Protoclusters of galaxies: the golden synergy between observations and simulations

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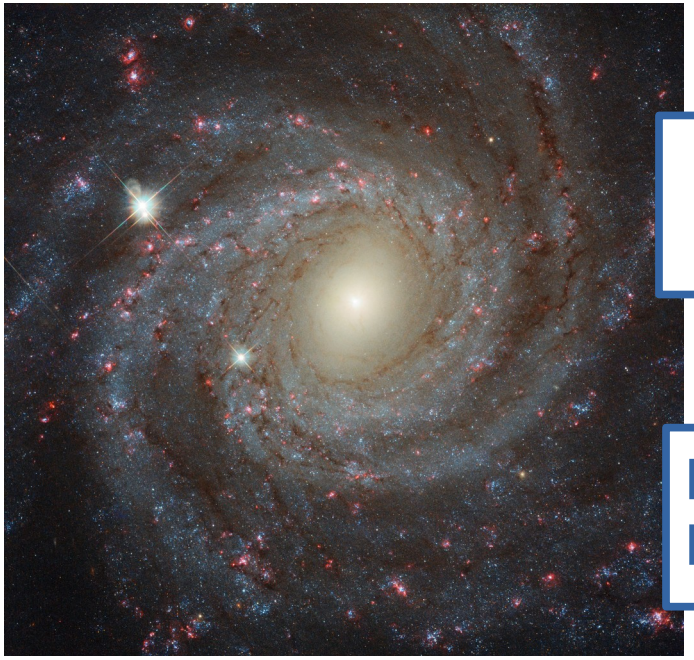
With the collaboraion of
G.De Lucia, F. Fontanot, M.Spinelli, B.Lemaux
and the C3VO Collaboration

Motivation

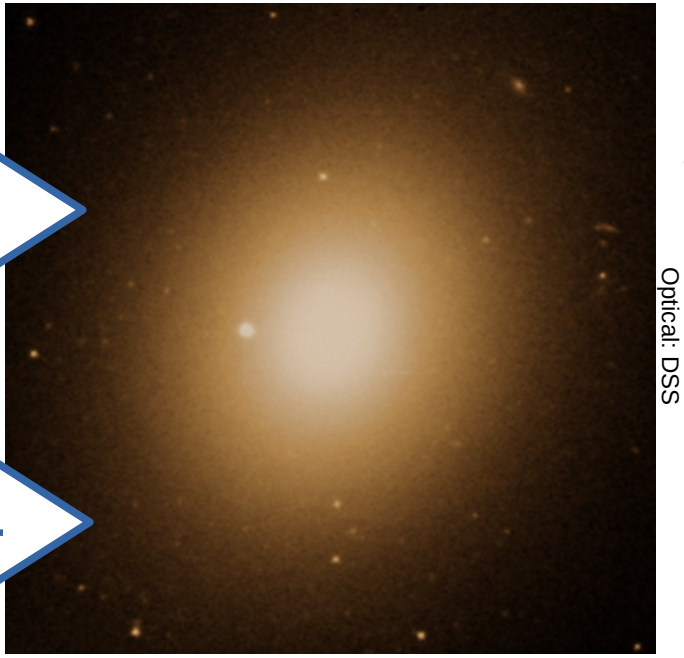
Study how environment affects galaxy evolution



Credit: ESA/Hubble, NASA

EVOLUTION

DENSER ENVIRONMENT



Credit: X-ray: NASA/CXC/Stanford Univ/N.Werner et al; Optical: DSS

- Spiral / disk-like morphology
- Young stellar populations: blue colour (unless dusty)
- Reservoir of cold gas: active/star forming
- Less massive

- Spheroidal/elliptical morphology
- Old stellar populations: red colour
- No or small reservoir of cold gas: passive/quiescent
- More massive

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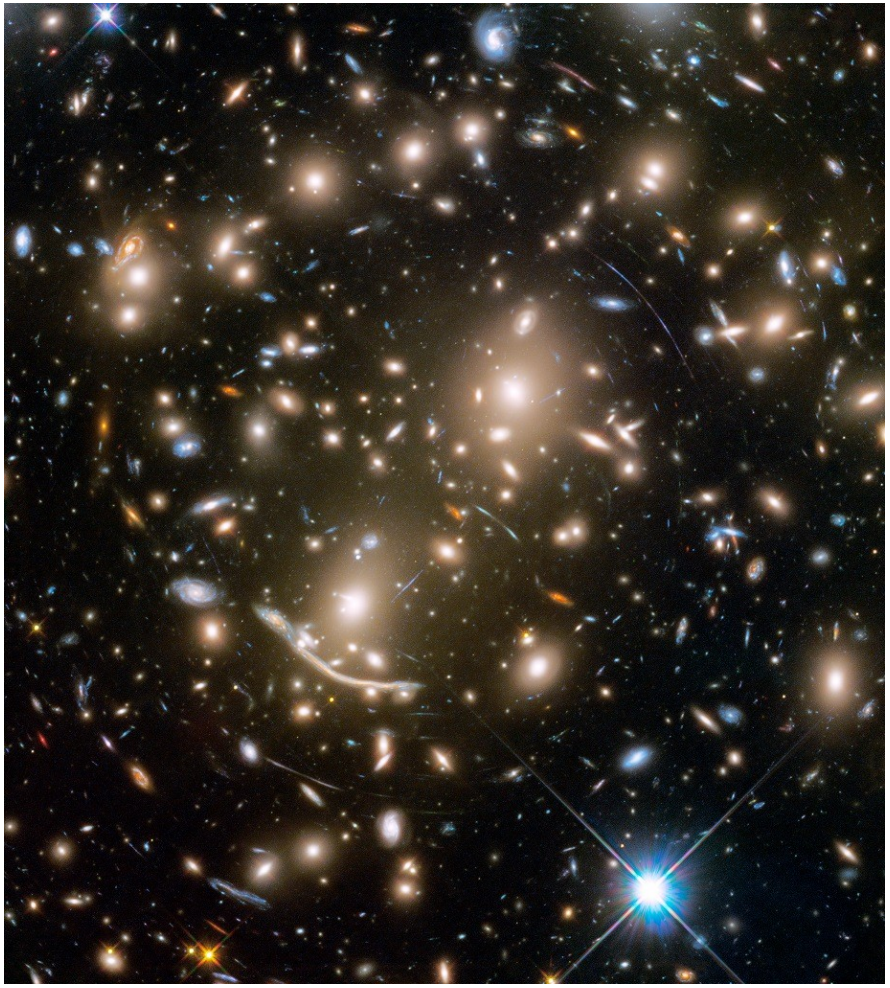


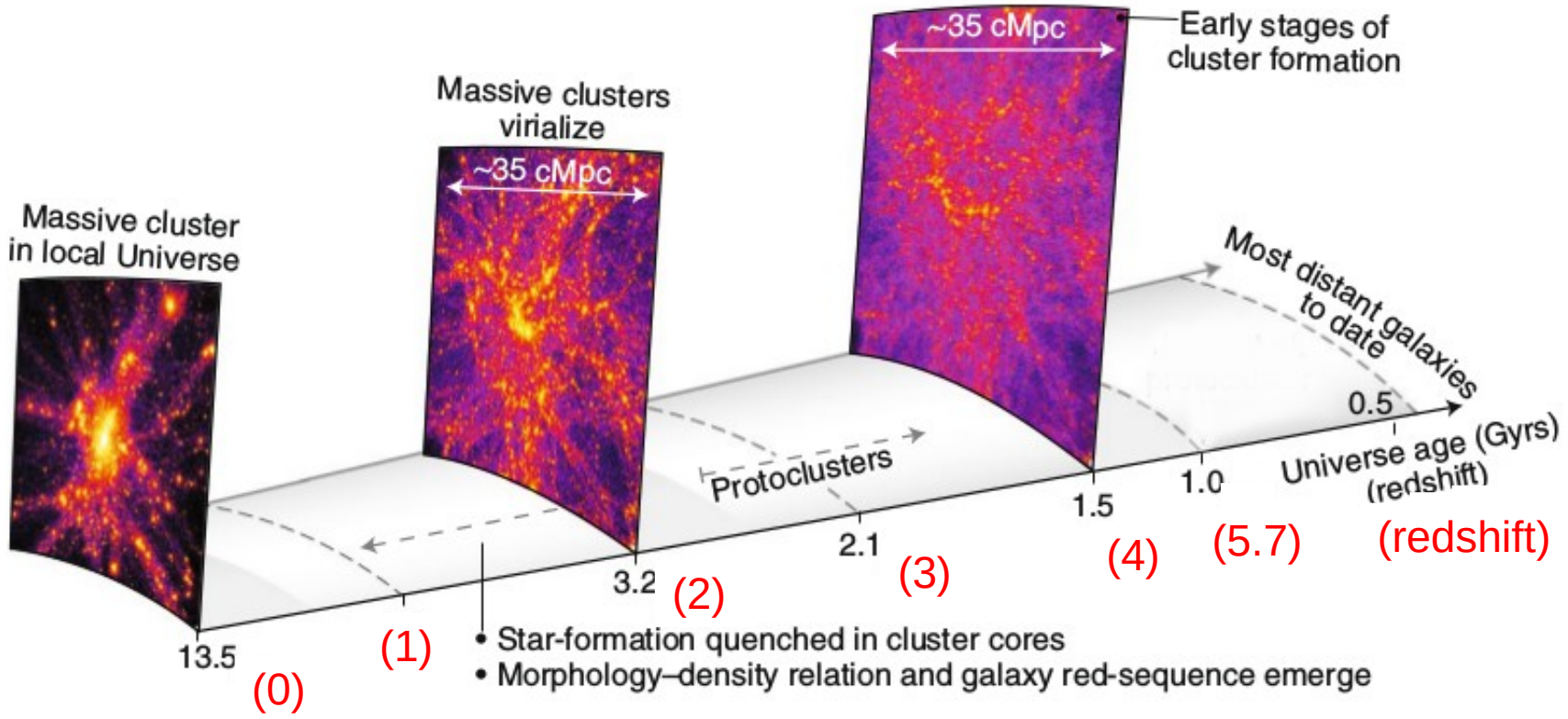
Credits: NASA, ESA, Jennifer Lotz and the HFF Team (STScI)

In the local universe we observe the final stages of such evolution

→ go back in time to track the on-set of the environmental effects and the time scales of galaxy transformation

Motivation

But environment evolves as well, so we need to study the co-evolution of galaxies and dark matter structures



Rosati 2018

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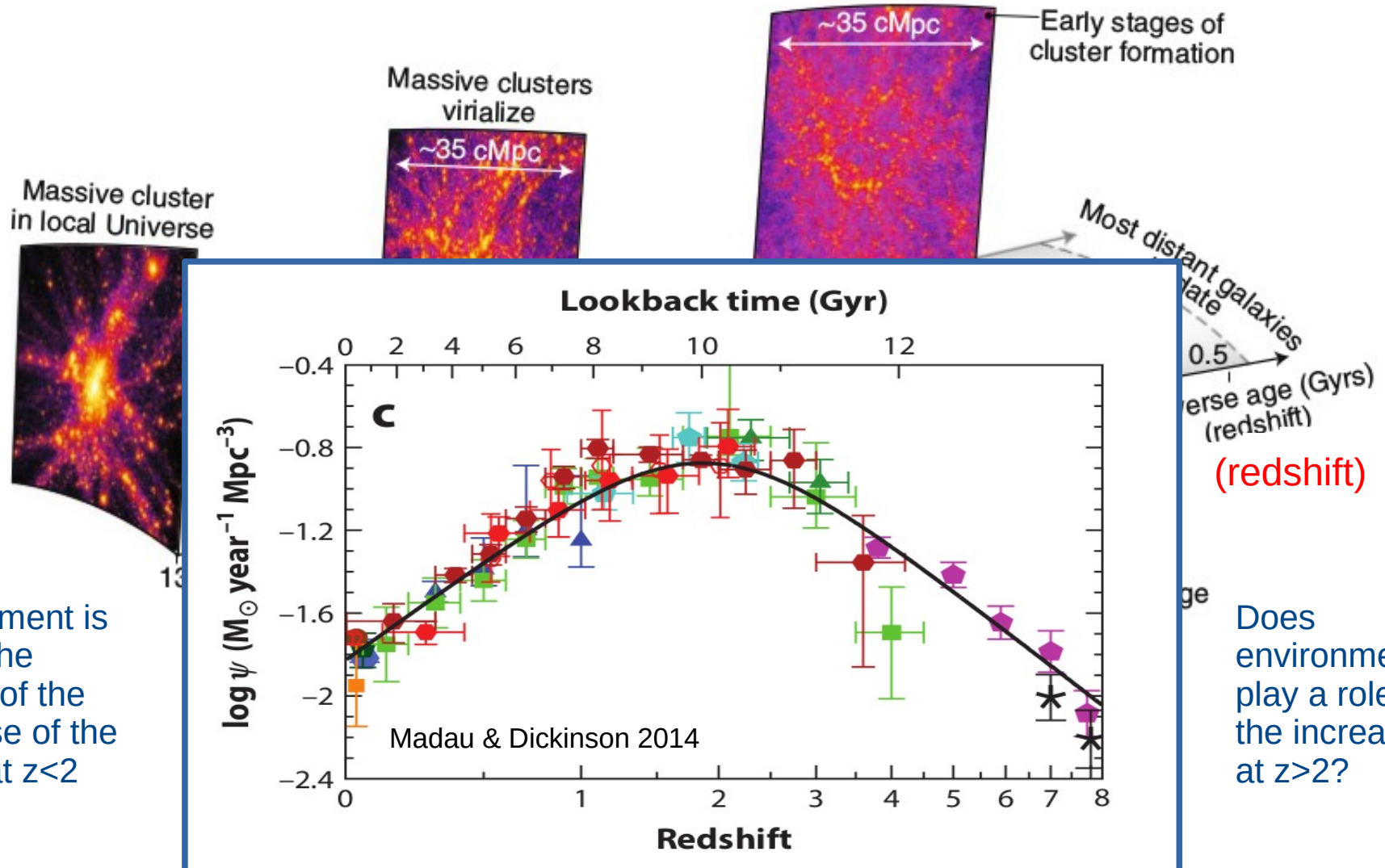

Environment is one of the causes of the decrease of the SFRD at z<2

Does environment play a role in the increase at z>2?

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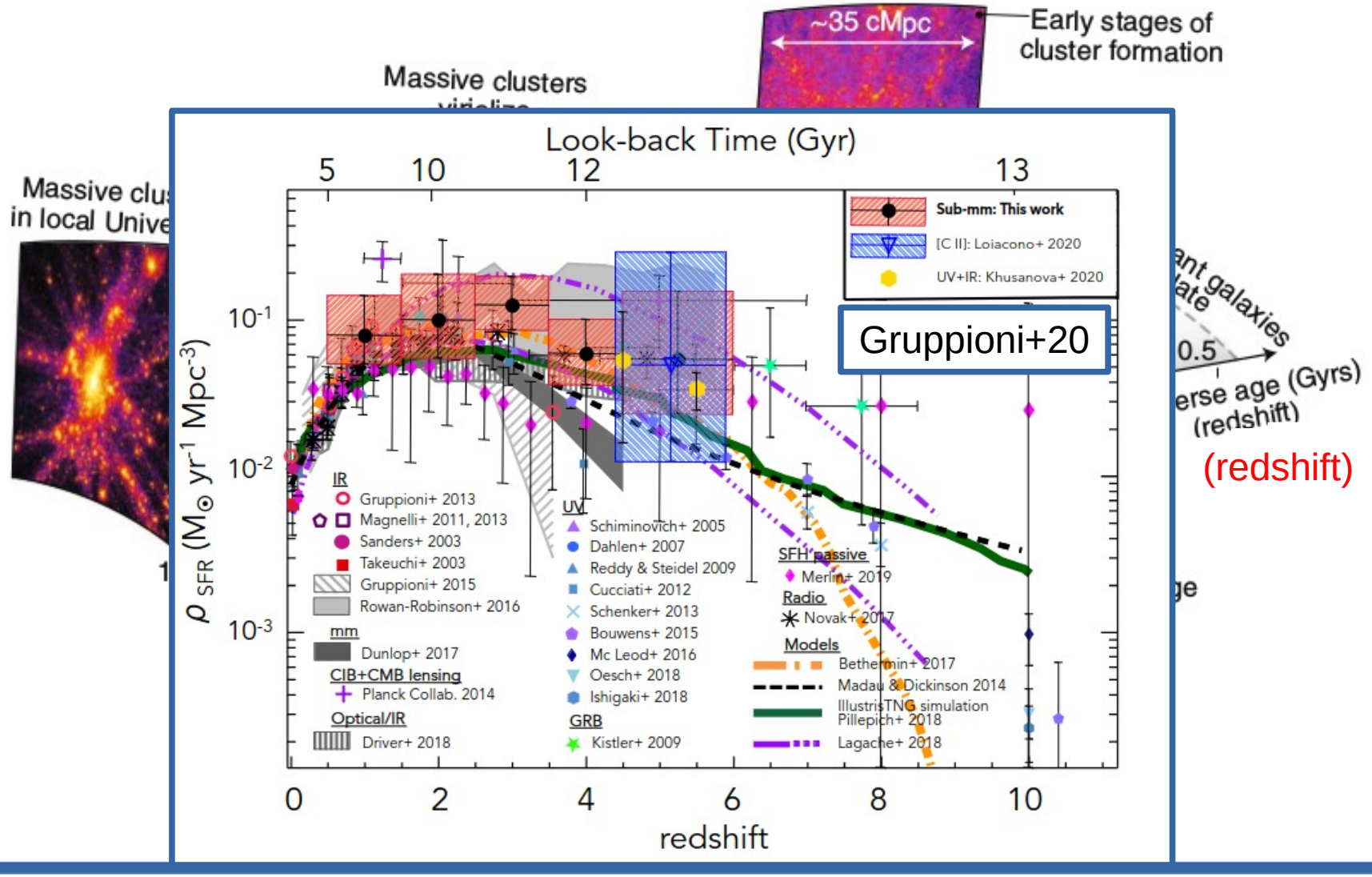

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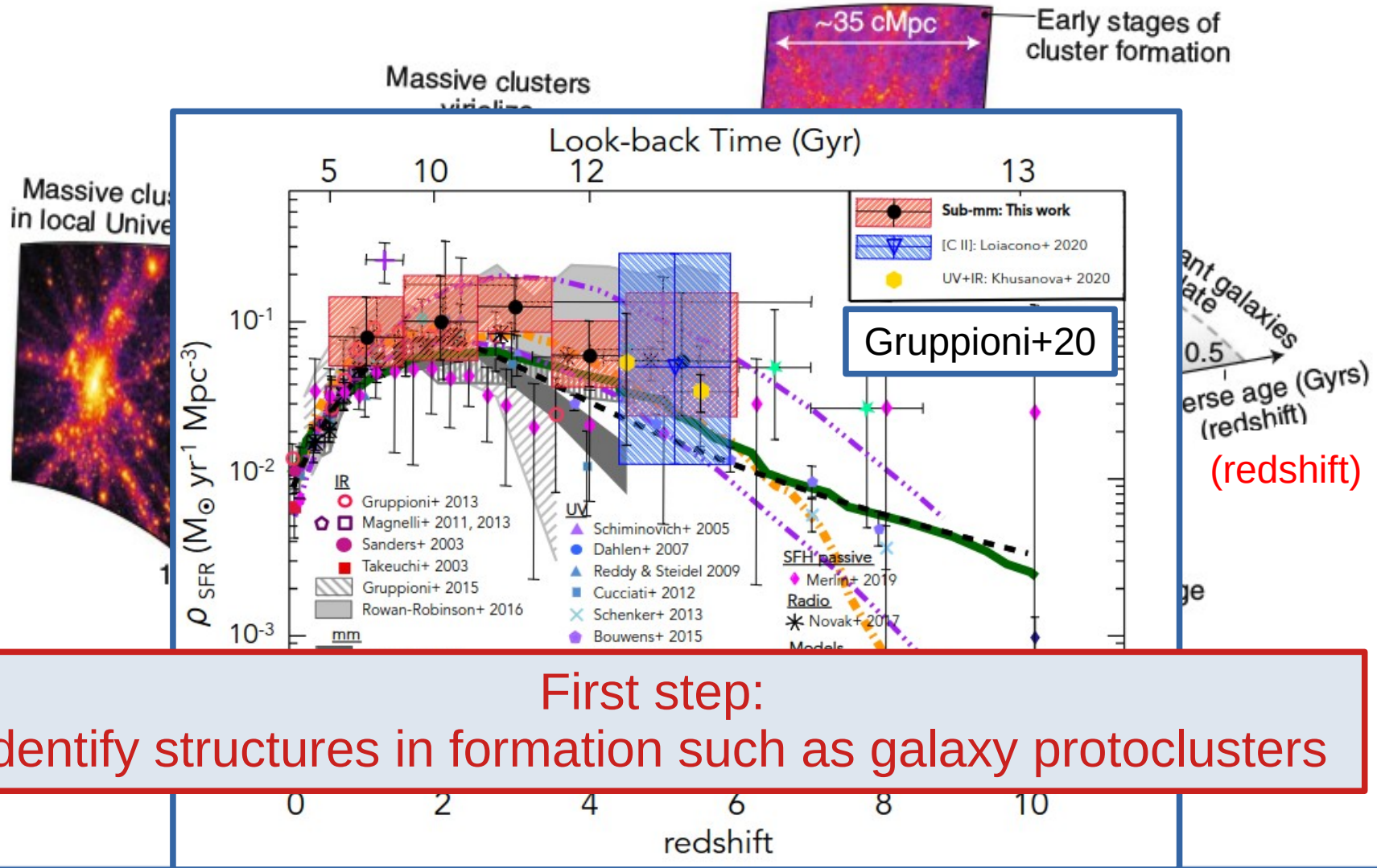
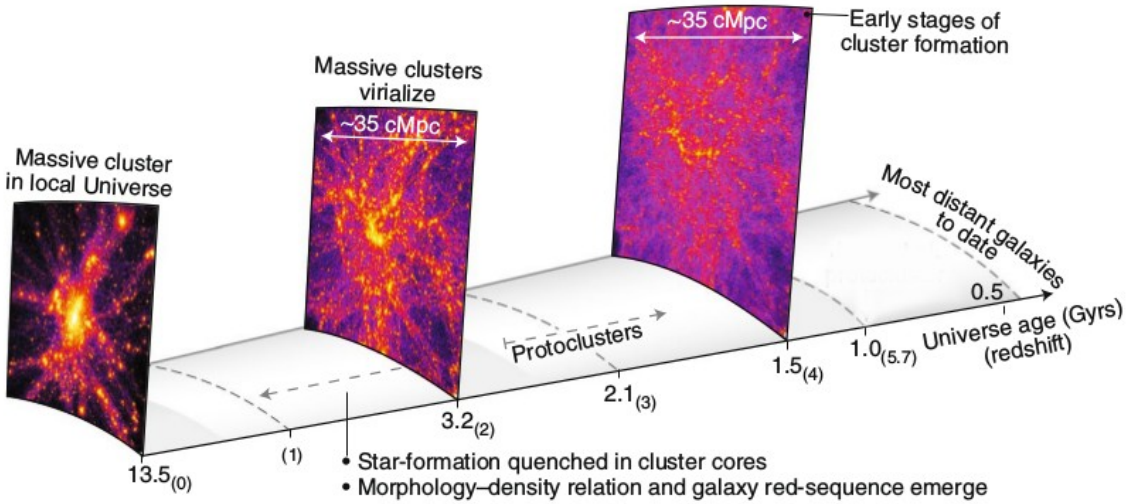


First step:
identify structures in formation such as galaxy protoclusters

Galaxy clusters vs proto-clusters



Galaxy clusters:

- Collapse:
  - deep potential well and virialization
    → $\delta_m \geq 200$
  - roughly regular shape
  - intra-cluster medium heated
    → diffuse Xray emission

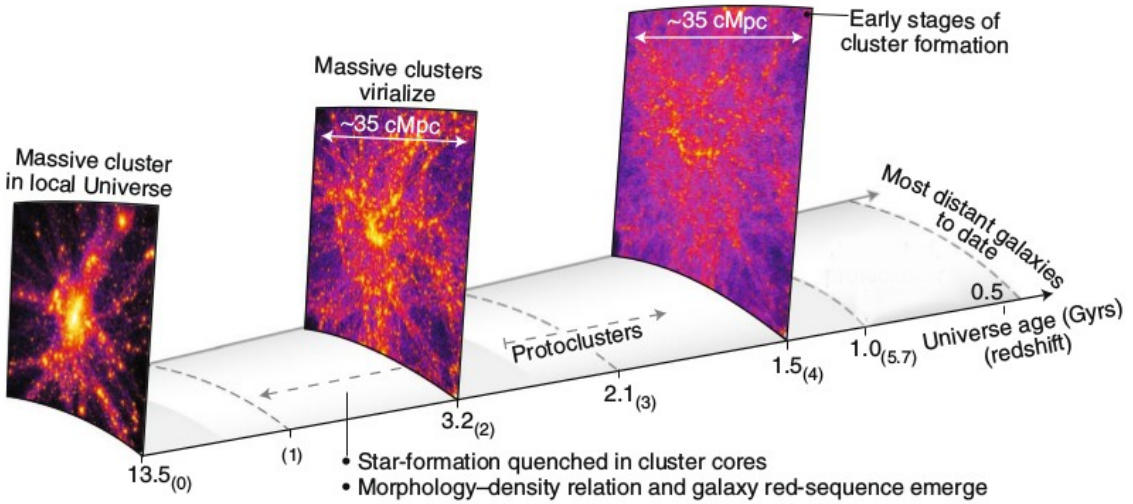
- Star formation quenched in galaxies:
  - **quiescent population** dominates the core
  - presence of the so called “red sequence”

Galaxy proto-clusters:

- overdensity of galaxies
  - collapse on-going?
    → δ_{gal} **~2-20**
  - large spatial dimensions (>>1 Mpc)
  - irregular shape

- **high level of star formation:**
  - quenching on going?
  - presence of passive galaxies? (red sequence in formation?)

Galaxy clusters vs proto-clusters



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Mass distribution

Galaxy populations

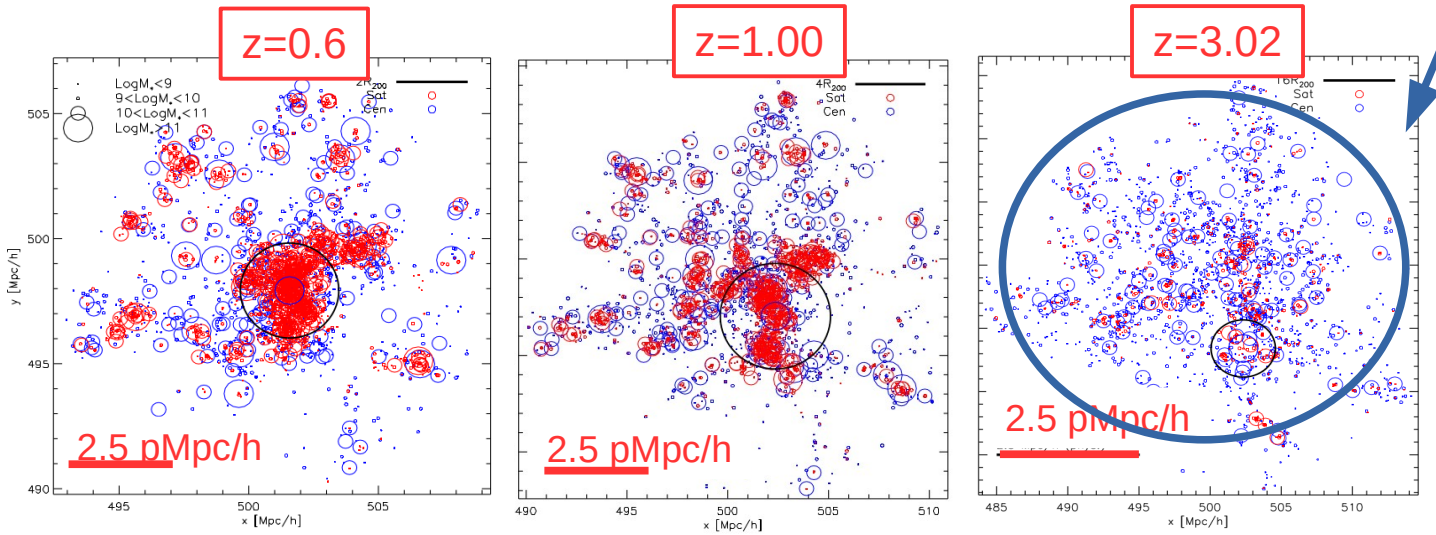
Mass distribution (from simulations)

- Low density contrast
- Most of the mass still distributed in filaments on scales of tens of Mpc

(Chiang+13, Muldrew+15, Contini+16…)

Ideally, we would like to identify this entire structure

Take a cluster at z=0, and follow its progenitors back in time:



Adapted from Contini+16

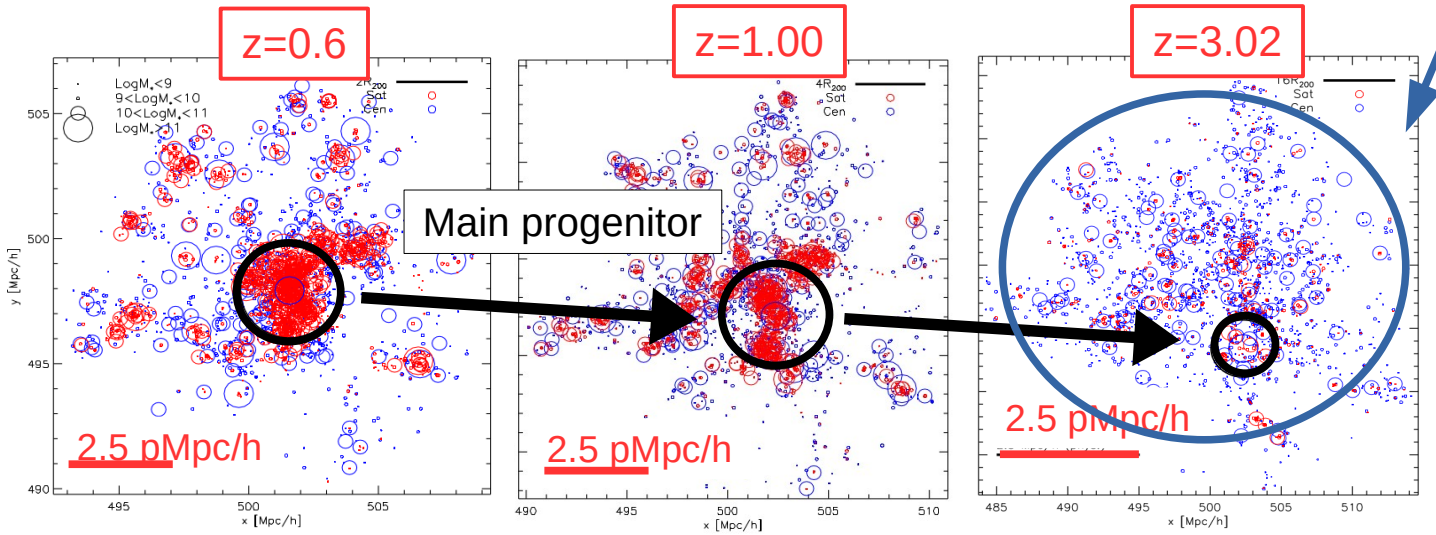
Mass distribution (from simulations)

- Low density contrast
- Most of the mass still distributed in filaments on scales of tens of Mpc
- does the “main progenitor” truly define the proto-cluster?

(Chiang+13, Muldrew+15, Contini+16…)

Ideally, we would like to identify this entire structure

Take a cluster at z=0, and follow its progenitors back in time:



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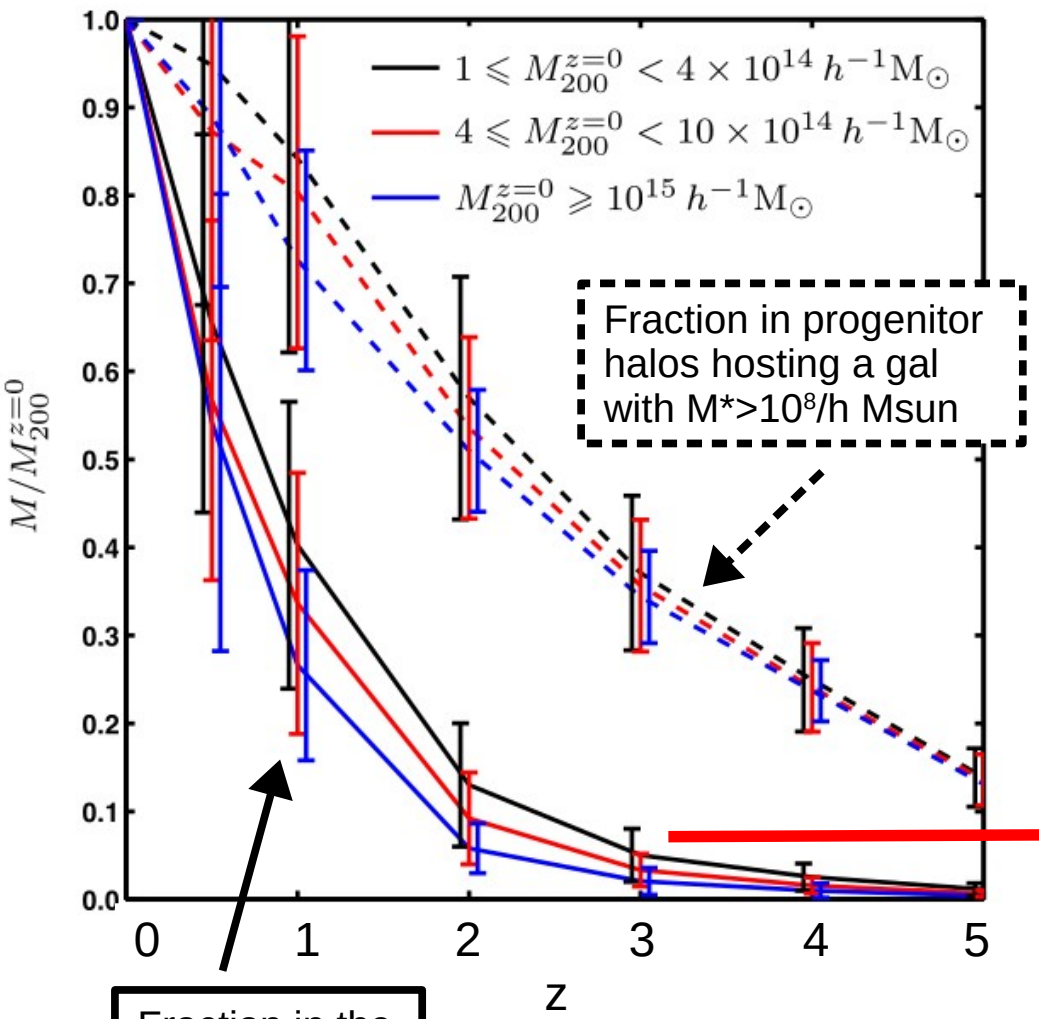
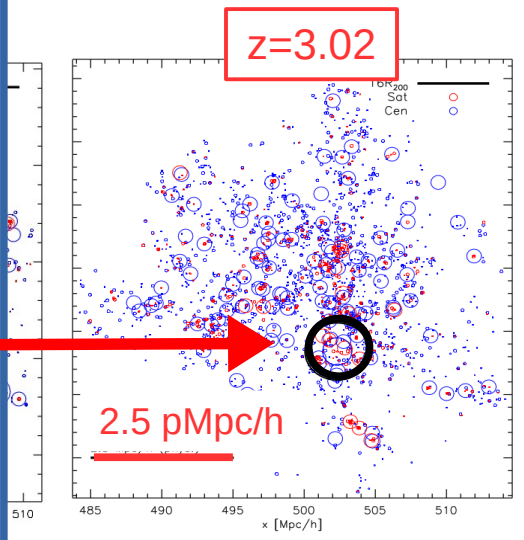


At z=3:

- <10% of the final M200(z=0) is in the main halo (Muldrew+15)
- **40% of its progenitors are enclosed in a box with size = 15Mpc/h** (Contini+16)

ogenitors back in time:



Galaxy populations
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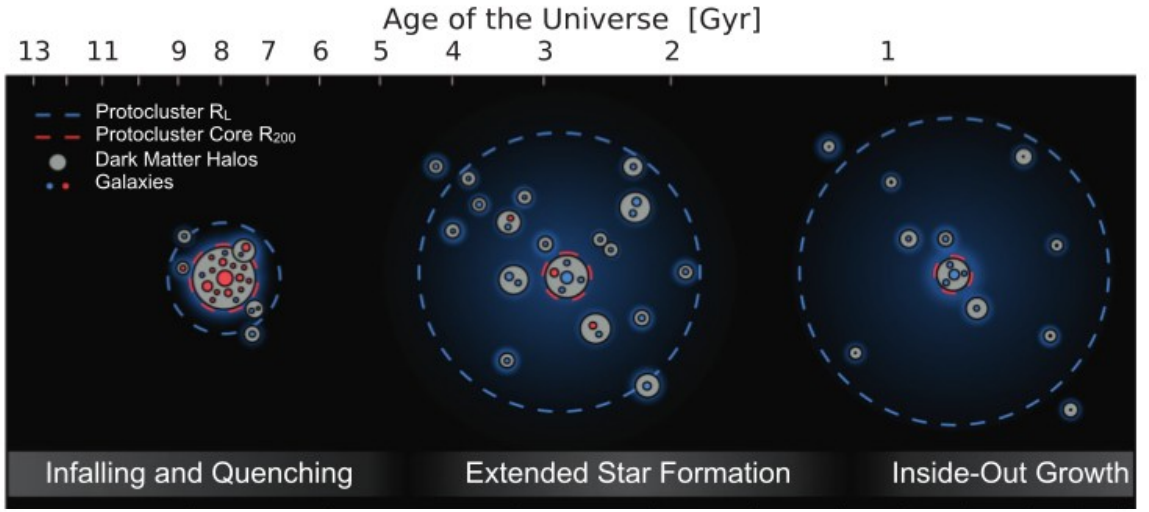
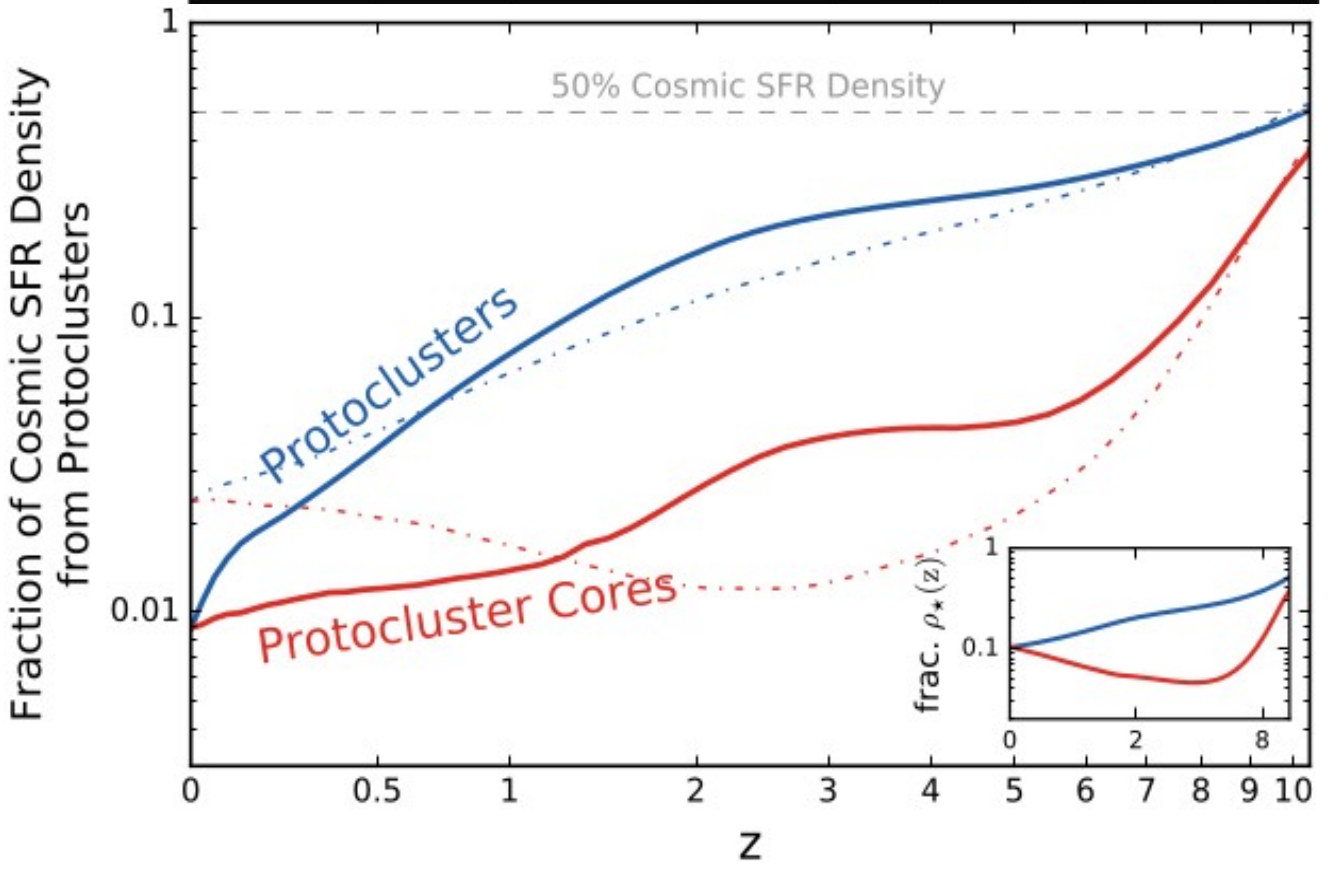




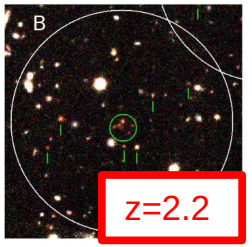
Adapted from Chiang+17

The search for galaxy proto-clusters in the real life

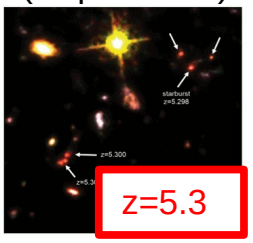
1) At fixed z, proto-clusters can show different states of evolution for both structures and galaxies (eg Muldrew+15)

- Gas cools in high-density DM halos soon after their formation:
  → population of SF galaxies?
- Large reservoirs of gas + high merger rate: trigger supermassive black holes, formation of quasars and radio galaxies
  → rapidly quenching population?

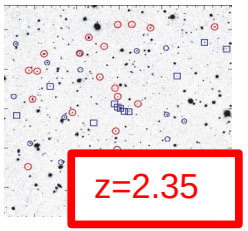
Red galaxies
(Spitler+12...)



SF galaxies
(Capak+11...)

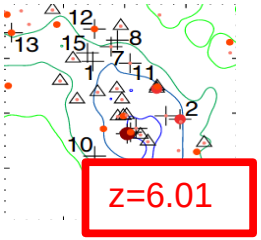


Hα emitters
(Hatch+11...)

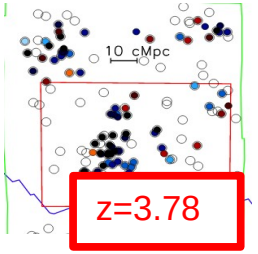


LAEs
(Venemans+07...)

LBGs
(Toshikawa+12)

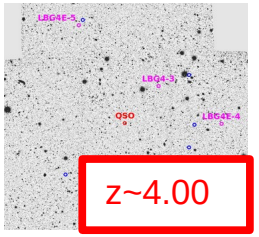


Balmer break / LAE
(Shi+19)



Dust-obscured
(Oteo+18)

Around AGN
(Adams+15)



Around Radio galaxies
(Galametz+13)

[See Overzier+19 for a review]

The search for galaxy proto-clusters in the real life

1) At fixed z, proto-clusters can show different states of evolution for both structures and galaxies (eg Muldrew+15)

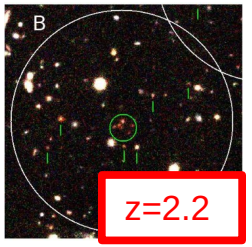
2) They are difficult to identify

- Lower density contrast and **most of the mass still distributed in filaments on scales of tens of Mpc**

  → Mainly single and serendipitous detections, or targeted around AGNs

  → Very different overdensities, redshift, shapes, and volumes

Red galaxies
(Spitler+12...)



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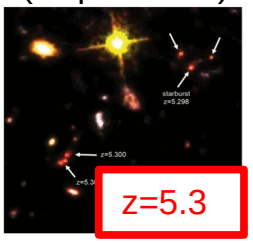

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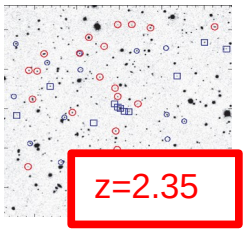

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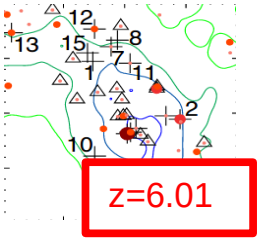

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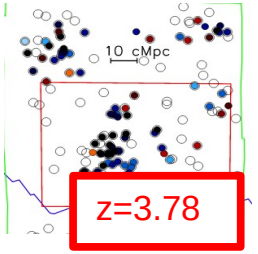

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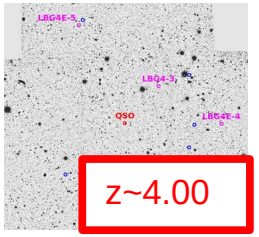
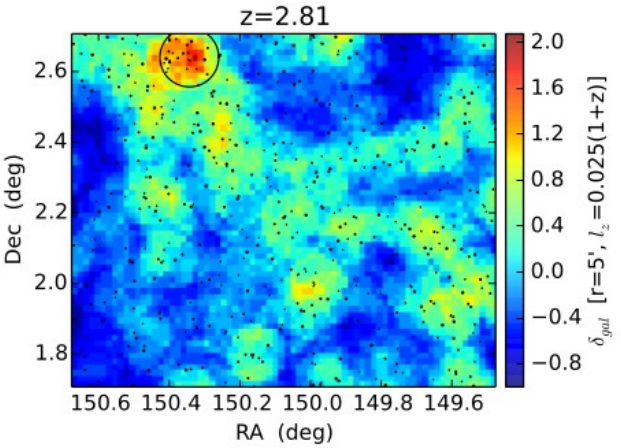


Around Radio galaxies
(Galametz+13)

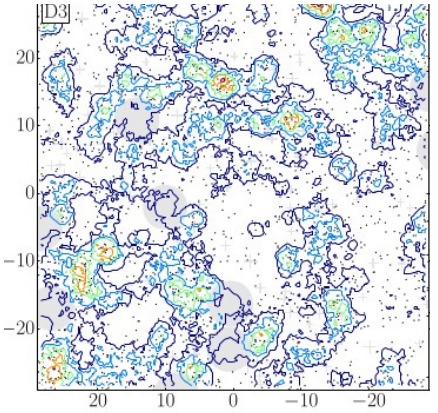
[See Overzier+19 for a review]

Systematic searches
(… on which scales?)

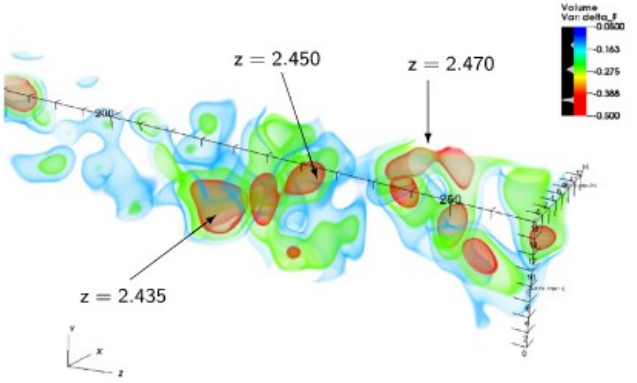
- **Deep imaging surveys: drop-outs or proper photo-z** (e.g, Chiang+14, Toshikawa+16,18)
- **Narrow-band filters surveys** (e.g. Harikane+19)
- **Deep spec-z surveys** (e.g. Diener+13, Franck&McGaugh+16, Guaita+20)
- **Synergy between deep spec-z and photo-z surveys** (Sarron+21, Hung+ in prep)
- **Tomographic studies: infant ICM in protoclusters as signature in the background galaxies spectra** (e.g., Lee+16,18, Cai+16, Newman+20)
- **Dark matter density field inferred from the reconstructed primordial density fields** (e.g. Ata+21)



Chiang+14



Toshikawa+16

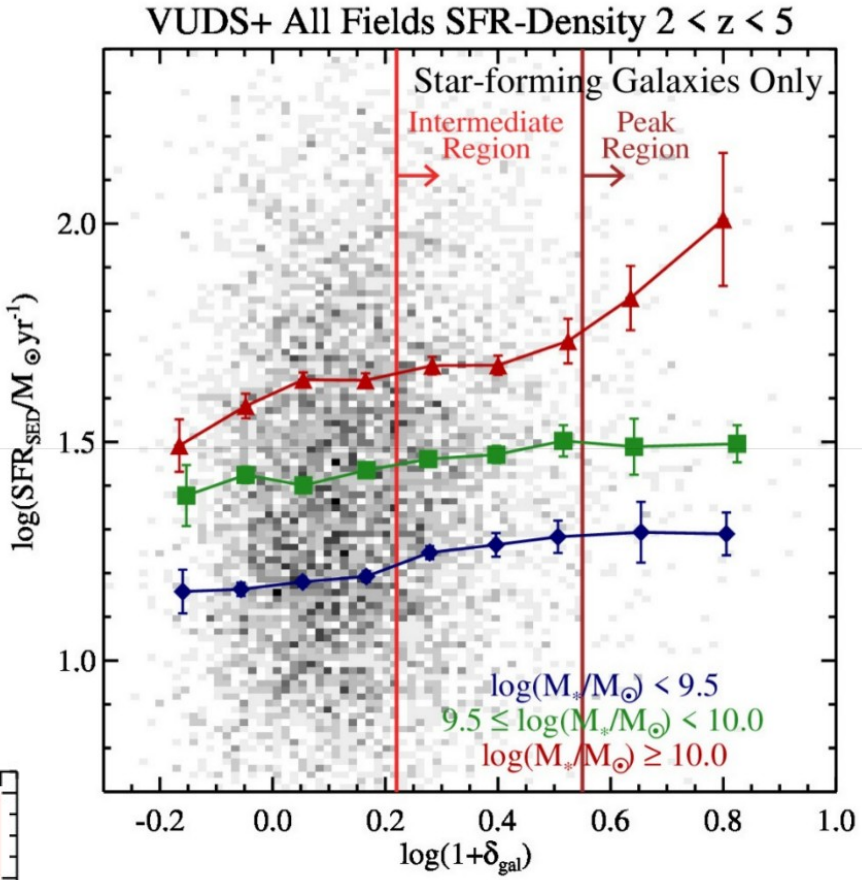


Lee+14

Galaxy populations in larger samples

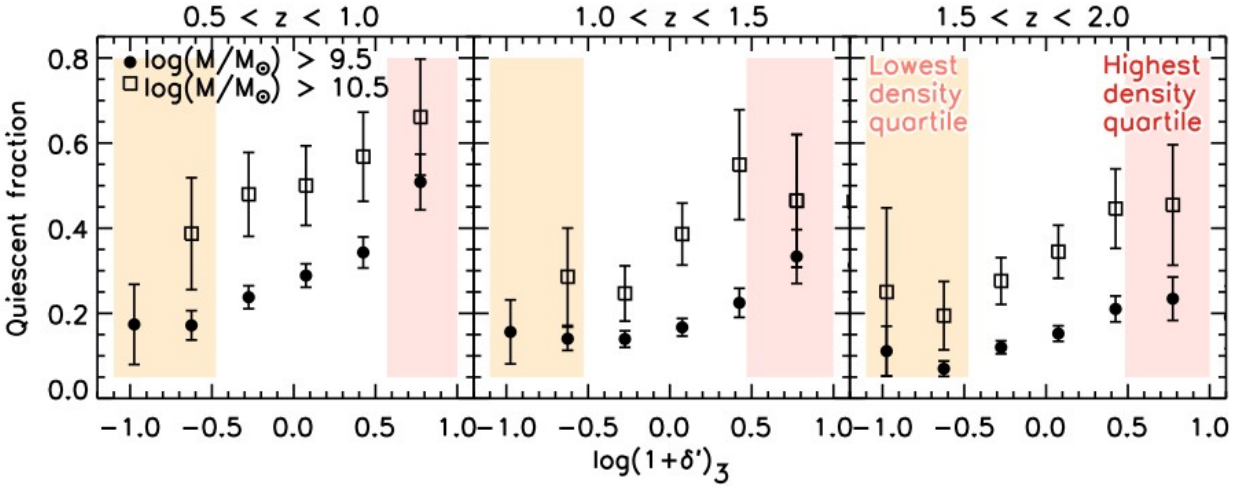
(the long story short)

- Possible scenario: accelerated evolution of galaxies in proto-clusters
  → proto-clusters often associated with high levels of dust-obscured burst of SF (eg Casey+16 for overview)
  → very quick stellar mass assembly: after the star-bursts, the fraction of red galaxies increase very rapidly at about 1.5<z<2.5 (Cooke+15)



Lemaux+2022

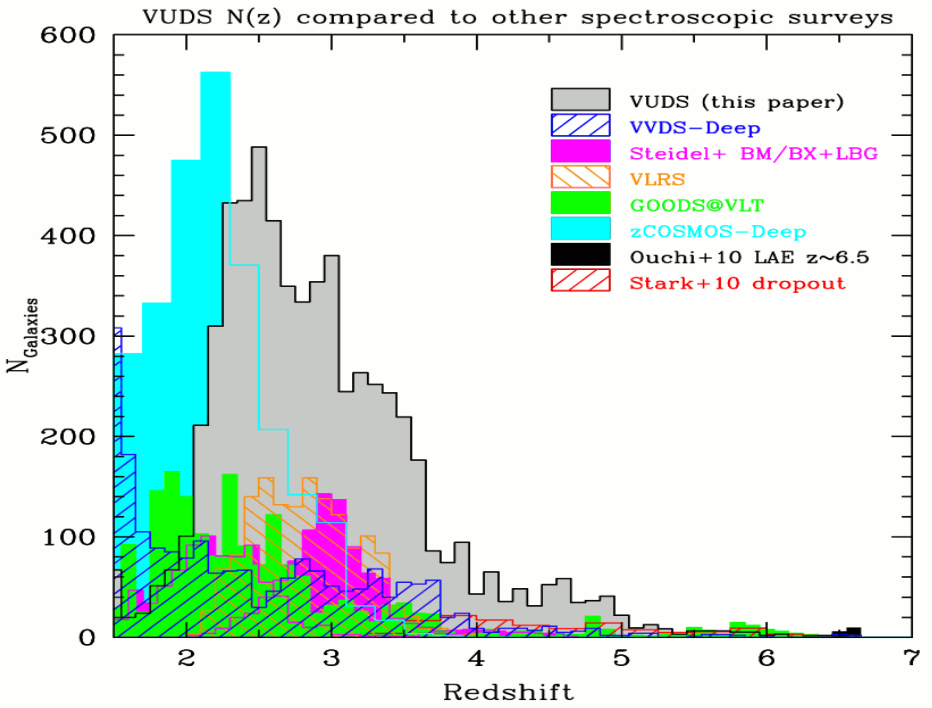
Kawinwanichakij+17

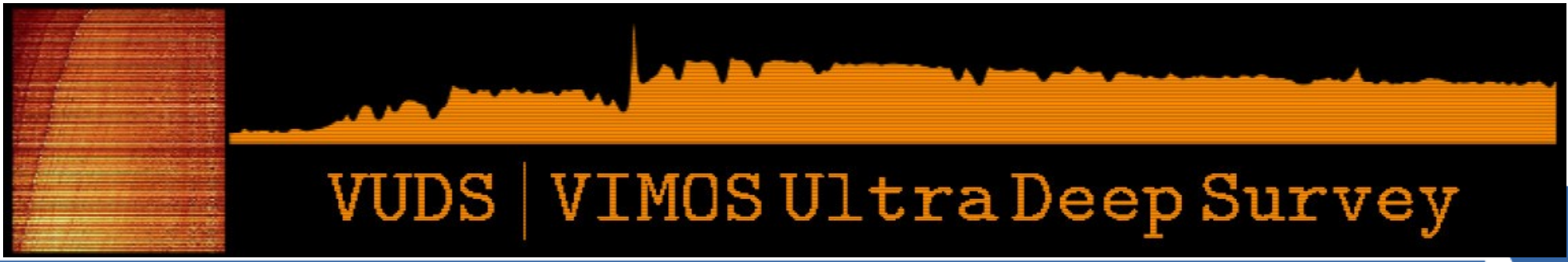


The VIMOS Ultra-Deep Survey – VUDS

Le Fevre et al, 2015, A&A, 576A, 79L

- 10000 spectra in 3 fields (CFHTLS-D1, ECDFS, COSMOS, 1 deg^2 in total)
- Mainly photo-z + magnitude target pre-selection
- Blue + Red VIMOS LR grisms (3800-9400A coverage)
- 14h exp. time per grism
- At least 10-bands imaging in each field





Charting Cluster Construction with VUDS and ORELSE (C3VO)

VUDS: spectroscopic redshift survey of ~10000 very faint galaxies to study the main phase of galaxy assembly in $2 < z \simeq 6$.

ORELSE: Systematic search for structures on scales greater than 10 Mpc/h around 20 well-known clusters at redshifts of $0.6 < z < 1.3$.

FOLLOW-UP of detected structures with

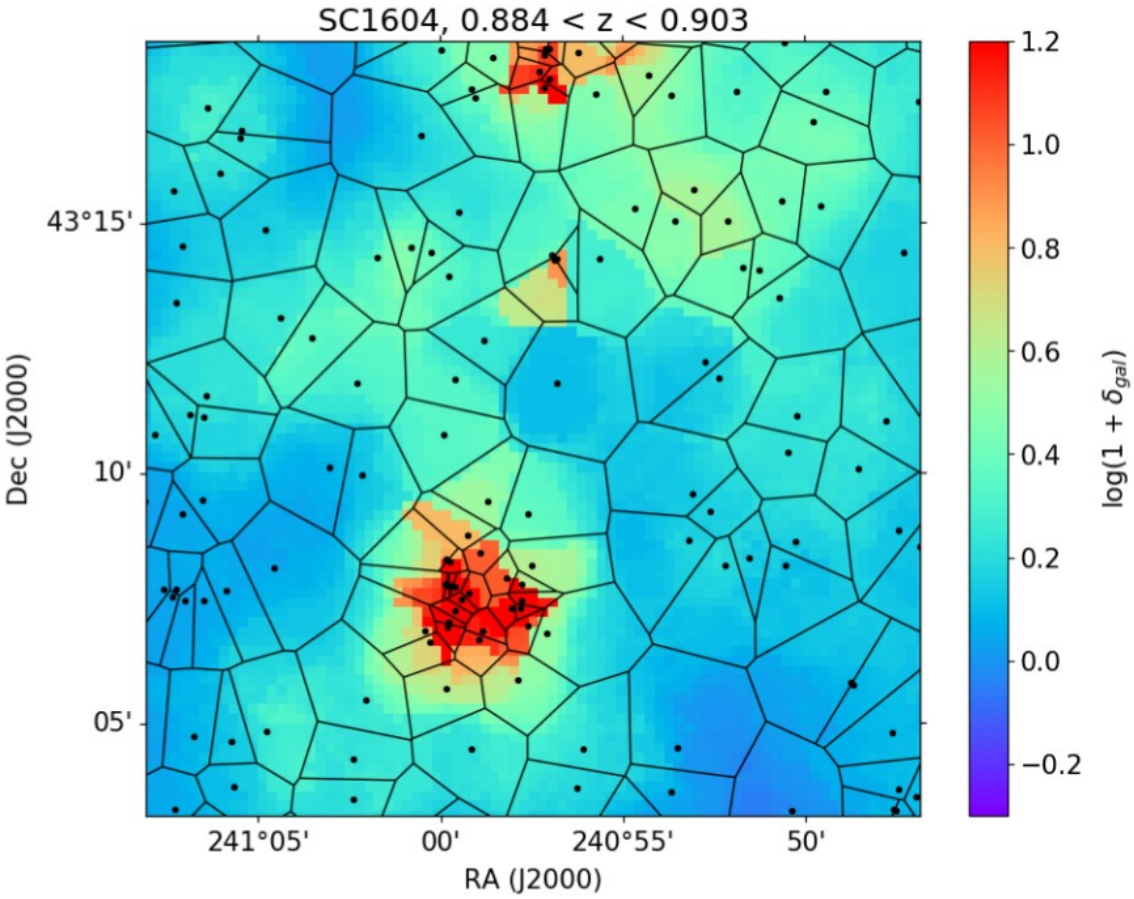
- WFC3 (spec+img) @HST
- DEIMOS and MOSFIRE @ Keck
- MOIRCS and SWIMS @SUBARU
- NOEMA
- ...

MEMBERS and FRIENDS: Lori Lubin, Brian Lemaux, Roy Gal, Lu Shen, Denise Hung, Olga Cucciati, Ben Forrest, Ekta Shah, Debora Pelliccia, Priti Staab, Olivier Le Fèvre, Christopher D. Fassnacht, Finn Giddings, Adam Tomczak, Po-Feng Wu, Dale Kocevski, Gordon Squires, Margherita Talia, Gayathri Gururajan, Weida Hu, Roberto Decarli, Gianni Zamorani, Metin Ata, Andrew Newman...

Systematic search for overdensity peaks: the Voronoi Monte Carlo method (VMC)

- Work in redshift slices of ~7.5 pMpc (dz~0.02 at z=2.4)
- **Use of both spec-z and photo-z**
- Photo-z are used statistically: 100 Monte-Carlo realizations drawing photo-z from their PDF
- Compute 2D Voronoi-Tessellation in each slice, for each realization (spec-z stay fixed). Get a surface density value for each pixel for each realization.
- For each slice, the final density field is the median of the 100 realizations, on a grid of 75x75 pkpc cells
- Pile up the redshift slices along the l.o.s. to build the 3rd dimension

Example of VMC map at z=0.9 from Hung+19

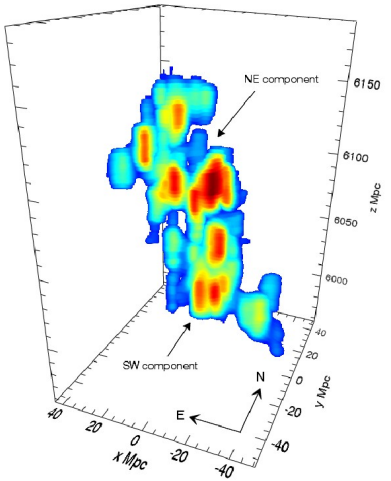


Identify "structures" as volumes with overdensity above a given threshold

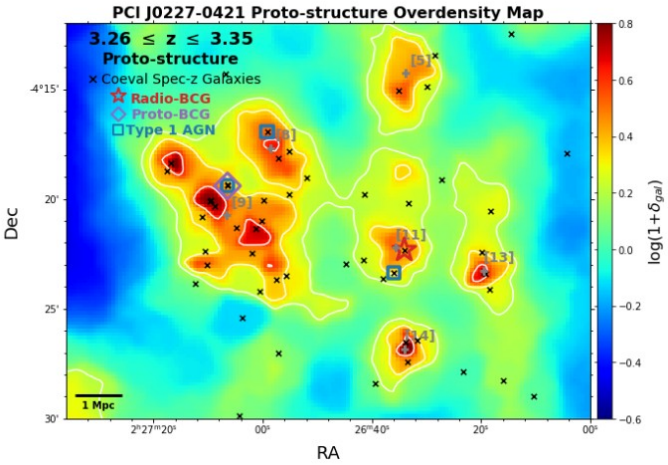
Systematic search for overdensity peaks: the Voronoi Monte Carlo method (VMC)

Method applied to the entire VUDS sample
→ tens of proto-structures in 1 deg^2 over 2<z<5
→ Hung et al in prep.

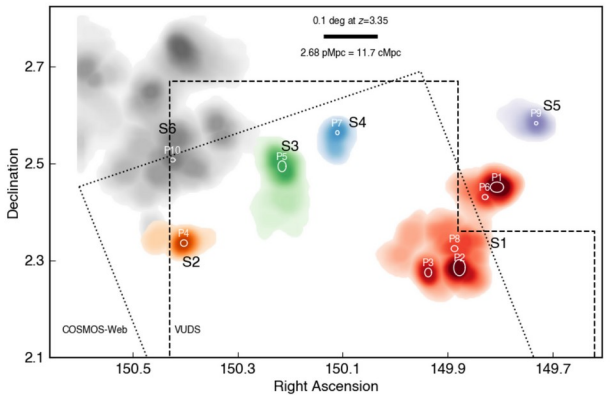
z=2.4 (Cucciati+18, Giddings+in prep.)



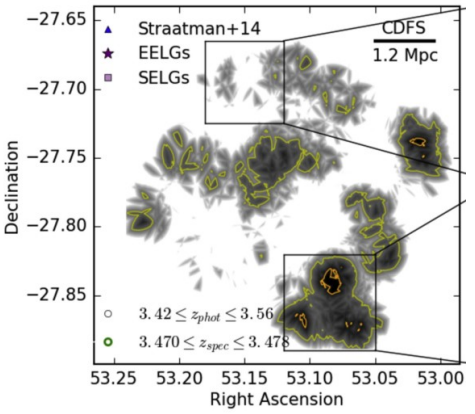
z=3.3 (Lemaux+14, Shen+21)



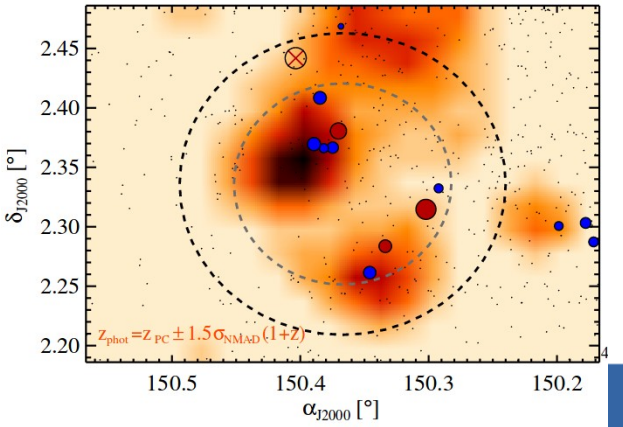
z=3.3 (McConachie+22, Forrest+23)



z=3.5 (Forrest+17, Shah+in prep.)



z=4.57 (Lemaux+18, Staab+in prep.)



Synergies with simulations

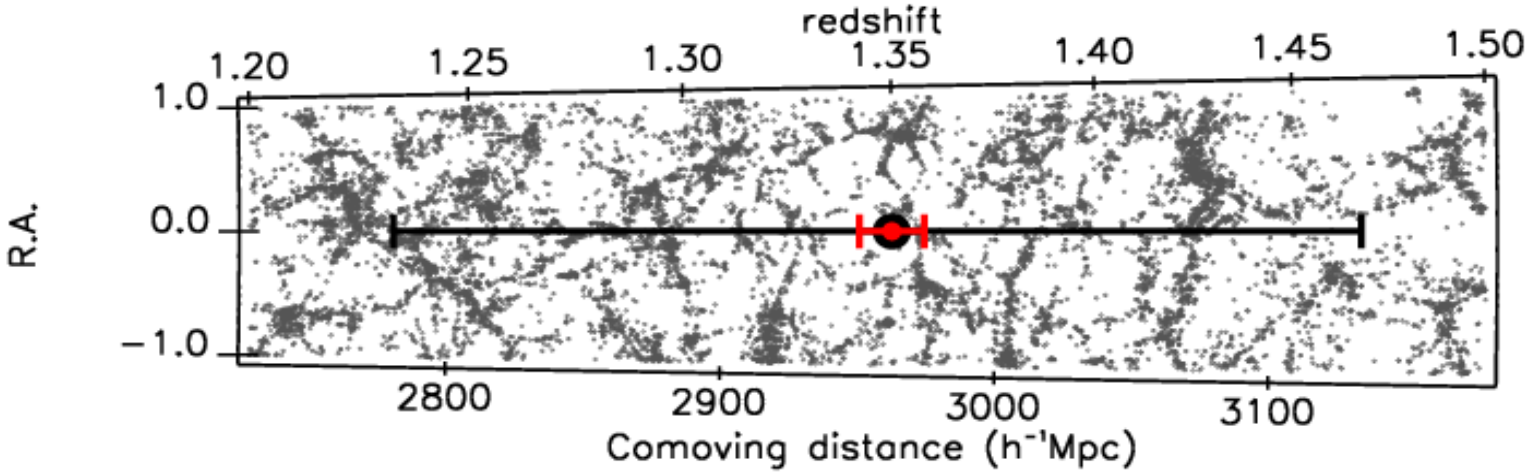
1) identification

2) galaxy and structure (co)evolution

Synergies: identification

1) Identification

→ exploits the link between DM distribution and its embedded galaxy populations to assess how robustly we are reconstructing the environment based only on galaxies (our tracers)



The Hyperion proto-supercluster as a test case

- Local surface density re-scaled into units of sigma (σ) of the log-normal distribution of the overdensity field δ

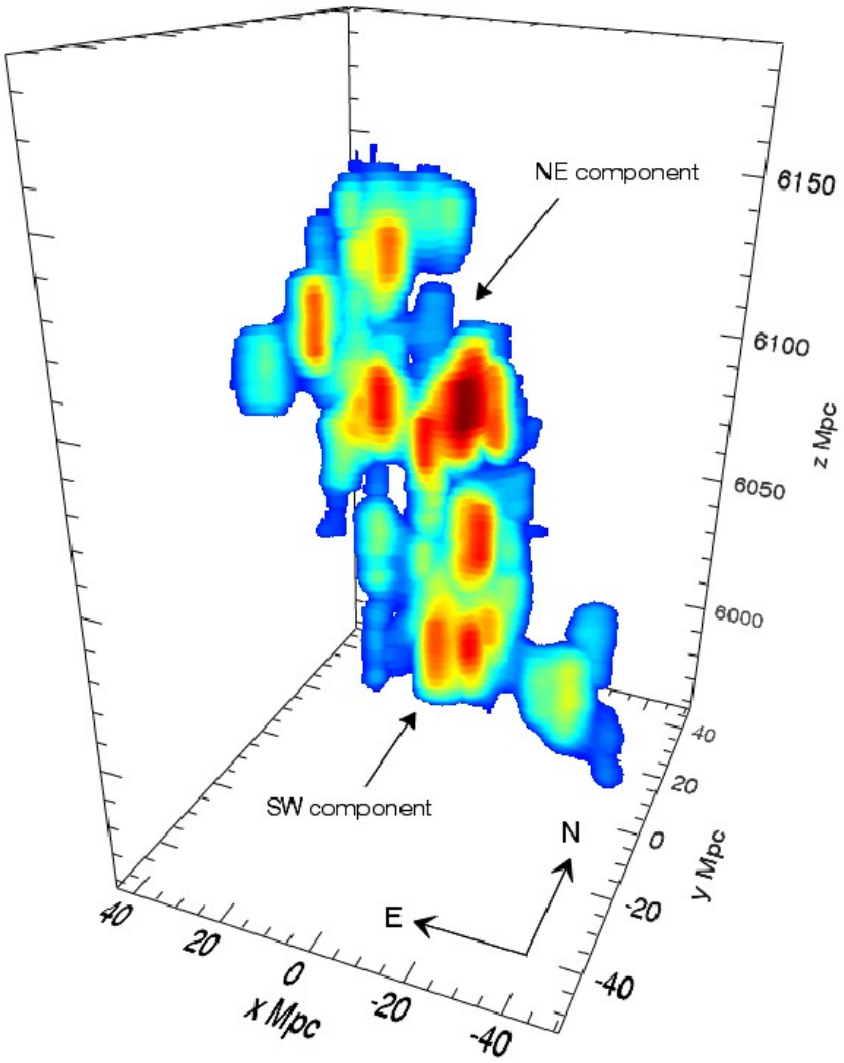
  → Hyperion defined as the contiguous volume with overdensity δ at least 2σ above the mean δ

- **Max extent ~60x60x150 cMpc**
- **Vol ~ 10^5 $cMpc^3$**
- **M_{TOT} ~ 5x10^{15} Msun**

  → from V, δ_g and bias

- 7 peaks with 10^{13} - 3x10^{14} M_{TOT}

Cucciati+2018

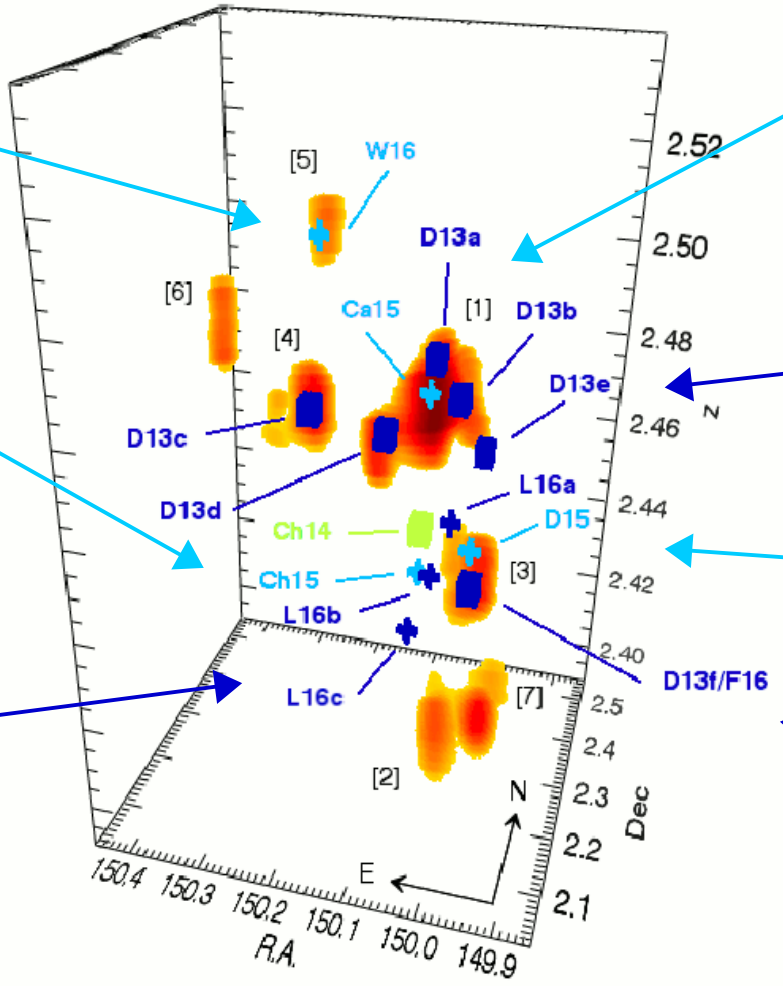


Reassembling the pieces of a bigger picture

W16: Wang et al 2016:
CO
→ 2.494 < z < 2.515

Ch15: Chiang et al 2015:
LAEs
→ 2.428 < z < 2.456

Lee et al 2016: 3D Lya forest tomographic mapping:
→ 2.43 < z < 2.44
→ 2.445 < z < 2.455
→ 2.46 < z < 2.478



Ca15: Casey et al 2015:
submm starbursting galaxies + AGNs
→ 2.463 < z < 2.487

D13: Diener et al 2013:
optical from zCOSMOS-Deep

D15: Diener et al 2015:
optical follow-up
→ 2.439 < z < 2.453

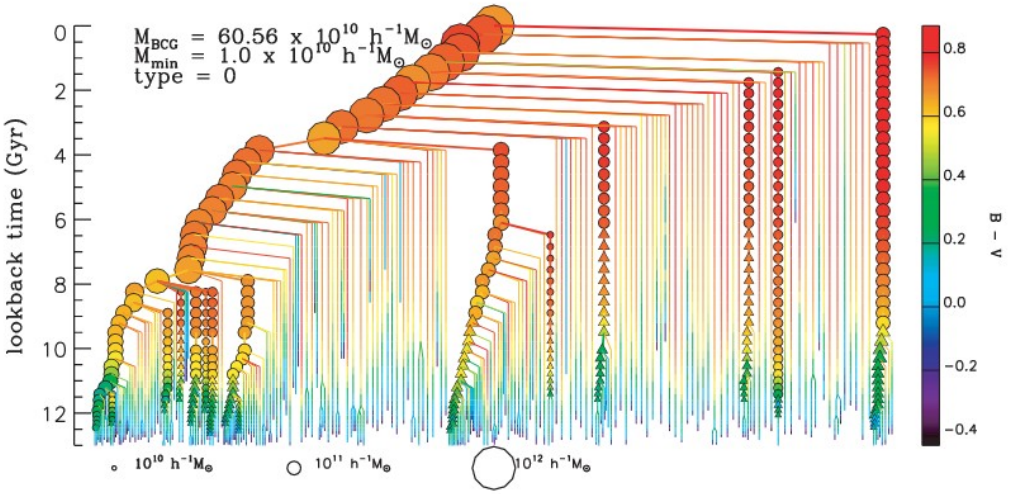
F16: Franck et al. 2016:
Spec-z from NED archive

Cucciati+2018

The GAEA galaxy formation model

- Semi-analytic model run on the Millennium Simulation (Springel+05
- Based on the model described in De Lucia & Blaizot 2007
- Constantly updated since then, up to the two most recent versions by Hirschmann+17 and Fontanot+20)

  → see also all references therein, and also Zoldan+19, Xie+20, Spinelli+20

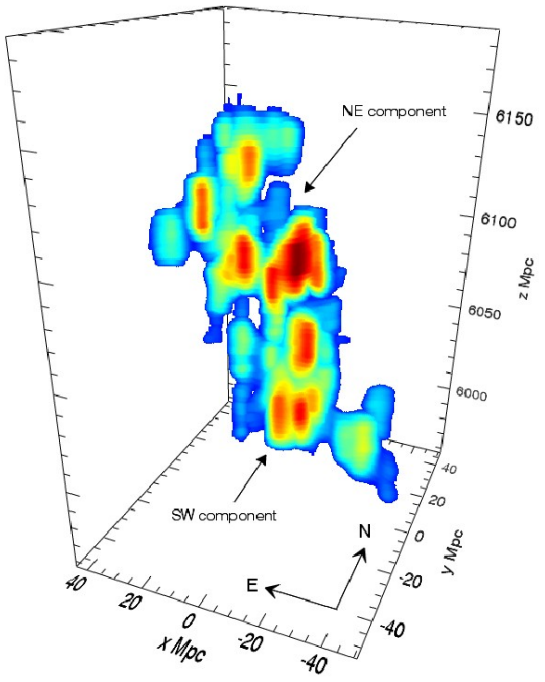


Built a dedicated lightcone to fully preserve structures in their full original extent in the range of redshift of interest

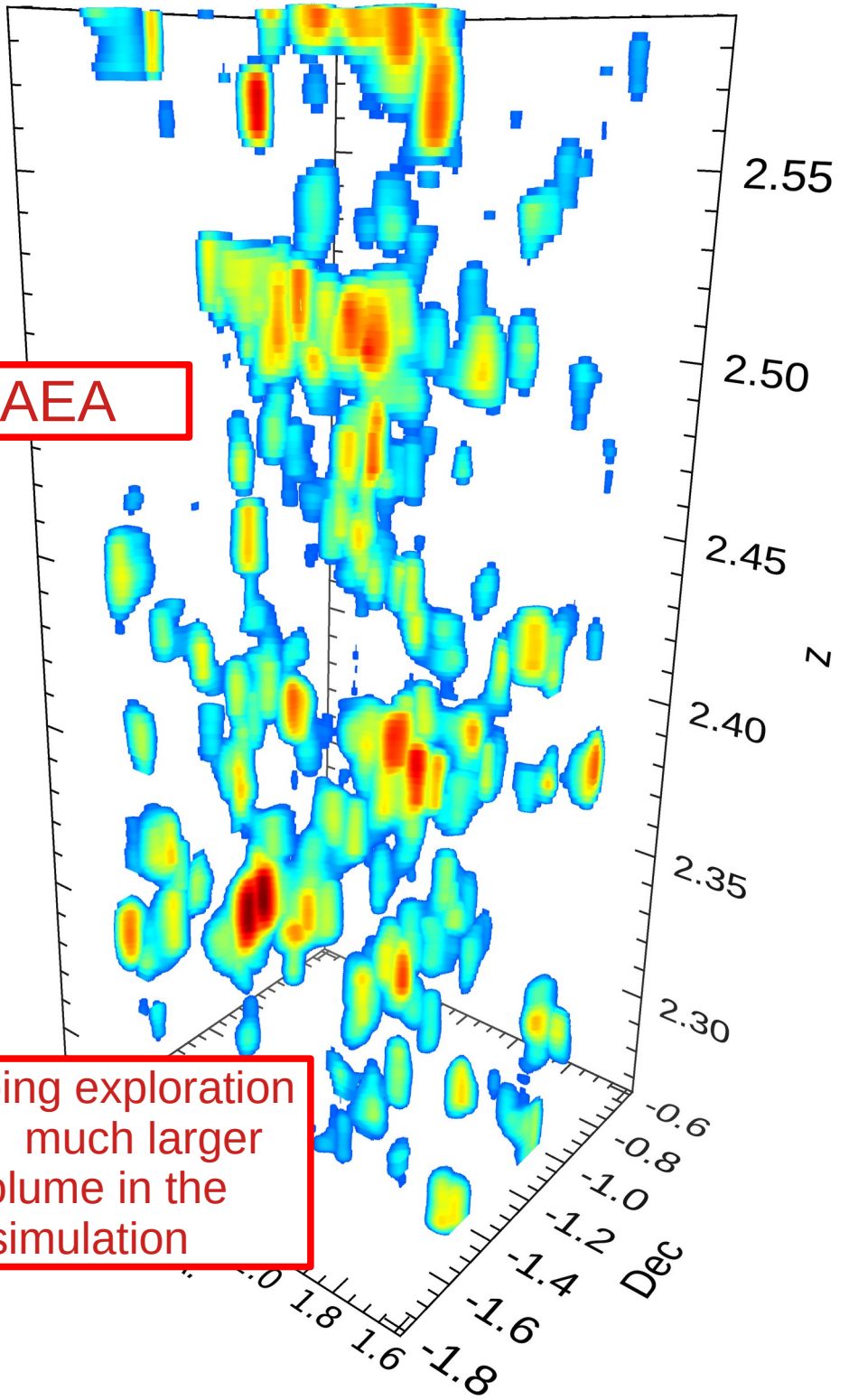
- Applied the same observational strategy to the lightcone as in VUDS, to mimic our data

The Hyperion pro
as a tes

Hyperion



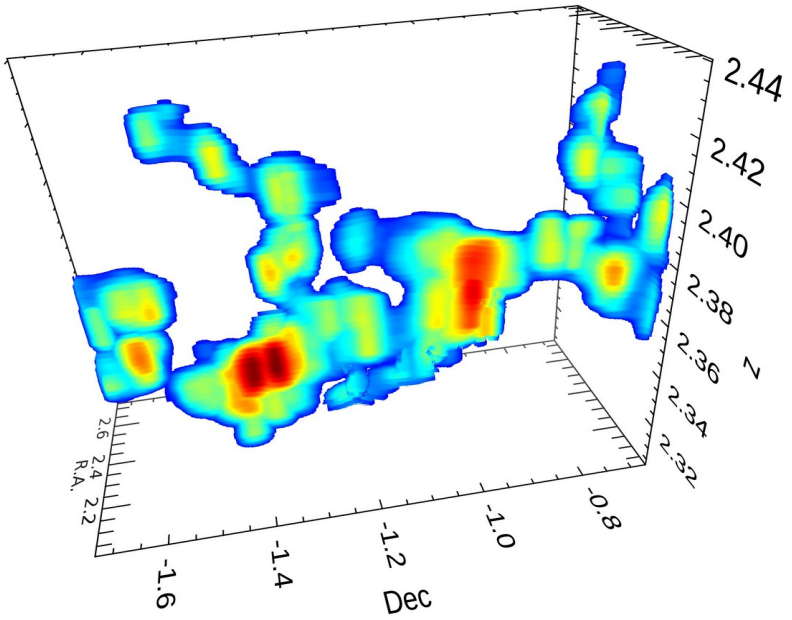
GAEA



Ongoing exploration of a much larger volume in the simulation

Cucciati+2018

Zoom-in onto a Hyperion-like structure



	HYPERION	GAEA
Volume (cMpc3)	~10^5	~10^5
Mass (Msun)	~$5x10^{15}$	~$6x10^{15}$
Max ext. (cMpc)	60x60x150	69x103x151

Cucciati+in prep

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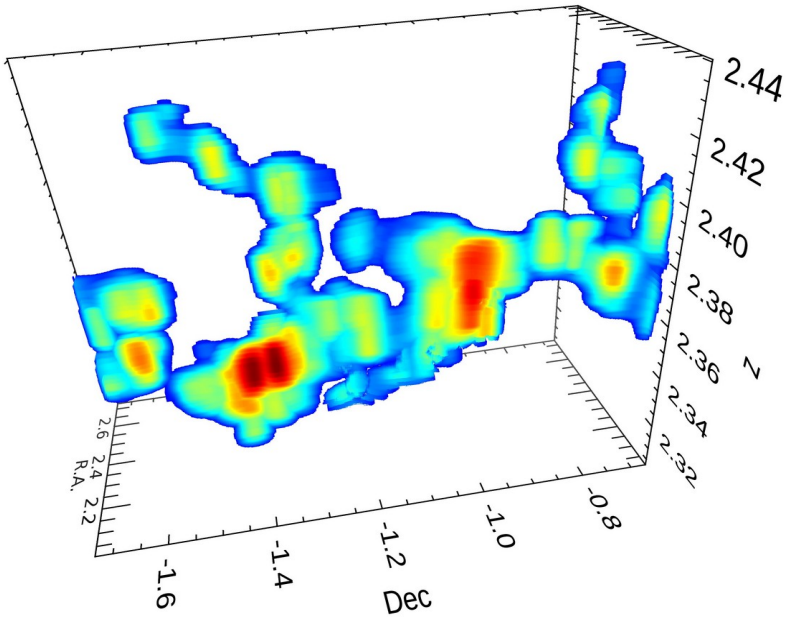

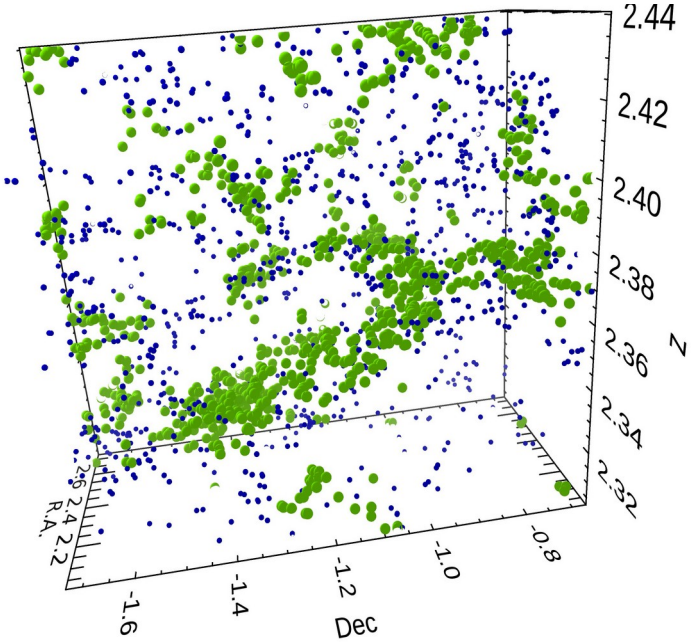

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All galaxies in the mock with i < 25
→ but only ~25% used with their specz for the density reconstruction!

→ Green: within contour levels as in Hyperion

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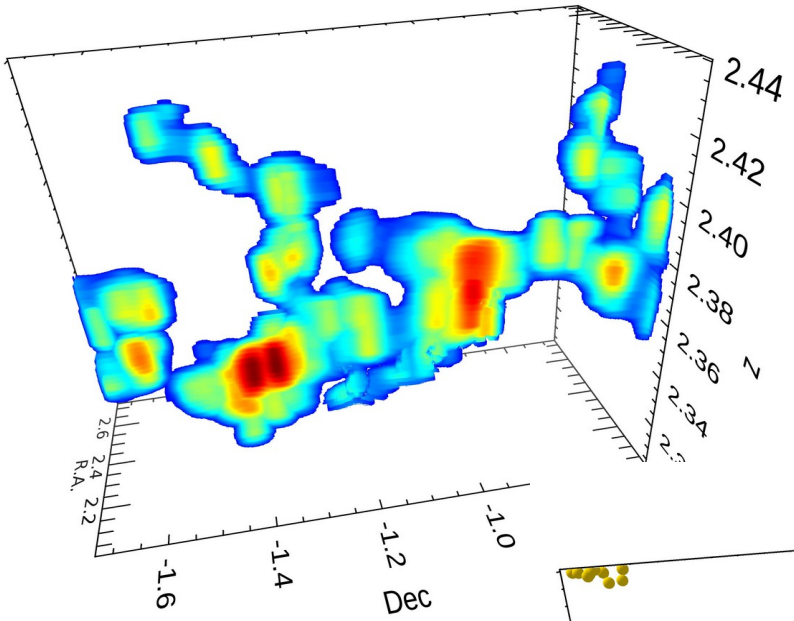
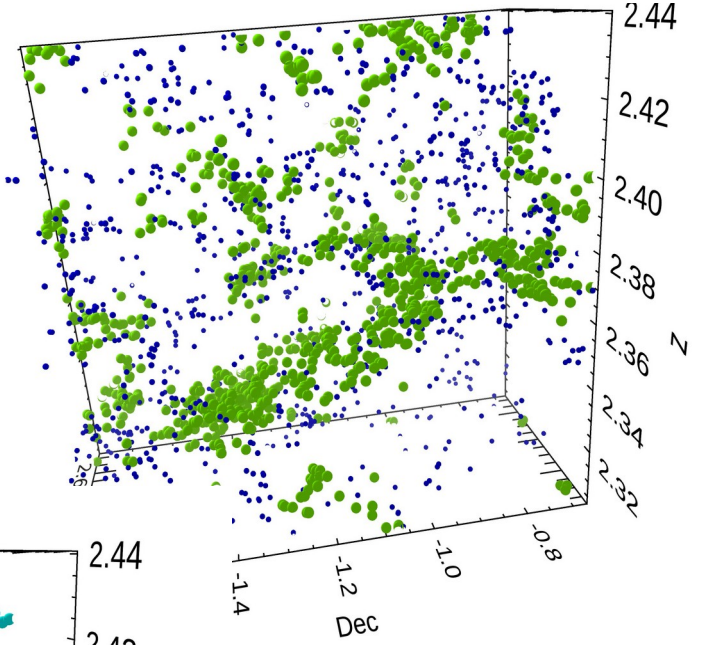
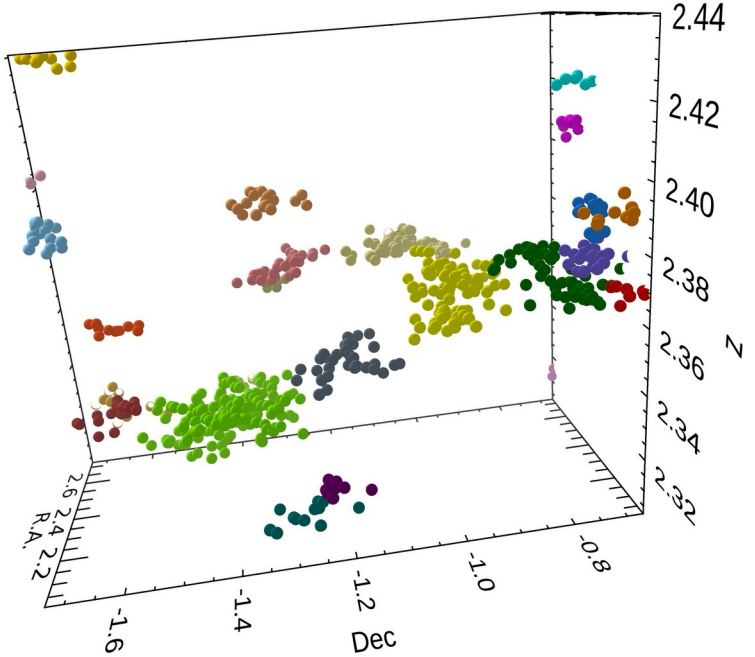
Zoom-in onto a Hyperion-like structure







	HYPERION
Volume (cMpc3)	~10^5
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Max ext. (cMpc)	60x60x150

Protoclusters: progenitors of z=0 clusters with log(MTOT,z=0)>14

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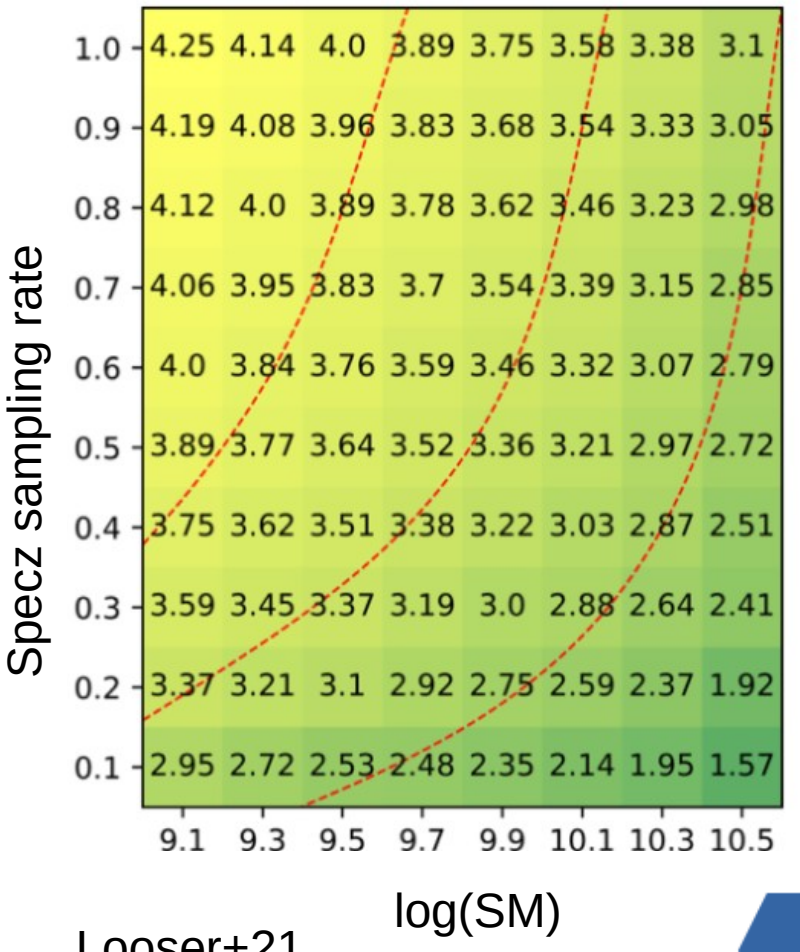
Synergies: identification (bonus)

1) Identification

→ identification also fundamental to plan the observational strategy of future surveys

→ especially important to plan spectroscopic surveys: targets to be chosen wisely due to high T_exp

log(N) of recovered groups of at least two members



Looser+21

Synergies with simulations

1) identification

2) galaxy and structure (co)evolution

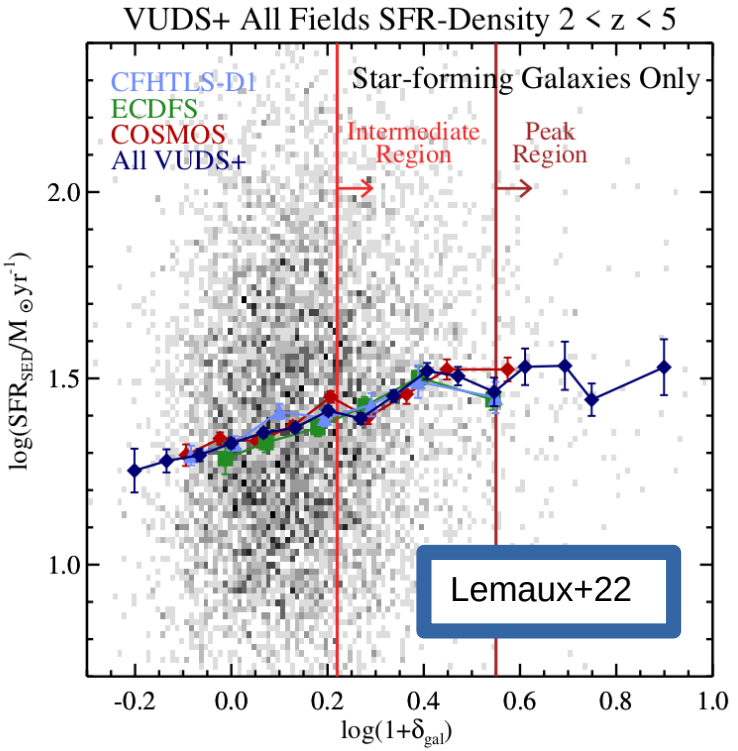
Synergies: evolution

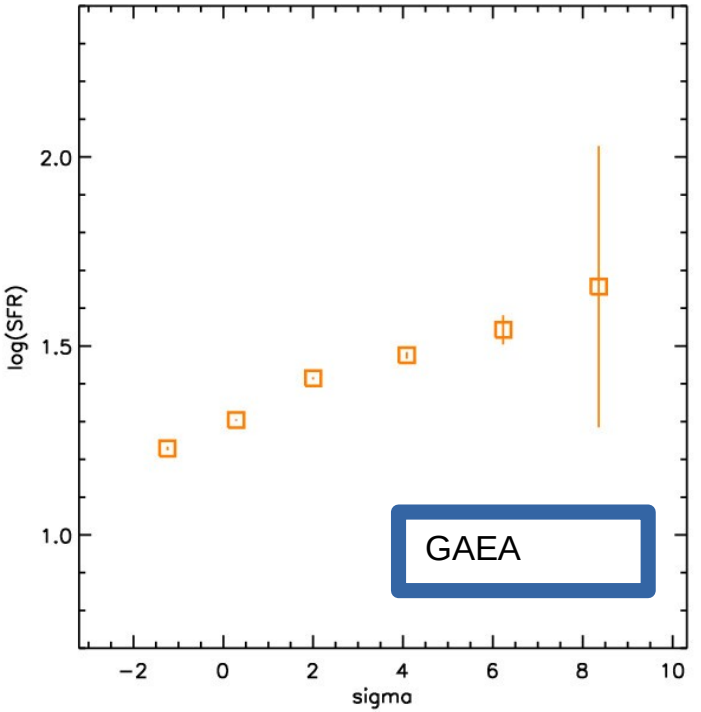
2) Galaxy and structure (co)evolution

→ feedback to simulations, to refine the prescriptions for physical processes

→ feedback to observers to help interpret observational results

→ insights to observers on how to plan proposals to tackle more specific questions





Synergies: evolution

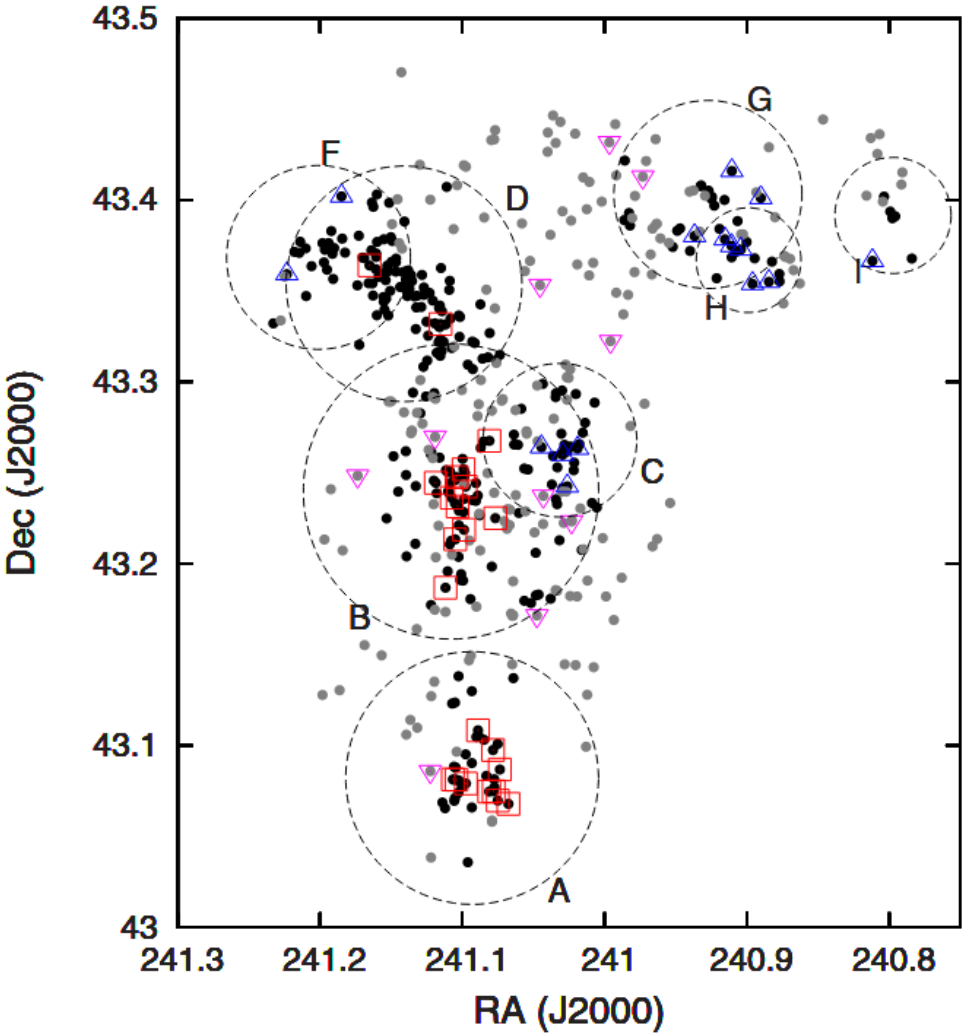
2) Galaxy and structure (co)evolution

→ link progenitors and descendants both in terms of galaxy populations and structure evolution (eg environmental histories of galaxies)

Progenitor and descendant?

A possible descendant of Hyperion

→ **Supercluster SC1604 at z~0.9**
(ORELSE Survey, PI L.Lubin)



Wu+14

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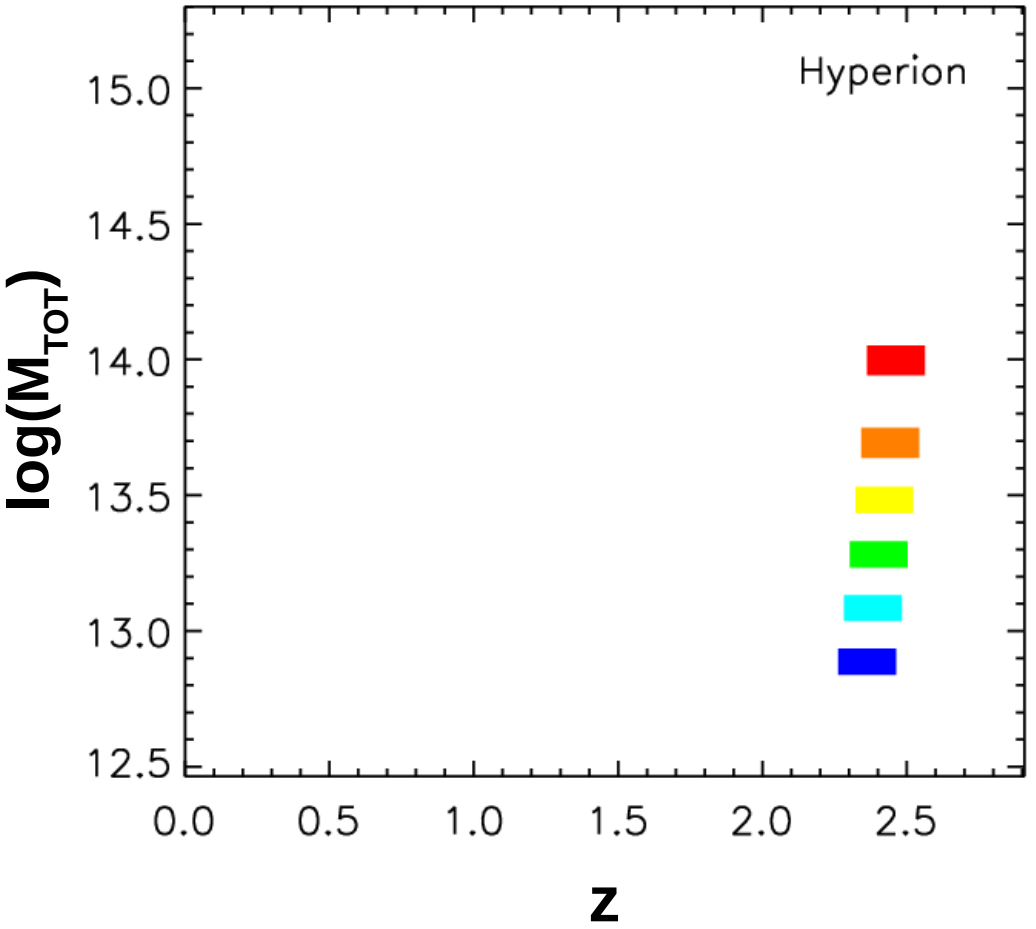
Predicted evolution of single halos

Millennium Simulation



Cucciati+, in prep

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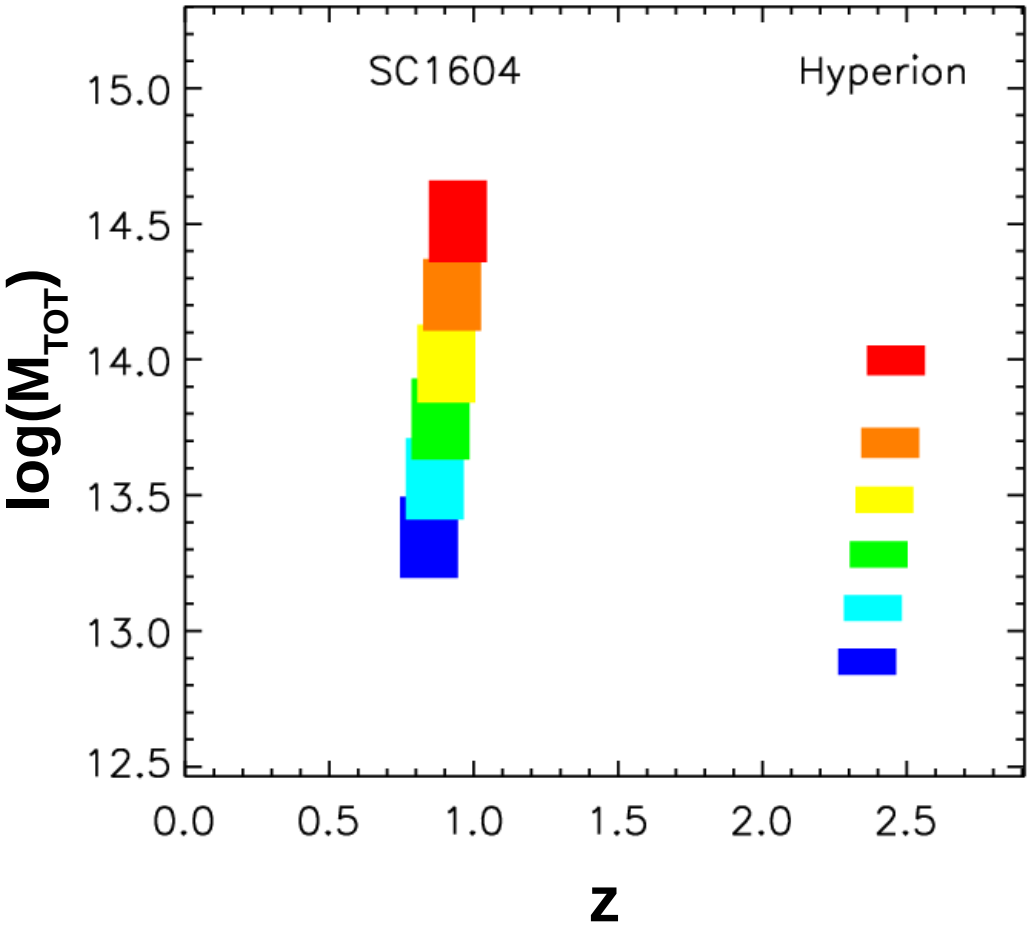

Cucciati+, in prep

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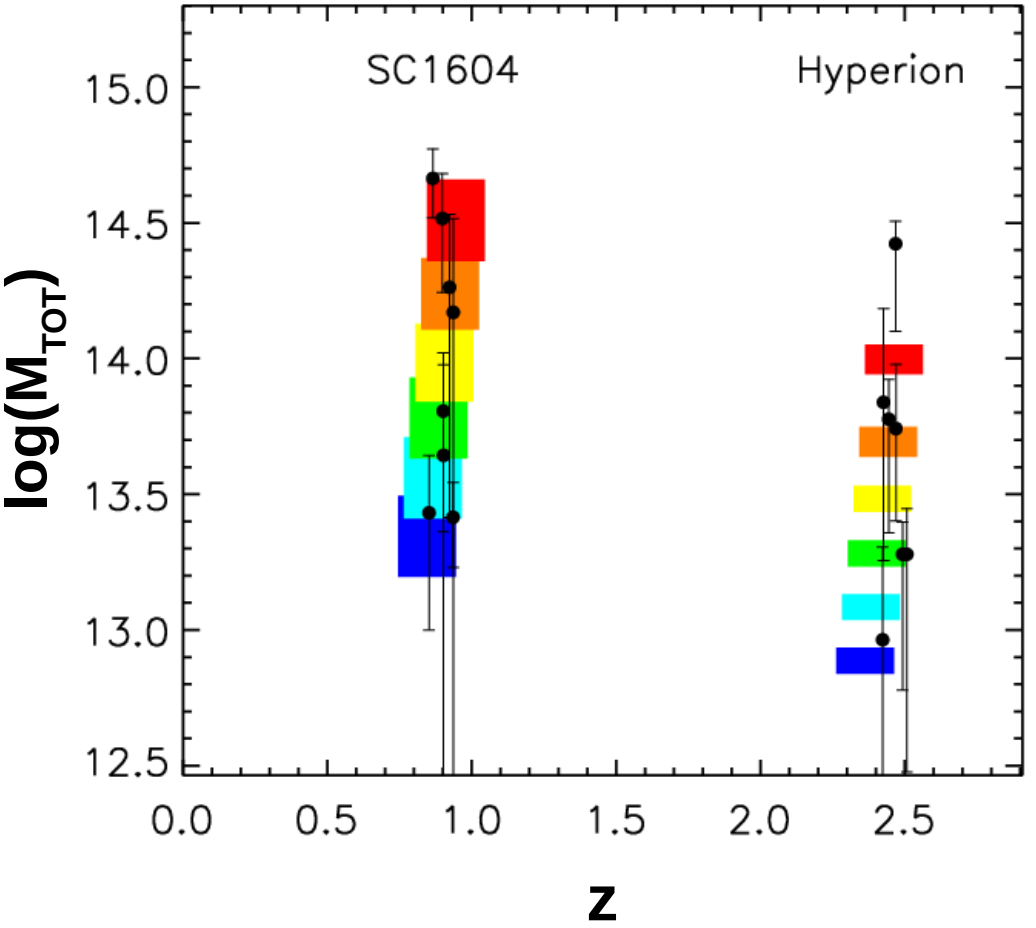
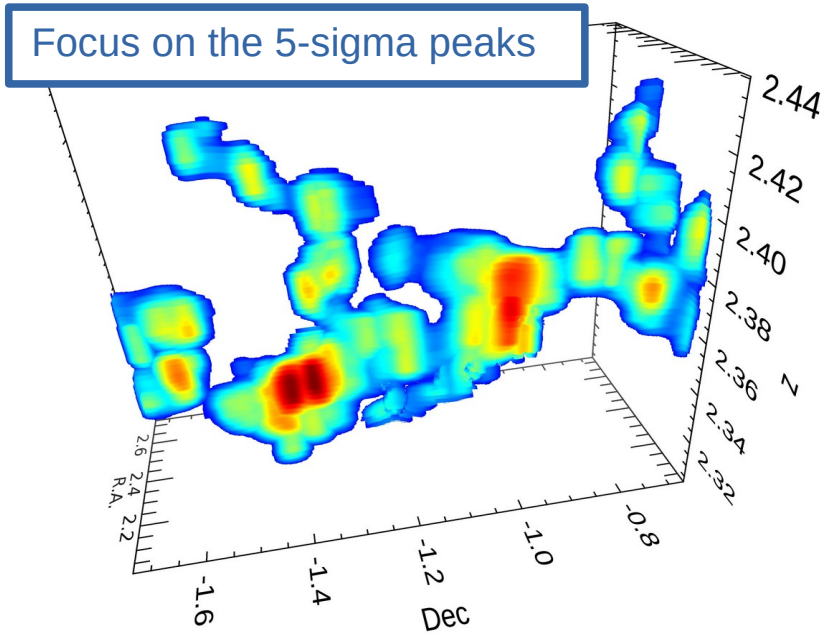
Data



Cucciati+, in prep

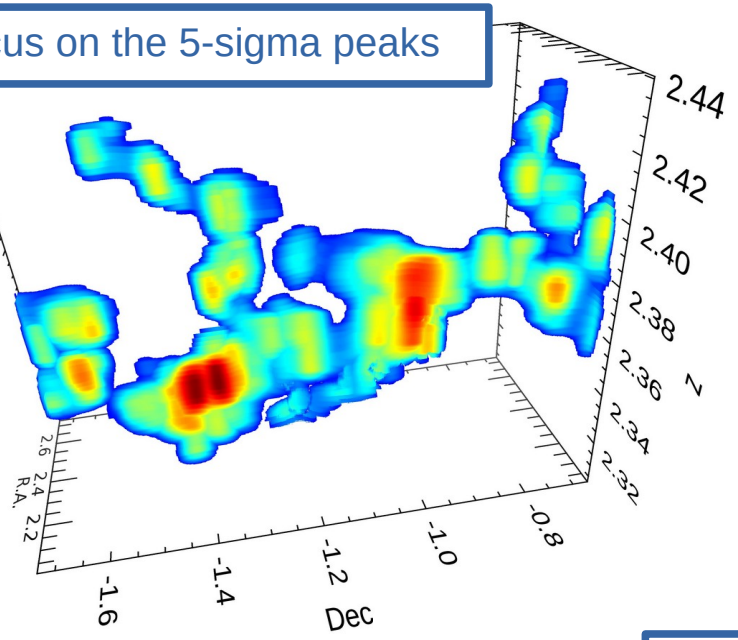
Progenitor and descendant?

Focus on the 5-sigma peaks

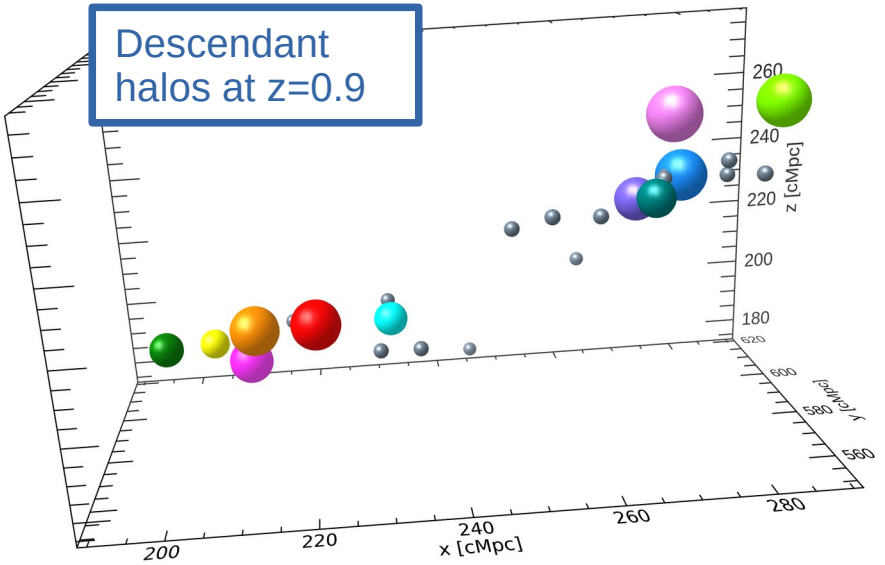


Progenitor and descendant?

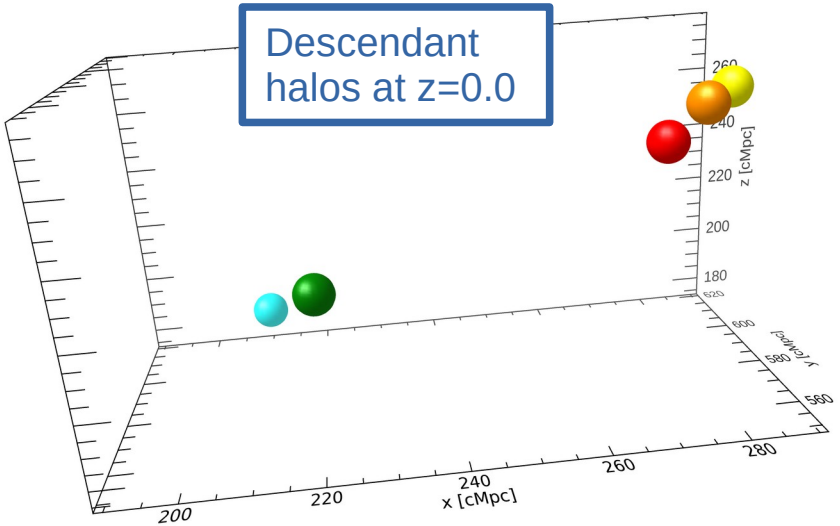
Focus on the 5-sigma peaks



Descendant halos at z=0.9



Descendant halos at z=0.0



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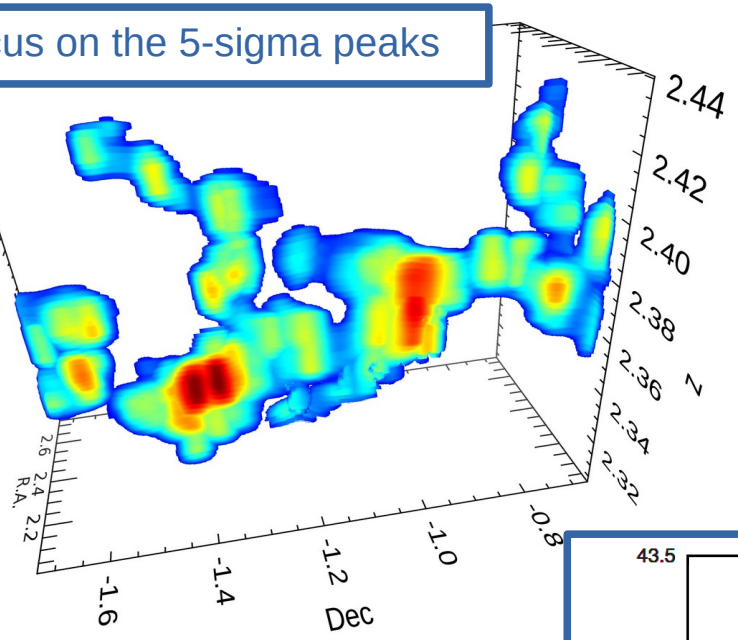

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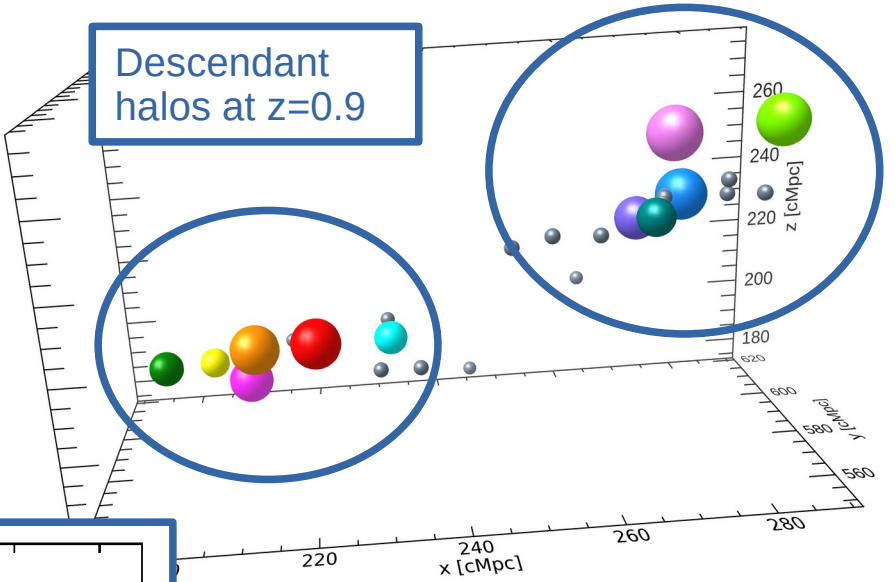

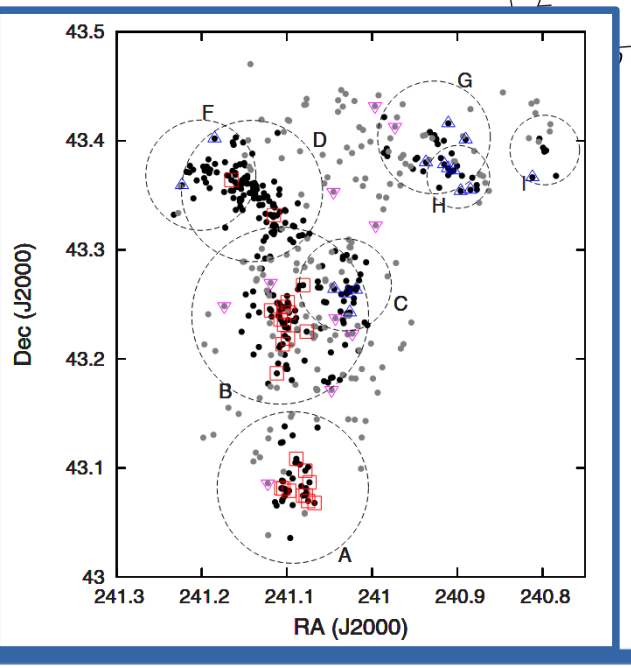

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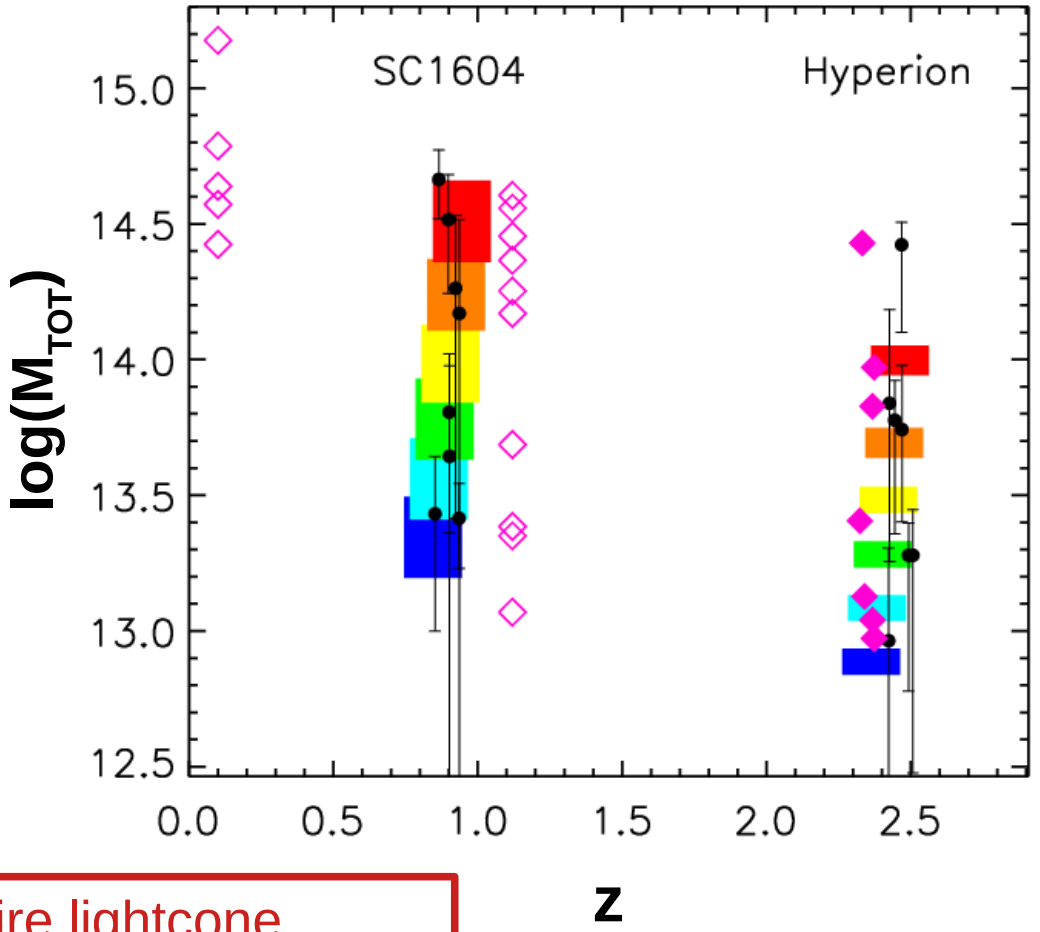
Hyperion-like structure in the mock

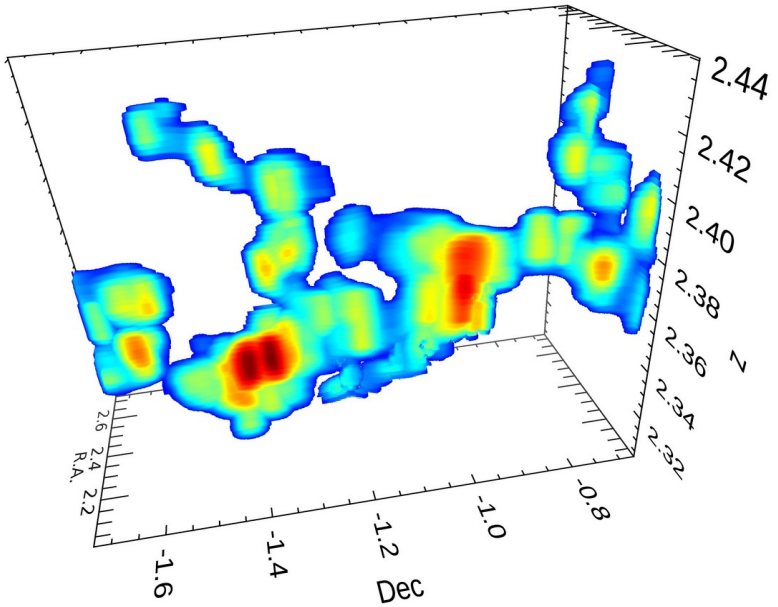


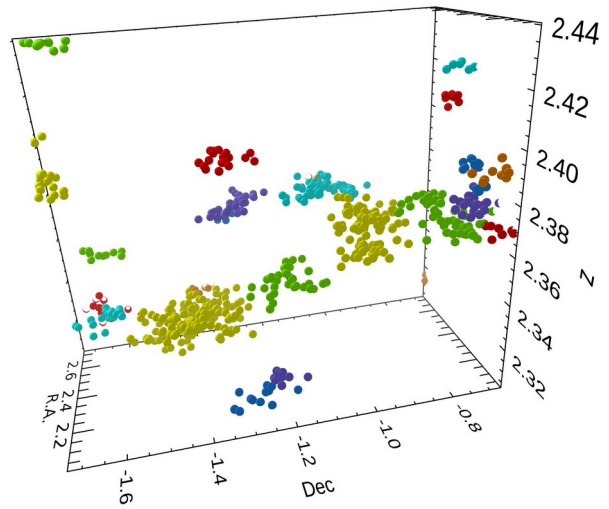
Many similar structures in the entire lightcone, still to be analysed and understood

Cucciati+, in prep

Summary

- Proto-clusters exist in a wide range of evolutionary states, even at fixed z
- Need models of galaxy formation, properly linked to the evolution of dark matter, to understand observational findings
- **Hyperion** is an interesting test case as a unique self-consistent experiment for LSS and galaxy evolution studies... but **need to generalise the analysis** to larger samples/volumes
- Further step: exploit simulations to understand the environmental history of galaxies and how it shapes galaxy properties





- Perspectives for proto-clusters studies
  - Systematic and homogeneous search in wide surveys: PFS@subaru, MOONS@VLT, Euclid, Roman Space Telescope,...
  - Need to be matched by corresponding mock galaxy catalogues: engage the communities of “observers” and “simulators” in a **continuous two-way feedback**