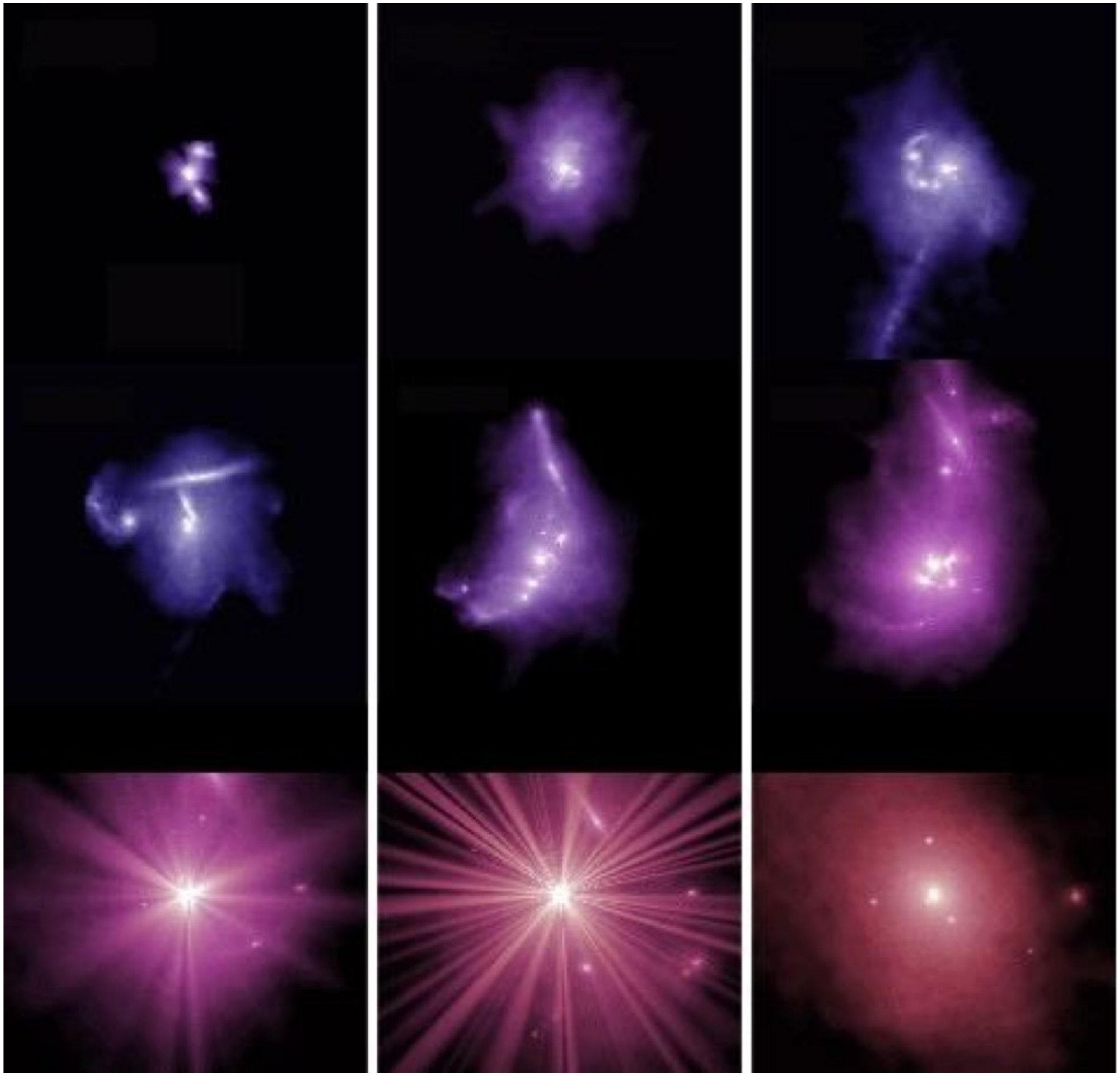
Astronomy 537



Lecture 17: Galaxy Formation II

What about formation of ellipticals?

Old, single age stellar population, not rotationally supported.

- Complete star formation before disk could form?
  - does not agree so well with the hierarchical picture

- OR, only disk systems formed, E's made by mergers (recall Toomre sequence).
  - evidence for a small 'frosting' of younger stars
  - counter-rotating cores
  - Butcher-Oemler effect: more blue galaxies in high redshift clusters than in low redshift clusters
  - Morphology-density relation: more blue galaxies in the field, more red galaxies in cluster cores

Effects of the Environment on Galaxy Type

- Spirals are generally found in galaxy groups
- Ellipticals are more prevalent in rich clusters
- cD galaxies are only found at the center of rich clusters

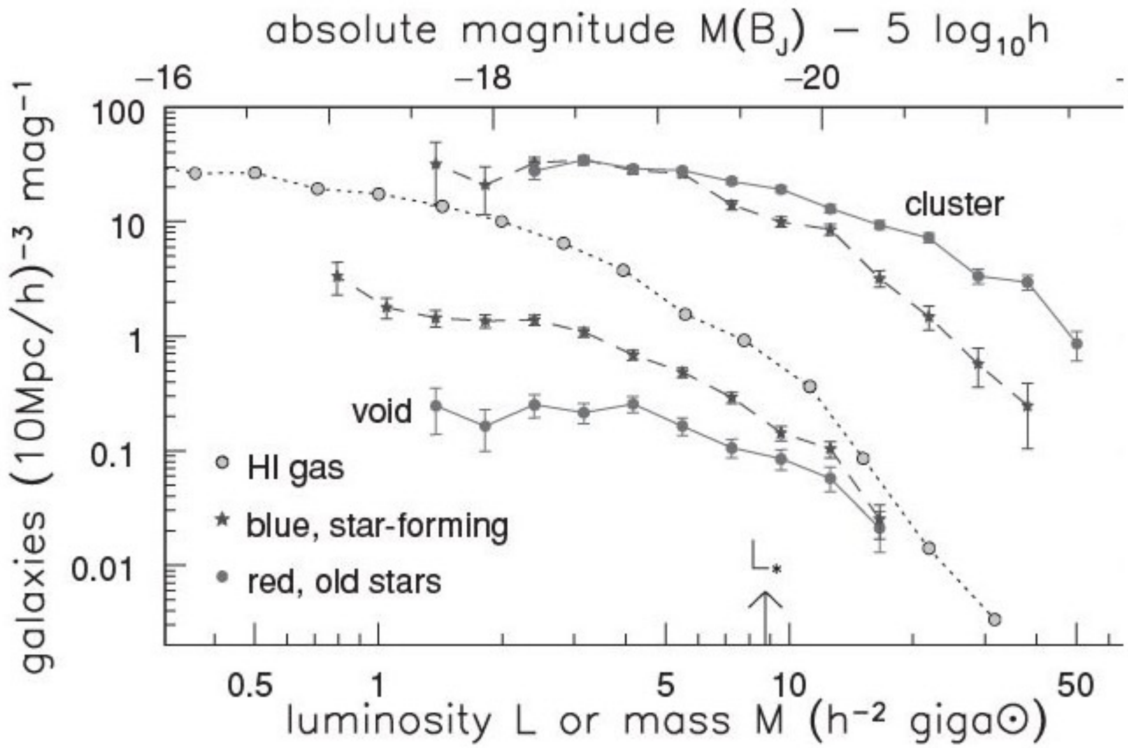
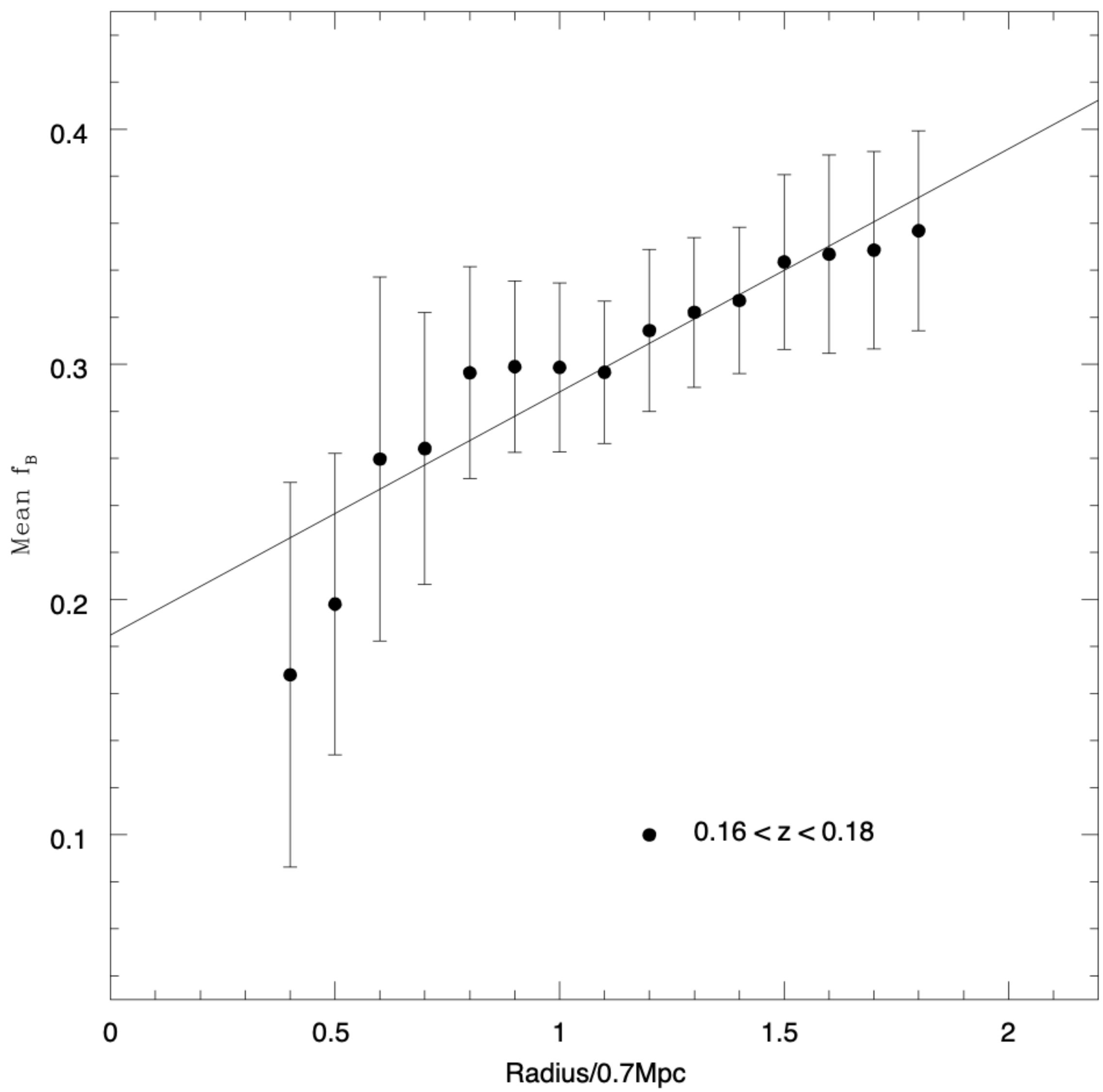


Fig. 7.11. Luminosity functions of blue star-forming galaxies (stars) and red galaxies (filled dots). Bright red galaxies predominate in clusters, but dim blue galaxies are more frequent in the low-density field or void regions. Clouds of neutral hydrogen, found in low-density regions, resemble blue galaxies in that small systems are far more common than big ones – D. Croton, 2dF survey; M. Zwaan, HIPASS.

Morphology – Density relation (Dressler 1980)

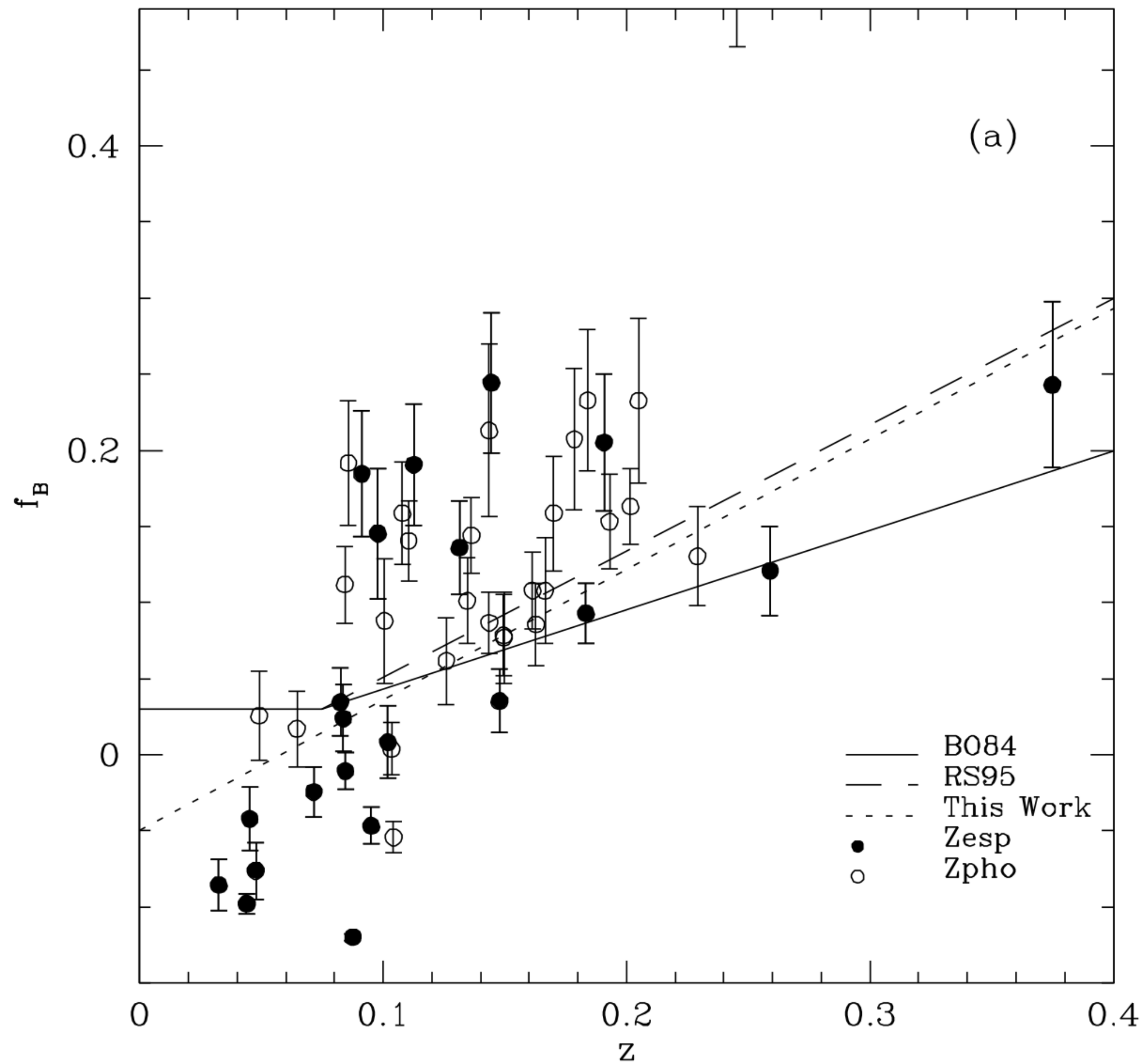


Margoniner & De Carvalho 2000

FIG. 5.—Dependence of the fraction of blue galaxies on the physical region of a cluster.

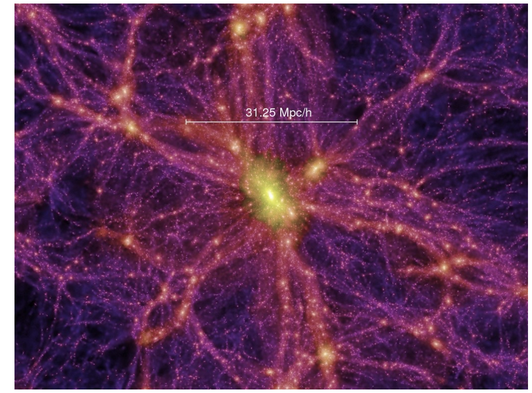
Butcher – Oemler effect

Blue fraction in central 0.7 Mpc of cluster



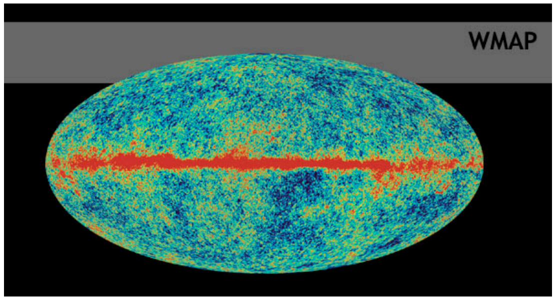
Margoniner & De Carvalho 2000

Progress in the last 10-20 years

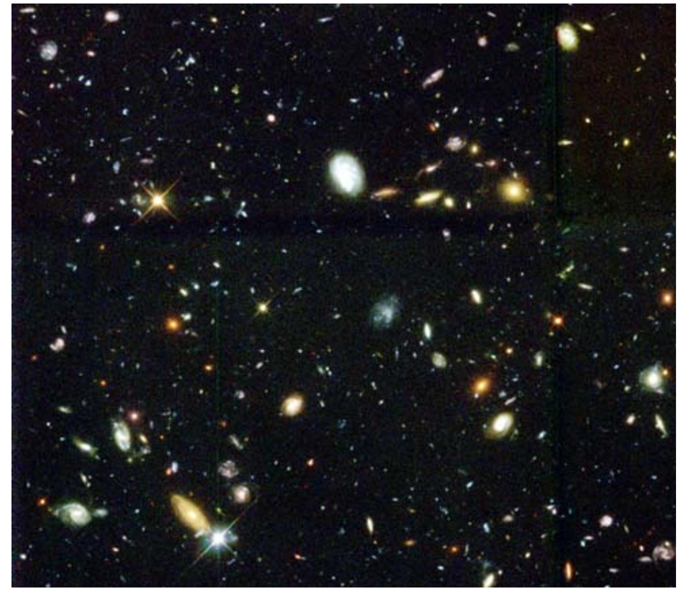


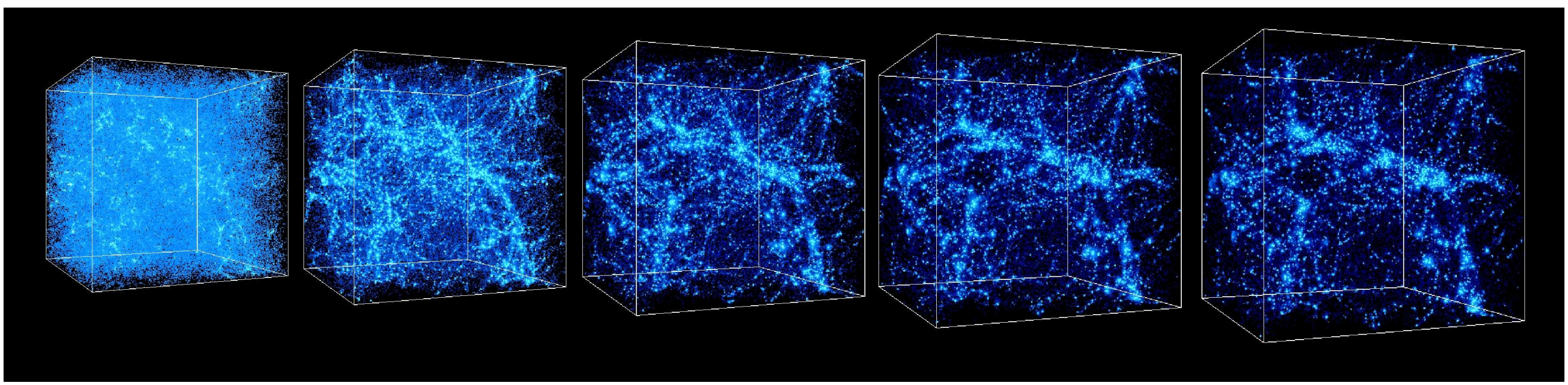
- ΛCDM paradigm shown to be consistent with broad range of observations (CMB, Ly-α forest, weak lensing, galaxy clustering, galaxy clusters)
- galaxy surveys:
  - large homogeneous samples at low z
  - huge progress in discovering & cataloging high-z galaxies
  - build-up of panchromatic view of the Universe
- development of detailed simulations of dark matter and (to some extent) gas processes
- developments of (not totally im-)plausible picture for galaxy formation within this framework

Putting it all together

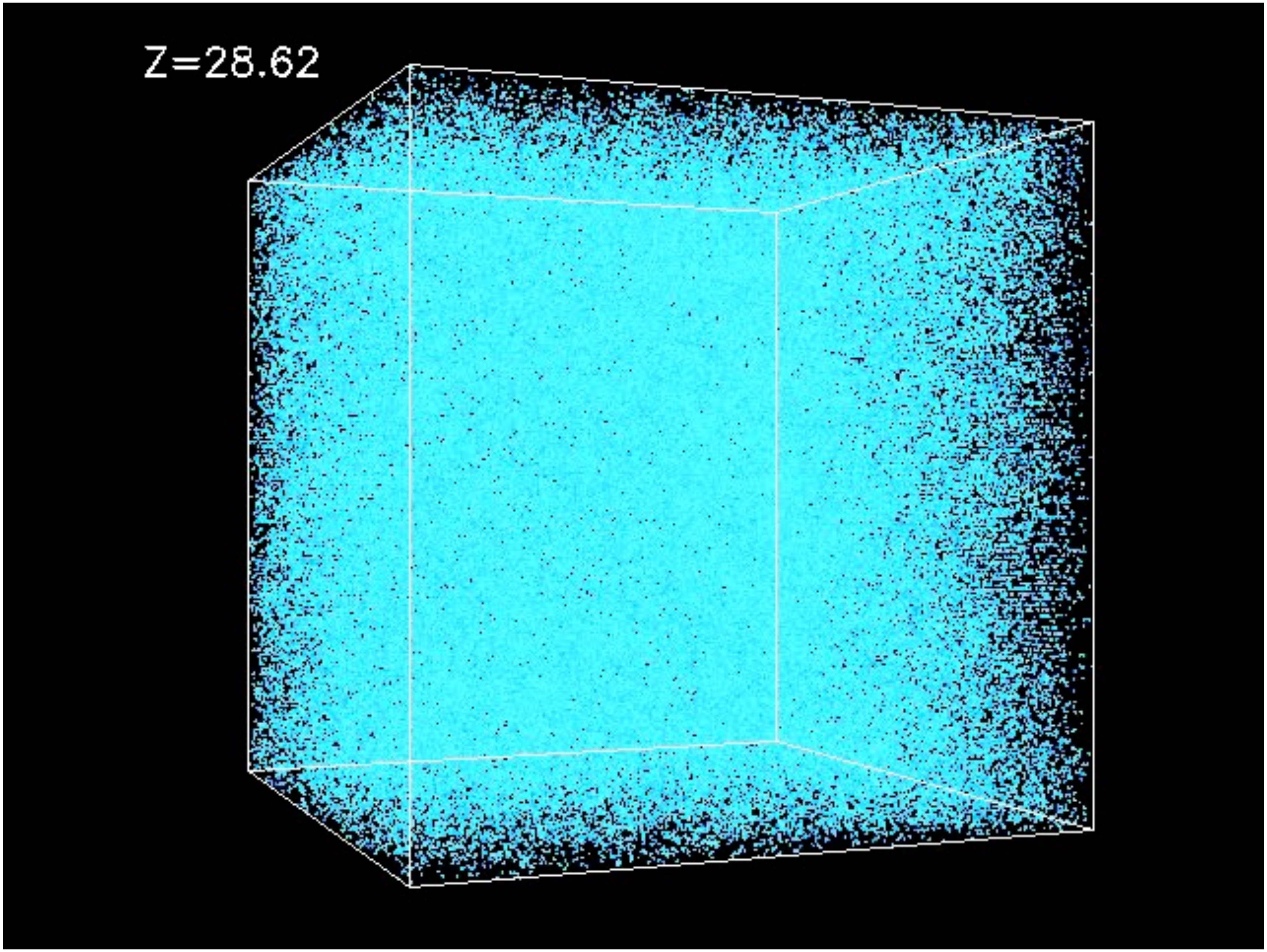


Numerical simulations are used to trace the gravitational collapse of matter (dark+luminous) across cosmic time

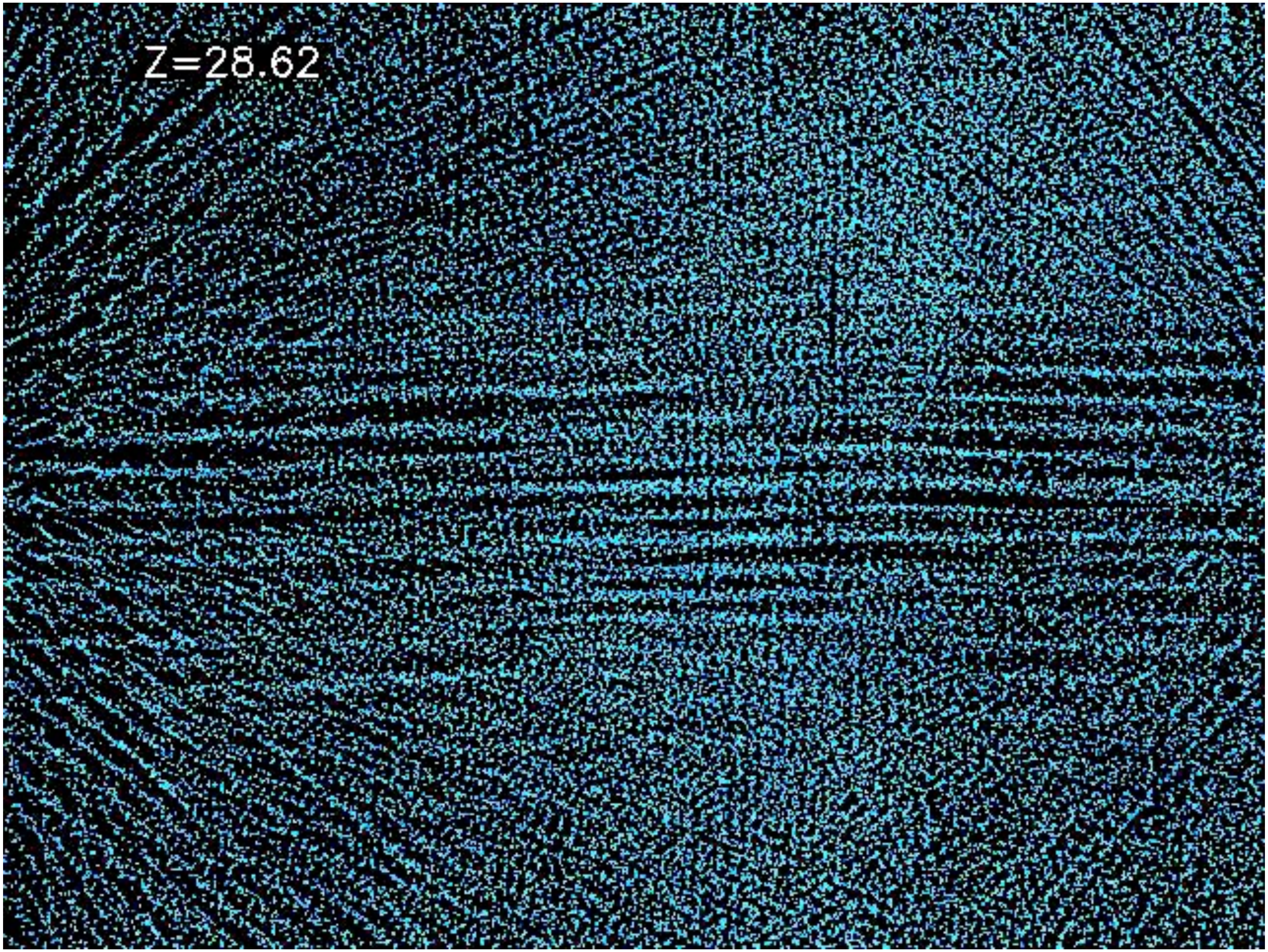




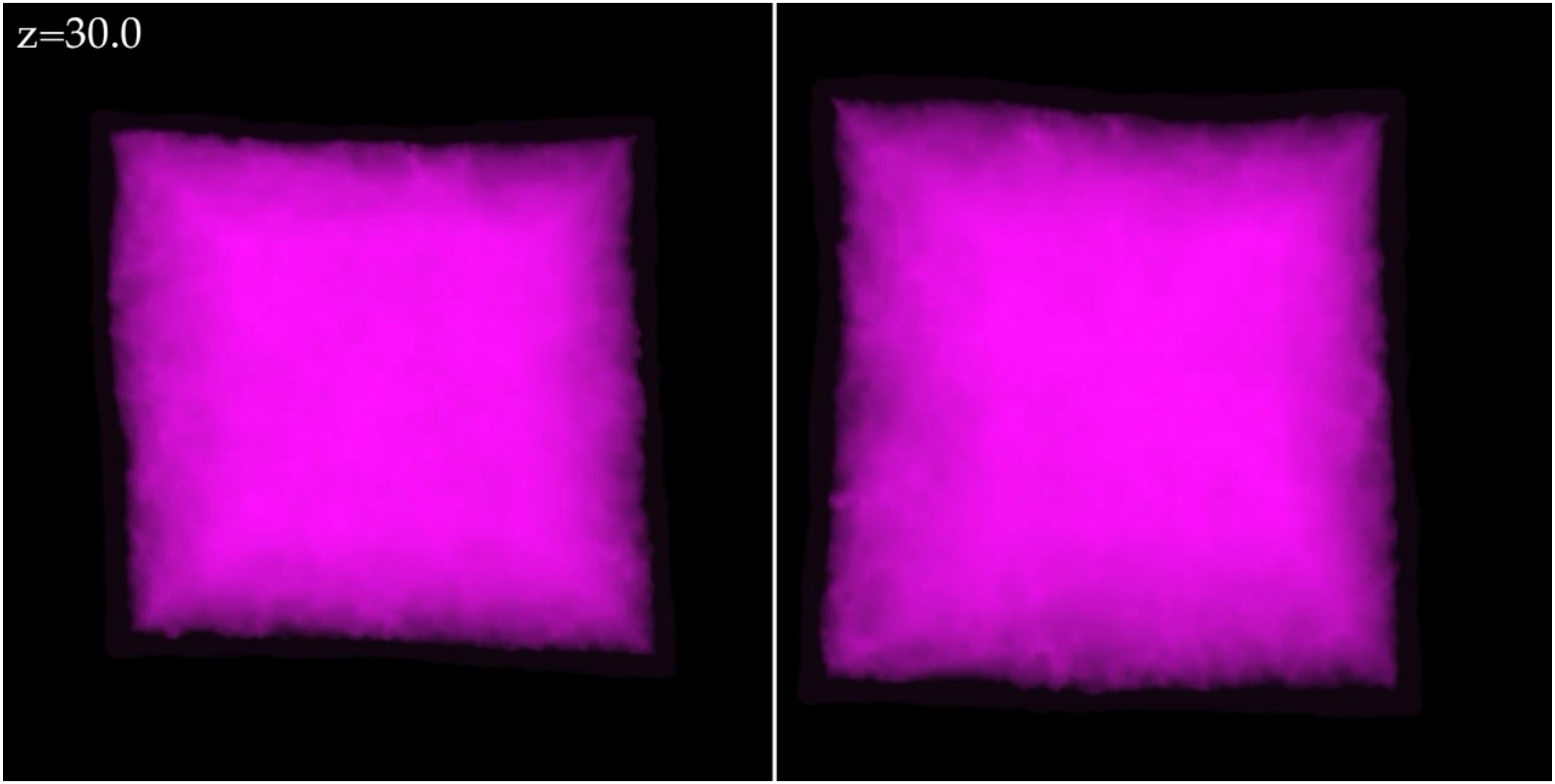
Simulating the Universe



Growth of structure - The Cosmic Web



FIRE simulation of the creation of a disk galaxy



Journal Class

- **Probing diffuse radio emission in bridges between galaxy clusters with uGMRT**
- Pignataro et al. 2024

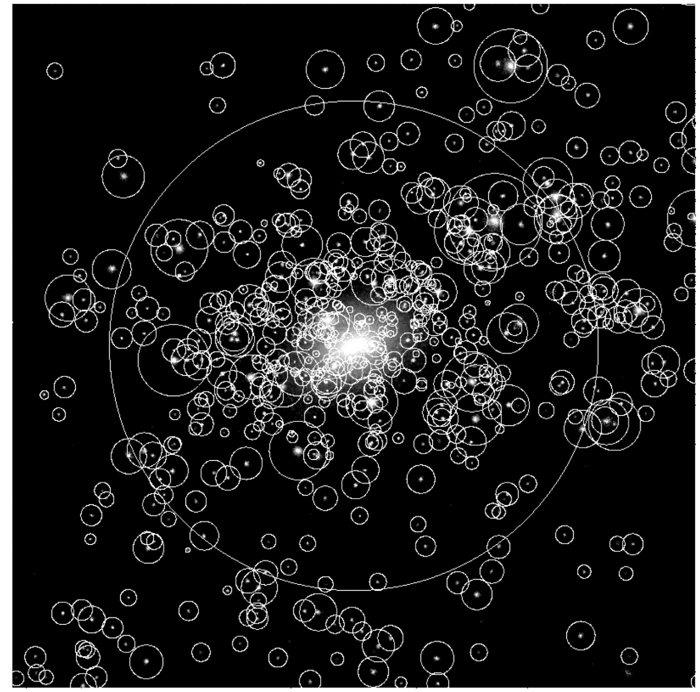
Discussion leader: **Shane Li**

Note: To encourage discussion everybody must pose at least one question during the group discussion

The "Missing Satellite Problem"

- Models/simulations predict large numbers of satellites => Logarithmic slope of the faint end of the CDM mass function ~ -1.8 (Press-Schechter value)
  - Kauffmann *et al.* (1993)
  - Klypin *et al.* (1999)

- But the current census does not count them (light not mass):
  - Faint end slope of the optical LF
  - Faint end slope of the HIMF



The HI Mass Function

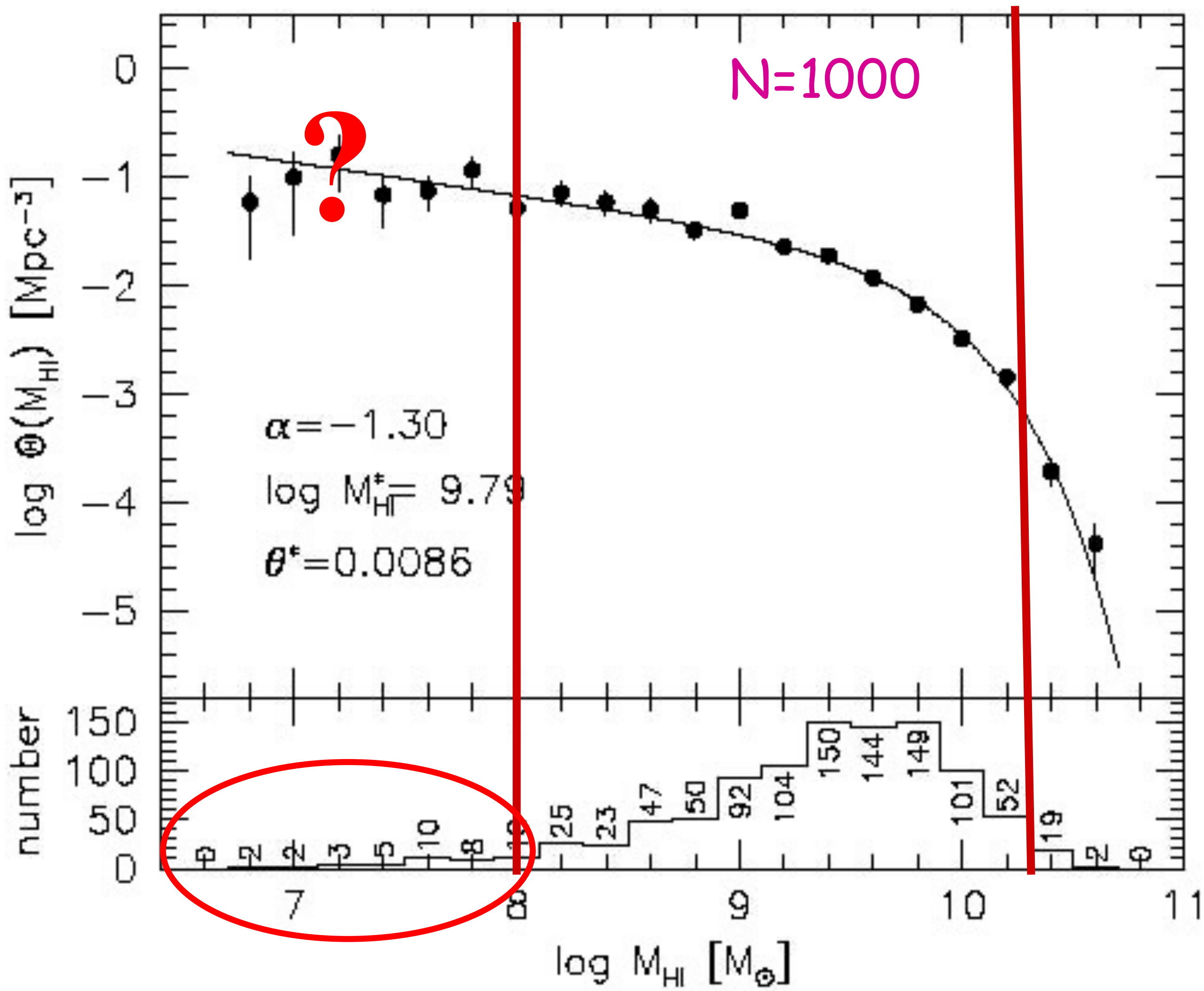
- Previous surveys have included few (if any) objects with HI masses less than 10^8 $M_\odot$.
- At lowest masses, differ by 10X:

Rosenberg & Schneider (2000)

versus

Zwaan et al. (1997)

- Statistics
- Systematics



Parkes HIPASS survey:
Zwaan et al. 2003

HIMF @ z=0 Challenges

- Need better statistics: larger, more sensitive surveys

- At the faint end, all the galaxies are nearby
  - Redshift distances are highly unreliable
  - Large Scale Structure affects accuracy of flow models

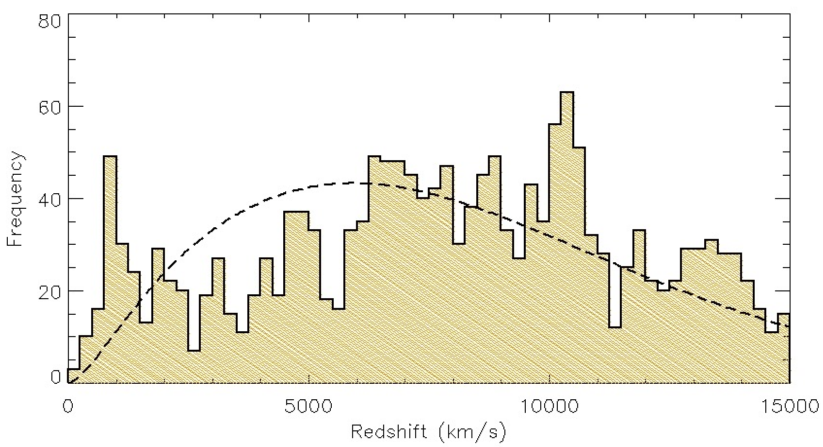
    Masters, H & G 2004, ApJ 607 L115

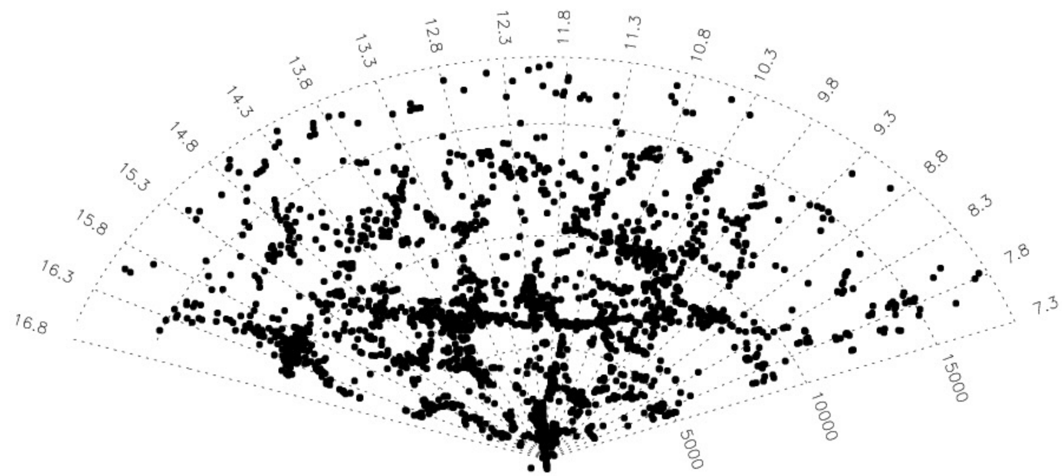
- Need a "fair sample" to overcome (and allow study of) cosmic variance
  - $\Sigma(1/V_{max})$ corrections must account for Large Scale Structure
    - Not just that space density varies with distance
    - Fractional volume of space occupied by regions of a particular density do too

    Springob, H & G 2005, ApJ 621, 215

Cosmic variance

Must sample enough volume to acquire a "fair sample"

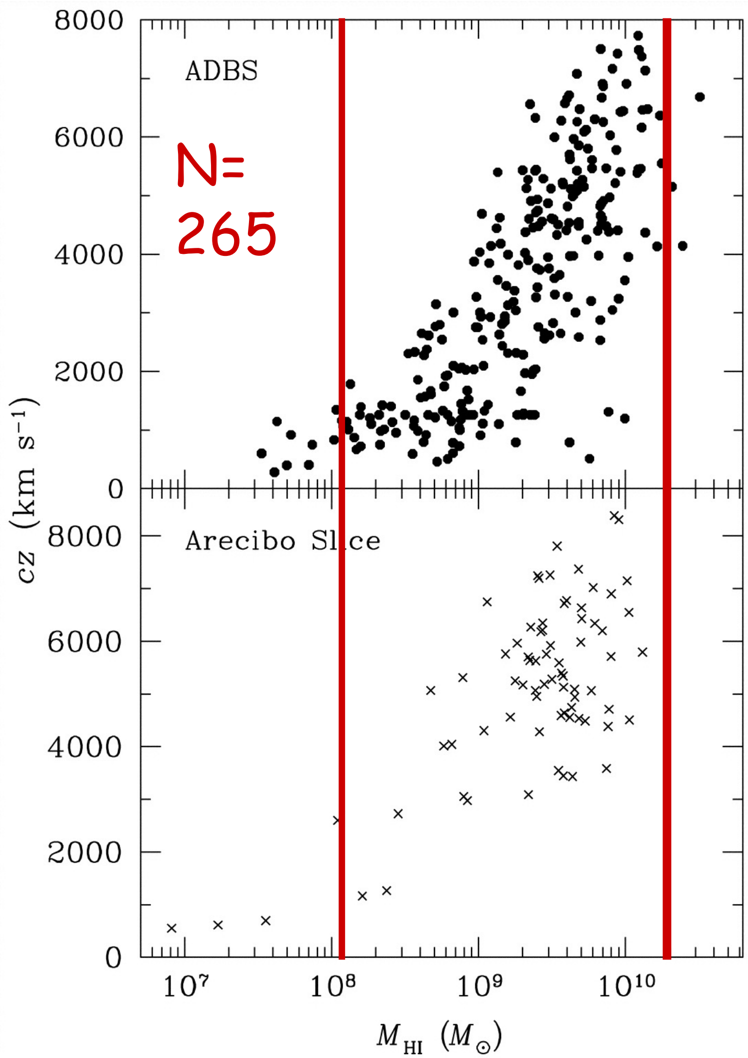




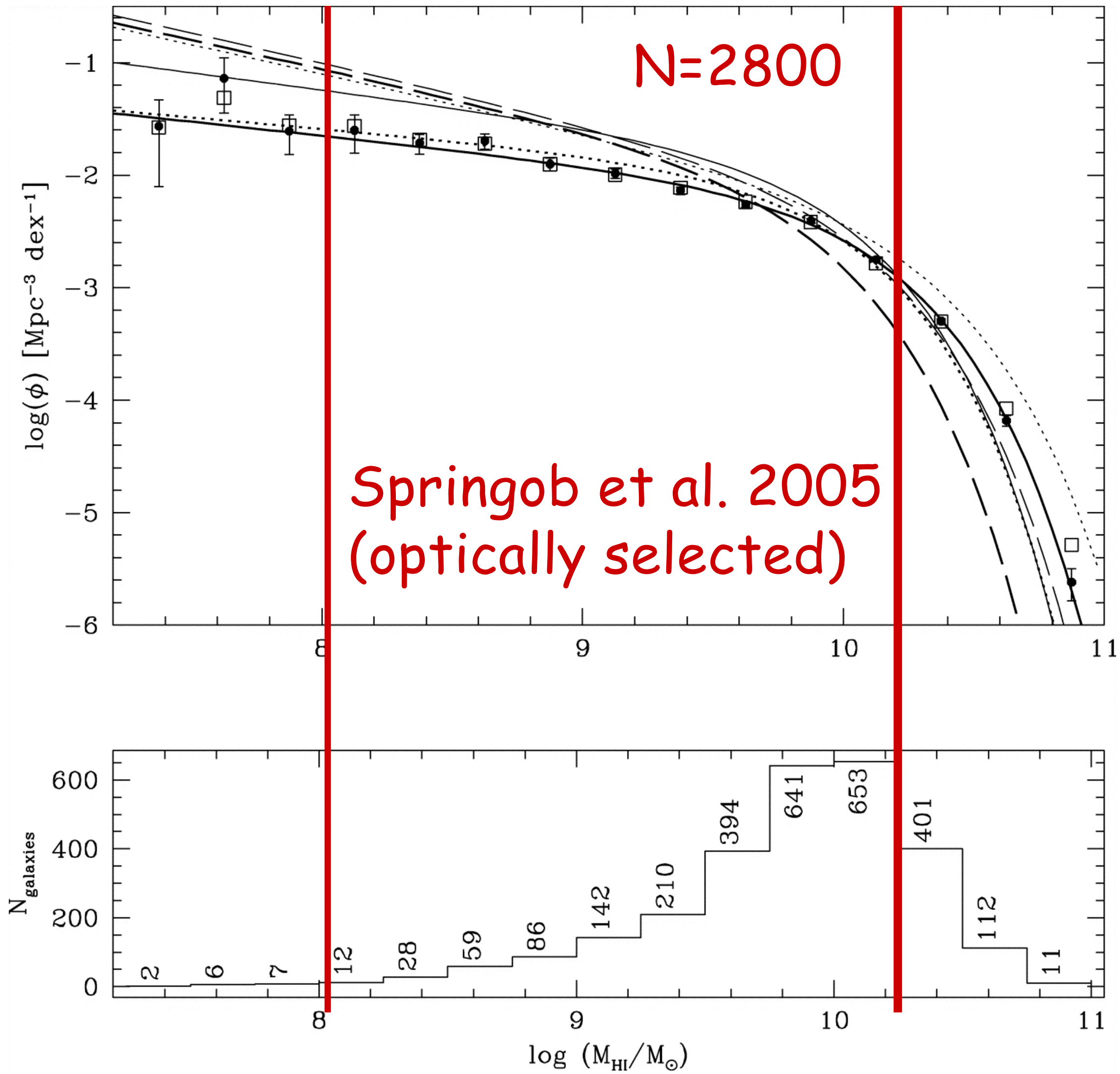
If we covered a similar slice in the opposite part of the sky (coming....) we would see a very DIFFERENT redshift distribution

At these distances, 540 square degrees is not enough.

Statistics, statistics, statistics



Rosenberg & Schneider 2002



Environment & the HIMF

Previous studies based only on Virgo have suggested that the HIMF in Virgo is flatter than in the field

- Only a single cluster
- Very small number statistics/systematics vs comparison
- Is this just HI deficiency?
- Watch out for morphological biases

Inconsistency: Symptom of inadequate volume?

Kovač, Oosterloo & van der Hulst (2005): CanVen

- Similar to Virgo (low mass slow flatter)

BUT……..

Zwaan et al. (2005): HIPASS

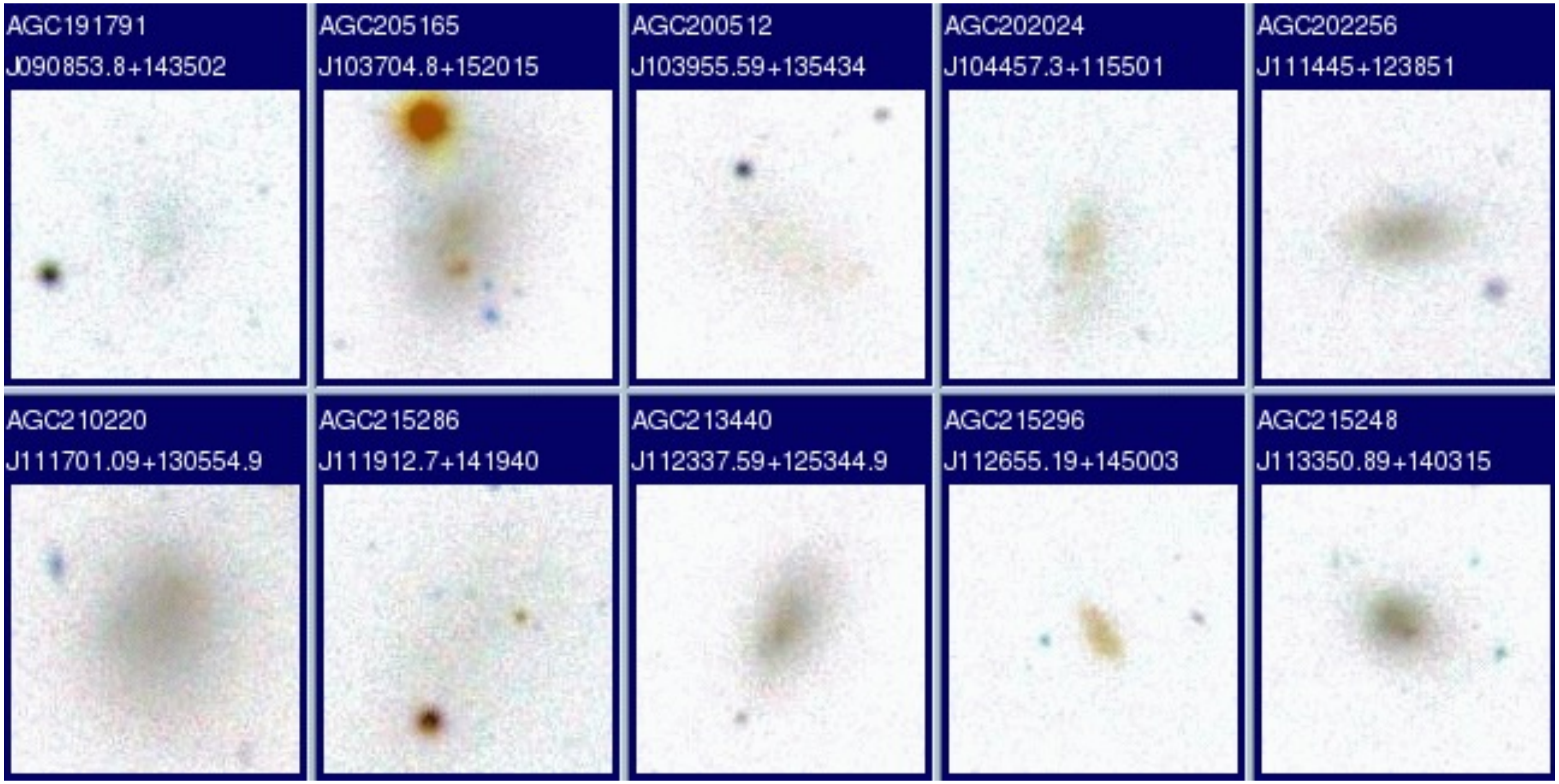
- Higher density regions => more low masses

HI and the "missing satellite" problem

- HIPASS result: no cosmologically significant population of HI-rich dark galaxies: ALFALFA agrees… but HIPASS $M_{HI} > 10^8\ M_\odot$
- ALFALFA is specifically designed (wide area, high velocity resolution) to detect hundreds of objects with $M_{HI} < 10^{7.5}\ M_\odot$
  - Low HI mass
  - Narrow HI line width + exclude face-on objects
  - Will *only* be detected nearby => need to sample *cosmologically significant volume*
- Future studies will focus on extending
  Deeper in HI Mass than ALFALFA in Local Supercluster

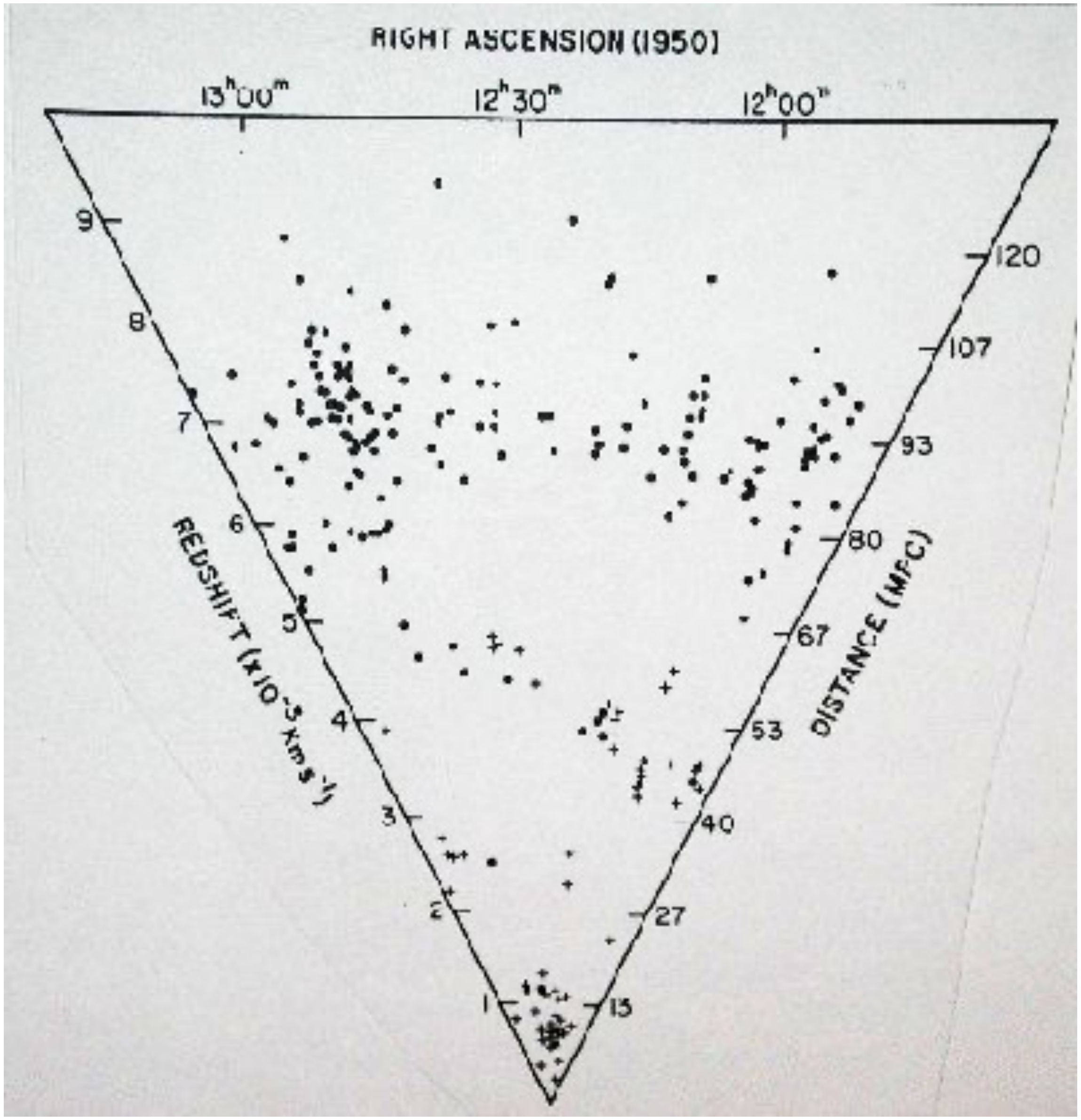
Lowest HI mass objects

log $M_{HI} < 7.2$



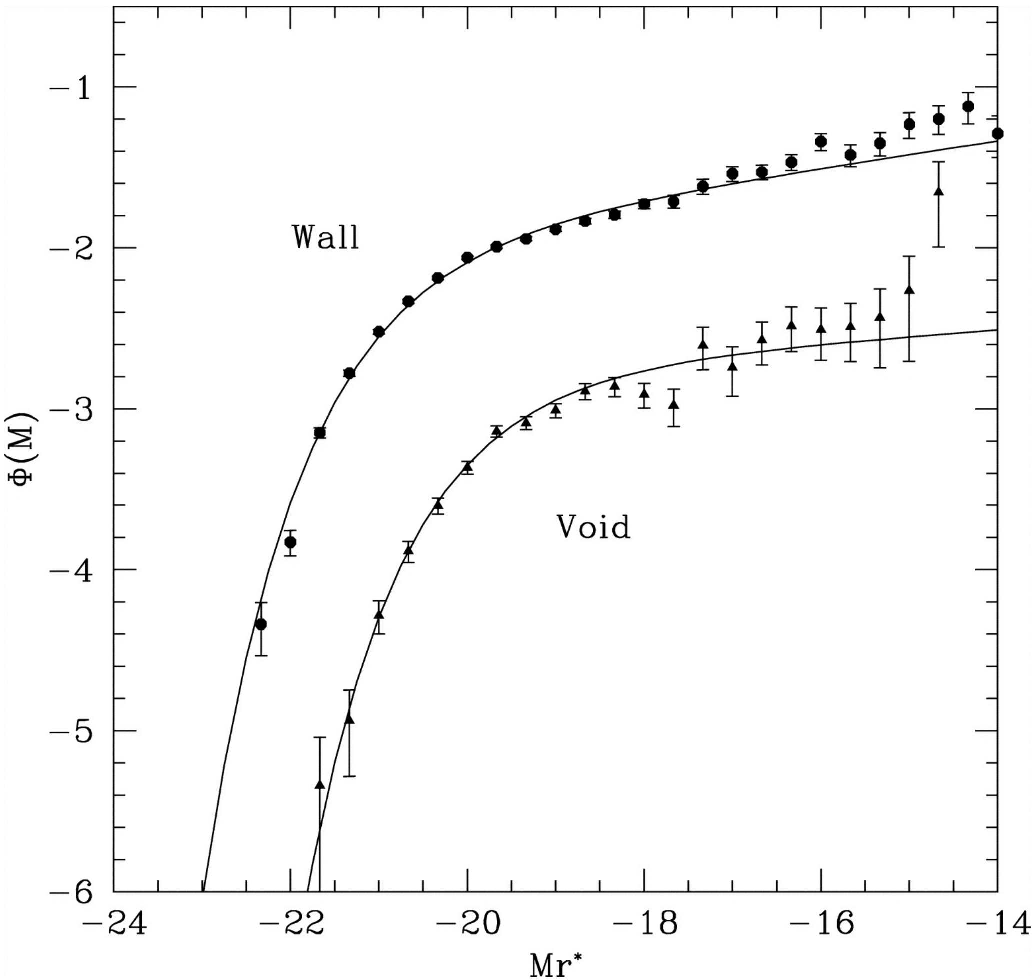
ALFALFA has already detected more objects with log $M_{HI} < 7.5$ than all other previous blind HI surveys combined

Voids and Superclusters



Gregory & Thompson (1978)

Luminosity function of void galaxies



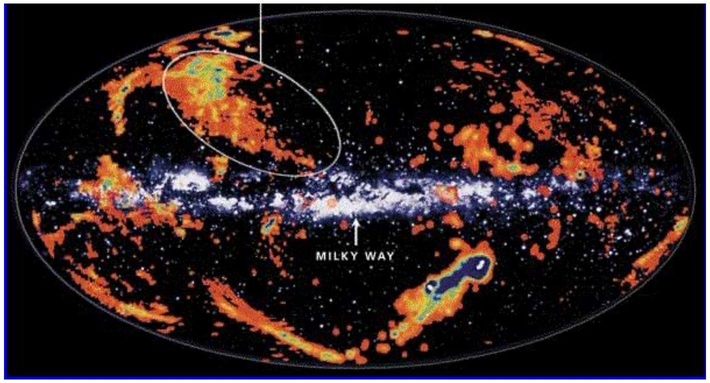
Void LF has a faint M* but a similar faint-end slope, compared to the overall LF

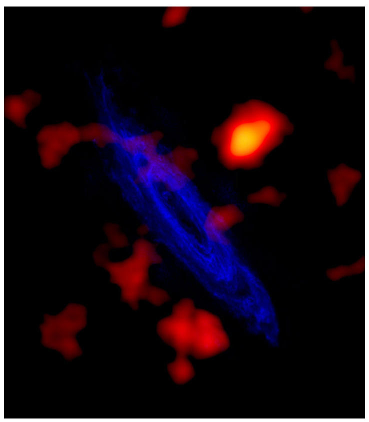
Void galaxies are blue, disk-like and have high Hα equivalent width => good HI targets

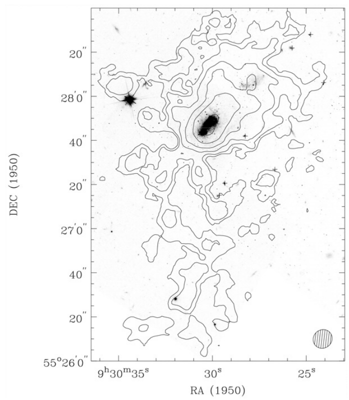
Void galaxies in the SDSS: Hoyle et al (2005)

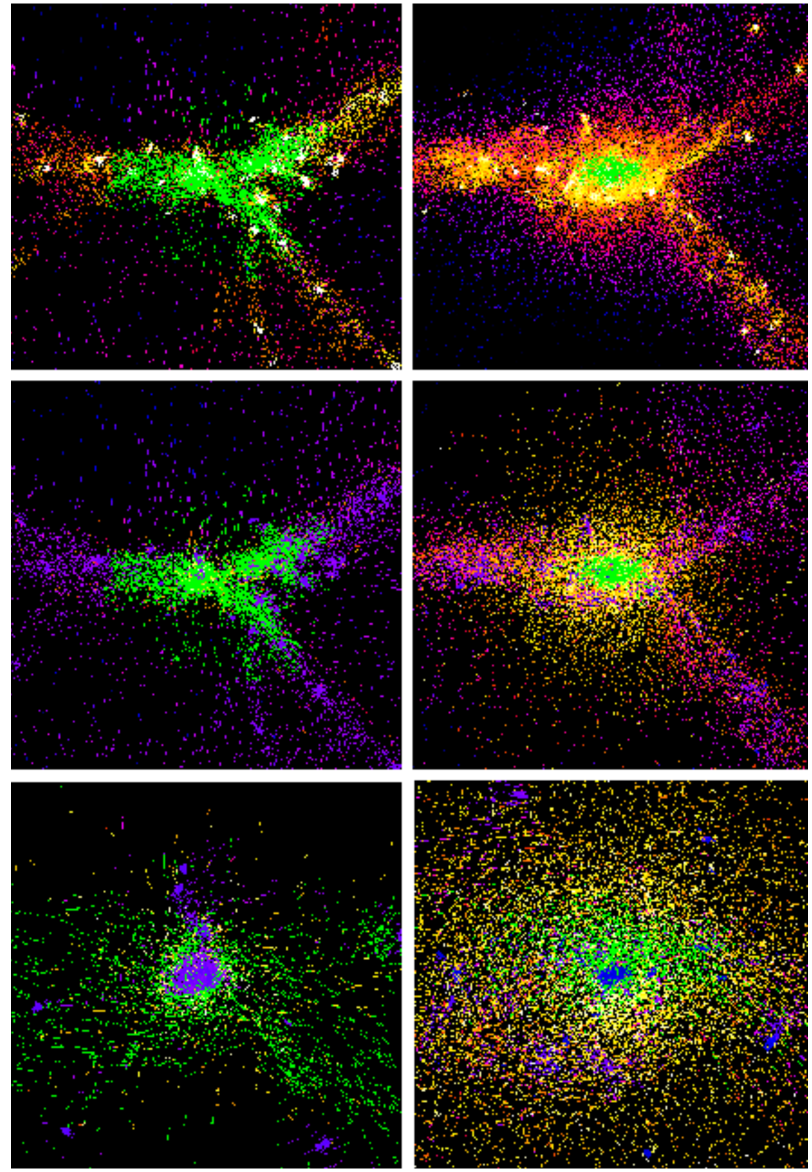
1000 galaxies in lowest density cells of total 155,000 galaxies (SDSS 2005)

How and when do galaxies acquire their gas?



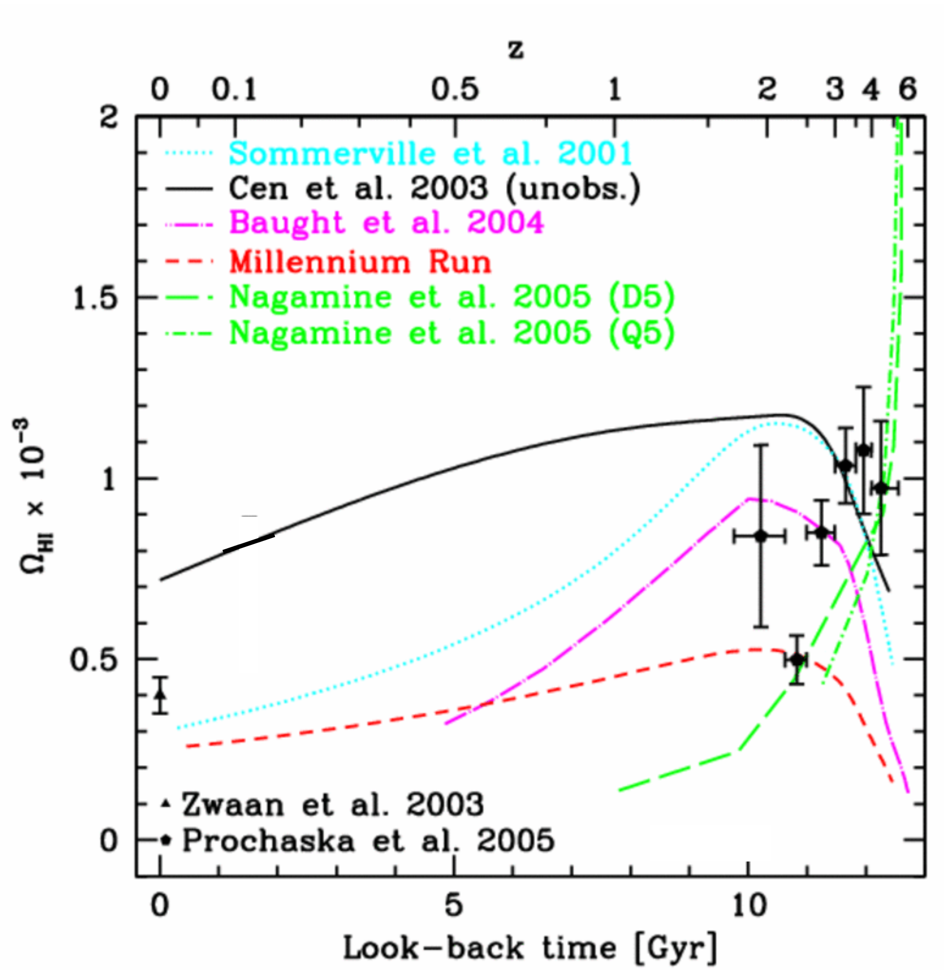


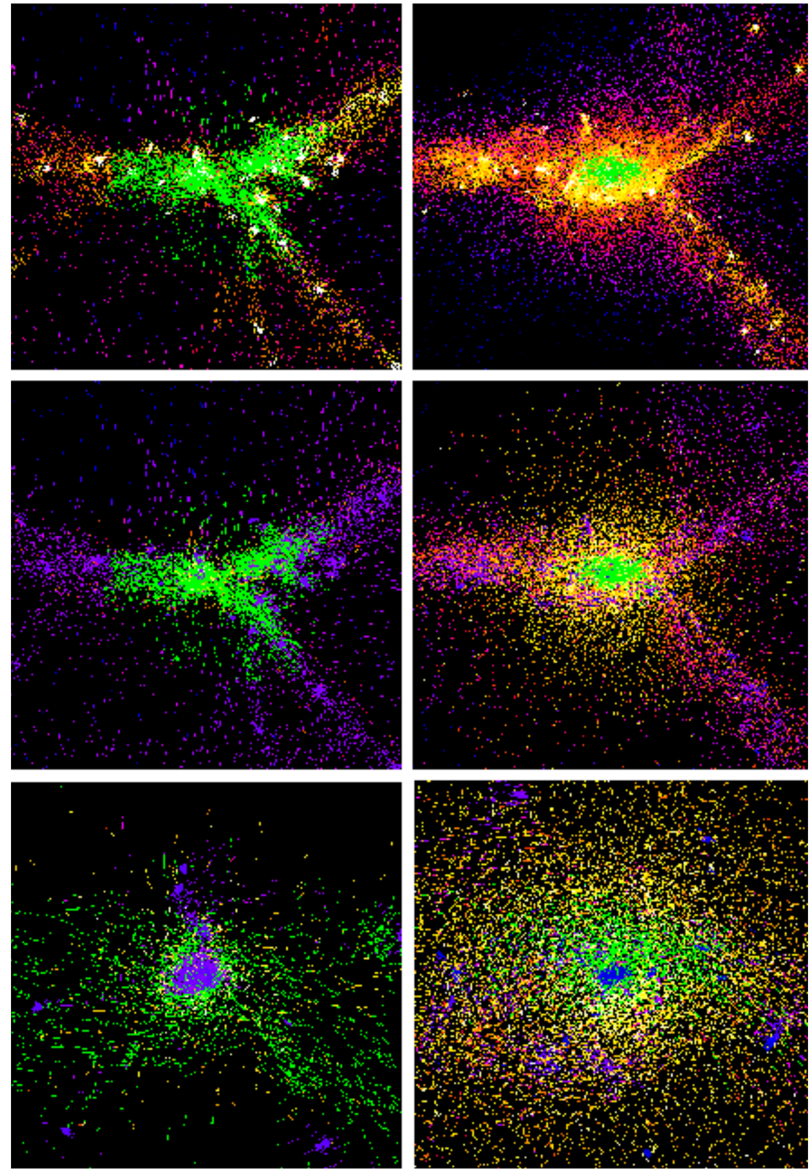




Kereš *et al.* (2005)

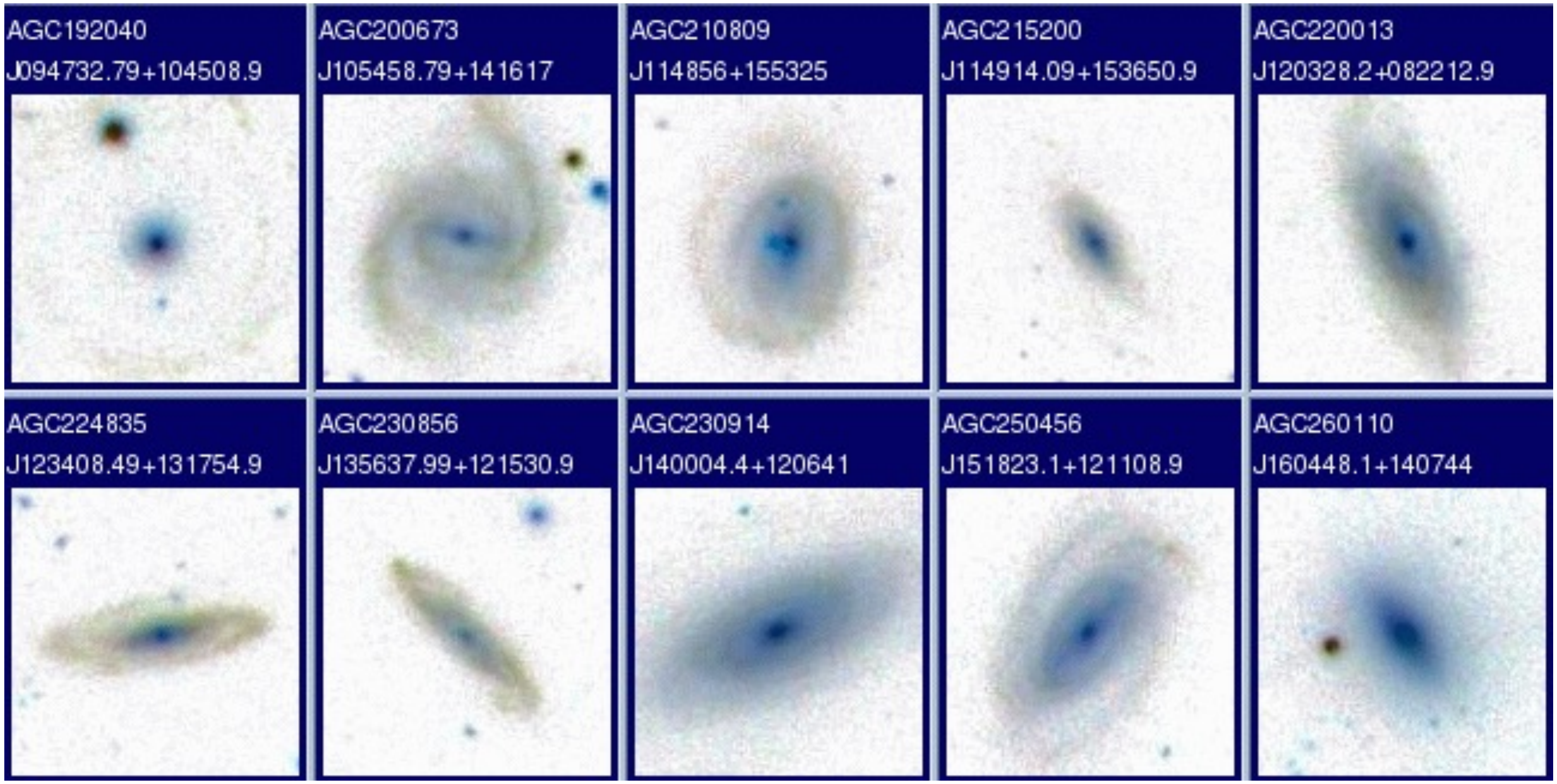
How and when do galaxies acquire their gas?





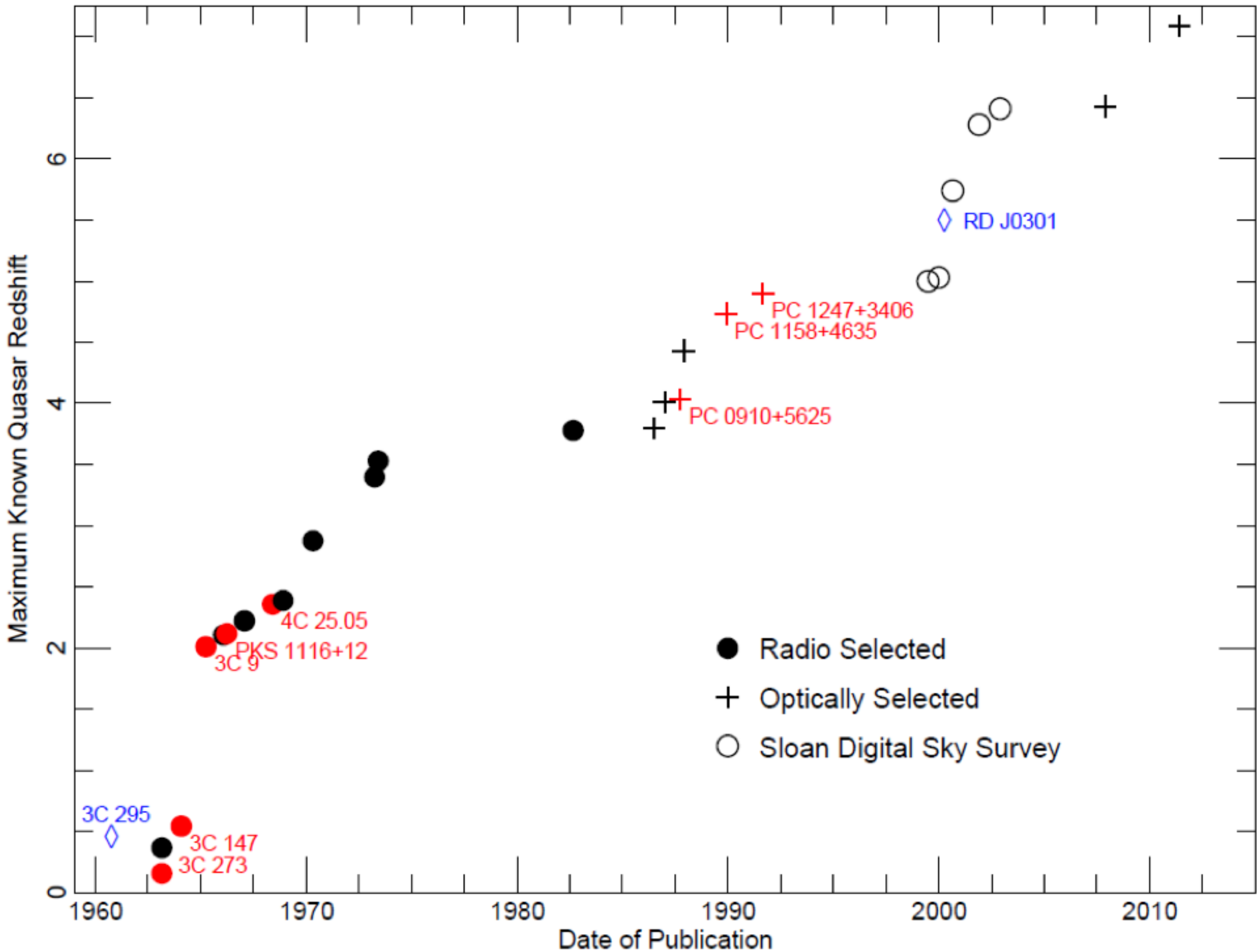
Kereš *et al.* (2005)

Highest mass objects: Challenge for SKA

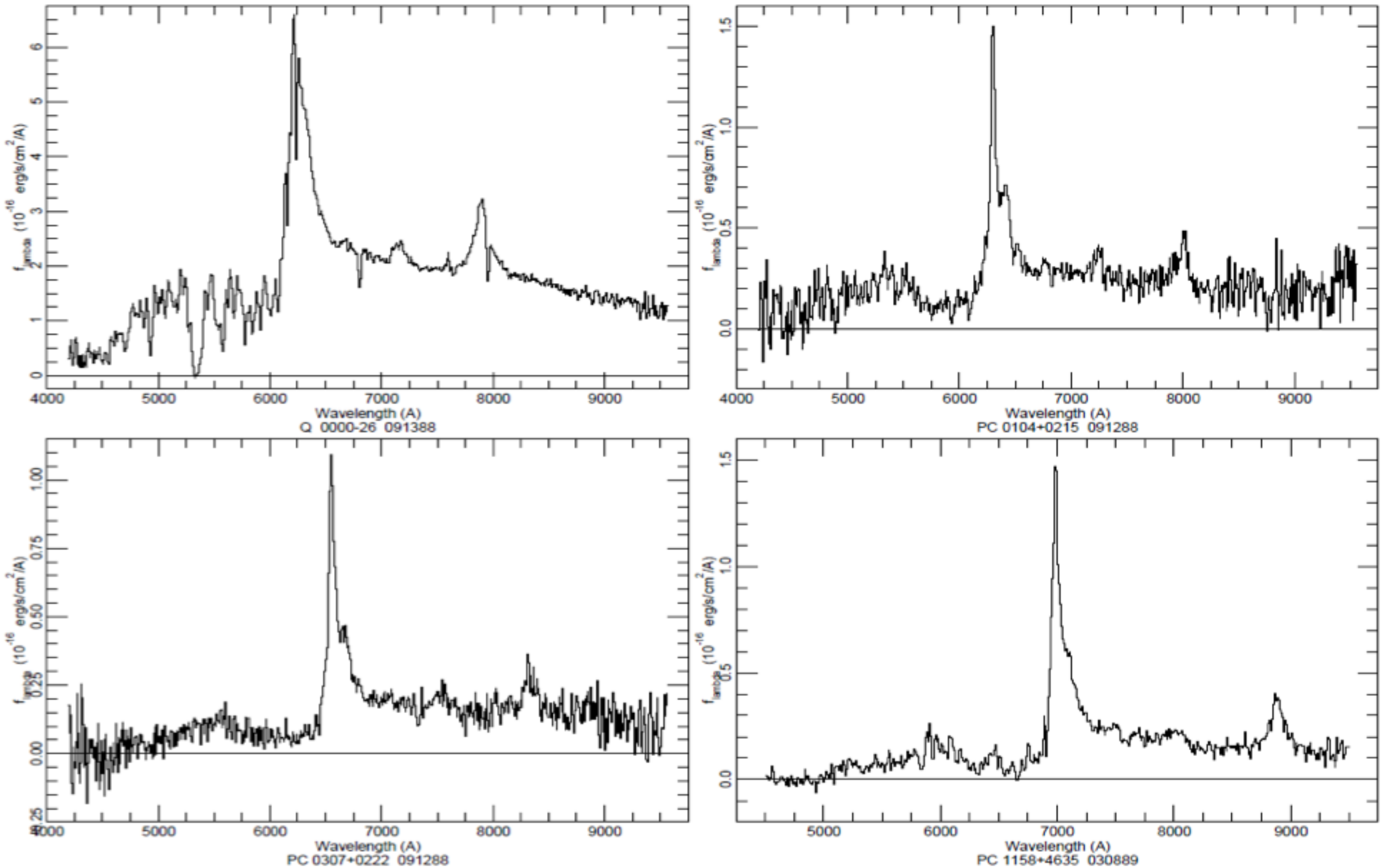


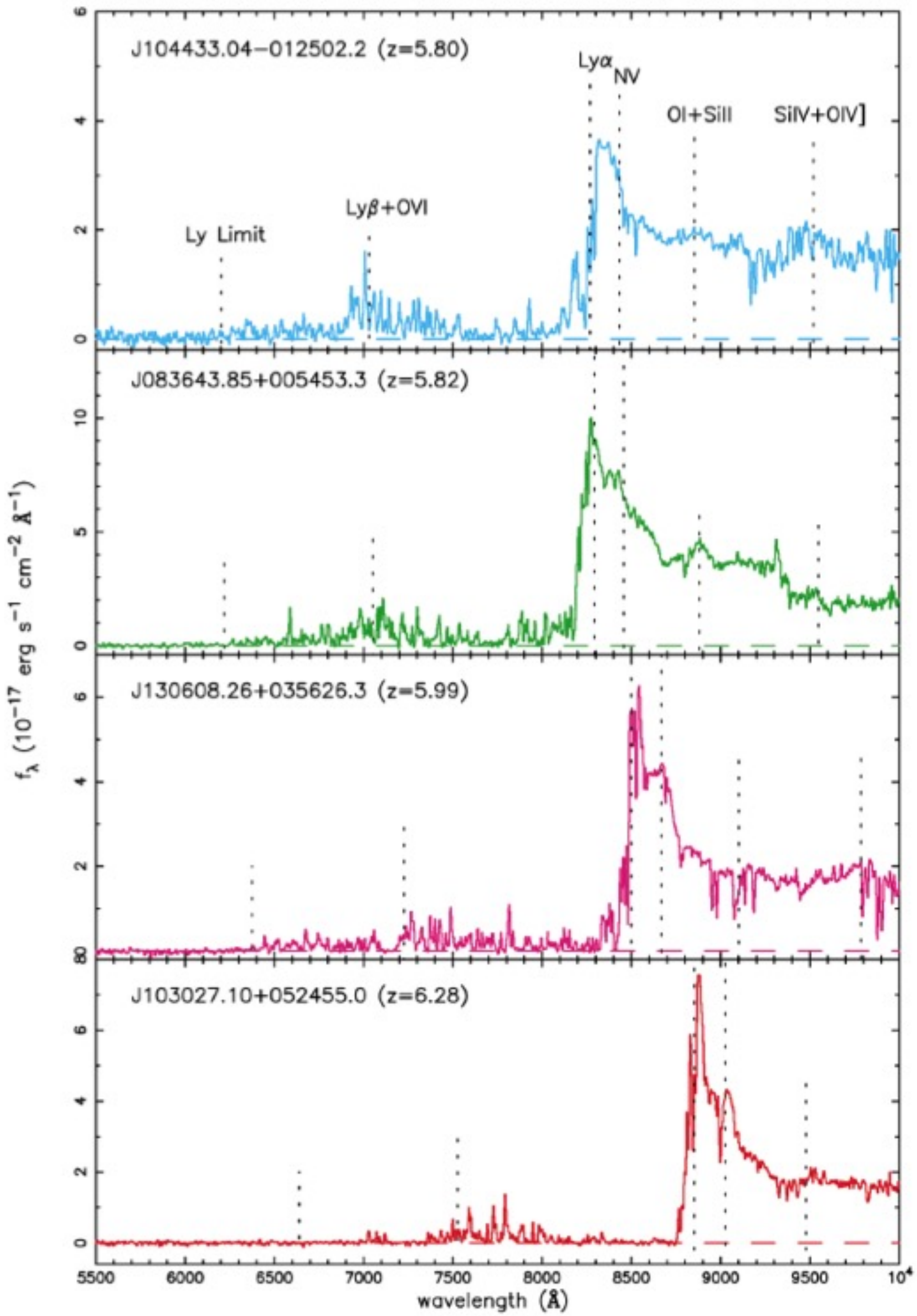
ALFALFA has already detected more than twice as many objects with log M_{HI} > 10.4 than all other previous blind HI surveys combined

High Redshift Quasars



Indications of rapid increase of H I Opacity at z ~ 4

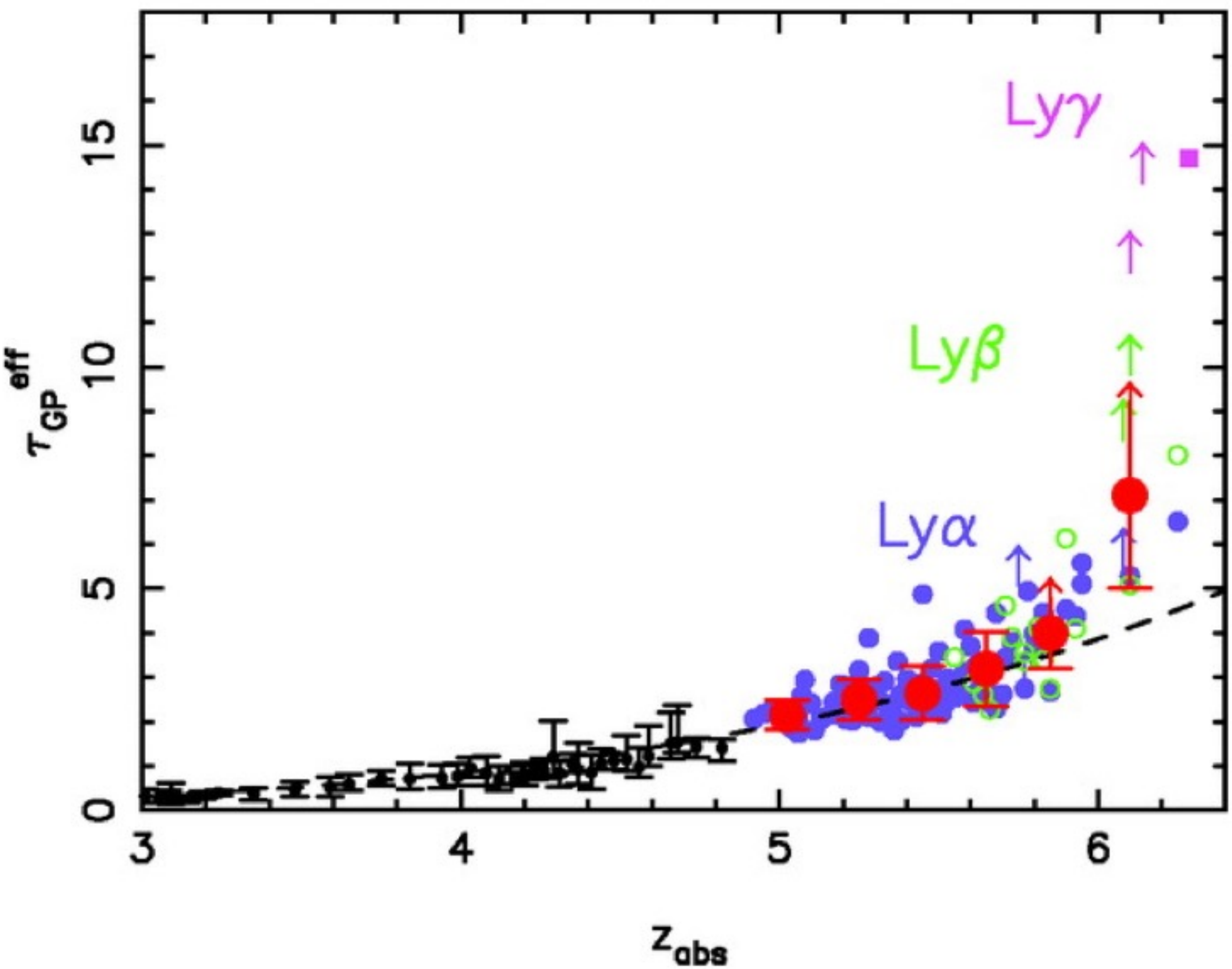




Detection of Gunn-Peterson Troughs in z ~ 6 Quasars in 2001

Becker et al (2001)

Rapid increase in H I Opacity at z ~ 6



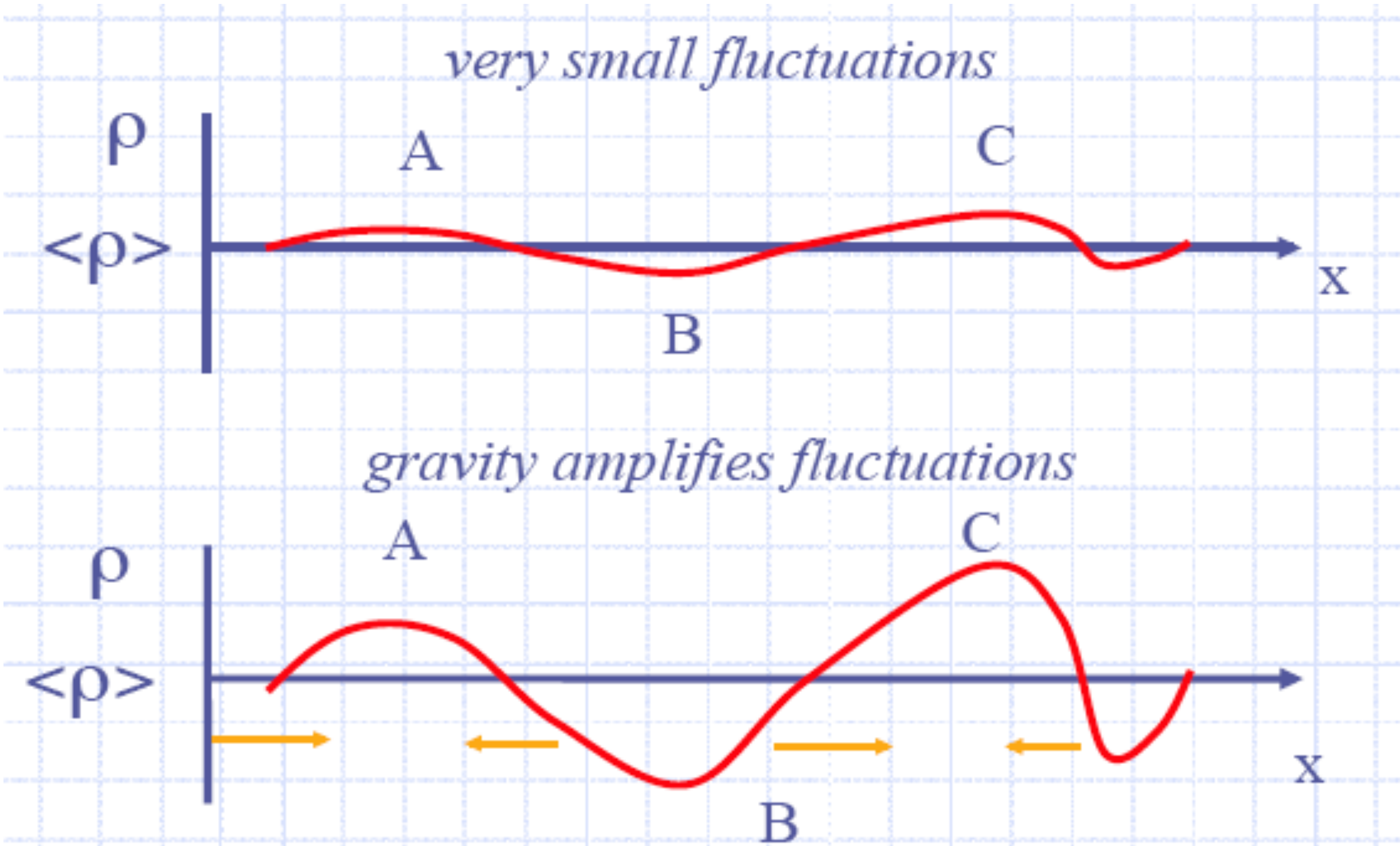
Fan et al (2006)

Structure formation - the big picture

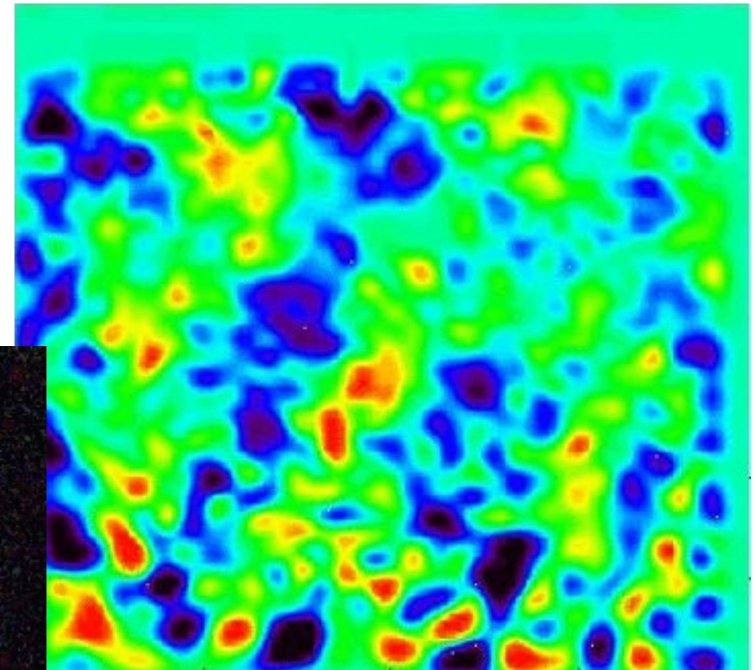
Structure formation is theory of transition from a very homogeneous state in the early universe, as reflected in the CMB, to the structure of galaxies and clusters we observe today.

- Quantum fluctuations from inflationary era were 'stretched' to cosmic scales
- Density fluctuations frozen in until matter-radiation equality
- Density fluctuations grow during matter-dominated era (>10,000 yr ABB) due to gravitational instability at the sound speed
- Astronomical structures form when fluctuation amplitude becomes large

Gravitational instability

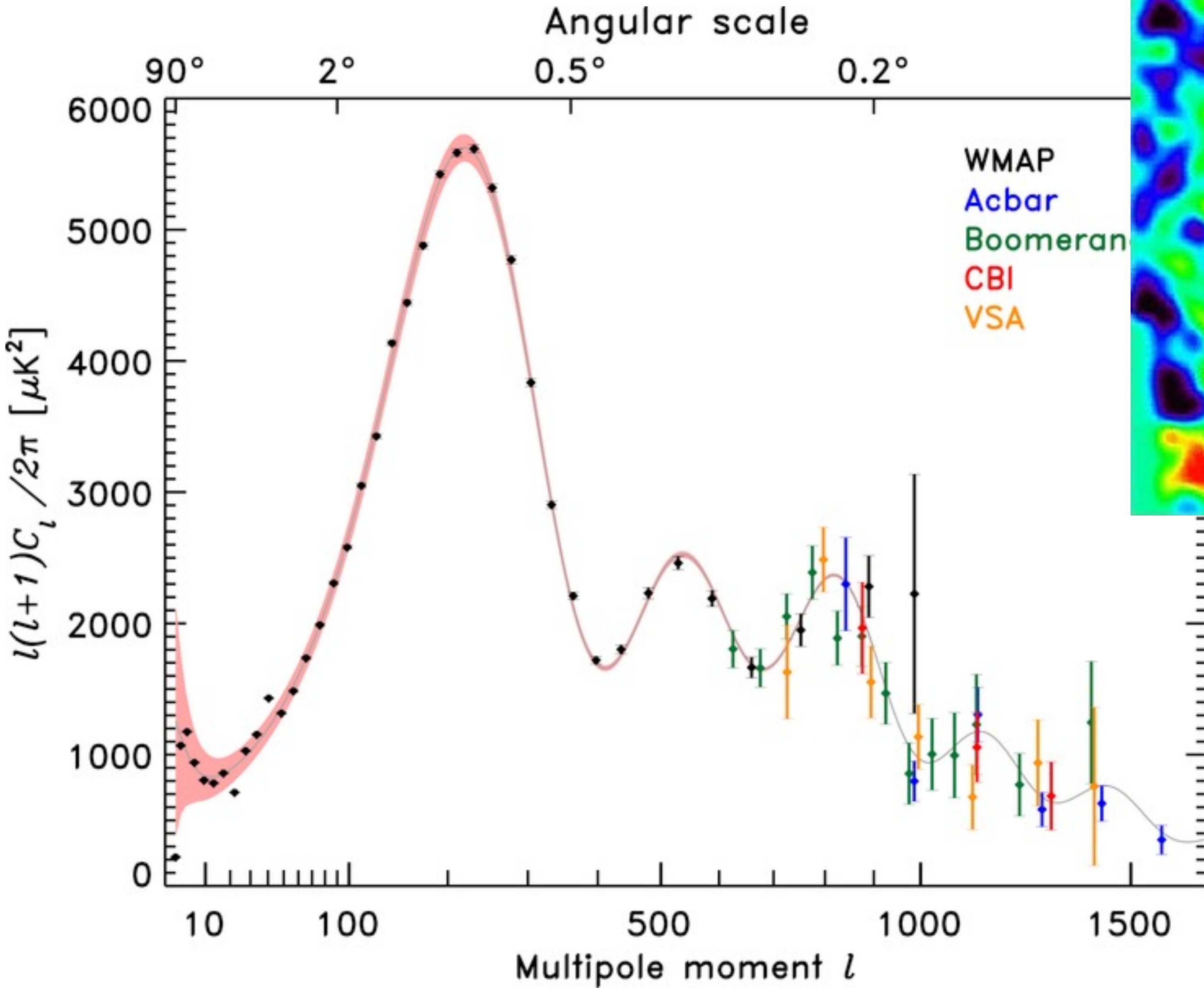


From CMB, we know that at the time of recombination perturbations were about 10^{-5} of the average density.

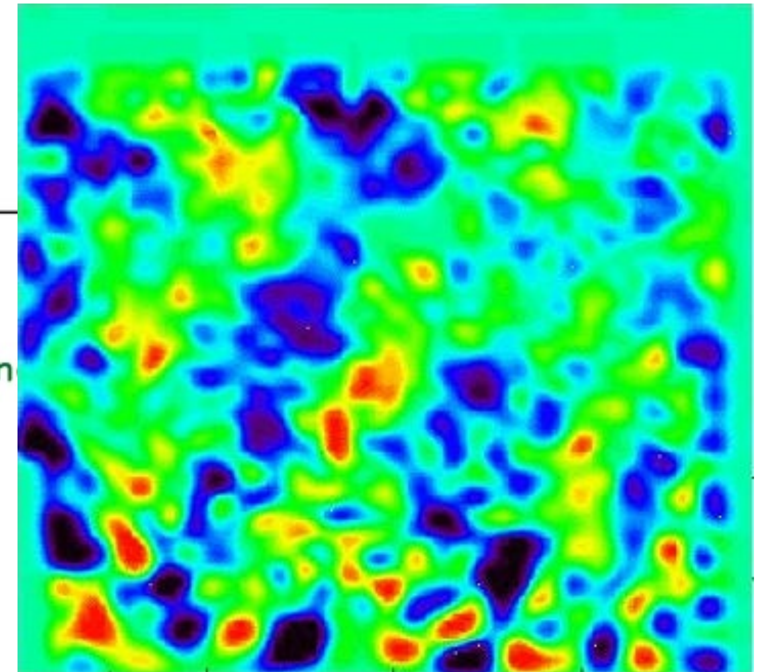


Now, it is about 10^{5} (in a galaxy).

How do we get there?



Angular scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ [μK^2]
WMAP
Acbar
Boomeran
CBI
VSA
10
100
500
1000
1500
Multipole moment l



Sound Horizon

- Electrons in the early universe scatter the photons which provide most of the pressure
- If there is a pressure gradient then the electrons will move down it, pulling protons with them. This drives a spherical sound wave.

The comoving sound horizon r_s is the integral of the sound speed over conformal time from the Big Bang ($z = \infty$) to the redshift of recombination ($z_* \approx 1090$).

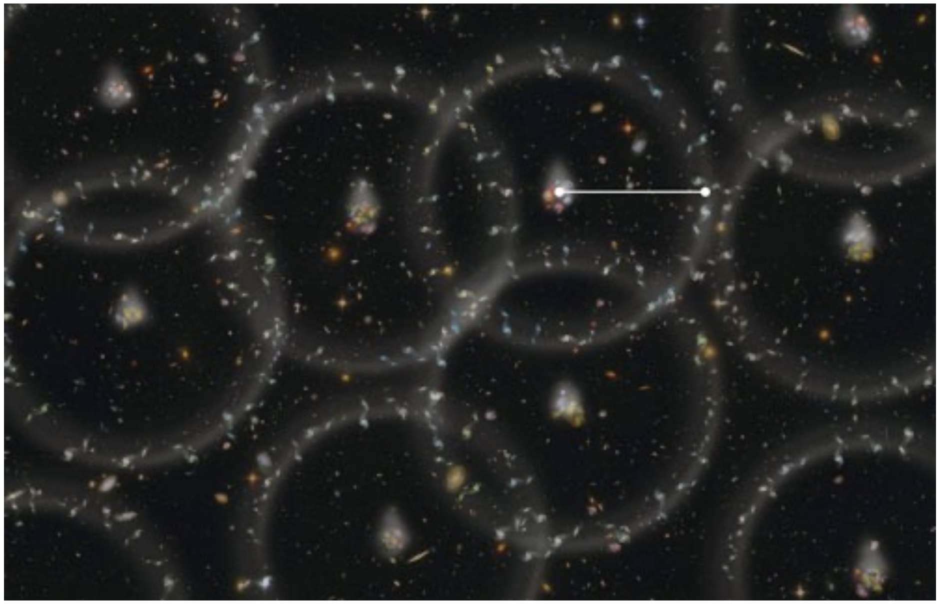
$$r_s = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)}\, dz$$

Assuming matter dominates:

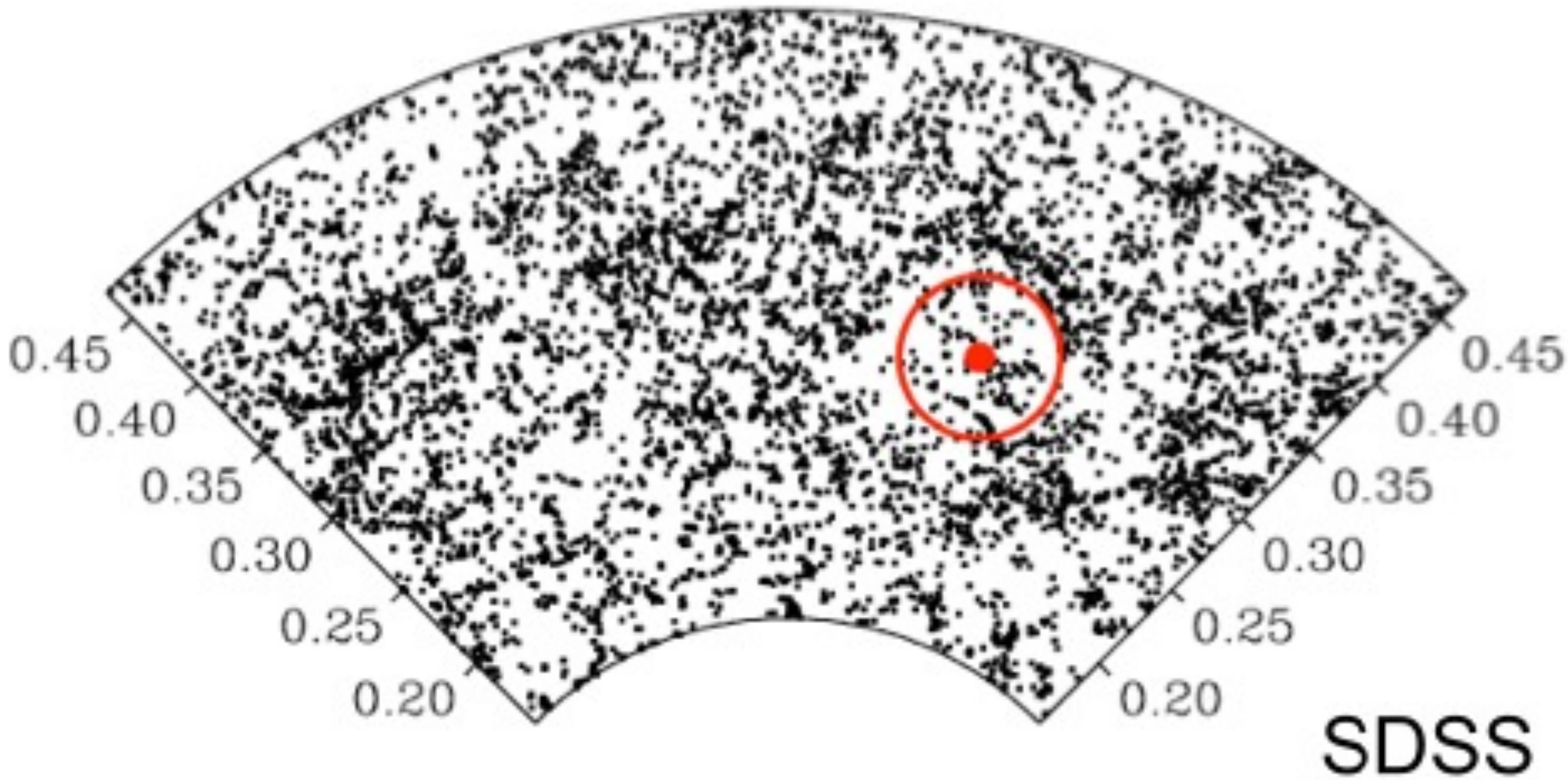
$$H(z) \approx H_0 \Omega_m^{1/2} (1 + z)^{3/2}),$$

And c_s is approximately c/sqrt(3)

After recombination, universe is transparent and photons fly off, leaving baryons behind

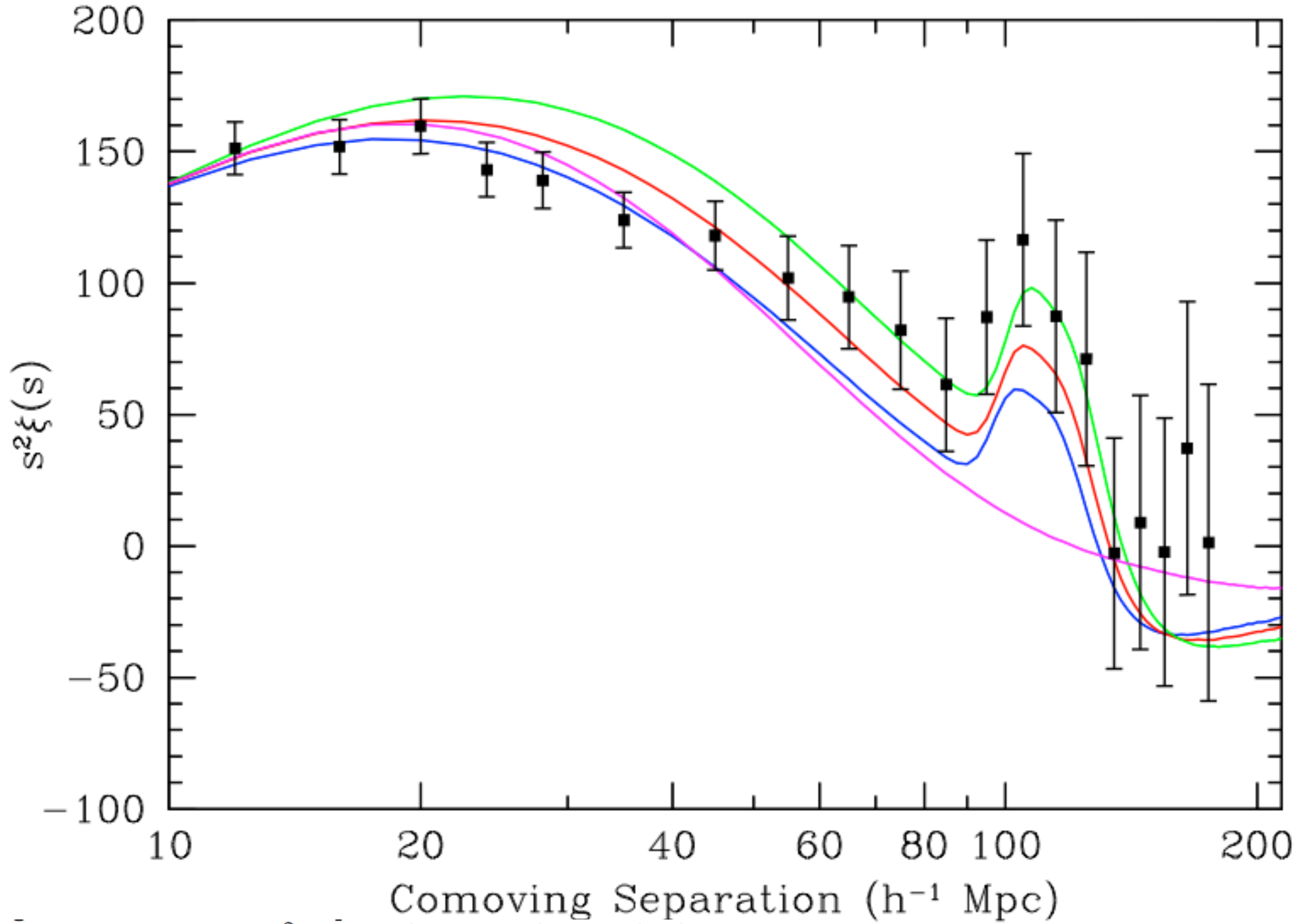


Baryon Acoustic Oscillations



Eisenstein et al. 2004

Baryon Acoustic Oscillations



axis. The models are $\Omega_m h^2 = 0.12$ (top, green), 0.13 (red), and 0.14 (bottom with peak, blue), all with $\Omega_b h^2 = 0.024$ and $n = 0.98$ and with a mild non-linear prescription folded in. The magenta line shows a pure CDM model ($\Omega_m h^2 = 0.105$), which lacks the acoustic peak. It is interesting to note that although the data ap-

Eisenstein et al. 2004

- **Worksheet:** Problem: Tracking the Acoustic Sound Horizon. Starting from the physical sound horizon, estimate the Baryon Acoustic Oscillation (BAO) scale for the distribution of galaxies.