

Tracing the Circumgalactic Medium with the Cosmic Origins Spectrograph

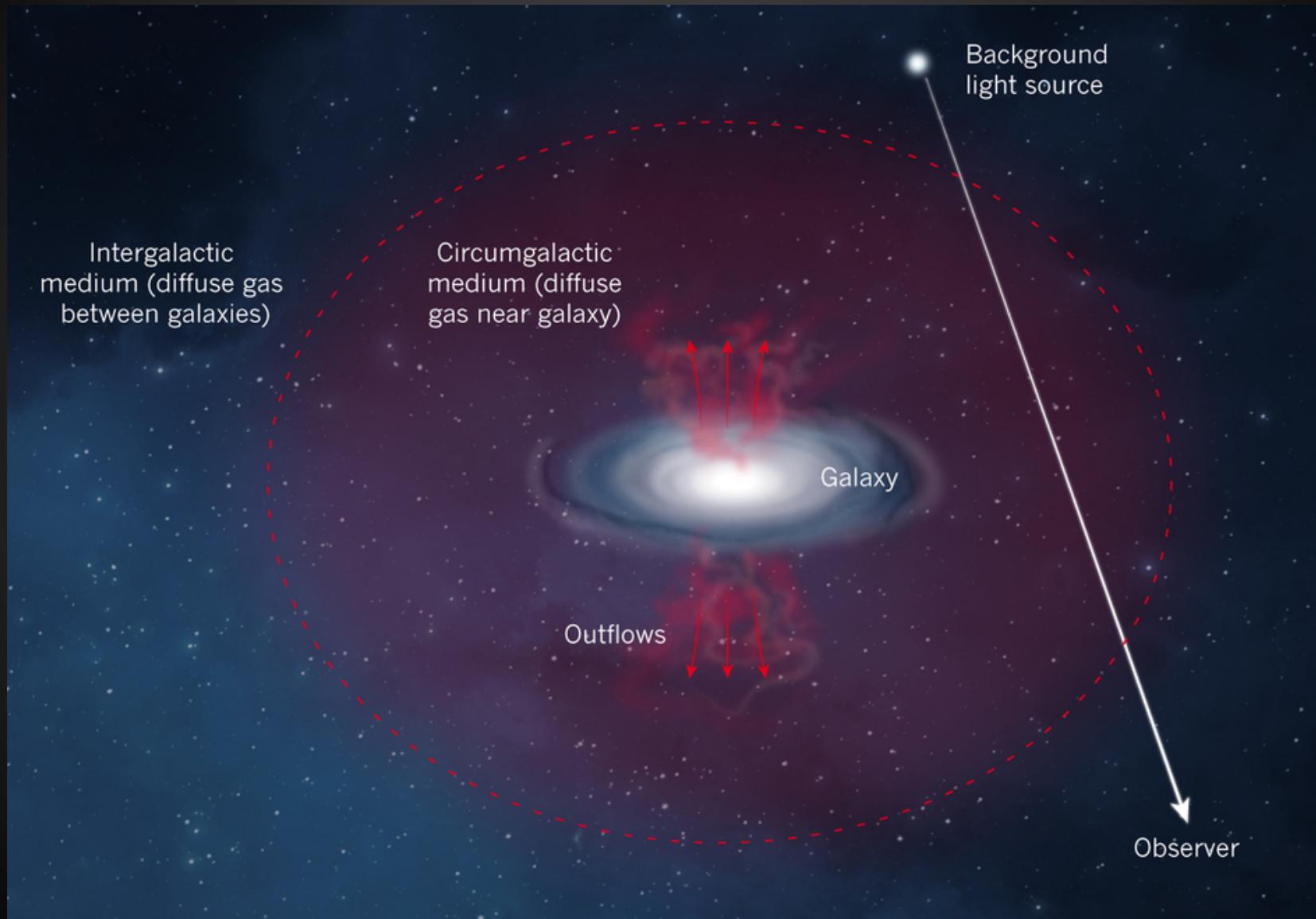
David M. French

Advisor: Bart Wakker

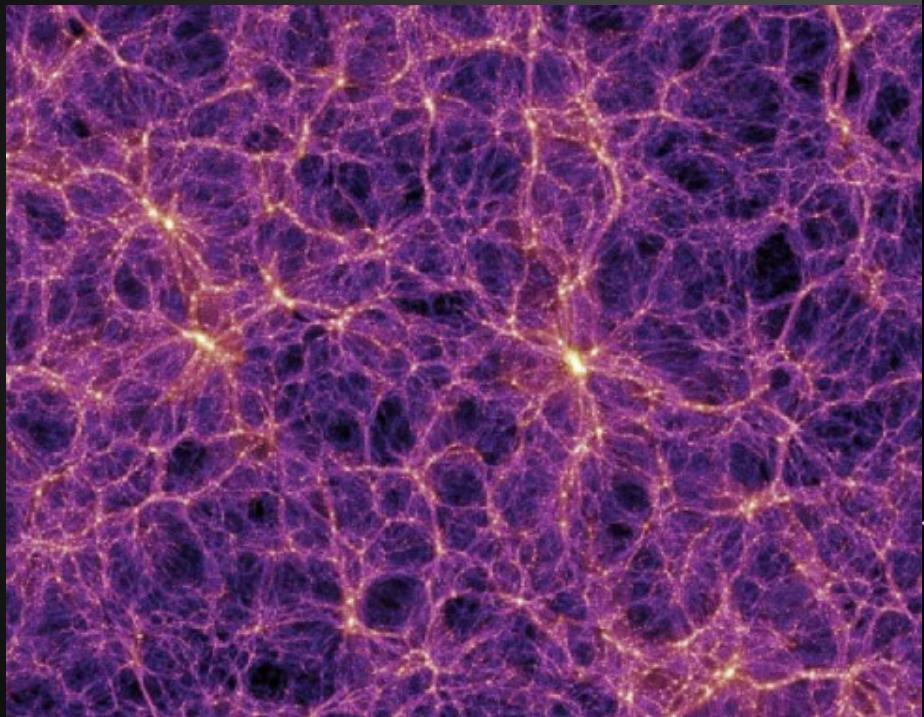
University of Wisconsin - Madison

April 25, 2016

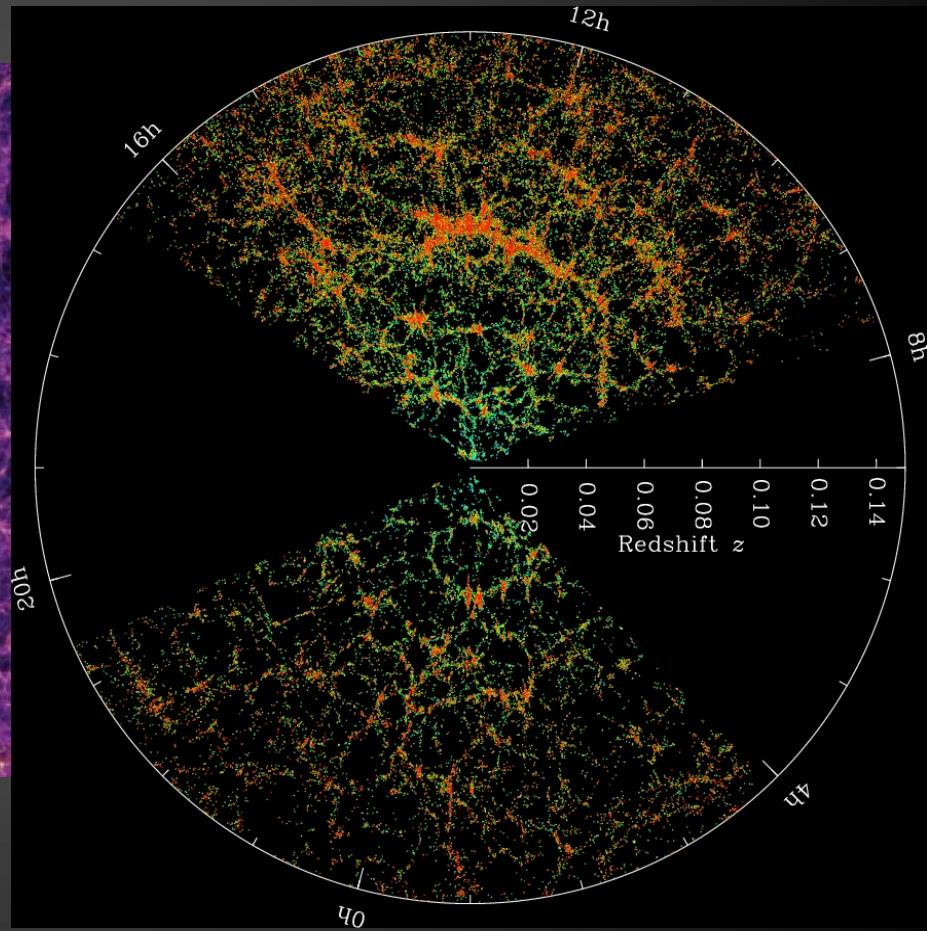
Defining the CGM



Gas in the Universe



The Millenium Simulation



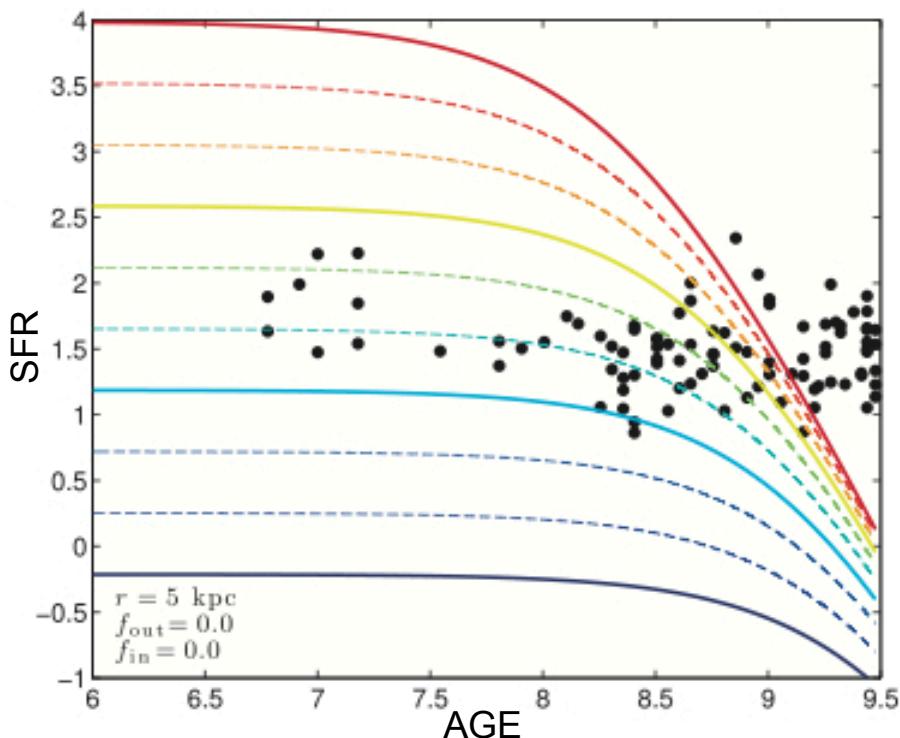
SDSS Collaboration

The gas nearby galaxies

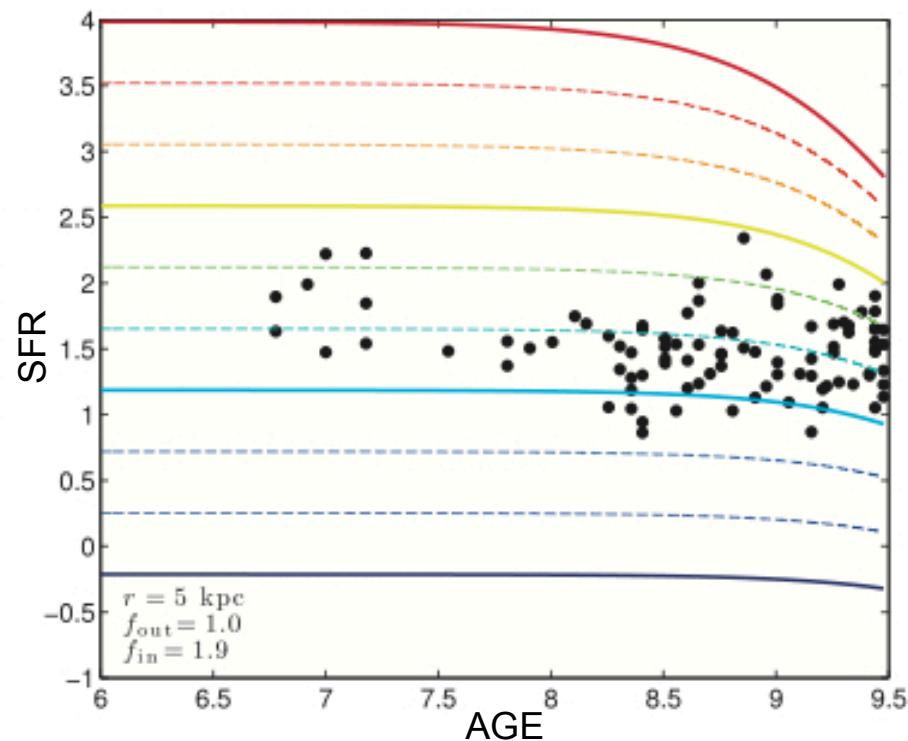
- Gas and galaxies both follow DM potential
- Do they “know” about each other?

Accretion required

With no accretion

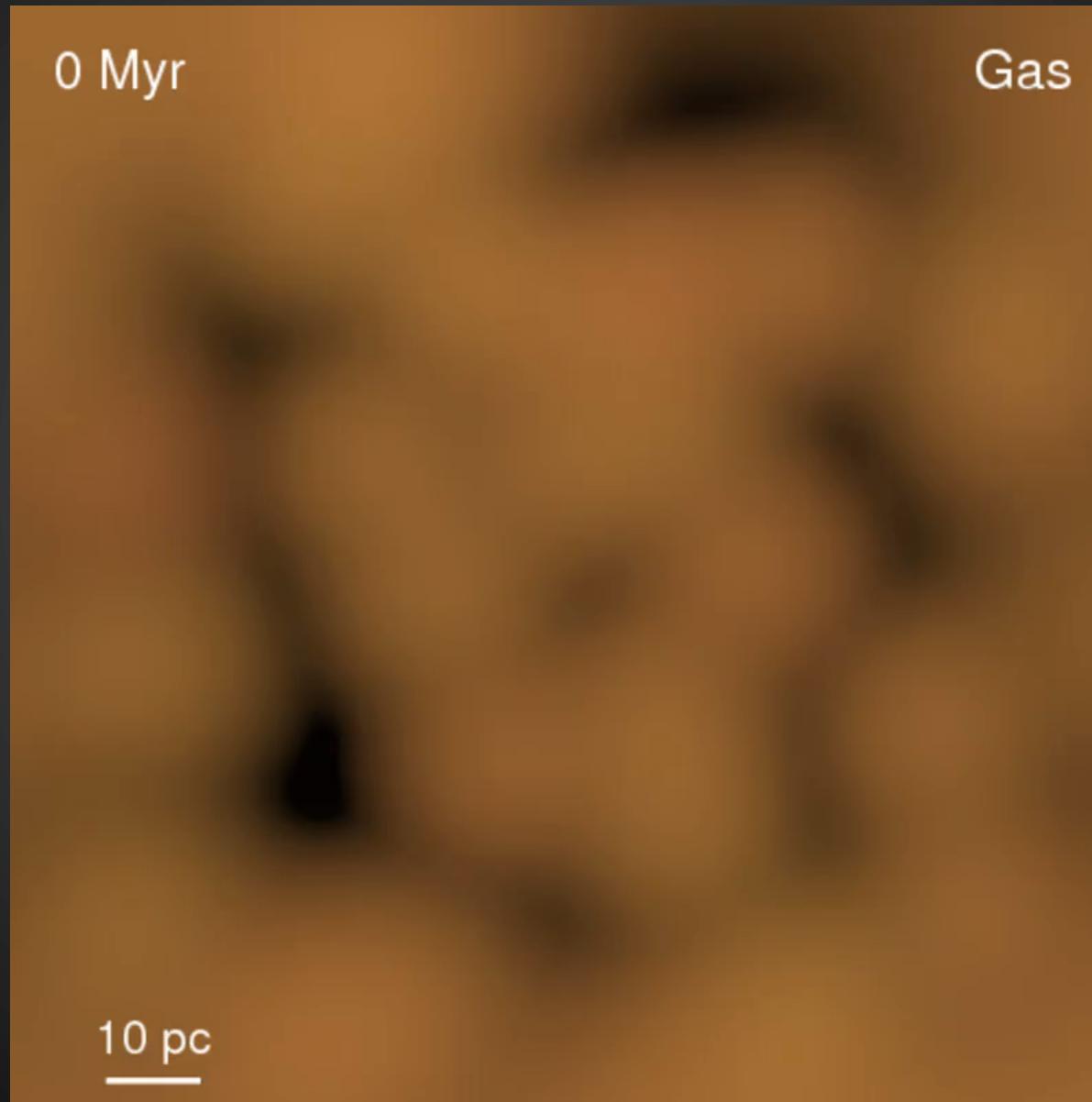


With accretion

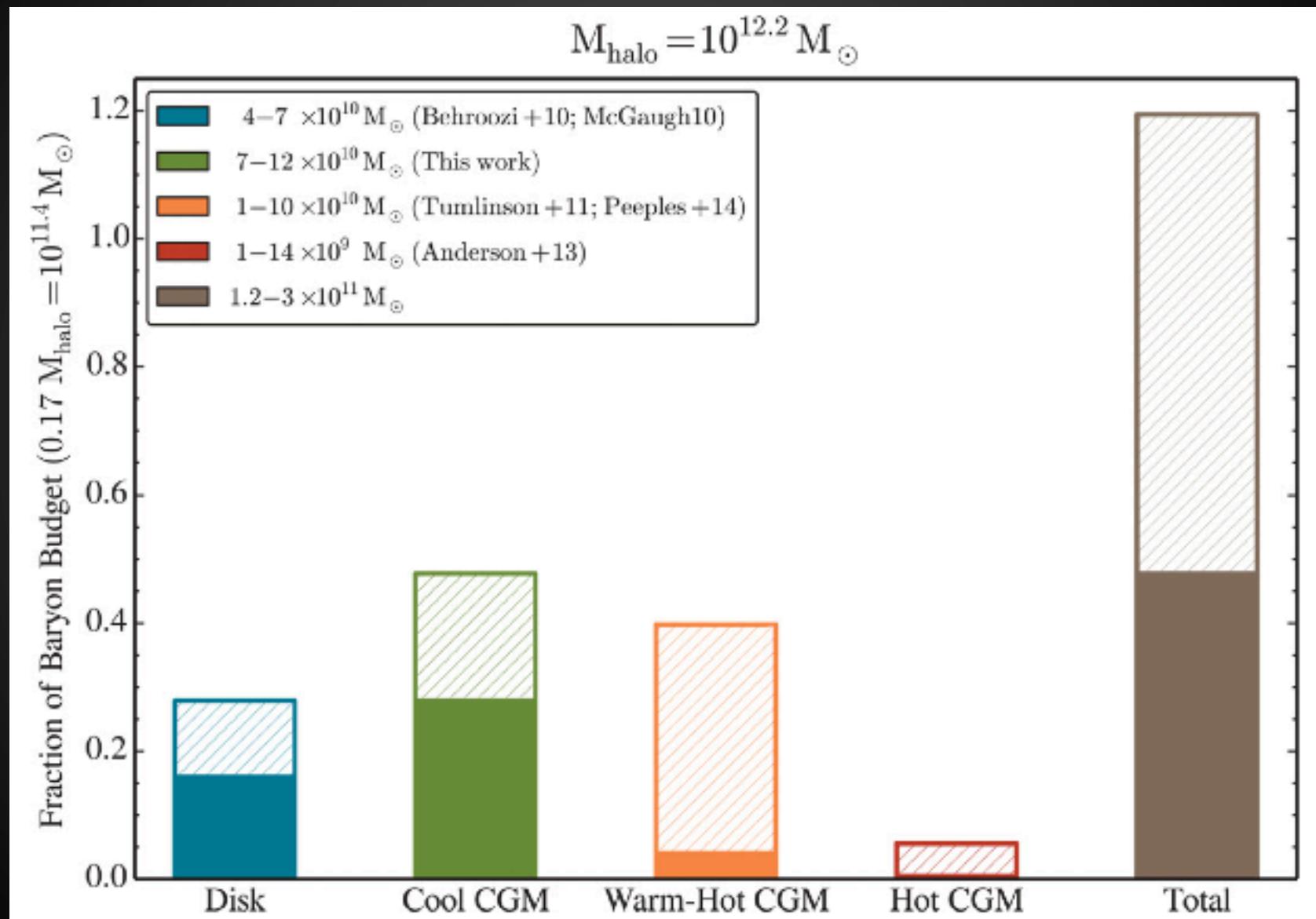


Erb 2008

Outflows and feedback



Baryon Budget



Understanding the CGM

- Galaxies need to continue accreting gas over cosmic time to match observations



- Feedback kicks gas out of galaxies

Understanding the CGM

- Galaxies need to continue accreting gas over cosmic time to match observations



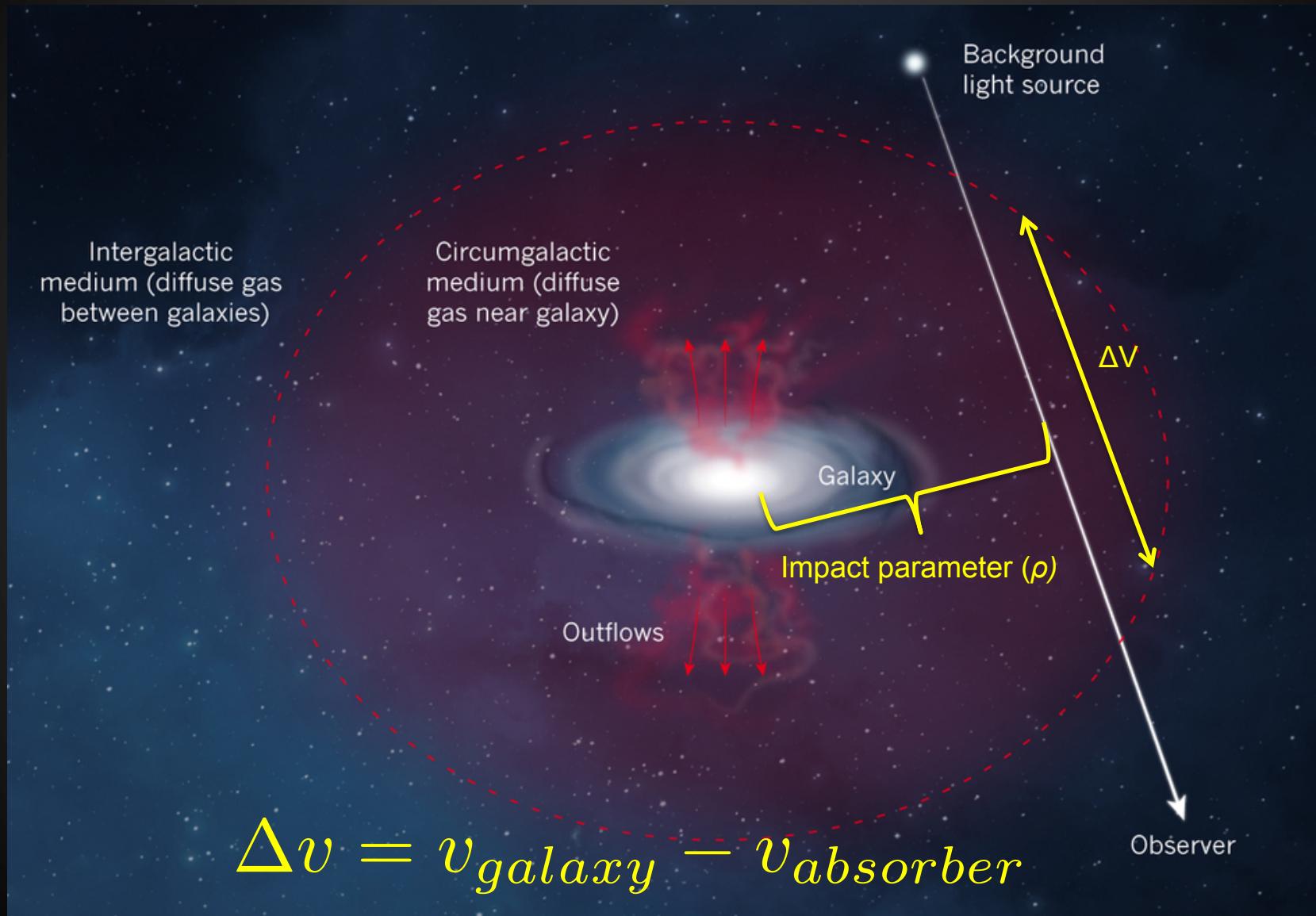
- Feedback kicks gas out of galaxies

★ How do the properties of gas correlate with associated galaxy properties?

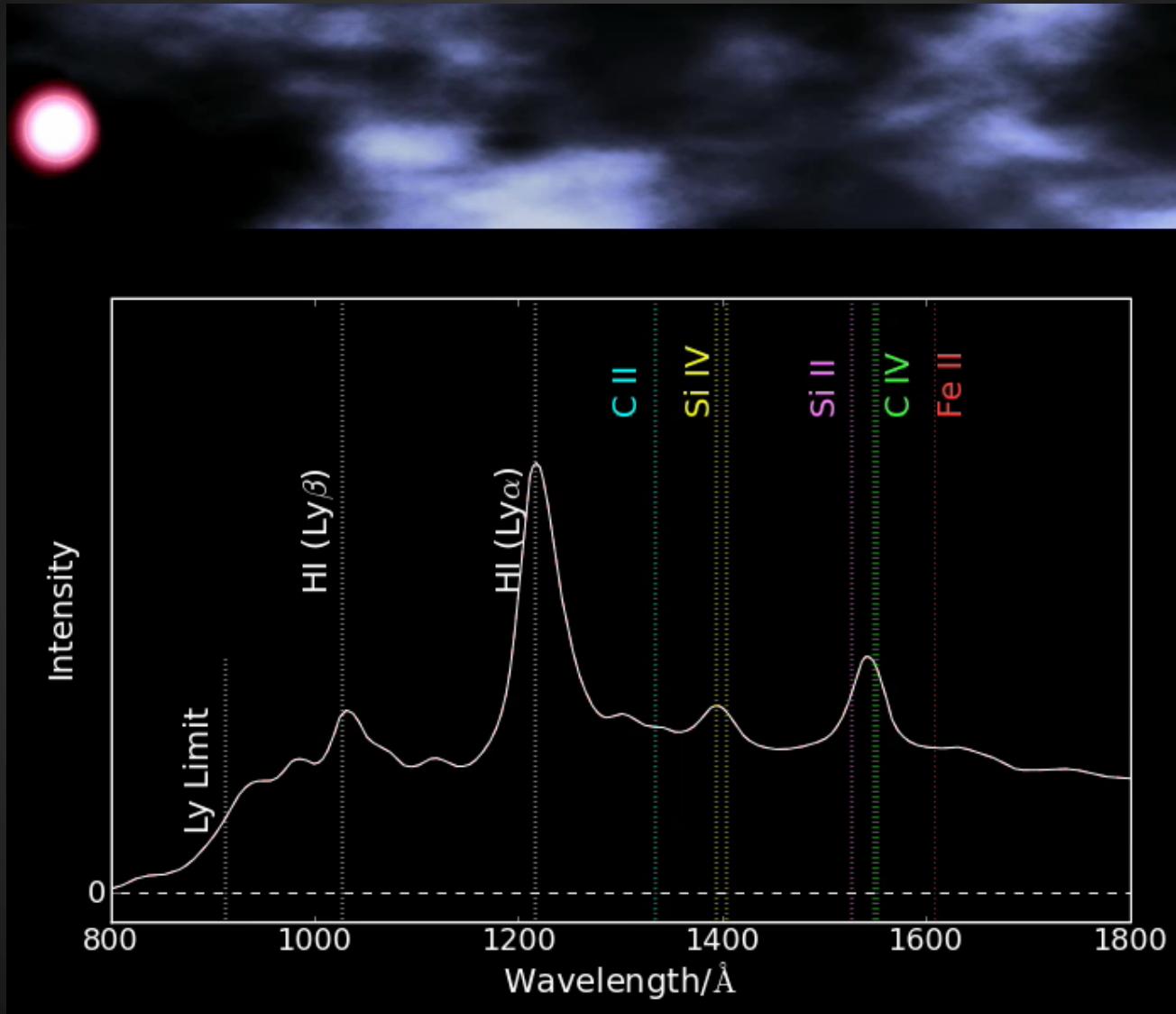
Science Outline

- *Use archival COS sightlines (~ 300)*
- *Stay close ($cz < 10,000$ km/s)*
 - *Available galaxy data complete to $\sim 0.1 L^*$*
- *Automate associating galaxies – absorbers*
- *Ask: (absorber velocity, EW, frequency)
as a function of
(Galaxy size, inclination, position)*

Defining the CGM

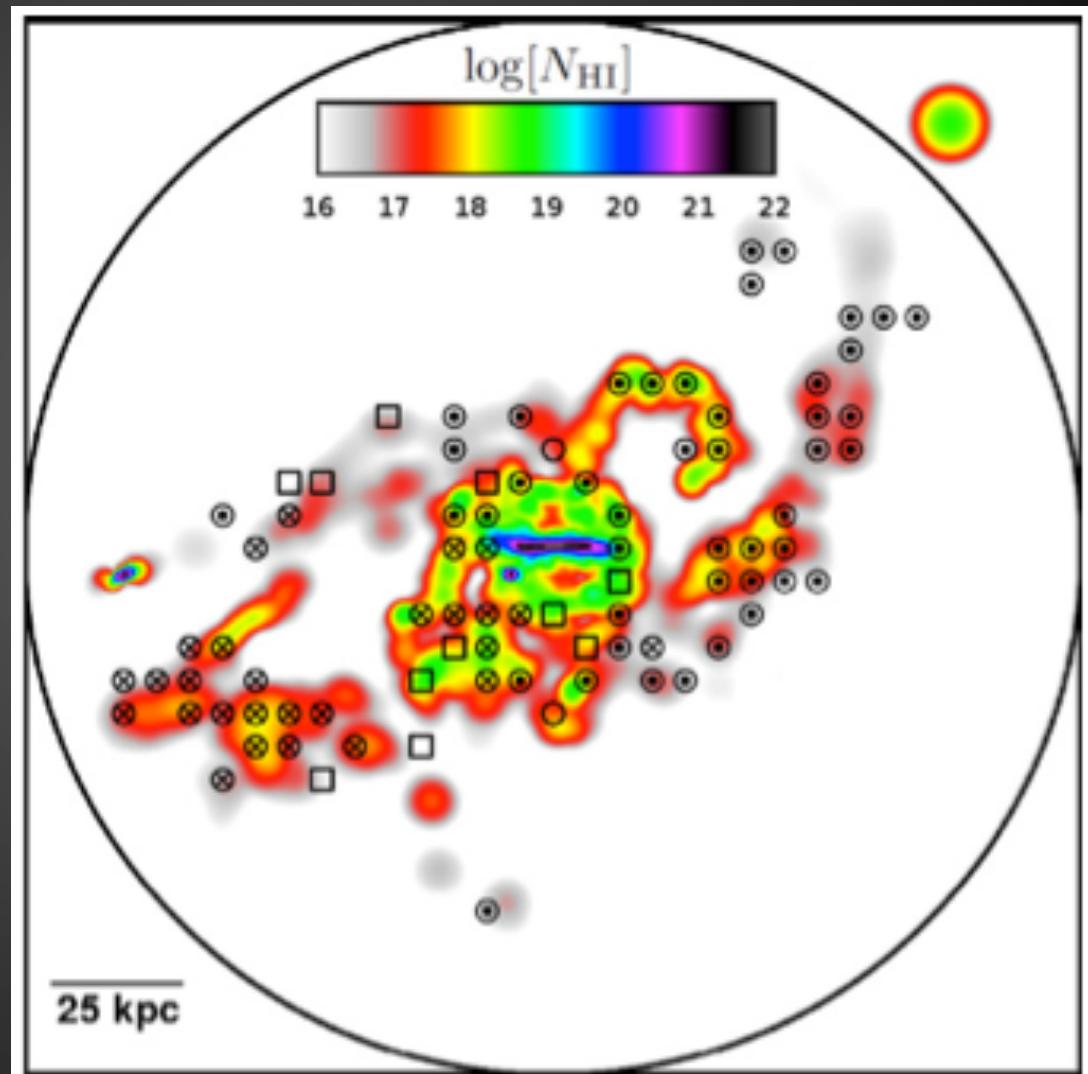


Method



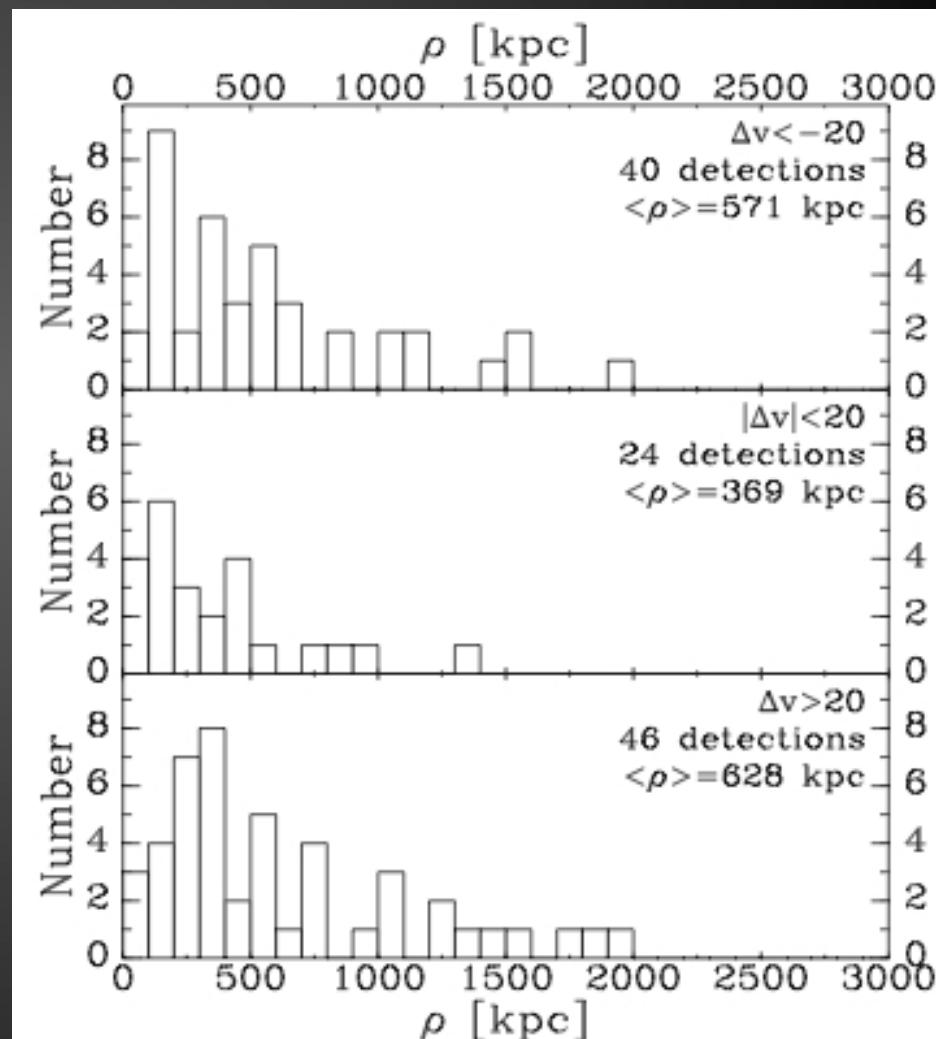
Does the CGM gas rotate with the galaxies?

- *Simulations say: yes!*
- *QSO sightlines through the halo should be able to trace this*

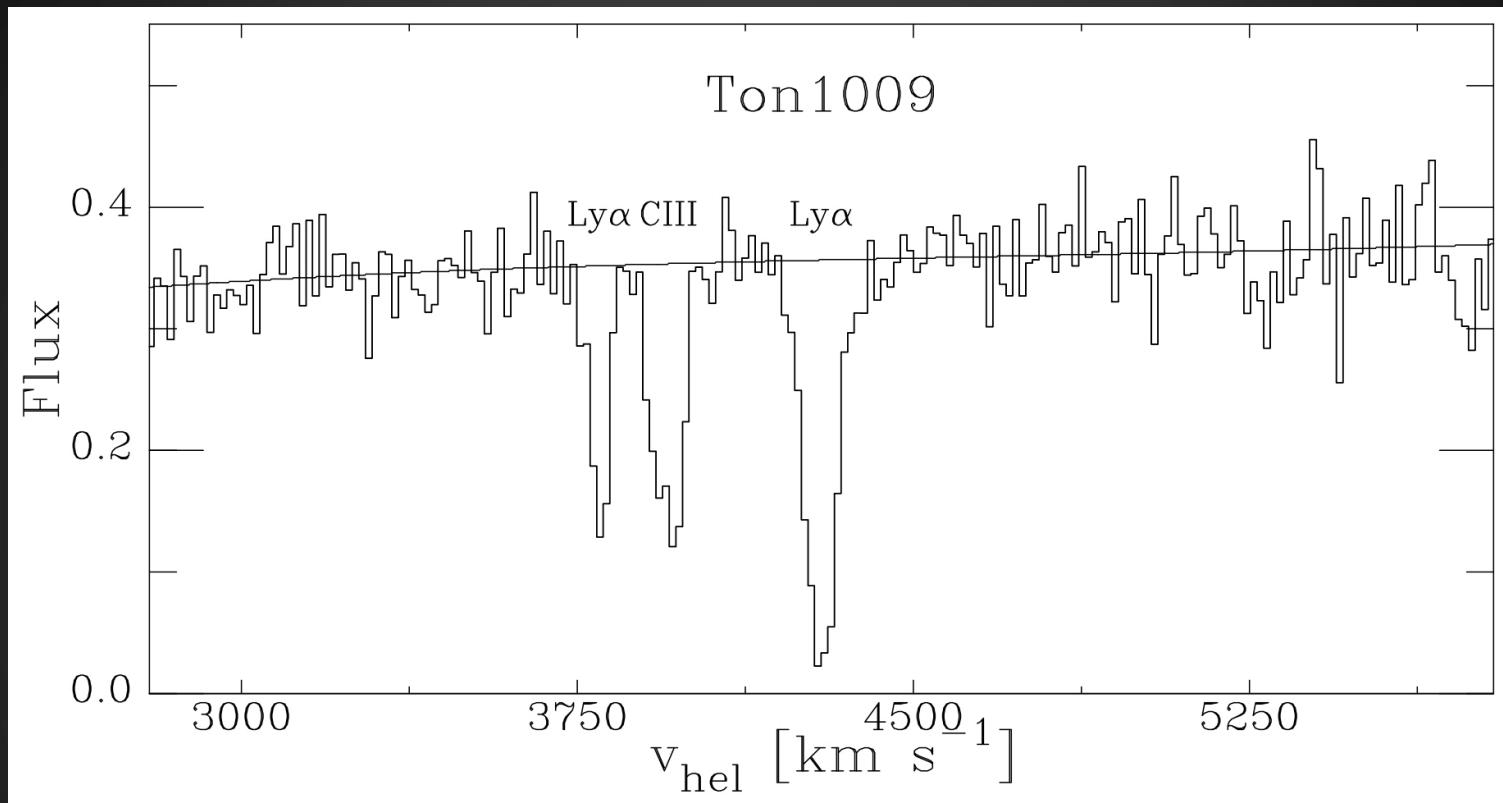


Does the CGM gas rotate with the galaxies?

- *Simulations say: Yes!*
- *Observations: Unclear*
 - Wakker & Savage 2009
– sample of 4
 - Closer absorbers have smaller Δv
 - $\Delta v = v(\text{galaxy}) - v(\text{gas})$



Associating galaxies with absorbers



Is this Ly α absorber associated with a galaxy?

Associating galaxies with absorbers

- Define a likelihood:

$$\mathcal{L} = e^{-\left(\frac{\rho}{R_{vir}}\right)^2} e^{-\left(\frac{\Delta v}{200}\right)^2}$$

- ρ = impact parameter
- $\Delta v = v_{galaxy} - v_{absorber}$
- R_{vir} = viral radius of the galaxy
- Require $\mathcal{L}_1 \geq 5 * \mathcal{L}_2$ and $\mathcal{L} \geq 0.001$

Associating galaxies with absorbers

- Define a likelihood:

$$\mathcal{L} = e^{-\left(\frac{\rho}{R_{vir}}\right)^2} e^{-\left(\frac{\Delta v}{200}\right)^2}$$

$$\mathcal{L} = 0.27 \text{ for } \Delta v = 200 \text{ km/s}, \rho = 1 R_{vir}$$

Associating galaxies with absorbers

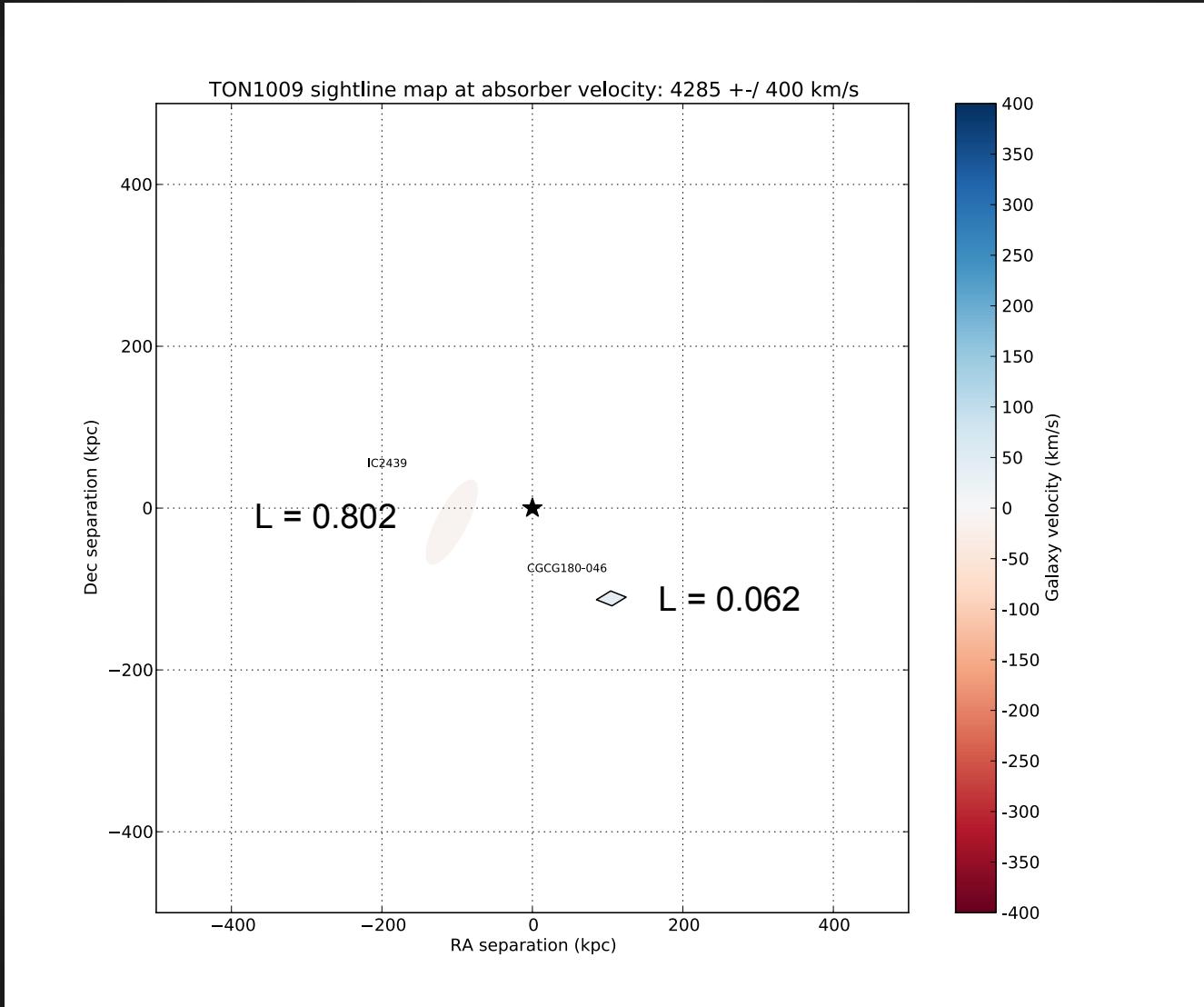
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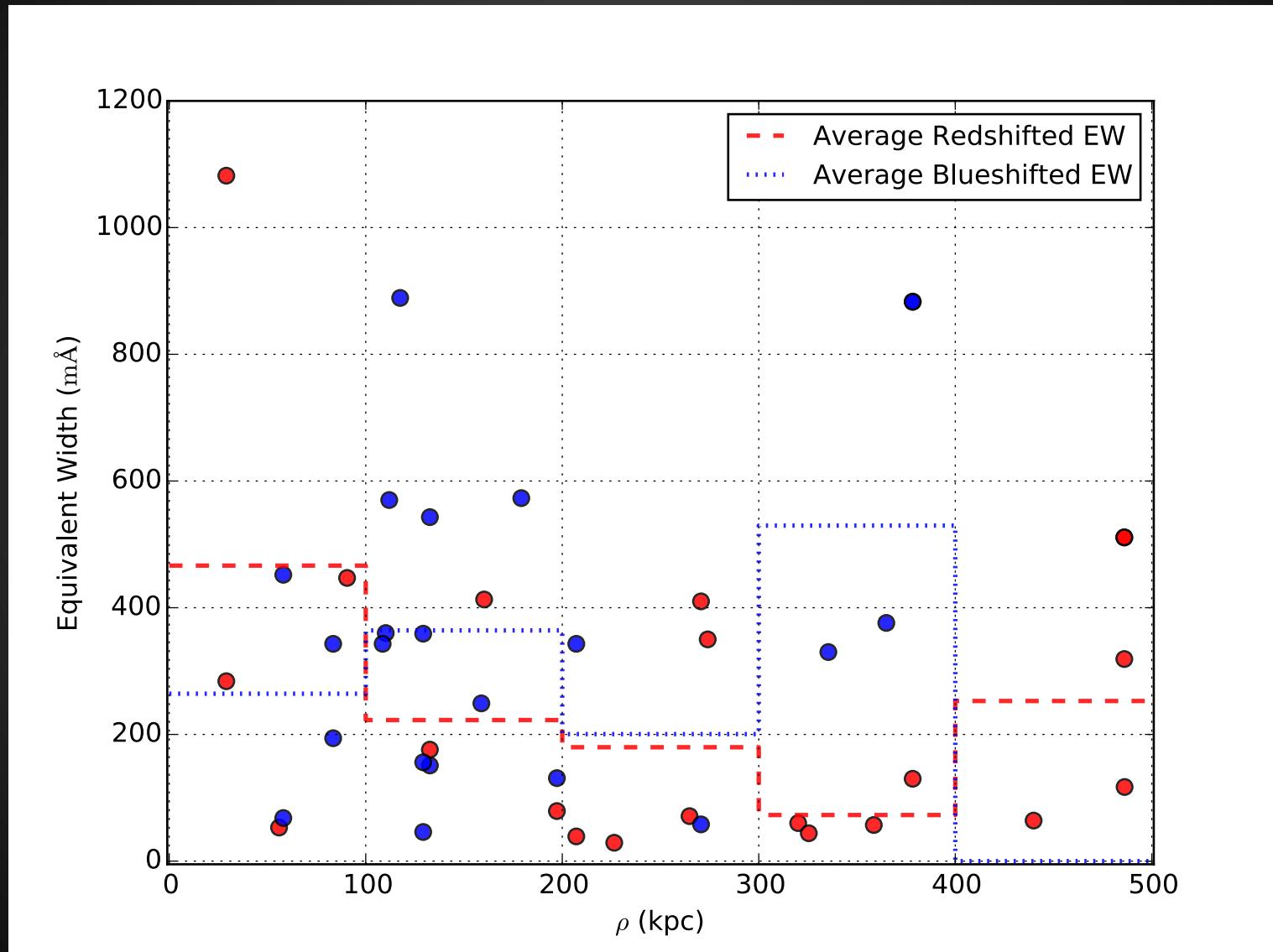
Associating galaxies with absorbers



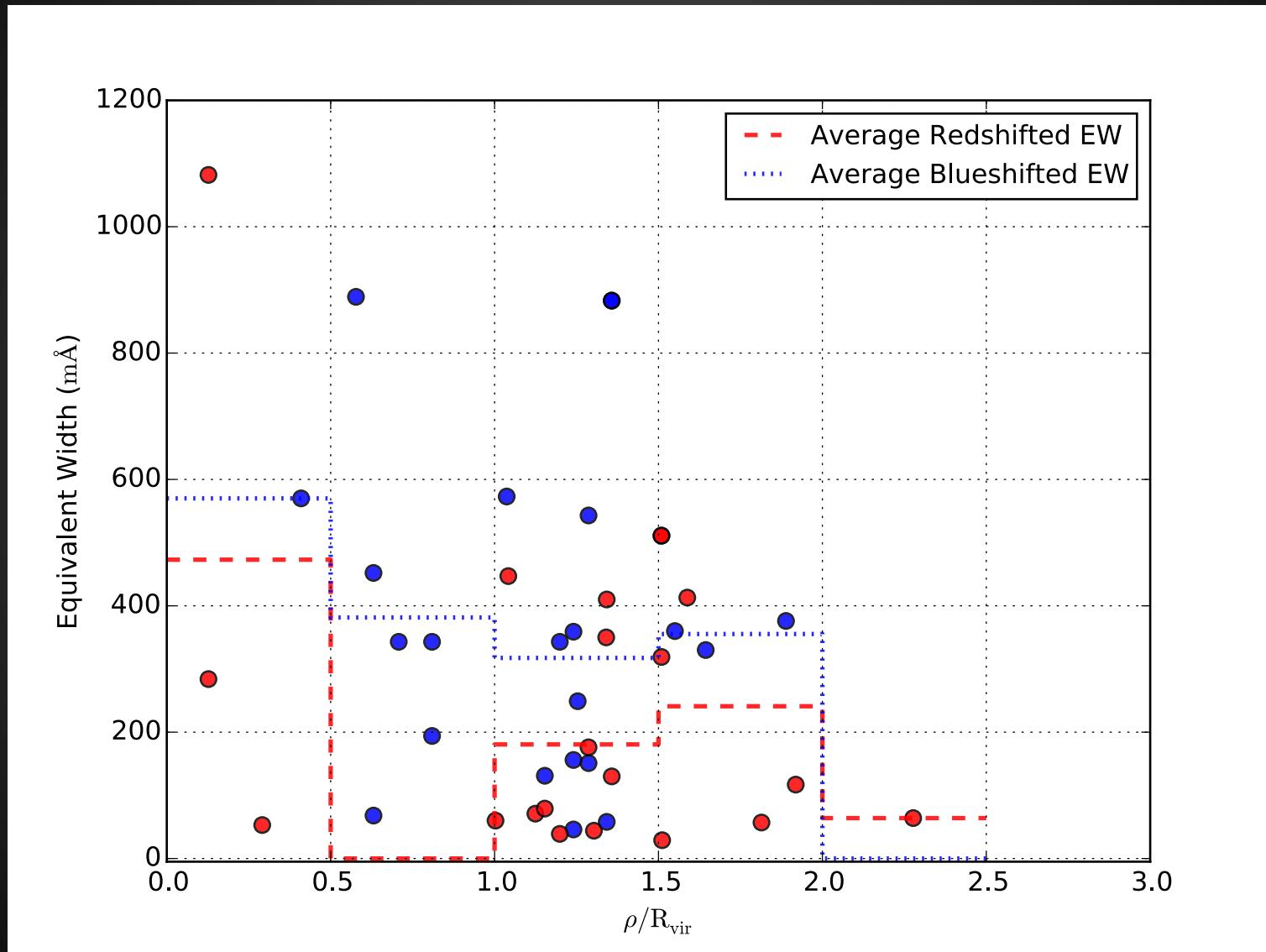
Results so far...

- 35 COS sightlines analyzed
- 175 Ly α lines
 - 41 associated
 - 44 ambiguous (no best match)
 - 88 IGM (no galaxies nearby)

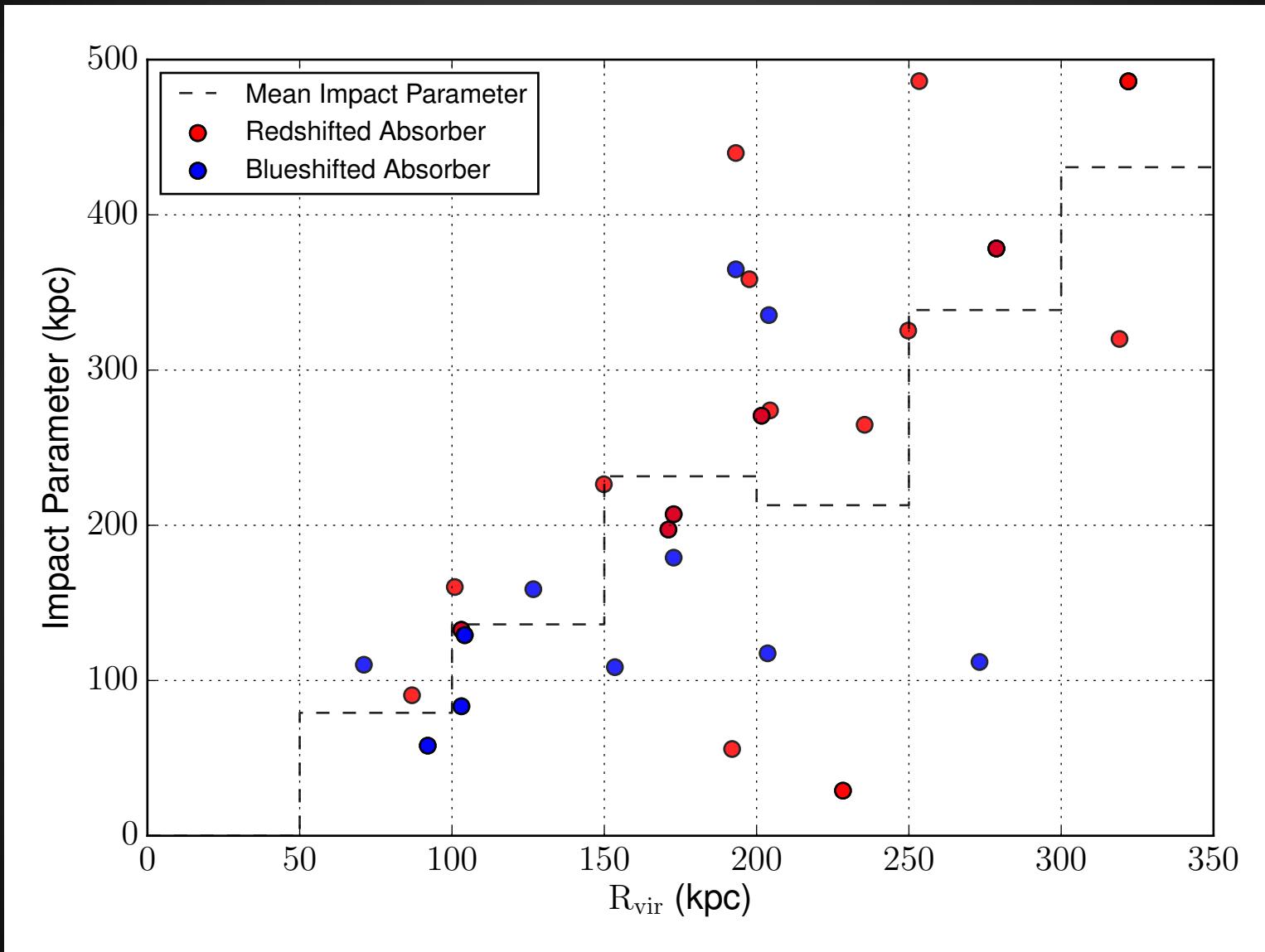
Impact parameter



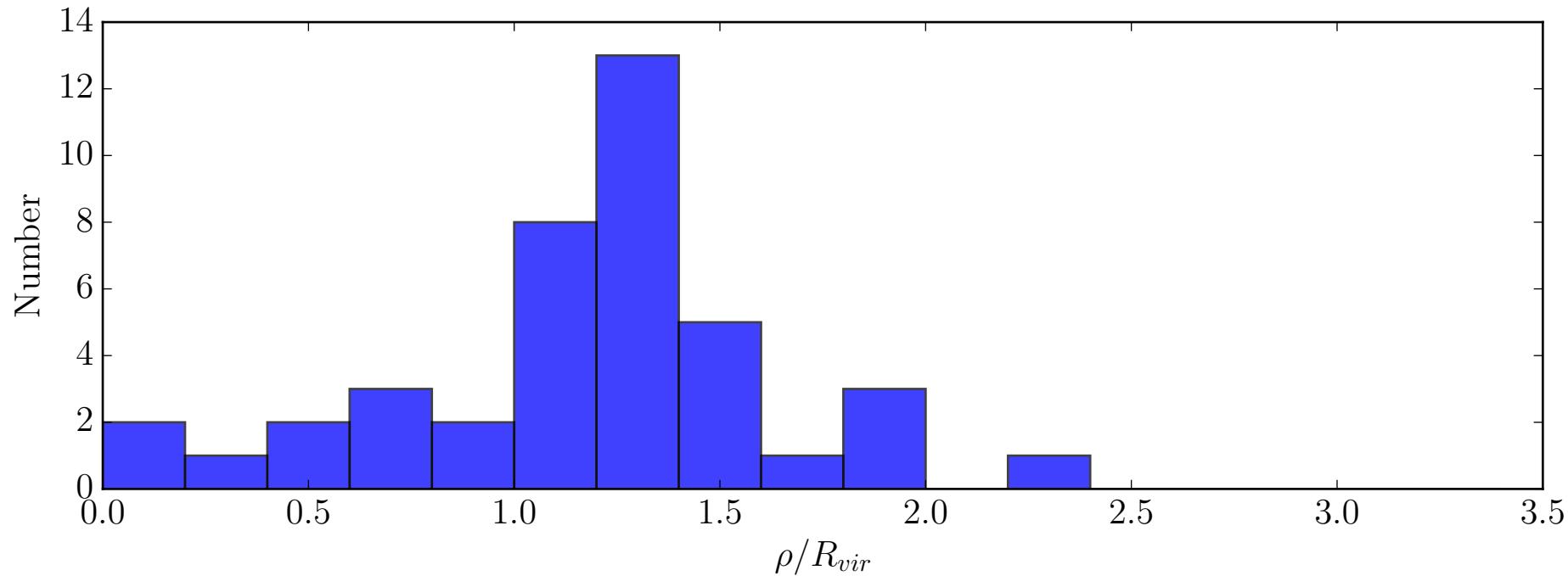
Impact parameter / R_{vir}



Impact parameter vs R_{vir}



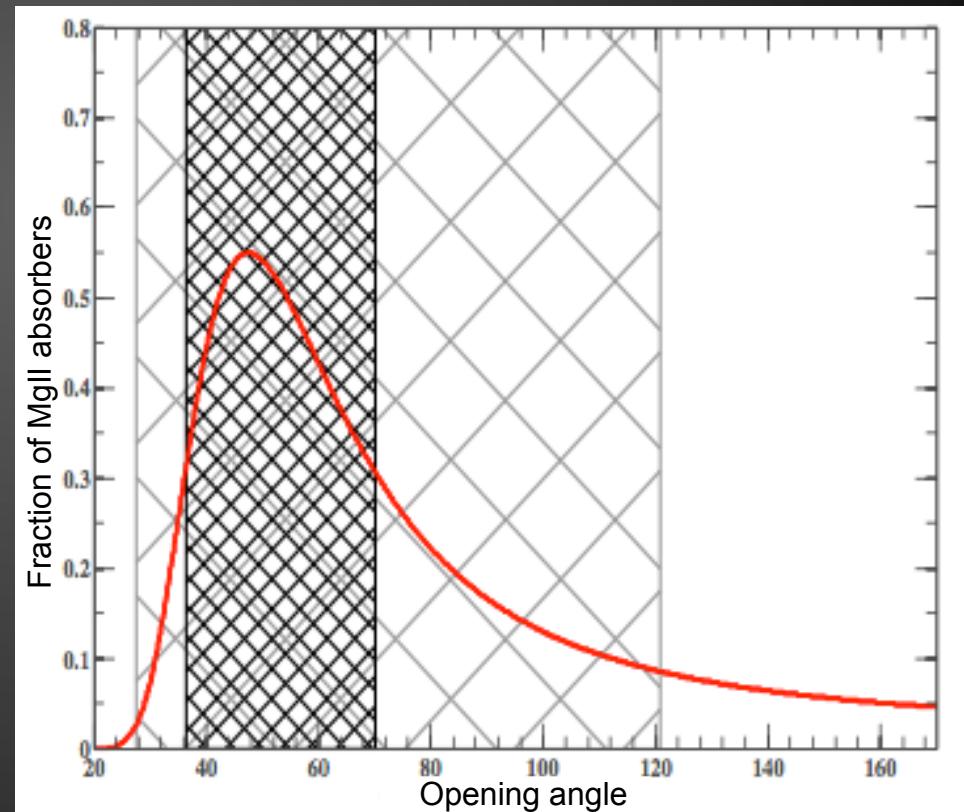
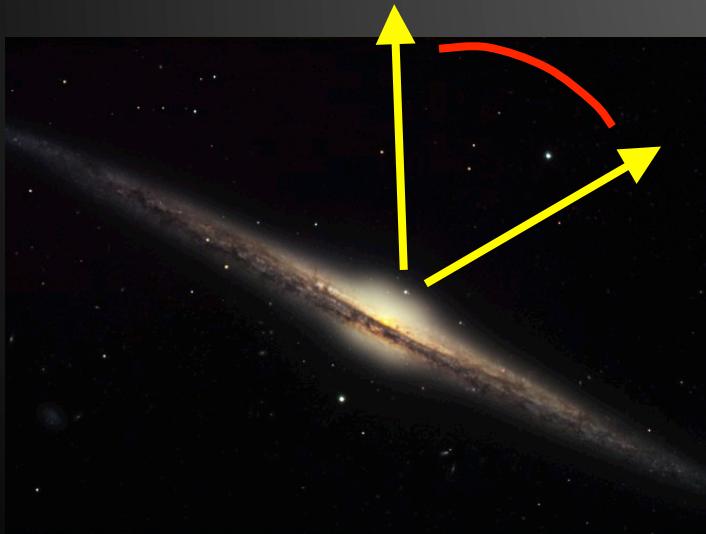
Impact parameter / R_{vir}



Most absorbers are found around $\frac{\rho}{R_{vir}} = 1.24$

How do CGM gas properties depend on galaxy orientation?

- Major vs minor?
- Bordoloi et al. 2014 predict 45° opening angle for MgII

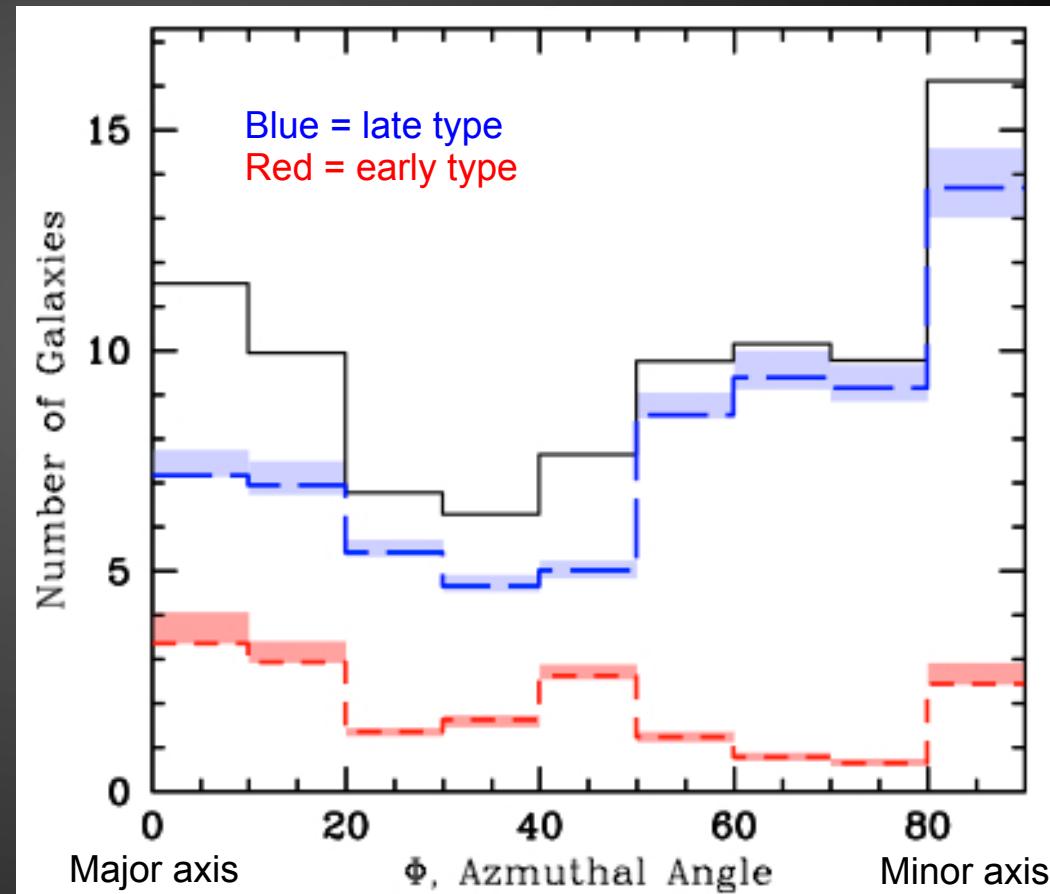
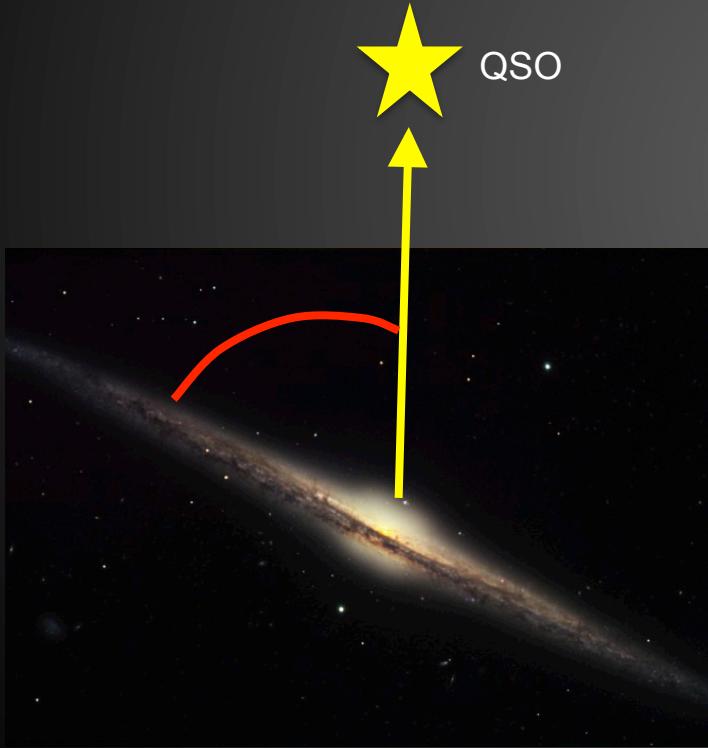


Credit: Bruce Hugo & Leslie Gaul, Adam Block, NOAO, AURA, NSF

Bordoloi et al. 2014, ApJ, 784, 108

How do CGM gas properties depend on galaxy orientation?

- Kacprzak et al 2012 find bimodal MgII absorption

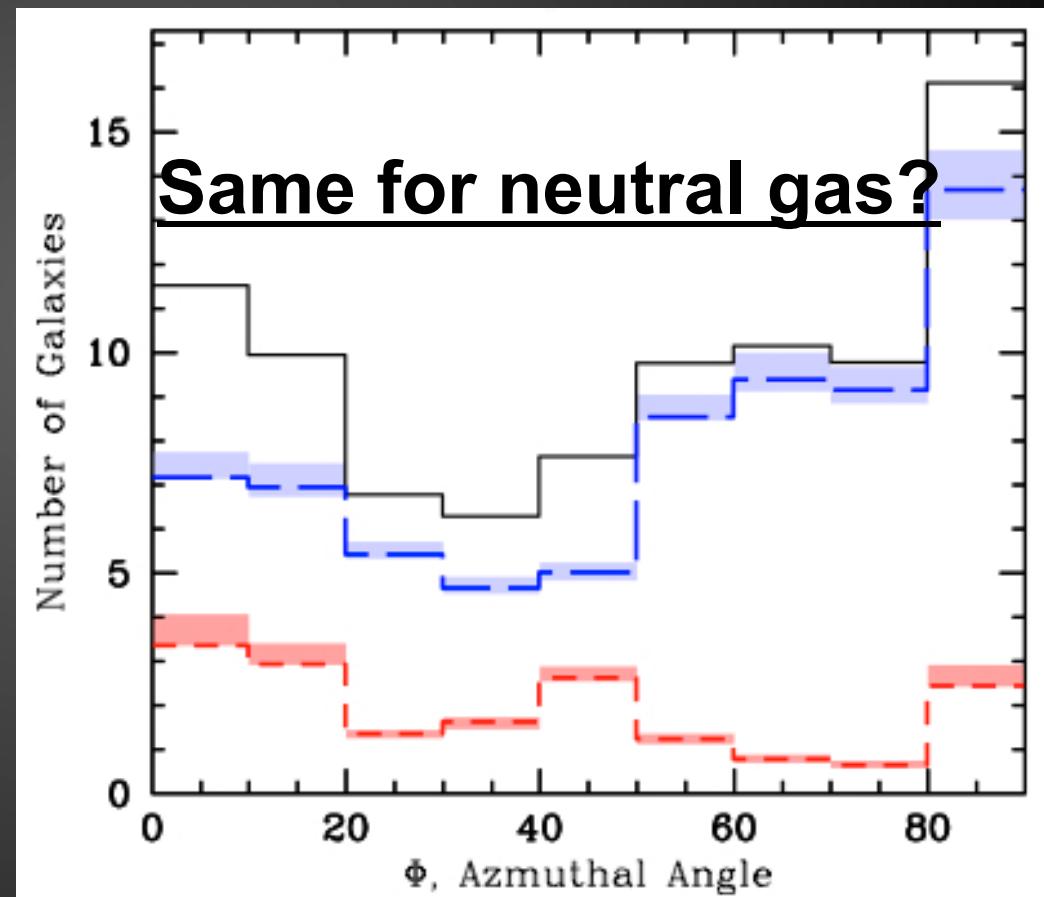
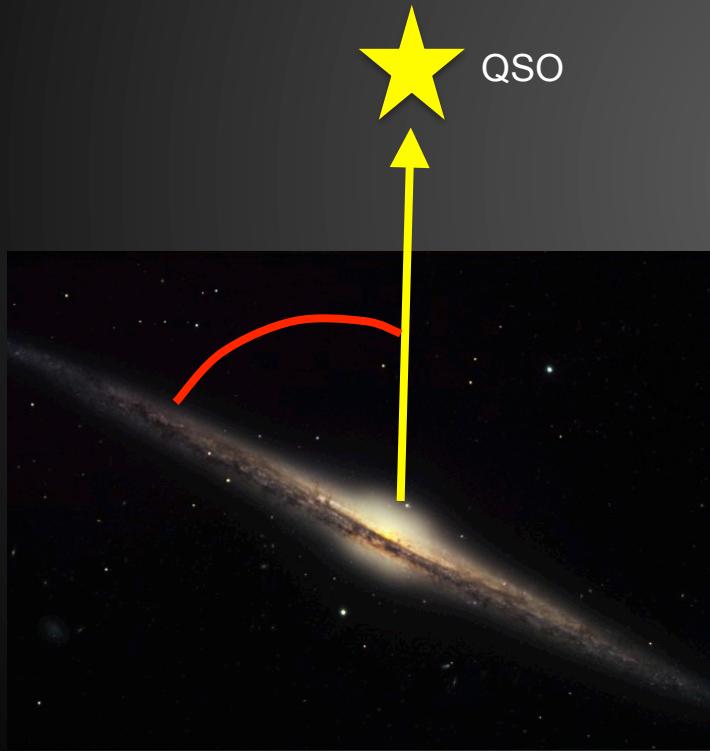


Credit: Bruce Hugo & Leslie Gaul, Adam Block, NOAO, AURA, NSF

Kacprzak et al. 2012

How do CGM gas properties depend on galaxy orientation?

- *Major vs minor?*

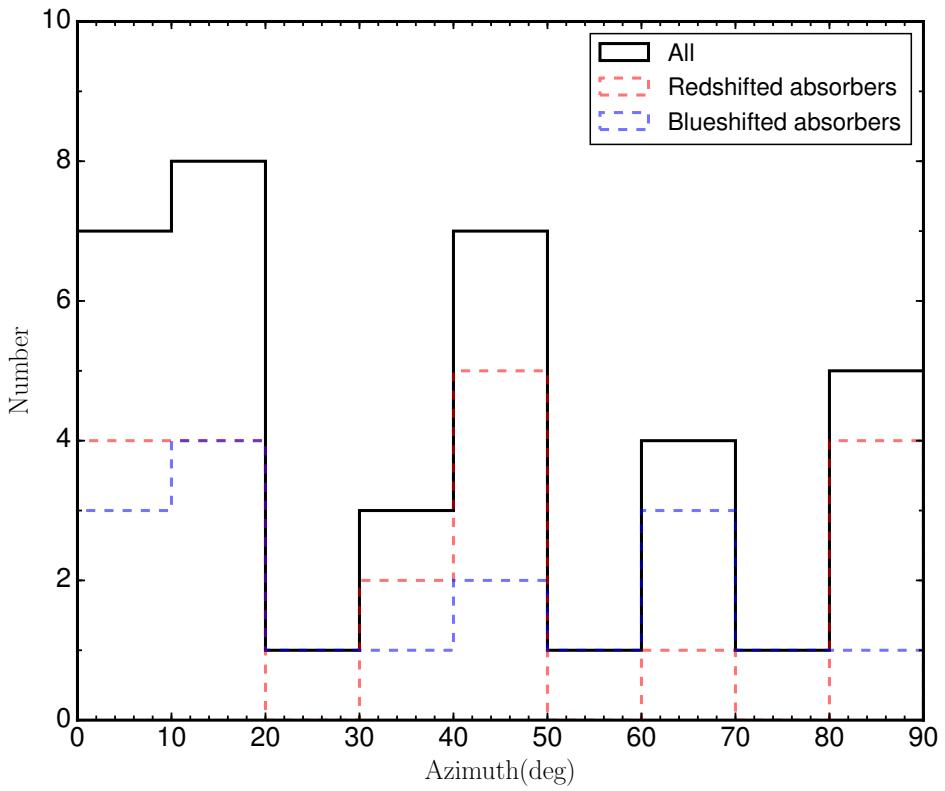


Credit: Bruce Hugo & Leslie Gaul, Adam Block, NOAO, AURA, NSF

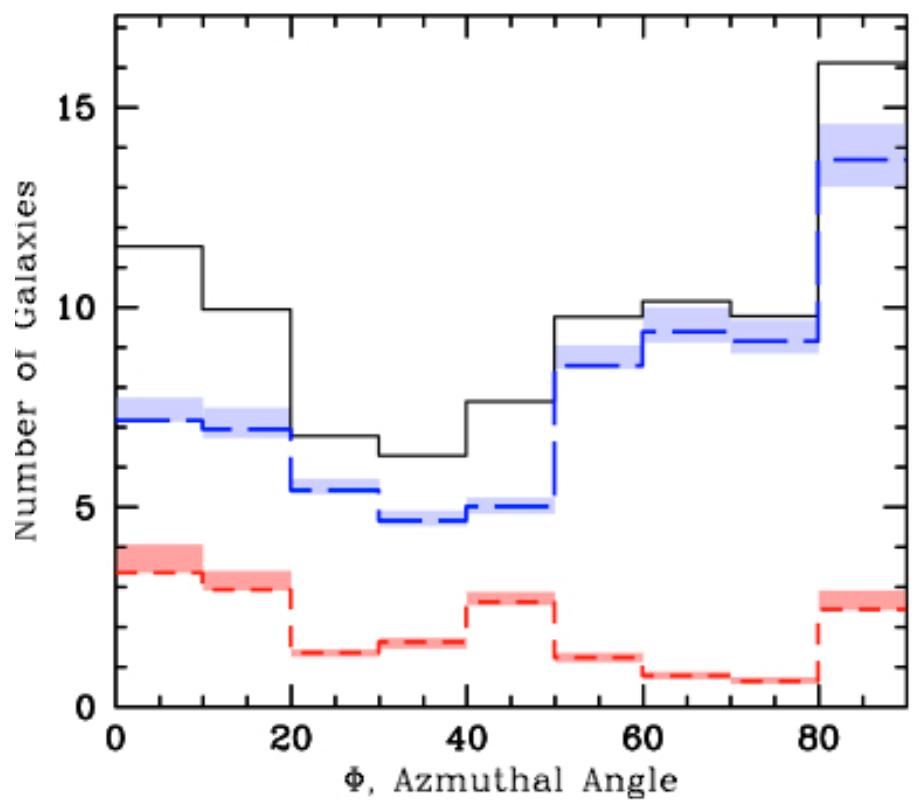
Kacprzak et al. 2012

How do CGM gas properties depend on galaxy orientation?

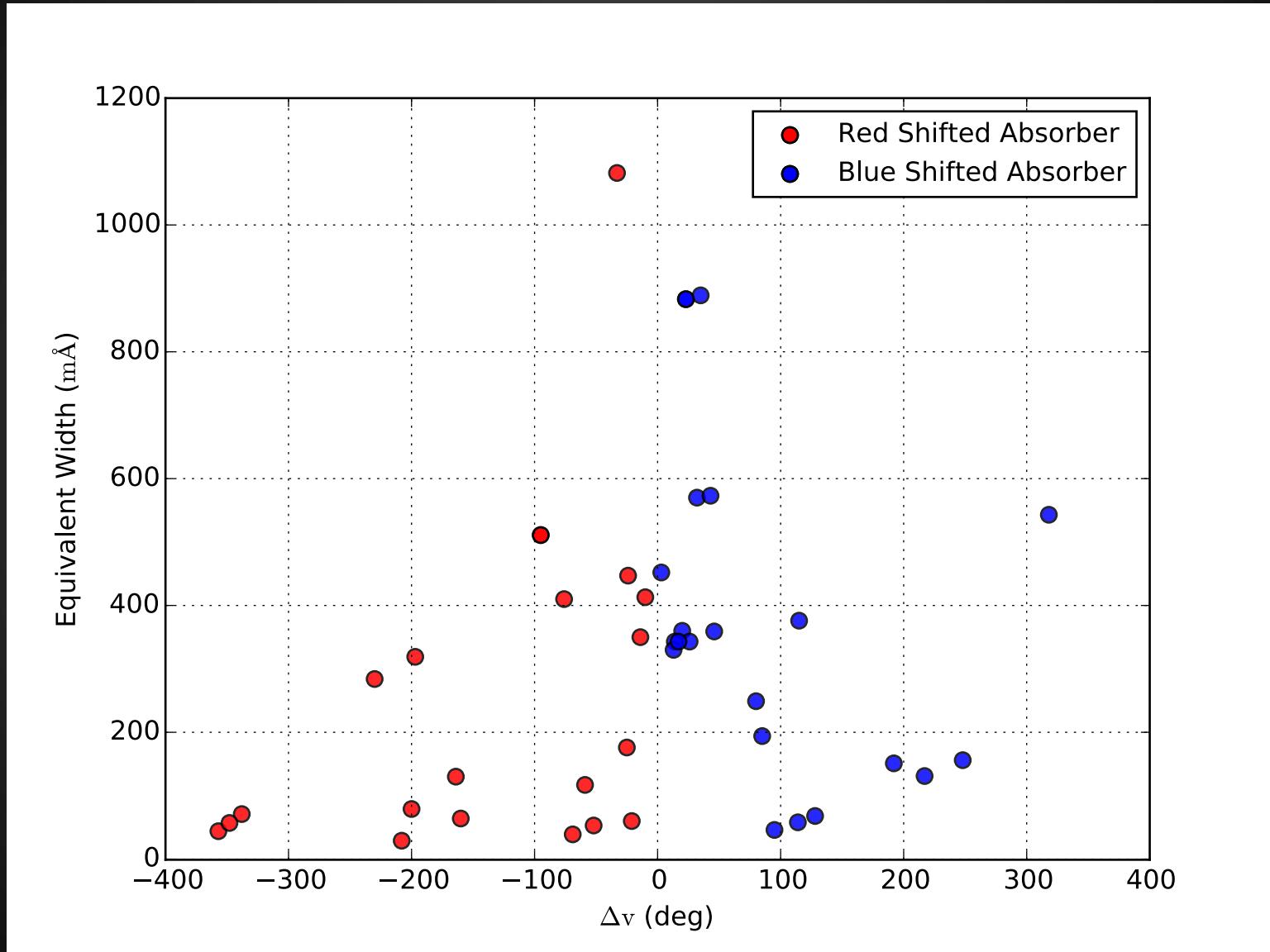
Lya



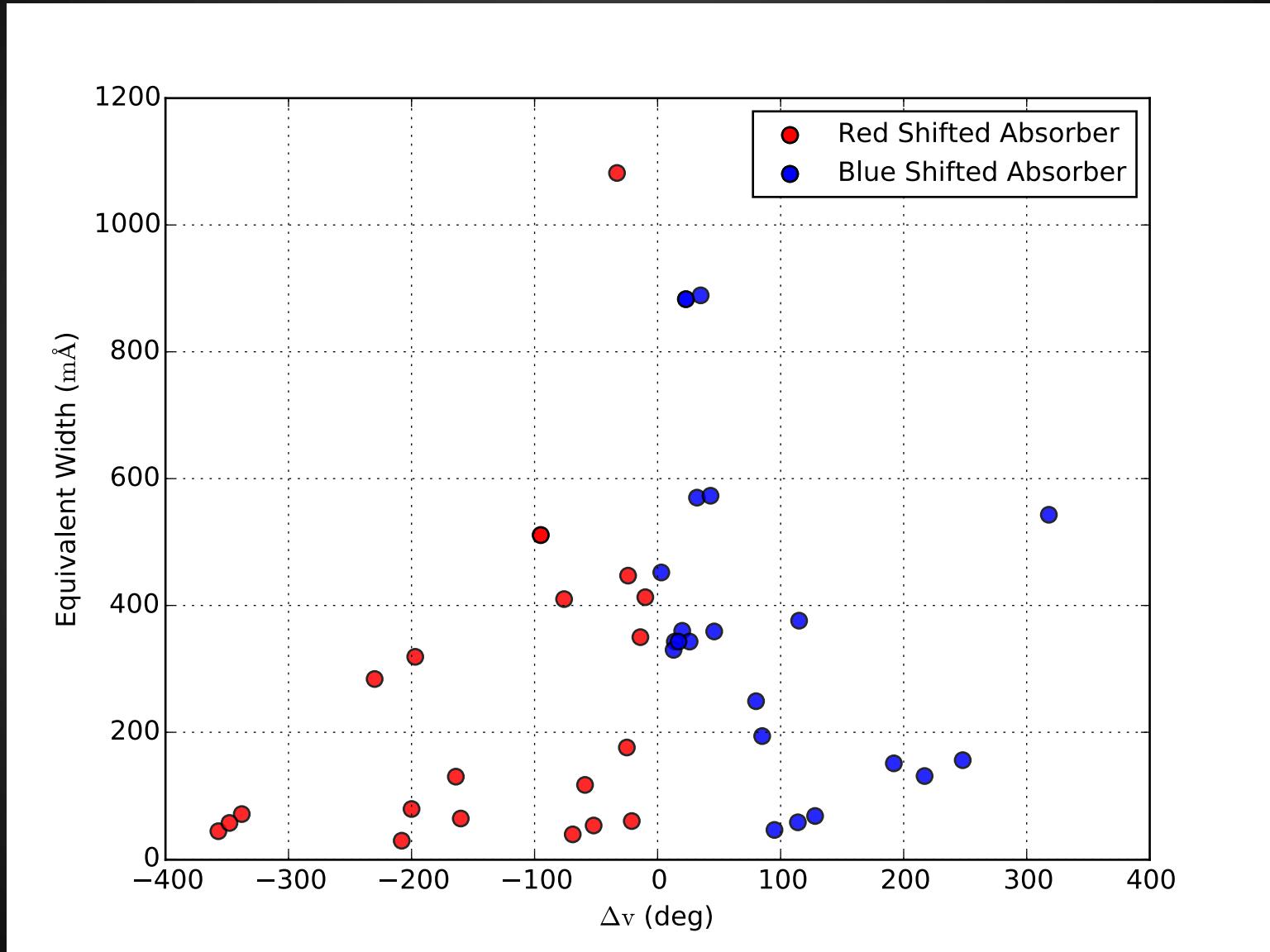
MgII



EW vs Δv

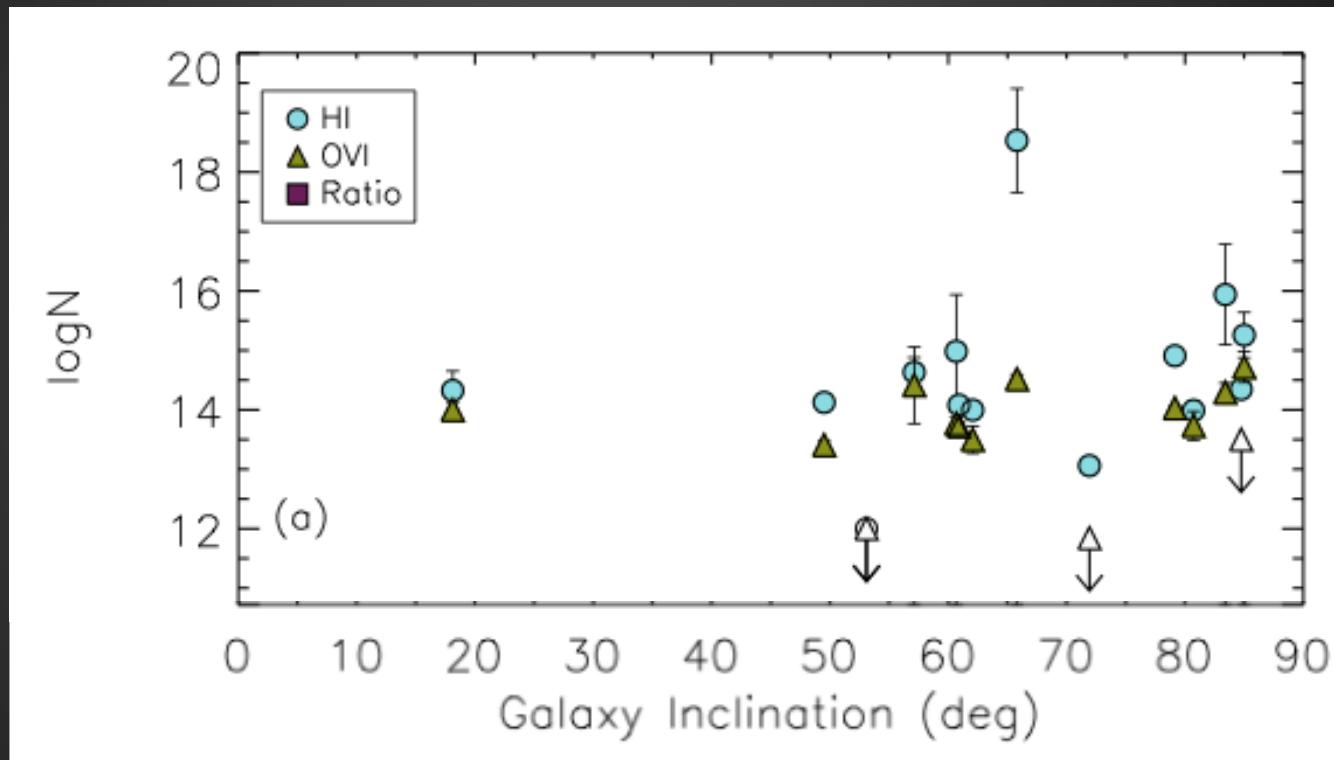


EW vs Δv



How do CGM gas properties depend on galaxy inclination?

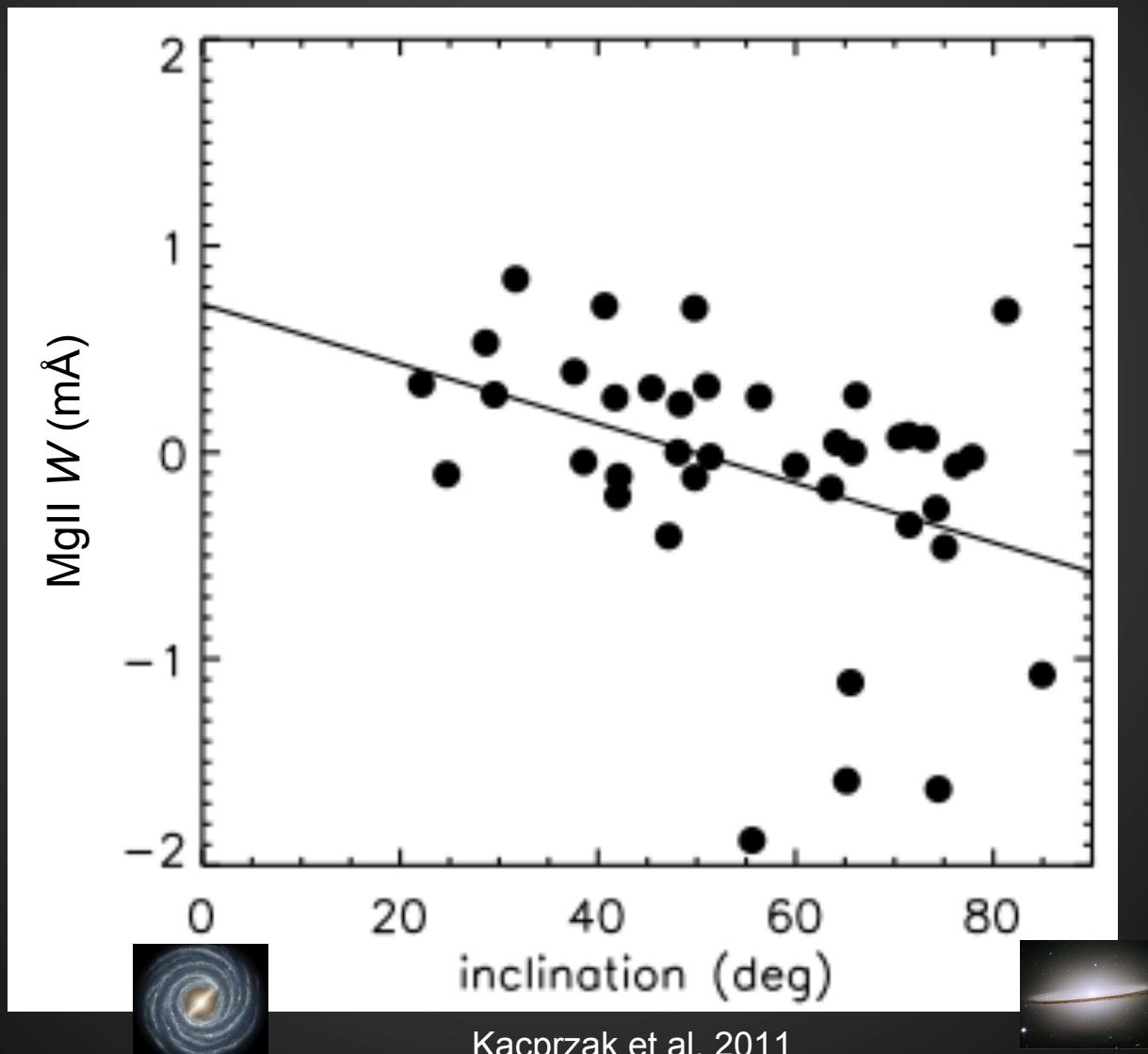
No?



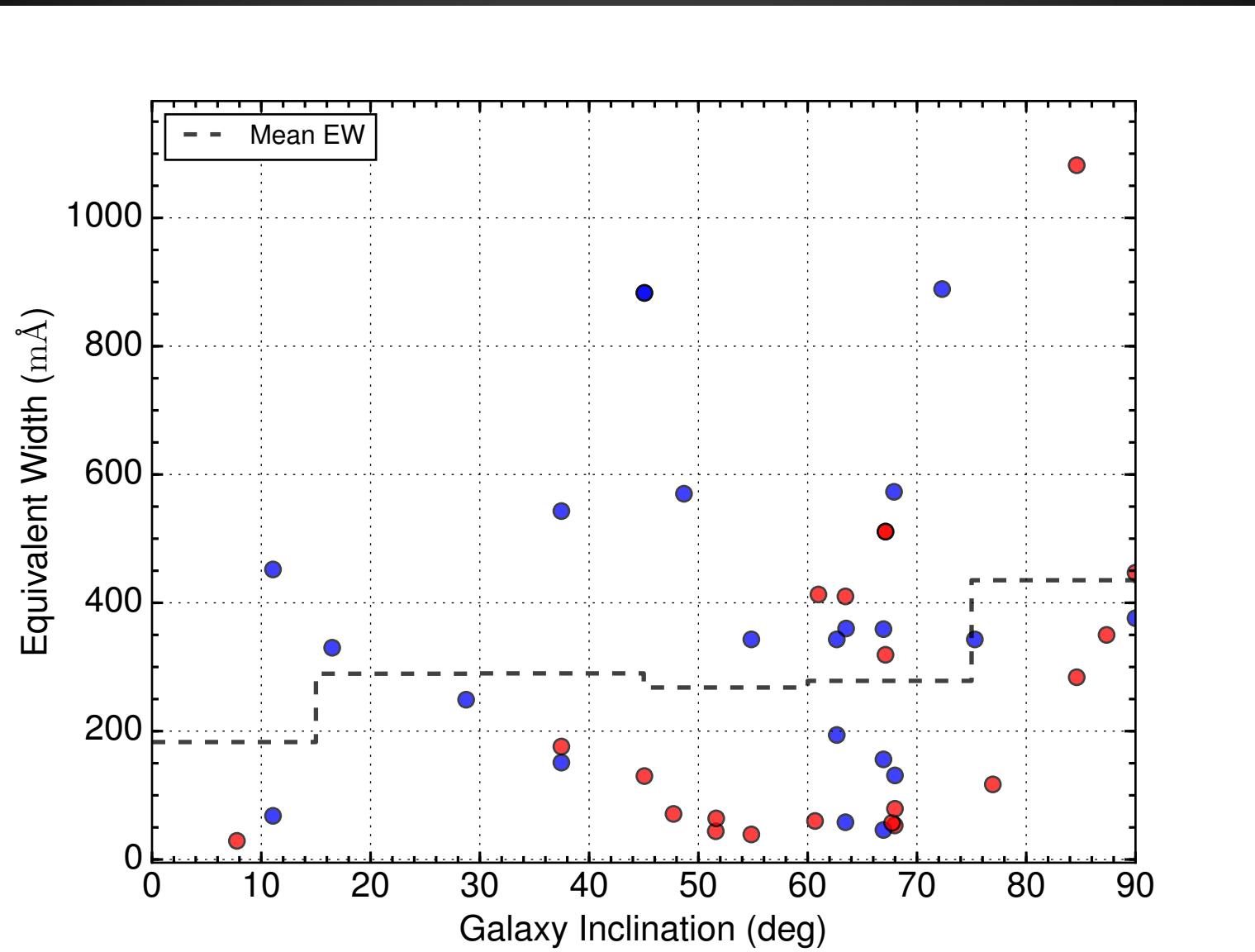
Mathes et al. 2014

How do CGM gas properties depend on galaxy inclination?

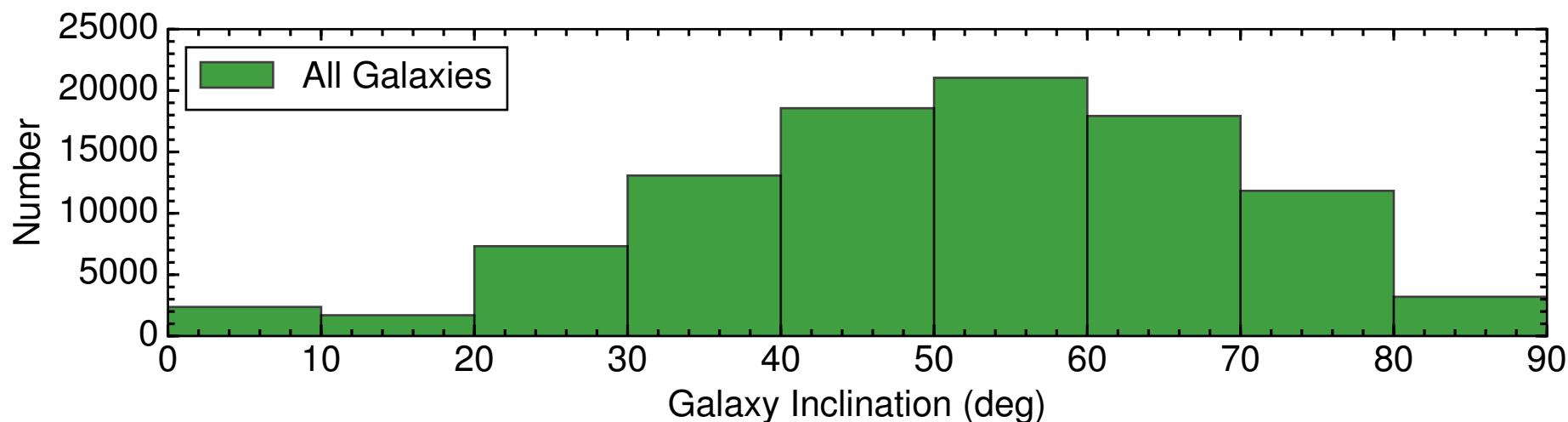
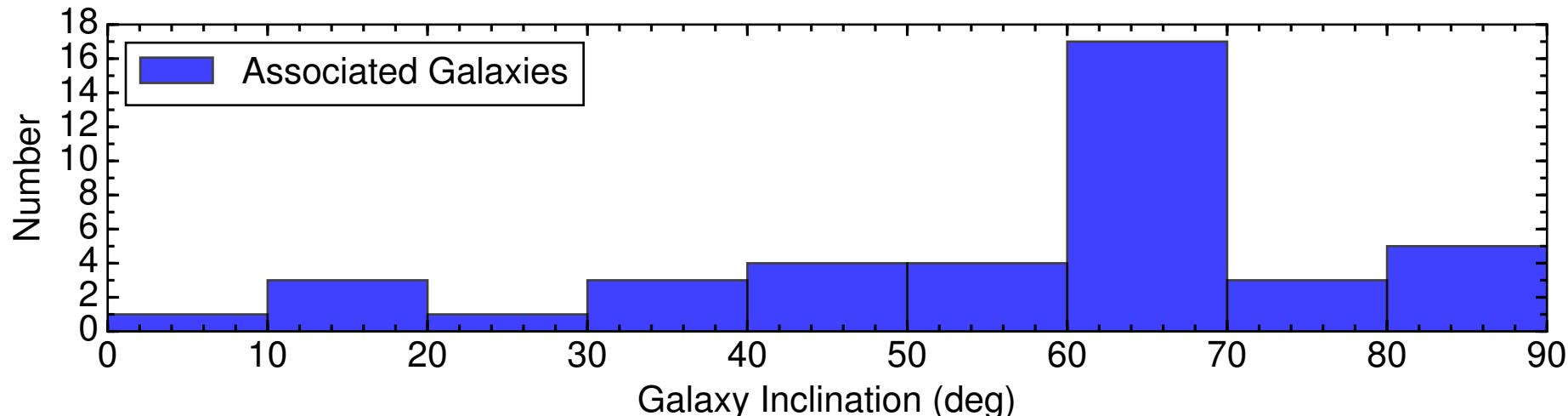
Maybe?



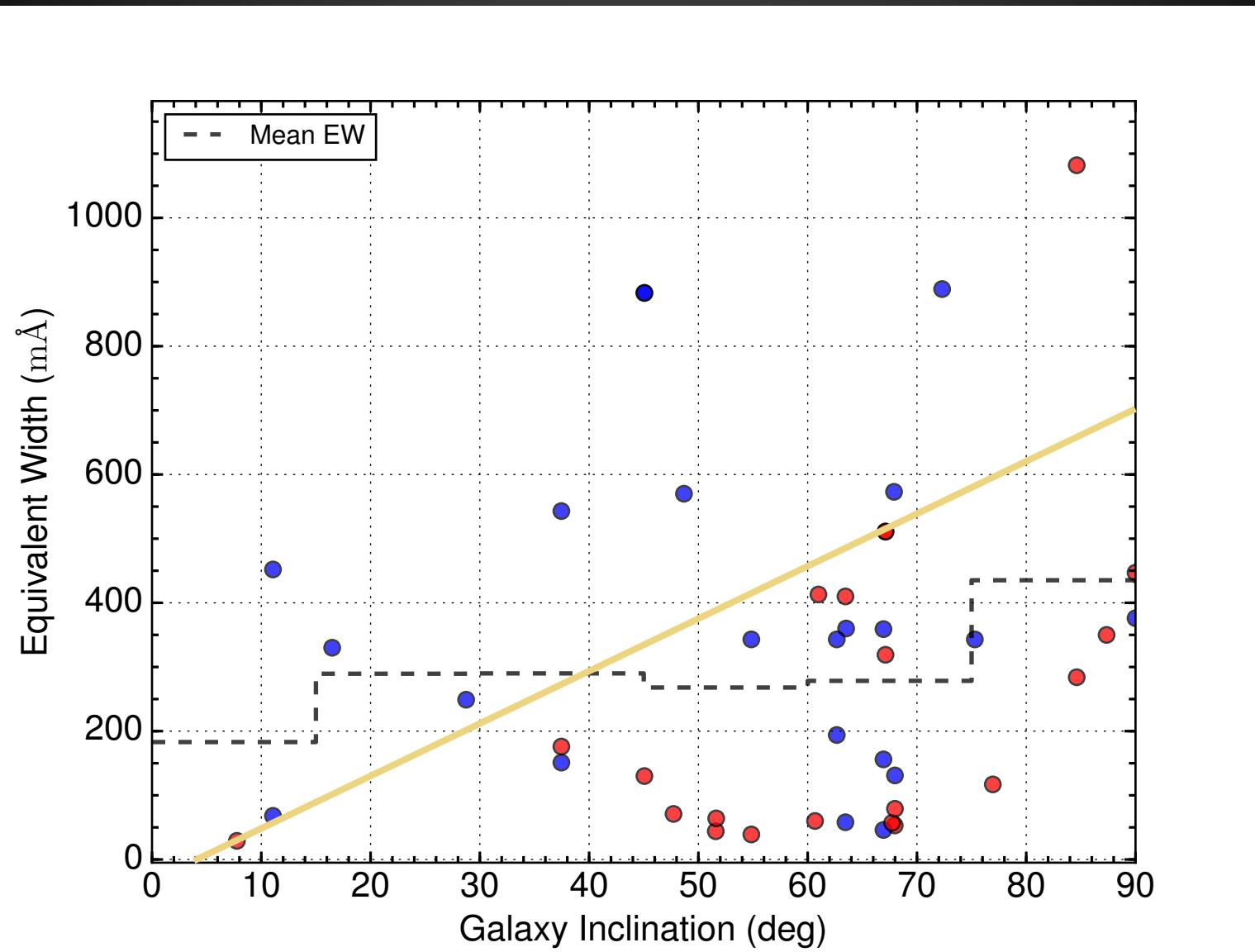
Galaxy Inclination



Galaxy Inclination



EW dichotomy



EW dichotomy

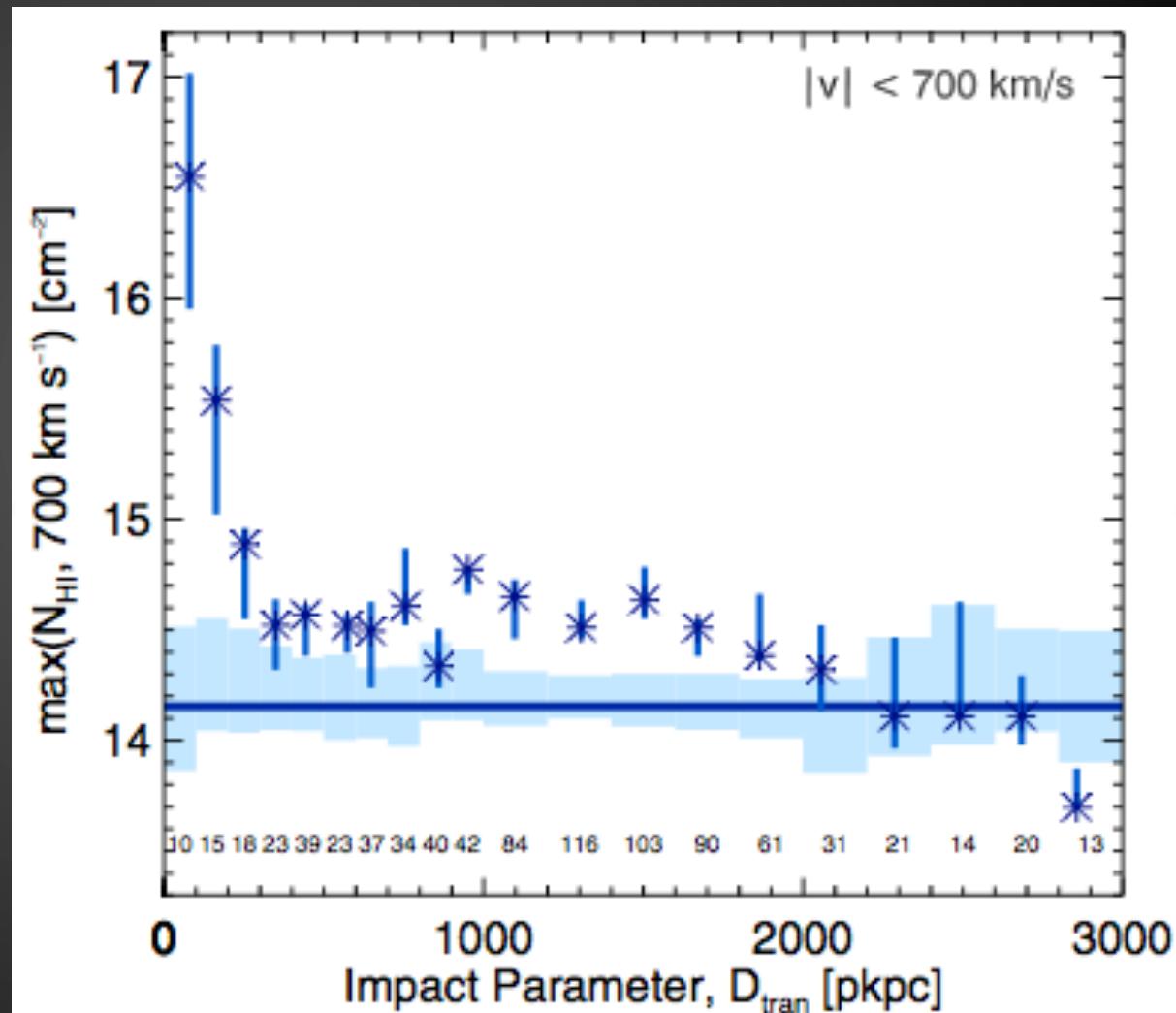
- Median EW(blueshifted) = $343 \pm 10 \text{ m}\text{\AA}$
- Median EW(redshifted) = $124 \pm 9 \text{ m}\text{\AA}$
- The difference: KS p-value = 0.04

Summary:

- Define likelihood – a reproducible method for associating absorption with nearby galaxies
- EW – Impact parameter anti-correlation with R_{vir}
- Absorbers are more common near highly inclined galaxies
- Absorbers most commonly found near $R \sim 1.25 R_{vir}$
- Azimuth dependence is unclear
- Median EW increases with decreasing Δv
- Redshifted absorption weaker than blueshifted?

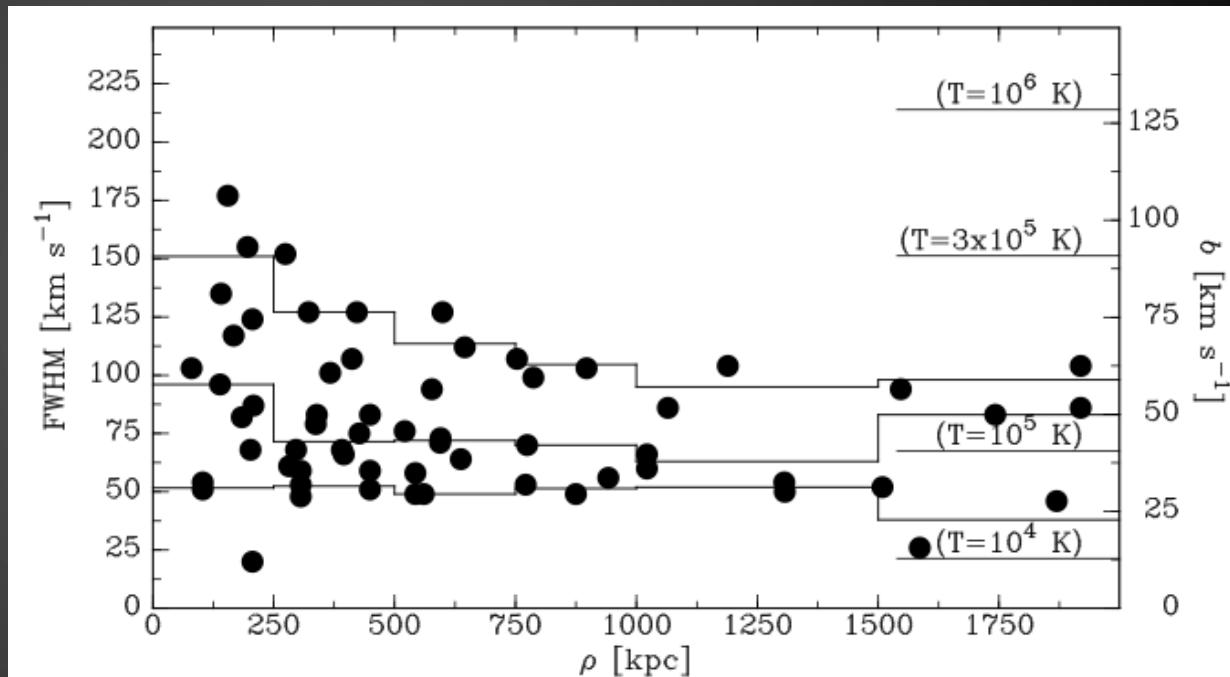
What is the influence of nearby galaxies on the CGM gas properties?

- Rudie et al. 2012 find elevated N_{HI} out to 2 Mpc from galaxies at $z = 2$
- Other groups measure larger Ly α equivalent widths closer to galaxies



What is the influence of nearby galaxies on the CGM gas properties?

- Wakker & Savage 2009 find Ly α FWHM anti-correlates with impact parameter at $z = 0.015$
- Cause?
- Galaxy properties?



Wakker, B.P., Savage, B.D., 2009, ApJS, 182, 378

Increasing the sample size

- 300+ archival COS quasar sightlines
- Redshift limit: $cz = 10,000$ km/s
 - *Faint galaxies:*
 - 97% of absorbers found within 400 kpc of a $0.1L^*$ galaxy in nearby Universe (Wakker & Savage 2009)

Increasing the sample size

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- Redshift limit: $cz = 10,000$ km/s
 - *Faint galaxies:*
 - 97% of absorbers found within 400 kpc of a $0.1L^*$ galaxy in nearby Universe (Wakker & Savage 2009)
- Better statistics: 400+ galaxy - absorber systems
- Search for all absorber systems within 400 km/s and 2 Mpc of galaxies, and vice-versa

Search around galaxies first

- Search for galaxies around absorbers, or absorbers around galaxies?
- Wakker & Savage (2009):
 - 50% of absorbers have galaxies within 400 kpc
 - 97% of galaxies have absorbers within 400 kpc
- Need a dataset of ALL galaxies within survey volume

Compiling a galaxy dataset

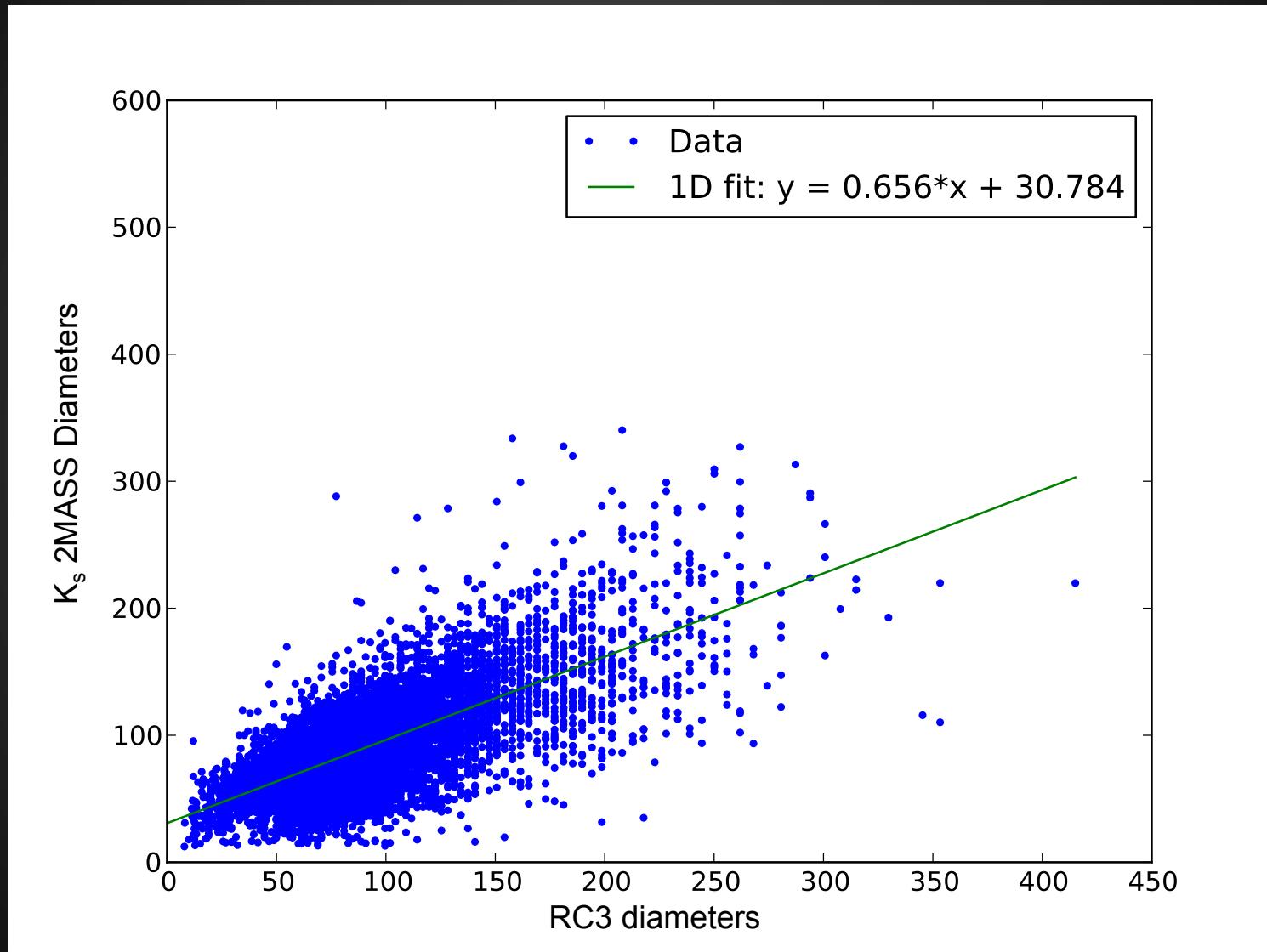
- The NASA Extragalactic Database (NED)
 - Over 100,000 galaxies with $cz < 10,000$ km/s
 - Includes SDSS, 2MASS, 2dF, 6dF, and many smaller datasets
- I have obtained:
 - positions
 - redshifts
 - diameters
 - morphology
 - redshift-independent distance
 - inclination
 - position angle
 - photometry
 - etc...
 - *Homogenize data*

Compiling a galaxy dataset

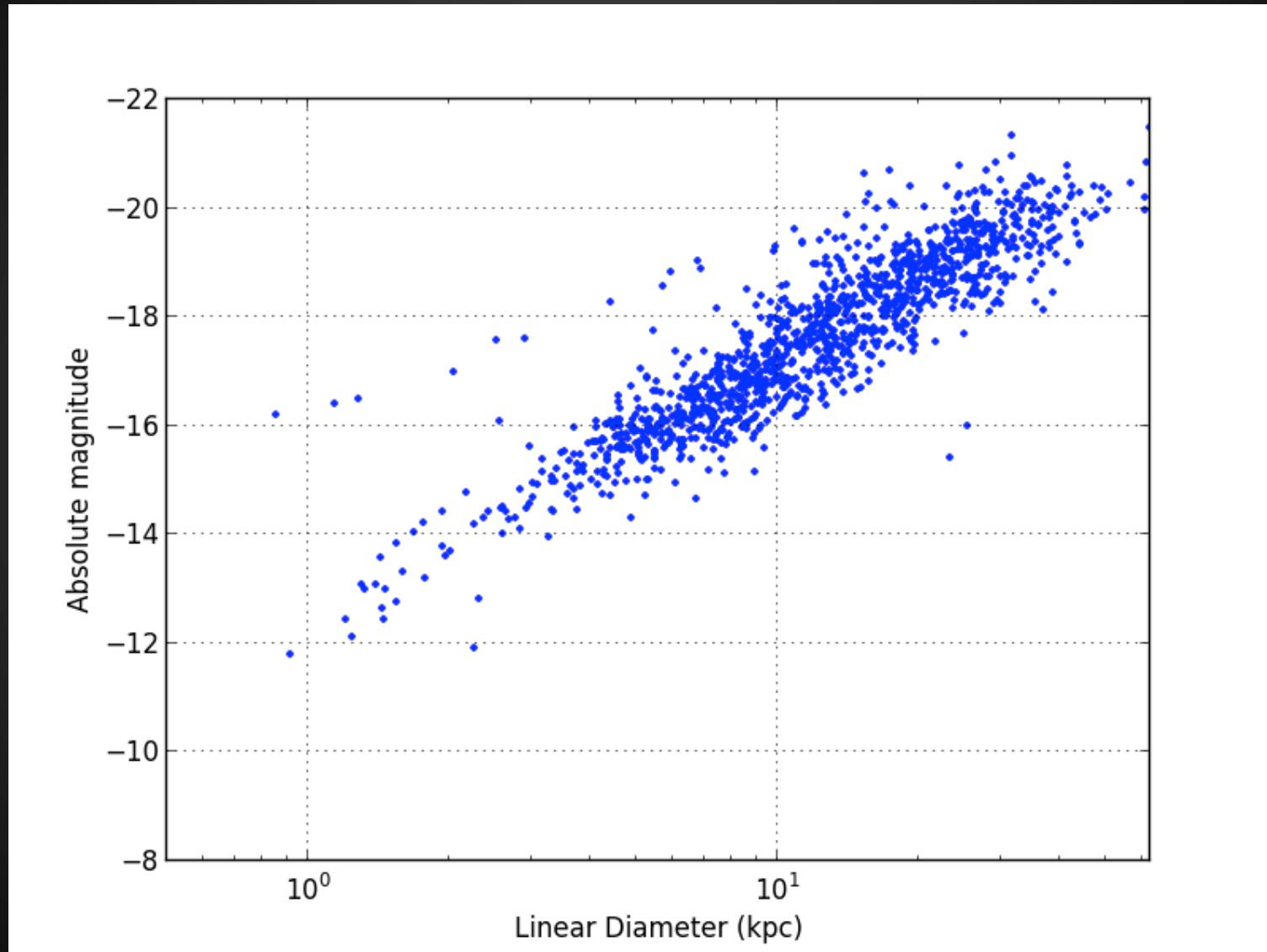
Homogenize data:

- Normalize diameters to 2MASS values
- Compute L/L_* ratios based on photometry

Ex: Normalize diameters to 2MASS



Ex: Magnitude - Diameter Relation



Additional Observations

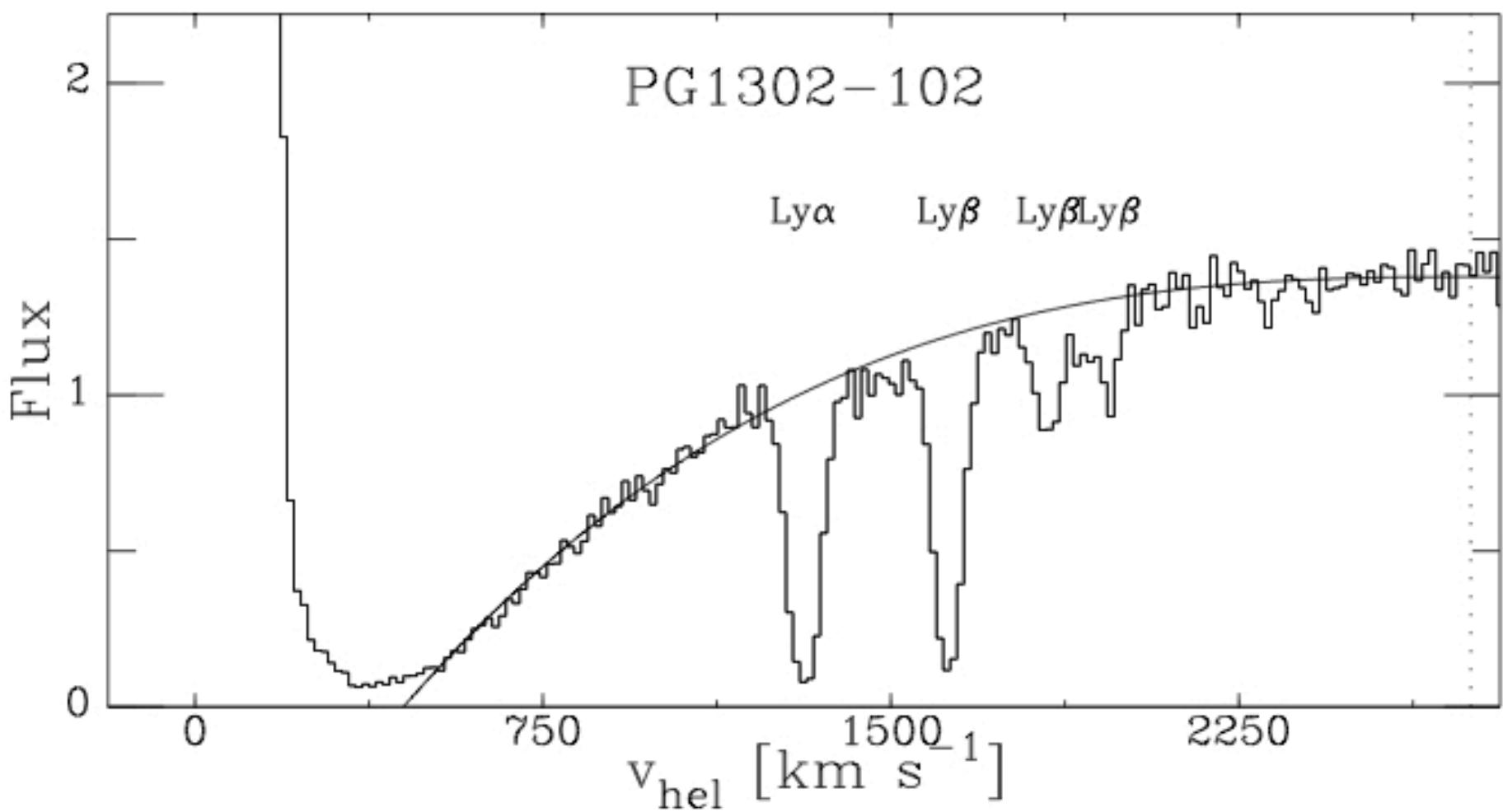
Solving the absorber-galaxy rotation problem:

- Obtain galaxy rotation velocities with WIYN and SALT
 - ~400 galaxies * 0.1 highly inclined ($>70^\circ$) = 40 targets
- MaNGA & ASKAP – WALLABY (Wakker – Col)
 - ~1100 MaNGA galaxies within 2 Mpc of a COS sightline
 - WALLABY will map the 21cm sky out to $cz = 60,000$ km/s, providing rotation curves for all galaxies with dec $<30^\circ$

Pilot Study

- 35 COS sightlines within 500 kpc of large galaxies
- 154 Ly α systems:
 - 32% unambiguous galaxy pairings
 - 51% are 500 kpc or 400 km/s away from a galaxy
 - The remainder are ambiguous associations

PG1302-102: Detected Absorption



French et al. in prep

Method

- Measure absorption in the foreground of a bright QSO:

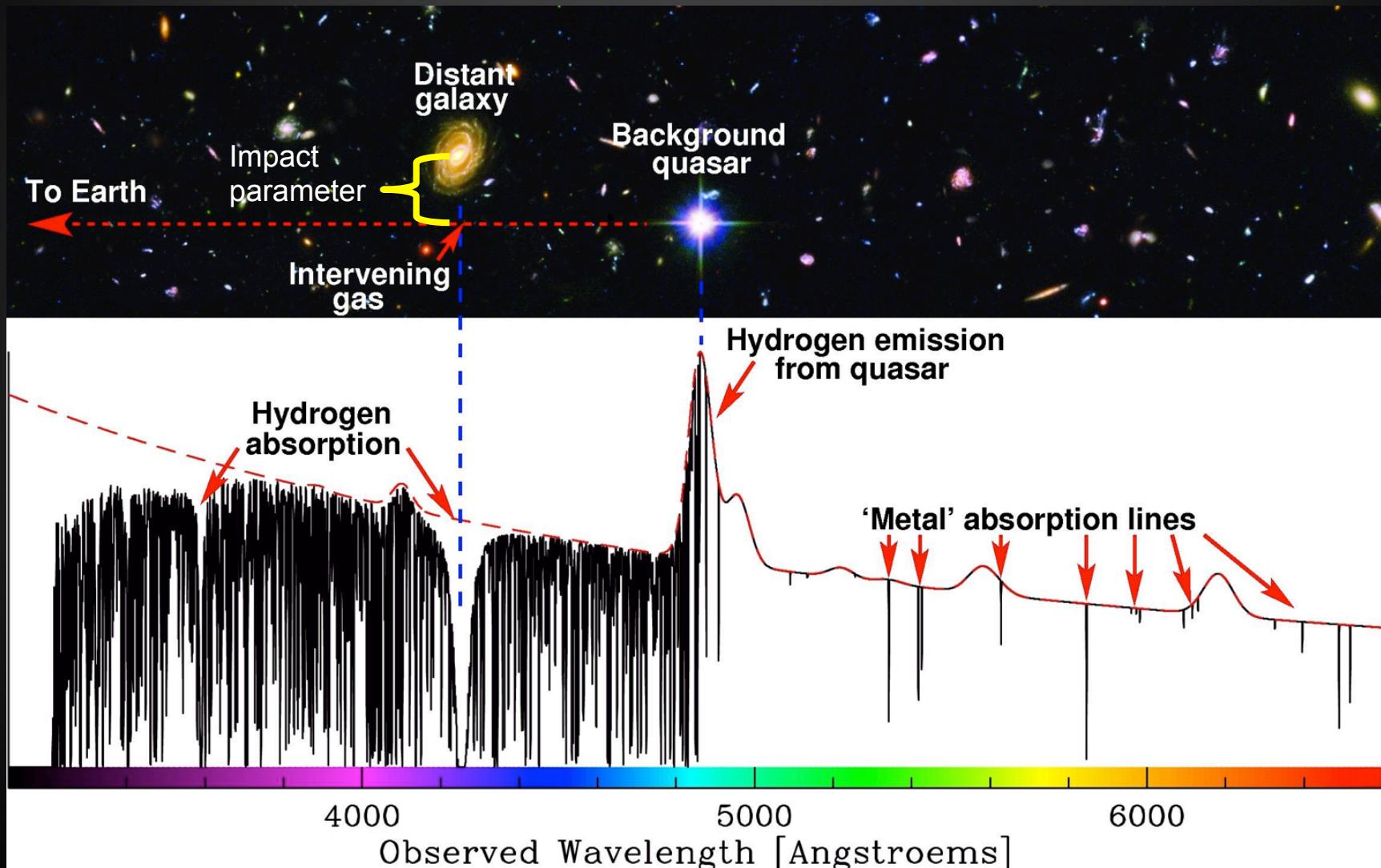
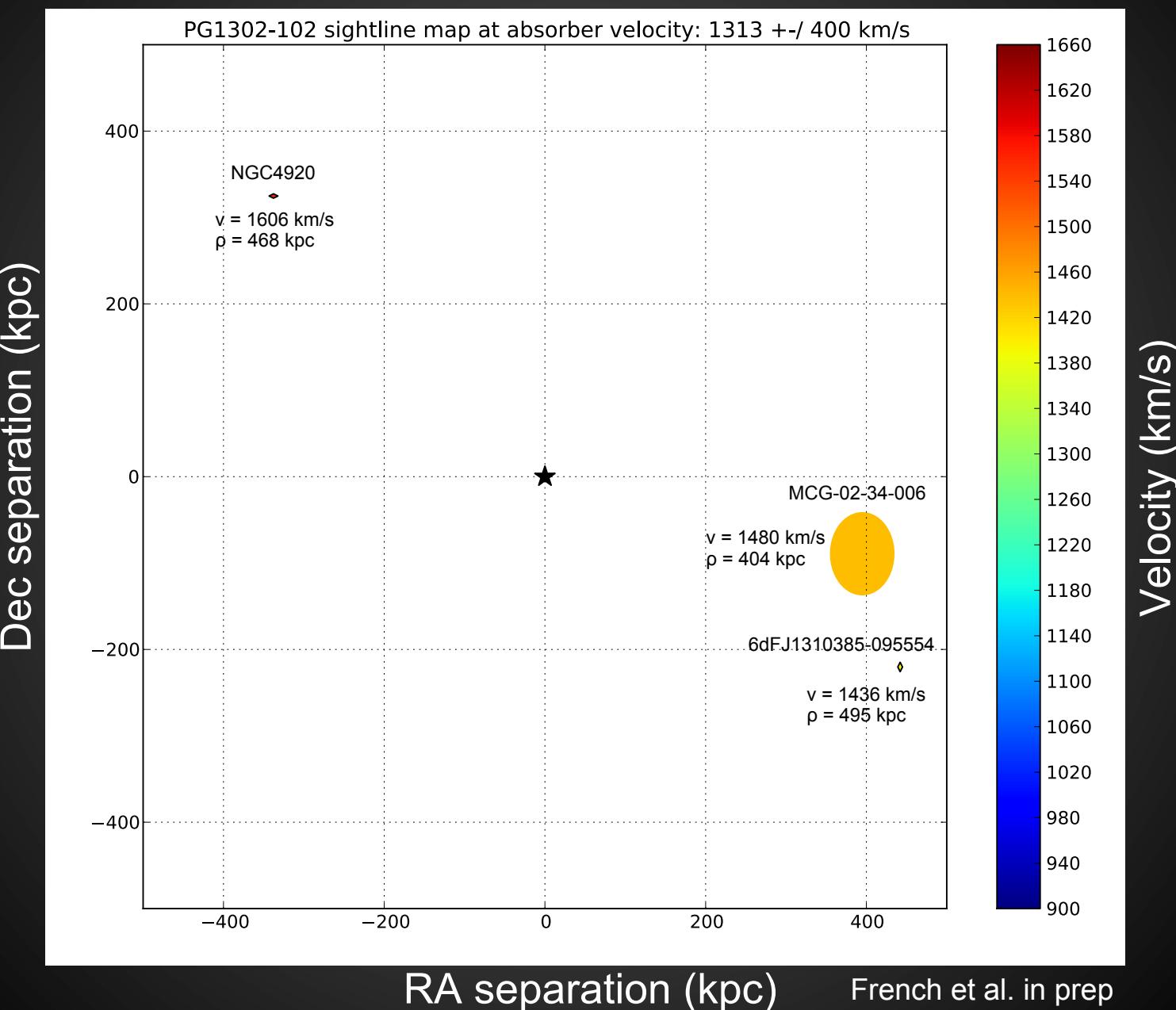


Image Credit: Michael Murphy & ESO

Example: PG1302-102 sightline

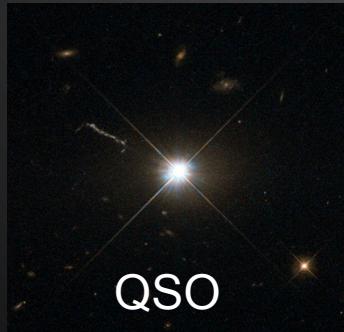


Pilot Study: Azimuth

Question: How does galaxy orientation correlate with detected absorption?



Credit: Bruce
Hugo & Leslie
Gaul, Adam
Block, NOAO,
AURA, NSF



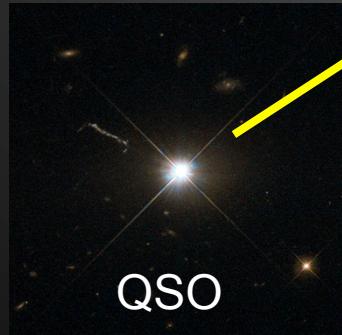
QSO

Credit: ESA/NASA & Hubble

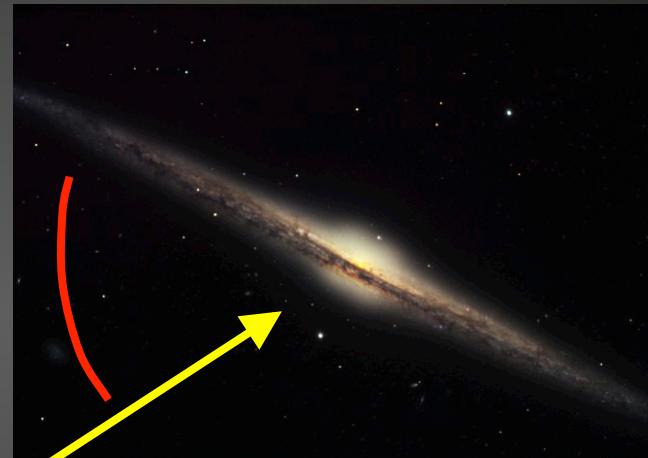
Pilot Study: Azimuth

Question: How does galaxy orientation correlate with detected absorption?

Azimuth =



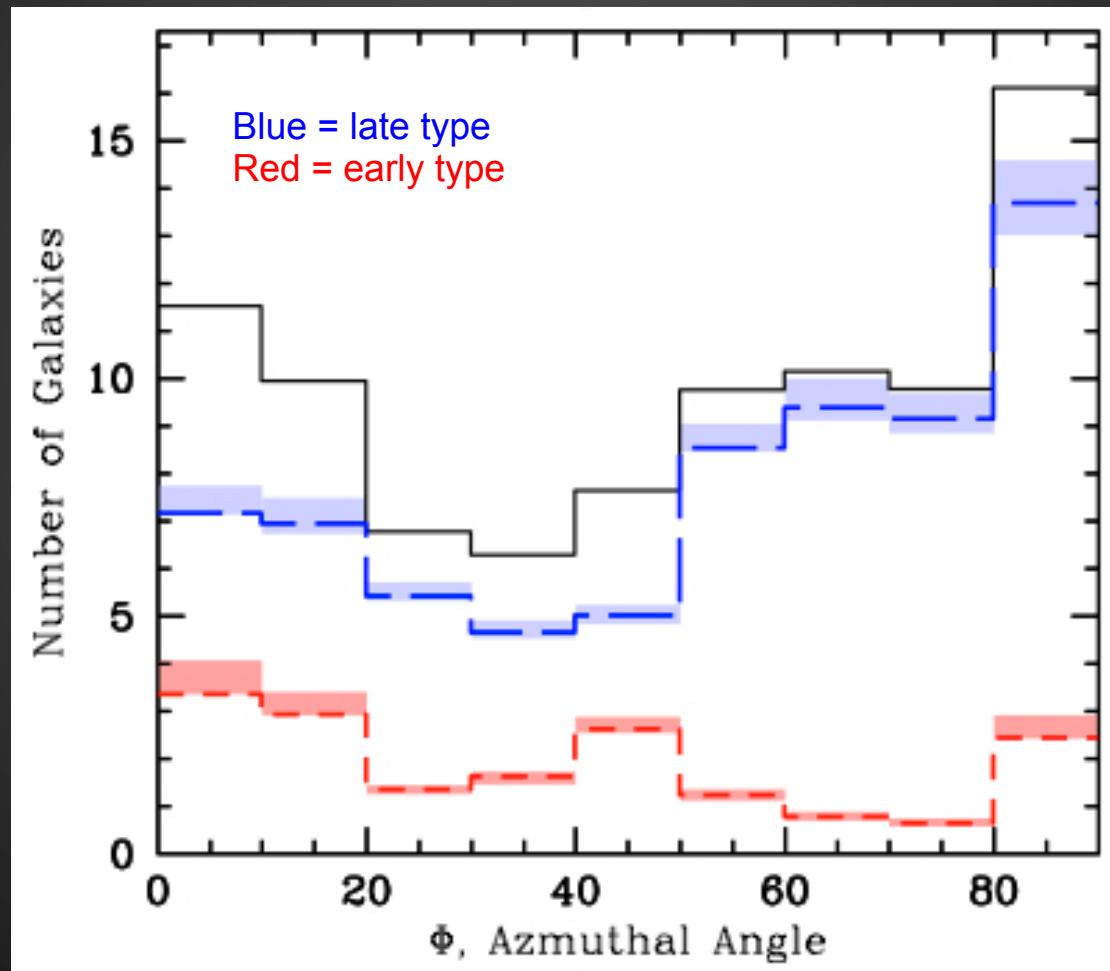
Credit: ESA/NASA & Hubble



Credit: Bruce
Hugo & Leslie
Gaul, Adam
Block, NOAO,
AURA, NSF

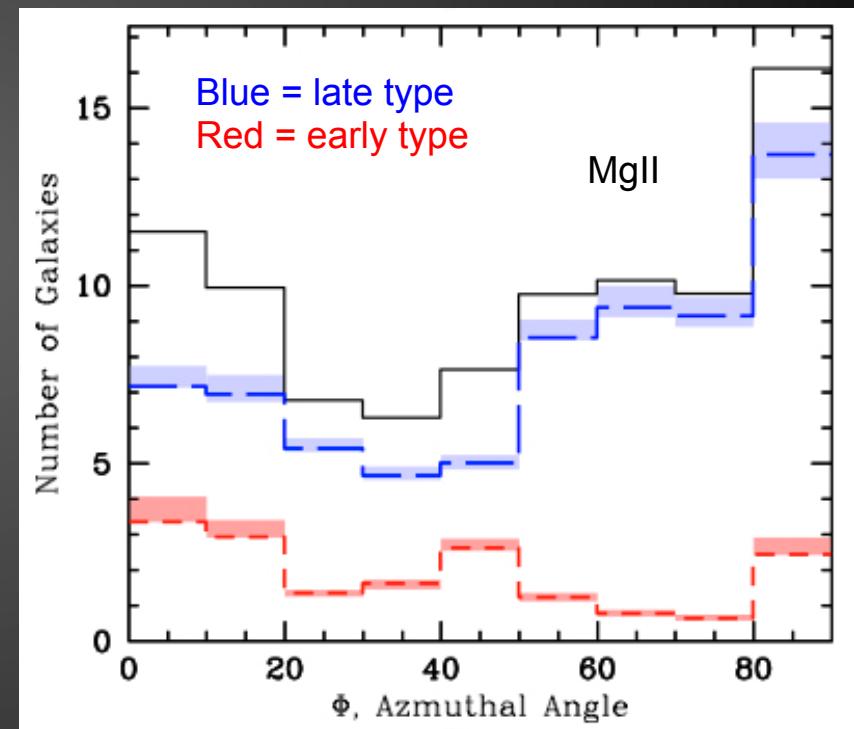
Pilot Study: Azimuth

- Kacprzak et al. 2012 find azimuth dependence:



Pilot Study: Azimuth

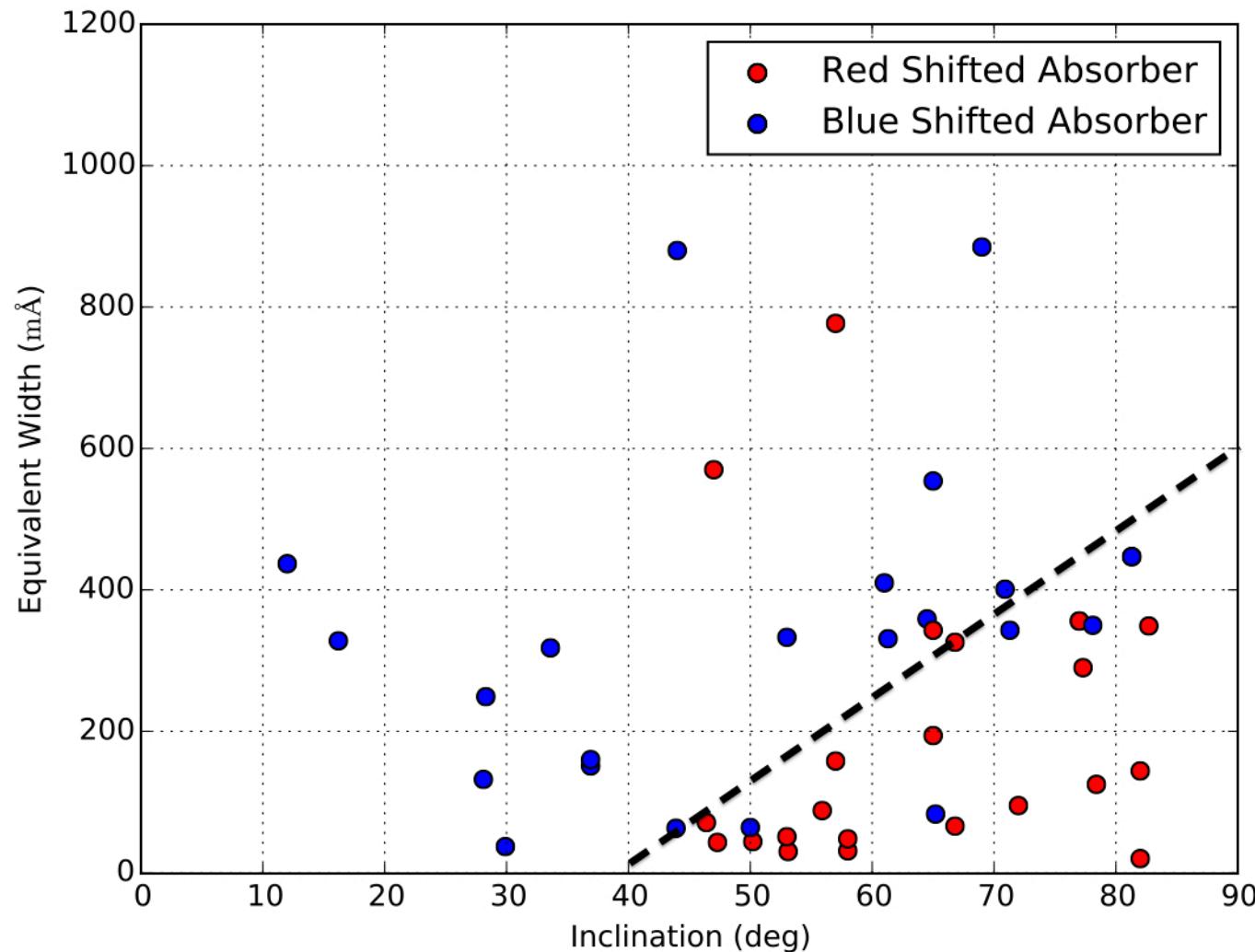
HI \rightarrow Ly α



French & Wakker, in prep

Kacprzak et al. 2012

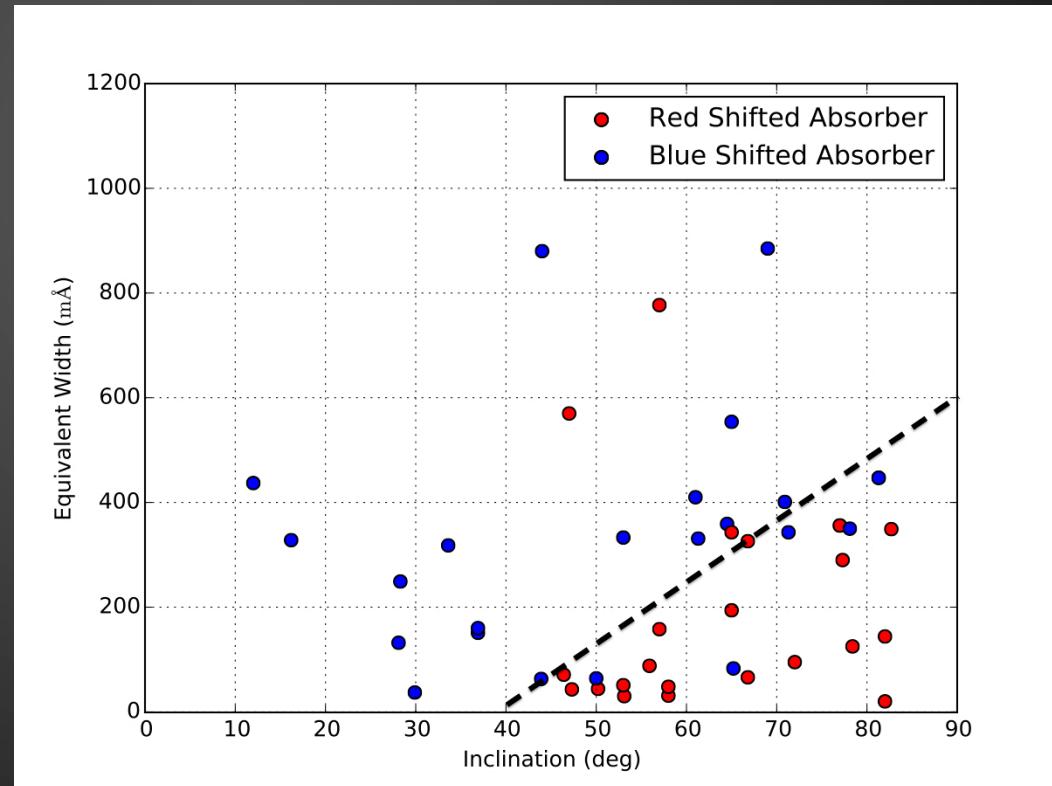
Pilot Study: Inclination



Pilot Study: Inclination

Difference:

- $W(\text{redshifted}) = 192 \pm 10 \text{ m}\text{\AA}$
- $W(\text{blue shifted}) = 366 \pm 14 \text{ m}\text{\AA}$



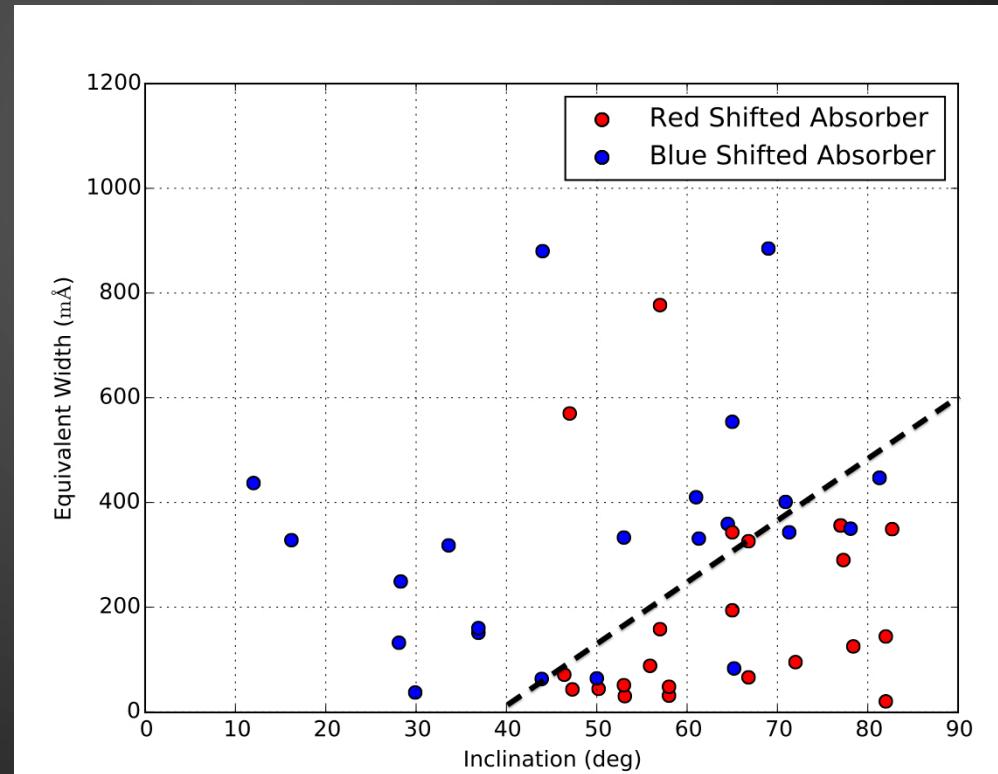
Pilot Study: Inclination

Difference:

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Possible inflows/
outflows?

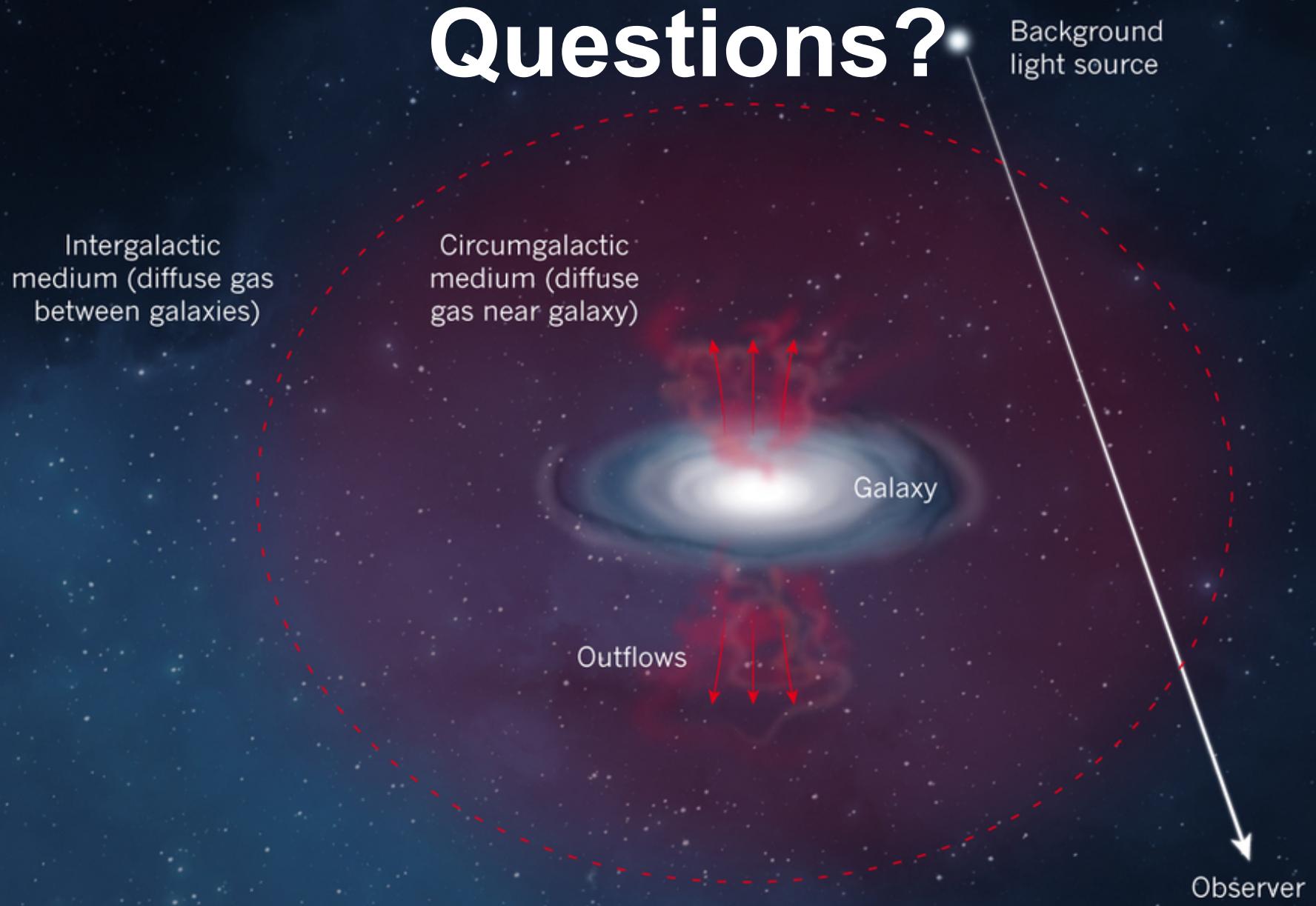
More analysis
needed



Summary

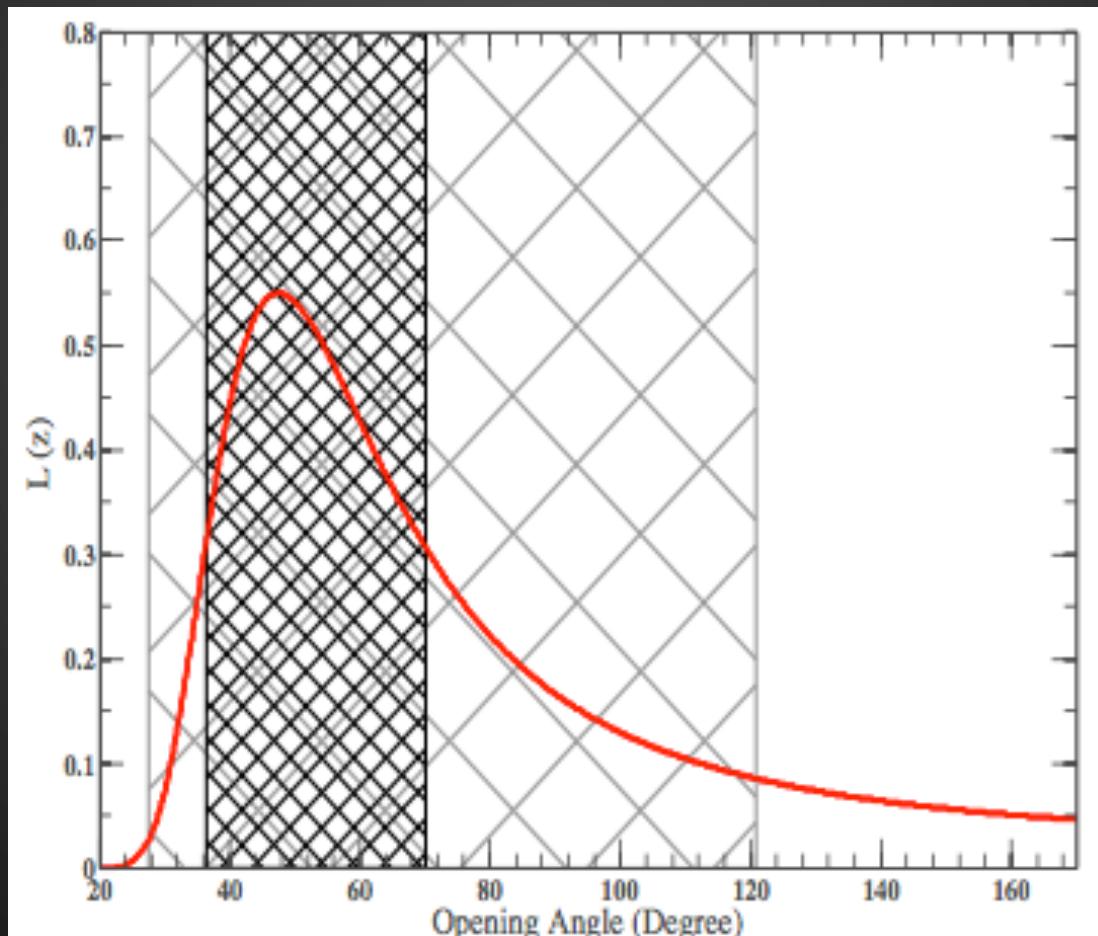
- 300+ archival COS sightlines to background QSOs
- Local galaxy catalog ($cz \leq 10,000$ km/s)
 - Additional WIYN and SALT observations
- Four Questions:
 - Rotation
 - Inclination/orientation
 - Galaxy environment
 - Field vs group
- Largest, most complete survey of the local CGM to date

Questions?



Question 4:

- *How does detected absorption depend on galaxy inclination?*



Method:

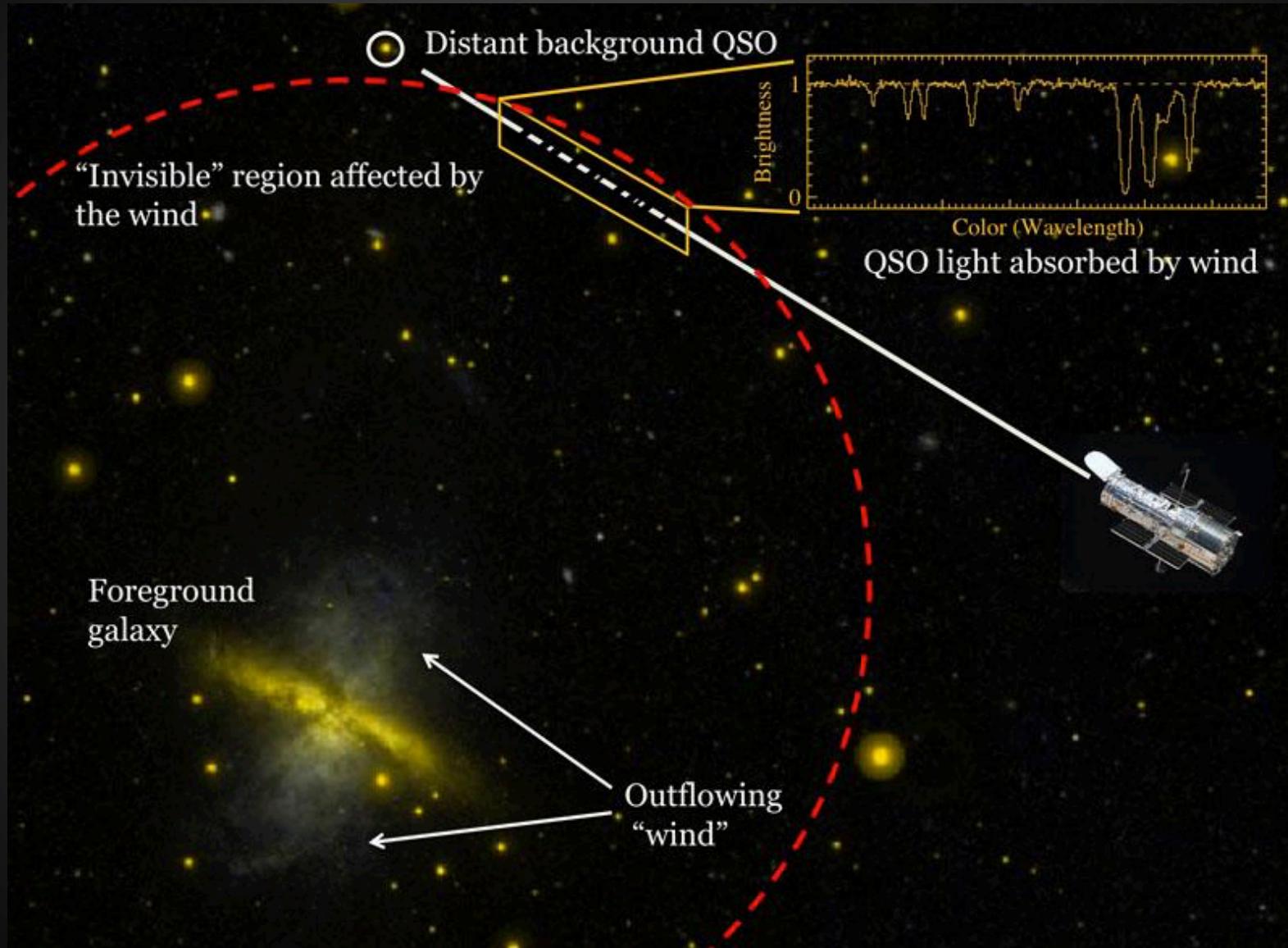
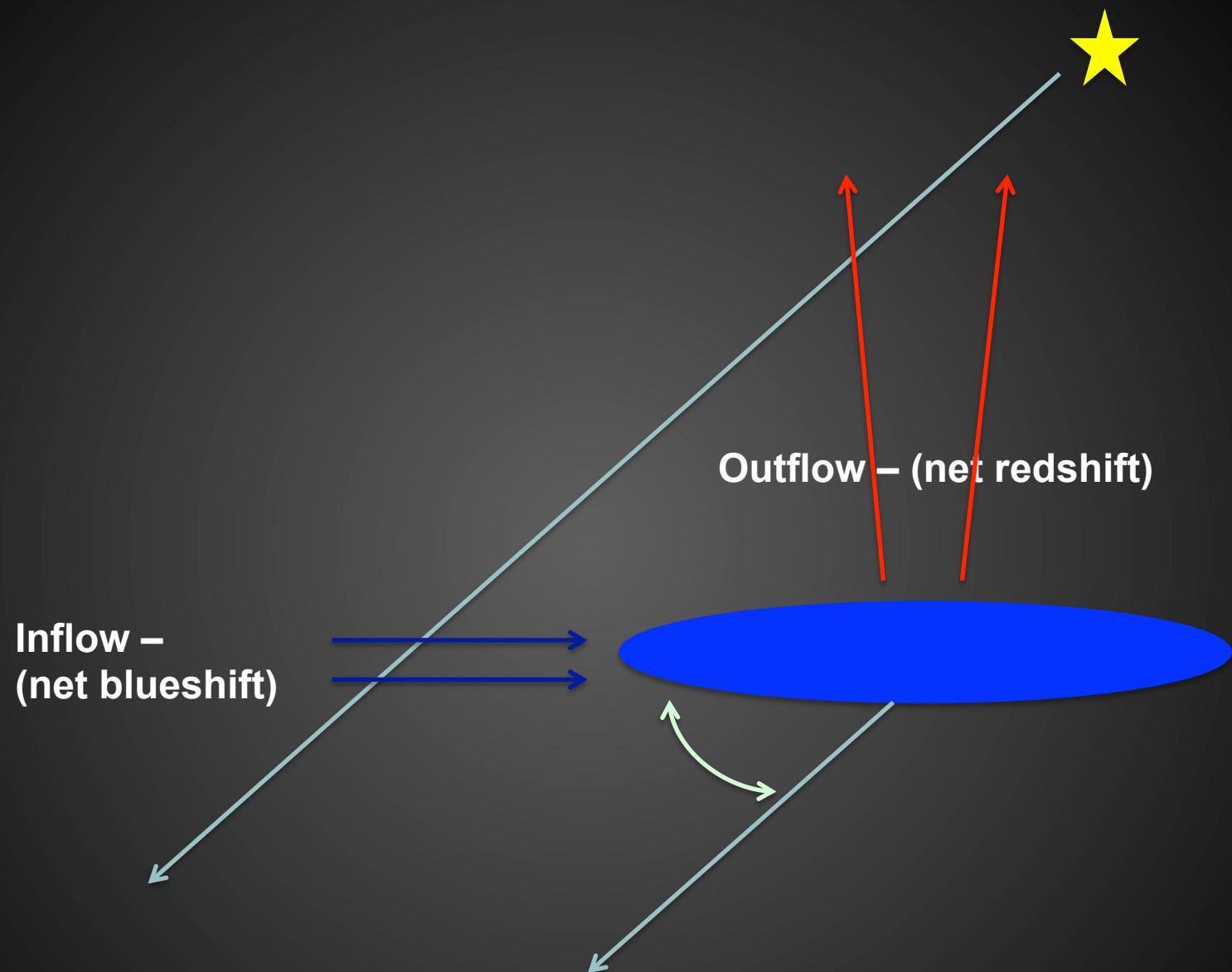
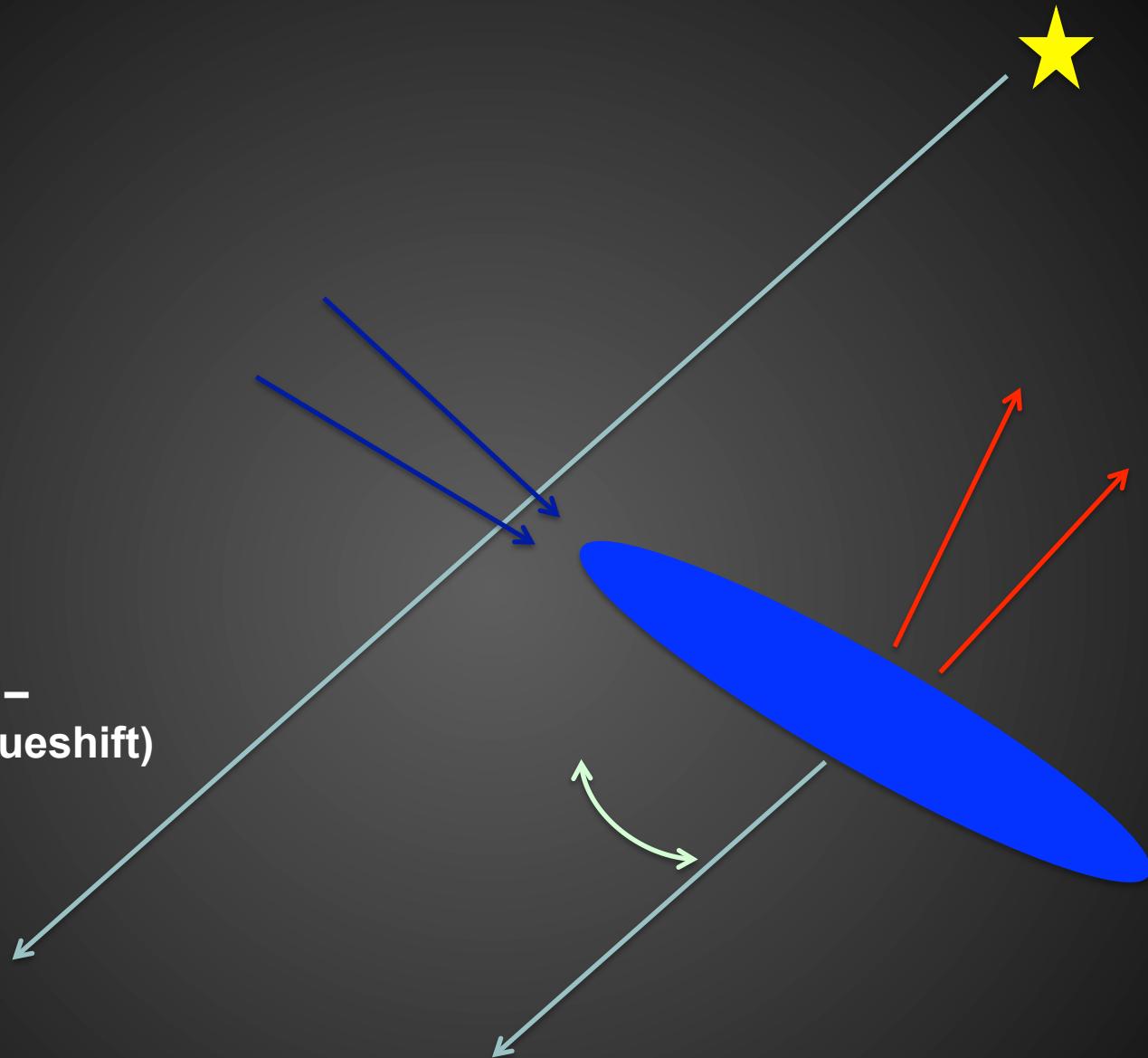


Image Credit: Todd Tripp & NASA GALEX



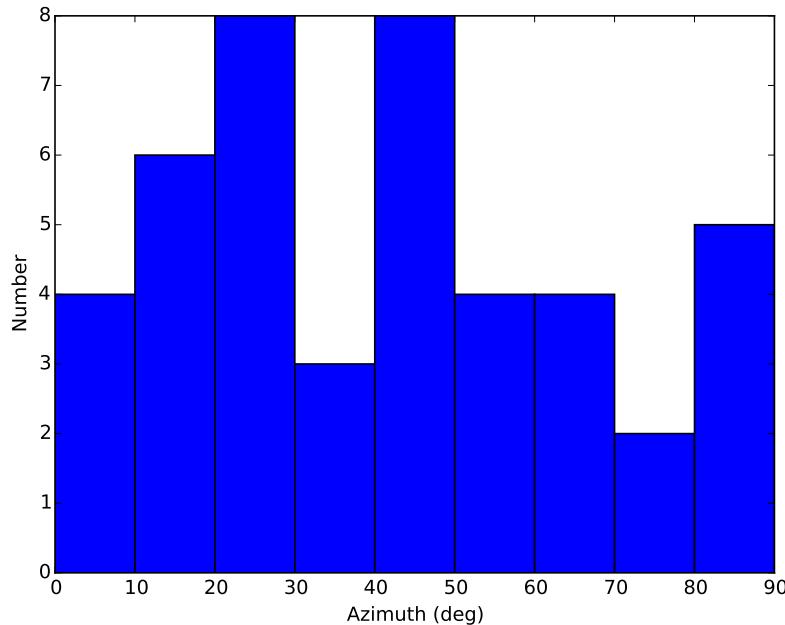
Inflow –
(net blueshift)



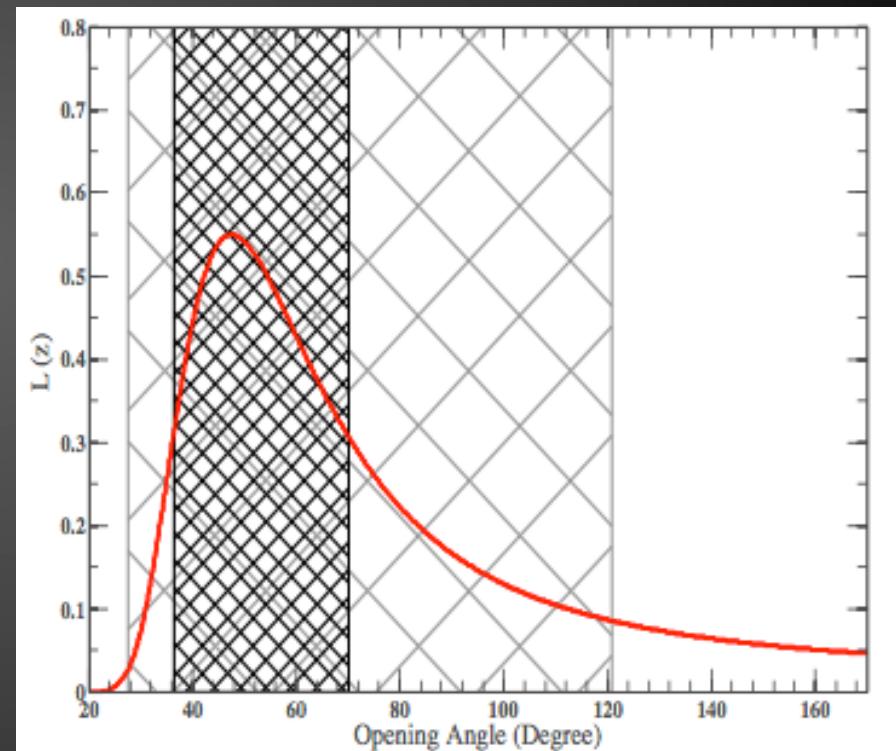
Pilot Study: Azimuth

I find:

- Bordoloi et al. 2014:



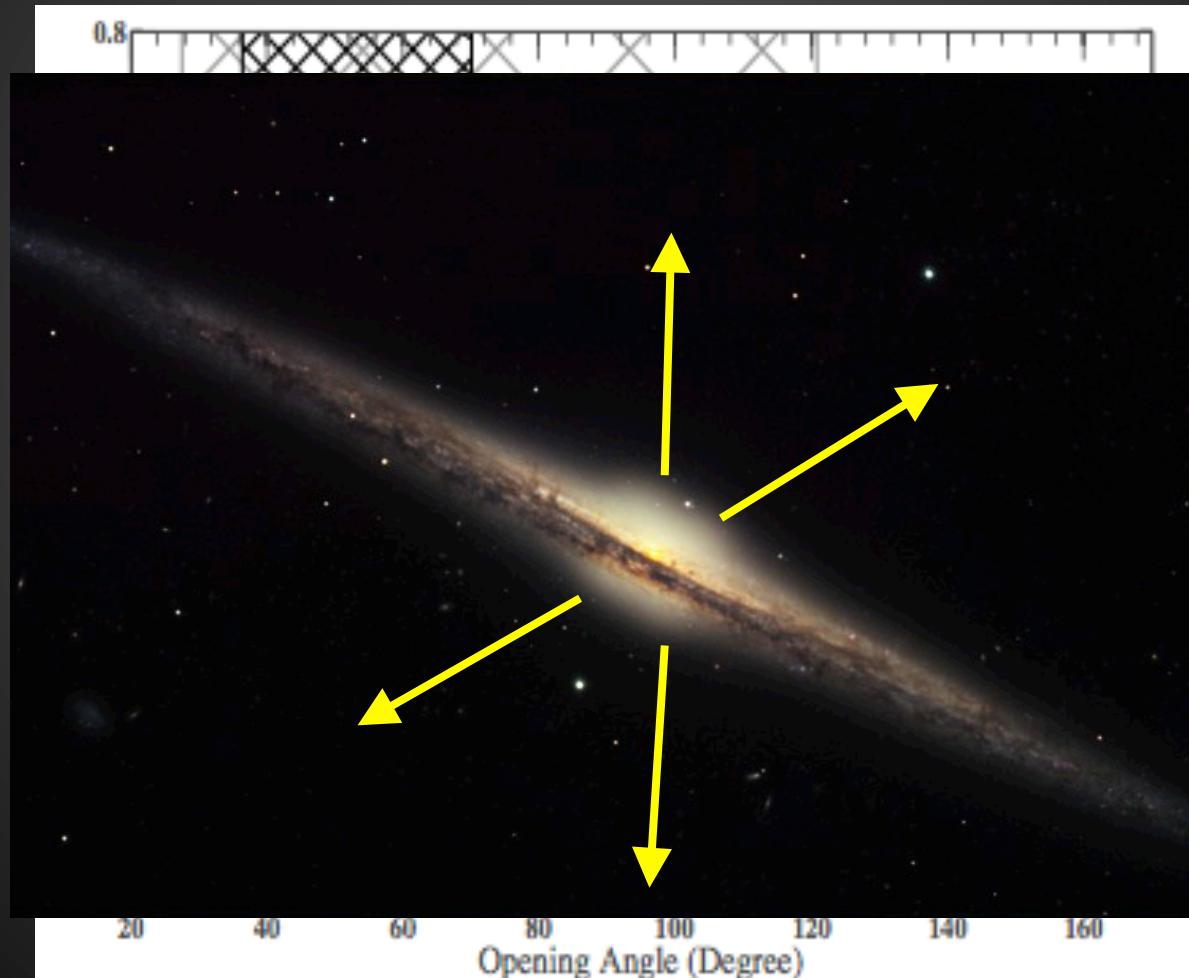
French et al. in prep



Bordoloi et al. 2014, ApJ, 784, 108

Pilot Study: Azimuth

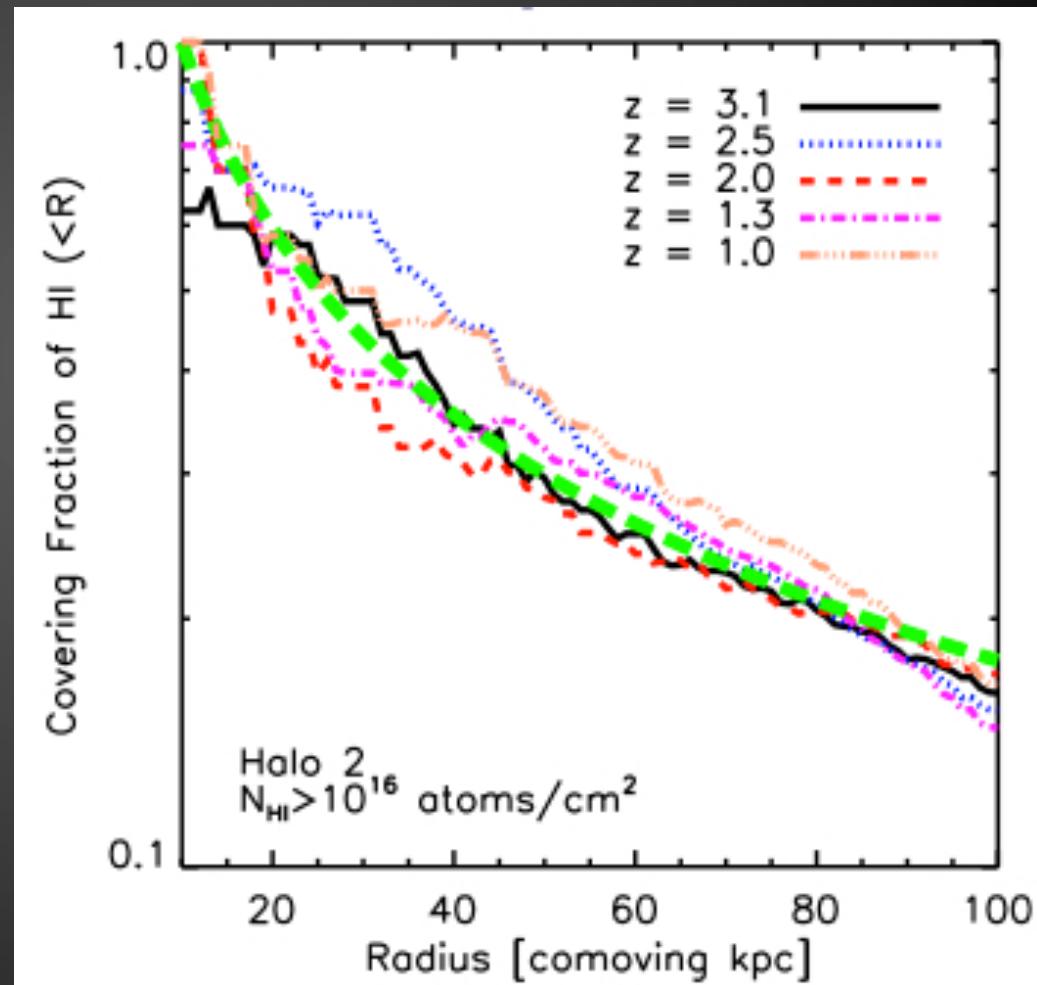
- Bordoloi et al. 2014 predict absorption opening angle:



Do the properties of absorbers depend on the galaxy environment?

Simulations:

- Gas covering fraction falls off quickly
- Need more complete observational results



Is there a difference in gas properties between field and group galaxies?

- Yoon & Putman find no $W - \rho$ correlation in the Virgo Cluster
- Wakker & Savage find fewer Ly α absorbers near galaxy groups
- *Membership dependence?*
- *New group catalogs (e.g. Tully 2015) necessitate a reevaluation*

