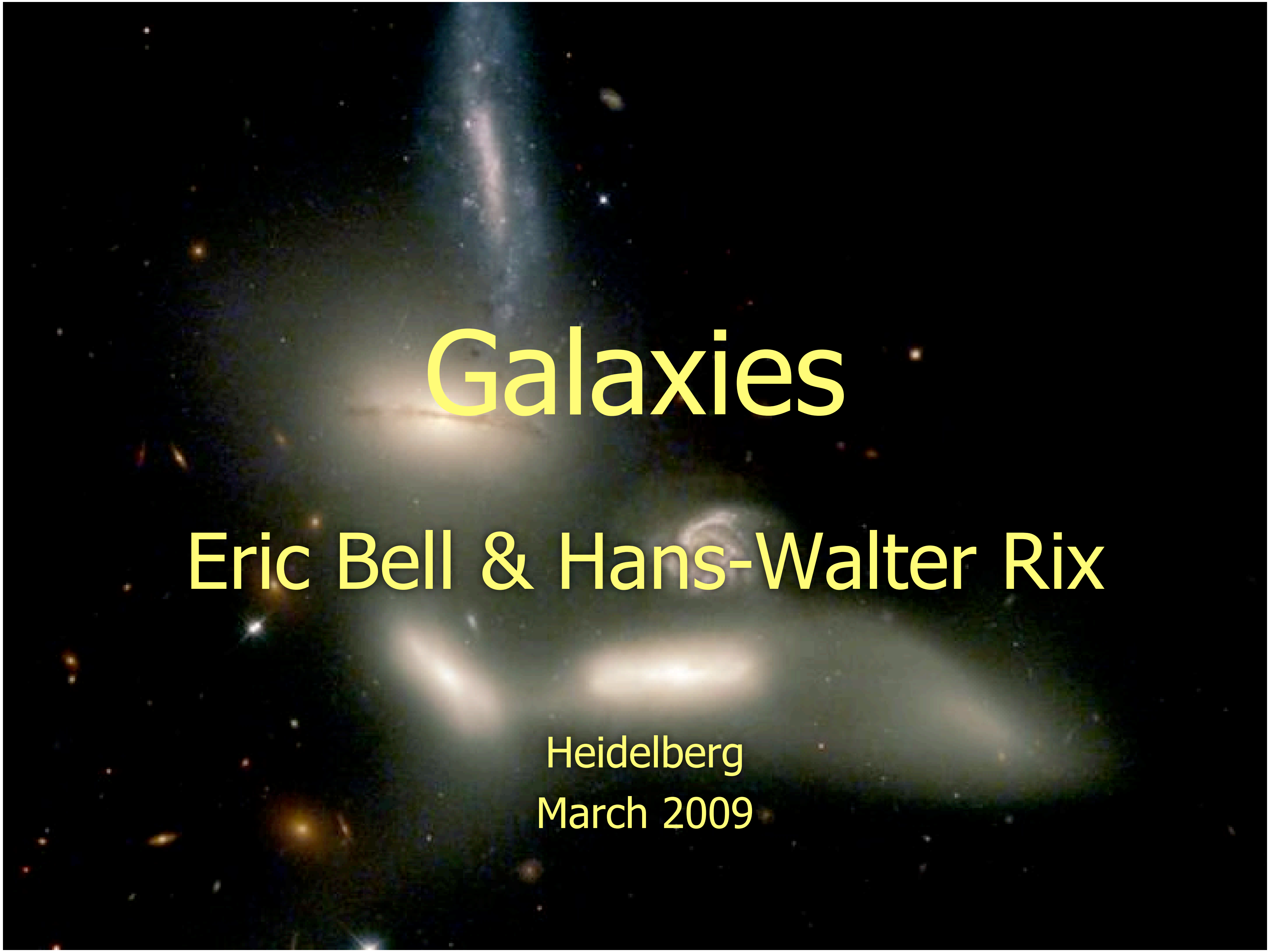


Galaxies

Eric Bell & Hans-Walter Rix

Heidelberg

March 2009

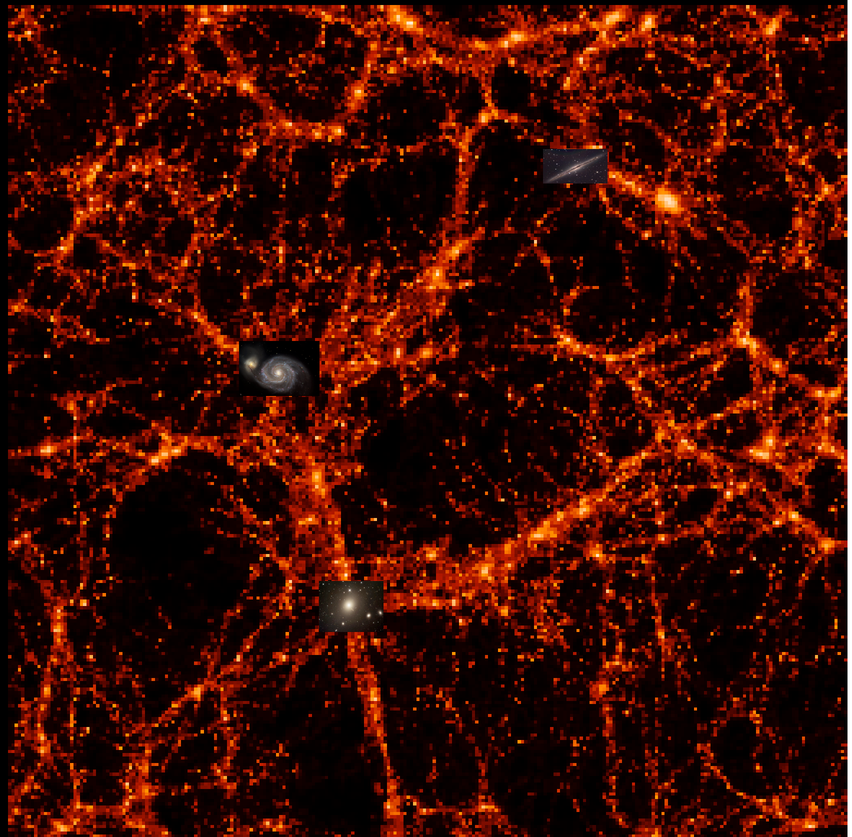

Introduction to Galaxies
Key concepts

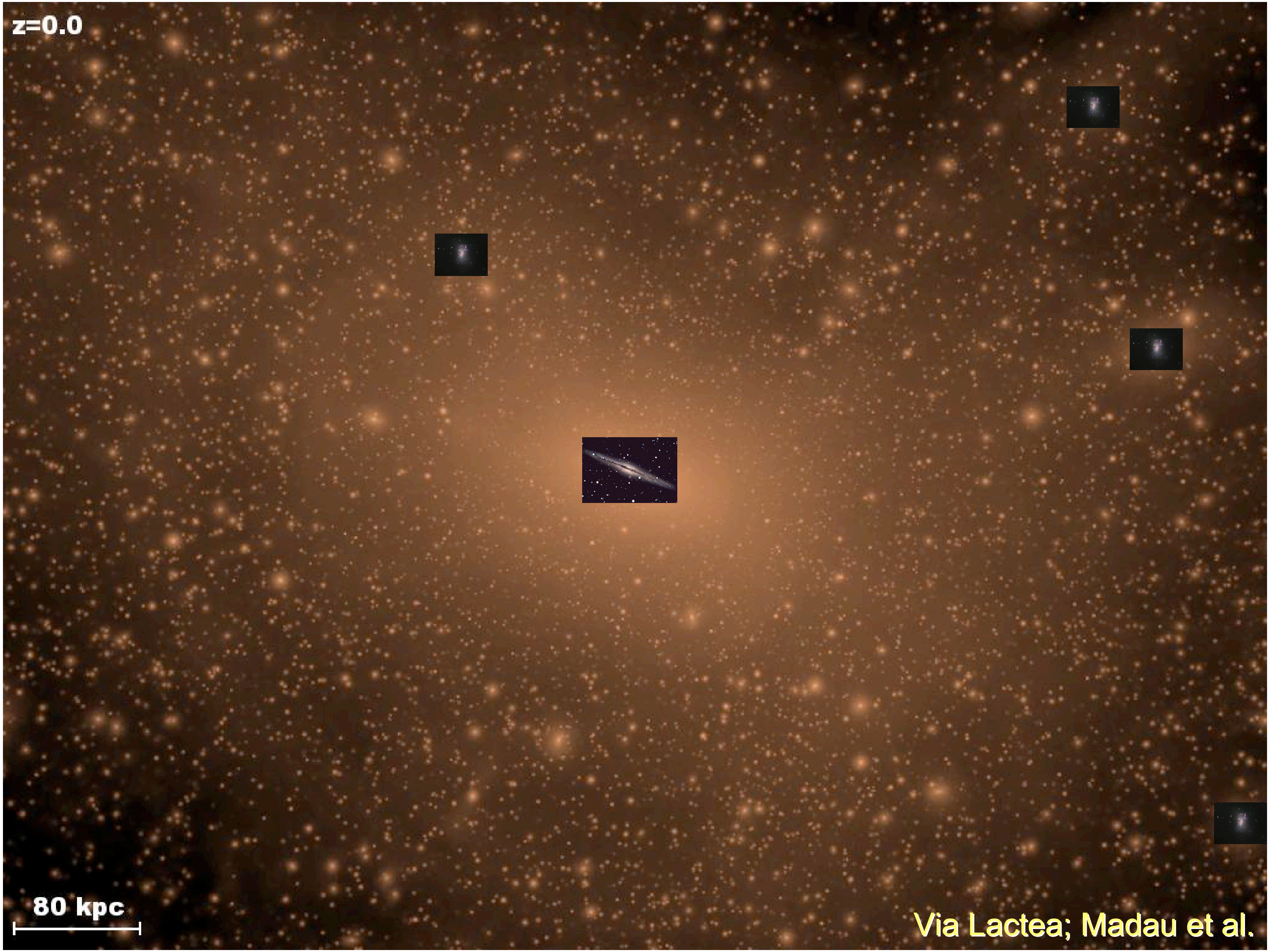
Galaxies - what are they?

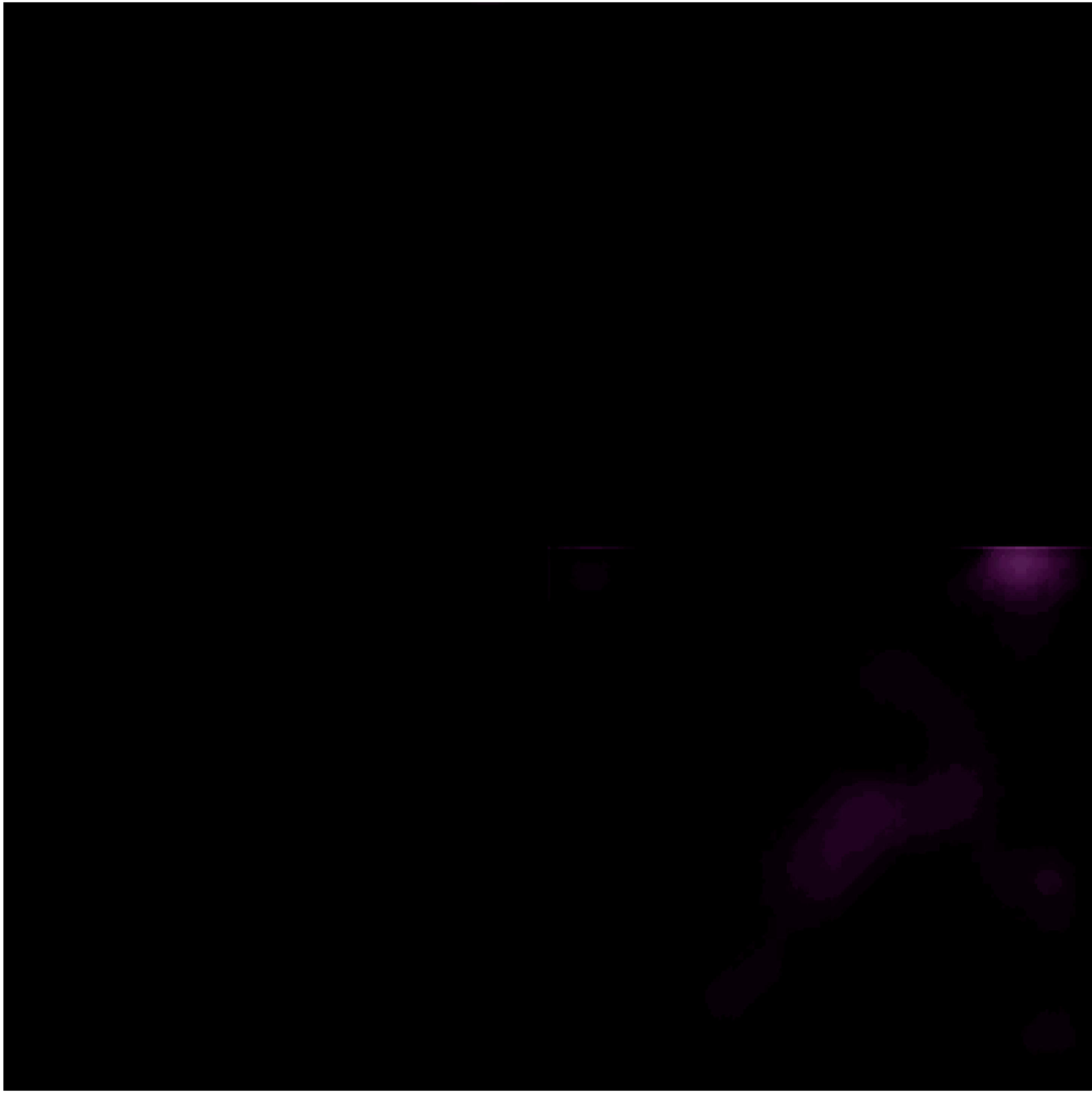
1) Overdense, grav. bound collections of stars and gas

Galaxies - what are they?

2) 'Condensates' of normal matter at the centers of much larger dark matter halos
   - ~50x more dark matter than stars




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



Martin White

Cluster formation animation

Top left: gas

Top right: galaxies

Bottom left: SZ

Bottom right: X-ray

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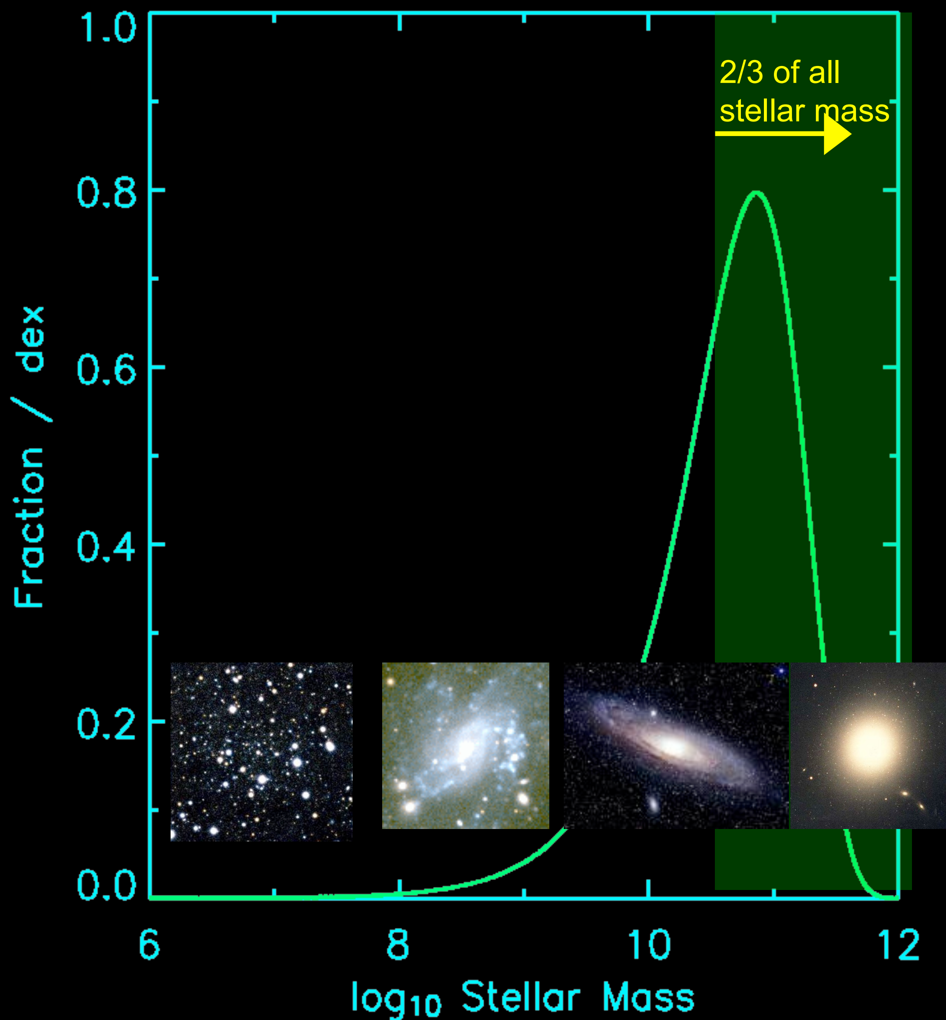
Galaxies have a range of masses…

Dark matter halo mass spectrum scale free (equal mass per log interval in mass)

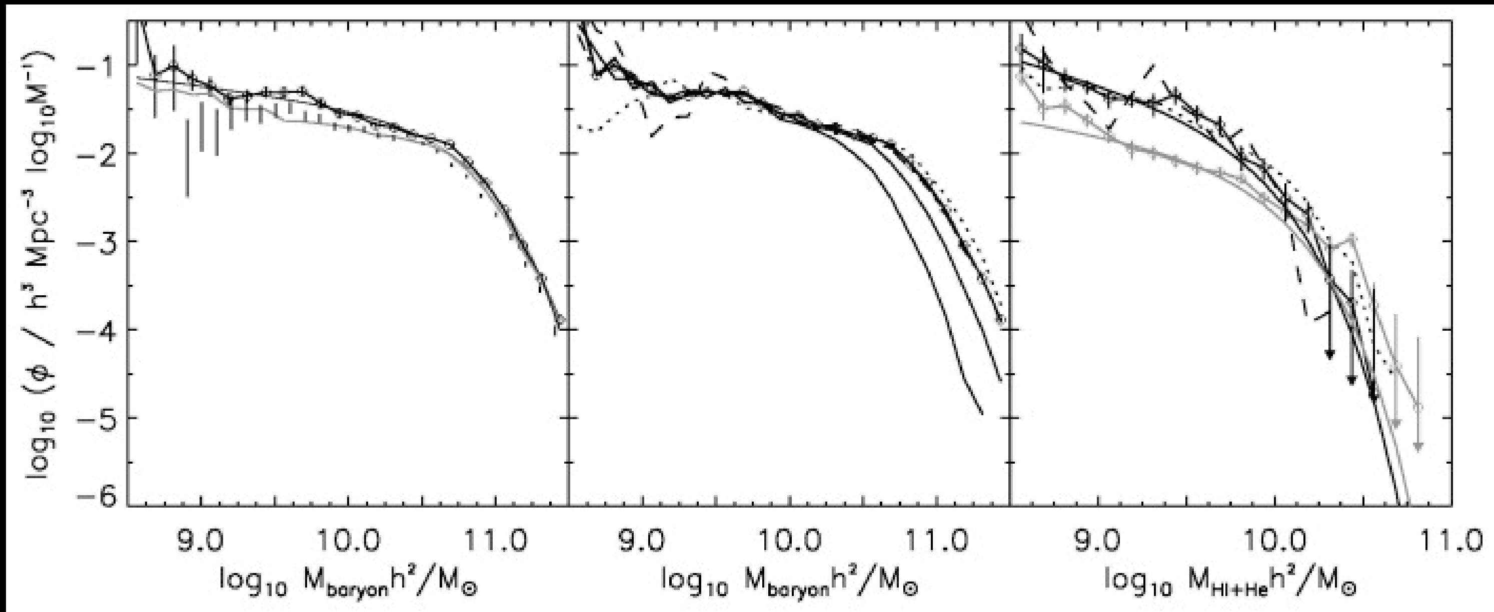
>x10^8 dynamic range in stellar mass

Most stars live in galaxies within x3 of $6x10^{10}M_{sun}$



Bell et al. 2003

Baryonic mass function



Bell et al. 2003

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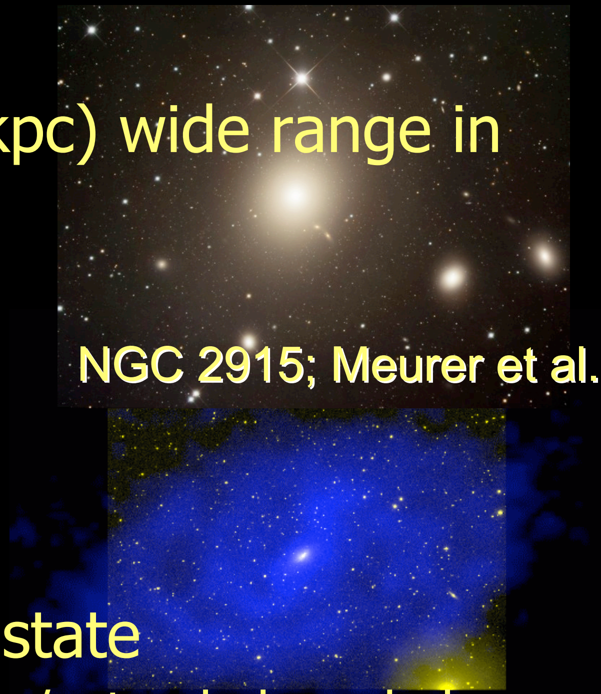
Galaxies and gas

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

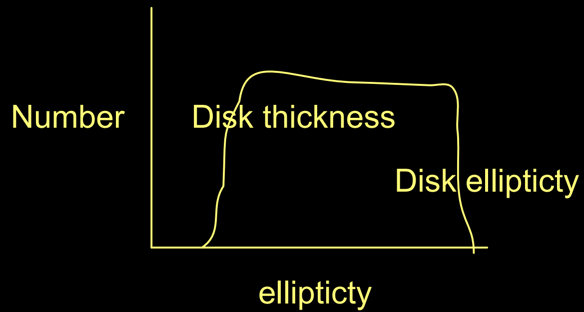


NGC 2915; Meurer et al.

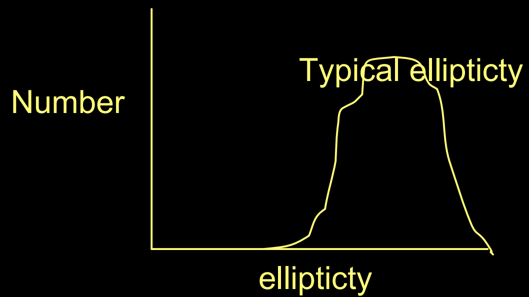
- BUT, most gas in warm/hot state
  - 80-90% of baryons in filaments/extended gas halos…
  - Can see this clearly in clusters; hard in lower-density environments (abs spectroscopy of high-ionisation species is required)

Galaxy structure

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



- Spheroids (lost/randomised this AM)

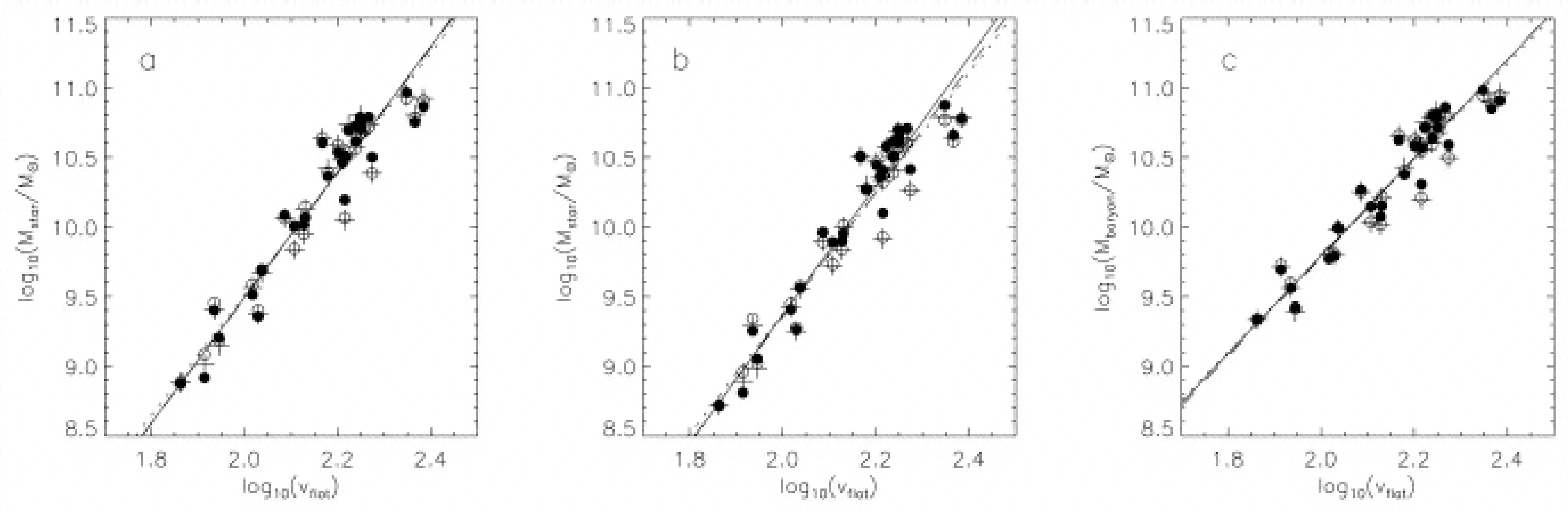


Astonishing regularity

- 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

Tully-Fisher relation

- Bell & de Jong 2001 (from Verheijen's thesis sample)



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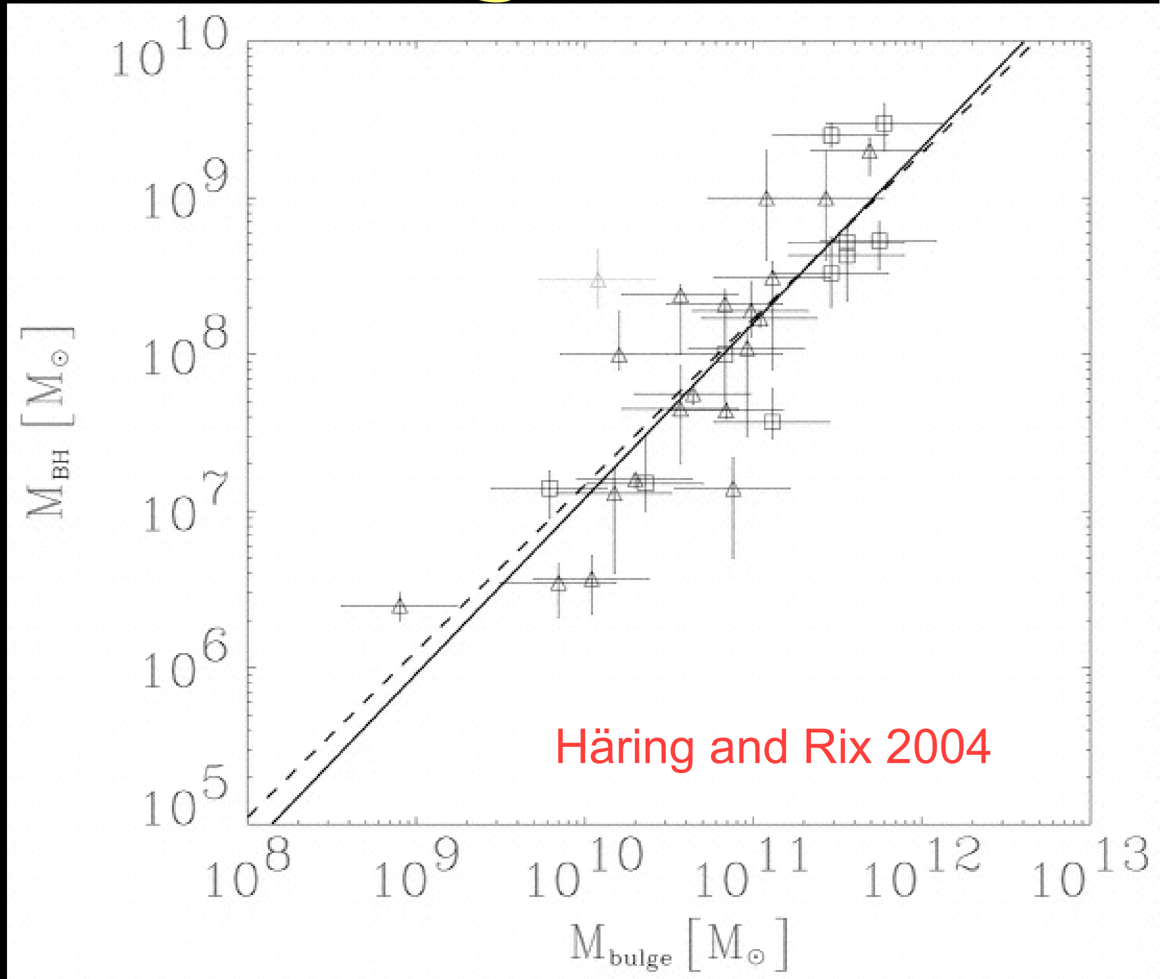
Black holes and galaxies…

Black hole mass-bulge mass correlation

Scatter <0.3 dex

Possibility of a link between bulge formation and BH formation



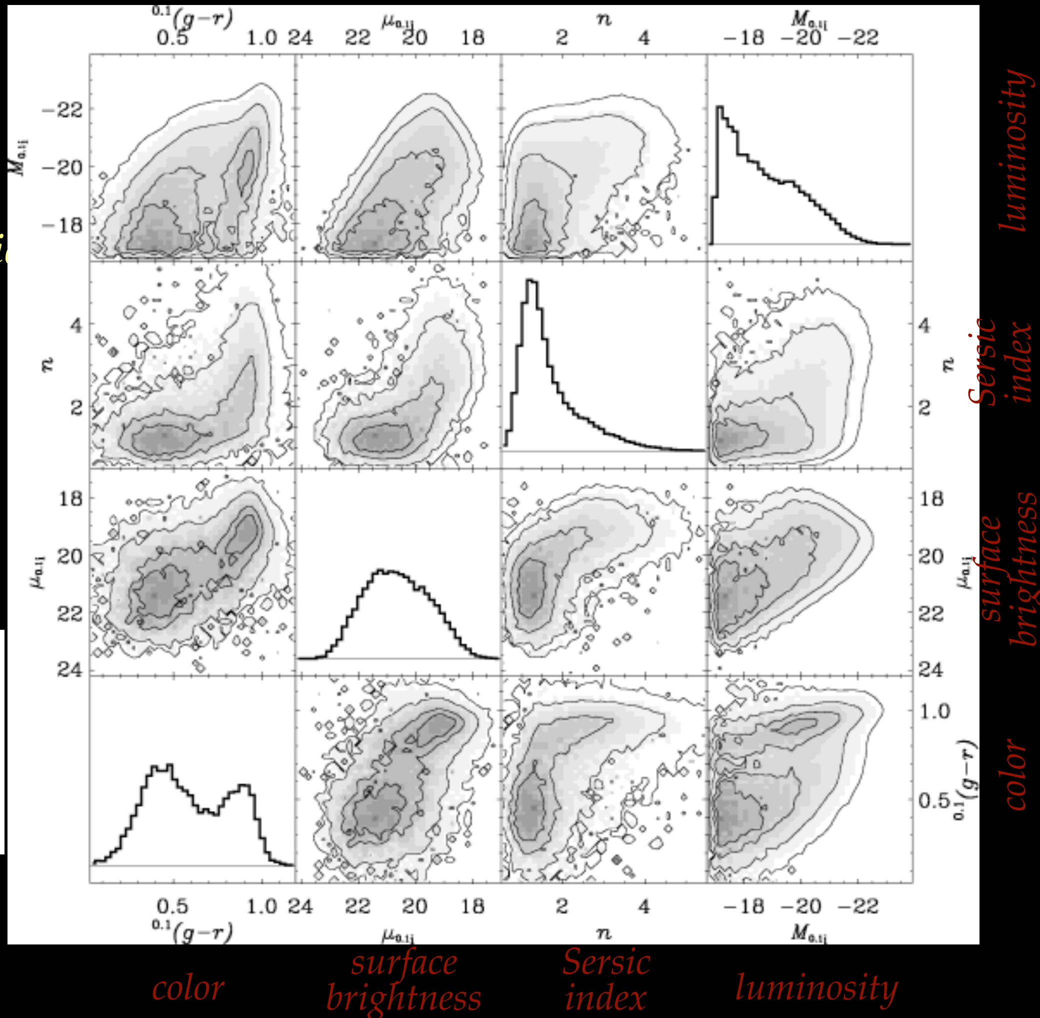
Gross galaxy properties

1. Choose properties which:
   a. *correlate with morphology*
   b. *SDSS can robustly measure*
   c. *simulations can hope to predi*

2. For example:
   d. *color*
   e. *surface brightness*
   f. *luminosity*
   g. *Sersic index (profile shape)*

$$I(r) = A \exp\left[-\left(\frac{r}{r_0}\right)^{1/n}\right]$$

3. Measure environment on 1 Mpc



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

- Feedback : all self-regulatory processes of galaxy formation
- Supernovae / Stellar winds --> outflow of hot, metal-enriched gas
- Possible AGN winds / feedback

Dynamics

- Gas : collisional
- Stars + DM : collisionless

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Galaxy formation

Dynamical assembly
history - a probe
largely of dark matter
= disks, conservation AM
= spheroids, mergers/int

z: 49.5

Star formation history -
a probe of the physics
of normal matter

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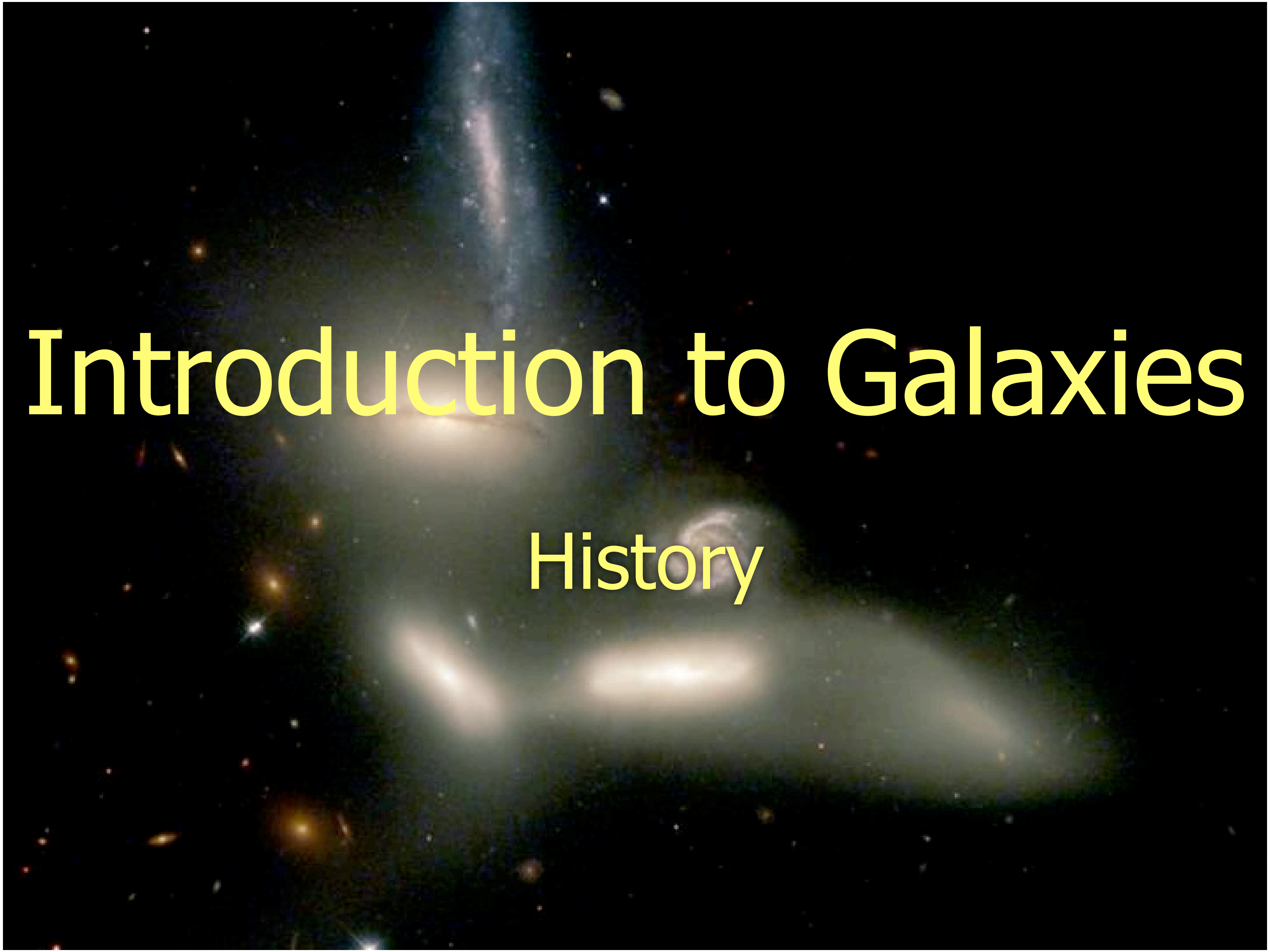
Matthias Steinmetz, AIP

Eric Bell

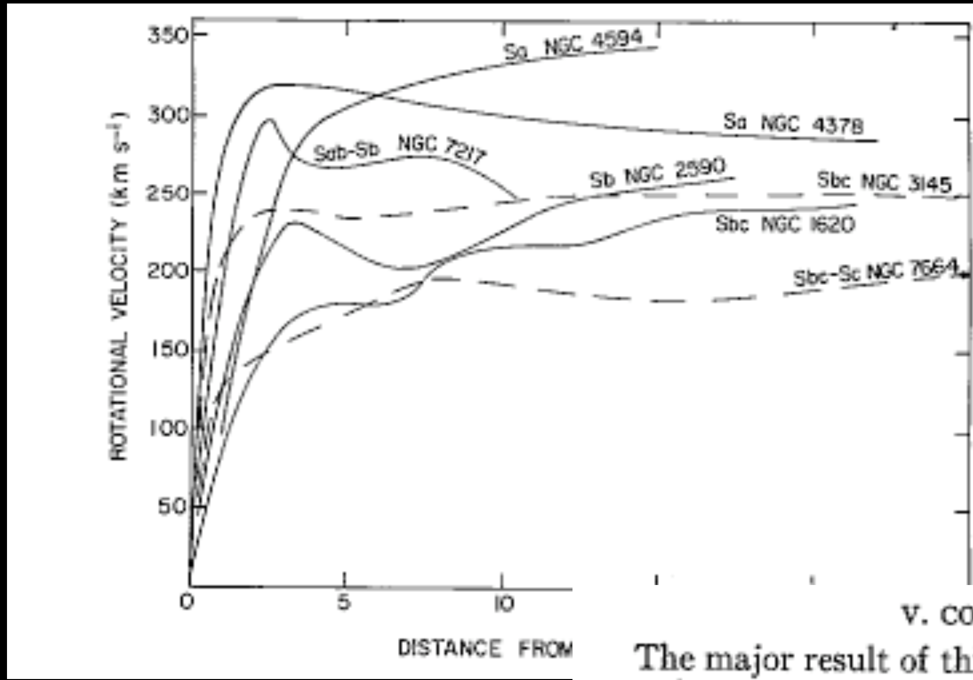


Introduction to Galaxies

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

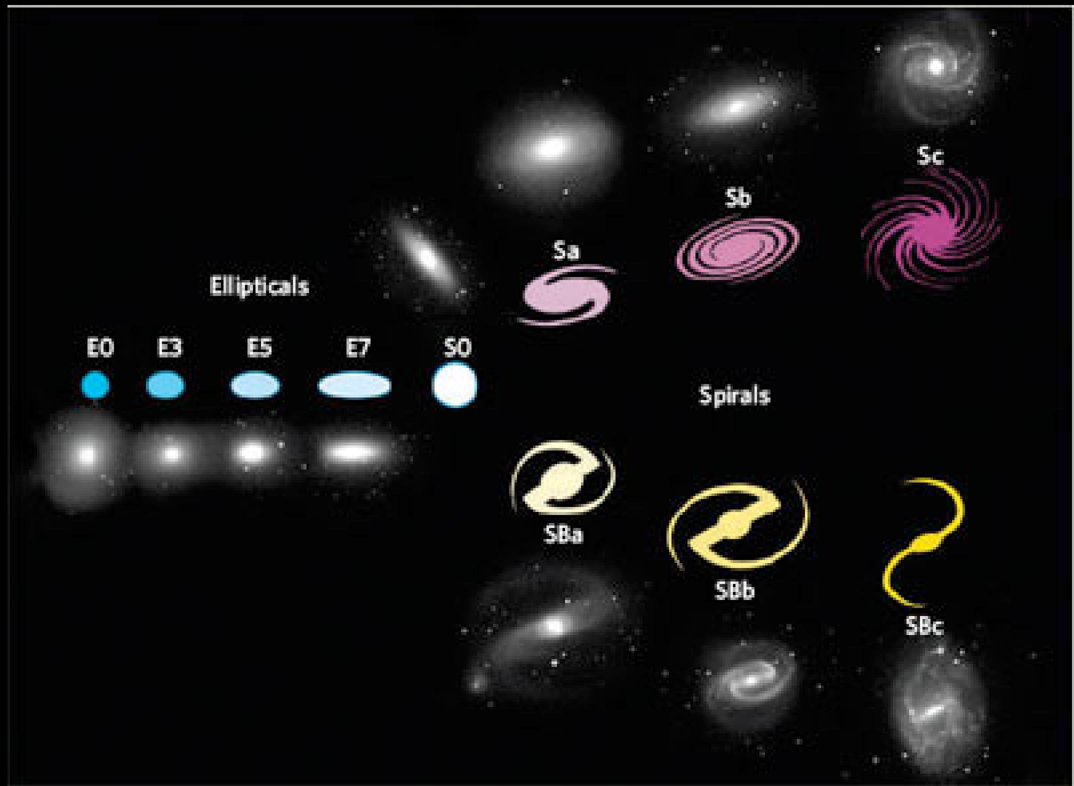


Rubin et al. 1978

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.

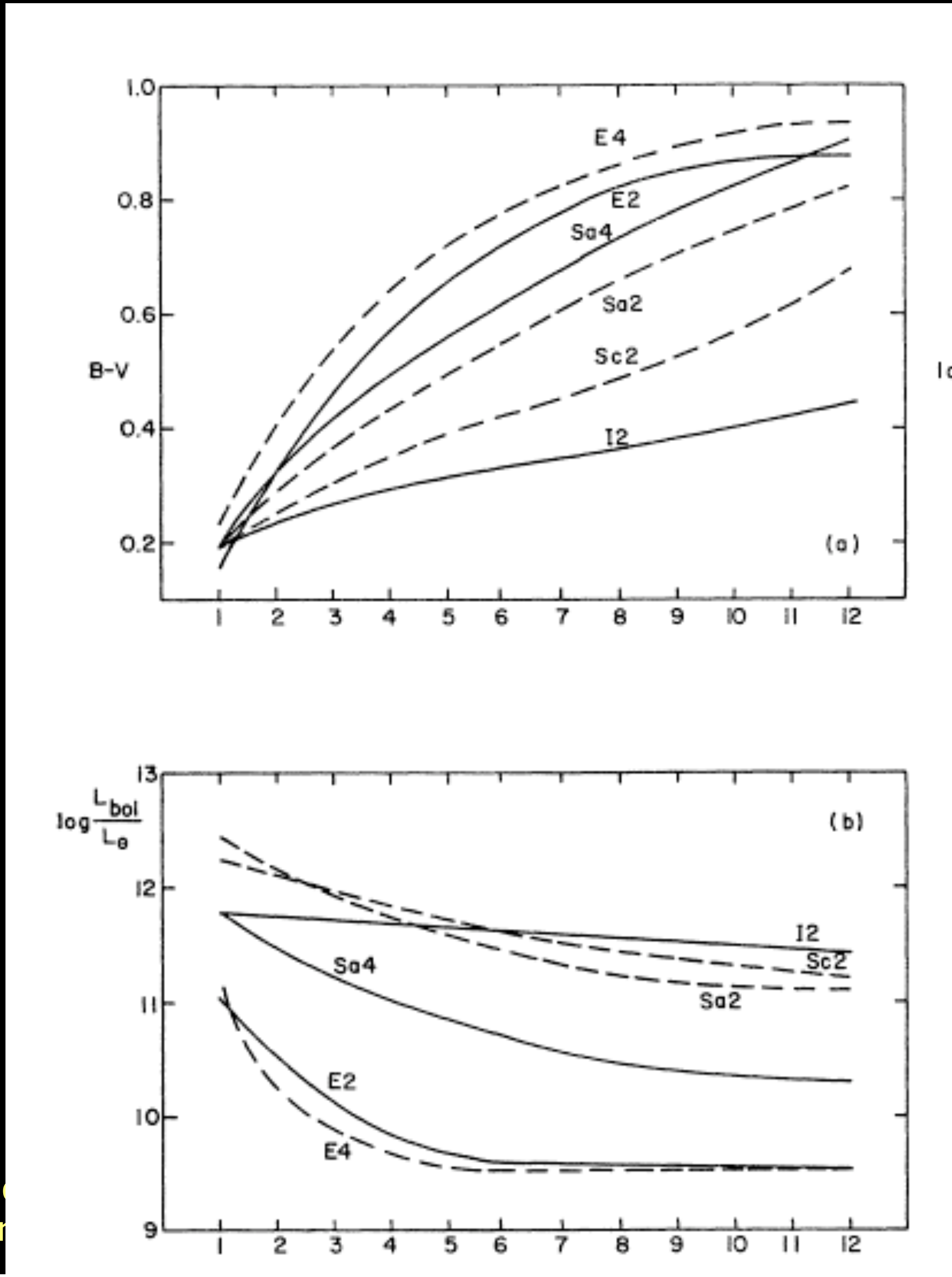
Hubble sequence



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.



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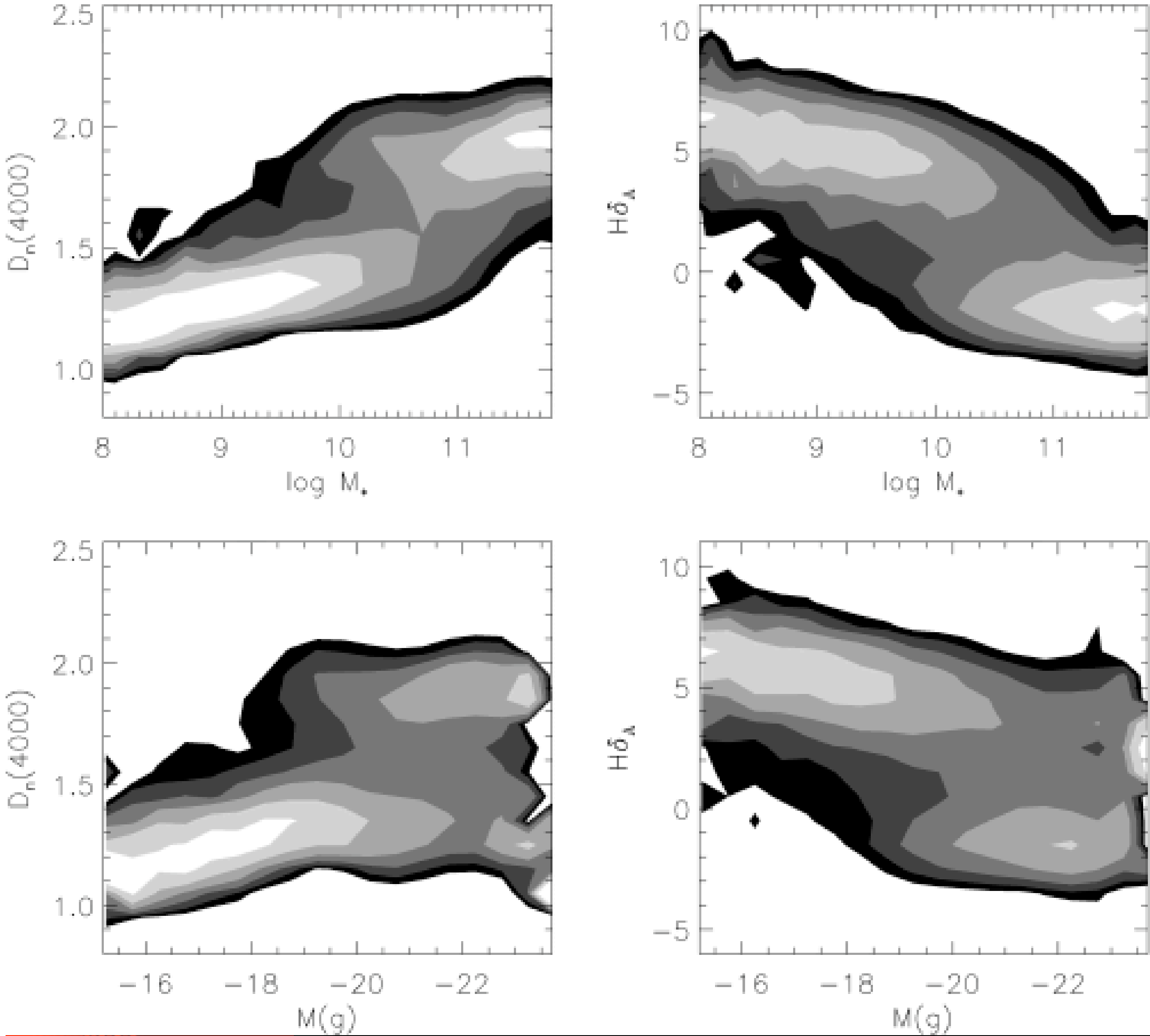
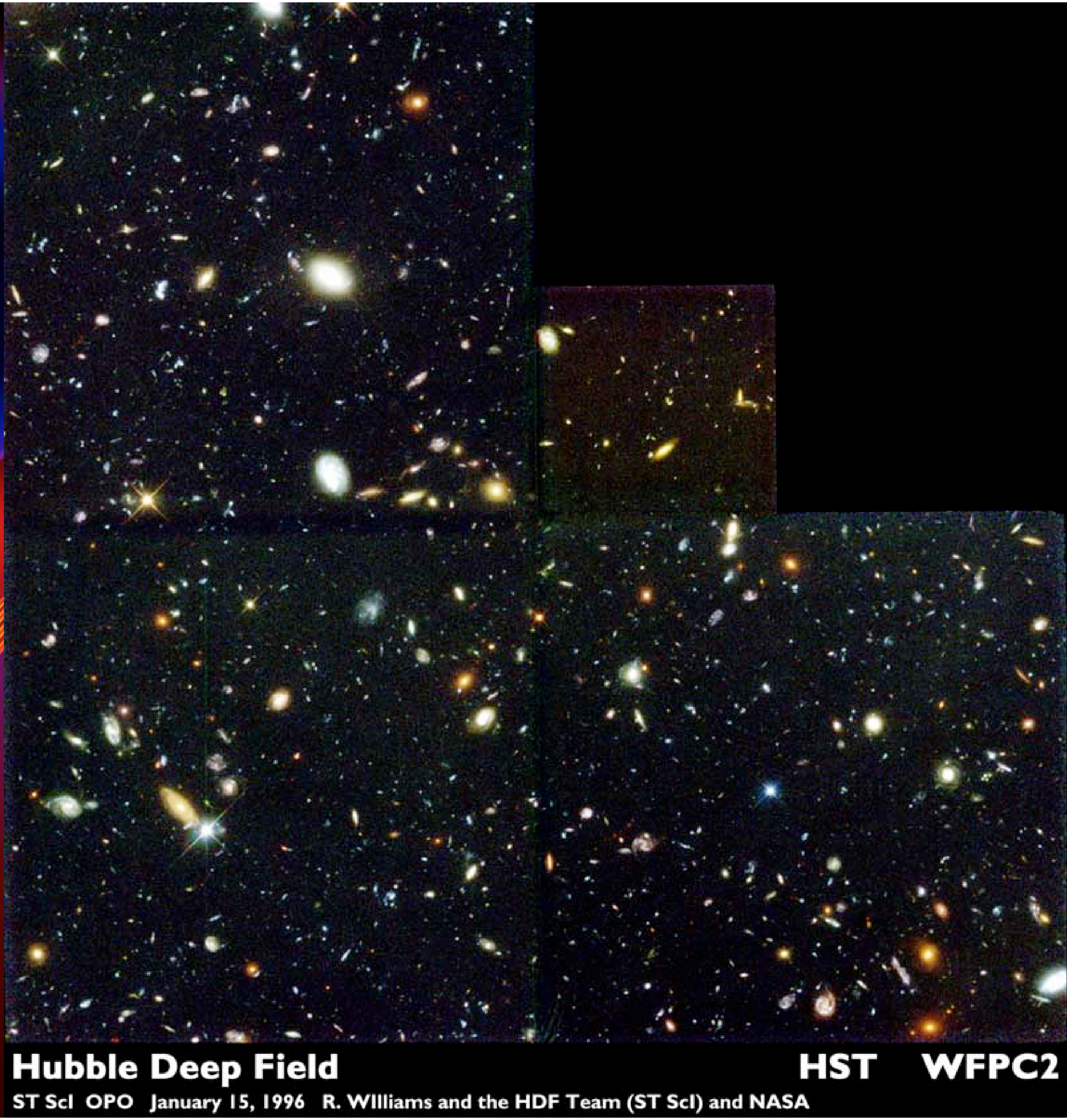
Some selected landmarks since

- 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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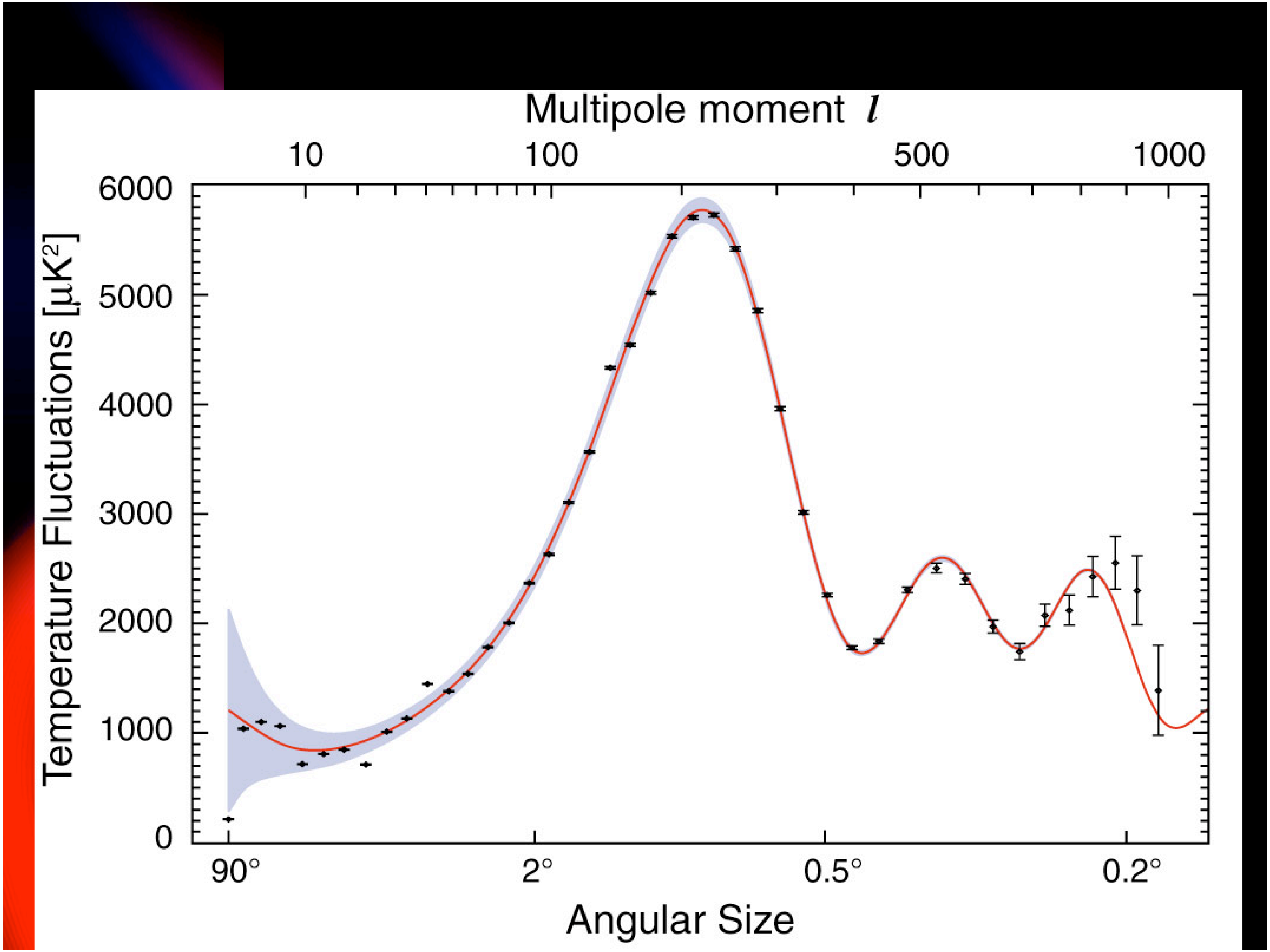


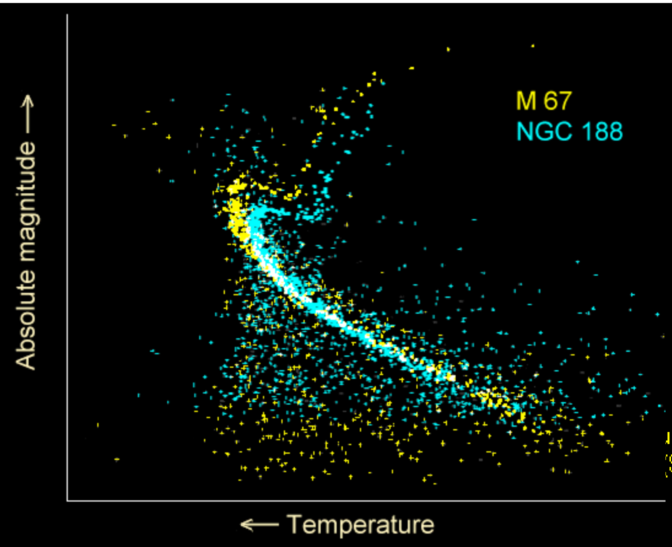
Multipole moment l
10
100
500
1000
6000
5000
4000
3000
2000
1000
0
Temperature Fluctuations [μK²]
90°
2°
0.5°
0.2°
Angular Size

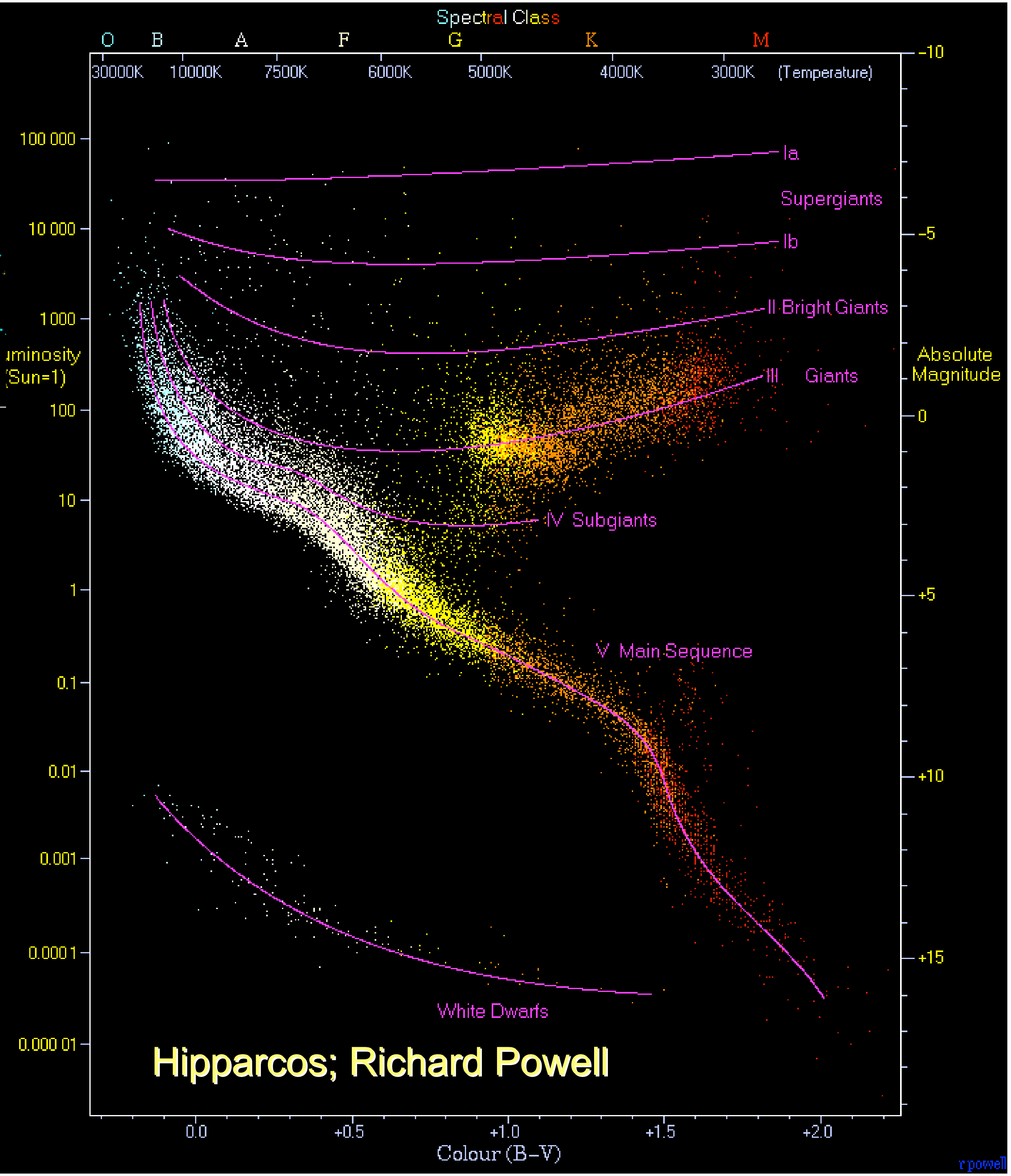
Introduction to Galaxies

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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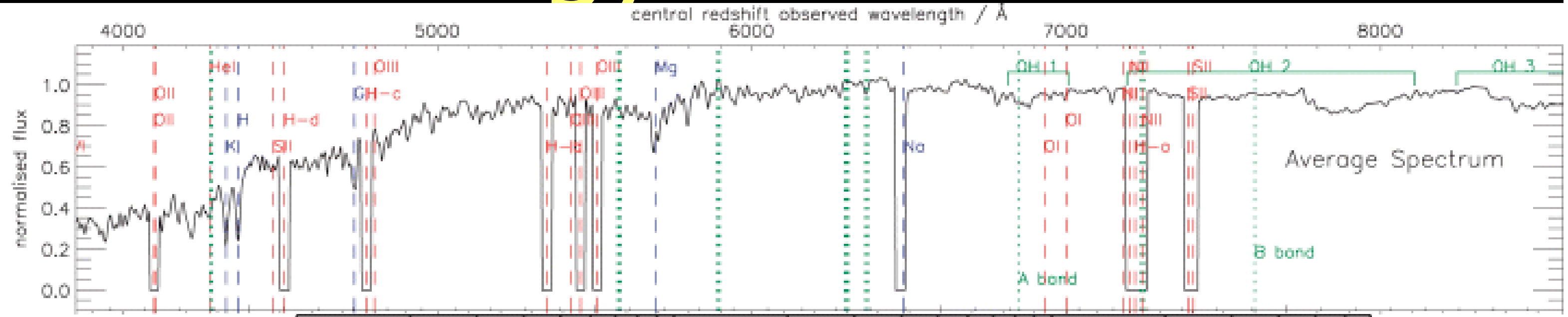
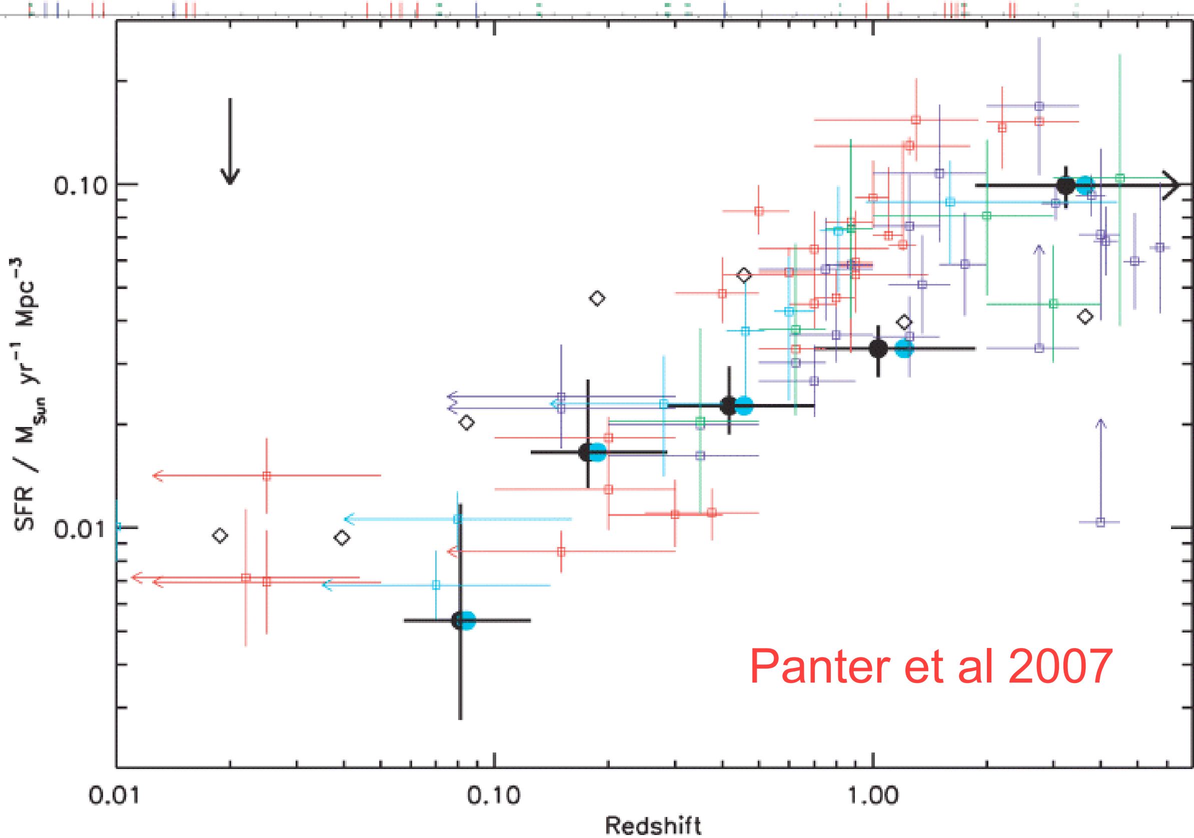
Archaeology II



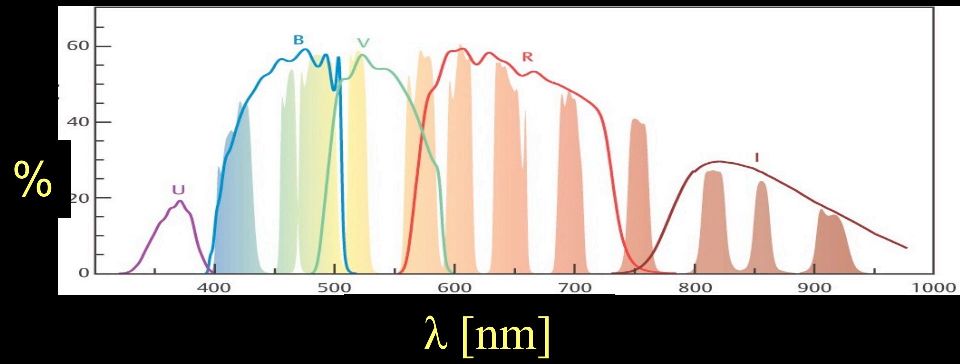


COMBO-17 and GEMS…

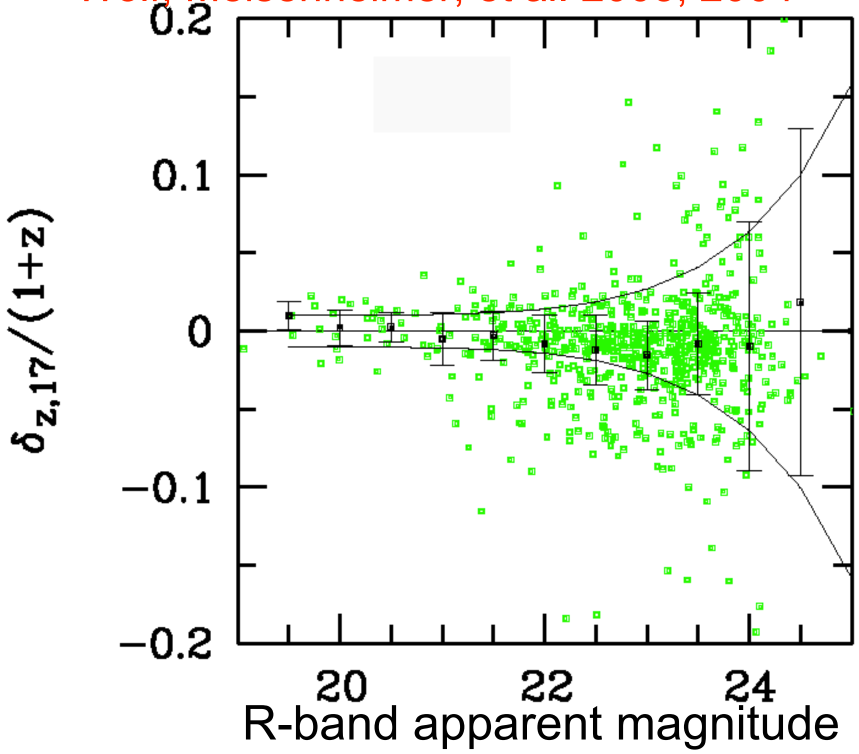
3 x ¼ square degree
Yields ~ 25000 galaxies
with $\partial z/(1+z) \sim 0.02$
99% complete

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

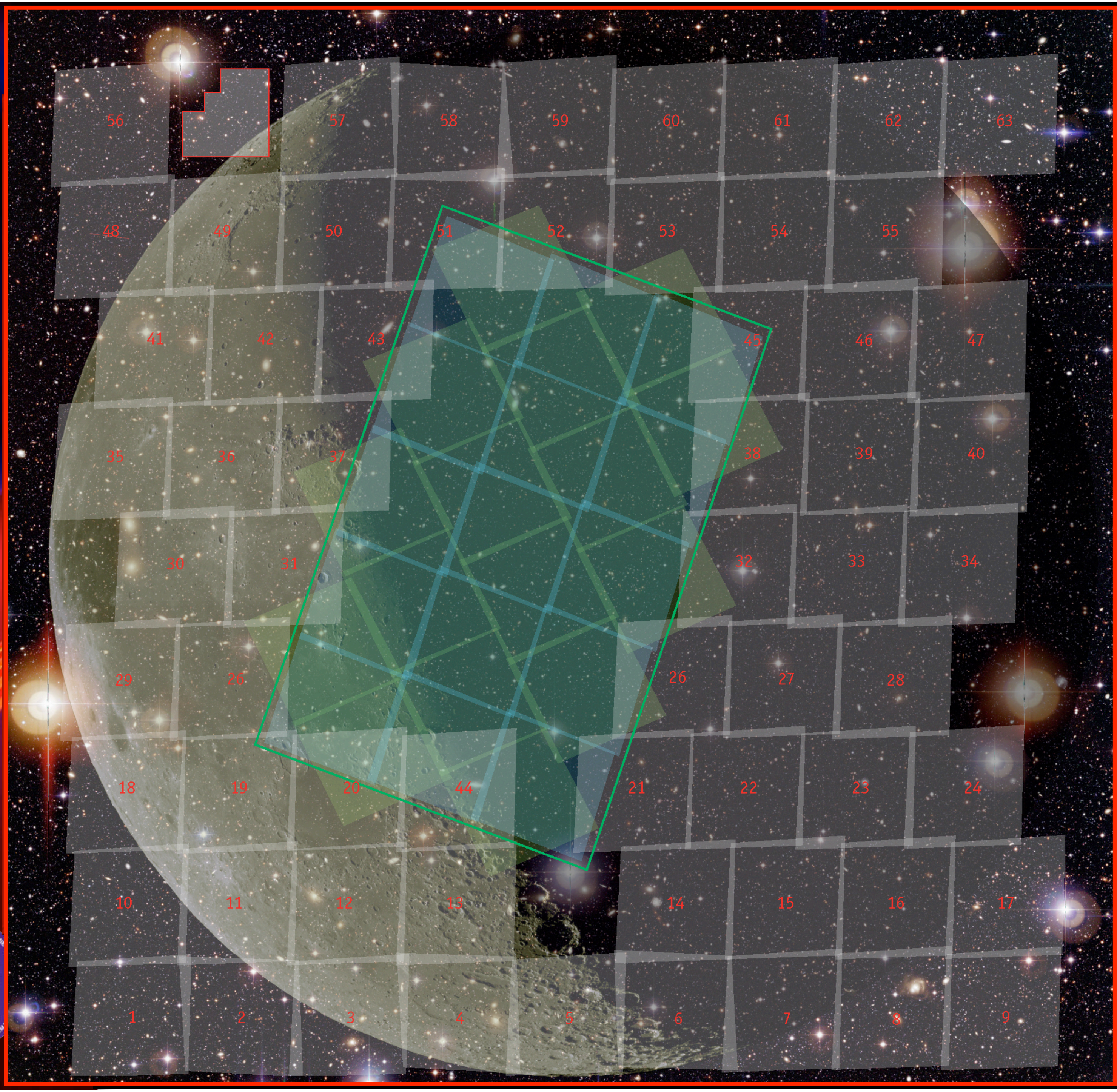
Angular resolution 0.7”
for the deep R-band images
= 5kpc at z~0.7



Wolf, Meisenheimer, et al. 2003, 2004



ell


56 57 58 59 60 61 62 63
48 49 50 51 52 53 54 55
41 42 43 45 46 47
35 36 37 38 39 40
30 31 32 33 34
29 26 27 28
18 19 20 44 21 22 23 24
10 11 12 13 14 15 16 17
1 2 3 4 5 6 7 8 9

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Physics…

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

694 KENN

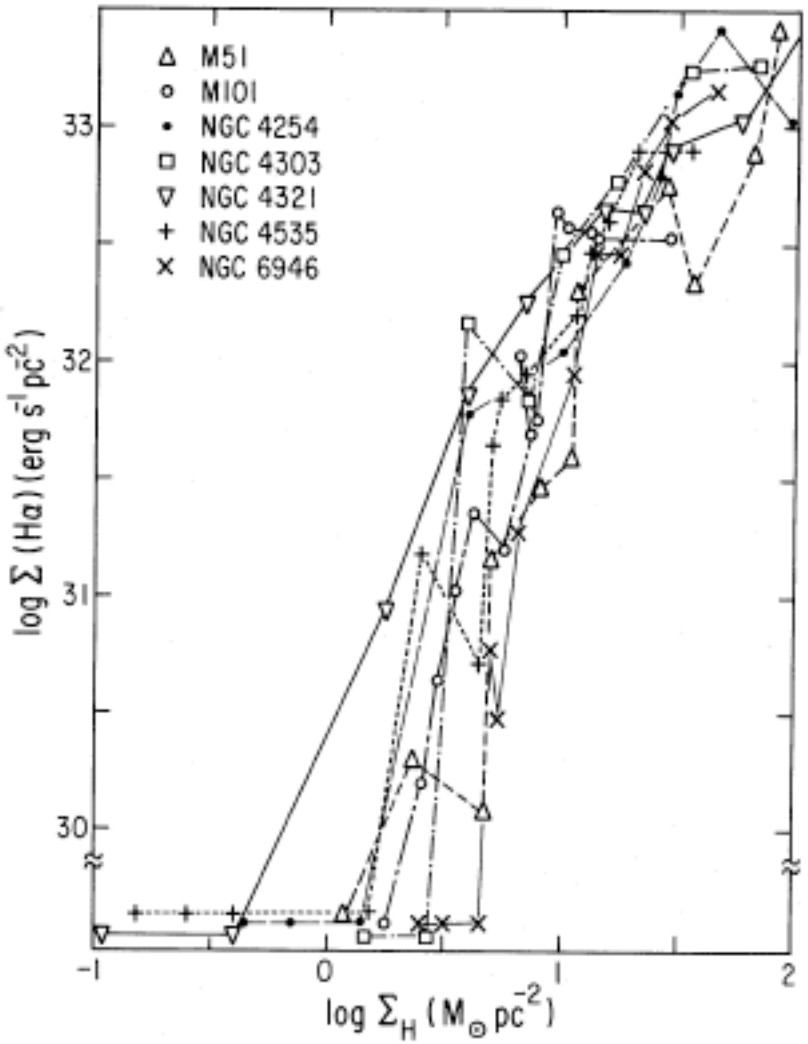

FIG. 8.—Dependence of Hα surface brightness on total (H I + H_2) hydrogen surface density, for seven giant Sc galaxies. Each point represents the Hα and gas densities averaged at a given galactocentric radius, and lines connect points at adjacent radii. The points at the bottom denote regions where no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

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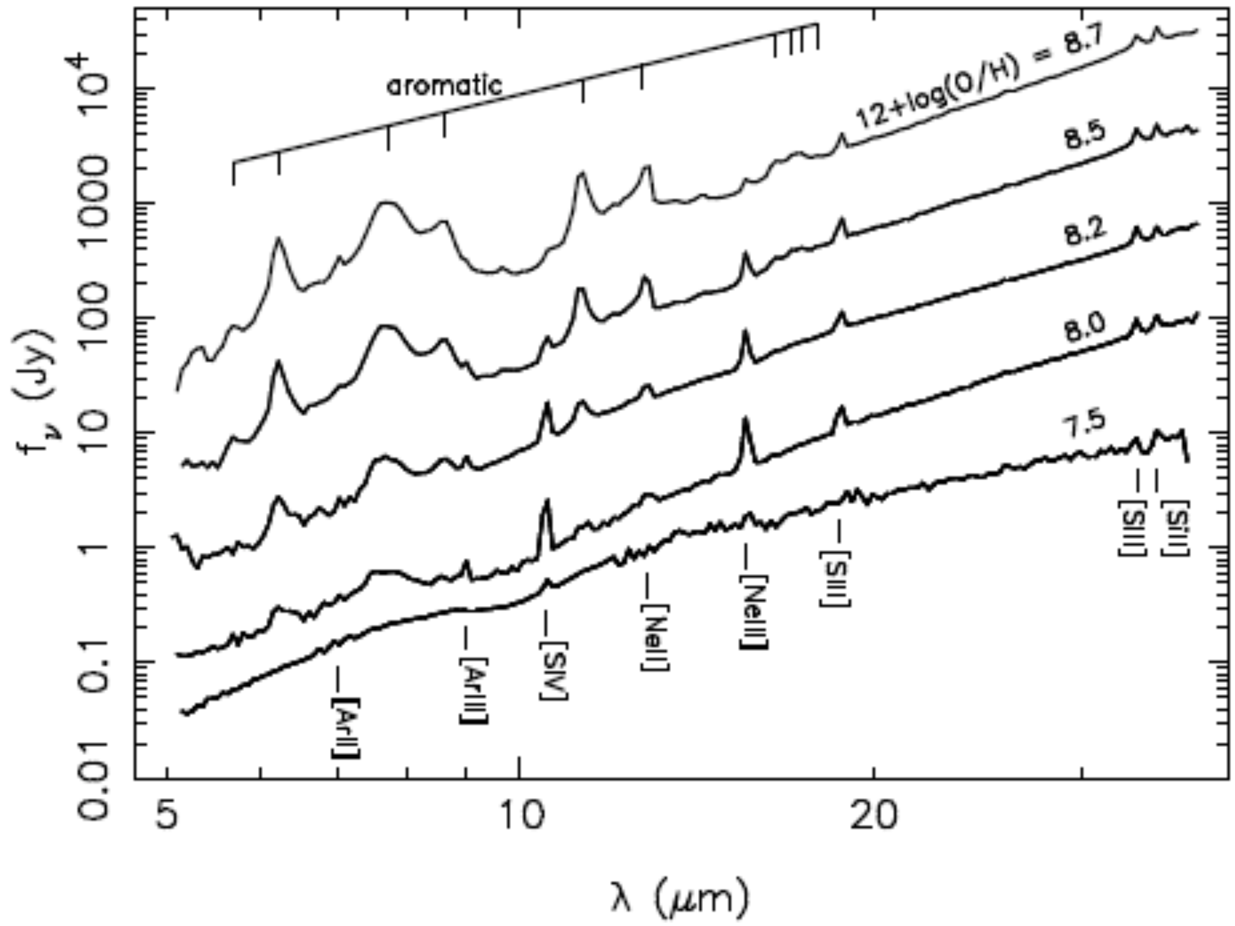

FIG. 8.— Spectra binned according to metallicity. From bottom to top, the average metallicity [12 + log(O/H)] is 7.5, 8.0, 8.2, 8.5, 8.7. The spectra were normalized at 10 μm and shifted for display purposes.

Engelbracht et al 2008

Introduction to galaxies

- Galaxies are baryonic condensate 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

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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

What is galaxy research about?

- Explain galaxy population as consequence of initial conditions (+ stability arguments + feedback)
- Understand astonishing regularity of galaxy population
- Understand galaxies well enough to make them (even better) cosmological diagnostics
- Test of galaxy formation
- Have fun!

Questions for Monday

- If there were dark matter halos without galaxies in them, how could you go about finding out?
- Massive galaxies are red, massive galaxies are in dense environments. How could one tackle the problem of best finding out what is 'driving’ this correlation?
- In simulations of merger --> obscured star-burst --> optically bright QSO phase, this is the time ordering. How would you go about figuring out whether nature obeys this time order?
- If you had the, say, Andromeda galaxy perfectly resolved into stars (to make CMDs) etc, what (broadly) interesting questions would you ask of the data?

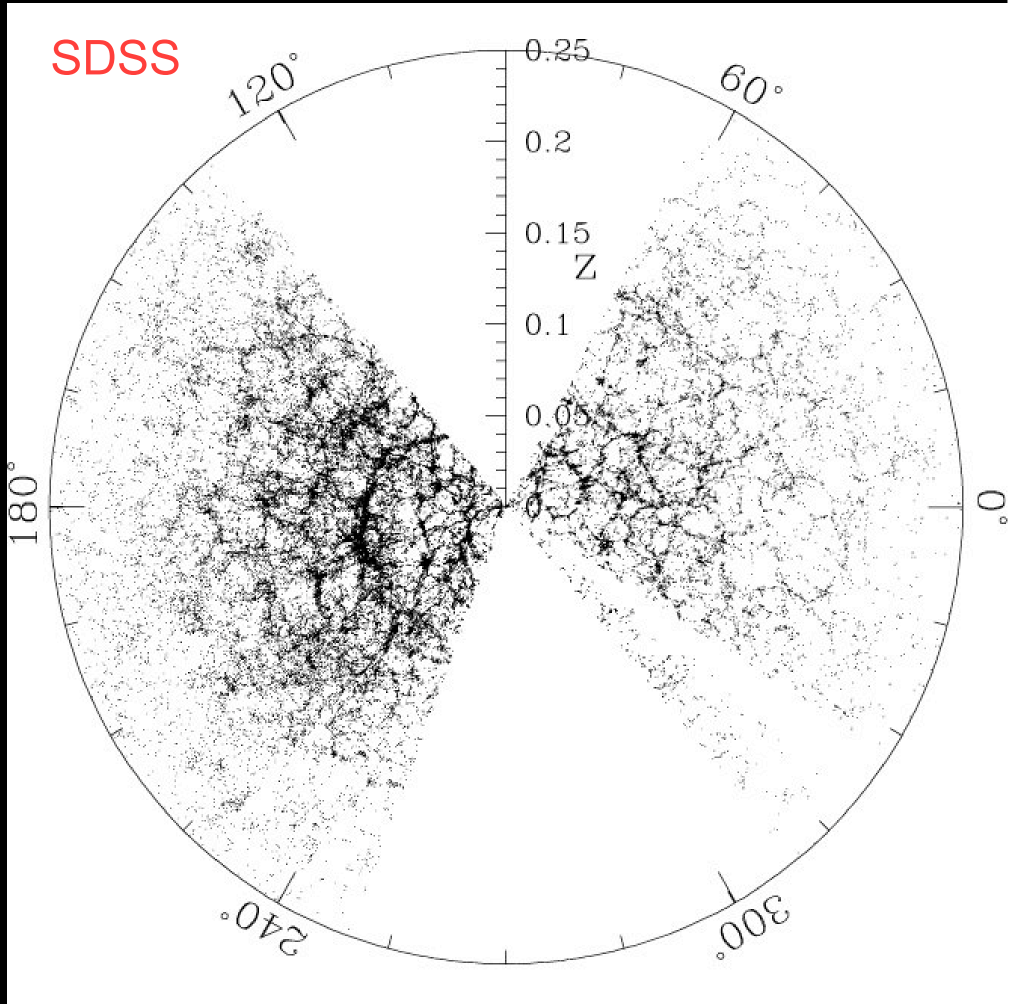
Questions for Monday…

- How would you go about estimating the ratio of 'dry' mergers (mergers with no new stars), vs. 'wet' mergers (i.e. mergers that go along with possibly obscured, IR-bright star-bursts)?
- How would you go about running an ab-initio (dark matter) simulation that actually resembles our Local Group (Milky Way, M31, M33, etc...)?
- How could you go about finding out whether spiral arms or bars are long-lived phenomena (would retain their 'shape' for longer than t_dyn)?
- If (some) galaxies contained not yet merged binary black holes, how could you tell?
  - (What should their orbital velocities be?)

Luminosity and mass functions

- Redshift survey
  - Apparent magnitude limited
- e.g., SDSS
  - 14.5<r<17.77

- 2 choices for LF
  - Thin shells
    - Limited dynamic range, small number statistics
  - V_{max}
    - Evolution and k-corrections get mixed up with LF…



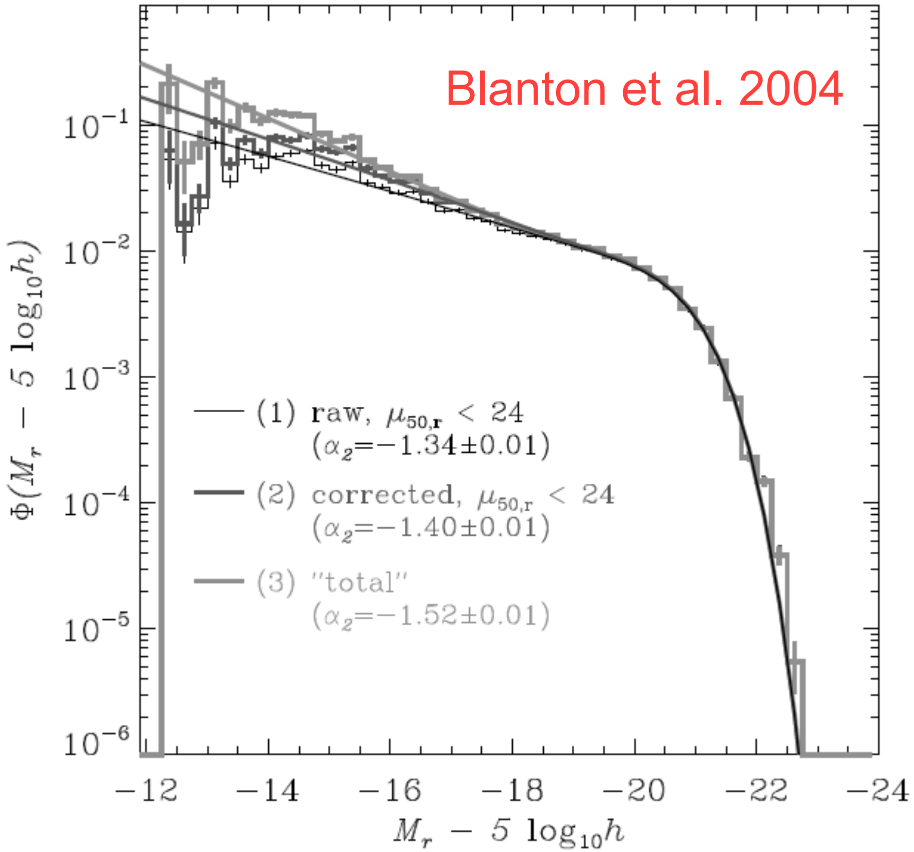
Luminosity and mass functions : V_{max} method

- Instead of making histogram of luminosities or masses of galaxies as observed, weight them by $1/V_{max}$
  - V_{max} is the maximum volume over which a galaxy can be seen
- V_{max} should account for k-corrections, and one can debate over how one deals with evolution
- If stellar mass, no k-corrections needed for luminosities, but still needed for V_{max}

Result

Schechter (1976) function to the $V/V_{\max}$ data points:

$$\phi(L)\mathrm{d}L = \phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right)\frac{\mathrm{d}L}{L^*},$$



The smooth lines in Figure 7 represent fits to the luminosity function using a double Schechter function:

$$\Phi(L)dL = \frac{dL}{L_*}\exp(-L/L_*)\left[\phi_{*,1}\left(\frac{L}{L_*}\right)^{\alpha_1} + \phi_{*,2}\left(\frac{L}{L_*}\right)^{\alpha_2}\right] \qquad (6)$$

Stated in terms of absolute magnitude $M = -2.5\log_{10}(L)+$ const this equation is:

$$\Phi(M) = 0.4\ln 10 dM \exp\left(-10^{-0.4(M-M_*)}\right)\left[\phi_{*,1}10^{-0.4(M-M_*)(\alpha_1+1)} + \phi_{*,2}10^{-0.4(M-M_*)(\alpha_2+1)}\right] \qquad (7)$$

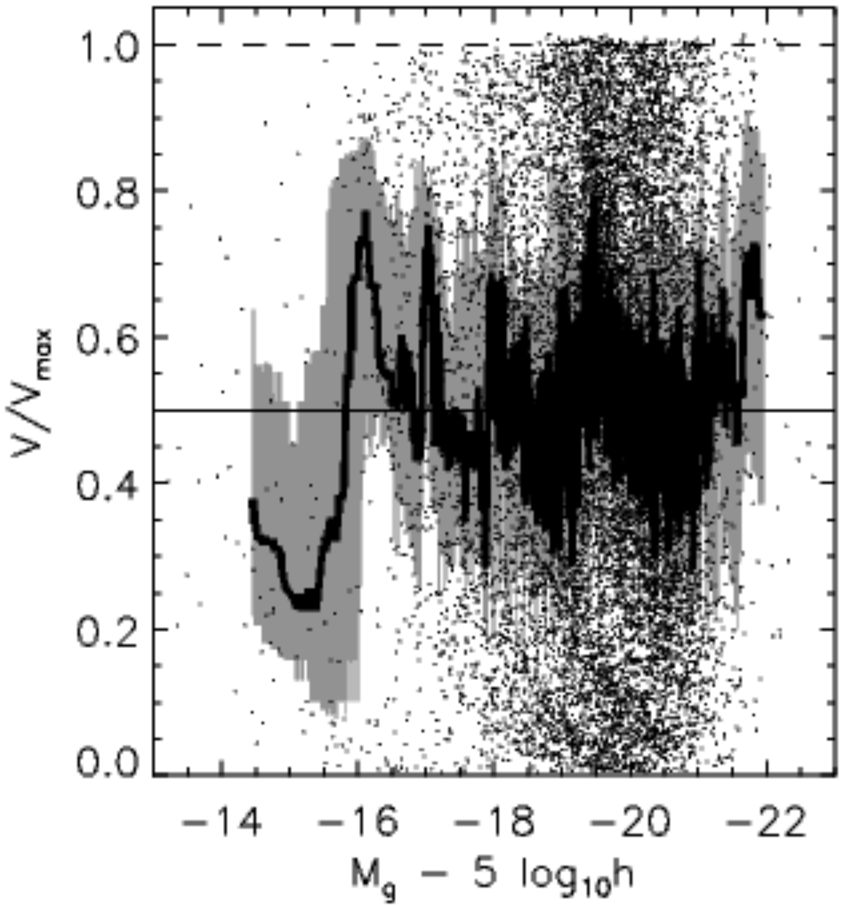


FIG. 10.— V/V_{max} against g-band absolute magnitude. The median (*thick solid line*), and upper and lower quartiles (*shaded area*), are shown as a function of g-band absolute magnitude. The average value for the whole sample is 0.509 ± 0.003, reasonably consistent with the expected value of 0.5 (*thin solid line*).

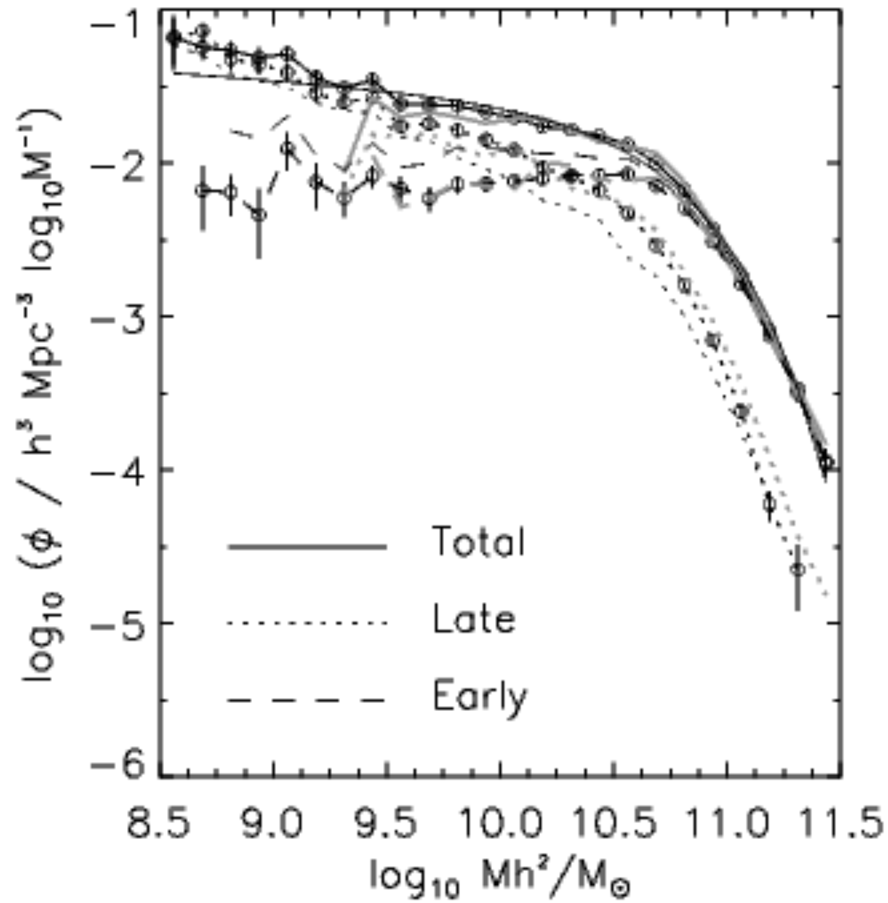


FIG. 17.— g-band derived stellar MF. The solid line represents the total MF. The black dotted and dashed lines represent the MF for late and early-type galaxies, separated using the $c_r = 2.6$ criteria. The thin solid line is our Schechter function fit to the MF. Overplotted in grey are the K-band derived stellar MFs for the total sample and the two morphological subsamples from Fig. 16. The thin black dashed and dotted lines show the g-band MFs of color-selected early and late-type galaxies. The data points included in this plot are tabulated in Table 5.

TABLE 2
SYSTEMATIC ERROR BUDGET

Quantity (1)	Error (2)	Source (3)
		Luminosity Function
ϕ^*	10%	Uncertainty in exact sky coverage (3%), completeness (7%), Poisson error in normalization (1%), and differences between behavior of the $10 < K < 13.5$ sample and our EDR sample
M^*	5%	Uncertainty in absolute calibration of *ugrizK* system
	10%	*K only:* Extrapolation to total
α	0.1?	*Optical:* from departures from a Schechter function
	$^{+0.1}_{-0.6}$	*NIR:* from strong departures from a Schechter function, and LSB galaxy incompleteness
j	15%	*Optical:* from ϕ^* and M^* uncertainty
	$^{+35\%}_{-15\%}$	*NIR:* from ϕ^*, M^* and α uncertainty
		Stellar Mass Function
M^* & ρ	30%	Dust, bursts of SF, galaxy age, and absolute calibration uncertainty
	$^{+0\%}_{-60\%}$	Stellar IMF

References. — (1) Fukugita et al. (1996)

Note. — Column (1) describes the quantity, (2) the contribution to the systematic error budget, (3) describes the error in more detail, and (references (section number or literature citation).