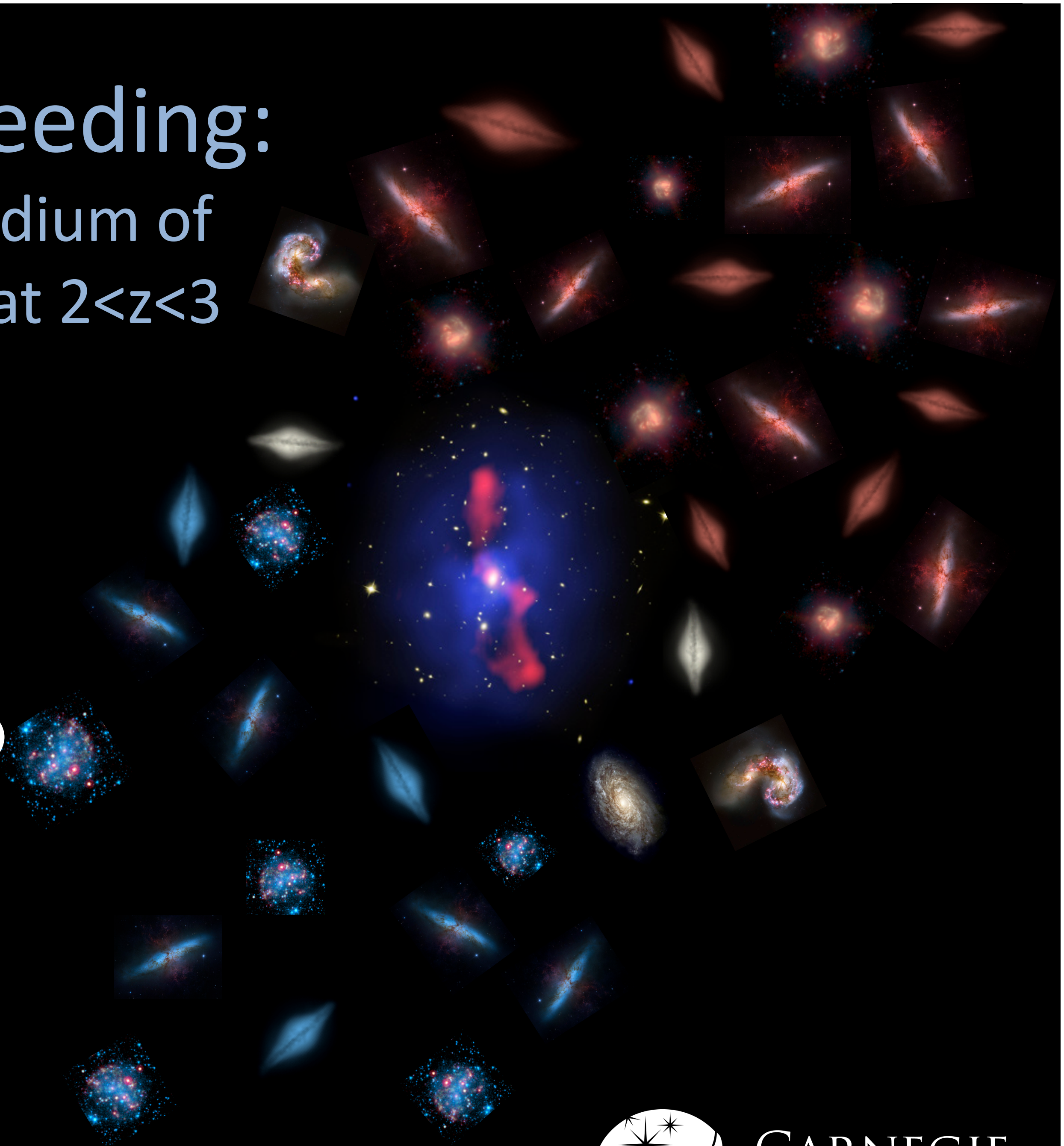
Feedback and Feeding:

The Circumgalactic Medium of Star-Forming Galaxies at $2<z<3$

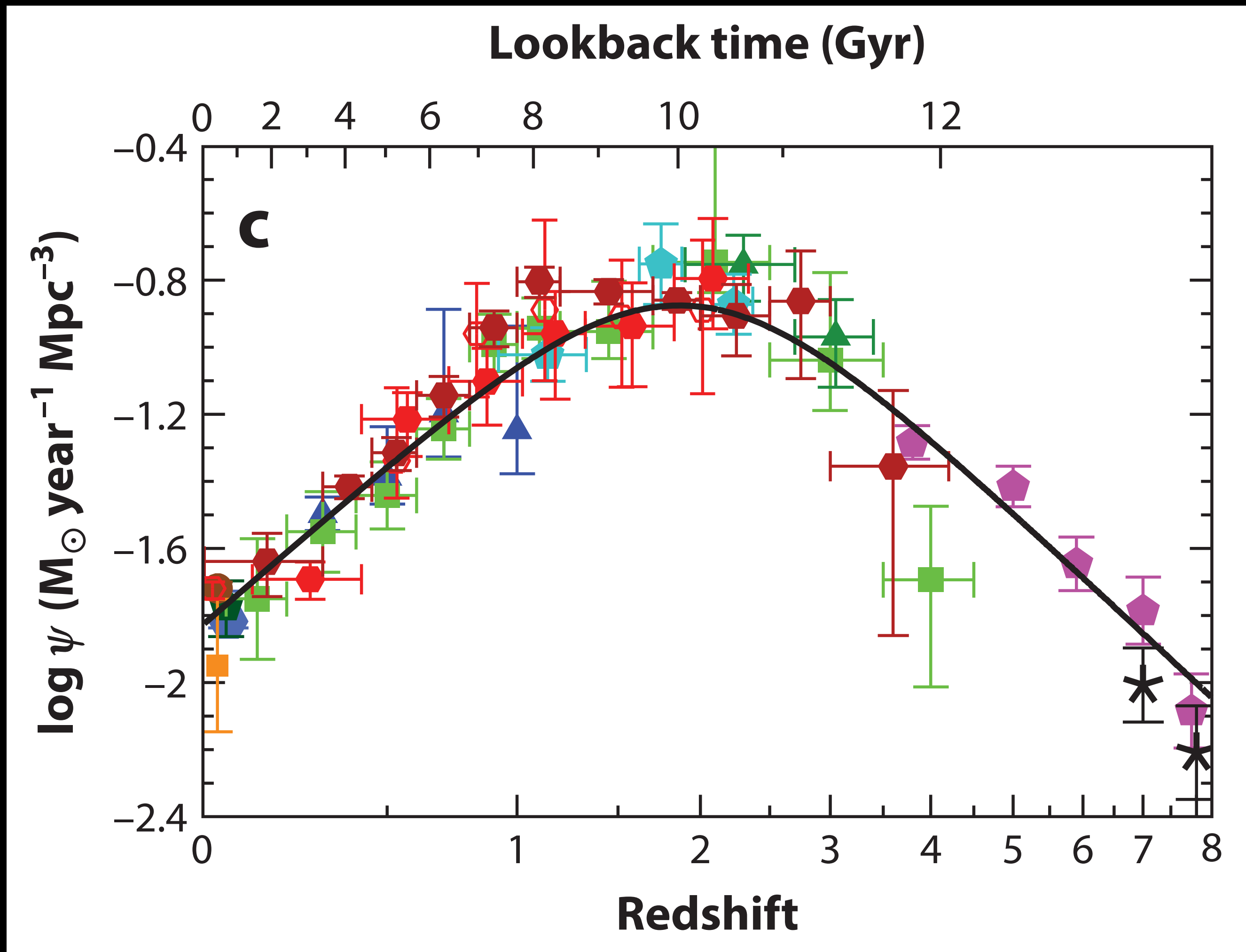
Gwen Rudie (Carnegie)

Allison Strom (Carnegie)
Cameron Hummels (Caltech)
Chuck Steidel (Caltech)
Max Pettini (Cambridge)
Ryan Trainor (Franklin & Marshall)
Naveen Reddy (UC Riverside)
Alice Shapley (UCLA)



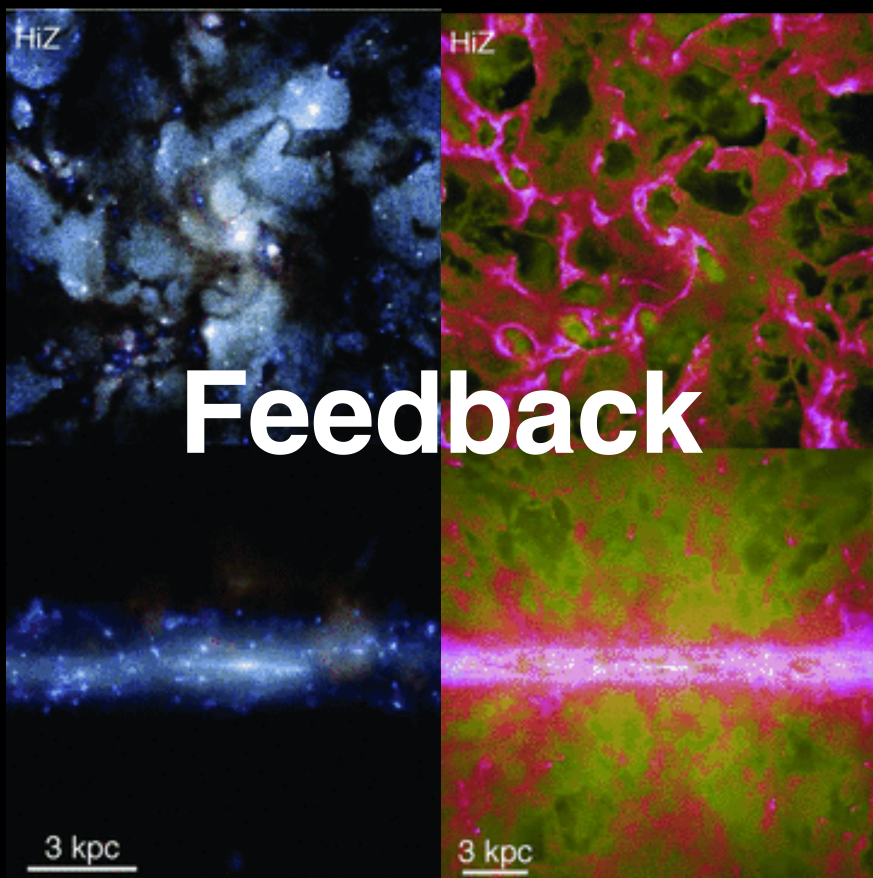
Carnegie Science

The Cosmic Peak of Star Formation

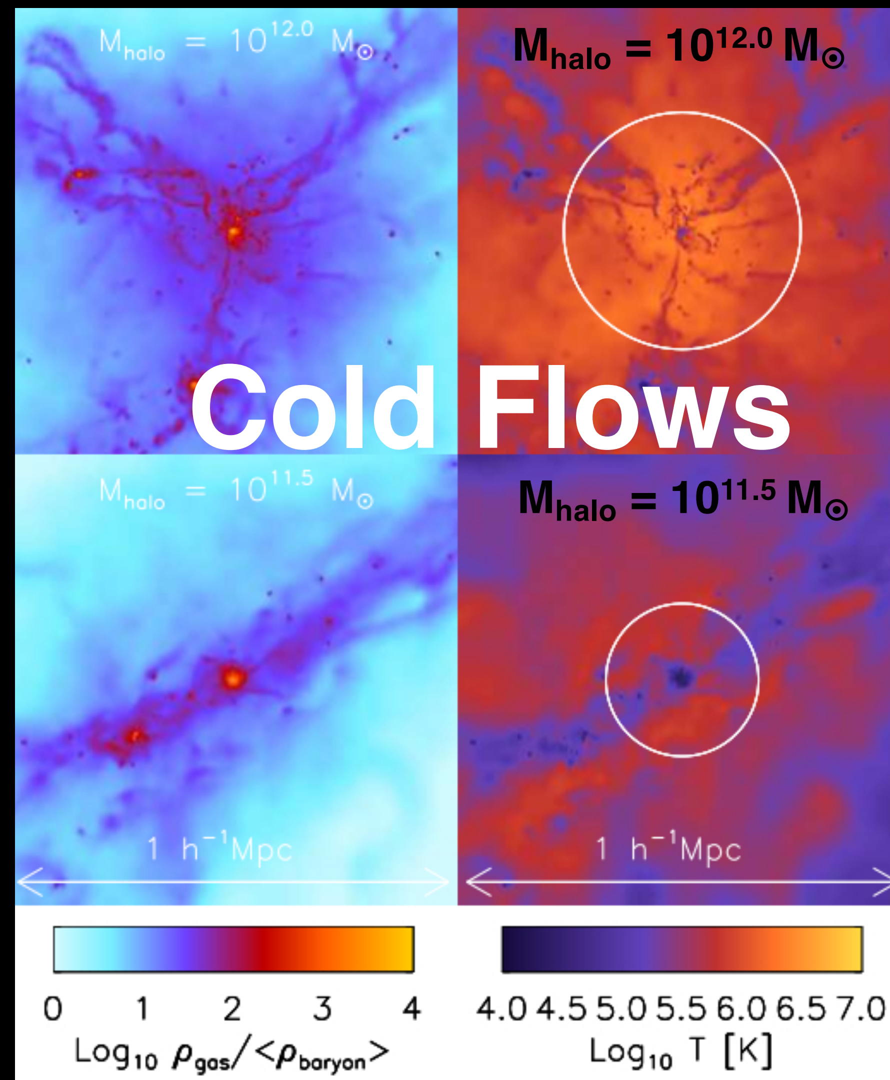


Madau & Dickinson 2014

The Cosmic Peak of Gas Flows

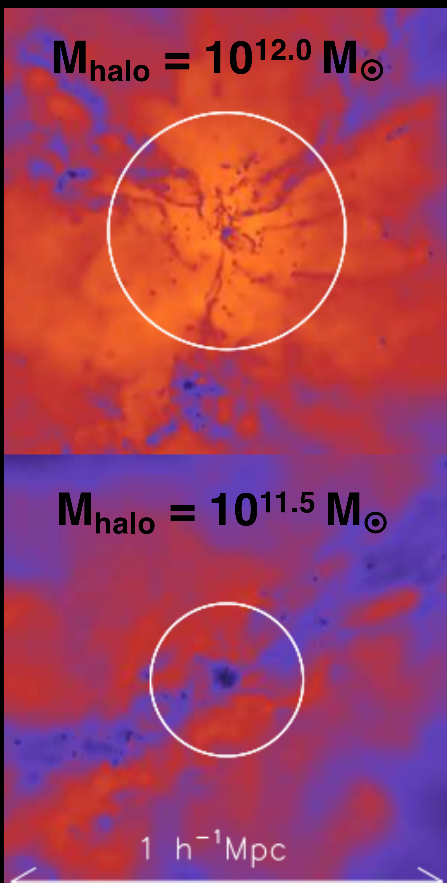


Hopkins, Quataert, & Murray 2012

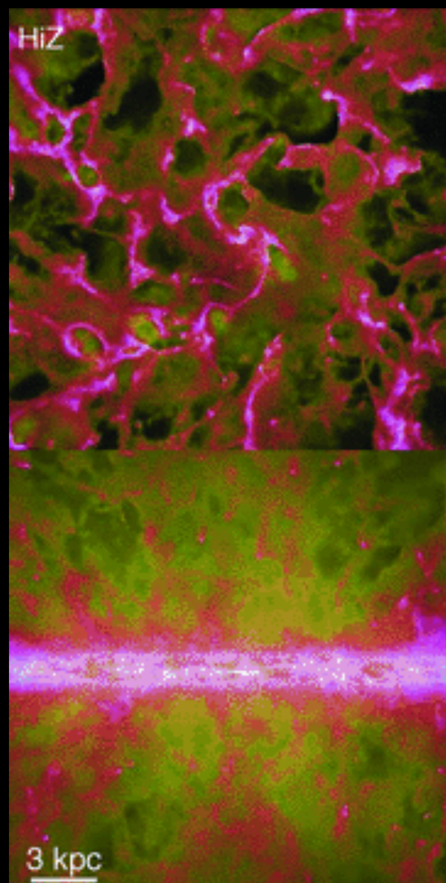


van de Voort, et al. 2010

Understanding How Gas Flows Shape and Regulate Galaxies



van de Voort, et al. 2011



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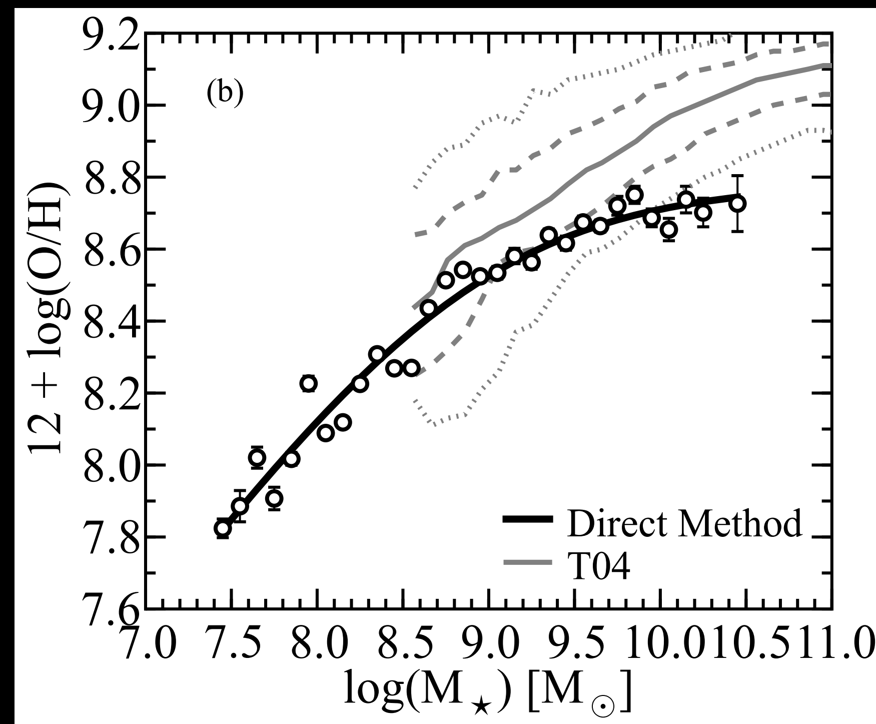
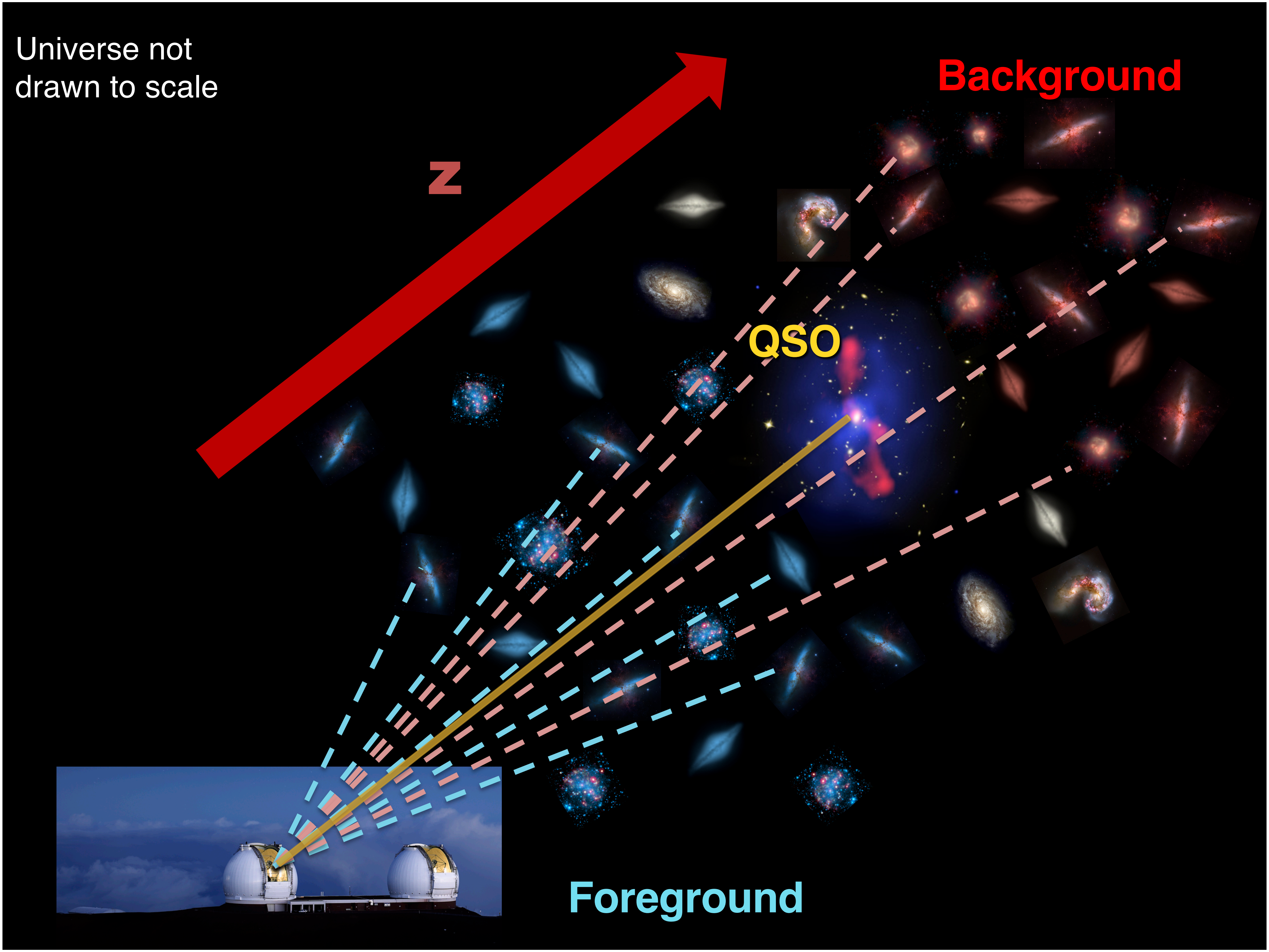


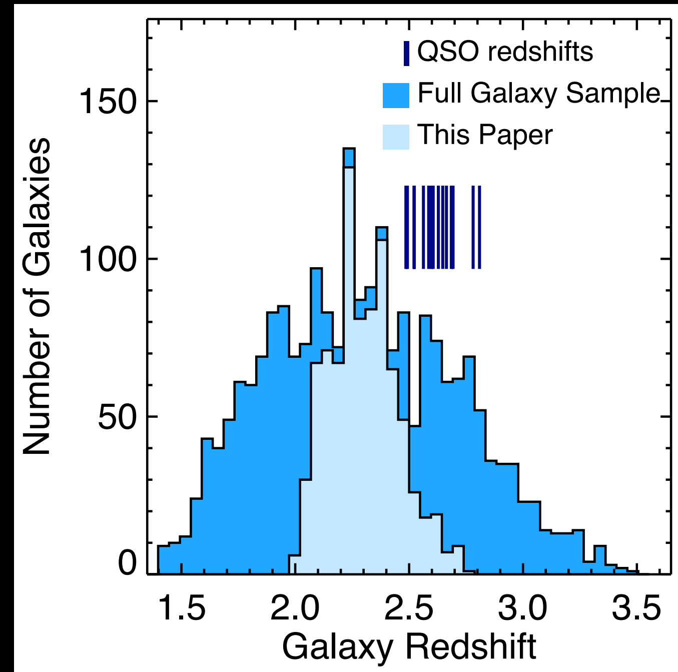
Andrews & Martini 2013

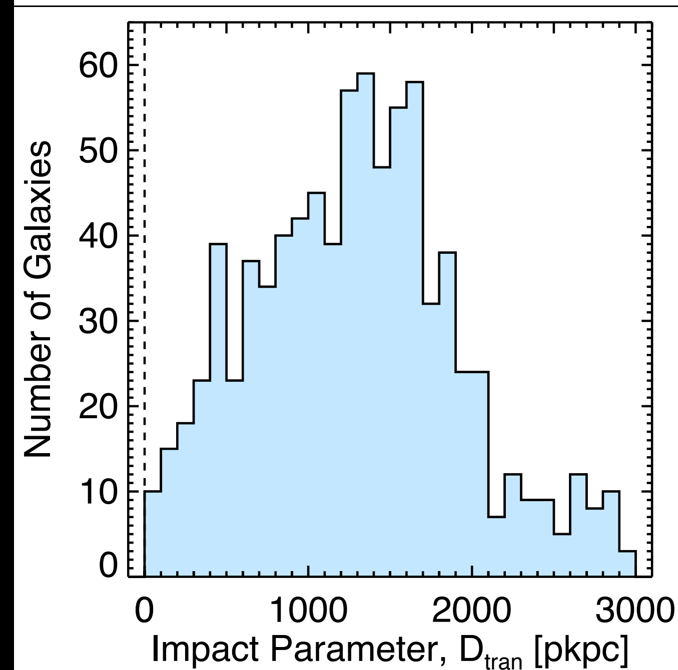


Universe not drawn to scale
z
Background
QSO
Foreground

The Keck Baryonic Structure Survey

- 15 fields with the brightest QSOs in the sky $2.5 < z < 2.9$ at the Peak Epoch of Star Formation
- HIRES QSO spectra
  - 7 km/s resolution
  - S/N 50 – 200 (Lyα)
- Large Galaxy Redshift Survey
  - >2300 galaxies with Keck/LRIS
  - >1100 galaxies with Keck/MOSFIRE
    - ~400 with J, H, and K bands
  - >900 with CGM constraints
- Focus on 8 galaxies probed @ $R<R_{vir}$

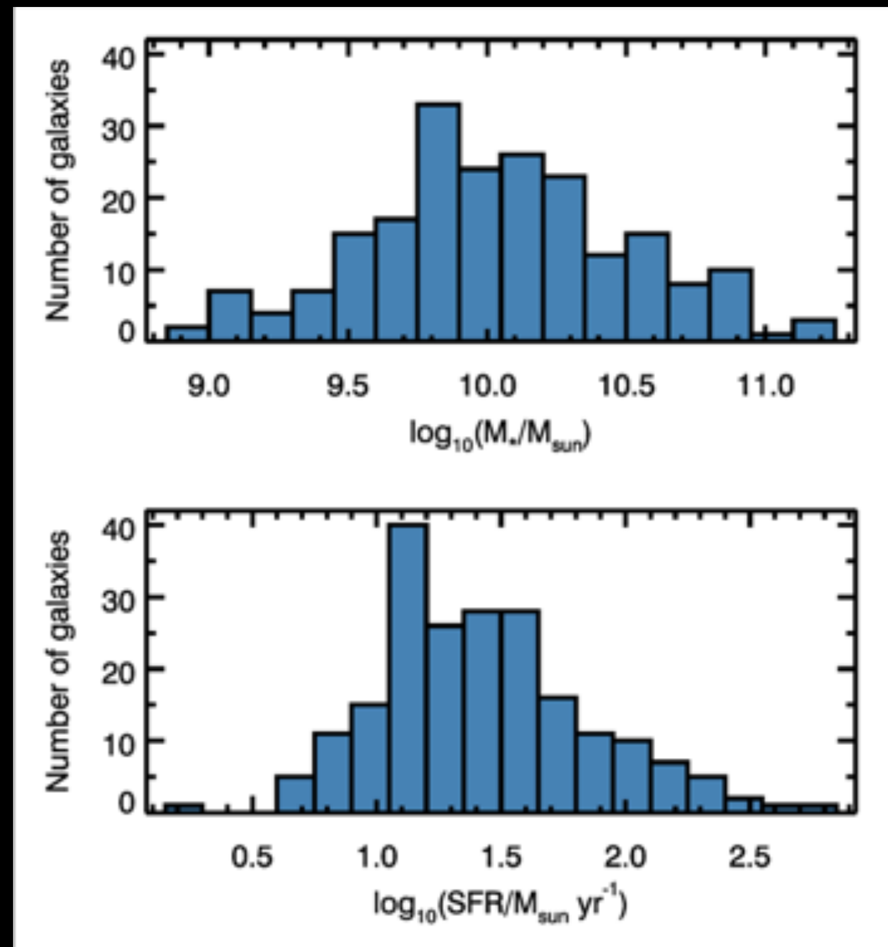




GCR+ 2012a

The KBSS Galaxy Sample

- $0.25\ L^* < L < 3\ L^*$
- 30 Myr < Age < 3 Gyr
- SFR ~ 3-300 $M_\odot$/yr
- $10^9 < M_* < 10^{11}\ M_\odot$
- $\langle M_{DM} \rangle \sim 10^{11.9}\ M_\odot$
- Virial Radius ~ 90 kpc



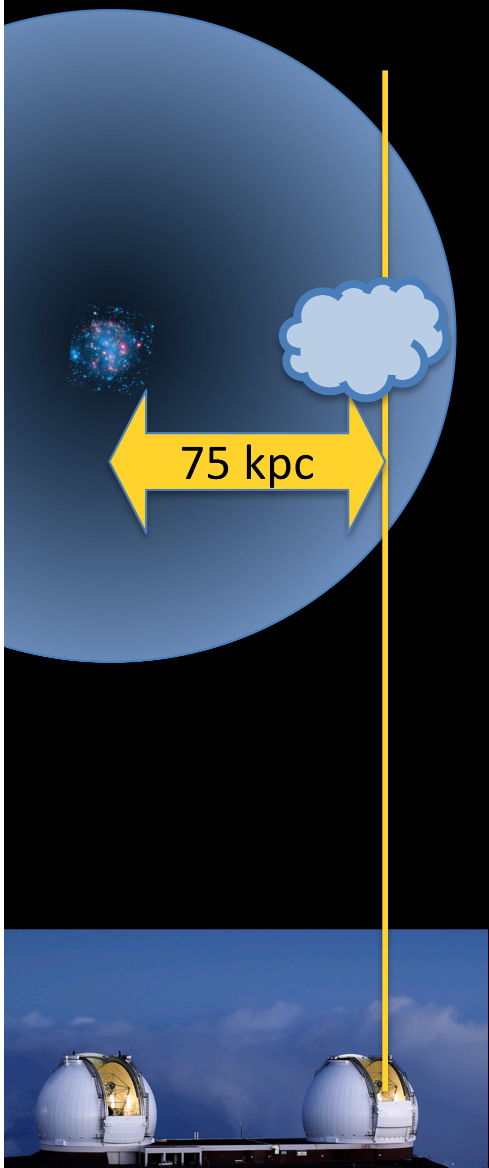
Strom et al. 2017

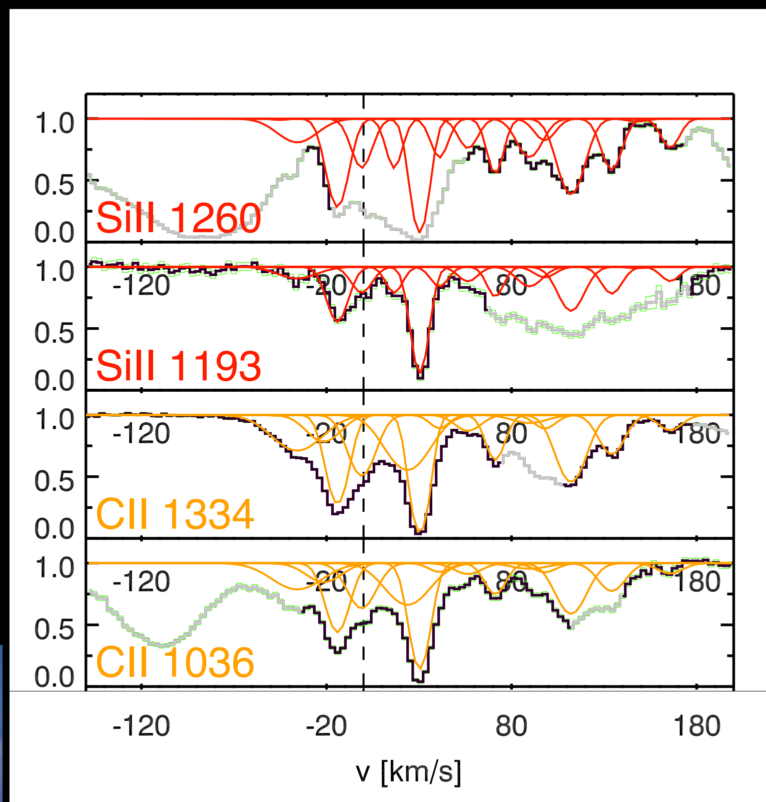
Trainor et al. 2012; Reddy et al. 2008; Strom et al. 2017

The High-Redshift CGM:

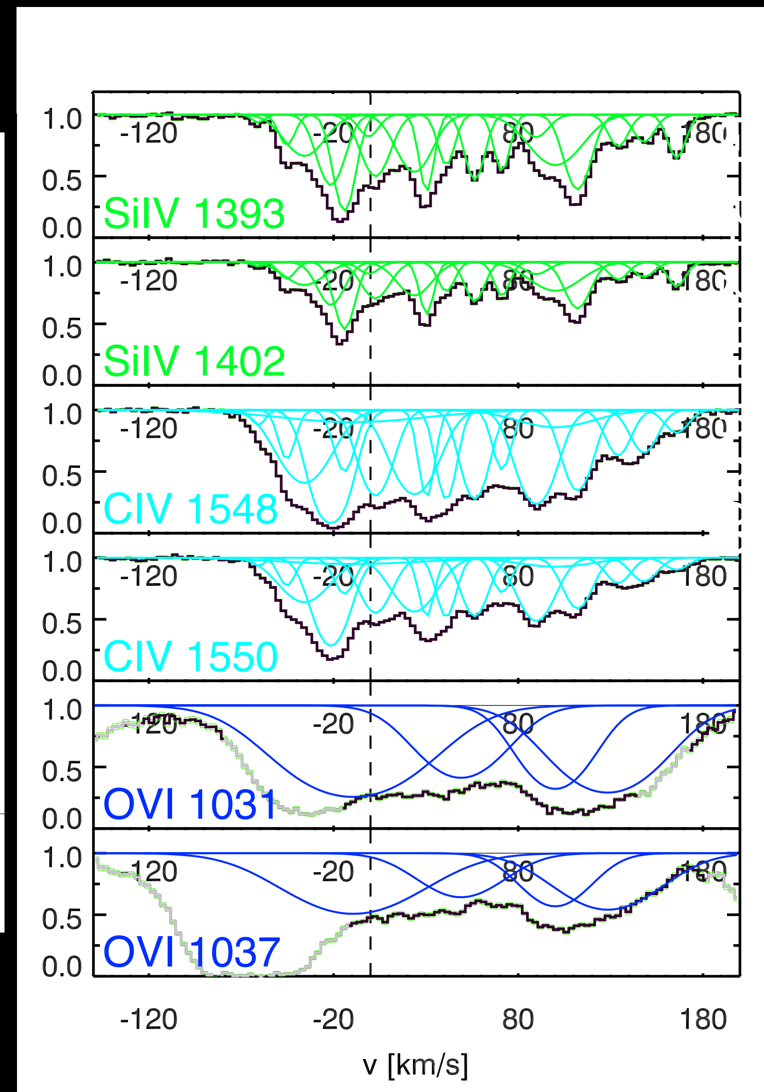
What does the CGM look like?

The CGM is Multiphase and Kinematically Complex





GCR+ 2019



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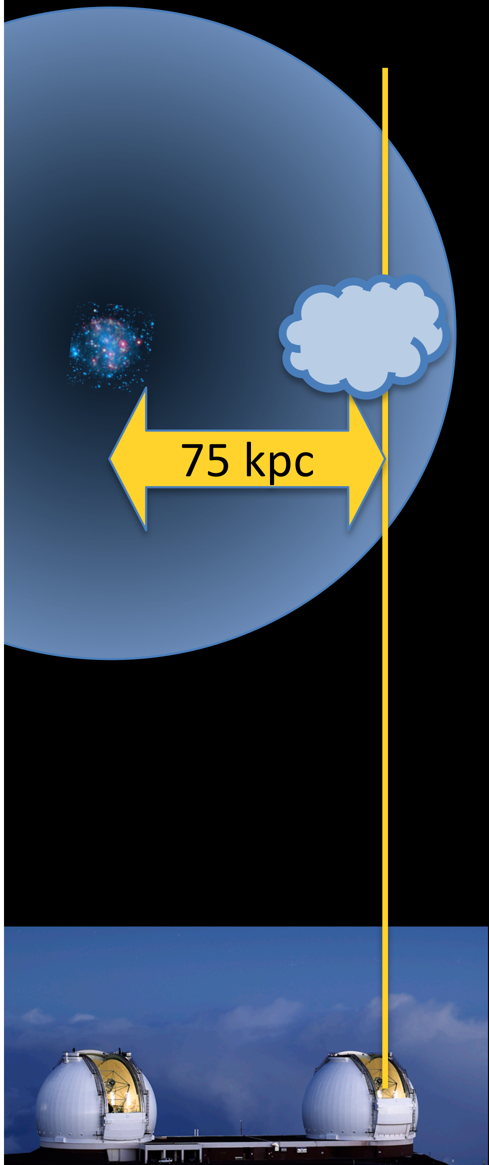
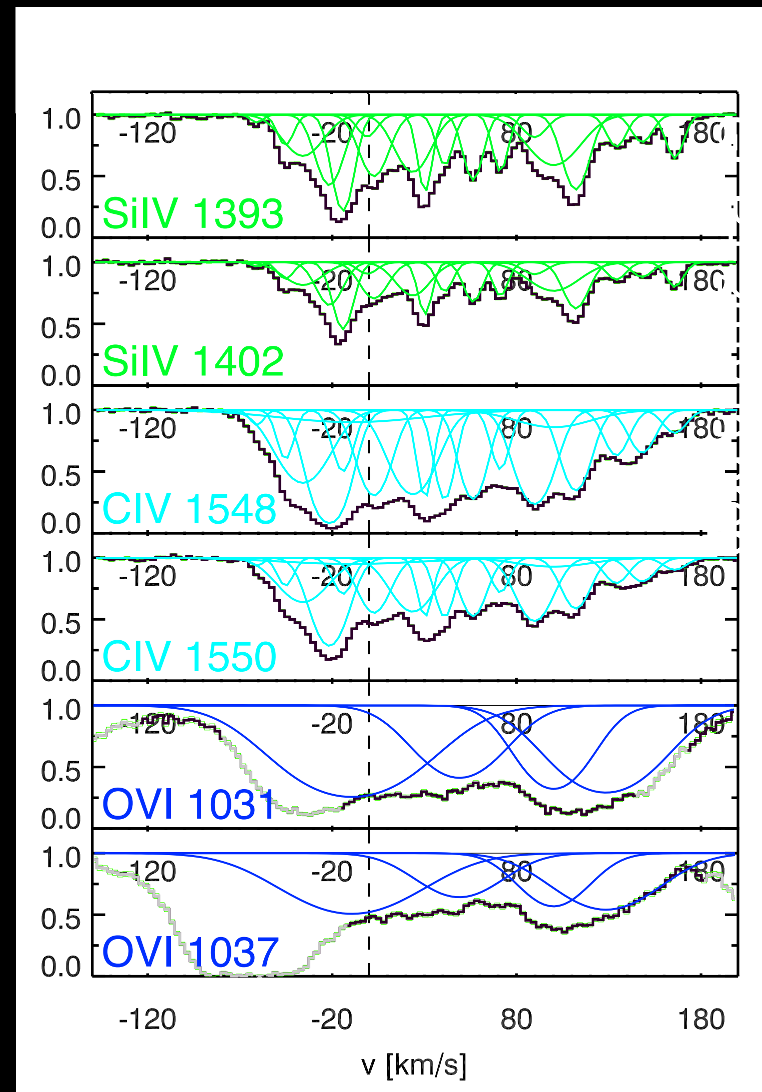
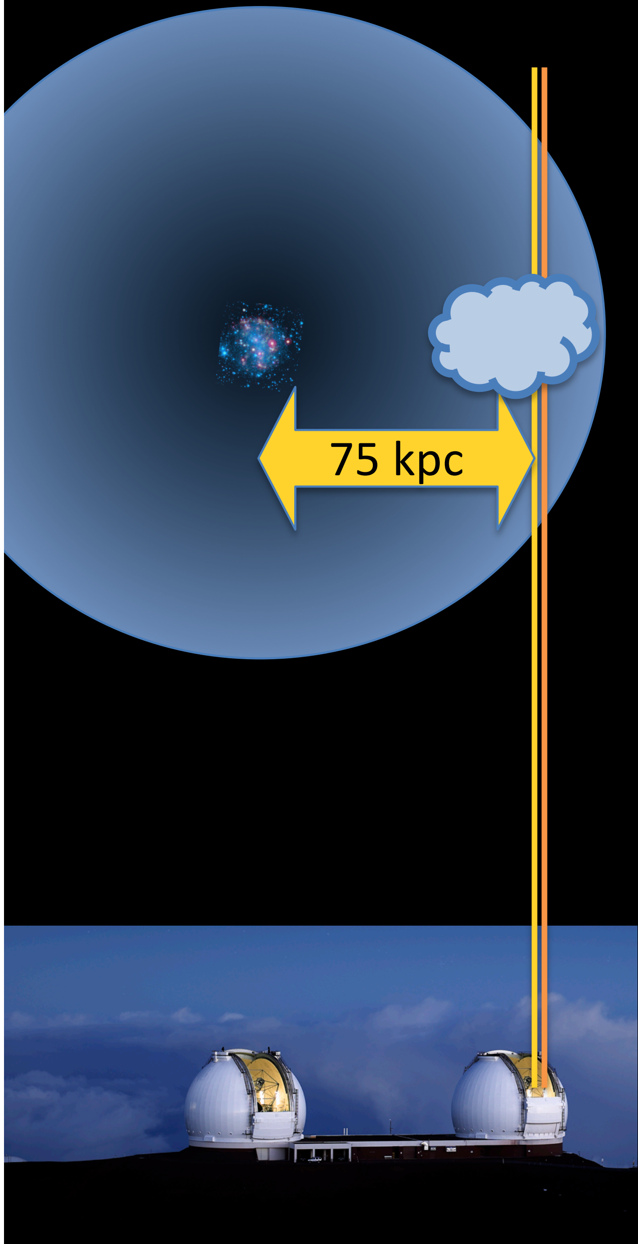


- Low and high ions have different kinematic structure from the highest ionization species OVI

- OVI absorption is found in the same velocity range and lower ionization gas



How large are gas clouds in the CGM?



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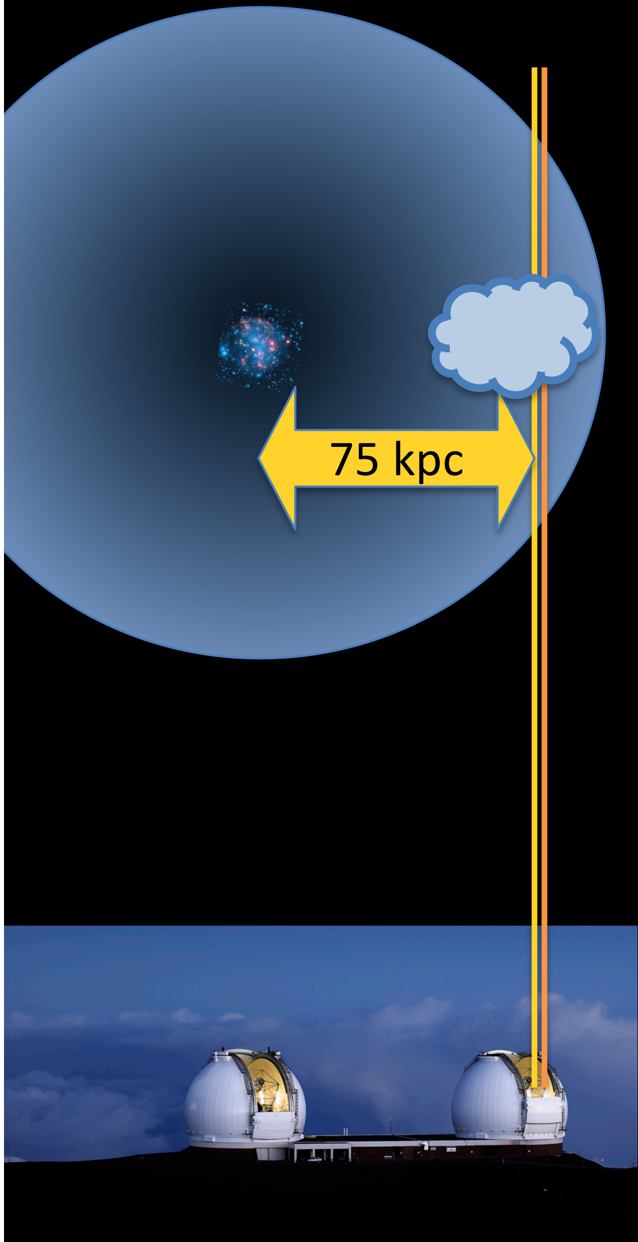
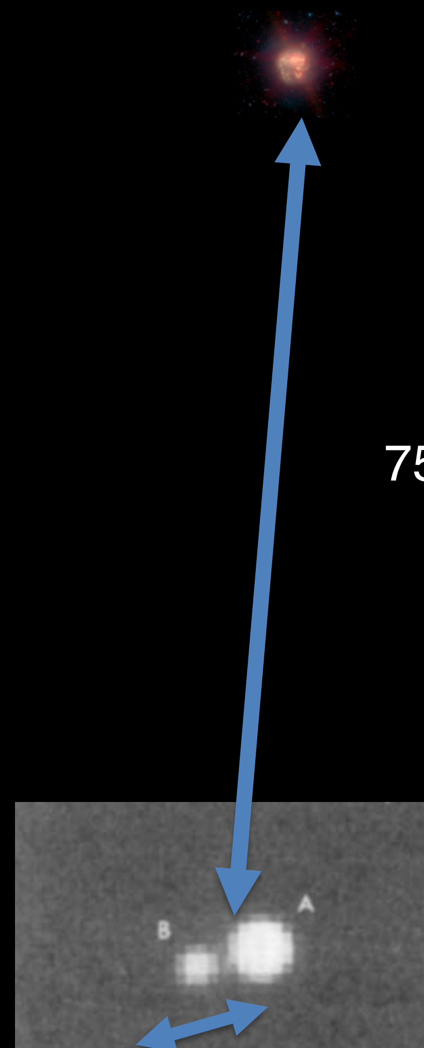
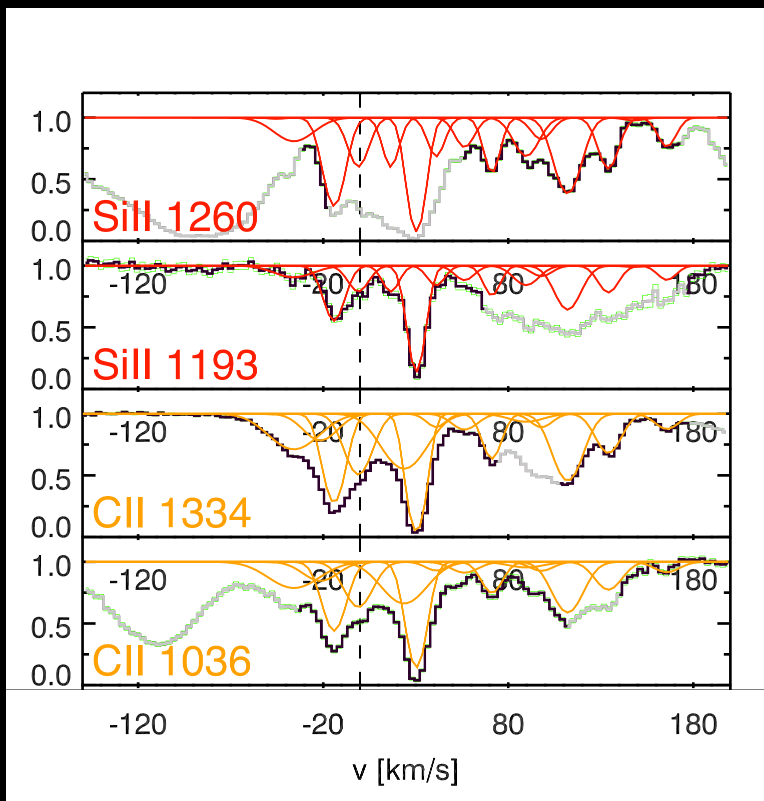
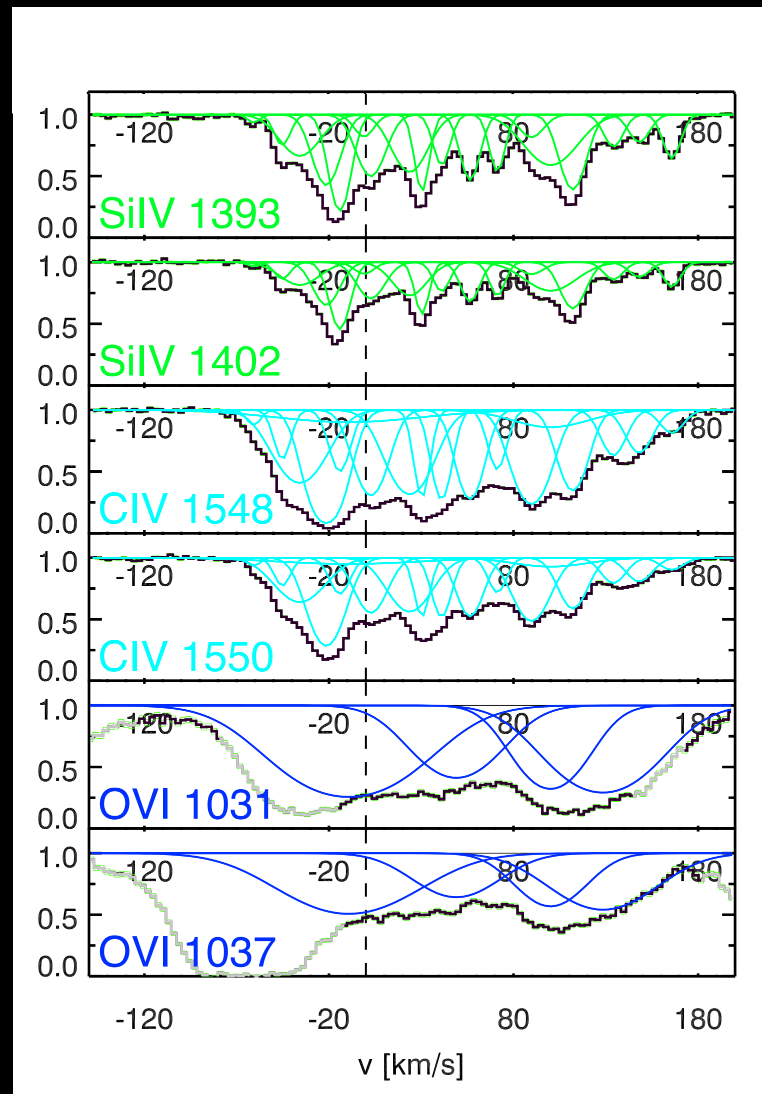




The size of absorbing clouds are typically small (<400pc) in all but OVI absorbers





GCR+ 2019

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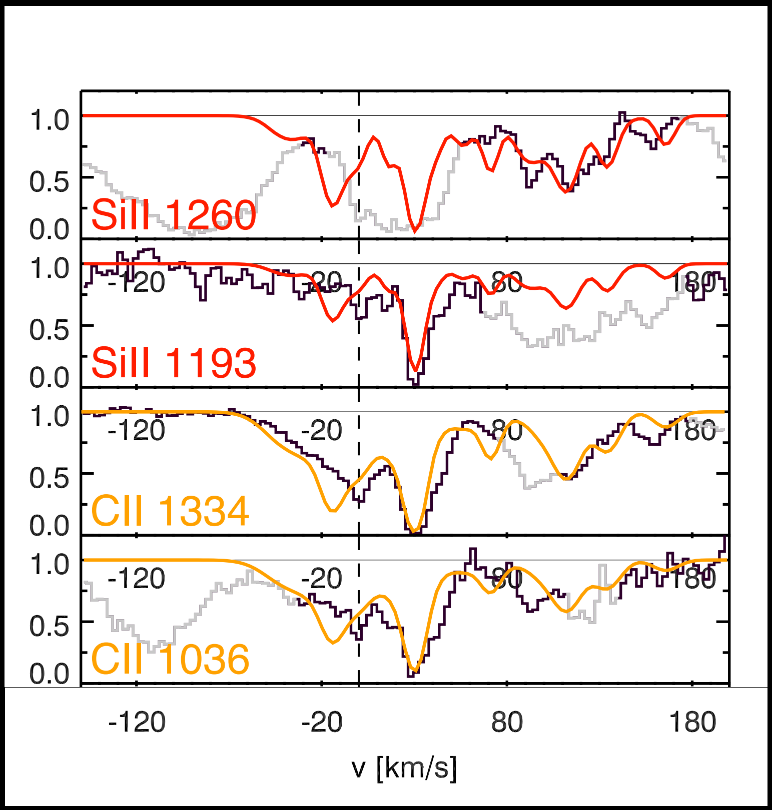

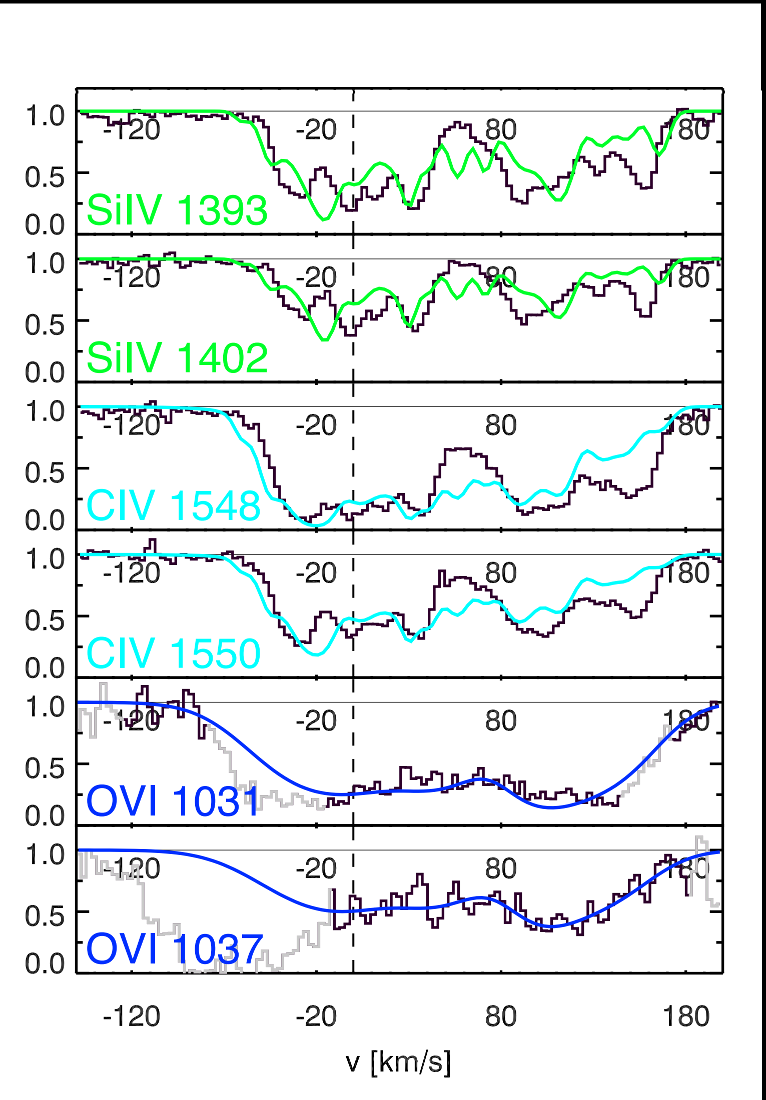

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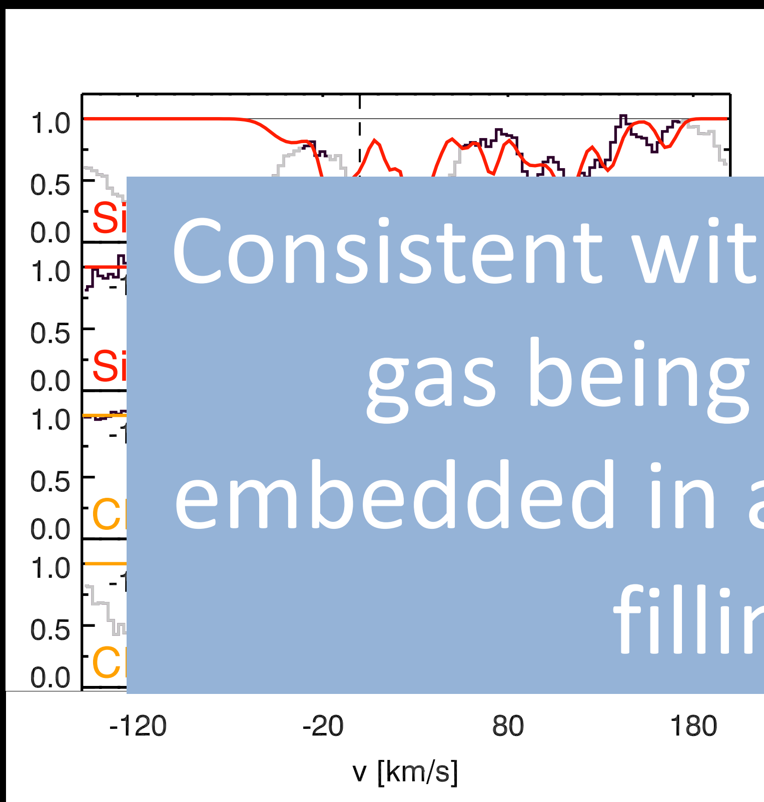
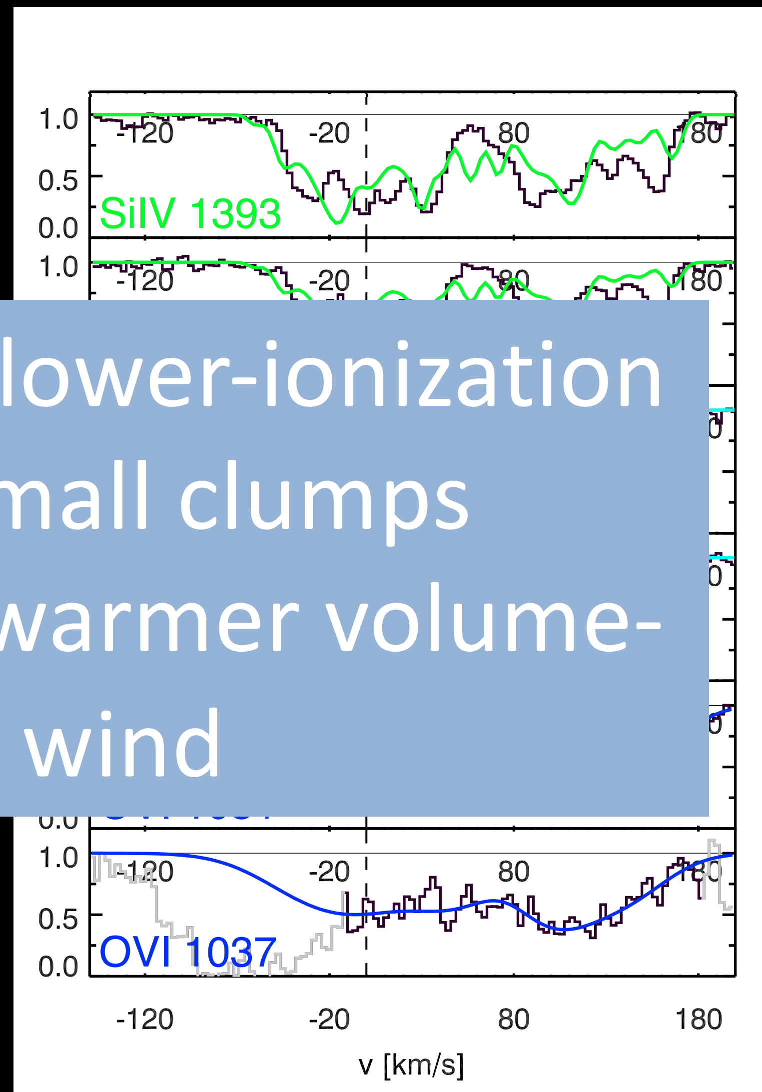
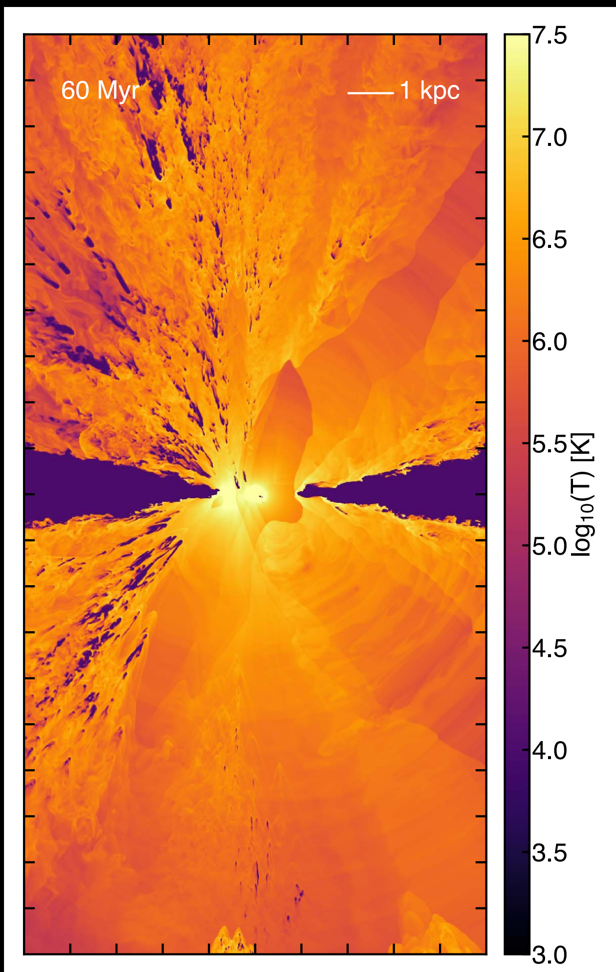




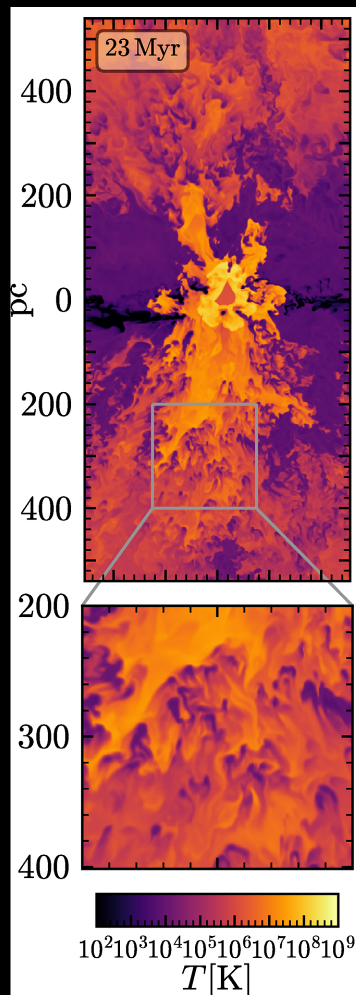
GCR+ 2019

Consistent with lower-ionization gas being small clumps embedded in a warmer volume-filling wind

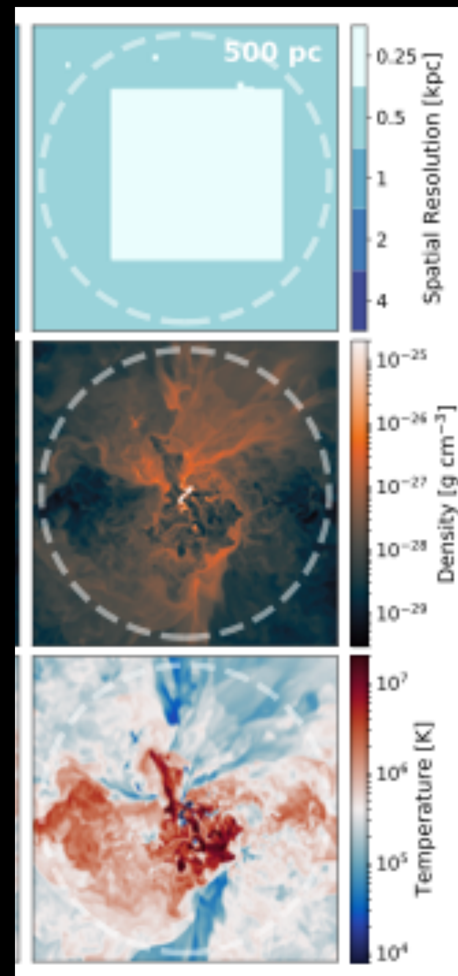
The small sizes of CGM clouds presents an enormous challenge for simulations, but novel approaches appear promising for future direct comparisons with observations.



Schneider+ 2018



Fielding+ 2018



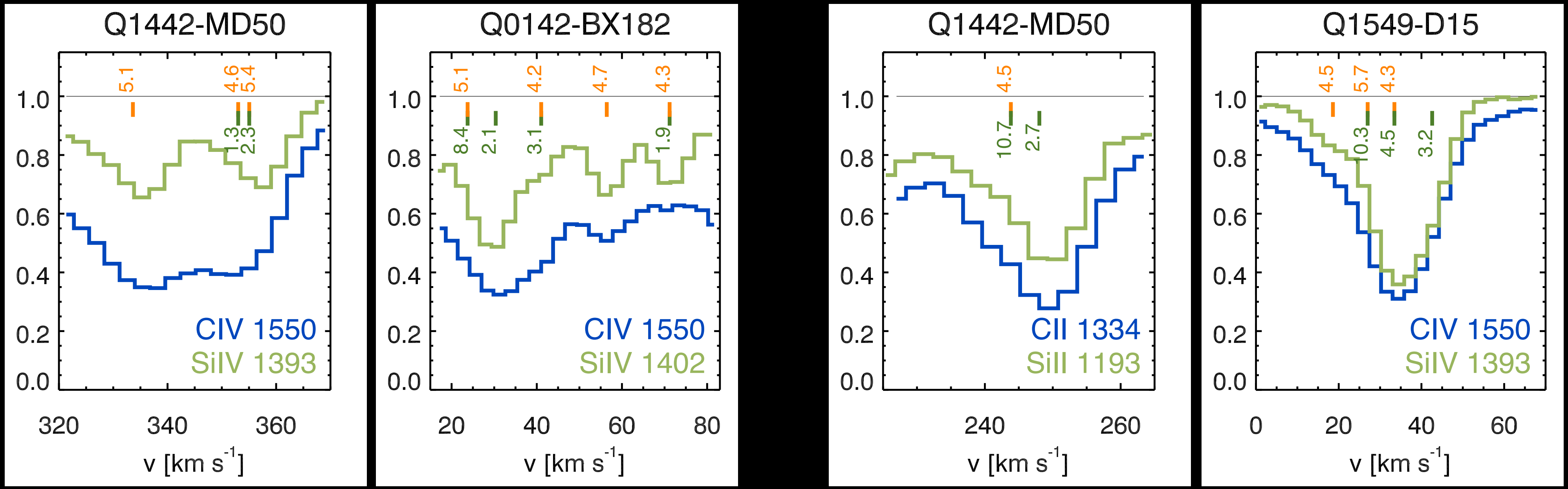
Hummels+ 2018

What are the physical conditions of gas in the CGM?

What does this tell us about accretion and outflows?

Thermal and Turbulent Broadening

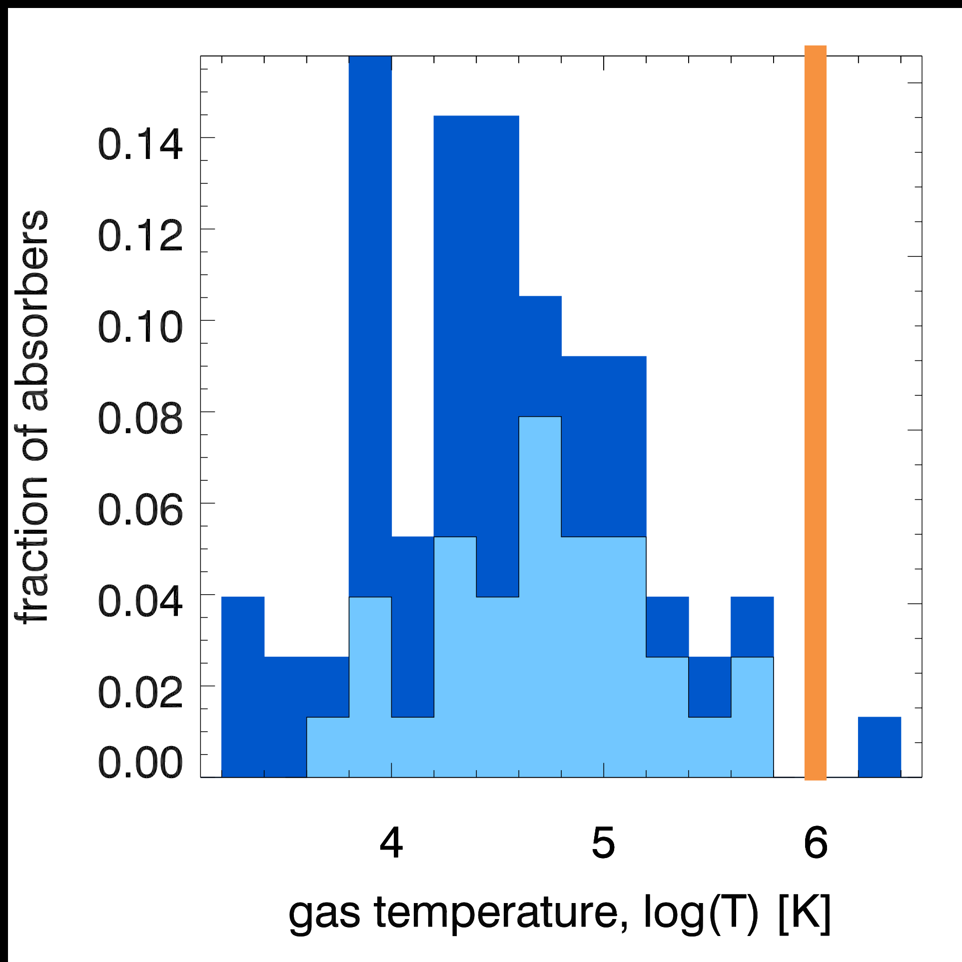
Thermal | Turbulent



GCR+ 2019

The width of absorption lines encodes the gas temperature and turbulence.

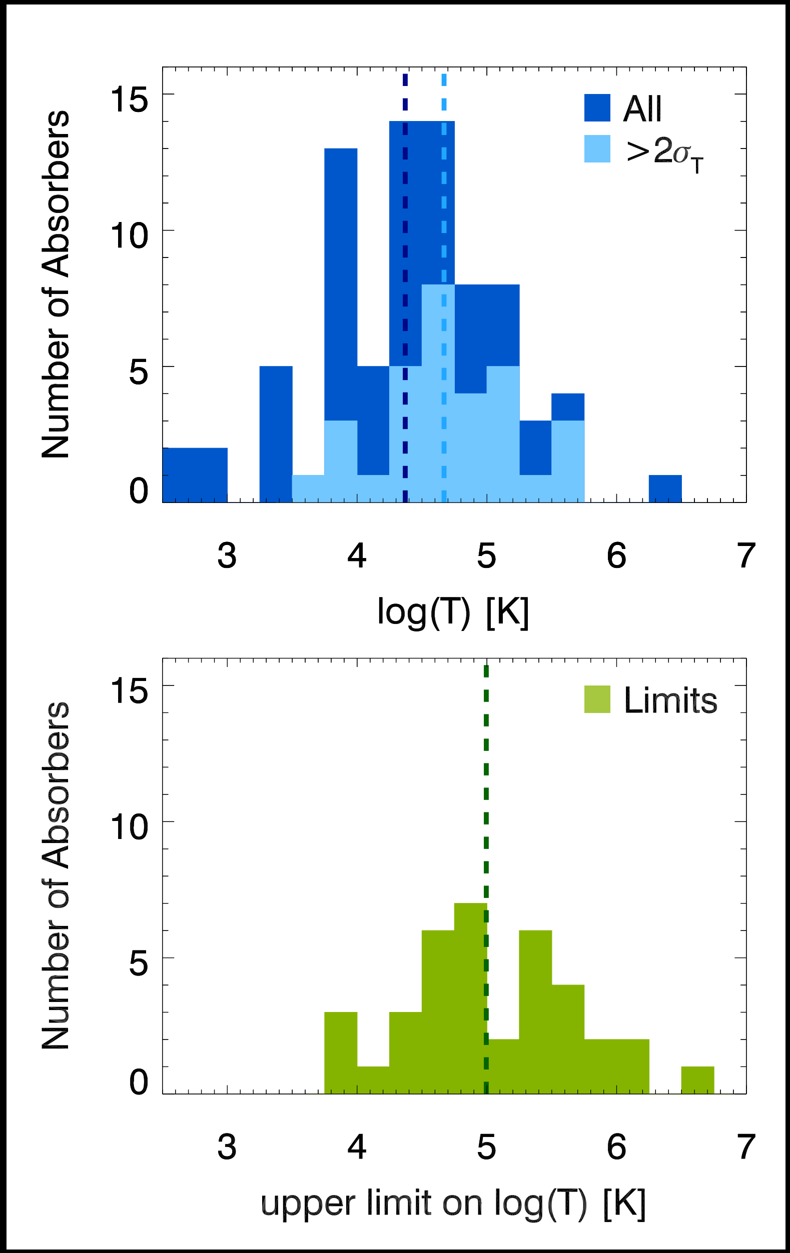
Gas Temperatures within R_{vir}



GCR+ 2019

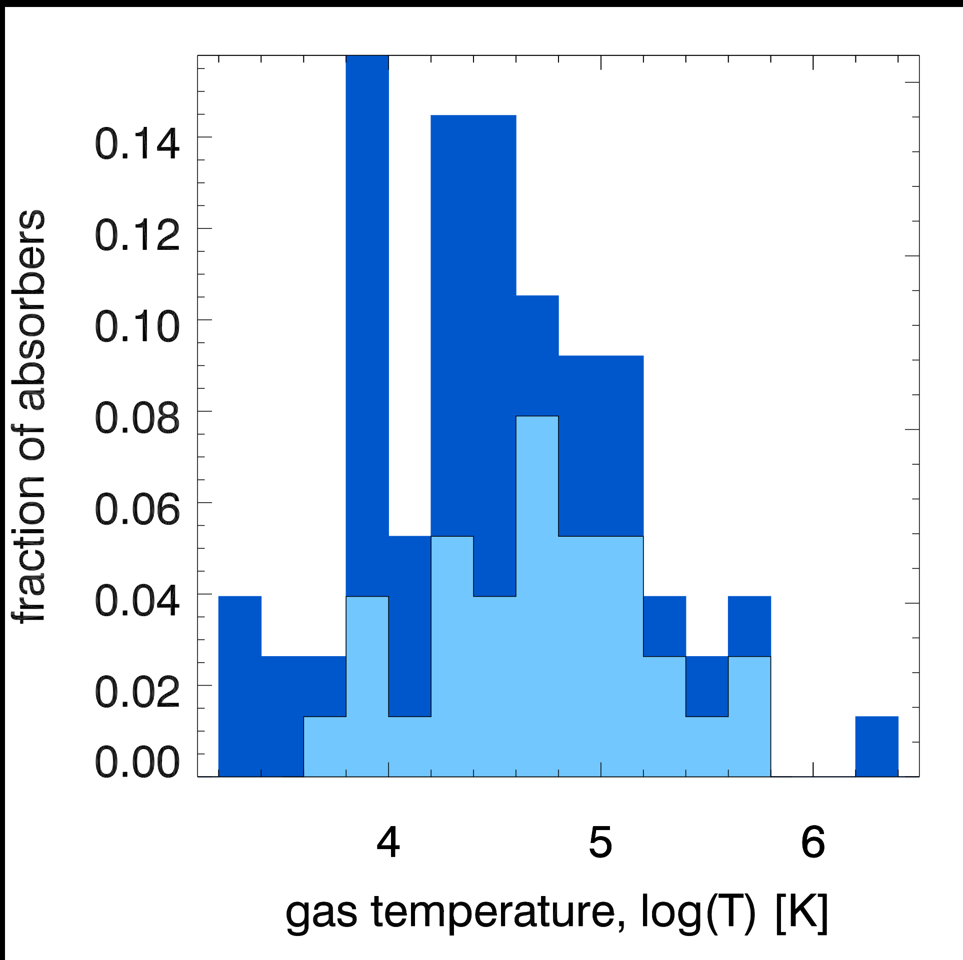
Gas Temperature

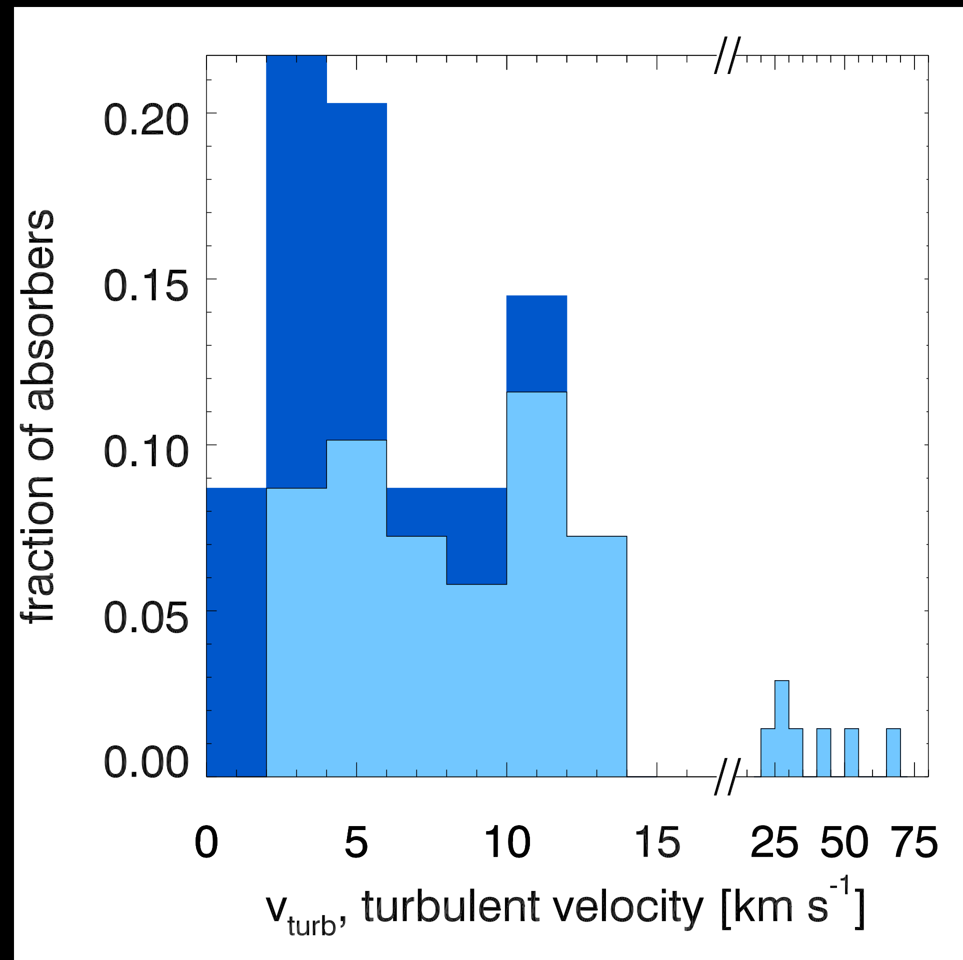
- The median temperature for the sample (including upper limits) is $T \leq 10^{4.5}$ K
- ~half of the absorbers have intermediate temperatures
  - $10^{4.5} \leq T \leq 10^{5.5}$ K
- Most of the (detected) gas is hotter than the IGM and cooler than T_{vir}
- Intermediate temperature gas cools rapidly, so its persistence requires constant reheating or replenishment of the warm gas phase



GCR+ 2019

Gas Temperatures and Turbulent Velocities within R_{vir}





GCR+ 2019

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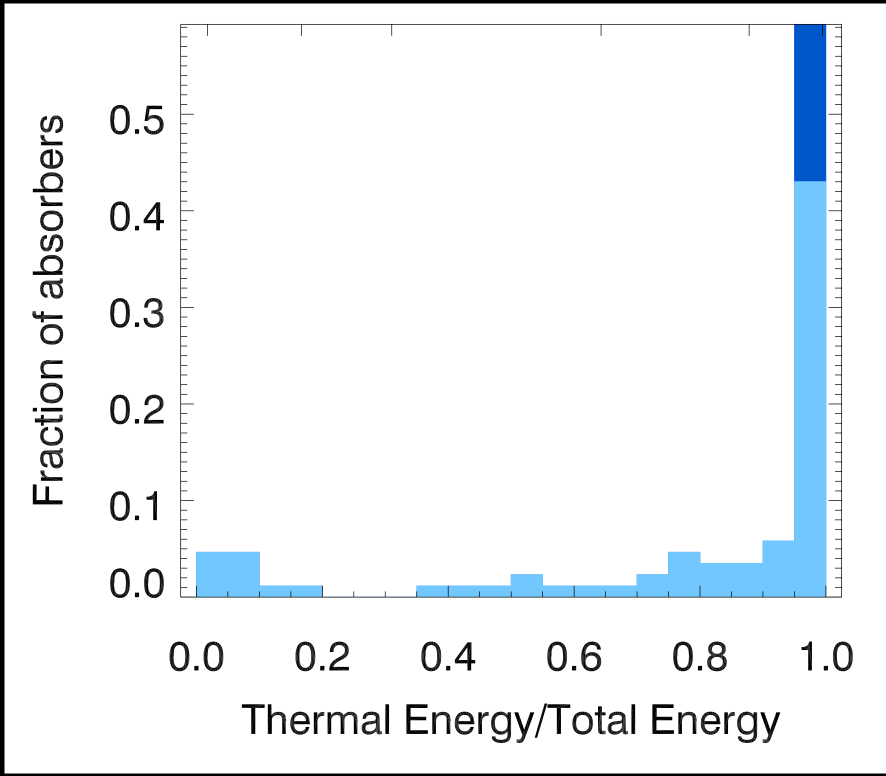
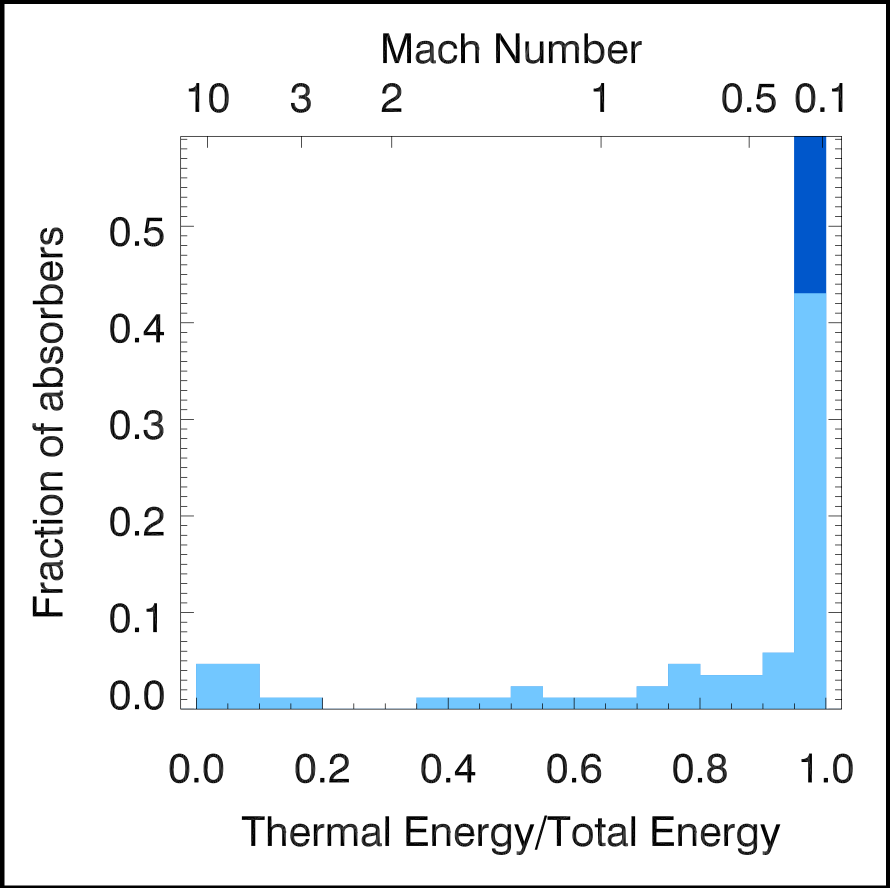


GCR+ 2019

The internal energy of the detected gas is dominated by thermal energy

Gas Temperatures and Turbulent Velocities within R_{vir}



GCR+ 2019

The internal motions within CGM 'clouds' are subsonic

Physical State of High-z CGM Gas

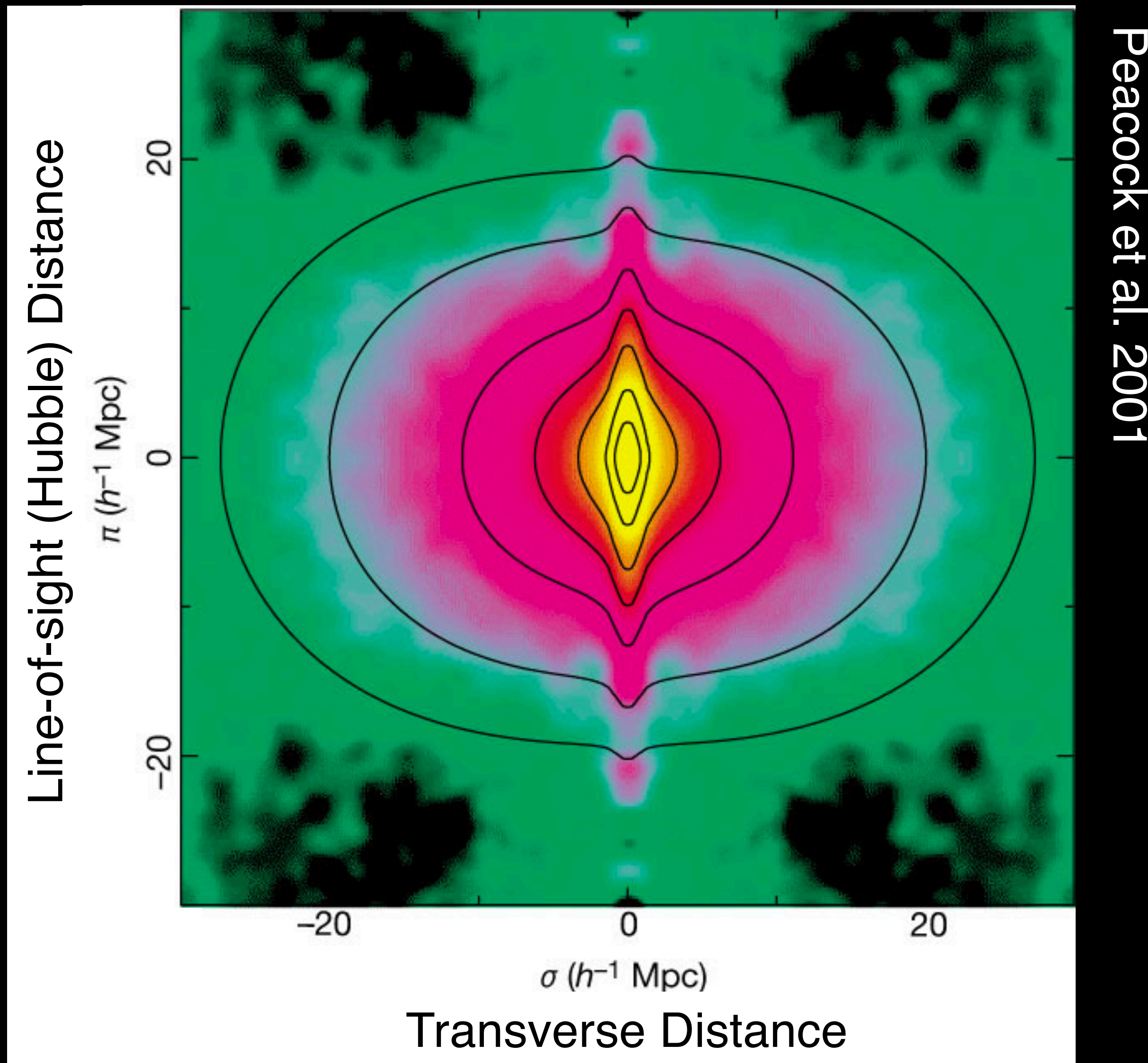
- Gas exists at a wide range of temperatures
  - Broadly consistent with paradigm of cold flows + hot gas from outflows or virial shocks

- Kinematics and Chemical enrichment of hot gas is needed to disentangle processes

Can we detect inflows
and outflows in the CGM?

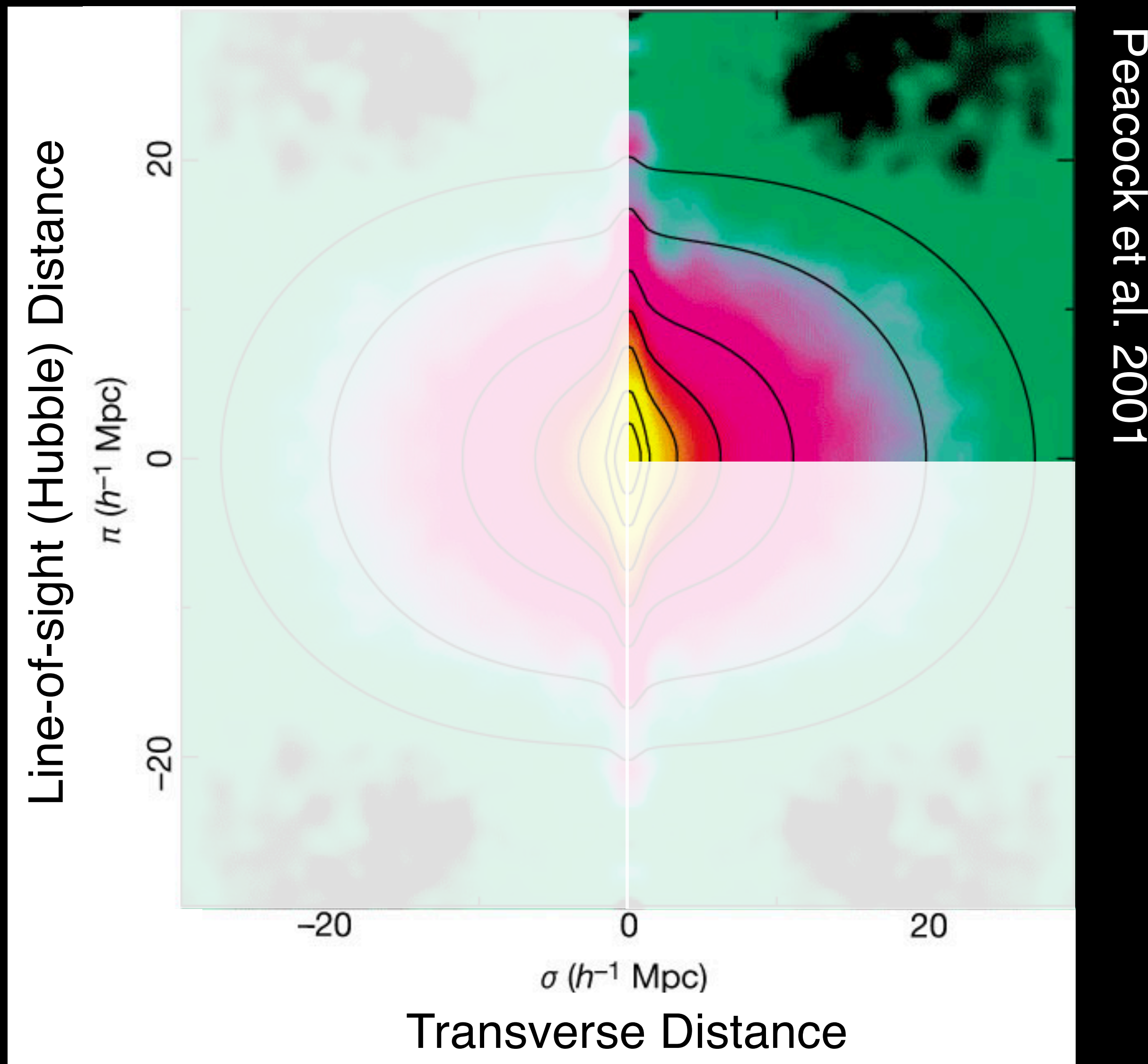
What can the CGM kinematics
tell us about feedback?

Redshift Space Distortions



Galaxy Correlation Function from the 2dF GRS

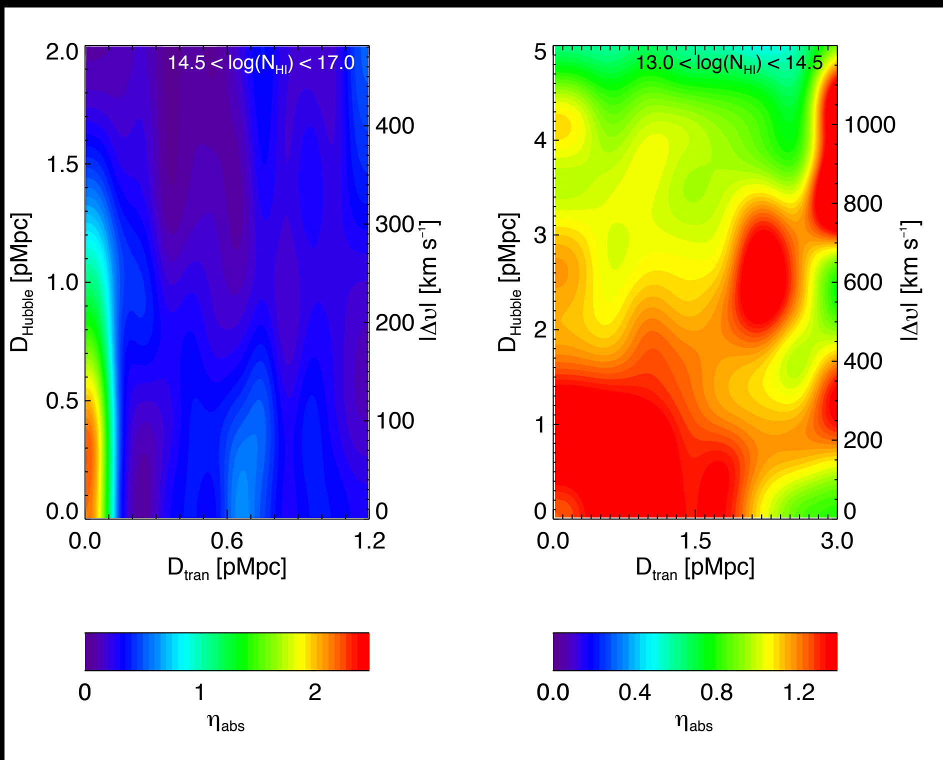
Redshift Space Distortions



Galaxy Correlation Function from the 2dF GRS

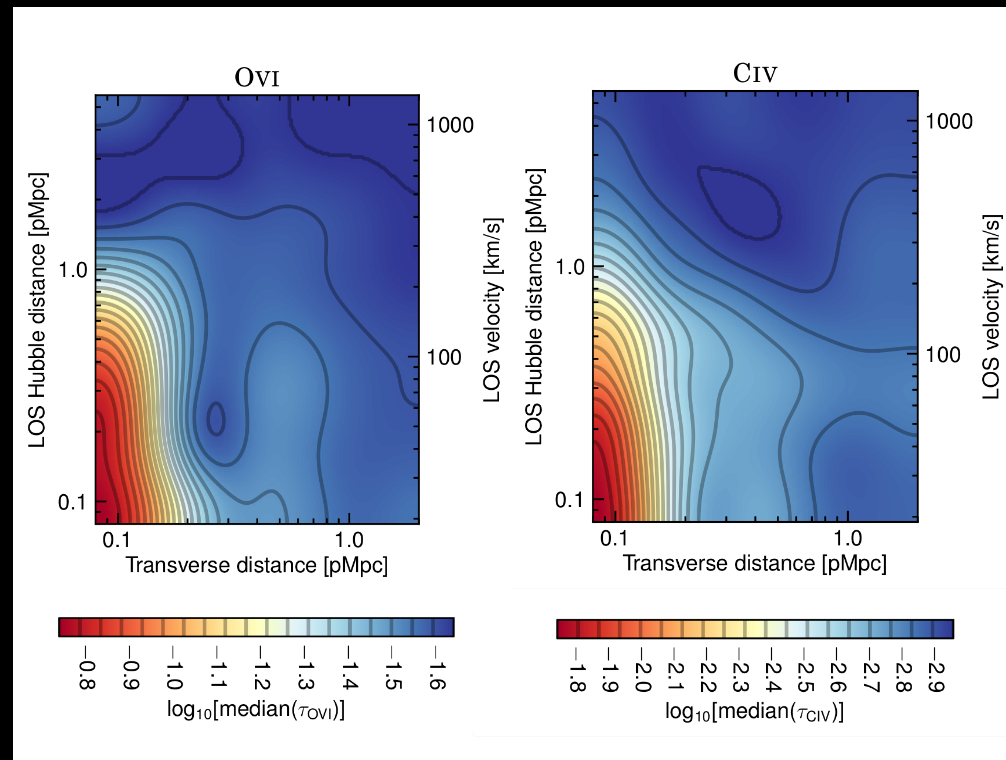
Redshift Space Distortions: Gas Kinematics

Hydrogen



GCR+ 2012a and Rakic+ 2012

Metals

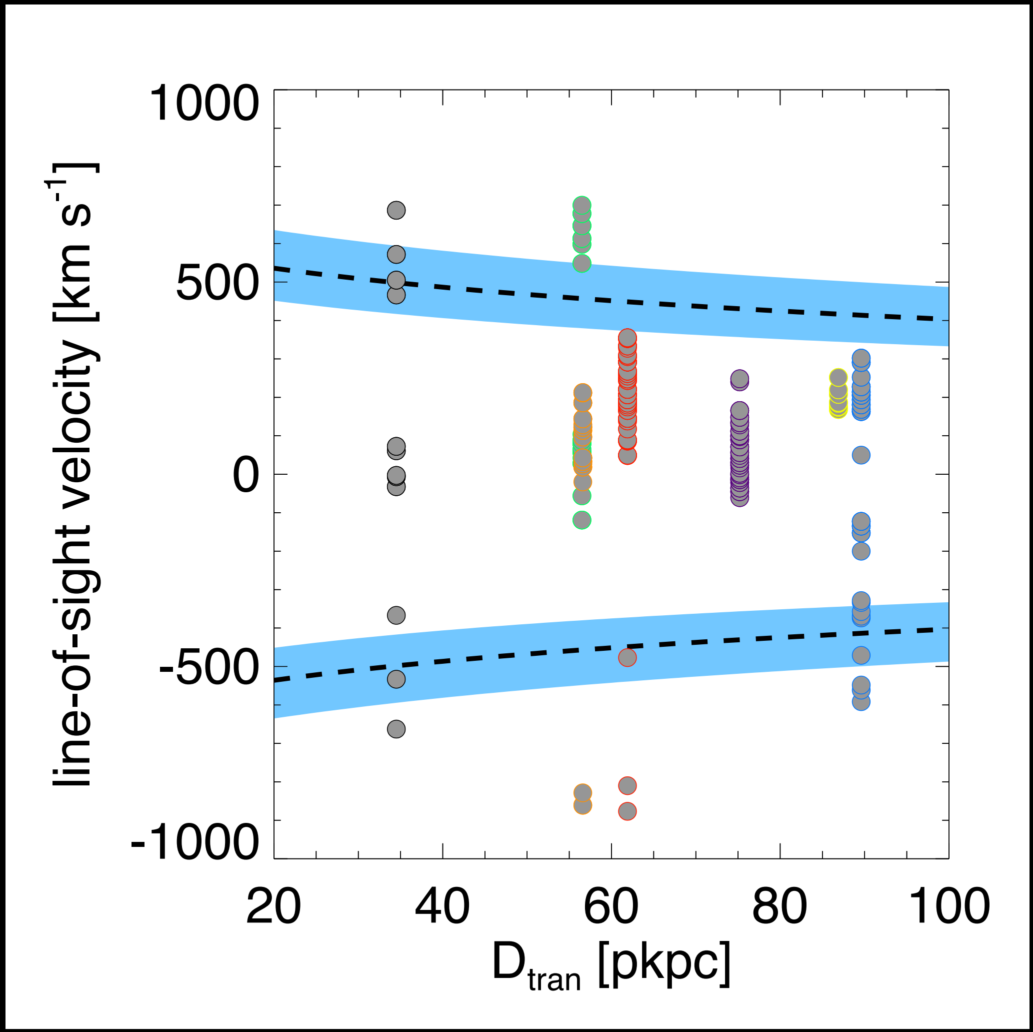


Turner et al. 2014

HI and Metals show coherent inflow on Mpc scales

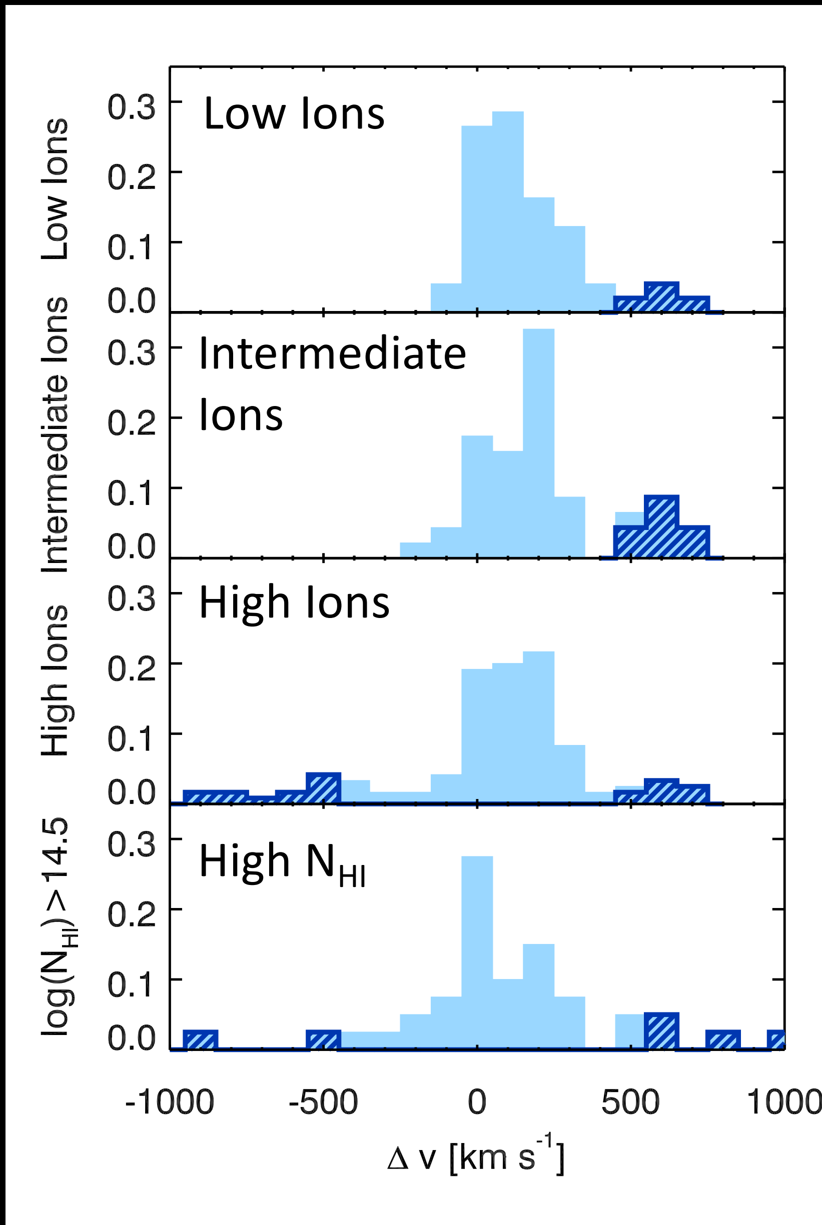
Large peculiar velocities at small scales suggestive of outflows

Most KBSS galaxies have unbound metal-enriched gas within 100 kpc and 1000 km/s



GCR+ 2019

Unbound Halo Gas



GCR+ 2019

- Appears most often in high ions (CIV, SiIV, NV, & OVI)
- Not commonly associated with high-N_{HI} gas
- Gas is likely highly ionized, metal rich, or both
- For 5 galaxies with unbound CIV, 20% of N_{CIV} is unbound

- If this gas is due to outflows, it represents metal-enriched material that would be permanently removed from the galaxy.

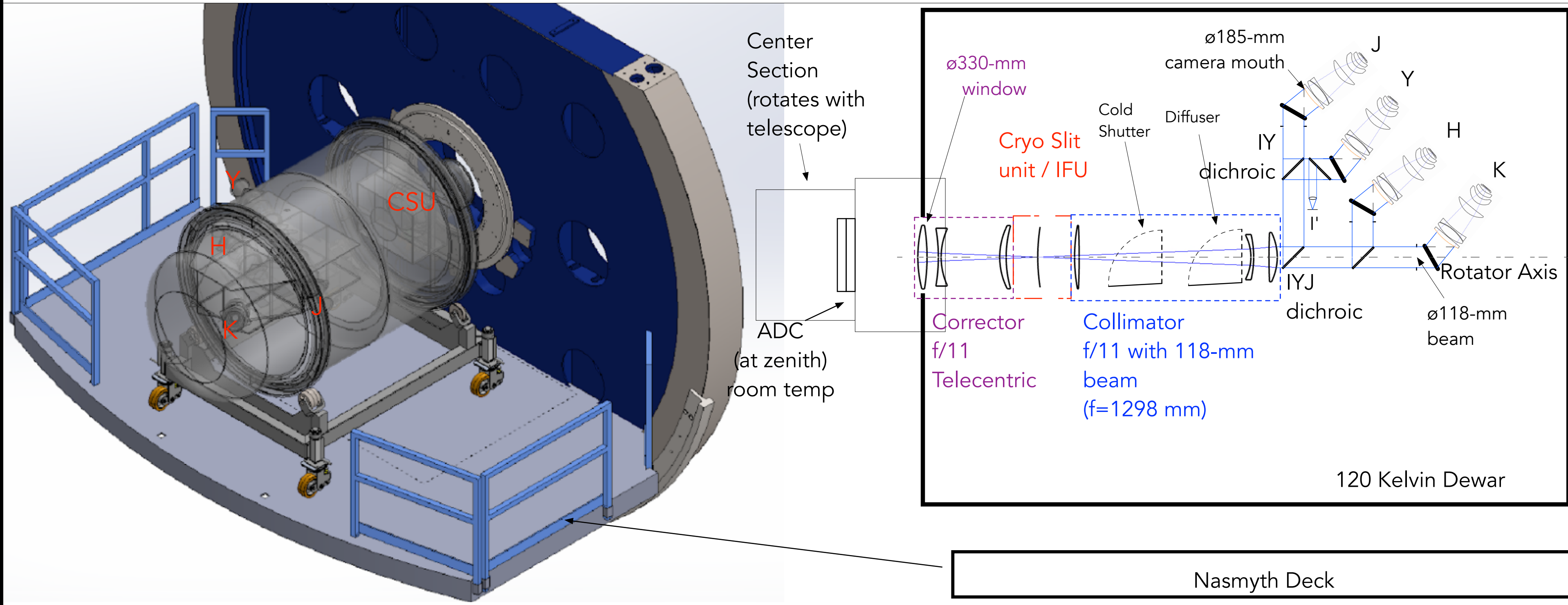
Furthering our understanding of the High-Redshift CGM

- Model the ionization conditions within these high-redshift CGM clouds
  – Measure metallicities and constrain masses

- Connect with lower-redshift CGM observations
  – The Cosmic Ultraviolet Baryon Survey (CUBS)
  – HST Cycle 25 Large GO program to study the CGM at $0.4<z<0.8$ during the turn down of cosmic Star Formation

Prospects for the Future: MIRMOS

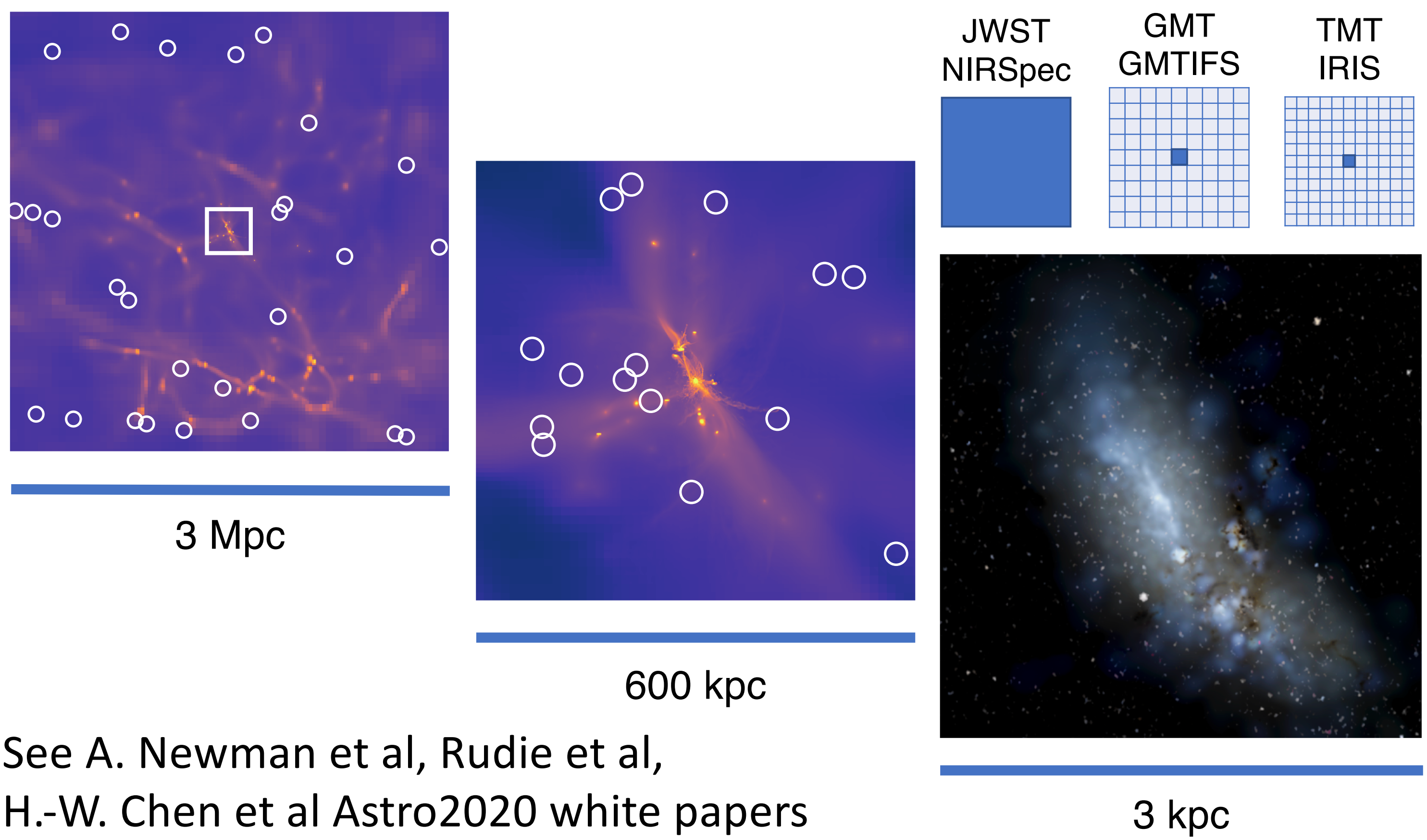
Magellan Infrared Multiobject Spectrograph



PI: Nick Konidaris, PS: Andrew Newman and Gwen Rudie

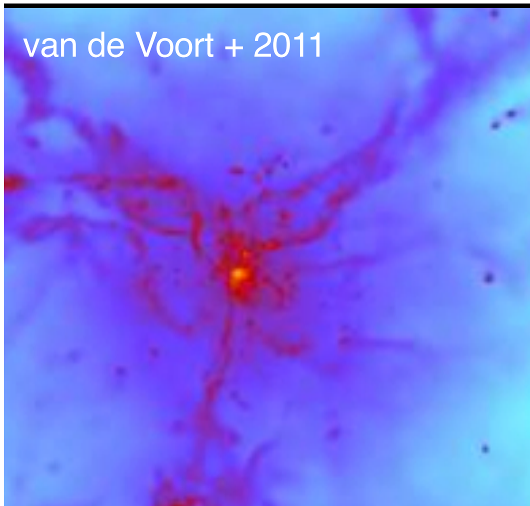
- Increase the sample of high-z galaxies with absorption line probes
- Study the CGM in rest-optical emission lines

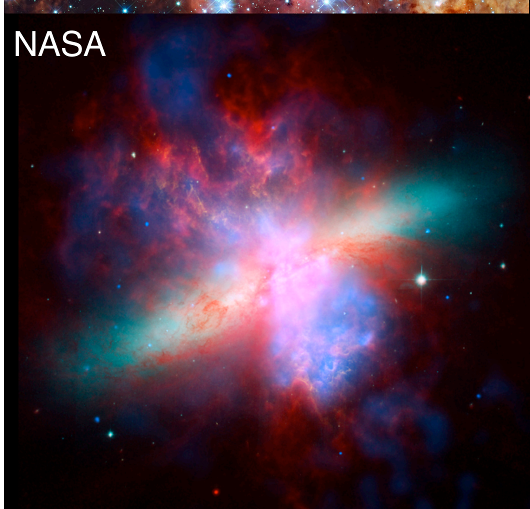
Prospects for the Future: GMT & TMT



See A. Newman et al, Rudie et al, H.-W. Chen et al Astro2020 white papers

- Resolve the CGM with thirty-meter class telescopes and connect to resolved studies of galaxies
  – Background galaxies with high spatial density can be used to map the CGM of individual galaxies





Conclusions

- Cool and warm metal-bearing gas 'clouds' in the CGM are small (<400pc) while the likely hotter OVI-bearing gas appears to be more volume filling
  - Consistent with a picture where hot outflowing winds carry along or seed the formation of cooler dense clumps
- Gas in the CGM exhibits a wide range of temperatures
  - Broad agreement with theoretical paradigm of cold flows + outflows/accretion shocks
  - Gas at intermediate temperatures have a short cooling time so the CGM must be constantly heated or cooling to form this gas
- Gas Kinematics shows evidence of inflows and outflows
  - 70% of galaxies with detected metals have unbound gas
  - Unbound gas appears to be more highly ionized and potentially metal rich