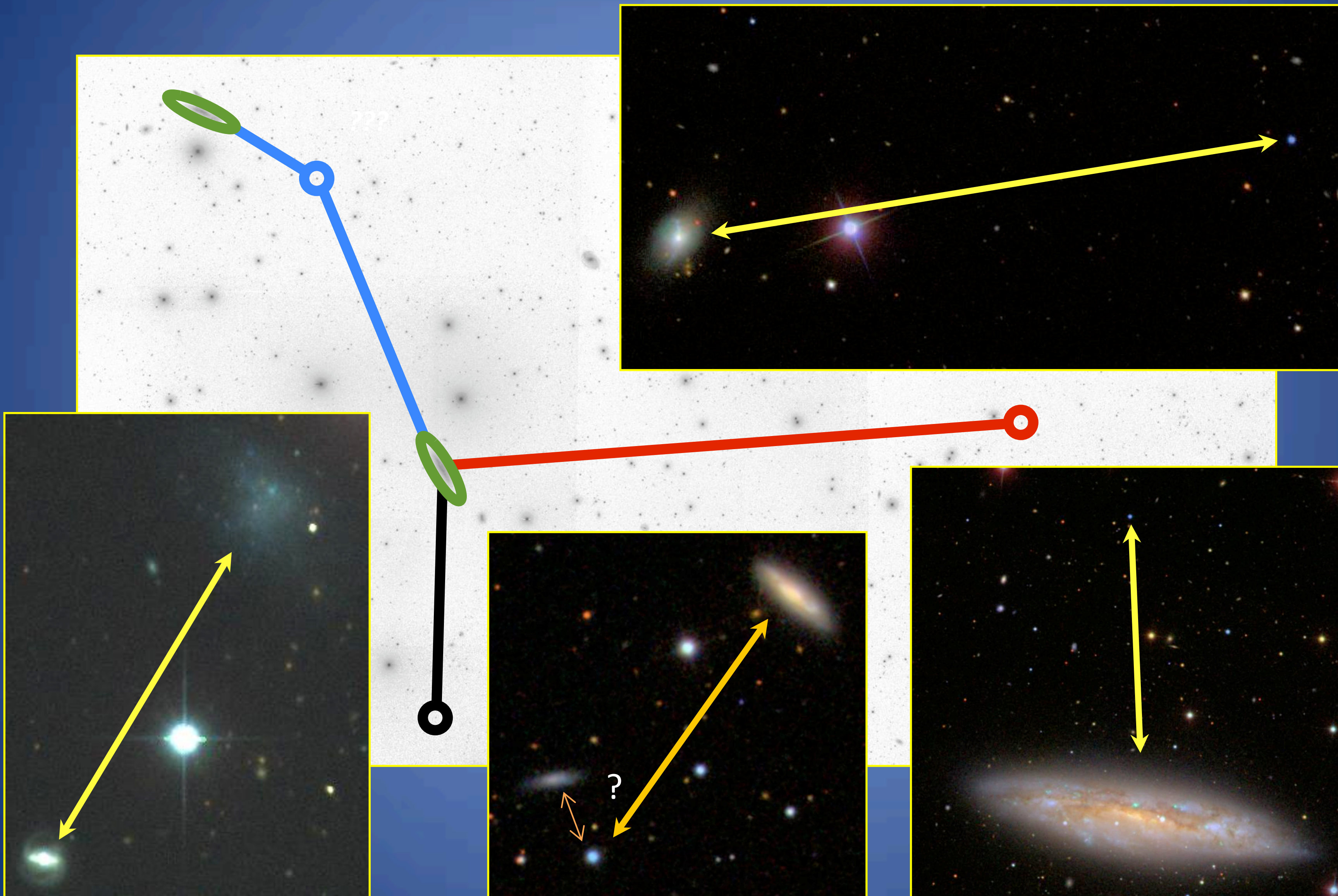
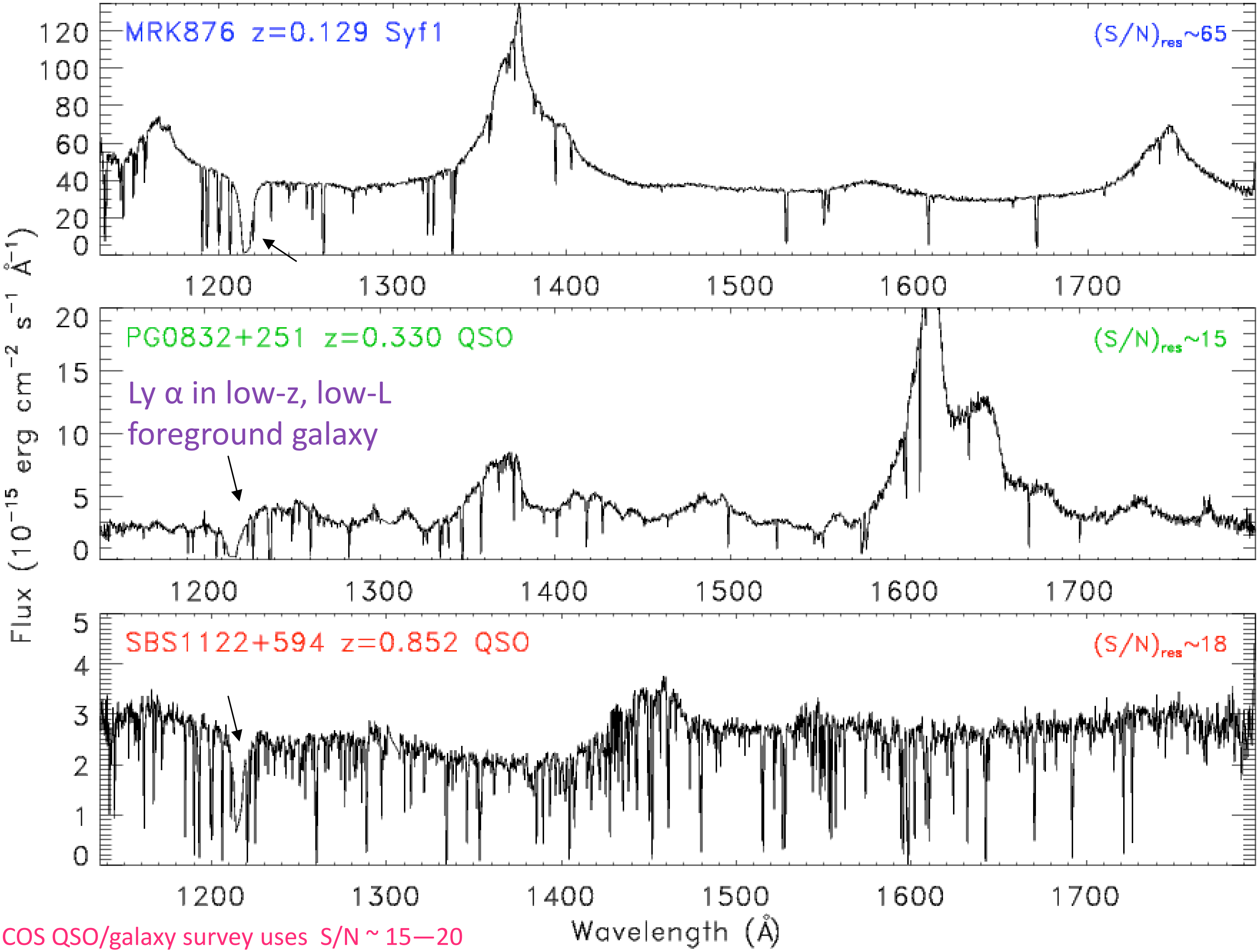
GAS IN SPIRAL GALAXY GROUPS:
THE COS GTO TEAM Survey of QSO/Galaxy Pairs
(Targeted Galaxies are Late-Type at L < L*)





COS QSO/galaxy survey uses S/N ~ 15—20

COS GTO TEAM QSO/GALAXY SURVEY:

1. "**TARGETED**" COS QSO/GALAXY PAIRS (Stocke & **Keeney** primaries)

12 TARGETS, 11 GALAXIES PROBED, 13 ABSORBERS DETECTED.

L_{GALAXY} = 0.003 TO 0.8 L* SFR: from < 10^{-3} TO 1 $M_{\odot}$ yr^{-1}

2. "**SERENDIPITOUS**" STIS QSO/GALAXY PAIRS (**Keeney**, Stocke, **Danforth, Syphers** & Yamamoto primaries)

35 TARGETS OBSERVED 42 CGM Absorbers Detected .

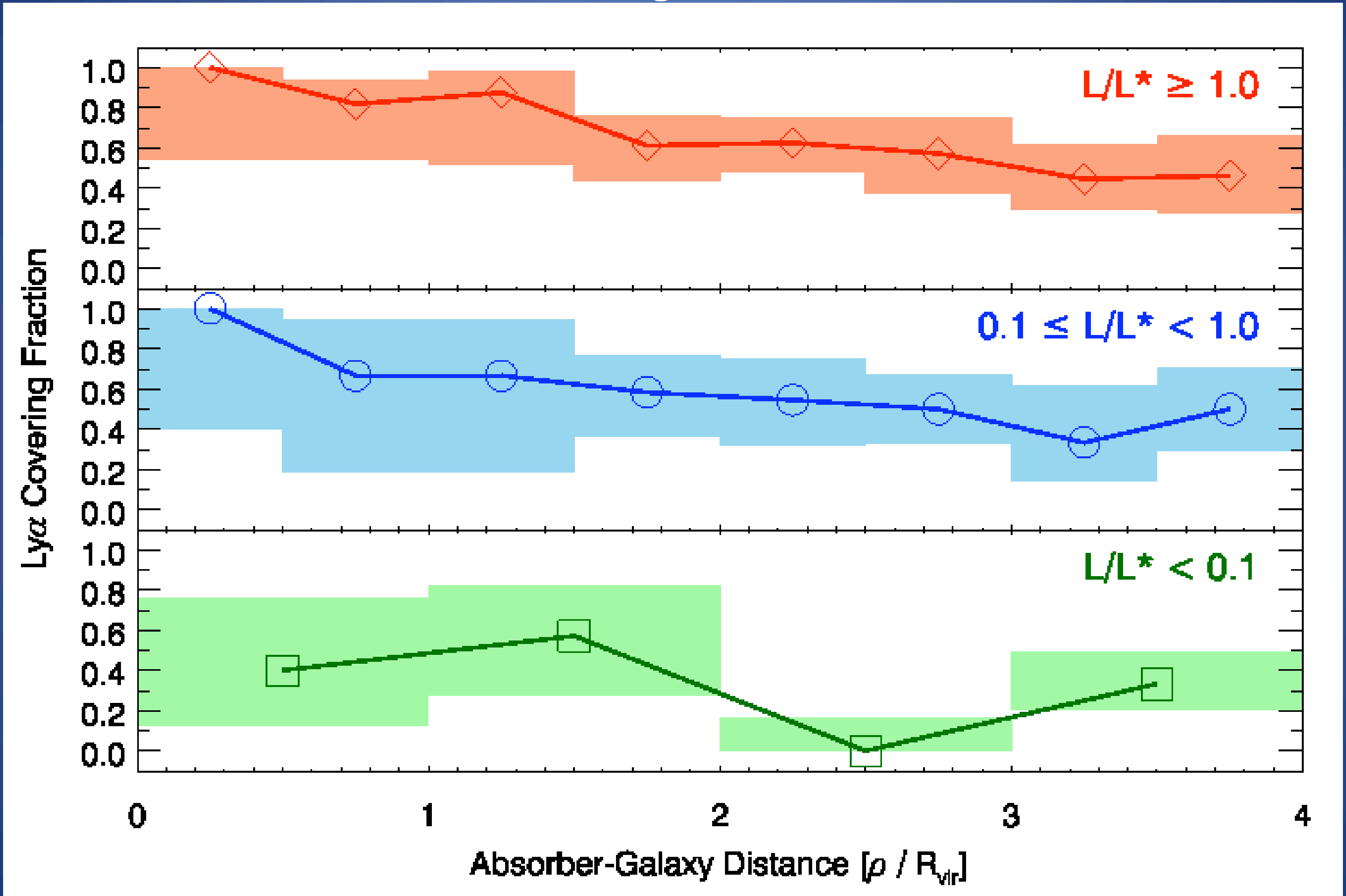
WITH STIS E140M GRATING AT SNR ~ 5—15 PER RESSEL

(500 absorbers total at log N_{HI} $\geq$ 13.0 [Danforth & Shull 2008; Tilton et al. 2013] & 700 galaxies $\leq$ 1 Mpc from the sightline [Keeney, in prep])

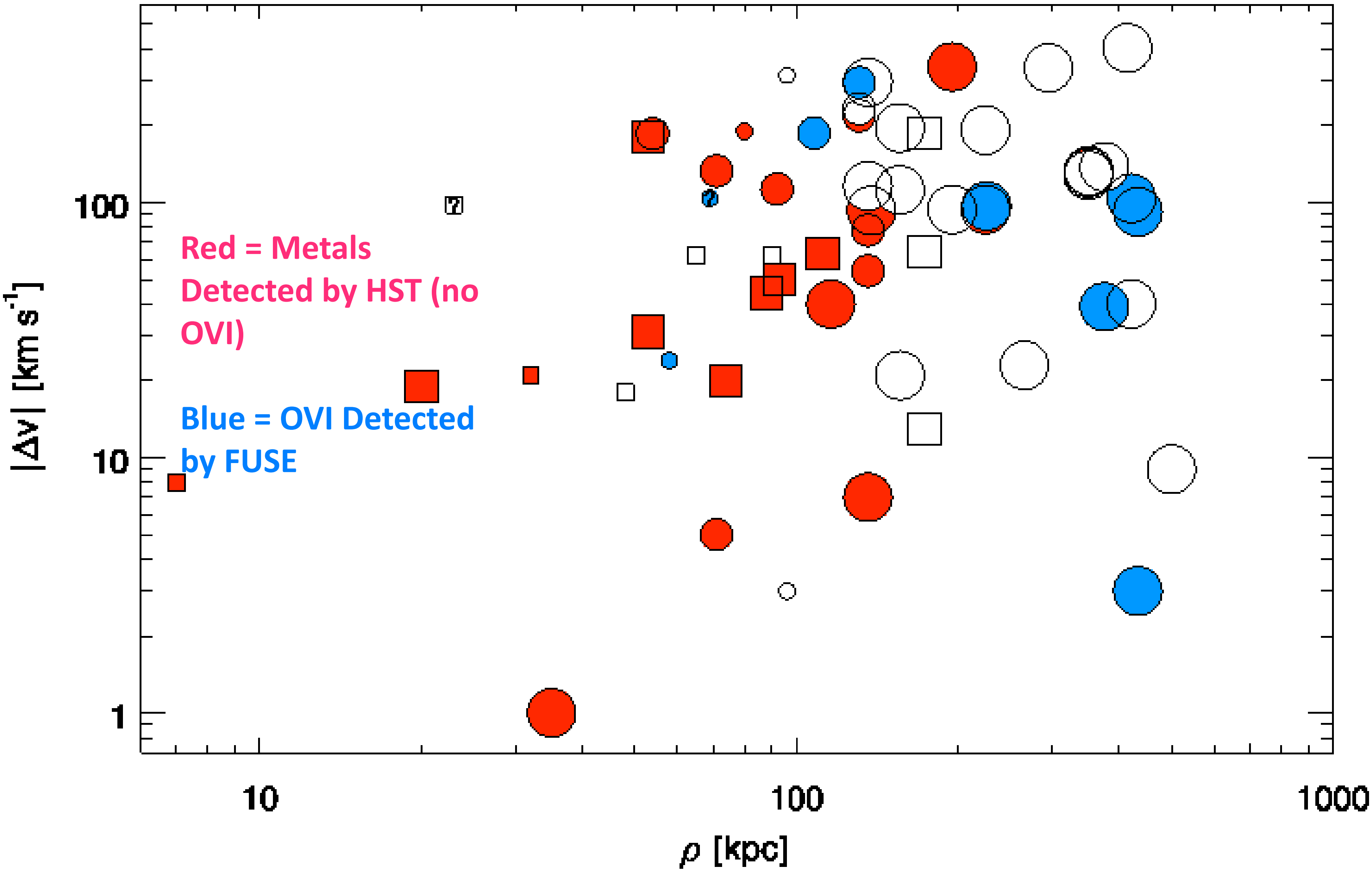
L_{GALAXY} = 0.01 TO 9 L^{*}

[see Stocke et al. 2013 for details of this survey]

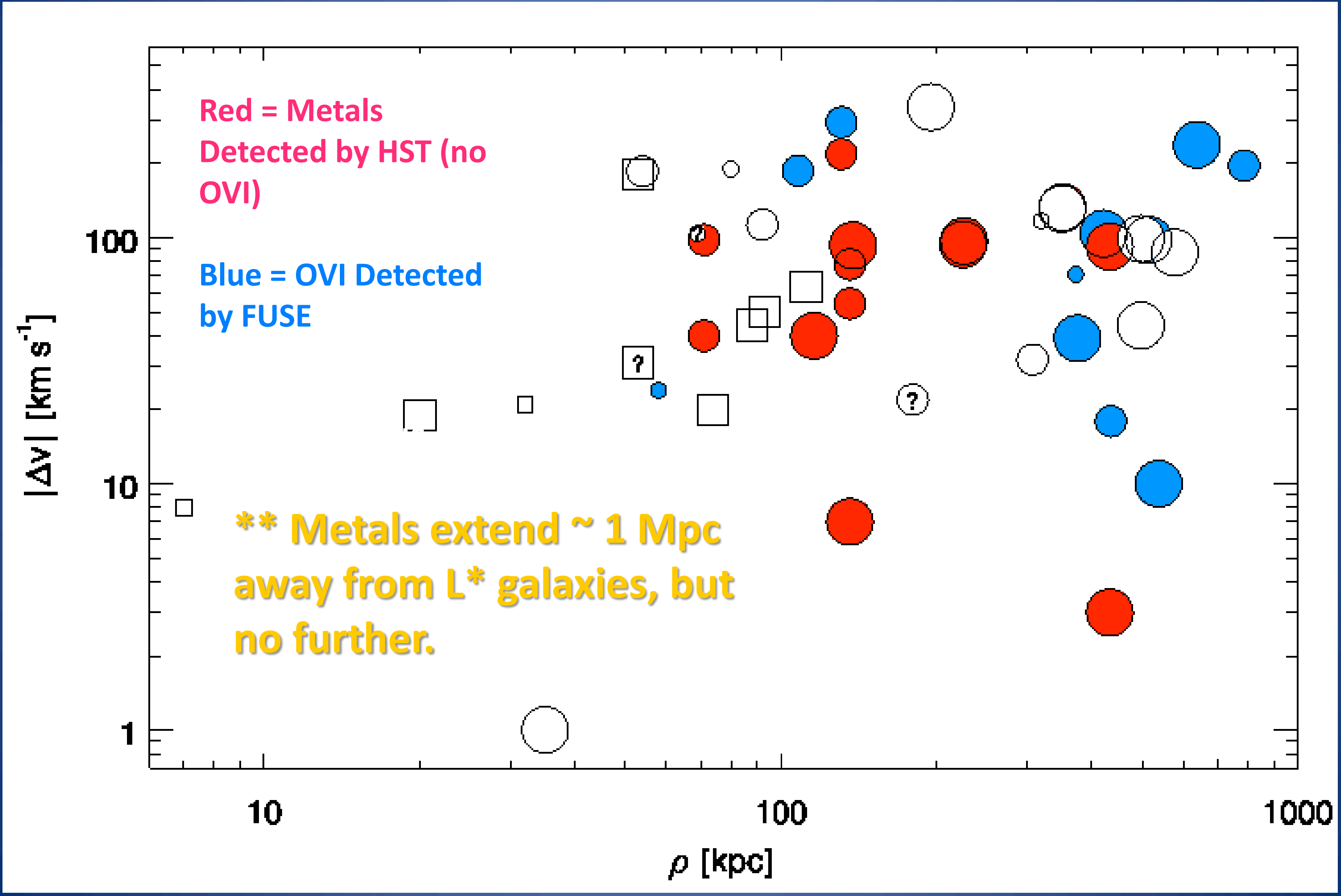
Covering factors very high (~100%) inside 1 VIRIAL RADIUS for L > 0.1L* galaxies; ~50% for dwarfs → filling factor of clouds is substantial.



PROBING THE CGM: THE 10% OF Ly α ABSORBERS CLOSEST TO GALAXIES

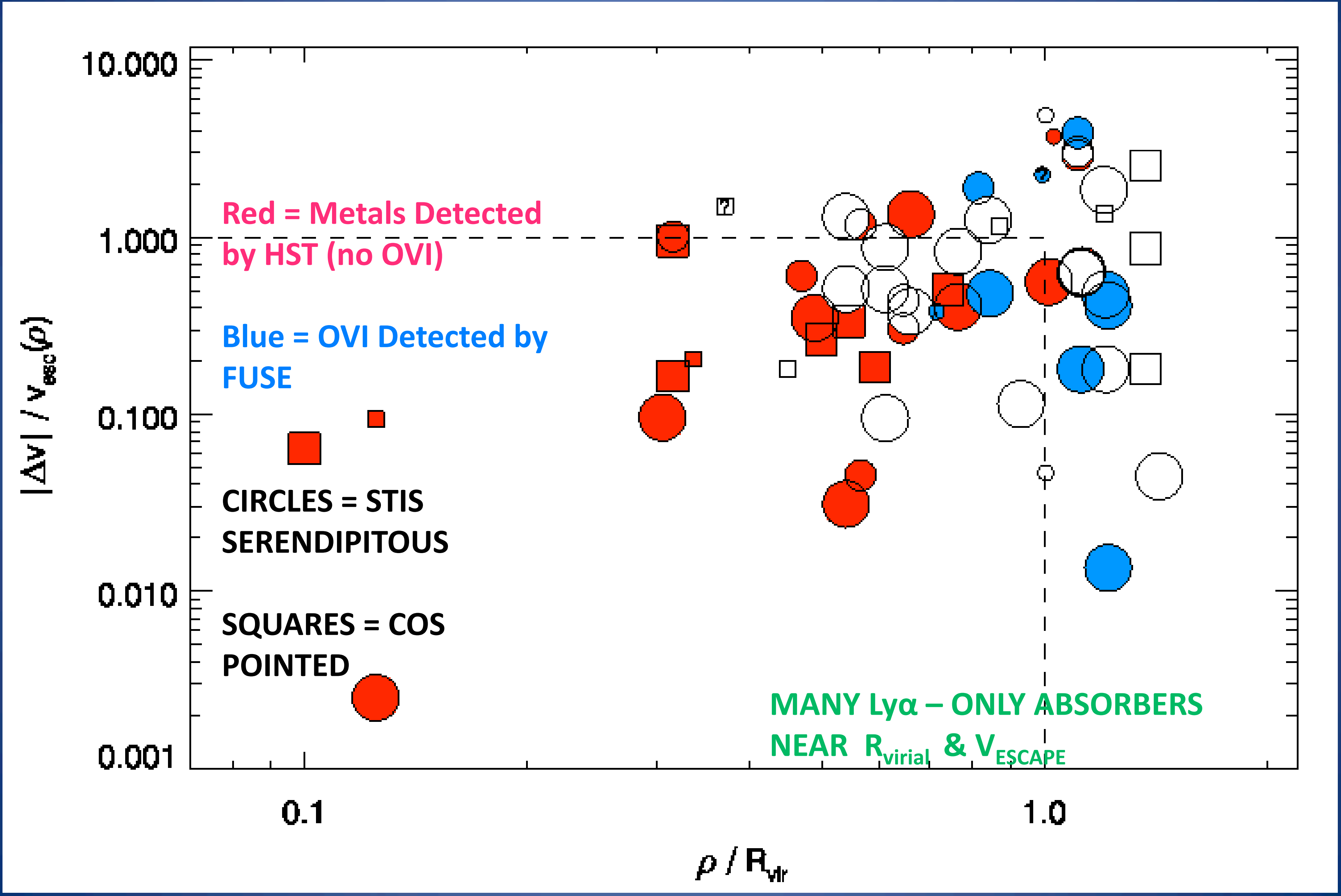


OVI best indicator of Spread of Metals: Probably due to higher Ionization parameter (lower densities) further from galaxies

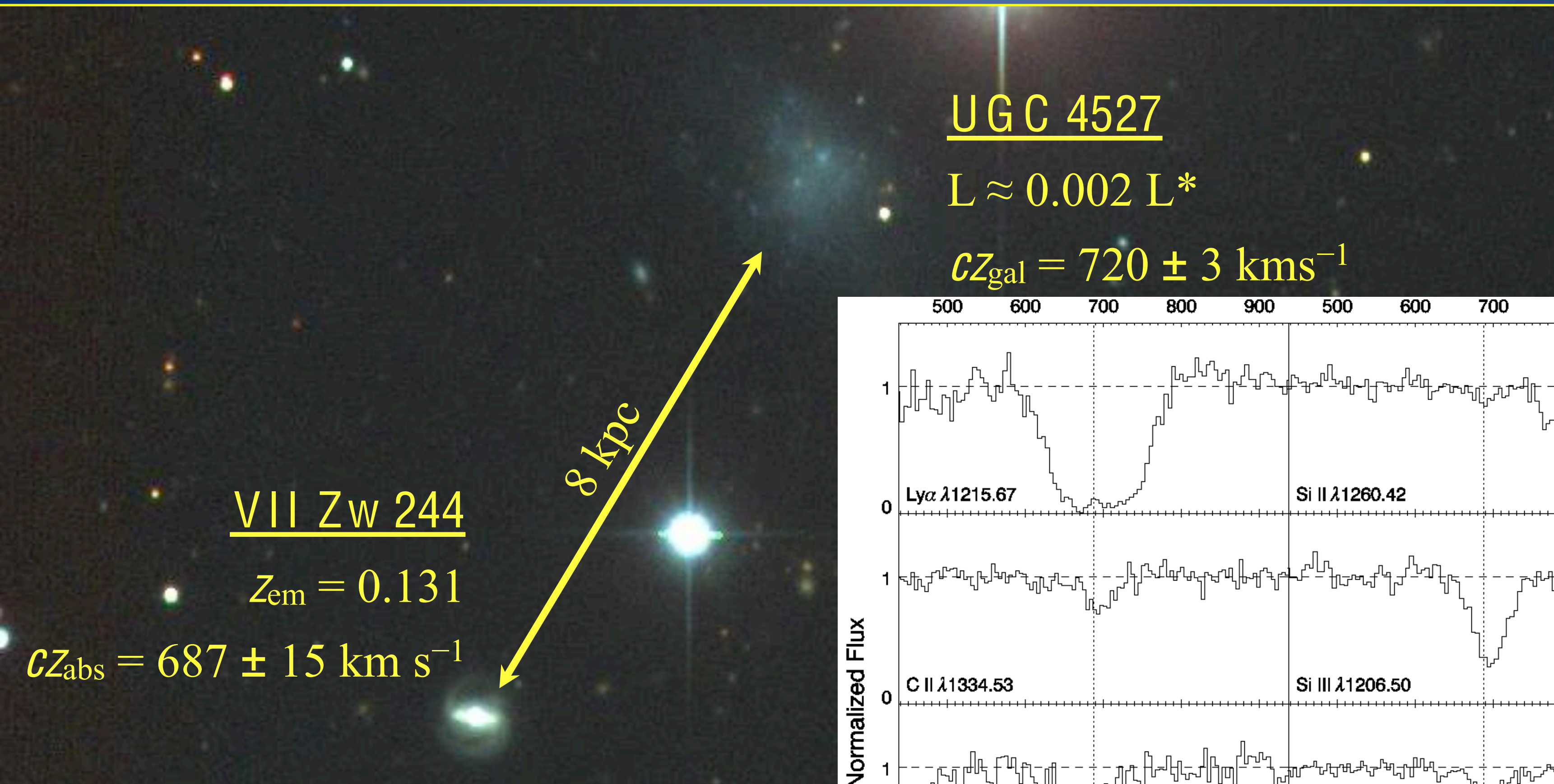


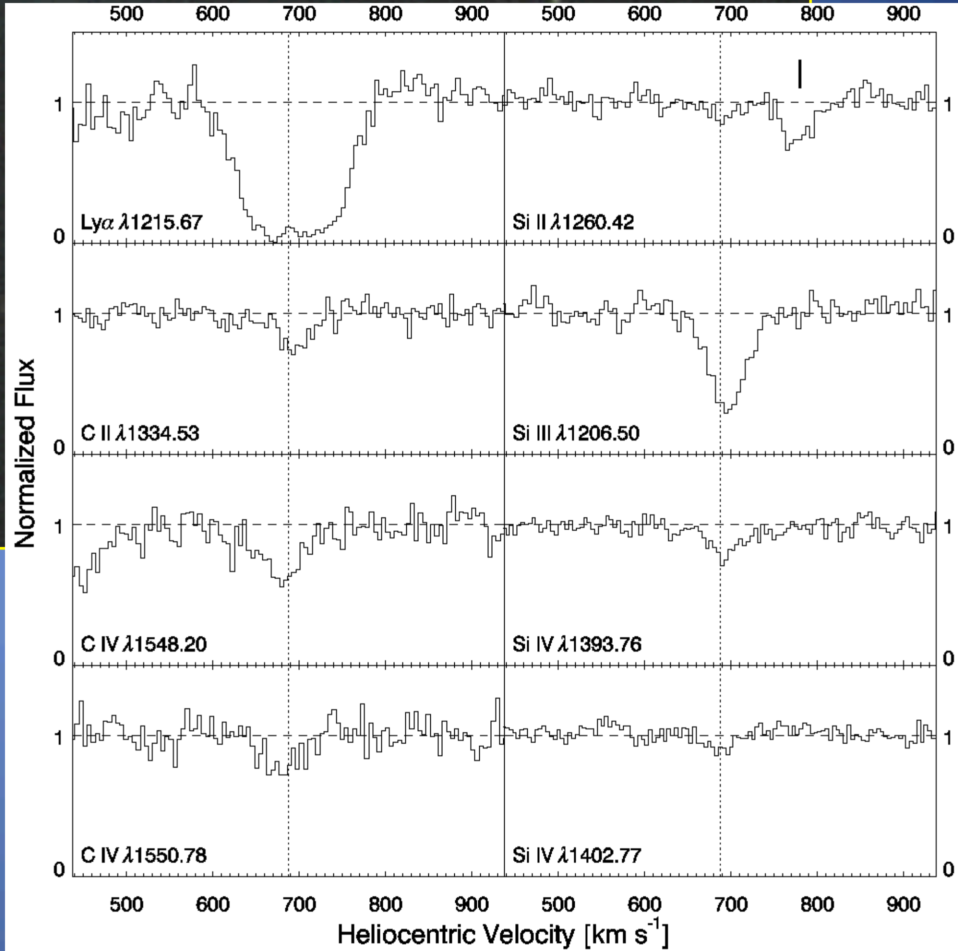
CGM Absorbers: Location and Relative Radial Velocities:

X-AXIS: Impact Parameter/Virial Radius . Y-AXIS: Radial Velocity Difference / Escape Velocity



UGC 4527 / VII Zw 244





Isolated Low Surface Brightness Galaxy

Highly-ionized gas at |Δv| = 9 km s^{-1}

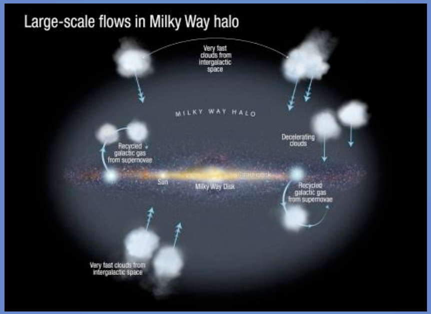
Probably will not escape into IGM

Total Mass in Warm CGM Clouds

- Covering fractions of ~ 100% ➔ given the observed range of cloud sizes, this high covering requires : a volume filling factor of ~ 5%
- Cloud size of 0.1--30 kpc (diameter) based on photo-ionization modeling ➔ ~ 4,000 "**warm" clouds** (> 1 kpc) reside within R_{virial} for super-L* galaxies (fewer for smaller galaxies) .
- Individual clouds have masses of ~10^{4-8} $M_{\odot}$
- Thus, the warm CGM of each L* galaxy has a TOTAL mass of ~ 8 × 10^9 $M_{\odot}$ ➔ ~ 50 % of the stellar mass of the galaxy
- These more distant CGM clouds have 10X more mass than the SiIII HVCs close around the Milky Way (Shull, Collins, & Giroux 2009; Howk & Lehner 2011)

INCORPORATING COS HALOs, COS GTO & STIS "SERENDIPITOUS" CGM CLOUD DETECTIONS

????



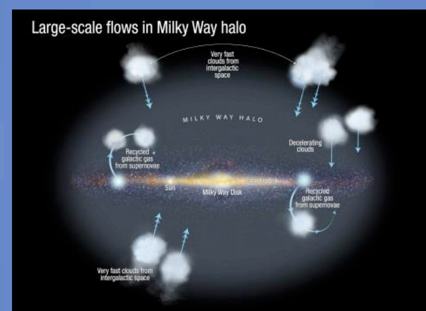
Highly ionized HVCs
(Shull, Collins & Giroux 2009; Lehner & Howk 2011)

Warm clouds contain $5 - 10 \times 10^9$ Mo at 10^4 K
➔ 10 –20 times mass in close-in warm HVC clouds

Similar results from COS Halos Team; Werk et al. 2013

INCORPORATING COS HALOs, COS GTO & STIS "SERENDIPITOUS" CGM CLOUD DETECTIONS

????



Warm clouds contain 5 –10 x 10^9 Mo at 10^4 K + 3-6 X 10^9 $M_\odot$ at 10^{5-6} K (Tumlinson et al. 2011)

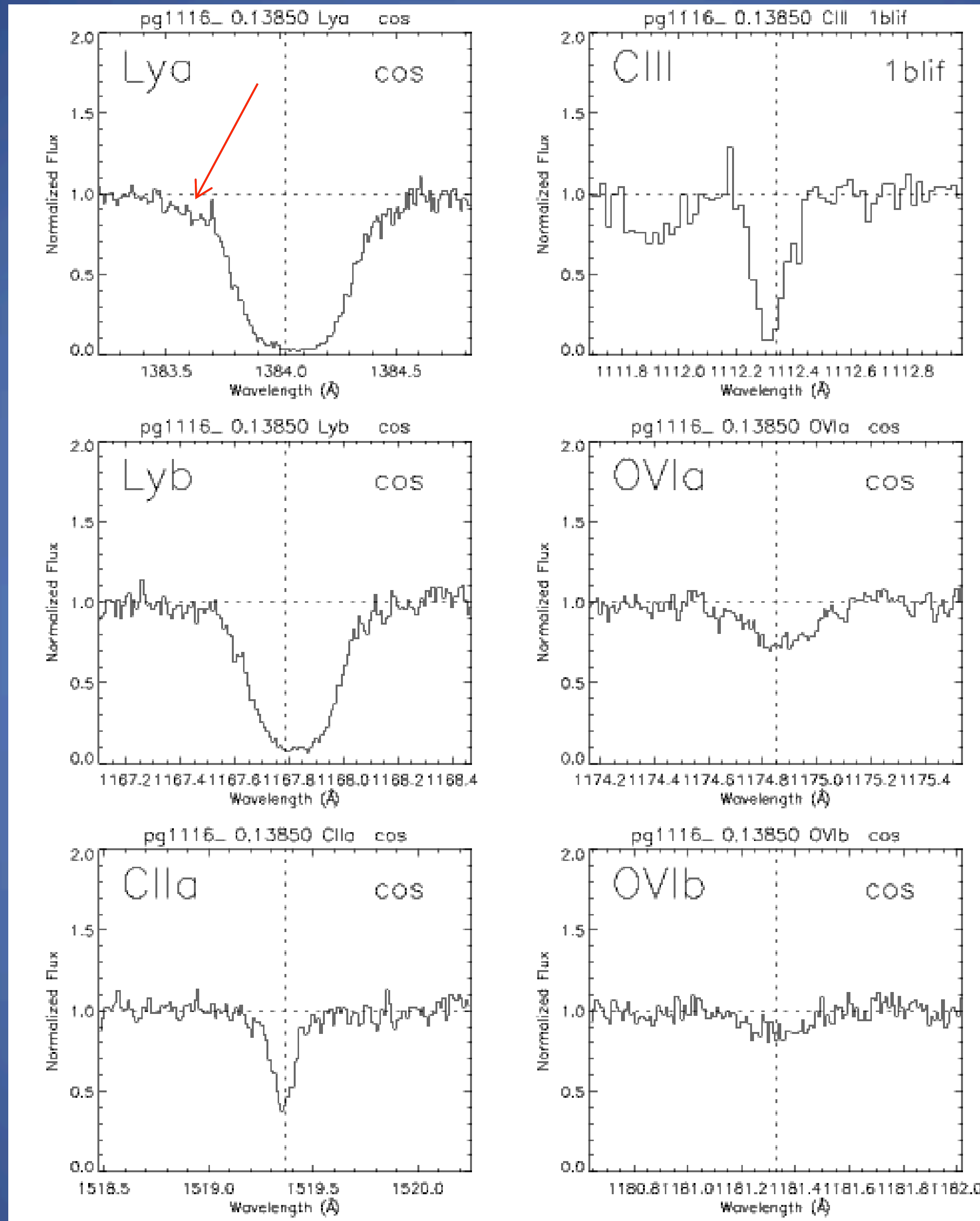
= ~ 10^{10} Mo in warm + WHIM CGM gas in these clouds

Shocks? What is doing the shocking?

PG 1116+215 SIGHTLINE

S/N ~ 40:1

@ Z=0.138



Charles Danforth, trail runner and BLA finder (deluxe)

LOW C IONS:

$b = 10\ km\ s^{-1}$ ➔

$b_{HI} = 34\ km\ s^{-1}$

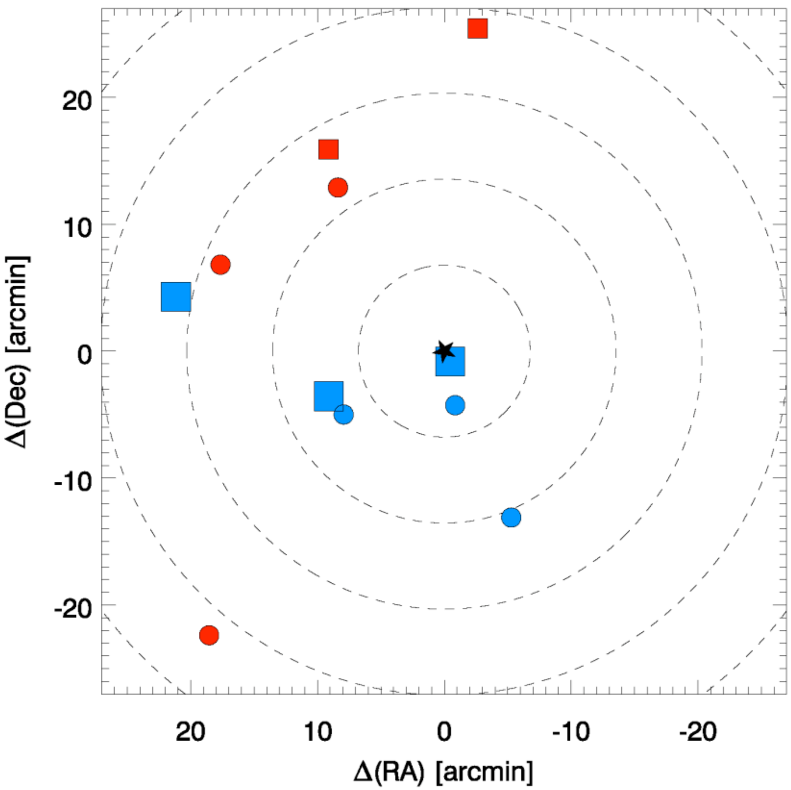
OVI GIVES:

$b = 34\ km\ s^{-1}$

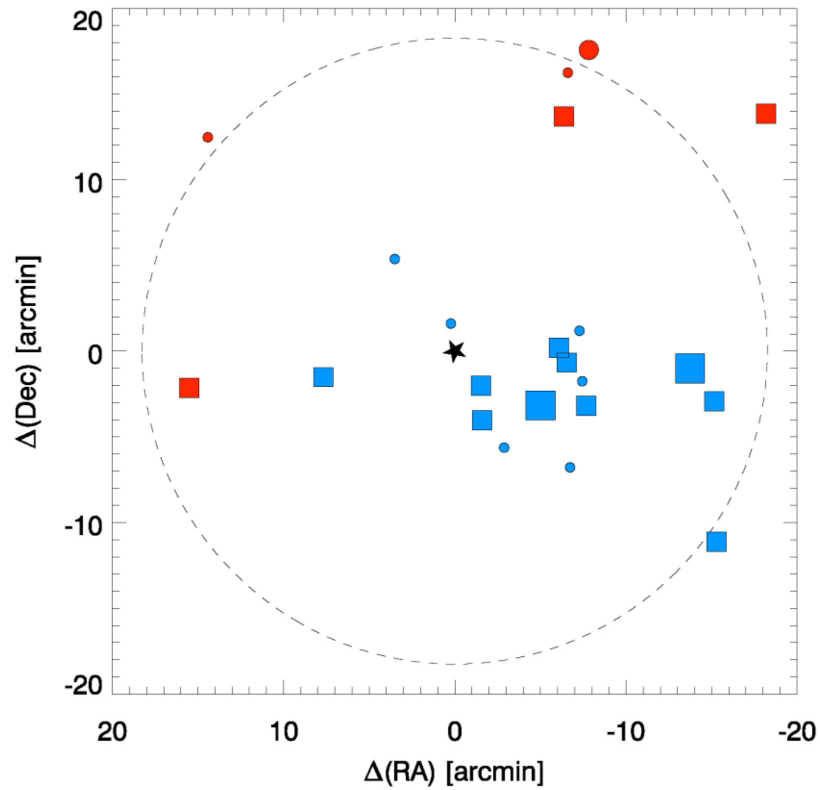
➔

$b_{HI} = 130\ km\ s^{-1}$

PG 1116+215 z=0.138 BLA ABSORBER



PG 1259+593 z=0.046 non-BLA ABSORBER



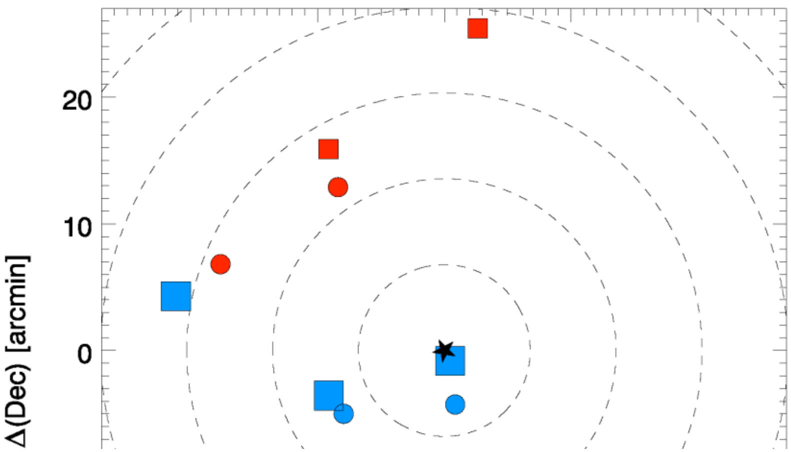
BOTH ABSORBERS ARE ASSOCIATED WITH **SMALL SPIRAL-RICH GROUPS OF GALAXIES** OF COMPARABLE RICHNESS (5 OR 6 AT L > 0.3L*)

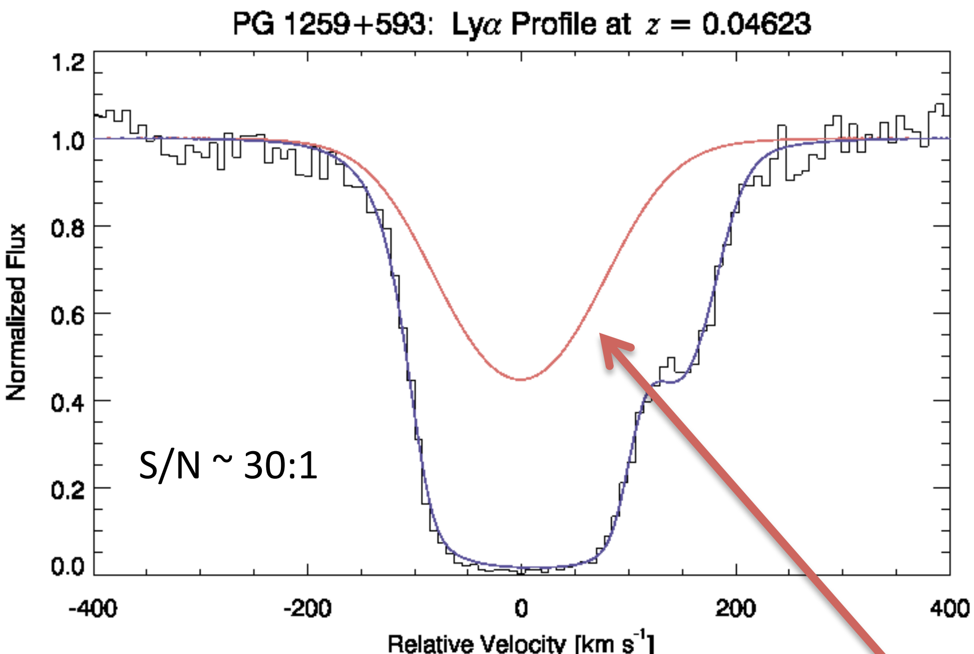
But PG1116 group has a higher velocity dispersion:

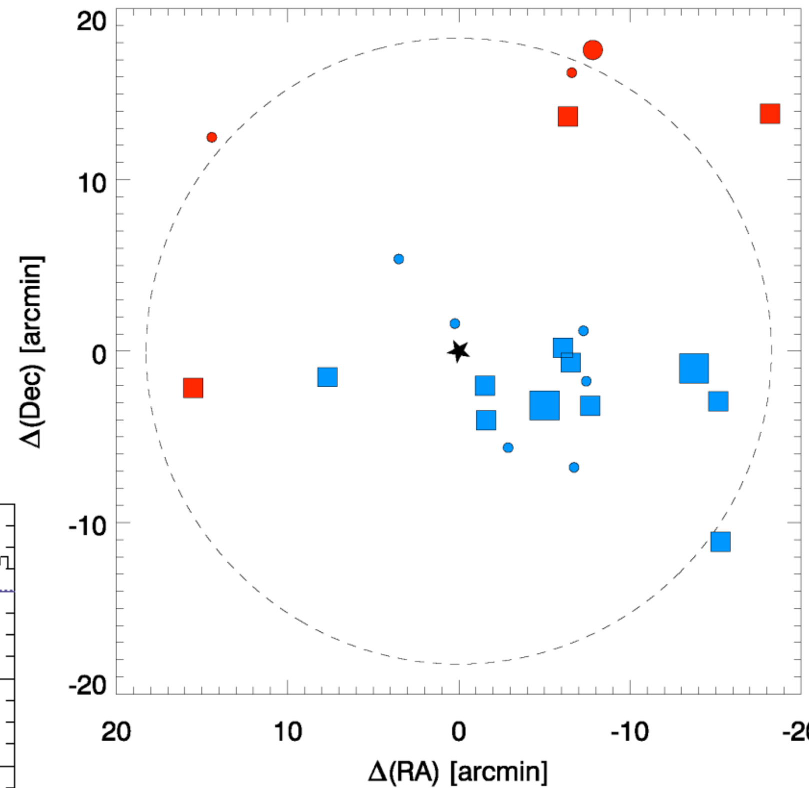
σ = 120 km/s	**σ = 70 km/s**
→ predicts b(HI)= 140 km/s	**predicts b(HI)= 85 km/s**
And log T ~ 6.25	**and log T ~ 5.85**

PG 1116+215 z=0.138 BLA ABSORBER

PG 1259+593 z=0.046 non-BLA ABSORBER







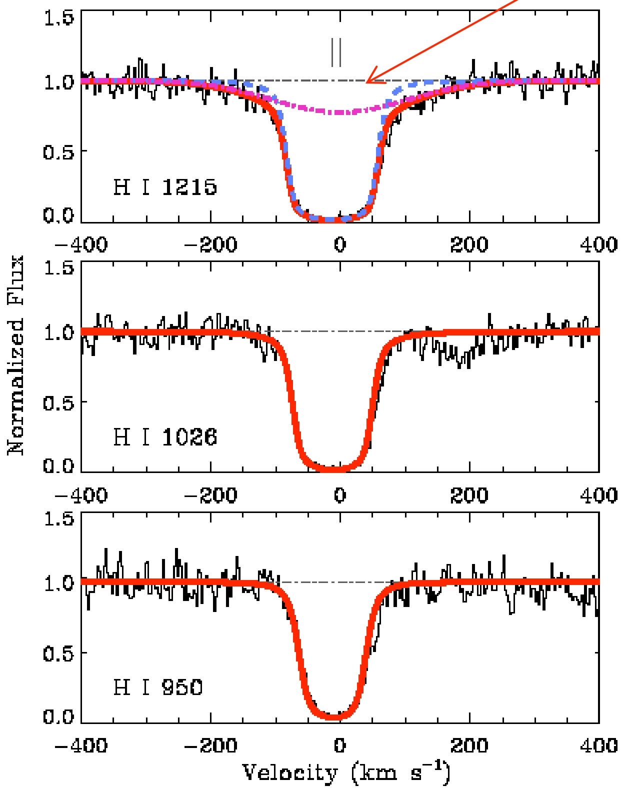
σ = 70 km/s:

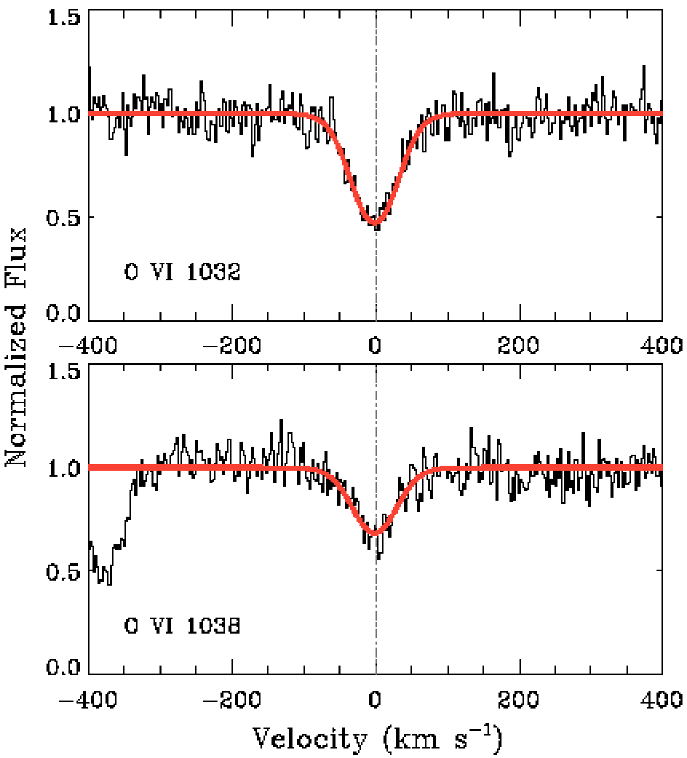
predicts b(HI)= 85 km/s and log T ~ 5.85, which can be hidden EASILY in the Ly alpha profile

HE 0153-4520: z=0.226 HI + OVI SYSTEM: BROAD Lyα + OVI on top of a narrower H I absorber ! (S/N ~ 34:1)

NARROW, PHOTOIONIZED ABSORBER: log N_{HI} = 16.6 and with b=26 km/s

BROAD ABSORBER: log N_{HI} = 13.6 and with b=110: km/s
O VI: log N=14.2 and b=37 km/s





ALSO HAS: C II, C III, N II, N III, Sii II, Si III ➔ Log U = -2.6 ➔
Cannot account for O VI !

b-values ➔ log T ~ 6.2 °K :
O VI velocity offset: 10—15 km/s

IMPLICATIONS *if* BLA systems are SPIRAL-RICH GALAXY GROUP GAS

WHAT WE SEE | **WHAT MULCHAEY et al (1996) predicted**

WHAT WE SEE	WHAT MULCHAEY et al (1996) predicted
log T = 6.1 K	log T = 6.3 K
(based on b_{HI} ≈ 100 km/s)	**(based on σ ≈ 100 km/s)**
log N_H = 19.9 cm^{-2}	**log N_H ≈ 20 cm^{-2}**

assumed size (radius) ≈ 400 kpc

inferred gas mass ≈ 10^{10-11} $M_\odot$

THEN: For the # density of spiral-rich galaxy groups ≈ 10^{-3} Mpc^{-3}

→ Ω_b ≈ 20% of total {SOLVES SPIRAL GALAXY BARYON DEFICIT PROBLEM & HELPS SOLVE COSMIC BARYON PROBLEM}

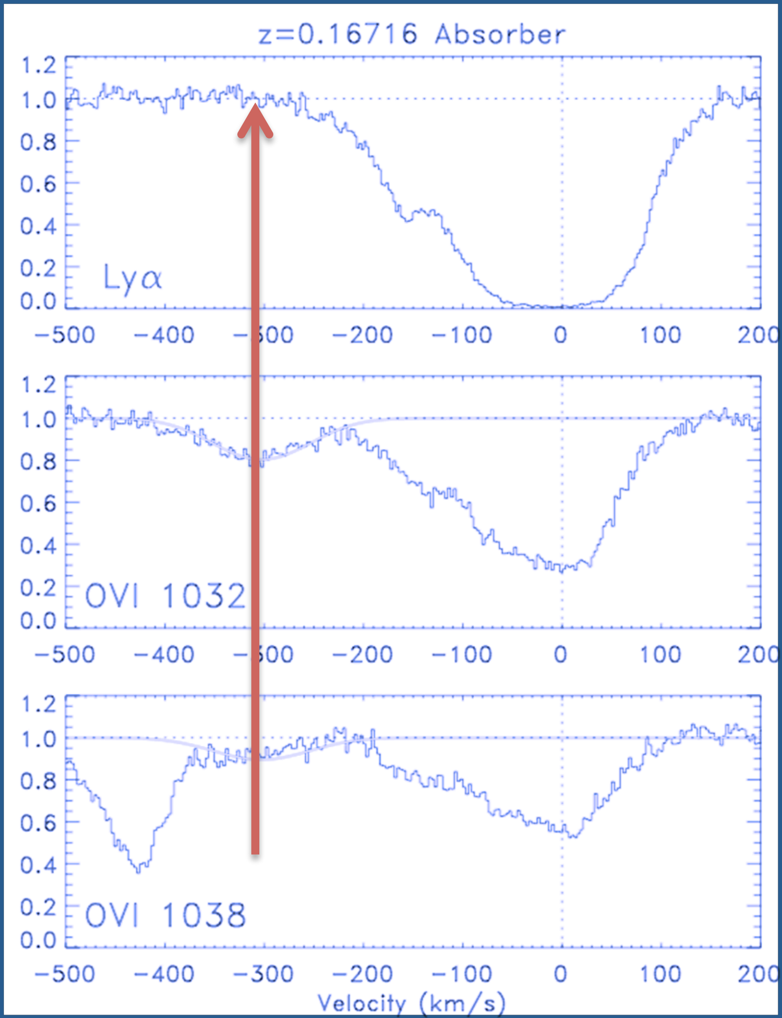
Reasons to believe that spiral-rich groups contain 10^6 K gas halos.

1. **A few BLAs and broad shallow OVI absorbers have been found in high-S/N spectra.**

For example, here is an unusual example with very broad, shallow OVI and NO HI Lyman alpha ➔ **T ≈ $10^{6.0-6.5}$ K** (Savage et al. 2010 ApJ 719, 1526).

Preliminary & uncertain very broad (b > 85 km/s) BLA accounting yields

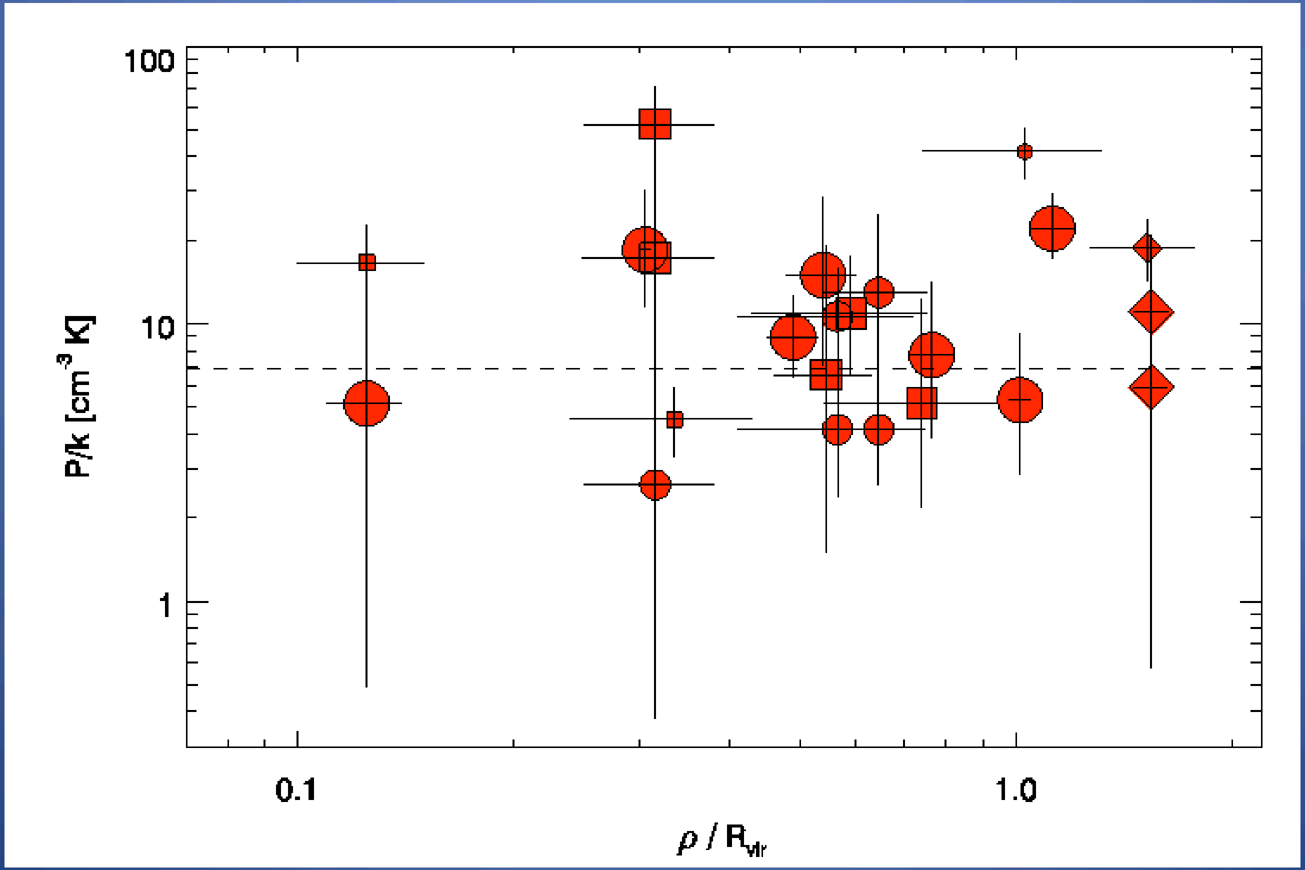
dN/dz (BLAs) = 2—6 ➔ estimated size of absorbing region at 100% covering factor is R ~ 500—1000 kpc, assuming that all spiral galaxy groups have such gas (ρ ~ 10^{-3} Mpc^{-3}).



Reasons to believe that spiral-rich groups contain 10^6 K gas halos.

1. **A few BLAs and broad shallow OVI absorbers have been found in high-S/N spectra.**

2. **Warm, photo-ionized CGM clouds have relatively constant internal pressures** out to a virial radius away from their nearest galaxies ➔ in pressure equilibrium with a hotter, diffuse gas which has a relatively constant pressure over a region > virial radius in extent (see Fang, Bullock & Boylan-Kolchin 2013 ApJ for application to the Local Group)



Reasons to believe that spiral-rich groups contain 10^6 K gas halos.

1. **A few BLAs and broad shallow OVI absorbers have been found in high-S/N spectra.**
2. Warm, photo-ionized CGM clouds have relatively **constant internal pressures .**
3. **Observational extrapolation from elliptical-dominated small groups** whose hot gas is observed in X-ray bremsstrahlung at log L_x = 40.3—43 ergs s^{-1} (Mulchaey 2000 Ann Revs Astr Ap). Observed properties below are obtained by very different methods:

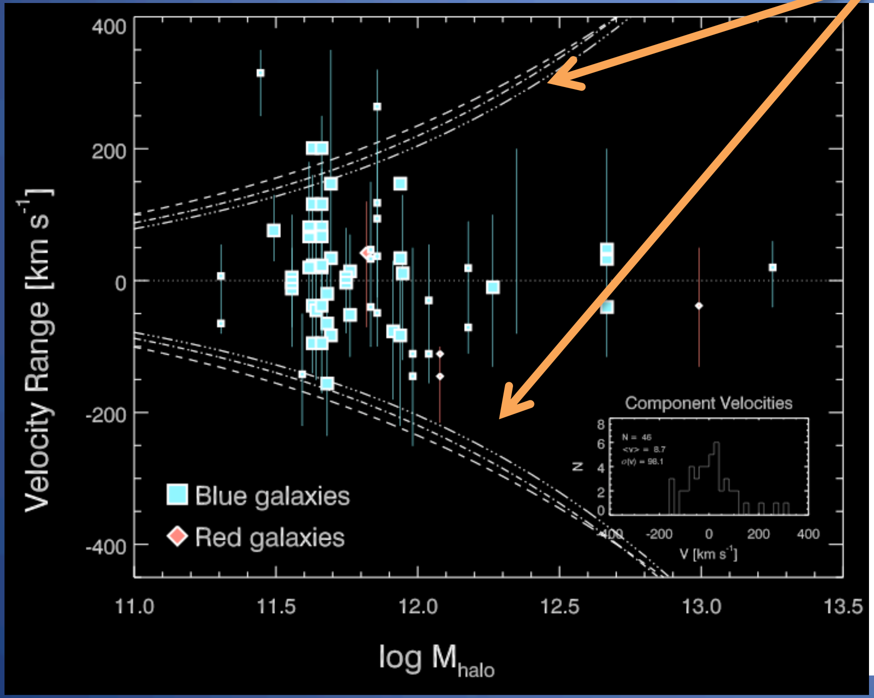
MASS IN SOLAR MASSES	ELLIPTICAL GROUPS	SPIRAL GROUPS
MASS IN STARS	**4 X 10^{11} TO 3 X 10^{12}**	**3 X10^{10} TO 9 X 10^{11}**
MASS IN GAS	**5 X 10^{10} TO 2.5 X 10^{12}**	**2 X10^{10} TO 7 X 10^{11}**
TOTAL DYNAMICAL	**~ 10^{13}**	**~ 10^{13}**
TOTAL BARYONS	**~ $10^{12.3}$**	**~ $10^{12.3}$**
METALLICITY	**FROM 10-20% TO 50-60%**	**<10% TO >100% Solar**
TEMPERATURE	**5 x 10^6 to 5 x 10^7 K**	**7 x 10^5 to 5 x 10^6 K**
Velocity dispersion	**100—600 km/s**	**50—150 km/s**
Extent	**0.1—0.6 R(virial)**	**~ R(virial)**

Reasons to believe that spiral-rich groups contain 10^6 K gas halos.

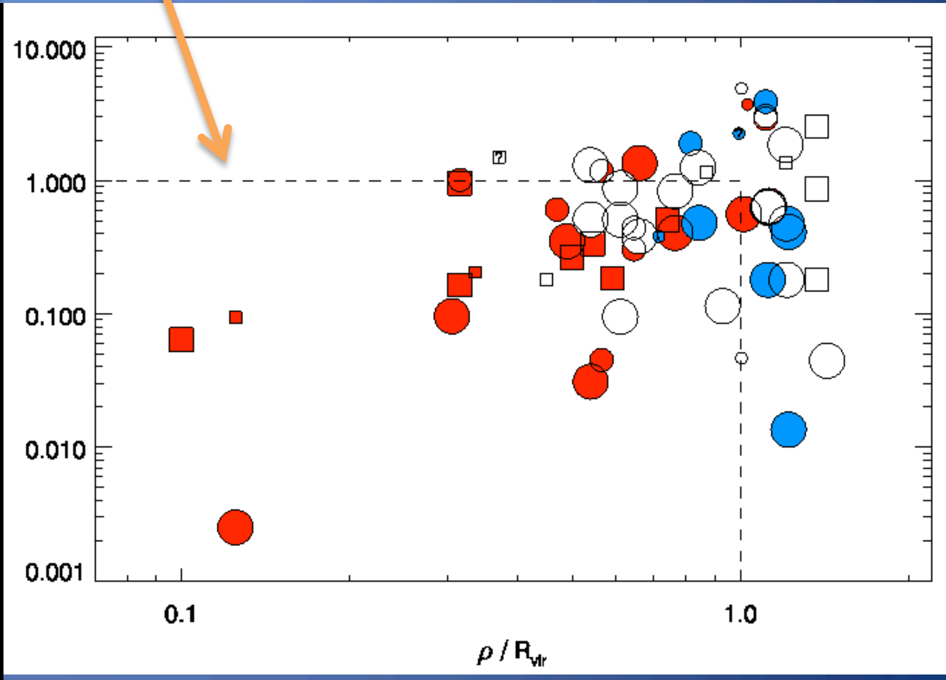
1. **A few BLAs and broad shallow OVI absorbers have been found in high-S/N spectra.**
2. Warm, photo-ionized CGM clouds have relatively **constant internal pressures .**
3. **Observational extrapolation from elliptical-dominated small groups.**
4. **Theoretical Expectations (e.g., McGaugh et al. 2000; Klypin et al. 2001) are that spiral galaxy groups should be nearly "closed boxes" and so should contain the cosmic ratio (5:1) of dark matter to baryons.**

ESCAPE VELOCITY

(Tumlinson et al. 2011)



(Stocke et al. 2013)



*** LITTLE INDICATION FOR GAS ESCAPING OR FALLING IN AT LARGE VELOCITIES ➔ SPIRAL GALAXY GROUP GAS PROBABLY COMES FROM GALAXIES IN THE GROUP

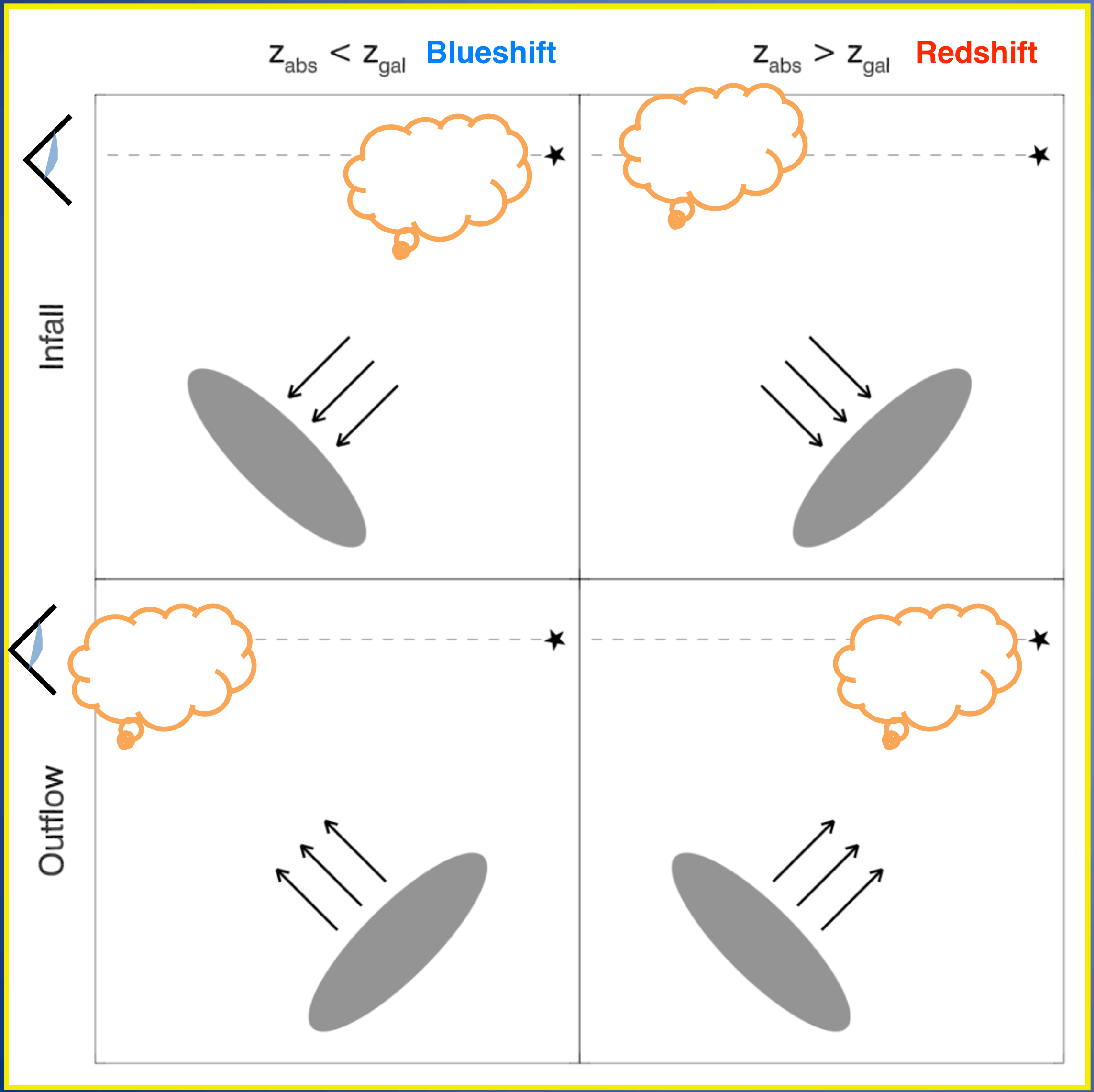
INCLUDING new COS results on BLAs: This is a cartoon view of a spiral-rich group

3D ORIENTATION + SIGN OF Δv + assumption of nearly vertical motion ➔ INFALL OR OUTFLOW

More HII regions on top than bottom (top edge is closer to us) + Sub-DLA at Δv = -44 km/s relative to galaxy ➔ INFALL.

(Stocke, Keeney & Danforth 2010).

Is Absorbing Gas Infalling or Outflowing?



3D orientation + assumption that cloud motion is nearly perpendicular to galaxy disk + sign of galaxy/cloud velocity difference ➔ definitive infall/outflow discrimination.

Ways to Determine Orientation:

1. High-res Imaging to look at distribution of H II regions (numbers and integrated luminosities).

2. GALEX NUV/FUV image ratio.

3. High-res Spectroscopy to look at Balmer decrement as a function of position in the galaxy.

SUMMARY

1. **HST/COS & STIS UV SPECTRA SAMPLE THE CGM OF LOW-Z GALAXIES at very high probability given b < R_virial**

2. **BARYON CENSUS** IN MASSIVE (~2L*) SPIRALS:

- **20% STARS & DISK GAS** (Fukugita, Hogan & Peebles)
- **15% CGM WARM AND OVI-ABSORBING GAS** (COS/GTO + Tumllinson et al 2011)
- **< 10% CORONAL GAS** (Anderson & Bregman 2013)
- ➔ ~50% "MISSING" BUT **....HOT GAS AT 10^6 °K FILLING SPIRAL GROUPS !!**

(Savage et al 2010; **Stocke et al . 2013**; Stocke et al. in prep)

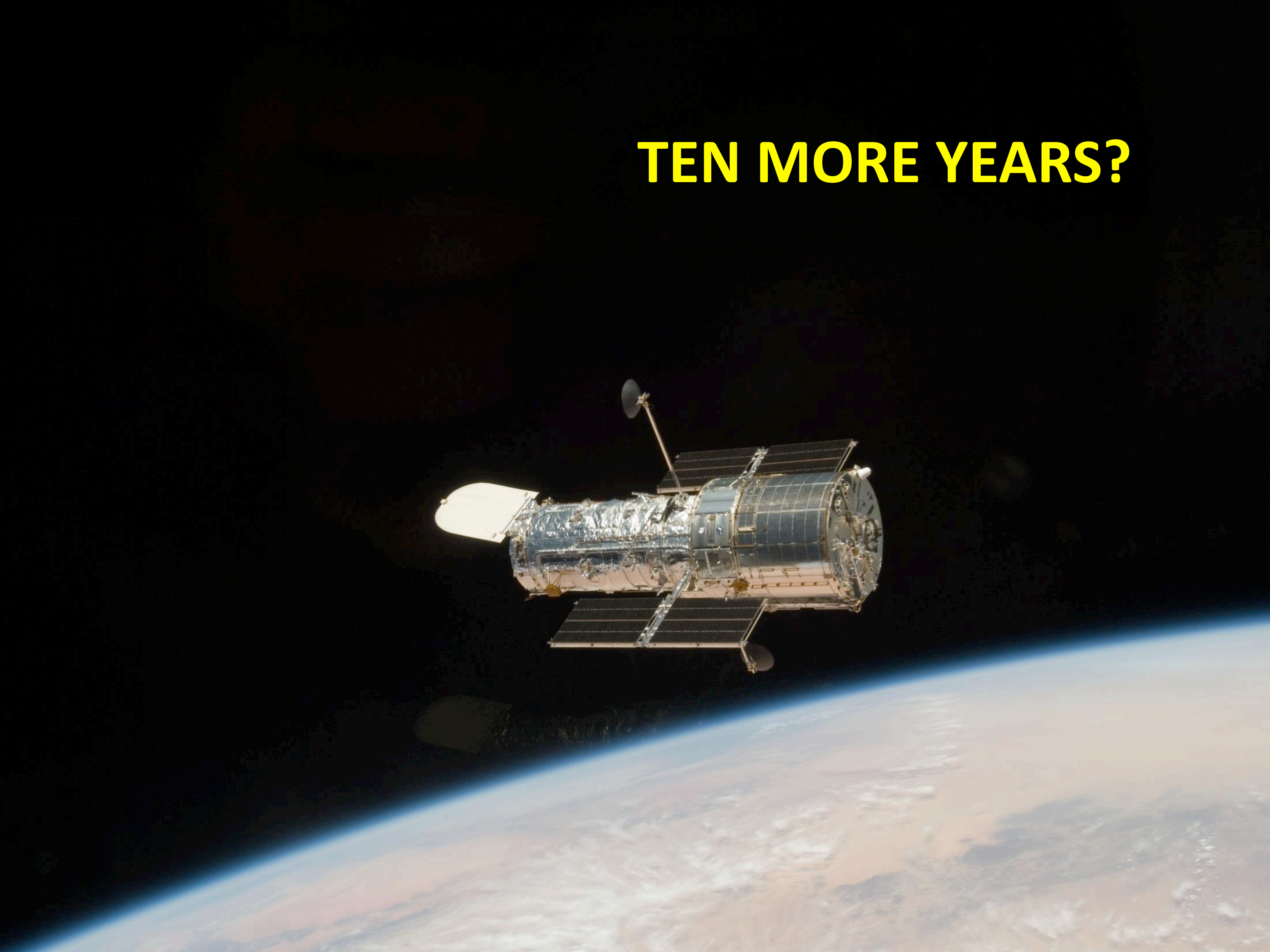
3. HOT SPIRAL GROUP ICM CAN CONTRIBUTE **≥ 20% TO COSMIC BARYON INVENTORY**

4. **BASICS OF GALACTIC CHEMICAL EVOLUTION CONFIRMED:**

- LARGE RESERVOIR OF CGM GAS FOR ACCRETION.

- **RECYCLING** ("GALACTIC FOUNTAINS"), **UNBOUND OUTFLOW** ("WINDS") **& INFALL** ("COLD ACCRETION') **ALL DETECTED AT ~ 1 $M_{\odot}$ PER YEAR FOR A MILKY WAY SIZE GALAXY** *** **can determine infall/outfow specifically in some cases.**

- **SPECULATION: Development of hot intra-group medium inhibits accretion of cold clouds which causes rapidly declining SFR from z = 1 to 0 (Keres et al.).**


TEN MORE YEARS?