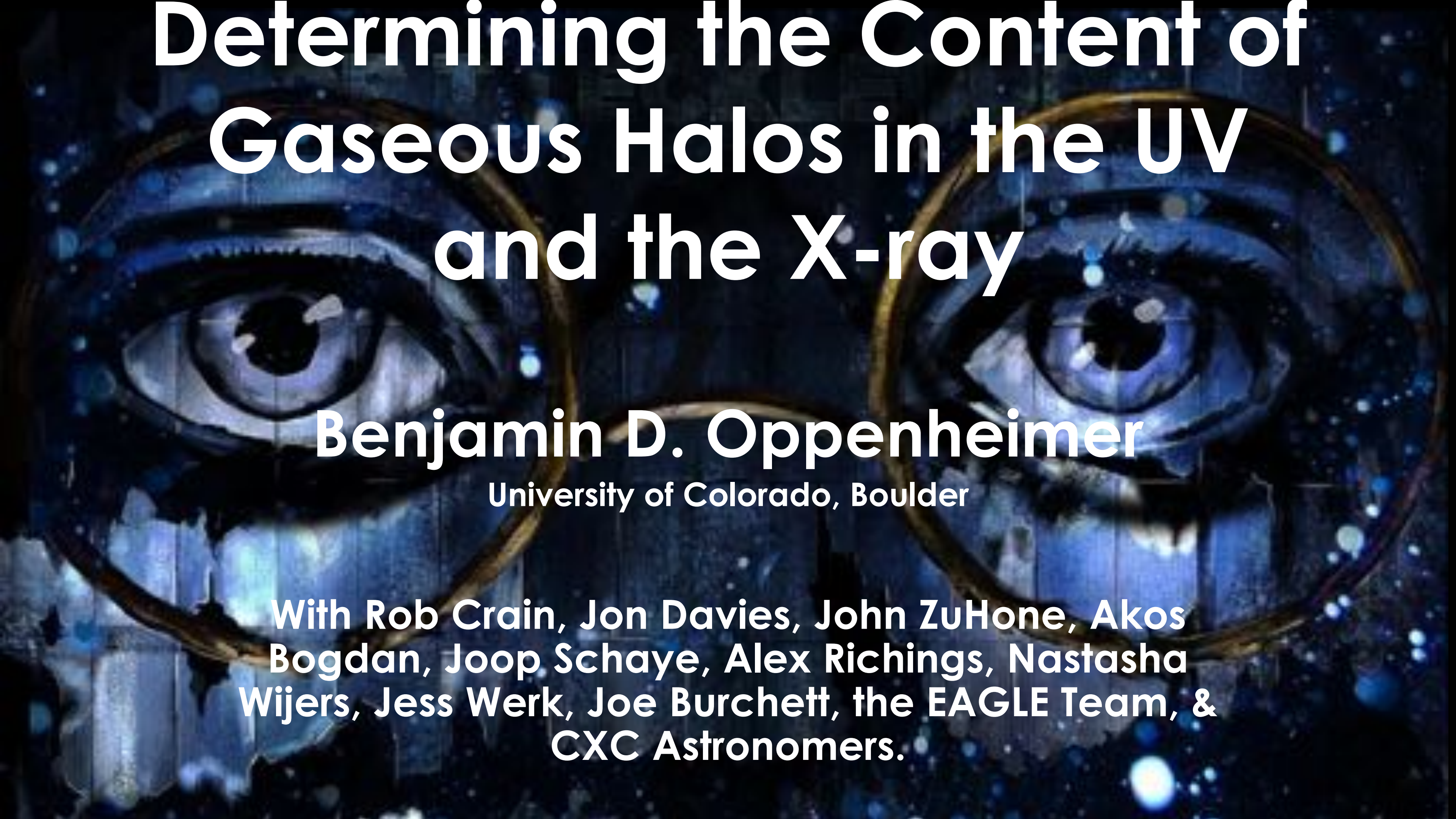


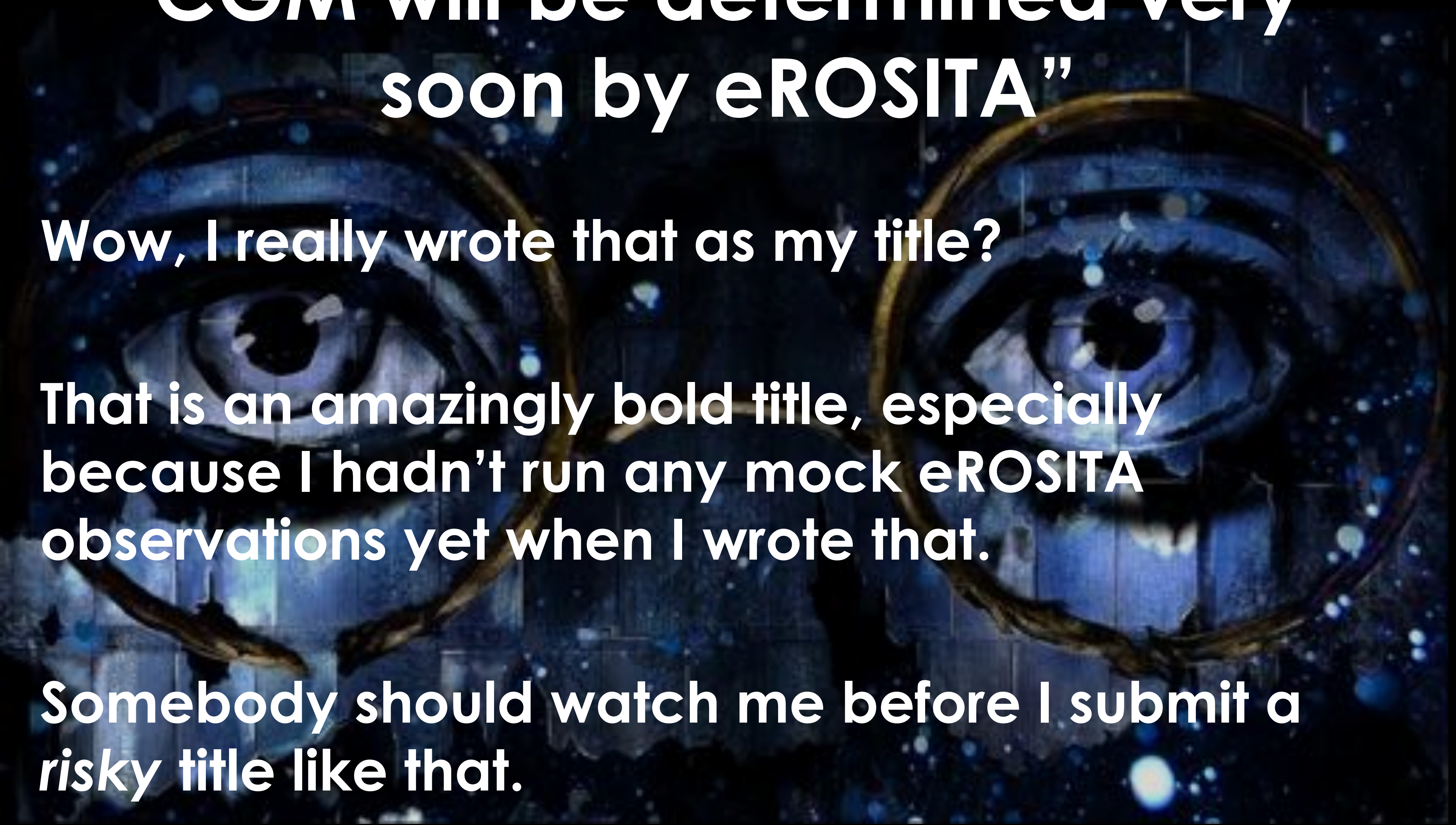
Determining the Content of Gaseous Halos in the UV and the X-ray

Benjamin D. Oppenheimer
University of Colorado, Boulder

With Rob Crain, Jon Davies, John ZuHone, Akos Bogdan, Joop Schaye, Alex Richings, Nastasha Wijers, Jess Werk, Joe Burchett, the EAGLE Team, & CXC Astronomers.

CGM Berlin 2019

Original Title: "The Content of the CGM will be determined very soon by eROSITA"



Wow, I really wrote that as my title?

That is an amazingly bold title, especially because I hadn't run any mock eROSITA observations yet when I wrote that.

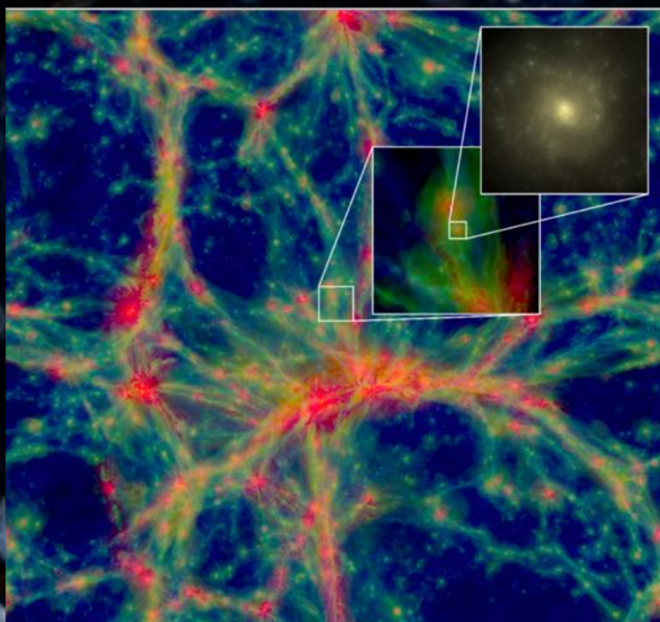
Somebody should watch me before I submit a *risky* title like that.

Who here is worried about LMXB's and HMXB's contaminating your CGM X-ray Emission Signal?

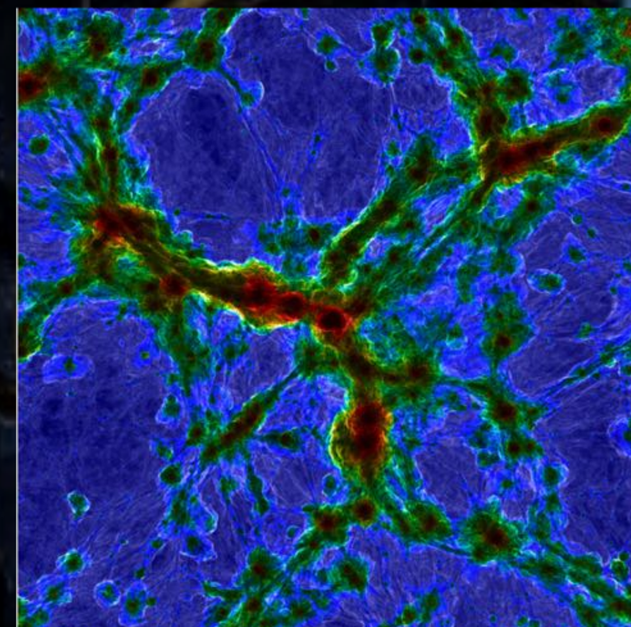
Akos Bogdan (CfA)

Neither is this person.

EAGLE and Illustris-TNG

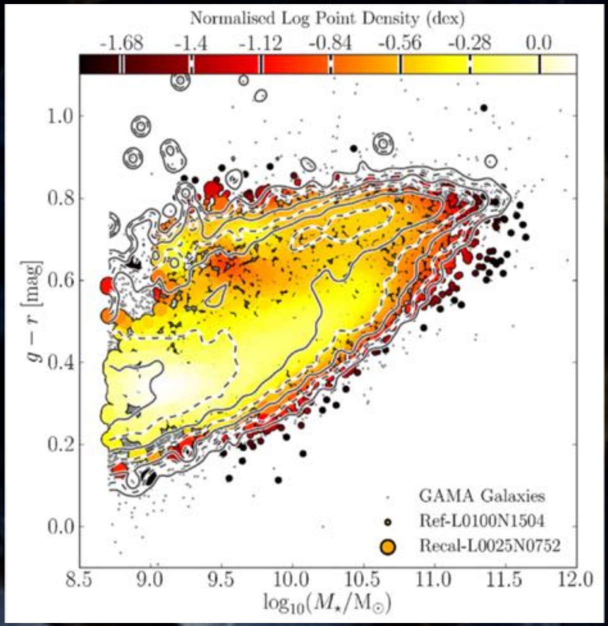


EAGLE- Schaye+ (2015), Crain+ (2015) SPH, 2×1504^3, 100 Mpc box

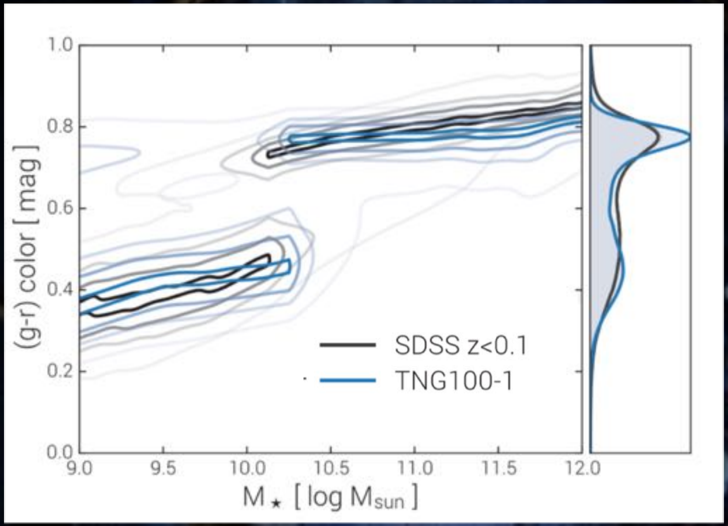


TNG- Pillepich+ (2018), Nelson+ (2018a)
Moving Mesh, $\sim 2 \times 1820^3$, 100 Mpc box

Tuned to match the galaxies in the local Universe.



Trayford+ 2015



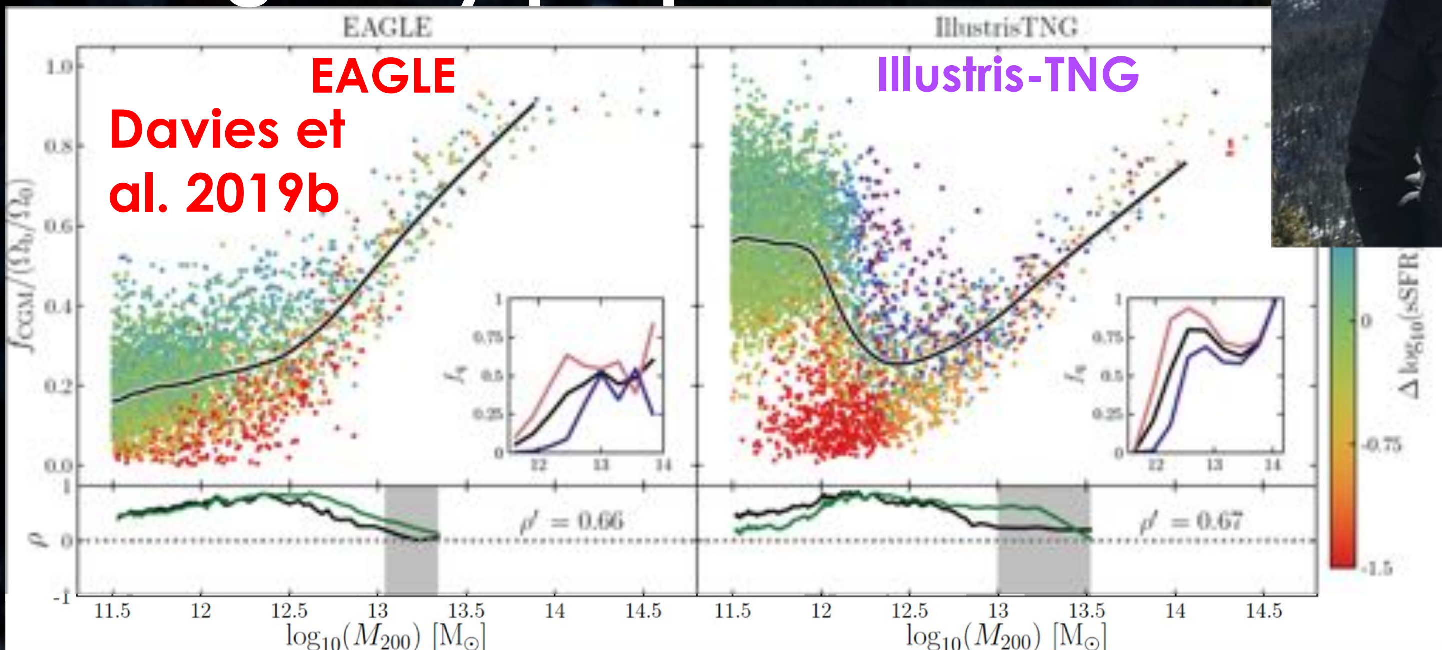
Nelson+ 2018a

Galaxy stellar masses, sizes, and SMBH masses were considered when calibrating subgrid models for stellar and SMBH feedback. See Crain+ 2015, Pillepich 2018

Gaseous observations are more genuine predictions* of the models to make the observed galaxy properties

Jon Davies (LJMU)

f_{CGM}



M_{200} M_{200}

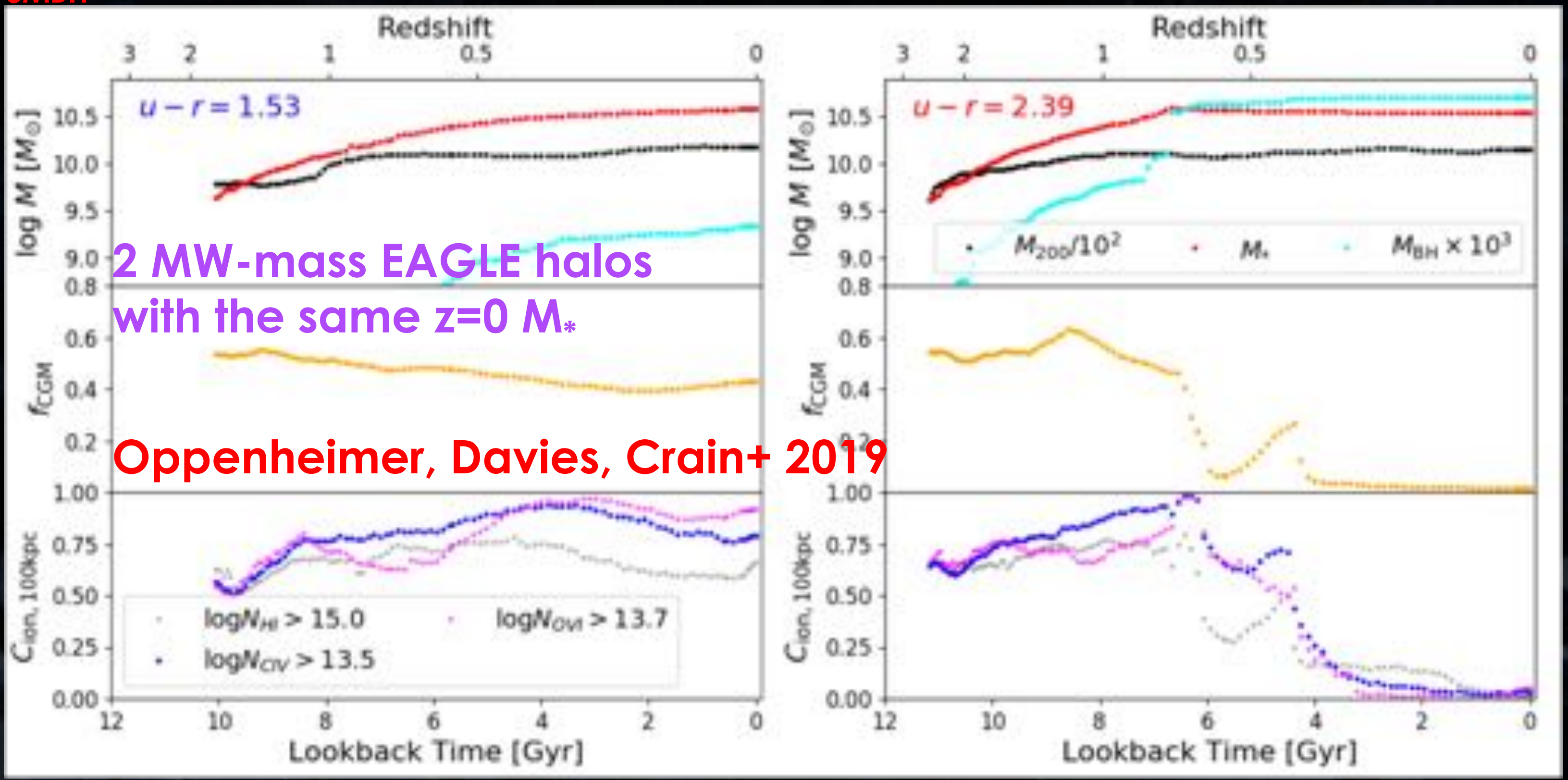
The gaseous content of halos, defined here as f_{CGM}, is highly correlated with galaxy sSFR: less CGM, less accretion and star formation, shown here at z=0.

$$f_{\mathrm{CGM}} \equiv M_{\mathrm{gas}}(R < R_{200})/M_{200}(R < R_{200}) \times \Omega_{\mathrm{M}}/\Omega_{\mathrm{b}}$$

*TNG does apply gaseous baryon constraints of groups (e.g. M_{200}>~$10^{13.5}$ M_{sol}). Pillepich+ (2018)

SMBH Feedback Evacuates Gas from the CGM and Transforms a Galaxy into the Red Sequence

Jon Davies (LJMU) et al. 2019a wrote the original paper finding the CGM-M_{SMBH} anti-correlation in EAGLE



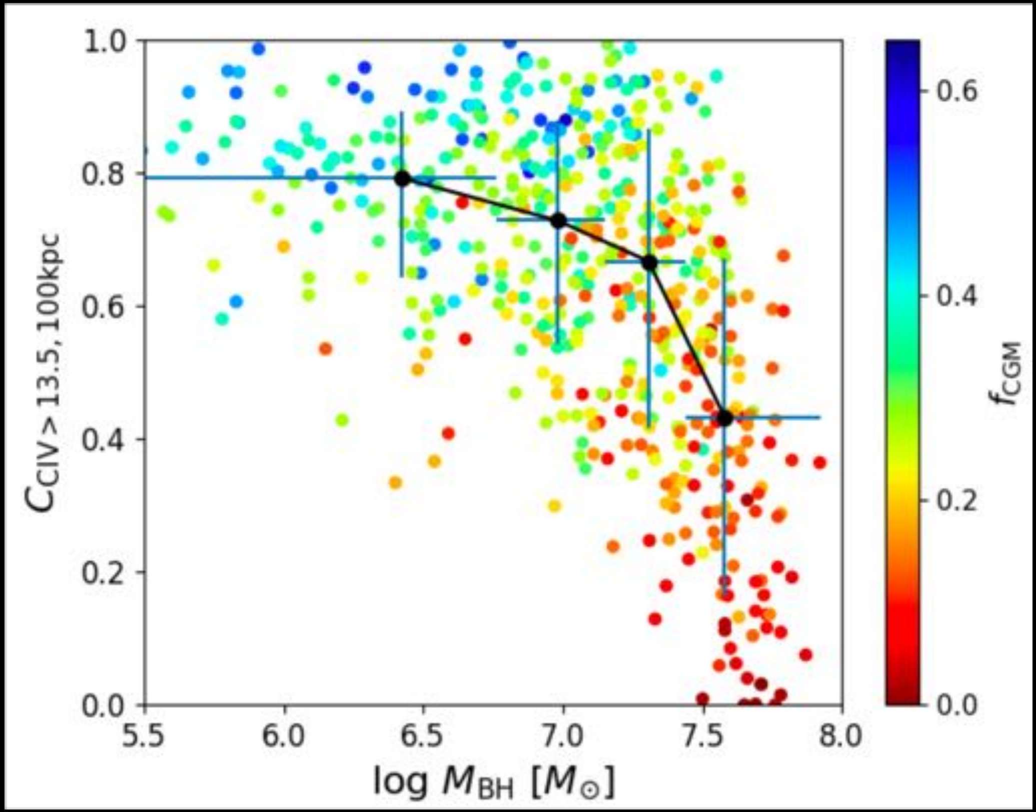
Higher M_{BH} -> More integrated BH feedback -> Capable of unbinding much of the CGM -> Reduced Accretion -> Less Star Formation -> "Quenched" Appearance of a Galaxy

CIV Absorption provides a good proxy for f_{CGM} in the very local Universe.

C IV covering fraction of $10^{13.5}$ cm^{-2} absorbers within 100 kpc declines by a factor of 2.5x from lowest to highest M_{BH} quartile.

f_{CGM} shows the same decline.

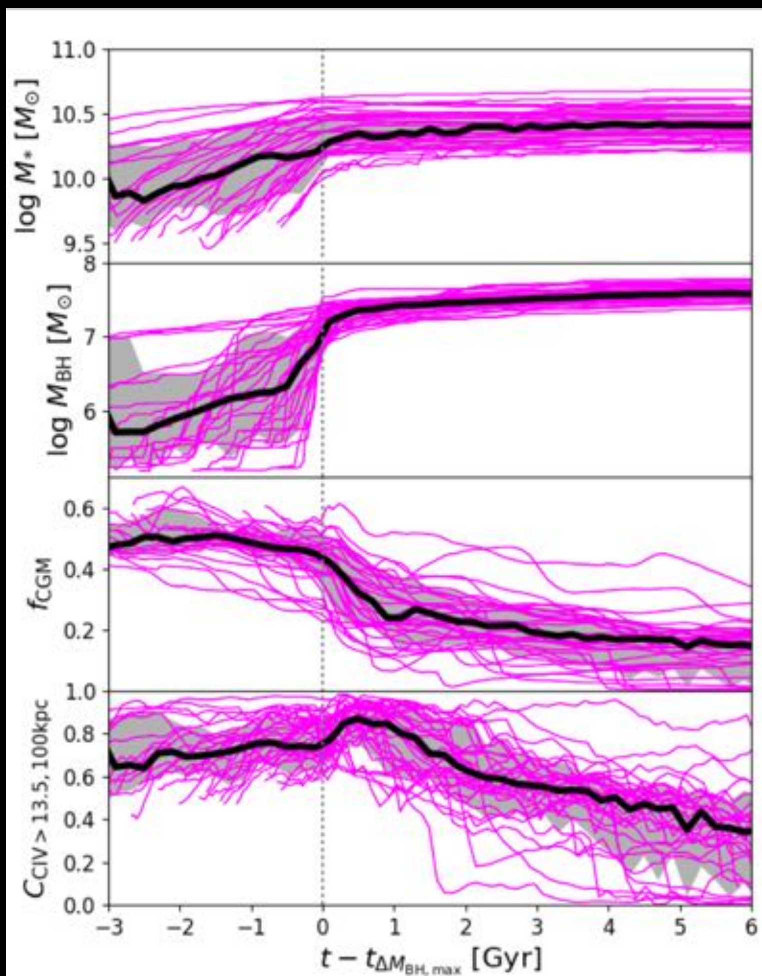
This is enticing because it is observationally obtainable, right Joe Burchett and Jess Werk?

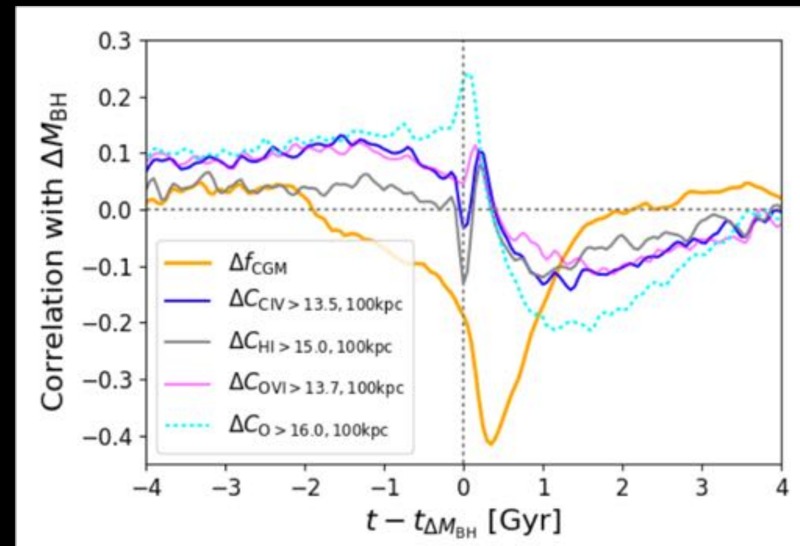


Oppenheimer, B.D.; Davies, Jon; et al. 2019

The CGM immediately reacts to black hole feedback in EAGLE

Deep data dive into 100 TB EAGLE Database

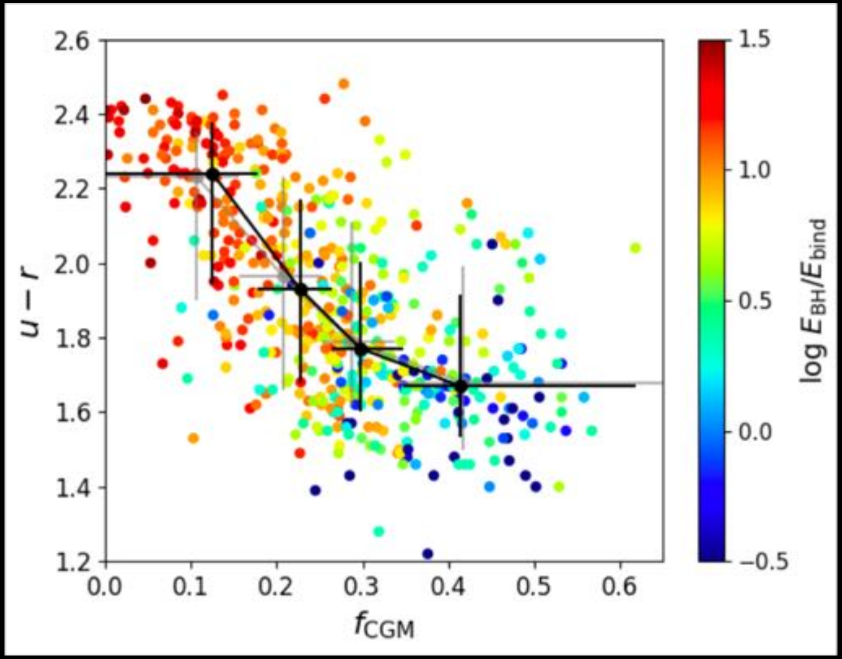




Oppenheimer, B.D.; Davies, Jon; et al. 2019

1) The most massive BH growth phase in a galaxy's history results in 1 Gyr of baryon clearing.
2) Correlating all ΔM_{BH} with CGM properties finds instantaneous (<100 Myr) response with baryon clearing peaking at 300 Myr, but also an short-lived spike in metal enrichment.

A galaxy's color can be a causal result of the CGM gas content.



Oppenheimer, B.D.; Davies, Jon; et al. 2019

3) The reddest quartile of L* galaxies have total CGM masses that are 2.5x lower than the bluest quartile.

2) Baryon lifting is a direct result of integrated SMBH growth.

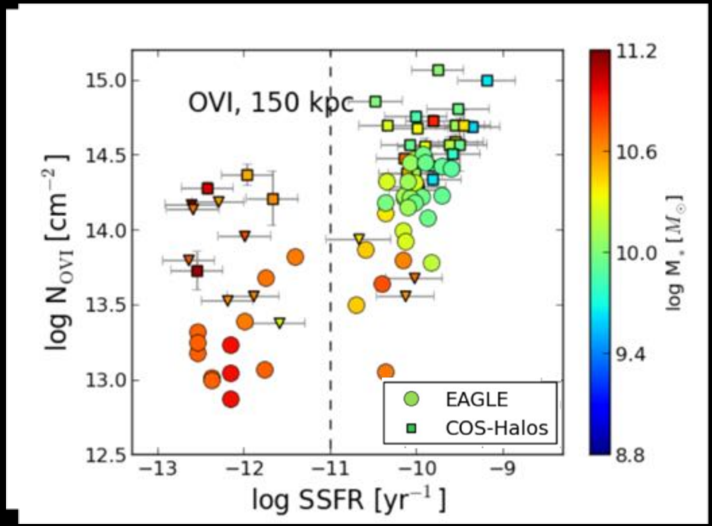
1) Halos hosting massive SMBHs, evacuated CGMs, and red colors are fundamentally different- they have earlier formation times. (Davies+ 2019a)

Davies+ (2019a) also makes soft X-ray emission and thermal Sunyaev-Zel'dovich predictions.

The UV CGM is a crucial test for these models

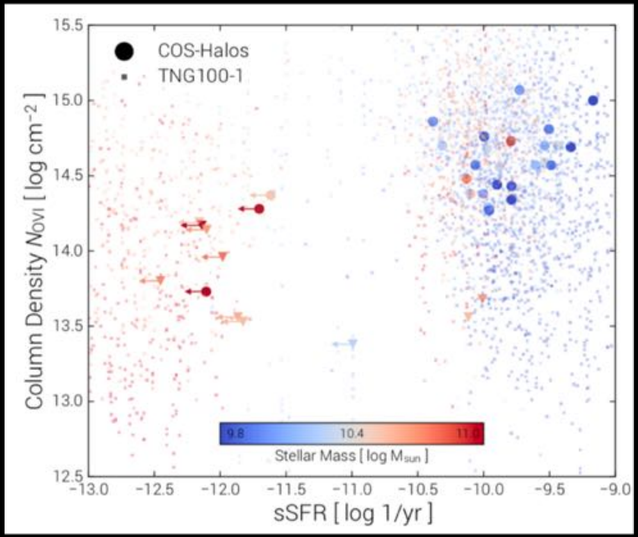
COS-Halos CGM O VI correlation with galactic sSFR at z~0.2 is reproduced using both models.

Oppenheimer et al. 2016



EAGLE-CGM zoom simulations that include higher resolution zooms with non-equilibrium effects. O VI is too weak around star-forming galaxies.

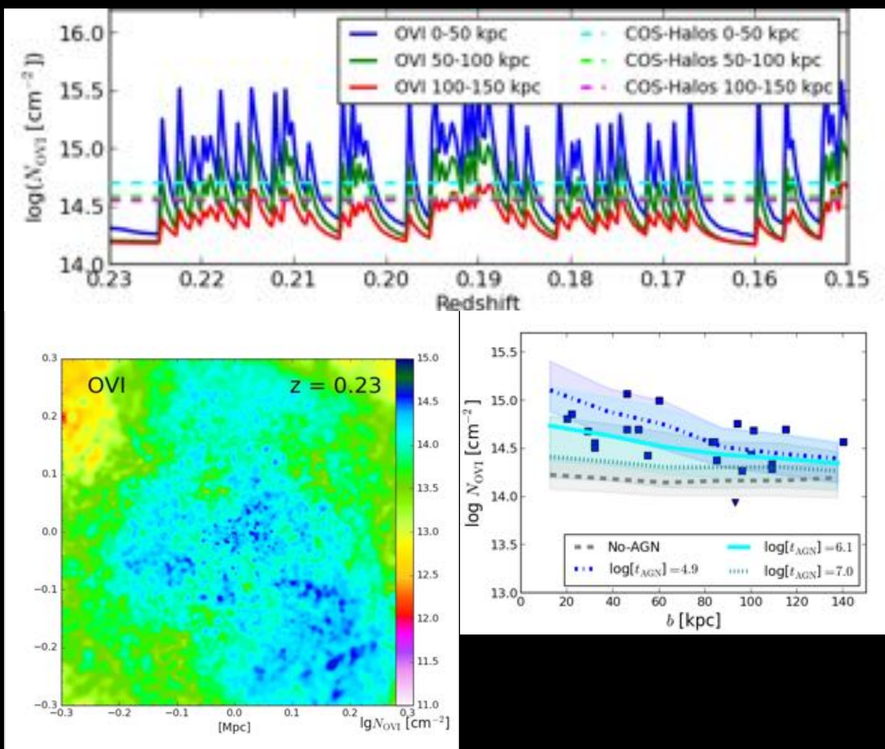
Nelson et al. 2018b



Illustris-TNG fits the observed distribution of O VI column densities. Star-forming and passive galaxies arise in similar mass halos (10^{12} M_{sol}).

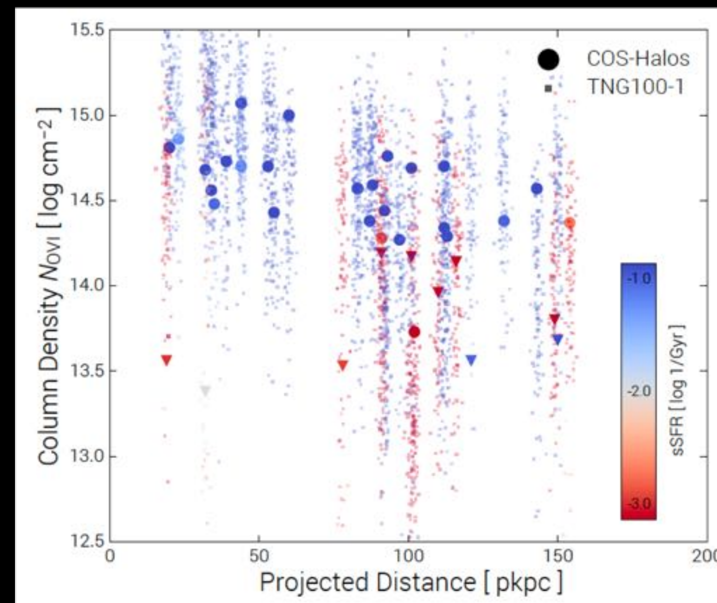
Flickering AGN can enhance O VI if typical SF Galaxies have had AGN episodes in last 10^7 yrs

Oppenheimer et al. 2018a



EAGLE-CGM time-dependent, non-equilibrium ionization effect enhances O VI.

Nelson et al. 2018b



The O VI in TNG rises in the inner 100 kpc in the equilibrium calculation, because there are more warm-hot baryons there.

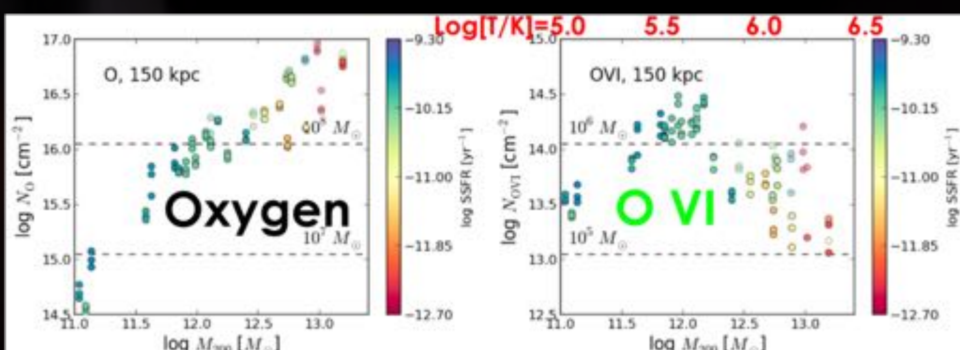
Two Differing Pictures of the Origin of OVI around COS-Halos-like Galaxies?

The EAGLE Picture

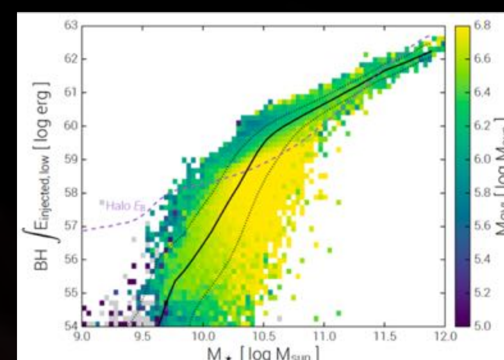
"Virial temperature thermometers" cause O VI to arise in the same halos as star-forming galaxies with $T_{vir}<10^6$ K, but becomes ionized to X-ray ions when $T_{vir}>10^6$ K around more massive passive halos. Oppenheimer+ (2016)

The IllustrisTNG Picture

The O VI properties of galaxy halos changes rather dramatically at a similar halo mass, as baryon clearing by AGN feedback evacuates much of the CGM at around Milky Way halo masses (Nelson+ 2018b). Should predict less CGM around passive galaxies than star-forming galaxies.



Adapted from Opp.+ 2016



Nelson+ 2018b

More Incidental CGM-Galaxy Relation

More Causal CGM-Galaxy Relation

Of course, SMBH baryon clearing happens in EAGLE too (Davies+ 2019a, Opp. 2019a, Davies 2019b), and the virial temperature thermometer effect exists in Illustris and TNG (Suresh+ 2017). However, the CGM properties in the two simulations differ more along the above lines.

eROSITA all-sky survey can stack halos of know locations of galaxies.

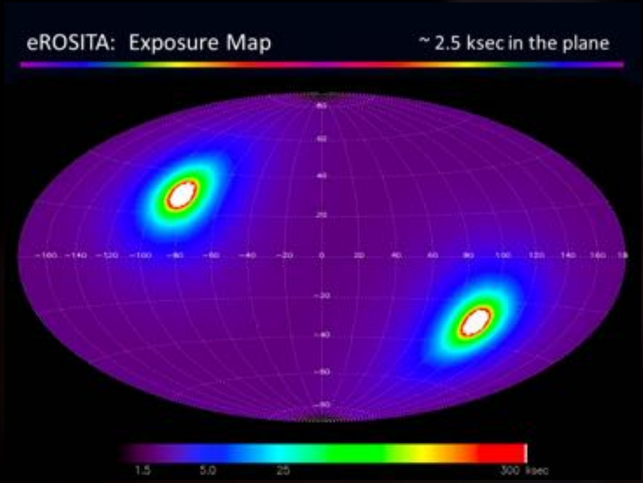
Idea came out of a discussion with Akos Bogdan (CfA). Stack thousands of galaxies. Idea is to stack thousands of z=0.03-0.05 galaxies. Run simulations to make predictions of future stacks.

Over eROSITA's 4 yr mission, it will survey ~2 ksec everywhere in the plane of the sky.

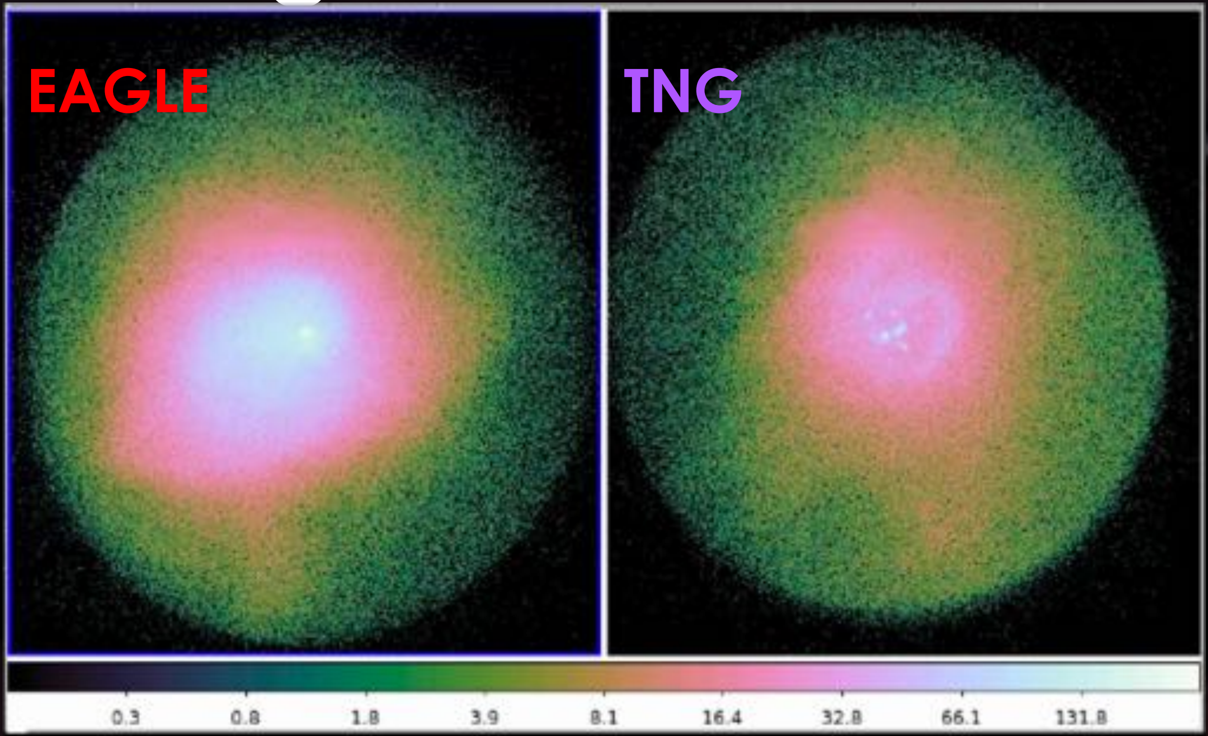
Factor of 30 deeper than ROSAT, 15" angular resolution

Today, I will show z=0.01 stacks from both EAGLE and IllustrisTNG simulations. Hundreds of galaxies, but could be realistic if the whole sky is available at the end of the survey.

EAGLE and TNG have different predictions.



X-ray maps- eROSITA 2 ksec integration of cluster

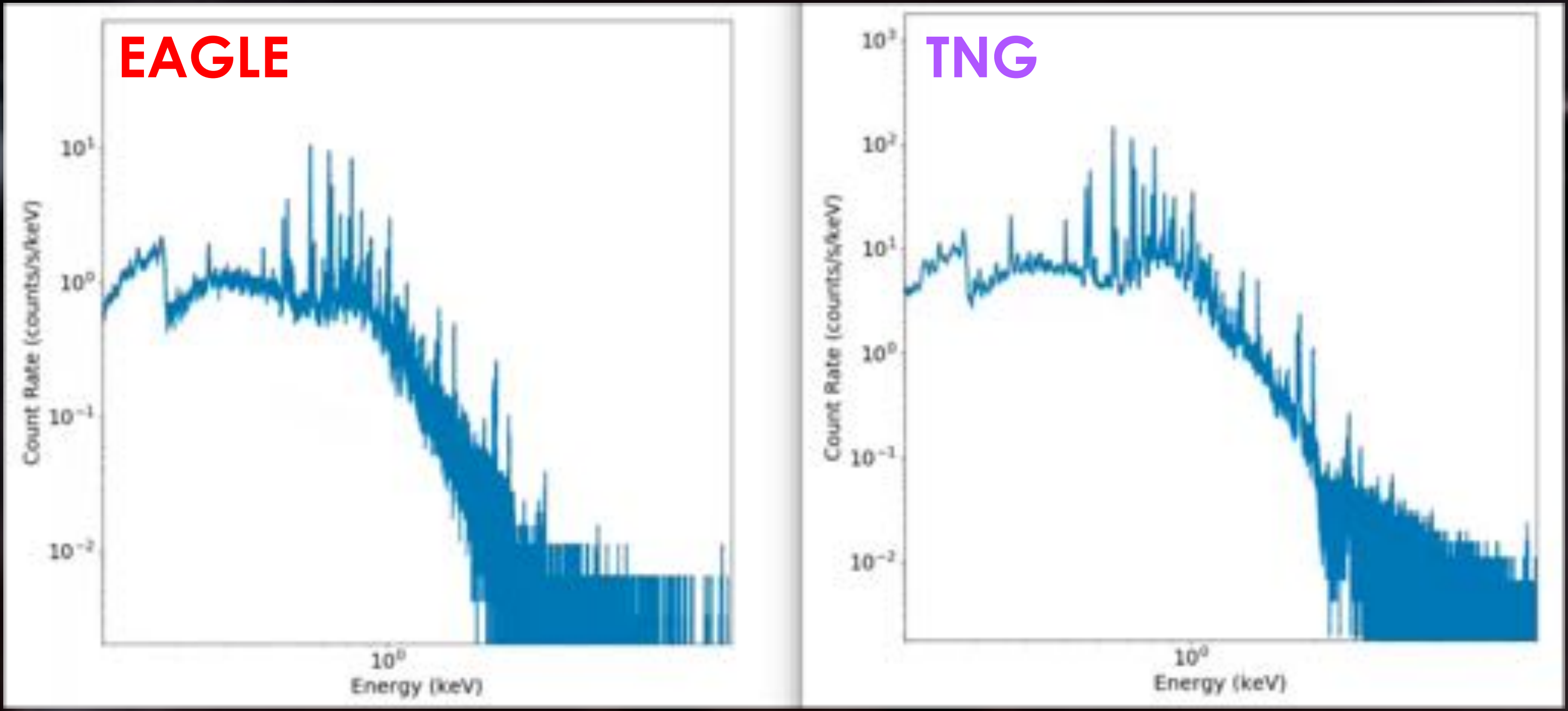


Real Telescope

Left: is not real (yet).

$M_{200} = 10^{14.5}\ M_{sol}$ Load clusters/groups/galaxies into YT, and use pyXSIM to generate mock simput files. Use Sixte to mock eROSITA 2 ksec observations. (Also can use SOXS to create Chandra/Lynx/ATHENA observations).

X-ray maps- eROSITA 2 ksec integration of cluster



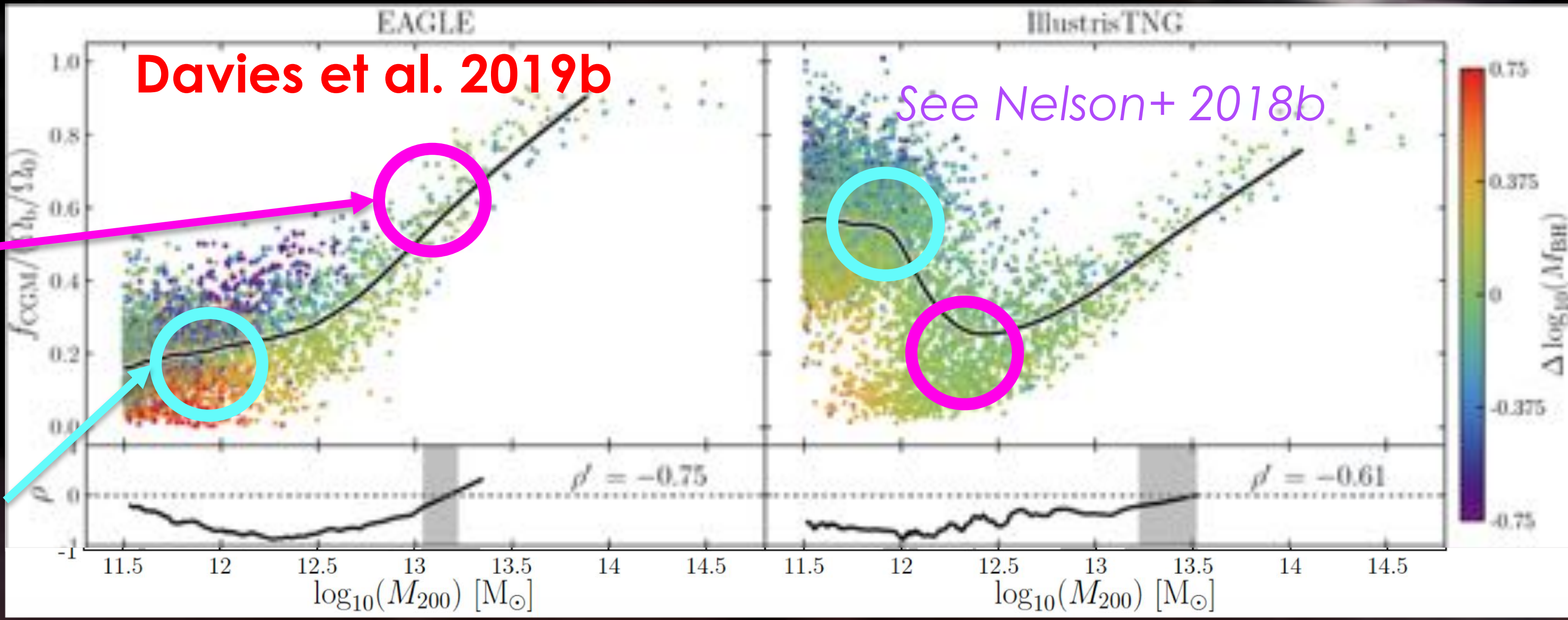
$M_{200} = 10^{13.0}\ M_{sol}$ (spectra with a high resolution spectrometer– not eROSITA)

X-rays can distinguish TNG and EAGLE

Gas content is much higher in star-forming galaxies than passive galaxies in Illustris-TNG, especially in the Milky Way halo mass regime-> *more diverse CGM's at M_{200}~10^{12} M_{sol}*

COS-Halos-like Passive

COS-Halos-like Star-Forming



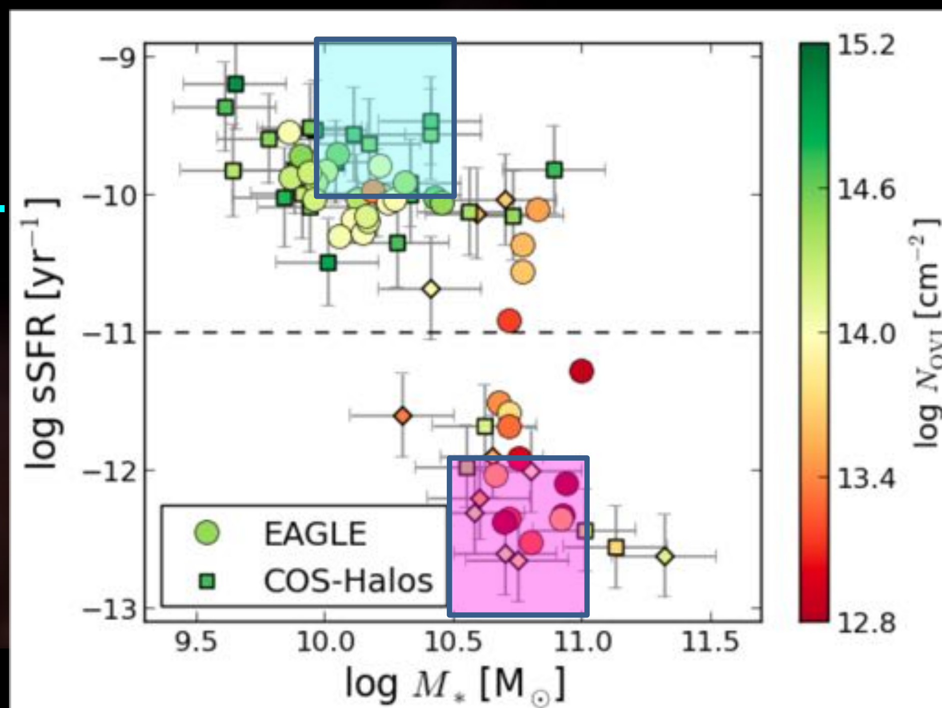
EAGLE's gas content is higher in passive halos that we predict live at higher mass than in Illustris-TNG

An X-ray Experiment we can perform with eROSITA: Stacking COS-Halos-like galaxies to see how star-forming vs. passives X-ray halos appear

Real Telescope

COS-Halos Star-Forming-like

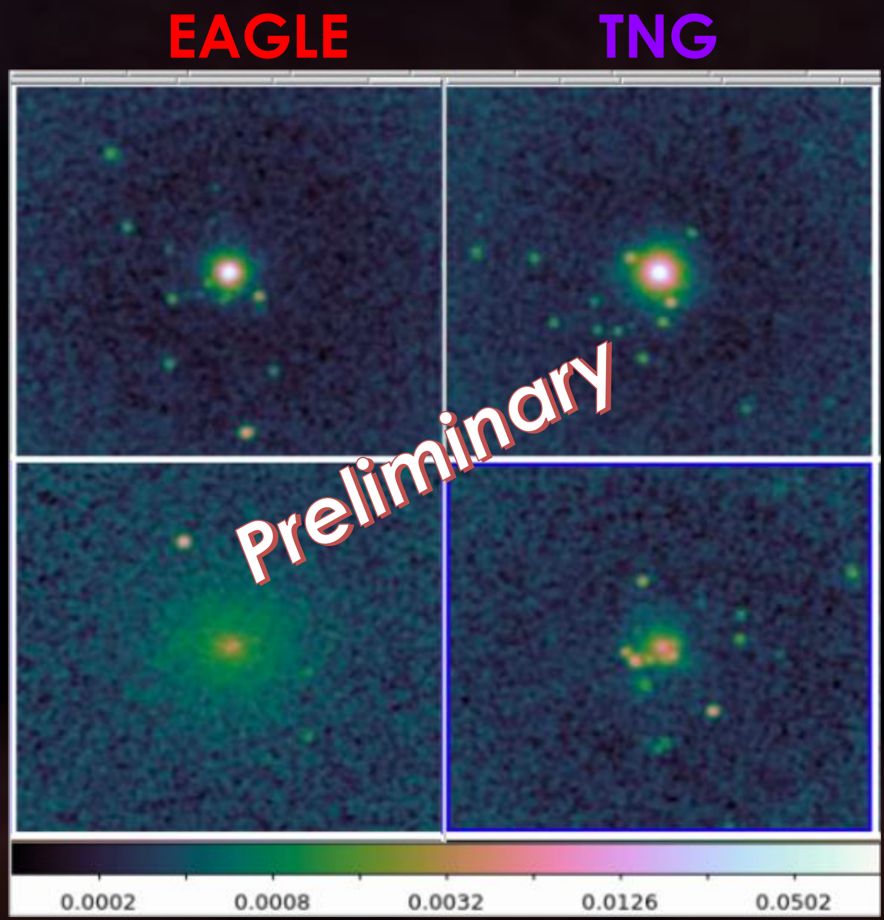
COS-Halos Passive-like



$M_*=10^{10.0\text{-}10.5}$ M_{sol}, sSFR>~10^{-10} yr^{-1}
250 galaxies

$M_*=10^{10.5\text{-}11.0}$ M_{sol}, sSFR<10^{-12} yr^{-1}
150 galaxies

X-ray maps- eROSITA 2 ksec stacks of galaxy halos



COS-Halos Star-Forming-like

$M_*=10^{10.0-10.5}$ M_{sol}, sSFR>~10^{-10} yr^{-1}
250 galaxies

COS-Halos Passive-like

$M_*=10^{10.5-11.0}$ M_{sol}, sSFR<10^{-12} yr^{-1}
150 galaxies

FoV of 300x300 kpc

In EAGLE, passives live at higher halo masses, which should be detectable within a few years with eROSITA. In TNG: CGMs more effectively cleared by SMBHs around passive galaxies, which live at lower masses.

Summary: Focused on Q2- How are galaxies, gas flows, and the CGM related?

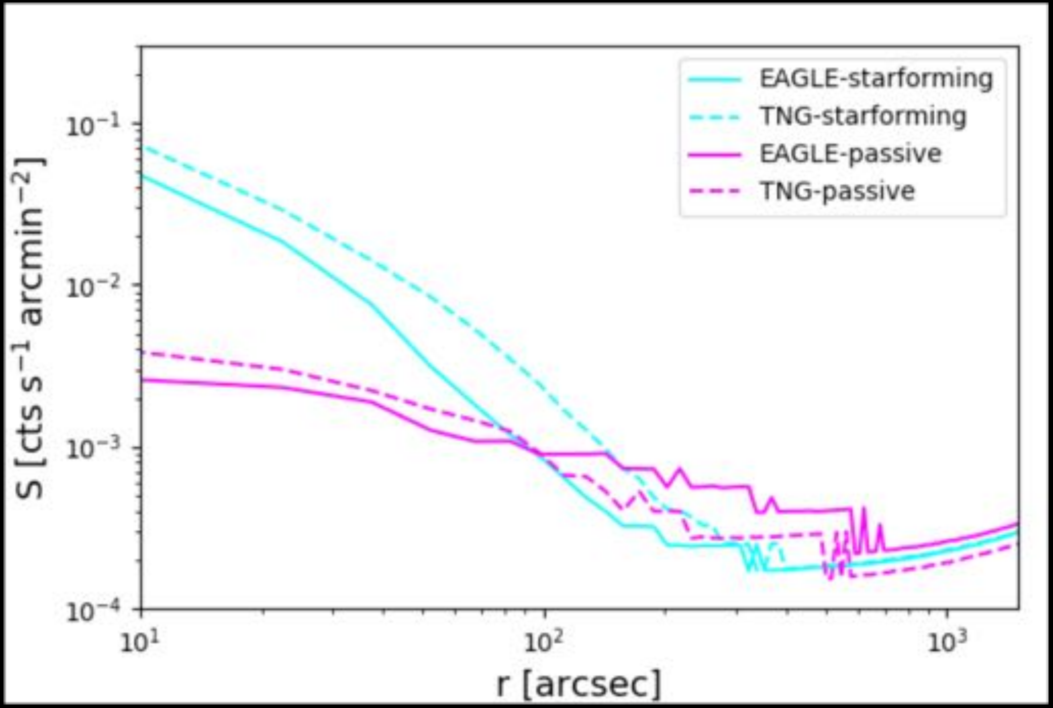
1) **Two sets of simulations predict the content of the CGM is anti-correlated with the mass of the central black hole.**

2) AGN feedback can immediately clear gas from the CGM beyond R_{200} on <100 Myr timescales.

3) Detections of hot halos in the X-ray can determine what type of halos star-forming and passive galaxies live in. eROSITA appears to possess the ability to do this in a few years. CIV is also predicted to be a great tracer of CGM gas content.


Rab

eROSITA stacks of 240 galaxies in low-mass bin: X-ray luminosity scales with sSFR for both EAGLE and TNG



EAGLE

TNG

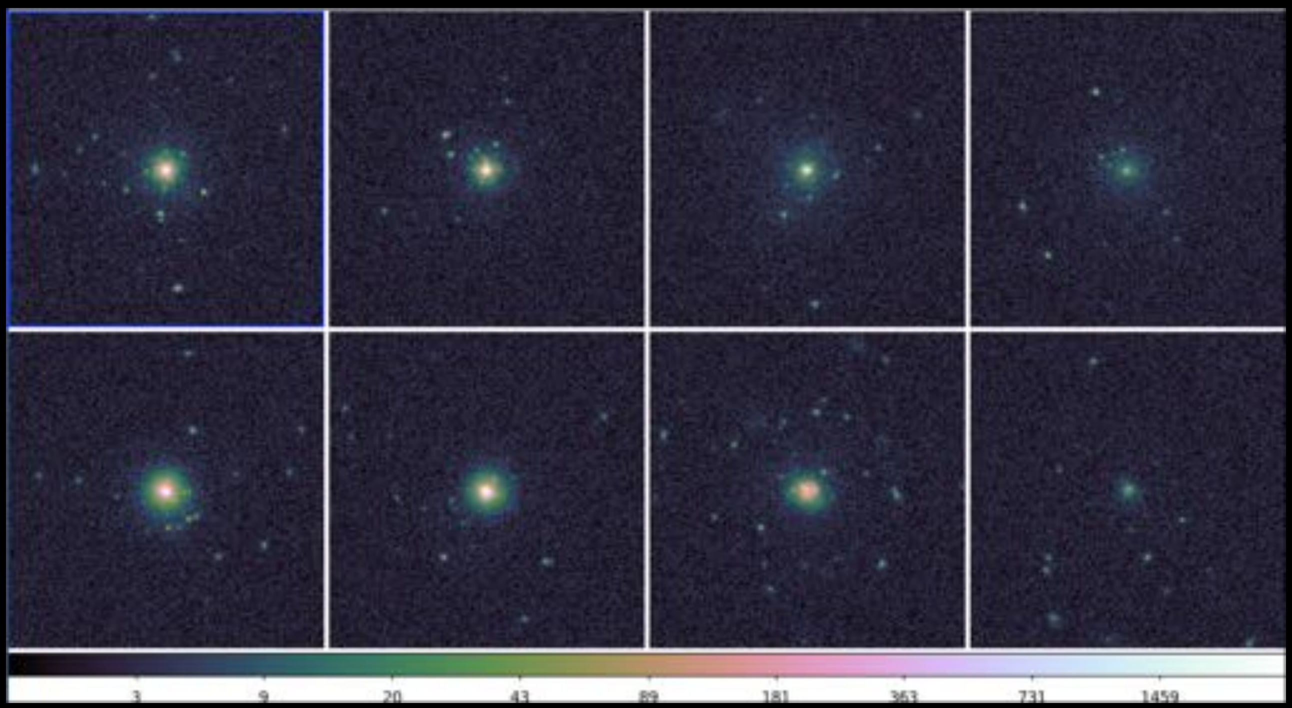
$M_* = 10^{10.2\text{-}10.7}\ M_{sol}$

eROSITA stacks of 240 galaxies in low-mass bin: X-ray luminosity scales with sSFR for both EAGLE and TNG

Highest sSFR 2nd sSFR Quartile 3rd sSFR Quartile Lowest sSFR

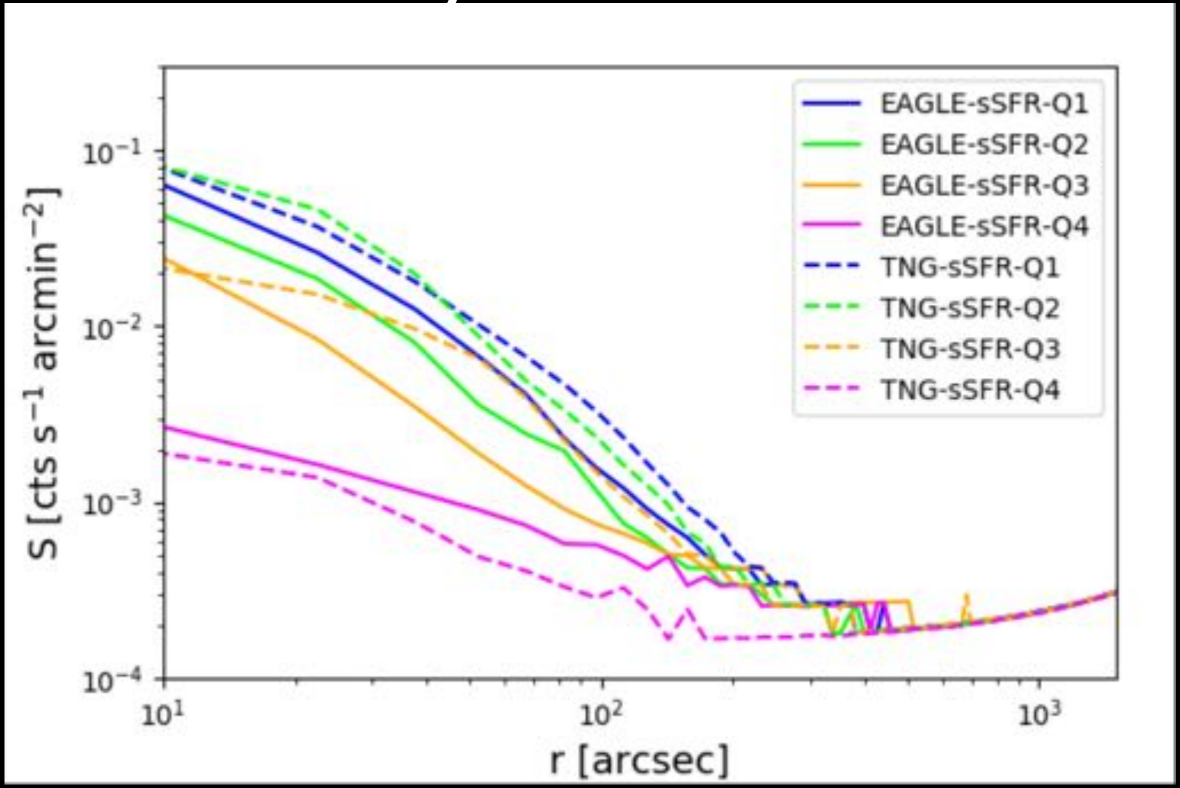
EAGLE

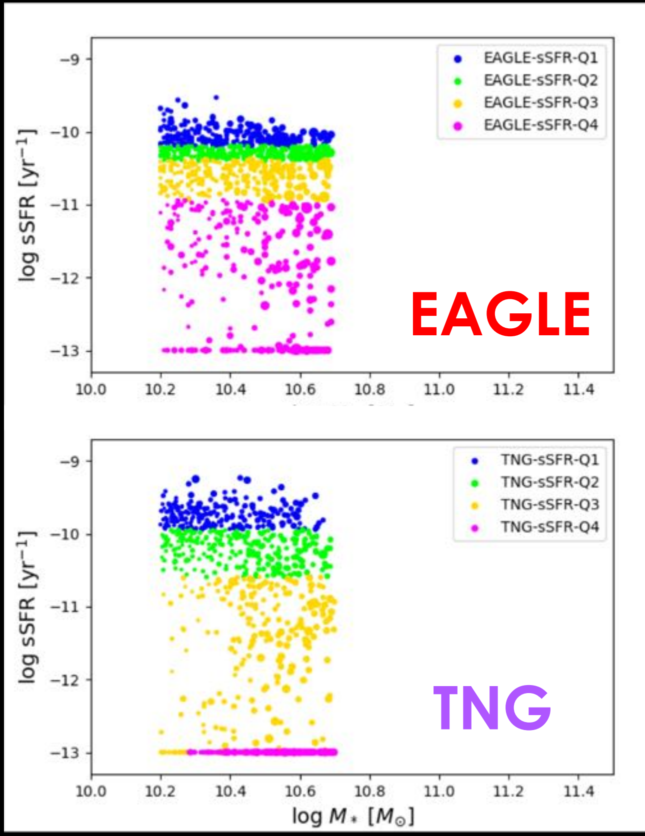
TNG



$M_* = 10^{10.2\text{-}10.7}\ M_{sol}$, 530 kpc FoV, z=0.01

eROSITA stacks of 240 galaxies in low-mass bin: X-ray luminosity scales with sSFR for both EAGLE and TNG





$M_* = 10^{10.2\text{-}10.7}\ M_{sol}$