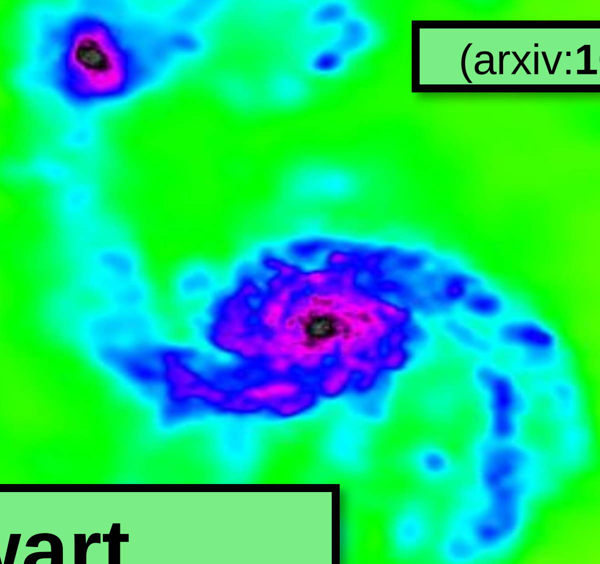
Observing the End of “Cold Flows”: Orbiting Circum-galactic Gas as a Signature of Cosmological Accretion

(arxiv:**1012:2128** and arxiv:**1103.4388**)



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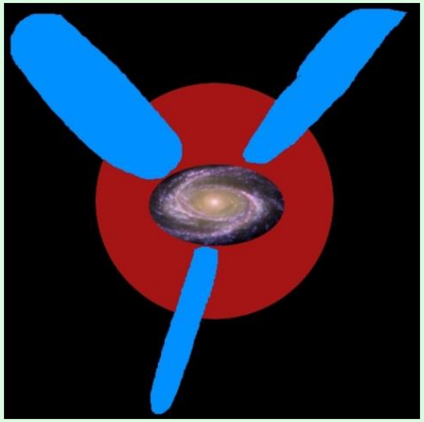
Motivation:

Paradigm shift in our understanding of galaxy formation:

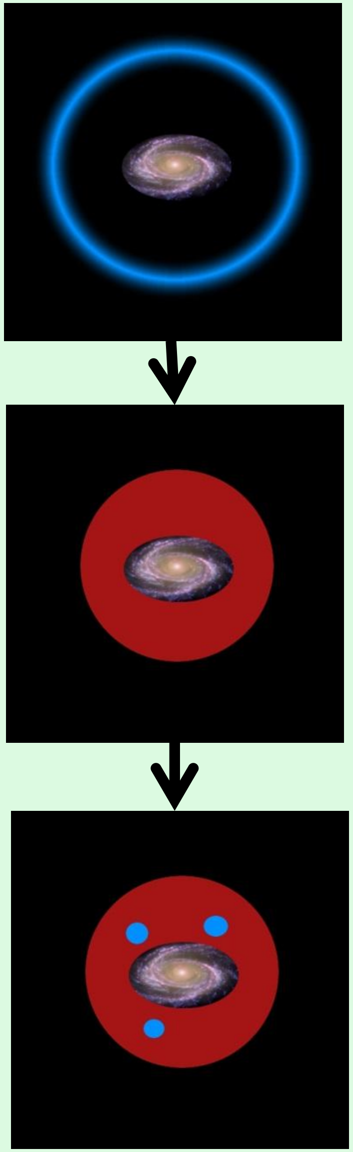
New “cold mode” accretion if either:

a) High redshift galaxies (z>2), or

b) Less massive galaxies ($M_{\mathbf{vir}} < M_{\mathbf{sh}} \sim 10^{\mathbf{12}} M_{sun}$)



Shock-heat paradigm:

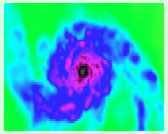


Motivation:

This "cold mode" gas accretion is expected from analytic theory & simulations, but so far there is no clear observational signature. Many open questions:

- How are cold gaseous halos built and maintained? Smooth accretion? Mergers?
- How much halo gas is there? What is its angular momentum? Redshift evolution? Mass dependence? Radial dependence?
- Can theoretical properties be confirmed (or excluded) by observations?

Main Objective:



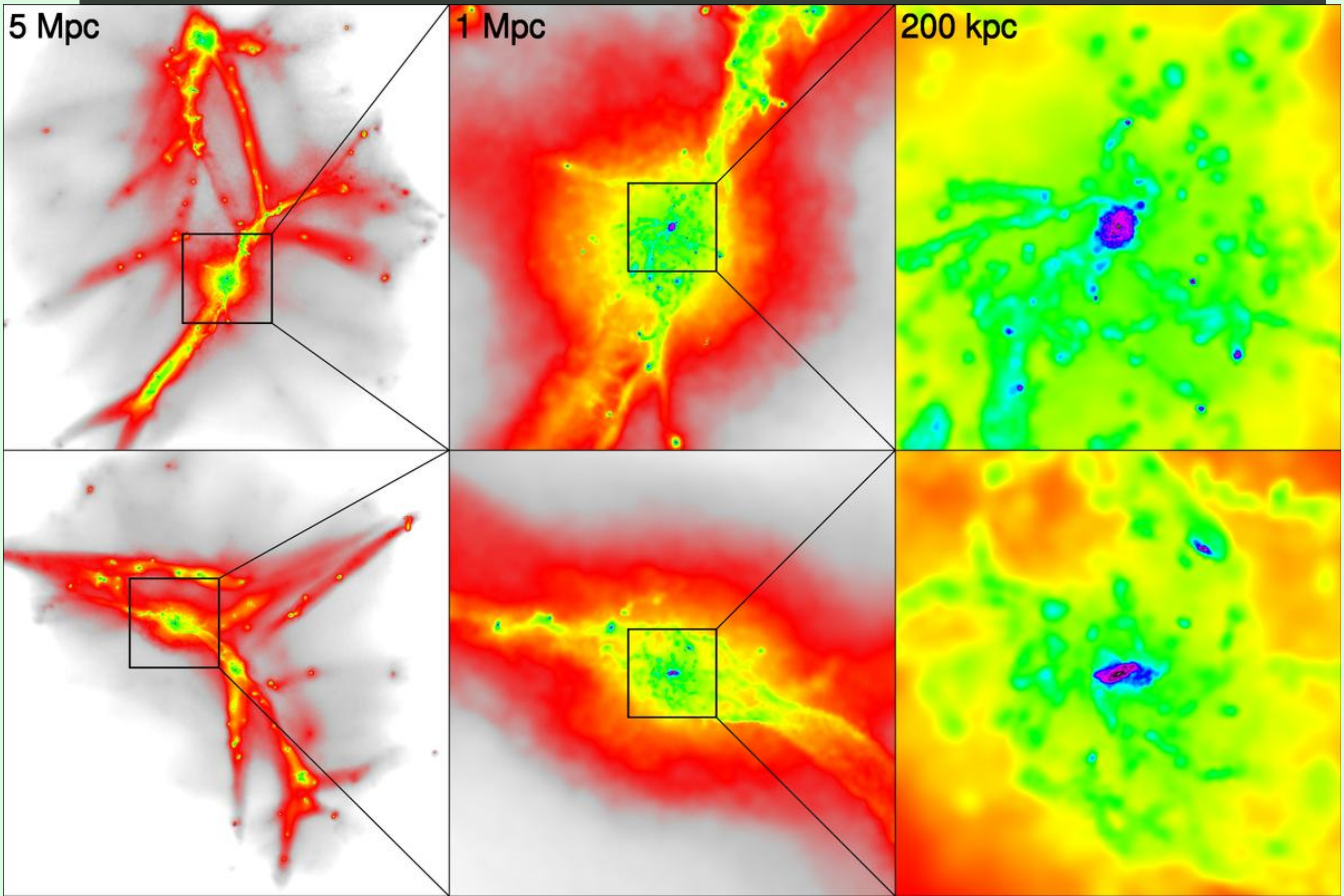
Find observable signature of cold mode gas accretion onto galaxies, using cosmological hydrodynamic simulations.

Our focus:

1. Radial extent and covering fractions of accreted cold gas in galaxy halos

2. Total mass and kinematics of this accreted gas

Our Simulations



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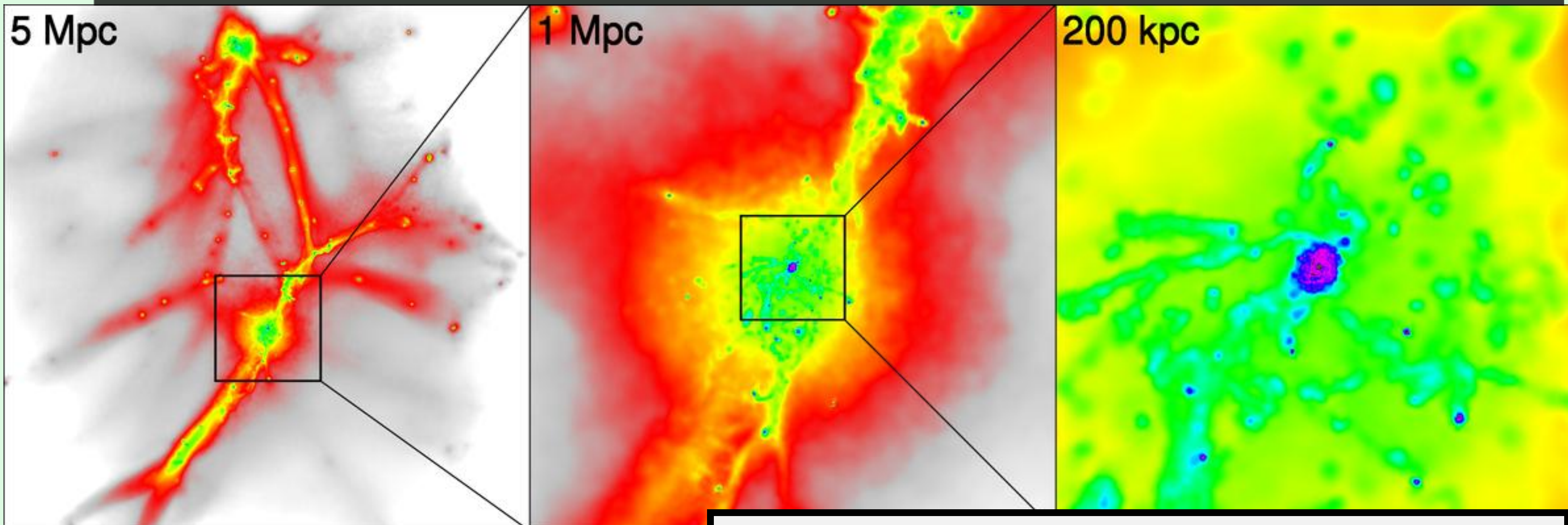


GASOLINE (SPH code)

Some stats:

WMAP3 cosmology: Ω_0=0.24, Λ=0.76, h=0.73, σ_8=0.77, Ω_b=0.042

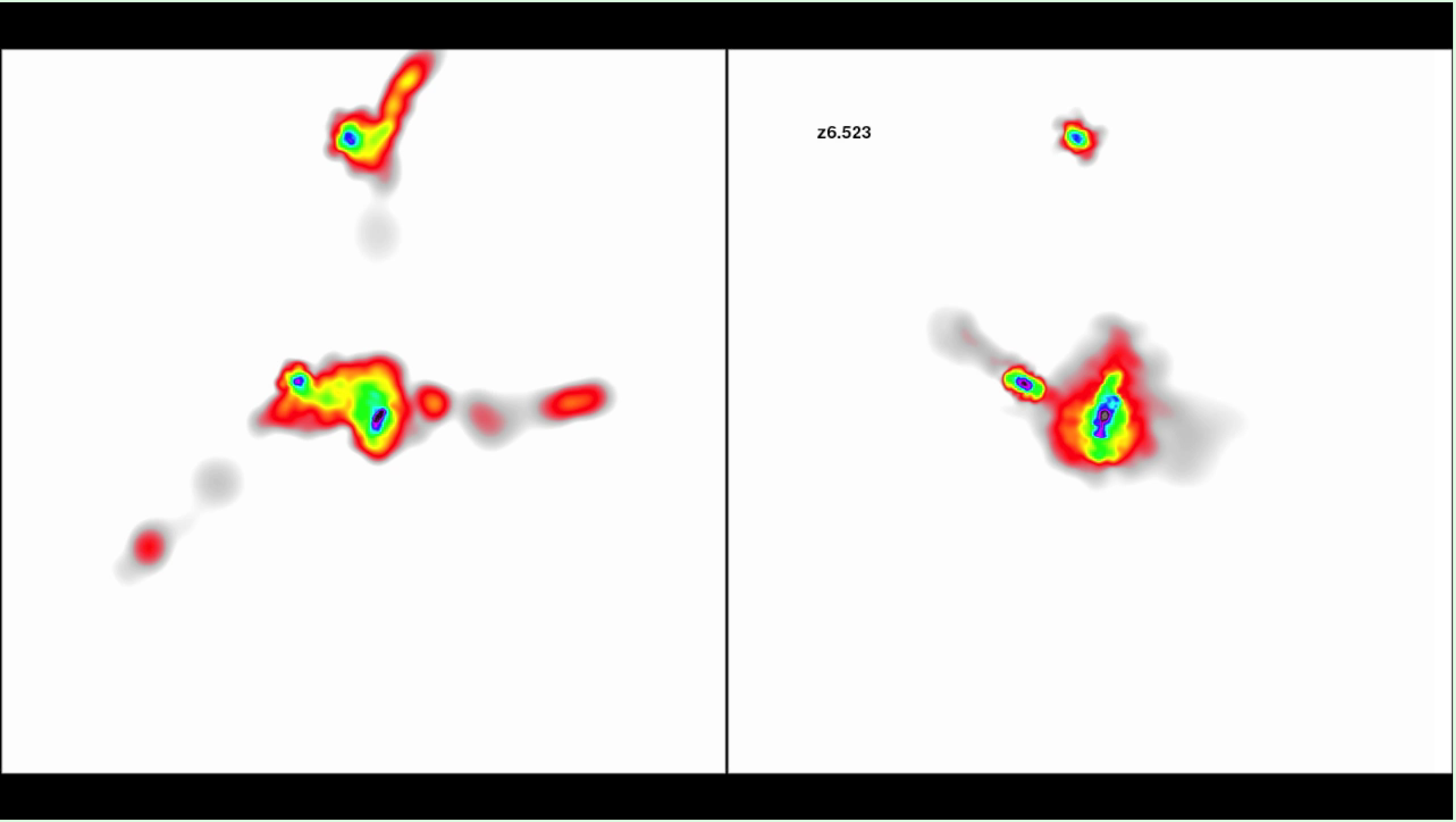
m_{DM}, m_{gas}, m_{star} ~3e5, 4e5, 1e5 M_{sun}, N_p~4 million,

Spatial resolution ~ **300 pc**. Final (z=0) halo mass: **M_{vir} ~2e12 M_{sun}**

'Blast-wave' feedback of Stinson et al. '06; Haardt & Madau '96 UV field;

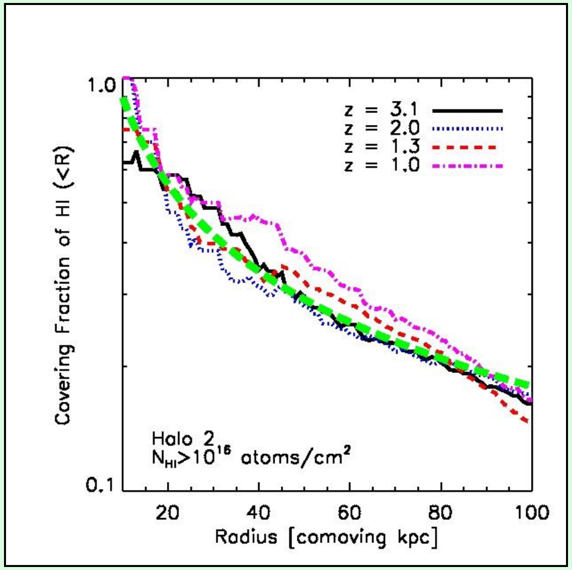
NOTE: **no strong galactic outflows** here.

Our Simulations



Cool Gas ($T<10^5$)   Stars

Covering Fraction of Cold Gas

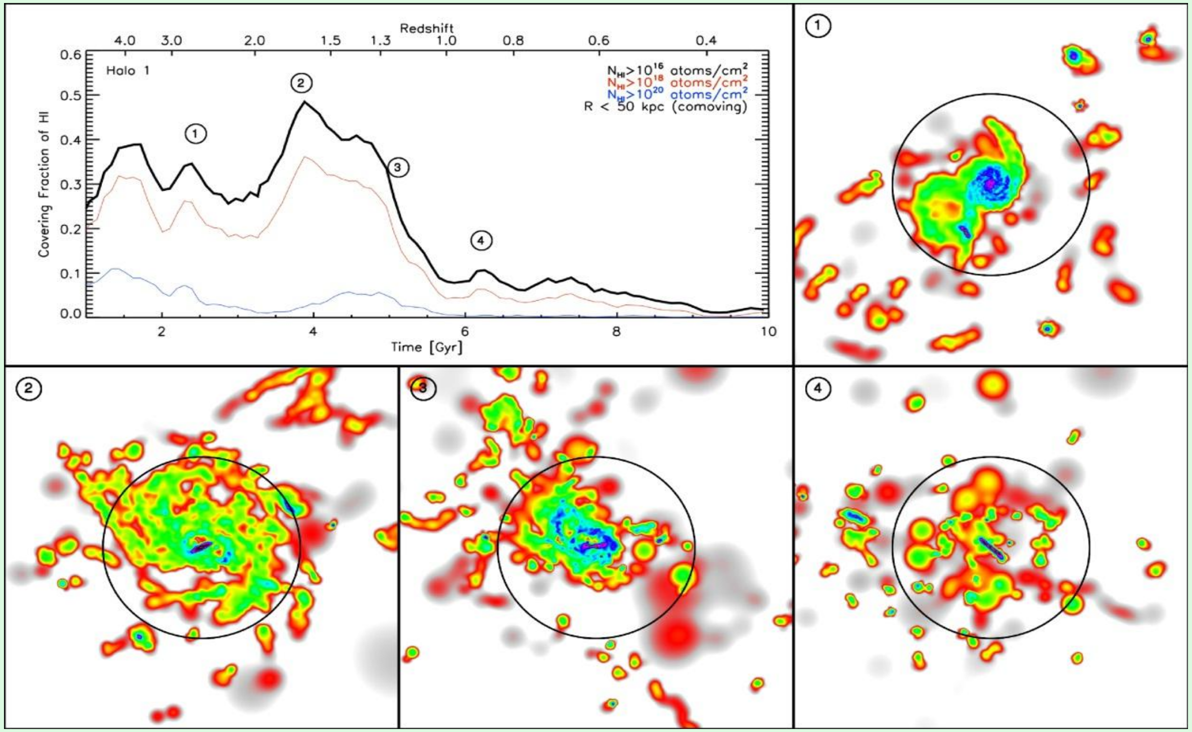


Enclosed covering fraction of HI (fractional area where $N_{HI} > 10^{16}$ atoms/cm^2) is a power law in R.

$CF(<R) = (R/R_0)^{-0.7}$; R_0 ~10 kpc (co-moving)
(Power law slope steepens by ~0.1 per factor of 10 in N_{HI})

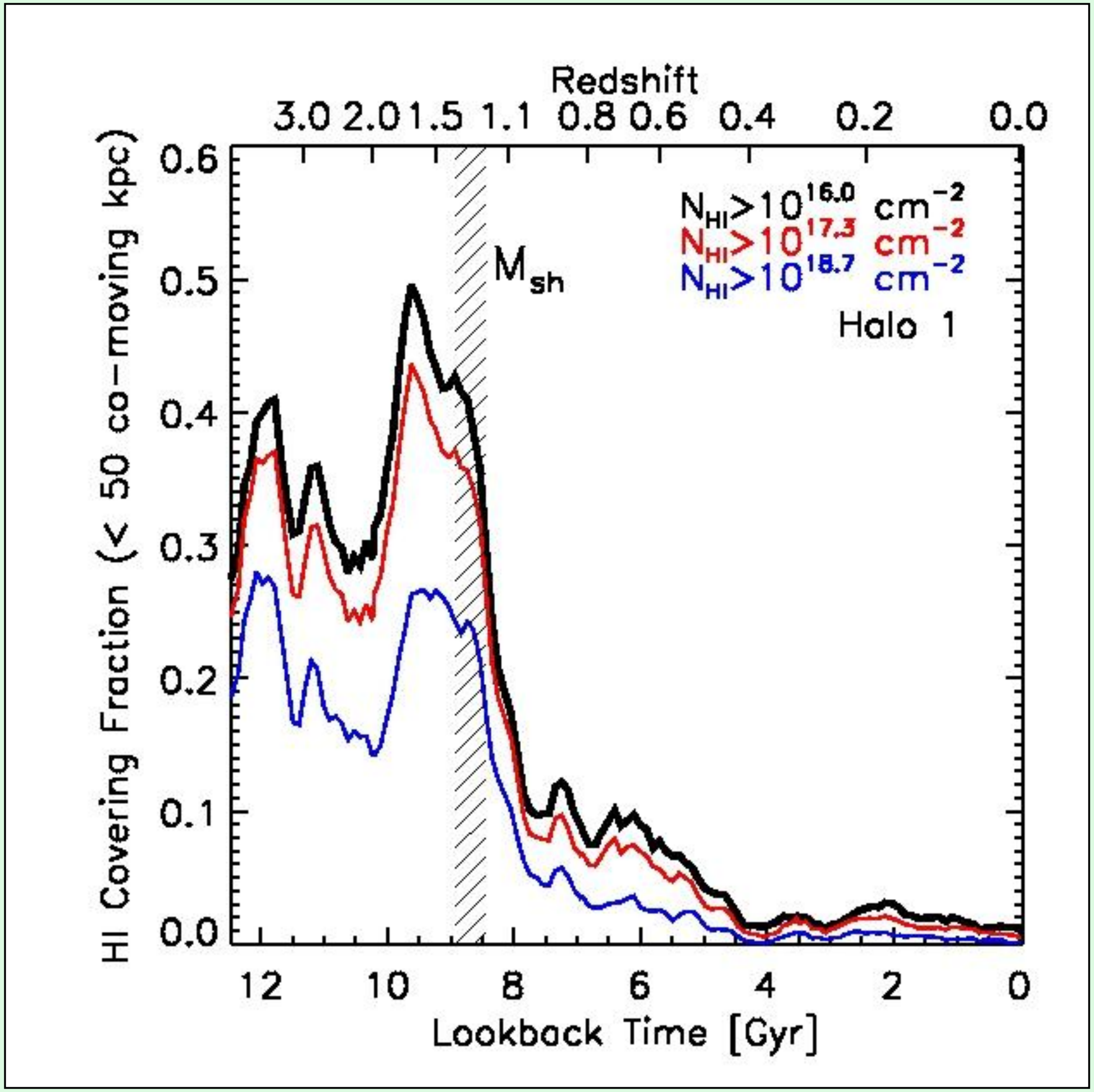
Pick a radius and look at time evolution: CF(<50 kpc) ~ 30-40%, details depends on recent gas accretion.

CF drops abruptly at late times. Why?...



Covering Fraction of Cold Gas

In galaxy formation theory, there is a critical mass to shock-heat infalling gas: $M_{sh} \sim 10^{12}\, M_{sun}$
(Dekel & Birnboim 2006)



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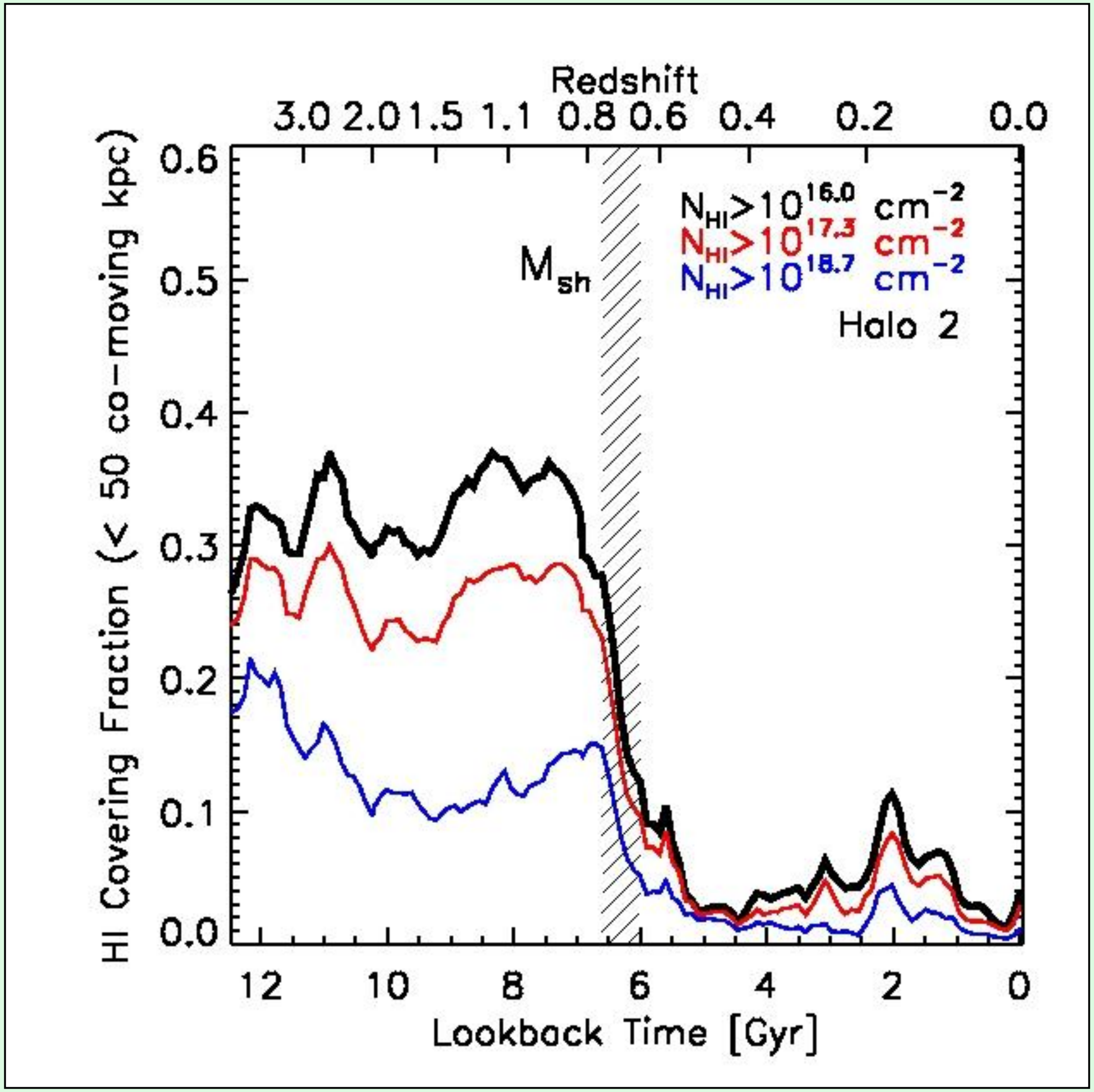
After M_{sh} our galaxies can't sustain cold gas halo → reduced CF.



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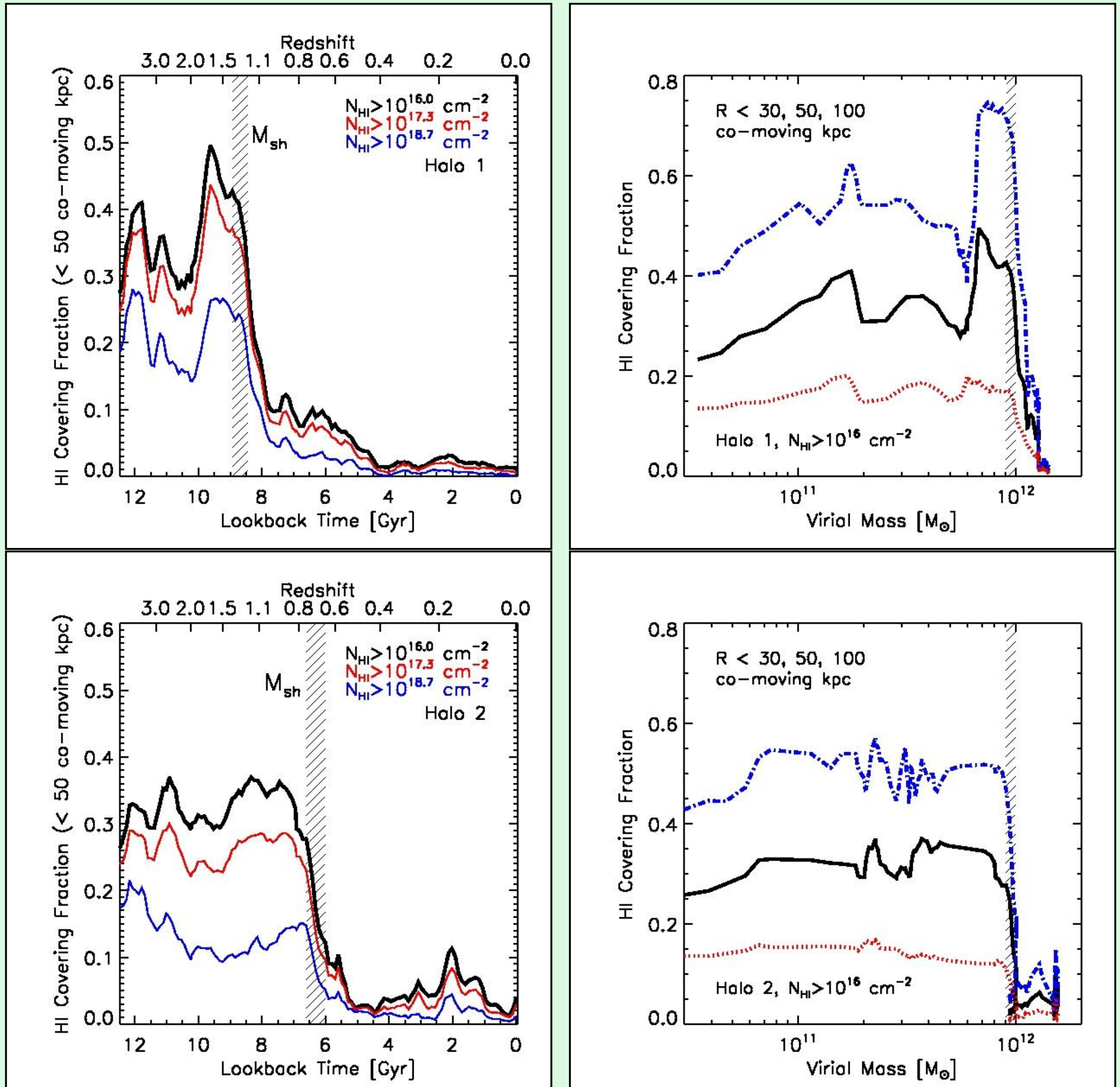
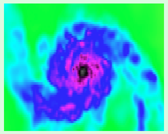
This is observable… ***if accreted*** halo gas is distinguishable from ***outflows***.



Objective:



Find observable signatures of cold gas accretion onto galaxies.

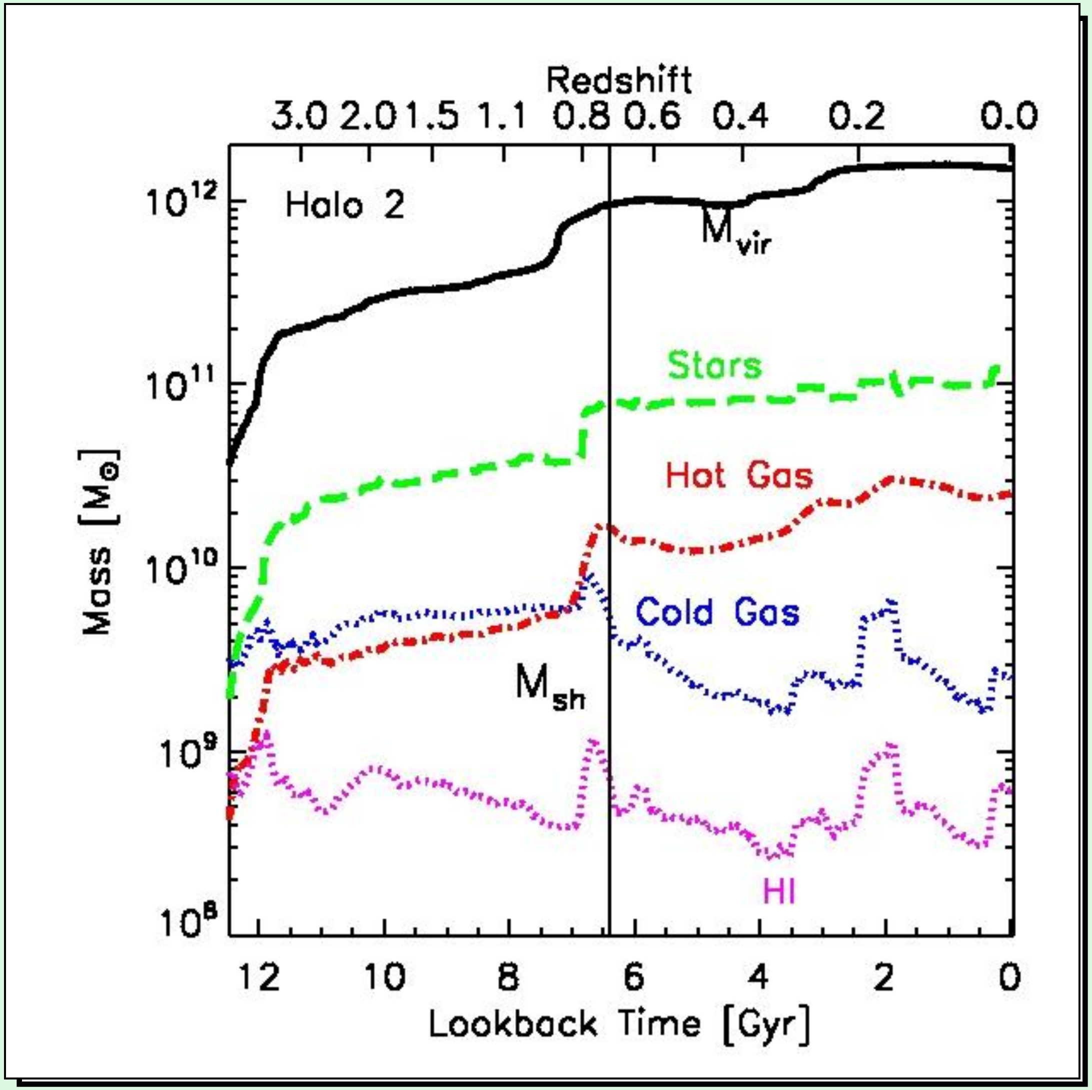
✓ 1. Radial extent and covering fractions of accreted cold gas in galaxy halos

Signature found! CF (from accreted gas) drops for massive galaxies... but this relies on distinguishing accreted gas from outflows.

→ **2. Look at physical properties of this accreted gas.**

Evolution of Mass:

(R<100 co-moving kpc)



Halo gas dominated by cold gas at early times (until halo mass > M_{sh}).

HI tracks cold gas.

Cold gas is consumed, minimal values at later times (maintained by galaxy and satellites)

Evolution of Angular Momentum:

(R<100 co-moving kpc)

Reminder: galaxy angular momentum often characterized by “spin parameter,” λ

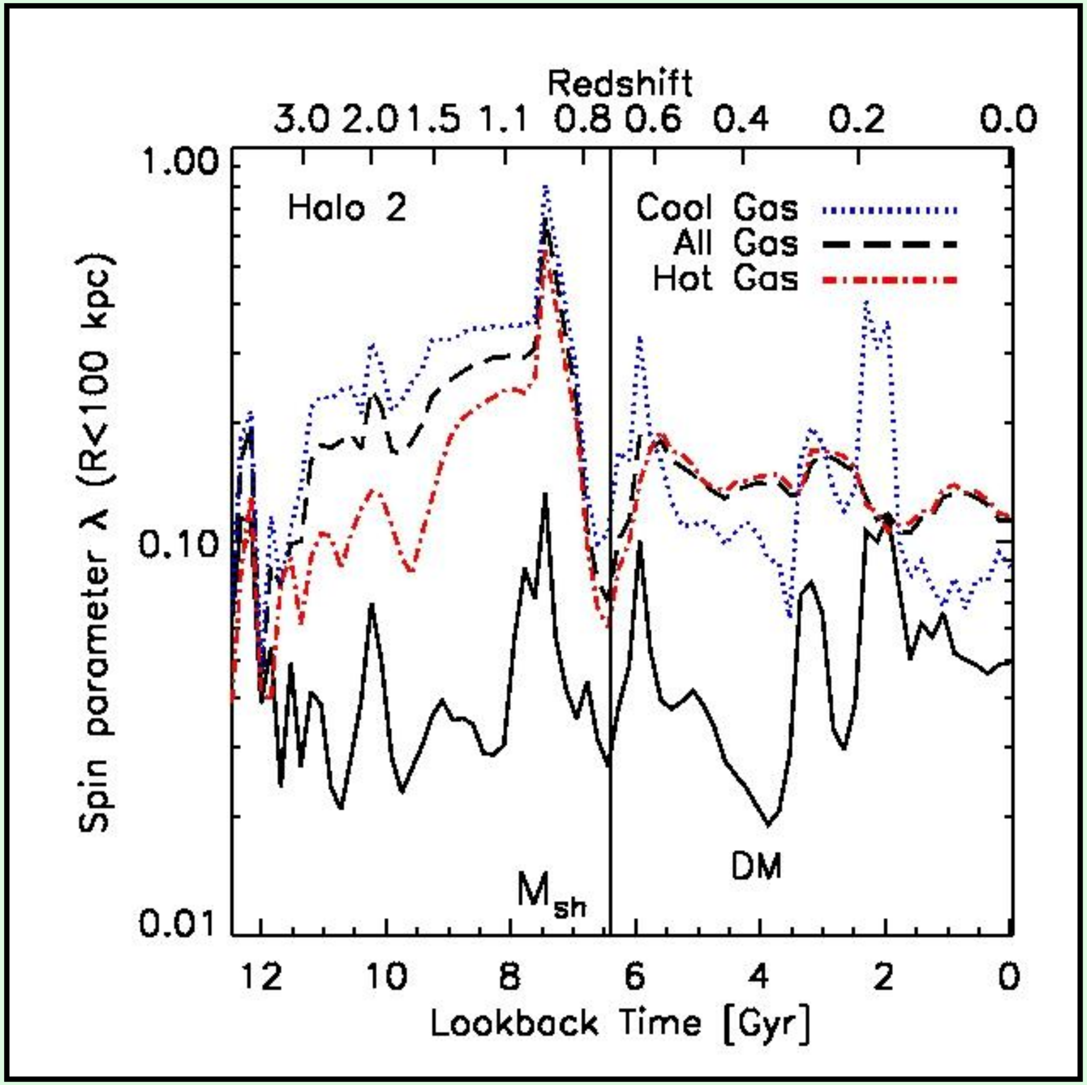
$$\lambda_x \equiv \frac{j_x}{\sqrt{2}V\ R}$$

j = specific angular momentum of a component (dark matter, gas, etc.) within a sphere of radius R;

V = the circular velocity measured at R.

Evolution of Angular Momentum:

(R<100 co-moving kpc)



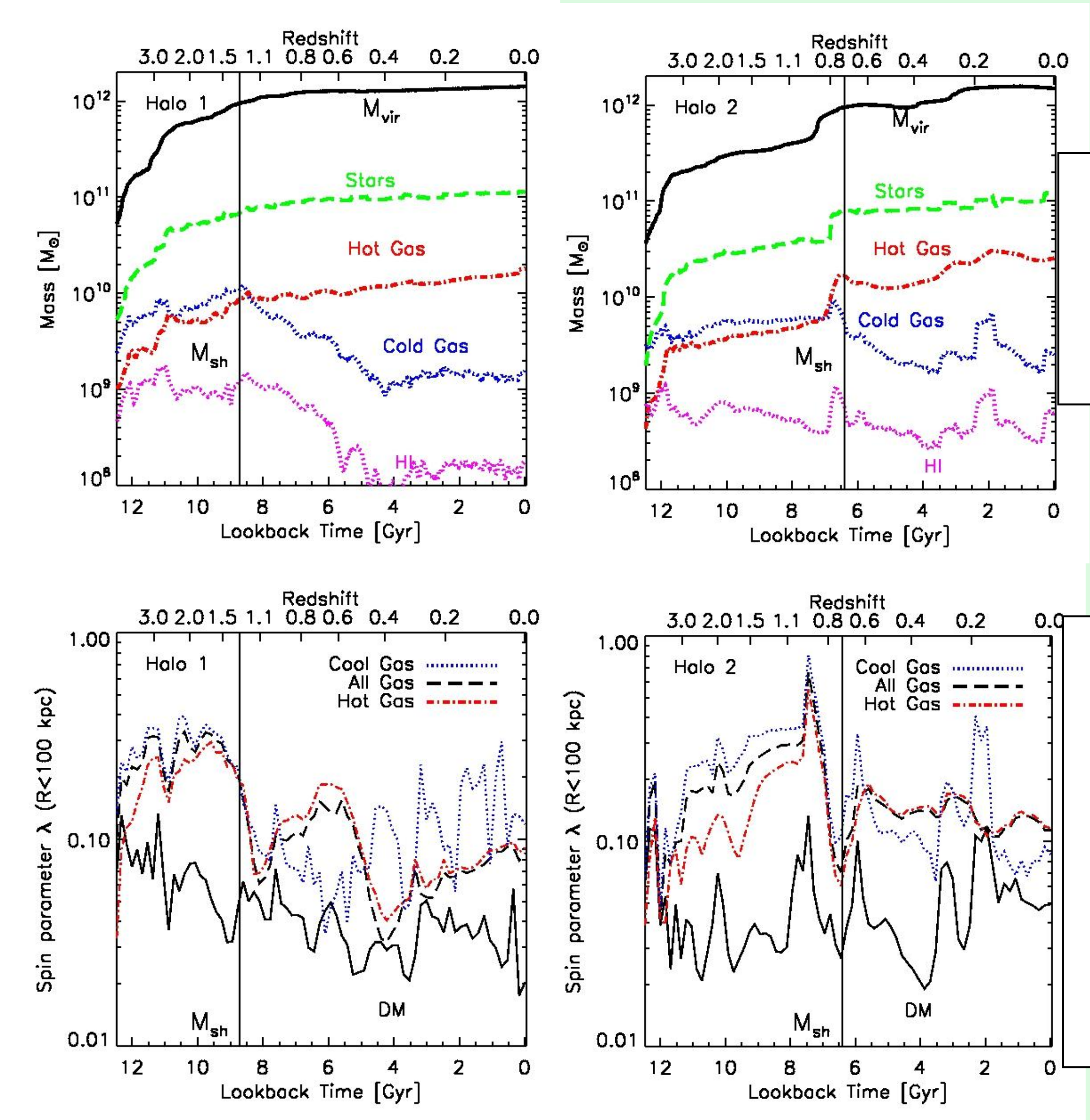
Mergers "spin up" the halo, both DM and gas (the spikes in λ).

High angular momentum DM ejected from halo. Harder to lose high angular momentum (collisional) gas particles.

Low angular momentum gas sinks to center, forms stars. (see also Kimm+ '11)

$$\lambda_x \equiv \frac{j_x}{\sqrt{2} V R}$$

Similarities in Both Simulations:



Mass

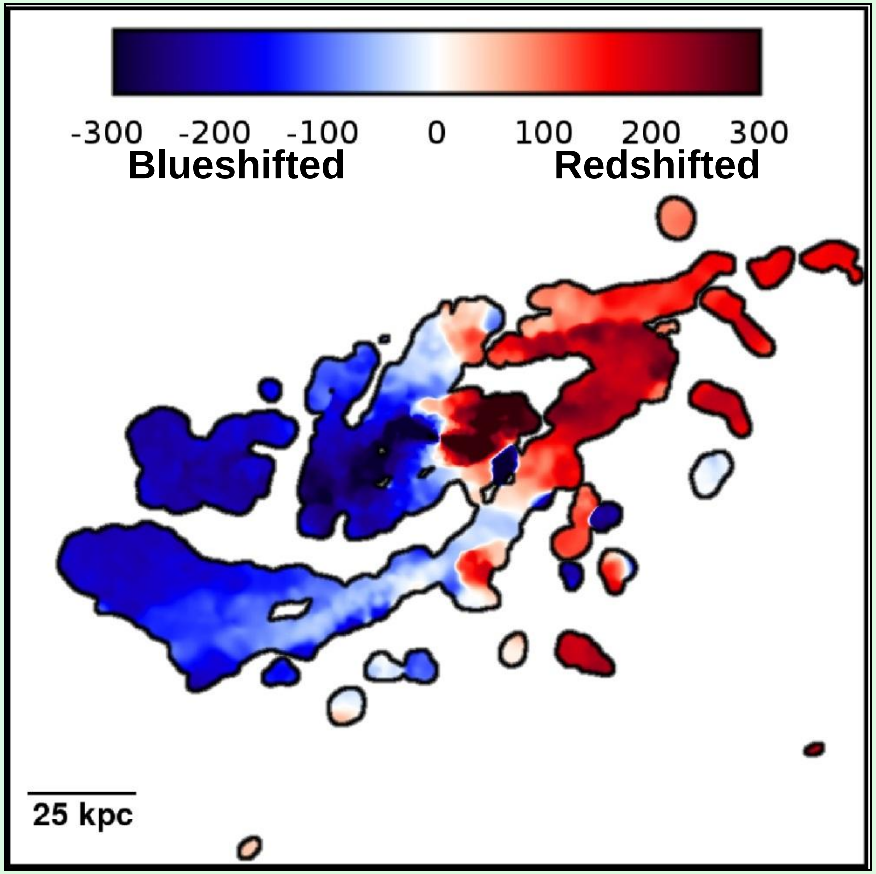
Reservoir of cold halo gas drops at $M_{vir} > M_{sh}$

Mergers/accretion "spin up" the halo (DM and gas).

Ang. Mom.

Gas retains ~5 times more ang. momentum than the dark matter!

Coherent Rotation of Halo Gas:



With λ_{gas} so high, is there any ***coherent*** rotation of halo gas?

Since this gas is from accretion only (not outflows) it eventually falls in to the galaxy disk and forms stars.

Possible correlation between rotation of halo gas and the galaxy?

Yes! Accreted halo gas co-rotates with the disk, even out to ~100 kpc.

But can this be observed?

How to observe cold halo gas…

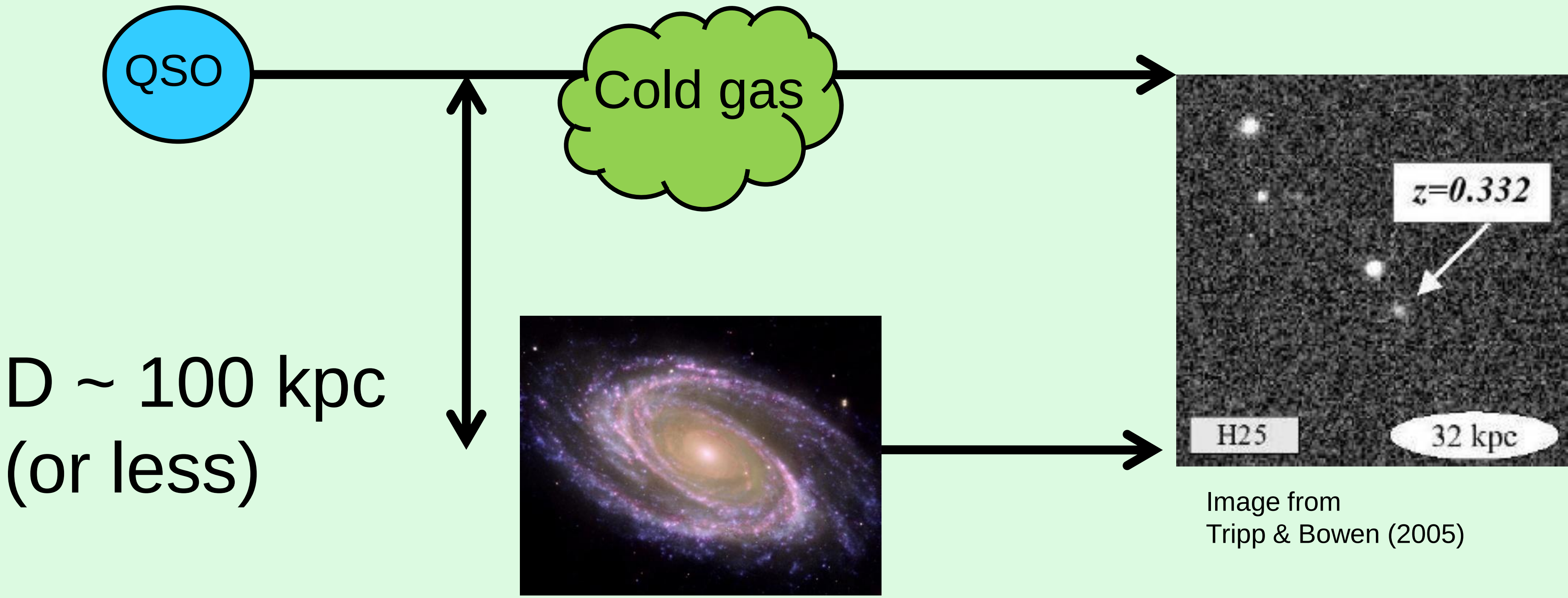
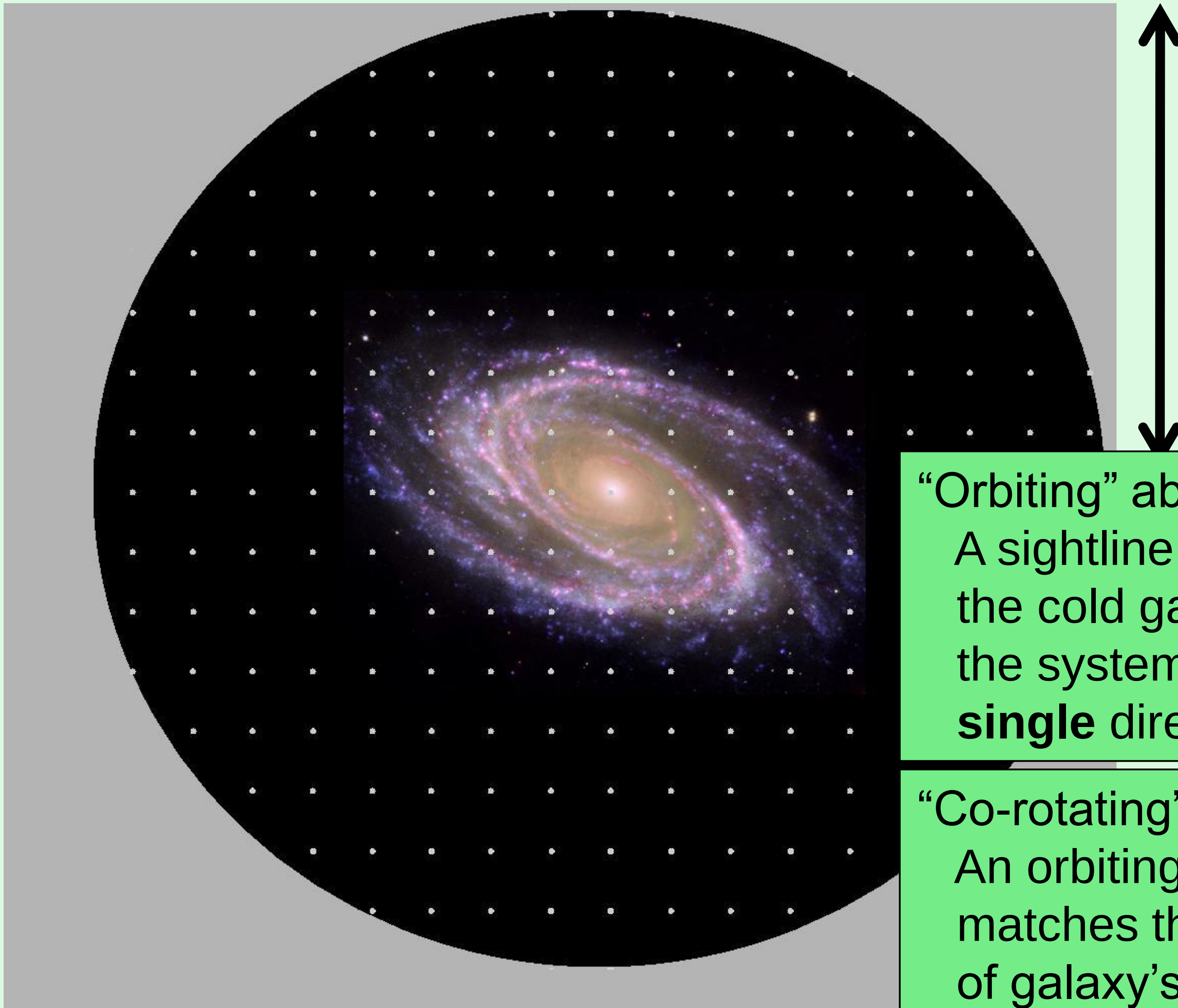


Image from
Tripp & Bowen (2005)

…via absorption

Creating Mock "Observations"



$R_{\mathbf{outer}}$ = 100 kpc (co-moving)

$N_{\mathbf{grid}}$ ~ 1000

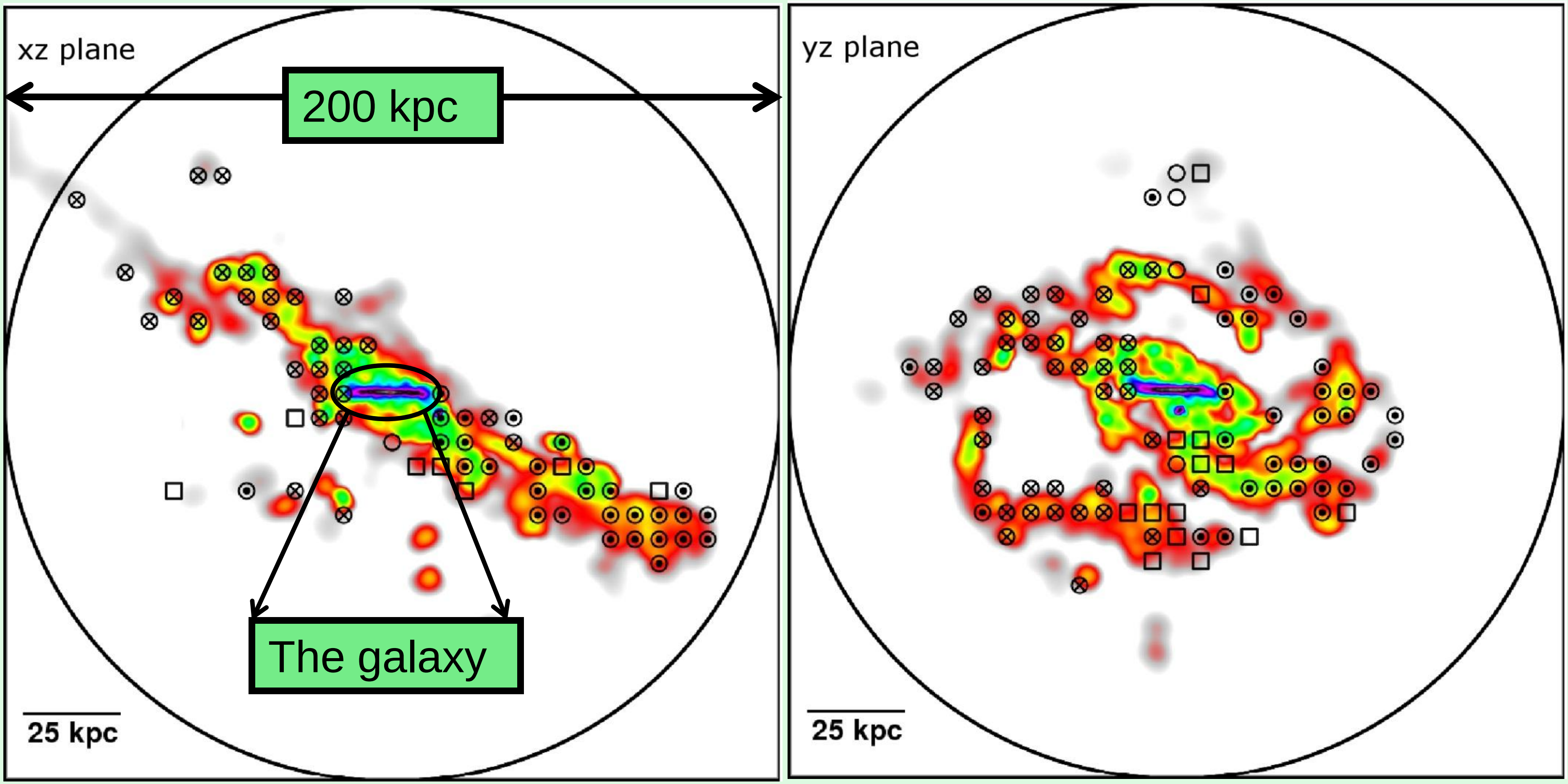
"Orbiting" absorption:
A sightline where >90% of the cold gas is offset from the systemic velocity in a **single** direction.

"Co-rotating" absorption:
An orbiting sightline that matches the nearest side of galaxy's rotation.

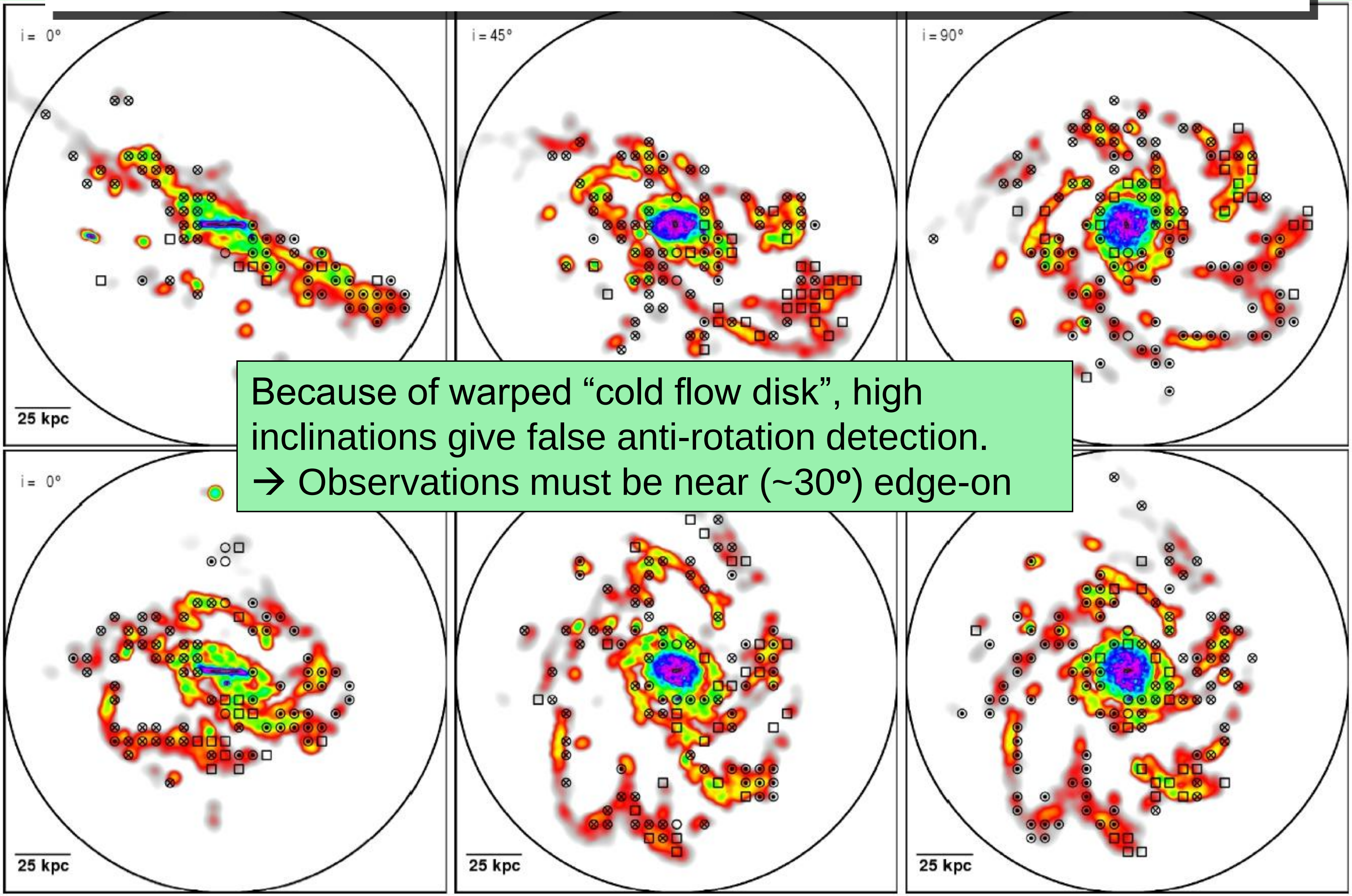
Halo Gas Kinematics

Accreted gas typically forms "cold flow disk"
→ aligned with large-scale filament.
→ extends to ~ 100 co-moving kpc
Co-rotating fraction ~ 70%

Circle-dot: "out of" image
Circle-X : "into" image
Squares : at systemic.

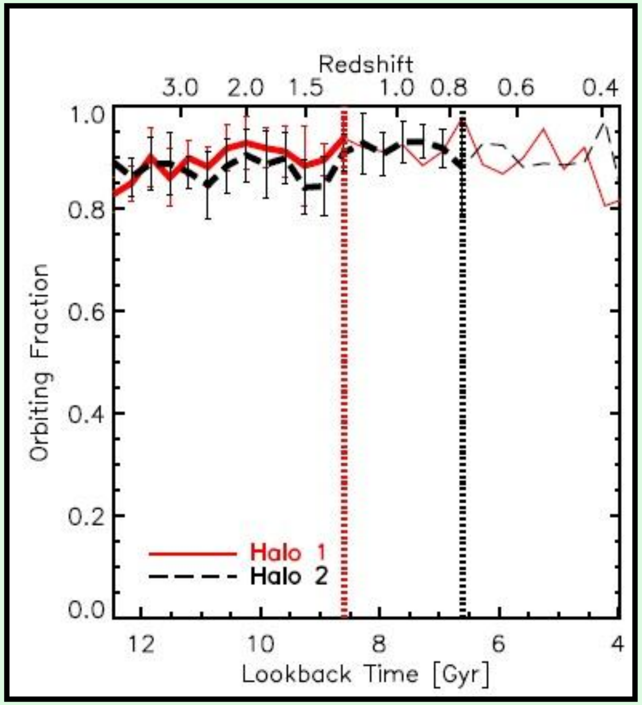


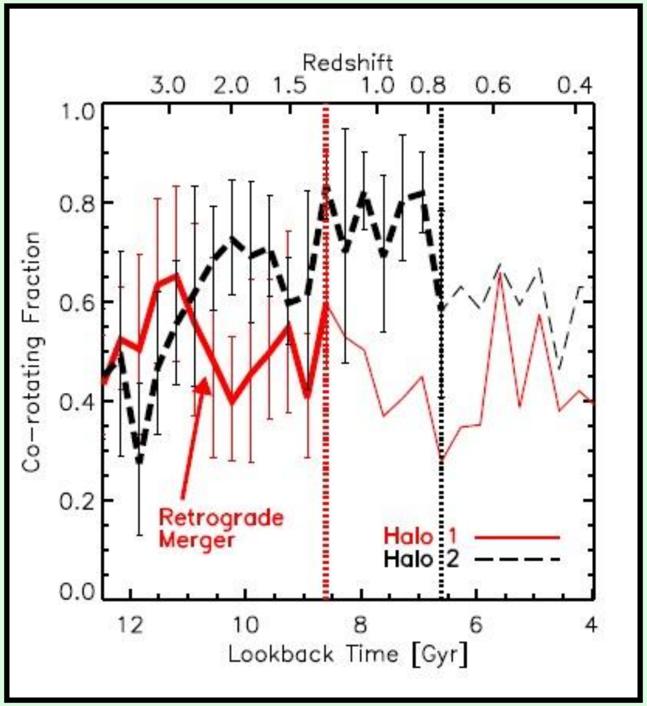
Effect of Inclination



Because of warped "cold flow disk", high inclinations give false anti-rotation detection.
→ Observations must be near (~30º) edge-on

Accreted gas over time





Even when galaxies not in cold mode accretion, accreted cold gas orbits the galaxy (velocity offsets).

Co-rotation more stochastic, but majority of gas co-rotates for relaxed, cold mode galaxies.

Co-rotation over time

Majority of cold accreted gas co-rotates

- co-rotation fraction ~60-80% across multiple epochs (3<z<1) for both simulated galaxies

Caveat 1: the galaxy must be relatively stable. Lower co-rotation fractions result from:

- Violent galaxy formation on short timescales at (z > 3)
- Retrograde major merger that re-define angular momentum axis of the galaxy (co-rotation returns over time).

Caveat 2: galaxy must be in cold-mode accretion (before the covering fraction and cold halo gas mass both drop).

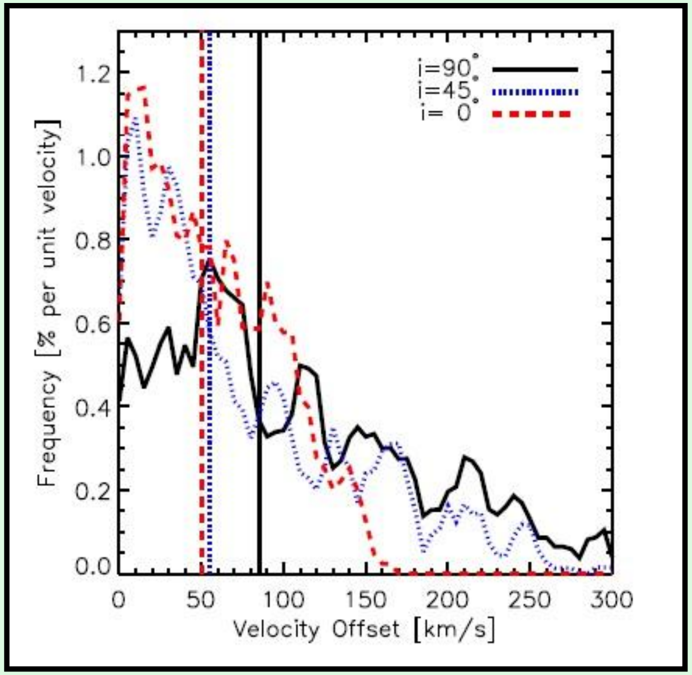
- Co-rotation signal dies once galaxies are massive enough to shock-heat infalling gas ($M_{vir} > M_{sh} \sim 10^{12}\ M_{sun}$).

Can Outflows Co-rotate?

This signature only matters if it ***distinguishes*** between infalling gas and outflows/winds/feedback.

Spherical Outflows: should not orbit with velocity offsets from systemic in a *single* direction.

Bi-conical Outflows: should only show single-sided velocity offsets in near-polar projections, precisely where accreted gas is *least* reliable / *least* likely to show rotation.



Even high angular momentum gas blown out of a rotating disk will only rotate at ~25 km/s at 40 kpc (conserving angular momentum)

→ **No,** outflows should **not** orbit/co-rotate the way accreted gas does.

But can co-rotation *really* be observed?

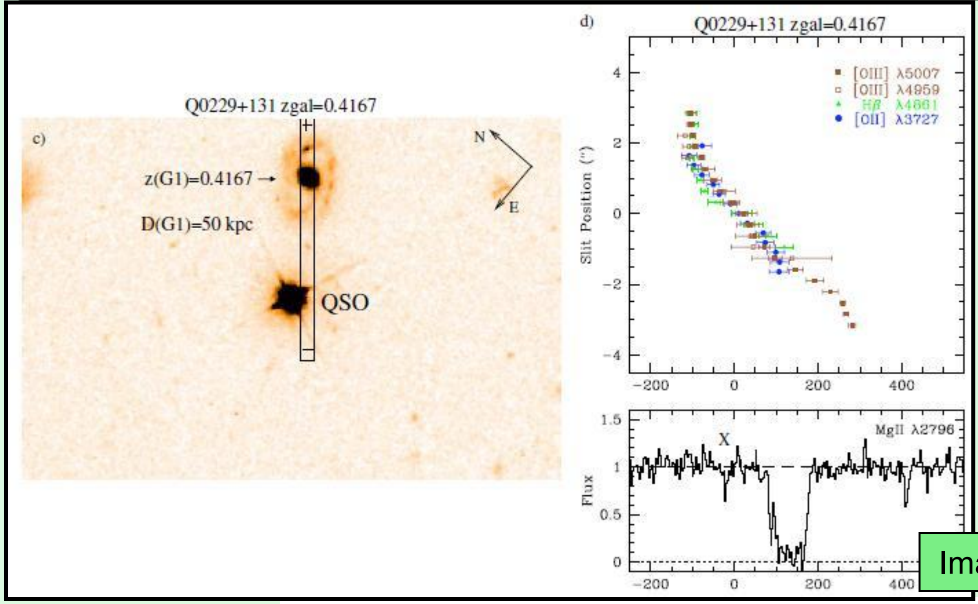


Image from Kacprzak+ ‘10

Steidel+ 2002; Ellison+ 2003; Chen+ 2005; Kacprzak+ 2010;

Compared kinematics of cold absorption gas (using Mg II lines) to galaxy rotation curve.

It has already been observed!

Our results (variation over time and orientation → range):

Velocity Offset: **85% ± 5%**
Co-rotation: **70% ± 10%**

Observations (combined sample, low number statistics → errors):

Velocity Offset: **74% ± 20%**
Co-rotation: **56% ± 18%**

Further (qualitative) agreements…

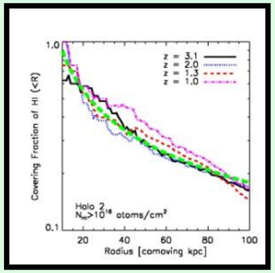
Kacprzak+ '11: sample of more massive galaxies (~1.9 L*) that should sample galaxies *more massive than the transition mass*:

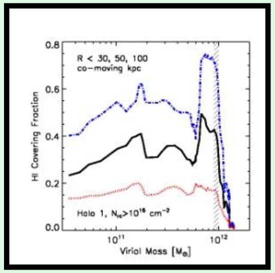
- Found significantly lower orbiting fraction (velocity offsets) ~ 40-50% (instead of 70% for less massive sample)
- Co-rotation is more rare for these systems

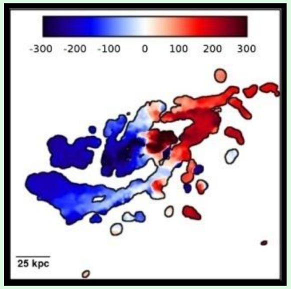
Kacprzak+ (submitted): sample of less massive (<L*) intermediate redshift galaxy/absorber pairs:

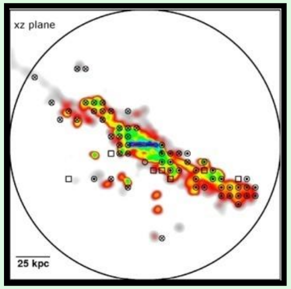
- Equivalent width, optical depth, both correlate with galaxy inclination.
- Suggests co-planar geometry coupled to galaxy inclination (consistent with warped "cold flow disk" picture)

Summary









Look in hydrodynamic simulations at ***accreted*** halo gas**:**

- HI gas extends to ~100 co-moving kpc.
- Covering fraction of HI gas drops off as power law in R.
- CF(<50 co-moving kpc) drops from ~30-40% to ~5% after DM halo reaches critical shock-heating mass (M_{sh}~10^{12} M_{sun})

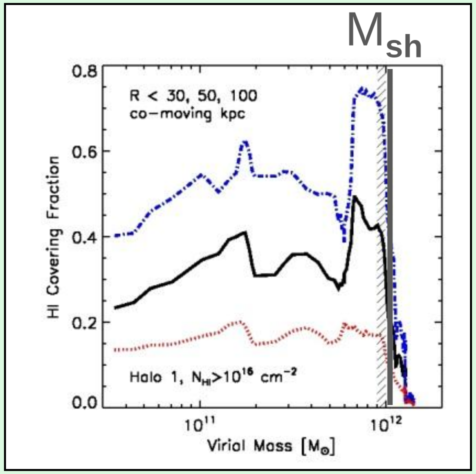
- λ_{gas} ~ 5 times higher than DM halo. This gas is spun up by mergers, fed by ongoing infall, eventually falls onto disk.

- Cosmological gas accretion in LCDM inevitably leads to co-rotation of cold halo gas with the galactic disk. Typically in the form of a "cold flow disk" aligned with filament.

- This co-rotation signature can be observed. Limited observations agree remarkably well with our simulations.

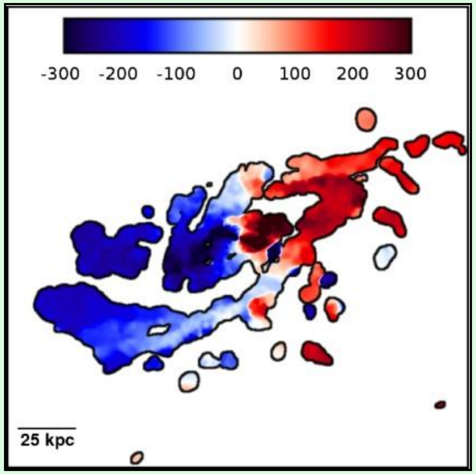
Conclusion:

Goal: find observable signature of cold gas accretion onto galaxies. ✓



Covering fraction of accreted gas drops after transition mass, M_{sh}.

Accreted gas co-rotates with galactic disk, distinguishing it from outflows in an observable way



The covering fraction of co-rotating cold gas should drop substantially for massive galaxies. **This signature is observable in absorption!**