# ILLUMINATING THE PHYSICAL PROCESSES OF GALAXY EVOLUTION WITH THE COSMIC MICROWAVE BACKGROUND


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with
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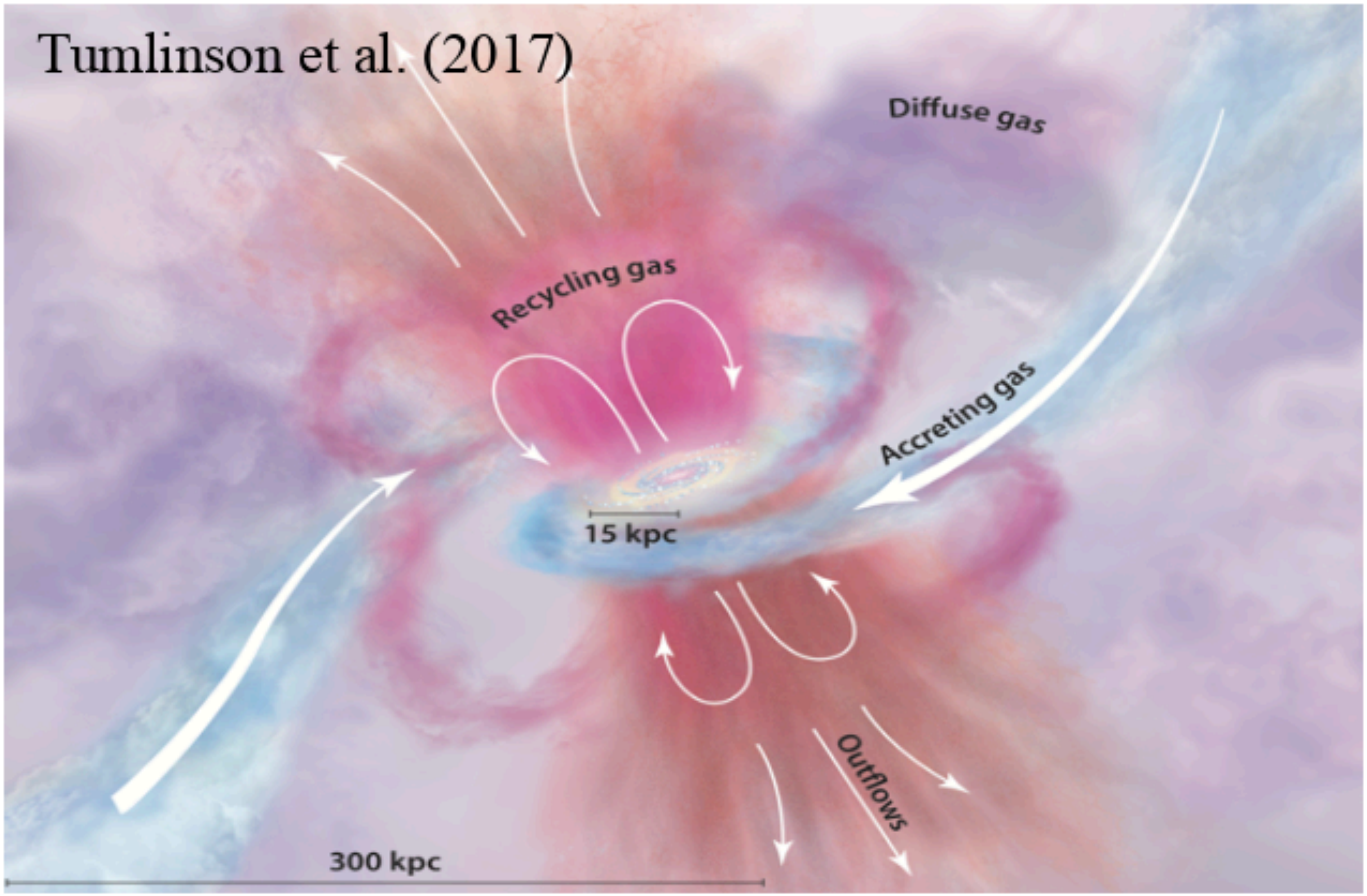
Colin Hill (Columbia, Flatiron)
David Spergel (Simons Foundation)
& the ACT Collaboration

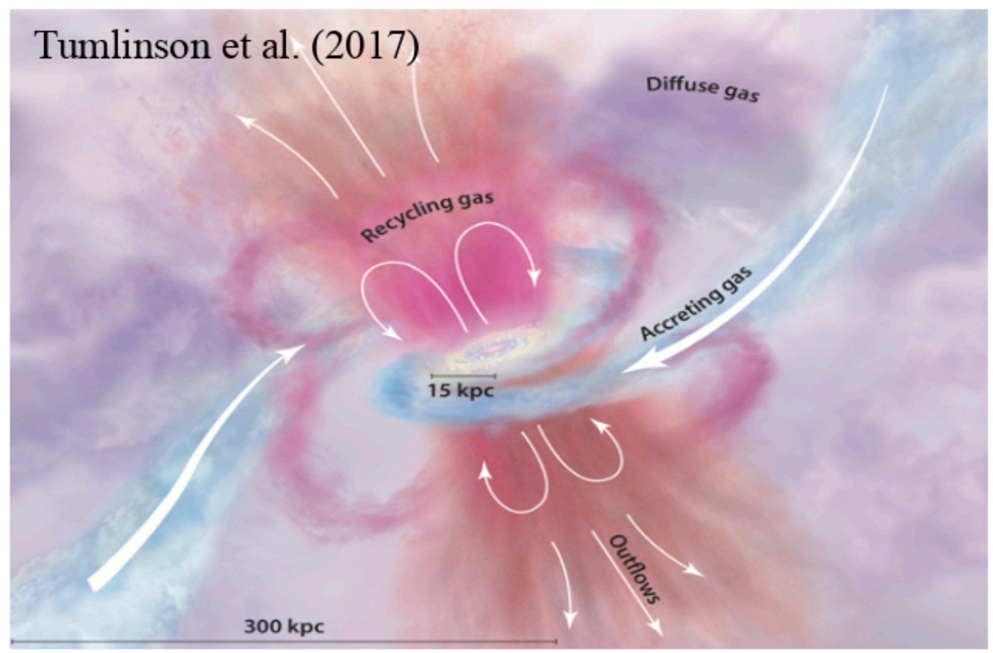

mmUniverse June 30 2023

# The Circumgalatic Medium (Cosmic Ecosystems)




The CGM and IGM contain 90% of all cosmic baryons; they are a key ingredient of galaxy formation and their properties reflect the physics of feedback.

# The Circumgalatic Medium (Cosmic Ecosystems)

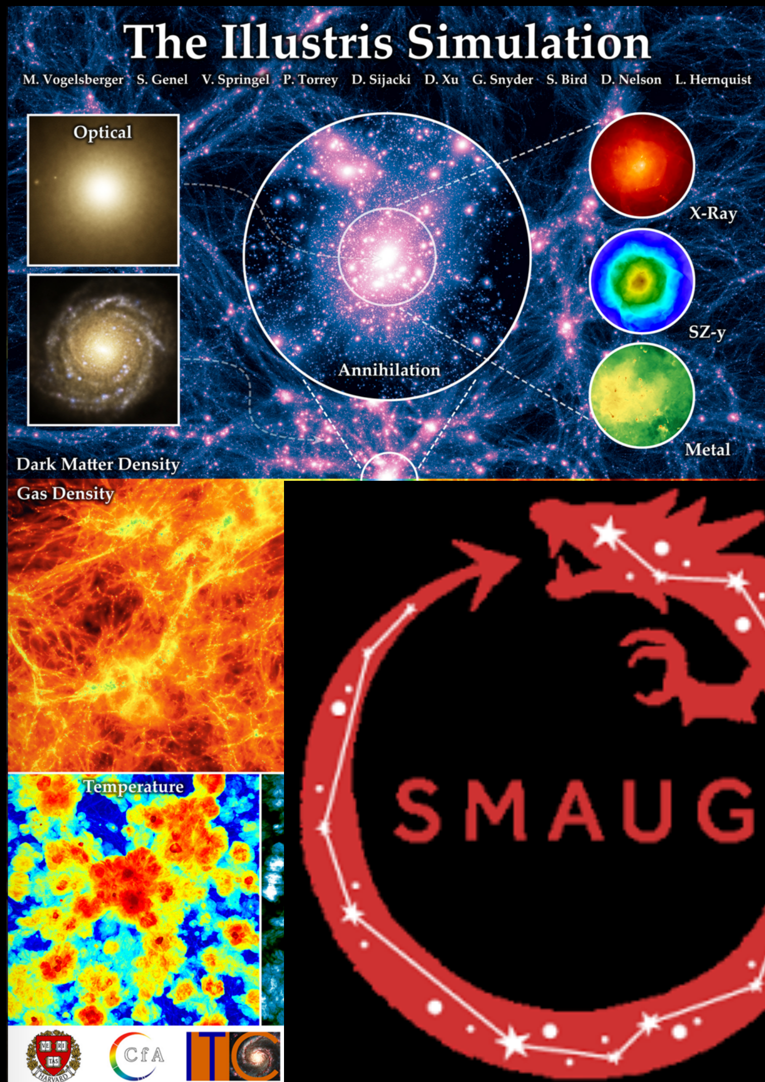



The CGM and IGM contain 90% of all cosmic baryons; they are a key ingredient of galaxy formation and their properties reflect the physics of feedback.

**Outer CGM**

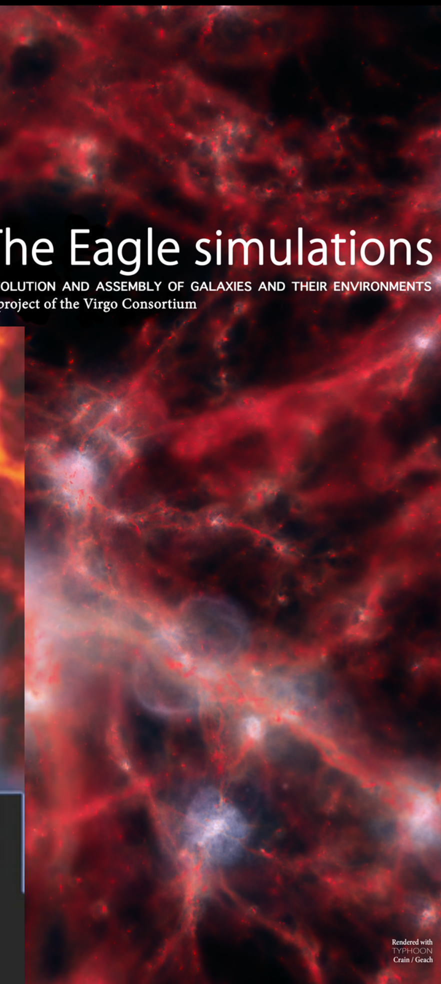
**IGM**

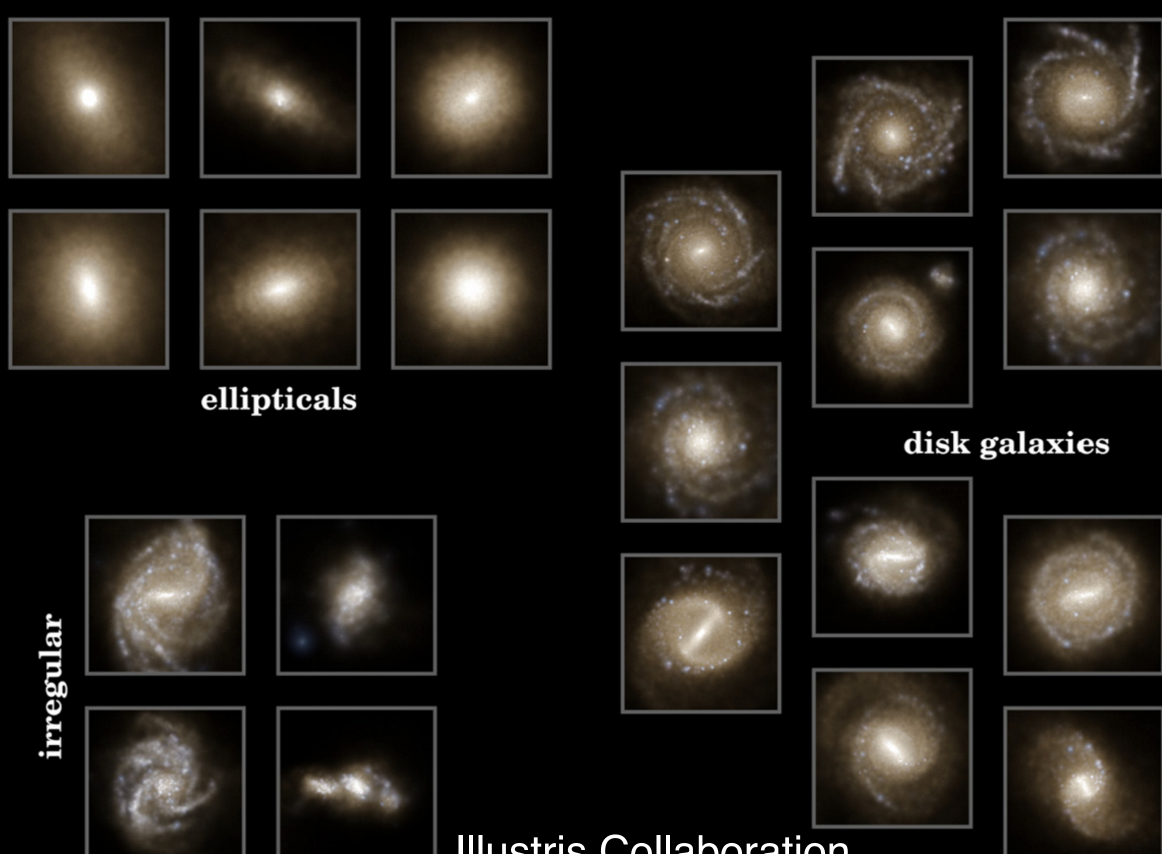
# Cosmological Simulations




SMAUG

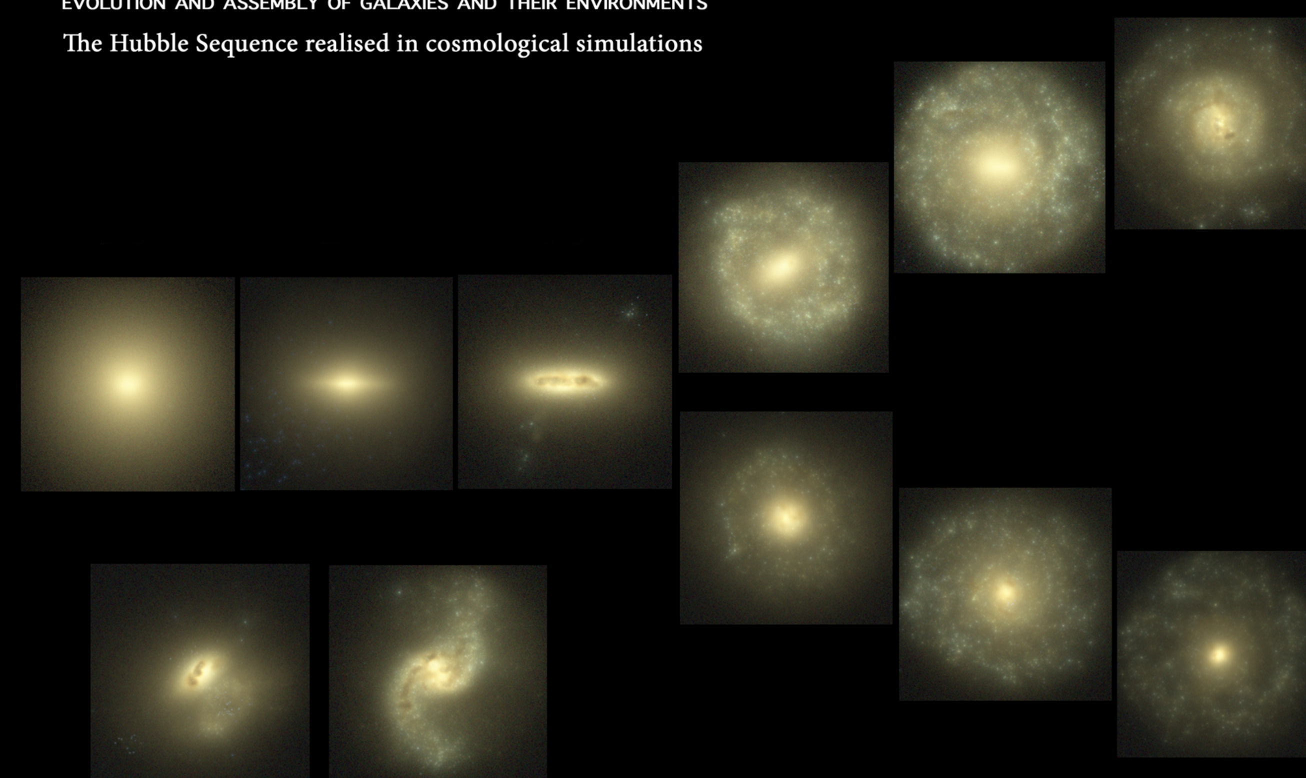



Illustris Collaboration

The Eagle Simulations
EVOLUTION AND ASSEMBLY OF GALAXIES AND THEIR ENVIRONMENTS
The Hubble Sequence realised in cosmological simulations

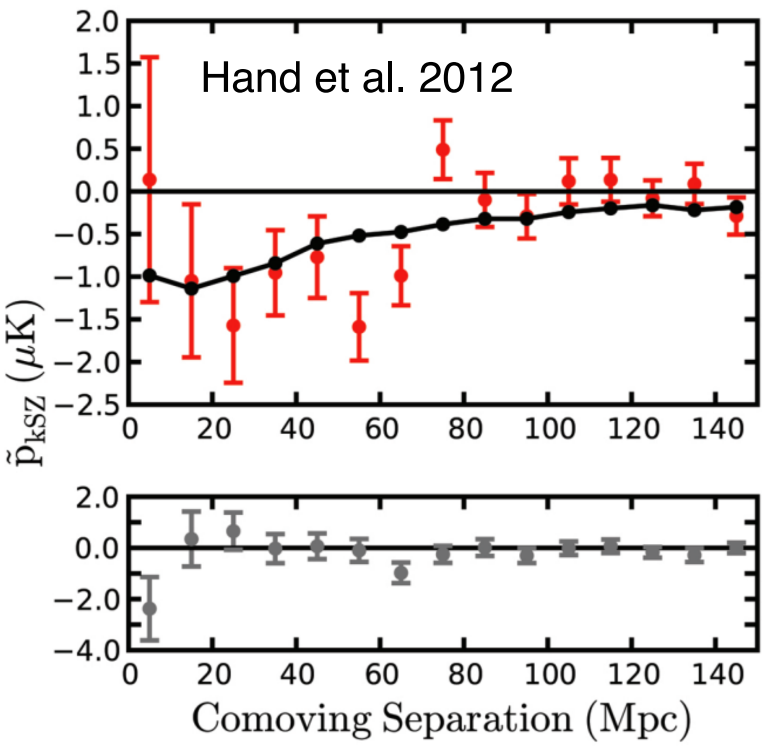


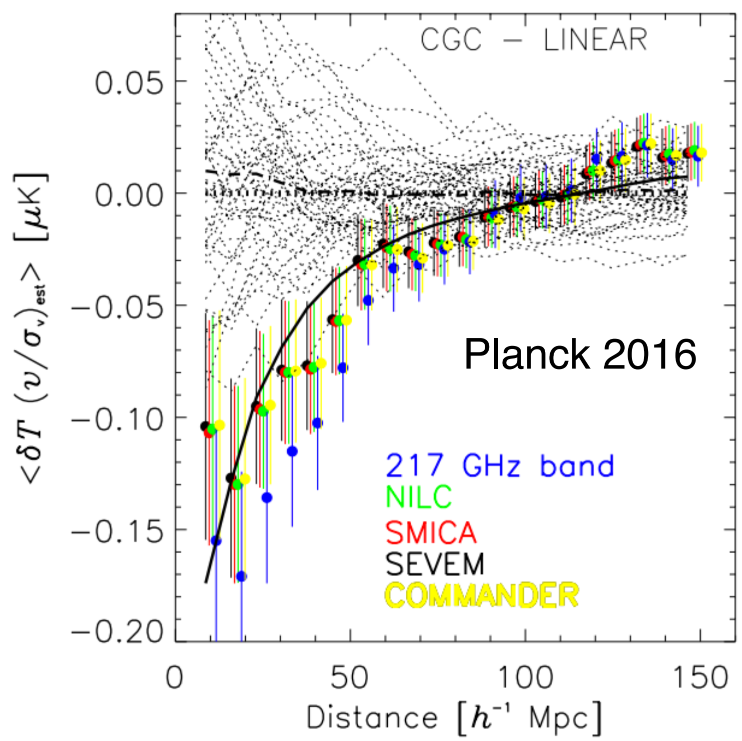
New observational window into the thermodynamic properties of the outer Circumgalactic Medium

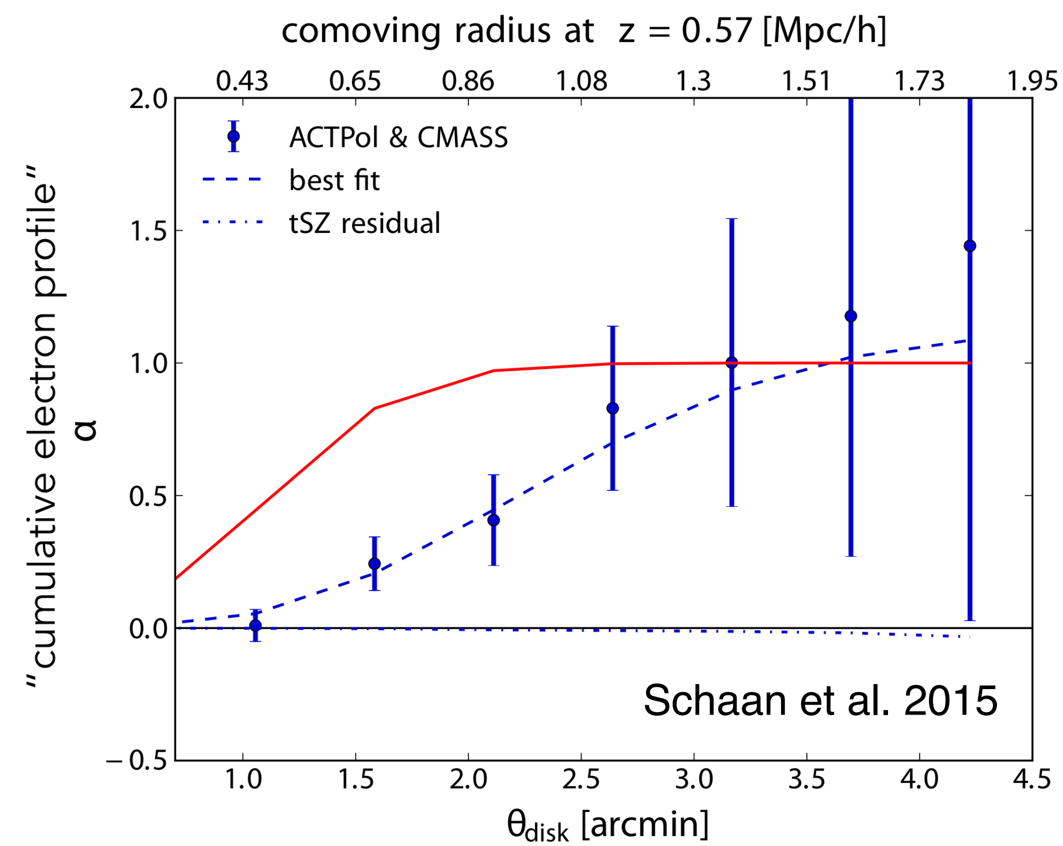
Feedback Processes

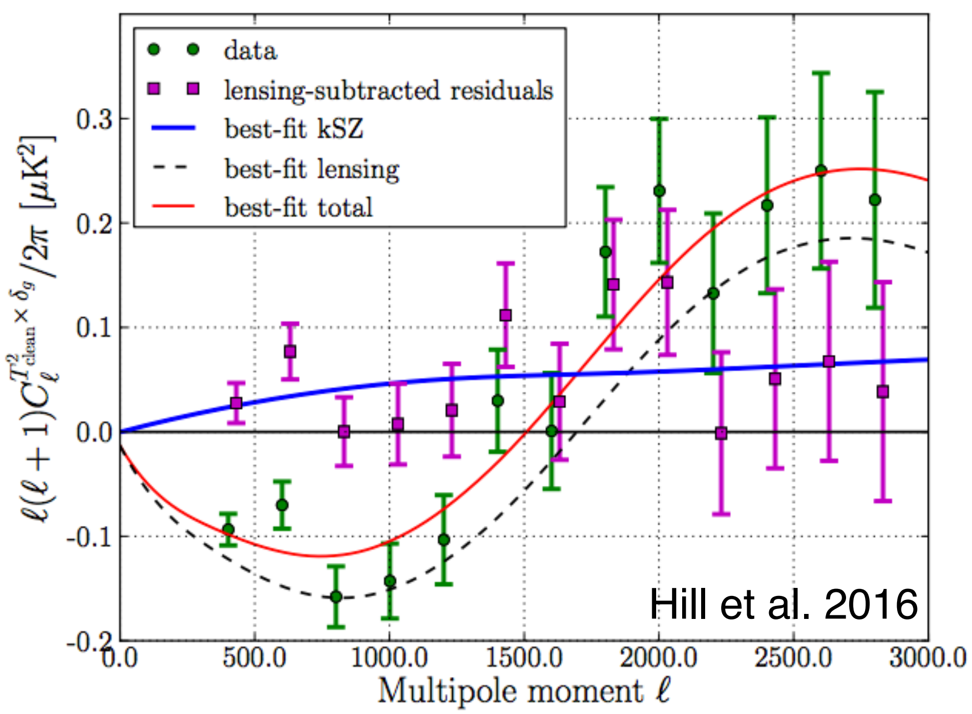
Numerical Simulations

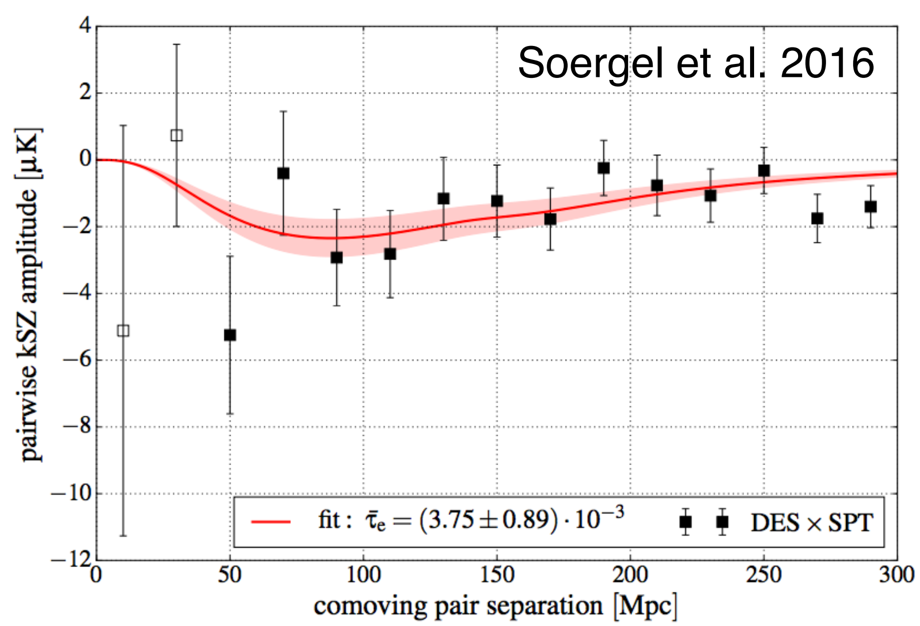
# Emergence of kSZ cross-correlation detections

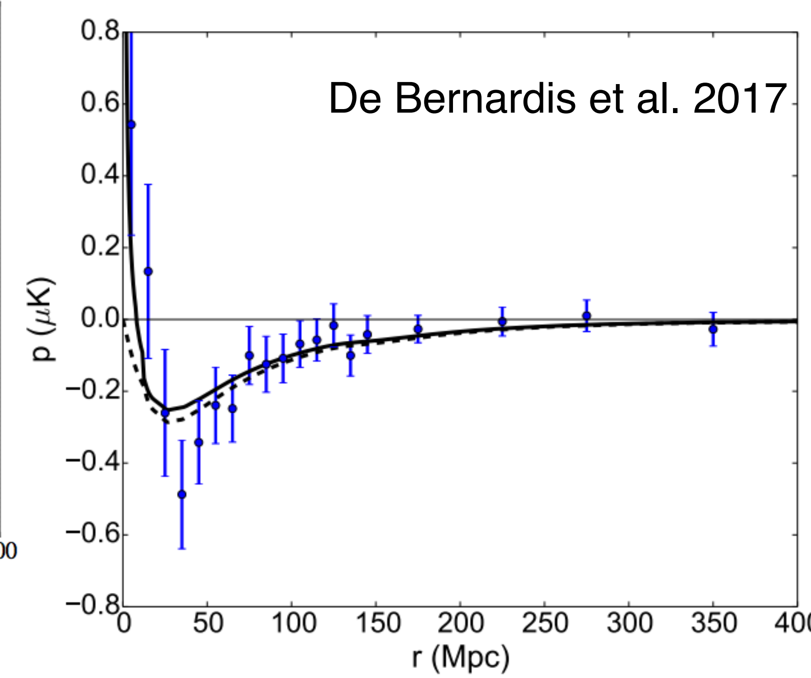


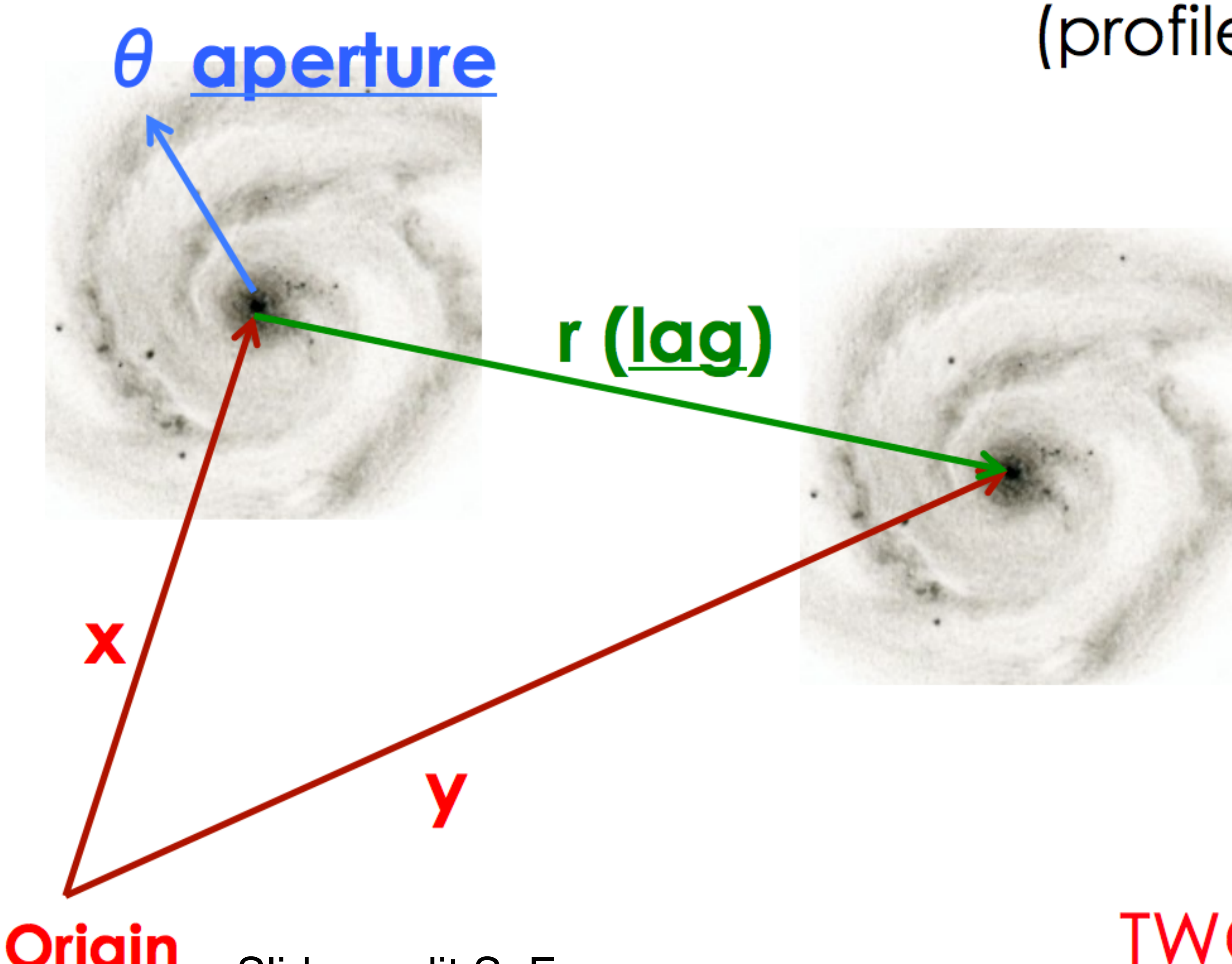

Update: Calufut et al 2021, Tanimura et al. 2022, Mallaby-Kay et al 2023

# What is measured in kSZ cross-correlations?

$$\left(\frac{\Delta T}{T}\right)_{\mathrm{kSZ}}(\mathbf{x}+\boldsymbol{\theta}) = -\tau(\boldsymbol{\theta})\; v_r(\mathbf{x}) \qquad \text{(+ 2-halo)}$$

<u>optical depth</u> (profile)

<u>\`bulk' radial velocity</u>




- Vary **r** at fixed $\boldsymbol{\theta}$ → velocity field on large scales
- Vary $\boldsymbol{\theta}$ at fixed **x** → gas profile and abundance.

Slide credit S. Ferraro

TWO different measurements!

# Measuring the density profile

$$\left\langle \frac{\Delta T}{T}\overbrace{(\mathbf{x}) \quad v_r^{\mathrm{rec}}(\mathbf{x})}^{\text{zero lag}} \right\rangle (\theta) = \sigma_{v_r}^2 \; \tau(\theta)$$

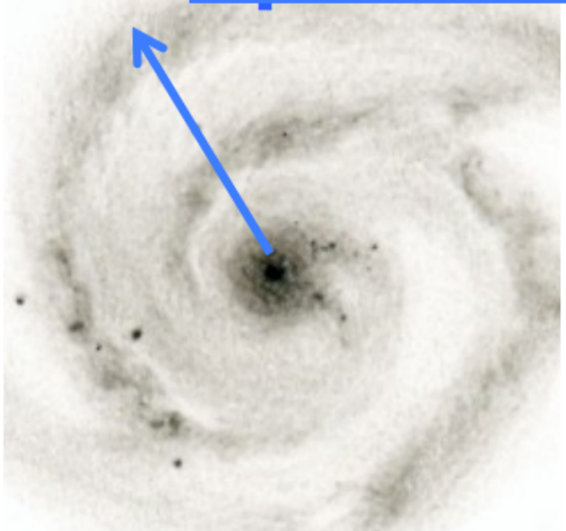
aperture

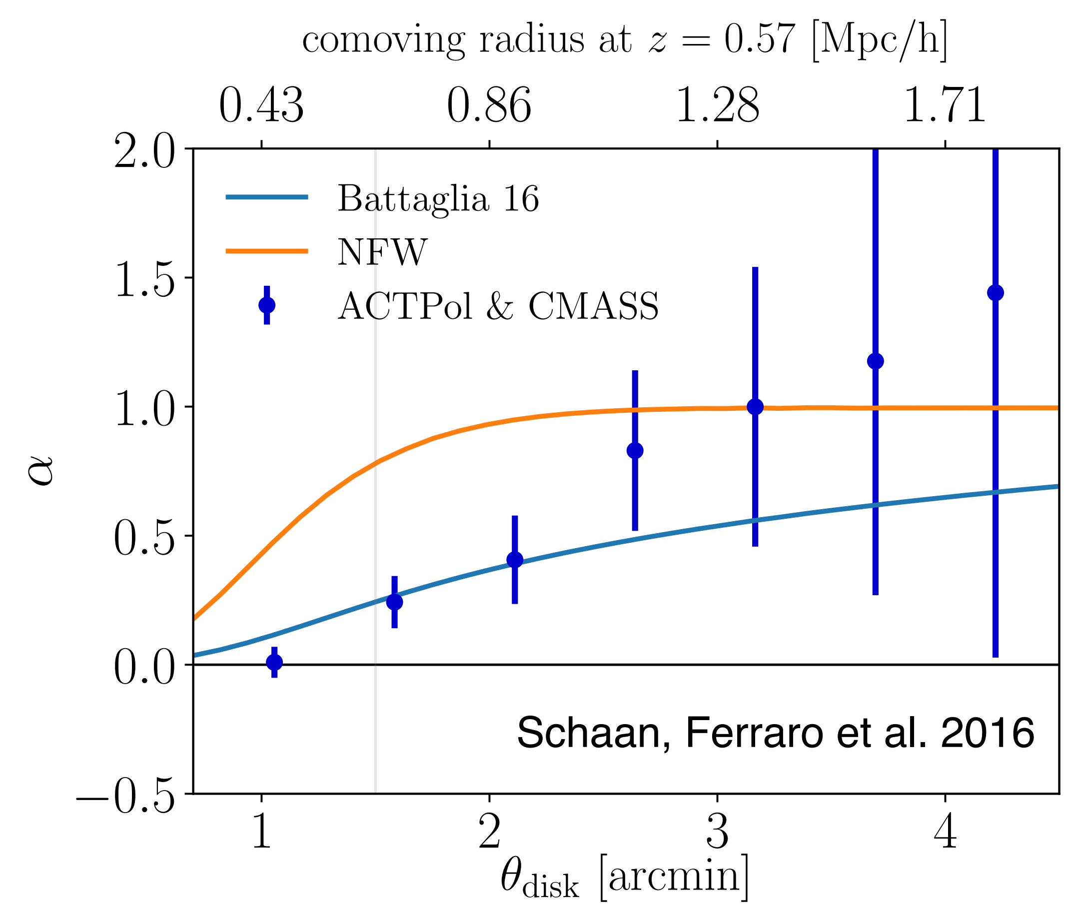
Ho et al. 2009
Li et al. 2014

**cosmology** (independent of $\theta$ )

**optical depth** (profile)

$\theta$ aperture

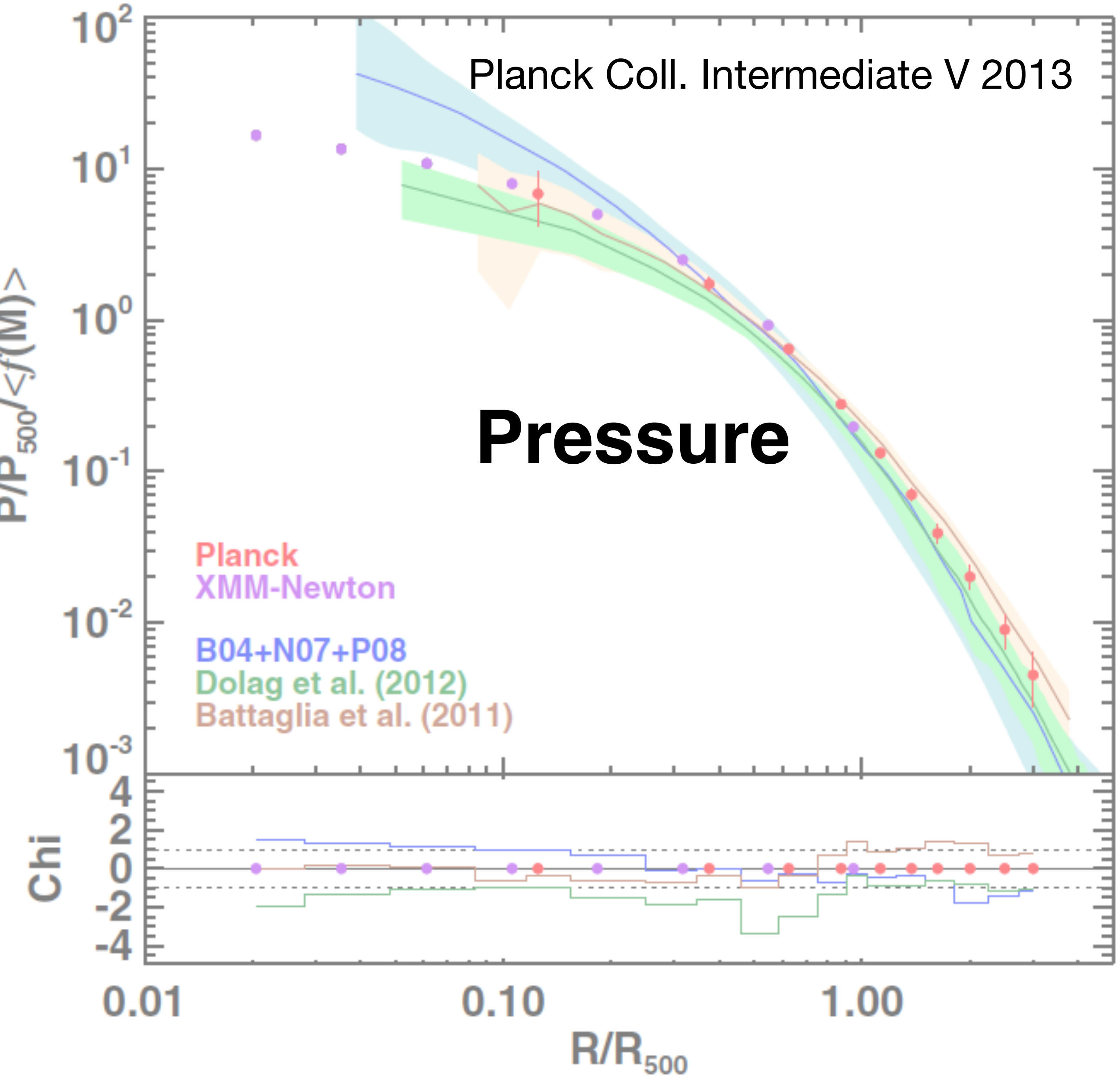




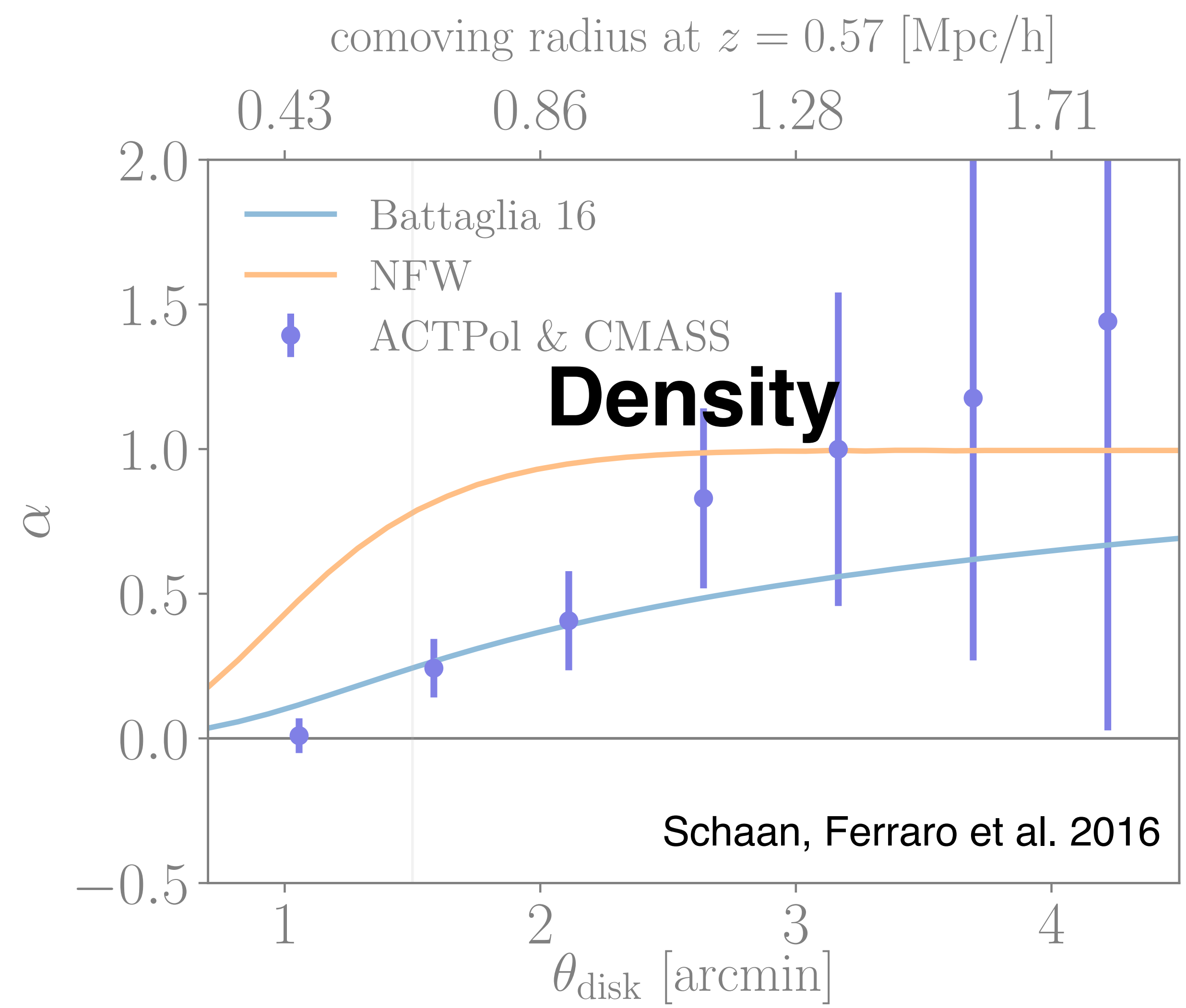

Measurement of the cumulative free electron density profile (un-biased)

Slide credit S. Ferraro

# Combining tSZ & kSZ measurements



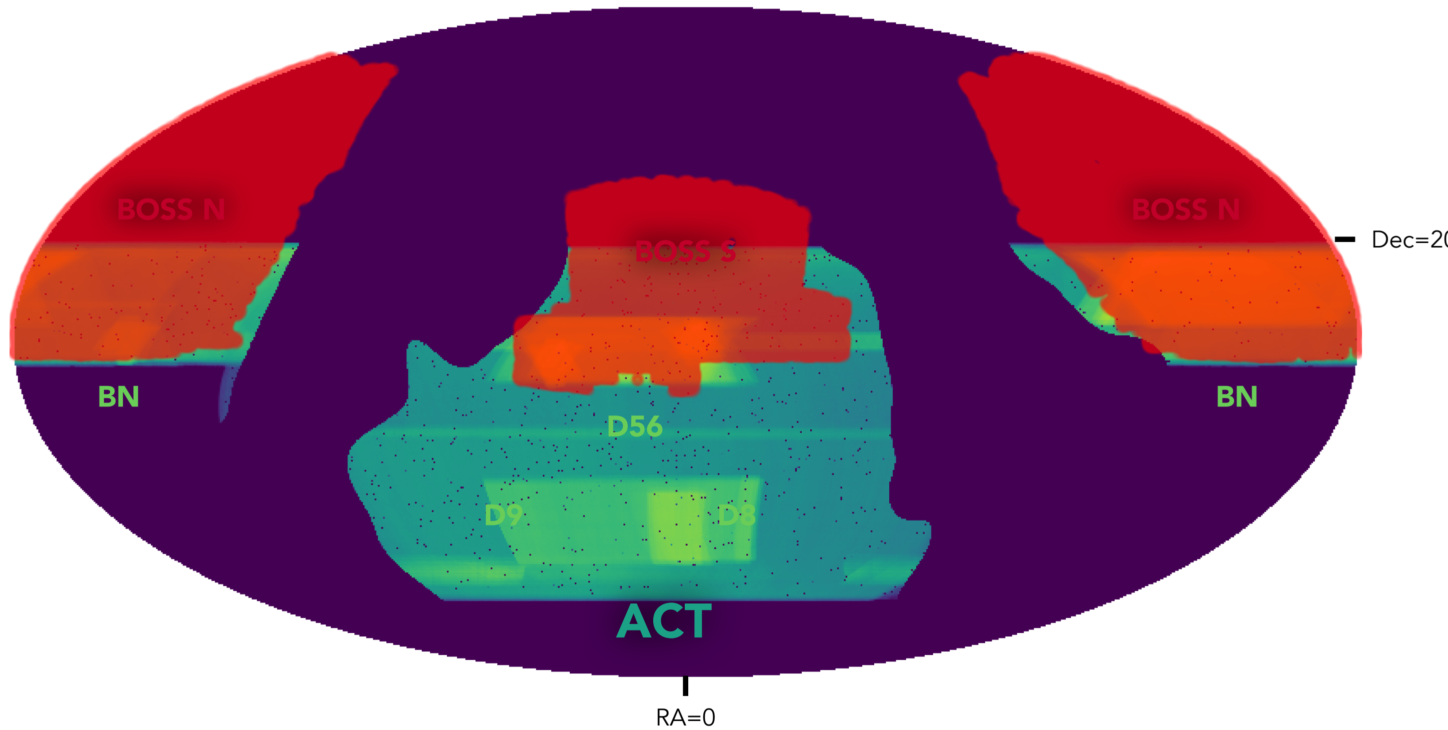

&




Previously, Knox+2004 Sehgal+2005 proposed to constrain T, $\tau$ & $v_{pec}$

Constraint dominant physical processes in galaxy formation and the CGM

# Combining BOSS & ACT+Planck




**BOSS CMASS**

~400k objects

Galaxy groups, $10^{13} M_{\odot}$

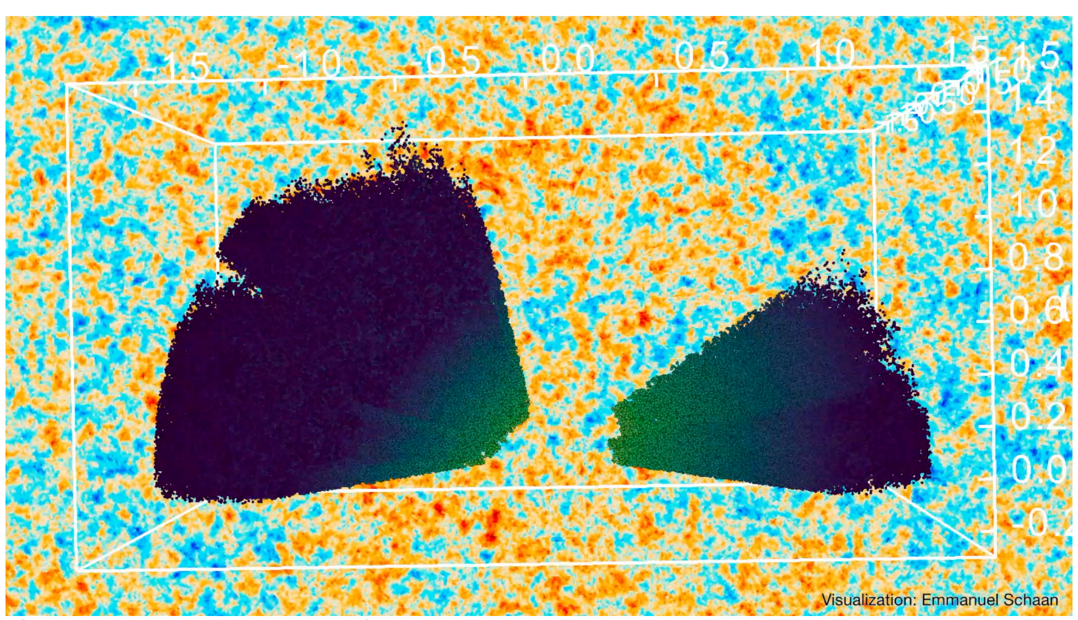
Spectroscopic sample, z = 0.4 - 0.7

**ACT + Planck**

ACT DR5 + Planck,150GHz and 98GHz

*Naess+20*

ACT DR4 ILC maps *Madhavacheril+20, Choi+20, Aiola+20*

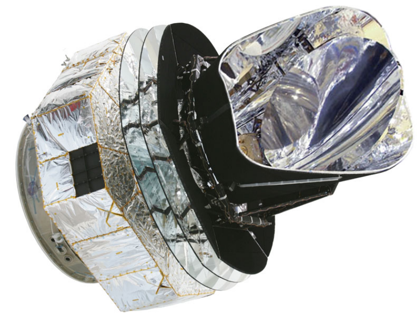



Slide credit E. Schaan

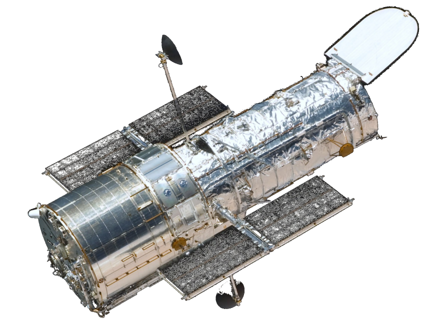
*Image: Debra Kellner*

# Measurement summary

## ACT + Planck (microwave)



## Hubble *(optical)*



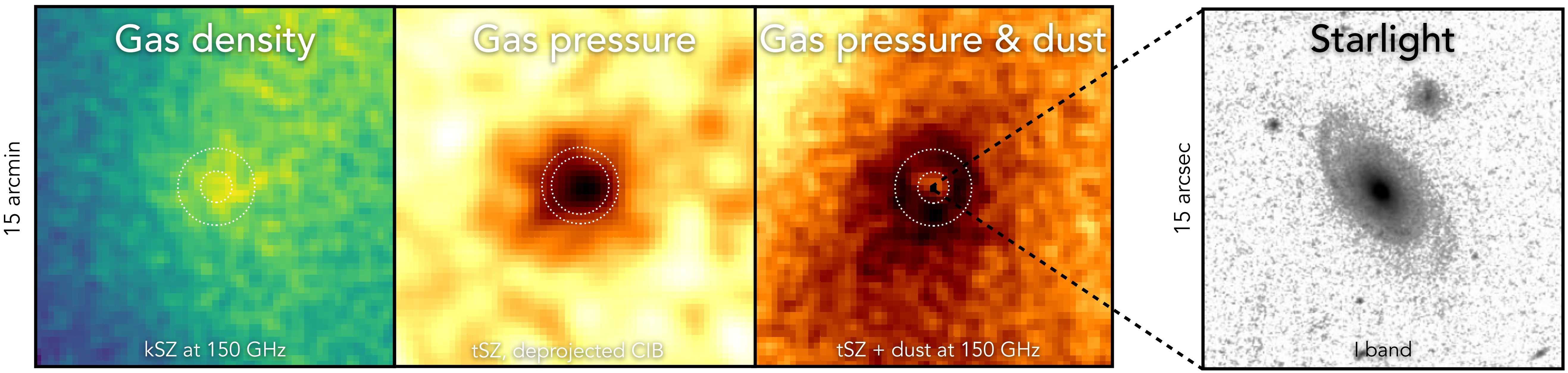



*Figure: E Schaan. ACT+Planck microwave images: Schaan et al 2020. HST ACS I band image: Masters et al 2011. ACT photo: John Ward. Planck photo: ESA/AOES Medialab. HST photo: NASA.*

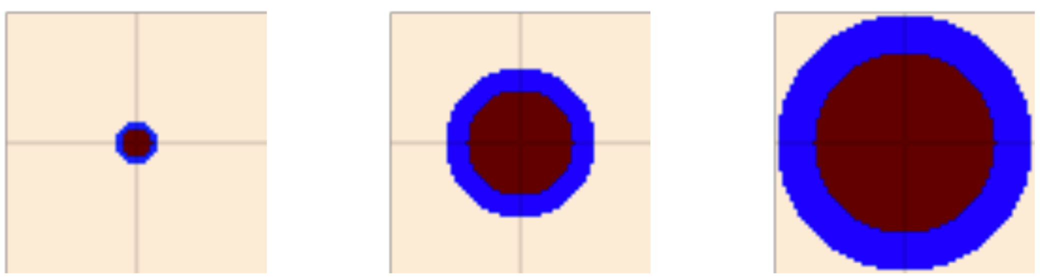
Gas density & pressure
far outside the virial radius
around low mass galaxy groups

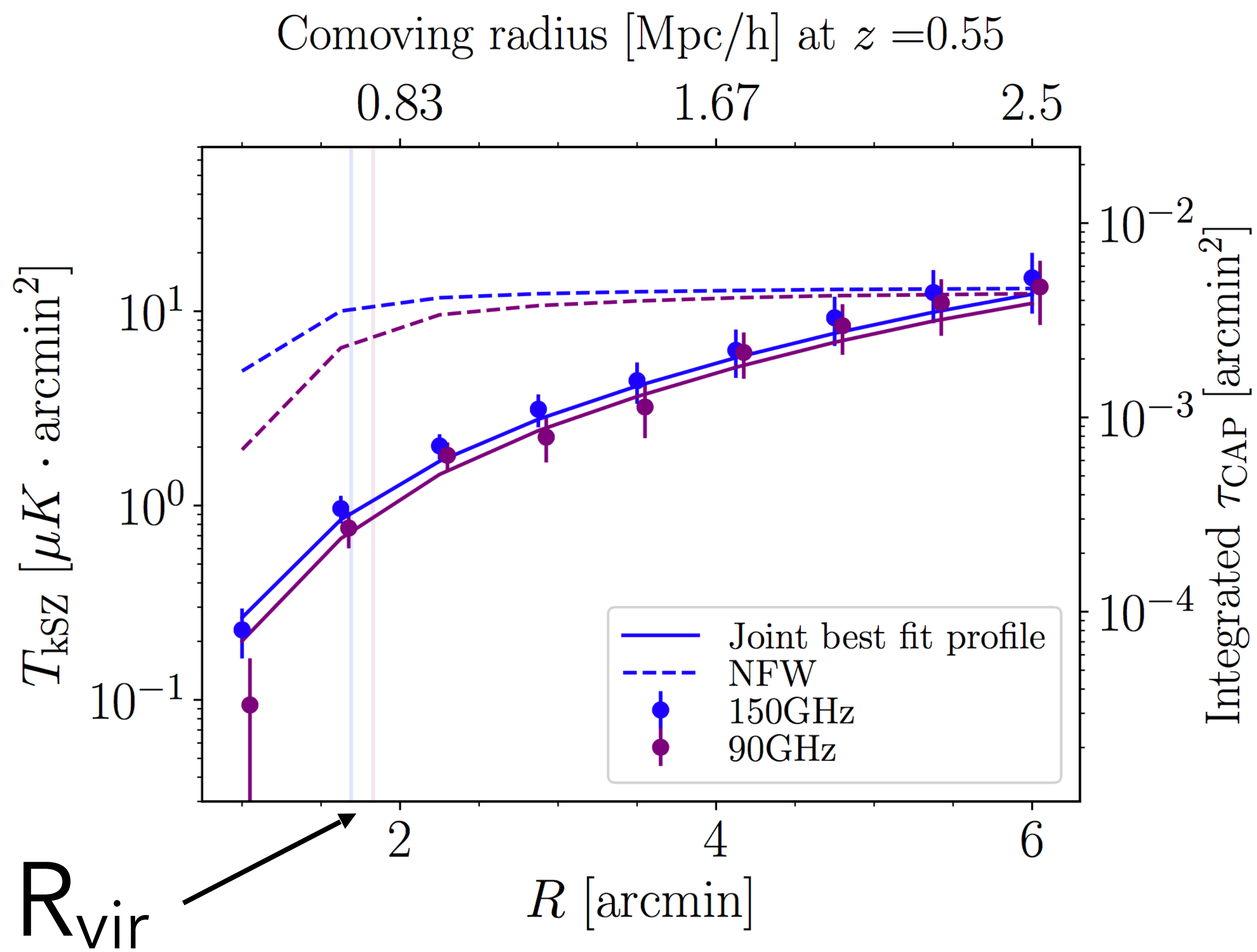
Slide credit E. Schaan

# kSZ: measuring the gas density profile

Compensated Aperture Photometry filter (CAP)

$\theta_d = 1'$ $\theta_d = 3.5'$ $\theta_d = 6'$





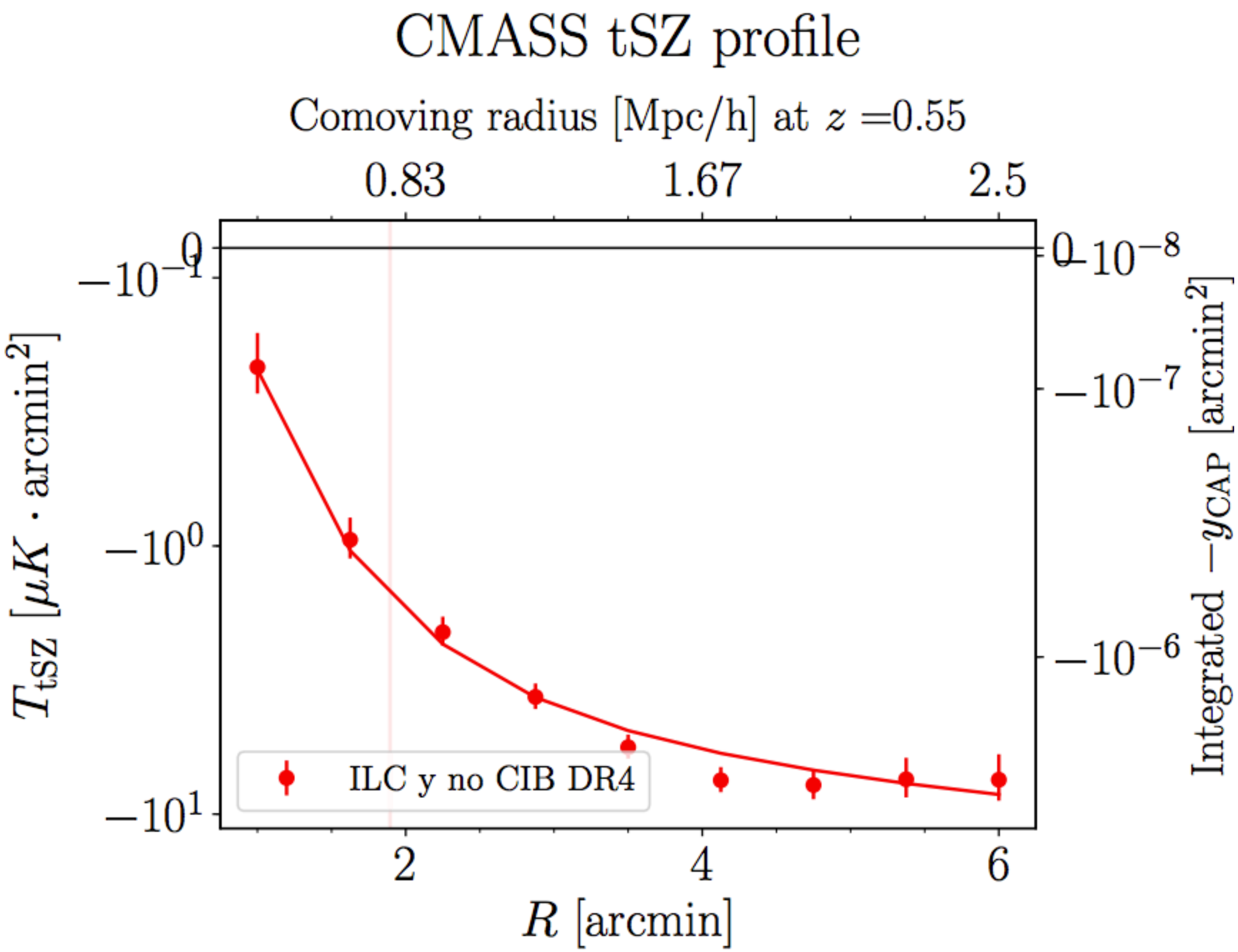

*Schaan Ferraro Amodeo Battaglia & ACT 20*

No-kSZ rejected at 6-8σ, but difference from NFW is >90σ

Gas is a lot more extended than the Dark Matter! Result of feedback, star formation, accretion, adiabatic mixing etc.

Slide credit S. Ferraro

# tSZ: measuring the gas pressure



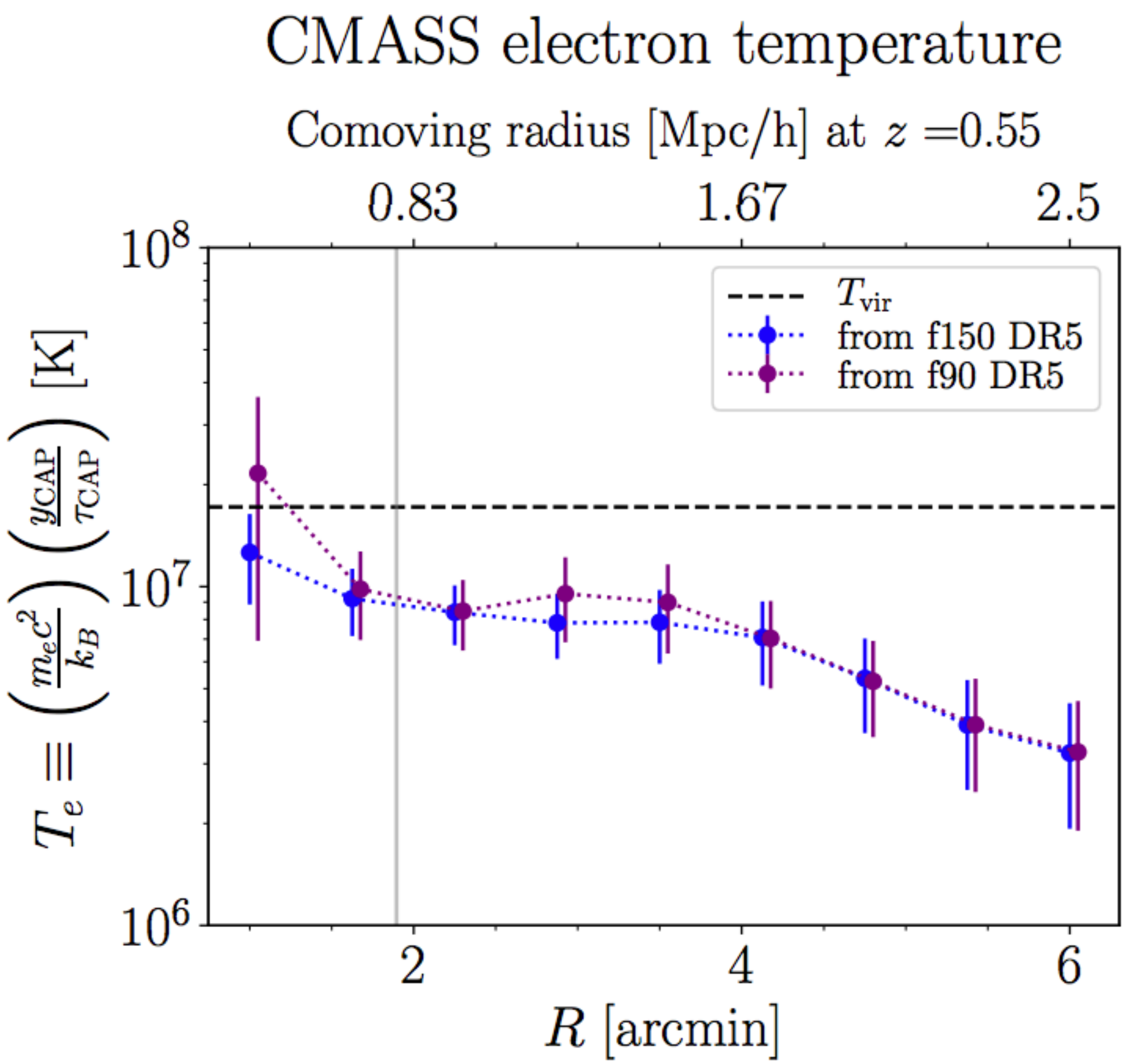

Sensitive to dust emission from these galaxies (FYST!)

Slide credit S. Ferraro

# tSZ / kSZ = gas temperature

$$\frac{\delta T_{\rm tSZ}}{T_{\rm CMB}} = f(\nu)\,\tau\left(\frac{v_{\rm thermal}}{c}\right)^2 \quad \propto\ \tau\ T_e$$

$$\frac{\delta T_{\rm kSZ}}{T_{\rm CMB}} = \tau\frac{v_{\rm bulk}}{c} \quad \propto\ \tau$$



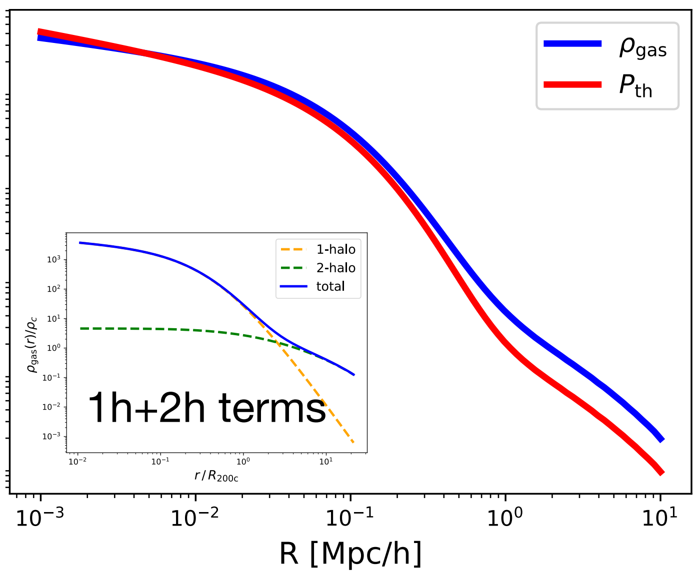

*Schaan Ferraro Amodeo Battaglia & ACT 21*
*Amodeo Battaglia Schaan Ferraro & ACT 21*

Slide credit S. Ferraro

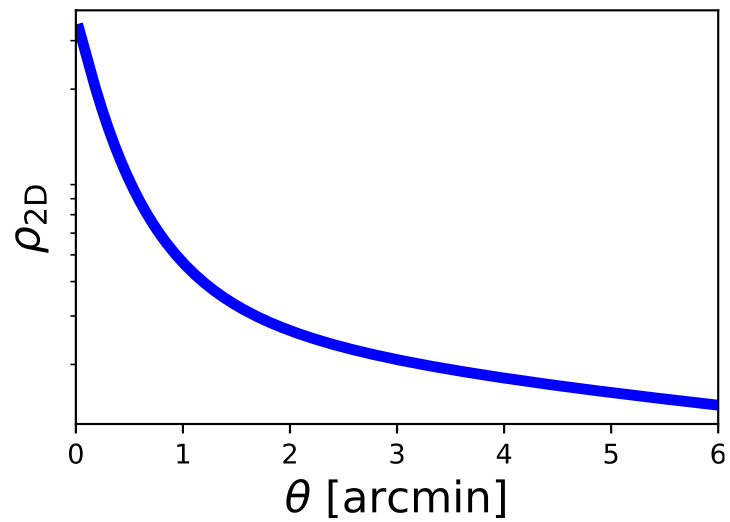
# From Models to Observations

Mop-c-GT: Model-to-observable projection code for Galaxy Thermodynamics

## 3D theoretical profiles

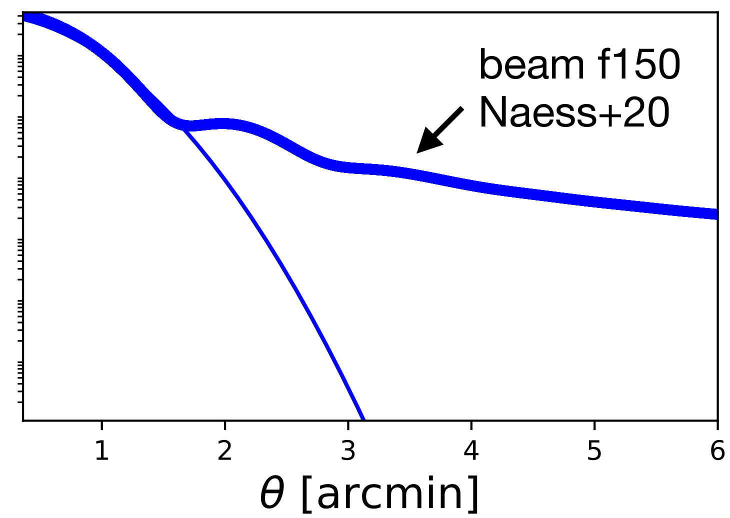



## line-of-sight projection



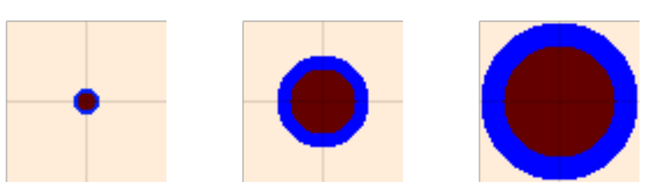

$\otimes$

## beam convolution

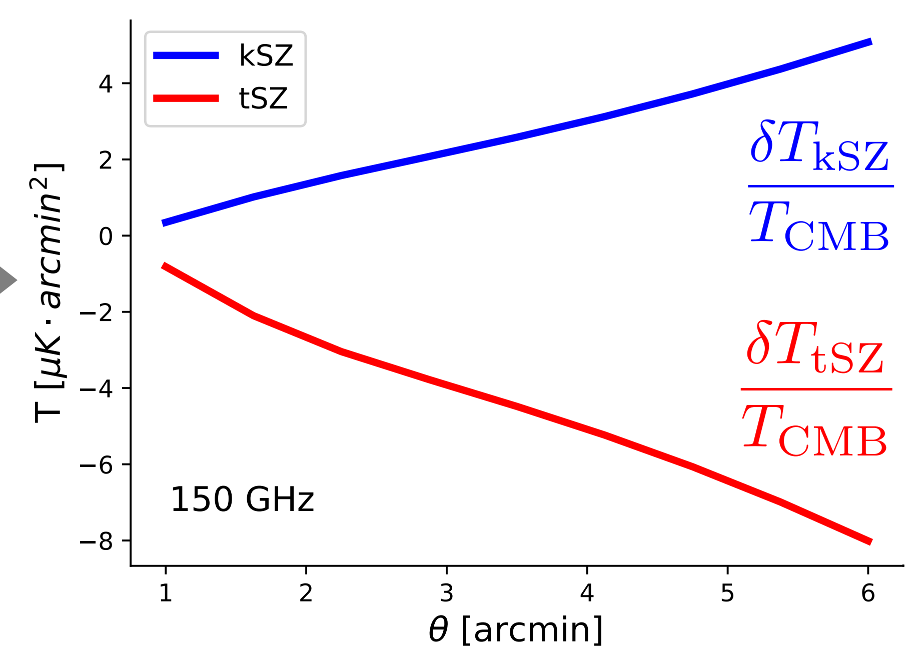



## aperture photometry filtering

$\theta_d = 1'$ $\theta_d = 3.5'$ $\theta_d = 6'$



## 2D observed profiles

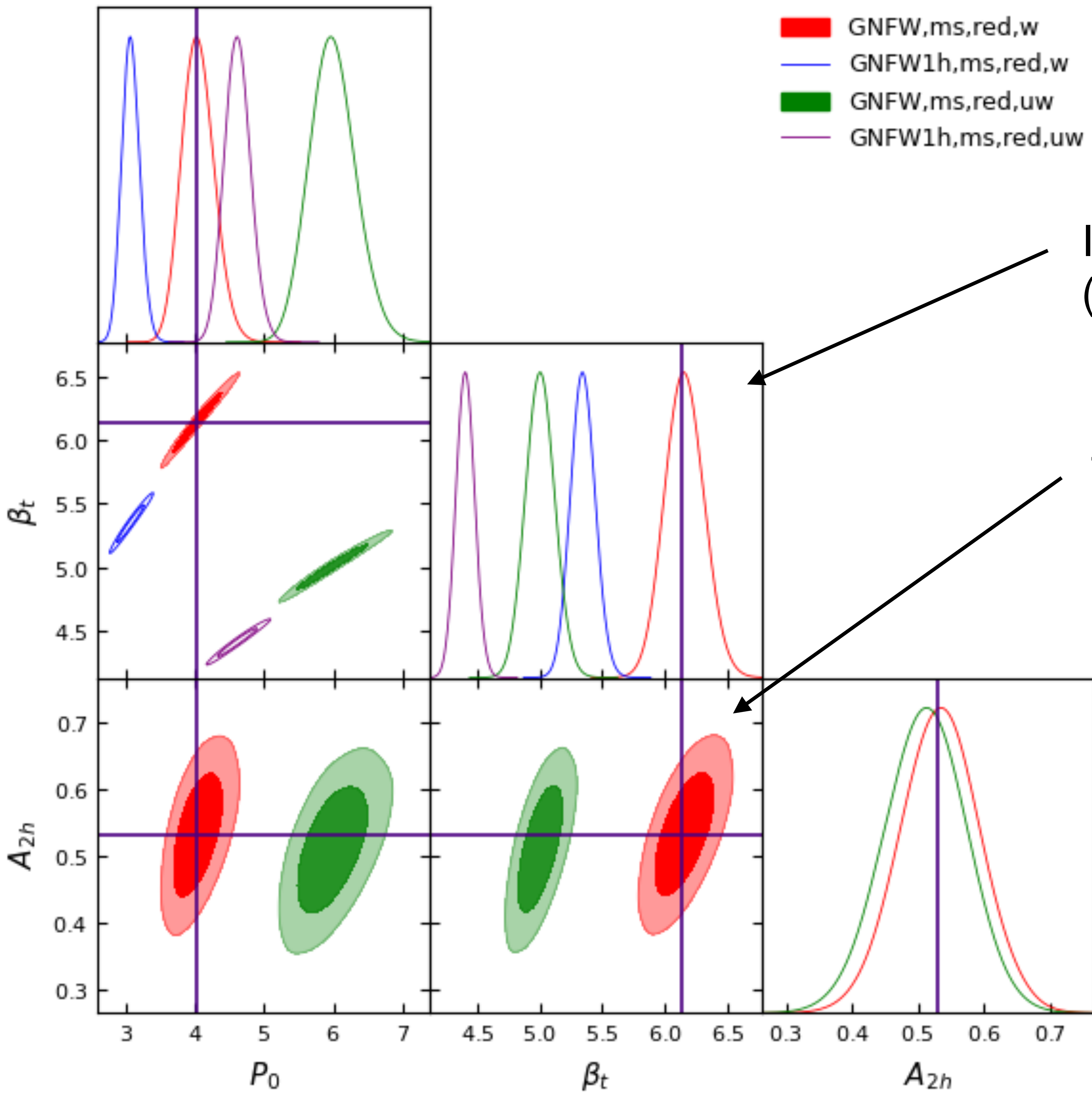



$$\frac{\delta T_{\rm kSZ}}{T_{\rm CMB}} = \tau \frac{v_{\rm bulk}}{c}$$

$$\frac{\delta T_{\rm tSZ}}{T_{\rm CMB}} = f(\nu)\ \tau \left(\frac{v_{\rm thermal}}{c}\right)^2$$

Slide credit S. Amodeo

# Modeling Choices Systematics (part 1)




What matters?

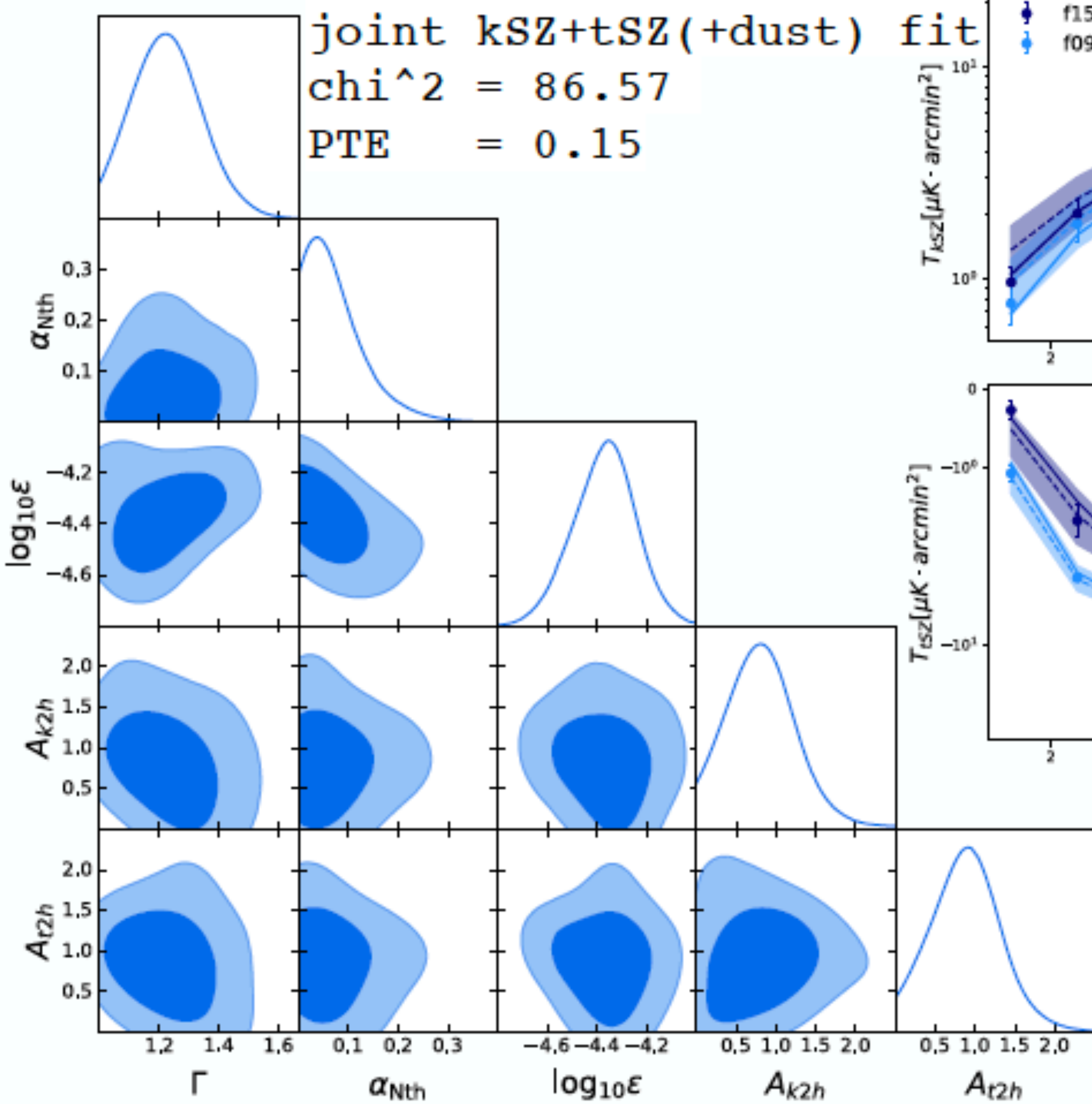
Including neighboring galaxies (2-halo term)

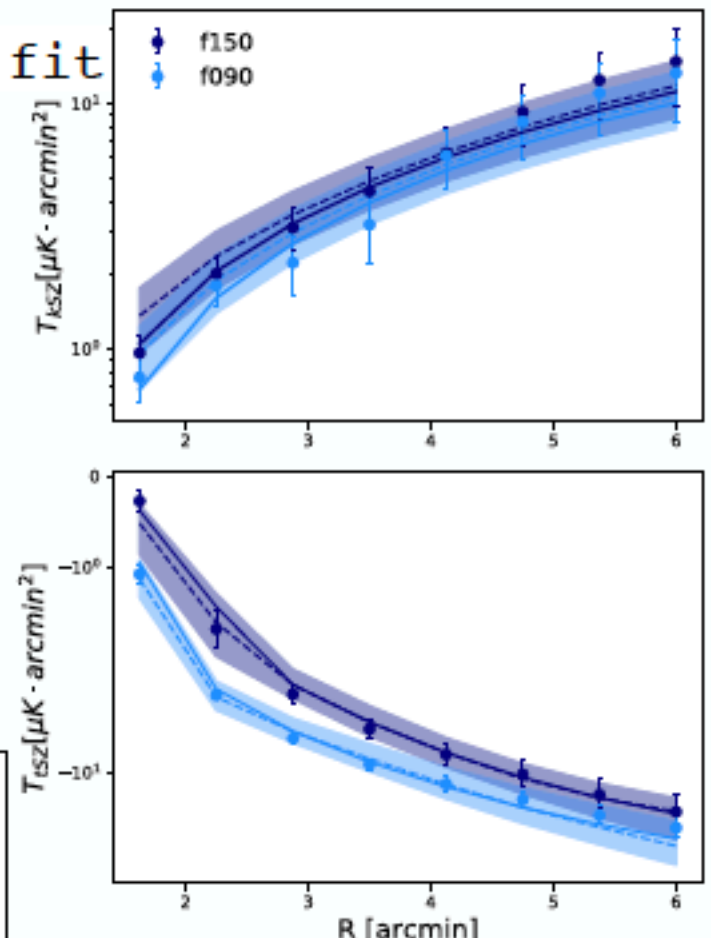
The weighting of the sample

Sample selection
Total mass vs Stellar Mass
(Not Shown)

**Moser et al 2021**

# Joint kSZ + tSZ fit to a polytropic gas model




**~30% of total energy is injected by feedback**

**< 20% of total pressure within $R_{200}$ is non thermal**

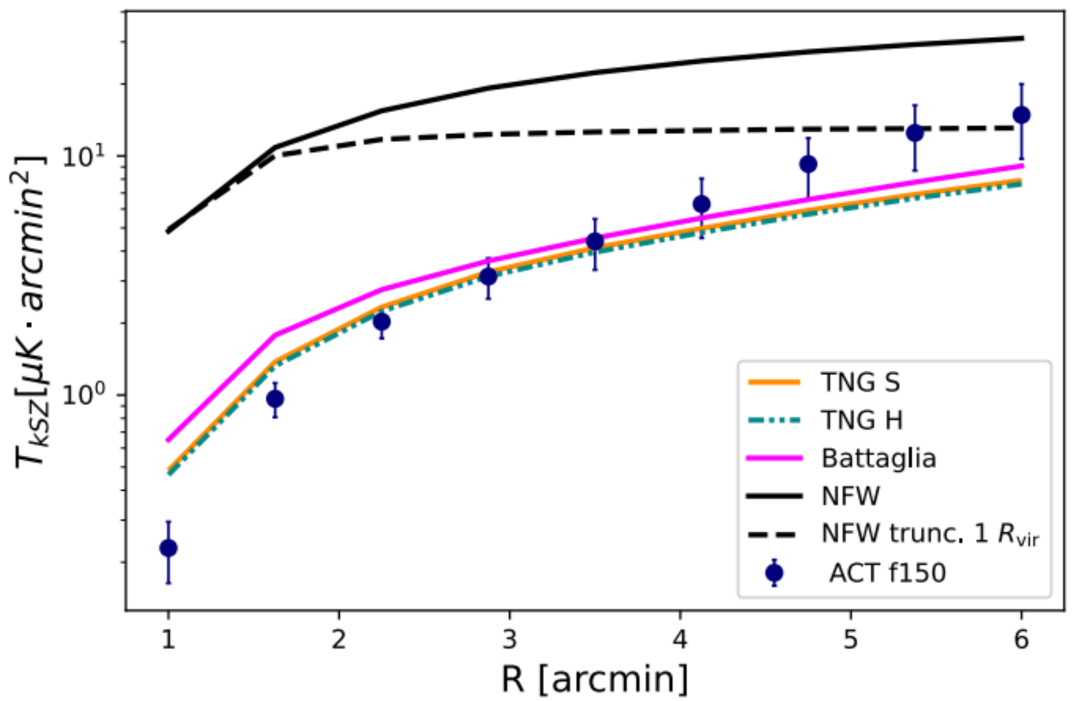
| Parameter | Description | Prior | Constraints ($1\sigma$) |
|---|---|---|---|
| | **OBB model** | | |
| $\Gamma$ | Polytropic index | $[1, 5/3]$ | $1.2 \pm 0.1$ |
| $\boldsymbol{\alpha_{\rm Nth}}$ | **Non-thermal pressure norm.** | **[0.0, 0.8]** | $\mathbf{0.04^{+0.07}_{-0.03}}$ |
| $\boldsymbol{\epsilon}$ | **Feedback efficiency** | $[\mathbf{10^{-4.8}}, \mathbf{10^{-4.0}}]$ | $\mathbf{(40 \pm 9) \times 10^{-6}}$ |
| $A_{\rm k2h}$ | Two-halo density amplitude | [0, 5] | $0.8 \pm 0.5$ |
| $A_{\rm t2h}$ | Two-halo pressure amplitude | [0, 5] | $0.9^{+0.3}_{-0.5}$ |

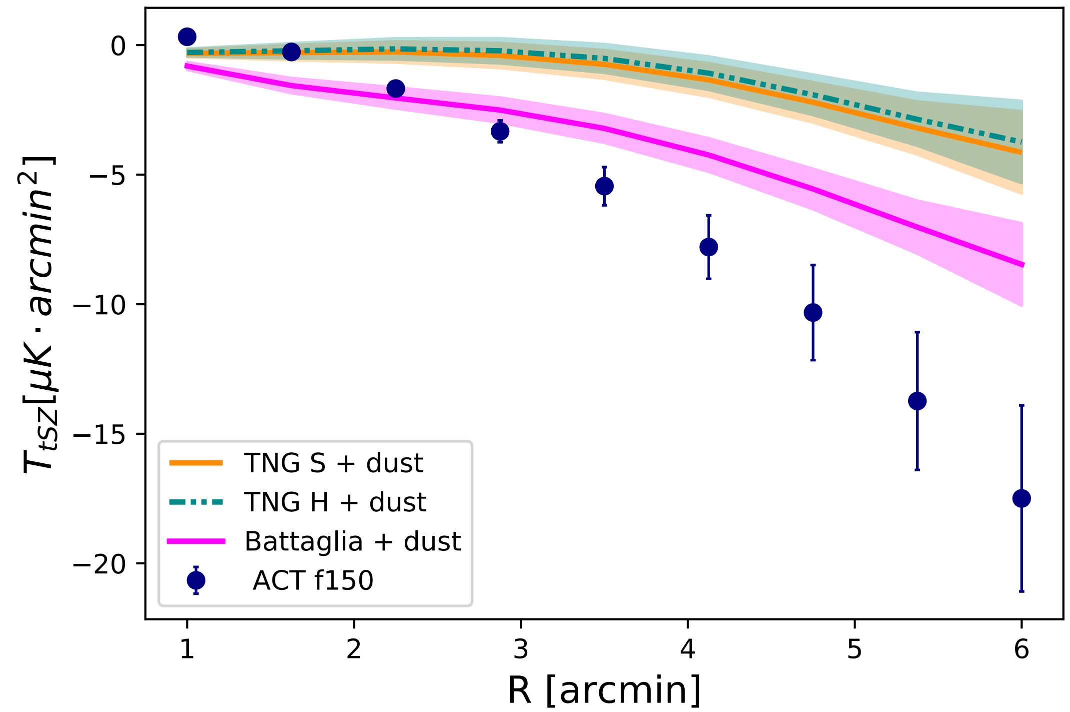
Slide credit S. Amodeo

*Amodeo Battaglia Schaan Ferraro & ACT 21*

# Comparison to Cosmological Simulations

dust correction included




*Amodeo Battaglia Schaan Ferraro & ACT 20*

The most striking feature is the lack of density and pressure at large radii

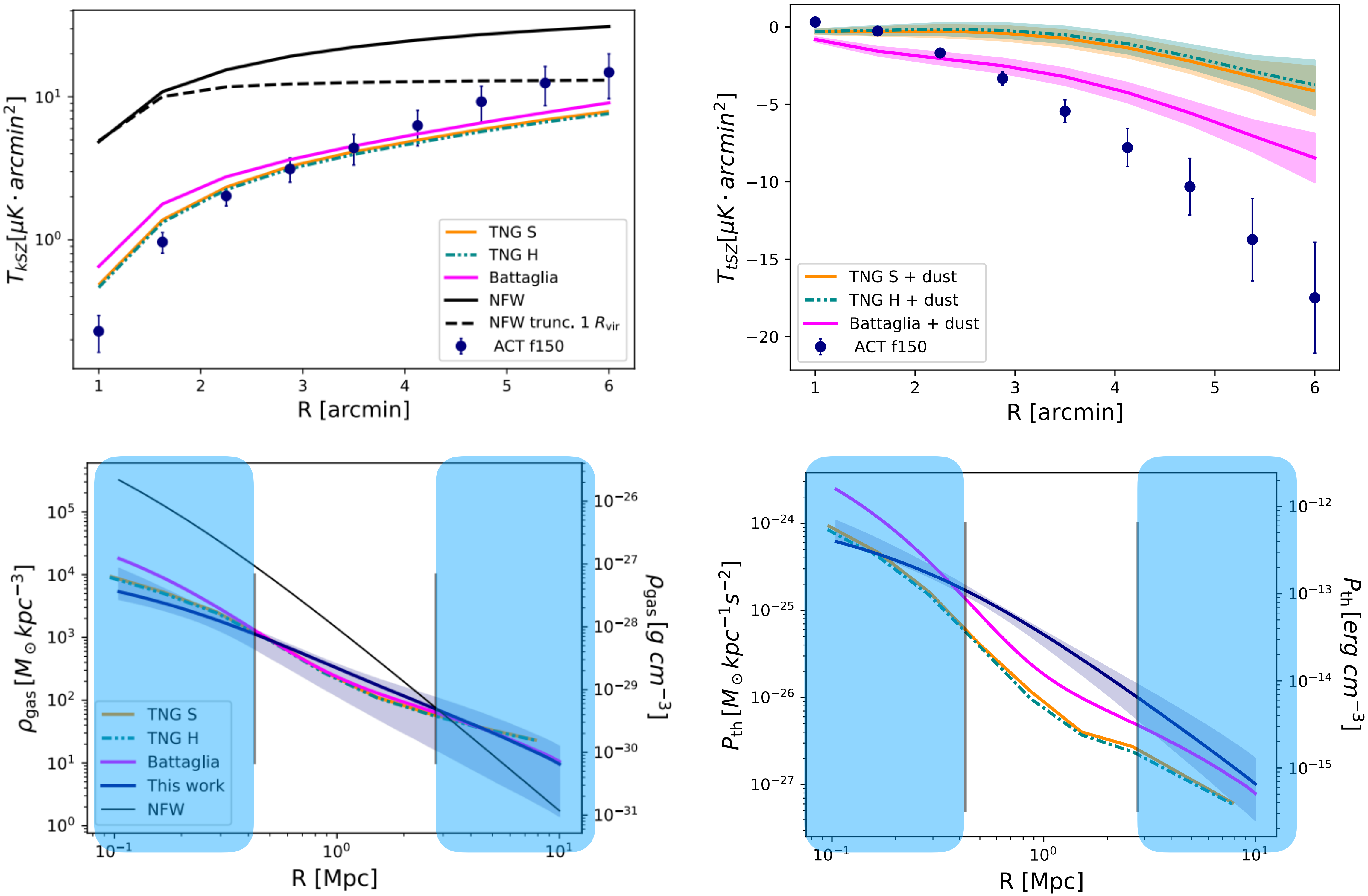
The errors are highly correlated at these radii

PTEs are reasonable for density ranging from 0.07 - 0.15 but 0 for pressure

Easier to understand this with radial averaged 3D profiles

# Comparison to Cosmological Simulations

**dust correction included**




*Amodeo Battaglia Schaan Ferraro & ACT 20*

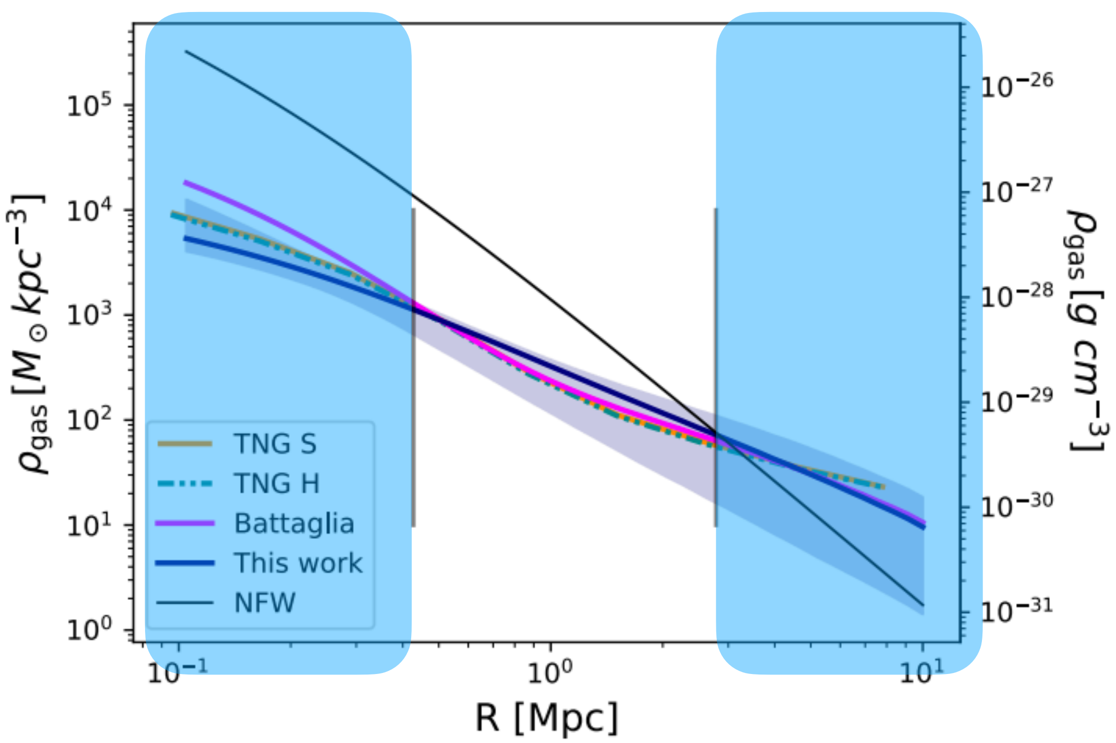
# Comparison to Cosmological Simulations

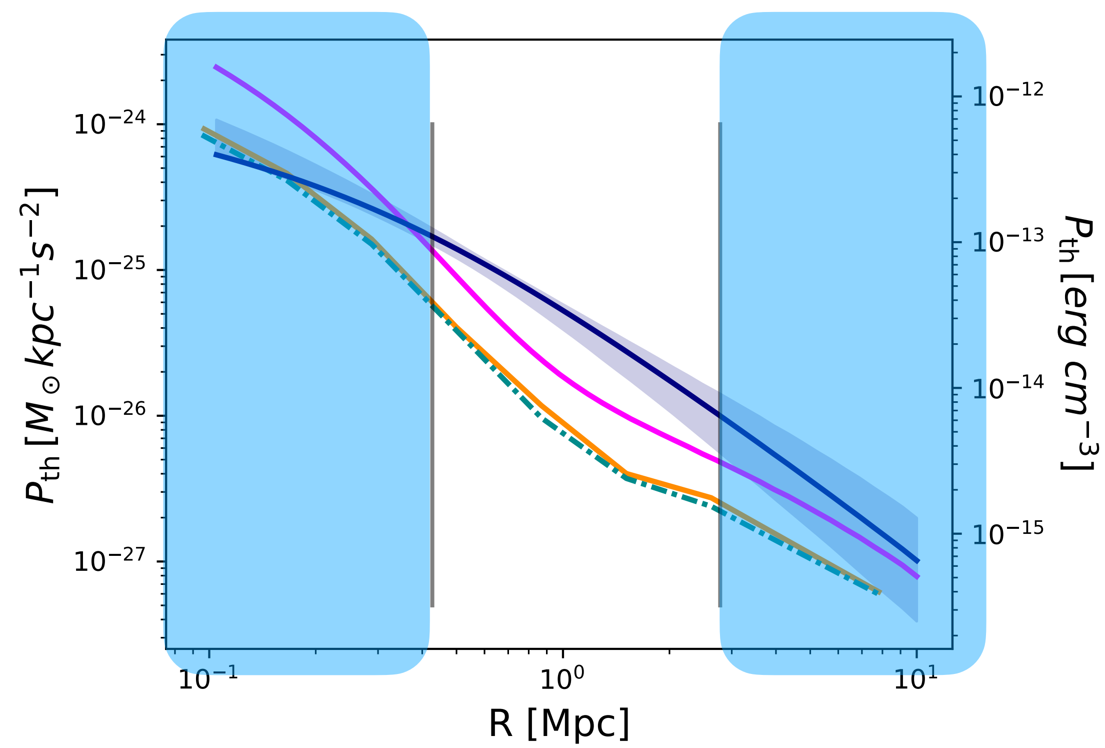
Predicting the gas profiles on these large scales is challenging

Why do the simulations under predict the amount of CGM pressure at these larger radii?

Choices in how the energy is injected and how that energy propagate through the CGM. Could there be cold clumps in the CGM?

Should enable further refinement of the current sub-grid feedback models.



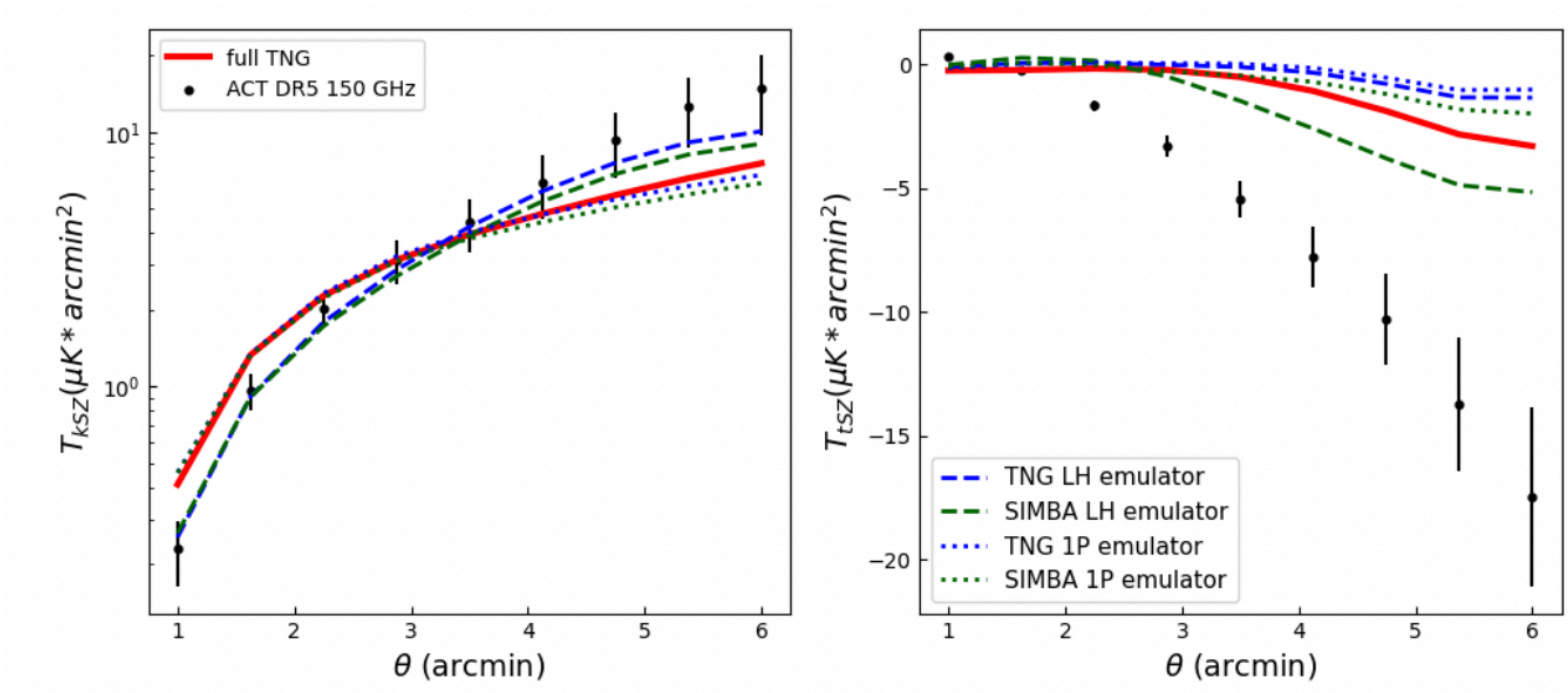




*Amodeo Battaglia Schaan Ferraro & ACT 20*

# Comparison to Cosmological Simulations

Using CAMELS we created emulators for the density and profiles
-> function of sub-grid feedback parameters

Look for best fit parameters (independently) -> Can we fit the pressure

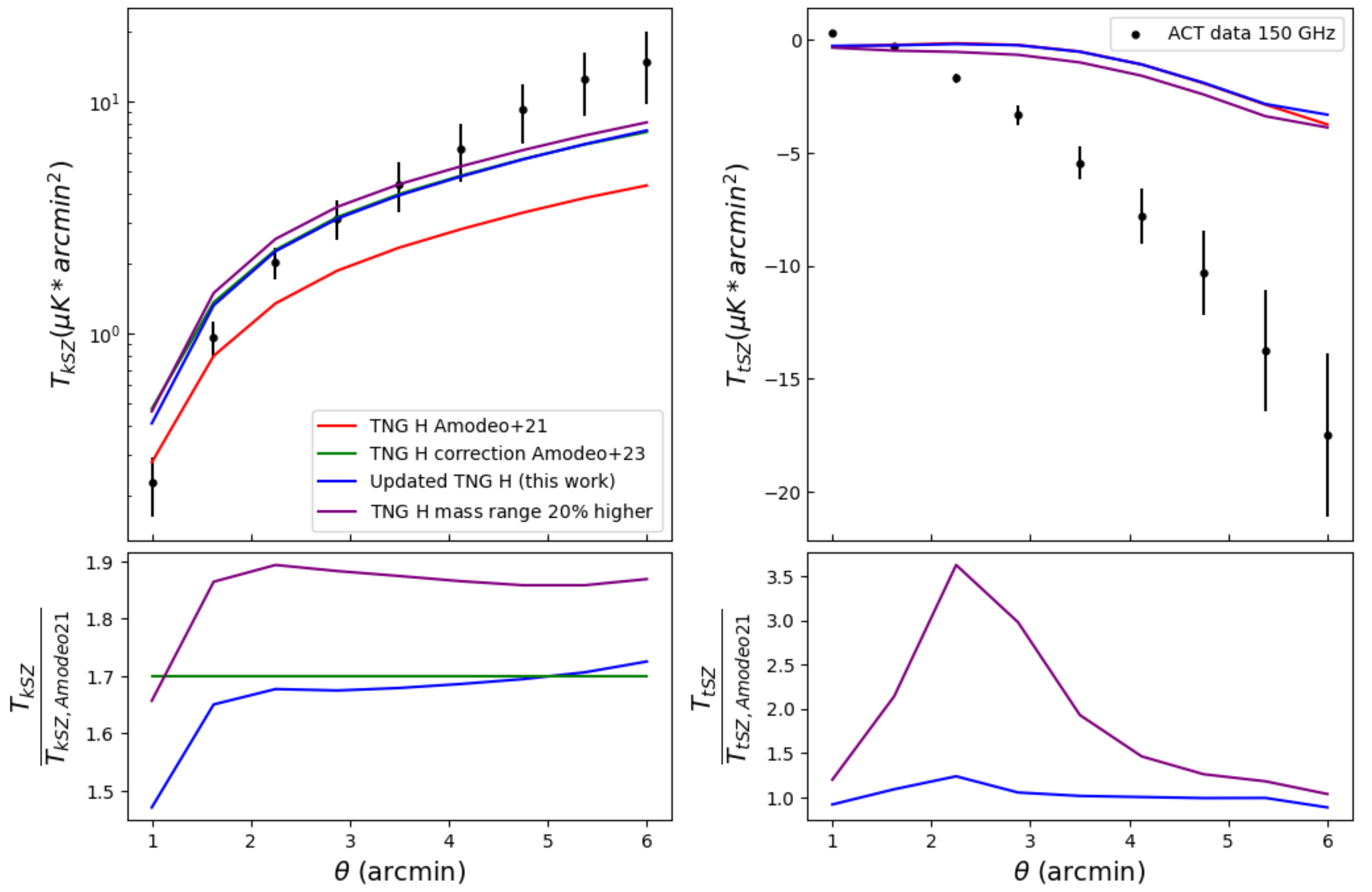



Moser+22

Moser (Thesis)
With Erwin and Daisuke

# Looking for more systematics

Moser+23 in prep

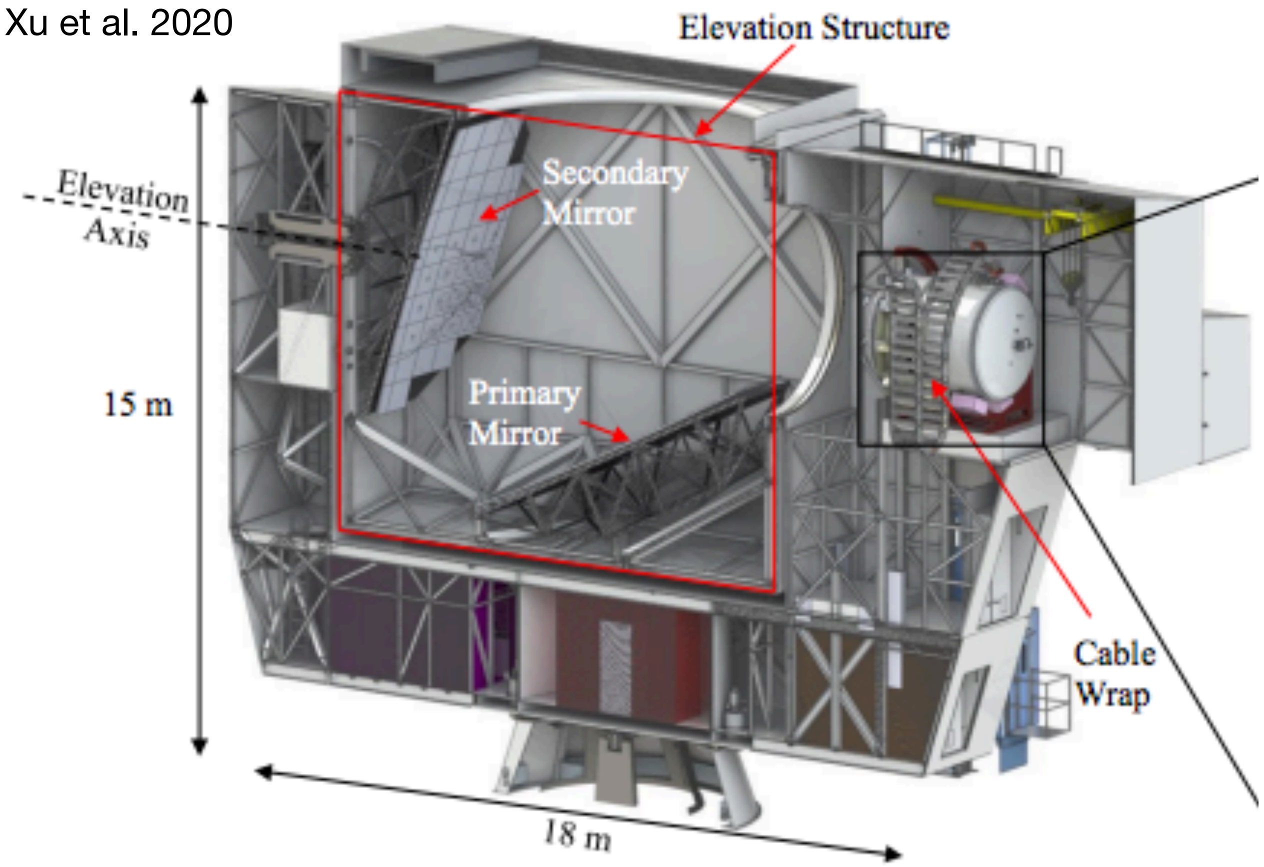



Studied a range of different systematics in the analysis:
beams, convolution methods, line of sight integration ranges
Changes are minimal. Dust corrections are important and will be in the future

# The Simons Observatory

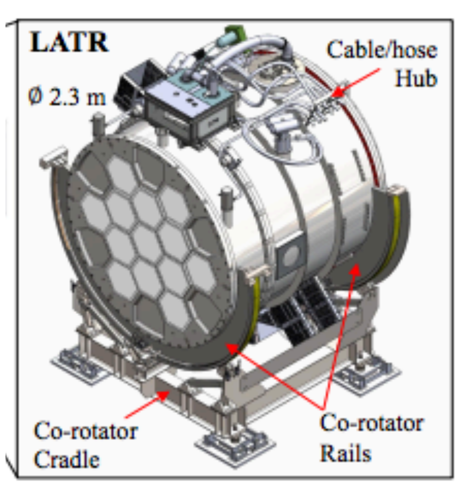
## large aperture telescope

Xu et al. 2020

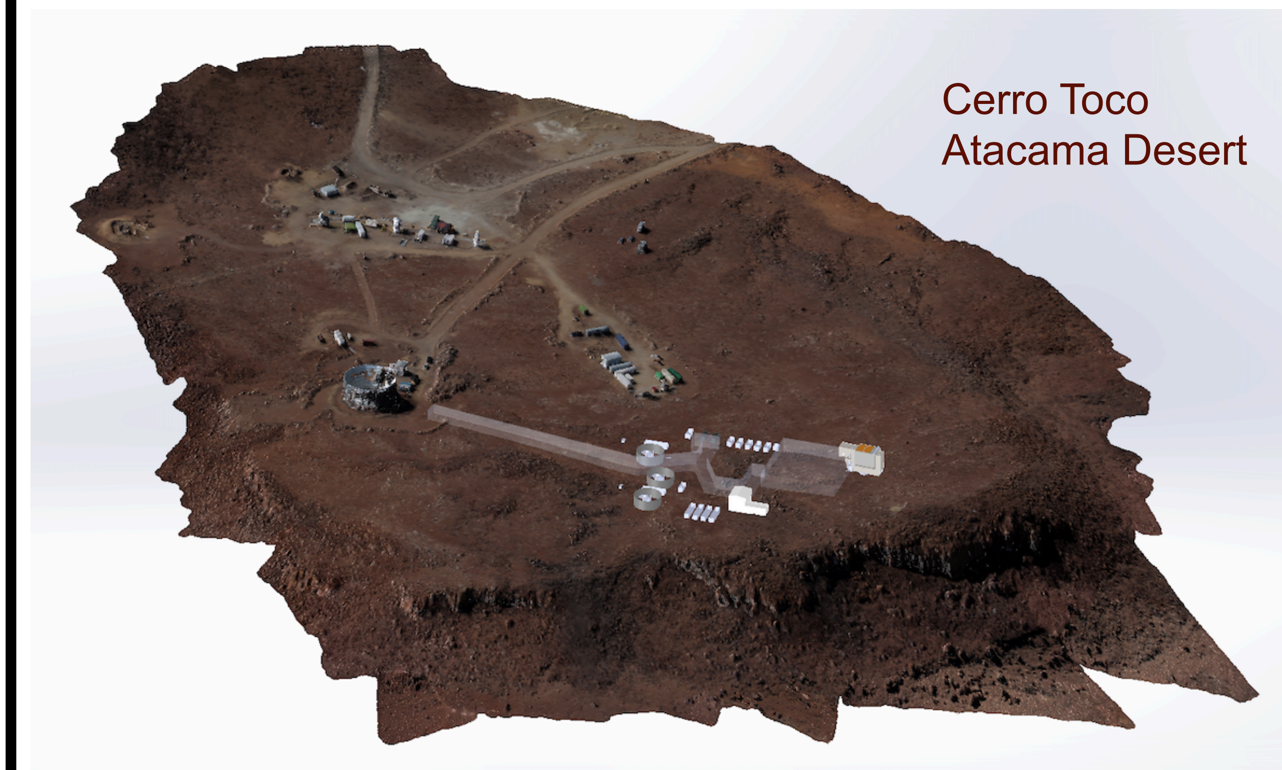



6 m crossed Dragone fed by up to 13, 38 cm optics tubes. baseline=7 tubes for SO, with baseline pixels:

- One tube: 30/40 GHz
- Four tubes:  90/150 GHz
- Two tubes: 220/270 GHz

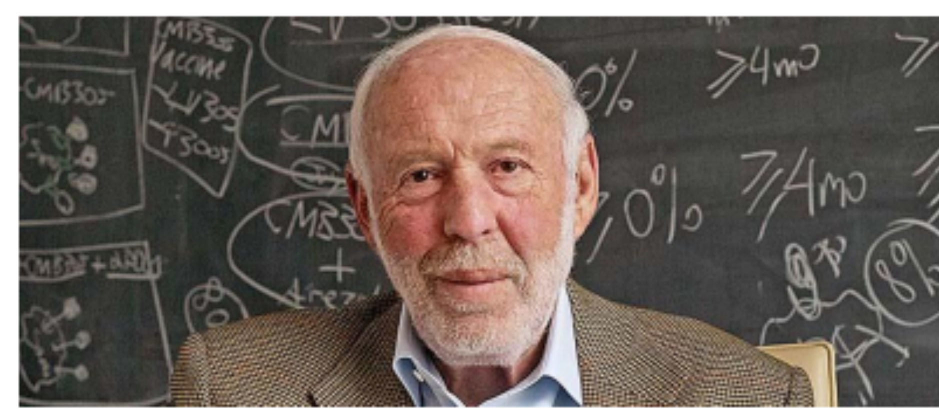



Small aperture telescopes as well




SIMONS FOUNDATION

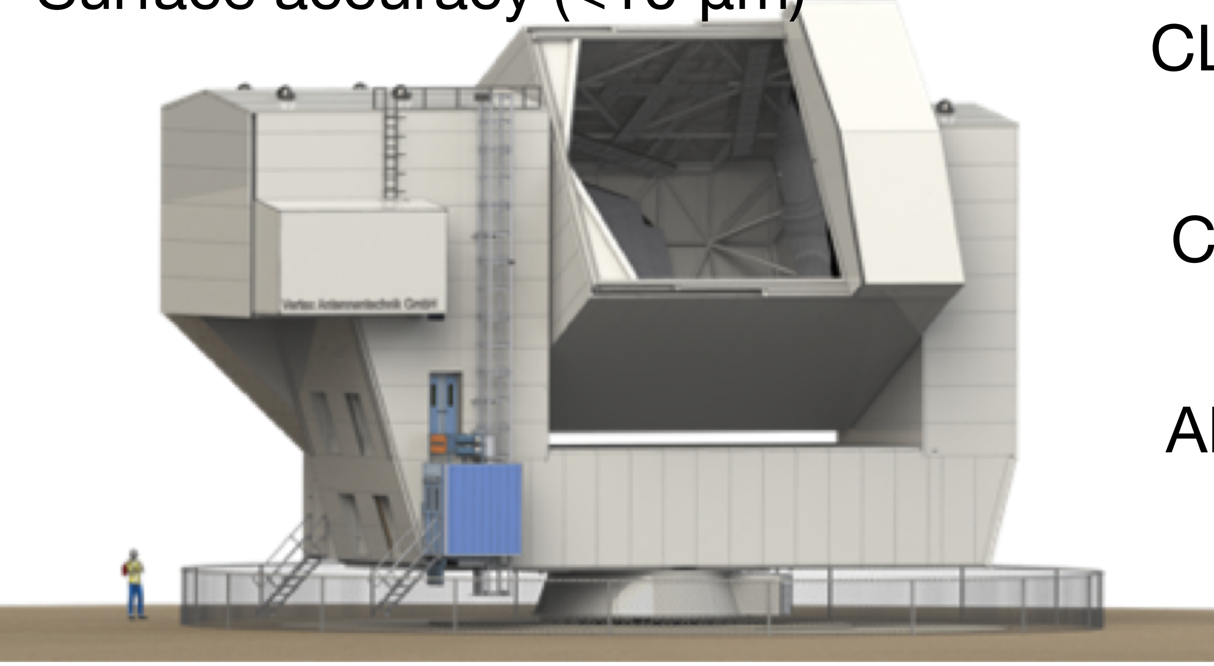
HEISING-SIMONS FOUNDATION



# FYST - Telescope & Site

Parshley+ (arXiv:1807.06678)
Stacey+ (arXiv:1807.04354)

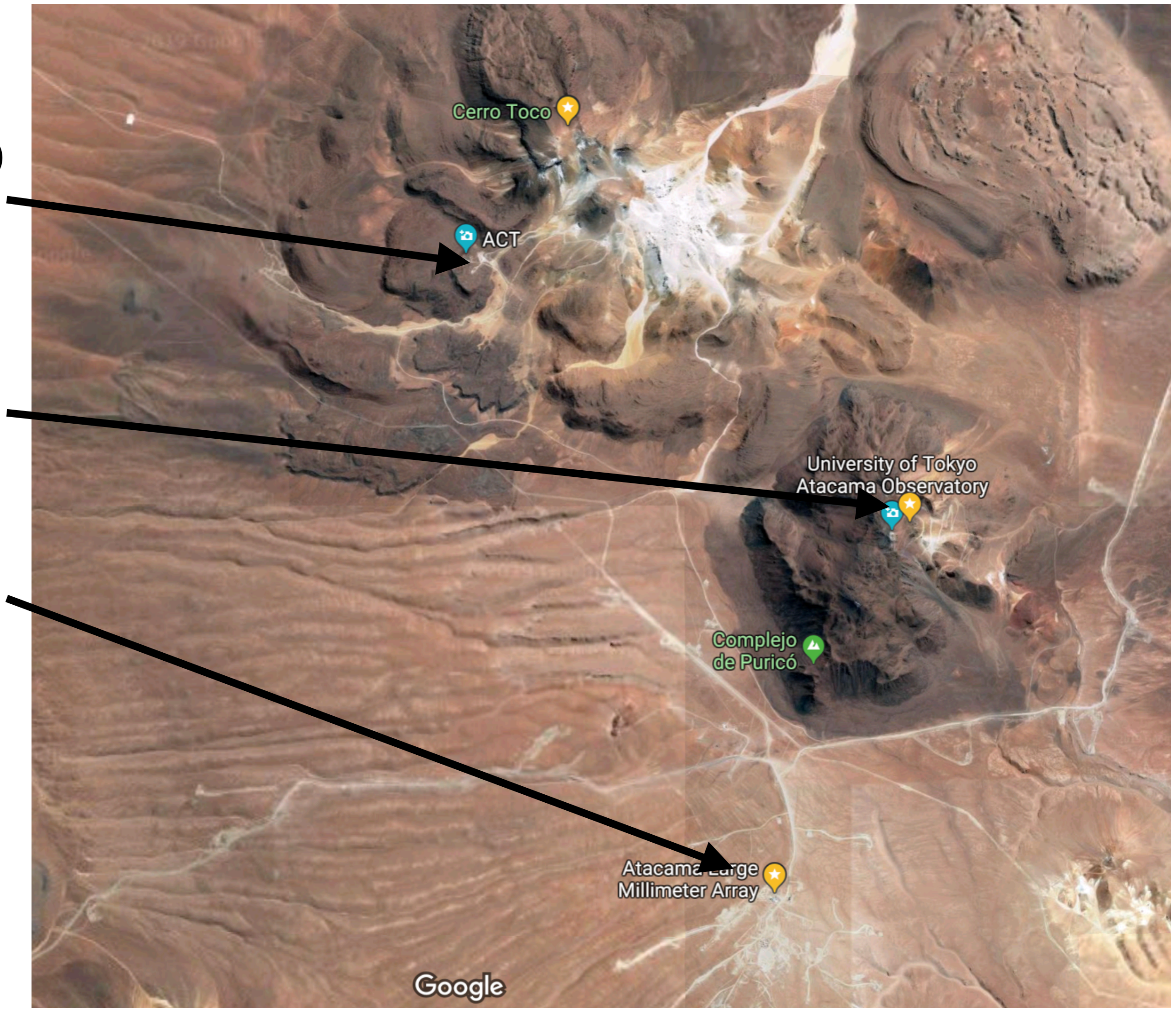
High throughput, Large FOV,
Surface accuracy (<10 μm)

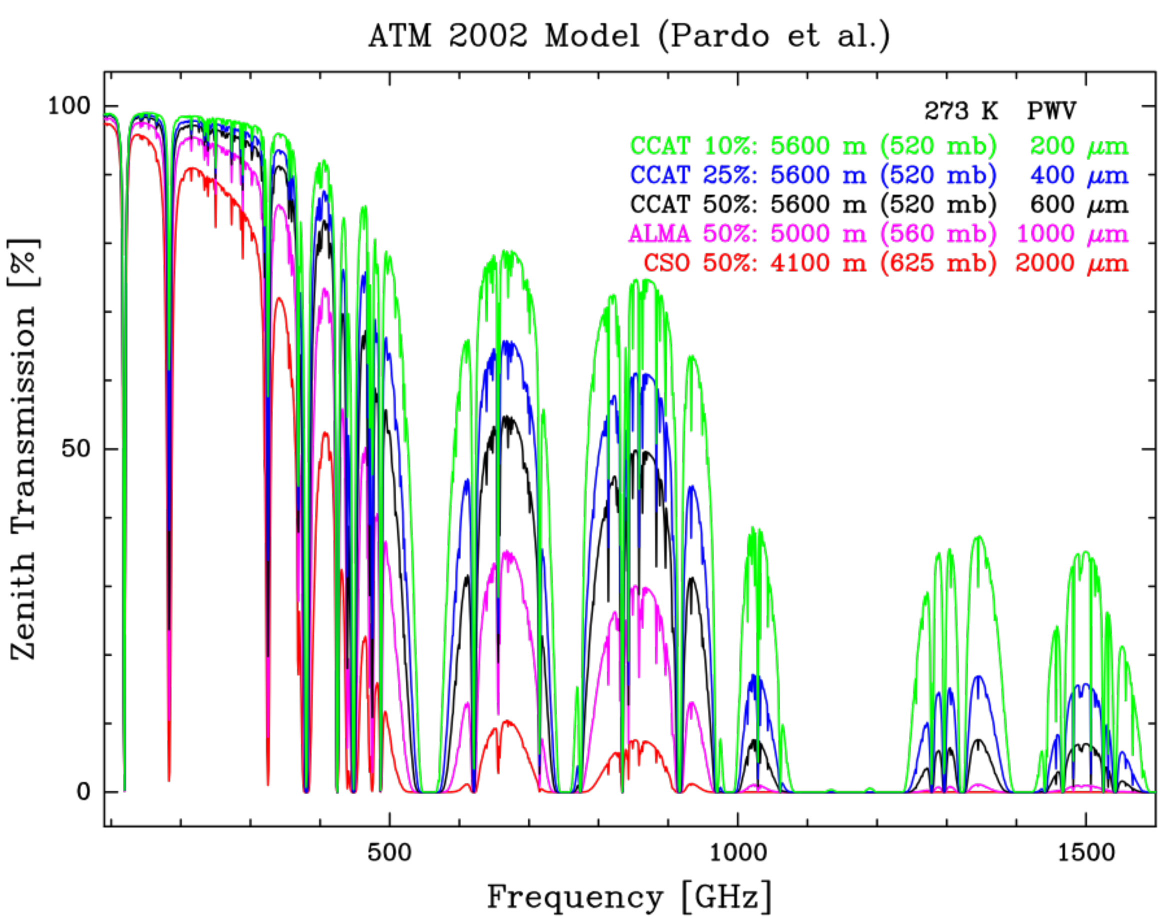


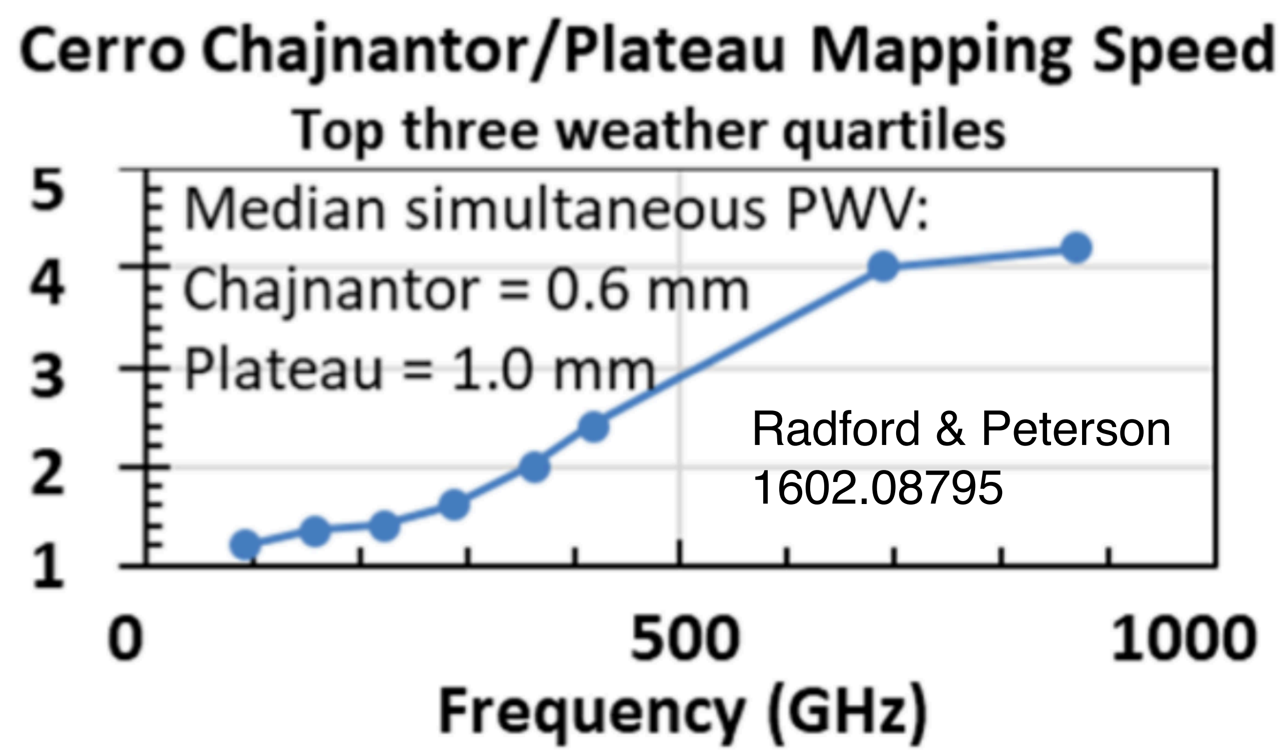
ACT, SO
CLASS

CCAT

ALMA



# CCAT - PrimeCam

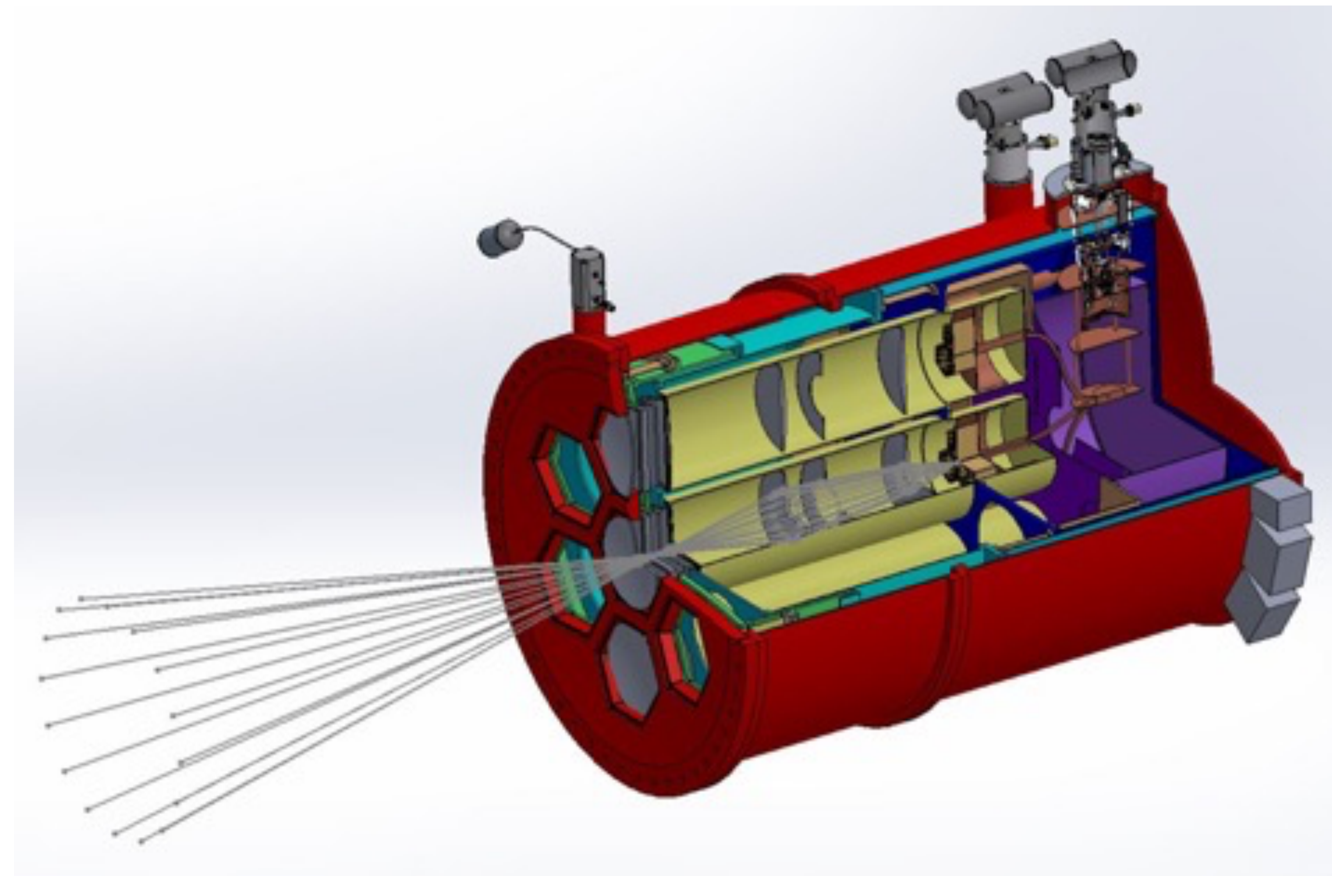
Spanning the mm to sub-mm

7 instrument modules aka. “optics tubes” populated with KID arrays at 100 mK

- EOR-Spec - Fabry-Perot interferometer module(s)

- Broadband modules (220), **270**, **350**, (410), **850** GHz

Each optics tube FoV up to ~1.3 degree



Vavagiakis+ (arXiv:1807.00058 )

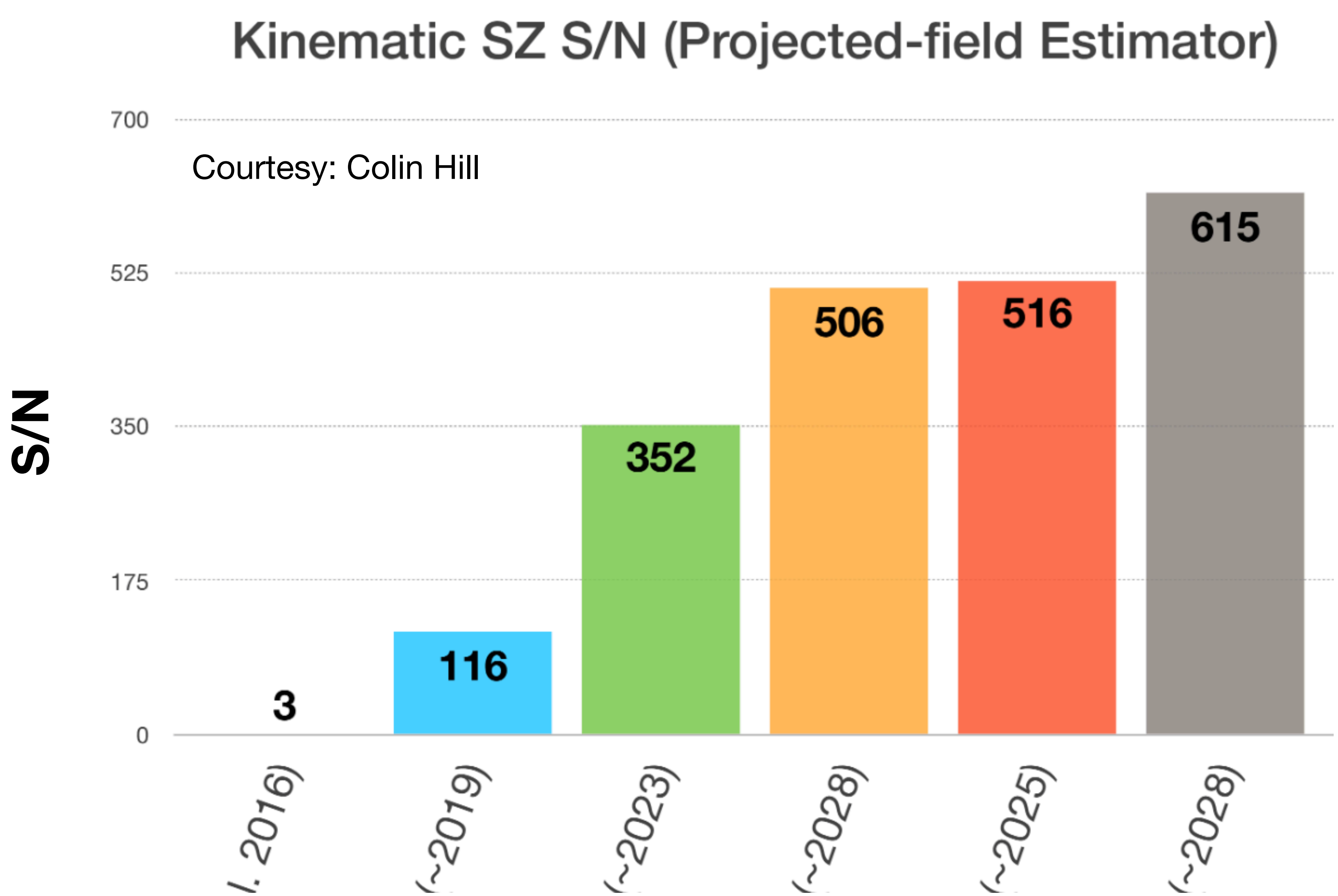
The FYST is being built in parallel with the SO LAT

At the moment not all the modules of PrimeCam are funded - First light late 2024

# Astro2020 Science White Paper

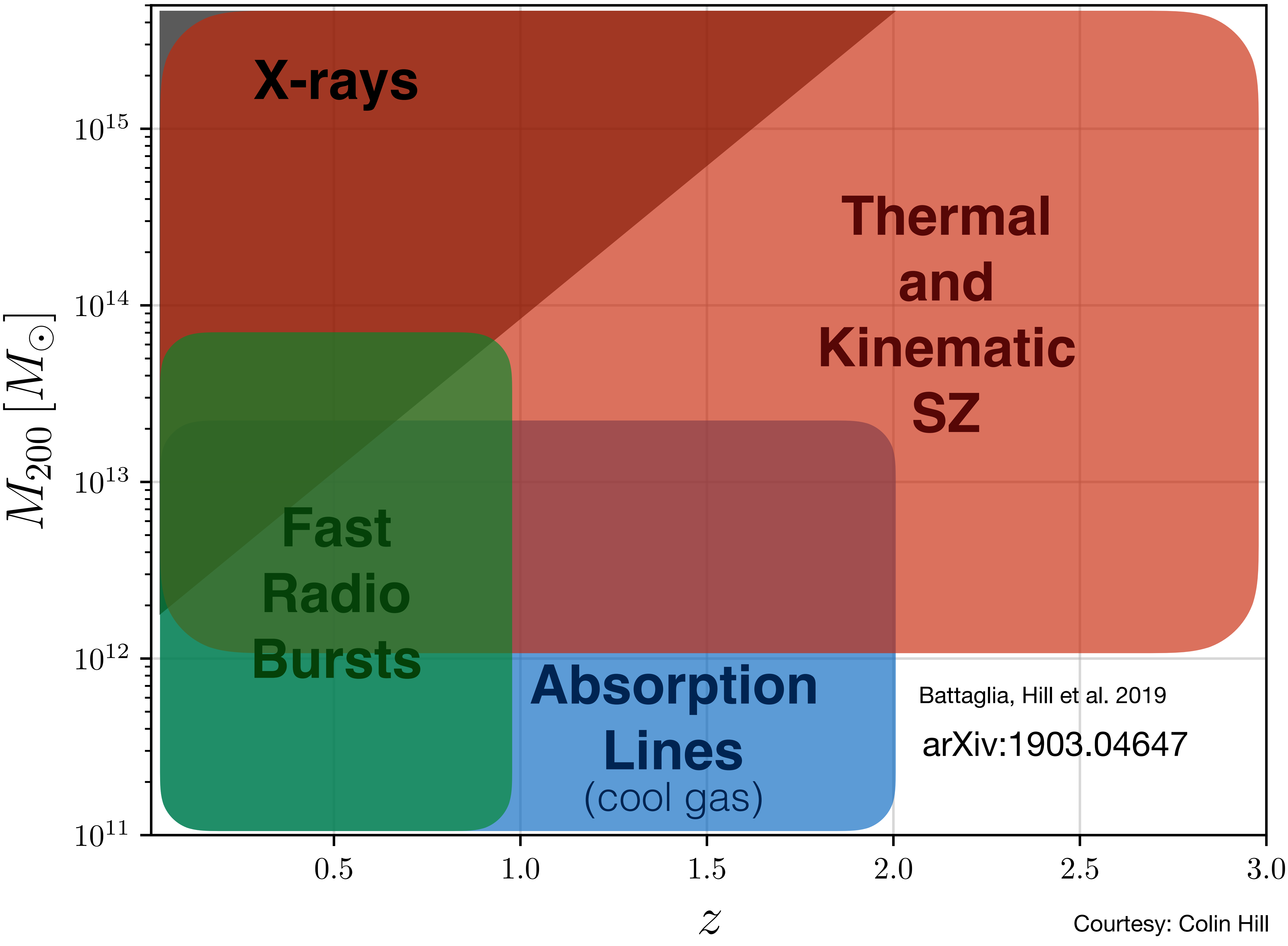
# Probing Feedback in Galaxy Formation with Millimeter-wave Observations

arXiv:1903.04647



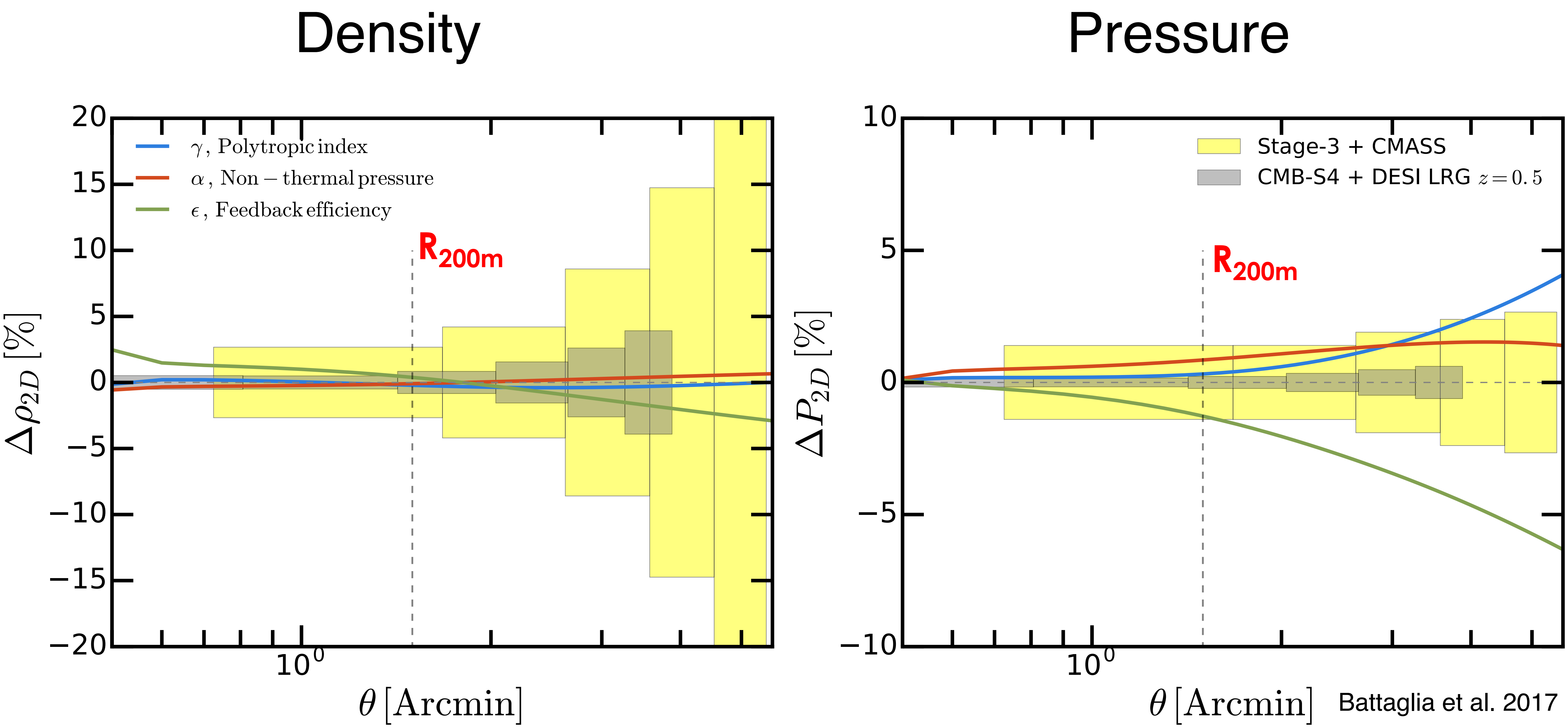

Battaglia, Hill et al. 2019

Sensitivity to Gas Properties Near $r_{200}$



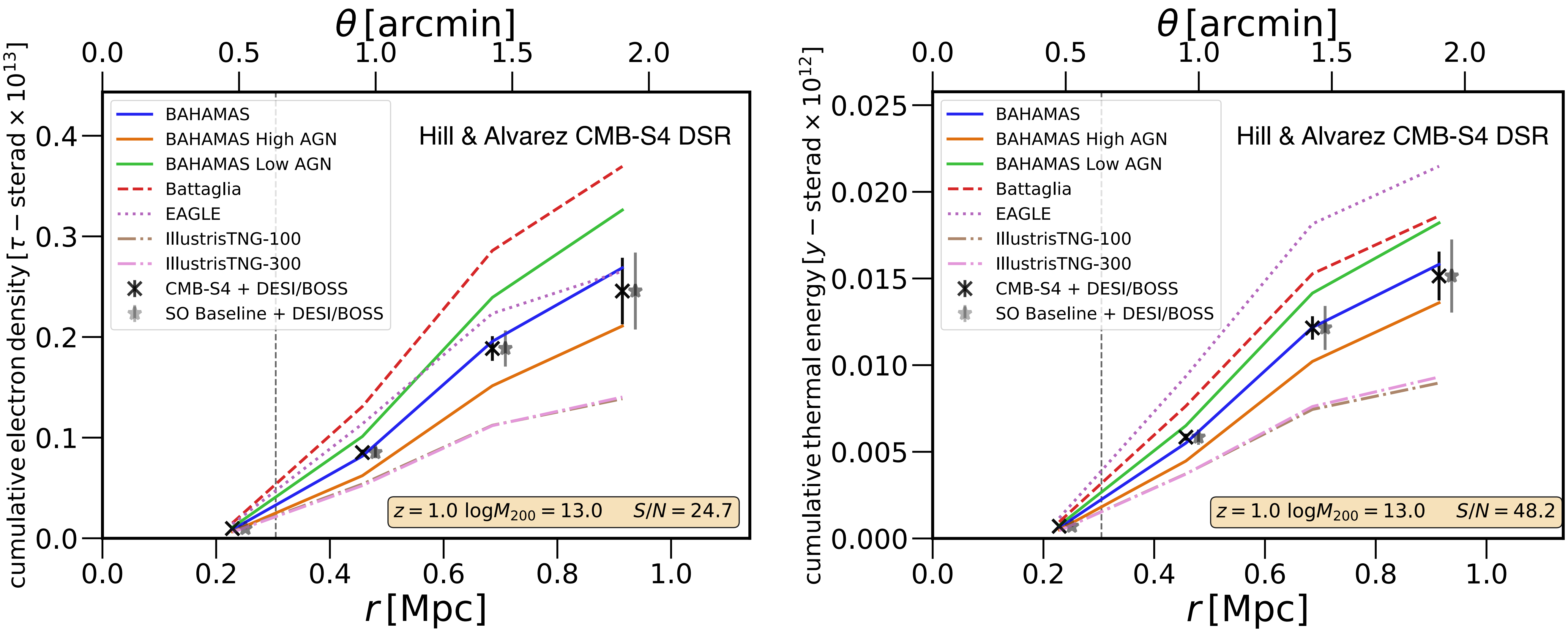

Courtesy: Colin Hill

# Combining tSZ & kSZ measurements forecasts




The improvement seen here is coming from:
Higher resolution, lower noise, and a larger sample

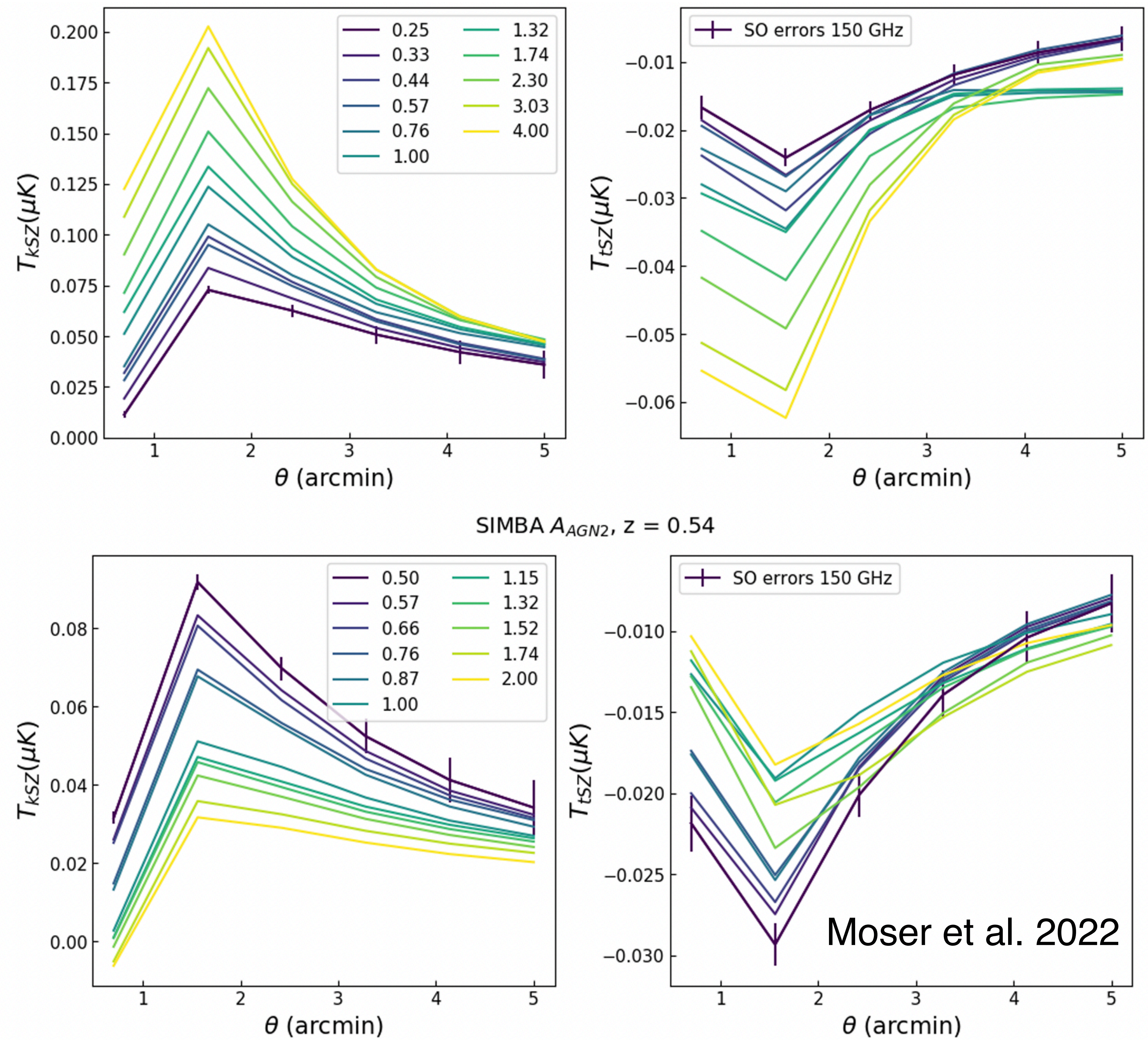
# Forecasted Constraints and Comparison to Hydro-Sims



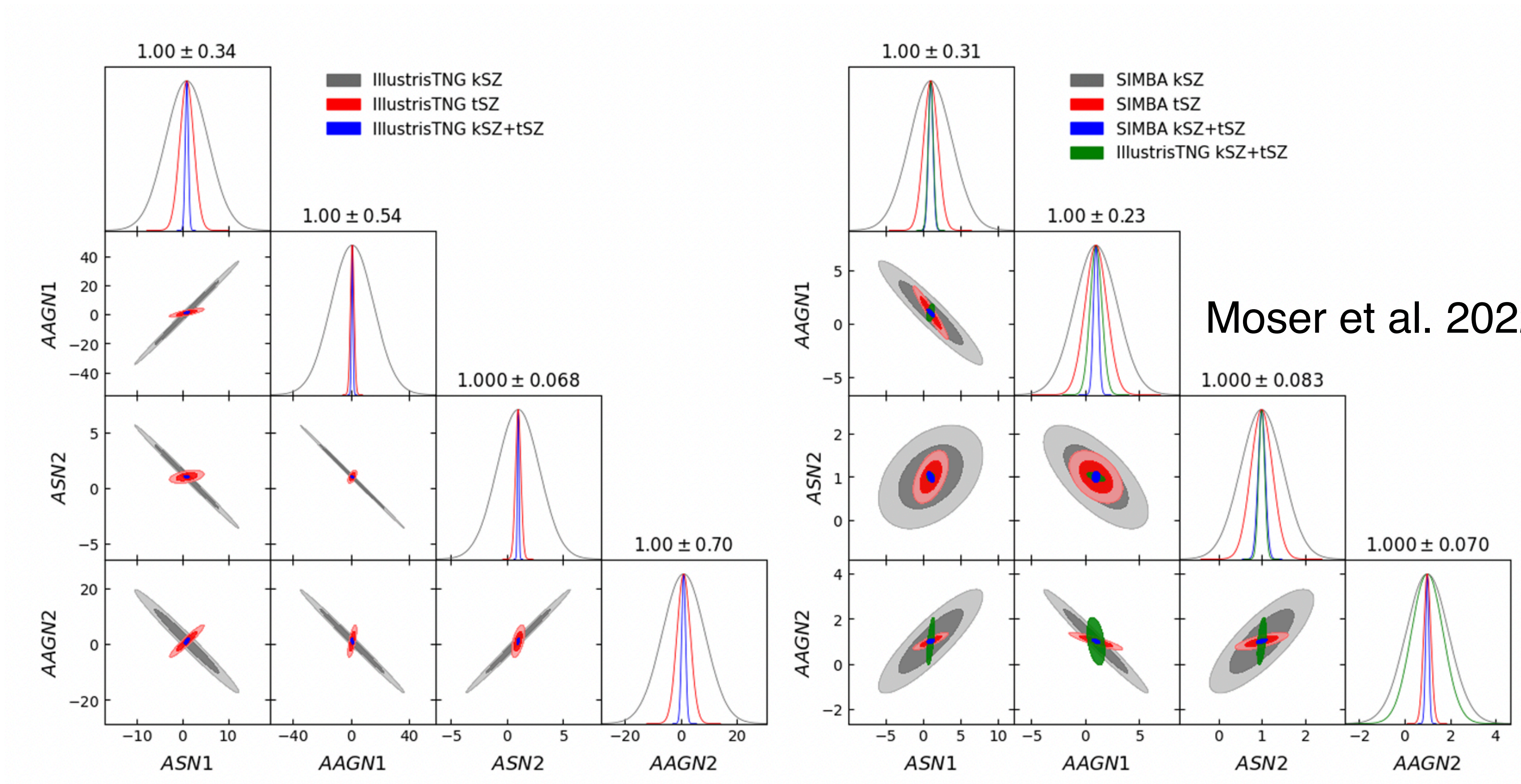

CMB-S4 will “rule out” all current galaxy formation models

ACT is already in tension with current sims

# Forecasted Constraints on sub-grid models CAMELS



# Forecasted Constraints on sub-grid models CAMELS




Moser et al. 2022

SO + CCAT will provide constraints to models of sub-grid physics

New observational window into the thermodynamic properties of the outer Circumgalactic Medium

Feedback Processes

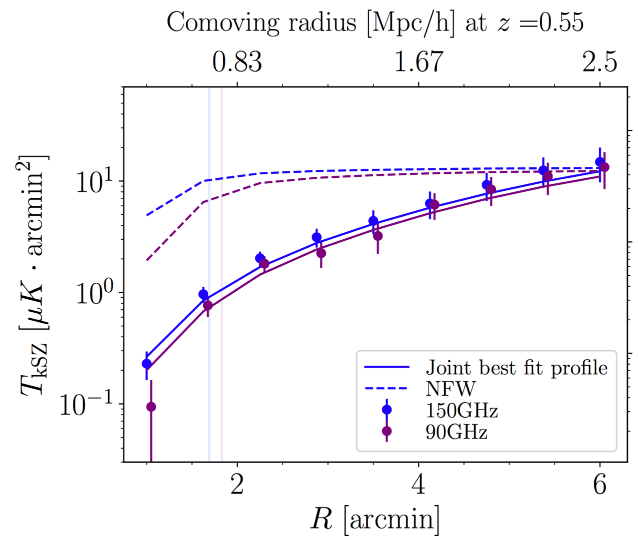
Numerical Simulations

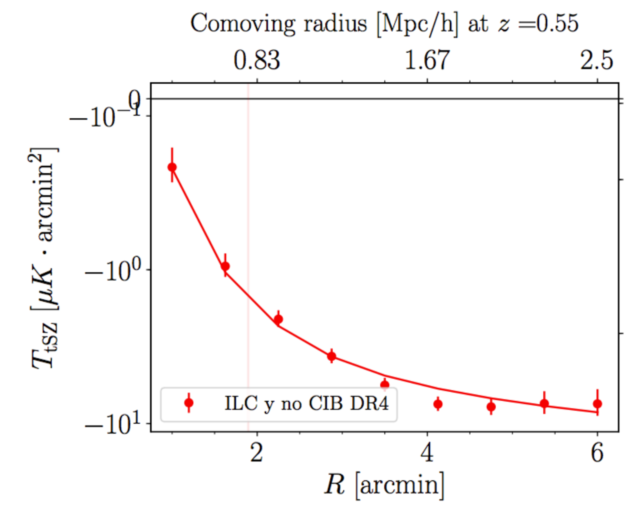
New observational window into the thermodynamic properties of the outer Circumgalactic Medium

## SZ cross-correlations

Soon gas density and pressure profiles

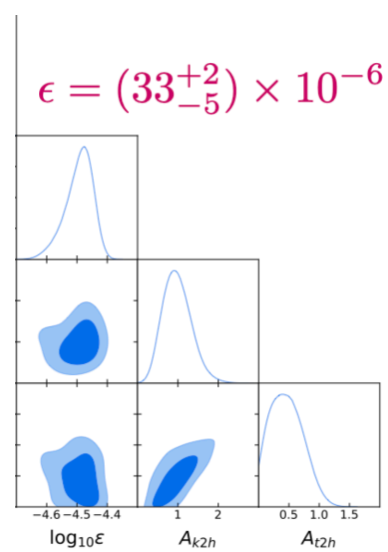
M > $10^{12}$ $M_\odot$, out to high-z



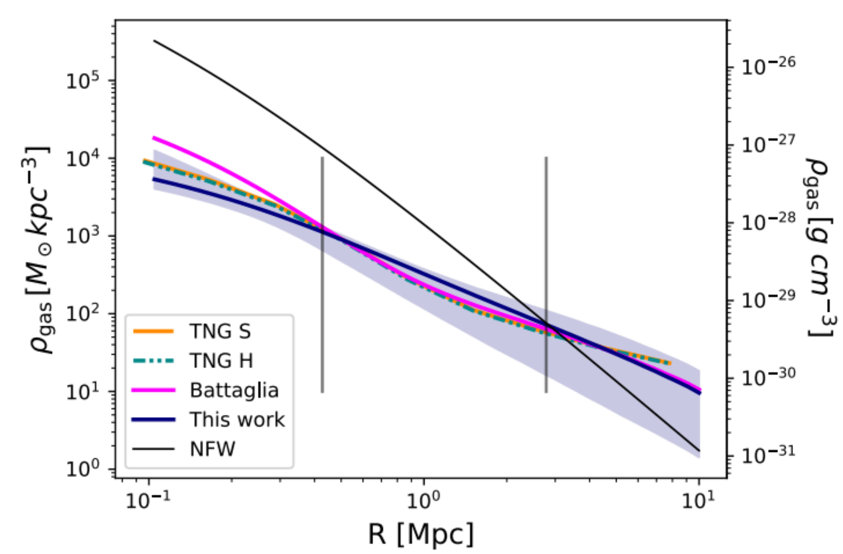

Feedback Processes

Energy injected in CMASS is ~30% of the binding energy




Numerical Simulations

Predictions from simulations for pressure fail at large radii - New models needed!




This is just the tip of the iceberg!

**Thank you**

**Questions?**