Galaxies

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Heidelberg

March-April 2008

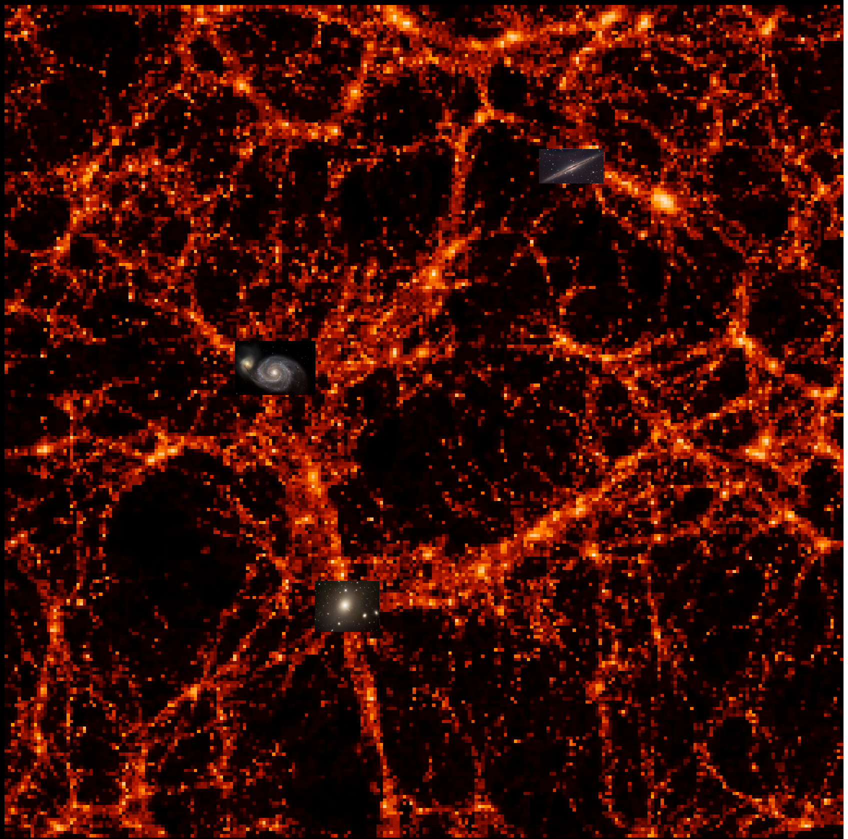

Introduction to Galaxies
Key concepts

Galaxies - what are they?

1) Huge collections of stars and gas

Galaxies - what are they?

2) Small 'smudges' of normal matter in a huge dark matter halo
   - ~50x more dark matter than stars



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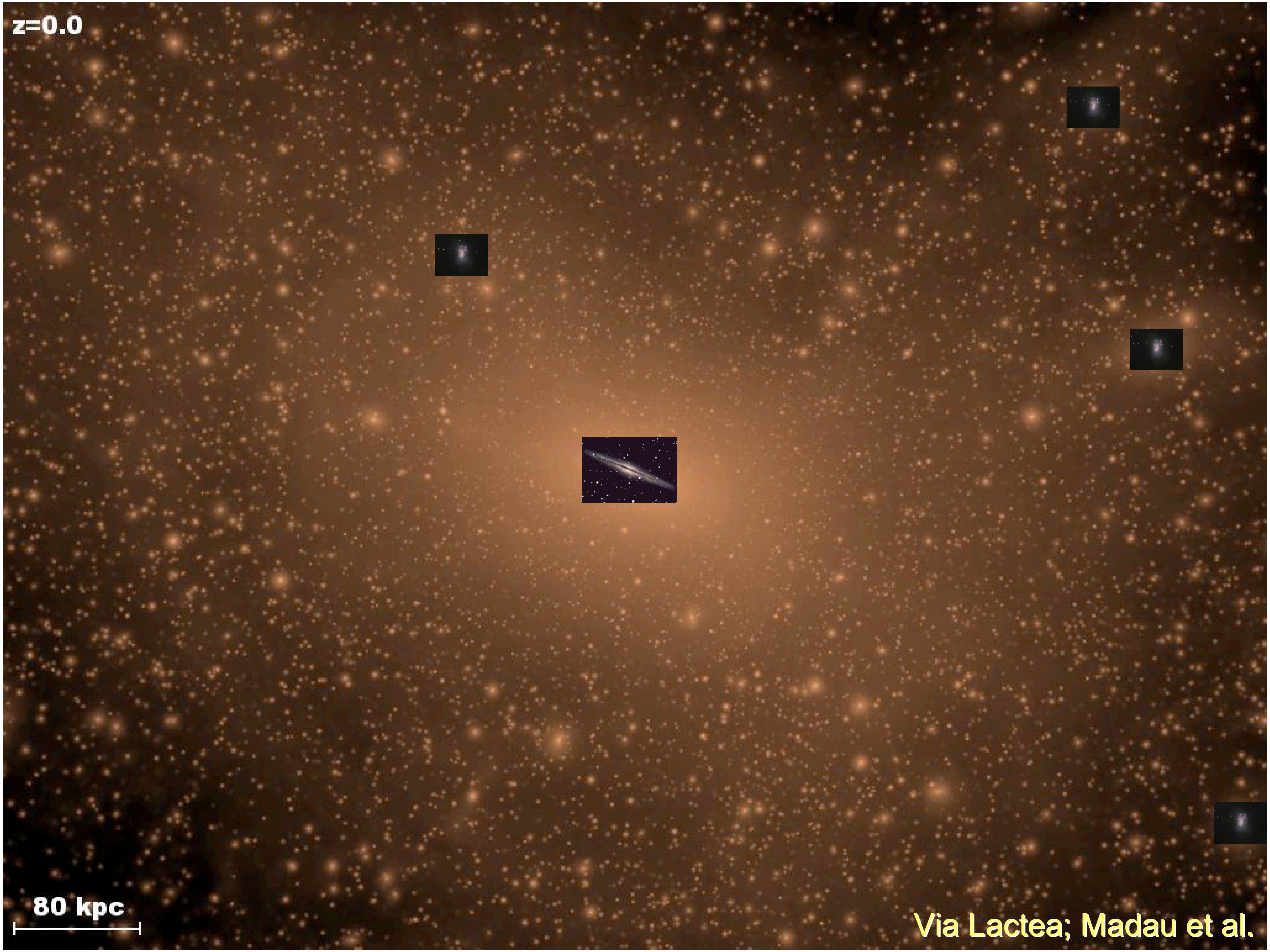
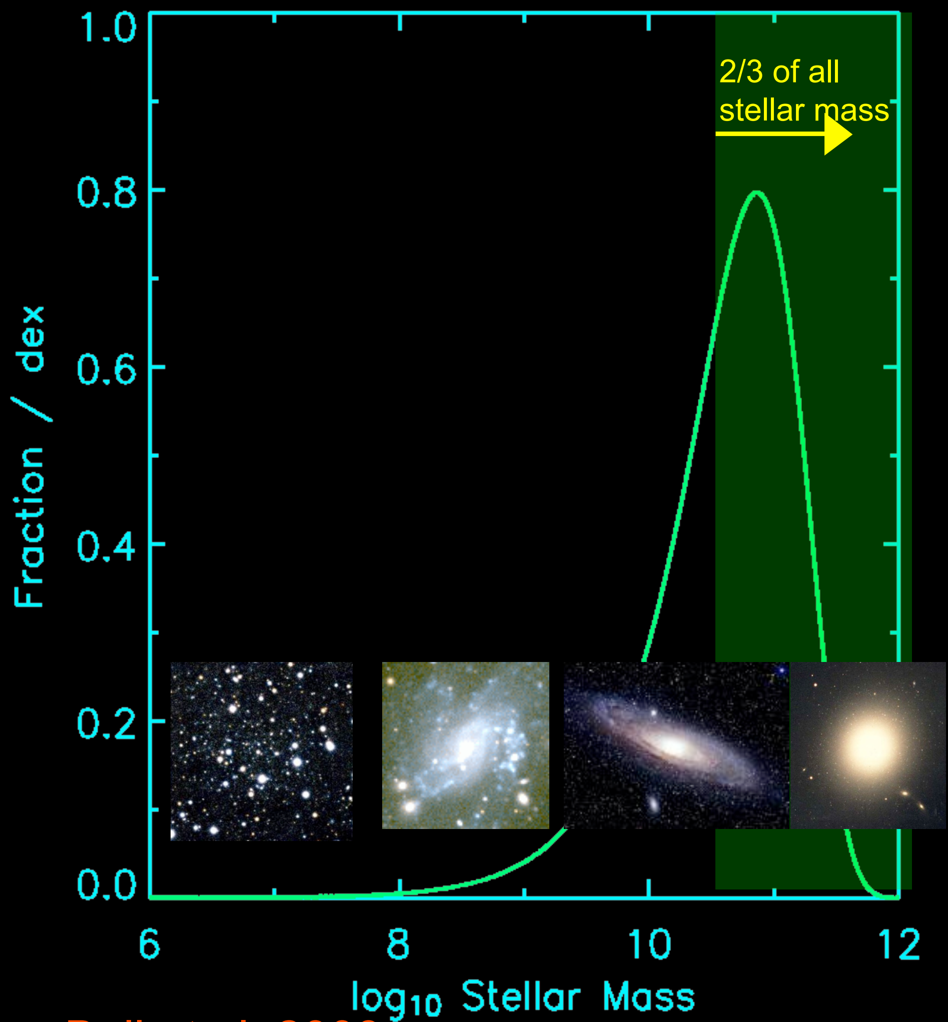

z=0.0
80 kpc
Via Lactea; Madau et al.

Galaxies have a range of masses…

Dark matter halo mass spectrum scale free

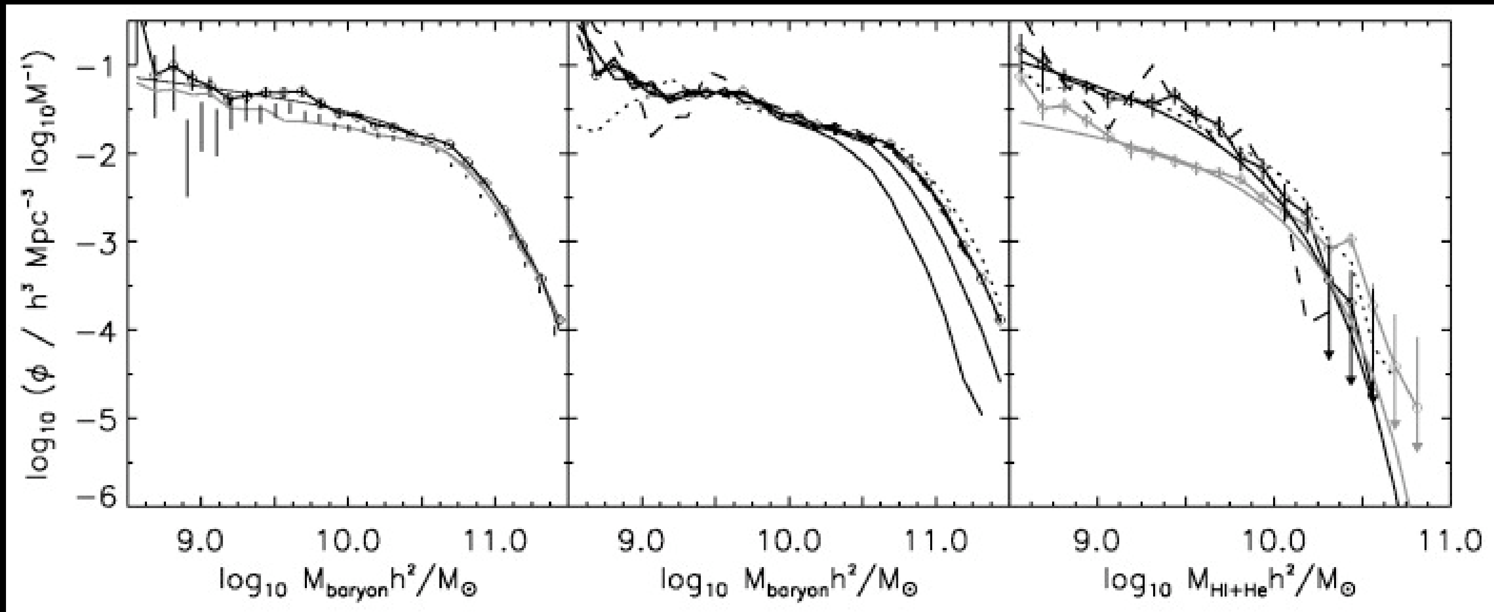
but…

massive galaxies dominate total stellar mass of universe



Bell et al. 2003

Baryonic mass function



Bell et al. 2003

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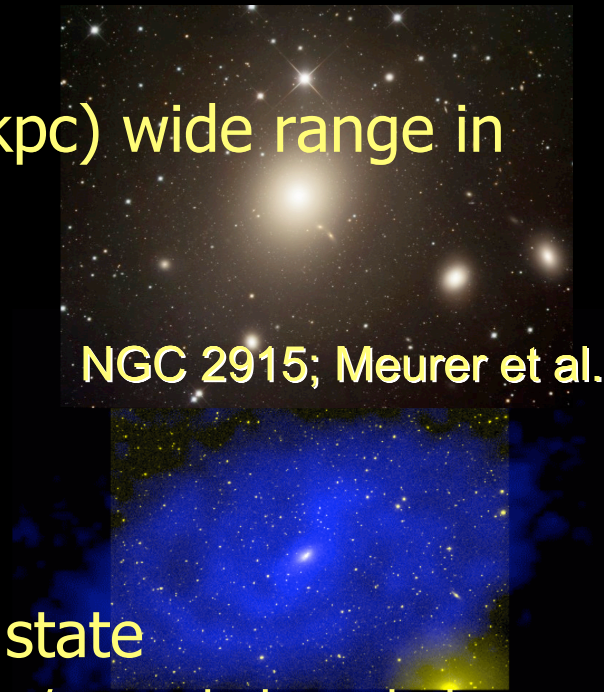
Galaxies and gas

- Main body of galaxies (<30kpc) wide range in gas contents
  - Almost gas-free
  - >95% cold gas (HI/H2)

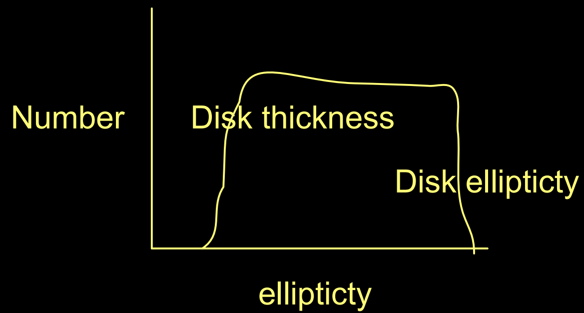


NGC 2915; Meurer et al.

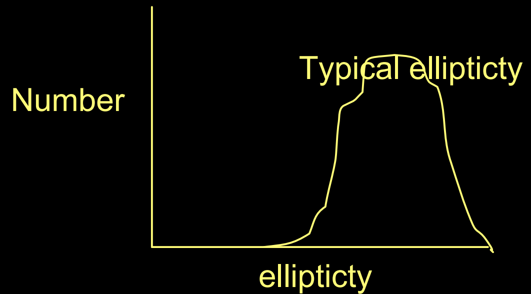
- BUT, most gas in warm/hot state
  - 80-90% of baryons in filaments/extended gas halos…
  - Can see this clearly in clusters; hard in lower-density environments (abs spectroscopy of high-ionisation species is required)

Galaxy structure

- Disks (conserved *some* ang. mom.)



- Spheroids (lost/randomised this AM)



Astonishing regularity

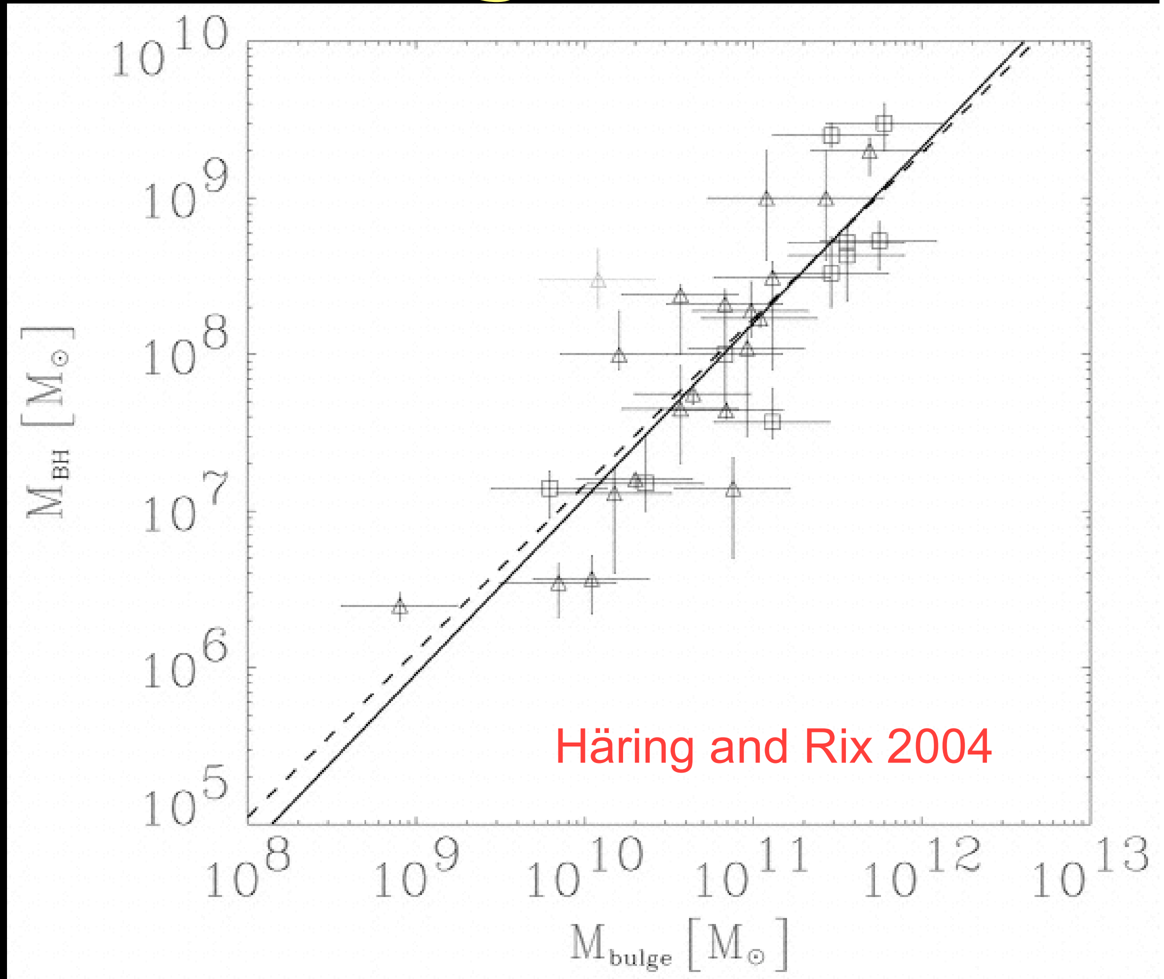
- Given e.g., stellar mass
  - Can predict rotation velocity/velocity dispersion to 30%
  - Can predict size to factor of 2
  - Can predict halo mass in which galaxy lives in >50% of cases
  - Can predict disk contribution to light to 40% (much better at lowest and highest masses)
  - Can predict black hole mass to x3

Black holes and galaxies…

Black hole mass-bulge mass correlation

Scatter <0.3 dex

Possibility of a link between bulge formation and BH formation



Galaxy formation

Formation of the dark matter halo

- Gas pressure at early times stops baryons from clumping
- DM - no pressure - can clump at will, acts as seeds for galaxy formation

Gas accretion / cooling

- After recombination, everything neutral
- After reionisation, everything ionised, sets minimum mass scale for galaxies (where pressure support = gravity)

Growth through accretion of gas (smooth, stuff that cannot cool into halos) and merging (where stars / cold gas already formed)

- Accretion could conserve some angular momentum (comes from torques as galaxies turn around and collapse; c.f., coffee cup; Fall & Efstathiou 80; Mao, Mo & White 98)
- Merging randomises angular momenta (adds some orbital AM to the galaxy; Toomre & Toomre 1972)

Galaxy formation

Star formation in the cooled gas

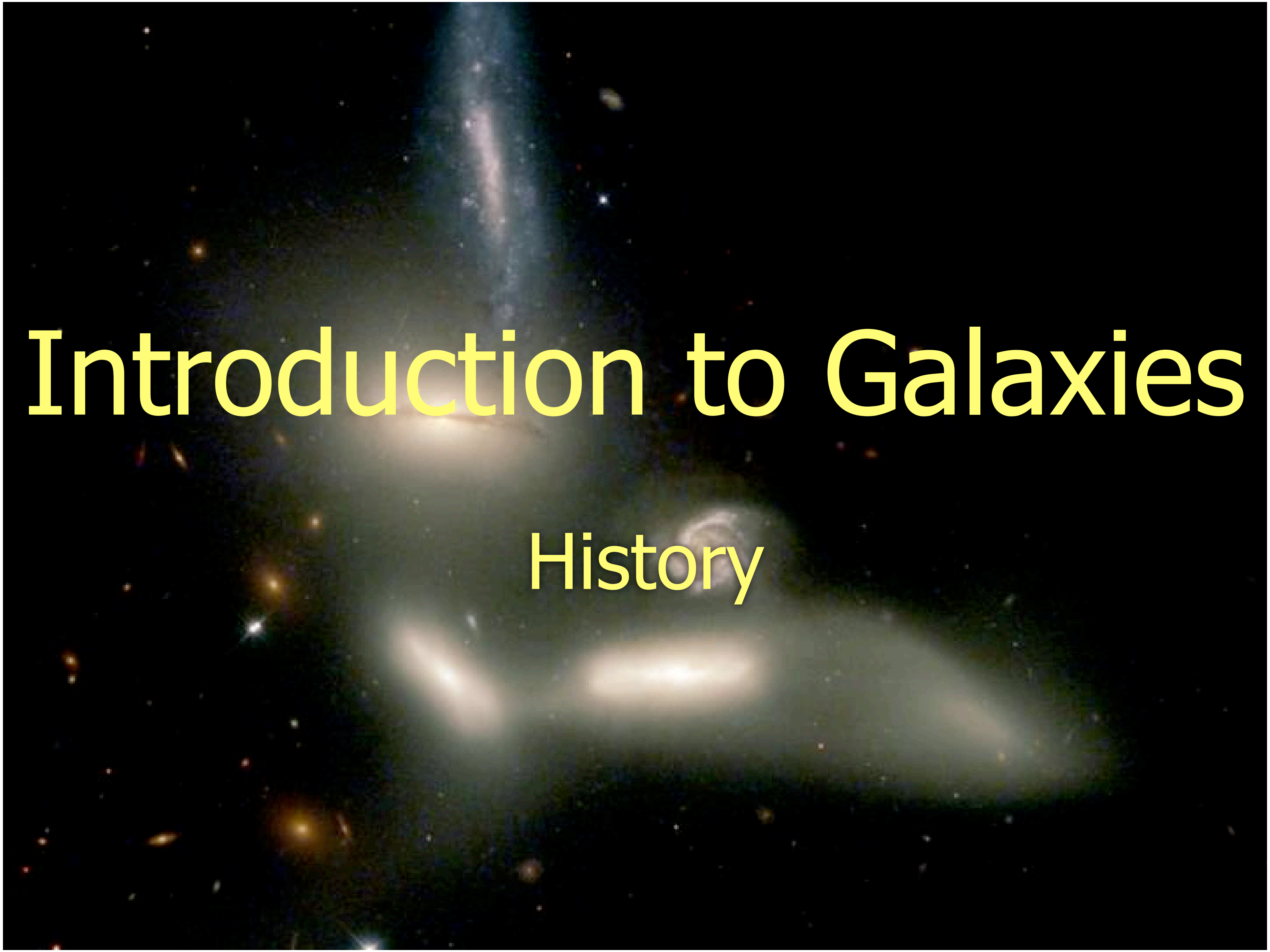
- SFR ~ gas density*E

Feedback

- Supernovae / Stellar winds --> outflow of hot, metal-enriched gas
- Possible AGN winds / feedback

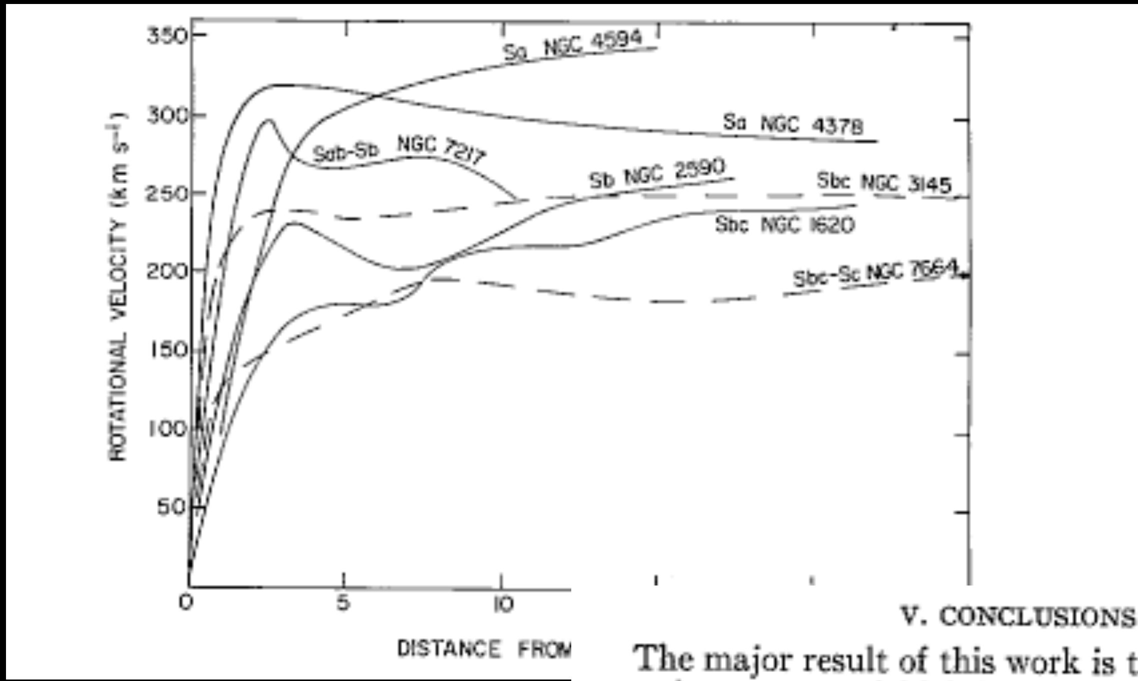
Introduction to Galaxies

History



A brief history of galaxies

- ‘Discovered’ in 1910 (when it was realised that they were outside of the Milky Way)
- Expansion of Universe late 1920s
- Dark matter discovered in 1930s (Zwicky); rediscovered in 1970s (Rubin/Bosma)
- Structure - Hubble sequence
- CMB + BBNS, establishes cosmological framework
- First serious discussion merging 1970s

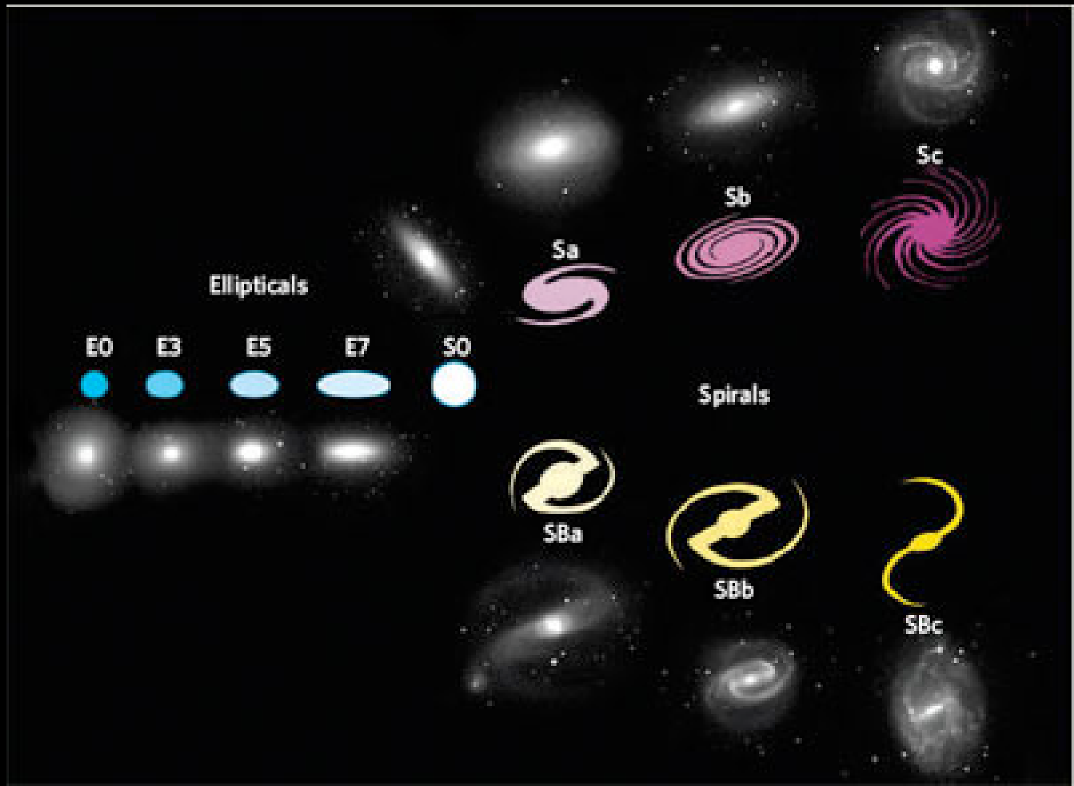


Rubin et al. 1978

V. CONCLUSIONS

The major result of this work is the observation that rotation curves of high-luminosity spiral galaxies are flat, at nuclear distances as great as $r = 50$ kpc. Roberts and his collaborators (Roberts 1976) deserve credit for first calling attention to flat rotation curves. Recent 21 cm observations by Krumm and Salpeter (1976, 1977) have strengthened this conclusion. These results take on added importance in conjunction with the suggestion of Einasto, Kaasik, and Saar (1974), and Ostriker, Peebles, and Yahil (1974) that galaxies contain massive halos extending to large r. Such models imply that the galaxy mass increases significantly with increasing r which in turn requires that rotational velocities remain high for large r. The observations presented here are thus a necessary but not sufficient condition for massive halos. As shown above, mass distributions from disk models or spherical models adequately reproduce the observed velocities. The choice between spherical and disk models is not constrained by these observations.

Hubble sequence



Beatrice Tinsley

- ‘Invented’ galaxy evolution
- 100 papers in 14 years
  - No large collaborations
- Unable to get faculty position at Univ. Texas
  - Divorced and left her two adopted children --> Lick Obs.
  - Then on to Yale
- Died 1981 of cancer, aged 40

Beatrice Tinsley, a gifted and dedicated teacher, mentor and scientist.

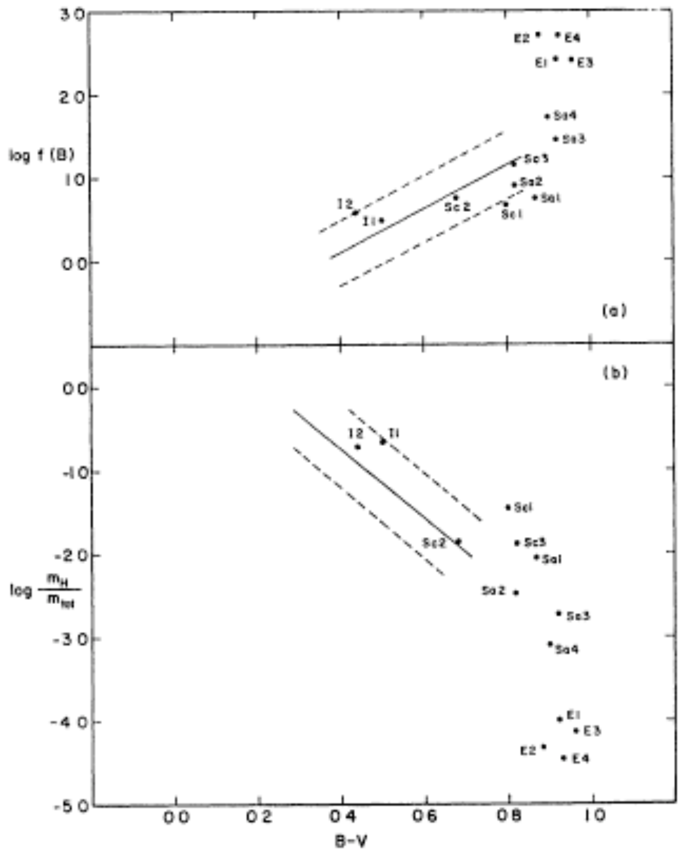


FIG. 3.—Relations between color and (*a*) mass-to-light ratio in *B* light (solar units), and (*b*) fract of total mass in hydrogen gas, for observed galaxies and computed galaxies at 12 × 10⁹ years. Solid li are the mean linear relations of Holmberg (1964), and broken lines indicate the range of values he served. Points for computed galaxies are numbered as in Table 3.

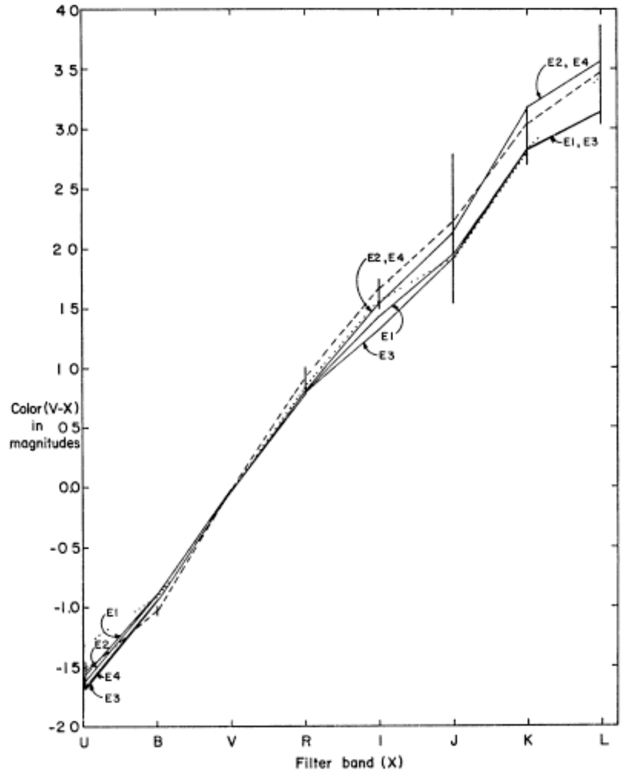


FIG. 4.—Colors of observed E and S0 galaxies and computed galaxies at 12 × 10⁹ years. The broken line is the mean of 5 E galaxies observed by Johnson (1966*a*), and vertical lines show the ranges observed. Solid lines show computed galaxy colors, the sequences being numbered as in Table 3. The dotted line shows de Vaucouleurs' (1966) reduction of Johnson's data.

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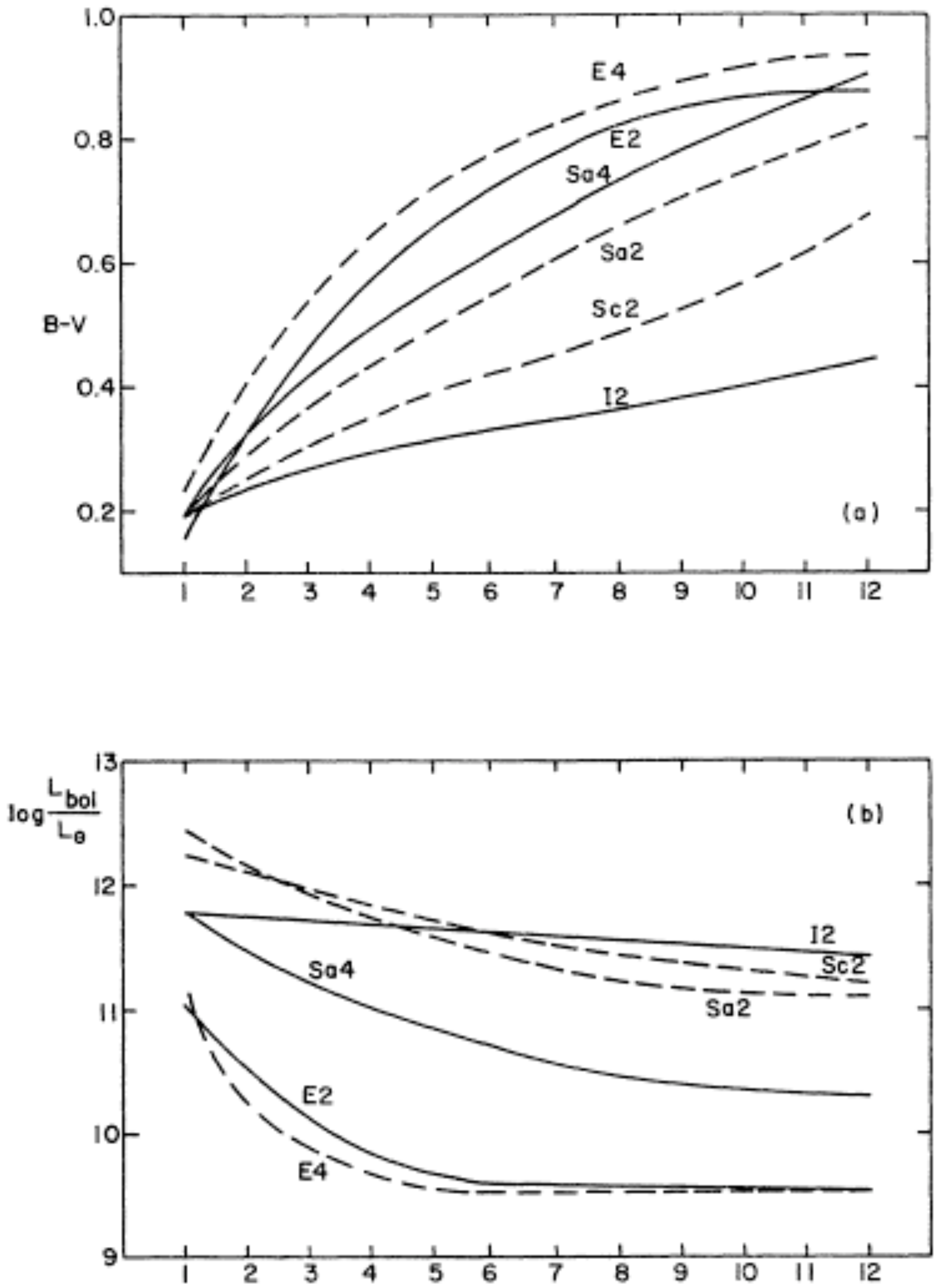

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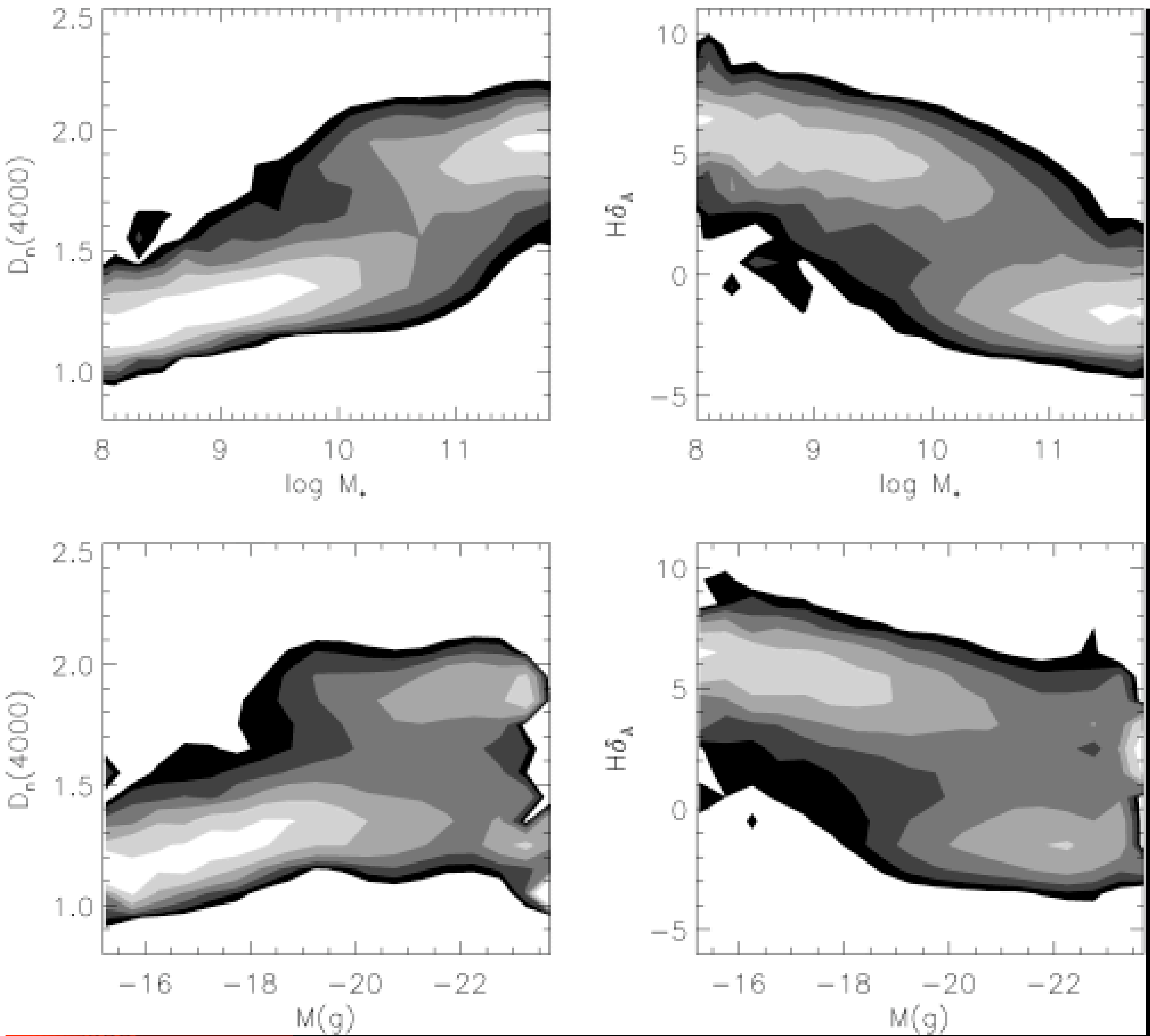
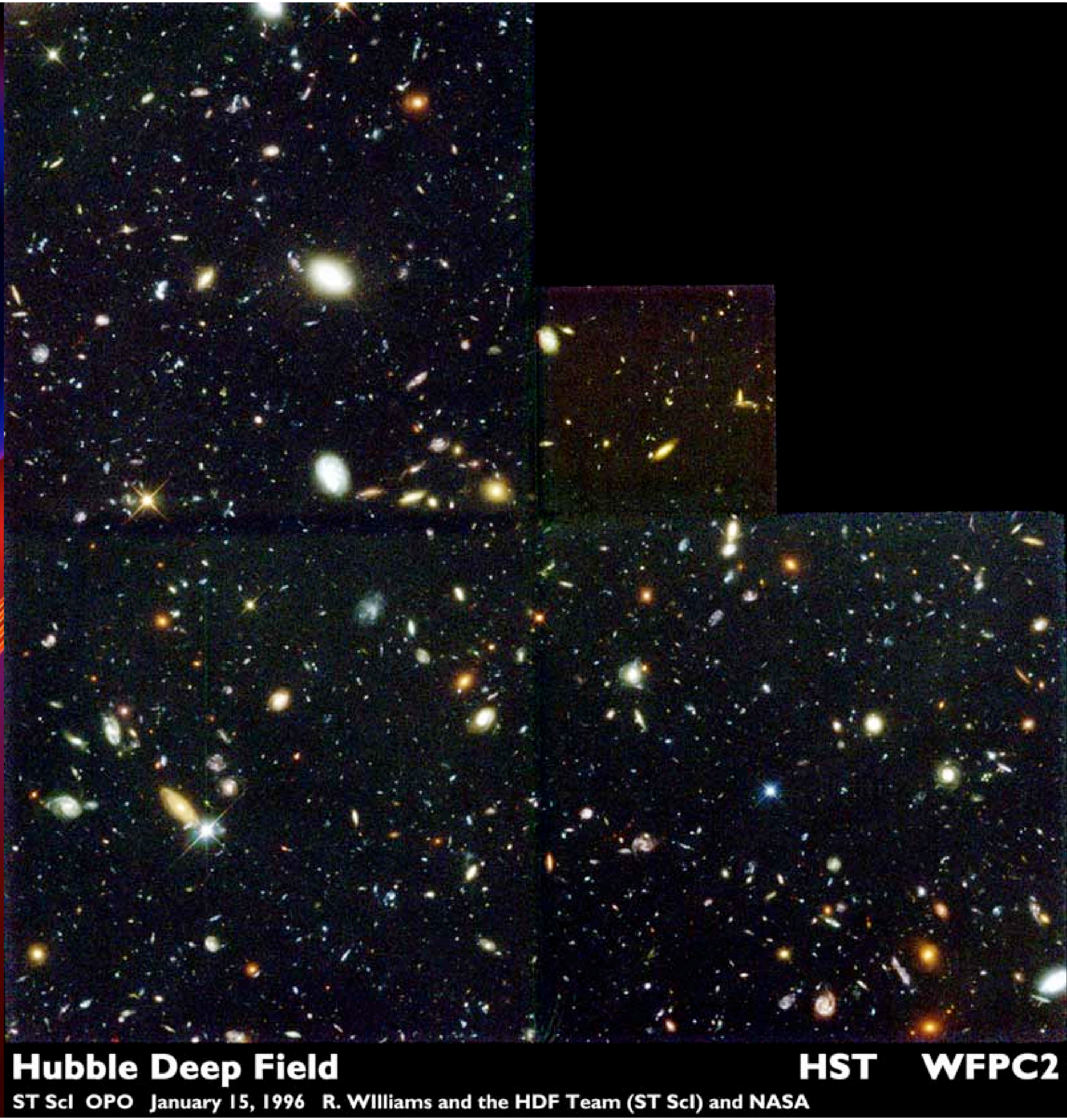
Some selected landmarks since

- Morphology-Density relation (1980)
- CFRS - first large-scale high-z survey
- HDF - galaxy evolution hits the big time; evolution of galaxy structures -- realisation that mergers are perhaps reasonably frequent
- 2dF / SDSS - a real low-z reference sample, has transformed Xgal astronomy
- Cluster cosmology --> SN --> WMAP



Kauffmann et al. 2003


Hubble Deep Field
HST WFPC2
ST ScI OPO January 15, 1996 R. Williams and the HDF Team (ST ScI) and NASA

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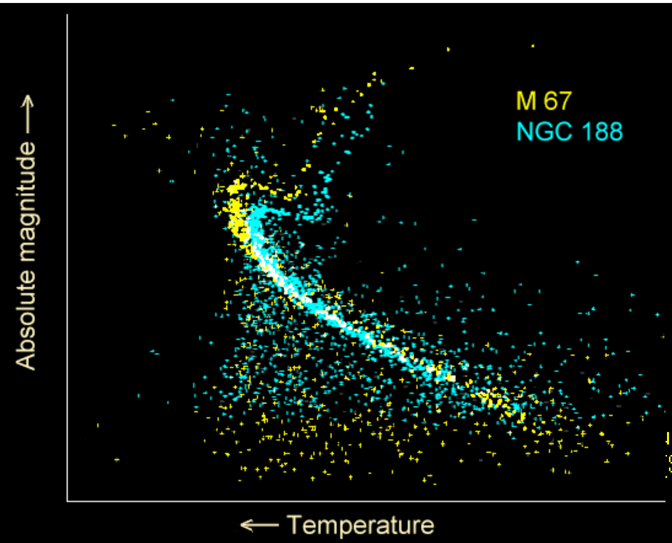
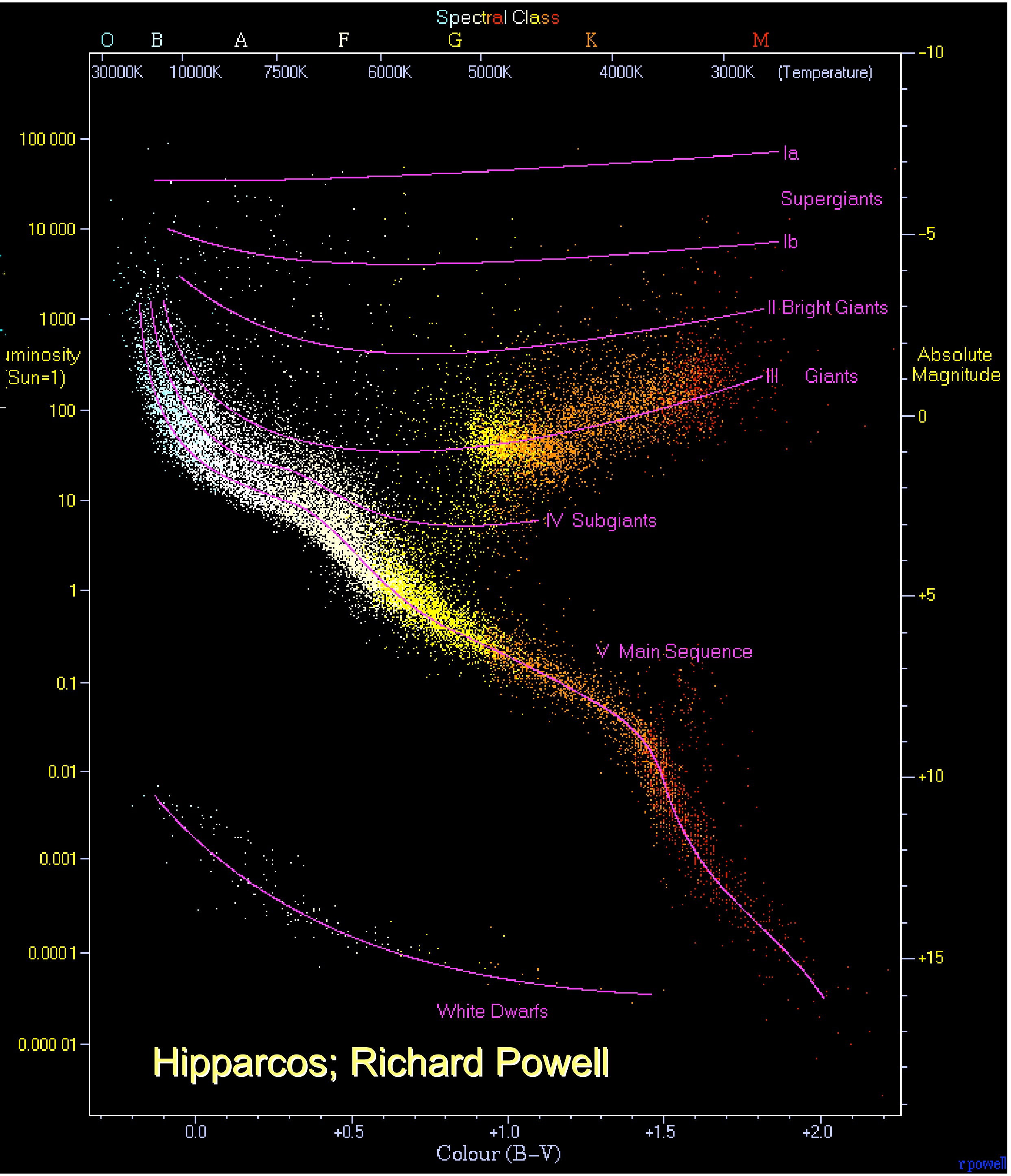
Introduction to Galaxies
Basic approaches

Approaches

- Archaeology
  - Formation history on an object-by-object basis
- Systematic study of the population, and its evolution (census / lookback)
  - Watch populations change
- `Experiments'
  - Study of controlled samples where you try to isolate effects of one quantity on another
  - E.g., star formation law, dust properties as a function of excitation/metallicity, etc.





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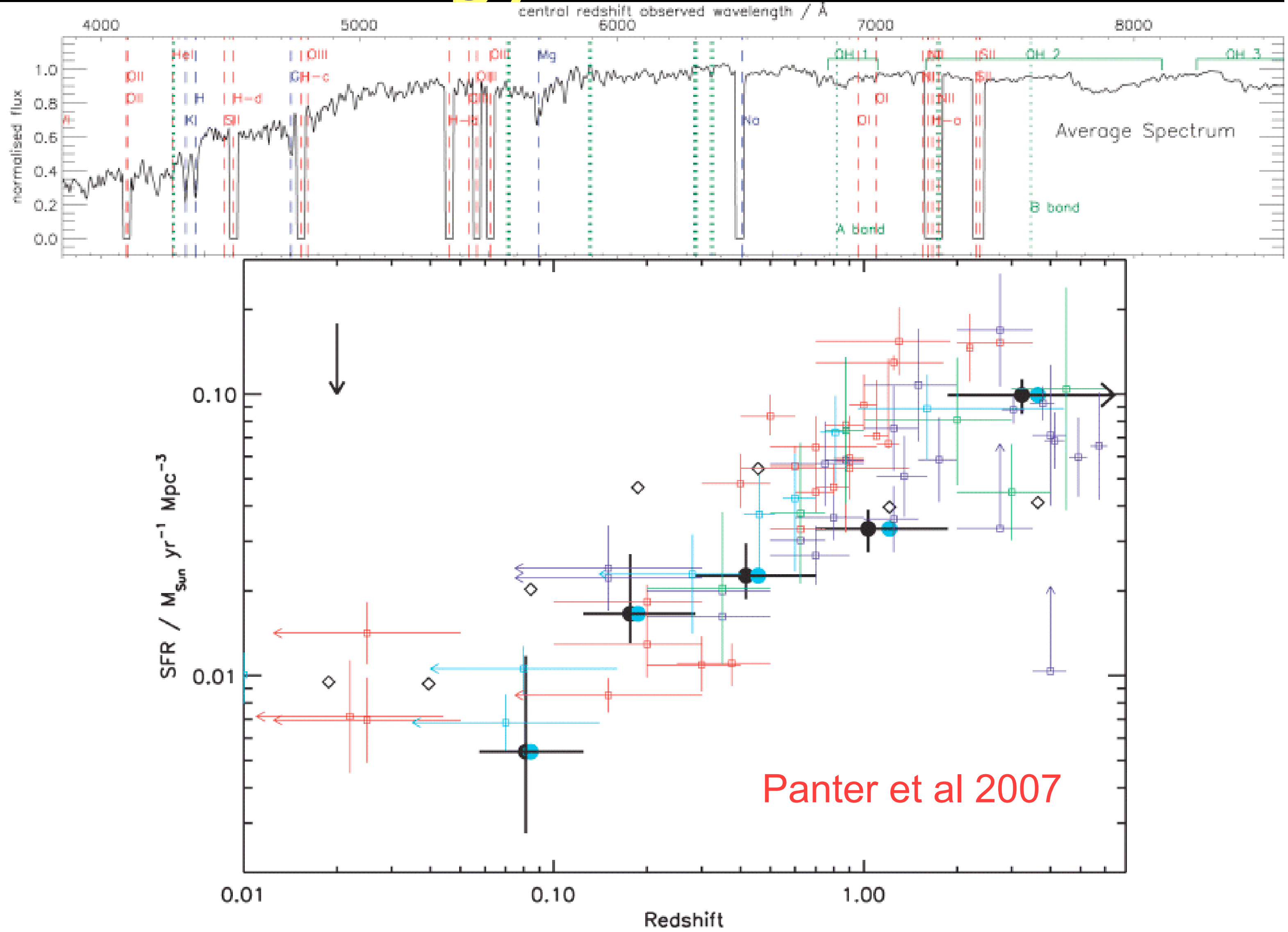
Archaeology II



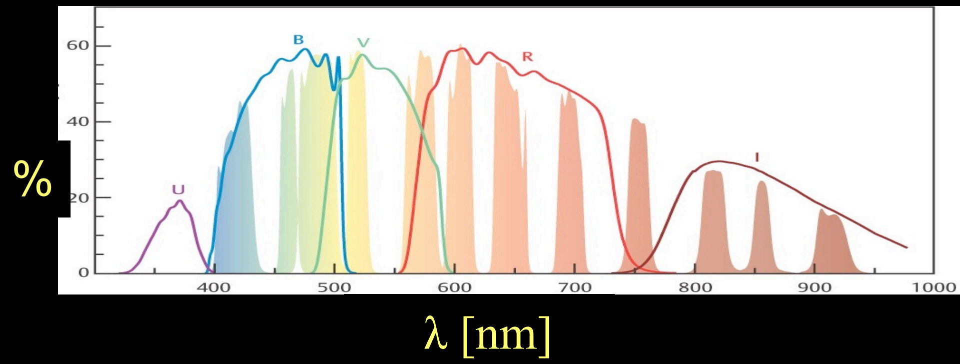
Introduction
Disk Evolution
  Look-back
  SFR
  Mass
  Mergers
  Summary
Stellar Halo
Summary
Challenges

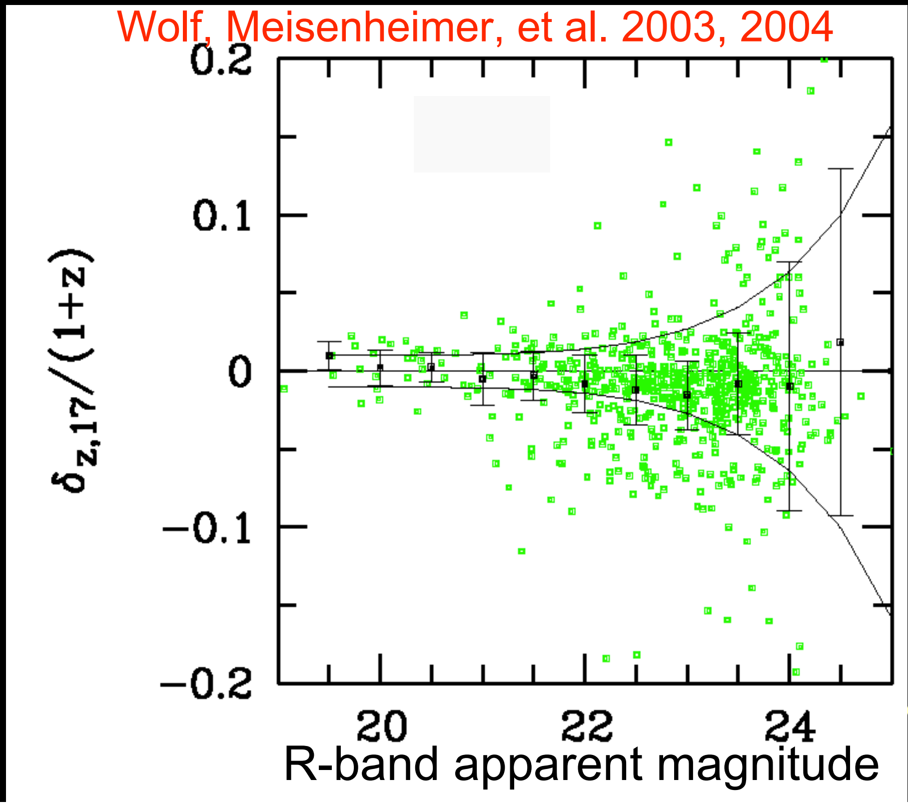
COMBO-17 and GEMS...

3 x ¼ square degree
Yields ~ 25000 galaxies
with ∂z/(1+z) ~ 0.02
99% complete

Optical only → z<1 only
Magnitudes and rest-frame colors accurate to ~0.1 mag

Angular resolution 0.7”
for the deep R-band images
  = 5kpc at z~0.7





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Physics…

- Star formation threshold
  - SFR surface density as a function of gas surface density
- Kennicutt 1989

694 KENN

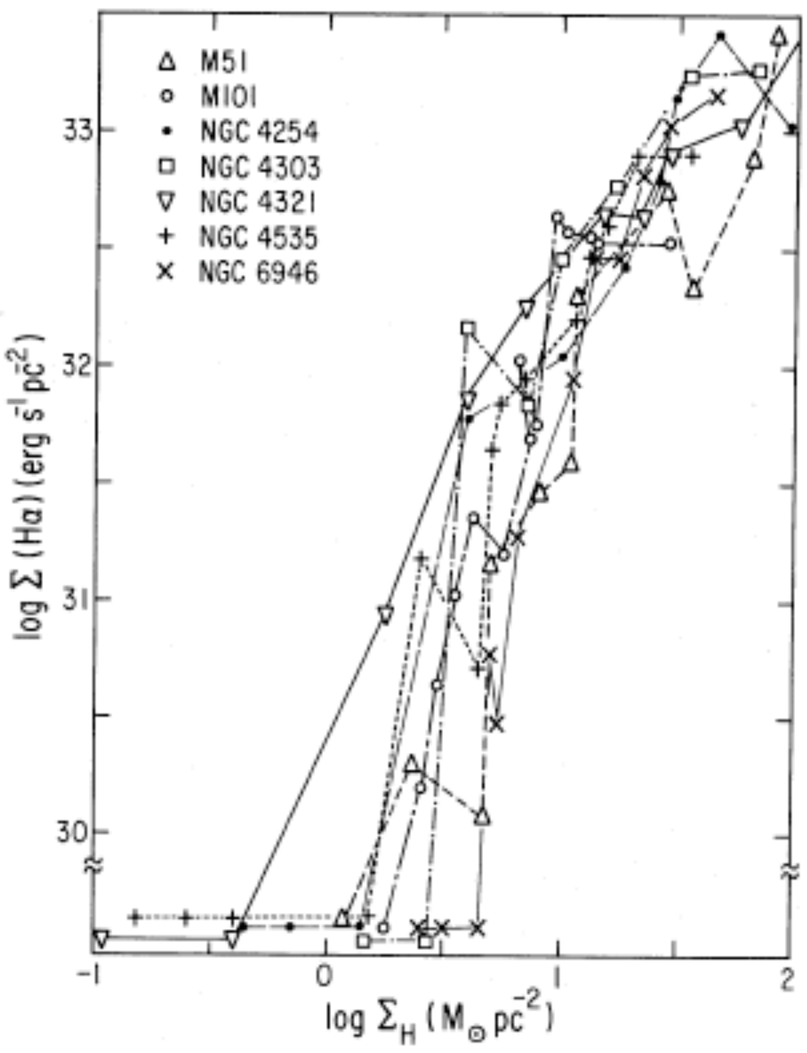

FIG. 8.—Dependence of Hα surface brightness on total (H I + H_2) hydrogen surface density, for seven giant Sc galaxies. Each point represents the Hα and gas densities averaged at a given galactocentric radius, and lines connect points at adjacent radii. The points at the bottom denote regions where no Hα emission was detected.

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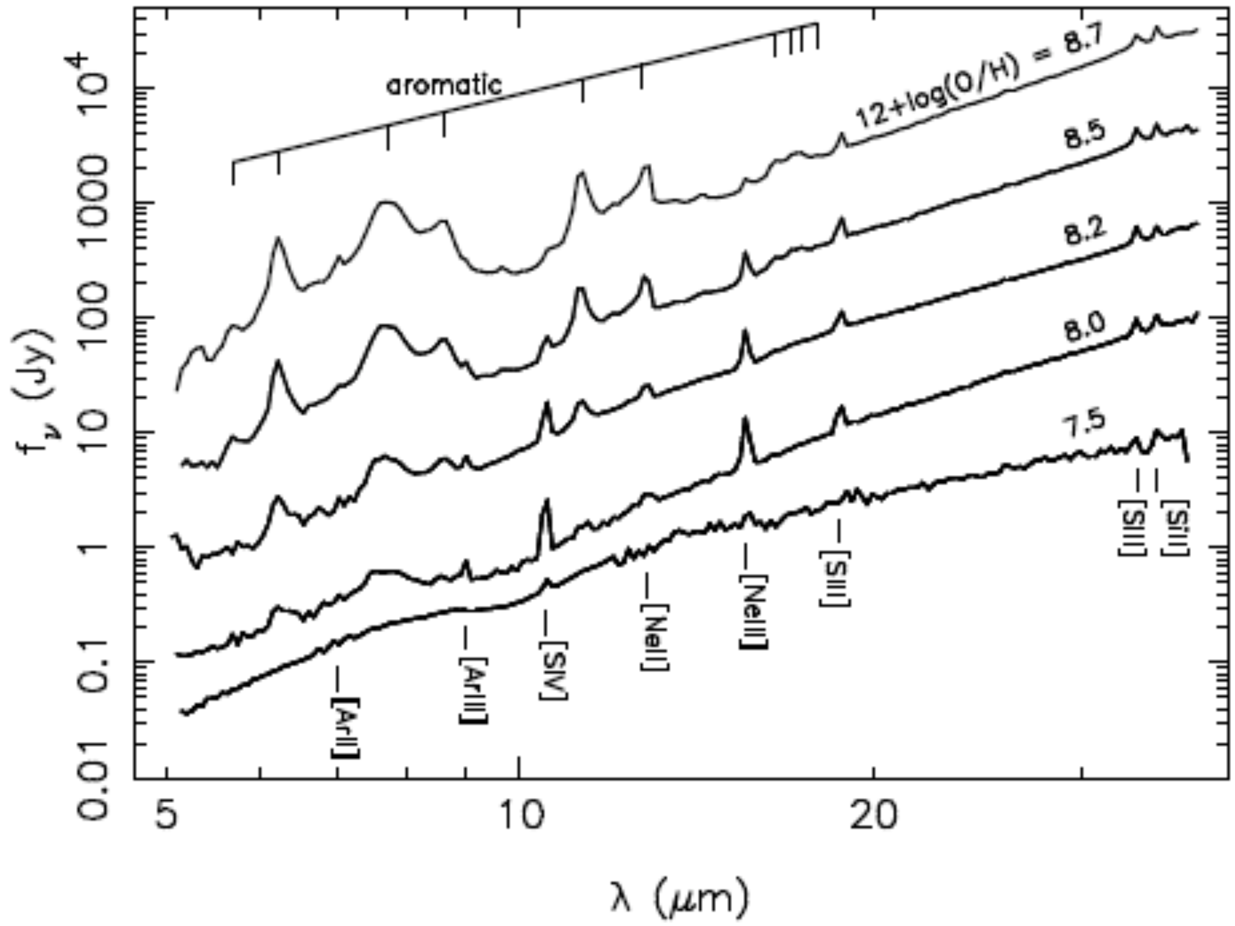

FIG. 8.— Spectra binned according to metallicity. From bottom to top, the average metallicity [12 + log(O/H)] is 7.5, 8.0, 8.2, 8.5, 8.7. The spectra were normalized at 10 μm and shifted for display purposes.

Engelbracht et al 2008

Introduction to galaxies

- Galaxies are baryonic residue in center of DM halo
- Stellar + cold gas MF =/= DM MF and…
- Most baryons warm/hot (not in gals)
  - why?
- Astonishing regularity, but….
- Galaxy formation complex
  - Dark matter halo formation + growth (merging)
  - Gas collapse and cooling
  - Star formation, coupling of energy and mass --> IGM

Introduction to galaxies II

- Key historical landmarks in galaxy evolution…
  - CMB, Helium --> Big Bang
  - Discovery of dark matter
  - Realisation that galaxies evolve
  - Dark matter mass function =/= gal. mass function
    - Central importance of feedback

Introduction to galaxies III

- Three main approaches
  - Census of galaxies; Look-back surveys (cataloging entire populations, and watching them change)
  - Archaeology (trying to figure out history of individual objects)
  - Physics