General Plan

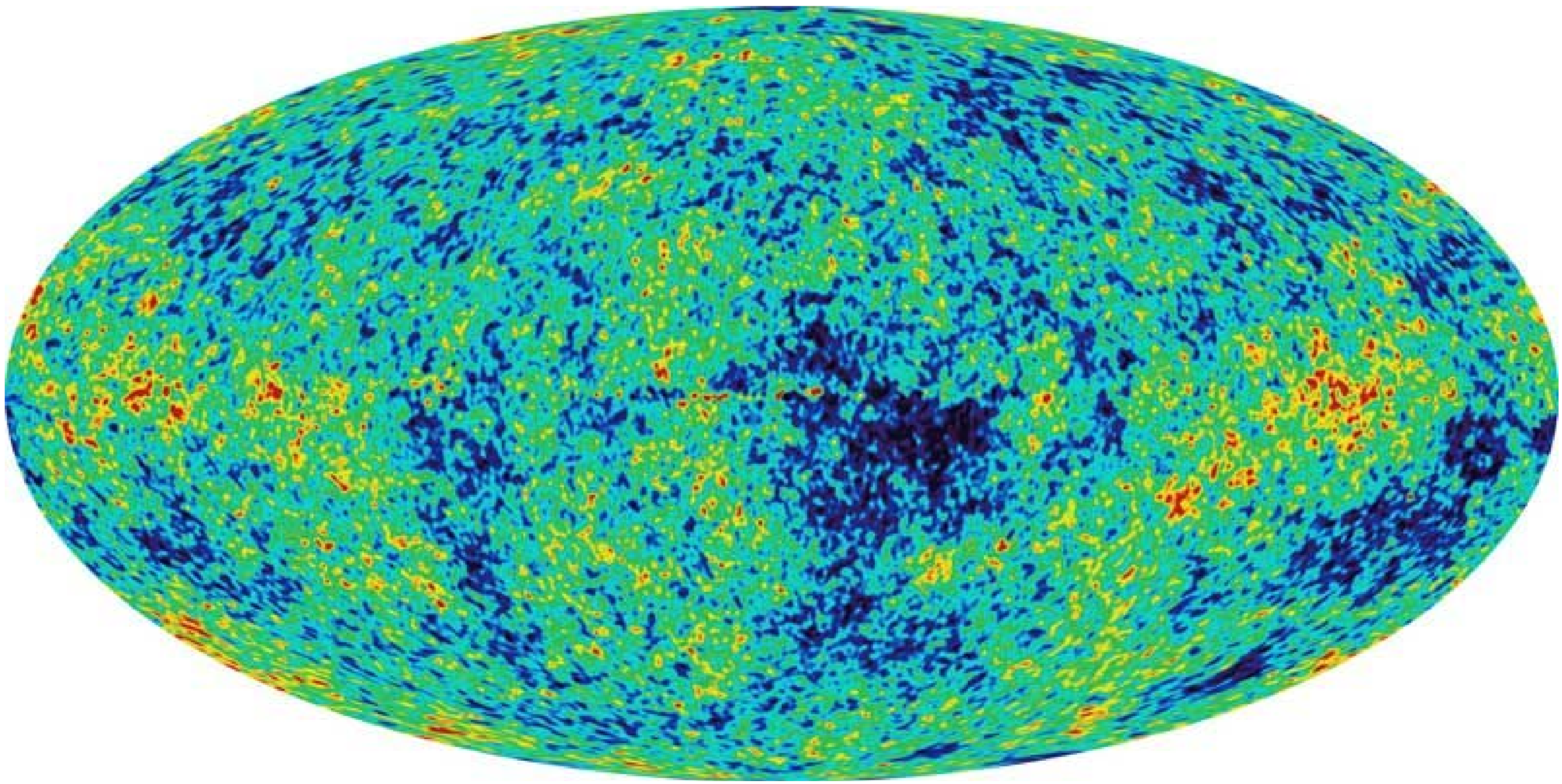
- Lectures 1/2: How to make a galaxy
- Lecture 2/3: What galaxies look like over cosmic time
- Lecture 4: Challenges

Making galaxies

Gravitational collapse and models for galaxy formation

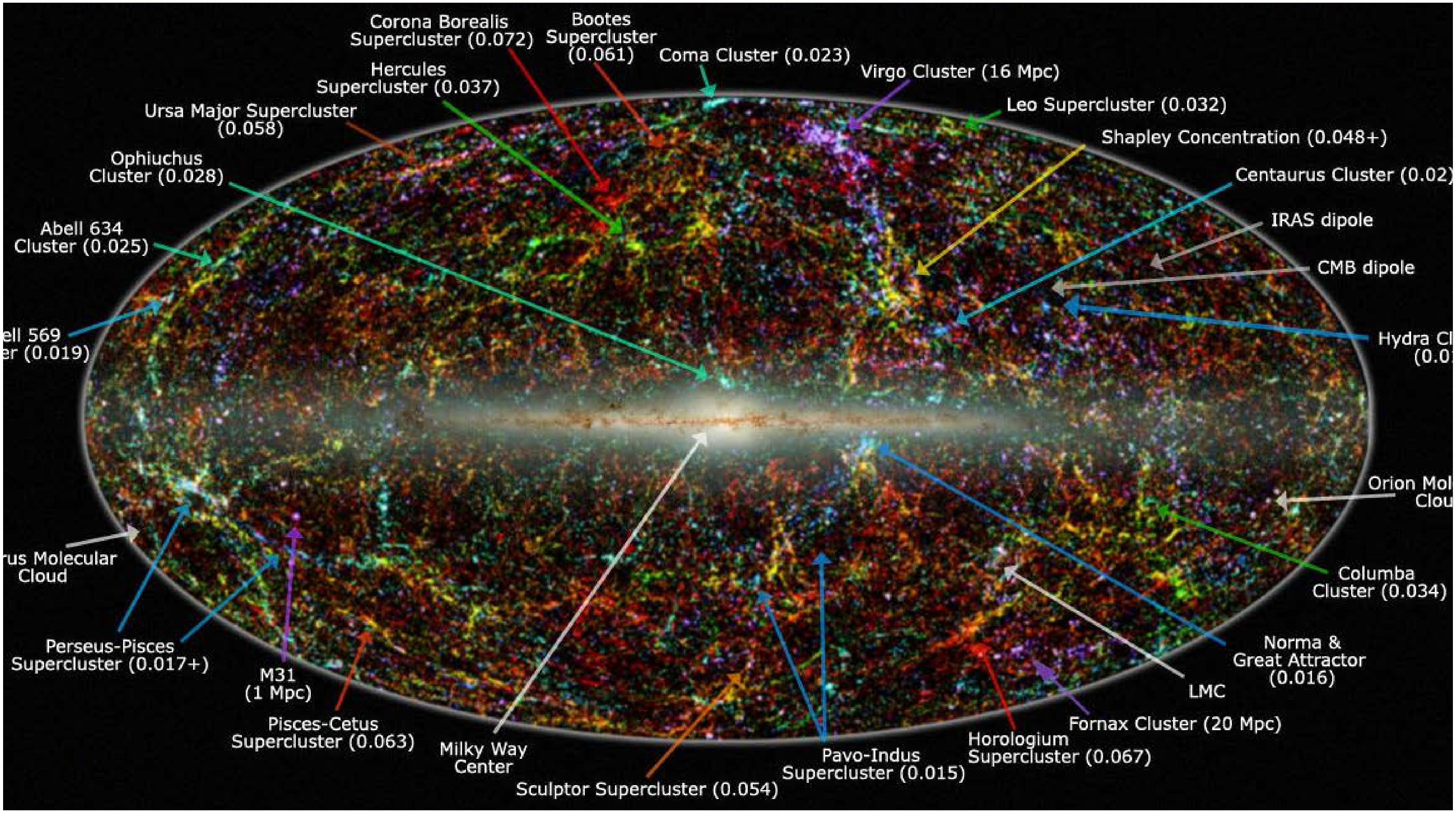
 

Fluctuations in the Cosmic Microwave Background (CMB)



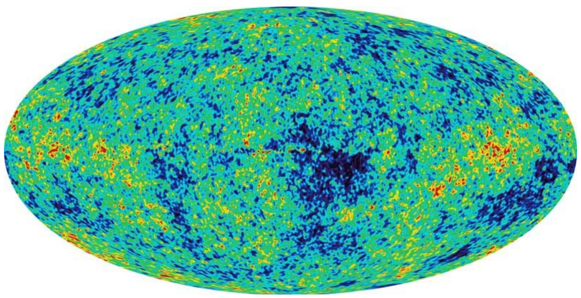
Q: What do we mean by a fluctuation	$\Delta\rho/\rho$
Q: How big are these fluctuations	10^{-5}
Q: What redshift are we looking at?	1000

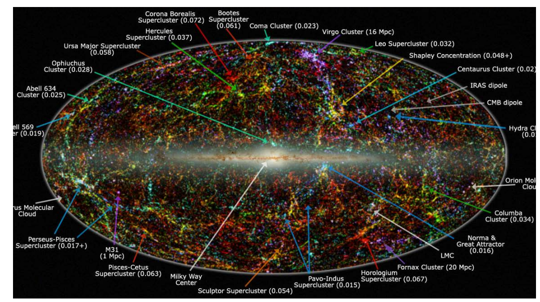
Fluctuations in the Local Galaxy Distribution



Q: How big are these fluctuations?

10 for superclusters, 1000 for clusters and 1,000,000 for galaxies



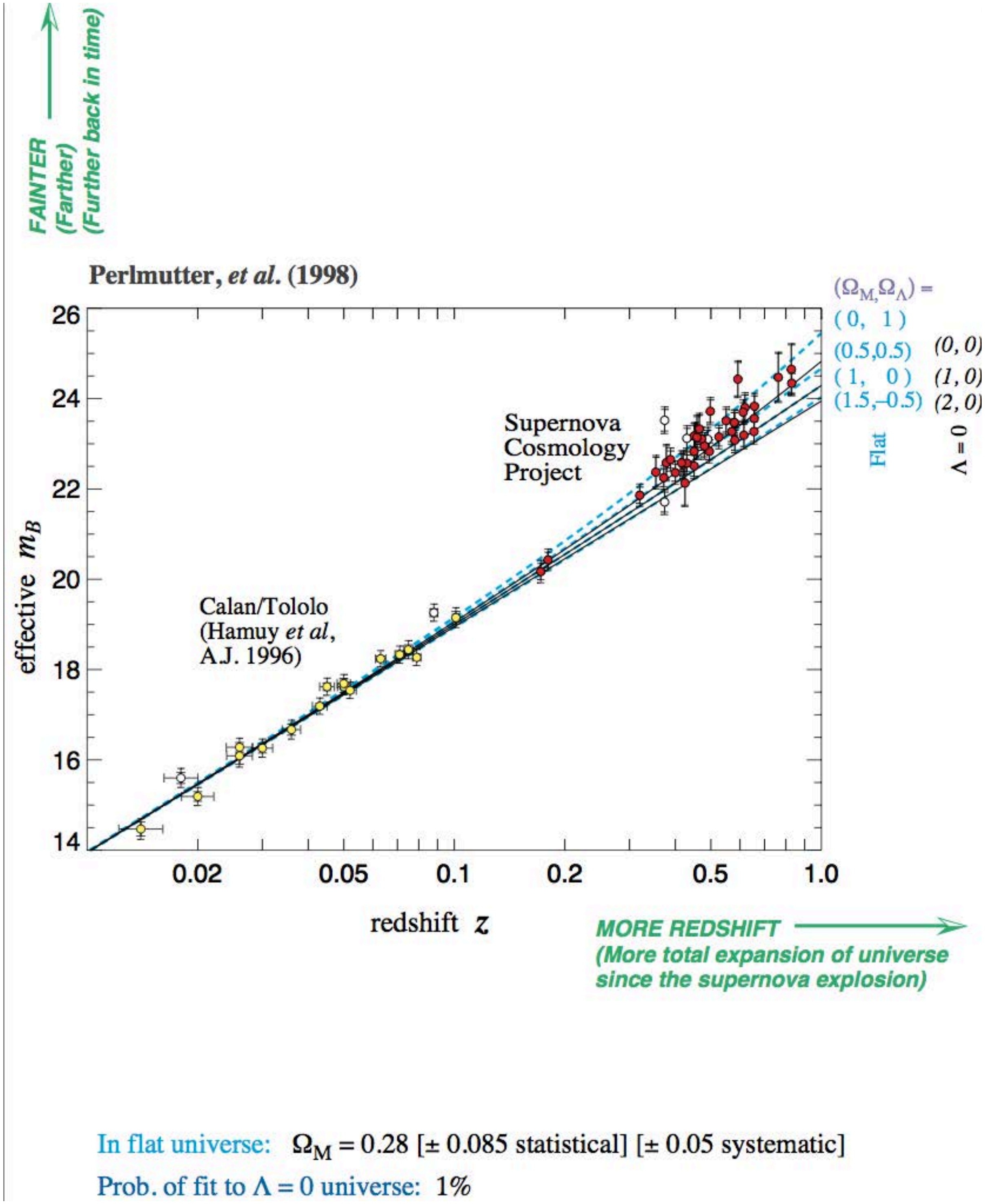


Our challenge is to grow a galaxy by a factor of $\sim 10^{11}$ over a redshift range of 1000, corresponding to 13.7 Gyr

I’m going to assume you know we live in an expanding Universe.

I’m going to assume you’ve heard of the Freidmann Equation

Let’s talk about how to describe the expansion



Solve the Freidmann Equation ignoring Dark Energy (for now)

$$\ddot{R} = -\frac{\Omega_0 H_0^2}{2 R^2}$$

$$\dot{R} = \frac{\Omega_0 H_0^2}{R} - \frac{c^2}{R^2}$$

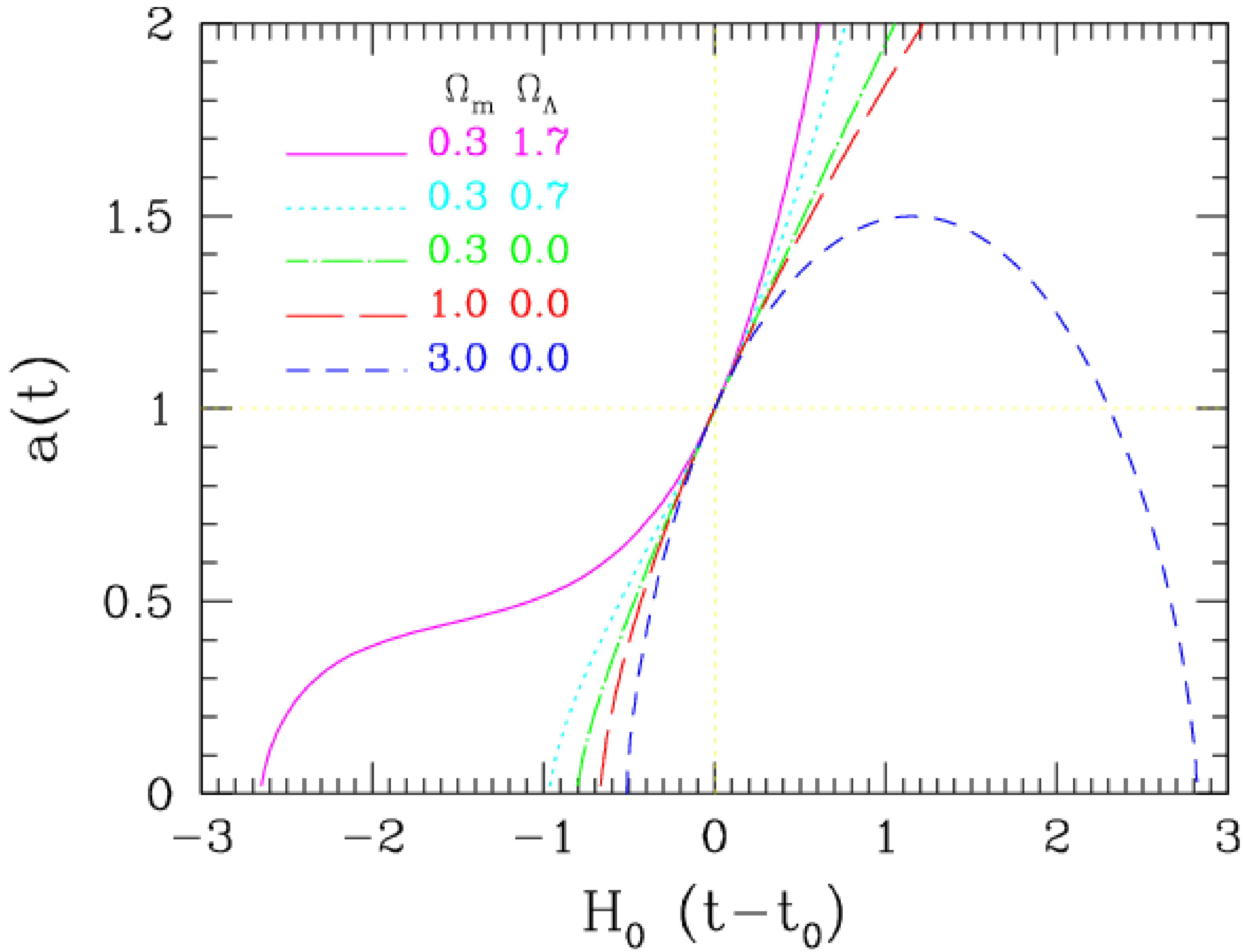
Where R = radius of curvature at the current epoch (“the size of the Universe”) = 1/(1+z). If Ω=1:

$$R = \left(\frac{3 H_0 t}{2}\right)^{2/3}$$

$$\kappa = \frac{1}{R^2} = \frac{(\Omega_0 - 1)}{(c / H_0)^2}$$

If Ω≠1 spatial curvature κ is defined as at left. So if Ω is 0 then the curvature is 0 (flat)

If you solve the Freidmann equations with dark energy, you get the curves below which show that Dark Energy is ignorable to 0th order to understand the ideas of collapse… Einstein-de Sitter is a pretty good approximation.



See Longair pp. 255-257, or Peacock §15.2

Growth of small perturbations in an expanding medium is a solved problem in hydrodynamics. Need (i) Poisson's equation; (ii) Continuity; (iii) Equations of motion. COMBINE AND LINEARIZE BY DOING A TAYLOR EXPANSION. Assume a wave equation type solution.

Density contrast: $\Delta = \frac{\delta\rho}{\rho_o}$

Long wavelength limit

$$\frac{d^2 \Delta}{d^2 t} + 2\left(\frac{\dot{R}}{R}\right)\frac{d\Delta}{dt} = \Delta\left(4\pi G\rho_0 - \cancel{k^2 c_s{}^2}\right)$$

($\mathbf{k}$ is the wave-vector in co-moving coordinates, c_s is the sound speed)

$$\frac{d^2 \Delta}{d^2 t} + 2\left(\frac{\dot{R}}{R}\right)\frac{d\Delta}{dt} = 4\pi G\rho_0 \Delta$$

Einstein-de Sitter case in the long-wavelength limit

The critical density is $\rho_c = \frac{3 H_0^2}{8 \pi G}$. Clearly this scales with the scale factor according to R^3 so we have $\rho_c(t) = \frac{3 H_0^2}{8 \pi G R^3}$. Substituting this into the right-hand side of the equation and eliminating H_0 using $R = \left(\frac{3}{2} H_0 t\right)^{2/3}$, which is the scale-factor vs. cosmic time relation for this cosmology, yields the following form for the right-hand side:

```
Δ 4 π G (3 H0^2)/(8 π G R^3) /. Solve[R == ((3/2) H0 t)^(2/3), H0]
```

$$\left\{\frac{2 \Delta}{3 t^2}, \frac{2 \Delta}{3 t^2}\right\}$$

Clearly

$$\frac{\dot{R}}{R} = \frac{2}{3 t}$$

implies R $\propto t^{2/3}$ (it's just a separable 1D ODE). So our wave equation simplifies to

$$\frac{d^2 \Delta}{d^2 t} + \frac{4}{3 t} \frac{d\Delta}{dt} - \frac{2}{3 t^2} \Delta = 0$$

This is trivial to solve:

```
wave = D[Δ[t], {t, 2}] + 4/(3 t) D[Δ[t], t] - 2/(3 t^2) Δ[t] == 0;

DSolve[wave, Δ[t], t]
```

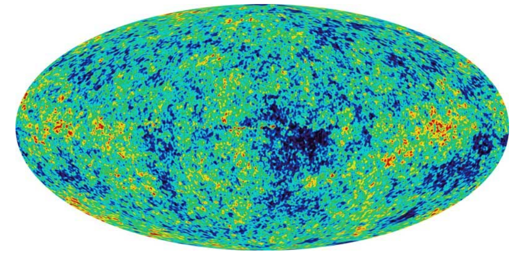
$$\left\{\left\{\Delta[t] \to t^{2/3} C[1] + \frac{C[2]}{t}\right\}\right\}$$

$$\Delta \propto t^{2/3} \propto \mathrm{R} = (1+z)^{-1}$$

$$\Delta \propto (1+z)^{-1}$$

These linear fluctuations grow <u>slowly</u>!

What have we learned?



- We conclude that large-scale structures did not condense out of the primordial plasma by the sorts of rapid collapse that forms stars.
- The mean background density declines with redshift according to $(1+z)^3$, so something that is now bound (no longer participating in the expansion) and has an overdensity $\Delta \sim 10^6$ today had $\Delta \sim 1$ at a redshift of 100. The *upper limit* to the redshift of collapse for this object is therefore z=100.
- Note that galaxies have $\Delta \sim 10^6$ today, clusters have $\Delta \sim 10^3$ today (upper limit of collapse is therefore z=10), and superclusters have $\Delta \sim$few so have left the linear regime very recently.
- Once structure enters the regime $\Delta > 1$ then the equations above of course no longer apply, and we can no longer use the linearized equations above, and that's sort of the whole point.

Track the growth from $\Delta = 10^{-5}$ to 1 using these linear equations and then some new non-linear physics must apply to make things collapse much more rapidly. WHAT IS THIS NON-LINEAR PHYSICS? Well, it's still gravity…

Non-linear collapse of perturbations in an expanding Universe (spherical collapse model)

- We now want to understand the behaviour of the density contrast once it becomes large.
- The linear analysis becomes invalid once the density contrast is of order unity
- A simple model to use (which captures much of the relevant physics) is a density perturbation described as an over-dense sphere.
- As a concrete example, we will study the dynamics of an $\Omega_0>1$ sub-Universe embedded in a flat Universe.

General parametric solutions to the Freidmann Equation (no dark energy)

For Ω<1:

$$R = a(\cosh\phi - 1)$$
$$t = b(\sinh\phi - \phi)$$
$$a = \frac{\Omega_0}{2(1-\Omega_0)}$$
$$(\text{For } \Omega < 1)$$
$$b = \Omega_0 \Big/ \left(2 H_0 (1-\Omega_0)^{3/2}\right)$$

For Ω>1:

$$R = a(1-\cos\theta)$$
$$t = b(\theta - \sin\theta)$$
$$a = \frac{\Omega_0}{2(\Omega_0 - 1)}$$
$$(\text{For } \Omega > 1)$$
$$b = \Omega_0 \Big/ \left(2 H_0 (\Omega_0 - 1)^{3/2}\right)$$

The parameter θ is known as the conformal time. These equations can be expressed as *Mathematica* functions as follows:

```
In[1]:= R[θ_, Ω_] := (Ω / (2 (Ω - 1))) (1 - Cos[θ])

In[2]:= t[θ_, Ω_, H_] := (Ω / (2 H (Ω - 1)^(3/2))) (θ - Sin[θ])
```

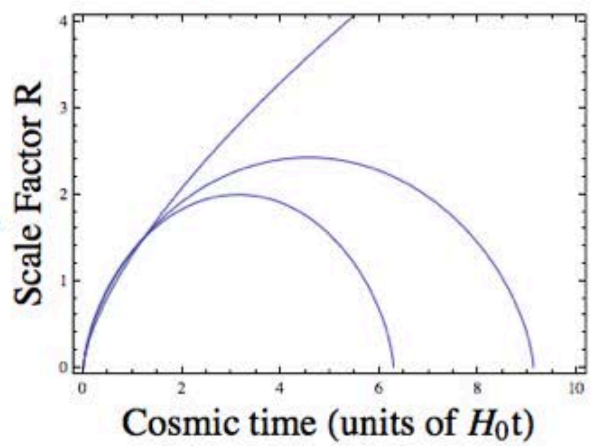
Our reference model describing the density of the smooth background is an Einsten-de Sitter model (Ω=1) where the scale size varies as $t^{2/3}$:

$$R = \left(\frac{3 H_0 t}{2}\right)^{2/3}$$

Let's compare the scale factor in both our sub-Universe and the background Universe.

```
In[22]:= Block[{$DisplayFunction = Identity, H = 1, Ω1 = 1.7`, Ω2 = 2},
   p1 = ParametricPlot[{t[θ, Ω1, H], R[θ, Ω1]}, {θ, 0, 2 π}];
   p2 = ParametricPlot[{t[θ, Ω2, H], R[θ, Ω2]}, {θ, 0, 2 π}];
   p3 = Plot[((3 H t)/2)^(2/3), {t, 0, 20}]];
Show[p1, p2, p3, PlotRange → {{0, 10}, {0, 4}}, Frame → True, Axes → False,
 FrameLabel → {Style["Cosmic time (units of H₀t)", Large],
   Style["Scale Factor R", Large]}, AspectRatio → 0.7]
```

Out[23]=

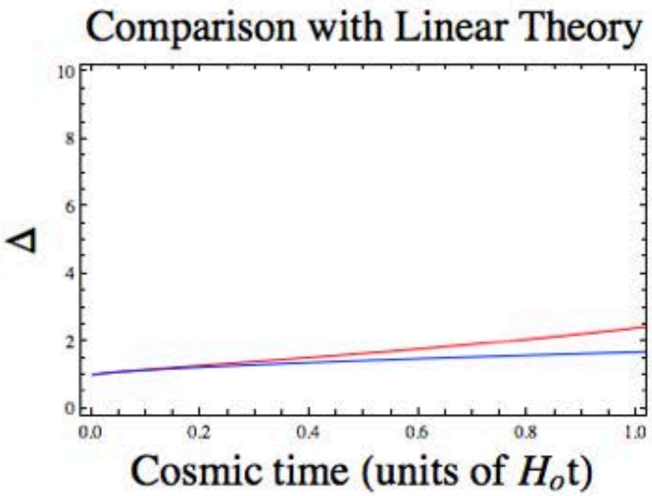


Divide one curve by the other to get Δ(t)

Here is the behaviour of a small overdensity (for $H_0 = 75$) which starts off with Δ=0.05, ie. sub-Universe has Ω=1.05, background Universe has Ω=1.

```
In[25]:= collapsePlot[1.05, PlotRange → {{0, 1}, {0, 10}}]
```

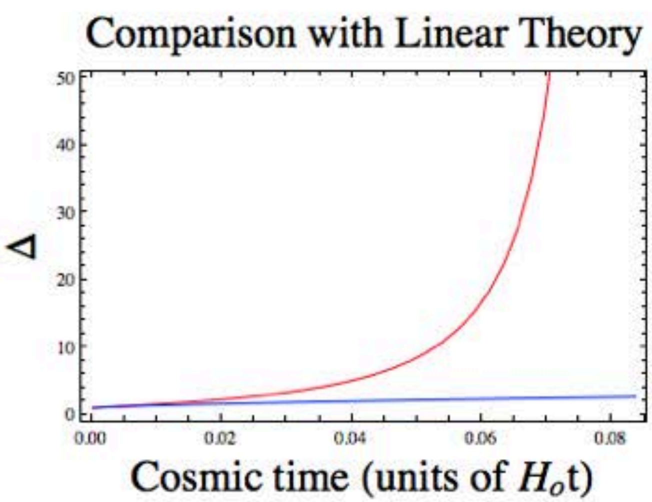
Out[25]=



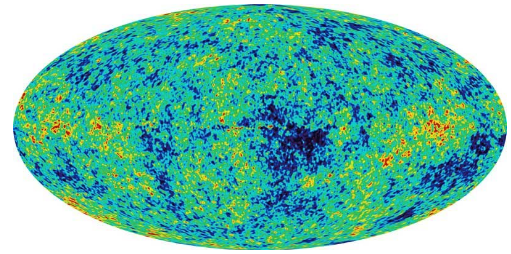
Contrast this with a slightly larger overdensity (Δ=1, ie. sub-Universe has Ω=2, background Universe has Ω=1).

```
In[26]:= collapsePlot[2, PlotRange → {0, 50}]
```

Out[26]=



What have we learned?



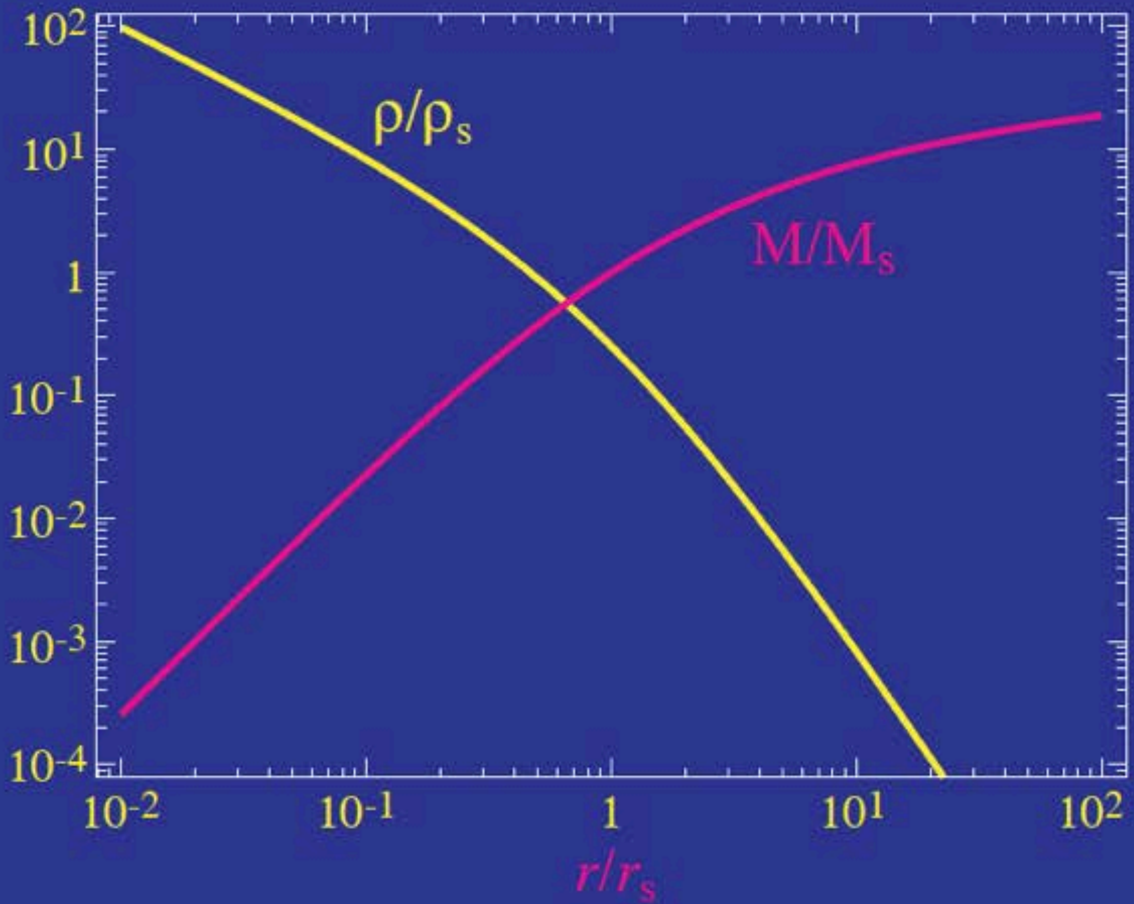
- There are four interesting epochs… the end result of which is a collapsed high-density nugget of dark matter... a HALO
- i) **agreement with linear theory** (regime where $\Delta<1$)
- ii) **turnaround** (occurs when the conformal time $\theta=\pi$)
- iii) **collapse** (occurs, in principle, when the conformal time $\theta=2\pi$... but never really happens of course, in the sense that the perturbation doesn't just collapse into a black hole!). Before this happens other physics kicks in (eg. violent relaxation or phase mixing if we're dealing exclusively with dark matter, or dissipation if we're talking about baryonic material). Thus what really happens is...
- iv) **virialisation.** This is a little subjective to define. On the basis of the virial theorem, a density constrast of ~200 (corresponding roughly to when the sphere has collapsed to half its maximum size at $\theta=3\pi/2$) is a sensible definition, and this is why you'll often see people (e.g. Piero) talking about r_{200}, the radius in which the density is 200 times the background, and defining this as the virialized regime.

> *The "rule of thumb", according to Peacock's excellent book (Cosmological Physics), is to assume linear theory applies until the density contrast predicted by linear theory is a little greater than unity, then assume virialization has occurred.*

NFW Halo

- Density profile well-described by (Navarro, Frenk & White 1997)

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$



Taken from Wayne Hu's Treiste tutorial

Halo Temperature

- Motivate with isothermal distribution, correct from simulations

$$\rho(r) = \frac{\sigma^2}{2\pi G r^2}$$

- Express in terms of virial mass M_v enclosed at virial radius r_v

$$M_v = \frac{4\pi}{3} r_v^3 \rho_m \Delta_v = \frac{2}{G} r_v \sigma^2$$

- Eliminate r_v, temperature $T \propto \sigma^2$ velocity dispersion^2
- Then $T \propto M_v^{2/3} (\rho_m \Delta_v)^{1/3}$ or

$$\left(\frac{M_v}{10^{15} h^{-1} M_\odot}\right) = \left[\frac{f}{(1+z)(\Omega_m \Delta_v)^{1/3}} \frac{T}{1\mathrm{keV}}\right]^{3/2}$$

- Theory (X-ray weighted): $f \sim 0.75$; observations $f \sim 0.54$. Difference is crucial in determining cosmology from cluster counts!

Press-Schechter Mass Distribution for Halos: the ideas

Gaussian fluctuations

$$p(\Delta) = \frac{1}{\sqrt{2\pi}\,\sigma(M)}\, e^{-\frac{\Delta^2}{2\sigma^2(M)}}$$

↓

Halos above some critical density instantly collapse

$$F(M) = \frac{1}{\sqrt{2\pi}\,\sigma(M)} \int_{\Delta_{crit}}^{\infty} e^{-\frac{\Delta^2}{2\sigma^2(M)}}\, d\Delta$$

1.69

↓

Fluctuations have a power-law power spectrum

$$P(k) = |\Delta_k|^2 \propto k^n$$

Press-Schechter mass distribution

$$\boxed{N(M) = \frac{\bar{\rho}}{\sqrt{\pi}} \frac{\gamma}{M^2} \left(\frac{M}{M_*}\right)^{\frac{\gamma}{2}} e^{-(M/M_*)^{\gamma}}}$$

$$\gamma = 1 + (n/3) \qquad M_* = M_*(t_0)\,(t/t_0)^{4/3\,\gamma}$$

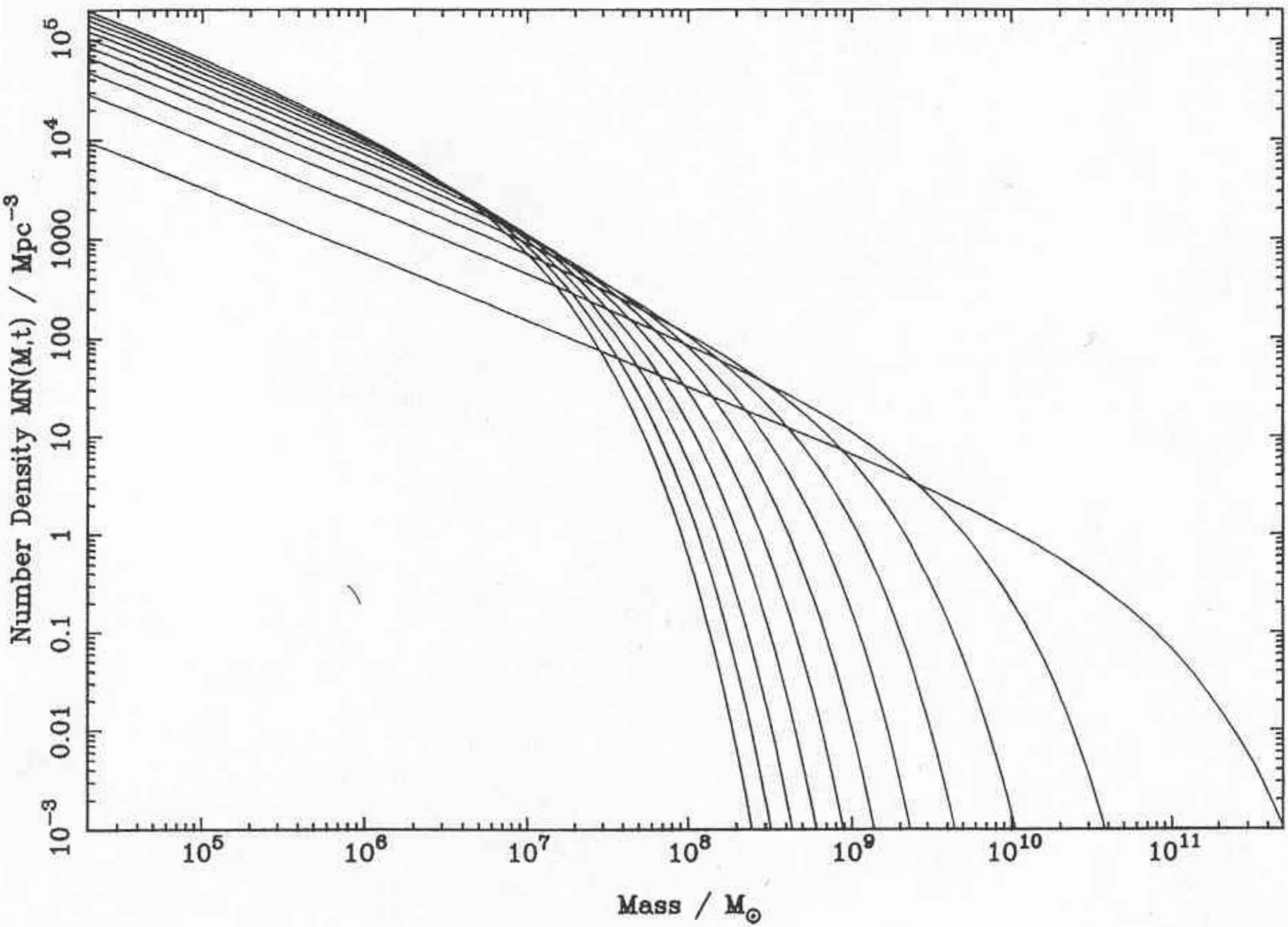


Fig. 16.4. Illustrating the variation of the form of the Press-Schechter mass function as a function of cosmic time (Courtesy of Dr. Andrew Blain).

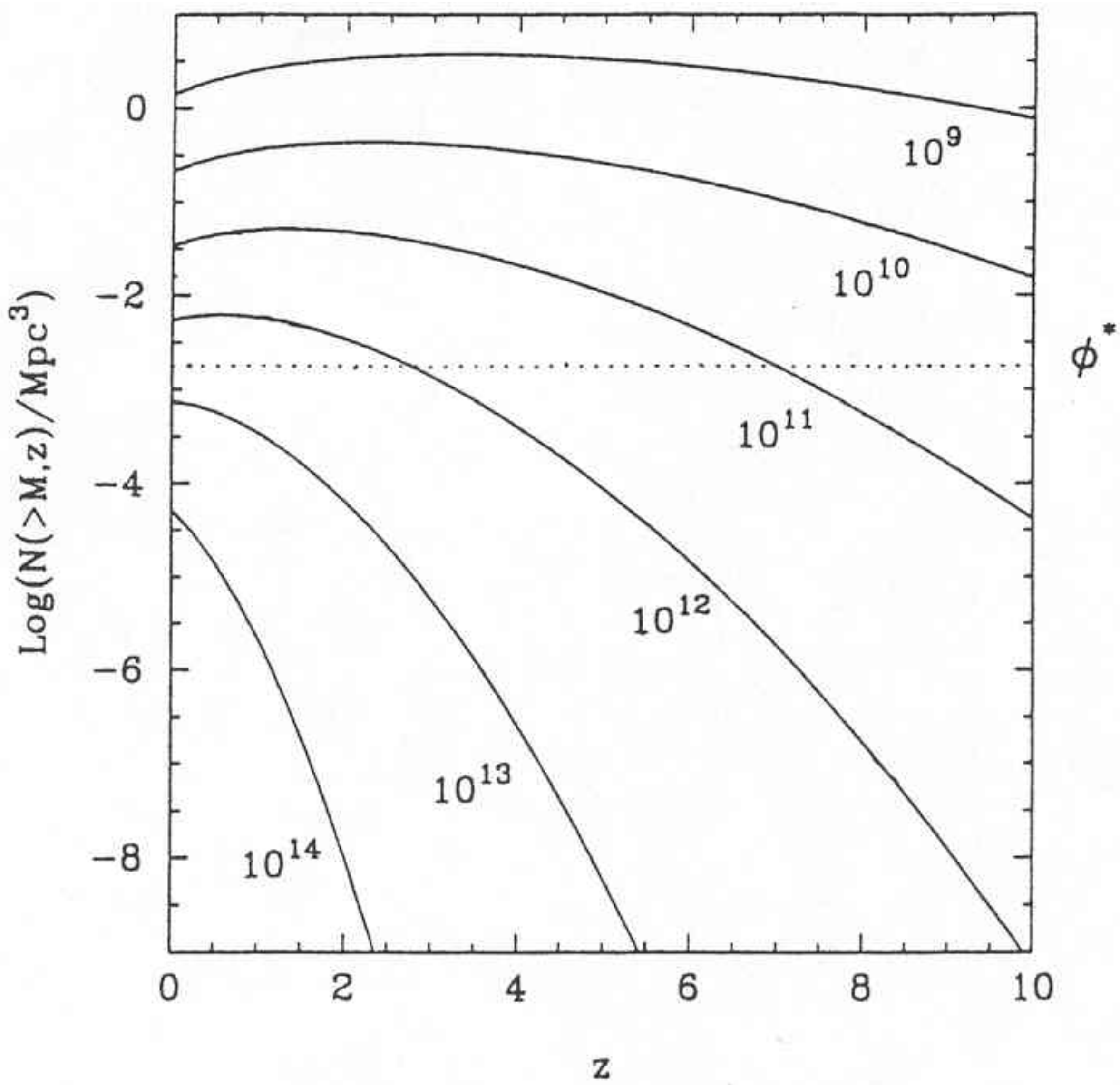
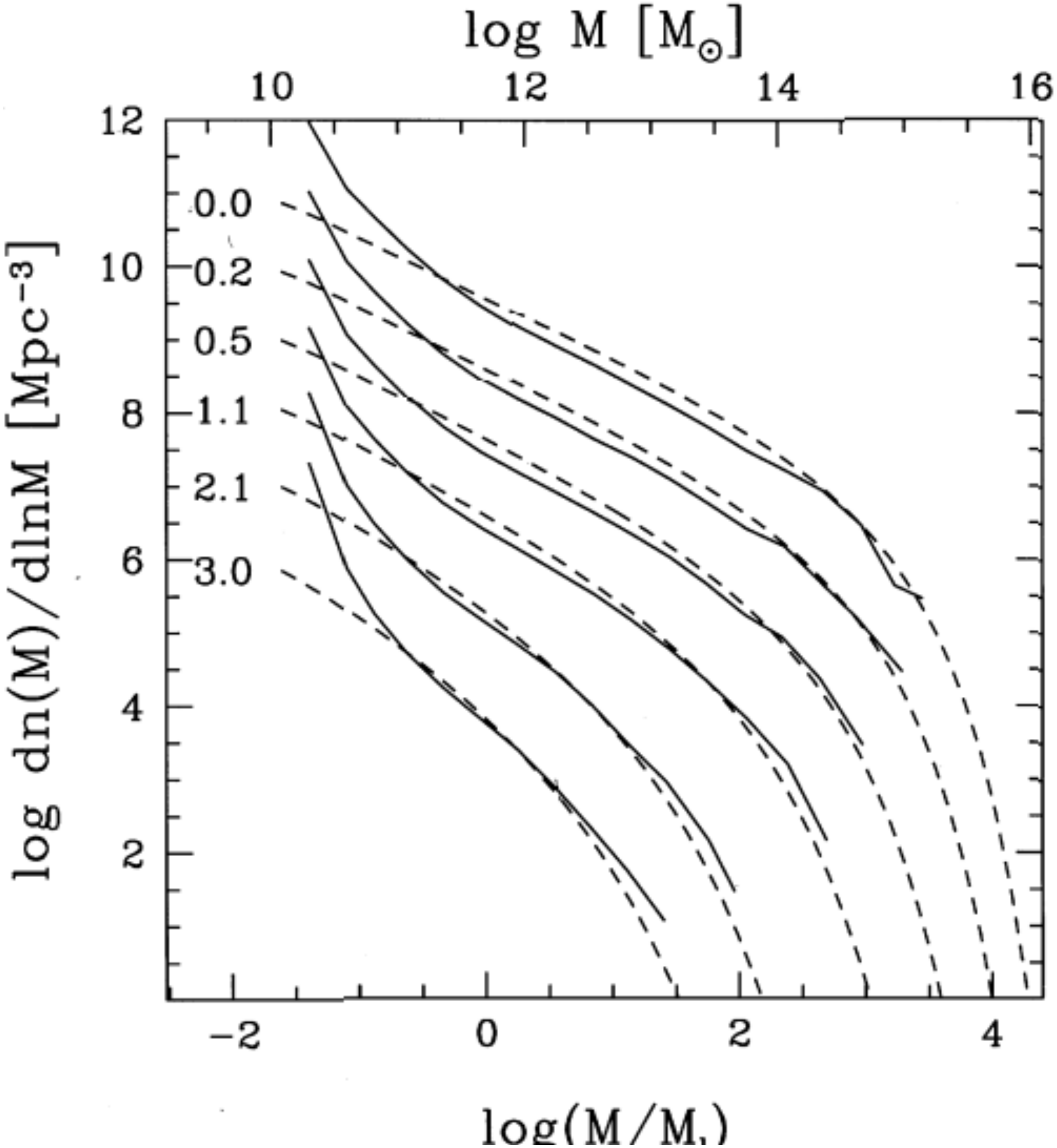


Fig. 16.5 The evolution of the comoving number density of dark matter haloes with masses greater than M as a function of redshift for a standard Cold Dark Matter model with $\Omega_0 = 1$. The curves have been derived using the Press-Schechter form of evolution of the mass spectrum which is a good fit to the results of N-body simulations. The dotted line labelled ϕ^* shows the present number density of L^* galaxies. (after Efstathiou 1995).

Somerville, Rachel S., Lemson, Gerard, Kolatt, Tsafrir S. & Dekel, Avishai
Evaluating approximations for halo merging histories.
Monthly Notices of the Royal Astronomical Society **316** (3), 479-490.
doi: 10.1046/j.1365-8711.2000.03467.x

Figure 1 The mass function of haloes predicted by the standard Press–Schechter model (dashed lines), and fc
simulations (solid lines) at redshifts of (from top to bottom) z=0, 0.2, 0.5, 1.0, 2.0 and 3.0.



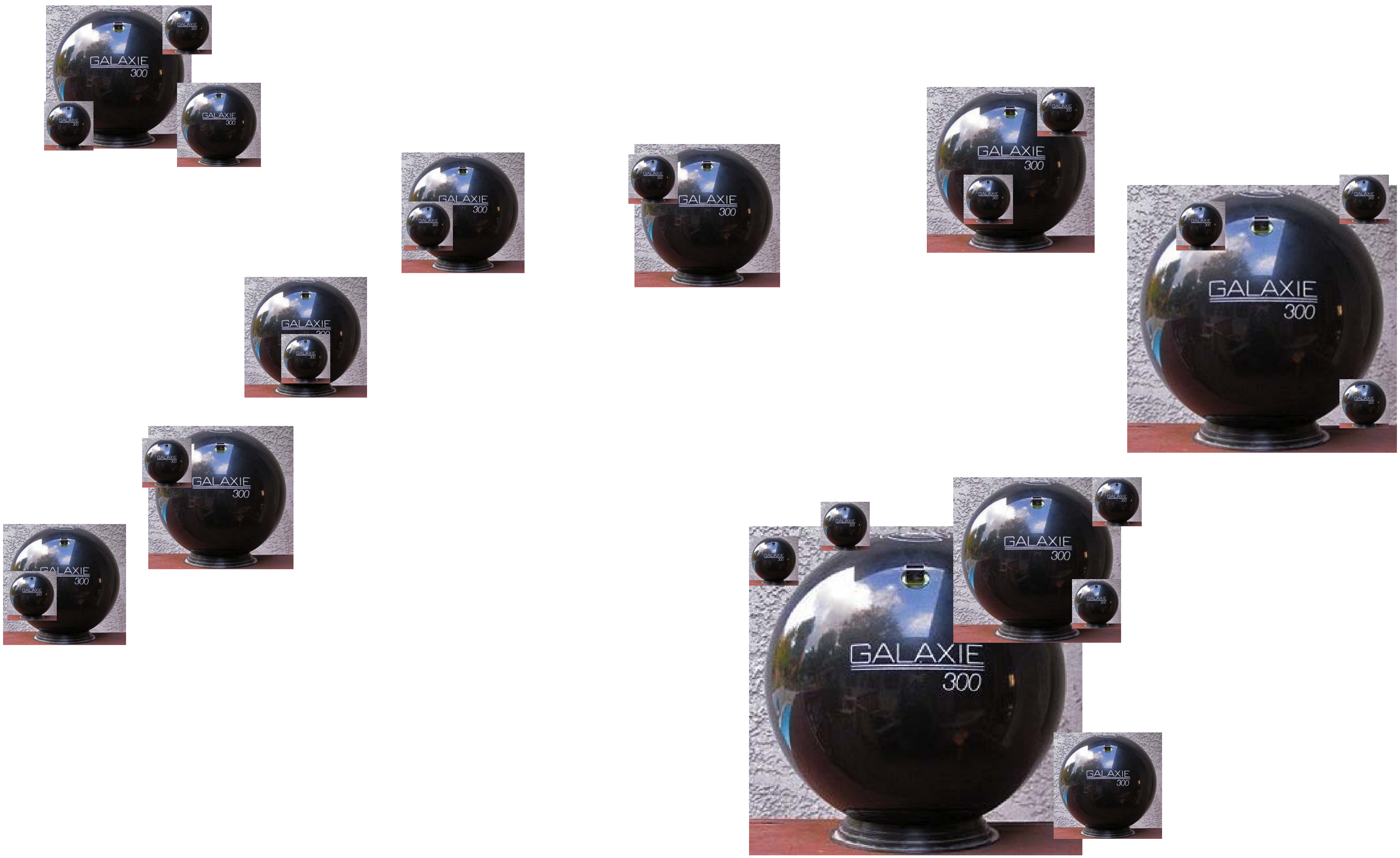
The formalism works surprisingly well!

Confused?

Linear regime

Non-linear regime

Hierarchical clustering - halos group together to form bigger halos and map out the large scale structure



Hierarchical clustering of dark matter halos

Mon. Not. R. Astron. Soc. **000**, 1–16 (2009) Printed 18 September 2009 (MN LaTeX style file v2.2)

Resolving Cosmic Structure Formation with the Millennium-II Simulation

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18 September 2009

ABSTRACT

We present the Millennium-II Simulation (MS-II), a very large N-body simulation of dark matter evolution in the concordance ΛCDM cosmology. The MS-II assumes the same cosmological parameters and uses the same particle number and output data structure as the original Millennium Simulation (MS), but was carried out in a periodic cube one-fifth the size ($100\,h^{-1}$ Mpc) with 5 times better spatial resolution (a Plummer equivalent softening of $1.0\,h^{-1}$ kpc) and with 125 times better mass resolution (a particle mass of $6.9 \times 10^6\,h^{-1}\,M_\odot$). By comparing results at MS and MS-II resolution, we demonstrate excellent convergence in dark matter statistics such as the halo mass function, the subhalo abundance distribution, the mass dependence of halo formation times, the linear and nonlinear autocorrelations and power spectra, and halo assembly bias. Together, the two simulations provide precise results for such statistics over an unprecedented range of scales, from halos similar to those hosting Local Group dwarf spheroidal galaxies to halos corresponding to the richest galaxy clusters. The "Milky Way" halos of the Aquarius Project were selected from a lower resolution version of the MS-II and were then resimulated at much higher resolution. As a result, they are present in the MS-II along with thousands of other similar mass halos. A comparison of their assembly histories in the MS-II and in resimulations of 1000 times better resolution shows detailed agreement over a factor of 100 in mass growth. We publicly release halo catalogs and assembly trees for the MS-II in the same format within the same archive as those already released for the MS.

Key words: methods: N-body simulations – cosmology: theory – galaxies: halos

1 INTRODUCTION

In order to understand how galaxies form and evolve in their cosmological context, we must understand the properties of dark matter halos over a wide range of physical scales and across virtually all of cosmic history. Numerical simulations provide one of the best methods for approaching this problem and have proven invaluable for studying the growth of cosmological structure and, in particular, of dark matter halos. Increasing computational power and improved algorithms have led to a steady and rapid increase in the ability of N-body simulations to resolve the detailed internal structure of dark matter halos over substantial cosmological volumes.

Perhaps the most widely-used N-body simulation of cosmological structure formation to date has been the Millennium Simulation (Springel et al. 2005, hereafter MS), which followed more than ten billion particles within a simulation volume of $(500\,h^{-1}\,\mathrm{Mpc})^3$. This provided sufficient mass resolution to see the formation of halos hosting $0.1\,L_*$ galaxies and sufficient volume to obtain good statistical samples of rare objects such as massive cluster halos and luminous quasars. It also enabled the implementation of physical models for the formation and evolution of galaxy/AGN populations throughout a large and representative cosmological volume (Croton et al. 2006; Bower et al. 2006). Since 2005, when the first results from the MS were published, most new

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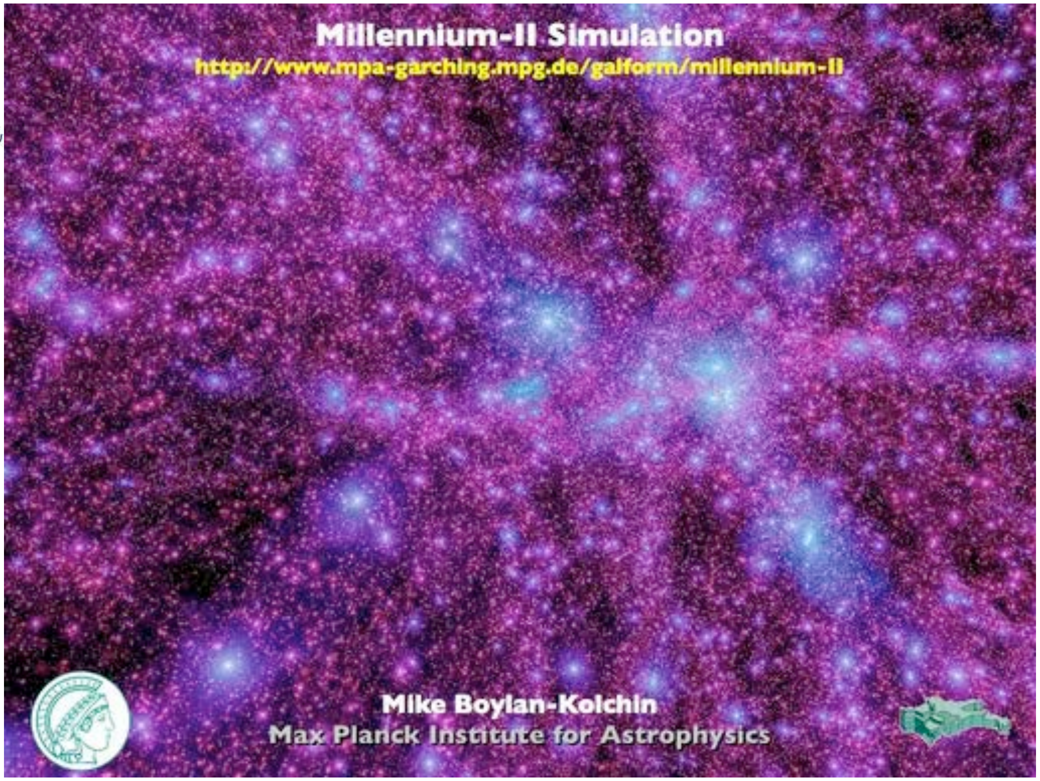
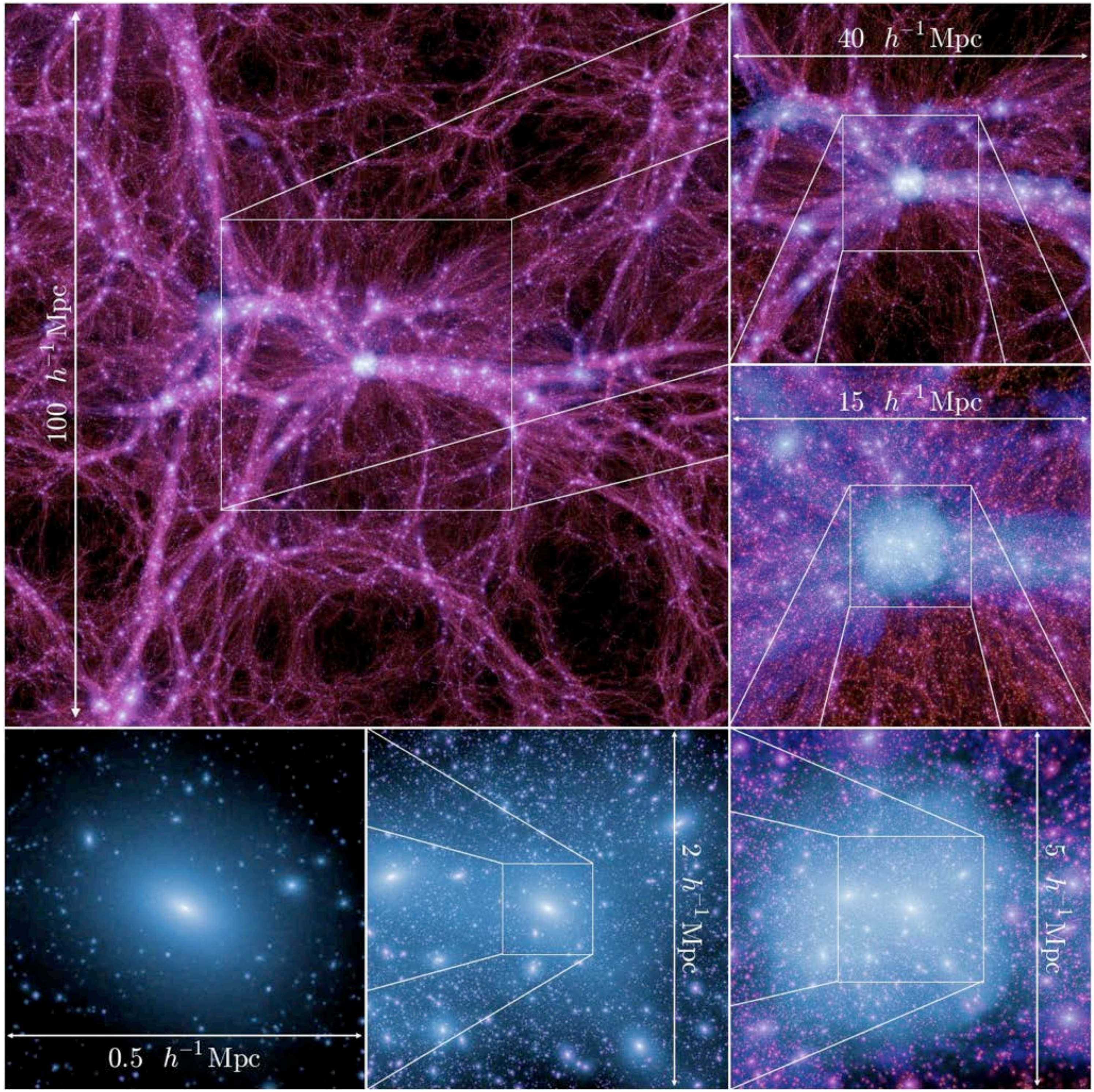


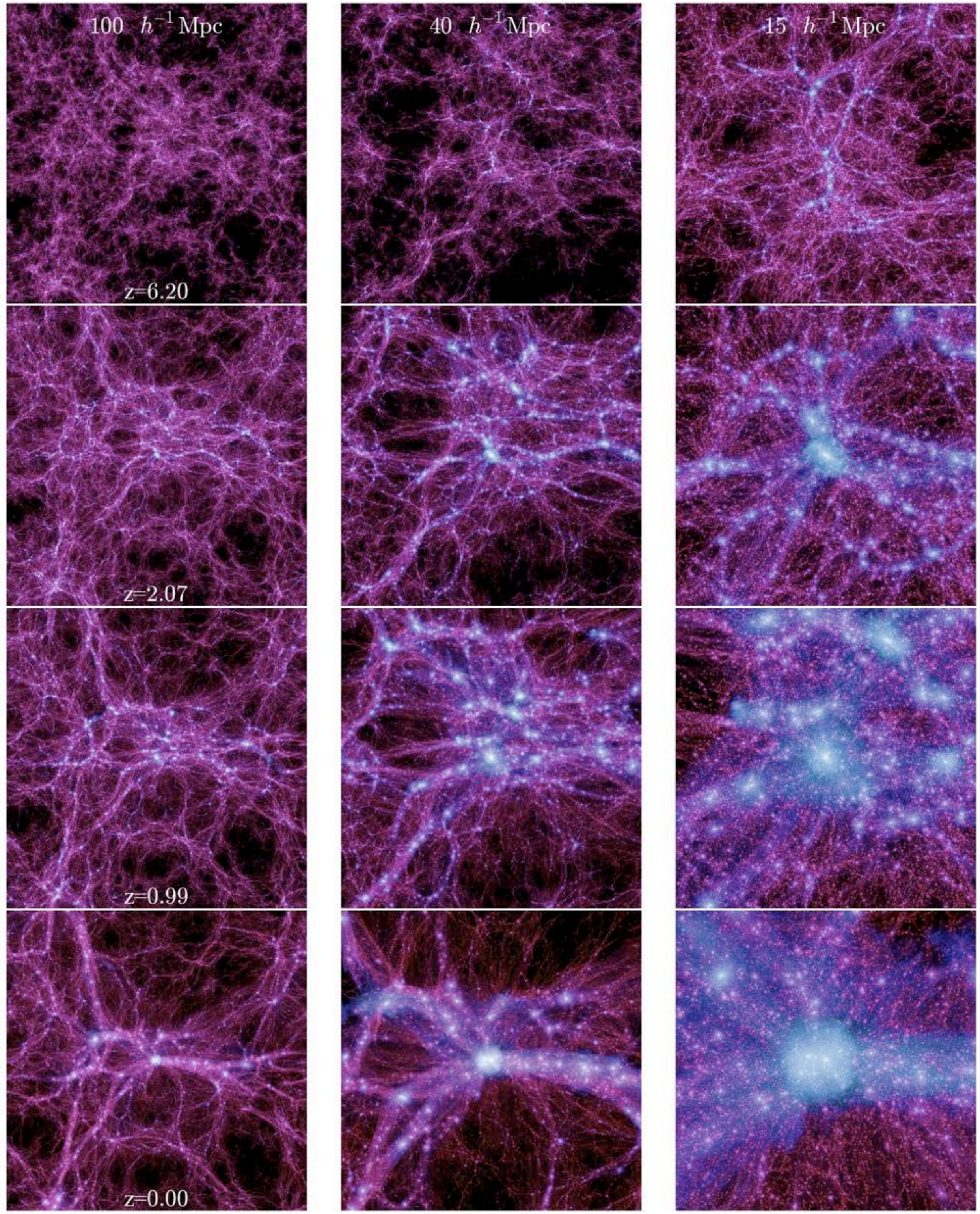
Zoom into the most massive halo at z=0

Boylan-Kolchin et al. (2009)



Time evolution

Boylan-Kolchin et al. (2009)



2 h^{-1}Mpc box at z=0

Boylan-Kolchin et al. (2009)

THE ASTROPHYSICAL JOURNAL, 568:52–70, 2002 March 20

CONCENTRATIONS OF DARK HALOS FROM THEIR ASSEMBLY HISTORIES

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Received 2001 August 9; accepted 2001 November 19

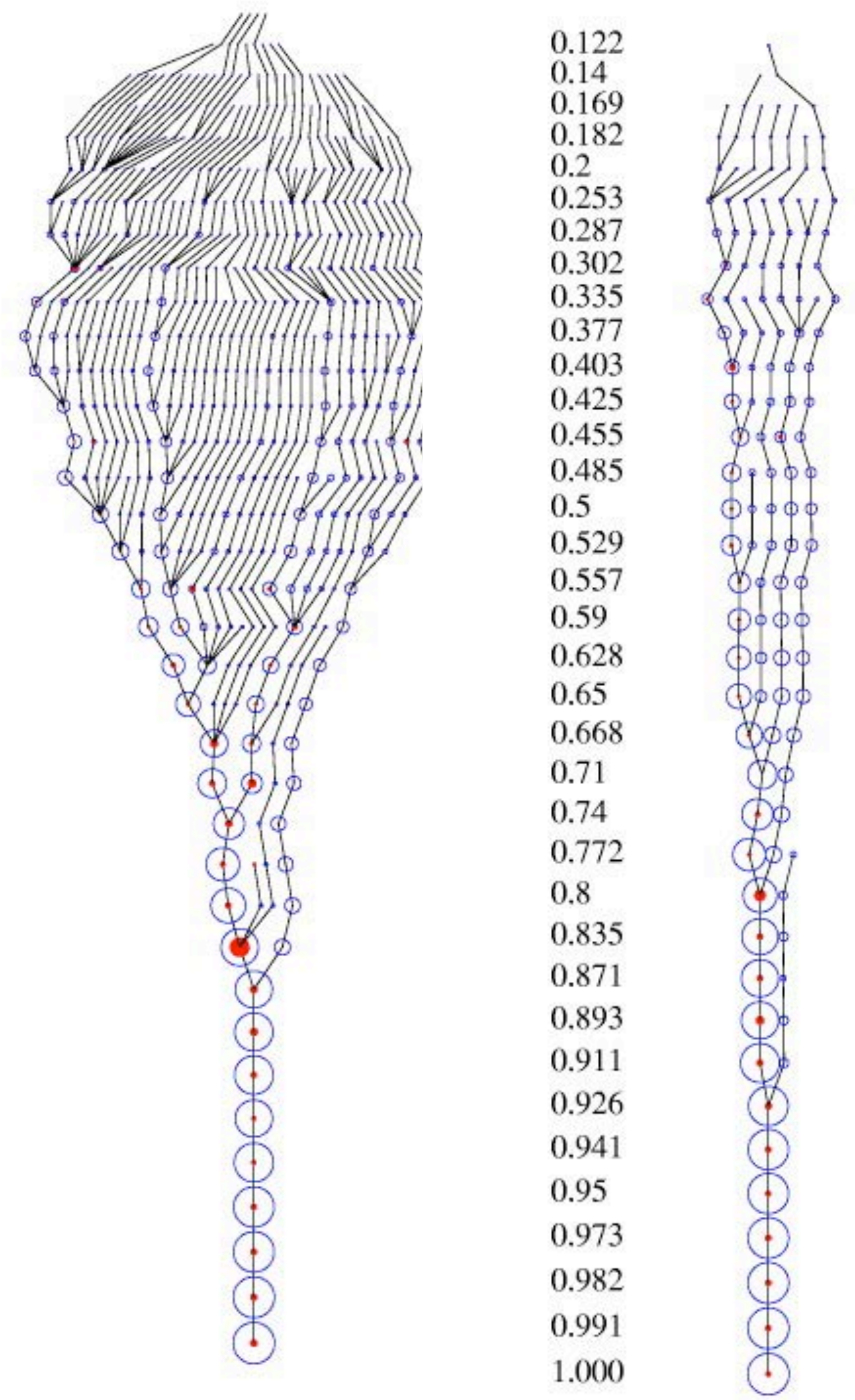
ABSTRACT

We study the relation between the density profiles of dark matter halos and their mass assembly histories using a statistical sample of halos in a high-resolution N-body simulation of the ΛCDM cosmology. For each halo at $z = 0$, we identify its merger history tree and determine concentration parameters $c_{\rm vir}$ for all progenitors, thus providing a structural merger tree for each halo. We fit the mass accretion histories by a universal function with one parameter, the formation epoch a_c, defined when the log mass accretion rate $d\log M/d\log a$ falls below a critical value S. We find that late-forming galaxies tend to be less concentrated, such that $c_{\rm vir}$ "observed" at any epoch a_o is strongly correlated with a_c via $c_{\rm vir} = c_1 a_o/a_c$. Scatter about this relation is mostly due to measurement errors in $c_{\rm vir}$ and a_c, implying that the actual spread in $c_{\rm vir}$ for halos of a given mass can be mostly attributed to scatter in a_c. We demonstrate that this relation can also be used to predict the mass and redshift dependence of $c_{\rm vir}$ and the scatter about the median $c_{\rm vir}(M, z)$ using accretion histories derived from the extended Press-Schechter (EPS) formalism, after adjusting for a constant offset between the formation times as predicted by EPS and as measured in the simulations; this new ingredient can thus be easily incorporated into semianalytic models of galaxy formation. The correlation found between halo concentration and mass accretion rate suggests a physical interpretation: for high mass infall rates, the central density is related to the background density; when the mass infall rate slows, the central density stays approximately constant, and the halo concentration just grows as $R_{\rm vir}$. Because of the direct connection between halo concentration and velocity rotation curves and because of probable connections between halo mass assembly history and star formation history, the tight correlation between these properties provides an essential new ingredient for galaxy formation modeling.

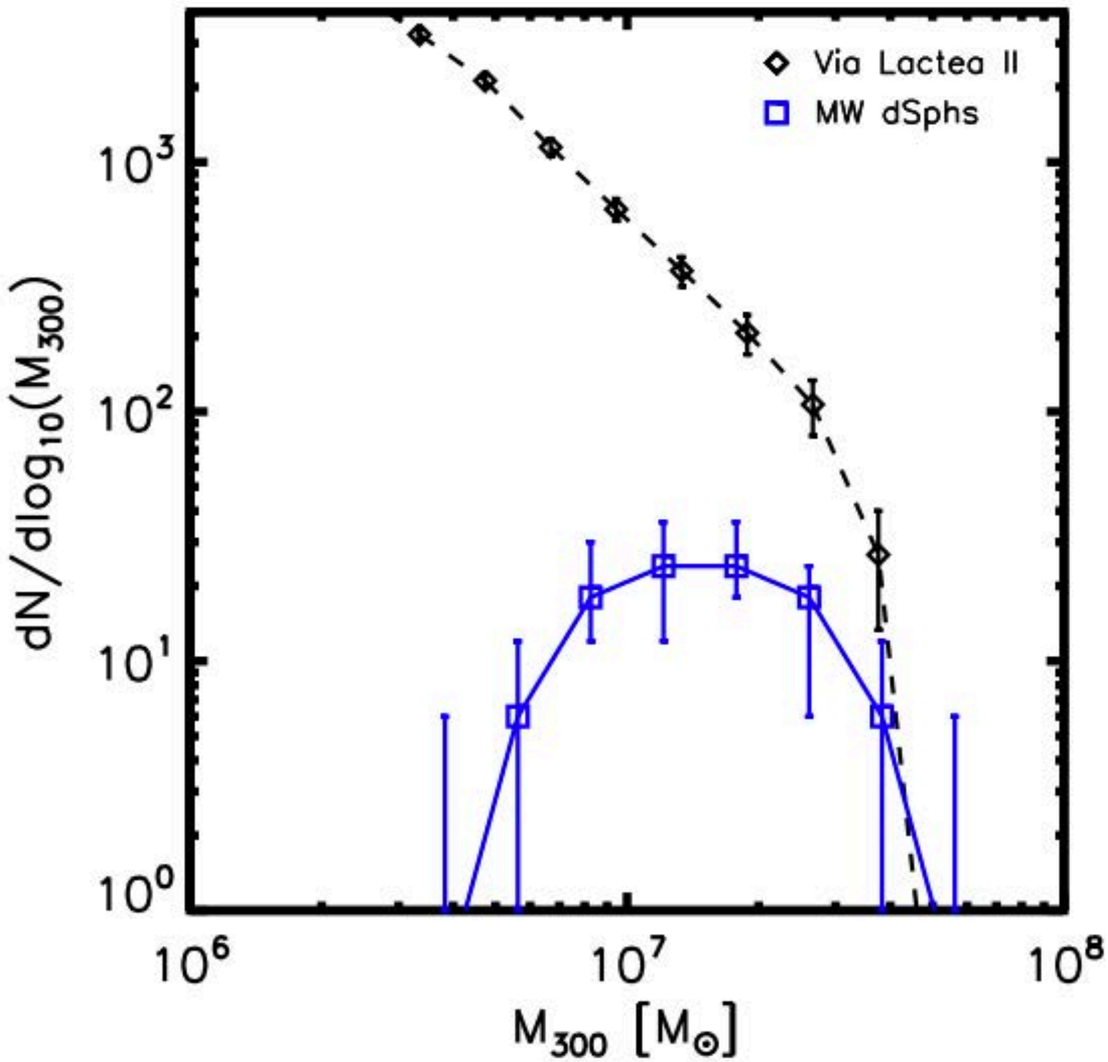
Subject headings: cosmology: theory — dark matter — galaxies: evolution — galaxies: formation — galaxies: halos — galaxies: structure

On-line material: color figures

Merger Tree



Structural merger trees for two halos. This diagram illustrates the merging history of a cluster mass halo (*left*; $M_{vir} = 2.8 \times 10^{14}\, h^{-1}\, M$ and $c_{vir} = 5.9$) and a galaxy mass halo (*right*; $M_{vir} = 2.9 \times 10^{12}\, h^{-1}\, M$ and $c_{vir} = 12.5$) at $a = 1$. The radii of the outer and inner (*filled*) circles are proportional to the virial and inner NFW radii, R_{vir} and R_s, respectively, scaled such that the two halos have equal sizes at $a = 1$. Lines connect halos with their progenitor halos. All progenitors with profile fits ($M > 2.2 \times 10^{11}\, h^{-1}\, M$) are shown for the cluster mass halo; all progenitors ($M > 2.2 \times 10^{10}\, h^{-1}\, M$) are shown for the galaxy mass halo. The scale factor a at the output time is listed in the center of the plot. The width of the diagram is arbitrary



Bullock 2010

Huge failure?
Or...

Fig. 1.6. Mass function for $M_{300} = M(< 300\text{pc})$ for MW dSph satellites and dark subhalos in the Via Lactea II simulation within a radius of 400 kpc. The short-dashed curve is the subhalo mass function from the simulation. The solid curve is the median of the observed satellite mass function. The error bars on the observed mass function represent the upper and lower limits on the number of configurations that occur with a 98% of the time (from Wolf et al., in preparation). Note that the mismatch is about ~ 1 order of magnitude at $M_{300} \simeq 10^7\, M_\odot$, and that it grows significantly towards lower masses.

... huge bias?

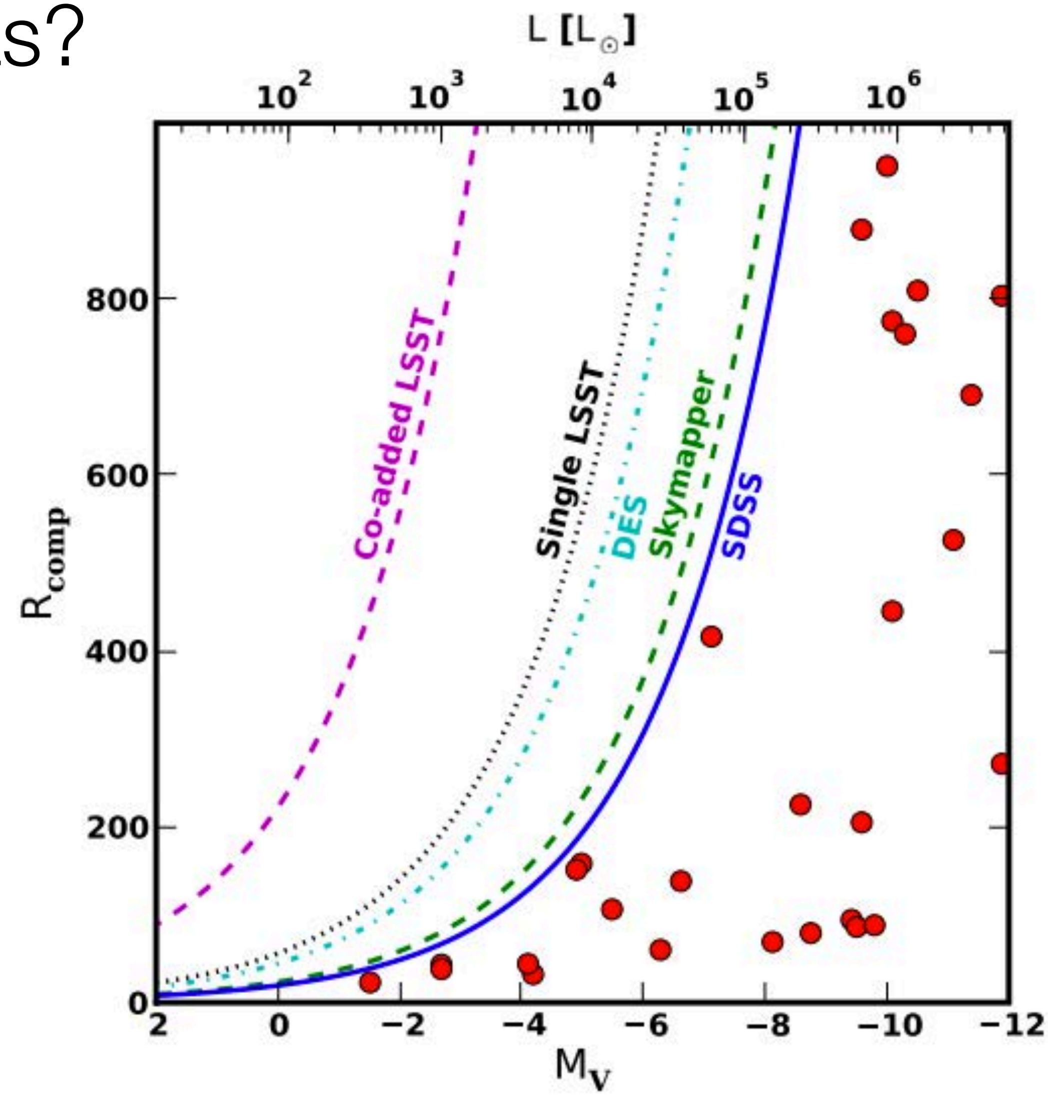
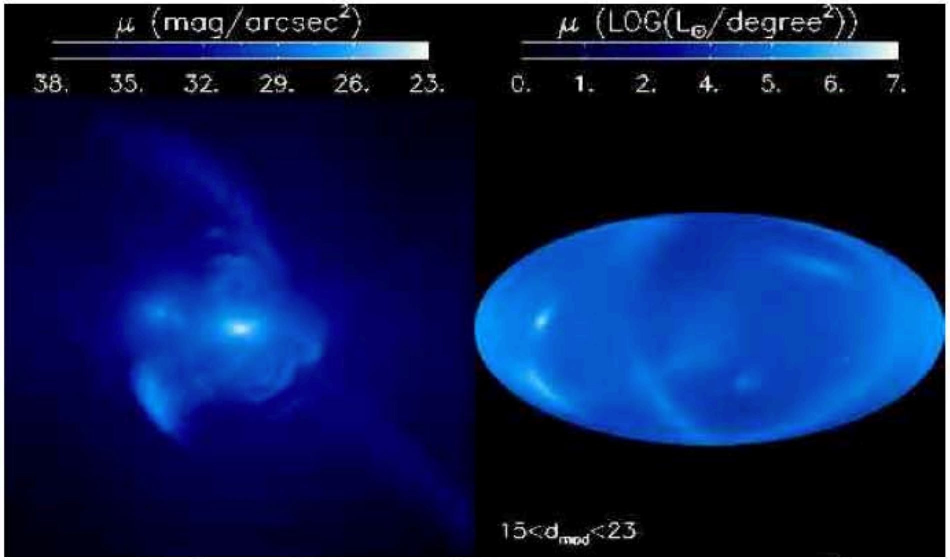
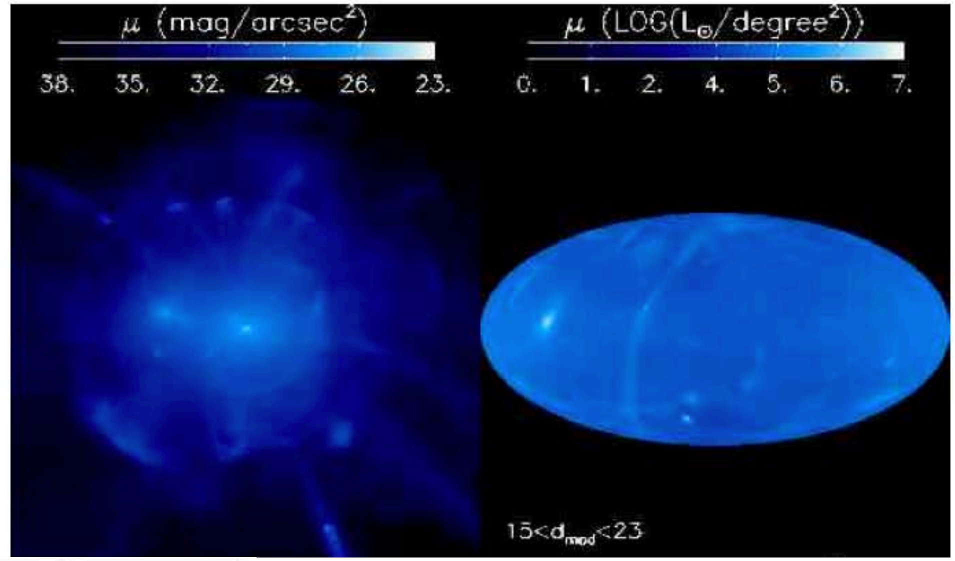
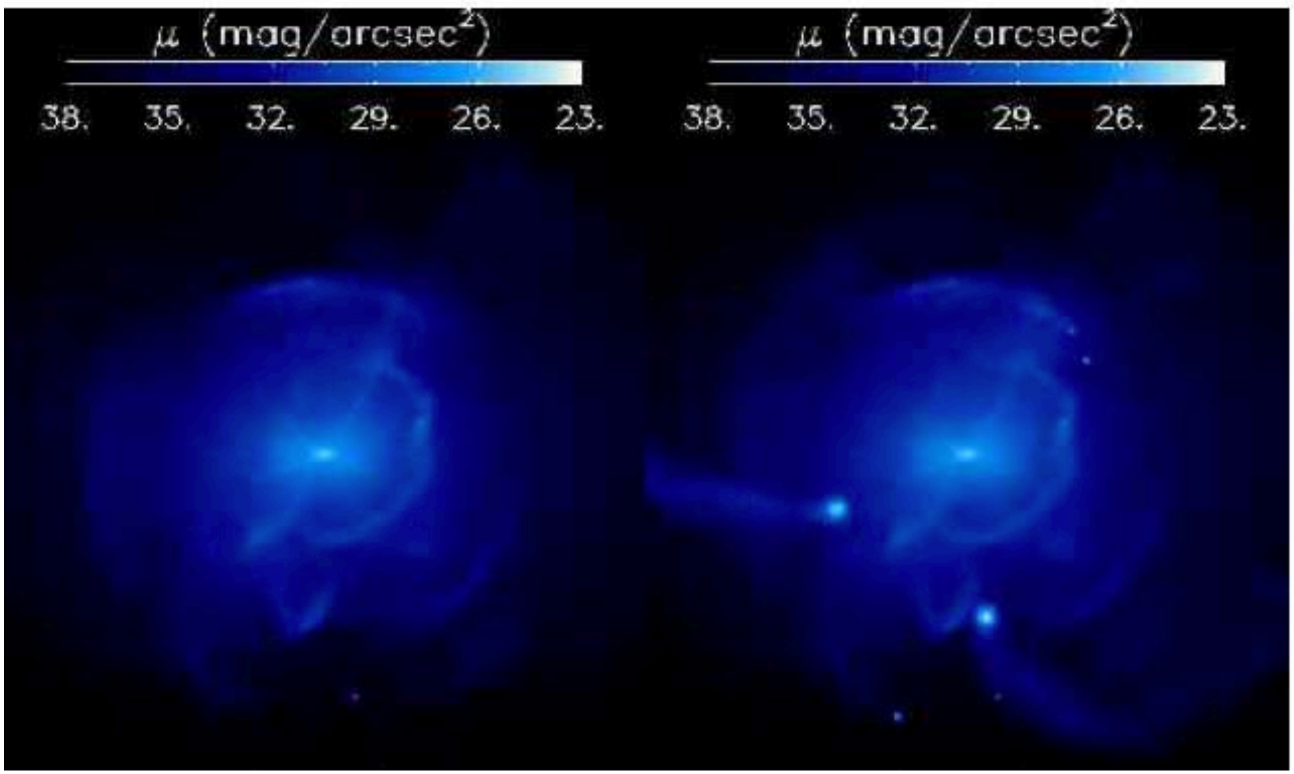


Fig. 1.12. Maximum radius for detection of dSphs as estimated by Tollerud et al. (2008) shown as a function of galaxy absolute magnitude for DR5 (assumed limiting r-band magnitude of 22.2) compared to a single exposure of LSST (24.5), co-added full LSST lifetime exposures (27.5), DES or one exposure from PanSTARRS (both 24), and the SkyMapper and associated Missing Satellites Survey (22.6). The data points are SDSS and classical satellites, as well as Local Group field galaxies.

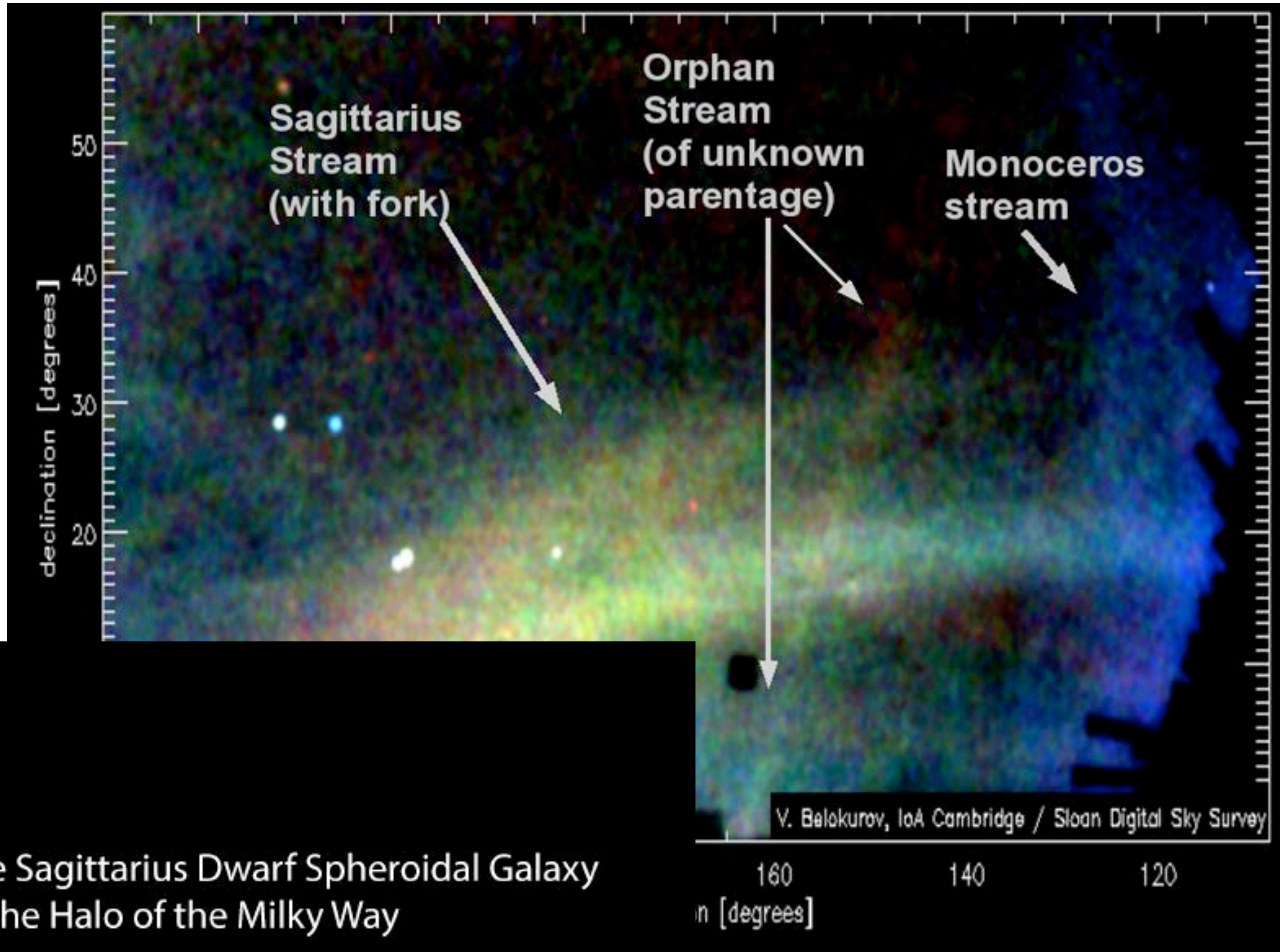
Related problem: missing substructure.
e.g. Johnston et al. 2008

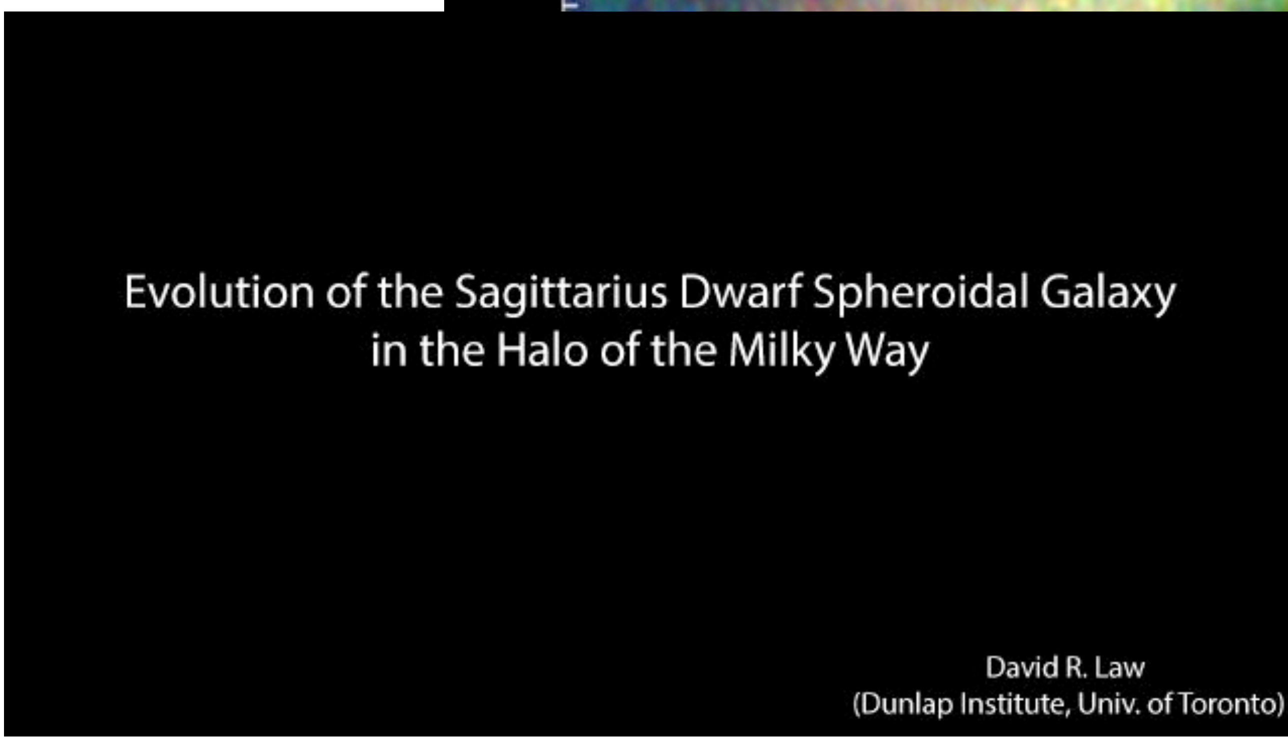






The lesson: abundant substructure is a concrete prediction of the model

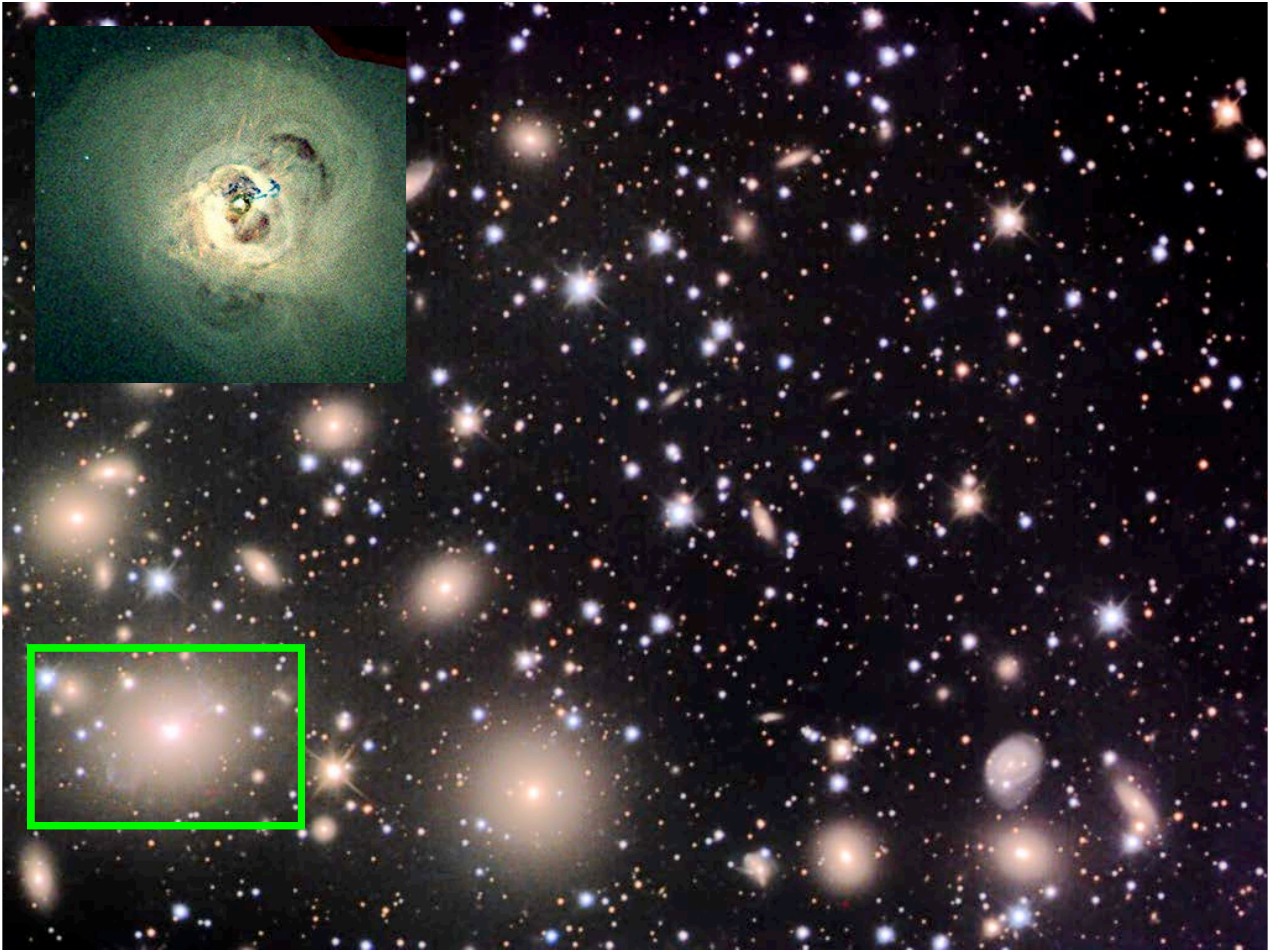


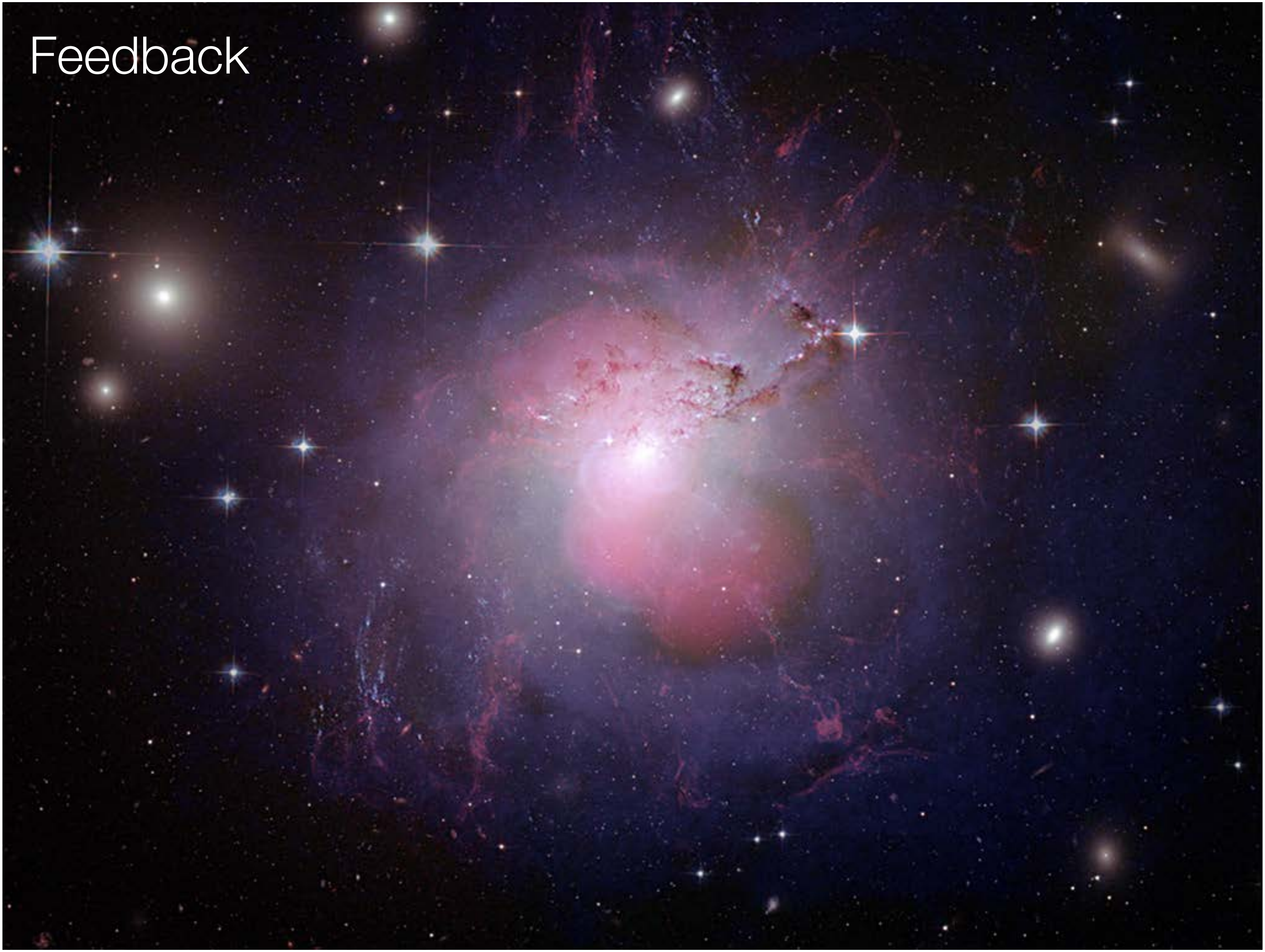


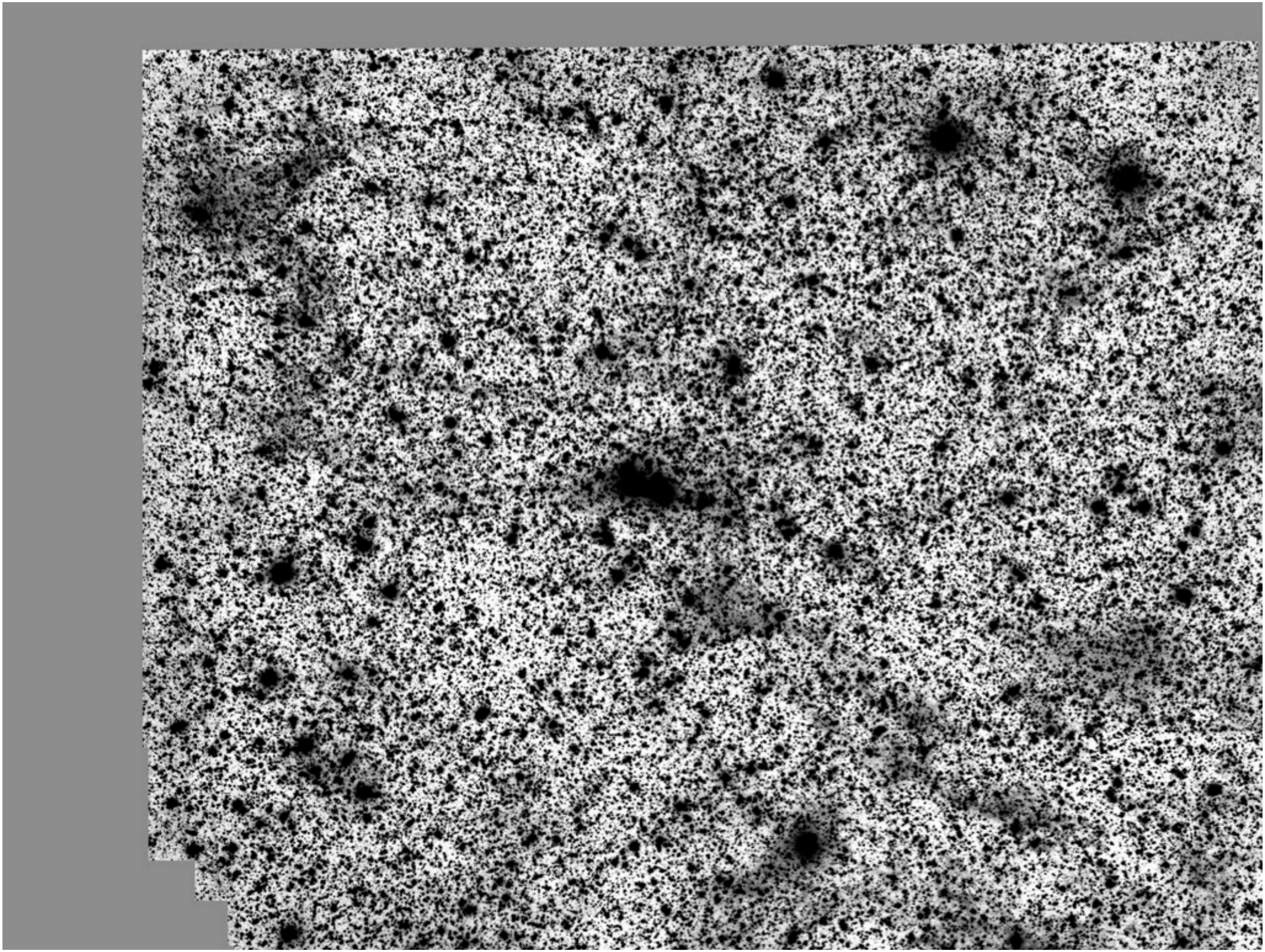
… but far too few.

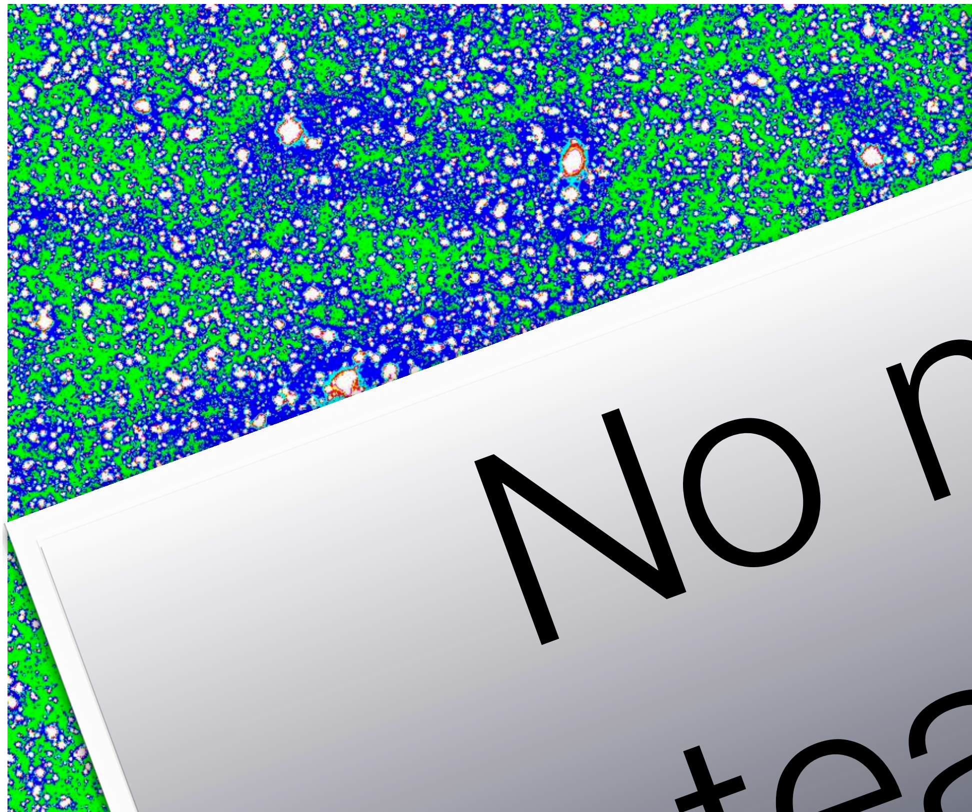
7)

Tease




Feedback





No more teasing

DANGER

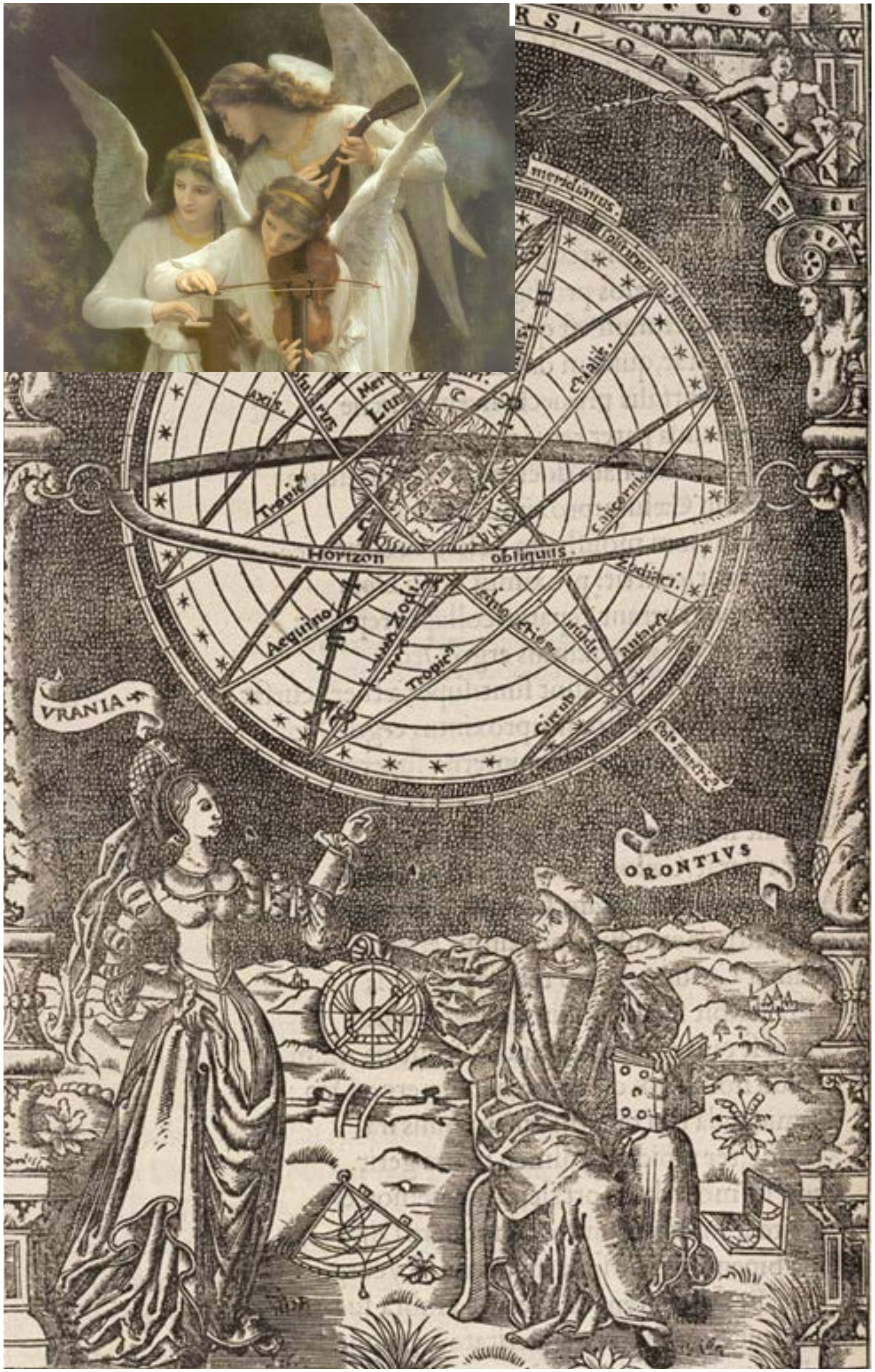
Baryons Ahead

What we model

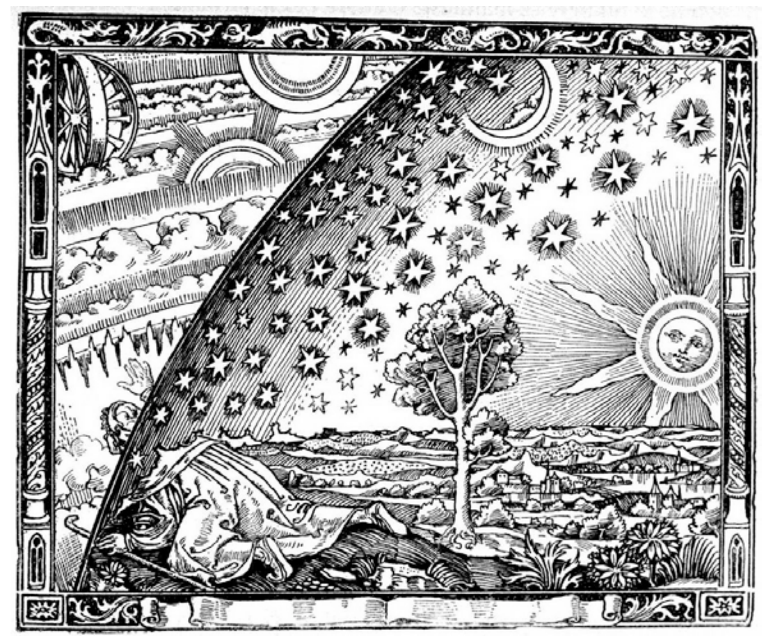
Mysterious Dark Matter Particles

What we observe

Stars and Gas



Popular cosmological models from the past based on making models of stuff you cannot see



Although we're once again modeling things we can't see, I do not think we're in any danger of repeating past mistakes… but you should try to convince yourselves of this too.

What we model

Just gravity
(simple)

What we observe

All forces of Nature
(complicated)

Gastrophysics 101

As gas collapses with the dark matter into halos it converts gravitational energy into thermal energy. From the virial theorem:

$$2\,K = -U$$

$$2\,N_p\,k\,T = \frac{G\,M\,m_{gas}}{R} = \frac{G\,M\,N_p\,m_H}{R}$$

$$\begin{aligned} T &= \frac{G\,M\,m_H}{3\,k\,R} \\ &= 3.5\times 10^6 \left(\frac{M}{10^{12}\,M_\odot}\right)\left(\frac{50\text{ kpc}}{R}\right)\text{K} \end{aligned} \tag{1}$$

This gas is hot! Compare it to the gas temperature in the ISM (tens of K). We need to cool it to form stars. How?

At high temperatures, via free-free emission (Bremstahlung). At lower temperatures via bound-free & bound-bound transitions. These depend on metallicity. Also depends on density as n^2.

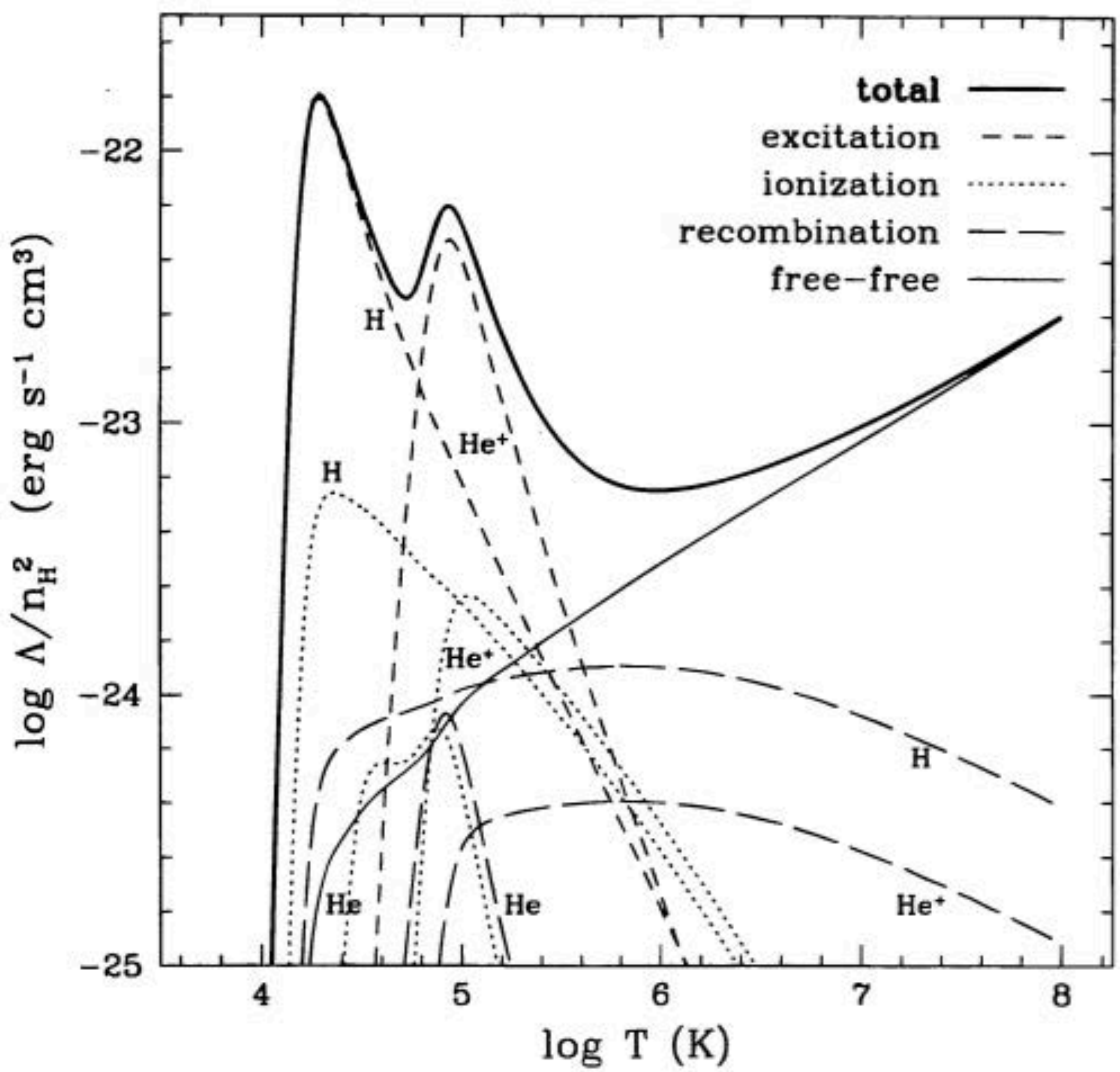


FIG. 1.—Cooling rates as a function of temperature for a primordial composition gas in collisional equilibrium. Heavy solid line shows the total cooling rate. The cooling is dominated by collisional excitation (*short-dashed lines*) at low temperatures and by free-free emission (*thin solid line*) at high temperatures. Long-dashed lines and dotted lines show the contributions of recombination and collisional ionization, respectively.

The gas loses energy at a rate:

$$\frac{dE}{dt} = -n^2 \Lambda(T)$$

And the cooling time is:

$$\tau_{cool} = \frac{E}{|dE/dt|} = \frac{3 N k_B T}{N^2 \Lambda(T)} = \frac{3 kT}{n \Lambda(T)}$$

It is interesting to consider what happens when the cooling time is less than the gravitational collapse time, which is $\tau_{grav} \propto \frac{1}{\sqrt{G \rho}} \sim n^{-1/2}$, and the Hubble time.

Clearly high density regions cool and collapse fast. Very low density regions won't cool or collapse. Very massive things tend to collapse later (and at lower density) so they don't have time to collapse, which implies an upper limit to galaxy masses.

One can argue that a characteristic galaxy mass scale can be set by requiring the cooling time to be shorter than the dynamical time. You get ~10^{12} solar masses that way. You have to assume the gas is all at the same density though, which seems dodgy. See David Weinberg's excellent notes: http://www.astronomy.ohio-state.edu/~dhw/A825/notes8.pdf

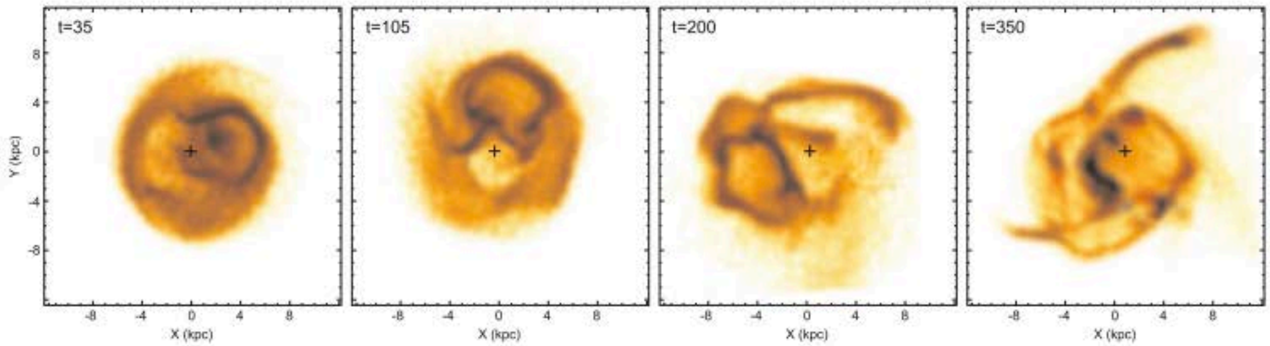


Fig. 8. Snapshots of the disk mass density in the model, with time indicated in Myr. The halo mass center is marked by the black + symbol. The initial conditions are closely similar to the first snapshot, with a uniform disk density. The last snapshot shown here is slightly before the projection reproducing the UDF 6462 morphology (Fig. 9). We note that the asymmetrical aspect produced by the initial disk-halo offset is amplified by a long spiral arm extension and the outer location of one of the clumps.

A differentially rotating disk is stable if

$$Q \equiv \frac{\sigma_R \kappa}{3.36 G \Sigma} > 1.$$

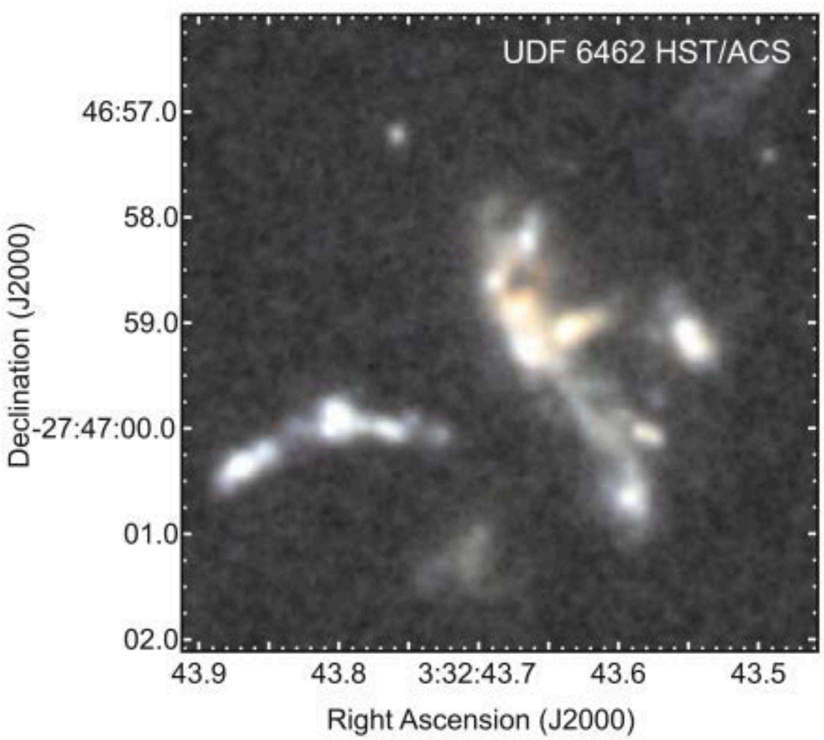


Fig. 1. Color image of the UDF 6462 clump-cluster from optical multi-band ACS imaging. The bent-chain UDF 6911 is visible to the left.

Bournaud et al. 2011

If you dump enough gas even into a very dynamically hot system you can make it unstable… the mechanisms we have described so far are self-regulating. But maybe we have been discounting an important mechanism? COLD FLOWS.

Brooks et al. 2009

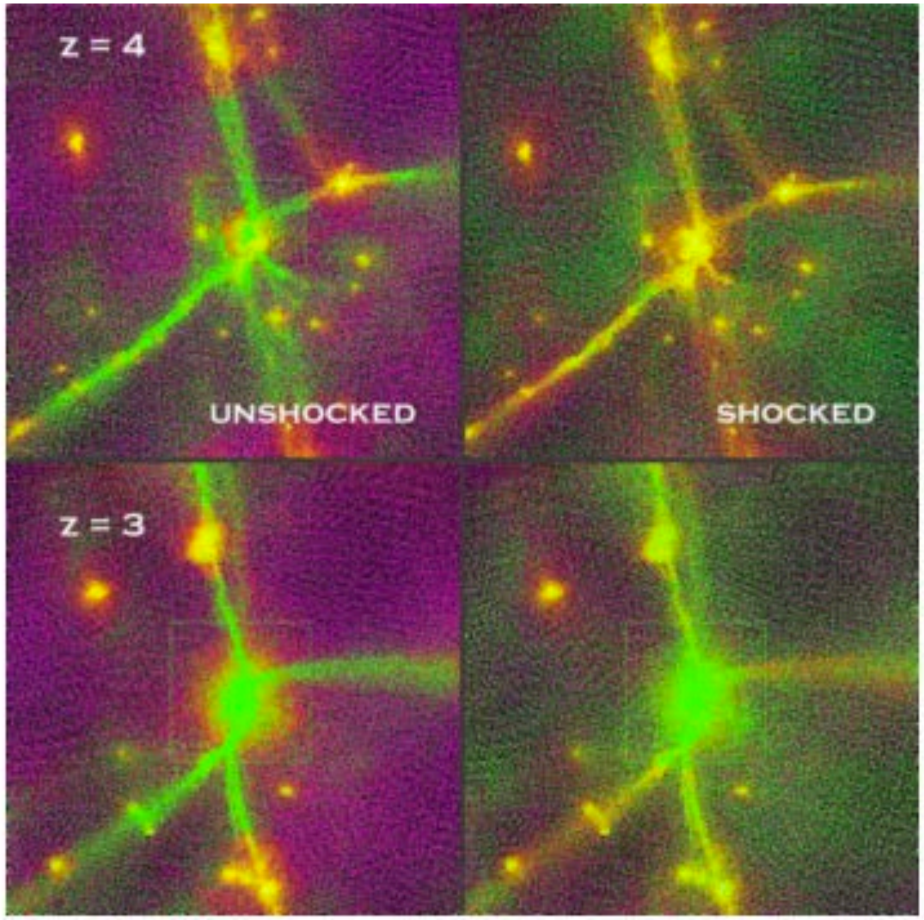
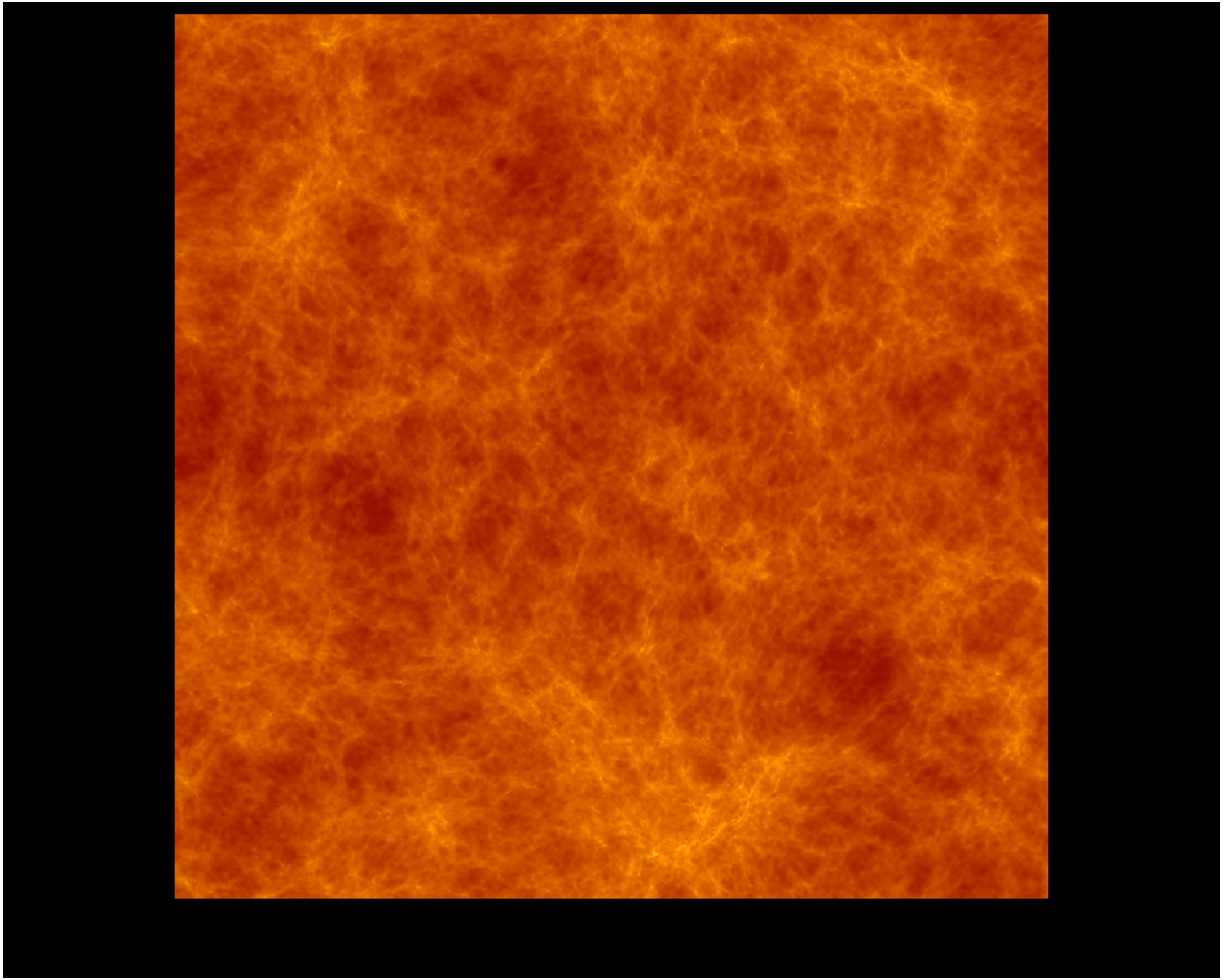


FIG. 5.— Images from our MW1 simulation at redshifts 4 and 3, identifying gas that will be smoothly accreted to the galaxy as either unshocked or shocked gas. *Left column:* The distribution of particles that will be (or have been) accreted but remain unshocked are marked in green. *Right column:* Particles that will be (or have been) shocked as they are accreted are shown in green. The underlying colors represent a gas density map, for reference, with black being least dense and white being the densest structures. The frames are centered on the main MW1 progenitor at each of the redshifts shown. Each frame is ∼1 comoving Mpc on a side. Faint, green boxes indicate R_{vir} at each time.



Brooks et al. 2009

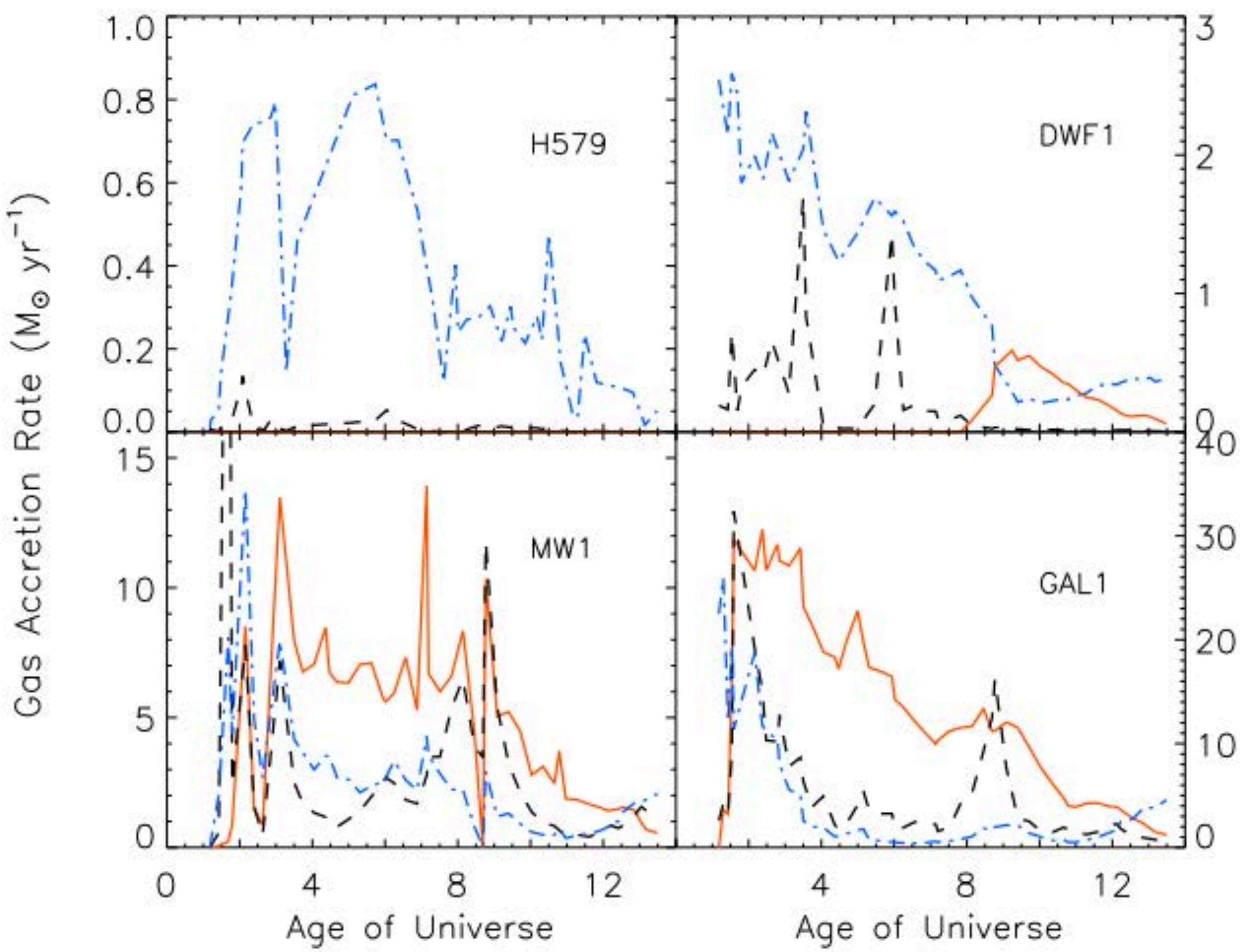


FIG. 3.— This plot is the same as Fig. 2 except that the "smooth" gas accretion rate has been divided further into "shocked" (red, solid line) and "unshocked" (blue, dot-dashed line) accretion. The "clumpy" gas accretion rate is shown by the black, dashed line. The present epoch, $z = 0$, occurs at 13.7 Gyr.

Brooks et al. 2009

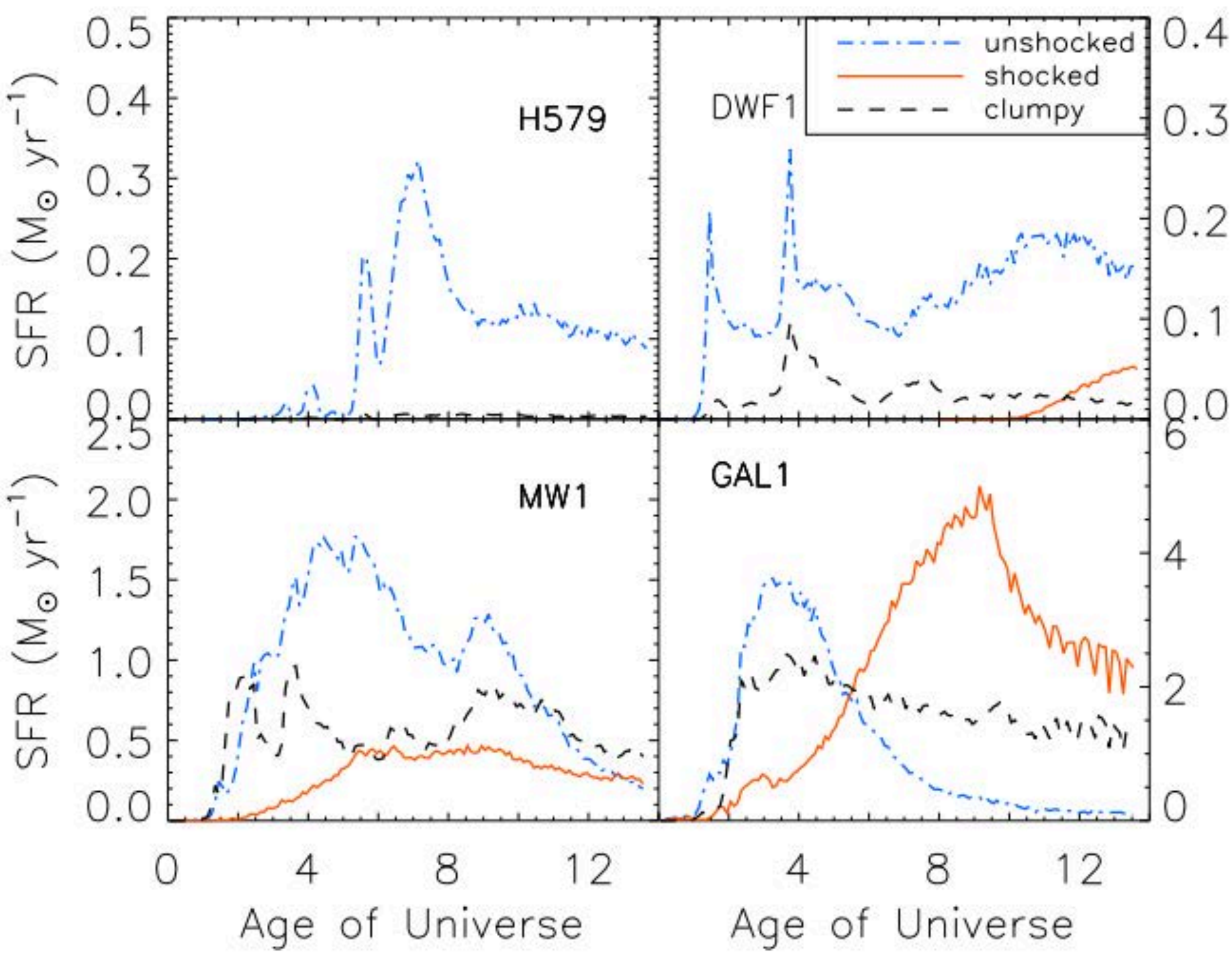


FIG. 7.— The star formation history for those stars that are in the disk of each galaxy at $z = 0$. The star formation rates are broken down according to the accretion mode of the gas progenitor particles. Stars that formed from "clumpy" accreted gas are represented by the black, dashed line. The star formation rate of stars formed from smoothly accreted, unshocked gas is shown by the blue, dot-dashed line. Finally, the star formation rate for stars formed from smoothly accreted, shocked gas is shown in red (solid line). $z = 0$ occurs at an age of 13.7 Gyr.

Brooks et al. 2009

The wimpier the galaxy the more cold flows matter.

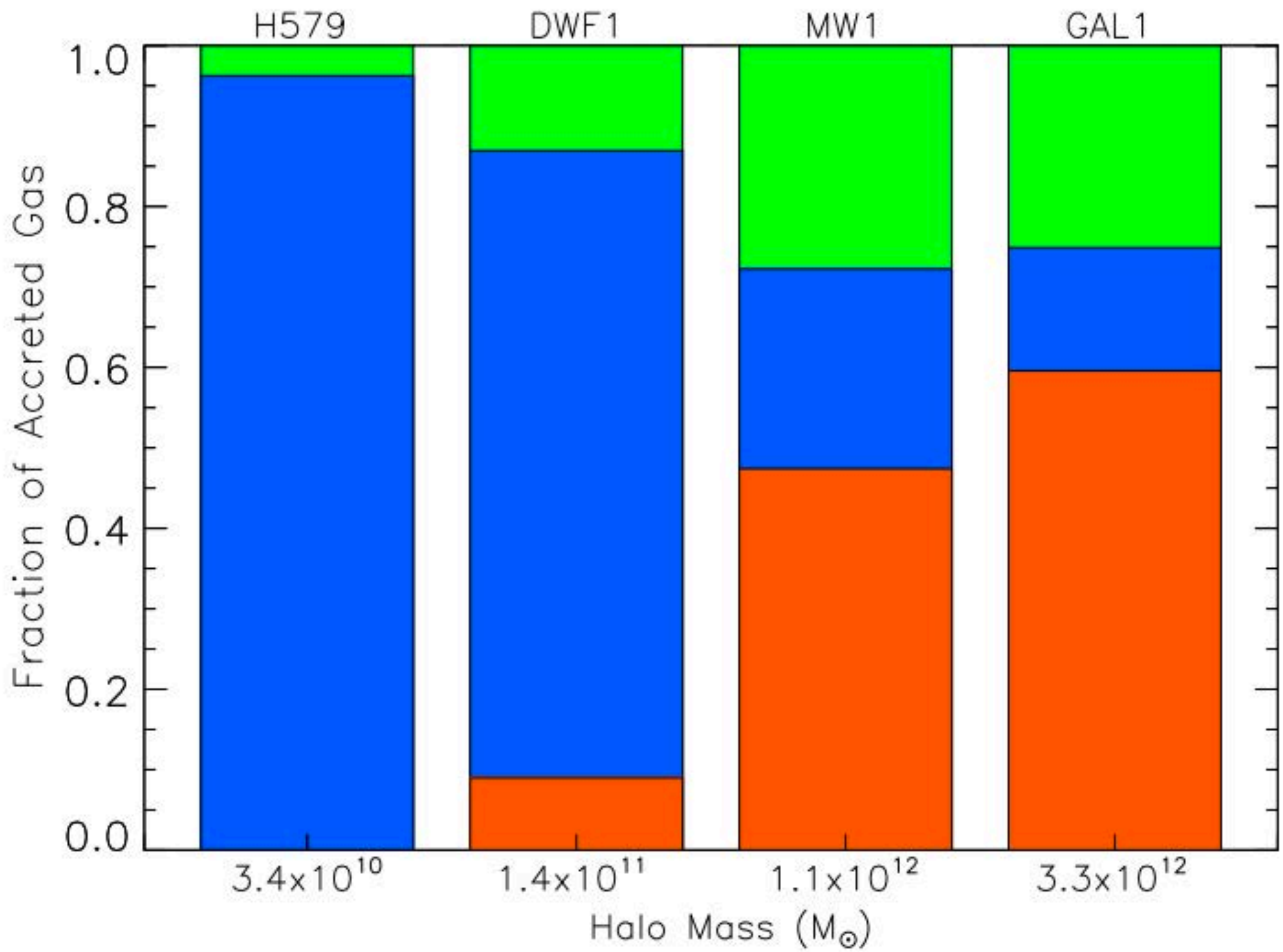


Fig. 1.— This plot shows the fraction of gas that has been accreted at the virial radius since $z = 6$ that has been accreted as "clumpy" ;reen, top), "unshocked" (blue), and "shocked" (red) gas. Together, the unshocked and shocked gas make up the total of smoothly :creted gas that never belonged to another galaxy halo (see Section 3.2). The total halo masses (in $M_\odot$) of each of the four galaxies are sted below their respective bar.

Semi-analytical modelling

Durham School

Mon. Not. R. Astron. Soc. 319, 168–204 (2000)

Hierarchical galaxy formation

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ABSTRACT
We describe the GALFORM semi-analytic model for calculating the formation and evolution of galaxies in hierarchical clustering cosmologies. It improves upon, and extends, the earlier scheme developed by Cole et al. The model employs a new Monte Carlo algorithm to follow the merging evolution of dark matter haloes with arbitrary mass resolution. It incorporates realistic descriptions of the density profiles of dark matter haloes and the gas they contain; it follows the chemical evolution of gas and stars, and the associated production of dust; and it includes a detailed calculation of the sizes of discs and spheroids. Wherever possible, our prescriptions for modelling individual physical processes are based on results of numerical simulations. They require a number of adjustable parameters, which we fix by reference to a small subset of local galaxy data. This results in a fully specified model of galaxy formation which can be tested against other data. We apply our methods to the ΛCDM cosmology ($\Omega_0 = 0.3$, $\Lambda_0 = 0.7$), and find good agreement with a wide range of properties of the local galaxy population: the B- and K-band luminosity functions, the distribution of colours for the population as a whole, the ratio of ellipticals to spirals, the distribution of disc sizes, and the current cold gas content of discs. In spite of the overall success of the model, some interesting discrepancies remain: the colour–magnitude relation for ellipticals in clusters is significantly flatter than observed at bright magnitudes (although the scatter is … given luminosity, that a …

MPE School

Mon. Not. R. Astron. Soc. 303, 188–206 (1999)

Clustering of galaxies in a hierarchical universe – I. Methods and results at $z = 0$

Guinevere Kauffmann, Jörg M. Colberg, Antonaldo Diaferio and Simon D. M. White
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Accepted 1998 October 12. Received 1998 September 21; in original form 1998 May 27

ABSTRACT
We introduce a new technique for following the formation and evolution of galaxies in cosmological N-body simulations. Dissipationless simulations are used to track the formation and merging of dark matter haloes as a function of redshift. Simple prescriptions, taken directly from semi-analytic models of galaxy formation, are adopted for gas cooling, star formation, supernova feedback and the merging of galaxies within the haloes. This scheme enables us to explore the clustering properties of galaxies, and to investigate how selection by luminosity, colour or type influences the results. In this paper we study the properties of the galaxy distribution at $z = 0$. These include B- and K-band luminosity functions, two-point correlation functions, pairwise peculiar velocities, cluster mass-to-light ratios, $B - V$ colours, and star formation rates. We focus on two variants of a cold dark matter (CDM) cosmology: a high-density ($\Omega = 1$) model with shape-parameter $\Gamma = 0.21$ (τCDM), and a low-density model with $\Omega = 0.3$ and $\Lambda = 0.7$ (ΛCDM). Both models are normalized to reproduce the I-band Tully–Fisher relation of Giovanelli et al. near a circular velocity of 220 km s^{-1}. Our results depend *strongly* both on this normalization and on the adopted prescriptions for star formation and feedback. Very different assumptions are required to obtain an acceptable model in the two cases. For τCDM, efficient feedback is required to suppress the growth of galaxies, particularly in low-mass field haloes. Without it, there are too many galaxies and the … ong turnover on scales below 1 Mpc. For ΛCDM, feedback … L_* galaxies are produced and the correlation function is too … perfect, both come close to reproducing most of the data. … ng some of the critical physical processes, we conclude that … conclusions about the values of cosmological parameters … observational work on global star formation and feedback … ange of possibilities.

… galaxies: haloes – dark matter – large-scale structure of

Santa Cruz School

Mon. Not. R. Astron. Soc. 310, 1087–1110 (1999)

Semi-analytic modelling of galaxy formation: the local Universe

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[1]*Racah Institute of Physics, The Hebrew University, Jerusalem*
[2]*Physics Department, University of California, Santa Cruz*

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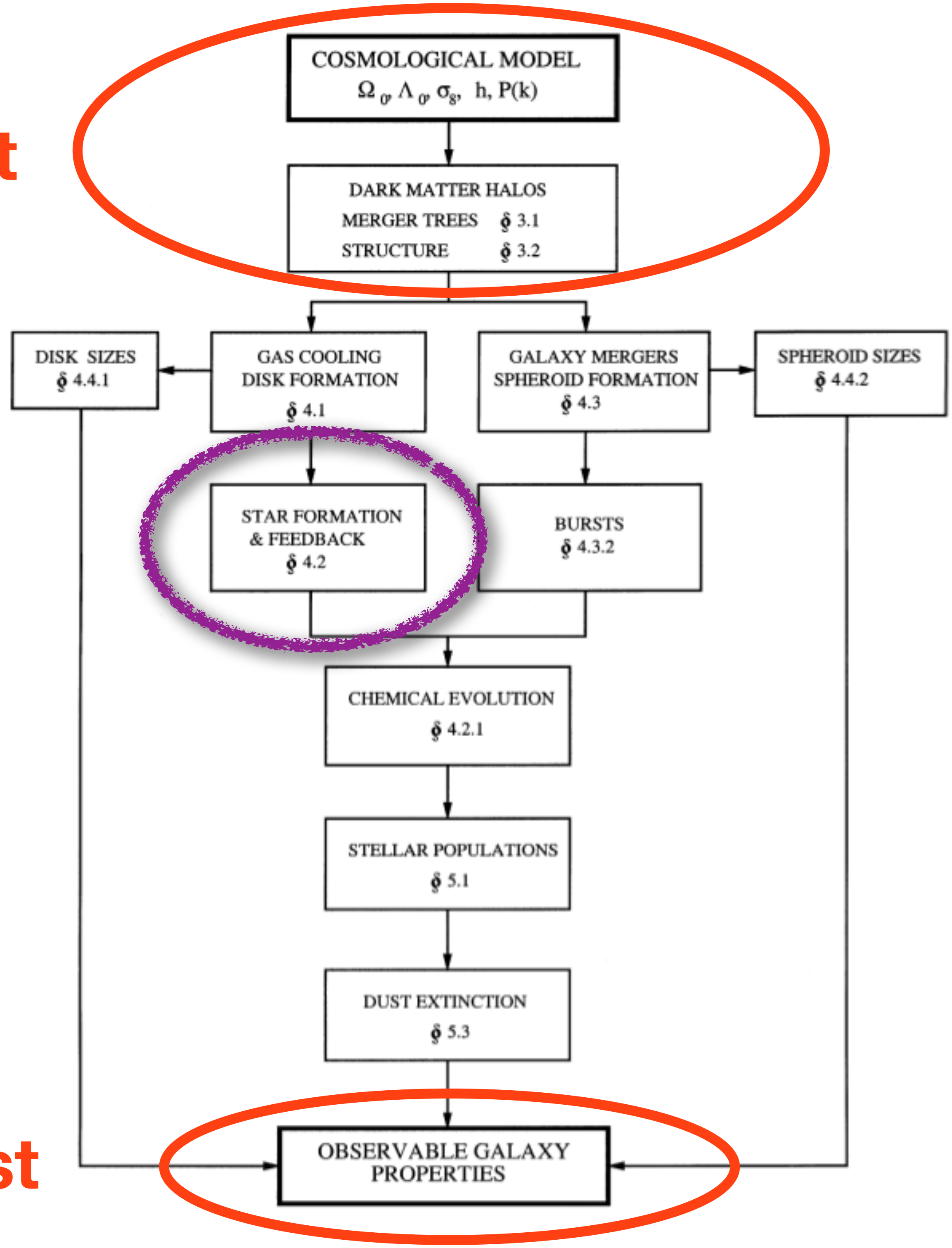
ABSTRACT
Using semi-analytic models of galaxy formation, we investigate galaxy properties such as the Tully–Fisher relation, the B- and K-band LFs, cold gas contents, sizes, metallicities and colours, and compare our results with observations of local galaxies. We investigate several different recipes for star formation and supernova feedback, including choices that are similar to the treatment by Kauffmann, White & Guiderdoni and Cole et al., as well as some new recipes. We obtain good agreement with all of the key local observations mentioned above. In particular, in our best models, we simultaneously produce good agreement with both the observed B- and K-band LFs and the I-band Tully–Fisher relation. Improved cooling and supernova feedback modelling, inclusion of dust extinction and an improved Press–Schechter model all contribute to this success. We present results for several variants of the CDM family of cosmologies, and find that models with values of $\Omega_0 \simeq 0.3$–0.5 give the best agreement with observations.

Key words: galaxies: evolution – galaxies: formation – cosmology: theory.

Robust

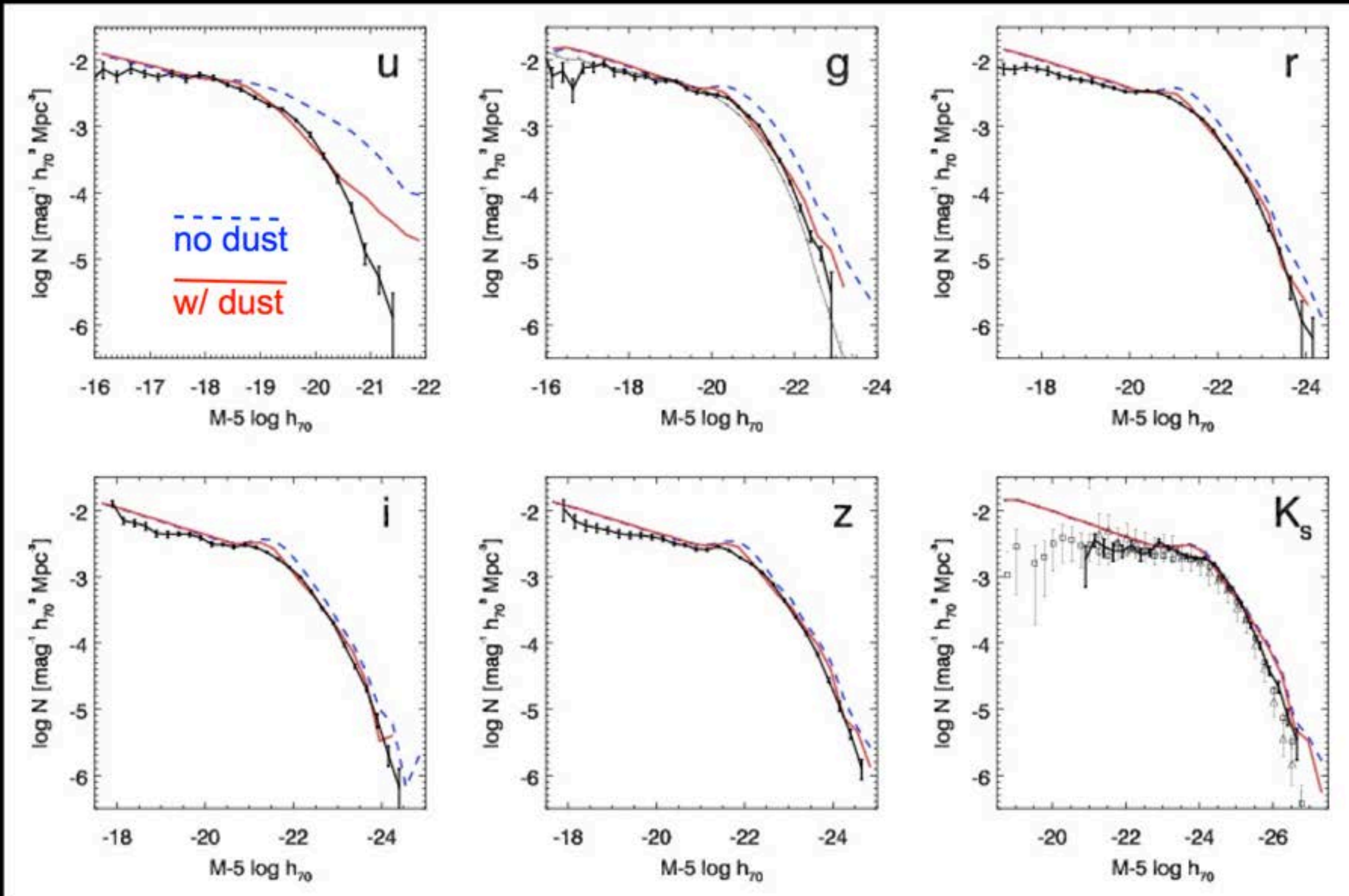
Educated guesses with lots of free parameters that can be used to mainly "postdict" observations, and let you sort-of understand stuff in a general way. Wonderfully useful, if you don't take them too seriously.



Robust

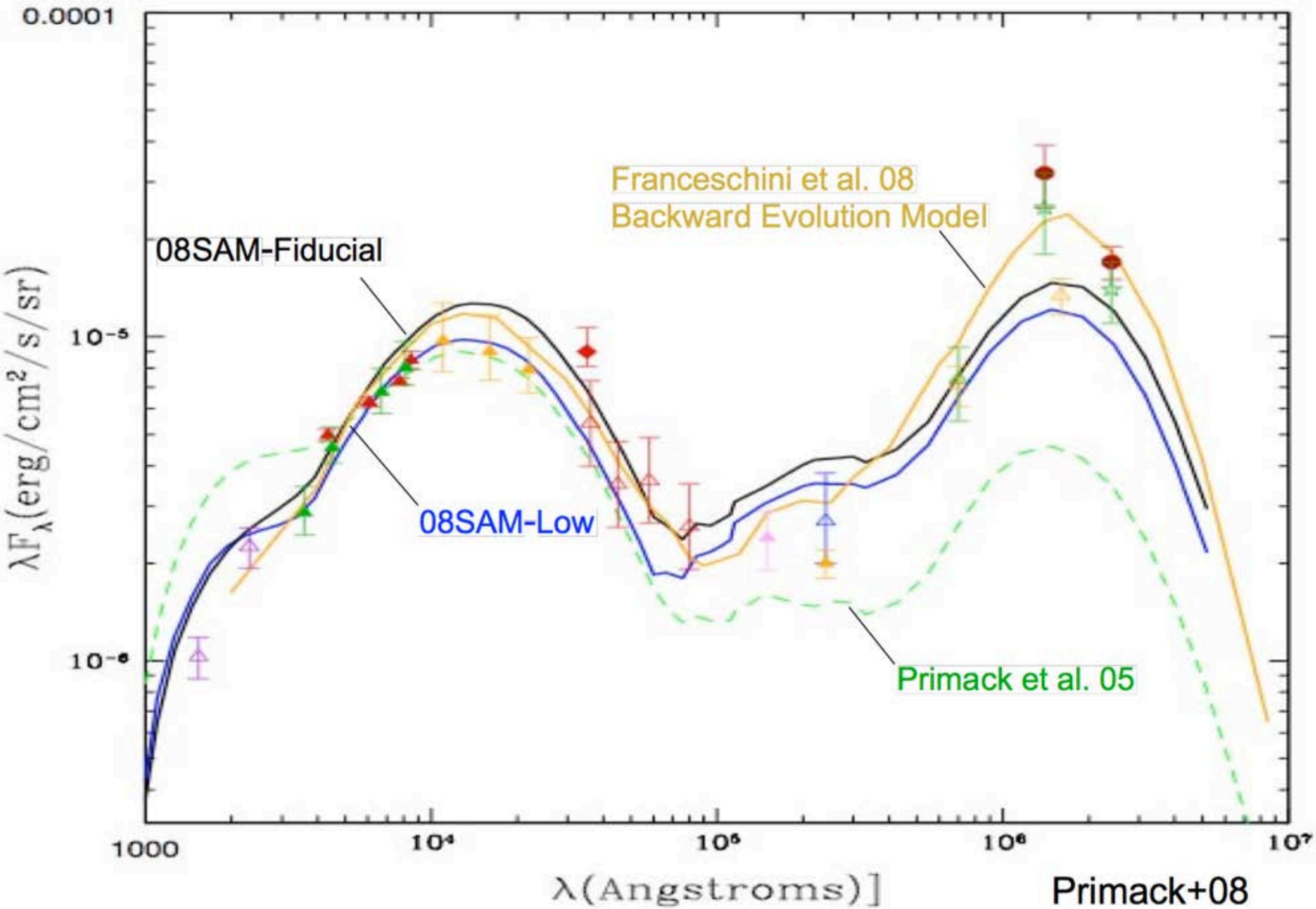
Many notable successes

Luminosity Functions

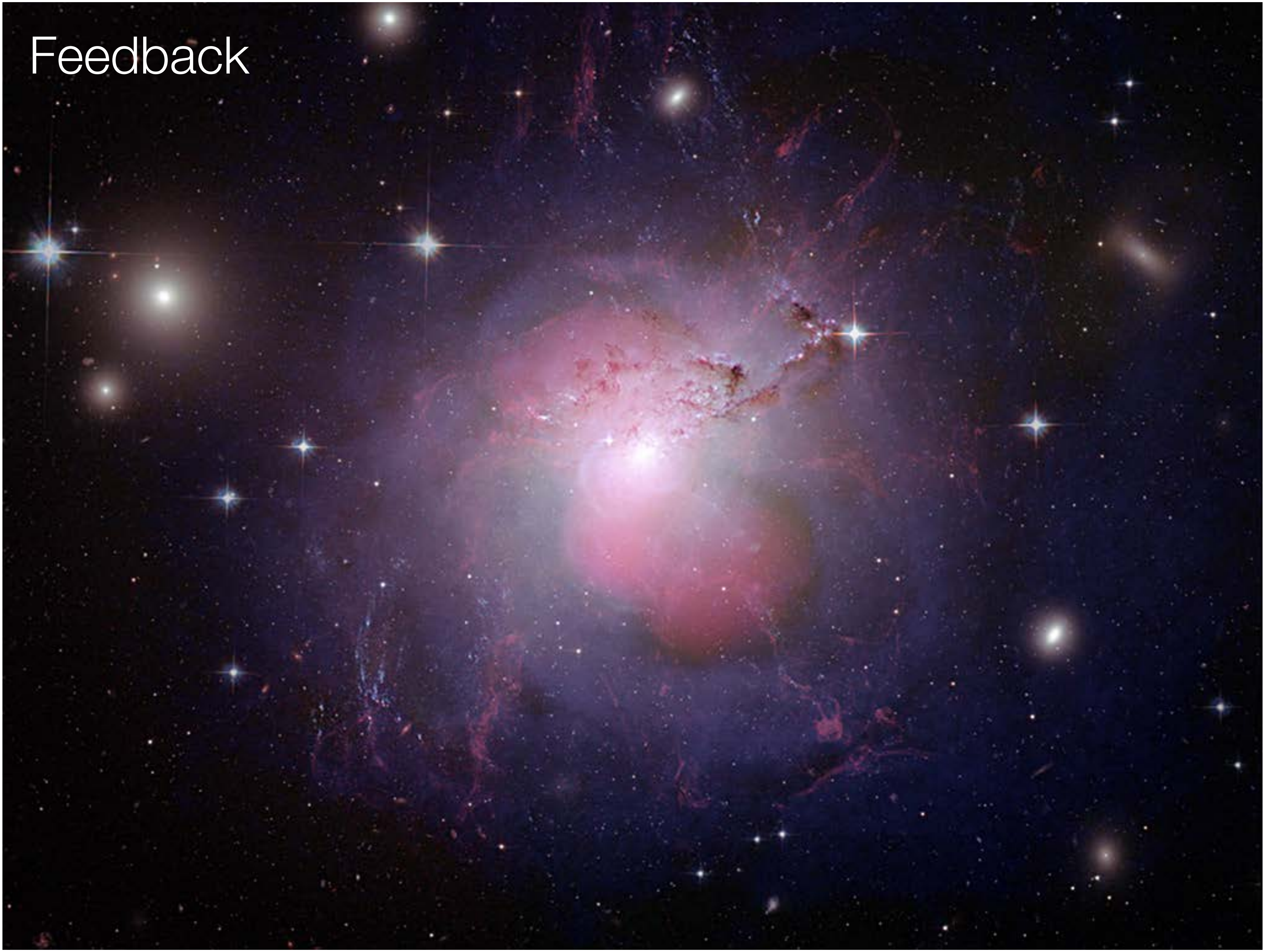


Somerville et al. 2008

Extragalactic Background Light



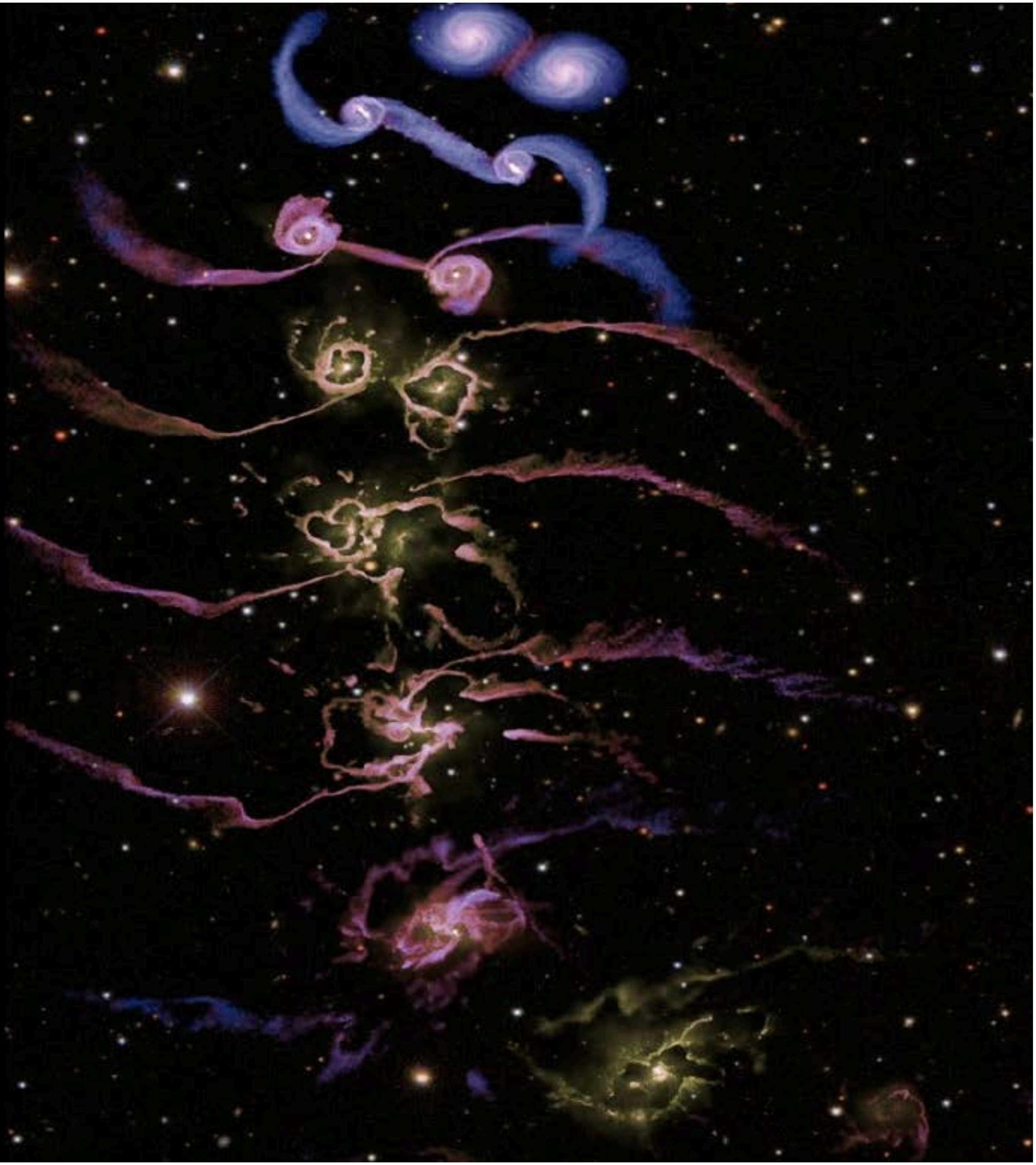
Primack+08


Feedback

SOLUTION:

Feedback during merger-driven growth of black holes in quasars?

Springel, Di Matteo, Hernquist 2005



Show Simon White’s slides of
Darren Croton’s slides here

Main things to remember

- In an expanding universe, the collapse of a spherically symmetric perturbation results in a virialized object whose average density is about 200x the mean density of the Universe at the time the thing collapsed.

- For a given virial mass (from Press-Schechter) you can use this density to work out a characteristic radius R, velocity dispersion ($\sigma^2 \sim GM/R$), and virial Temperature $T \sim GMm_p/(k\ R)$. You can plausibly assume that any gas that participates in the collapse gets heated to this virial temperature and then has to figure out a way to cool. You can work out the cooling time from the temperature and density.

- As the Universe evolves halos cluster together hierarchically to build up larger galaxies. Mergers 'reset the clock' on cooling by heating up the gas.

- Semi-analytical models try to capture some of the physics of virialized gas cooling in shocks turning into stars in halos. Gas cooling depends critically on things like the density profile (since gas cools as density squared), feedback (very uncertain, very important), and merger rates (set via simulations; the "semi" in semi-analytical). Some things, like cold flows, aren't captured by this approach because they manage to get gas into galaxies without shocks heating things up to the virial temperature.