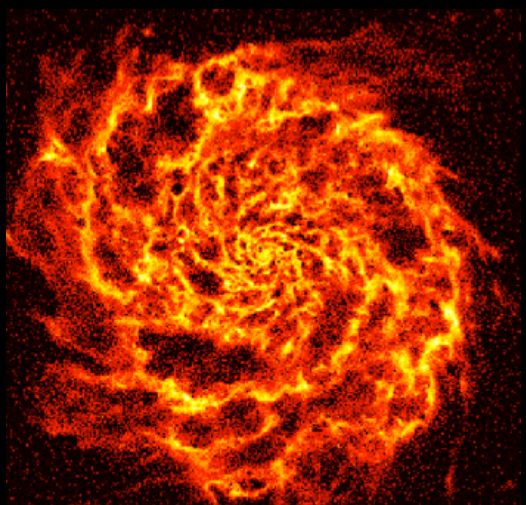
IGM@50, Spineto Italy

June-09-2015

Galaxies on FIRE: Stellar Feedback and flows of gas in galactic halos



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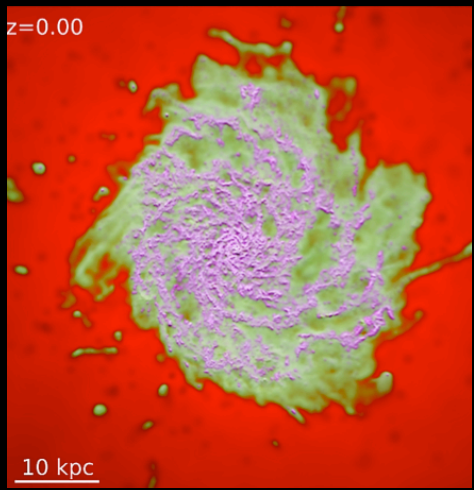
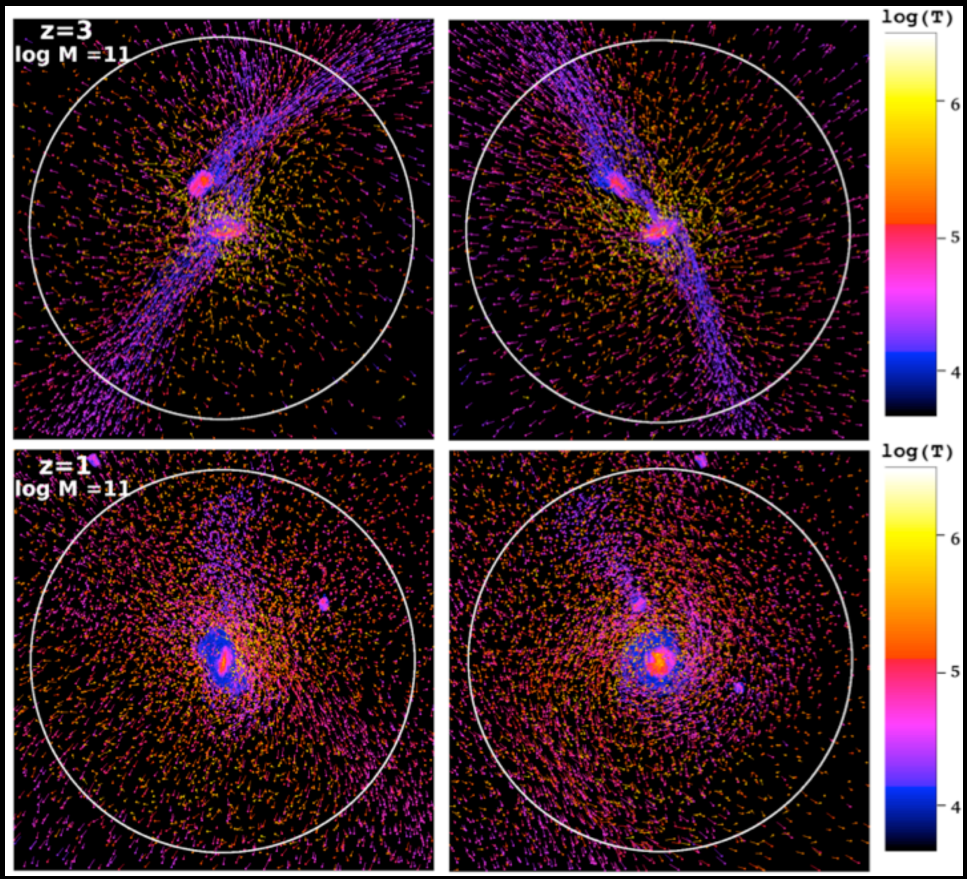


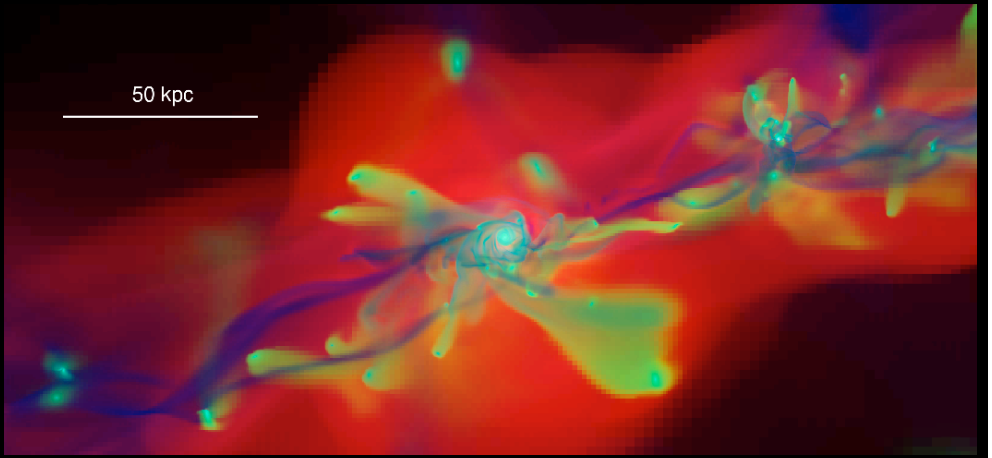
With: P. Hopkins, C-A. Faucher-Giguere, A. Muratov, E. Quataert, N. Murray, B. Dong and the FIRE team

Galaxy evolution: interplay between infall and outflows

-Infall of gas from the IGM via cold and hot mode accretion supplies long-term star formation activity of galaxies. *It is "easy" to measure theoretically.*



Keres+2005, 2009 (SPH without feedback)

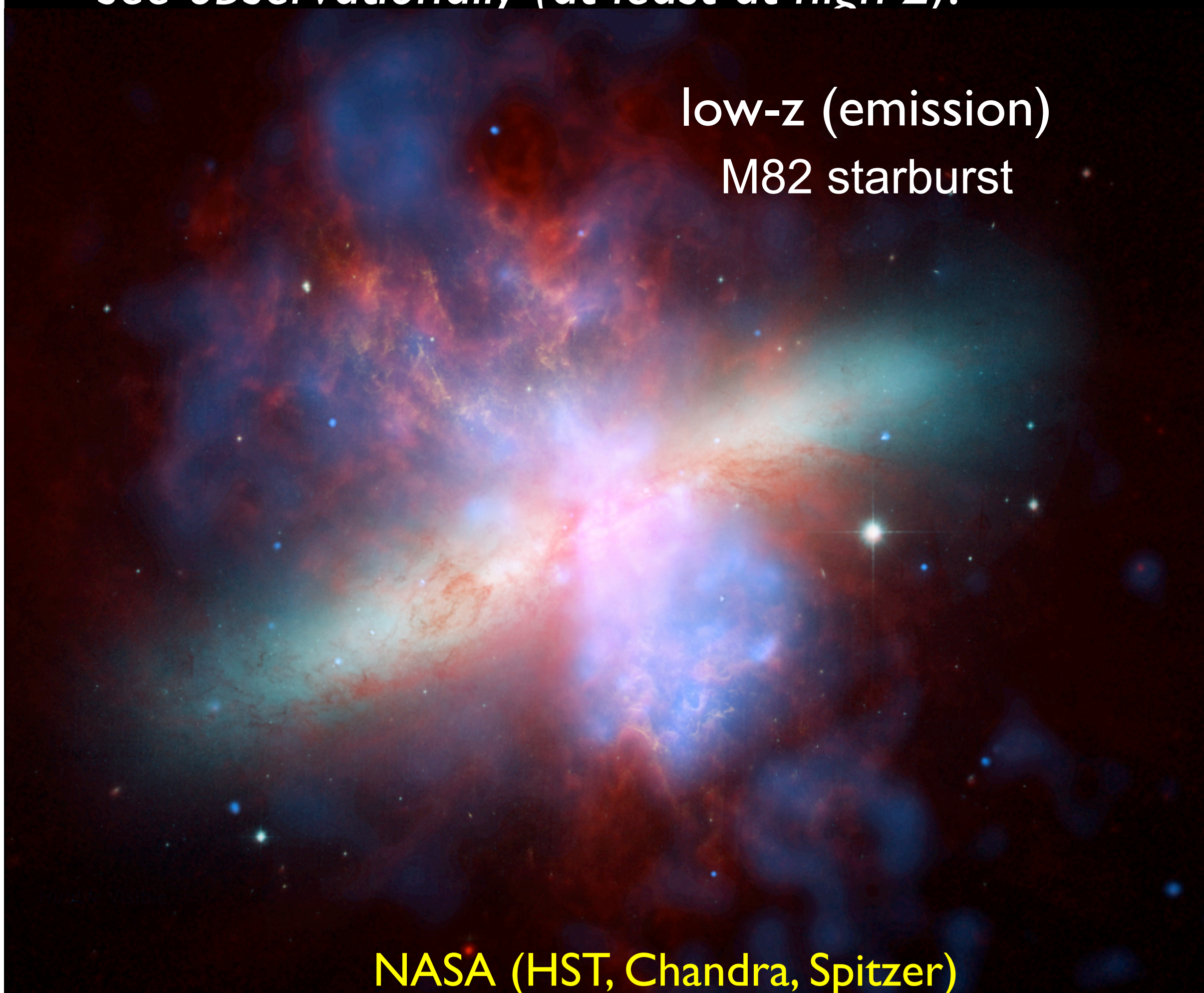


Agertz+2009 (AMR with weak feedback)

See also: Dekel&Birnboim'06, Dekel+'09, Brooks+'08,Nelson+'15

Galaxy evolution: interplay between infall and outflows

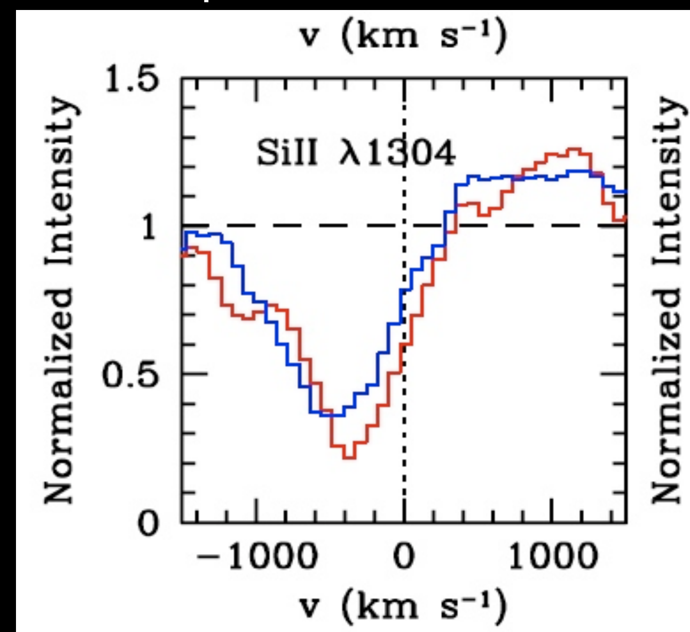
-Outflow of material from galaxies regulate their growth. *Outflows are easy to see observationally (at least at high-z)!*



NASA (HST, Chandra, Spitzer)

high-z (absorption)

Stacked spectrum of LBGs at z~2.5



Steidel+2010
(see also Rubin+'10 ,Weiner+'09)

To understand galaxy evolution we need to account for gas infall and gas outflow processes and their mutual interaction!

How to model star formation feedback in cosmological simulations?

- Infall occurs naturally as structure collapses, but feedback is more complex.
- At a typical resolution SN feedback overcools (Katz '92), i.e. affects too much gas, which cools fast without generating appreciable momentum (e.g. Kim&Ostriker '14)
- Two common methods to generate efficient outflows from galaxies:
- **Hydro decoupling**: winds are implemented "by hand" assuming mass loading and velocity that scales with galaxy properties.
    - Often not allowed to interact with the ISM and nearby gas until they leave the galaxy (Springel & Hernquist '03, Oppenheimer & Dave '06, Vogelsberger+ '14).
- **Cooling prevention**: gas heated by SNe is not allowed to cool for ~10 Myrs (orders of mag. longer than the actual cooling time) to allow it to escape the galaxy.
    - High-resolution simulations (e.g. Stinson+06, Governato+2010). Allows bursty star formation, but cooling prevention does not allow realistic ISM and wind treatment.

Need to incorporate ISM details...

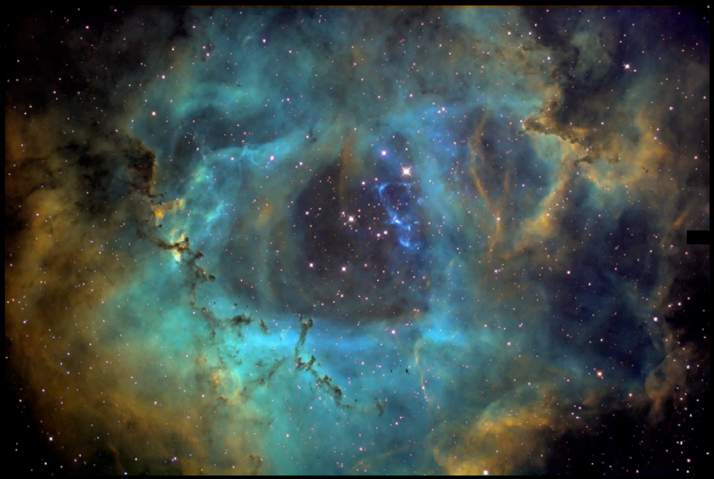
- Real gas affected by star formation can cool and responds to hydrodynamics! How to enable winds to develop self-consistently?
- Multiple processes occur in star forming regions: radiation pressure on dust, photo-ionization and heating, stellar winds, photo-electric heating and finally supernova type II explosion (~4-25 Myr later).
- All can be important at different stages of the evolution of a star cluster! (e.g. Lopez et al. 2013).

Star cluster in 30 Doradus

HII regions around young cluster in Rosette Nebula

Cosmological simulations: FIRE Project

- **F**eedback **I**n **R**ealistic **E**nvironments: galaxies simulated with a physical model of star formation driven feedback within the multi-phase ISM in fully cosmological environment!
- FIRE resolves scales of giant molecular clouds in a multi-phase ISM and includes a range of relevant feedback processes in addition to SN energy and momentum! We account for momentum accumulated by expanding remnant when cooling radius is unresolved.
- Most of these feedback mechanisms act before SN explode, lowering local densities and boosting efficiency of SN feedback: ***no hydro decoupling no cooling prevention***!
- Simulations use modern P-SPH scheme (can do K-H, R-T etc.)
- *Goal: how local feedback affects galaxy evolution and the cycle of baryons?*

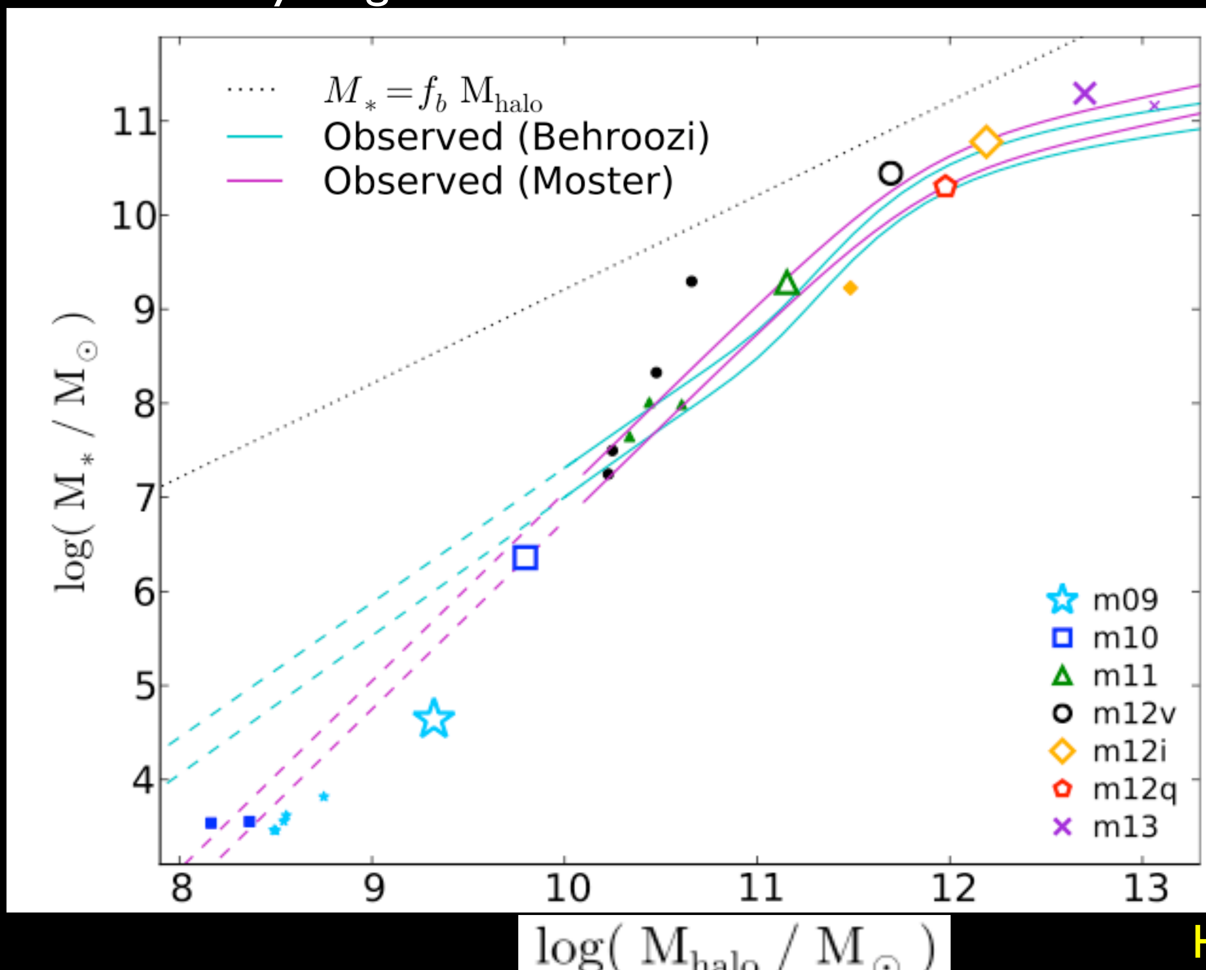


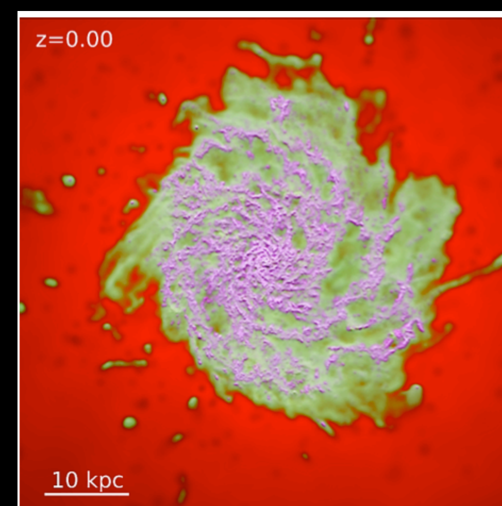
?

- We allow gas to cool to <1000K and allow SF only in locally self-gravitating molecular gas with densities n_H >10-100 cm^{-3}
- FIRE includes some of the highest resolution zoom-in cosmological simulations to date: m_g ~ few 10^2 to few 10^4 Msun and ~2-20pc hydro resolution in dense ISM.
- As soon as stars form they start providing momentum and energy input to their surroundings based on STARBURST99 stellar population model (Leitherer et al. '99).
- Important to include momentum feedback: even if thermal energy cools out, it is harder to get rid of momentum.

FIRE: feedback regulates galaxy masses

- Comparison with observations tests the model: not tuned, input comes from SPS.
- Halo masses from ~10^9 to < 10^{13}Msun: use to study various aspect of galaxy evolution: very good match to stella-mass halo-mass relation.
- Also a good match to mass-metallicity relation and star formation histories of galaxies and matter density of galaxies..

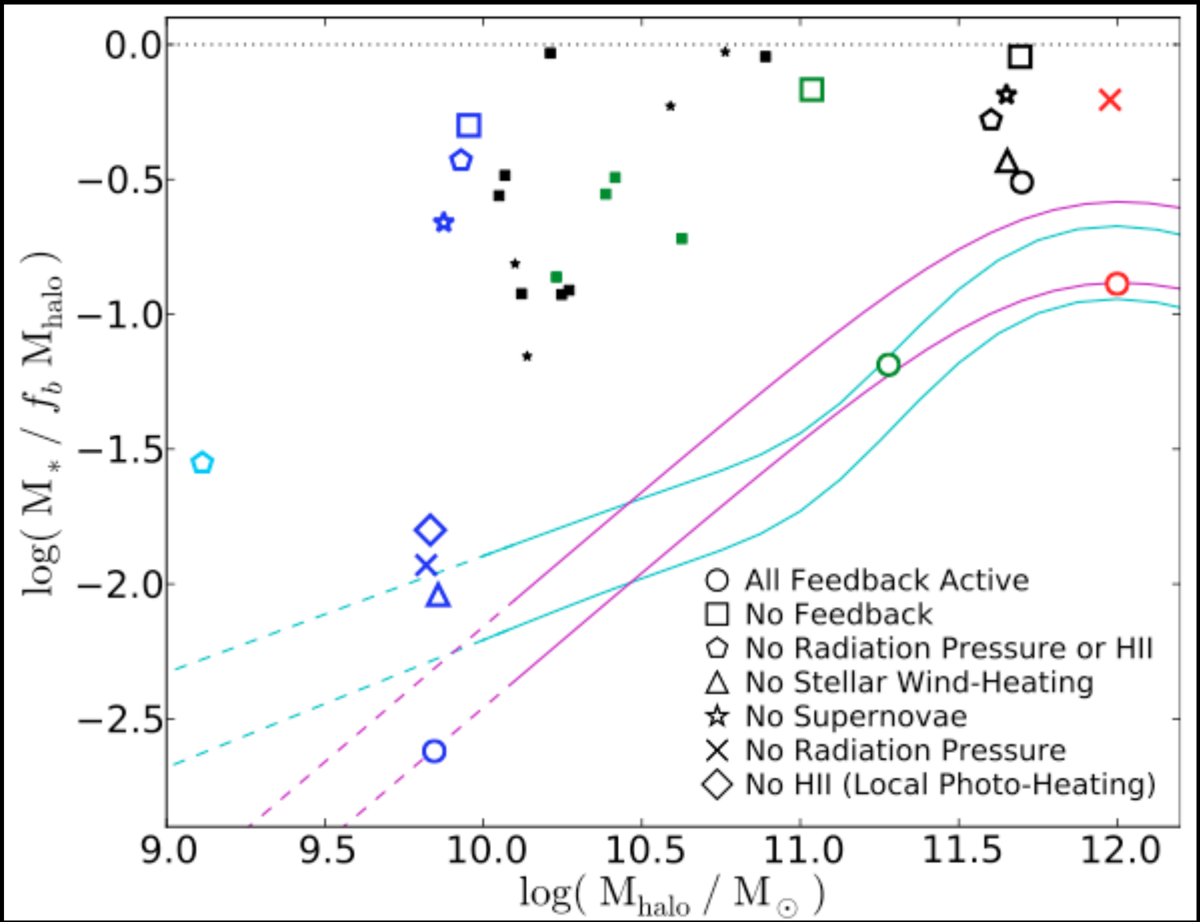




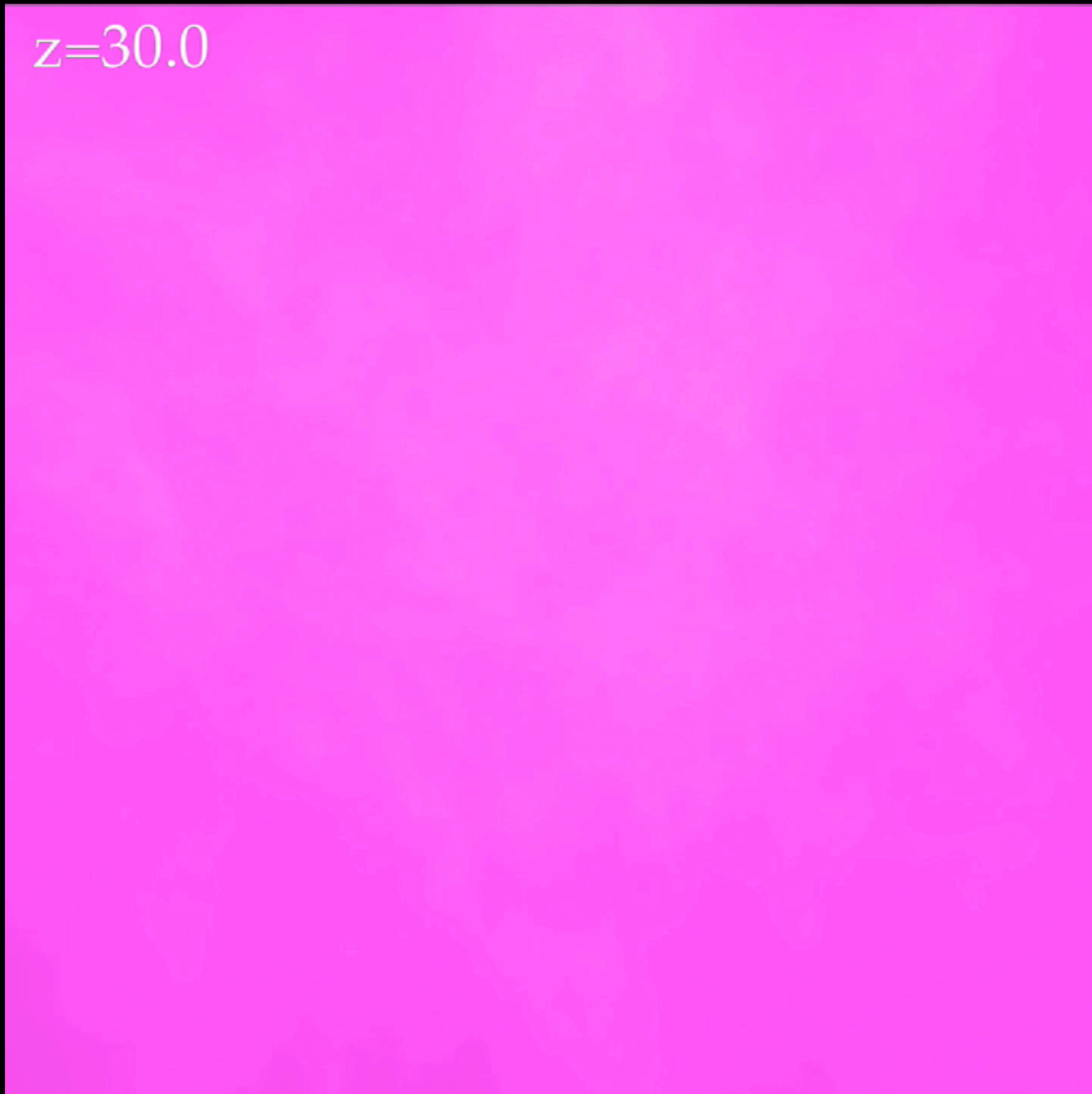
Hopkins, Keres et al. 2014

Critical to include a range of feedback mechanisms

- It is critical to include a whole range of feedback mechanisms that operate in star forming regions. Different feedback mechanisms couple non-linearly.

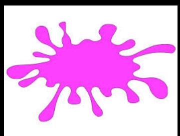


50 kpc scale, ~MW mass, magenta-cold, green-warm, red-hot gas

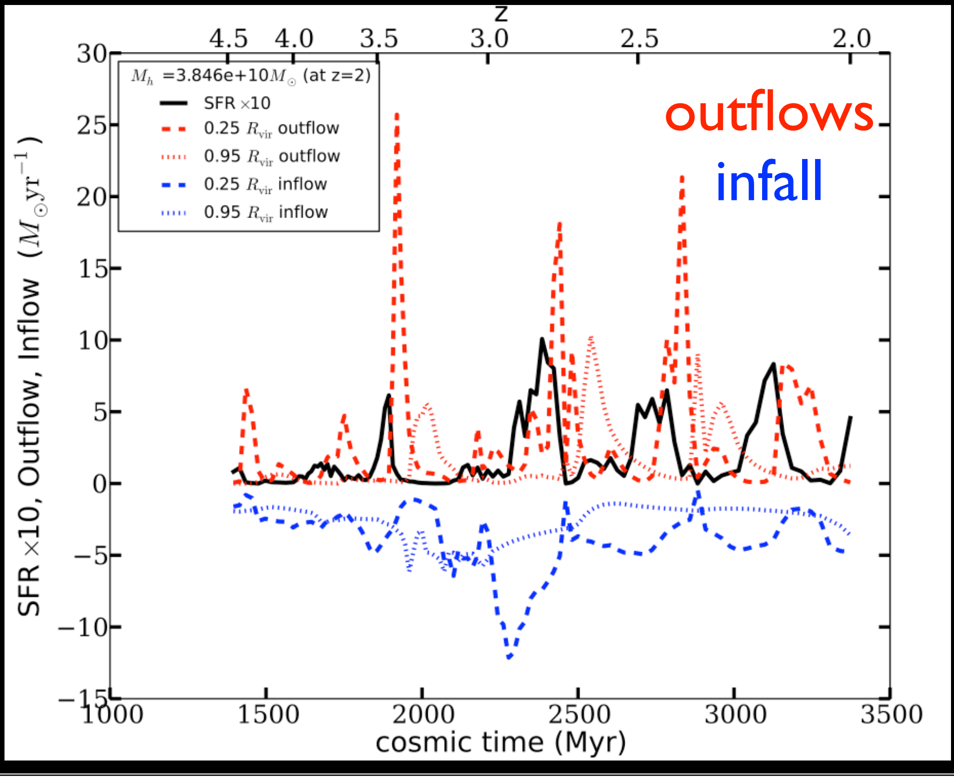


Star formation driven outflows

- Star formation in FIRE is bursty! Bursts drive gas outflow episodes.
- Some material leaves the virial radius, typically tens of percents of the outflow, but a large fraction recycles within the CGM: infall is typically stronger in the inner halo.
- Outflows temporarily suppress the infall, which usually quickly re-establishes as a mixture of IGM infall and recycled outflows. Typically more continuous than outflows.
- Cycle of infall, star formation and outflows... we can follow this in detail! Lower mass galaxies evolves in a SPLASHY POOL/BATHTUB model.

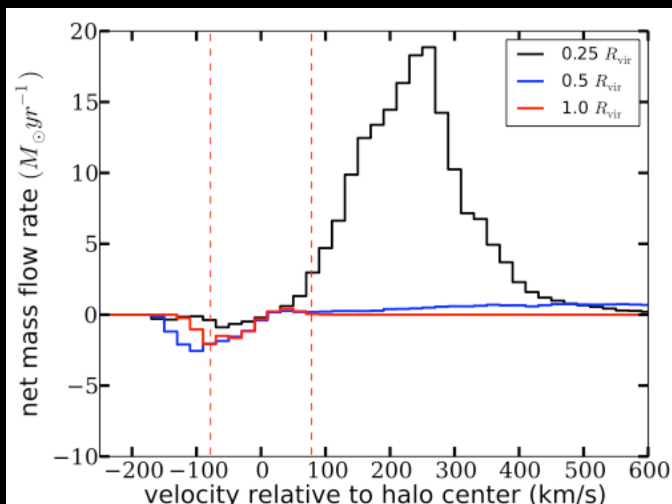


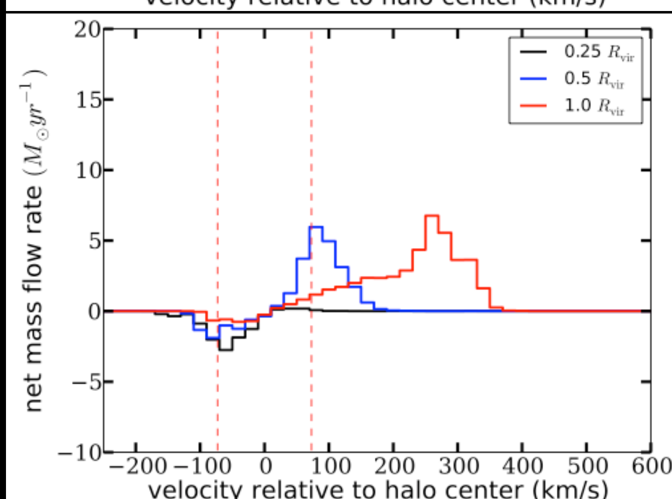
Muratov, Keres et al. 2015



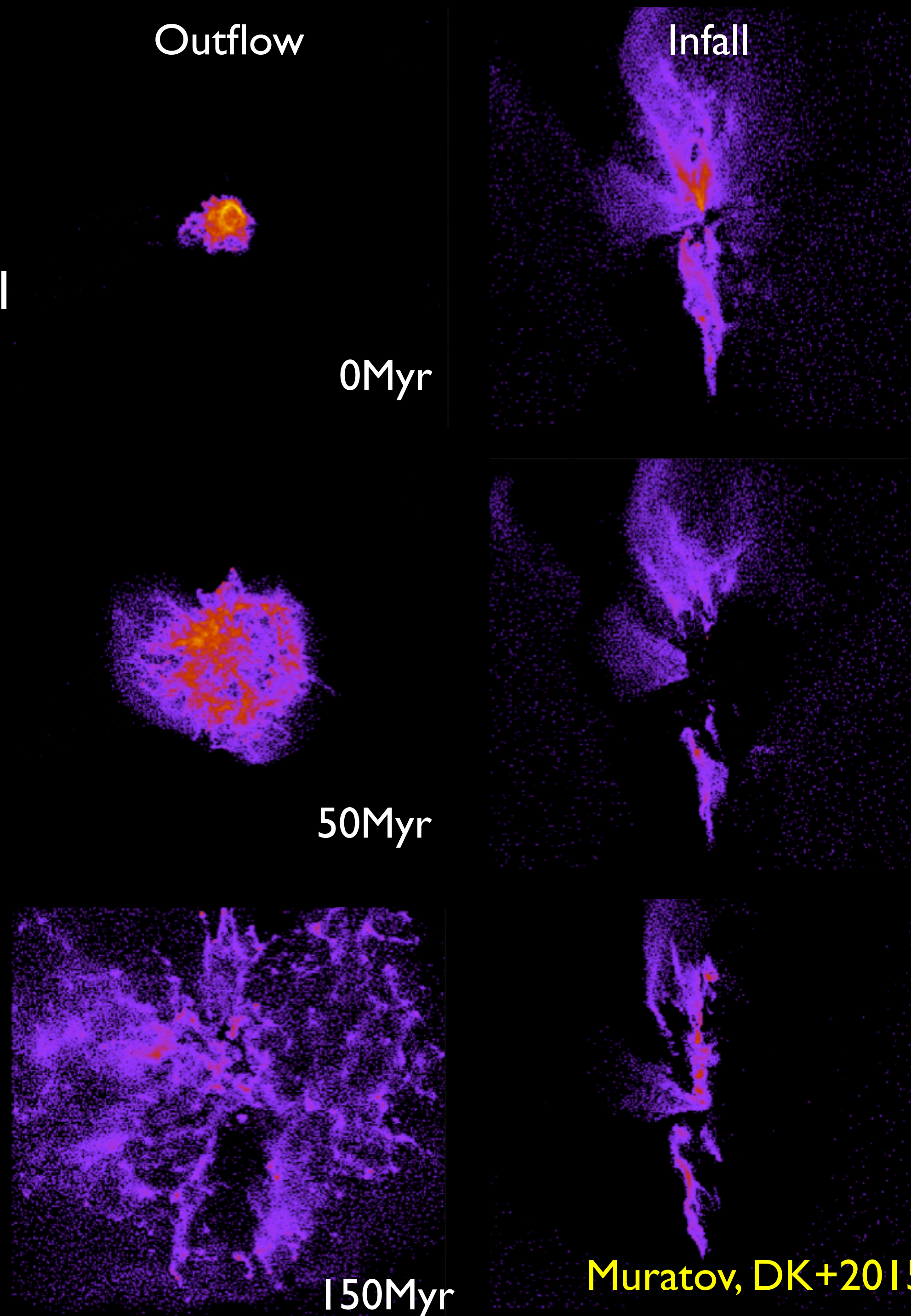
Infall-outflow interaction

Outflows are much faster than infall and can temporarily disrupt the infall in the inner halo!





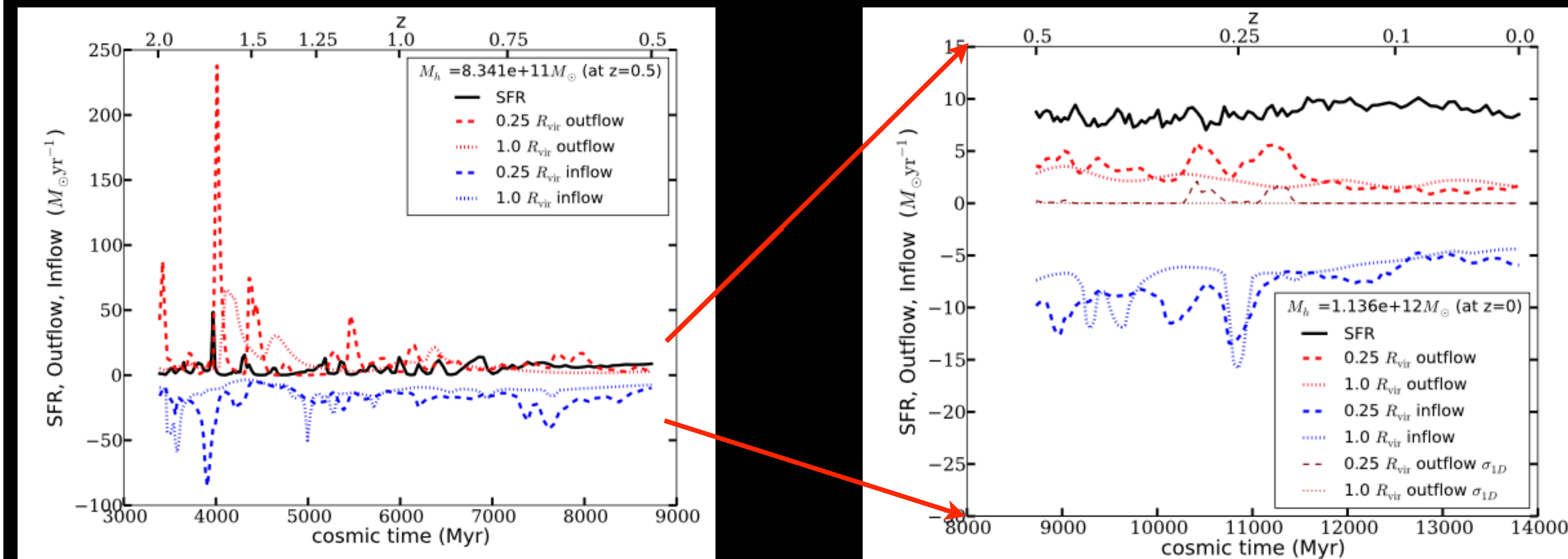
z~3, ~80pkpc region~2Rvir on a side



Muratov, DK+2015

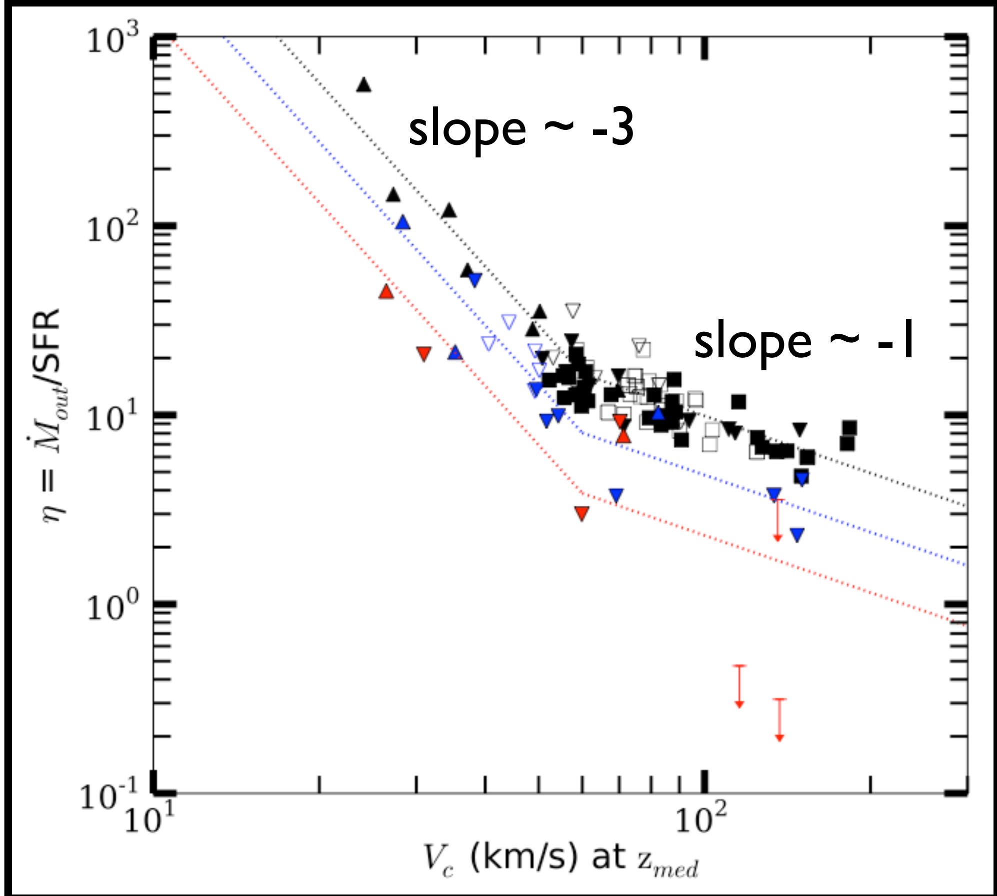
Lack of low redshift outflows

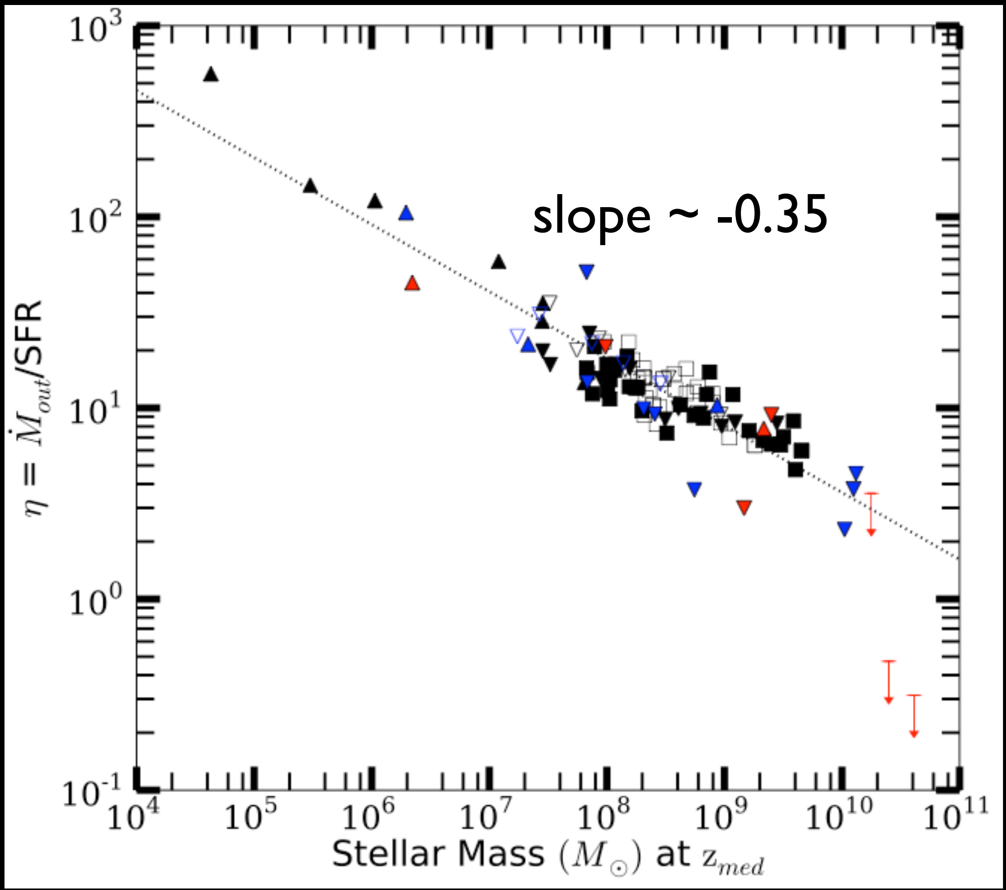
- MW-mass galaxies are building large extended disks at z ~<1.
- Star formation is more continuous at low redshift, driven by almost constant infall, no outflows at large radii (only local fountains and tidally stripped material).
- Less concentrated SF? Lower SFR? Deeper potential wells? Less frequent disturbers?



How much material is expelled?

- Time averaged mass loading of gas expelled through inner halo (0.25Rvir) decreases with increased halo mass and with redshift: << 1 in Milky Way mass halos at z=0.

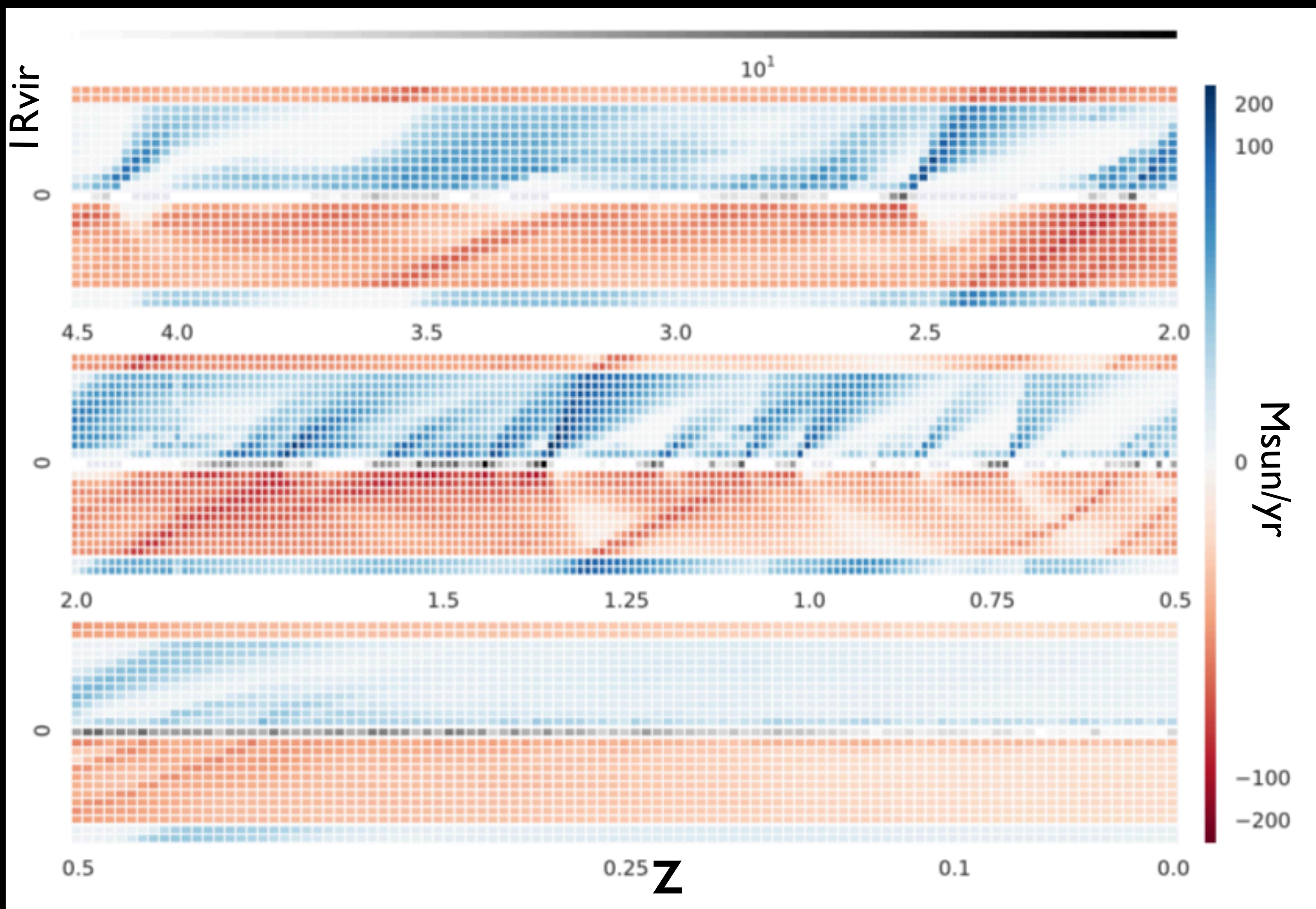




Muratov, Keres+ 2015

At high redshift outflows are almost always present in halos

-There is a ~70Myr delay between a SF episode and outflow at 1/4Rvir
-Instantaneously measured mass loading has very large variations at a given mass or SFR!

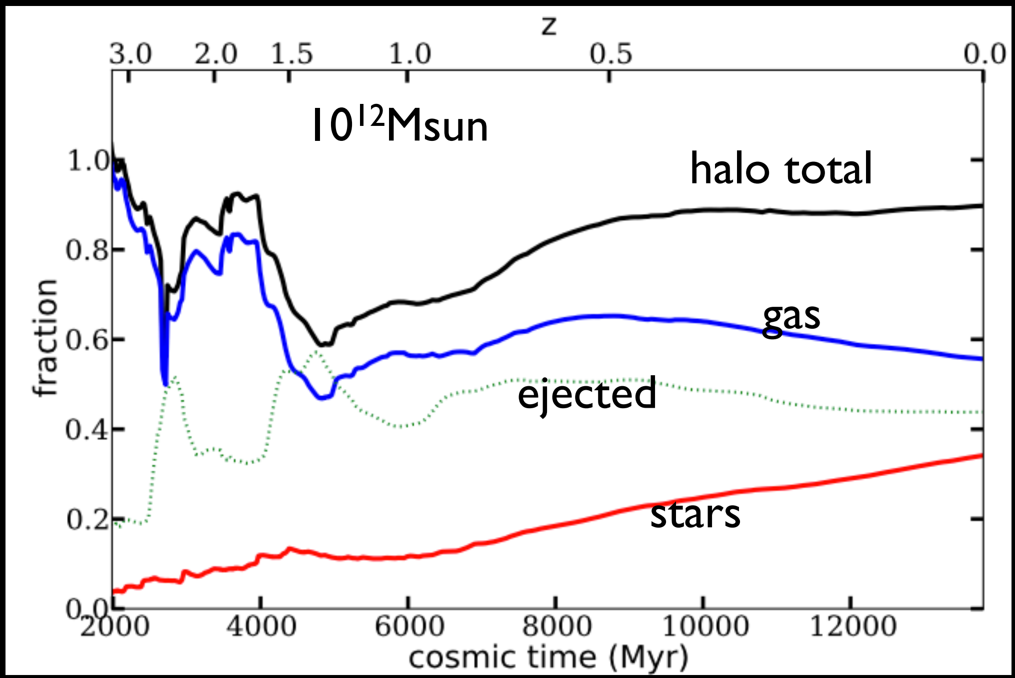


Do winds leave the halo?

- Amount of material that was ejected out of Rvir is larger than the amount of stars within a galaxy!

-Large fraction of outflows recycles back into the CGM of MW mass galaxies.

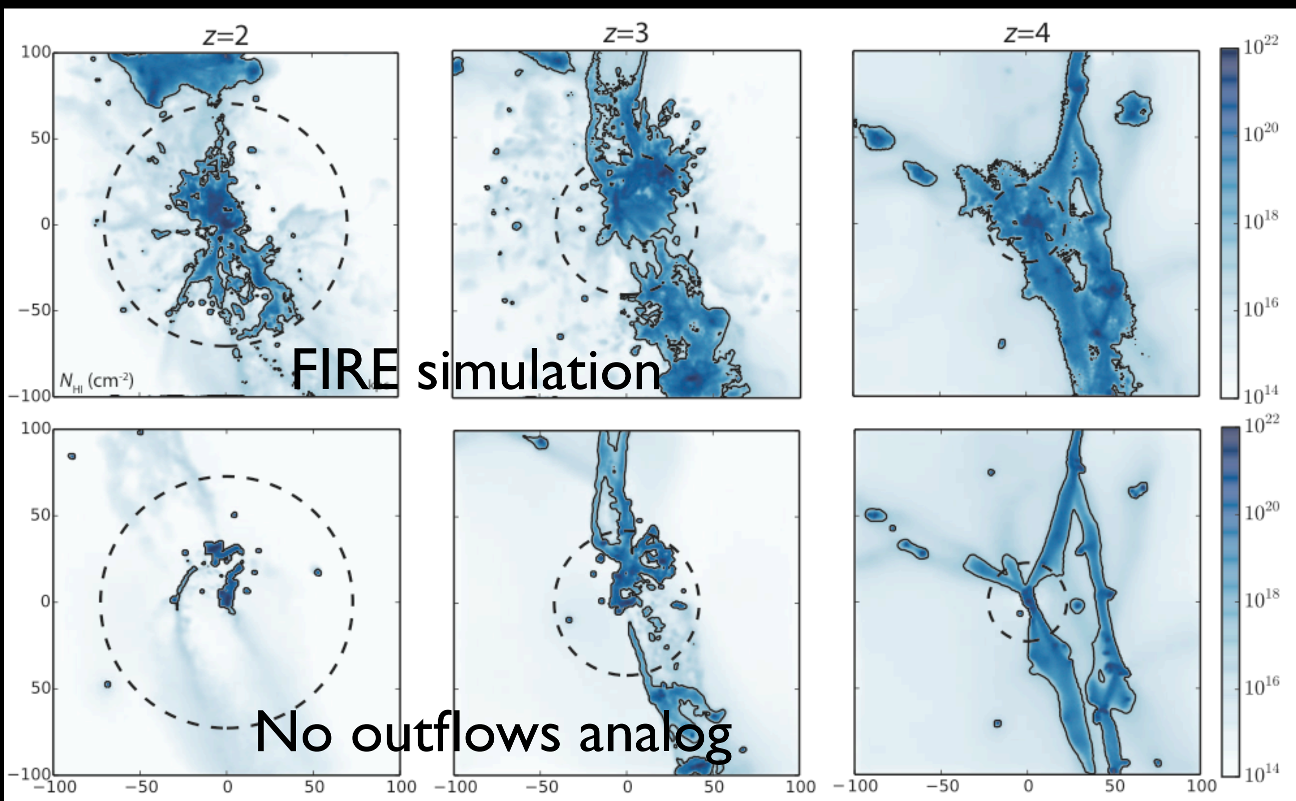
-This means that gas infalling from the CGM, especially at late times, is not primordial.

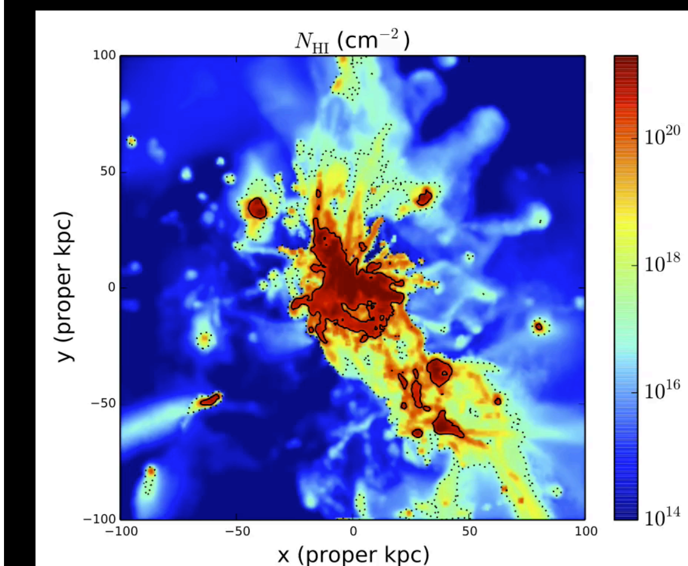


Muratov, DK et al., 2015

Infall-outflow interaction and halo absorbers

- Stellar feedback increases the covering factor of the HI Lyman Limit absorbers by a factor of ~2-3: directly (winds) and indirectly (broader infall region)
- Contribution from infalling and outflowing gas changes 10-90%. Overall LLS covering factor of ~LBG hosting halos is in good agreement with observations (more in Faucher-Giguere's talk)





Faucher-Giguere et al. 2015

Conclusions

- FIRE uses physical stellar feedback model in cosmological simulations with few pc resolution without cooling prevention or hydrodynamic decoupling.
- It regulates both star formation within galaxies and the evolution of galaxies: good match to stellar mass-halo mass, mass-metallicity, matter-density etc.
- Local feedback produces multi-phase galactic winds that lower galaxy masses and eject material into the CGM and IGM.
- Infall is more continuous than the outflows, but typically has much lower velocity.
- Winds have high mass loadings at high-redshift that decreases with mass and redshift: large scale winds are largely absent from low redshift ~MW like galaxies.
- Some of the outflowing material can leave the virial radius, but large fraction of gas stays in halos.
- Stay tuned, more results from FIRE coming out soon!