The BoRG survey: observations meet theory

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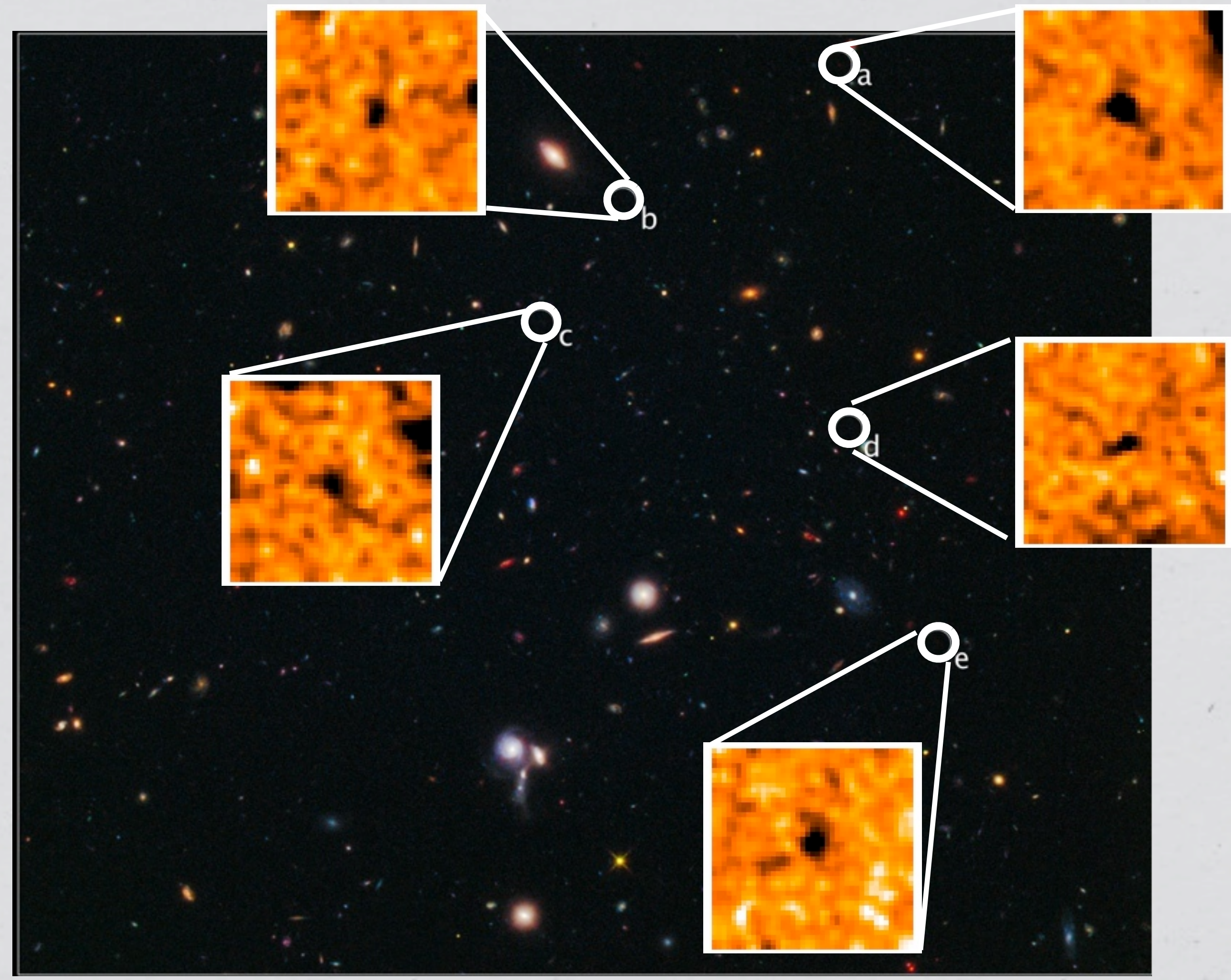
"First Galaxies and Faintest Dwarfs" KITP meeting, 13 February 2012

The farthest proto-cluster

★Hubble discovery of group of five galaxies at z~8 (~650 million years after Big Bang)

★One ultra-bright (for its time*) plus four M* companions



Trenti et al. (2012a)

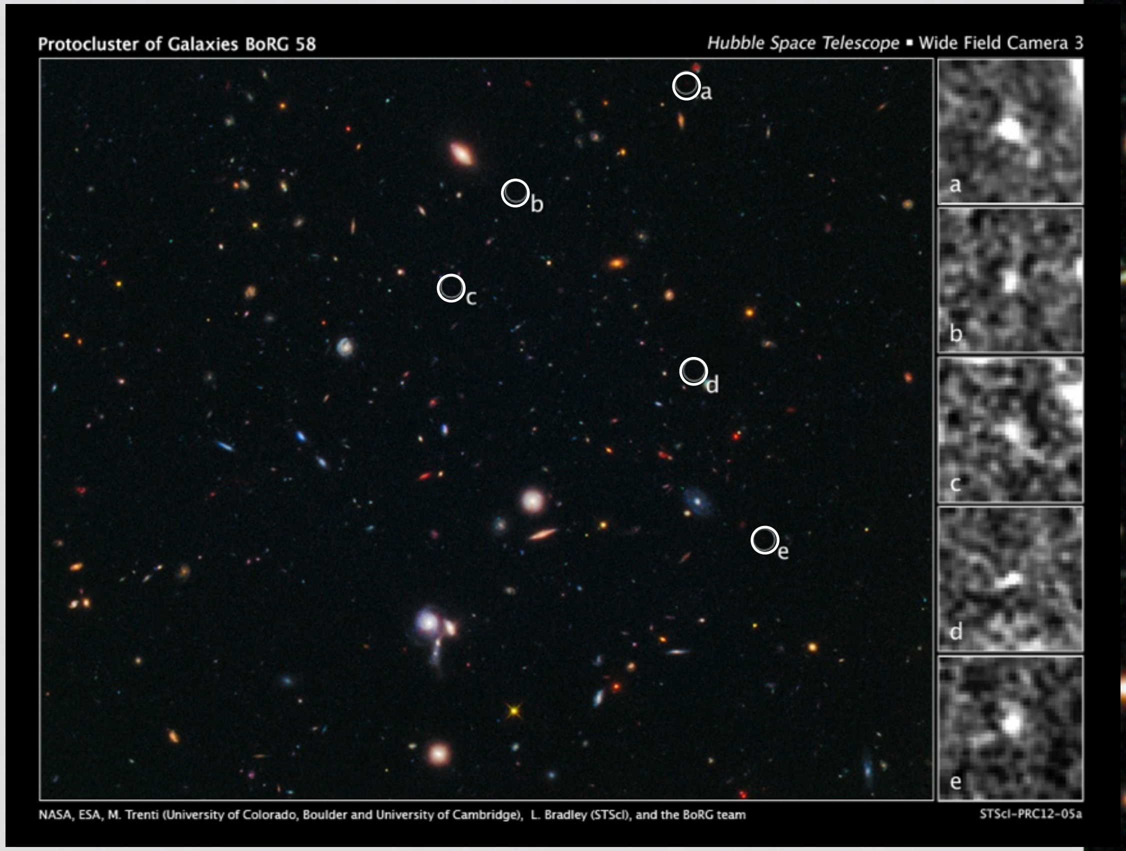
*But… only tiny dot in Hubble image (~1 photon/second)

★We are witnessing infancy of future galaxy cluster

Test of early galaxy formation

★Earliest stages of galaxy & cluster formation have been realm of computer simulations

★Expectation: Brightest galaxies are surrounded by companions

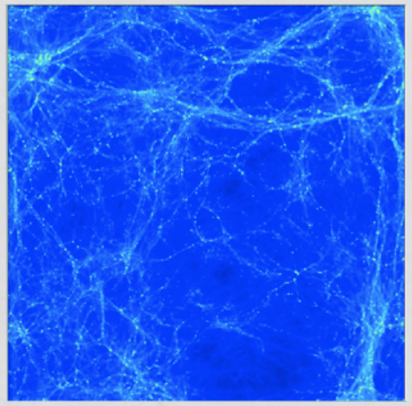


Exactly what we see with Hubble!

★The proto-cluster galaxies, observed at ~650 million years, formed earlier: ~300 million years after Big Bang

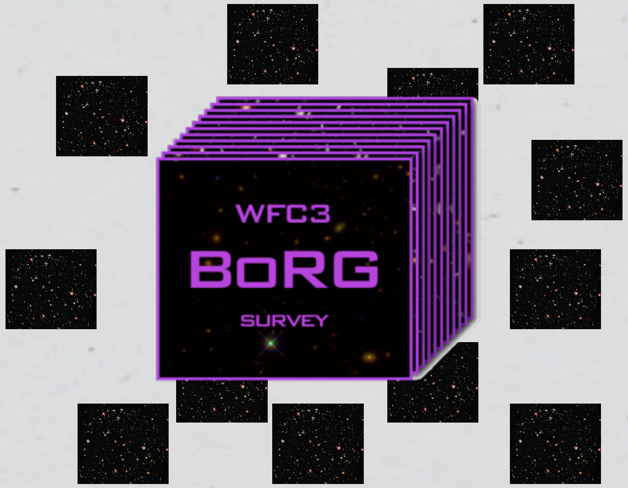
Outline

★Star Formation During the Dark Ages: From Population III stars to the First Galaxies



★Observations meet theory: interpreting the luminosity function from the Hubble Ultradeep Field

★Hunting for the brightest and most massive galaxies and protoclusters at z~8: the BoRG survey



The beginning: first stars

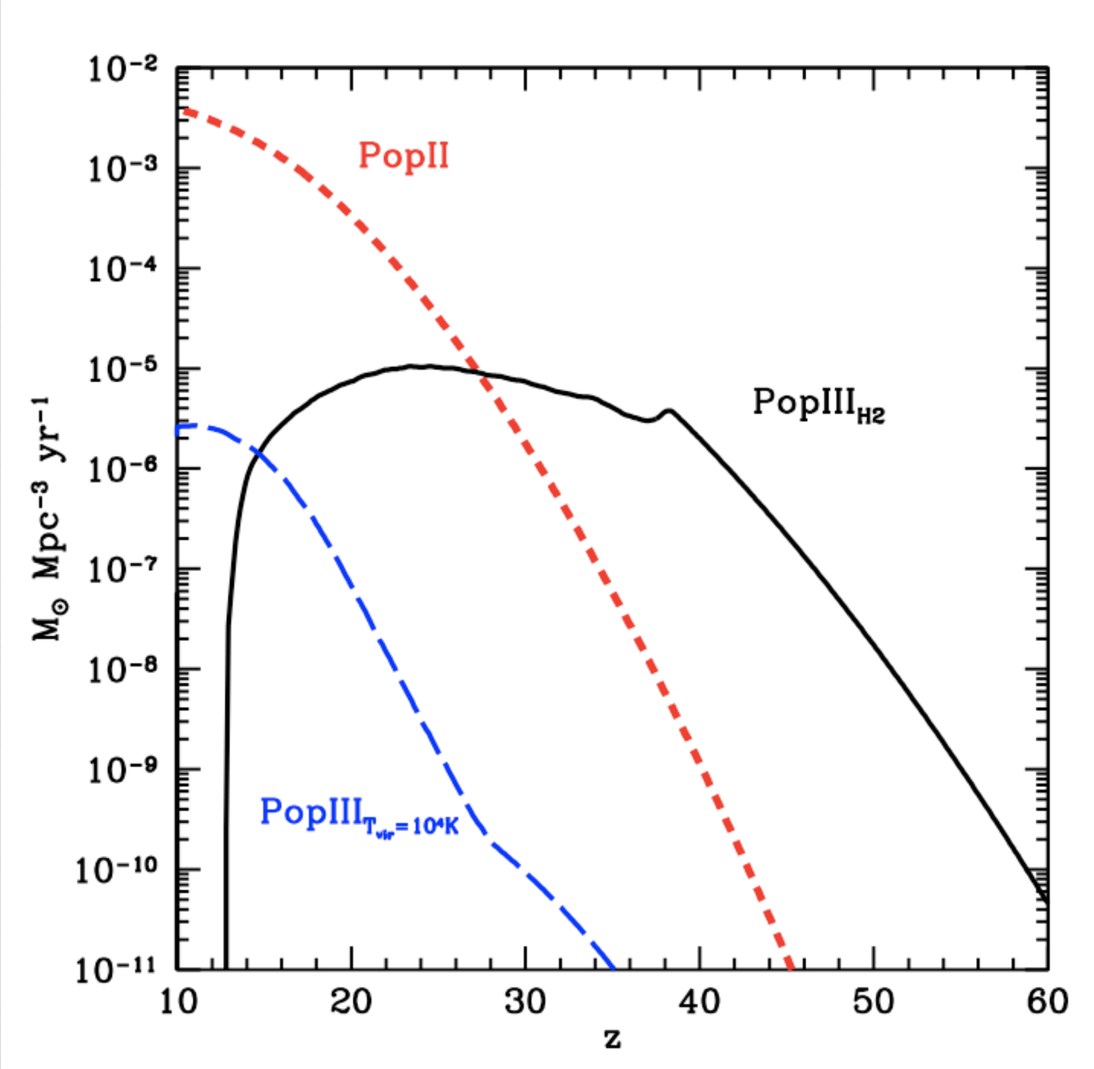
★ First PopIIIs form at z~60 in minihalos ($M_h < 10^6 M_{sun}$)

- SFR grows exponentially at lower z

★ Radiative feedback can suppress cooling (H_2 photodissociation)

- Self-regulated PopIII SFR at z<35

Star formation rate versus redshift



Trenti & Stiavelli (2009)

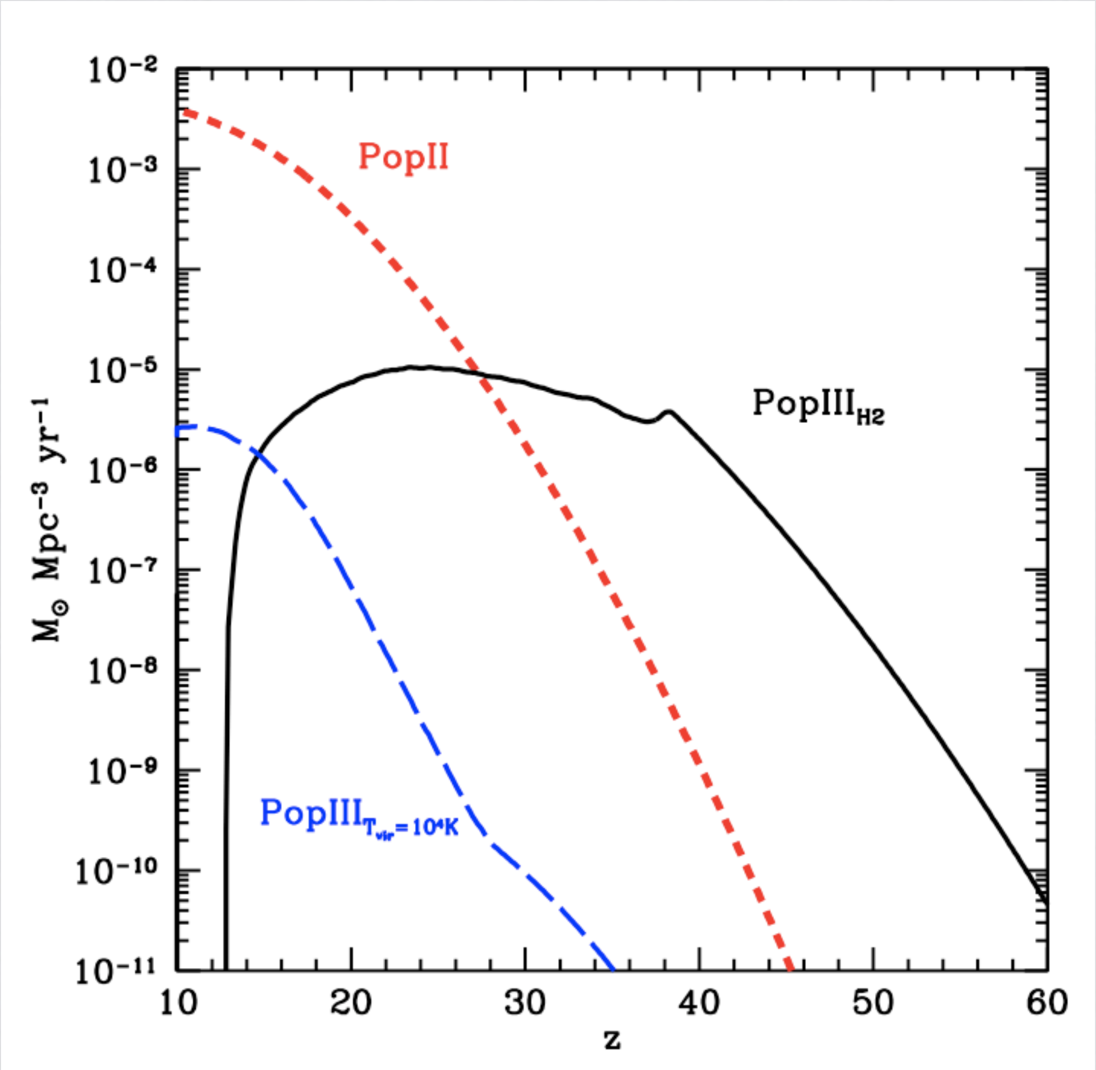
PopIII/PopII interplay

★ Metal enriched star formation takes over at z<25

★ Still, the bulk of metal free stars are formed at z<20

★ PopIIIs can form at yet lower redshift in metal-free halos with $T_{vir} \sim 10^4$ K ($M \sim 10^8$ M_{sun})

Star formation rate versus redshift

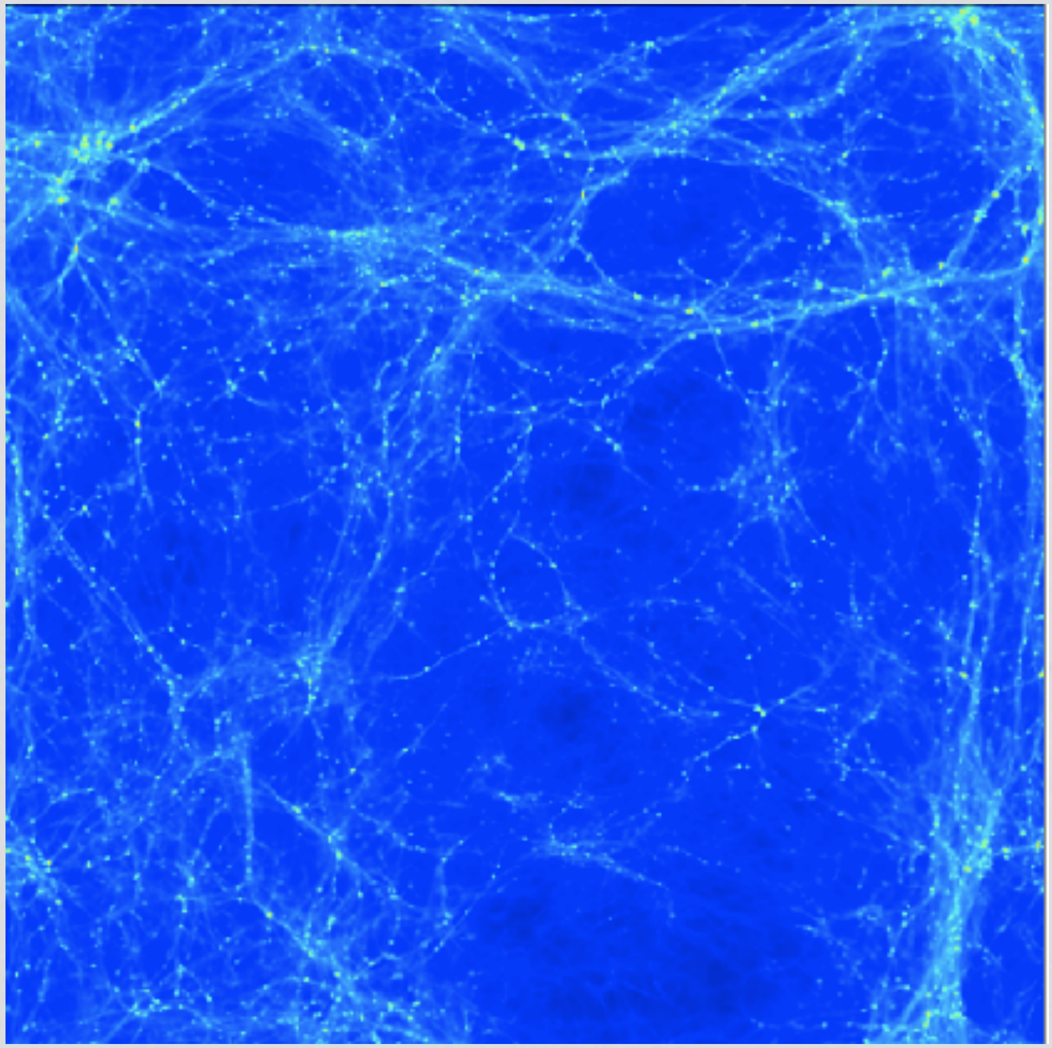


Trenti & Stiavelli (2009)

Star Formation in the epoch of Reionization

★PopIII/PopII star interplay regulated by:

- radiative feedback
- chemical feedback
  - self-enrichment
  - metal outflows

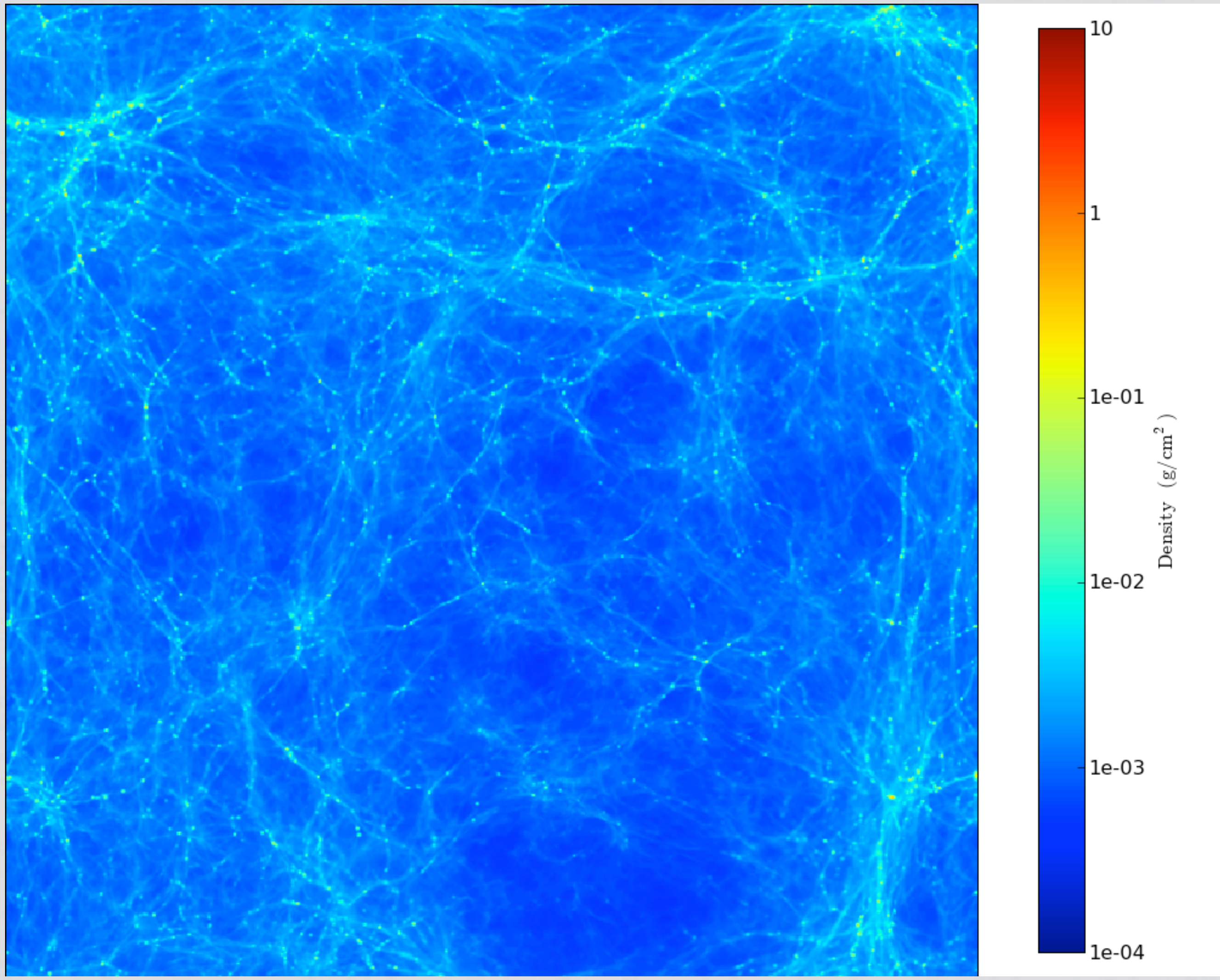


★Simulations are needed

Epoch of Reionization: First Galaxies and Metal-free stars

- ★ Large Scale Structure already present at z~6-10
- ★ Overdensities: First galaxies [metal enriched]
- ★ Voids: Metal-free stars

Structure at early times: density projection



10^3 Mpc^3 box, $N=2x1024^3$, $z_{end}=6$

Trenti, Stiavelli & Shull (2009)

Simulating the First Galaxies

★ Simulations are approaching dynamic range to form first galaxies from first principles

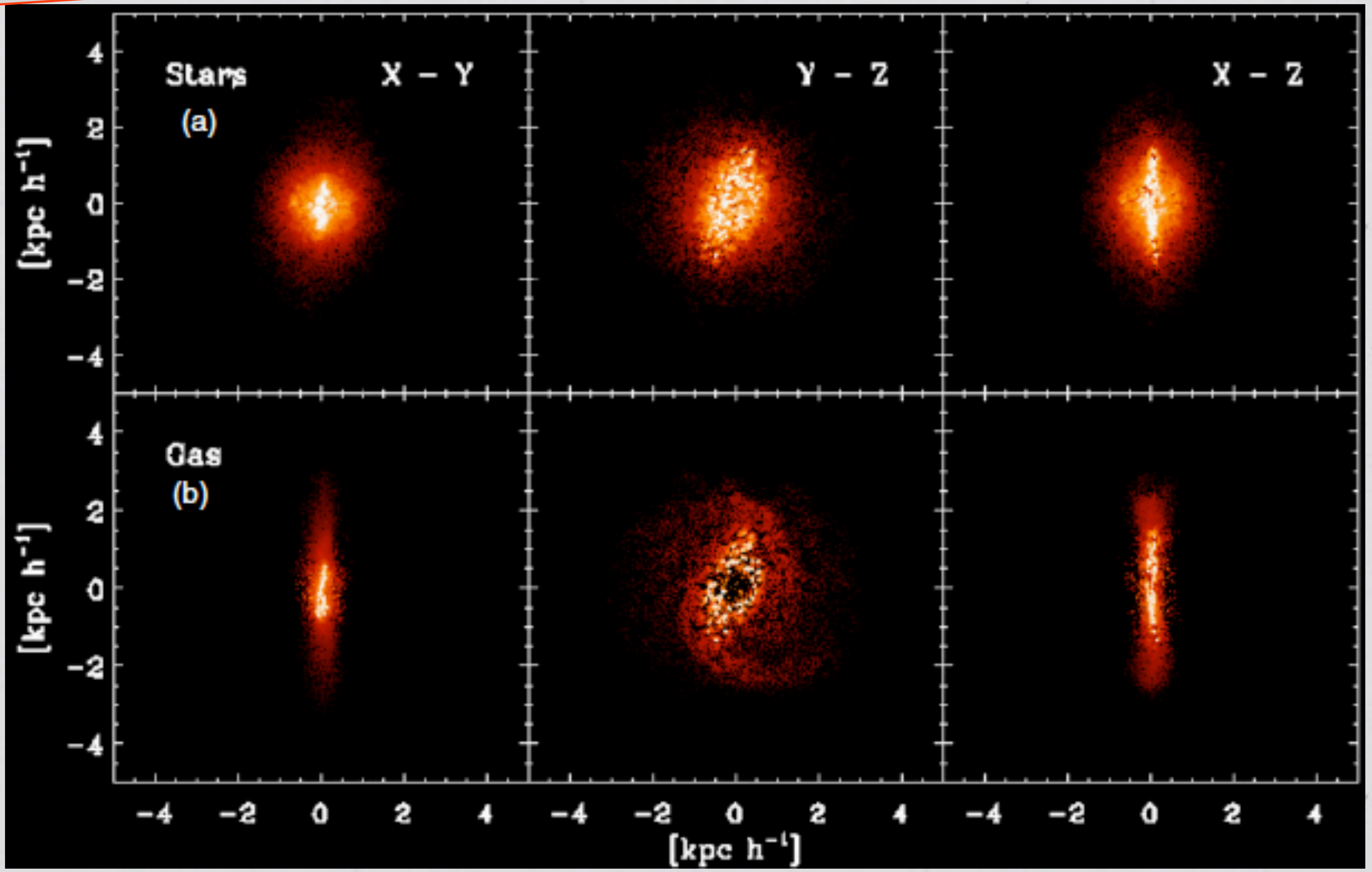
Observations provide direct model testing!

A disk galaxy at z=10.2

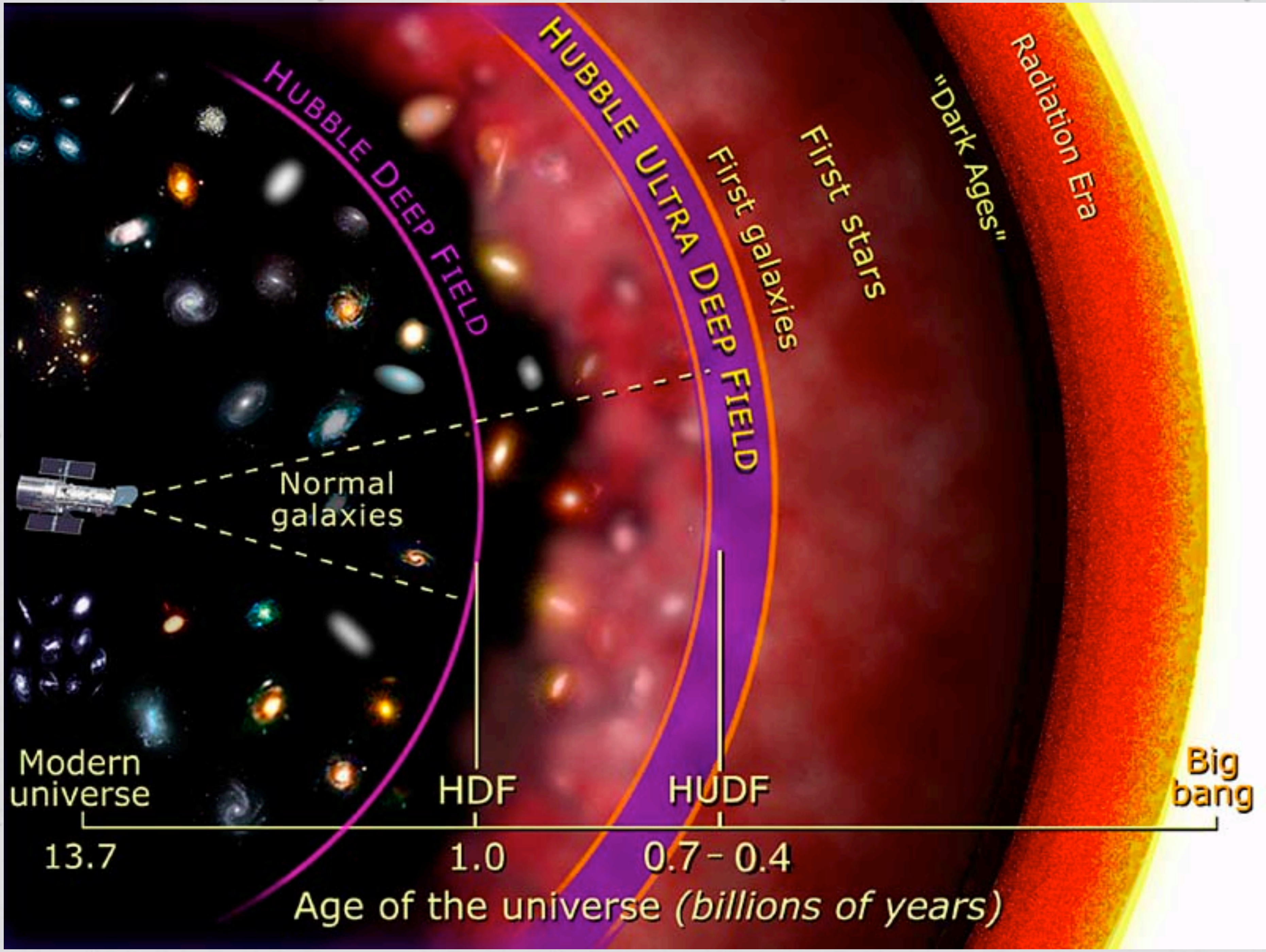
Stellar Mass	1.7e9 Msun
Disk Gas Mass	4.1e9 Msun

SPH-hydro simulation with $n=2x1024^3$

Romano-Diaz, Choi, Shlosman & Trenti (2011)



Observing the First Galaxies



HUDF09: Highest-z Galaxies

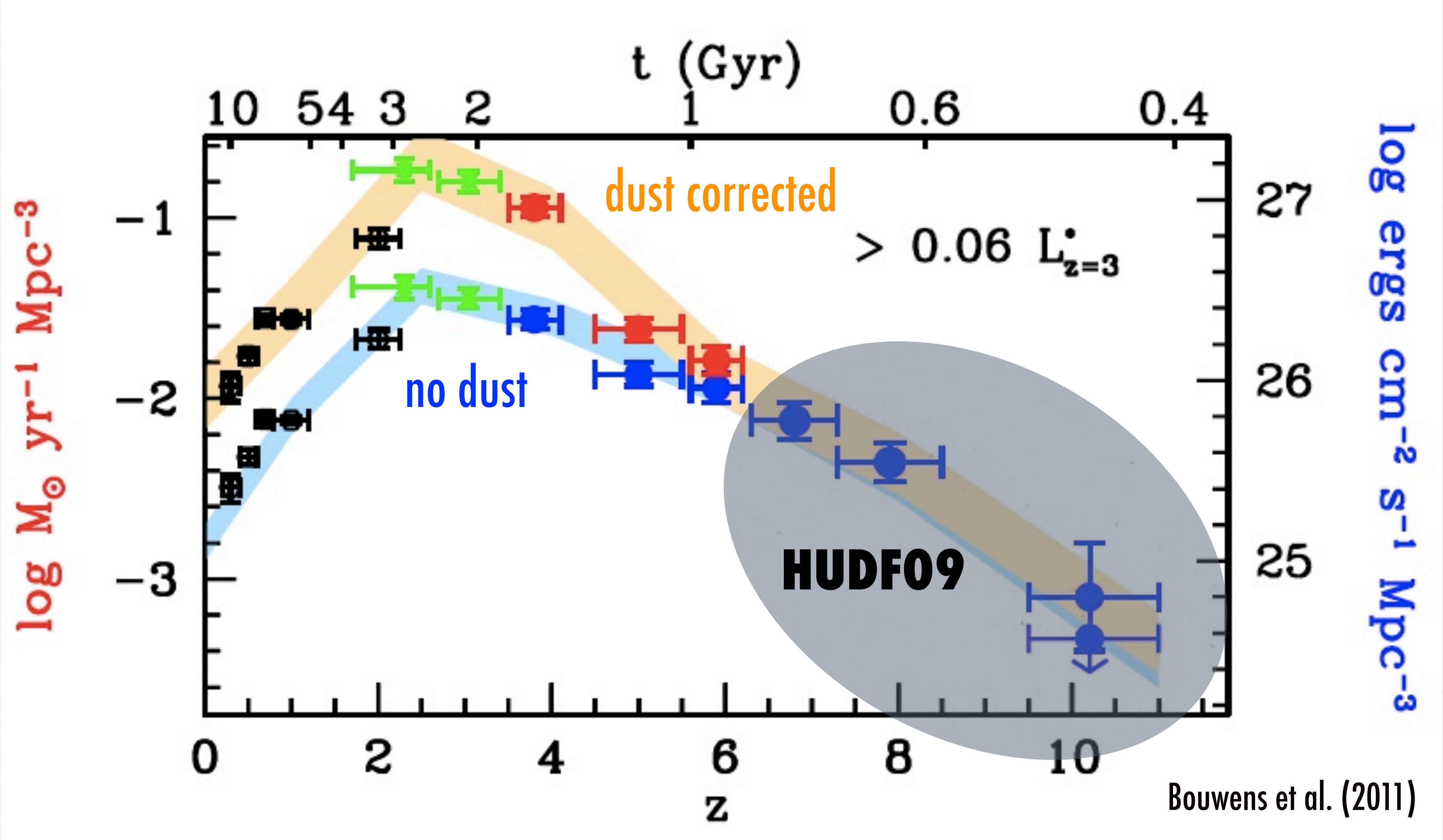
★Cycle 17 Treasury program with WFC3 (PI Illingworth): deepest near-IR image

★Exciting results from the dataset [see Pascal's talk] (16 papers from our team):

- ★frontier of galaxy detection extended to z~10
- ★properties of galaxies at z~7-8
- ★**galaxy luminosity function evolution**

Cosmic star formation history

★Star formation declines steadily at high z: Do we understand why?



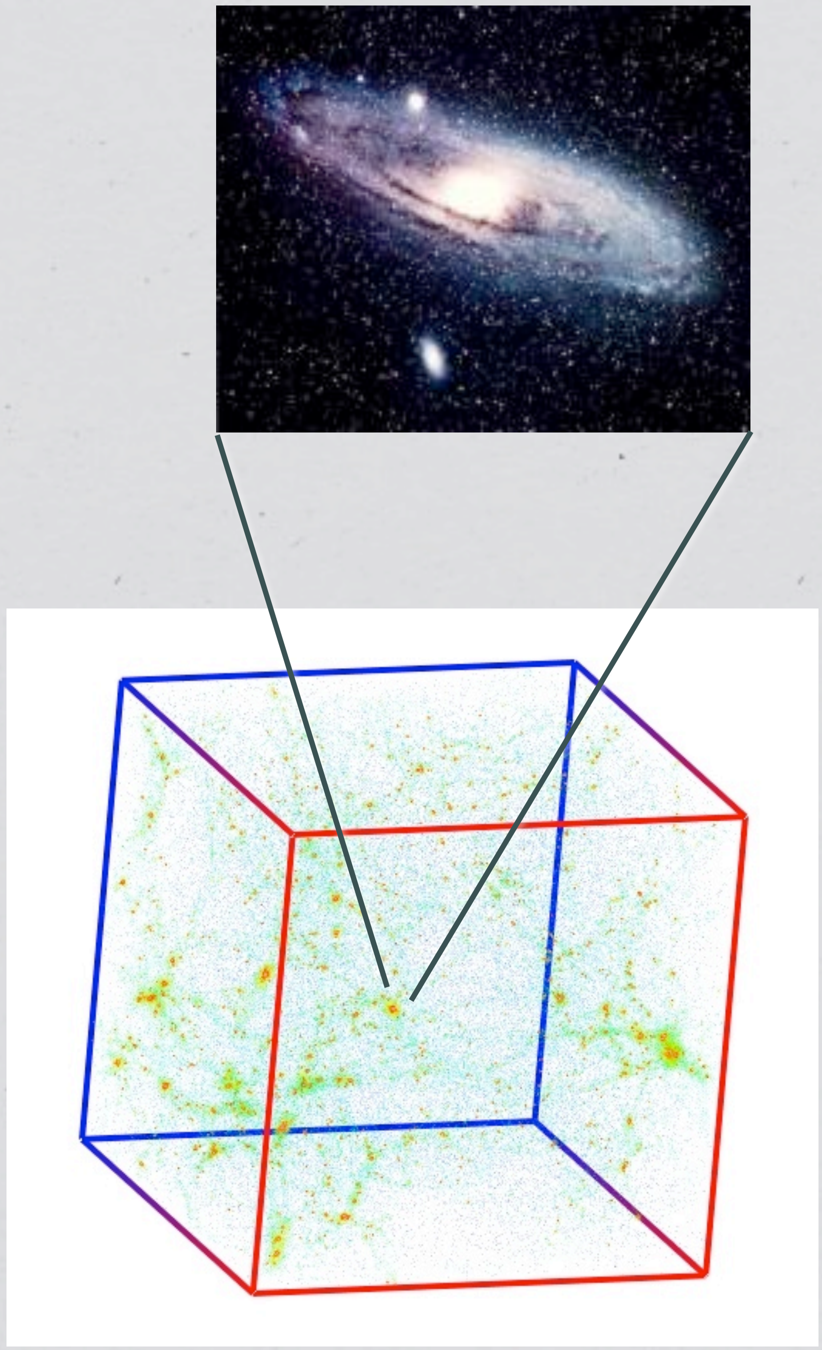
Luminosity Function Evolution

★ Progressively less large scale structure at high z

- Halos at fixed mass rarer

★ Model to link dark matter halo mass function to galaxy luminosity function

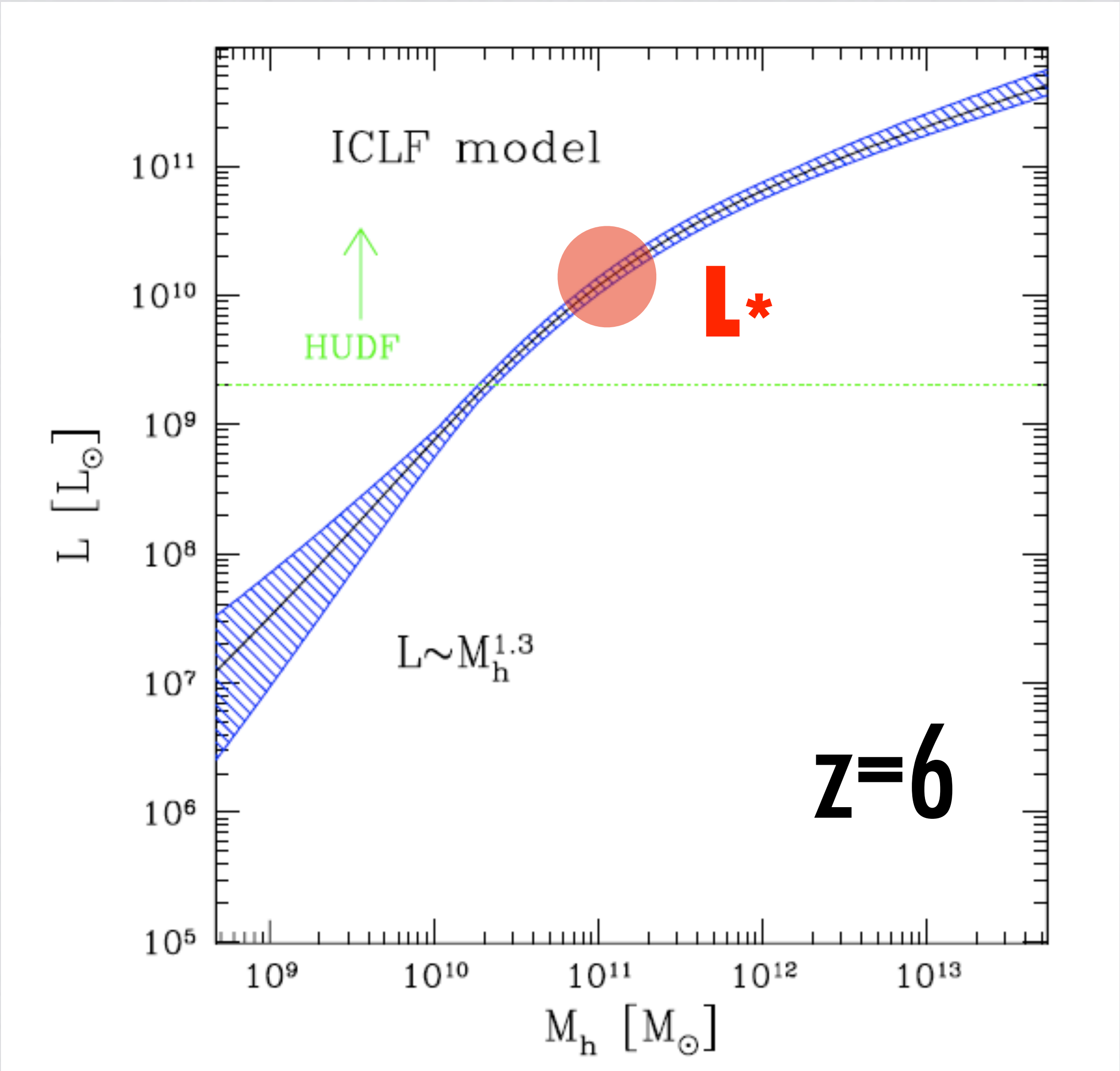
- One galaxy per halo, if recently assembled (merger within 200Myr)



Mass-luminosity relation

- ★Model assumes brighter galaxies in more massive halos
- ★$L(M_h)$ calibration at z=6
  - z=6 L_* galaxy lives in ~10^{11} M_{sun} halo
- ★$L(M_h)$@z=6 combined with 4≤z≤6 halo MF to validate model

Galaxy luminosity vs. dark matter halo mass

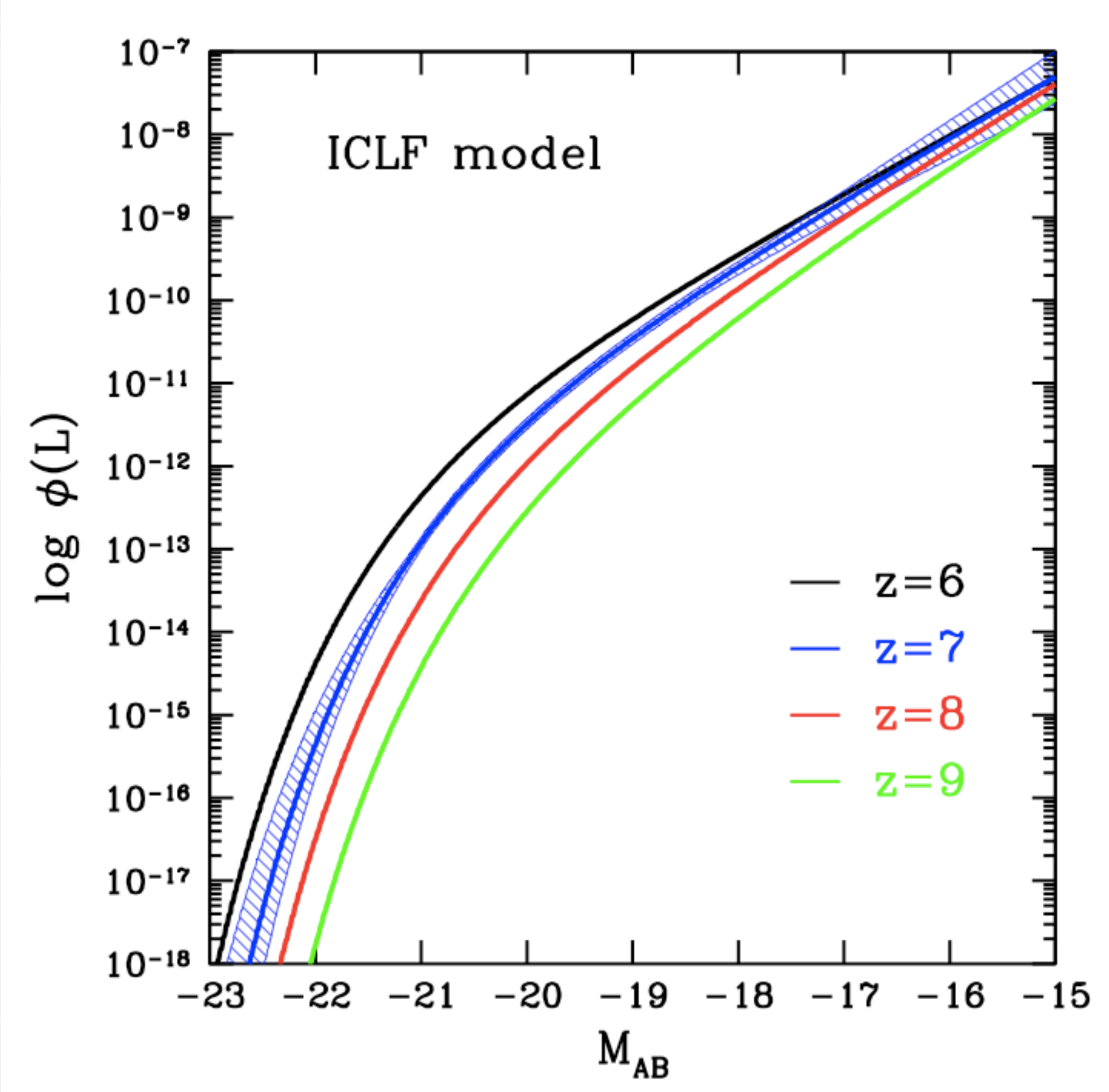


Trenti et al. (2010a)

Luminosity function evolution

★As redshift increases:

- Relatively more faint than bright galaxies (steeper LF faint end)
- LF normalization decrease moderately from z=6 to z=8



Trenti et al. (2010a)

Luminosity function evolution

★Predictions match observations very well

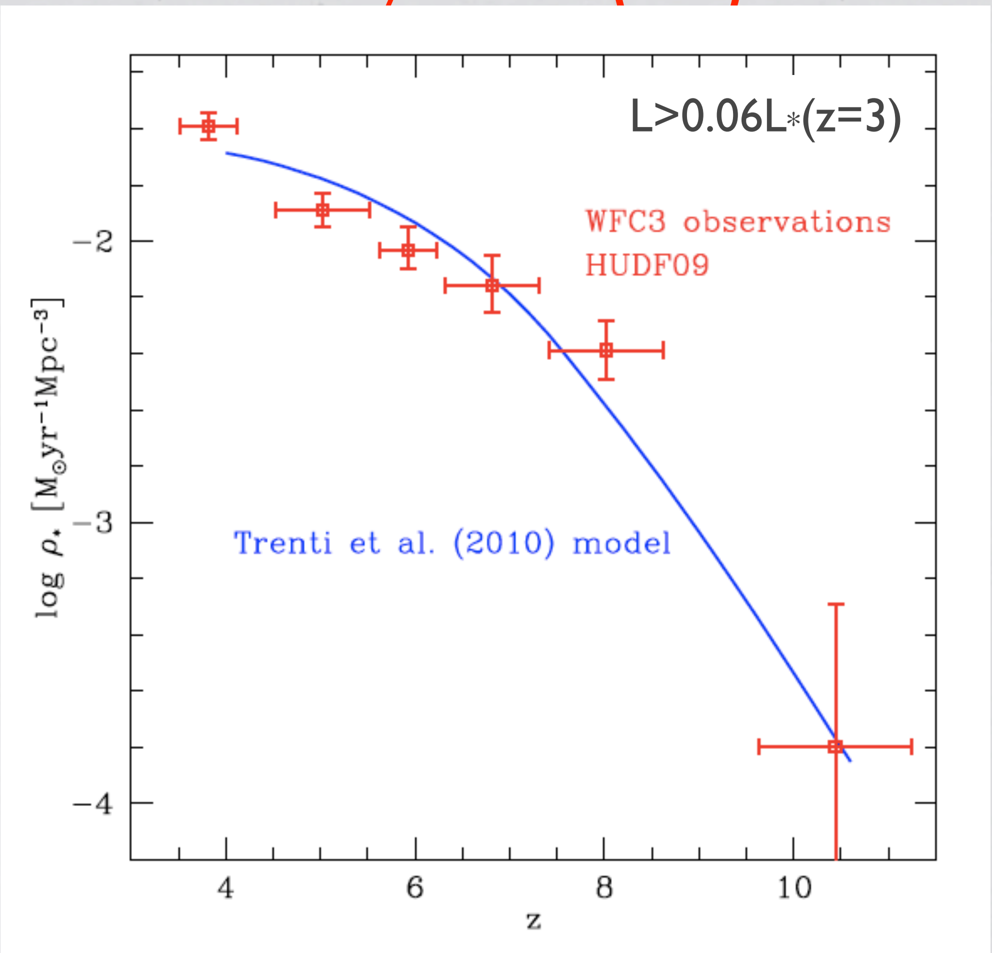
FIRST EPOCH HUDF DATA (2009)

Table 2: Predicted dropouts for HUDF09 field

		Observed	$ICLF_{200Myr}$
z~7	z-drop	16	13.4 ± 5.8
z~8	Y-drop	5	5.3 ± 3.1

Trenti et al. (2010a)

HUDF+ERS/CANDELS (2011)



Oesch et al. (2011)

★And good agreement with numerical simulations (e.g., Jaacks et al. 2011)

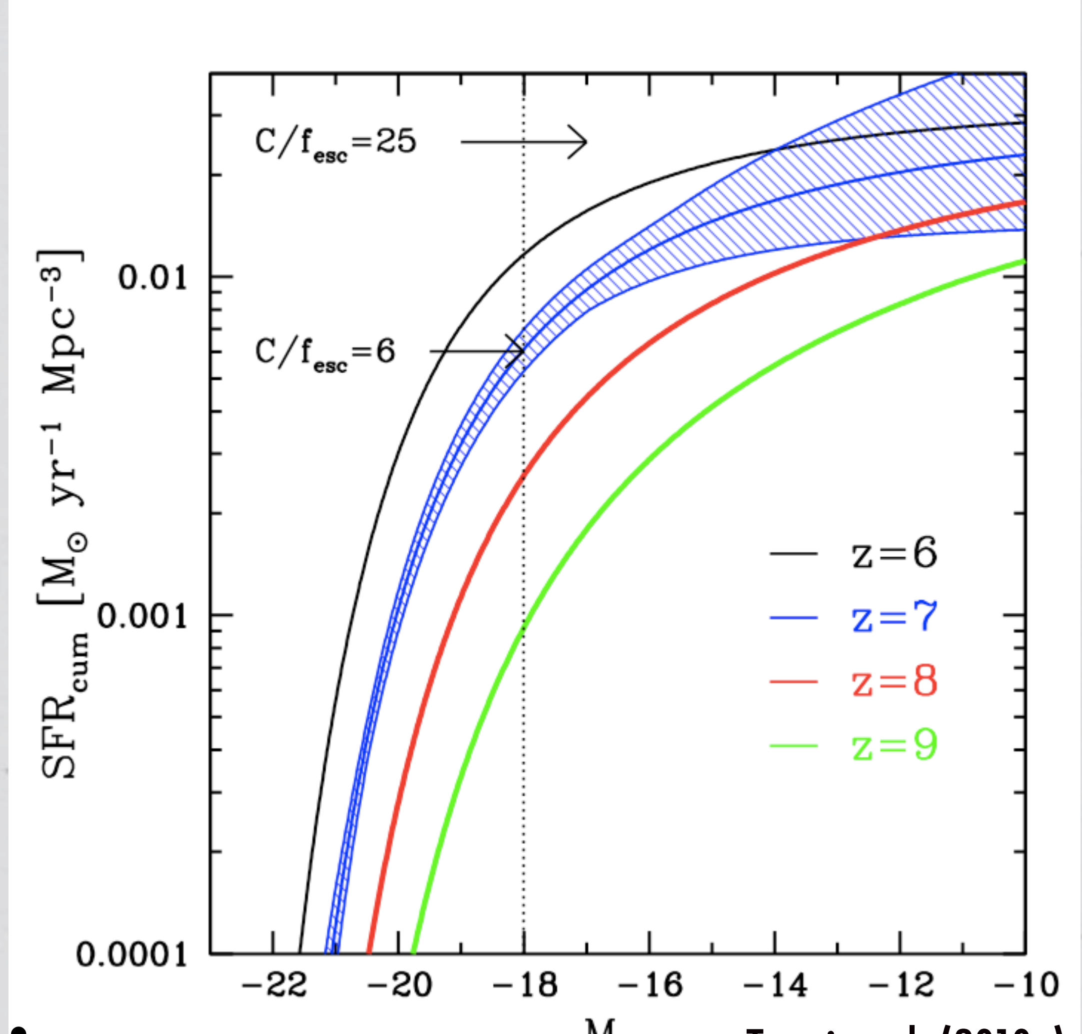
Reionization by galaxies: theory

★z~6 galaxies we see are barely able to keep Universe ionized

★**Are galaxies main agents of reionization?**

★Our model highlights large expected contribution from sources below detection limit (>75%@z=7): **Reionization by galaxies possible!**

Cumulative star formation rate, and critical values for reionization

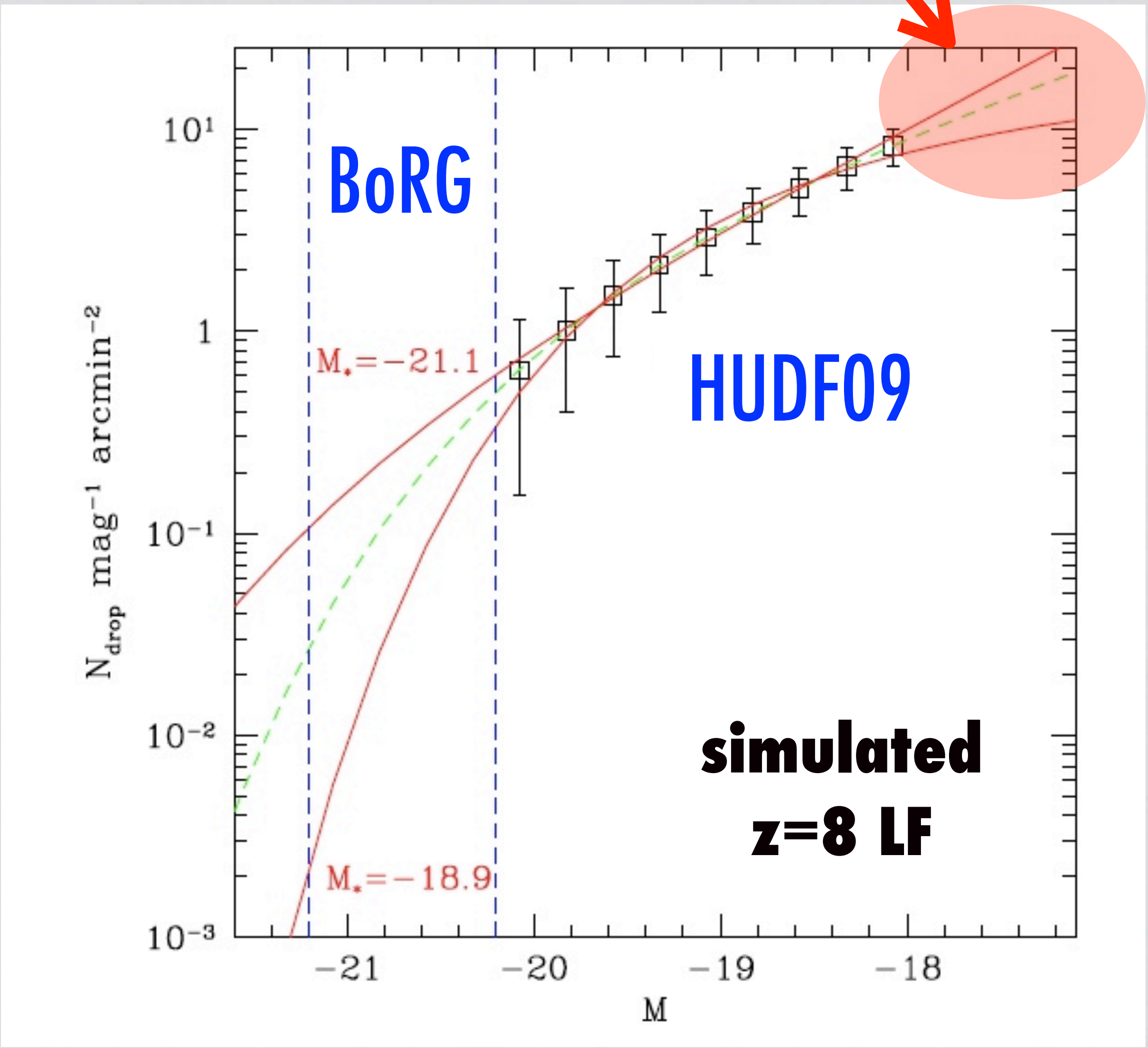


Trenti et al. (2010a)

Observations: Galaxies as agents of reionization?

- ★ Goal: accurate measure of faint end of galaxy luminosity function
- ➡ **Method: Combination of ultradeep and wide area HST observations to break fit degeneracy**

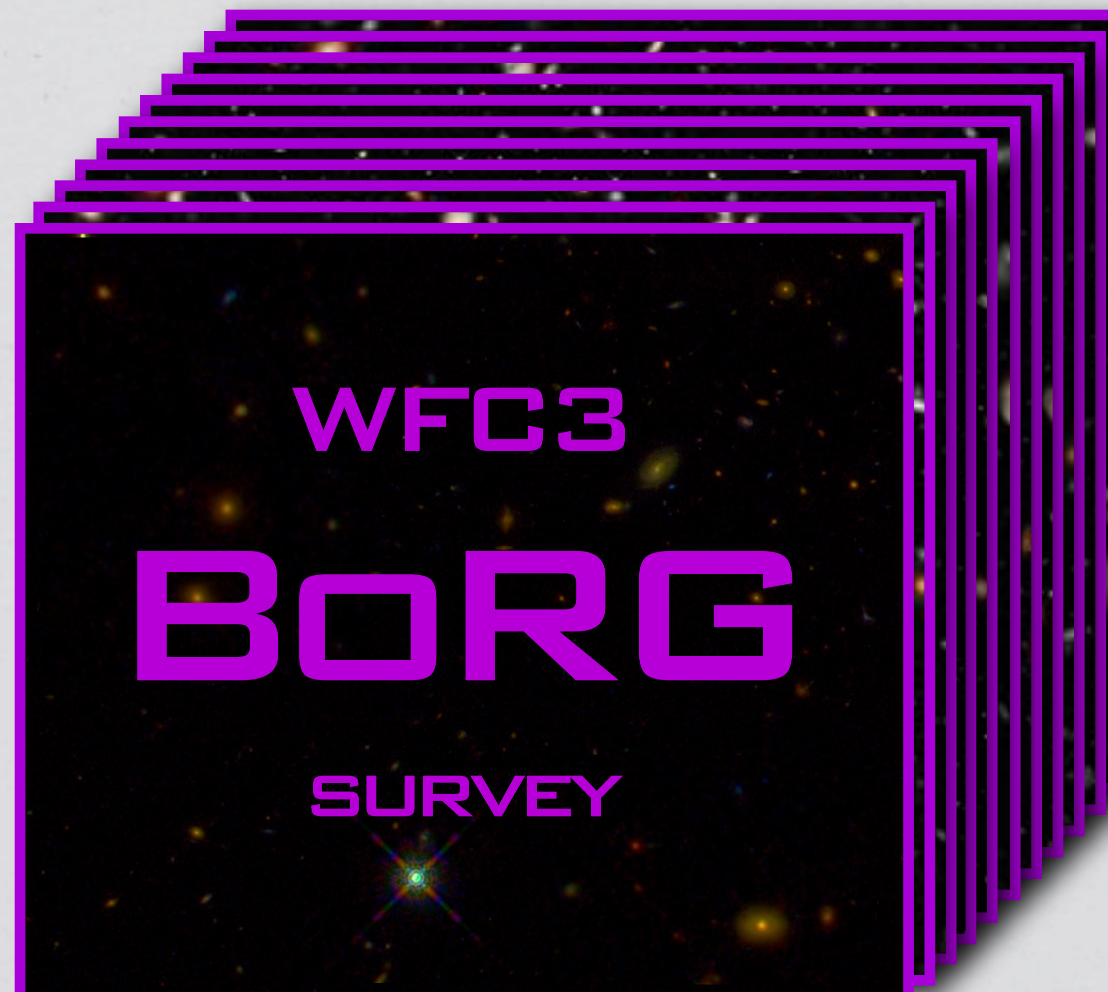
Reionizing sources



The HST BoRG Survey

★The Brightest of Reionizing Galaxies Survey

- Complements ultradeep data
- ~250 arcmin^2 to date
- 4 filters [V,Y,J,H]
- 4-6 orbits/visit: m_{lim}~27
- **Primary goal: identify Y-band dropouts (z~8)**

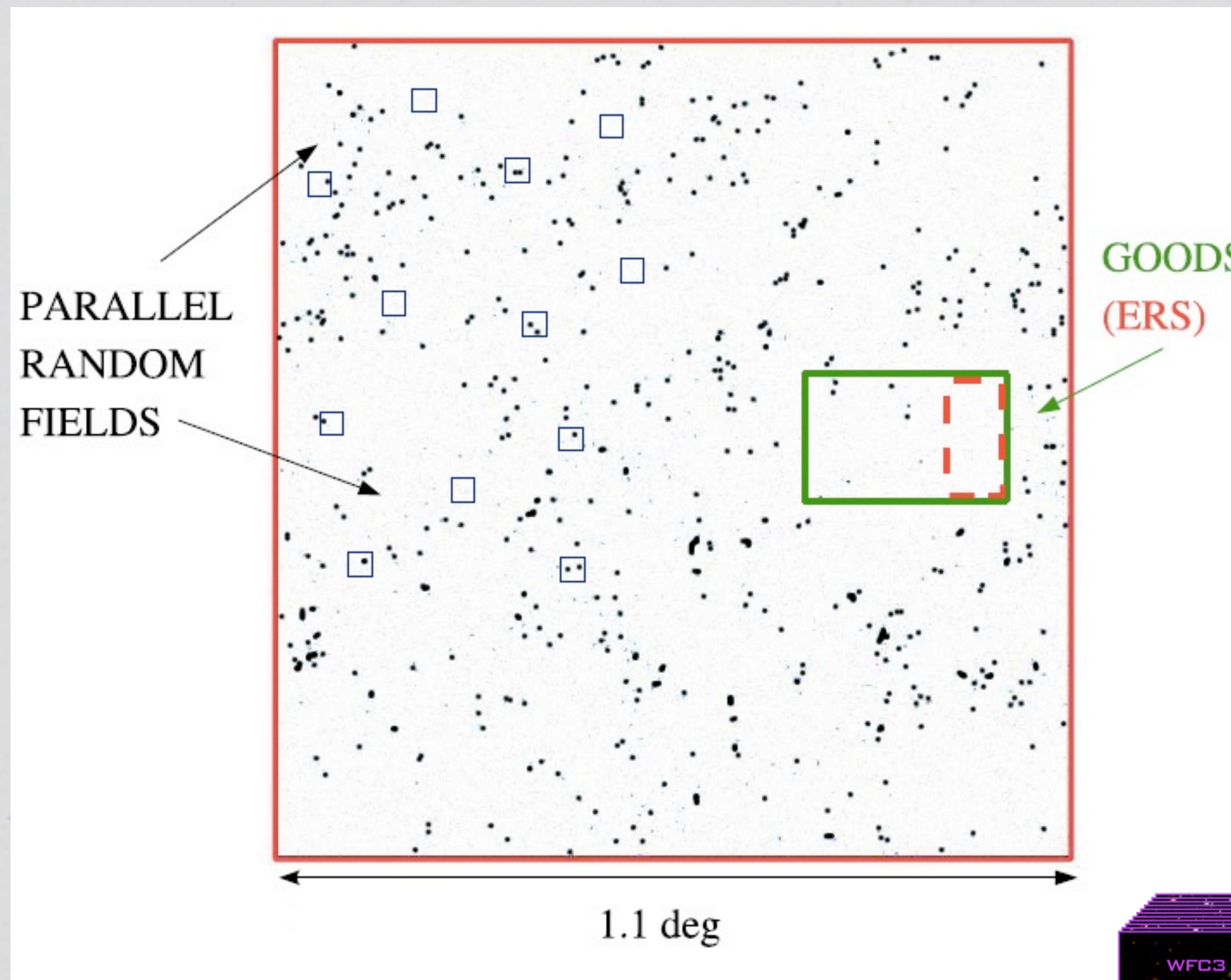


BoRG: beating cosmic variance

★Pure-parallel observations:

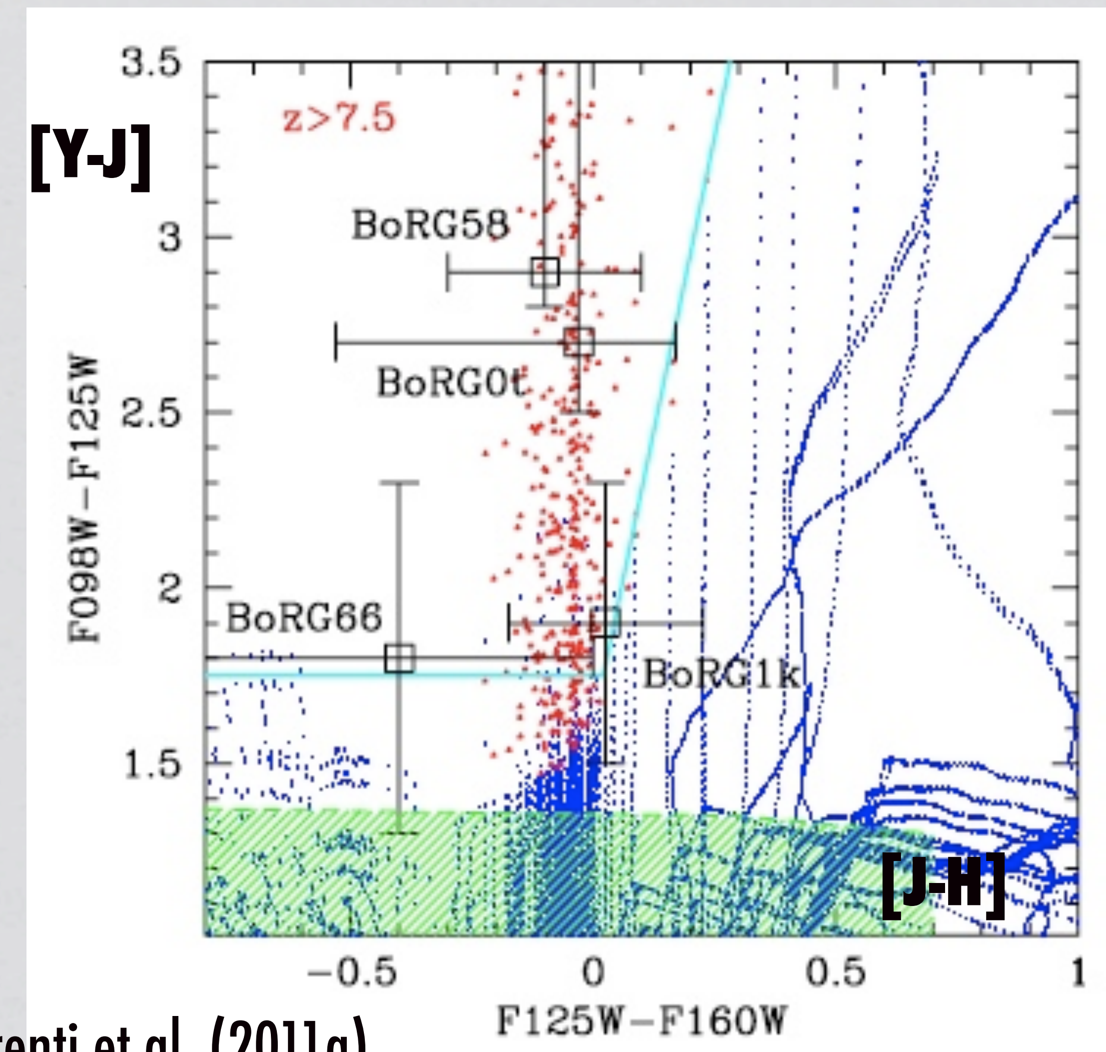
- random pointings optimal to avoid cosmic variance in LF measure

Simulated distribution of Y-dropouts with $m_{AB}<26.8$ from cosmological simulation of Trenti & Stiavelli (2008)

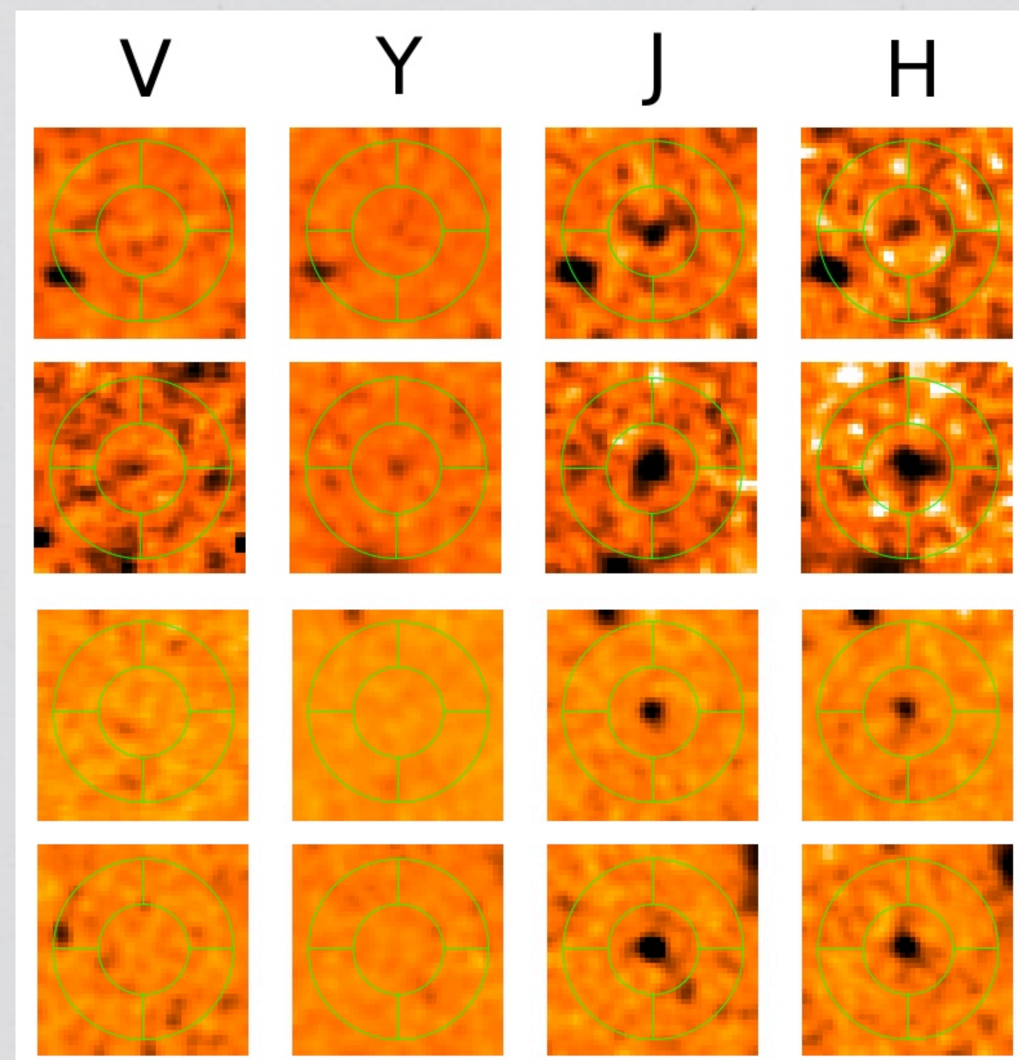


Some z~8 galaxies from BoRG

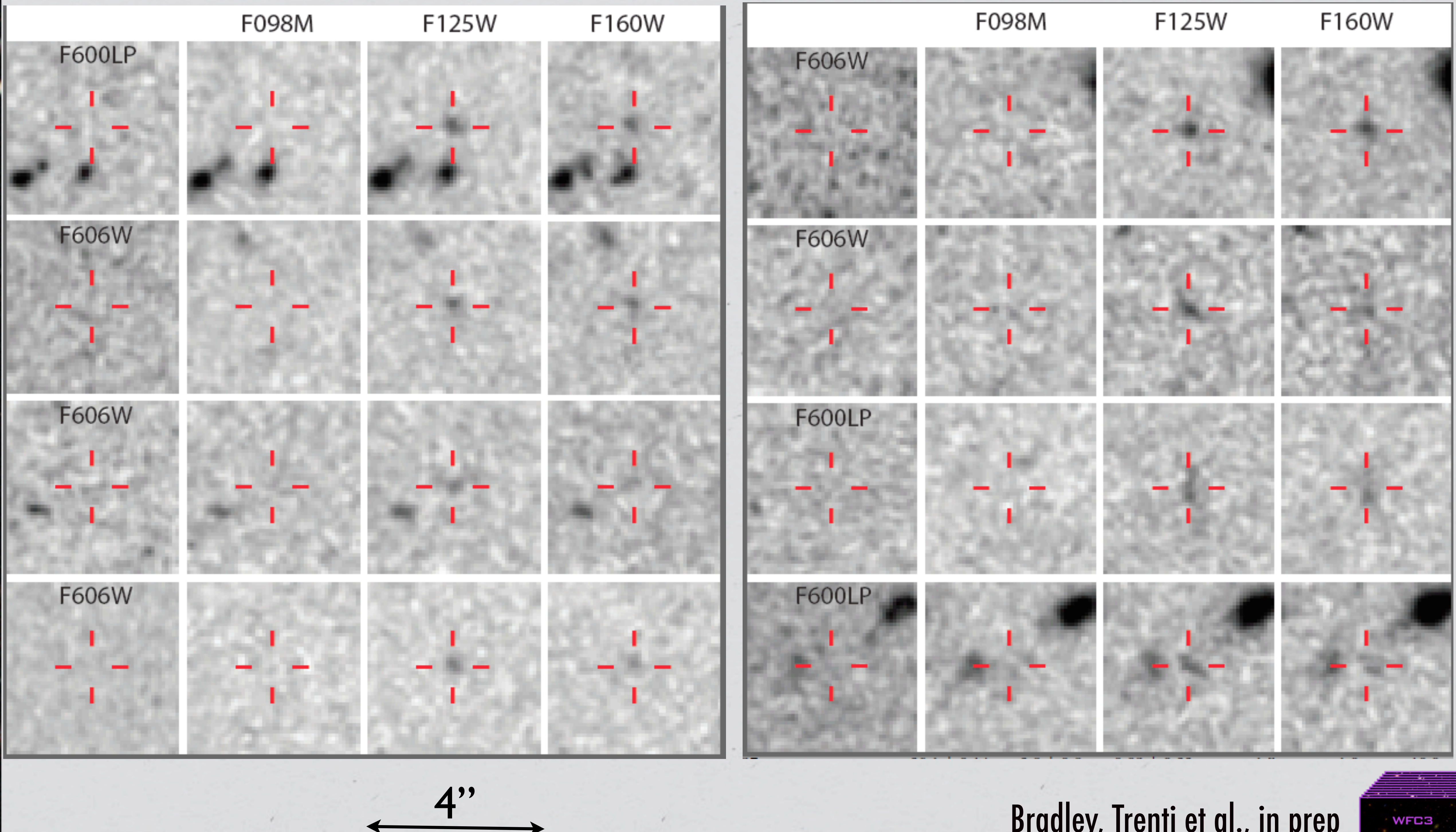
- ★ BoRG identifies the most luminous z~8 galaxies: n=8 with m_J<26.5; n>20 with m_J~27
- ★ A few candidates (from initial data) are below:



Trenti et al. (2011a)



The z~8 galaxies from BoRG



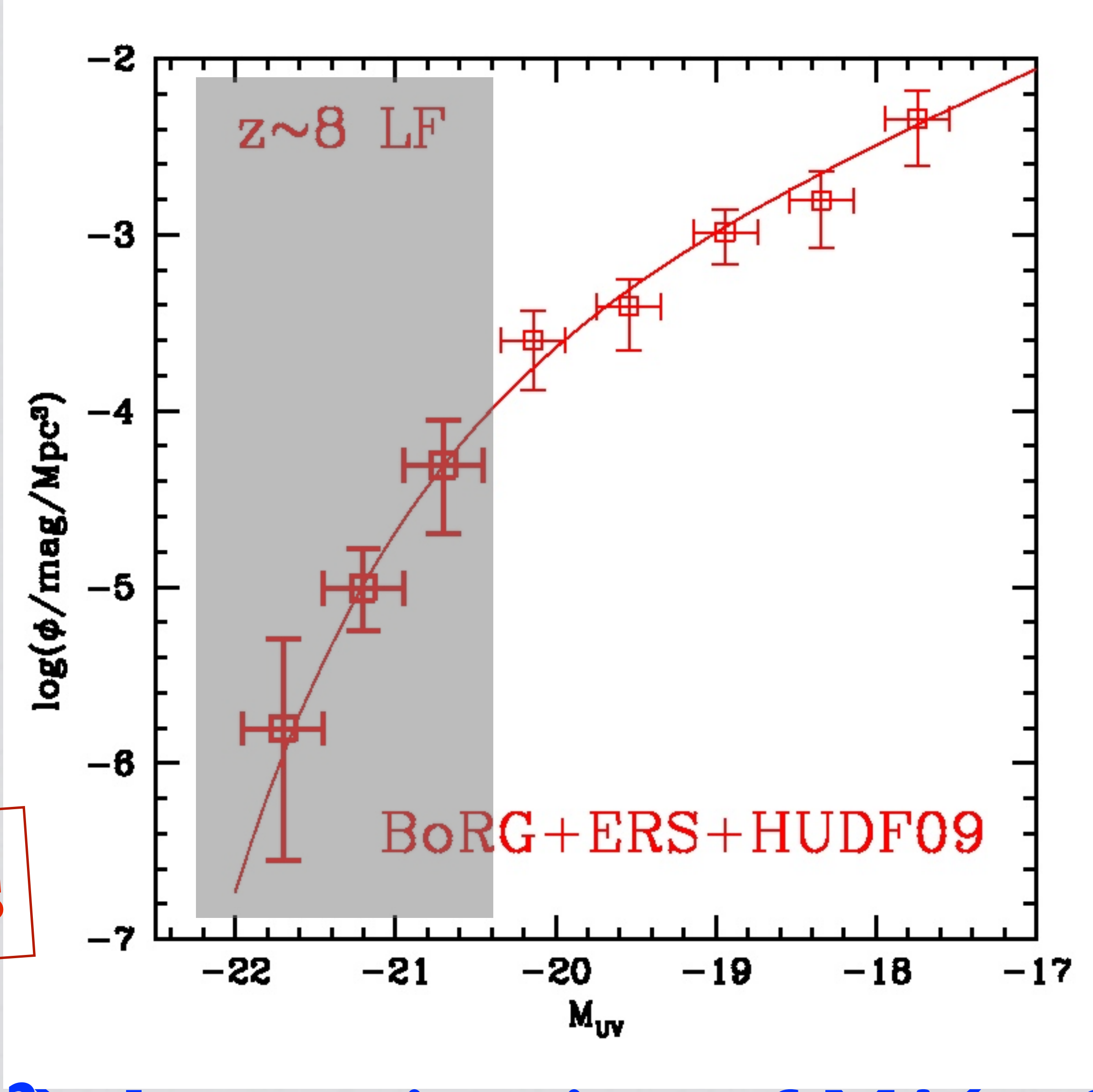
Bradley, Trenti et al., in prep

LF determination from BoRG

Bradley, Trenti et al., in prep

★ Combining bright BoRG detections with faint-end from ultradeep data:

- M*= -20.0±0.3 (68% CL) @ z=8



Exponential bright-end!

Largest area (~250 arcmin²) determination of M*(z=8)

[CANDELS area ~80arcmin², Oesch et al. 2012, Yan et al. 2012]

WFC3 BoRG SURVEY

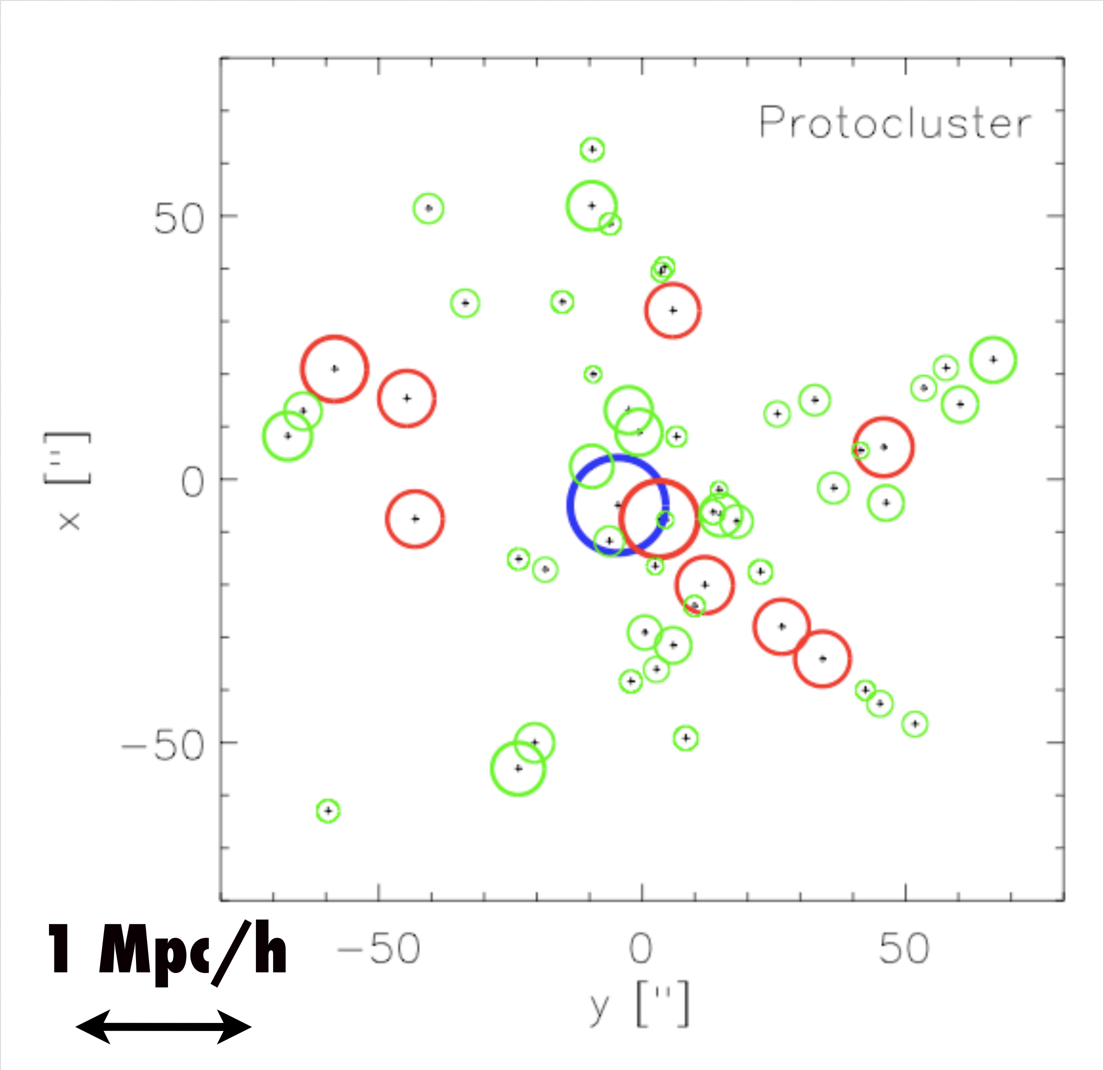
BoRG sources: proto-cluster beacons

★Theoretical expectation:

- Bright z~8 sources live in overdensities (M_h~5×10^{11} M_{sun}) with high dark-matter halo clustering (bias b~8)

  - clustering of fainter dropouts around BoRG bright sources

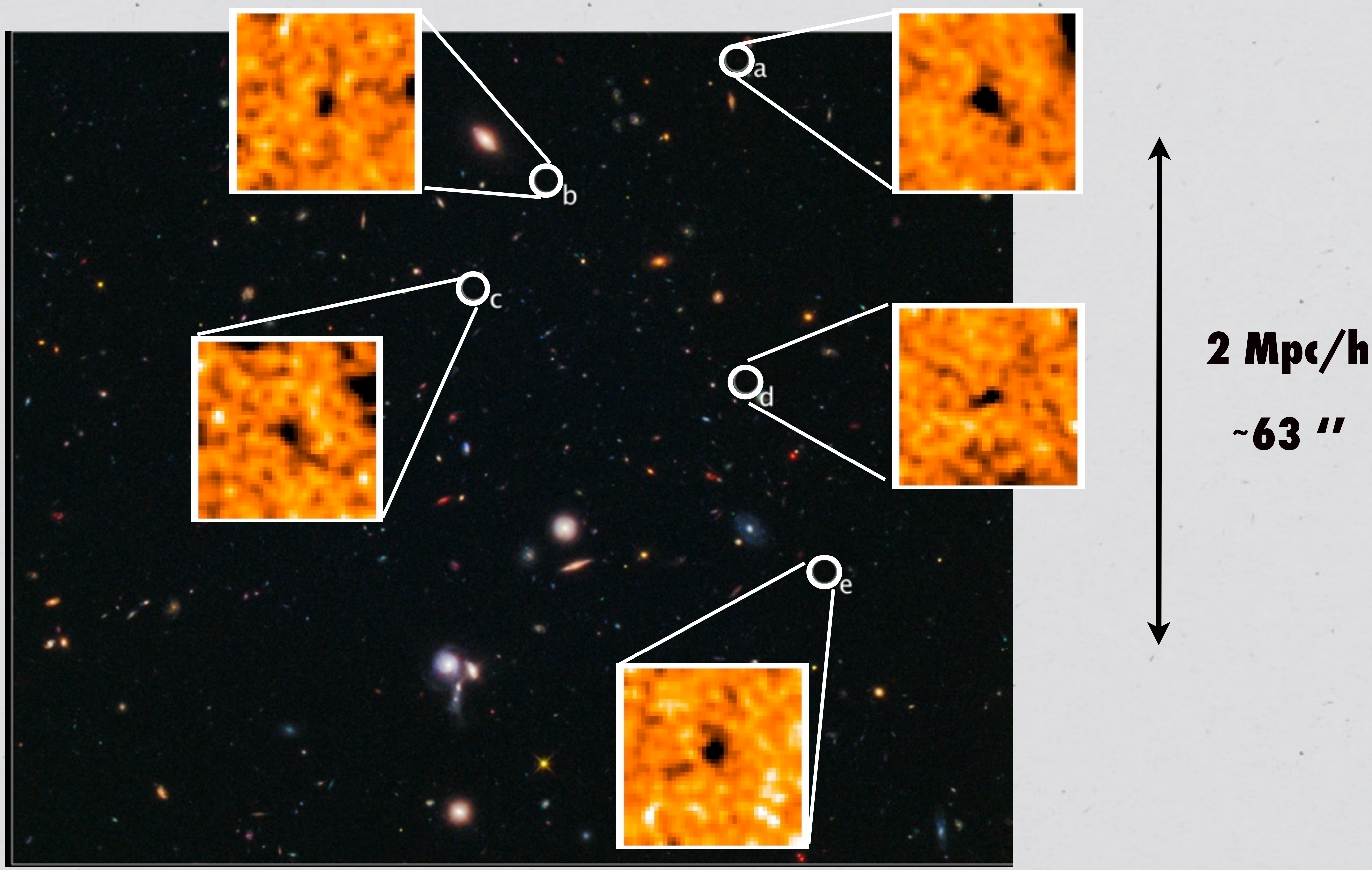
Clustering from cosmological simulation



Trenti et al. (2012a)

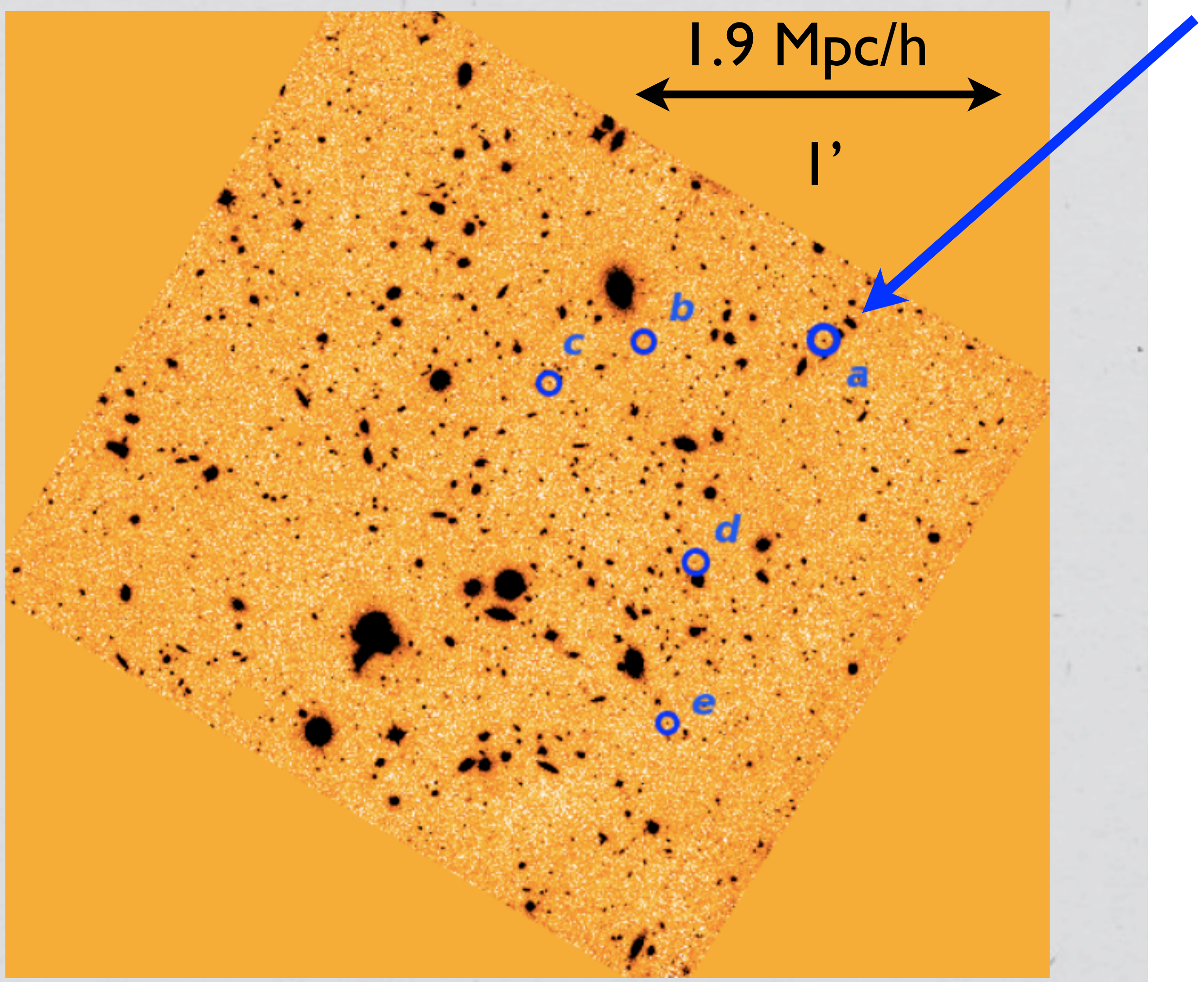
A z~8 proto-cluster candidate

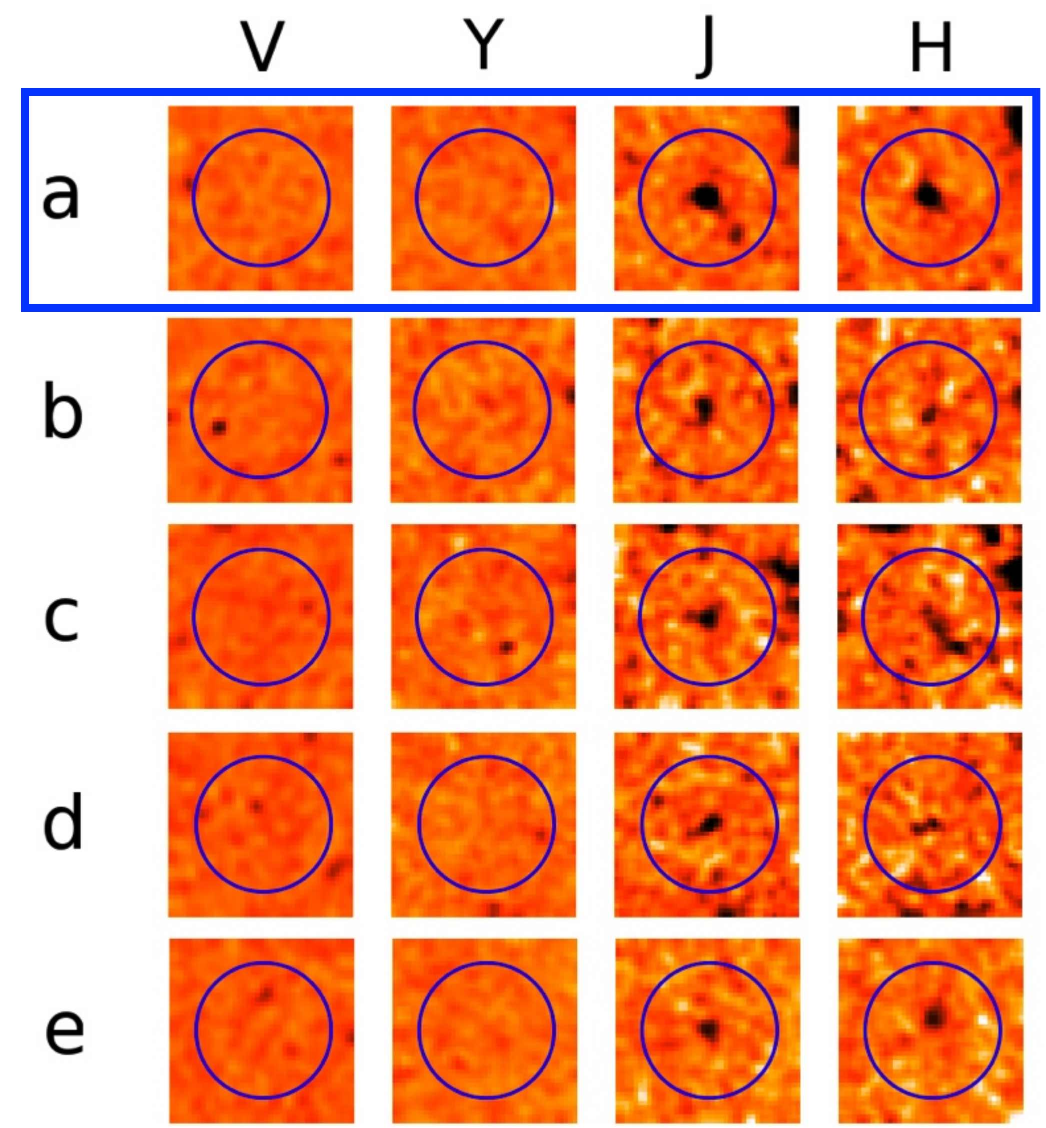
★Fainter z~8 companions seen in BoRG58



A z~8 proto-cluster candidate

- proto-cluster signal at >99.97% CL
  - (from simulations including cosmic variance)
  - observations consistent with theory expectations



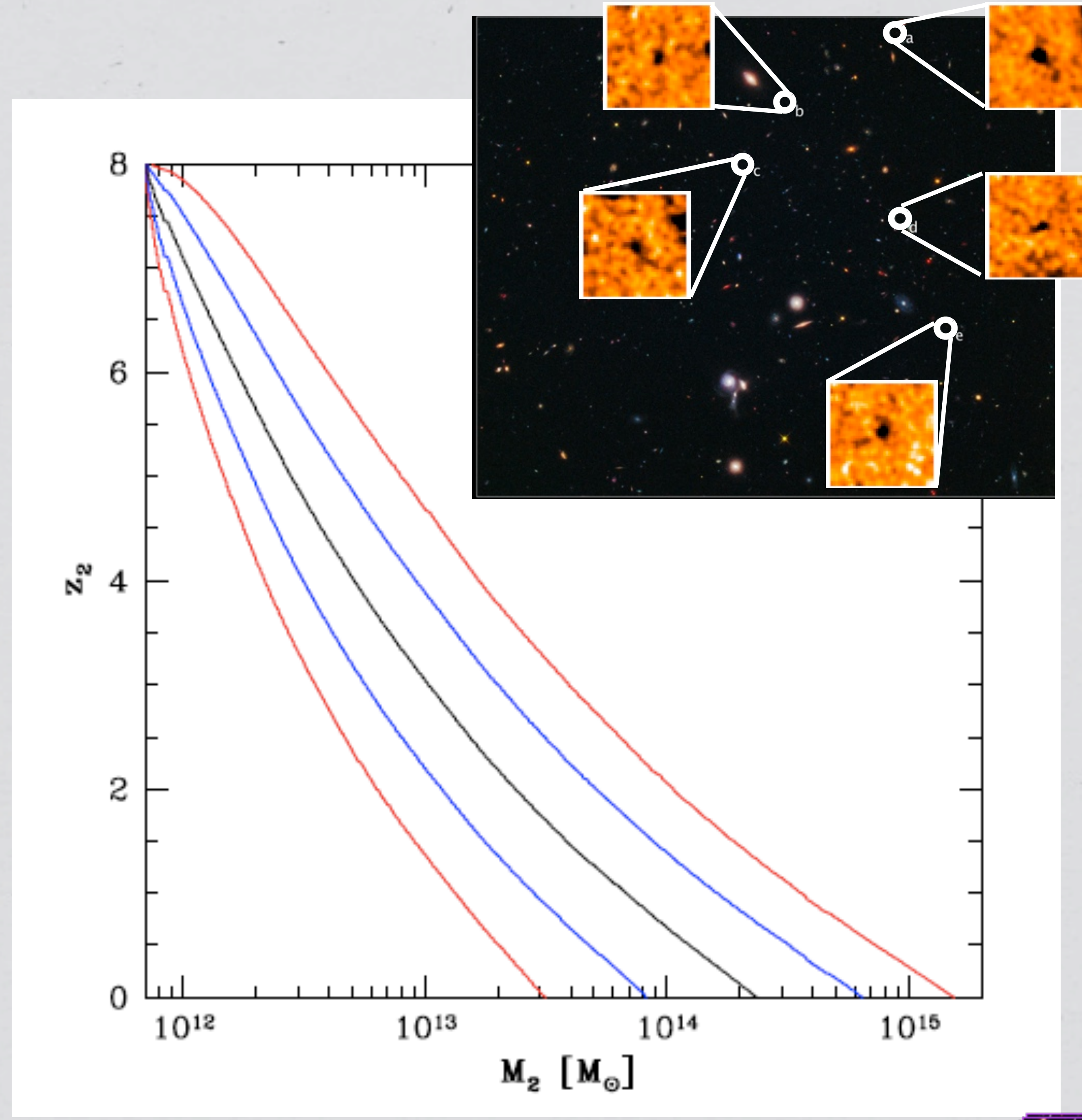


Trenti et al. (2012a)

Proto-cluster evolution

★ BoRG proto-clusters are progenitors of today's galaxy clusters

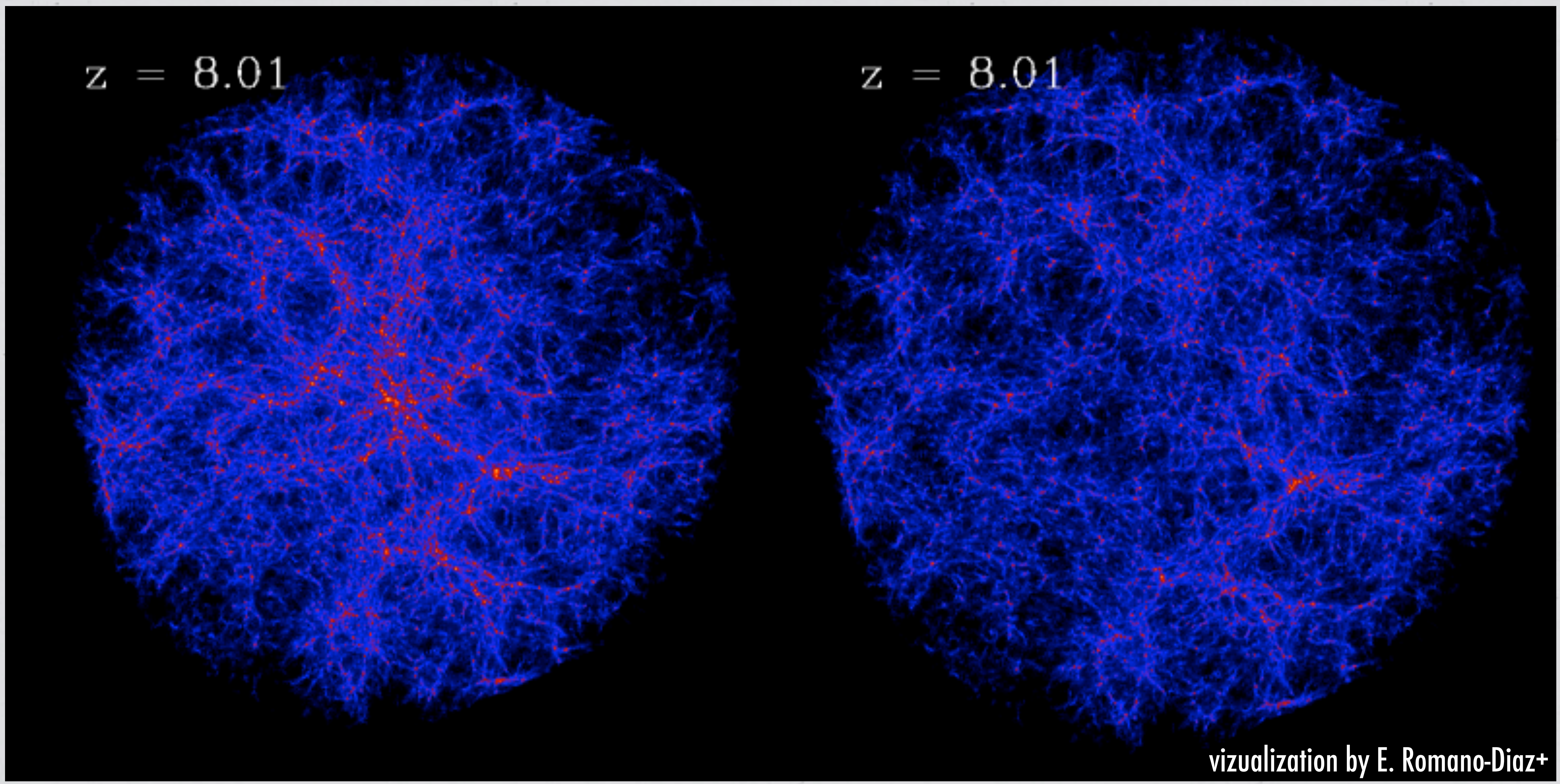
- DM halo mass $M > 2x10^{14}\ M_{sun}$ by z=0



Trenti et al. (2012a)

Proto-cluster: Past and Future

Proto-Cluster Region **Average Region**



20 Mpc/h

Trenti et al. (2012a)

We are the BoRG: your data will be assimilated

★BoRG is growing:

- **~140 additional orbits scheduled in 2012**

- + use of archival data (COS-GTO/Hippies survey)

★**Goal: quadruple area**

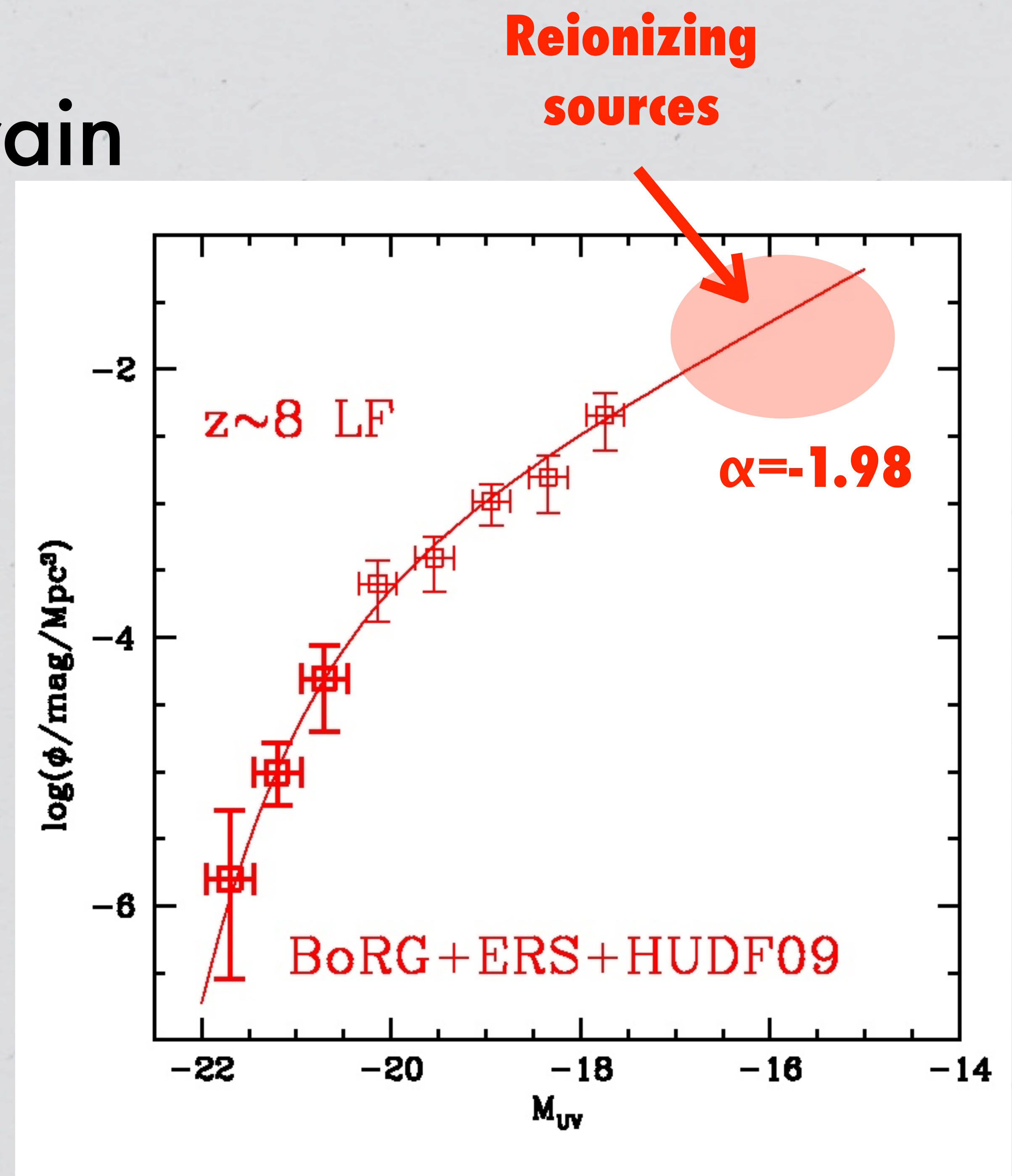
(solid measure of LF bright-end + discovery of more protoclusters)

WFC3 BoRG SURVEY

Testing the luminosity function extrapolation

- ★ BoRG+HUDF09 constrain agents of reionization *under Schechter LF assumption (and/or physical LF model)*

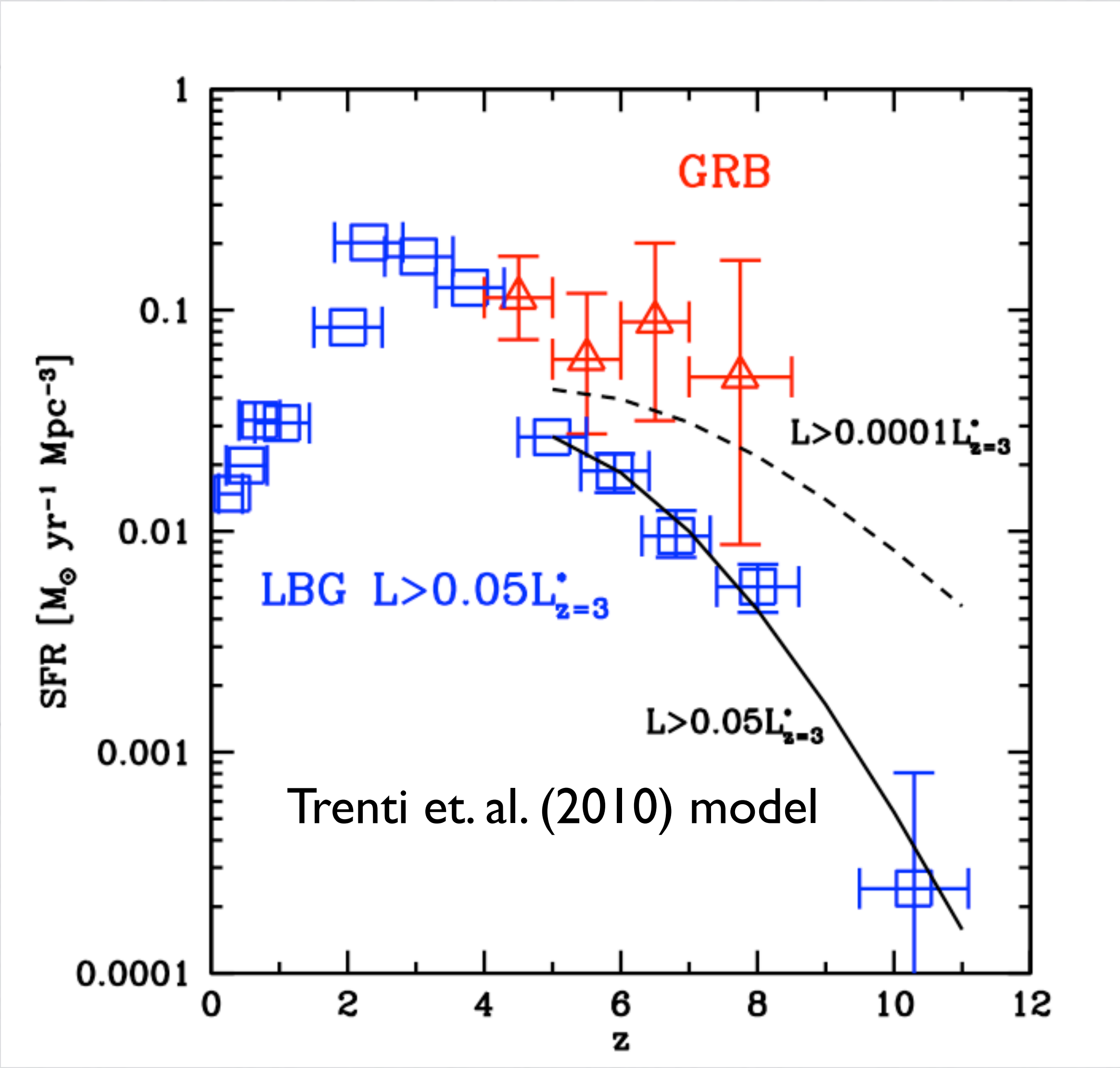
- ★ Can we test star formation in faint galaxies **directly**?



Star formation rate from GRBs

★GRB rate estimates **total** star formation
(e.g., Kistler et al. 2009; Robertson & Ellis 2012)

- ★no galaxy luminosity cut-off
- ★excess at high-z consistent with our model predictions
- ★but... several assumptions from GBR rate to SFR

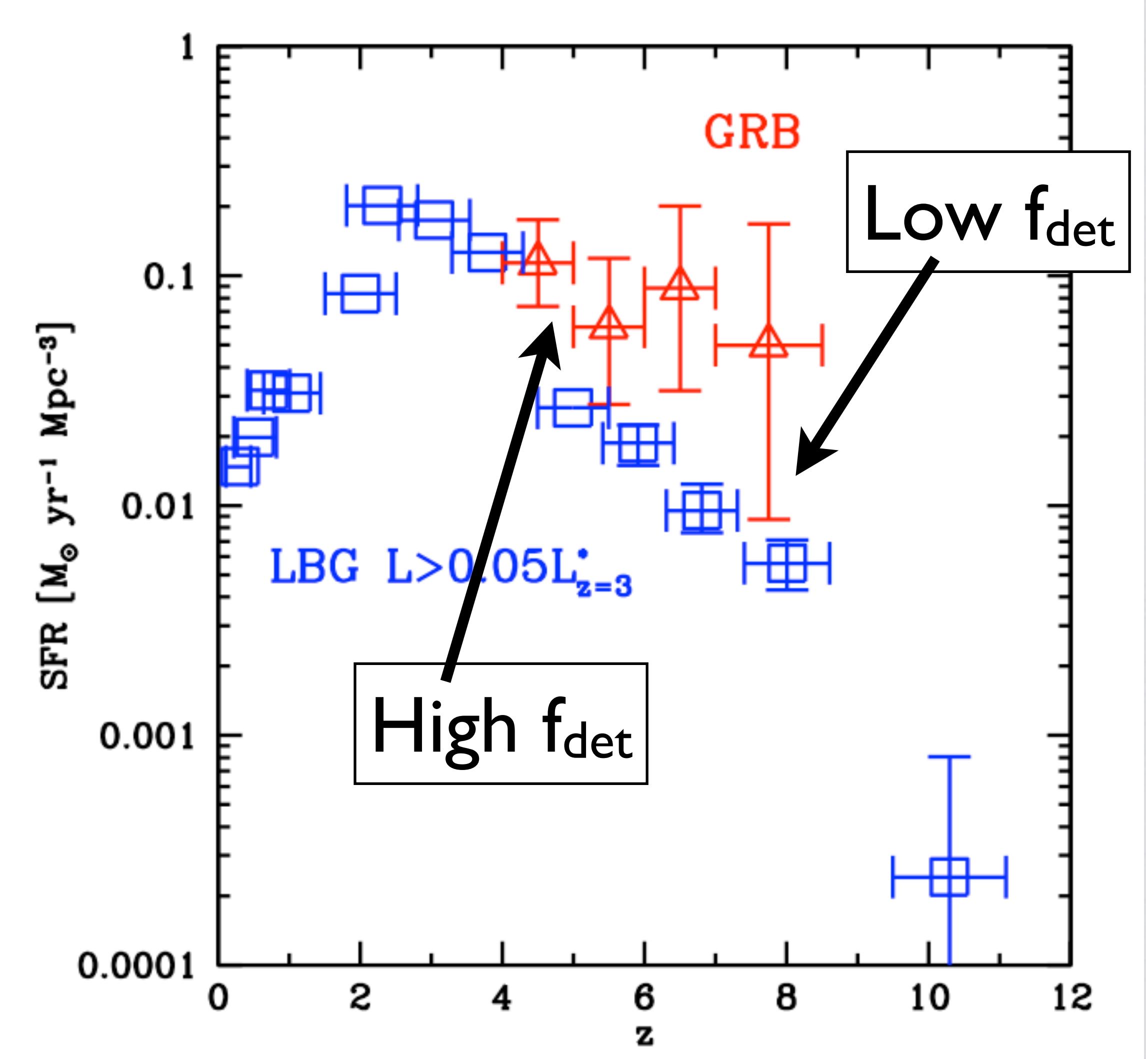


Trenti et al. (2012b), ApJL submitted

GRB host detection as model test

$$f_{det}(L > L_{lim}, z) = \frac{\dot{\rho}_*^{(LBG)}(L > L_{lim}, z)}{\dot{\rho}_*^{(GRB)}(z)}.$$

★The fraction of GRB hosts detected to $L>L_{lim}$ quantifies missing star formation *with little dependence on model assumptions!*

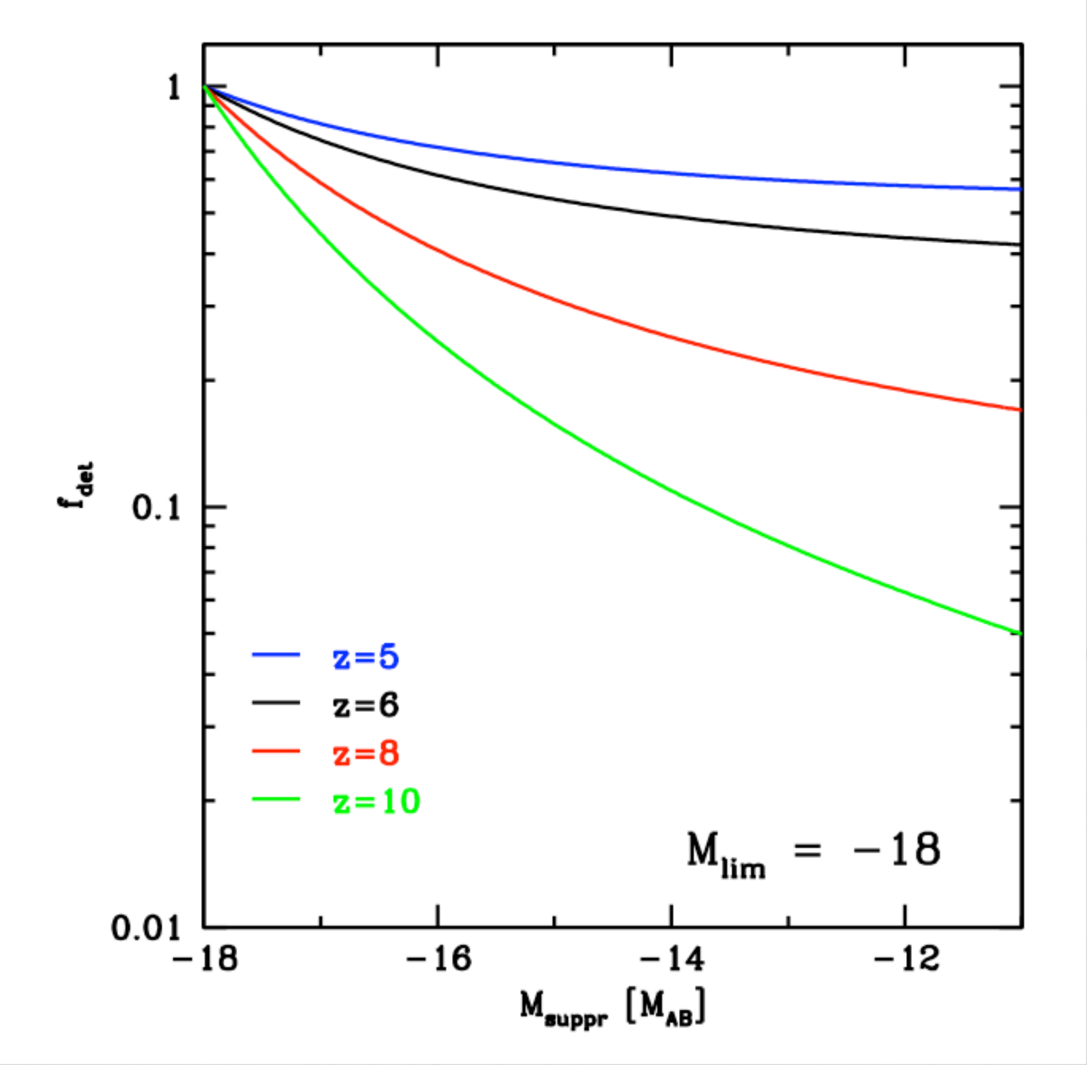


Trenti et al. (2012b), ApJL submitted

GRB hosts probe reionization

$$f_{det}(L > L_{lim}, z) = \frac{\dot{\rho}_*^{(LBG)}(L > L_{lim}, z)}{\dot{\rho}_*^{(GRB)}(z)}.$$

- ★ f_{det} from all 19 GRBs at z>4 can provide definitive answer on presence of very faint galaxies (with M>-15)
- ★ measure within reach of HST!



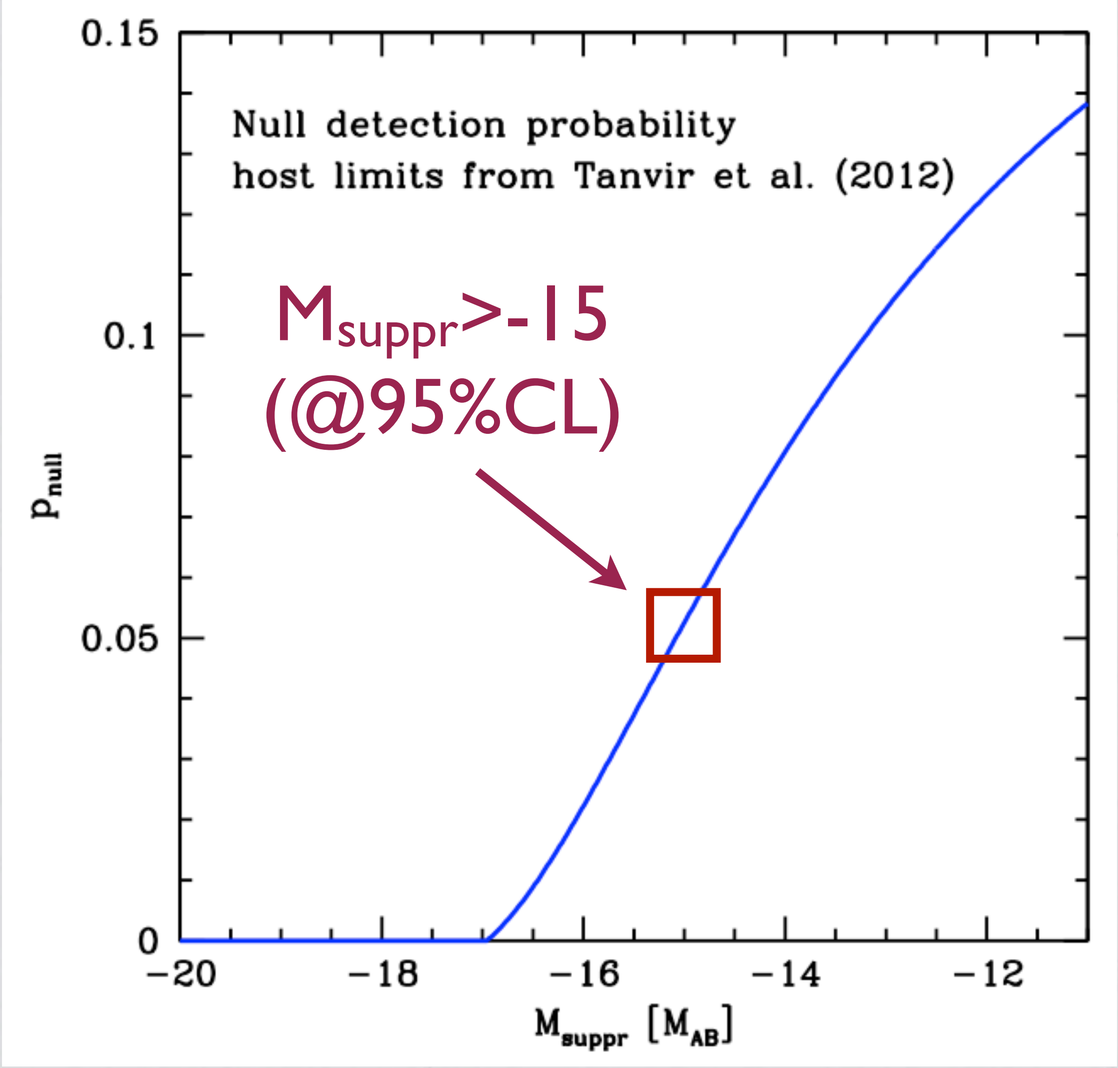
Trenti et al. (2012b), ApJL submitted

GRB hosts probe reionization

★ Tanvir et al. (2012) just posted non-detection limits from HST search of GRB hosts at z>5 (6 targets)

★ Our analysis of their limits proves at >95% confidence that **M_{AB}>-15 galaxies are present at z>5:**

★ ~3 mag improvement over HUDF limit!



Trenti et al. (2012b), ApJL submitted

Summary

- The first Gyr after the Big Bang is characterized by a complex interplay between metal free (first stars) and metal enriched (first galaxies) star formation
- Hubble's WFC3 opened a new window on this epoch, properties of galaxies at $z>7$ characterized with good samples: tests of theoretical models, including clustering
- Preliminary evidence suggests that a large number of (faint) galaxies were present, producing enough ionizing photons to be consistent with WMAP τ_e measurement
- To constrain their luminosity function we need the right mix of deep (HUDF like) and wide (BoRG like) surveys
- GRB host galaxy surveys have exciting prospects for inferring star formation in the lowest luminosity galaxies