The Circumgalactic Medium

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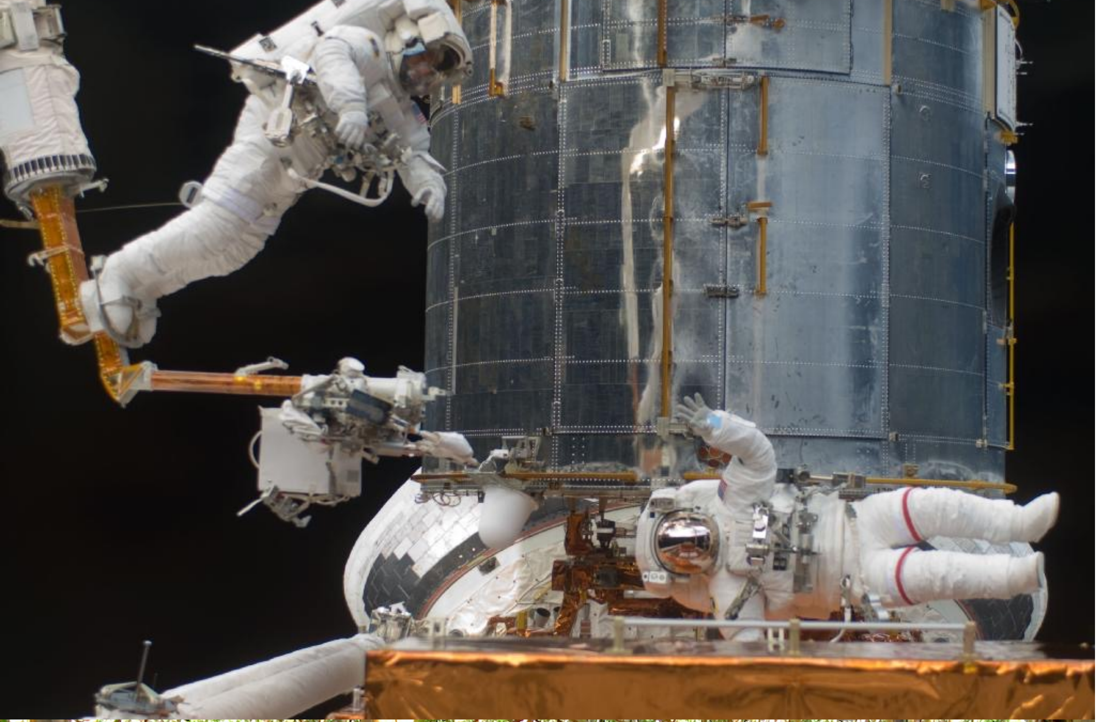
Tumlinson, Peeples, & Werk (2017)



A Review Talk for
Astronomy 511 at the
University of Victoria

By Prof. Jessica Werk



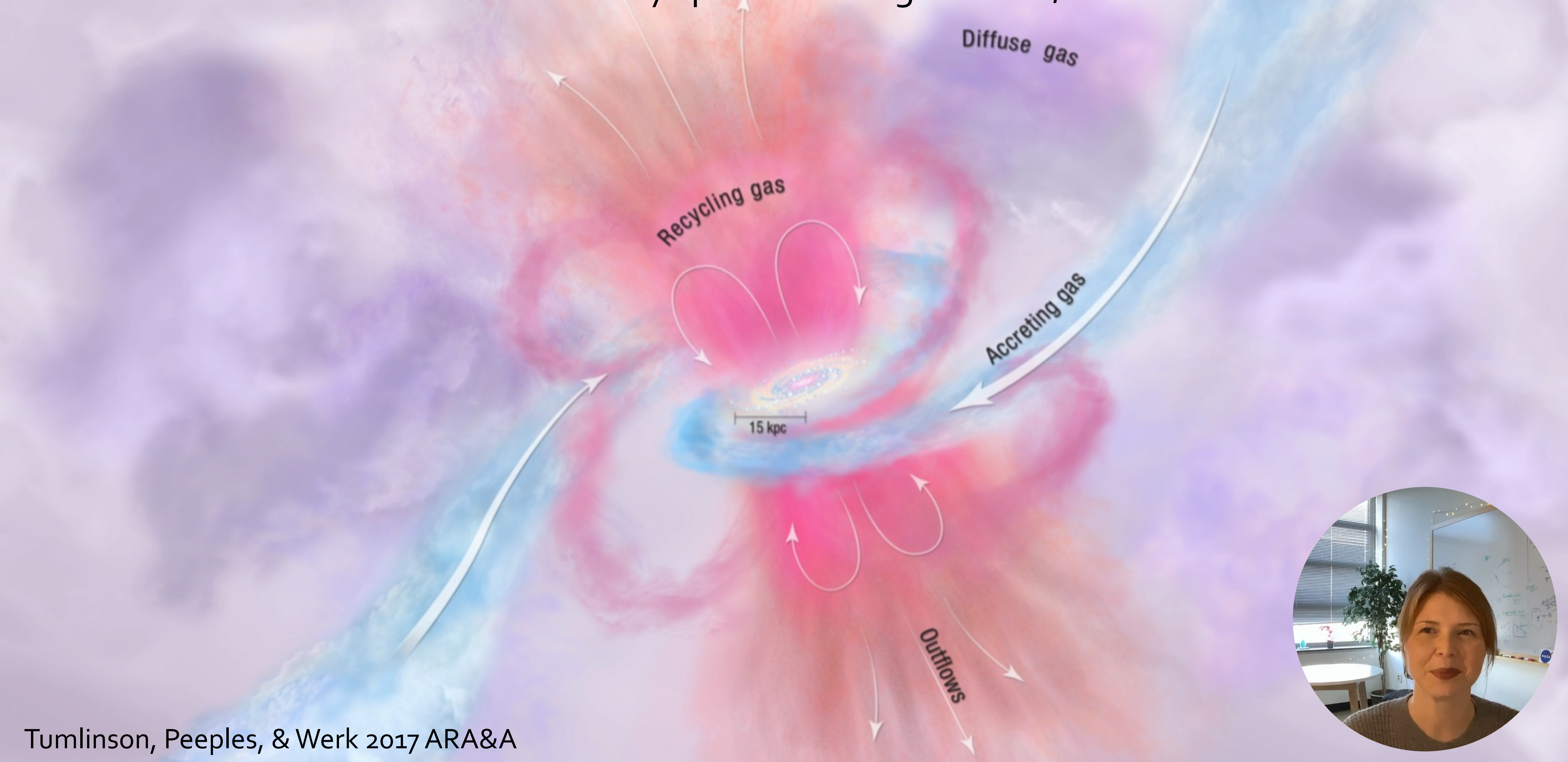
2009 was a banner year

- Top: Astronauts John Grunsfeld & Andy Feustel installing COS on HST.

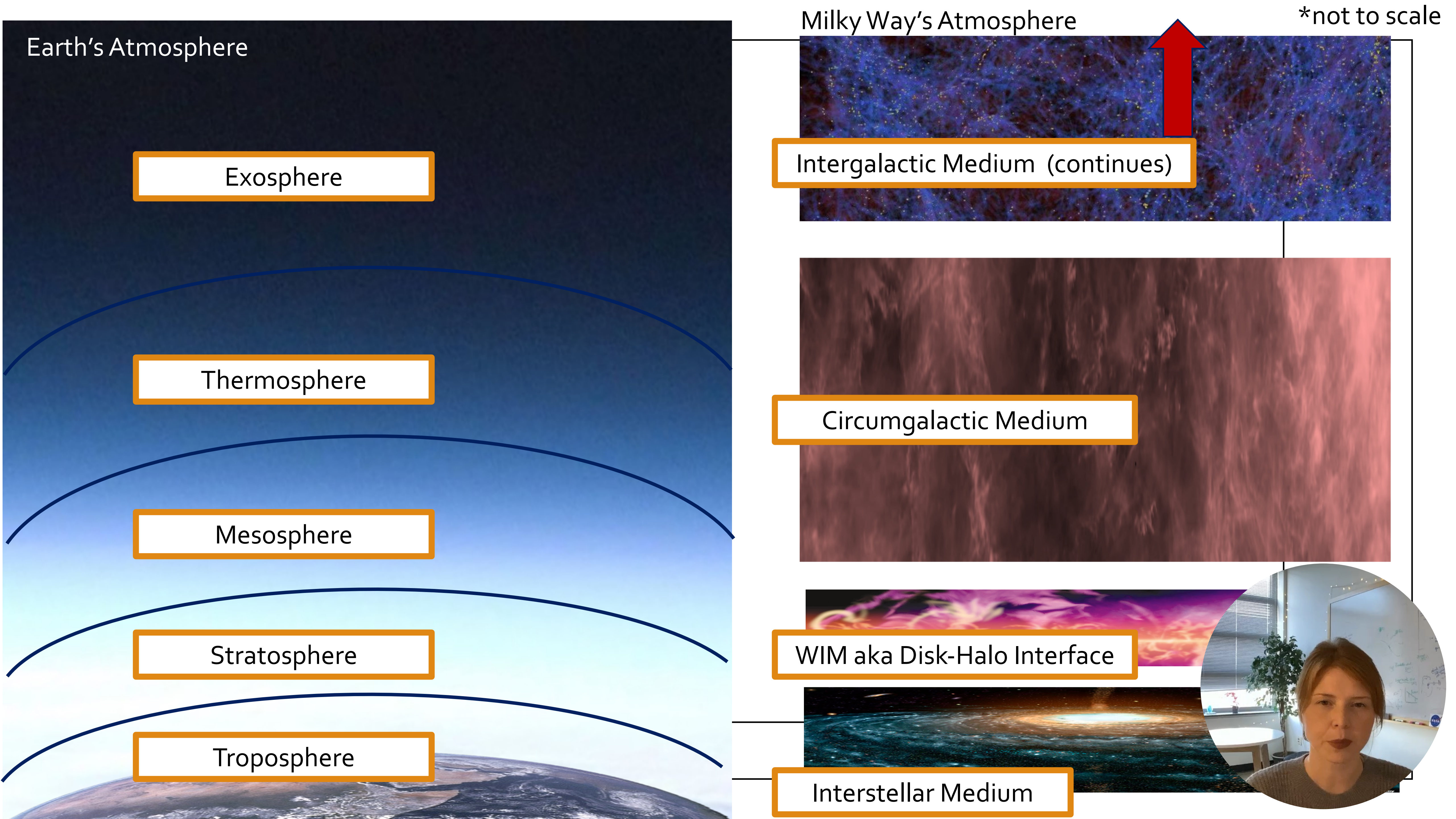
- Bottom: Pre-Ph.D with advisor Prof. Mary Putman.

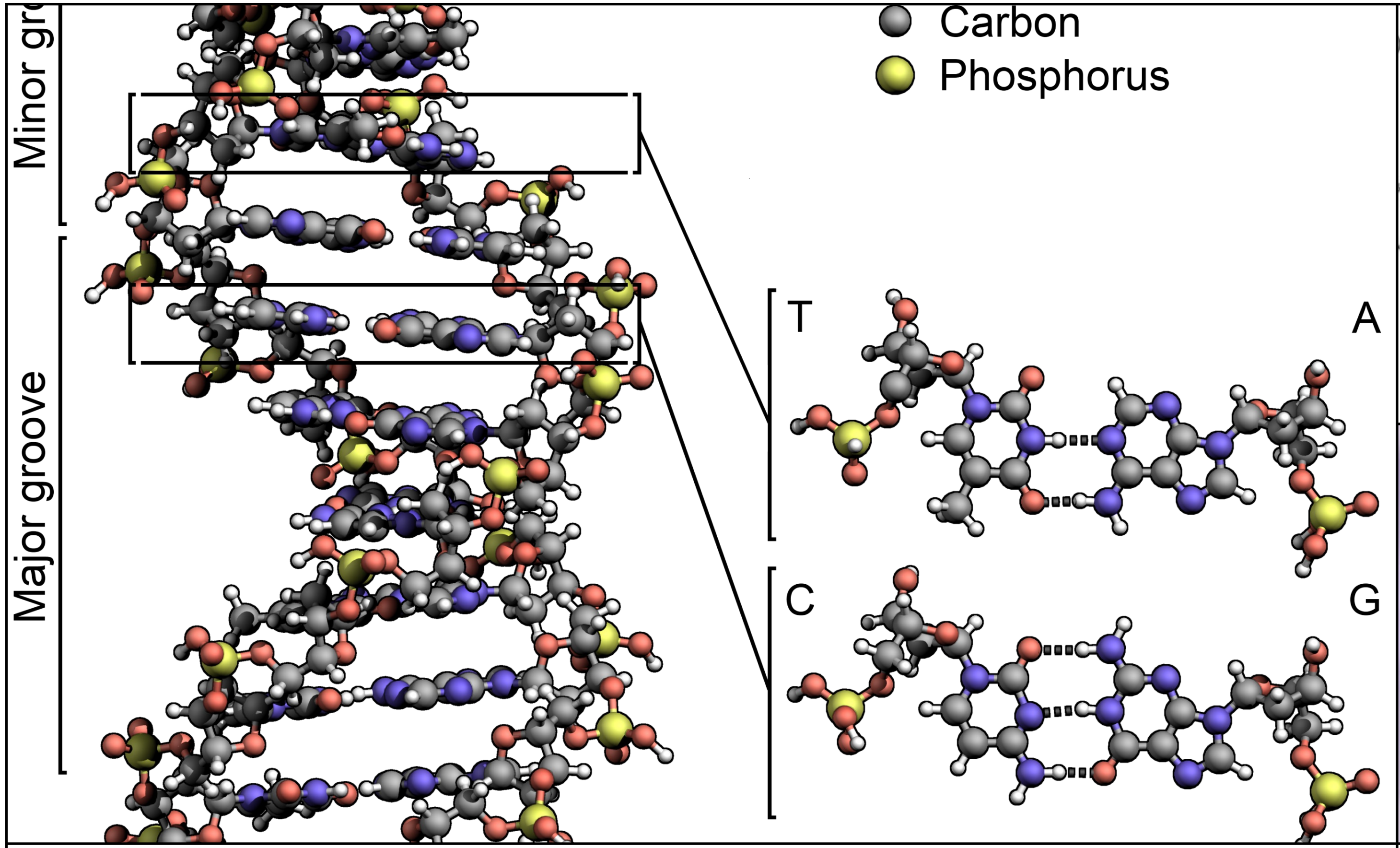
Circumgalactic Matter Matters in Galaxy Evolution

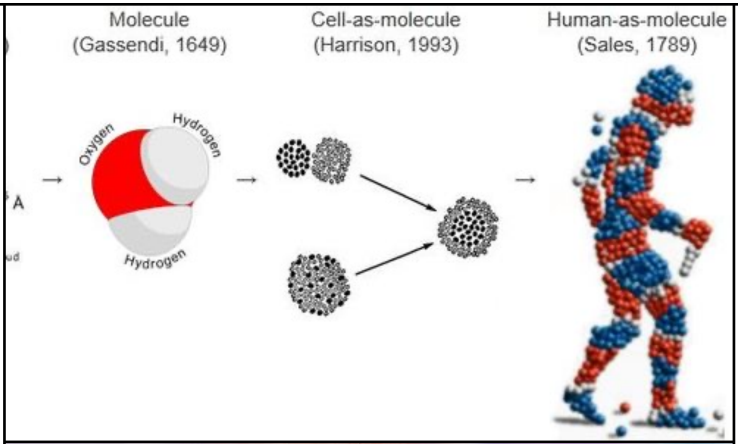
New discovery space in the age of HST/COS

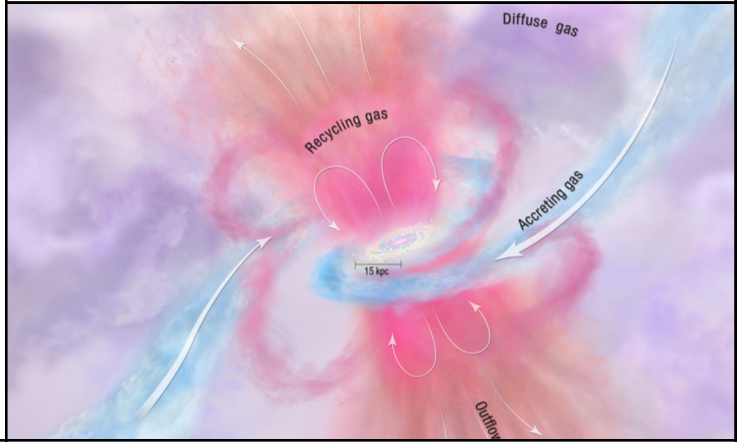


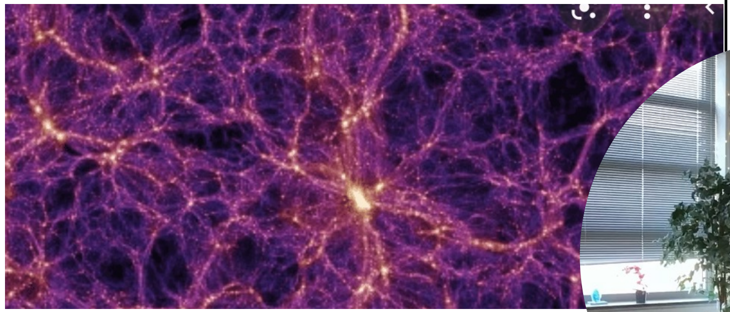
Tumlinson, Peeples, & Werk 2017 ARA&A


Earth's Atmosphere
Exosphere
Thermosphere
Mesosphere
Stratosphere
Troposphere
Milky Way's Atmosphere
*not to scale
Intergalactic Medium (continues)
Circumgalactic Medium
WIM aka Disk-Halo Interface
Interstellar Medium









The Baryon Cycle: From Small to Large Scales

We are just temporary, self-aware, collections of assorted atoms…

The History of the CGM Is the History of YOU

Talk Outline

Part 1

Review of CGM Science and Measurement Techniques

Part 2a

The Main CGM Results: Physical State, Total Mass, and Metal Budget

Part 2b

Interpretation: Inflows, Outflows, Recycling and Quenching

Part 3

Progress, Open Problems, and Growth Areas

The Circumgalactic Medium. Tumlinson, Jason; Peeples, Molly S.; Werk, Jessica K. ARA&A vol. 55, pp 389 - 432

Intrinsic Spectrum of a Quasar

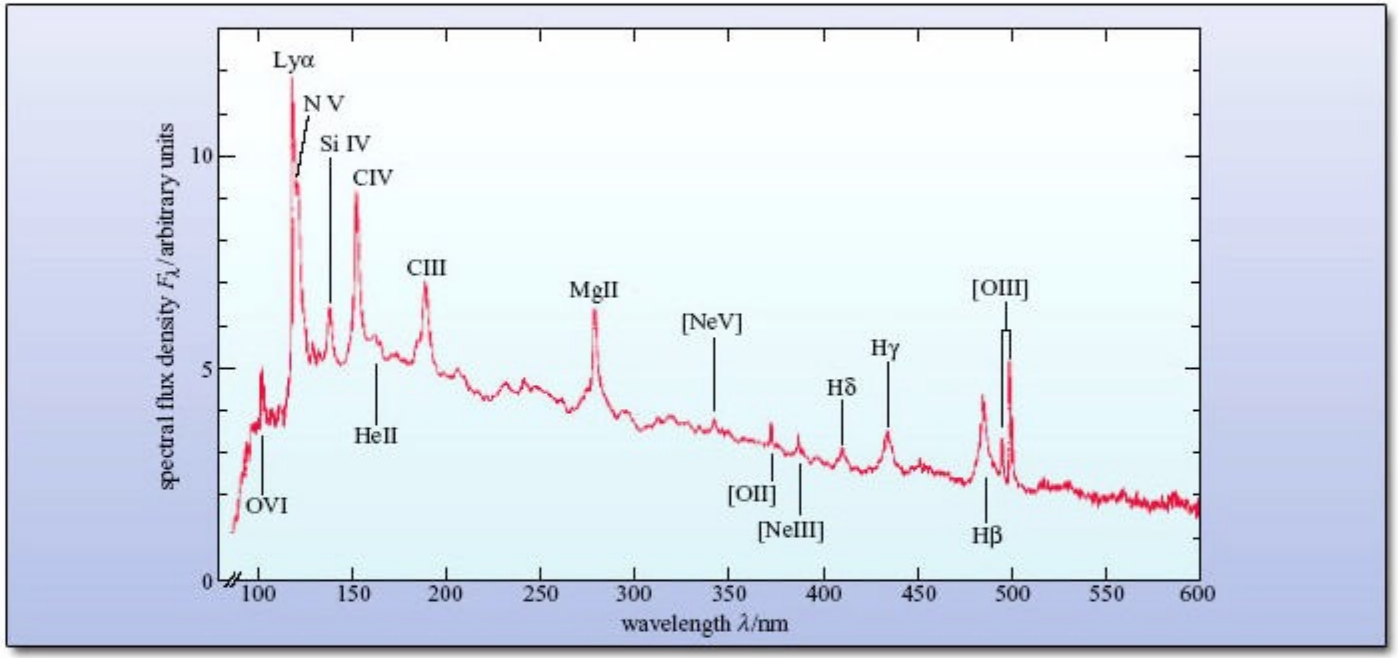
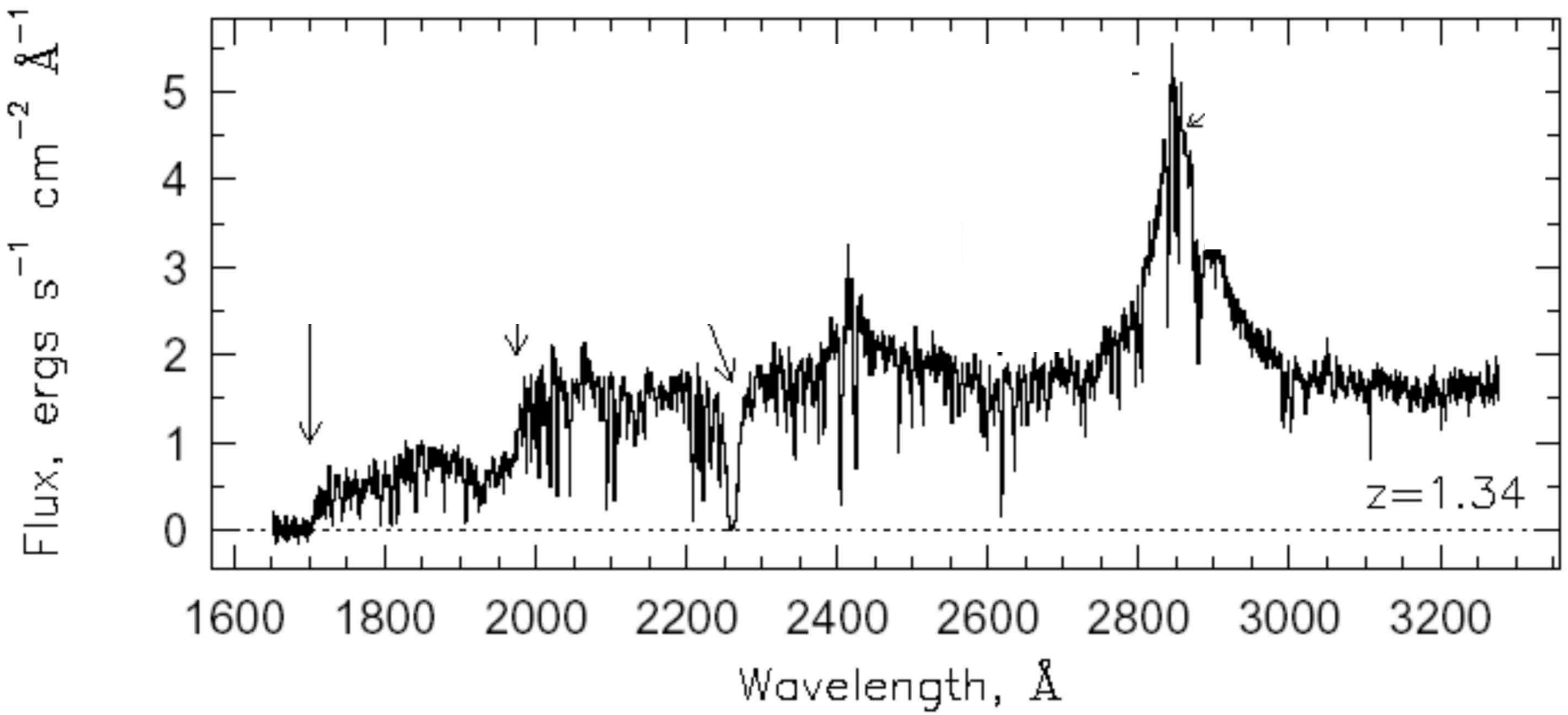


Figure 16: The mean optical spectrum of a sample of more than 700 quasars. The individual spectra were all corrected to remove the effect of red-shift before the spectra were averaged. Note the broad emission lines

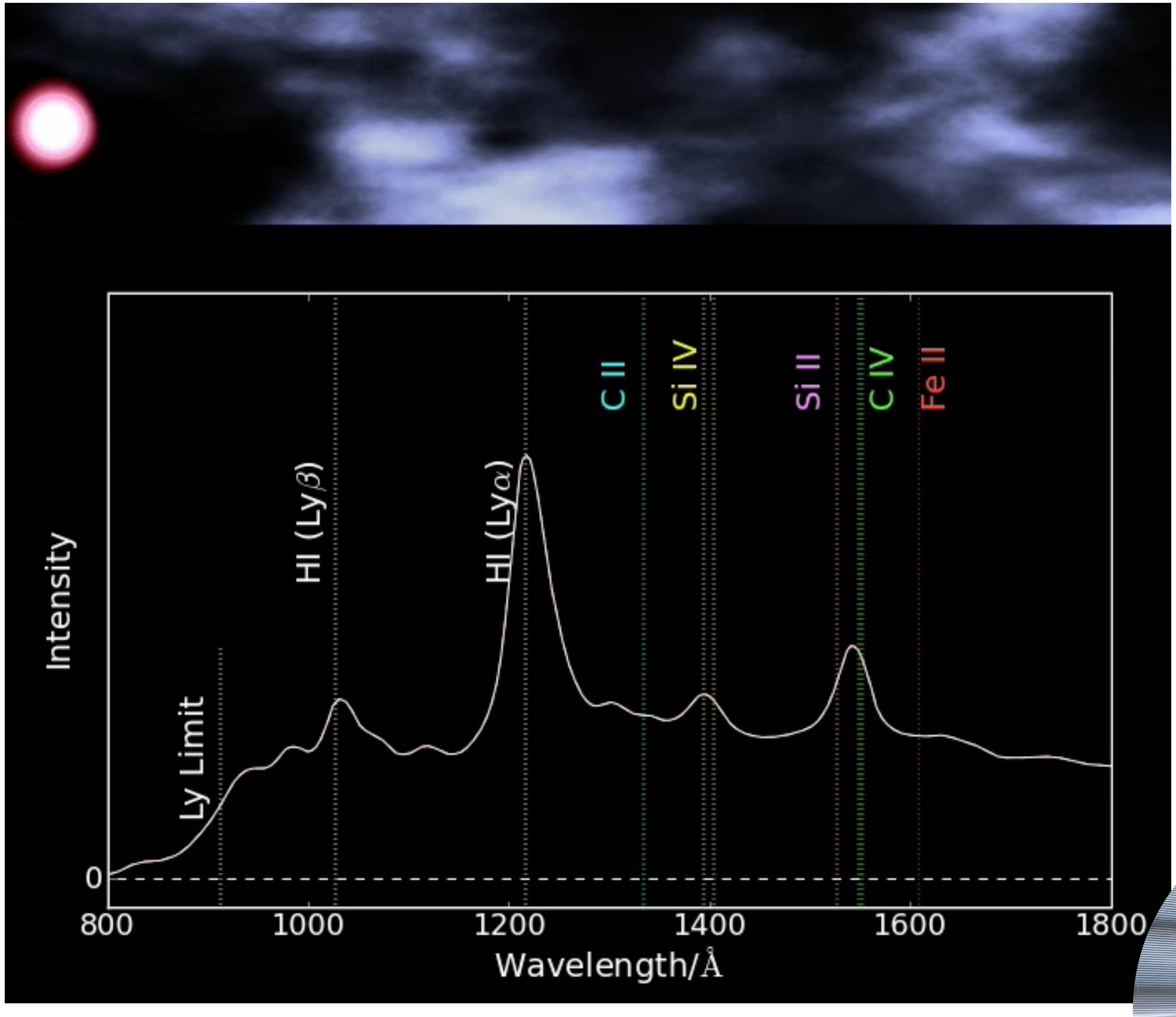
An Introduction to Active Galactic Nuclei, Cambridge University Press

Spectrum of a Quasar: What We Actually See



Features: Absorption lines everywhere!

Quasars as Background Sources



Emission lines become redshifted; absorption lines in the foreground reflect redshifts of intervening gas clouds

THE ASTROPHYSICAL JOURNAL, Vol. 156, May 1969

ABSORPTION LINES PRODUCED BY GALACTIC HALOS

JOHN N. BAHCALL*
Institute for Advanced Study

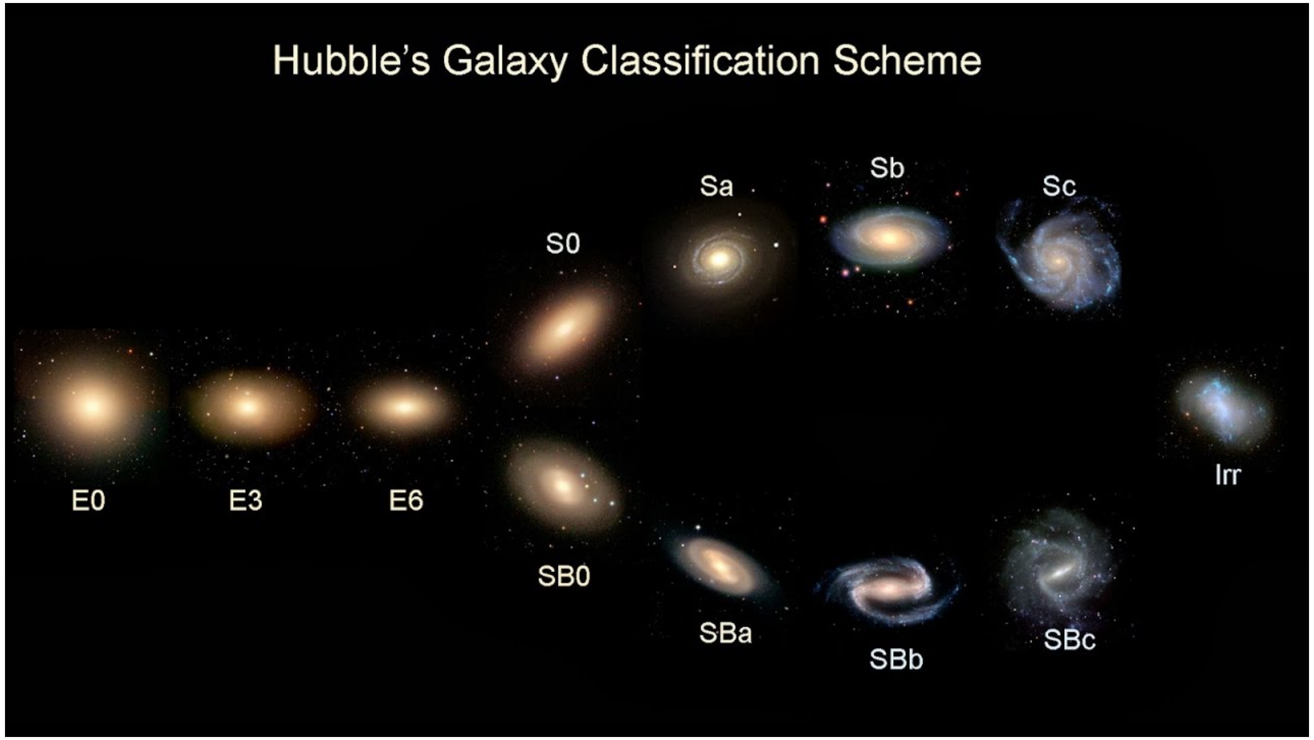
AND

LYMAN SPITZER, JR.
Princeton University Observatory
Received March 24, 1969

ABSTRACT

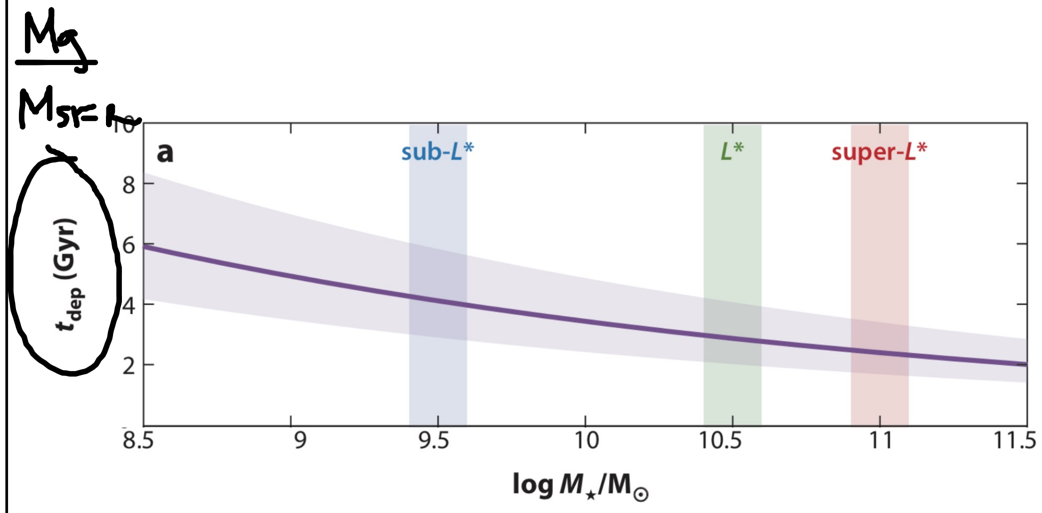
We propose that most of the absorption lines observed in quasi-stellar sources with multiple absorption redshifts are caused by gas in extended halos of normal galaxies.

The Major Problems of Galaxy Evolution



The answers all feature gas flows through the CGM

Q1. How do galaxies sustain their star formation?

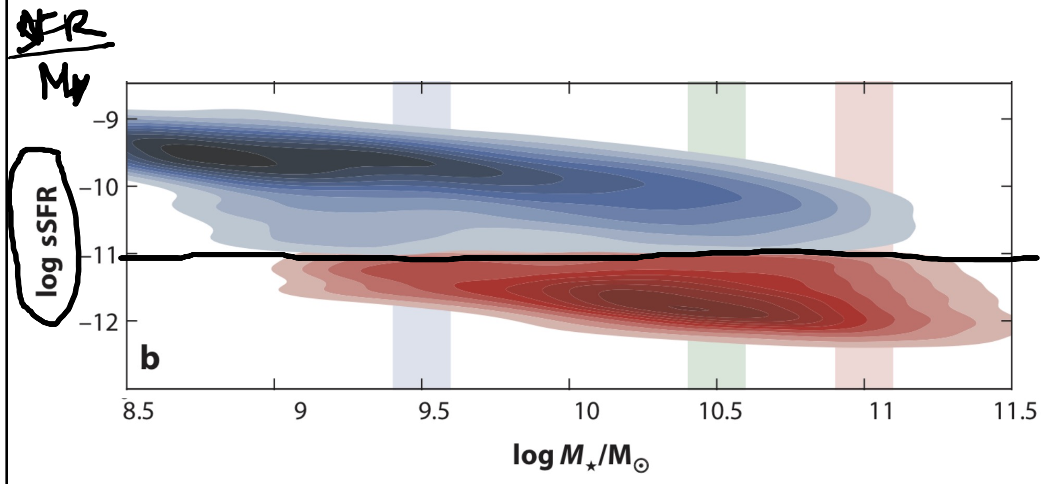


Depletion time = $M_{gas} / \dot{M}_{sfr}$

ISM gas only lasts for a very small fraction of the time most massive galaxies have been forming stars

Implies an external gas supply

Q2. What quenches galaxies and what keeps them that way?

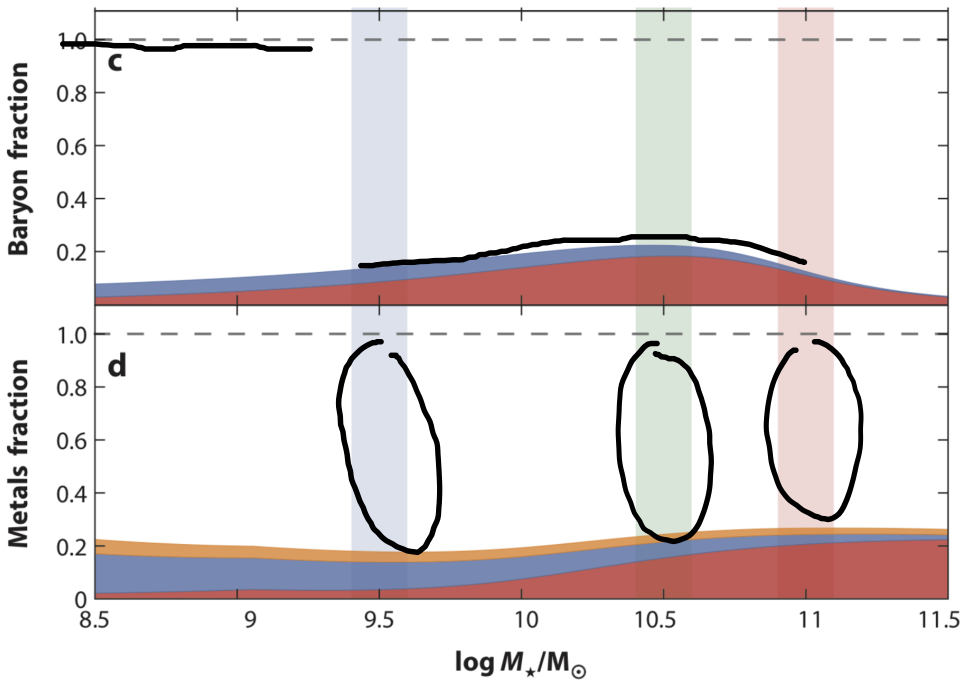


The famous galaxy bimodality

To stop star formation, you must cut off the gas supply. You can heat it up, evacuate it, rip it off.

Various quenching scenarios produce different signatures in the CGM.

Q3. Why do galaxies lack their fair share of baryons? And where are the metals?



Red = stars, Blue = ISM, orange = dust

Compared to the cosmological fraction, the stars and ISM are missing baryons. Stars and ISM do not contain all the metals (aka "Nature's Tracer Particles") generated by the stars they have made.

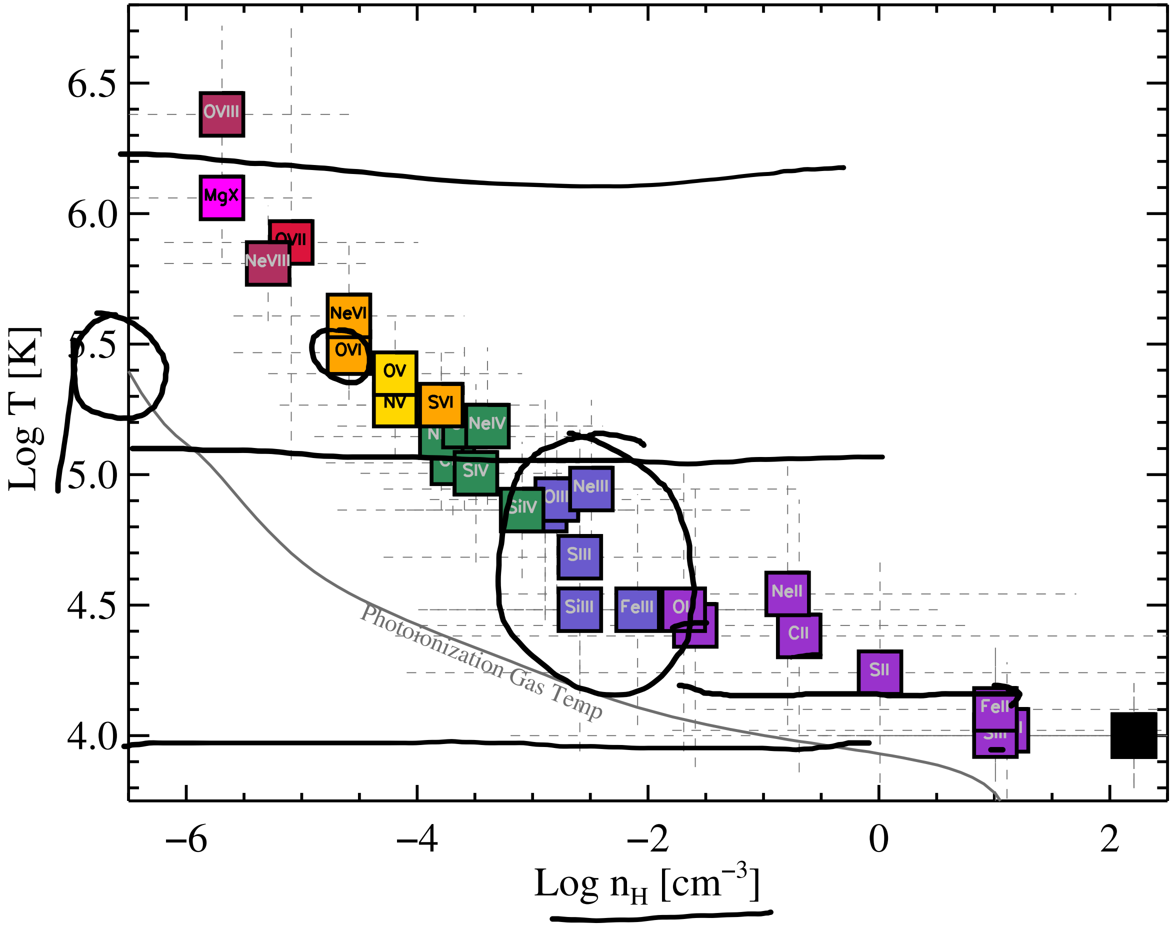
Are they actually "missing" or are they in the CGM?

How We Study the CGM

- Absorption Lines (Tranverse)
- Stacking Experiments
- Down the Barrel Absorption Lines
- Emission Maps (Only the densest gas)
- Simulations (Zoom-In, Cosmological, Idealized)

The Low-Redshift CGM is Best Viewed in the Ultraviolet

- HI: 1215, 1025… Å
- MgII: 2803, 2796, Å
- SiII: 1526, 1260…Å
- SiIII: 1206 Å
- SiIV: 1402, 1393 Å
- CIV: 1550, 1548 Å
- OVI: 1031, 1037 Å
- NeVIII: 770, 780 Å



Plot adapted from Tumlinson, Peeples, & Werk, ARA&A 2017

UV-Ion Observability

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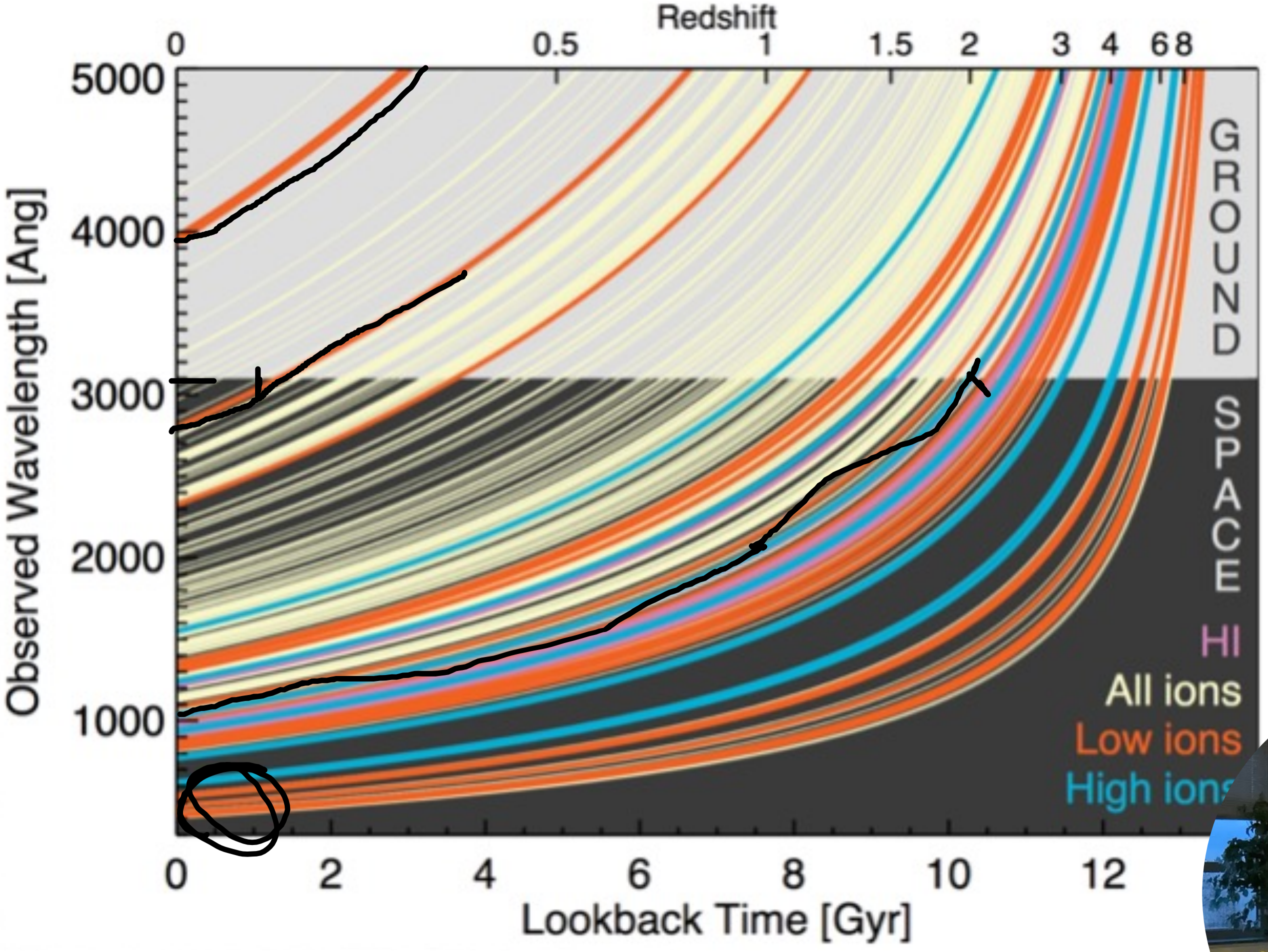
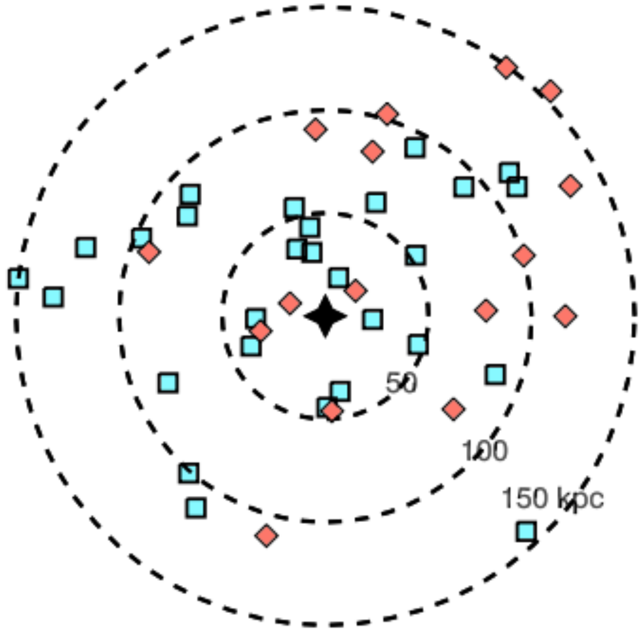
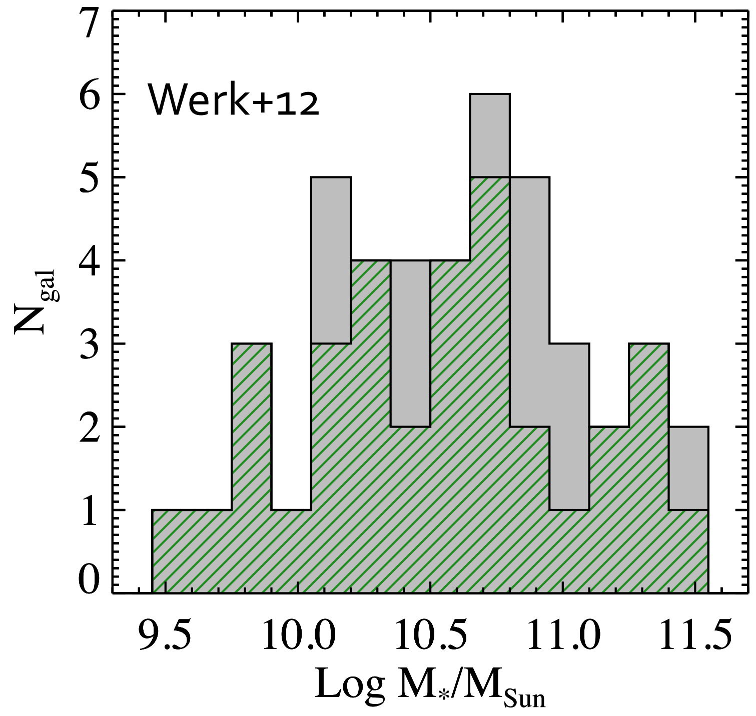


COS-Halos: An Survey of The CGM of z~0.2 L* Galaxies

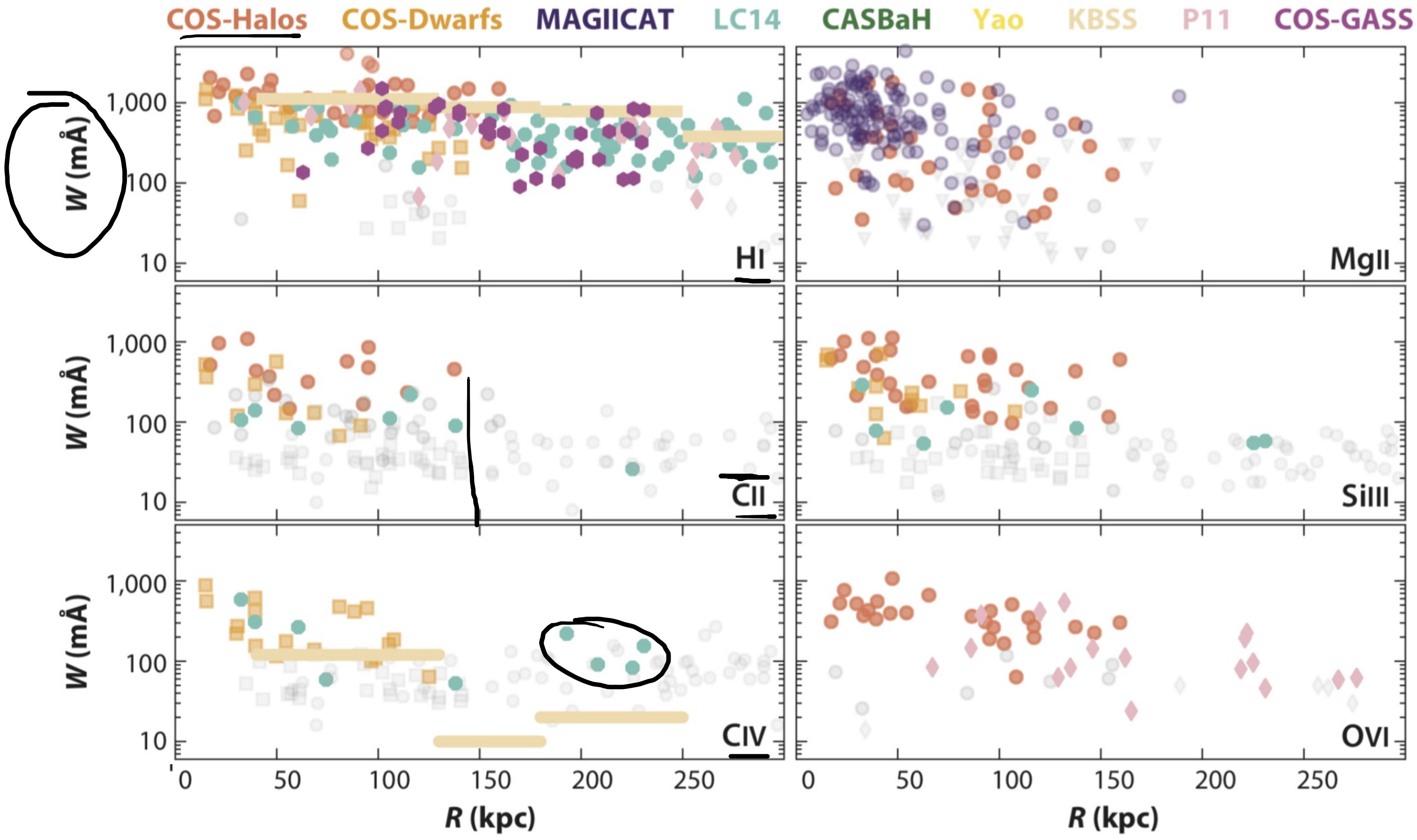
- 30 star-forming; 14 non-SF galaxies
- COS + HIRES for QSOs
- Keck/LRIS for galaxies





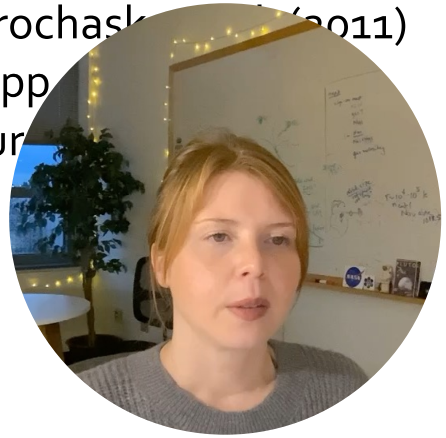
COS-Halos Team: Jason Tumlinson, J. Xavier Prochaska, **Jessica Werk**, Todd Tripp, Rongmon Bordoloi, Romeel Davé, Amanda Ford, Andy Fox, Chris Howk, Neal Katz, Nicolas Lehner, John O'Meara, Ben Oppenheimer, Molly Peeples, Ken Sembach, Chris Thom, and David Weinberg

Empirical Results: Large Covering Fractions of Multi-Phase Ions

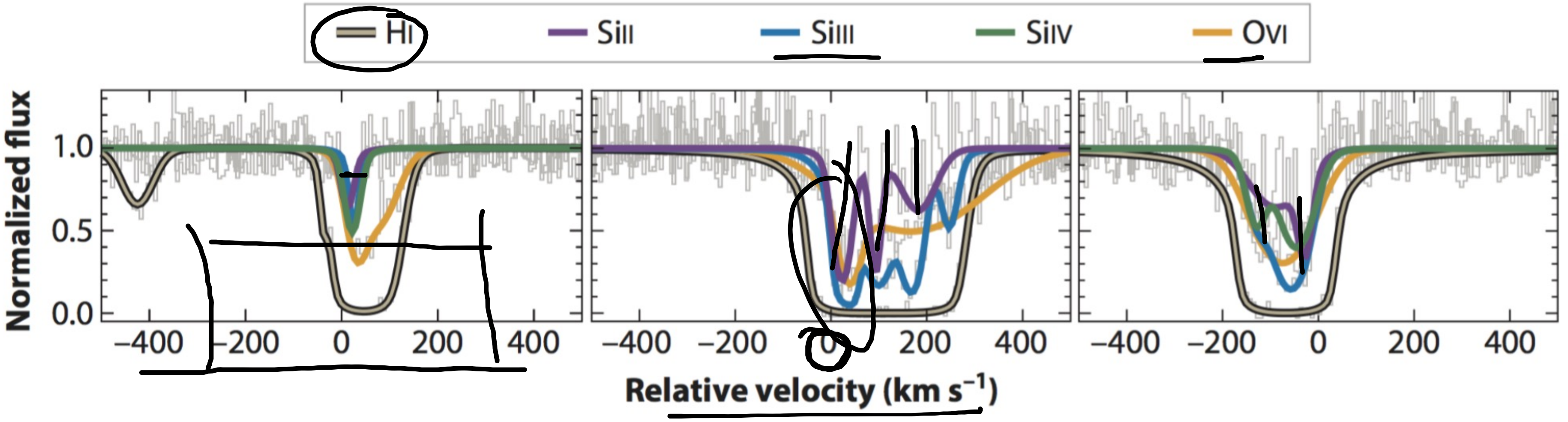


The Surveys

COS-Halos: Tumlinson et al. (2013);
Werk et al. (2013)
COS-Dwarfs: Bordoloi et al. (2014)
COS-GASS: Borthakur et al. (2015)
MAGIICAT: Nielsen et al. (2013)
LC14: Liang & Chen (2014)
KBSS: Rudie et al. (2012);
Turner et al. (2015)
P11: Prochask... (2011)
CASBaH: Tripp...
Bur...



Complex Kinematic Correspondence Between Different Ionization States



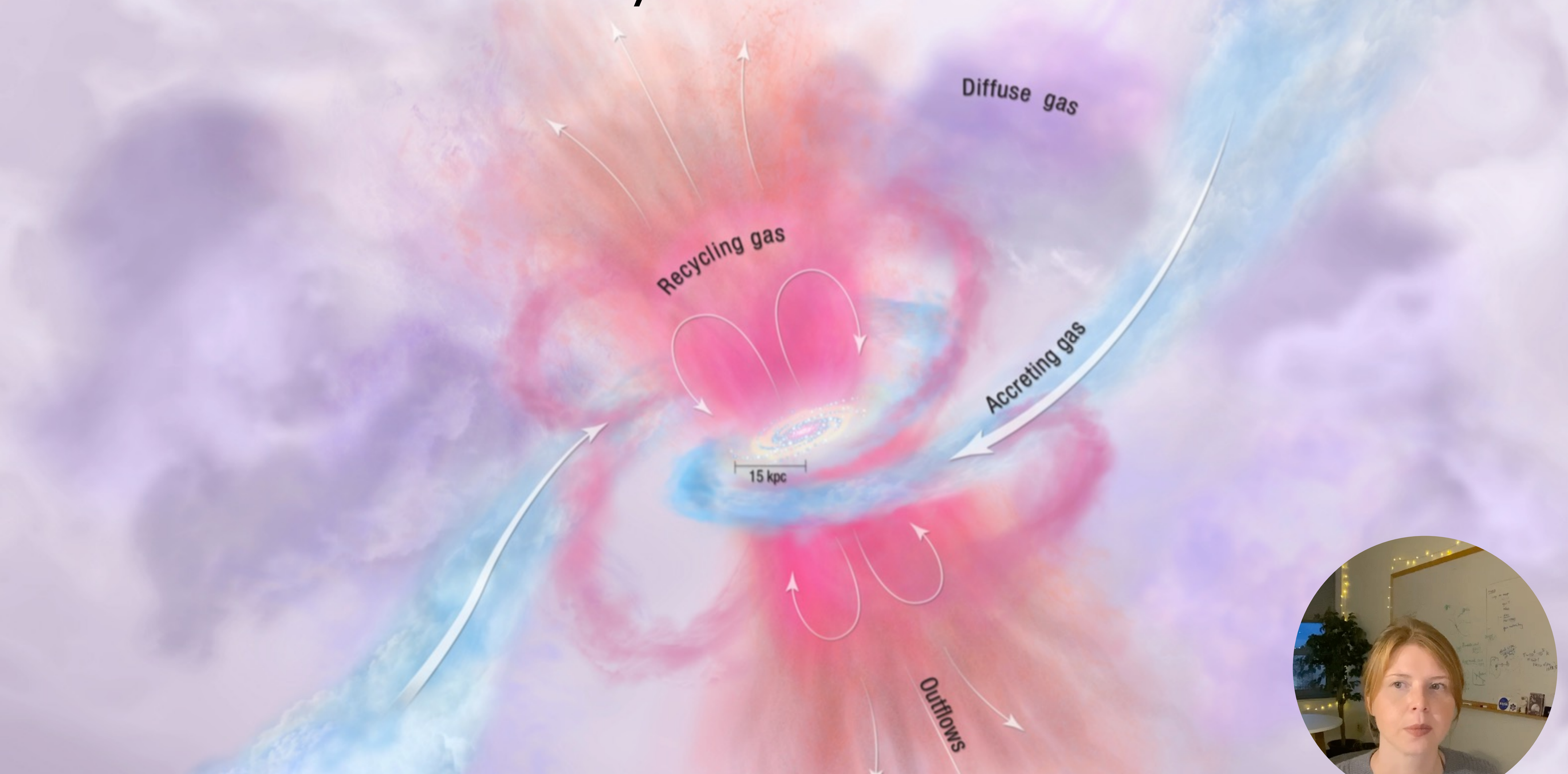
$b_{th} = \left(\frac{2kT}{m}\right)^{\frac{1}{2}}$

$b^2 = b_{th}^2 + b_{nt}^2$

McQuinn & Werk (2018); Werk et al. (2016), Tripp et al. (2008), Muzahid et al. (2012), Savage et al. (2014), and more

kinematics can reveal influence of the galaxy's gravitational potential, bulk flows, and turbulence in the

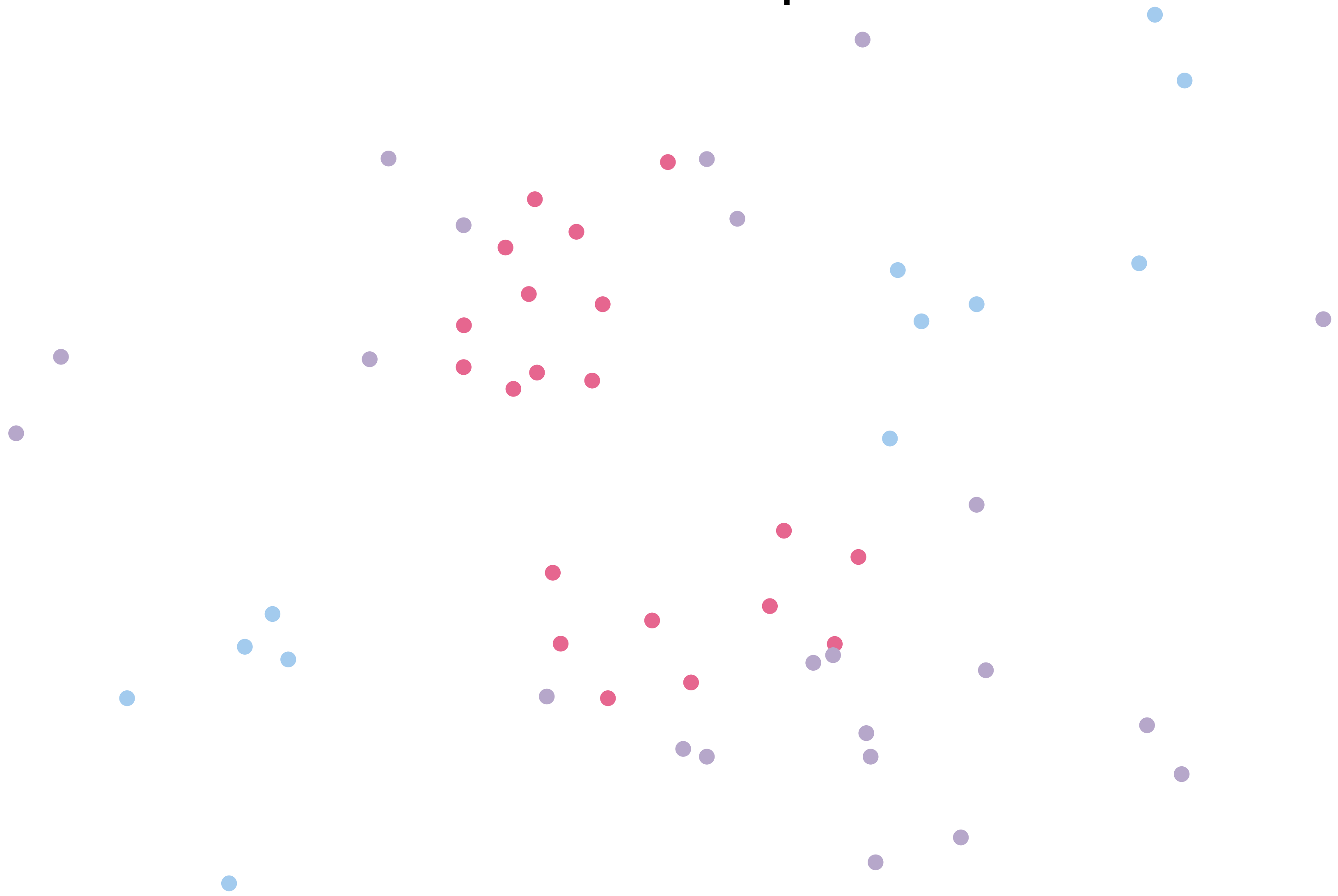
How We Study the CGM: What We Want



Tumlinson, Peeples, & Werk 2017 ARA&A

What We Have:

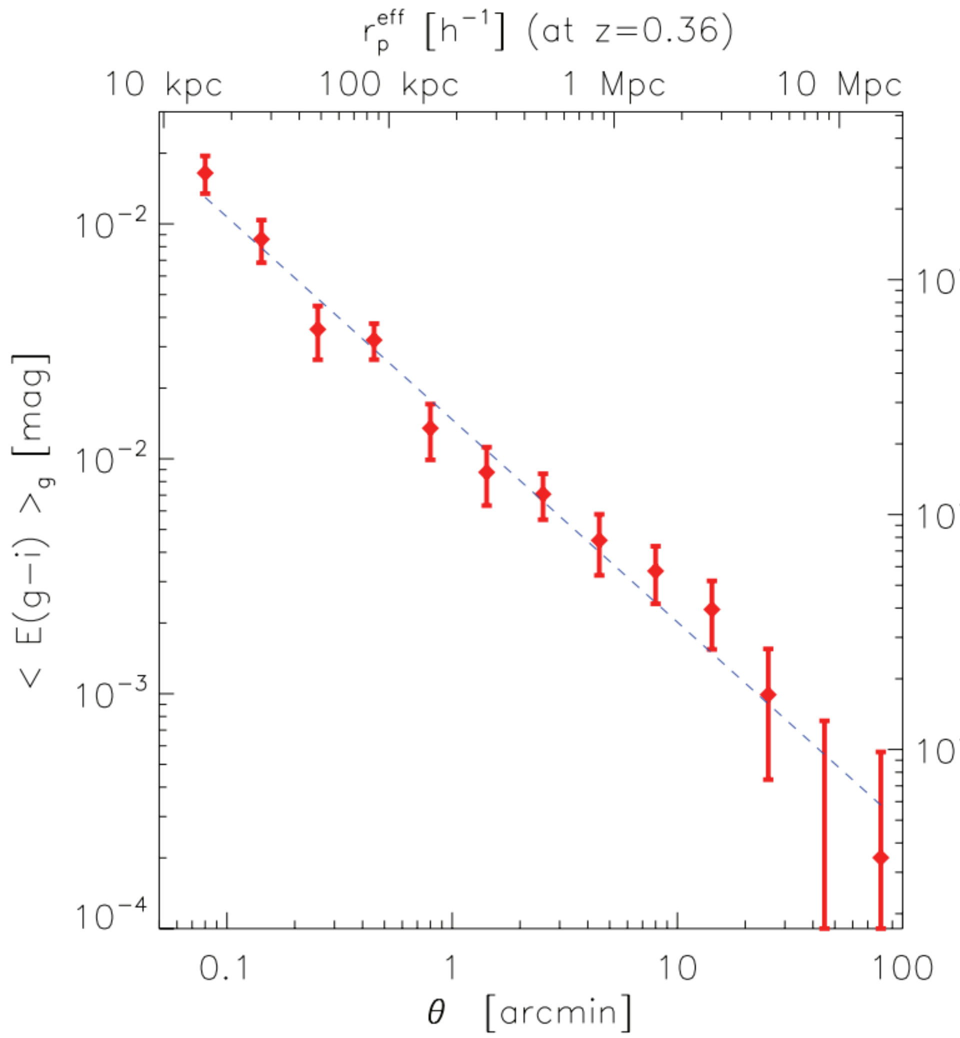
Current Constraints from Absorption “Statistical Maps”



NB: Points have been enlarged by a factor of ~100000; and are all around *different* galaxies.

Stacking: Powerful Tool but Averages Out Individual Features

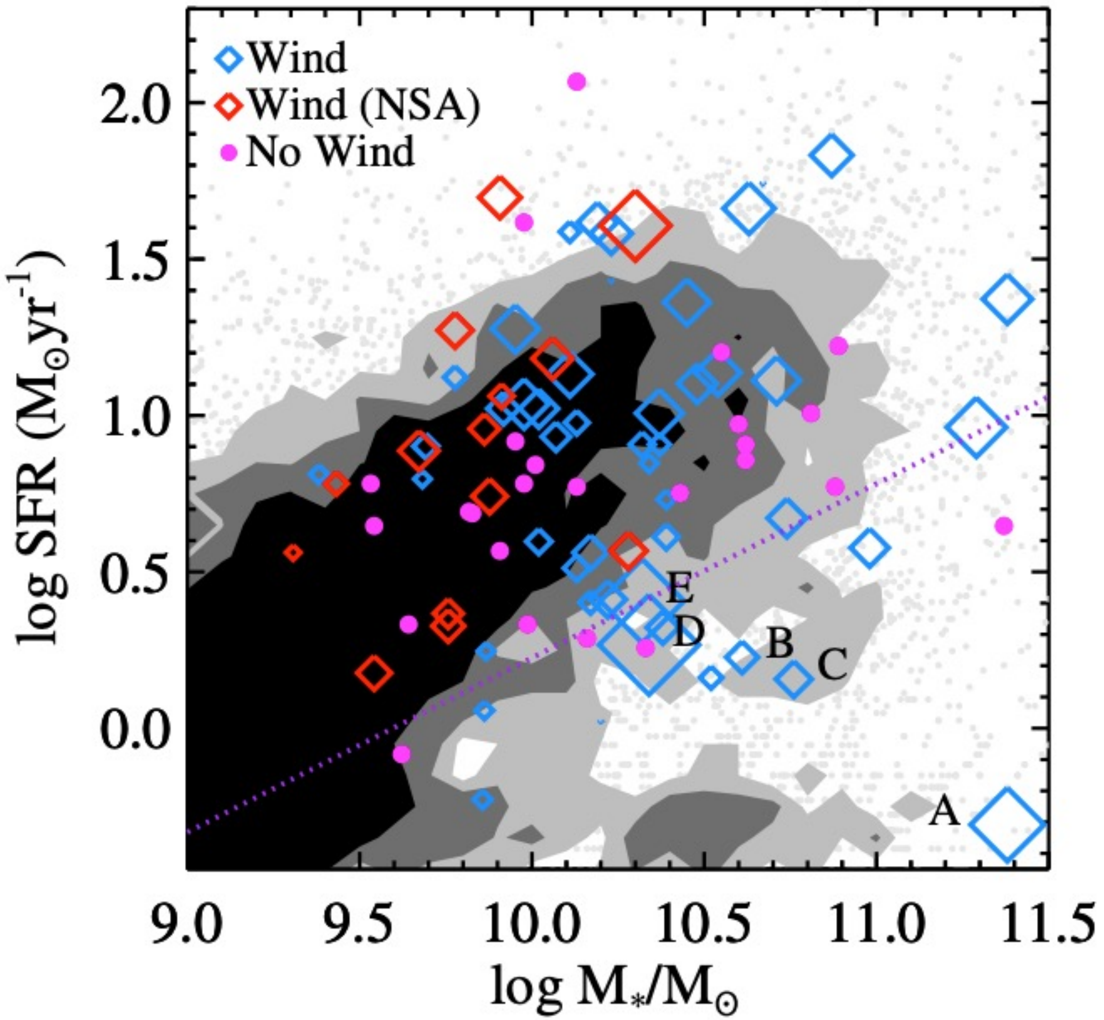
Menard+10



The amount of dust found in the CGM is found to be comparable to that in the disks of galaxies

Down the Barrel Measurements

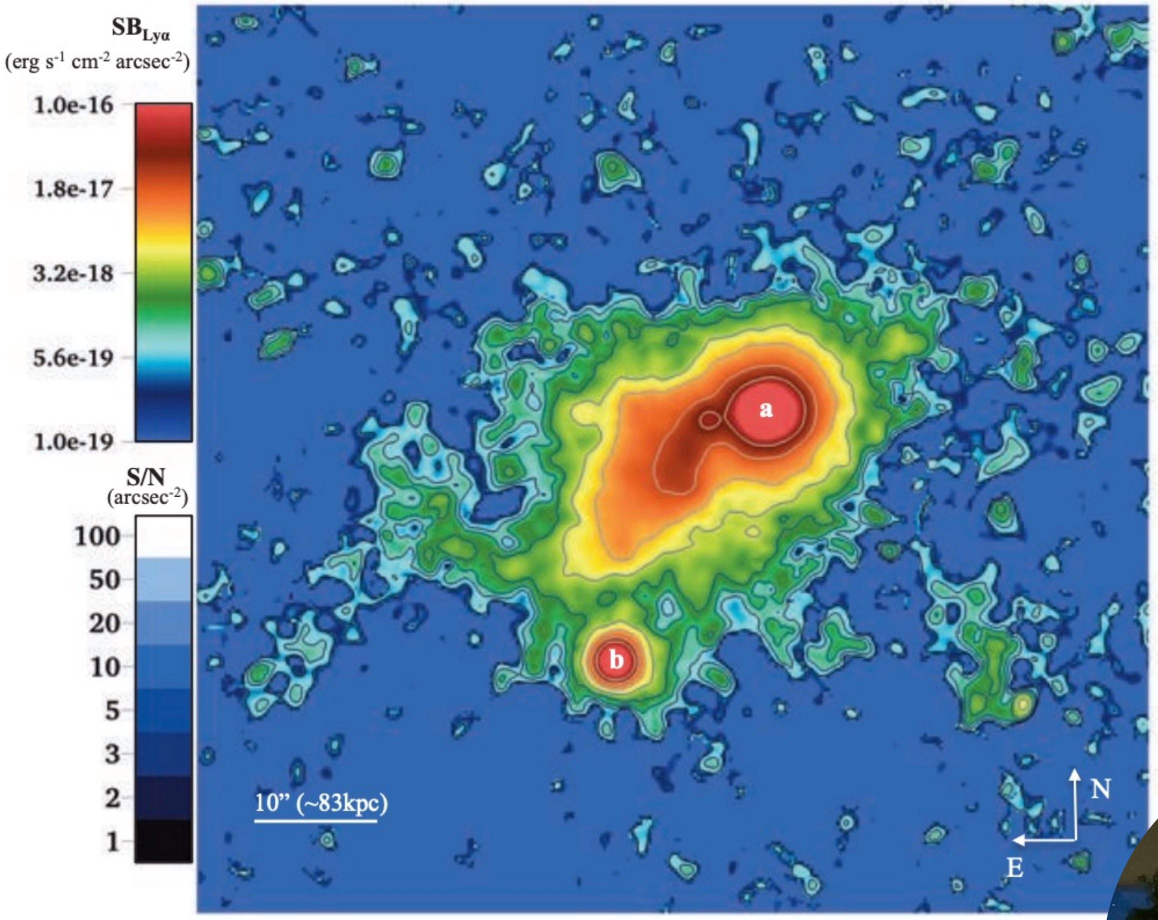
Rubin et al. 2014



The detected outflows are a viable source of cool material for replenishment of the CGM

Emission Line Maps

Cantalupo et al. 2014

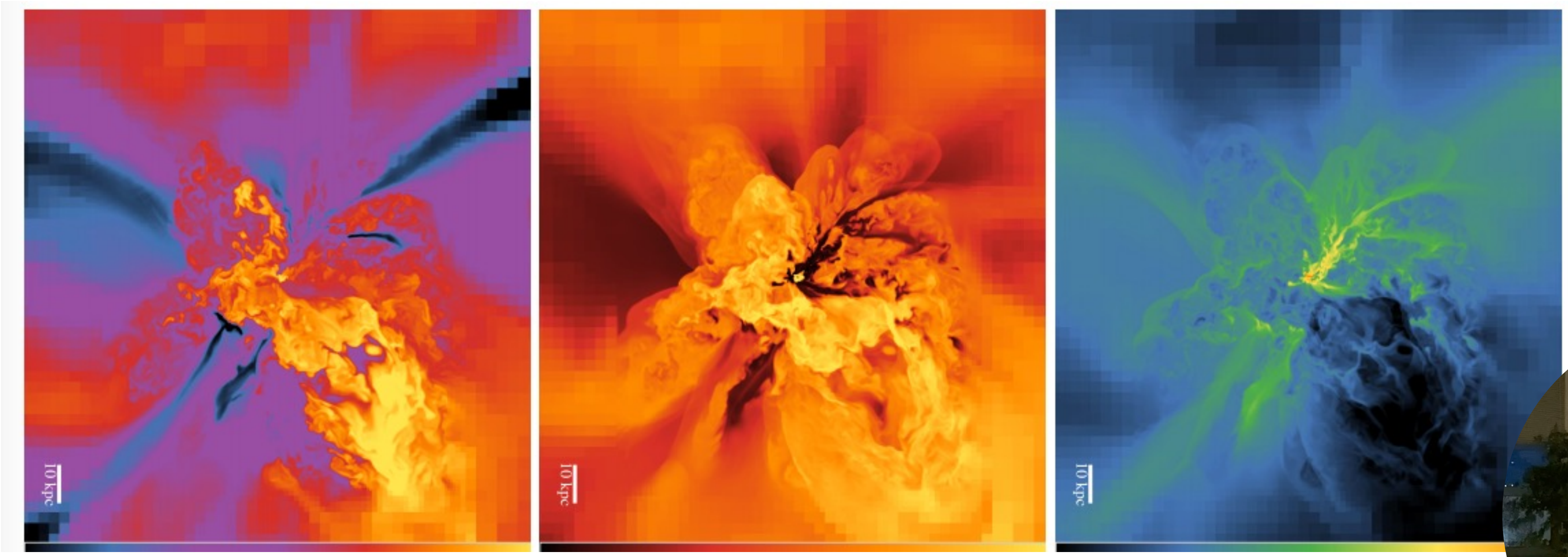


Extended Lyα emission observed out to ~ 100 kpc away from z ~ 2.5 galaxies and QSOs

Simulations

Produce spatial distribution of metals, density, temperature maps combined with gas kinematics and absorption measures

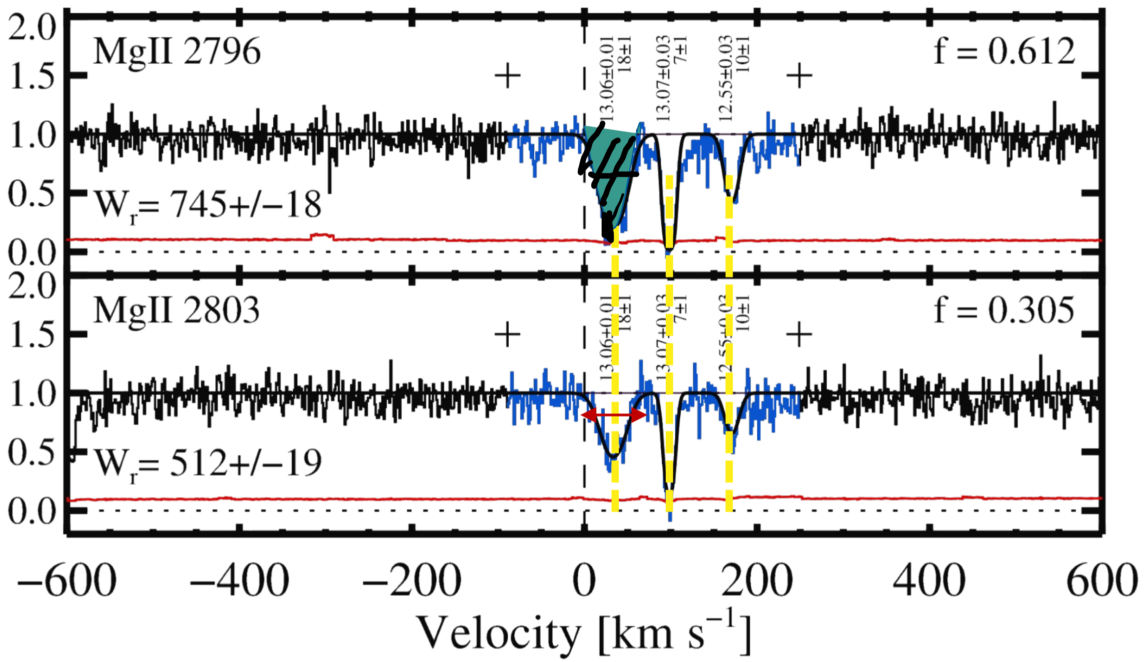
Galaxy from FOGGIE simulation, Peeples et al. 2018



metallicity temperature density

Techniques for Probing The Gas Phase Structure

- **Absorption line profiles → kinematics of different ions**
- Column density ratios among different ions in various ionization states compared to Ionization models (e.g. *Cloudy*)
- Comparisons with simulations and semi-analytic predictions



Relative velocity: v_{cen}

Width: Doppler *b* parameter

Strength: Equivalent Width → column densi

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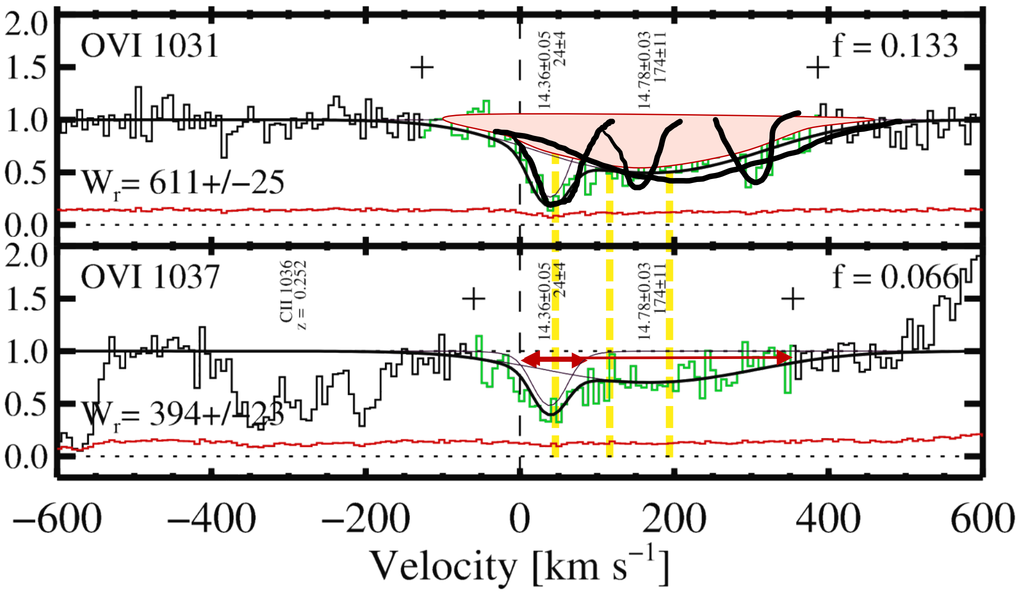

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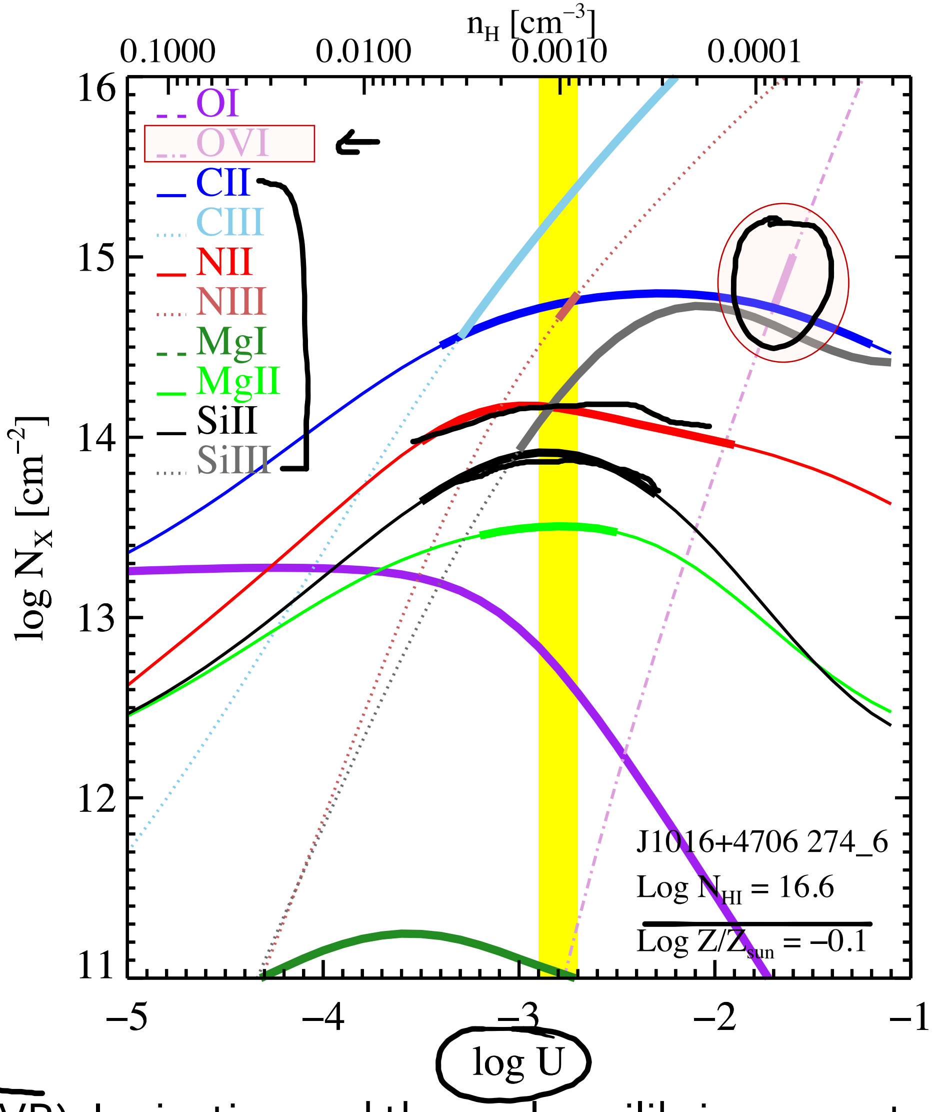
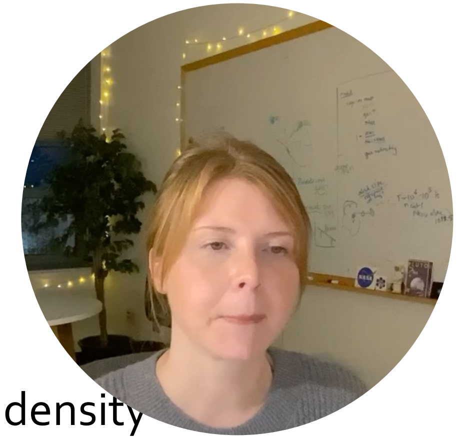




Assume: Ionizing Radiation Field (e.g. UVB); Ionization and thermal equilibrium; constant density

The phase structure you infer often depends strongly upon your initial assumptions.

For Example:

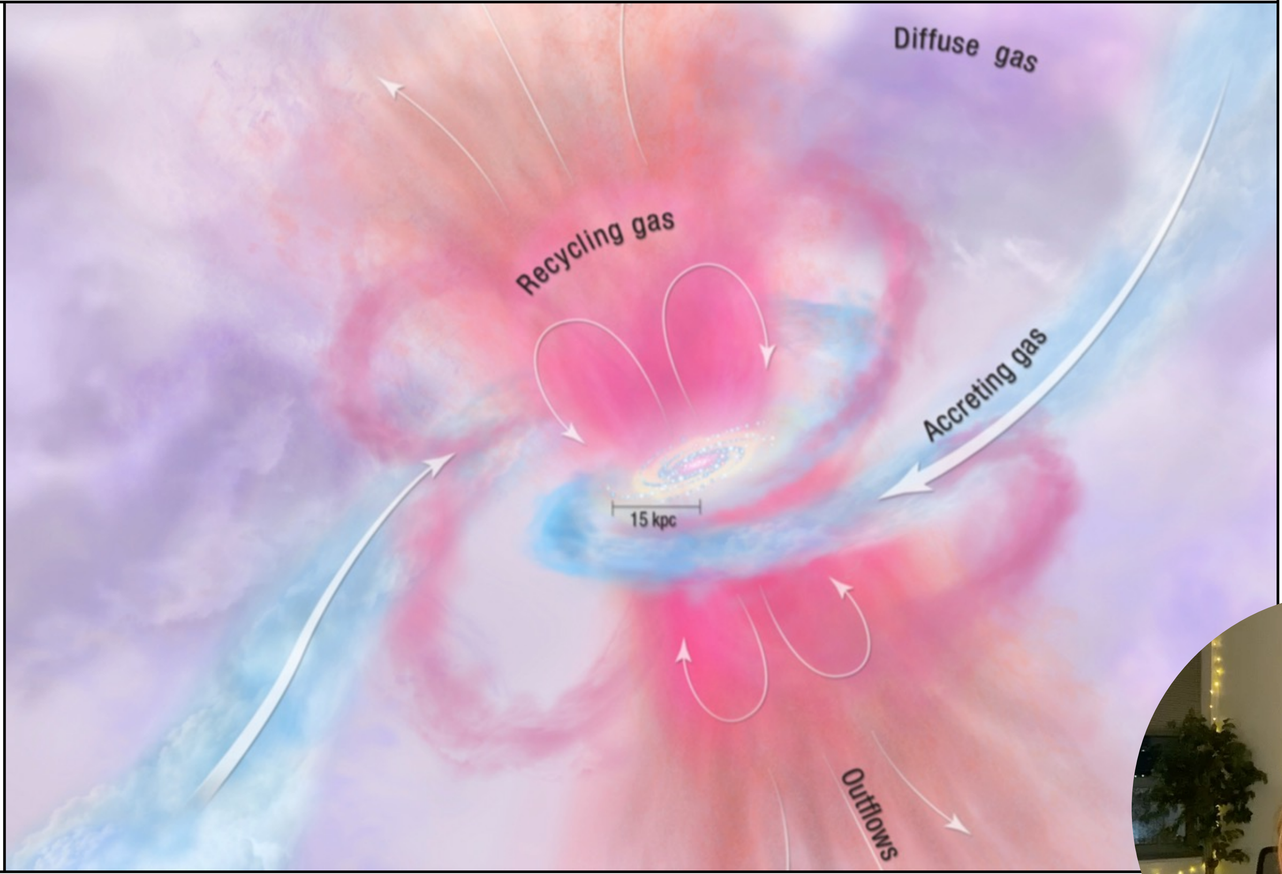
1. background radiation field,
2. geometry/density structure
3. the importance of collisional ionization
4. Shocks/Turbulence/Magnetic Fields???

Image from Shneider et al. 2020; The Astrophysical Journal, 895:43 (24pp), 2020 May 20

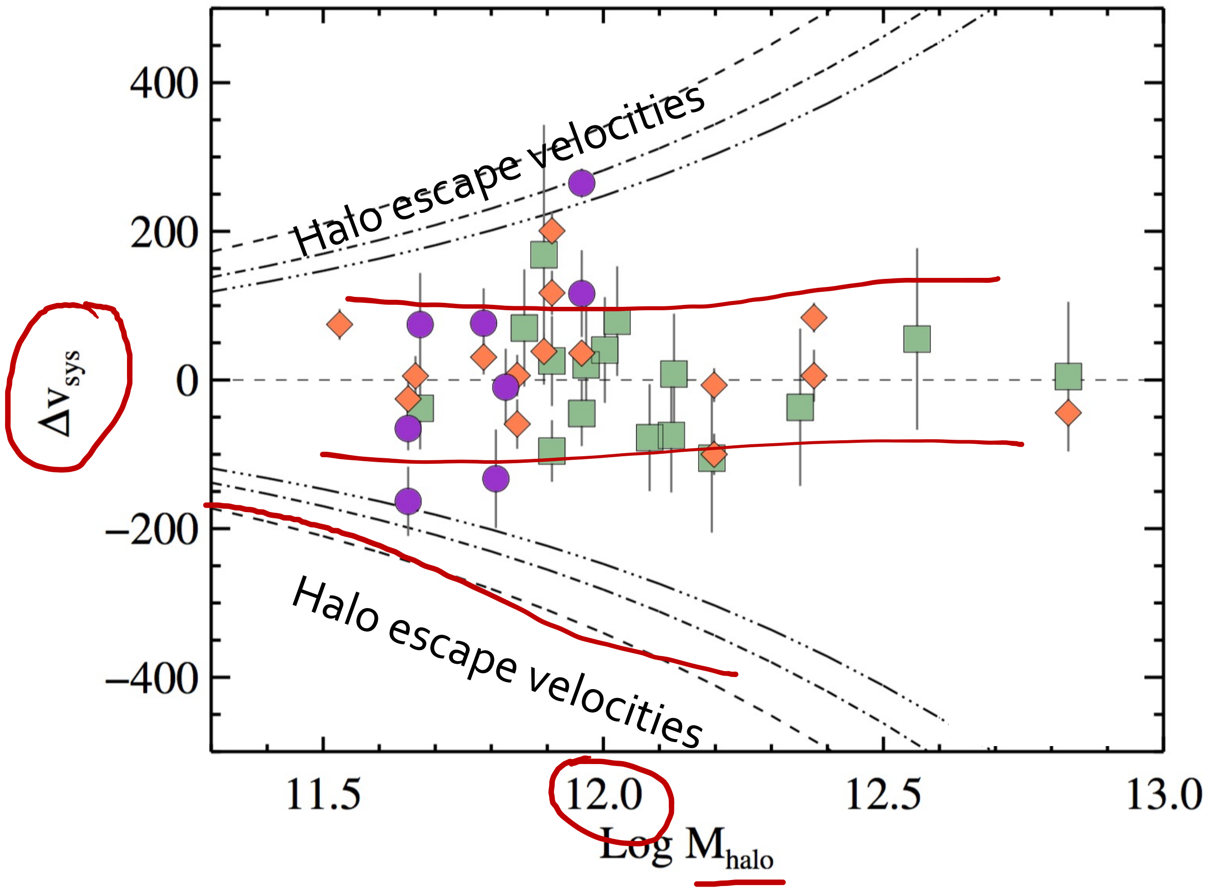
Part 2

a. The Main CGM Results: Physical State, Total Mass, and Metal Budget

b. Interpretation: Inflows, Outflows, Recycling and Quenching



Absorption Velocities Show Small Kinematic Offsets from Host Galaxies

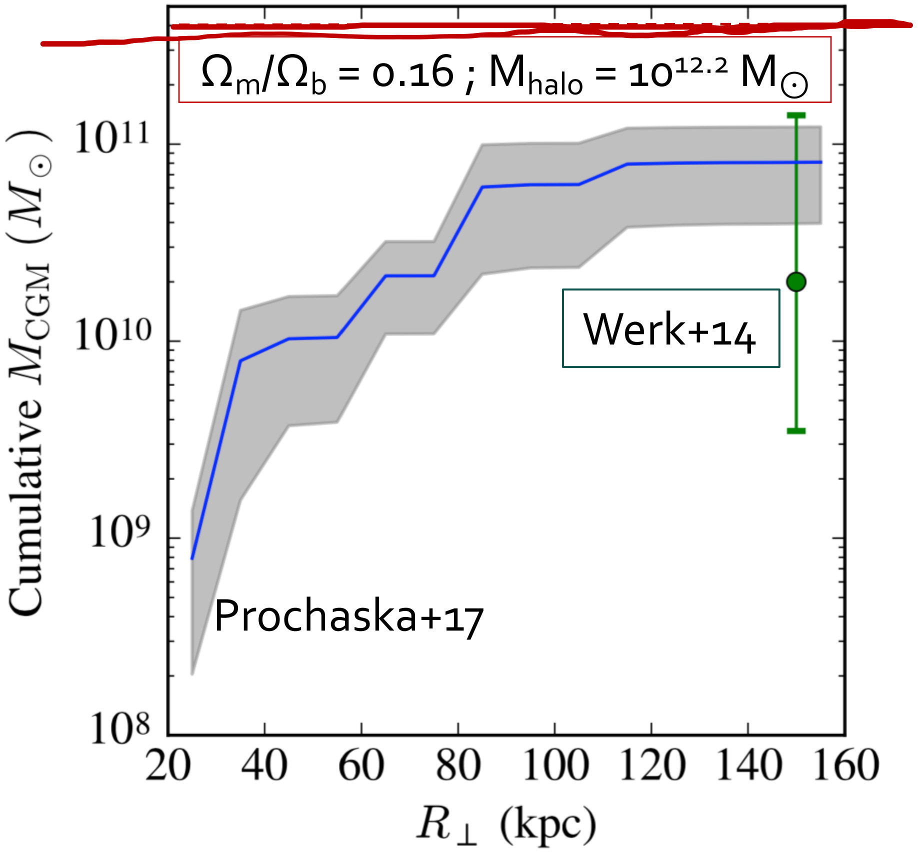


Werk et al. 2016

$$\Delta v \sim 50 - 150\ km\ s^{-1}$$

Observations strongly hint that CGM gas is bound to the galaxy ha

UV Observations Imply a Massive Reservoir of Photoionized ~10^4 K Gas



Despite Significant Uncertainties in Modeling, Analyses Agree:

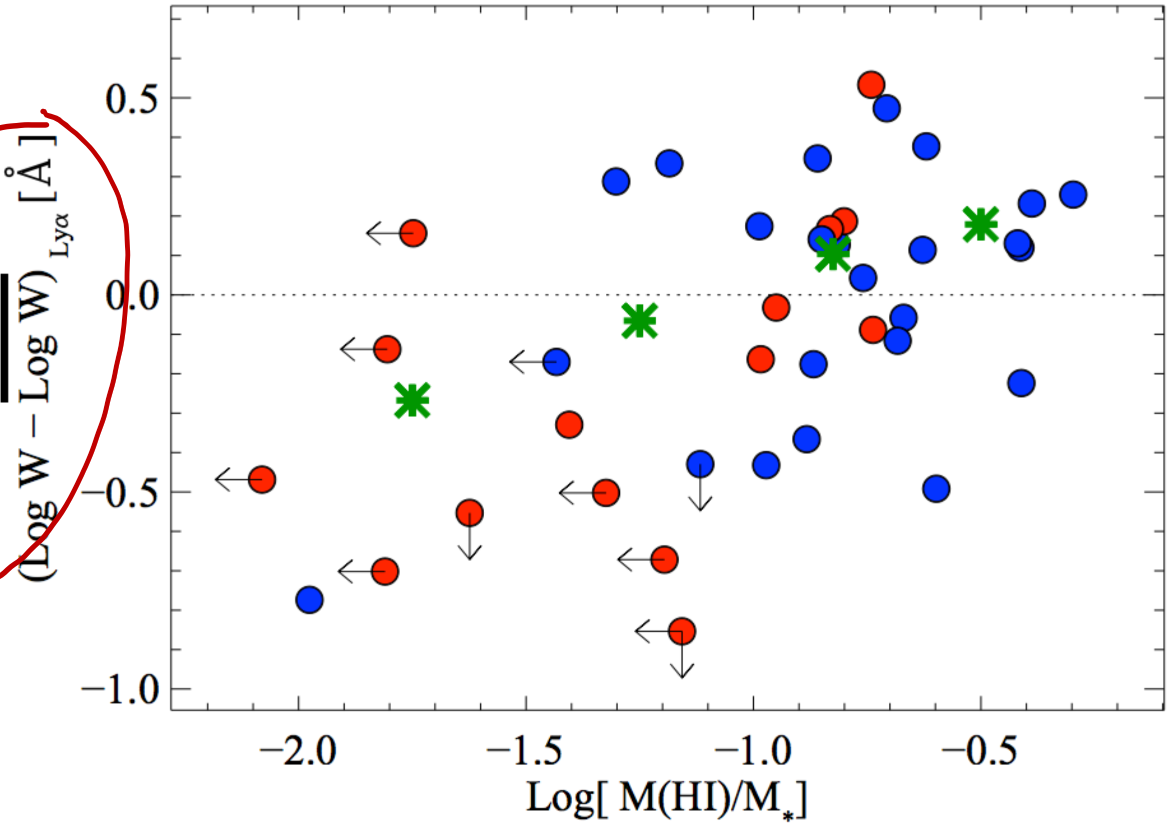
Prochaska et al. 2011: $M_{photo} \geq 10^{10}\ M_\odot$
Stocke et al. 2013: $M_{photo} \geq 10^{10}\ M_\odot$
Werk et al. 2014: $M_{photo} \geq 10^{10}\ M_\odot$
Stern et al. 2016: $M_{photo} \geq 10^{10}\ M_\odot$
Prochaska et al. 2017: $M_{photo} \geq$
Keeney et al. 2017: $M_{photo} \geq$

NB: Low densities unavoidable $n_{photo} \lesssim 10^{-2.5}\ cm^{-3}$

Galaxies with More Cold Gas in Their ISM Have More Cold Gas in Their CGM

Borthakur et al. (2015)

CGM

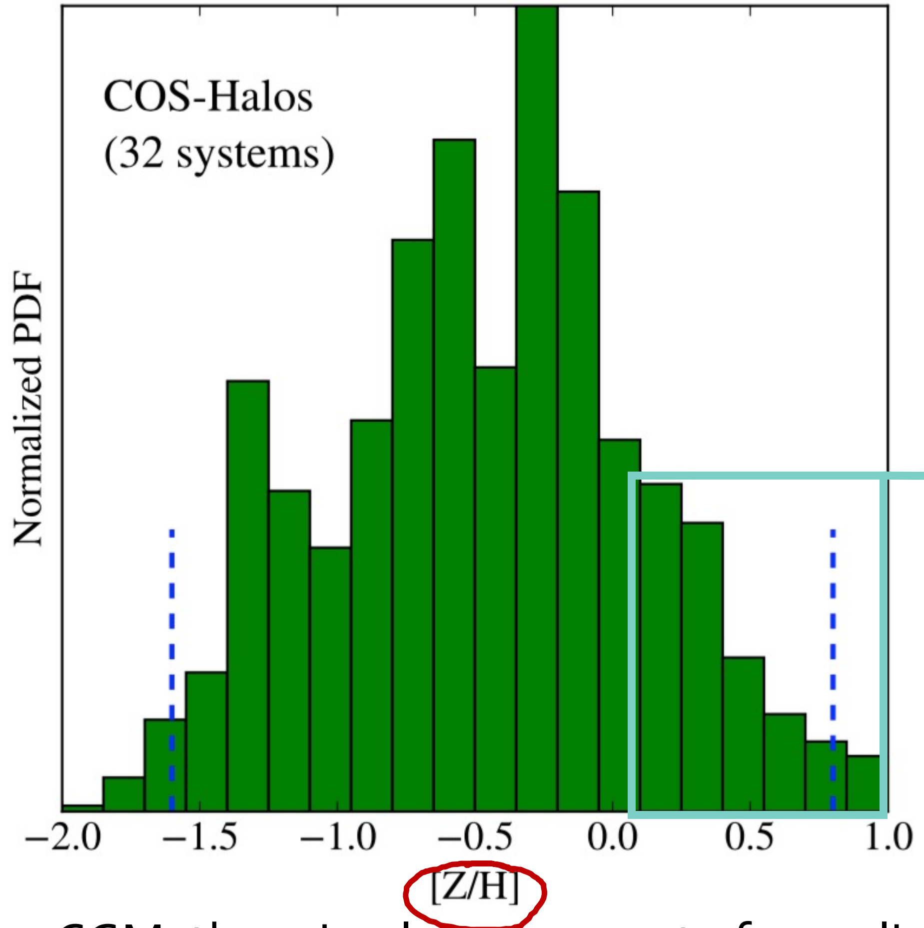


ISM

This correlation implies a connection between circumgalactic fuel and star f

Gas in CGM is Not Pristine

Prochaska et al. (2017)

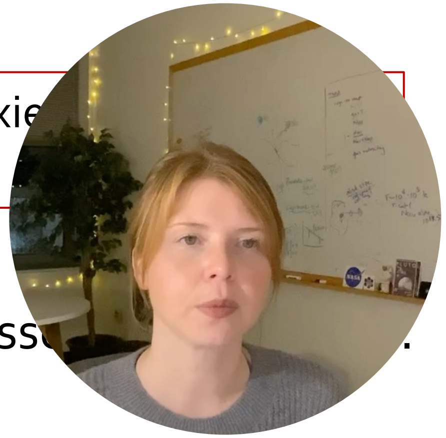


$Mean\ L^{*}\ Z_{CGM}\ \approx 0.3\ Z_{\odot}$

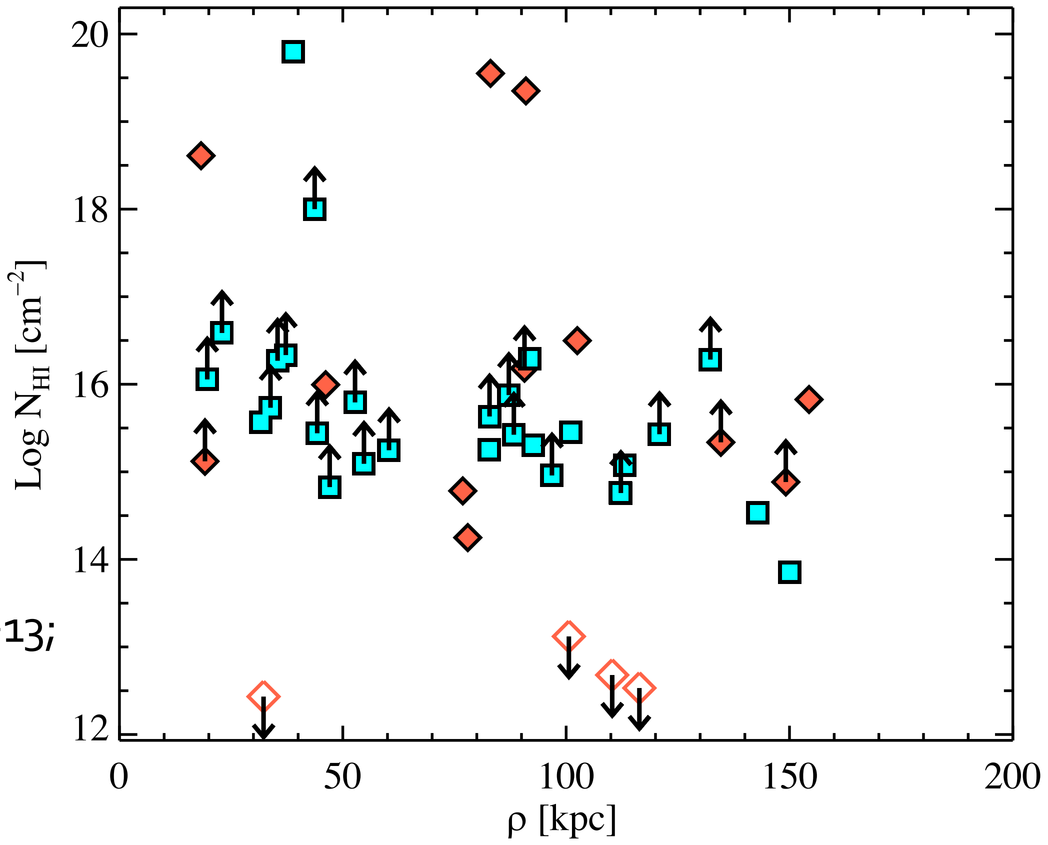
25% of the sample has > 50% of their PDFs $> Z_{\odot}$!
The super solar gas lies at R > 75 kpc

Many of the metals “missing” from galaxie
Peeples et al. (2014)

In the CGM, there is a large amount of recycling of material that has already been processe .



HI is Ubiquitous around SF and non-SF Galaxies



SFR > 0.1 $M_\odot$ yr^{-1} (blue, star-forming)

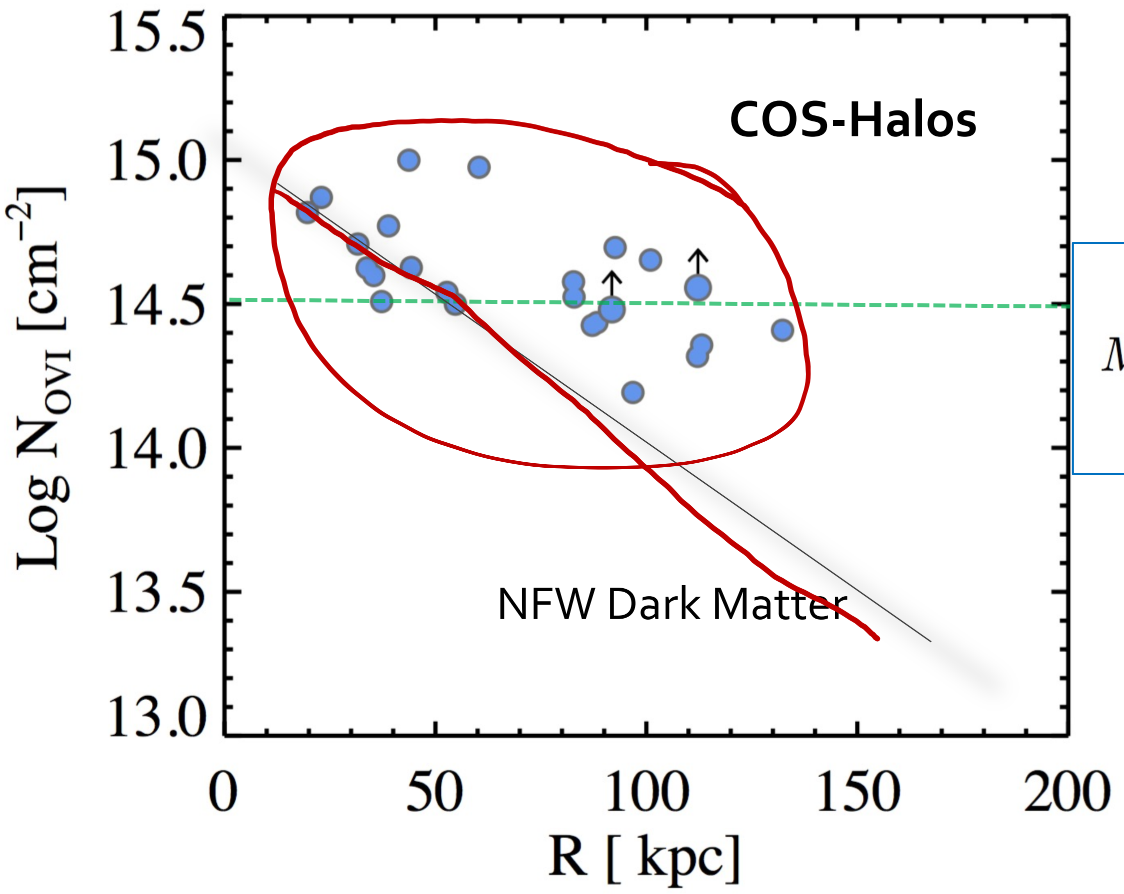
SFR < 0.05 $M_\odot$ yr^{-1} (red, quiescent)

COS-Halos: Thom+12, Tumlinson+13;
COS-GTO: Keeney+17
LRGs: Zhu+15, Faredy??

The CGM of quiescent galaxies harbors a significant amount of "unuse

OVI is Ubiquitous Around Star-Forming Galaxies

Tumlinson et al. (2011), Stocke et al. (2014), Johnson et al. (2015) Werk et al. (2016), Faerman et al. (2017)

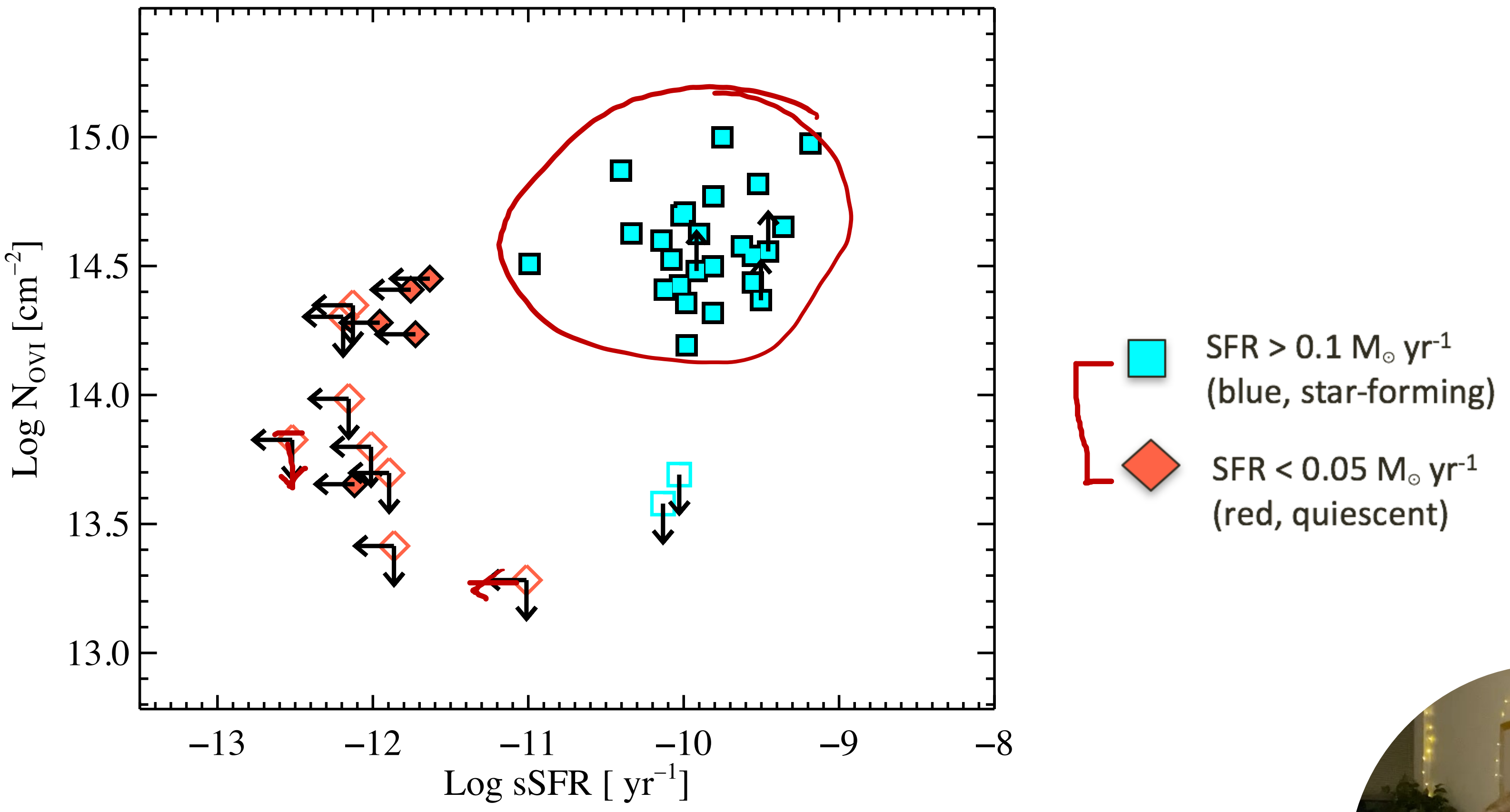


$N_{OVI} \approx 10^{14.5}$ cm^{-2}

At a minimum implies:

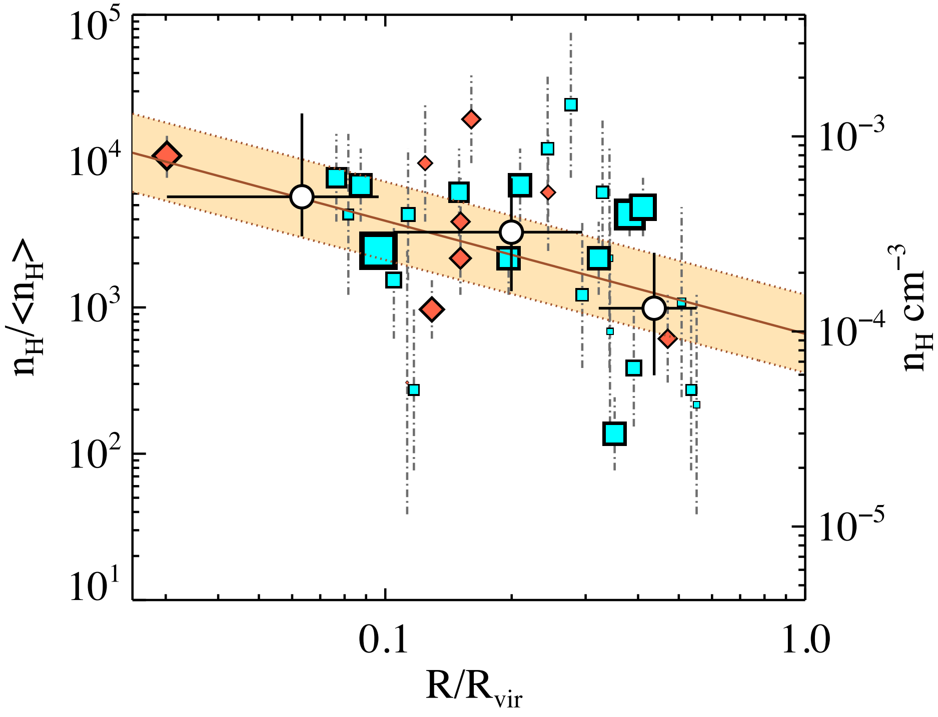
$$M = 8 \times 10^9 M_\odot \left(\frac{0.1}{f_{OVI} Z}\right) \left(\frac{N_{OVI}}{10^{14.5} \mathrm{cm}^{-2}}\right) \left(\frac{R}{200\mathrm{kpc}}\right)^2$$

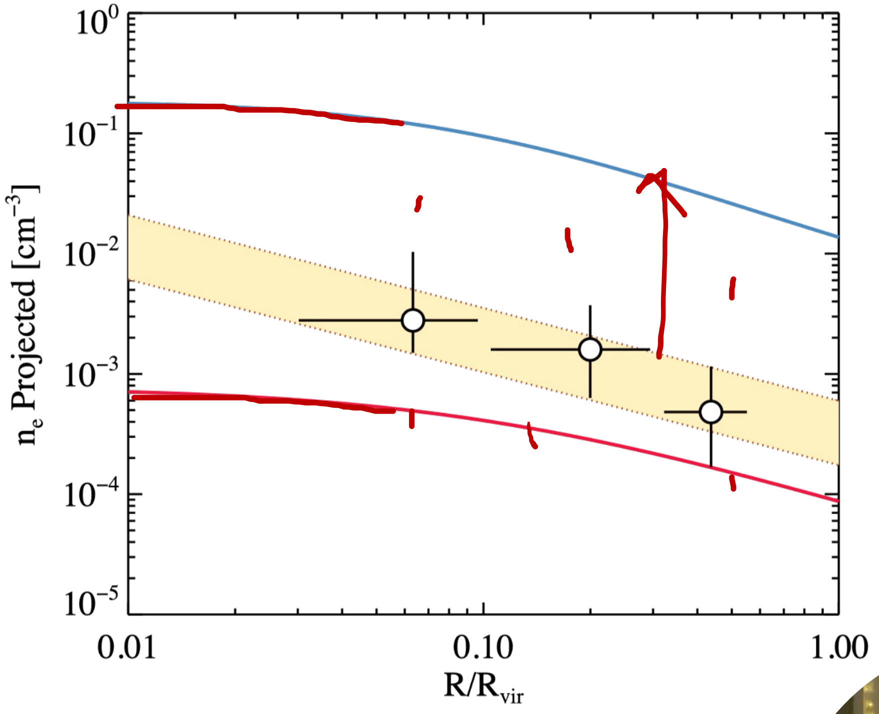
OVI is Nearly Absent Around Non-Star-forming Galaxies



Quenching appears to modify the abundance of high ions in L* halos while leaving the low ions mostly unaffected (Tumlinson+11)

Very Low Gas Densities of 10^4 K Material

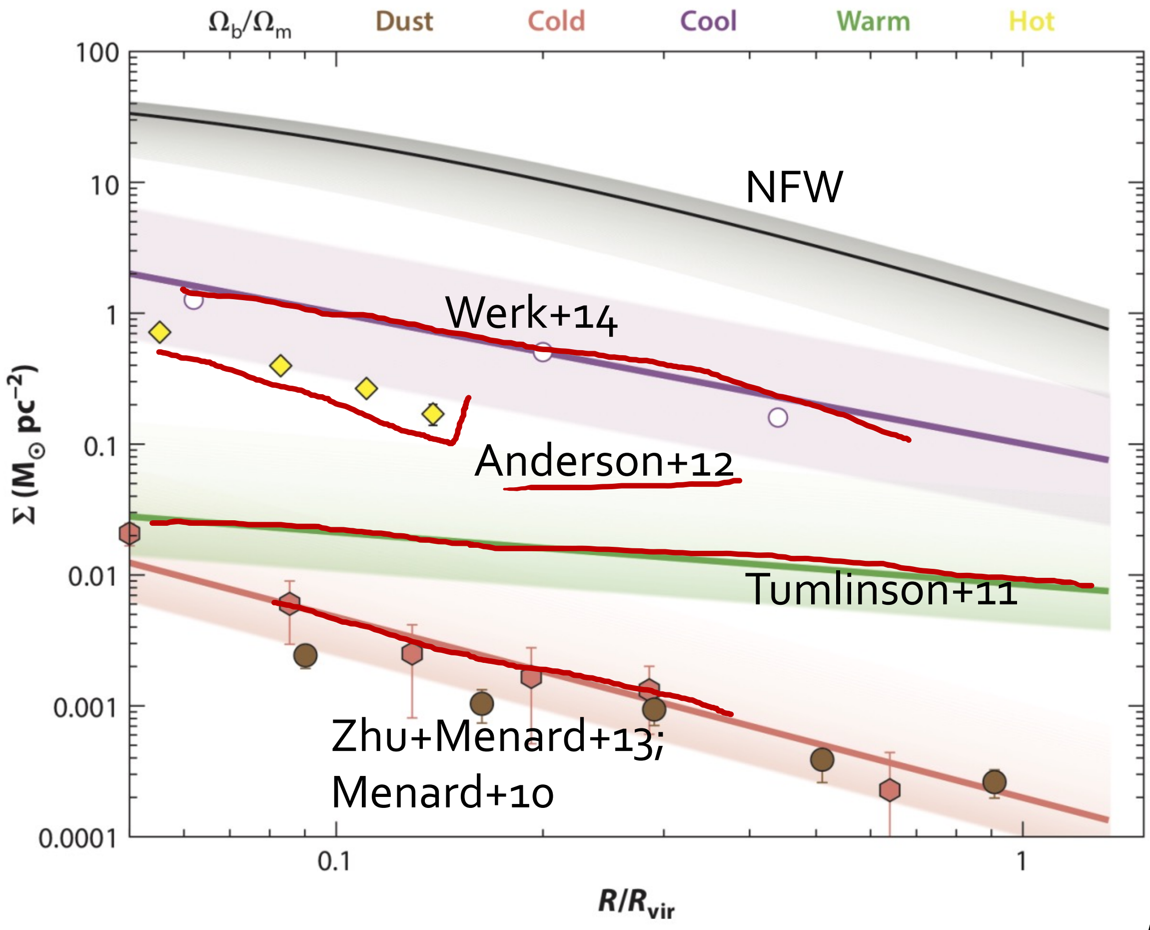




NB:
Corrected from Werk+14 by factor of 4 for HM2001; HM2012 roughly consistent with Werk+14

Derived gas volume densities are greater than an order of magnitude l
predictions from standard two-phase models in which cool clouds are i
equilibrium with hot, coronal gas (Werk+14)

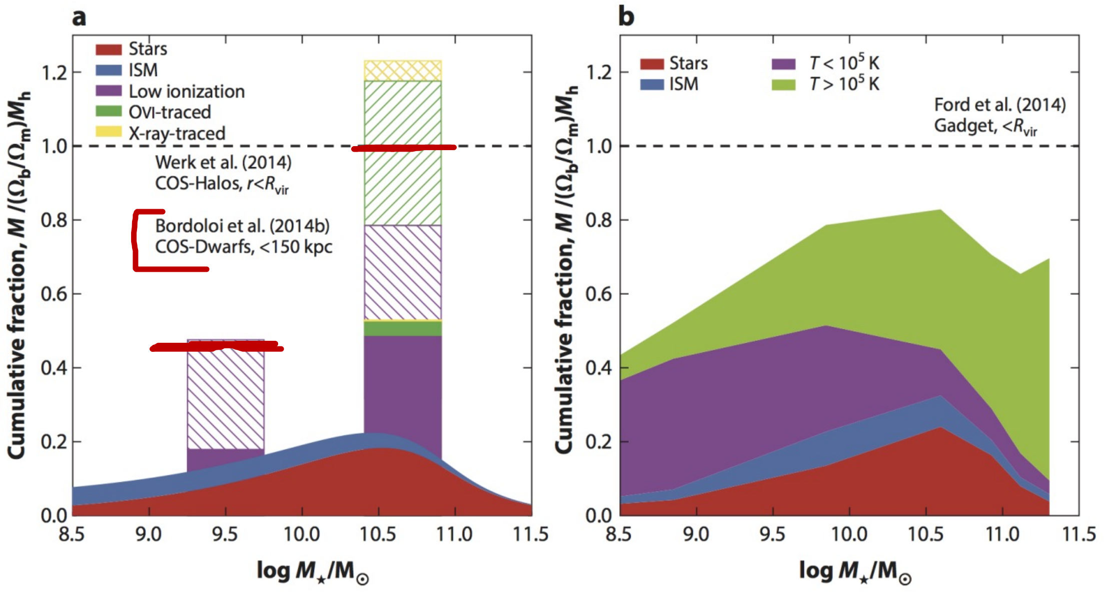
Synthesis of CGM Mass Density Results



"cold gas" (pink), "cool gas" (purple), "warm gas" traced by O vi (green), X-ray emitting gas (yellow), and dust (brown)

The "what" and the "where"

CGM Baryon Budgets for All Phases (Obs + Sims)



There are predictions from simulations that we can test

L* galaxies may have baryon fractions consistent with Ω_b when you account for the CGM

Metal Census of CGM around star-forming galaxies

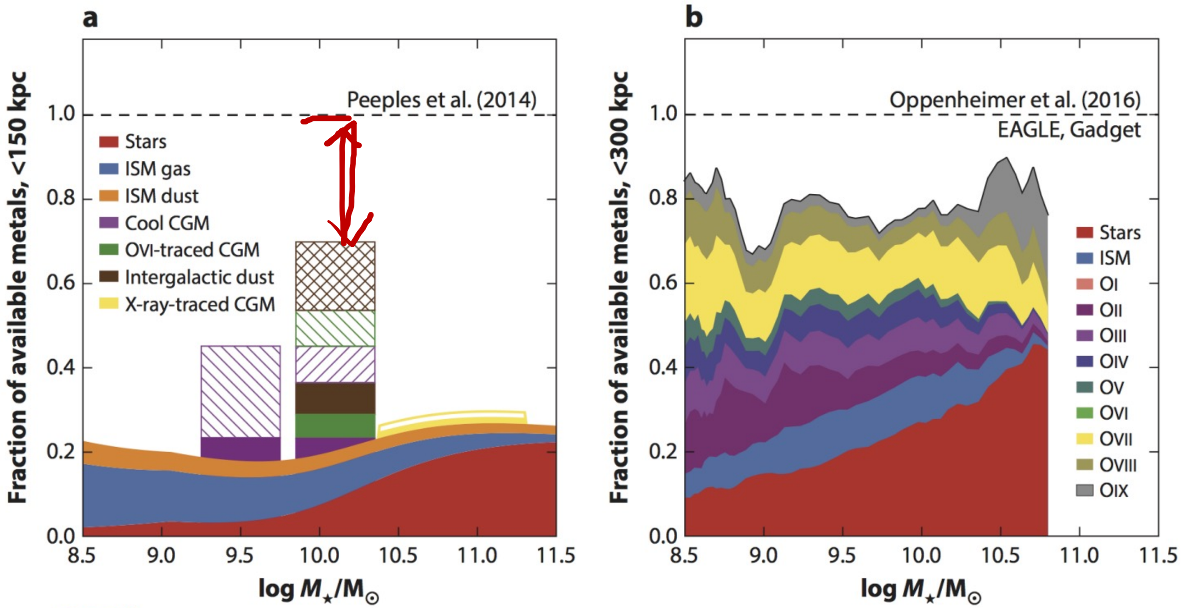
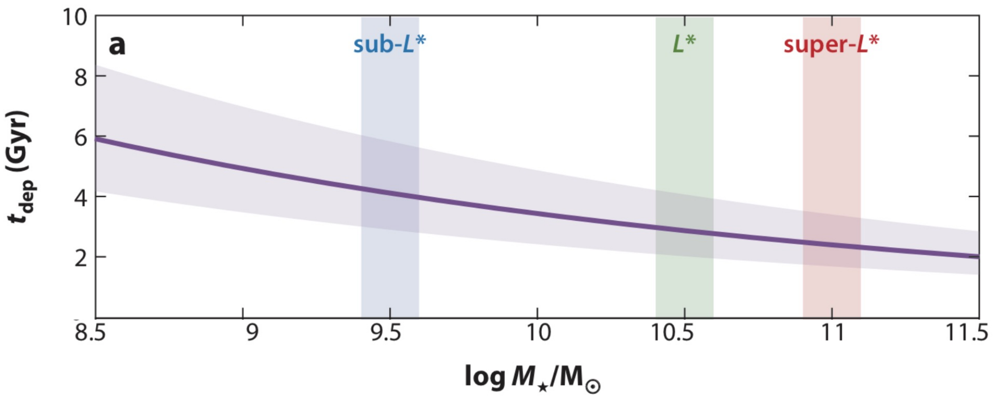


Figure 9

Galaxies are still missing their metals even when you account for those in the CGM

Q1. How do galaxies sustain their star formation?

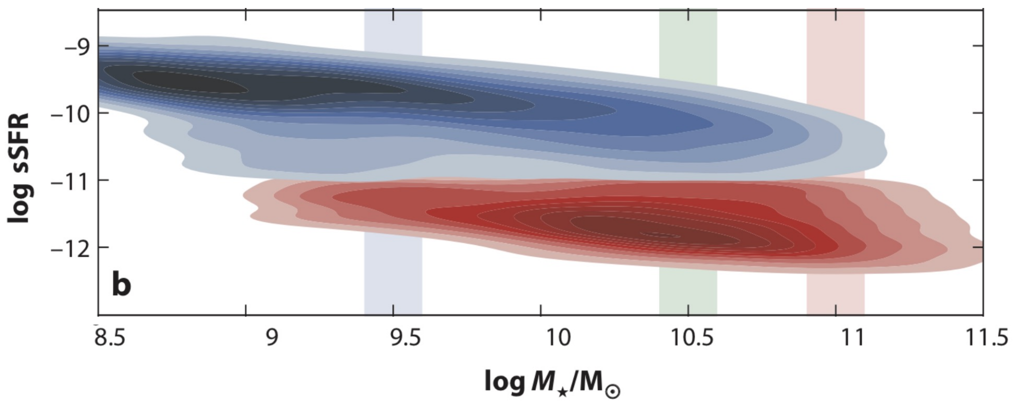


Depletion time = $M_{gas} / \dot{M}_{sfr}$

Progress: Most galaxies have enough fuel in their CGM. But the presence of fuel does not mean they are actively fueling. Metal-enriched accretion appears to be happening, but evidence is scarce for "pristine" inflows. Metal-enriched outflows are ubiquitous.

How do accretion rates vary with mass?

Q2. What quenches galaxies and what keeps them that way?

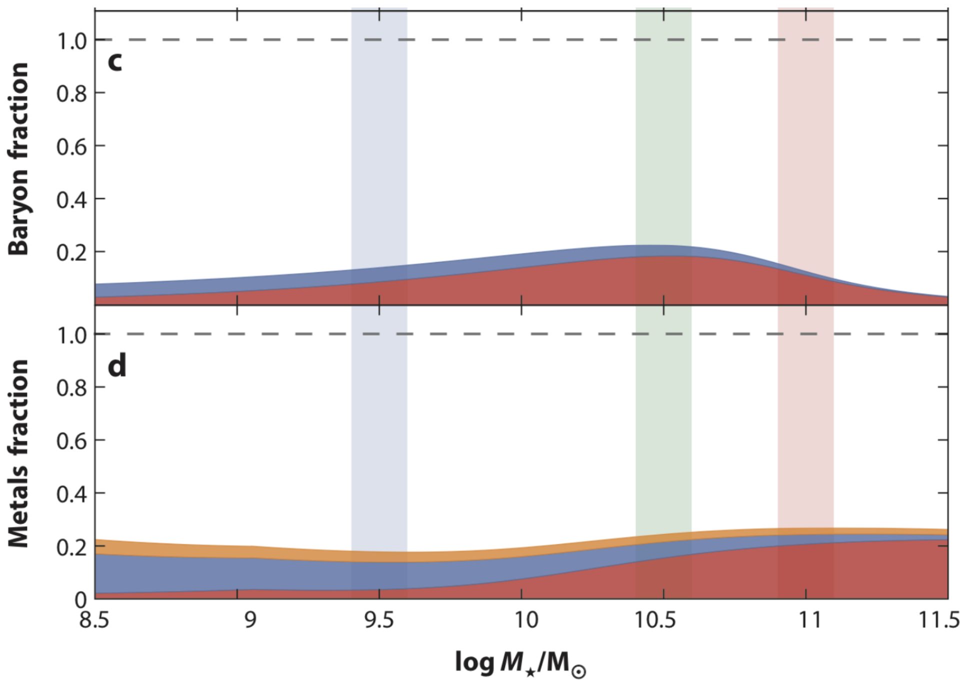


The famous galaxy bimodality

Progress: presence of cool gas in the halos of massive red galaxies is well established. The basic paradox of quenching remains: what happens to the halos of passive galaxies to quench their star formation, keep it quenched, and yet leave cold gas present in their halos? OVI may be a clue…

Does the CGM empty out or get consumed when galaxies quench?

Q3. Why do galaxies lack their fair share of baryons? And where are the metals?



Red = stars, Blue = ISM, orange = dust

Progress: L* galaxies are probably not missing any baryons when you consider their CGM. Baryon fractions as a function of mass are measurements we are still making…but it is looking like dwarfs are missing mass AND metals. Galaxies of most masses are still missing metals. Recycled accretion arises from the ejection of metal-enriched galactic winds that lack the energy to escape the halo entirely.

Emerging Picture: "recycling", rather than "accretion and feedback" is how galaxies acquire their gas

Part 3

Open Problems, Future Prospects, and New Results!

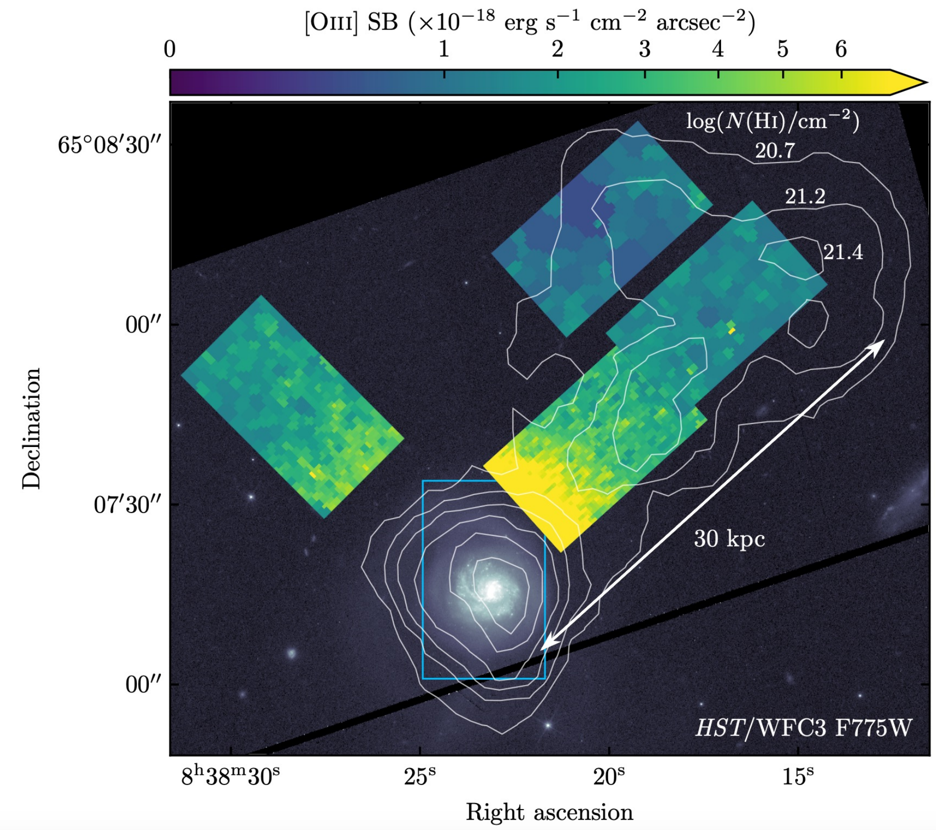
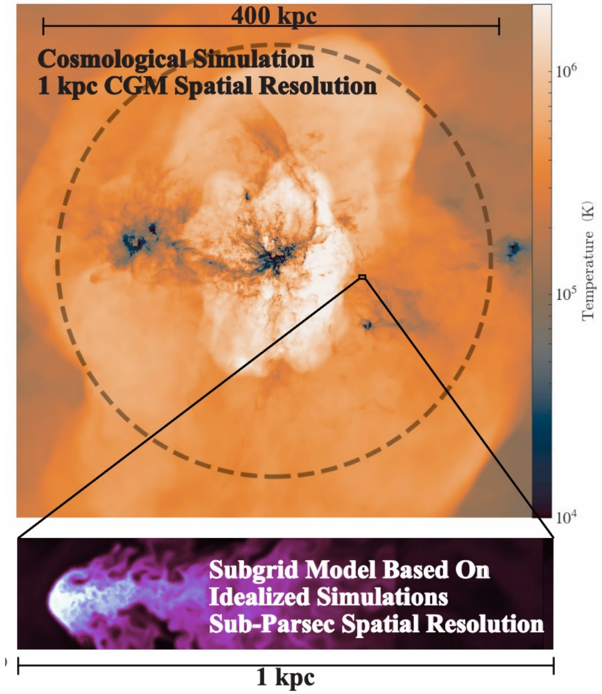
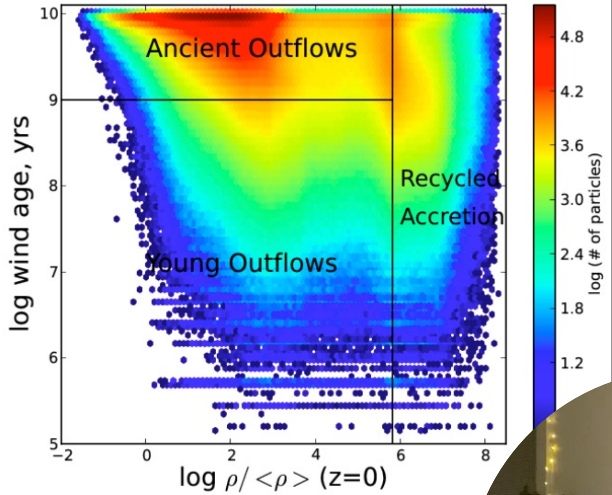


Image from Nielsen et al. 2023; eprint arXiv:2311.00856

Open Problems

- The scale problem
- Mass flows and fate problems
- The "how" and the "when"





There is work to be done…

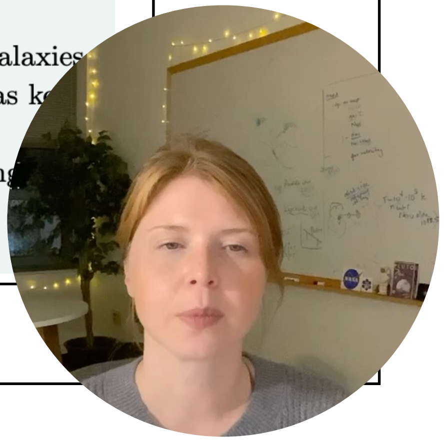
Theory in Need of More Data

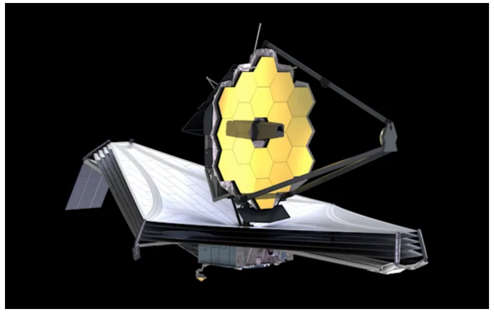
1. What is the mass and composition of the CGM at high-redshift and in low-z $M_\star <$ 10^{10} $M_\odot$ galaxies, and how do these constrain galaxy evolution models?
2. What is the small-scale density and kinematic structure of the CGM, and what does it tell us about the physics?
3. What does the CGM do as galaxies quench? Does cool, neutral gas extend into the inner CGM of passive galaxies?
4. Where are the metals that are still missing from the census? What are the elemental abundance ratios in CGM gas, and how do they depend on the galaxy's mass and star formation history?

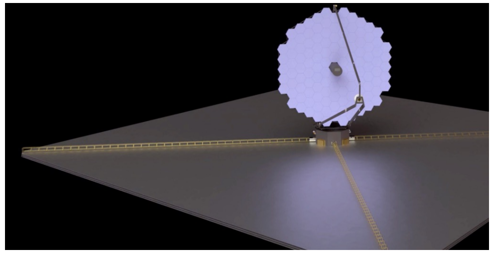
Data in Need of More Theory

1. Are there any clean observational tests or theoretical discriminants between the various heuristic models of feedback?
2. Are there self-consistent models of quenching that produce a red sequence of galaxies and yet leave a significant mass of cold CGM? How is the remaining cold gas k from accreting?
3. What do the detailed kinematic profiles of the multiphase suite of absorbing tell us about the physical and dynamic structure of the CGM?

And we have made progress on answering a few of these questions.

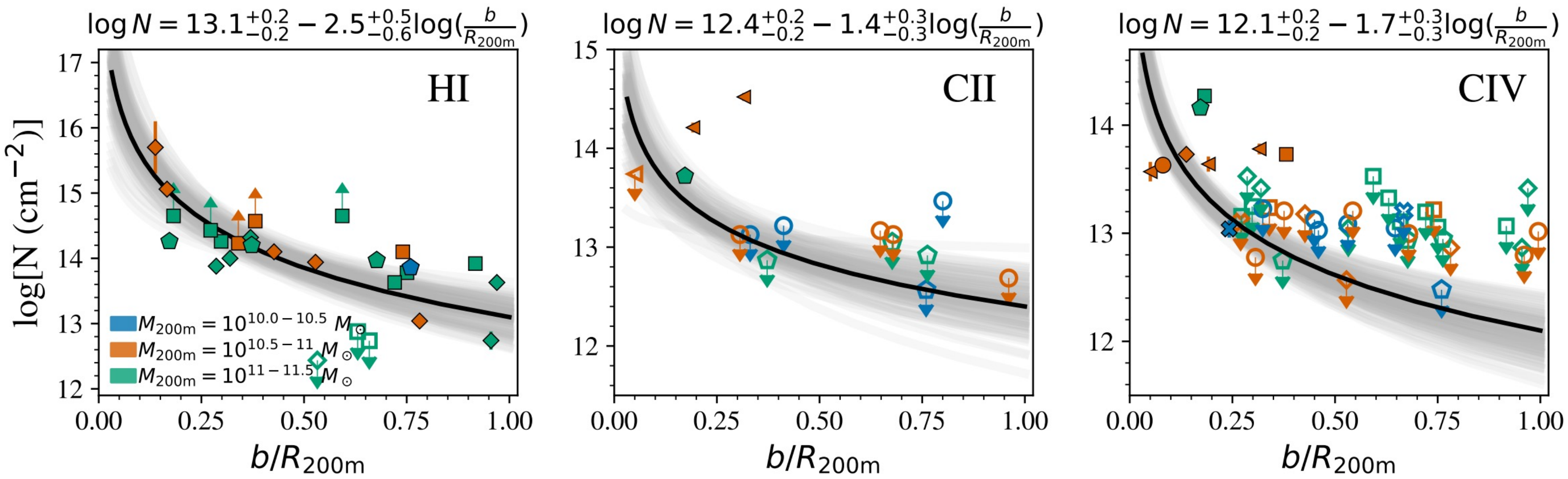






Future Prospects for Data

CMB-S4, JWST, HWO, ATHENA

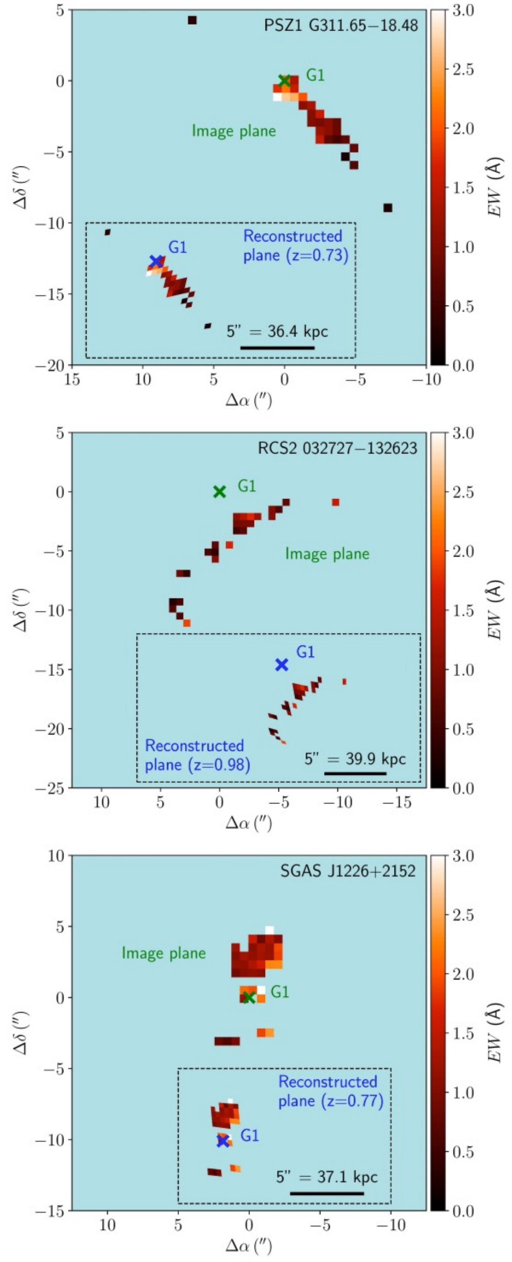


Zheng +2023: Dwarf galaxies' cool CGM likely harbors only ~10% of the metals ever produced!

A Comprehensive Investigation of Metals in the Circumgalactic Medium of Nearby Dwarf Galaxies

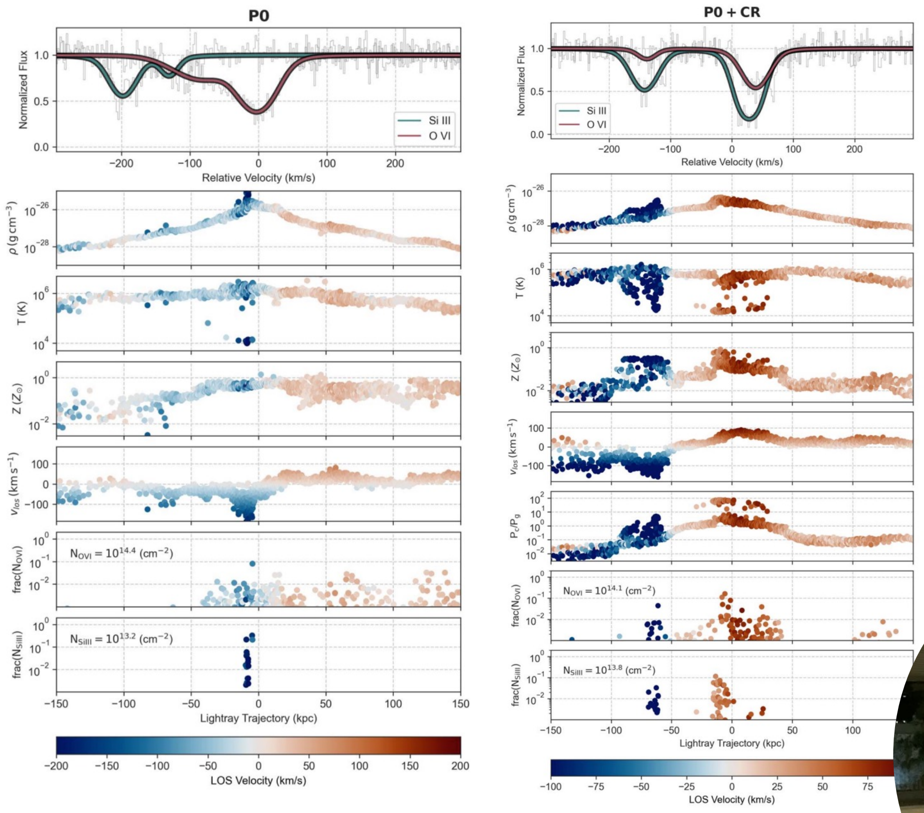
Directly constraining the spatial coherence of the z ~ 1 circumgalactic medium

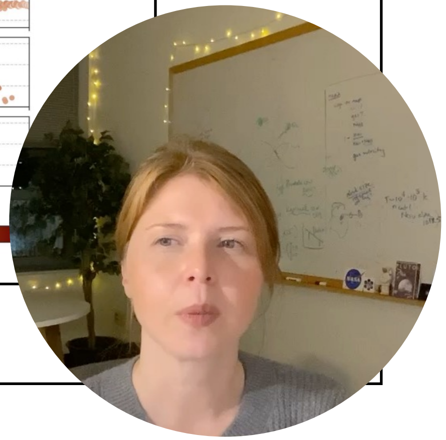
Afruni +2023: We find $1.4 < C_{length}/\mathrm{kpc} < 7.8$ (95% confidence). This measurement represents the scale over which the cool gas tends to cluster in separate structures.



The Impact of Cosmic Rays on the Kinematics of the Circumgalactic Medium

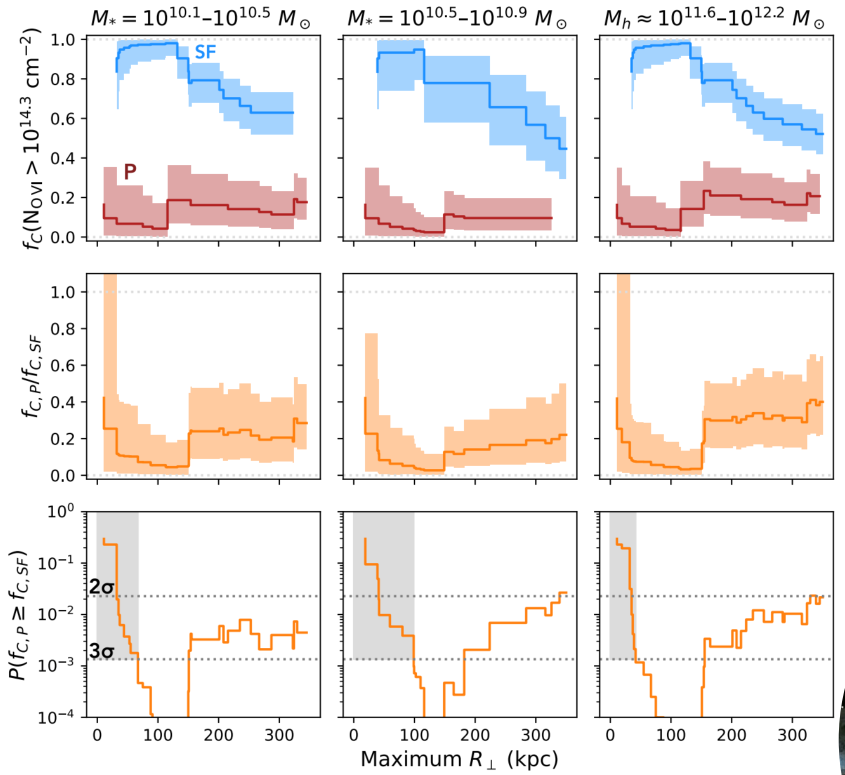
Butsky +22: The presence of cosmic-ray pressure in the inner CGM creates narrower O VI absorption features and broader Si III absorption features, a quality that is consistent with observational data.





The CGM² Survey: Quenching and the Transformation of the Circumgalactic Medium

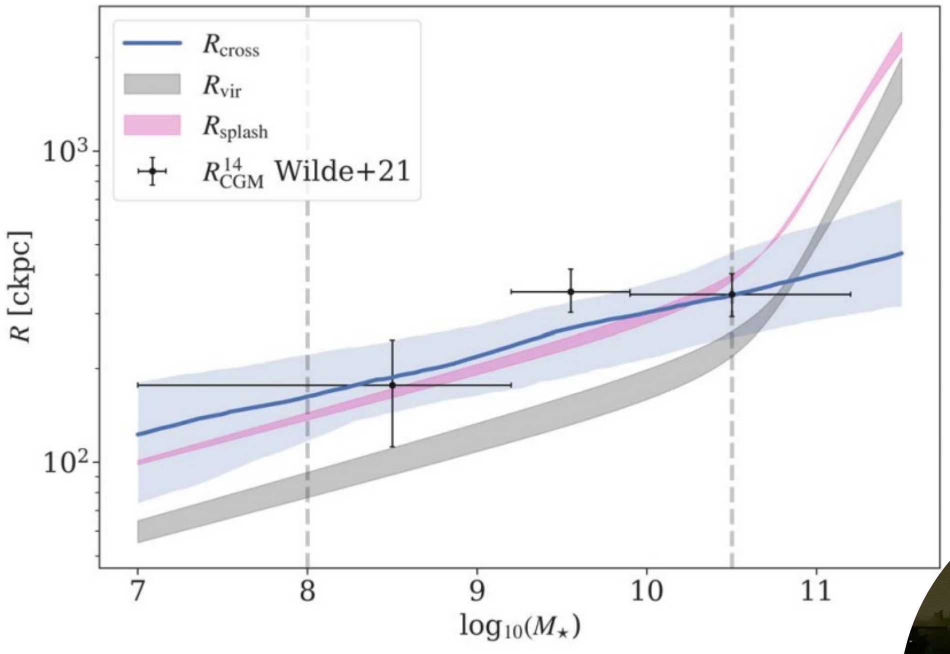
Tchernyshyov +23: Even when controlling for stellar mass, the O VI covering fraction within 150 kpc is higher around star-forming galaxies than around passive galaxies with greater than 3σ-equivalent statistical significance.



This difference is evidence for a CGM transformation that happens together with galaxy quenching

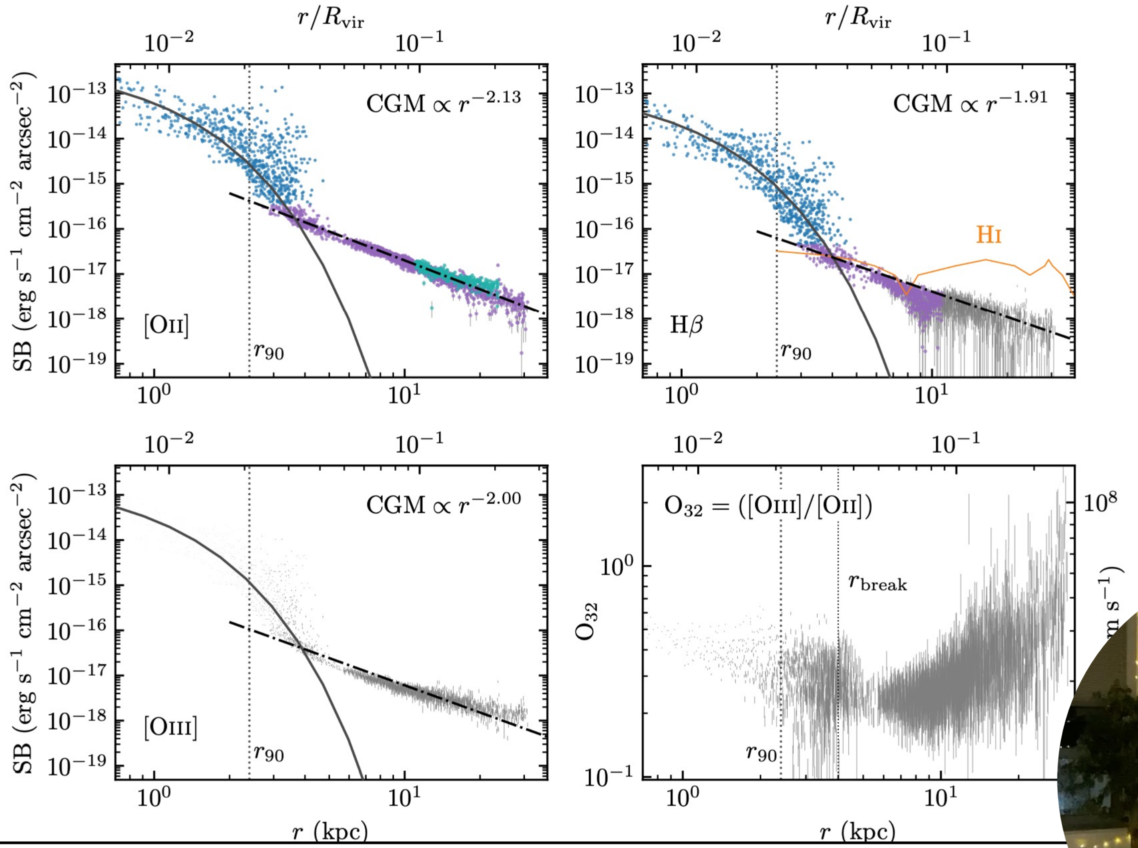
CGM²: Empirically, HI Extends beyond R_{vir} at All Halo Masses

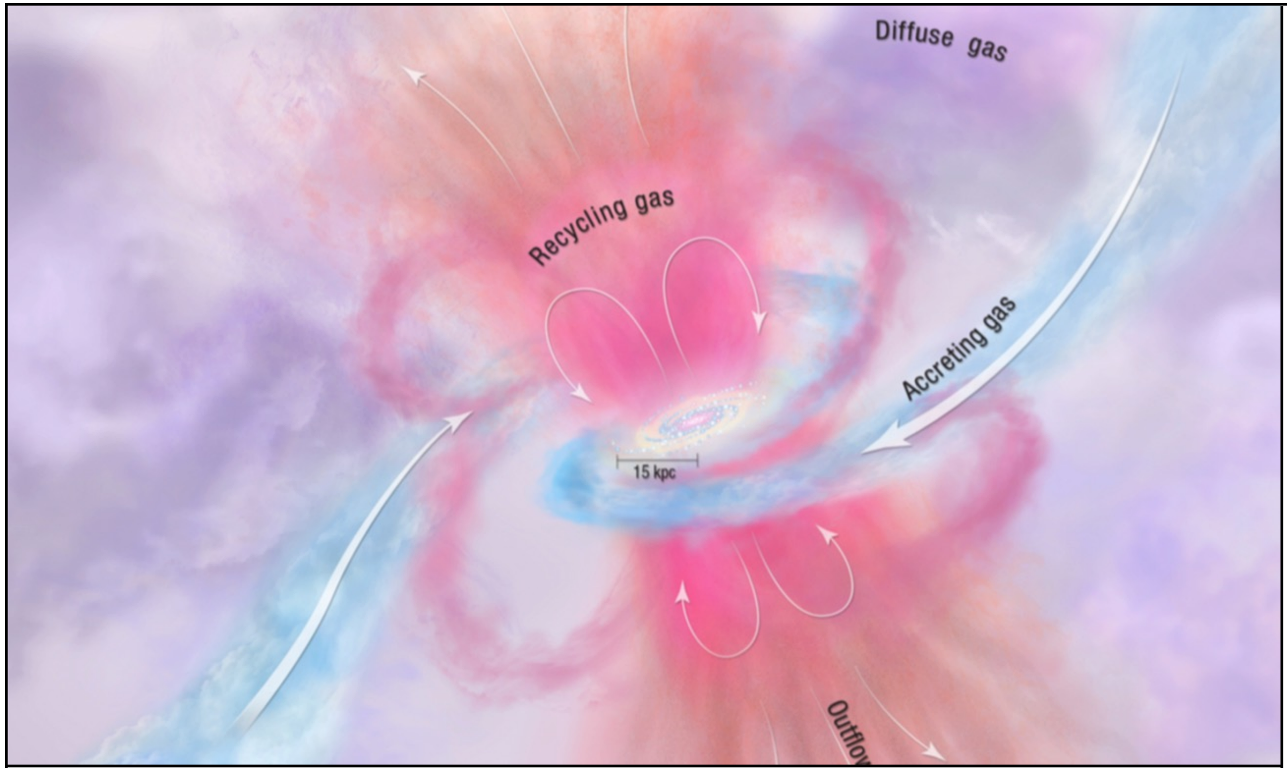
Wilde +21 and 23: For sub-L* and L* galaxies, we find that $R_{CGM} \approx 2.0 \pm 0.6\ R_{vir}$. Additionally, we find excellent agreement between R_{CGM} and the theoretically determined splashback radius for galaxies in this mass range.



Revealing the disk–circumgalactic medium transition with emission mapping

- Nielsen +23: a break in the slope of the surface brightness profile of [OII] and Hbeta may signal the boundary between ISM and CGM.





Galaxies are Cosmic Ecosystems

- Their atmospheres are a crucial component central to their evolutionary story
- Significant progress on understanding the content and nature of the CGM since 2010
- Exciting new discoveries will be happening through the 2030s