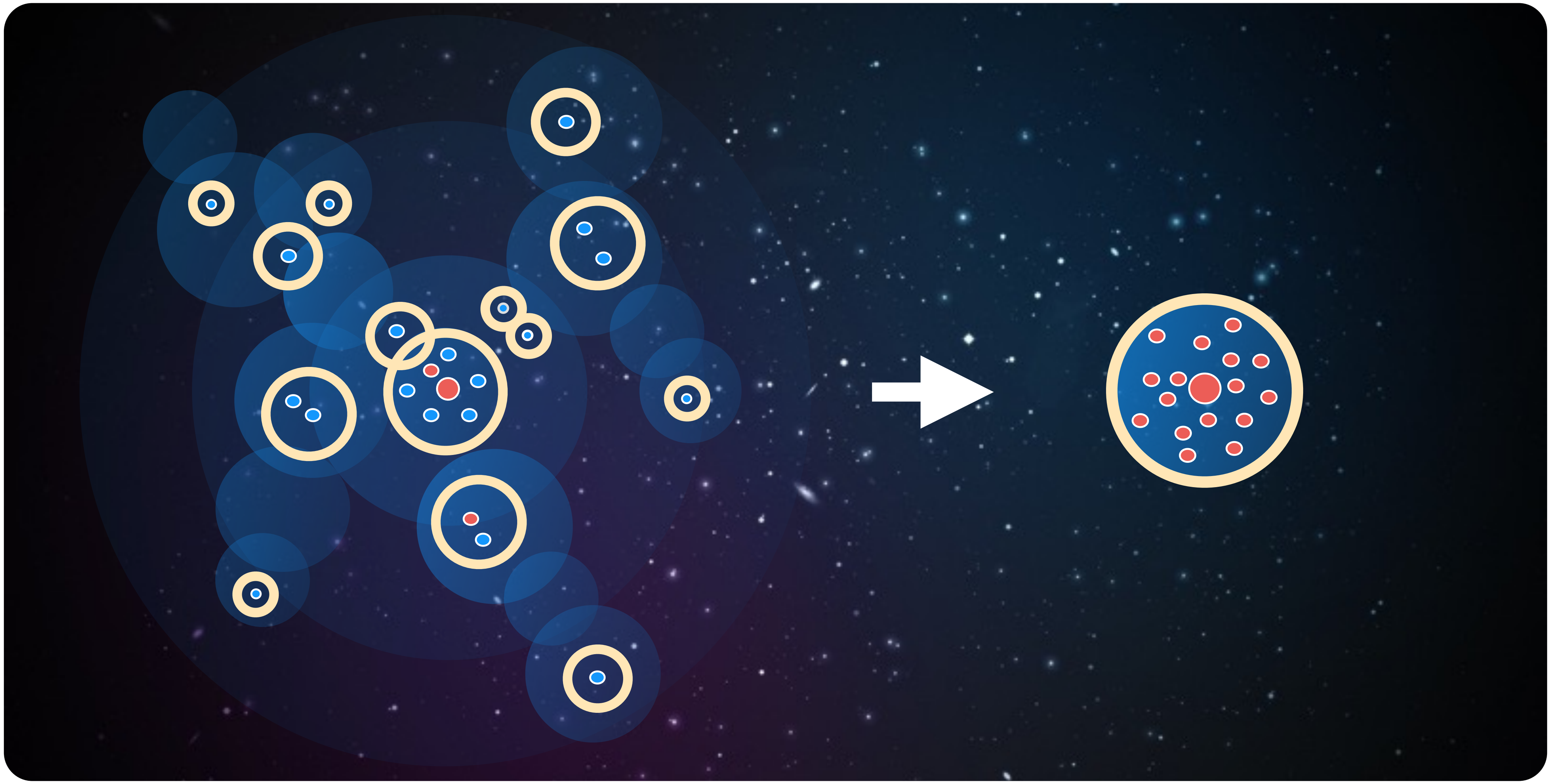
Galaxy Proto-clusters as an Interface between Structure, Cluster, and Galaxy Formation



Yi-Kuan Chiang

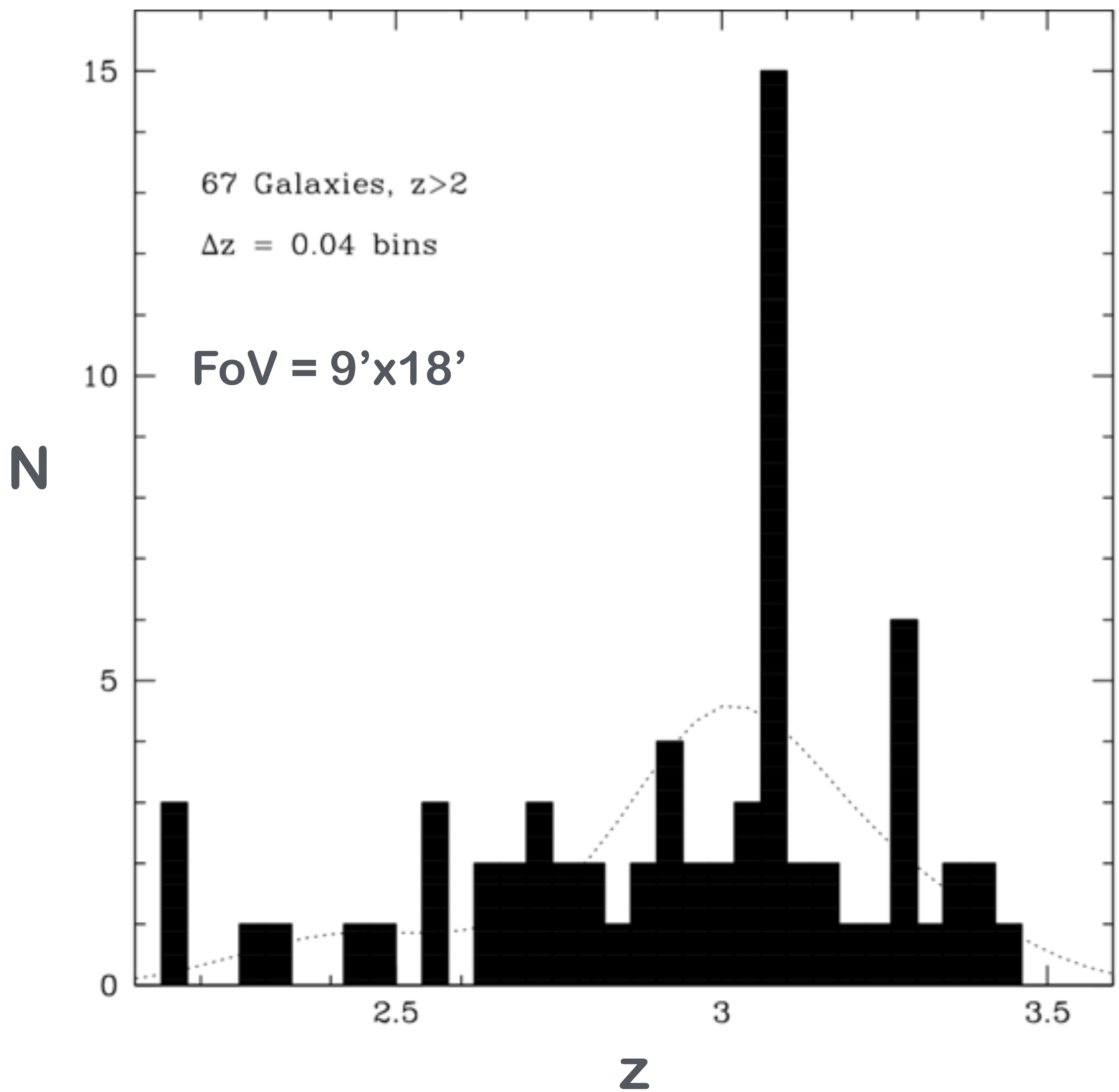
UT Austin

With: Roderik Overzier & Karl Gebhardt

A Proto-cluster at z=3.09 in the SSA22 Field

Steidel+98

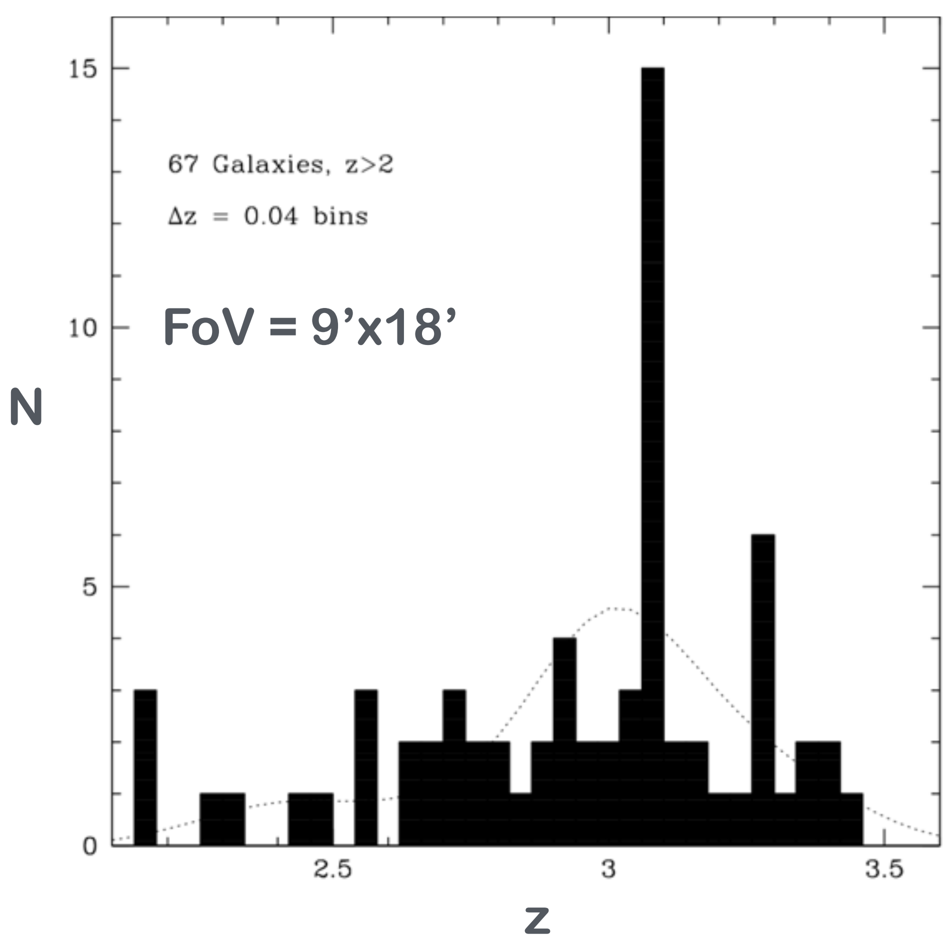
LBG redshift distribution



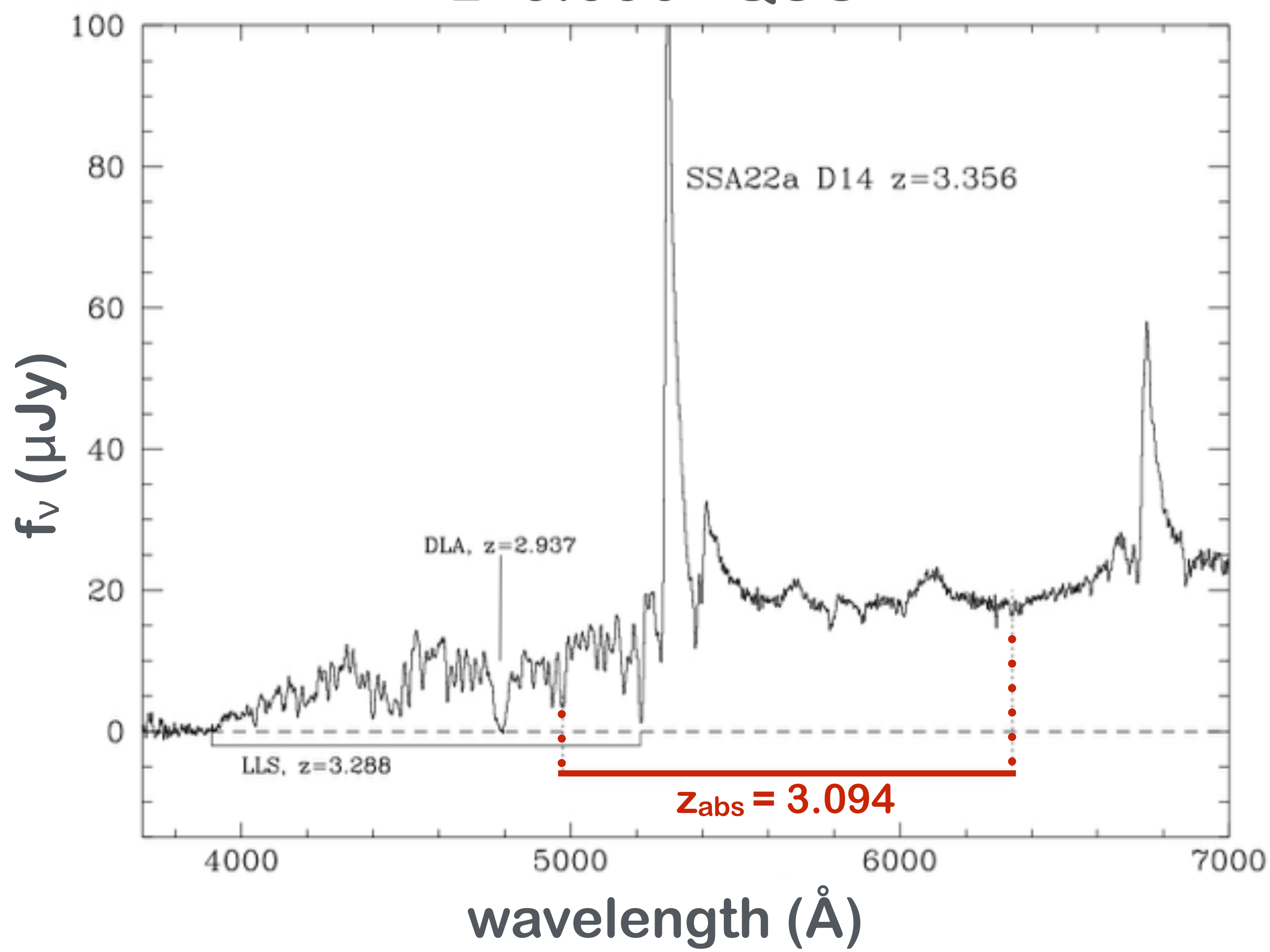
A Proto-cluster at z=3.09 in the SSA22 Field

Steidel+98

LBG redshift distribution



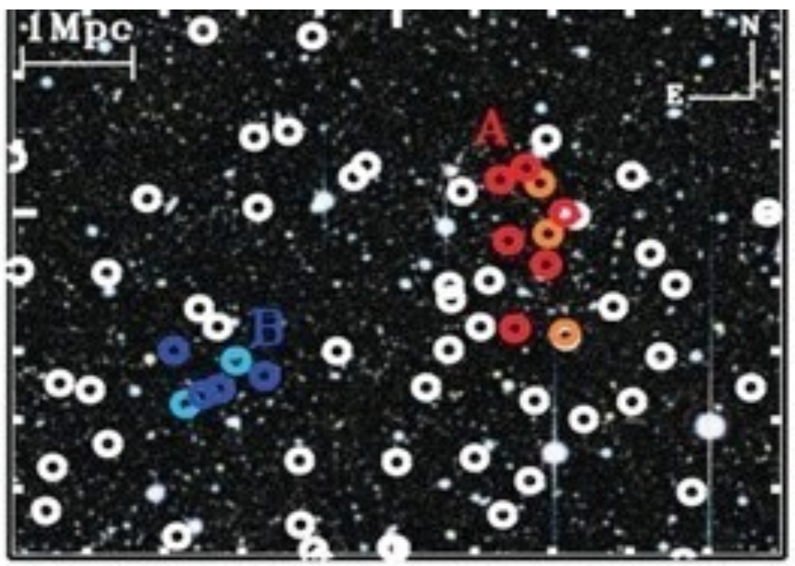
z=3.356 QSO



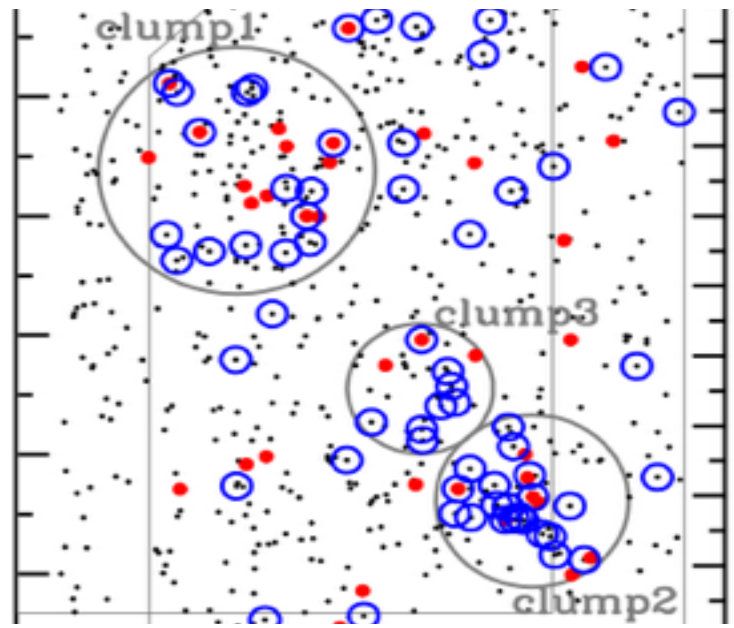
The "Proto-cluster Zoo"

25+ known structures at z = 2 – 6 (see Chiang+13 for a recent compilation)

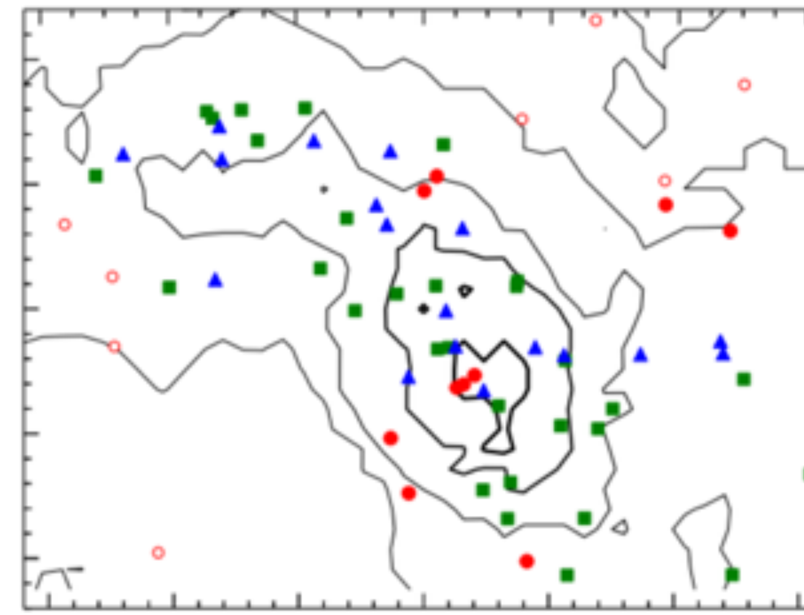
Ouchi+05, LAE, z=5.7



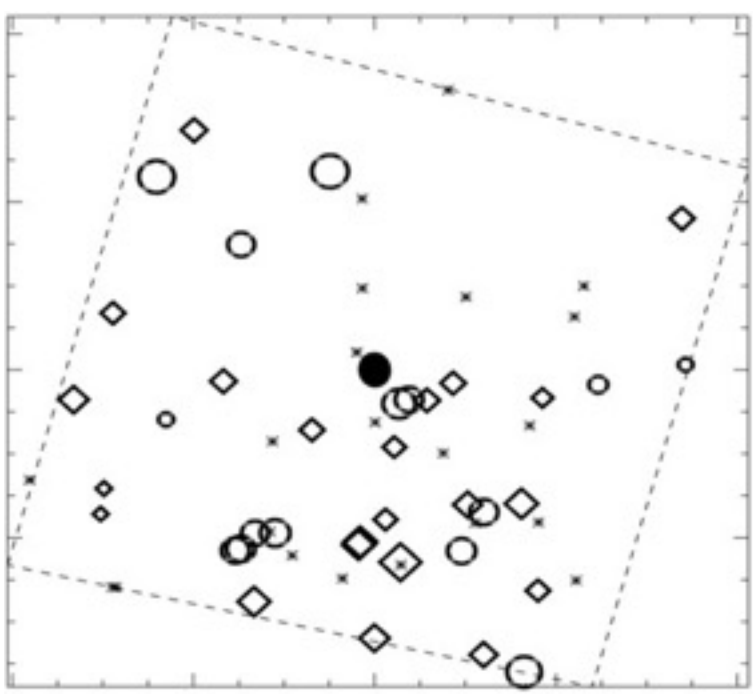
Hayashi+12, Hα, z=2.53



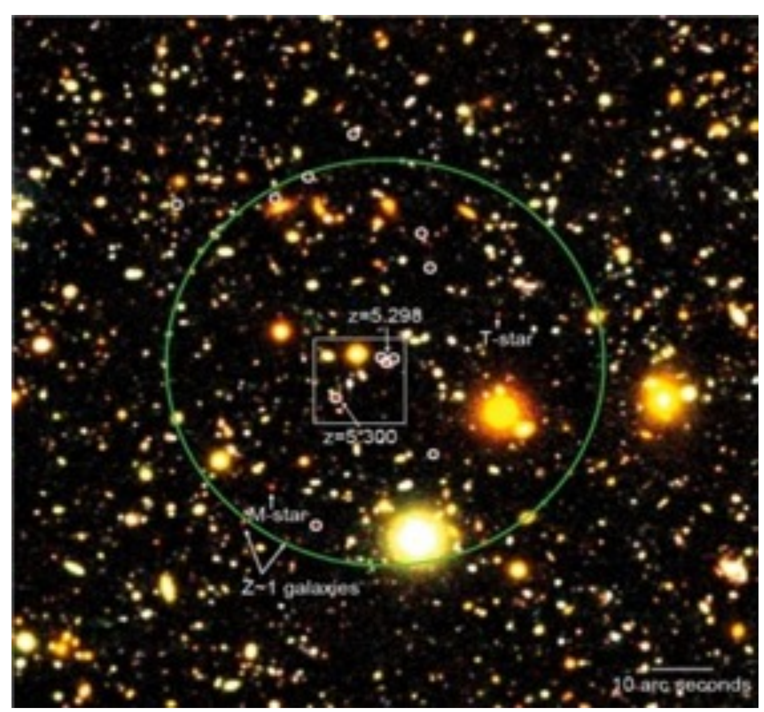
Toshikawa+12,14, LBG, z=6



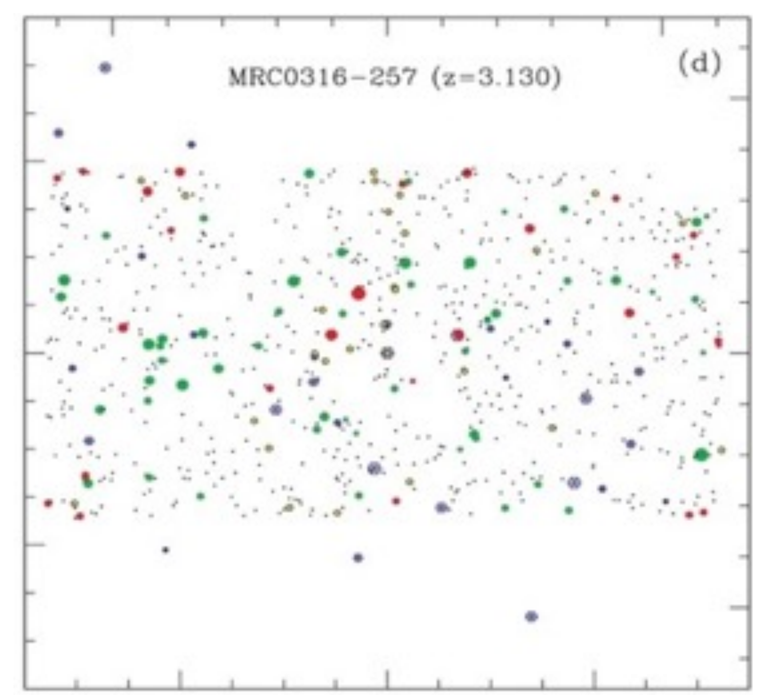
Venemans+07, LAE, z=2.86



Capak+11, SMG, z=5.3

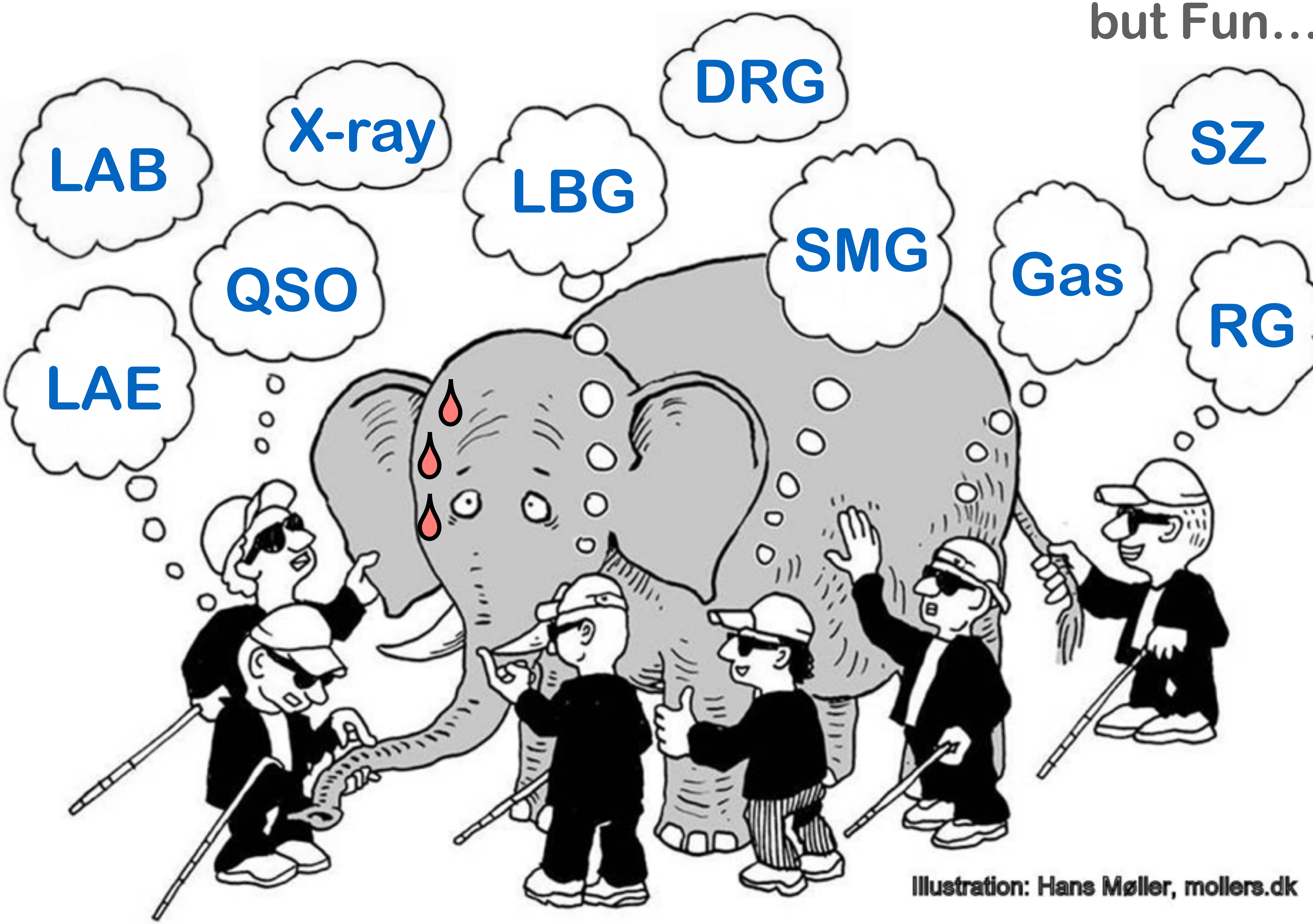


Kodama+07, JHK, z=3.13



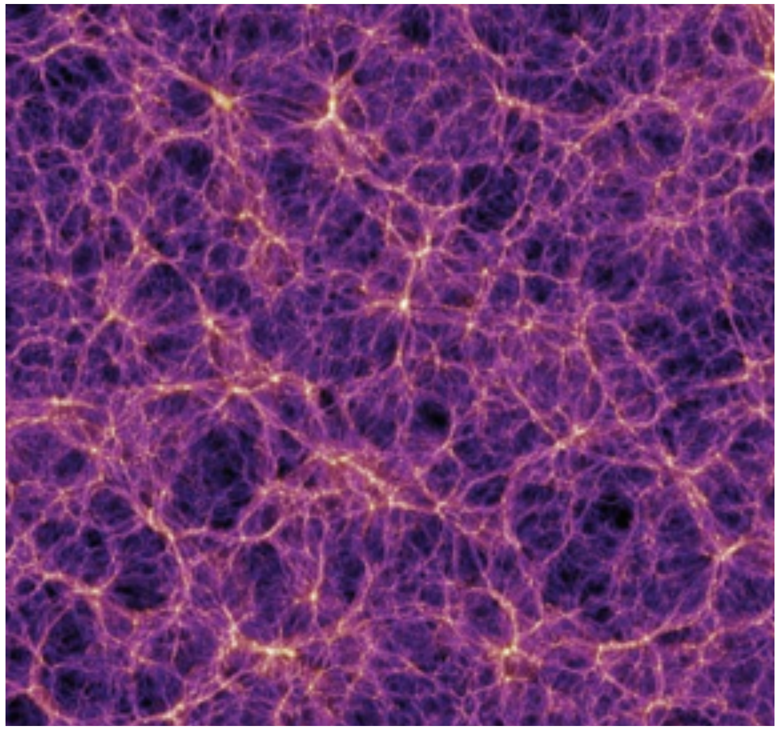
Proto-cluster Observations are Very Challenging

but Fun…



From large-scale to small-scale

Structure Formation

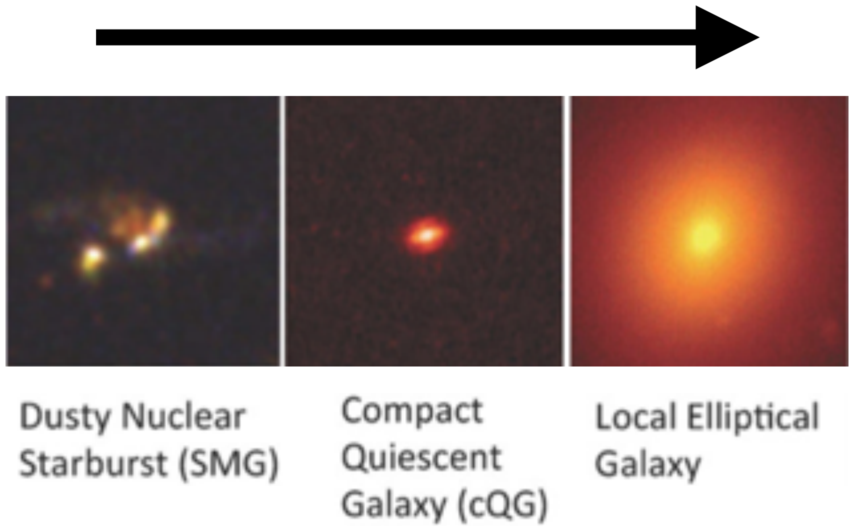


Springel+05

Cluster Formation

Abell 1689, Chandra+HST

Galaxy Formation



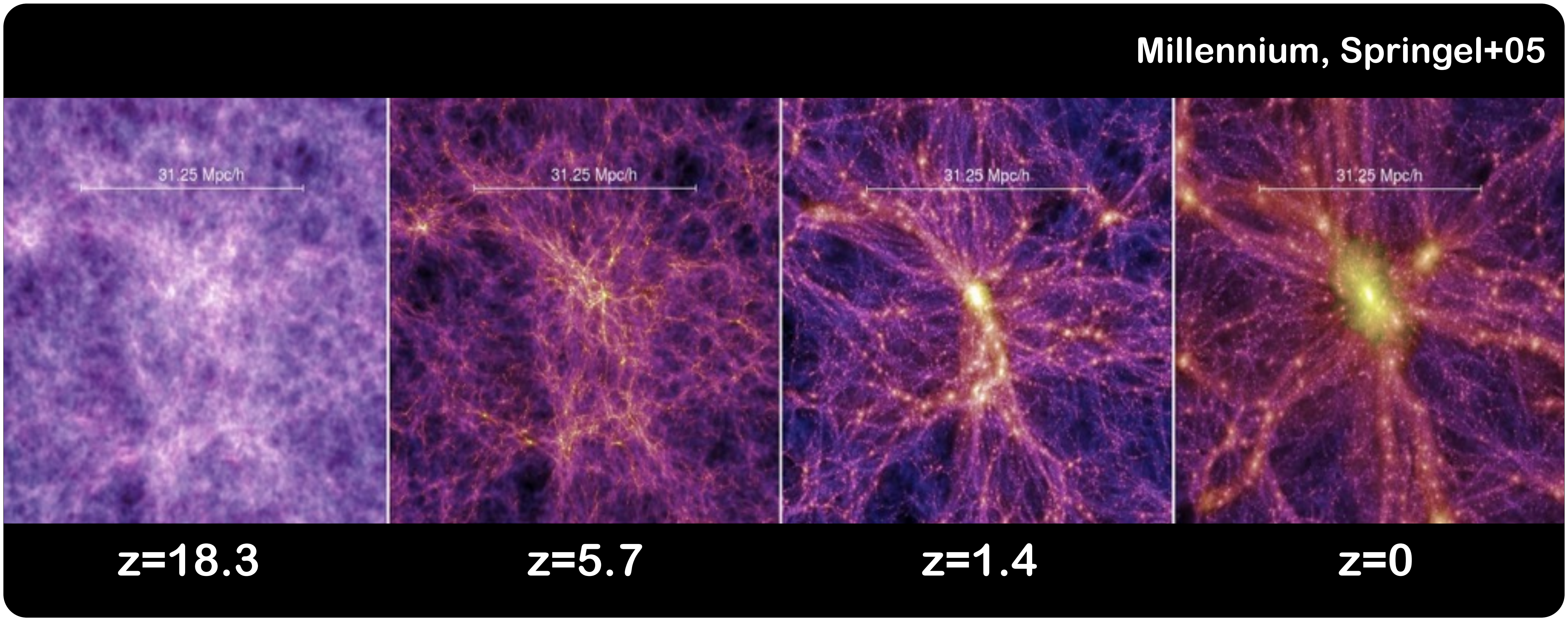
Toft+14

Part I

Large-scale / top-down view —

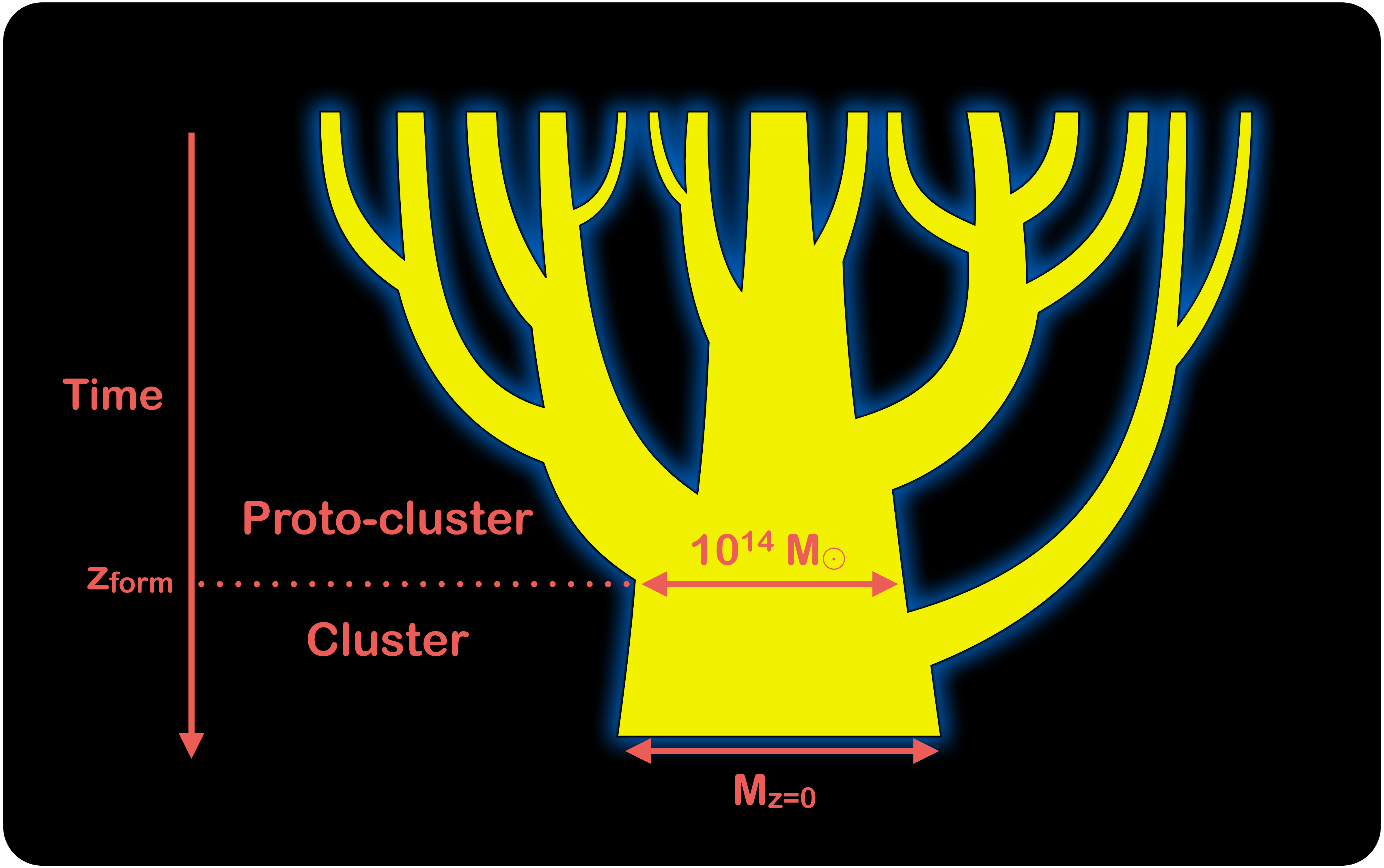
1. **Dark Matter Structure Formation**

The "hubs" of cosmic matter network



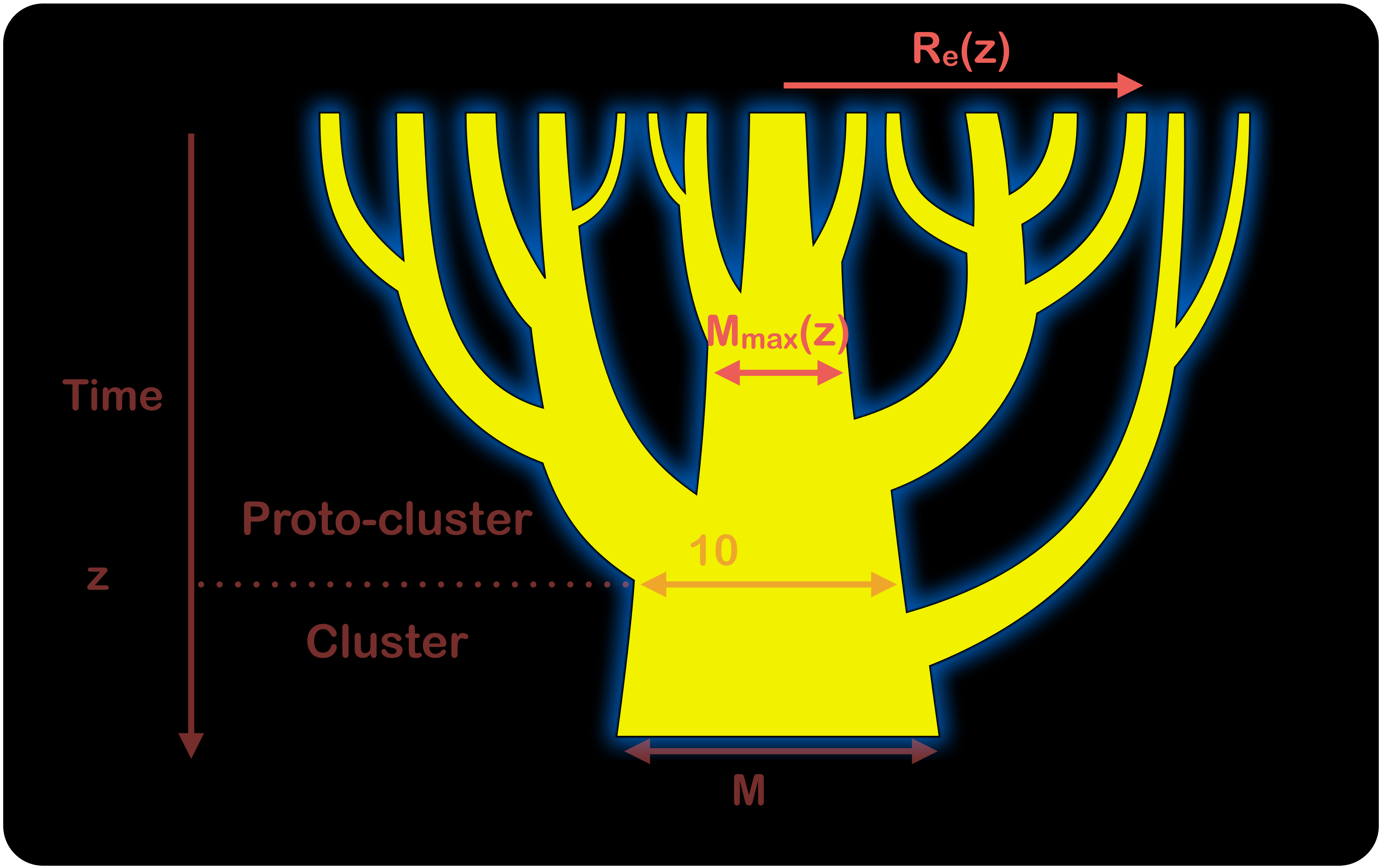
The "hubs" of cosmic matter network

(see Chiang+13)



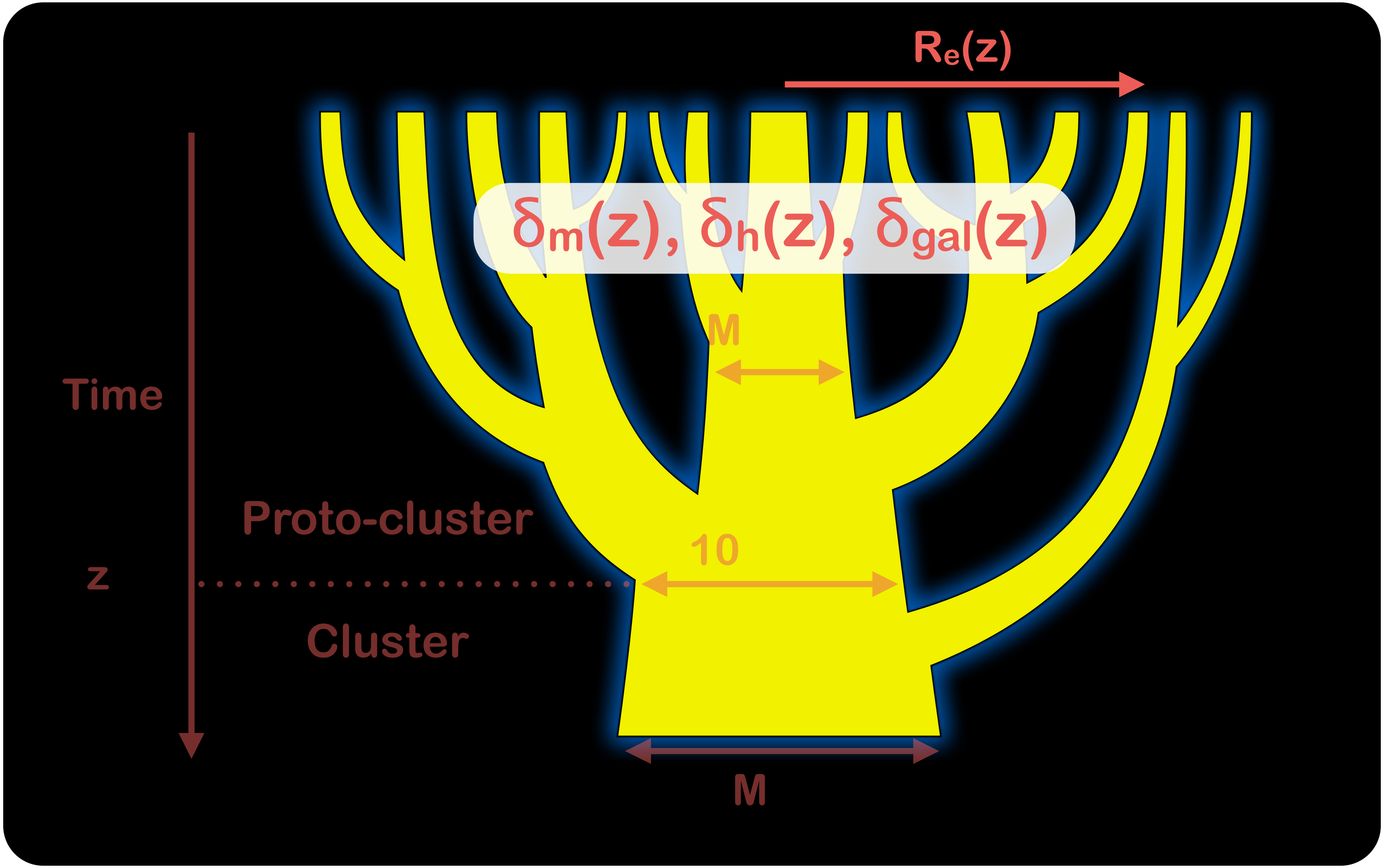
The "hubs" of cosmic matter network

(see Chiang+13)



The "hubs" of cosmic matter network

(see Chiang+13)



Chiang+13

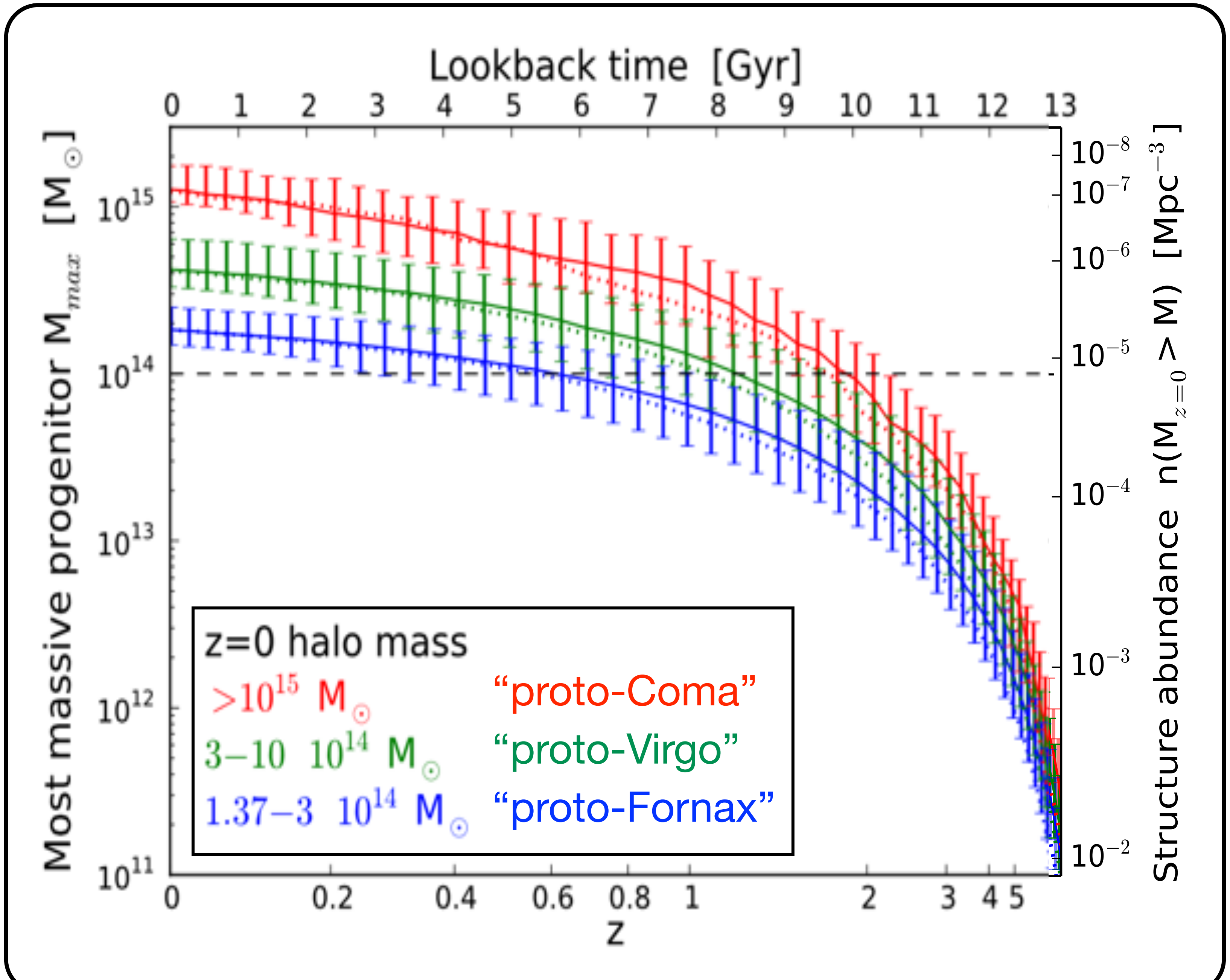
Simulation Predictions of the Model Parameters as a Function of z and $M_{z=0}$

Sample:

2832 Clusters in the MR (Springel+05, Guo+13) and SAM (Guo+11, 13)

Simulation Predictions :

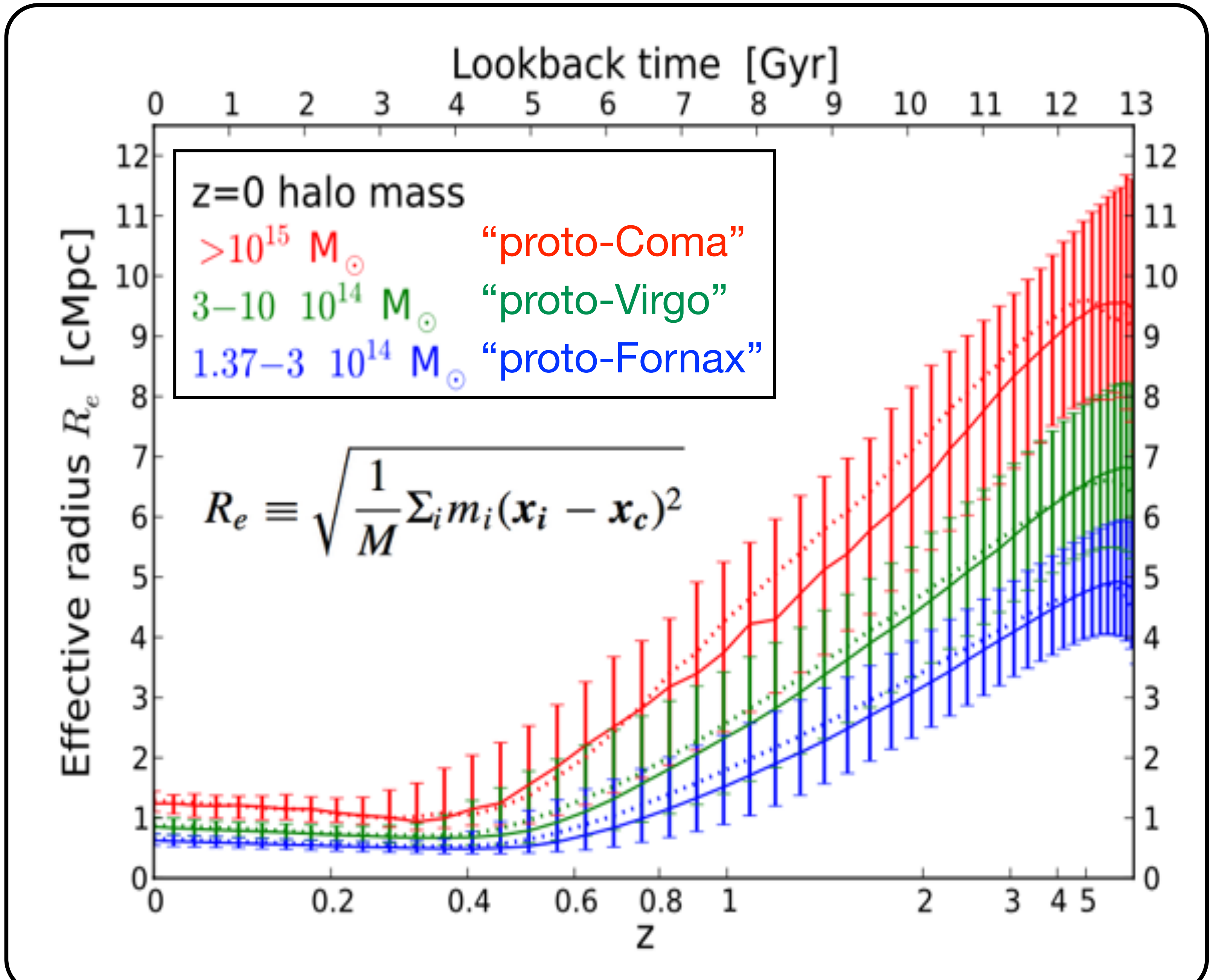
Core Mass Growth $M_{max}(z)$



- ~10x growth from z=2 to z=0
- First clusters (10^{14} $M_\odot$) formed at z=2 and evolve to "Coma" (10^{15} $M_\odot$) at z=0
- Small (< 0.1 dex) difference between WMAP1 (solid) & WMAP7 (dotted lines)

Chiang+13

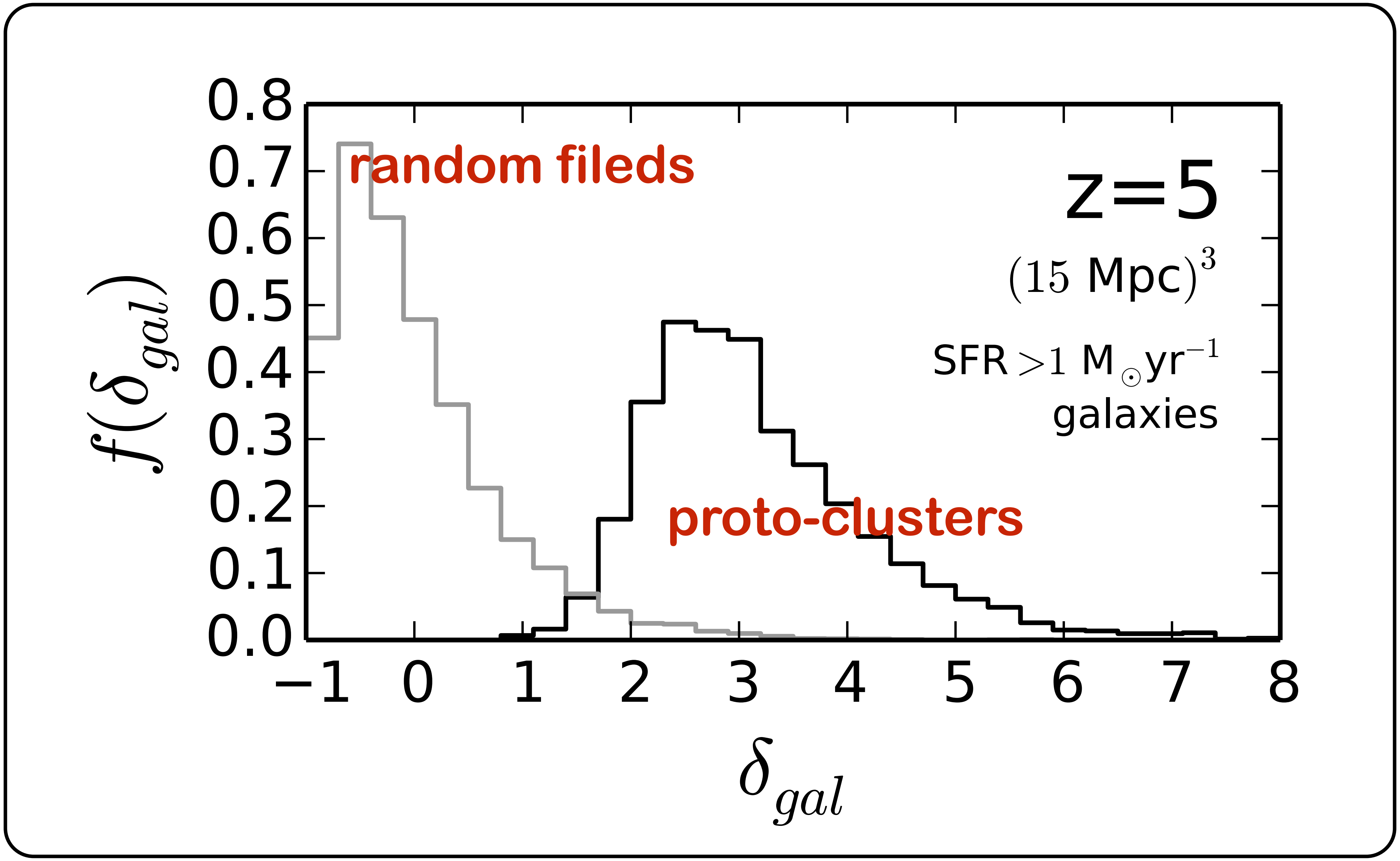
Simulation Predictions : Size Growth $R_e(z)$



- **R_e increases strongly with increasing z and $M_{z=0}$**
- **The actual boundary of proto-clusters ~ 1.5–2 R_e**
- **D ~ 15 arcmin at z ~ 2 — Need wide field instruments**

Chiang+13

Indeed, Proto-clusters ≈ Large-scale Galaxy Overdensity



Chiang+13

Part II

Small-scale / bottom-up view —

2. **Galaxy formation using proto-clusters as laboratories**

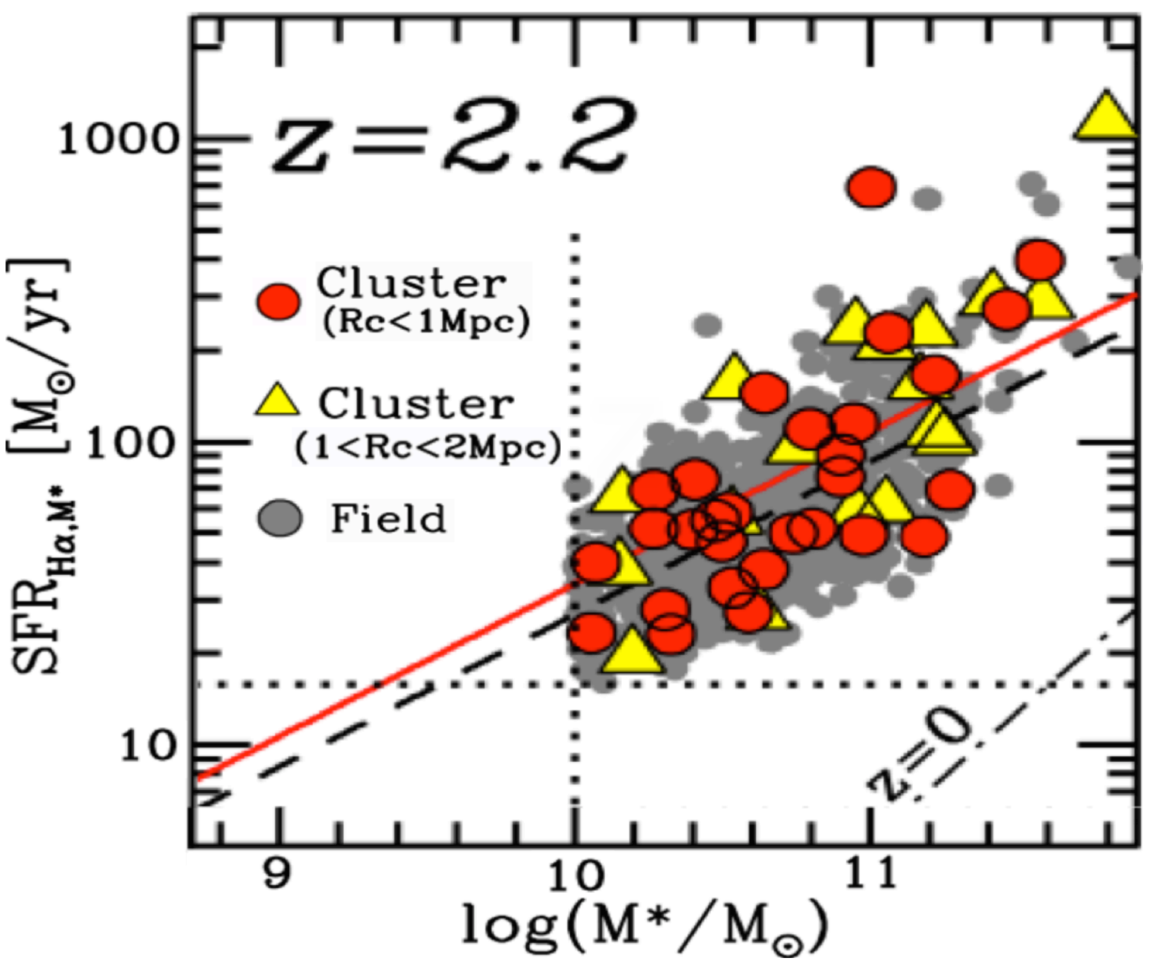
Member Galaxies Experience an Extreme Life Cycle

Fast Early Growth Followed by Strong Quenching

Proto-cluster | **cluster**

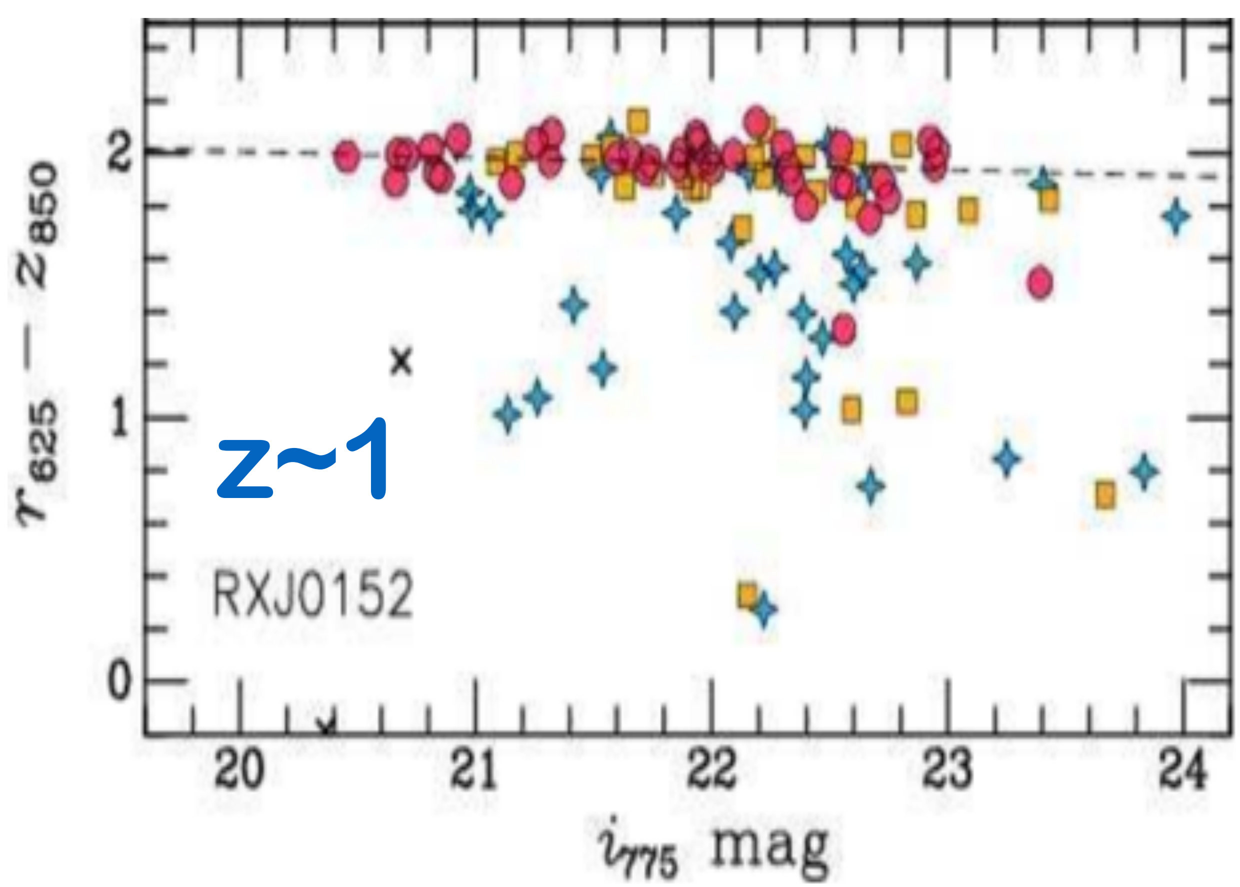
SF

(and/or star-burst phase? e.g., casey+15)



Koyama+13

Red-sequence

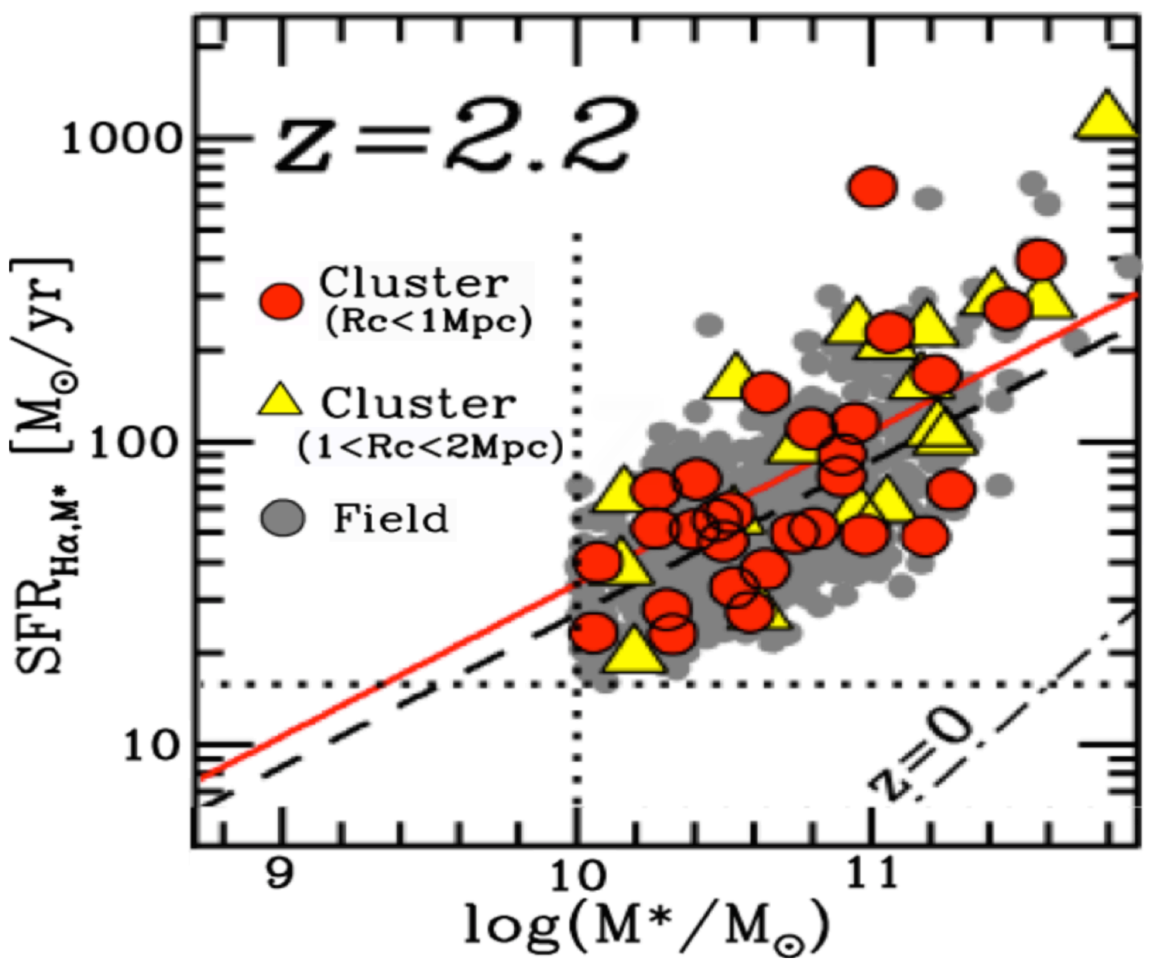


Blakeslee+06

Quenching Must Happen in (Proto-)clusters

Proto-cluster

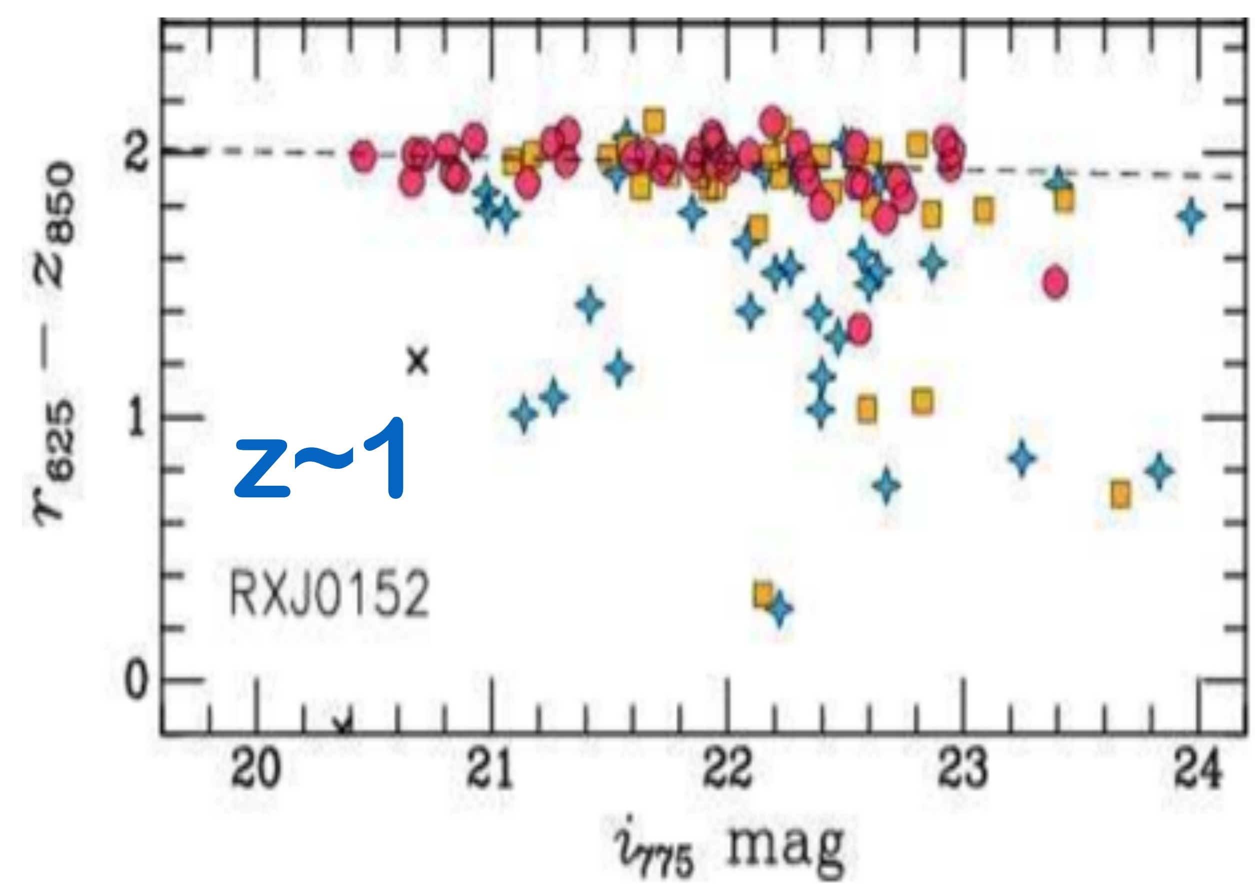
SF
(and/or star-burst phase? e.g., casey+15)



Koyama+13

cluster

Red-sequence



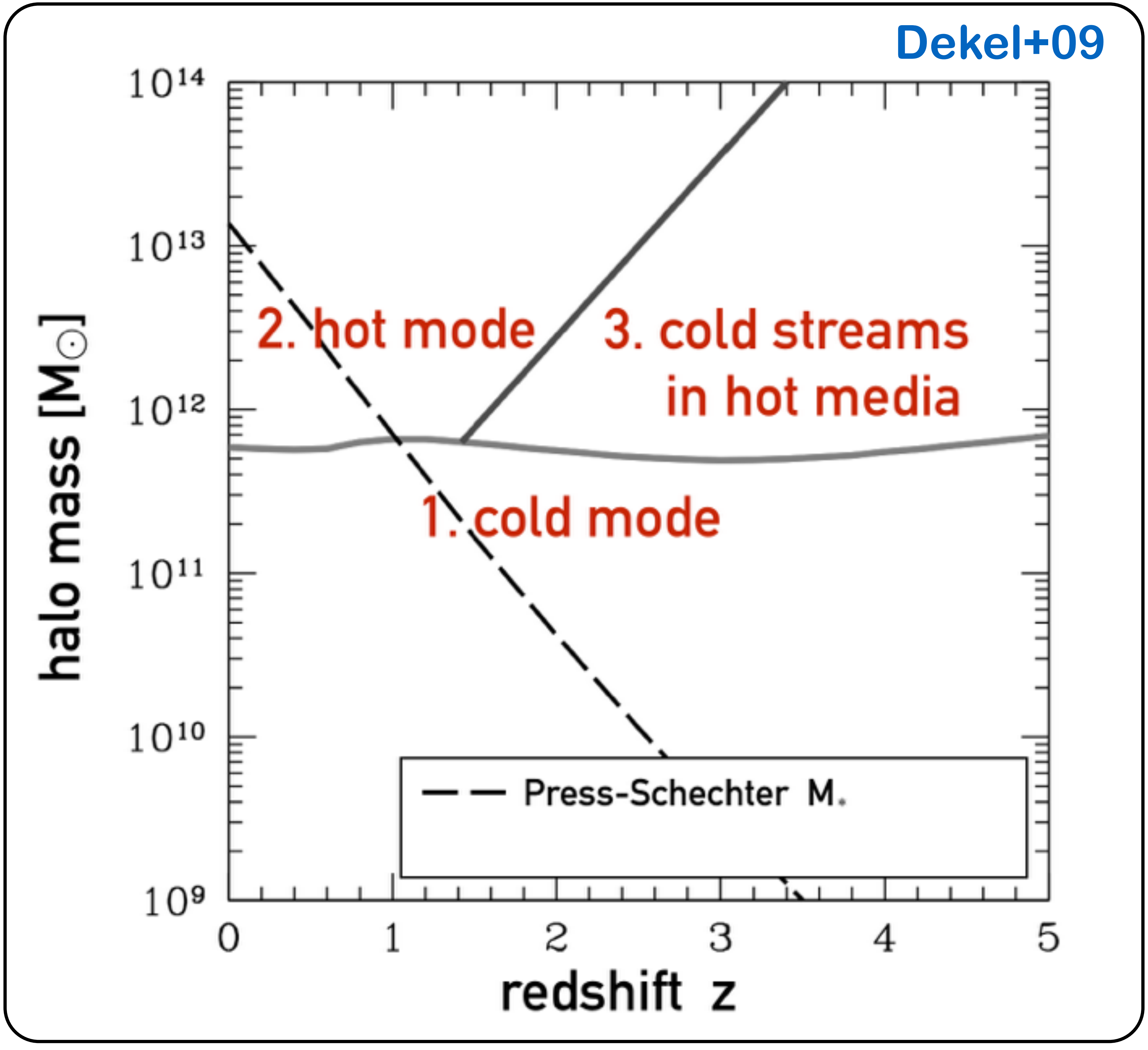
Blakeslee+06

Largely Reduced Galaxy Progenitor Bias via Their Connection to Cluster Evolutionary Path

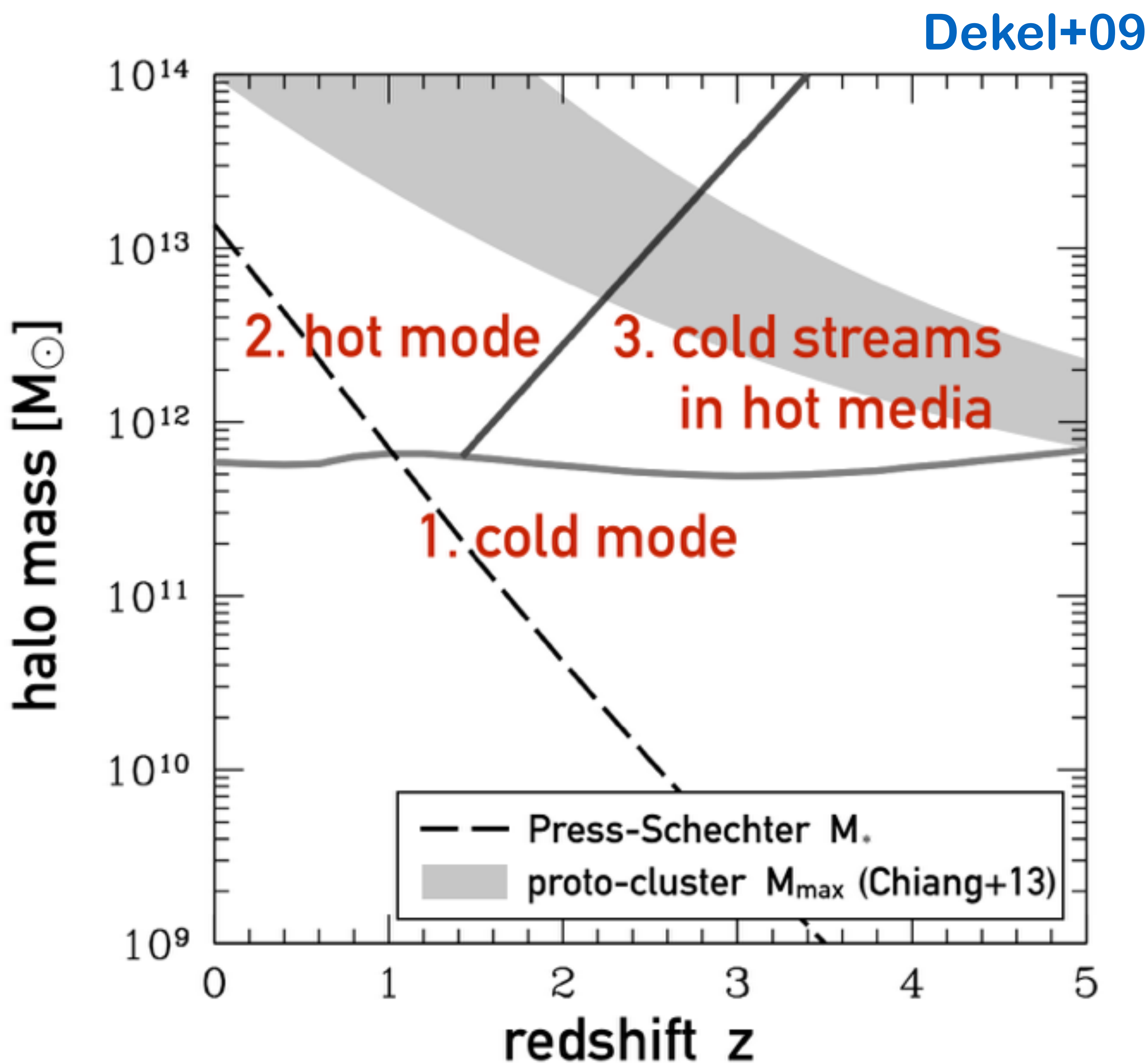
Ideal Regions to Study Two Long-hypothesized Physical Drivers of Galaxy Growth —

1. Galaxy Mergers
2. Cosmic Cold Gas Accretion

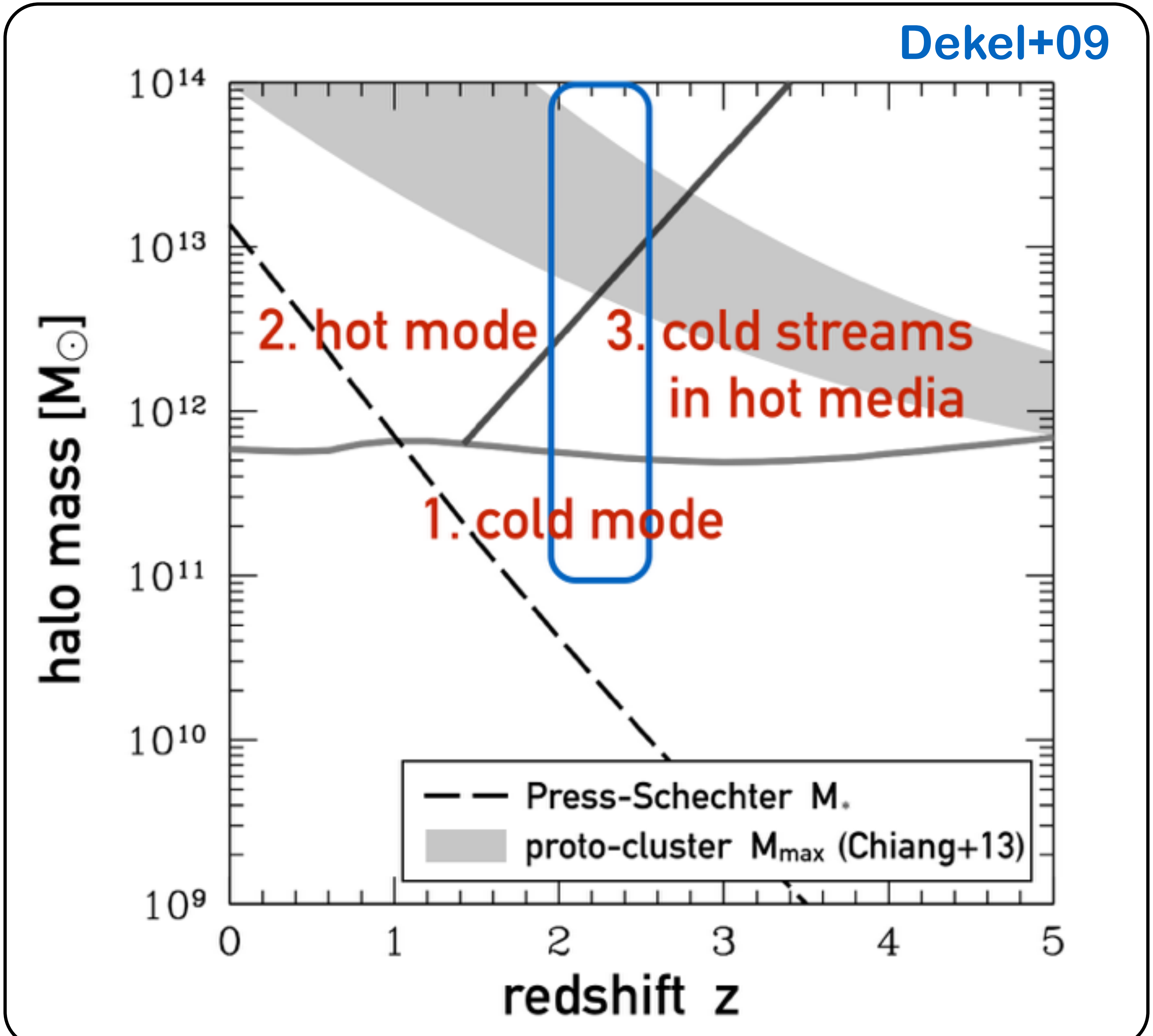
Gas Accretion & Cooling in Different Regimes



Gas Accretion & Cooling in Different Regimes

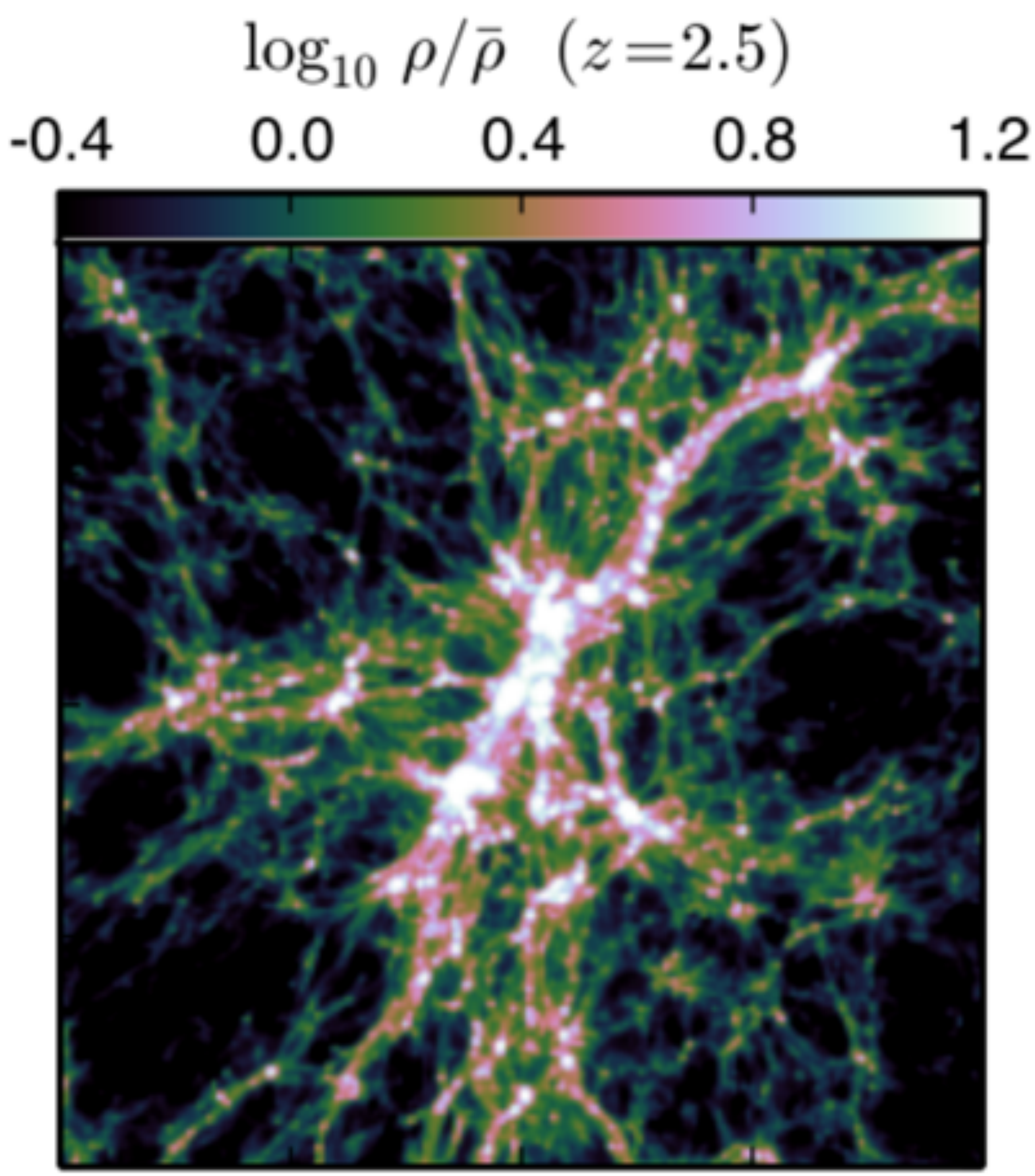


PCs at Cosmic Noon Host Coeval Halos of all 3 Modes

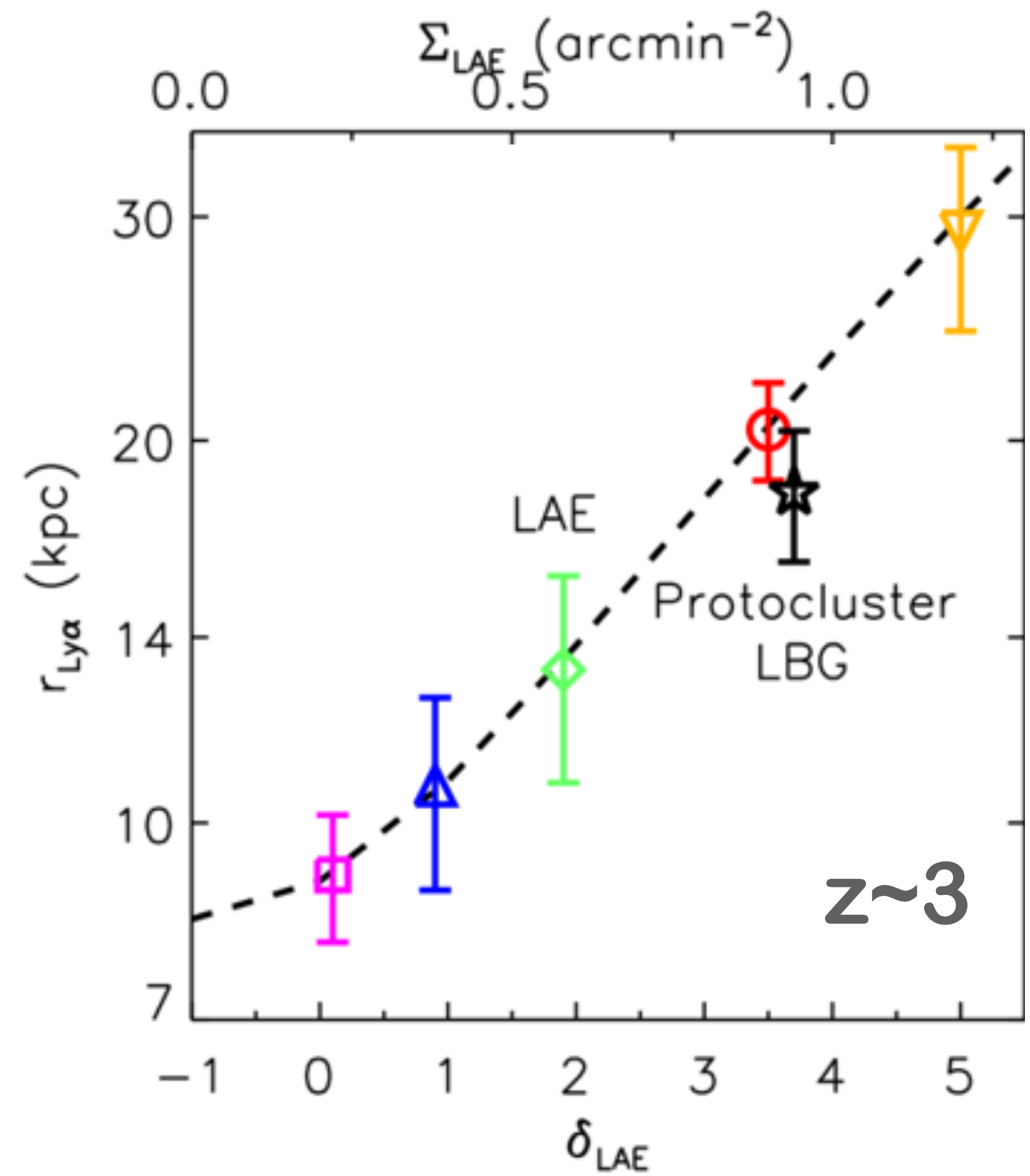


Environment Study at High-z is Extremely Challenging

Example: Lya Blobs vs Environment



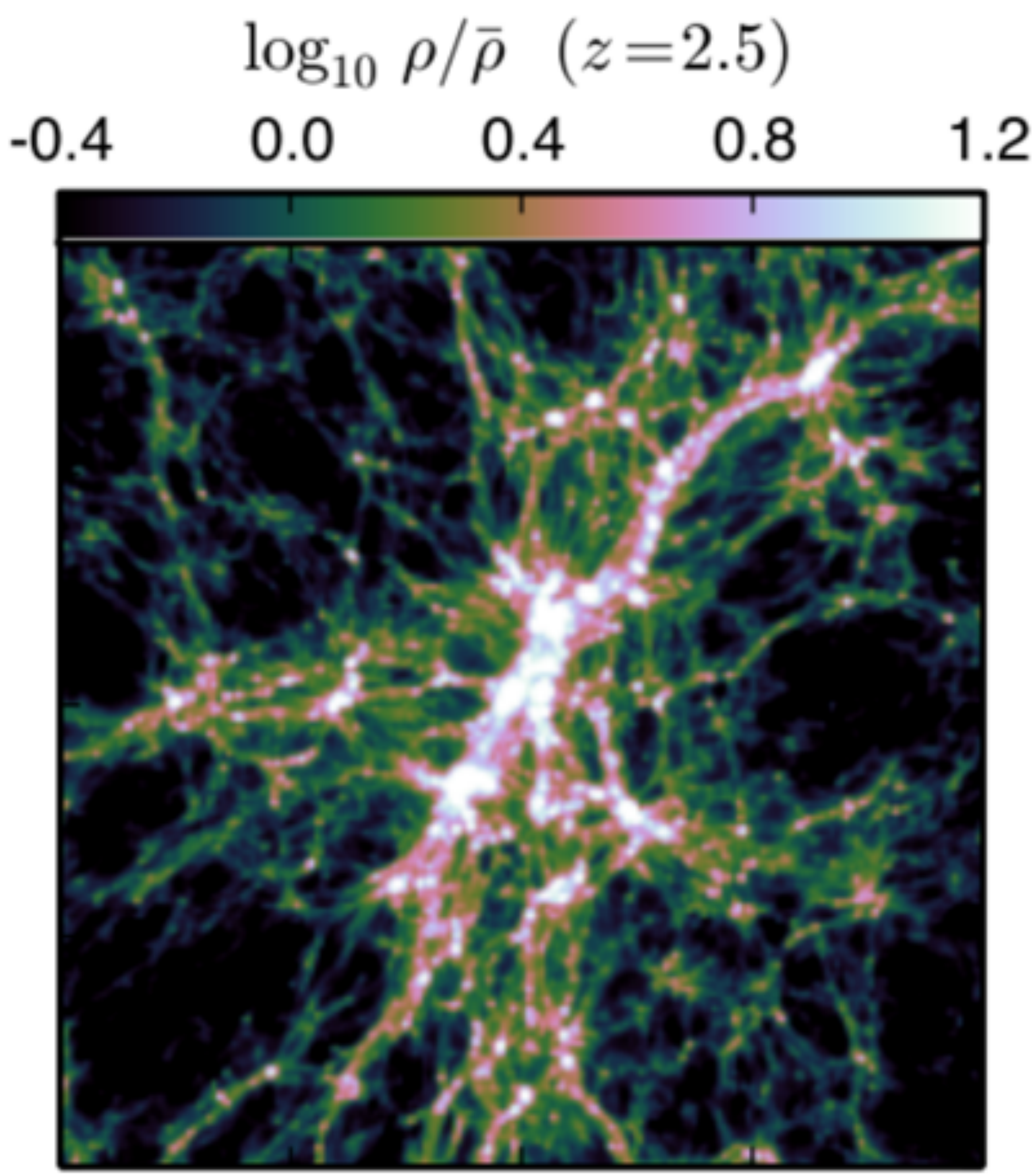
Stark+14



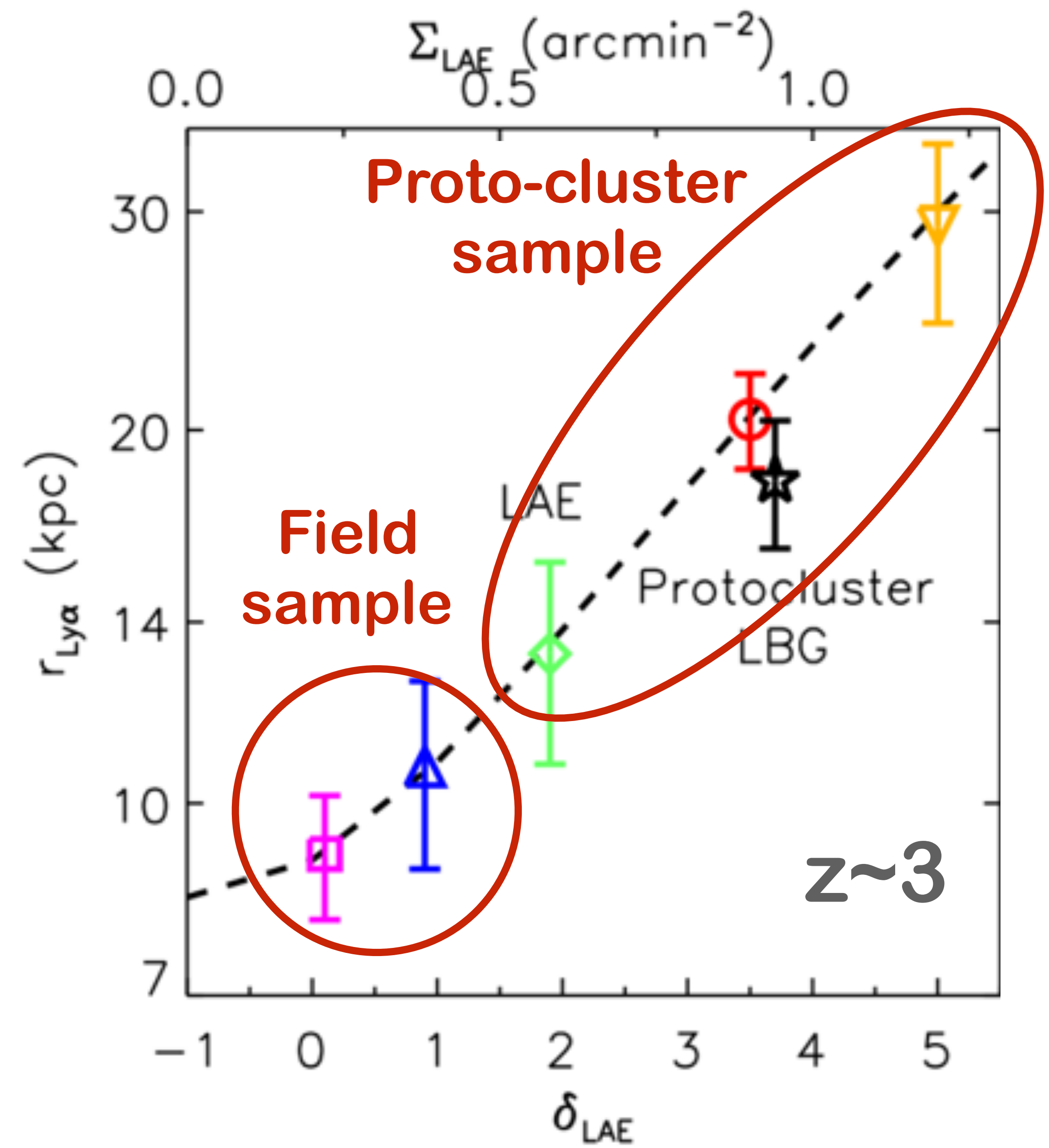
Matsuda+12

Environment Study at High-z is Extremely Challenging —
Proto-clusters Largely Extends the Dynamic Range

Example: Lya Blobs vs Environment



Stark+14



Matsuda+12

Part III

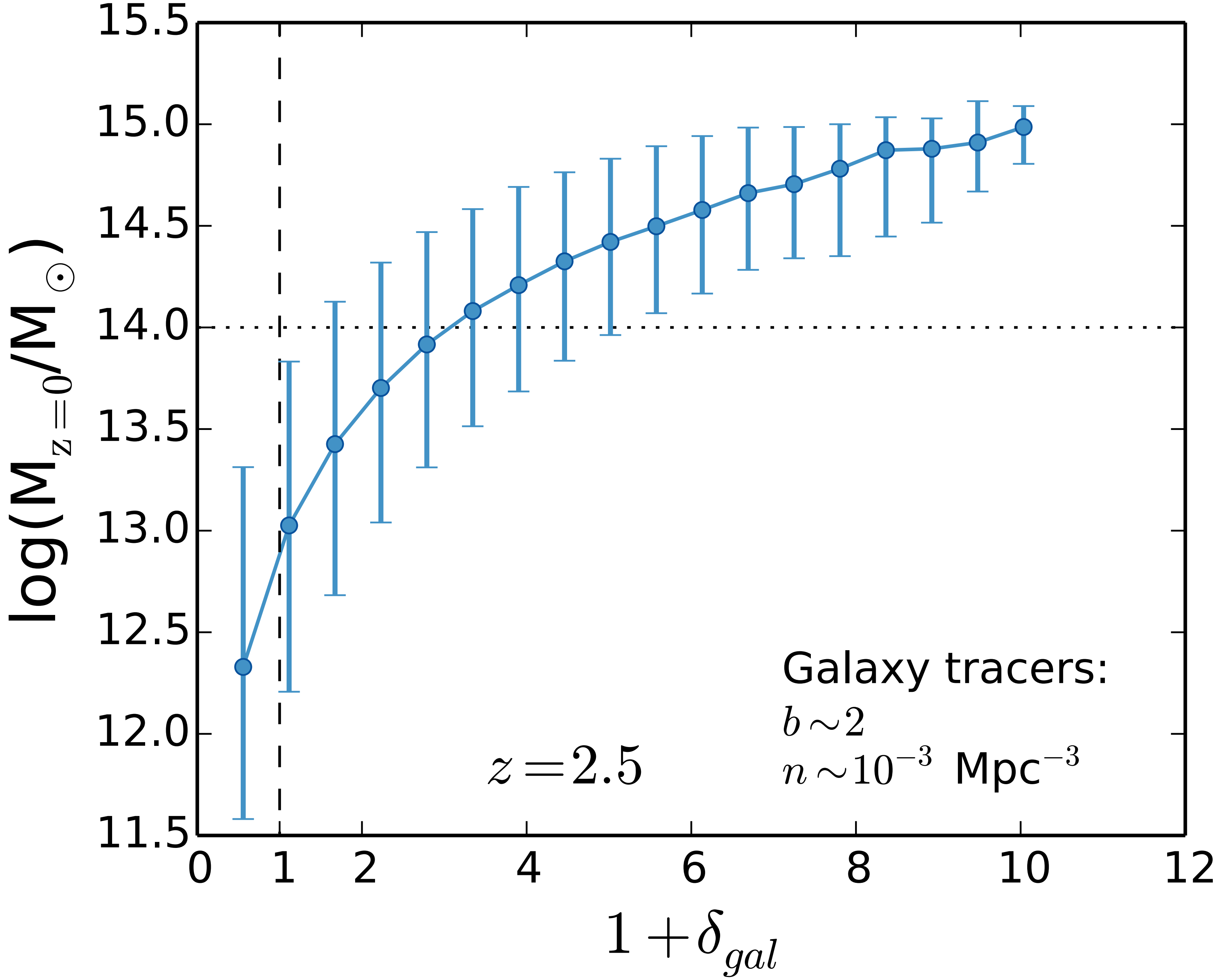
3. Constructing statistical samples of proto-clusters at z ~ 2

- Photo-z (COSMOS)
- Spec-z follow-up (KMOS, GMOS, FMOS…)
- Emission line galaxy survey (HETDEX)

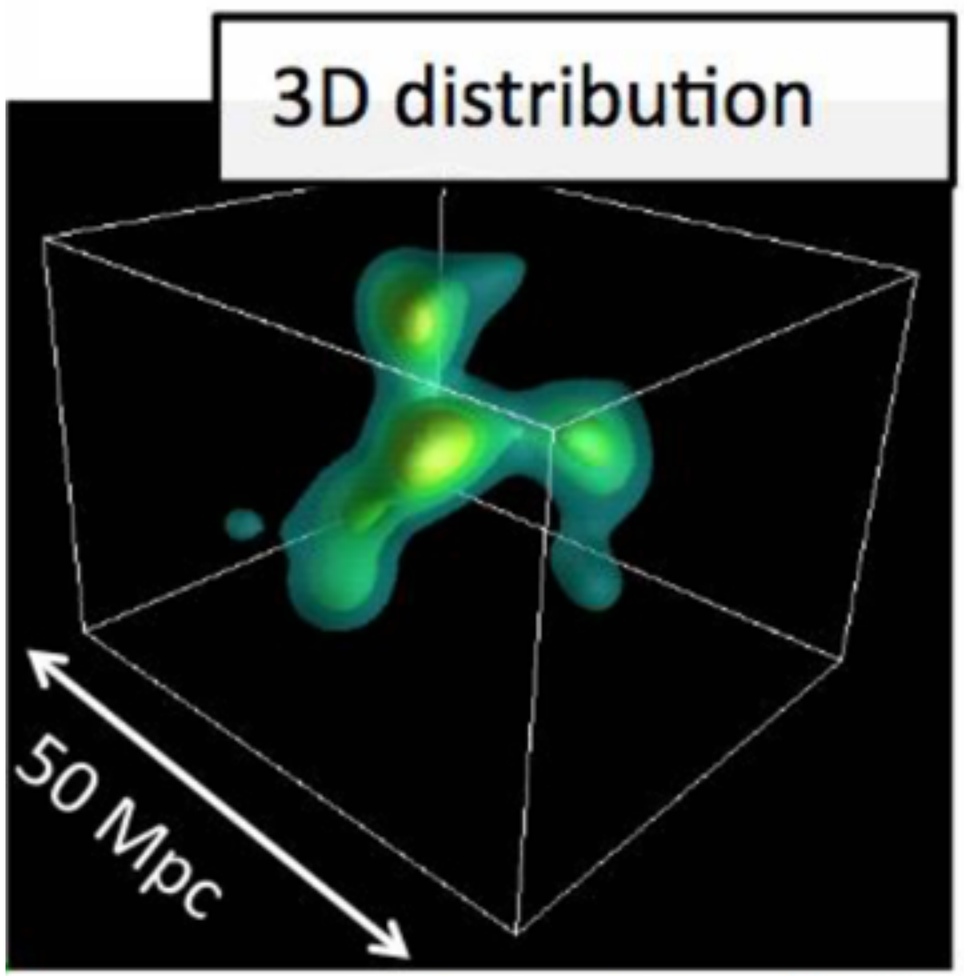
$M_{z=0}$ — δ_{gal} Relation

Simply mass conservation in Lagrangian volume

Chiang+13, 15



SSA22

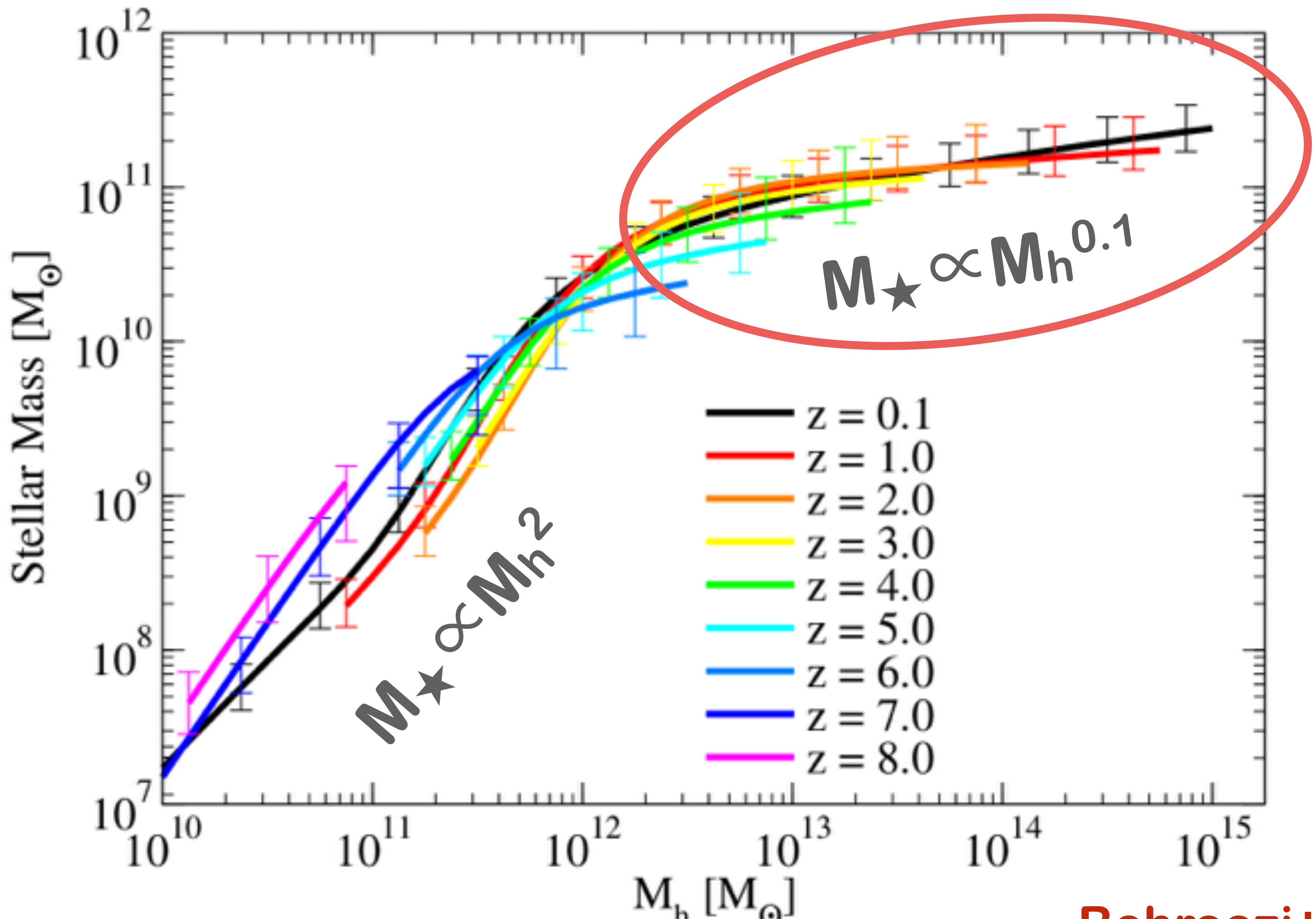


Steidel+98, Matsuda+05

10-20 cMpc (effective-diameter) scale galaxy overdensity

In contrast, it's impractical to get $M_{z=0}$ using single halo $M_{max}(z)$ via SMHM

0.3 dex error in M_{star} prop. to 3 dex uncertainty in M_h



Behroozi+13

Strategies for Proto-cluster Searches

1. Wide field surveys for rare structures, each 10+ arcmin across
2. Precise redshifts to suppress line-of-sight projection effects
3. Highly biased tracers are not necessary
4. A high tracer number density is needed to suppress the Poisson shot noise
5. Selection function in 3D space…

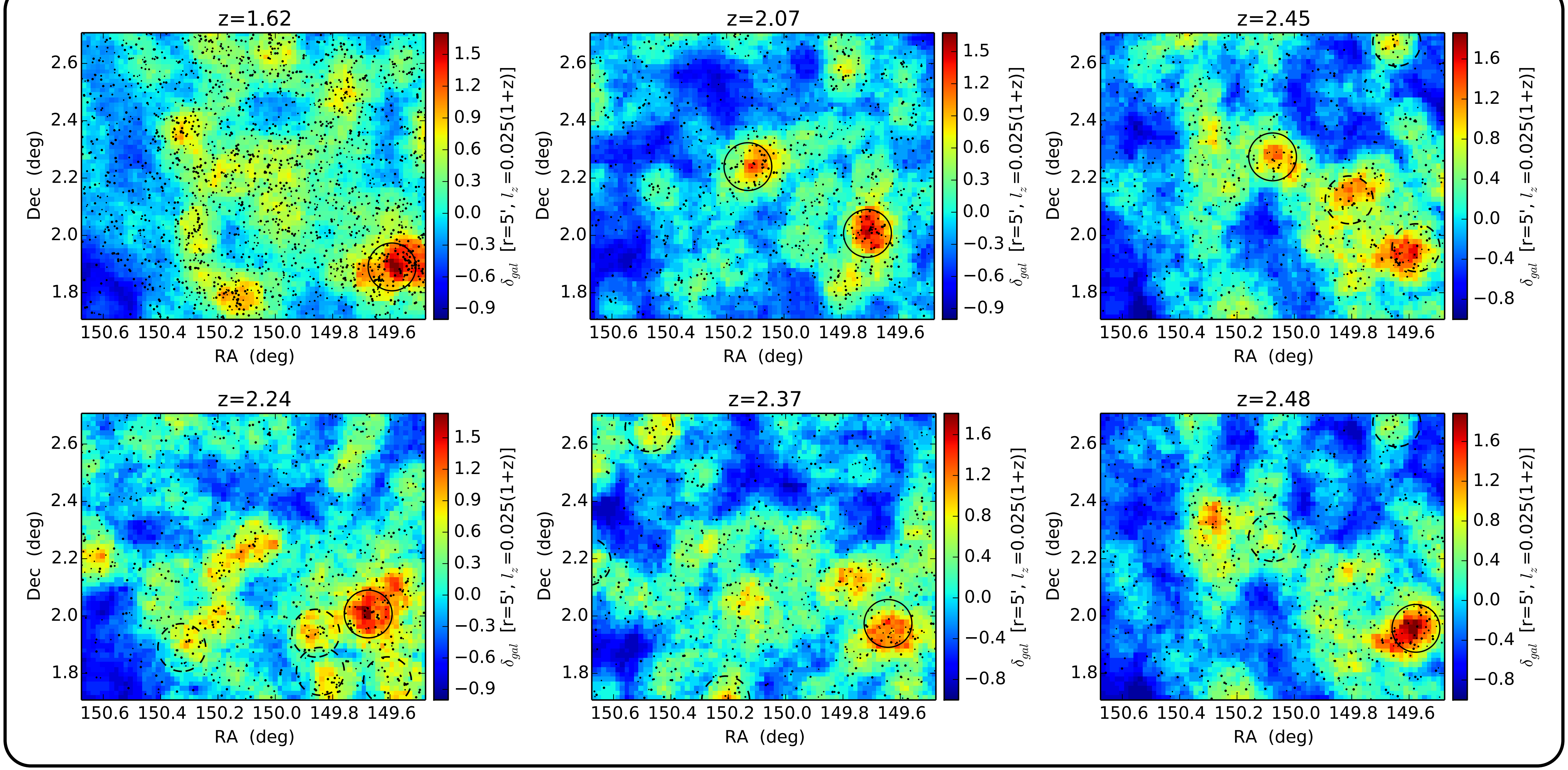
Building a Statistical Sample of Proto-clusters with High Data Quality/Homogeneity in COSMOS — Photo-z

Chiang, Overzier, & Gebhardt 2014

1. Large enough volume to contain >100 proto-clusters at $2<z<3$
2. High quality photo-z to select proto-clusters
3. Rich multiwavelength photometry to study galaxy population

36 proto-cluster candidates (70% confidence) in COSMOS

Chiang, Overzier, & Gebhardt 2014



- Recovers 2 previously known structures
- First statistical sample with high data quality and homogeneity
- Great potential for galaxy formation studies

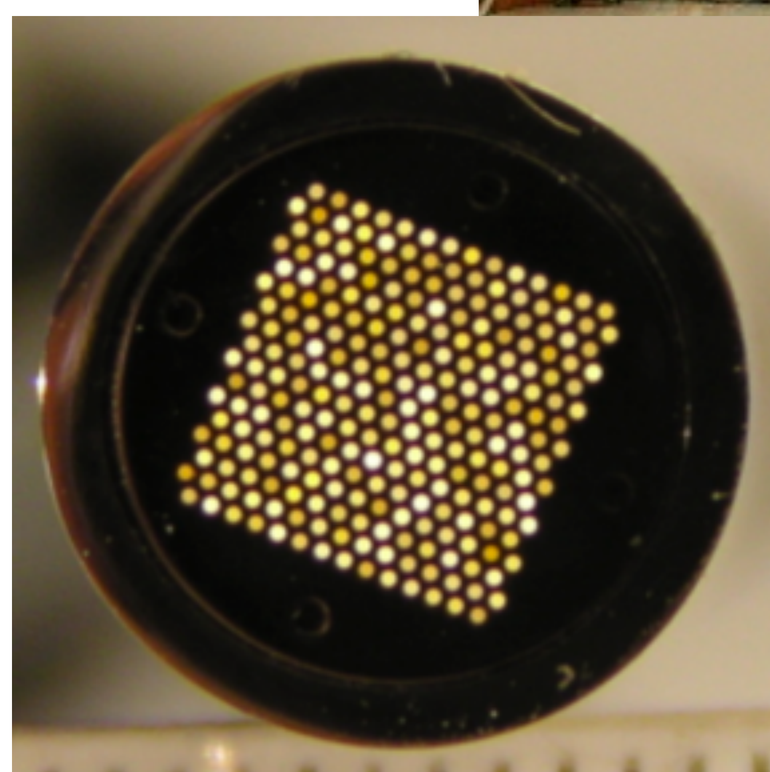
HETDEX Pilot Survey (HPS) Adams+11

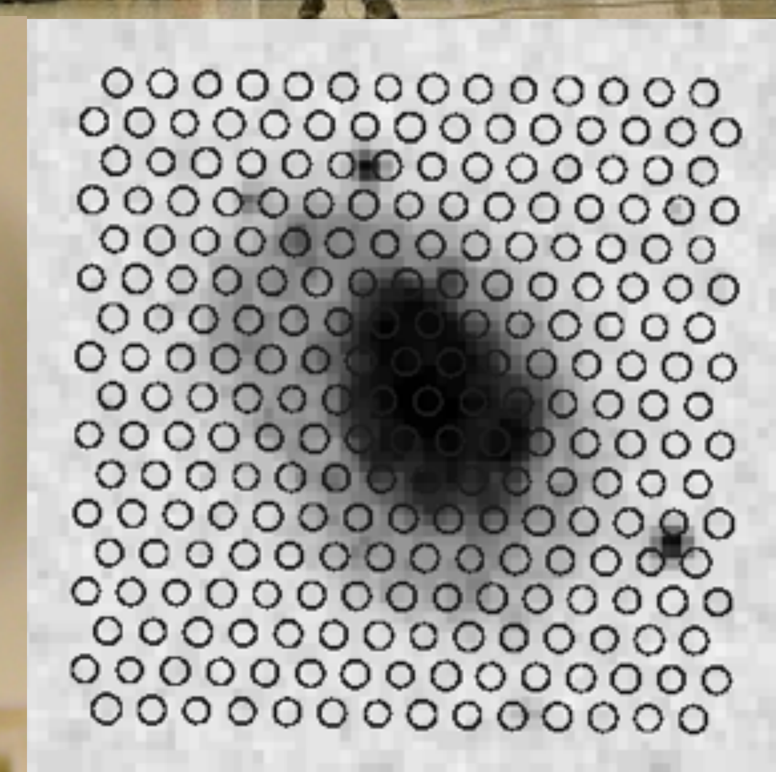
IFU Blind Spectroscopy

Highly Homogenized Selection Function in 3D

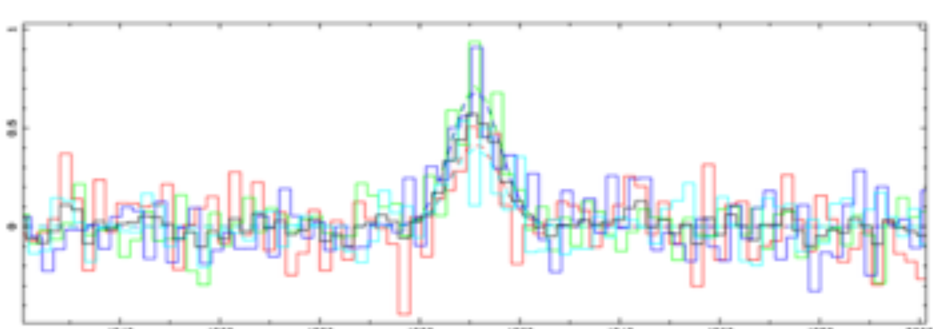
2.7m Harlan J. Smith Telescope

246 Fibers (4”)
1.7 x 1.7 arcmin^2 FoV





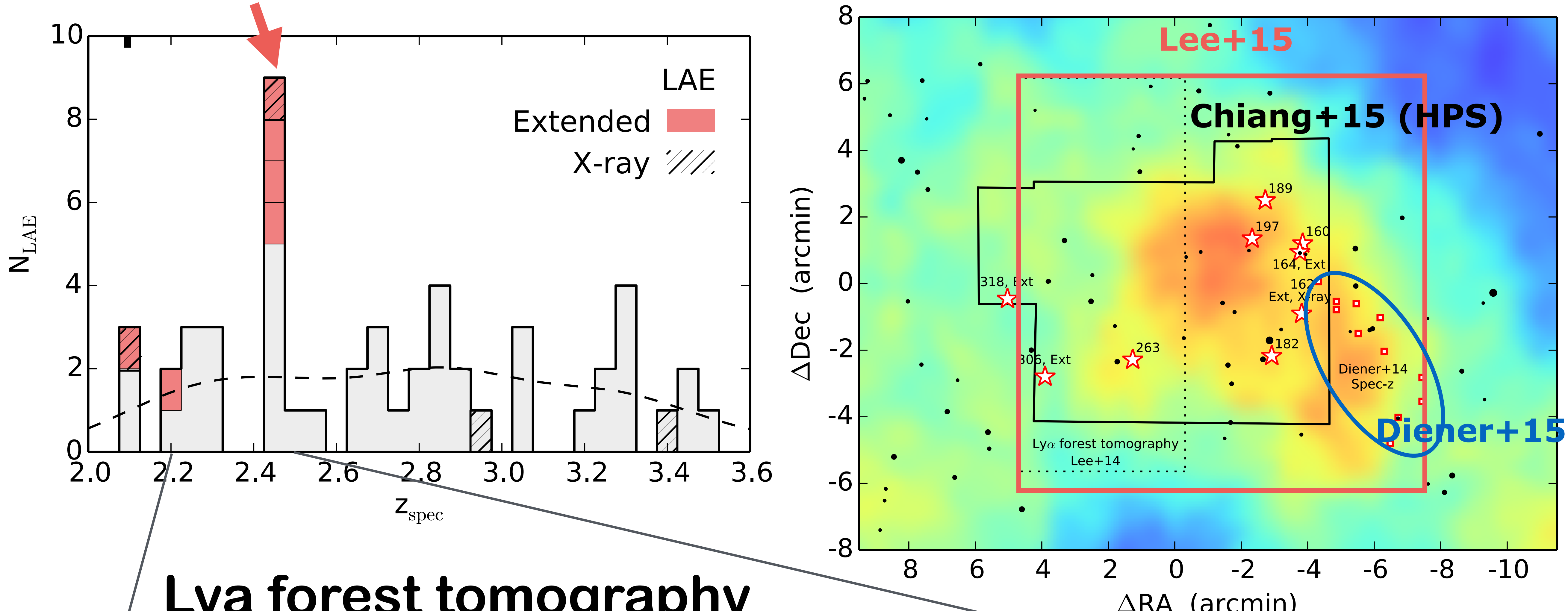
Lya emitters at 1.9 < z < 3.8



A proto-Virgo at z=2.44 with extreme overdensities in LAEs, Lya Blobs, LBGs, and extended neutral IGM

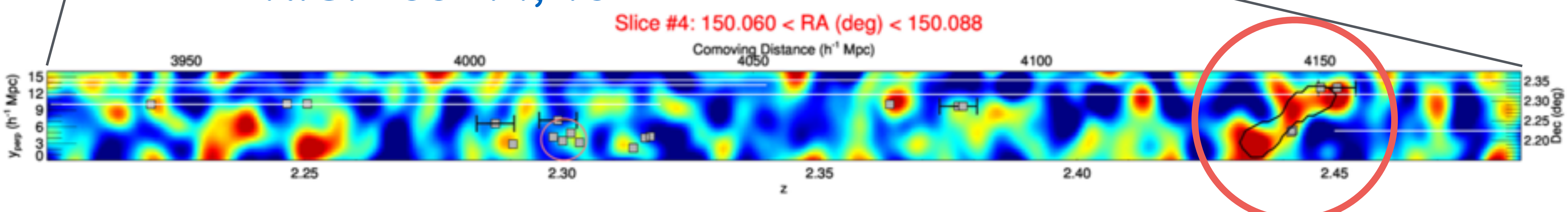
LAEs in HPS-COSMOS

Chiang+15



Lya forest tomography

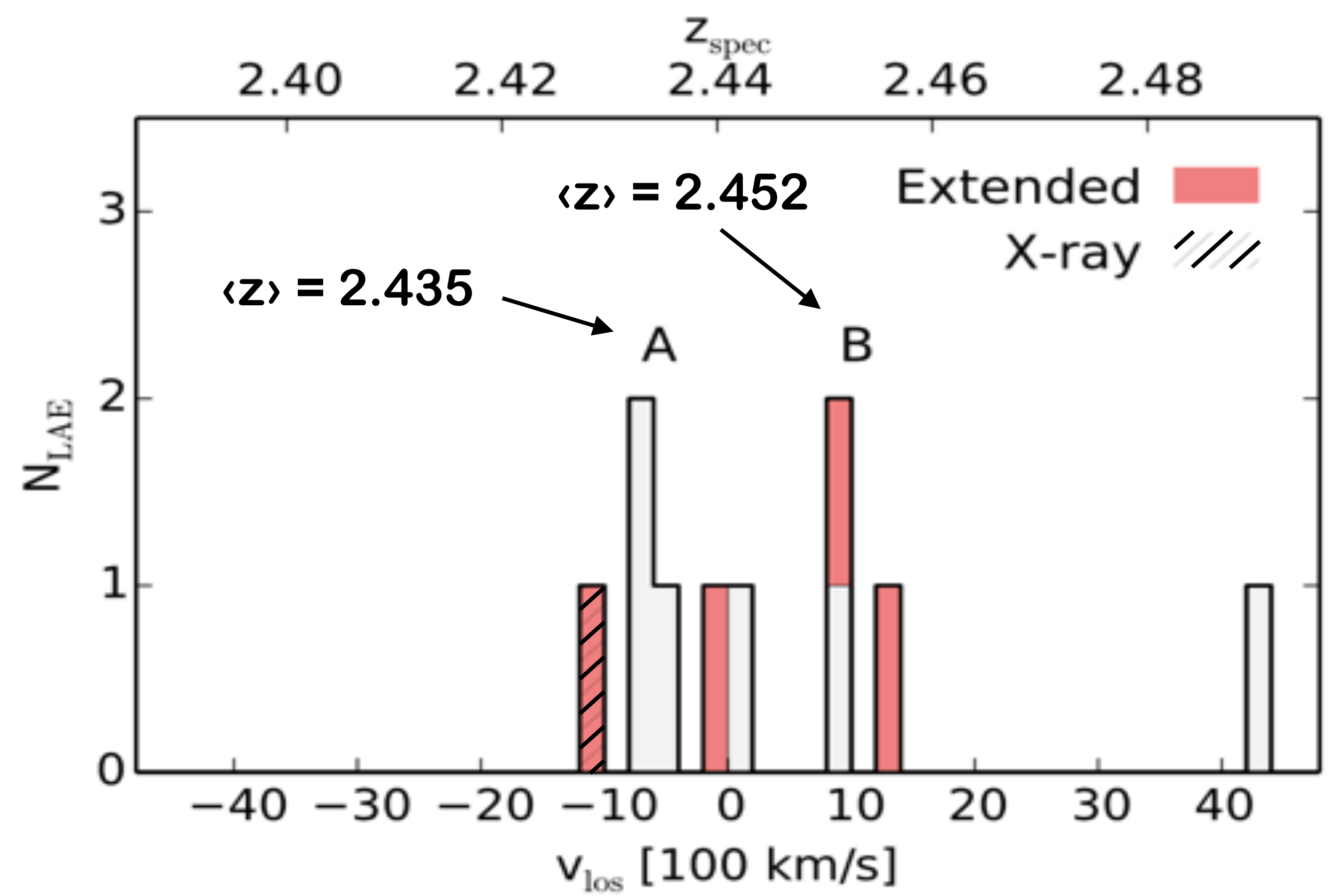
K.G. Lee+14, 15



LAE, LAB

HETDEX Pilot
Chiang+15

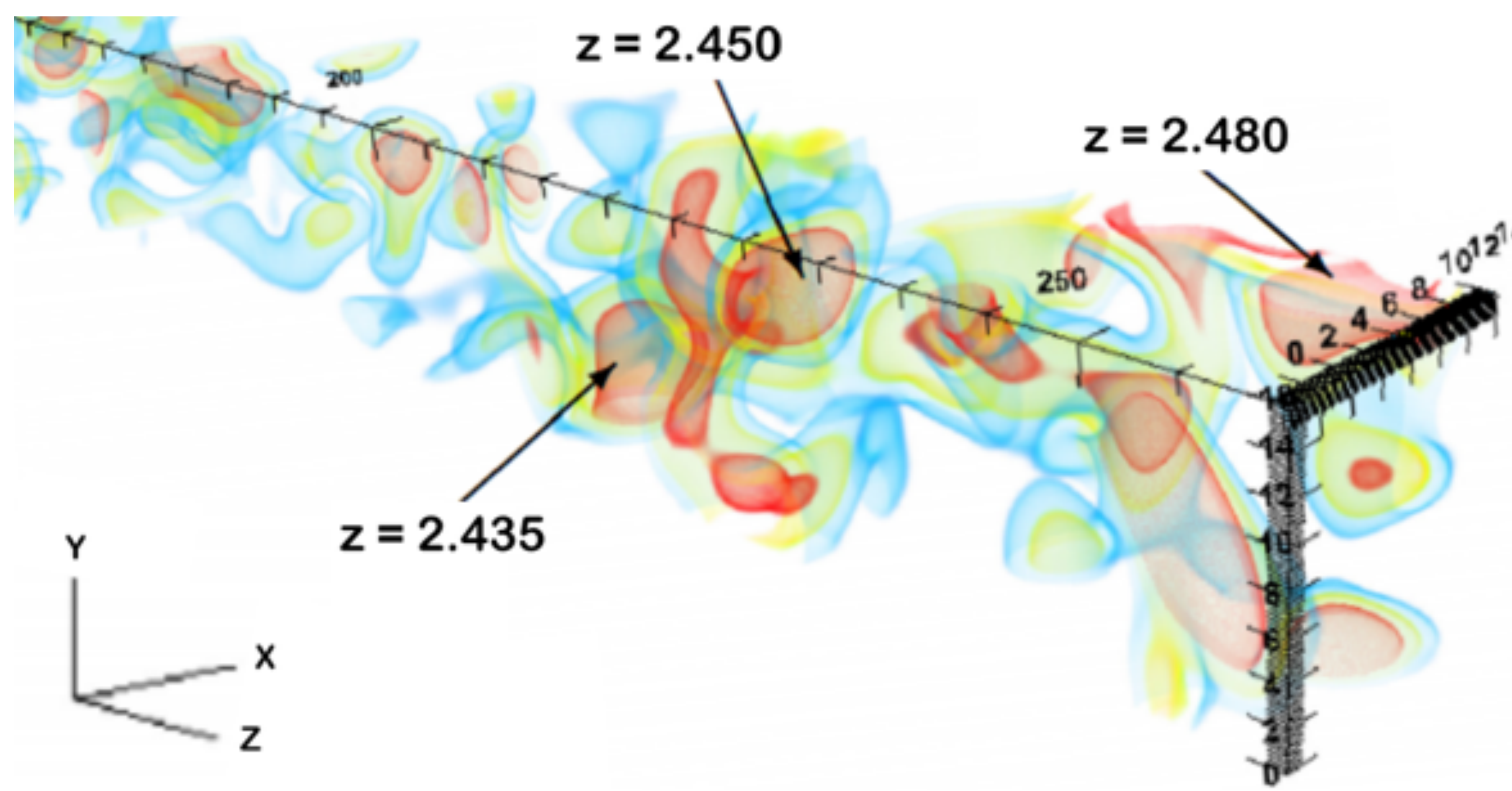
$\log M_{z=0} = 14.5\ ^{+0.4}_{-0.4}$

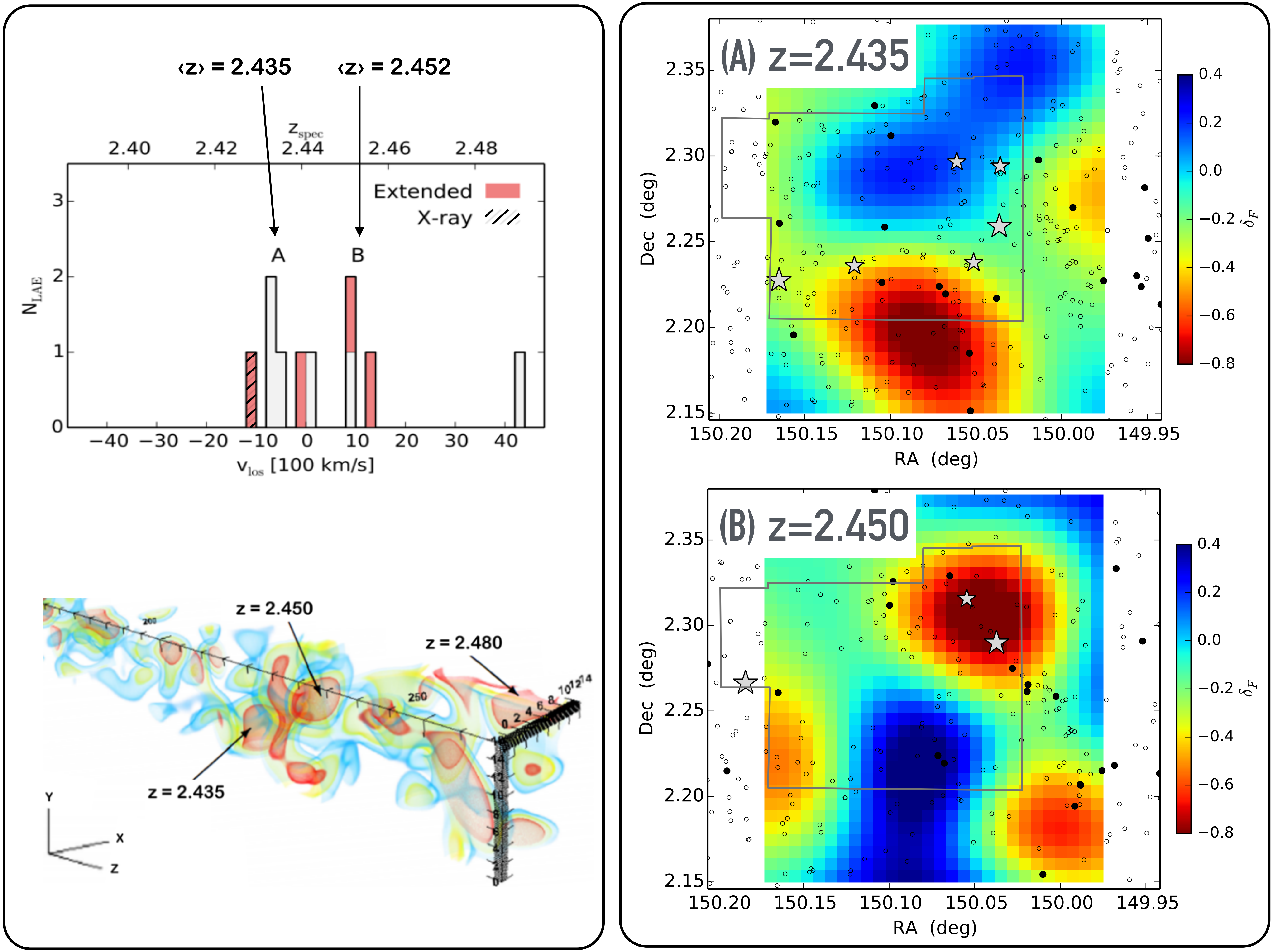


IGM

CLAMATO
Lee+15

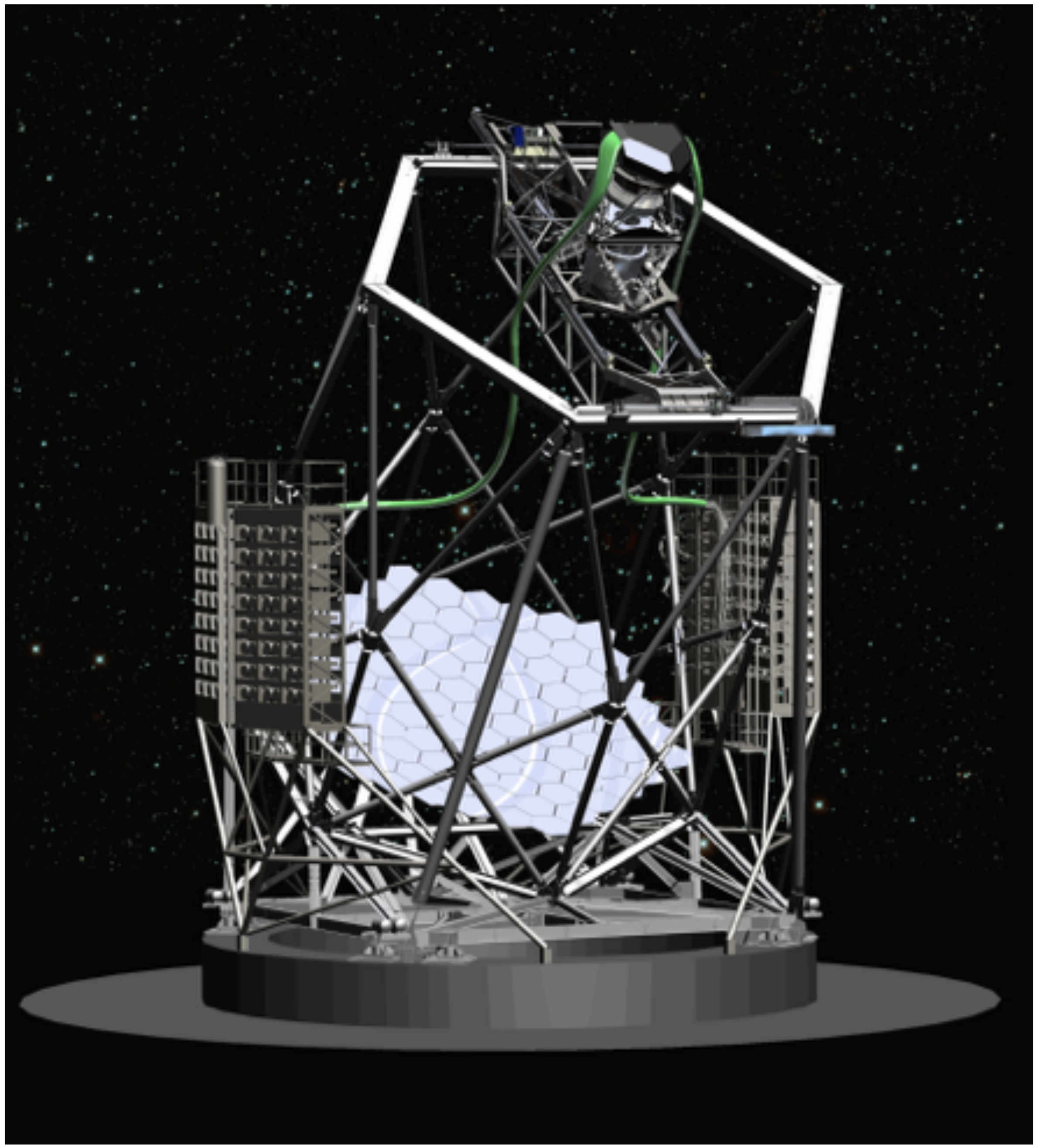
$\log M_{z=0} = 14.5\ ^{+0.2}_{-0.5}$





‹z› = 2.435
‹z› = 2.452
z_{spec}
2.40
2.42
2.44
2.46
2.48
Extended
X-ray
A
B
N_{LAE}
0
1
2
3
−40
−30
−20
−10
0
10
20
30
40
v_{los} [100 km/s]
z = 2.450
z = 2.480
z = 2.435
Y
X
Z
(A) z=2.435
(B) z=2.450
Dec (deg)
RA (deg)
2.35
2.30
2.25
2.20
2.15
150.20
150.15
150.10
150.05
150.00
149.95
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
δ_F

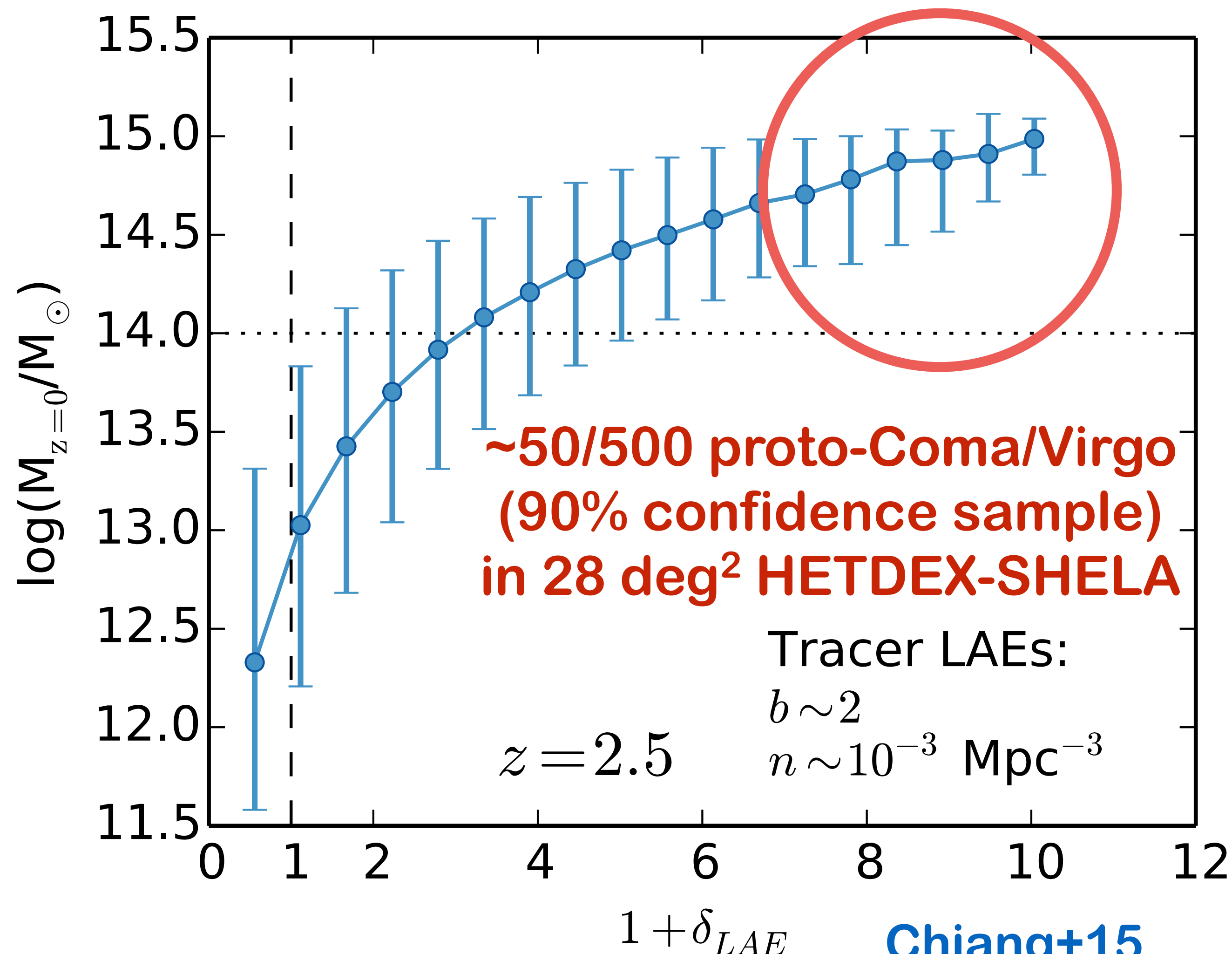
Hobby-Eberly Telescope Dark Energy Experiment (HETDEX)



~10^6 LAEs at $2 < z < 3.5$

$L_{Lya} > 2x10^{42}$ erg/s

Mock presented in Chiang+15



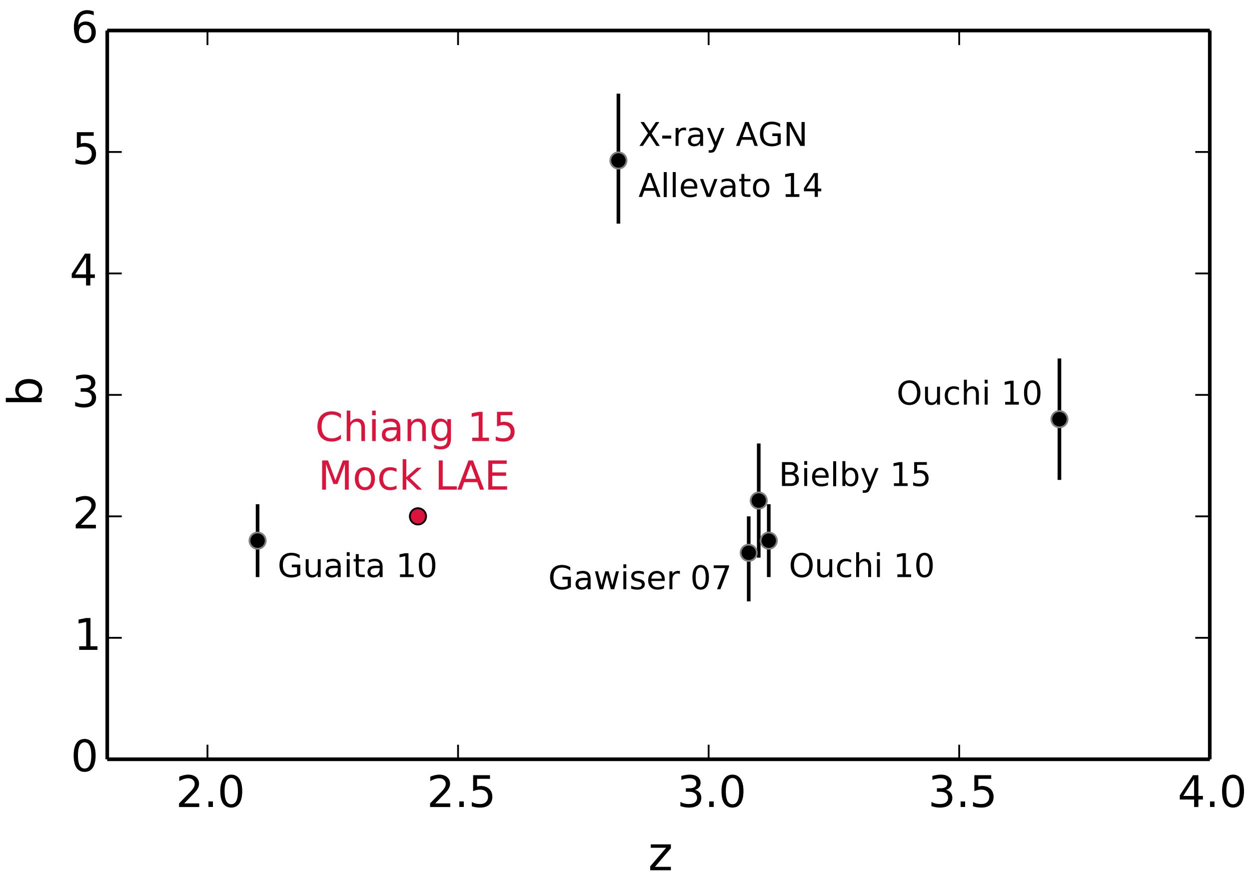
Chiang+15

THE UNIVERSITY OF TEXAS AT AUSTIN · McDonald Observatory · LMU USM · AIP · MPE · TEXAS A&M · PENNSTATE · INSTITUT FÜR ASTROPHYSIK GÖTTINGEN · UNIVERSITY OF OXFORD · NSF · MAX-PLANCK-GESELLSCHAFT

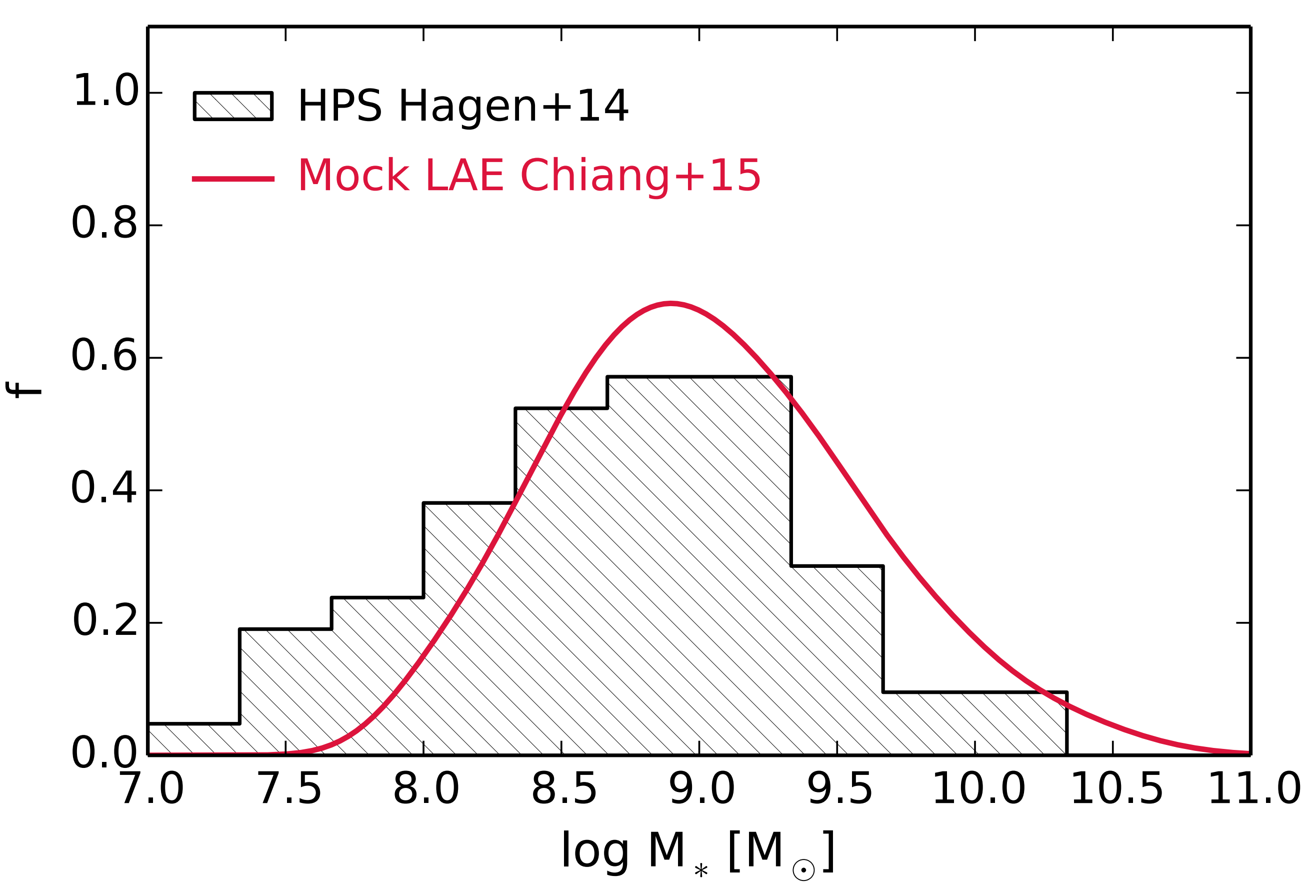
Mock LAE Catalogs in Chiang+15 — post-processed SAM

A mature tool to interpret large-scale structures

Bias

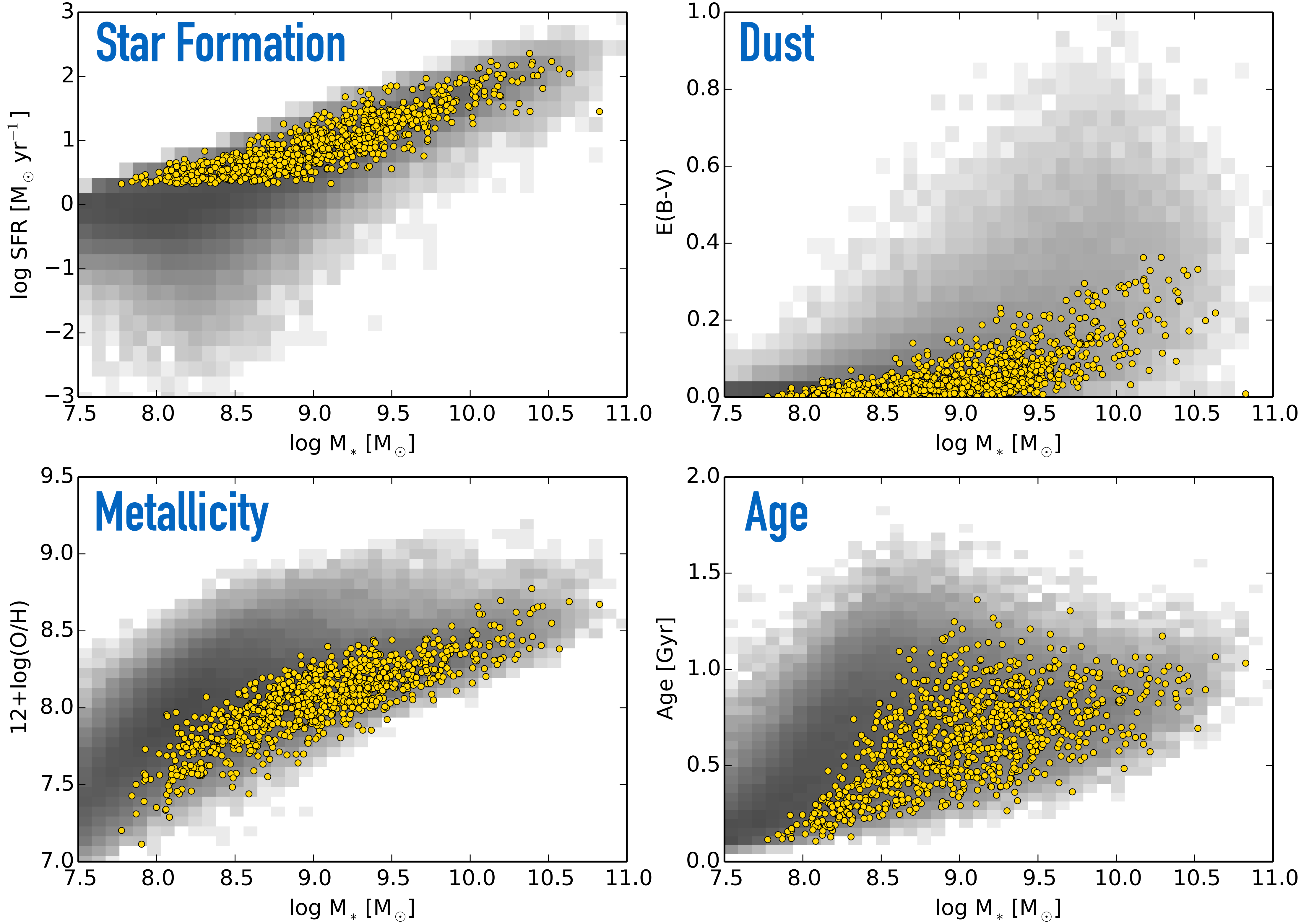


$M_\star$ — the scatter of the bias

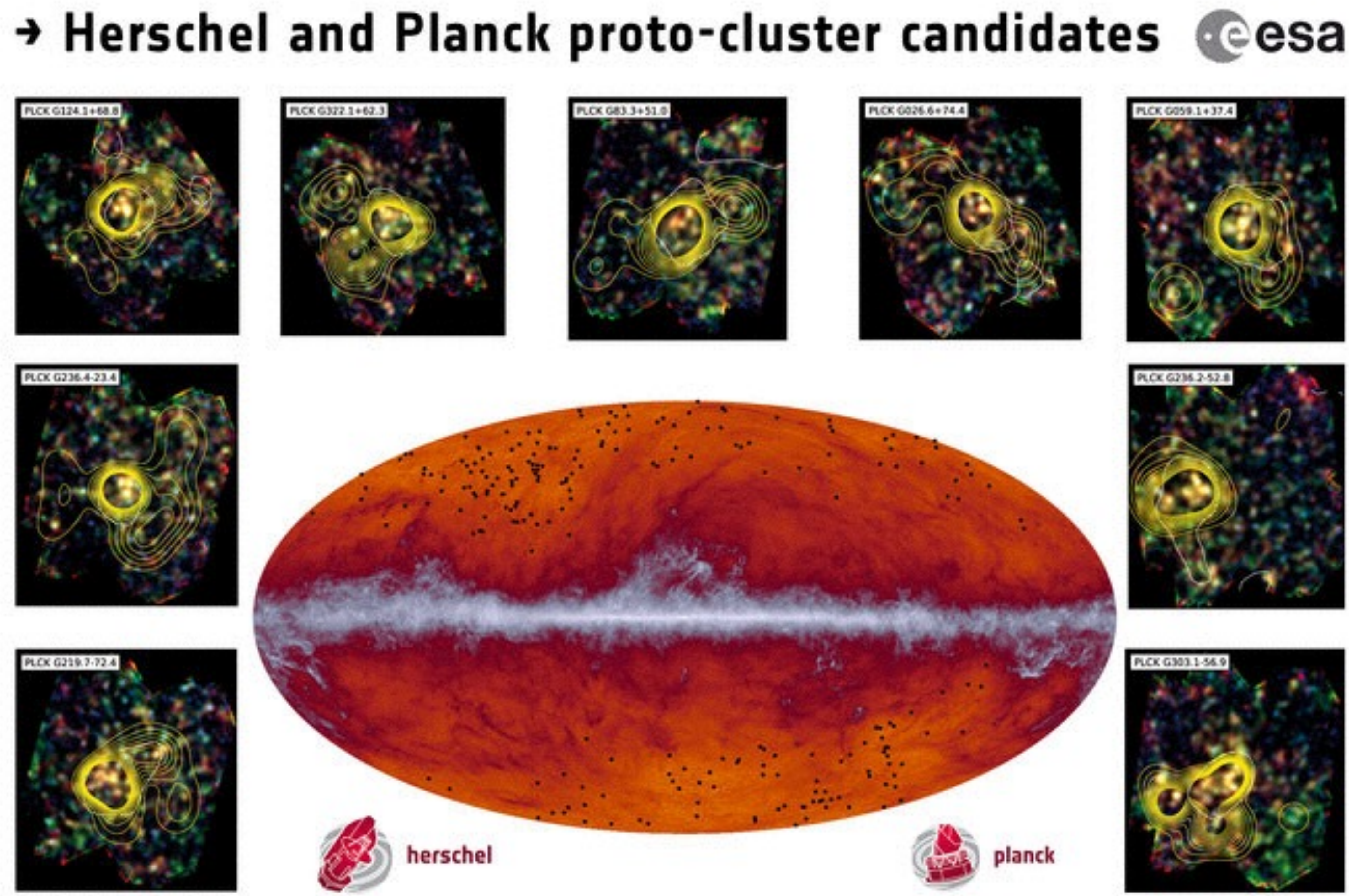


Mock LAE Catalogs for the Use of LSS in Chiang+15

Also Reveals Interesting Physical Properties of LAEs

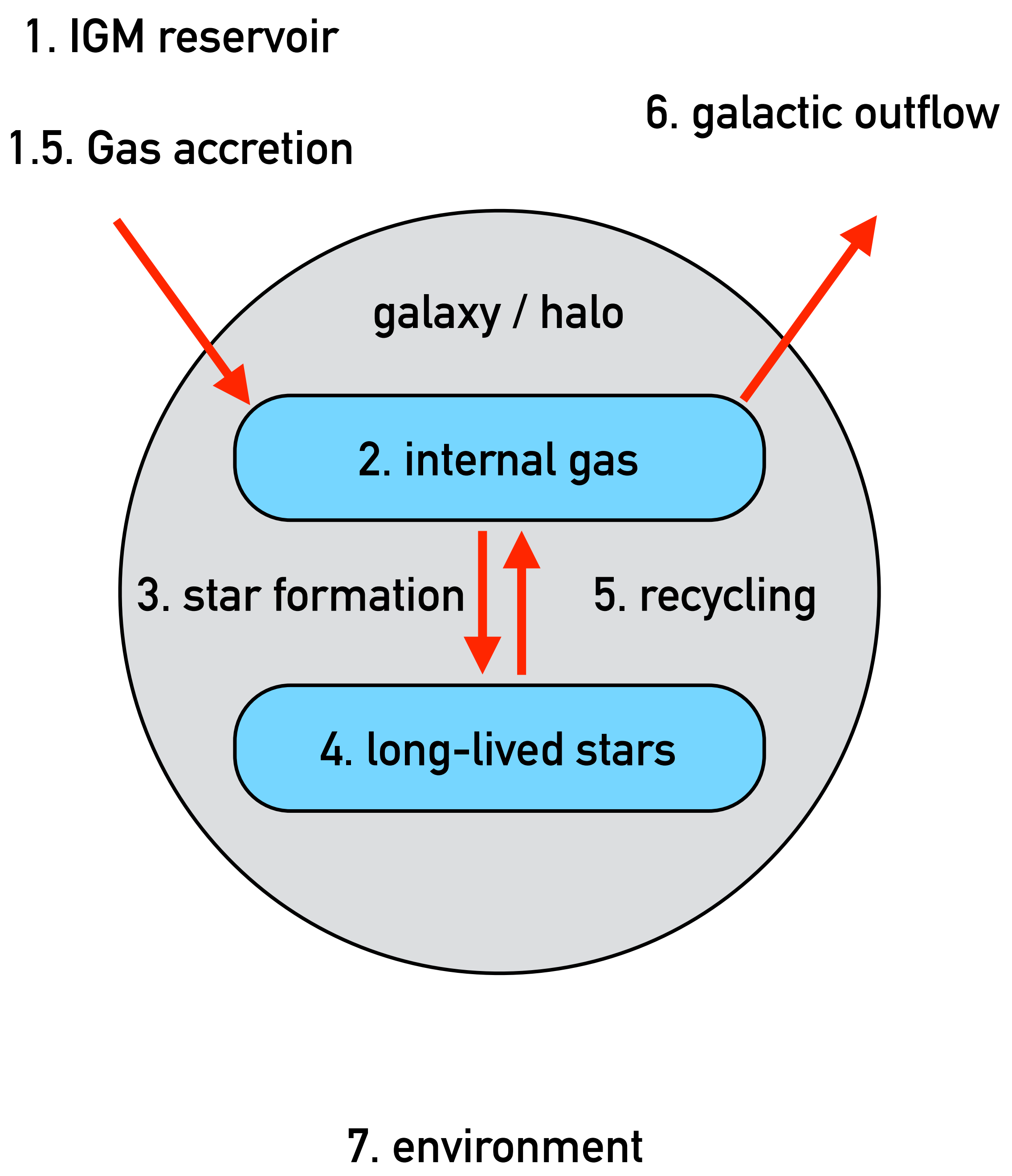


234 Planck Cold CIB Peaks
Overdensities of DSFGs Revealed in Herschel Follow-ups



Planck Collaboration, H. Dole, D. Guéry, G. Hurier+ 2015

We Now Have a Suite of Probes for Many of the Elements of Baryon Cycle at $z \gtrsim 2$



target quantities	observations	example
1	gas absorption	CLAMATO Lya tomography
2	sub-mm & radio	ALMA, JVLA
3, 4, 7	rest-optical spectroscopy	MOSFIRE, KMOS
3, 4	optical-IR photometry	COSMOS, MB surveys
3, 6, 7	rest-UV spectroscopy	all large telescopes
7	redshift survey	HETDEX, DESI, WFIRST

Summary:

1. Simulations already provide sophisticated predictions of proto-clusters especially on large-scales

2. Proto-clusters can be identified observationally via galaxy overdensity on a large scale that matches the Lagrangian volume

3. Not just overdensities — they provide magnified signatures of galaxy growth, quenching, baryon cycle, and environmental impacts

4. Both large statistical sample and detailed case studies are needed, and it's time to make significant progress with the up coming surveys

Thanks