Galaxy Formation: Birth of the Cool

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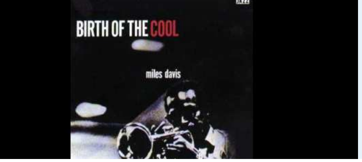
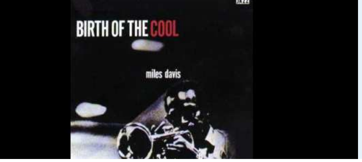


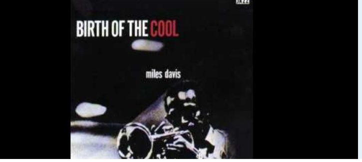
There are four basic elements (Empedocles)

- **Inflation**: produces small-amplitude fluctuations with a nearly scale-invariant spectrum, which grow by gravitational instability.
- **Cold dark matter (CDM)**: the dominant form of matter is non-baryonic, weakly interacting, and pressureless; the mean density of this component, in units of the critical density, is $\Omega_{\rm CDM} \approx 0.25$.
- **Vacuum energy**: e.g., a cosmological constant, or "quintessence", causes the expansion of the universe to accelerate at late times; the energy density of this component is $\Omega_\Lambda = 1 - \Omega_m$, so space is flat.
- **Dissipative gas dynamics**: baryons, with mean density $\Omega_b \approx 0.02h^{-2}$, fall into the dark matter potential wells, dissipate their acquired gravitational energy, settle into cold, dense clumps at the centers of dark matter halos, and form stars.



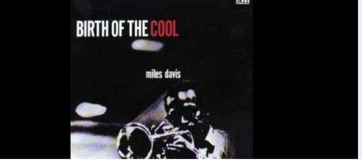
Things are looking Good

- The microwave background anisotropies power spectrum.
- The light-element abundances.
- The Type Ia supernova Hubble diagram.
- The Lyα forest including its origin, flux distribution, line strength distribution, metal lines, damped systems, and helium absorbers both at high and low redshift.
- The abundance of galaxy clusters.
- Large scale structure.
- Many galaxy population properties at low and high redshift, particularly their clustering.



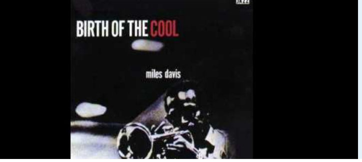
Not all is well

- Why does CDM predict steep central density profiles while observations seem to indicate that dark matter profiles have shallow central density cores?
- Why are too many satellite galaxies predicted compared to observations?
- Why are the predicted sizes of galaxy disks so small?
- Why does the global star formation rate of the Universe drop drastically at low redshift?
- Why is the shape of the dark matter halo mass function so different than the galaxy mass function?
- Why is there an inconsistency between the predicted galaxy luminosity function and the predicted zero point of the Tully-Fisher relation?

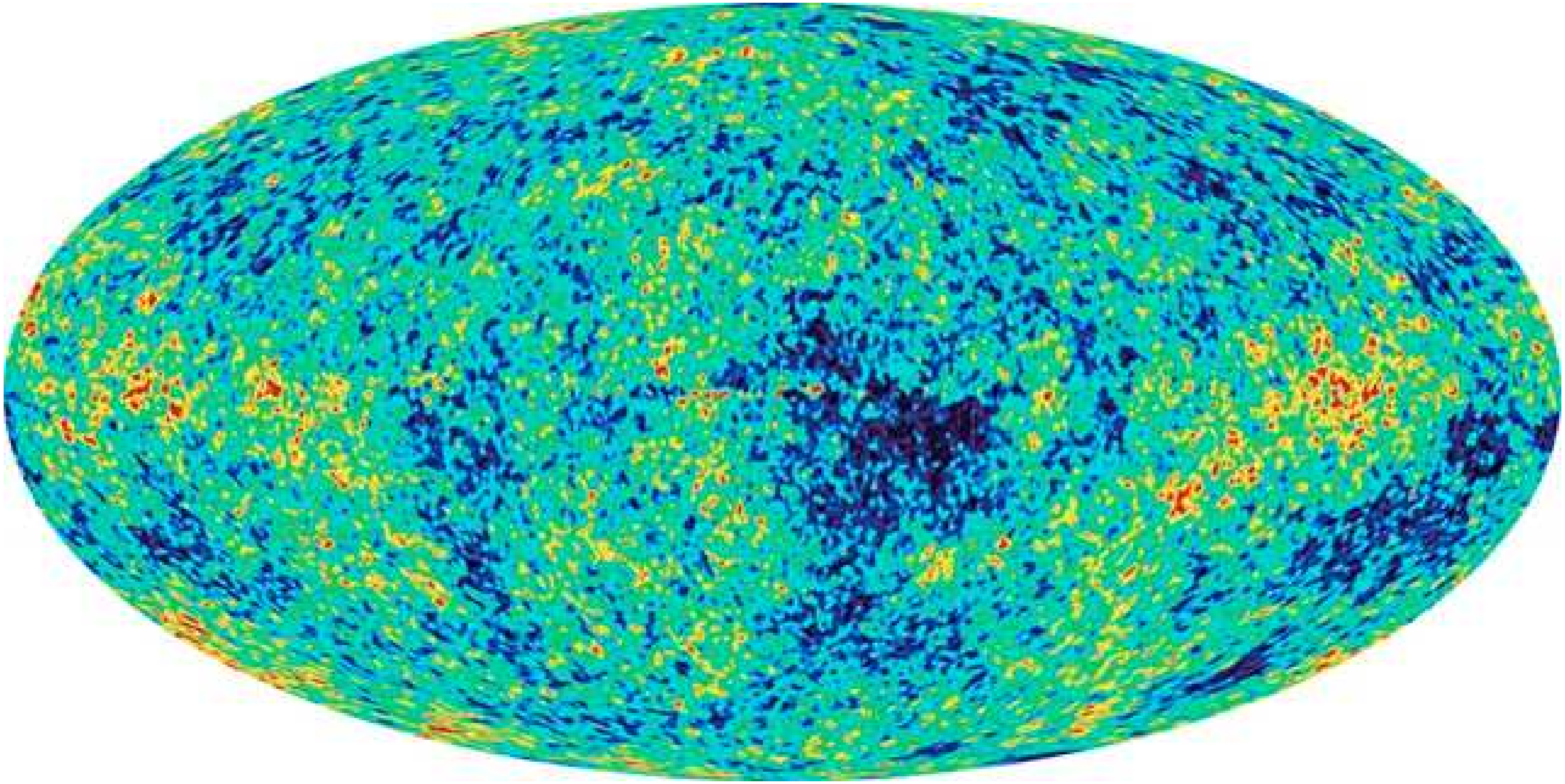


Observed dichotomies in galaxy properties

- Red sequence vs. blue cloud galaxies
- Spheroidal components vs. disk components
  - Total spheroidal mass fractions estimated to range from 40% to 75%.
- Satellite galaxies vs. central galaxies
  - Above a fixed luminosity about 33% of galaxies are satellites.
- Metallicity increasing with mass vs. metallicity constant with mass.
  - SDSS finds transition at $2 \times 10^{10} \mathrm{M}_{\odot}$.
- Active galaxies vs. sedentary galaxies.
- Cool core vs. hot core clusters.



Galaxy Formation for Observers



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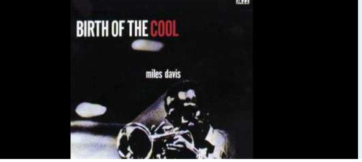

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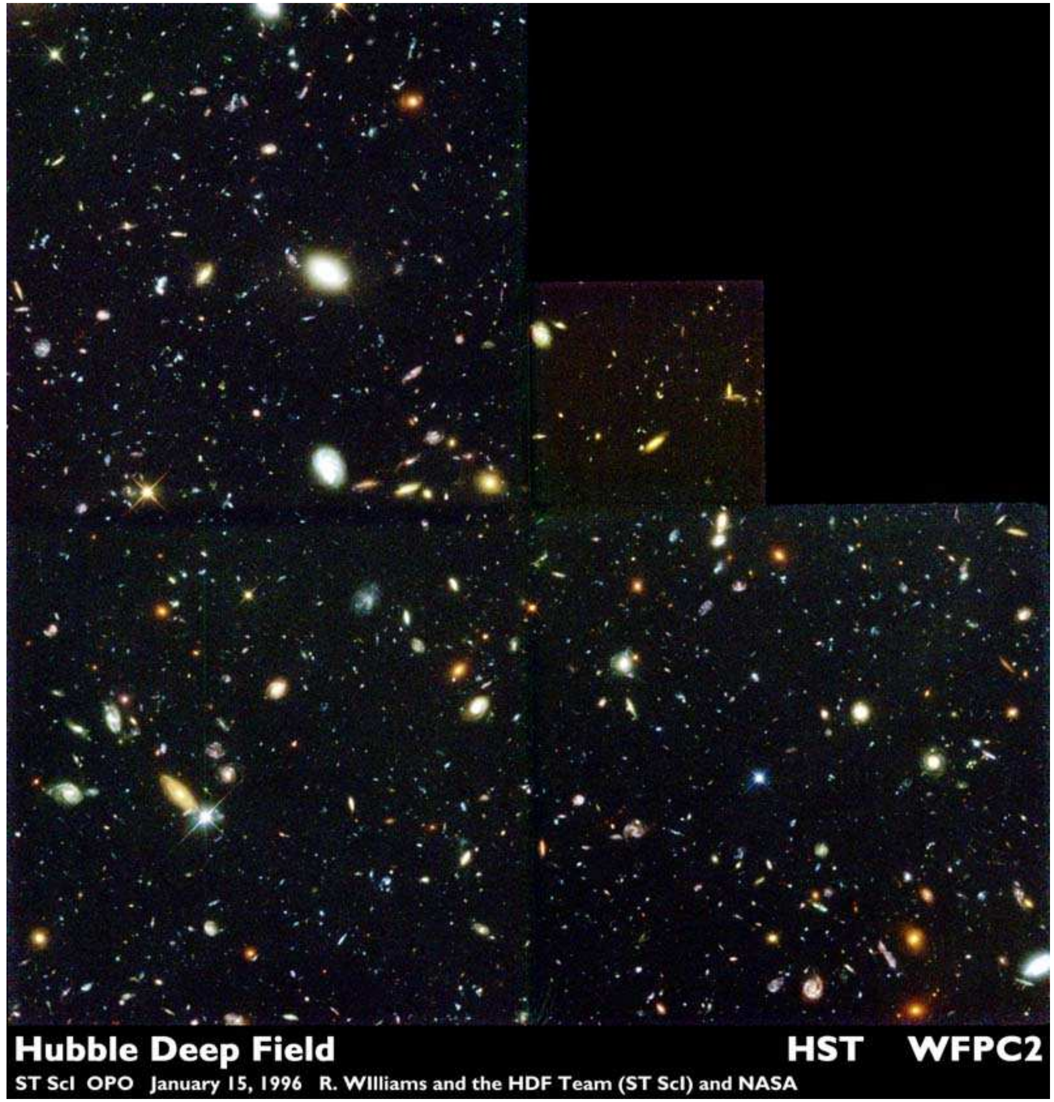

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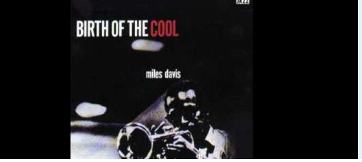

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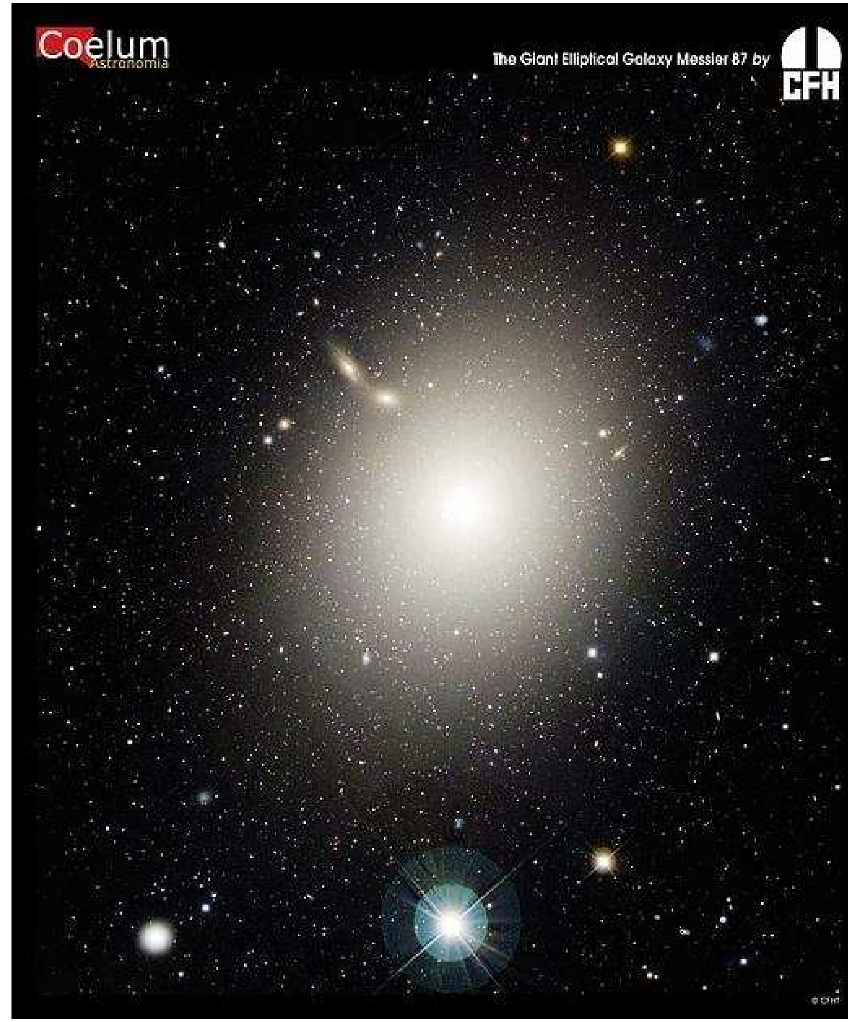

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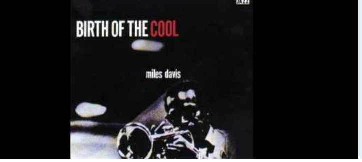
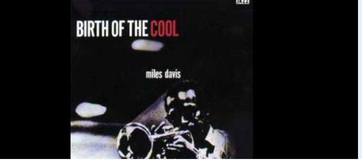


Galaxy Formation for Theorists

- Simulating galaxies is hard.
  - Galaxies are highly nonlinear; a very large dynamic range is necessary.
  - Gas dissipative processes, e.g. cooling, are very important.
  - Star formation and feedback is important but poorly understood.



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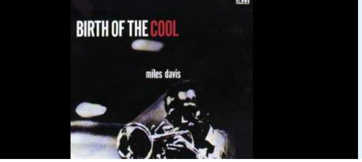
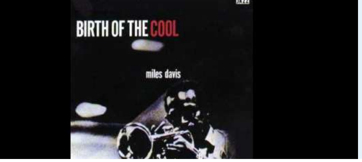
- Two complementary approaches:
  - Semi-Analytic Methods (SAMs): phenomenological.
  - Hydrodynamic simulations: computationally expensive.
    - Compromise between volume and resolution.
    - Star formation (and feedback) still phenomenological.



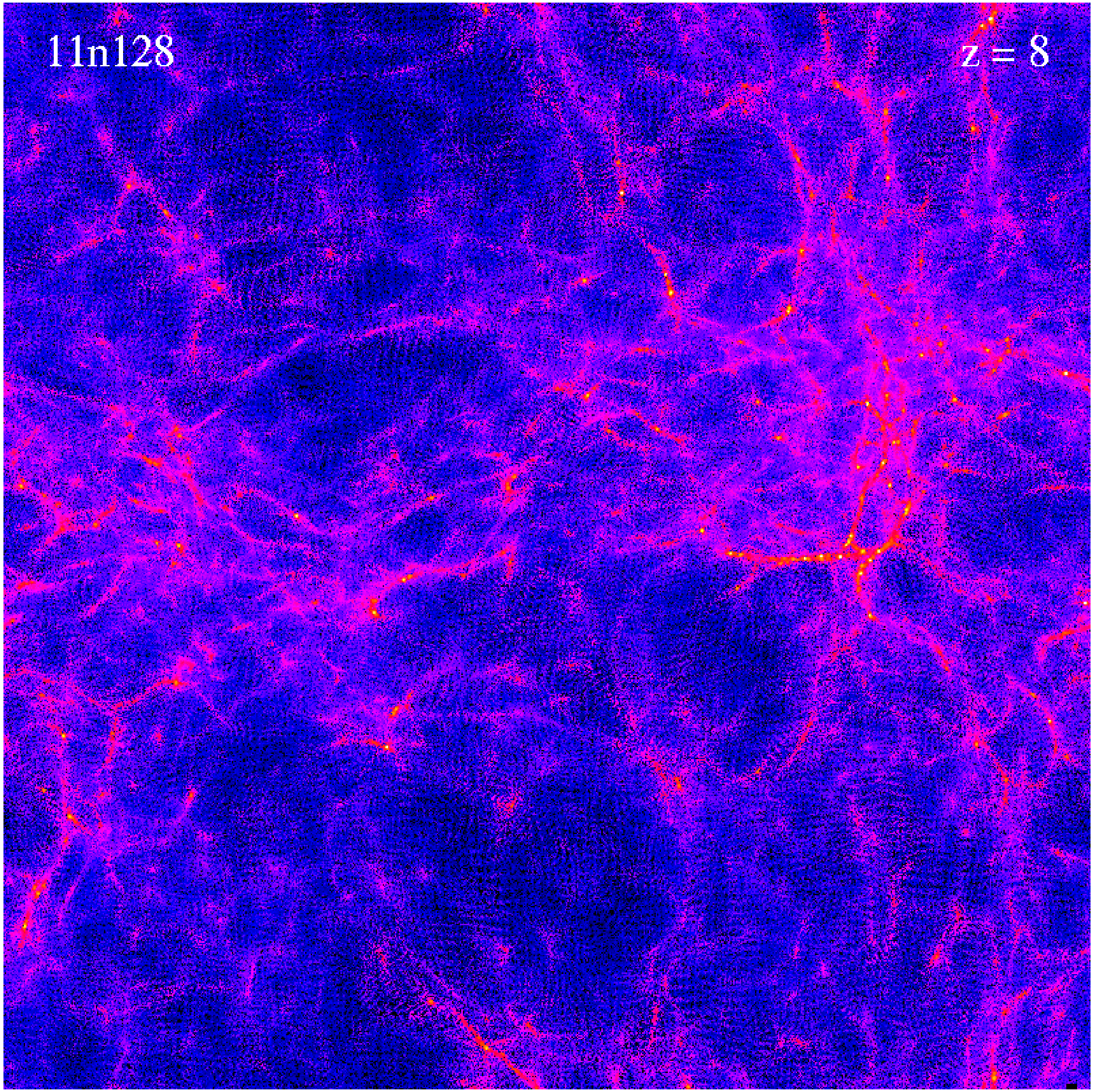
Assumptions, There are Always Assumptions

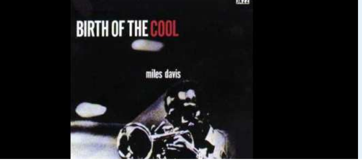
- Both radiative (assuming primordial abundances) and Compton cooling are included. Included the effects of ionizing (UV) background radiation under the optically thin assumption. We use the field computed by Haardt & Madau (1996).
- Star formation and its associated supernova feedback is included heuristically using **local** physical criteria.

- Assume $\Omega = 0.26$, $\Lambda = 0.74$, $H_0 = 71$ km/sec/Mpc, $n = 1.0$ and $\sigma_8 = 0.75$ consistent with WMAP.
- Assumed $\Omega_b = 0.022h^{-2}$, consistent with nucleosynthesis constraints and high redshift D.
- Used cold dark matter (CDM) initial perturbation spectra.

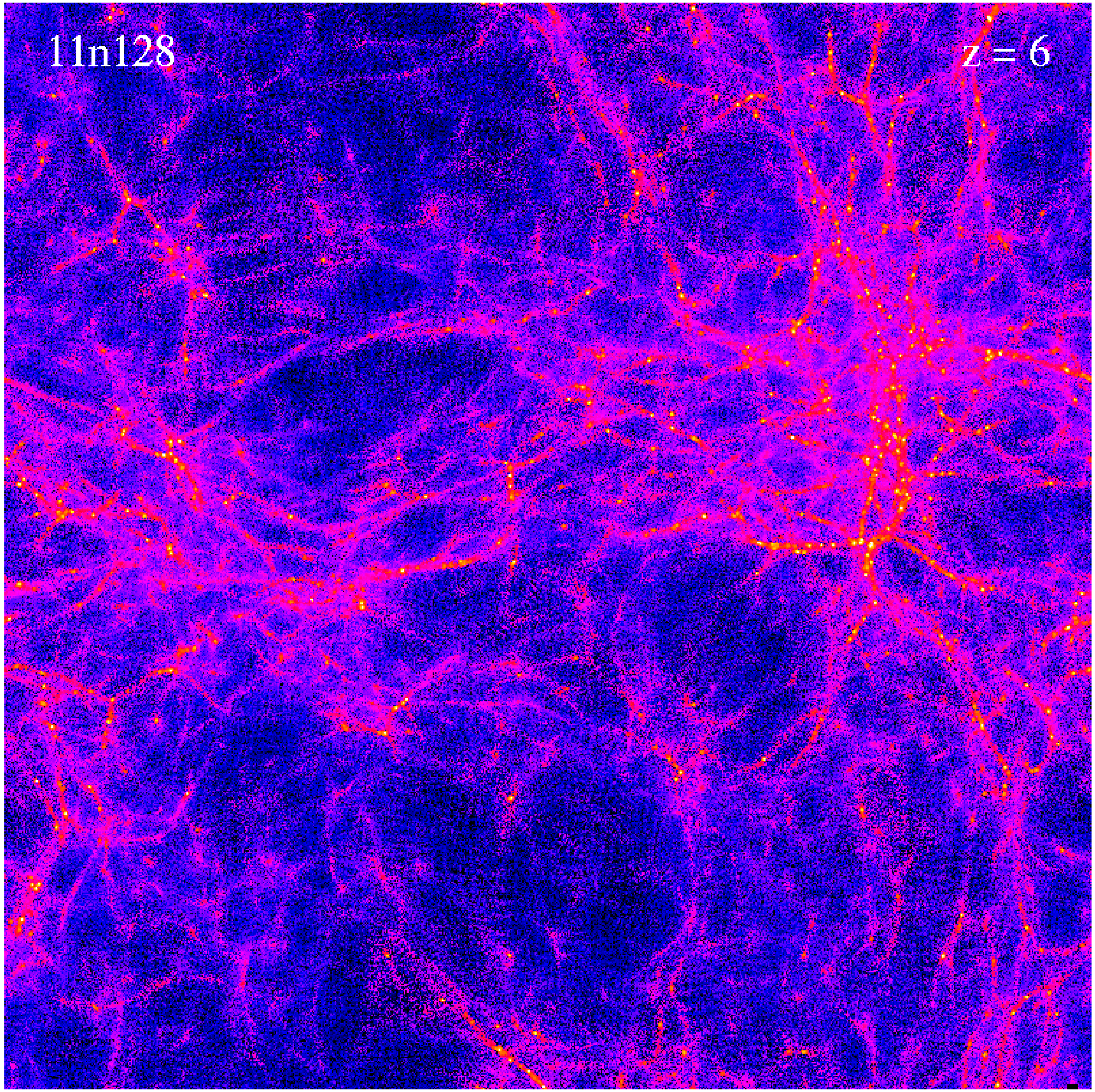


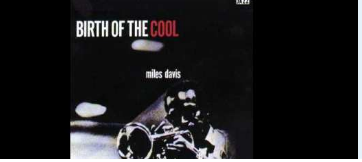
16 Mpc on a side at z=8



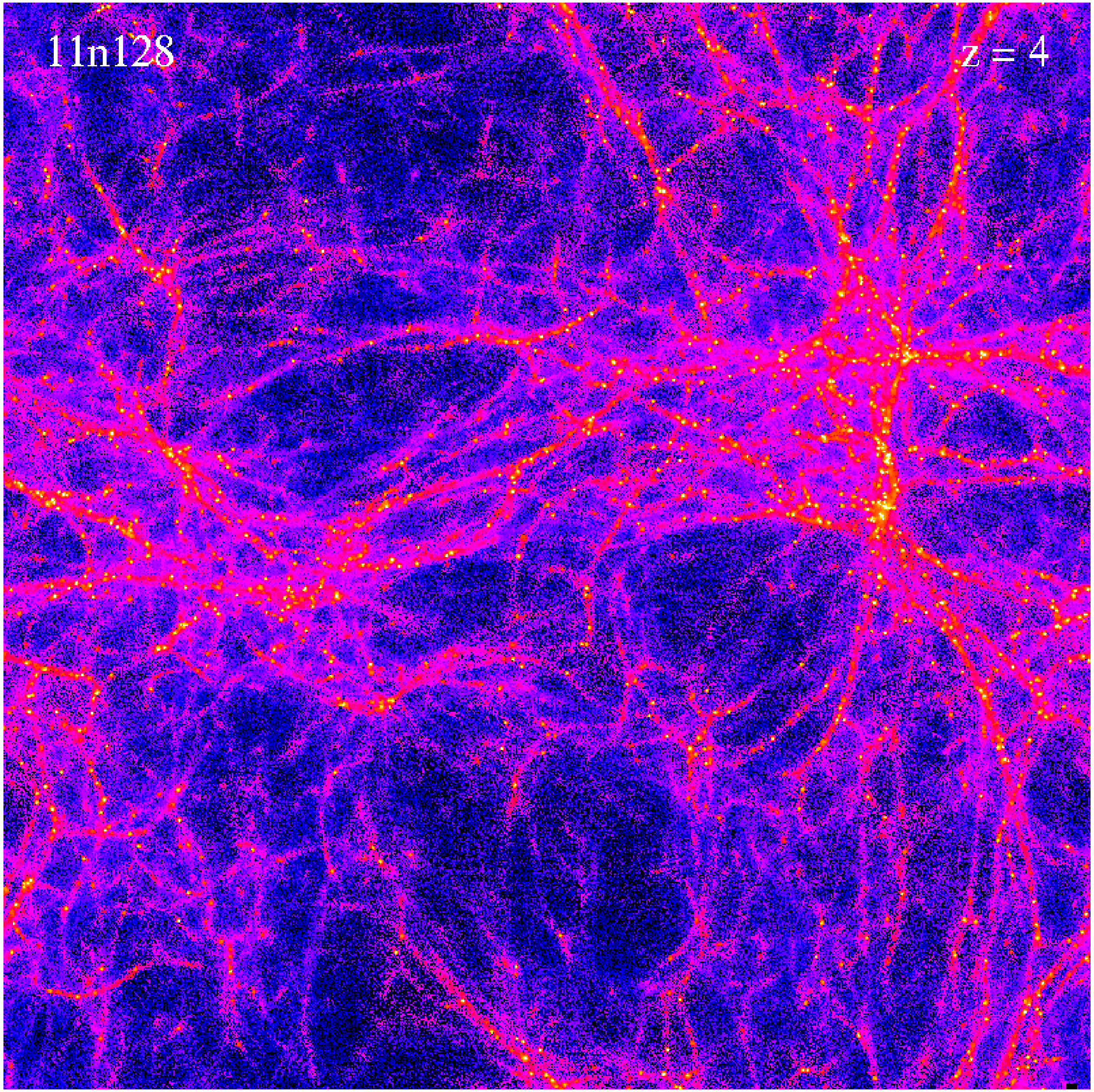


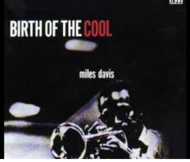
16 Mpc on a side at z=6



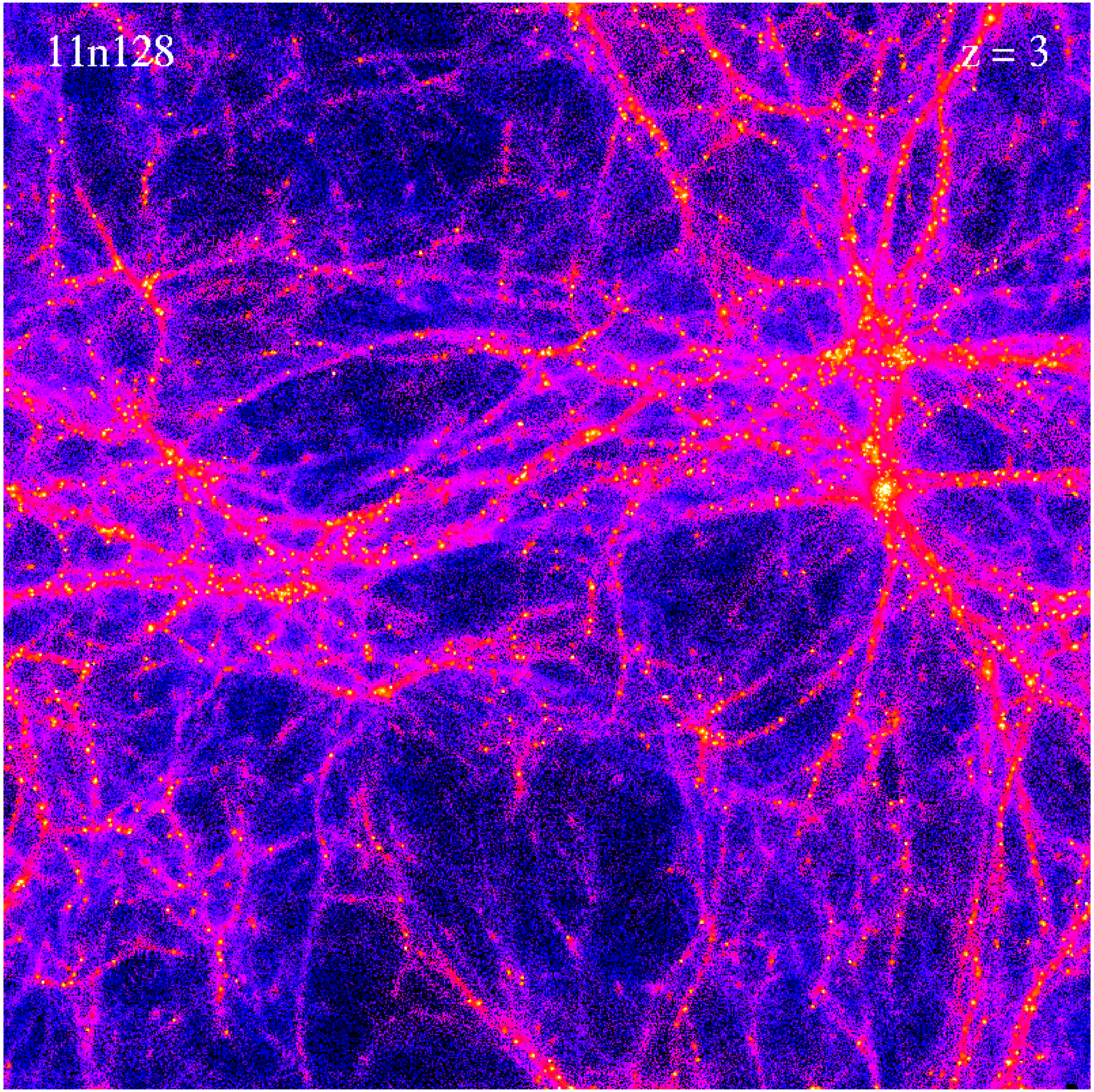


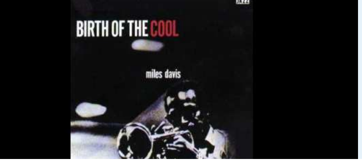
16 Mpc on a side at z=4



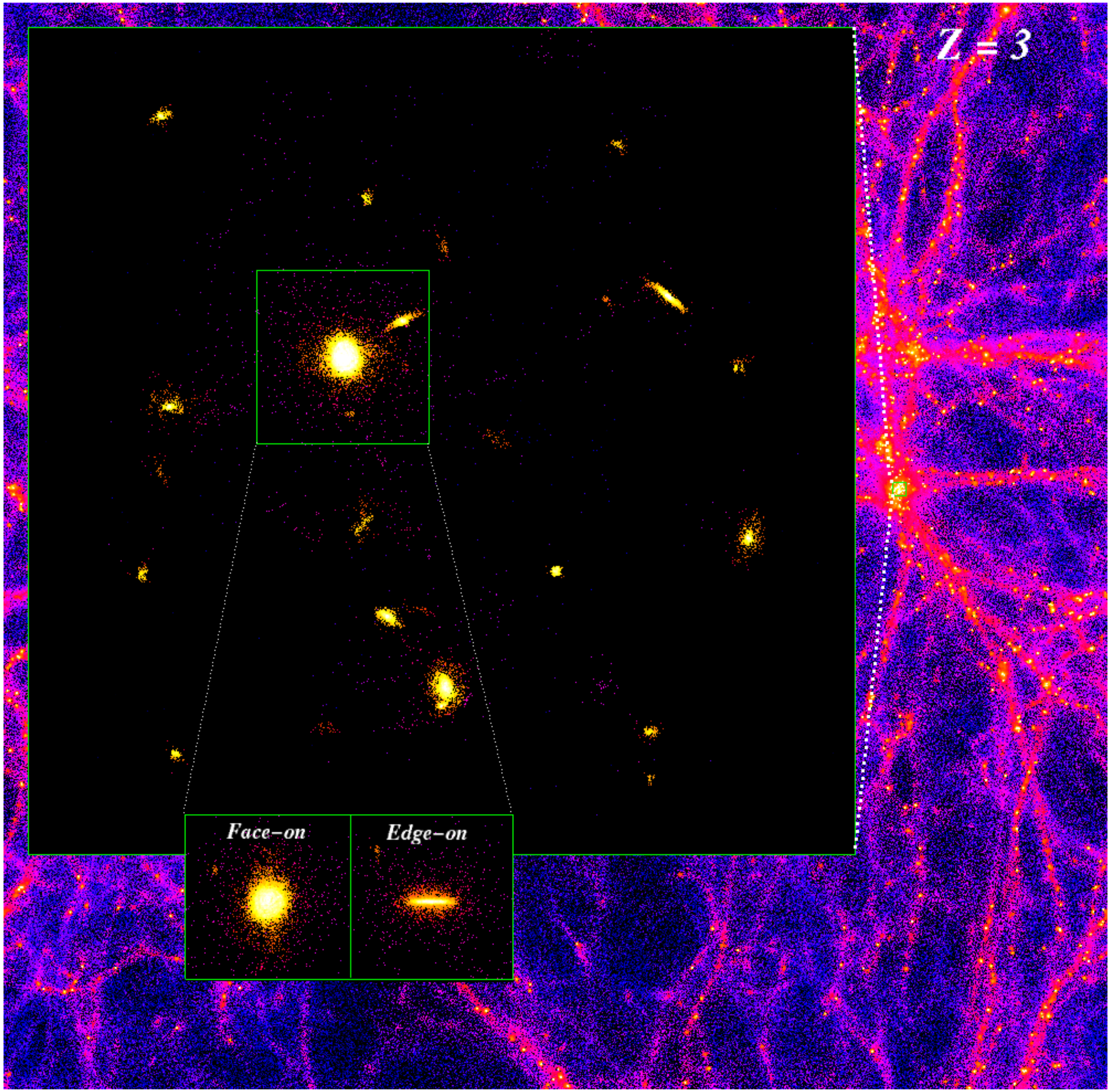


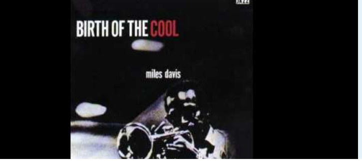
16 Mpc on a side at z=3



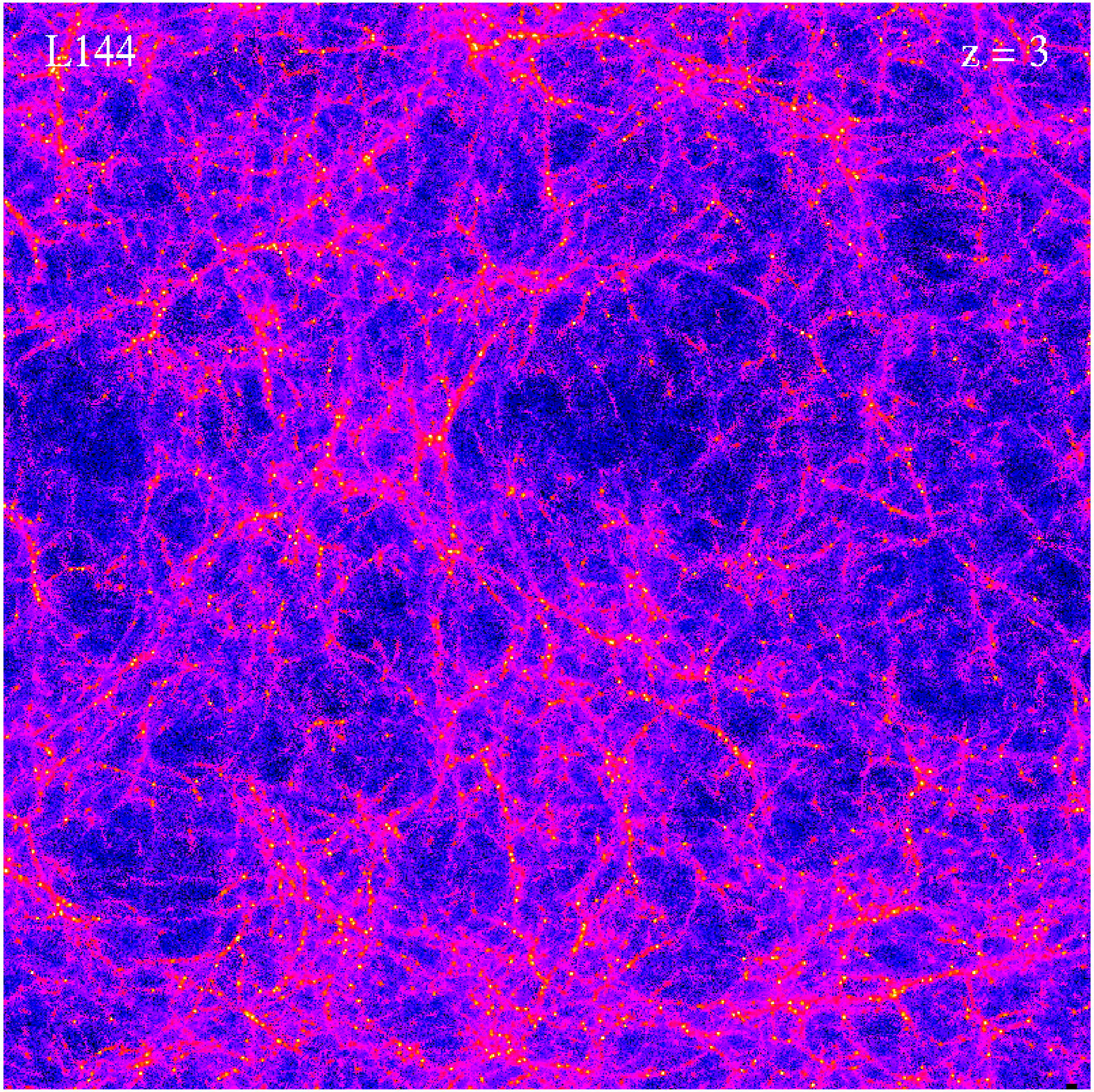


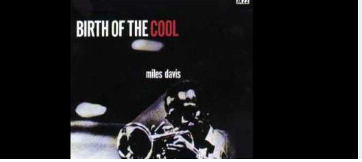
16 Mpc on a side at z=3



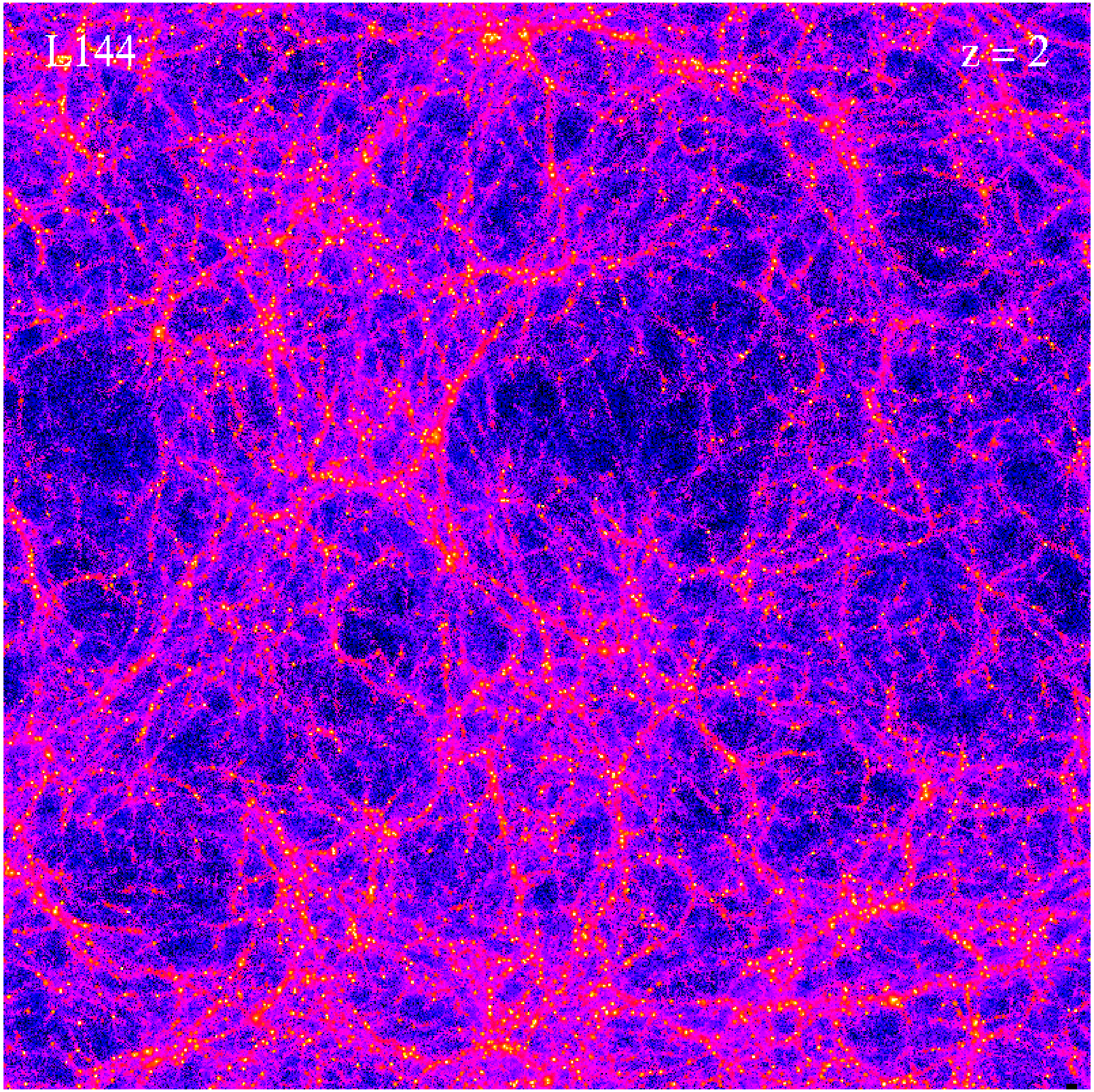


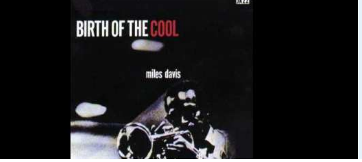
70 Mpc on a side at z=3



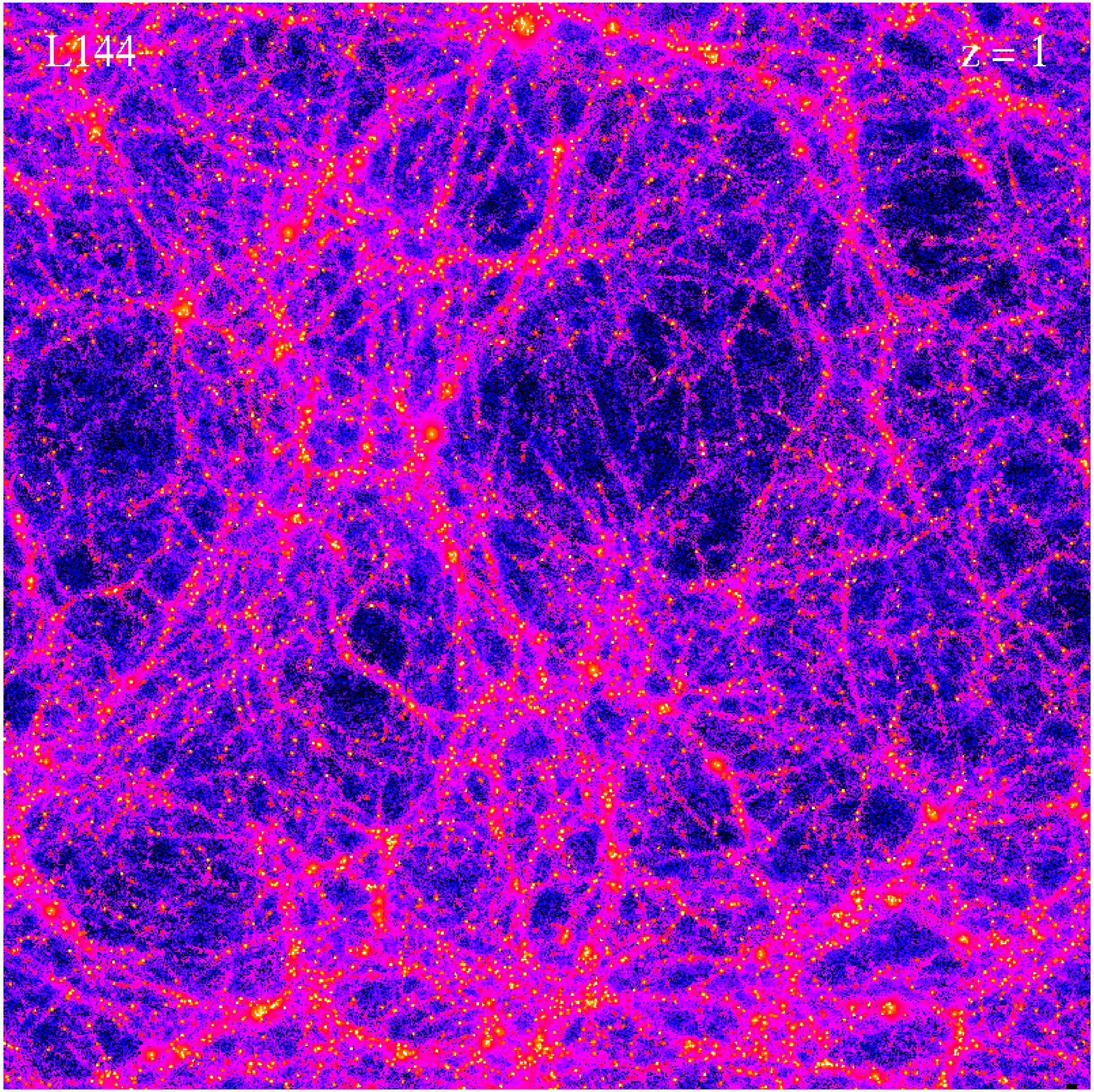


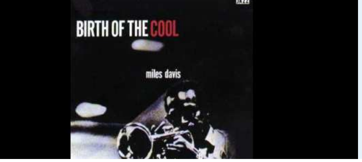
70 Mpc on a side at z=2



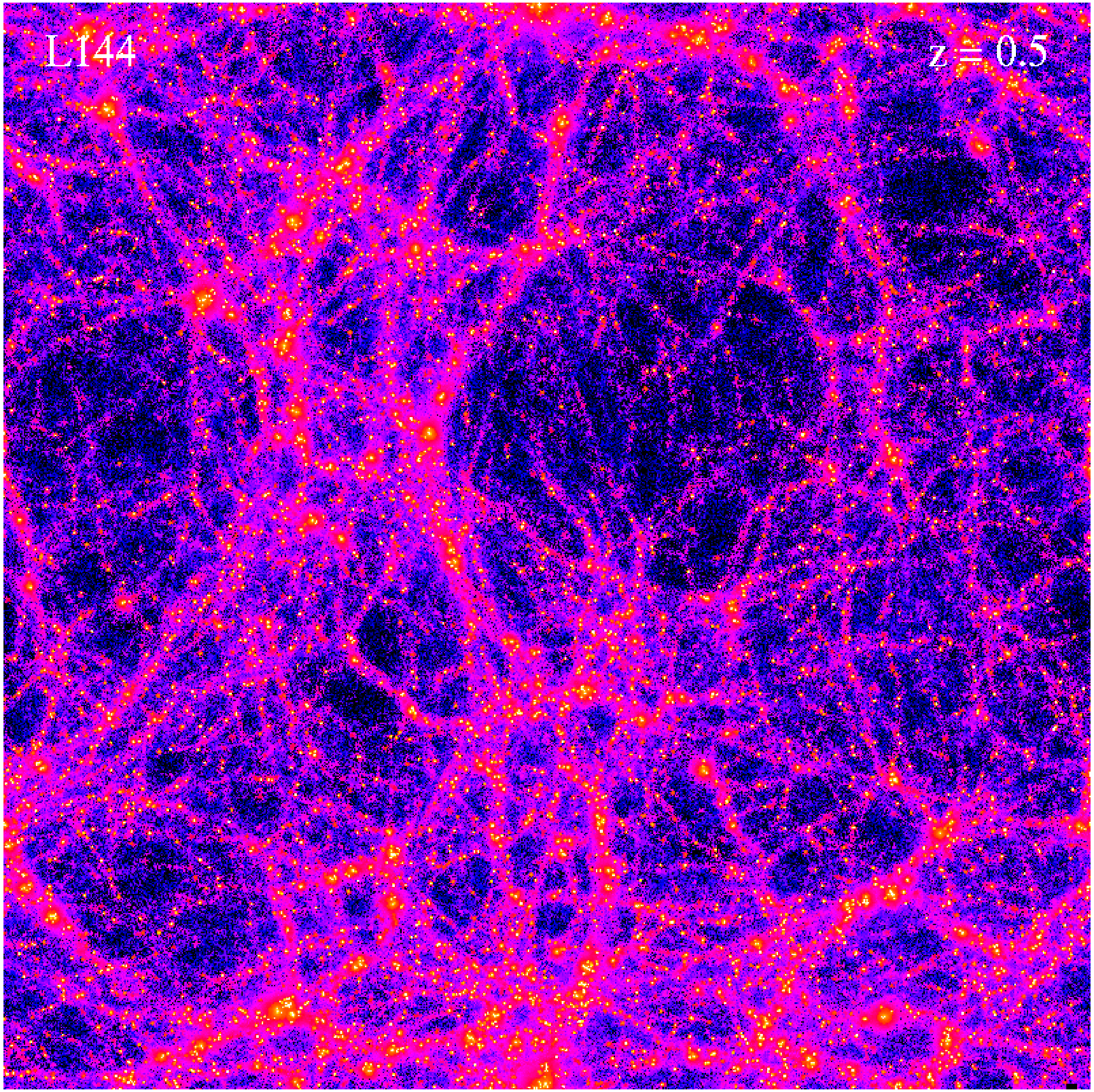


70 Mpc on a side at z=1

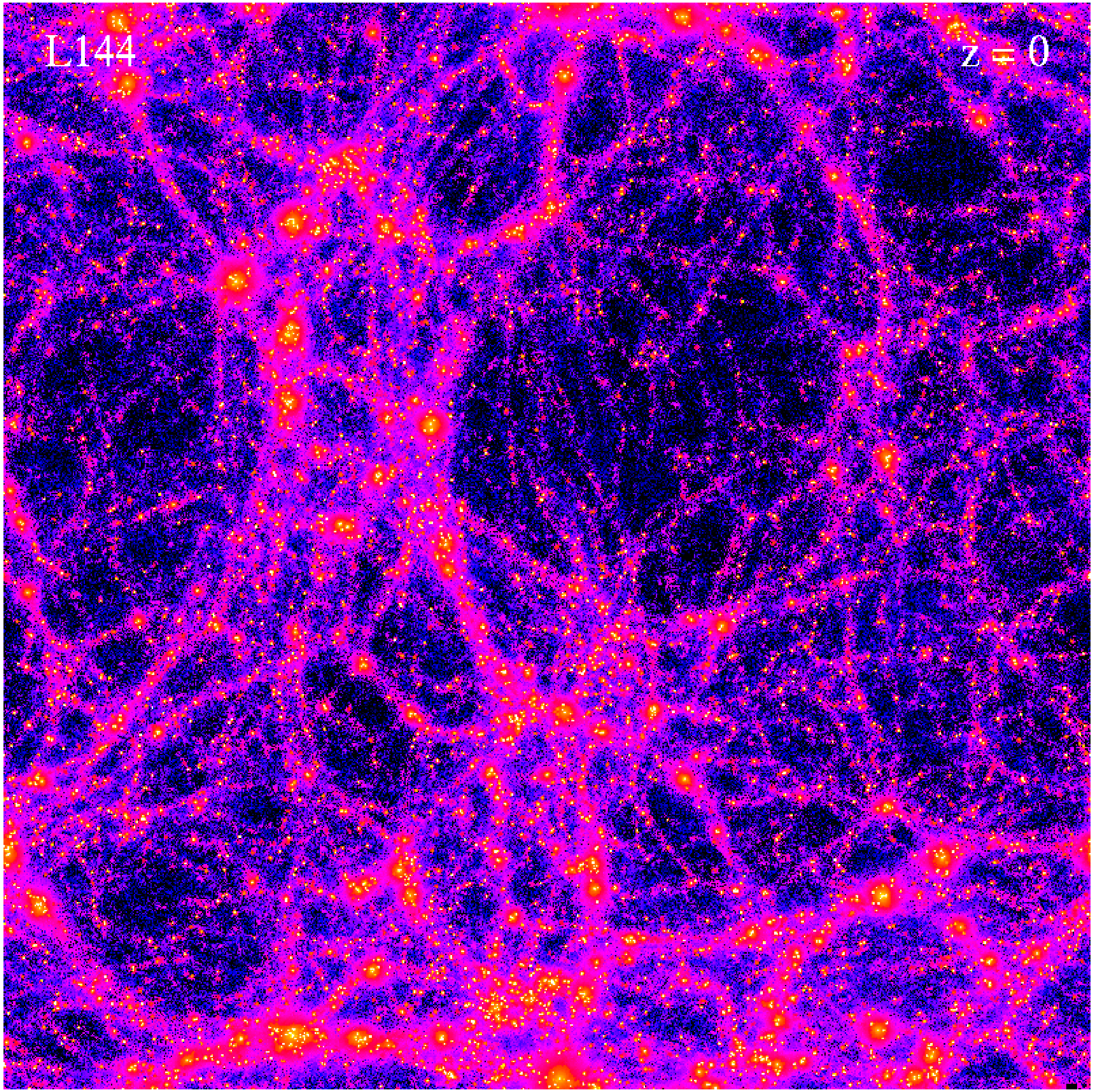


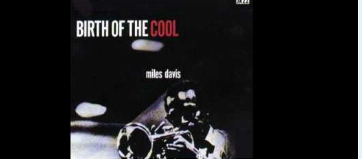


70 Mpc on a side at z=0.5

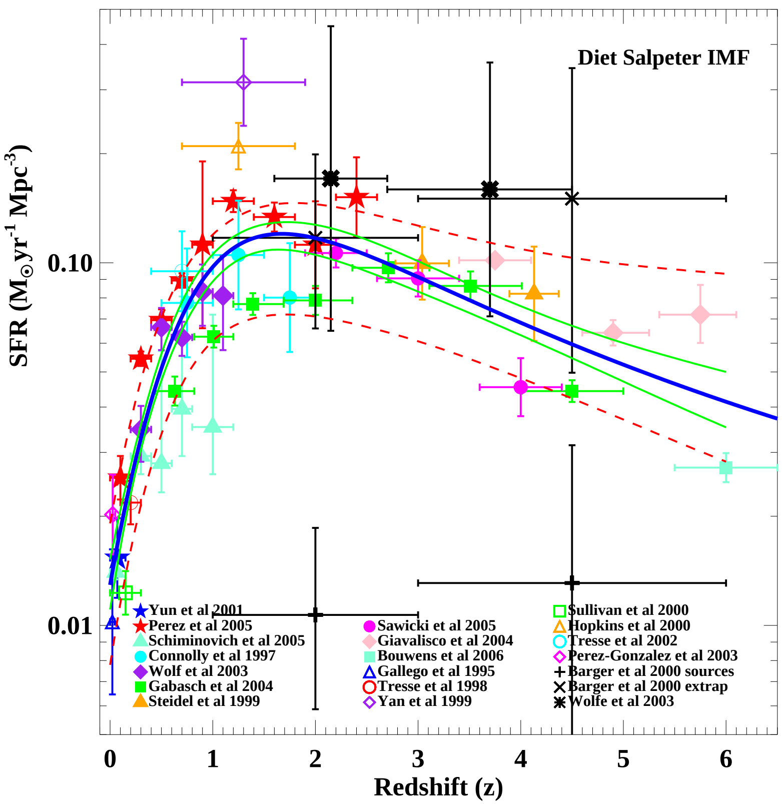


70 Mpc on a side at z=0

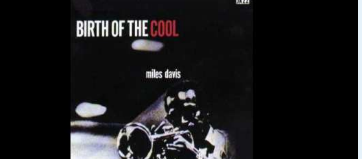




Problem Redux



- Why does the average star formation rate of the Universe decline rapidly towards low redshift?



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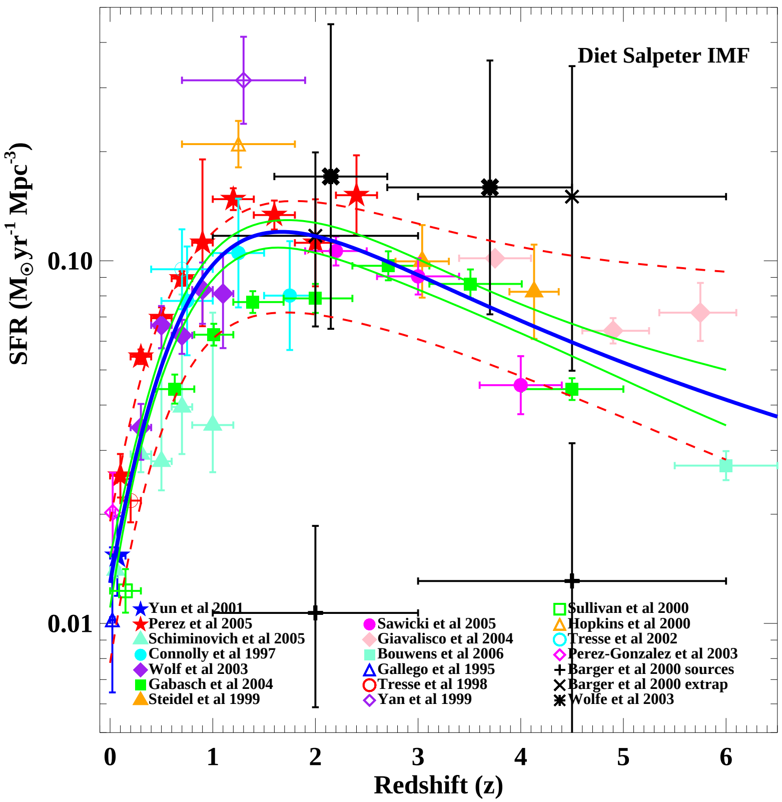
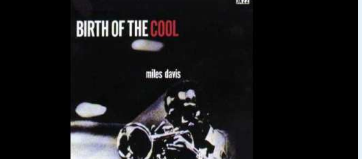
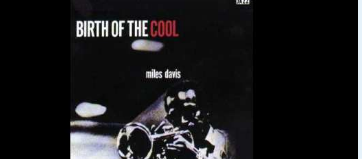


- Why does the average star formation rate of the Universe decline rapidly towards low redshift?
  - Why don’t elliptical galaxies have disks?
  - What is the origin of the density-morphology relation?



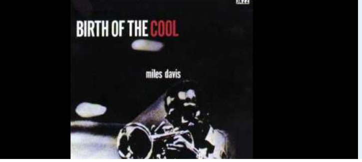
Galaxy Formation Orthodoxy

- Gas falling into a dark matter potential well is shock heated to approximately the halo virial temperature.
- Gas in the dense, inner regions of this shock heated halo radiates its thermal energy, settles into a centrifugally supported disk, and forms stars.
- Mergers of disks can scatter stars onto disordered orbits, producing spheroidal systems, which may regrow disks if they experience subsequent gas accretion.
- Merging dominates over smooth accretion in hierarchical models of galaxy formation.



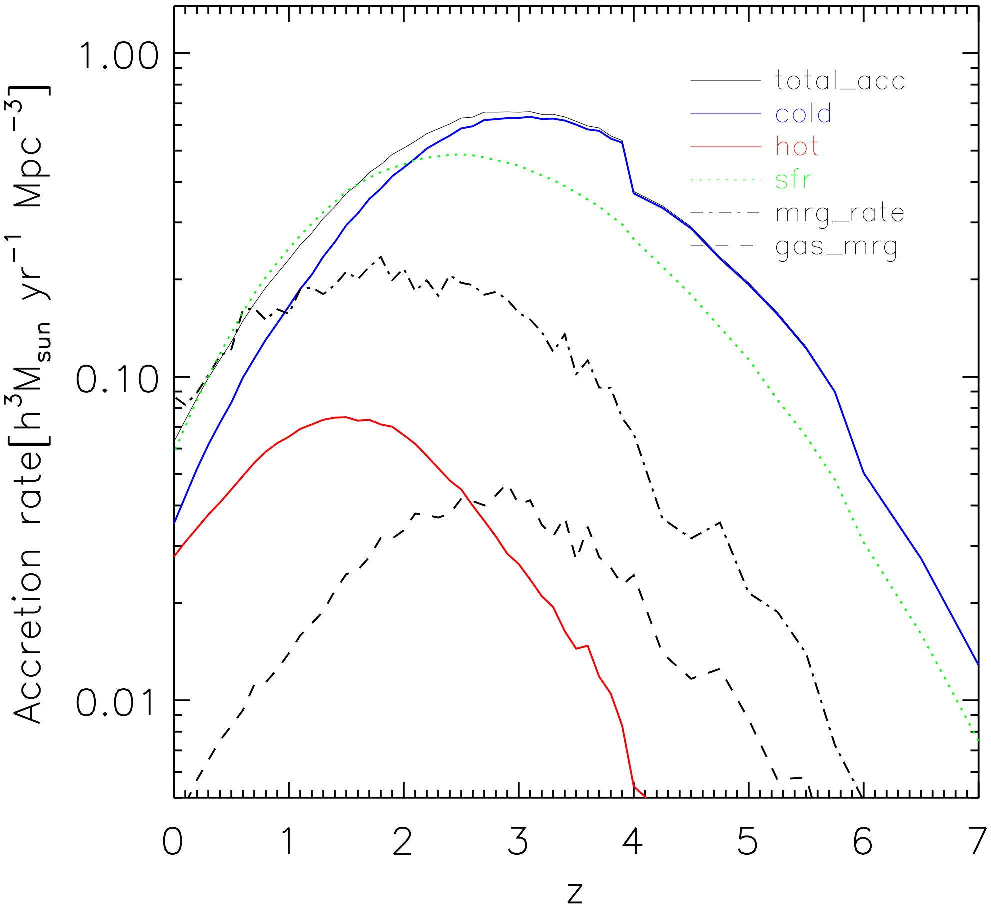
There are two of ways a galaxy can grow in this world . . .

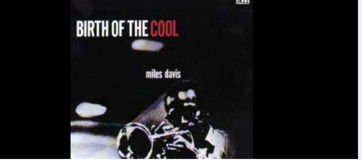
- Merging with smaller galaxies.
  - Can add both stars and gas.
- Smooth accretion of gas.



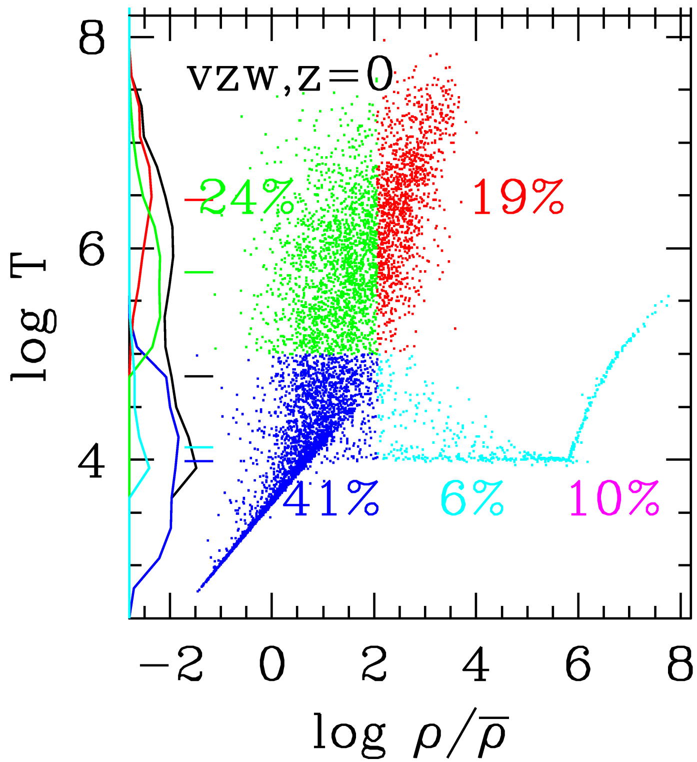
There are two of ways a galaxy can grow in this world . . .

- Merging with smaller galaxies.
  - Can add both stars and gas.
- Smooth accretion of gas.
  - Dominates gas accretion at all redshifts.
  - Dominates total accretion at $z > 1$.

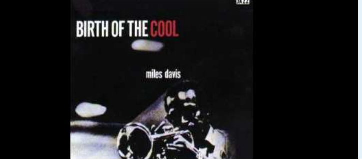




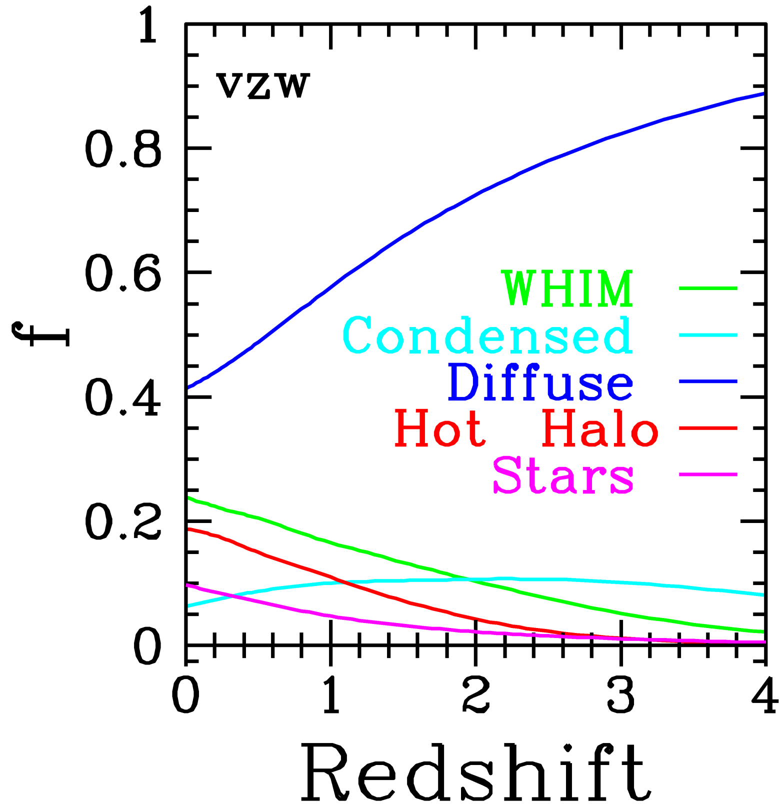
Where’s the Gas?



- Shock heated halo gas with $\rho/\bar{\rho} > 100$ and $T > 10^5$ K.
- WHIM gas with $\rho/\bar{\rho} < 100$ and $T > 10^5$ K.
- Radiatively cooled, dense gas with $\rho/\bar{\rho} \geq 100$ and $T \lesssim 10^5$ K.
- Low density, highly ionized gas with $\rho/\bar{\rho} \leq 100$ and $T \leq 10^5$ K.

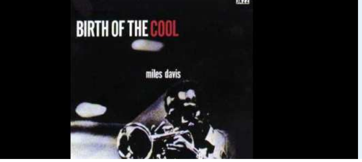


Where was the Gas?

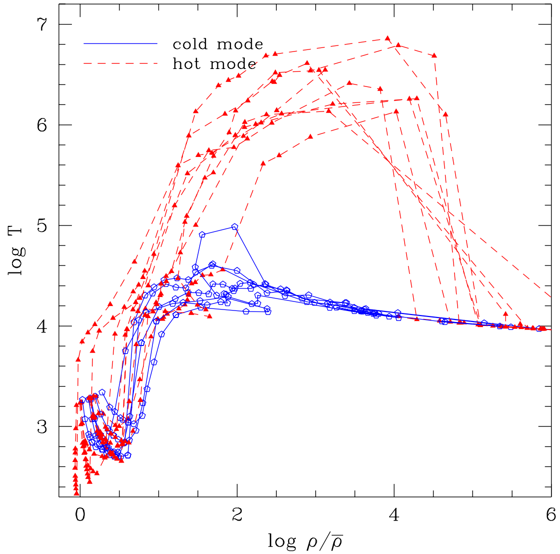


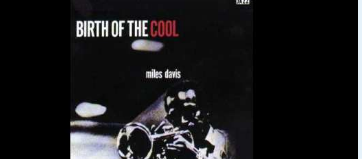
- Diffuse gas dominates at all redshifts.
- Condensed phase almost constant with time.
- Other phases grow with time at the expense of the diffuse phase.

There are two types of smooth accretion in this world . . .



- Hot: Classic (Rees & Ostriker, White & Rees)
  - Gas is heated to the virial temperature in an accretion shock at the virial radius.
  - The gas accretion rate is determined by the cooling time from this high temperature.





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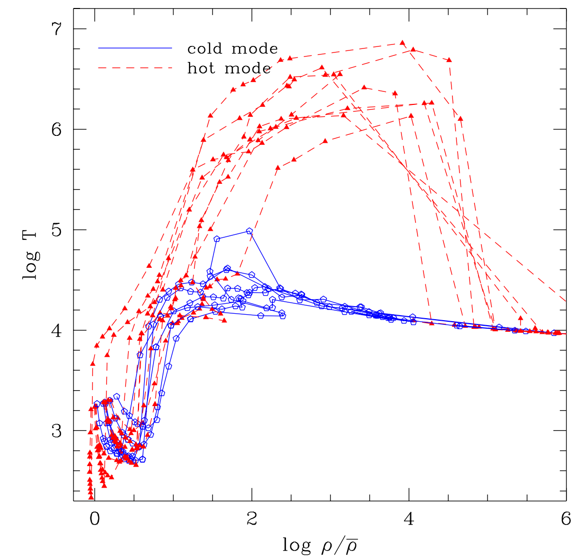
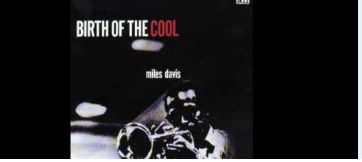
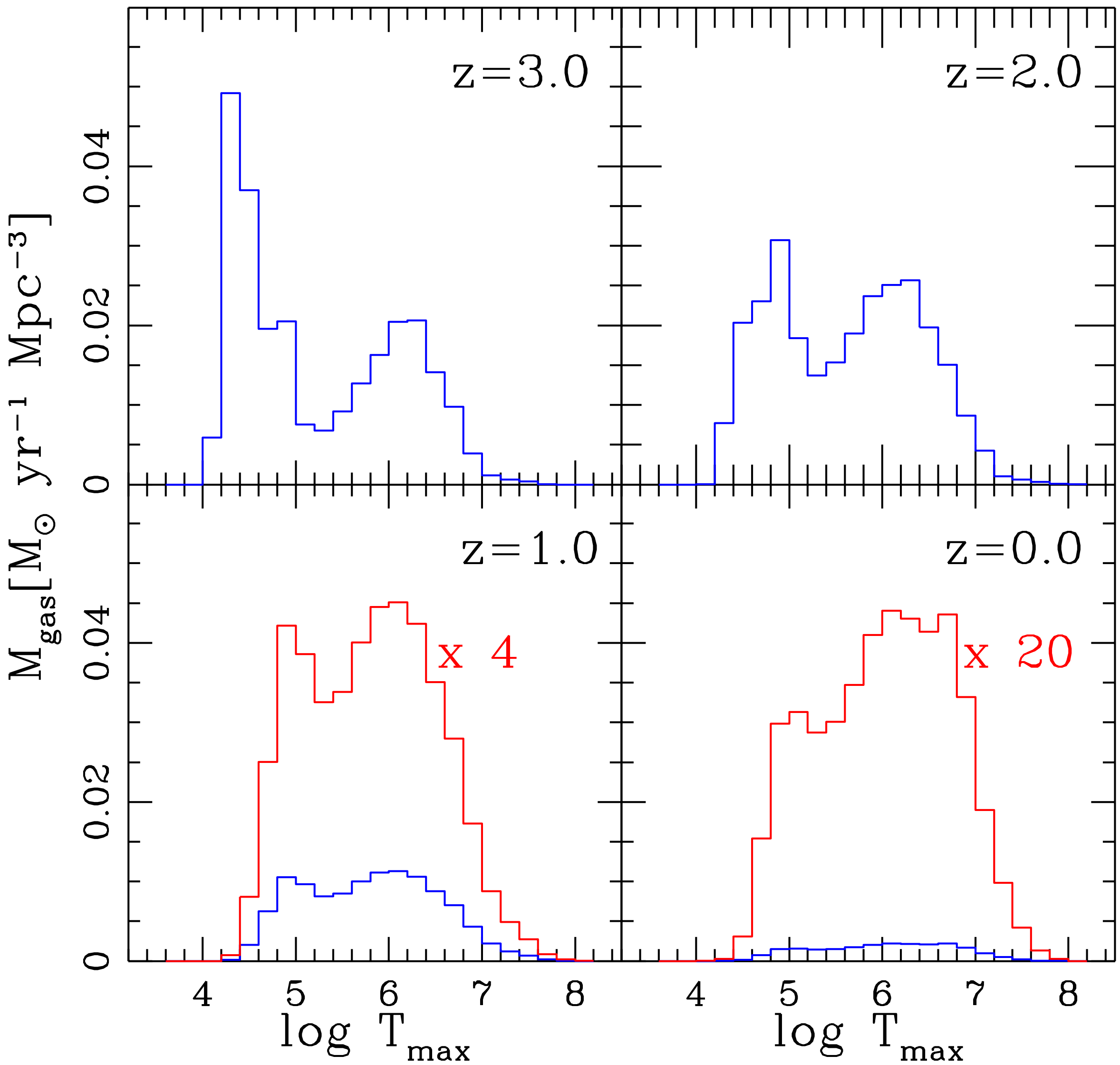


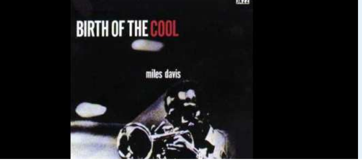
- Cold: Modern (Keres et al, Birnboim & Dekel)
  - The gas is never heated but remains cold as it enters the galaxy.
  - The gas accretion rate is determined by large scale dynamical flows.



There are two types of smooth accretion in this world ...

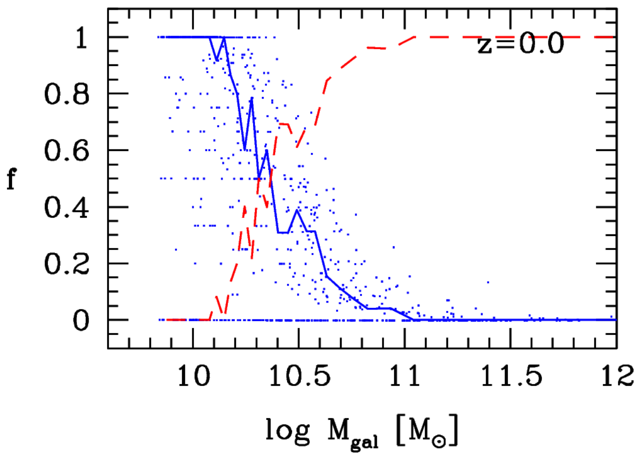
- Distribution of T_{max} is clearly bimodal.
- Cold mode: 10^4–10^5K
- Hot mode: 10^6–10^7K, typical of T_{vir}.
- Local minimum at $\sim 2.5 \times 10^5$K.

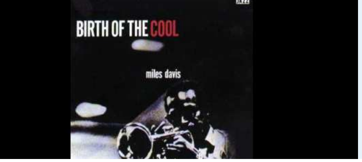




There are two types of smooth accretion in this world . . .

- At low z cold mode dominates in low mass galaxies and hot mode dominates in high mass galaxies.
- Transition between modes at $\sim 2 \times 10^{10} M_{\odot}$; same mass where SDSS finds a marked shift in galaxy properties.
- At high z cold mode dominates at all masses.





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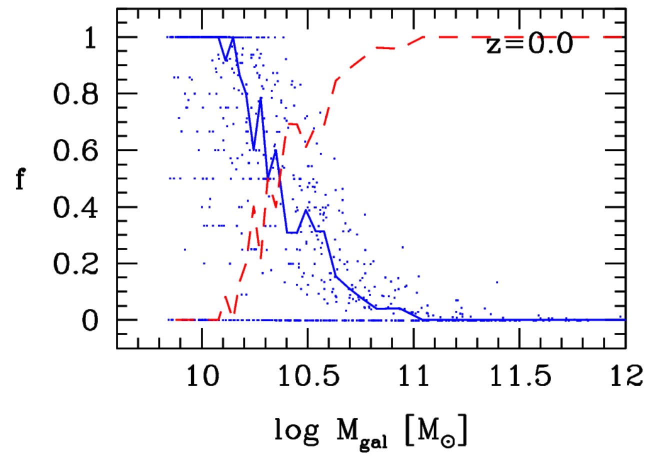
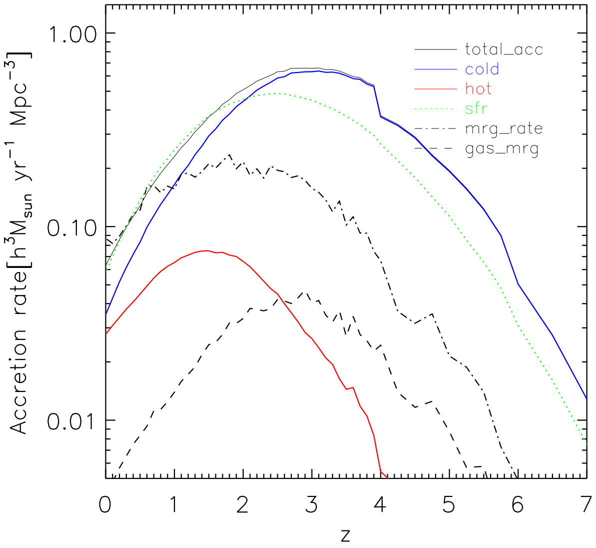
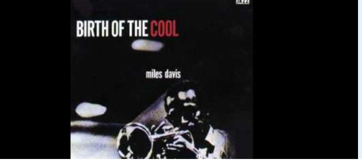
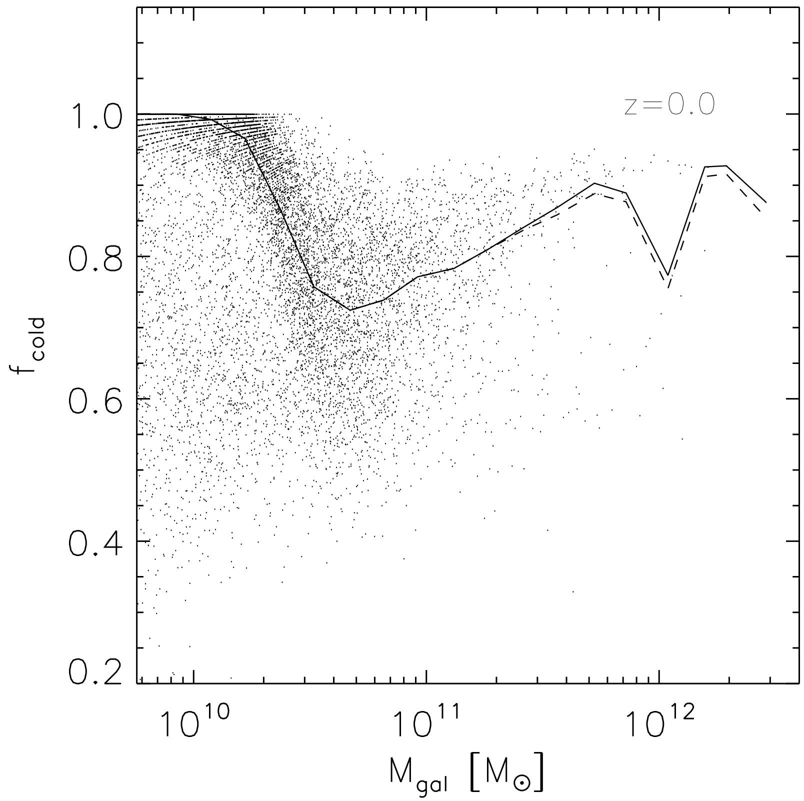
- Cold mode dominates at all z.
- Global SFR follows smooth accretion.



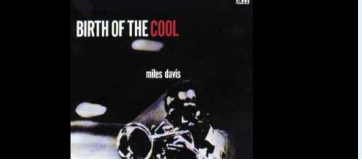




Cold mode rules, hot mode's for fools

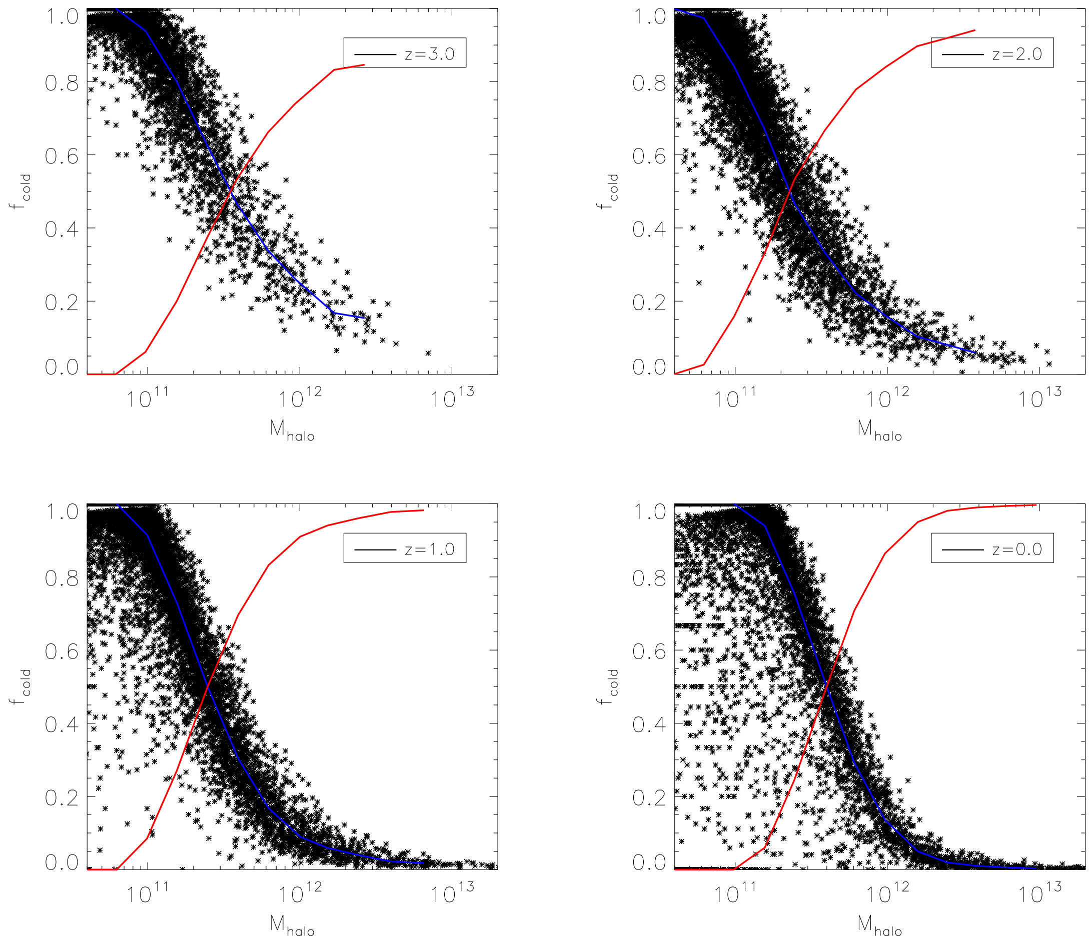


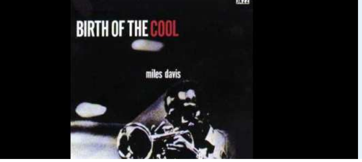
- Cold mode dominates total accreted mass at all galaxy masses.
- Hot mode is only a detail of galaxy formation.



There are two types of halo gas in this world . . .

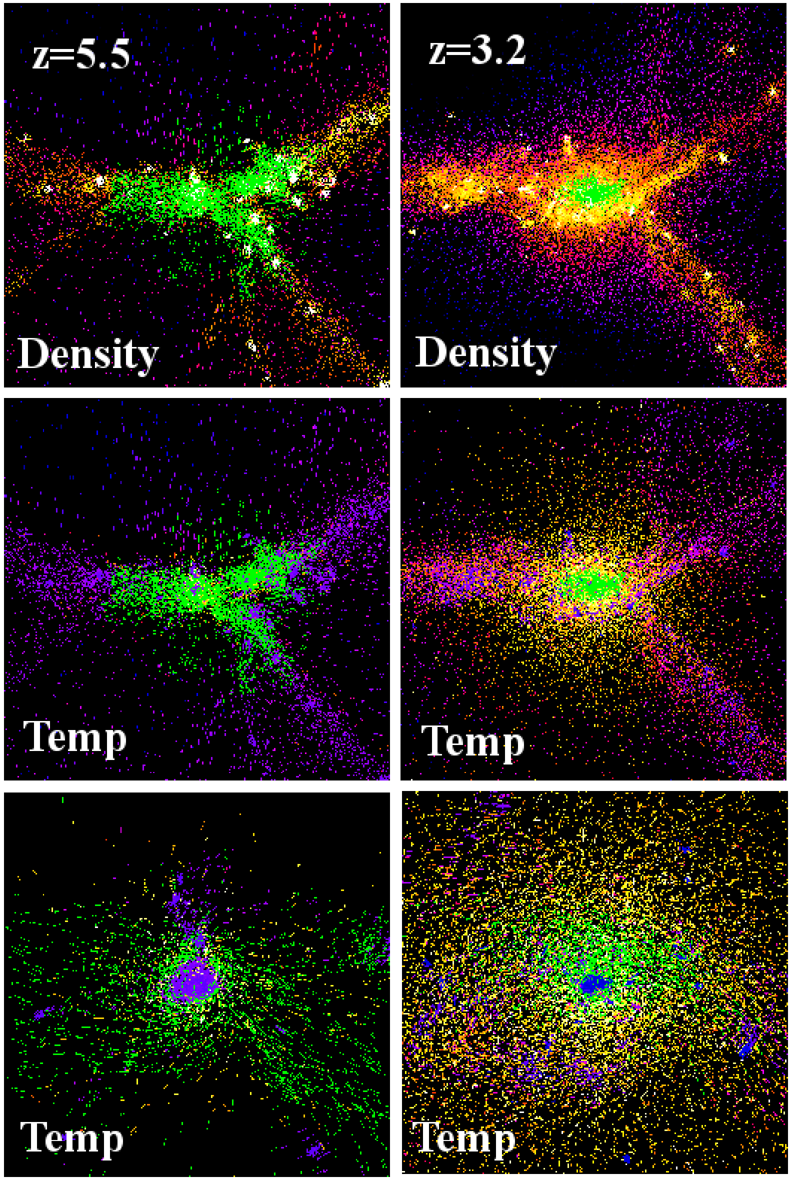
- Halo mass transition at $\sim 3 \times 10^{11} M_\odot$
- Almost no redshift dependence.
- At low z:
  - Cold mode $\Rightarrow$ cold halo gas
  - Hot mode $\Rightarrow$hot halo gas.
- At high z cold flows penetrate hot halo gas.

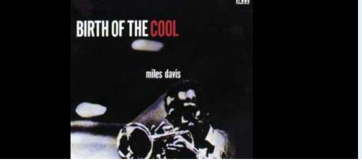




There are two accretion geometries in this world

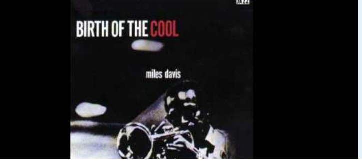
- Green: accreting gas
- Left: Cold mode ($z = 5.5$)
  - All halo gas in filaments.
  - Cold gas, no virial shock
  - Filamentary accretion.
- Right: Hot mode ($z = 3.2$)
  - Quasi-spherical halo filled with hot gas.
  - Quasi-spherical accretion.



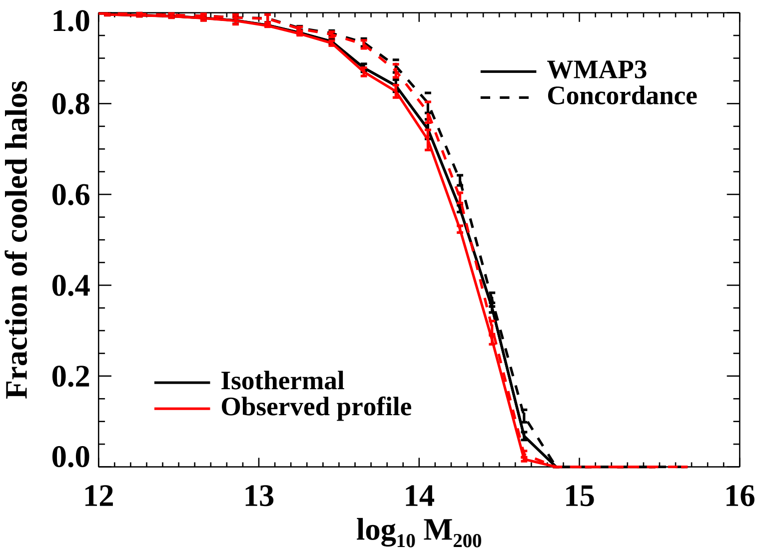


Some Reasons Why Being Cool is Cool

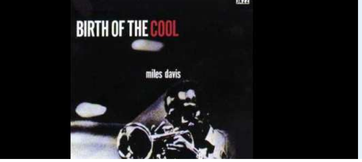
- At early times halos have lower mass and the scale of filaments matches that of galaxies, the “Cold Mode” dominates and accretion rates are large. At late times filaments are much larger than galaxies, reducing the “Cold Mode” and mainly leaving the less efficient “Hot Mode”. Hence, gas accretion rates slow.
- Halos are more massive and structure evolves more quickly in regions of high galaxy density. Hence gas accretion will slow earlier in these regions and may help to explain the lack of disks around elliptical galaxies and the density-morphology relation.
- One might not expect adiabatic contraction to occur in “Cold Mode” galaxies.
- Unlike in the standard model, galaxy disks in “Cold Mode” galaxies could form with the same specific angular momentum as galaxy dark matter halos.



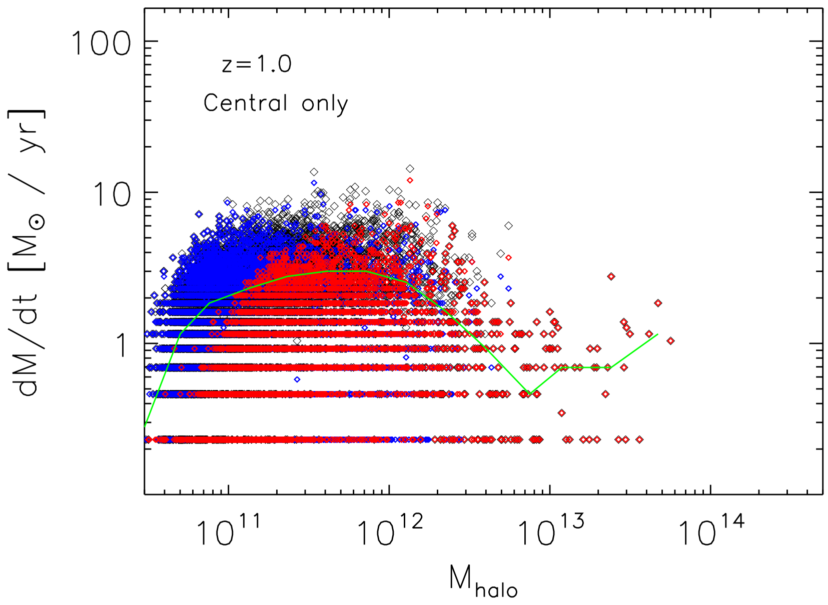
Some Like it Hot, Some Not



- Assume that halo gas is reheated during its last major merger.
- Sharp transition in mass between cooling and noncooling halos.
- Transition occurs around same mass where x-ray properties change.
- The question is not how to stop cooling flows in clusters but how to start them.

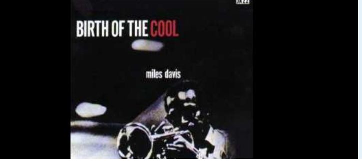


Entering the age of cool

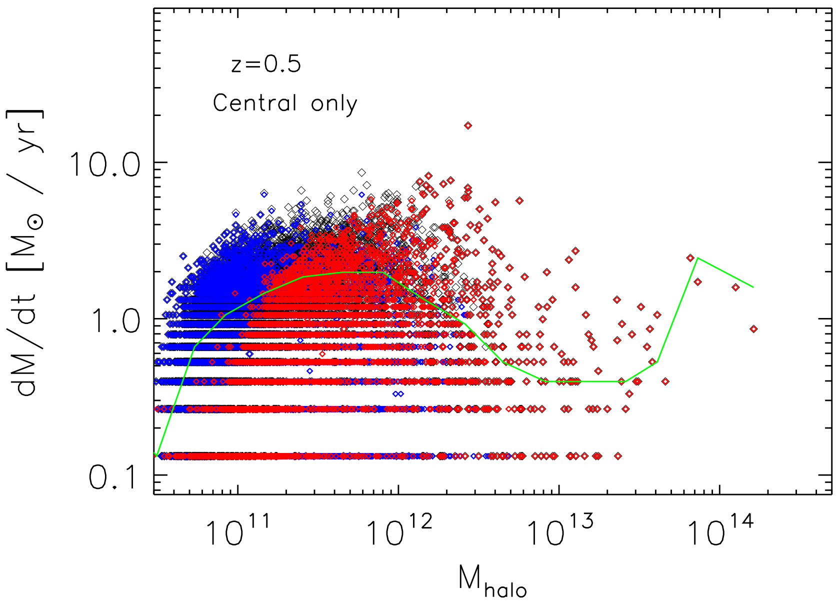


$z = 1.0$

- At $z = 1$ halos only cool slowly.

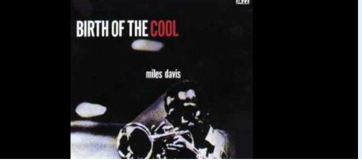


Entering the age of cool



$z = 0.5$

- At $z = 1$ halos only cool slowly.
- At $z = 0.5$ halos only cool slowly.



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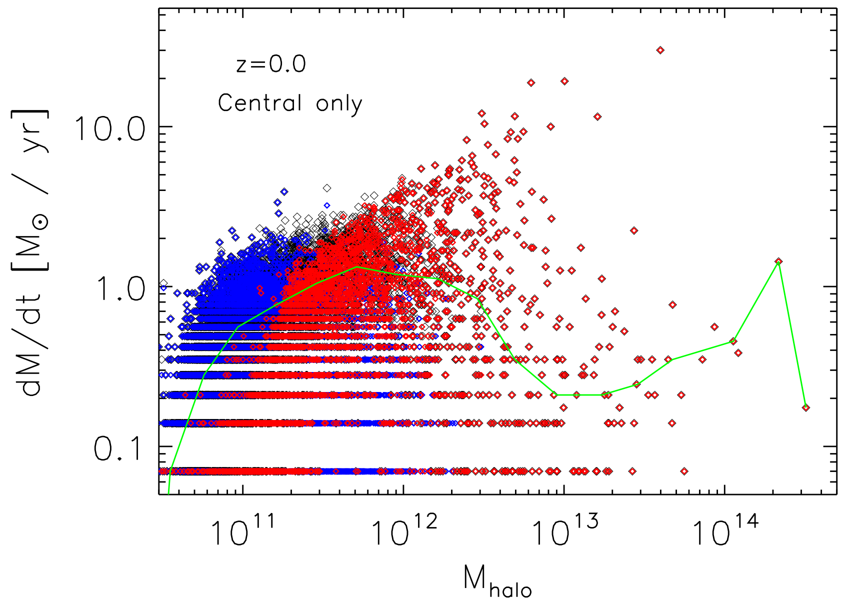
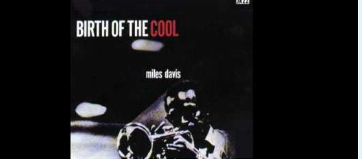


$z = 0.0$

- At $z = 1$ halos only cool slowly.
- At $z = 0.5$ halos only cool slowly.
- Bimodal distribution of halos today: fast cooling and slow cooling.



Conclusions

- Smooth accretion is more important than merging.
- The global star formation history of the Universe follows the smooth accretion: supply side star formation.
- Cold mode accretion dominates the formation of galaxies and standard hot mode accretion is only a detail of galaxy formation.
- At high redshifts all galaxies are dominated by cold mode accretion.
- At low redshifts massive galaxies dominated by hot mode accretion.
- Naively expect massive halos ($> 10^{14.5}$) not to have even hot mode accretion at low redshift.
- Much work remains to be done.