The Geometry and Kinematics of Circumgalactic Gas

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Swinburne University of Technology

Collaborators: Glenn Kacprzak, Chris Churchill, Michael Murphy, Sowgat Muzahid & Jane Charlton

Geometry and Kinematics of the CGM

Galaxy Evolution and the Baryon Cycle

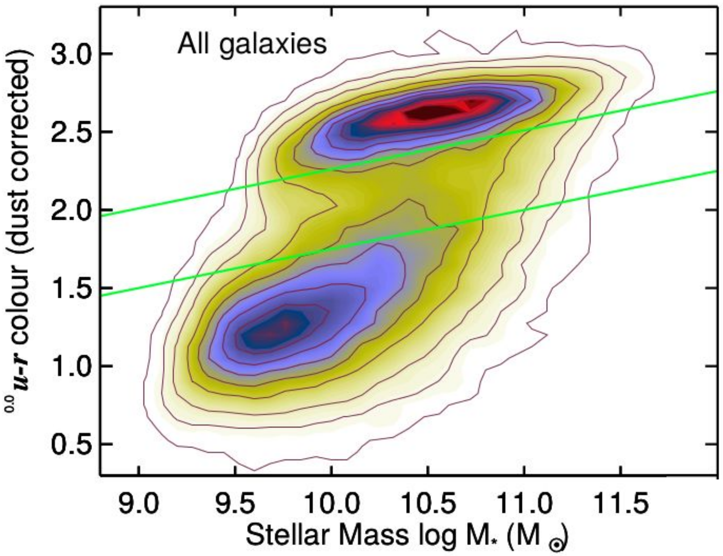
The Circumgalactic Medium (CGM) + Quasar Absorption Line Technique

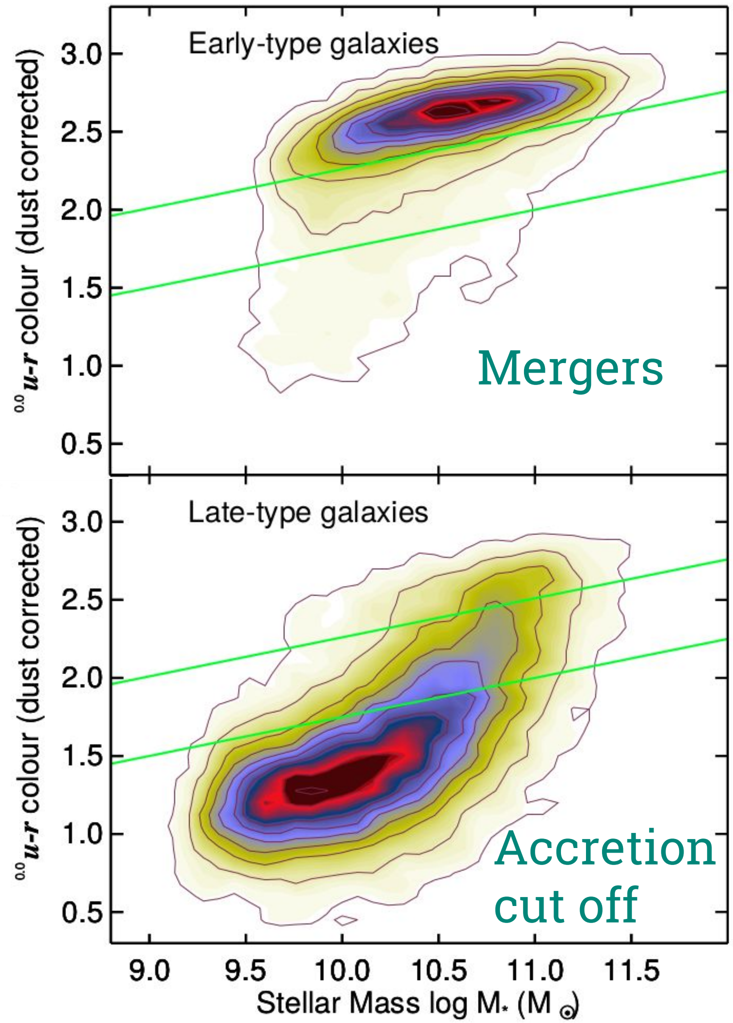
Geometry + Kinematics of the Isolated Galaxy CGM:

- Low Ionization CGM
- High Ionization CGM

Galaxy Environment

Galaxy Evolution: Color-Magnitude Diagram





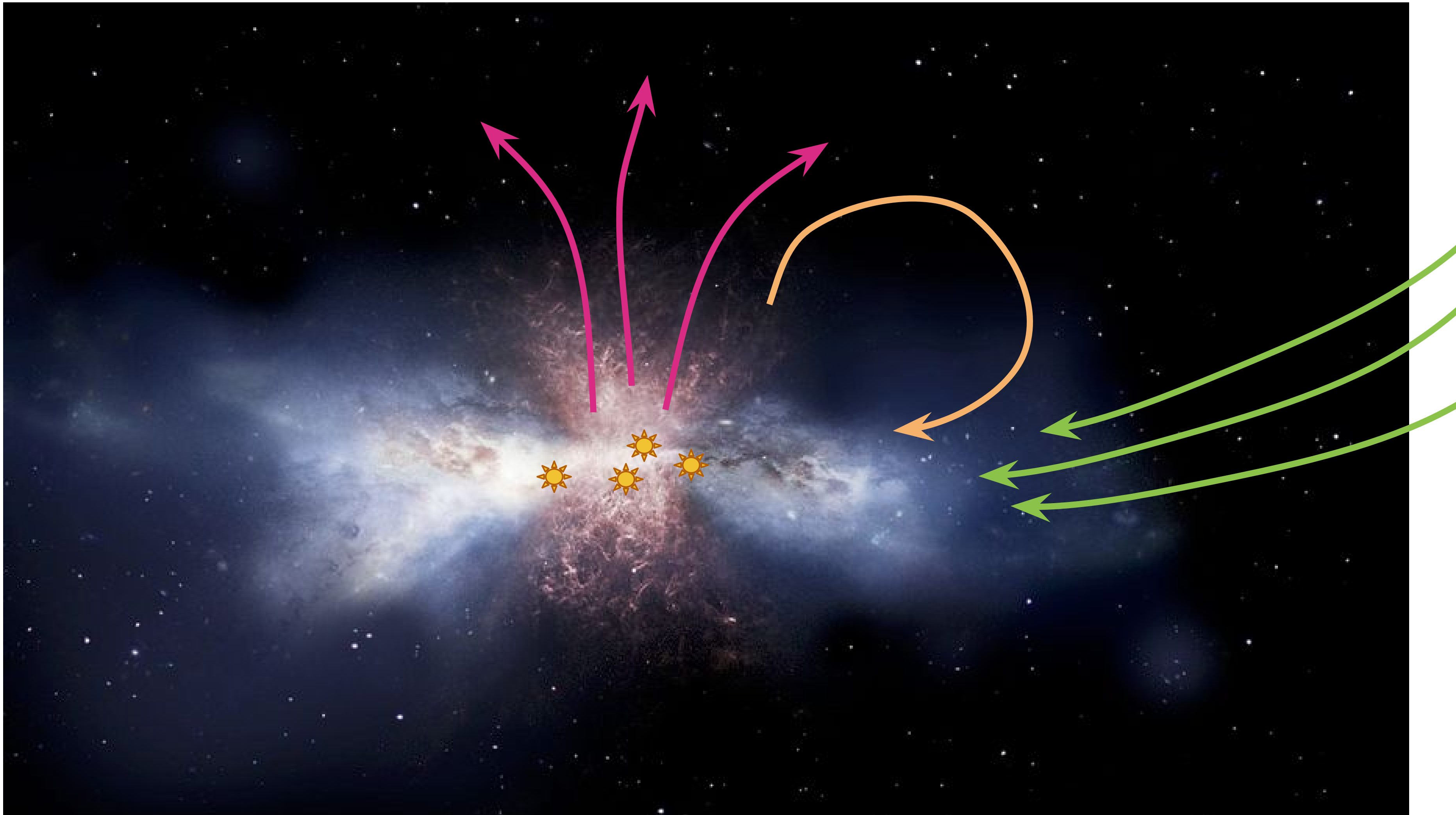
Star-forming blue cloud

Passive red sequence

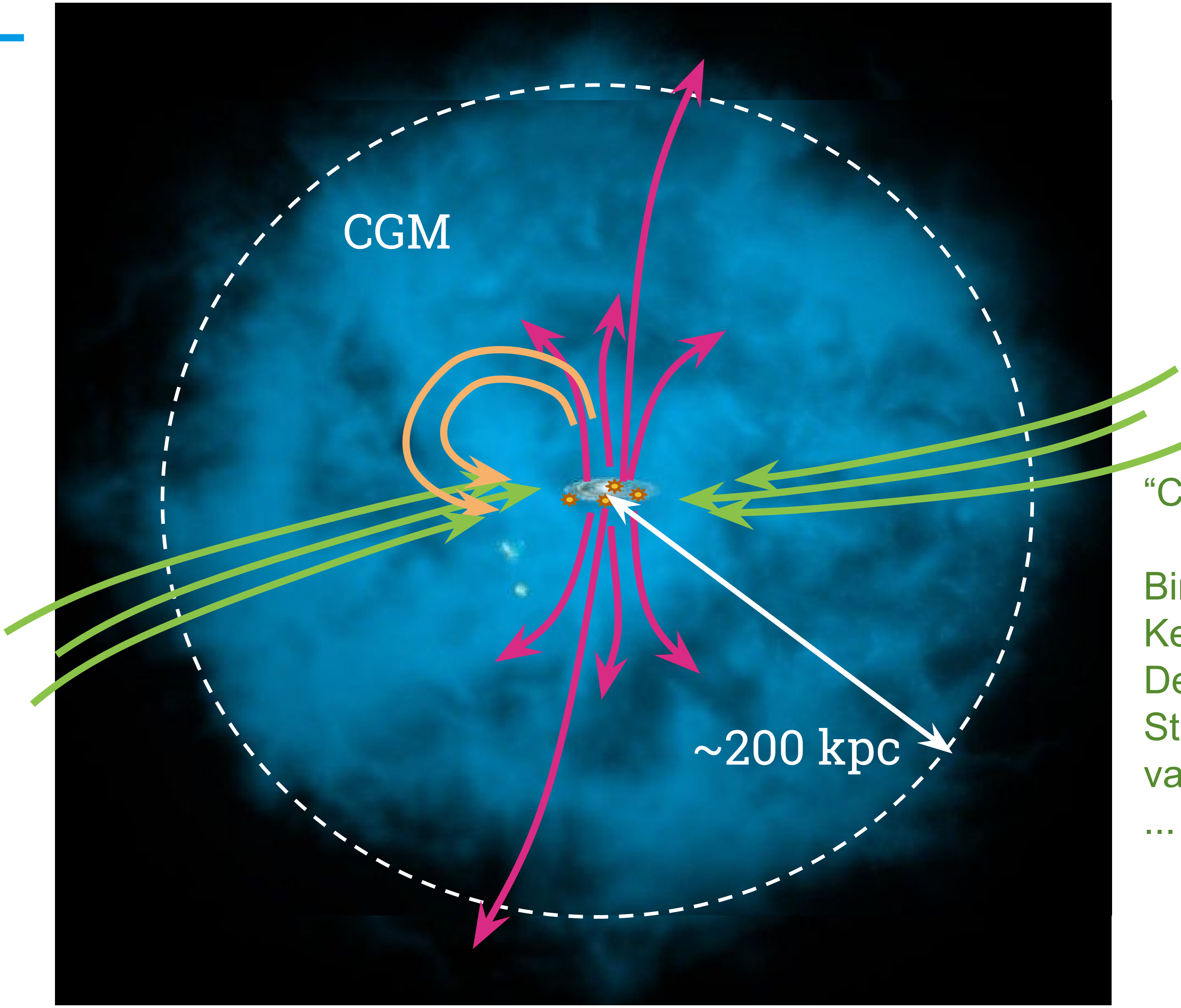
Transitional green valley

Schawinski+ 2014

Gas Regulation - The Baryon Cycle



Gas Regulation - Circumgalactic Medium



"Cold-Mode Accretion"

Birnboim & Dekel 2003
Keres+ 2005, 2009
Dekel & Birnboim 2006
Stewart+ 2011
van de Voort+ 2011
...

Circumgalactic Medium (CGM)

CGM important laboratory for probing the baryon cycle of galaxies

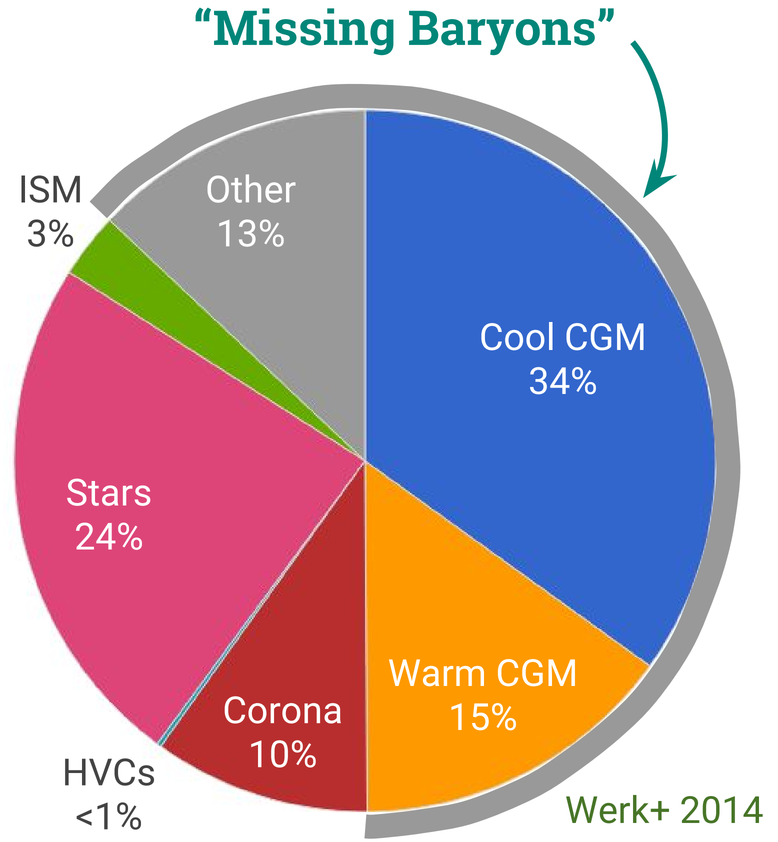
Multiphase, diffuse gas

Test cold-mode accretion (e.g., Birnboim work)

Feedback in simulations - different feedback prescriptions result in different CGM properties

Baryon budget - solution to missing baryons problem? ~60% missing
->CGM more massive than previously thought

Metallicity bimodality



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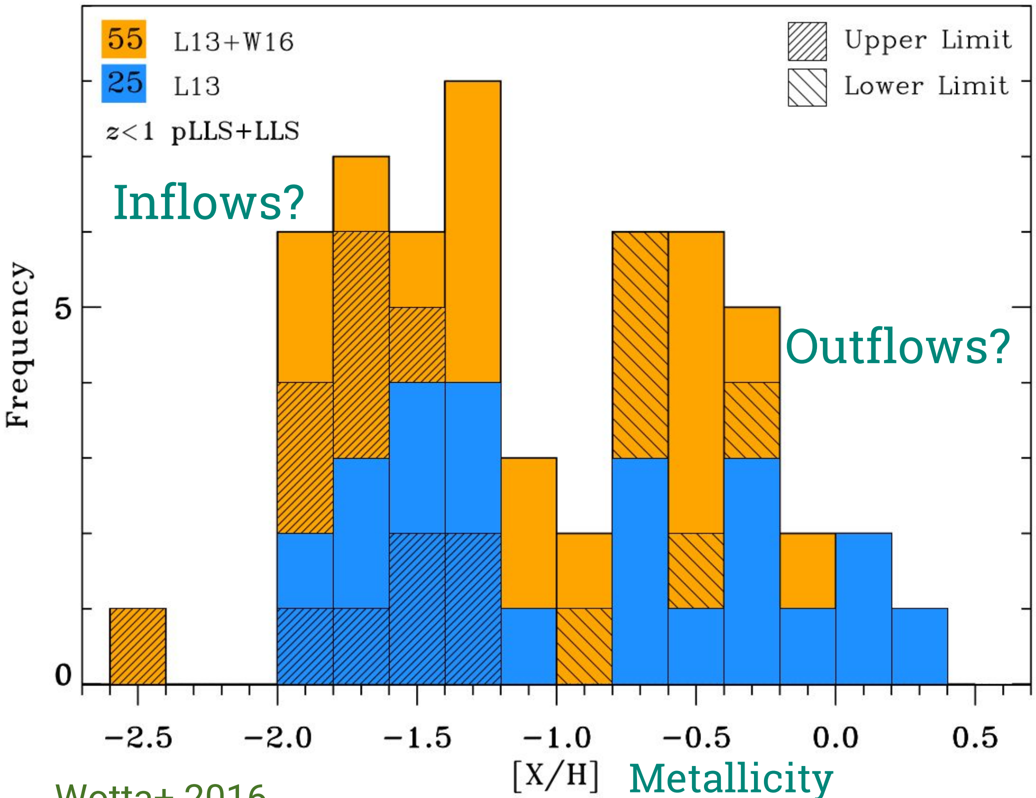
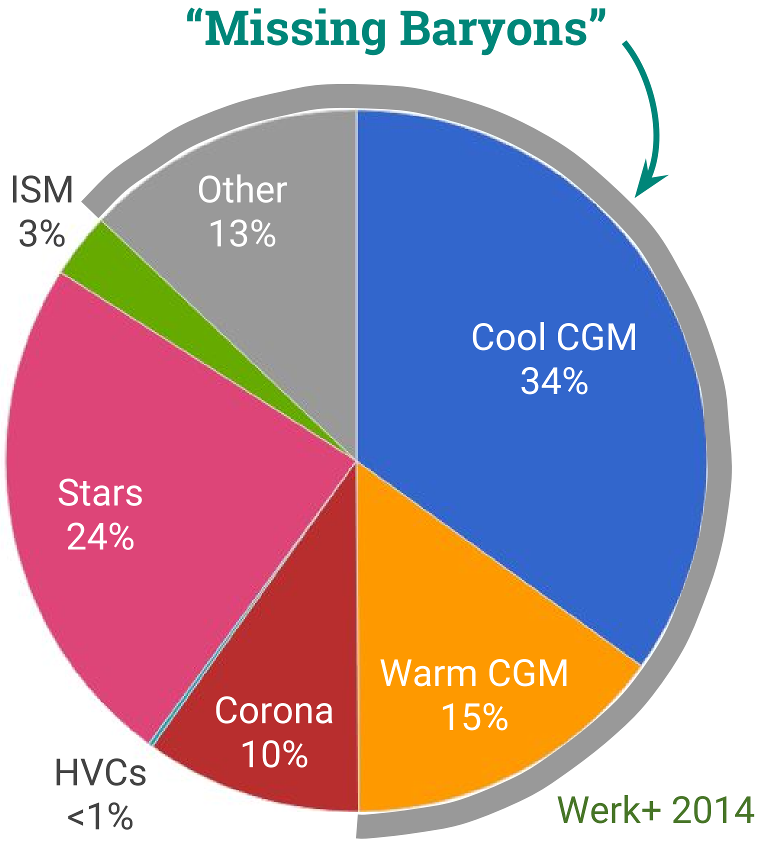


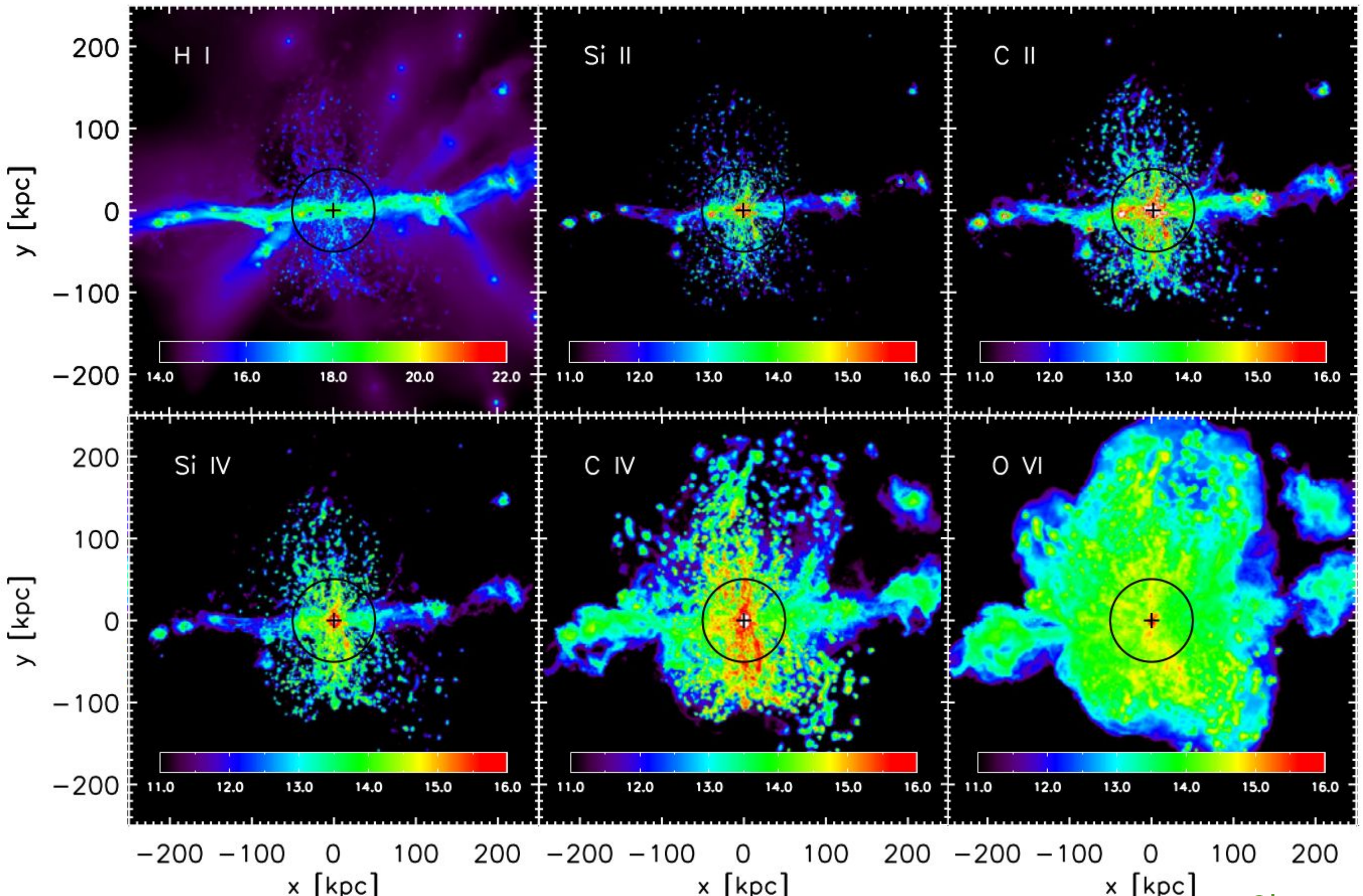
Wotta+ 2016
Also: Lehner+ 2013



Werk+ 2014

CGM in Simulations

z=2.8, Eris2 simulation
black circle = R_{vir}

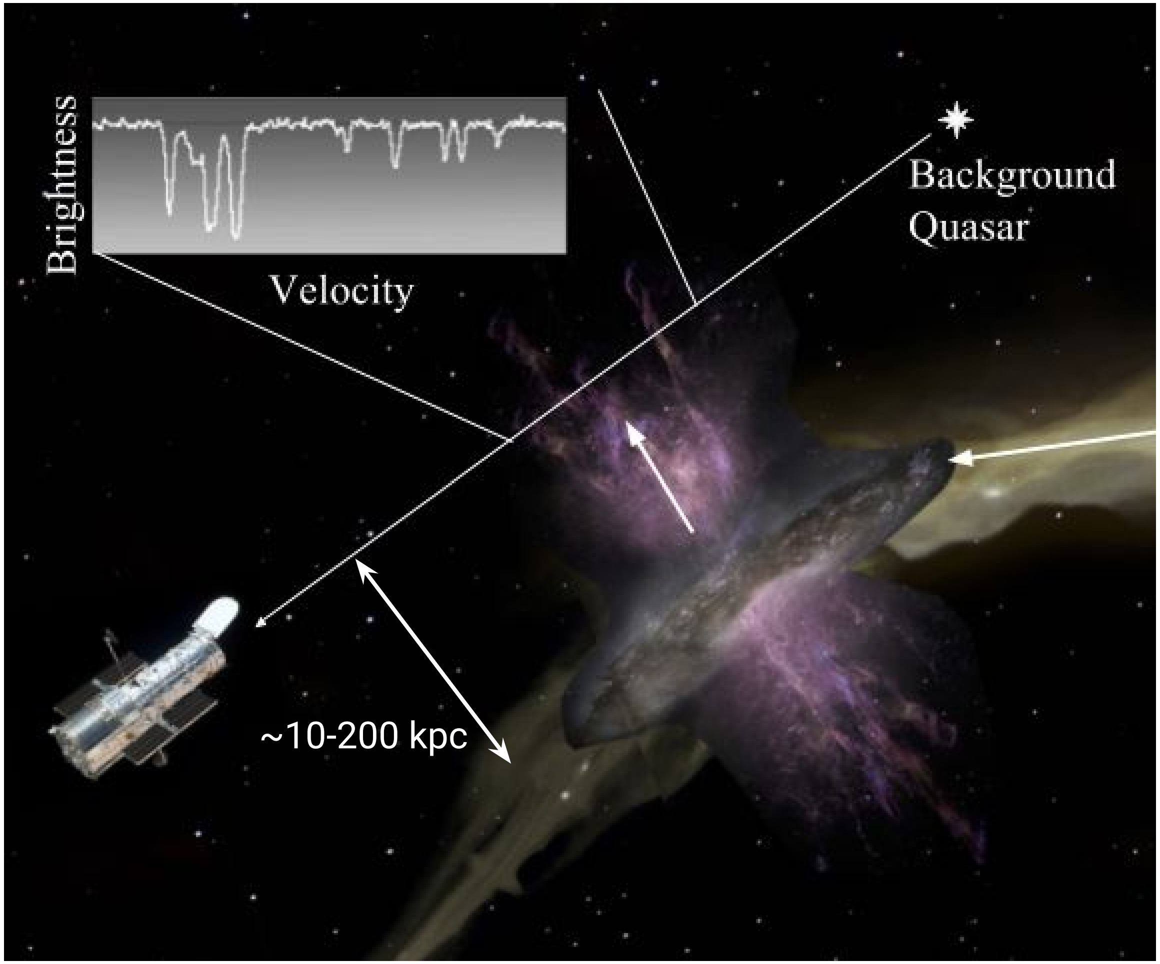


Low Ionization CGM

High Ionization CGM

Shen et al 2013, ApJ, 765, 89

Quasar Absorption Line Technique



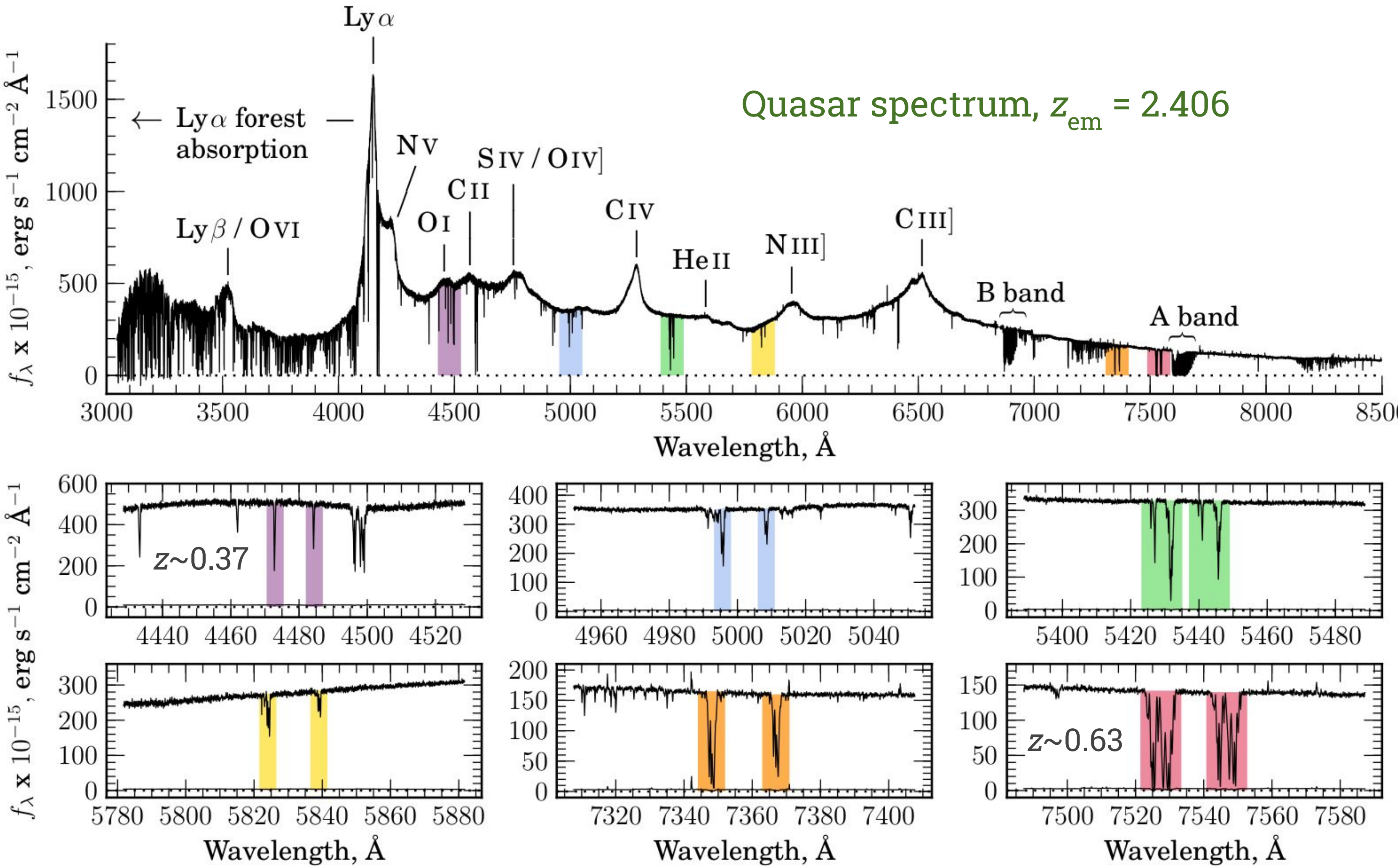
Quasar sightline is a pencil beam

Typically only 1 quasar sightline per galaxy

Collect many galaxies with 1 sightline!

Other methods: Background galaxy, host galaxy, GRBs, stars (MW only)

MgII Doublet Absorption



MgII Doublet Absorption

Extensive work with MgII quasar absorption lines spanning ~3 decades

e.g., Bergeron 1986, Bergeron & Boisse 1991, Steidel+ 1994, Lanzetta+ 1995, Churchill+ 2005, Chen+ 2010, Kacprzak+ 2011, and many more!

Observable in the optical over redshift range: $0.1 < z < 2.5$ (~10 Gyr difference!)

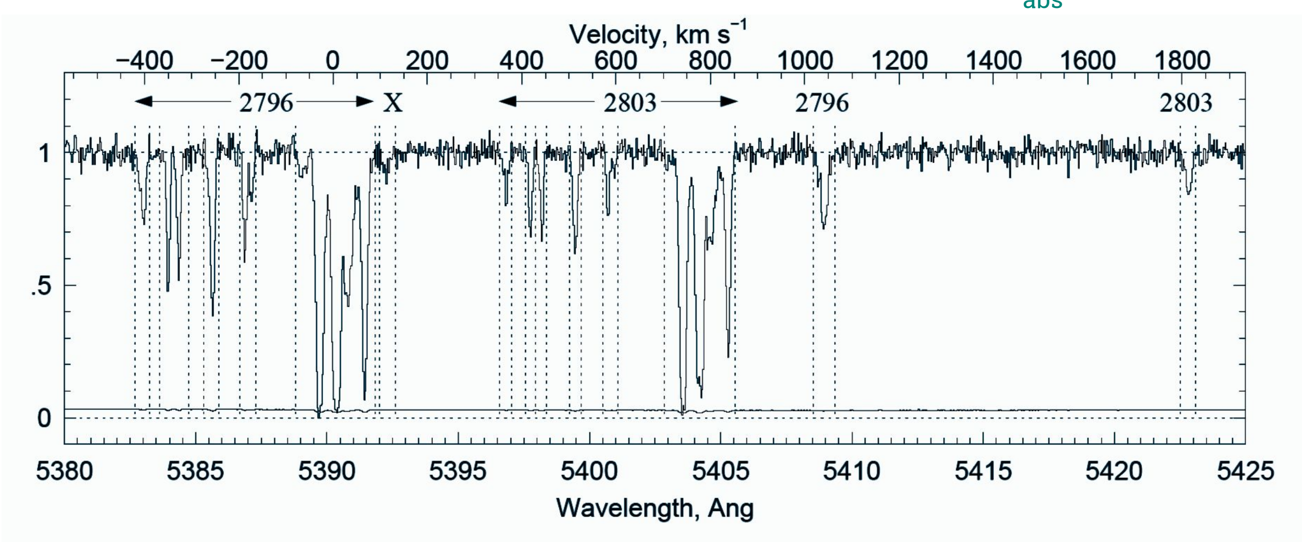
Temperature: $10^{4.5}$ K photoionized gas ("cool" gas in CGM work)

HI column densities: $16 < \log N(\mathrm{HI}) < 22$

Density: $n_H \sim 10^{-1}$ g cm^{-3}

Q1206+459

z_{abs}=0.927



MgII Doublet Absorption

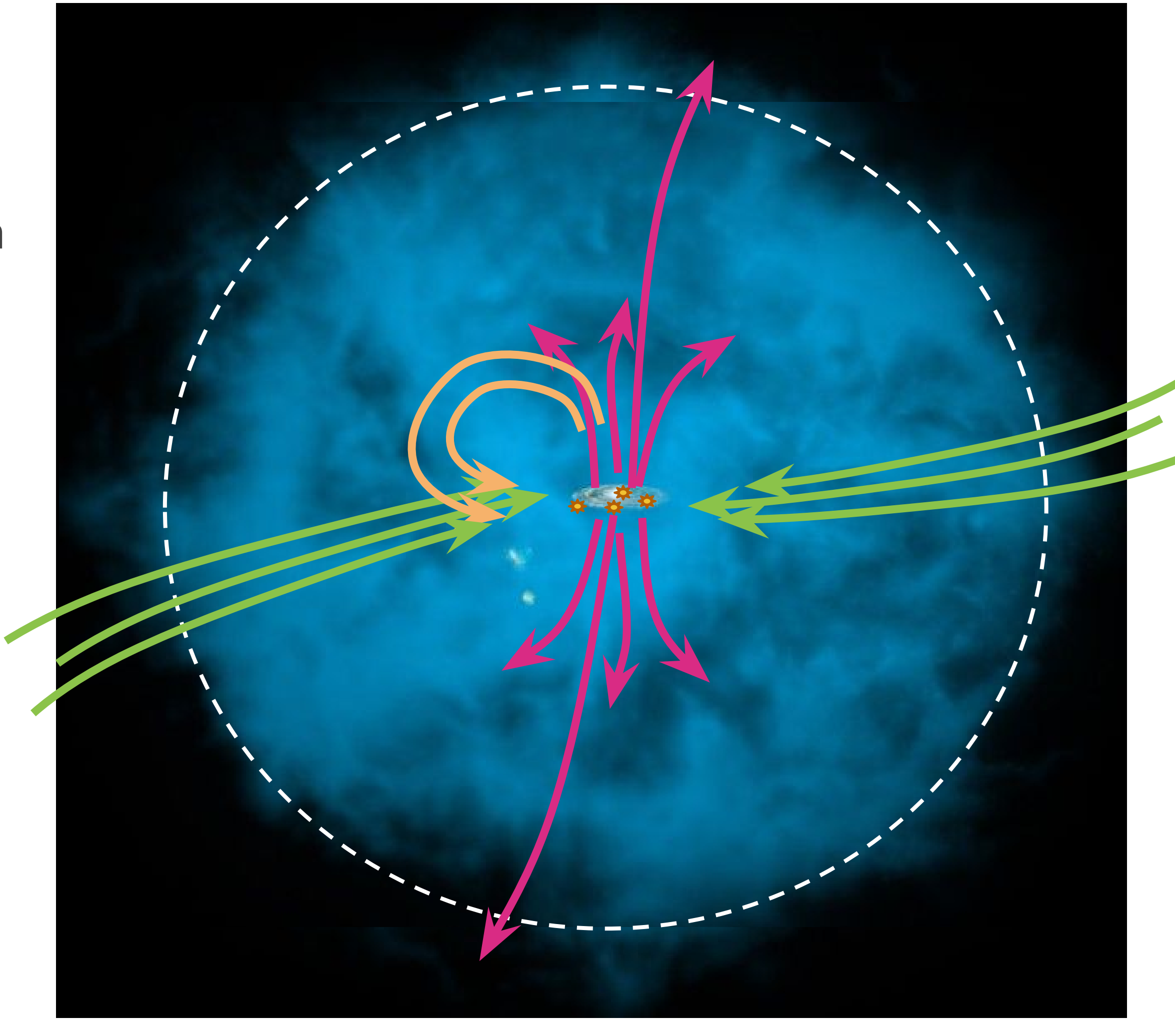
Attributed to:

Accretion along dark matter filaments, add angular momentum
  e.g., Rubin+ 2012, Martin+ 2012

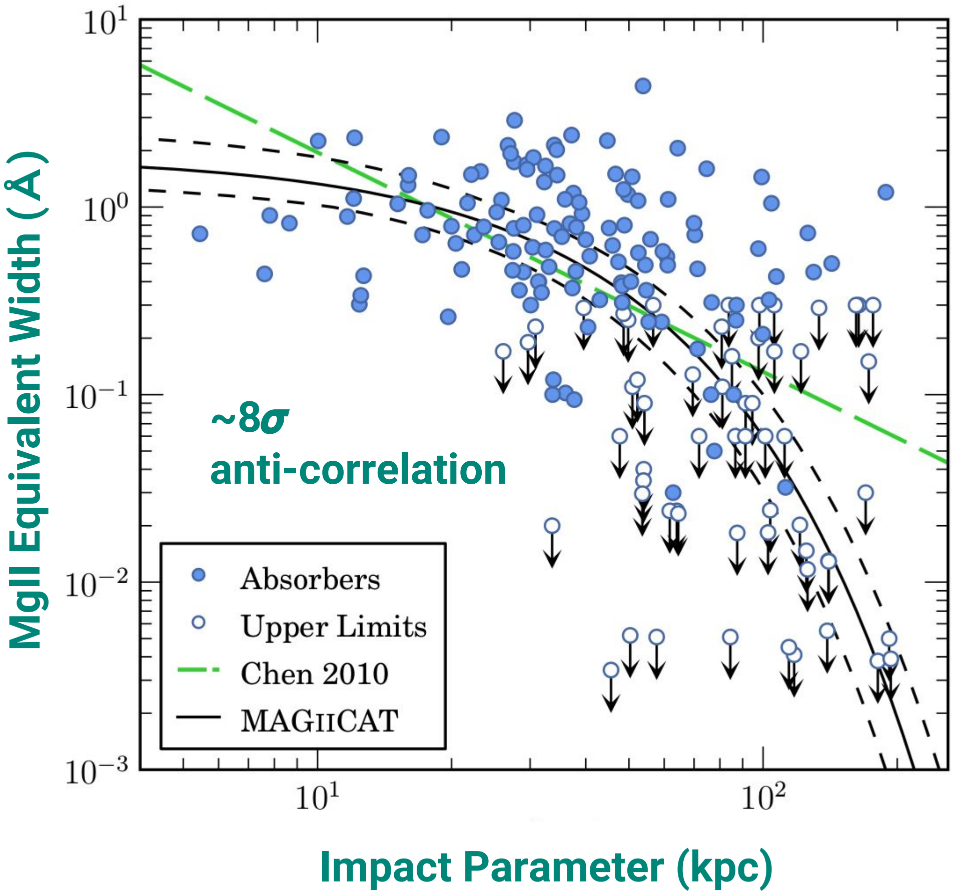
Outflows from SN feedback & stellar winds; bipolar
  e.g., Bouche+ 2012, Bordoloi+ 2014, Rubin+ 2014

Recycled Accretion as a galactic fountain
  e.g., Ford+ 2014 (simulations)

Merging satellite galaxies
  e.g., Martin+ 2012



Low Ionization CGM - MgII



MgII Absorber--Galaxy Catalog
-> **MAGIICAT**

182 **isolated** galaxies
120 with measured absorption
62 with upper limits on absorption

D < 200kpc

z_{gal} = 0.1-1.1

HIRES/Keck or UVES/VLT quasar spectra for ~70 absorber--galaxy pairs

HST images for ~60 galaxies

Nielsen+ 2013a,b, 2015, 2016;
Churchill+ 2013a,b; Kacprzak+ 2012

Self-Similar CGM

Halo abundance matching with Bolshoi simulations (Klypin+ 2011, Trujillo-Gomez+ 2011)

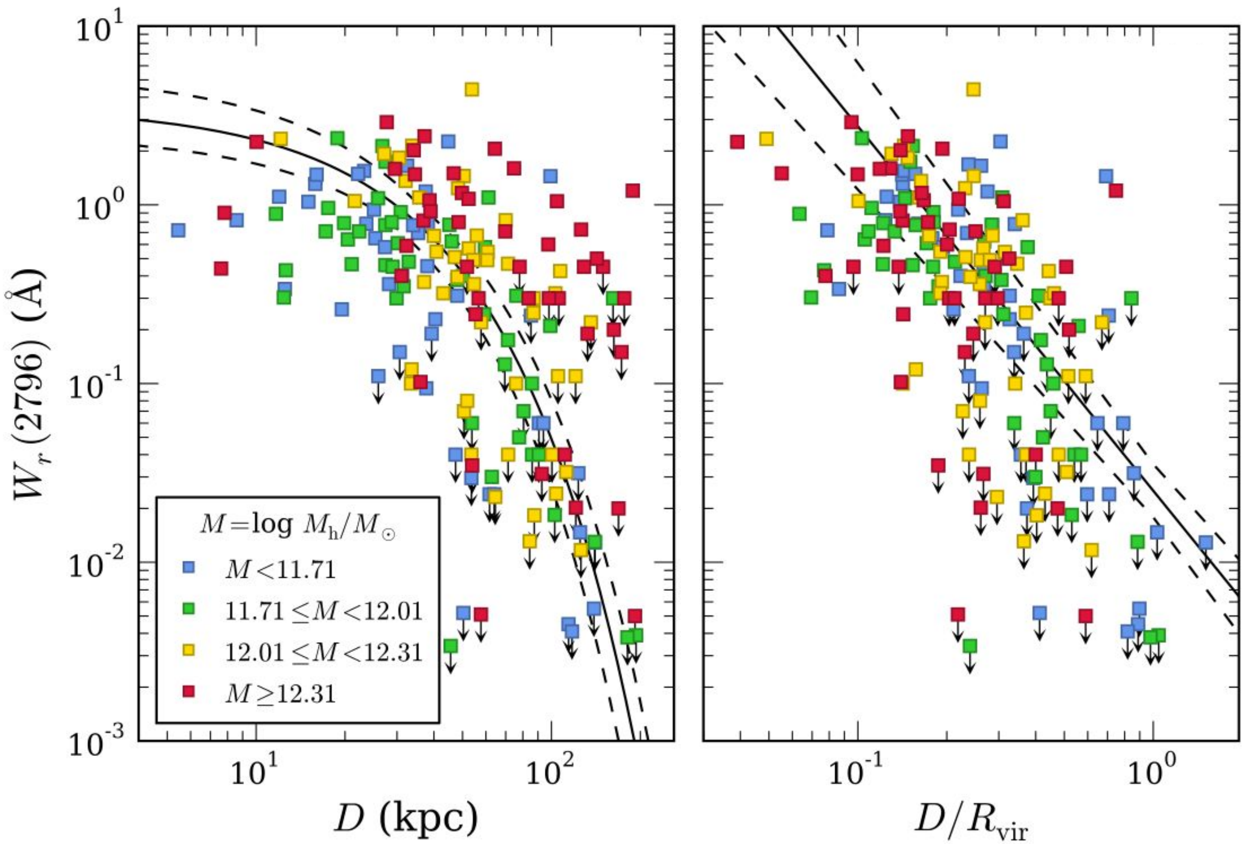
$10.7 < \log (M_h/M_{sun}) < 13.9$

Majority between $11 < \log (M_h/M_{sun}) < 13$

More massive galaxies have a larger CGM

Absorption mostly within $0.5\ R_{vir}$

Churchill+ 2013a,b (MAGIICAT III)



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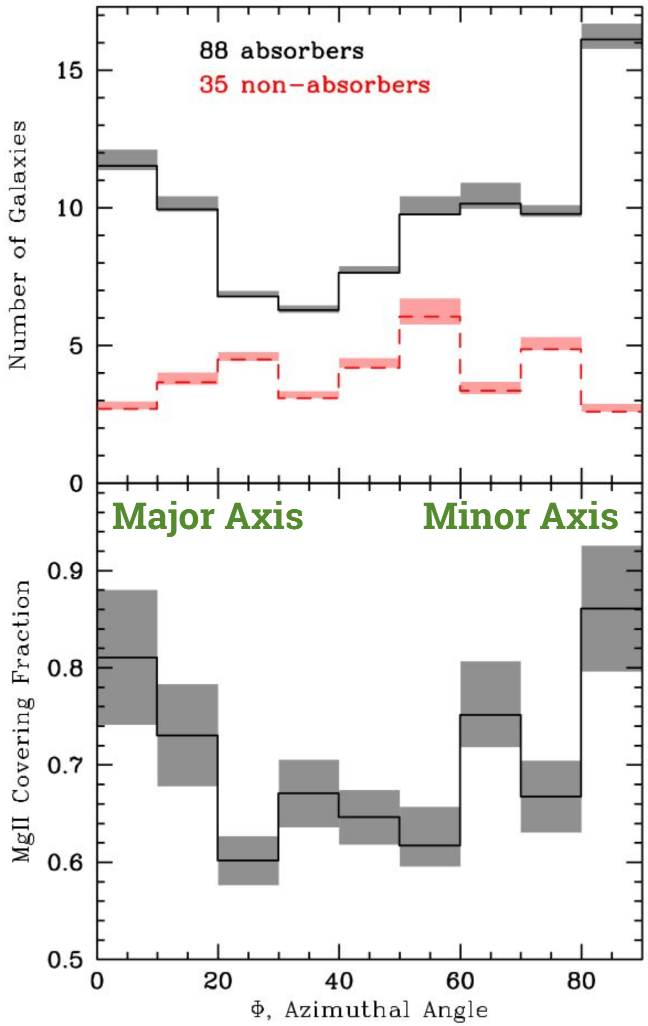
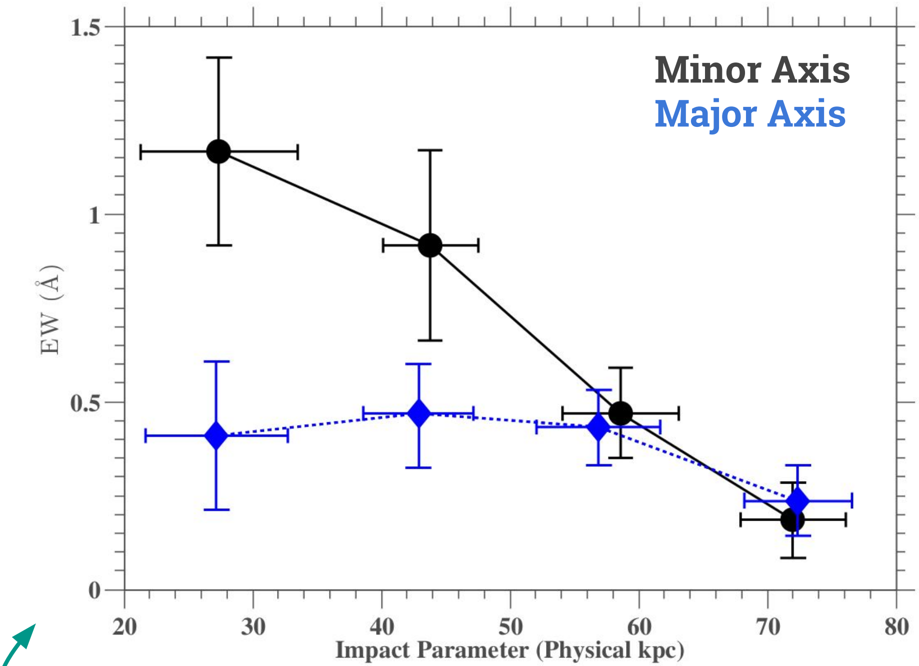
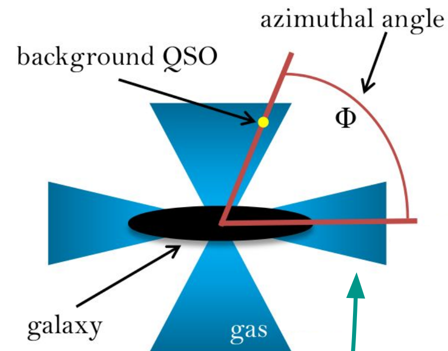


MgII



Also see: **Bordoloi+ 2011**, Bouche+ 2012, Lan+ 2014

Toy model:

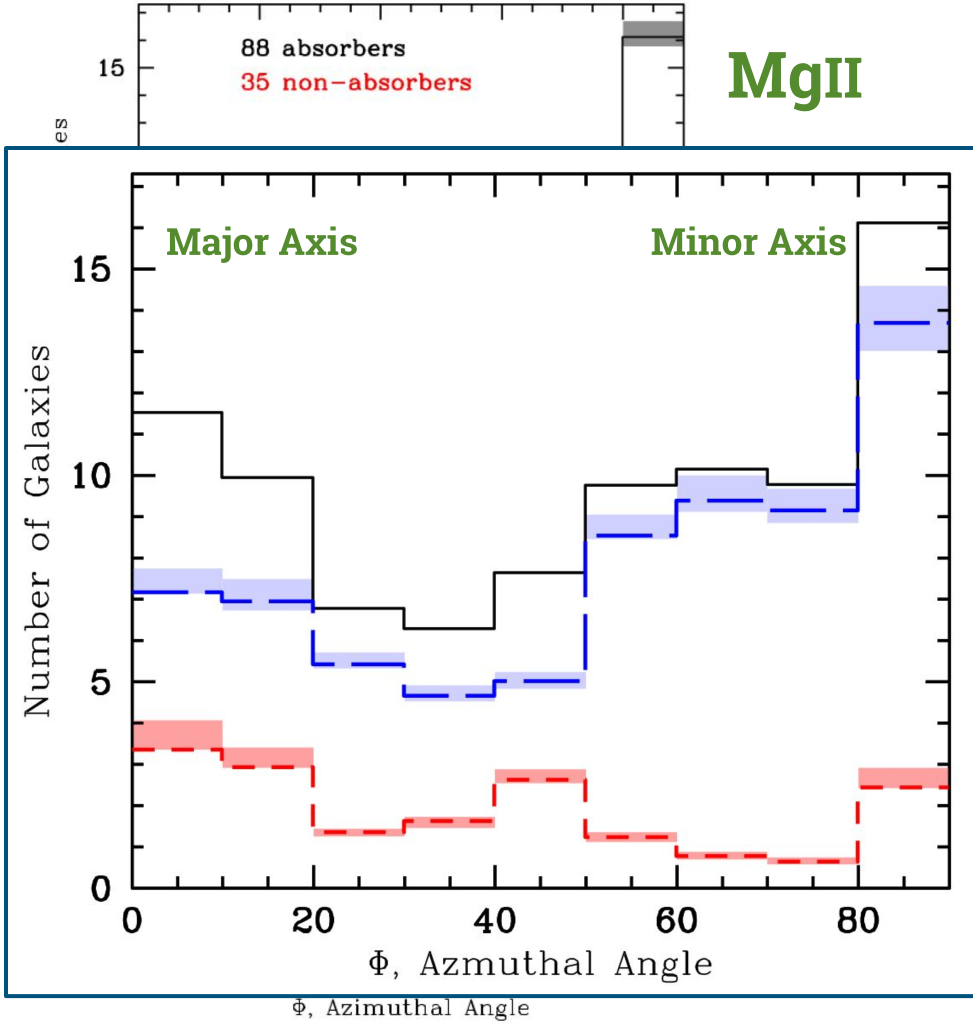


Bipolar outflows, Large EWs

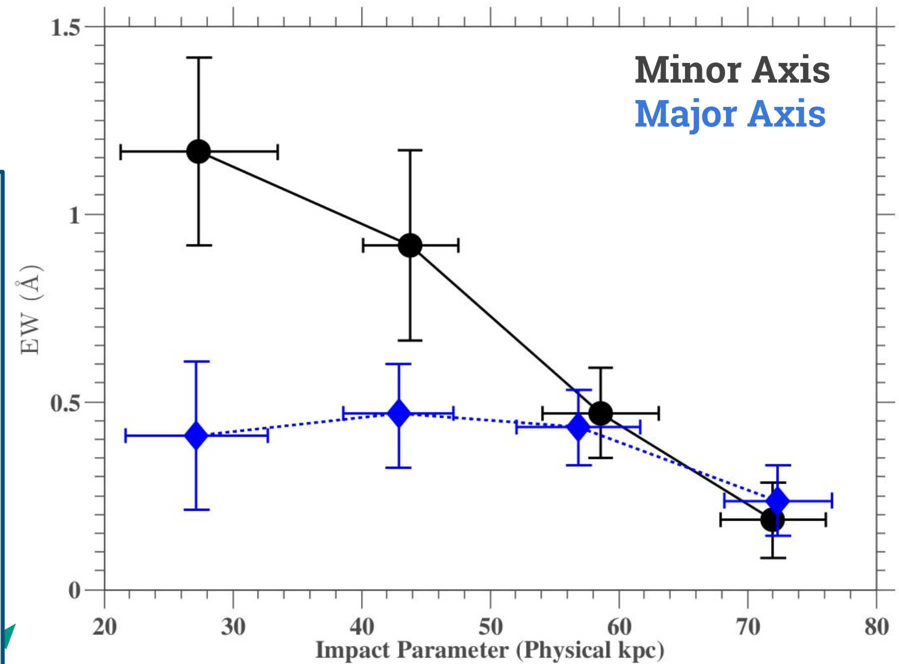
Accretion, Rotation

Kacprzak, Churchill, Nielsen 2012, ApJ, 760, L7

Azimuthal Angle Distribution



MgII



doloi+ 2011,
2, Lan+ 2014

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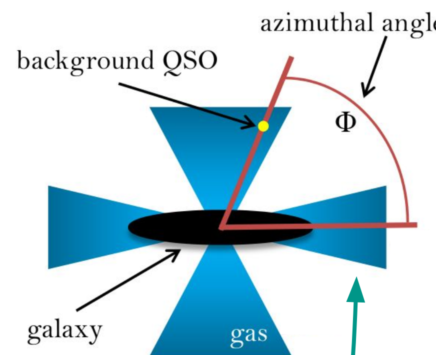

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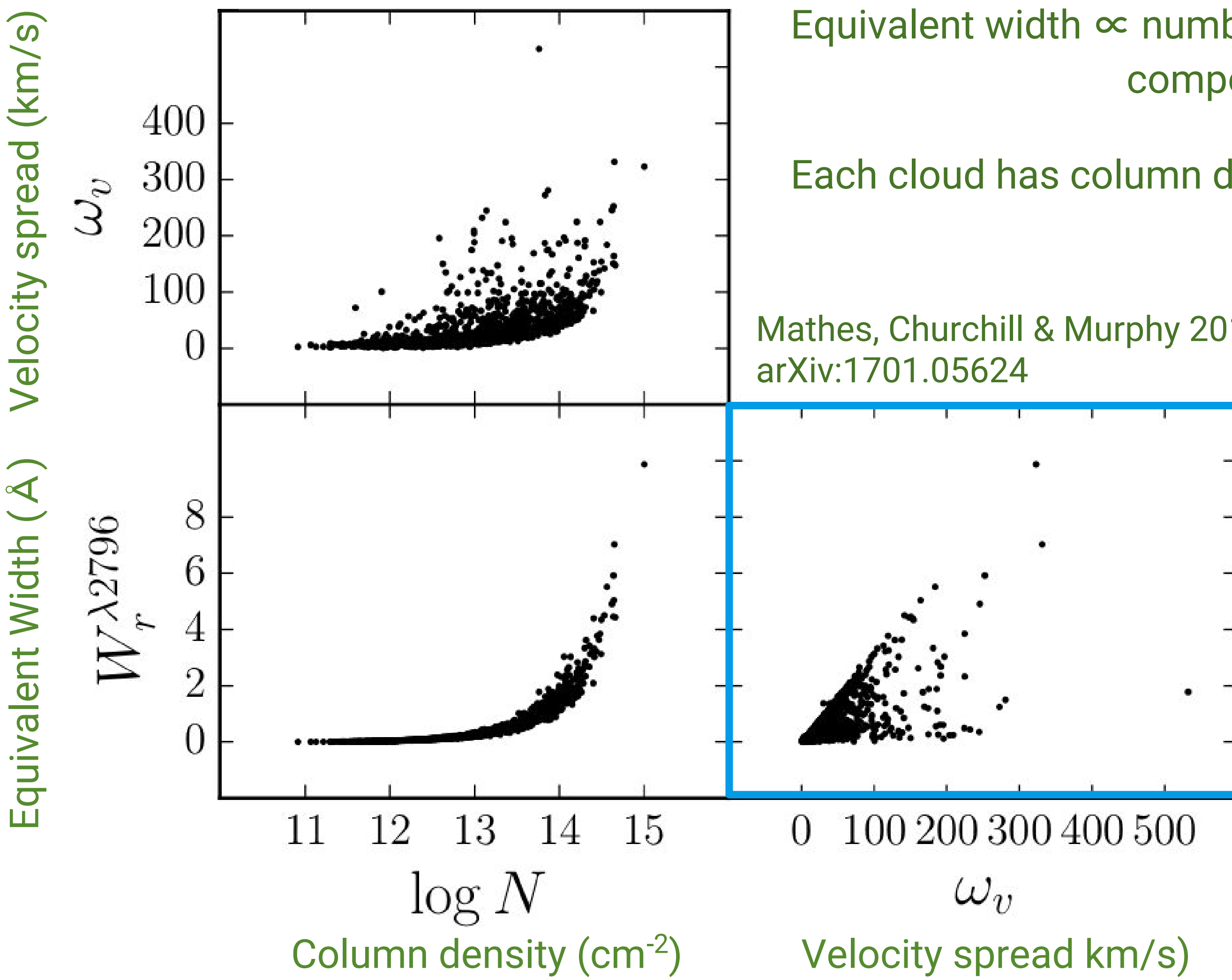
Azimuthal Angle Distribution

Equivalent Width -> Kinematics



Equivalent width ∝ number of fitted components (clouds)

Each cloud has column density + velocity

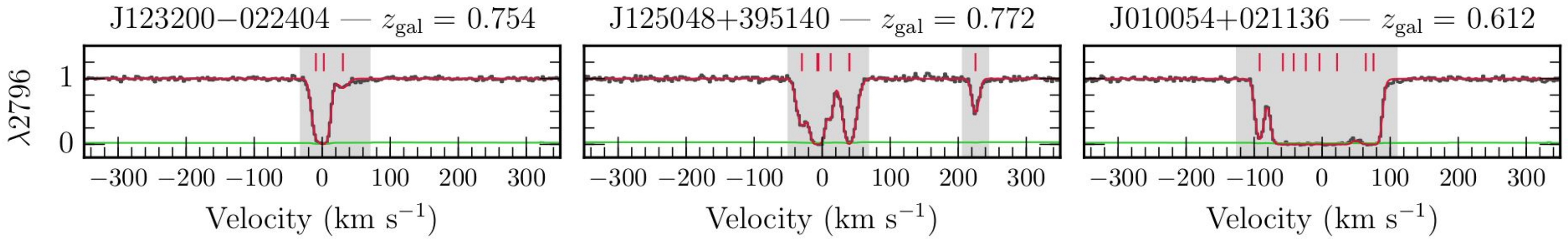
Mathes, Churchill & Murphy 2017, arXiv:1701.05624

Absorption Kinematics

+*HST* images

MgII

MAGIICAT: 30 absorbers with HIRES/Keck or UVES/VLT spectra; $\mathbf{z_{gal}=0.3\text{-}1.0}$

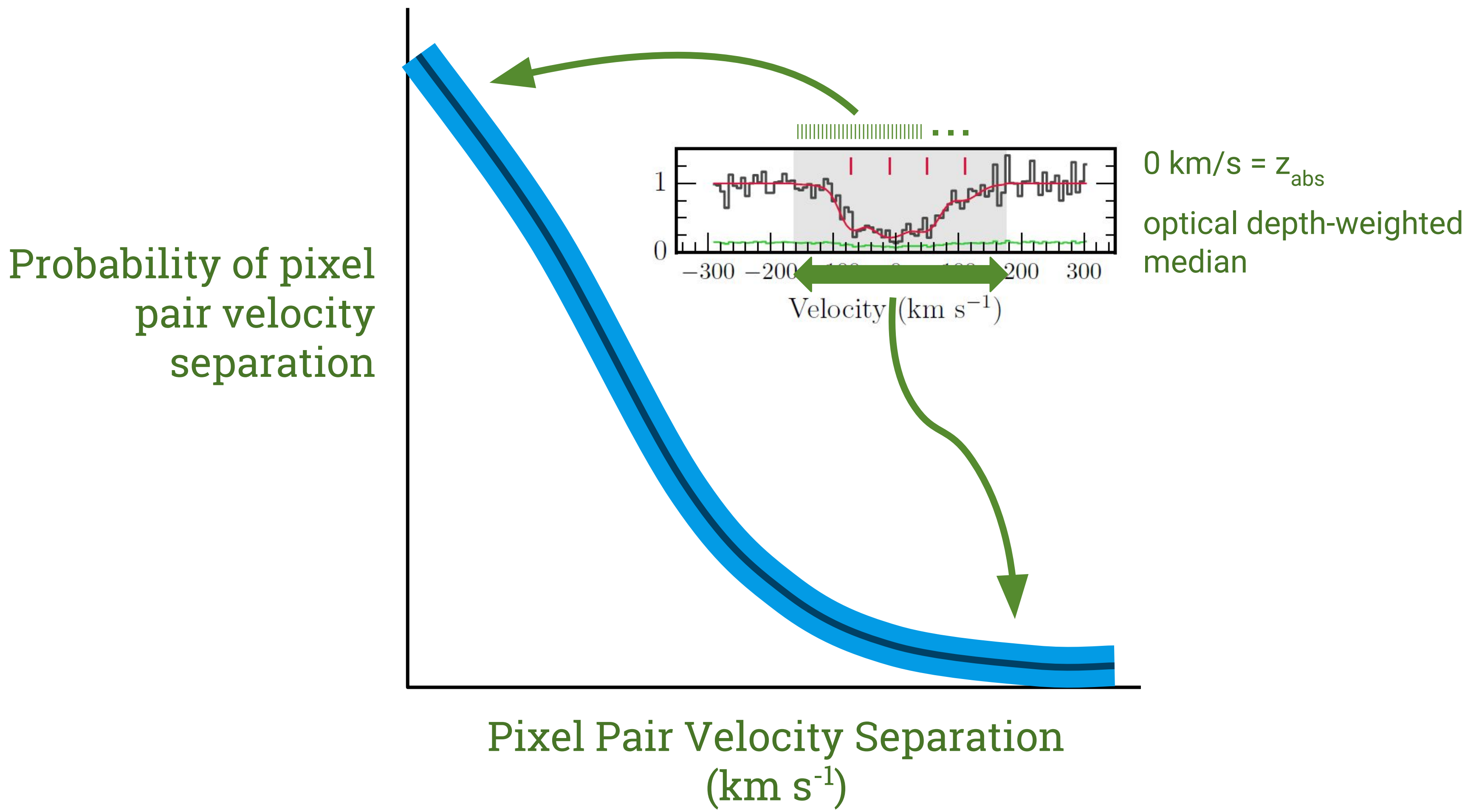


0 km/s = z_{abs} = optical depth-weighted median of absorption

MAGIICAT: Nielsen+ 2013a,b, 2015, 2016; Churchill+ 2013a,b; Kacprzak+ 2012

Absorption Kinematics: Pixel-Velocity TPCF

(**T**wo-**P**oint **C**orrelation **F**unction)

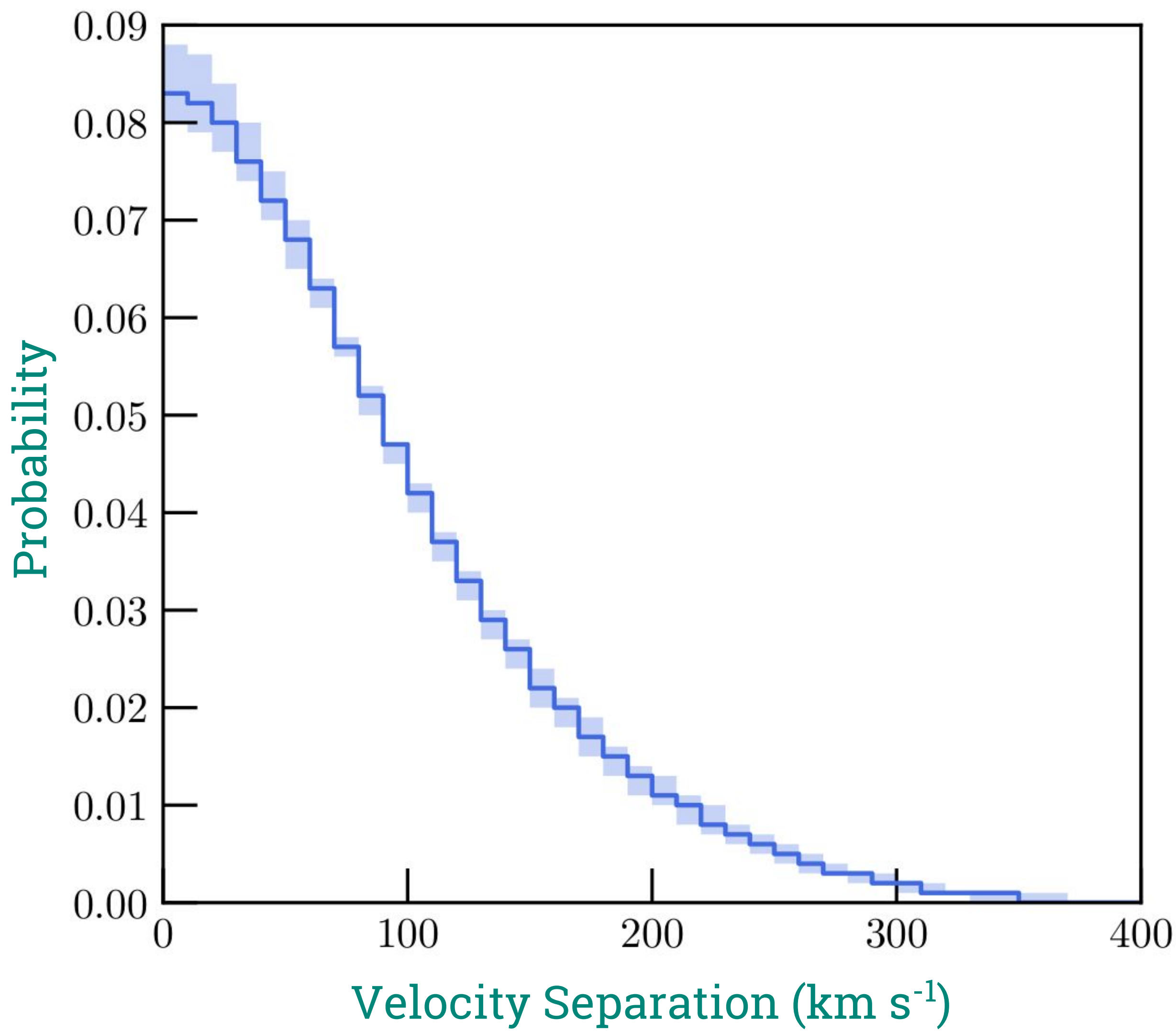


46 MgII absorber−galaxy pairs
<z_{gal}> = 0.656

All **isolated** galaxies

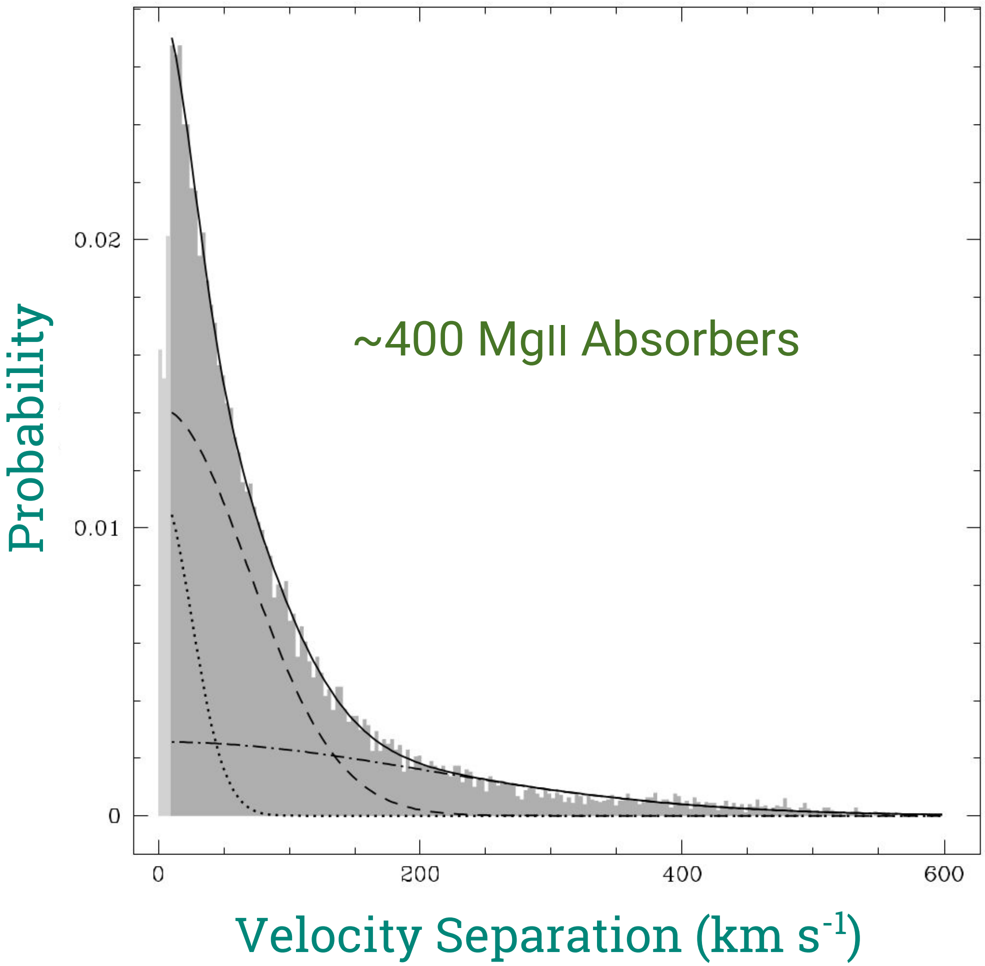
Galaxies are within *D<200* kpc of background quasar

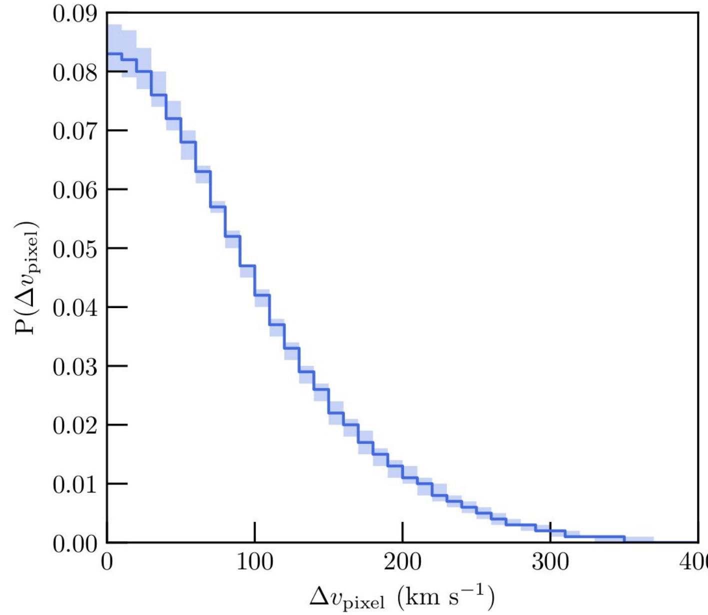
(Not all galaxies in this sample have *HST* images available)



Full Sample Pixel-Velocity TPCF

Jessica Evans Thesis, 2011, NMSU





Previous works fit Gaussians to TPCF. Attributed to:

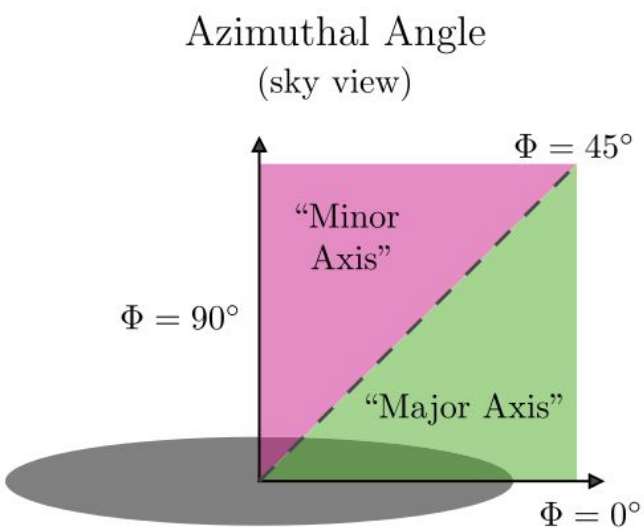
Motions within galaxy and between galaxy pairs (Petitjean & Bergeron 1990)

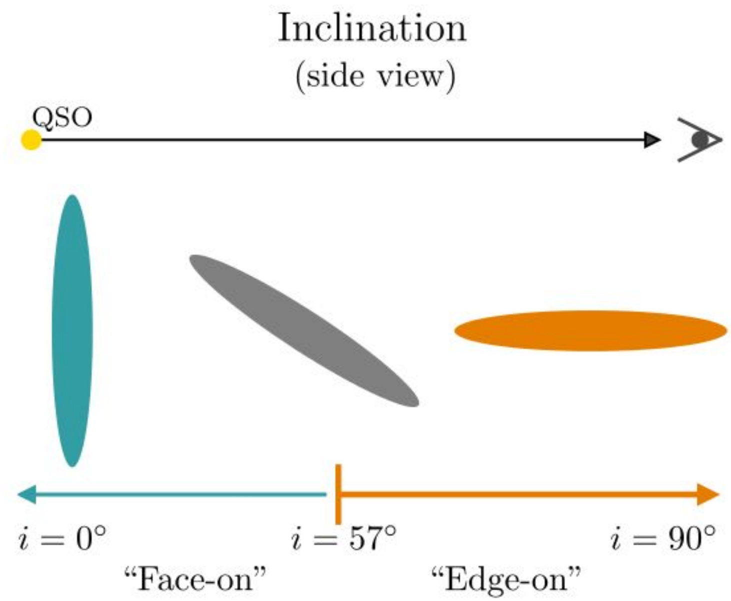
Vertical dispersion in galaxy disks and rotational motion (Churchill+ 2003)

Different Gaussians due to different galaxy evolutionary processes?

Full Sample Pixel-Velocity TPCF

Galaxy Orientation Subsamples





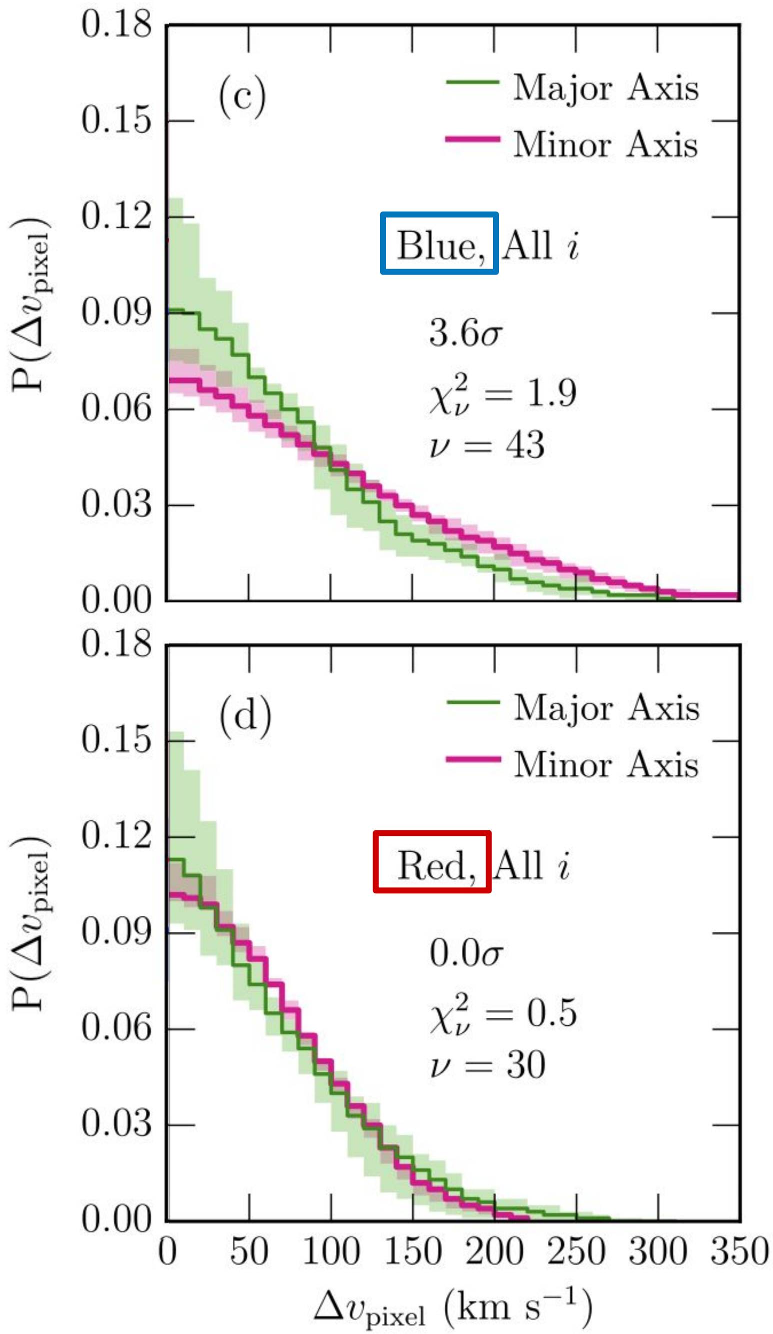
Galaxy Color Cuts **MgII**

Blue Galaxies *B−K < 1.4*

Red Galaxies *B−K ≥ 1.4*

Galaxies modeled with GIM2D in HST images

Nielsen+ 2015, ApJ, 812, 83 (MAGIICAT V)

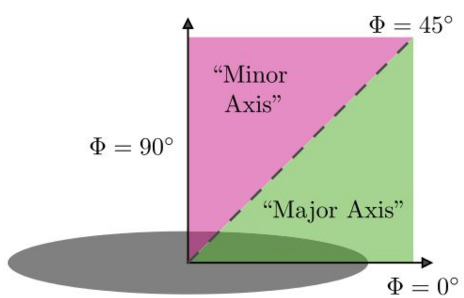


MgII

Color & Azimuthal Angle

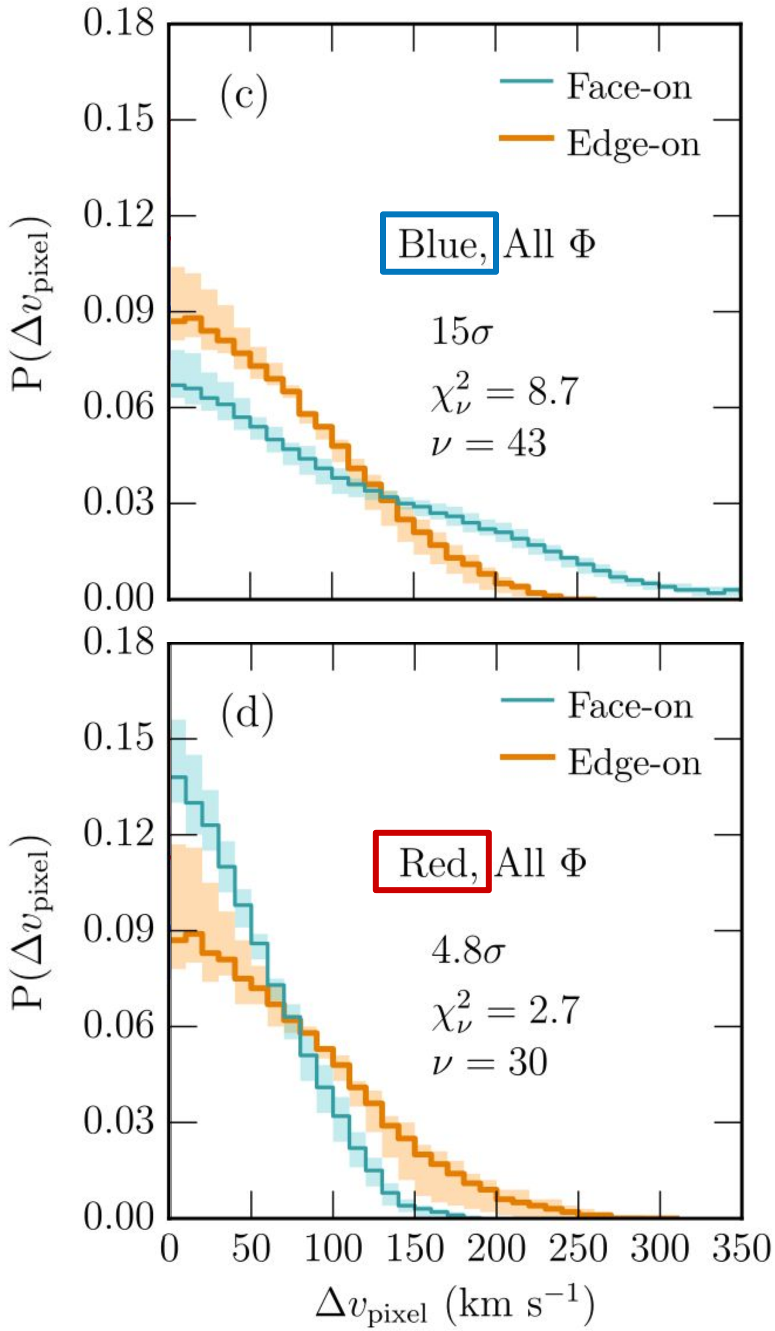
Velocity spreads larger along **Minor Axis** for **Blue galaxies** -> outflows?

No difference in the TPCFs for **Red galaxies** with **Major** and **Minor axes** -> gas just rotating around galaxy?



<B−K> = 1.4

Nielsen+ 2015, ApJ, 812, 83 (MAGIICAT V)

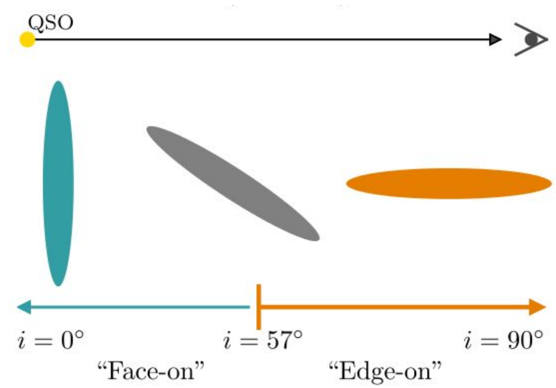


MgII

Color & Inclination

Velocity spreads greatest for **Face-on**, **Blue galaxies** -> outflows?

Velocity spreads for **Edge-on** same for **Blue** and **Red** -> rotating gas?



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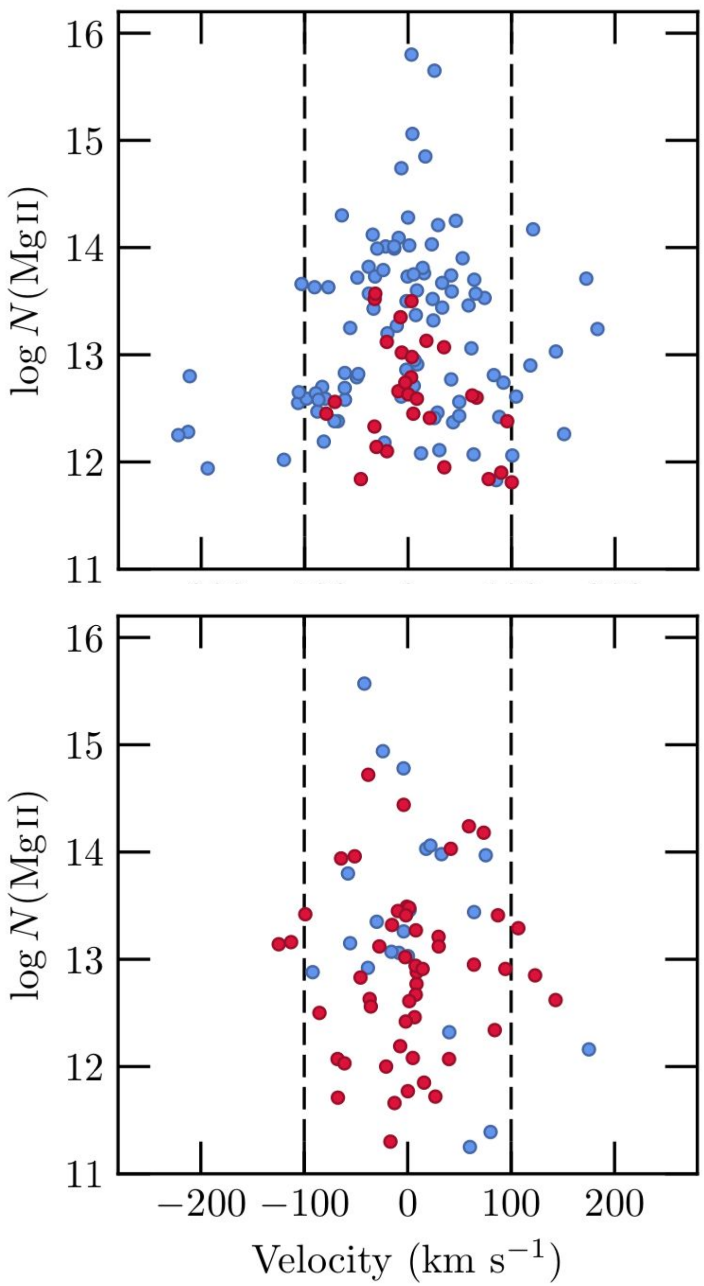
MgII

Column Densities



Minor Axis

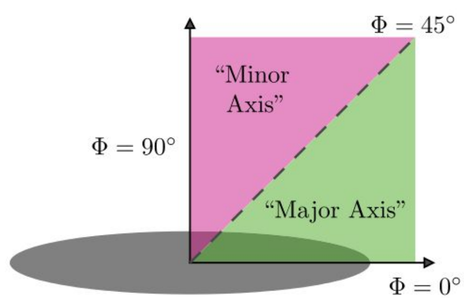
Major Axis

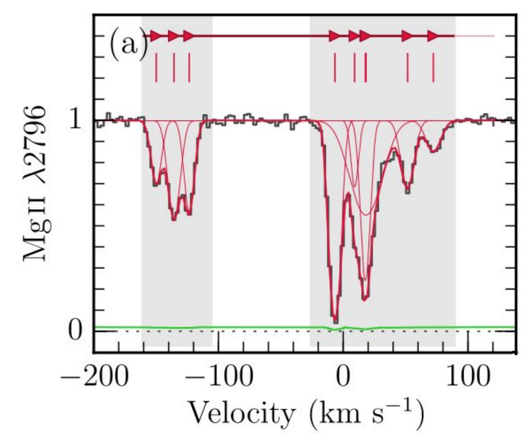
"Cloud" column densities + velocities

Highest velocity components found along **Minor Axis** -> clumpy outflows?

Column densities smaller for **Red** galaxies along **Minor Axis**

<B−K> = 1.4





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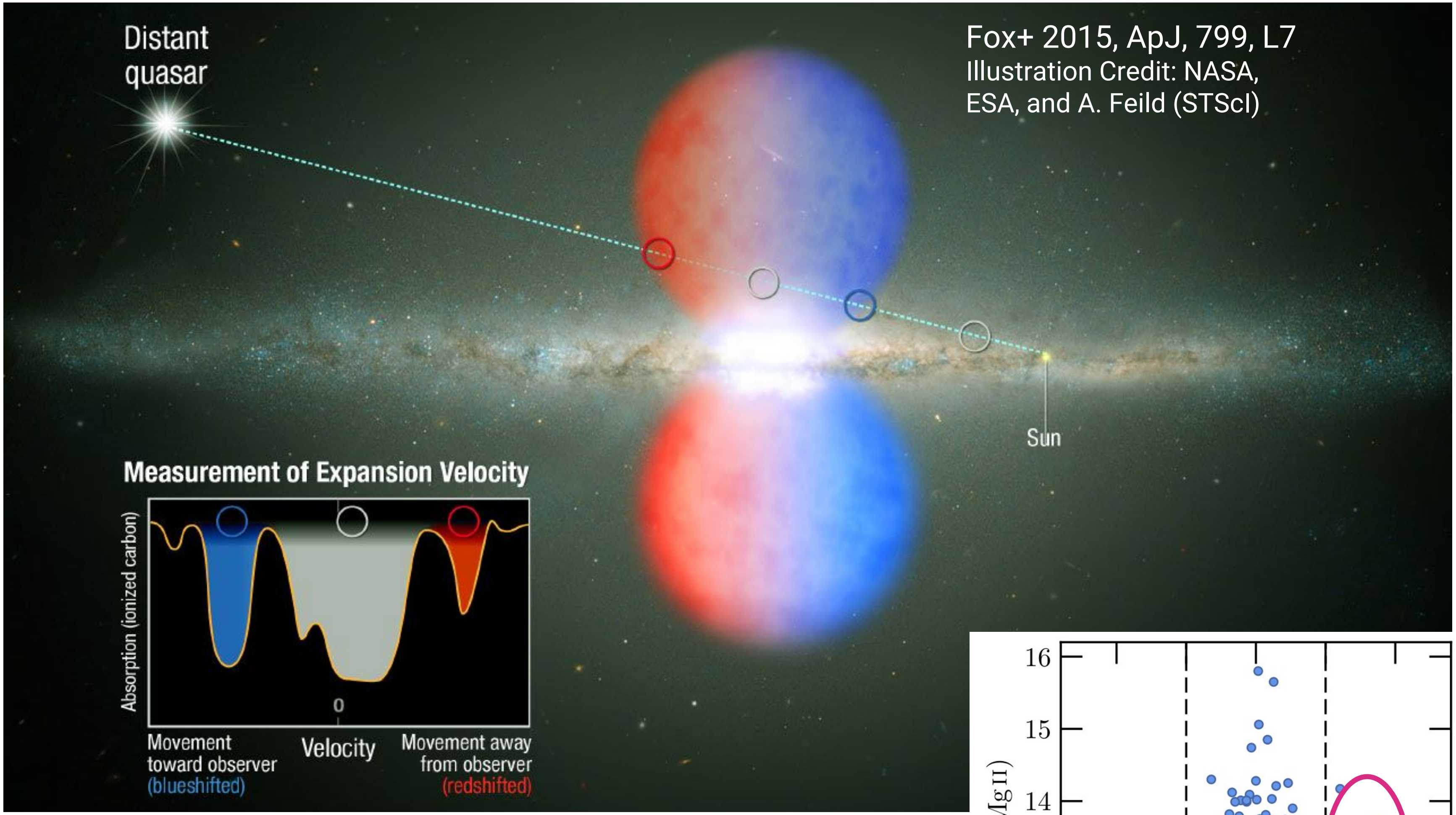
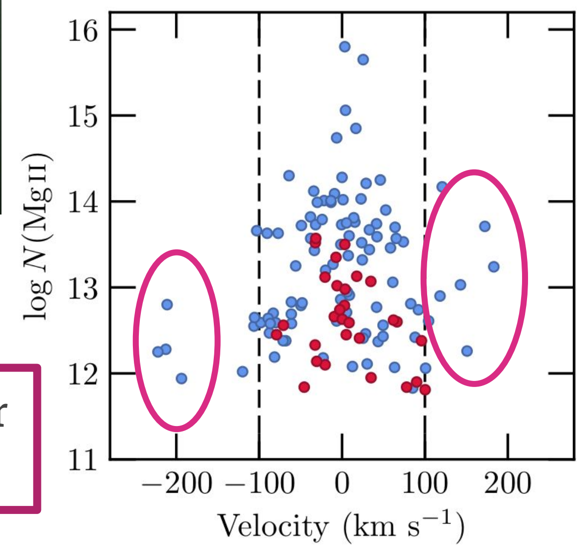
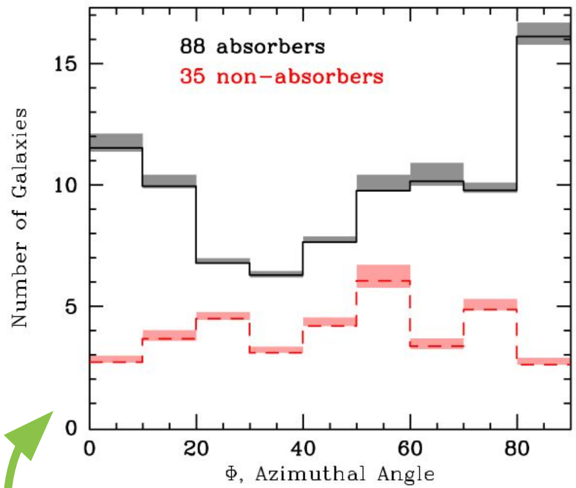
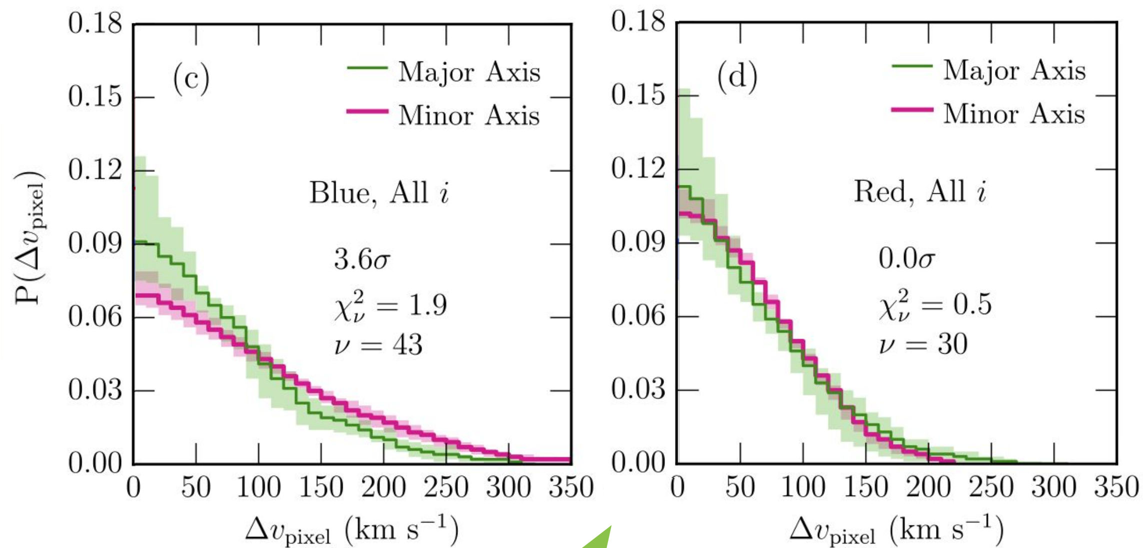




Milky Way Fermi Bubble

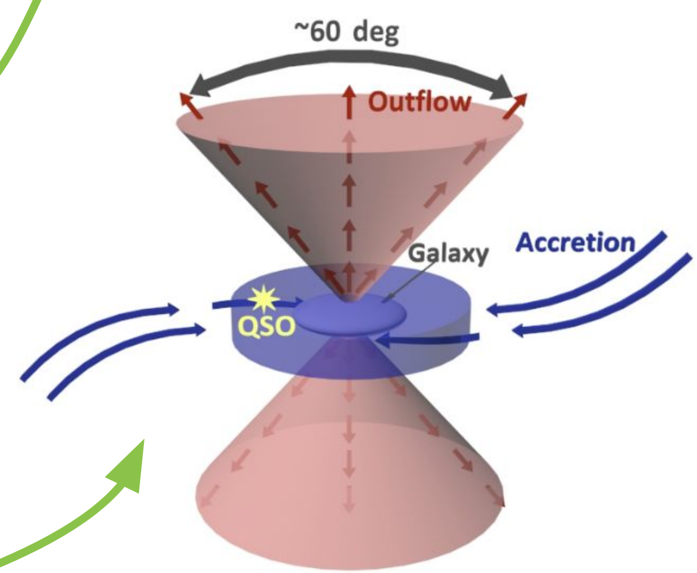
Minor Axis





MgII

- — ϕ distribution-dependent
- — kinematics dependent on galaxy orientation and color
- — traces outflows and accretion
- — outflows have largest absorber velocity spreads, clumpy



Bouché+ 2013, Science, 341, 50

Nielsen+ 2015, ApJ, 812, 83 (MAGIICAT V)

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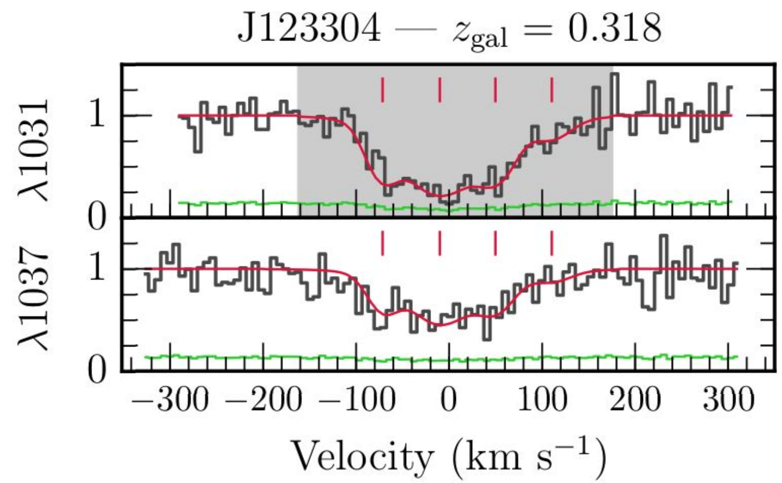


OVI doublet absorption: $\lambda\lambda$1031, 1037 Å

Most extensively studied by COS-Halos team

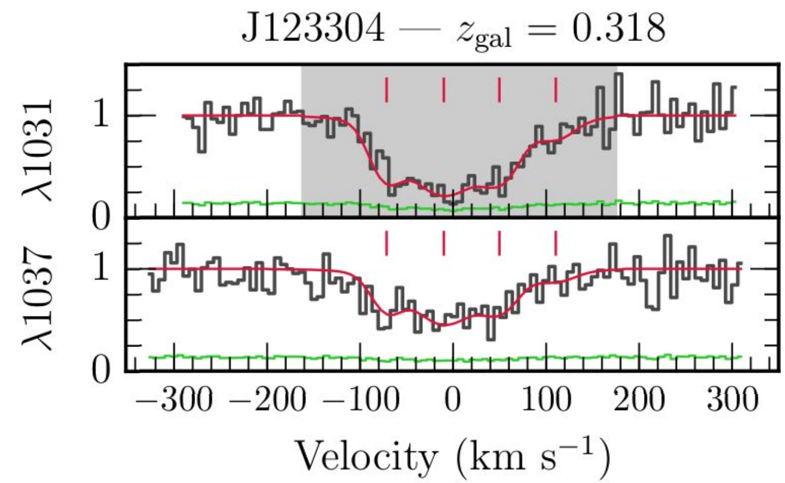
- Tumlinson+ 2011, 2013; Werk+ 2012, 2013, 2014, 2016
- Others: Tripp+ 2000; Prochaska+ 2011; Mathes+ 2014; Muzahid+ 2012 ...

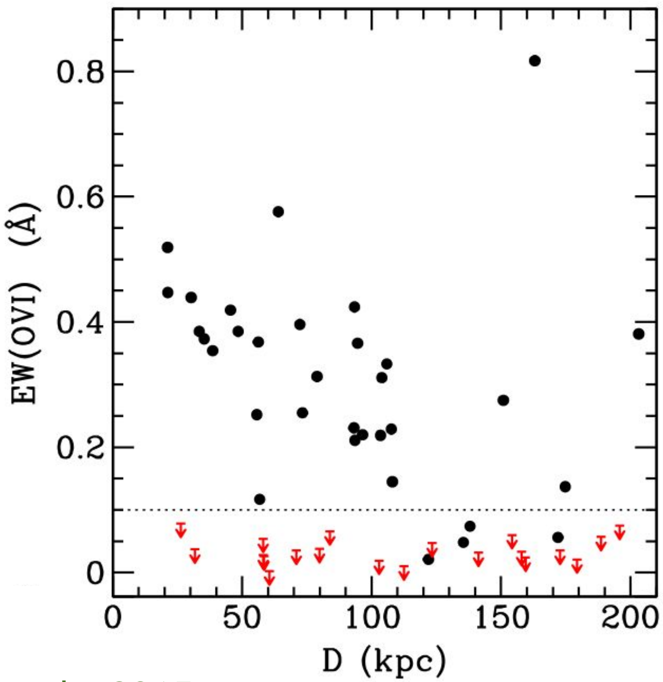
Observable in the UV at z<0.7 by Cosmic Origins Spectrograph on *HST*

Temperature: ranges from T=10$^{4.8}$ K (photoionized) to T=10$^{5.5}$ K (collisionally ionized)

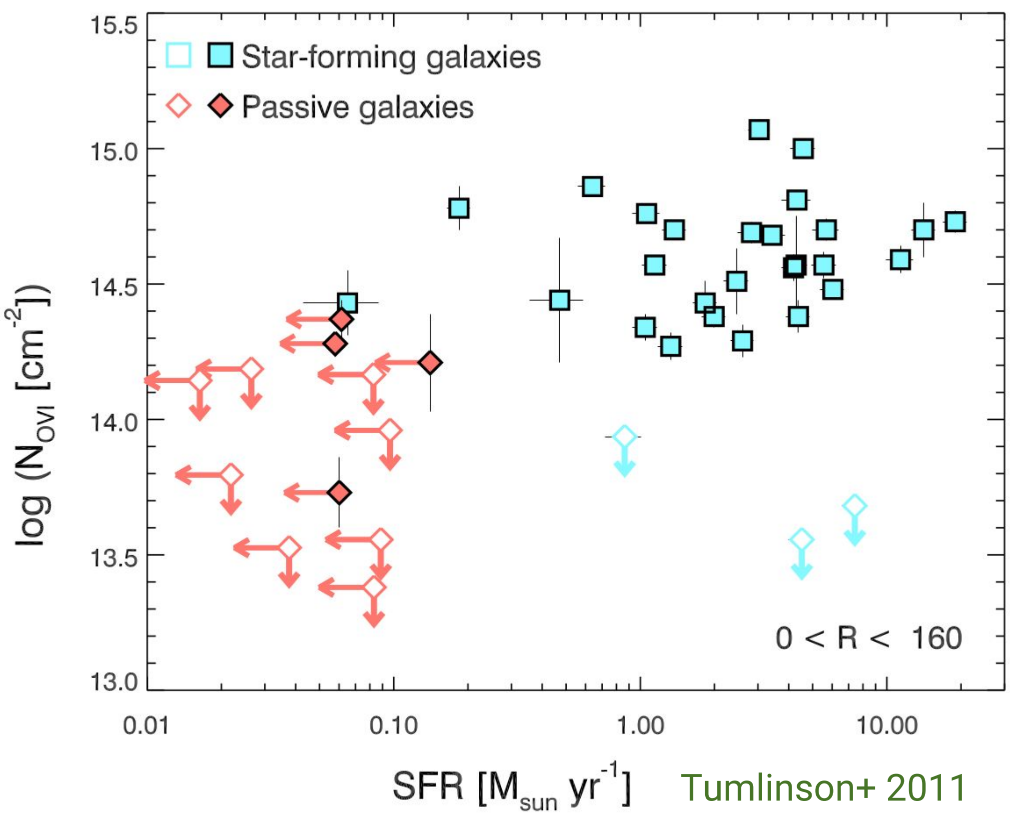
Density: n_H~10^{-4} g cm^{-3}

High Ionization CGM

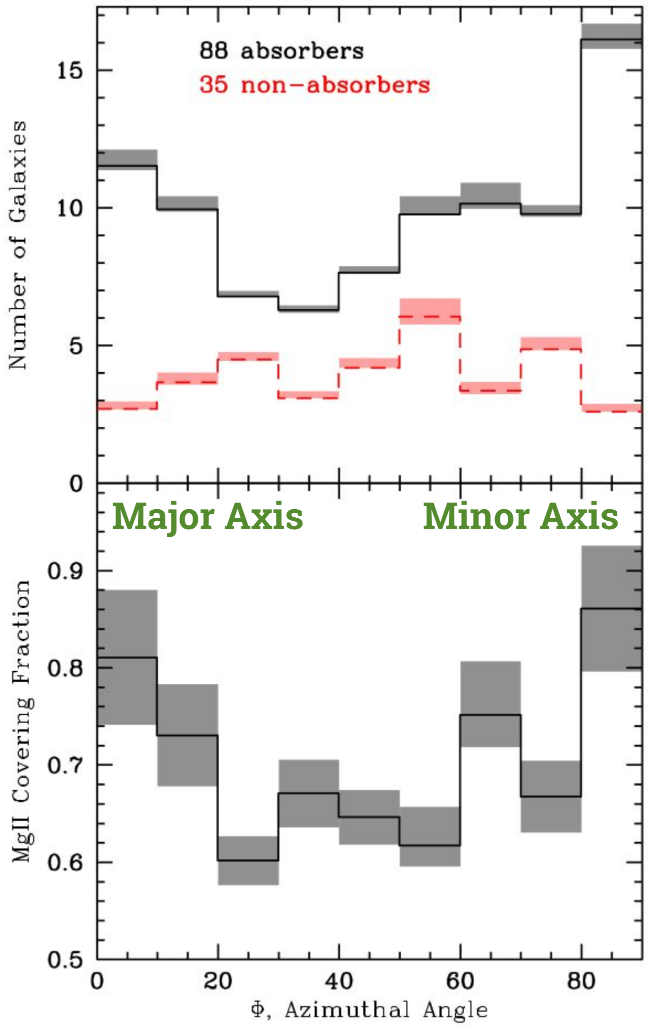




Kacprzak+ 2015



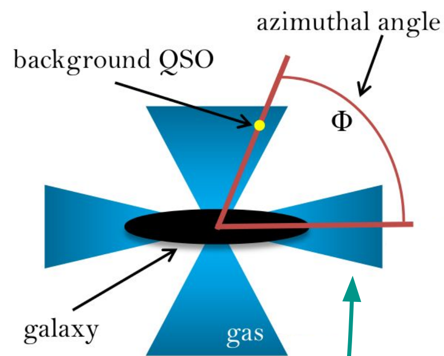
Tumlinson+ 2011



MgII

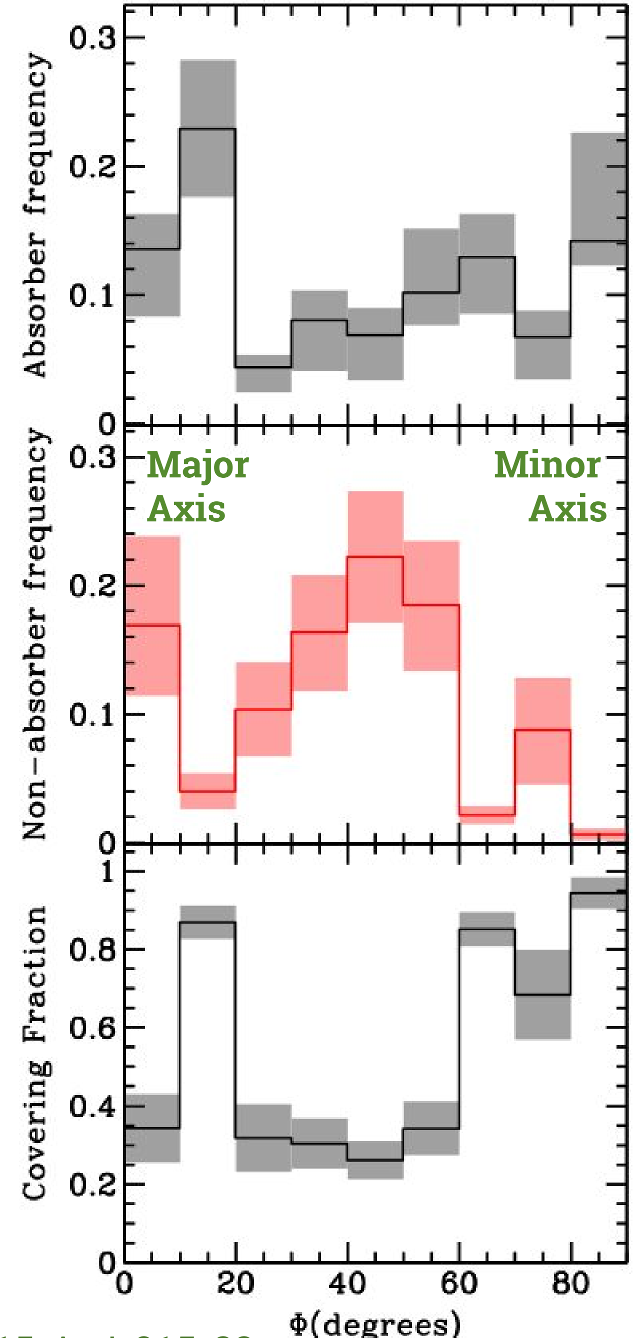
OVI

Toy model:



Bipolar outflows, Large EWs

Accretion, Rotation



Kacprzak, Churchill, Nielsen 2012, ApJ, 760, L7

Also see: Bordoloi+ 2011, Bouche+ 2012, Lan+ 2014

Azimuthal Angle Distribution

Kacprzak+ 2015, ApJ, 815, 22

Absorption Kinematics

+*HST* images

MgII

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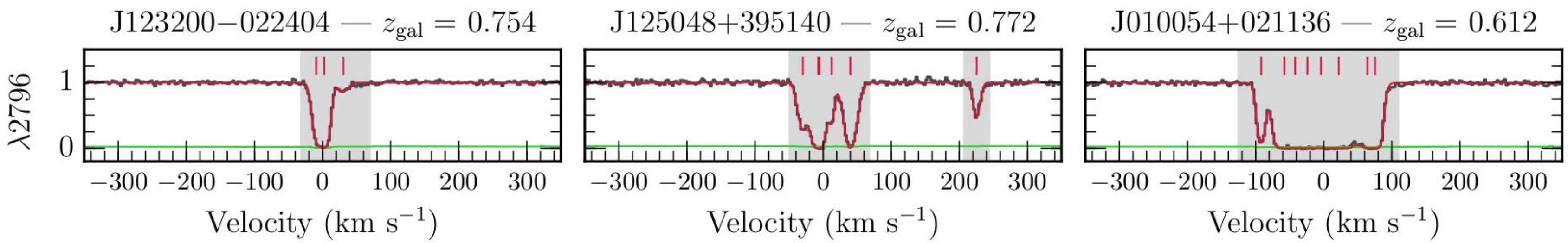
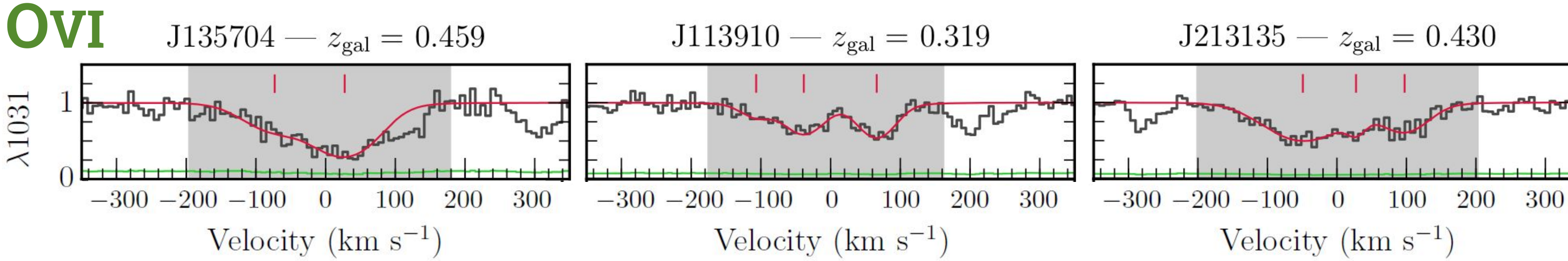


Multiphase Galaxy Halos: 29 absorbers with COS/*HST* spectra; $\boldsymbol{z=0.1\text{-}0.7}$

OVI



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MAGIICAT: Nielsen+ 2013a,b, 2015, 2016; Churchill+ 2013
Multiphase Galaxy Halos: Kacprzak+ 2015; Muzahid+ 2015; Nielsen+ 2017

30 MgII absorber–galaxy pairs
<z_{gal}> = 0.656

29 OVI absorber–galaxy pairs
<z_{gal}> = 0.244

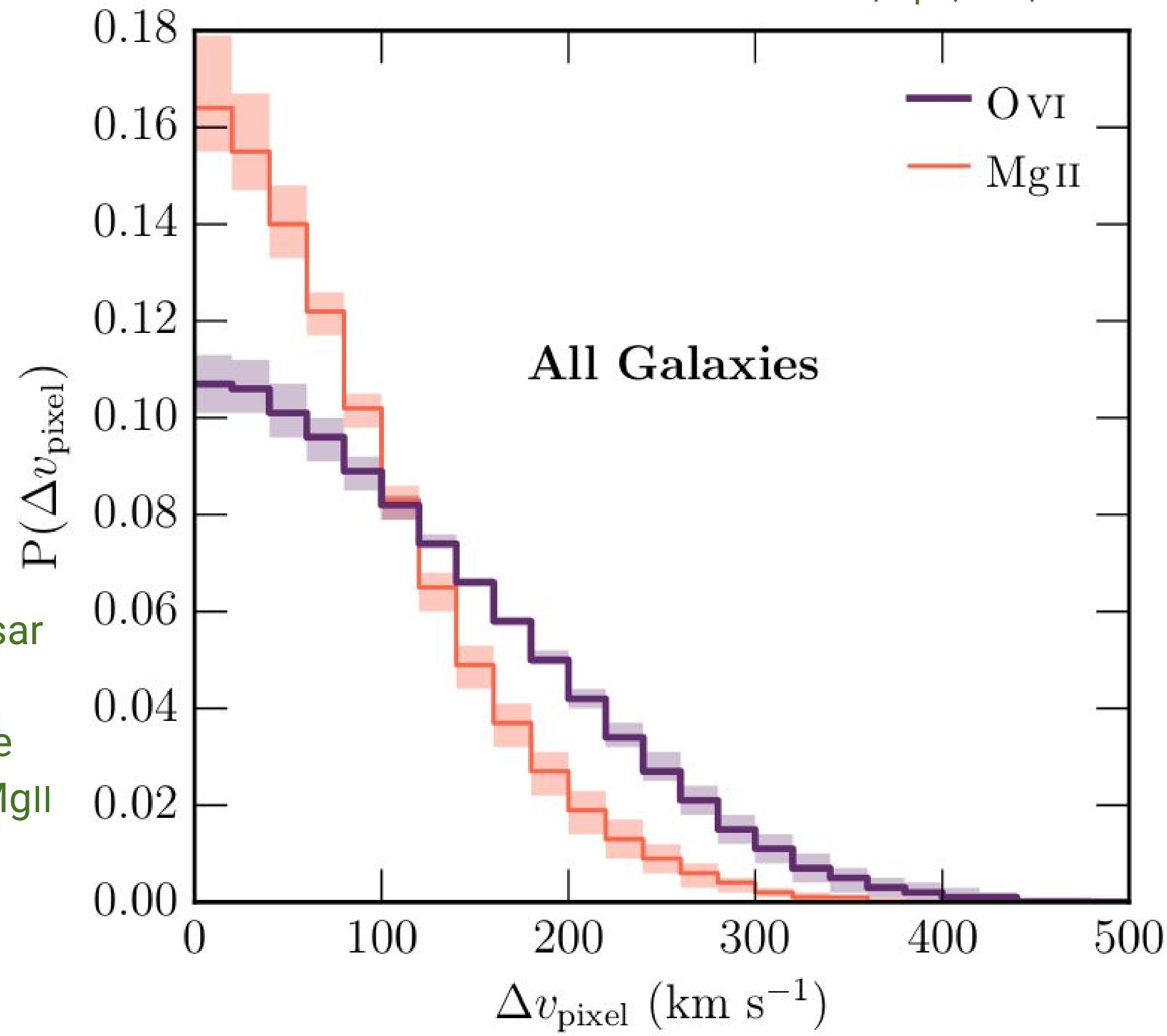
All isolated galaxies

Galaxies are within
D<200 kpc of background quasar

OVI absorbers statistically have larger kinematic spread than MgII

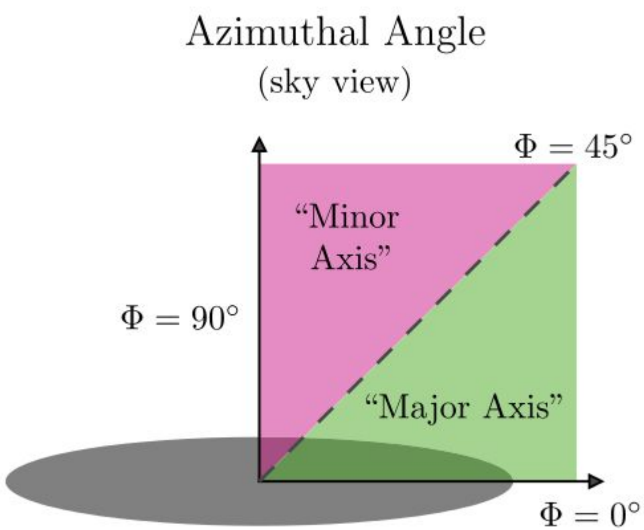
(all galaxies have *HST* images)

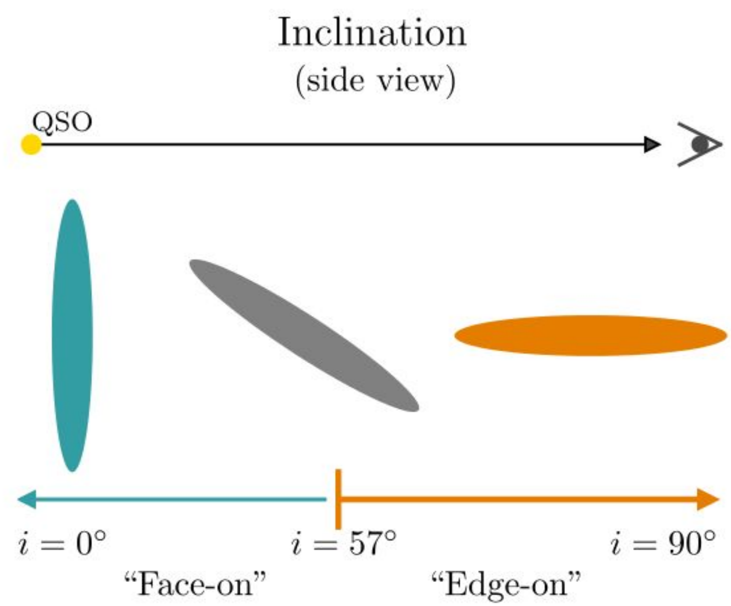
Nielsen+ 2017, ApJ, 834, 148



Full Sample Pixel-Velocity TPCFs

Galaxy Orientation Subsamples





$<i>=51^\circ$ for OVI

Galaxy Color Cuts	**MgII**	**OVI**
Blue Galaxies	*B−K < 1.4*	*B−K < 1.66*
Red Galaxies	*B−K ≥ 1.4*	*B−K ≥ 1.66*

Galaxies modeled with GIM2D in HST images

Nielsen+ 2015, ApJ, 812, 83 (MAGIICAT V)
Nielsen+ 2017, ApJ, 834, 148

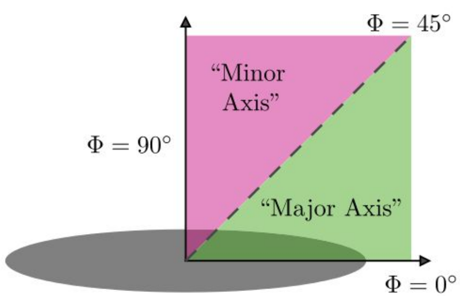
OVI

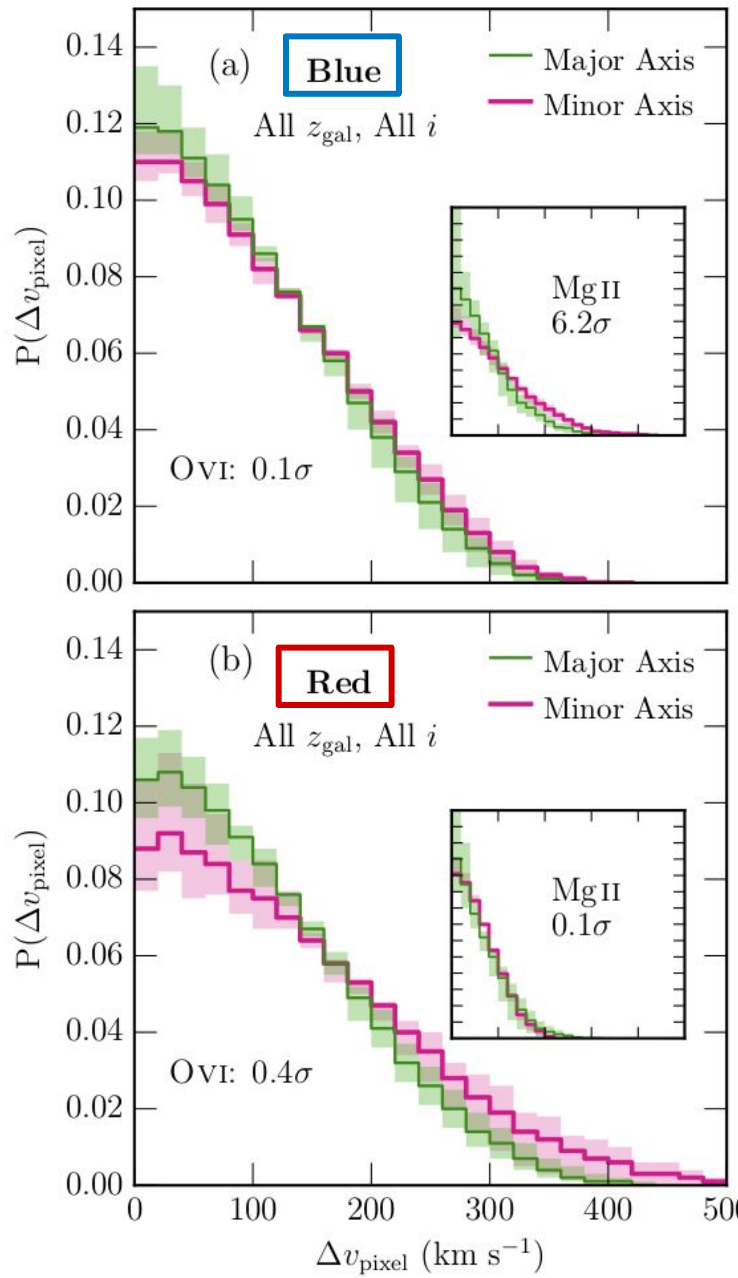
Color & Azimuthal Angle

No differences in the OVI TPCFs between subsamples

Kinematics are the same regardless of galaxy azimuthal angle and color subsample combinations

<B−K> = 1.66





Nielsen+ 2017, ApJ, 834, 148

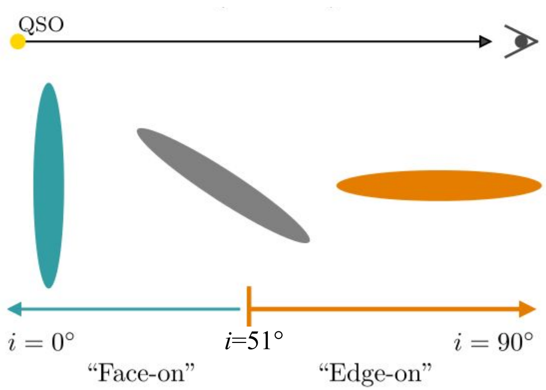
OVI

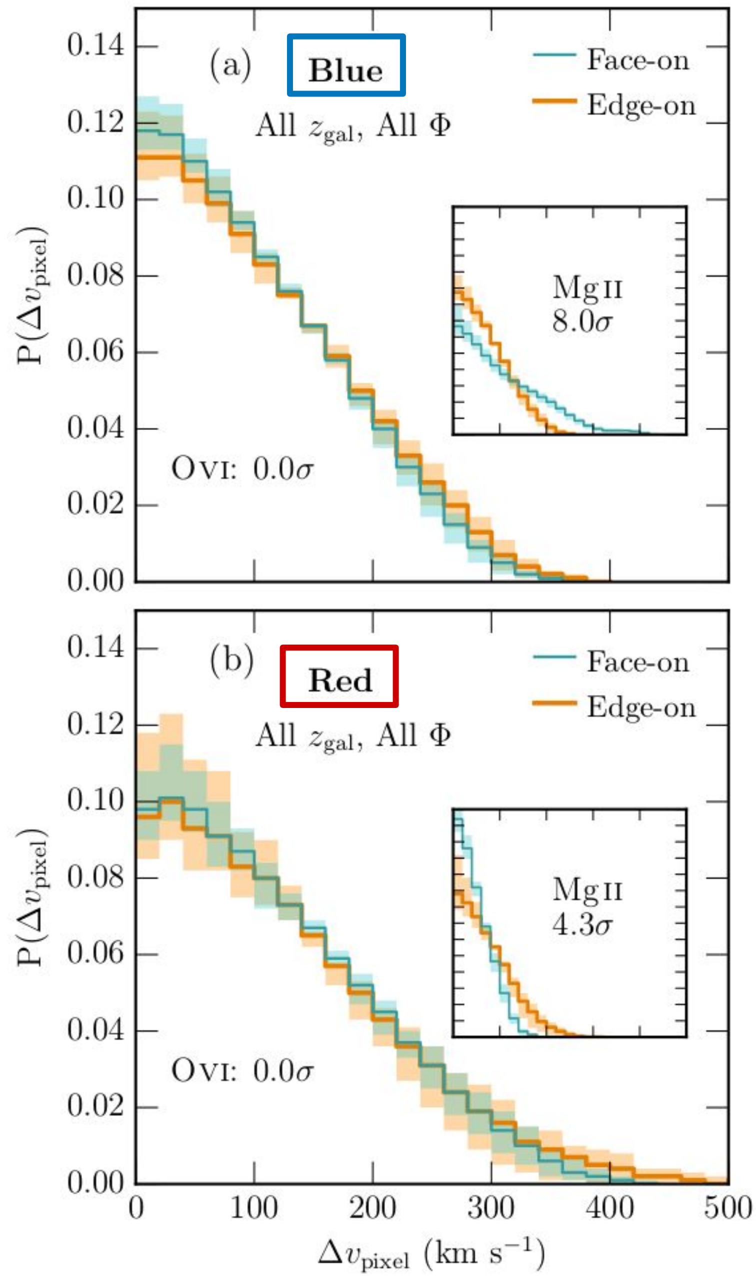
Color & Inclination

No differences in the OVI TPCFs between subsamples

Kinematics are the same regardless of galaxy inclination and color subsample combinations

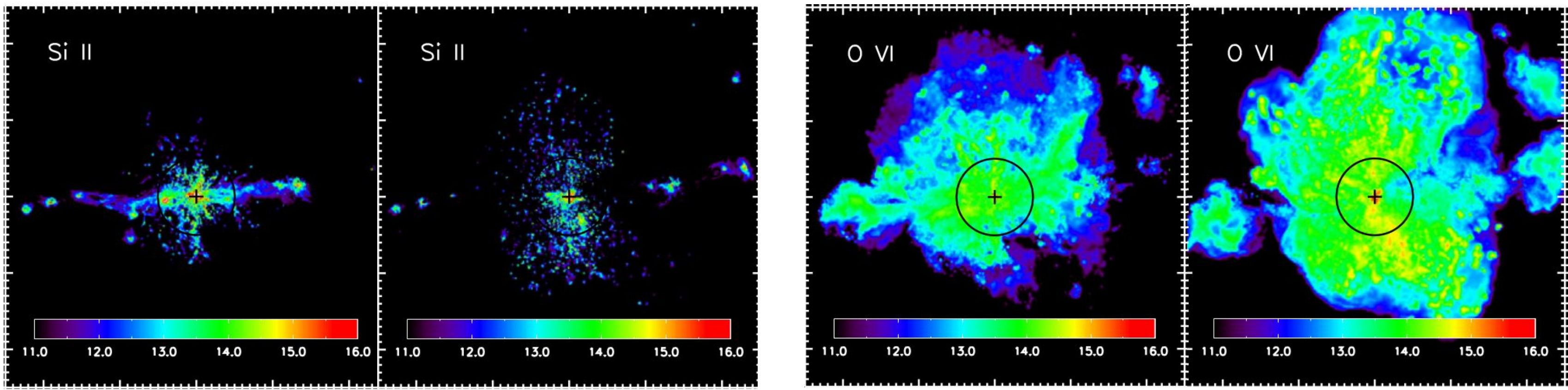
<B−K> = 1.66



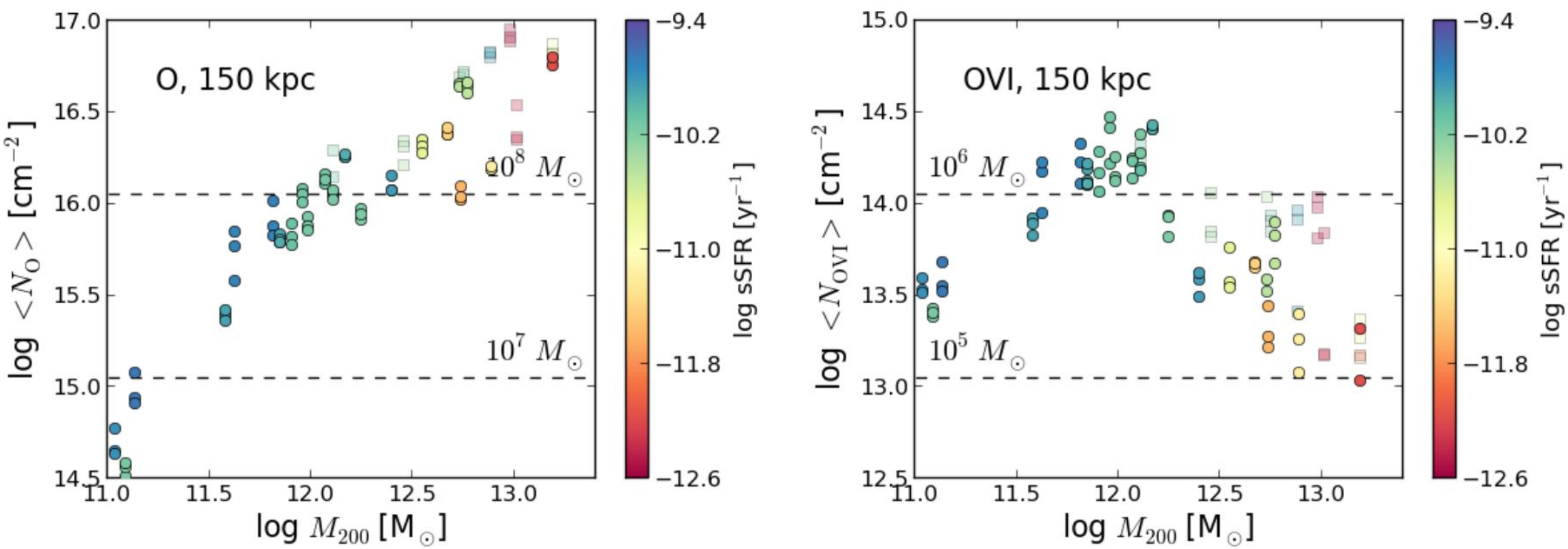


Nielsen+ 2017, ApJ, 834, 148

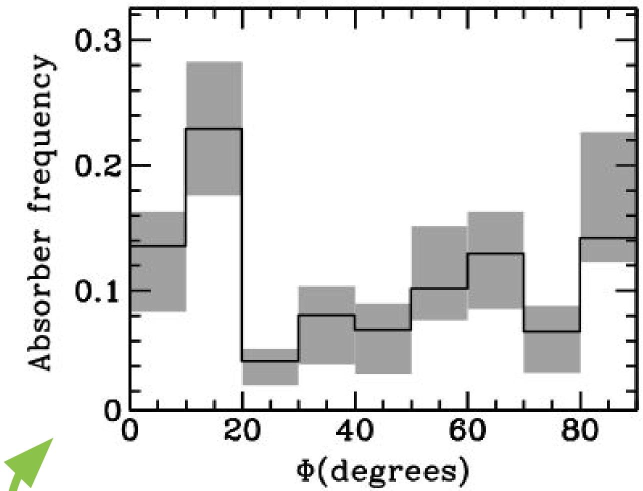
Infalling gas Outflowing gas Infalling gas Outflowing gas

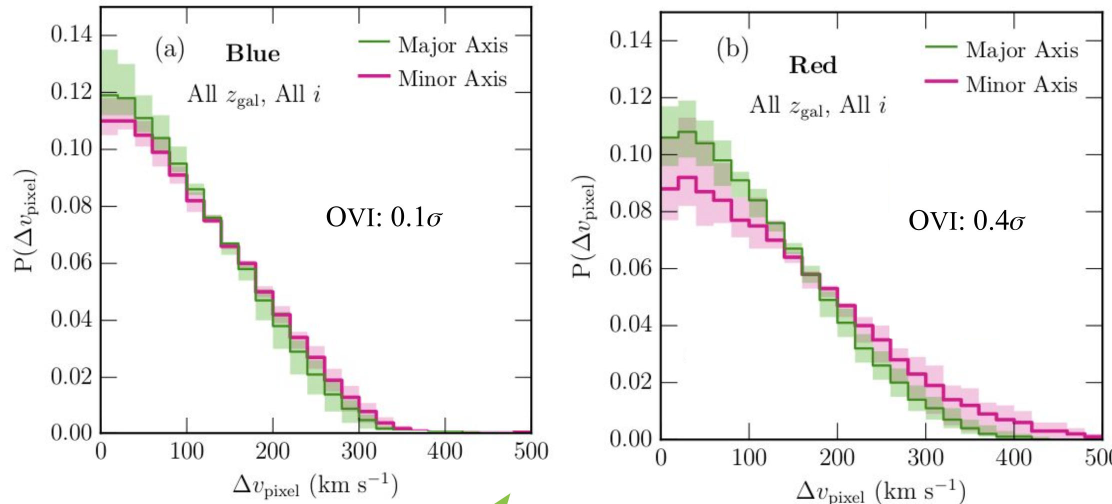


Shen+ 2013



Oppenheimer+ 2016

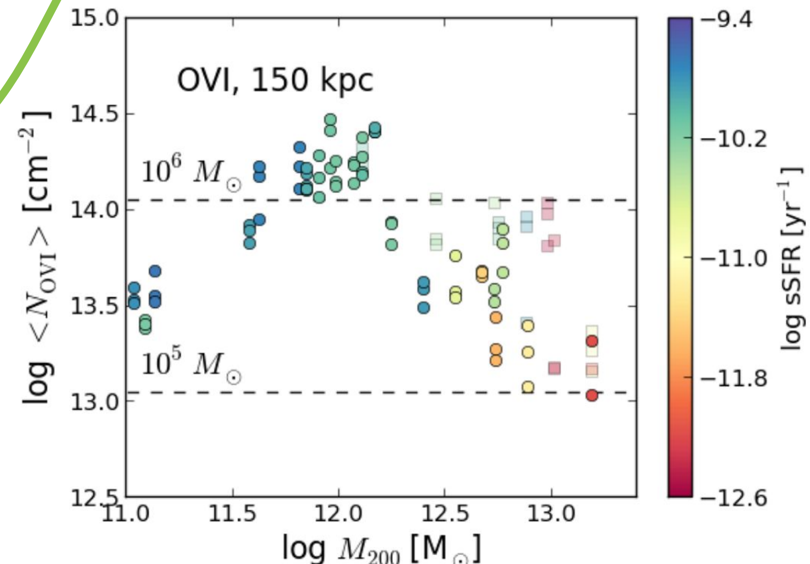




OVI

– ϕ distribution-dependent
– kinematically uniform

– ionization conditions?
ionized >OVI for ϕ~20°–50°?



Oppenheimer+ 2016
MNRAS, 460, 2157

Nielsen+ 2017, ApJ, 834, 148

Geometry and Kinematics of the CGM

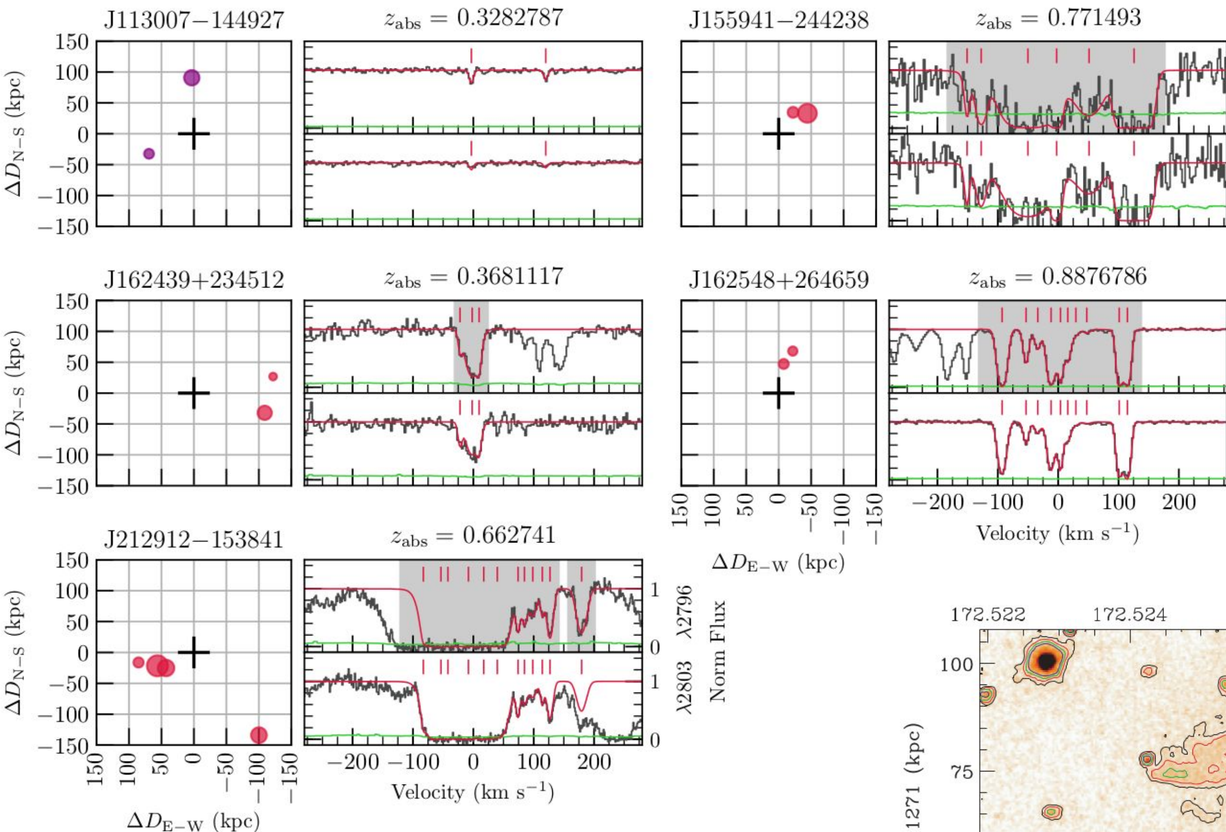
Galaxy Evolution and the Baryon Cycle

The Circumgalactic Medium (CGM) + Quasar Absorption Line Technique

Geometry + Kinematics of the Isolated Galaxy CGM:

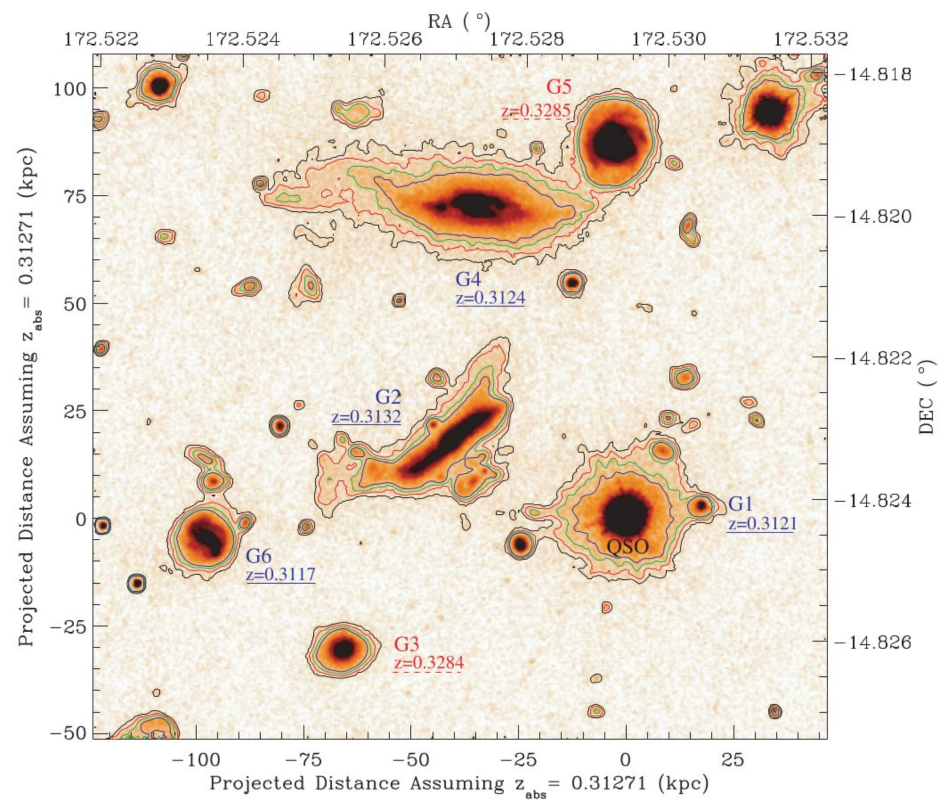
- Low Ionization CGM
- High Ionization CGM

Galaxy Environment



MgII

Nielsen+ in prep

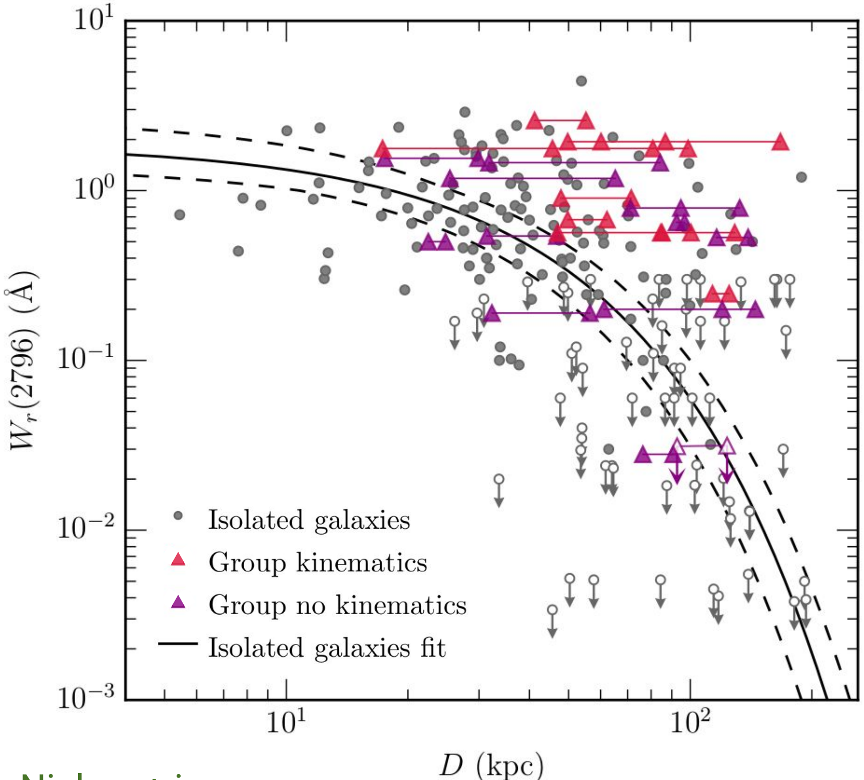


Kacprzak+ 2010

New:

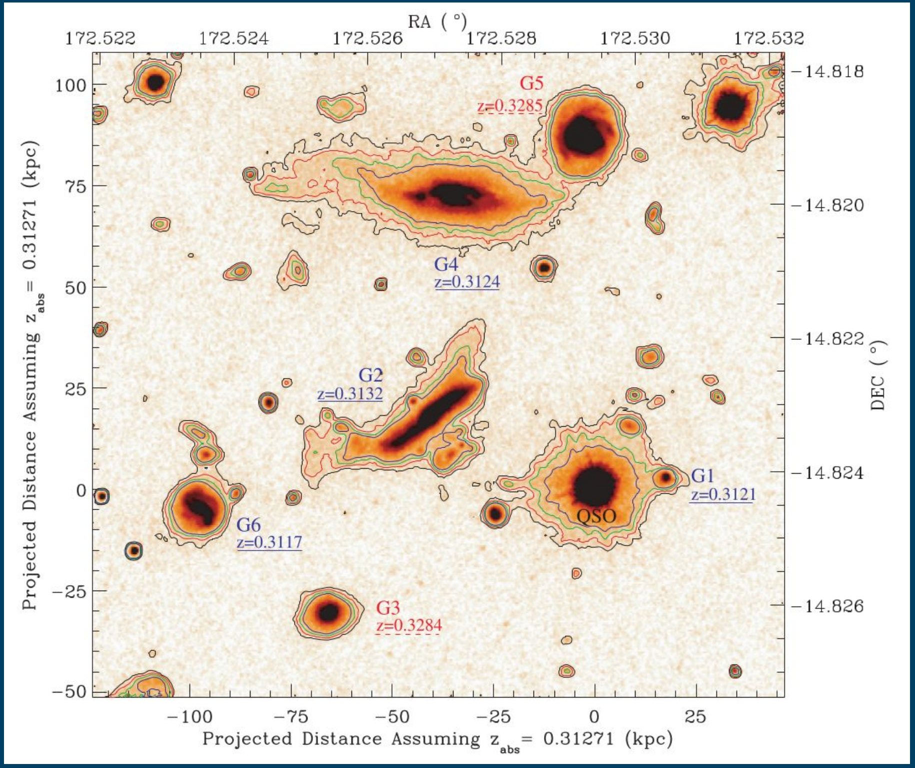
Galaxy Environment

MgII

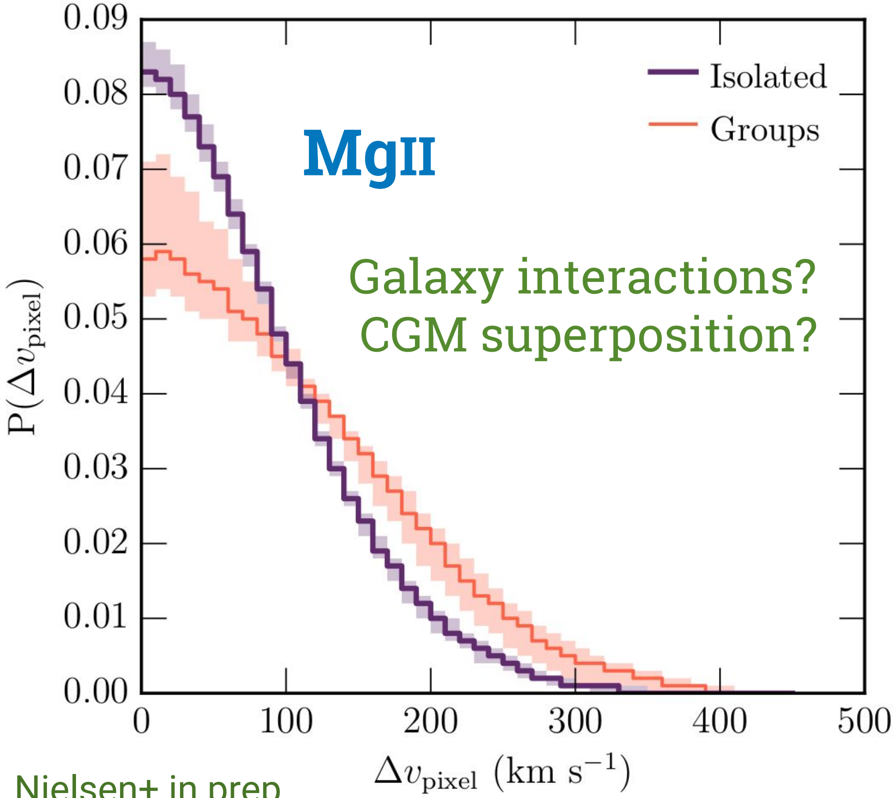


Nielsen+ in prep

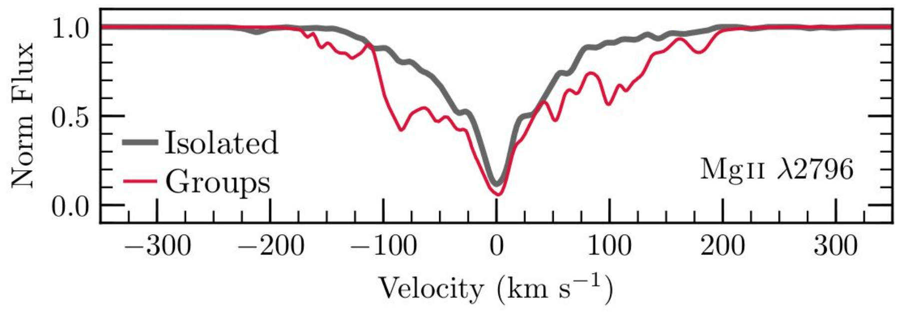
New:
Galaxy Environment



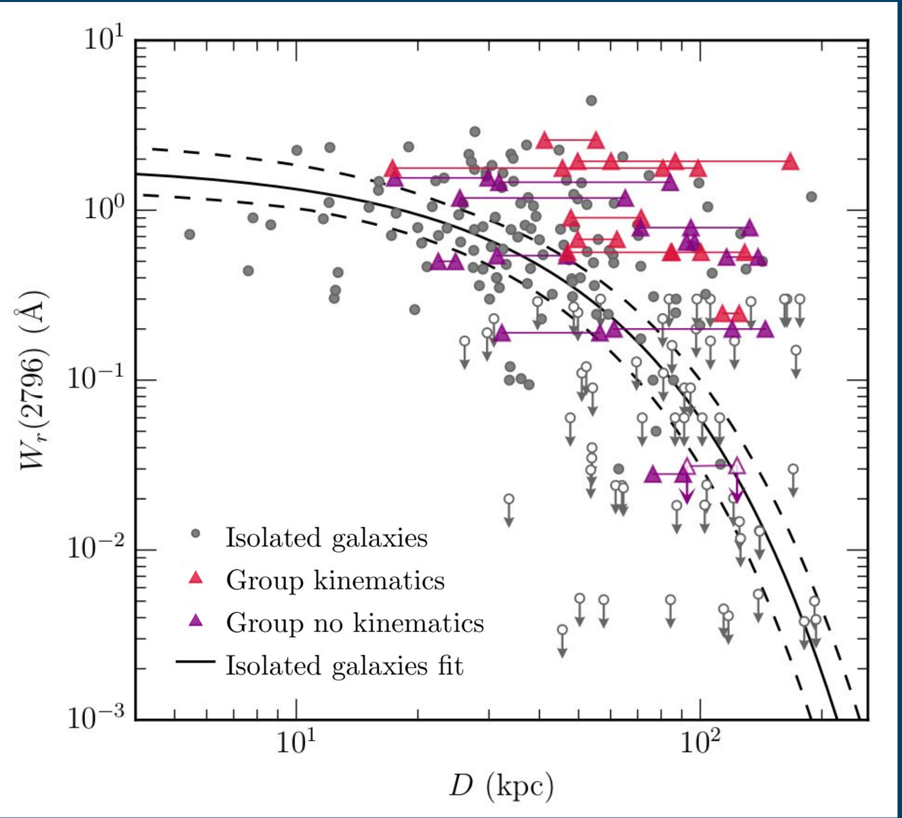
Kacprzak+ 2010



Nielsen+ in prep

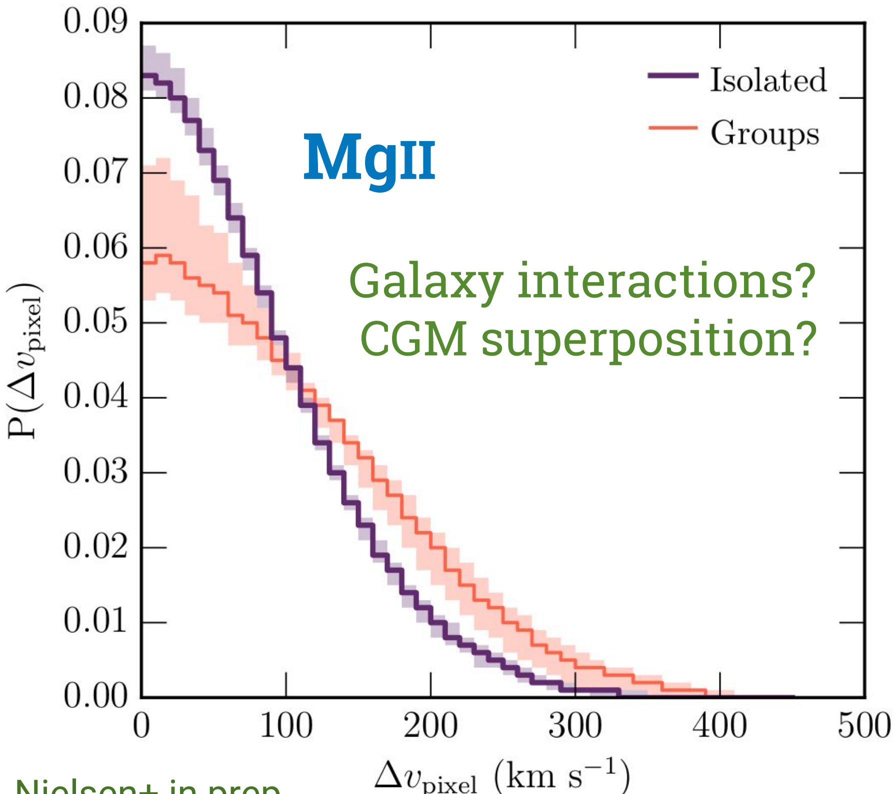


Nielsen+ in prep

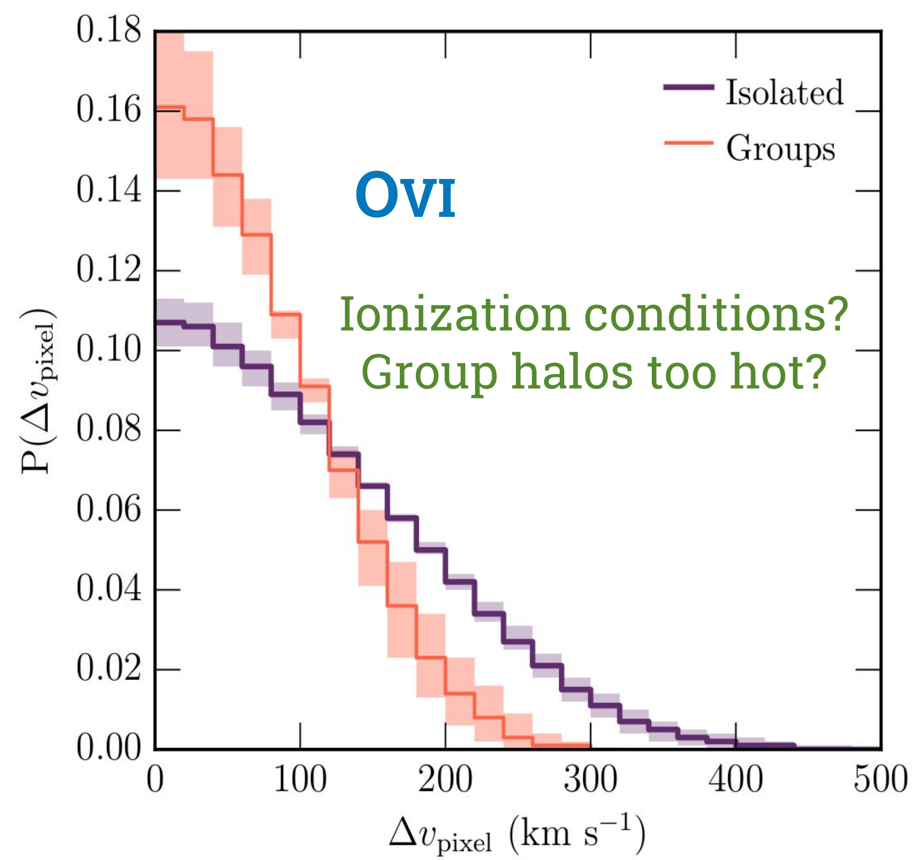


New:
Galaxy Environment

Stephanie Pointon
Swinburne PhD Student



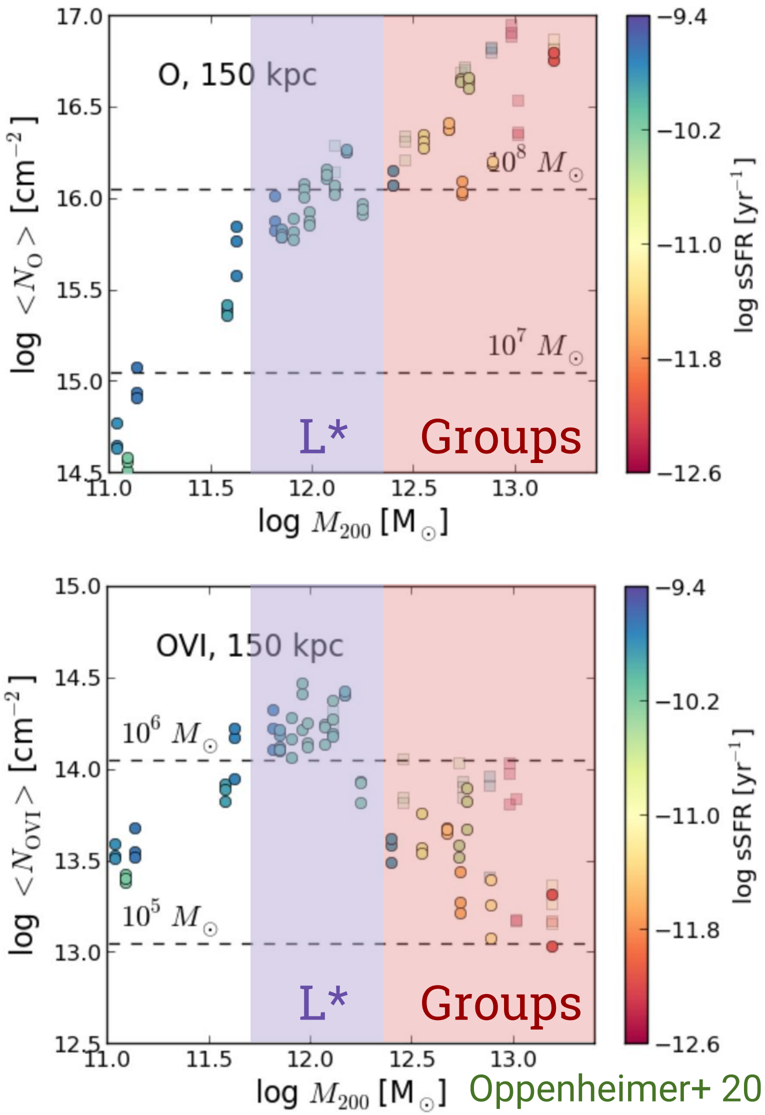
Nielsen+ in prep



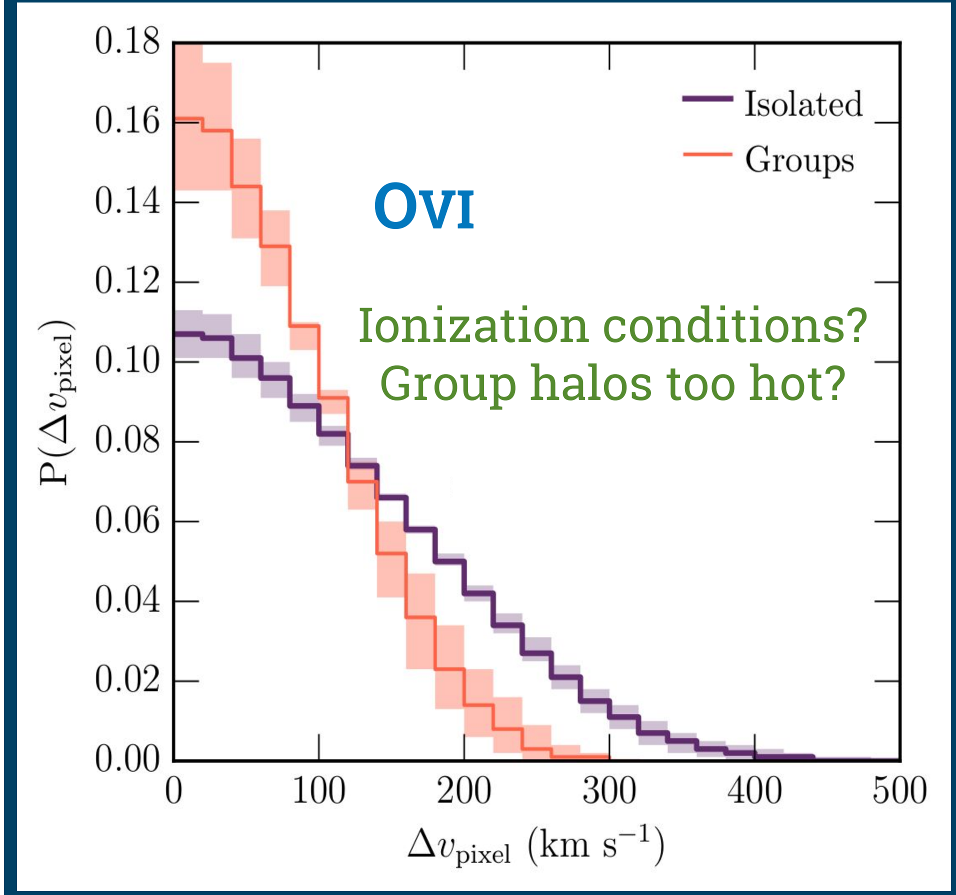
Pointon, Nielsen+ ApJ, submitted

New:
Galaxy Environment

Stephanie Pointon
Swinburne PhD Student



Oppenheimer+ 2016
MNRAS, 460, 2157



Pointon, Nielsen+ ApJ, submitted

New:
Galaxy Environment

Summary

Low Ionization CGM (MgII)

Presence of gas is azimuthal angle dependent: prefers **major** and **minor** axes

Largest absorber velocity dispersions for **blue**, **face-on**, and **minor axes** galaxies

Outflowing gas appears to be clumpy

Accreting/rotating gas has smaller velocity dispersions and larger column densities

Red galaxies may have rotating gas, but little/no outflowing gas

High Ionization CGM (OVI)

Presence of gas is azimuthal angle dependent: prefers **major** and **minor** axes

Kinematics same regardless of galaxy color, azimuthal angle, or inclination

Ionization conditions vary with azimuthal angle?

Galaxy Environments

Galaxy interaction signatures in MgII?

CGM too hot in OVI?