

# Astronomy

## 330

Lecture 25

08 Dec 2010



# Outline

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- ▶ **Review:**
  - ▶ Basic cluster properties
- ▶ **Clusters**
  - ▶ Identification
  - ▶ Types
  - ▶ Lensing
  - ▶ SZ effect
  - ▶ Evolution of cluster populations
    - ▶ The state of HI sensitivity



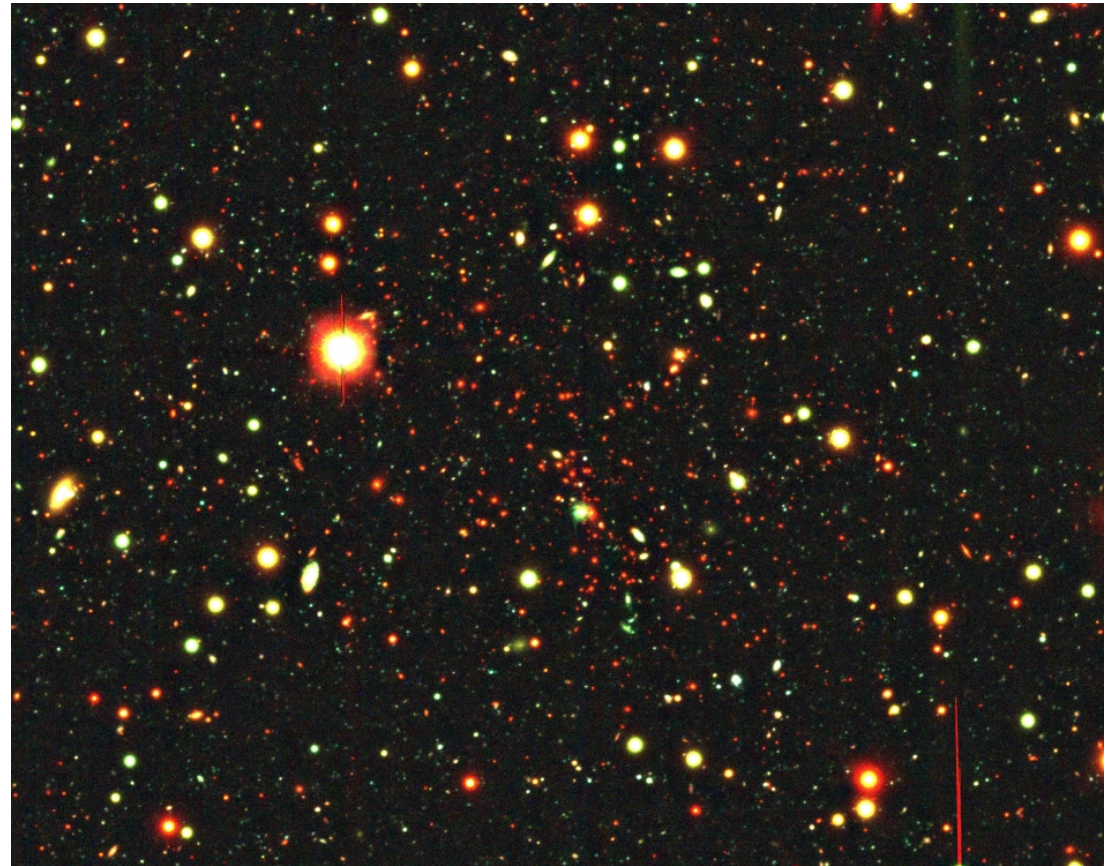
# Galaxy Clusters

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MS0451:  $z=0.54$ ,  $\sigma=1354$  km/s,  $L_x=40e44$  ergs/s

- ▶ Contain 10% of all galaxies
- ▶ Dark matter dominated
  - ▶ (M/L > 100)
- ▶ Galaxy evolution different in clusters
- ▶ Tracers of growth and evolution of large scale structure
  - ▶ “Easily” identified at high  $z$

(Can you say “Malmquist Bias”?)



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WIYN Long-Term Variability Survey

Crawford et al. 2006, 2008

# Galaxy Clusters (continued)

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- ▶ Early work of Abell (1958) → optical plates
- ▶ Abell's criteria
  - ▶ “Richness” (1-5)
    - ▶ # of galaxies brighter than 2 magnitudes fainter than the 3<sup>rd</sup> brightest member (*Why 3<sup>rd</sup>?*)
    - ▶ → proportional to total # of galaxies in cluster
  - ▶ Compactness: galaxies only counted within 1.5 Mpc radius of cluster center
- ▶ Space density of clusters:  $N(\text{Richness} > 1) = 10^{-5} \text{ Mpc}^{-3}$ 
  - ▶ average separation between clusters  $\sim 50 \text{ Mpc}$  if randomly distributed.
  - ▶ Clusters correlated on scales  $\sim 26 \text{ Mpc}$ 
    - ▶ Not random!
  - ▶ Compare to galaxies:
    - ▶  $N = 10^{-2} \text{ Mpc}^{-3}$  for galaxies of “typical” luminosity
    - ▶ Average separation of  $\sim 5 \text{ Mpc}$



# Basic properties of galaxy clusters

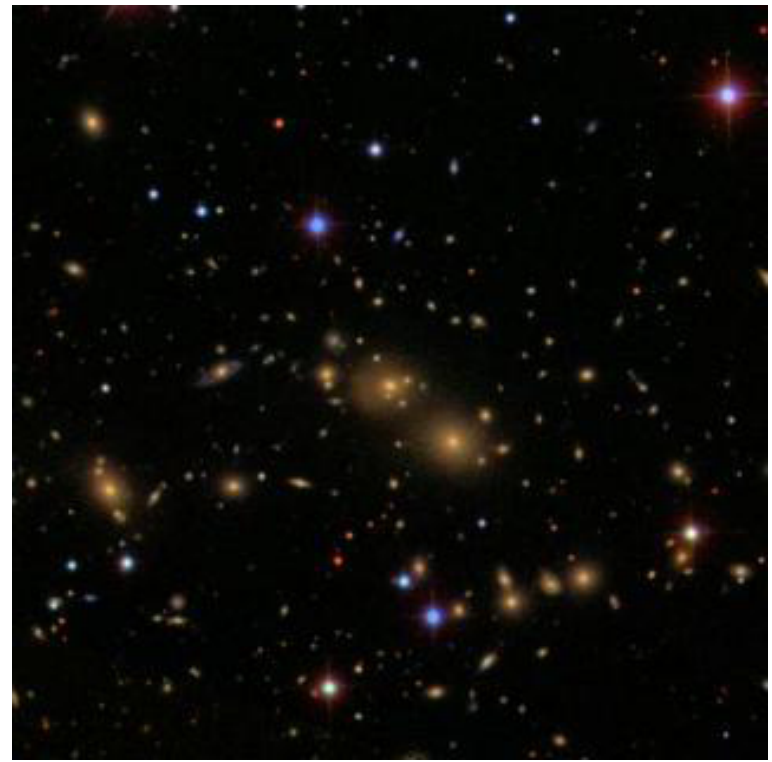
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- ▶ Mass  $\sim 10^{15}M_{\odot}$  or greater
- ▶ Velocity dispersions  $\sim 1000 \text{ km s}^{-1}$
- ▶ Radius  $\sim$  few Mpc
- ▶ Population  $\sim$  few 100 galaxies
  - ▶ Schechter LF defined from galaxy clusters



# Identifying Clusters - Imaging

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MS 0451  
 $z=0.53$

CL1322  
 $z=0.75$

MS 1054  
 $z=0.83$

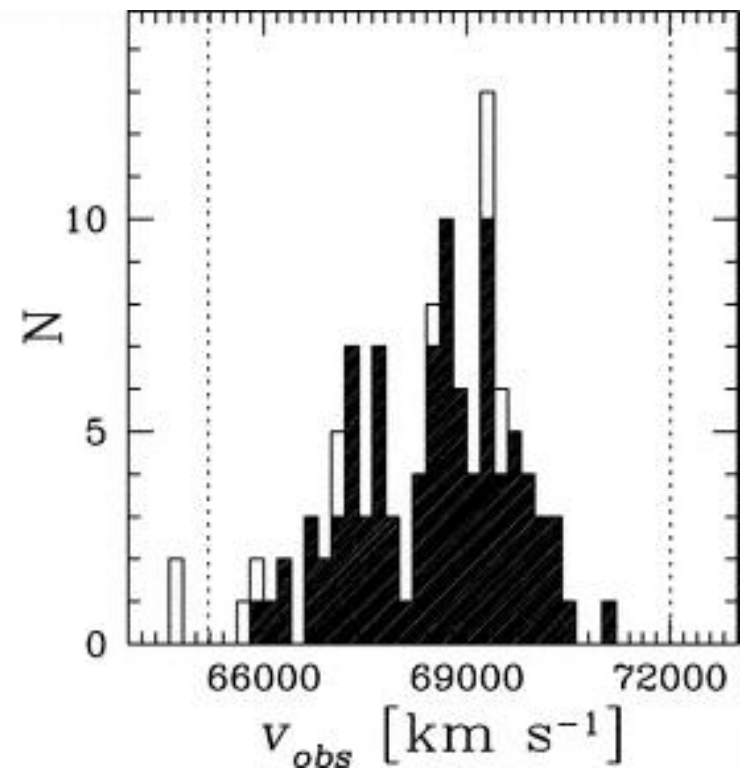
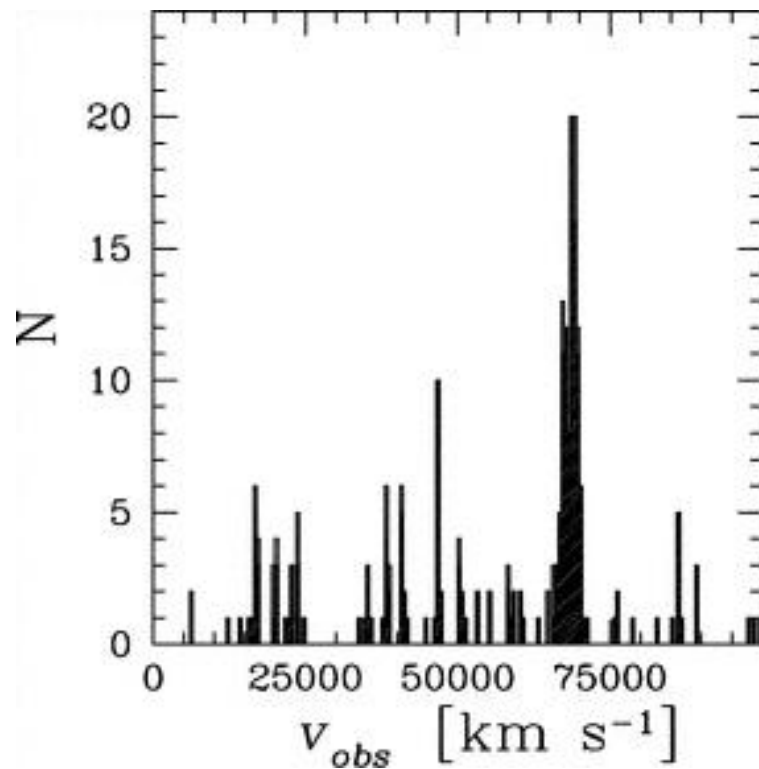
CL0016  
 $z=0.55$

CL1325  
 $z=0.72$

CL 1604  
 $z=0.90$

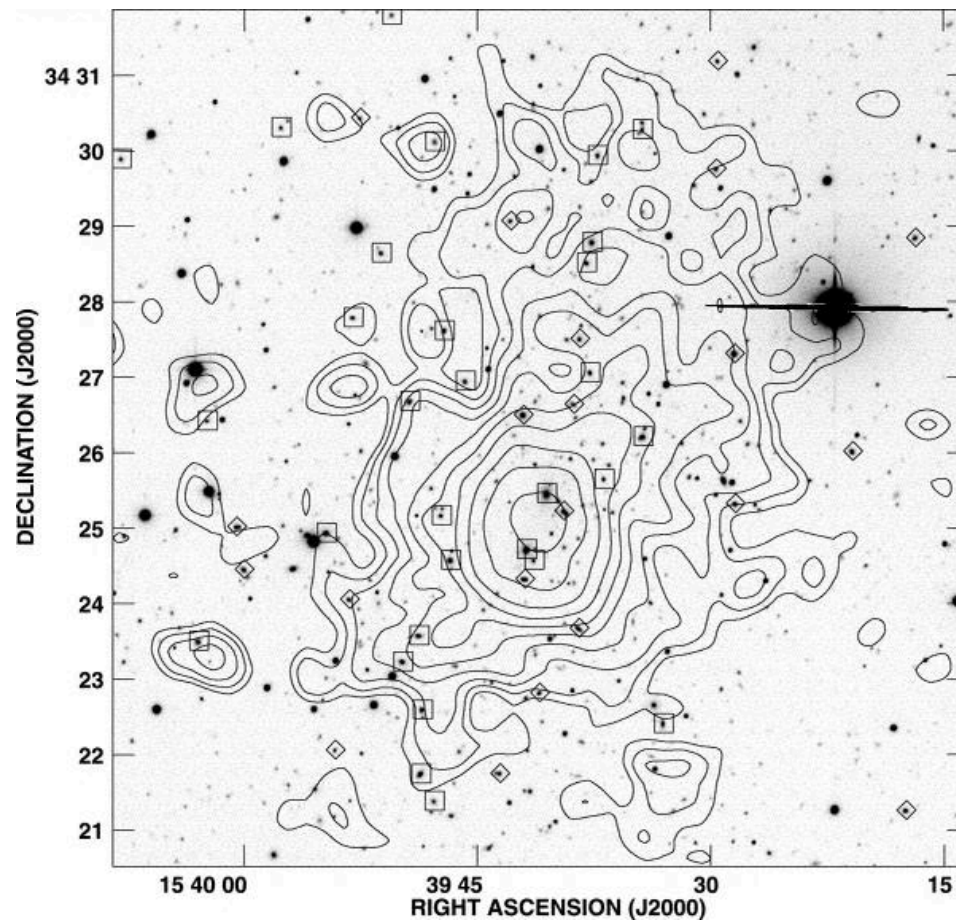
# Identifying Clusters - Spectroscopy

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# Identifying Clusters – X-Rays

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# Cluster types

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- ▶ **Spiral-rich**

- ▶ E:S0:S → I:2:3 → similar to field
- ▶ Asymmetric structure
- ▶ Really clusters or superposition of field galaxies in filaments?
  - ▶ Projection effects! (increase with distance,  $z$ )

- ▶ **Spiral-poor**

- ▶ E:S0:S → I:2:I

- ▶ **Centrally dominant (cD)**

- ▶ 1,2 dominant galaxies (ellipticals)
- ▶ Few spirals (< 20%)
- ▶ Spherical distribution of galaxies



# Clusters as Isothermal Spheres

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- ▶ **Hydrostatic equilibrium:**

- ▶ pressure support balances gravitational potential →

$$dp_{\text{gas}}/dr = -GM_{\text{cluster}} \rho_{\text{gas}}/r^2$$

- ▶ Assume: Ideal gas law →

$$p_{\text{gas}} = \rho_{\text{gas}} k_B T_{\text{gas}} / \mu m_H \quad (\mu = \text{mean mass})$$

□  $(3/2 k_B T = 1/2 \mu m_H v^2)$

- ▶  $(\rho_{\text{gas}} k_B T_{\text{gas}} / \mu m_H) [ (1/\rho_{\text{gas}})(d\rho_{\text{gas}}/dr) + (1/T_{\text{gas}})(dT_{\text{gas}}/dr) ]$   
 $= -(GM_{\text{cluster}} (<r) \rho_{\text{gas}})/r^2$

- ▶ **thus,**

- ▶ cluster mass  $M_{\text{cluster}}$  goes as  $T_{\text{gas}}, \rho_{\text{gas}}$
- ▶ X-ray luminosity,  $L_X$  (free-free emission, or thermal brehmsstrahlung) depends on density and temperature



# Characteristic values revisited

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- ▶ **Cluster masses**
  - ▶ Galaxies  $\rightarrow 10^{12} - 10^{14} M_{\odot}$
  - ▶ Gas  $\rightarrow \text{few} \times 10^{12}$  to  $\text{few} \times 10^{14}$
  - ▶ Gravitational  $\rightarrow 10^{13} - 10^{15} M_{\odot}$
  
- ▶ More mass in gas than stars, dark matter dominated !



# Sunyaev-Zeldovich (S-Z) Effect

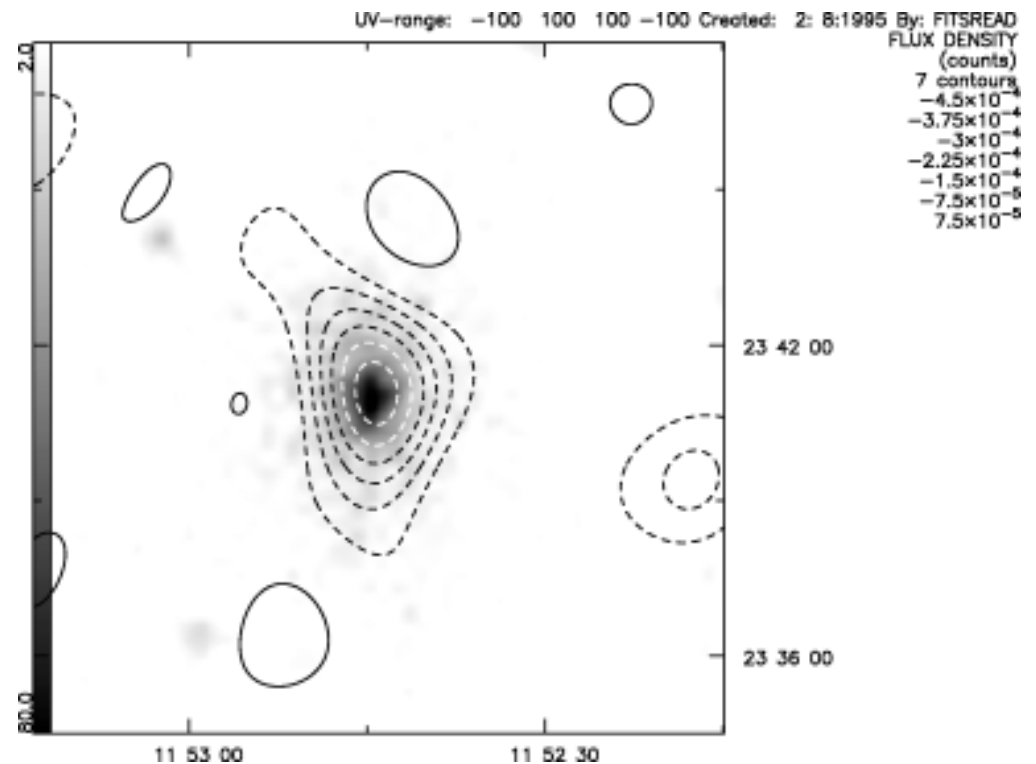
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- ▶ CMB + hot plasma →
  - ▶ Compton scattering → distortions in the CMB BB spectrum
  - ▶ Source of hot plasma? ← Galaxy clusters
- ▶ Compton scattering optical depth
  - ▶  $y = \int (k_B T / m_e c^2) \sigma_T N_e dl$ 
    - ▶  $\sigma_T$  is the Thompson cross section
    - ▶ Integral is along line of sight
    - ▶ Recall  $T_e$  is a function of cluster mass
- ▶ Decrement in Rayleigh-Jeans region of spectrum
  - ▶  $\Delta I/I = -2y \rightarrow \sim 10^{-4}$
- ▶ Hot gas from clusters affects microwave background
  - ▶ → best measured in radio part of the spectrum
  - ▶ → search tool for distant clusters
  - ▶ Map large scale structure, find clusters, measure cluster masses
    - ▶ Detection via radio continuum observations



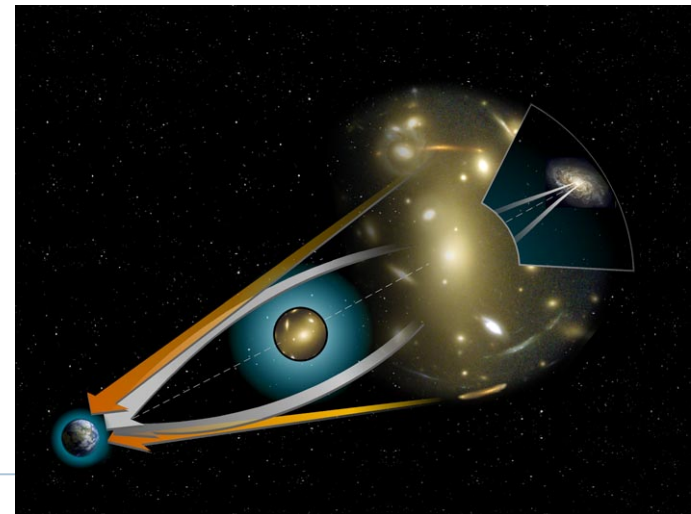
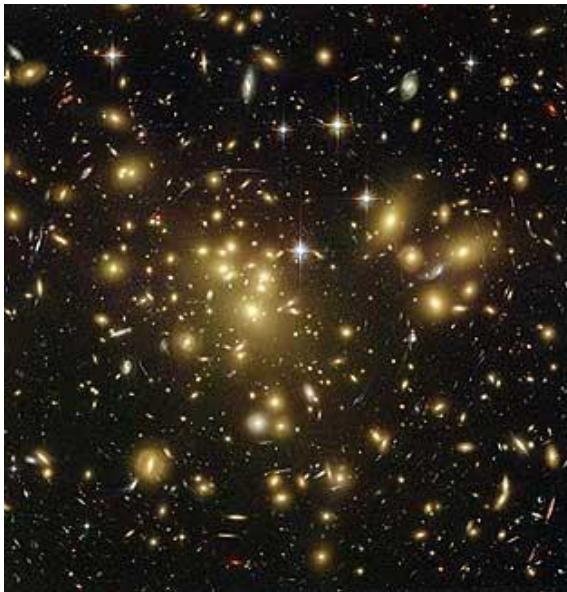
# Sunyaev-Zeldovich (S-Z) Effect

- ▶ CMB photons scatter off hot electrons in ICM
  - ▶ Statistical net gain of energy → CMB spectrum shifted to slightly higher energies → decrement in intensity at Rayleigh-Jeans limit ( $h\nu \ll kT$ )
  - ▶ Amount of decrement → integral of pressure (NT) along line of sight



# Strong Lensing

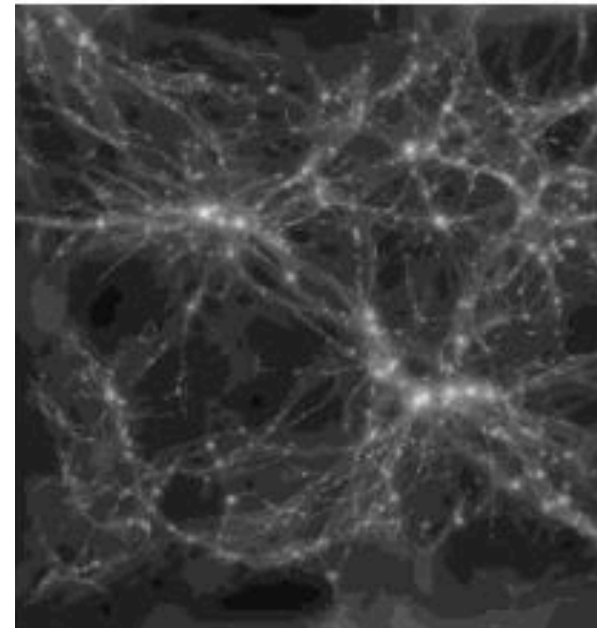
- ▶ Probe cluster potential independent of (Newtonian) dynamics
- ▶ Use cluster as giant telescope to amplify distance sources.



# Cluster Evolution

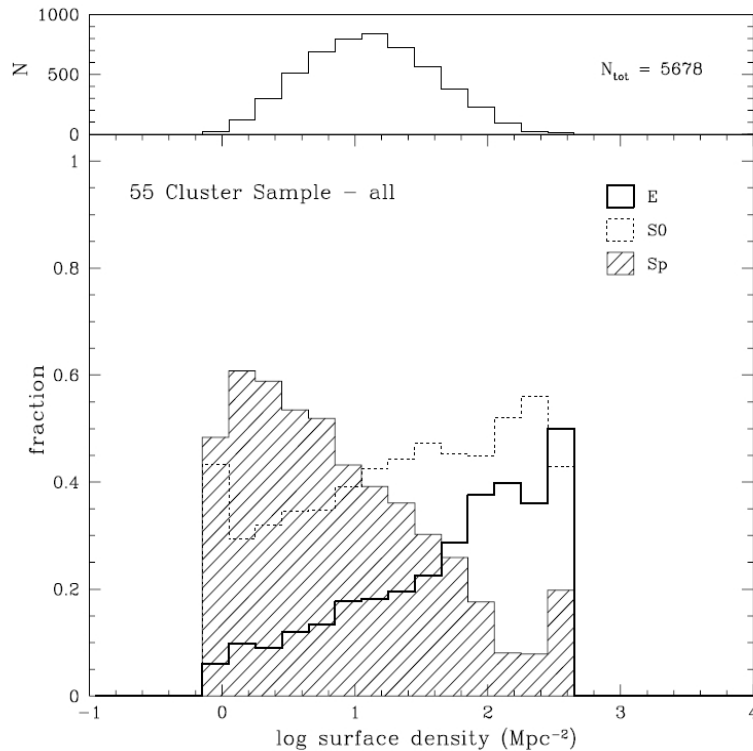
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- ▶ **Why might we expect it?**
  - ▶ What does density determine?
- ▶ **What might we expect, say, for evolutionary time-scales in dense environments relative to the field?**
  - ▶ Stellar evolution?
  - ▶ Gas-consumption rates?
  - ▶ Dynamical processes (merging)?
- ▶ **How would cluster selection-effects impact our assessment of evolution?**
  - ▶ If density is important, what *types* of clusters will be most *easily* detected at *large* distances?
  - ▶ How about *projection* effects?

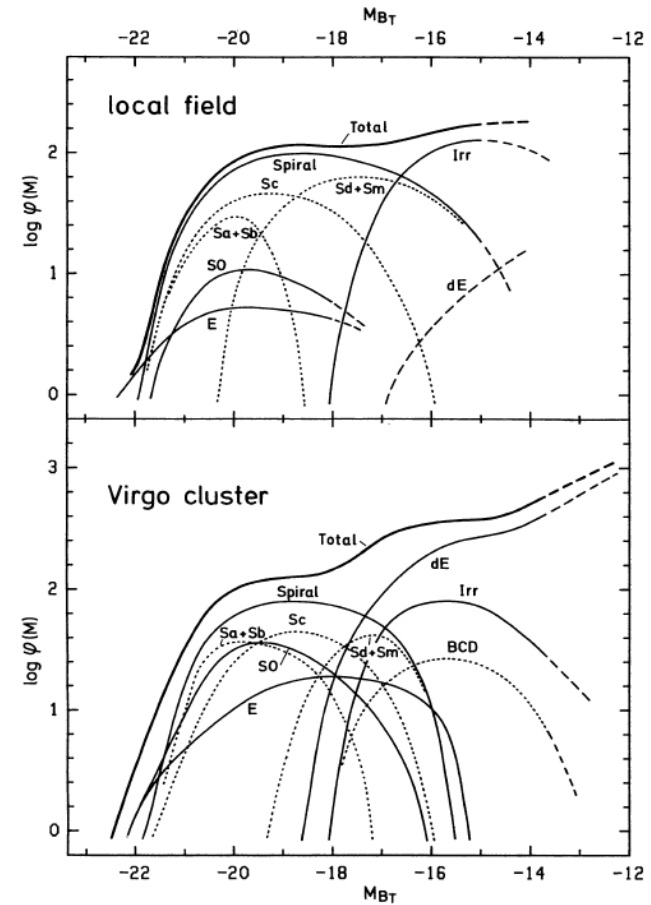


# Cluster vs the field: an environmental view

- ▶ The morphology-density relationship
  - ▶ E's, S0's, and dE's more common in clusters



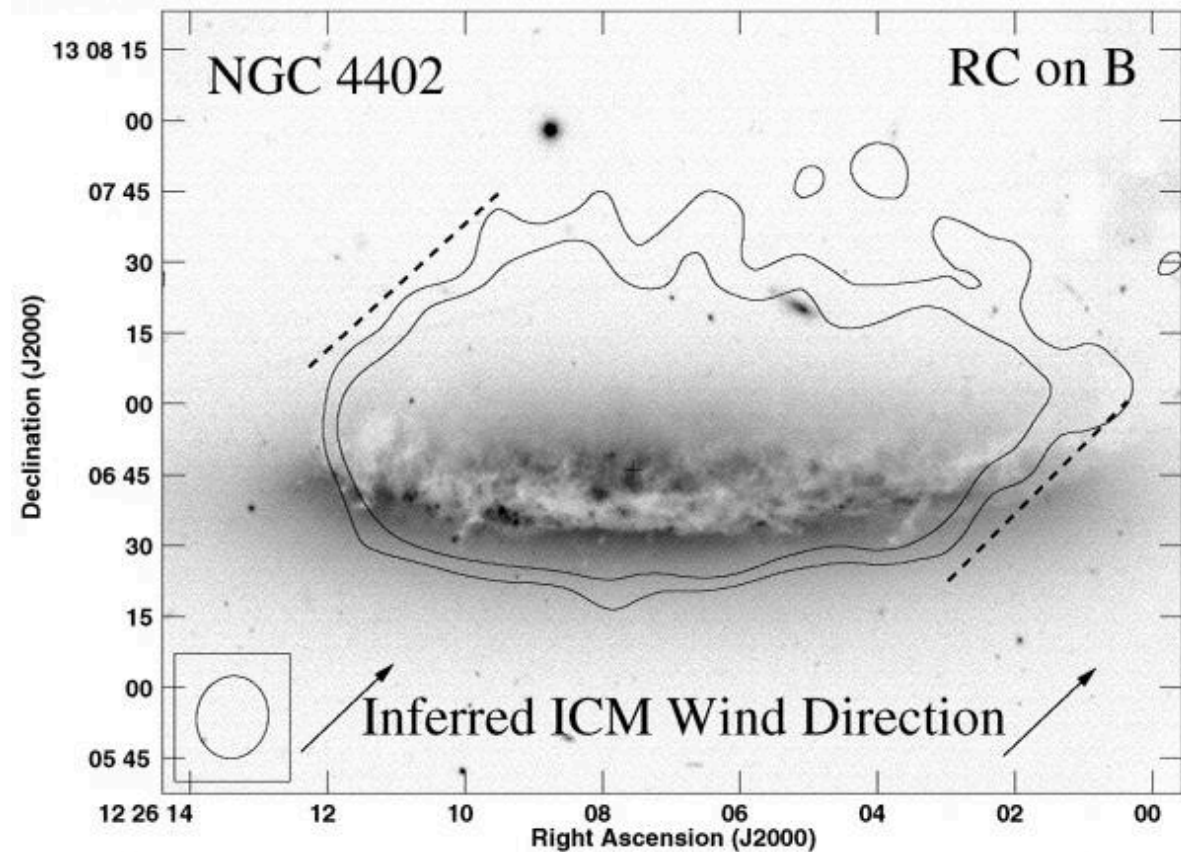
Dressler et al. '97



Binggeli et al. '88

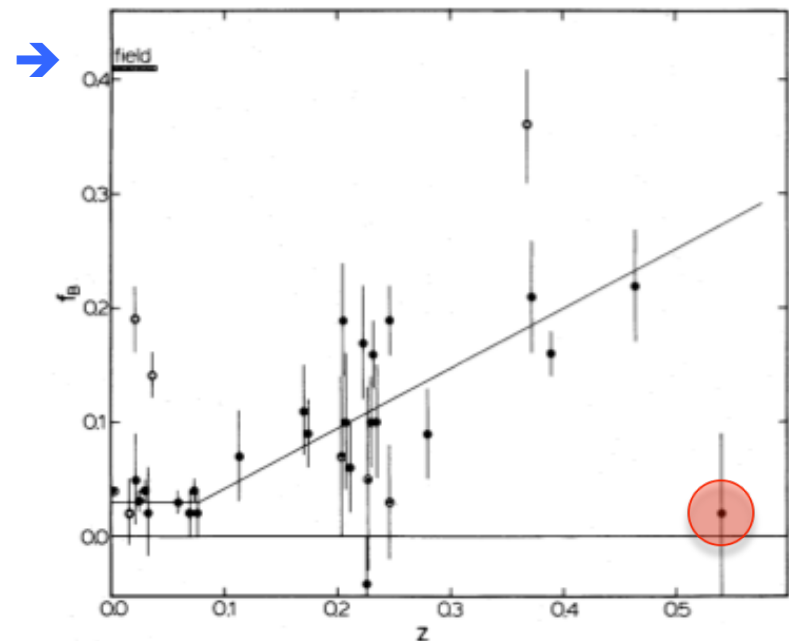
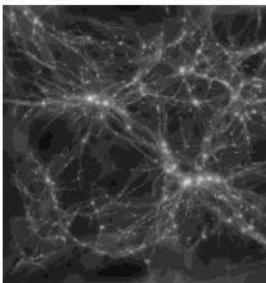
# Ram-pressure stripping

- ▶ Spirals undergo stripping, interactions in rich cluster environments
- ▶ How does this affect star-formation, galaxy colors, and morphology?



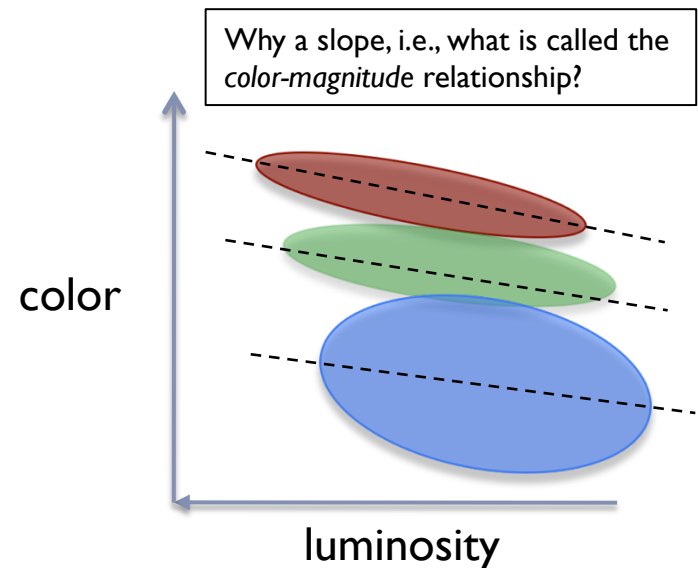
# Cluster Evolution: Butcher-Oemler Effect

- ▶ (Also known as the BO or “moving target” effect)
- ▶ Original claim: (1984, ApJ, 285, 426)
  - ▶ Moderate  $z$  clusters have larger fractions of blue galaxies
- ▶ Counter examples
  - ▶ e.g., CL0016+16
- ▶ Later amended to
  - ▶ spectroscopically younger:
    - ▶ “E+A” galaxies
      - Higher velocity dispersions
      - Less centrally concentrated
    - ▶ More AGN
    - ▶ More star-bursting galaxies
- ▶ Don’t forget projection!
- ▶ Sample selection?



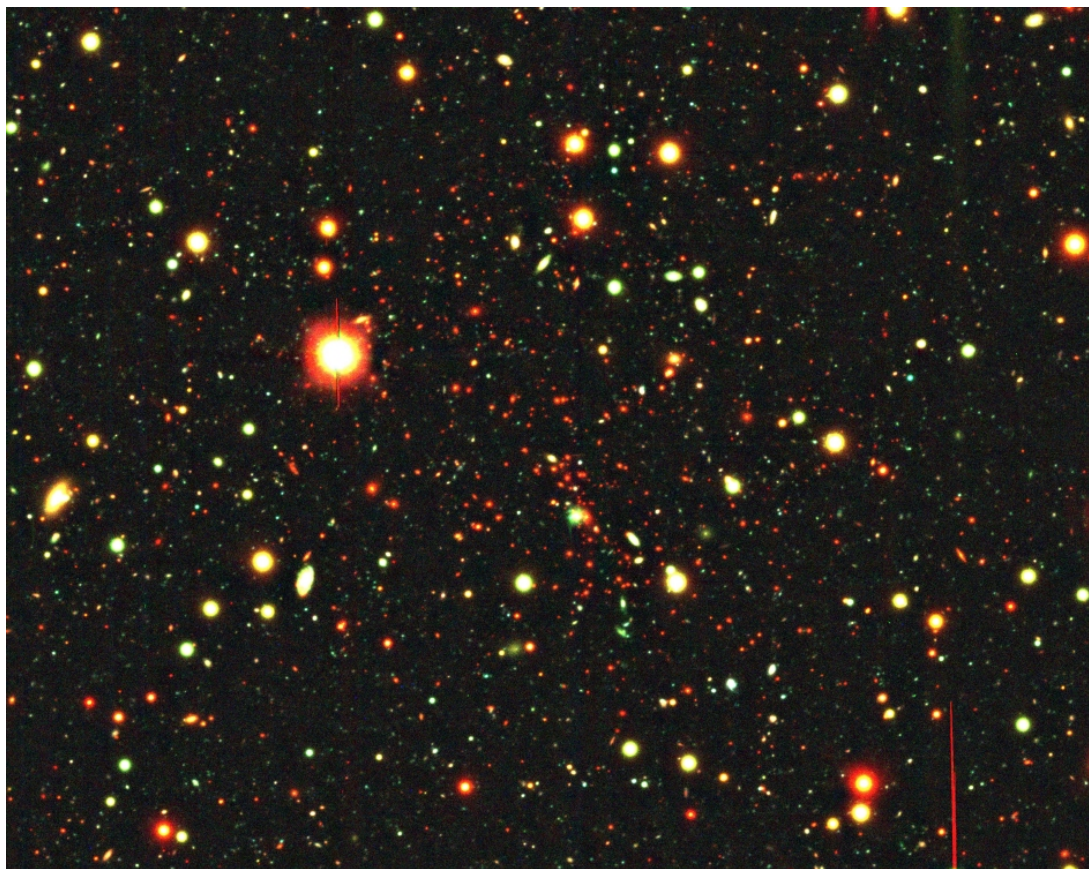
# Cluster Evolution: the red sequence

- ▶ If clusters had more blue galaxies yesterday
  - ➔ they have become red by today.
  - ➔ The luminosity function (LF) for different morphological or spectral types should change with time
- ▶ Specifically, the LF for red galaxies should grow with time.
  - ▶ If the LF slope changes, that tells us whether the “growth” of the red populations is for high- or low-mass objects, i.e., what the blue galaxies at higher redshift are progenitors of today.
    - ▶ Crude spectral types:
      - ▶ Red sequence
        - Red and dead (today: E's and S0's)
      - ▶ Blue cloud
        - Vigorously star-forming (today: intermediate to late-type spirals and dlrrs)
      - ▶ Green valley
        - Weakly forming stars (today: early-type spirals and some lenticulars)



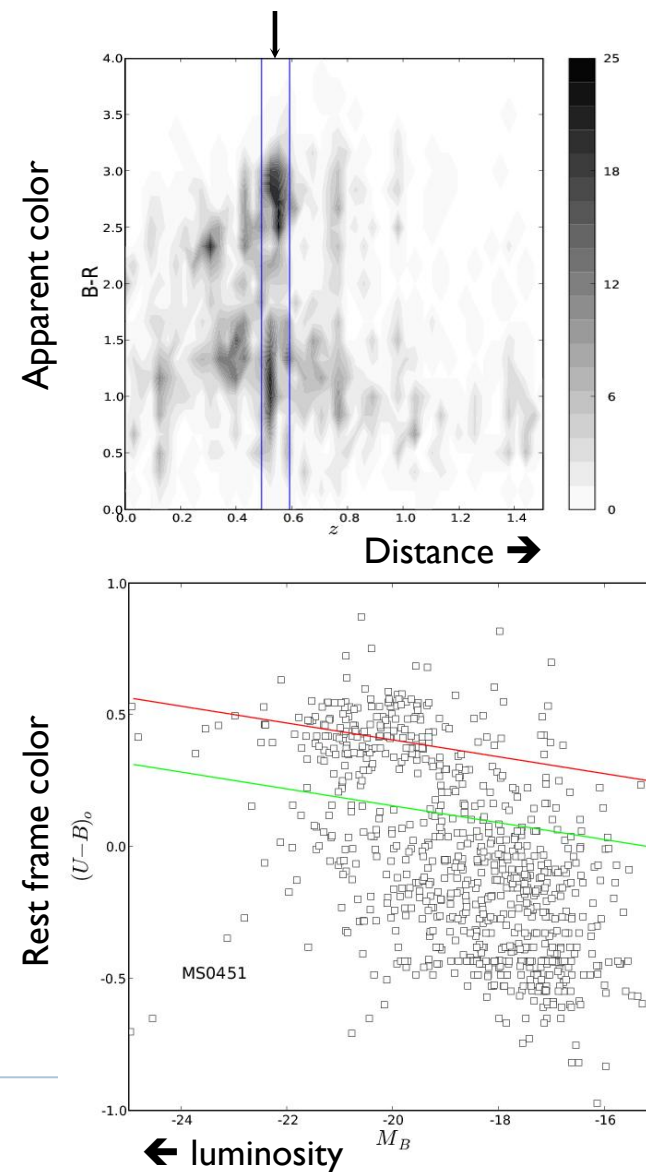
# At $z=0.5$ , the red sequence is well-formed

MS0451:  $z=0.54$ ,  $\sigma=1354$  km/s,  $L_x=40e44$  ergs/s



WIYN Long-Term Variability Survey

▶ Crawford et al. 2006, 2008



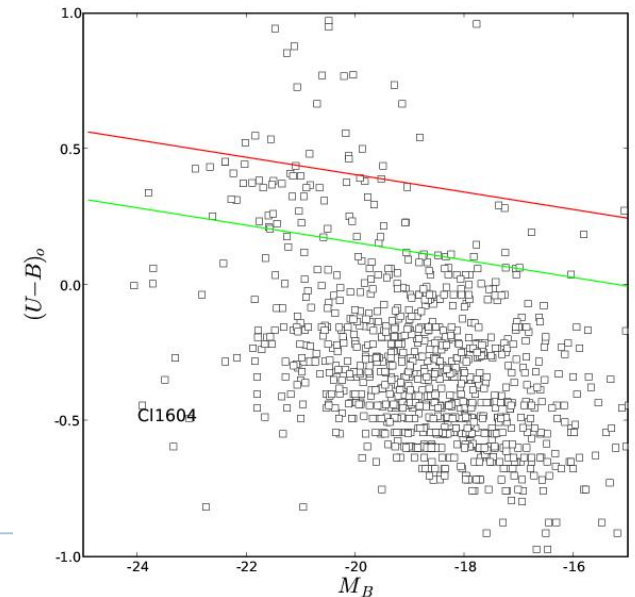
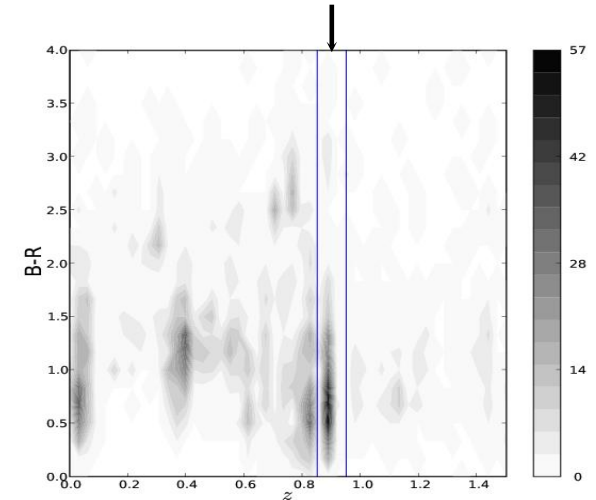
# At $z=0.9$ , the blue cloud dominates . . . even in rich clusters

CL1604:  $z=0.9$ ,  $\sigma=982$  km/s,  $L_x=2e44$  ergs/s



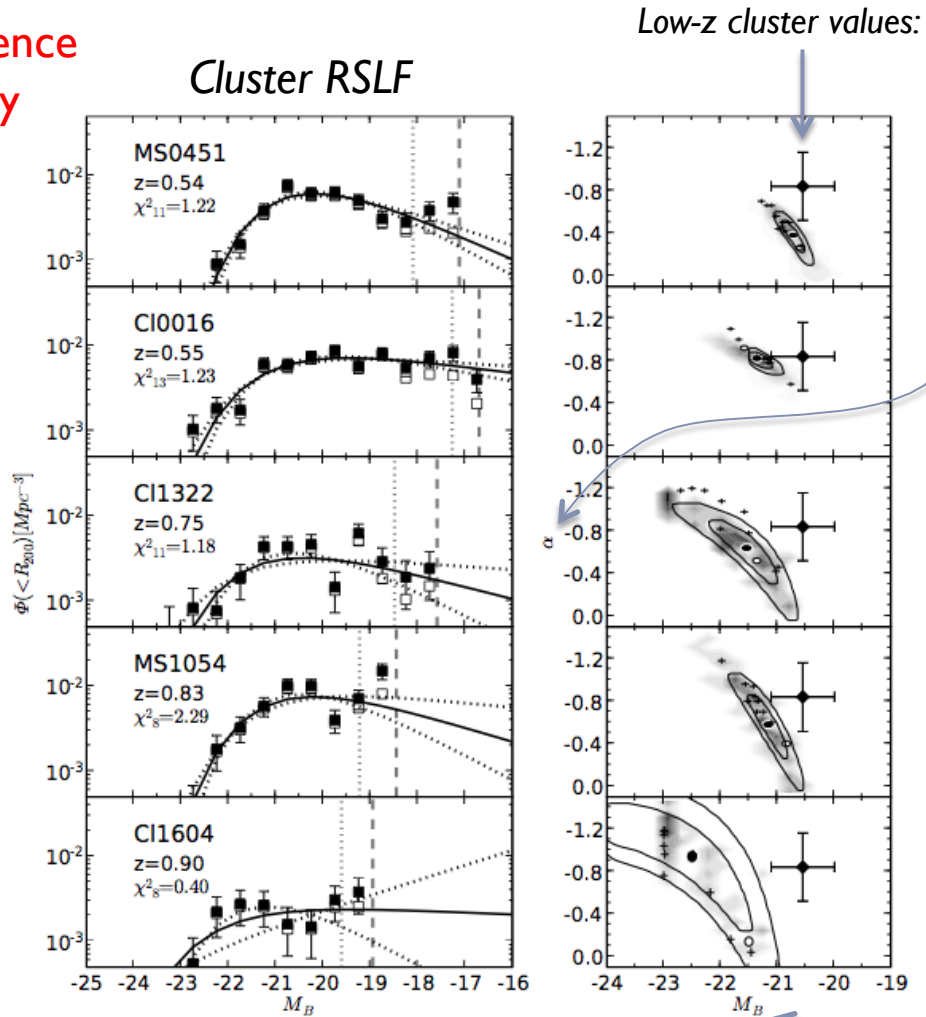
WIYN Long-Term Variability Survey

▶ Crawford et al. 2006, 2008

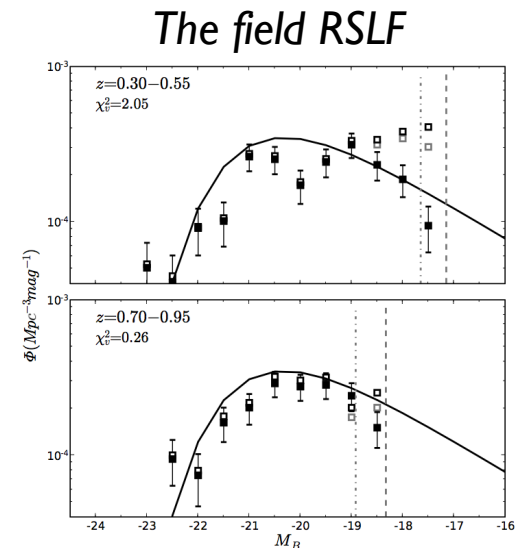


# Cluster luminosity functions to $z=1$

Red sequence  
Luminosity  
functions  
(RSLF)



$\alpha$  is faint-end slope;  
more negative  $\alpha$  means  
steeper, upward slope

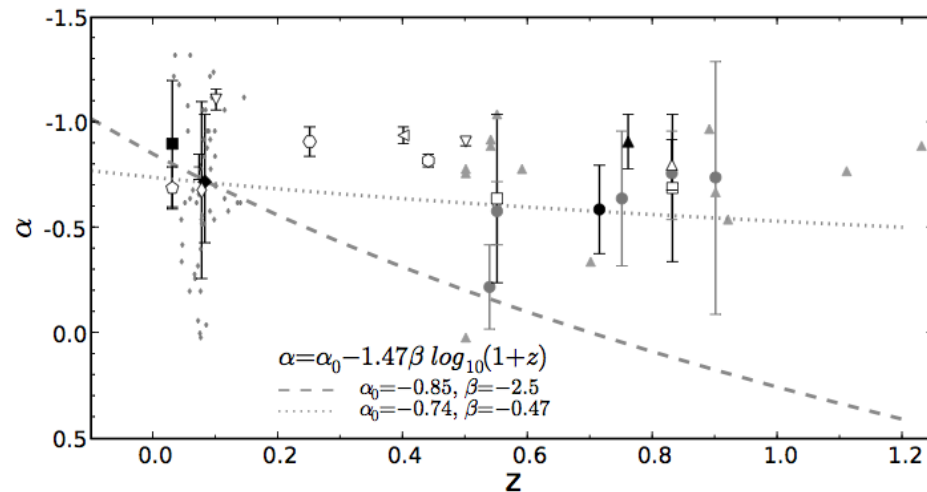
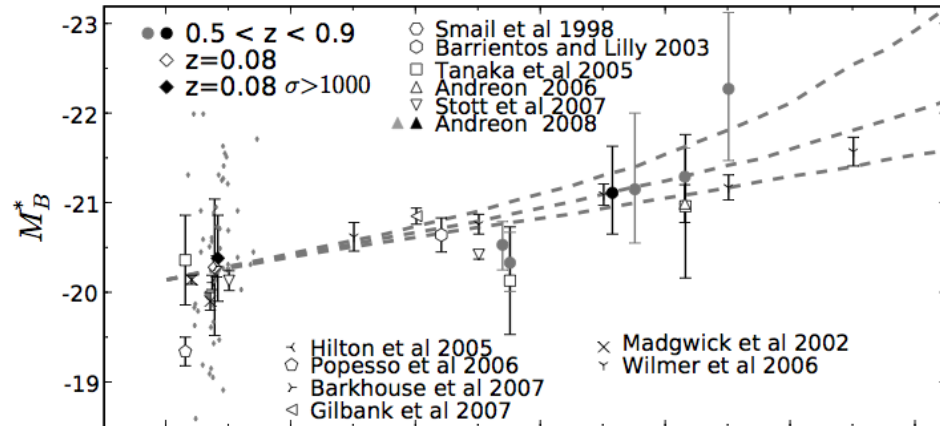


Knee of LF

# Luminosity Function Evolution

Consistent with *passive*\* luminosity evolution

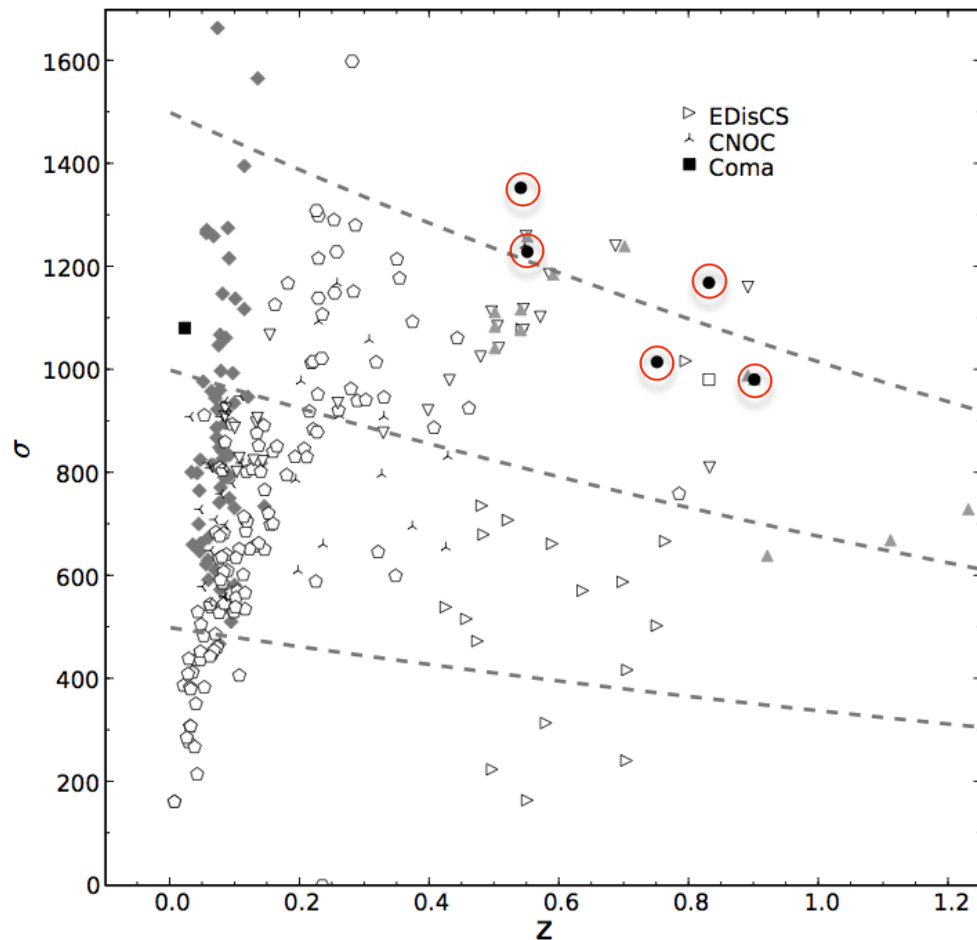
\* *Passive evolution* refers to the evolution of stellar populations in the HR diagram (CMDs) in the absence of further star-formation.



# Don't forget selection effects...

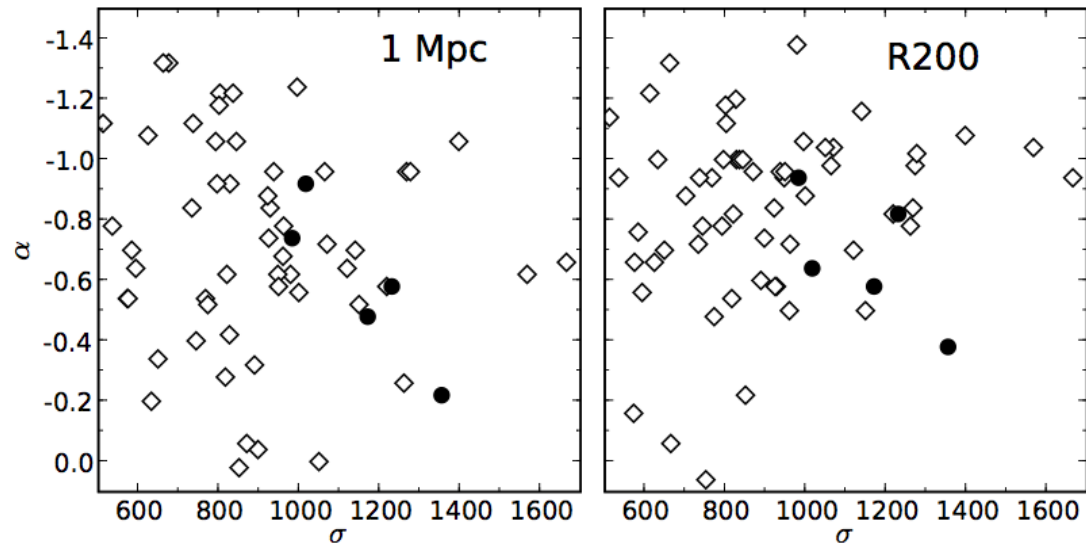
Cluster mass, or its proxy,  $\sigma$ , grow with time as more and more mass falls in to and virializes with the cluster potential.

The clusters studied most intensively at higher redshifts are as large or larger than most known clusters in the local volume (they are rare).



## ...Combined with cosmological variance

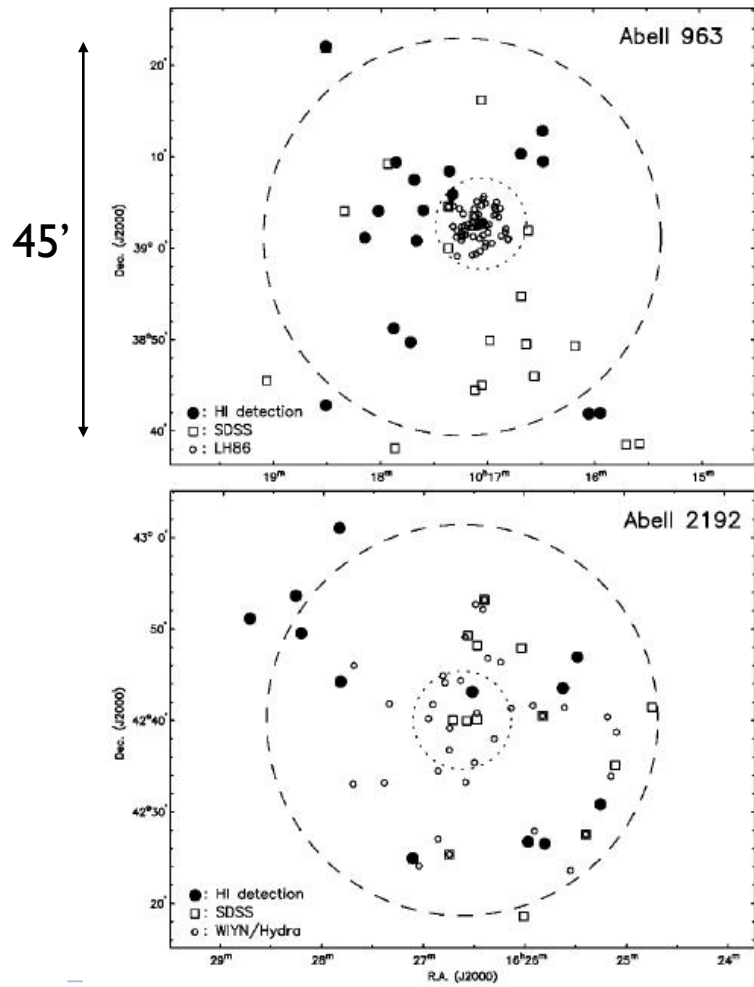
Faint-end slope  
of the red-  
sequence LF



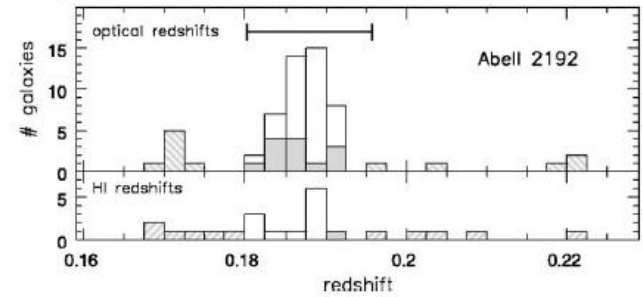
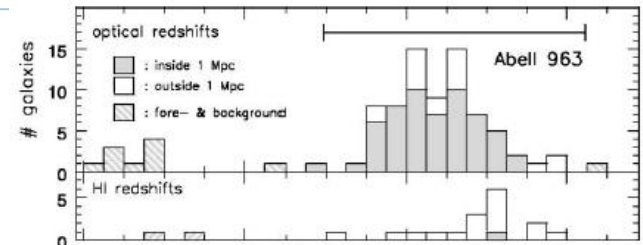
- Clusters exhibit a wide range of faint-end slopes.
- If there is a correlation with other cluster properties (there must!) it has not yet been determined.
- It does appear that the inner-cluster regions have larger (more positive)  $\alpha$ , indicative of a relative dearth of dwarf systems.
- What's the cold gas doing?

# HI View: State of the Art:

Verheijen et al. 2007 (van Gorkum)

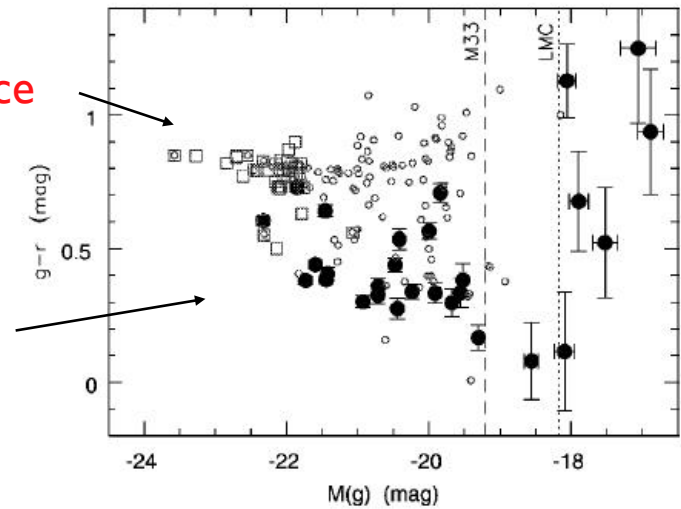


$z=0.2$



Red sequence

Blue cloud



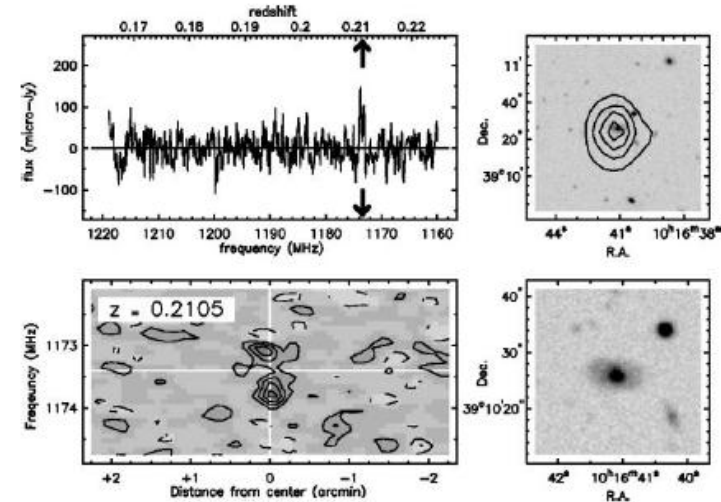
Westerbork

NB: 200h of 1000h total to come!

# HI View: State of the Art

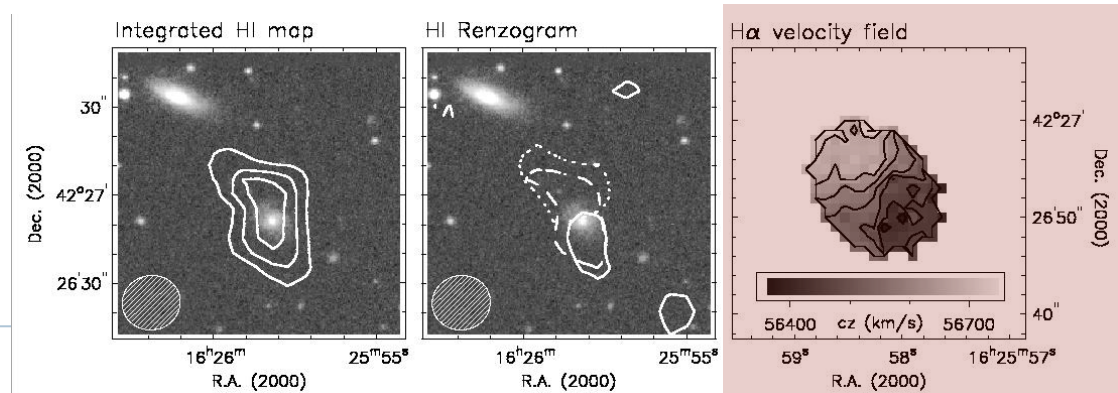
- ▶ Solid detections for 42 sources in 2 x 0.4 deg<sup>2</sup> fields
  - ▶ expect 200 sources in 1000h
- ▶ Limited spatially-resolved kinematic information
- ▶ H $\alpha$  offers detailed kinematic supplement + SFR map
  - ▶  $t=80$  min, 3.5m telescope (CA)
  - ▶ 16x16 array of 1" fibers (PMAS)

A963 - Westerbork



A2192 (z=0.19) - VLA

$$M_{\text{HI}} = 7 \times 10^9 M_{\text{sun}}$$



Verheijen & Dwarakanath '08



# The State of HI Sensitivity

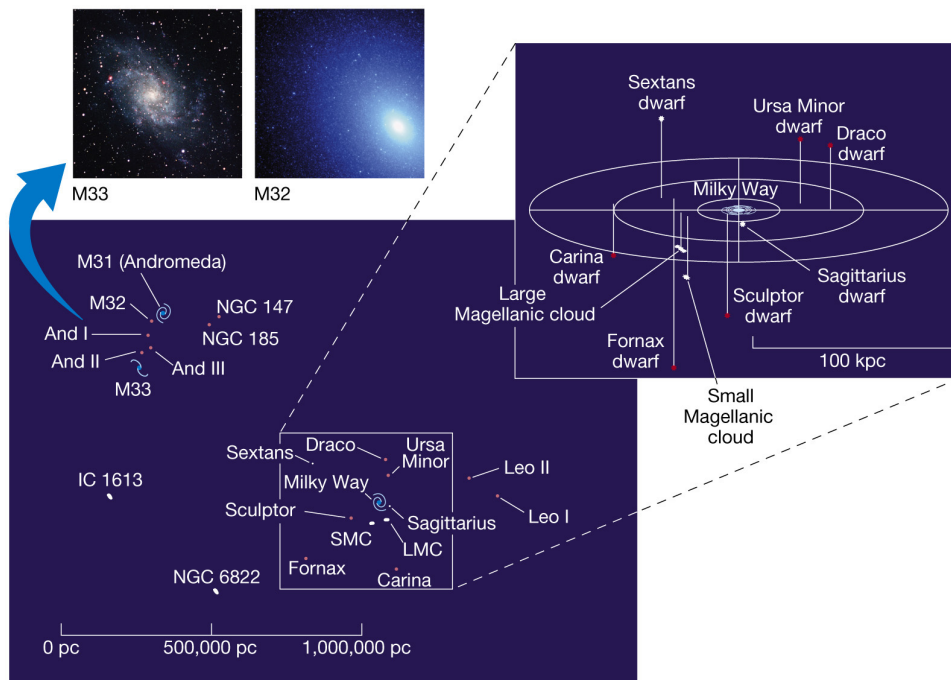
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- ▶ Heroic efforts
- ▶ Awesome data
- ▶ ... but sensitivity is pitiful compared to optical and infrared data
- ▶ Really need SKA

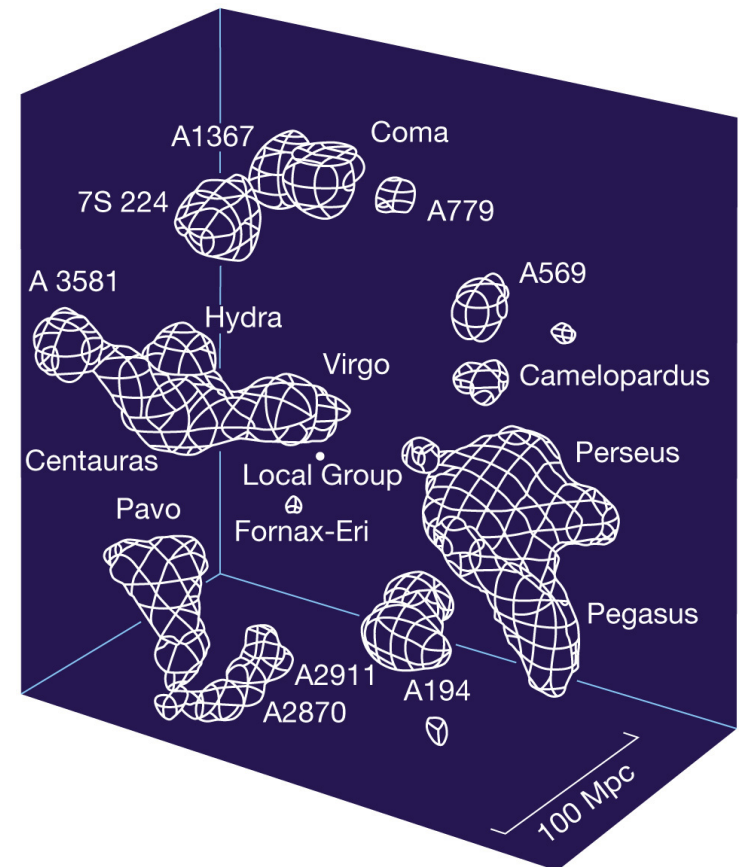


# Large Scale Structure: revisited

## ▶ Local Group (1 Mpc):



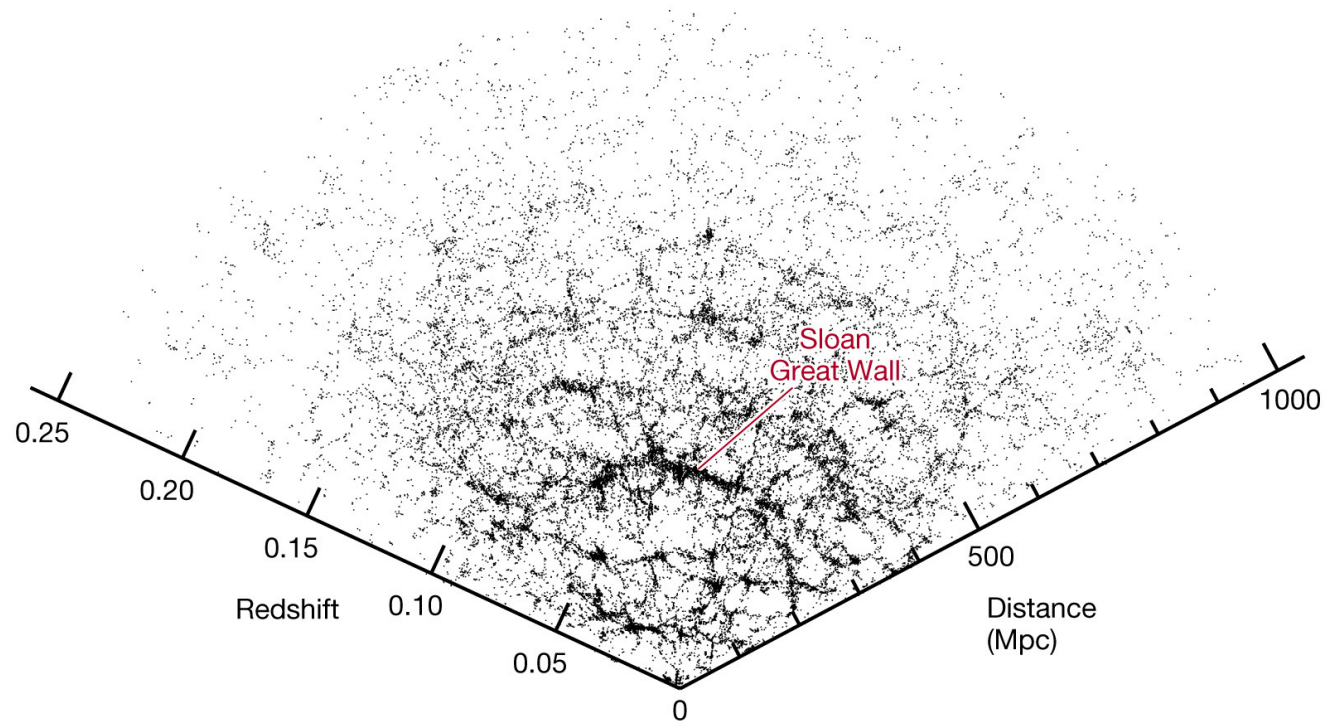
## ▶ Local volume (100 Mpc):



# Large Scale Structure: revisited

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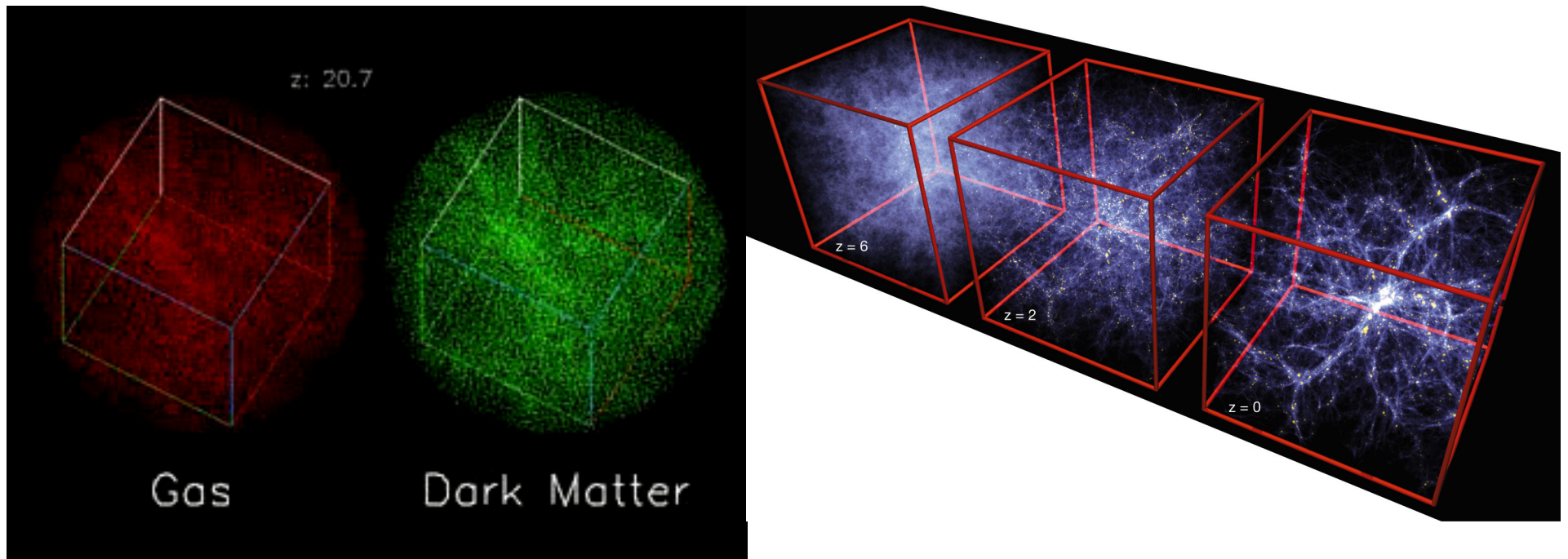
- ▶ **Filaments and voids**
  - Great Attractor
  - Characteristic scales: 40-120 Mpc



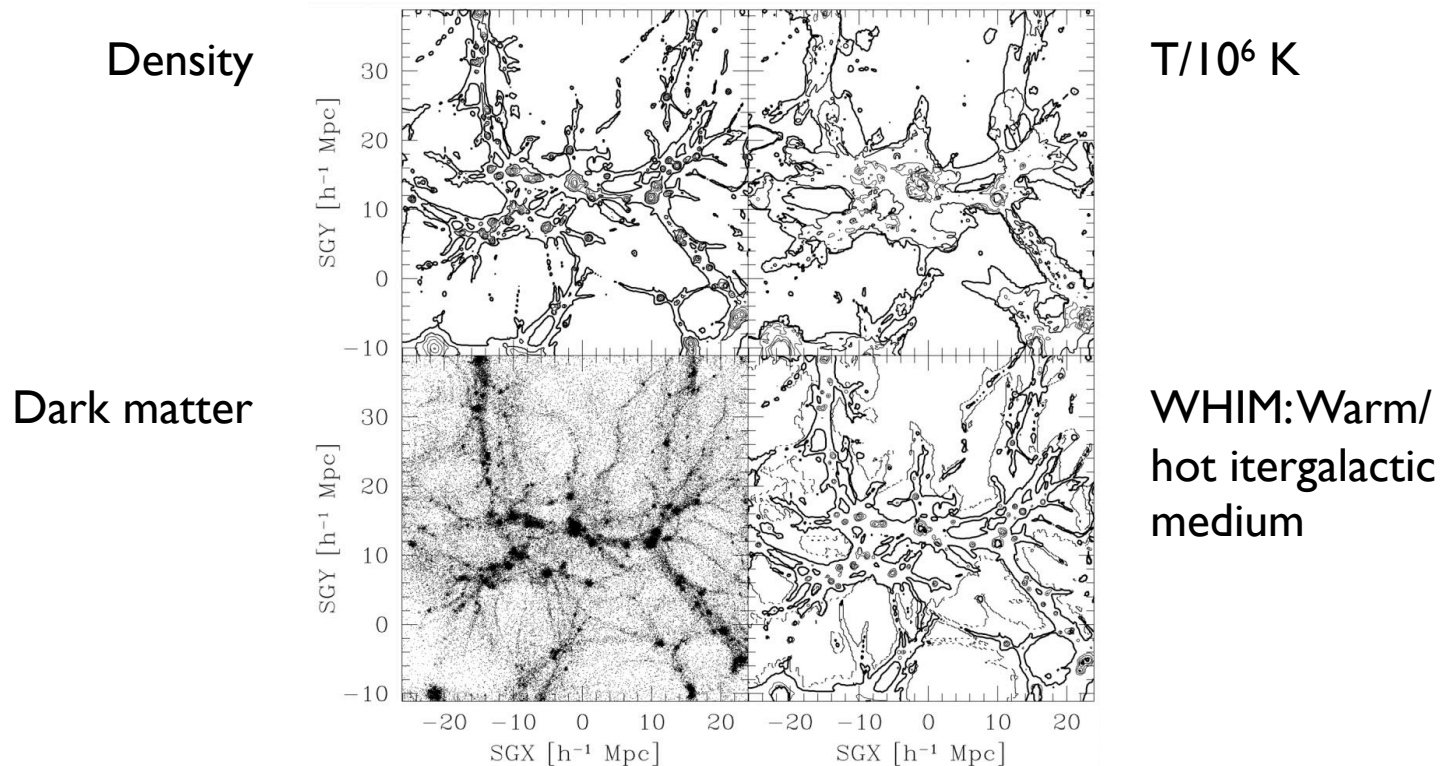
# Large scale structure of the Universe

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## ▶ Fly-through of the Cosmic Web

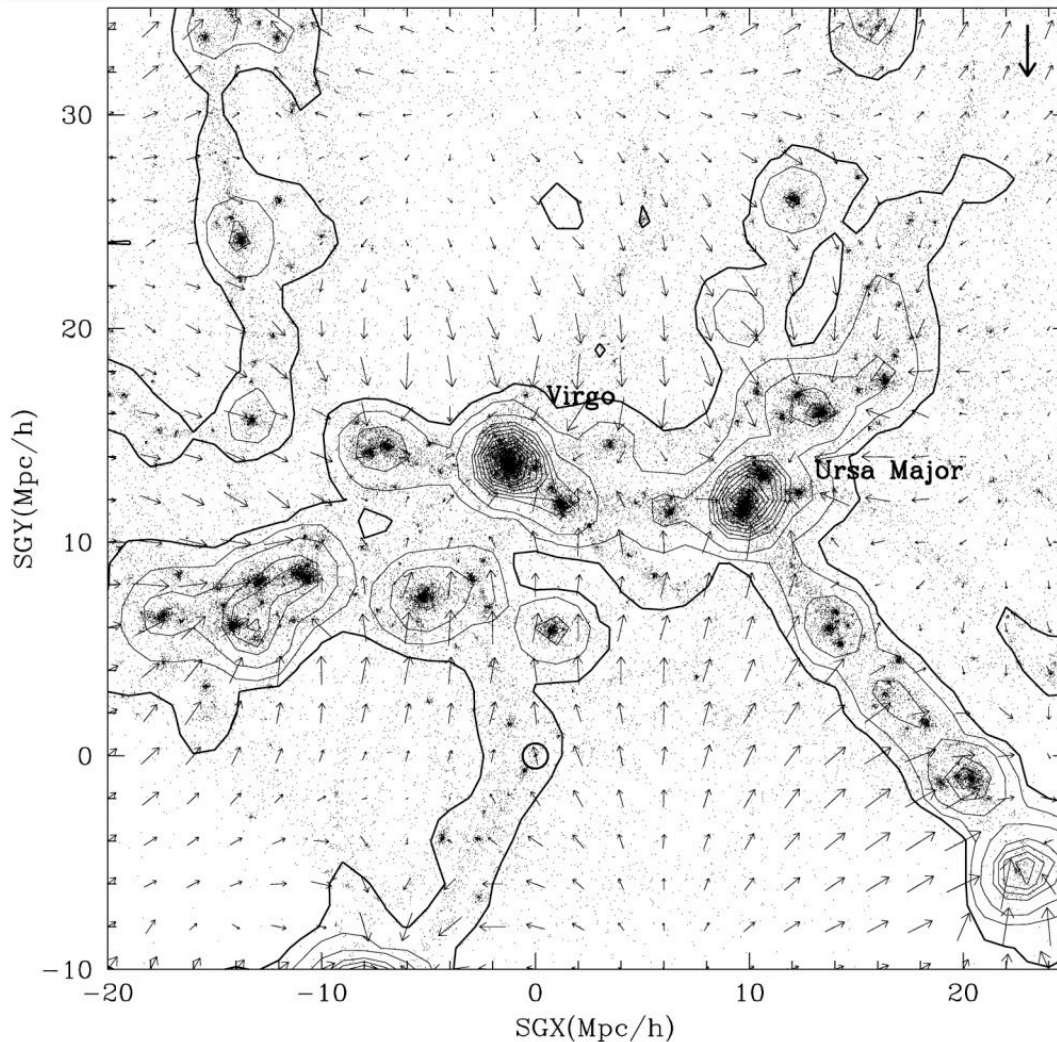


# The Cosmic Web



- WHIM: Claimed to contain the bulk of normal matter (baryons) in the universe
  - but this is based on scant number of QSO absorption lines-of-sight
- How was the WHIM produced? (structure/galaxy formation)
- How has it been kept at  $10^6 \text{ K}$  degrees over a Hubble time?
- Is there cold gas too? (how do you detect it?)

# Cosmic Streaming



- ▶ What does  $H_0$  mean?
- ▶ Over what scales (spatial)?
- ▶ What kinematic scales?

Klypin et al. 2003

# Superclusters

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- ▶ **The Peculiar Velocity Field and the Great Attractor**
  - ▶ Motions: Earth, Sun, Milky Way, Local Group, Virgo!
    - ▶ The observed motion of the Virgo Cluster implies something extremely massive in the direction of the southern Milky Way → The Great Attractor
- ▶ **Observed Superclusters**
- ▶ There are collections of clusters in the nearby Universe (Perseus-Pisces ridge); usually not spherical (like individual clusters)
- ▶ **Finding the Great Attractor**

