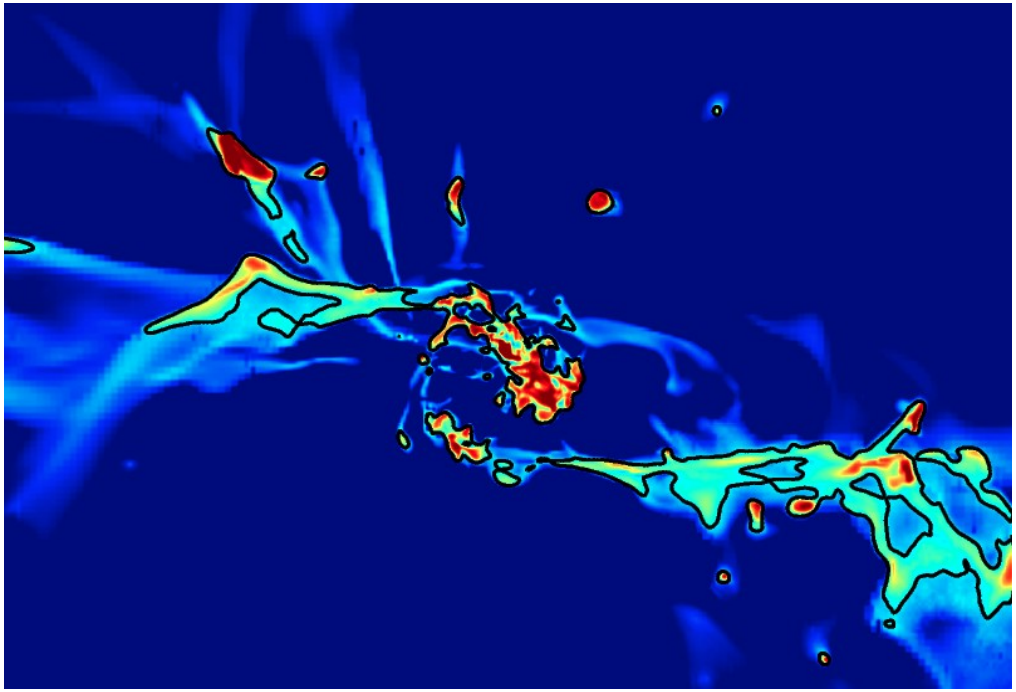
Detecting cold gas accretion in high-redshift galaxies:
insight from numerical simulations



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In collaborations with:

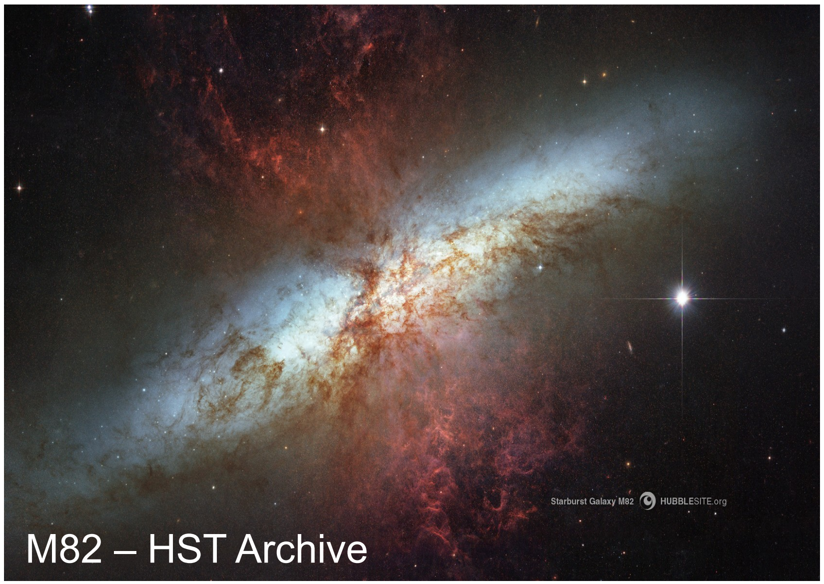
Xavier Prochaska, Daniel Kasen, Avishai Dekel, Daniel Ceverino and Joel Primack

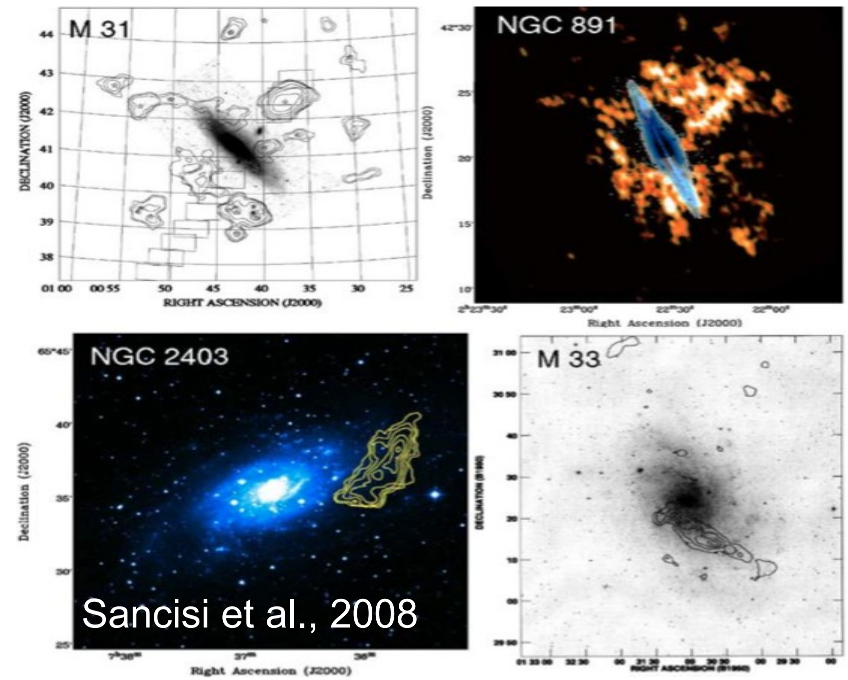
(Fumagalli et al., 2011 arXiv:1103.2130)

Gas in galaxies: from cosmic web to molecular clouds

14-18 June 2011 - Kloster Seeon, Germany

Inflows, outflows... how and when


M82 – HST Archive

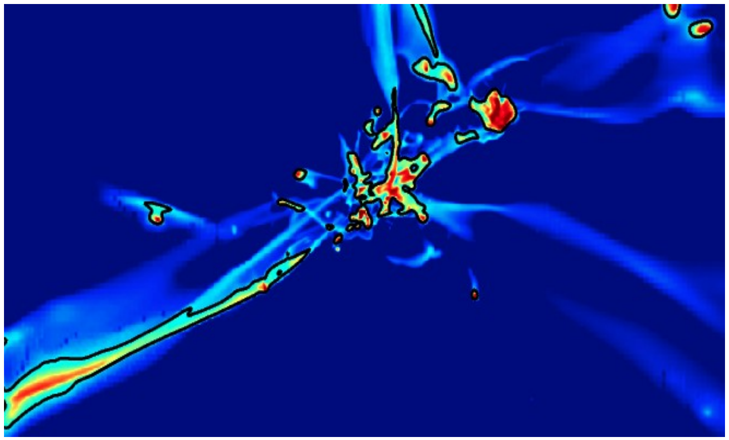


Sancisi et al., 2008

- Outflows: inferred from absorption/emission spectroscopy at different redshifts and needed to simulate “realistic” galaxies
- Inflows: needed to sustain galaxy star formation and a generic feature of galaxy simulations

The balance between outflows/inflows is a key element of galaxy evolution

Predictions of cold accretion

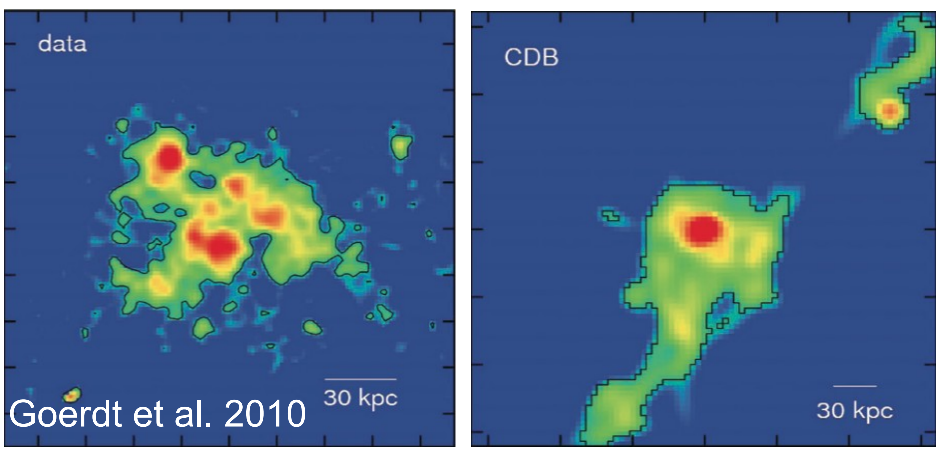


Simulations predict that cold gas (< 10^5 K) in narrow streams and satellites is the dominant source of fresh fuel for star formation at high-z

(Katz et al., 2003; Kereš et al., 2005,2009; Dekel&Birnboim,2006; Dekel et al.,2009; Faucher-Giguère et al.,2011)

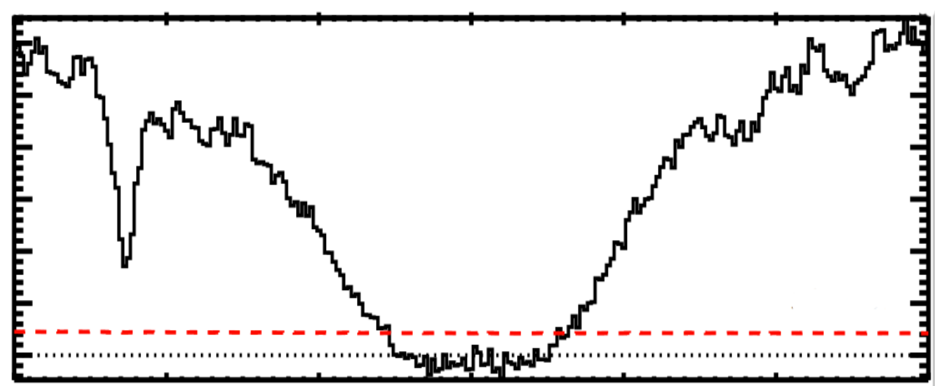
Ways to detect cold mode accretion:

Lyα in emission



(e.g. Haiman et al. 2000; Fardal et al. 2001; Furlanetto et al. 2005; Dijkstra & Loeb 2009; Goerdt et al. 2010; Matsuda et al. 2010; Faucher-Giguère et al., 2010)

Absorption lines

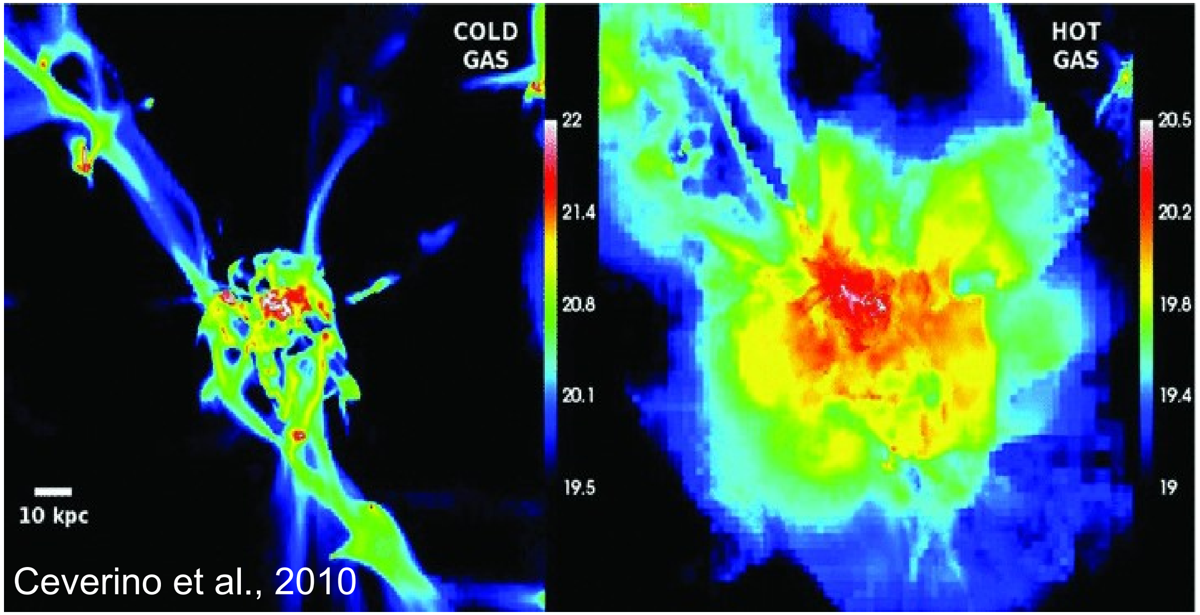


(Stewart et al. 2010; Faucher-Giguère & Kerěs 2011; Kimm et al, 2011; MF et al., 2011)

Numerical simulations

We use high resolution (35-70 pc) AMR cosmological hydrodynamical simulations (Ceverino et al., 2009; 2010) using the ART code

(Kravtsov, Klypin & Khokhlov 1997; Kravtsov 2003)



Physics included:

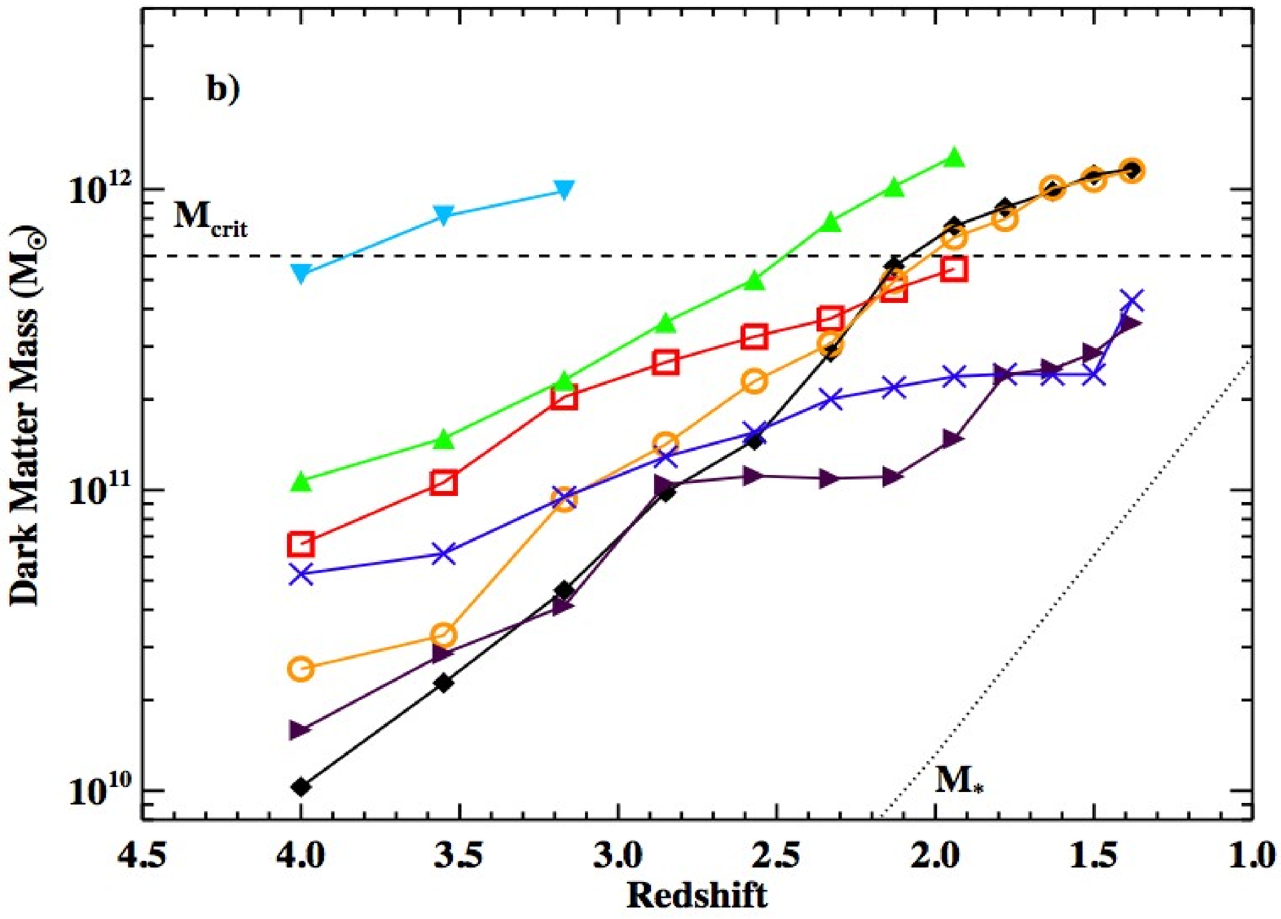
- Gas cooling (< 10^4 K)
- Stellar photo-heating
- UVB + self-shielding
- Stochastic star formation for $n_H > 1$ cm^{-3}
- Metal enrichment (SNIa-II)

Stellar feedback is implemented and gives rise to outflows of hot gas with velocities of few hundreds km/s . The outflow mass flux is up to 1/3 of the inflow one.

Numerical simulations

We use seven galaxies at z=1.5-4.

The simulations reproduce observed scaling relations at similar redshifts.



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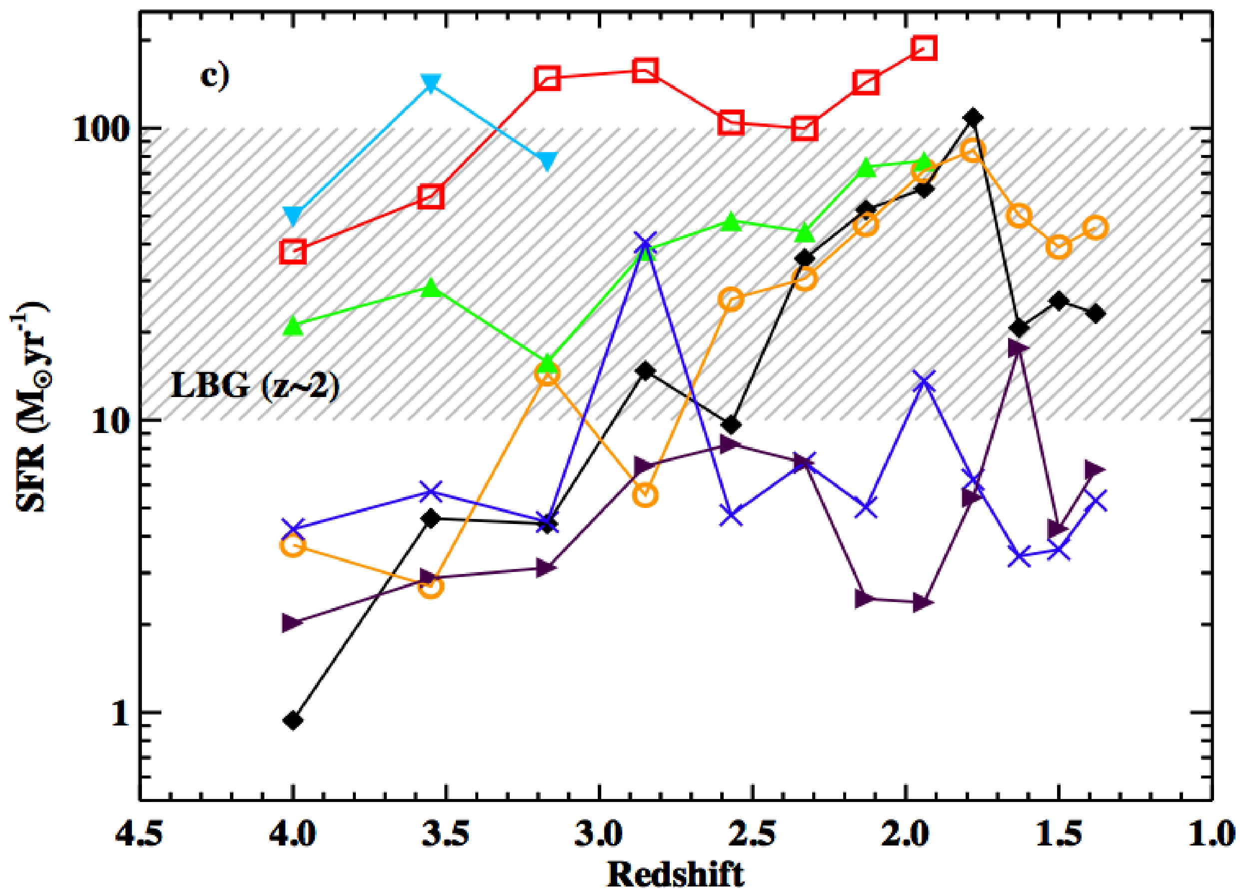


Radiative transfer post-processing

Sensible estimates of the neutral hydrogen require radiative transfer

(e.g. Faucher-Giguère & Kerěs 2011; Altay et al., 2010; McQuinn et al., 2011)

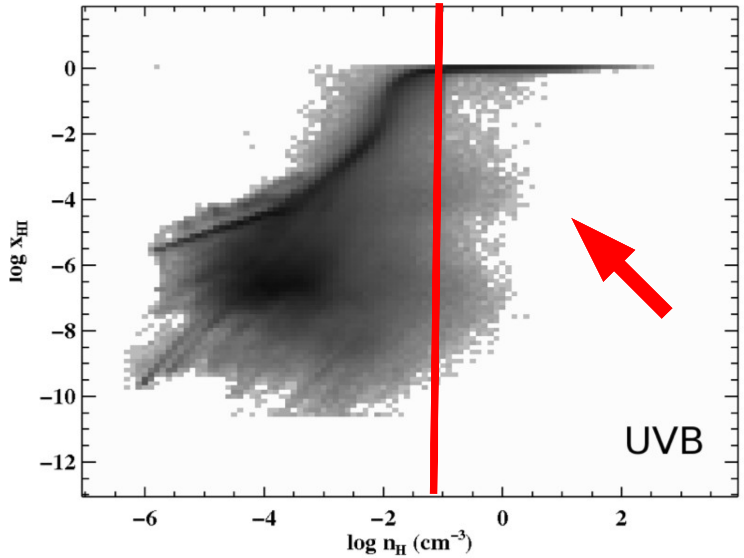
Our Monte Carlo RT code includes:

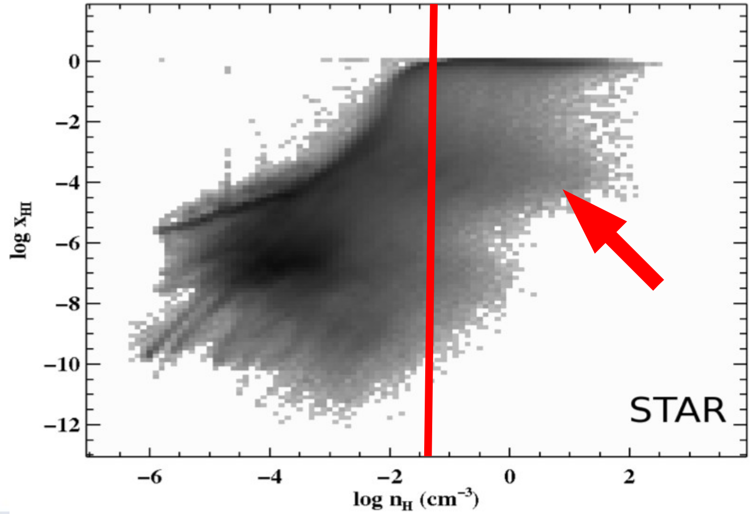
- Collisional ionization
- UV background
- Stellar radiation
- Dust scattering and absorption

(Kasen et al., 2006;2011)

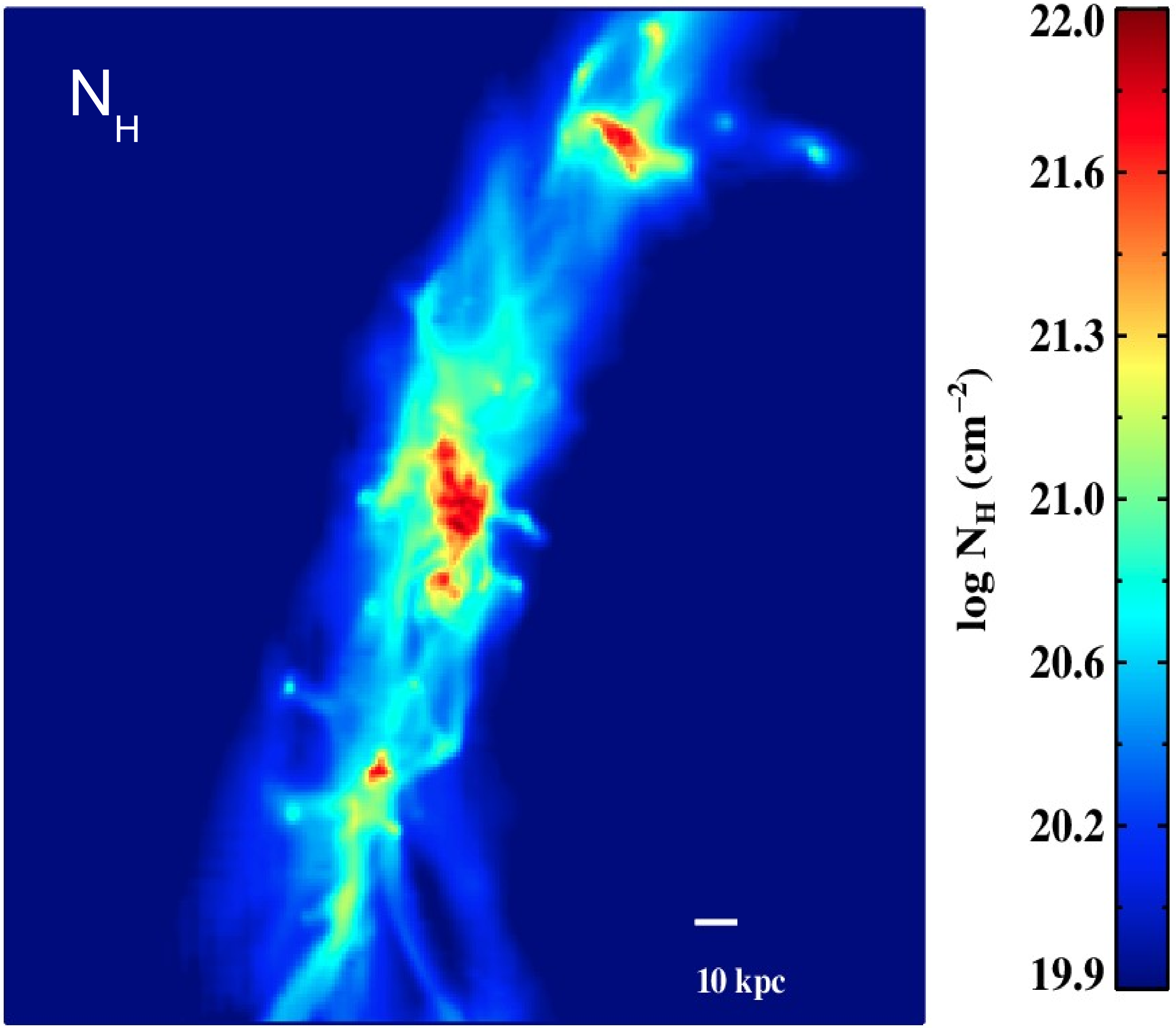
We obtain ≤ 10% escape fraction at the virial radius

Local sources matter.





Radiative transfer post-processing



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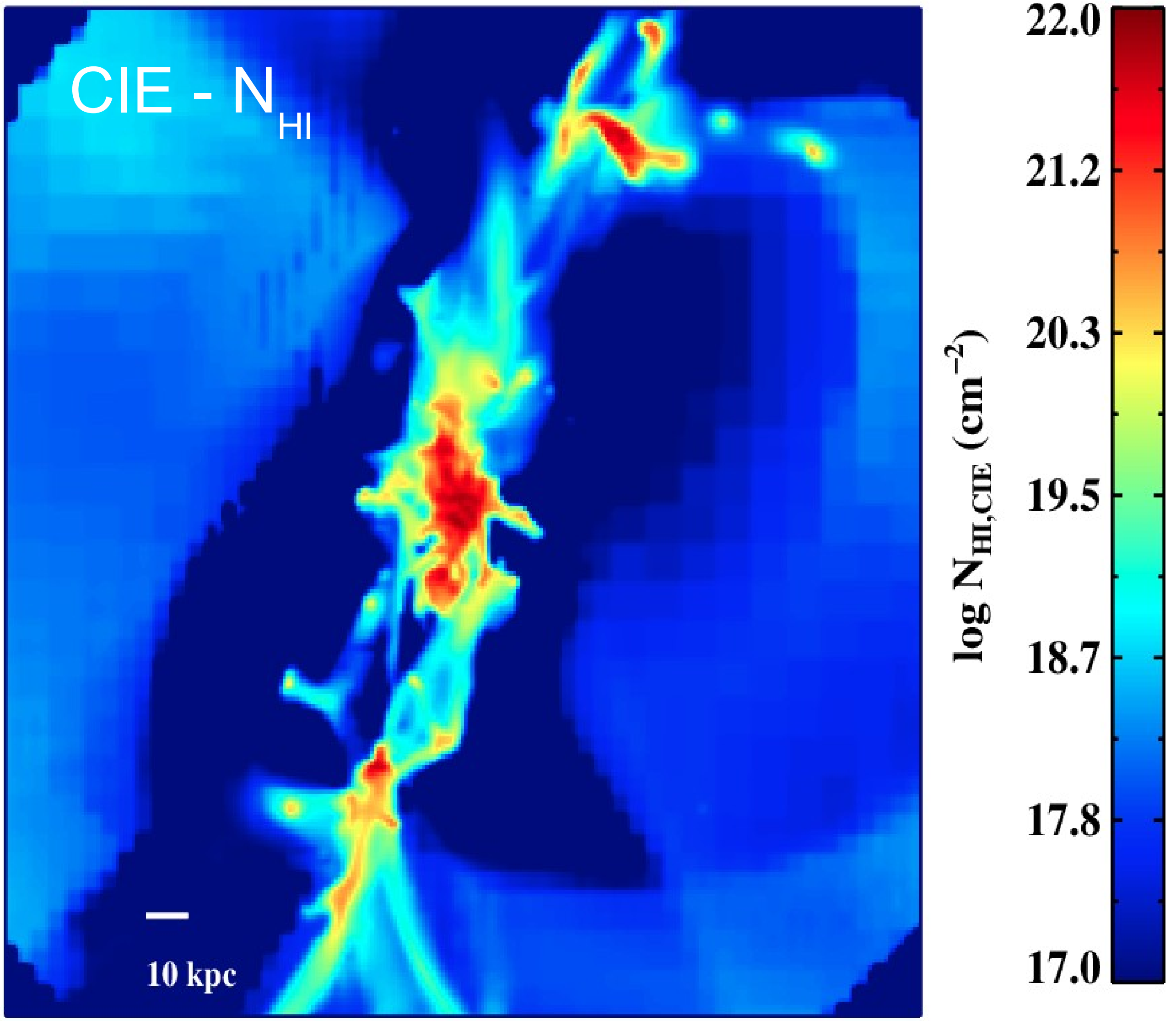

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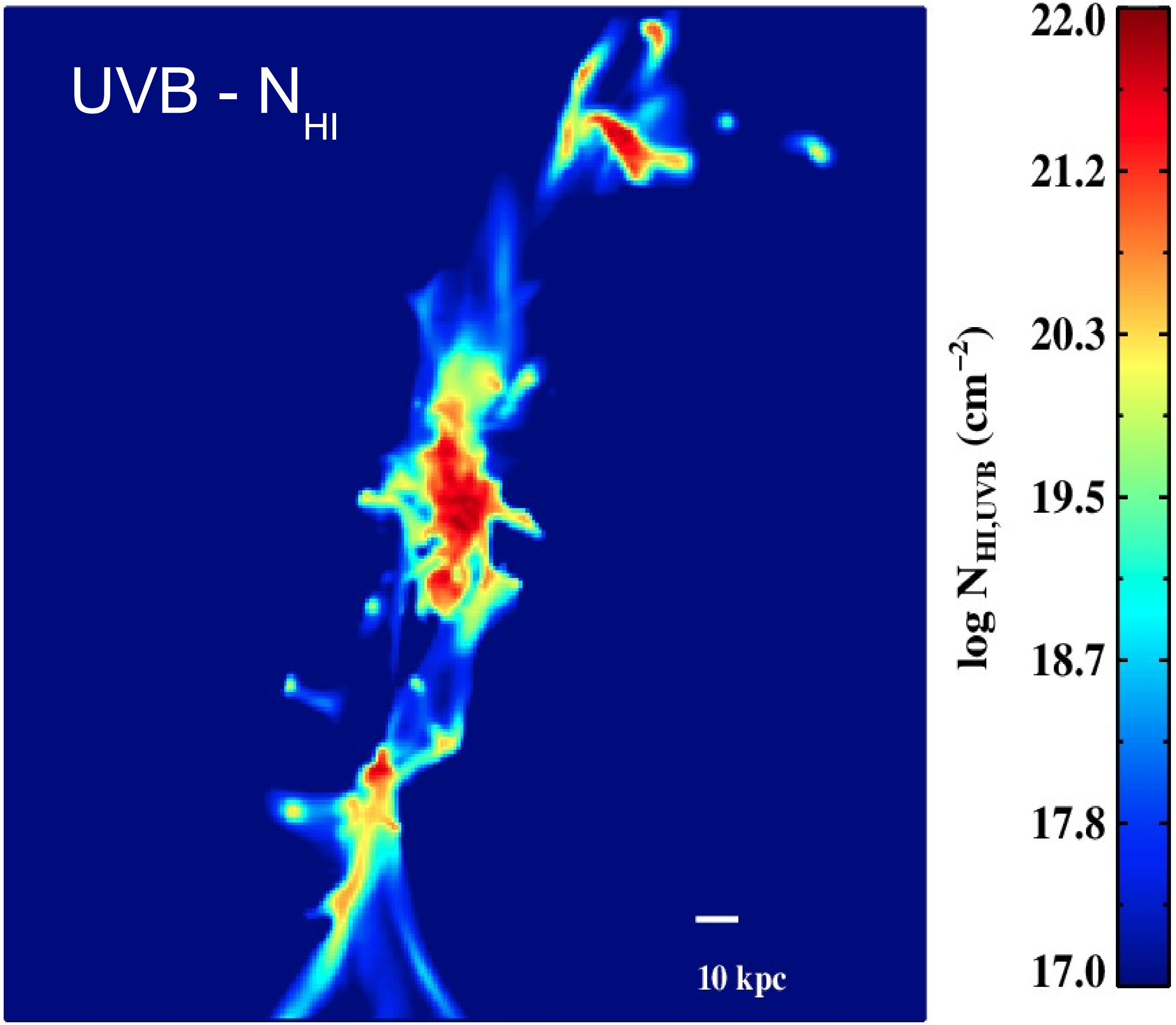

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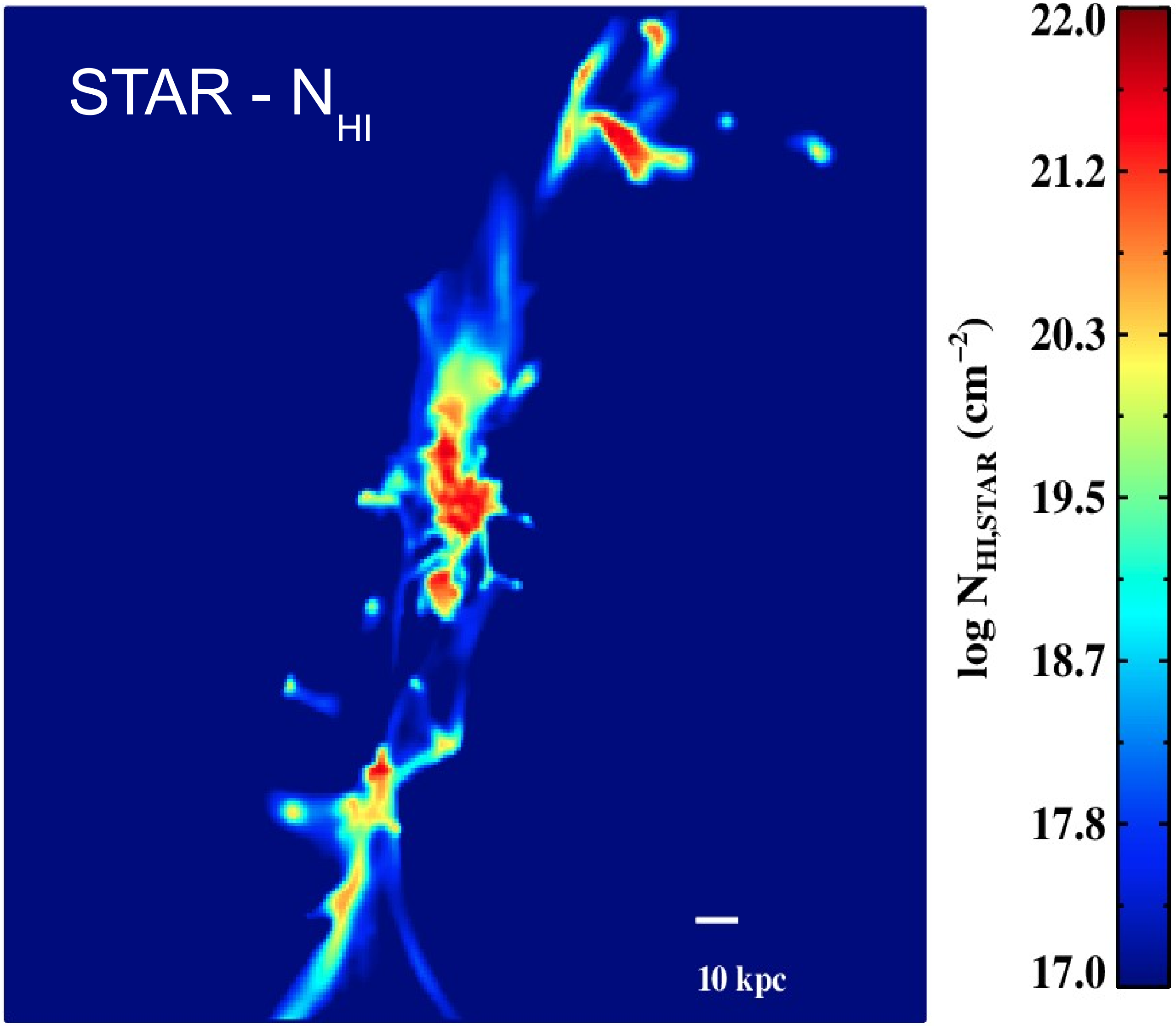
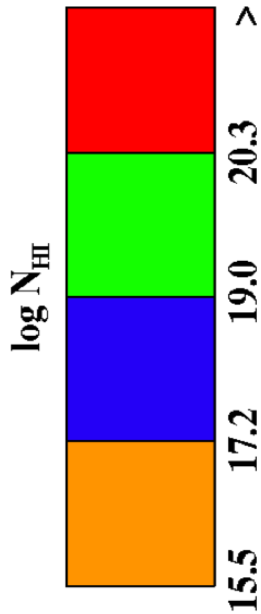


Covering factor of neutral hydrogen

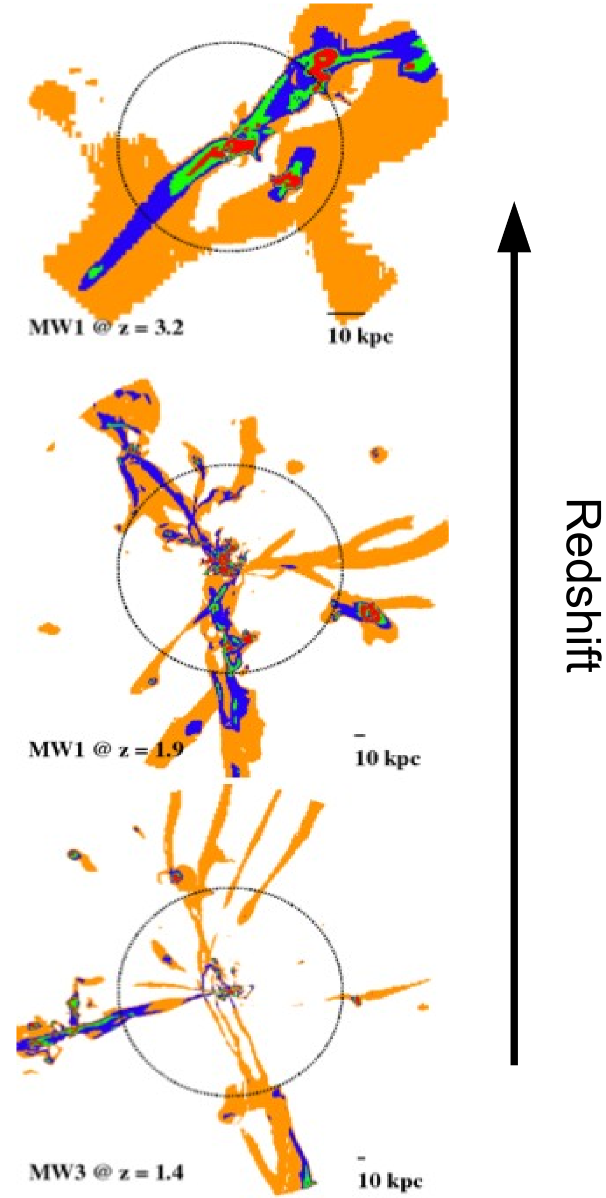


Galactic neutral gas

Optically thick gas

Ionized gas (LLS)

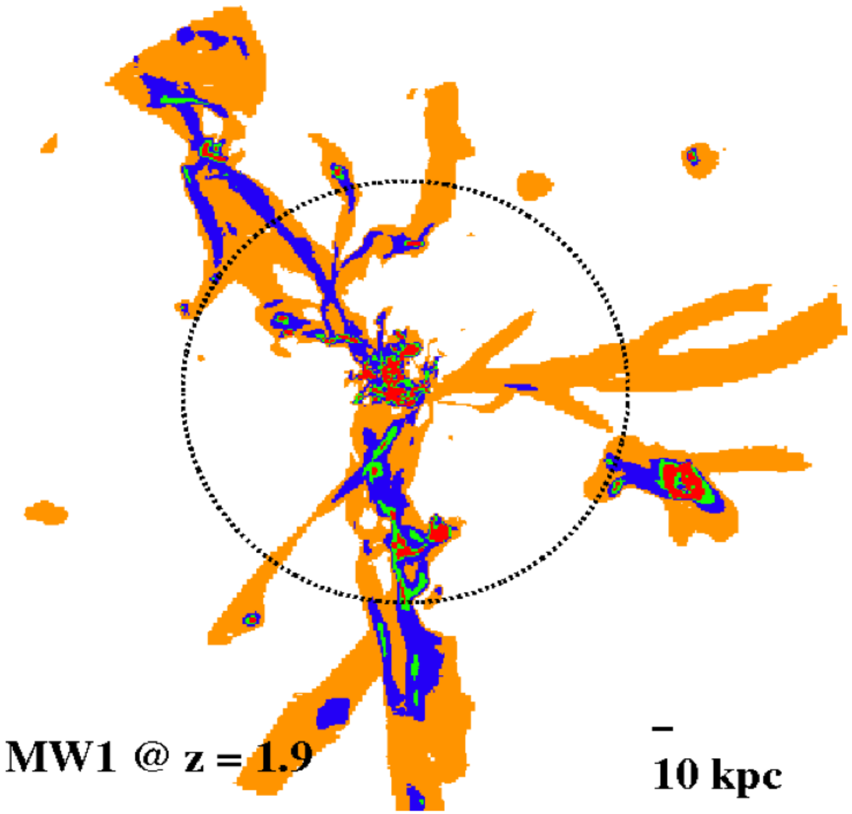
Optically thin gas



- The covering factor decreases with time following universal expansion
- Neutral gas is more concentrated in satellites and central disks at later time
- Streams are more irregular at later time

(e.g. Dekel et al., 2009; Kerěs & Hernquist 2009; Stewart et al. 2010; Faucher-Giguère & Kerěs 2011)

Covering factor of neutral hydrogen



At R_{vir}, the covering factor is:

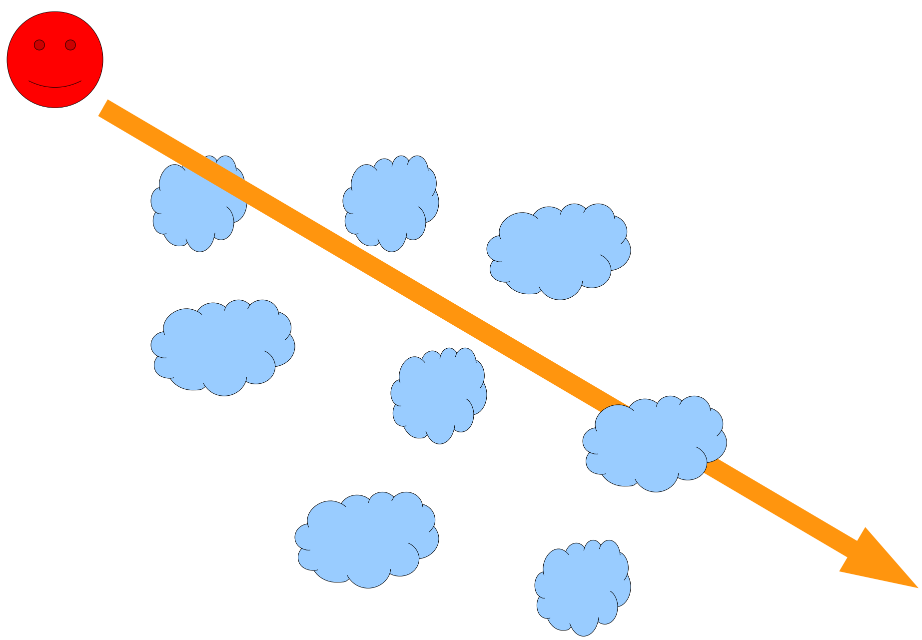
- Optically thin gas 20 - 60%
- Ionized gas (LLS) 6 - 25%
- Galactic neutral gas 1 - 5%

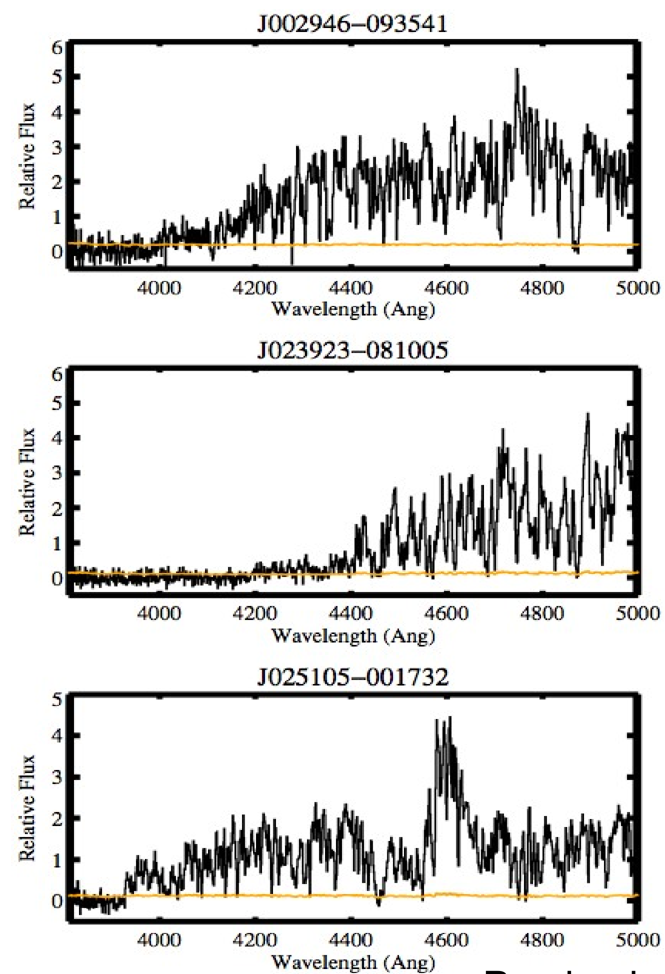
- Most of the optically thin gas and of the LLSs are associated with the streams
- Half of the area that is covered by optically thick gas resides outside the virial halo
- A significant fraction of the neutral gas is located within halos with half of the galactic gas cross section outside the central disks

Small coverage ≠ small incidence

Surveys of systems in foreground of quasars probe the cross section and number density of absorbers, not just the covering factor.

(e.g. Péroux et al., 2003; O'Meara et al., 2007; Noterdaeme et al., 2009; Prochaska et al., 2010)

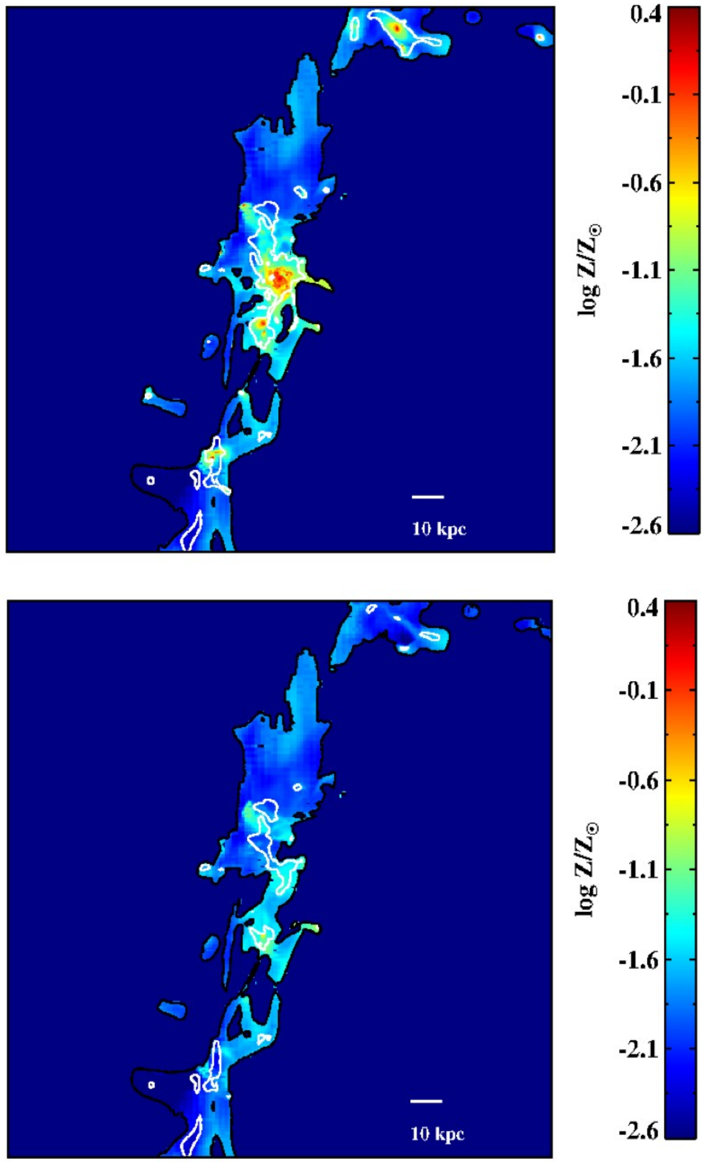




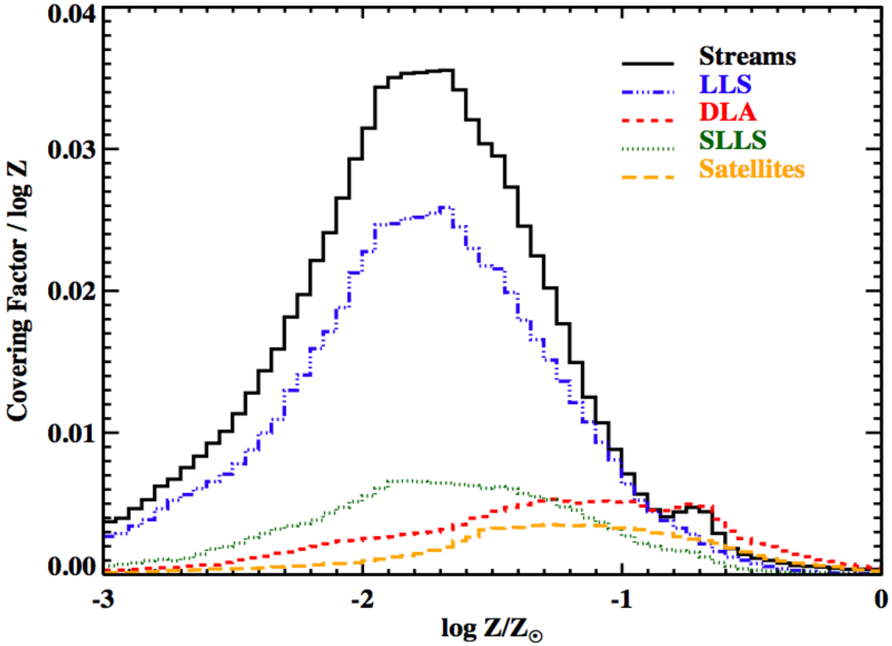
Prochaska et al., 2010

- Cold streams contribute non-negligibly to the LLS population
- Massive disks contribute to the highest column densities

Other diagnostics: metallicity



Cold streams are metal poor (1% solar), albeit non primordial.



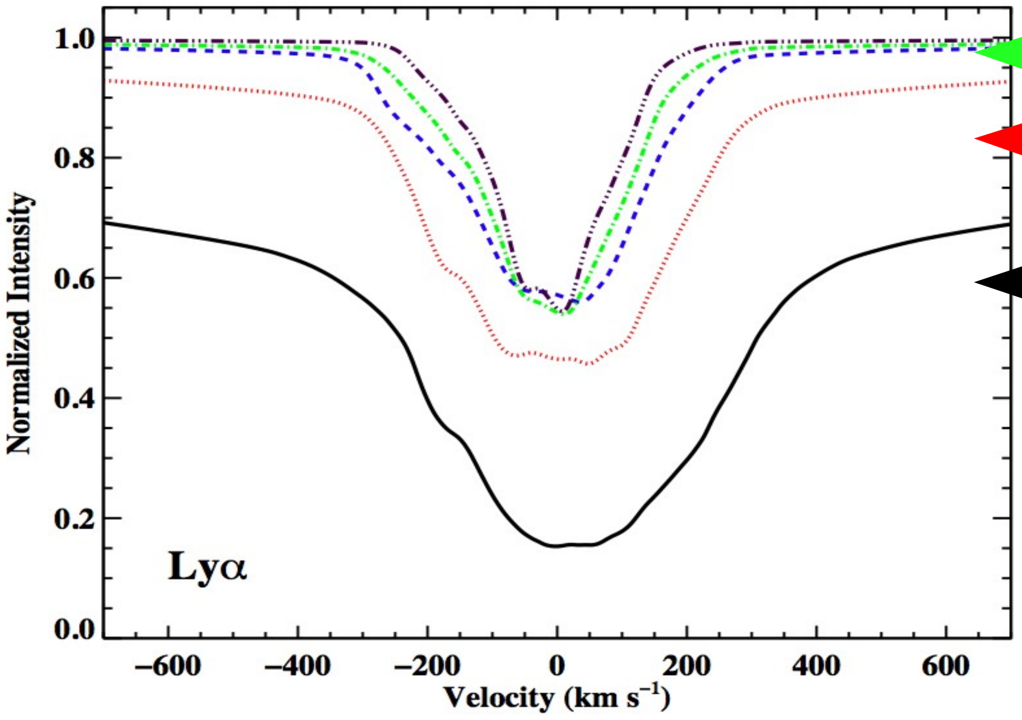
- The low metal content of cold streams is a key element to separate them from the more metal rich gas in outflows.

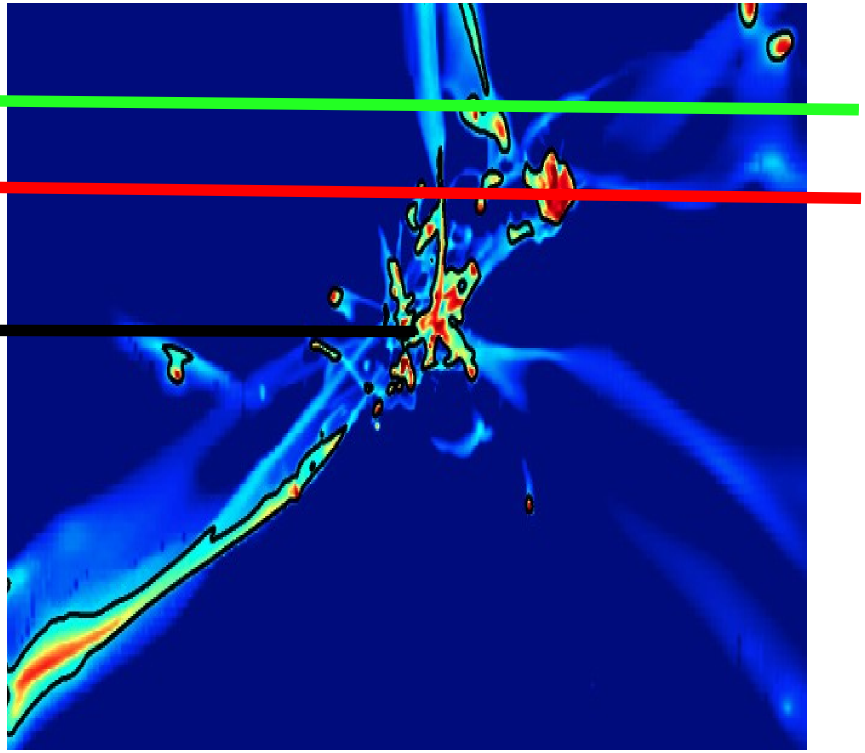
(e.g. Prochaska et al., 1999; Cooksey et al., 2008; Kacprzak et al., 2010; Kimm et al., 2011;Thom et al., 2011; Ribaudo et al., 2011)

Other diagnostics: kinematics

Simulations with cold streams reproduce the observed kinematics of Lyα but underpredict the strength of low ionization metal lines

(cf. Steidel et al., 2010; Powell et al., 2010; Kimm et al., 2011)





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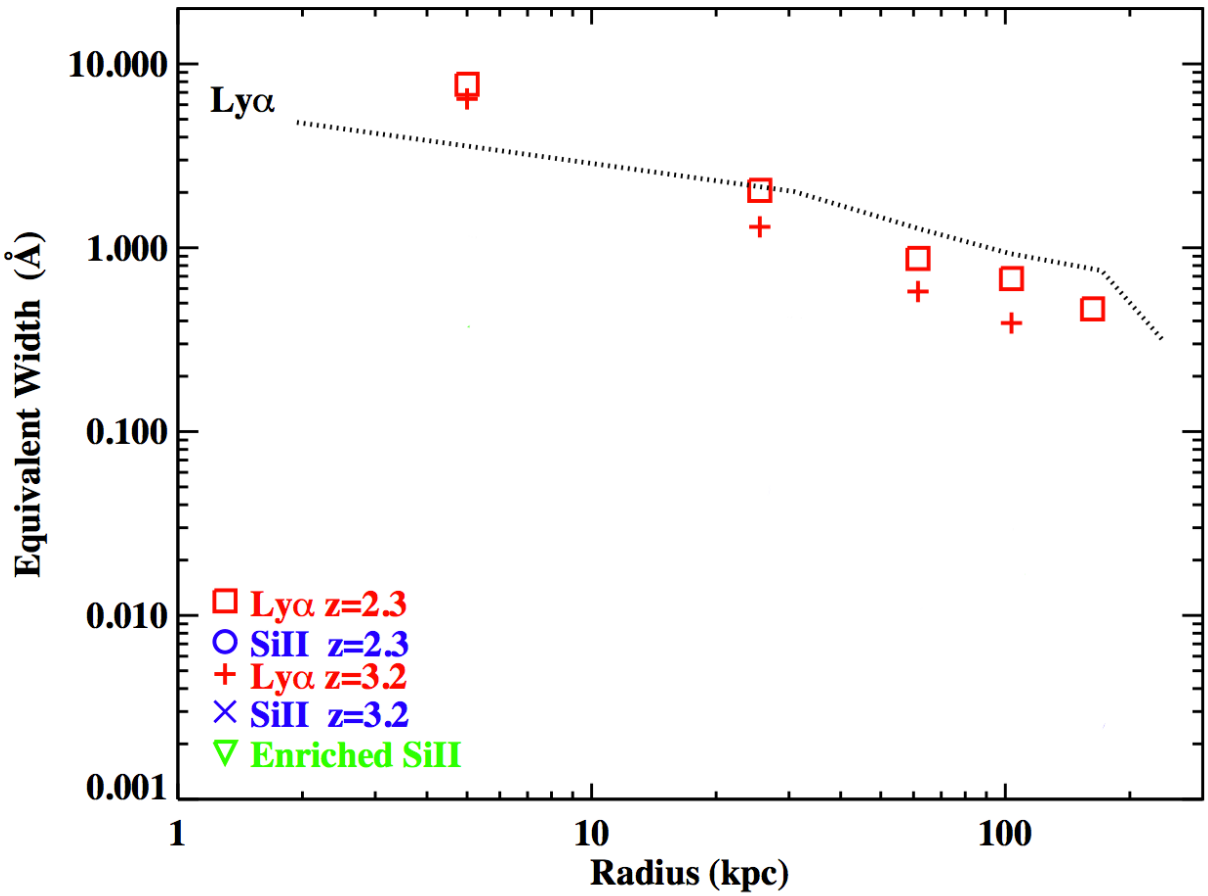

- Cold streams are not at odds with observation of cold gas in the LBG surroundings.

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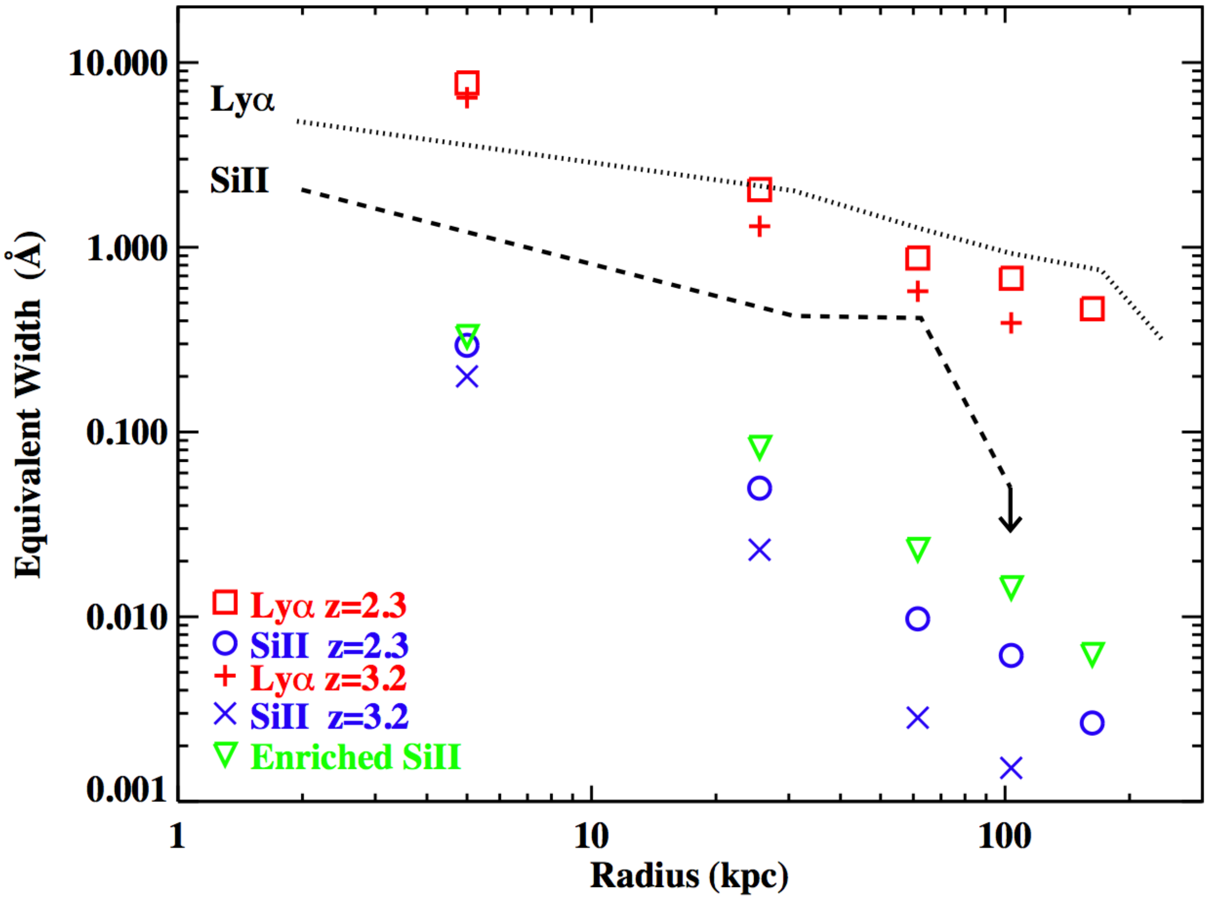
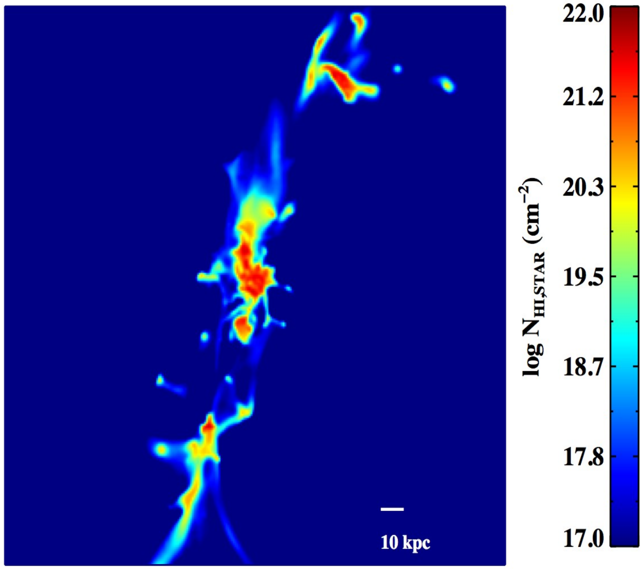
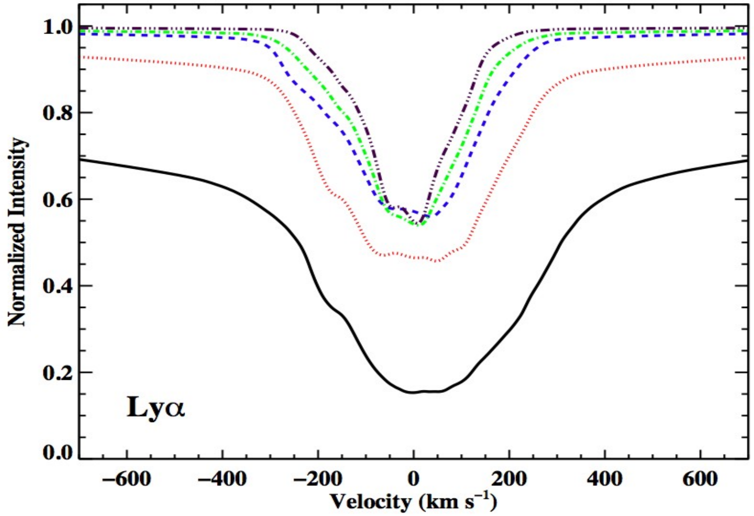


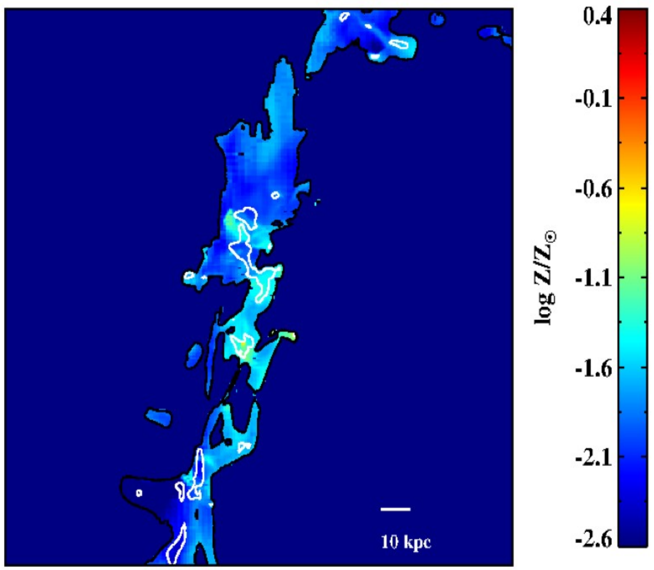
- The low covering factor and low metallicity make metal lines non-ideal tracers of cold streams
- To match the observed opacity in metal lines the contribution from nearby galaxies, small clumps of cold gas embedded in a warmer medium, and/or galactic outflows are required.

Cold streams are metal poor LLSs

- Cold streams are mostly ionized
- The covering factor of optically thick gas is below 25% at all redshifts
- Cold streams contribute non negligibly to the LLSs population
- Cold streams are metal poor, yet non primordial ($Z \sim 1\% \, Z_{sun}$)
- They exhibit quiescent kinematics (200-300 km/s)







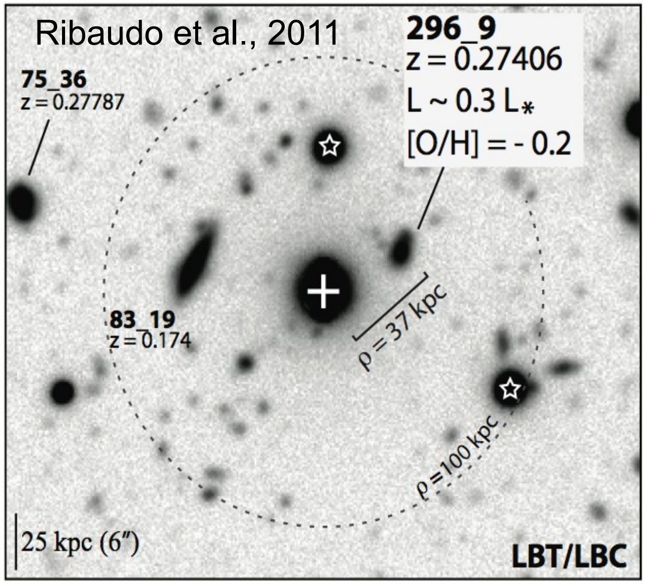
Have cold streams been detected?

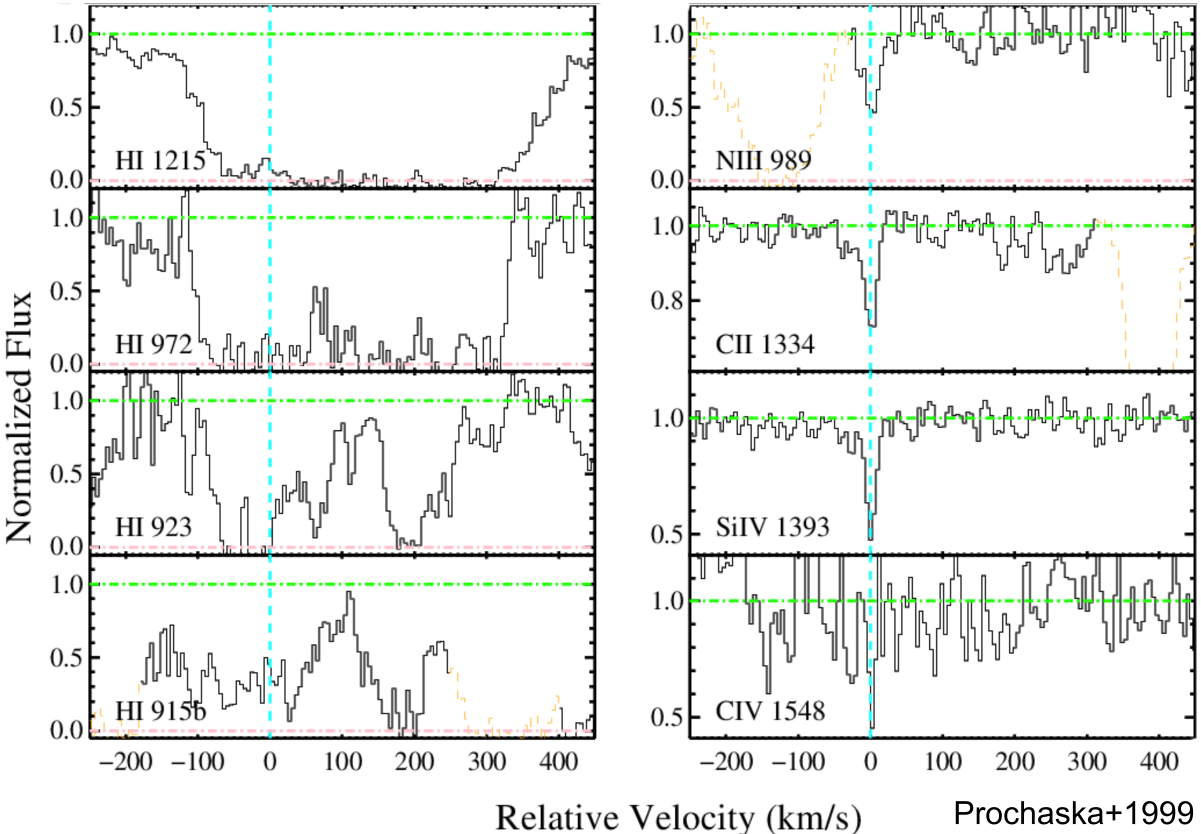
While the population of LLSs is likely to trace gas in a variety of phases, the discovery of metal poor LLSs could be the first detection of cold streams

(e.g. Prochaska et al., 1999; Tripp et al., 2005; Cooksey et al., 2008; Thom et al., 2011; Ribaudo et al., 2011)

Observational work should provide:

- The fraction of metal poor LLSs
- Samples of galaxy-absorber pairs



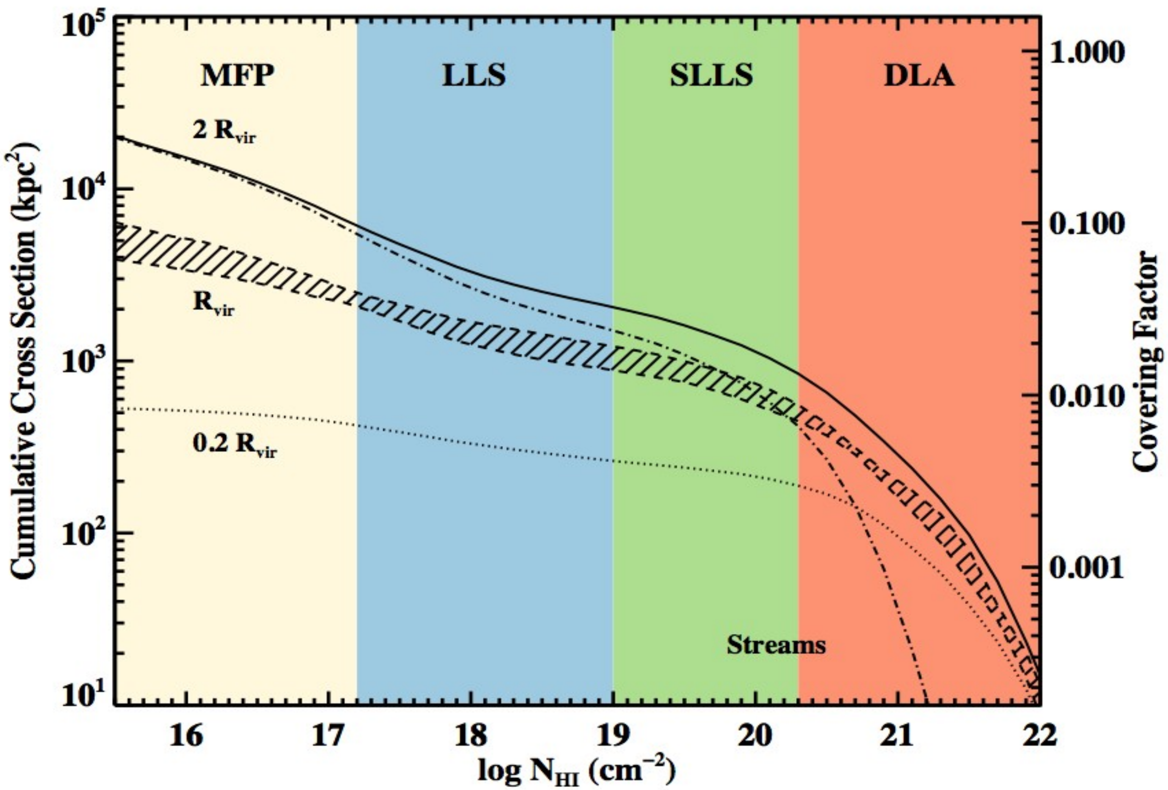


Prochaska+1999

Future work with simulations should characterize:

- How cold flows and outflows coexist and interact
- The kinematics of low and high ionization metal lines

Covering factor of neutral hydrogen



At R_{vir}, the covering factor is:

- MFP 20 - 60%
- LLS 6 - 25%
- DLA 1 - 5%

- Most of the MFP gas and of the LLSs are associated with the streams
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- A significant fraction of the neutral gas is located within halos with half of the DLA cross section outside the central disks

(compare with Stewart et al. 2010; Faucher-Giguère & Kerĕs 2011)

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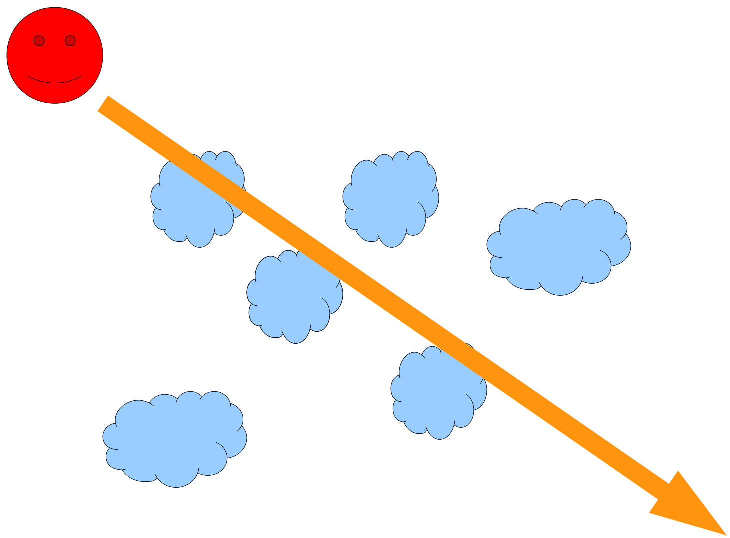

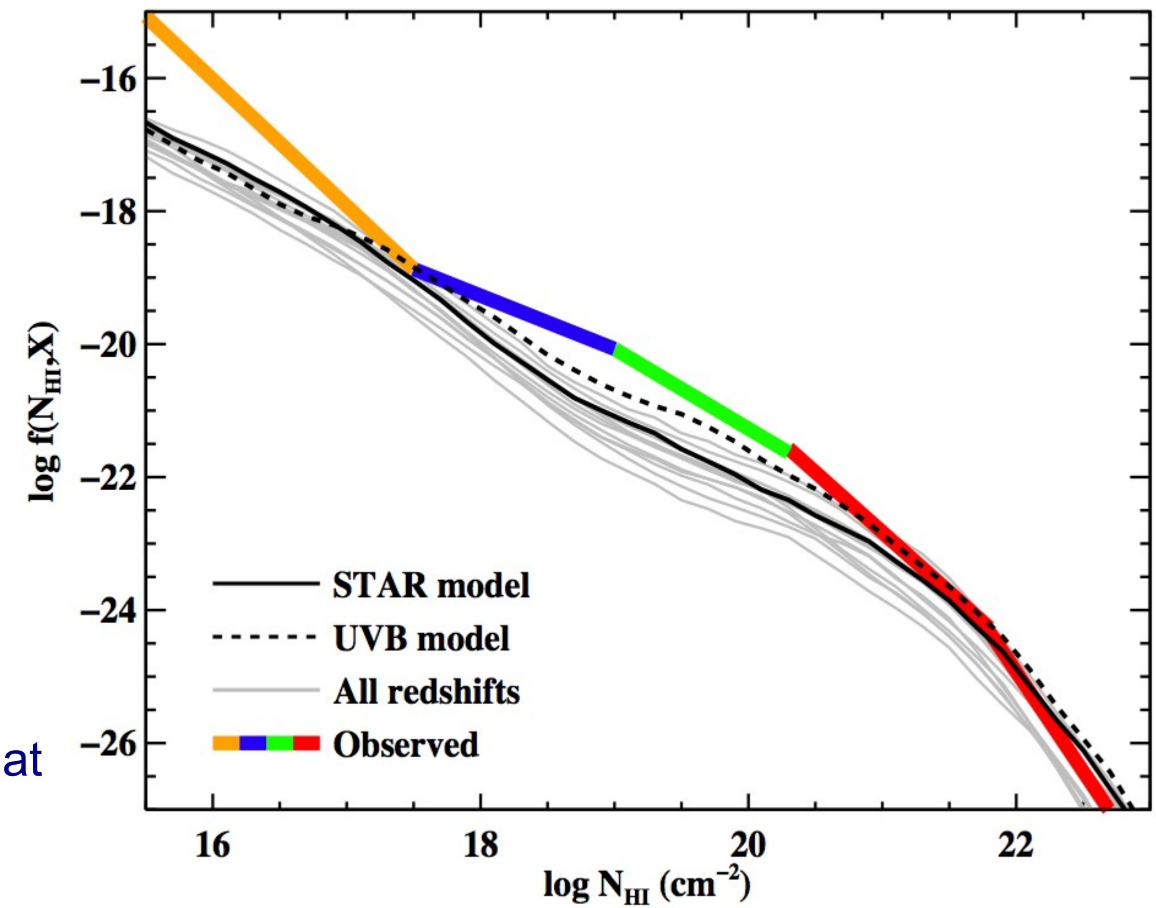

- Cold streams contribute non-negligibly to the LLS population
- Massive disks shape the f(N,X) at the highest column densities

(cfr. Razoumov+2006; Nagamine+ 2007; Pontzen+ 2008; Tescari+ 2009; Cen+ 2010; Altay+2010; McQuinn+ 2011)

Other diagnostics: kinematics

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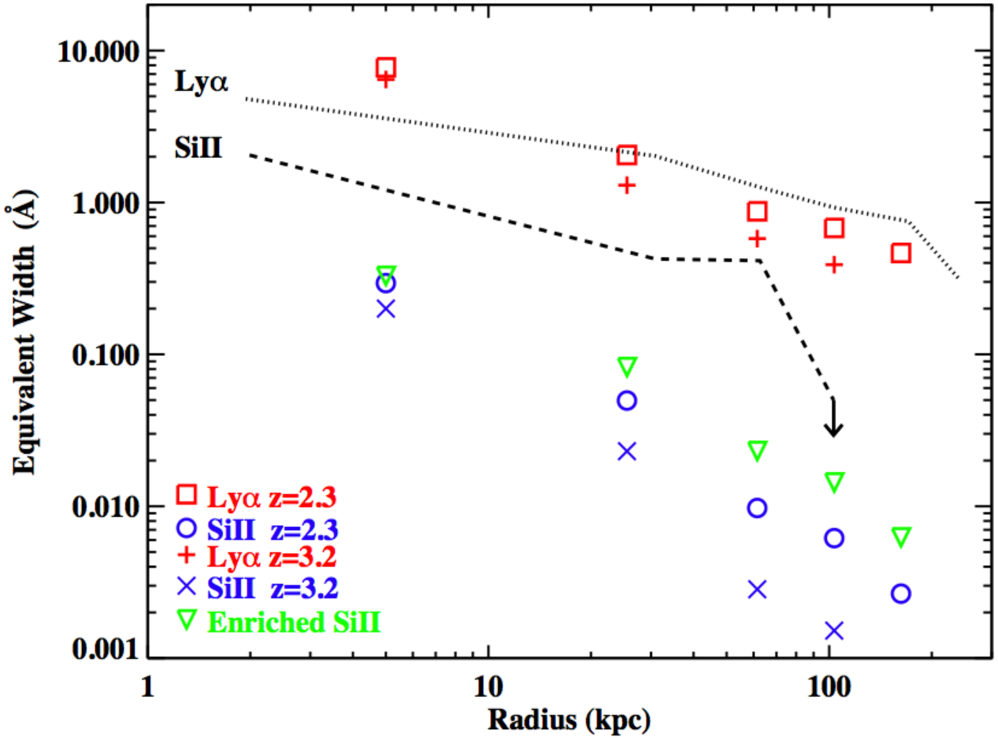
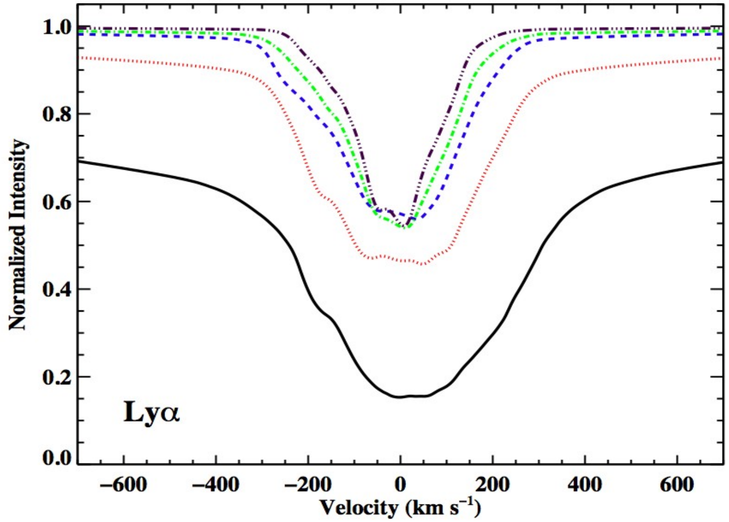


- The low covering factor and low metallicity make metal lines non-ideal tracers of cold streams
- Cold streams are not at odds with present observation of cold gas in the surroundings of LBGs.



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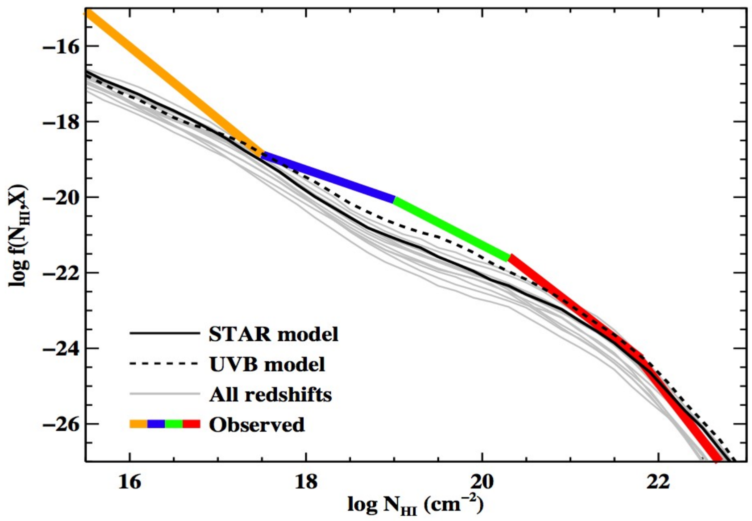

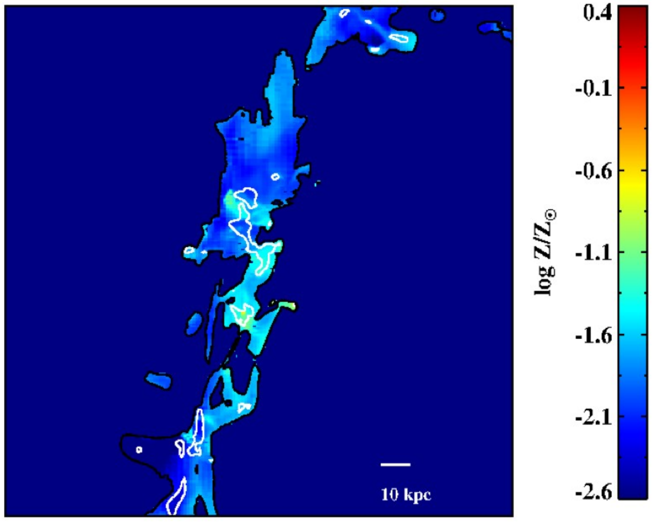

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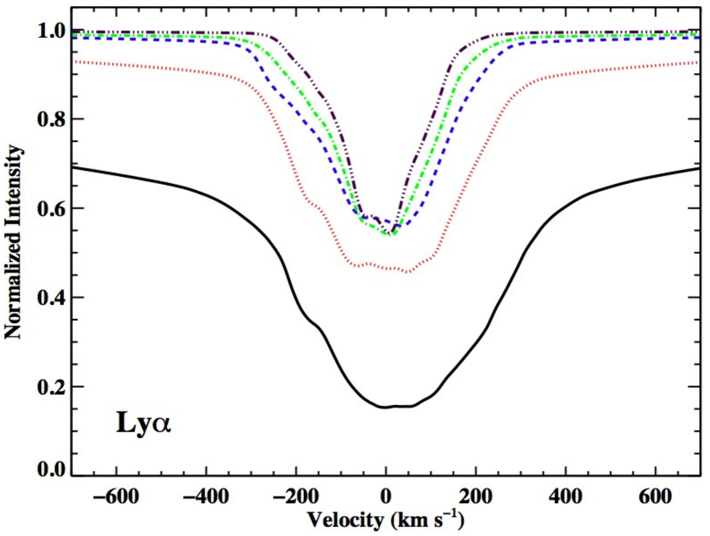

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