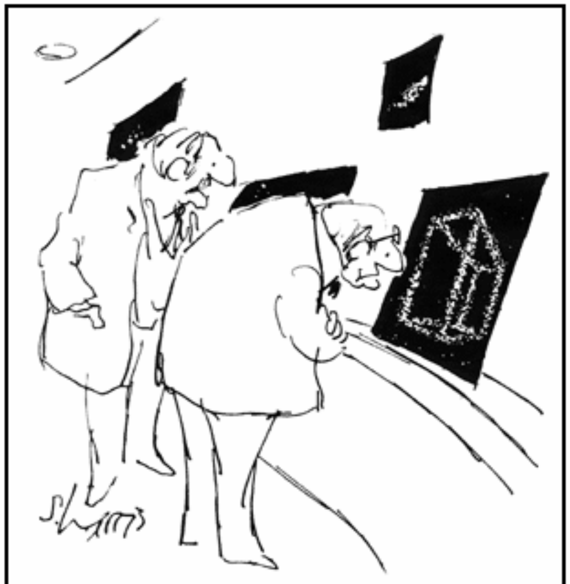
Galaxy Formation

Where did the galaxies come from:

- From homogeneity to structure…
  - Gravitational evolution of dark matter
  - Formation of dark matter halos
- Galaxy formation



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

© Sidney Harris

Galaxy Formation- Basic Processes

Early Universe- sets the conditions

power spectrum of fluctuations - denser ones collapse first

Formation of the dark matter halo

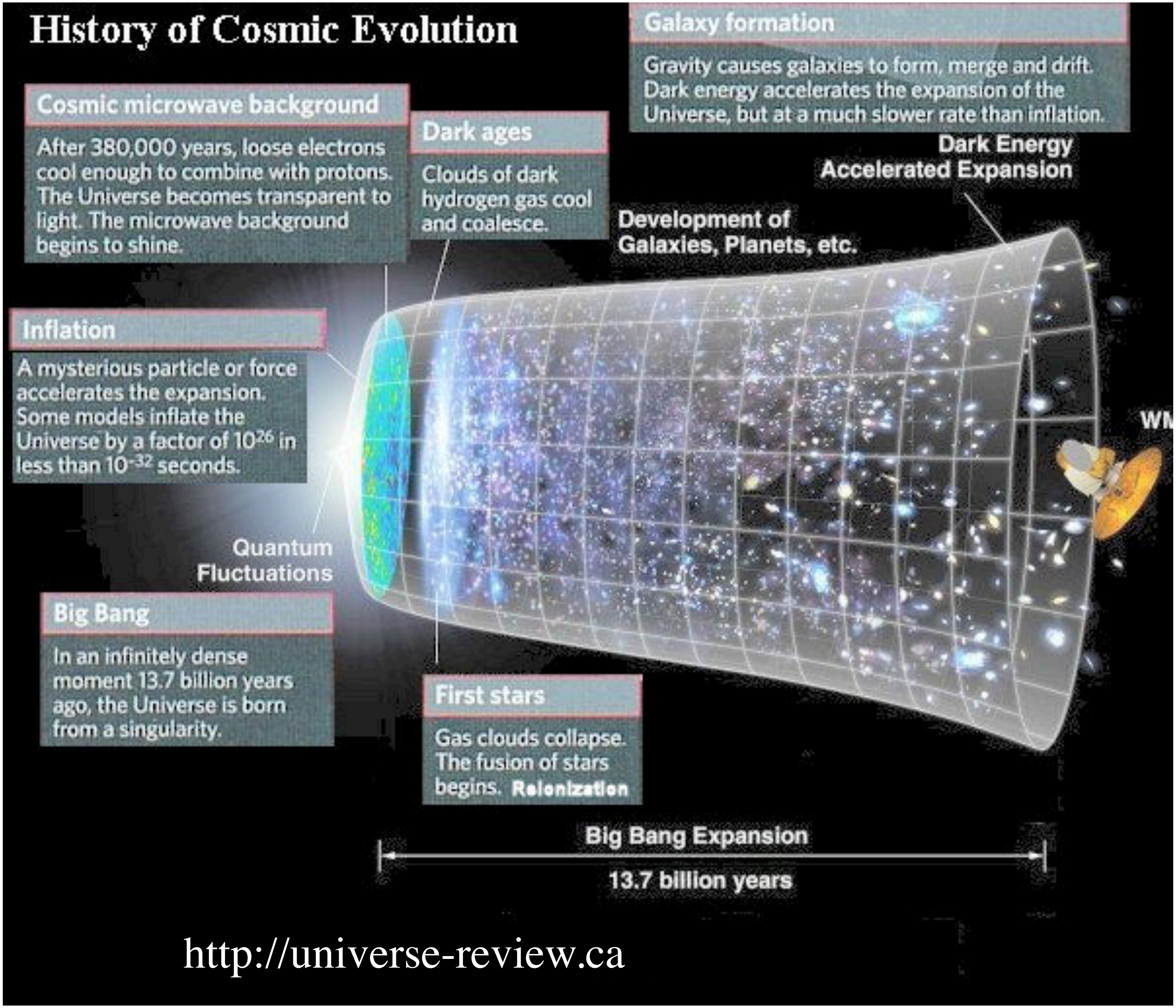
- Gas pressure at **very early** times stops baryons from clumping
- Dark Matter - has no pressure - can clump at will, acts as seeds for galaxy formation

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

Galaxy formation

Gravity causes galaxies to form, merge and drift. Dark energy accelerates the expansion of the Universe, but at a much slower rate than inflation.

Cosmic microwave background

After 380,000 years, loose electrons cool enough to combine with protons. The Universe becomes transparent to light. The microwave background begins to shine.

Dark ages

Clouds of dark hydrogen gas cool and coalesce.

Inflation

A mysterious particle or force accelerates the expansion. Some models inflate the Universe by a factor of 10^{26} in less than 10^{-32} seconds.

Big Bang

In an infinitely dense moment 13.7 billion years ago, the Universe is born from a singularity.

First stars

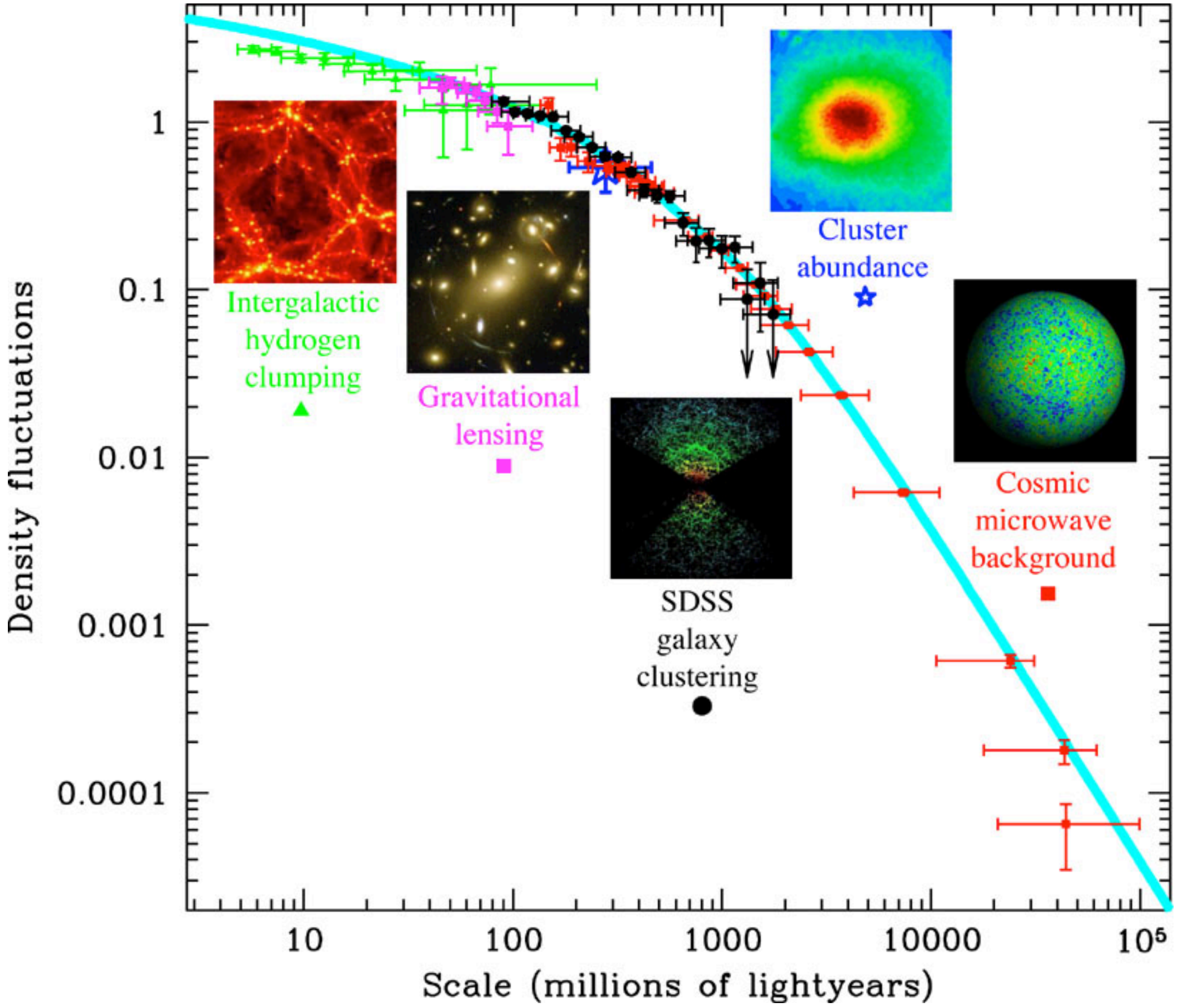
Gas clouds collapse. The fusion of stars begins. Reionization

http://universe-review.ca

Power Spectrum of Fluctuations

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

Lumpiness of universe



Tegmark 2004

size of box

Hierarchical Formation of Structure

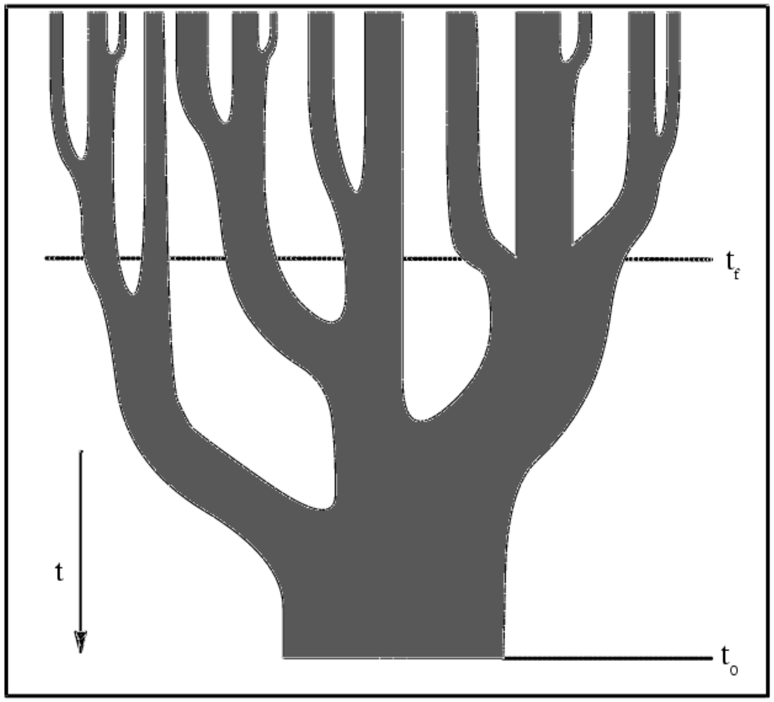
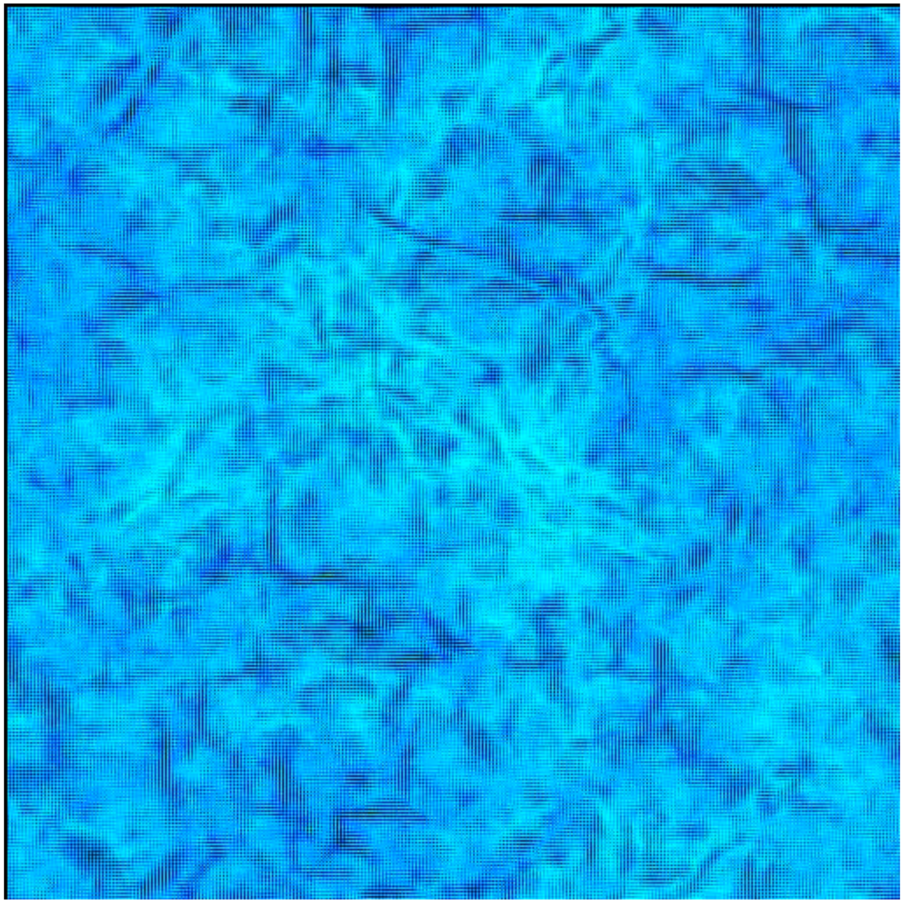
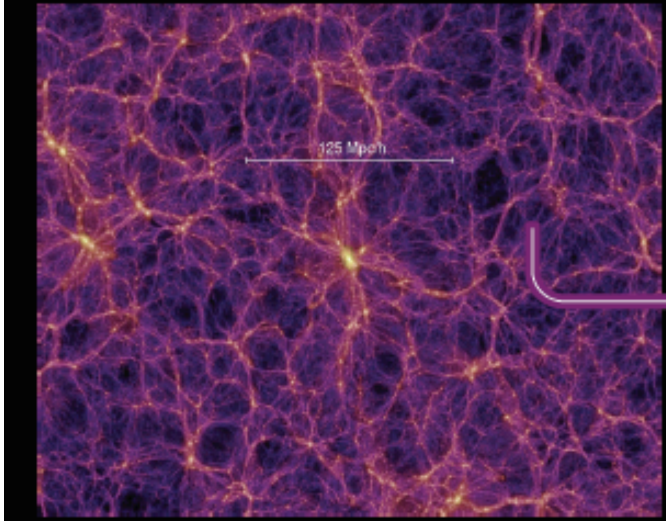


Figure 6. A schematic representation of a "merger tree" depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the widths of the branches of the tree represent the masses of the individual parent halos. Slicing through the tree horizontally gives the distribution of masses in the parent halos at a given time. The present time t_0 and the formation time t_f are marked by horizontal lines, where the formation time is defined as the time at which a parent halo containing in excess of half of the mass of the final halo was first created.

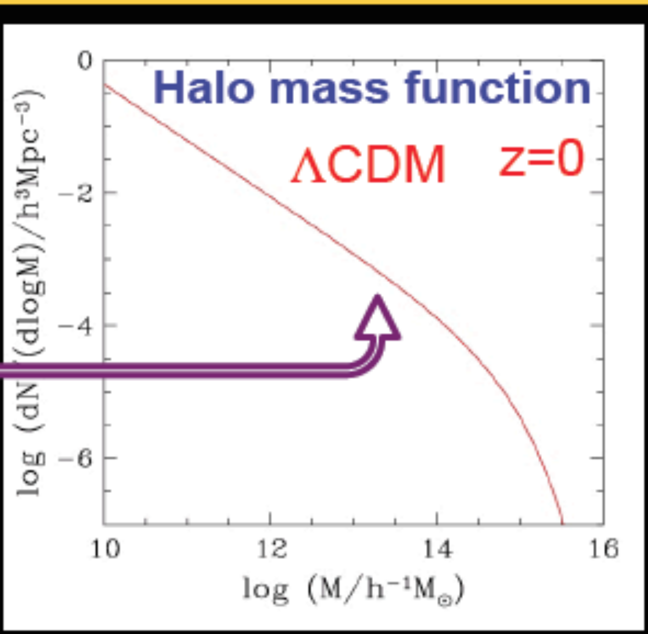


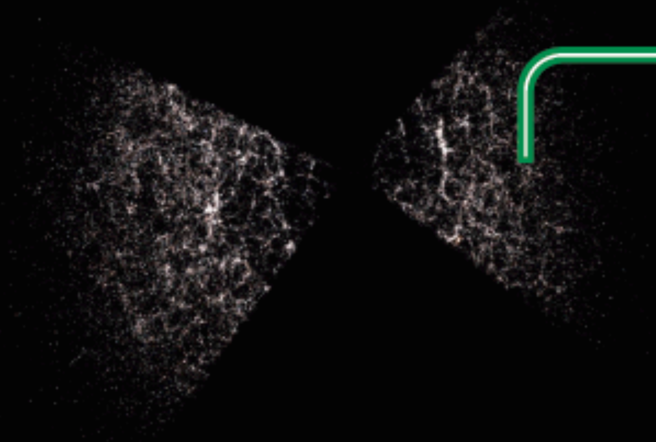
Bode

The abundance of dark halos

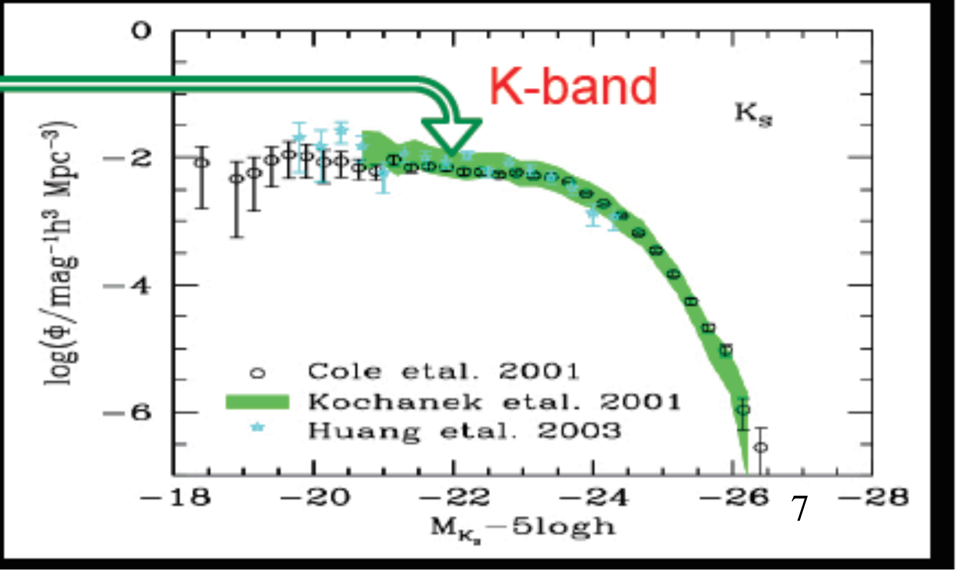


Millennium run





2dFGRS



C. Frenk

III : THE FORMATION OF STRUCTURE

- computer models to model the growth, then collapse, of inhomogeneities
  - Result is a "numerical simulation" of evolution in the Universe
- Simulations:
  - Simulate the evolution of the Universe in a large "box" of space.
  - "Box" is typically large (10s to 100s of Mpc) compared to clusters but small compared to observable Universe (8 Gpc)
  - Start off with "initial conditions" of nearly uniform distribution of matter, with small inhomogeneities
    - Use "spectrum of perturbations" consistent with CBR observations and correlation functions from redshift surveys
    - Start at time long after matter/radiation decoupling ($z \approx 1000$, 400,000 yrs after Big Bang)…

    …but still early enough that inhomogeneities are small

- Numerical programs on supercomputers are used to evolve the governing equations
- Typically need 100,000 or more equivalent CPU hours on supercomputer with 100 or more processors (would take >10 years to run model on a desktop!)
- Follow motions of 100s of millions of particles, each representing mass up to 10^{10} stars (10% of MW mass)
- Physics in equations includes:
  - Expansion of Universe ("box" shown in images is in comoving coordinates; i.e. continuously rescaled to fit screen)
  - gravity of dark matter and baryons
  - Gas pressure forces (only on baryons), if included
  - Dark energy (cosmological constant), if included
- Gravity causes fluctuations to grow: mass condenses into regions that initially had highest density

The complexity of the systems and the physics involved requires numerical simulation !

The “Millenium simulation”

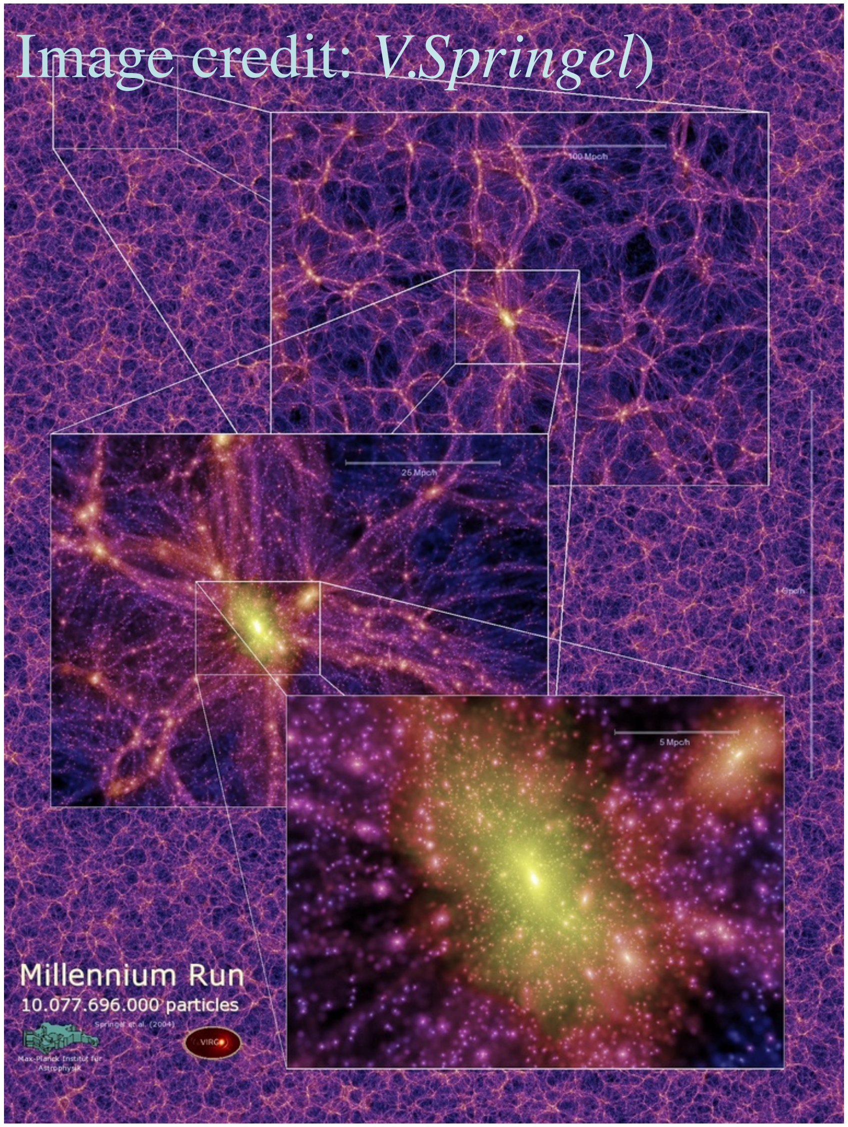


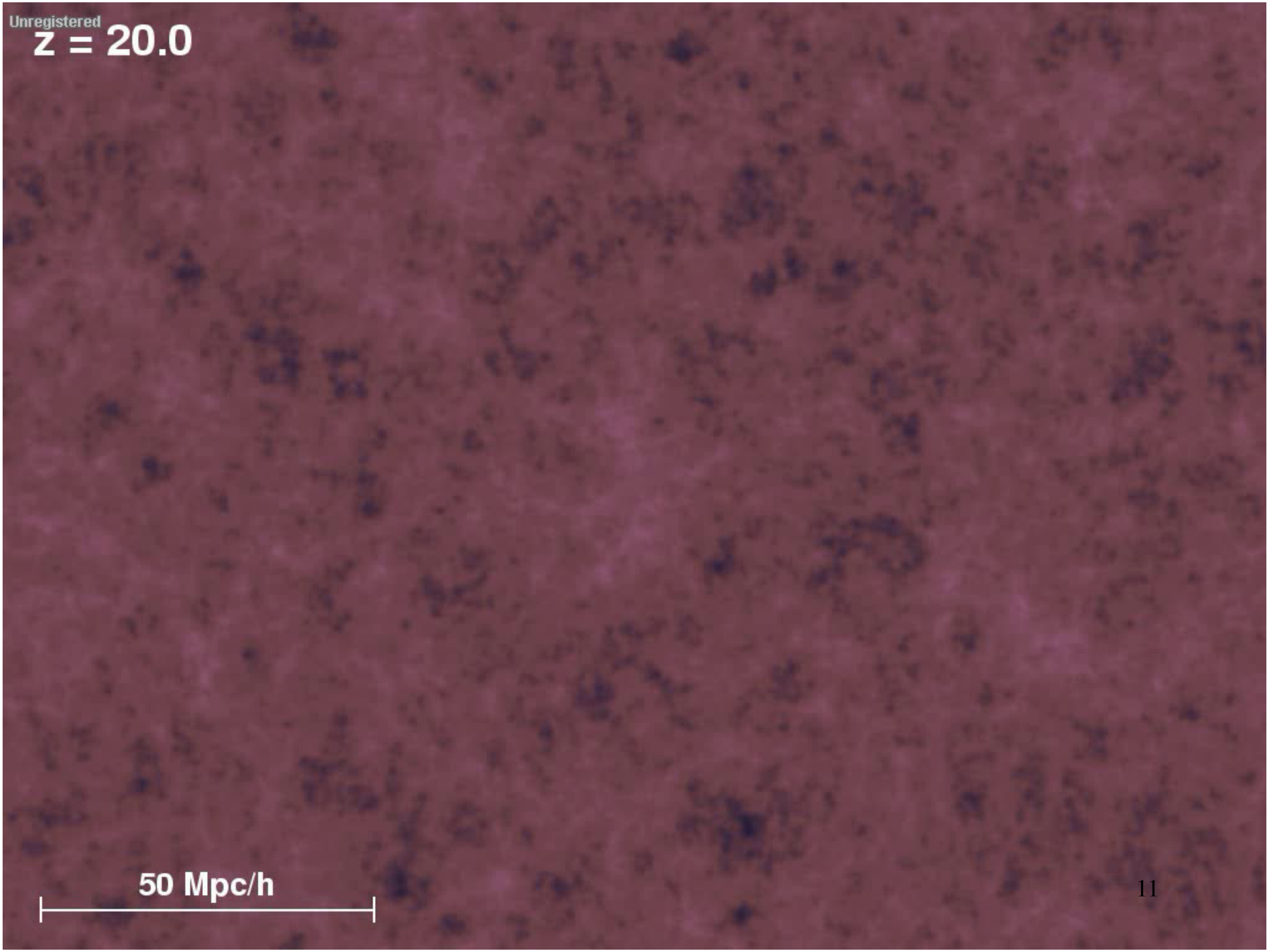
Image credit: *V.Springel*)

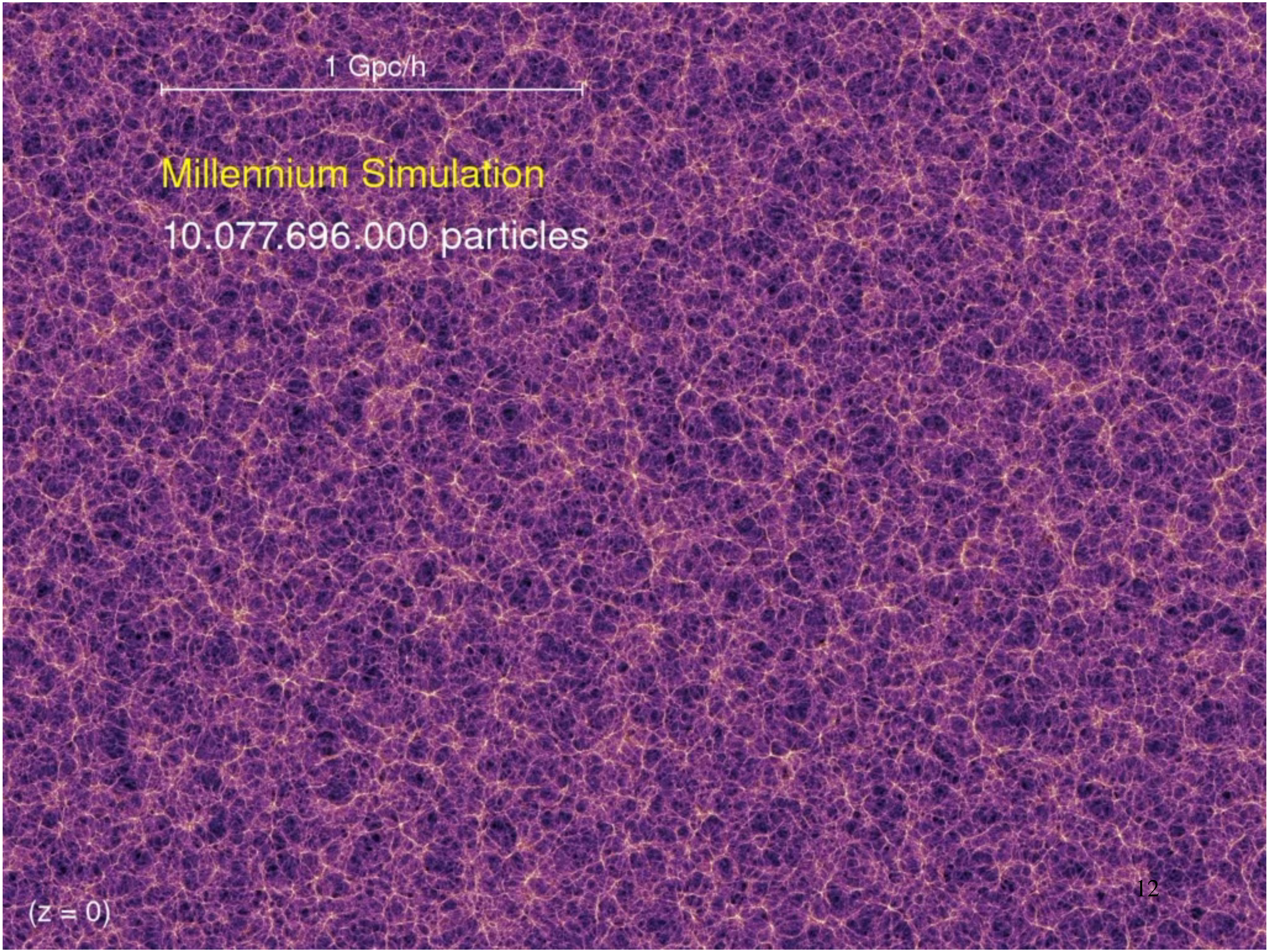
The largest N-body simulation carried out to prior to 2011

- Follows what becomes 20 million galaxies over 2 billion years
- Volume (2 Glyr)^3
- More than 10^{10} particles
- 25 Terabytes of data produced

- In this picture color corresponds to the logarithm of the density (dark purple low, yellow high)

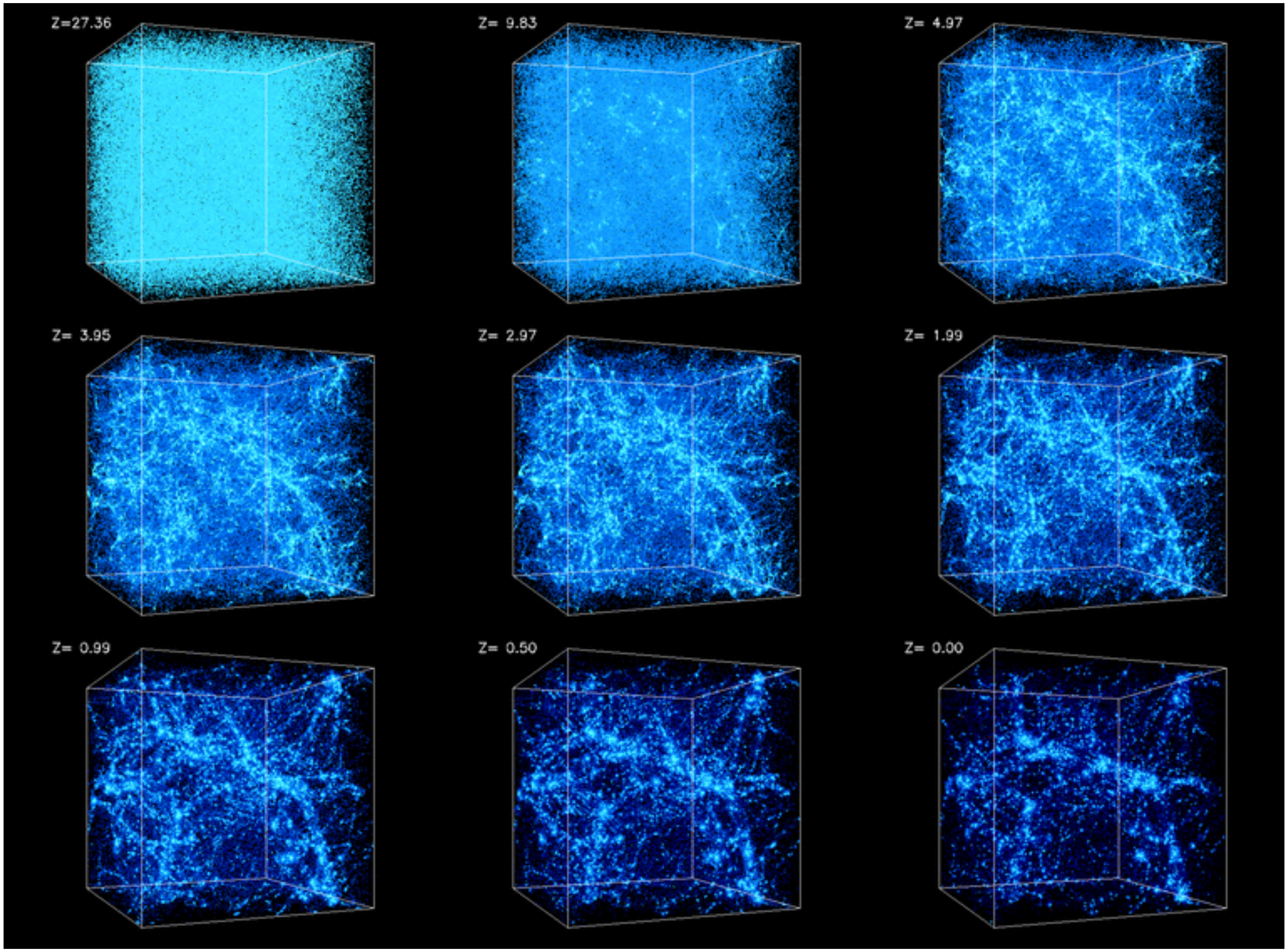
20Mpc thick slice at z=0 with 4x zoomed regions


Unregistered
z = 20.0
50 Mpc/h


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)

- Can perform simulations with somewhat smaller box to focus on details, e.g.:
  - Large scale structure
    - this should be similar to that seen in redshift surveys
  - Dynamics within clusters and groups of galaxies
    - up to half of all galaxies in the Universe are thought to be part of groups or clusters
  - Galaxy formation

Formation of large-scale structure: snapshots



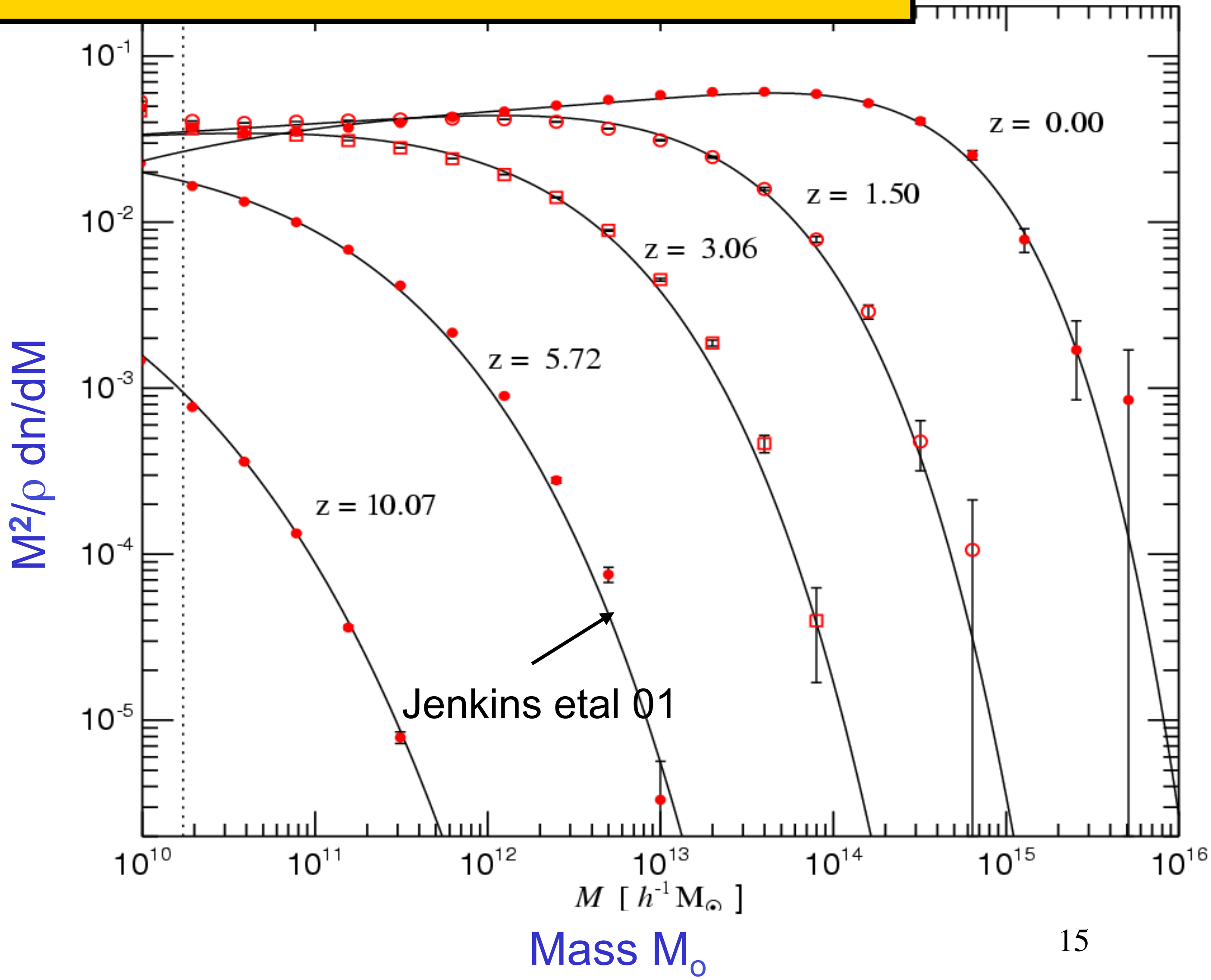
Credit: Andrey Kravtsov (U. Chicago) and Anatoly Klypin (New Mexico State U.)

Growth of Dark Matter Halos from Numerical Simulation

Jenkins et al 2001

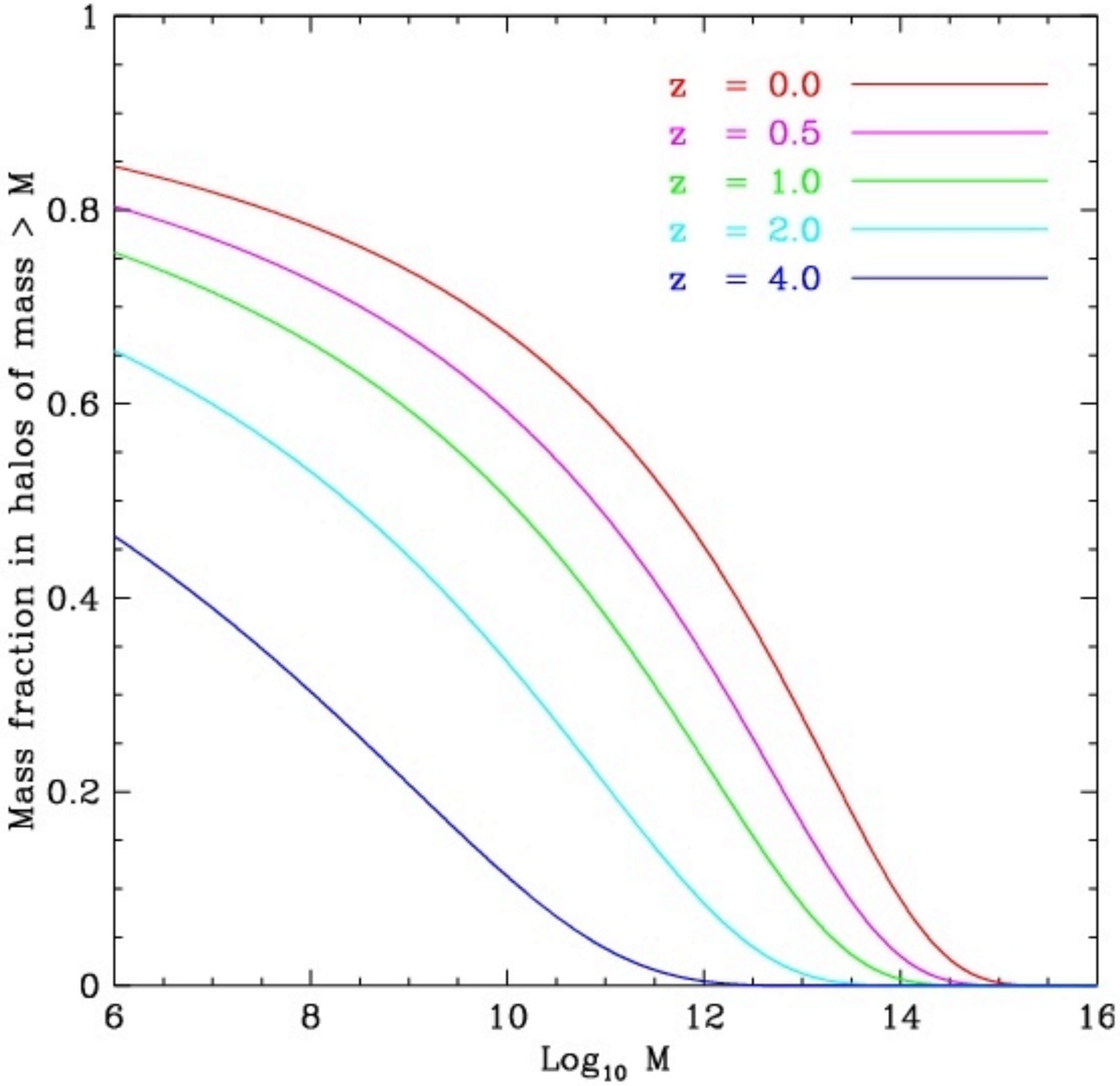
At z = 0 half of all mass is in lumps of M > $2.10^{10}M_\odot$

And ~90% in halos M > $210^6M_\odot$



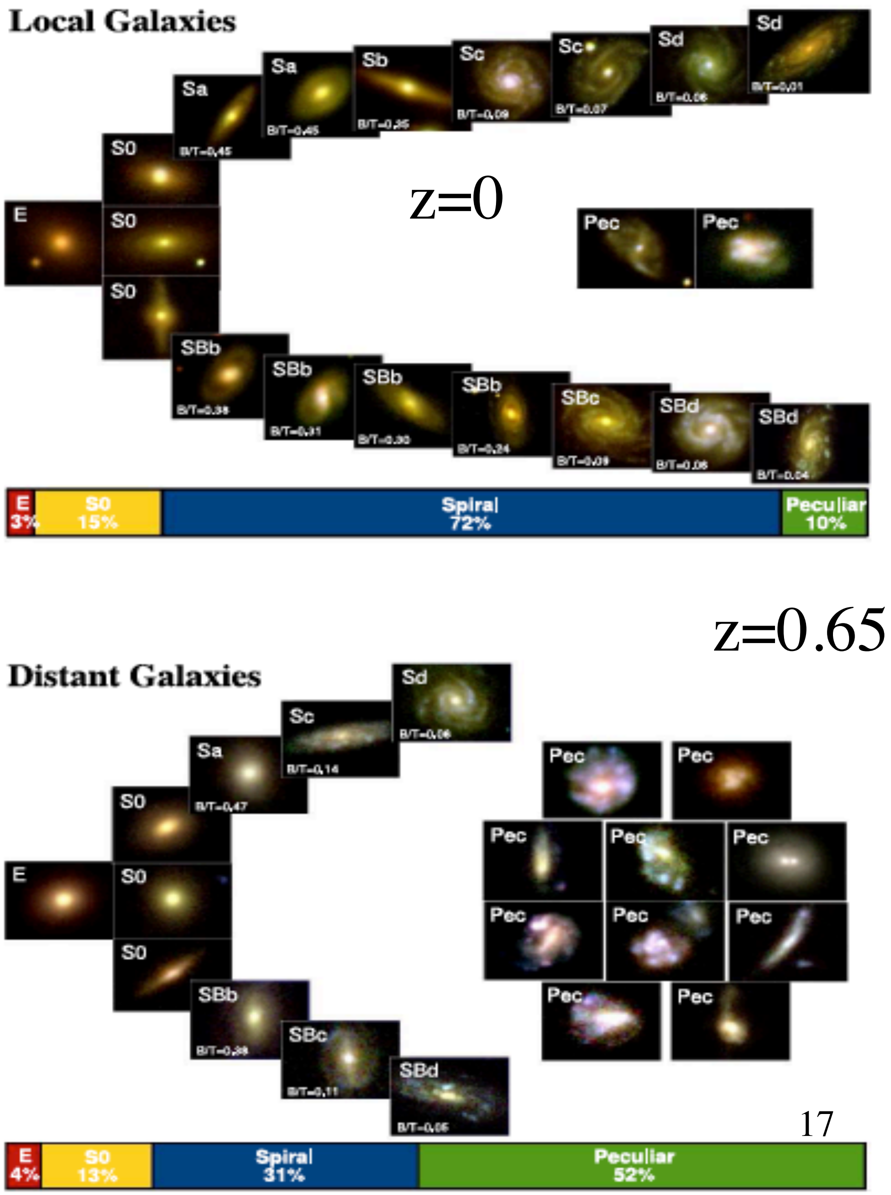
Springel et al 2005

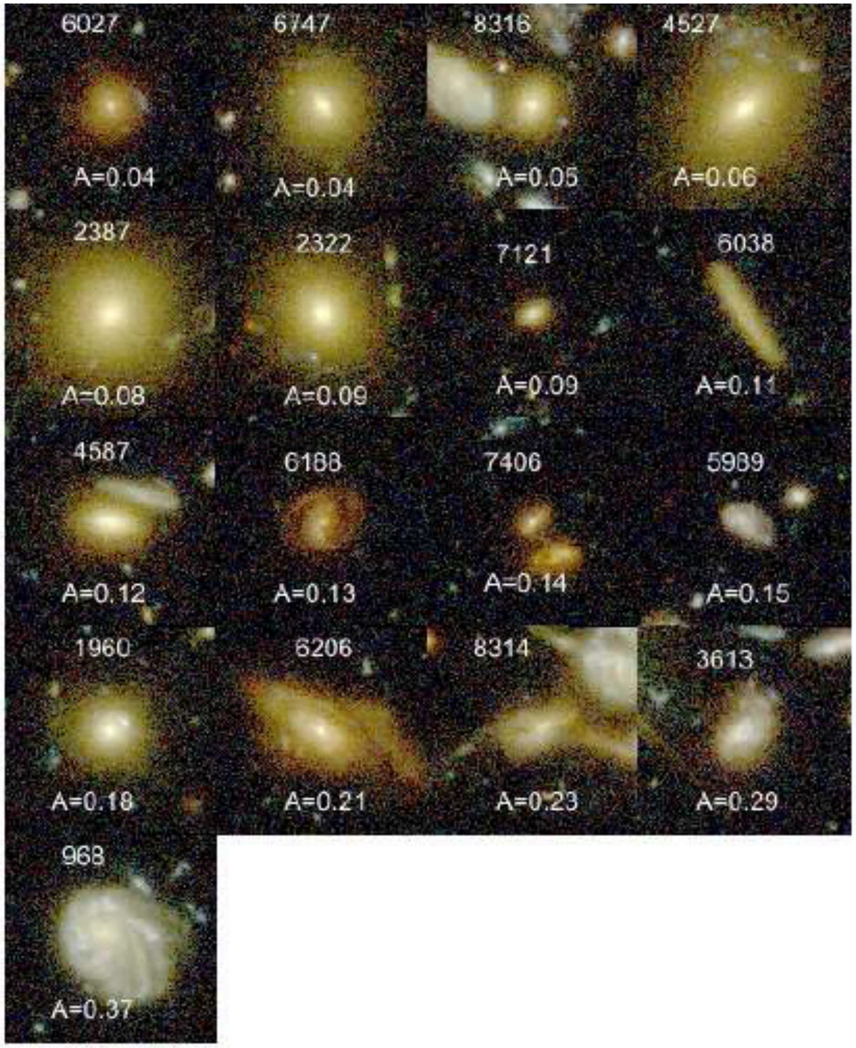
Results from simulations on growth of dark matter halos



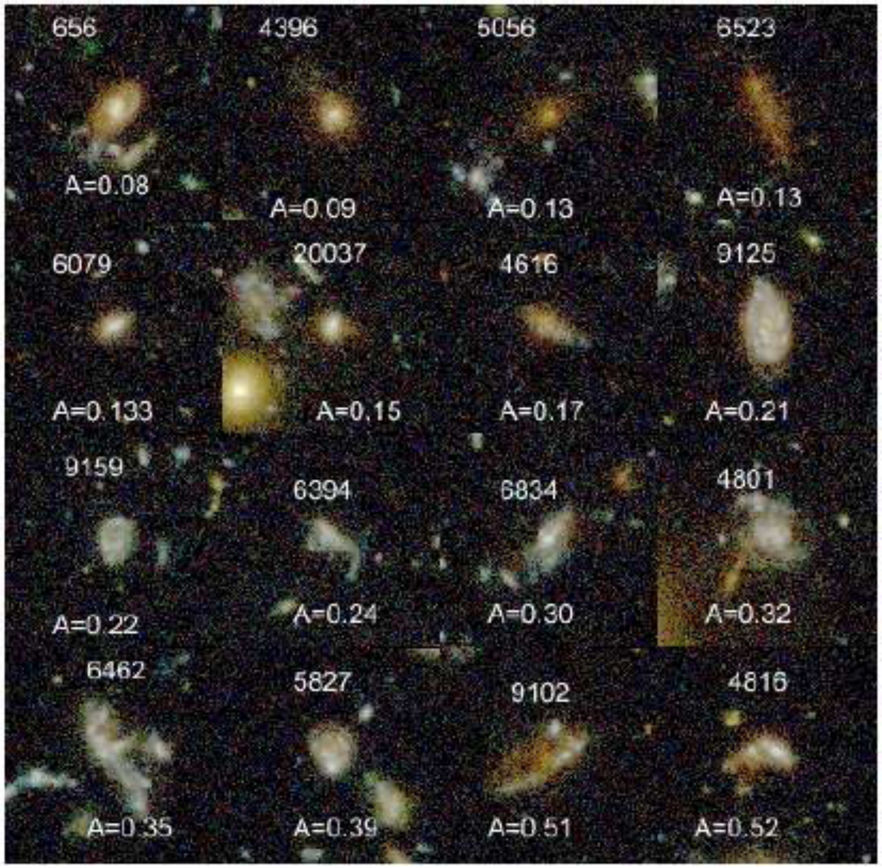
Changes Across Cosmic Time

- 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

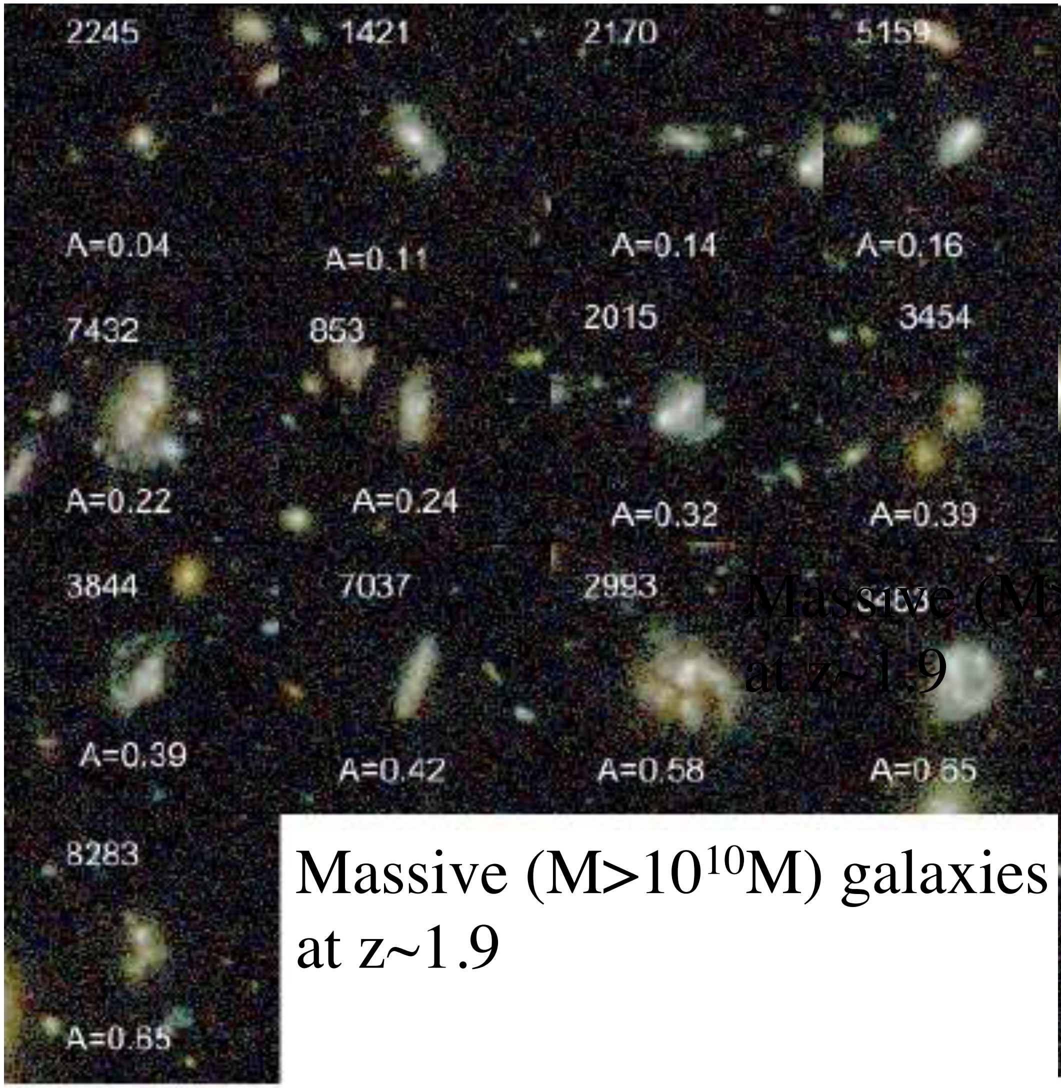

R. Delgado-Serrano et al.: How was the Hubble sequence 6 Gyrs ago?



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

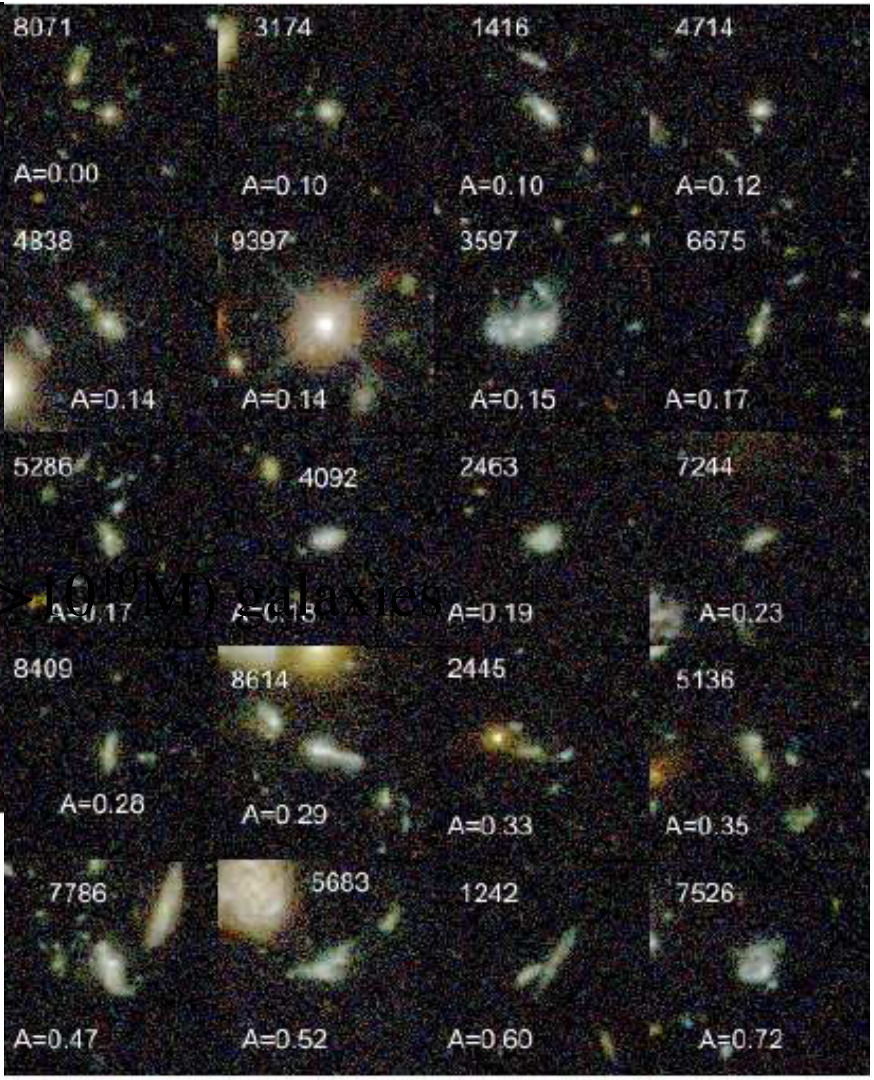


Massive ($M>10^{10}M$) galaxies at z~1.4



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

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

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 ?

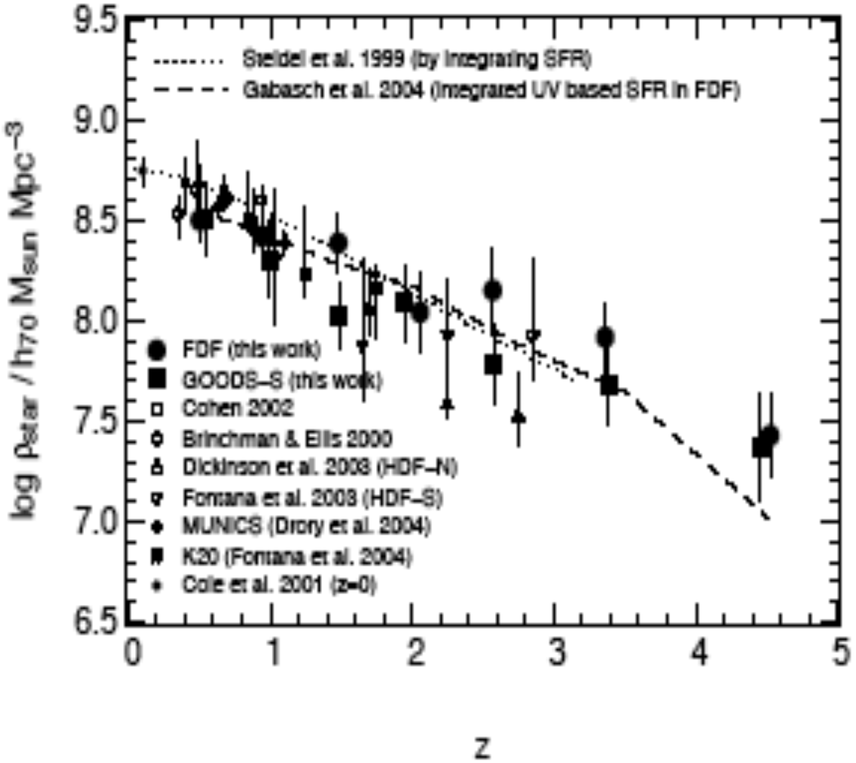


FIG. 3.— The total stellar mass density of the universe as a functi
redshift. We also show the integral of the star formation rate as a dotted
and dashed line.

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

Non-Gravitational Physics in 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

Outflow from starburst M82

- 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

Can AGN feedback work in practice?

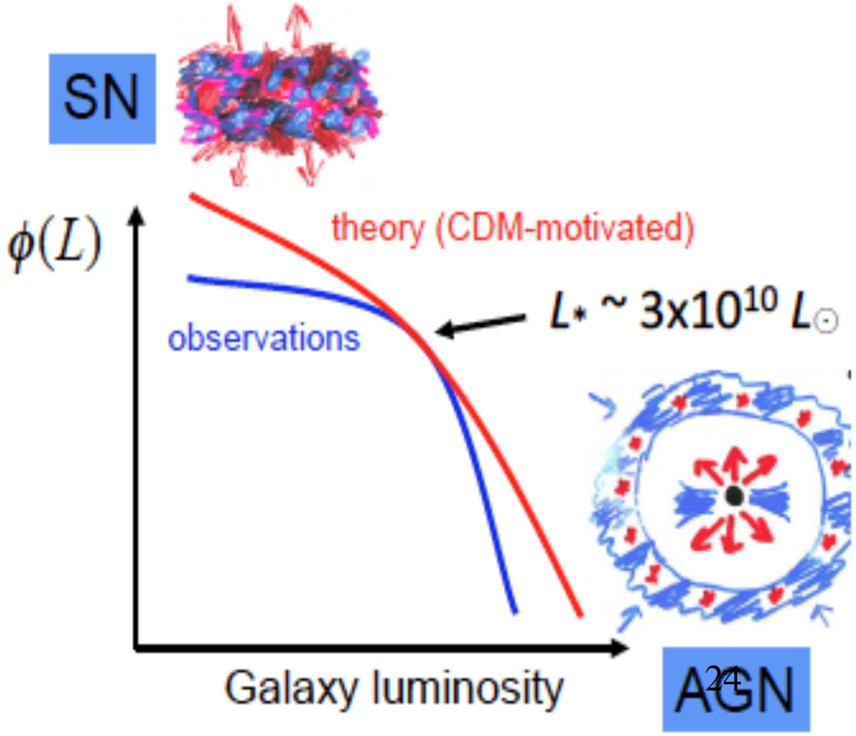
- We will discuss this more later, but it seems as if AGN Feedback is critical in forming the most massive galaxies. Effect on lower mass galaxies is not certain.
- Seem to need two types of AGN feedback
  - Quasar mode (Kauffmann & Haehnelt 2000)
    - Powerful outflow evacutes gas and quenches star 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

Galaxy Formation

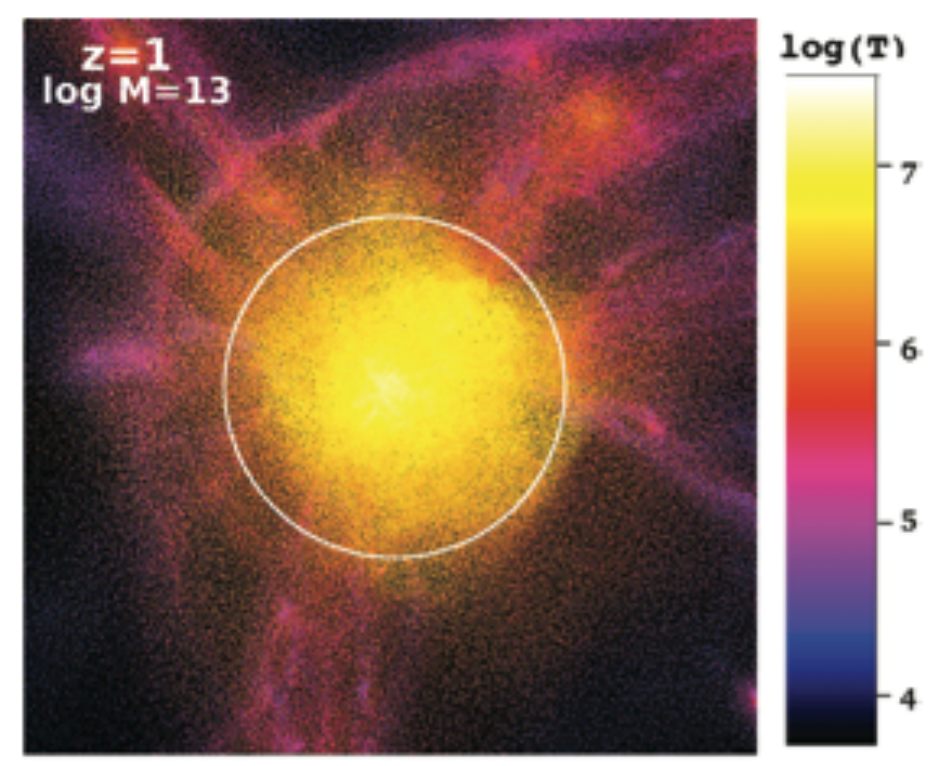
- Theory provides the mass function of dark halos. Observation yields the luminosity function of galaxies
- The basic set of ideas:
- small initial density fluctuations grow with time due to gravitational instability.
- the dark matter collapses into haloes with a quasi-equilibrium state through violent 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

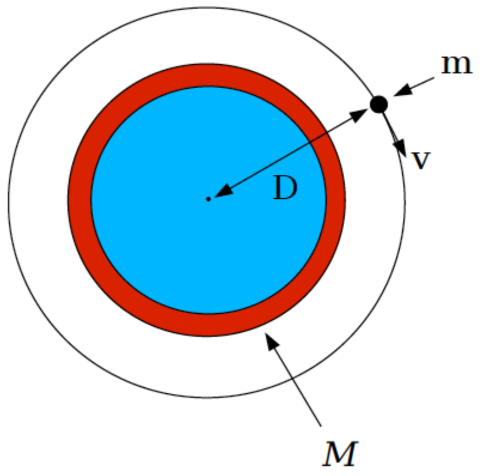
a (set of) concentric (co-planar), circular orbits.

→ 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 ∝ M^{-2}
    - Halos grow only through merging (mass accretion ~ scale free)

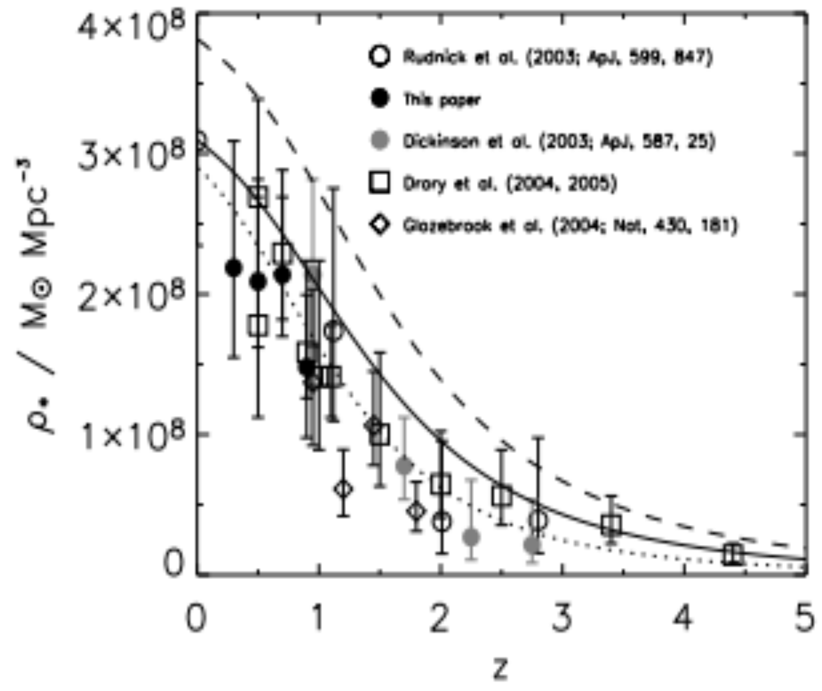
- After reionization- 4 main processes
  - Gas accretion / cooling from cosmic web
  - Gas cooling rate ∝ n^2
  - Depends on metallicity
  - Hot mode (virial temp) / cold mode
- Star formation
  - SFR ∝ H_2 mass Empirical star formation laws
    - SFR ∝ gas density $^{1.4}$ (Kennicutt 1998)
    - SFR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

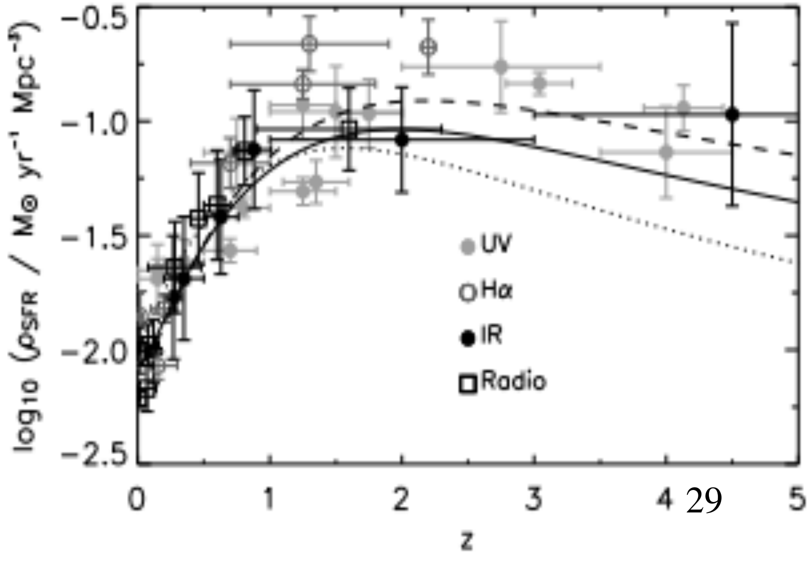
Merging- dark matter halos and their baryonic contents can merge

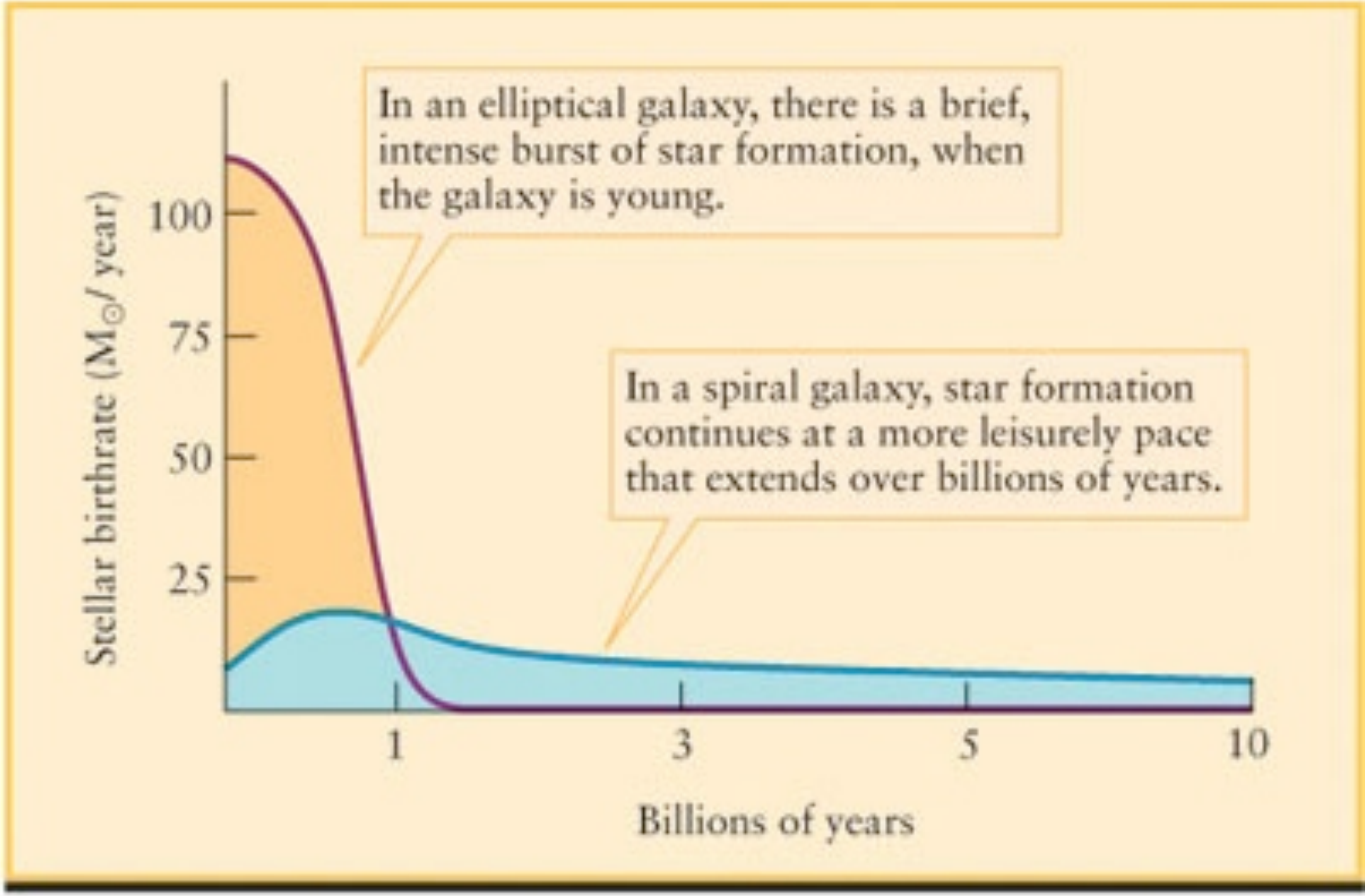
morphology changes

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







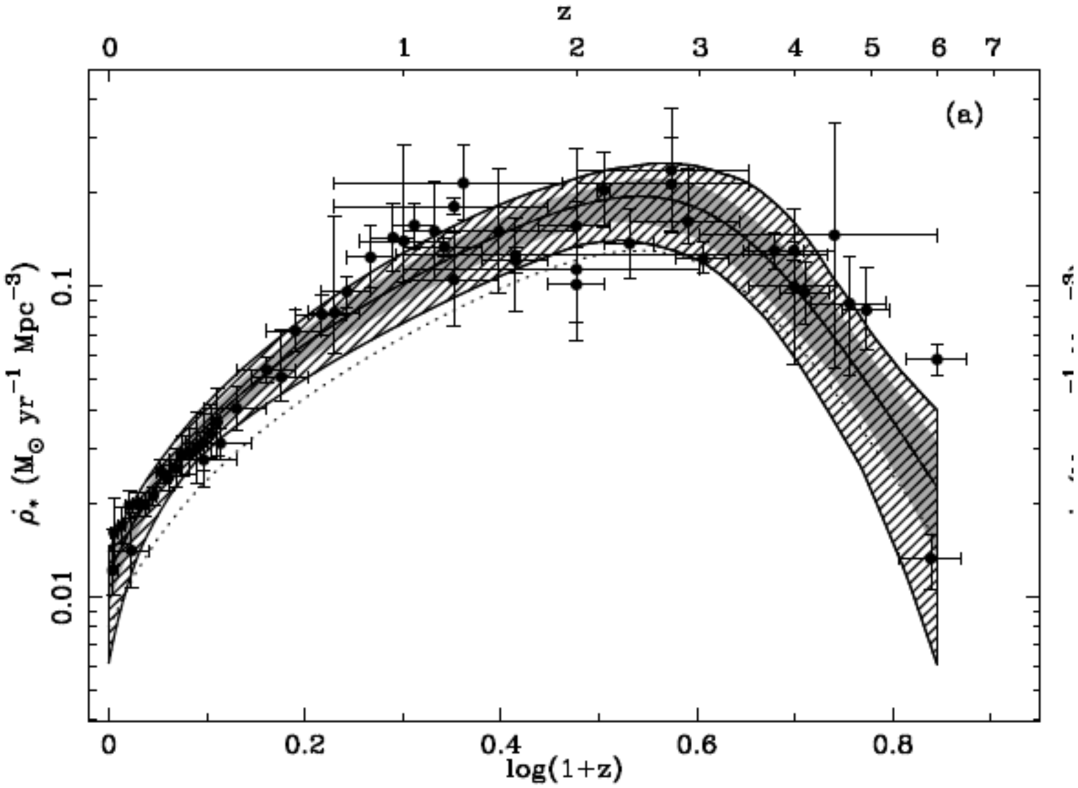
In an elliptical galaxy, there is a brief, intense burst of star formation, when the galaxy is young.

In a spiral galaxy, star formation continues at a more leisurely pace that extends over billions of years.

(c) The stellar birthrate in galaxies

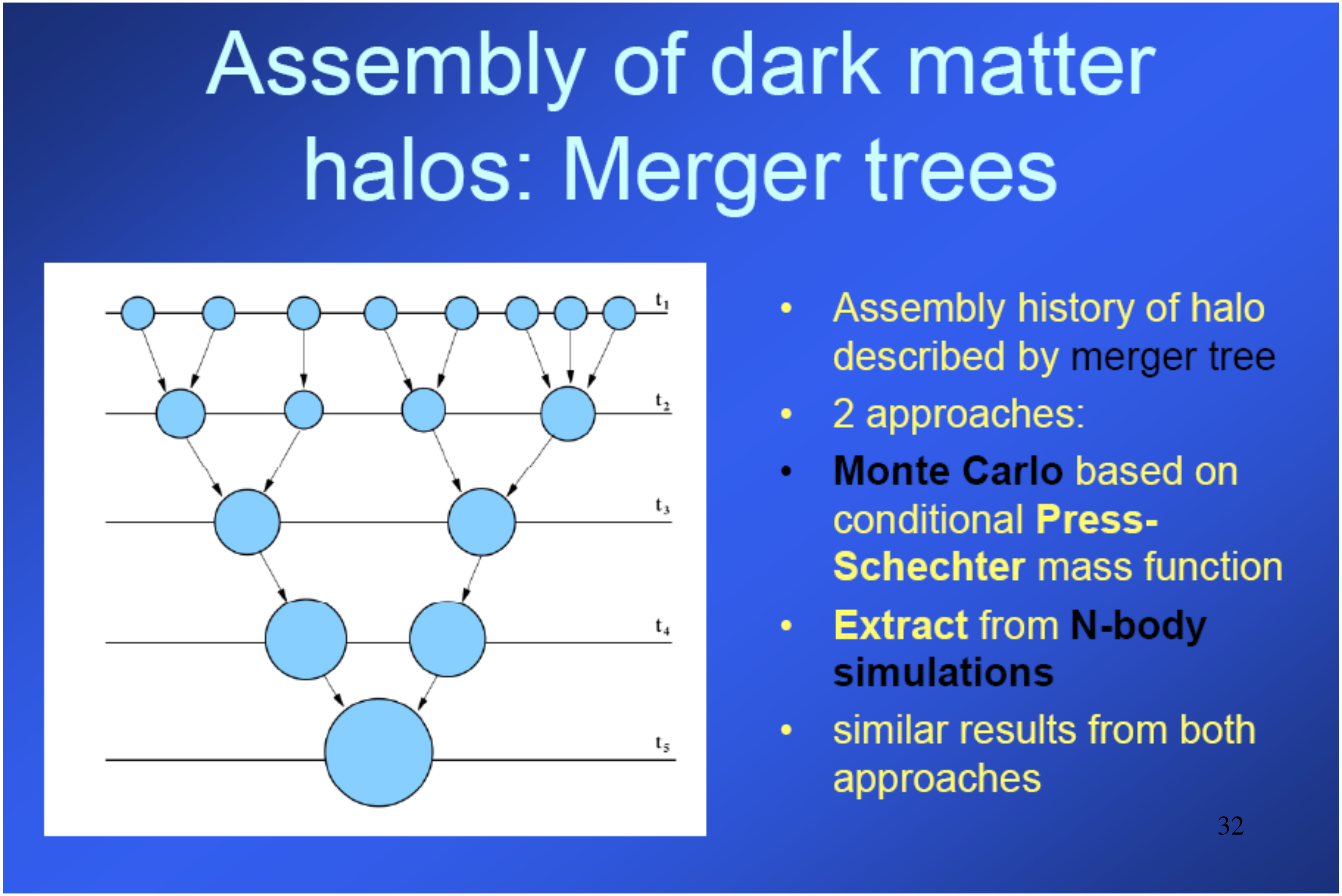
Star Formation History of the Universe

- 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

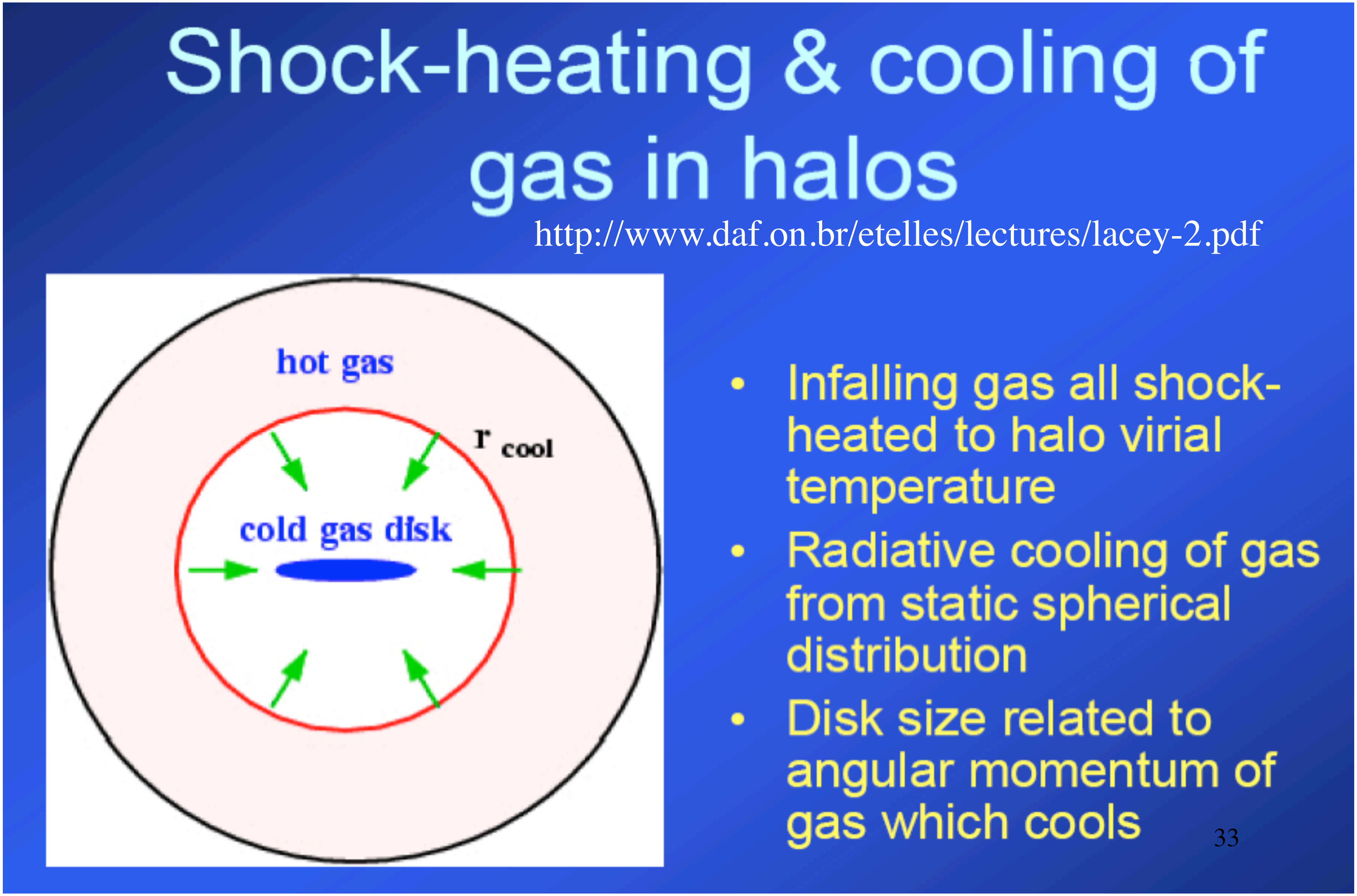
http://www.daf.on.br/etelles/lectures/lacey-2.pdf



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

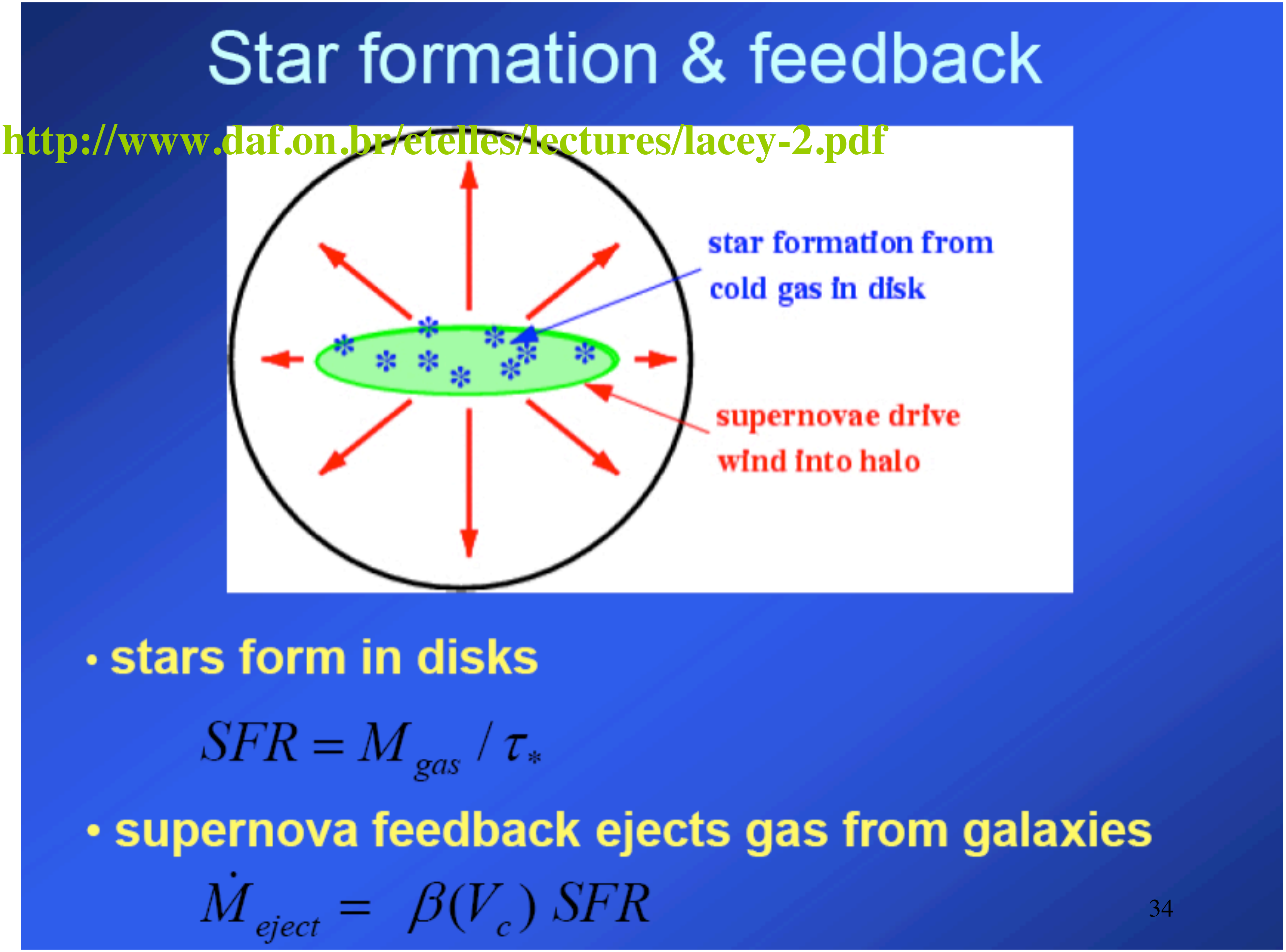
Hot Mode Accretion



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

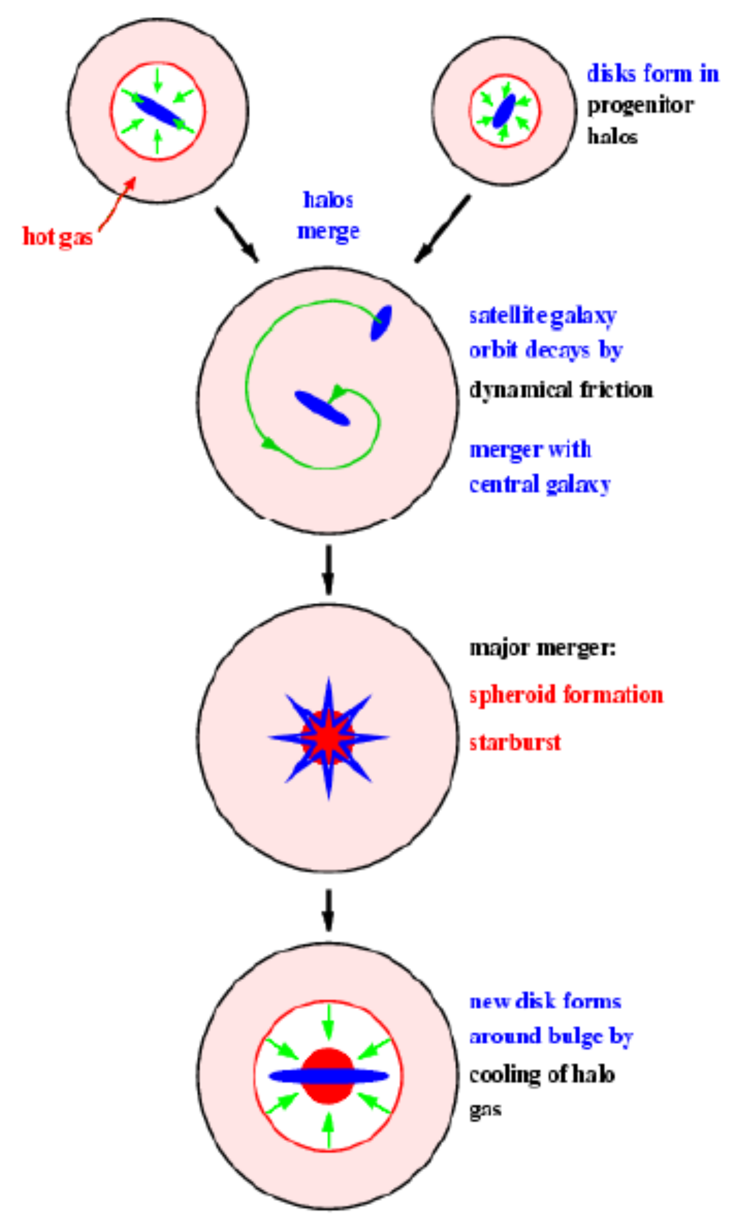
- stars form in disks

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

- supernova feedback ejects gas from galaxies

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

Galaxy mergers & morphology

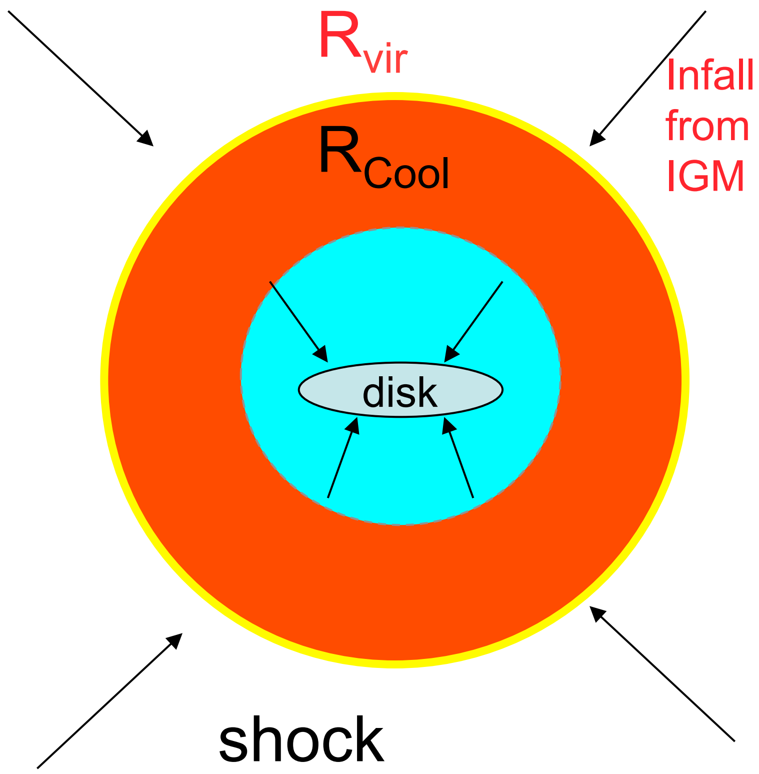


- halos merge
- galaxies merge by dynamical friction
- major mergers make galactic spheroids from disks
- mergers trigger starbursts
- spheroids can grow new disks

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

How 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 ($M_{vir} < 3 \times 10^{11} M_\odot$), 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…)

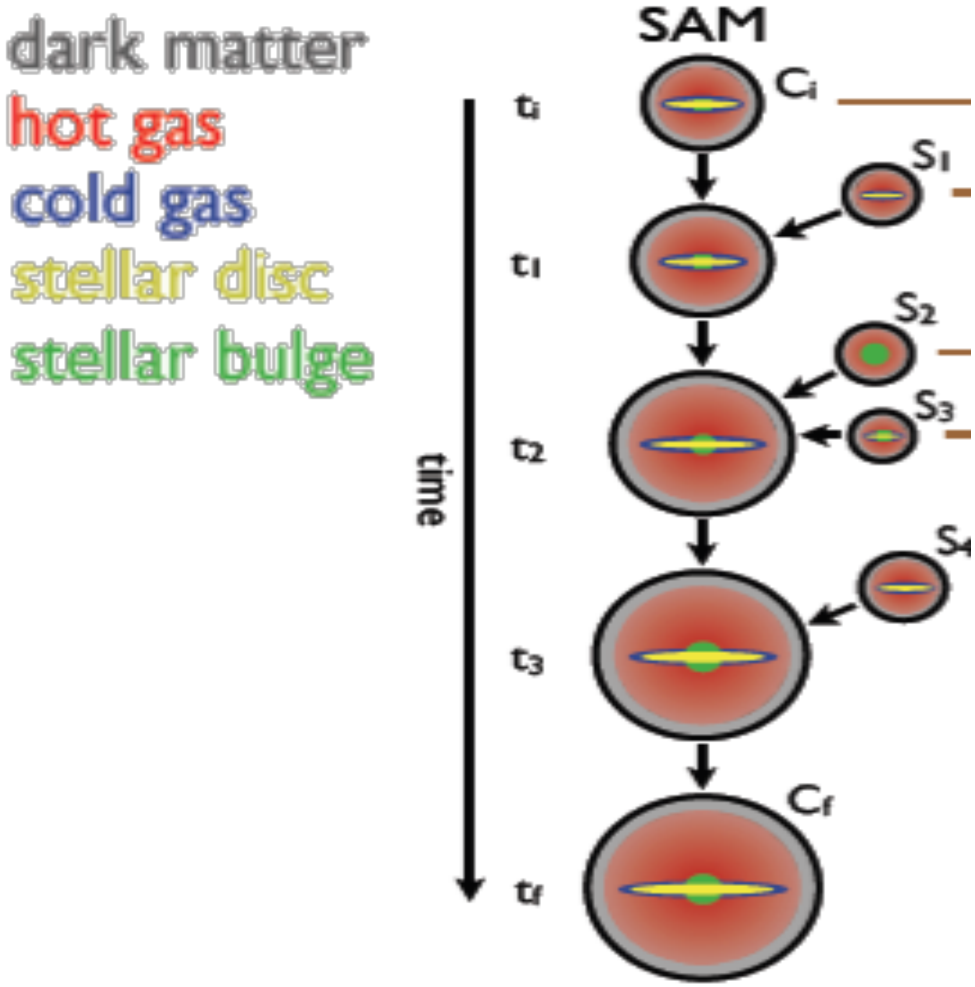
Stellar evolution (spectro-photometric evolution, yields, SN I/II rates,…)

taken from **J. Blaizot** presentation

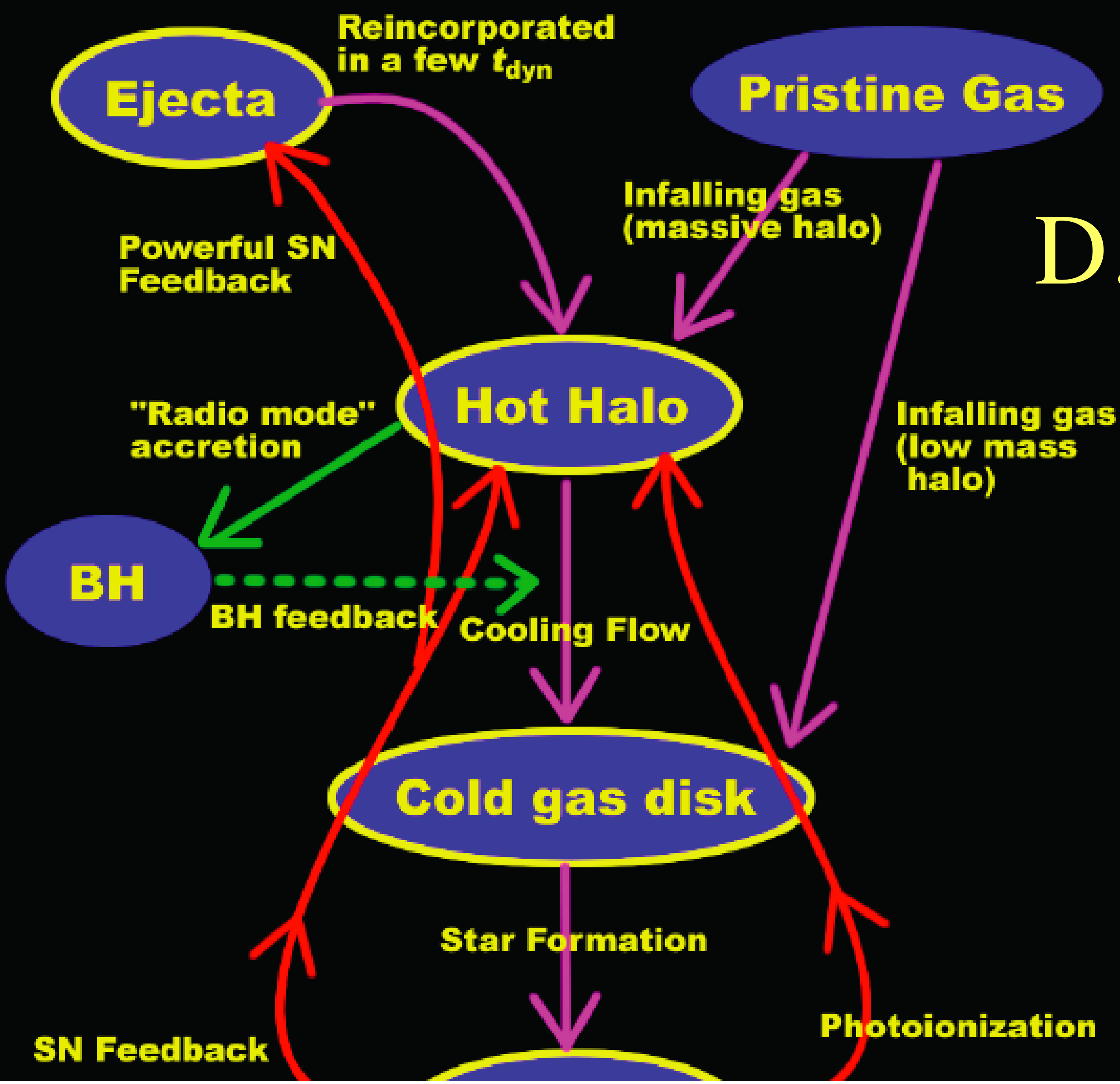
How to Include Baryonic Physics

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

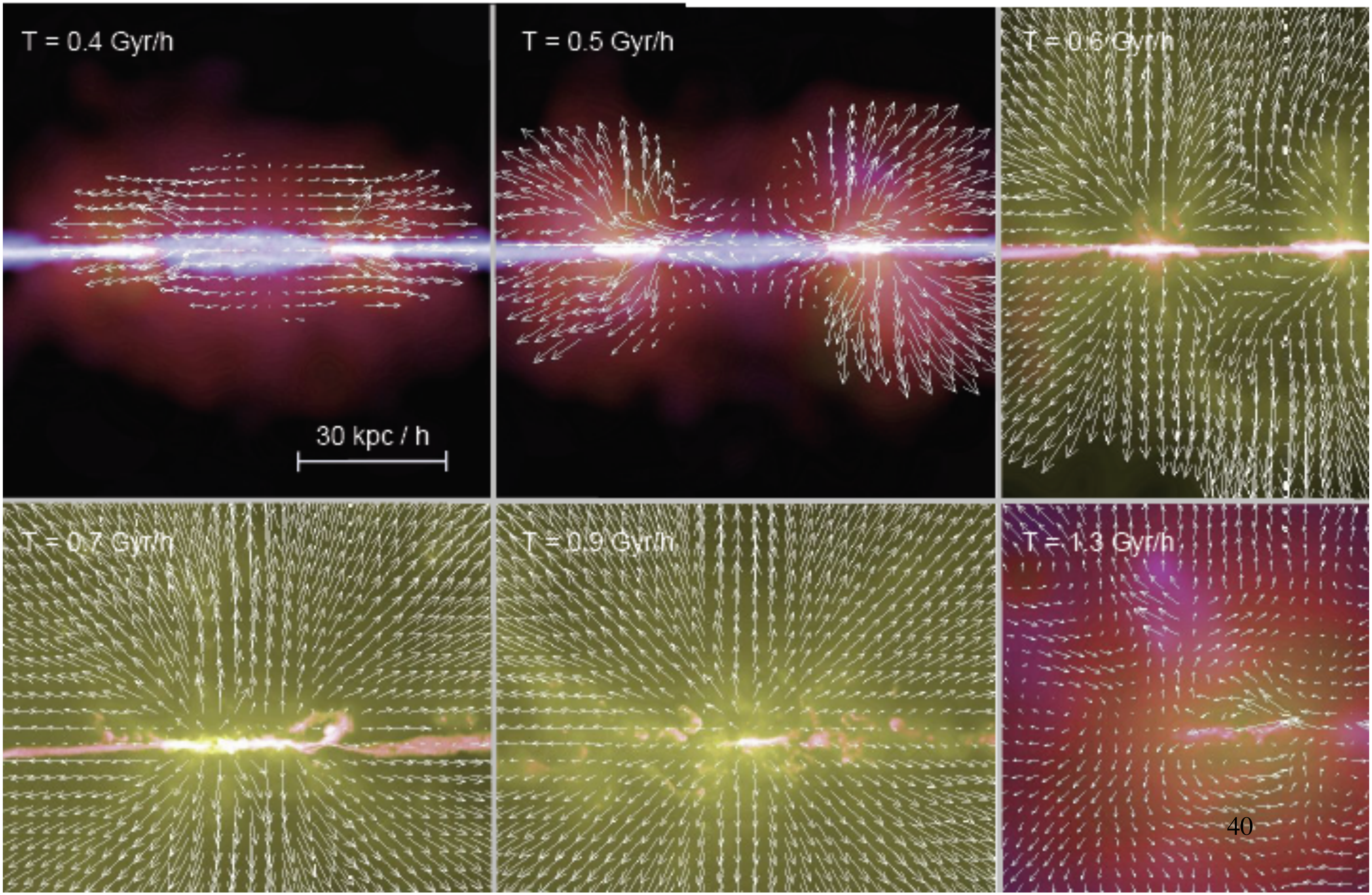


D. Croto

- Schmidt law s
- SFR depende
- satellite gas s
- morphologic
- assembly thr
- starbursts th
- Magorrian re

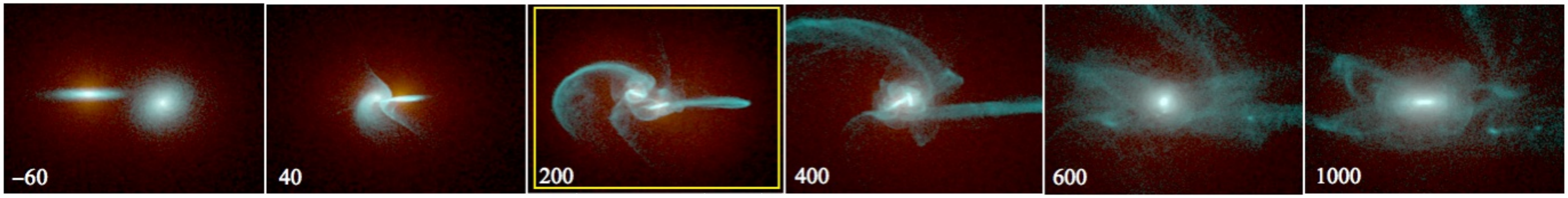
The feedback by the central black activity may drive a strong quasar wind

GAS OUTFLOW BY AGN FEEDBACK (outflow reaches speeds of up to ~1800 km/se



Galaxies 'Can' Change Over Cosmic Time

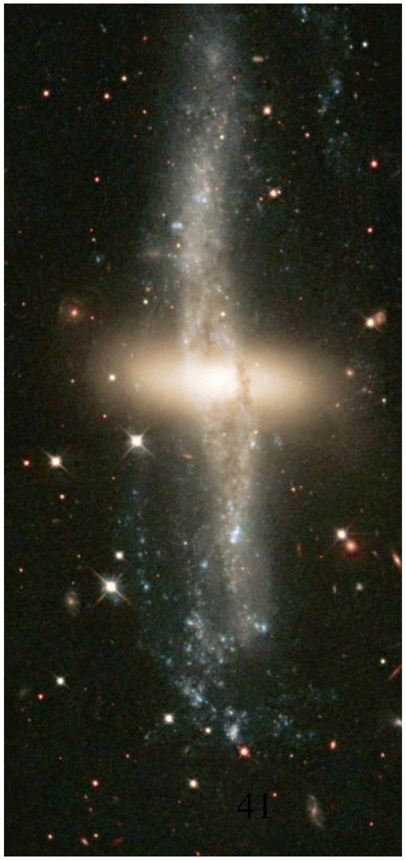
Computer calculation of the collision and merger of two equal-sized spiral galaxies



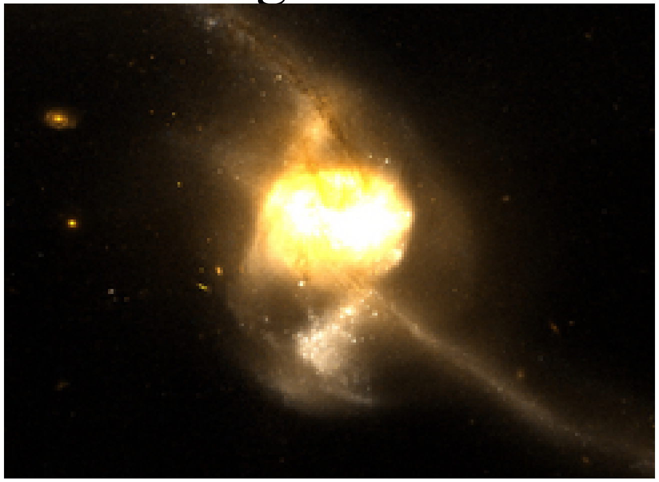
The Mice: Hubble Space Telescope

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

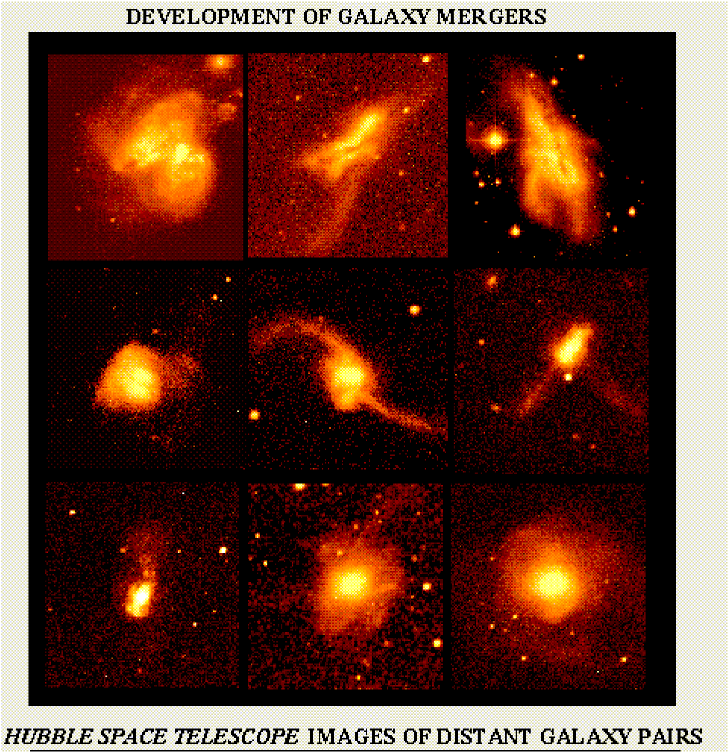
Polar ring galaxy
-evidence for gas accretion?

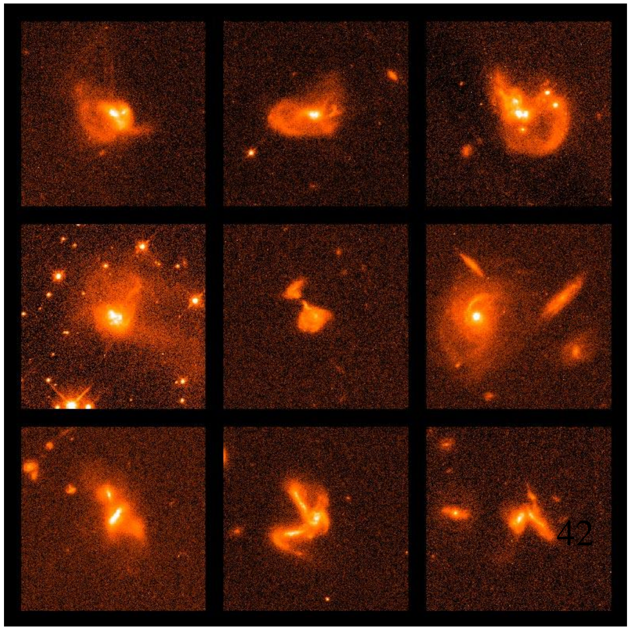


Mergers are responsible for the largest starbursts



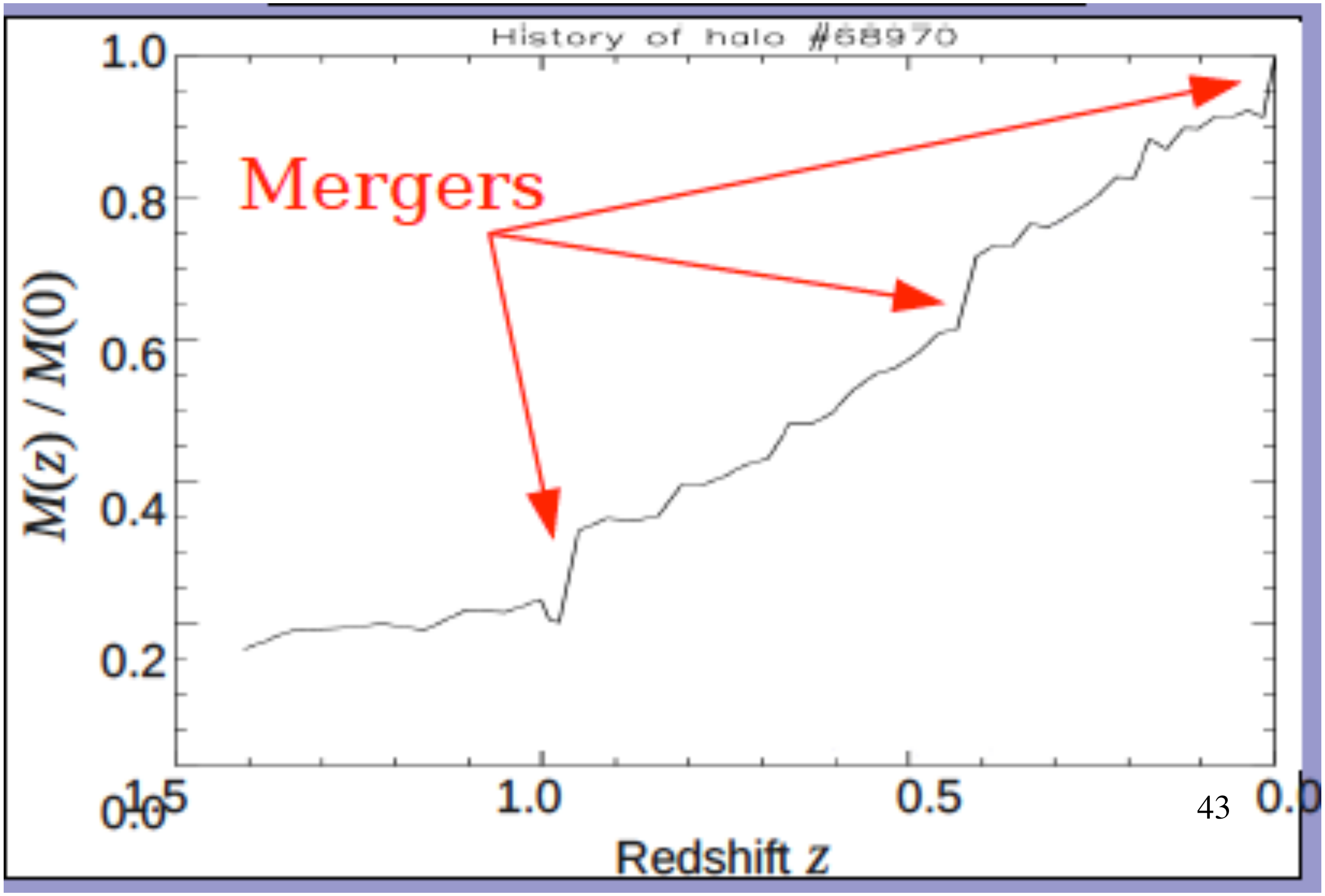
al. 1999





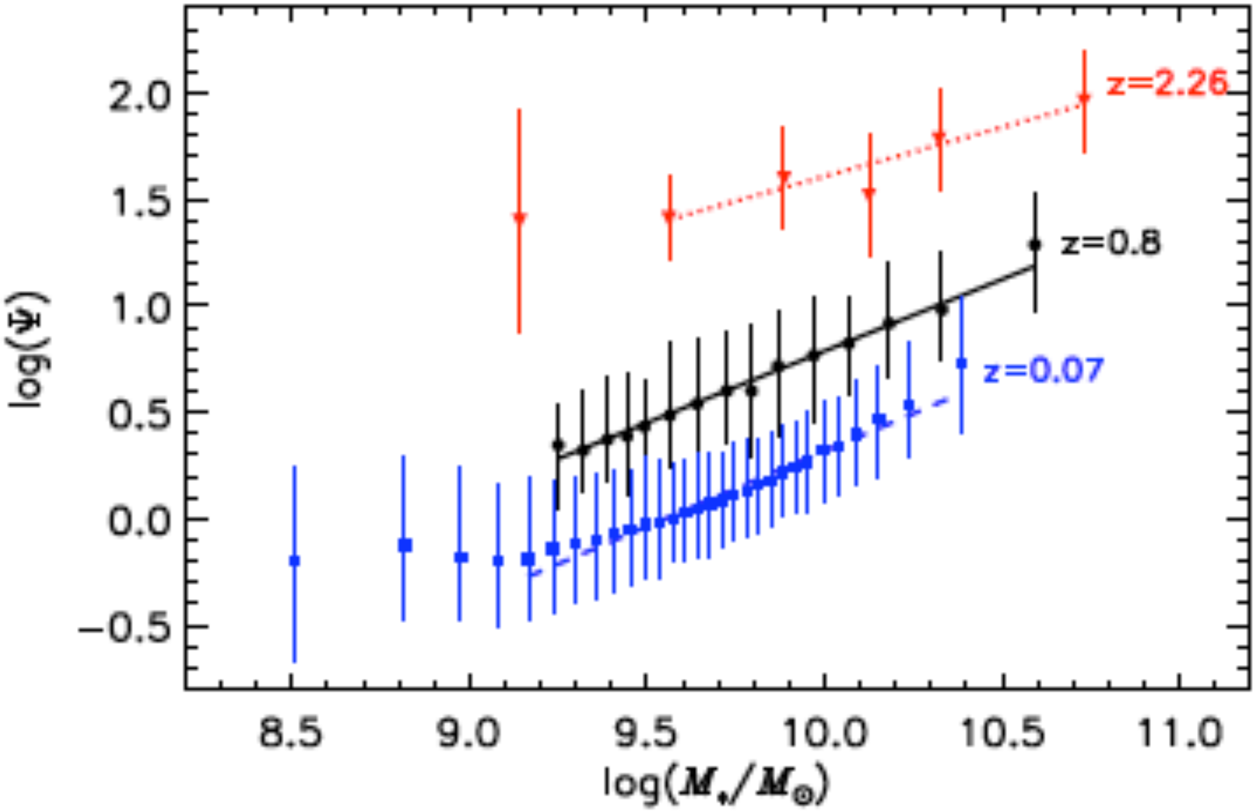
- The most intensely-SF galaxies in the local universe are merging systems

- 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