Astronomy 730

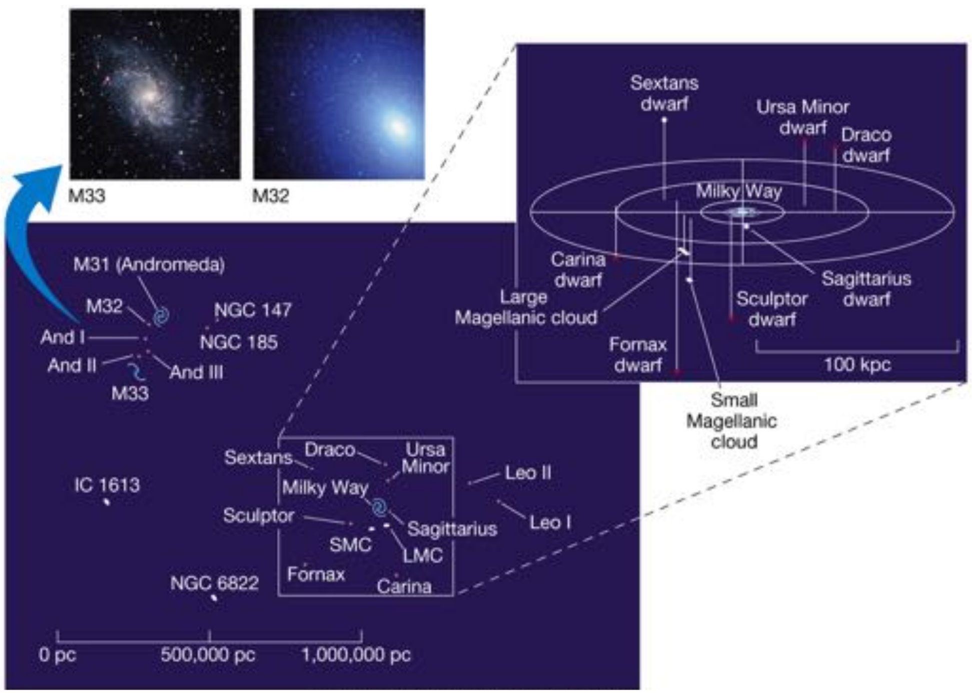
Environment

Outline

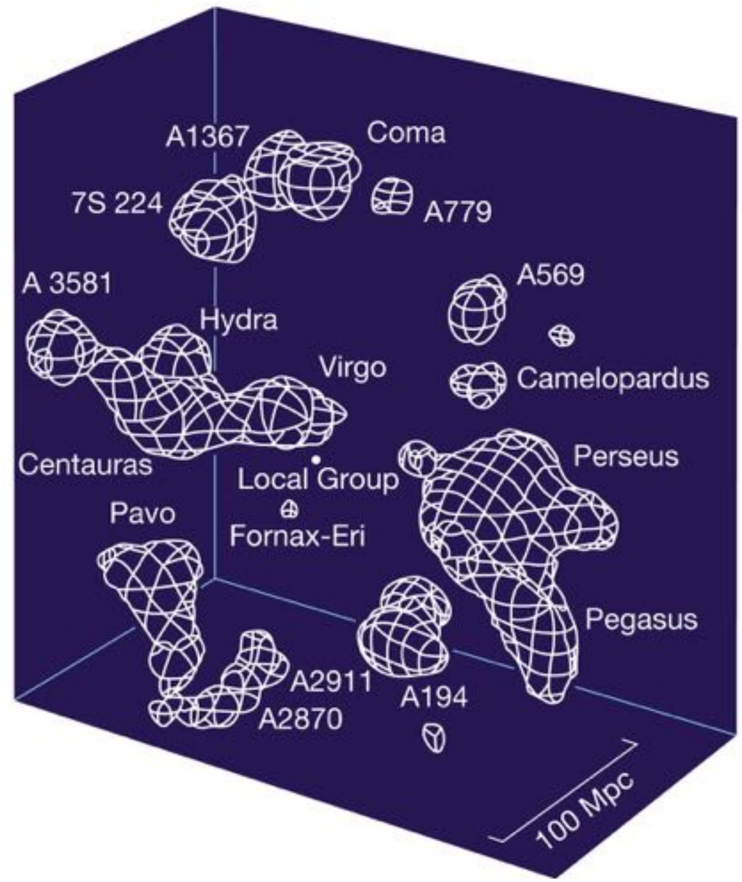
- Environment
  - Trends and processes
  - Groups
  - Clusters
    - Identification
    - SZ effect
    - Lensing
    - HI

Large Scale Structure: revisited

- Local Group (1 Mpc):



- Local volume (100 Mpc):

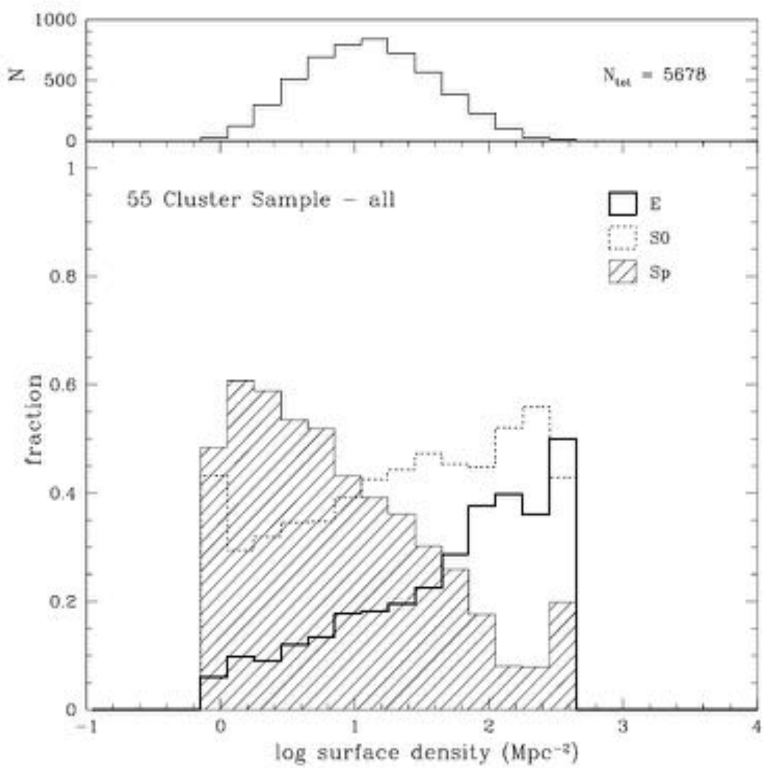


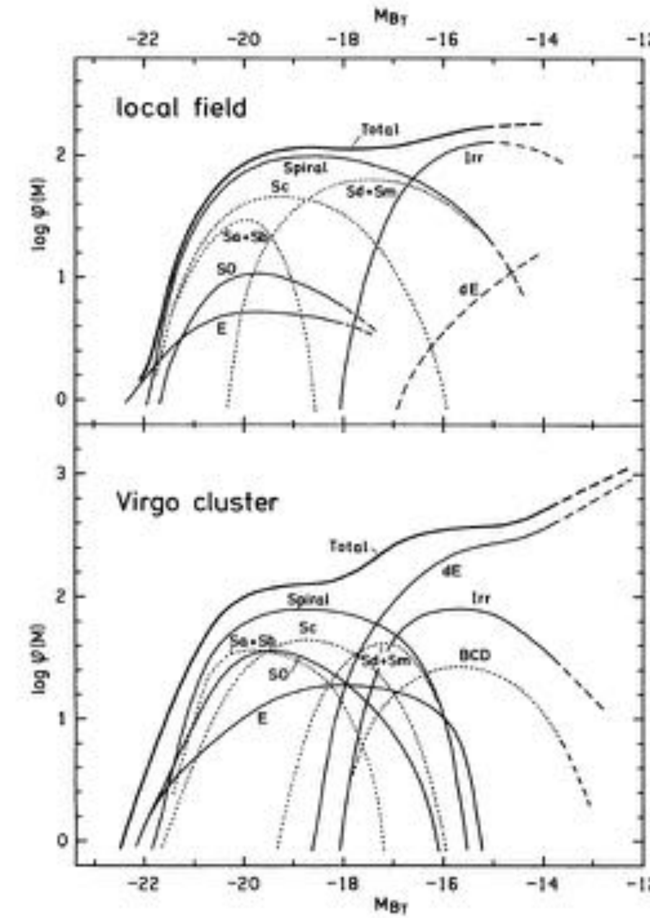
Environment

- Galaxy properties vary with environment
  - Luminosity function (Eke et al. 2004)
  - Color/morphology
    - Morphology-density relationship
      - Galaxies in richer environments tend to be earlier-type, with older stellar populations (redder)
  - Star formation rate
    - Galaxies in richer environments tend to have less star-formation per unit mass

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

Cluster vs the field: an environmental view

- The morphology-density relationship
  - A more modern (but not necessarily better) photometric view:
- Also be aware of model-dependent notion (and classification) of galaxies as
  - Central vs Satellite
    - e.g., Knobel et al. 2015
- And these potentially semi-fictitious (i.e., unclear what is cause and what is effect) terms in the current literature:
  - Environmental quenching
  - Mass quenching
    - Morphological quenching (and other circularities)

Peng et al. 2010

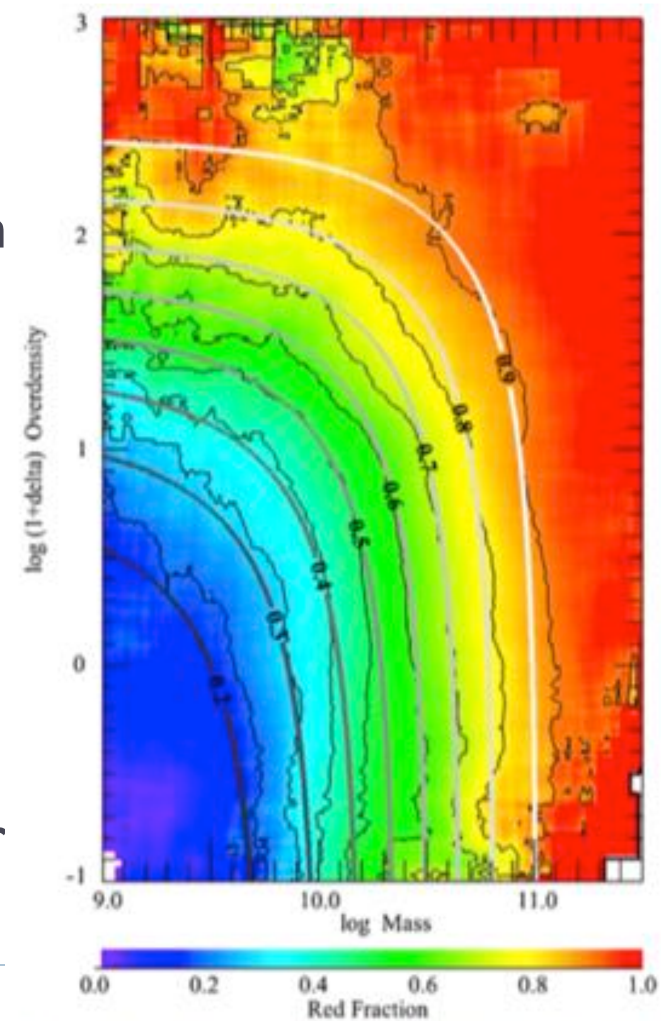


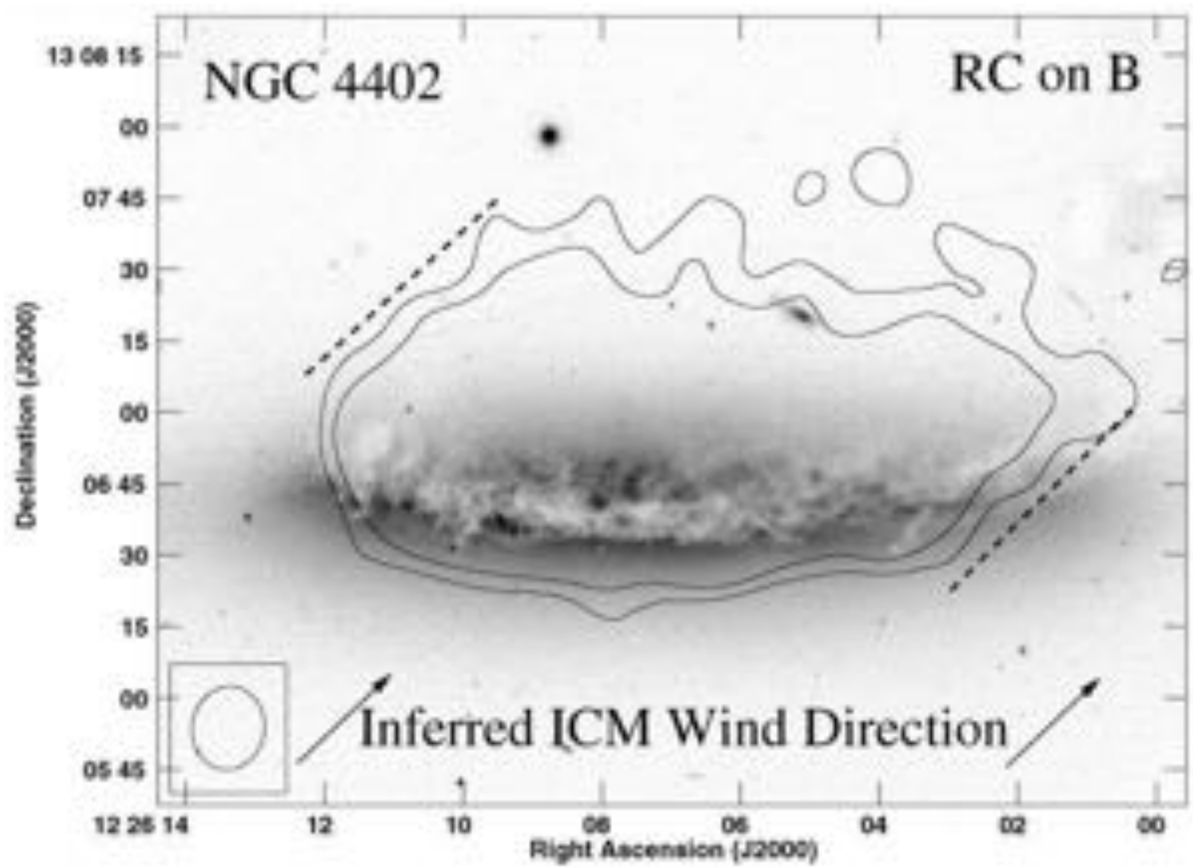
Figure 6. Red fraction in SDSS as functions of stellar mass and environment.

Environment: Physical Processes

- Ram-pressure stripping
- Dynamical friction in dense medium
  - e.g., stars in dense star cluster, or dwarf-galaxy / globular-cluster moving through stellar distribution governed by shape of the potential/density distribution
  - Also applies to galaxies near center of galaxy cluster
- Impulsive/high velocity encounters : large relative velocities
  - Velocity of encounter >> internal velocities of galaxies involved
    ➔ galaxy "harassment"
  - Galaxies moving through galaxy cluster (one-on-one interaction)
  - Retrograde galaxy-galaxy interactions
- Tidal effects: weakly bound
  - Dissolution of star-clusters / dwarfs
  - Outskirts of large galaxies in equal-mass encounters
- Mergers : small relative velocities
  - Most likely to occur in groups

Ram-pressure stripping

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



Kenney et al.

Groups: Morphology, Gas and Dynamics

- Morphology-Gas-Contents-Dynamics:
  - Dynamically *evolved* groups have large elliptical fractions (F = 0.6-1.0) and extended X-ray halo
  - Dynamically *young* groups have small elliptical fractions (F = 0.0-0.2) and largely neutral gas
  - Corresponding relationships between velocity dispersion, L_X, and early-type fraction (Brough et al. 2006)
    - $F = 0.27 \log_{10} L_X - 10.8$
    - $F = 0.76 \log_{10} \sigma - 1.2$

Spiral rich ➔ elliptical dominated	⟺	Cool, neutral ➔ hot, ionized

- The Role of Interactions
  - Evolution traced by interactions
  - Interactions produce ellipticals & enhance star formation
    - Convert binding energy into heating and dispersing gas
    - Tidally remove neutral gas from galaxies
    - Star formation induced ejection of hot gas from individual galaxies
  - Tidally stripped neutral gas ➔ heated in the intra-group medium
  - Galaxy mergers ➔ heating of intergalactic medium

Environment: Pre-Processing

- If mergers are key to building ellipticals, and are most commonly found in clusters, how are they formed?
- Pre-processing:
  - Ellipticals are made in groups falling into clusters
    - ***Clusters are made up of merged groups***

Summary

- 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

What are Galaxy Groups? (you're in one)

A fuzzy definition:

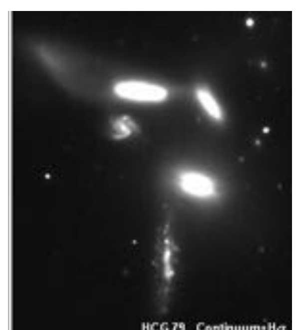
- 3-10 members with $M_V < -19$ within a radius of 0.5 Mpc (Zirbel 1997)
- "poor cluster" (Bahcall 1980)
  - ~30 members with m such that $m_3 < m < (m_3+2)$
  - m_3 is the magnitude of the 3rd brightest member
- N > 4 with 200 km s^{-1} < σ < 400 km s^{-1} (Carlberg'01)
- $M_{halo} \sim 10^{12} - 10^{14} M_\odot$ (Eke 2004)
- Compact groups ➔ "few" galaxies with separations of a "few" galactic radii
- GEMS Sample (Broughet al. 2006)
  - N ~ 3-20
  - $\sigma \sim$ 280 to 430 km s^{-1}
  - $R_{500} \sim$ 0.22-0.56 Mpc
    - Radius at which density = 500 × ρ_{crit}
  - log L_X (erg s-1) ~ 40.7 to 42.11
    - 2/16 with upper limits ~ 40.5

What aren't groups?
Groups aren't clusters…

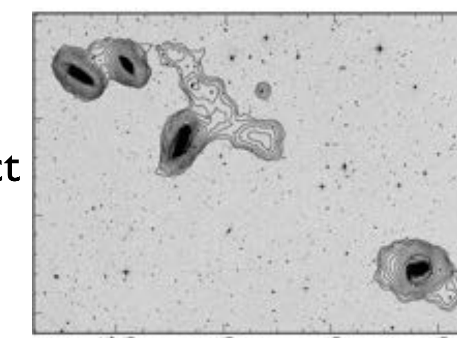
Clusters are made of many 100's to 1000's of galaxies;

have masses far in excess of 10^{15} $h^{-1}M_\odot$; and

have velocity dispersions (galaxy-galaxy) of 500-2000 km/s.



Compact groups



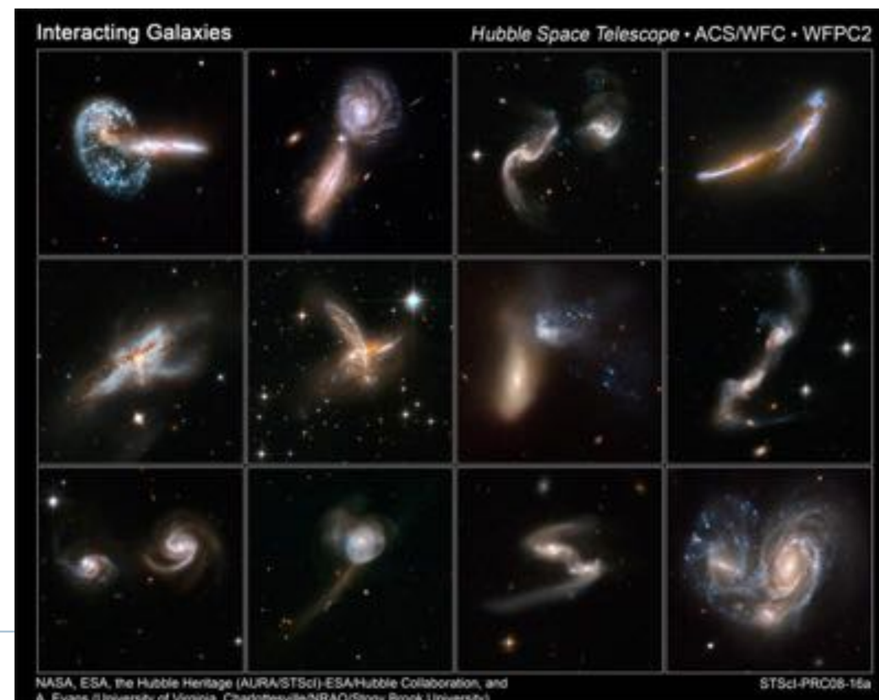
- Groups have also been defined by the luminosity and extent of their X-ray emission

Why Galaxy Groups are important

- 70% of nearby galaxies reside in groups
  - What is the impact of the group environment on galaxy evolution?
  - What is the impact of galaxy evolution on the group environment?
- Groups may hold the key to the baryon budget of the Universe
  - What is the density of the intra-group medium?
- Groups define the large scale structure
  - What can groups tell us about the formation of large scale structure?

- Group velocity dispersion ~ internal velocity dispersion of individual galaxies
  - Galaxy-galaxy mergers *more* likely in groups than clusters
  - Ram pressure stripping & "harrassment" *less* likely
  - Galaxies more likely to be falling into a "dense" environment for the first time
- ***Corollary:***
  - It's very hard to merge galaxies in clusters
  - They are moving too fast (relative to binding energy, i.e., internal motions)

Transformative mergers



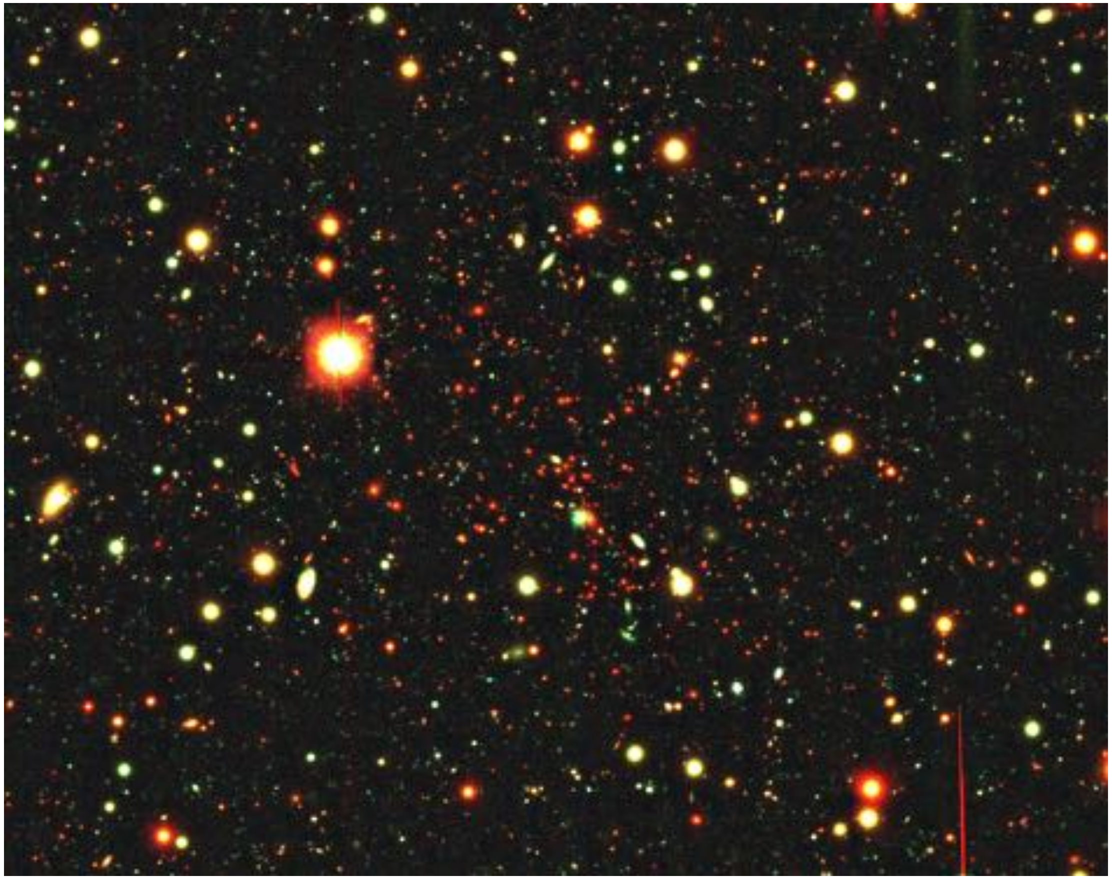
Galaxy Clusters

- Gravitational Mass ~ 10^{13}-$10^{15} M_\odot$
  Galaxies ~ $10^{12} – 10^{14}$ $M_\odot$
  Gas ~ few ×10^{12} to few ×10^{14}
- Velocity dispersions ~1000 km/s
- Radius ~ few Mpc
- Population ~ few 10^2-10^3 galaxies

- 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 3rd brightest member (*Why 3rd?*)
    - ➔ proportional to total # of galaxies in cluster
  - Compactness: galaxies only counted within 1.5 Mpc radius of cluster center
- Space density of clusters:

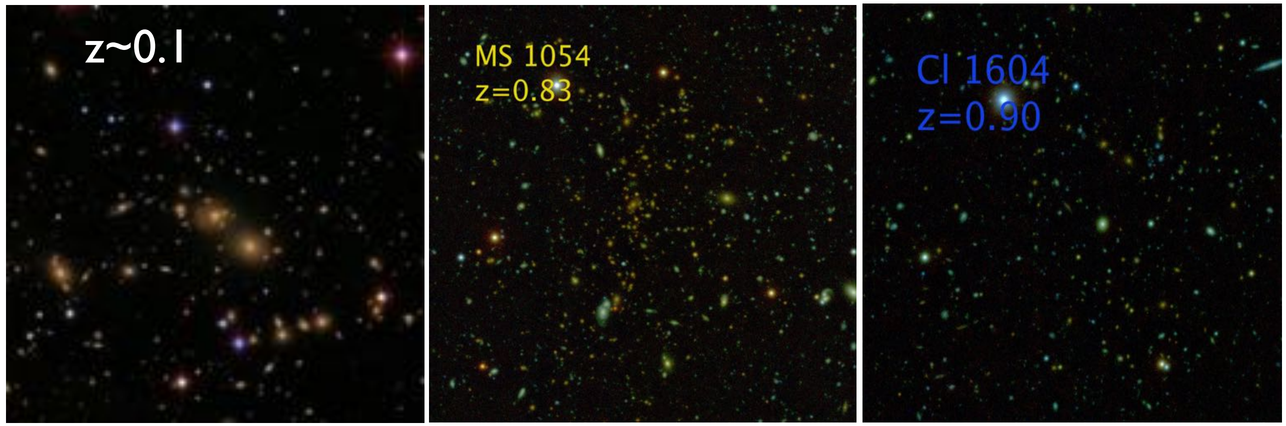
  $N(\text{Richness}>1) = 10^{-5}\ \text{Mpc}^{-3}$
  - average separation between clusters ~ 50 Mpc if randomly distributed.
  - Clusters correlated on scales ~26 Mpc
    - Not random!
  - Compare to galaxies:
    - $N = 10^{-2}\ \text{Mpc}^{-3}$ for galaxies of "typical" luminosity
    - Average separation of ~ 5 Mpc

Cluster types

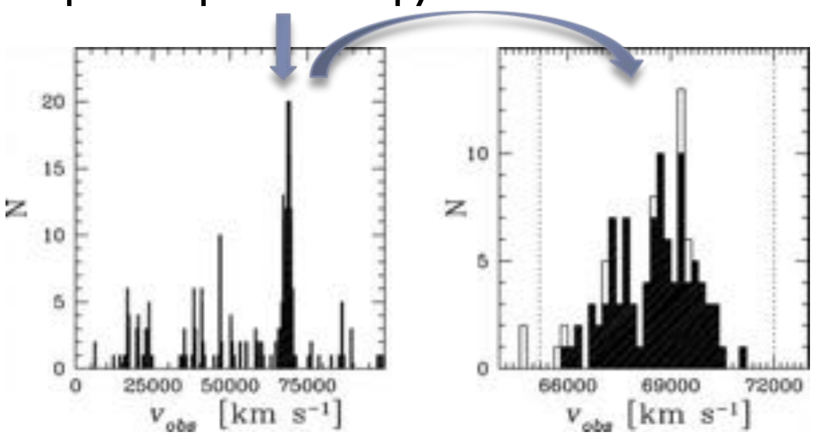
- Spiral-rich
  - E:S0:S ➔ 1:2:3 ➔ similar to field
  - Asymmetric structure
  - Really clusters or superposition of field galaxies in filaments?
    - Projection effects! (increase with distance, z)
- Spiral-poor
  - E:S0:S ➔ 1:2:1
- Centrally dominant (cD)
  - 1,2 dominant galaxies (ellipticals)
  - Few spirals (< 20%)
  - Spherical distribution of galaxies

Identifying Clusters

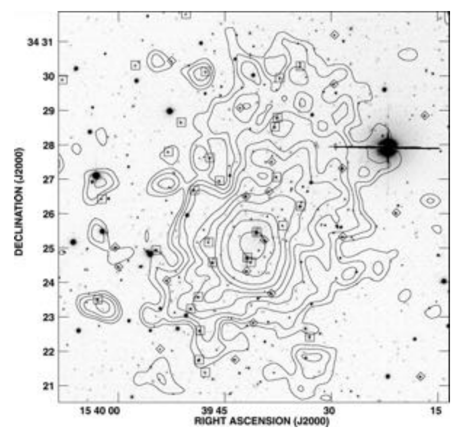
Optical Imaging



Optical spectroscopy



X-ray Imaging

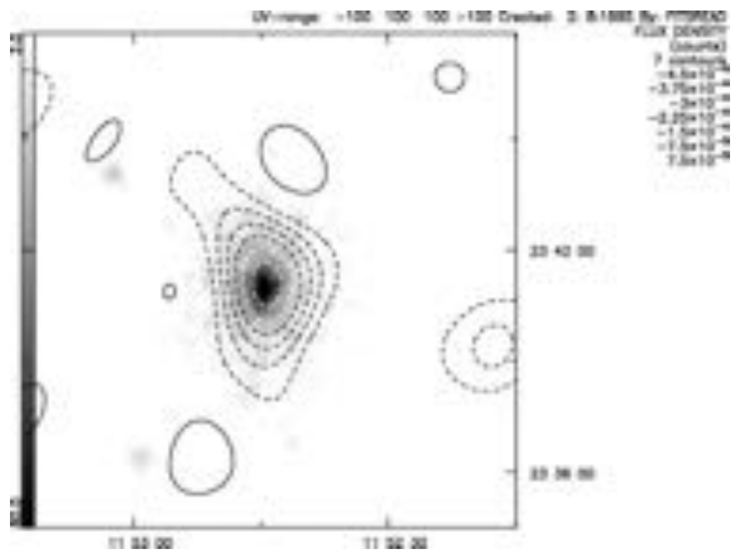


- Hydrostatic equilibrium:
  - cluster mass $M_{cluster}$ goes as T_{gas}, ρ_{gas}
- X-ray luminosity, L_X (free-free emission, or thermal brehmsstralung) depends on density and temperature

Sunyaev-Zeldovich (S-Z) Effect

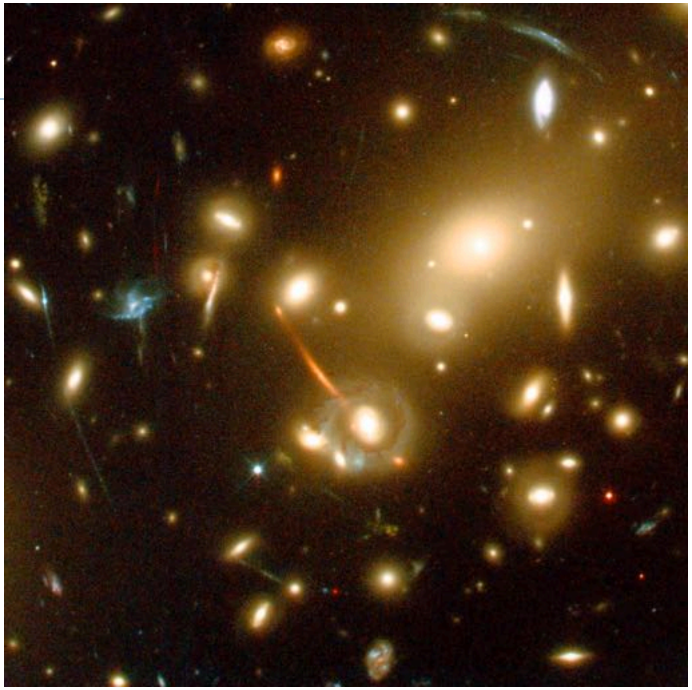
- CMB photons scatter off hot electrons in ICM
  - Statistical net gain of energy → CMB spectrum shifted to slightly higher energies → decrement in intensity at Rayleigh-Jeans limit ($h\nu << kT$)
  - Amount of decrement → integral of pressure (NT) along line of sight

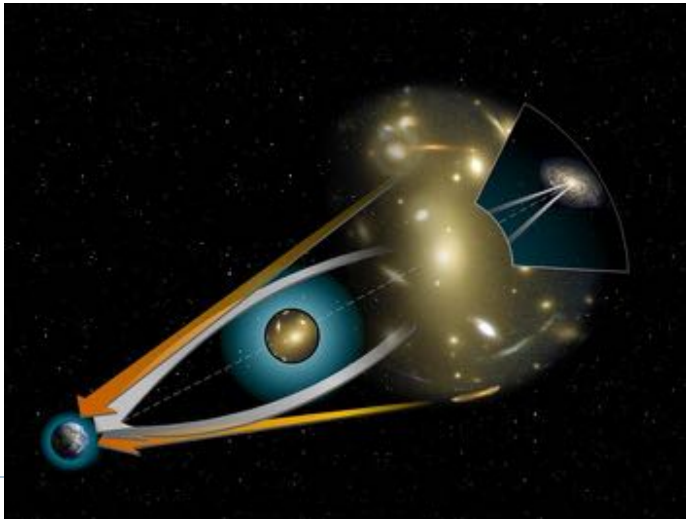
- CMB + hot plasma →
  - Compton scattering → distortions in the CMB BB spectrum
  - Source of hot plasma? ← Galaxy clusters
- Compton scattering optical depth
  - $y = \int (k_B T / m_e c^2) \sigma_T N_e dl$
    - σ_T is the Thompson cross section
    - Integral is along line of sight
    - Recall T_e 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



Strong Lensing

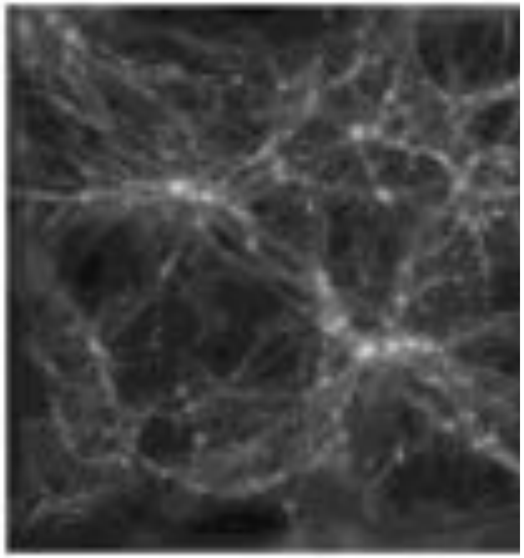
- Probe cluster potential independent of (Newtonian) dynamics
- Use cluster as giant telescope to amplify distance sources.





Cluster Evolution

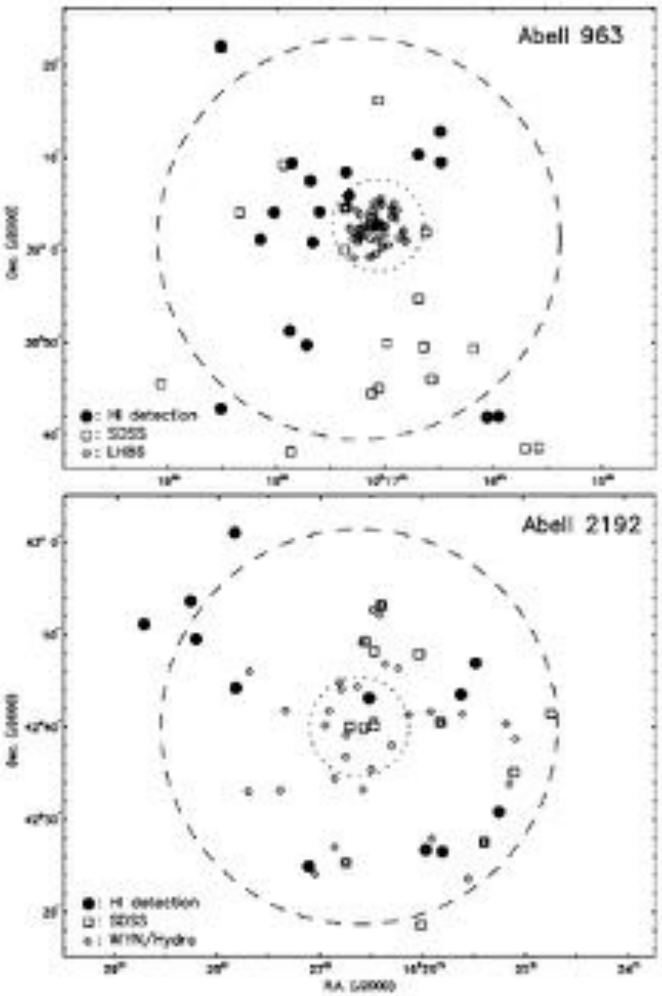
- Why might we expect it?
  - What does density determine?
- What might we expect, say, for evolutionary time-scales in dense environments relative to the field?
  - Stellar evolution?
  - Gas-consumption rates?
  - Dynamical processes (merging)?
- How would cluster selection-effects impact our assessment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



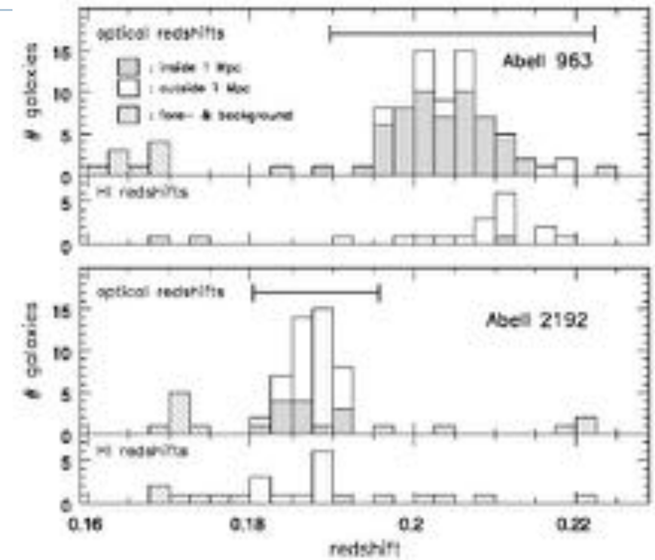
HI View: State of the Art:

Verheijen et al. 2007 (van Gorkum)

45’

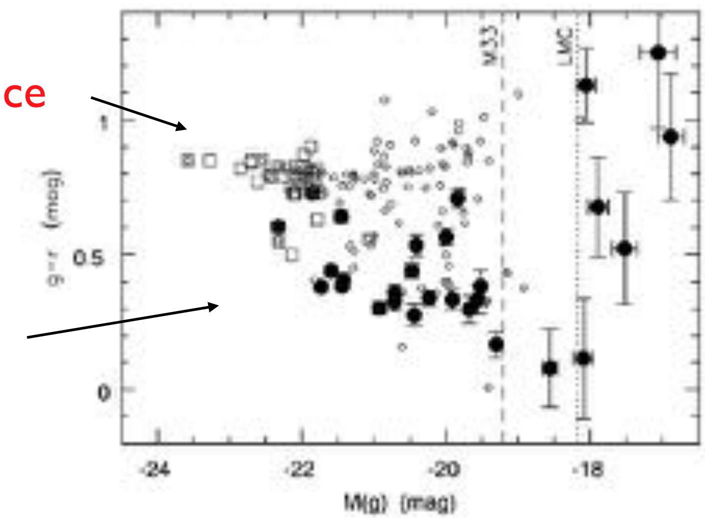


z=0.2



Red sequence

Blue cloud



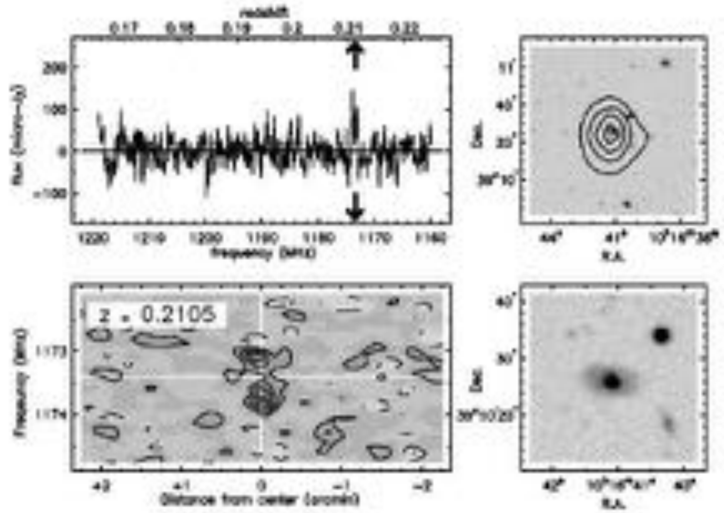
- Westerbork

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

HI View: State of the Art

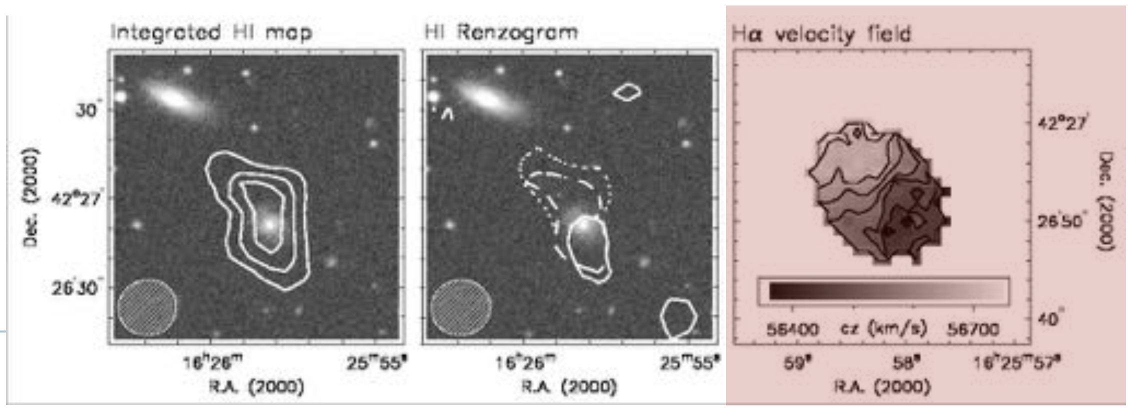
- Solid detections for 42 sources in 2 x 0.4 deg^2 fields
  - expect 200 sources in 1000h
- Limited spatially-resolved kinematic information
- Hα offers detailed kinematic supplement + SFR map
  - t=80 min, 3.5m telescope (CA)
  - 16x16 array of 1" fibers (PMAS)

A963 - Westerbork



Verheijen & Dwarakanath '08

A2192 (z=0.19) - VLA $M_{HI}=7x10^9\ M_{sun}$



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