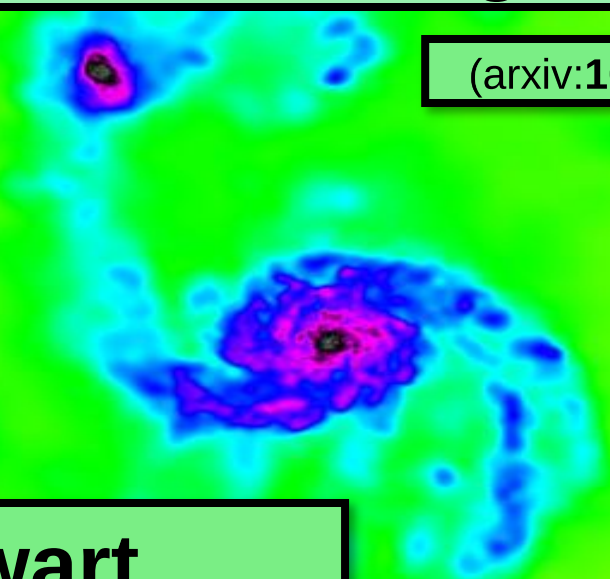
Observing the End of Cold Flows: Orbiting Circum-galactic Gas as a Signature of Cosmological Accretion

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



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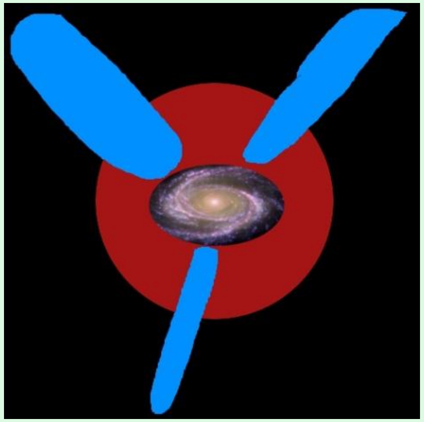
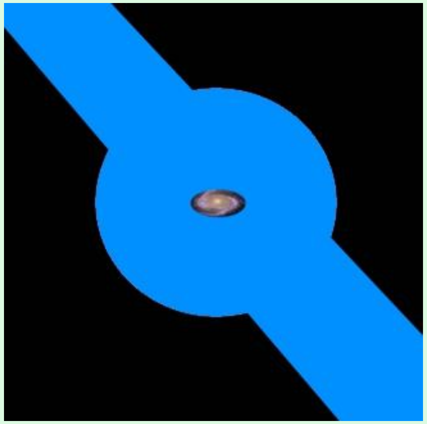
Motivation:

Paradigm shift in our understanding of galaxy formation:

New “cold mode” accretion paradigm if either:

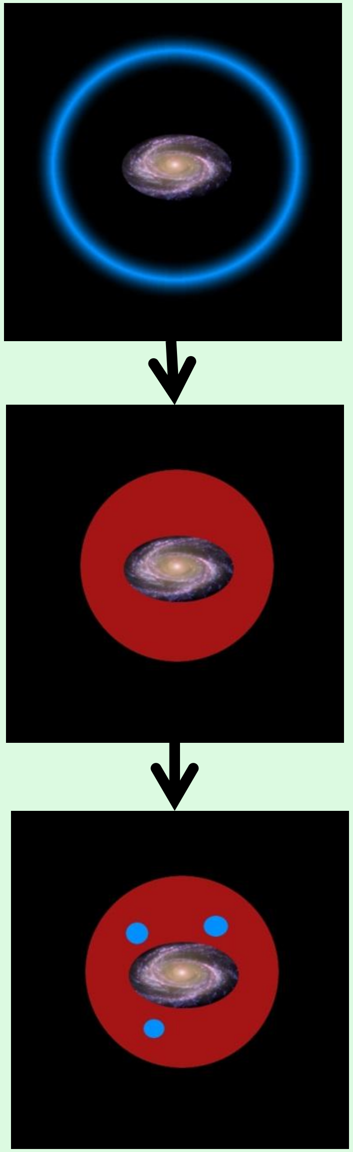


1) “cold streams”: all high redshift galaxies (z>2)



2) “cold mist”: low mass galaxies at moderate to low redshift ($M_{vir} < M_{shock} \sim 10^{12}\ M_{sun}$)

Shock-heat paradigm:



Motivation:

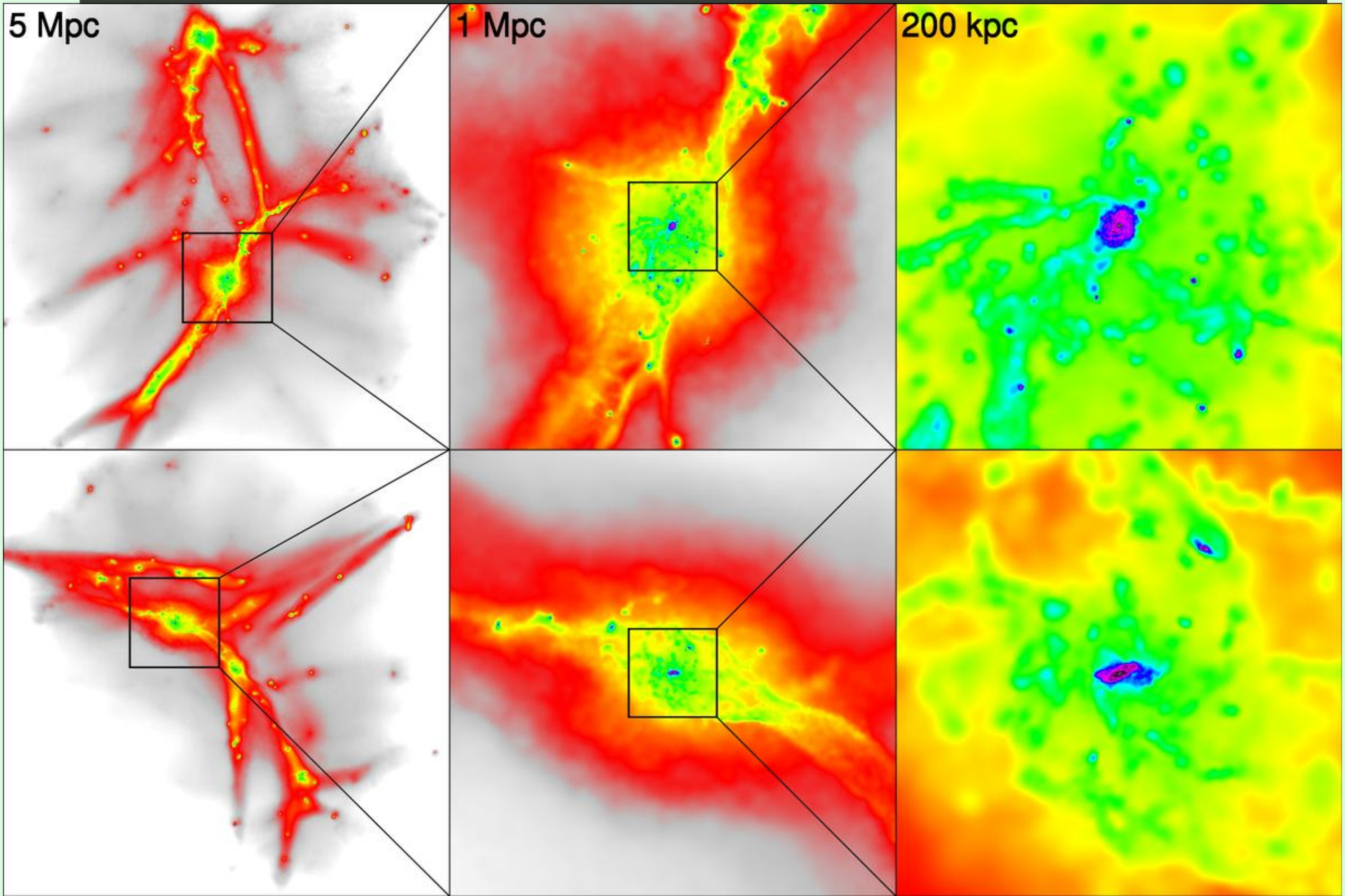
This “cold mode” gas accretion is expected from analytic theory & simulations, but so far there are few (if any) clear, testable observational signatures.

Objective:

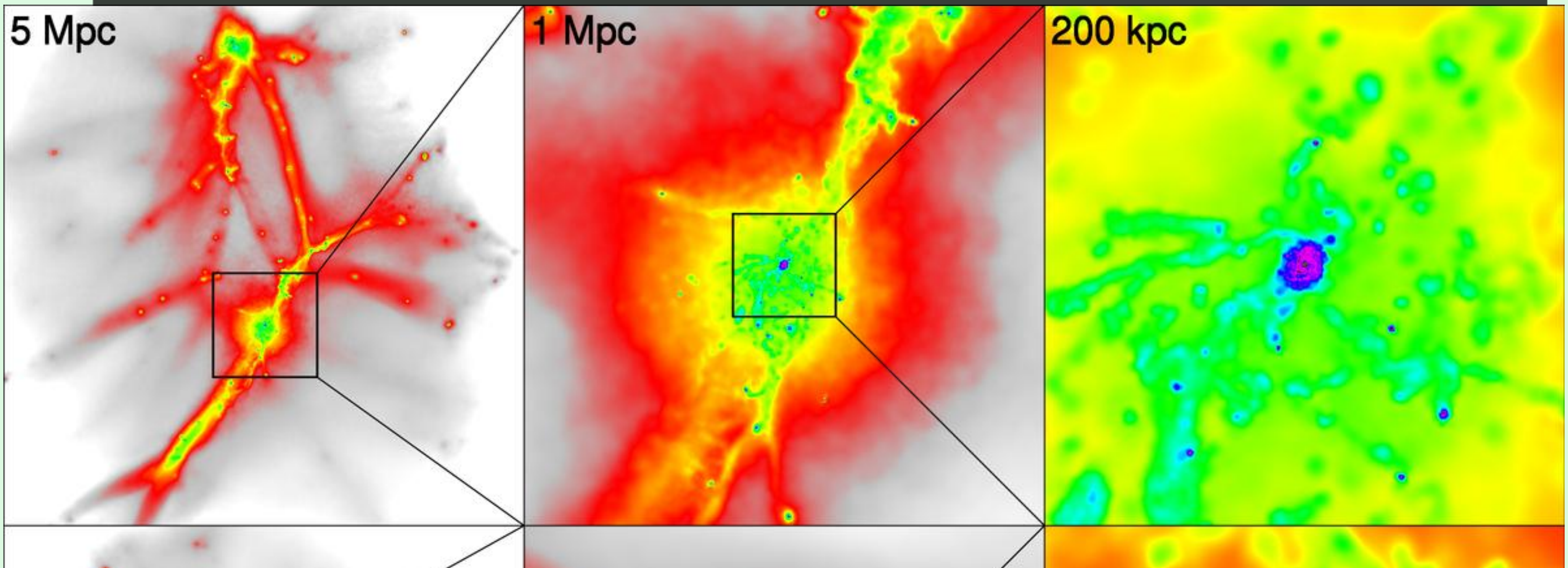
Find observable signature of cold mode gas accretion onto galaxies (using SPH sims.)

1. Radial extent and covering fractions of cold-mode gas in galaxy halos
2. Angular momentum of cold-mode gas

Our Simulations



Our Simulations



Some stats: (SPH code GASOLINE)

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

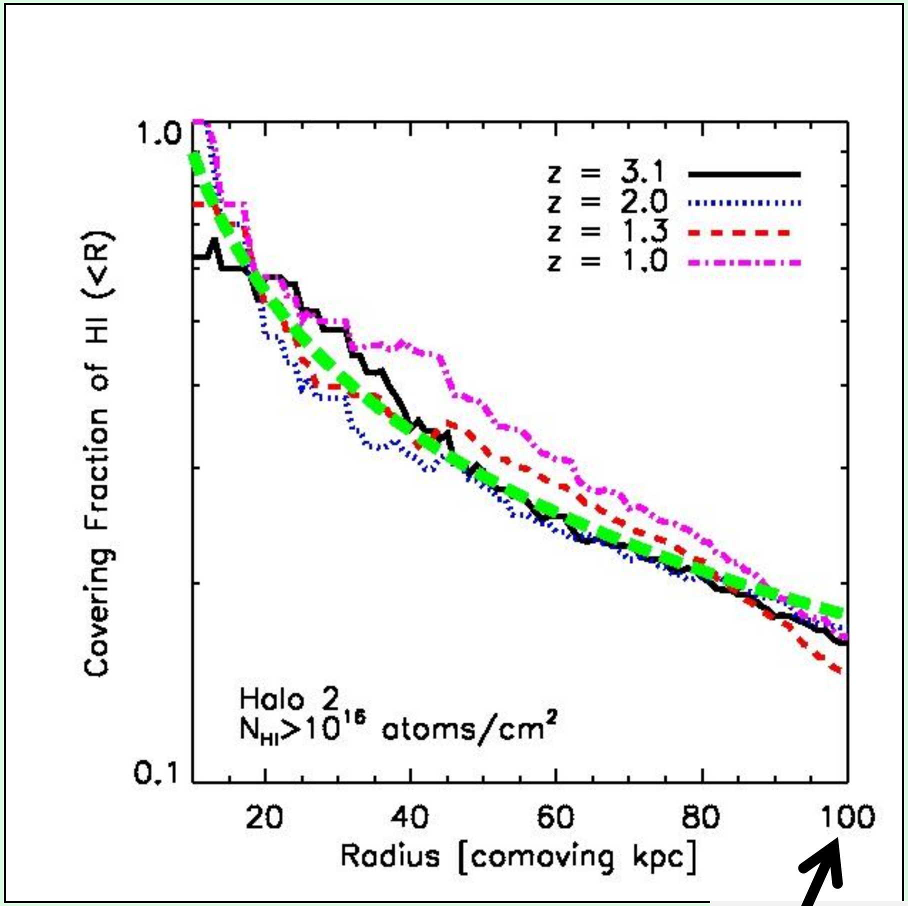
Spatial resolution ~ 300 pc.

Final (z=0) halo mass: **M_{vir} ~2e12 M_{sun}**

NOTE: no strong galactic-scale outflows in these galaxies.

(thermal feedback scheme, models SN blast waves)

Covering Fraction of Cold Gas



~ $R_{vir}/2$

Covering fraction of neutral hydrogen ($N_{HI} > 10^{16}$ cm^{-2}) well-fit by a power law in R (similar to Steidel+10 for z=2-3)

$CF(<R) = (R/R_0)^{-0.7}$; R_0 ~10 kpc

(Power law slope steepens by ~0.1 per factor of 10 in N_{HI})

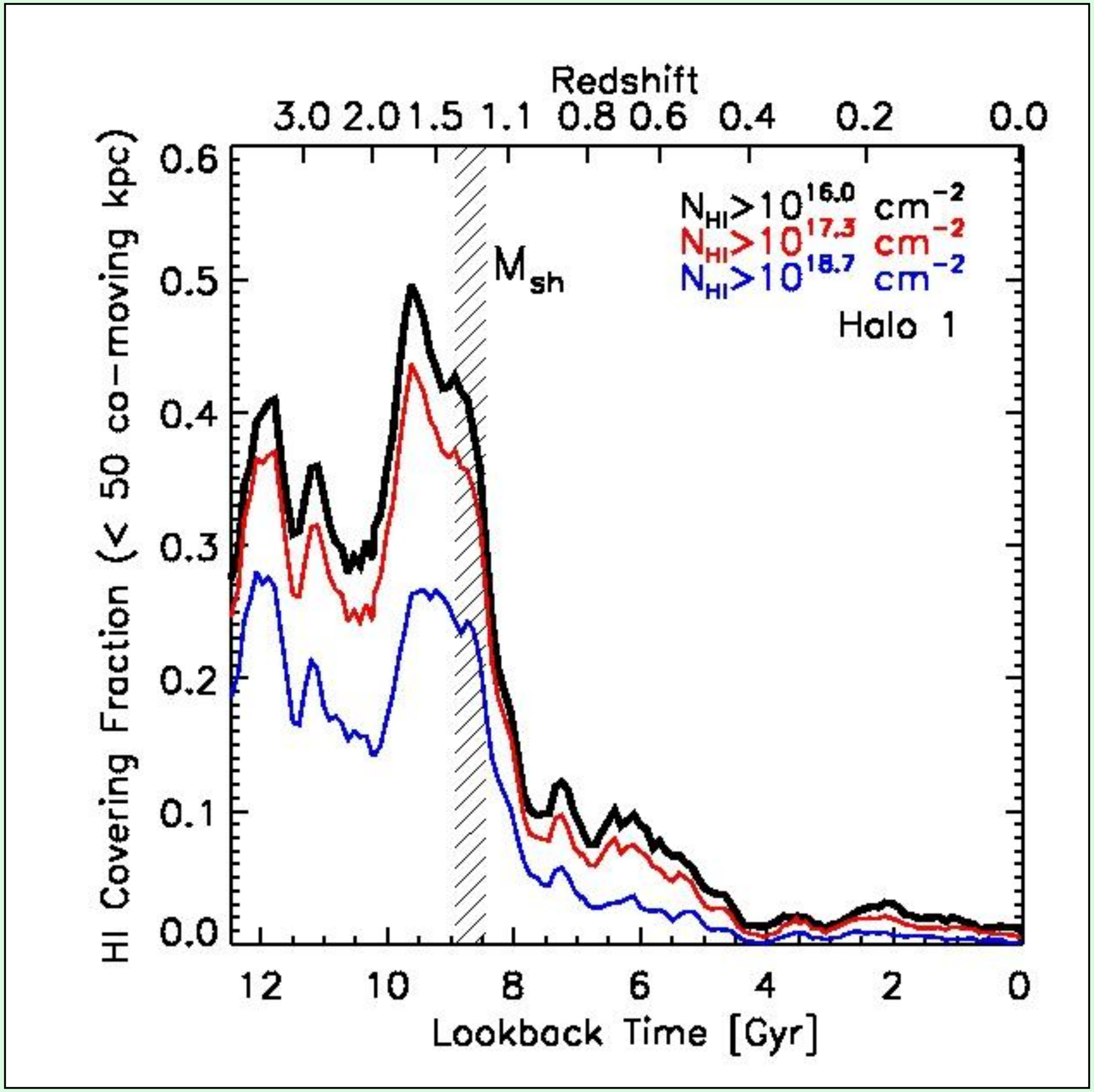
Q: How best to compare CF at different times?

A: Pick a fixed co-moving radius.

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)

See also:
Faucher-Giguère & Keres ’10;
Fumagalli+10; Kimm+10



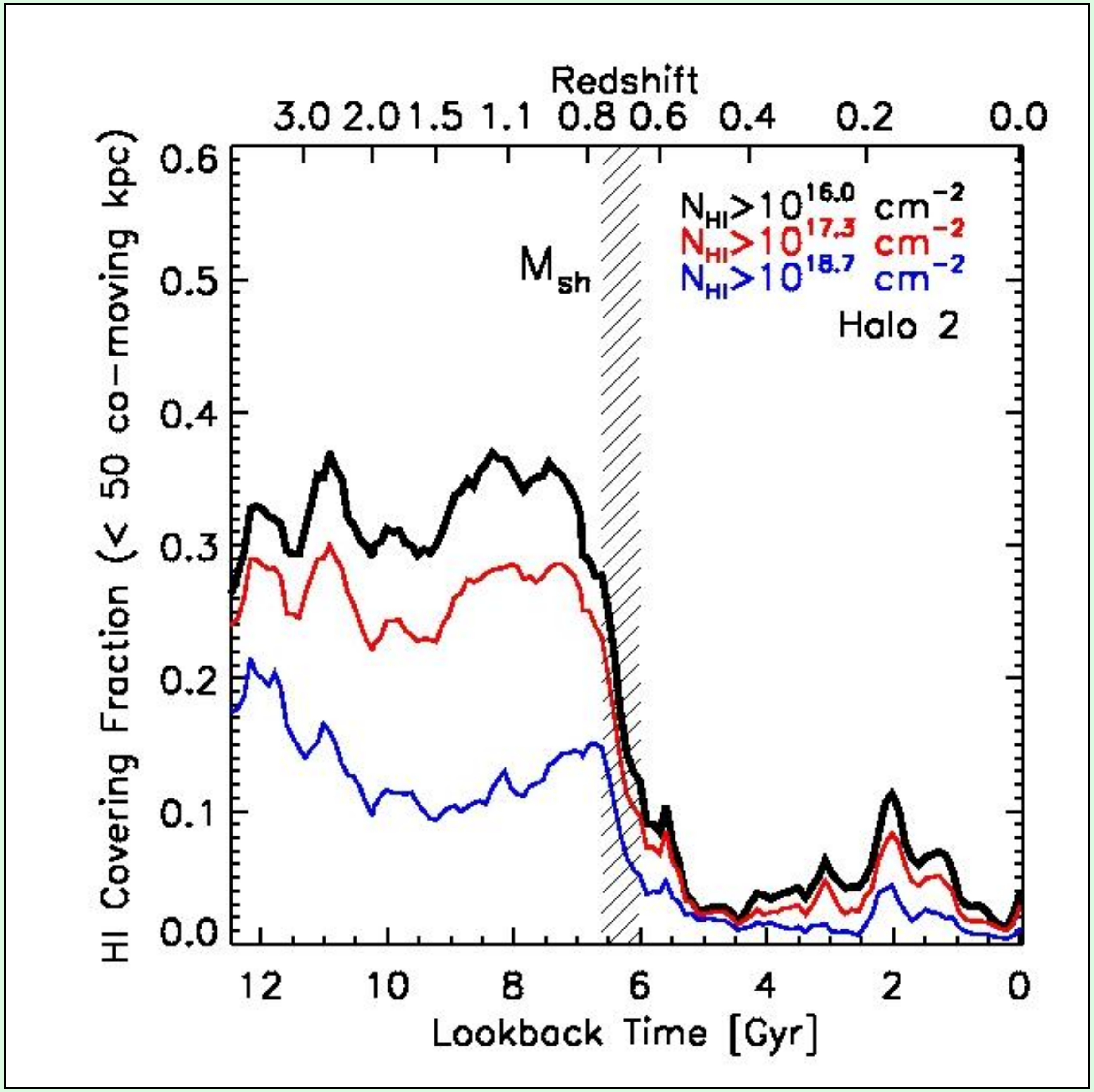
Covering Fraction of Cold Gas

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

(Dekel & Birnboim 2006)

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

See also:
Faucher-Giguère & Keres '10; Fumagalli+10; Kimm+10



Objective:

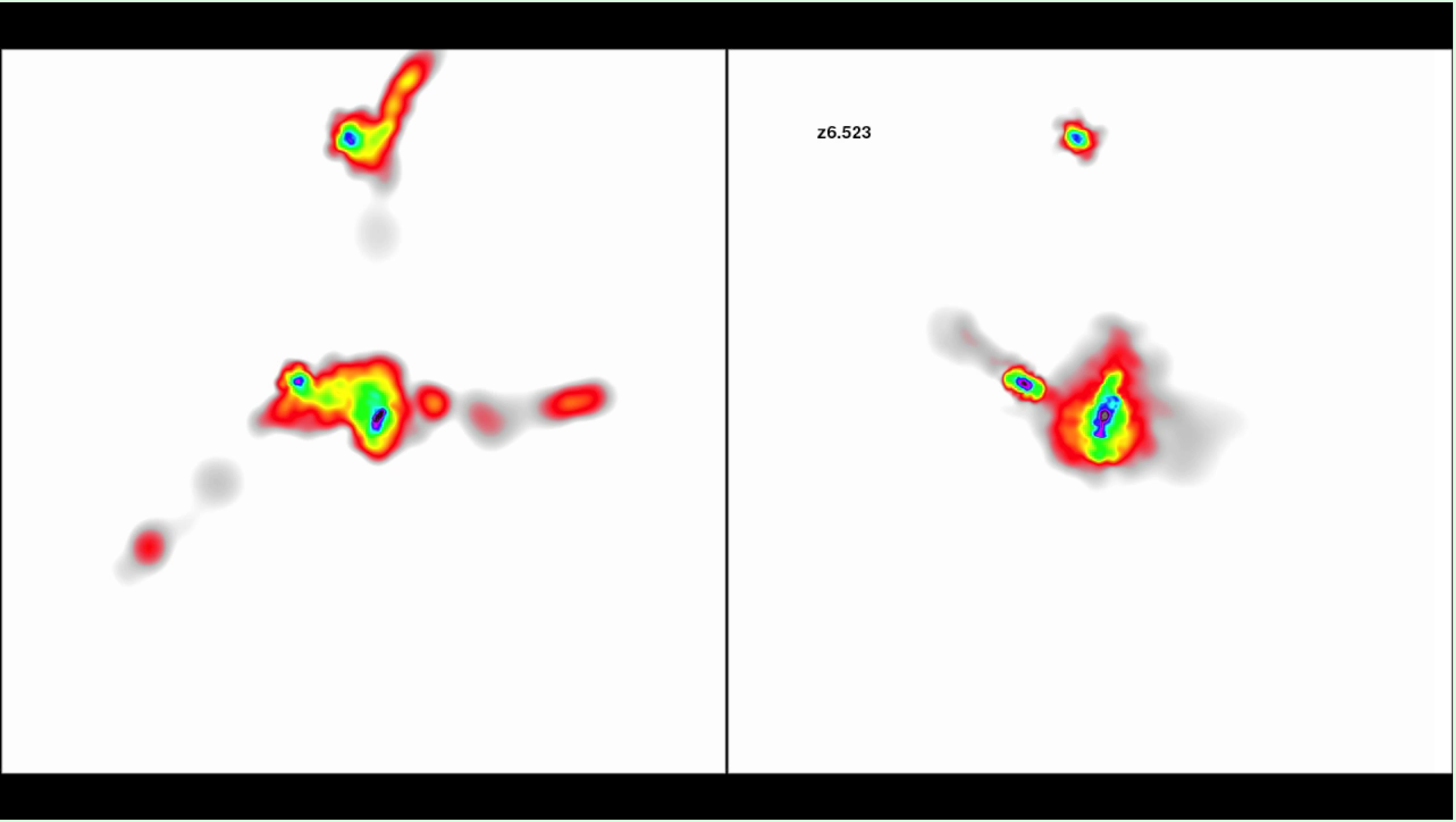
Find observable signature of cold mode gas accretion onto galaxies.

✓ 1. Radial extent and covering fractions of cold-mode 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 kinematics of accreted gas.**

Our Simulations



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

Angular Momentum:

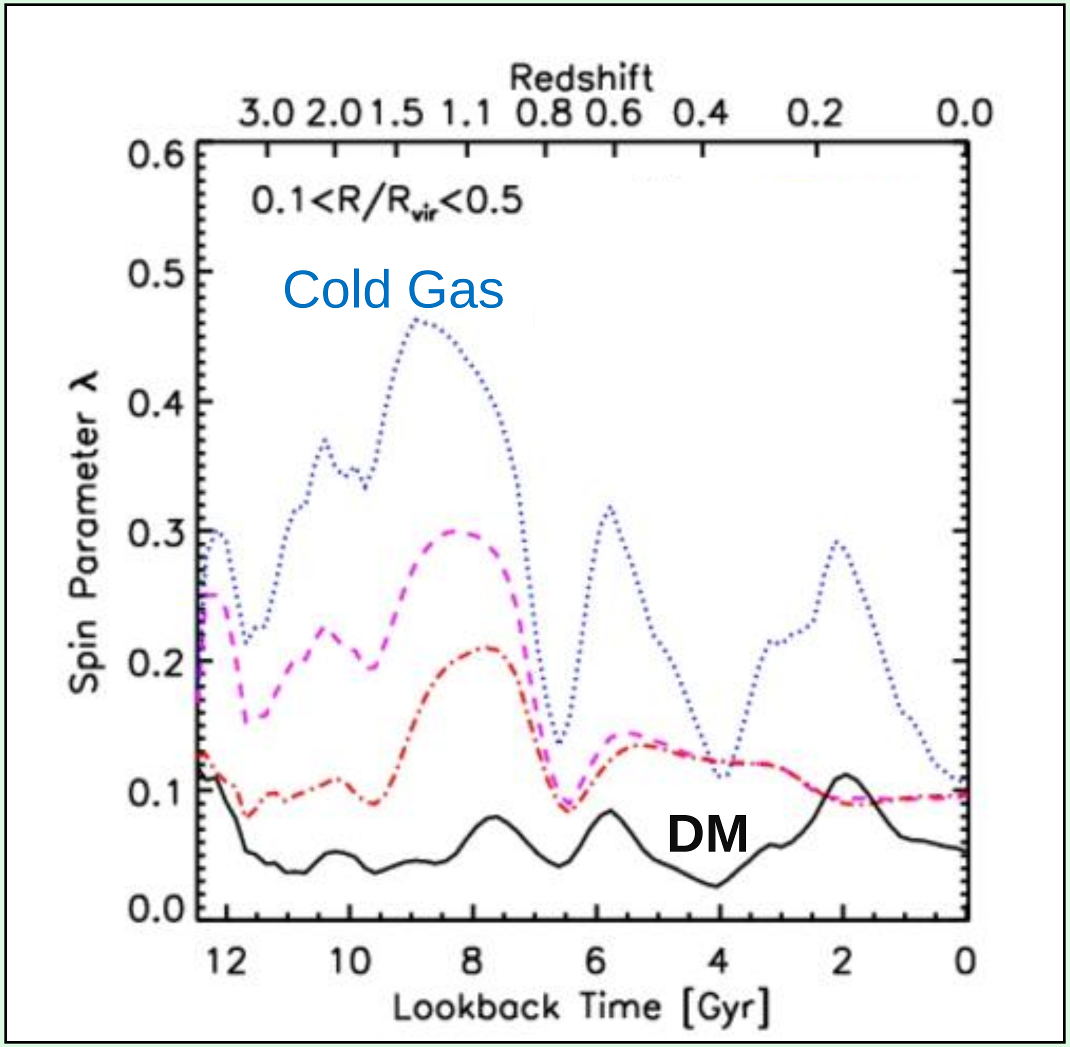
Galaxy angular momentum often characterized by “spin parameter,” λ

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

j_x = J/M = specific angular momentum of a component x (dark matter, gas, etc.) within a sphere of radius R;

V = the circular velocity at R

Angular Momentum:



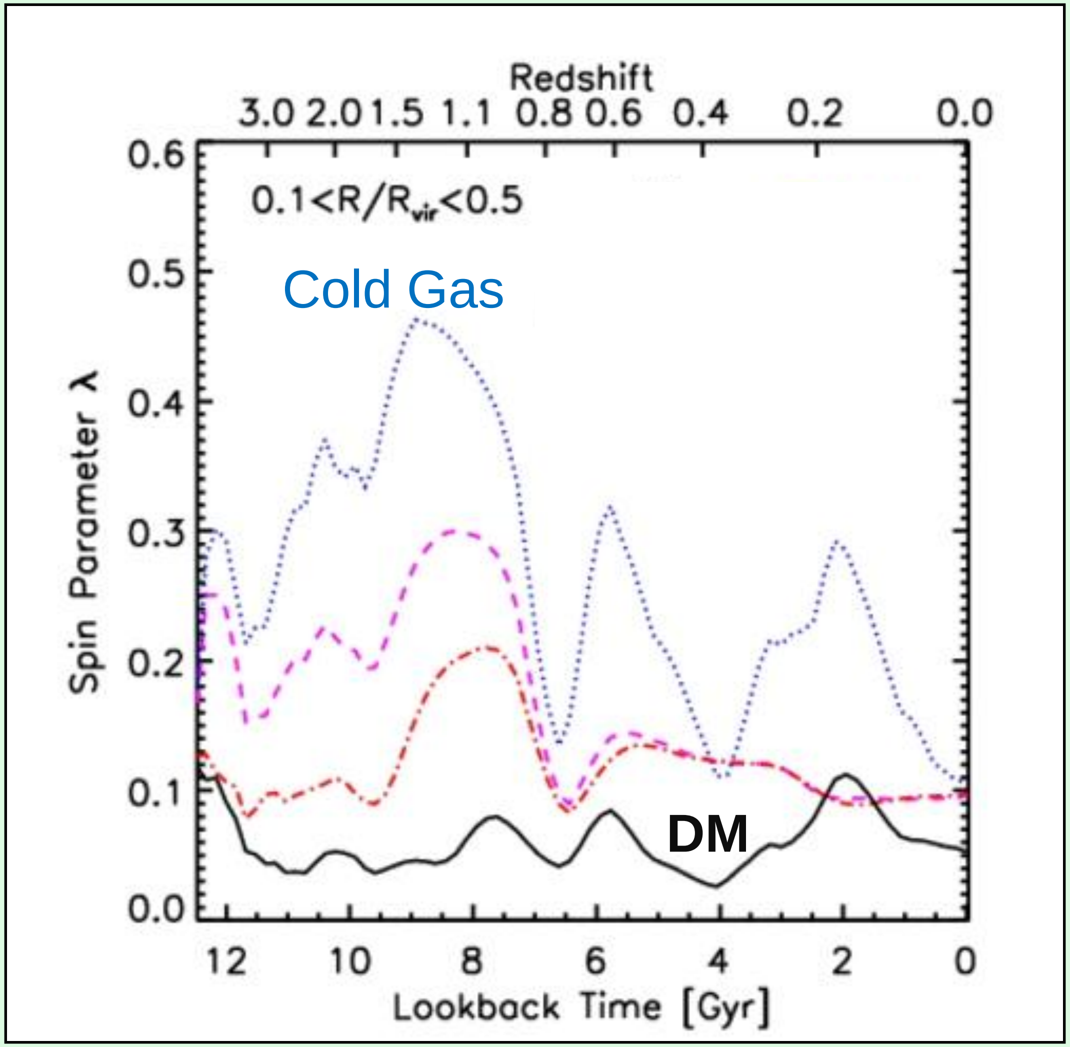
Mergers/accretion "spin up" the halo, both DM and gas (the peaks in λ).

But gas has much more angular momentum than the dark matter.

What's going on?

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

Angular Momentum:



Spin parameter well studied in N-body simulations

Roughly constant over time for DM halo (λ~0.05)

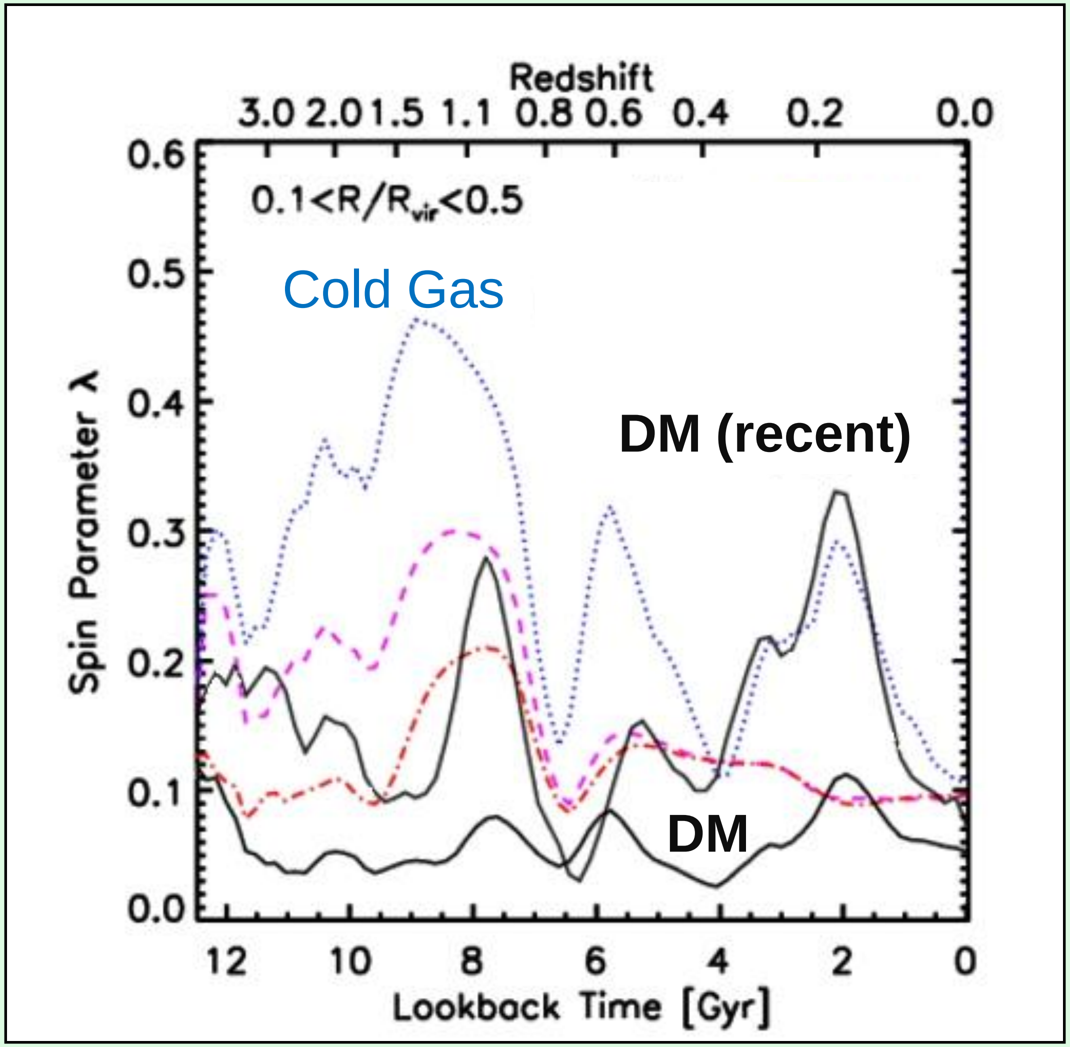
(e.g. Maccio+ ‘07, Bett+ ’10)

But V, R both increase in time for any given galaxy

→ newly accreted material has higher spin

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

Angular Momentum:



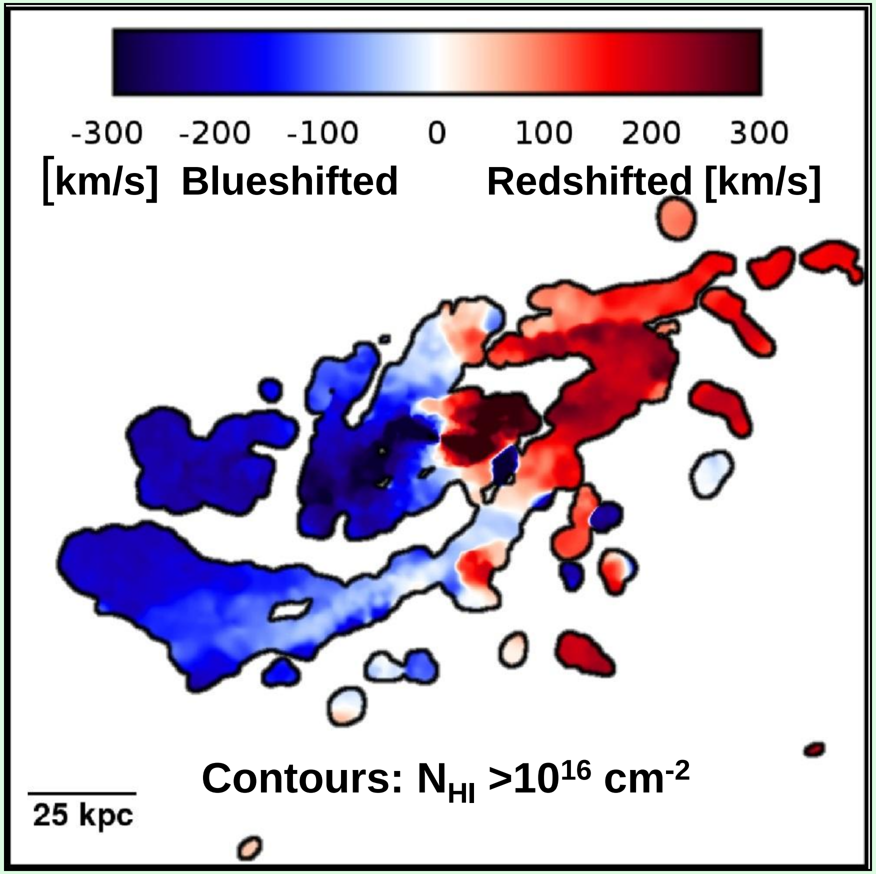
Cool gas stays in inner halo for ~ halo dynamical time (2 Gyr at z=0)

→ Compare spin of gas to spin of **recent** DM accretion

→ Much higher spin than total for halo. Halo gas and recent DM more similar.

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

Coherent Rotation of Halo Gas:



Halo gas from recently accreted material.

Eventually falls into galaxy, builds disk, forms stars.

With λ_{gas} so high, could there be ***coherent*** rotation of halo gas? Possible correlation between rotation of halo gas and the galaxy?

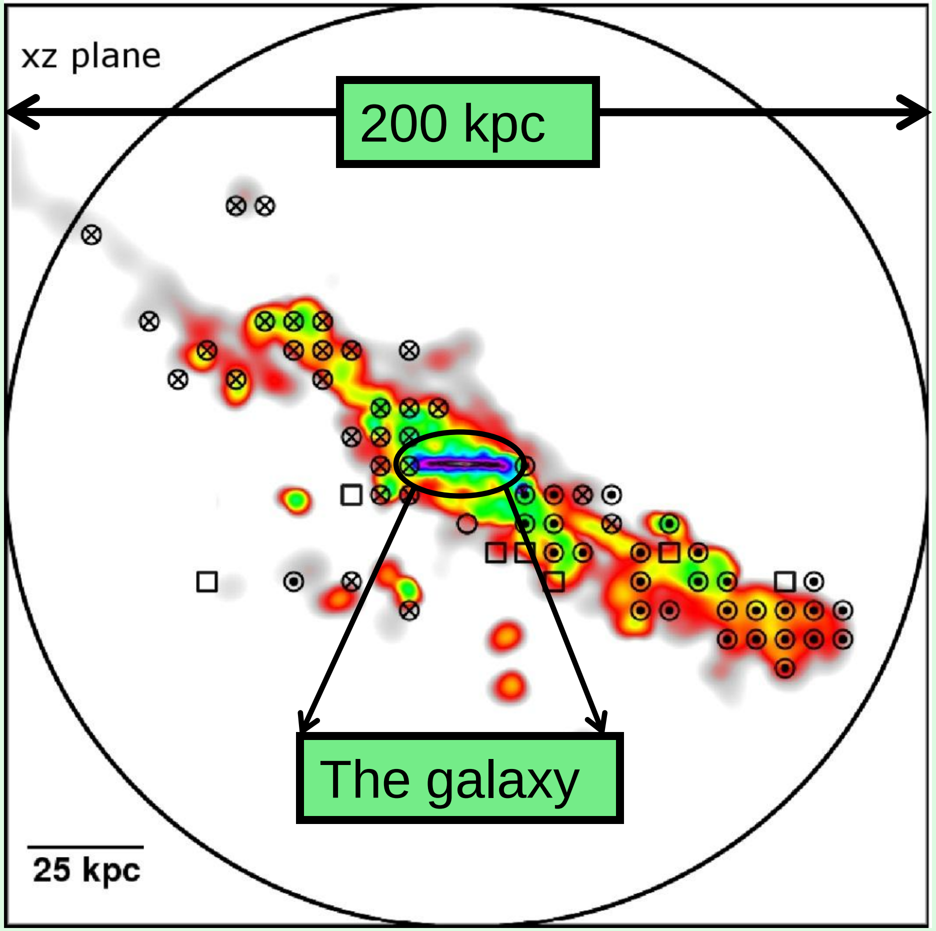
Yes! Cold-mode halo gas co-rotates with the disk, even out to ~100 kpc.

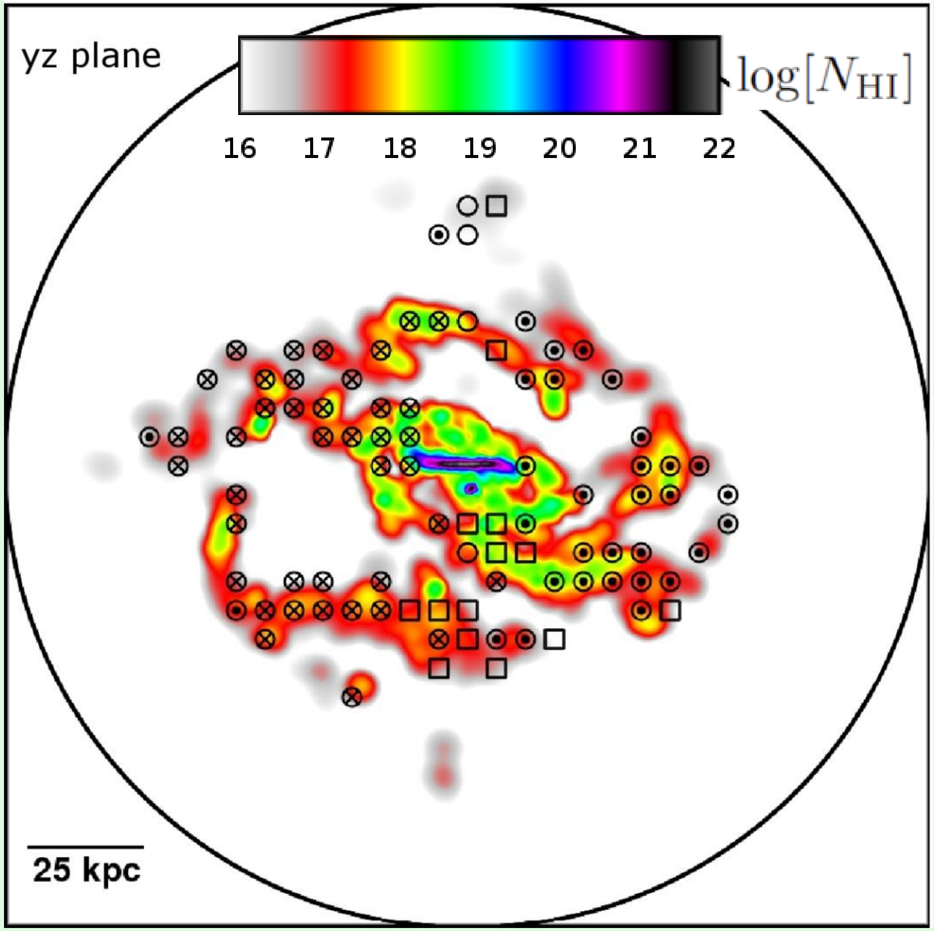
This is observable!

Halo Gas Kinematics

Inflow often (not always) forms “cold flow disk”
→ aligned with large-scale filament.
→ can extend to ~ 100 kpc
Below: co-rotating fraction ~ 70%

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





But can co-rotation *really* be observed?

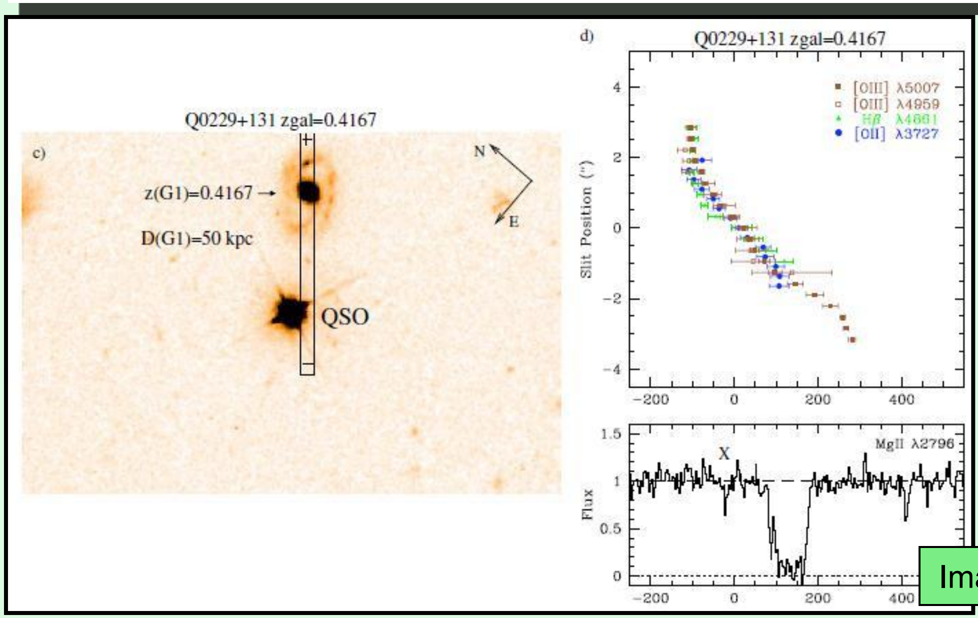


Image from Kacprzak+ '10

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):

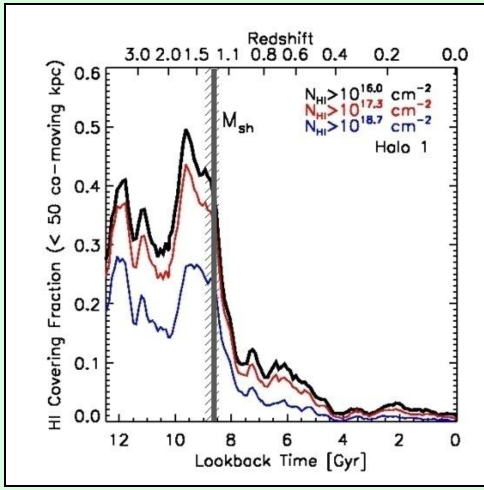
Velocity Offset: **85% ± 5%**
Co-rotation: **70% ± 10%**

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

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

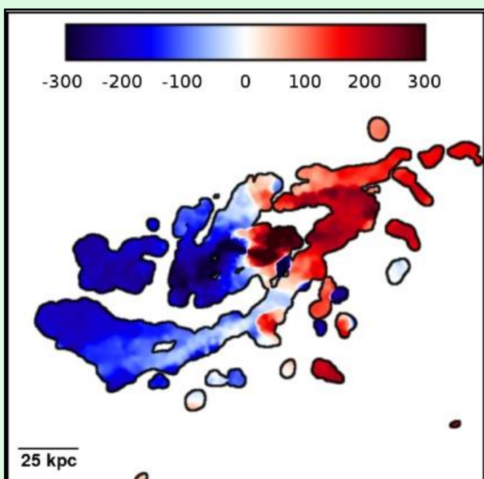
Conclusion:

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!**

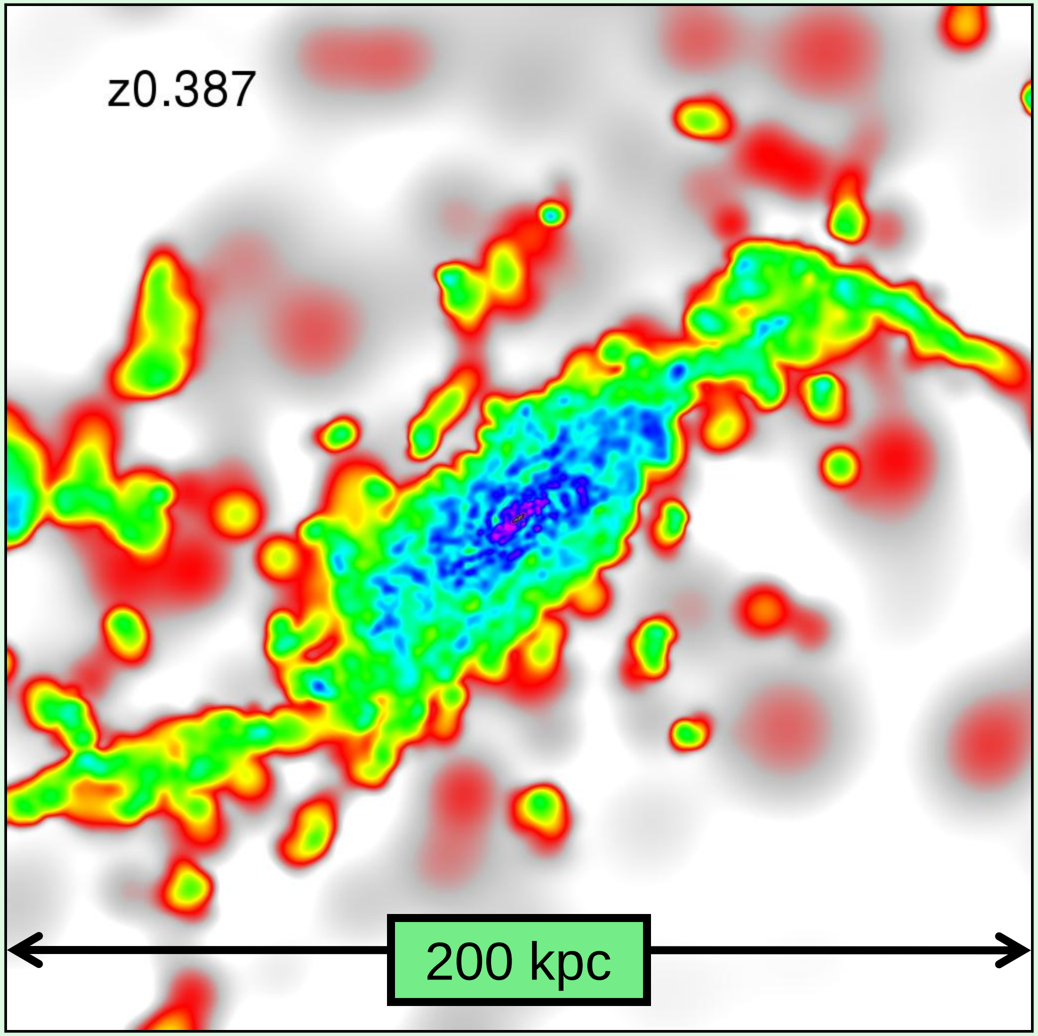
Extra Slides

Aside (Work in Progress):

Less massive halo
(below cold-mode cutoff)

“Cold flow disk”, moderate covering fraction at low-z

CF drop not dominated by redshift, but by halo mass

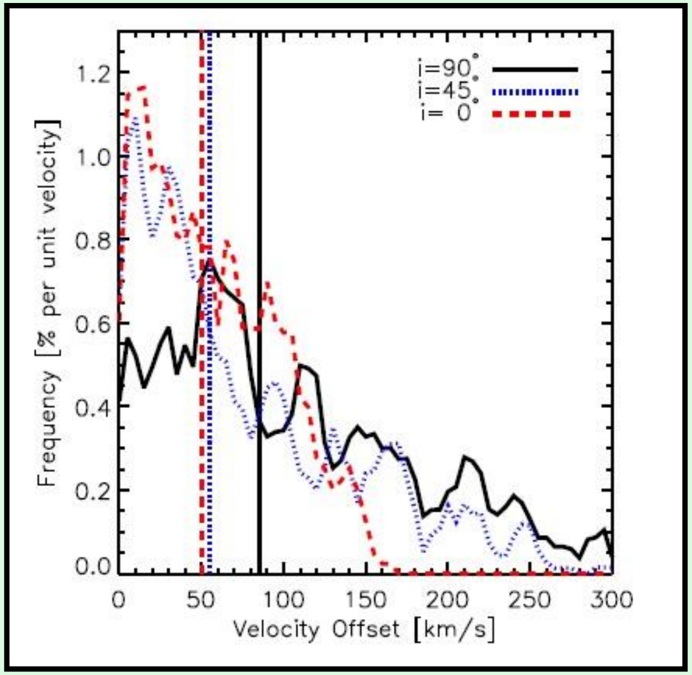


Can Outflows Co-rotate?

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.

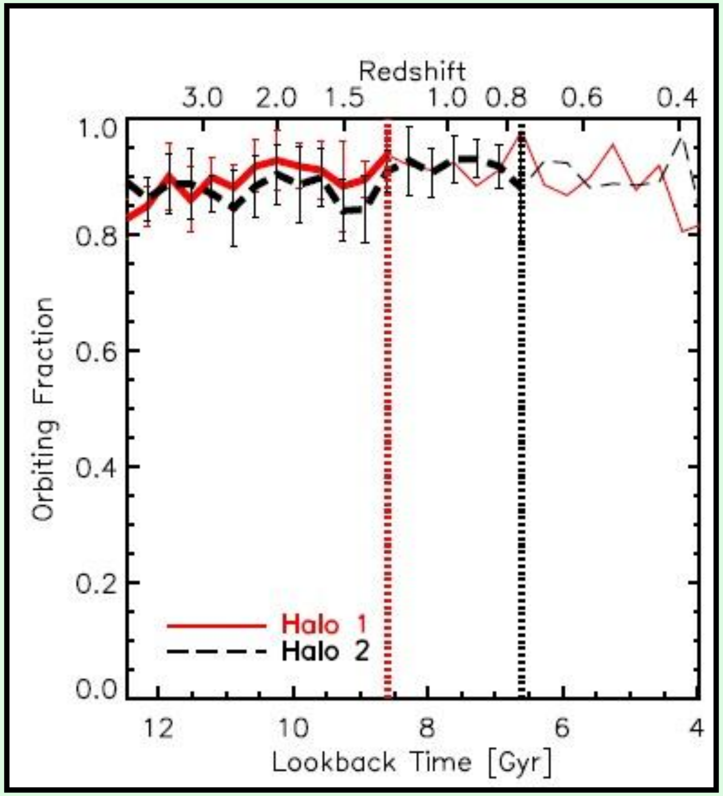
Bi-conical Outflows: should only show single-sided velocity offsets in near-polar projections, precisely where accreted gas is *least* reliable / *least* likely to show rotation.

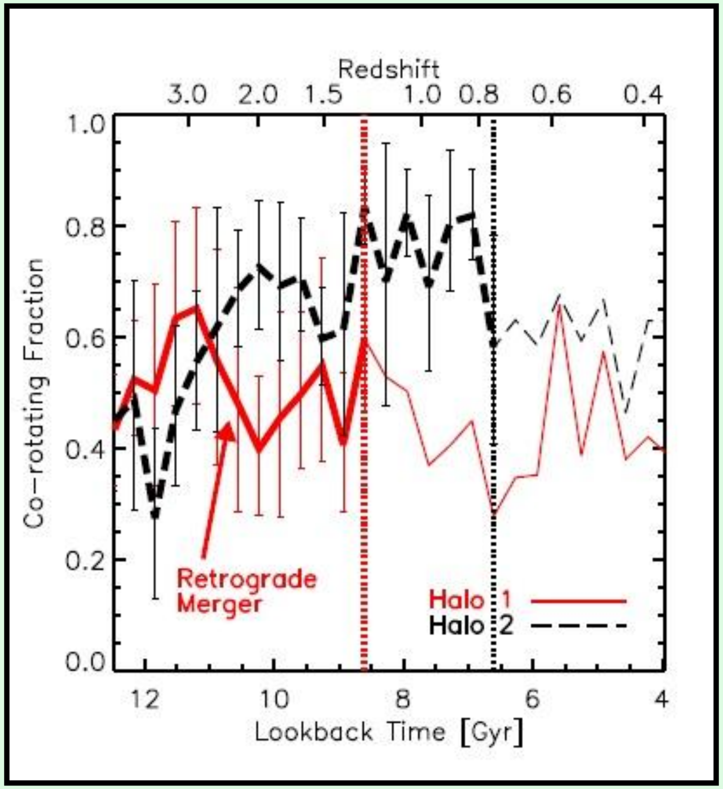


Even high angular momentum gas blown out of a rotating disk will only rotate at ~25 km/s at 40 kpc (conserving angular momentum)

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

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 ($M_{vir} > M_{sh} \sim 10^{12}\ M_{sun}$).