The Gas-rich Halos of Massive ‘Red & Dead’ Galaxies

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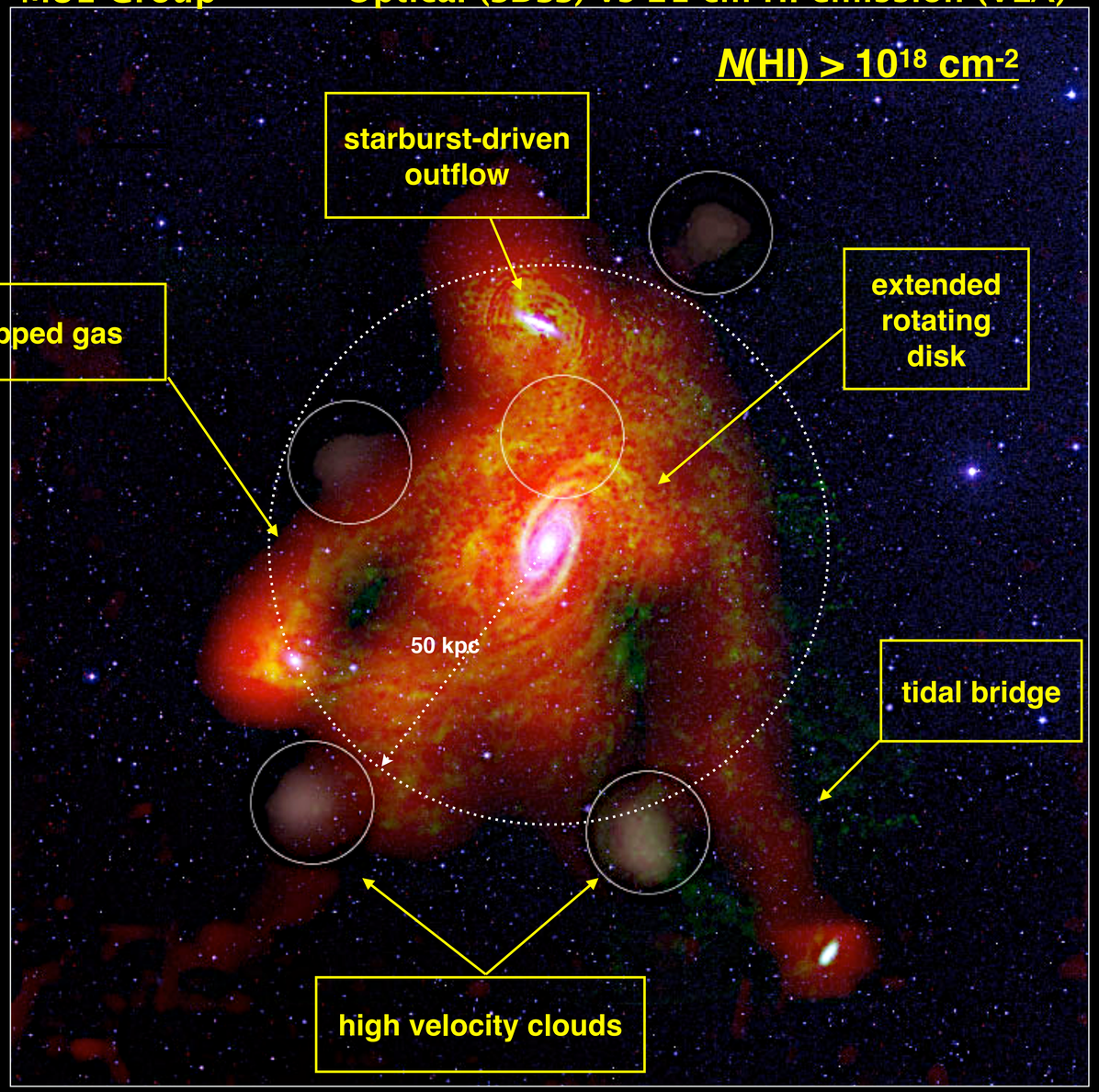
The Circumgalactic Medium (CGM): a gaseous ecosystem



Galaxies accrete gas from the intergalactic space, which fuels star formation.

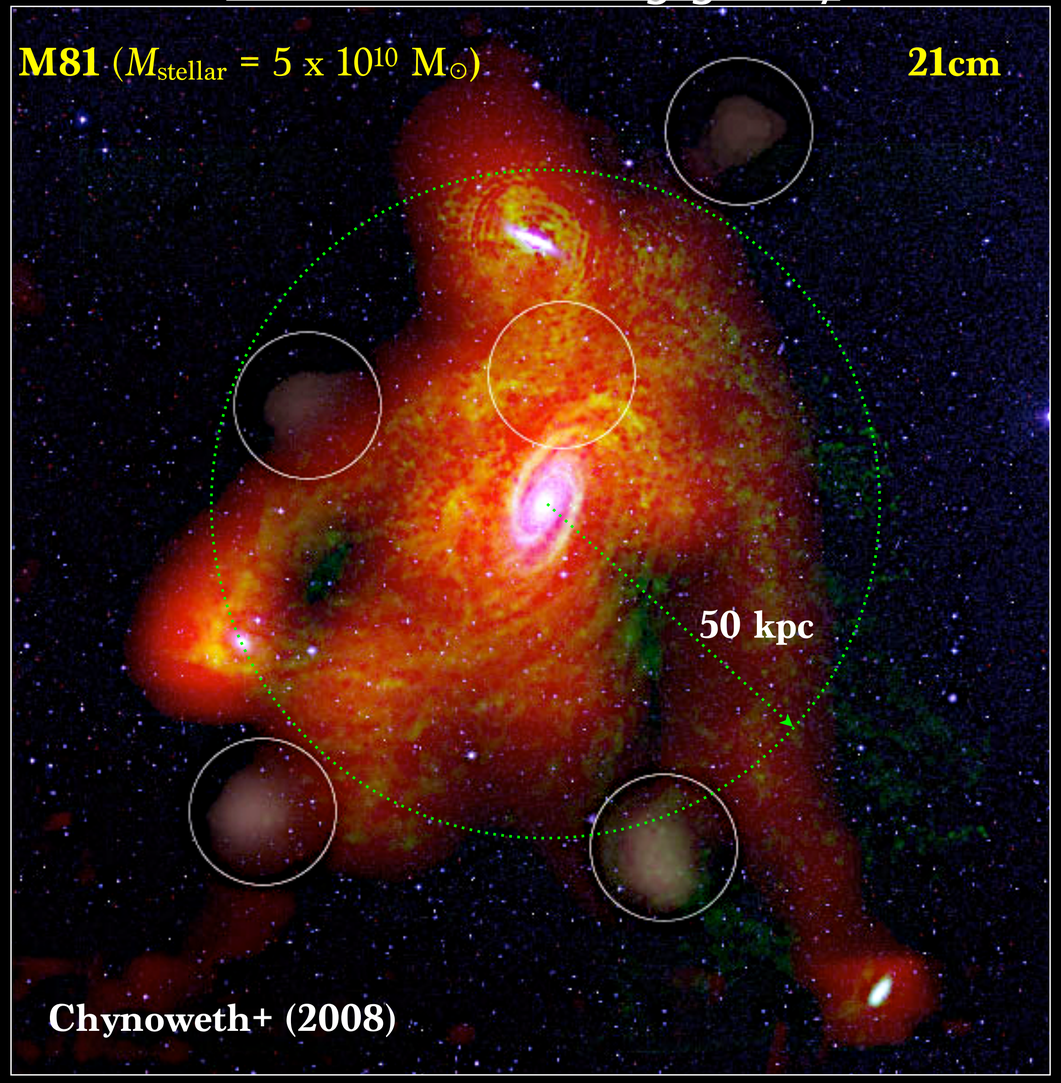
Feedback and other processes in galaxies can drive winds, heat the gas, and regulate future accretion.

The CGM bears the imprint of this complex interaction.

Chynoweth+08

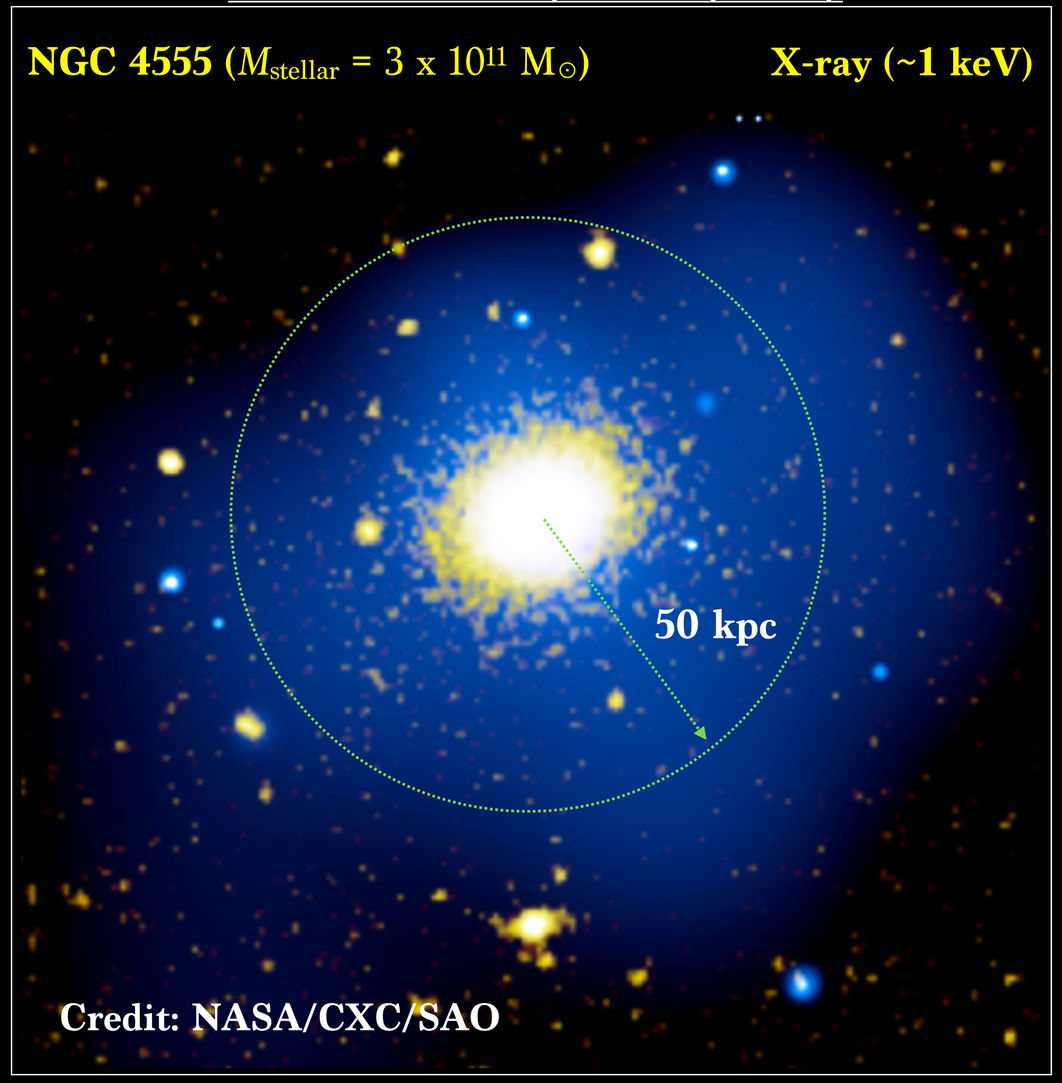
Galaxy-gas coevolution: what's the relationship between galaxy & halo gas?

An L* star-forming galaxy



Tons of cool gas

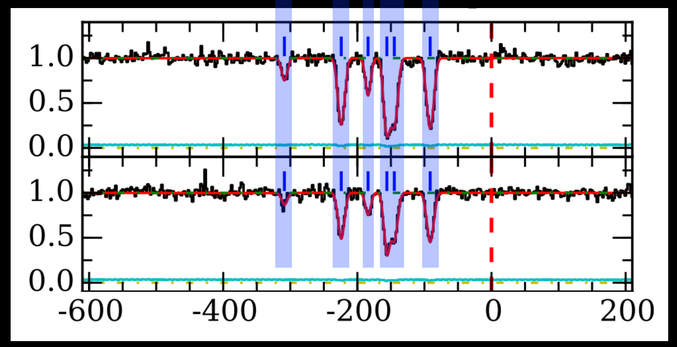
A massive elliptical galaxy



Hot (not cool) gas?

Detecting diffuse gas beyond the local Universe with absorption spectroscopy

A suite of absorption lines imprinted on the background QSO spectrum by foreground gas



Foreground galaxy at z_{gal}

Background QSO at $z_{qso} > z_{gal}$

projected distance d

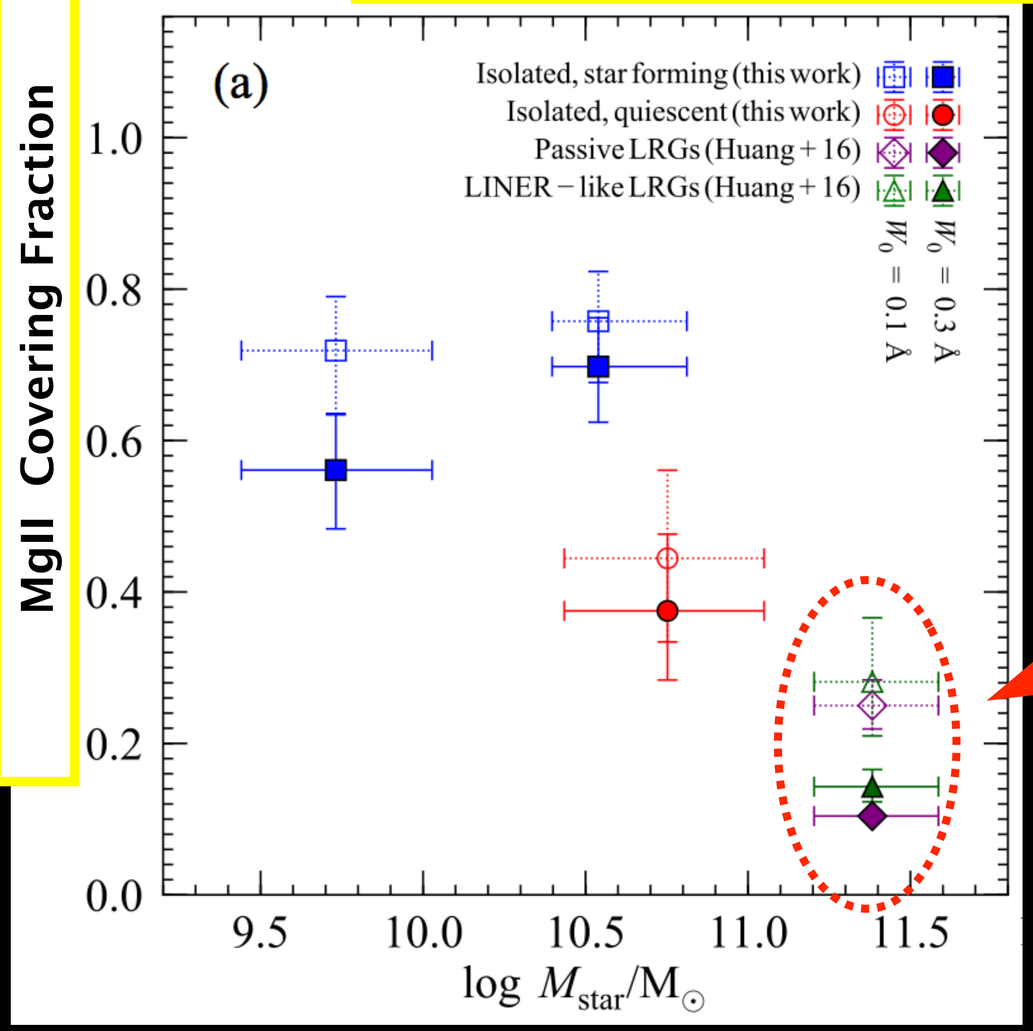
Observer

Correlation between CGM and galaxy properties at z<1

The incidence of chemically enriched cool (T~10^4 K) gas in the CGM declines with increasing mass, but it is definitely non-zero in massive quiescent halos

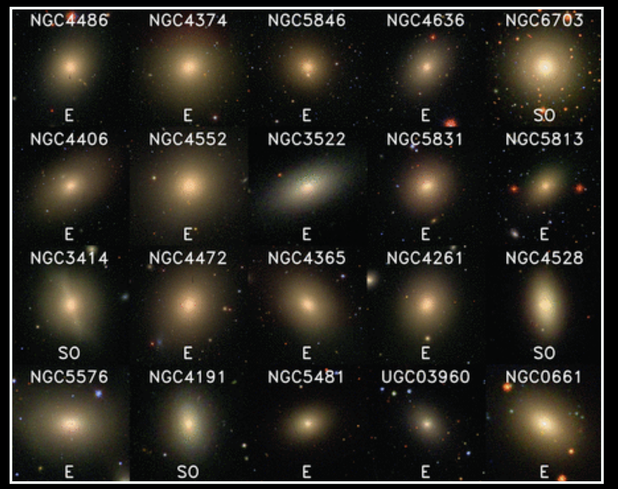
Increasing galaxy mass

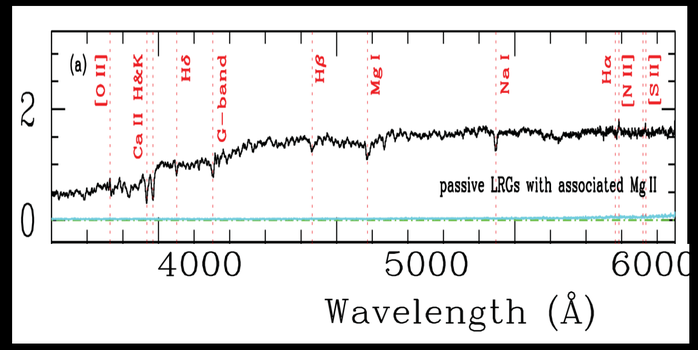
MgII Covering Fraction



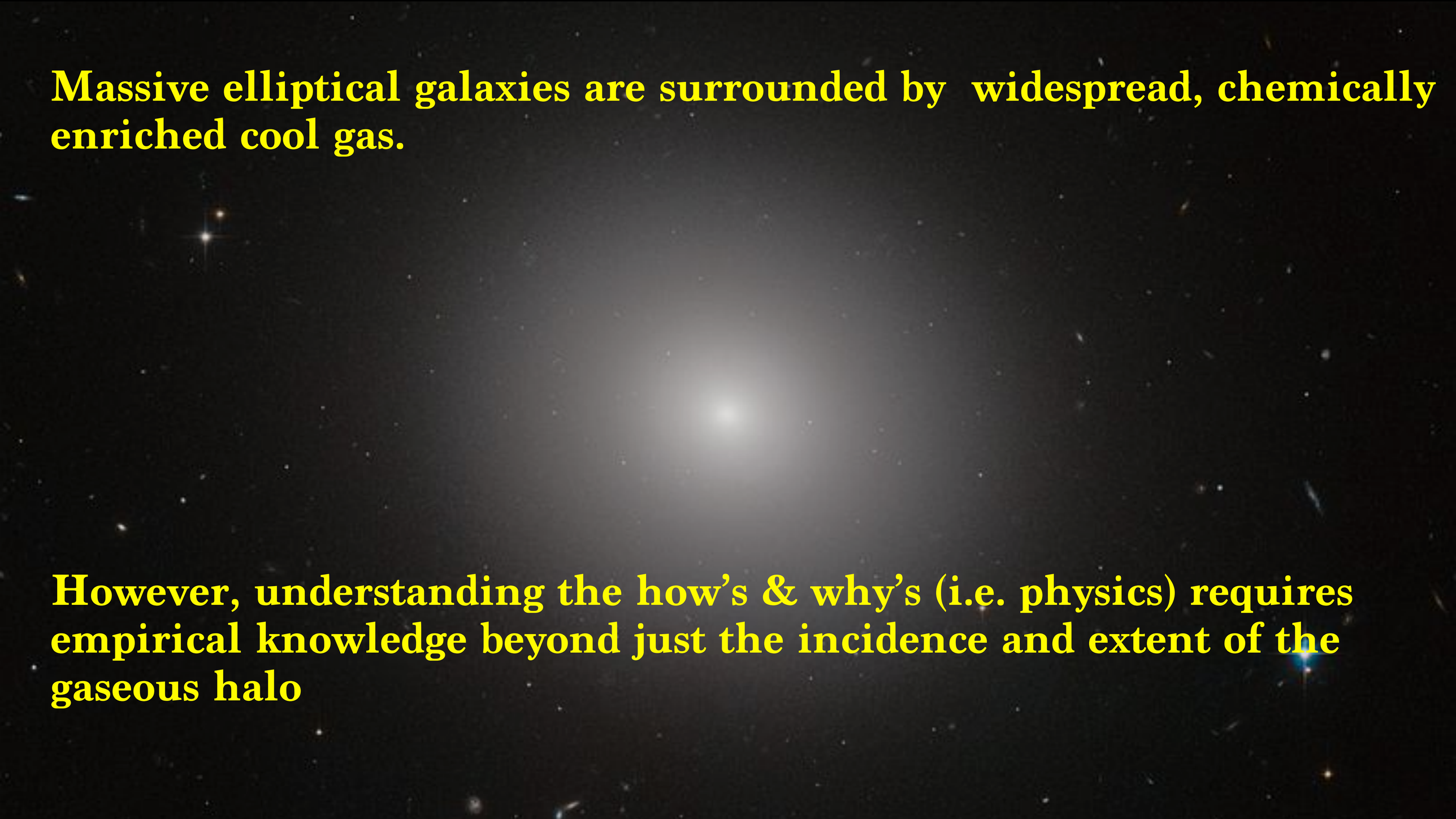
Cool CGM covering fraction in ellipticals: >15% on ~100 kpc scales

z~0.5 Luminous Red Galaxies (LRGs)





Chen+ (2010); Huang+ (2020)


Massive elliptical galaxies are surrounded by widespread, chemically enriched cool gas.
However, understanding the how's & why's (i.e. physics) requires empirical knowledge beyond just the incidence and extent of the gaseous halo

How much cool gas is in the CGM of massive elliptical galaxies?

The COS-LRG survey: an HST/COS program characterizing the CGM of z~0.5 LRGs

Zahedy et al. 2019 (MNRAS, 484, 2257)
Chen, Zahedy et al. 2018 (MNRAS, 479, 2547)

- Luminous Red Galaxies (LRGs) at z~0.5 are the distant counterparts of nearby ellipticals: high-mass galaxies with old stellar populations (>5 Gyr), and little star formation.

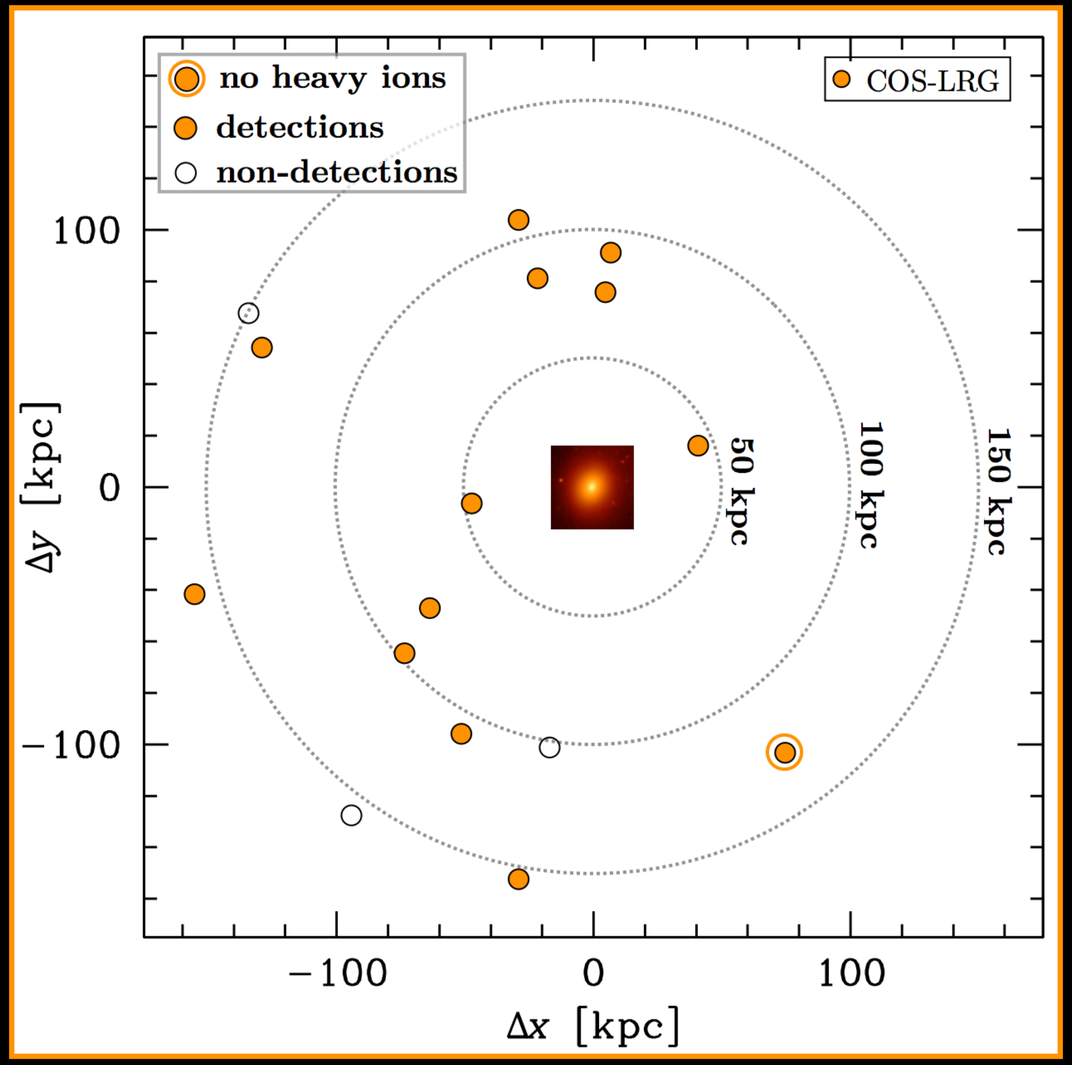
- **Goal:** Leverage Hubble's UV sensitivity to constrain the bulk of the gas (hydrogen) in the CGM of LRGs

- ***Mass-limited***: 16 SDSS LRGs with $M_{\rm star}$ >10^{11} $M_\odot$, each found at d < 160 kpc (~1/3 R_{200}) from a background QSO.

- ***Absorption-blind***: No prior knowledge of the presence/absence of absorption features

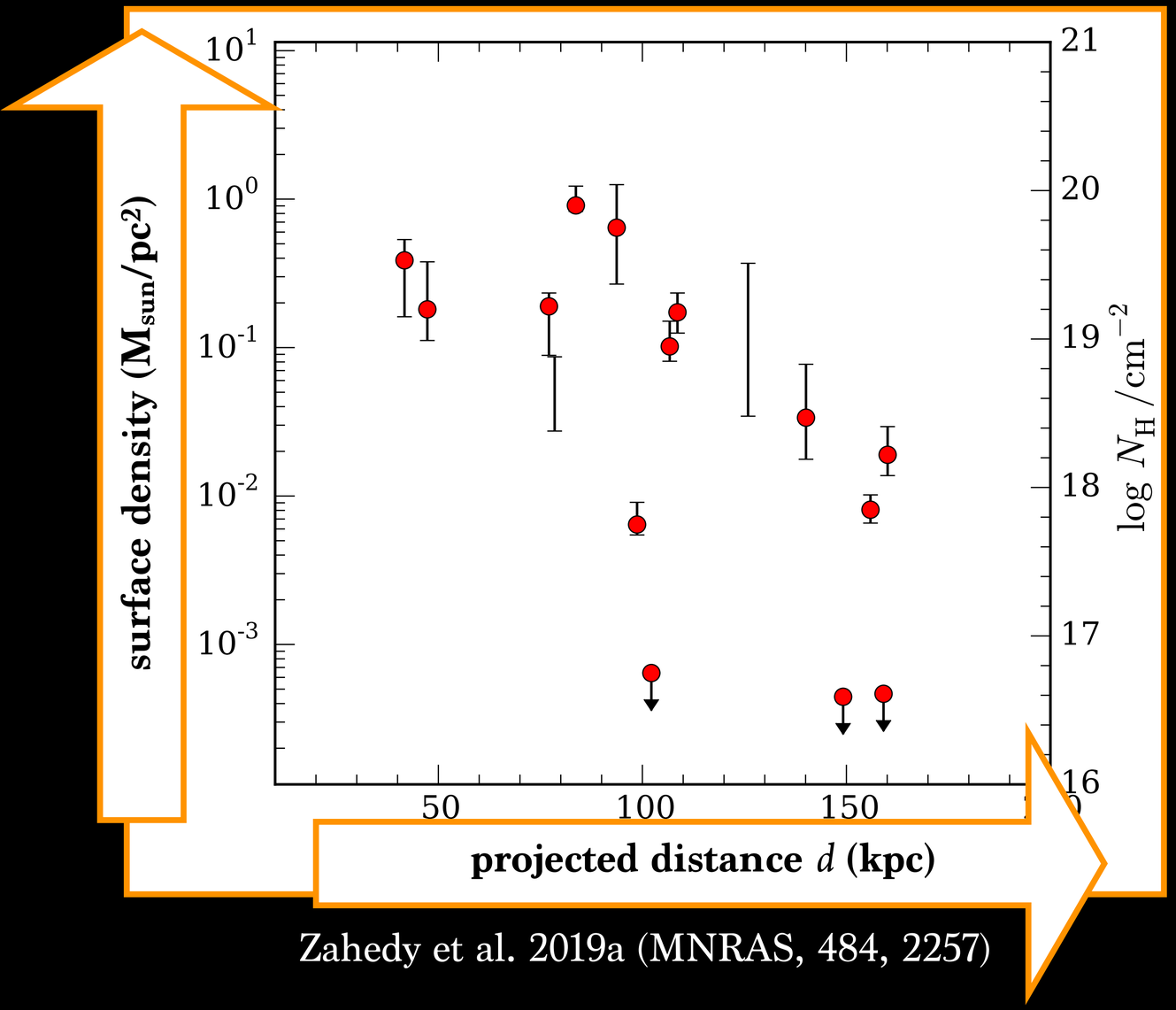
The COS-LRG survey: characterizing the CGM of massive ellipticals

High incidence of chemically enriched CGM: HI and ionic metals detected in ≈ 75% of LRGs



Chen, Zahedy et al. 2018 (MNRAS, 479, 2547)

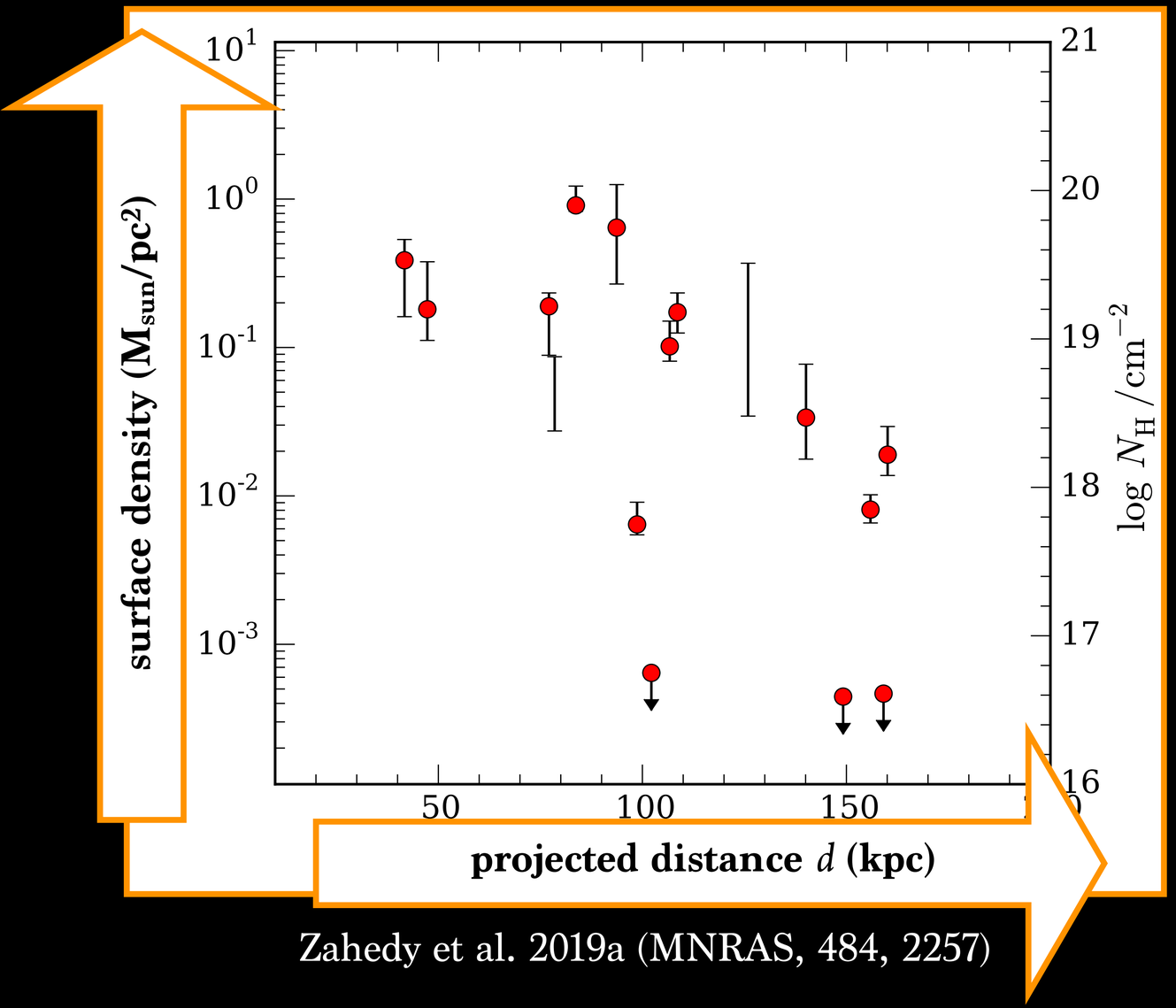
Mass surface density profile of cool gas around massive quiescent galaxies



Zahedy et al. 2019a (MNRAS, 484, 2257)

The large reservoir of cool (~10^4 K) gas in massive quiescent halos

Cool gas mass (< 160 kpc) ~ 2 x 10^{10} $M_\odot$



Zahedy et al. 2019a (MNRAS, 484, 2257)

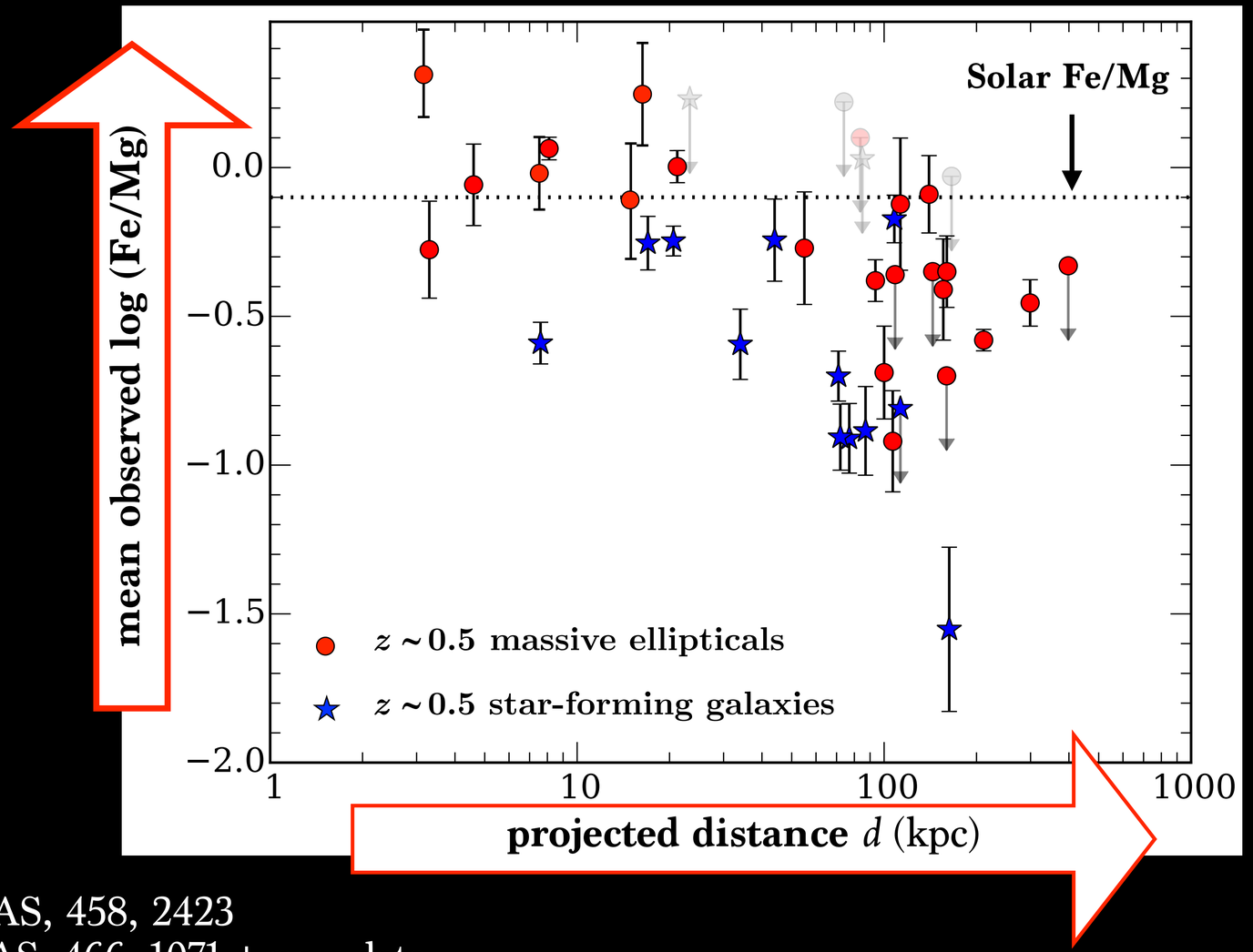
This is comparable to the cool CGM mass of L* star-forming galaxies!

see: Chen+ 2010; Prochaska+ 2011; Stocke+2013; Werk+ 2014; Stern+ 2016

What physical processes shape the gaseous halo on both small (~kpc) and large (~100 kpc) scales?

Chemical composition of the gaseous halo: a systematic study of [Fe/α]

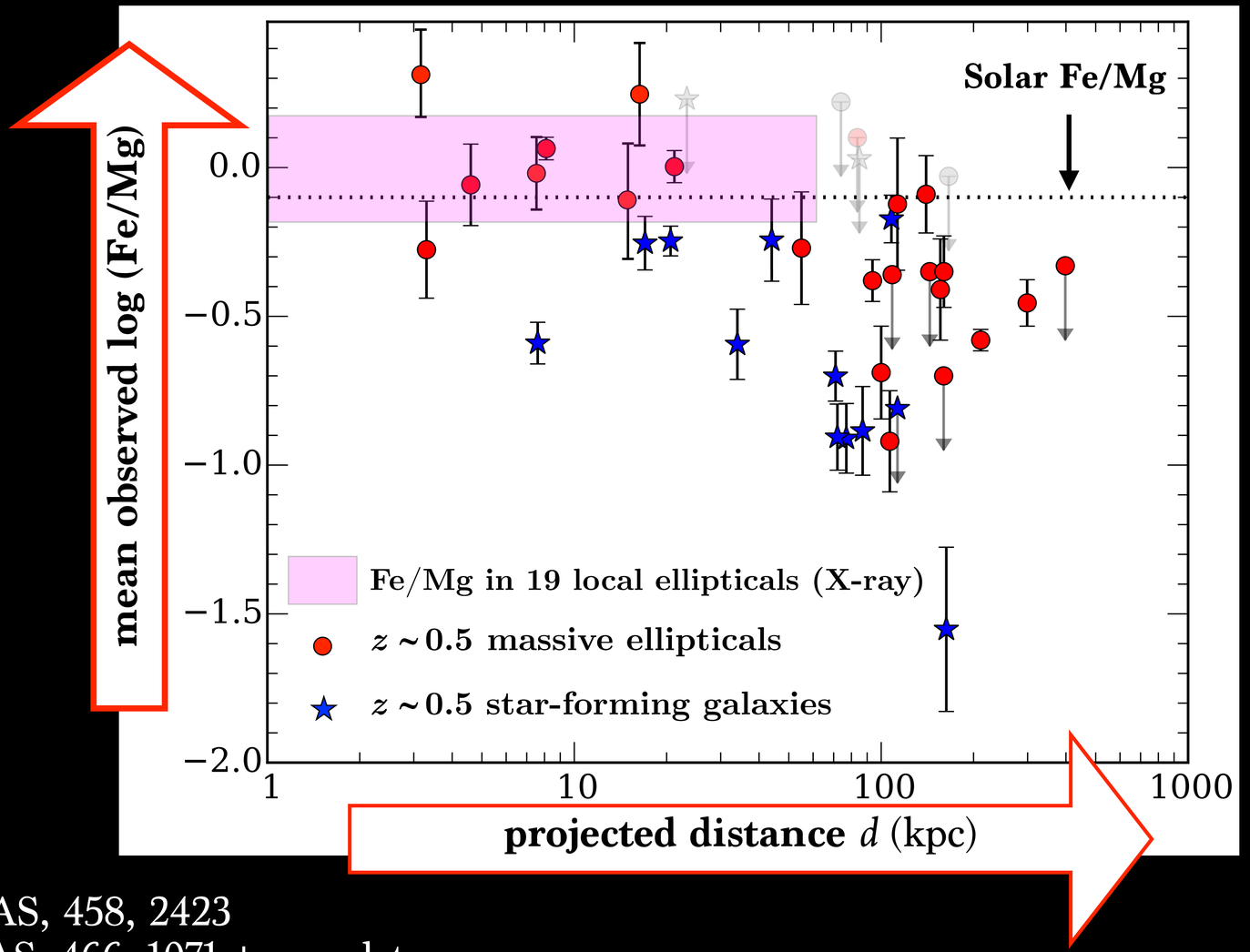
Elevated gas-phase [Fe/α] at d < ~30 kpc in quiescent halos indicates significant chemical enrichment ($f_{Ia} \gtrsim$ 20%) from Type-Ia supernovae in the inner halo of elliptical galaxies



Zahedy et al. (2016), MNRAS, 458, 2423
Zahedy et al. (2017), MNRAS, 466, 1071 + new data

Chemical composition of the gaseous halo: a systematic study of [Fe/α]

Similar chemical signatures between cool & hot gas support the scenario that condensation from hot halo is an important mechanism of cool gas formation in massive ellipticals (at least in the ISM at r < ~ 10 kpc)



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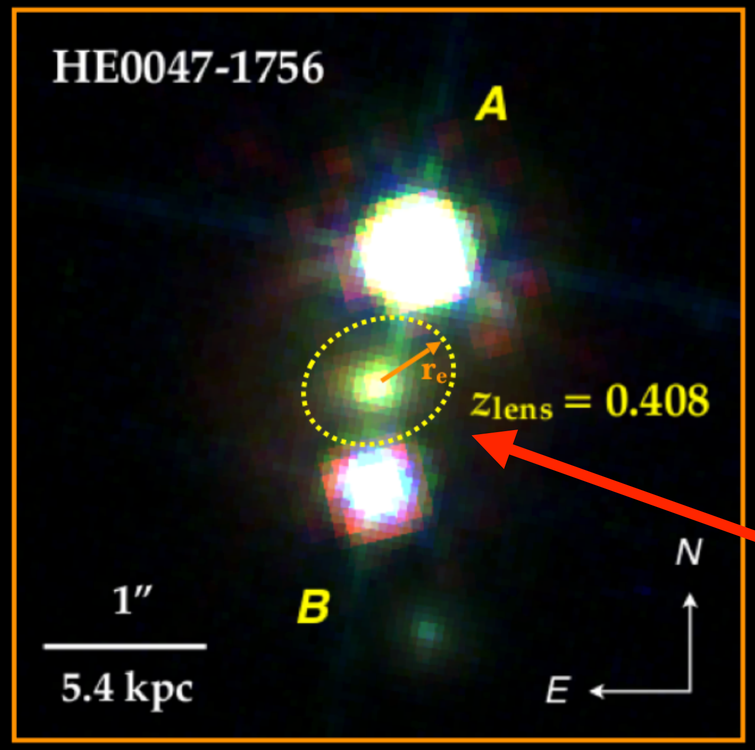
Multiphase ISM in a massive elliptical lens galaxy at z=0.4

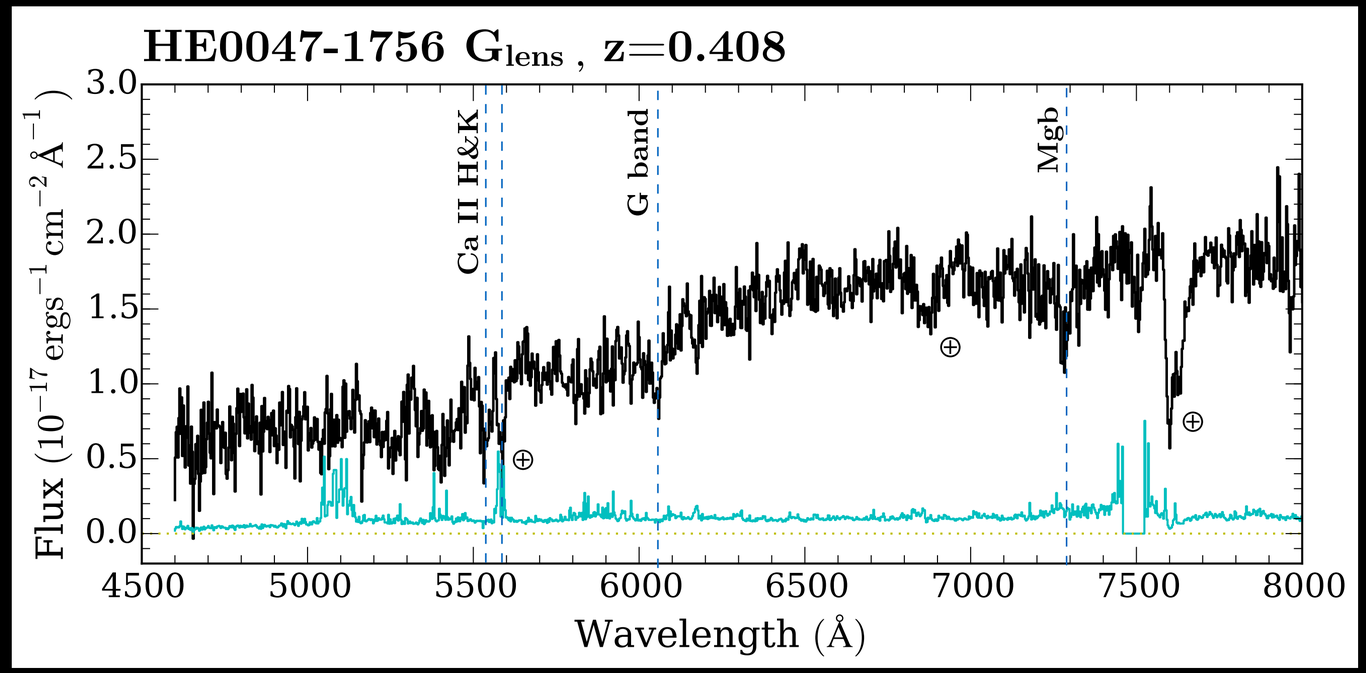


Galaxy properties

Massive ($M_{star} \approx 10^{11}\ M_\odot$)

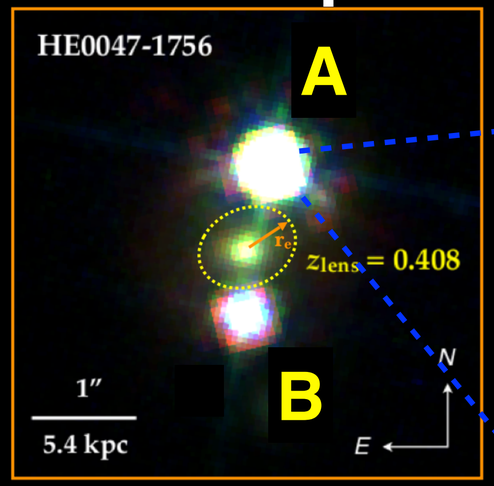
Elliptical (Sérsic index $n \approx 4$)

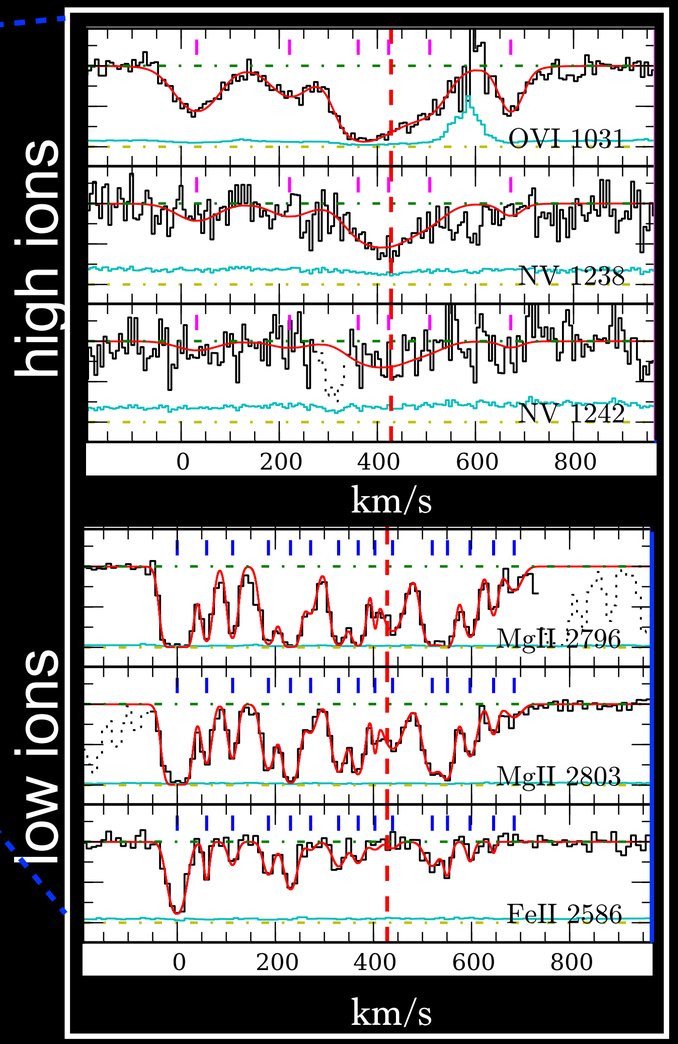
Quiescent (SFR < 0.1 $M_\odot$ yr^{-1})



Zahedy+ (2020a)

Multiphase ISM in a massive elliptical lens galaxy at z=0.4





Gas properties at 4-5 kpc

Plenty of neutral gas

N(HI) ≈ 10^{20} cm^{-2} (both A & B)

Some molecular gas present!

f_{H_2} ~5% (A); <0.1% (B)

Gas is highly enriched

[Fe/H] ~ solar; [Fe/α] > 0.1

Lots of highly ionized gas !

log N(OVI) /cm^{-2} = 15.2

Strong & broad OVI absorption indicates abundant transitional temperature (~10^5 K) gas:

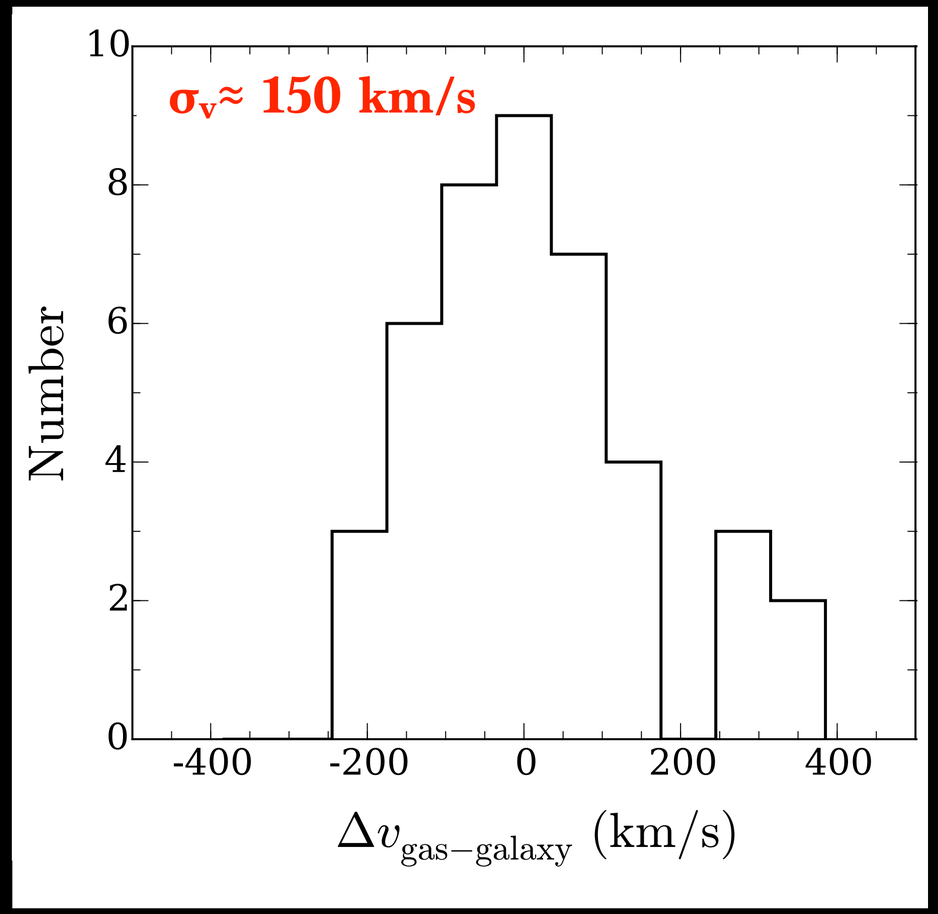
- If radiatively cooling from a hot (~10^6 K) corona, the inferred accretion rate is 0.5-1.5 $M_\odot$/yr .
- The galaxy's lack of star formation (<0.1 $M_\odot$/yr) suggests most of it is returned to the coronal phase, implying a heating rate of ~10^{48} erg/yr within the galaxy.

Zahedy+ (2017b, 2020a)

Suppressed gas velocity dispersion in CGM of ellipticals

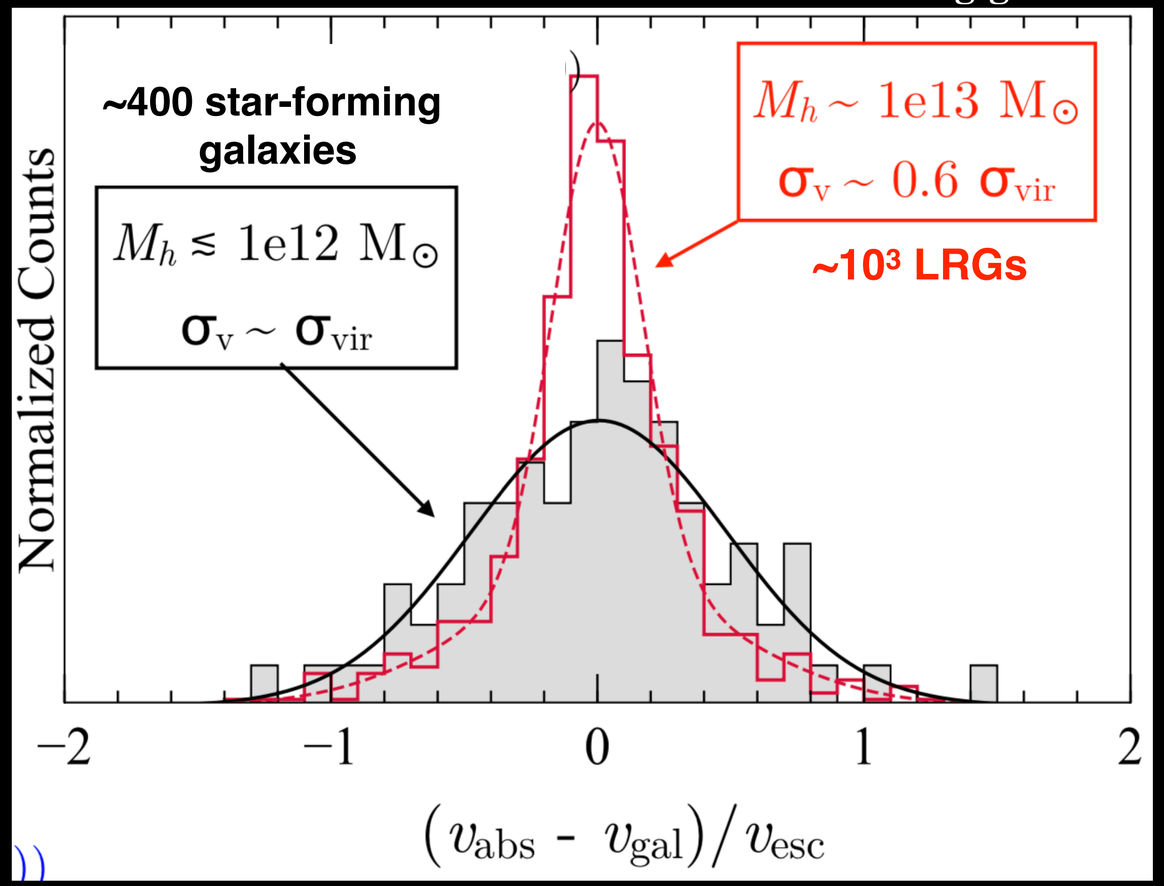
Observed velocity dispersion of cool CGM gas around sub-L* and L* galaxies is consistent with virial motion, but it is sub-virial ($\approx 0.6\ \sigma_{\rm vir\text{-}1D}$) for massive ellipticals with $M_{\rm star} > 10^{11}\ M_{\rm sun}$

COS-LRG



Zahedy et al. 2019a (MNRAS, 484, 2257)

Gas kinematics: LRGs vs lower-mass star-forming galaxies



Huang et al. (2020)

The Gas-rich Halos of Massive 'Red & Dead' Galaxies

Summary

- Massive quiescent galaxies show a high incidence of cool gas on both small (~10 kpc, ISM) and large (~100 kpc, CGM) scales. A typical massive elliptical is surrounded by ~10^{10} $M_\odot$ of ~10^4 K gas, similar to star-forming galaxies.
- On ~10 kpc scale, the ISM has been significantly enriched by SNe Ia, pointing to SNe Ia as a potentially important maintenance/heating mechanism. In contrast, the outer CGM (~100 kpc scale) exhibits a more primitive chemical signature, consistent with gas originating from the intergalactic medium
- While large reservoirs of cool gas exist on ~100 kpc scales around massive ellipticals, interactions with the hot halo likely prevent most cool clouds formed at large distances from successfully accreting into the galaxy.