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How do galaxies get their gas?

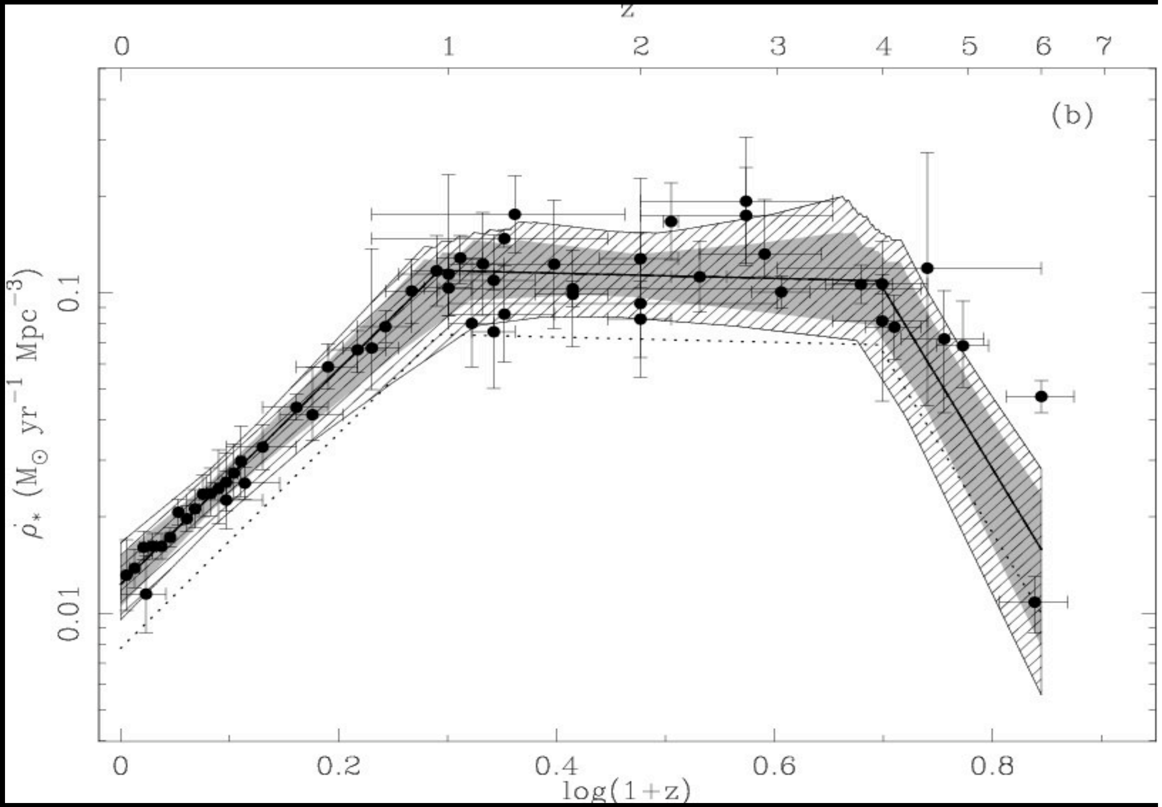
Dušan Kereš

ITC-CFA-Harvard

Collaborators: Neal Katz, Lars Hernquist, David Weinberg, Romeel Davé, Mark Fardal, Ben Oppenheimer

SFR density of the universe

- Why is SFR density so high at early times and decreases at low-z?
- What drives the cosmic star formation evolution?



Hopkins & Beacom 2006

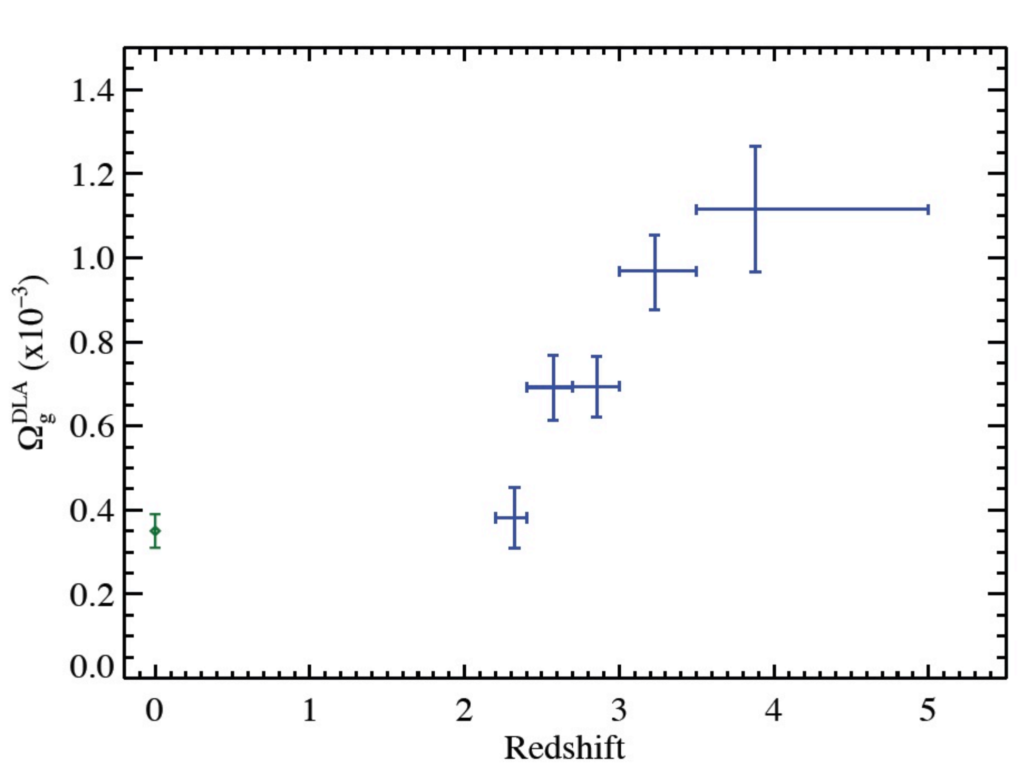
What drives the evolution in SFR density?

- A toy model (closed box):
  - Stars form from dense/galactic gas
  - Galaxies built their gaseous reservoirs at early times
  - High gas fractions can provide high SFRs at high redshift
  - Depletion of this gas can then slow down the star formation
  - Could explain some of the observed trends
- Is there enough “galactic” gas at high-z to support such scenario?

ρ_* z=0

Baryons in dense gas

- DLAs: column densities typical of the gaseous galactic disks
- Amount of gas in DLAs at high-z is much less than the mass locked in stars at z=0.
  - Supply of gas is needed
- Amount of dense HI gas stays constant from z=2 to 0
- A majority (~80%) of stars form after z=2 (Marchesini+ '08)
  - Supply of gas is needed
- Molecular phase is short lived (1-2 Gyrs): adding molecules does not help
- Dense gas phase needs to be constantly re-supplied.

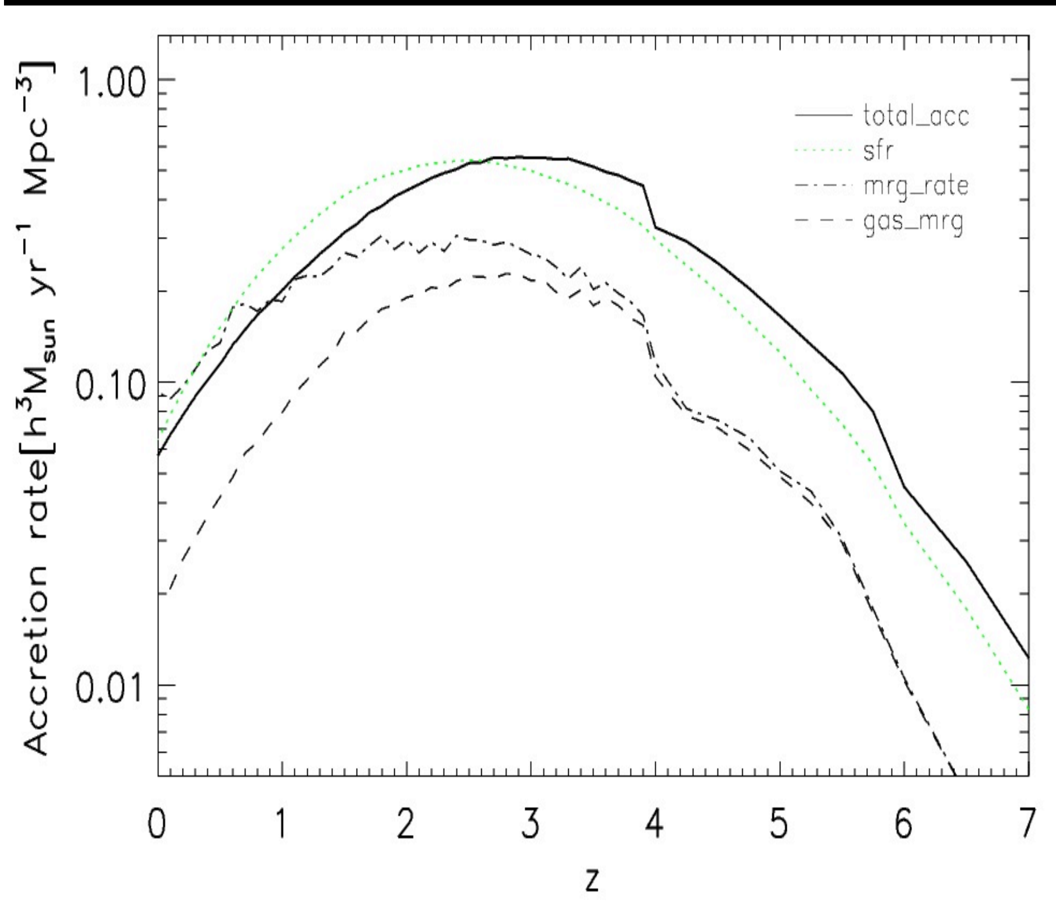


Prochaska & Wolfe '08

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, Star formation prescription
  - Two-phase sub-resolution model:
    - SN pressurize the gas, but does not drive outflows
    - Normalized to match the Kennicutt law
- Large volume 50/h Mpc on a side, with gas particle mass ~1.e8 $M_\odot$, but most of the findings confirmed with resolution study down to 1.e5 $M_\odot$
- Lagrangian simulations -> we have ability to follow fluid (particles) in time and space.
- Simulated galaxies: bound concentrations of stars and cold, dense gas

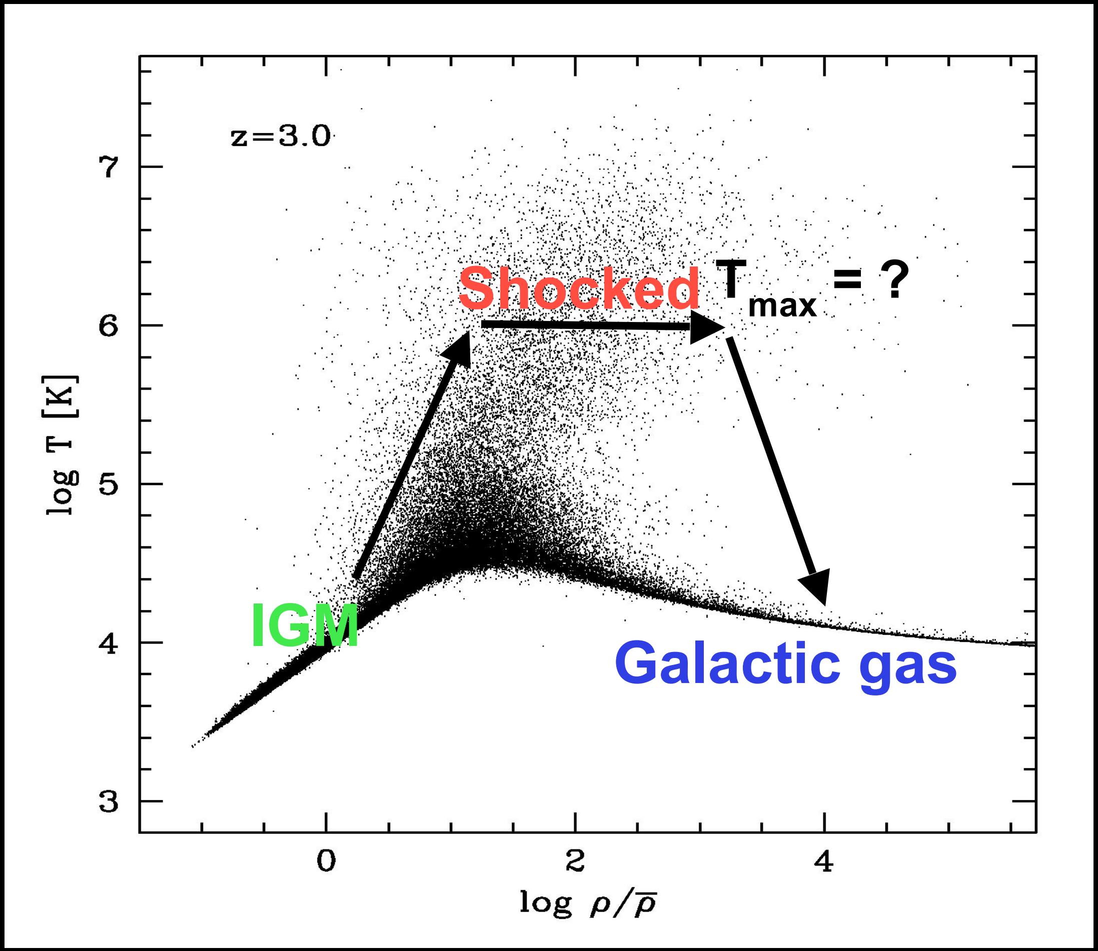
Global Accretion



- Galaxies grow through mergers and accretion of gas from the IGM
- Smooth gas accretion always dominates global gas supply (Murali+ '02, Keres+ '05, '08, Dekel+ 2009)
- Mergers are always happening and globally dominate mass growth after z=1
- Star formation follows the smooth gas accretion: short SF timescales
- The drop in the smooth gas supply causes the drop in the global star formation

Temperature history of accretion

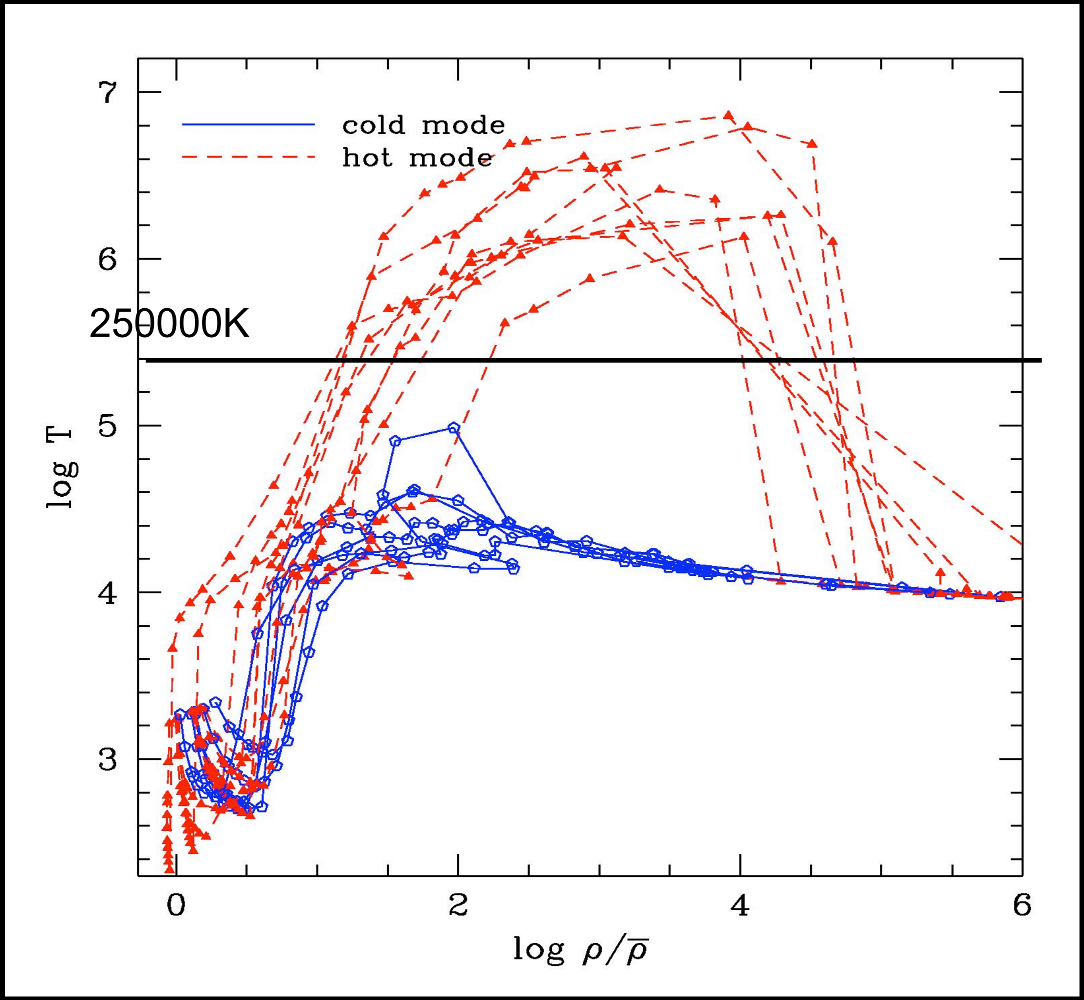
- We follow each accreted gas particle in time and determine its maximum temperature - T_{max} before the accretion event.
- In the standard model gas shock heats to virial temperature (~1.e6K) as it infalls into a halo: therefore we expected $T_{max} \sim T_{vir}$



Evolution of gas properties of accreted particles

- The gas that was not heated to high temperatures -> COLD MODE ACCRETION

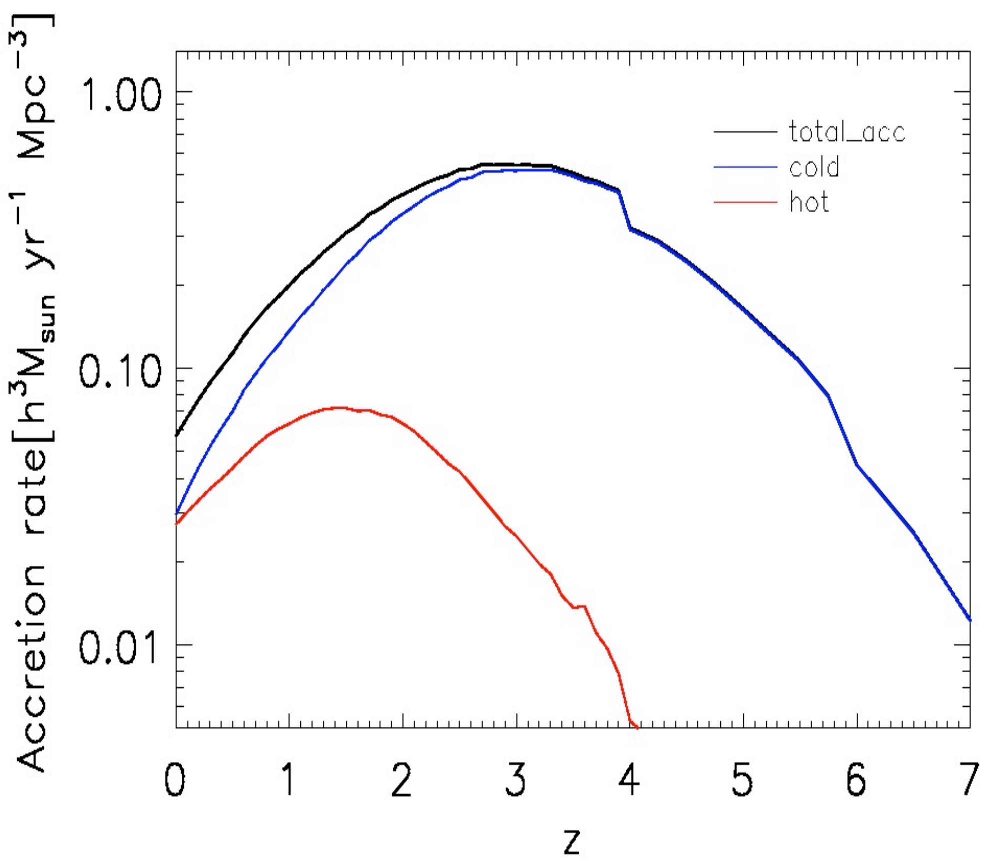
- The gas that follows the standard model -> HOT MODE ACCRETION



Katz, Keres+ 2002
Kereš+ 2005

Also, Birnboim & Dekel 2003, Dekel & Birnboim2006

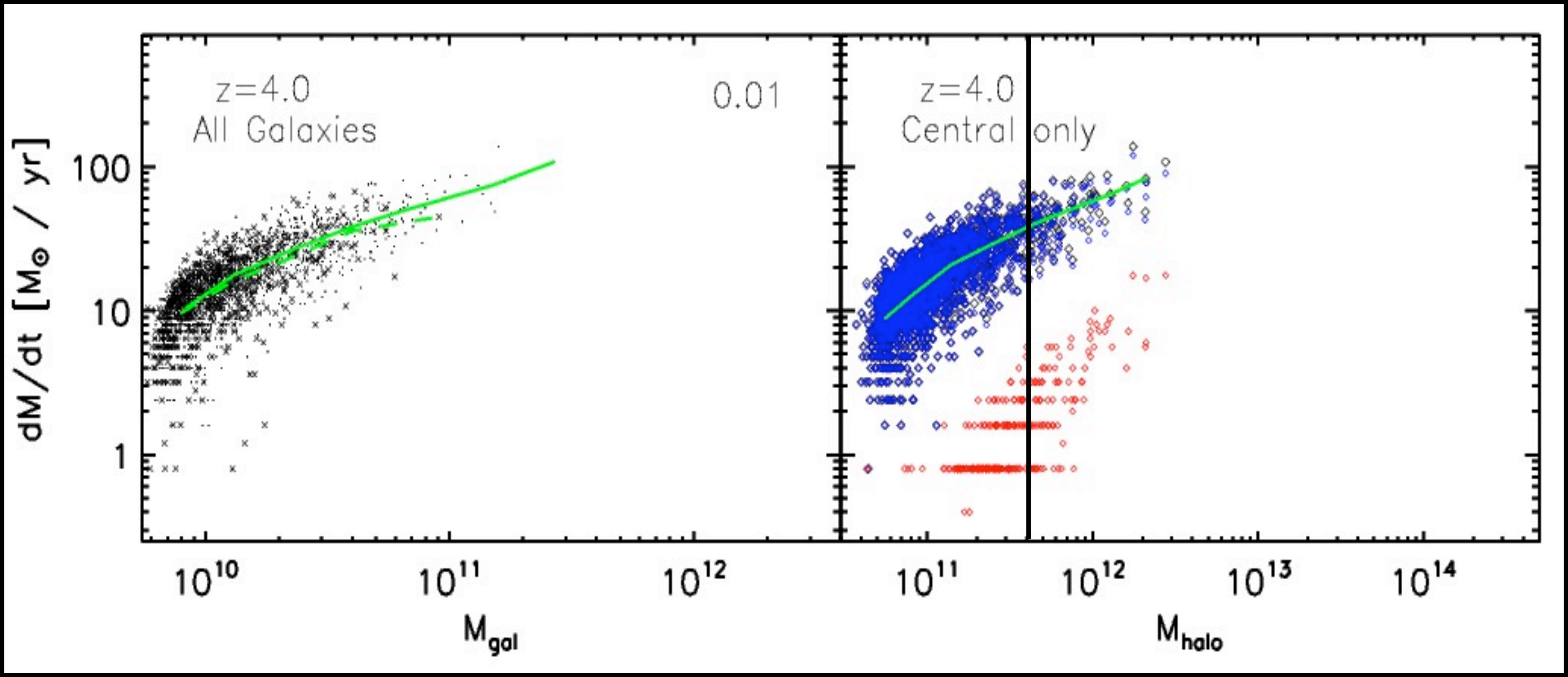
How important are these two accretion modes



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

Kereš+ 2005,2009

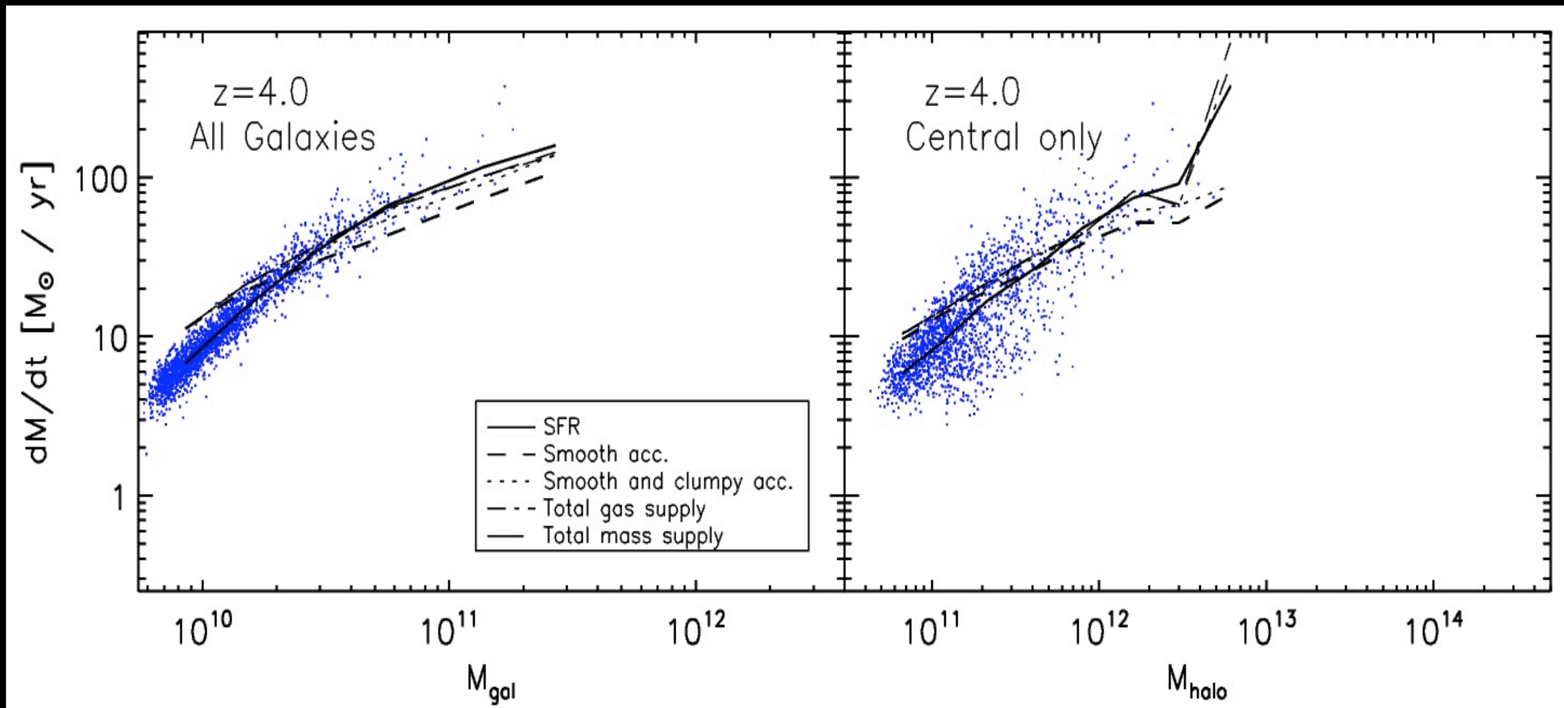
High-z accretion



Kereš 2007, Kereš et al. 2009

- Accretion rate is a strong function of mass
- Satellites accrete with similar rates as central galaxies
- Above 3e11Msun hot halo gas dominates (Birnboim&Dekel 2003, Keres+ 2005)
- Cold mode dominates, even above this transition mass
- Cooling from the hot atmosphere is not very important.

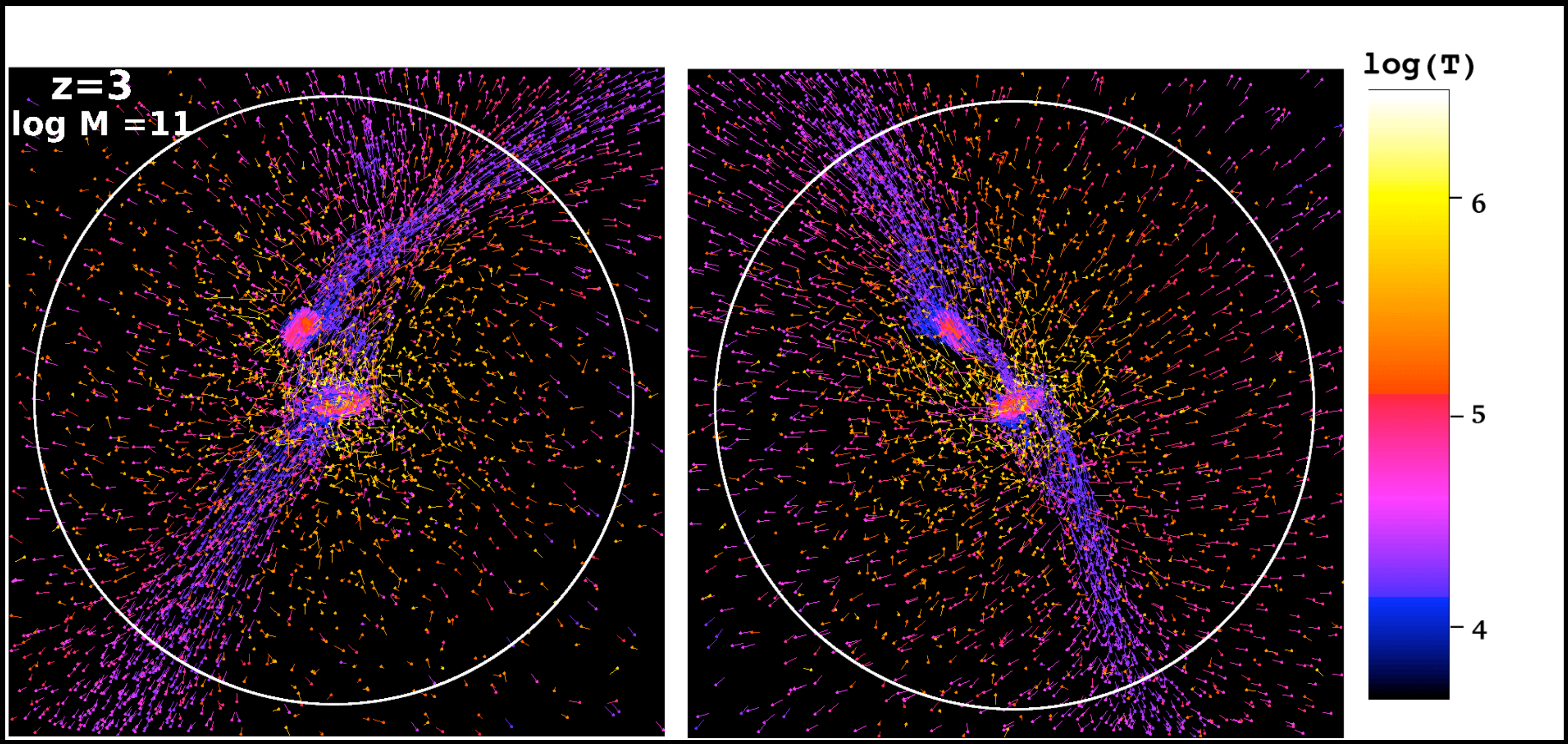
Gas supply and star formation



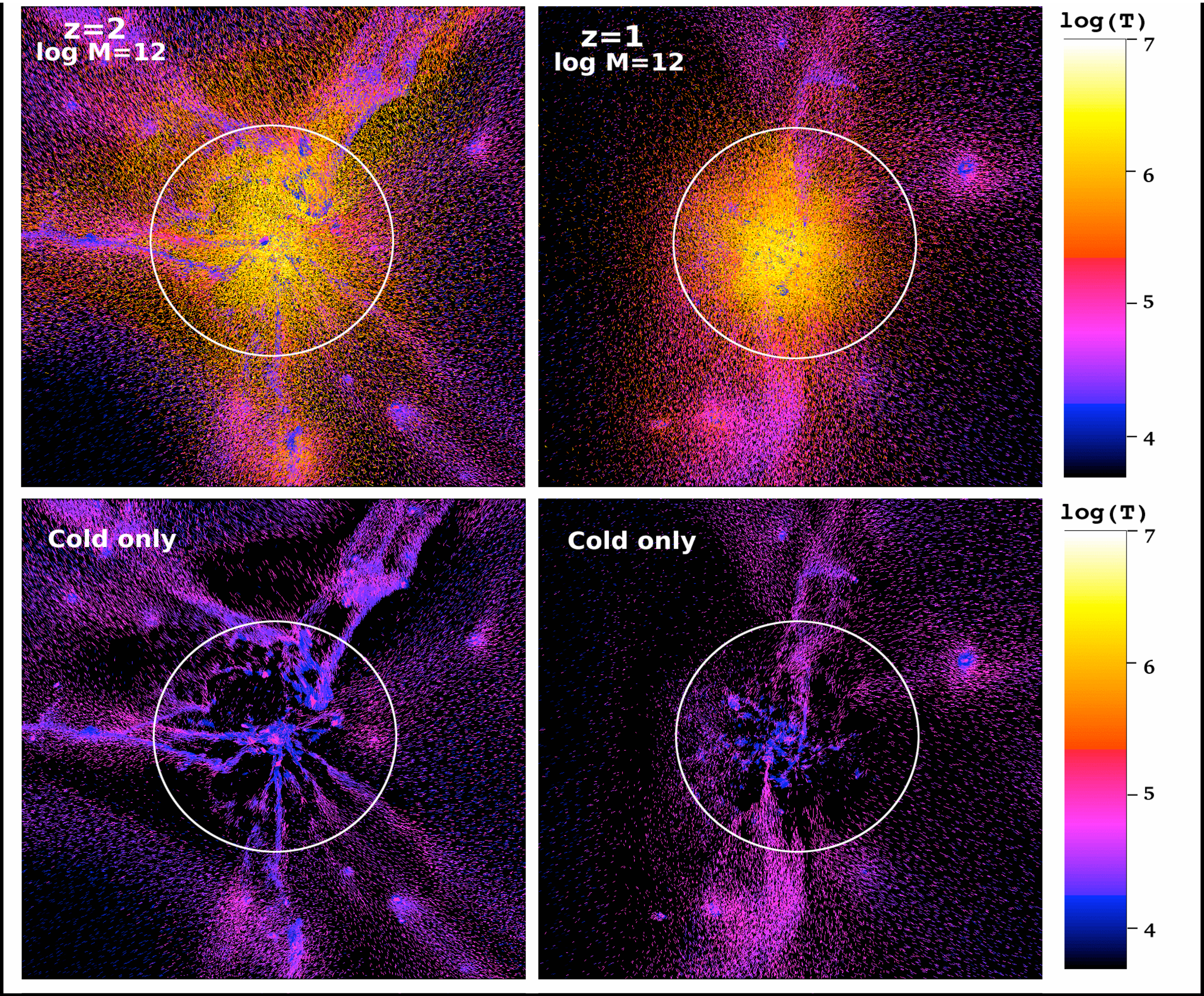
- Kennicutt law -> short SF timescale -> high-z galaxies have high SFR caused by the rapid gas supply
- Supply extends the “duty-cycle” of rapidly star forming galaxies
- Relation very tight in terms of stellar mass better than halo mass
- To match the observed z~2 SFRs (Genzel, Tacconi, Forster-Schreiber, Bouche et al.) all halo gas needs to go into a central galaxy:
  - Non trivial requirements (no hot halos, no satellite star formation).

Illustrations

800/h pc comoving resolution, m_p ~1.e6 M_sun



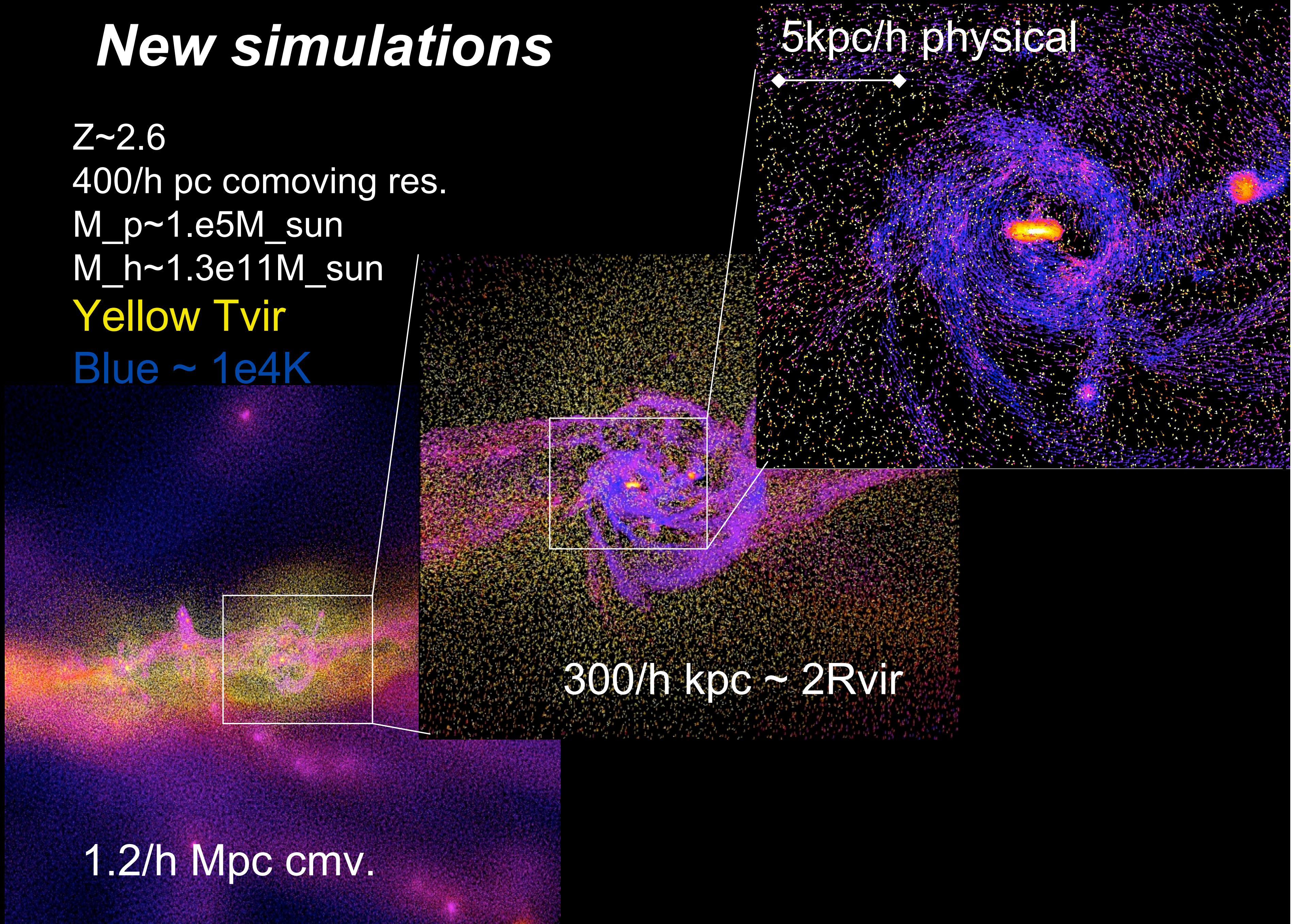
Kereš et al. 2009



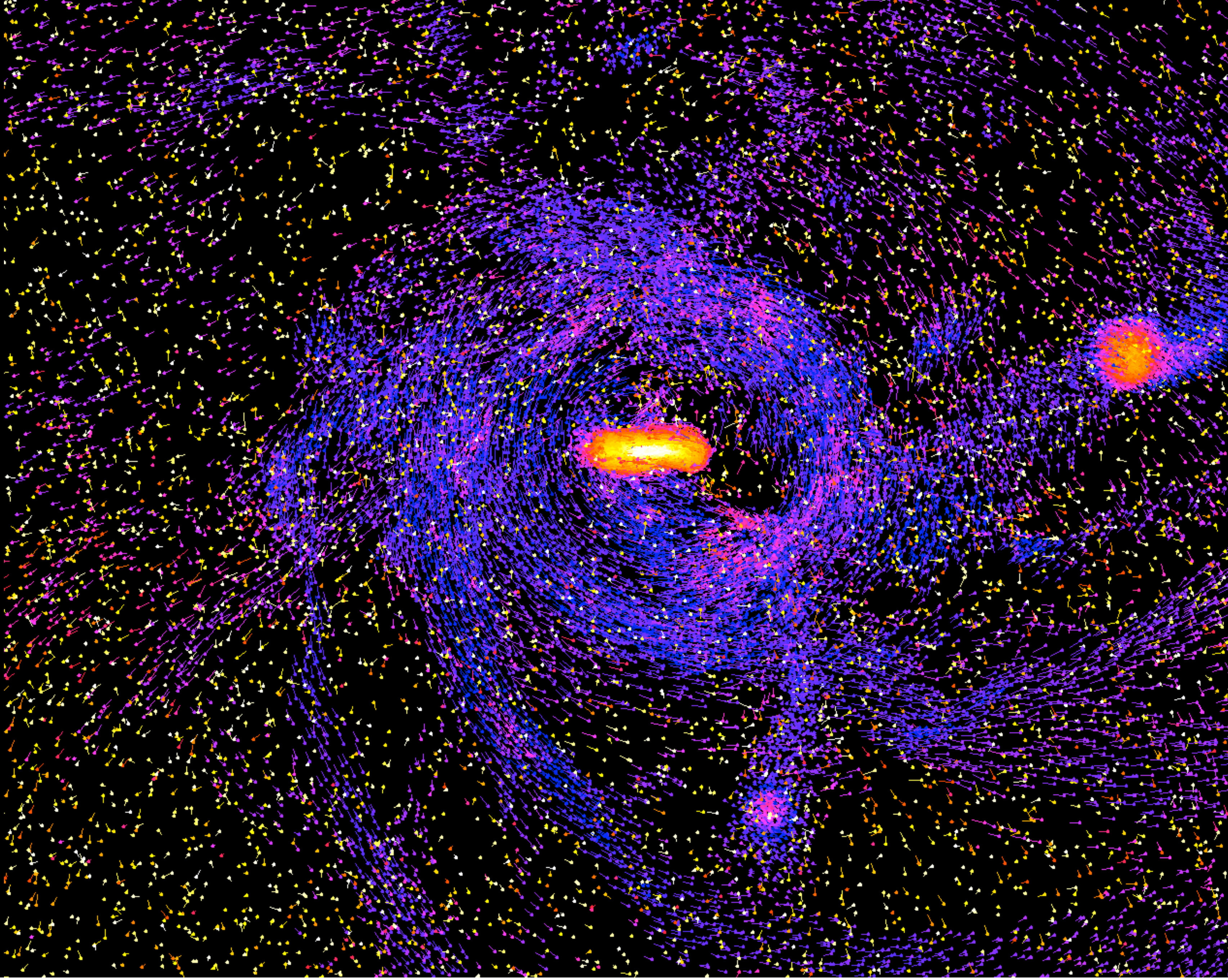
Kereš et al. 2009

New simulations

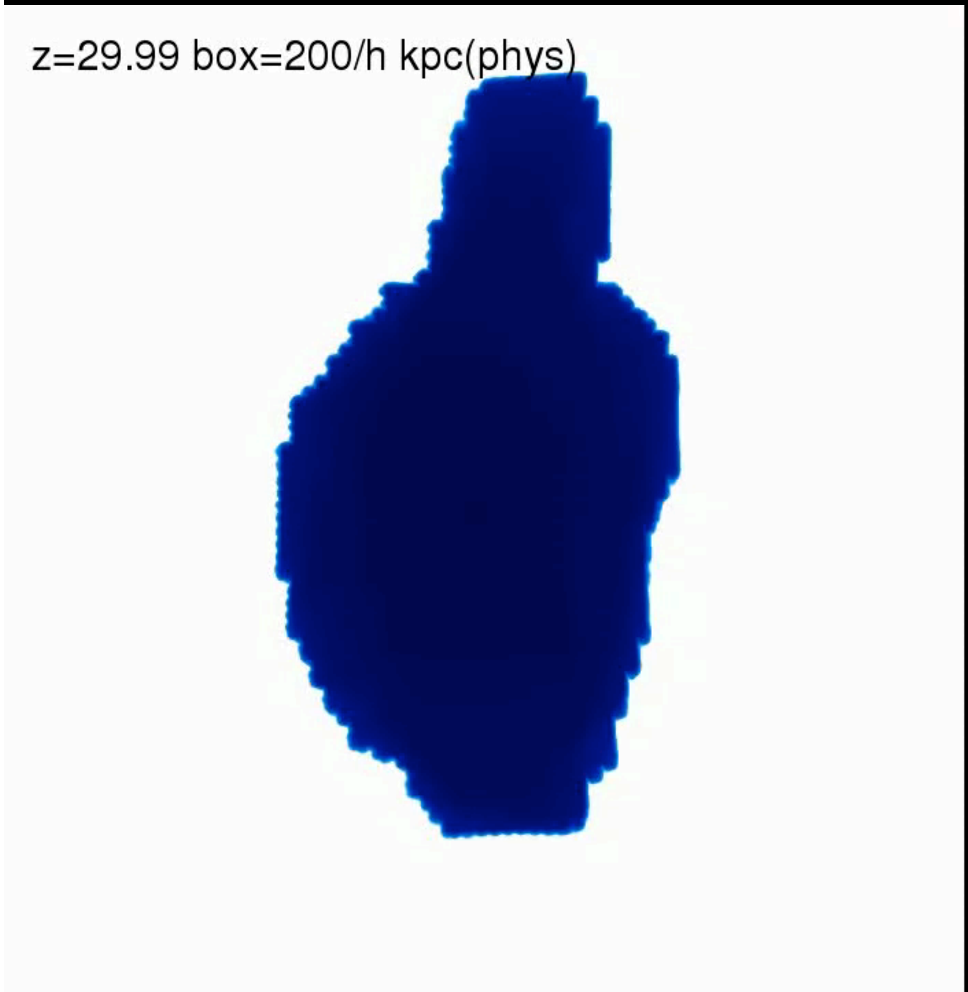
Z~2.6
400/h pc comoving res.
M_p~1.e5M_sun
M_h~1.3e11M_sun
Yellow Tvir
Blue ~ 1e4K



z~2.6, 130pc resolution, 25/h kpc (physical)~100kpc comoving



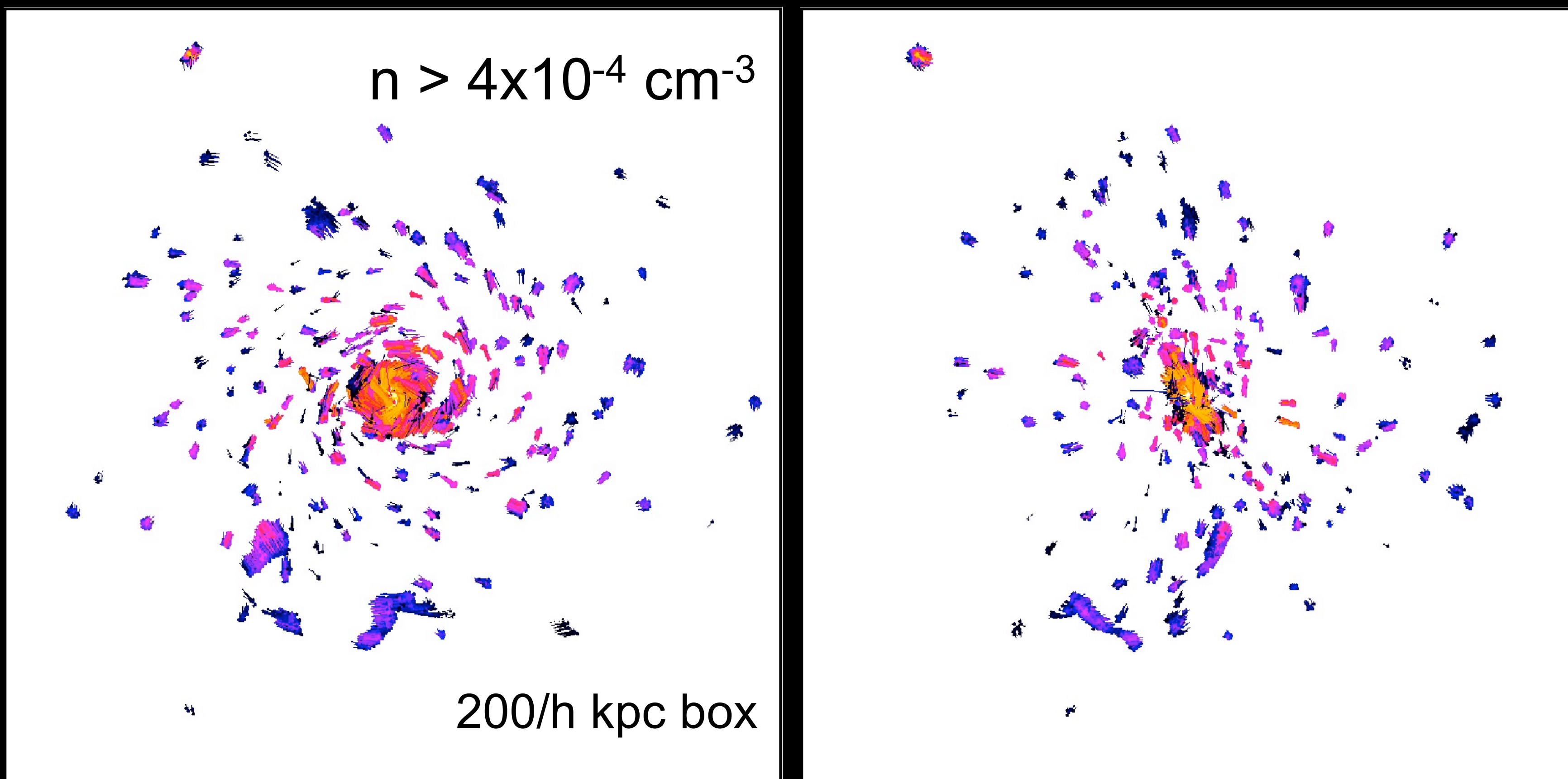
Halo mass at z=0, $7x10^{11}$M_sun
Gas particle mass ~10^5M_sun



Low-z accretion

- In a Milky Way size halos Incoming filaments do not connect to a galaxy in a halo center, instead they are shredded into cold halo clouds that are then infalling onto a galaxy (Kereš & Hernquist 2009).

Halo clouds at z=0



Keres & Hernquist '09

How do clouds form?

- Most clouds form from 1-1.5e5K gas (typical of low-z filaments), not from the 1.e6K virialized halo.
- Incoming filaments are compressed by the surrounding hot medium and shocks from structure formation (and from feedback).
- Penetrating filaments create density inversion in a gravitational field, susceptible to Rayleigh-Taylor instabilities.
- Cooling times in compressed filaments and R-T timescales for a ~2-3 kpc region that forms a cloud are similar.
- These likely act together to form clouds.

- Cloud masses are ~1.e6 Msun up to 1.e7Msun.
- In more massive systems cloud formation starts earlier
- Likely analogs to high-velocity clouds in the MW and halo absorbers at intermediate redshifts.
- Halo clouds provide gas supply for star formation in M* galaxies at lower redshift ($z<1$)
- They form outer disks, and perhaps trigger stochastic star formation in the outer disks (XUV disks).
- At high-z filaments penetrate very close to galaxies, harder to form such clouds, although more careful study is needed to address this question.

Summary

- Accretion of gas from IGM is the most important way of global gas supply to galaxies.
- High redshift ($z > 1.5$) smooth gas accretion is completely dominated by the cold mode filamentary accretion, even in massive halos
- Late time mergers disrupt filaments at intermediate radii in halos creating condition for cloud formation
- Halo clouds form naturally in a fully cosmological simulations
- High resolution is needed to model this process
- Accretion of cold gaseous clouds dominates the late time accretion in MW size halos providing new fuel for star formation