Astronomy 330

Lecture 23

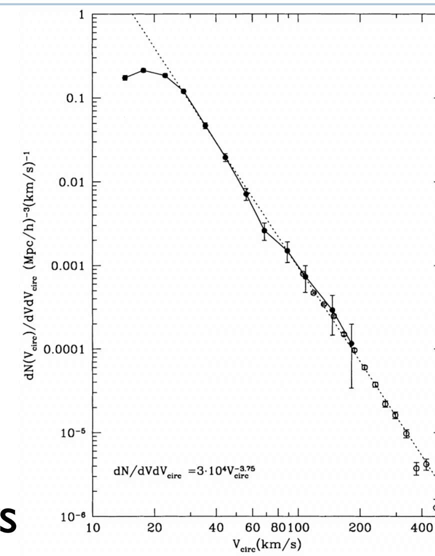
01 Dec 2010

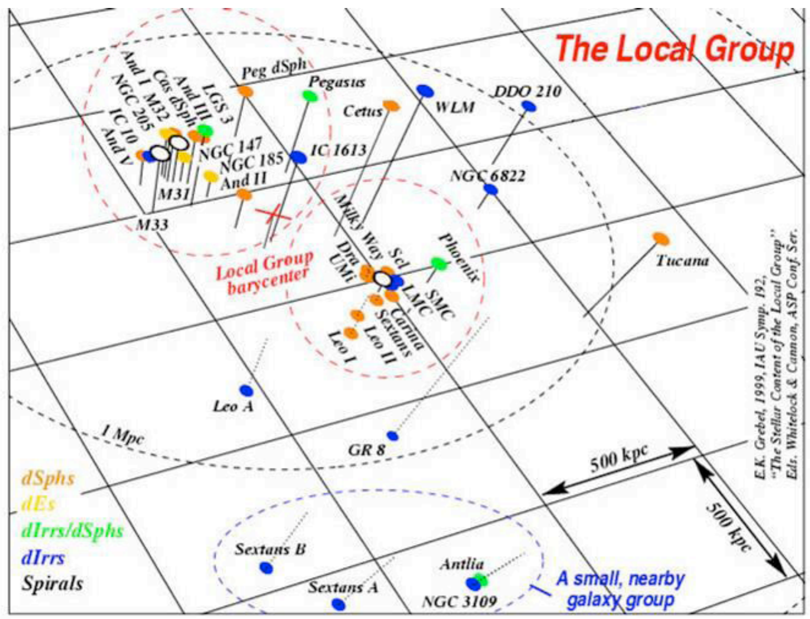
Outline

- Review:
  - Dwarf galaxies
    - Context of galaxy formation
    - Content of Local Group
    - Feedback
- Galaxy interactions
- Groups
  - Environment & gas content

Review: Dwarfs in the Local Group

- CDM structure formation: small things form first
- There ought to be many hundreds of dwarf-mass DM haloes in the local group ➔
- Detected 40+ and more every year

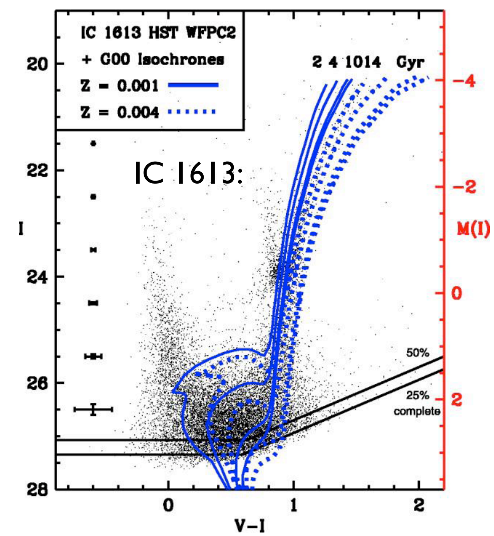


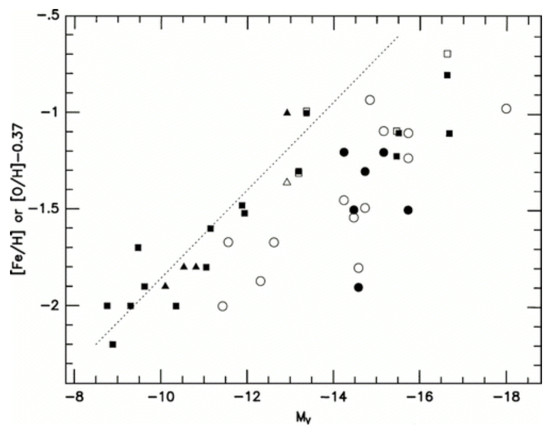


- Different types
  - Dwarf Ellipticals (dEs)
  - Dwarf Irregulars (dIrr, Sdm)
  - Intermediate/Transition
  - Dwarf Spheroidal (dSphs)
- Clustering properties
- Gas content
- Internal structure V_{rot} / σ
- Complex stellar populations

Review: Feedback, Stellar Pops & Abundances

- CMDs from HST reveal
  - complex SFH
  - all galaxies have some old stars
- Spectroscopy reveals:
  - low stellar abundance correlated with luminosity (and plausibly mass)
- Multi-wavelength imaging reveals:
  - SF has enough energy to blow out *all* gas
  - All gas is not always blown out (dIrr's)
  - SF and gas holes not always co-incident
- Inferences on *feedback* in dwarfs:
  - Energy from star-formation preferentially blows out enriched gas local to the clumpy star-formation.
  - Inefficient for blowing out all gas, particularly cold gas.
  - ➔ SF is on-going, but metal poor.





Galaxy Interactions

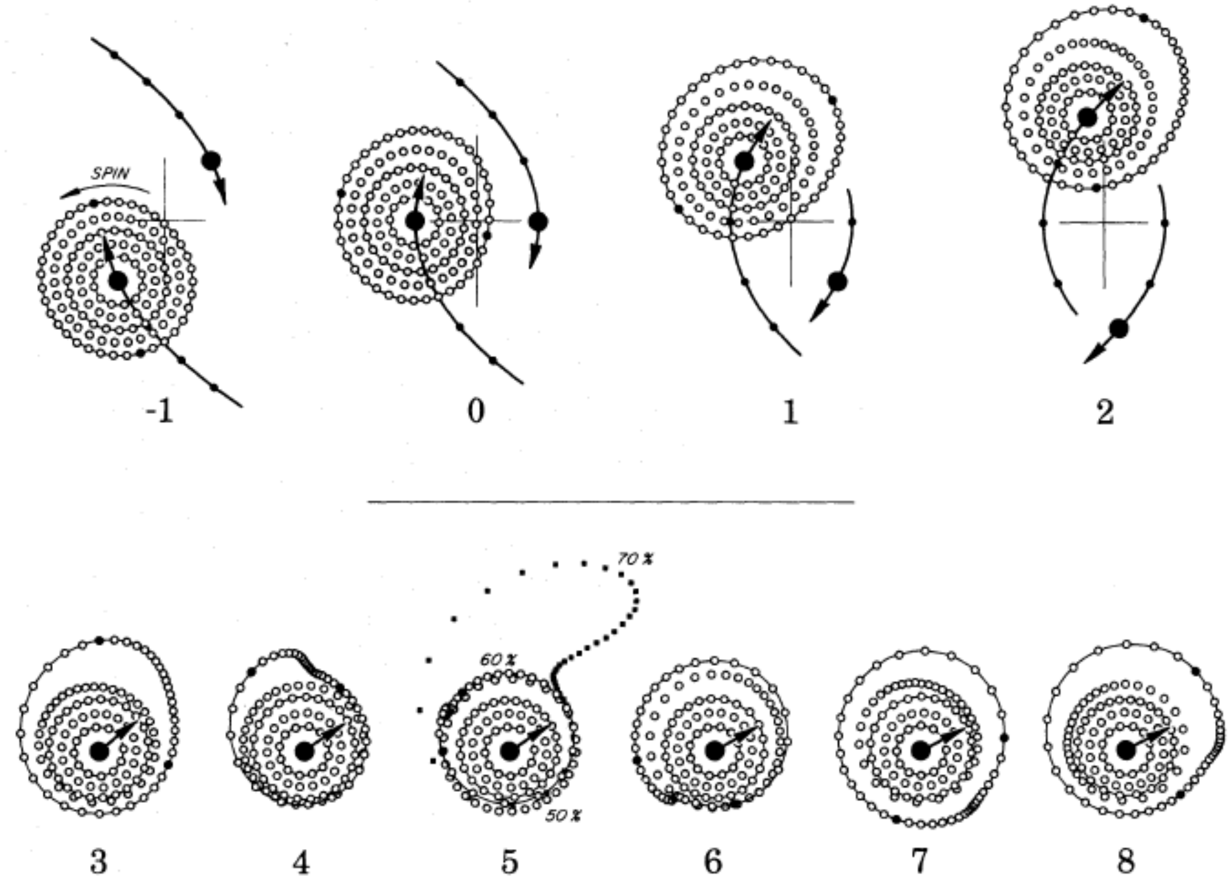
- Dynamical friction: dense medium
  - Dwarf / globular-cluster moving through stellar distribution governed by shape of the potential/density distribution
  - Galaxies near center of galaxy cluster
- Impulsive/high velocity encounters : large relative velocities
  - Velocity of encounter >> internal 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

Mergers

- Two galaxies of roughly equal mass
- Velocities ~ internal velocity
  - ➔ mergers tend to occur if orbital energy is negative (i.e. galaxies are bound to one another)
- Difficult to compute results analytically
  - ➔ requires simulations

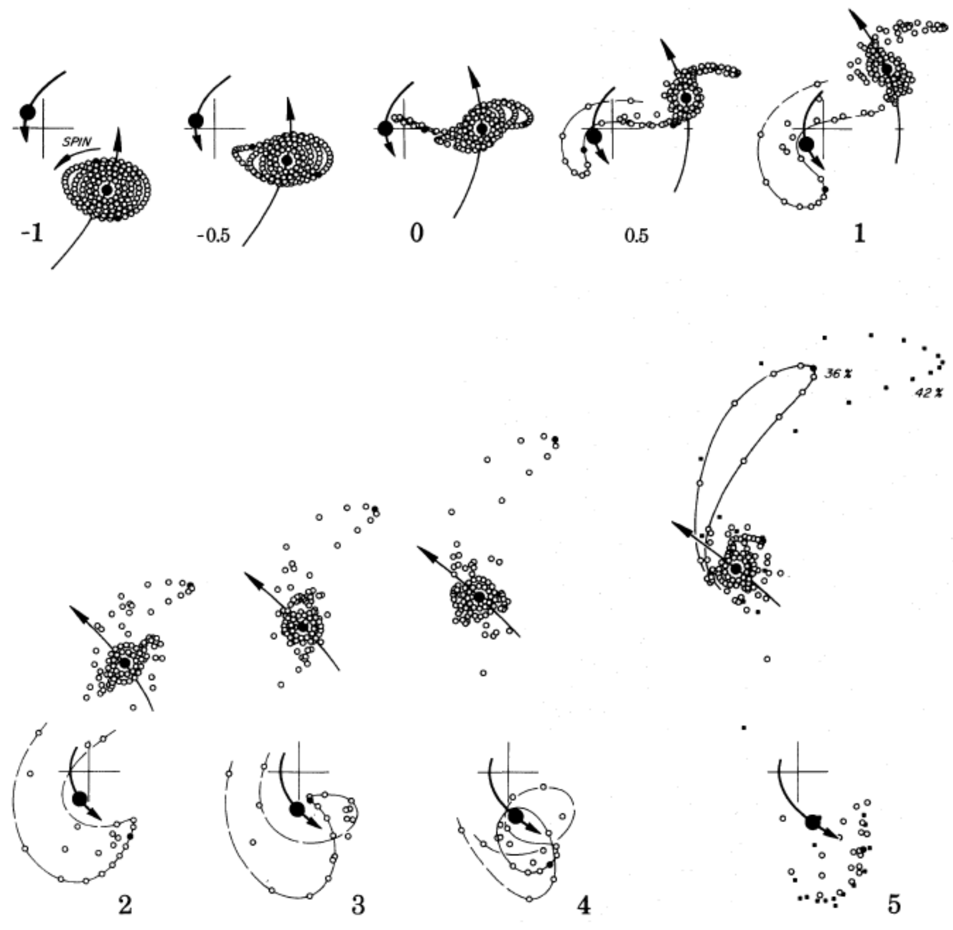
Early numerical results

- Toomre & Toomre: prograde



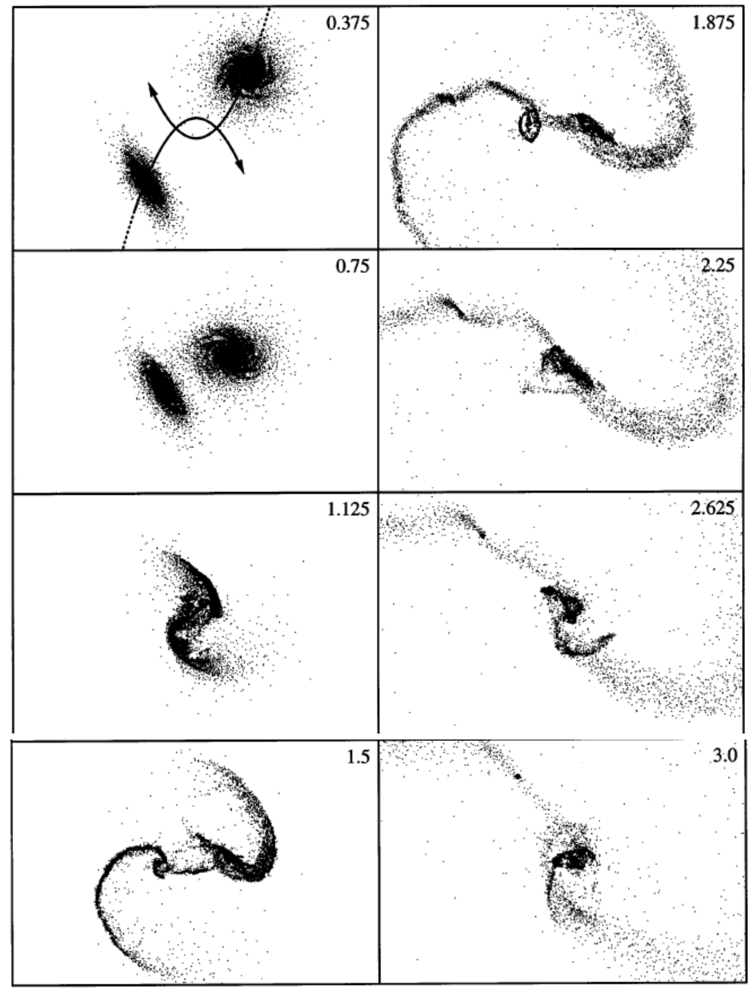
Early numerical results

- Toomre & Toomre: retrograde



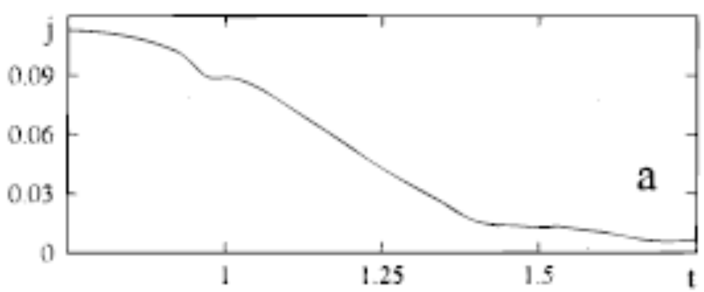
Modern N-body simulations

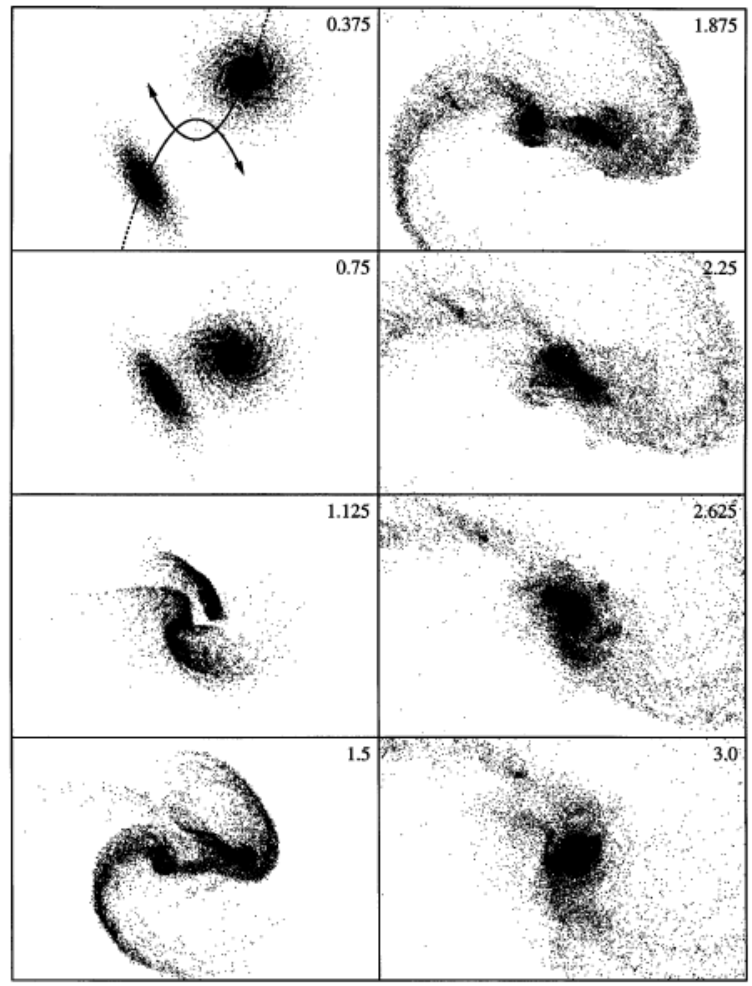
- Barnes & Hernquist
  - Equal-mass merger
  - Times in Gyr
  - retrograde



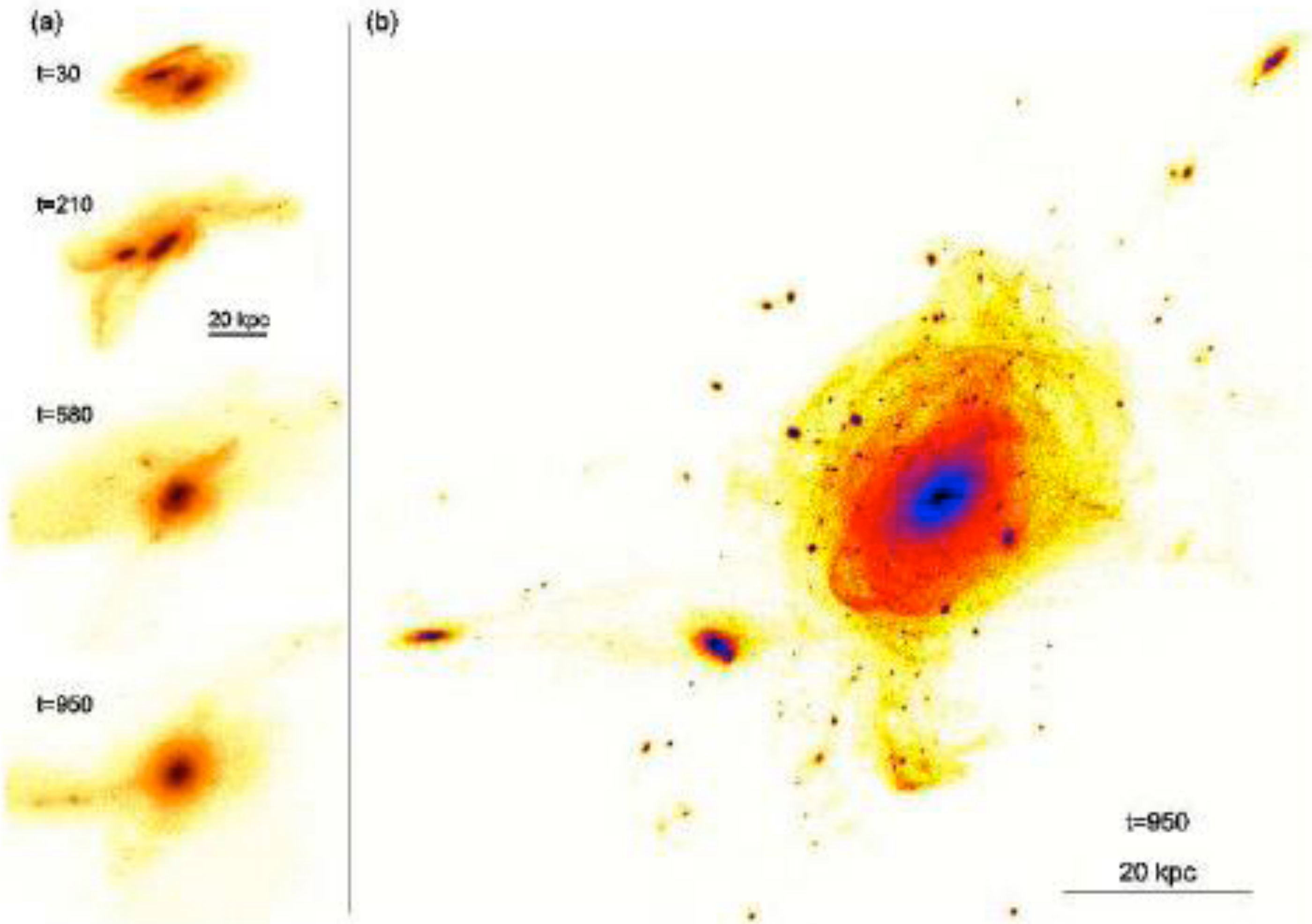
Modern N-body simulations

- Barnes & Hernquist
  - Equal-mass merger
  - Times in Gyr
  - Prograde
- Mergers → angular momentum decreases (gas)
- Resulting pile has almost $r^{1/4}$ distribution

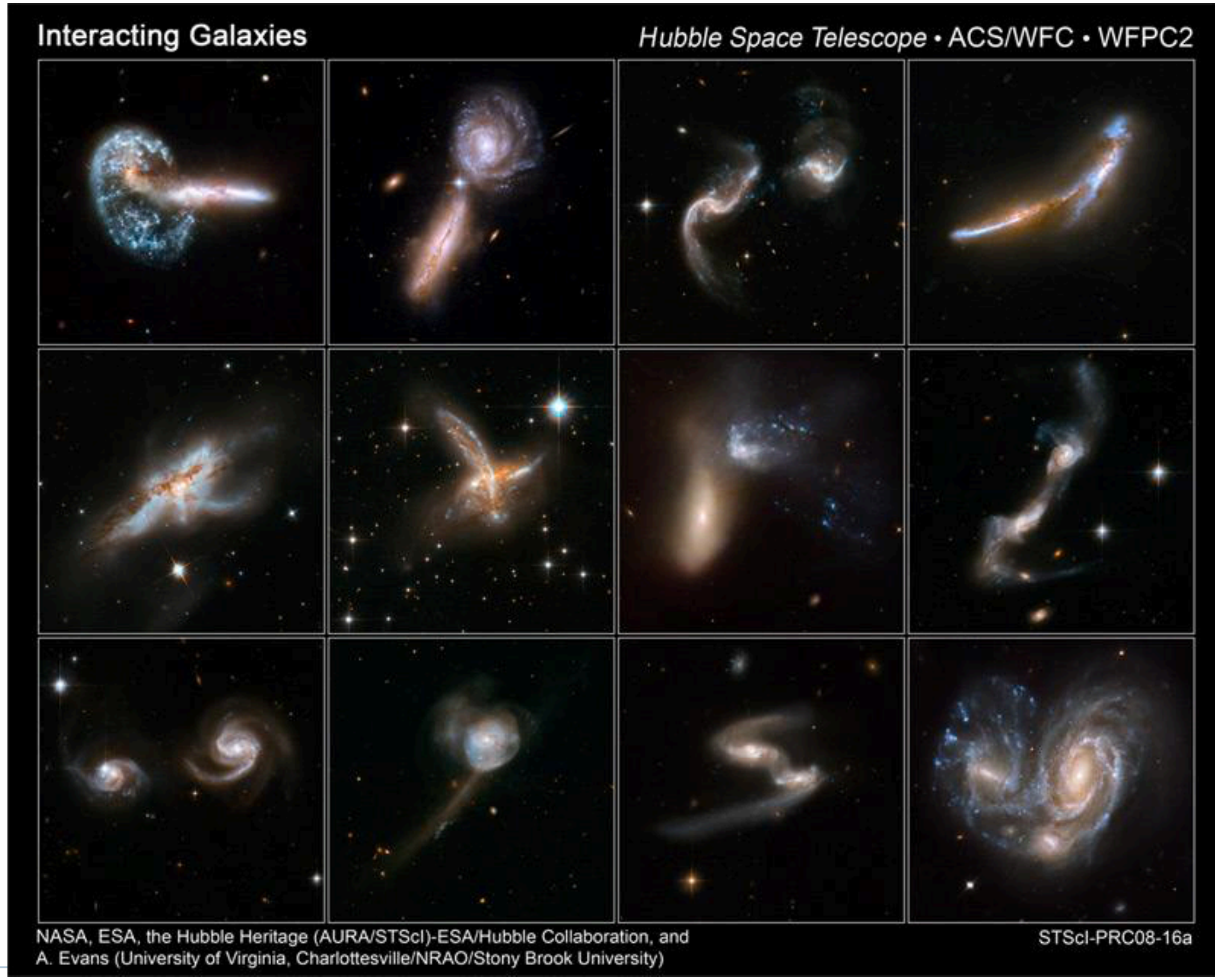




High-resolution simulation



The real deal



Why Galaxy Groups

- 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?

What are Galaxy Groups?

- 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 2001)
- $M_{halo} \sim 10^{12} - 10^{14} M_{\odot}$ (Eke 2004)
- Compact groups ➔ "few" galaxies with separations of a "few" galactic radii

What are Galaxy Groups?

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

What *aren't* Groups?

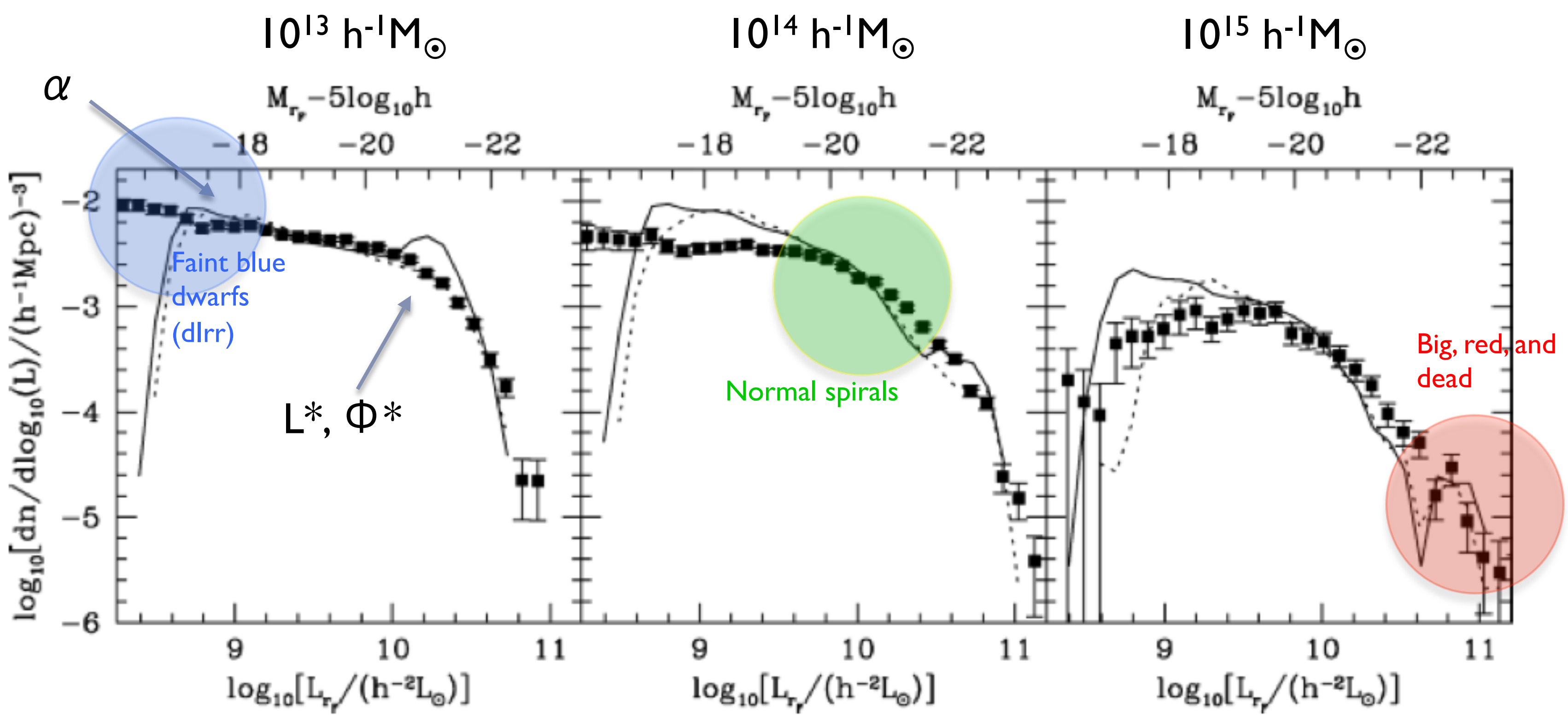
- Groups aren't clusters…
  - Clusters are made of many 100's to 1000's of galaxies,
  - have masses far in excess of $10^{15}\ h^{-1}M_{\odot}$, and
  - have velocity dispersions (galaxy-galaxy) of 500-2000 km/s.
- Group velocity dispersion ~ internal velocity dispersion of individual galaxies
  - Galaxy-galaxy 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)

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
- 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

Luminosity functions vs Environment

As a function of group environment (group total mass): Eke et al. (2004)



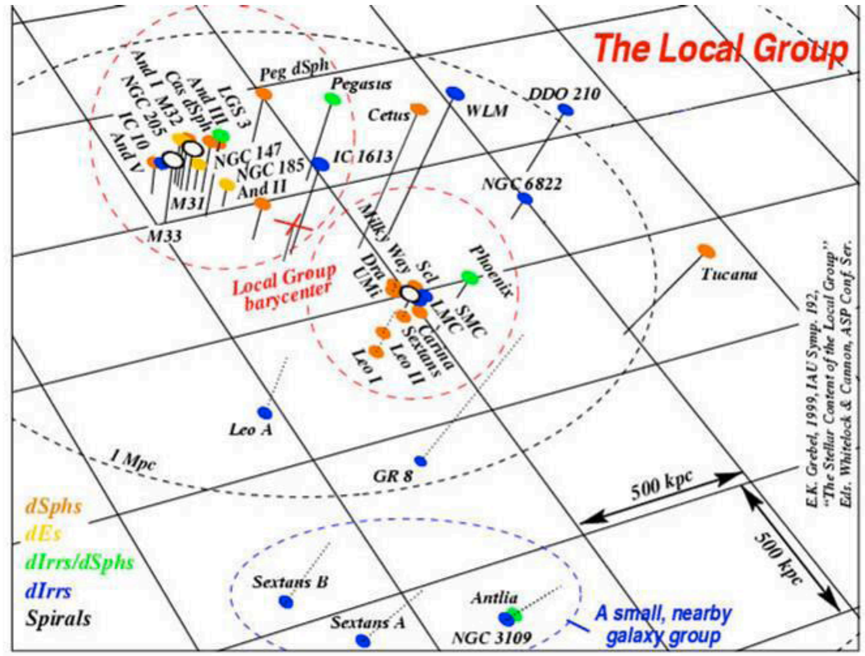
Red light (R_F band);
$h = H_0$ / 100 km s^{-1} Mpc^{-1}

Squares: actual data
Solid lines measured from simulations, corrected
Dashed lines measured from simulations, uncorrected

- Φ (s,L,c, $a_1 \ldots a_n$, V, σ, τ, z, $\mathcal{M}_*$, $\rho_{i;}$ e) -- e is environment

HI Content of the Local Group

- Gas-rich spirals
  - M31 (log $M_{HI}/M_\odot \sim 9.76$)
  - MWG (log $M_{HI}/M_\odot \sim 9.60$)
  - M33 (log $M_{HI}/M_\odot \sim 9.18$)
  - LMC (log $M_{HI}/M_\odot \sim 8.85$)
- Gas-rich irregulars
  - SMC (log $M_{HI}/M_\odot \sim 8.81$)
  - IC 10 (log $M_{HI}/M_\odot \sim 8.18$)
  - WLM (log $M_{HI}/M_\odot \sim 7.90$)
  - Sextans A (log $M_{HI}/M_\odot \sim 7.90$)
  - IC 1613 (log $M_{HI}/M_\odot \sim 7.78$)
  - Leo A (log $M_{HI}/M_\odot \sim 7.30$)
  - *Gas-rich irregulars tend to lie at large distances*
- Tidal Debris/HVCs
  - Magellanic Stream
  - M31/M33 bridge (Braun & Thilker2004)
  - HVC system



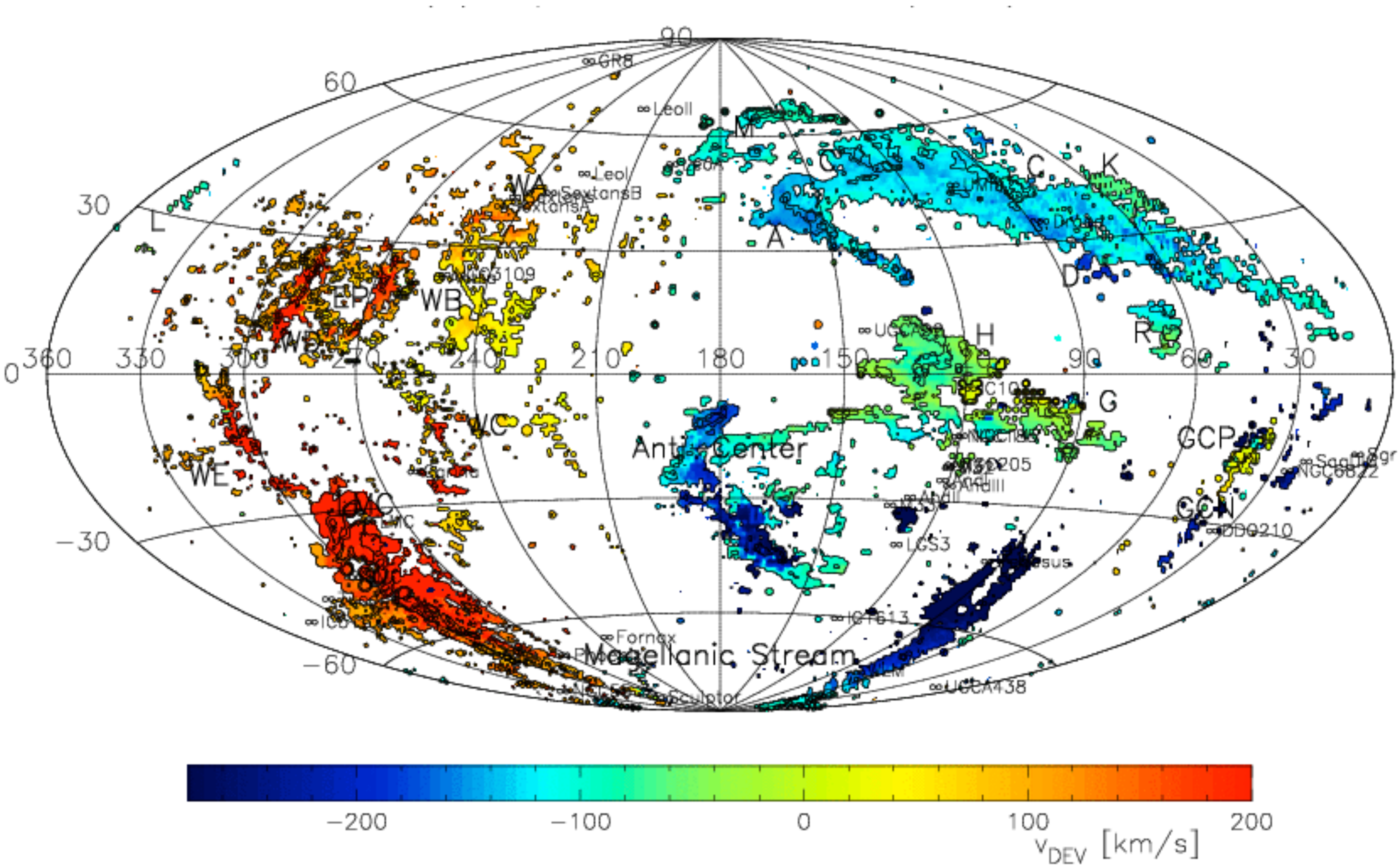
Total HI Mass of Local Group:

log $M_{HI}/M_\odot \sim 10.13$

$\sim 10\%\ M_{stellar}$

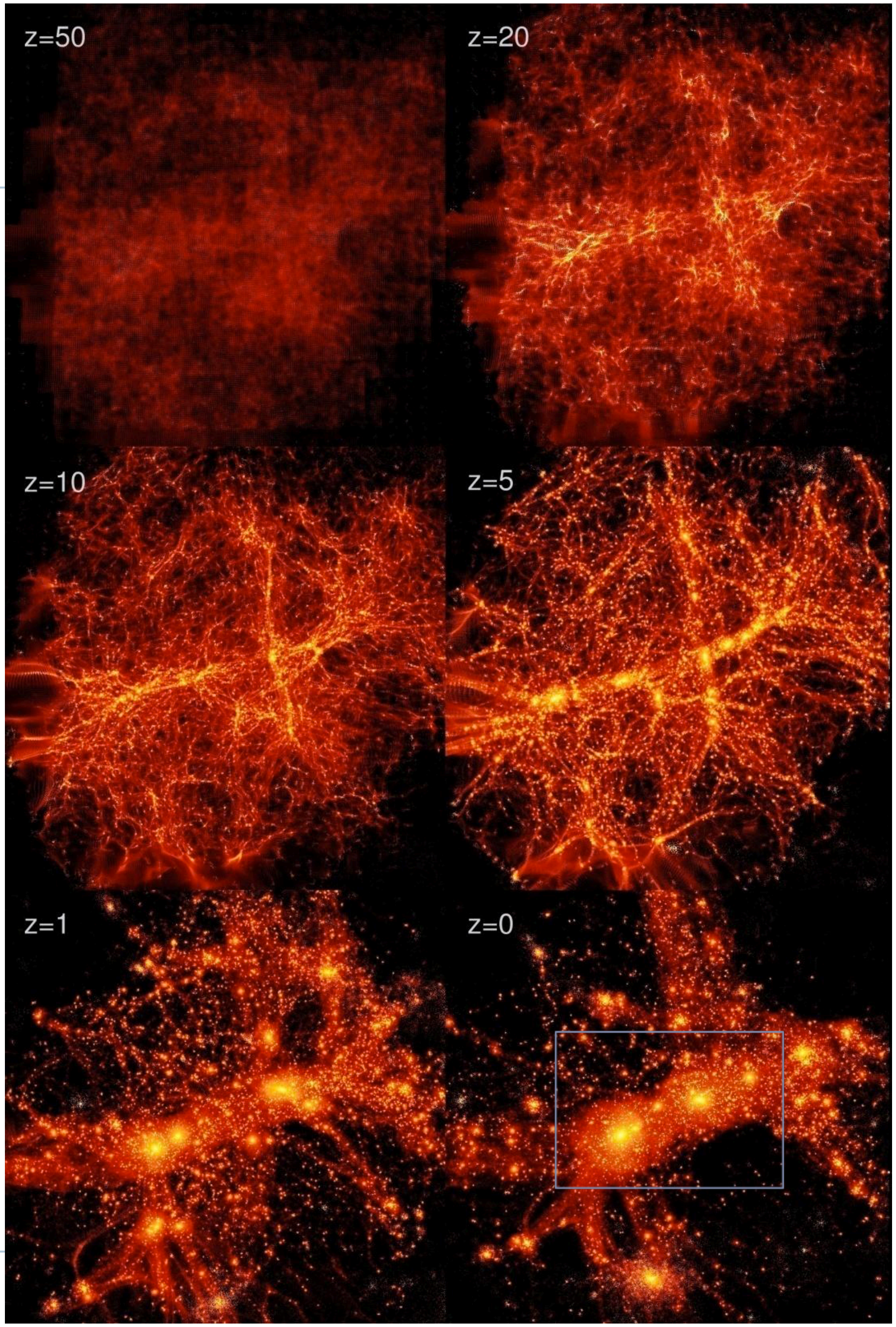
$\leq 1\%$ of $M_{dynamical}$

Milky Way/Local Group High Velocity Clouds



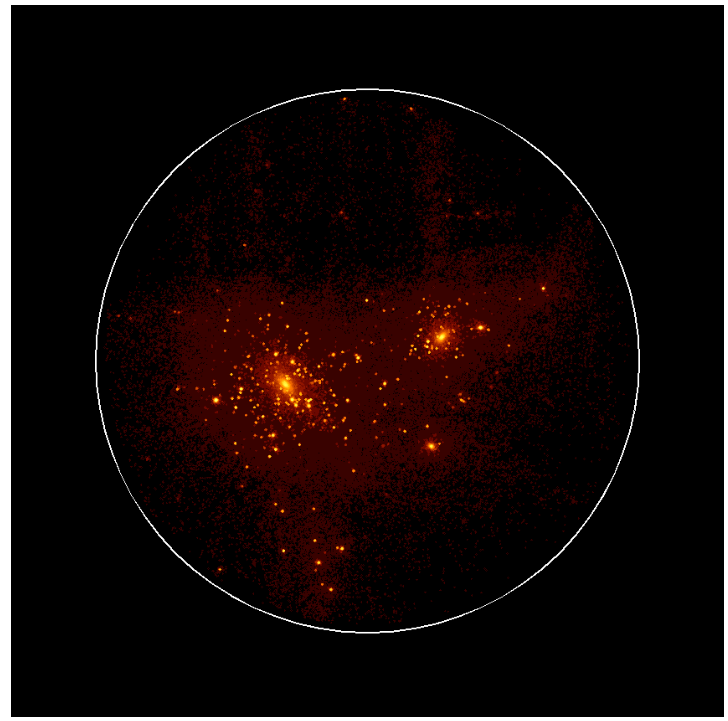
Simulations

- Simulation of the formation of the Local Group
  - B. Moore
  - http://nbody.net



Simulations:

- The Distribution of CDM halos & HVCs
  - B. Moore



Pure HI galaxies?

- There is no indication of a population of pure HI clouds (HVCs) in the intra-group medium.
- The HI mass function in the group environment is flat at the low mass end.
- Intra-group medium in "intermediate" groups is populated with tidally stripped HI as groups evolve

Groups: Morphology, Gas and Dynamics

- Morphology-Dynamics:
  - Optical surveys indicate that dynamically evolved groups have high elliptical fractions (F = 0.6-1.0), while dynamically young groups have small elliptical fractions (F = 0.0-0.2)
  - Corresponding relationships between velocity dispersion, L_X, and early-type fraction (Brough et al. 2006)
    - $F = 0.27 \log_{10} L_X - 10.8$
    - $F = 0.76 \log_{10} \sigma - 1.2$
- Gas Content vs Dynamics:
  - Evolved groups have extended X-ray halos
  - The gas content of dynamically young groups is largely in neutral gas ➔ no group with F=0 has a detected X-ray halo.

Groups: the role of interactions

- 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

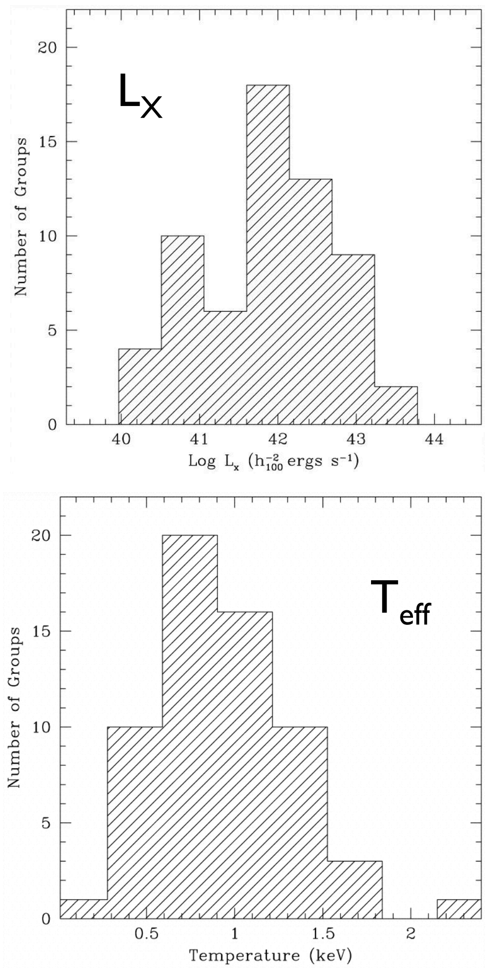
- Is it possible to trace group evolution by looking at the distribution of gas?

Group evolution: morphology & gas content

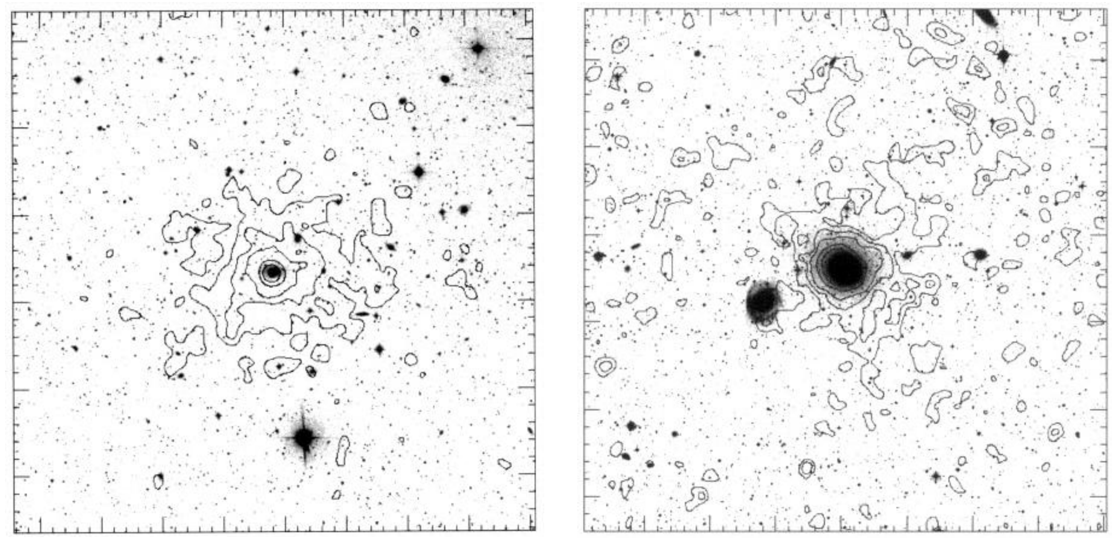
- Two trends observationally correlated:
  - Spiral rich ➔ elliptical dominated
  - Cool, neutral ➔ hot, ionized
    - None of the groups observed with $F_{spiral}=1$ have detectable X-ray halos
- Possible Scenarios:
  - Tidally stripped neutral gas is heated in the intra-group medium
  - Galaxy mergers
  - Heating of intergalactic medium
  - Compact groups are transient phenomena within larger loose groups ➔ development of common HI envelopes
- The hunt:
  - Measure the interaction/merger rate
  - Measure the total amount and distribution of neutral gas

X-ray properties

- Mulchaey et al. 2003: statistical properties



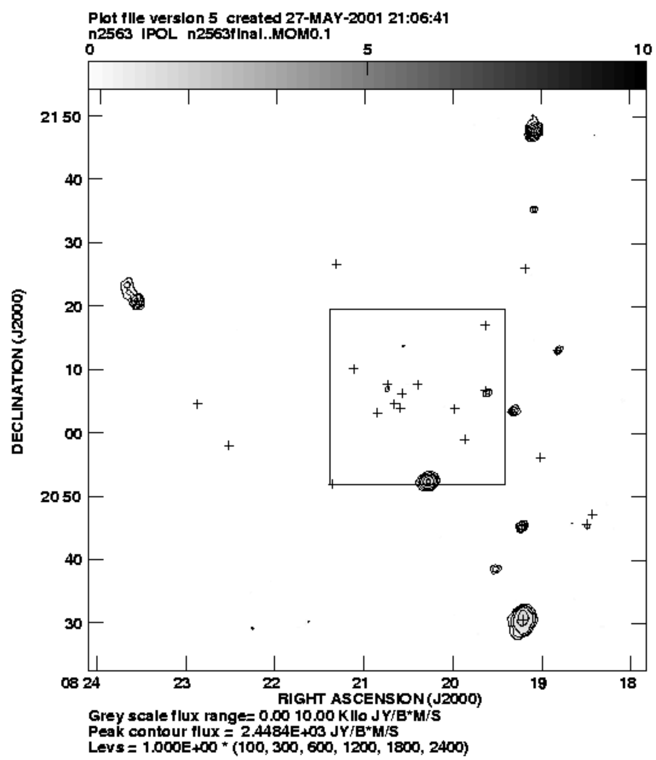
- Mulchaey & Zabludoff1998
  - Flux maps

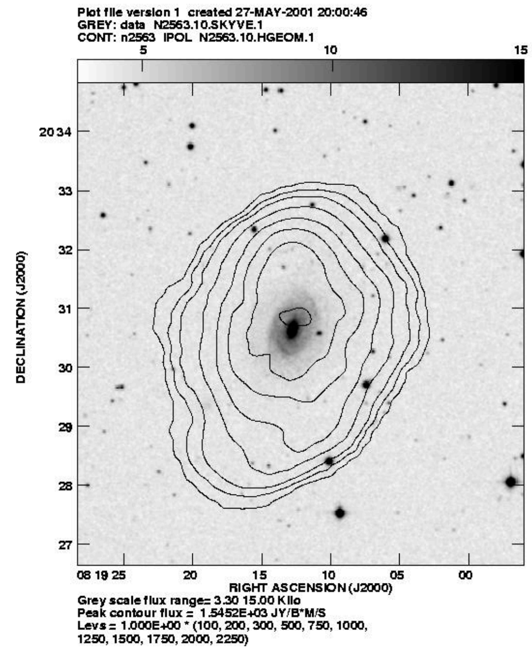


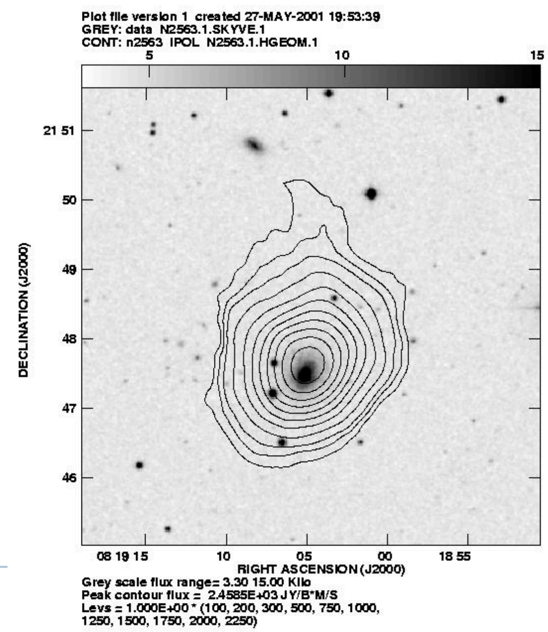
HI Properties

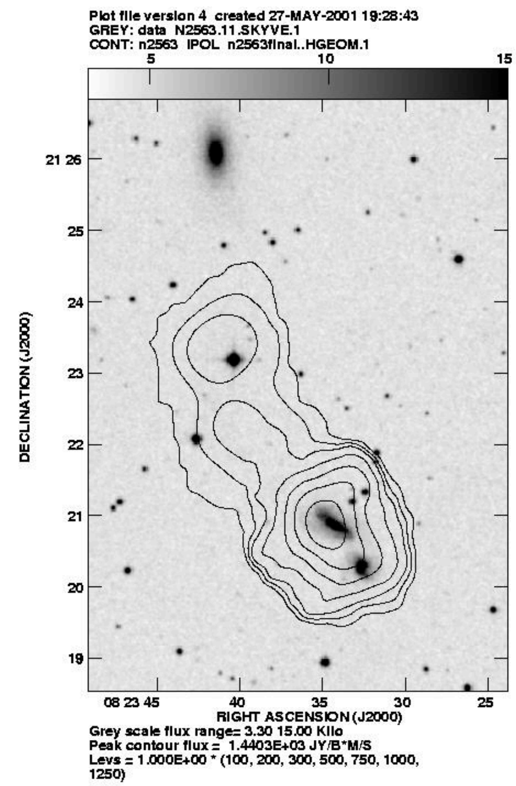
- Isolated sources
- Extended distributions
- Common envelopes?

Wilcots et al.





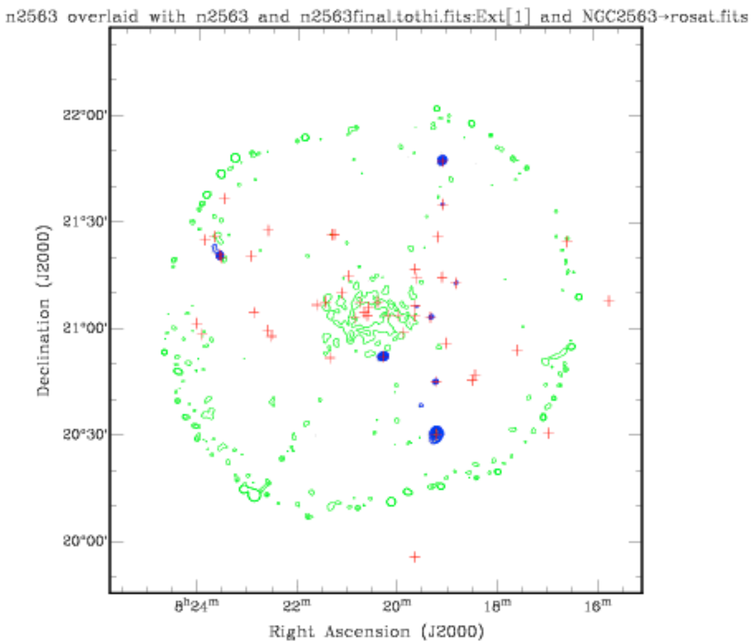




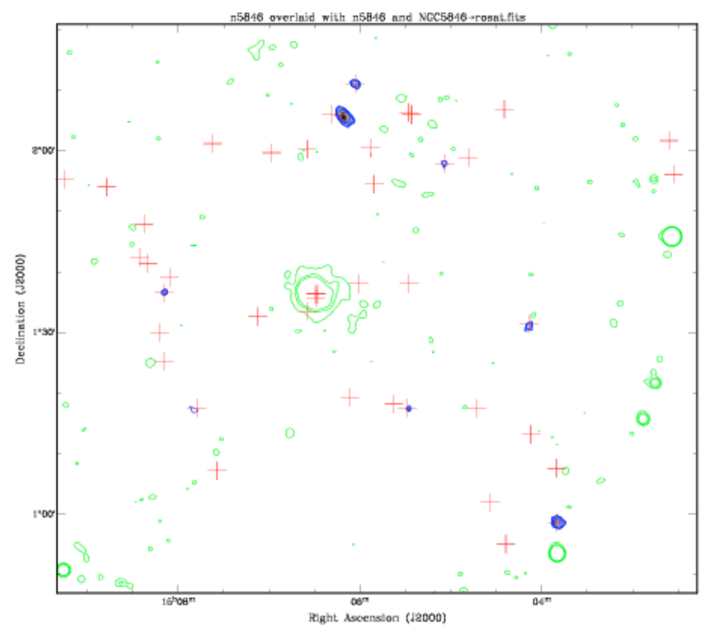
X-ray vs HI Group Emission

- HI detections
- All members
- X-ray emission

NGC 2563



NGC 5846



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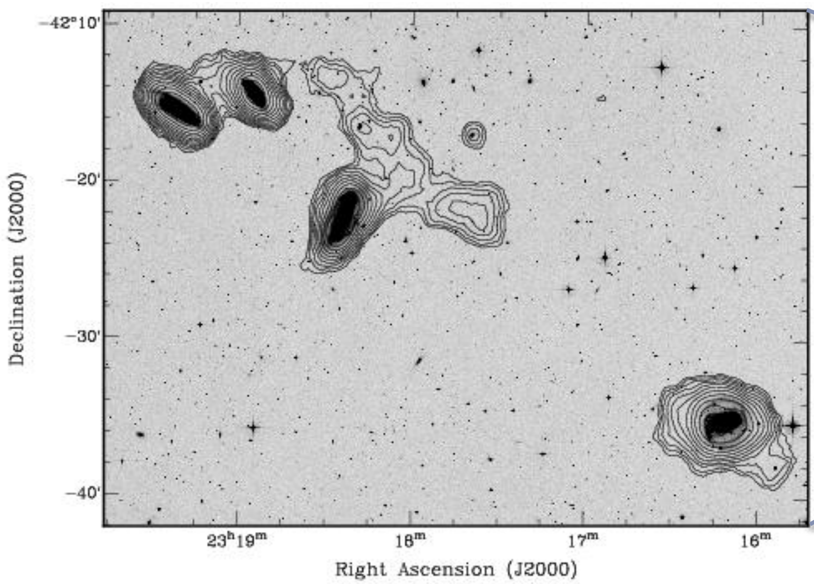
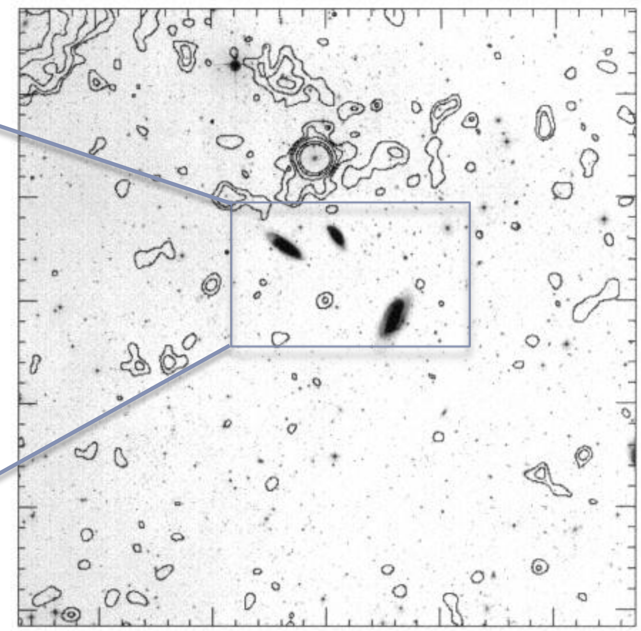
X-ray vs HI Group Emission

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

HI

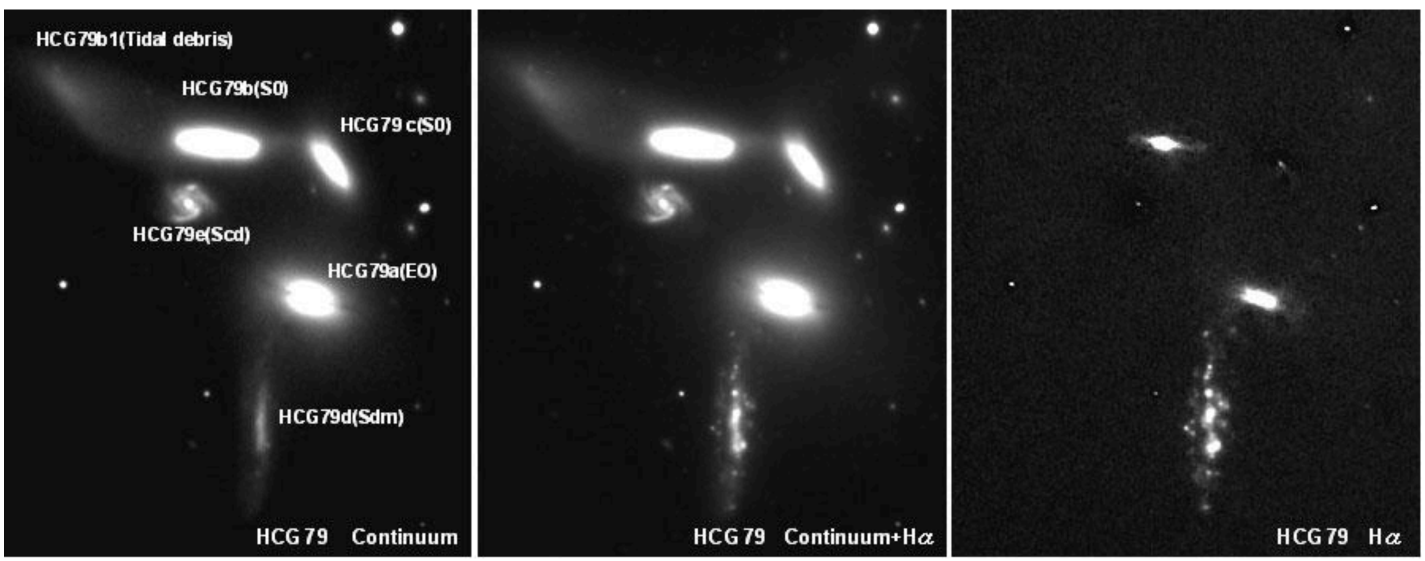


Xray



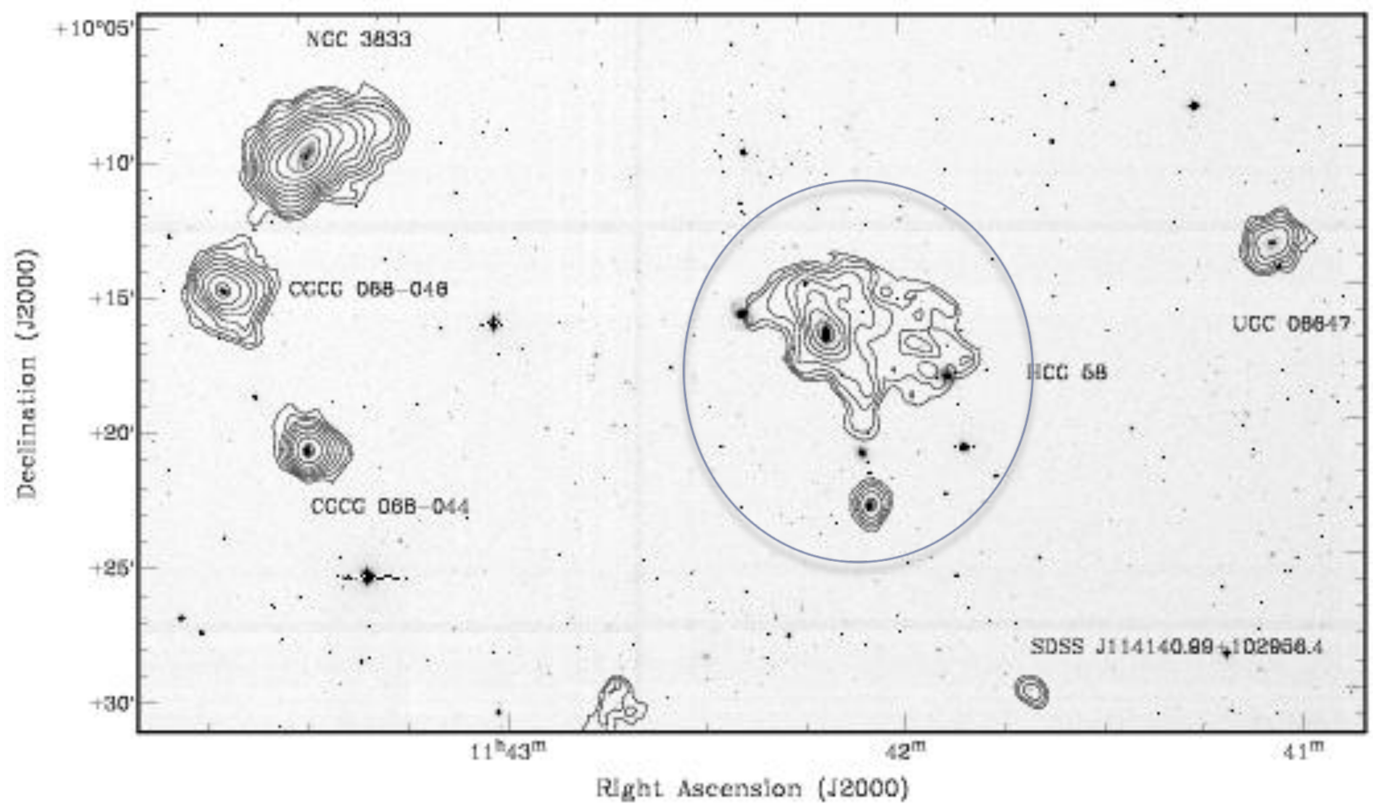
Compact Groups

- 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

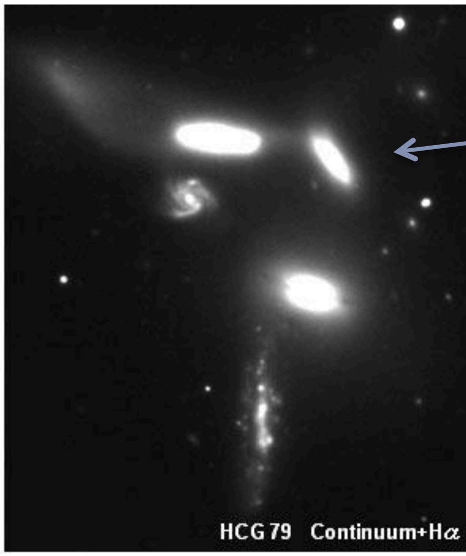


HCG 58 – Common HI envelope?

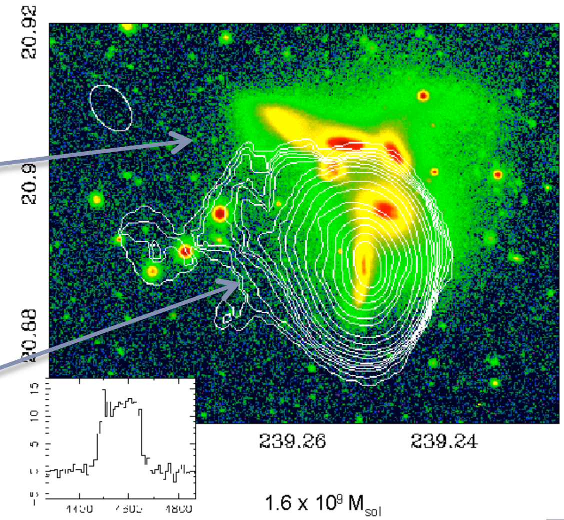
- Freeland et al. 2007: 21 cm contours



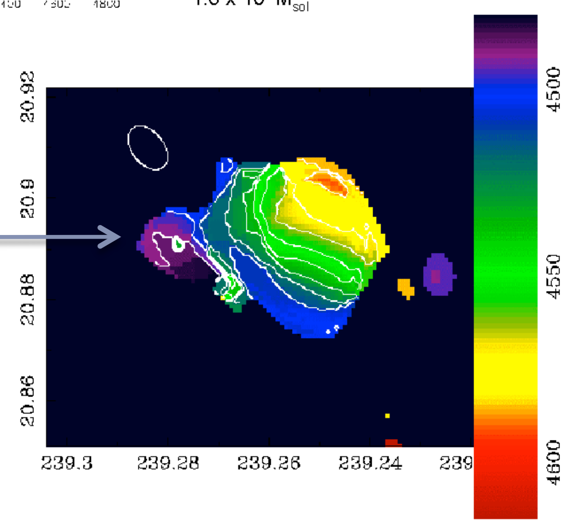
HCG 79 – Common HI envelope?



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