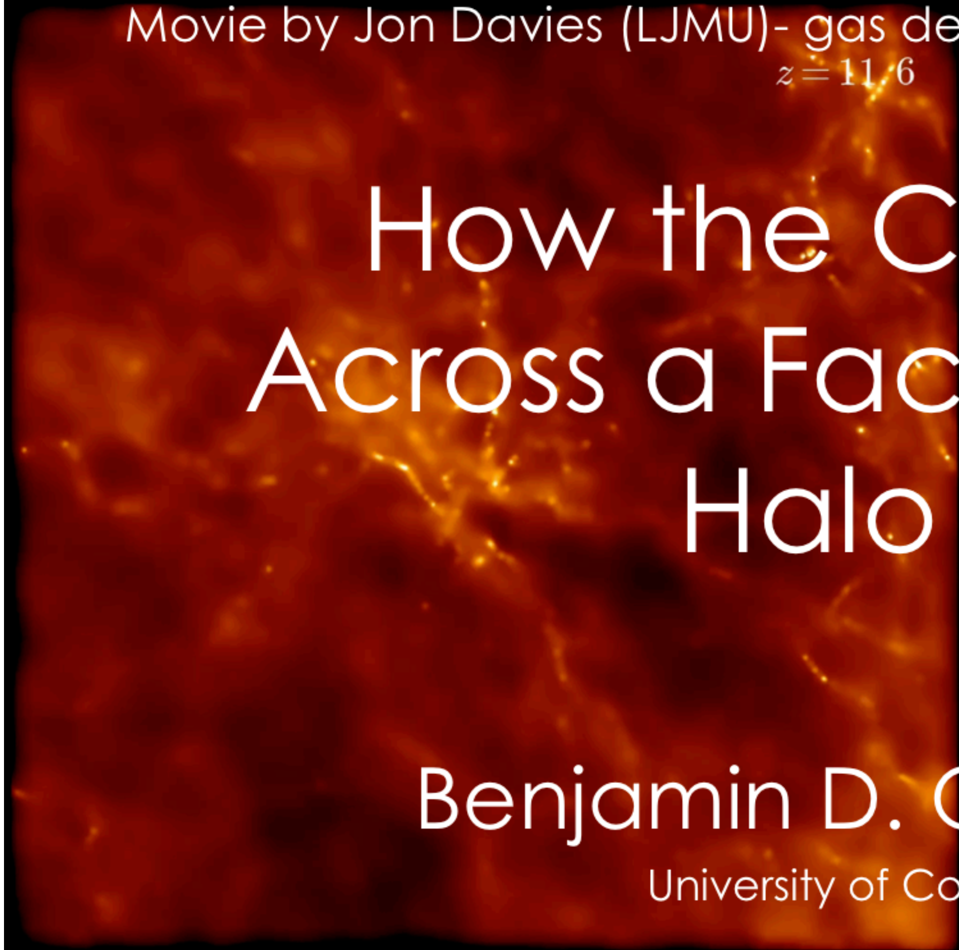
Movie by Jon Davies (LJMU)- gas density (left) and X-ray luminosity (right)



How the CGM Scales Across a Factor of 2000 in Halo Mass

Benjamin D. Oppenheimer
University of Colorado, Boulder

With Rob Crain, Joop Schaye, Ryan Horton, Alex Richings, Jessica Werk, Jon Davies, John Stocke, Nastasha Wijers, Trystyn Berg, Marijke Segers, & the EAGLE Team.

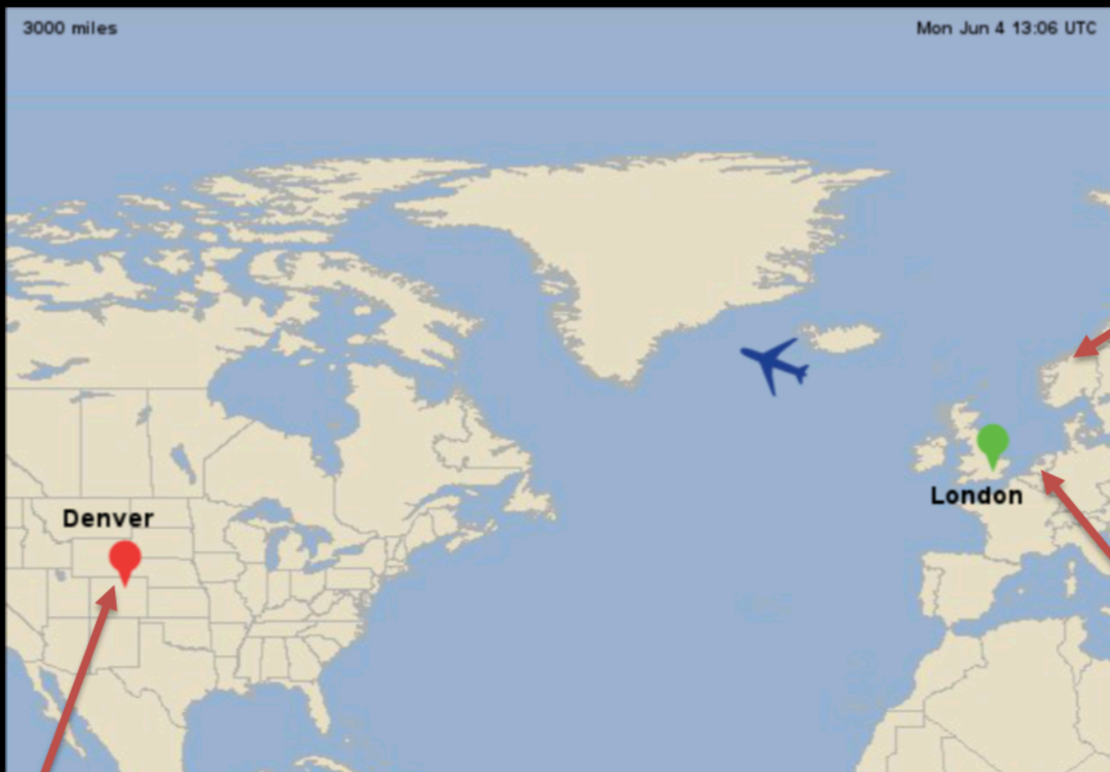
Circumgalactic Medium Workshop
Northwestern University

Northwestern CGM Outline

1. Metals
2. Mass
3. Dynamics

I'm here to pour gas on the raging arguments that define the CGM-Galaxy Connection. And hopefully start some new conflagrations.

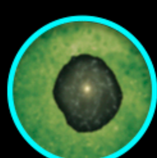
A Simulation Collaboration of 3 Institutions

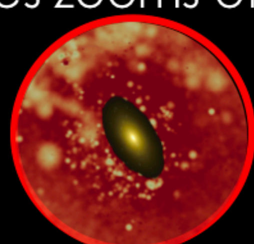


Liverpool John Moores University (LJMU)- **Crain, McCarthy-** EAGLE, BAHAMAS

Leiden- **Schaye, Bahe-** EAGLE, C-EAGLE /Hydrangea

CU Boulder- **Oppenheimer-** EAGLE-CGM- Non-equilibrium, high-res zooms of a range of halos.





All use thermal prescription for stellar and SMBH feedback

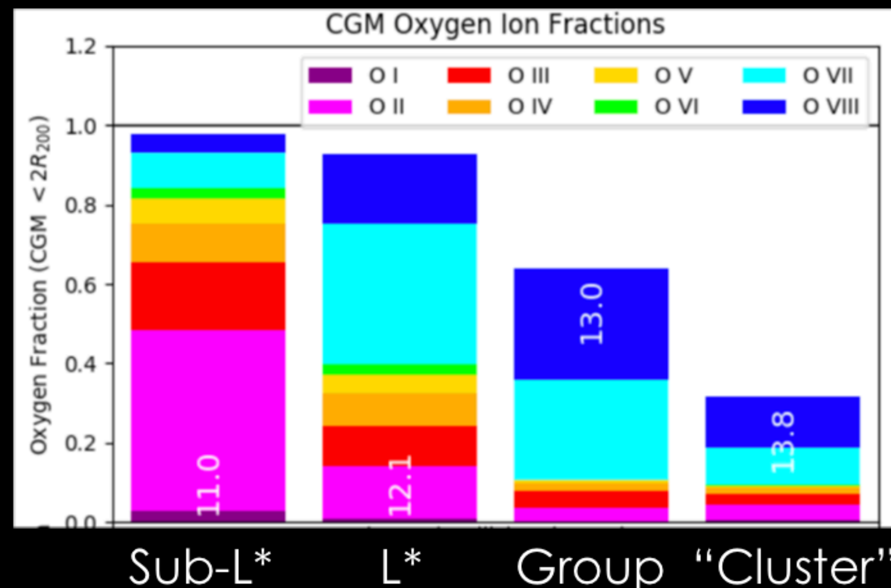
Northwestern CGM Outline

1. Metals
2. Mass
3. Dynamics

The CGM oxygen (metal) budget spans the entire range of ion states, and while it is important for counting, metals can reveal the fundamentals of CGM physics, dynamics, and evolution.

An accounting of metals (Peeples+ 2014) and reconfirmed by EAGLE-CGM zooms (Opp.+ 2016) find more oxygen (metals) in the CGM than in galaxies.

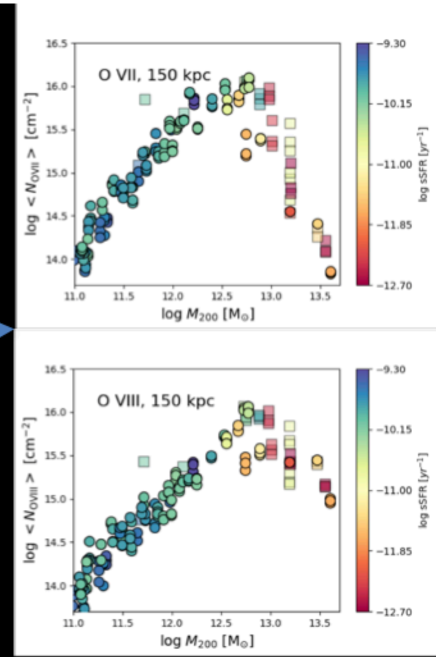
FIRE simulations have most metals in galaxies.



EAGLE-CGM: From Opp.+ (2016), but expanded in halo mass (white numbers).

O VI has a global CGM ionization fraction of at most 2-3% for sub-L* and L* and then dramatically declines.

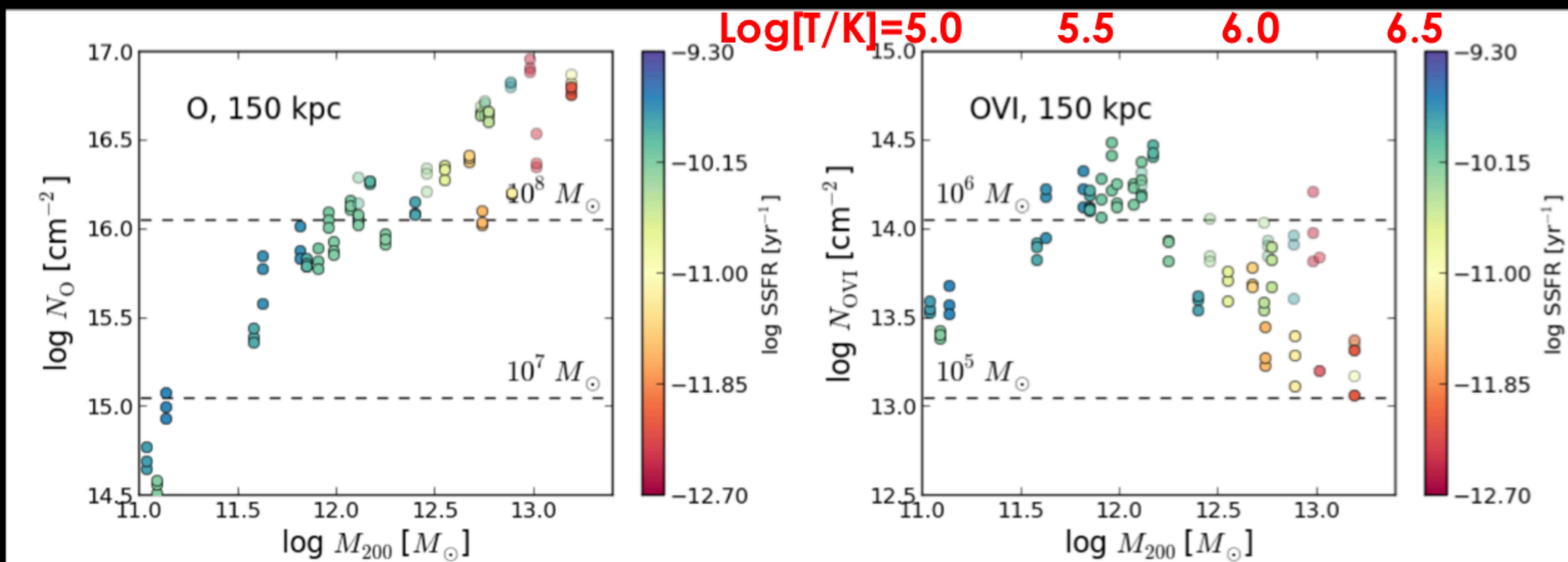
Collisionally ionized O VI has a temperature that traces L* halos. Passive galaxies live in halos with $T>10^6$ K, and traced by oxygen mainly in OVII and above.



O VI (and O VII & O VIII) are virial temperature thermometers.

$$T_{\rm vir} = 10^{5.69}{\rm K}\left(\frac{M_{200}}{10^{12}{\rm M}_\odot}\right)^{2/3}\left(\Omega_{\rm M}(1+z)^3+\Omega_\Lambda\right)^{2/3}$$

Wijers+ (in prep.)



Oppenheimer+ (2016) z=0.20

The Elusive Oxygen Ladder

The *Lynx* Baryon Working Group (Bregman, Kollmeier & Vikhlinin). Capturing >50% of oxygen around Milky Way-like galaxies.

Collisionally ionized O VI virial temperature haloes (Opp., Crain+ 2016) may have additional O VI enhanced by flickering AGN photo-ionizing the inner ~100 kpc *even if AGN is off most of the time* (Opp., Segers et al. 2018a).

Silicon low ions provide a proxy for the low oxygen ions, which are buried in the far-UV. (Opp., Schaye et al. 2018c)

O VIII (19 Å)

O VII (22 Å)

O VI (1032 Å)

O V(629 Å)

O IV (787 Å)

O III (702 Å)

O II (834 Å)

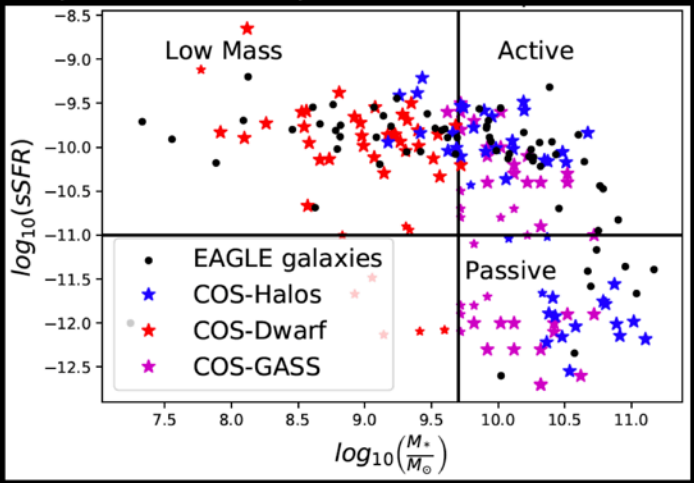
O I (1302 Å)

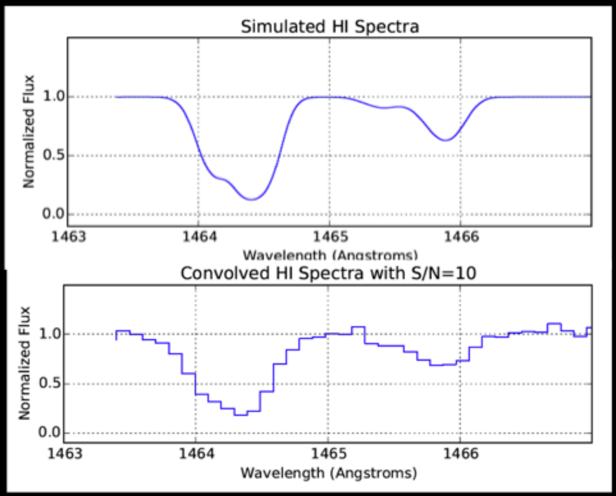
Northwestern CGM Outline

1. Metals
2. Mass
3. Dynamics

HI and the Missing Mass Problem of Halos

Accounting for all baryons through surveying H I Absorption.
Make mock spectra for direct comparison to real spectra.
Expand sample to COS-Halos, COS-Dwarfs, & COS-GASS.





Ryan Horton

Did you know most HI in the CGM is in a rotational supported extended disc?

A mass accounting of a $10^{12.0}$ M_{sol} halo (a la Werk+ 2014):
-Expect 1.6×10^{11} M_{sol} of baryons to be "closed"
-Galaxy component 3-5x10^{10} M_{sol}
-About 2-3x10^{10} M_{sol} of HI-traced mass corresponding to the cool (~10^4 K) component of the CGM.
-Hot halos (>10^5 K) and gas ejected beyond R_{200} is the rest.
-cf. to cool CGM from Prochaska+ (2017) who calculates $>M_{cool}$.

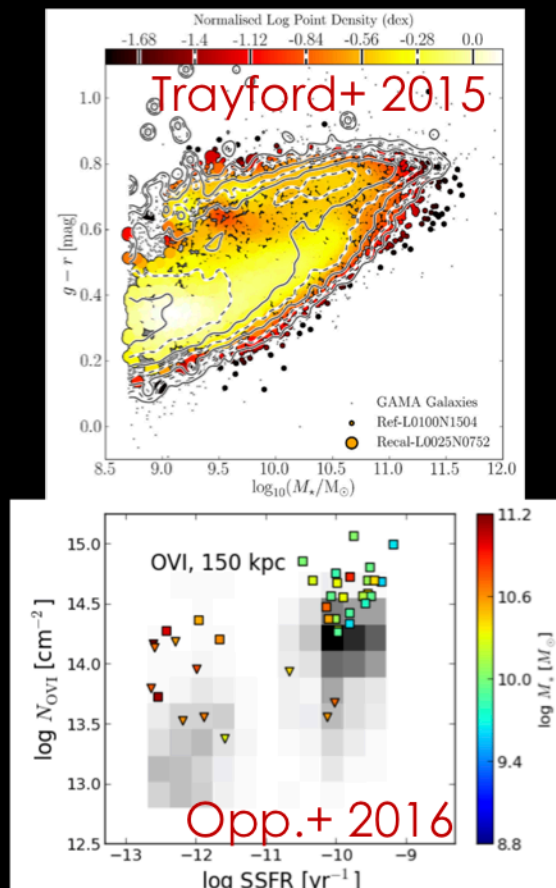
Different simulations are tuned to reproduce mainly galaxy properties. Probes of the gas can often be thought of as genuine predictions of the simulation model.

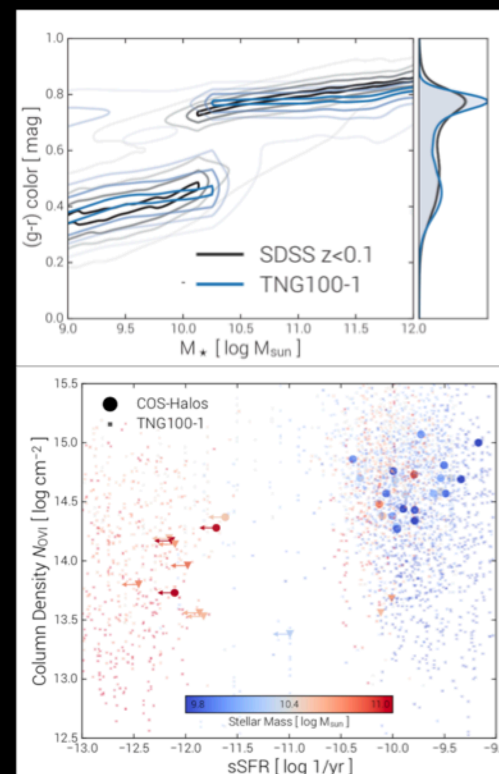
EAGLE/EAGLE-CGM Picture

Illustris-TNG Picture

Nelson+ 2018ab

Galaxies: Color Bimodality





CGM: COS-Halos OVI Bimodality

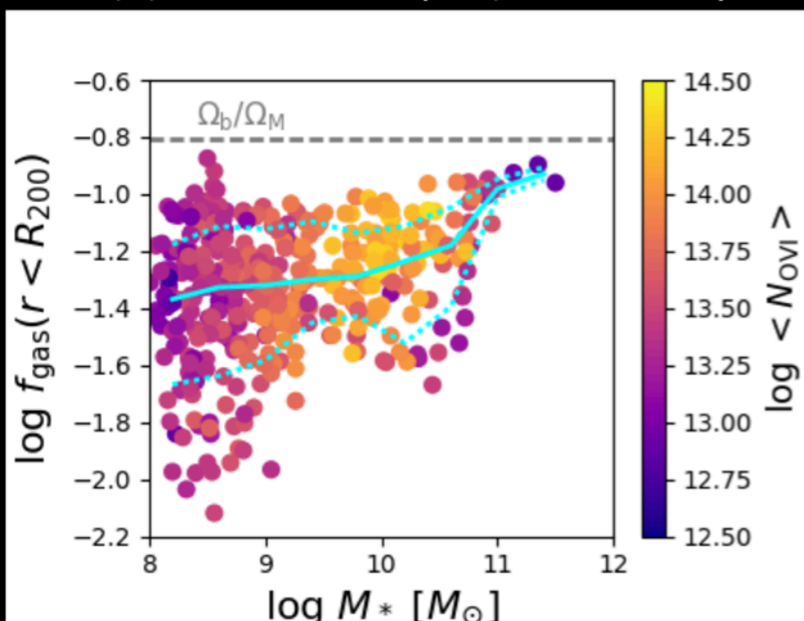
The halo gas fractions around ordinary galaxies is very different between EAGLE and Illustris-TNG.

EAGLE Stellar and AGN feedback combine to make a monotonic function of f_{gas} with stellar and halo mass.

Illustris-TNG has AGN feedback transform halo baryons and make a kink in the f_{gas}-M_* relationship.

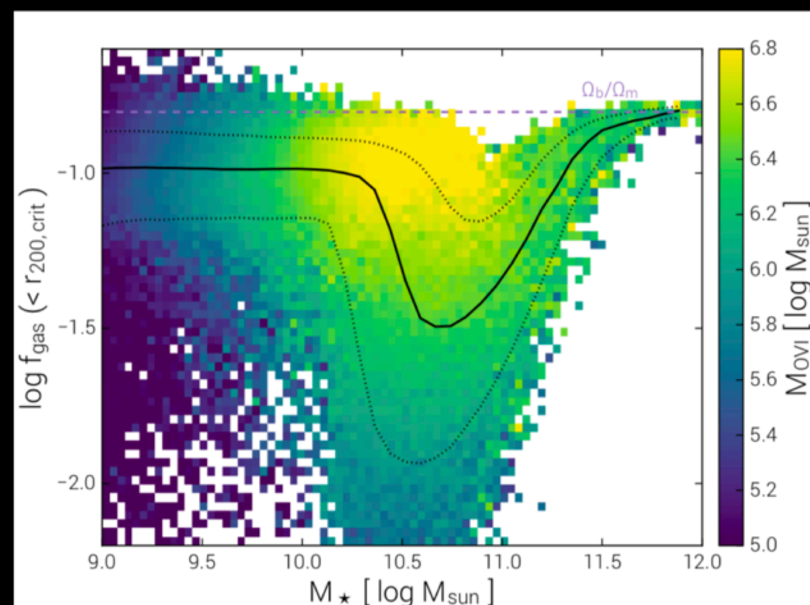
EAGLE-CGM Picture

Oppenheimer (unpublished)



Illustris-TNG Picture

Nelson+ 2018

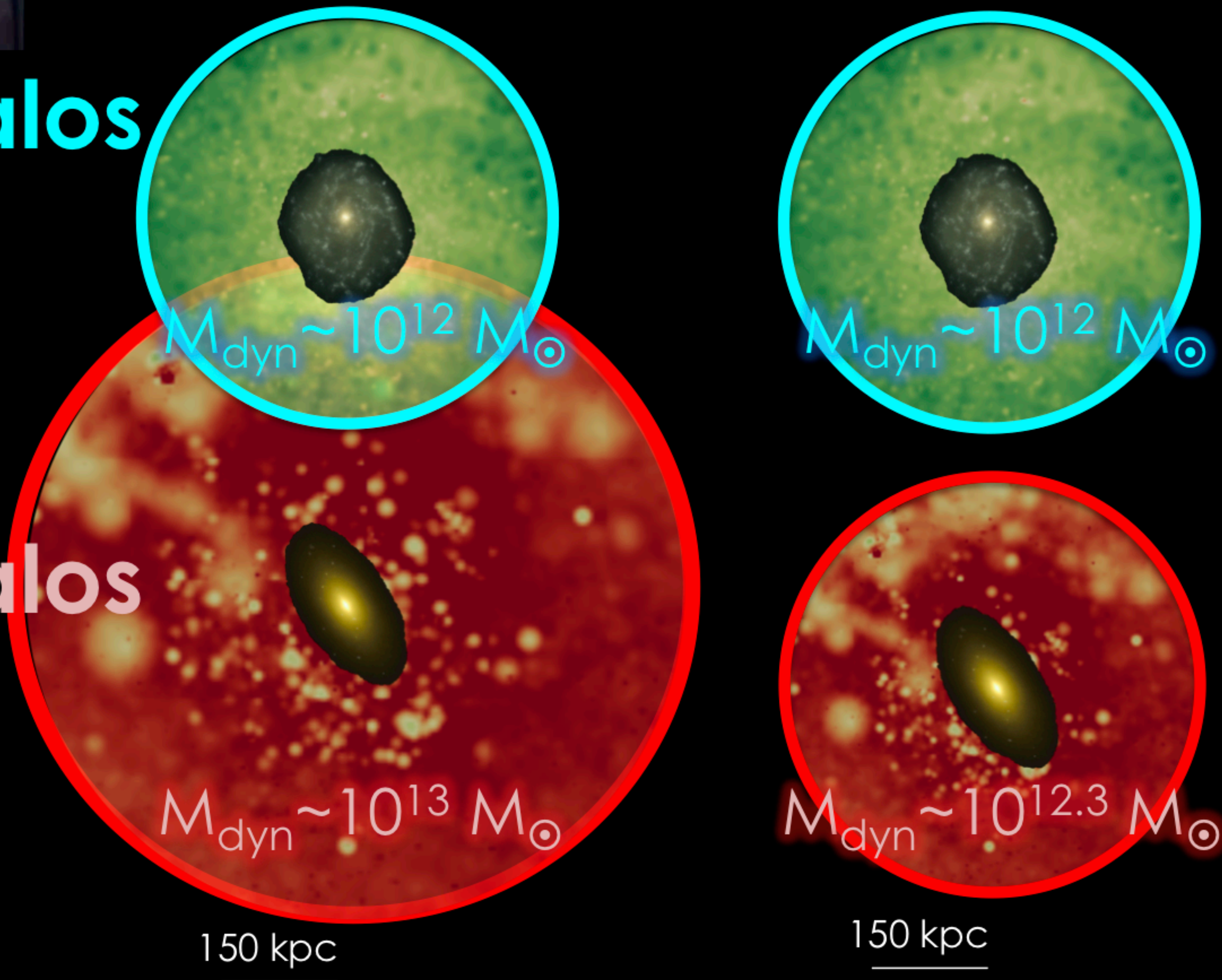


EAGLE-CGM Picture

Illustris-TNG Picture

COS-Halos Active Galaxy

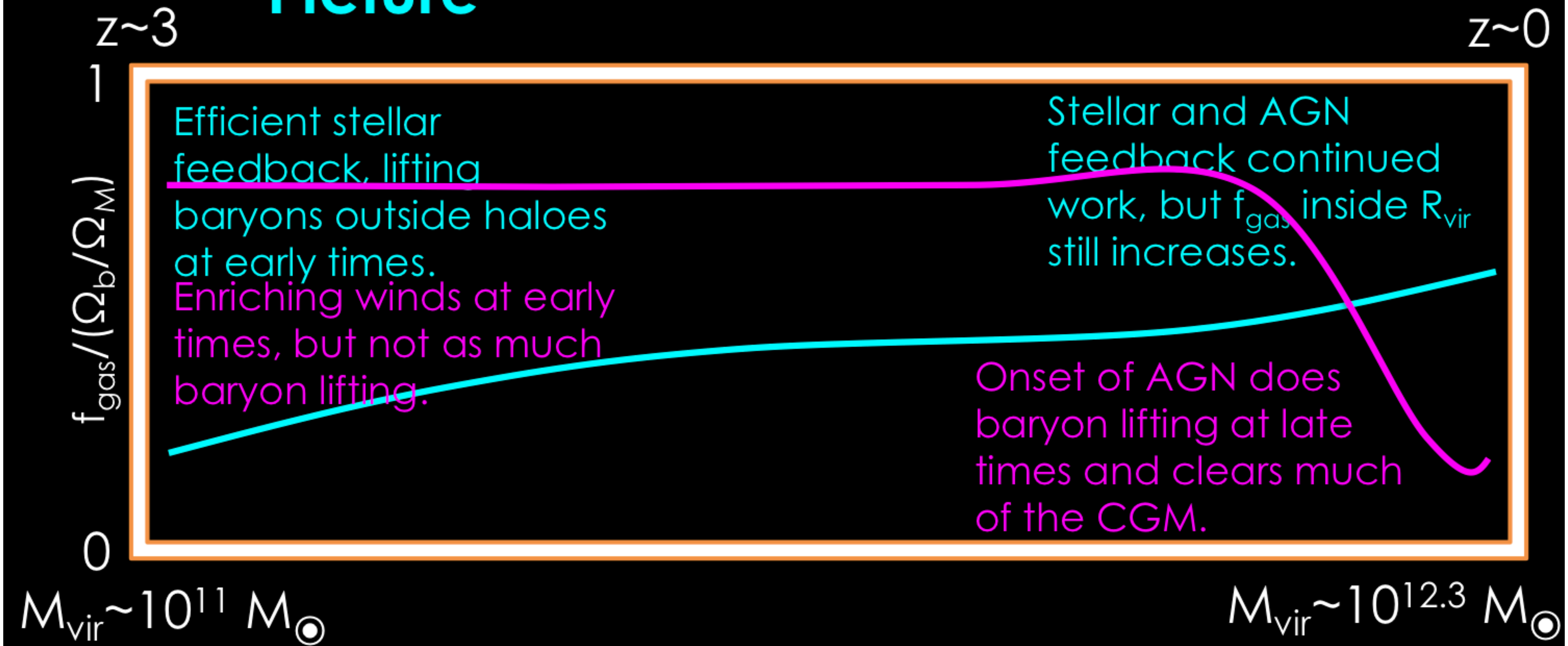
COS-Halos Passive Galaxy



An X-ray telescope that can distinguish these models is critical for understanding how and when superwind feedback operates around in L* halos.

EAGLE-CGM Picture

Illustris-TNG Picture



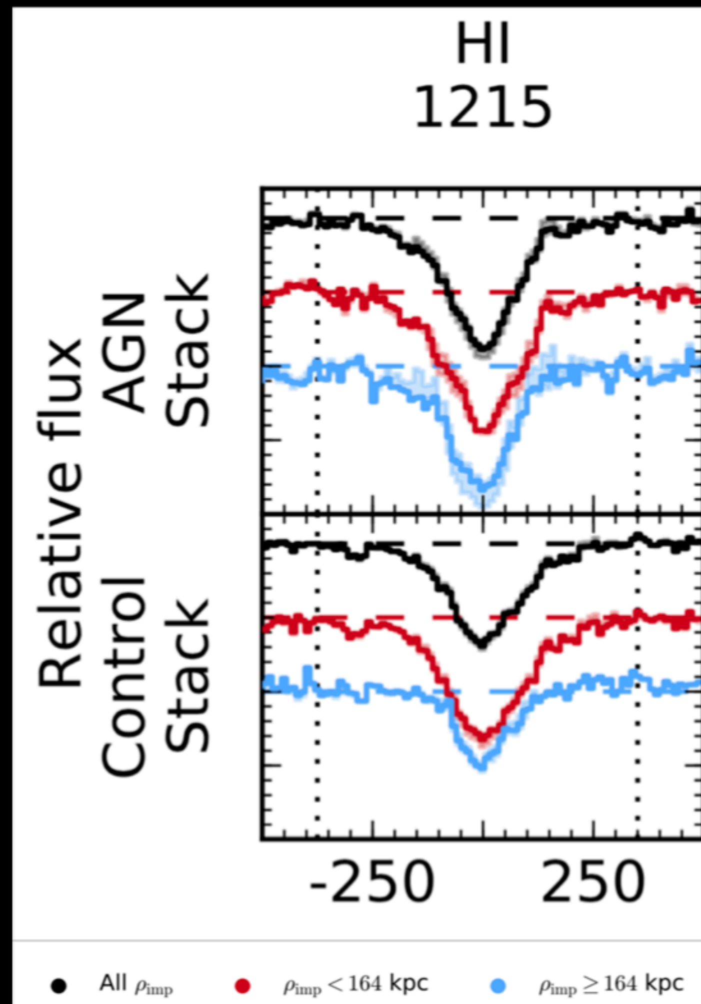
Assumed baryon fraction evolution inside M_{200} of an eventual ~$10^{12.3}$ halo at z=0.

COS-AGN- Berg+ (2018), don't see any difference between AGN and normal galaxies in their CGMs.

AGN have HI that is slightly stronger, but no real kinematic difference.

Remember, though that we cannot yet probe the inner CGM (<75 kpc).

Are Seyfert-like AGN just the beginning of bulge building and CGM evacuation for L* halos at low-z?



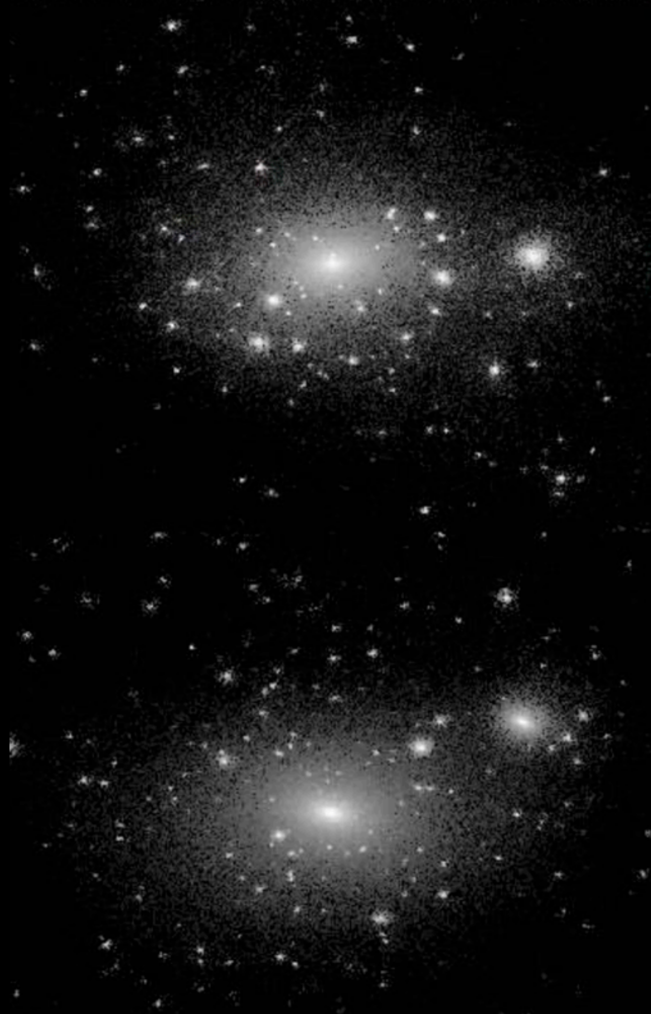
Northwestern CGM Outline

1. Metals

2. Mass

3. Dynamics

I begin with the question: is the CGM a scaled down version of the ICM?



Which one hosts a Milky Way (M_{200}~$10^{12.3}$ M_{sol}) and which one hosts the Virgo cluster?
Moore+ (1999)

Dark matter halos are self-similar to a very high degree.

The scalings from DM halos are expected to be:

$R \sim M^{1/3}$

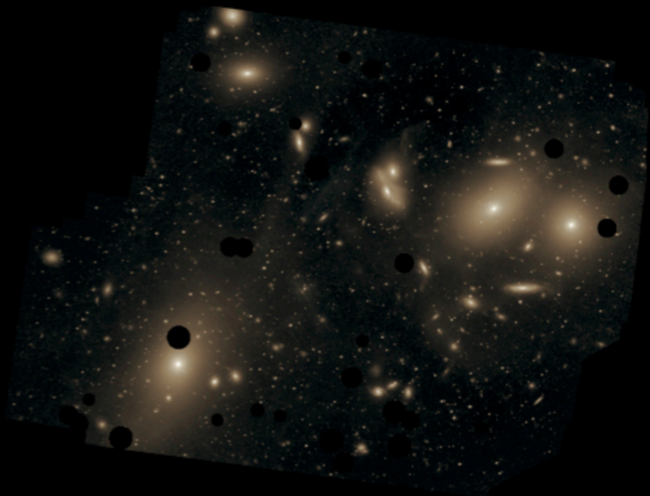
$v \sim M^{1/3}$

$E \sim M^{5/3}$

$J \sim M^{5/3}$

$T \sim M^{2/3}$

I begin with the question: is the CGM a scaled down version of the ICM?



Top Virgo Cluster
Bottom Milky Way

The galaxies that form in their centers certainly do not reflect that self-similarity.

What about the CGM?

Begin with: Is the CGM in hydrostatic equilibrium (HSE)?

The Euler momentum equation can be written as,

$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = -\frac{1}{\rho_{\rm gas}} \nabla P - \nabla \Phi.$$

Oppenheimer 2018

and use Gauss's theorem to integrate the various terms at a surface, with the gravitational term on the left in terms of mass, M_{tot}, and all other terms on the right (e.g. Fang+ 2009, Lau+ 2013, Nelson+ 2014, Suto+ 2013),

$$M_{\rm tot} = \frac{1}{4\pi G} \oint_{\partial V} d\boldsymbol{S} \cdot \nabla \Phi = \frac{1}{4\pi G} \oint_{\partial V} d\boldsymbol{S} \cdot \left(-\frac{1}{\rho_{\rm gas}} \nabla P - (\boldsymbol{v} \cdot \nabla)\boldsymbol{v} - \frac{\partial \boldsymbol{v}}{\partial t} \right).$$

What provides support to a hot halo?

The various terms can be calculated in a simulation:

$$M_{\rm tot} = M_{\rm therm} + M_{\rm rot} + M_{\rm stream} + M_{\rm acc}$$

Oppenheimer 2018b

$$M_{\rm therm} = -\frac{1}{4\pi G}\oint_{\partial V} dS \frac{1}{\rho_{\rm gas}}\frac{\partial P}{\partial R}, \quad (6)$$

$$M_{\rm rot} = \frac{1}{4\pi G}\oint_{\partial V} dS \frac{v_\theta^2 + v_\phi^2}{r}, \quad (7)$$

$$M_{\rm stream} = -\frac{1}{4\pi G}\oint_{\partial V} dS \left(v_r \frac{\partial v_r}{\partial R} + \frac{v_\theta}{R}\frac{\partial v_r}{\partial \theta} + \frac{v_\phi}{R\sin\theta}\frac{\partial v_r}{\partial \phi}\right), \quad (8)$$

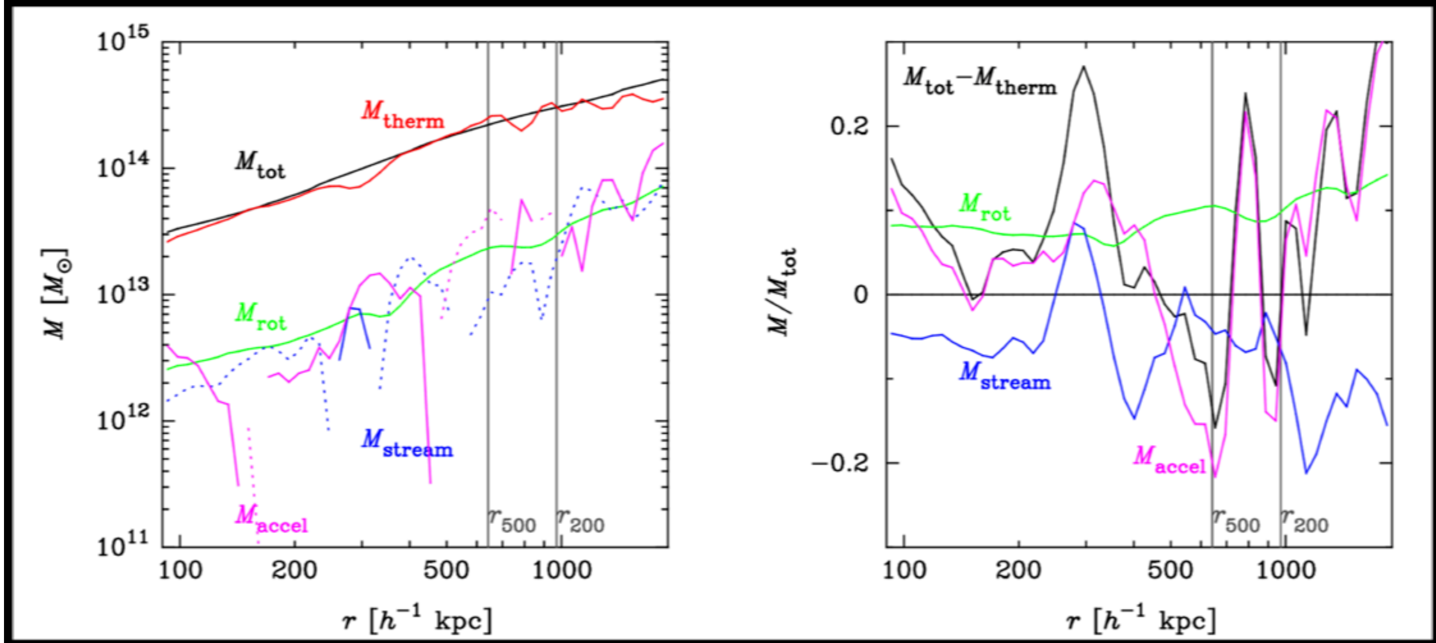
and

$$M_{\rm acc} = -\frac{1}{4\pi G}\oint_{\partial V} dS \frac{\partial v_r}{\partial t}. \quad (9)$$

Pure thermal HSE has $M_{\rm tot} = M_{\rm therm}$

$M_{\rm therm}$ is the thermal support (i.e. the dP/dr term), the $M_{\rm rot}$ is the centrifugal force term from tangential velocities, and $M_{\rm stream}$ are streaming radial velocities and is negative if there is net inflow inward. Acceleration term, $M_{\rm accel}$, of course describes non-zero accelerations, e.g. due to hydro or gravity.

Previous Cluster Results



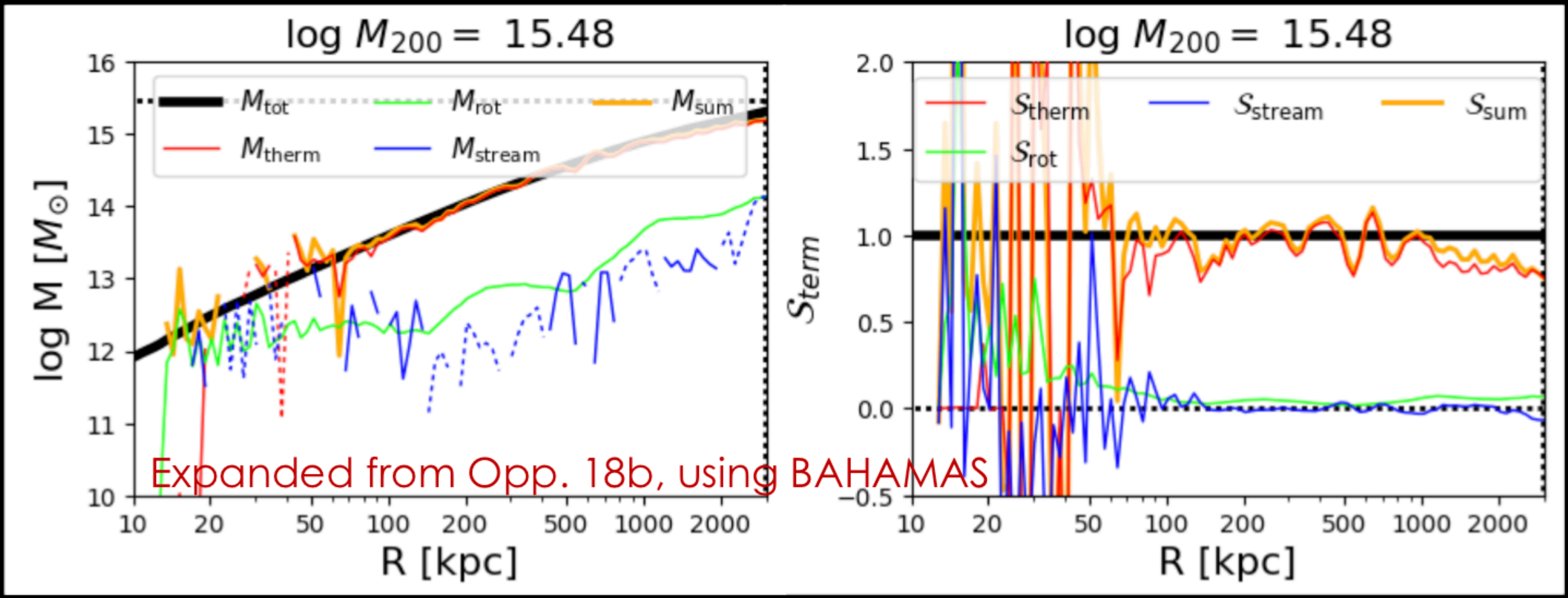
Suto+ (2013) from Cen Enzo cluster simulation

Finding that for a cluster mass (>10^{14} M_{sol}) gas (the ICM) is in hydrostatic equilibrium (HSE) at the 80-90% level, but there are deviations primarily due to "rotational" motions (M_{rot}), streaming (M_{stream}), and acceleration (M_{accel}).

Let us apply this analysis to lower mass haloes as well to see how self-similarity is broken.

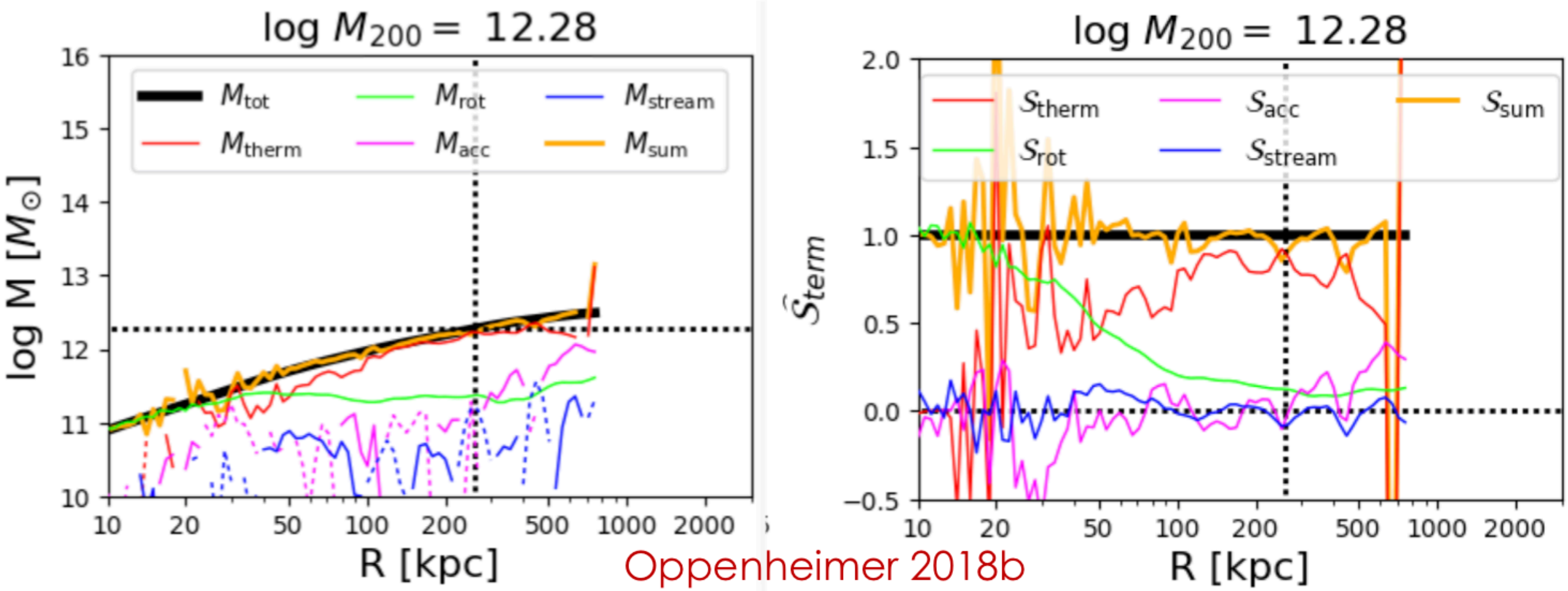
Similar results as other cluster simulations

The Intracluster medium around a Virgo-like cluster is in hydrostatic equilibrium at the 80-90% level. I talk about support terms: e.g. $S_{therm} = M_{therm}/M_{tot}$



S_{therm} is the thermal support (i.e. the dP/dr term) and is ~90%
S_{rot} is the centrifugal force term from tangential velocities and is ~10%
S_{stream} are streaming radial velocities and is a few %.
S_{accel} describes non-zero accelerations, not recorded for our clusters!
The $S_{therm} + S_{rot} + S_{stream} + S_{accel} = S_{sum}$ should sum to 1, or $M_{sum} = M_{tot}$.

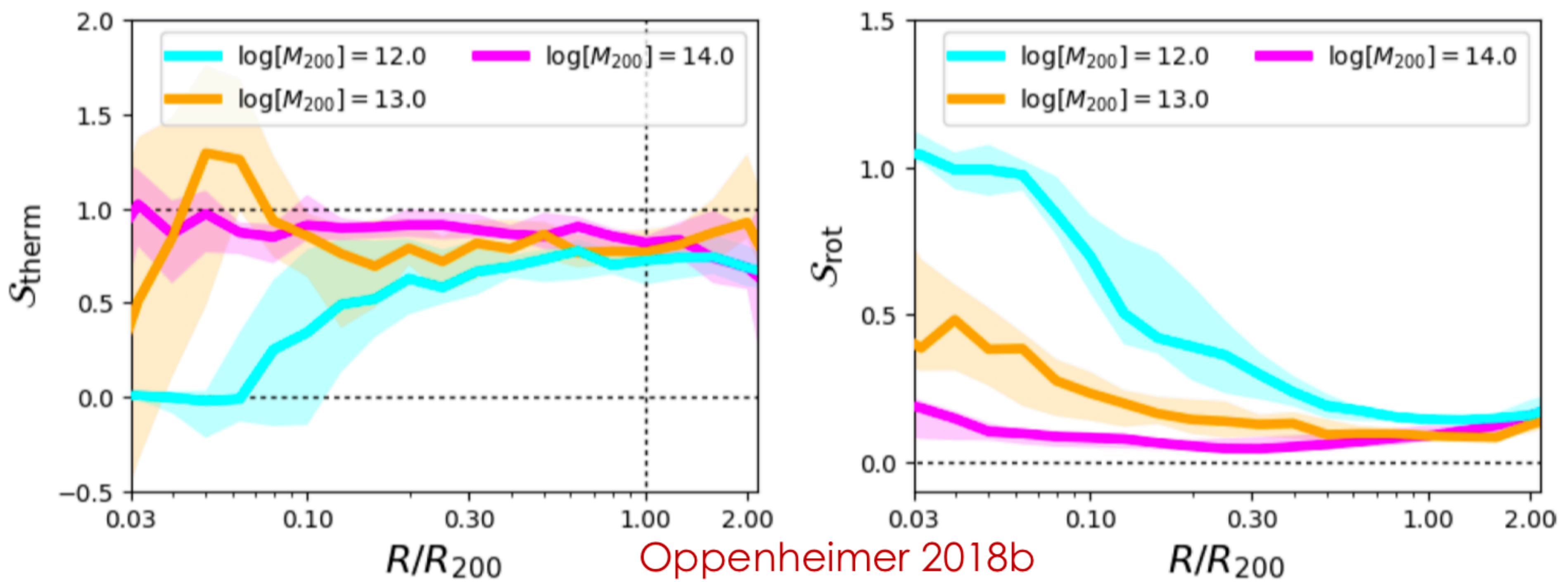
The CGM is not well-described by hydrostatic equilibrium around Milky Way-mass galaxies.



Feedback is more significant vs. binding energy. The CGM is more multi-phase here, so the result is messier.

The most unexpected finding- high tangential support of the inner hot halo!

The CGM is not well-described by hydrostatic equilibrium around Milky Way-mass galaxies.



Using zoom simulations for L* halos ($M_{200}=10^{12}$ M_{sol}) and group halos ($M_{200}=10^{13}$ M_{sol}) compared to cluster halos ($M_{200}=10^{14}$ M_{sol}) shows a progression.

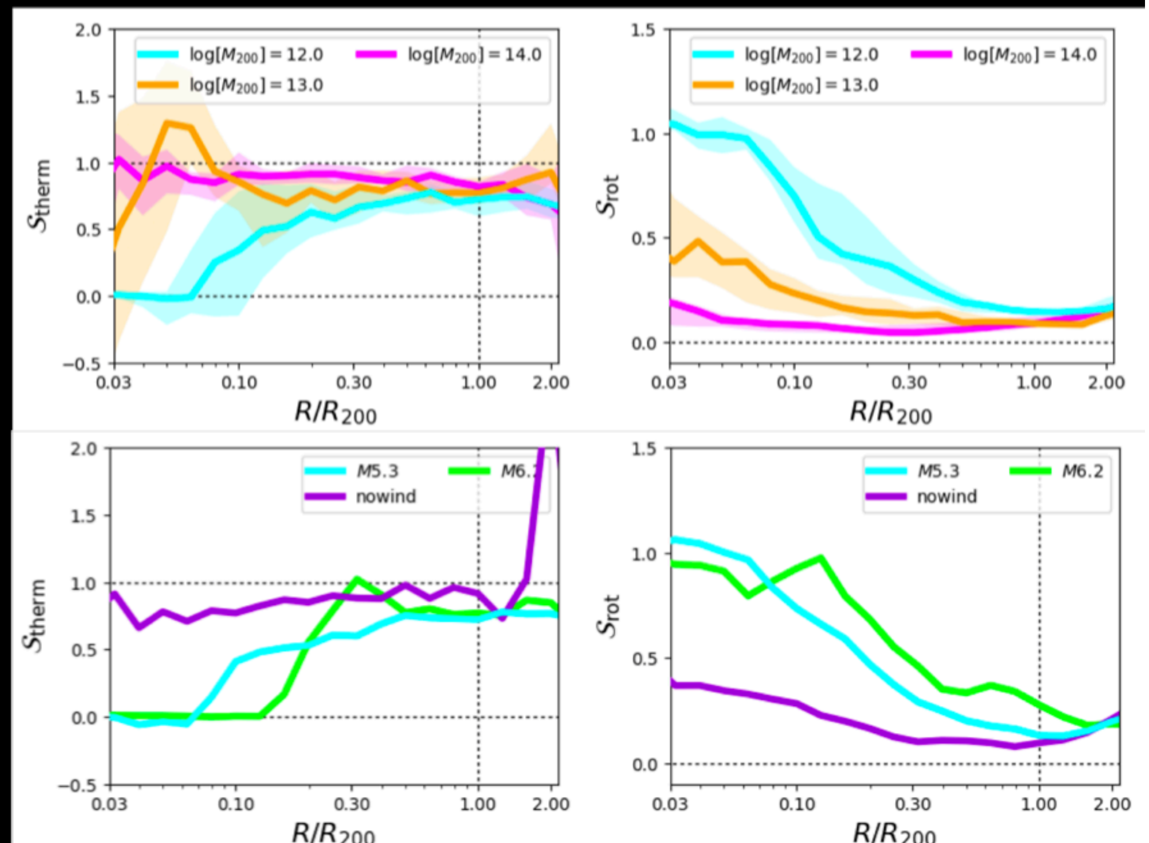
-More deviations from HSE at lower mass.

-I predict a sub-centrifugally spinning hot halos around Milky Way-like galaxies.

What causes the CGM to break self-similarity- Cooling or Feedback?

I compare EAGLE-100 clusters (pink) with "ineffective feedback" to L* galaxies without feedback (purple) to isolate the effect of cooling.

These two samples have similar descriptions for hydrostatic support, indicating that feedback is primarily responsible.

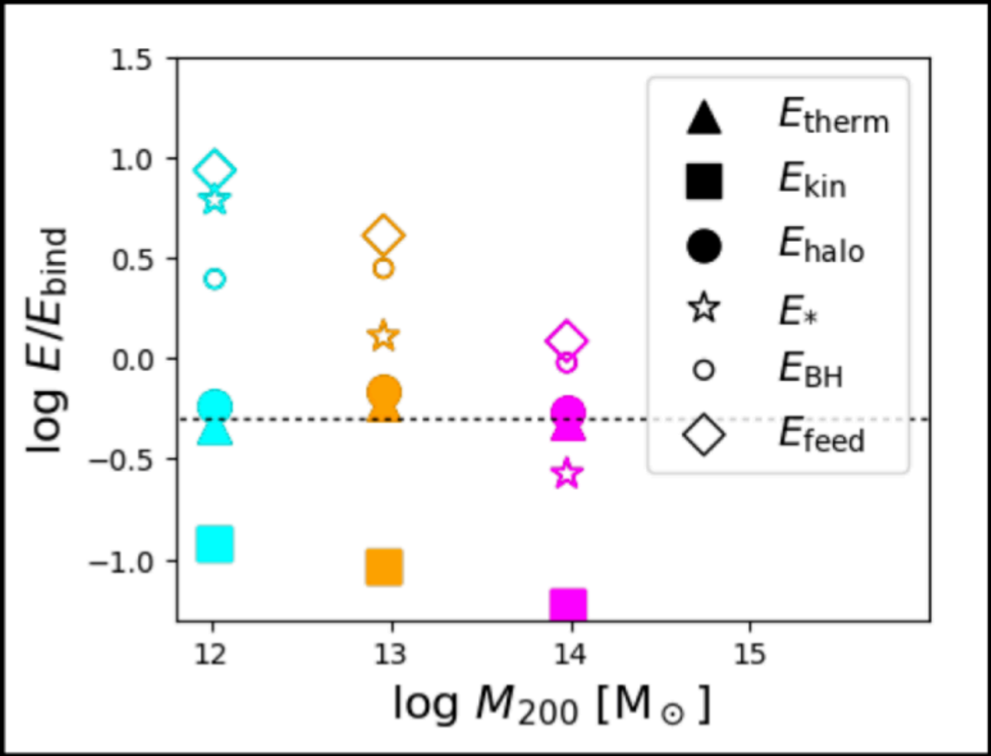


Oppenheimer (2018b)

What causes the CGM to break self-similarity- Cooling or Feedback?

L* halos have far more feedback energy imparted to their halos with respect to the binding energy (at least in EAGLE).

It is lucky feedback is not more efficient, because maybe we wouldn't have a MW galaxy to live in.



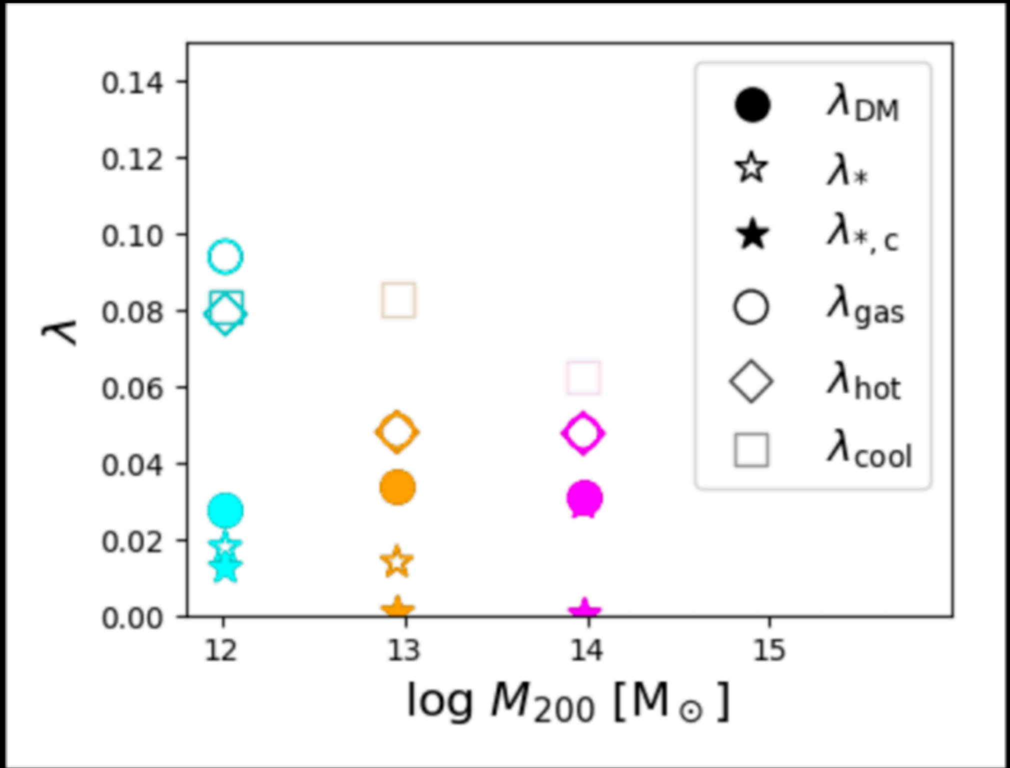
Oppenheimer (2018b)

Feedback spins up hot halos

Buoyant stellar thermal feedback allows hot gas to rise to R_{vir} and beyond around L* halos (Bower+ 2017).

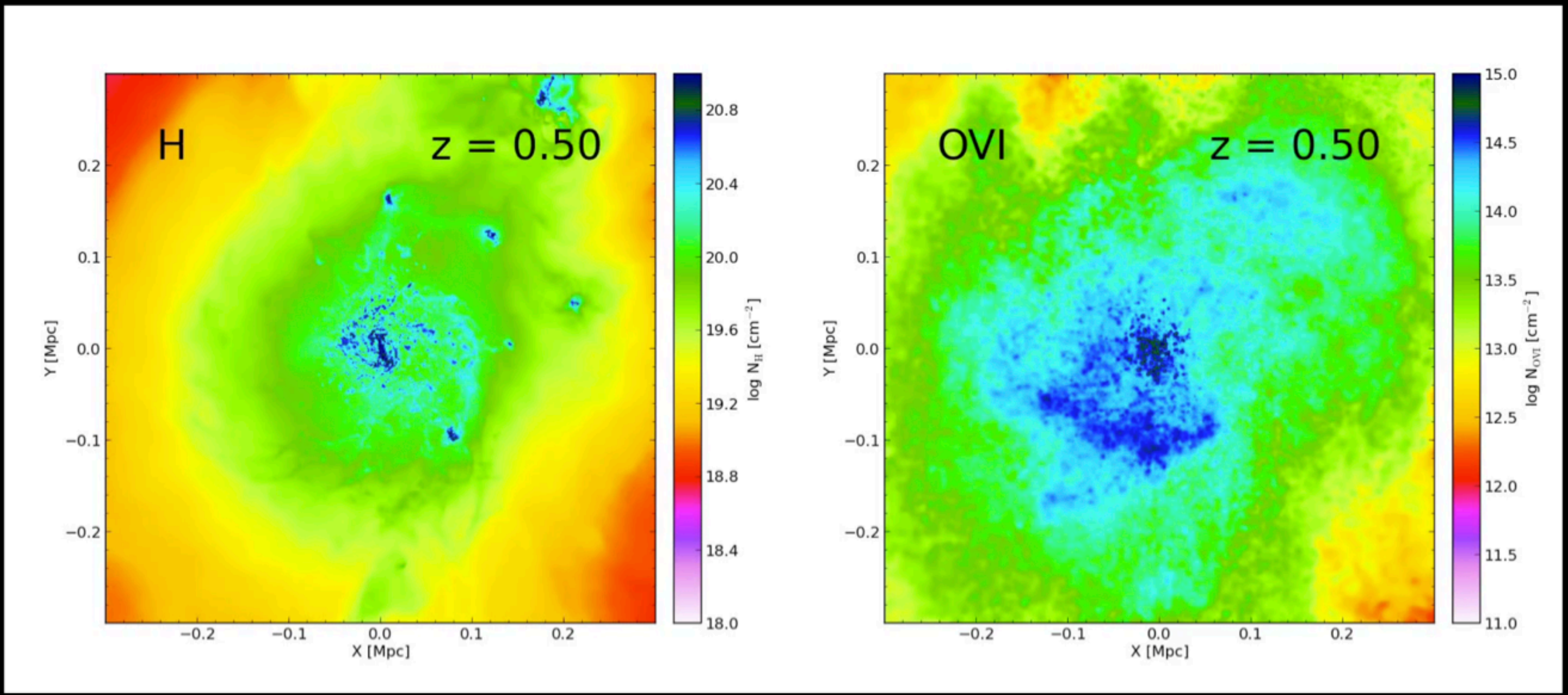
Much of this gas launched at z>1 makes up O VI halos observed by COS-Halos (Opp.+ 2016).

This gas also falls back into the inner halo, much of it remaining warm-hot (>10^5 K) and gives the hot halo significant spin.



Oppenheimer (2018b)- hot CGM spin is as much as cool CGM for L* halos, but there is more hot gas and hot total angular momentum- J_{cool} equals J_{hot} at ~90 kpc.

OVI halos are often sub-centrifugally spinning



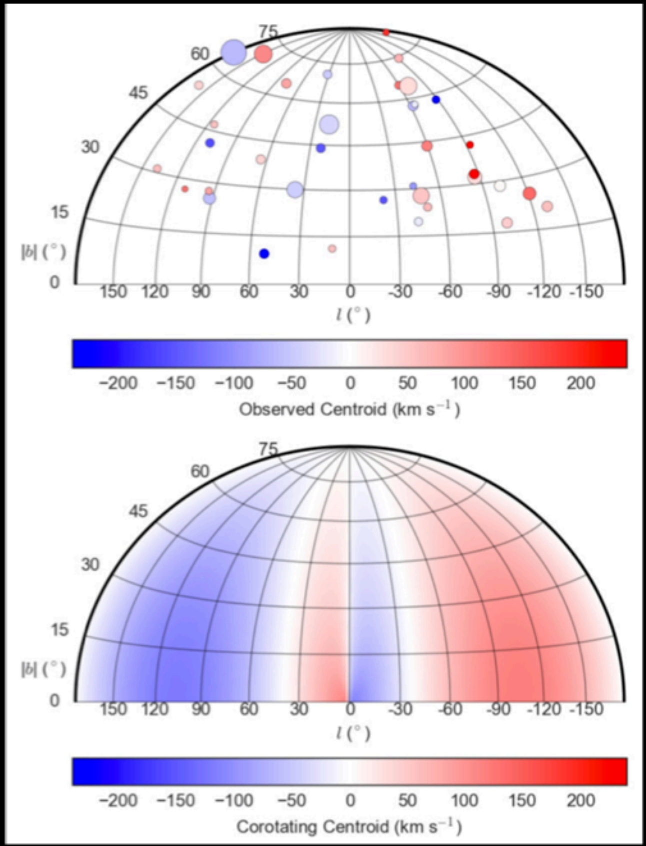
There is a sub-centrifugal rotating OVI halo tracing warm-hot CGM in this $10^{12.1}$ M_{sol} halo. For this galaxy, an HI disc is fed, but it is not the main stellar disc (see Stevens+ 2017).

Warm-hot halos ($T>10^5$ K) of L* galaxies rotate sub-centrifugally.

Simulated hot halos have significant spin, but also uncorrelated tangential motions, all fed by superwind feedback.

Rotation of hot halos are not just a theoretical constructs!

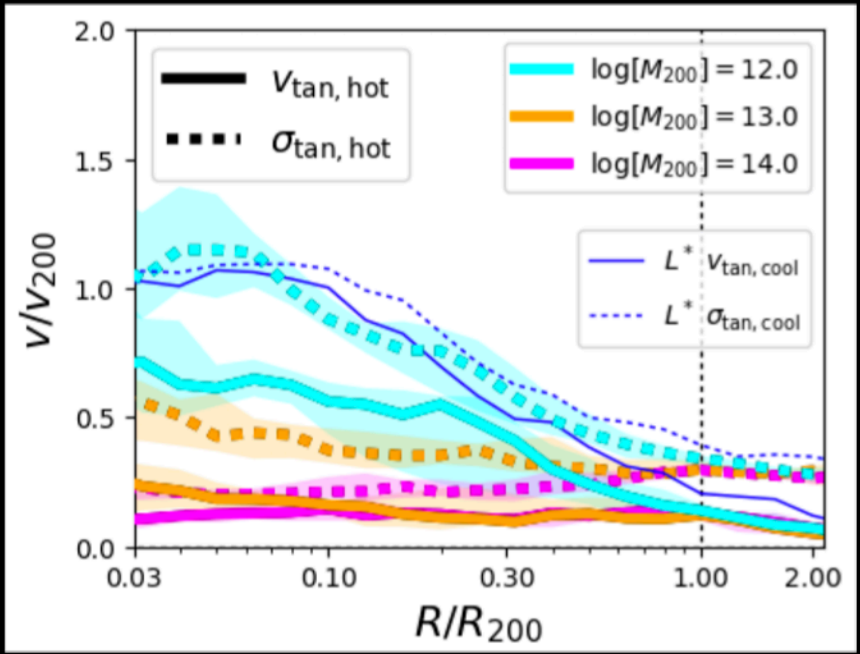
Our very own Milky Way hot halo is spinning at $v = 183+/-41$ km s^{-1}. This is sub-centrifugal rotation for our halo, ~240 km s^{-1}.



The MW Hot Halo at <50 kpc has net rotation in O VII.
Hodges-Kluck+ (2016); Miller+ (2016); Bregman+ (2017)

L* Hot halos rotate sub-centrifugally at slightly over half the virial velocity

L* hot halos have significant angular momentum from correlated rotation ($v_{tan,hot}$~0.5 v_{virial}), but that does not account for the total tangential support ($\sigma_{tan,hot}$).



Oppenheimer 2018b

Did you know the MW halo has more correlated rotation in its hot halo that is more well-aligned with its CGM cool disc than typical due to its quiescent merger history since z=1 resulting in our grand-design spiral morphology?

Northwestern CGM Outline

1. Metals
2. Mass Encore
3. Dynamics

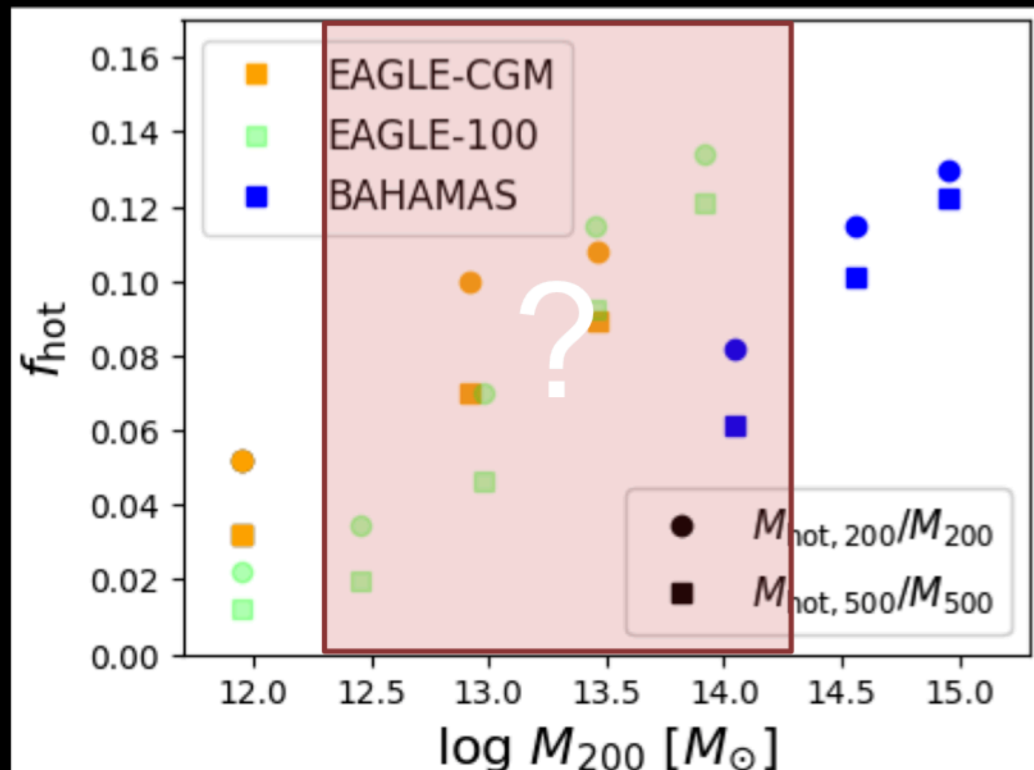
Is there an inflection point in the baryon content of halos as a function of mass?

BAHAMAS says poor clusters are evacuated of >half their baryons (from X-ray + S-Z).

EAGLE-100 (main box) is incorrect- poor clusters are not baryonically closed.

EAGLE-CGM zooms consider CGM observables (e.g. OVI halos around L* galaxies), but there are few constraints at $10^{12.5}$-$10^{14.0}$ M_{sol} halos.

Can SMBH feedback evacuate a majority of a rich group's/poor cluster's baryonic halo?

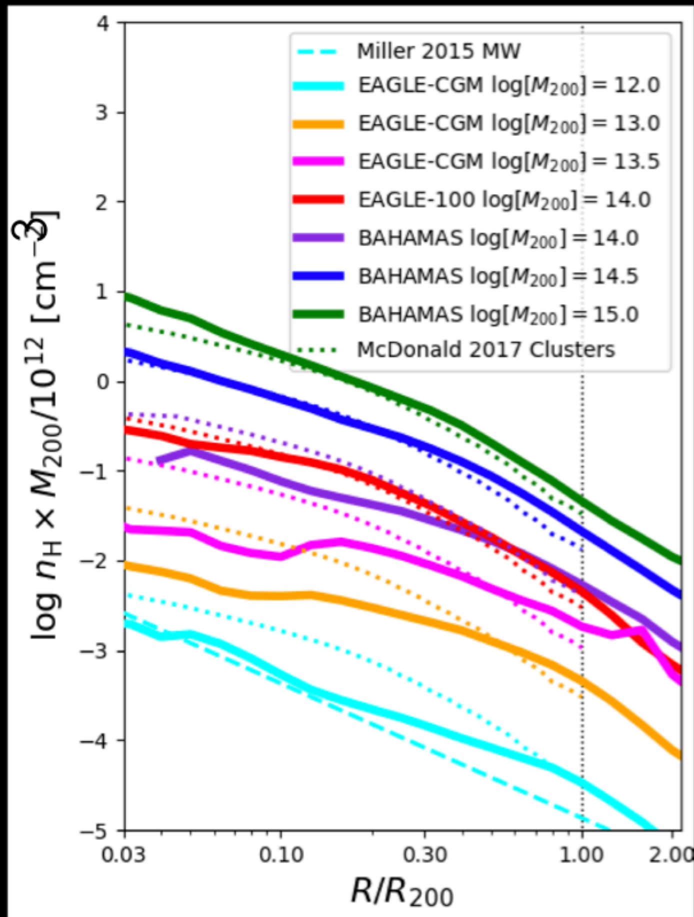


Oppenheimer+ (in prep.)

Hot Gas Profiles across a factor of 1000 in Mass

EAGLE-CGM profiles match up to predictions from Miller & Bregman (2015) OVIII emission profile in inner 50 kpc where it can be observationally constrained.

Did you know the MW halo density profile becomes flatter beyond 50 kpc?



Oppenheimer+ (in prep.)- McDonald+ cluster profile (baryonically closed) reproduced for each halo mass for uniform scale.

Conclusions

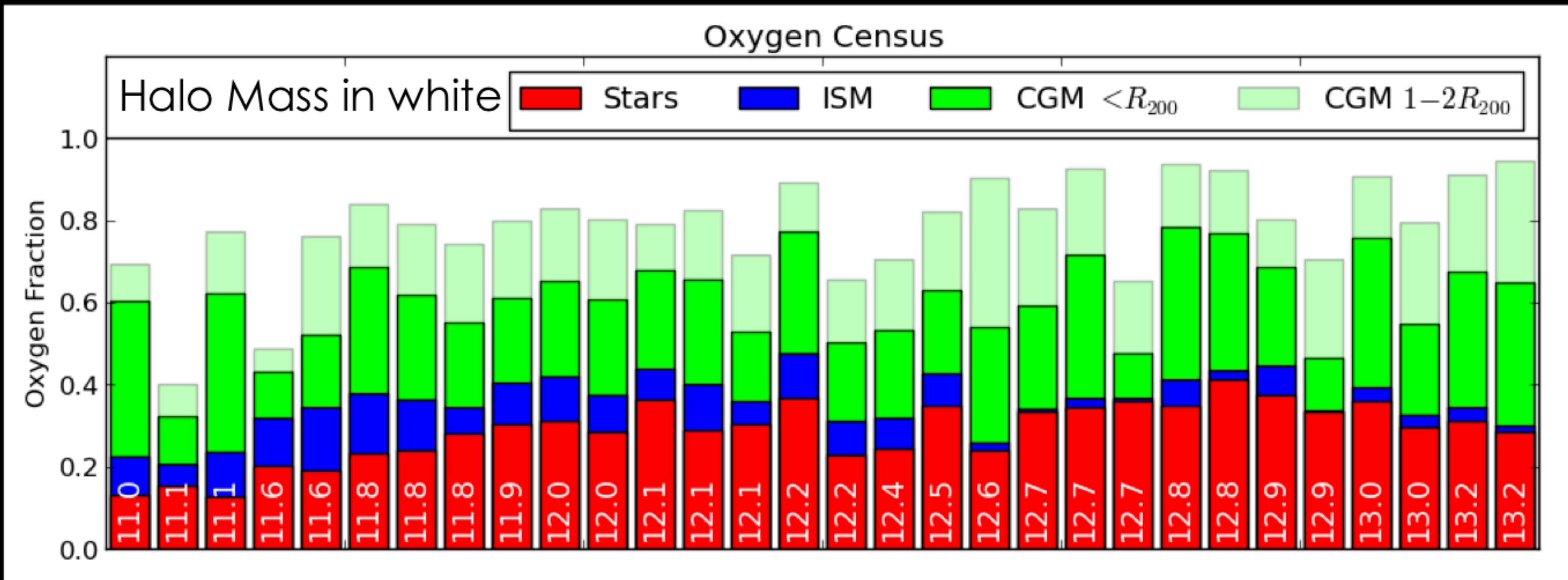
Metals: are fun, because their ions make a diverse rainbow of transitions that vary across halos. But they are also important because they provide insights into the physics of the baryon cycle: virial temperature thermometers, nature of cold accretion, AGN mass, energy, & radiative feedback, & more.

Mass: EAGLE and Illustris-TNG have very similar galaxy and COS-Halos predictions, but very different sequences of when feedback evacuates halos. The *Galaxy-SMBH-CGM Link* absolutely exists, but it's nature is currently unconstrainted.

Dynamics: Tangential velocity primarily provides support to the inner hot halos of L* galaxies. Thermal feedback spins up hot halos that rotate sub-centrifugally and obtain significant angular momentum.

Thanks Jonathan, CAFG, and Gretchen.
Questions?

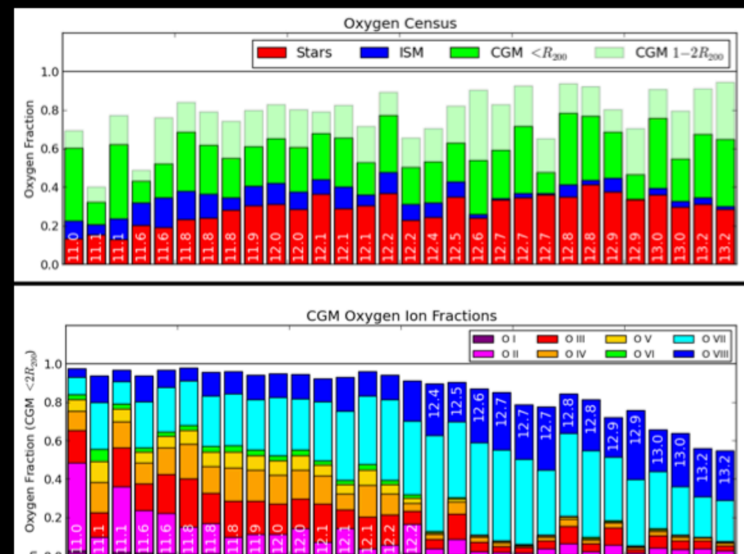
Most metals released from stars are ejected into the CGM and IGM.



Sub-L* --> L* --> Super-L*

The oxygen fraction yielded by stars O_{yield} divided in its various phases: Stellar, ISM, and CGM (shortfall is oxygen beyond 2 R_{vir}).

The CGM oxygen (metal) budget spans the entire range of ion states, and while it is important for counting, metals can reveal the fundamentals of CGM physics, dynamics, and evolution.



Sub-L* --> L* --> Super-L*

Very little oxygen in the CGM within $2xR_{vir}$ is O VI as shown by the green sliver. A global CGM ionization fraction of 2-3%.

Galaxies are diverse, what beyond halo mass best describes them?

There is no simple second parameter of galaxy formation that describes the morphology and appearance of ***central*** galaxies at the same halo mass.

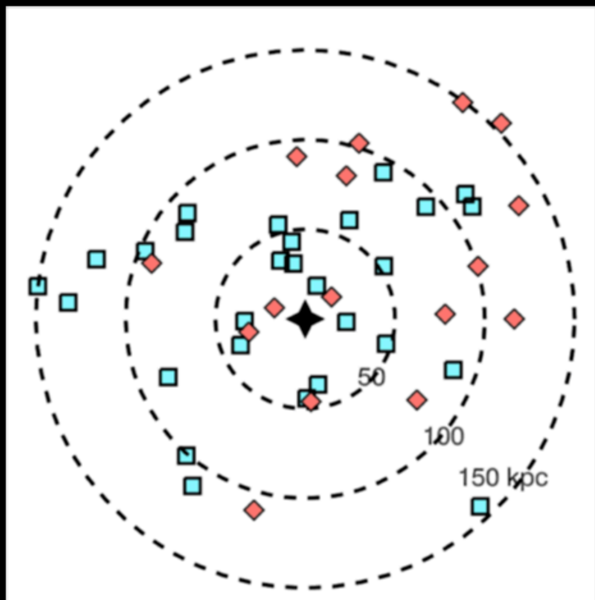
DM theory predicts that halo spin parameter, collapse time, or halo merger history differentiate the appearance of galaxies.

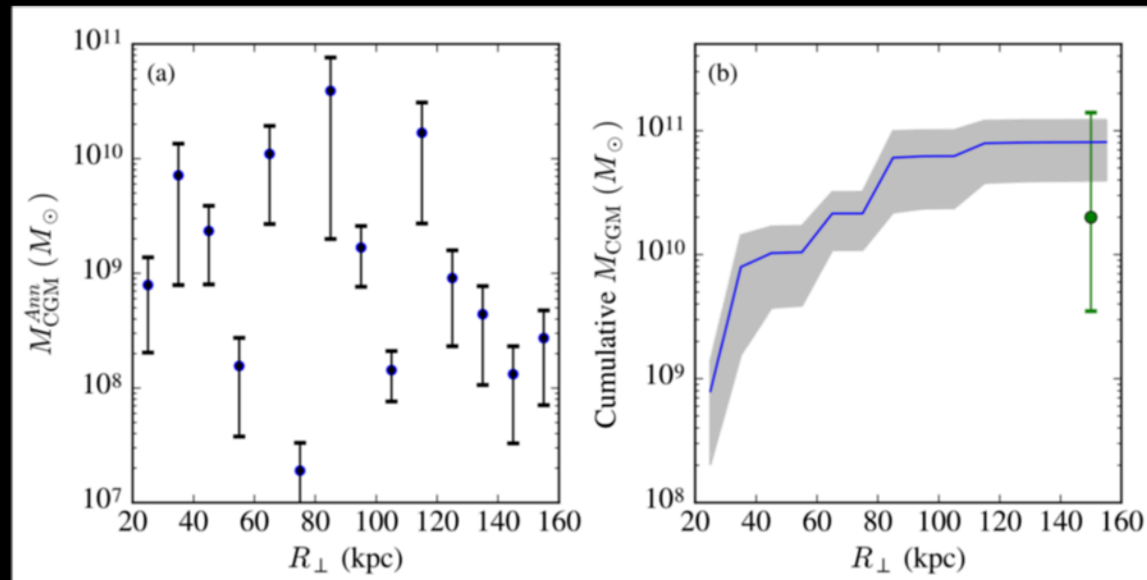
The angular momentum of the cool (~10^4 K) CGM (extended HI discs) is important for stellar discs. (Kyle Stewart's work).

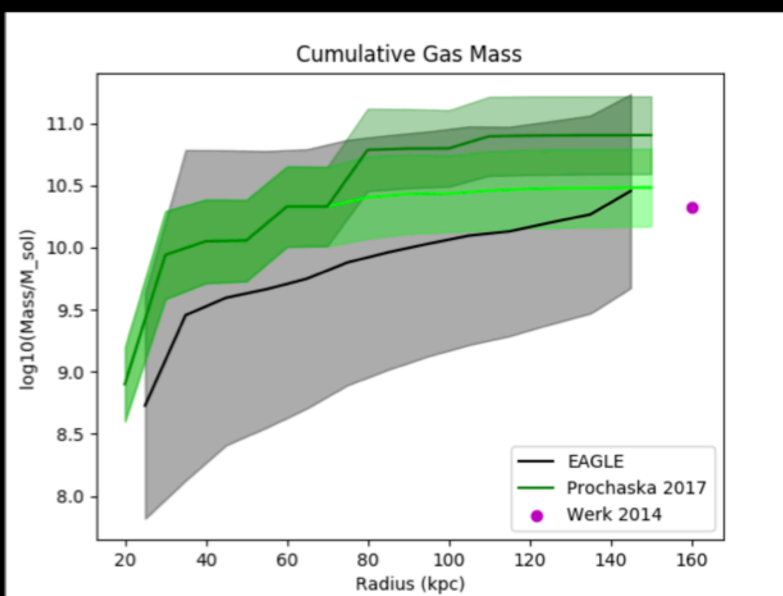
Recent work by Garrison-Kimmel with FIRE-2 finds the best predictor of today's morphology is halo gas spin parameter at z~1.

However, we need to ask fundamental questions about the CGM….

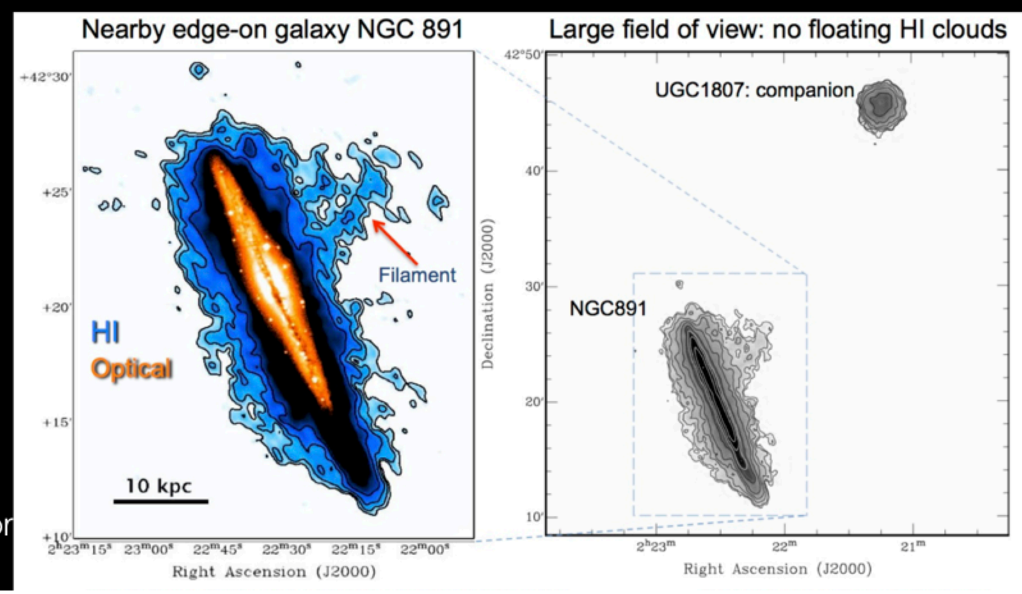
HI mass summed in COS-Halos



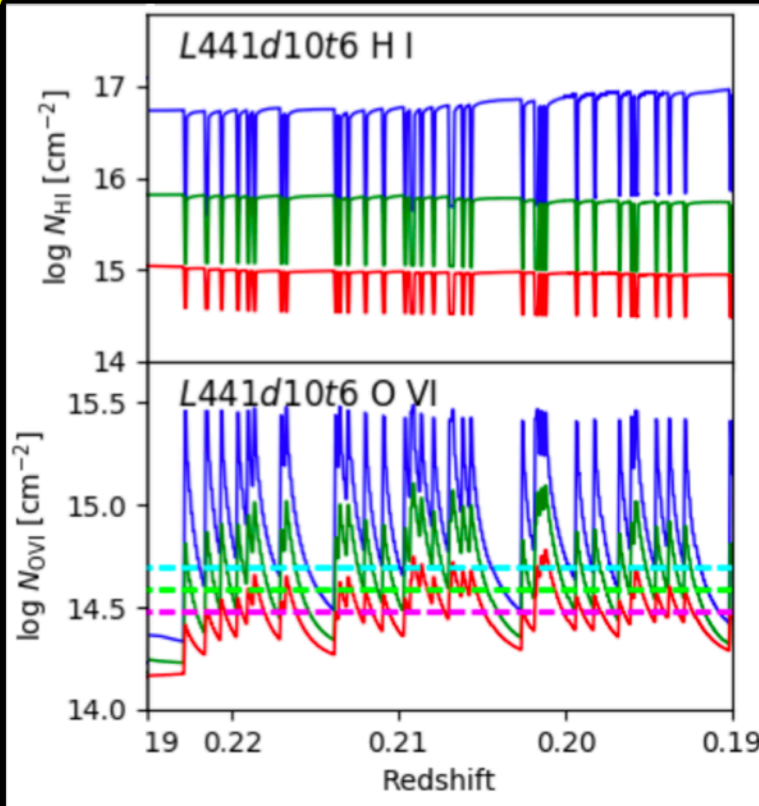


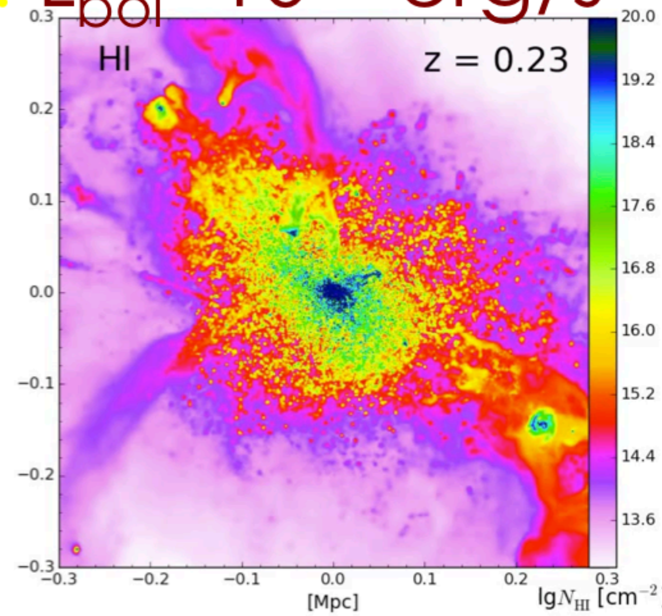


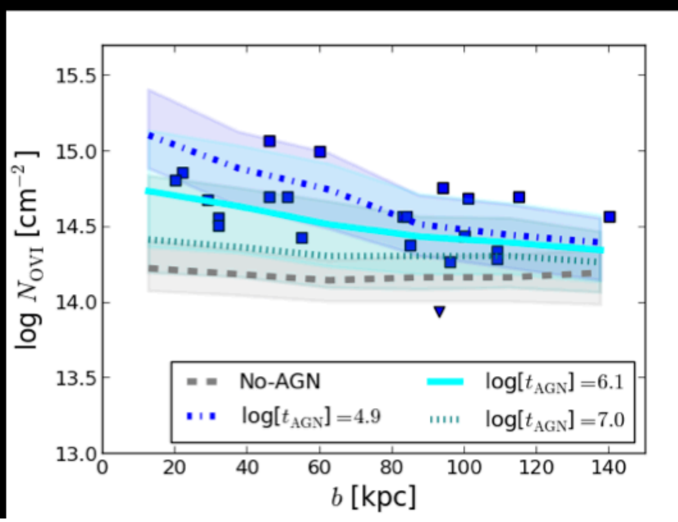
Nor

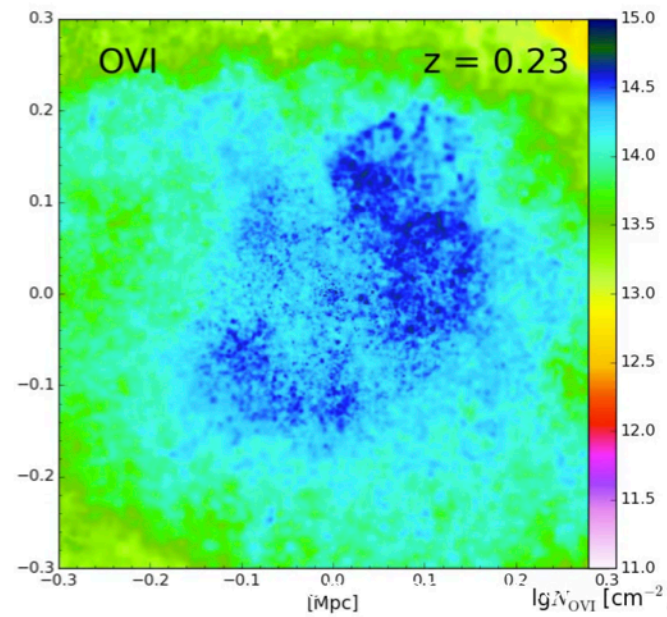


Dynamic NEQ-AGN Runs: $L_{bol}=10^{44}$ erg/s









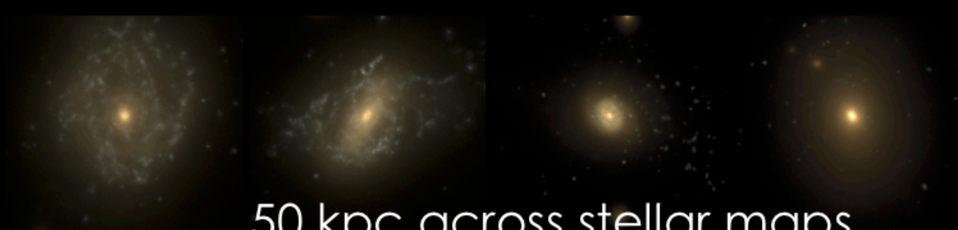
EAGLE-CGM Zooms

-Run zooms at 8x and 64x resolution main EAGLE simulation (Schaye+ 2015). Stellar and AGN feedback both included.

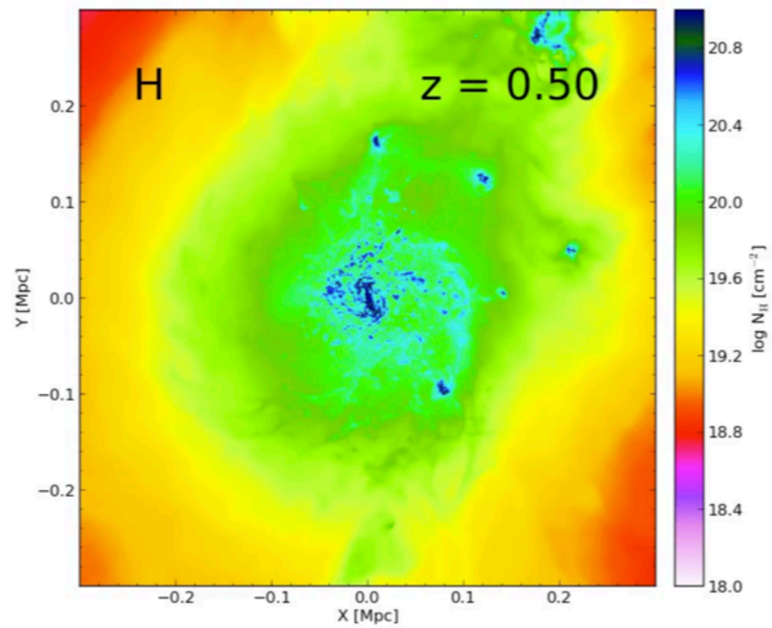
-Follow individual ions (e.g. O I- O IX) self-consistently using non-equilibrium ionization and cooling (Opp. & Schaye 2013a, Richings+ 2014a).

-Halos ranging from $M_{200}=10^{10.7}$ up to $10^{14.0}$ M_{sol}.

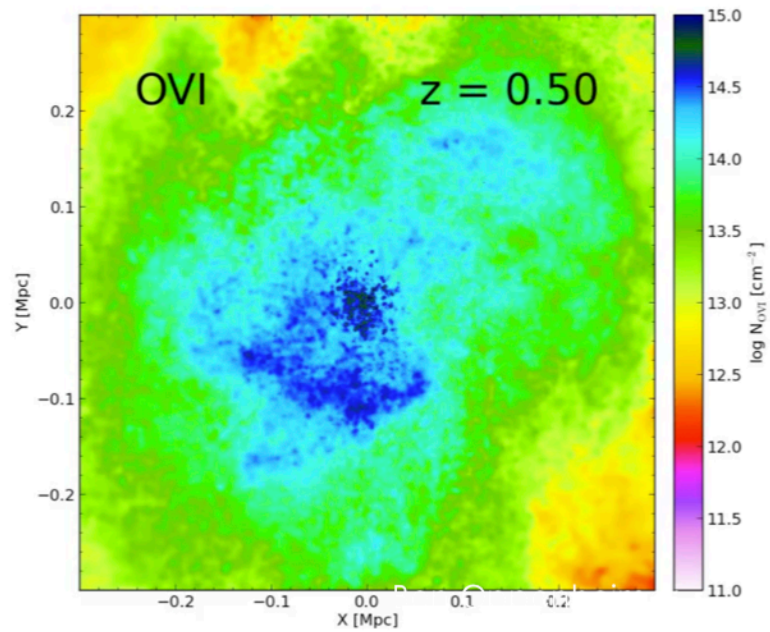
-Purpose to simulate range of galaxy morphologies observed by a survey like COS-Halos.



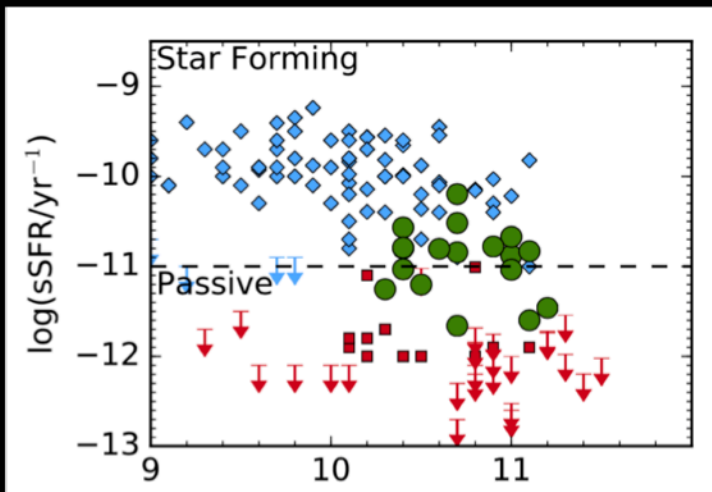
50 kpc across stellar maps

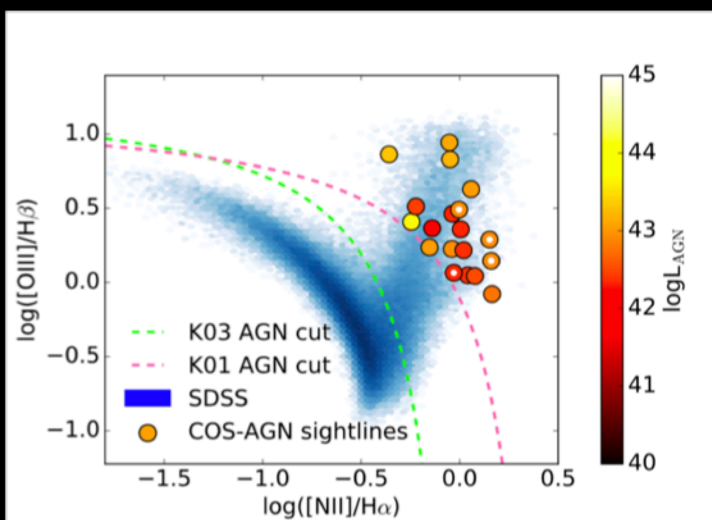


600 kpc across CGM maps



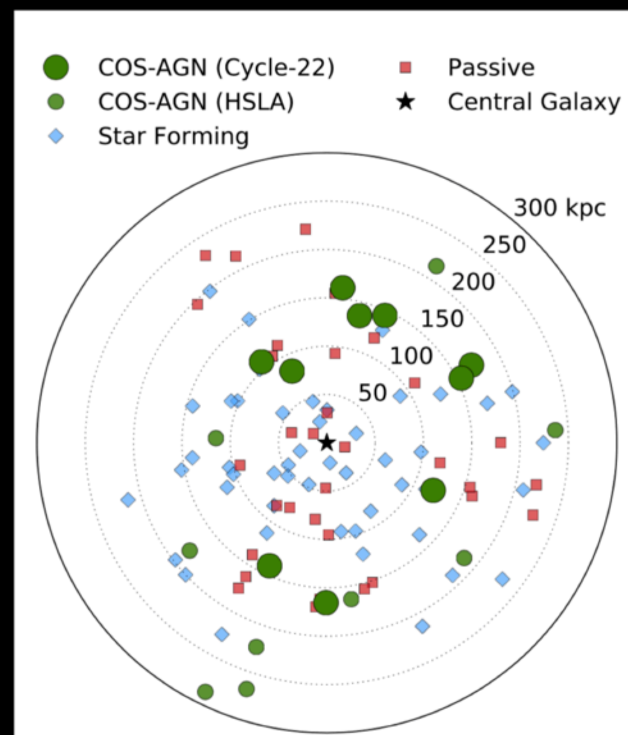
The COS-AGN Survey- sight lines probing active AGN halos.





PI- S. Ellison (**Trystyn Berg**-led paper)

Seyfert-level AGN- $L_{bol} = 10^{42}$-$10^{43.7}$ erg/s
Impact parameters- 80-300 kpc



Take away message #2

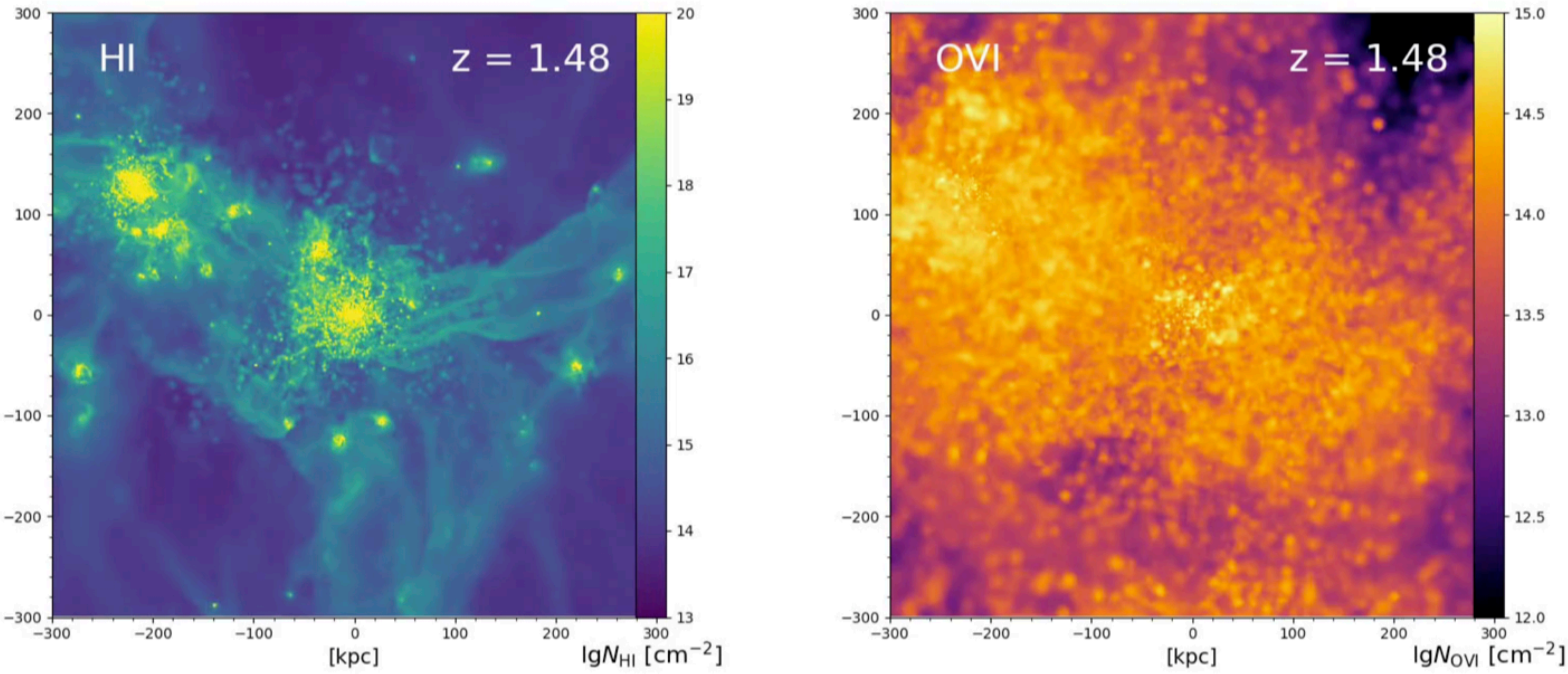
The CGM at least out to r=160 kpc is intimately tied to the nature of galaxies, but is the correlation between O VI and galactic star formation causal or incidental?

I will argue for the incidental relationship- O VI is *a virial temperature thermometer* and its lower levels around passive galaxies is not directly related to recent feedback.

A few options to distinguish models:

1) Look at the CGMs around AGN, especially inside 75 kpc
2) Build Lynx X-ray telescope to observe CGM O VII & O VIII
3) Observe the stellar population ages of z=0.2 passive galaxies.

The many Gyr transformation of the CGM



10 Gyrs of evolution transforming from a 10^{12} M_{sol} to a 10^{13} M_{sol} halo.