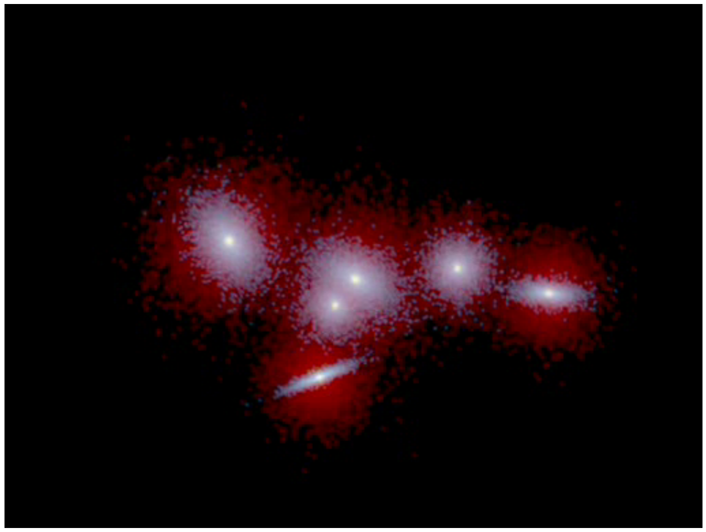
Computer simulation of galaxy collisions that make a big elliptical



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

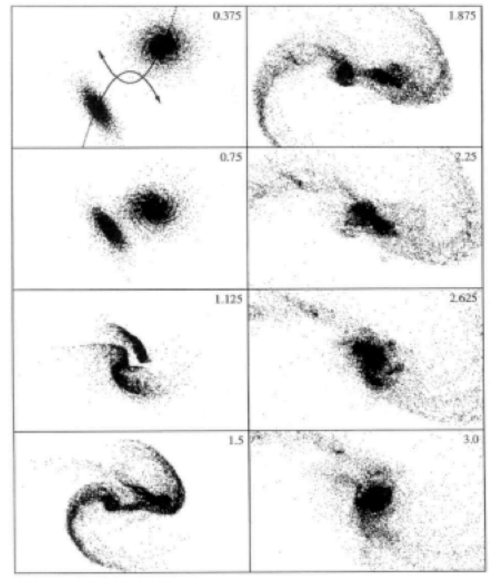
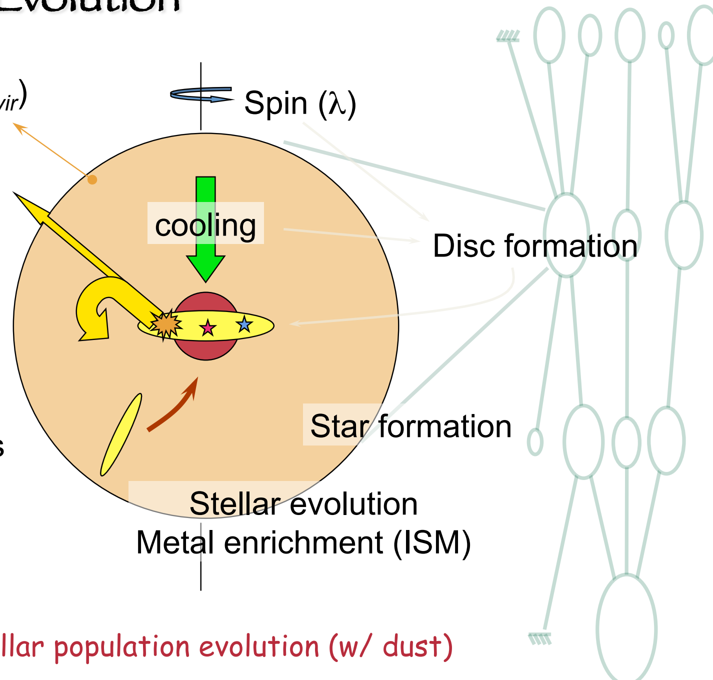


FIG. 4.—Evolution of the stellar distribution in encounter A, projected onto the orbital plane. The scale is the same as in Fig. 3.

- 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

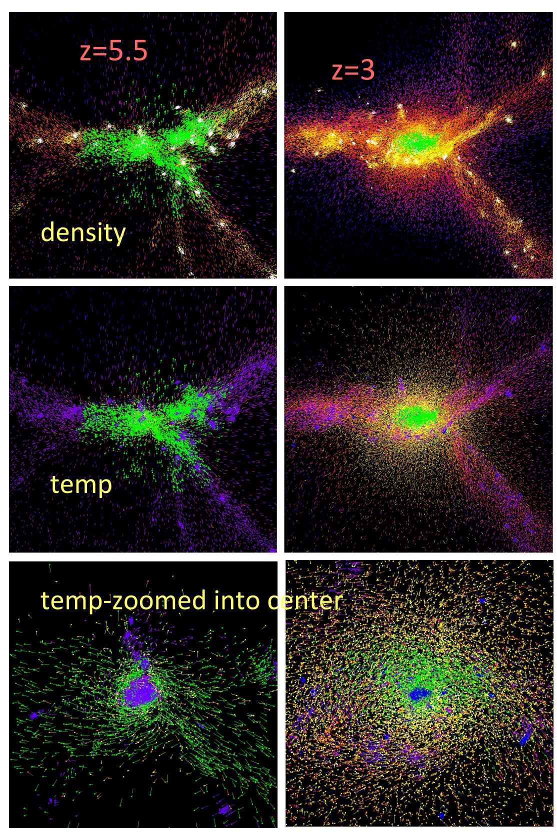


+ model of simple stellar population evolution (w/ dust)

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

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.

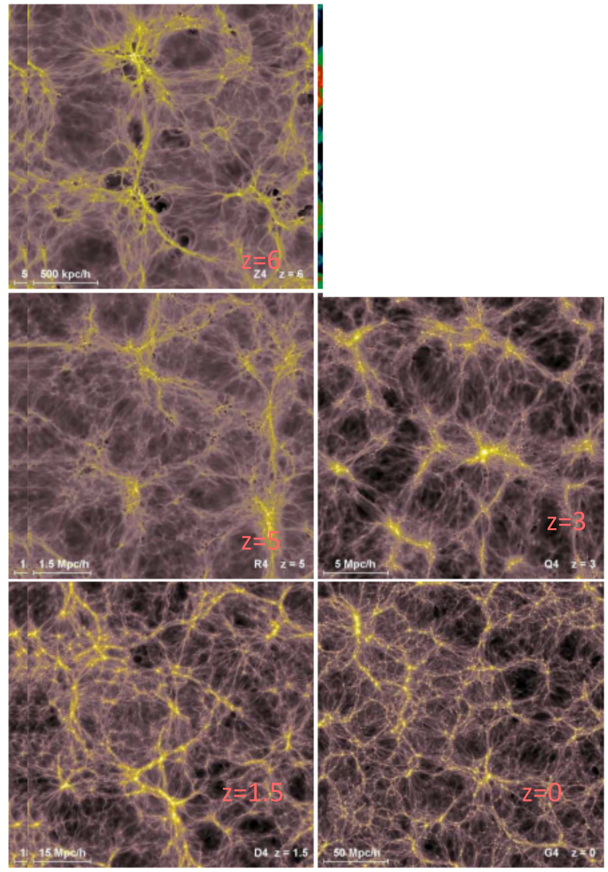
- In a major merger, the orbits of the disc stars are randomised, resulting in the destruction of the discs and the creation of an elliptical galaxy.
- After such a merger a new gas disc can be created and a new stellar disc formed
- And then the *tooth fairy* creates galaxies like we observe...

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

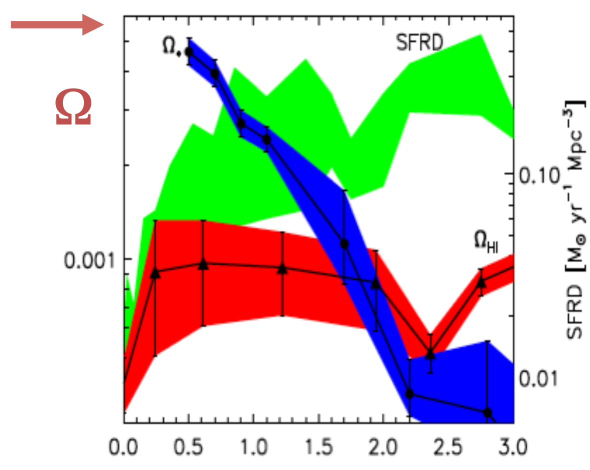


Patterns Change over Cosmic time

- 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

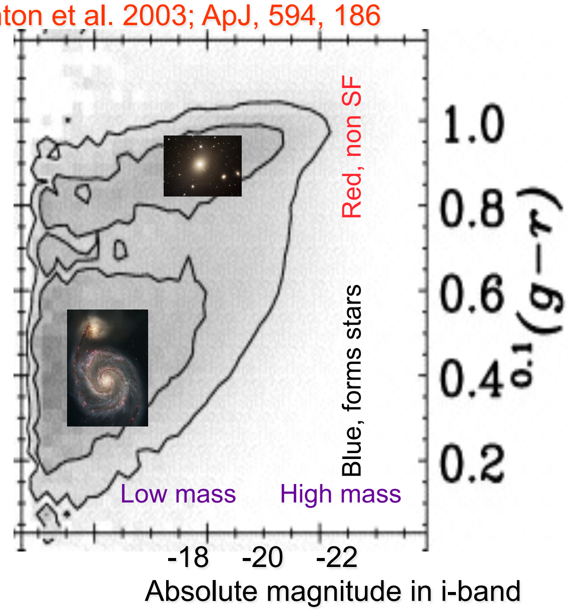


Putnam et al 2010

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

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

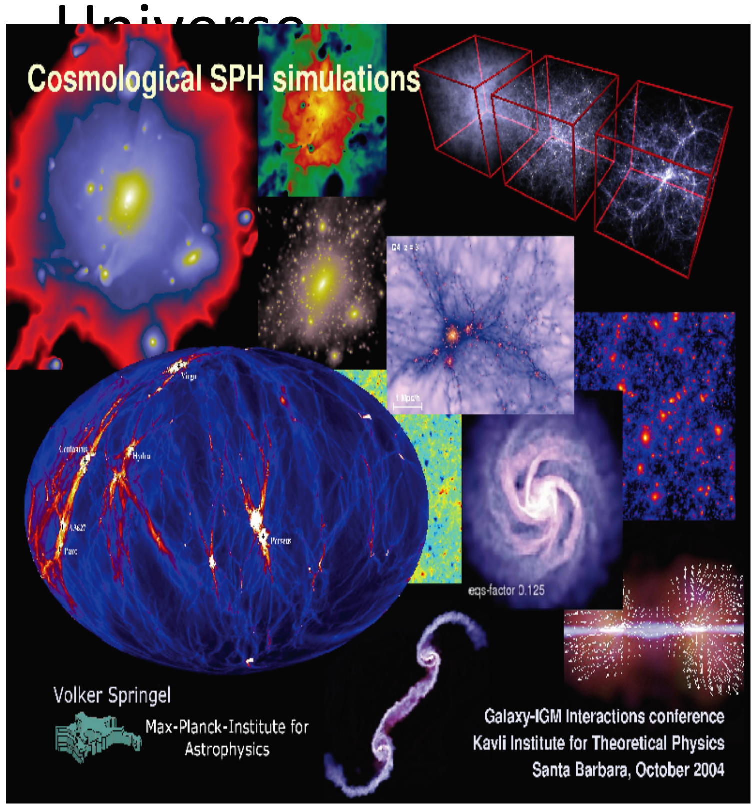
star formation

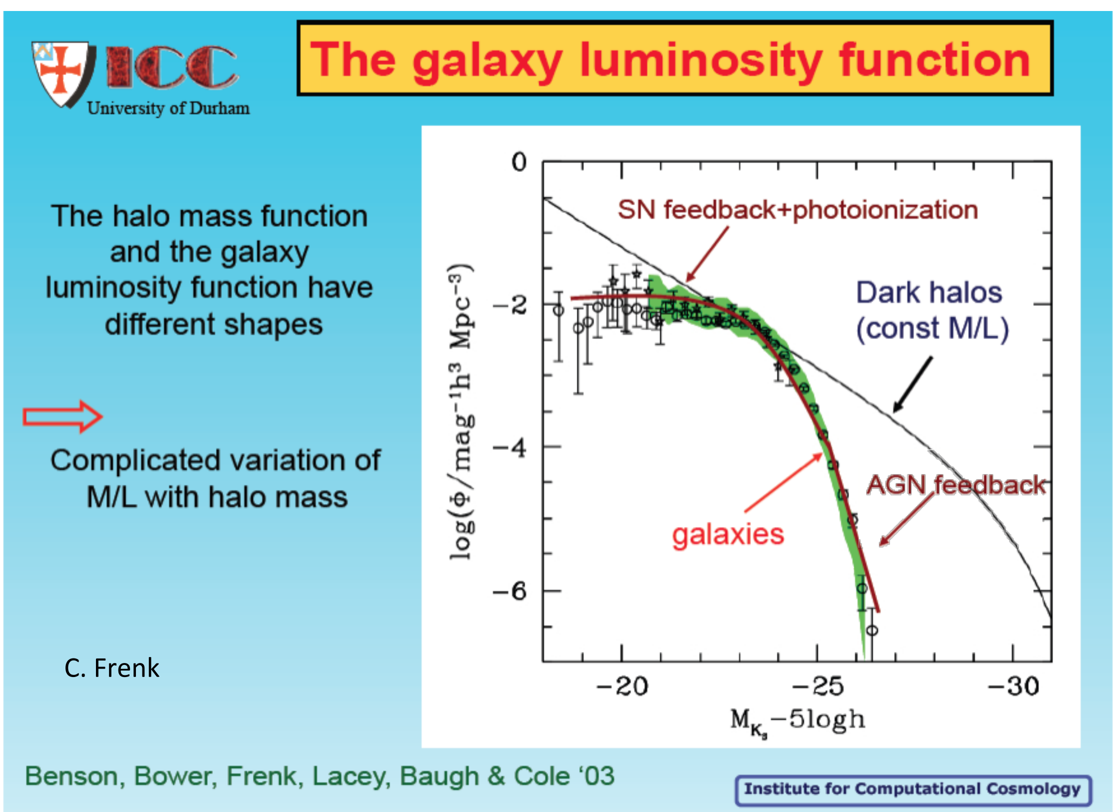
quasars

Have a major influence on galaxy formation

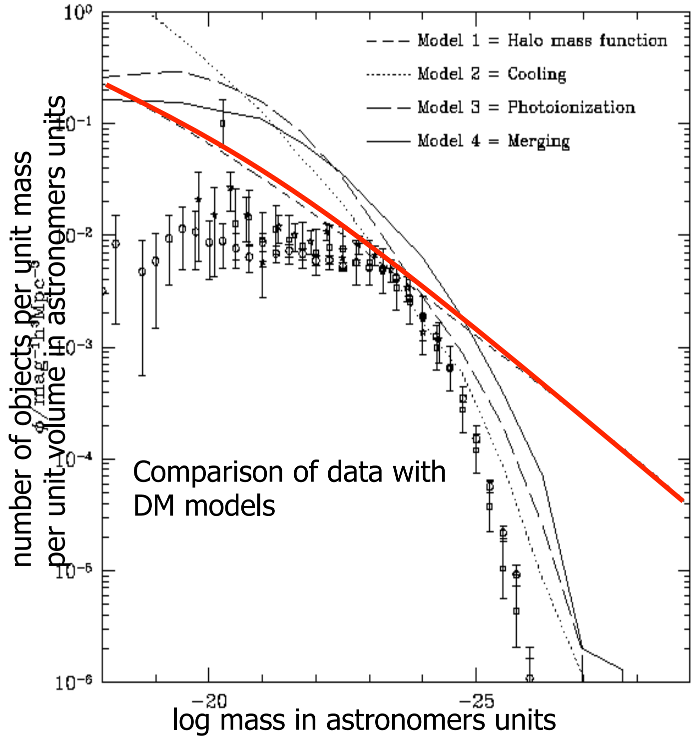
Formation of structure in the Universe

- 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





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

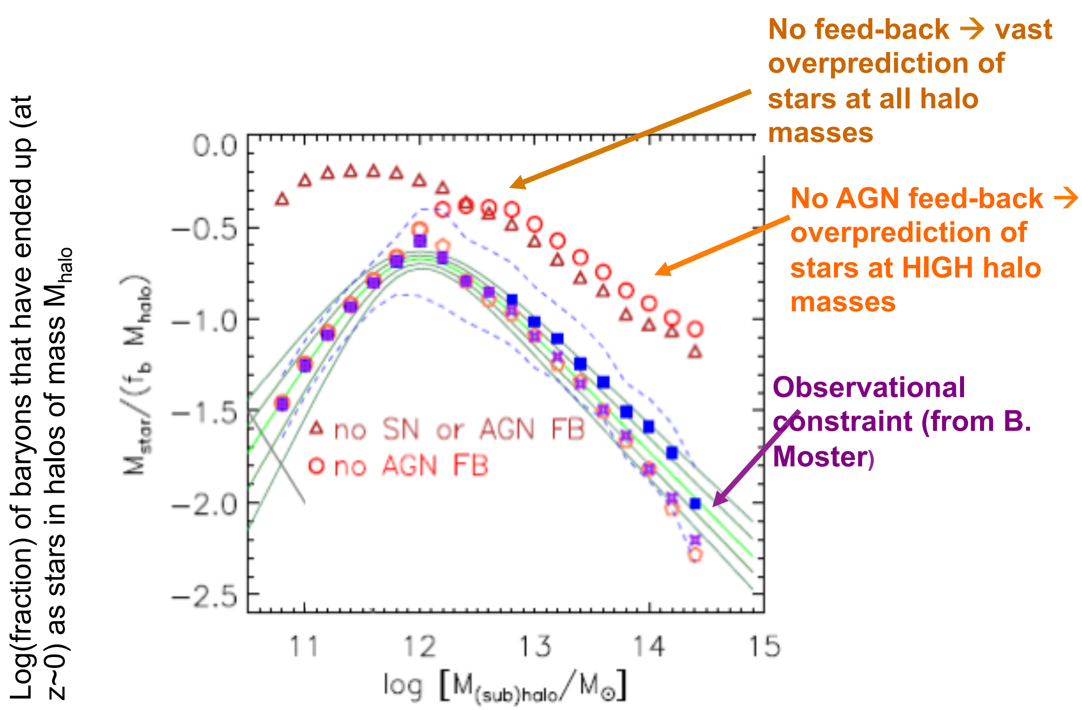


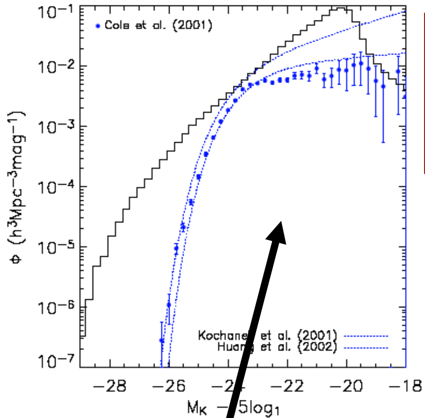
Observed relationship between number of dark matter halos of a given mass vs mass and the observed galaxy distribution

Galaxies do not trace the theoretically predicted dark matter halos !

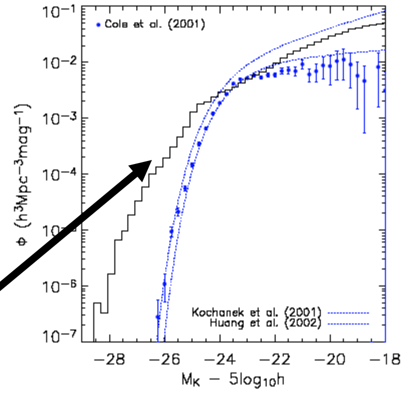
Why??

Comparison data—models (Somerville et al 08)





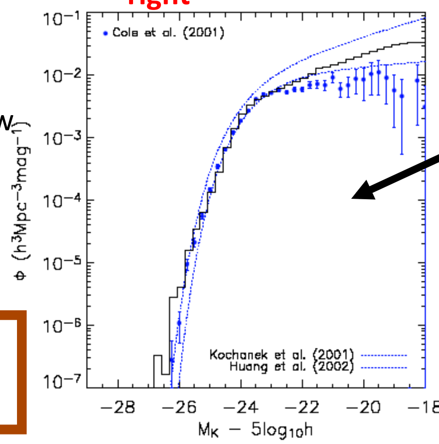
Calculation of K band galaxy luminosity function in N body simulation



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

Blue lines are data-black models



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

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 $\Delta E_{halo} = \varepsilon_{halo}\ \tfrac{1}{2}\, \Delta M_* V_{SN}^{\ 2}$ White & Frenk 1991

  Ejects gas $\Delta M_{eject} = \Delta E_{halo} / \tfrac{1}{2} V_{vir}^{\ 2} - \Delta M_{reheat}$ 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

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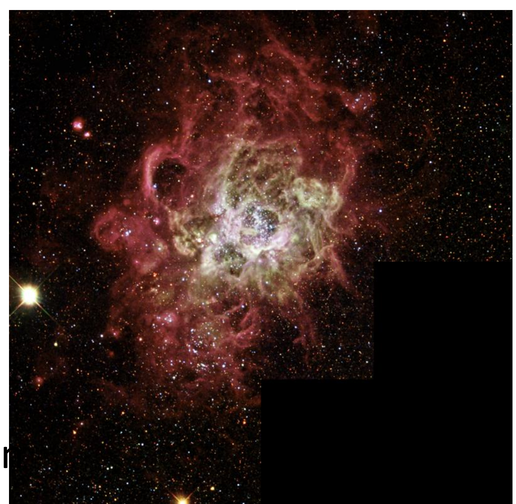
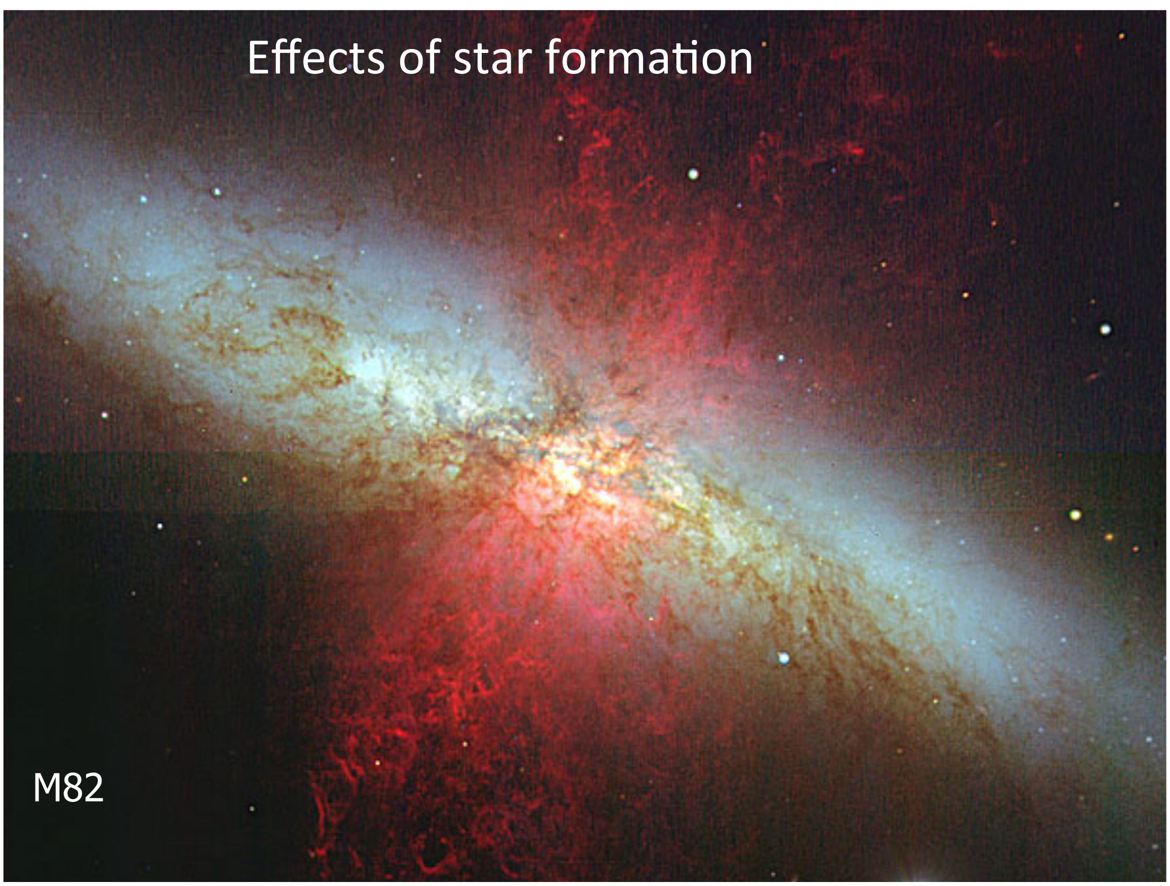


- Stellar winds and SNe
  - Comparable energy input
  - Disrupts birth clouds
  - Triggers new star formatio
  - Intense cases --> drives large-sc[redacted]s

Physics Beyond Gravity

- Starburst-driven galactic winds can transport mass, in particular metal enriched gas, and energy out of galaxies and into the intergalactic medium.
- These outflows directly affect the chemical evolution of galaxies, and heat and enrich the intergalactic and intracluster medium

- Similar phenomena can occur due to quasars



The Galactic Wind Can be Very Hot

- X-ray Image of M82 - only very hot ($T>2x10^6k$) gas emits in the x-rays