Astronomy 330

Lecture 24

03 Dec 2010

Outline

- Review:
  - Galaxy interactions: *transformative*
  - Groups:
    - Definitions
    - Environment & gas content
    - Pre-processing
- Clusters
  - Definitions, poperties types
  - Evolution and internal structure
  - SZ effect
  - Strong lensing

Review

- Galaxy interactions: *transformative*
  - Dynamical friction ← Slows lower-mass objects down to settle in a larger potential.
  - Tidal disruption ← Shreds weakly bound material.
  - Impulses ← High-velocity encounters: *clusters*
  - Mergers ← Low-velocity encounters: *groups*
- Groups:
  - Definition:
    - N_{gal} = 3-20, R = 0.25-0.5 Mpc, σ = 200-400 km s^{-1}, $M_{halo} \sim 10^{12} - 10^{14} M_{\odot}$
  - Environment, gas content, and evolution
    - {Early-type : late-type} fraction correlated with {presence : absence} of hot (X-ray) gas
    - Groups w/o X-ray gas are *dynamically* young. *What does this mean?*
  - Pre-processing:
    - Mergers most likely in groups (the Goldilocks effect)
    - Groups most likely to give rise to **morphology-density** relation between field and rich clusters.
      - Clusters are made of groups

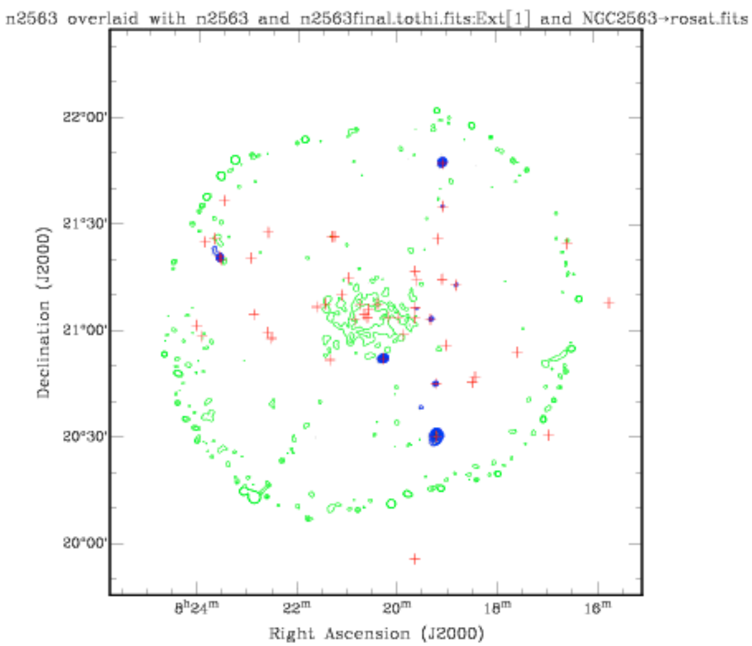
Group evolution: morphology & gas content

- Can group-evolution be traced by looking at the gas distribution?
  - Two trends observationally correlated:
    - Spiral rich ➔ elliptical dominated
    - Cool, neutral ➔ hot, ionized
    - None of the groups observed with $F_{spiral}=1$ have detectable X-ray halos
- Possible Scenarios and the hunt:
  - Tidally stripped neutral gas ➔ heated in the intra-group medium
  - Galaxy mergers ➔ heating of intergalactic medium
    - Measure the total amount and distribution of neutral gas
      - *What distinguishes between these two pictures?*
  - Compact groups are transient phenomena within larger loose groups ➔ development of common HI envelopes
    - Measure the interaction/merger rate
      - *How do you measure the rate?*
      - *How does the rate allow for inference of transience?*

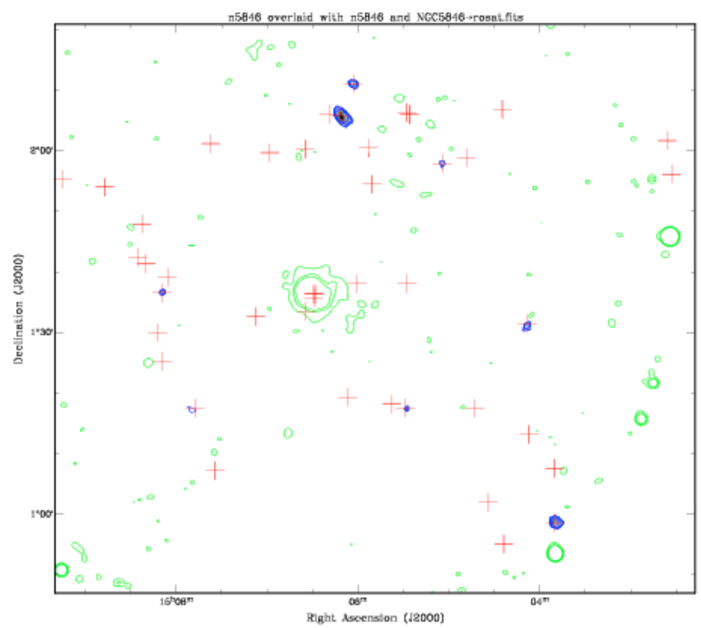
X-ray vs HI Group Emission

- HI detections
- All members
- X-ray emission

NGC 2563



NGC 5846

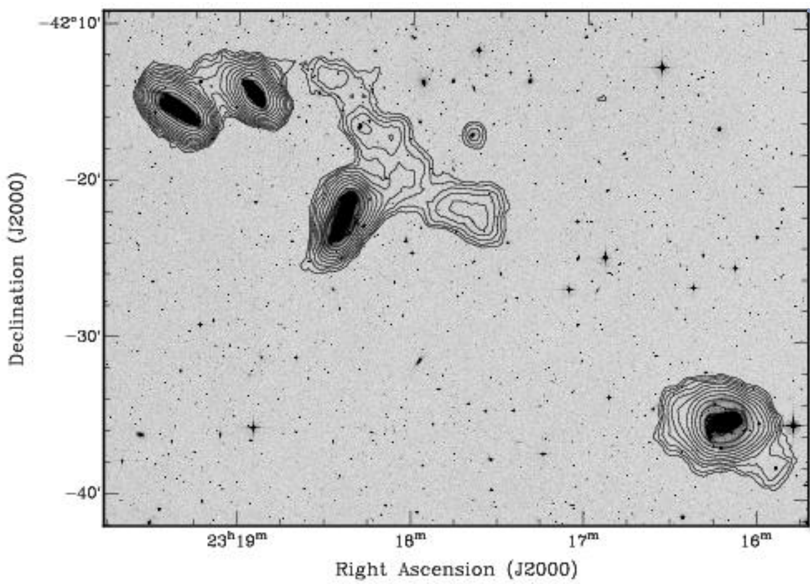


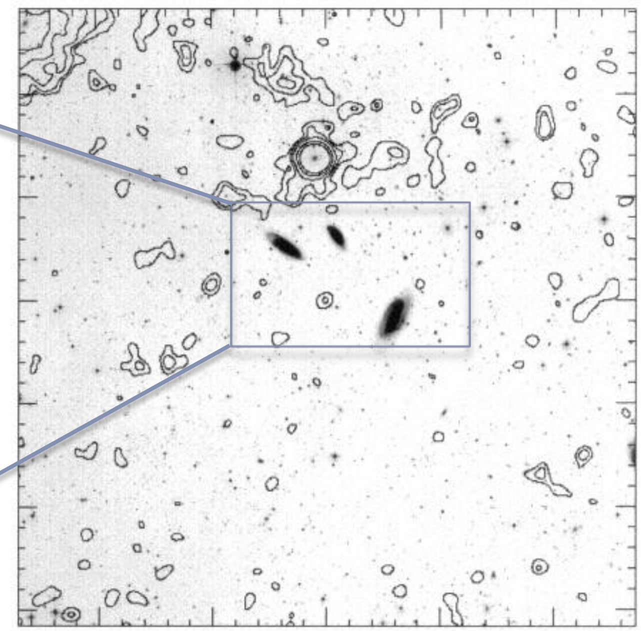
X-ray vs HI Group Emission

- Wilcots et al. (HI)
- Mulchaey & Zabludoff (X-ray)

Xray

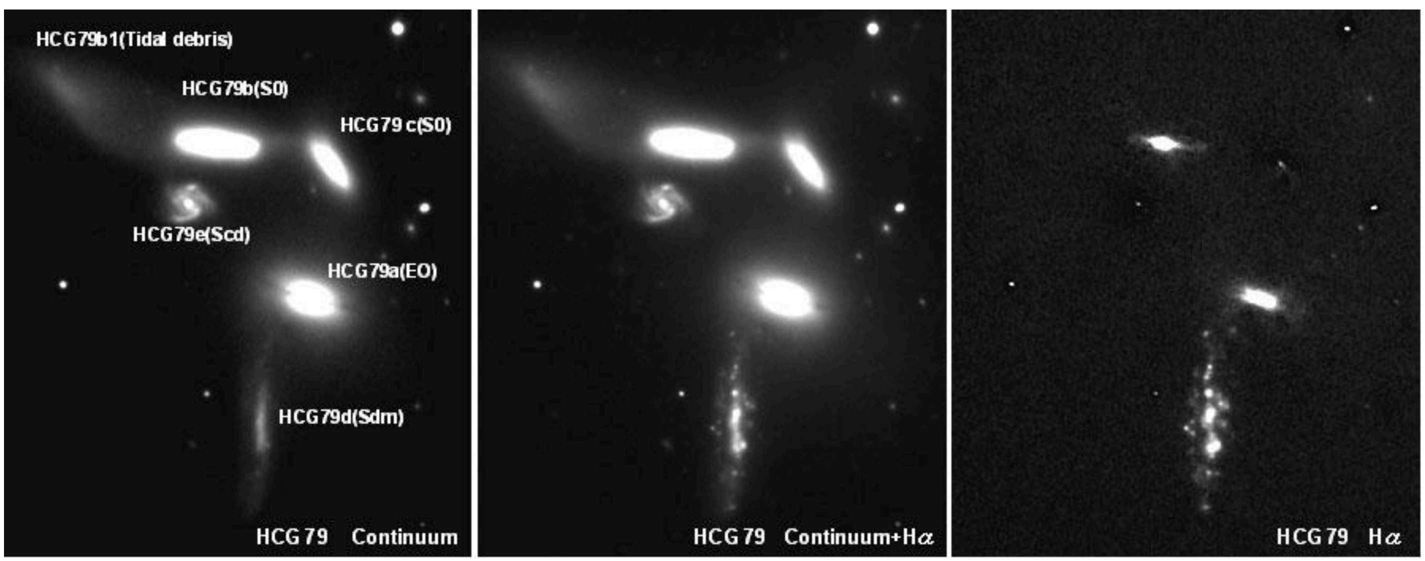
HI





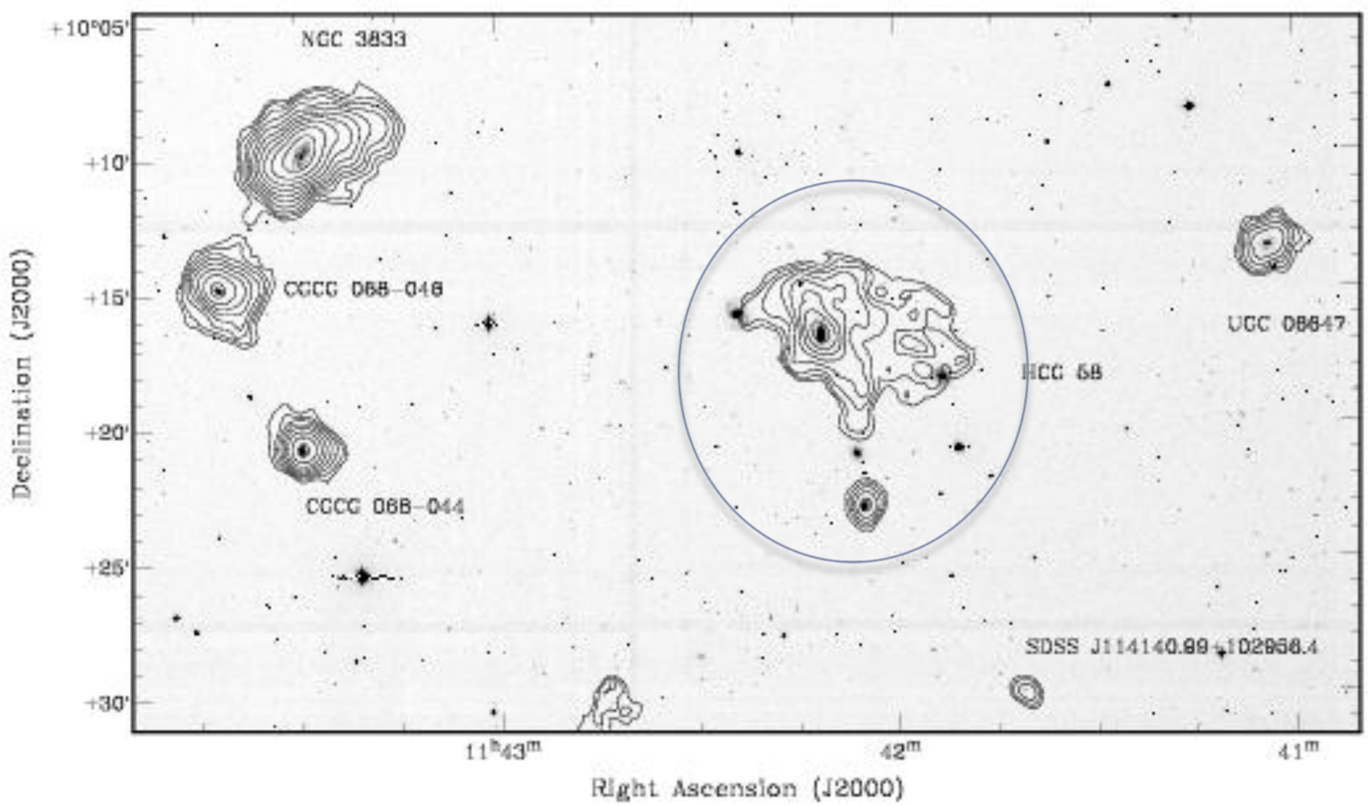
Compact Groups

- Hickson compiled a good source catalogue
  - Hickson Compact Groups (HCGs)
  - 4-5 galaxies
  - $R_{separation} \sim 50$ kpc
  - $\sigma < 200$ km s^{-1}
  - Crossing times << Hubble time

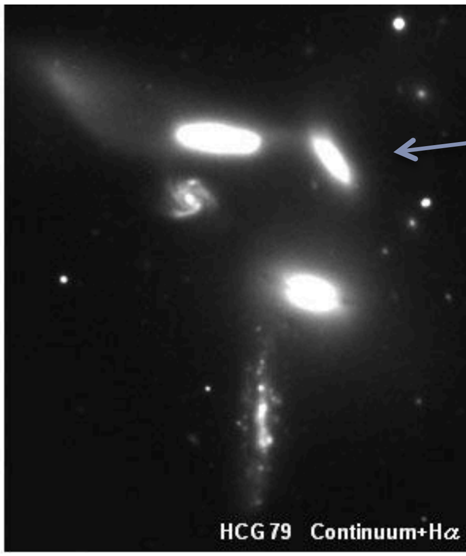


HCG 58 – Common HI envelope?

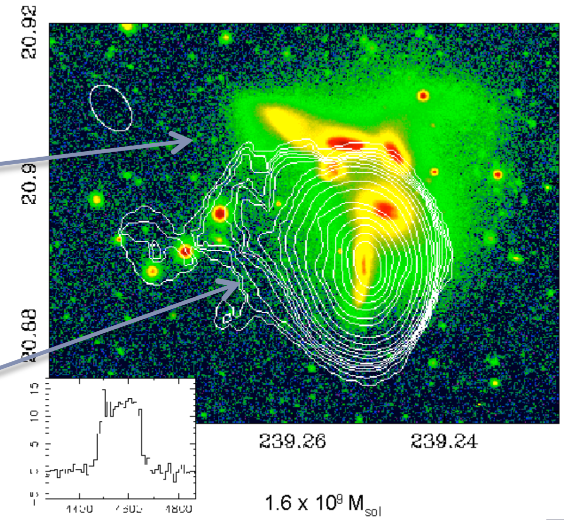
- Freeland et al. 2007: 21 cm contours



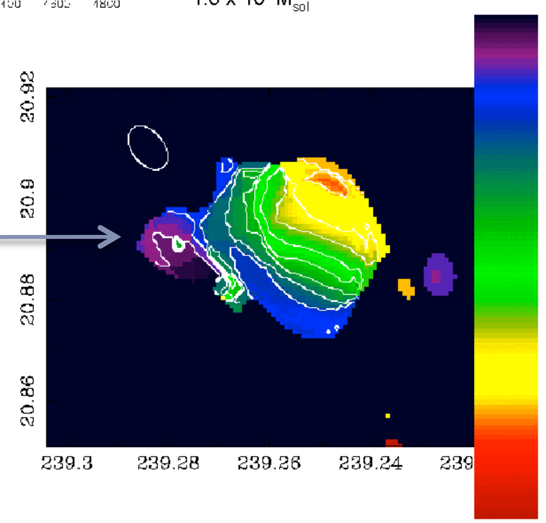
HCG 79 – Common HI envelope?



HI contours



HI isovels



The evolution of Group gas content

- Interaction rate much higher in "intermediate" groups.
  - Almost all HI detected galaxies are interacting or show signs of recent tidal encounters
  - "significant" amounts of tidally stripped neutral gas

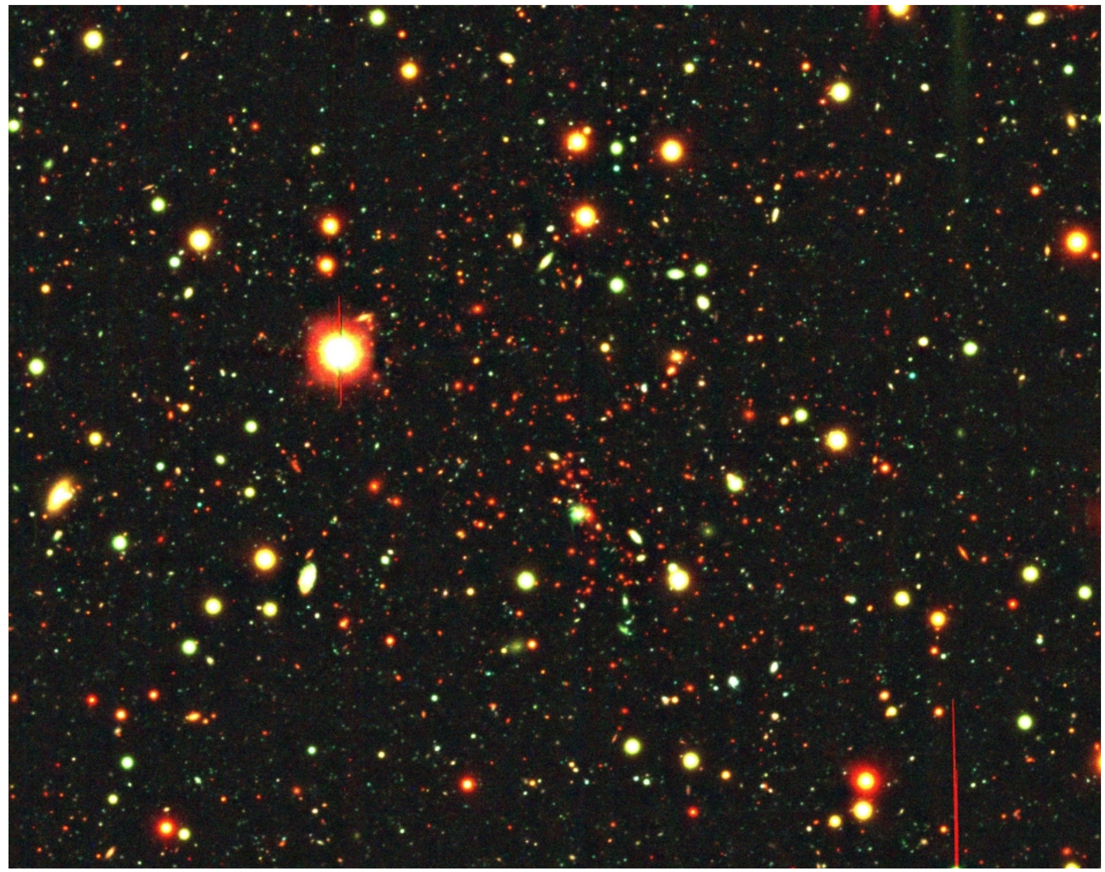
- HI detected galaxies remain outside of the X-ray halo in X-ray luminous groups
- No evidence of a population of pure HI halos (except tidally stripped material)
- Growth of common HI envelopes in HCGs
- Not enough HI to account for baryon budget

Galaxy Clusters

- 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"?)

MS0451: z=0.54, σ=1354 km/s, L_x=40e44 ergs/s



WIYN Long-Term Variability Survey
Crawford et al. 2006, 2008

Galaxy Clusters (continued)

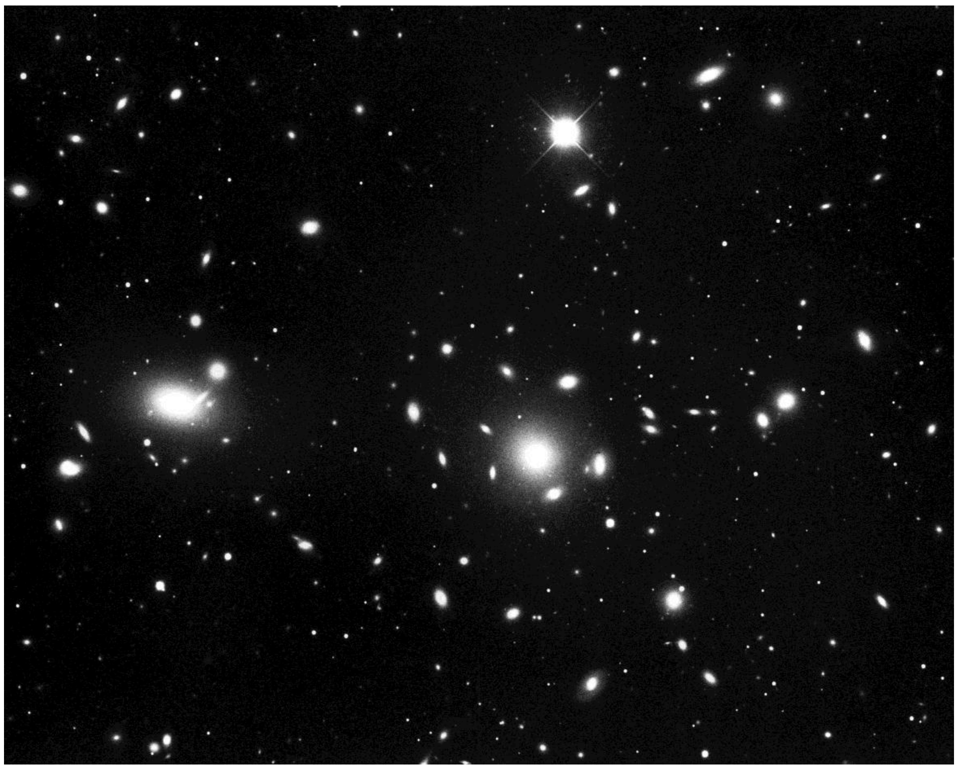
- Early work of Abell (1958) ➔ optical plates
- Abell's criteria
  - "Richness" (1-5)
    - # of galaxies brighter than 2 magnitudes fainter than the 3^{rd} brightest member (*Why* 3^{rd}*?*)
    - ➔ proportional to total # of galaxies in cluster
  - Compactness: galaxies only counted within 1.5 Mpc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

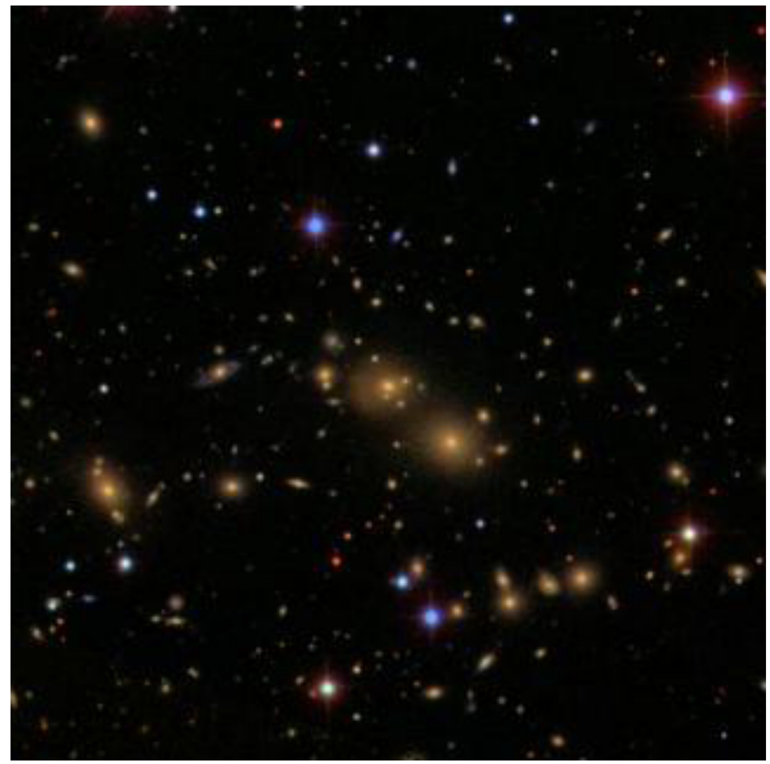
Stopped here

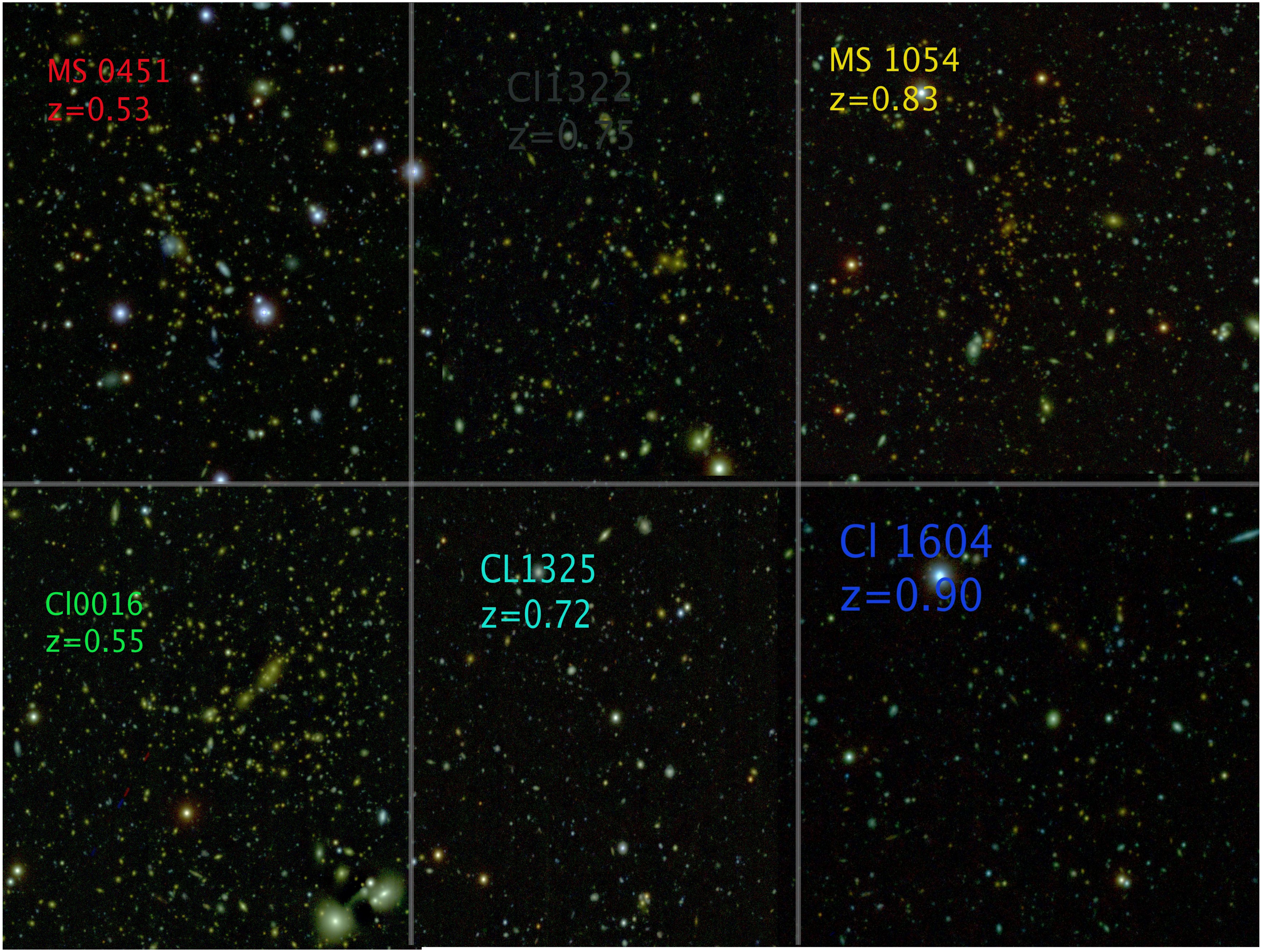
Basic properties of galaxy clusters

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

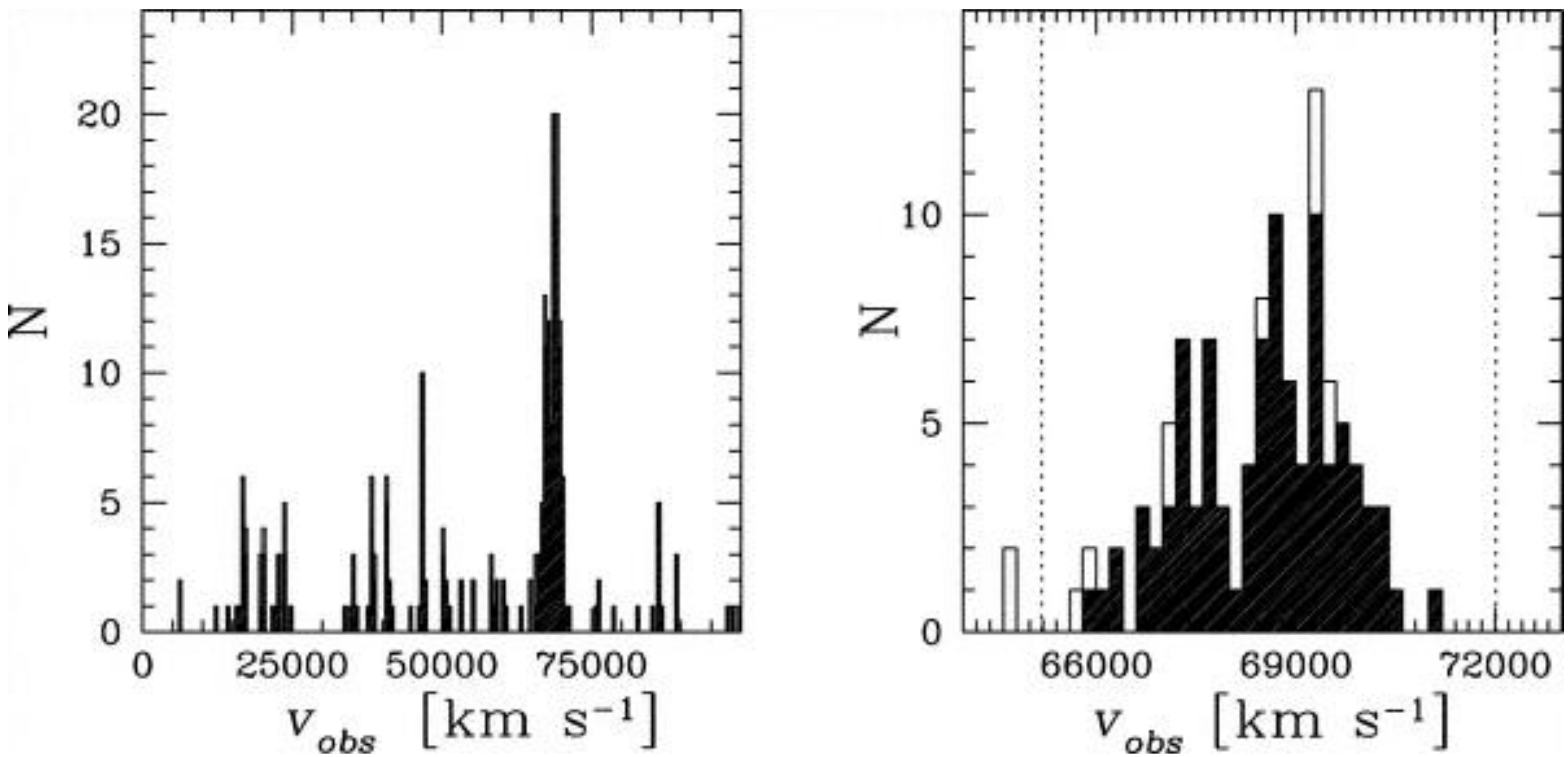
Identifying Clusters - Imaging



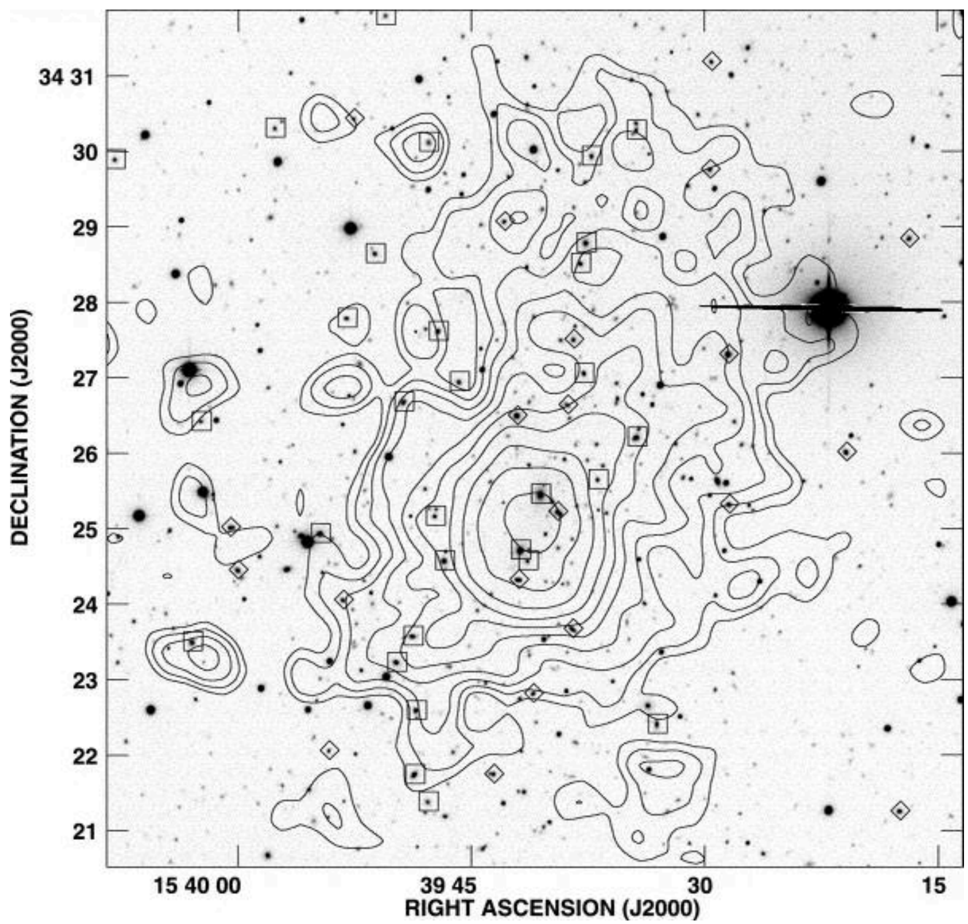



MS 0451
z=0.53
Cl1322
z=0.75
MS 1054
z=0.83
Cl0016
z=0.55
CL1325
z=0.72
Cl 1604
z=0.90

Identifying Clusters - Spectroscopy



Identifying Clusters – X-Rays



Cluster types

- Spiral-rich
  - E:S0:S ➔ 1:2:3 ➔ 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 ➔ 1:2:1
- Centrally dominant (cD)
  - 1,2 dominant galaxies (ellipticals)
  - Few spirals (< 20%)
  - Spherical distribution of galaxies

Clusters as Isothermal Spheres

- Hydrostatic equilibrium:
  - pressure support balances gravitational potential ➔

    $dp_{gas}/dr = -GM_{cluster}\,\rho_{gas}/r^2$
  - Assume: Ideal gas law ➔

    $p_{gas} = \rho_{gas} k_B T_{gas} / \mu\, m_H$ (μ = mean mass)
    - ($3/2\, k_B T = 1/2\, \mu\, m_H v^2$)
  - $(\rho_{gas} k_B T_{gas} / \mu\, m_H)\,[\,(1/\rho_{gas})(d\rho_{gas}/dr) + (1/T_{gas})(dT_{gas}/dr)\,]$

    $= -(GM_{cluster}(<r)\,\rho_{gas})/r^2$
- thus,
  - cluster mass $M_{cluster}$ goes as T_{gas}, ρ_{gas}
- X-ray luminosity, L_X (free-free emission, or thermal brehmsstralung) depends on density and temperature

Characteristic values revisited

- Cluster masses
  - Galaxies → $10^{12} – 10^{14}\ M_\odot$
  - Gas → few $\times 10^{12}$ to few $\times 10^{14}$
  - Gravitational → 10^{13}-$10^{15} M_\odot$

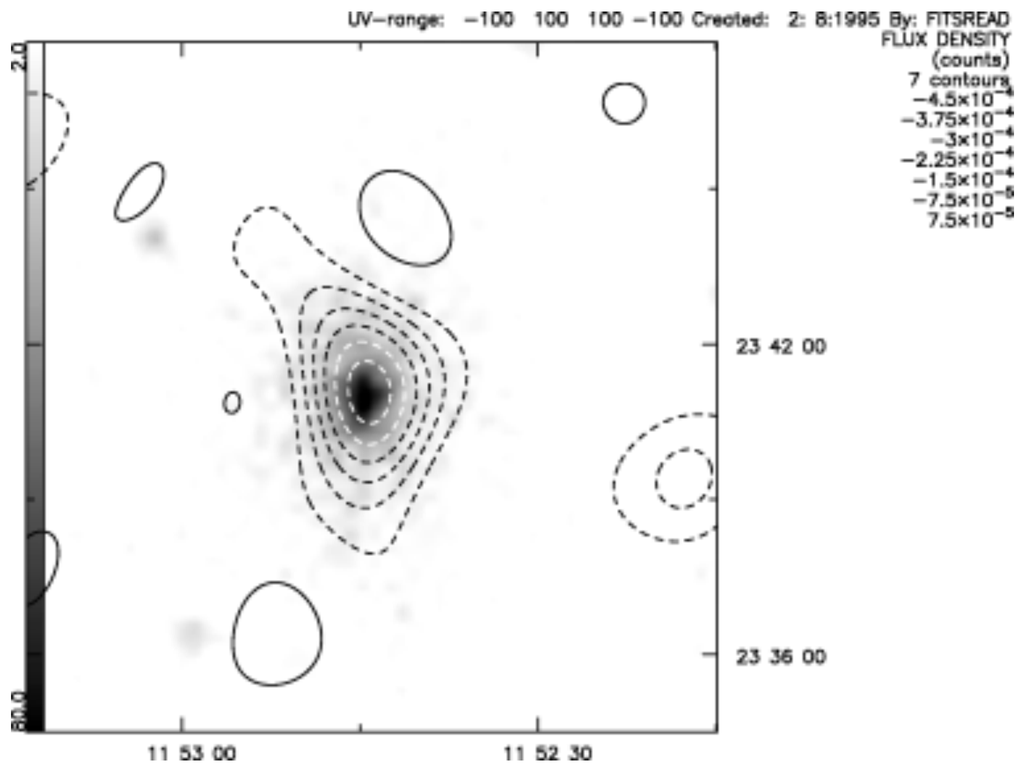
- More mass in gas than stars, dark matter dominated !

Sunyaev-Zeldovich (S-Z) Effect

- CMB + hot plasma ➔
  - Compton scattering ➔ distortions in the CMB BB spectrum
  - Source of hot plasma? ← Galaxy clusters
- Compton scattering optical depth
  - $y = \int (k_B T/m_e c^2)\, \sigma_T N_e dl$
    - σ_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
  - $\Delta I/I = -2y$ ➔ $\sim 10^{-4}$
- 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

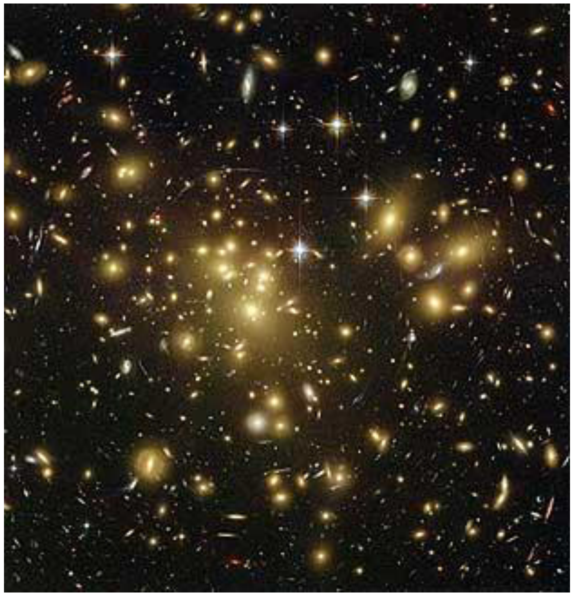
Sunyaev-Zeldovich (S-Z) Effect

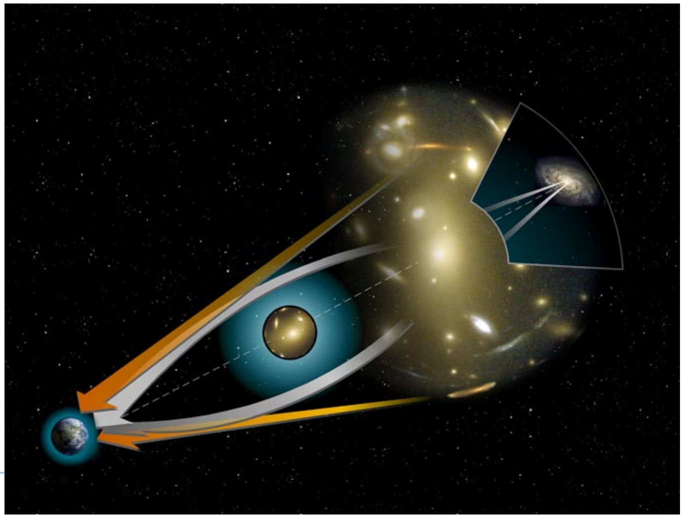
- CMB photons scatter off hot electrons in ICM
  - Statistical net gain of energy ➔ CMB spectrum shifted to slightly higher energies ➔ decrement in intensity at Rayleigh-Jeans limit (h ν << kT)
  - Amount of decrement ➔ integral of pressure (NT) along line of sight



Strong Lensing

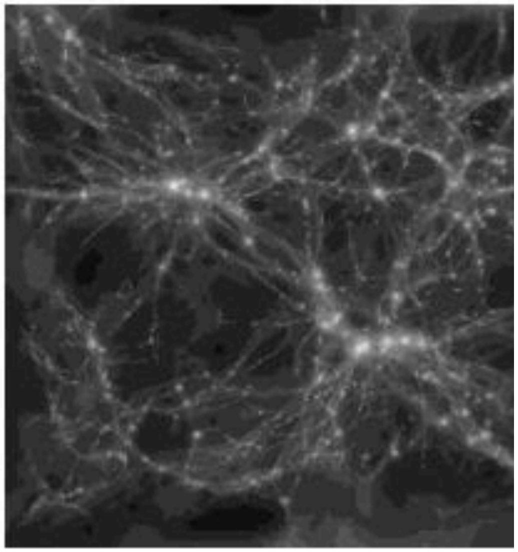
- Probe cluster potential independent of (Newtonian) dynamics
- Use cluster as giant telescope to amplify distance sources.





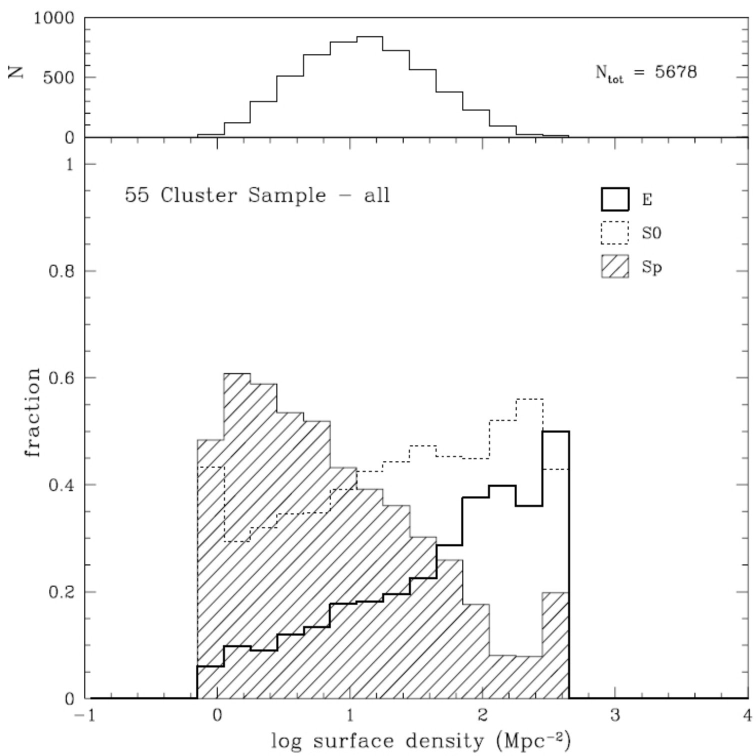
Cluster Evolution

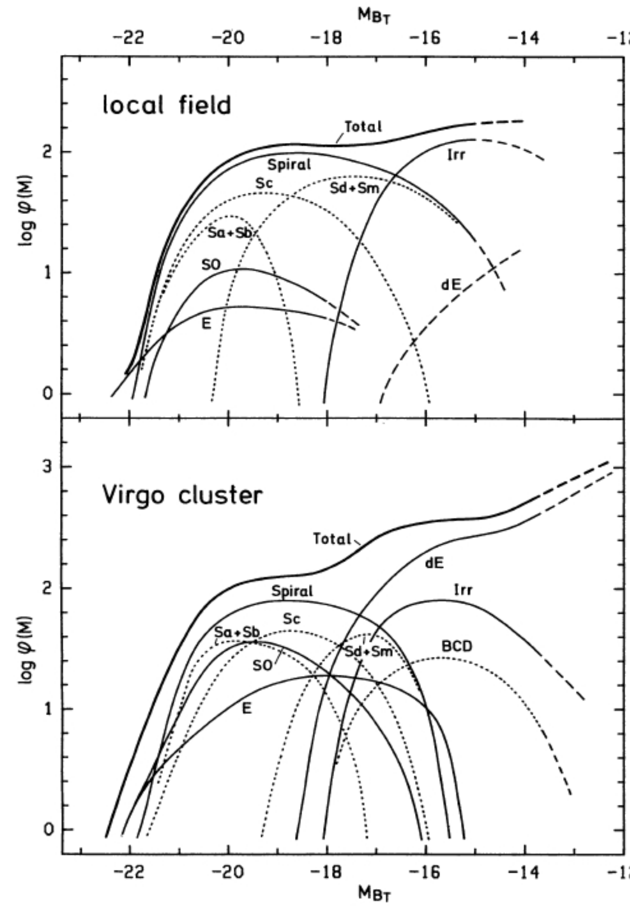
- Why might we expect it?
  - What does density determine?
- What might we expect, say, for evolutionary time-scales in dense environments relative to the field?
  - Stellar evolution?
  - Gas-consumption rates?
  - Dynamical processes (merging)?
- How would cluster selection-effects impact our assessment 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



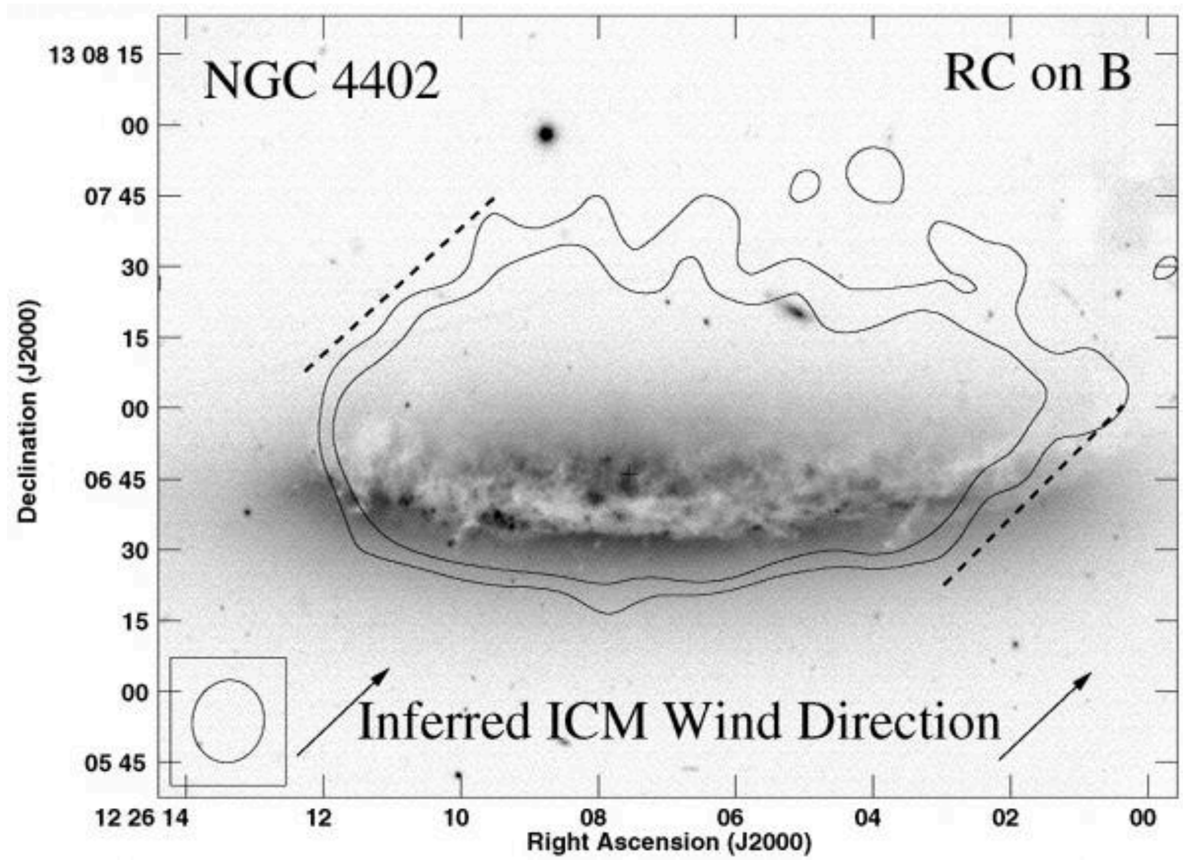


Dressler et al. '97

Binggeli et al. '88

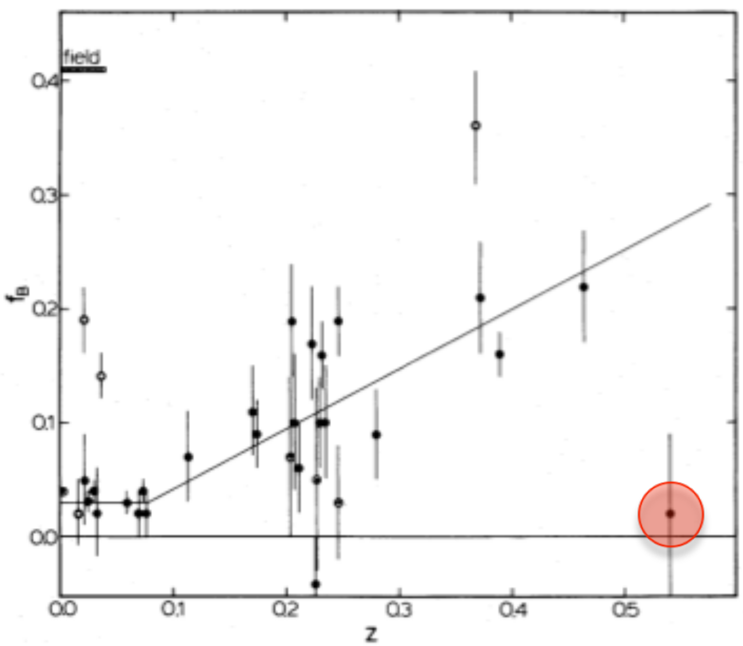
Ram-pressure stripping

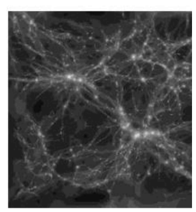
- Spirals undergo stripping, interactions in rich cluster environments
- How does this affect star-formation, galaxy colors, and morphology?



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?



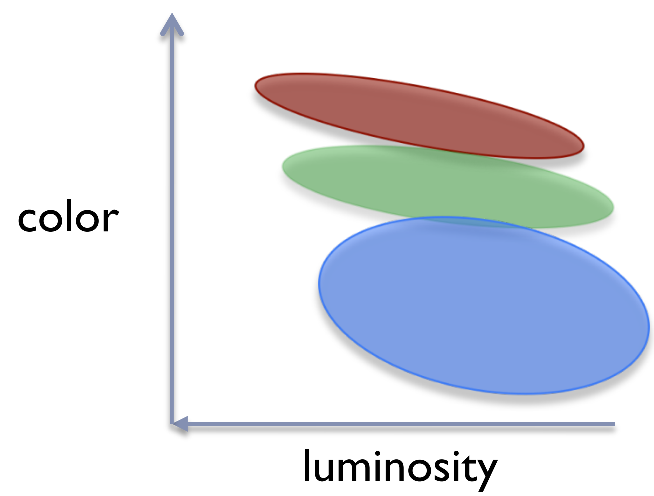


Cluster Evolution: the red sequence

- If clusters had more blue galaxies yesterday

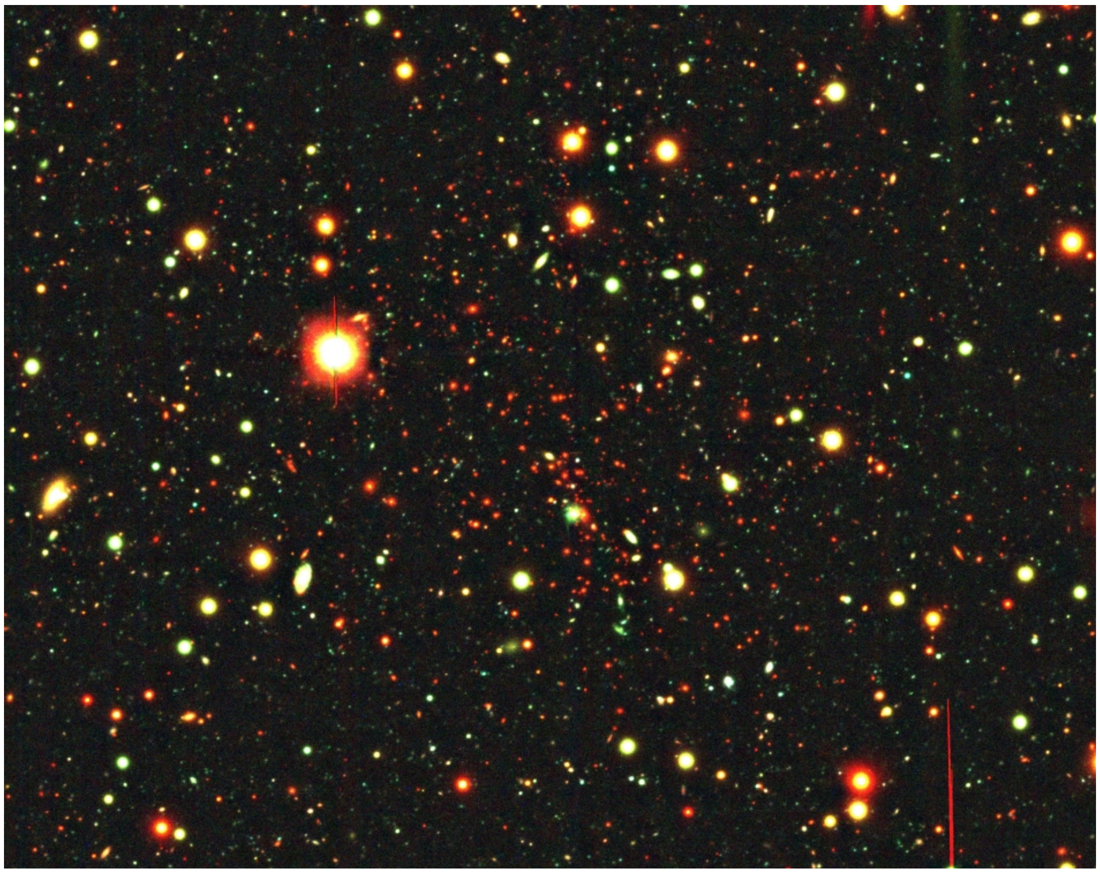
  ➔ they have become red by today.

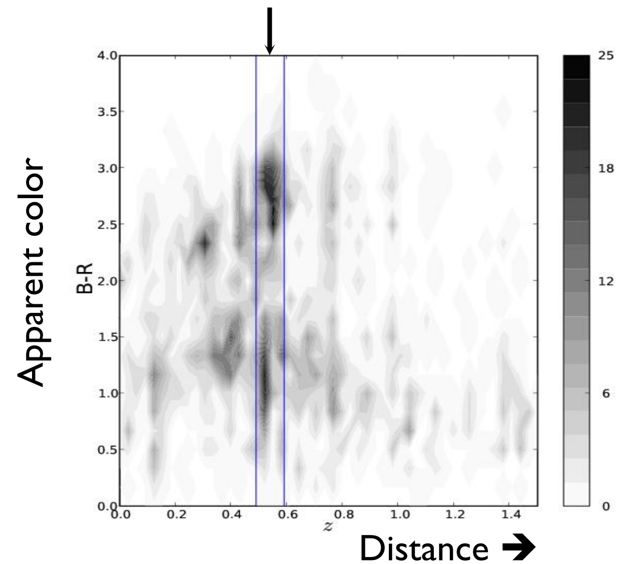
  ➔The luminosity function (LF) for different morphological or spectral types should change with time
- Specifically, the LF for red galaxies should grow with time.
  - If the LF slope changes, that tells us whether the "growth" of the red populations is for high- or low-mass objects, i.e., what the blue 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 dIrrs)
      - Green valley
        - Weakly forming stars (today: early-type spirals and some lenticulars)

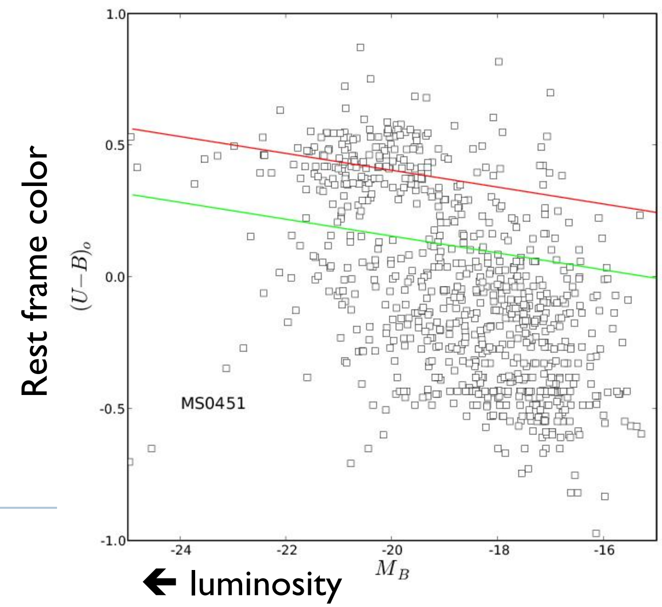


At z=0.5, the red sequence is well-formed

MS0451: z=0.54, σ=1354 km/s, L_x=40e44 ergs/s





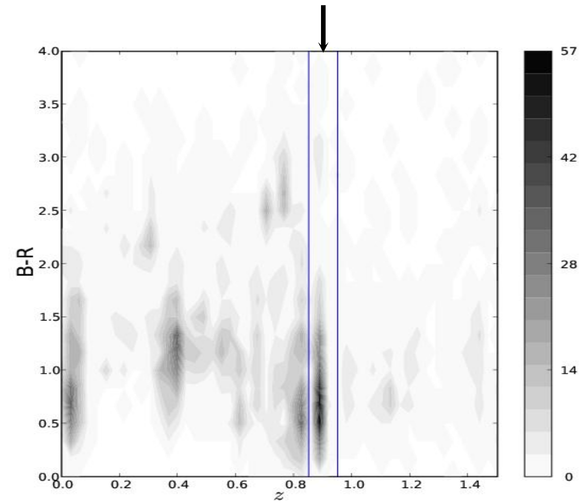


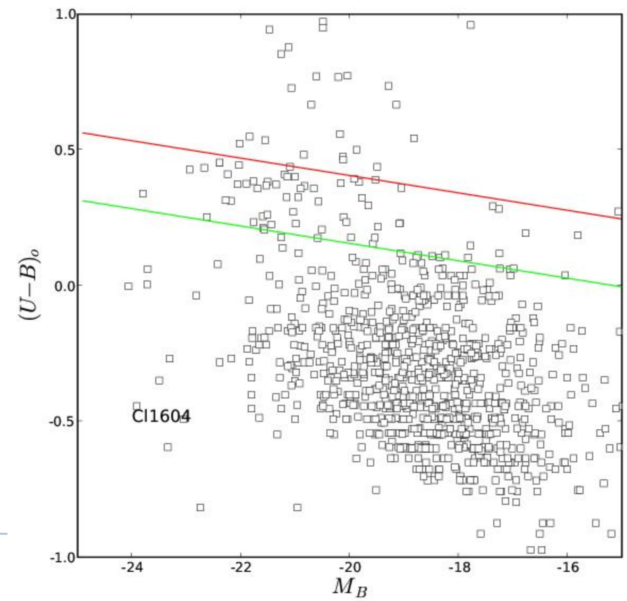
WIYN Long-Term Variability Survey

- Crawford et al. 2006, 2008

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

CL1604: z=0.9, σ=982 km/s, L_x=2e44 ergs/s





WIYN Long-Term Variability Survey

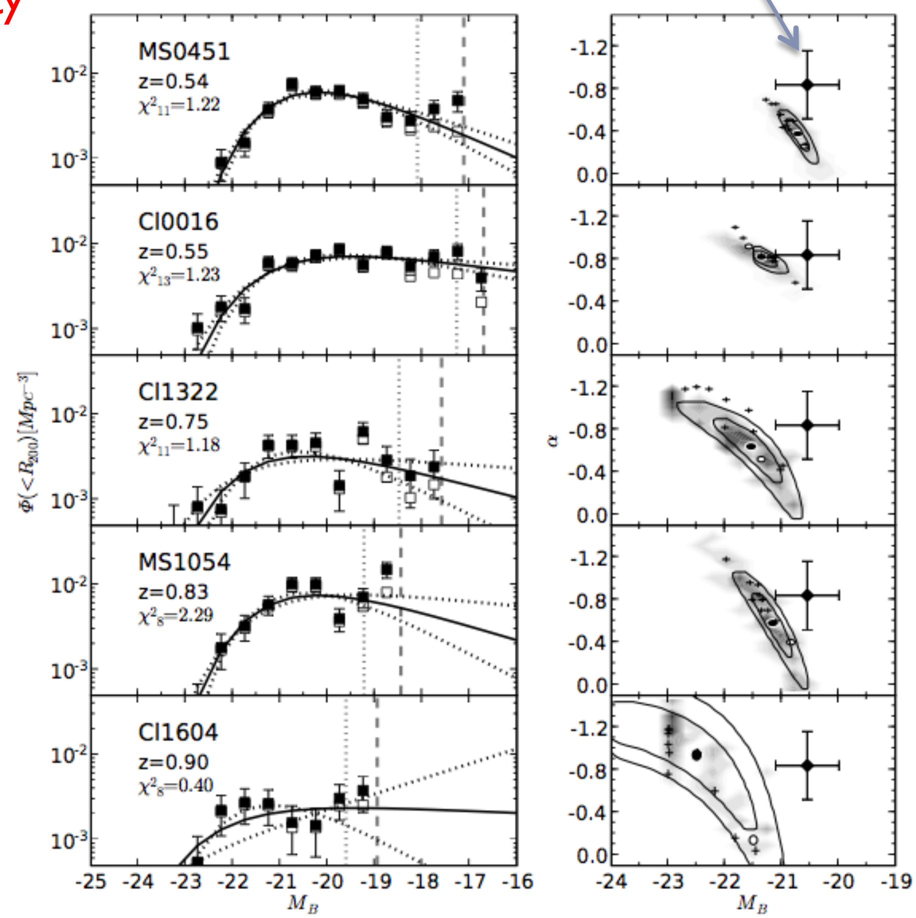
- Crawford et al. 2006, 2008

Cluster luminosity functions to z=1

Red sequence Luminosity functions (RSLF)

Cluster RSLF

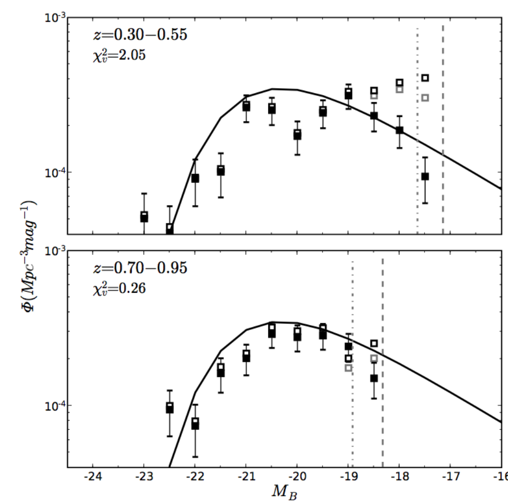
Low-z cluster values



Knee of LF

α is faint-end slope; more negative α means steeper, upward slope

The field RSLF

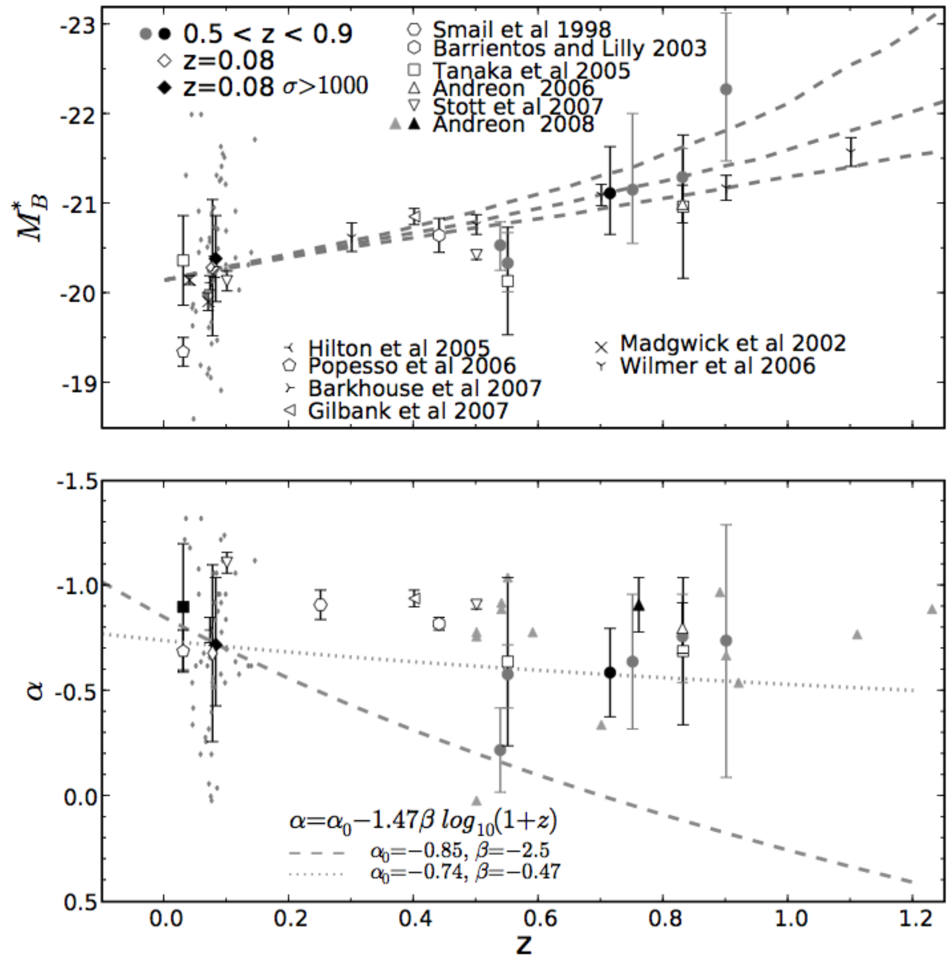


Crawford et al. 2009

Luminosity Function Evolution

Consistent with *passive** luminosity evolution

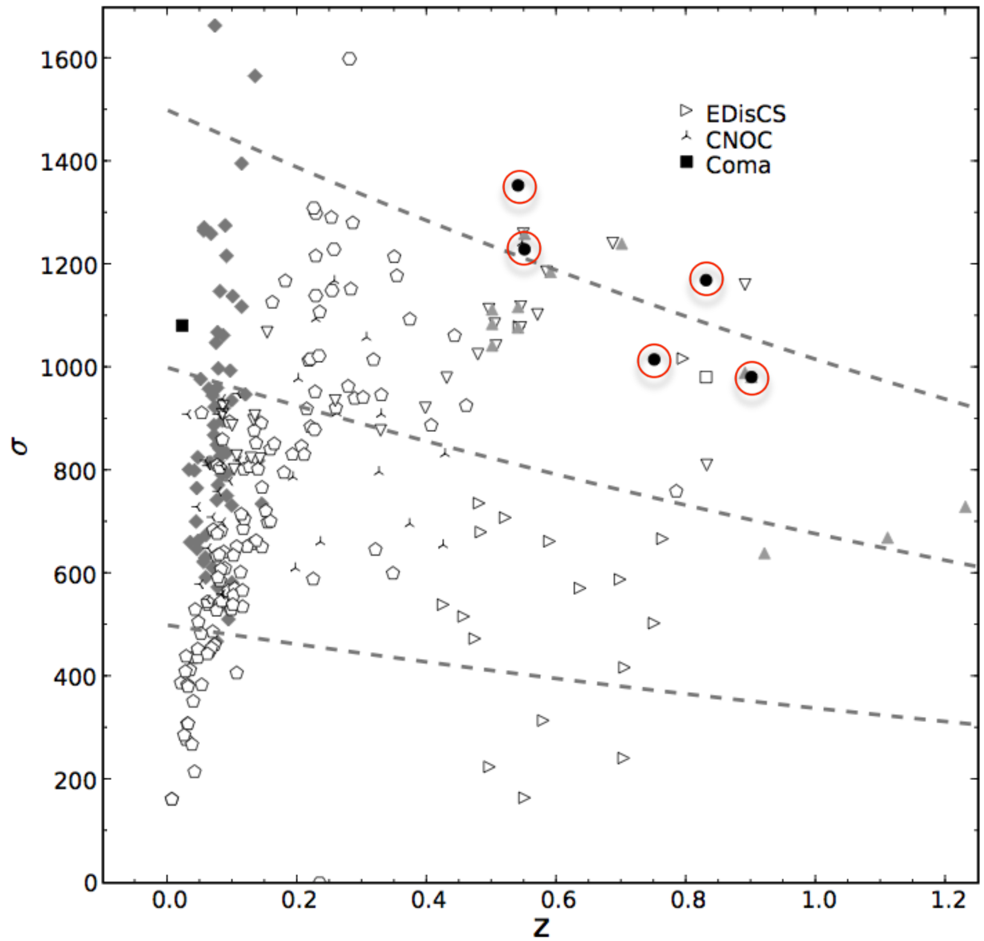
* *Passive evolution* refers to the evolution of stellar populations in the HR diagram (CMDs) in the absence of further star-formation.



Don't forget selection effects…

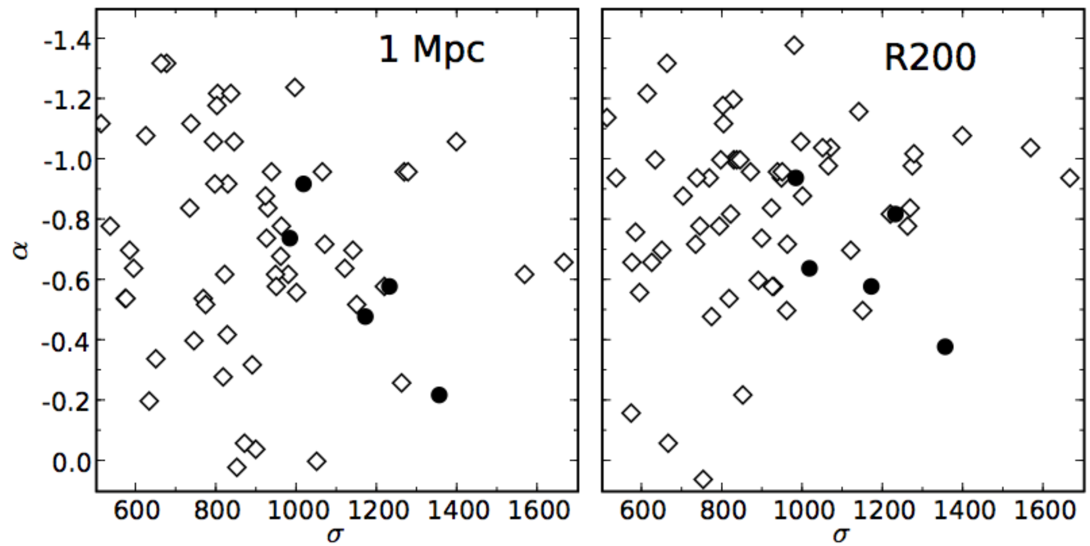
Cluster mass, or its proxy, σ, grow with time as more an more mass falls in to and virializes with the cluster potential.

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



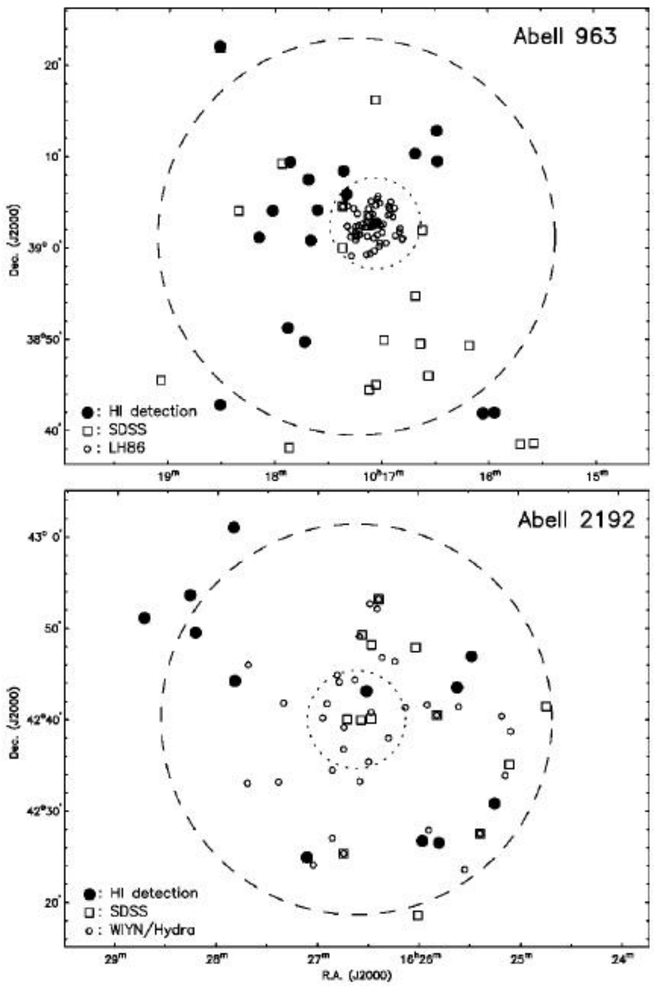
- Clusters exhibit a wide range of faint-end slopes.
- If there is a correlation with other cluster properties (there must!) it has not yet been determined.
- It does appear that the inner-cluster regions have larger (more positive) α, indicative of a relative dearth of dwarf systems.

- What's the cold gas doing?

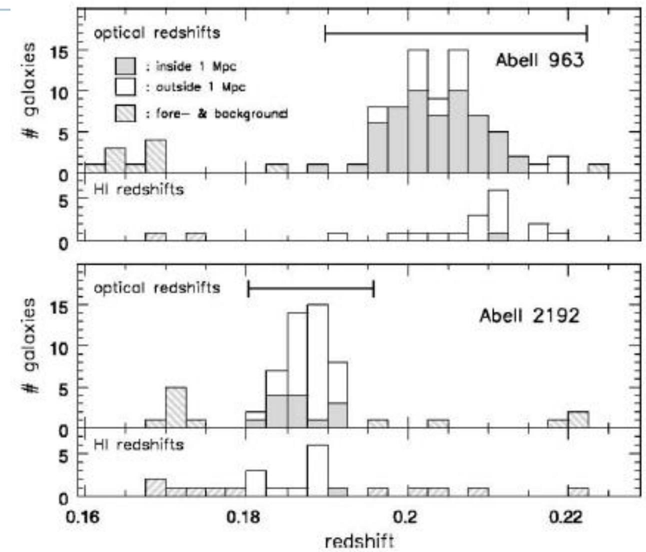
HI View: State of the Art:

Verheijen et al. 2007 (van Gorkum)

45'

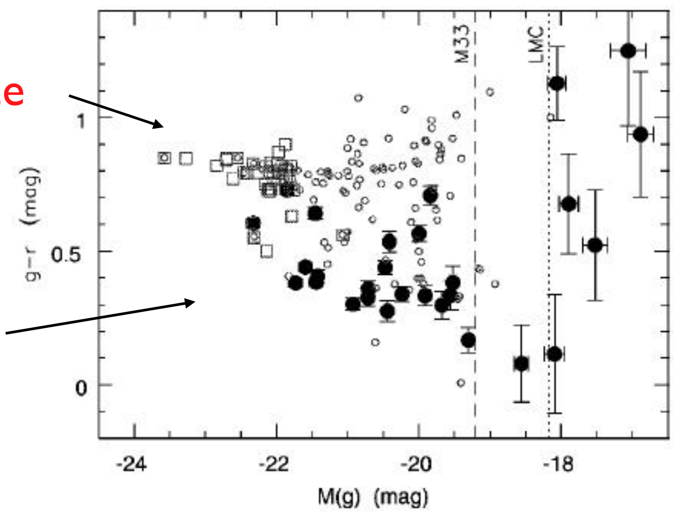


z=0.2



Red sequence

Blue cloud



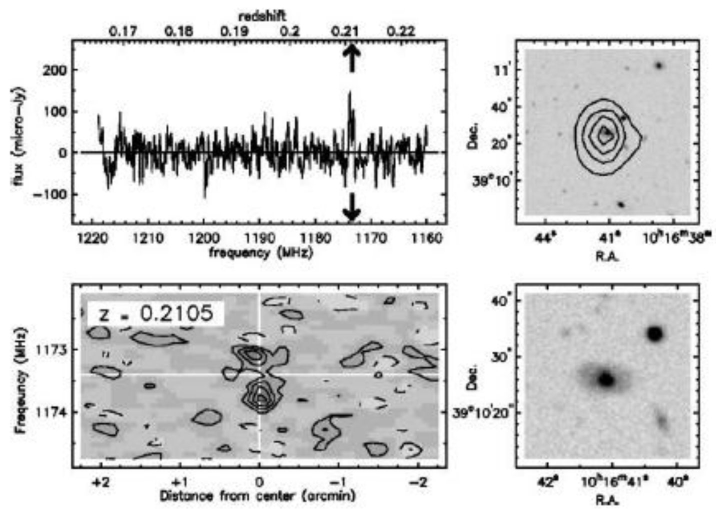
- Westerbork

NB: 200h of 1000h *total to come*!

HI View: State of the Art

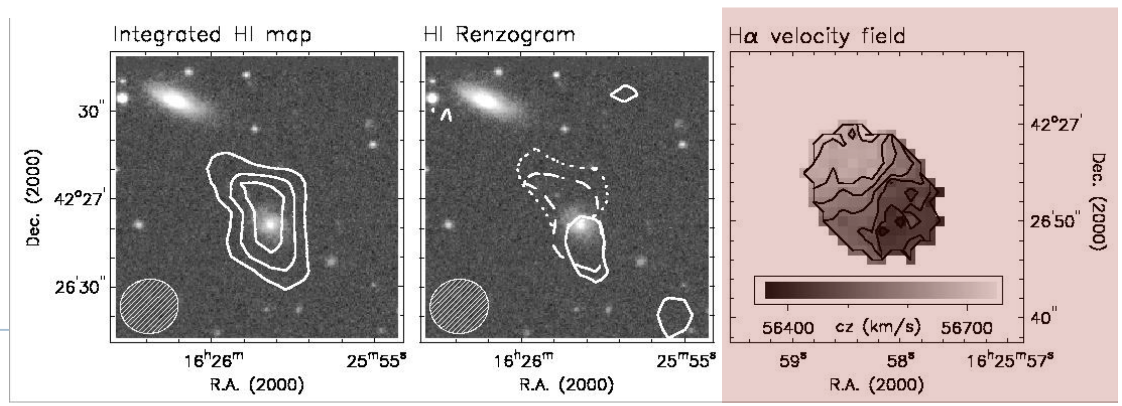
- Solid detections for 42 sources in 2 x 0.4 deg^2 fields
  - expect 200 sources in 1000h
- Limited spatially-resolved kinematic information
- Hα offers detailed kinematic supplement + SFR map
  - t=80 min, 3.5m telescope (CA)
  - 16x16 array of 1” fibers (PMAS)

A963 - Westerbork



A2192 (z=0.19) - VLA

M_{HI}=7x10^9 M_{sun}



Verheijen & Dwarakanath ‘08

The State of HI Sensitivity

- Heroic efforts
- Awesome data
- … but sensitivity is pitiful compared to optical and infrared data

- Really need SKA