Cold (and hot) mode accretion

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Moving-mesh: L. Hernquist, D. Sijacki, V. Springel and M. Vogelsberger
Where is the reservoir for cosmic star formation?

- What fuels long-term star formation activity of galaxies over Hubble time?
- Stars form in molecular gas.
  - However, consumption timescales are $<<$ age of the universe (e.g. Daddi et al. 2008, Genzel et al. 2010).
- Dense atomic gas?
  - Global density of HI is $<<$ than the stellar mass density at $z=0$.
  - Dense atomic phase also needs to be constantly re-supplied.
- Galaxies contain $<10\%$ of baryons, huge reservoir available in the (ionized) IGM.
- Gas from the ionized IGM supplies galaxies at all epochs!
- Interesting process to follow.

Cosmological HI mass density probed by DLAs

Prochaska&Wolfe ‘09
Temperature history of accreted gas

- Initial work done with Lagrangian SPH simulations, without outflows!
- We follow each accreted gas particle in time and determine its maximum temperature - $T_{\text{max}}$ - before the accretion event.
- In the standard model one expects $T_{\text{max}} \sim T_{\text{vir}}$
Temperature evolution of accreted gas is bimodal

- Gas heated to high $T$ -> HOT MODE accretion.
  - Cooling of the hot virialized atmospheres.
- Gas that was not heated to high $T$ -> COLD MODE ACCRETION.
  - Galaxies accrete fresh gas directly from cold dense intergalactic filaments.
- Division at $T_{\text{max}} = 2.5 \times 10^5 \text{K}$ (works well for high-$z$ accretion) (Katz, Keres, Weinberg, Dave 2003)
- Birnboim&Dekel 2003: explain how shock propagation starts from the inner halo and expands outwards in more massive halos.

Kereš et al. 2005
How important are these two accretion modes?

- Cold mode completely dominates the gas accretion at early times.
- Because of relatively short star formation timescales, it dominates high-z star formation.
- Hot mode is globally important at lower redshift. However, rates depend on: numerical method, metallicity, feedback etc. (e.g. Van de Voort et al. 2011, Faucher-Giguere et al. 2011).
- In simulations with outflows large fraction of low redshift gas supply can come from re-accreted material (Oppenheimer et al. 2010).
High-z cold mode accretion

- **Cold mode accretion** via dense filaments dominates at high redshift and in **halos below $3\times 10^{11} M_\odot$$^\text{(Katz et al. 2003, Keres et al. 2005).}** Cold, dense gaseous flows reach galaxies without strong shocks.

*Illustration from Gadget-2 SPH simulation without feedback (DK+ 2009)*
High redshifts: no strong dependence on the numerical method
- supported by analytic studies, different SPH and AMR simulations (e.g. Dekel & Birnboim 2006, Ocvirk et al. 2008, Brooks et al. 2009, Van de Voort et al. 2011).

\( M_{\text{vir}} \approx 3.5\times10^{11}\text{M}_\odot \)

Agertz, Teyssier, Moore 2009
Is cold infall neutral and can we detect it?

- Covering fraction of gas with $N_{\text{HI}} > 2 \times 10^{20} \text{cm}^{-2}$ is only 3-4% inside $R_{\text{vir}}$ at $z=2$ (in a halo that likely hosts Lyman Break Galaxies). Covering factor of LLS is $\sim 10-20\%$.
- After $z \sim 3$ most of the infalling material is in ionized form within $R_{\text{vir}}$.
- Large covering factor of outflows will wash out signatures of gas accretion in a stacked spectrum.
  - Detection even more difficult: low metallicity infall and not always large infall velocity.
- Need to extend predictions to low-$z$: extremely uncertain ....
- Simulations with realistic outflows are needed to properly explain observations:
  - Larger covering factors from winds
  - Distruption of cold filaments

*Faucher-Giguere & Kereš 2011*
Feedback and filamentary infall

- Zoom-in simulation of ~MW progenitors (Mh \( \sim 7 \times 10^{11} \text{M}_\odot \) at z=0): Gadget-3 frame.
- Gas particle mass \( \sim 4 \times 10^4 \text{Msun} \) (~8m particles within Rvir at z=0). Comoving force resolution 30/h at z=4, minimum smoothing length is \( \sim 5/h \text{ pc} \).
- Cold/molecular ISM clumps: HII heating, radiation pressure on embedded dust, stellar winds, and SN (Hopkins, Quataert, Murray). SF threshold n=100/cm^3. **NO COOLING DELAY, NO DECOUPLING.**
Hot halos

- For $M_h > 3 \times 10^{11} M_\odot$ halos contain mostly hot shock-heated gas (AMR and SPH give very similar results for transition from cold to hot halos)
  - Cooling of the hot gas -> hot mode accretion: inefficient in Gadget simulations but plays a significant role in mesh-based simulations (e.g. Agertz et al. 2009, Keres et al. 2012).
  - Cold filaments bring gas deeply into the halo but are not always reaching galaxies. Results depend on the code: early results suggested more efficient disruption of filaments in massive halos (Keres et al. 2005).

$SFR \sim 20 M_\odot/yr$

$SFR \sim 5 M_\odot/yr$

Kereš et al. 2009
AMR shows disruption/heating of filaments at larger radii in massive halos

2e12Msun, Ocvirk et al. 2008
Fraction of halo gas in a given phase does not directly translate to the gas accretion!

**GADGET**

**AREPO**

Transition from cold to hot halos in Gadget and Arepo (Springel ’10)

Fraction of cold and hot halo gas
Halo gas: example at $z=2$

$M \sim 6.5 \times 10^{11} \text{Msun}$, 1Mpc/h comoving region.
Differences between Arepo and Gadget

- Arepo filaments are warmer and less dense.
- At z~3-4 in both codes they can reach the central galaxy but one needs to use tracer particles to compare the actual accretion rates (e.g. M. Vogelsberger’s talk yesterday).
- At z~<3 filaments tend to get disrupted earlier in Arepo.
- Clumping of cold/warm gas in hot halos does not happen in moving-mesh.
- The largest difference between Arepo and Gadget, however, is the HOT GAS COOLING.
Milky Way mass halos in AREPO cool their gas efficiently

- Differences in hot halo cooling are connected to difference in gas heating owing during the ingall.
- This ows to incorrect energy dissipation from the subsonic turbulence in Gadget (Bauer&Springel 2012).
Higher SFRs in massive halos

Keres, Vogelsberger, Sijacki, Hernquist & Springel 2012
Gaseous disks in AREPO are larger

- Differences in hot mode infall, gas stripping from infalling satellites and formation and infall of the cold clumps produces large differences in morphology of galactic disks.

DK, Vogelsberger, Sijacki, Springel, Hernquist 2012
Open issues

• How deep do cold filaments penetrate as a function of mass and time?
• How do they get disrupted?
  – are they forming infalling clumps?
• Where and how do they join onto galactic disk and dissipate their potential energy.
• How efficient is hot halo cooling?
• How all of this changes in simulations with realistic feedback?
  – interaction of outflows with infalling gas
  – change of the hot gas halo structure
  – metal cooling
• Self-shielding, conduction...
Conclusions

• Infall of cold, dense filamentary gas dominates the accretion of fresh gas in high redshift galaxies and in halos below 3-4e11Msun.

• Accretion at lower redshift and in massive halos is more complex and theoretically less certain:
  – Direct cold mode, in a form of dense cold filaments is dramatically decreasing in massive (>1e12Msun halos) at low redshift, even though it might dominate the infall rate.
  – Cooling of the hot medium increases its importance at low redshift: much more important in moving-mesh.

• Low redshift accretion is very sensitive to resolution, code and physics implemented:
  – Theoretically not well constrained problem, the most acute in ~MW mass halos.