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Massive Structures of Galaxies at High Redshift

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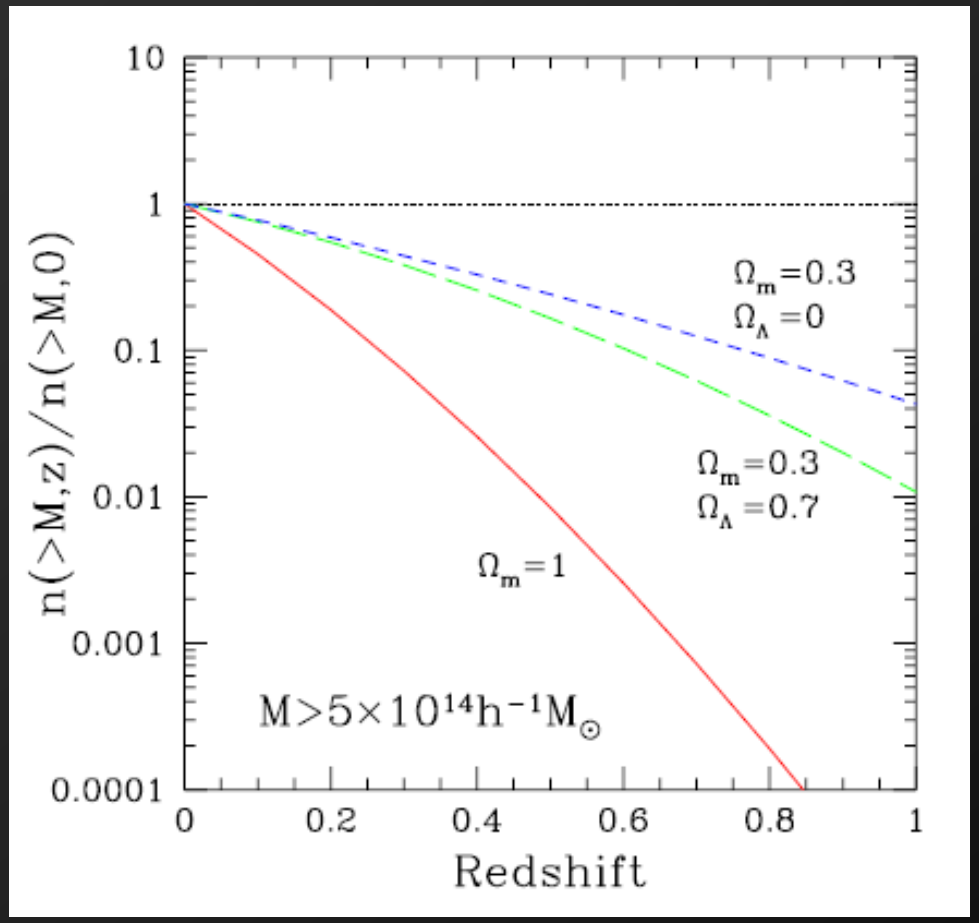
Galaxy Clusters

- The most massive, gravitationally bound object in the Universe ($\sim 10^{15}\ M_{\odot}$)
- 100-1000 member galaxies

Key factors

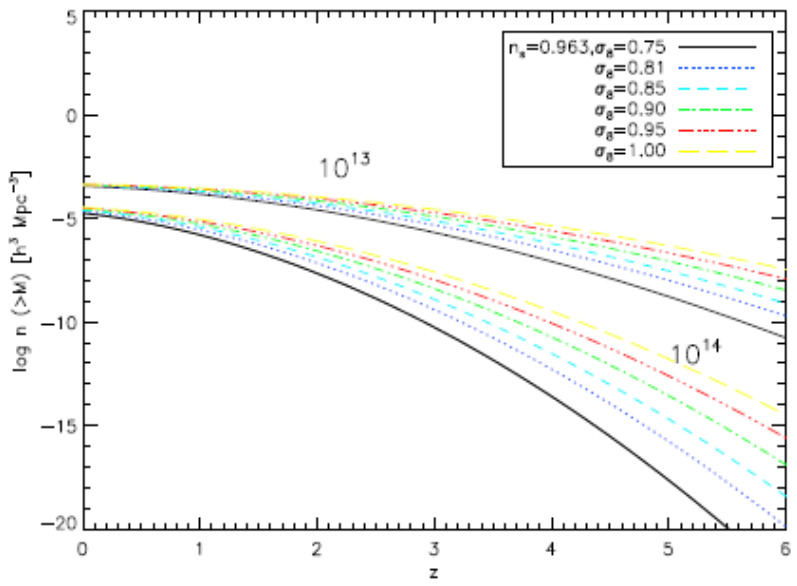
1. Mass
2. Time
3. Density Fluctuation

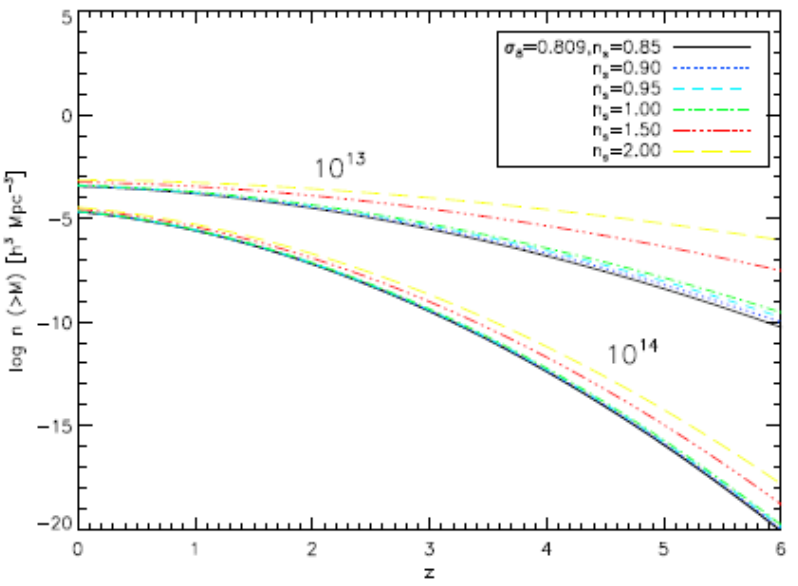
Dependence on Cosmology



Rosati et al. (2002)

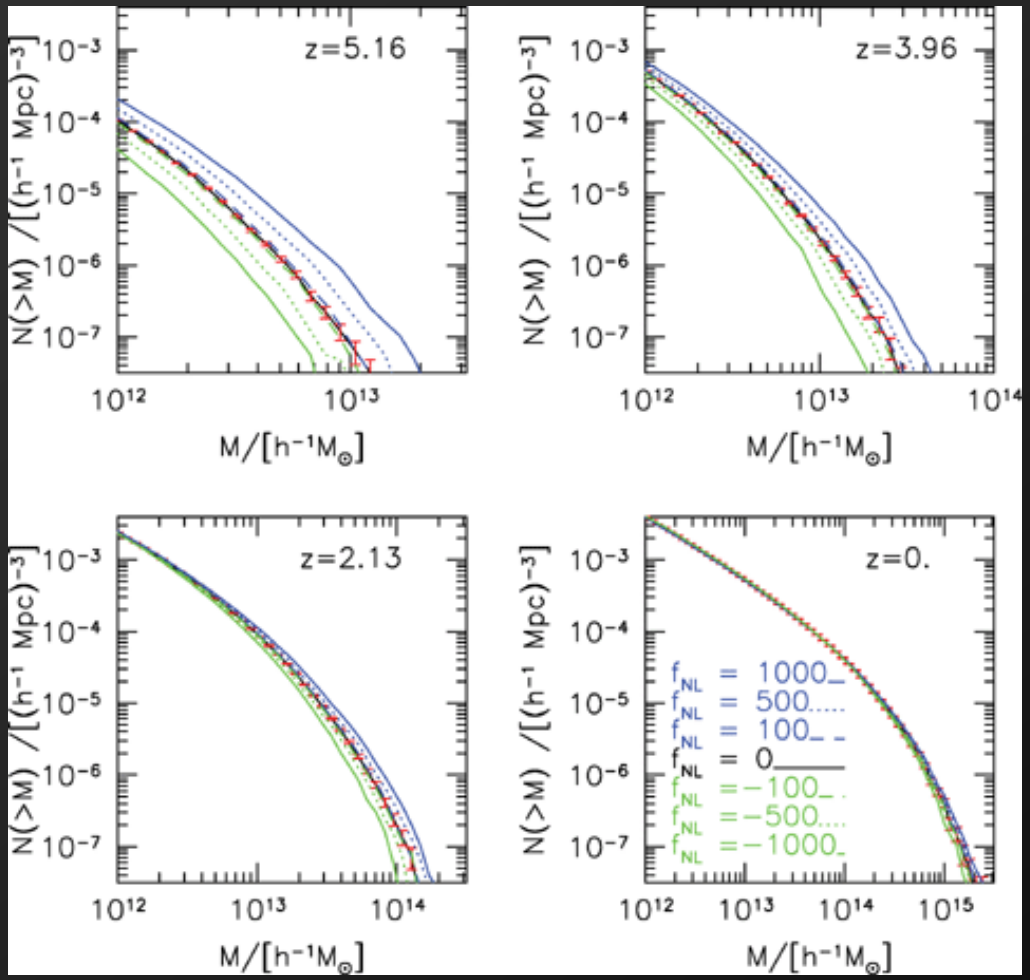
Abundance of Massive Halos





- Sensitive to initial parameters such as f_{NL} (non-Gaussianity), dark matter, initial density fluctuations

Non-Gaussianity



Grossi et al. (2007)

Cluster Search at High Redshift

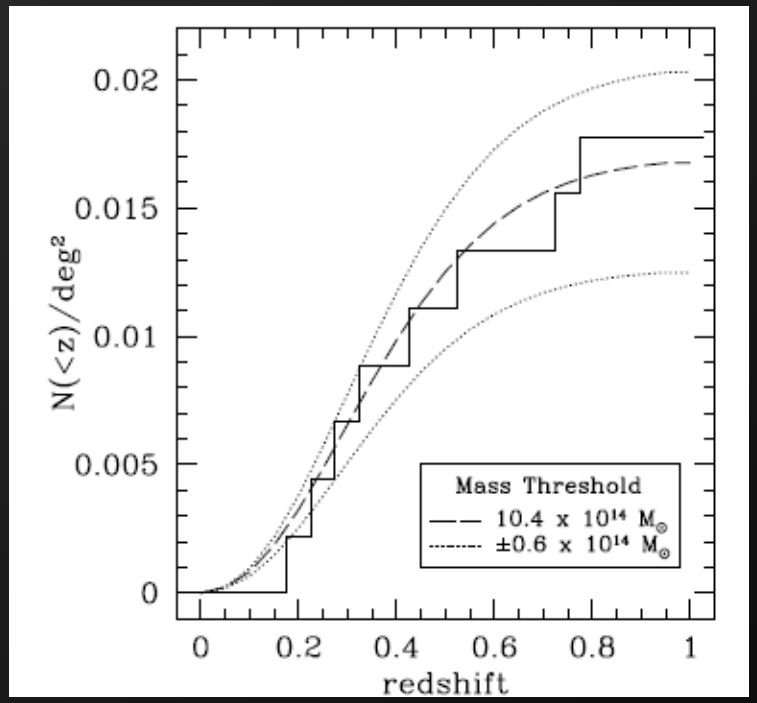
- X-ray → z < ~1
- SZ-effect → mostly z < ~1
- Color-selected sample
  - Red galaxies (Im 2005; Kodama et al. 2007)
  - Lyman break galaxies (e.g., Ouchi et al. 2005)
- Narrow-band imaging (Overzier et al. 2006; Venemans et al. 2007)
- Photometric/spec-z redshift (e.g., Kang & Im 2009; Kriek et al. 2009)
- Radio galaxies/quasars – signpost of over-dense regions at high redshift (Miley & De Breuck 2008)

Cosmological Implication: Clusters at z < 1

- X-ray clusters at <z>=0.55 (e.g., Vikhlinn et al. 2008)

- SZ clusters at z < 1 (e.g., Sehgal et al. 2010; Benson et al. 2011)

➔ Good agreement with ΛCDM (Ω_m= 0.255 $\pm$ 0.016, w=-0.973 $\pm$ 0.063, σ = 0.795 $\pm$ 0.016, from Benson et al. 2011)



Sehgal et al. (2010)

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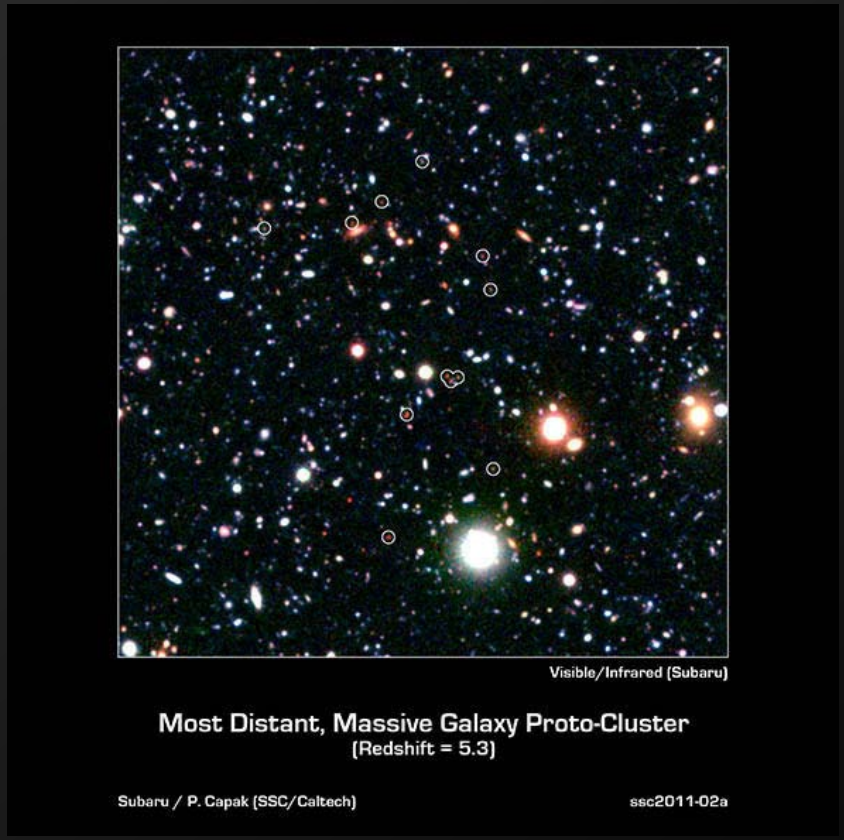
Recent proto-cluster studies

- Search for proto-clusters (Miley et al. 2004; Overzier et al. 2008, Matsuda et al. 2011; Capak et al. 2011,…; $1 < z < 5.3$)
- Some find very massive clusters at $z \sim 1.5$



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Implication of Massive Clusters at z > 1

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- "… the existence of the most massive clusters in our sample ... Provide a tension with the current ΛCDM model. … probability of finding … 1%." (Jee, et al. 2011, regarding 22 lensing clusters at z > 1)
- "…under ΛCDM cosmology, …there is only 7% change of finding a galaxy cluster similar to SPT-CL J2106-5844." (Foley et al. 2011, regarding z=1.13 cluster with M = 1.3 x 10^{15} $M_{\odot}$)
- "We find that [two clusters] are 2-3 inconsistent with ΛCDM." (Holz & Perlmutter 2012, regarding two massive clusters at z > 2)
- "For standard CDM structure formation, … this lens system *should not exist.*" (Gonzalez et al. 2012, regarding M = 5 x 10^{15} $M_{\odot}$ IDCS cluster at z=1.75)

But, see Mortonson et al. (2011)

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Massive Structures of Galaxies (MSGs) in GOODS Fields

- Instead of cluster (virialized), use “MSGs”
- Are CDF-S and GOODS-N fields representative fields of “field” populations?
- What are the numbers of MSGs not pre-selected by “radio galaxies” or “quasars”?
- Can theories explain the number density of MSGs?
- Galaxy population in MSGs

GOODS Fields

- Great Observatories Origins Deep Survey
- Two 160 arcmin^2 ~ 10^5 Mpc^3 per Δz=0.1
- HST/VLT/Subaru/KPNO/Spitzer/Chandra/Herschel imaging data at UBVizJHK, 3.6/4.5/5.6/8.0/24 micron + X-ray + FIR
- 6000 spectroscopic redshifts

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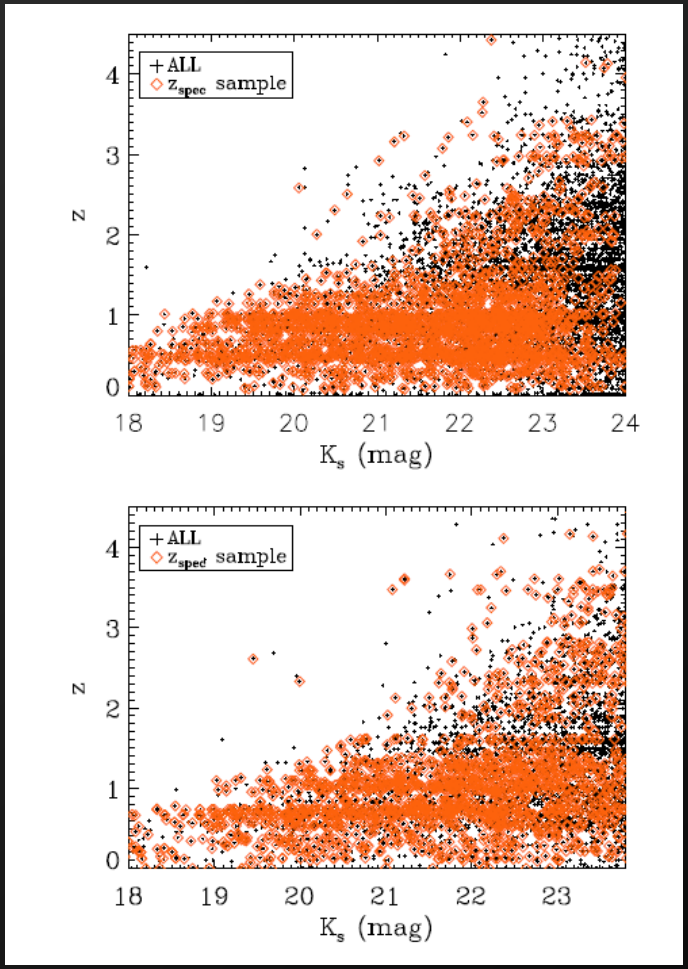
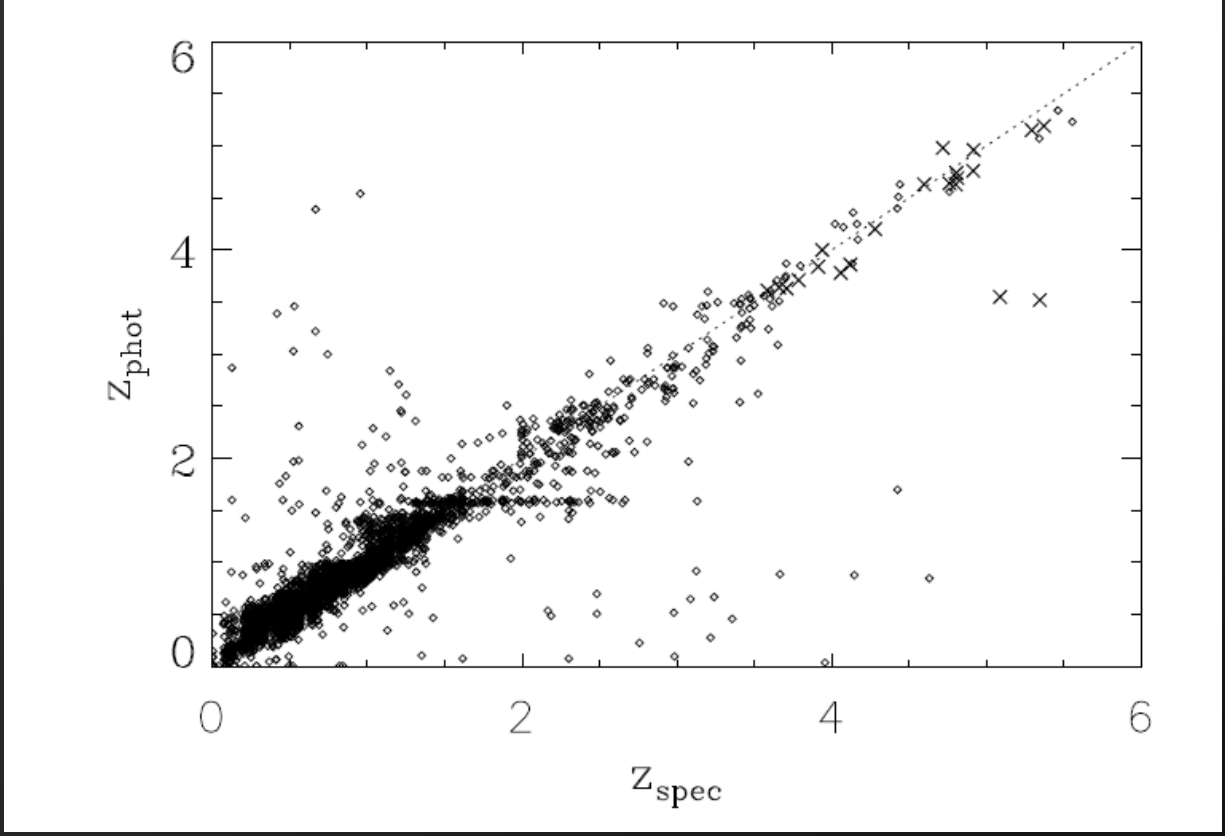
Sample

- Ks < 24 AB mag (for reliable zphot/stellar mass estimates) + z < 26 AB mag, U or B dropouts
- Photometric reshift using UBVizJHK3.6/4.5/5.6
- About 6000 spectroscopic redshifts

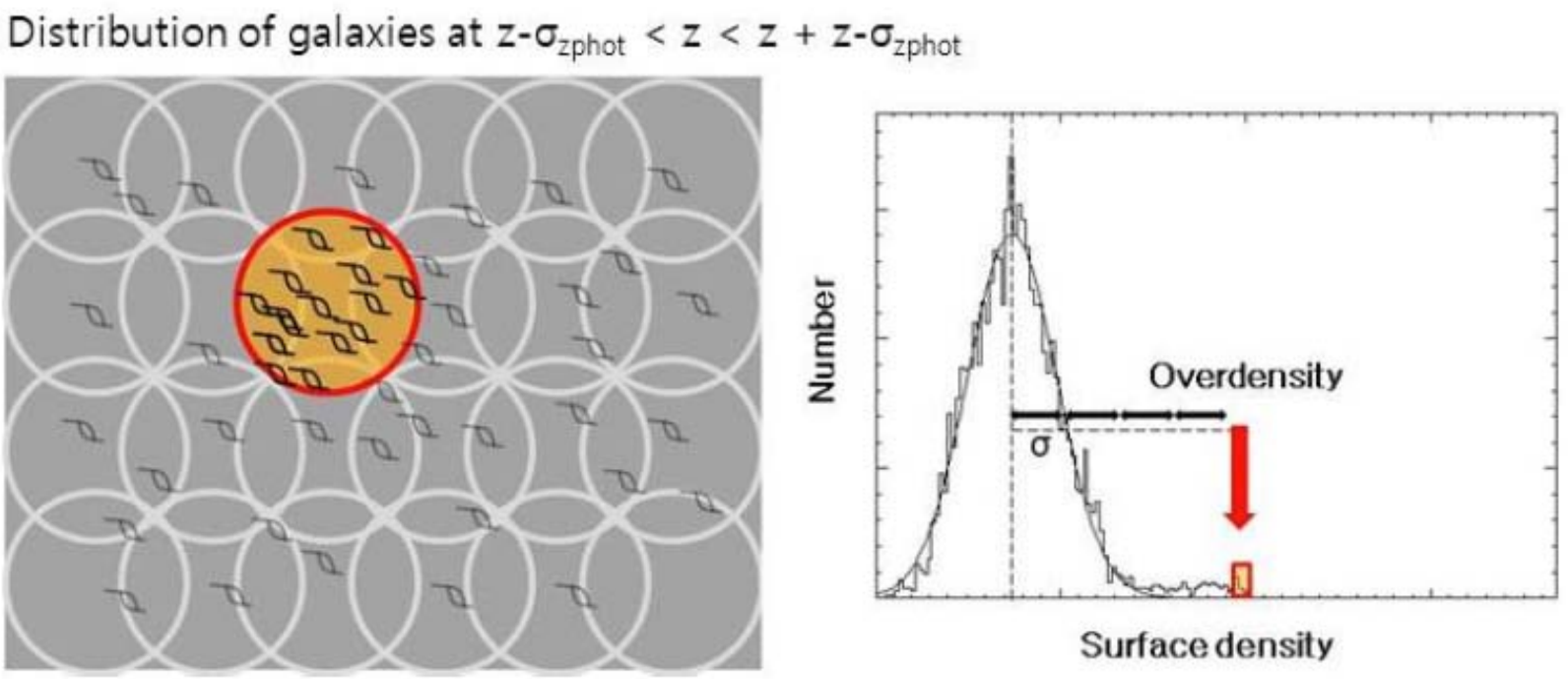


Photometric Redshifts



- BPZ (Benitez 2000) with 742 BC03 templates
- dz/(1+z) ~ 0.06 (but poor performance at 1.5 < z < 2)

Overdensity Search



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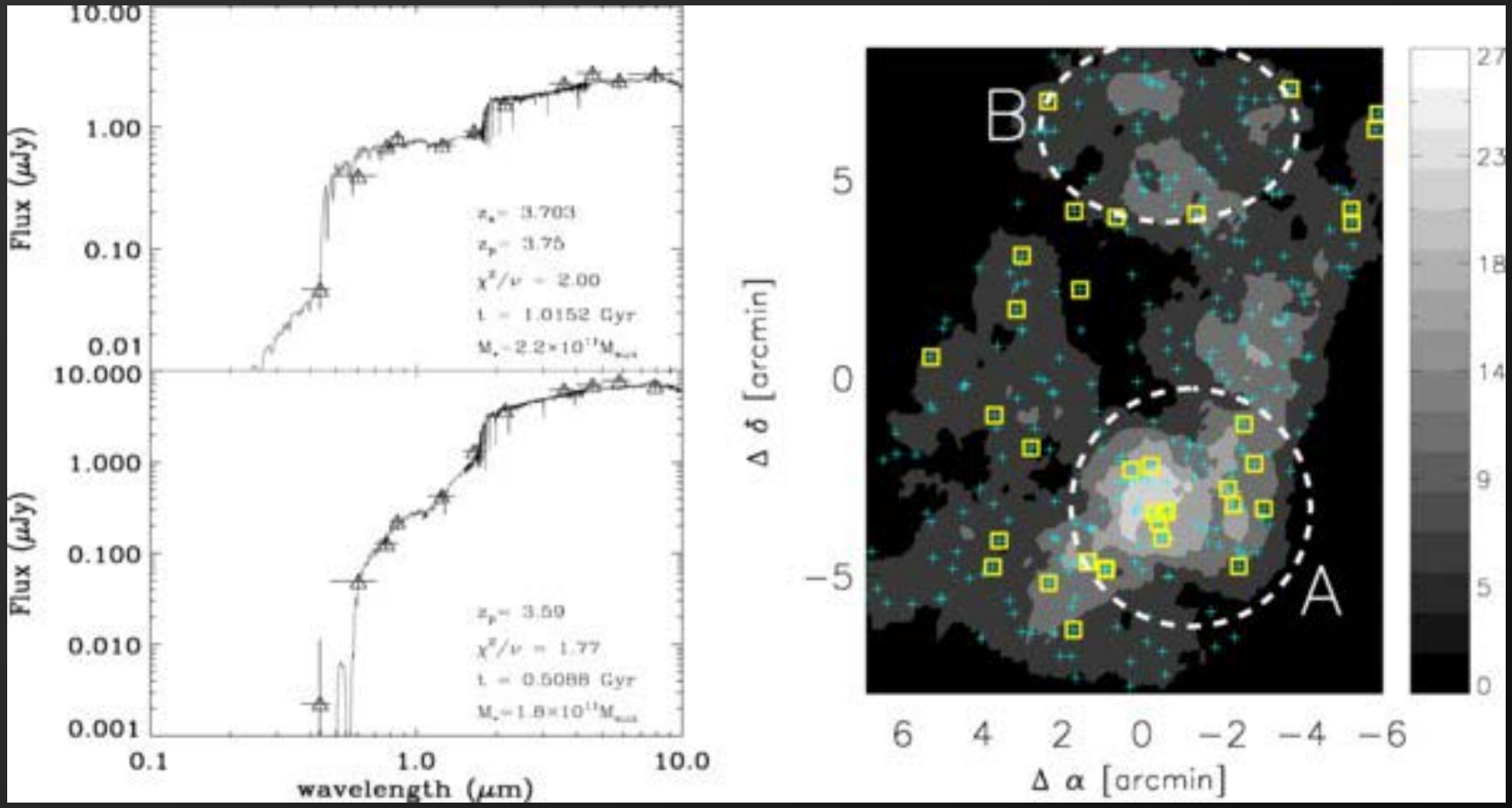
SED-fitting → Stellar Mass



Yellow squares: >10^{11} $M_{\odot}$ galaxies at z ~ 3.7
with age ~ 0.5 – 1 Gyr

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Comparison with Simulation

- Mock catalog from Millennium Simulation (De Lucia & Blaizot 2007; Kitzbichler & White 2007)
- Observational conditions (including zphot errors), imposed
- MSGs were searched in the simulation data
- Mass of halos associated with MSGs are summed, and their number density estimated
- Observational bias is estimated (interloper fraction)

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Mass of MSGs

- $M_{halo} = \Sigma M^* \rightarrow M_{halo}$ (Giodini et al. 2009)
- Correction for the interlopers (x2-3), incompleteness in mass function (x2-5)
- The number density is estimated per each redshift bin

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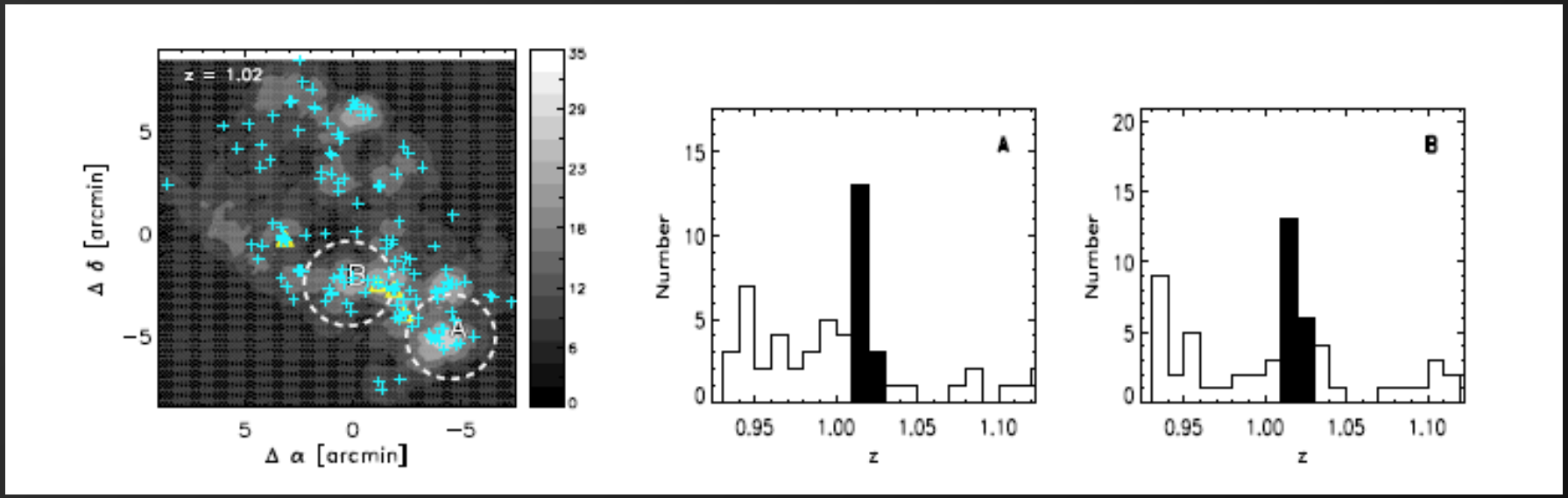
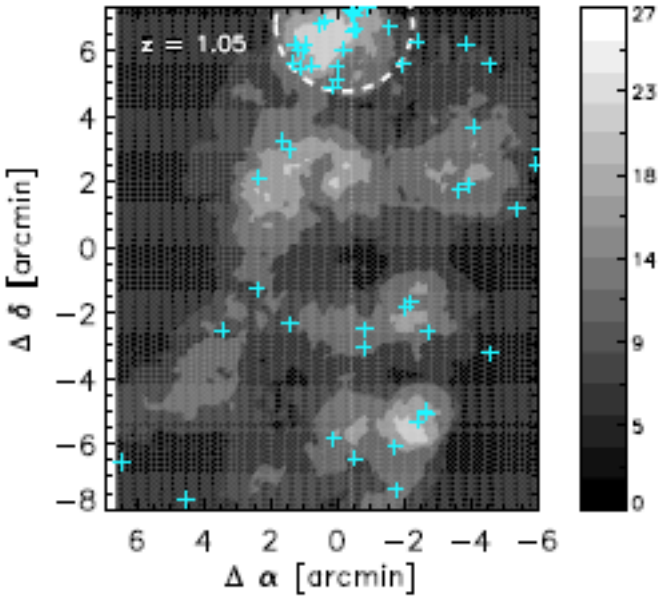
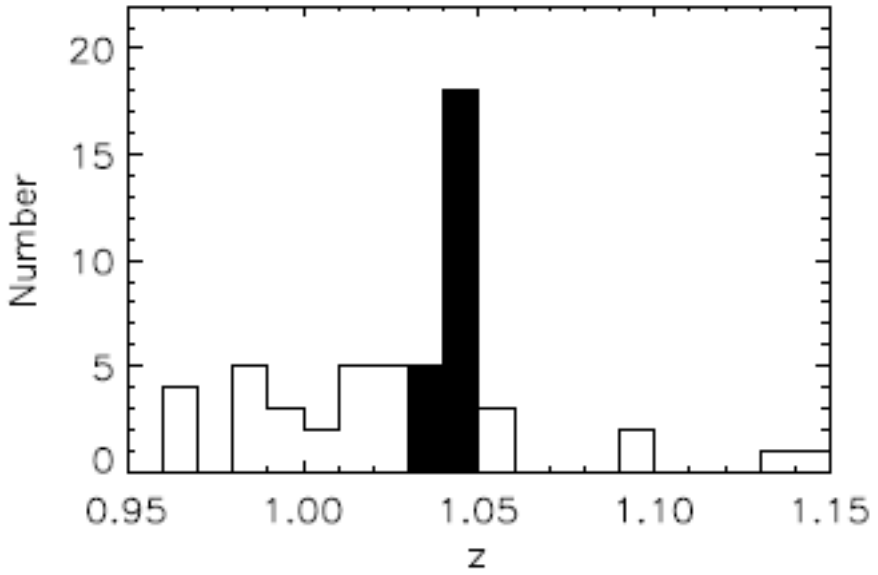
MSG at z ~ 1.02 in GOODS-N



- $\mathrm{Log}(M/M_{\odot}) = 15.08$

MSG at z ~ 1.05





- $\mathrm{Log}(M/M_{\odot}) = 13.69$
- Also see, Vanzella et al. (2006),

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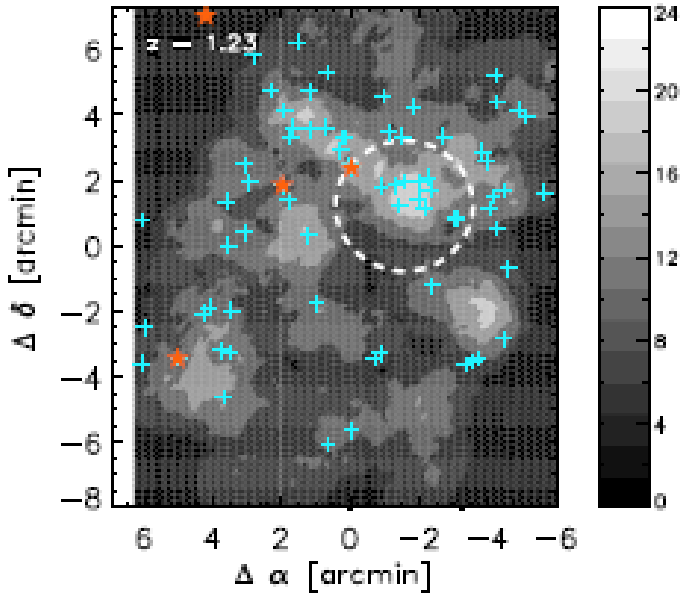
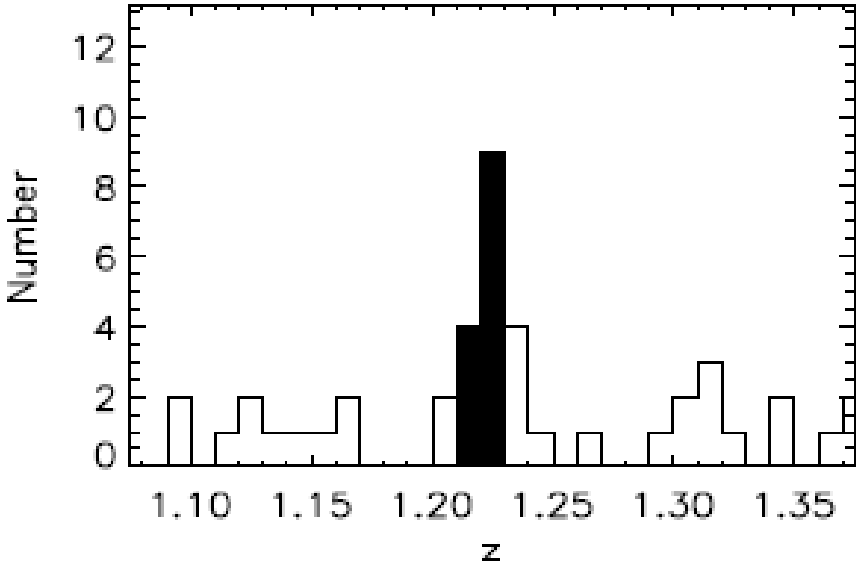
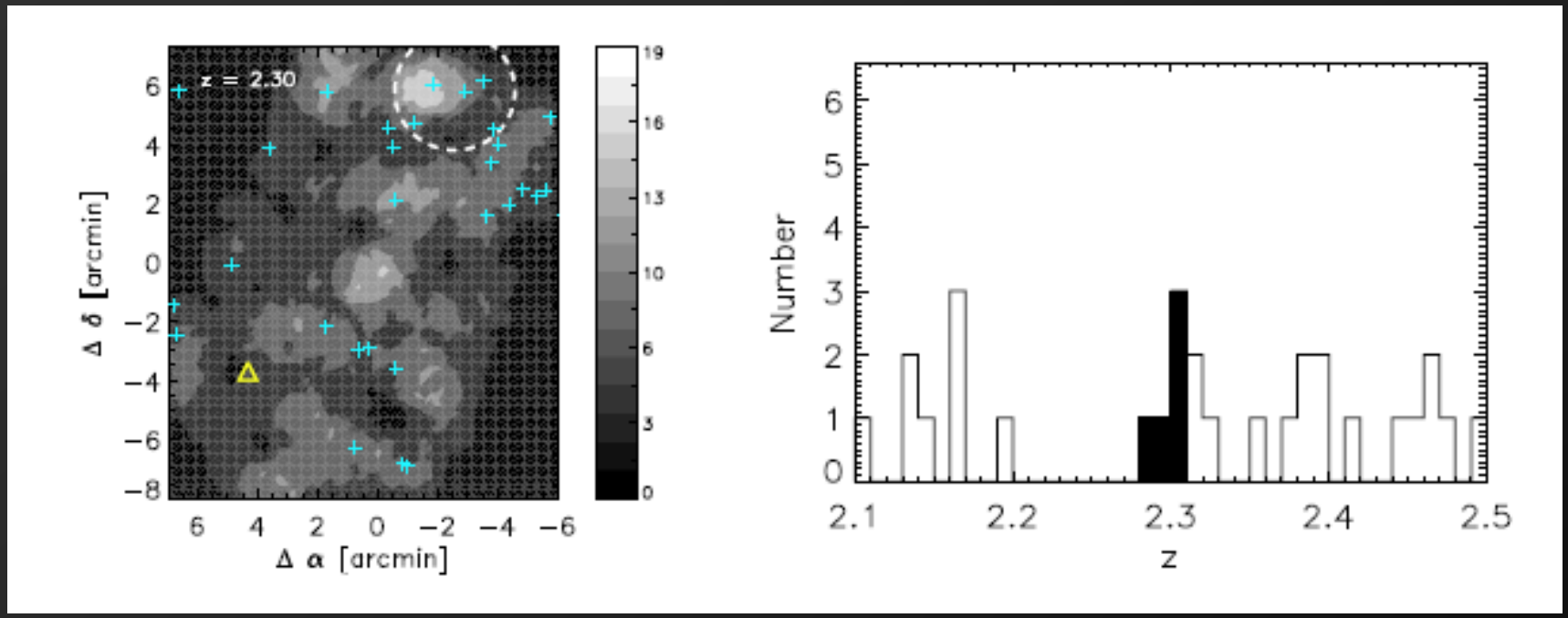
MSG at Z ~ 1.23





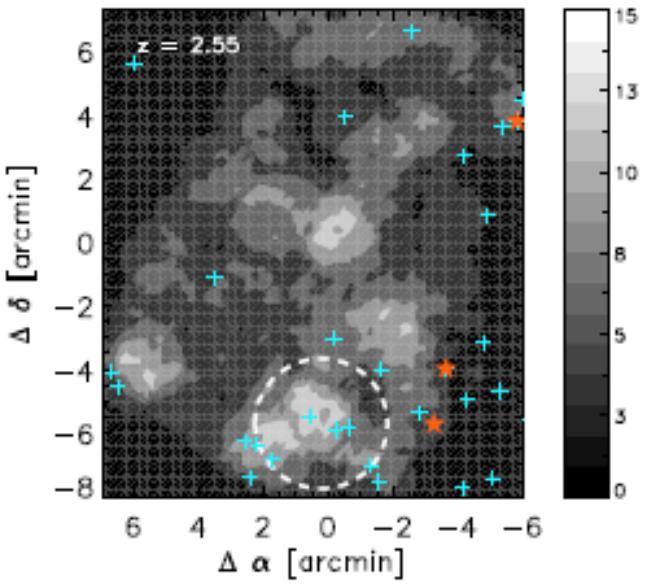
- $\mathrm{Log}(M/M_{\odot}) = 13.5$

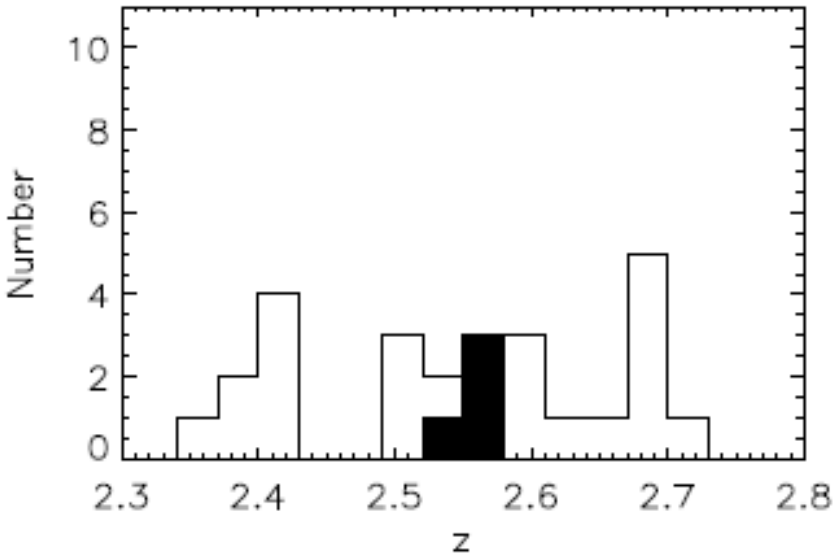
MSG at z ~ 2.3



- $\mathrm{Log}(M/M_{\odot}) = 13.84$

MSG at z ~ 2.55





- Log(M/$M_{\odot}$) = 13.74
- See also, Gilli et al. (2003)

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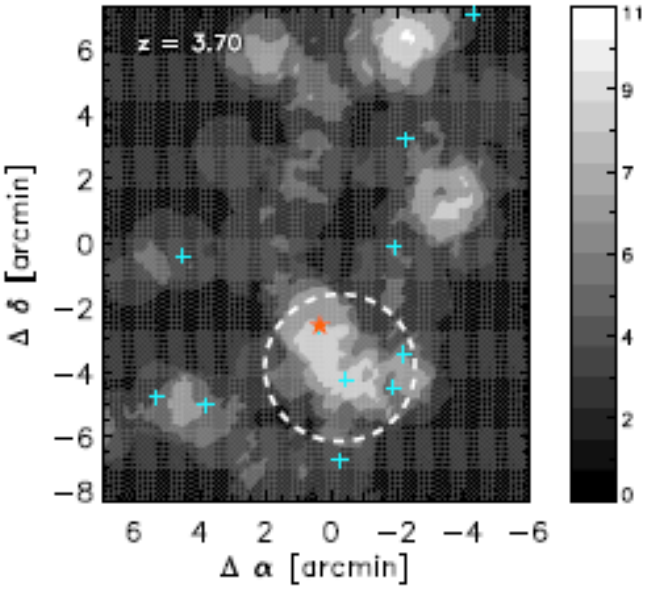
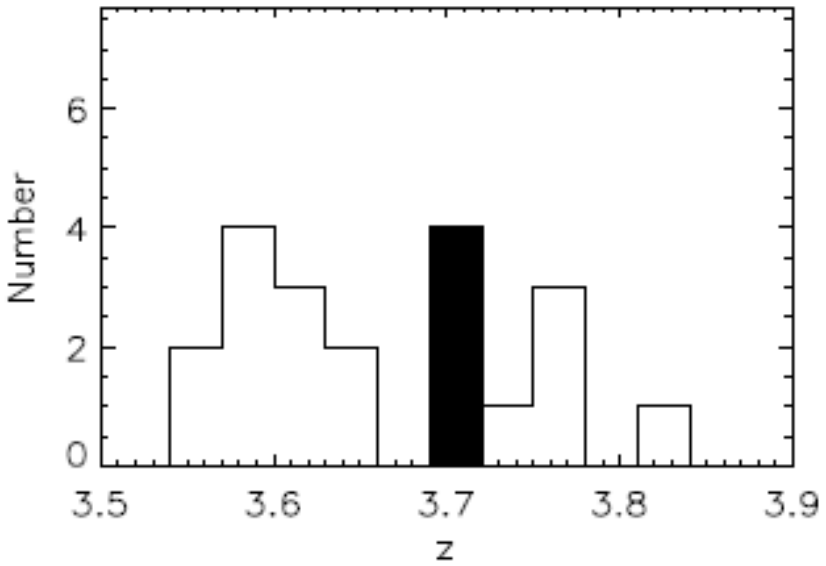
MSG at z ~ 3.7





- Log(M/$M_{\odot}$) = 14.1
- Kang & Im (2009)

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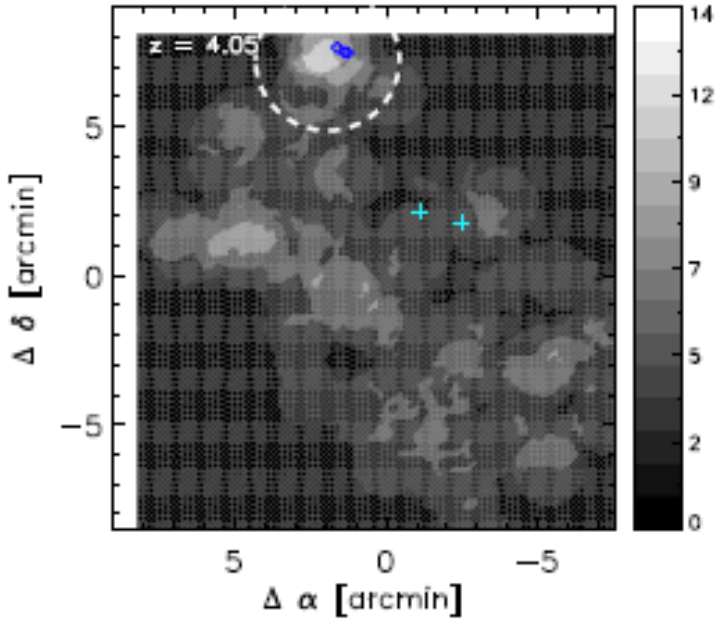
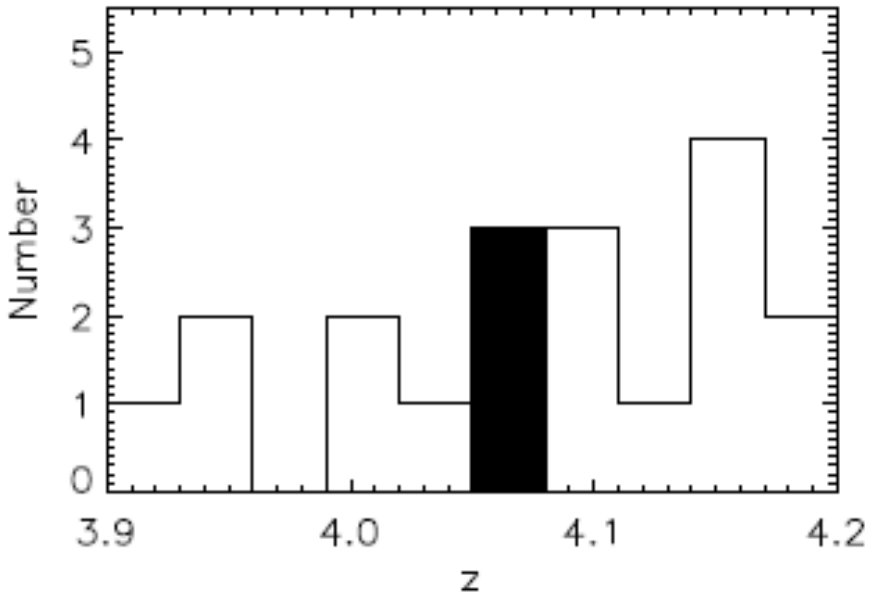
MSG at z ~ 4.05 in GOODS-N





- Log(M/$M_{\odot}$) = 14.05
- See Daddi et al (2009)

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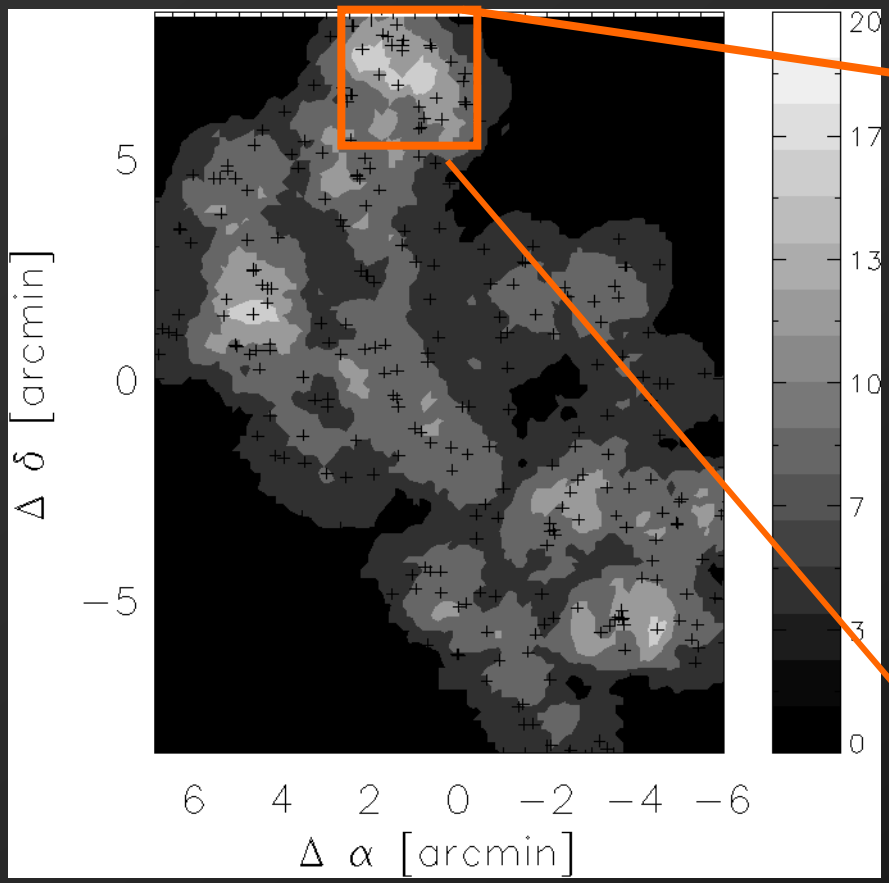
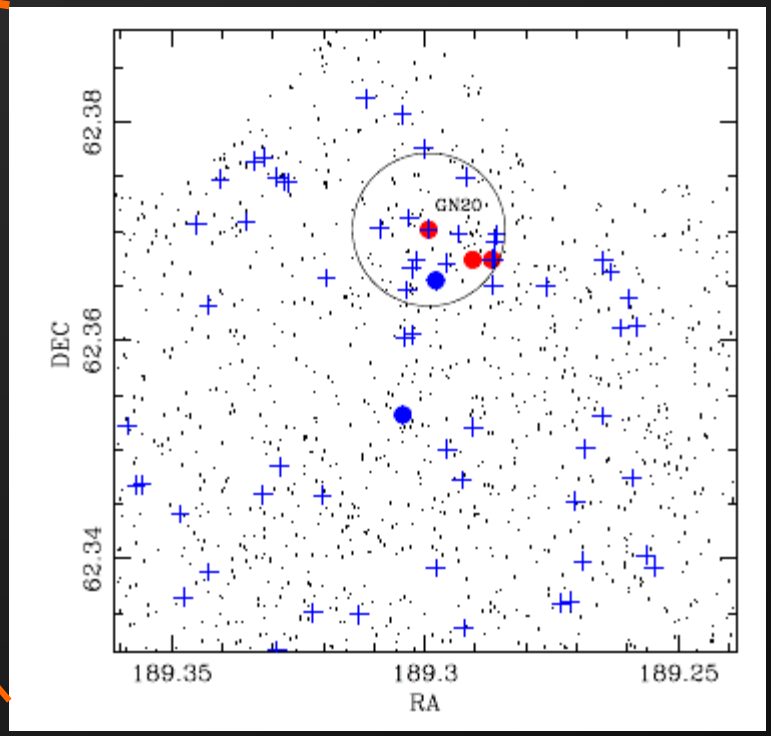
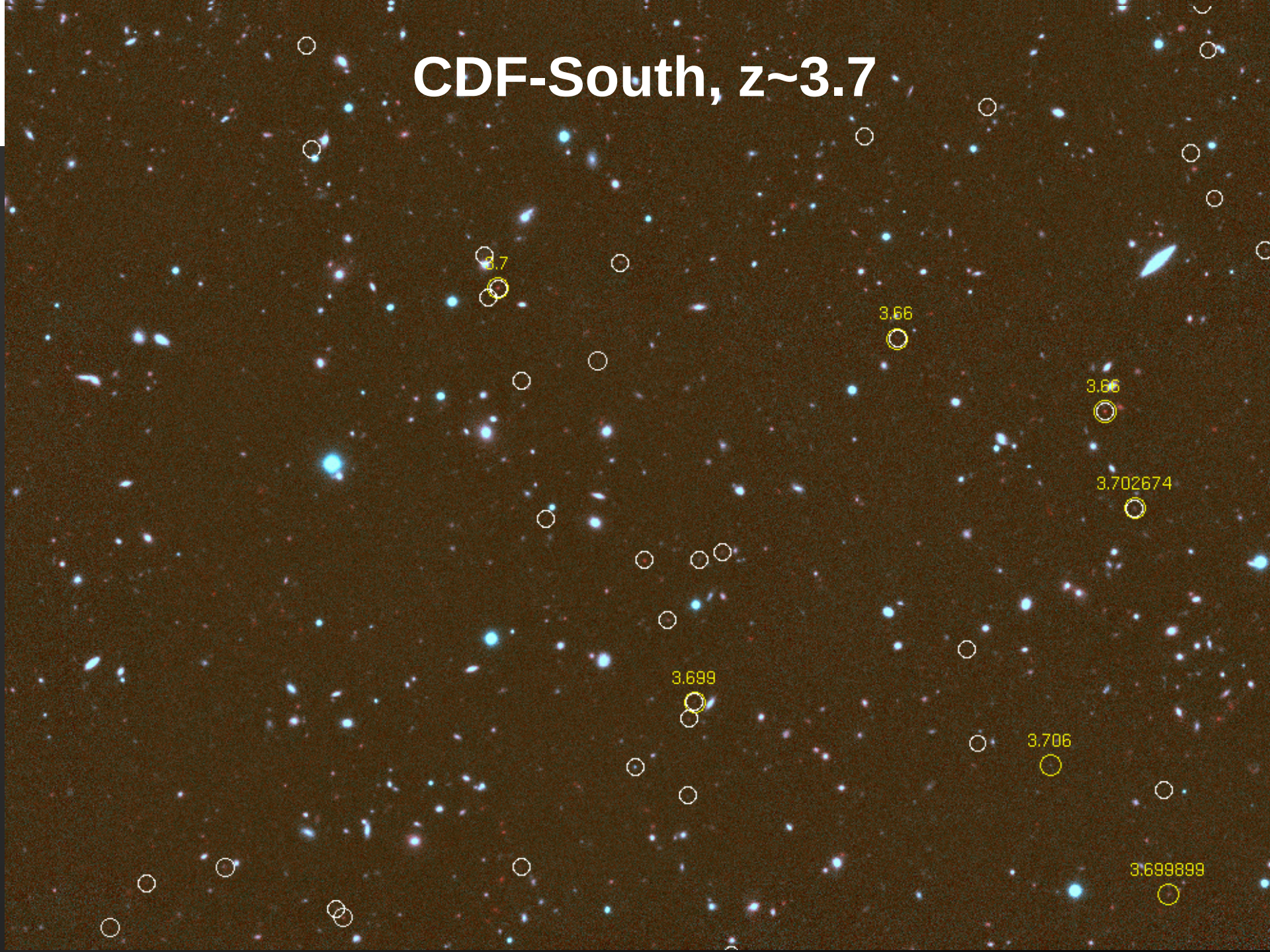
Overdensity at z ~ 4 in GOODS-N

Daddi et al . 2009





Proto-clusters in GOODS-N and CDF-S at 2 < z < 4 !
Mass ~ 10^{14} $M_{\odot}$


CDF-South, z~3.7
3.7
3.66
3.66
3.702674
3.699
3.706
3.699899

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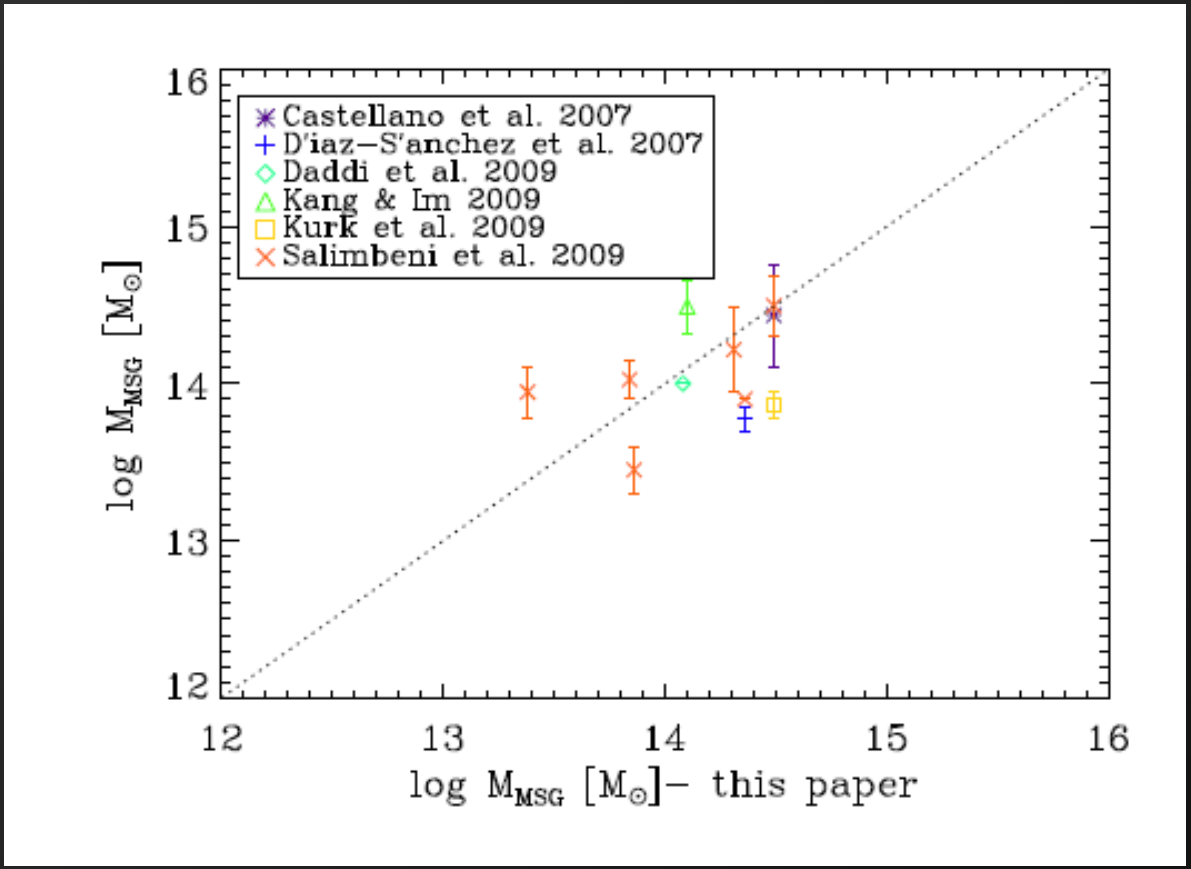
MSG Mass Comparison



- MSG mass scatter: 0.3 dex
- Systematic offset: -0.03 – 0.2 dex

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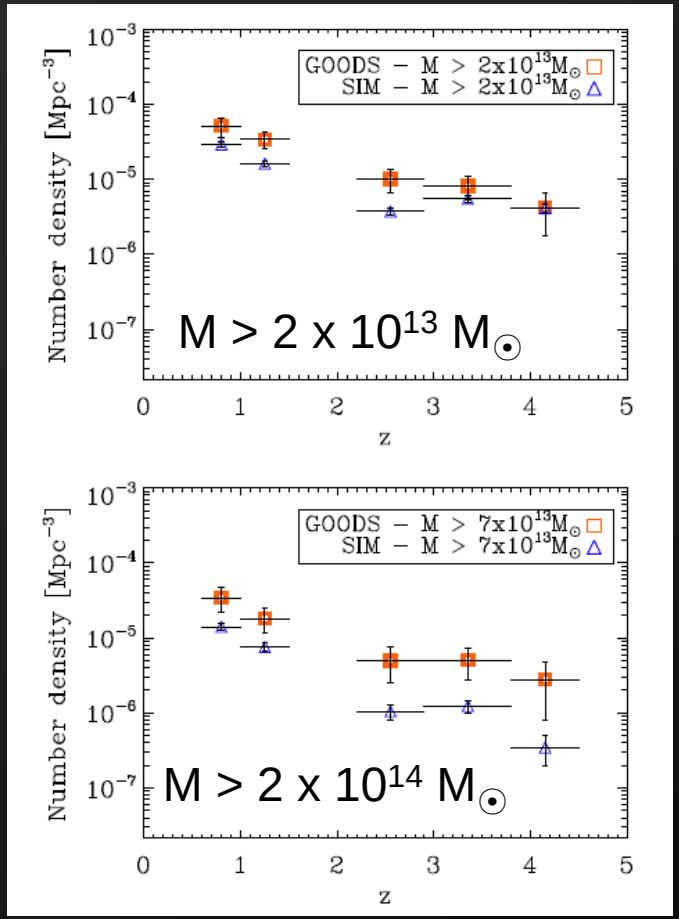
Comparison to ΛCDM Cosmology

- Comparison with the Millennium Simulation (red points)
- Too many MSGs at high redshift ➔ problem with the simulation under the ΛCDM cosmology?



Kang & Im (In preparation)

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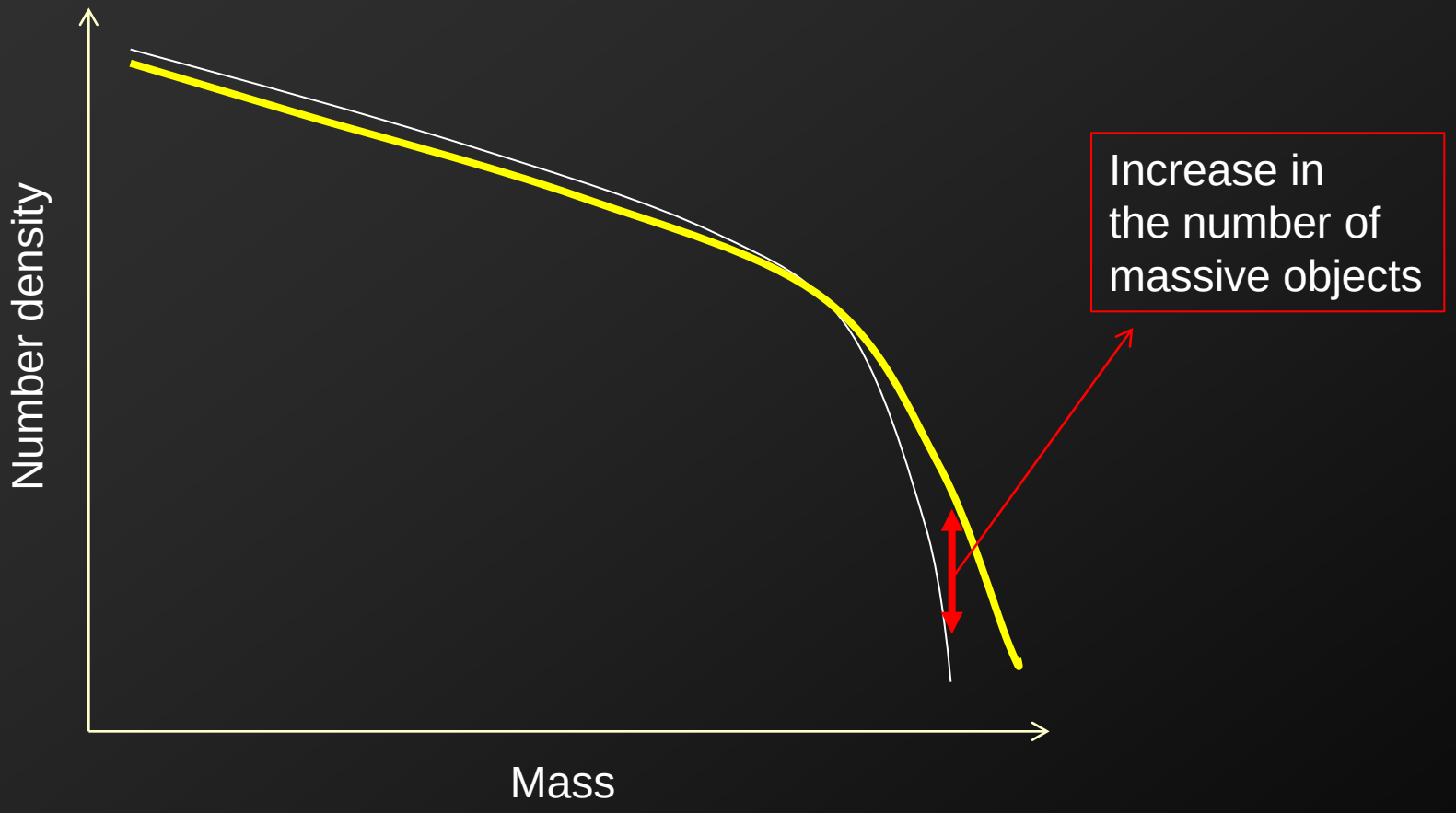
Bias from Measurement Errors



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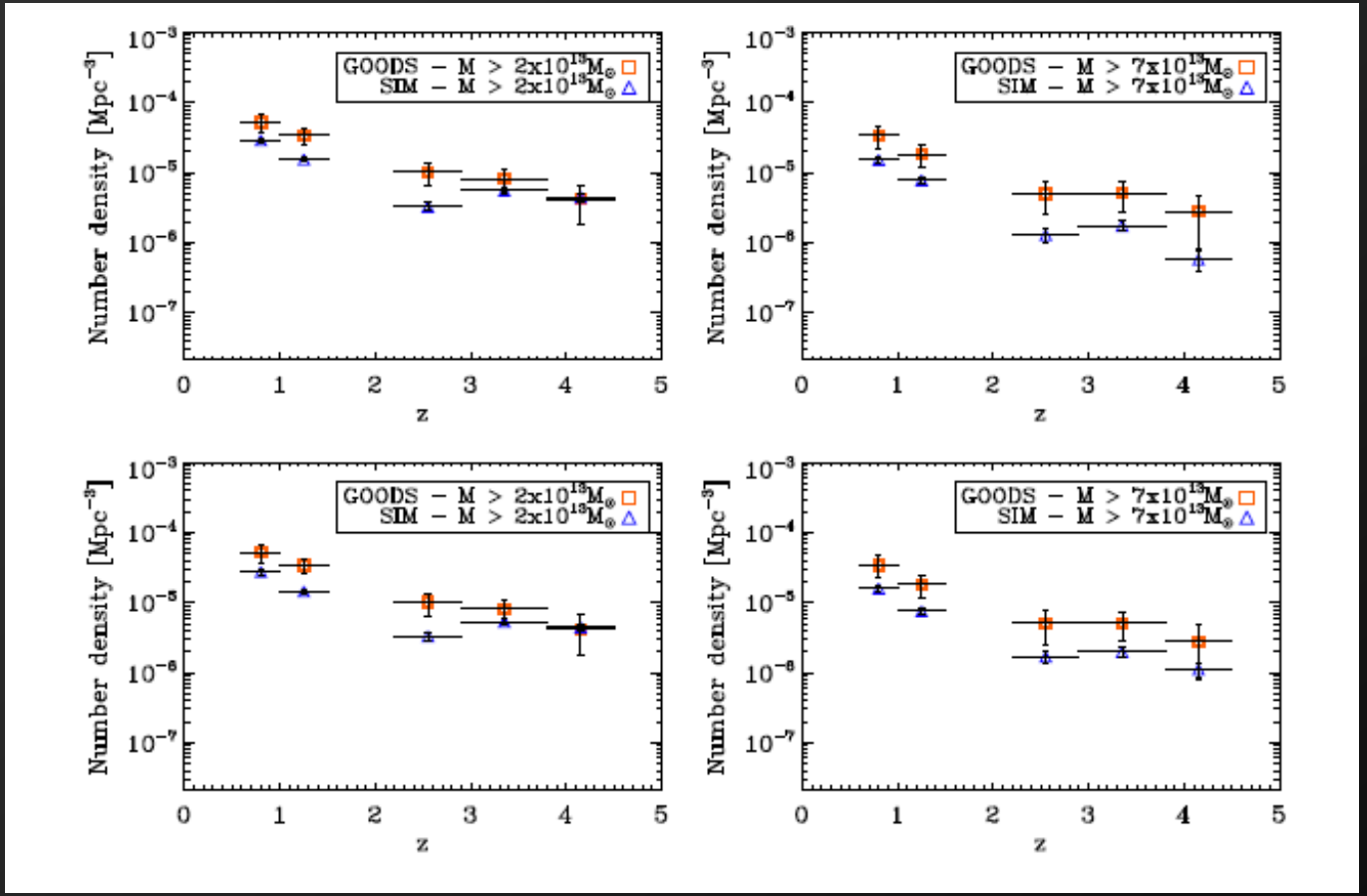
Increasing scatter in M_{MSG} estimates



σ=0.28

σ=0.35

σ=0.50

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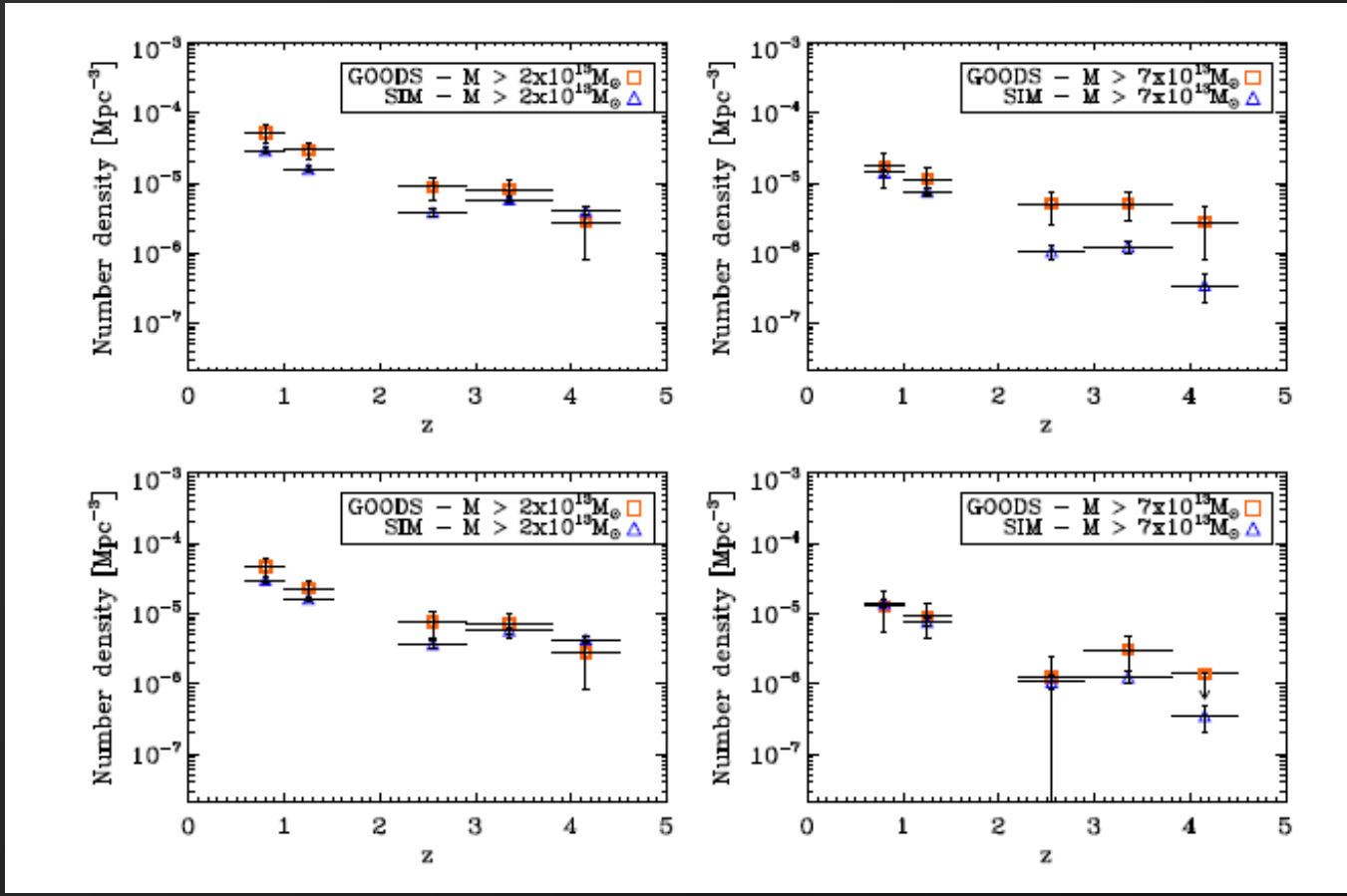
Systematic Offset in M_{MSG}

ΔM



0.1 dex

0.2 dex

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Summary

- Blind search of MSGs in the GOODS fields
- Discovery of 59 MSGs discovered at $0.7 < z < 4.5$ ($13 < \log (M/M_{\odot}) < 15$)
- Comparison with M-simulation result
  - Reasonable agreement with
    (1) less massive MSGs, (2) MSGs at $z < 1$
  - Too many massive MSGs at $z > 1.5$? (by 3-5 times)
  - Accurate mass estimate is a key, though

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Infrared Medium-deep Survey (IMS)

- J-band Imaging survey with UKIRT
- 23 AB mag (5-σ) over 150 deg^2

- High redshift quasars (z > 6.5)
- High redshift clusters (z > 1)

- Search for massive clusters is ongoing (J-W. Kim, M. Hyun, et al.)