Galaxy Formation

Galaxy Formation- Basic Processes

Early Universe- sets the conditions

power spectrum of fluctuations - denser ones collapse first

Formation of the dark matter halo

- Gas pressure at **very early** times stops baryons from clumping
- Dark Matter - has no pressure - can clump at will, acts as seeds for galaxy formation

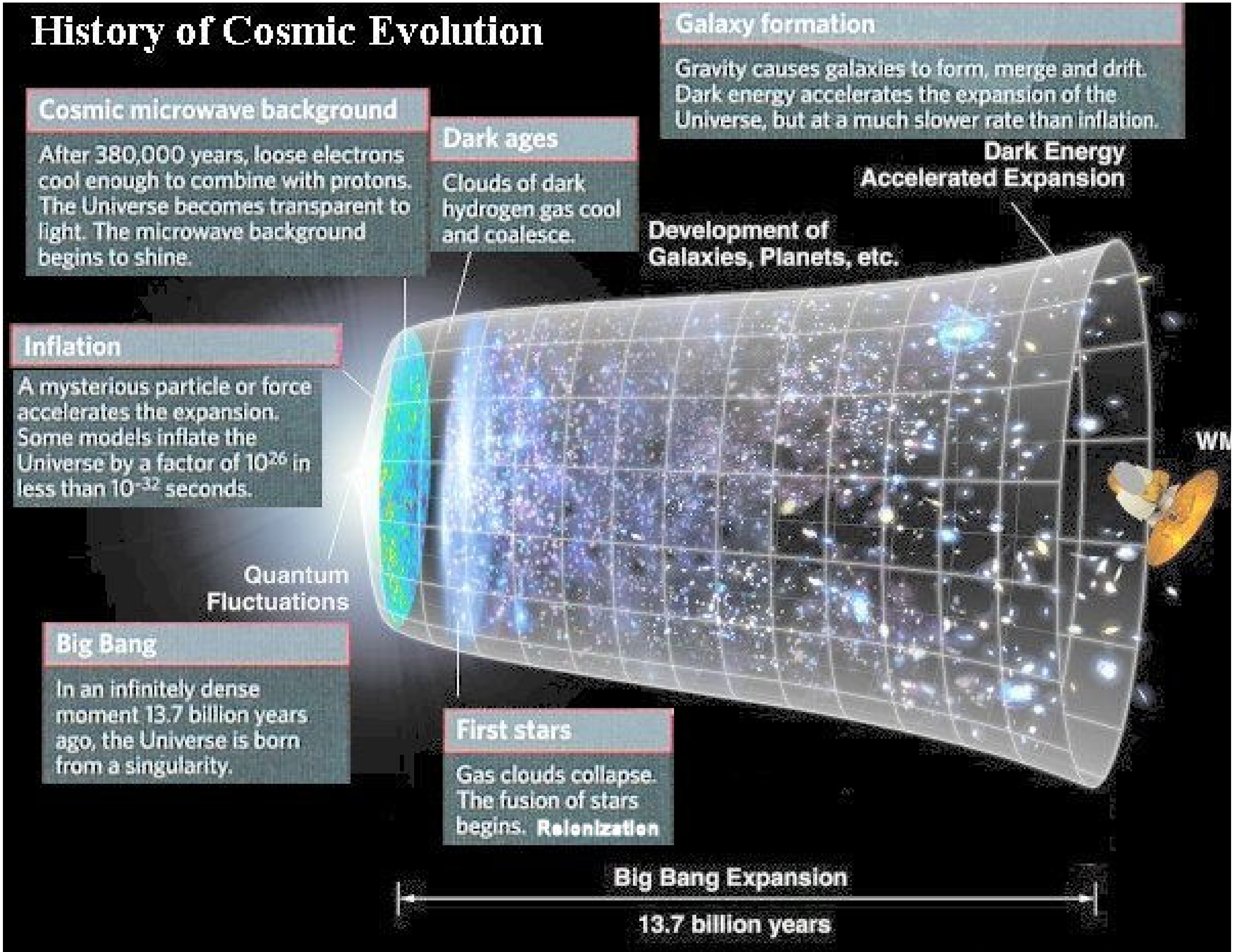
Gas accretion / cooling

- After recombination, everything neutral
- After reionization, everything ionized, 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 -spirals
- Merging randomises angular momenta - ellipticals

History of Cosmic Evolution



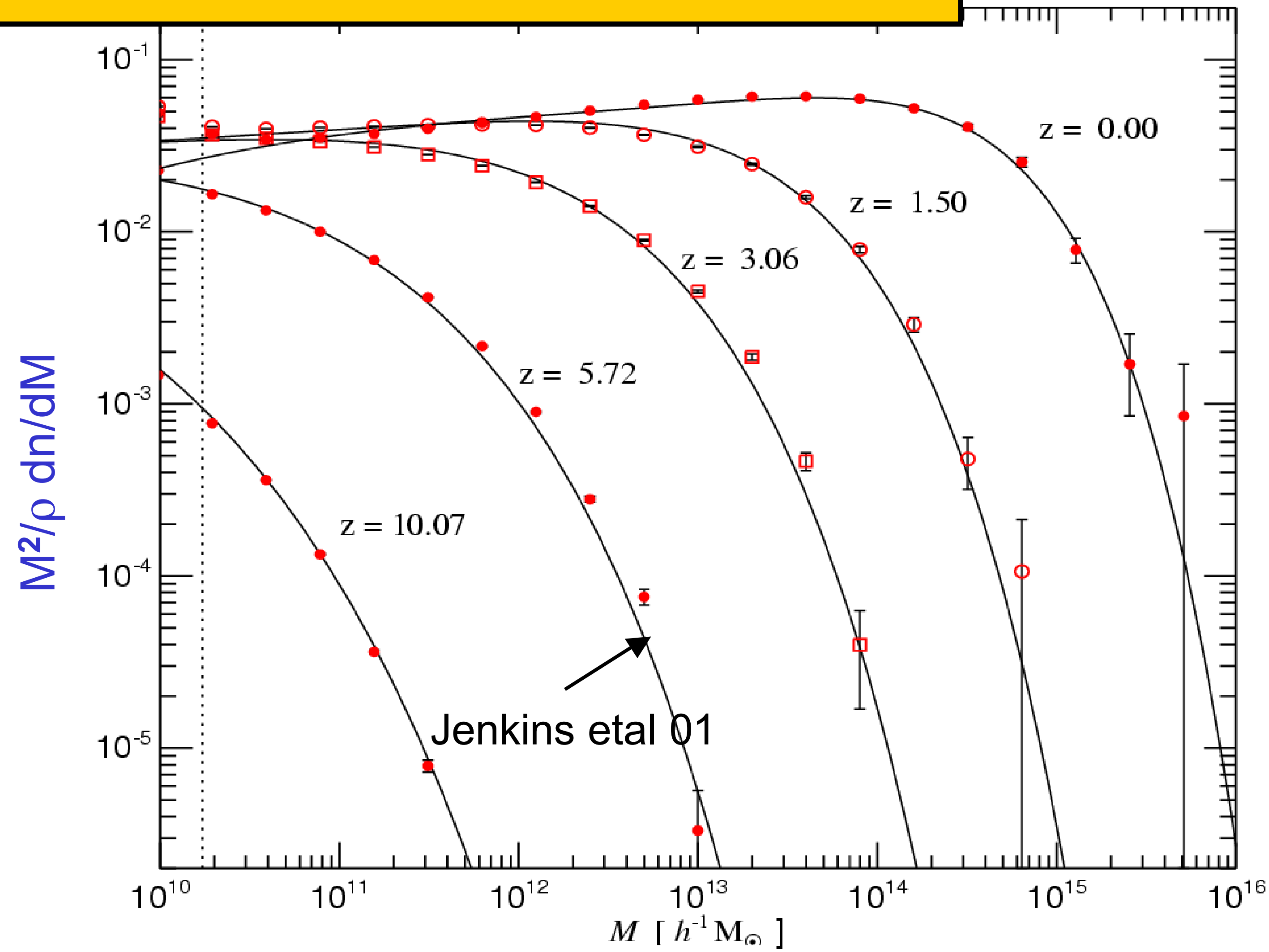
http://universe-review.ca

Growth of Dark Matter Halos from Numerical Simulation

Jenkins et al 2001

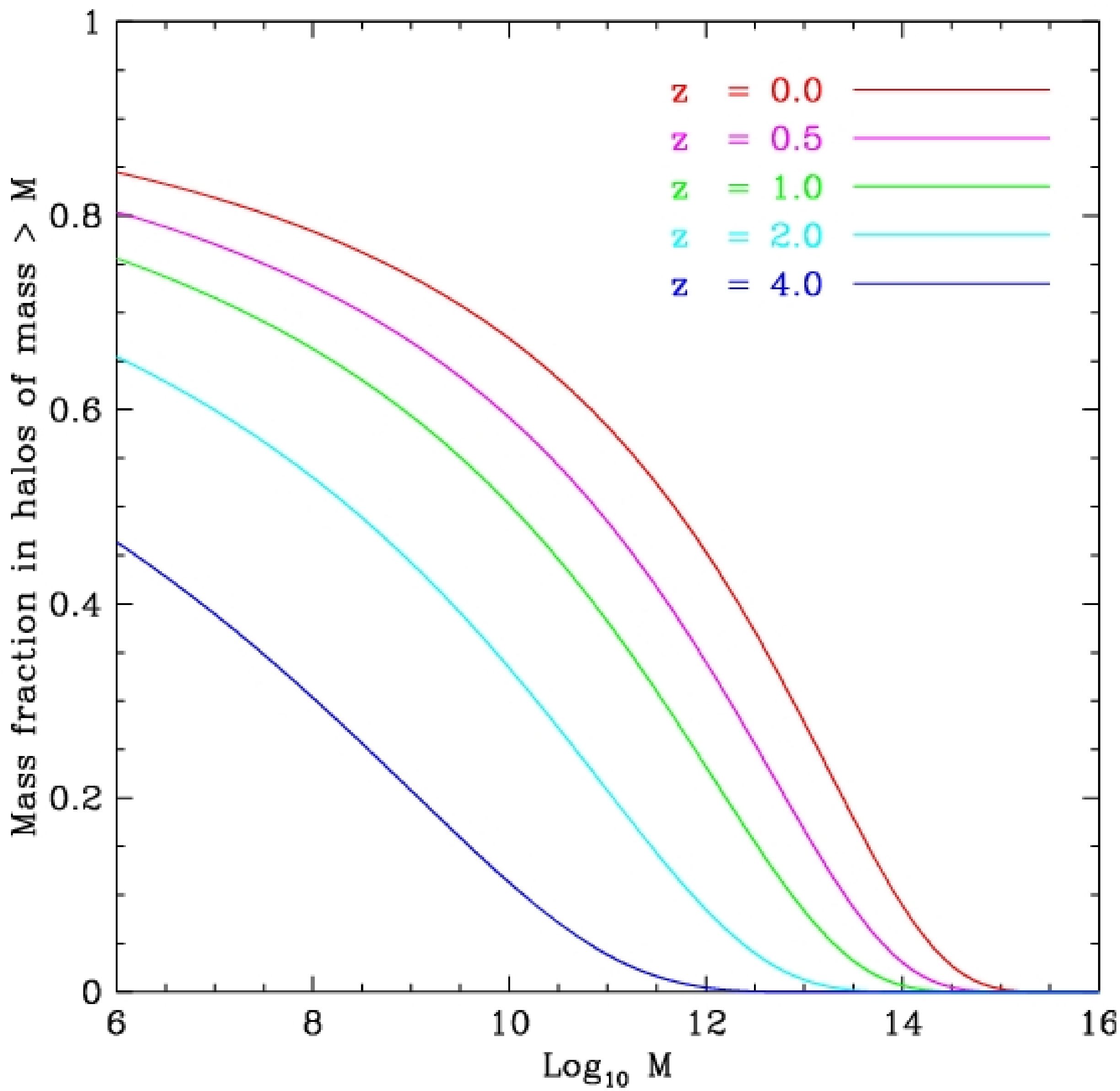
At z = 0 half of all mass is in lumps of M > $2.10^{10}M_O$

And ~90% in halos M > 210^6M_O



Mass M_o

Springel et al 2005

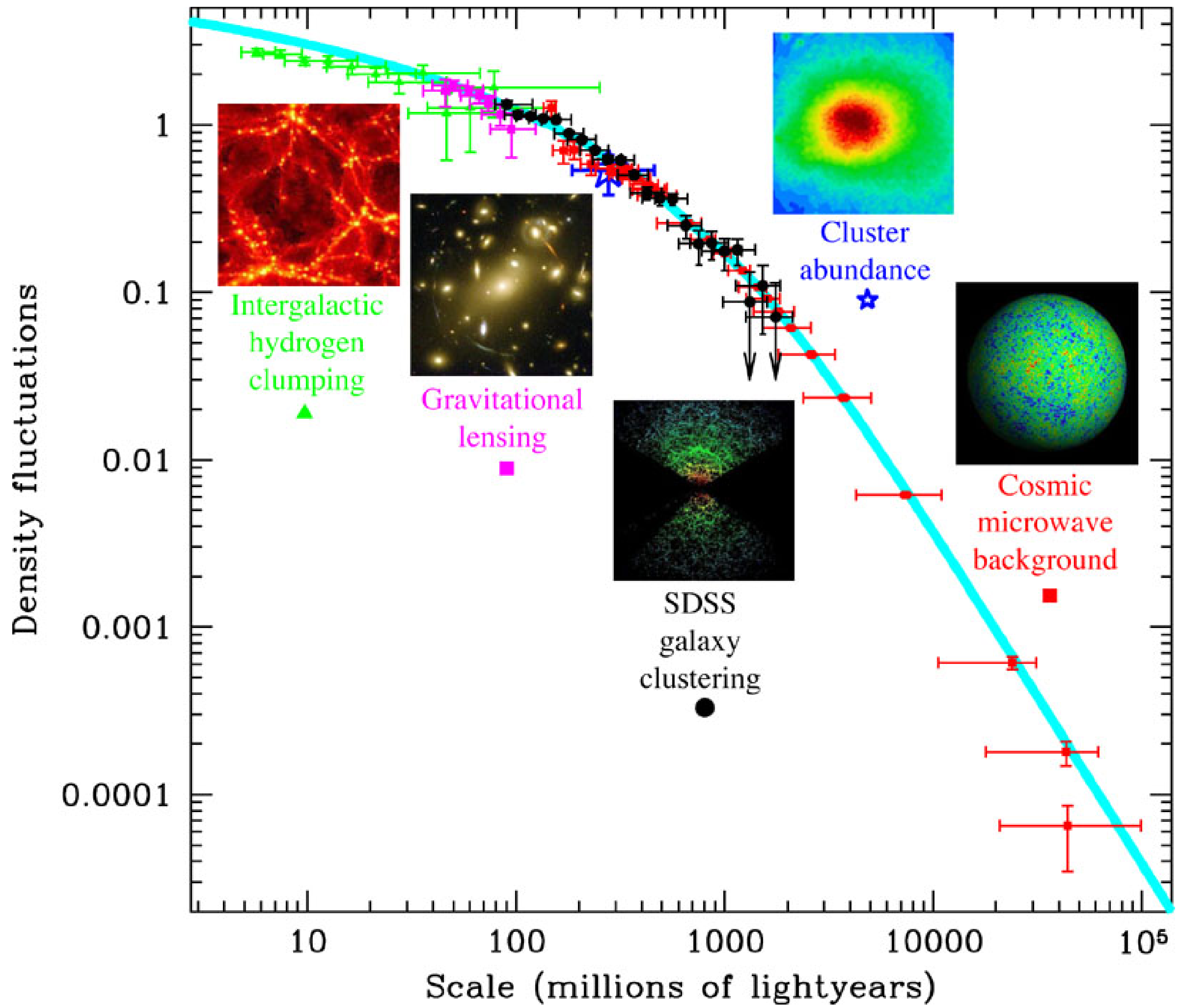


Mass fraction in halos of mass > M
Log10 M
z = 0.0
z = 0.5
z = 1.0
z = 2.0
z = 4.0
0
0.2
0.4
0.6
0.8
1
6
8
10
12
14
16

Power Spectrum of Fluctuations

- MWB has an extensive discussion of how fluctuations become collapsed objects

Lumpiness of universe

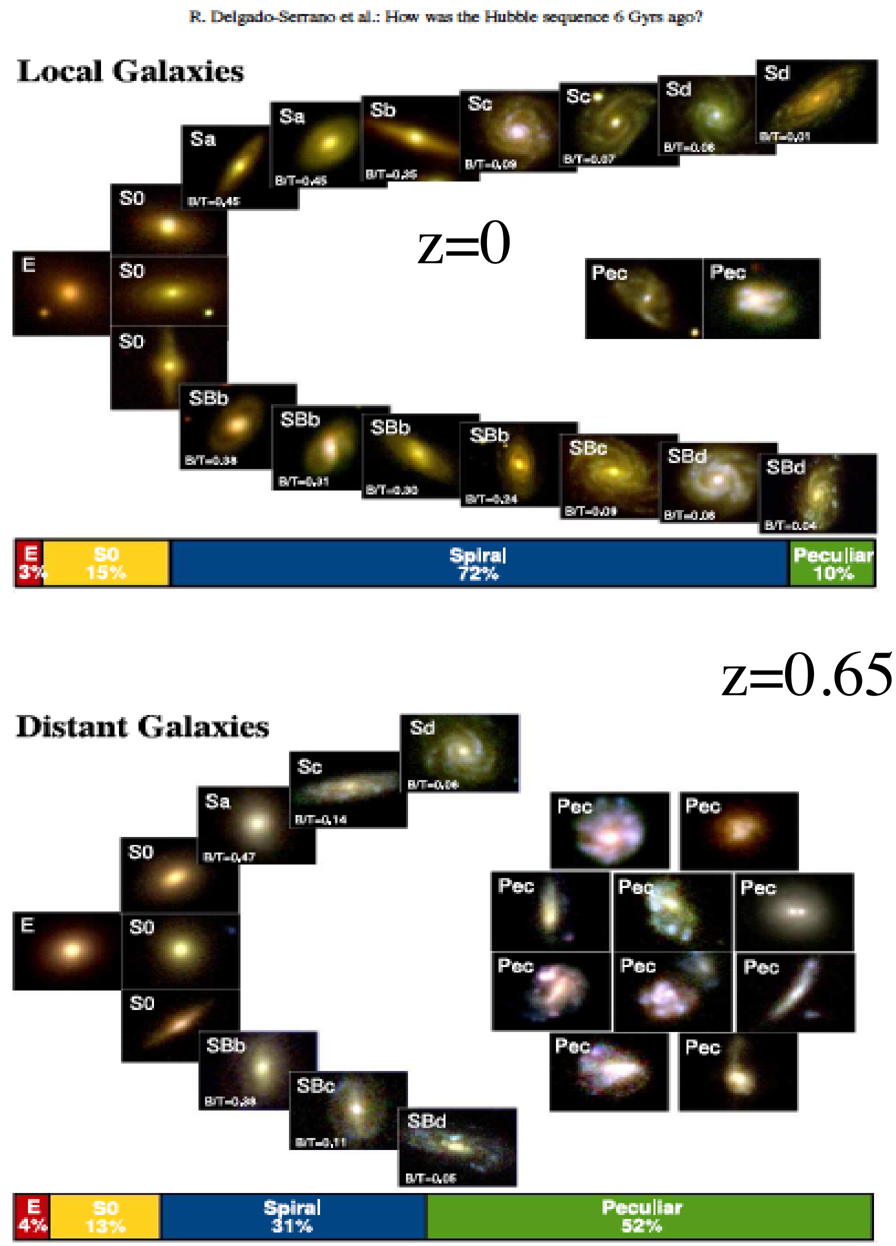


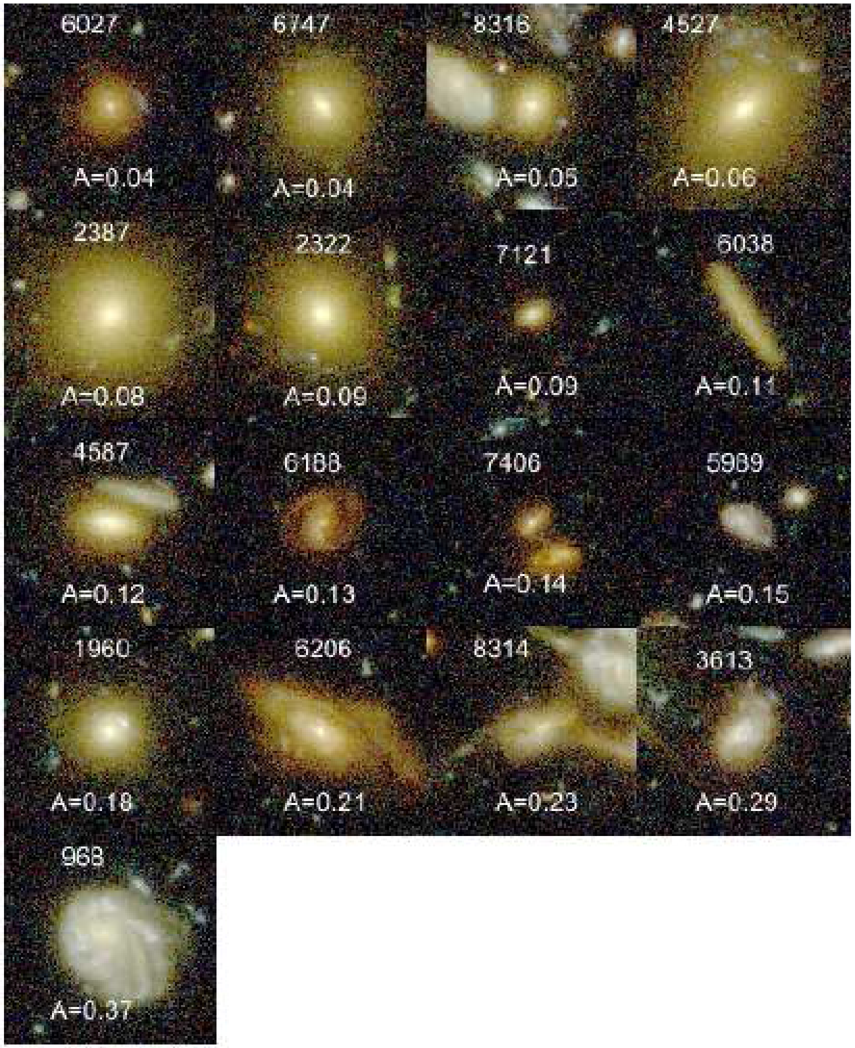
Tegmark 2004

size of box

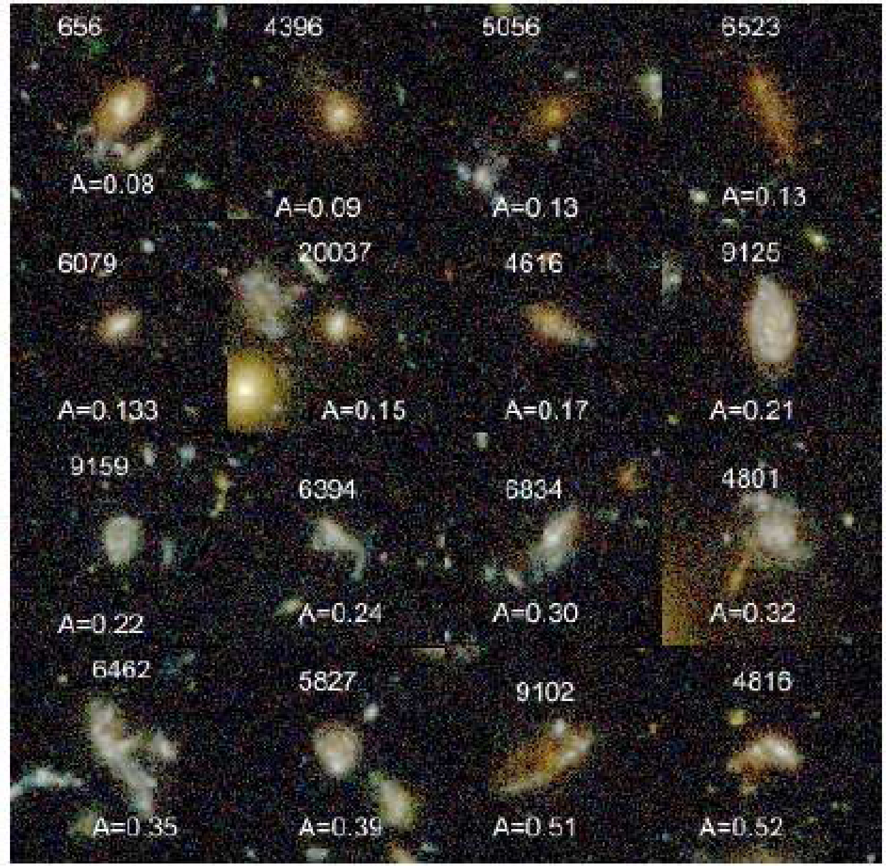
Changes Across Cosmic Time

- The Hubble sequence was established relatively recently, z<1.
  - Each bin contains 5% of the galaxies by number (Delgado-Serrano et al 2010)
- A z<0.65 the number elliptical and lenticular galaxies is roughly constant;
  - in contrast there is strong evolution of spiral and peculiar galaxies. Spiral galaxies were 2.3 times less abundant in the past, and peculiars a factor 5 of more abundant.
- more than half of the present-day spirals had peculiar morphologies, 6 Gyrs ago

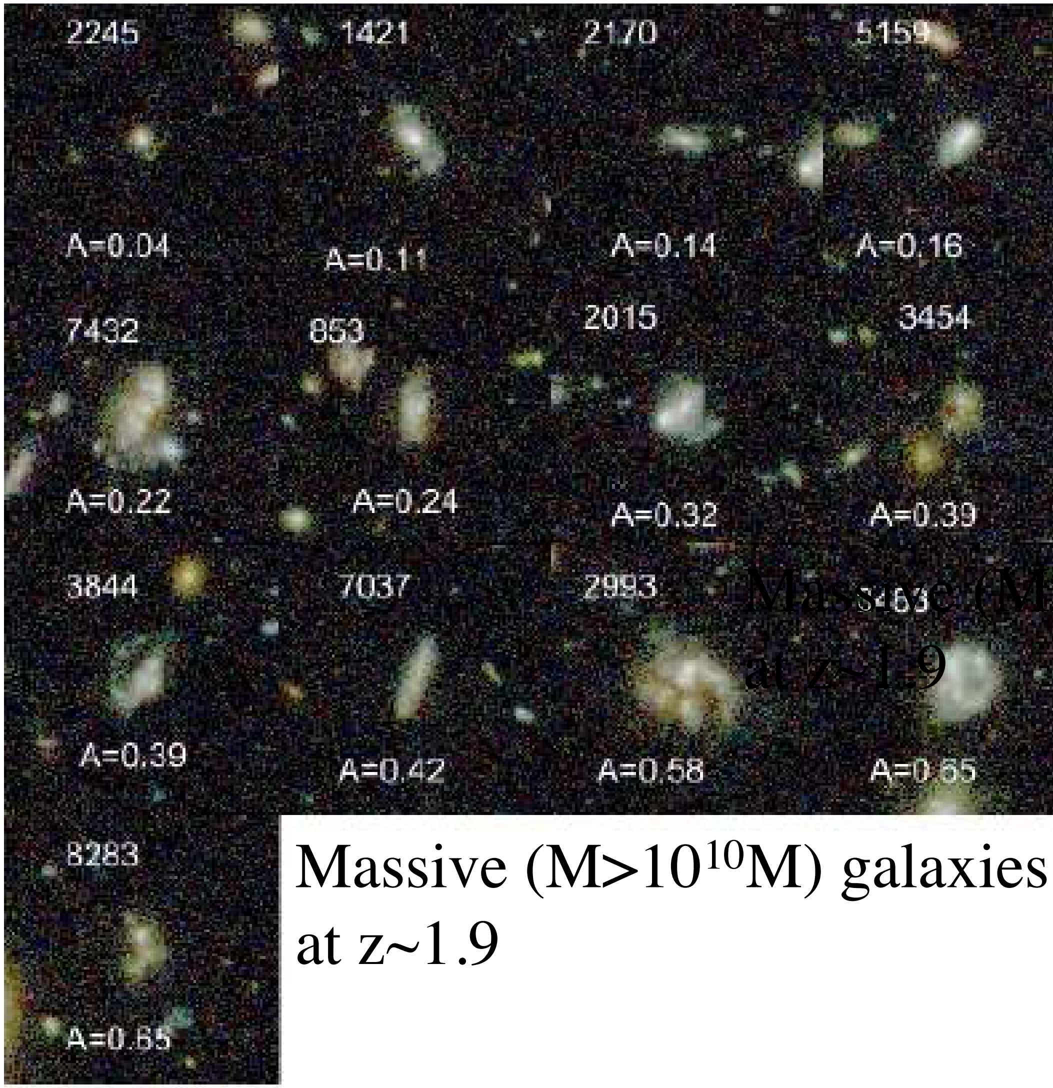




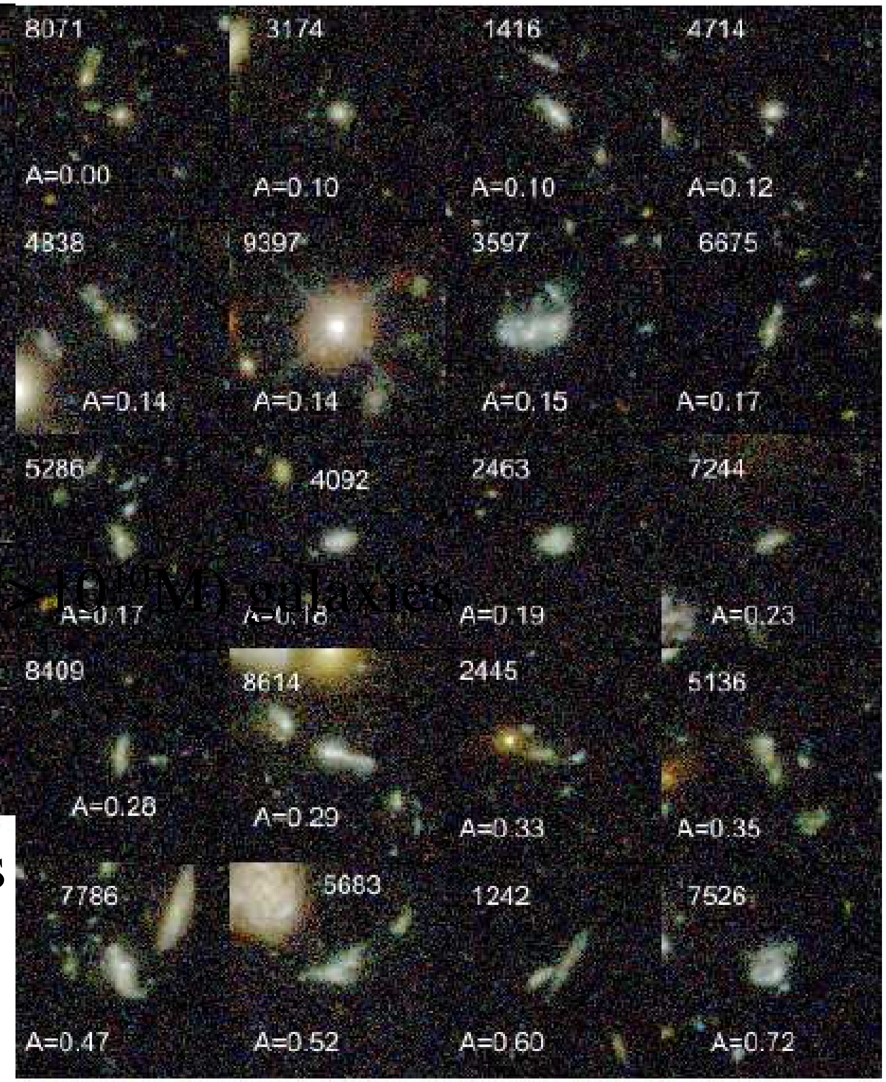
Massive (M>10^{10}M) galaxies at z~0.8



Massive (M>10^{10}M) galaxies at z~1.4



Massive (M>10^{10}M) galaxies at z~1.9



Systematic evolution in massive galaxy morphologies (Conselice et al 2008)

Massive (M>10^{10}M) galaxies at z~2.6

Components of a Galaxy

1) 3 galaxy 'components'

- Stellar distribution: bulge, disk, bars,
- Distribution of gas (and dust)
- Dark matter

2) The galaxy components only occupy a small part of phase space

- Tully-Fisher, the 'Fundamental Plane' and the Kormendy relations
- Morphology, mass vs. kinematics
- Stellar mass vs. halo mass

3) Morphology and structure vs. formation history

- the sizes of disk galaxies
- the shapes of massive galaxies

The fraction of galaxies with given properties and the nature of those properties changes with cosmic time in an 'organized' way (downsizing)

also morphologies change 'systematically' (no grand design spirals at high z, fewer classical ellipticals- more odd objects

Galaxy formation

Stars form in the cooled gas (H_2)

– SFR laws as we discussed, needs cold dense gas, Jeans critieria

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

- Dynamical assembly history-a probe largely of *dark* disks, conservation of angular momentum spheroids, mergers/interaction+infall
- Star formation history -

a probe of the physics of *normal matter*

The two are inexorably linked

Outflow from starburst M82

Formation of Large Scale structure

The standard theory of the formation of structure by the evolution of dark matter halos has been remarkably successful

But it has several "missing pieces"/problems

•How does gas become galaxies, clusters and groups?

•***What is the origin of the "feedback" process that controls efficiency of conversion of gas in to stars and governs the star formation rate in the universe?***

•Do galaxies actually form via cooling and what is the interaction with star formation ?

•How is the chemical evolution of galaxies connected with their formation ?

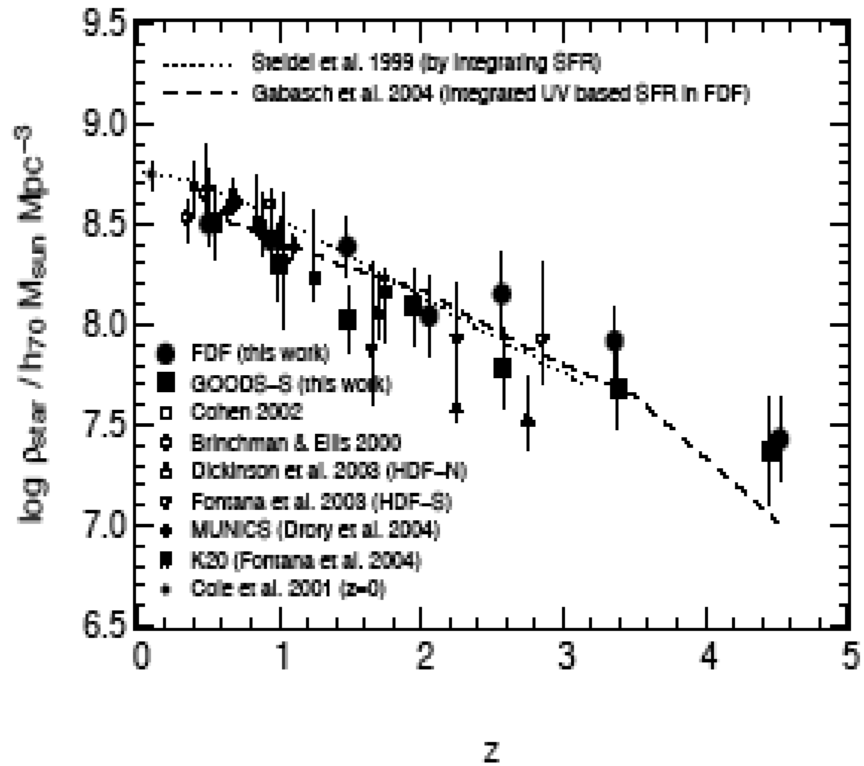


FIG. 3.— The total stellar mass density of the universe as a functic redshift. We also show the integral of the star formation rate as a dottec and dashed line.

Growth of galaxy mass vs redshift 50% of mass created at z<1 (Drory et al 2004, astro-ph 412167)

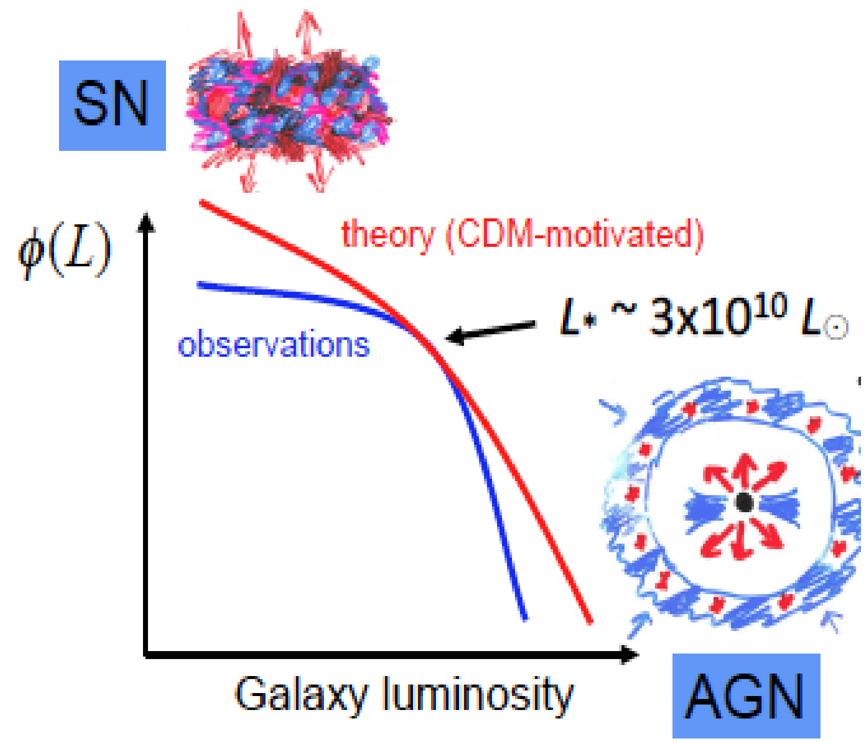
Galaxy Formation

- Theory provides the mass function of dark halos. Observation yields the luminosity function of galaxies
- The basic set of ideas:
- small initial density fluctuations grow with time due to gravitational instability.
- the dark matter collapses into haloes with a quasi-equilibrium state through violent relaxation,
- the baryonic matter falls into the potential wells of these haloes forming a hot gaseous halo
- The gas in this halo cools, which reduces the pressure support and causes the accretion of cold gas from the halo onto a central disc.

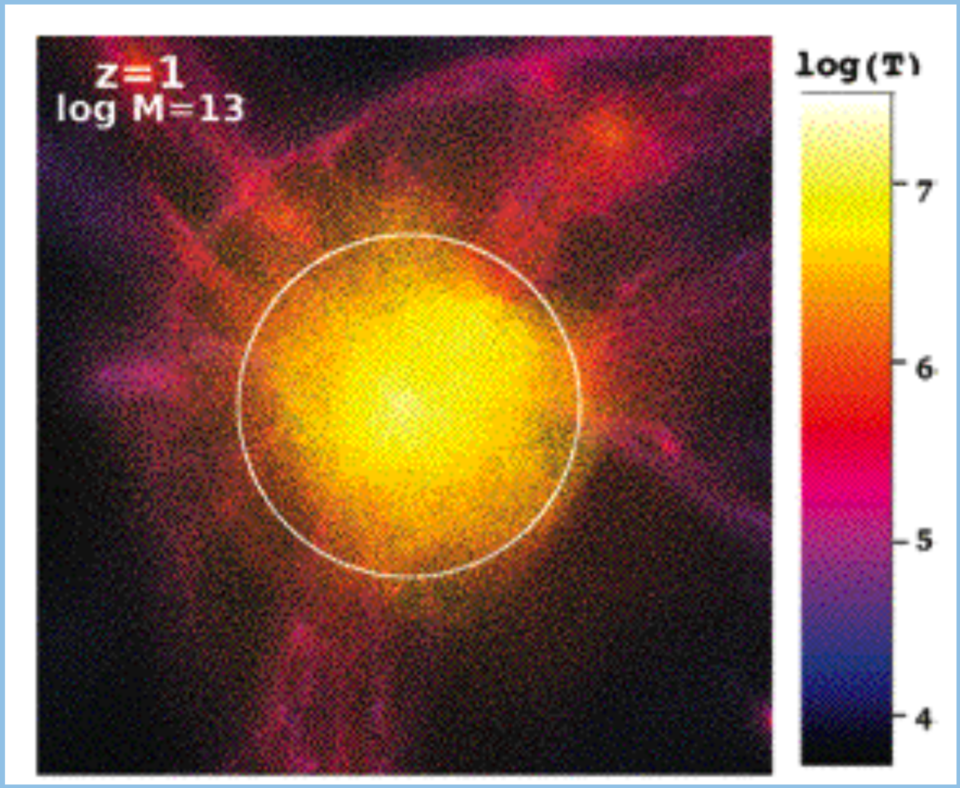
Sommerville et al 2012

•stars can form depending on the gas density on a characteristic timescale resulting in a rotating stellar disc

•mergers create ellipticals (?)



How Does Gas Get Into Galaxies



- IGM initially diffuse, cool gas
- Overdense regions form
- Majority of gas shock-heated as it falls into dark matter halo
- Cooling
- Star formation

Keres et al. 2009, MNRAS **395**, 160-179

Keres et al 2009

What about gas?

- continuous mass distribution
- gas has the ability to lose (internal) energy through radiation (no angular momentum loss through cooling)
- Two basic regimes for gas in a potential well of 'typical orbital velocity‘, v
  - $kT/m \approx v^2 \rightarrow$ hydrostatic equilibrium
  - $kT/m << v^2$, gas is cooler than the depth of potential

in the second case:

supersonic collisions → shocks → (mechanical) heating →(radiative) cooling → energy loss

For a given (total) angular momentum, the minimum energy orbit is

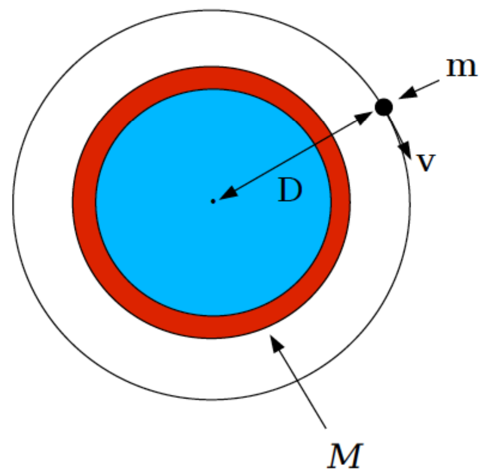
a (set of) concentric (co-planar), circular orbits.

→ cooling gas makes disks!

Galaxies Changing…

- What processes change galaxies over cosmic time
  - growth
    - mergers (dry, wet)
    - accretion
    - transformation
  - Harrasment
    - tidal stripping
    - ram pressure stripping
  - Evolution
  - Others (e.g. effect of AGN, starbursts)

Tidal Stripping



If the mass m is close enough to the particles in M then the particles closest to M are at risk of being removed or stripped from the larger body.

Mihos-

Galaxy Formation Basics - E Bell

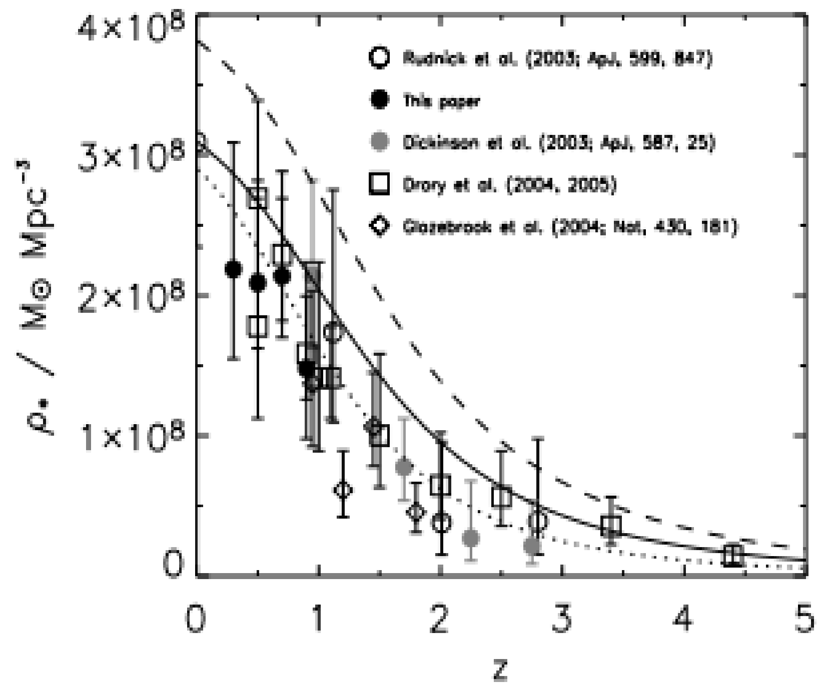
- Very Early Times
  - Dark matter accretion
    - Can collapse pre-recombination
    - Halo mass function $\propto M^{-2}$
    - Halos grow only through merging (mass accretion ~ scale free)

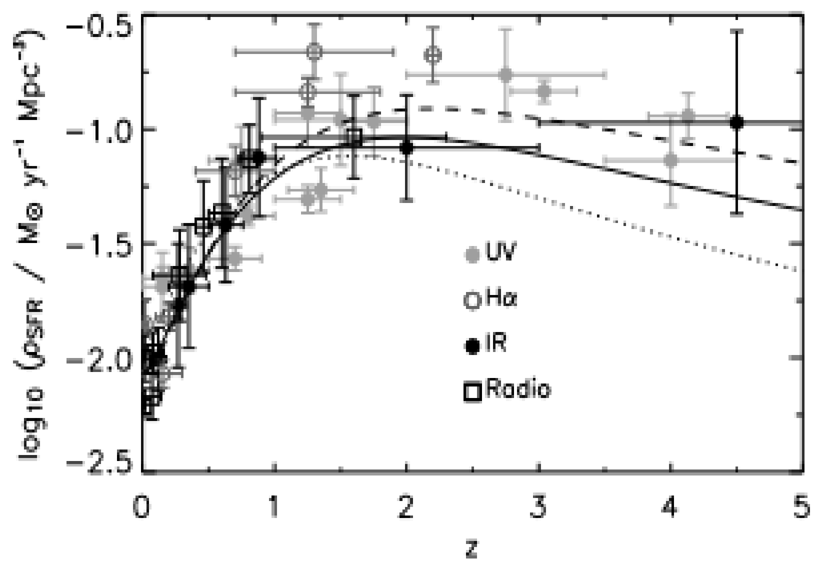
- After reionization- 4 main processes
  - Gas accretion / cooling from cosmic web
  - Gas cooling rate $\propto n^2$
  - Depends on metallicity
  - Hot mode (virial temp) / cold mode
- Star formation
  - SFR $\propto$ H_2 mass Empirical star formation laws
    - SFR $\propto$ gas density $^{1.4}$ (Kennicutt 1998)
    - SFR $\propto$ gas density / t_{dyn} (Kennicutt 1998)
- Feedback
  - Flows -out of galaxies
  - Redistributes metals
  - Regulation of SF
  - Suppresses low-mass galaxies
    - $E \sim E_{SN}$; $V \sim < V_{esc}$; $dM/dt \sim SFR$

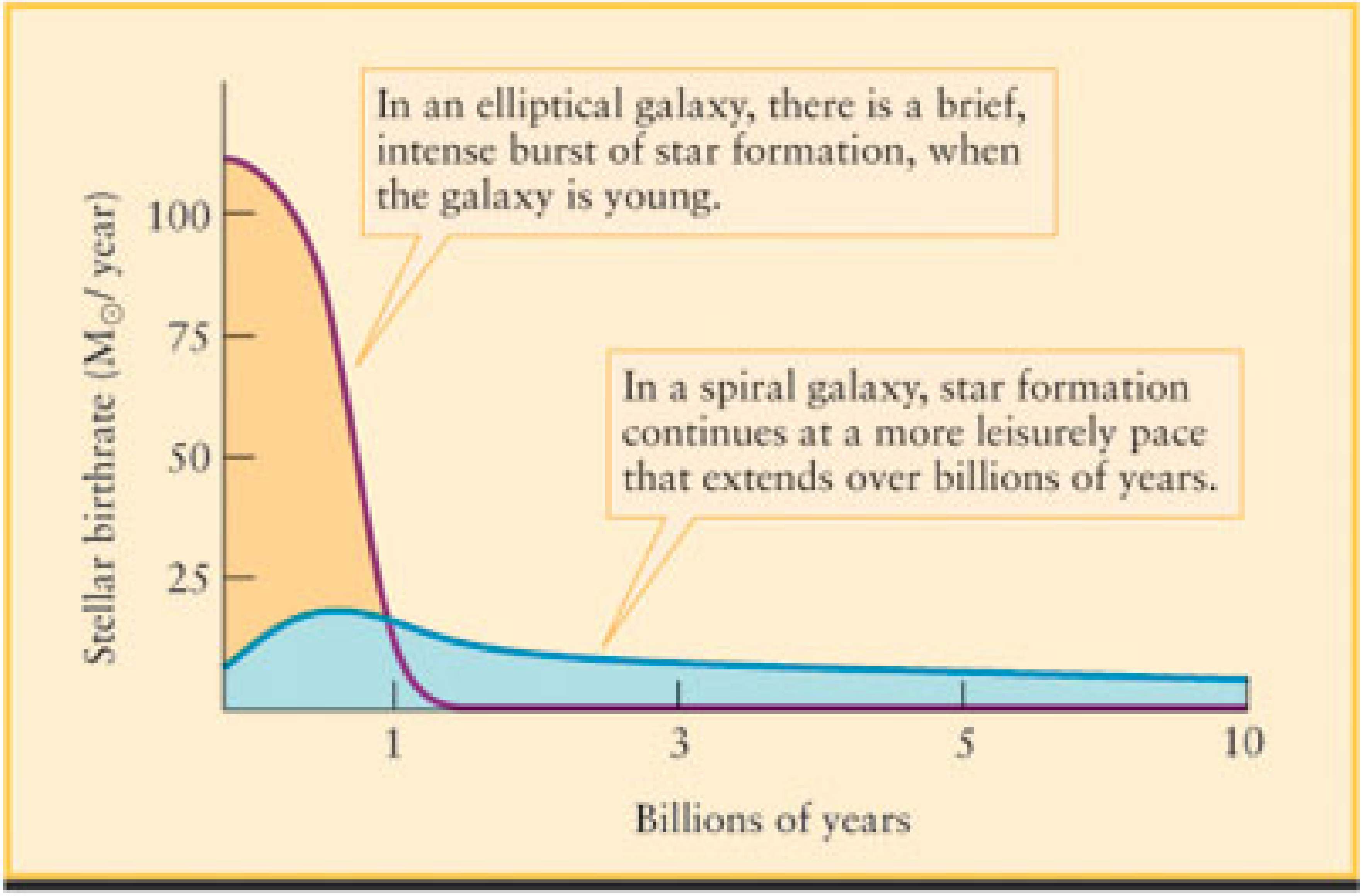
Merging- dark matter halos and their baryonic contents can merge morphology changes

Growth of galaxies

- About 1/2 of all stars are formed at z>1
- Cosmic star formation rate increases rapidly from now to z~1, flattens ; very uncertain z~3-4, drops at higher z
- This history of star formation is also accompanied by changes in the galaxy population
- Star formation in massive galaxies essentially ceases at z~1
- rapid growth of the quiescent galaxy population between z =2 and the present day, this growth appears to be intimately linked to the growth of galaxies with prominent bulges
- Number density of mass ($M>3x10^{10}M_{\odot}$) galaxies increases by a factor of 5 from z=2 to now





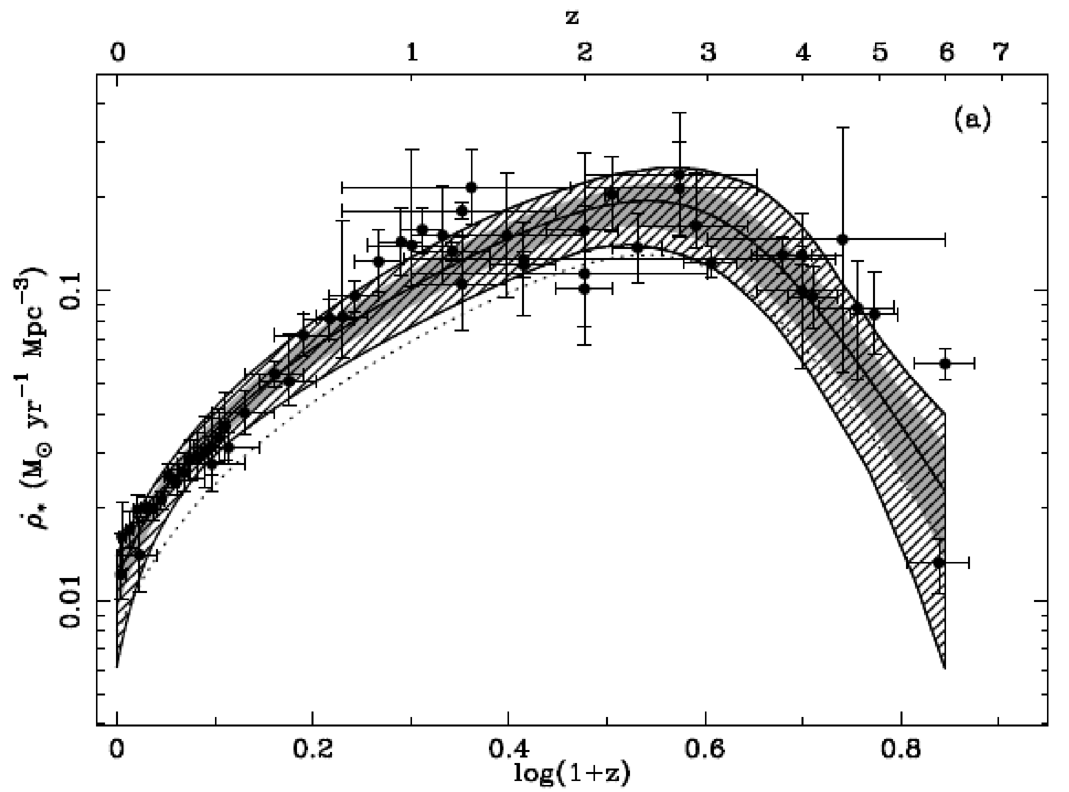


(c) The stellar birthrate in galaxies

Star Formation History of the Universe

- The rate of star formation peaked at z~2 when the universe was 3.3 Gyrs old-10Gyrs ago

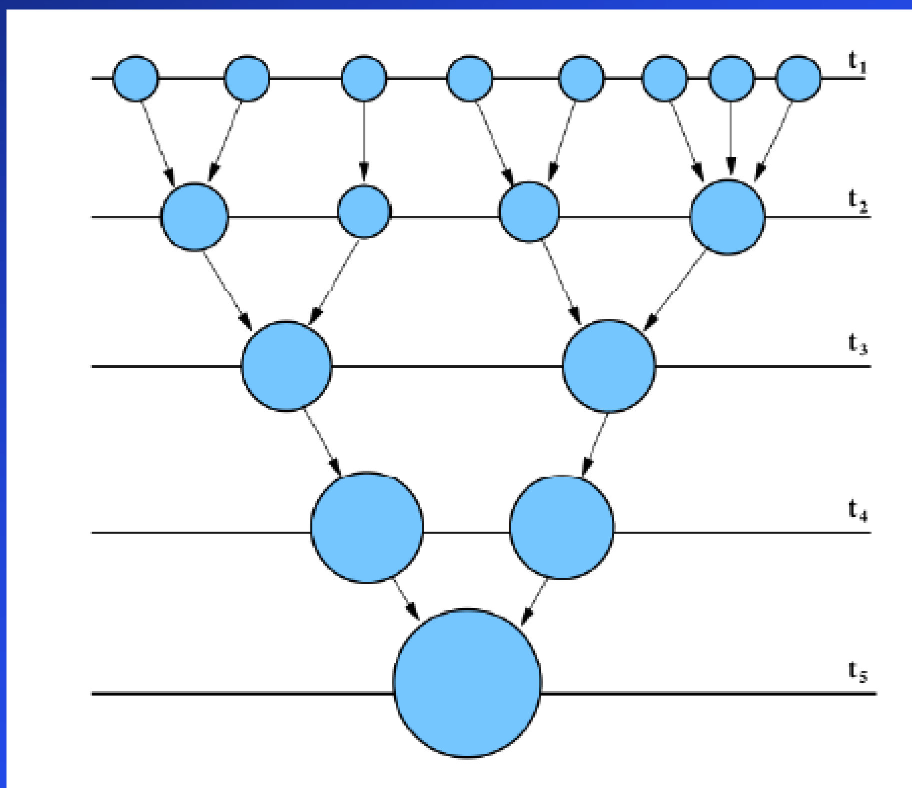
- Peak of elliptical galaxy star formation was at 2-4Gyrs after the Big Bang and stopped rapidly thereafter
- Spirals keep on going



Elements of the Modelling

http://www.daf.on.br/etelles/lectures/lacey-2.pdf

Assembly of dark matter halos: Merger trees

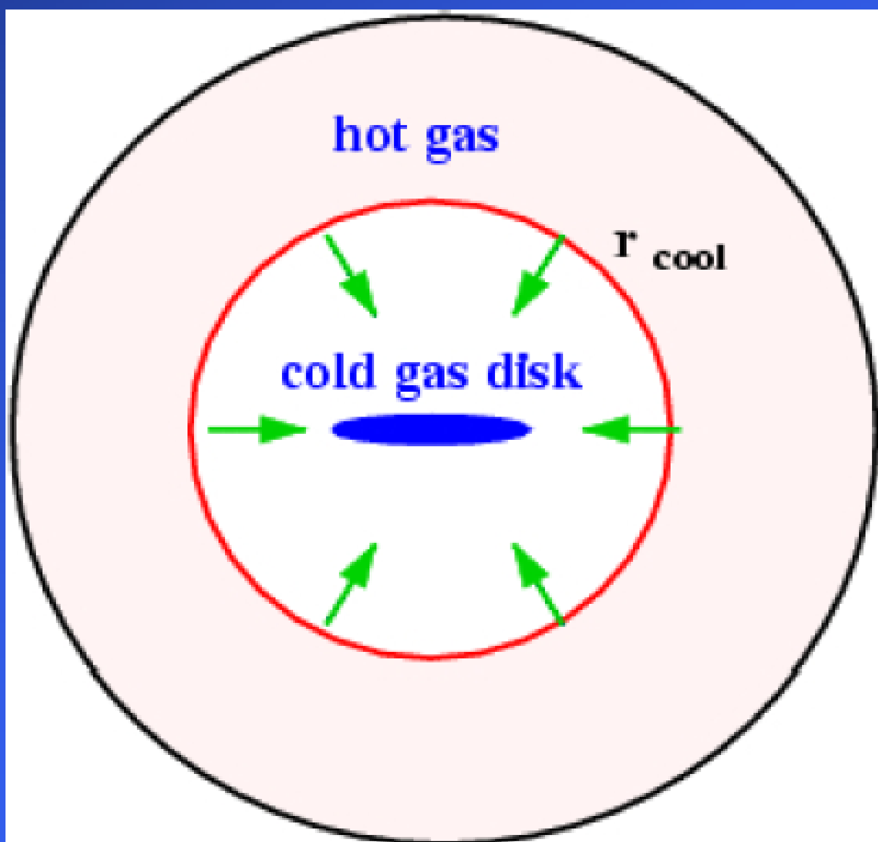


- Assembly history of halo described by merger tree
- 2 approaches:
- **Monte Carlo** based on conditional **Press-Schechter** mass function
- **Extract** from **N-body simulations**
- similar results from both approaches

Hot Mode Accretion

Shock-heating & cooling of gas in halos

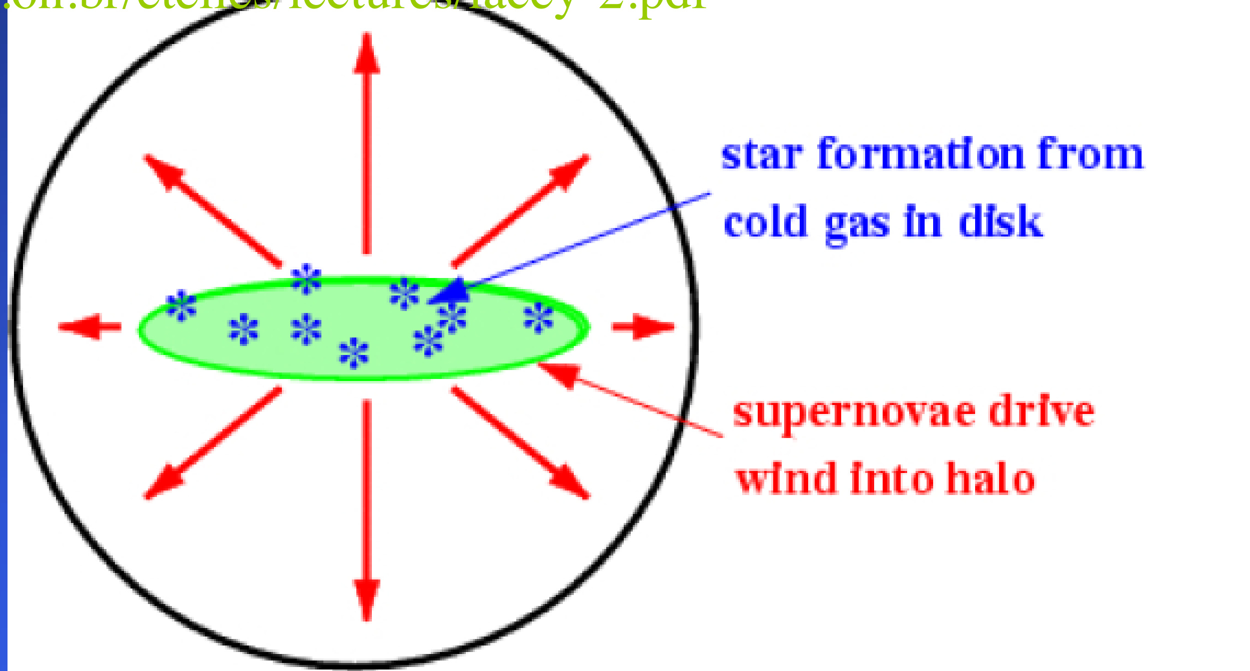
http://www.daf.on.br/etelles/lectures/lacey-2.pdf



- Infalling gas all shock-heated to halo virial temperature
- Radiative cooling of gas from static spherical distribution
- Disk size related to angular momentum of gas which cools

Star formation & feedback

http://www.daf.on.br/etelles/lectures/lacey-2.pdf



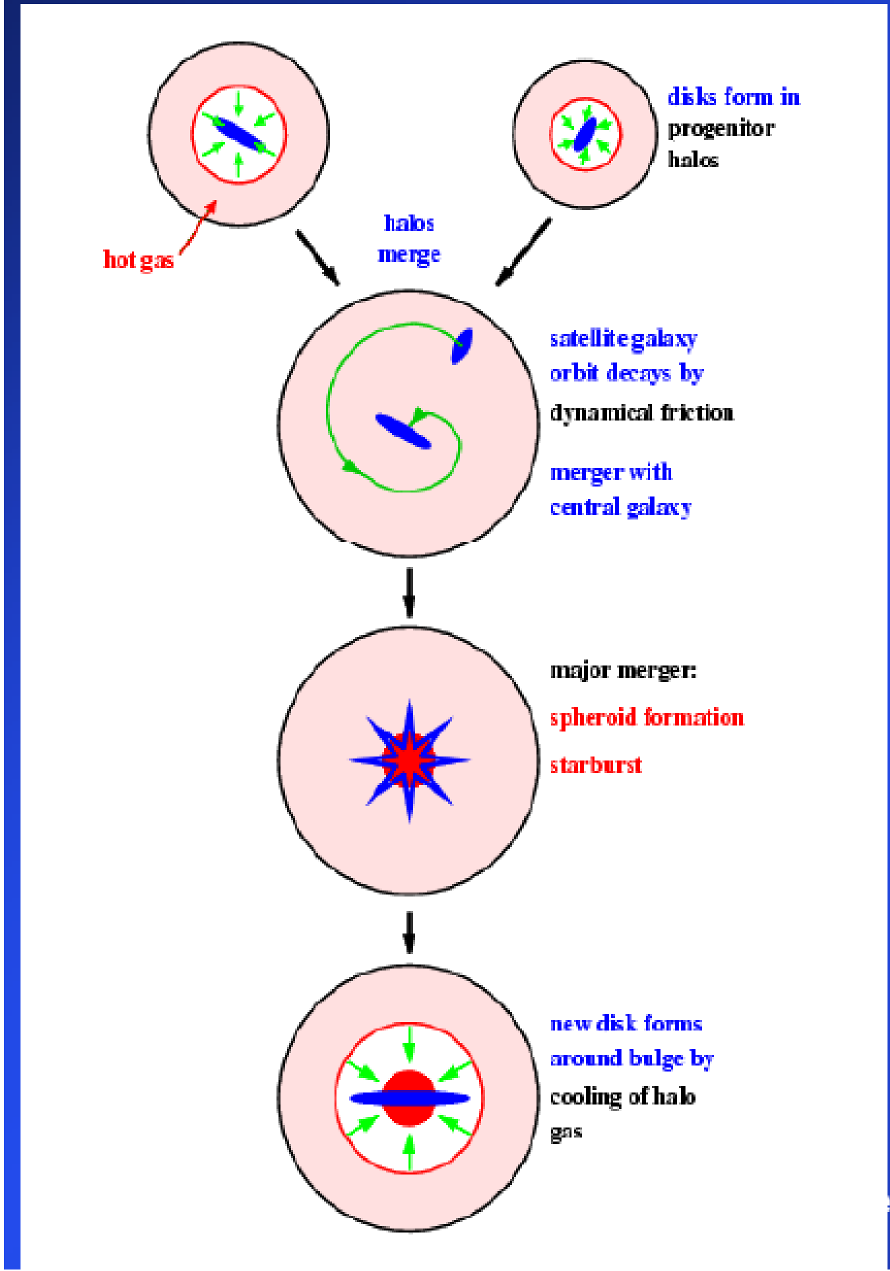
- **stars form in disks**

$$SFR = M_{gas} / \tau_*$$

- **supernova feedback ejects gas from galaxies**

$$\dot{M}_{eject} = \beta(V_c)\, SFR$$

Galaxy mergers & morphology



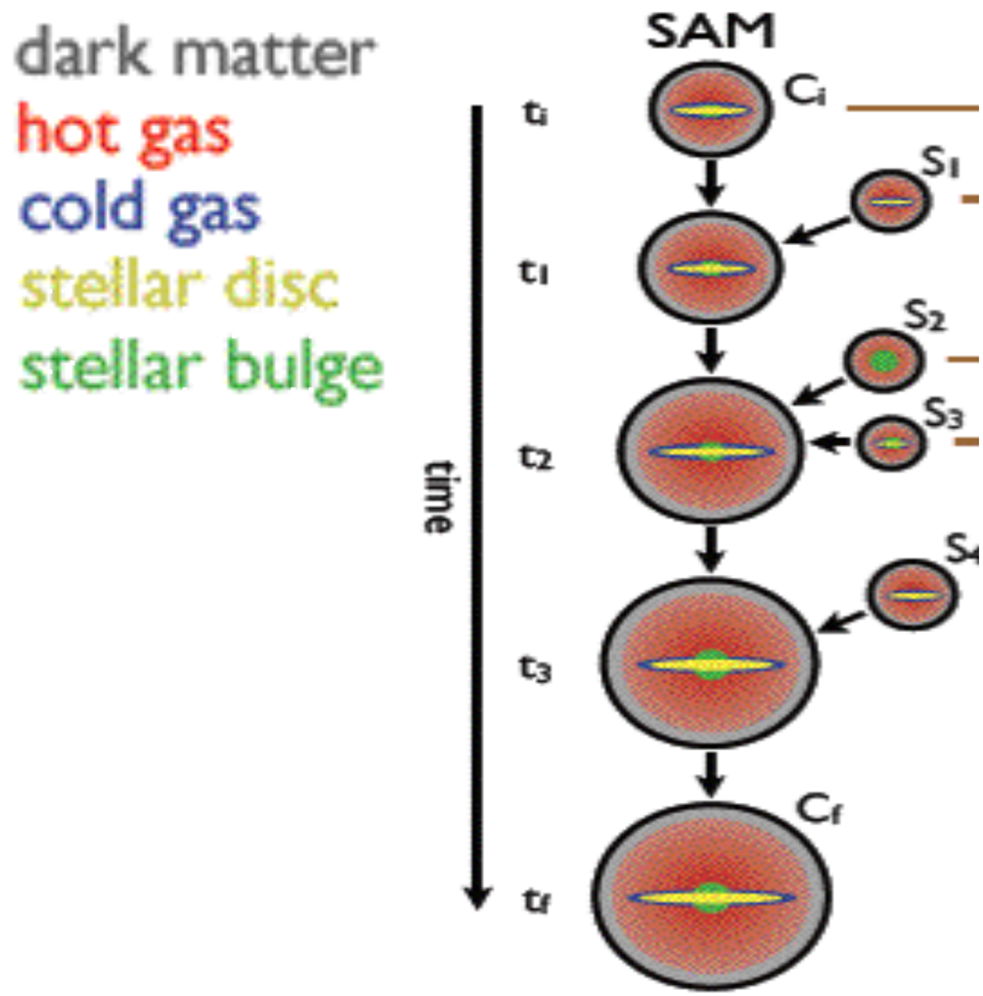
- halos merge
- galaxies merge by dynamical friction
- major mergers make galactic spheroids from disks
- mergers trigger starbursts
- spheroids can grow new disks

http://www.daf.on.br/etelles/lectures/lacey-2.pdf

How to Include Baryonic Physics

When baryonic physics is added to the dark matter N-body realizations a lot of the predictive power is lost in the addition of many adjustable parameters required to describe the many physical processes at work:

star formation, galactic winds, cold streams, supermassive black holes (formation, feedback), chemical evolution, galaxy mergers, starbursts, supernova feedback, dust effects etc, .

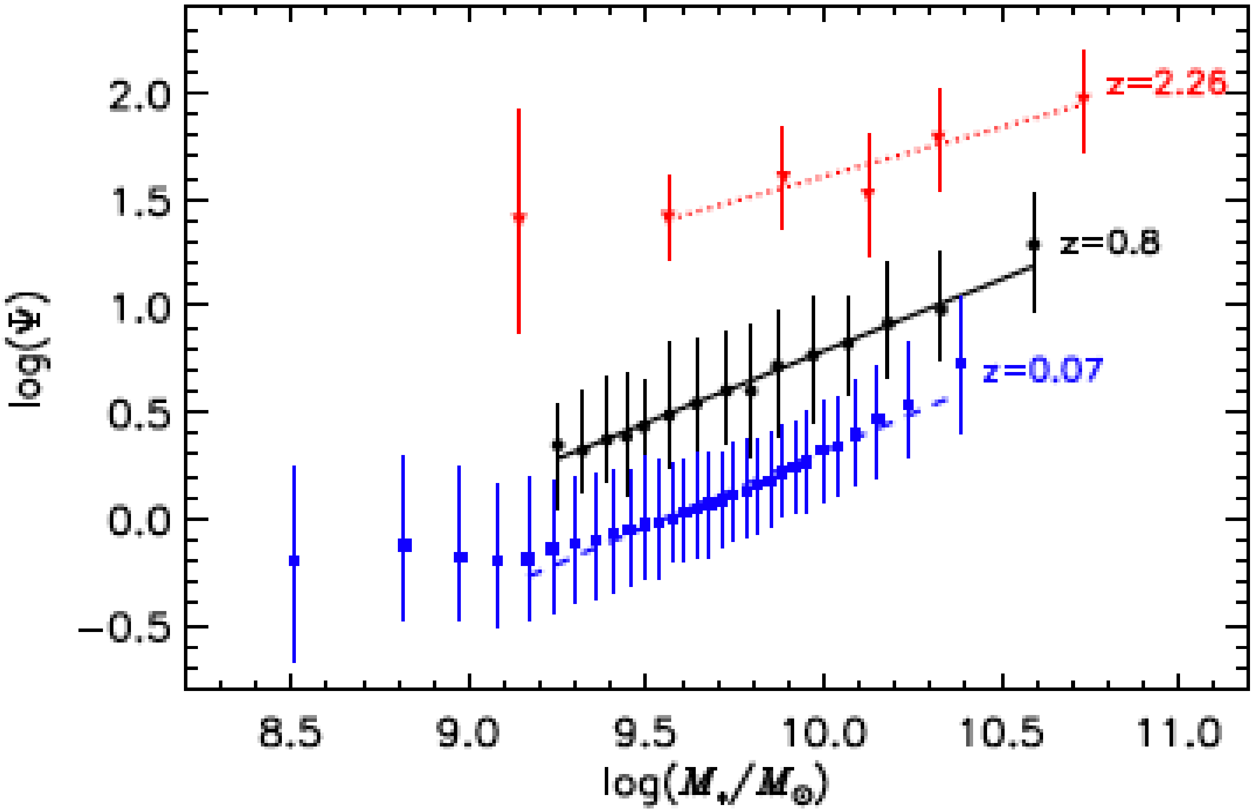


Moster, Maccio and Somerville

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

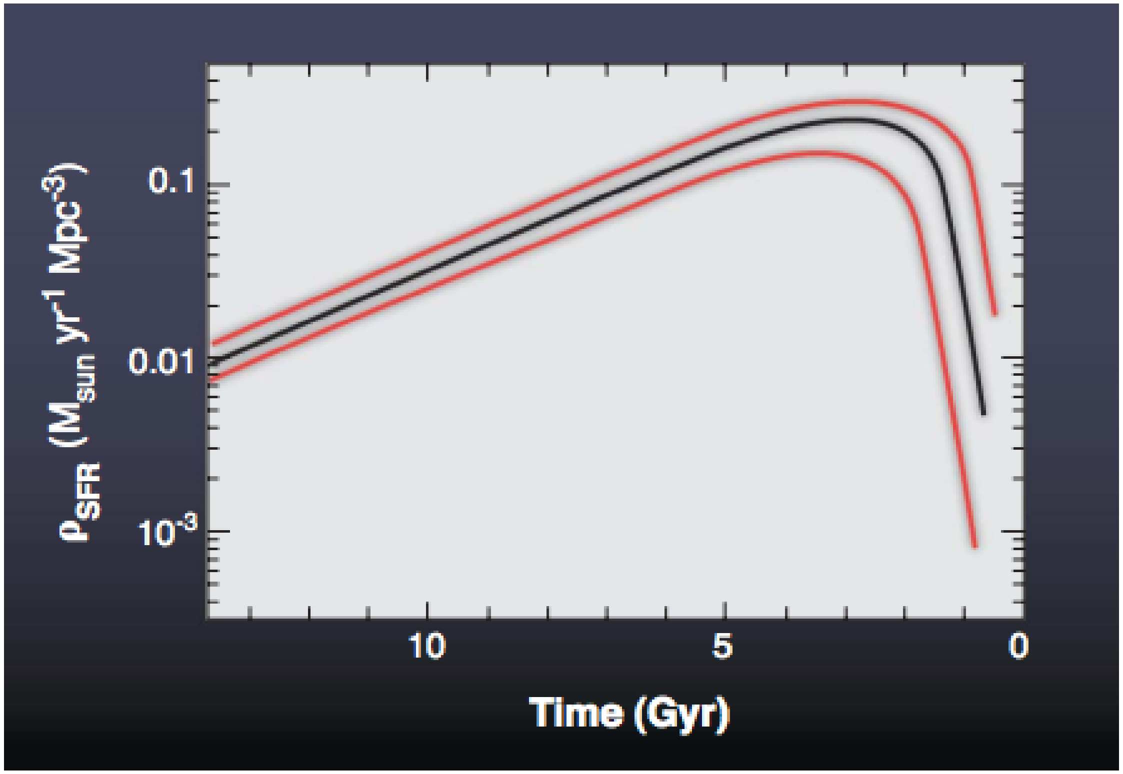


log mass

•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.

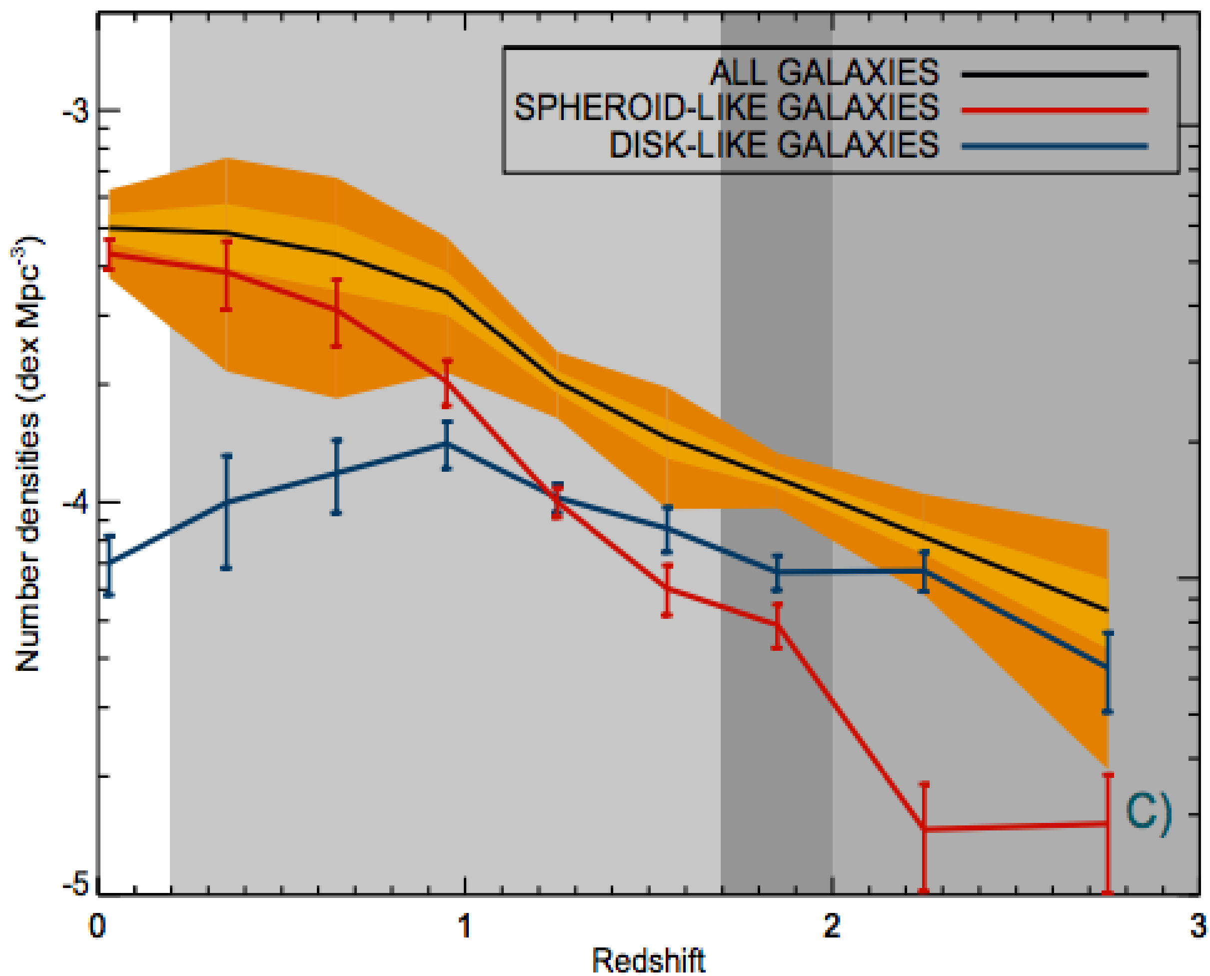


Dunlop 2011

Massive galaxies

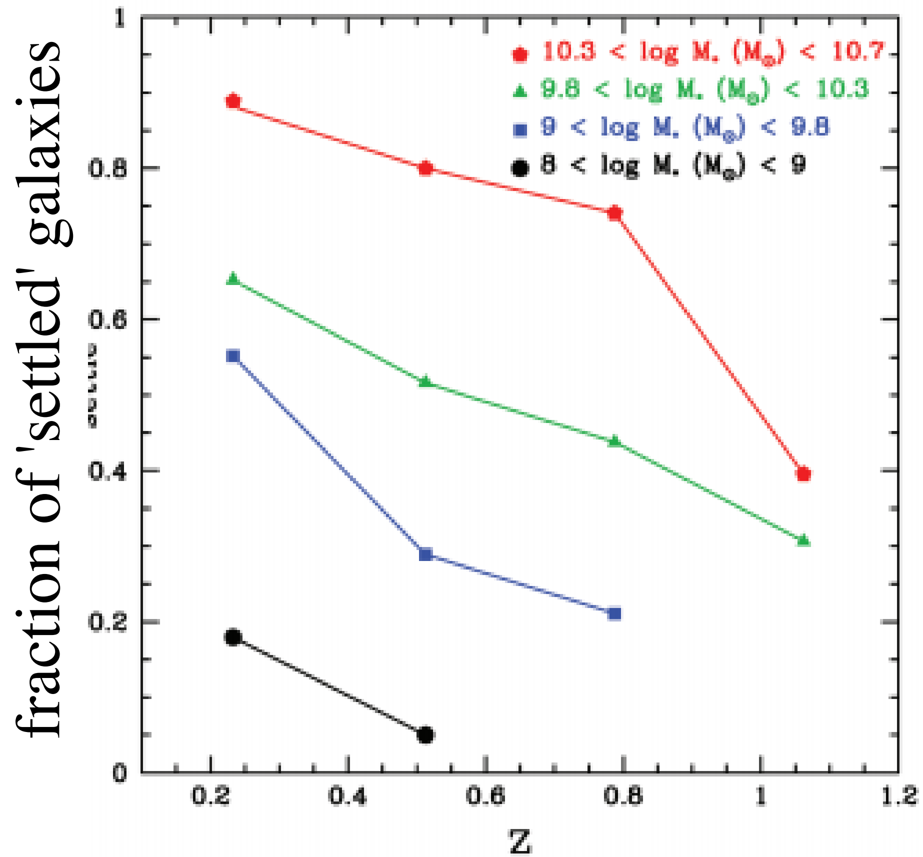
- As discussed previously at low redshift massive galaxies tend to be ellipticals
- However at high redshifts disklike galaxies are more important
- Also note the slow growth in the number densities of massive galaxies at low z- confirming their 'old' ages

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) .

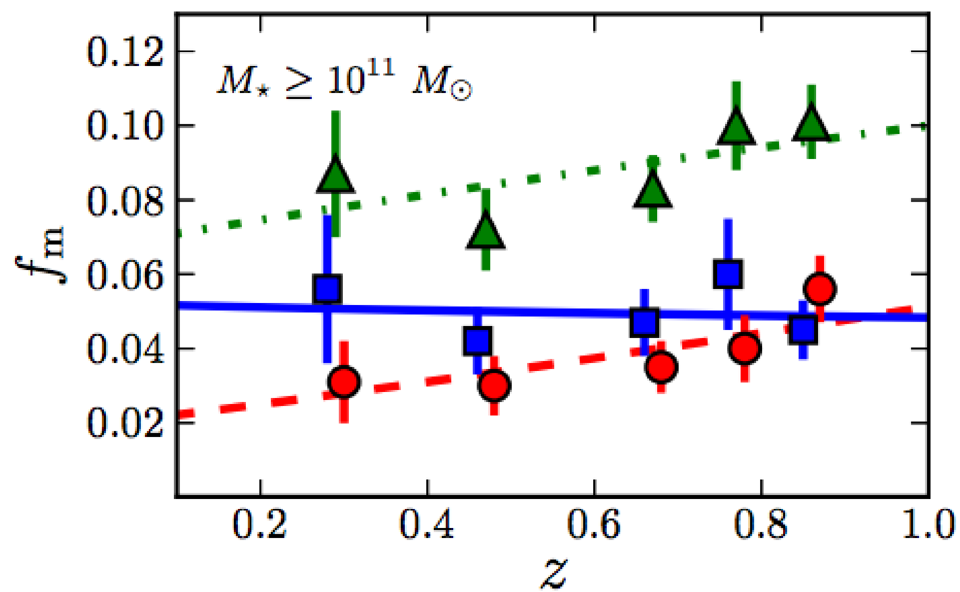


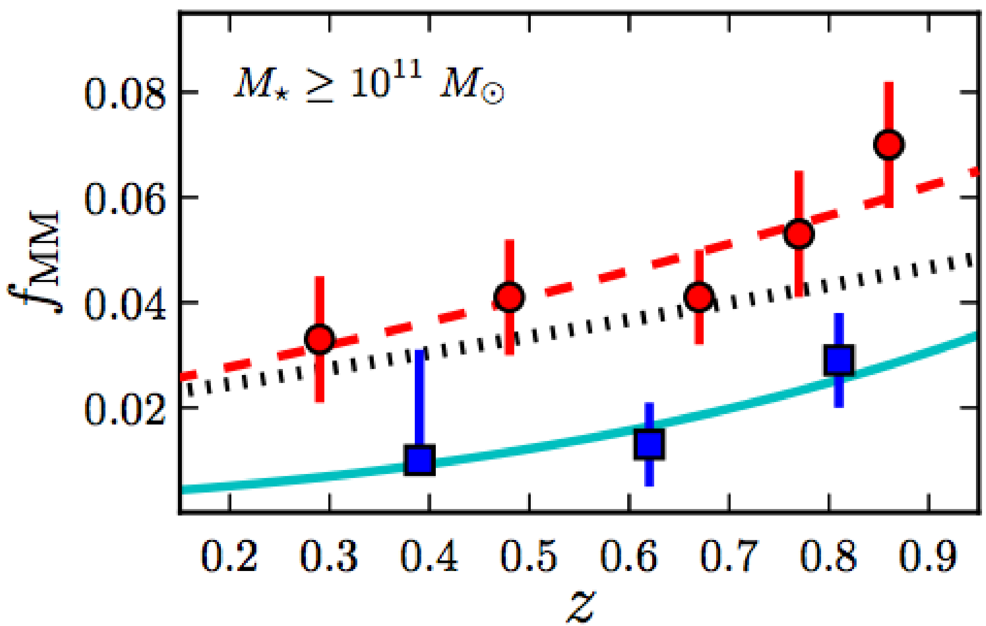
Kassim et al 2012

Mergers

Red major mergers
blue minor 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~; ~30% growth in mass



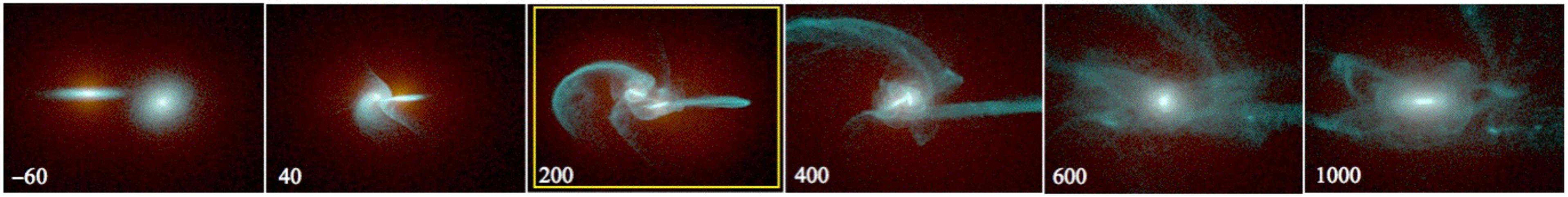


Red ellipticals
blue spirals

L´opez-Sanjuan 2012

Galaxies 'Can' Change Over Cosmic Time

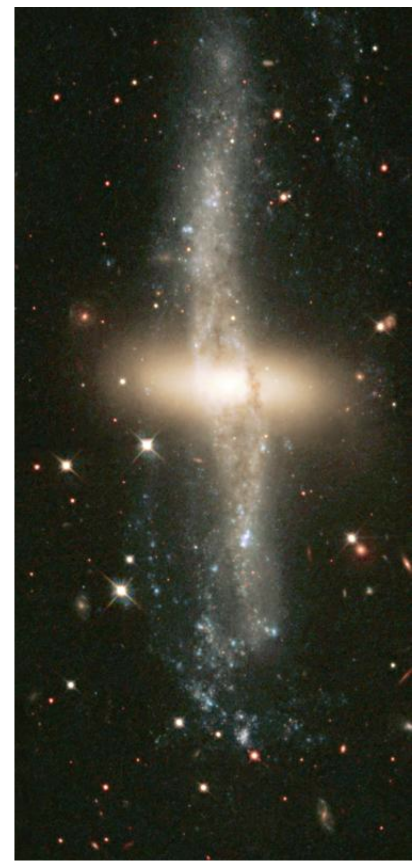
Computer calculation of the collision and merger of two equal-sized spiral galaxies



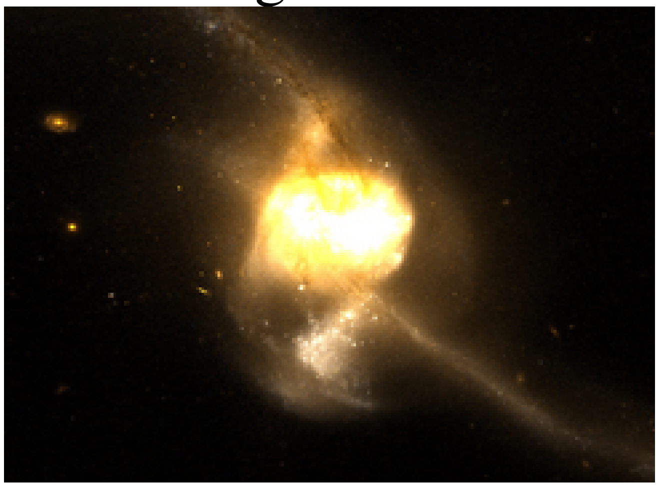
The Mice: Hubble Space Telescope

- Galaxies can grow via mergers and acquisition of gas. Mergers can be major or minor

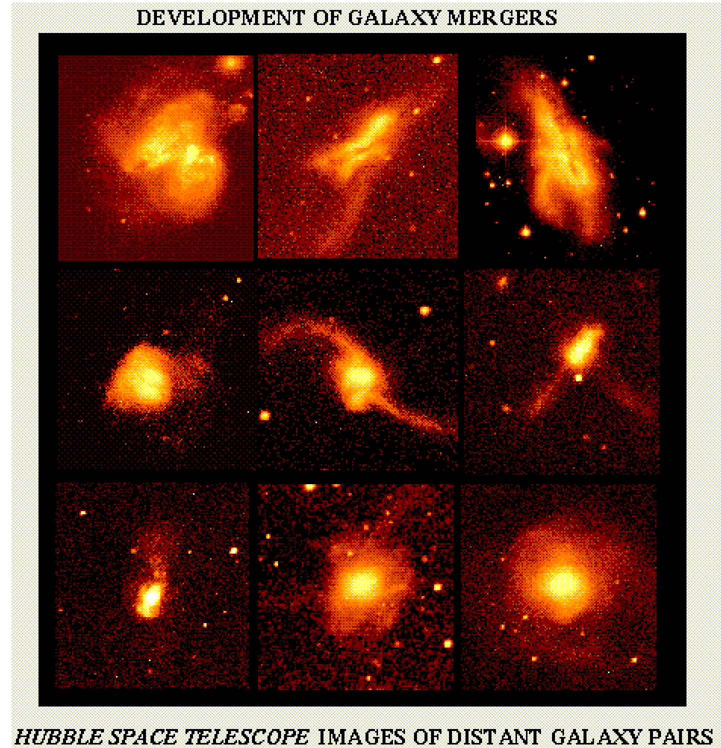
Polar ring galaxy -evidence for gas accretion?



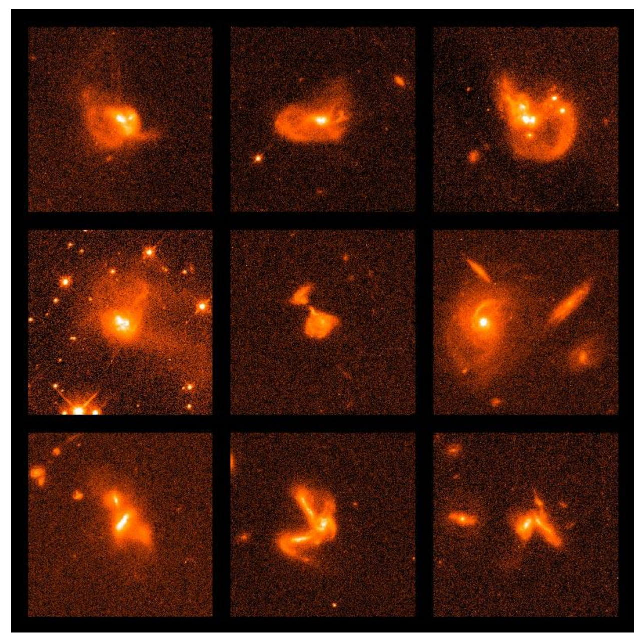
Mergers are responsible for the largest starbursts



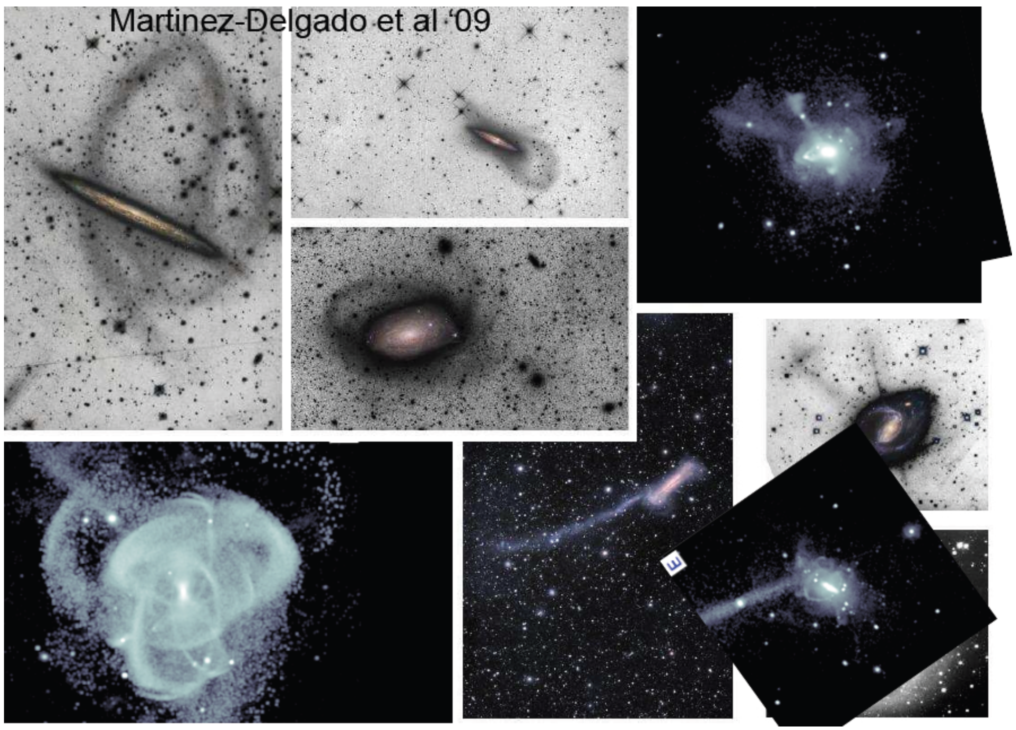
al. 1999



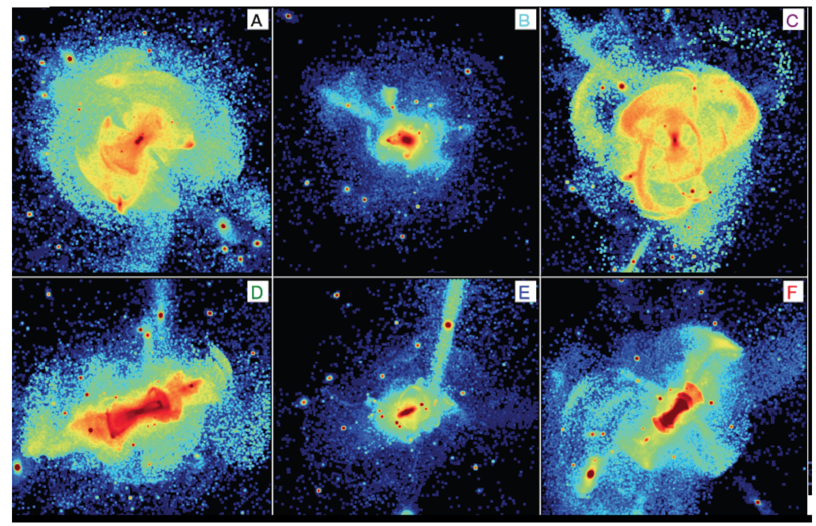
- The most intensely-SF galaxies in the local universe are merging systems



Simulated vs Observed Merging Galaxies



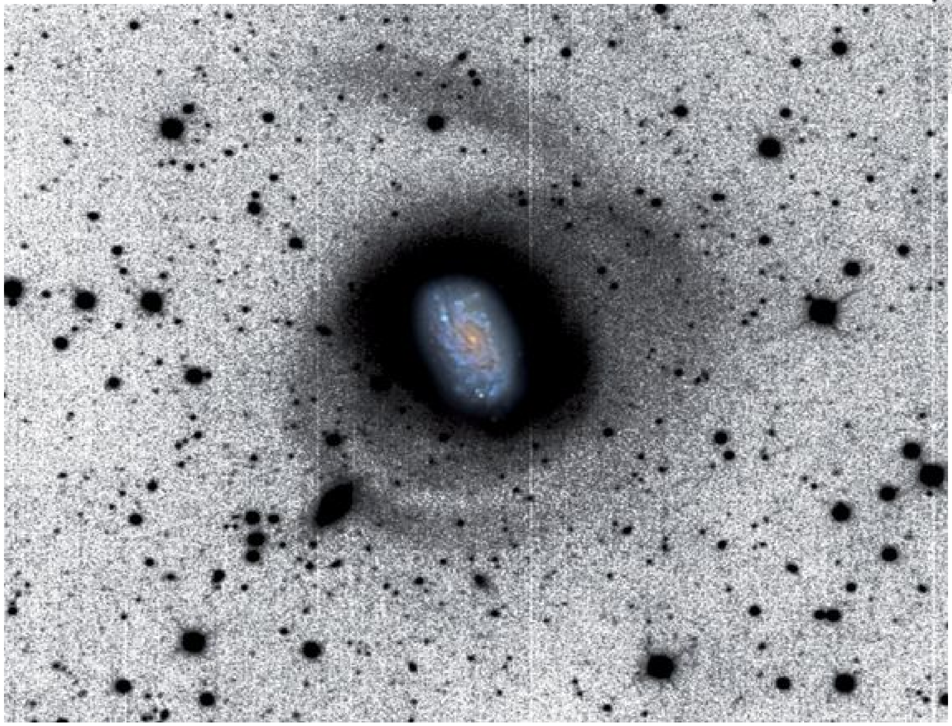
Observed merging galaxies



Simulated merging galaxies

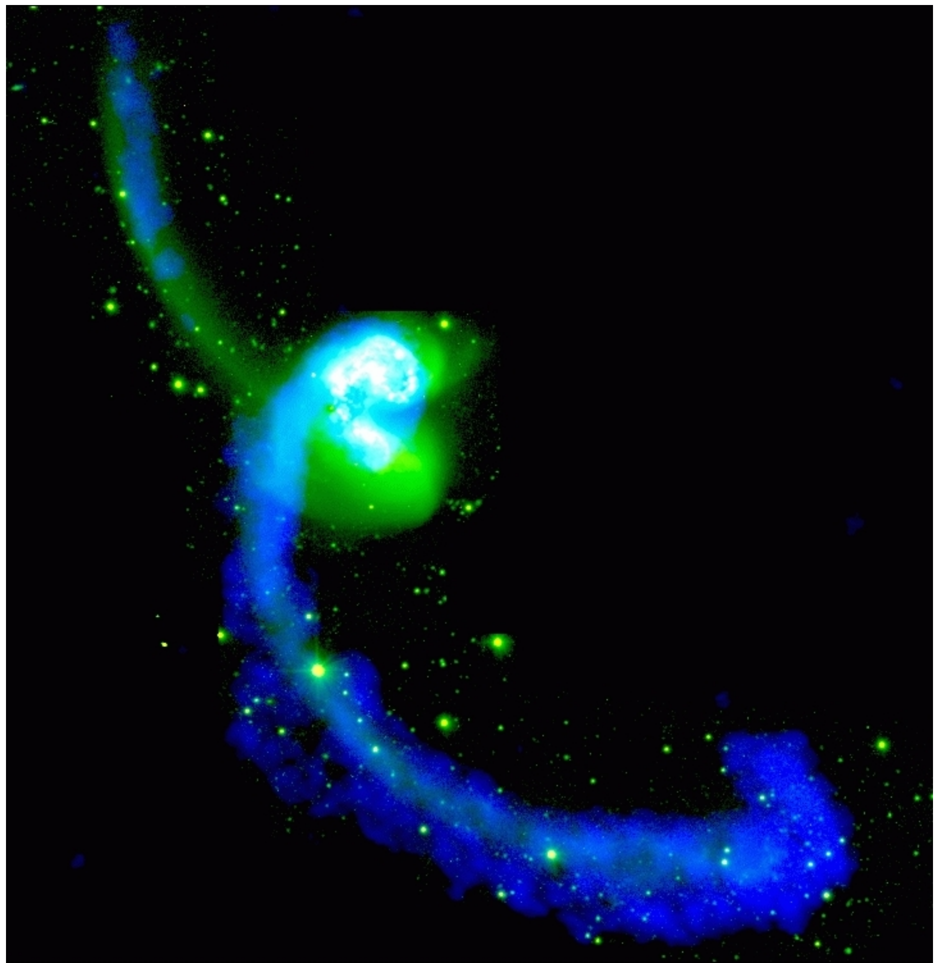
Evidence for Mergers

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



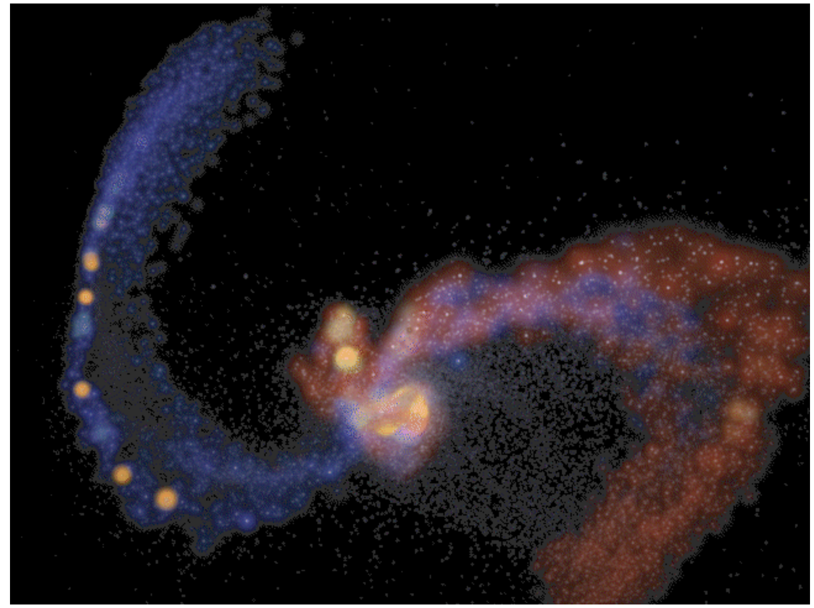
What does the Universe really do

The Antennae Galaxy- a galaxy in collision


NGC 4038/8 VLA HI (blue) and CTIO Optical (green), from Hibbard, van der Hulst & Barnes 2001

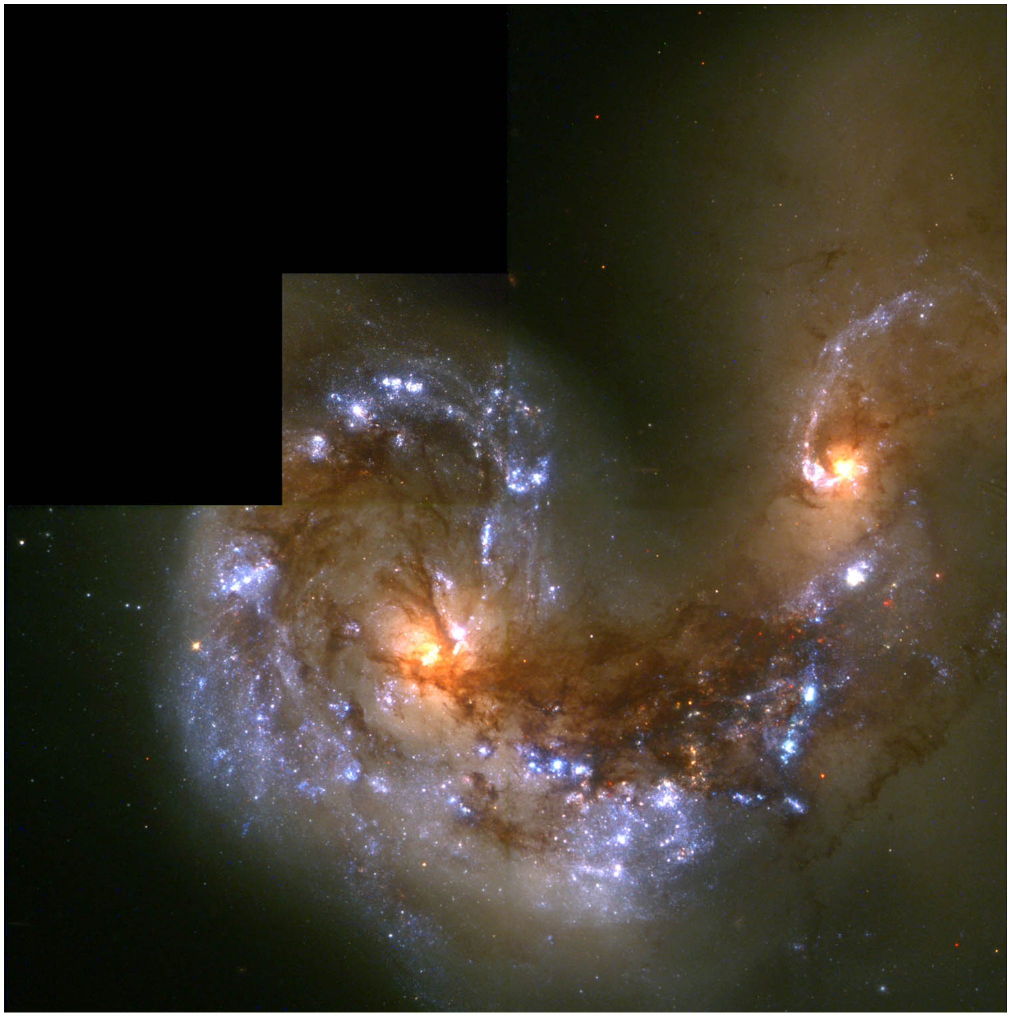
- Interactions and mergers: When galaxies collide, the resulting compression of the interstellar medium and the changing gravitational field can induce large amounts of star formation.
- Collisions also set in motion a chain of events that cause a lot of the gas from the two galaxies to fall down the 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?

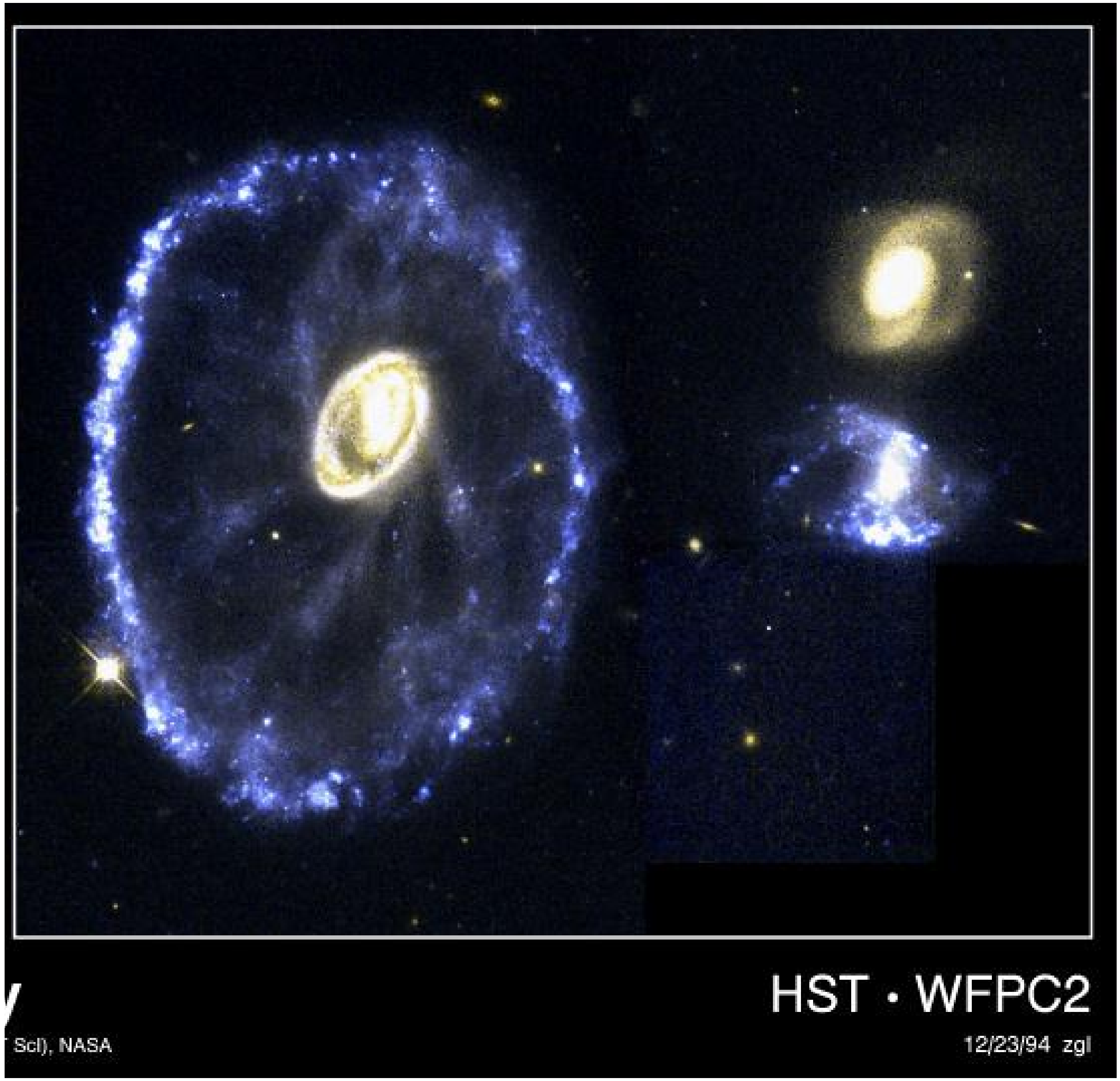


Theoretical merging disk galaxies. The gas is colored red and the stars blue.
The stars are distributed roughly as in the Antennae galaxy, and the gas has been collected into dense concentrations that become the sites for vigorous star formation

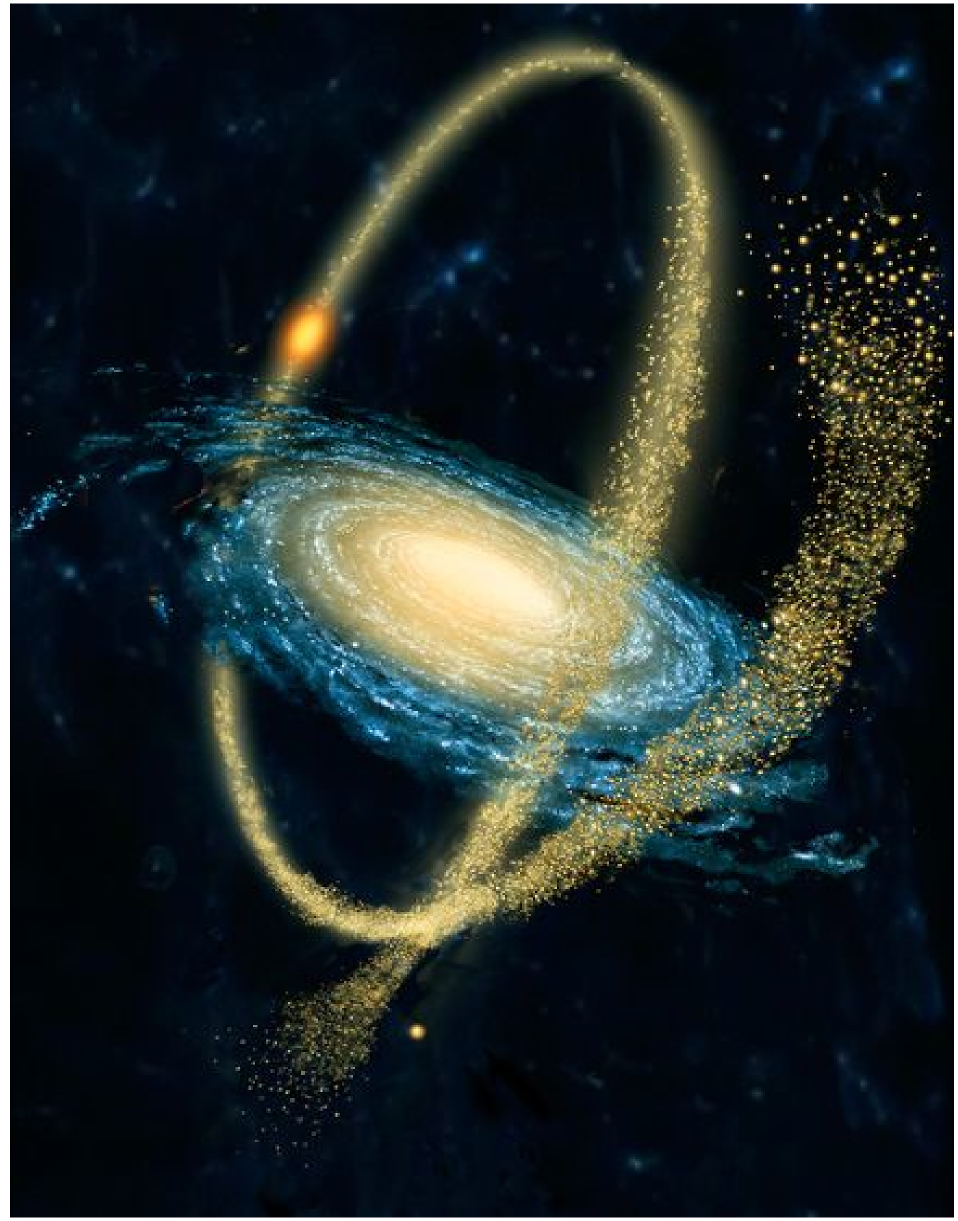
Close Up with HST



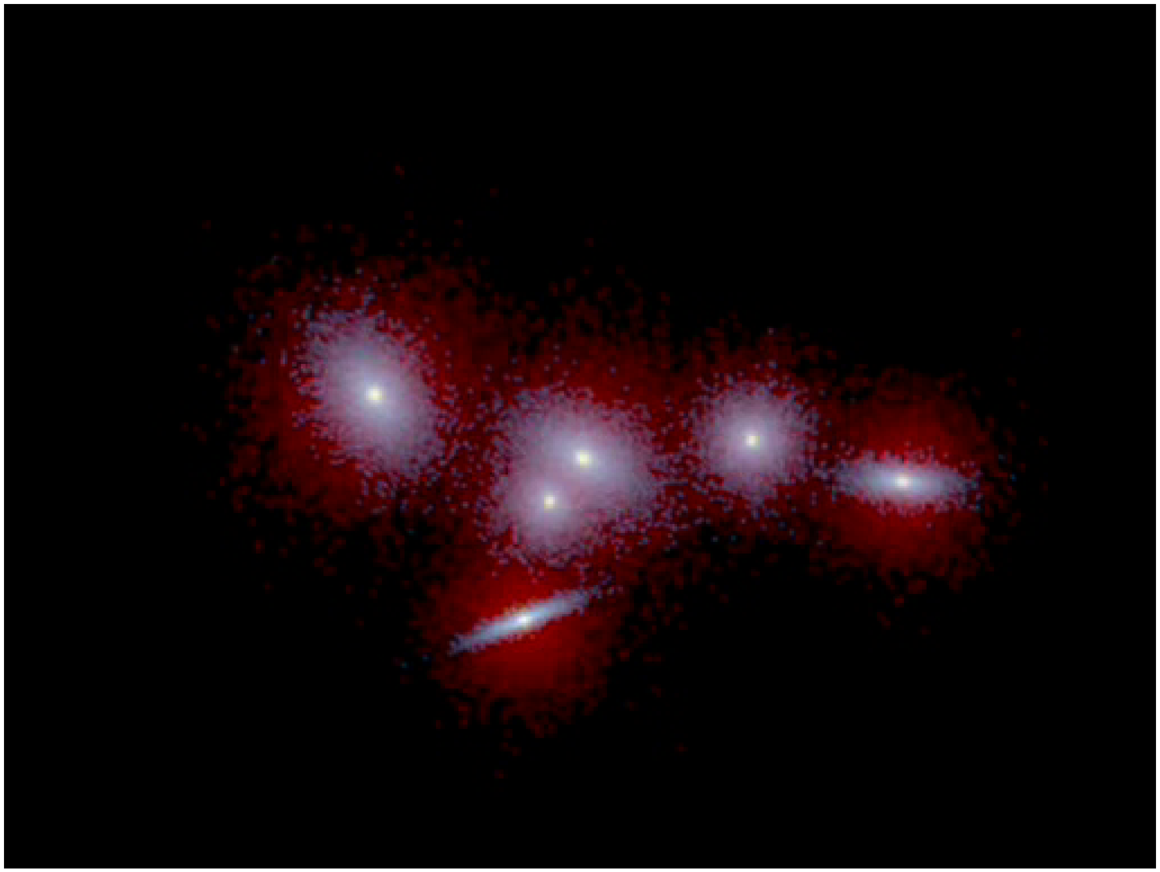
- A bulls-eye collision- the Cartwheel galaxy
- ring-like structure ~150,000 ly across (larger than the Milky Way)
- The ring is a wave of star formation traveling outwards at about ~10^2 km/sec
- As the wave passes outward it compresses and heats the matter that it passes through, triggering the star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

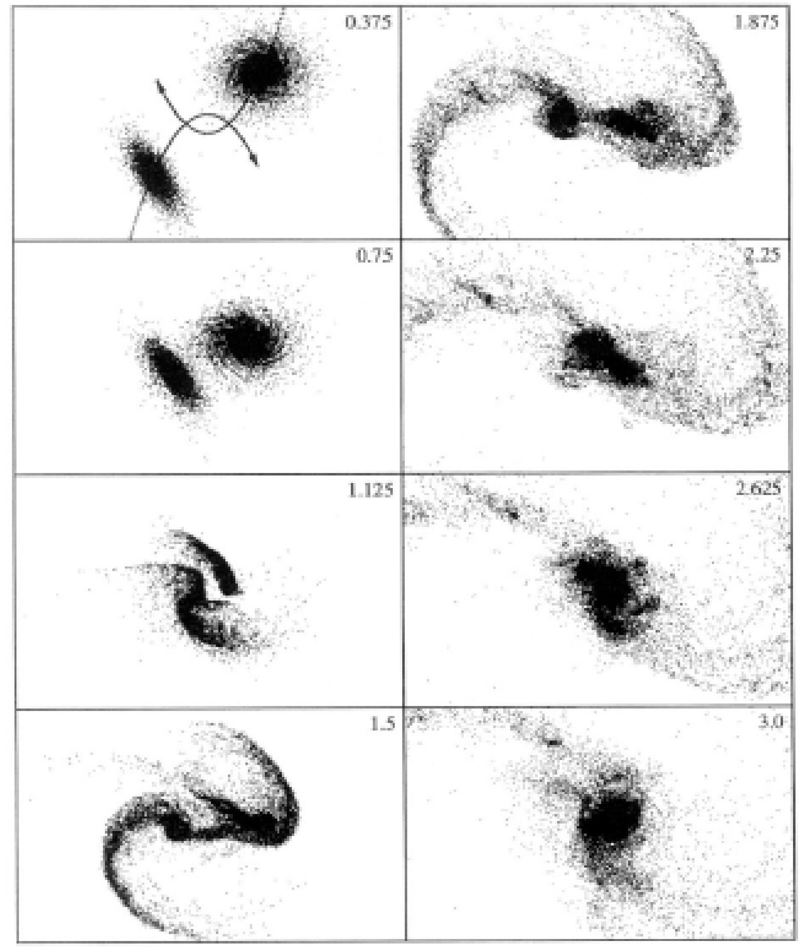


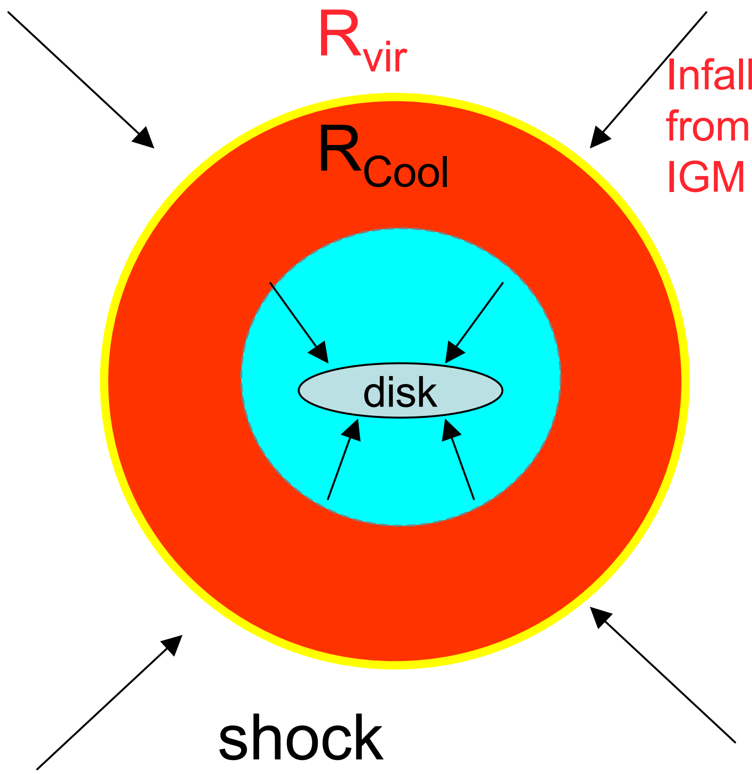
FIG. 4.—Evolution of the stellar distribution in encounter A, projected onto the orbital plane. The scale is the same as in Fig. 3.

- 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 (see on web page the discussion in the introduction of Moster, Maccio and Somerville)
    - dark matter and baryonic physics
    - 'correct' cosmology
    - high enough spatial and temporal resolution
    - large 'box' size (lots of galaxies formed)

How Gas Gets Into Galaxies

- Modes of Gas Accretion -
  - Hot Mode: (White&Rees 78) Gas shock heats at halo's virial radius up to T_{vir}, cools slowly onto disk. Limited by t_{cool}. Hydrostatic equilibirum $kT/m \sim v^2$
  - Cold Mode: (Binney 77) Gas radiates its potential energy away via emission at $T \ll T_{vir}$, and never approaches virial temperature. Limited by t_{dyn}. $kT/m \ll v^2$
- If $T_{gas} > T_{vir}$ little cooling happens
- Cold mode dominates in small systems ($M_{vir} < 3\times10^{11} M_{\odot}$), and thus at early times.



Bell 2009

Galaxy formation : Many relevant and interacting processes

Cooling (metallicity, structure, ...)

Star formation (threshold, efficiency, IMF, ...)

AGNs (BH growth, feedback, ...)

Dust (formation, distribution, heating & cooling, ...)

Galaxy formation & evolution

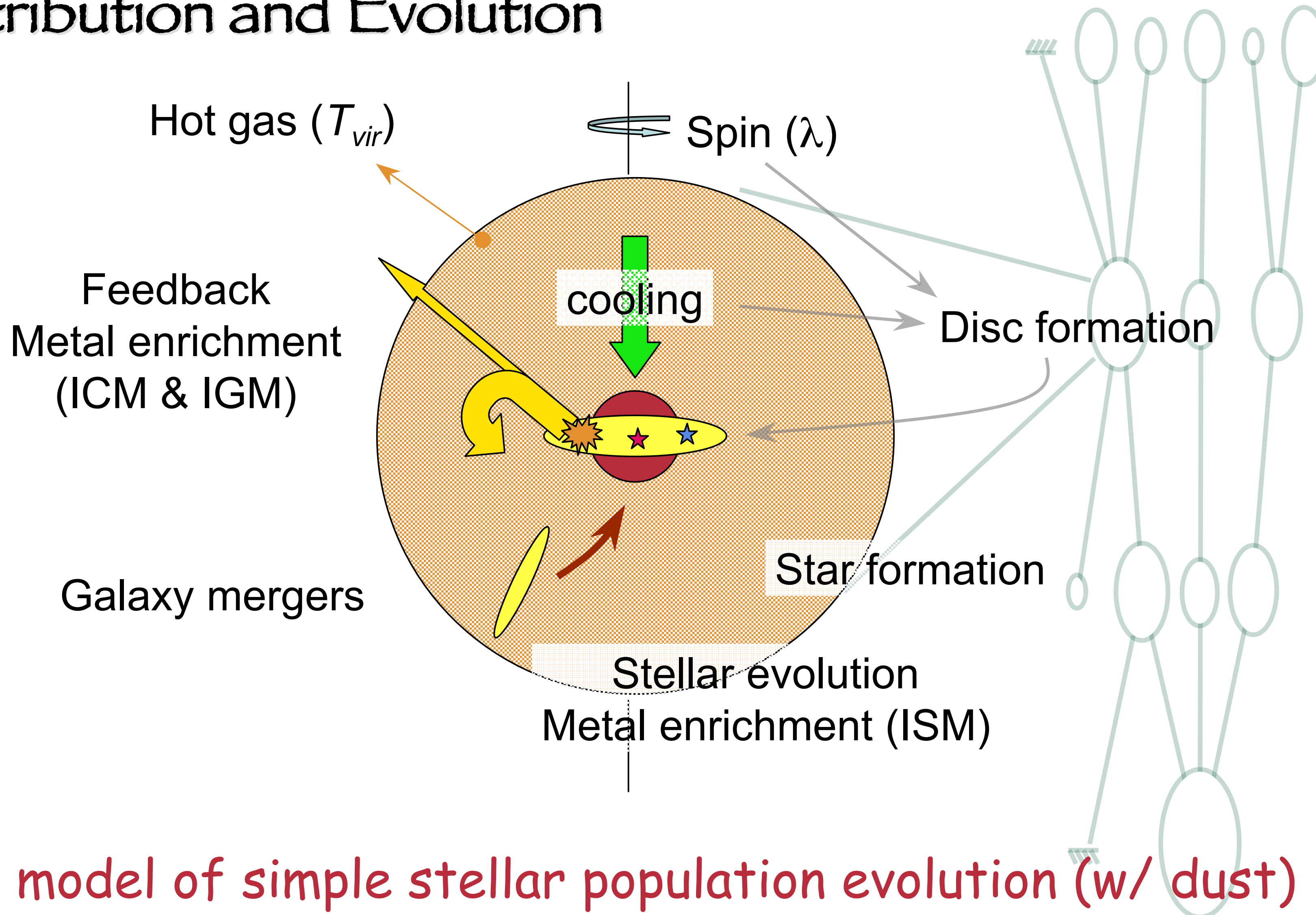
Galaxy interactions (morphological transformations, starbursts, intracluster stars, ...

Winds (IGM heating, enrichment, SN feedback, etc...)

Stellar evolution (spectro-photometric evolution, yields, SN I/II rates,...)

taken from **J. Blaizot** presentation

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

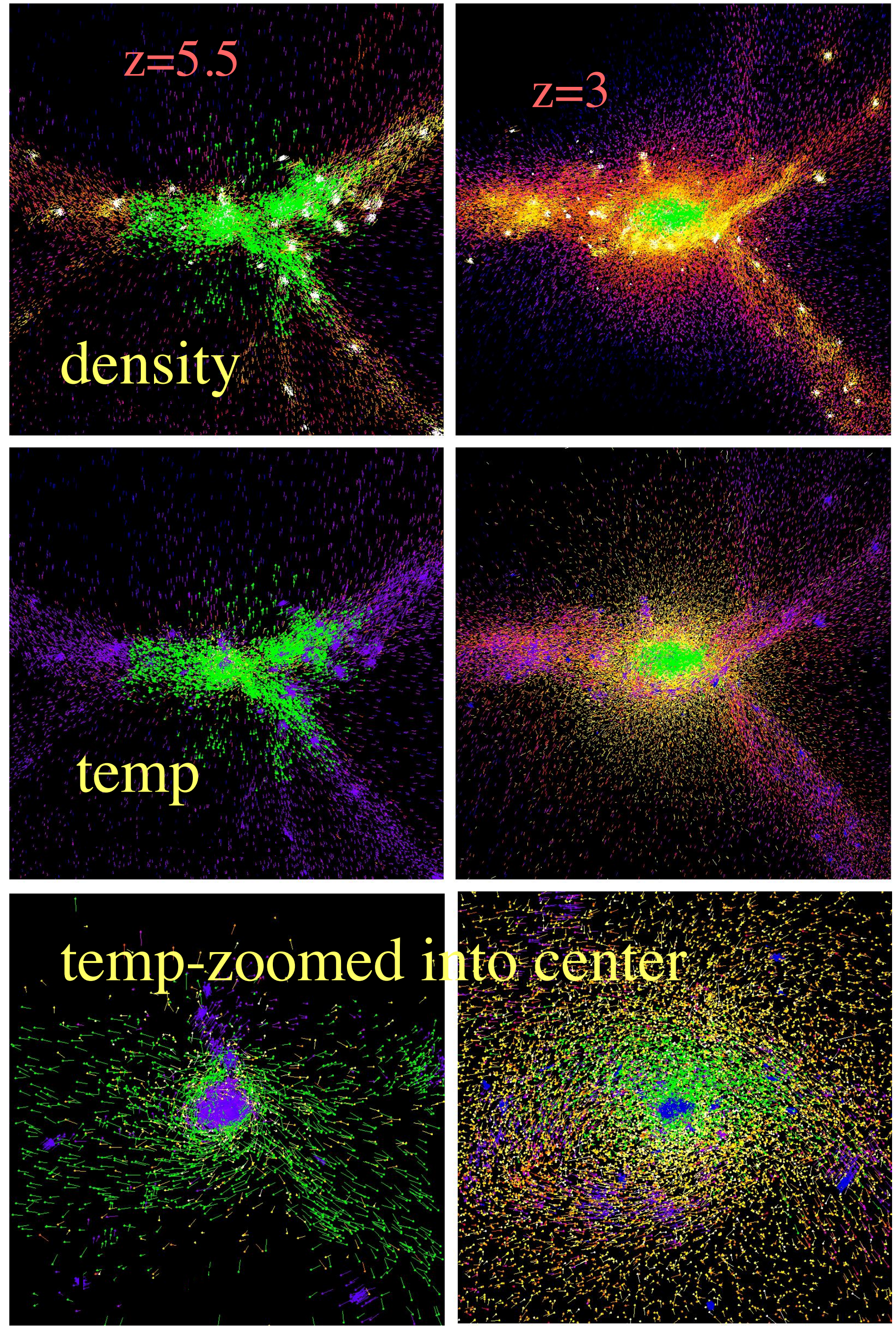


+ model of simple stellar population evolution (w/ dust)

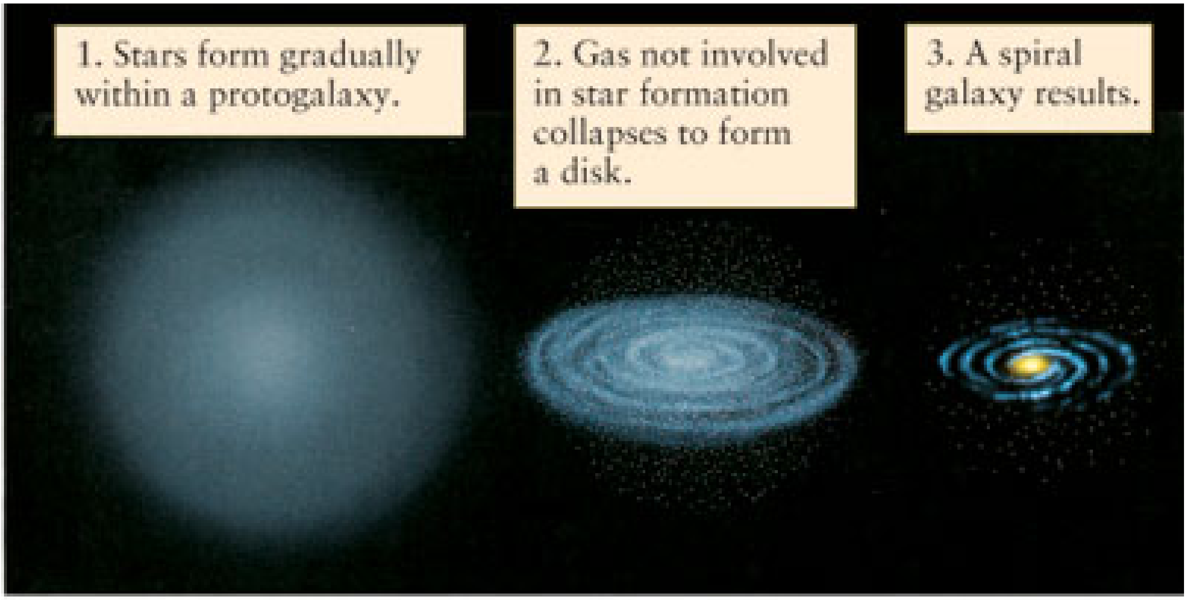
taken from J. Blaizot presentation

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.

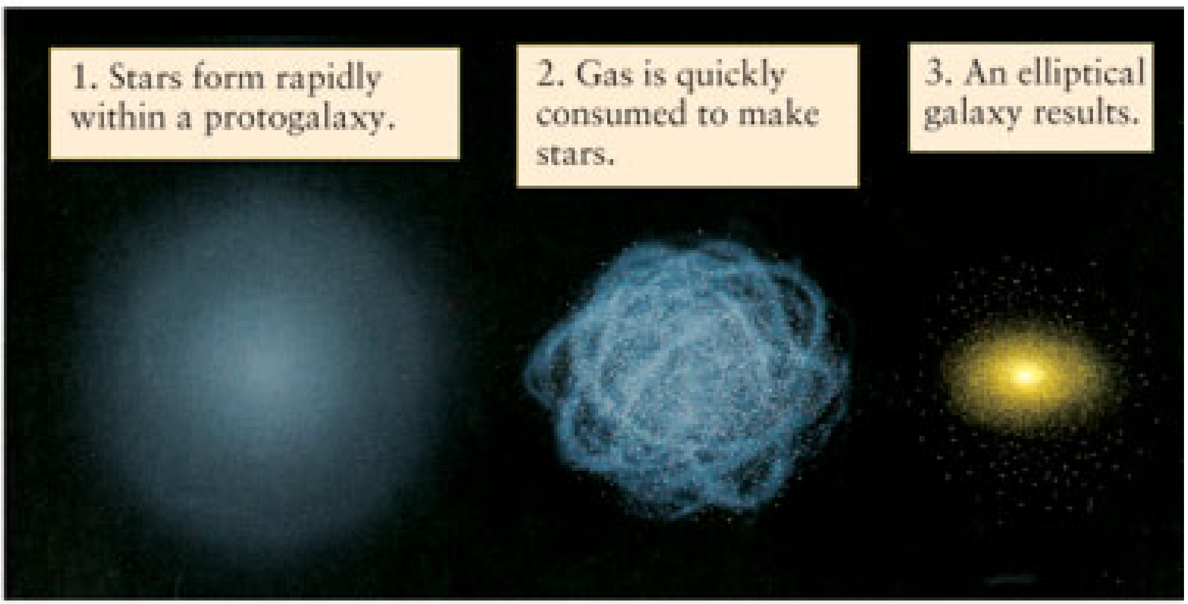


Keres et al 2005



(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.

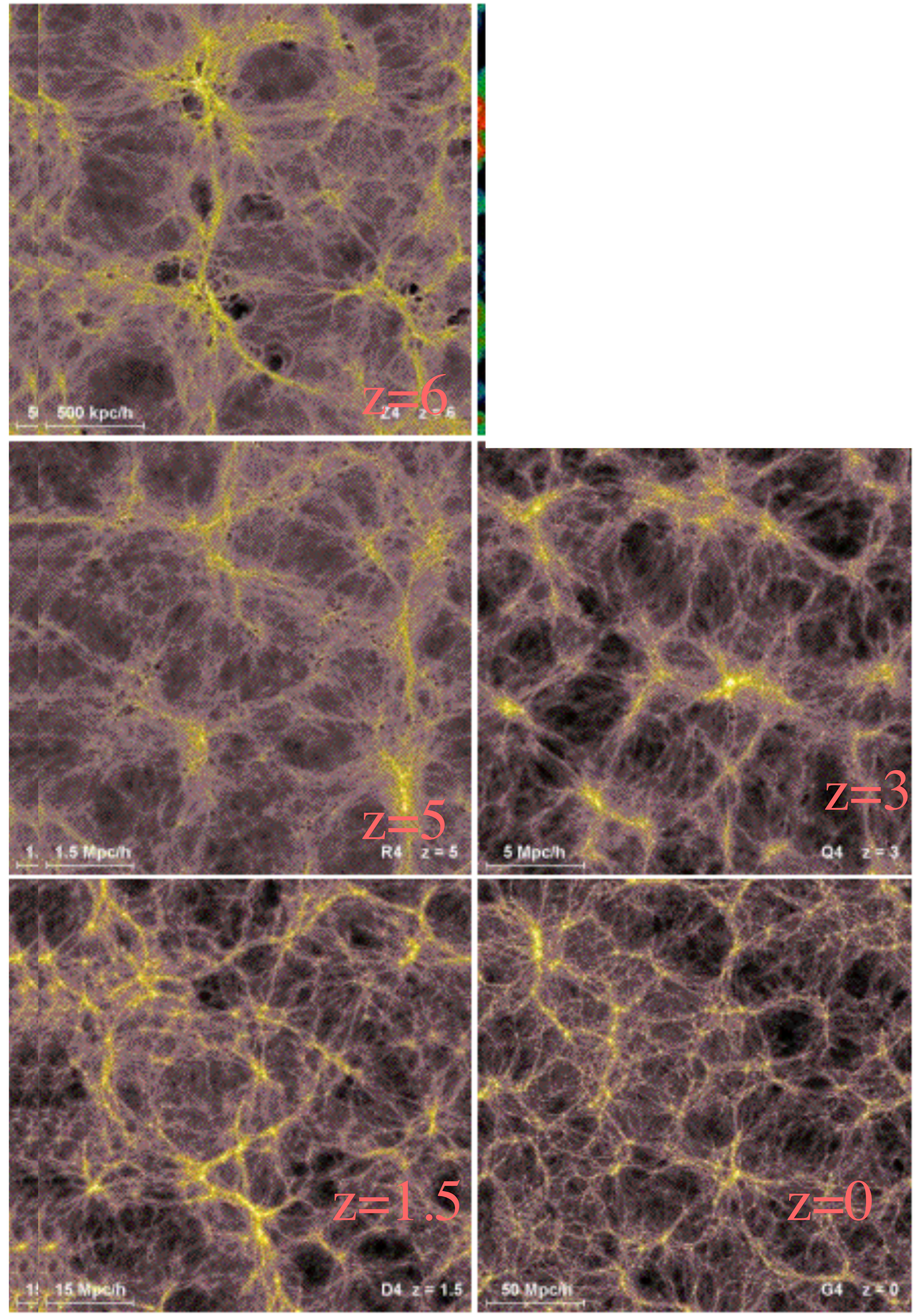
- In a major merger, the orbits of the disc stars are randomised, resulting in the destruction of the discs and the creation of an elliptical galaxy.
- After such a merger a new gas disc can be created and a new stellar disc formed
- And then the *tooth fairy* creates galaxies like we observe...

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

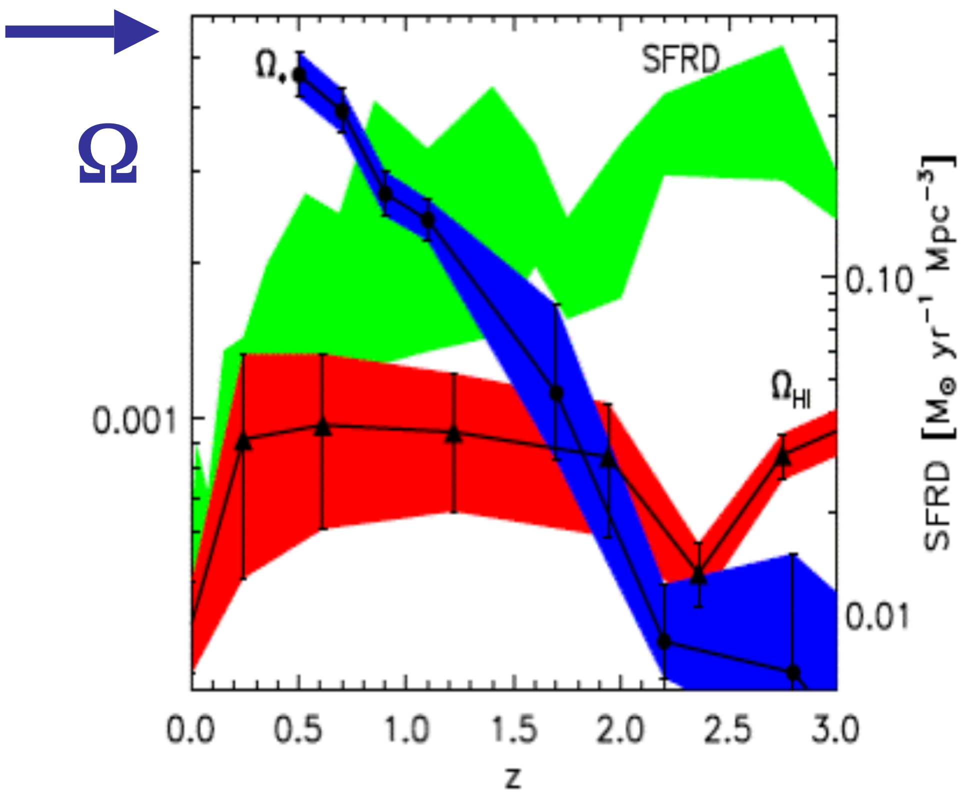


Patterns Change over Cosmic time

- 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

$\Omega_{\text{star is}}$ ~10% of the cosmic baryon density

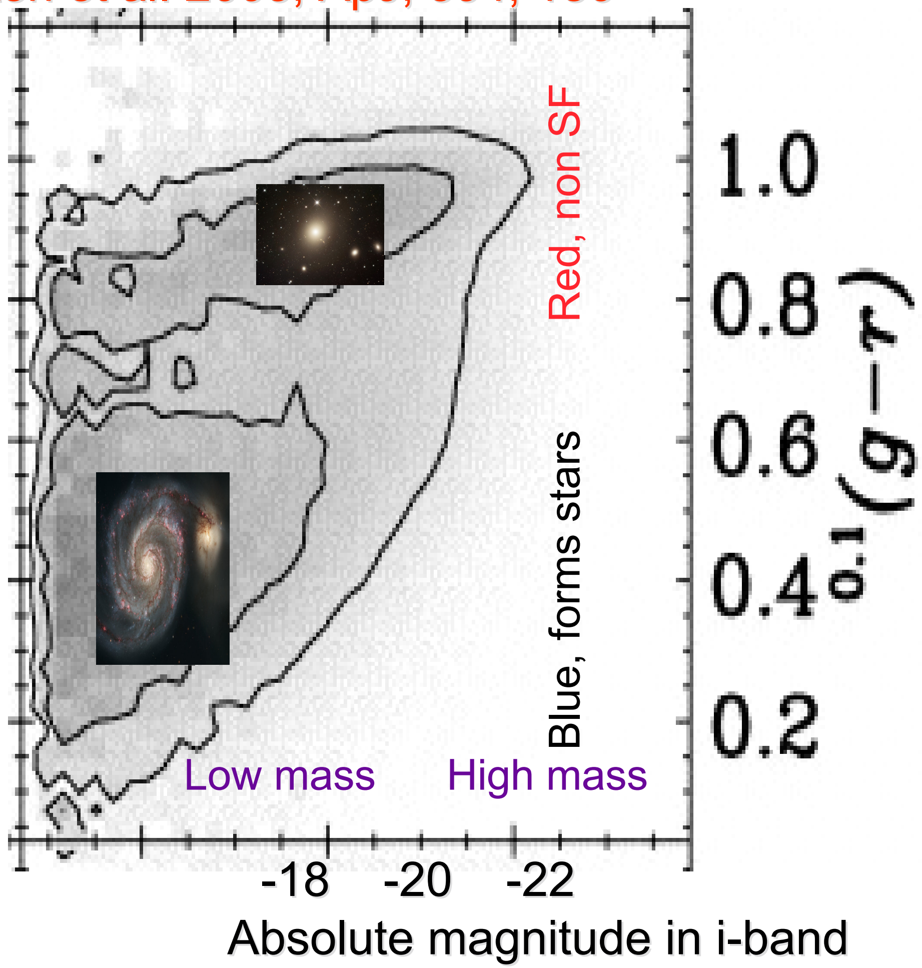


Putnam et al 2010

Key observation : correlation between *structure* and *star formation history*

- A bimodal galaxy population - transition mass of $3x10^{10}$ $M_\odot$
  - **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



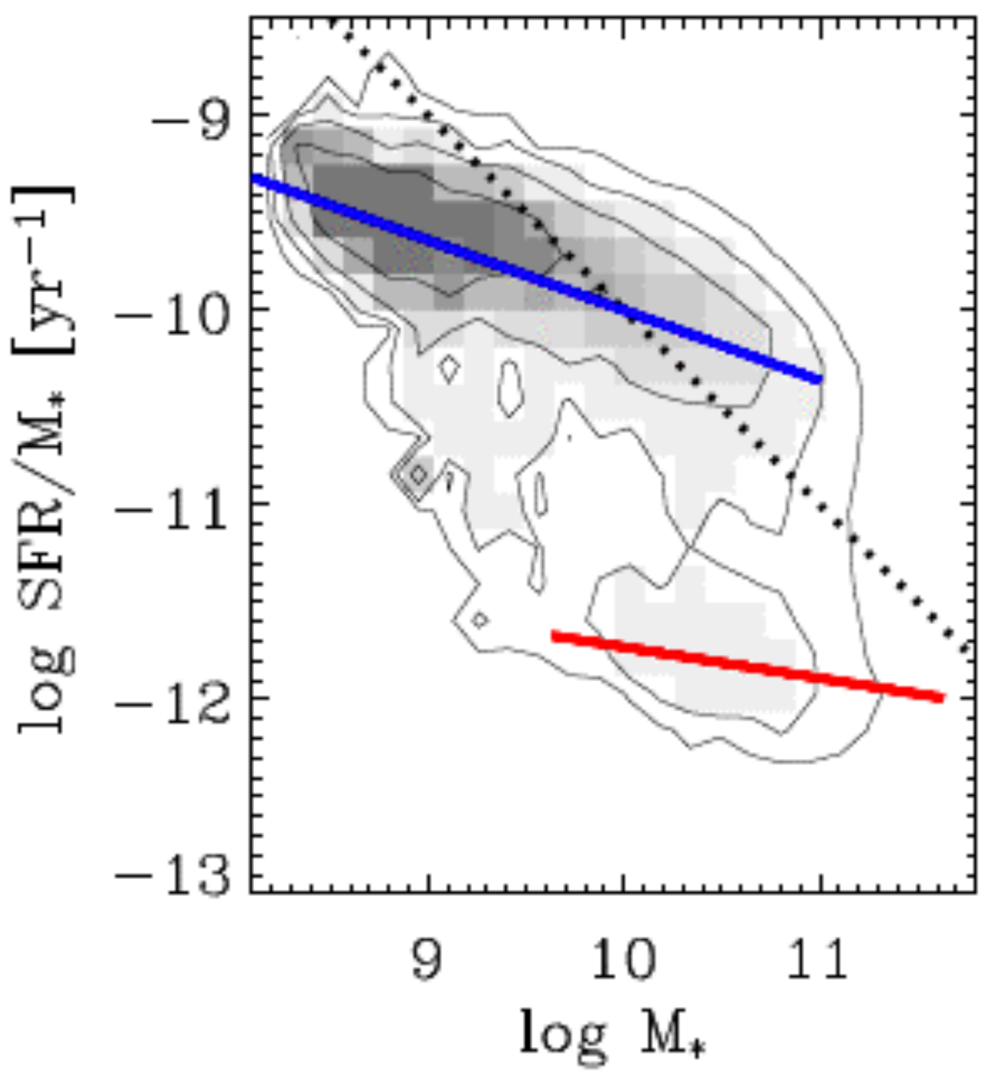
Cessation (quenching) of star formation is empirically correlated with
the existence of a prominent spheroid

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??



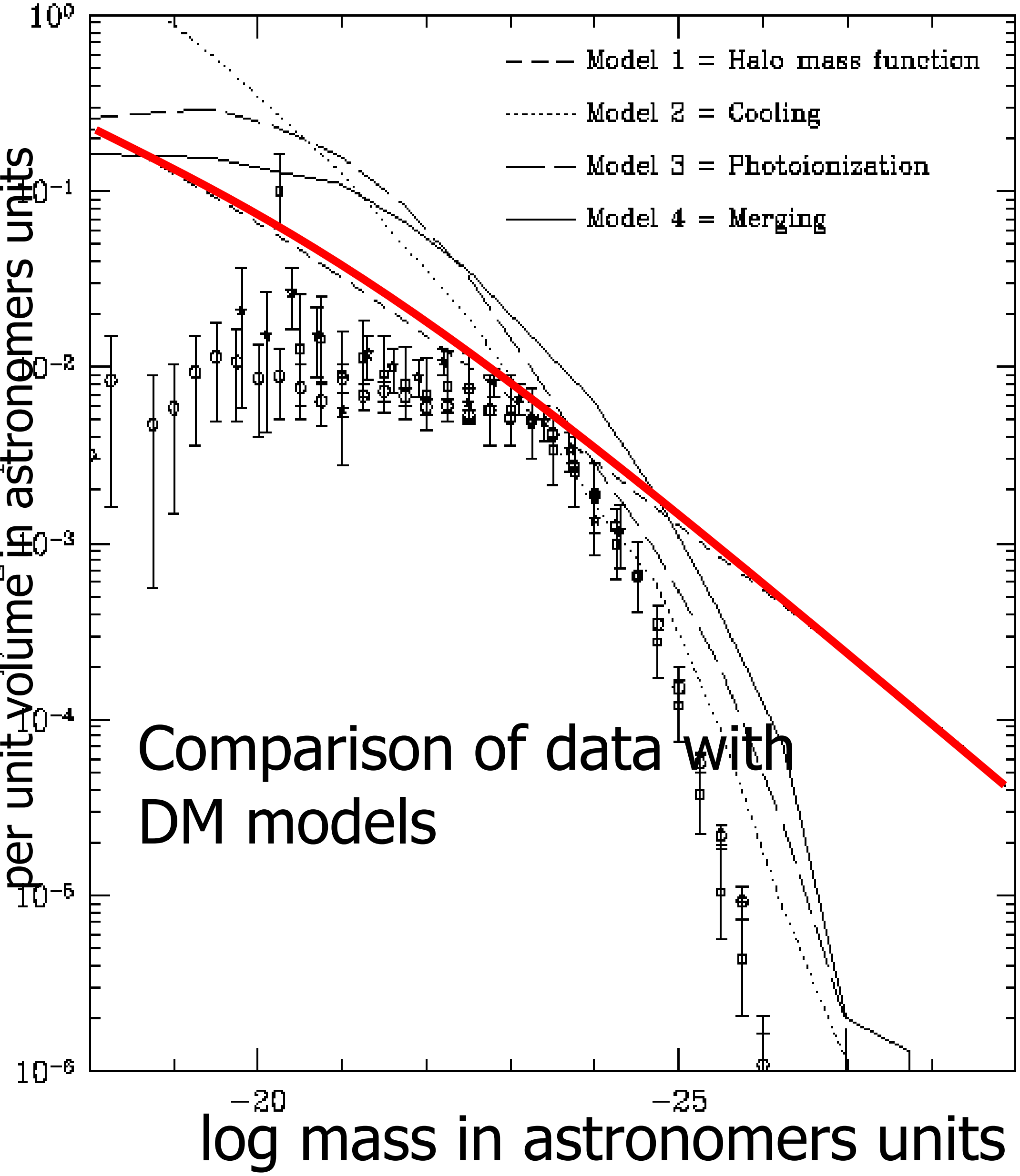
Biased galaxy formation

- 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

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



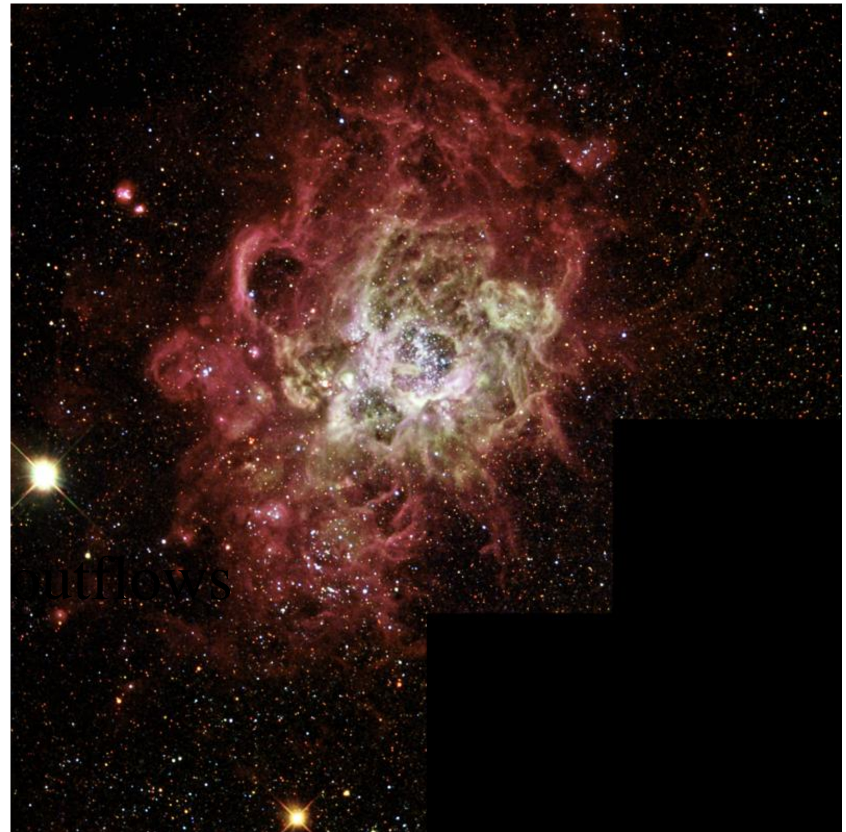
Observed relationship between number of dark matter halos of a given mass vs mass and the observed galaxy distribution

Galaxies do not trace the theoretically predicted dark matter halos !

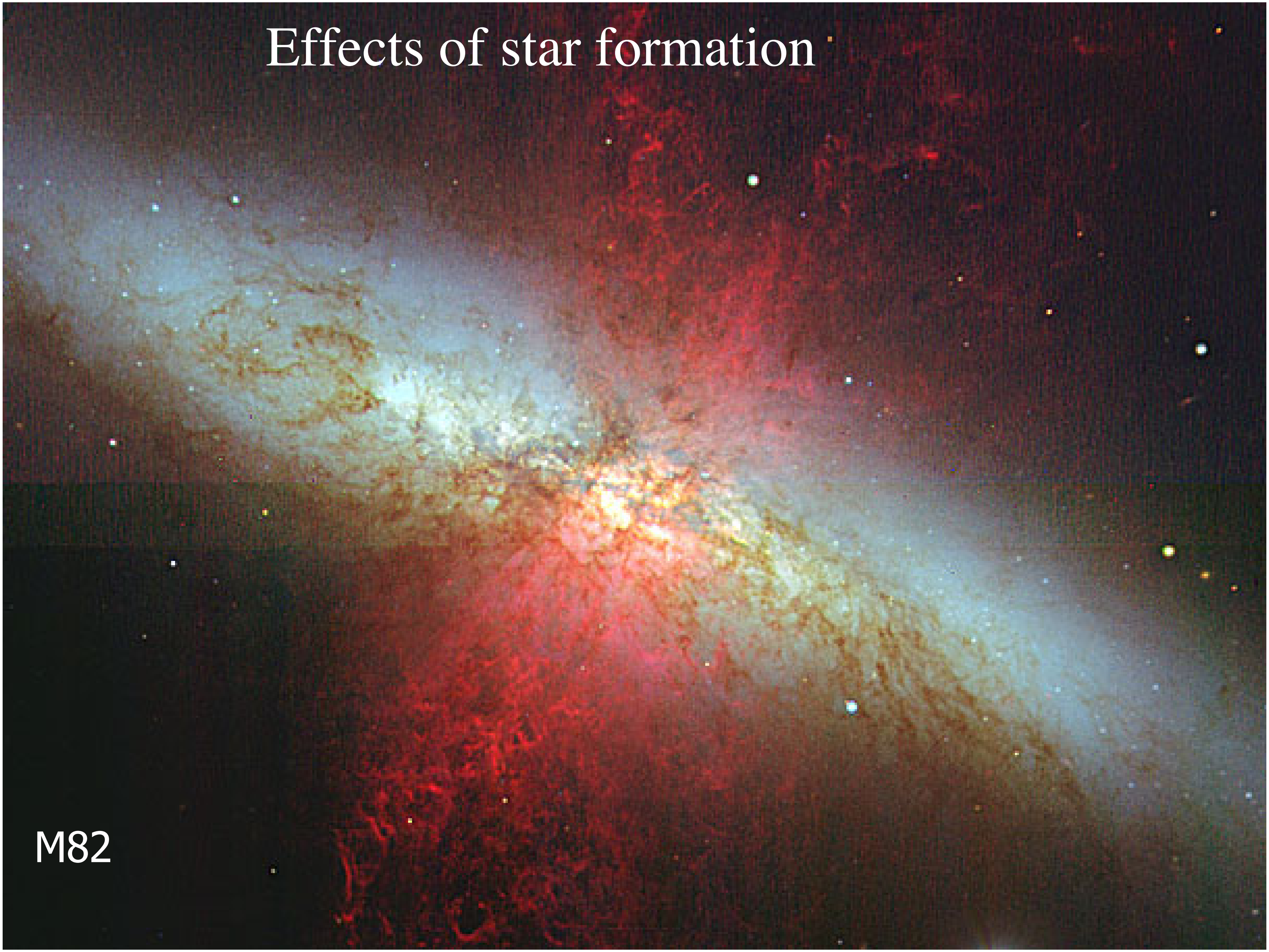
Why??

Feedback

- Stellar winds and SNe
  - Comparable energy input
  - Disrupts birth clouds
  - Triggers new star formation
  - Intense cases --> drives large-scale outflows



Effects of star formation



The Galactic Wind Can be Very Hot

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

- Sometimes the energy deposited in the interstellar medium of the starburst galaxy is so large that a 'galactic wind' occurs- ejecting heavy elements formed in the massive stars and other material into the intergalactic medium

Starburst

M82- grey/blue is starlight; red is ejected gas (dark lanes are due to dust
M. Westmoquette, L. Smith (UCL), J. Gallagher (Wisconsin)
WIYN//NSF, NASA/ESA

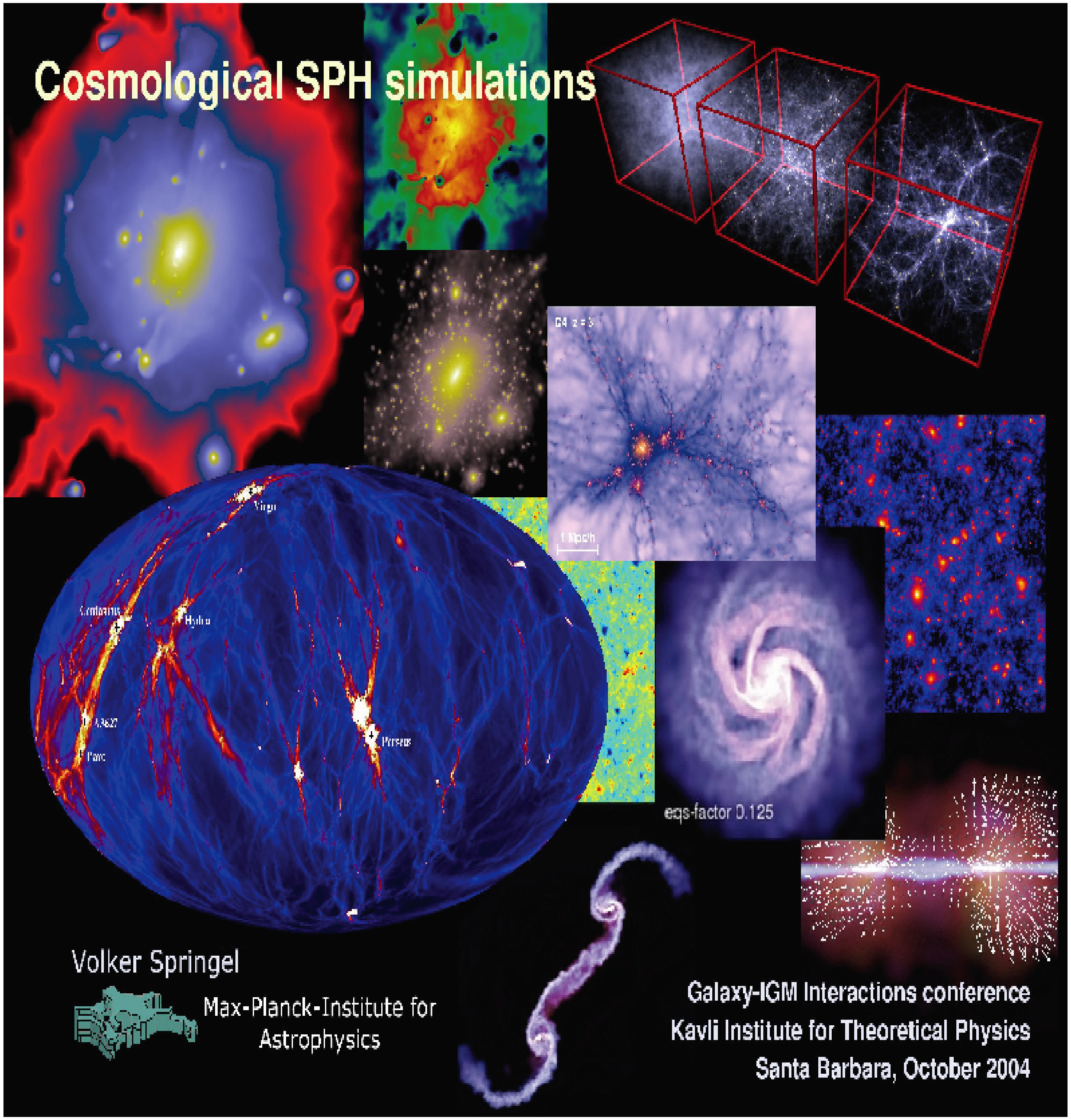
Physics Beyond Gravity

- 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

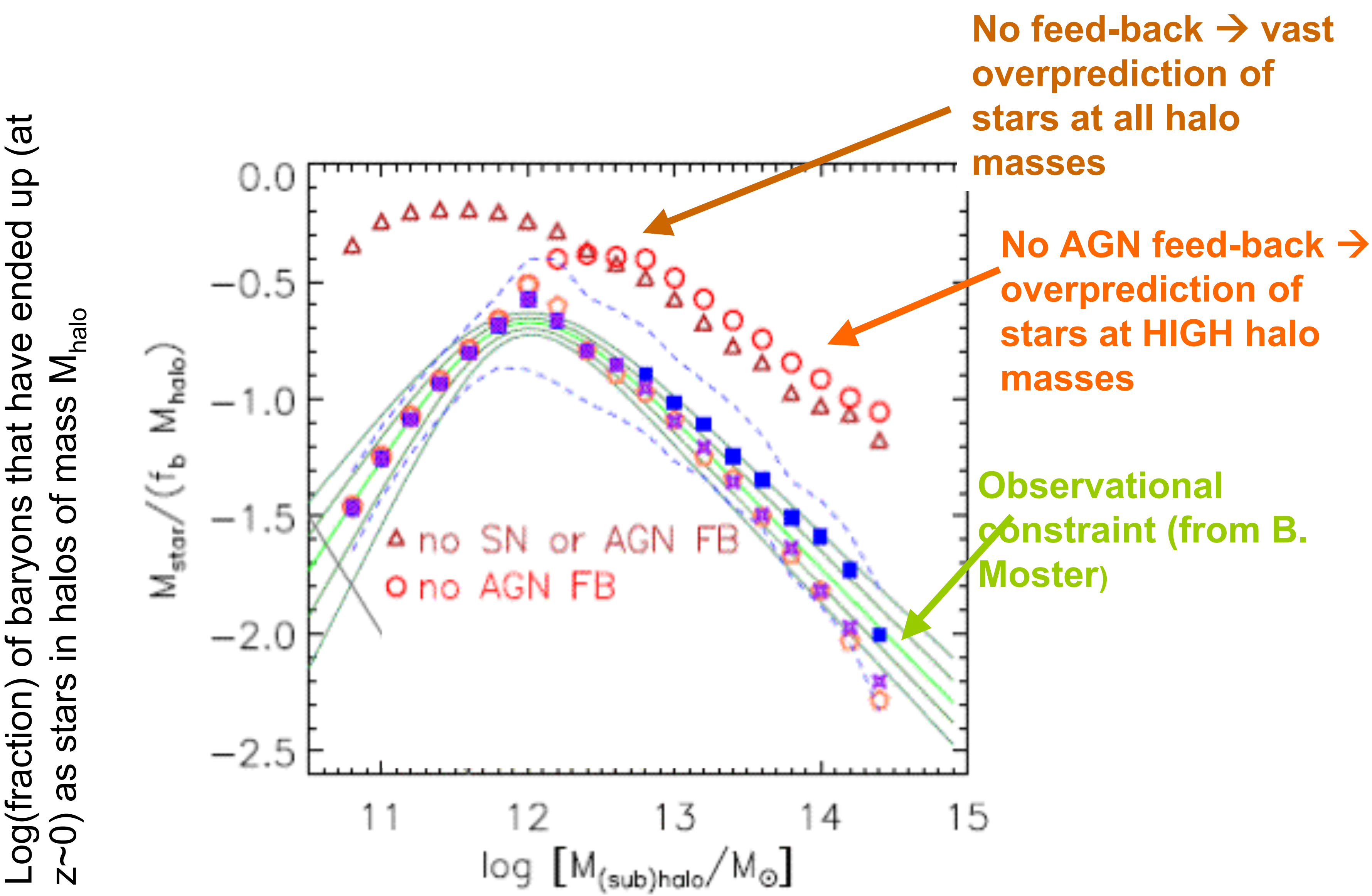
- Similar phenomena can occur due to quasars

Formation of structure in the Universe

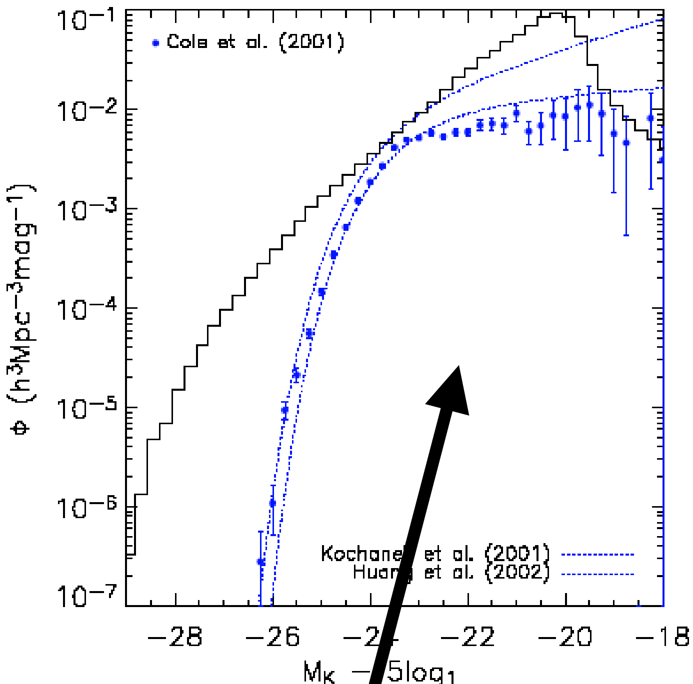
- Detailed numerical calculations of the formation of structure via the collapse of gravitational perturbations in a LCDM universe (Springel et al 2003, White et al 2004) show that one cannot ‘produce’ the present day universe without invoking ‘feedback’
- Similar results are obtained in analytic work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



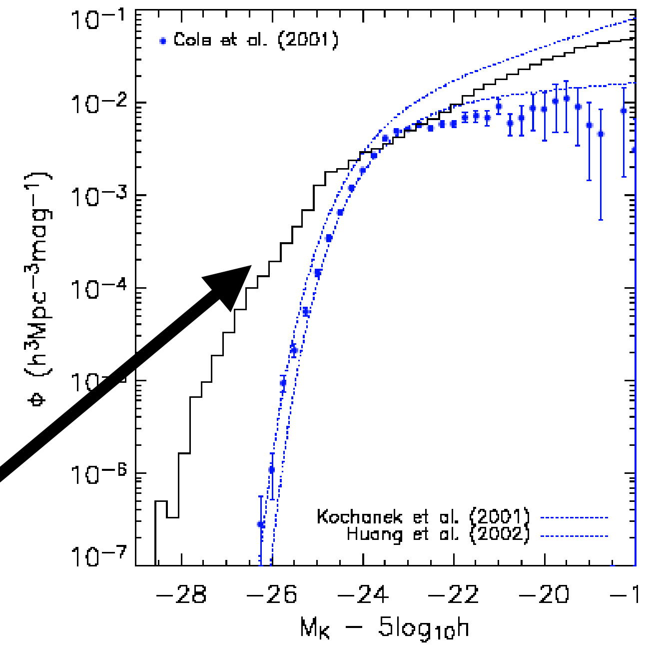
Comparison data—models
(Somerville et al 08)



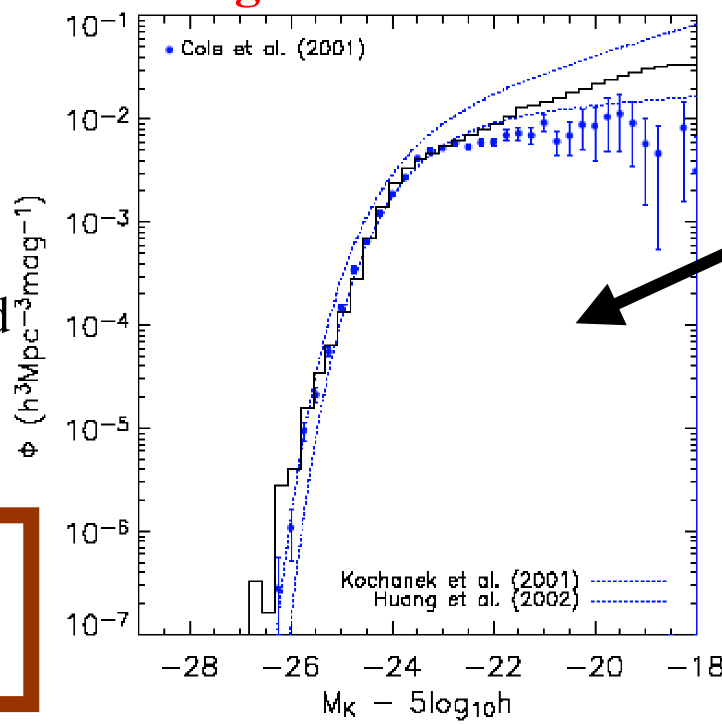
Calculation of K band galaxy luminosity function in N body simulation



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'**

Thanks to V. Springel and S. White

Blue lines are data- black models

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

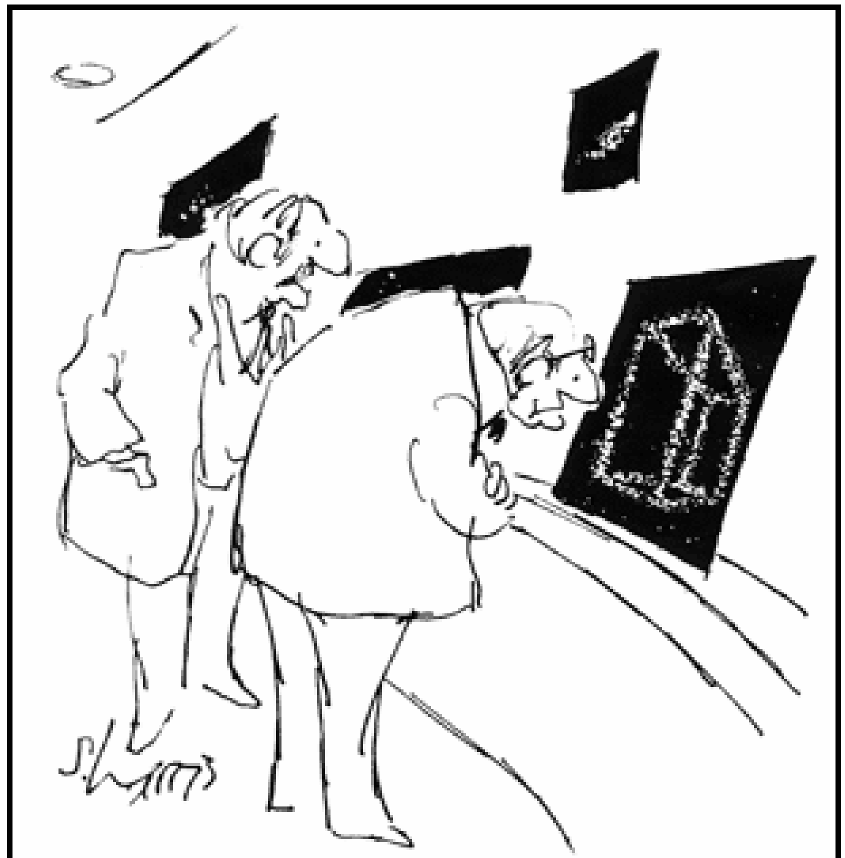
- AGN feedback

  "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

Story so far…

- Cooling/SF/stellar feedback cannot make a red sequence- need more energy than is available from these processes
  - 1/2 of all stellar mass today!



"You've seen spiral galaxies, you've seen elliptical galaxies..."

Summary

- Halo formation, cooling, star formation and stellar feedback
  - Star forming galaxies
  - Mix of spheroid-dominated and disk-dominated

- Observations
  - Almost all spheroid-dominated galaxies are red, non-star-formers
  - *Not* primarily environmental
  - Bulge is a necessary but not sufficient condition for quenching; suggests AGN feedback

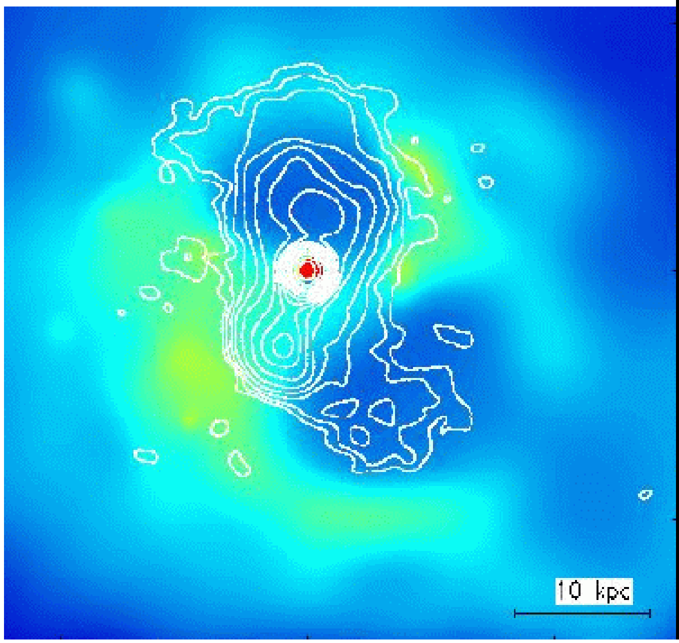
- Modelling AGN feedback
  - Quasar mode possibly important
  - Radio mode is likely to be vital
  - Qualitative successes, quantitative success is likely far off

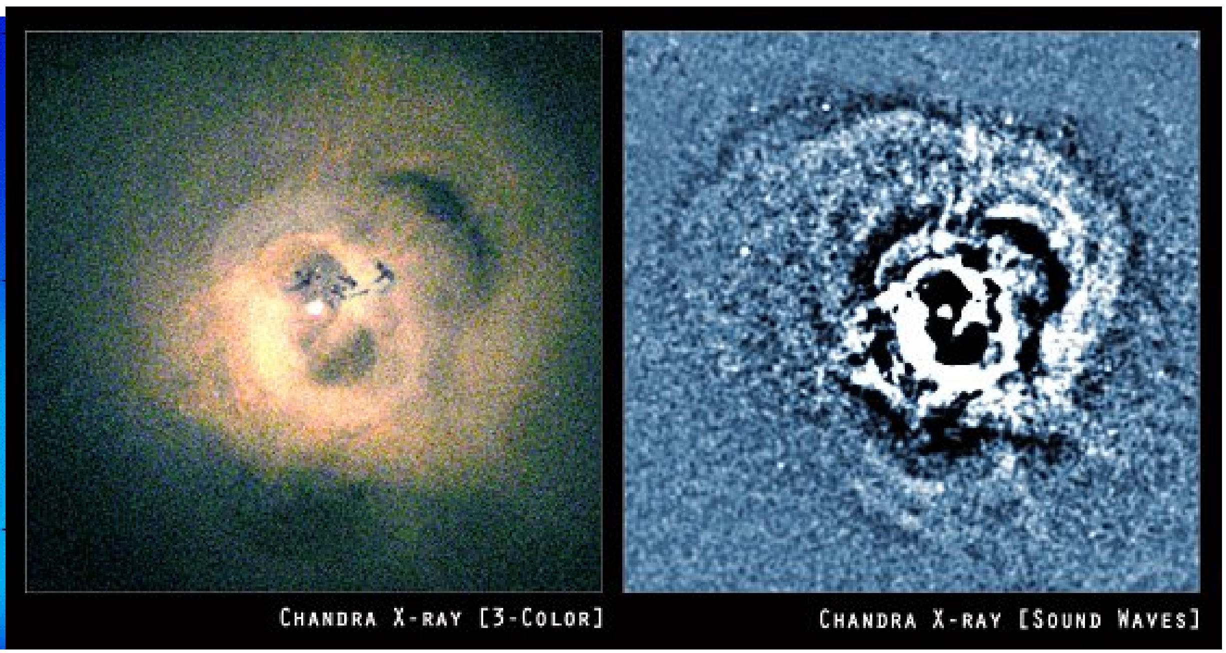
AGN feedback

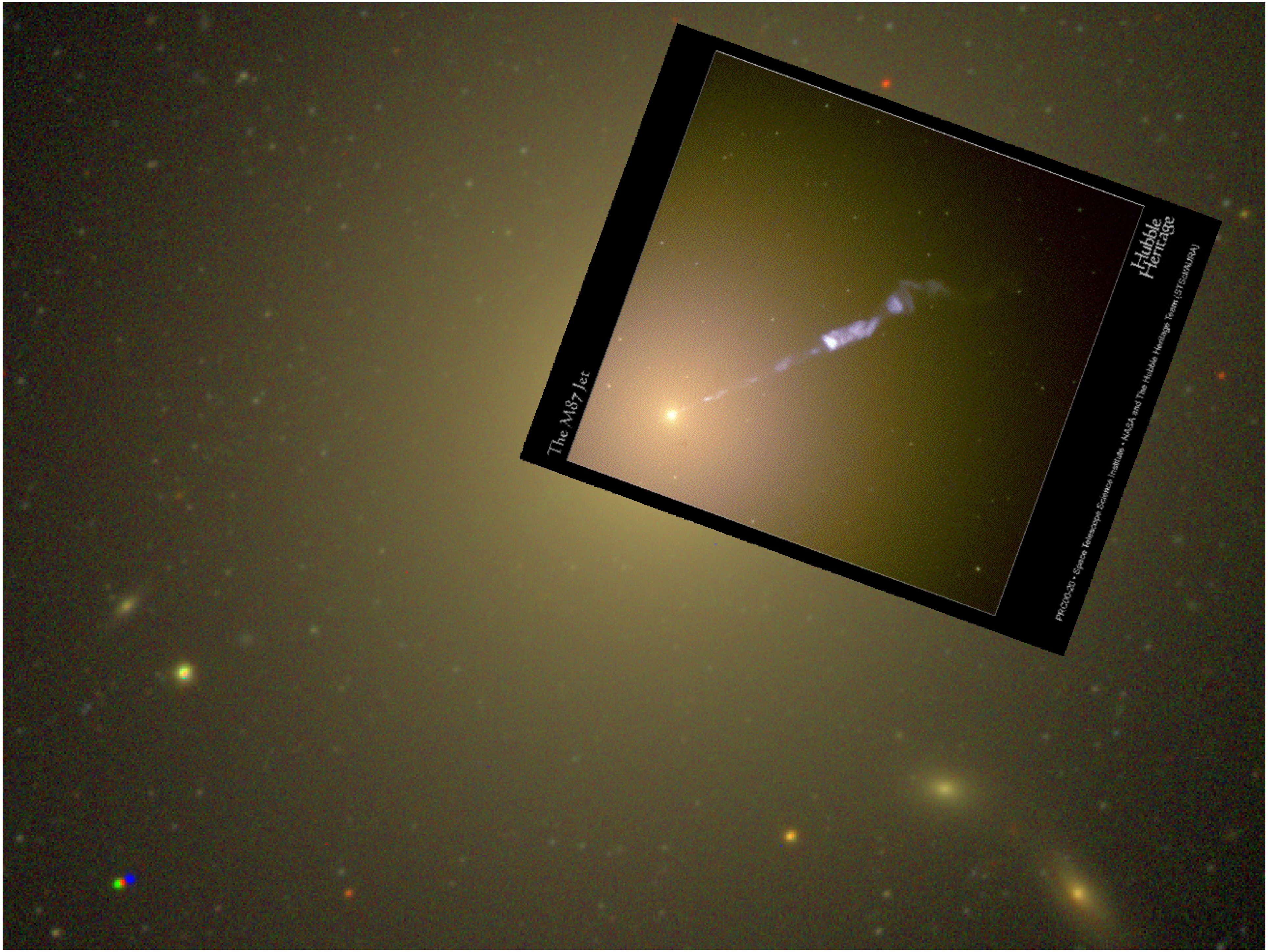
- mergers feed central black hole, giving rise to an ‘Active Galactic Nucleus’ (AGN)
- very efficient conversion of rest-mass to energy!
- this energy can couple to the cold gas in the galaxy & may drive powerful winds

Radio mode feedback?

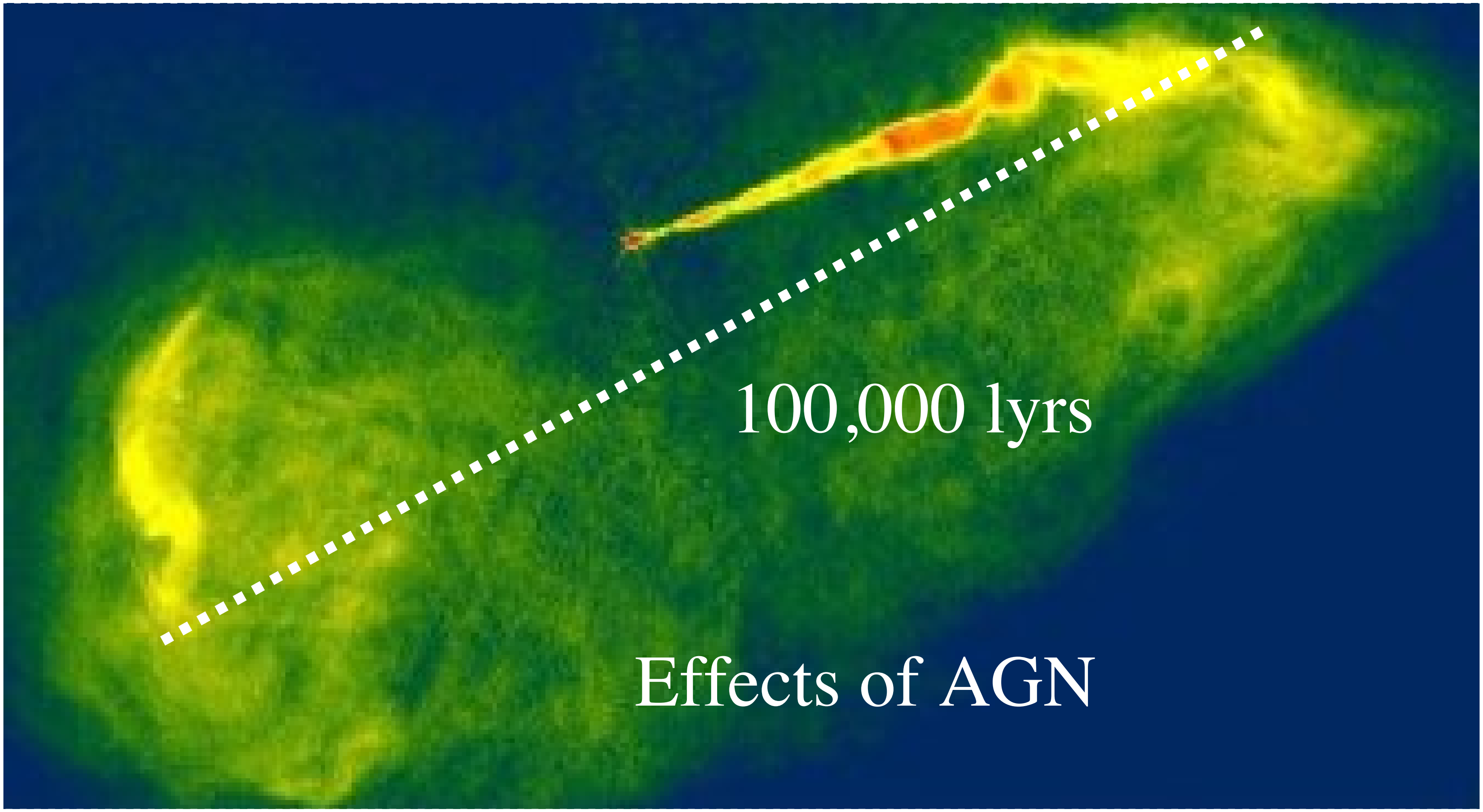
- Perseus cluster; bubbles and sound waves associated with hot gas bubbles blown by AGN jets…   Fabian et al.



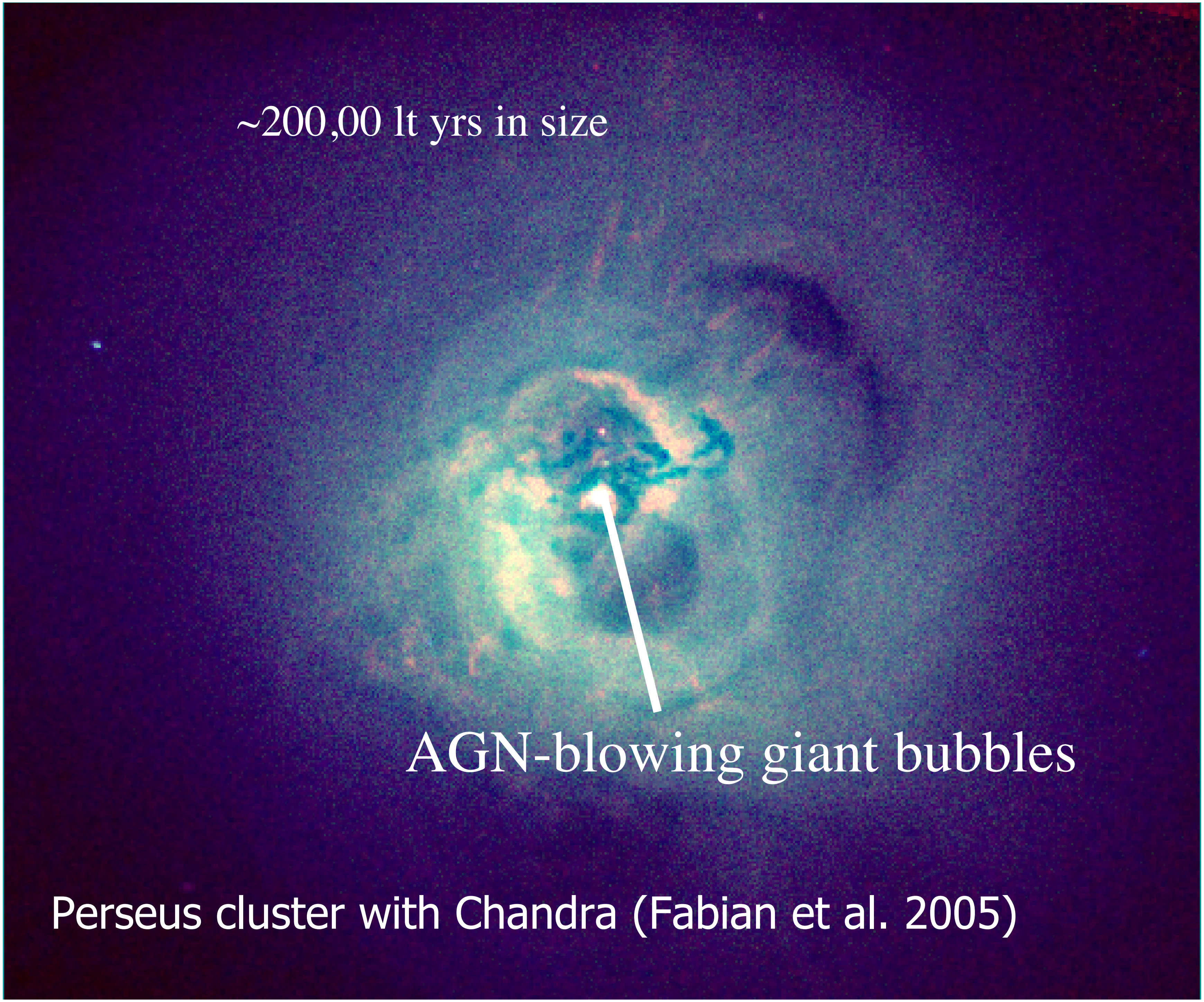




The M87 Jet
Hubble Heritage
PRC00-20 • Space Telescope Science Institute • NASA and The Hubble Heritage Team (STScI/AURA)



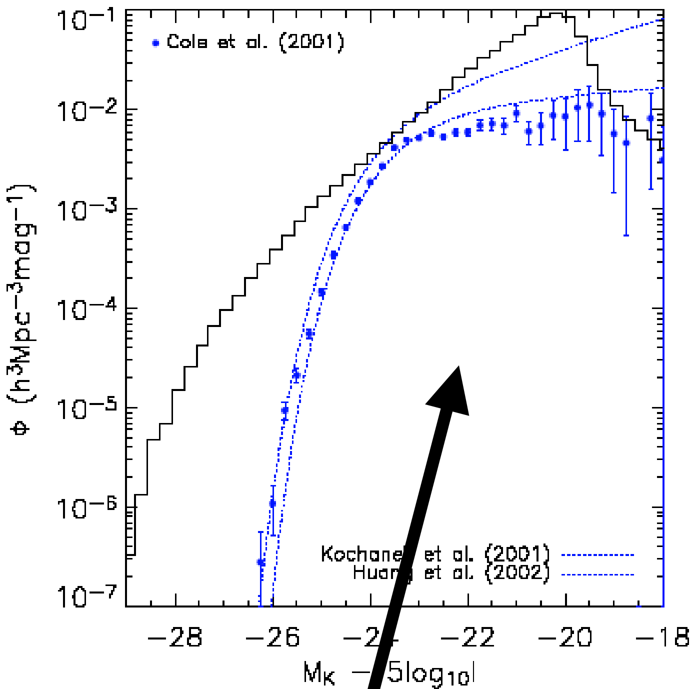
M87 with the VLA


~200,00 lt yrs in size
AGN-blowing giant bubbles
Perseus cluster with Chandra (Fabian et al. 2005)

Can AGN feedback work in practice?

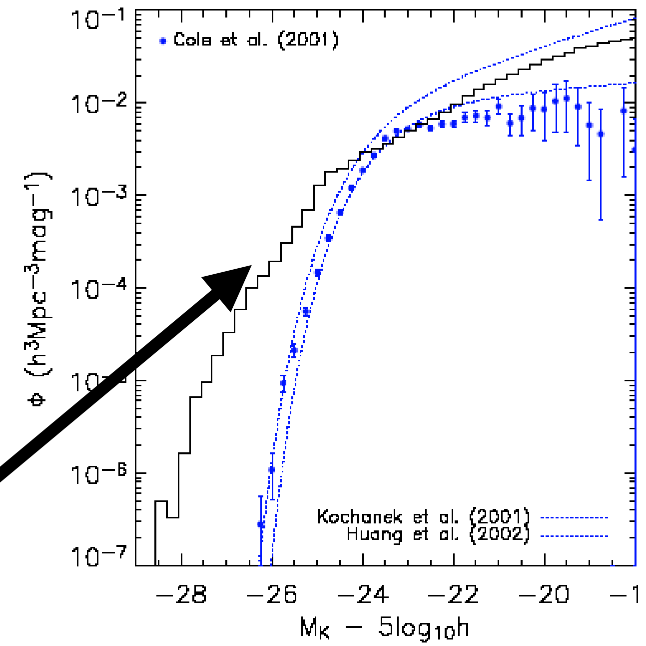
- Implementation in models
  - Quasar mode (Kauffmann & Haehnelt 2000)
    - Powerful outflow evacutes gas and quenches star formation immediately (
  - Radio mode (Croton et al. 2006)
    - Heating of hot gas envelope of galaxies stops further gas cooling
    - Very successful qualitatively
    - Particularly effective when have hot gas as working surface as in clusters of galaxies

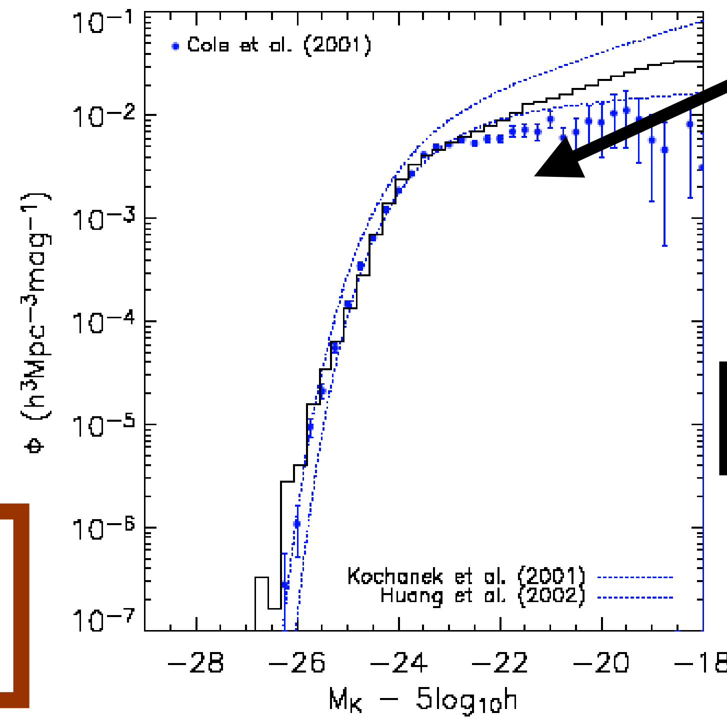
Calculation of K band galaxy luminosity function in N body simulation



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

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





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

V. Springel + S. White

Blue lines are data- black models

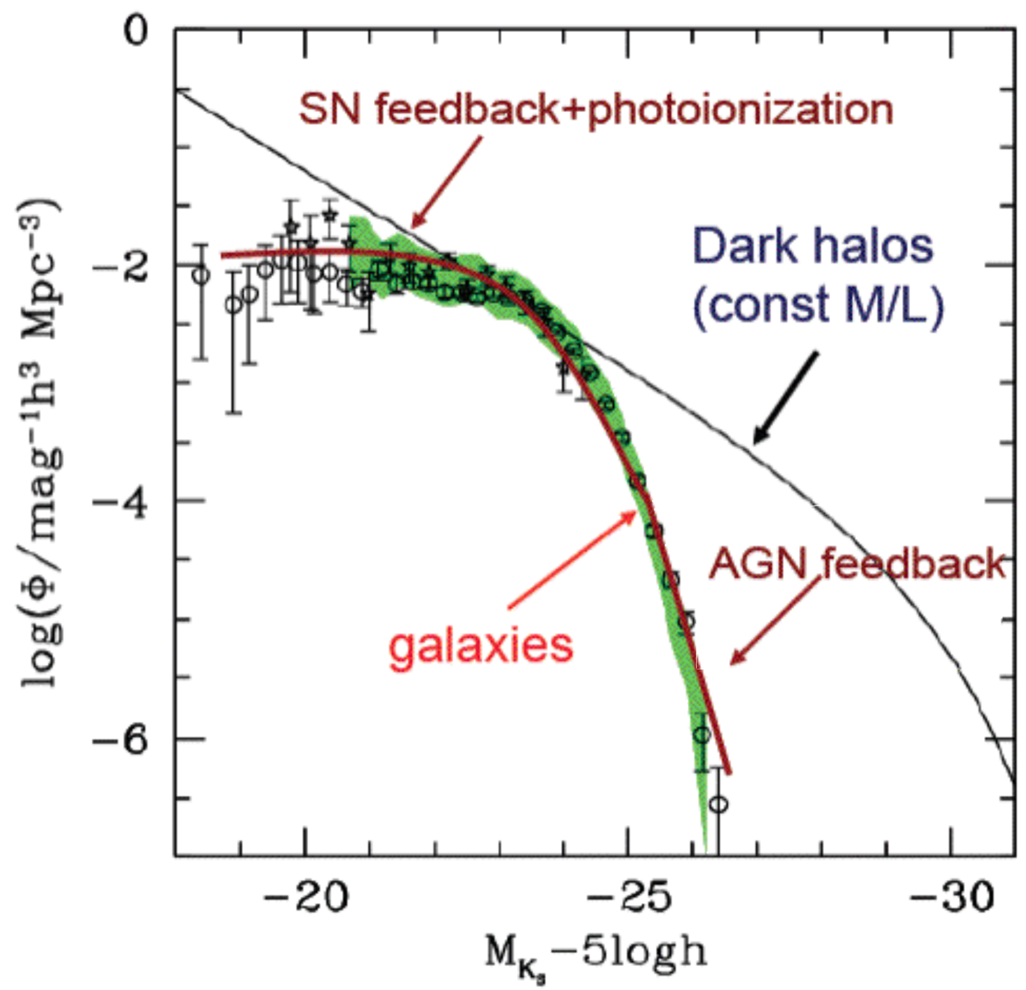
The galaxy luminosity function

University of Durham

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

Complicated variation of M/L with halo mass

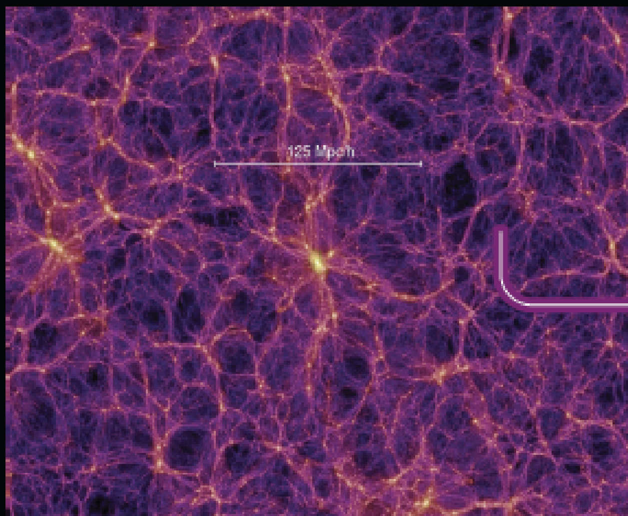
C. Frenk



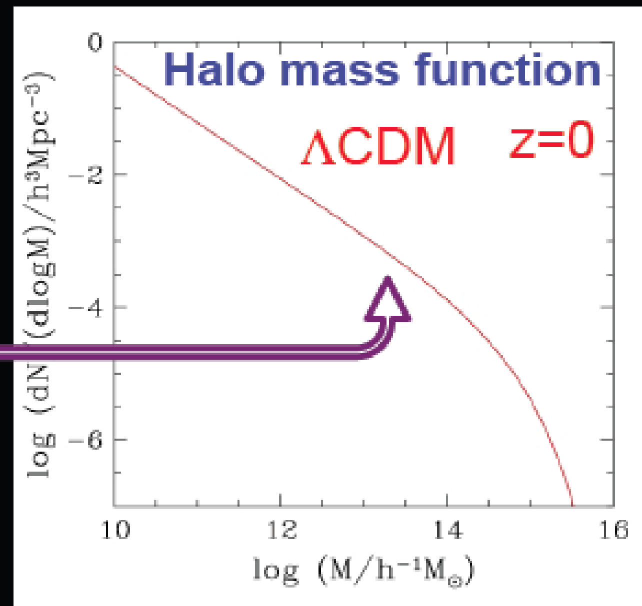
Benson, Bower, Frenk, Lacey, Baugh & Cole '03

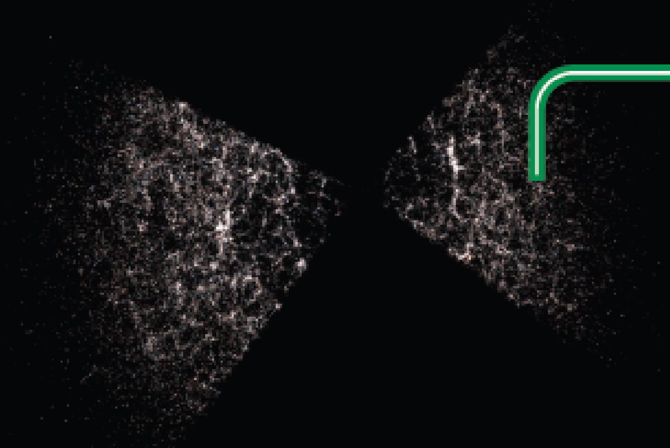
Institute for Computational Cosmology

The abundance of dark halos

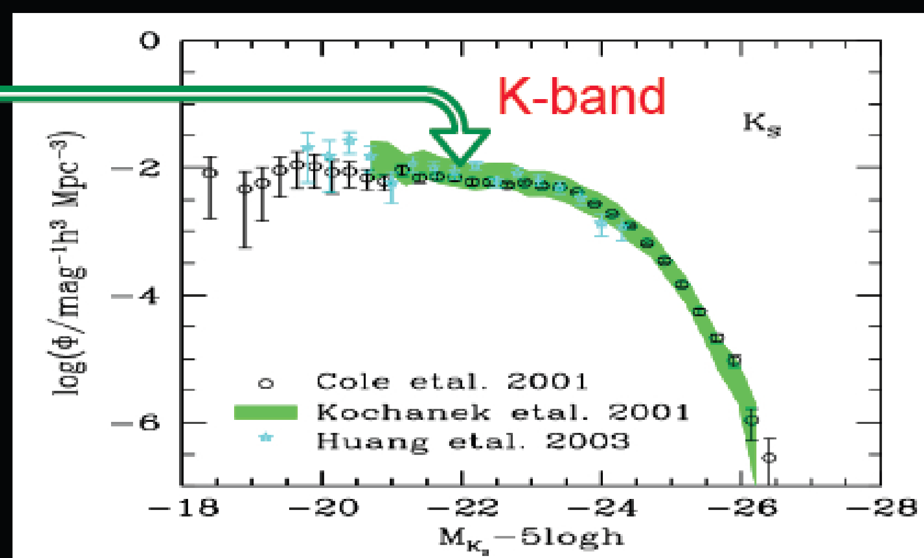


Millennium run





2dFGRS



C. Frenk