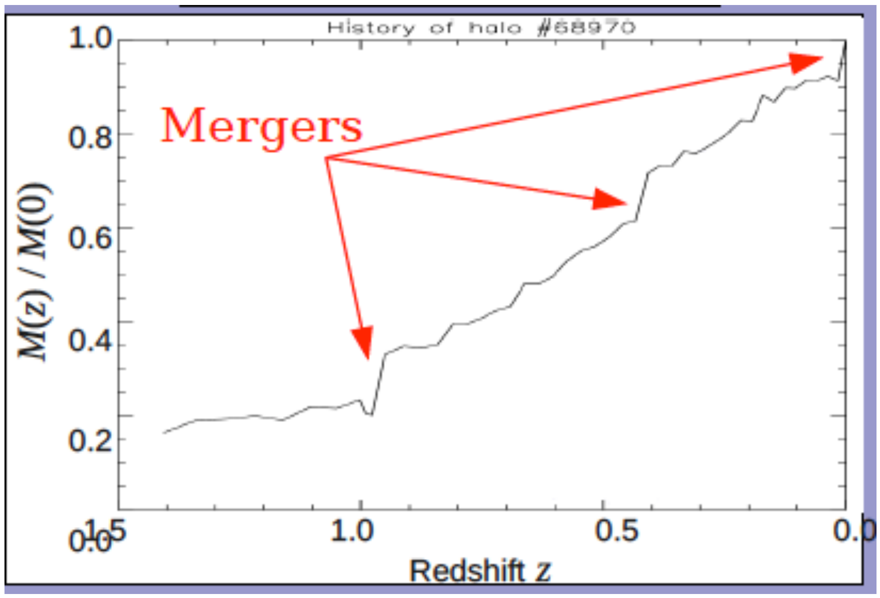
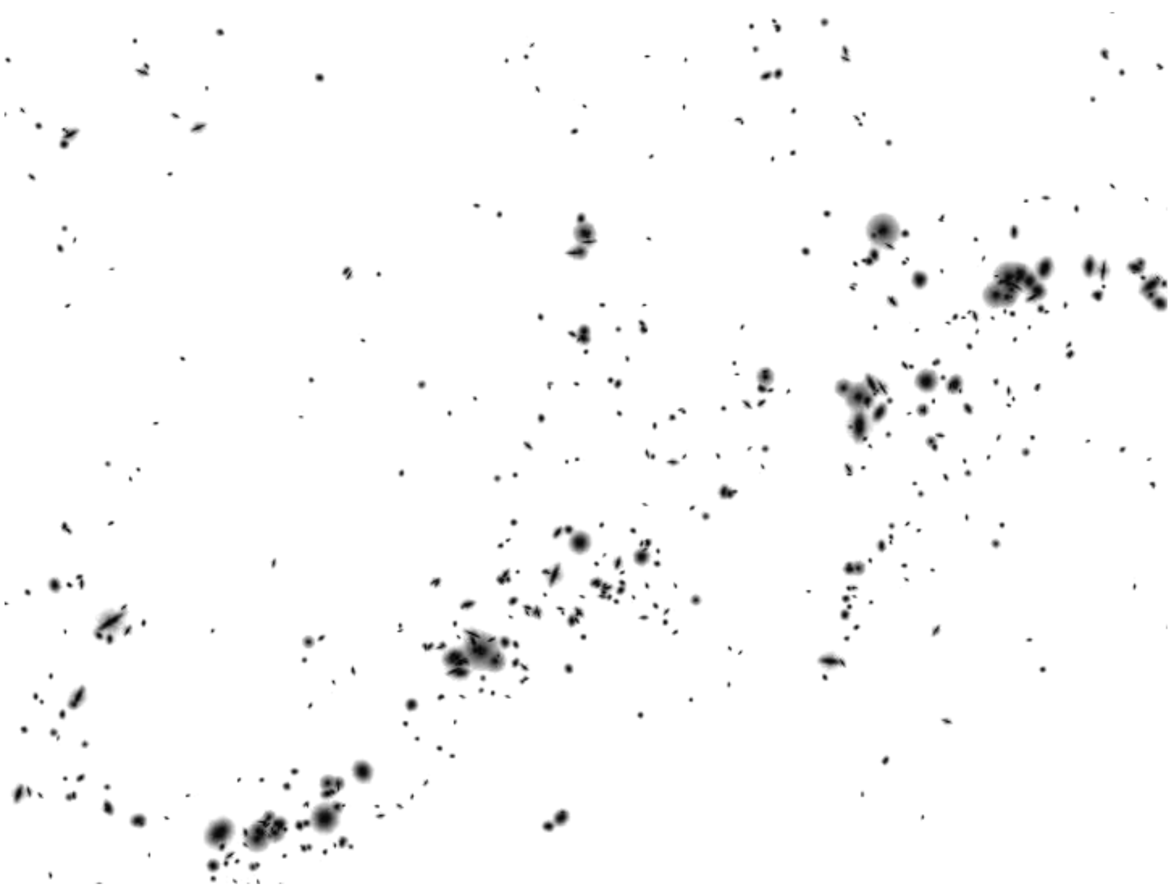
- Big mergers are rare, but increase the mass a lot

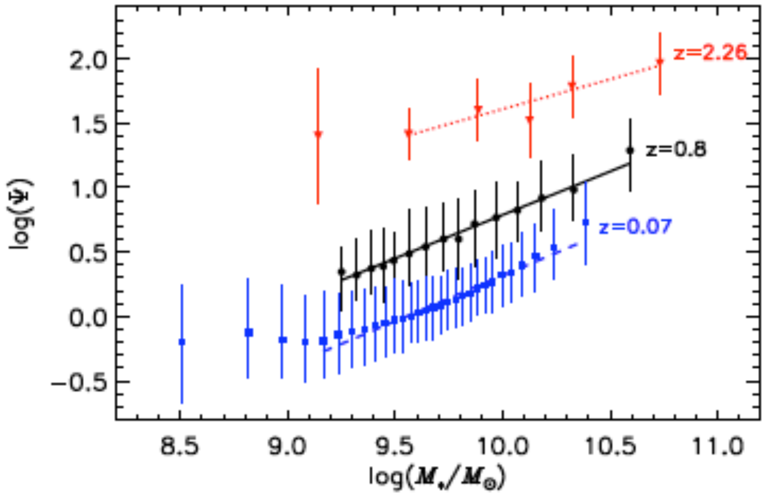




How Do Galaxies Grow

- At higher redshift there is a systematic change in the relationship between mass and star formation rate (Zahid et al 2012)
- Big galaxies grow first and fastest- *downsizing* (compared to CDM)

log star formation rate

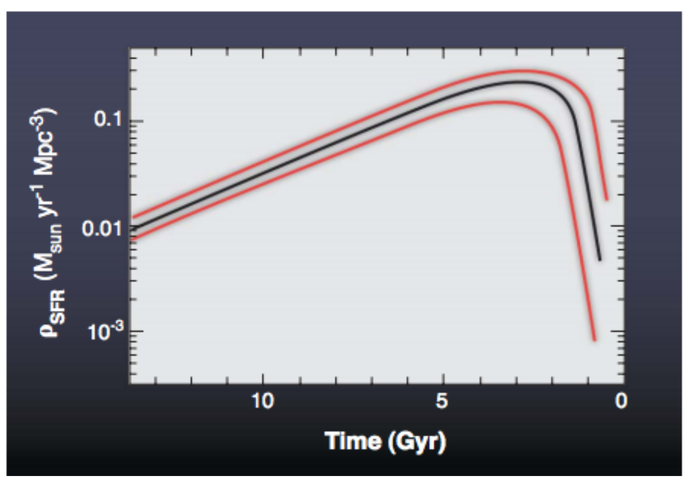


log mass

•Black z~0.8, **blue z~0.07**, red z~2.26

Things Change Over Cosmic Time

- Over the age of the universe the cosmic star formation rate (solar masses/yr/Mpc3) has change by over a factor of 30- dropping rapidly over the last 7 Gurs (since z~1)
- At high redshifts most star formation occured in the progenitors of todays luminous red galaxies, since z~1 it has occured in the galaxies that became todays spirals.

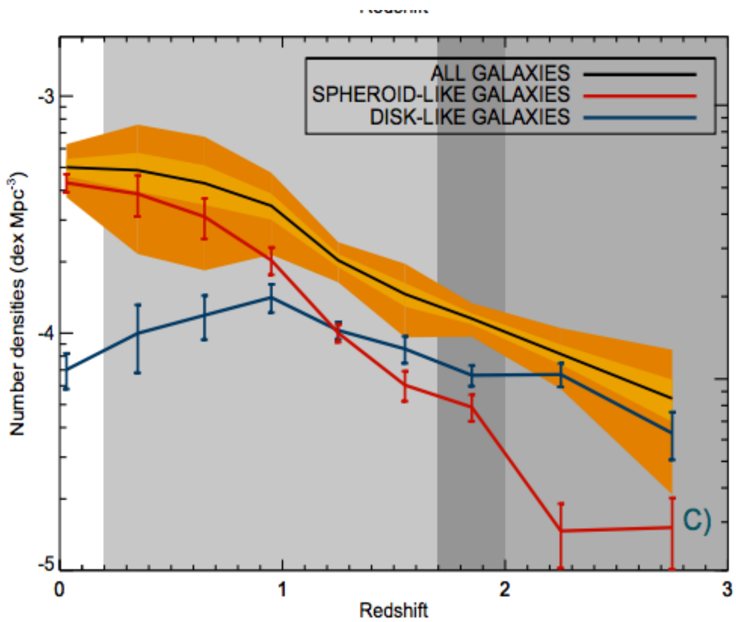


Dunlop 2011

Massive galaxies

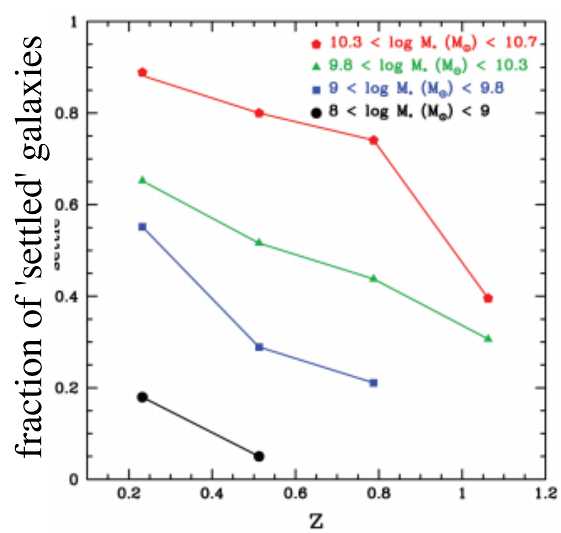
- As discussed previously at low redshift massive galaxies tend to be ellipticals
- However at high redshifts disk-like galaxies are more important
- Also note the slow growth in the number densities of massive galaxies at low z- confirming their 'old' ages

Buitrago 2012



'Blue" galaxy evolution

- blue galaxies do not evolve much since z< 1 in luminosity, stellar mass, or size, but they do evolve strongly in star-formation rate, molecular gas fraction, and morphology.
- 'blue' galaxies seem to have a life cycle: Early they are accreting baryons rapidly, undergoing mergers, have high star formation rates and possess a large amount of gas.
- Later accretion decreases along with their gas content and become 'quieter' with time (ordered velocities dominate over random) .

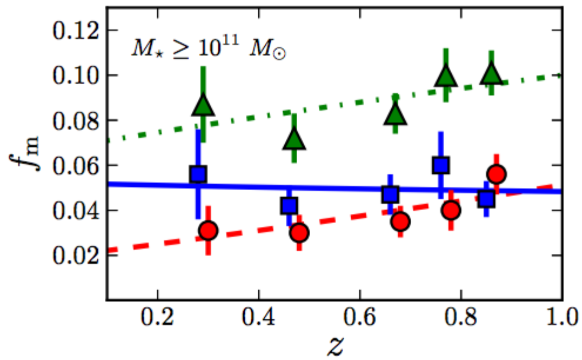


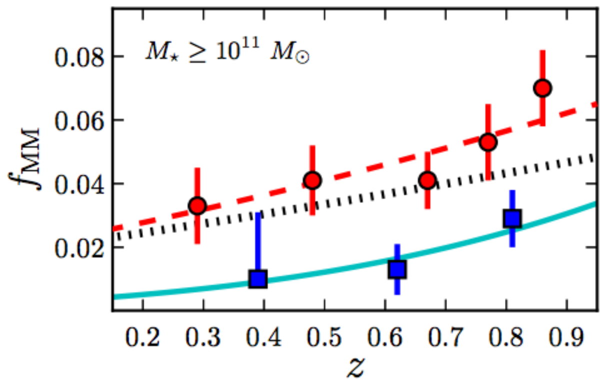
Kassim et al 2012

Mergers

- Merger fraction in massive galaxies a weak function of redshift with ellipticals having more mergers than spirals- as expected
- ~1/2 of a major merger per elliptical galaxy since z~1; ~30% growth in mass

Red major mergers
blue minor mergers

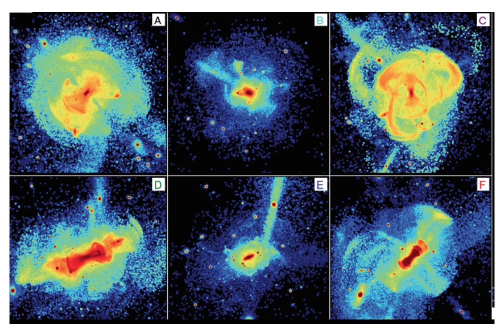




Red ellipticals
blue spirals

L´opez-Sanjuan 2012

Simulated vs Observed Merging Galaxies

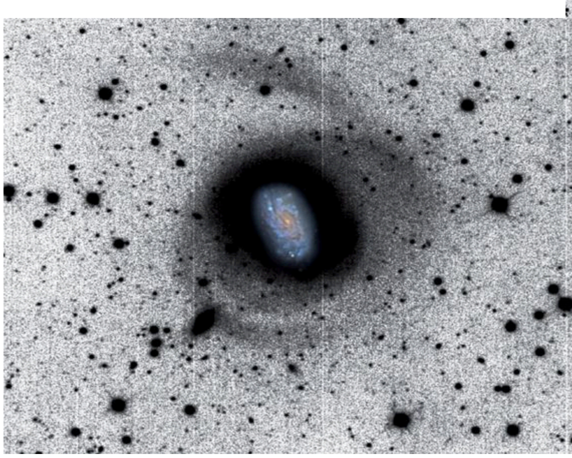


Simulated merging galaxies

Observed merging galaxies

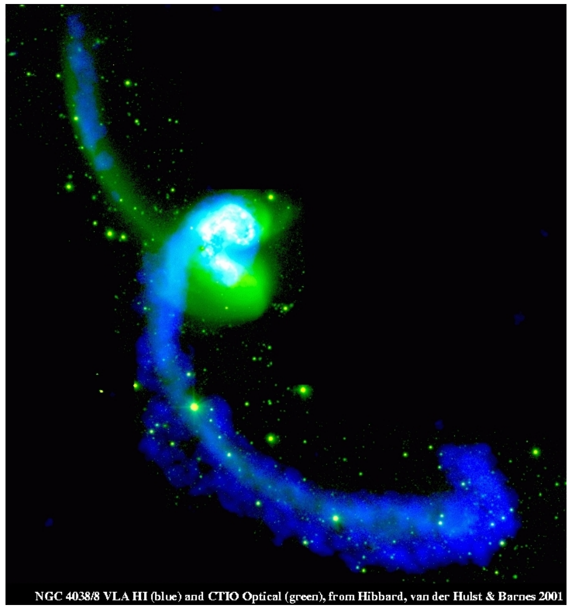
Evidence for Mergers

- faint extended emission similar to the streams seen in the Milky Way



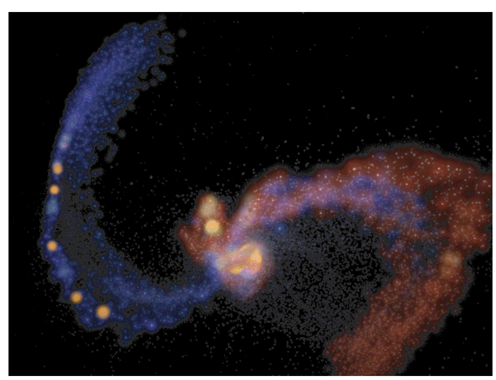
What does the Universe really do

The Antennae Galaxy- a galaxy in collision



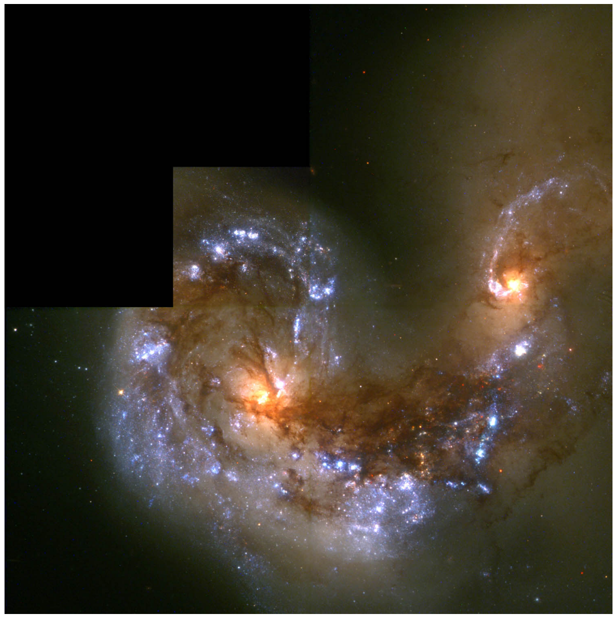
- Interactions and mergers: When galaxies collide, the resulting compression of the interstellar medium and the changing gravitational field can induce large amounts of star formation.
- Collisions also set in motion a chain of events that cause a lot of the gas from the two galaxies to fall down the gravitational well into the nuclear region of the merged galaxy, where the high gas density enhances the processes triggering star formation and provides a lot of fuel to make many stars.
-

Starbursts- What triggers a starburst?

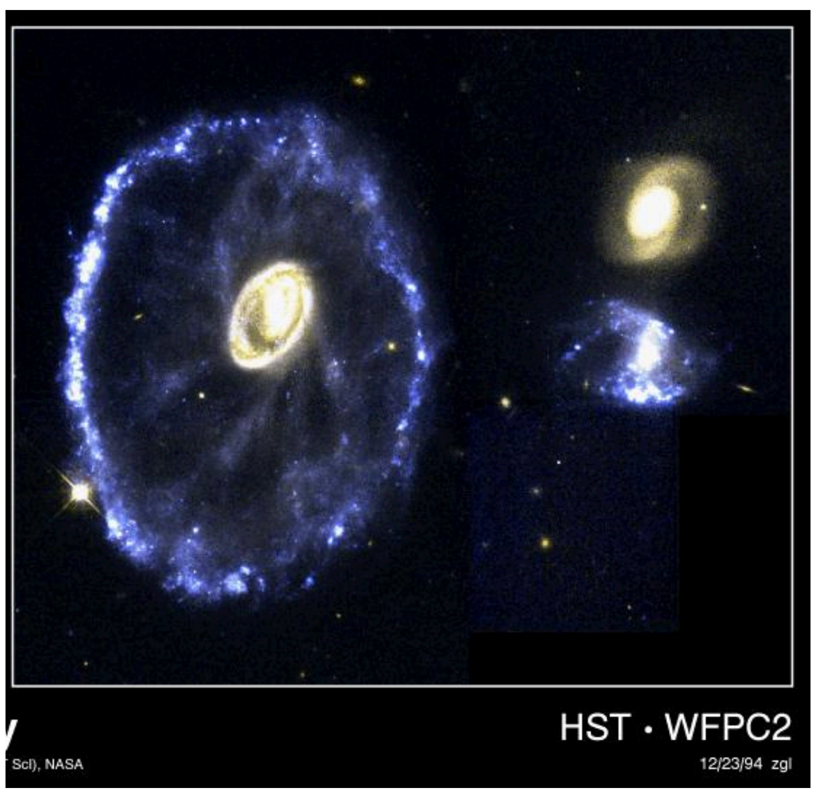


Theoretical merging disk galaxies. The gas is colored red and the stars blue.
The stars are distributed roughly as in the Antennae galaxy, and the gas has been collected into dense concentrations that become the sites for vigorous star formation

Close Up with HST

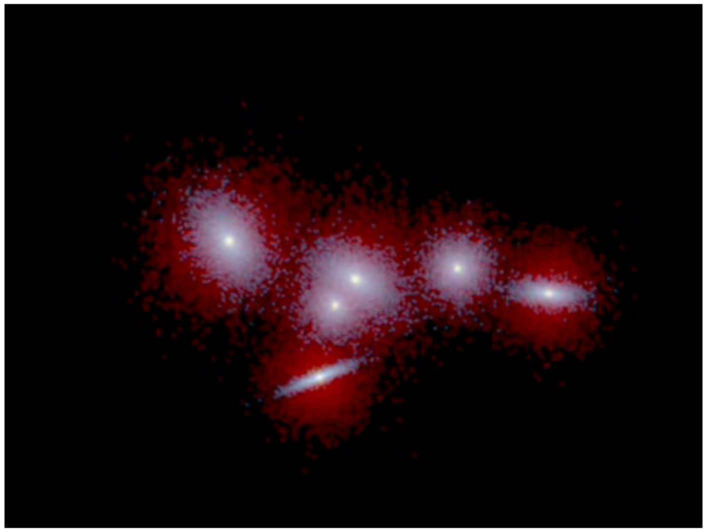


- A bulls-eye collision- the Cartwheel galaxy
- ring-like structure ~150,000 ly across (larger than the Milky Way)
- The ring is a wave of star formation traveling outwards at about ~10^2 km/sec
- As the wave passes outward it compresses and heats the matter that it passes through, triggering the star formation.



- spiral galaxies NGC 2207 and IC 2163 will slowly pull each other apart, creating tides of matter, sheets of shocked gas, lanes of dark dust, bursts of star formation, and streams of cast-away stars.

Computer simulation of galaxy collisions that make a big elliptical



J. Barnes, UH

What happens when two galaxies collide?

- On the largest scales, the changing gravitational fields cause the galaxies to distort producing streams of stars and gas ripped from each of the galaxies and thrown far from the center of mass... much of this material falls back
- Eventually (~500Myr) the system, settles back new galaxy which looks very different than either of the pre-merger galaxies
- When the interstellar clouds in each of the galaxies collide, they can trigger bursts of star formation resulting in very massive, luminous, short lived, stars being formed in large numbers and over small enough regions to produce a **'star-burst' system**.
  - If the cores have massive black holes, as we believe most massive galaxies do, the BHs can become active with luminosities $>10^{45}$ ergs/sec .

- individual stars, they are so small compared to their average distances that they rarely if ever interact

Why are massive galaxies spheroids?

1. Stars form from dense, cold gas
   – either in disks
   – or from gas that is (violently) shock compressed (result of a merger)
2. In ΛCDM larger (halos) form from the coalescence of smaller units

→ Stars in an (near) equilibrium system form from a disk and stay disk-like

→ 'Violent relaxation' shaking up stars (or stars formed during such an event) end up in spheroids

Problem with this scenario it that it requires that in nearly all massive galaxies a (major) merger occurred after star-formation was largely complete

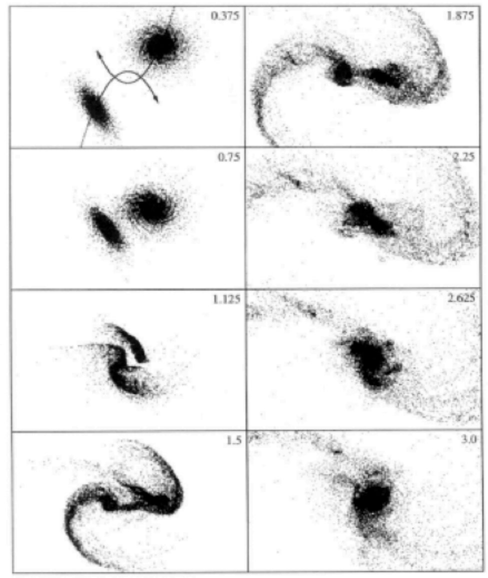
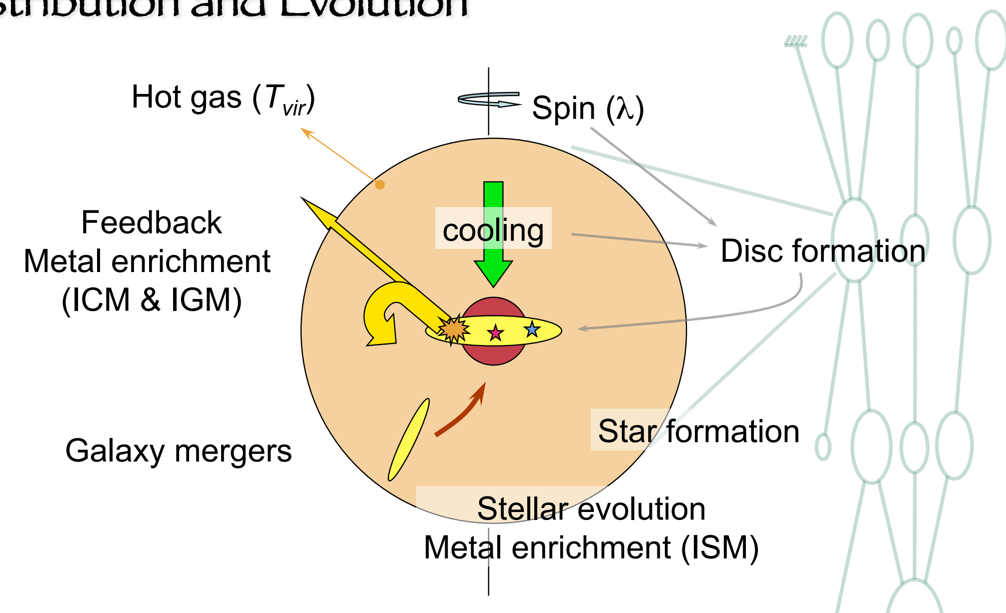


FIG. 4.—Evolution of the stellar distribution in encounter A, projected onto the orbital plane. The scale is the same as in Fig. 3.

- The models have to meet a *lot of tests*:
- correlations of galaxies internal properties with their formation history and environment- luminosity , stellar mass, star formation rate, and color, kinematics of galaxies.
  – the scaling relations between galaxy luminosity, stellar mass, radial size, and rotation velocity or velocity dispersion (the Fundamental Plane, the Tully-Fisher relation , Faber-Jackson etc)
  – the strong correlations between galaxy morphological or structural properties (e.g. spheroid vs. disk dominated) and spectral properties (color , metallicity, kinematics)

  – To do all this the simulations need a lot of details
    - dark matter and baryonic physics
    - 'correct' cosmology
    - high enough spatial and temporal resolution
    - large 'box' size (lots of galaxies formed)

What Physics Goes on Top of the Dark Matter Distribution and Evolution



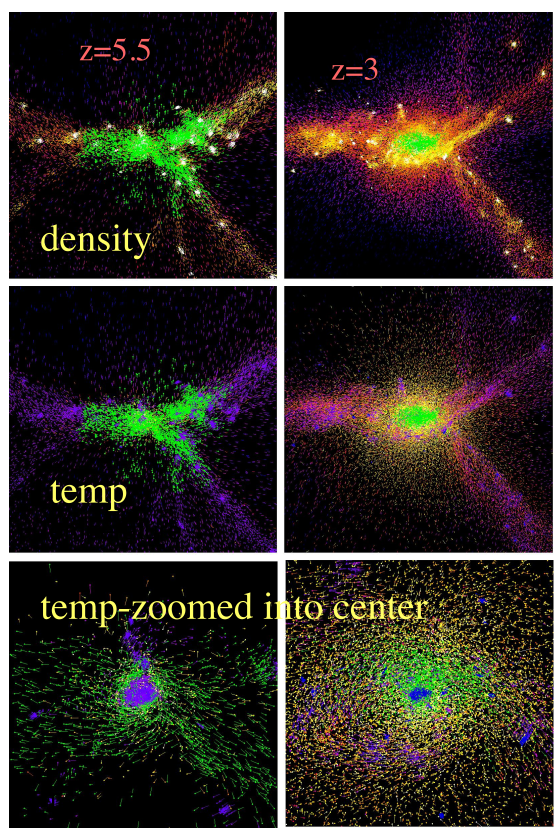
+ model of simple stellar population evolution (w/ dust)

taken from J. Blaizot presentation

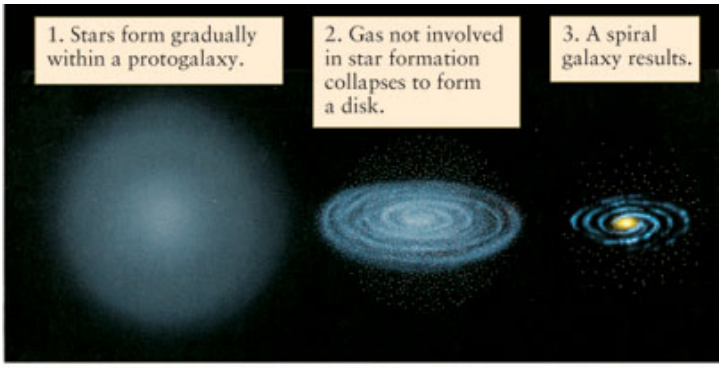
Accretion in a Growing Halo

(Keres at al 05; from Dave)

- Left panels: z=5.5, right panels: z=3.2.
- Halo grows from $M \sim 10^{11} M_{\odot}$-$10^{12} M_{\odot}$, changes from cold - hot mode dominated.
- Left shows cold mode gas as green; Right shows hot mode as green.
- Cold mode filamentary, extends beyond R_{vir}; hot mode quasi-spherical within R_{vir}. Filamentarity enhances cooling.

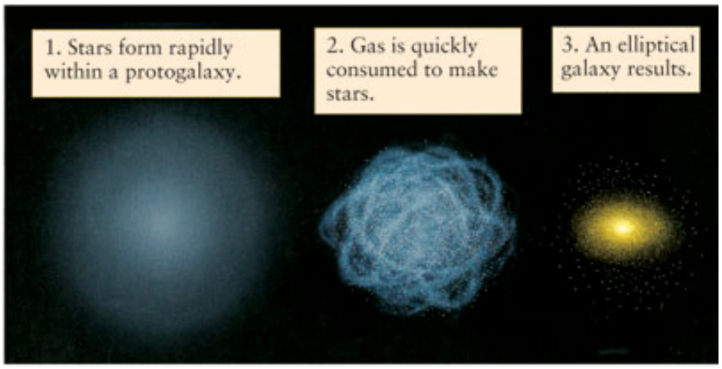


Keres et al 2005



(a) Formation of a spiral galaxy

High angular momentum halo



(b) Formation of an elliptical galaxy

Low angular momentum halo-another scenario for ETG formation

Galaxy Growth-Summary

- Galaxies can grow in 2 simple ways
  - infall of gas (rain)
  - merger with other galaxies- 2 types with (wet) and without (dry) much gas

  to re-phrase
- Galaxies can grow in mass by forming new stars or coalescence (merging) of pre-existing bits
- Both are important
  - its much easier to 'see' the mergers

  observationally and theoretically- but what really happens?

We now know that (Hogg et al 2012)

- ~ 25percent of galaxies similar to our Milky Way experienced a merger with mass ratio $m/M > 0.1$,
- ~ 10% experienced a merger with mass ratio $m/M > 0.33$ since z~2 (~10Gyrs) producing an average growth rate of 1 (blue galaxies like the W)-4 percent (red galaxies) per Gyr
- Thus about 50% of the mass of red (elliptical) galaxies over the last 5Gyrs has been due to mergers.

Summary Ellipticals-Massive galaxies since z~1

- Star-formation in most massive galaxies has essentially stopped at z<1 (7Gyrs)
  - “need” missing ingredient to stop/ quench star-formation ---central black hole feed-back?

- Overall stellar mass density in red’ n’ dead galaxies has doubled since z~1 Source: galaxies that have stopped forming stars
- Typical massive galaxy has undergone one (major, dry) merger since z~1
  - Boost total red sequence mass at the most massive end
- What about earlier??

The Standard Model- Summary

Additional physics

- Some of the newly created stars are massive and thus short-lived and these stars explode in supernovae .
- These supernova which can heat the surrounding gas, reducing the efficiency of star formation
- AGN provide another large source of energy to heat and move the gas.
- the combination of the two allows a wind to form blowing gas out of the galaxy reducing star formation

- At the 'same time' , dark matter halos constantly accrete new material and other galactic systems merge with it.
- Mergers may be accompanied by a strong burst of star formation

if the contain significant amounts of cold gas.

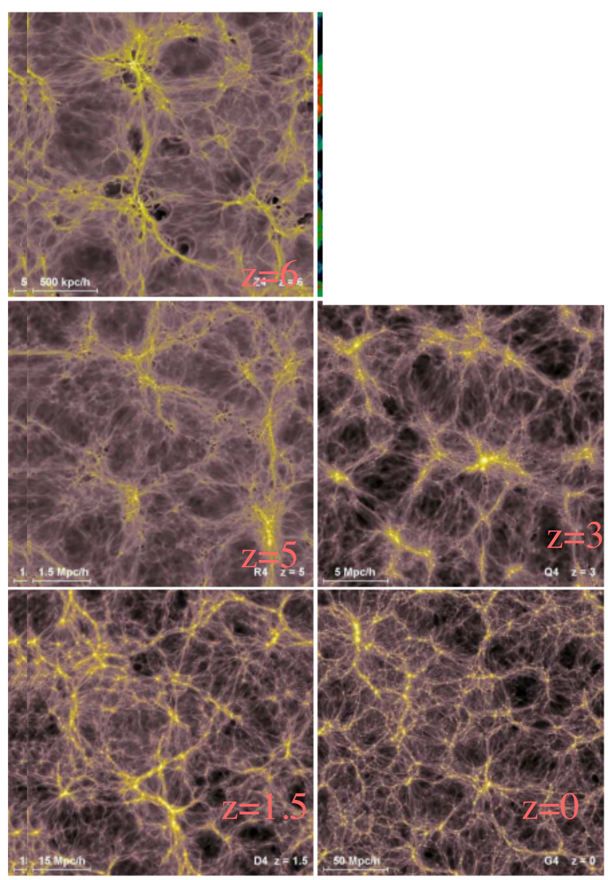
- In a major merger, the orbits of the disc stars are randomised, resulting in the destruction of the discs and the creation of an elliptical galaxy.
- After such a merger a new gas disc can be created and a new stellar disc formed
- And then the *tooth fairy* creates galaxies like we observe...

Spirals at Z<1

- Since 50% of the present-day stellar mass has been formed at z < 1 (last 8 Gyrs) almost all of it has been in spiral galaxies (!) - most of the emitted luminosity is in the IR (Luminous infrared galaxies-LIRGs)
- HST/ACS angular resolution ~ 200 pc at z=0.65 . - can be directly compared to SDSS galaxies at z=0. I
- morphologies show that galaxies have strongly evolved

Growth of Structure

- Simulation of baryonic density vs redshift

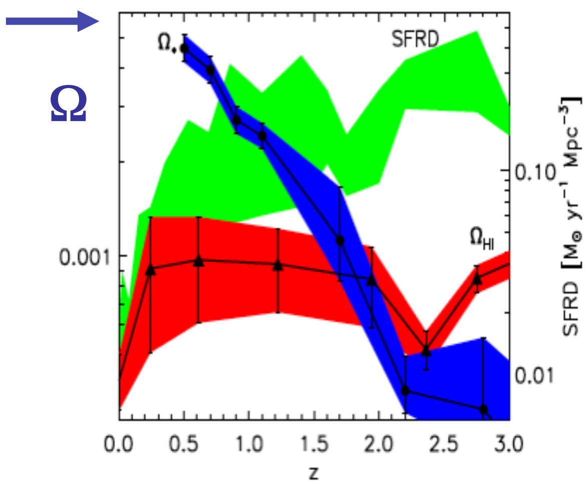


Patterns Change over Cosmic time

- The cosmological mass density of HI in galaxies (red) is nearly constant over the past~10 Gyr while the stellar density (blue) increases. Since stars must form from gas this shows the importance of ongoing gas accretion
- There has been a rapidly declining SFR (**green**) rate since z~1 (accompanied by a similar decline in active galaxies)

- Blue shows the mass density in stars compared to the closure density (Ω_{stars})
- Red shows the mass density in HI gas
- Green the cosmic star formation rate

Ω_{star} is ~10% of the cosmic baryon density

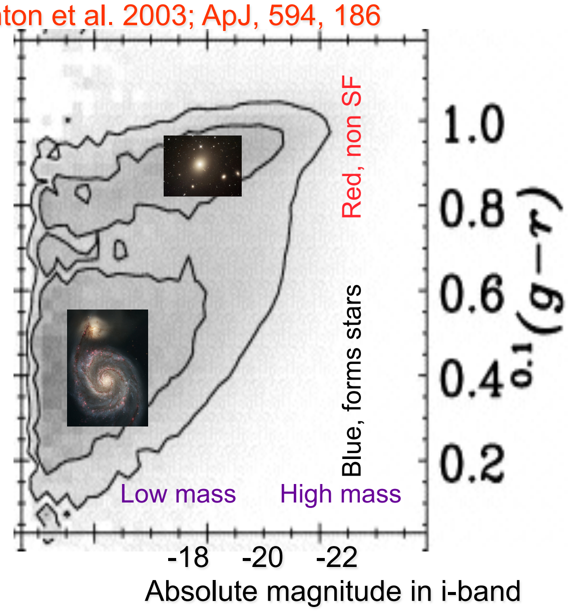


Putnam et al 2010

Reminder : correlation between *structure* and *star formation history*

- A bimodal galaxy population - transition mass of 3×10^{10} $M_\odot$
  - **Red sequence**
    - Mostly non-star-forming
    - Bulk of galaxies bulge-dominated
    - Most massive galaxies
  - **Blue cloud**
    - Star-forming
    - Bulk of galaxies disk-dominated
    - Lower mass galaxies

Blanton et al. 2003; ApJ, 594, 186



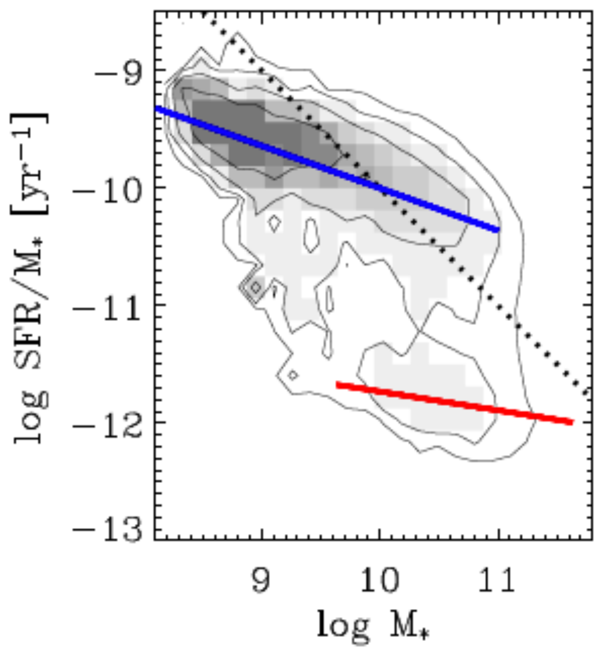
Cessation (quenching) of star formation is empirically correlated with
the existence of a prominent spheroid

galaxy 'bimodality' at redshift zero

- Bimodality in color space --> narrow distribution in SFR/M* (blue galaxies) with tail towards low SFR/M* (red sequence)

- Schiminovich+ 2008

What happens at higher redshift??



Biased galaxy formation

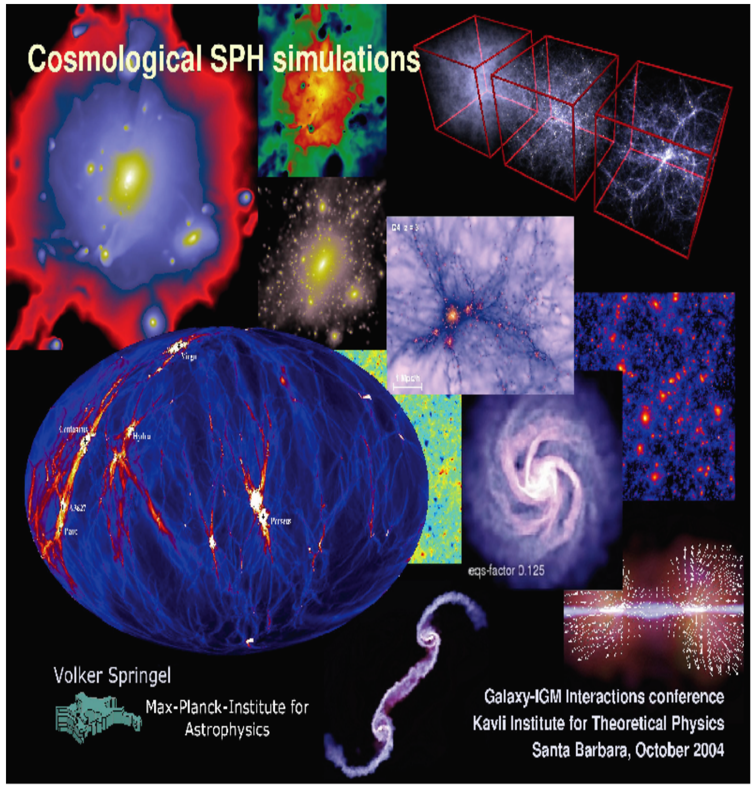
- The ingredients for galaxy formation involve not only dark matter but baryons
- So what can make the distribution of galaxies different than that of the dark matter?

- Baryons can be heated, and moved around by energy
- Baryons can cool and fall

It is now believed that these 'non-gravitational' processes (the jargon is **'feedback'**)
due to
star formation
quasars
Have a major influence on galaxy formation

Formation of structure in the Universe

- Detailed numerical calculations of the formation of structure via the collapse of gravitational perturbations in a LCDM universe (Springel et al 2003, White et al 2004) show that one cannot 'produce' the present day universe without invoking 'feedback'
- Similar results are obtained in analytic work
- The nature of the feedback is not clear, but must be related to star formation and AGN - the only possible sources with sufficient energy



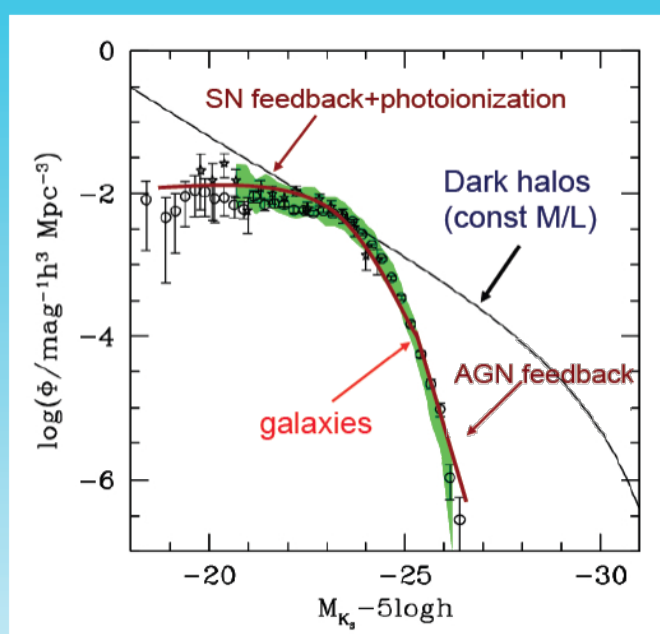
ICC University of Durham

The galaxy luminosity function

The halo mass function and the galaxy luminosity function have different shapes

⇨ Complicated variation of M/L with halo mass

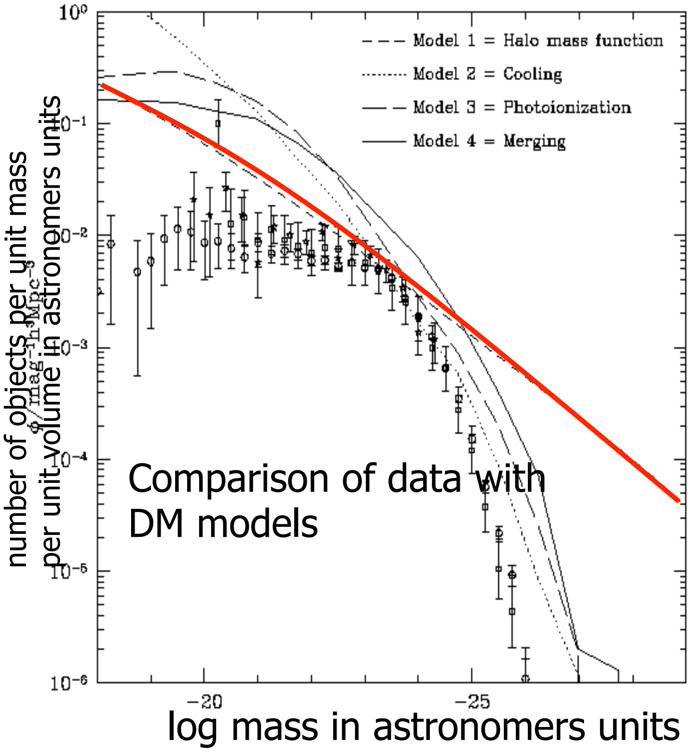
C. Frenk



Benson, Bower, Frenk, Lacey, Baugh & Cole '03

Institute for Computational Cosmology

Benson et al. (2003)- Red line is theoretical distribution of dark matter halos

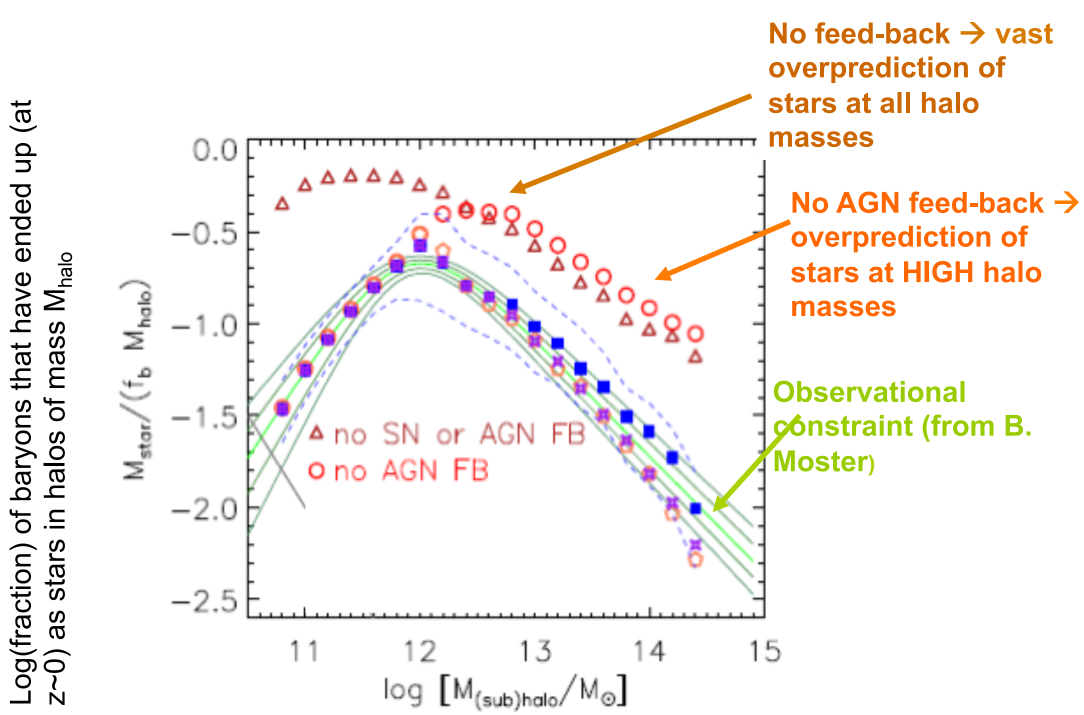


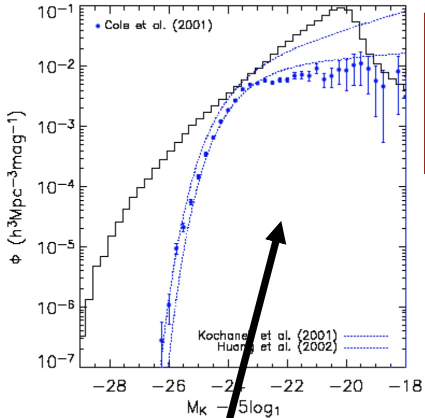
Observed relationship between number of dark matter halos of a given mass vs mass and the observed galaxy distribution

Galaxies do not trace the theoretically predicted dark matter halos !

Why??

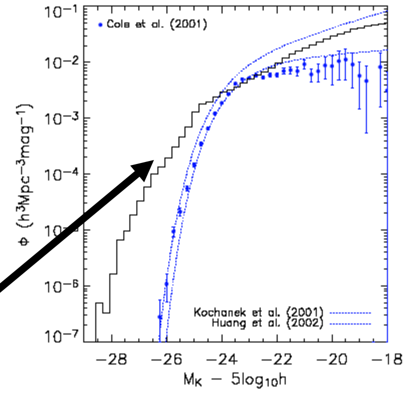
Comparison data—models (Somerville et al 08)



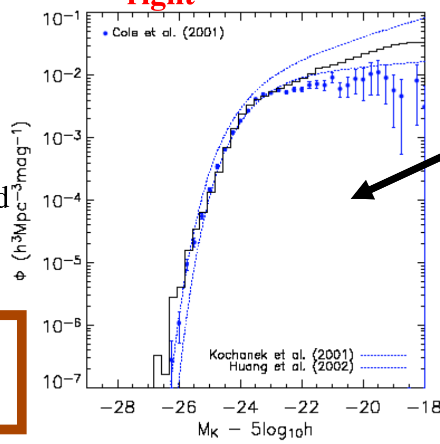


Calculation of K band galaxy luminosity function in N body simulation

Gravity+ hydrodynamics no AGN+ starburst+ reionization - **get low luminosity range 'right'**



Gravity+ hydrodynamics only- **get it all wrong**- low luminosity, slope, high luminosity slope and number and mass in galaxies



Gravity+ hydrodynamics +AGN+ starburst+ reionization - **get it all 'right'**

Blue lines are data- black models

Thanks to V. Springel and S. White

Feedback Effects on Galaxy Formation

- Reionisation/radiative feedback

  radiative heating produces large effective Jeans mass and suppresses gas fraction in halos with less than the *filter* mass

  $f(M, z) = f_0 / (1 + 0.26\, M_F(z) / M)^3$ Gnedin 2000; Kravtsov et al 2004

- Supernova feedback

  Reheats ISM $\Delta M_{reheat} = \varepsilon_{reheat}\, \Delta M_*$ Martin 1999

  Heats halo gas $\Delta E_{halo} = \varepsilon_{halo}\, ½\, \Delta M_* V_{SN}^2$ White & Frenk 1991

  Ejects gas $\Delta M_{eject} = \Delta E_{halo} / ½ V_{vir}^2 - \Delta M_{reheat}$ Kauffmann et al 1999

- AGN feedback

  "Radio" mode $\Delta M'_{cool} = \Delta M_{cool} - \eta\, M_{BH}^{\alpha}\, T_{clus}^{\beta}$ Croton 2004

  "Quasar" mode builds up BH masses, establishes Magorrian relation, feedback included in SN? Kauffmann & Haehnelt 2000