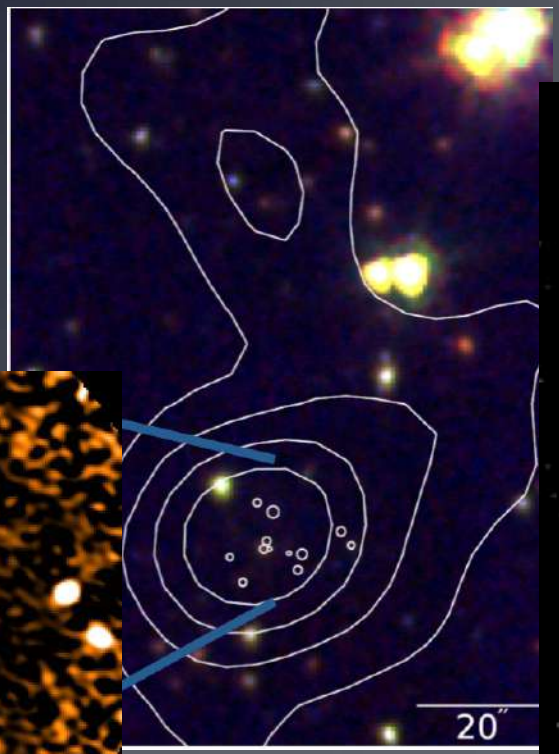
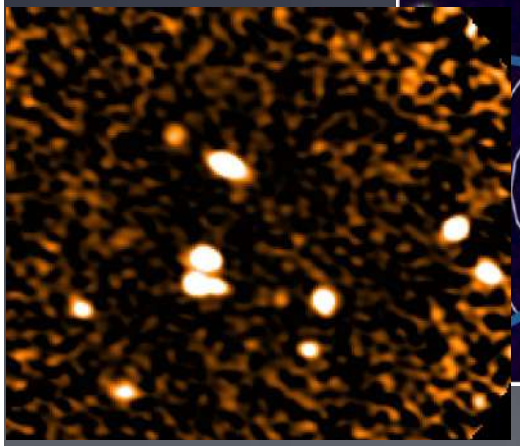
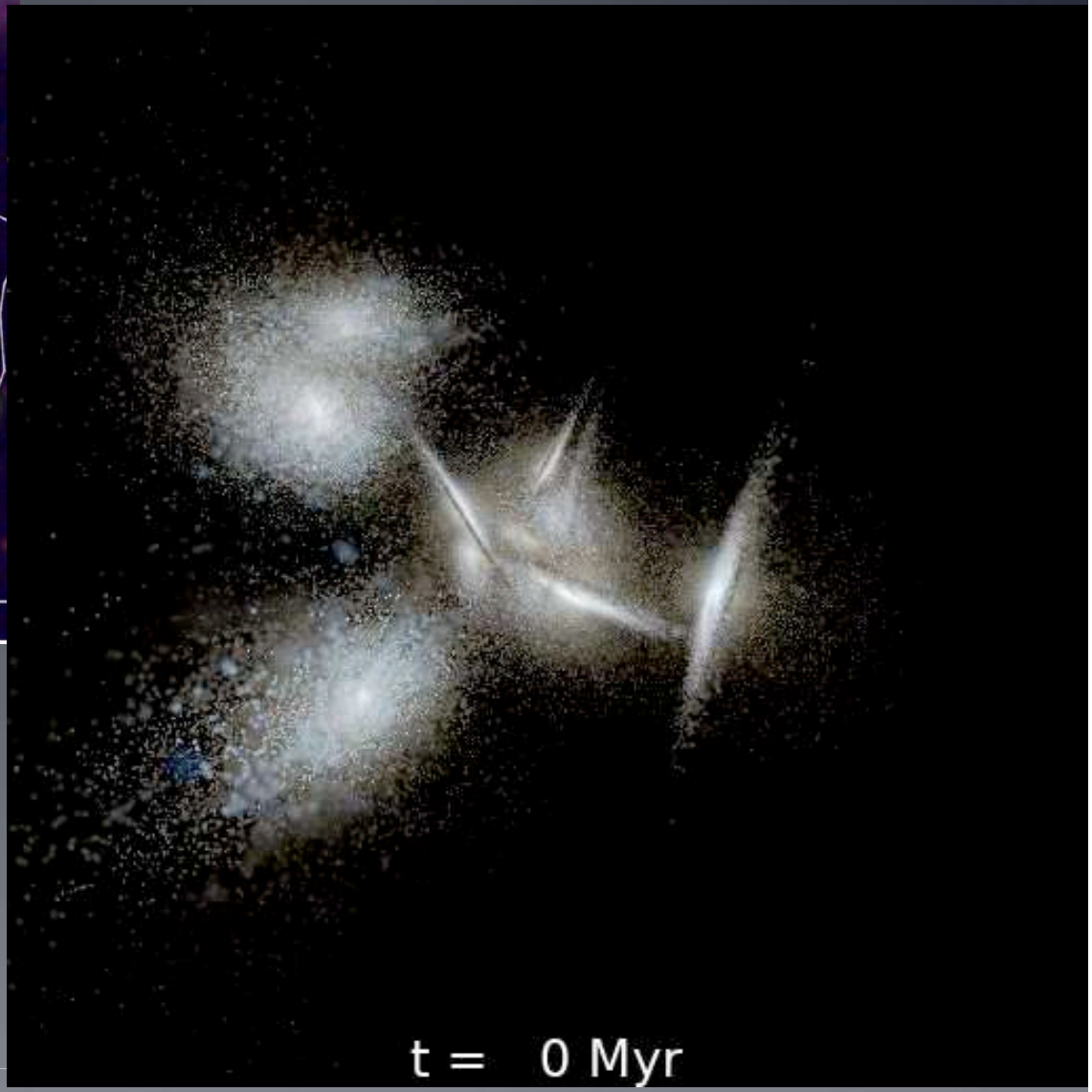
Uncovering Massive Galaxy Protoclusters at z=4-7 with the South Pole Telescope

SPT2349

z=4.31







Scott Chapman

(NRC,UBC,Dalhousie)

SPT collaboration

Hill R., Wang, G., K. Rotermund,

Weiss, A., Hayward, C., de Breuck, C.,

Vieira, J. Marrone, D. , Spilker, J., D. Scott

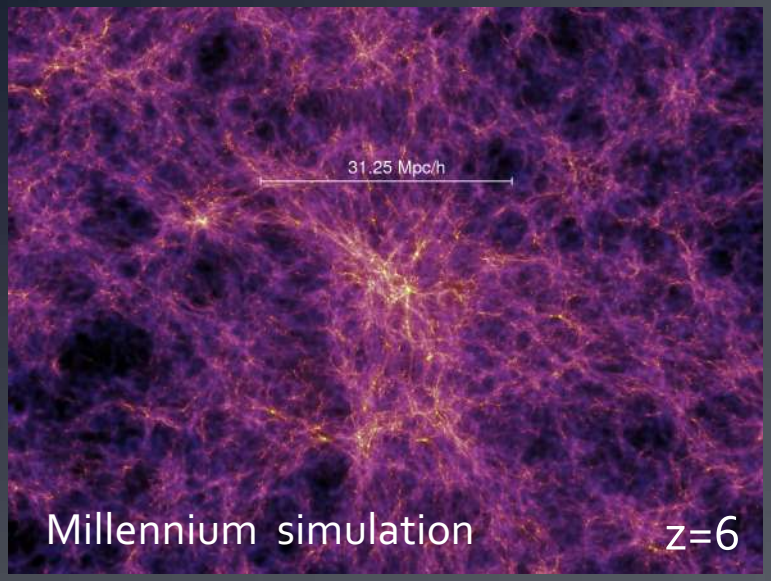
Outline

- Intro to galaxy clusters and proto-clusters
- South Pole Telescope surveys
- The SPT2349-56 protocluster
- An SPT-protocluster survey (SPT-PC)

Detecting rich galaxy **clusters**

Robust methods to detect massive clusters at $z < 1.5$:

- Sunyaev Zel'dovich effect
- Cluster red sequence
- X-ray hot ICM

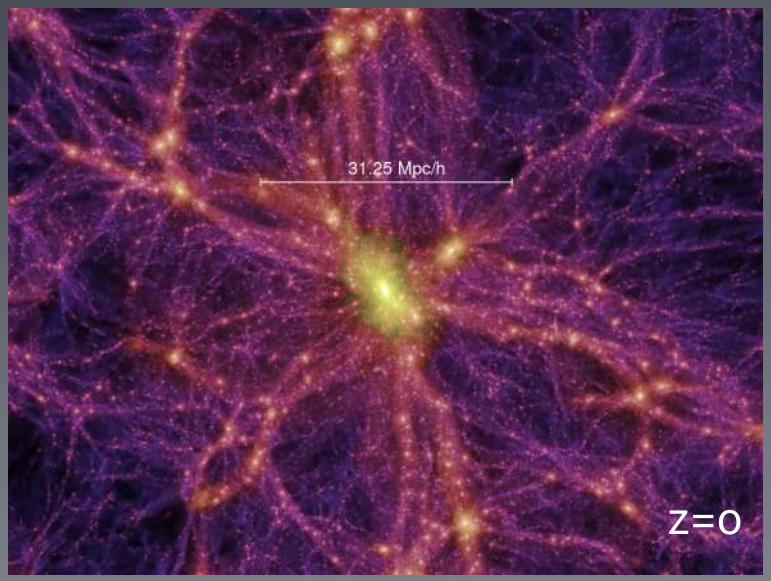


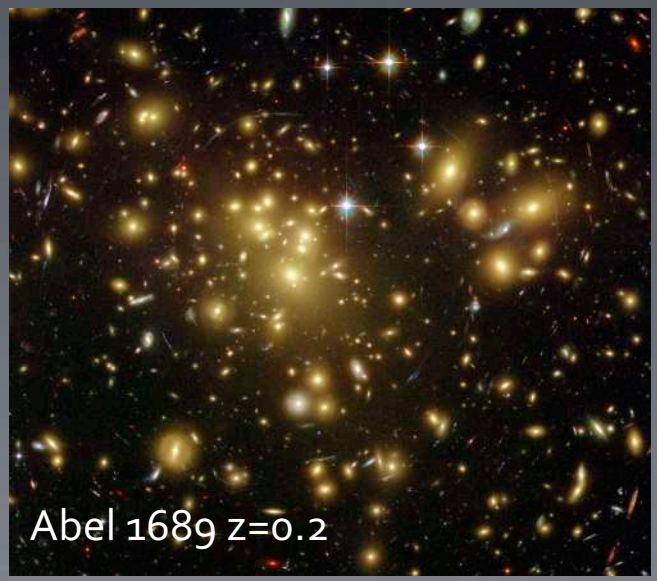
Progenitors of clusters – *Protoclusters* – are traced in simulations

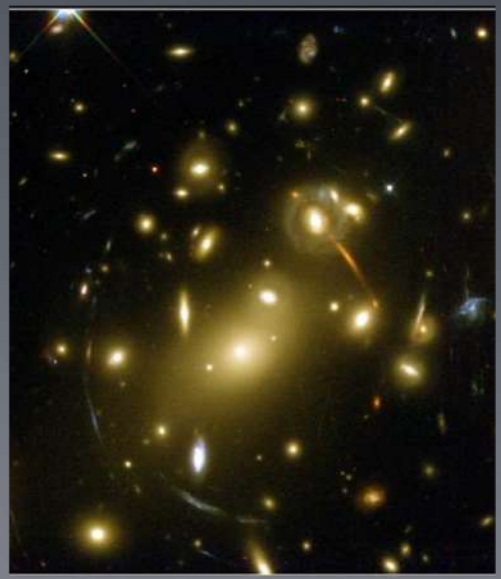
… and *probed observationally*

(how do we know an overdensity is a protocluster)

Massive Clusters detected out to z<2





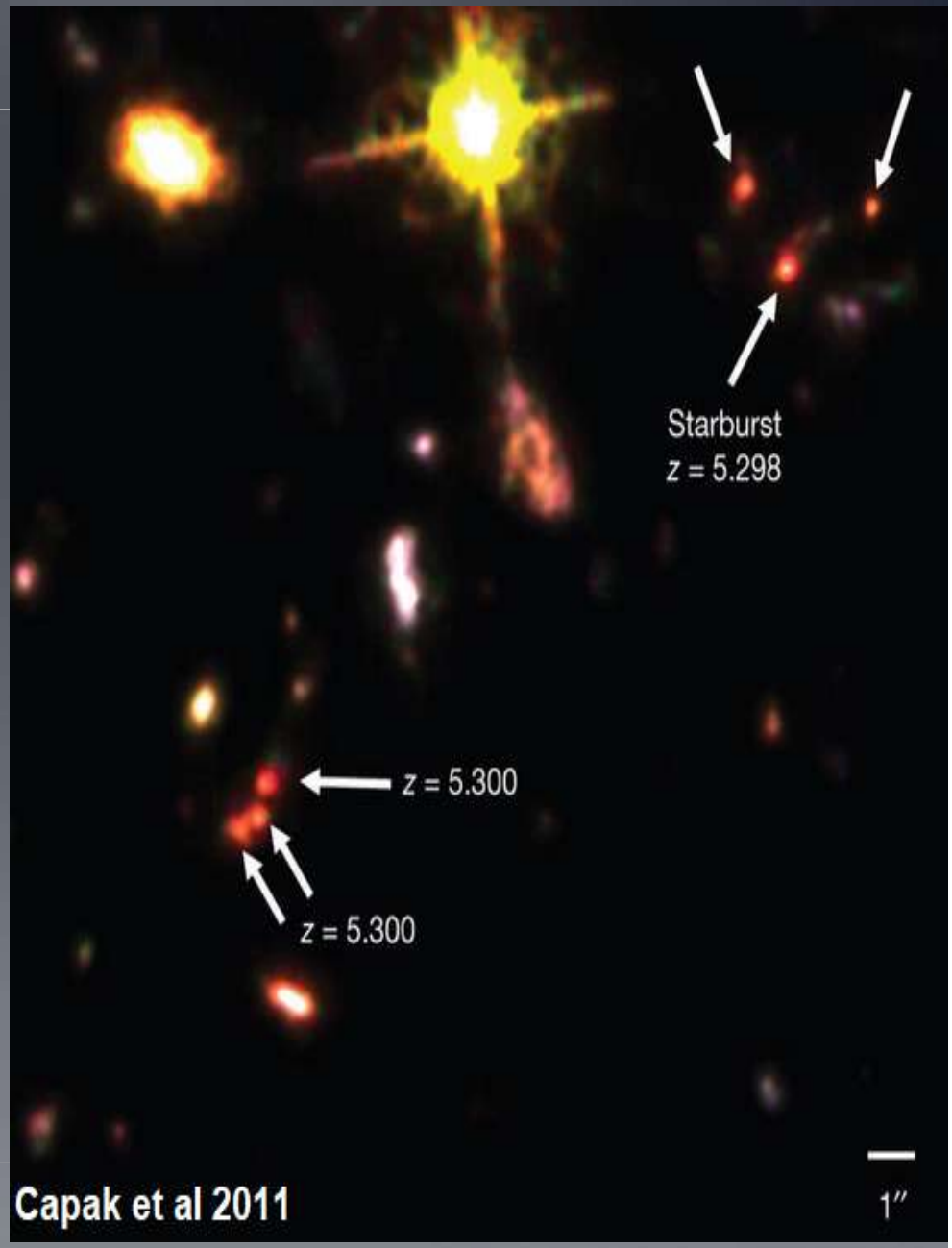


Detecting protoclusters

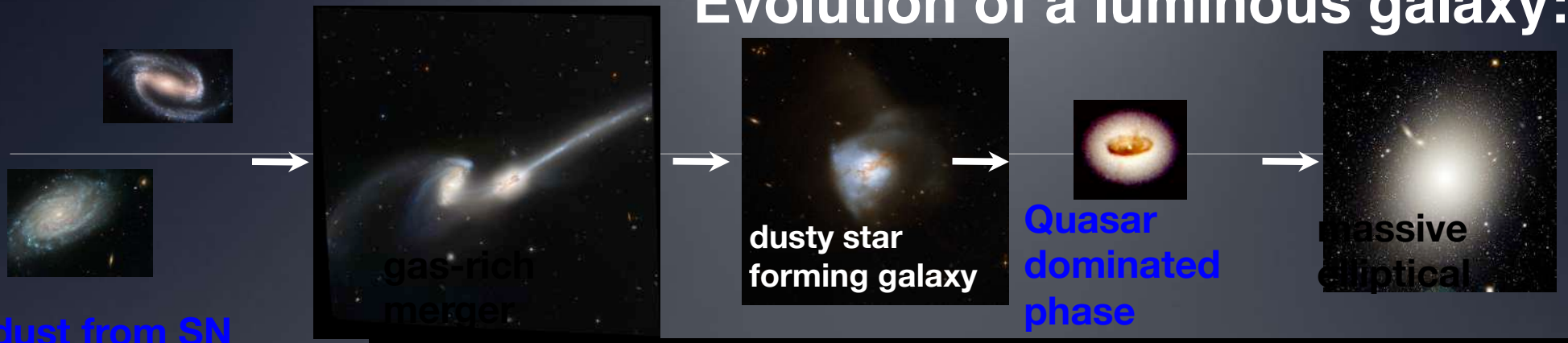
Not obvious what a protocluster is …

But detecting z > 2 overdensities can be accomplished observationally:

- Blind spectroscopic Lyman break galaxy surveys
- LBG and Narrow band searches for Lyα or Hα around quasars/radio galaxies
- Searches around known high-redshift submm-galaxies (SMGs)



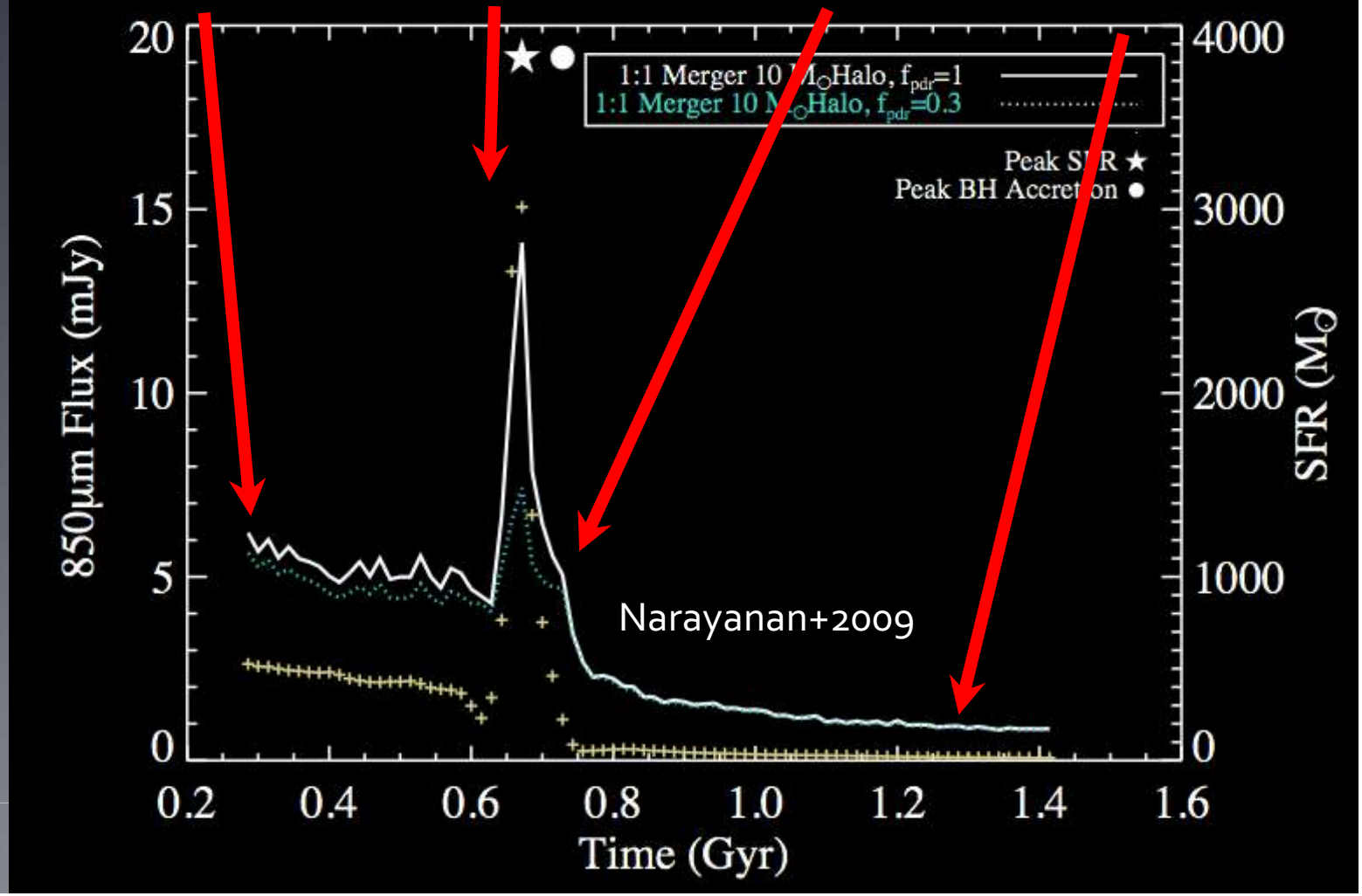
Evolution of a luminous galaxy:



dust from SN + debris disks

Short Timescales of Extreme Starburst:

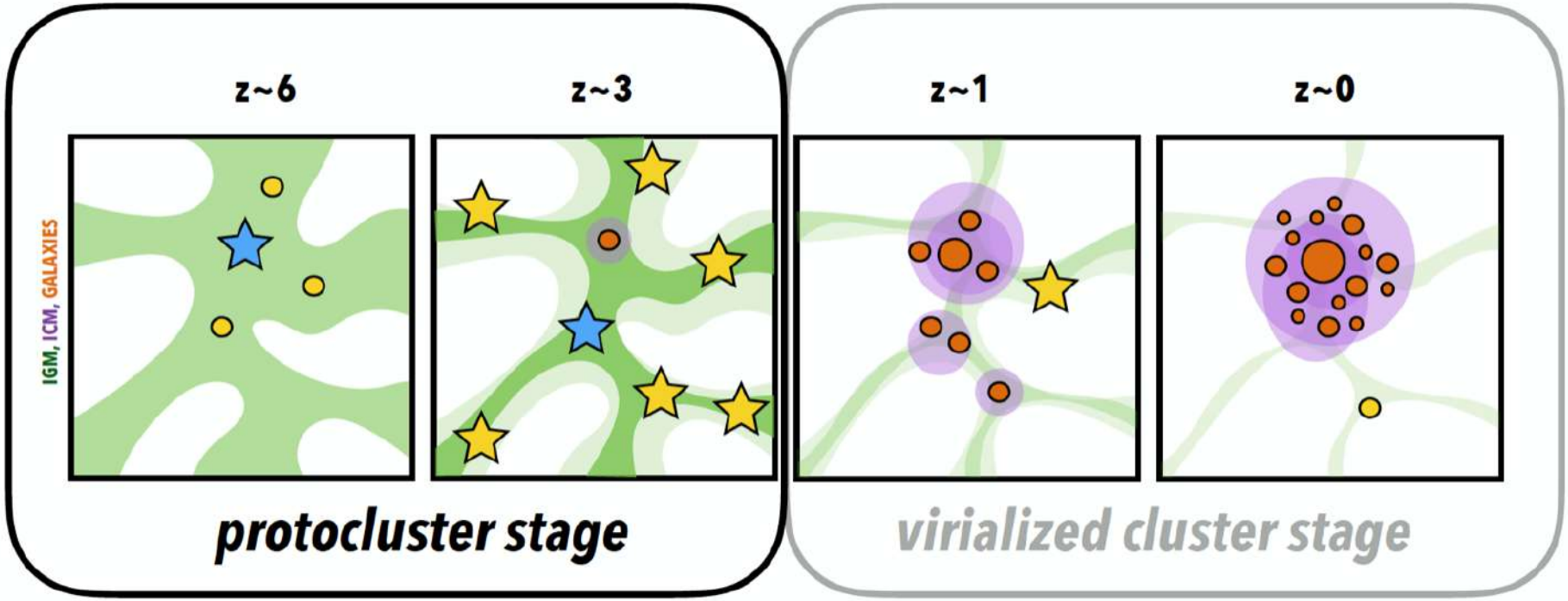
An important evolutionary phase of massive galaxy formation.



Protoclusters traced by luminous galaxies?

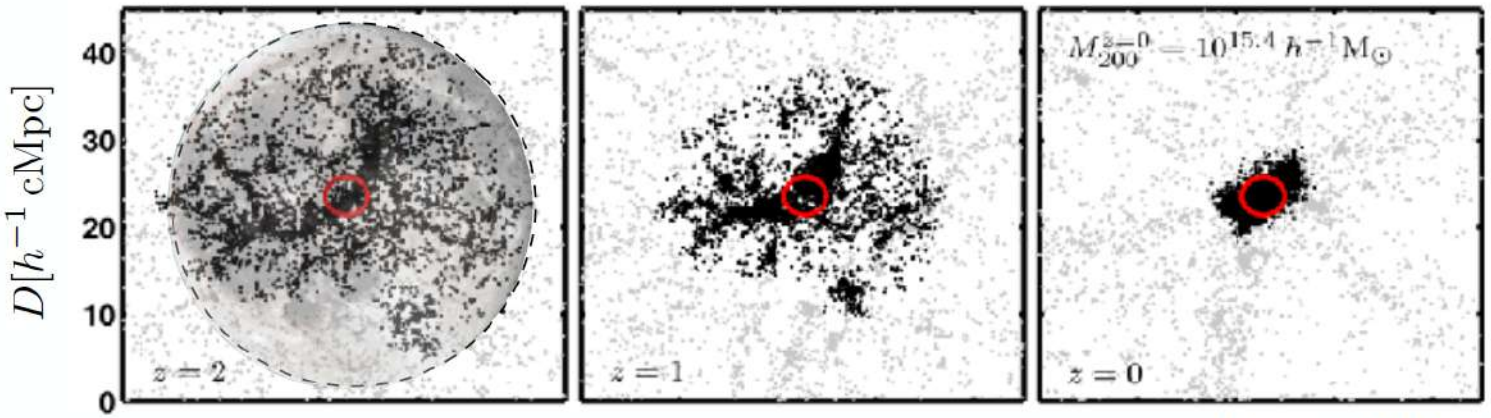
1. Can ULIRGs be useful tools in studying the assembly history of protoclusters (galaxy cluster progenitors)?

2. Do ULIRGs (at z>2) preferentially live in overdensities?



Courtesy of Caitlin Casey

Expectation from Simulations: Protocluster Size



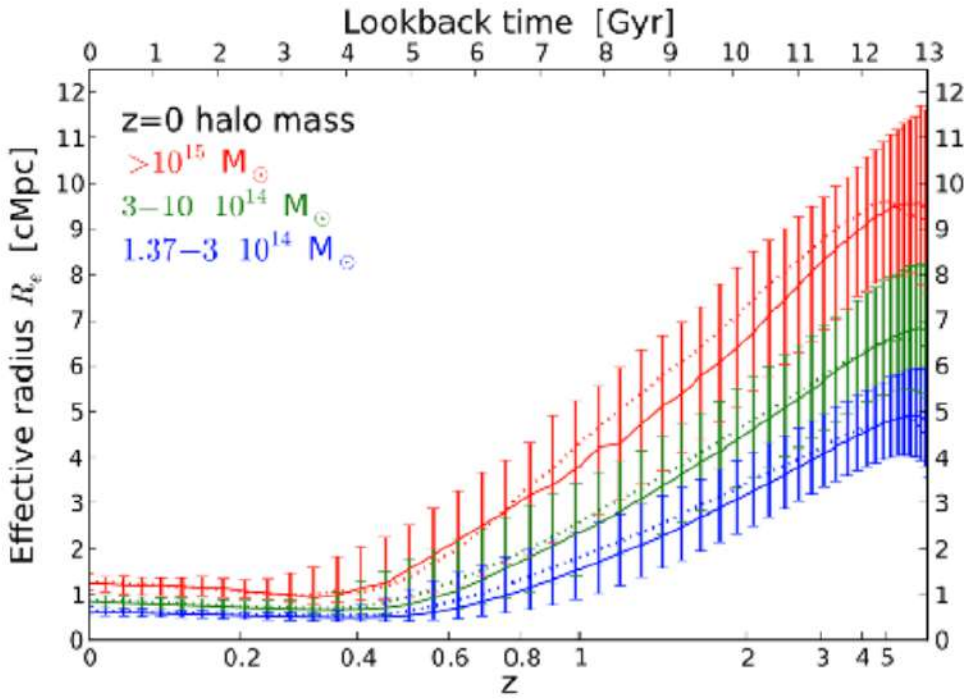
Muldrew et al. (2015)

Protoclusters are physically HUGE, and the most massive progenitors are the largest.

Volume collapses by a factor of ~100 between z=3 and z=0.5.

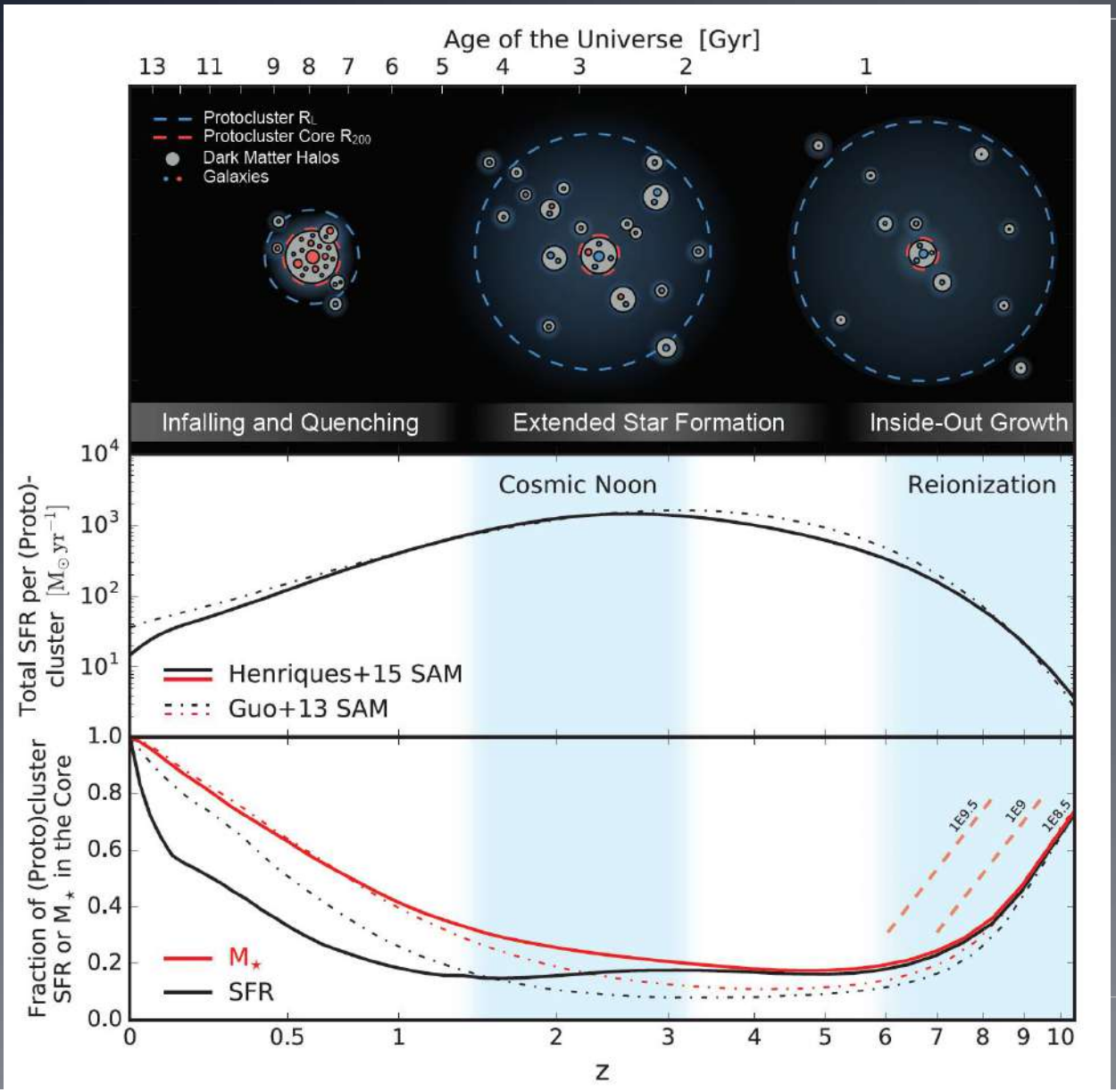
(Quantities measured related to protoclusters should consider this volume transformation)

LOOKING ON ~ARCMIN SCALES.



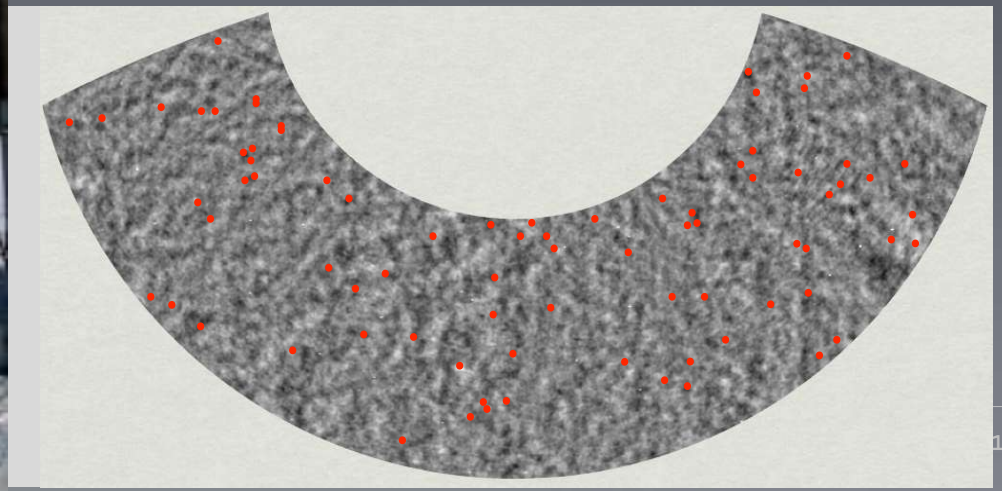
Chiang et al. (2013); see also Oñorbe et al. (2014)

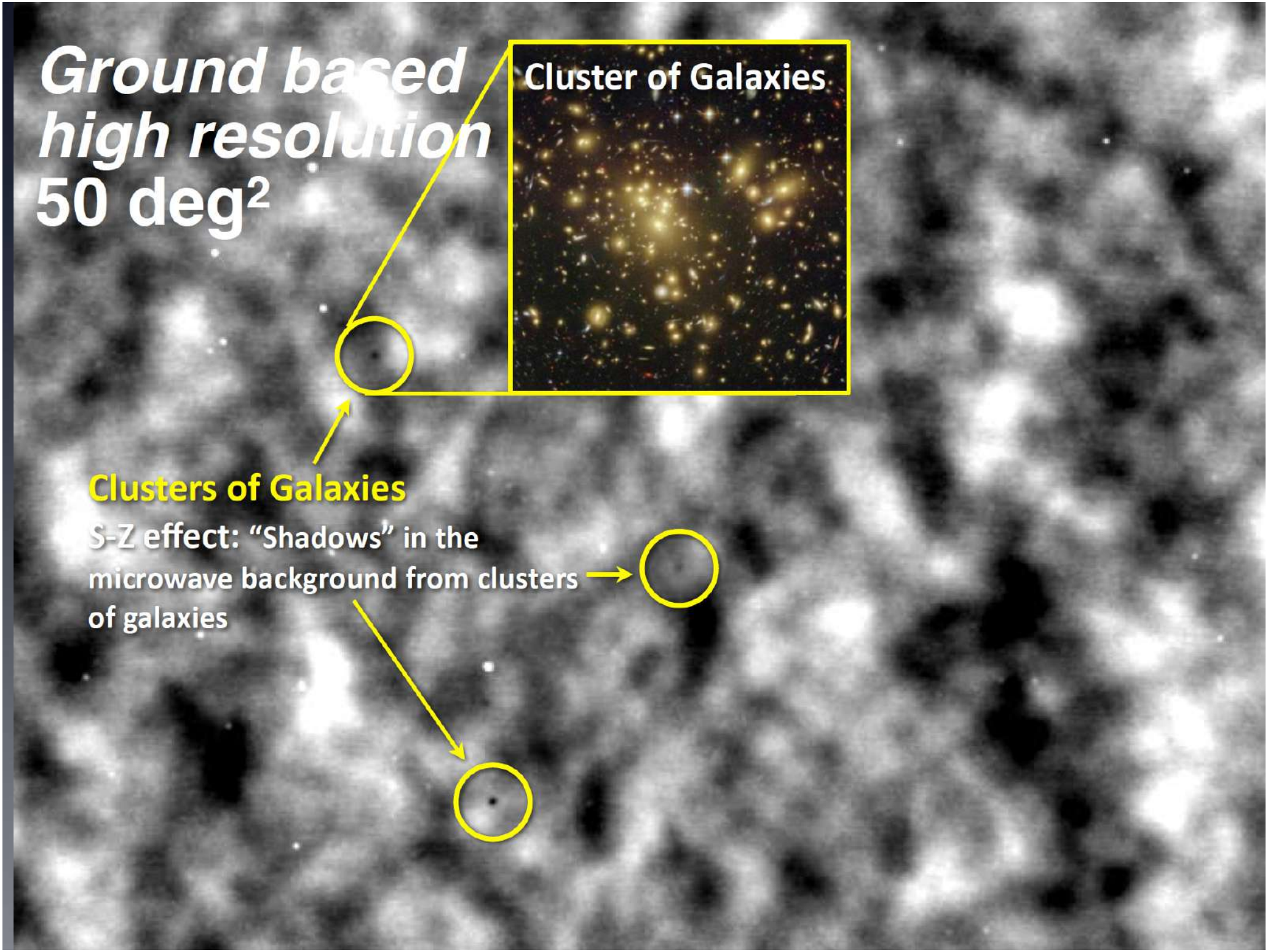
Early *inside-out* formation in protocluster core
(Chiang et al 2013,2017)



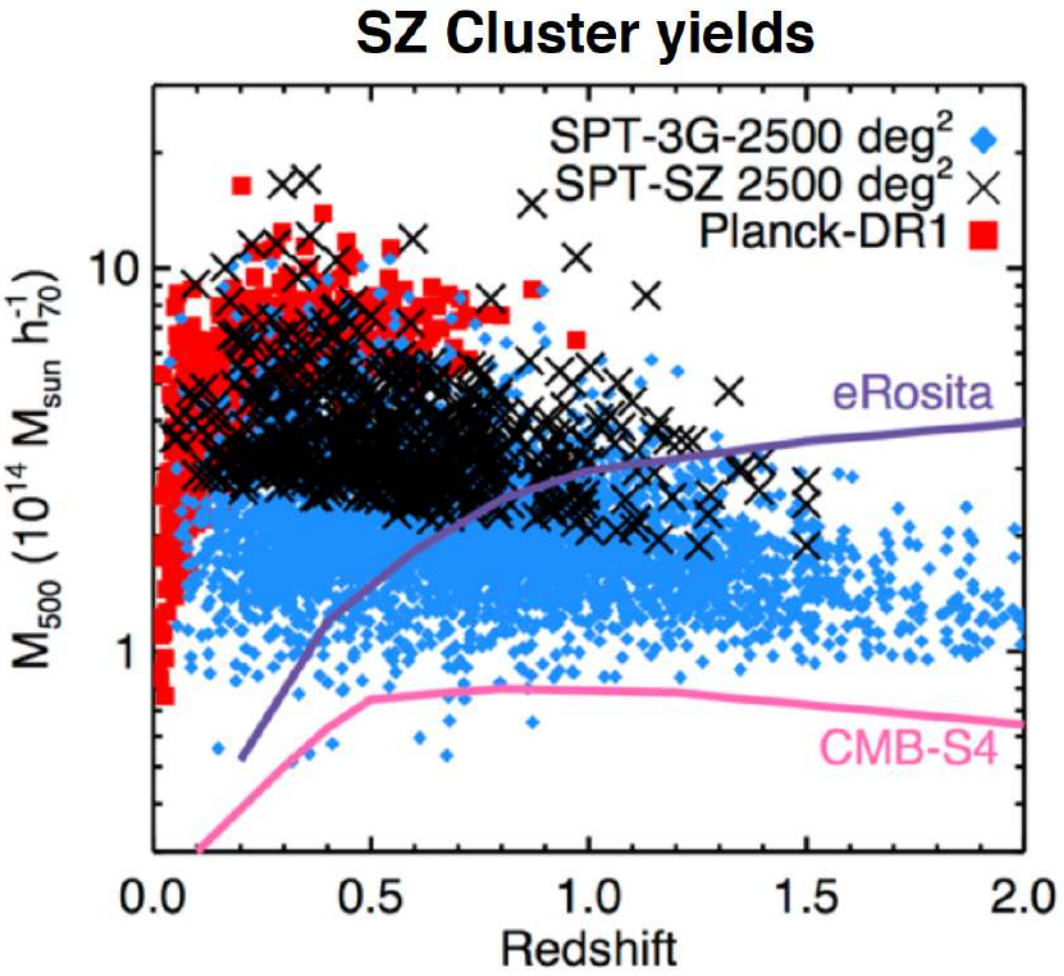
… finding early ‘cores’ as protocluster signposts (SPT-PCs)

SPT-SZ 2500 deg^2 @ 3mm,2mm, 1.4mm




Ground based
high resolution
50 deg²
Cluster of Galaxies
Clusters of Galaxies
S-Z effect: "Shadows" in the
microwave background from clusters
of galaxies

Expectations for SZ Cluster Surveys



Stage 2: $N_{\rm clust} \sim 1{,}000$

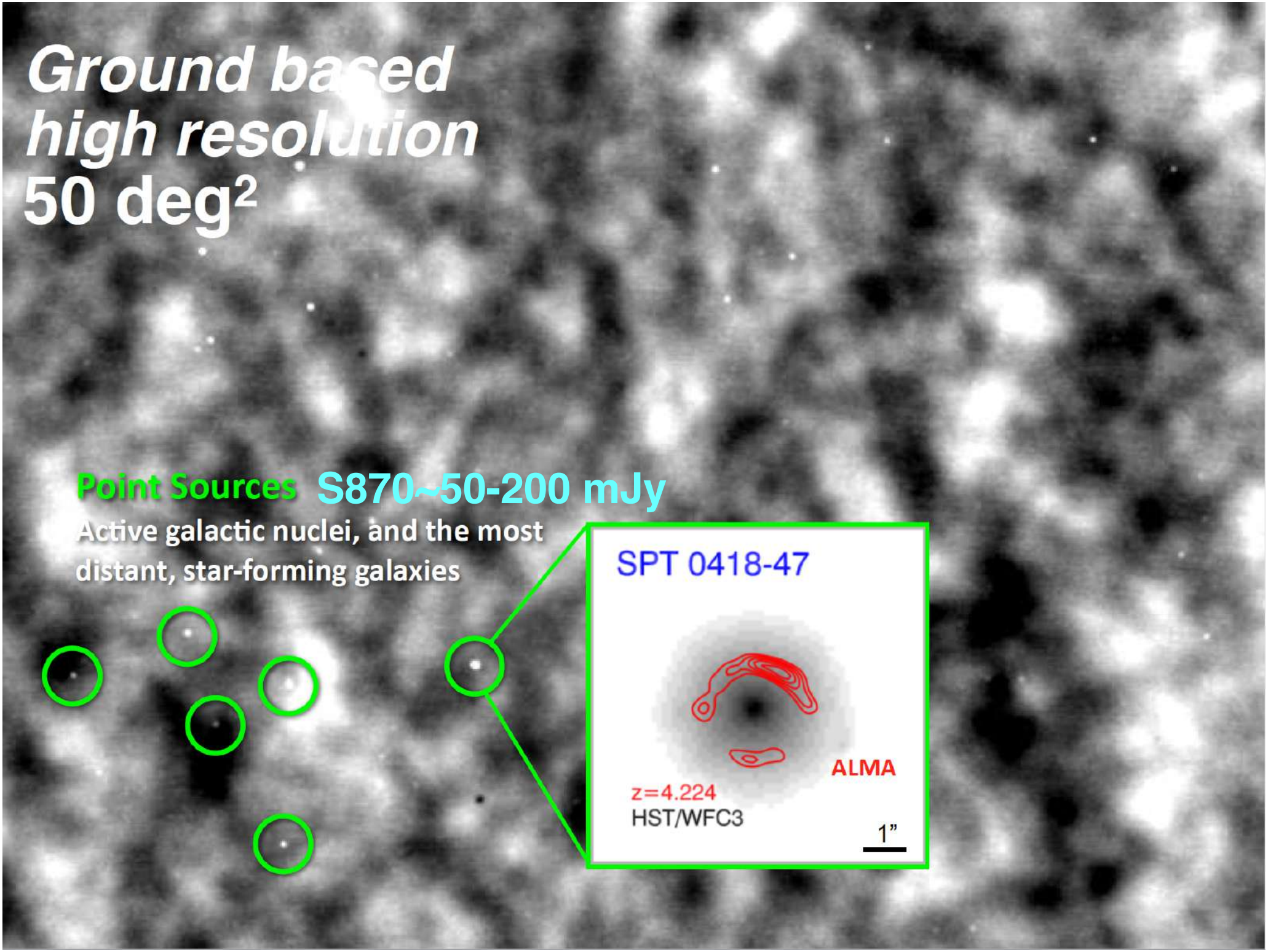
Stage 3: $N_{\rm clust} \sim 10{,}000$

CMB-S4: $N_{\rm clust} \sim 100{,}000$

CMB lensing will directly calibrate cluster mass SZ scaling:

CMB-S4: $\sigma(M) \sim 0.1\%$

for an extremely powerful probe of structure formation and dark energy.


Ground based
high resolution
50 deg²
Point Sources S870~50-200 mJy
Active galactic nuclei, and the most
distant, star-forming galaxies
SPT 0418-47
ALMA
z=4.224
HST/WFC3
1”

What if instead of

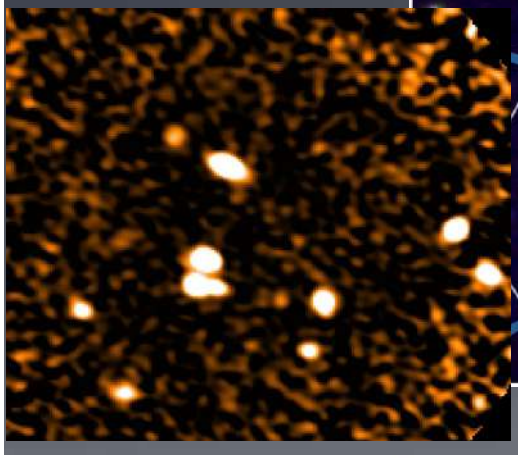
a single gravitationally lensed galaxy

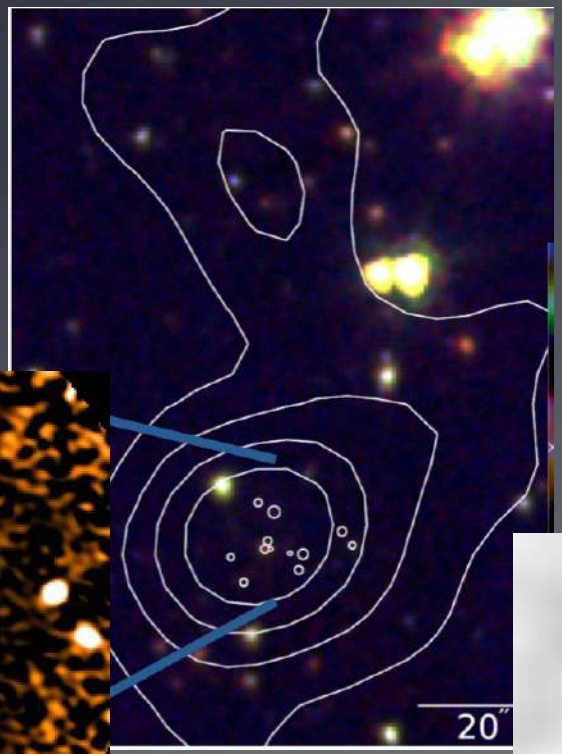
… an SPT source consisted of many unlensed galaxies?

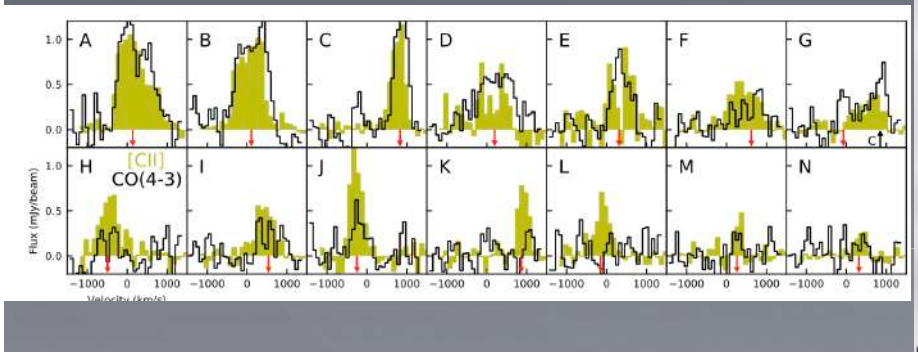
Extremely active ‘proto-cluster’ core regions in early Universe?

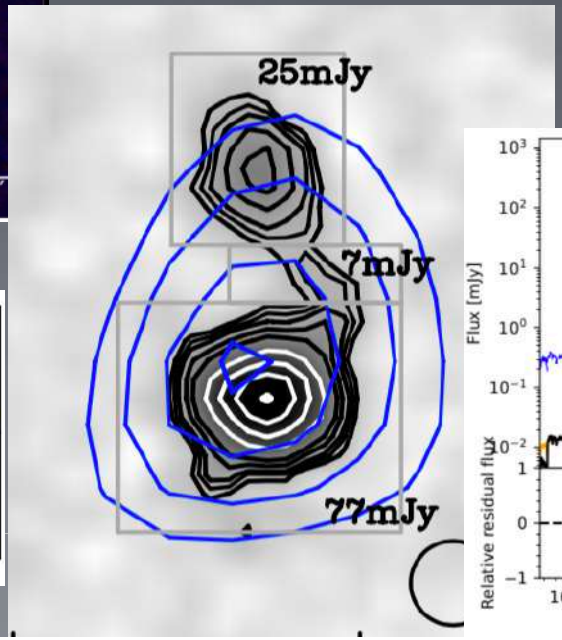
SPT2349-56 z=4.3 (Miller,Chapman+2018)

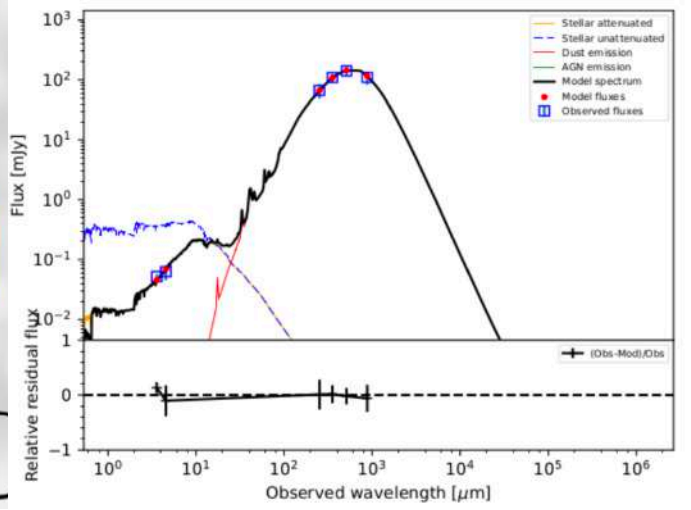
- 14 galaxies ID'd by ALMA at z=4.3
  - ~30% resolved in core
- Extended SPT (1') resolved by APEX
- L_{IR}~10^{14} Lsun. SFR ~ 17,000 M/yr, *and most concentrated system known*





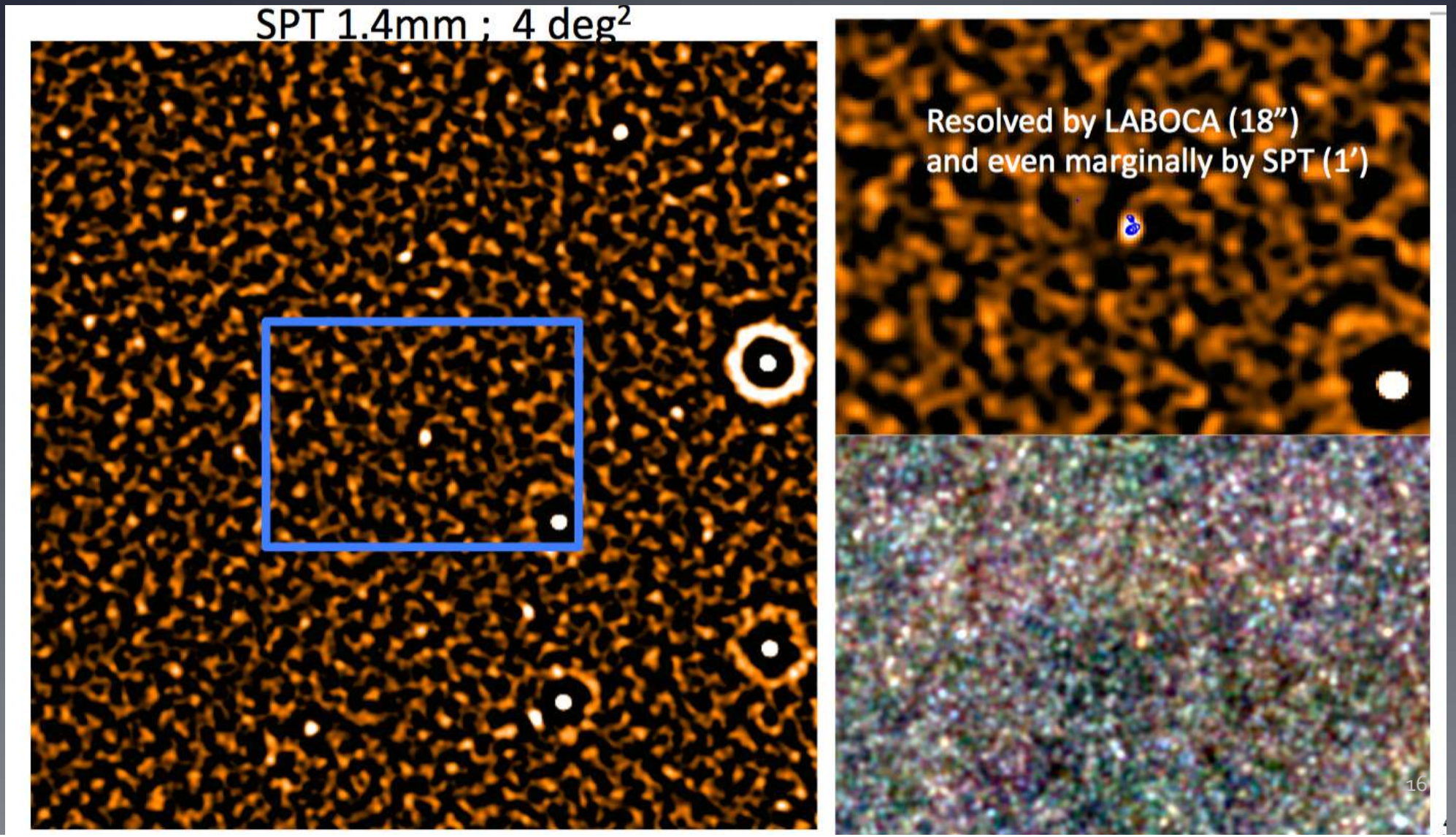






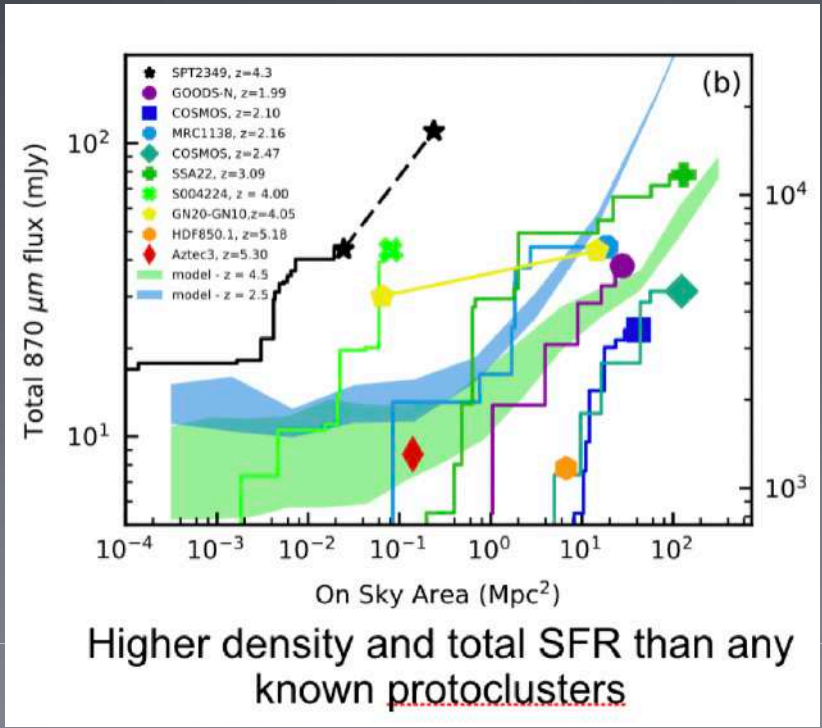
SPT-pol (deeper 400deg²)

SPT2349 detected at 12σ Clearly extended in SPT beam
Signature for deeper protocluster search



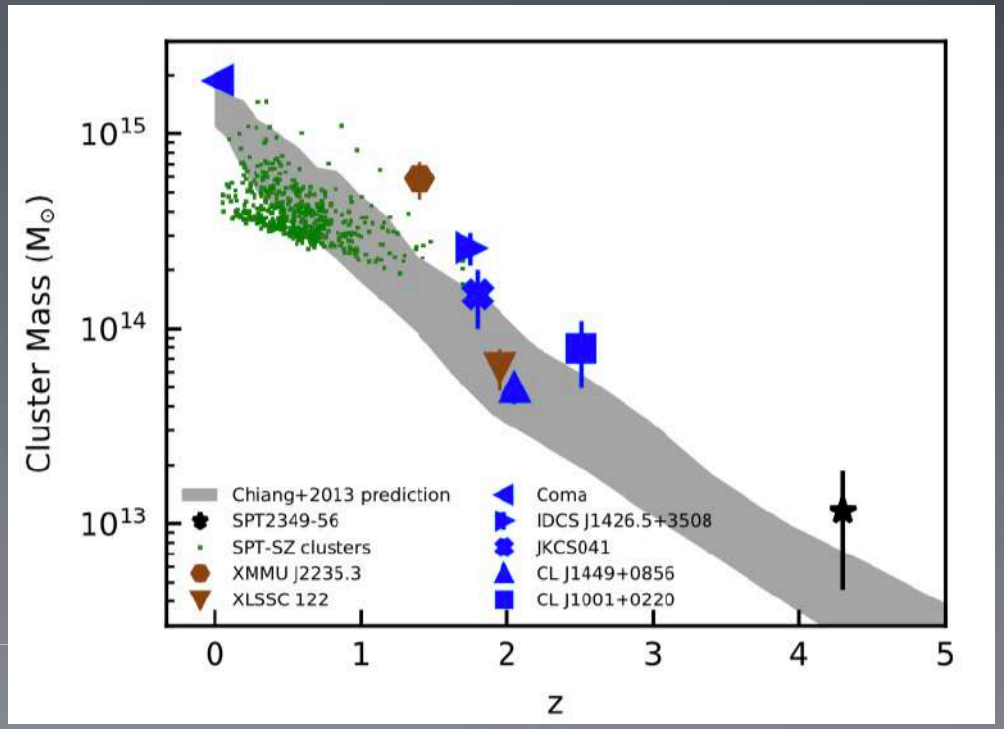
Key results Miller+18

- *Most concentrated, and highest total SFR system known*
- *17,000 Msol/yr*
- *Core: 1e6 Msol/yr / Mpc³*

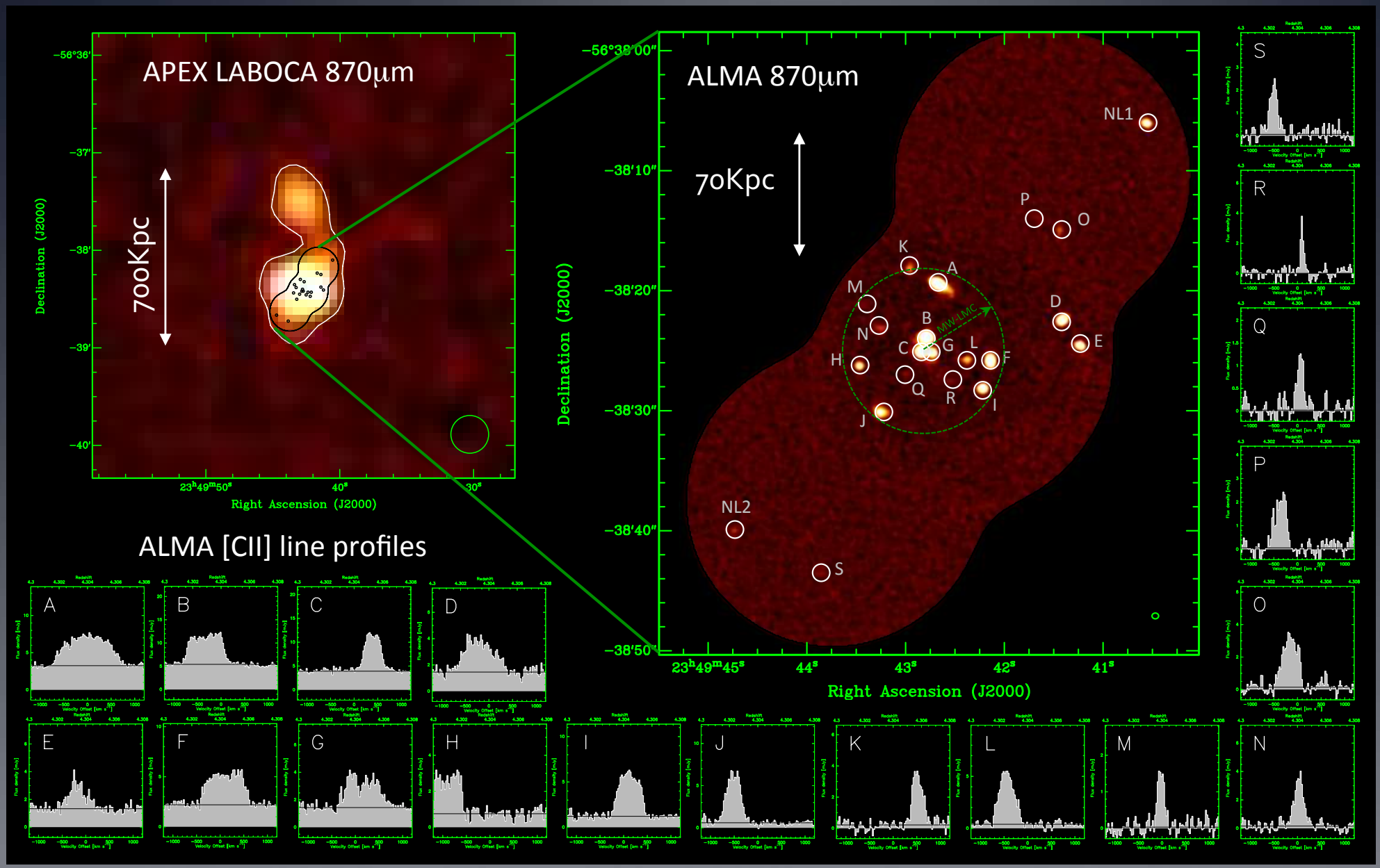


Higher density and total SFR than any known protoclusters

- Most massive halo (>10^{13} Msol) observed kinematically at z>4
- Progenitor of Coma-like cluster?



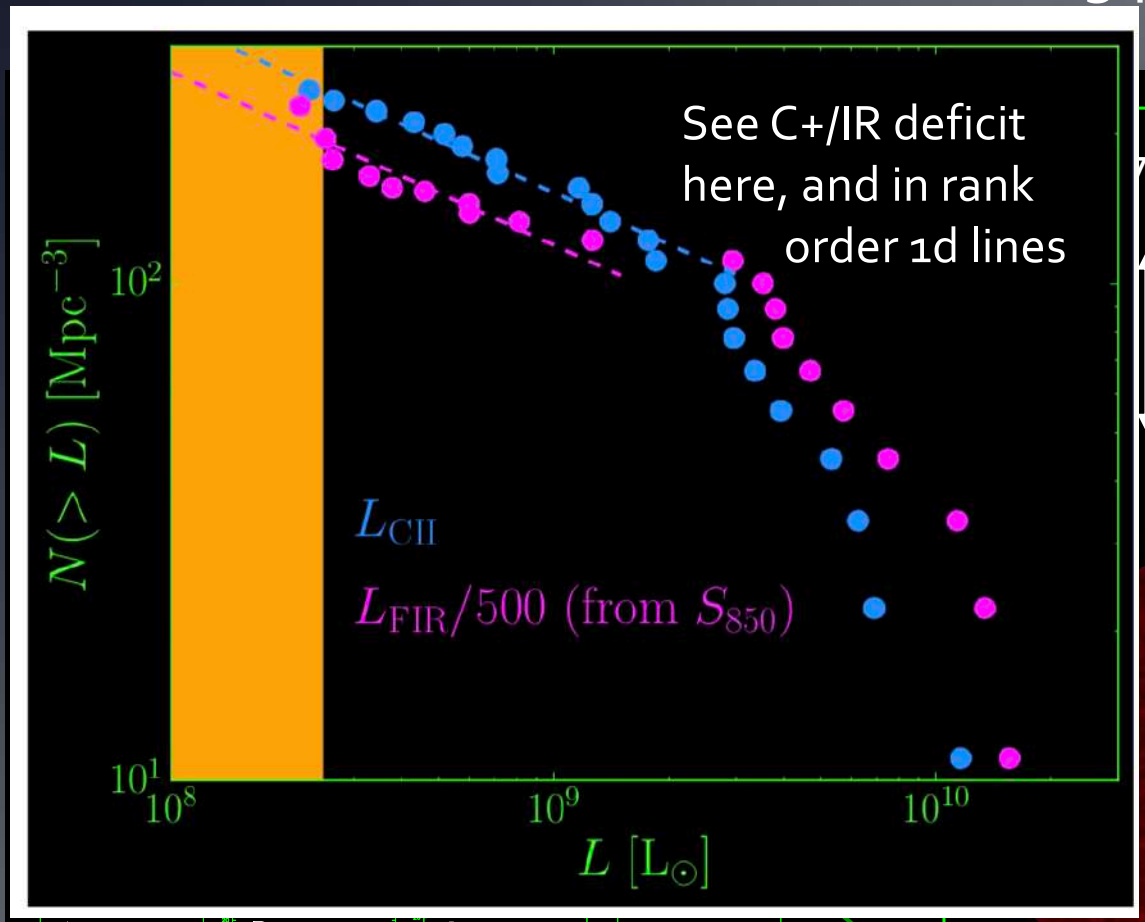
Proto-cluster SPT2349-56 @ z=4.3



update on Miller T.B., et al. 2018, Nature, 556, 469

25 individual members within 150kpc

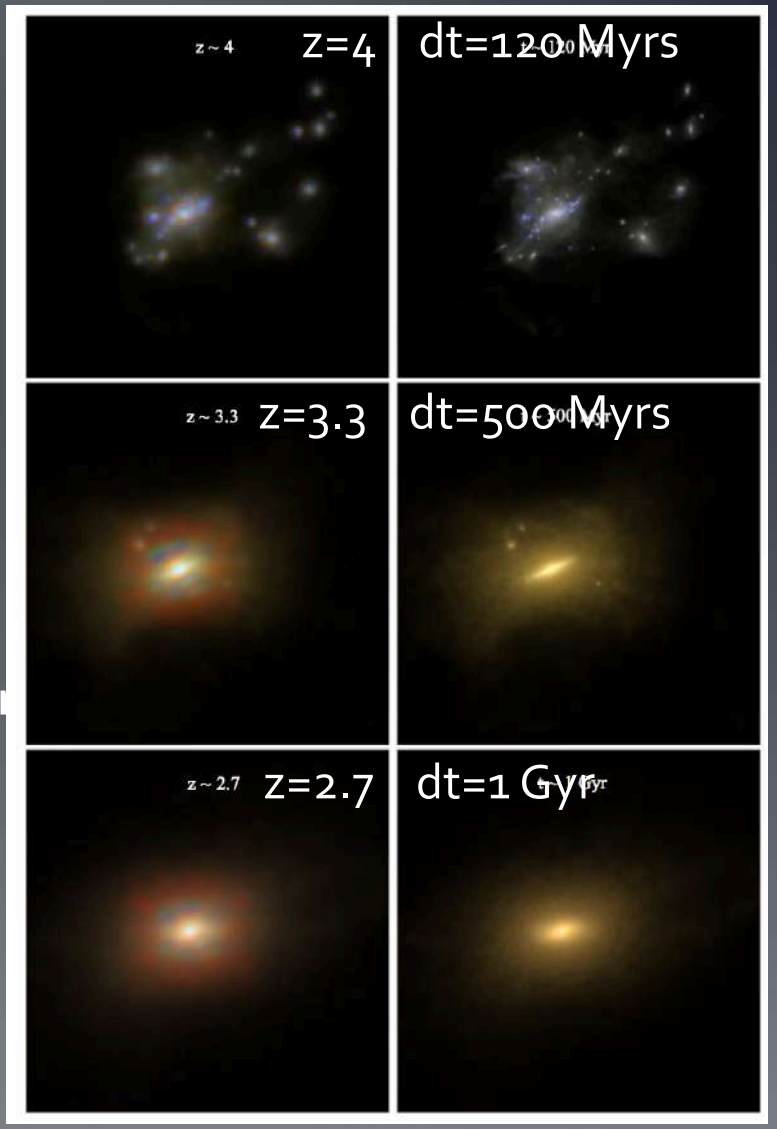
Proto-cluster core SPT2349-56 @ z=4.3

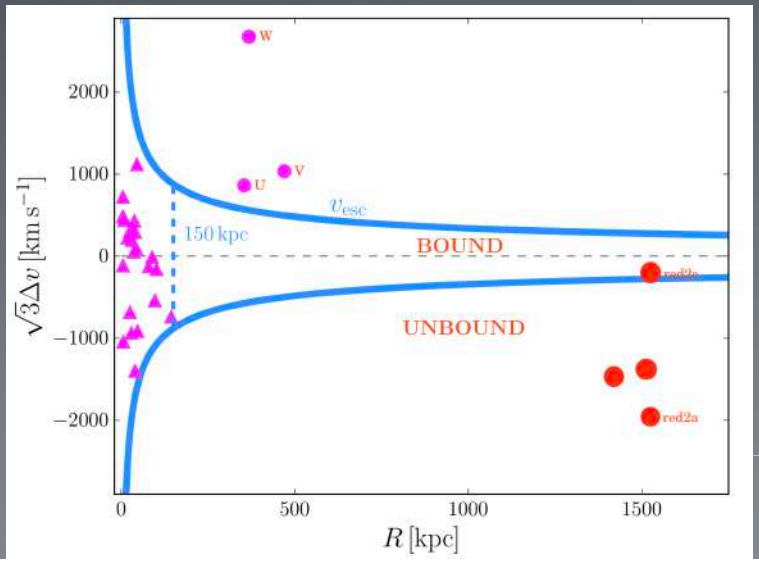


update on Miller T.B., et al. 2018, Nature, 556, 469

25 individual members within 150kpc

Witnessing cluster BCG formation





BCG in place after ~500Myr

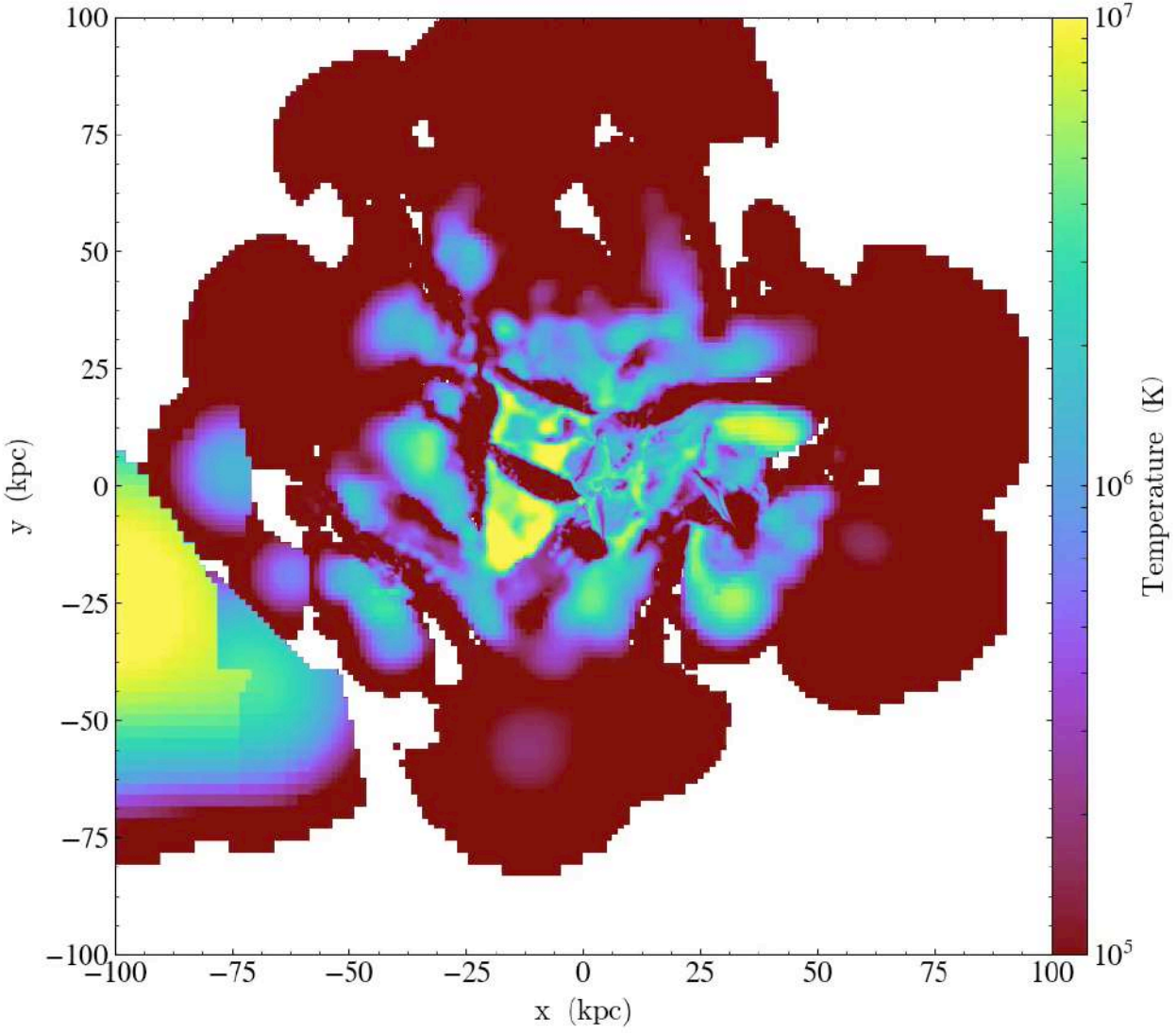
M_* increases 4x in this event

z=0: log(M_*) 12-13 M_{sol}

Rennehan+2020 arXiv: 1907.00977

Helping to establish the hot ICM?

Rennehan et al. 2019



- Gas seen is either

1) expelled from galaxies due to stellar feedback
2) heated/expelled as a result of shock-heating during collision.

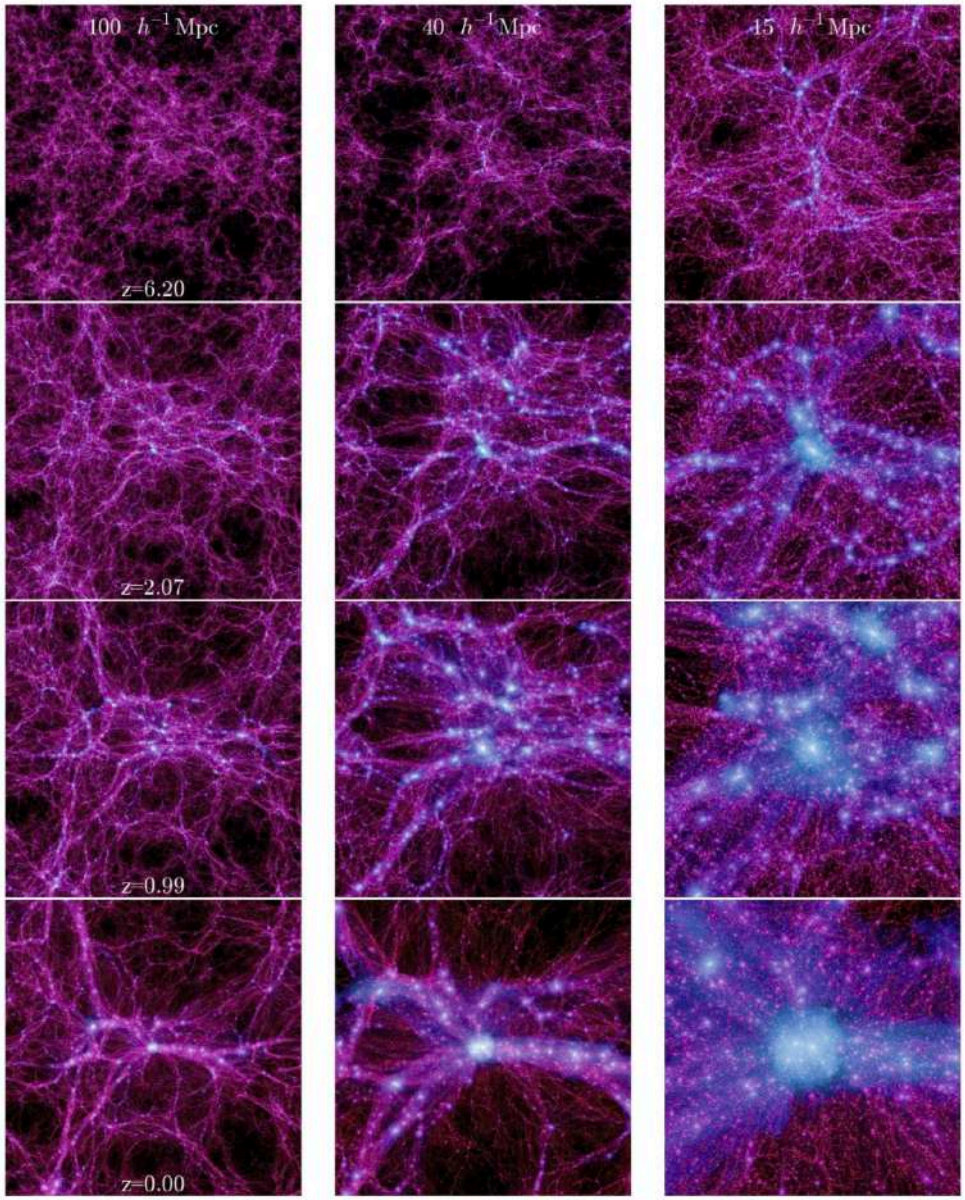
- not included:

1) cosmic gas that would normally be falling in
2) any halo gas associated with the galaxies

- 0.1Gyr: 80% above 10^6K, and 15% above 10^7K
- 1Gyr: 96% above 10^6K, and 30% above 10^7K

Why are protoclusters interesting

Coma-like cluster in Millenium
(Boylan-Kolchin et al. 2009)



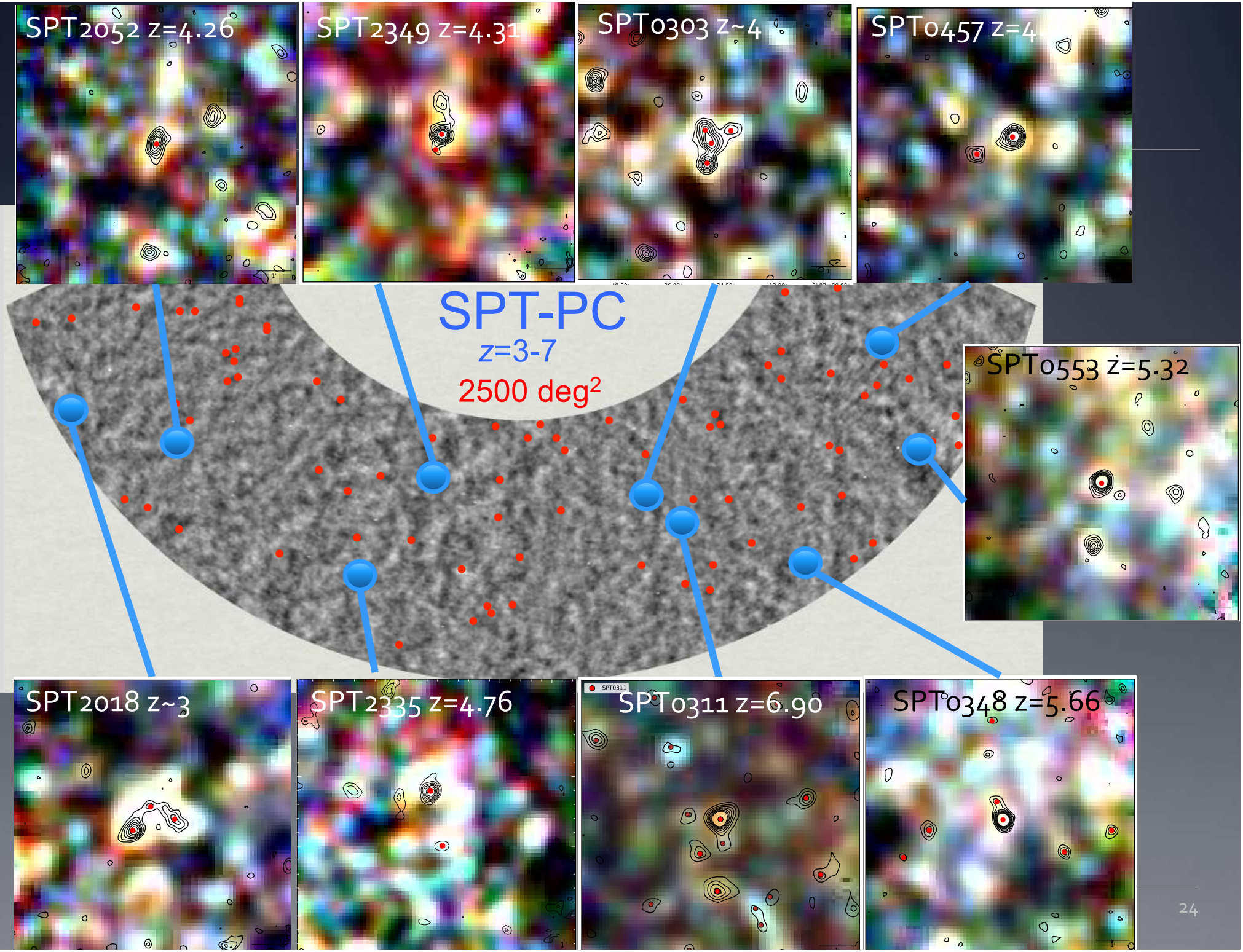
Much like rich clusters themselves, but at more formative stages:

- use as cosmological probes (σ8?),
- dark matter (sub-)structure,
- Formation of BCGs and other cluster galaxy populations,
- AGN feedback,
- red sequence evolution,
- environmental effects on galaxies,
- ICM enrichment & hydrodynamical evolution.
- formation and triggering of supermassive black holes in dense environments

An SPT proto-cluster survey

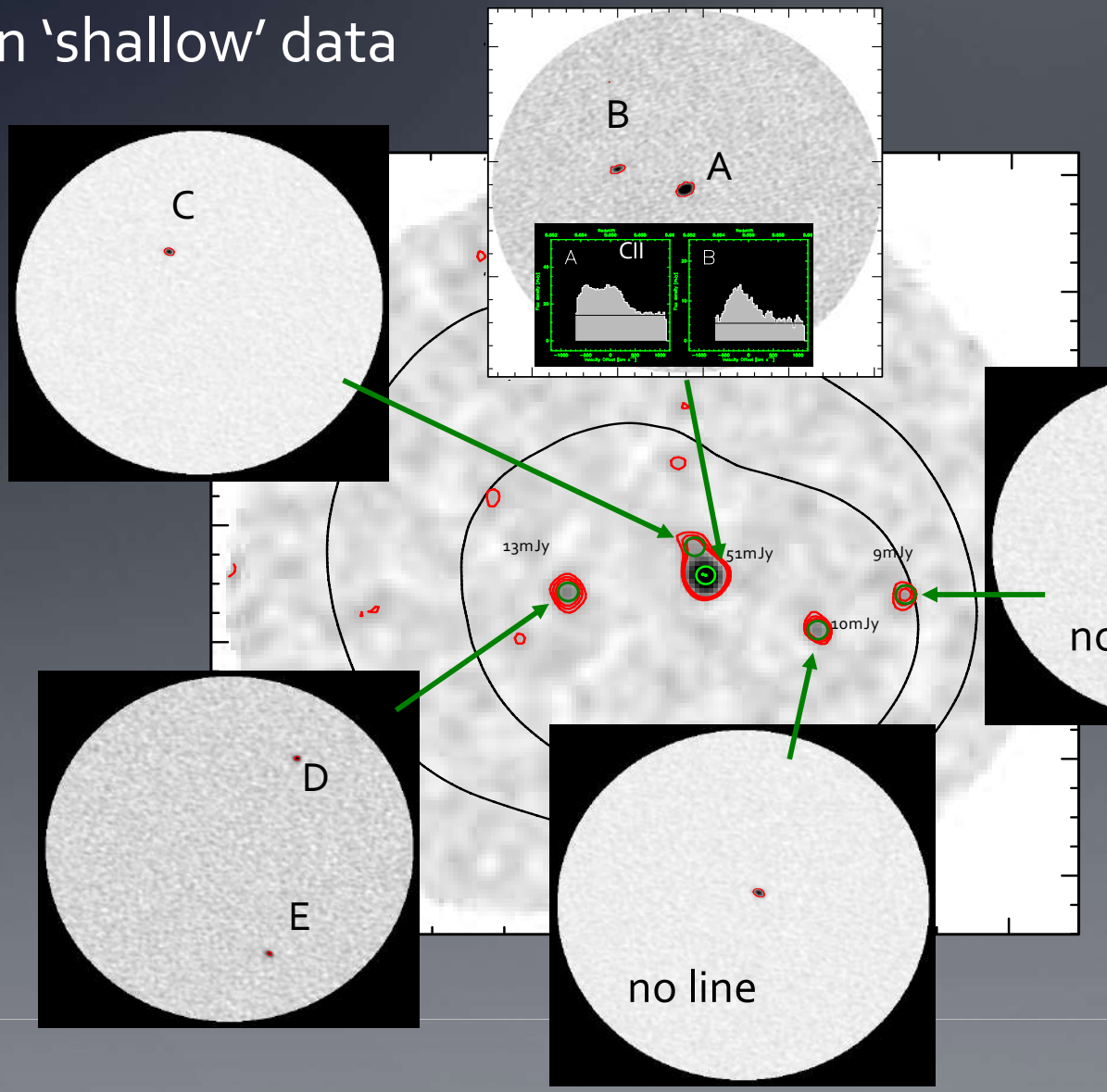
SPT2349 is clearly the most spectacular object of its kind in SPT-SZ

Knowing what to look for … can we find other SPT protoclusters?

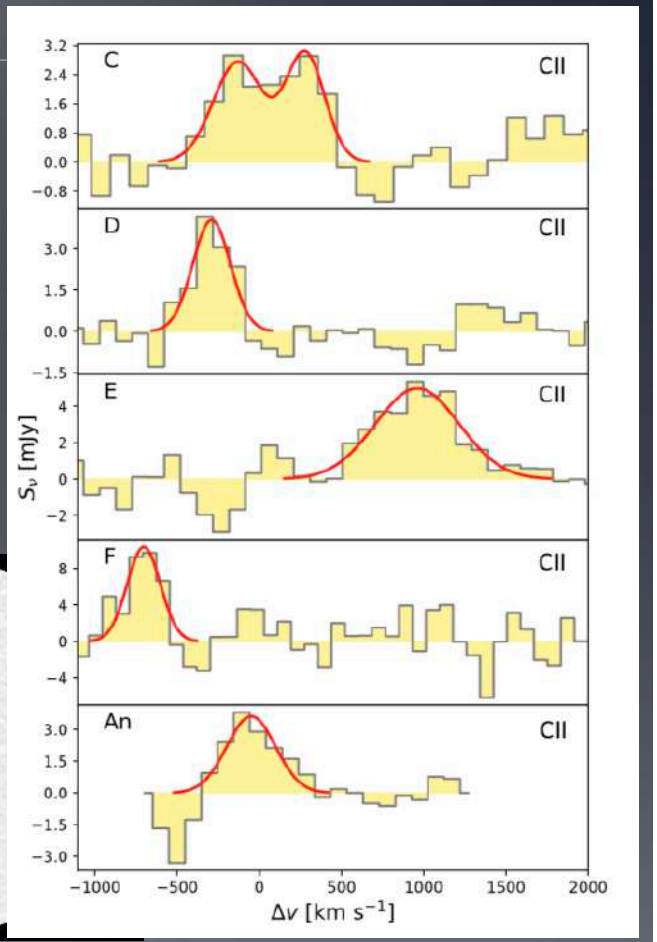

SPT2052 z=4.26
SPT2349 z=4.31
SPT0303 z~4
SPT0457 z=4
SPT-PC
z=3-7
2500 deg2
SPT0553 z=5.32
SPT2018 z~3
SPT2335 z=4.76
SPT0311
SPT0311 z=6.90
SPT0348 z=5.66

Ongoing ALMA line follow ups

SPT0348-62 (**z=5.6**). 8 SMGs detected in 'shallow' data



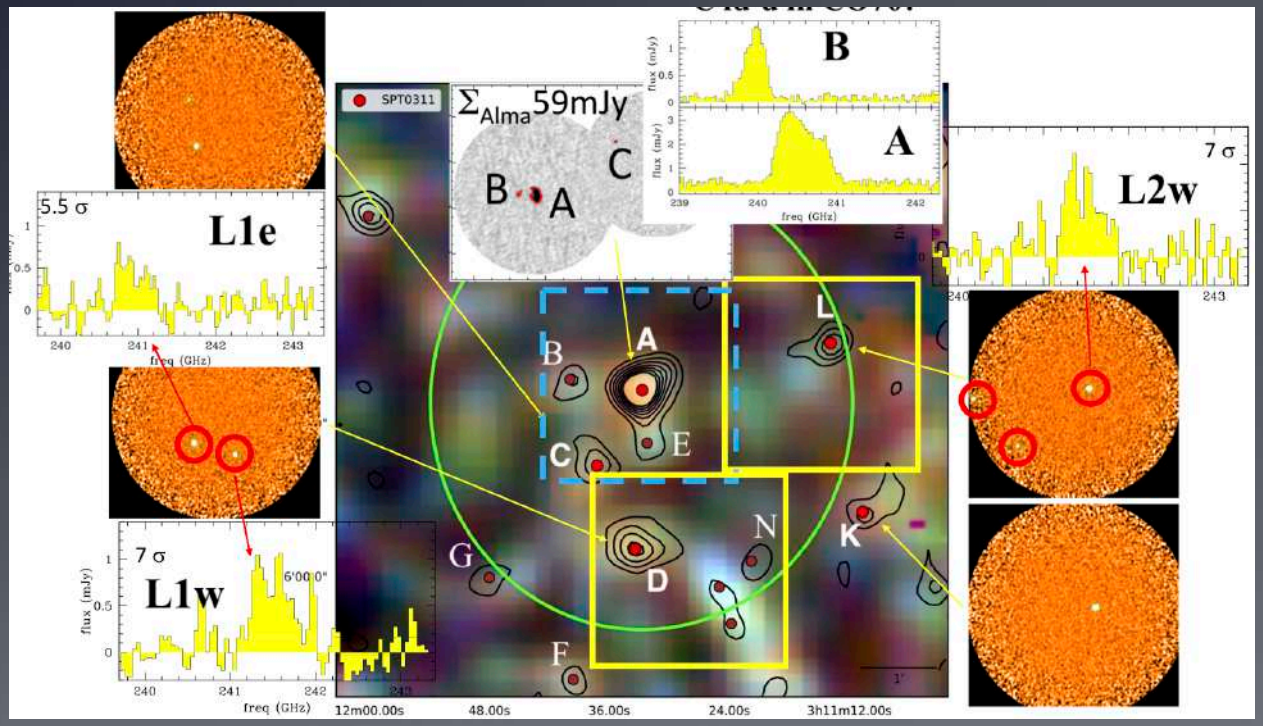
CII lines in SPT0348 satellites

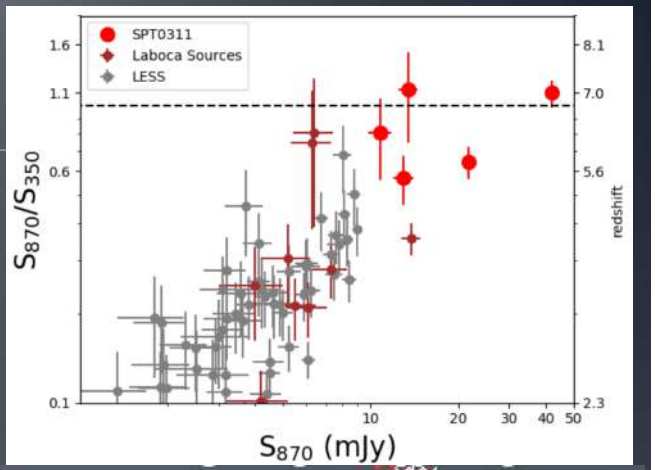


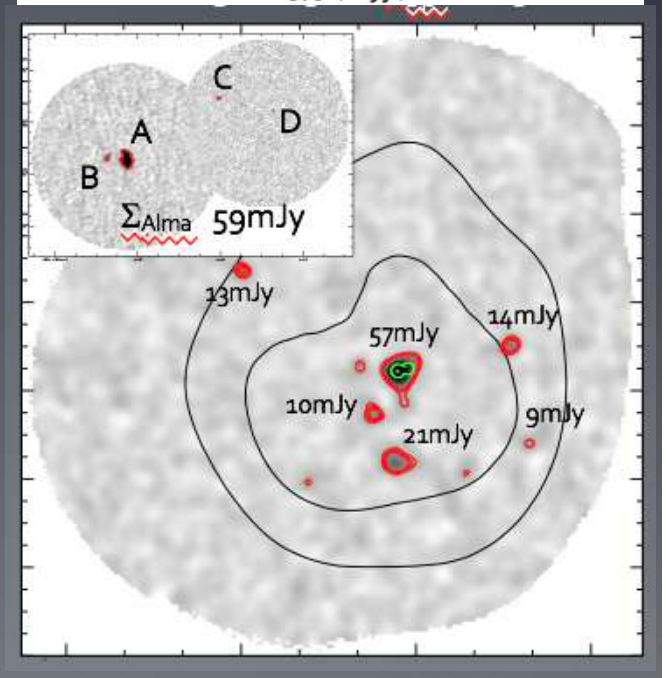
5/7 ALMA detected source are PC members
(non-detections could be due to limited velocity coverage)

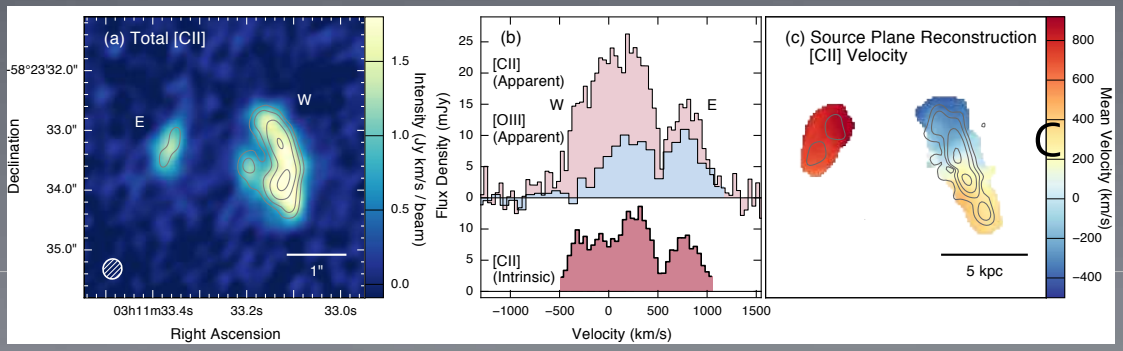
Ongoing ALMA line follow ups

SPT0311-58 (**z=6.9**). 6 SMGs identified at z=6.9 in 'shallow' C+ data







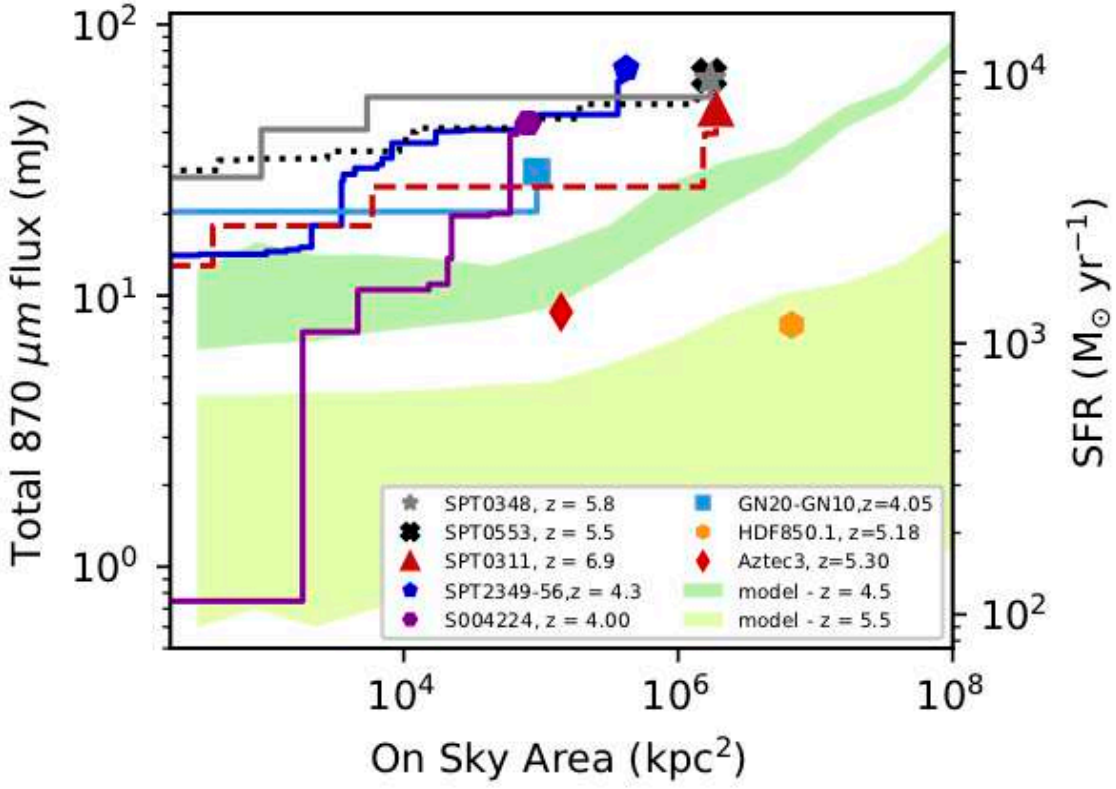


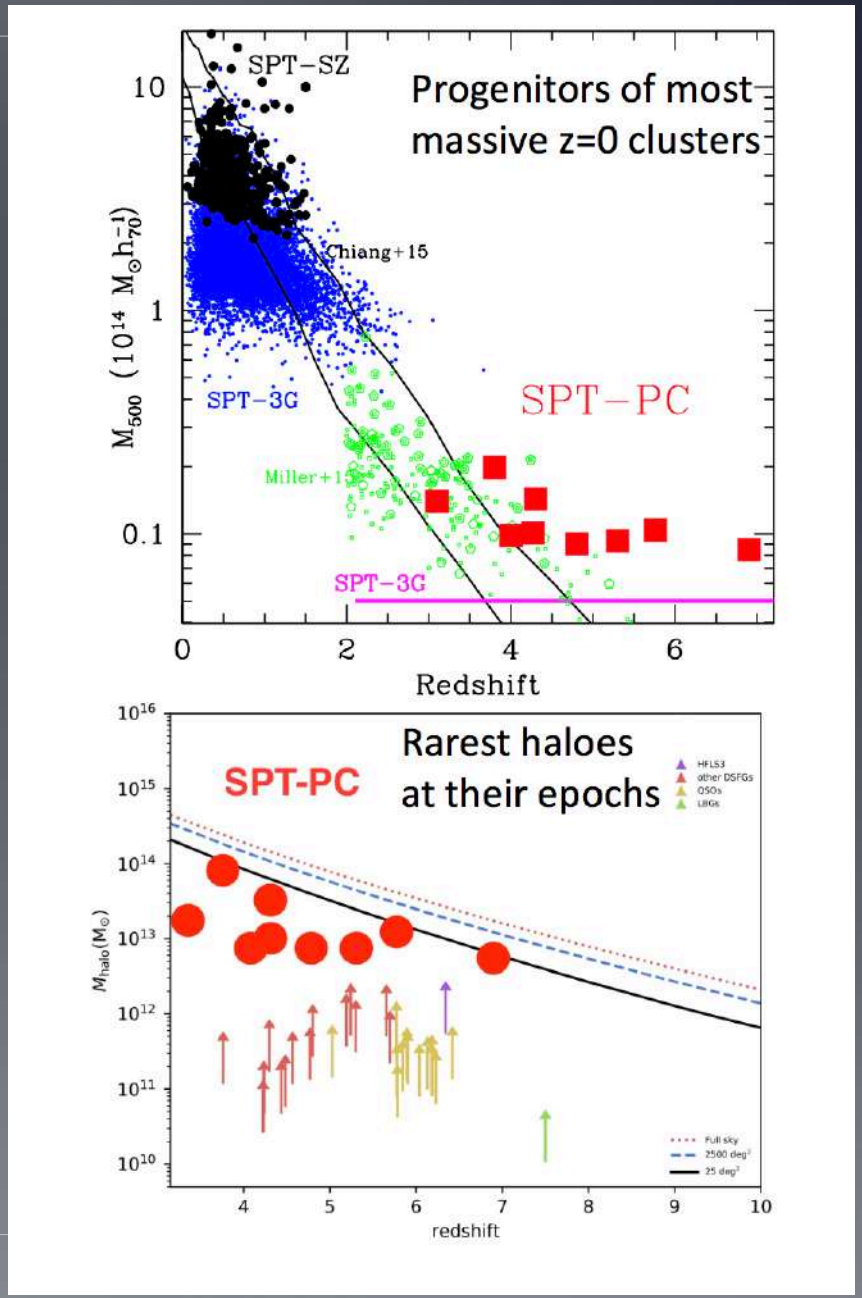
Chapman+20 in prep

Marrone+18 Nature, 553, 51

SPT-PC

These objects will be important for understanding early structure formation



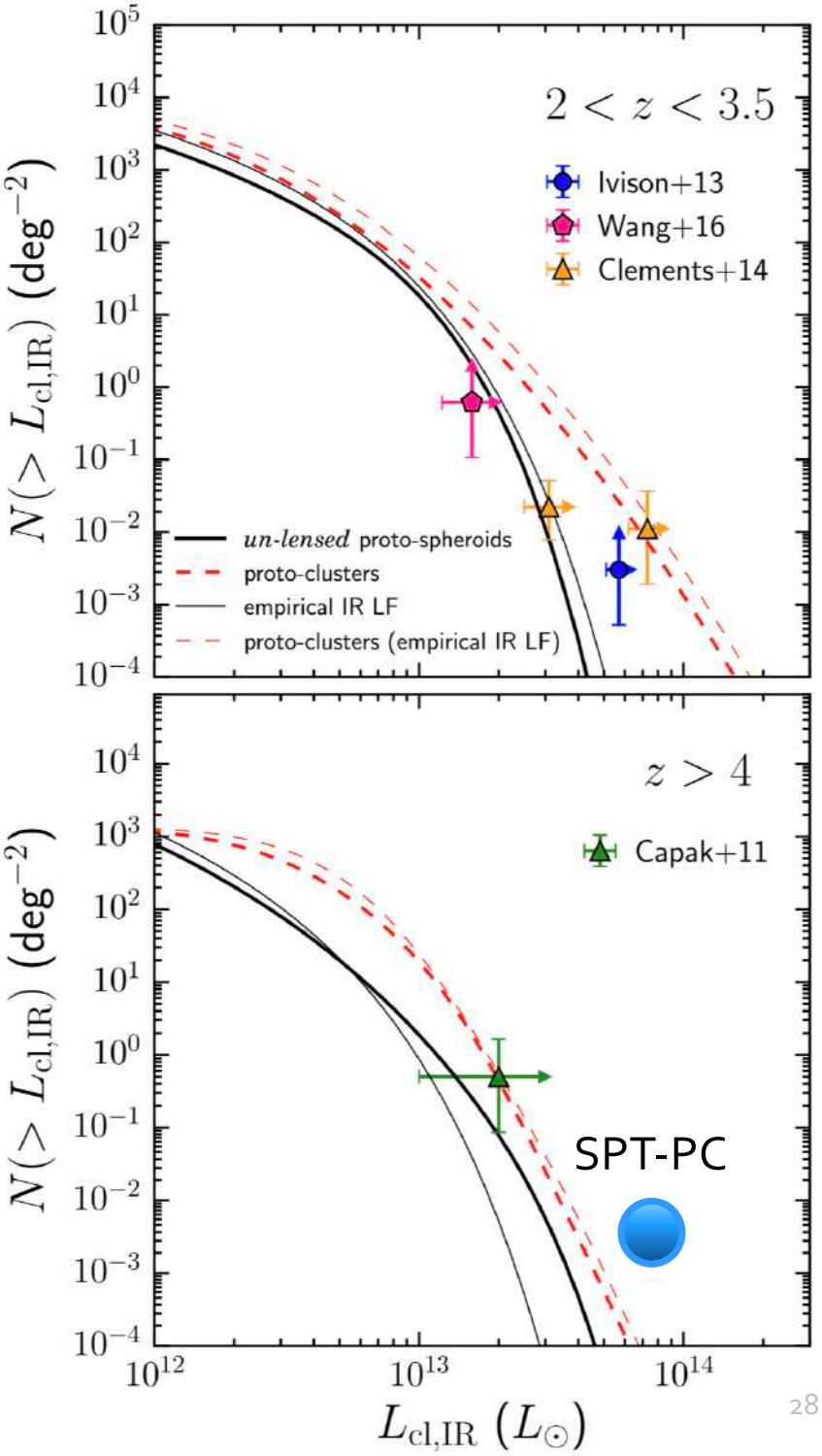


At z>5 the contrast with models is severe

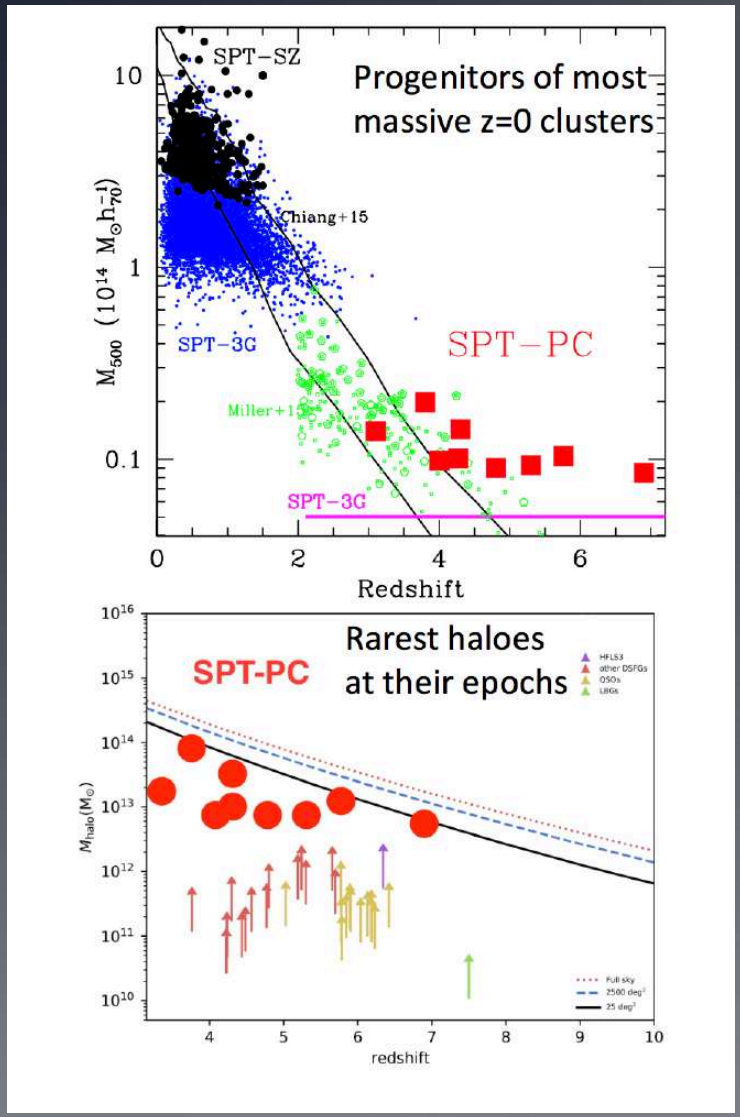
Compare to recent PC counts predictions

Negrello+2017: counts of protoclusters/cores

SPT shows there are clearly more than predicted



Summary



- Discovery of these PCs is only possible due to the synergy between large area surveys and sensitive interferometers in the submm

- SPT-PCs are unique systems to study the earliest phase of massive galaxy and cluster formation. They allow to study the evolution of the most massive DM halos out to z=7!

- BCGs form earlier than expected from most simulations and current observational wisdom (z>3-4 vs z~1-2)

High-z PCs will allow to study the evolution of the CO, CII and dust luminosity functions in cluster environments to investigate differences in the evolution between cluster and field galaxies.