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The Cold Mode Accretion

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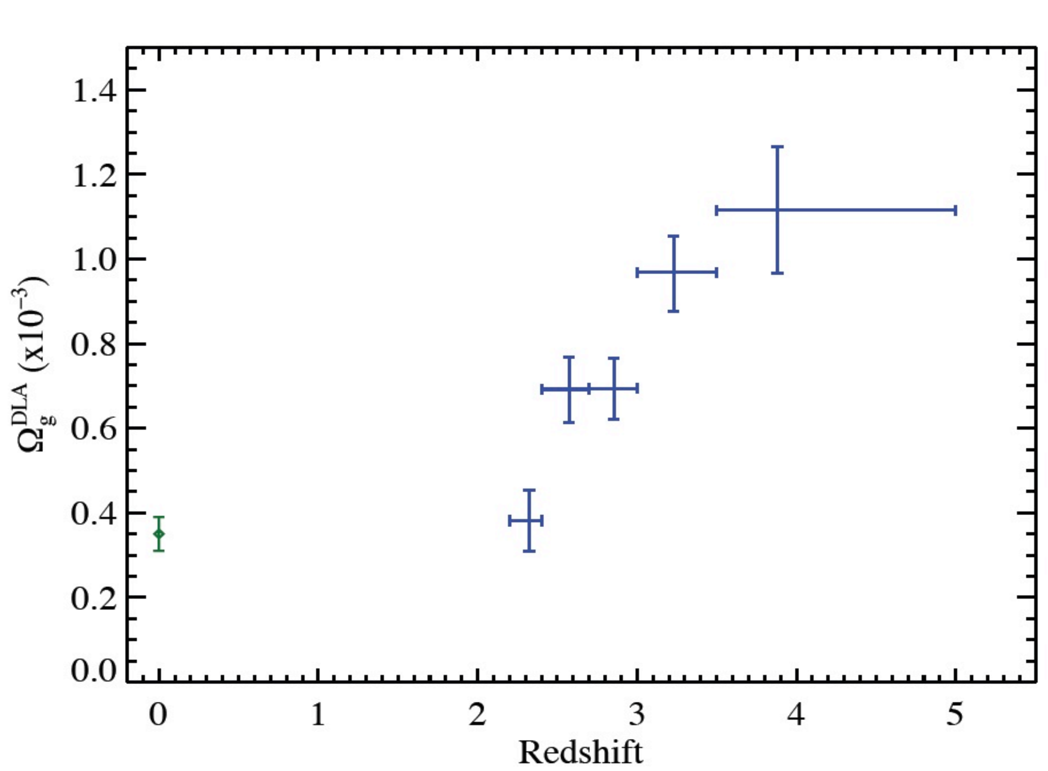
*ρ_* z=0

Gas supply is needed

- Galaxies are actively forming stars at all epochs. *What is the source of fuel for star formation?*
- Star form from molecular gas.
- Molecular gas consumption timescales are << t_H
  - > Additional gas reservoir is needed to support long term star formation.
- Dense atomic phase?
- Amount of HI at high-z is much less than the mass locked in stars at z=0.
- Dense atomic phase also needs to be constantly re-supplied.
- Galaxies contain only <10% of baryons-> huge reservoir available in the IGM
- Gas from the IGM supplies galaxies at all epochs !



Prochaska&Wolfe '08

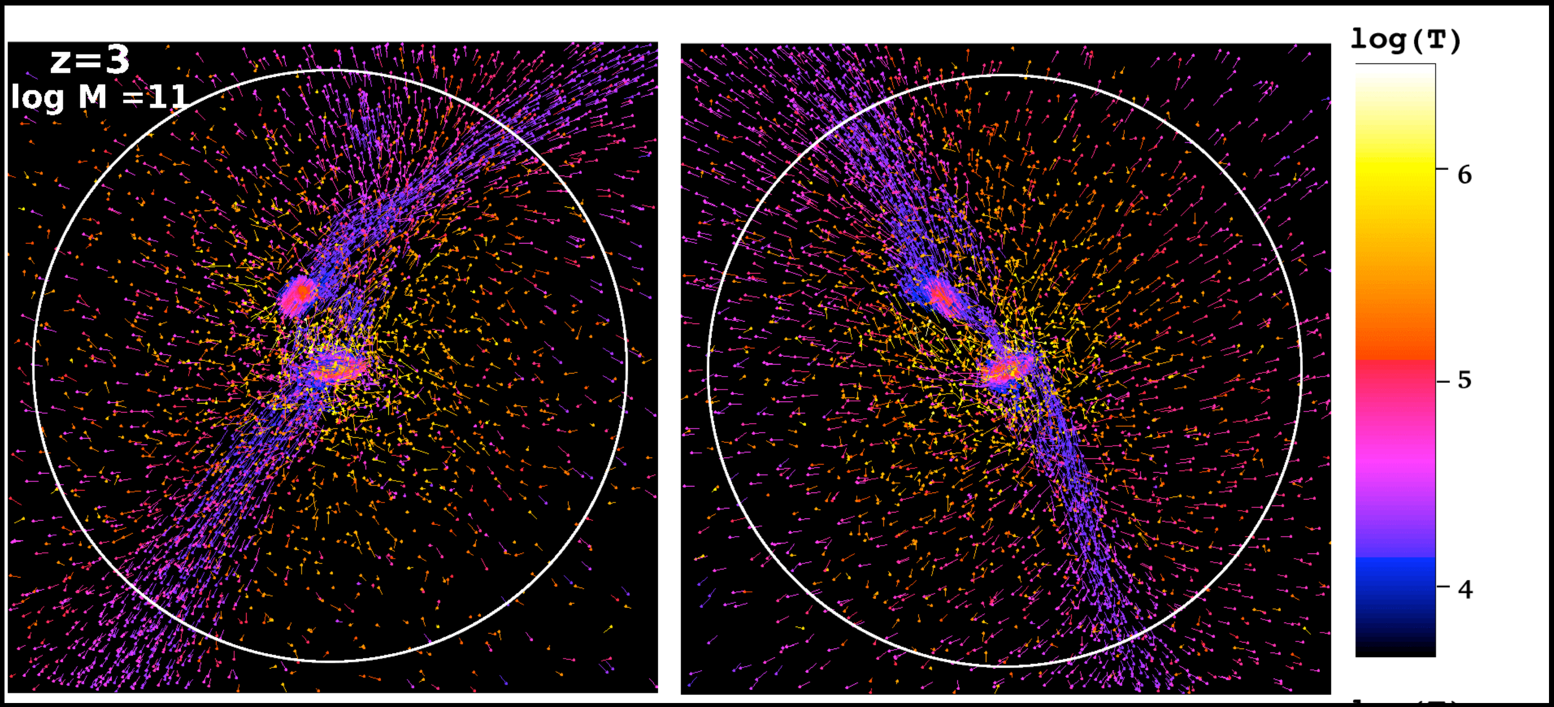
Gas accretion in simulations

- Galaxies accrete fresh COLD gas directly from cold dense intergalactic filaments:
  -> *cold mode accretion*.

- Or from cooling of the HOT virialized atmospheres:
  -> *hot mode accretion*.

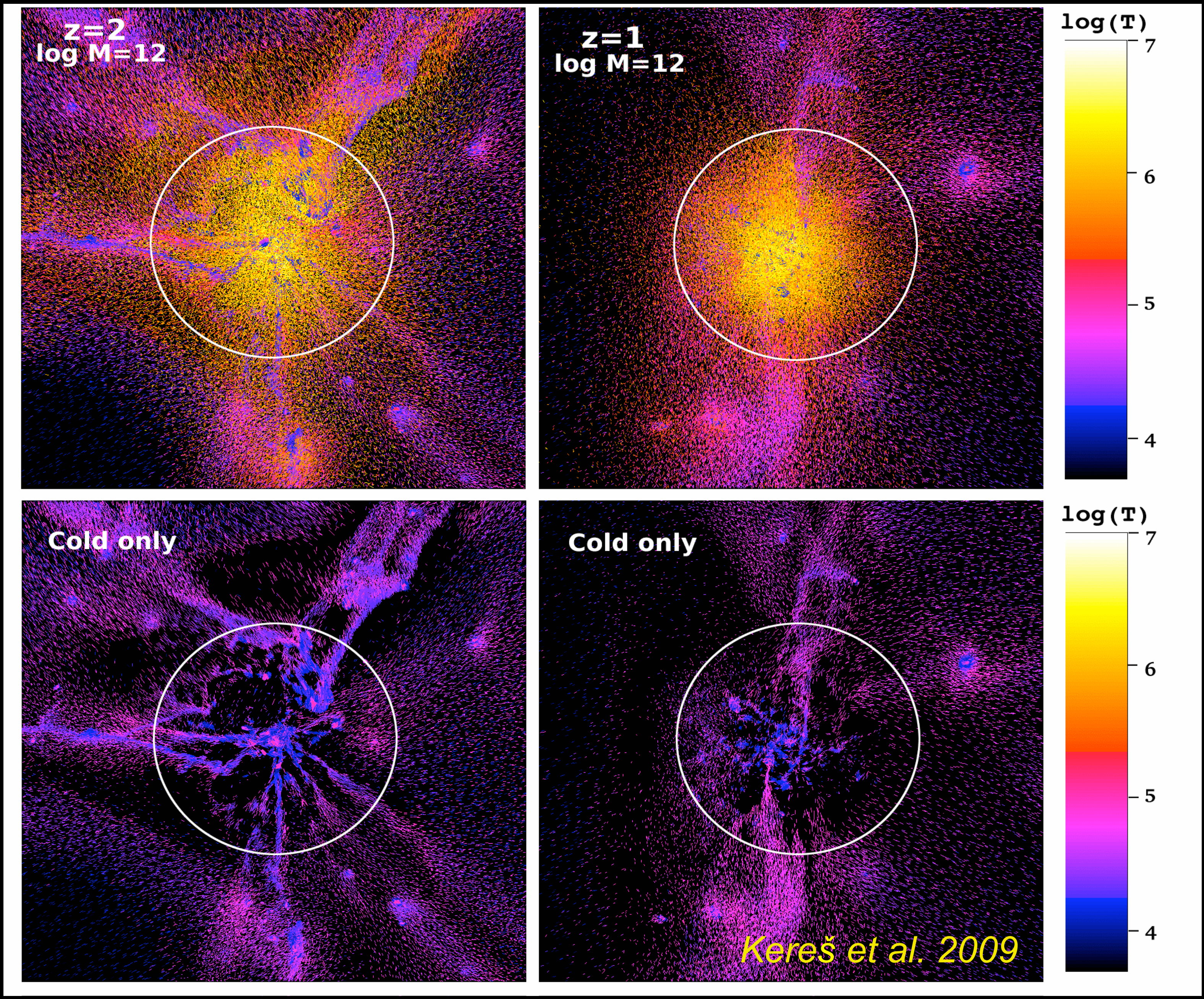
Examples from SPH simulations

- Gadget-3 (Springel 2005+), m_p ~10^6 $M_\odot$, resolution ~300pc (at z=3)
- Low mass halos contain mostly cold non-virialized gas



Kereš et al. 2009

-Massive halos contain mostly hot shock-heated gas



What we learned from theory?

- Based on the cosmological simulations and analytic arguments (*Kereš, Katz, Birnboim, Dekel, Ocvirk, Teyssier, Brooks, Agertz*, *Ceverino* and others), we know that:
  - Filamentary cold mode accretion of non-virialized gas is the dominant way of gas supply into high redshift galaxies.
  - Accretion from the IGM provides continuous fuel source and are driving a high star formation of these galaxies (e.g. Genzel et al.)
  - Filamentary gas is dense; virial shocks cannot propagate trough the filaments even in halos with dominant hot atmospheres.
  - Cold mode provides gas supply to sub-M* galaxies at lower redshifts.
  - Properties and geometry of filaments at fixed mass are changing with redshift.
  - Drop in cosmic density -> decreases of gas supply with time -> lower star formation rates at late times.

Robust global picture but:

- What happens to cold filaments within hot medium?
  - Should they survive as smooth flows?
  - How are these affected by instabilities?

- How is infalling gas slowed down and how it joins the disk?

- How is feedback from galactic winds and AGN affecting the incoming gas?

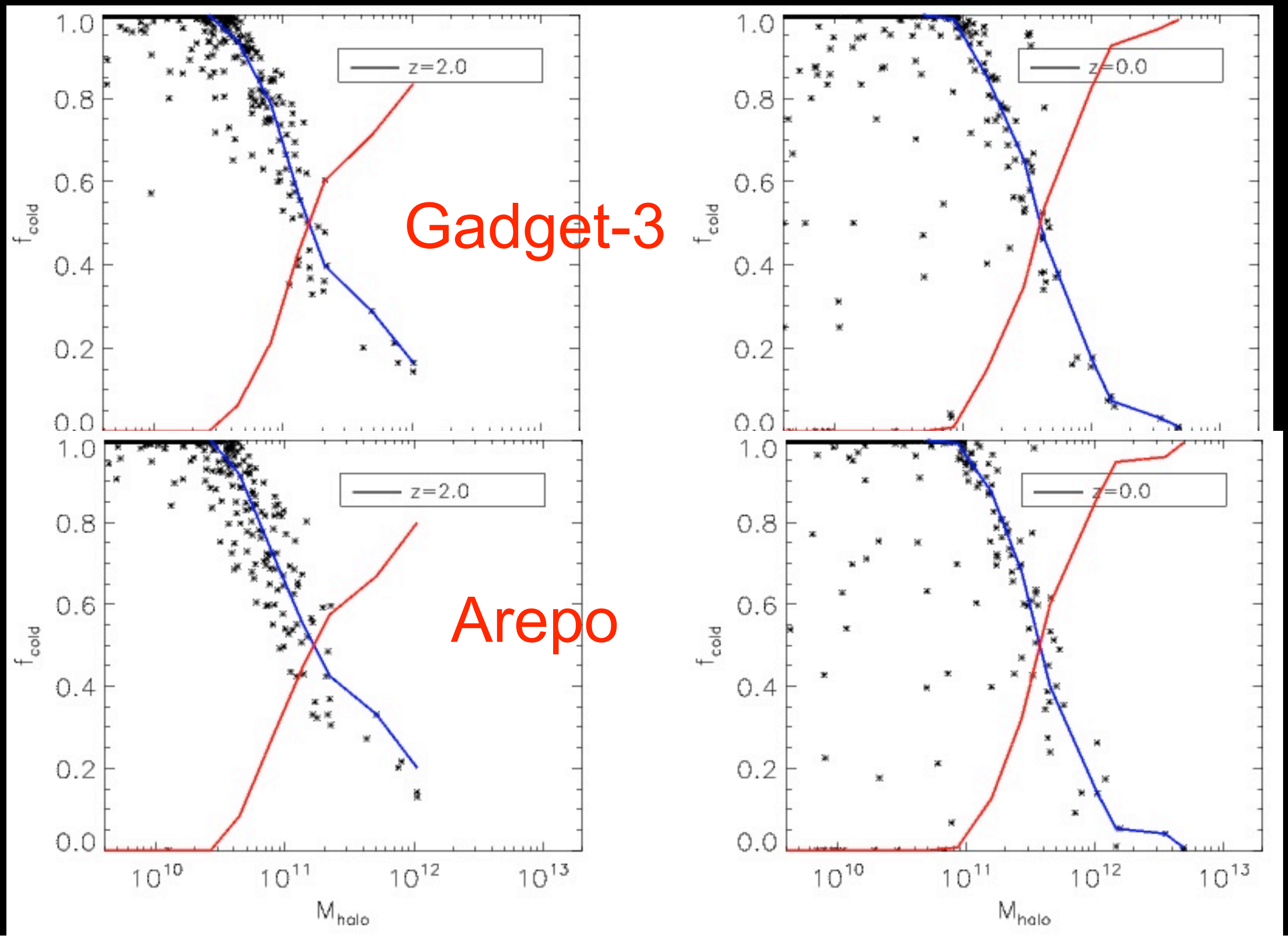
- How to *directly* detect cold mode accretion?

- To make progress we need to re-examine cold mode accretion:
  - Different simulation techniques
  - Higher resolution,
  - Interaction of outflows with infall (ask me later),
  - Predictions for the direct detections.

Different simulation techniques

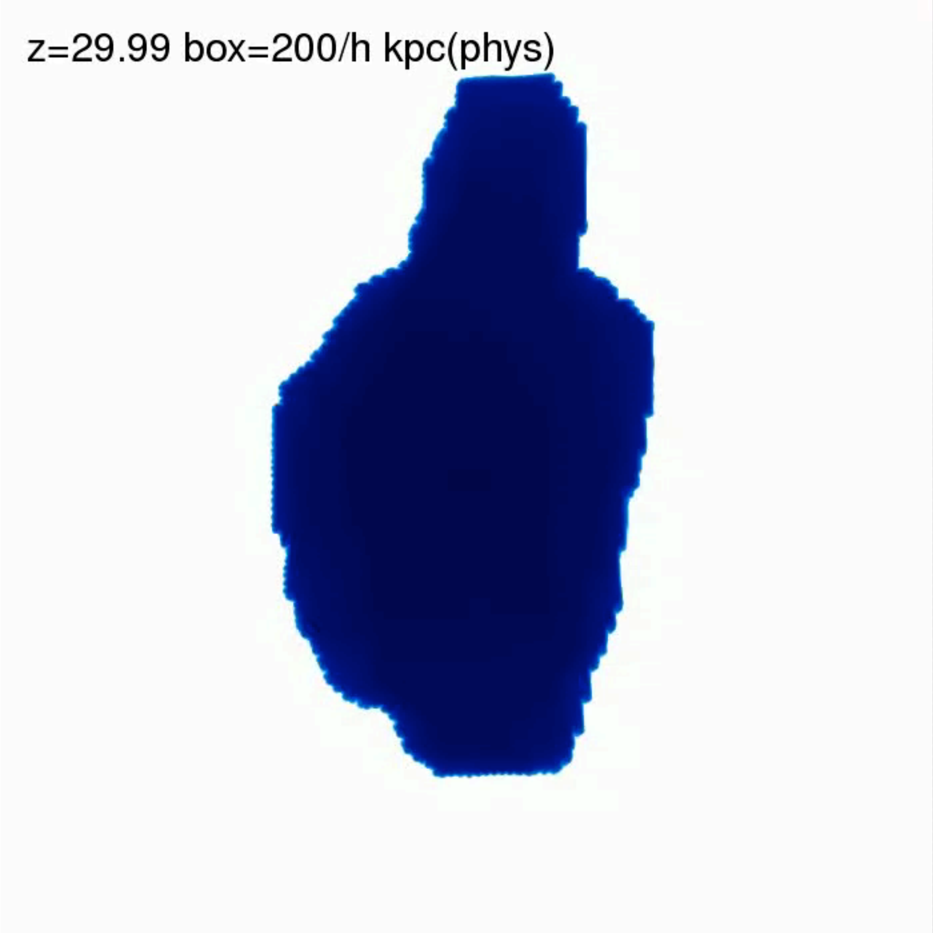
PRELIMINARY (work in progress)

- SPH code Gadget (Springel '05) and moving mesh code Arepo (Springel '10)
  - Same efficient gravity solver, can run on Gadget ICs, better shock capturing, treatment of the instabilities, naturally adaptive, Galilean invariance
- Same ICs: 10/h Mpc box 2x128^3 particles.
- Global properties of cold halo gas are largely insensitive to simulation technique



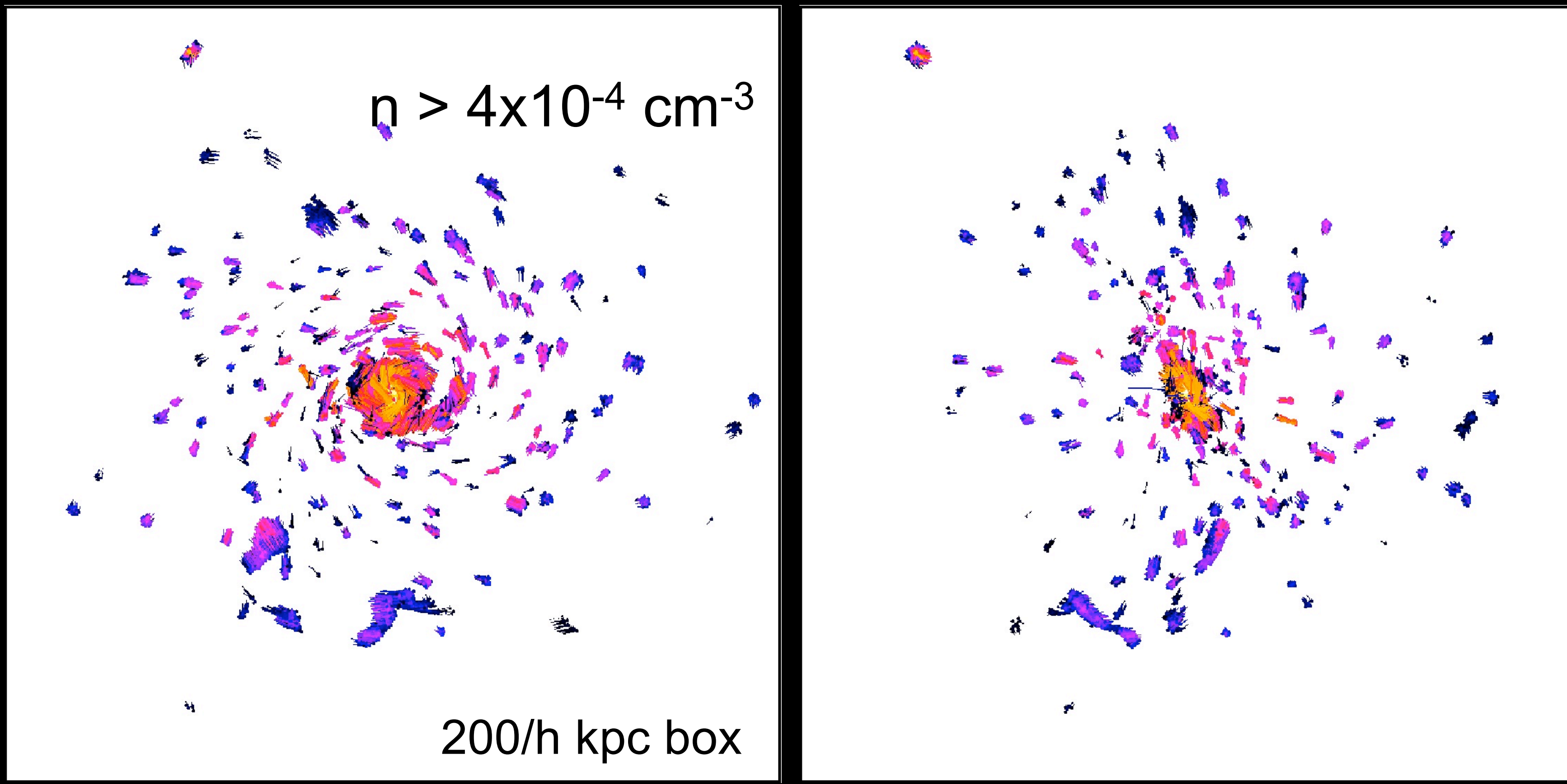
Higher Resolution

Halo mass at z=0: 7×10^{11}M_sun
Gas particle mass: ~4×10^{4}M_sun,
~8 million particles in a halo



Halo clouds at z=0

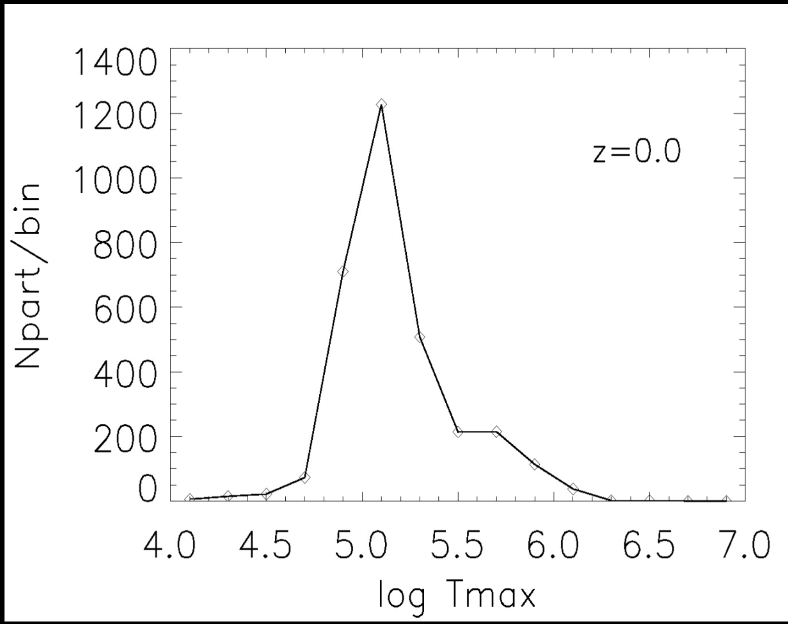
- At high resolution infalling gas forms clouds at late times
- Clouds infall from a flattened distribution in the disk plane.
- Large fraction of infall is co-rotating with galaxy



Kereš & Hernquist '09

Origin of clouds

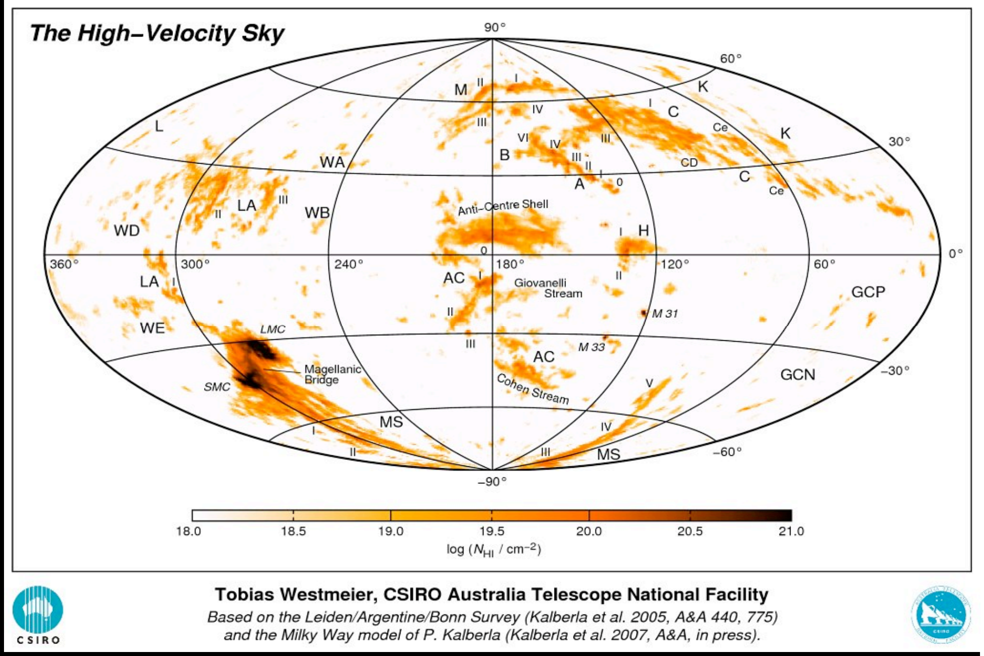
- Most clouds form from 1-1.5e5K infalling gas
  - Leftovers of cold mode accretion
- A fraction forms from hot halo.
- Penetrating filaments create density inversion in a gravitational field, susceptible to Rayleigh-Taylor instabilities.
  - Compressed by the surrounding hot medium and shocks from structure formation.
- Cooling and R-T timescales (at our resolution limit) ~ few 10^8yr, shorter than dynamical timescales of the system.
- Clouds masses are <1e6-1e7Msun: high resolution is needed to resolve them.
- Properties depend on resolution…

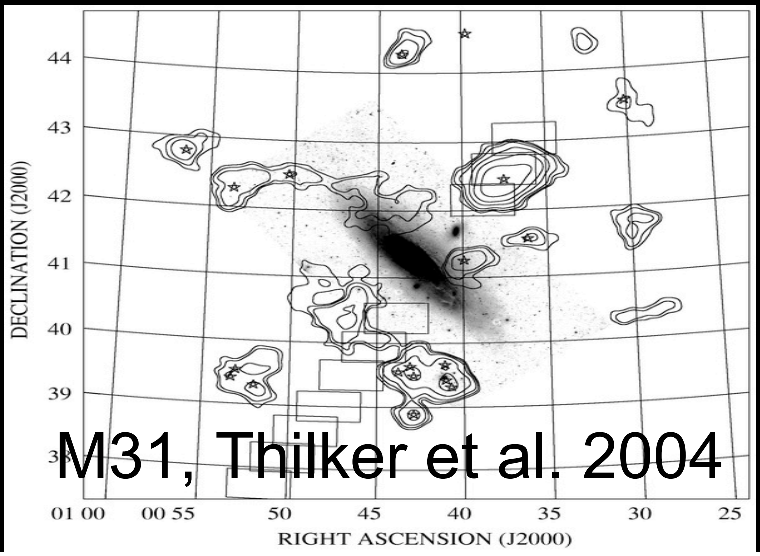


Observational Signatures

Nearby galaxies

- Only direct detection of the accreting gas comes from “local” HI observations.
- Milky Way: infalling high-velocity HI clouds.
  - Similar clouds around nearby galaxies.
- Simulated clouds broadly consistent with observations
  - ~1e6Msun,
  - log N_H(cm^{-2})~19-20
- Estimates of infall rates based purely on HVCs are biased low:
  - Large fraction of accretion is co-rotating with the disk, hard to separate in velocity space.
  - HI observations probe only dense, innermost clouds, the rest is ionized.
  - Work in progress





M31, Thilker et al. 2004

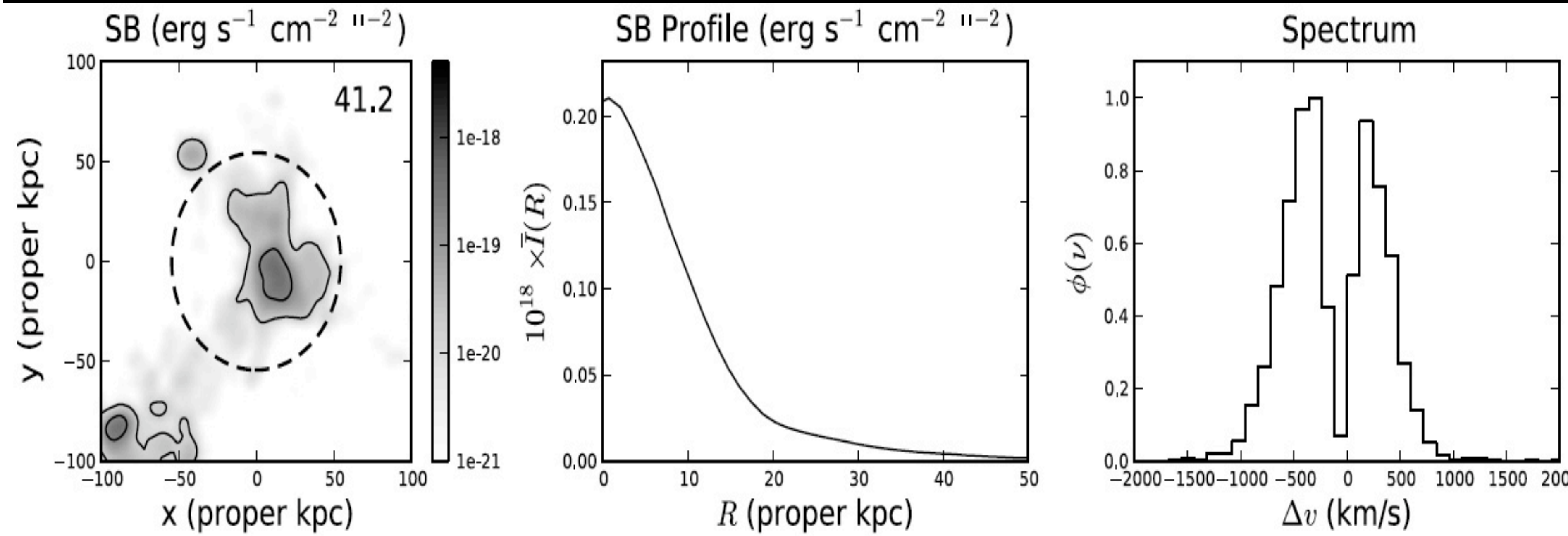
Higher redshift

- At intermediate redshift (z~0.5-1) MW size halos contain infalling (and outflowing) halo clouds. Wealth of MgII absorbers in QSO spectra (e.g. Chen & Tinker '08).

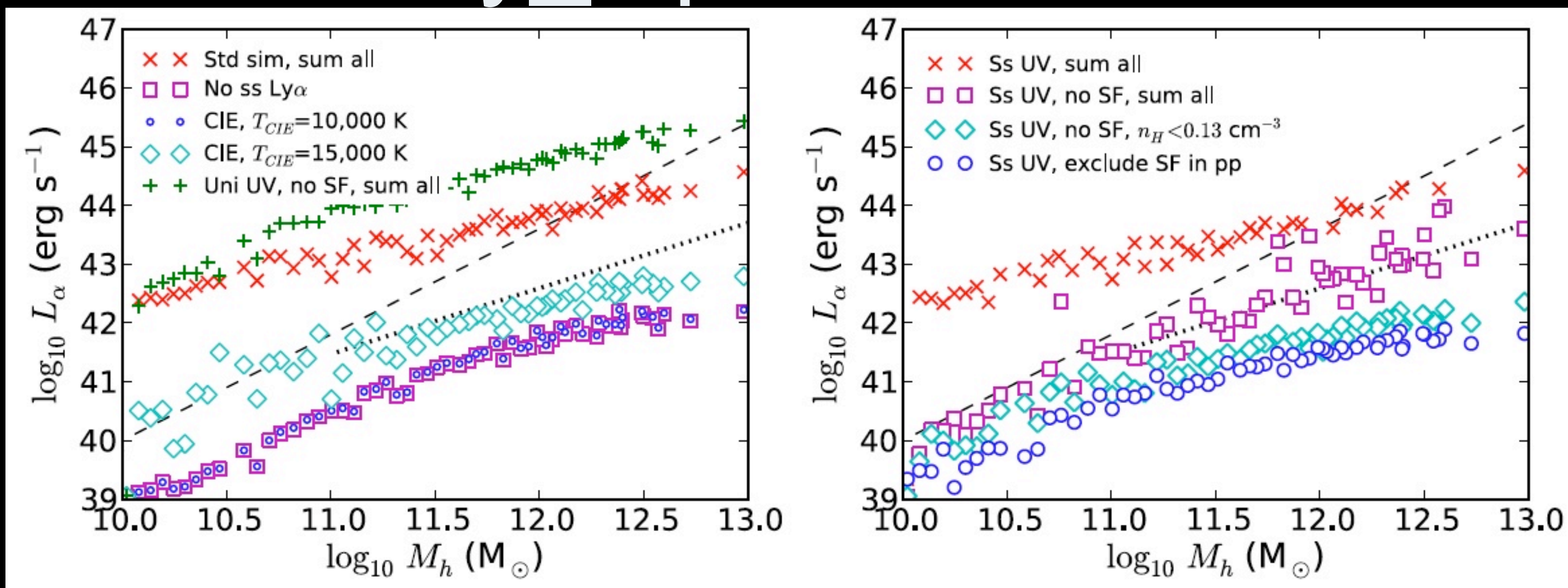
- At high redshift (z~3): absorption studies, both directly from galaxies and using background quasars and galaxies as probes of the halo gas (e.g. Steidel et al. 2010)
  - Most of these show signature of galactic outflows
  - Not very surprising as the infalling filamentary gas has a small cross-section and low metallicity.
  - No detailed predictions -> time to improve this.
  - Expensive simulations ….
- Direct Ly_alpha emission from the infalling gas in z~3 halos:
  - Cooling radiation form the infalling gas is a strong source of Ly_alpha emission (e.g. Katz &Gunn 1991, Fardal et al.2001, Dijkstra&Loeb 2009, Goerdt et al. 2010)
  - Complex: Need to precisely identify self-shielded regions and to do Ly-alpha line radiative transfer

Ly_alpha emission from simulated halos

- Faucher-Giguere, Keres et al. 2010 (arXiv:1005.3041)
- Ionizing radiation R-T, self-shielding & Ly_alpha line R-T.
- Example: 2.5e11Msun halo at z=3, form zoom-in simulation.
  - Cooling radiation from the halo gas emission is detectable and could contribute significant part of the Ly_alpha emission from extended blobs.



Luminosity function of Ly_alpha blobs



Faucher-Giguere, DK et al. 2010

- Predictions are extremely sensitive on the correct treatment of star forming and self-shielded regions (strong temperature dependence at 1-2e4K):
  - Orders of magnitude differences!
  - Need to be careful with previous work!
  - With star forming regions excluded, fraction of emission of brightest blobs comes from cooling radiation, additional sources are needed to get to ~1e44ergs/s.
  - Lower luminosity extended sources can be powered by the cooling radiation.

Summary

- Cold mode accretion is now a theoretically robust scenario.
- Interesting open questions remain.
- High redshift accretion is not yet directly detected.
- We should start making careful predictions for the direct observability of the accreting gas!
- This will help constrain different models of gas accretion in a very direct way.