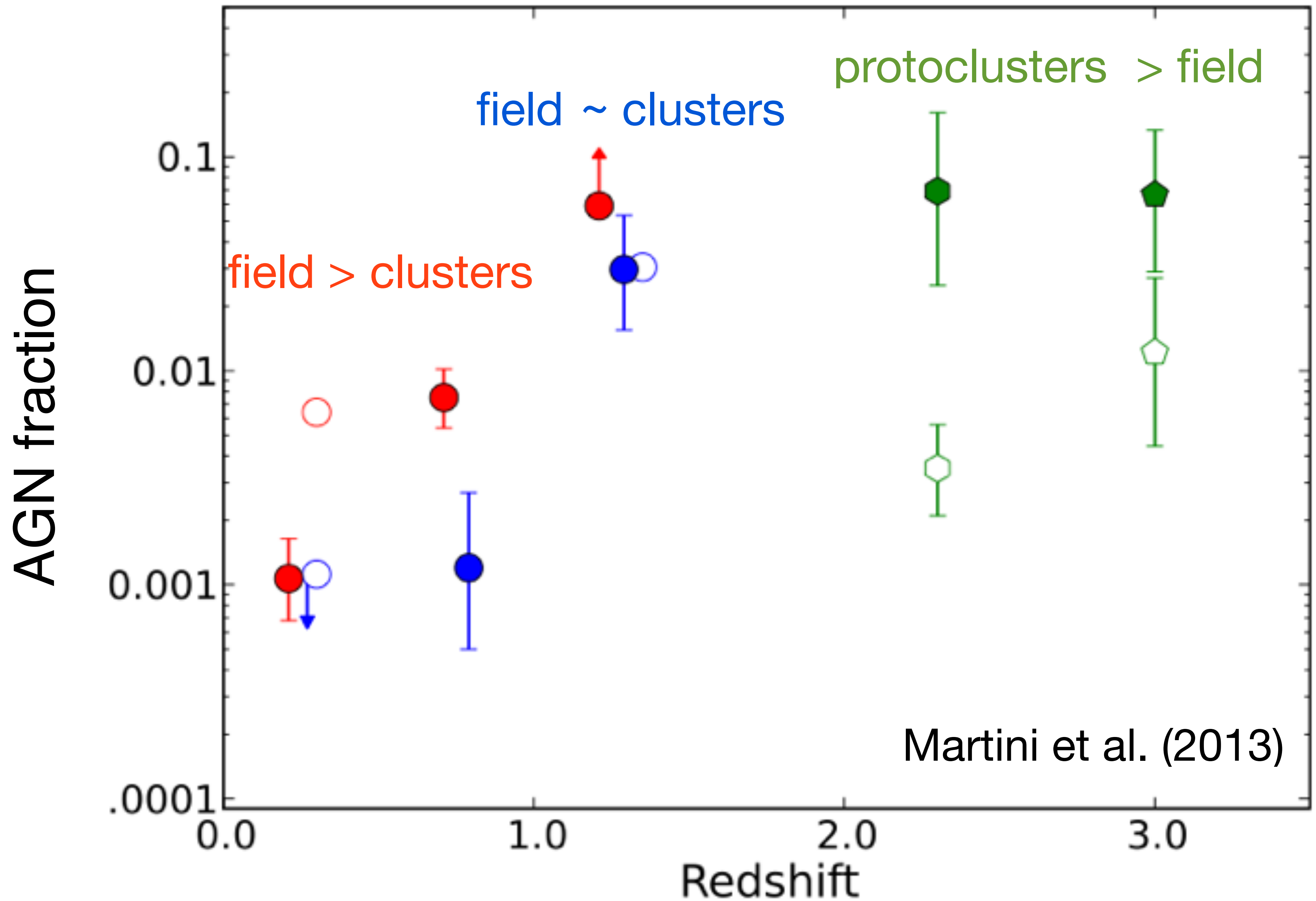
Enhanced Galaxy Evolution in a protocluster at z = 2.3





- SFGs in this region are ~1 Gyr older compared to the surrounding field
- Did they evolve faster due to the environment in the dense region (?)
- Did galaxies form earlier because the dense region collapsed earlier (?)

Evolution in the AGN fraction of galaxy clusters with redshift

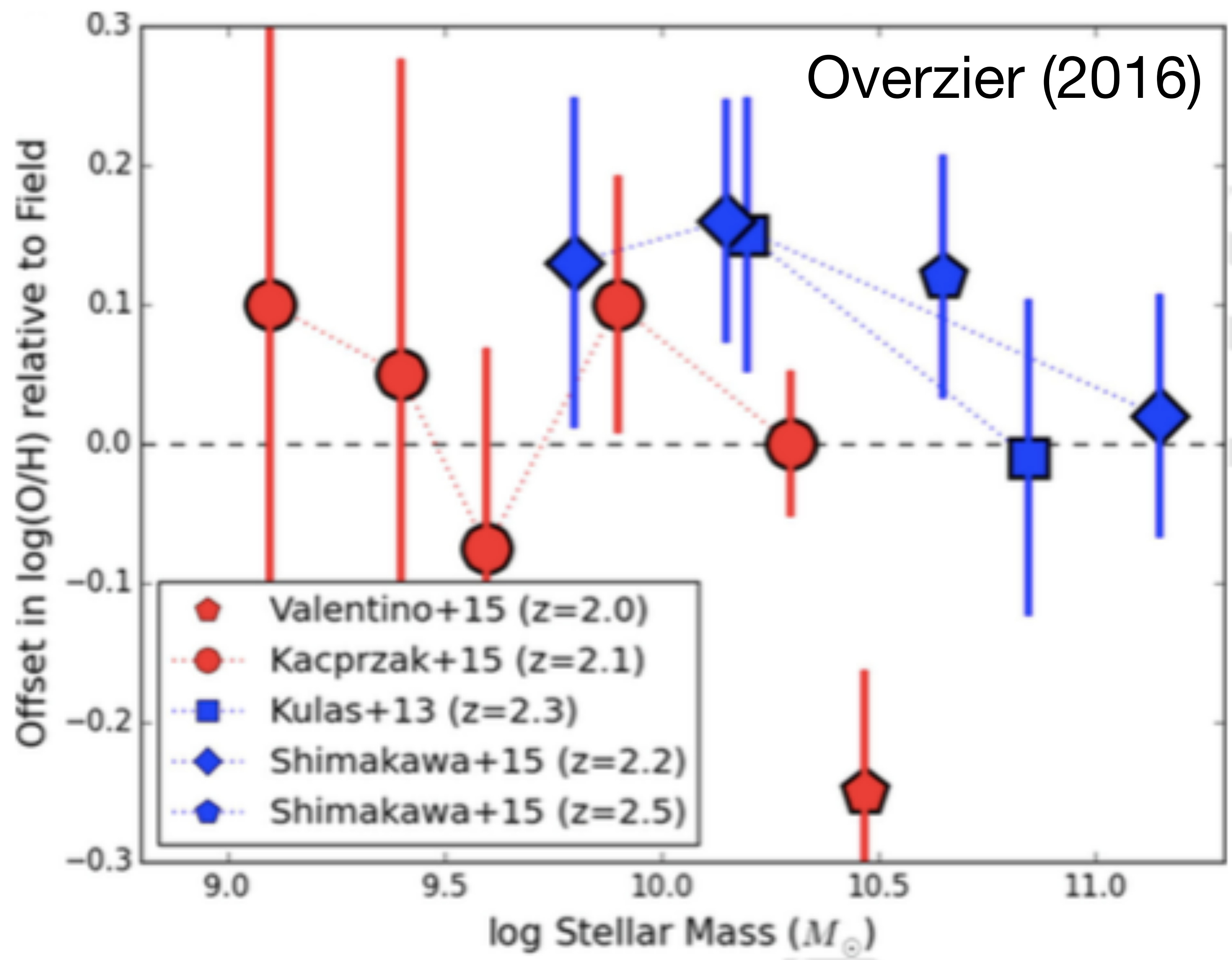


- AGN fraction in proto-clusters seems higher than in the field
- is it due to faster galaxy growth leading to more massive galaxies ?
- is it due to more frequent mergers in overdense regions ?
- is it due to more efficient inflows of gas in overdense regions ?

Gas-phase metal abundances of protocluster galaxies

Hydro simulations of cluster formation show that **environment should play some role, e.g.**

- **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)

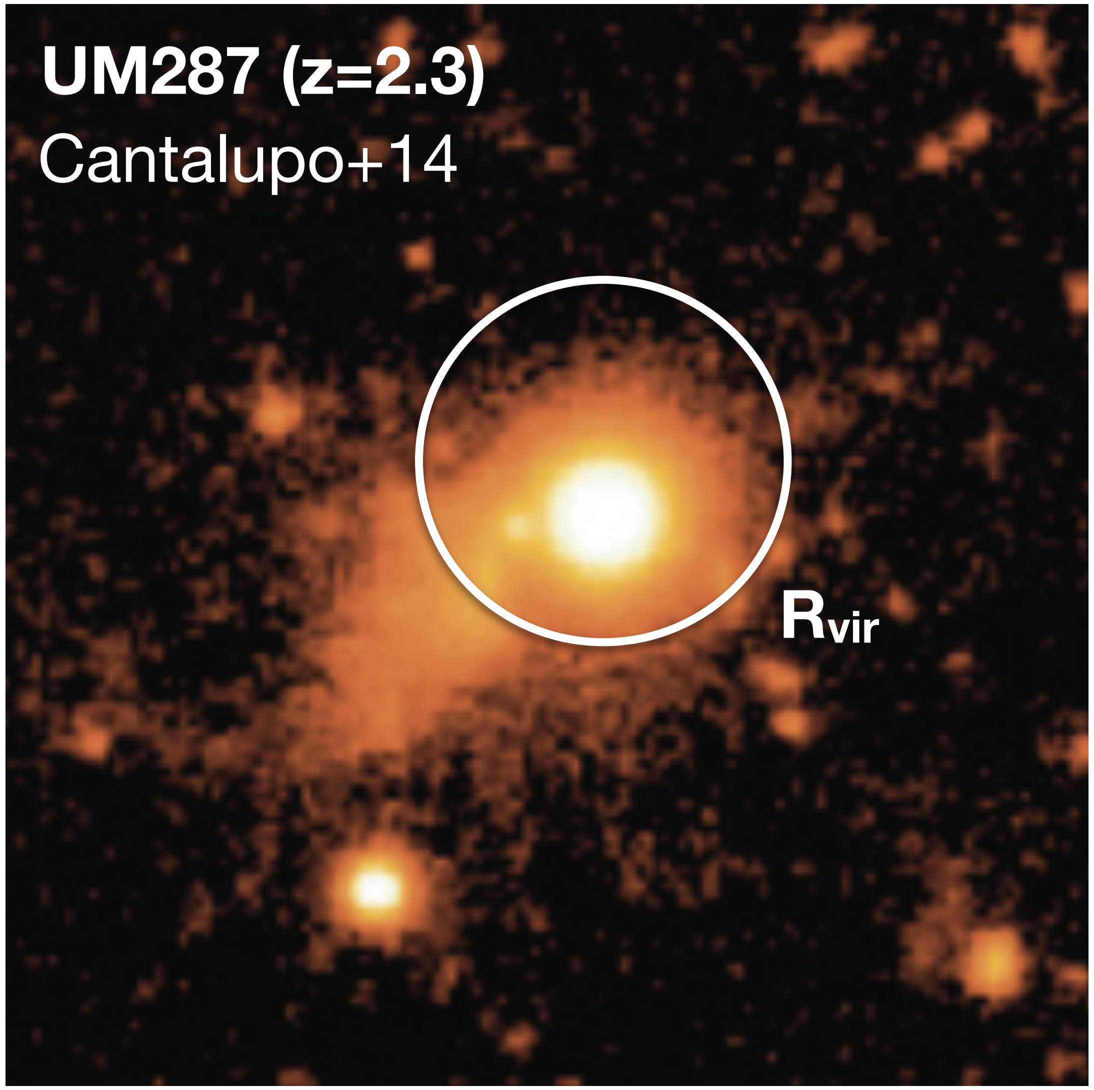


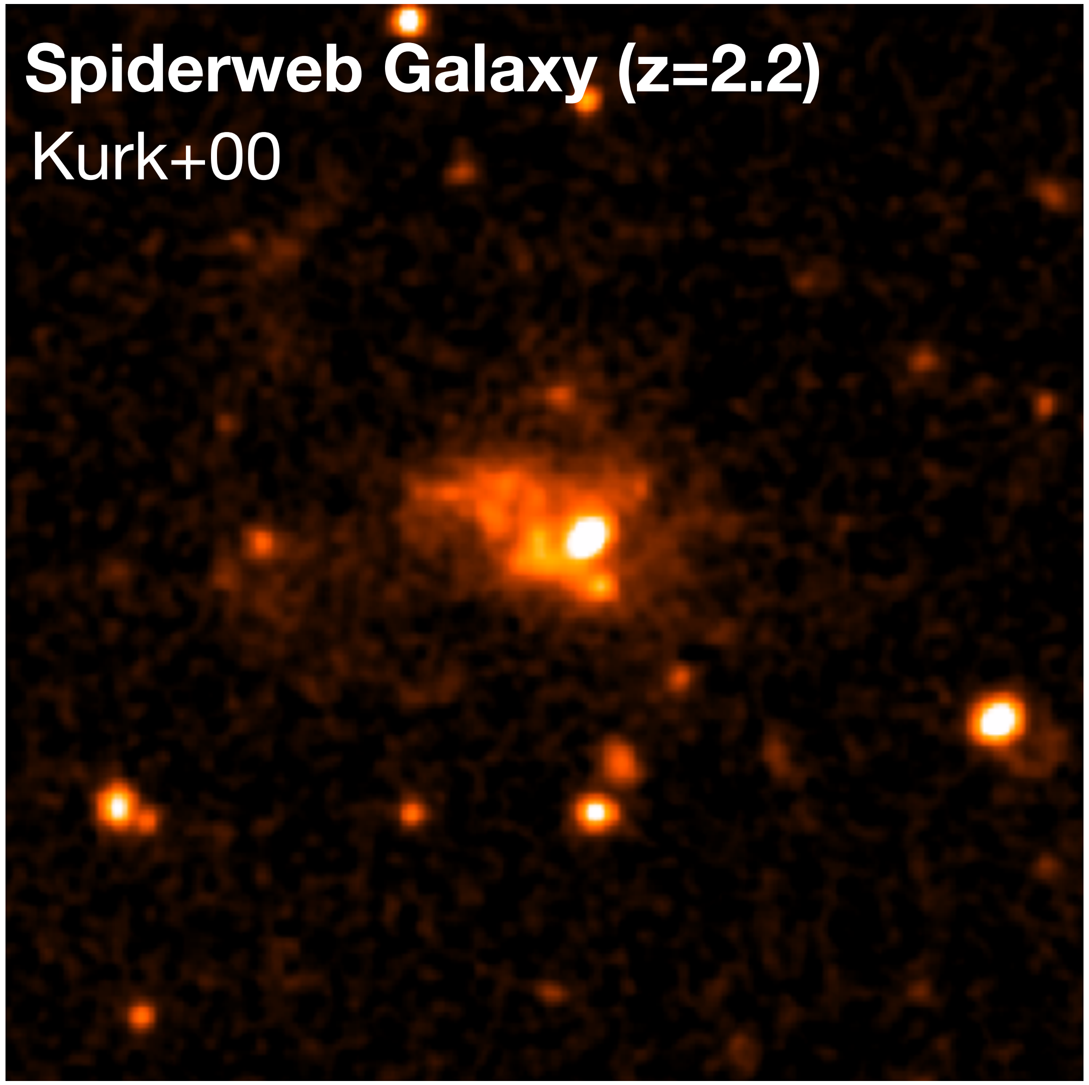
<u>**First measurements on 4 (proto)clusters completely inconclusive !**</u>

Caveats:

- **strong-line method, small samples, large errors, AGN contamination, …**

Large-scale ionized flows associated with PCs (“Lyα blobs”)

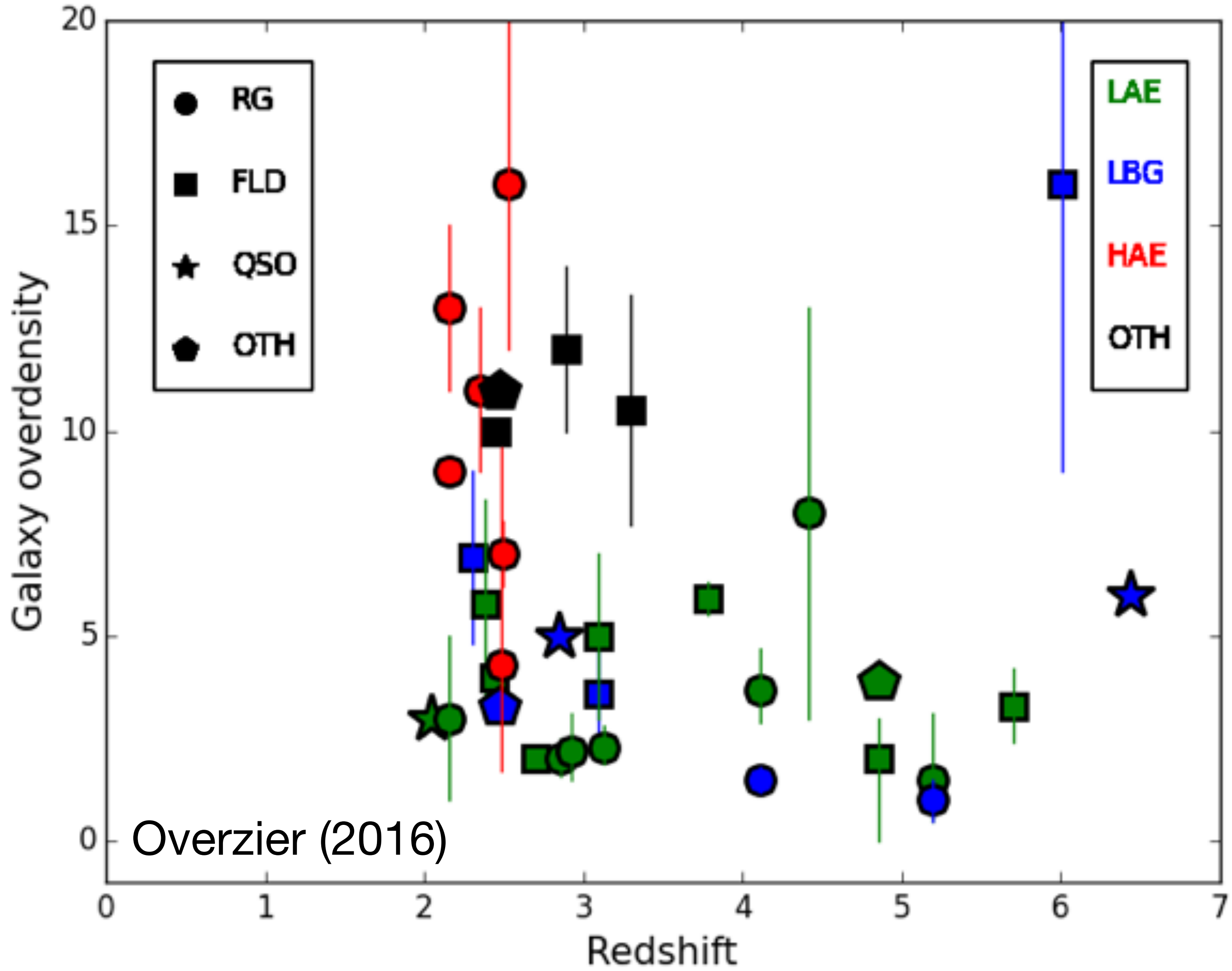




- $L_{Ly\alpha} > 10^{44}$ erg/s; sizes 100 - 500 kpc; mainly powered by AGN photoionization
- gas most likely produced by AGN-driven superwinds (?)
- but may also be gas accretion from the large-scale cosmic web (?)
- metallicity measurements show the material has been enriched (?)

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

A few words on how the protoclusters are being found



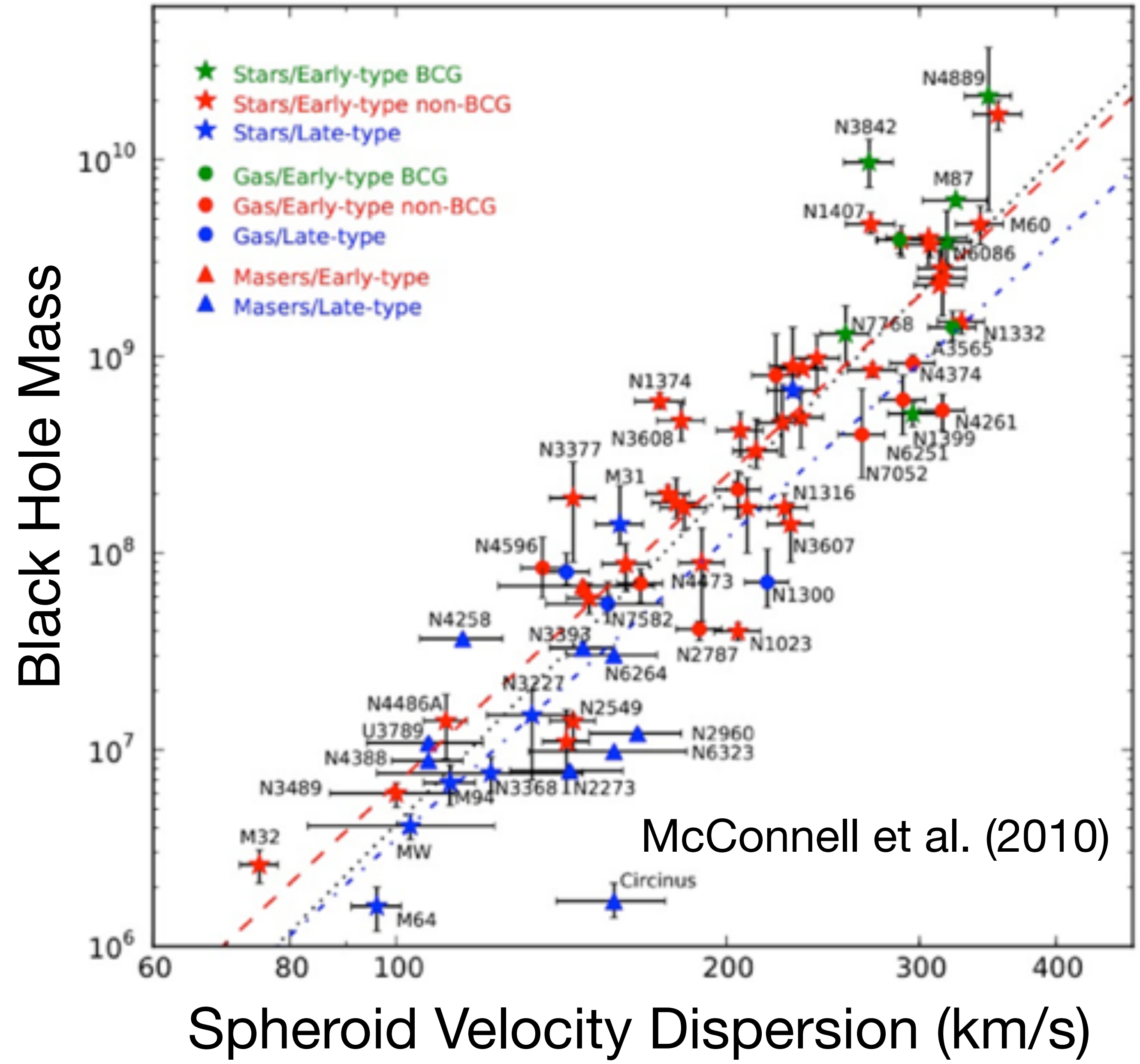
- using **cosmic "beacons"**, such as radio galaxies, quasars, SMGs, …
- recently also using Mpc-scale coherent **absorption ("Lya tomography")**
- large-scale overdensities in large photometric or spectroscopic **sky surveys** (majority of systems discovered by now)

Protoclusters, Radio Galaxies and Quasars

- local BCGs passed through a luminous quasar phase at z > 2

- radio galaxies and QSOs at high-z have the largest SMBHs, massive hosts, high SFRs, massive DM halos

- they are easily found at high redshift (“cosmic lighthouses”)



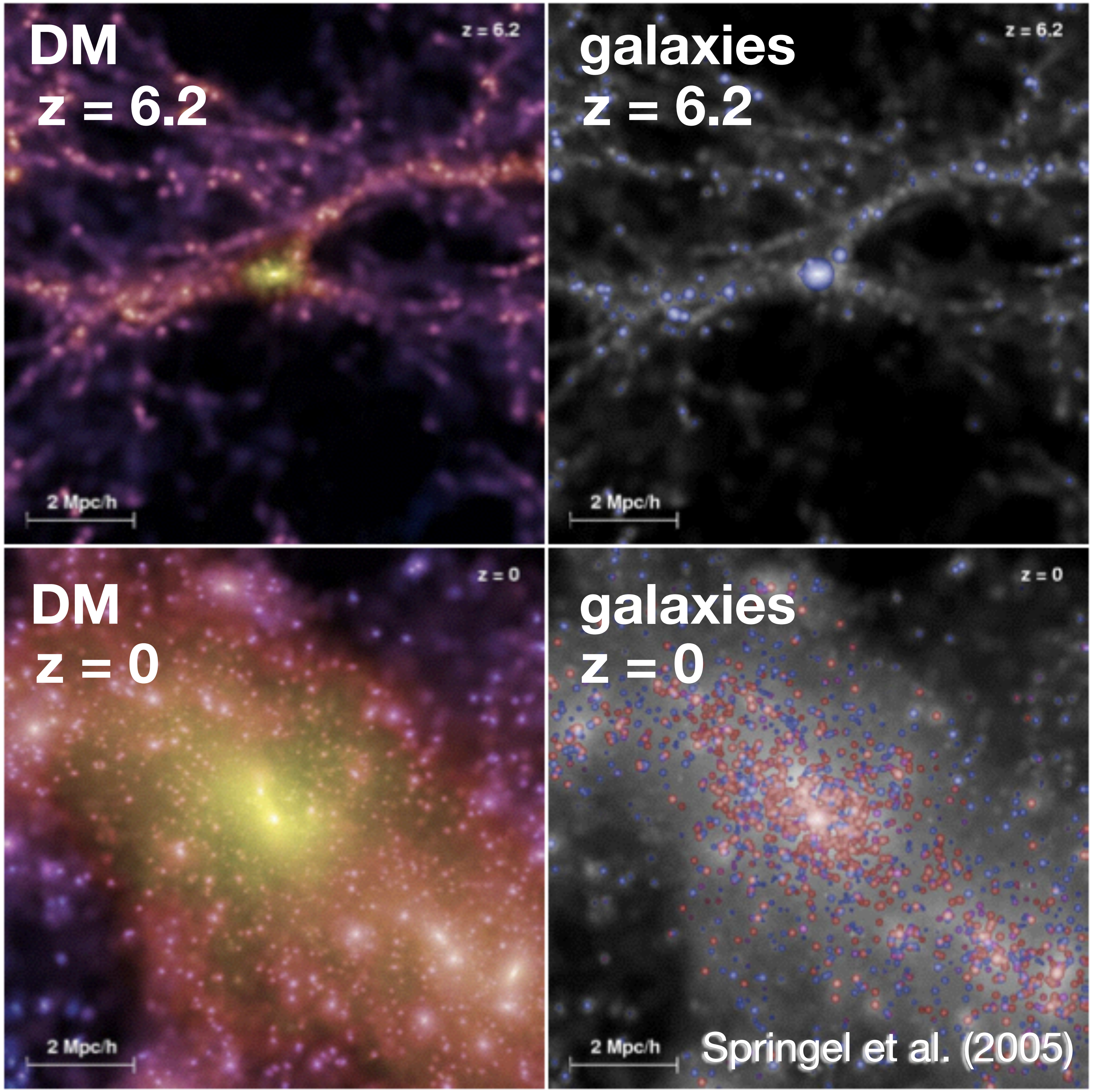
KEY RESULTS (1996 - 2017)

- **some spectacular structures found, primarily near radio galaxies at z = 2 - 5, but statistics not well known (literature bias!)**
- **searches near QSOs have been far less successful**
- **main reason for the difference not clear: halo mass? radio loudness / BH spin? host mass? QSO feedback effects (e.g., near-zone or QSO self-destruction)?**

The unexpected environments of QSOs at z ~ 6

The most massive halo in the Millennium Run simulations:

- at z ~ 6.2, the main progenitor halo hosts a luminous QSO and supermassive black hole
- surrounded by many fainter galaxies that should be easily detectable using, e.g., HST or narrow-band surveys

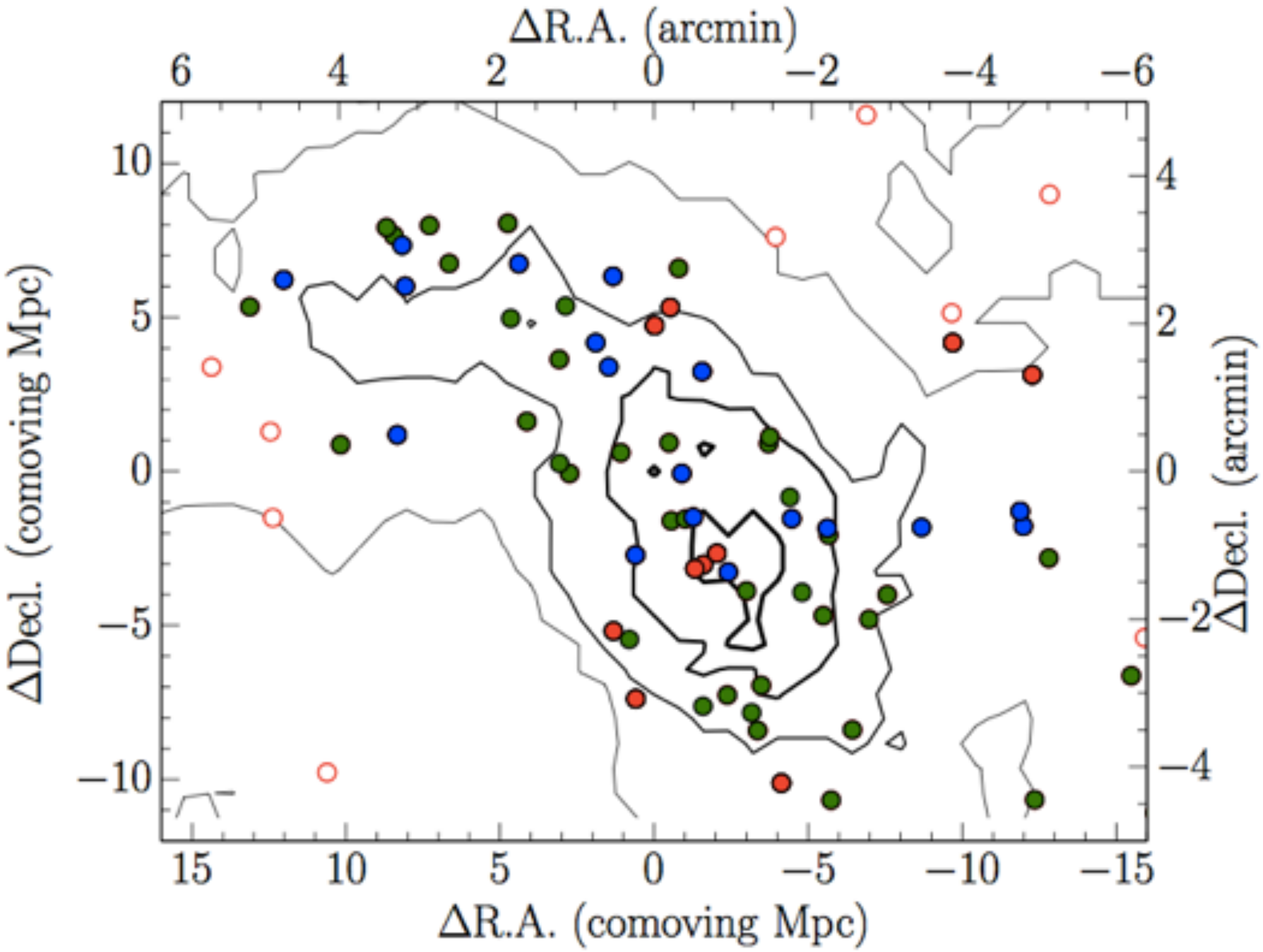


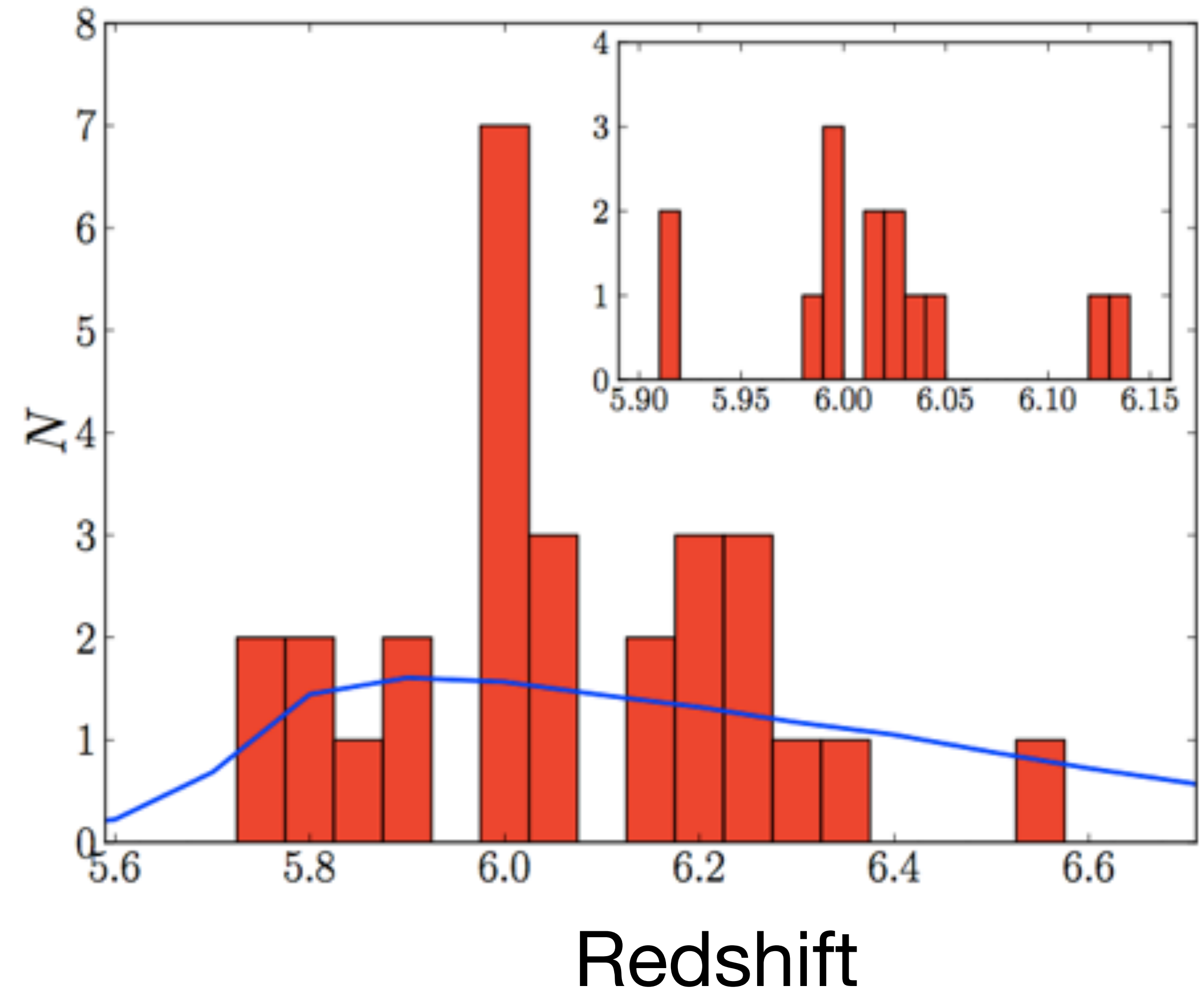
e.g. Stiavelli et al. 2005; Zheng et al. 2006; Overzier et al. 2009,2016; Kim et al. 2009; Angulo & White 2012; Bañados et al. 2016; Mazzucchelli et al. 2017; Goto et al. 2017

Nearly every observation of z~6 QSOs to date has failed to produce any significant large-scale structure associated with these QSOs (!)

The unexpected environments of QSOs at z ~ 6

Most distant galaxy proto-cluster at z = 6.0 (not a QSO!)



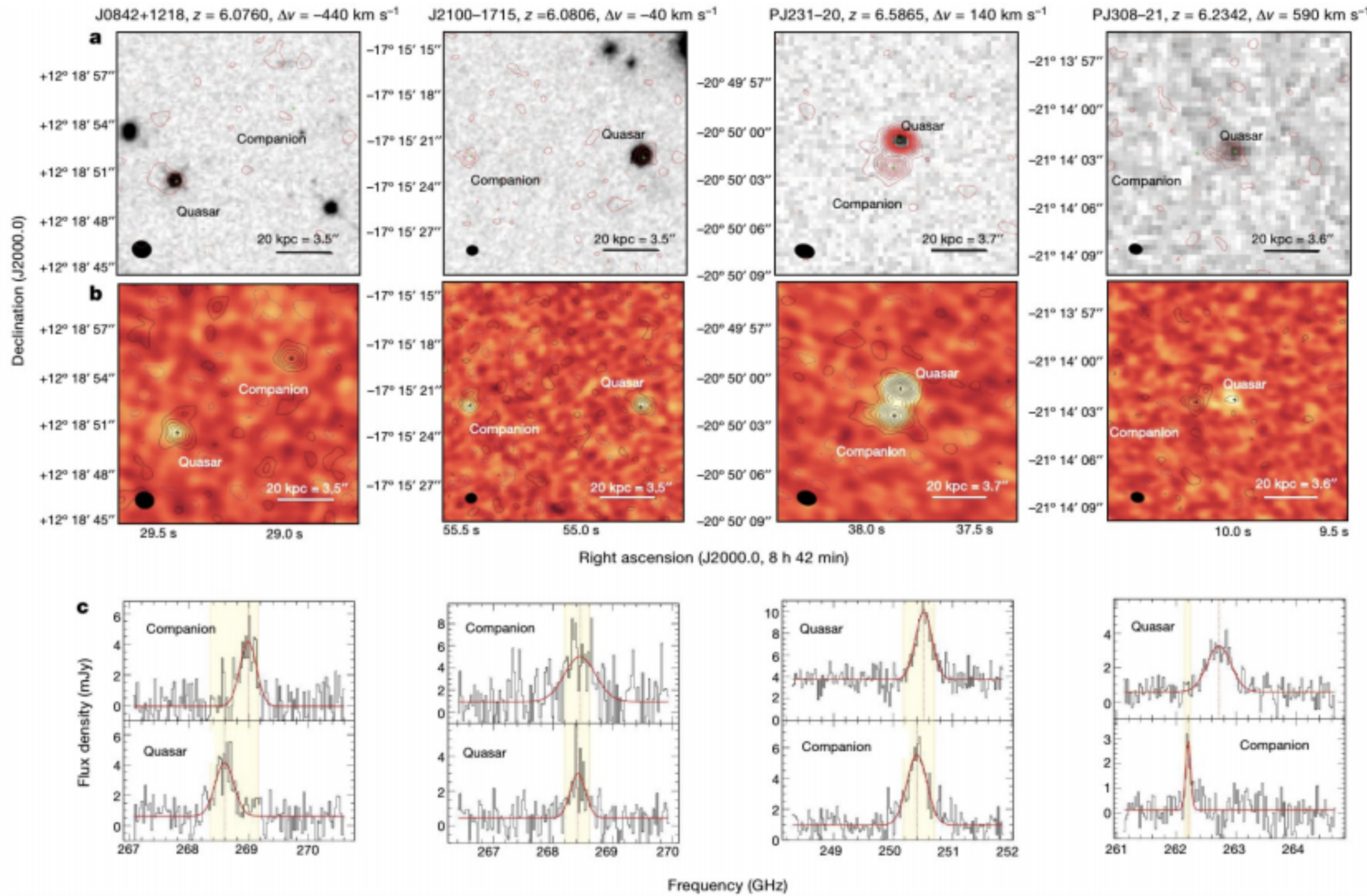


- 10 spectroscopic redshifts at z = 6.02 ± 0.02 within 10 x 15 Mpc region
- overdensity consistent with “proto-Coma” cluster seen in simulations
- the kind of structure everyone expects, but fails, to see around z ~ 6 QSOs

Toshikawa et al. (2014,2016)

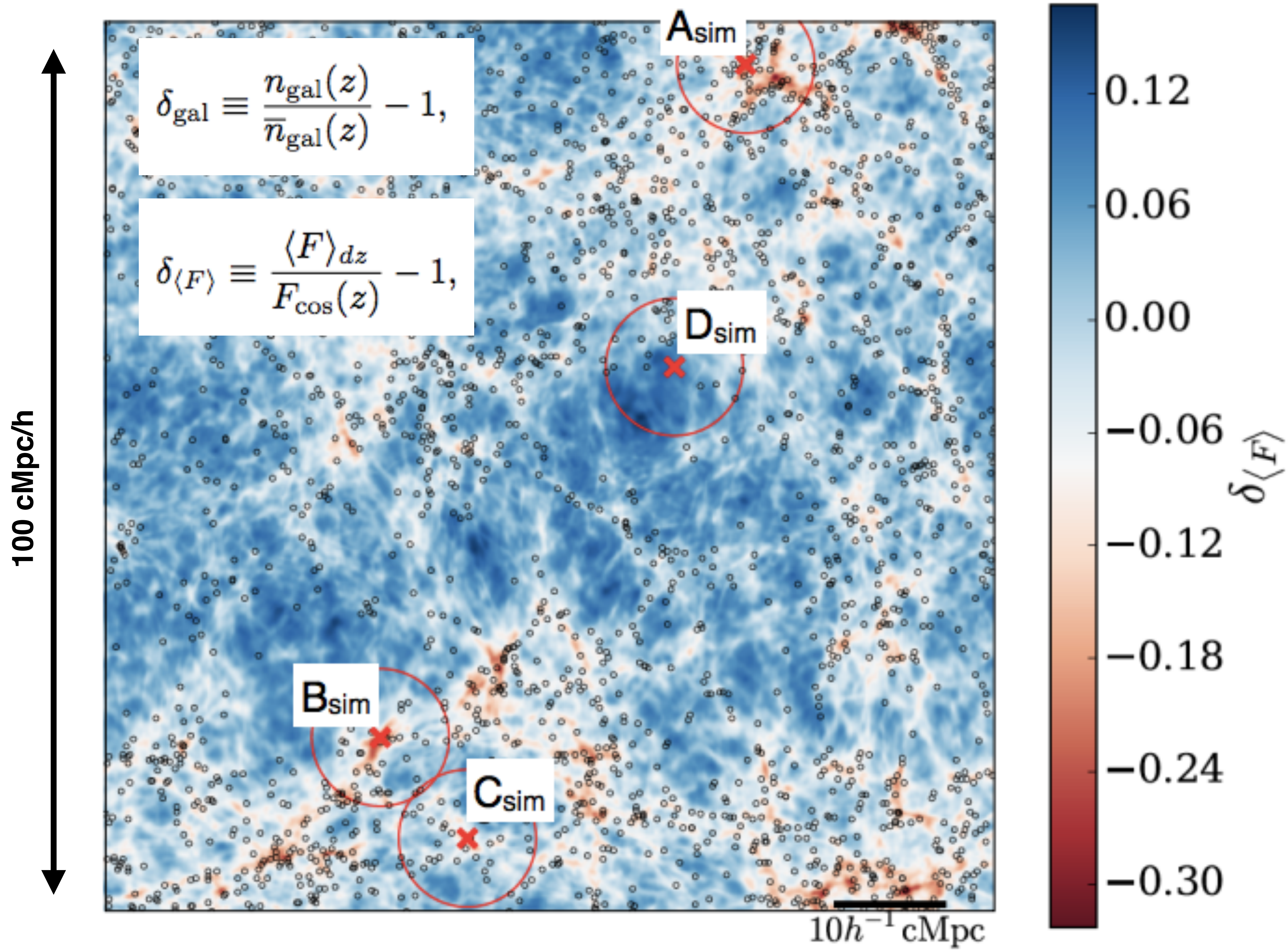
Breaking news:

4 out of 25 QSOs at z > 6 have “invisible” companions seen w/ ALMA



Decarli et al. (2017)

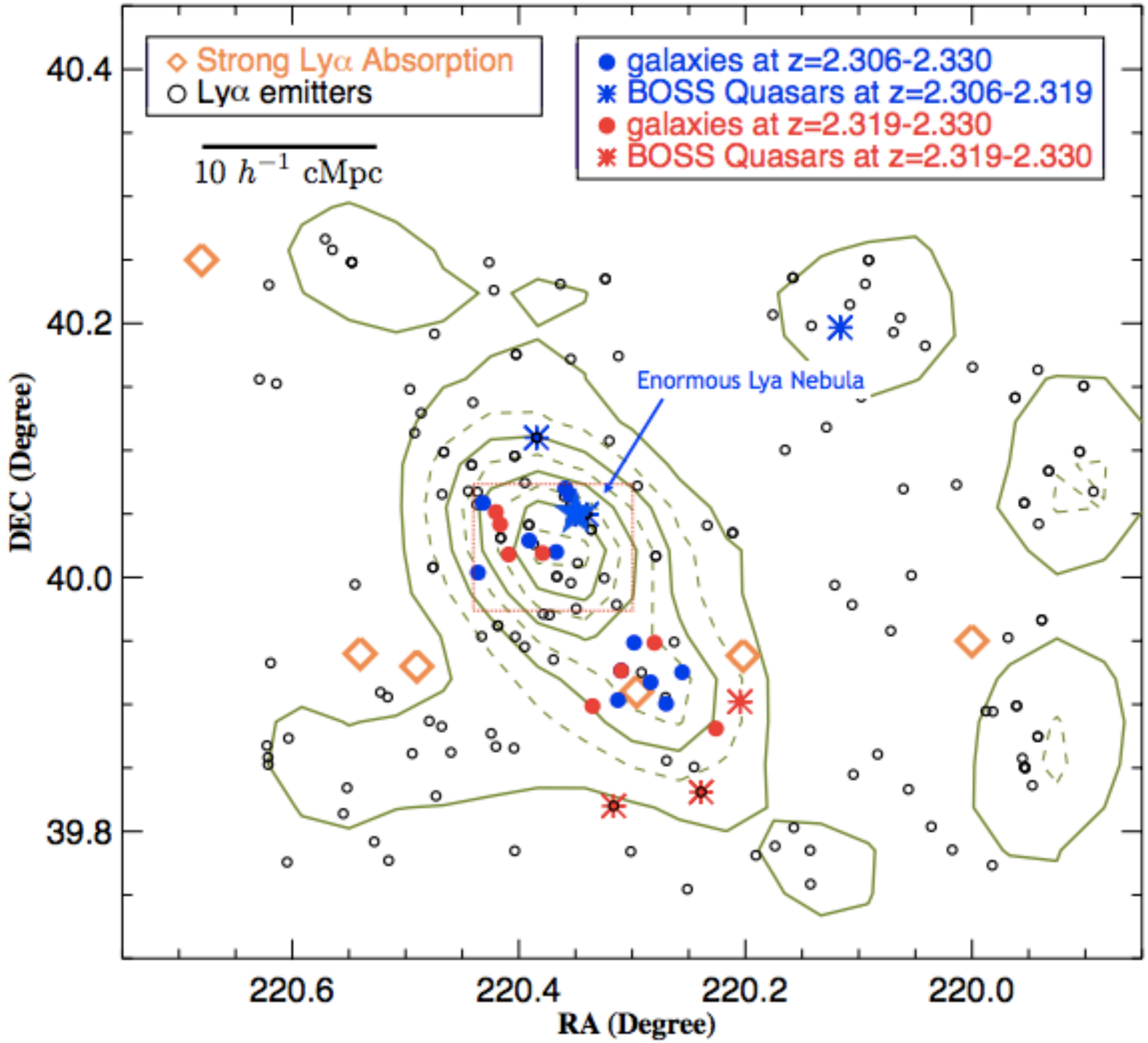
Lya "tomographic mapping" of the cosmic web at z > 2



Mukae et al. (2016)

Lya "tomographic mapping" of the cosmic web at z > 2

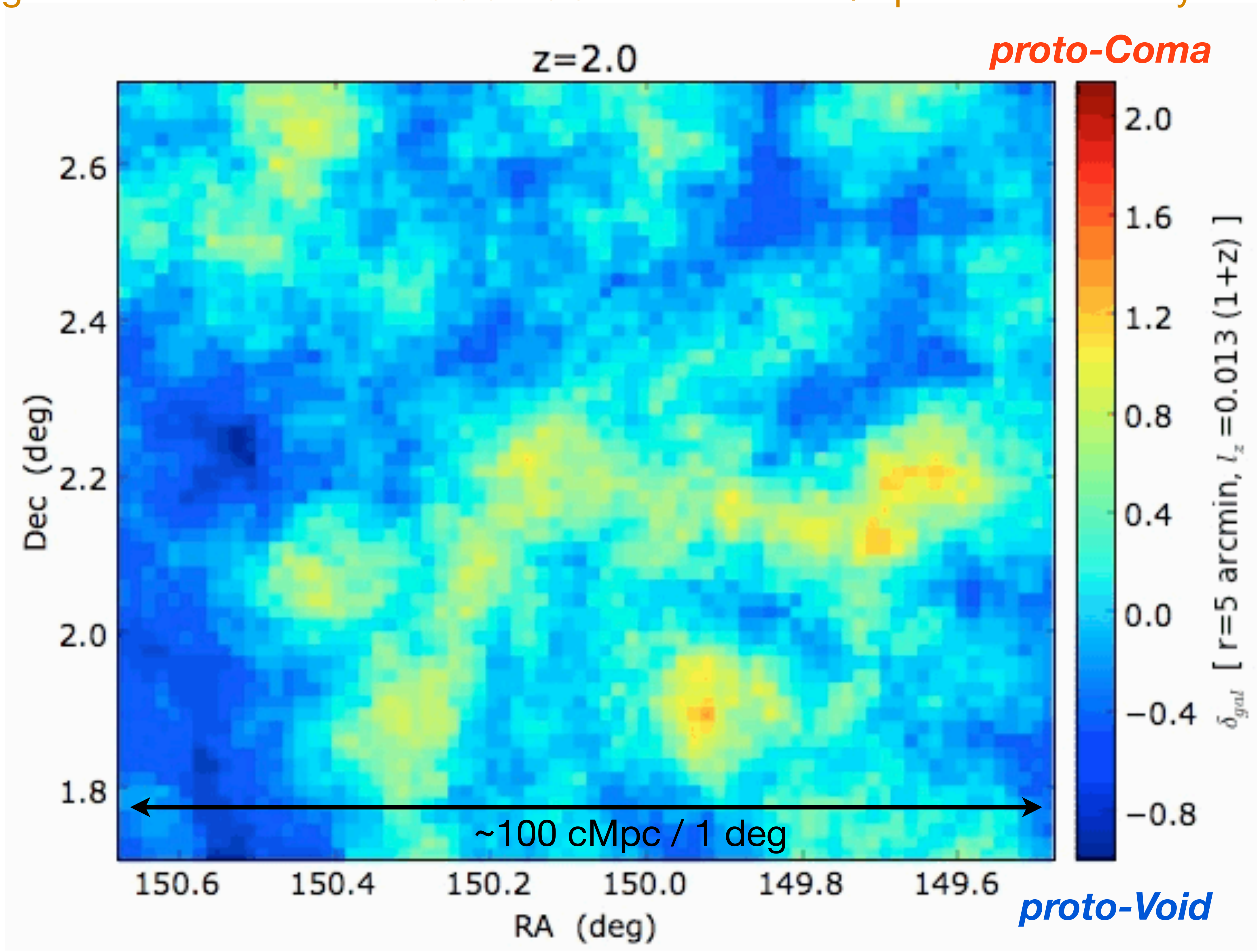
BOSS1441 at z = 2.32



Cai et al. (2015,2017)

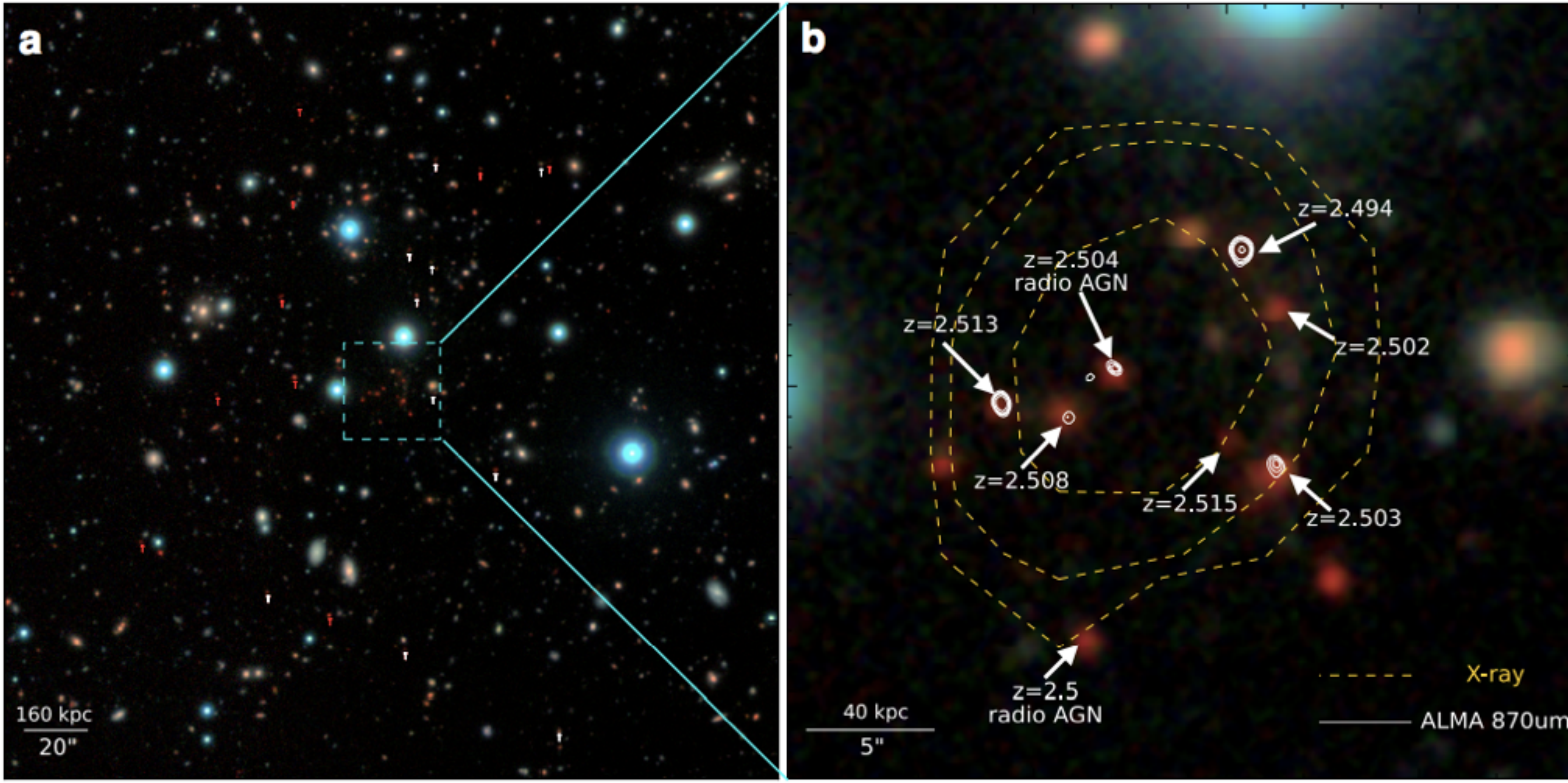
Searching more systematically in photo-z surveys

Dissecting the cosmic web in the COSMOS field with 7-10% photo-z accuracy



Chiang, Overzier & Gebhardt (2014)

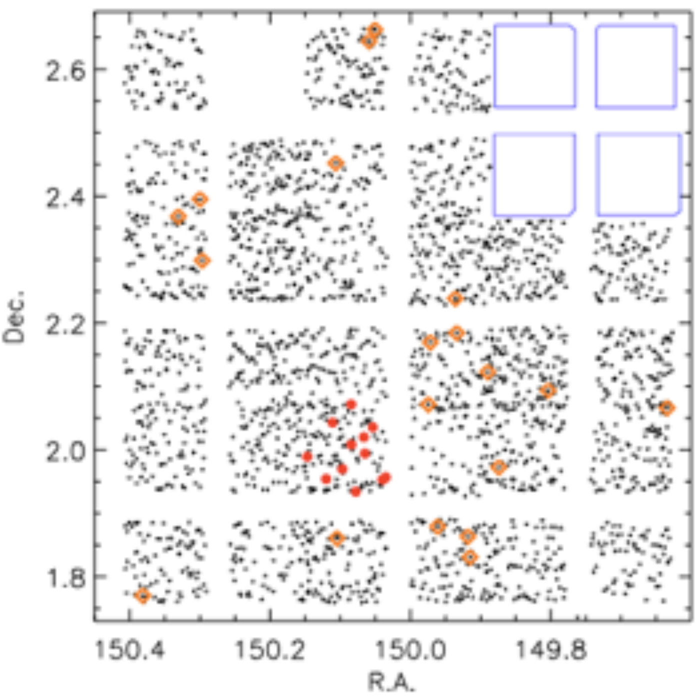
Most distant X-ray detected (proto)cluster at z = 2.5 (?)

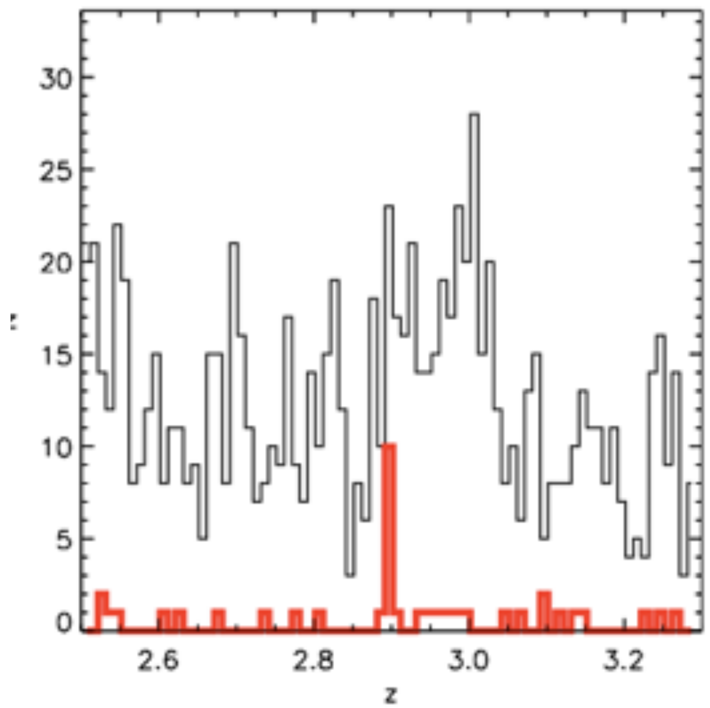


- first found in our photo-z sample of “Coma”-type protoclusters in COSMOS
- Wang et al. (2015) found a strong spec-z overdensity of quiescent galaxies
- velocity dispersions, X-rays (?) and M* point to mass of **log M = 13.9 ± 0.2**

Chiang et al. (2014), Wang et al. (2016)

Protoclusters from “blind” spectroscopic surveys

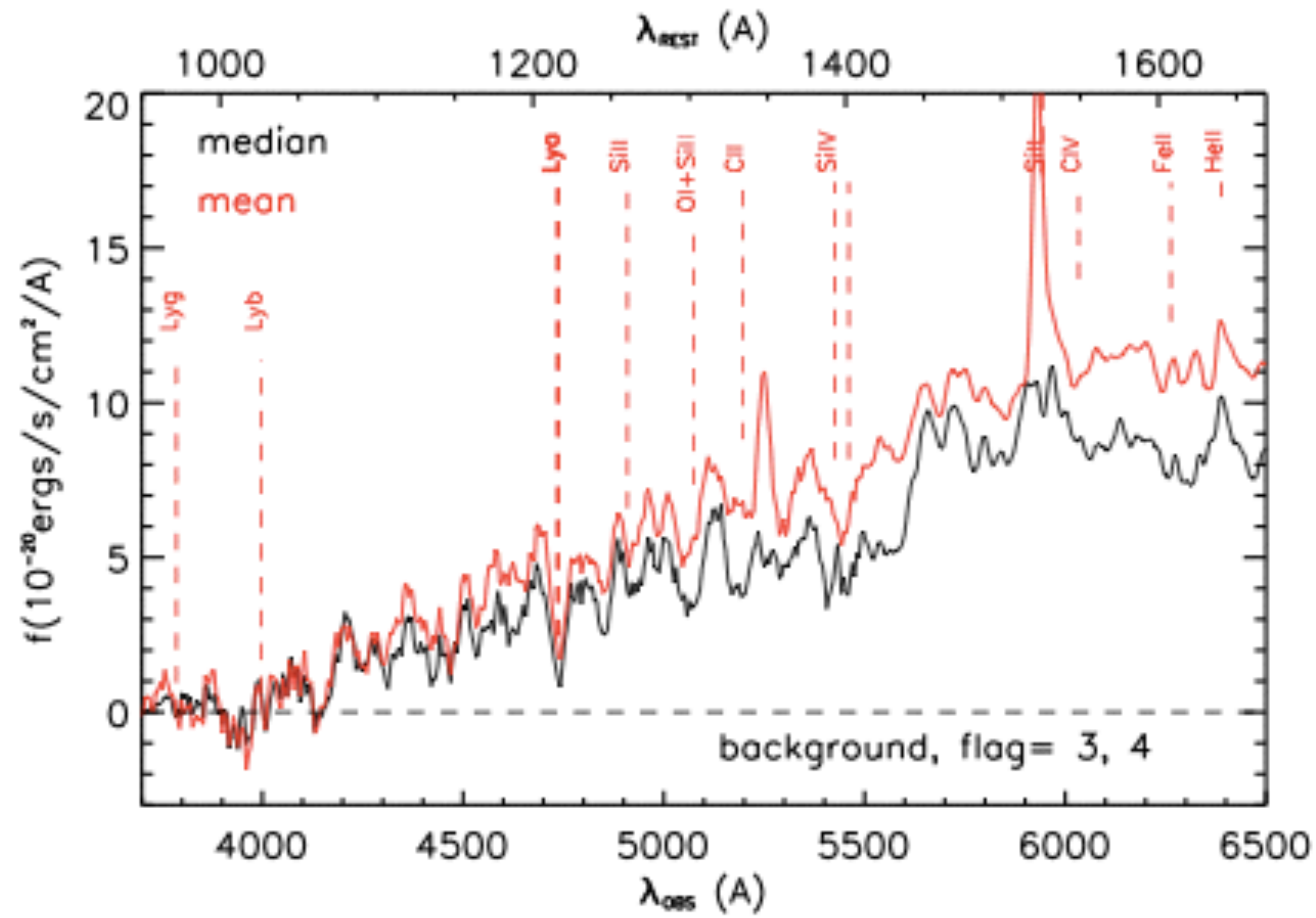




- VUDS is a densely sampled survey over 1 deg^2 targeting galaxies at z = 2 - 6 (LeFèvre et al. 2015)
- protoclusters at z = 2.9, 3.3 & 4.6
- 12 spec-z members with $\delta_{gal} \sim 12$
- $M_{z=0}$ of about 3 x 10^{15} M_o

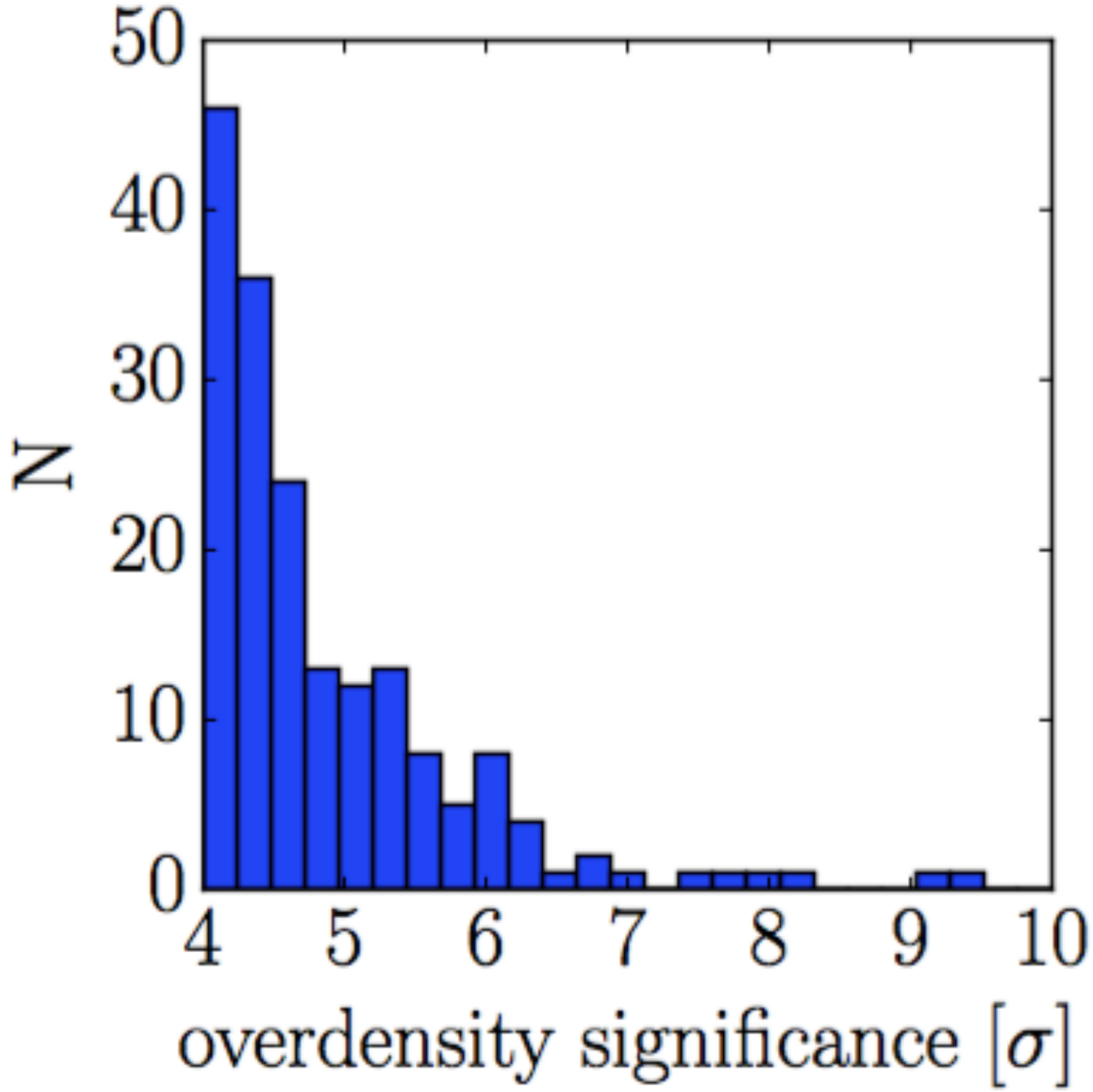
associated cold gas seen in absorption in background galaxy spectra:

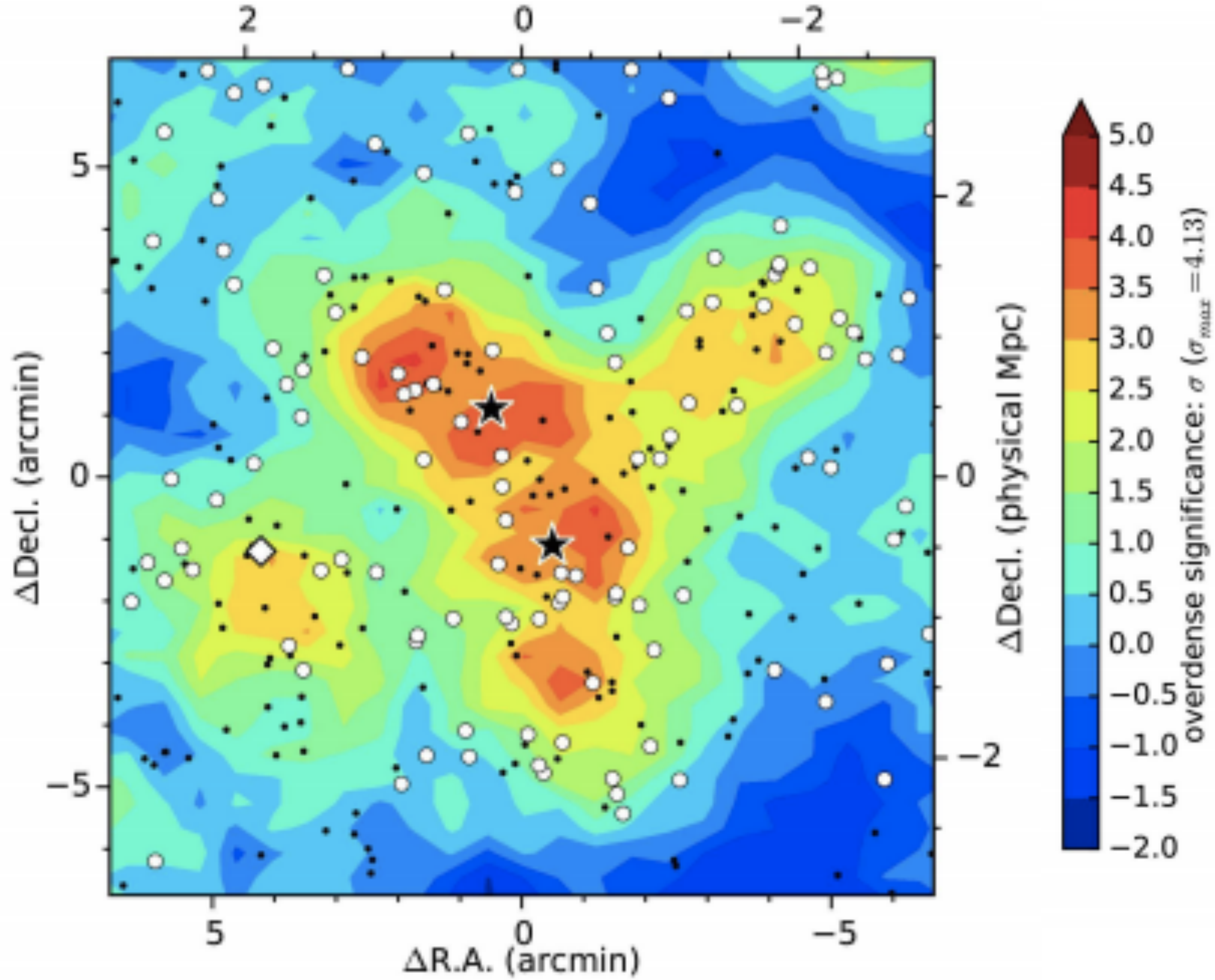
infalling gas from the cosmic web or outflowing gas blown out by the forming proto-cluster galaxies (?)



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

First results from the Subaru/HyperSuprimeCam Survey

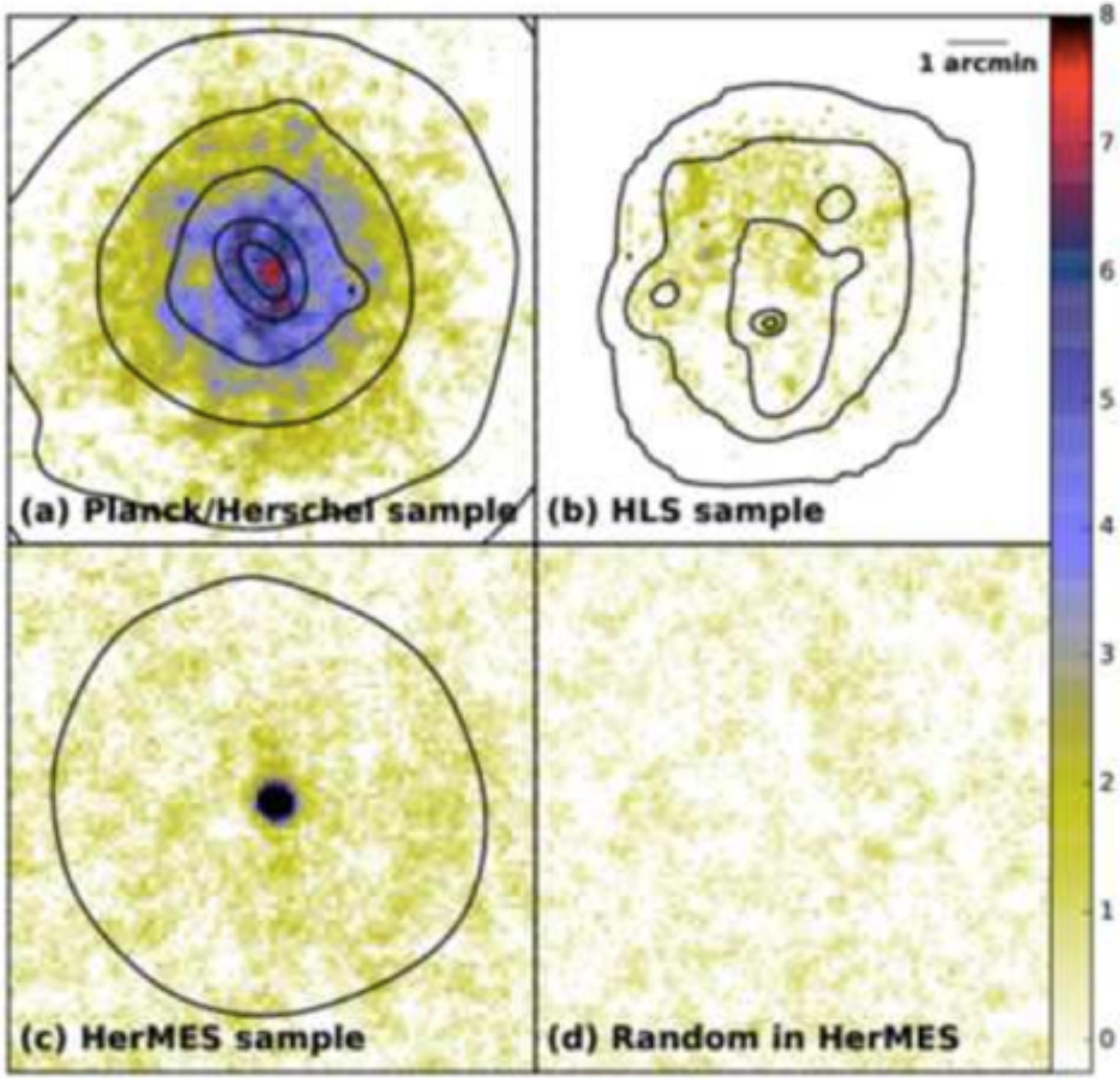




- **~200 high-fidelity protoclusters at z ~ 3.8 ± 0.3** (Toshikawa et al. 2017)
- **first analysis of co-incidence of protoclusters and (binary) quasars** (Uchiyama et al. 2017, Onoue et al. 2017)
- **first angular correlation function of z ~ 4 protoclusters** (Toshikawa et al. 2017)
- precursor to the **Subaru Prime Focus Spectrograph Survey** (~2019)

Protoclusters also appear as “cold spots” in the Planck maps

- 545 GHz excess emission relative to the 353 - 857 GHz interpolation

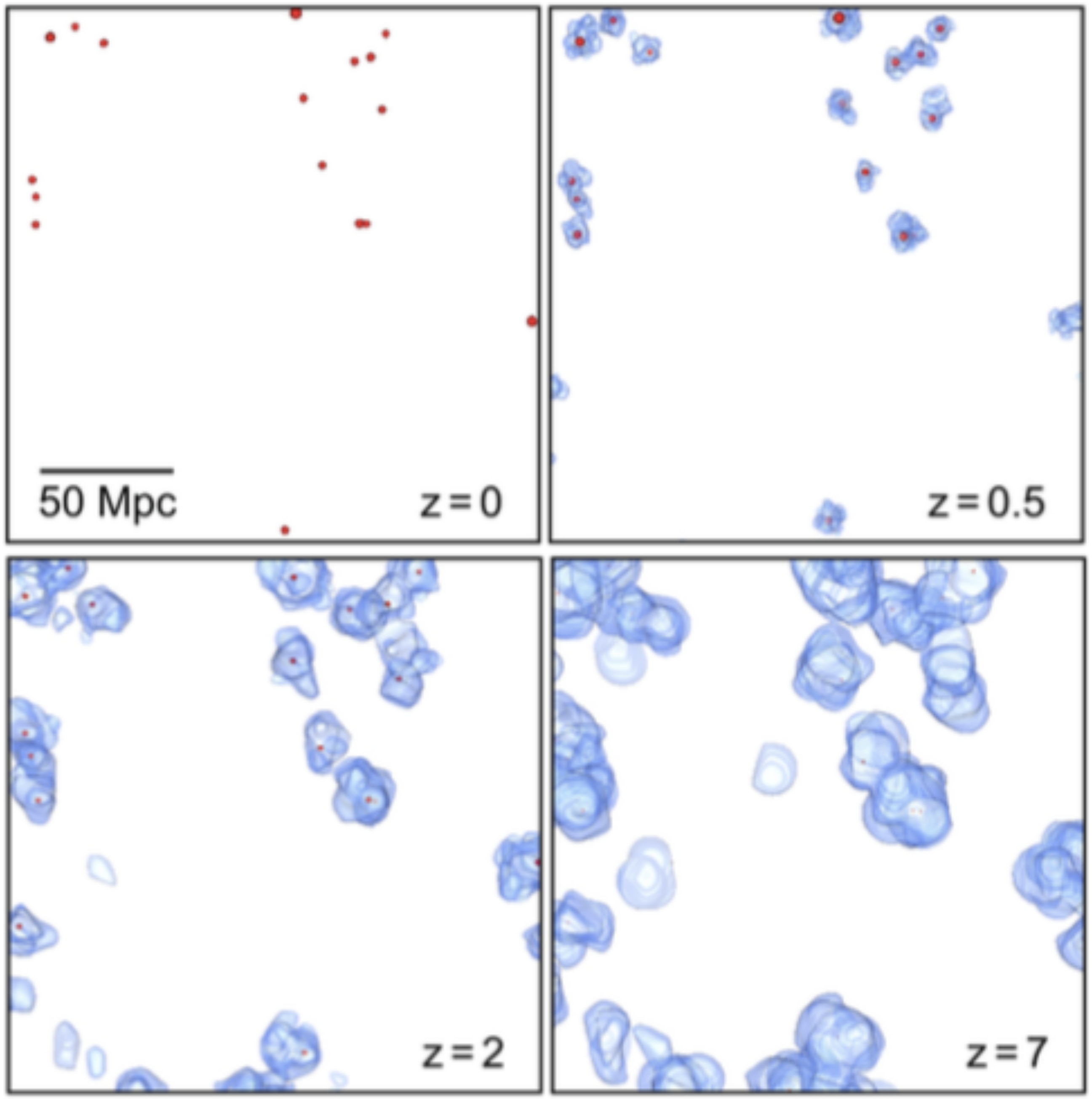


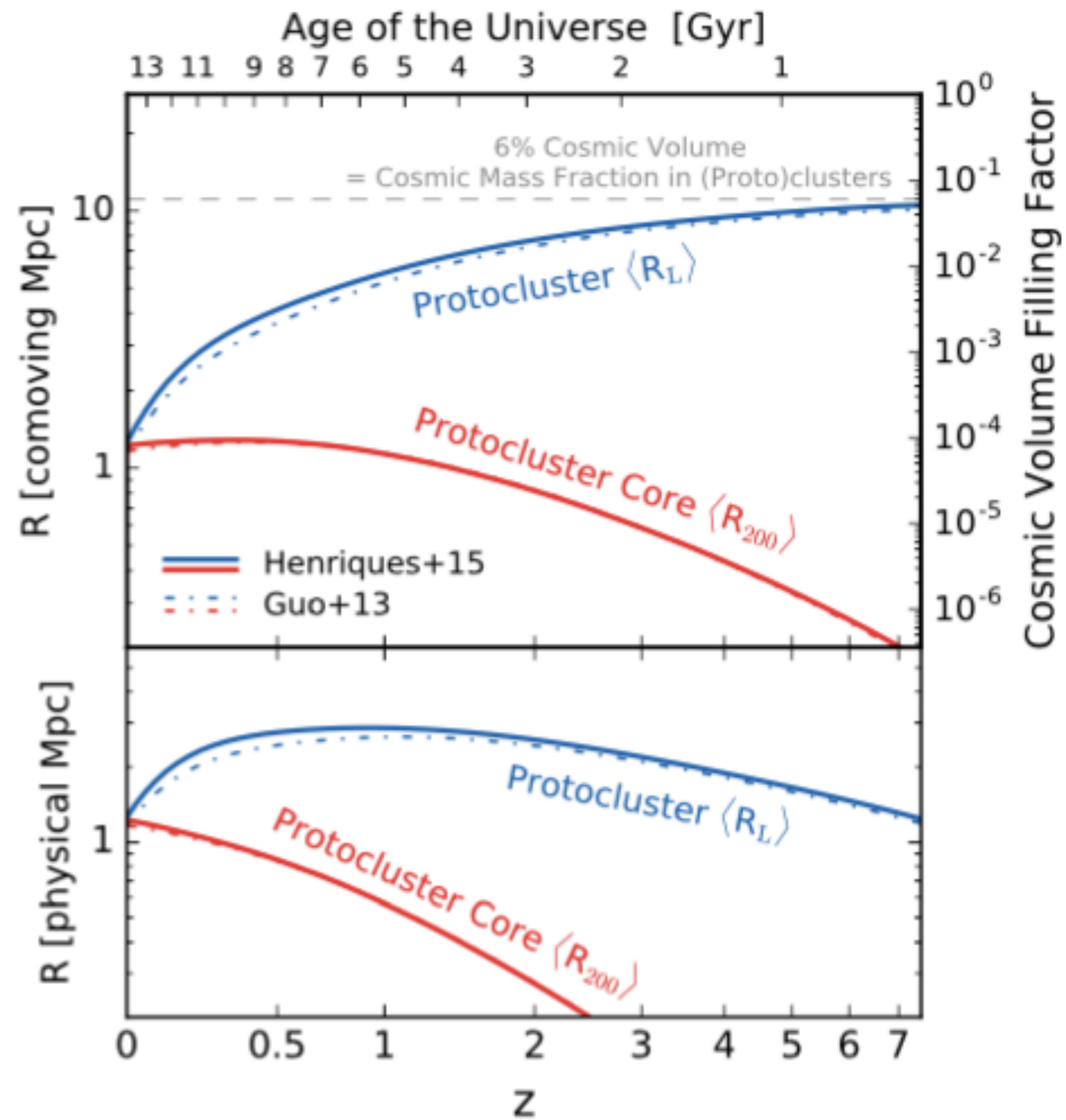
- about 1200 known to date
- Herschel/SPIRE shows they are large groups of dusty SFGs at z ~ 1 - 4
- relation to “unobscured” protoclusters not yet clear, perhaps later stage

Planck collaboration, Paper XXVII (2015)

The cluster contribution to the cosmic SFR density

- today, clusters only occupy ~0.01% of space
- however, by z > 6 the protoclusters occupy ~6% of the cosmic volume

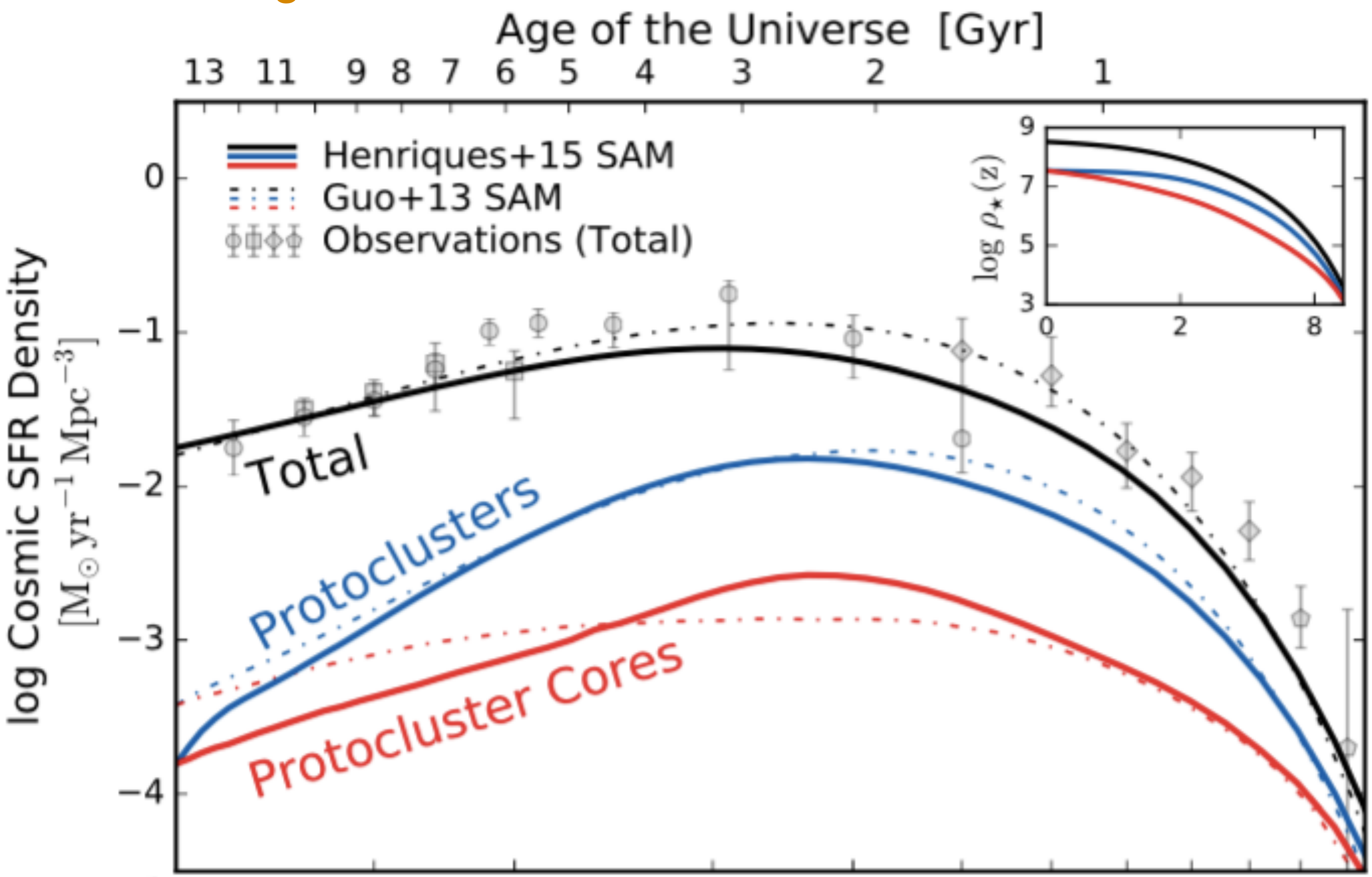




Chiang et al. (2017)

The cluster contribution to the cosmic SFR density

- 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
- the “cores” are insignificant



Chiang et al. (2017)

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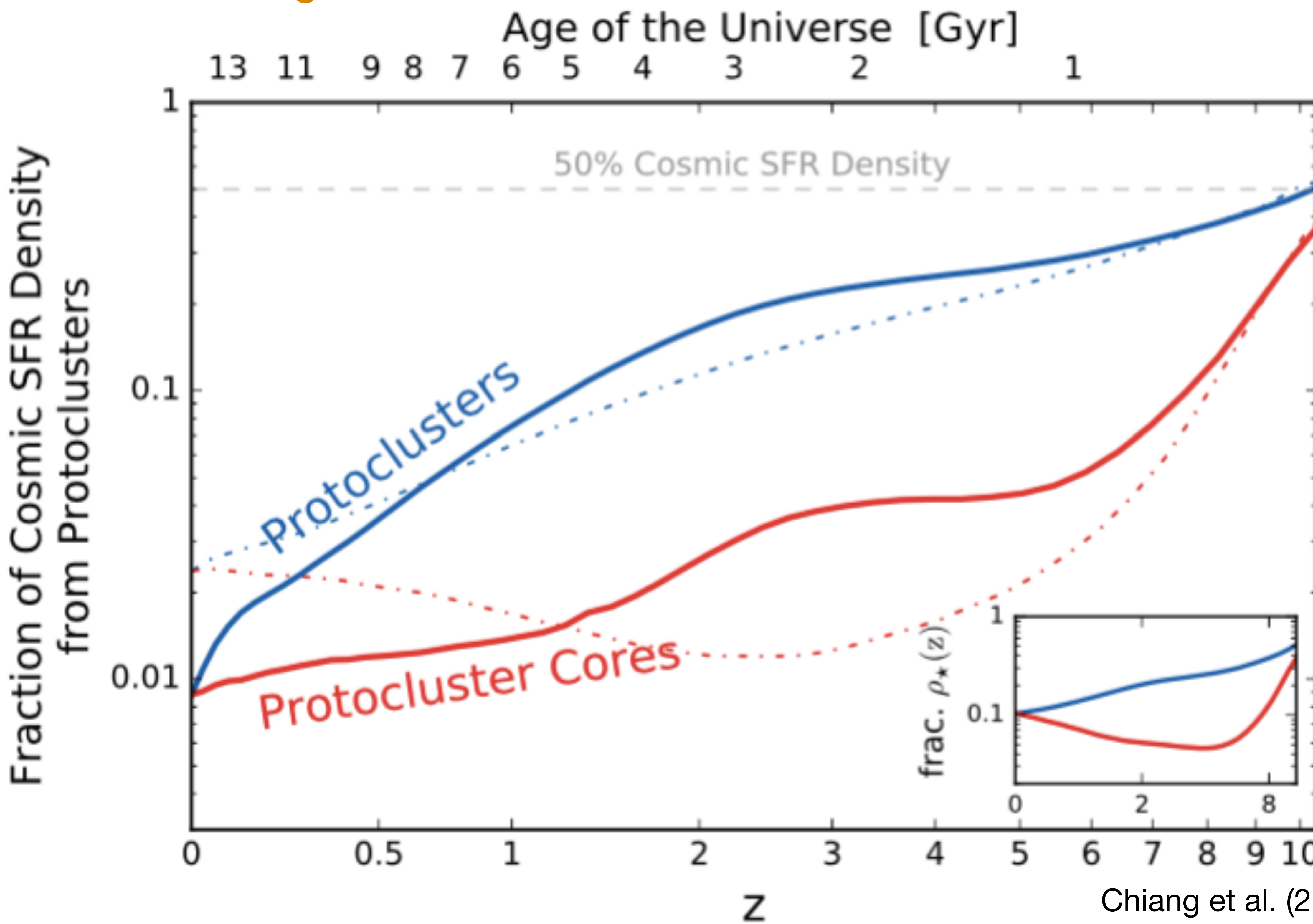
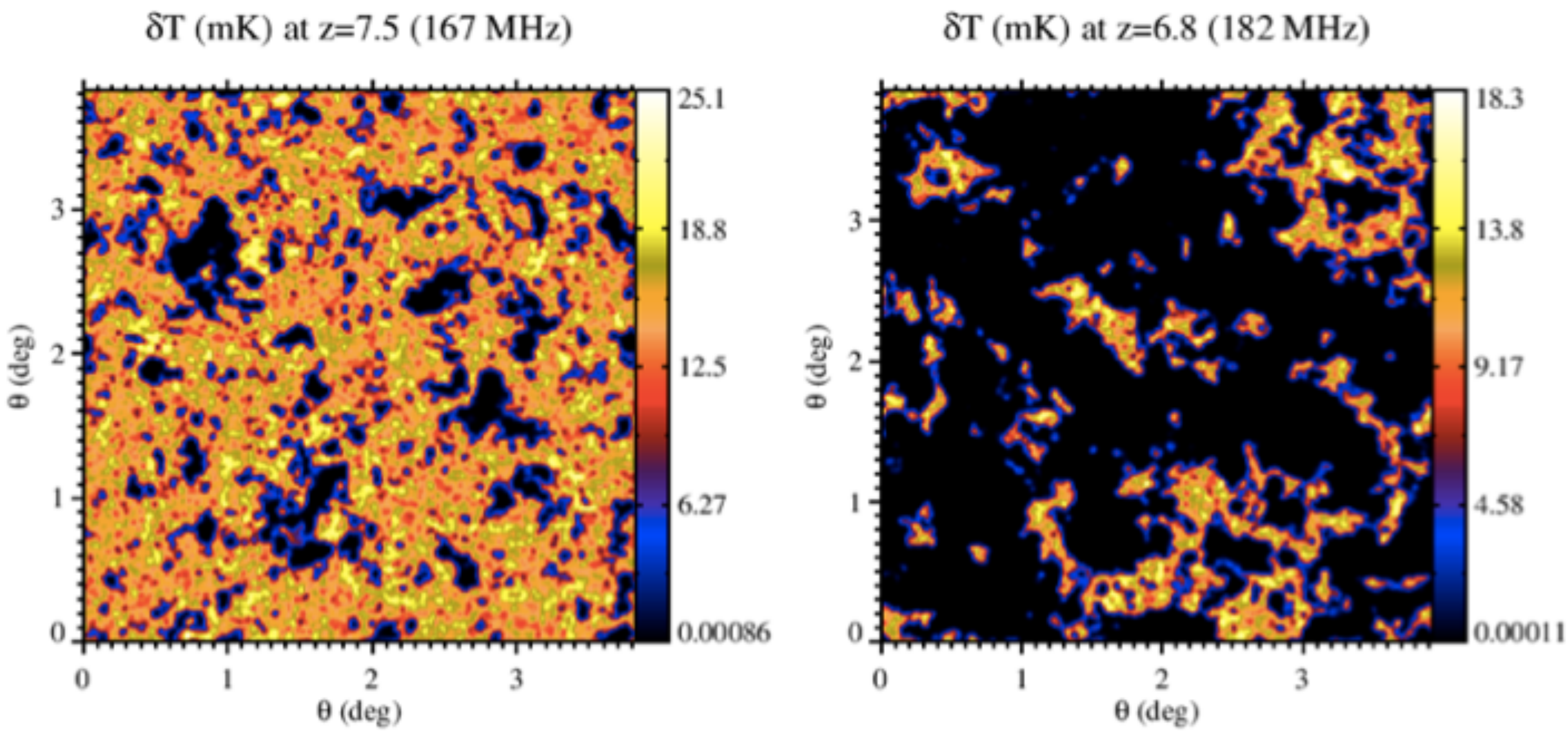


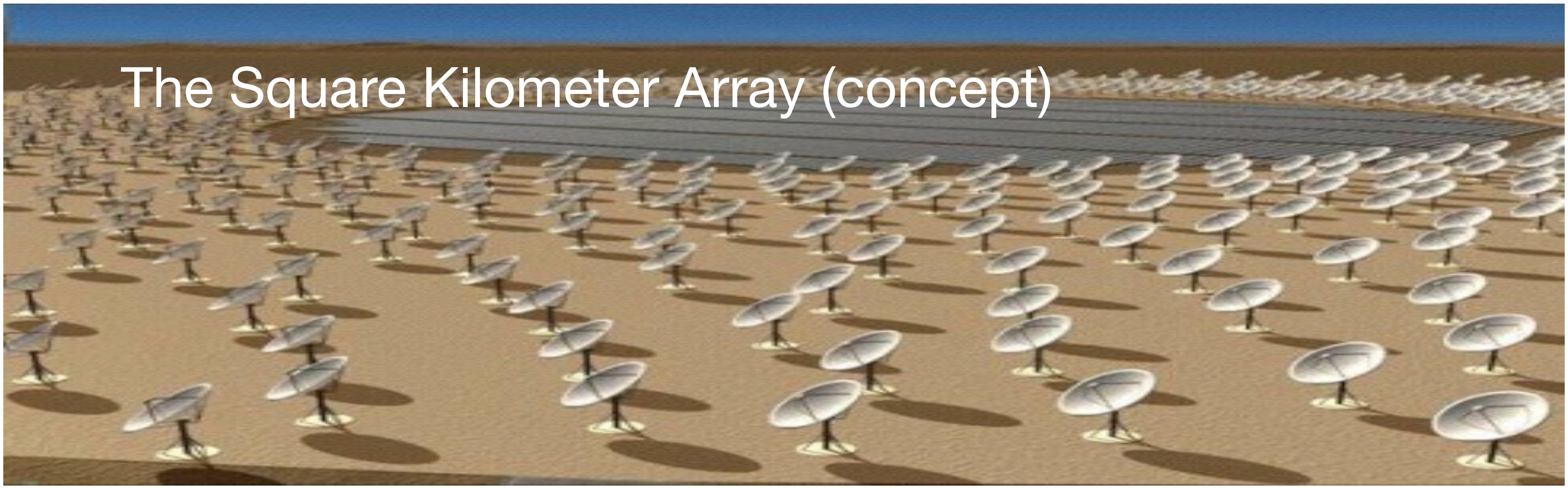
Chiang et al. (2017)

Protoclusters and the Epoch of Reionization

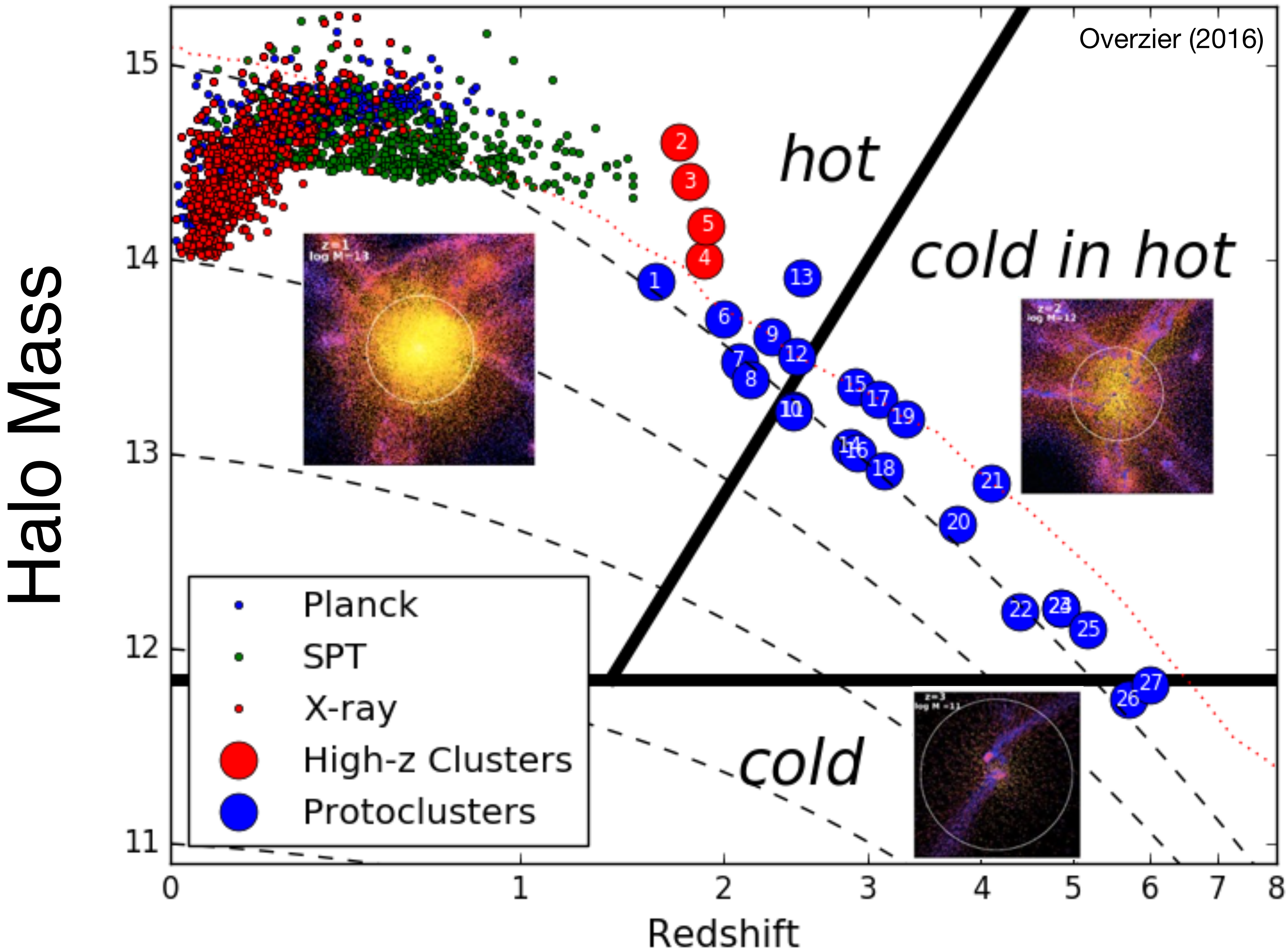


- radio 21 cm maps show the change in the distribution of neutral gas during the EoR
- the “dark” spots are regions around clusters where all neutral gas has been ionized

Mellema et al. (2013)



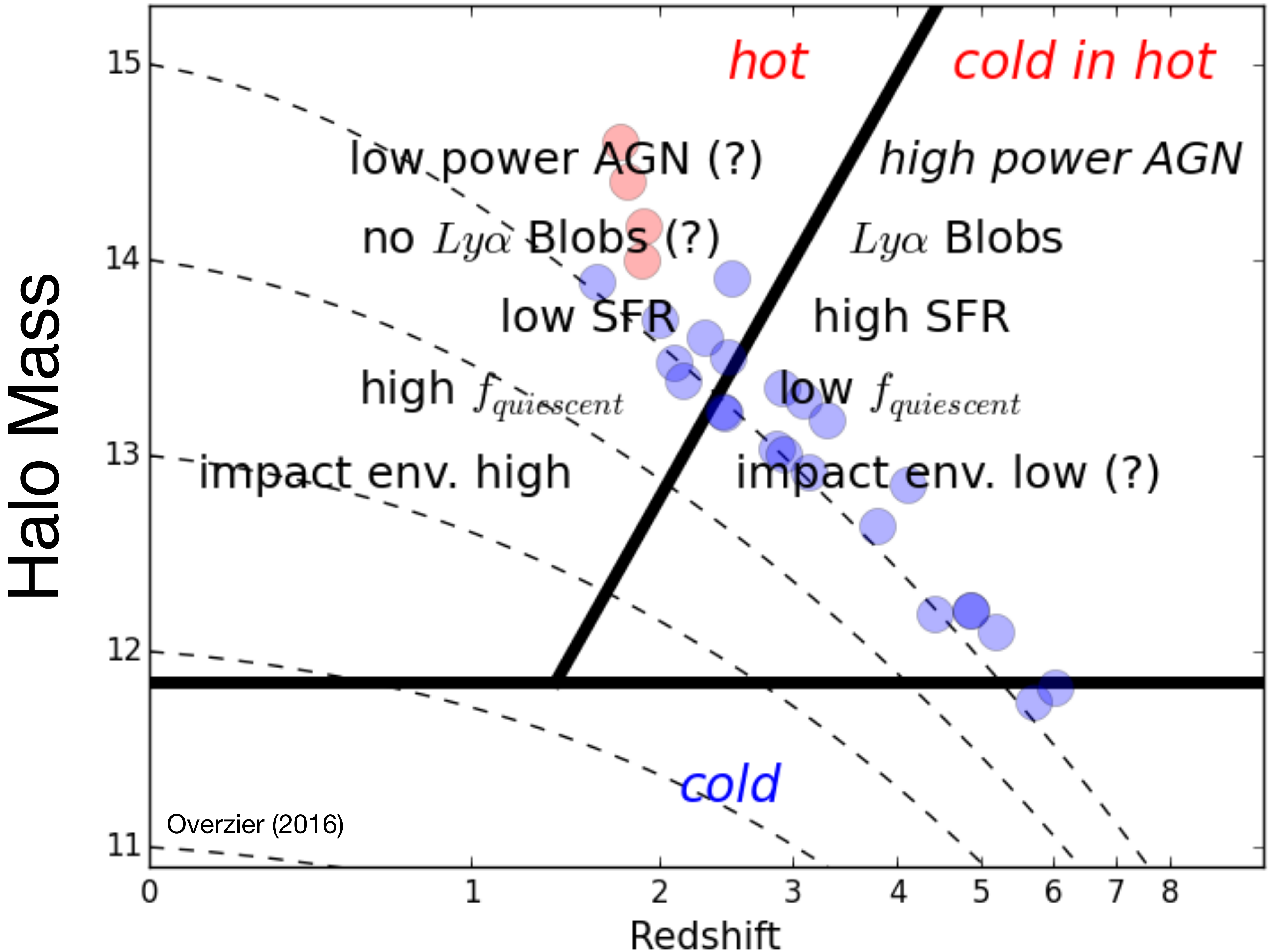
First attempt toward measuring cluster evolution



- (Proto)clusters should be the first structures to “switch off”

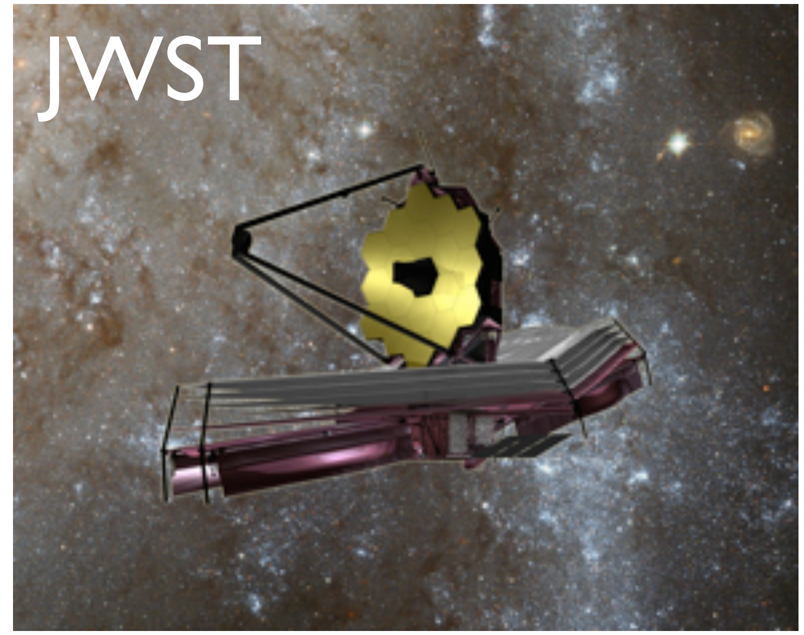
Overzier (2016)

Putting it all together…



Overzier (2016)

Targets wanted…



see Overzier (A&ARev, 2016) for a review

contact: overzier@on.br