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Cold mode of gas accretion

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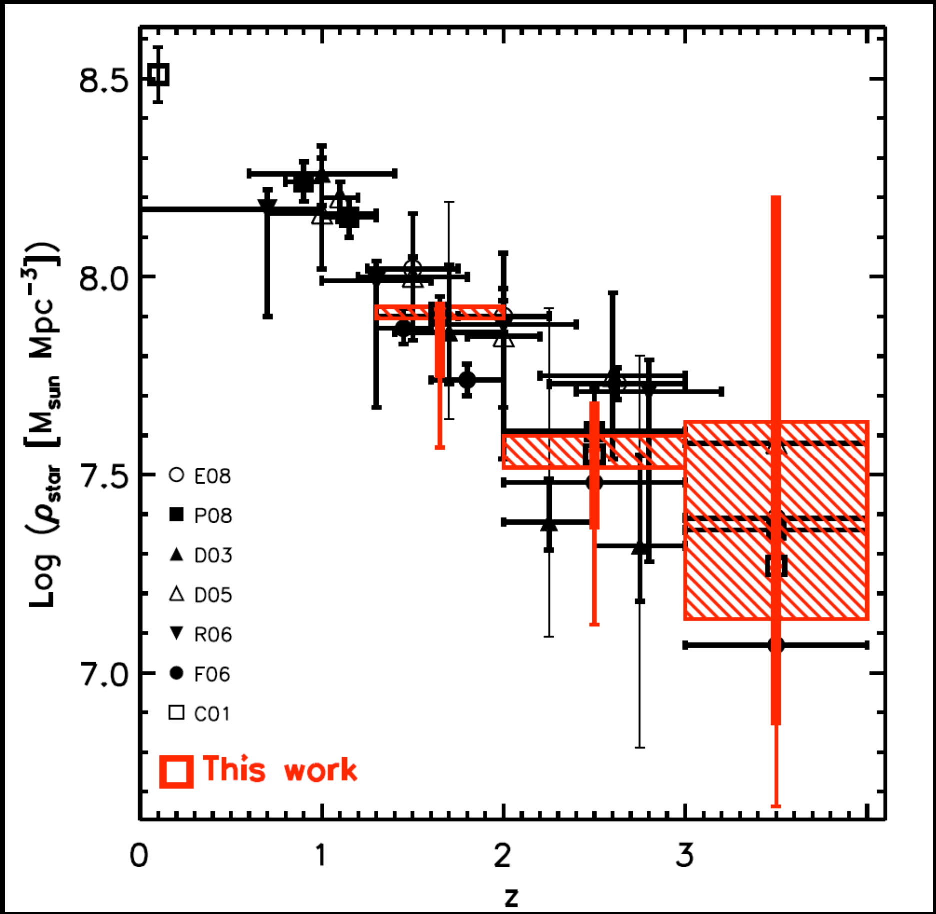
Talk outline

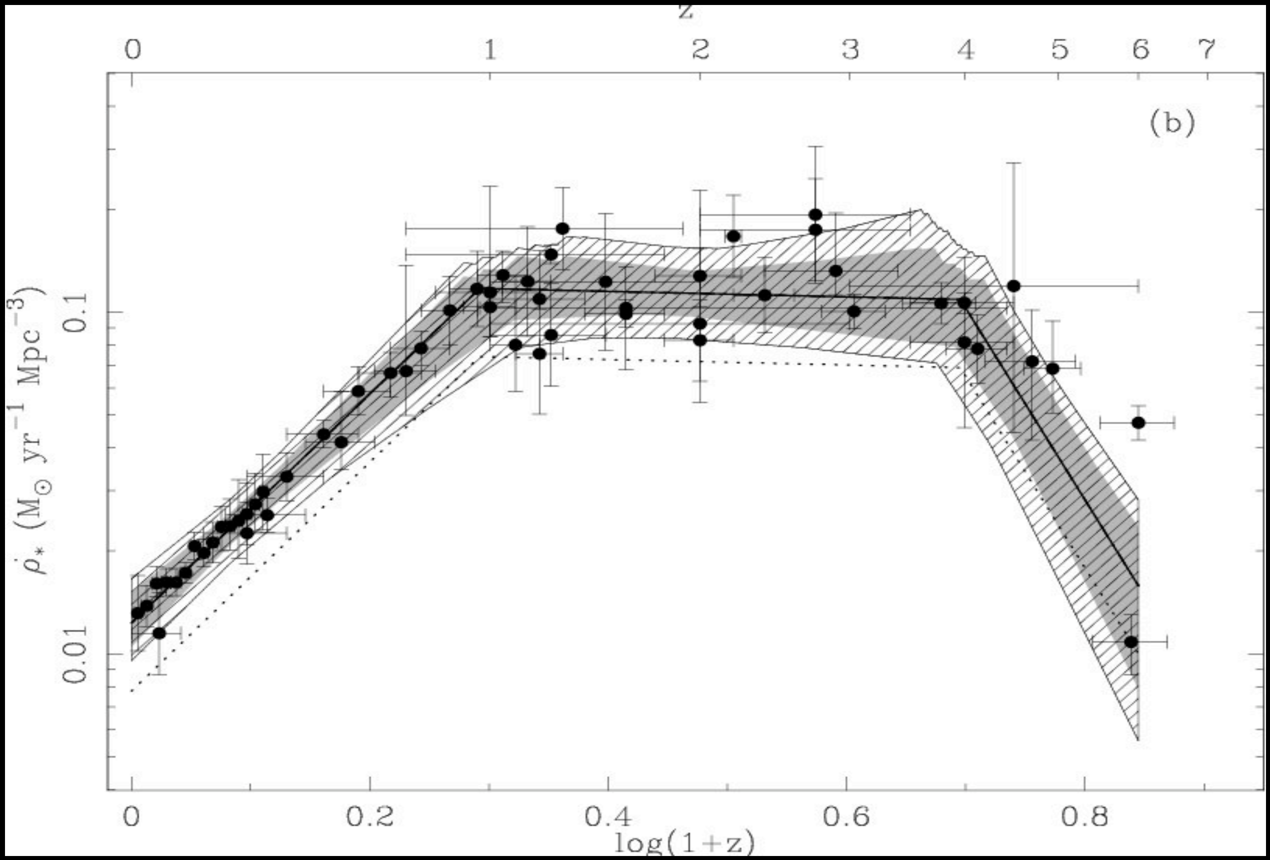
- Observations
  - A need for gas accretion
- Standard model of galaxy formation
- Simulations
  - Galactic gas supply in simulations
  - Efficient accretion at high redshift
  - Formation of halo clouds
  - Cloud properties
- How can we detect accreting material?
- What we need to improve in the future

Stellar mass locked in galaxies increases with time



Marchesini et al 2008

What drives the stellar mass growth?



Hopkins & Beacom 2006

What drives the star formation?

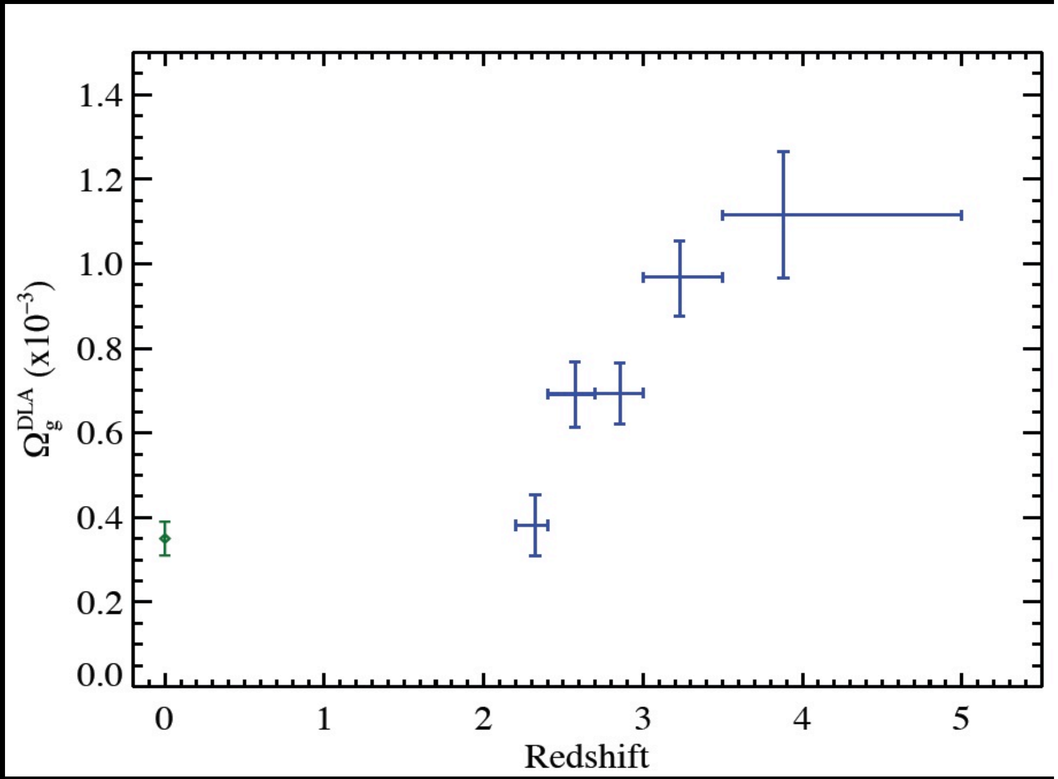
Stars form from the dense molecular gas

- Toy model:
- Galactic disks were gas rich at high z and are slowly consuming their gas.
  - High SFR early
  - Drops with time
  - Is this enough?
- Gas consumption timescales for molecular gas are short, especially a high-z (Kennicutt law - > short SFR timescales).
- Molecular phase needs to be re-supplied over time.

Gas in the dense atomic phase

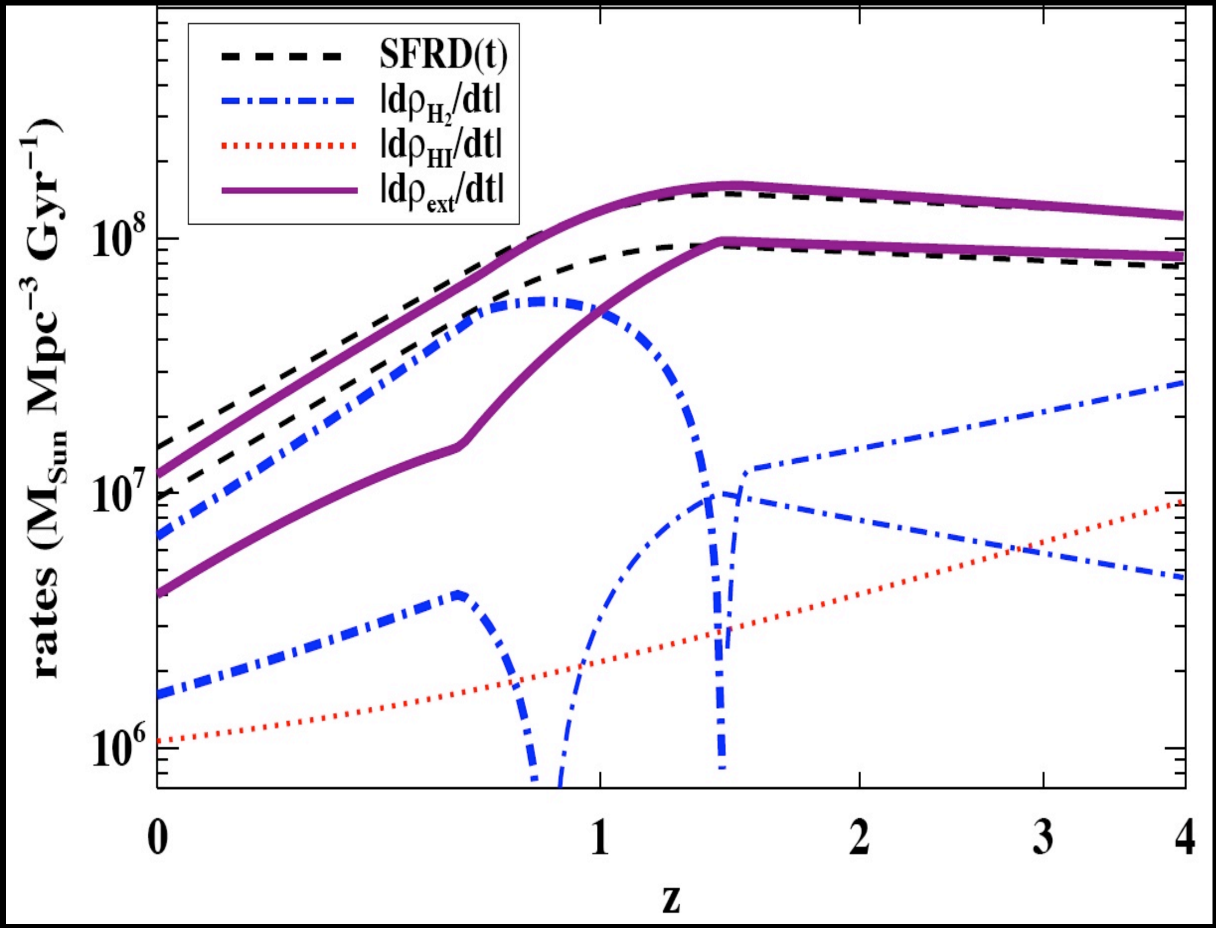
*ρ_* $z=0$

- Maybe from dense atomic gas?
- Amount of gas in DLA at high-z is less than the mass locked in stars at z=0.
- A majority of stars form after z=2. Dense HI phase stayed constant during this time
- DLA phase also needs to be constantly re-supplied.
- Huge reservoir available in the IGM



Prochaska&Wolfe '08

Adding it all together



Bauermeister et al. 2009

Milky Way

- SFR 1-3M_sun/yr (Kennicutt ‘01)
- Gas reservoir is < 5e9M_sun . Without gas supply this is spent in several Gyr.
- Star formation rate in Solar neighborhood has been relatively constant for several Gyrs: not much change in gas density despite large gas depletion (Binney et al. 2000)
- Infall likely needed

- Observations show that we need accretion of gas from the intergalactic medium at all redshift

The Theory

Standard Model

- E.g. White & Rees 1978

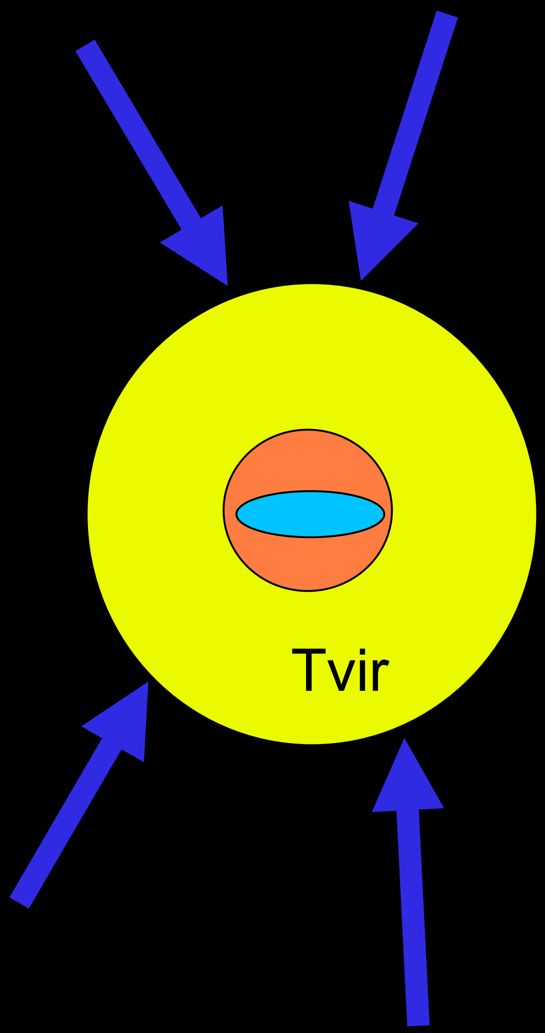
- Gas falling into a dark matter halo, shocks to the virial temperature T_{vir} at the R_{vir}, and continuously forms quasi-hydrostatic equilibrium halo.

$$T_{vir}=10^6(V_{circ} / 167 \text{ km/s})^2 \text{ K.}$$

- Hot, virialized gas cools, starting from the central parts, it loses its pressure support and settles into centrifugally supported disk –> the (spiral) galaxy.

- Mergers of disks can re-distribute the gas and produce spheroids.

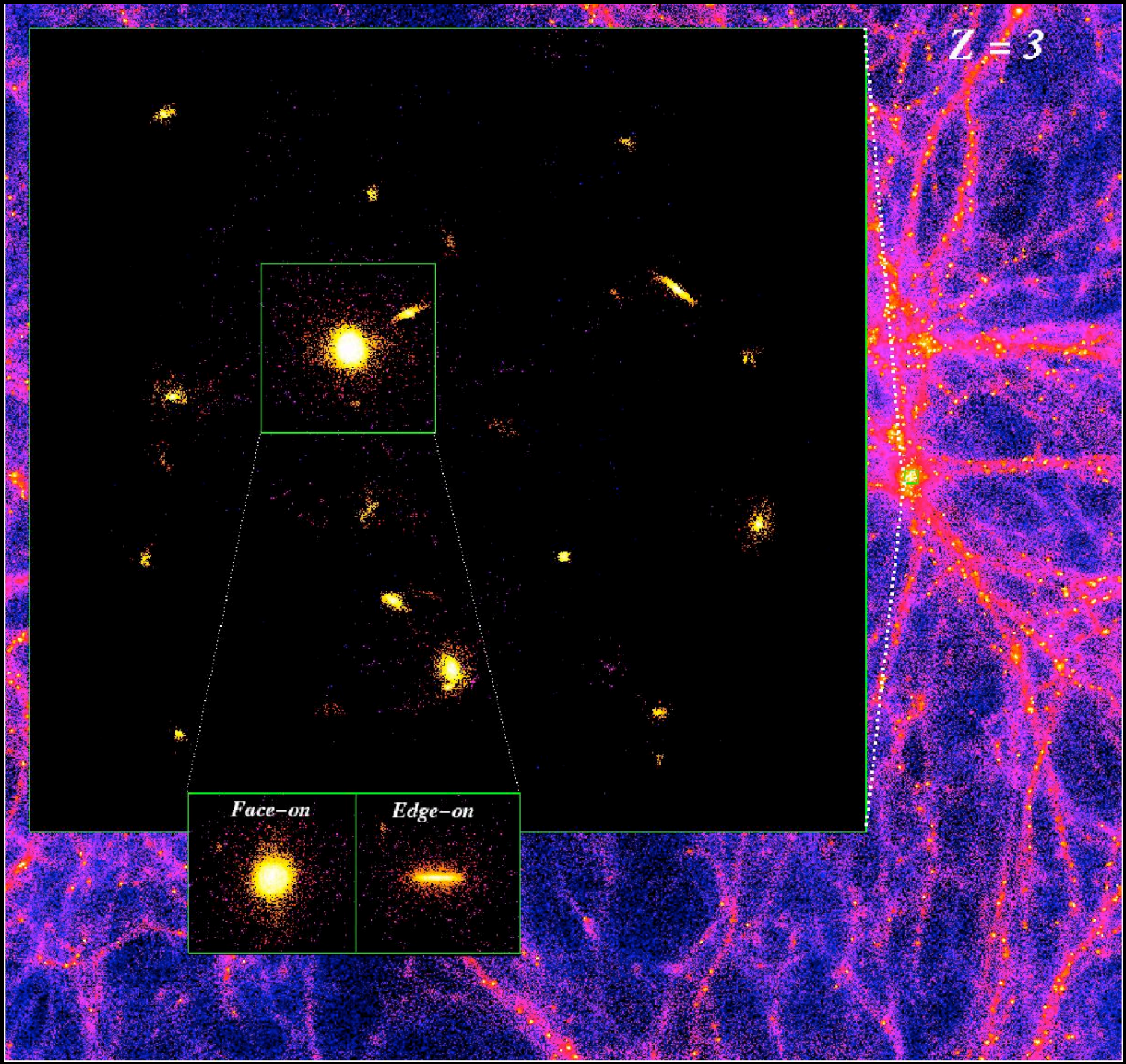
- The base for simplified prescriptions used in Semi-Analytic models – SAMs (e. g. White & Frenk 1991).



SPH simulations of the ΛCDM universe

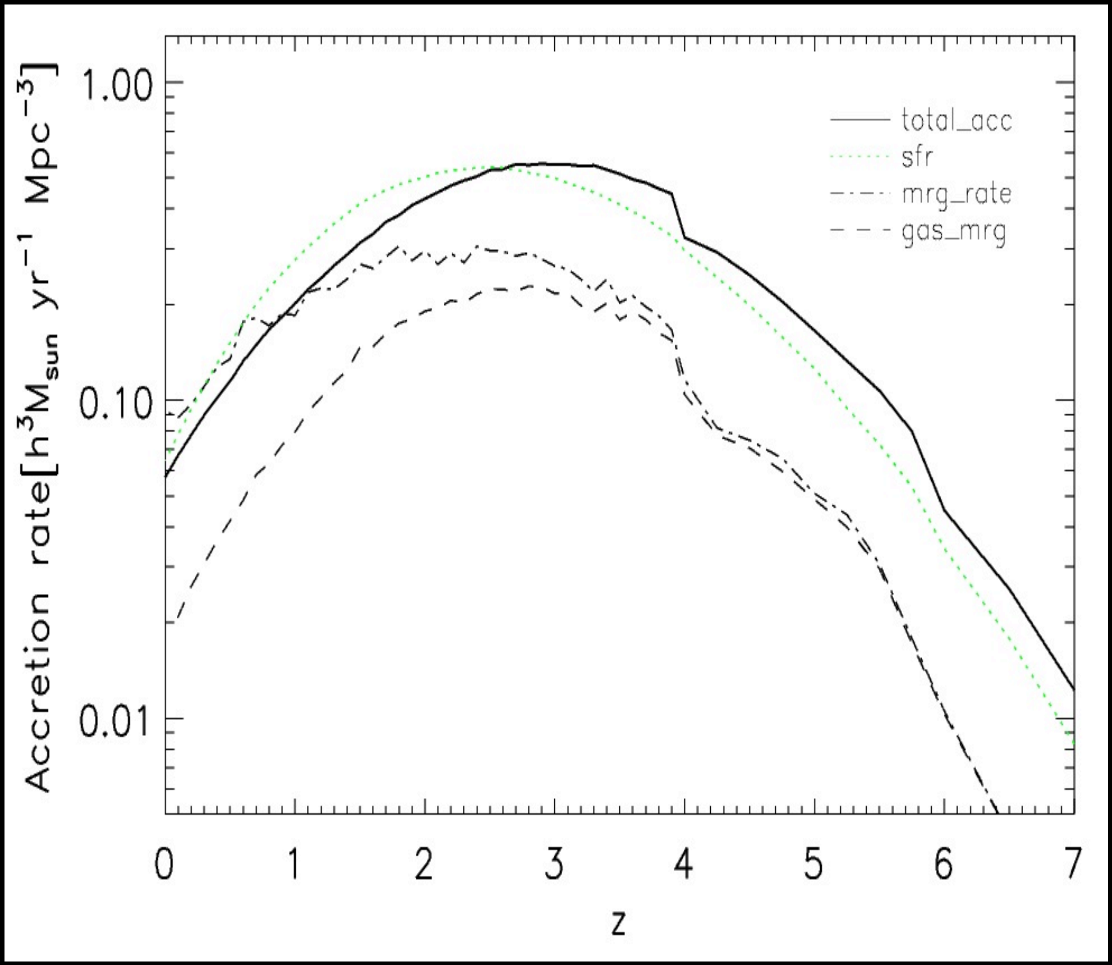
- Gadget-2, 3 (Springel 2005) SPH code: entropy and energy conservation; proper treatment of the "cooling flows"
  - Cooling (no metals), UV background, a star formation prescription
  - Two-phase sub-resolution model: SN pressurize the gas, but does not drive outflows
  - Star formation timescale is selected to match the normalization of the Kennicutt law.
  - Two-phase model provides effective star formation threshold density.
  - Usually no winds from supernovae
- Large volume 50/h Mpc on a side, with gas particle mass ~$8\times10^7\ M_\odot$, but most of the findings confirmed with resolution study down to $4\times10^4\ M_\odot$
- Lagrangian simulations -> we have ability to follow fluid (particles) in time and space.

- Our definition of a galaxy: highly overdense, bound concentrations of cold gas and stars.



From N. Katz

Global Accretion

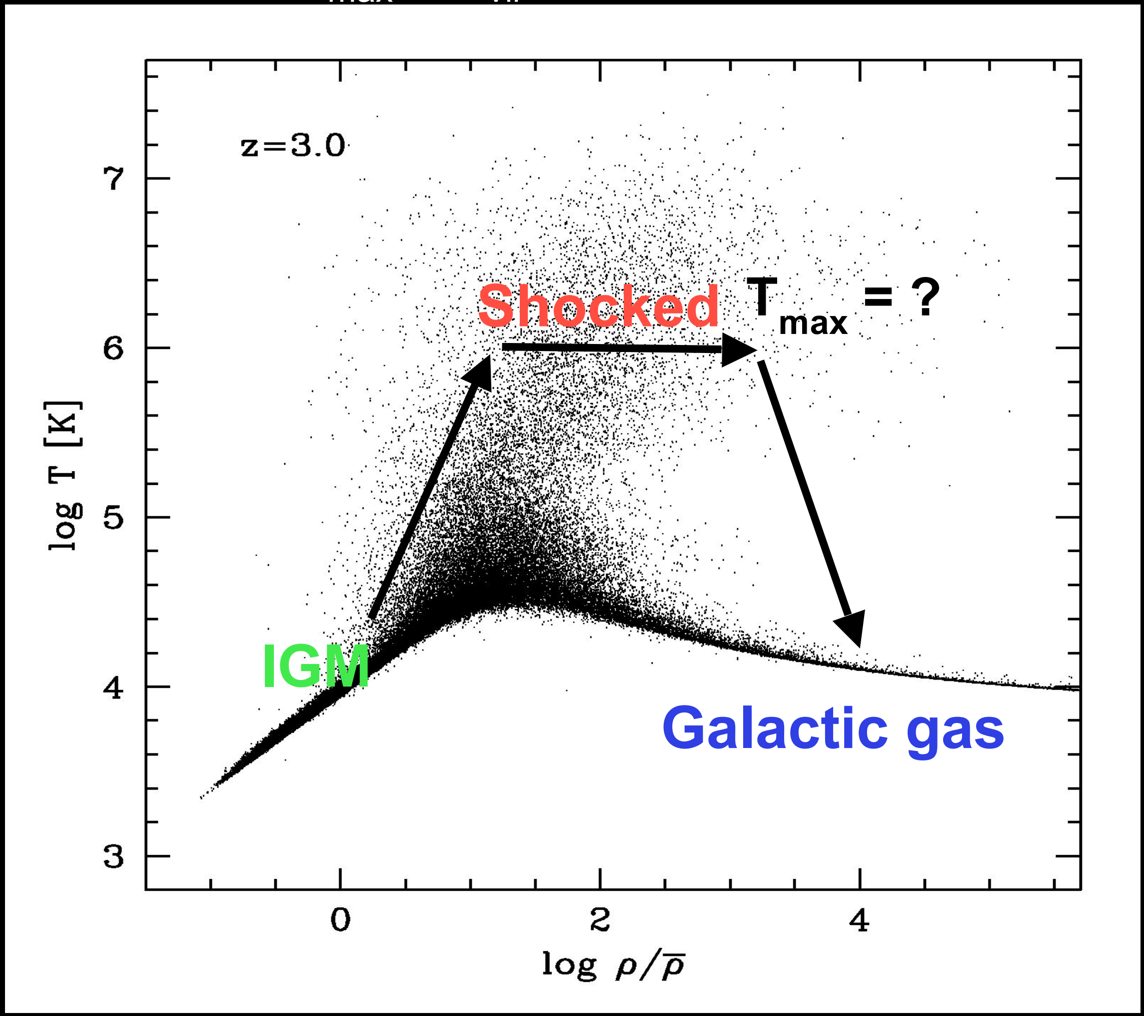


Kereš et al. 2009

- We count particles that joined galaxies between two outputs
- Galaxies grow through mergers and accretion of gas from the IGM
- Smooth gas accretion dominates global gas supply
  - always dominates growth of central galaxies in < $10^{12} M_\odot$ halos
- Star formation follows smooth gas accretion
- It is within factor of ~2 from the typical Madau plot (e.g. Hopkins & Beacom 2006)
- Mergers globally important after z=1

Temperature history of accretion

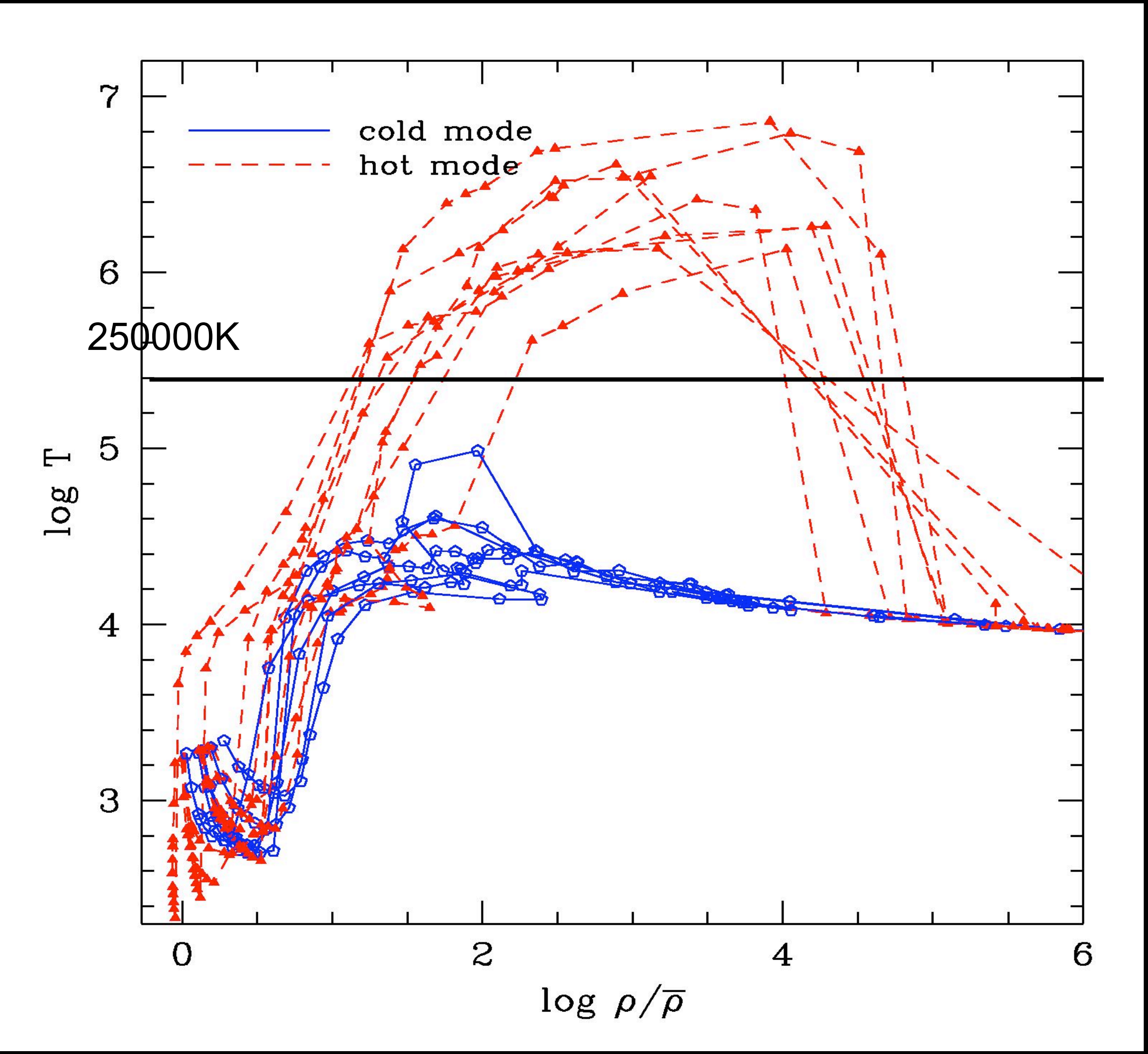
- We follow each accreted gas particle in time and determine its maximum temperature - T_{max} before the accretion event.
- In the standard model $T_{max} \sim T_{vir}$



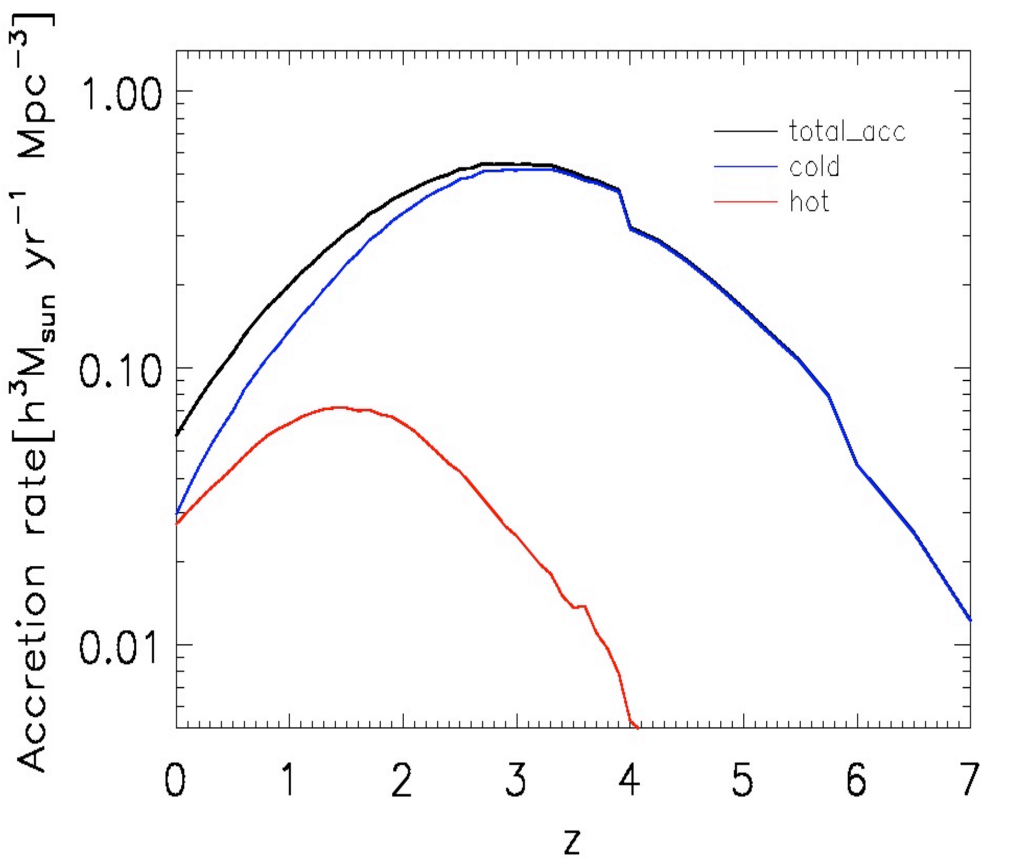
ρ-T evolution of accreted particles

- The gas that was not heated to high temperatures -> COLD MODE ACCRETION
- The gas that follows the standard model -> HOT MODE ACCRETION
- Empirical division of 2.e5K, but results are robust for 1.5-3e5K

Katz, Keres et al. 2002
Kereš et al. 2005



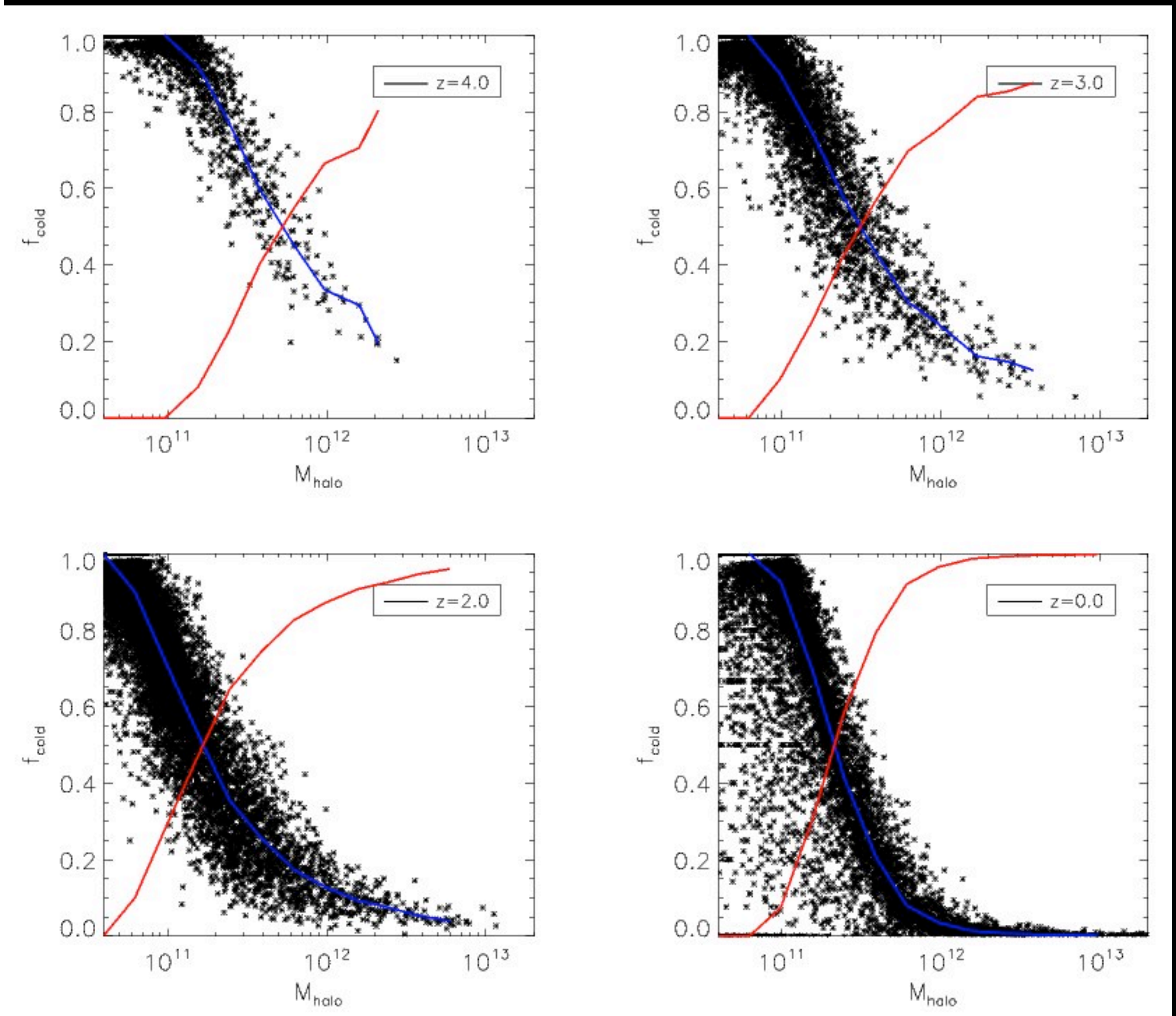
How important are these two accretion modes?



- Cold mode dominates the gas accretion at all times.
- Hot mode starting to be globally important only at late times

Kereš et al. 2009

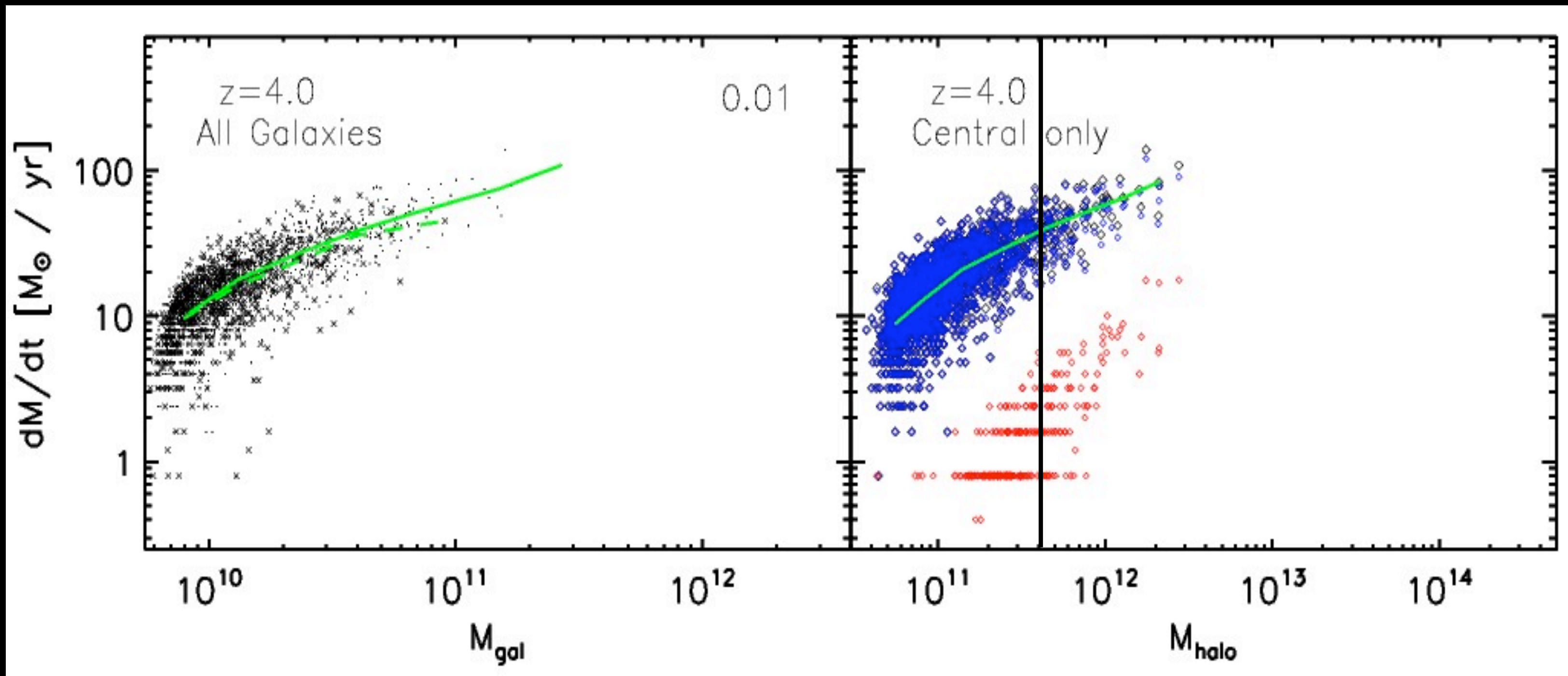
Low mass halos are not virialized



Kereš et al. 2009

- Halo gas, excluding the galaxies
- Cold: T < 2.5e5K (typically few 1.e4K)
- Transition at $M_h = 10^{11.4}\ M_\odot$
- Early hints (e.g. Binney 1977, Katz & Gunn 1991)
- Approximate description by Birnboim&Dekel 2003
- Shock cannot propagate if post shock cooling times are shorter than the gas compression time
- Condition valid at Rvir when $M_h \sim 1\times10^{11}\ M_\odot$
- More realistic transition is gradual, dense filaments survive within hot halos (Keres et al. 2005)

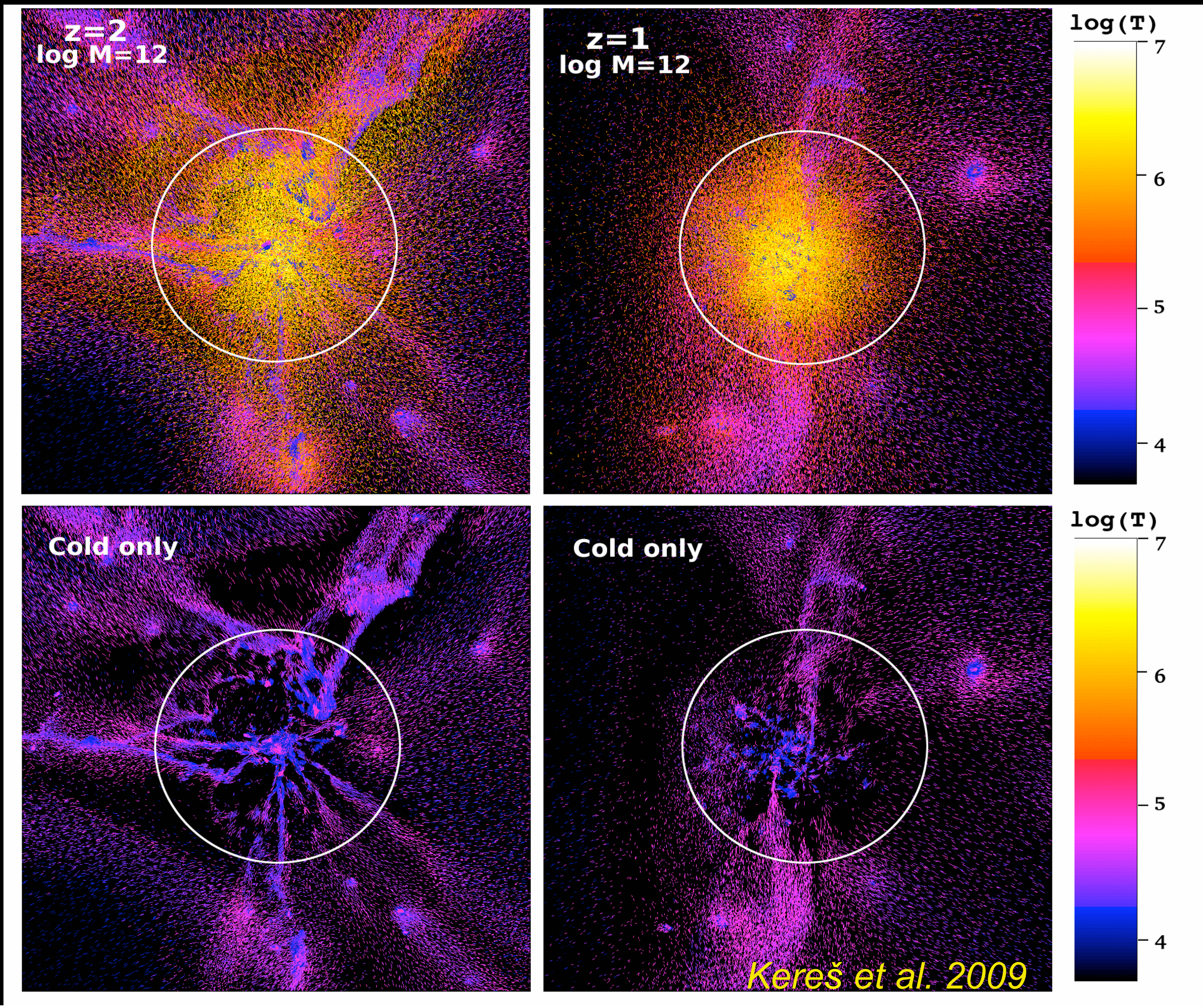
High-z accretion



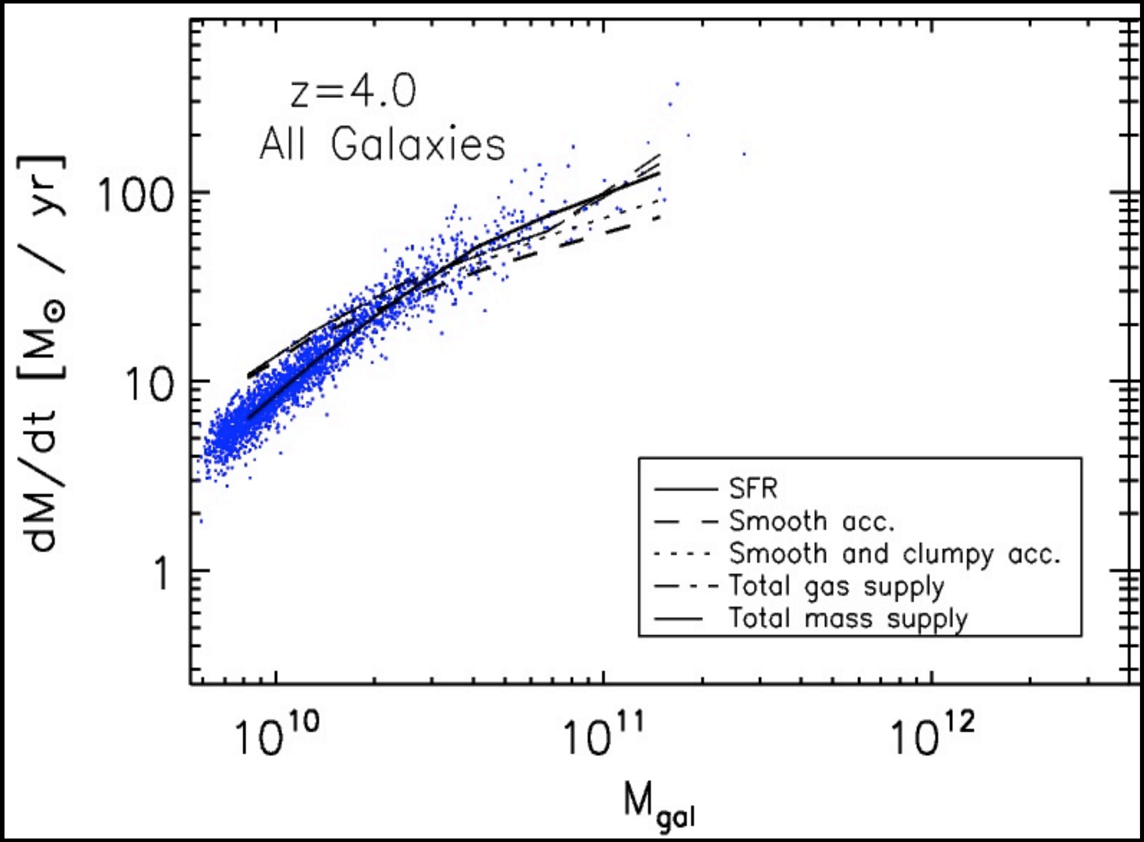
Kereš et al. 2009

- Gas accretion rate is a strong function of mass
- Satellites accrete with similar rates as central galaxies.
- Cold mode dominates at any halo mass.
- Even in massive halos full of hot gas cold mode filaments supply galaxies with cold gas.
- Cooling from the hot atmosphere not efficient
- Cold mode accretion follows infall into halos (within a factor of 2-3).

m_p ~1.e6 M_sun, resolution ~500pc (at z=2)



Total gas supply and star formation

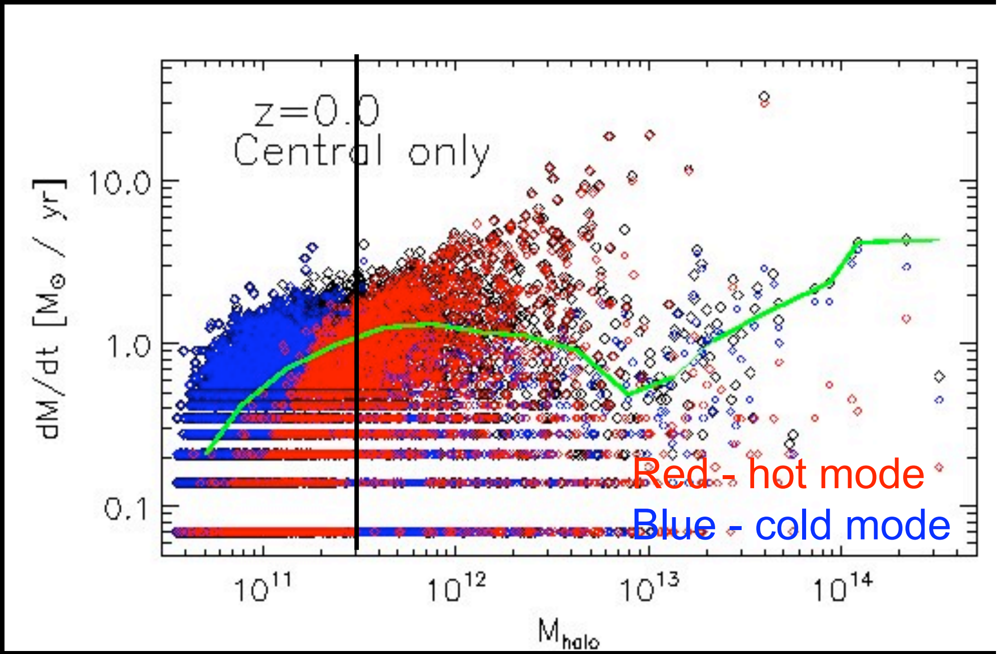


Kereš et al. 2009

- Kennicutt law suggests short star formation timescale -> high redshift galaxies have high SFRs caused by the rapid gas supply

Low-z accretion

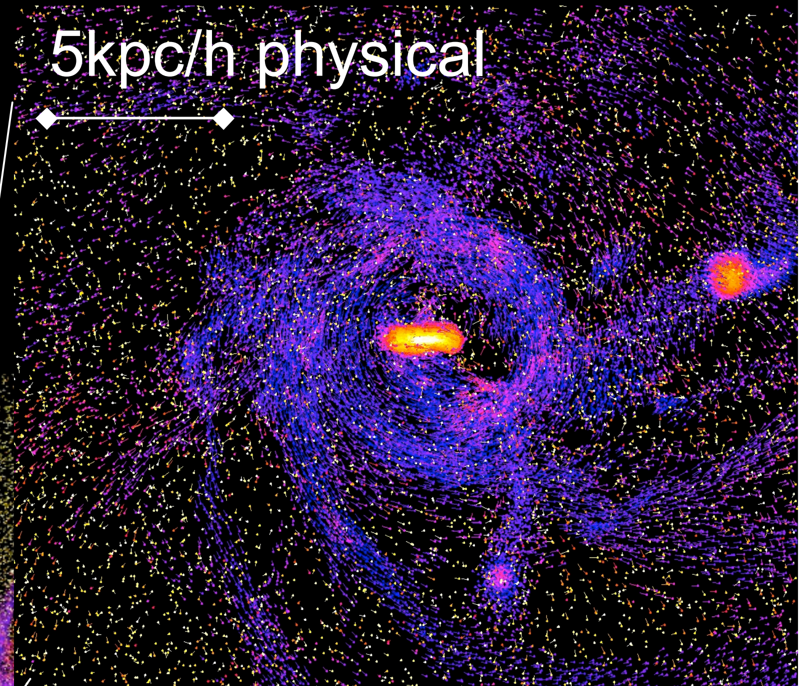
- Drastic accretion change over time, factor of ~30 from z=4 to 0.
- Some hot mode accretion around the transition mass.
- Halos more massive than $\sim 10^{12} M_{\odot}$ (an order of magnitude above transition) stop cooling hot gas
- At z~0, only a fraction of massive halos is able to cool the hot gas
- Massive halos have bimodal behaviour: either steep central density or large density cores
  - similar to the observed cool and non-cool core clusters.

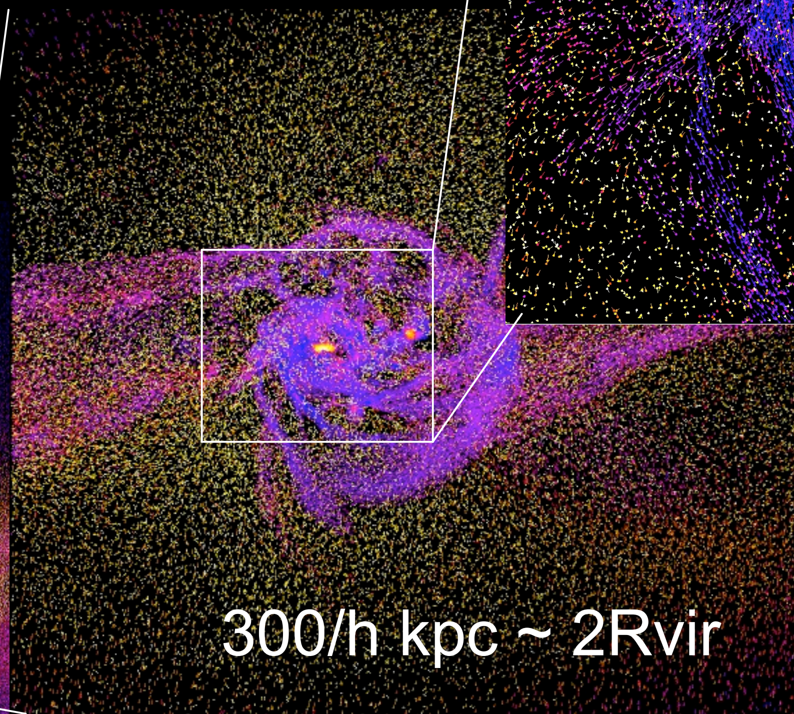


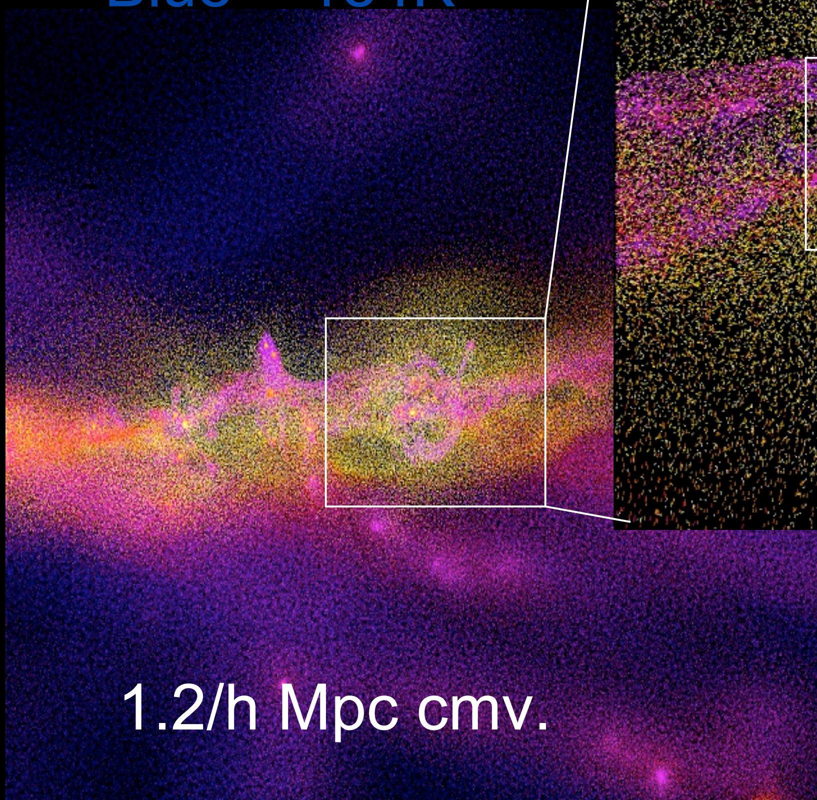
Kereš et al. 2009

New zoom-in simulations

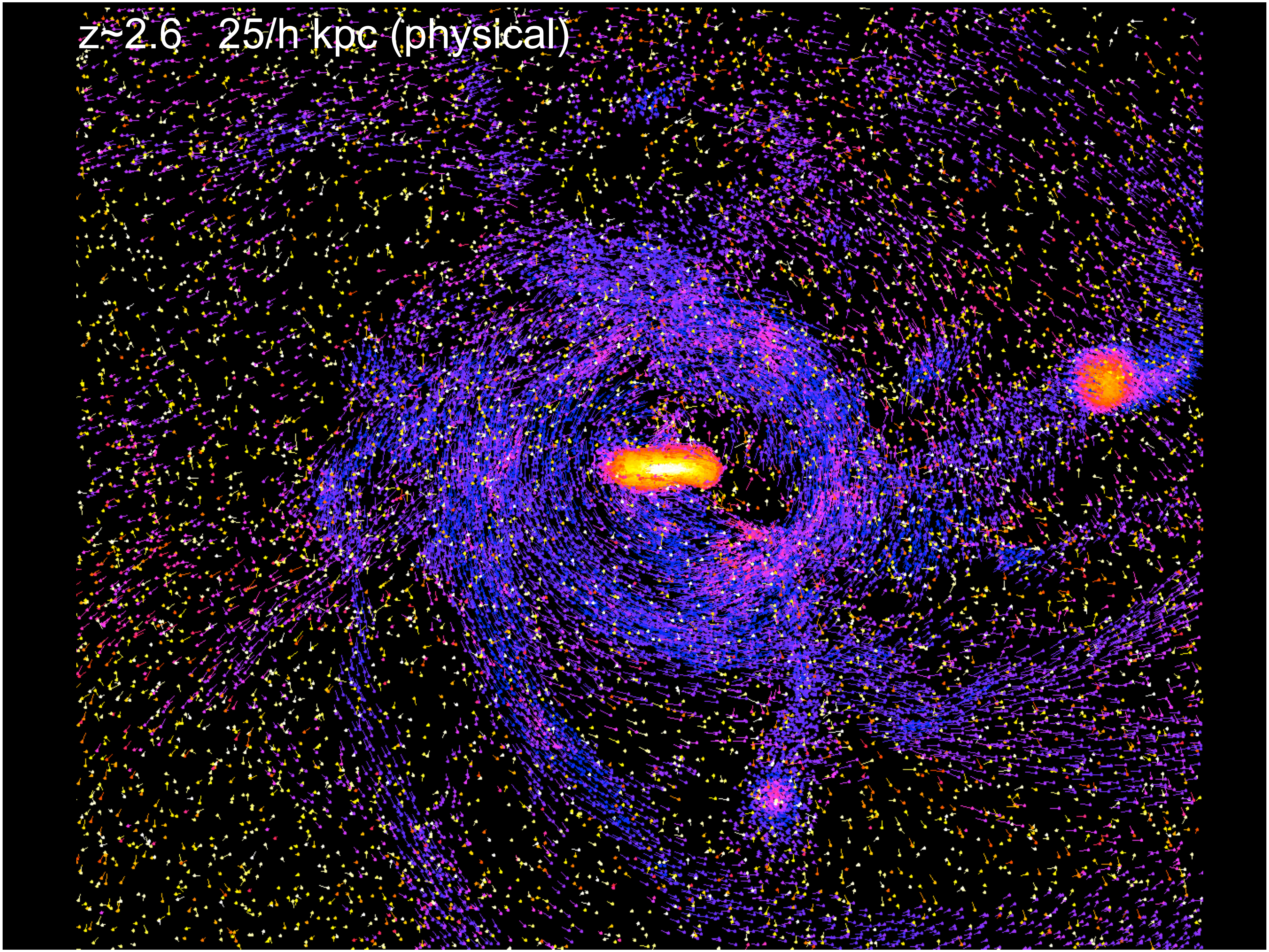
Z~2.6
110/h pc physical res.
M_p~1.e5M_sun
M_h~1.3e11M_sun
Yellow Tvir
Blue ~ 1e4K



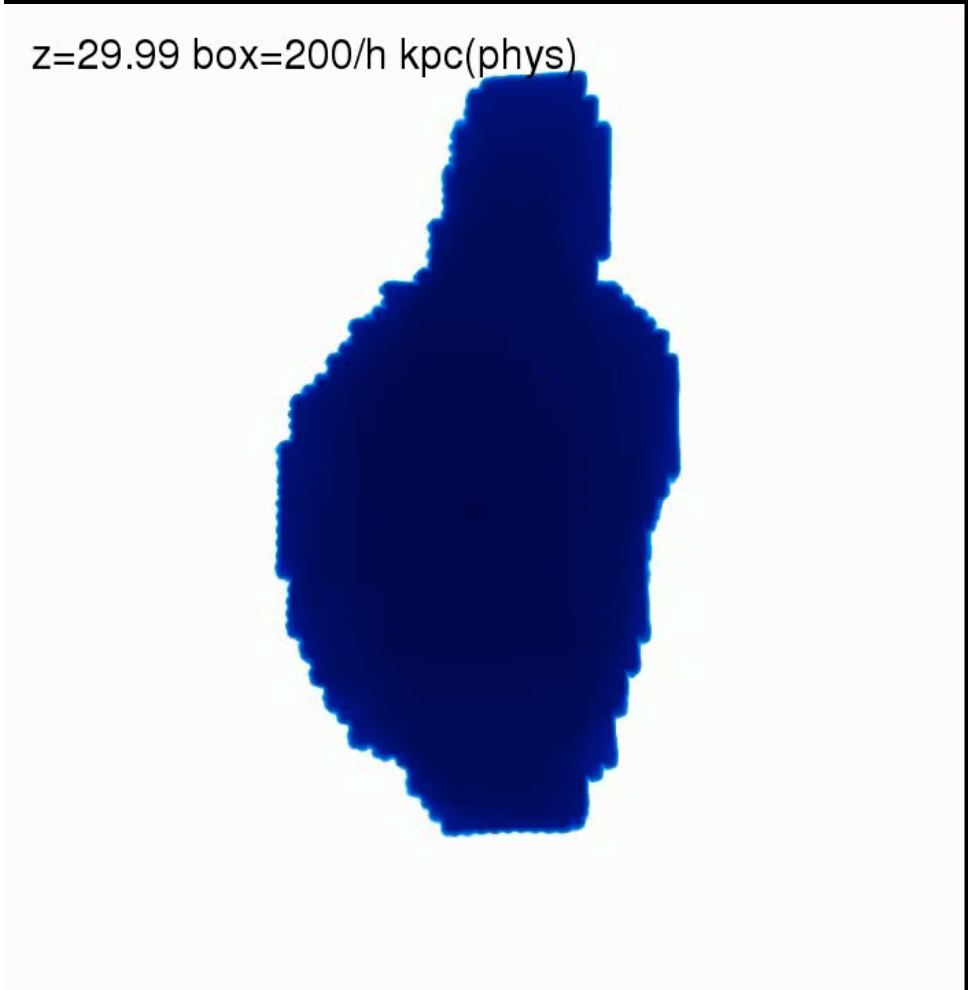




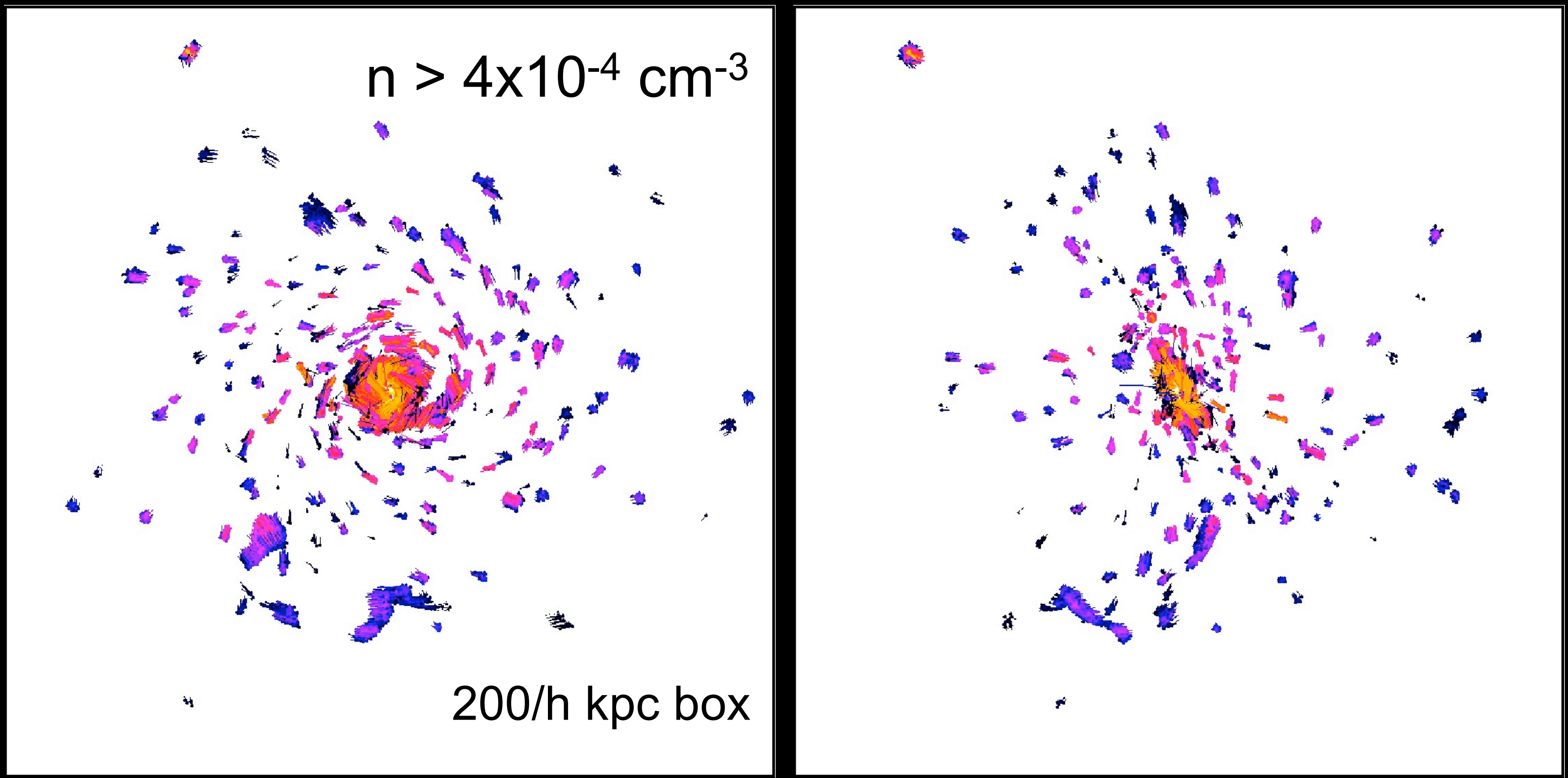
Simulation of a single halo takes a month on our local cluster!


z~2.6   25/h kpc (physical)

Halo mass at z=0, $7 \times 10^{11} M_{sun}$
Gas particle mass $\sim 10^5 M_{sun}$



Halo clouds at z=0

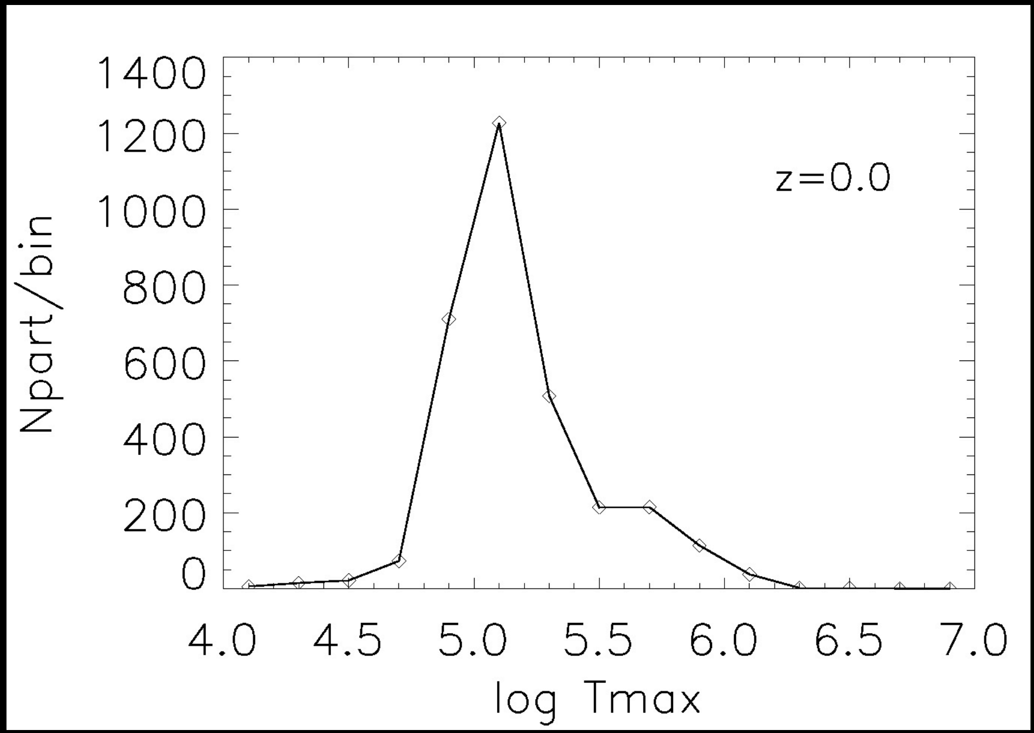


Kereš & Hernquist 2009

Cloud properties

- $T \sim 10^4$K clouds are surrounded by $\sim 10^6$K gas.
- Masses few 10^6 - 5×10^7 Msun.
- Total mass ~1-2 x 10^9 Msun
- Column densities $\sim 10^{18}$-10^{21} cm^{-2}
- 40/h x 60/h kpc region in halo center.
- Prominent rotational component, they are building the outer disk.
- Cloud properties are similar at $z < 1$
- These might be analogs of:
  - Halo absorbers at intermediate redshift (e.g. MgII)
  - Clouds observed around nearby galaxies (self shielded regions)
  - HVCs around the Milky Way (self shielded regions)

Thermal history



Kereš & Hernquist. 2009

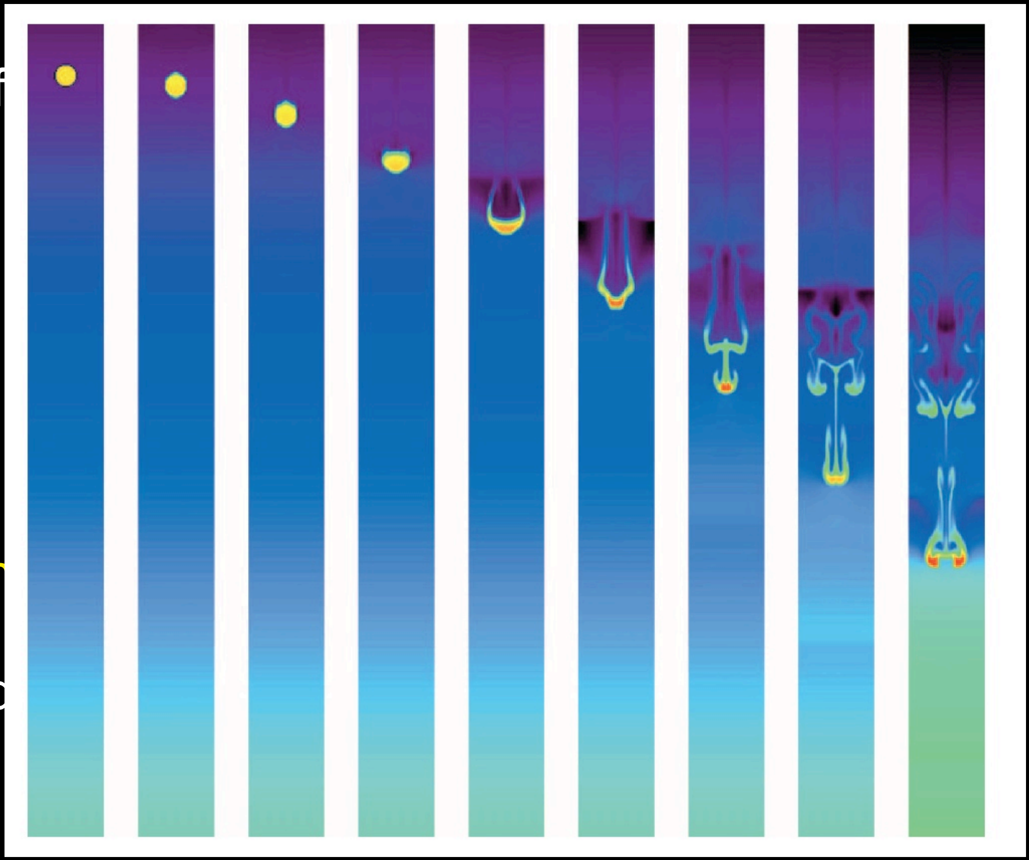
- We determine the maximum temperature ever reached by particles currently in clouds
- Clouds form out of 1-1.5 x 10^5 K gas, not from 0.5-1 x 10^6 K hot halo gas
- This is the temperature of low-z filaments that feed MW size galaxies

Cloud Formation

- Penetrating 1.e5K filaments create density inversion susceptible to Rayleigh-Taylor instabilities.
- These regions are further compressed by hot medium, shocks and ram pressure, triggering faster gas cooling and cloud formation.
- R-T and cooling instabilities have similar timescales in the regions where clouds form and act together to form them (both are comparable to the free fall time).
- Even more clouds forming with galactic winds:
  - More density inversion, more gas compression

Can simulated clouds survive?

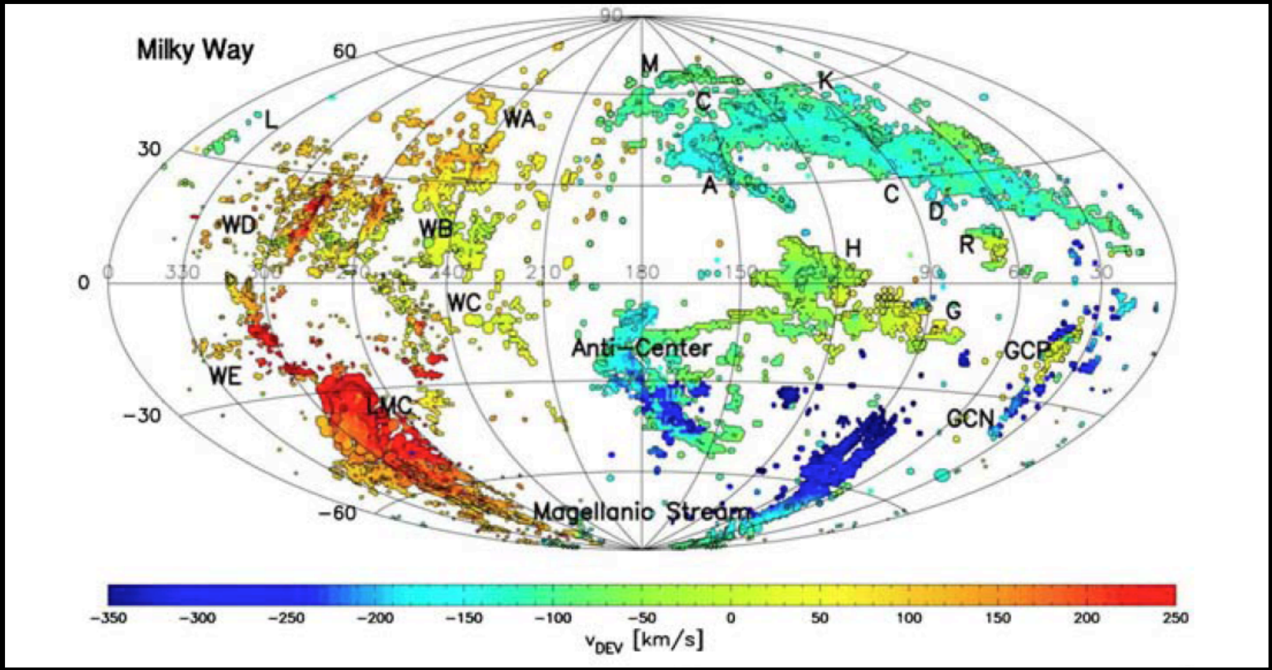
- SPH cannot reliable follow the cloud evolution
- R-T and K-H instabilities are responsible for the destruction of a cloud
- Typically an instability of the cloud size disrupts the cloud
- Details complex but simple criterion exists:
  - Clouds disrupt after they encompass mass in the hot medium comparable to their own mass
- For a simple orbit calculation and gas profile of simulated halo: Mc > 10^6 Msun survive
- Clouds < few 10^5 Msun do not survive intact. At these masses conduction is also important…



Murray and Lin 2004

Infalling gas around local galaxies

- Extra-planar clouds at distances up to 50kpc are detected around M31 and several other galaxies
- HVCs around MW, properties similar to simulated clouds
- Often showing infalling velocities, net infall 0.25M/yr (Wakker 1999)
- Similar net infall around other galaxies
- Low metallicities, similar column densities



Van Woerden et al. 2004

Consequences

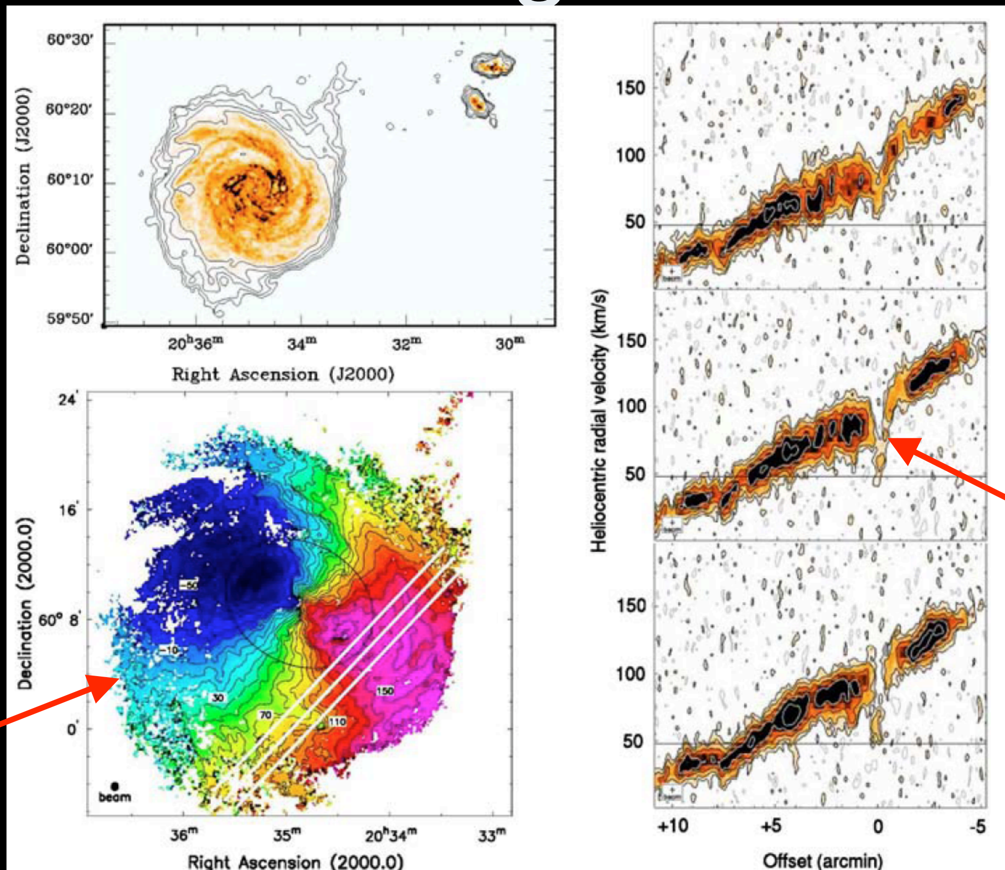
- Cold pressure supported clouds are supplying MW like galaxies with gas
- These clouds should exist to 50-70/h kpc radii and should be detectable around large star forming galaxies
- Only the inner population will have large HI column densities as lower density clouds at large radii are likely ionized.
  - HVC are probing only a part of the infalling gas
- A large fraction of infalling gas is co-rotating
  - Hard to separate galactic fountain gas from the IGM infall
- => rates of gas accretion around nearby galaxies are underestimated, possibly by large factors

- Interaction of clouds with disk might produce other observable features:
  - Structure of the outer disk
  - Interaction of realistic clouds with the disk can be resolved: e.g. holes in the HI disk
  - We need a larger sample of simulations and much larger observed sample of galaxies with clouds detected.
- If they survive in massive halos, within high pressure hot gas, this could enable them to become self-gravitating and lead to globular cluster formation: -->work in progress with Paul Torrey (graduate student at Harvard)

Signatures of cloud infall in external galaxies

NGC 6946

Boomsma 2007



Velocity wiggles

Holes punctured In the HI disk (out of the SF region)

- Simulated galaxies: outer disks often show warps, wiggles and slight change in AM direction (although see Chakrabarti&Blitz '09)
- Simulated clouds occasionally make "holes" in the outer disk

How to detect galactic accretion?

- So far the “confirmation of the cold mode” is indirect: e.g. high SFRs of high-z galaxies, that last for a long time (e.g. Genzel, Shapiro et al.)
- Simulations can now provide detailed predictions of observable properties of ->ongoing<- gas accretion at both low and high-z.
- What methods to use to “detect” gas accretion more directly?
- In local universe we could use HI but what about higher redshift?

At intermediate redshifts: Halo absorbers

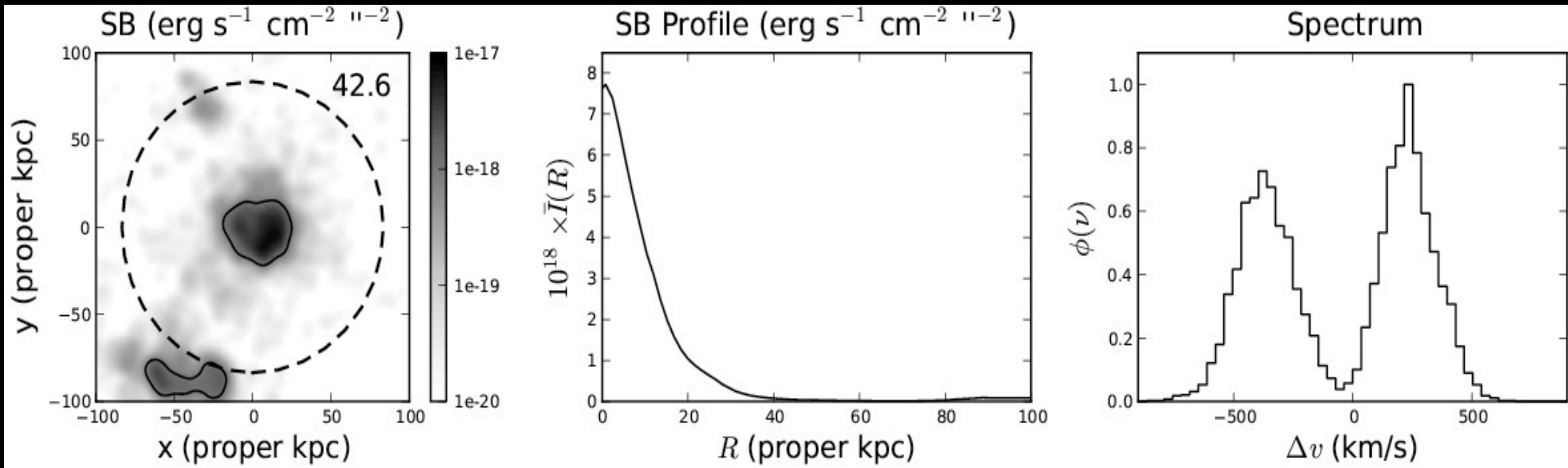
- Ly_alpha absorbers statistics are good only at high-z:
  - technical limitations
- It would be interesting to probe halos around z~1, where filamentary infall turns into clouds in the MW size galaxies
- QSO absorption systems at z~0.5-1.5 show MgII absorbers to 60-70kpc around galaxies,
  - log(N_HI) ~18-20, likely connected to Ly-limit systems
  - Believed to originate in ~ 10^4 K photo-ionized gas
- Cloud formation is important in the few 10^{11} - 10^{12} Msun halos
  - observationally constrained models suggest that these are the halos with the largest covering fractions (Tinker & Chen 2008).
- We need a larger sample of simulations, for a range of halo masses, to make detailed predictions and to compare these to observed statistics

Ly-alpha emission at z~3

- At z~3 Ly-alpha moves into optical window.
- Several dozens of sources of extended Ly_alpha emission were detected: Ly_alpha “blobs” (Steidel et al. 2000)
- High redshift halos contain a significant fraction of cold overdense gas
- This gas can be heated gravitationally, photo-ionized, photo-heated and also heated by galactic outflows (star formation driven winds and AGN)
- In all cases, typical emission probes the state of cold, dense halo gas.
- Detailed predictions are needed to demonstrate if a large part of this emission can be explained by gravitational heating of the infalling gas

- Ly-alpha is optically thick in line center even at low column densities -> line radiative transfer is needed
- Dense gas can self-shield. Our simulations assume universe is optically thin for UV radiation:
  - do not incorporate ionizing radiation R-T, we need post-processing.
- The gas properties are not modeled properly in self-shielded regions
  - One need to explore range of physically motivated assumptions

PRELIMINARY!



- Work done with C.-A. Faucher-Giguere (finishing his PhD)
- Gravitational and photo heating only, emission from galaxies (both stellar and gas) is not shown
- 5x10^{11} halo, simulated with intermediate resolution
- Extended emission to ~20kpc
- Intervening IGM absorption is not yet taken into account
- Similar to a blob observed by Nilsson et al. 2006
- Deeper observations could probe gas at larger radii.
- Work in progress, luminosity function, line profiles etc.

Problems and future progress

- Instabilities in the infalling gas need to be treated carefully:
  - Issues of cloud survivability and angular momentum transfer between cold infalling gas and hot medium
  - To understand the formation of late time disks we need to understand the interaction of clouds with the hot halo gas
- Need more results at low redshift from Eulerian and moving mesh codes
- Better calculation of emission and absorption from halos requires on-the-fly radiative transfer of local and global ionizing radiation
- Feedback processes need to be tested and implemented in a less resolution dependent way
- This might be crucial: outflows (in their simple realization) tend to increase covering fraction of cold gas

Conclusions

- Cold mode accretion is the dominant way of galactic gas supply and galactic growth at high redshift even in relatively massive halos.
- Filamentary nature very important, denser gas prevents shock propagation.
- Cosmological simulations can follow the formation of halo clouds form the “first principles”.
- In the MW size halos, infalling filaments turn into cold gaseous clouds that later infall onto galaxies, providing fuel for star formation
- This is likely the formation mechanism of a large fraction of halo absorbers and HVCs.
  – details depend on metallicity and other properties of halo gas)
- We are starting to make quantitative predictions for future observations of infalling halo gas. This will enable more direct tests and detections of ongoing gas accretion.