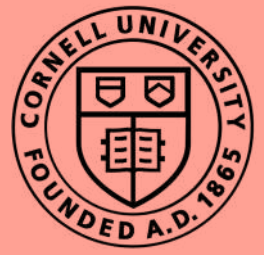
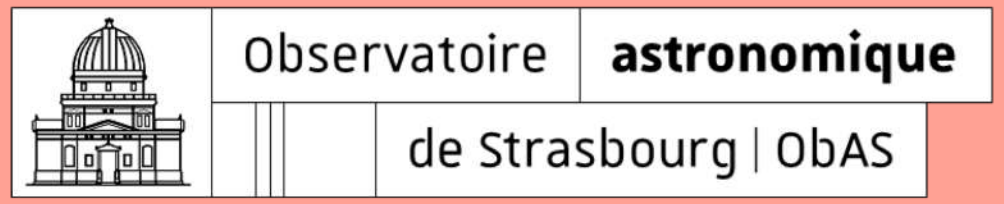
Constraining baryonic processes in galaxy halos with the SZ effects

Stefania Amodeo

with N. Battaglia, E. Schaan, S. Ferraro, E. Moser and the **ACT collaboration**





Amodeo et al. 2021 Phys. Rev. D 103, 063514 arxiv:2009.05558

Schaan et al. 2021 Phys. Rev. D 103, 063513 arxiv:2009.05557

Moser, Amodeo et al. 2021 ApJ 919, 2 arXiv:2103.02469

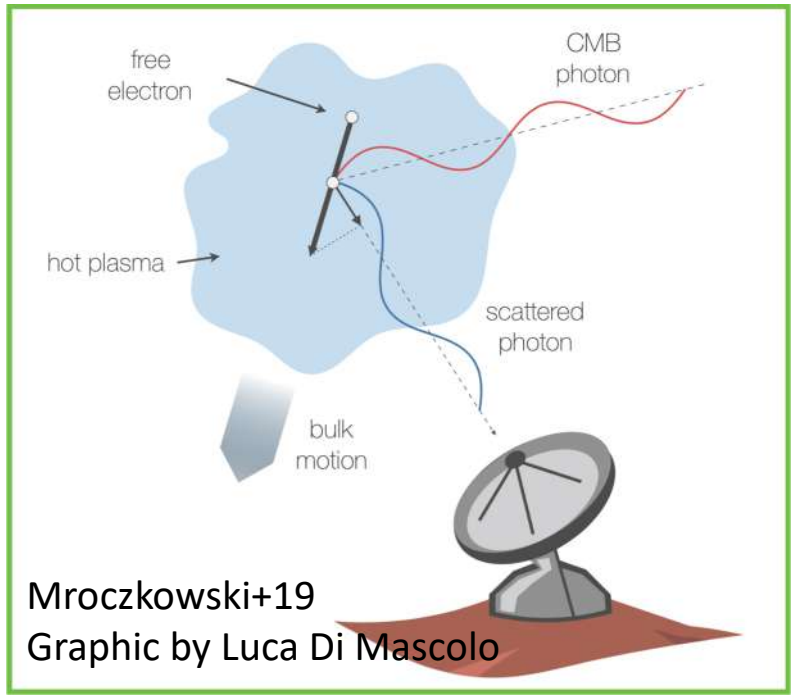
April 5th 2022

Cosmology seminar, UC Berkeley

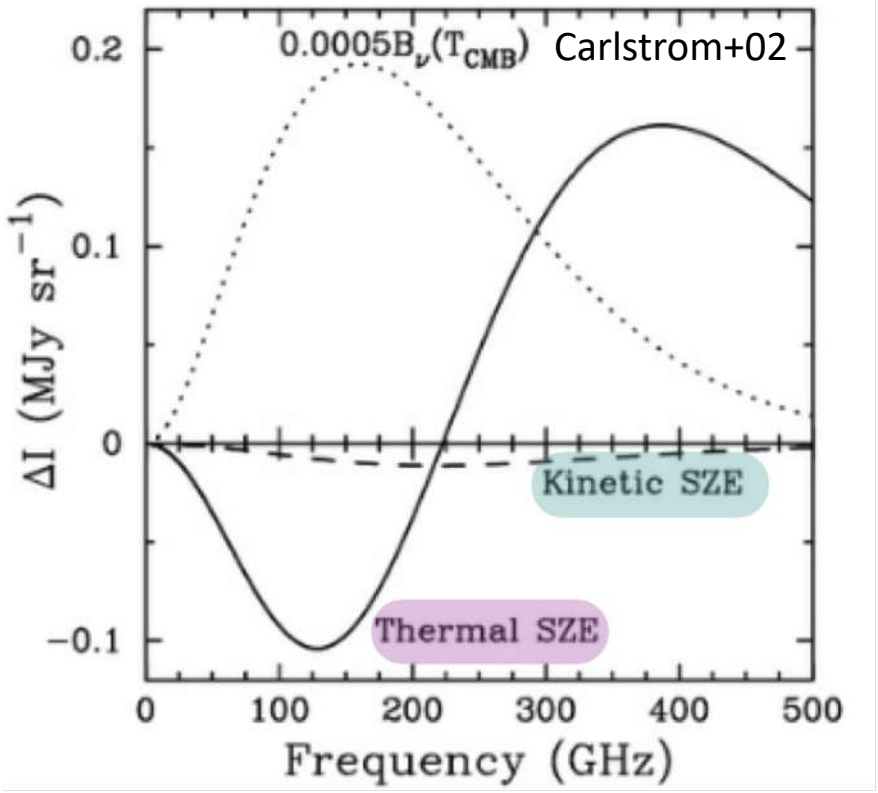
OUTLINE

- SZ effects as tracers of baryons in the intergalactic medium
- kSZ & tSZ detection with CMB obs and LSS surveys
- From observables to models: likelihood definition
- Results from ACT DR5 + *Planck* x BOSS
- Future outlook

Sunyaev-Zel'dovich effects



Mroczkowski+19
Graphic by Luca Di Mascolo



tSZ: hot gas

$$\frac{\Delta T(\nu)}{T_{\rm CMB}} = f_\nu \frac{\sigma_{\rm T}}{m_{\rm e}c^2} \int_{los} P_{\rm e}\, dl$$

kSZ: all ionized gas

$$\frac{\Delta T}{T_{\rm CMB}} = \int_{los} dl\, n_{\rm e}\, \sigma_{\rm T}\, \frac{v}{c}$$

Probes of gas density, pressure, temperature; independent of redshift
Uniquely suited to probe low-density regions

SZ cross correlation measurements

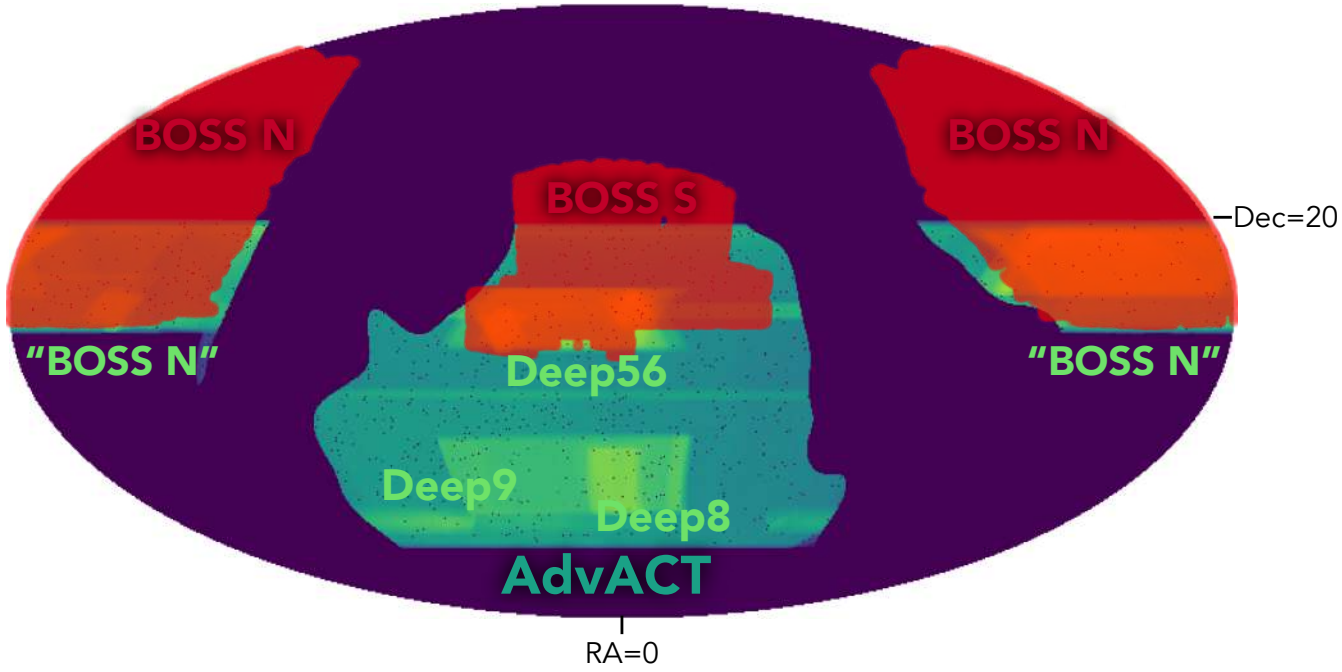


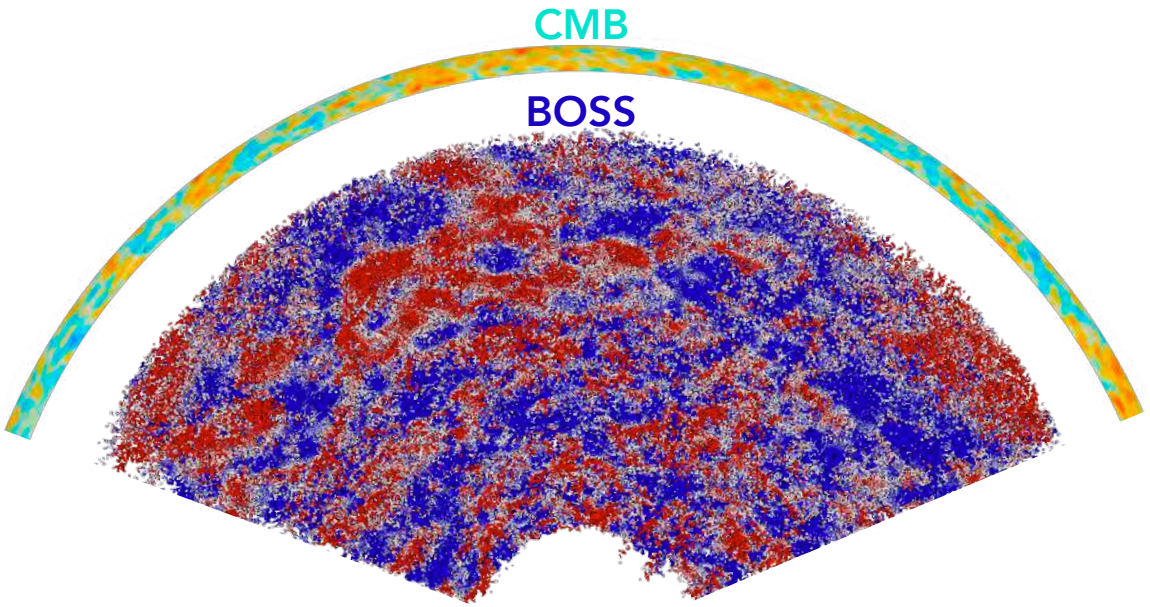
Fig: Schaan, Ferraro et al. 2021

BOSS/CMASS
~400k objects
Galaxy groups, $10^{13} M_{\odot}$
Spectroscopic sample, z = 0.4 - 0.7

ACT + Planck: 90, 150 GHz (Naess+20)
tSZ: T decrement
kSZ: l.o.s. velocity - weighted T
"velocity reconstruction"
(Planck15, Schaan+16)

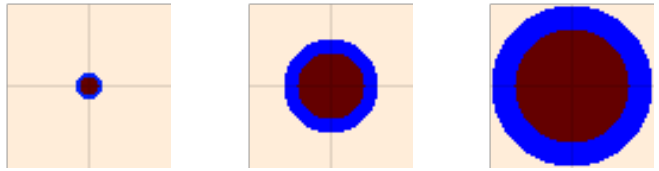
Herschel H-ATLAS: 600, 850, 1200 GHz
dust contamination (see back-up slides)

SZ cross correlation measurements



Stack CMB temperature maps
at the galaxies' positions

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



Aperture photometry filtering

tSZ: T decrement (includes dust thermal emission)

kSZ: l.o.s. velocity - weighted T
"velocity reconstruction" method
(Planck15, Schaan Ferraro+16)

ThumbStack pipeline
EmmanuelSchaan/ThumbStack

Schaan, Ferraro et al. 2021

SZ cross correlation measurements

ACT + Planck (microwave)

Hubble *(optical)*

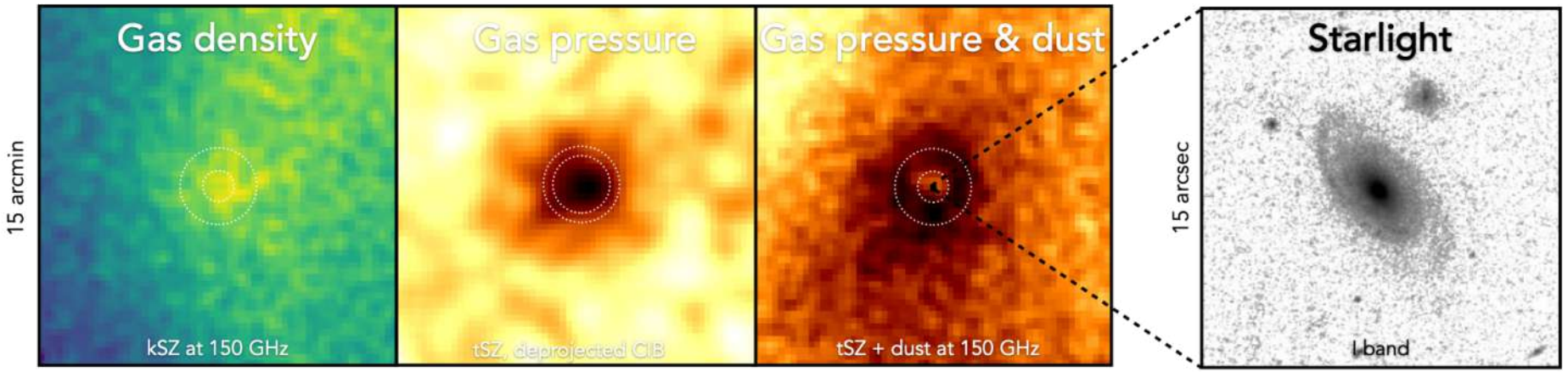
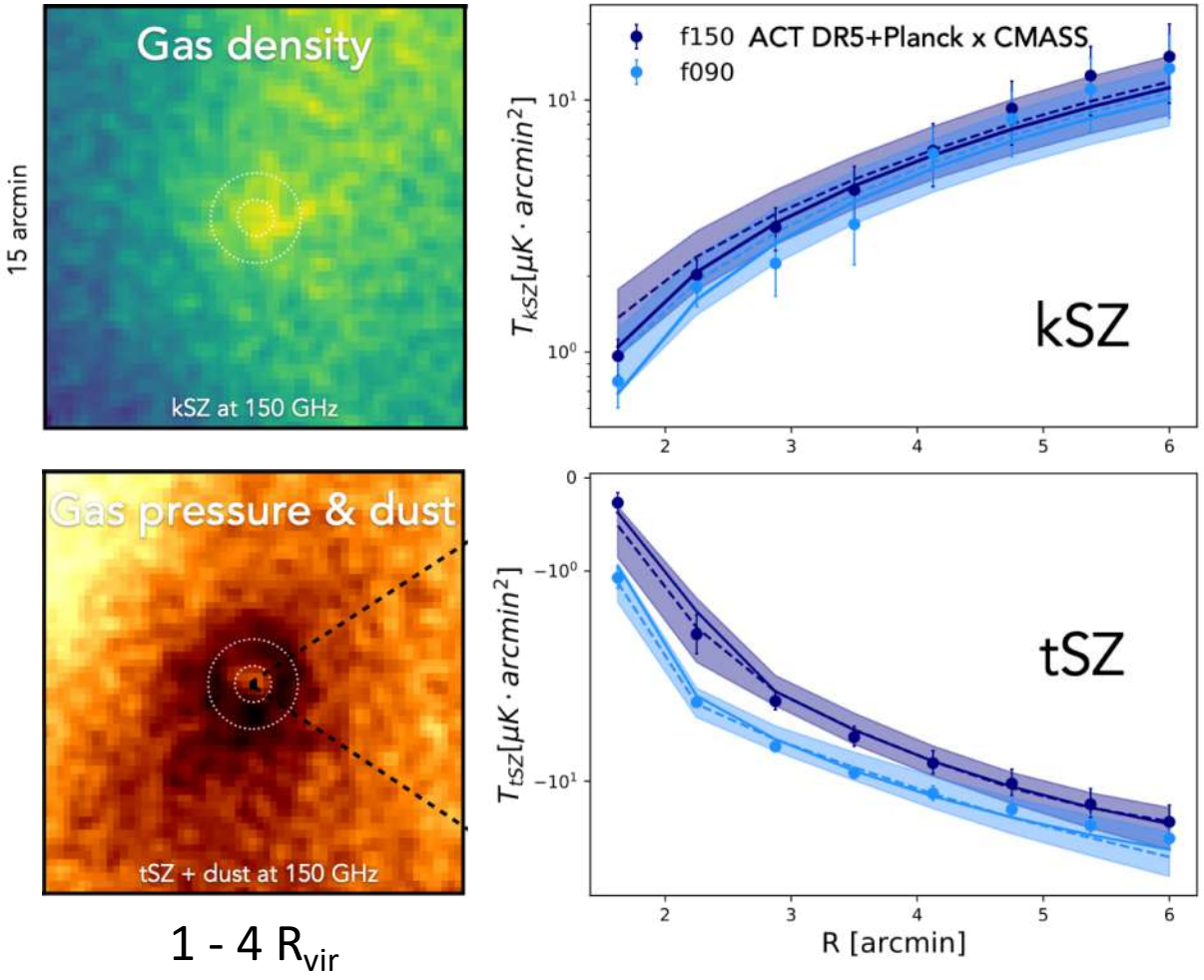


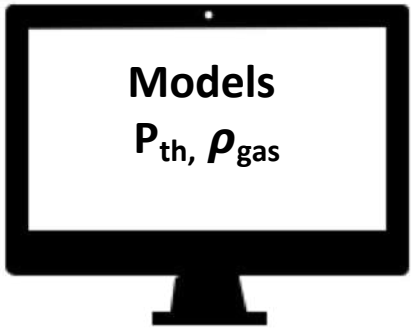
Figure: E Schaan. ACT+Planck microwave images: Schaan et al 2020. HST ACS I band image: Masters et al 2011. ACT photo: John Ward. Planck photo: ESA/AOES Medialab. HST photo: NASA.

From observables to models



1 - 4 R_{vir}

Schaan+21; Amodeo+21



Model-to-observable projection code

for Galaxy Thermodynamics

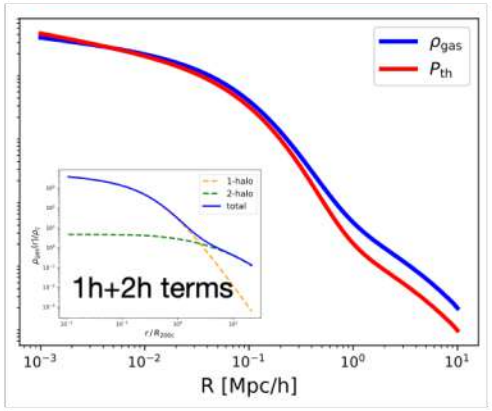
S. Amodeo, N.Battaglia

https://github.com/samodeo/Mop-c-GT

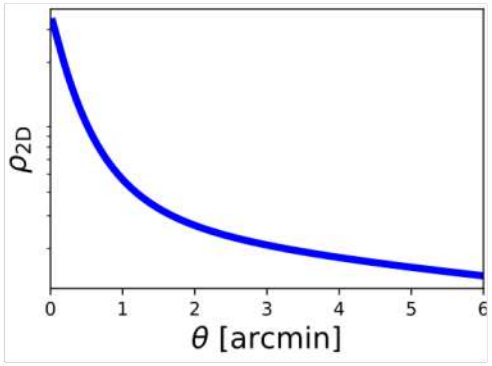
(implement line-of-sight projection, instrumental beam convolution, aperture photometry filter, …)

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

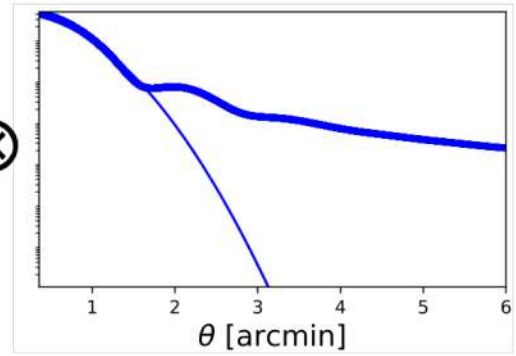
3D theoretical profiles



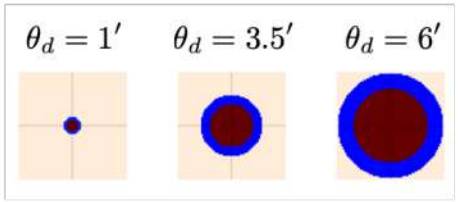
line-of-sight projection



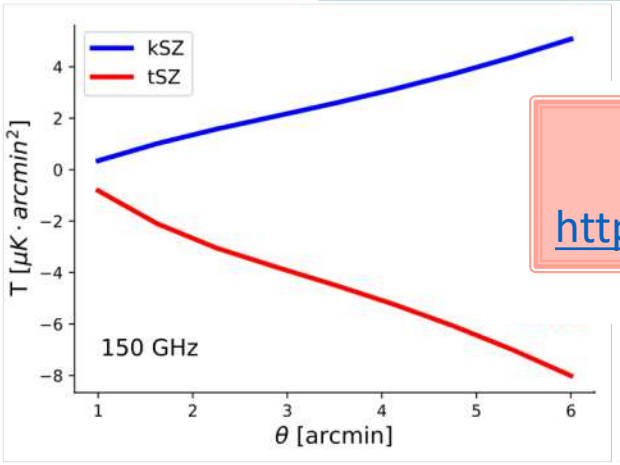
beam convolution



aperture photometry filtering



2D observed profiles

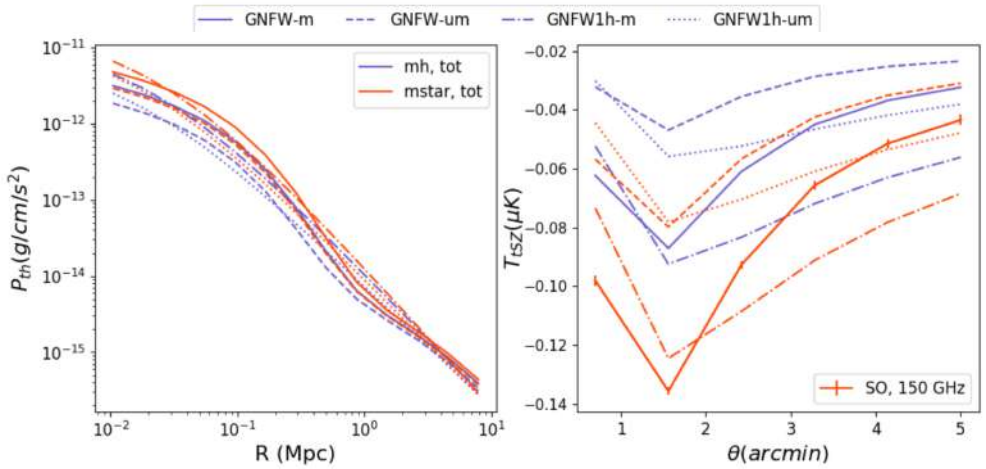


S. Amodeo, N.Battaglia

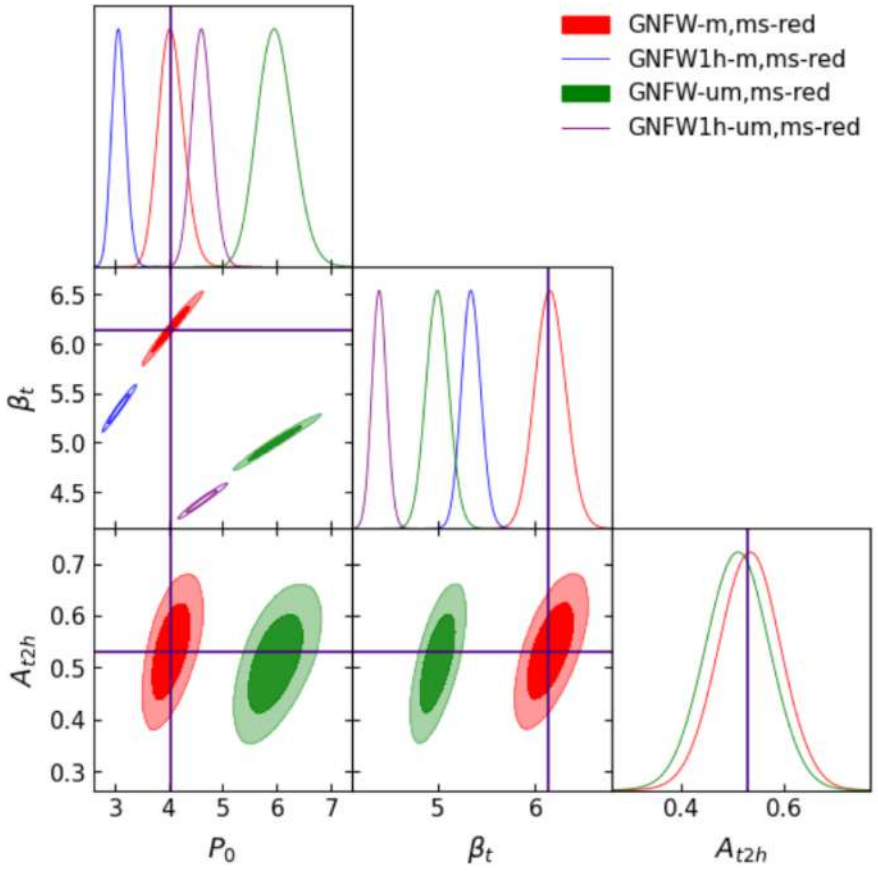
https://github.com/samodeo/Mop-c-GT

Modeling choices matter

Model CMASS using IllustrisTNG



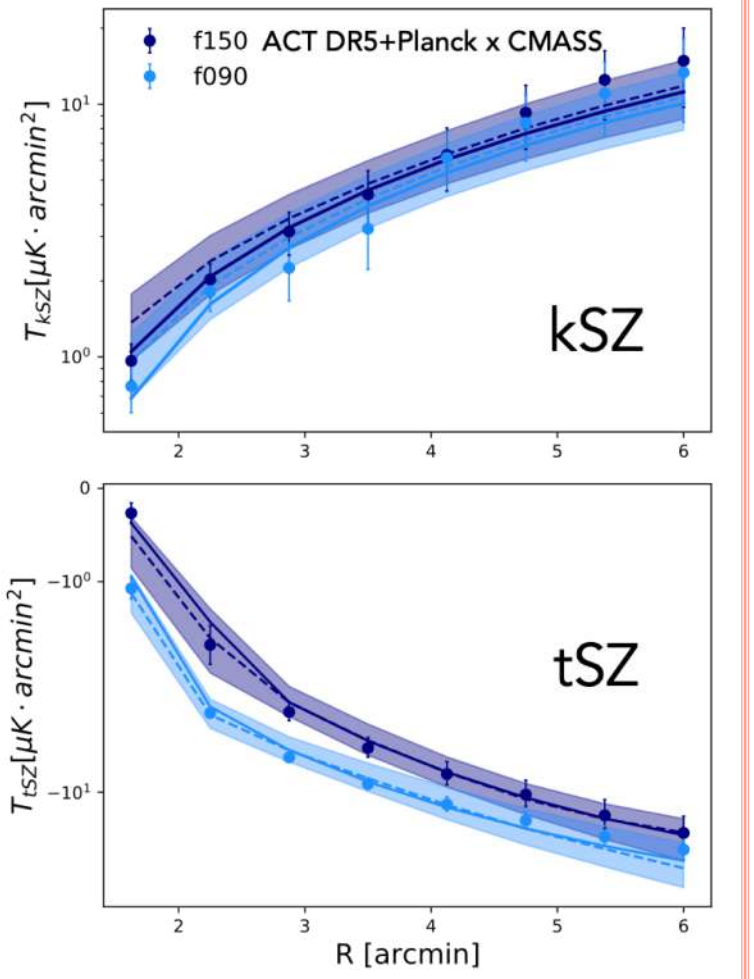
Sample Selection	
'ms' = Stellar mass-selected	'red' = Color-selected, $g - r > 0.6$
'mh' = Halo mass-selected	'tot' = No color selection
Fitting Model	
'm' = CMASS mass distribution matched	'GNFW' = With two-halo term
'um' = Unmatched	'GNFW1h' = No two-halo term

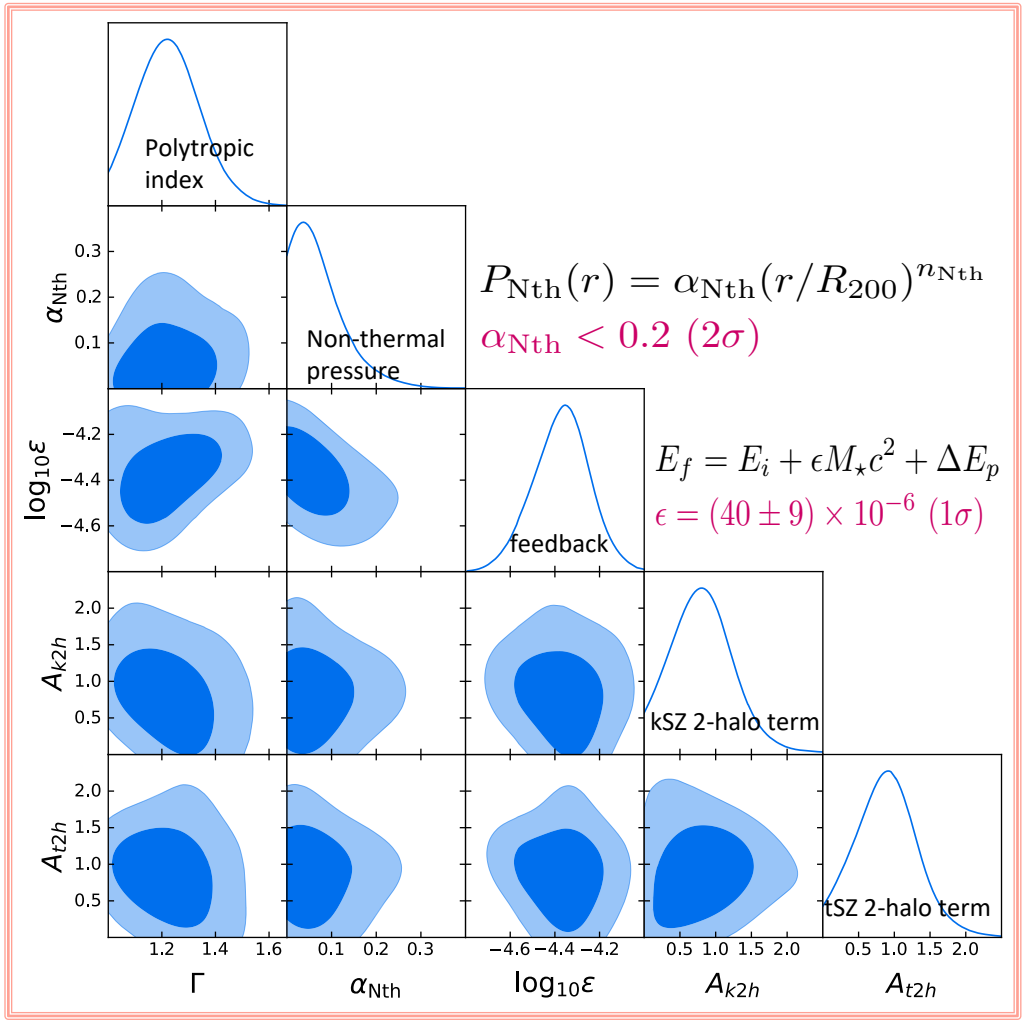


Moser, SA et al. 2021

Feedback & Non-Thermal Pressure

Joint kSZ + tSZ (+ dust) fit to a polytropic gas model $P \propto \rho^{\Gamma}$ (Ostriker et al. 2005)



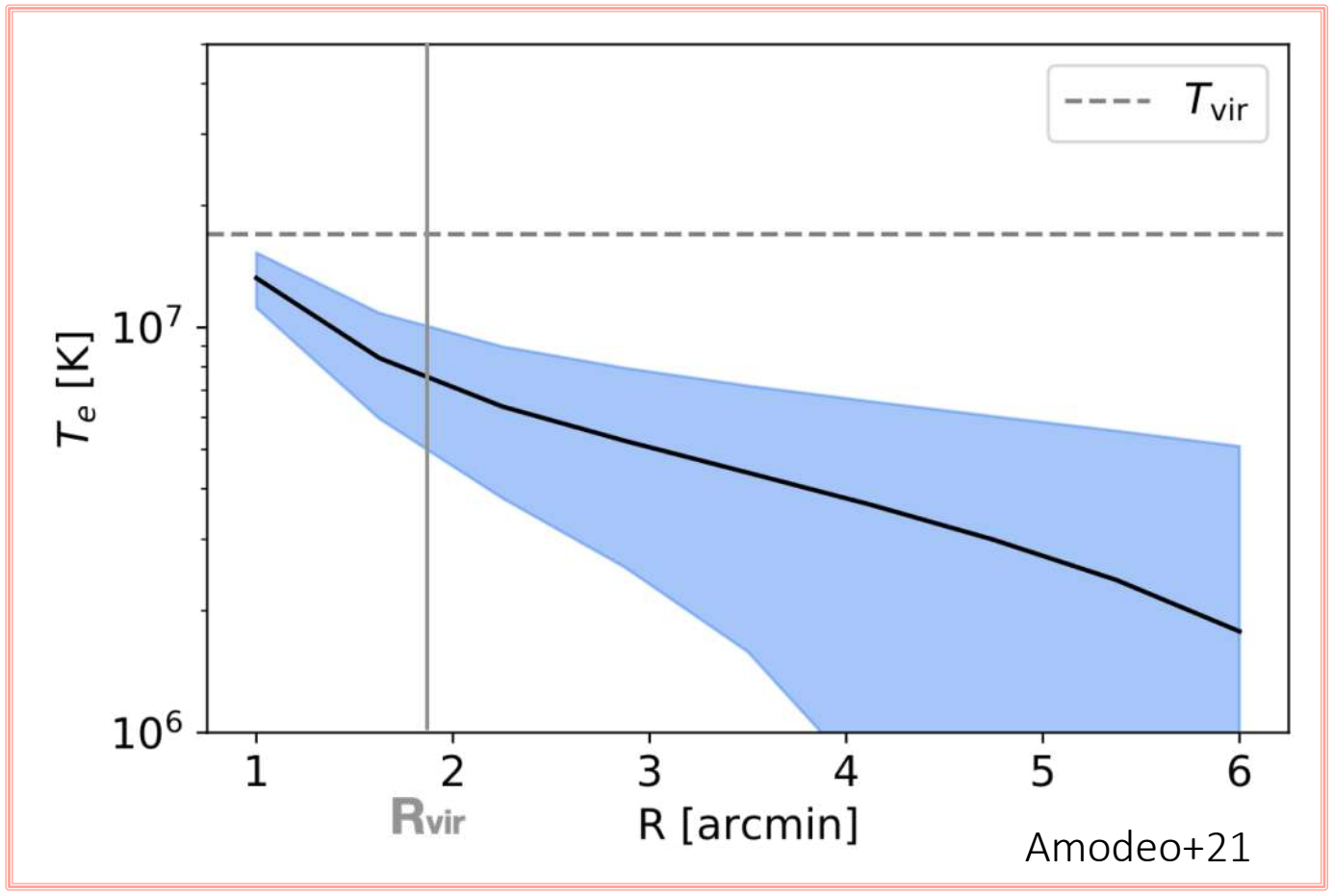


<20% of total pressure within R_{200} is non thermal

30% of total binding energy is injected by feedback

Amodeo+21

Gas temperature profile



$$\mathrm{tSZ} \propto \mathrm{n_e T_e}$$

$$\mathrm{kSZ} \propto \mathrm{n_e}$$

Baryon profiles

of group-sized halos

(M_{vir} ~ 3x10^{13} $M_\odot$)

beyond the viral radius

Measurements of the thermodynamic profiles beyond the virial radius

New observational window in the properties of the CGM/IGM gas

Impact on galaxy formation?

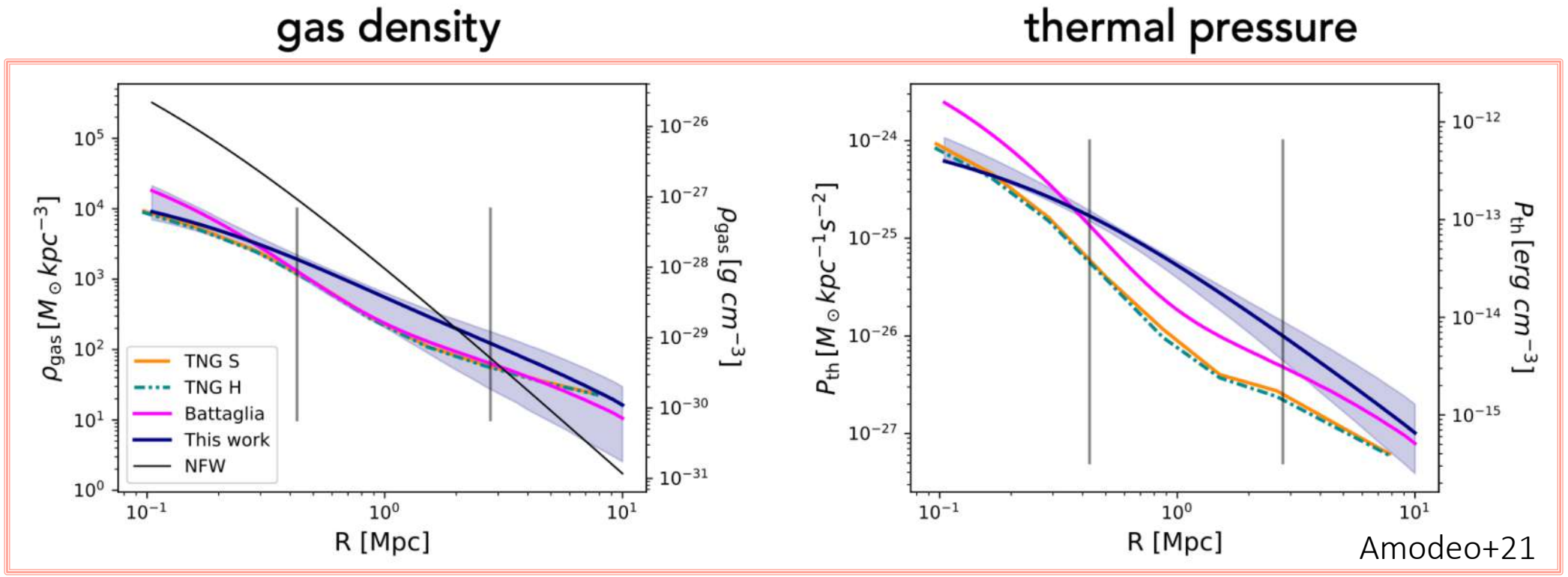
Non-trivial tests of the sub-grid feedback models in cosmological simulations

Impact on cosmology?

Empirical constraints on baryonic effects on the matter power spectrum

Comparison to Cosmological Simulations

Tests of sub-grid feedback models

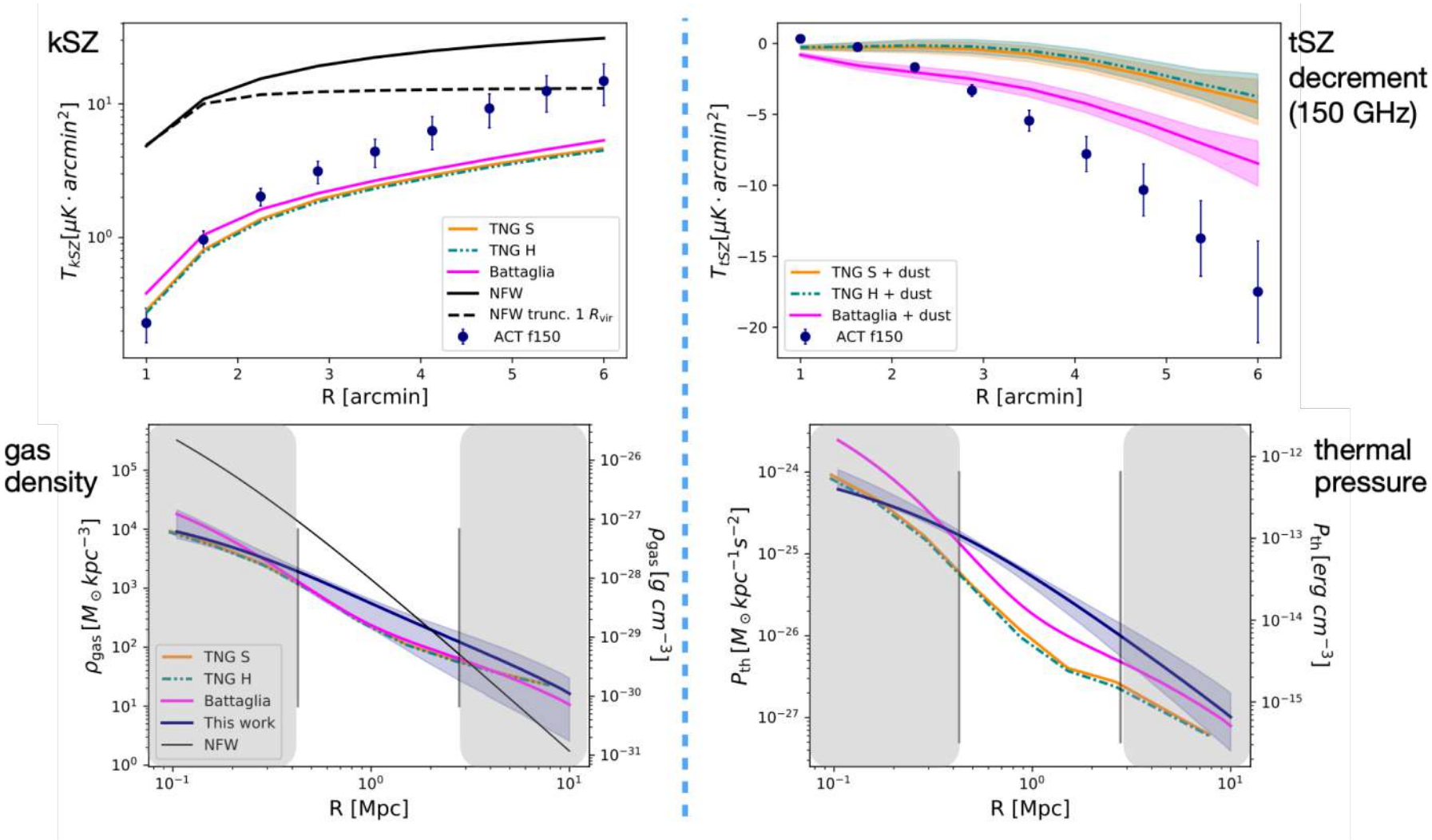


Less steep, more extended than the dark matter profile (NFW rejected at > 90σ)

Hydro sims (IllustrisTNG, Battaglia) under-predict the amount of pressure

Sub-grid stellar and AGN feedback models implemented in sims do not go that far

Comparison to Cosmological Simulations



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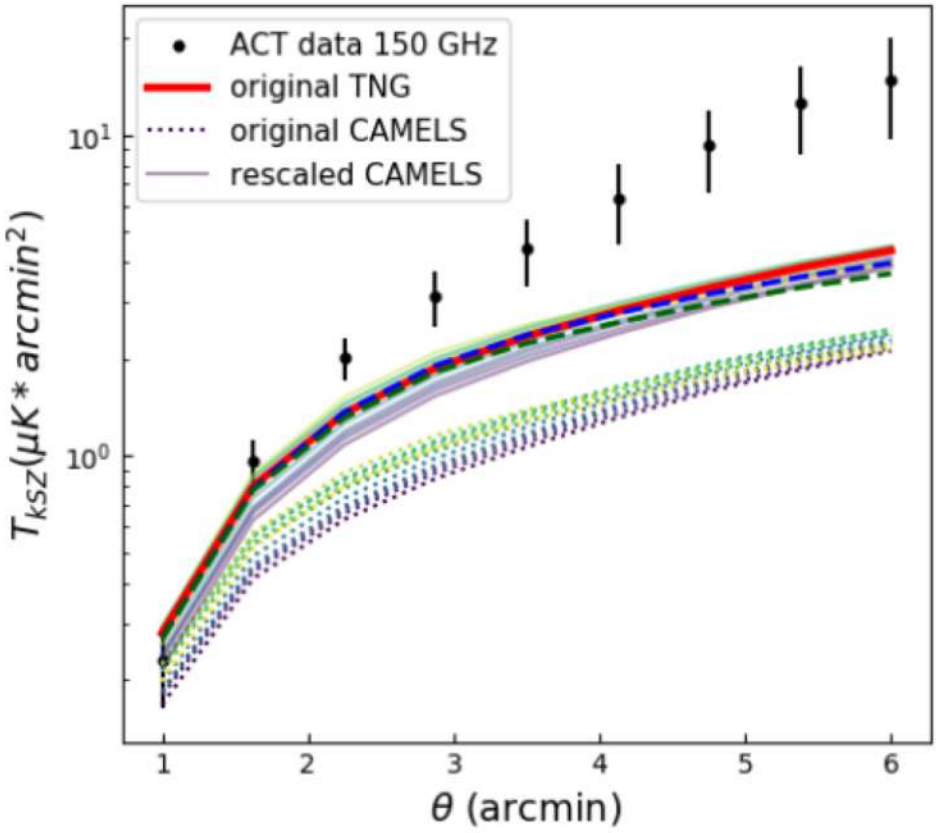
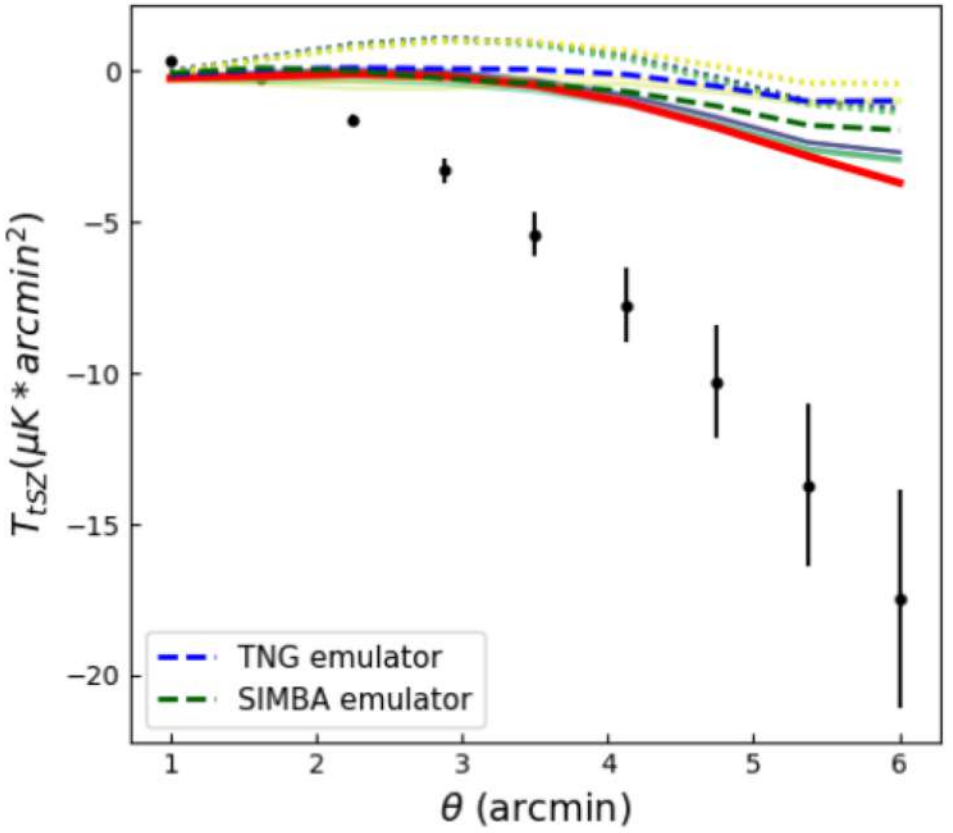
Comparison to Cosmological Simulations

CAMELS: Cosmology and Astrophysics with MachinE Learning Simulations



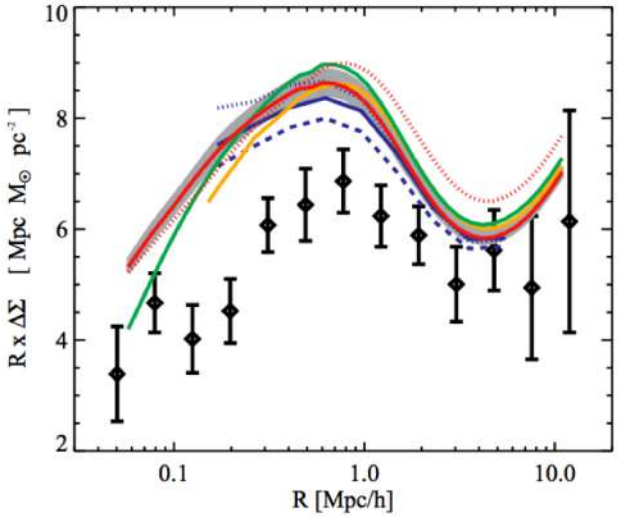


Vary ''wind speed'' parameter (A_{SN2})

Moser et al. 2022

Simulated tSZ profiles cannot reproduce ACT observations

Galaxy-galaxy lensing



Lensing is Low: Cosmology, Galaxy Formation, or New Physics?

Alexie Leauthaud[1,2], Shun Saito[3], Stefan Hilbert[4,5], Alexandre Barreira[3], Surhud More[2], Martin White[6], Shadab Alam[7,8], Peter Behroozi[6,9], Kevin Bundy[1,2], Jean Coupon[10],

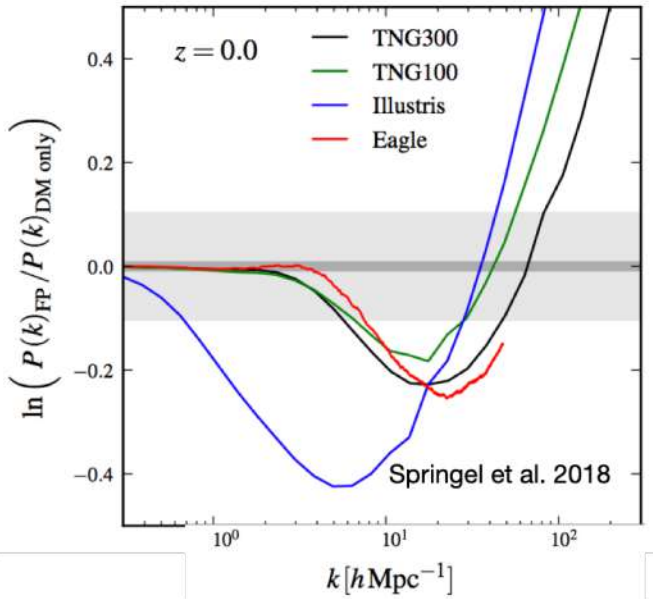
Lensing halo models that fit the large scale clustering of galaxies are discrepant with weak-lensing observations of the same galaxies

Baryons do not trace the DM on small scales

Baryon physics is much richer than DM

Implications for the matter power spectrum

Our observations directly probe baryon profiles in the mass range (CMASS) relevant for matter power spectrum



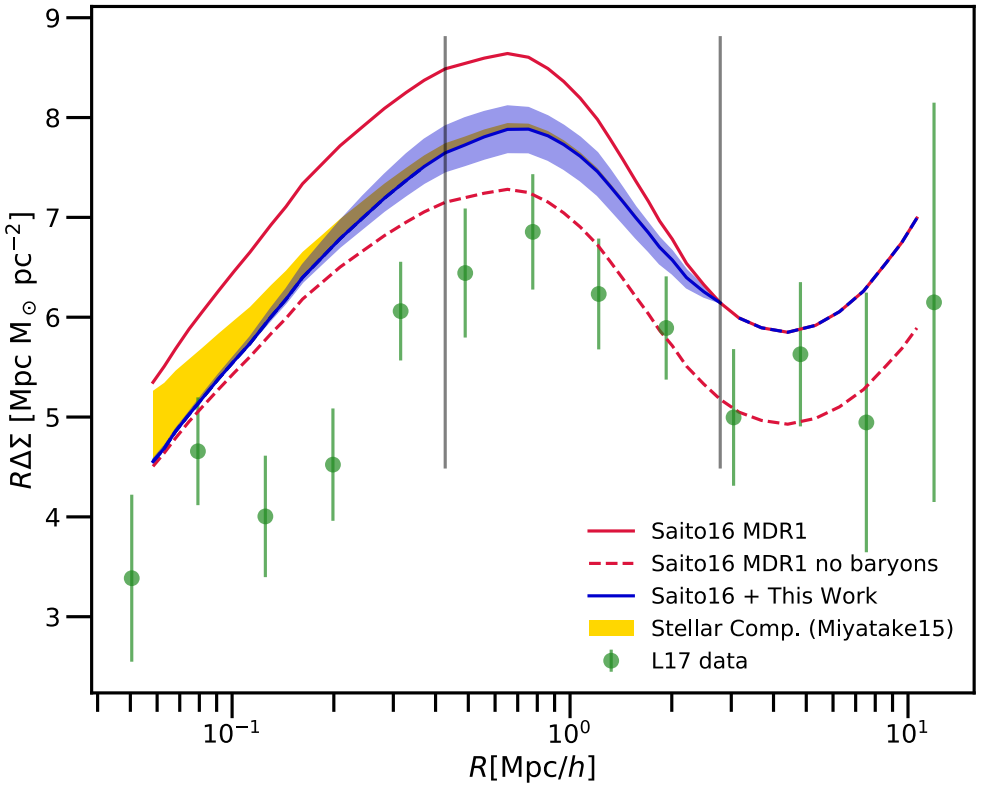
Implications for lensing observations

$$\Delta\Sigma(R) = \bar{\Sigma}(< R) - \Sigma(R)$$

$$\Delta\Sigma_{\rm tot} = \Delta\Sigma_{\rm DM} + \Delta\Sigma_{\rm b}$$

From Leathaud et al. 2017
decreased by the baryon fraction

From our kSZ measurements and
projected to 2 dimensions



Amodeo+21

"Lensing is low" (Leauthaud+17)

Including our gas density model from kSZ reduce the model vs data discrepancy by half

Full reconciliation is probably a combination of many effects

Future observations

Big improvement expected from:

More detectors

Wider frequency coverage

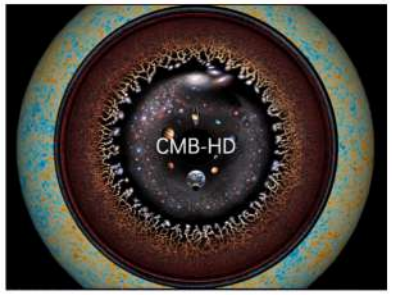
Higher resolution

Larger samples

CCAT-p

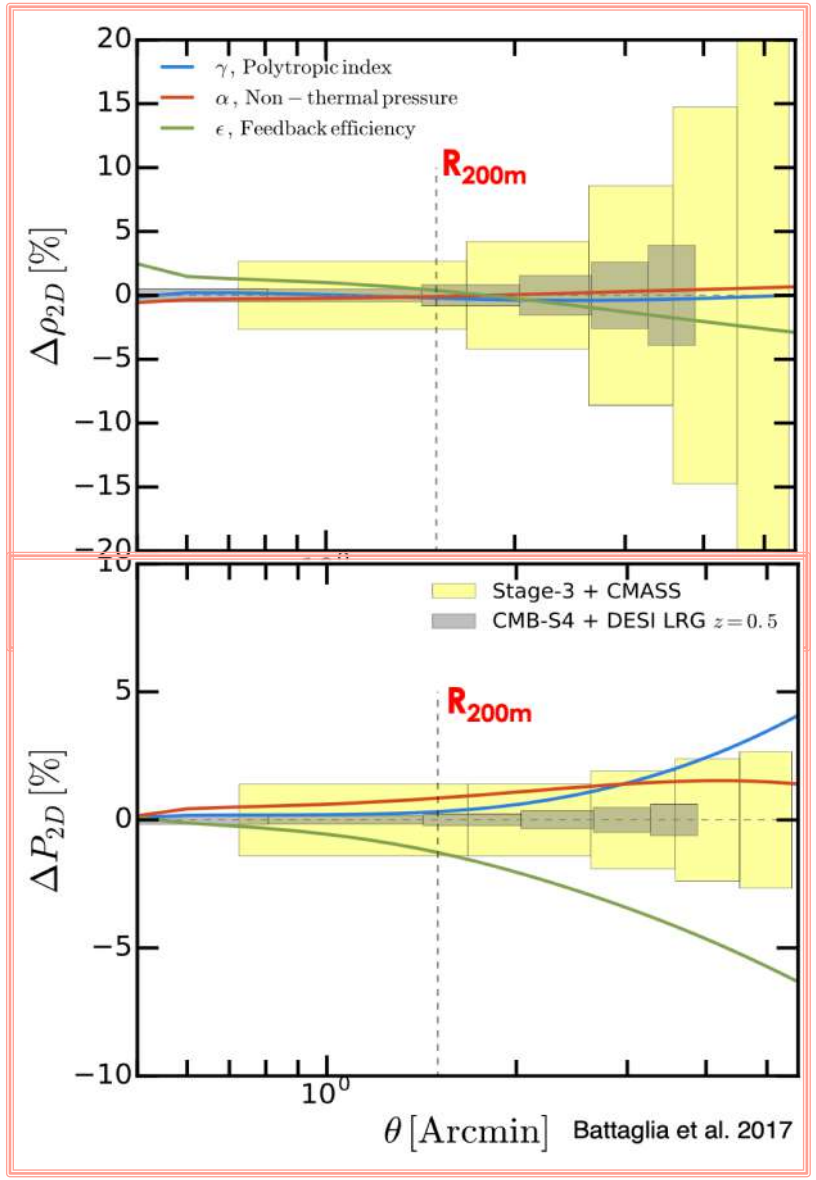
SIMONS OBSERVATORY

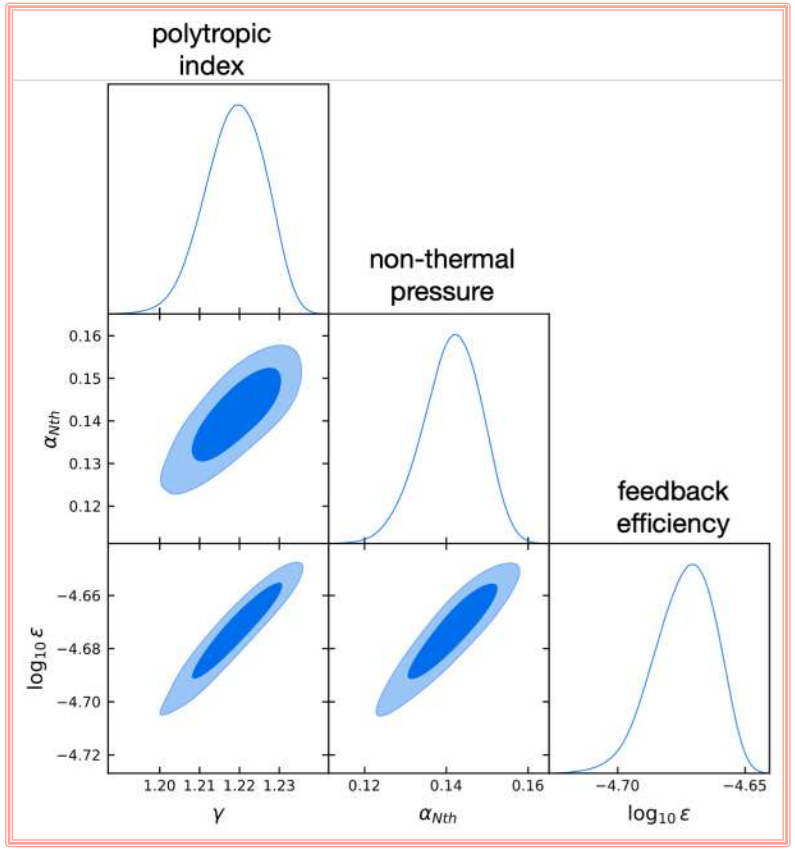
CMB-S4
Next Generation CMB Experiment



VERA C. RUBIN
OBSERVATORY

Combining tSZ & kSZ measurements forecasts





Forecasts for CMB-S4 x DESI

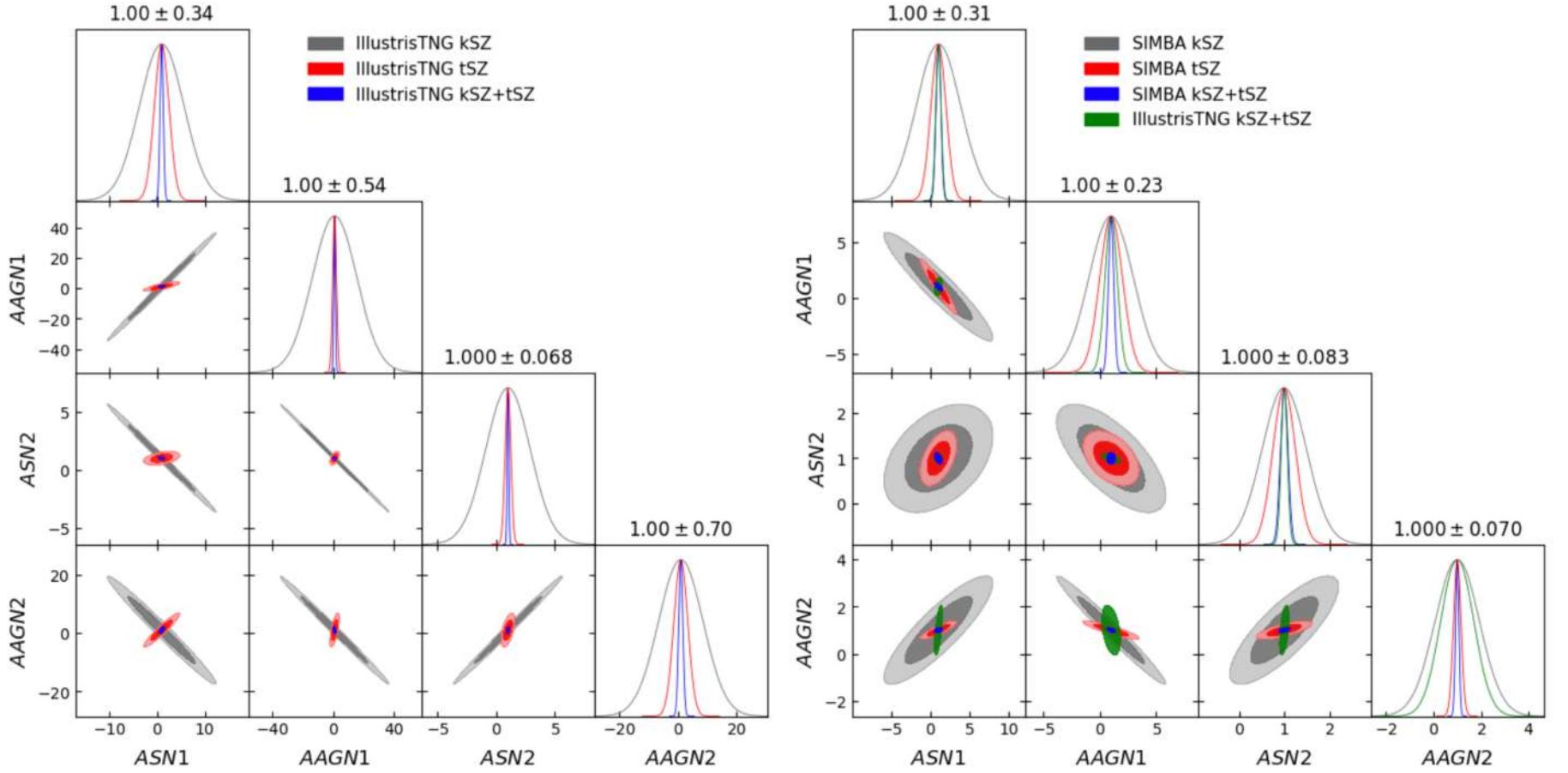
kSZ (~200σ) + tSZ (~500σ)

~3x10^6 galaxies

<5% constraints!

Feedback forecasts from CAMELS

DESI-like galaxy sample observed by the Simons Observatory



Fisher analysis

Constraints on all four feedback parameters, some within 10%

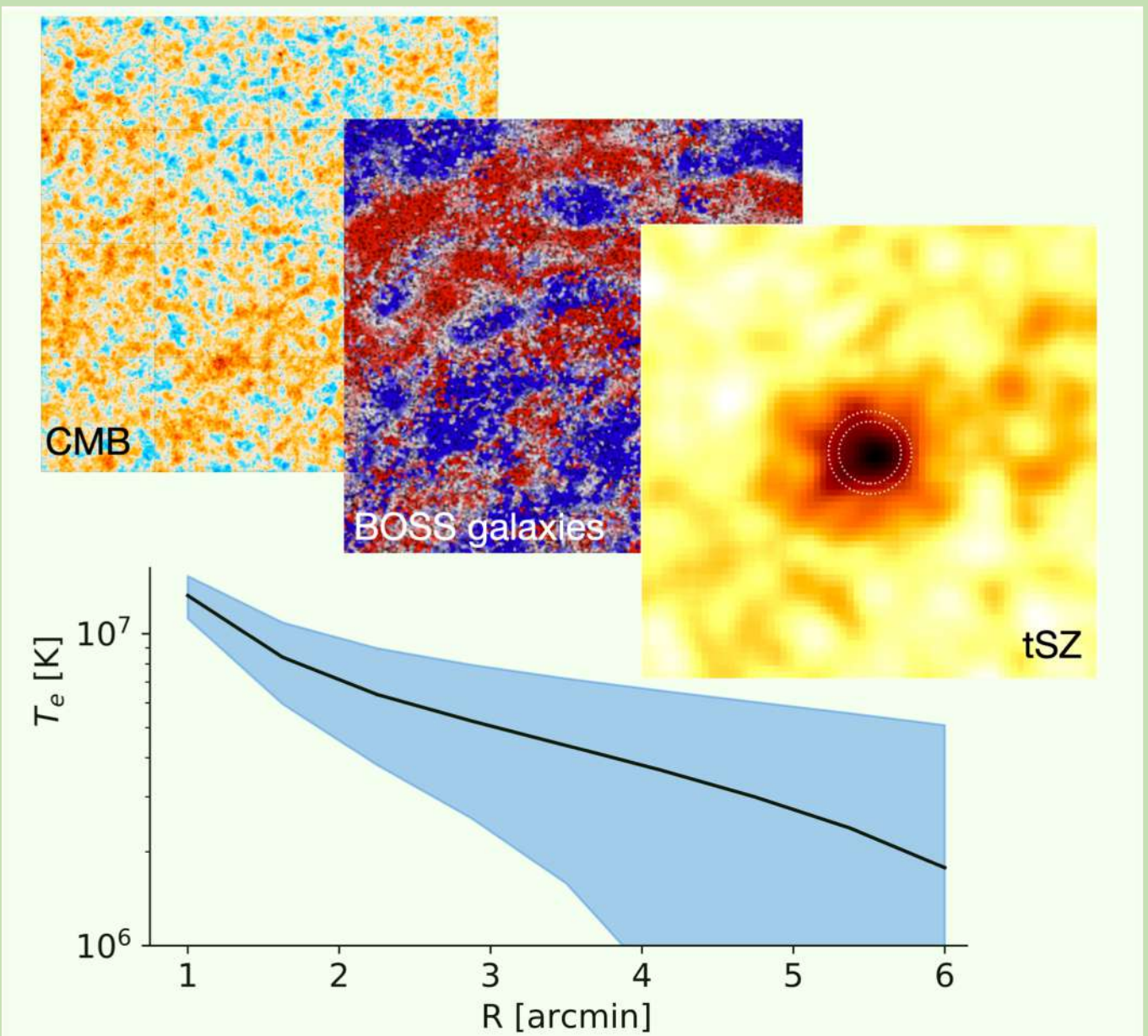
Astrophysical parameters: amplitudes of stellar and AGN feedback models

Moser et al. 2022

New observational window in the properties of the IGM gas

with kSZ & tSZ cross-correlation measurements

- Probe baryon profiles in low-density environments and out to the outskirts
- Constrain feedback, non-thermal pressure, gas temperature
- Tests of hydrodynamical simulations
- Improvements from new LSS surveys (e.g., DESI, PFS, Euclid) and future CMB exp. (e.g. SO, CCAT_Prime, CMB-S4)
- Refine binning in mass, galaxy property, redshift, etc.



ACT+*Planck* CMB: Naess et al. 2020
BOSS galaxies visualization and tSZ stacked map: Schaan et al. 2021
Temperature profile: Amodeo et al. 2021

Thank you!

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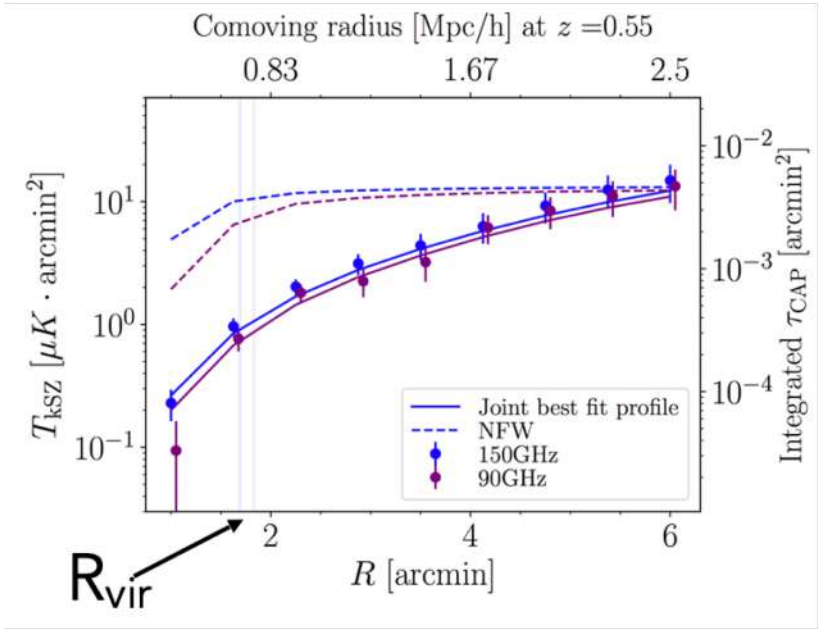
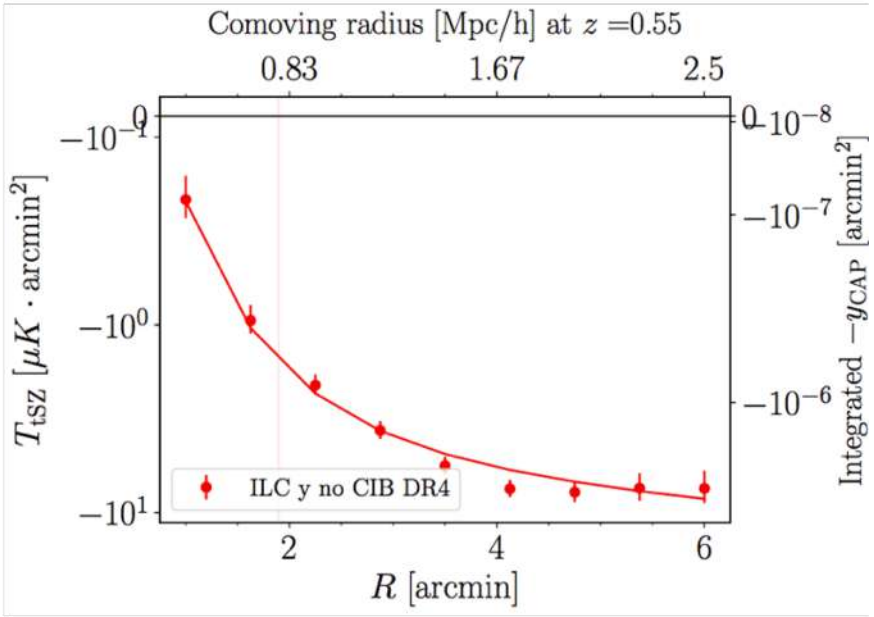
Backup slides

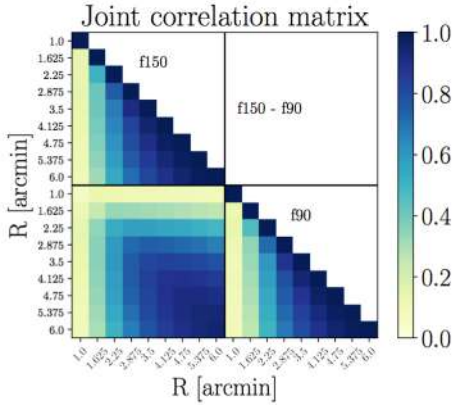
SZ cross correlation measurements

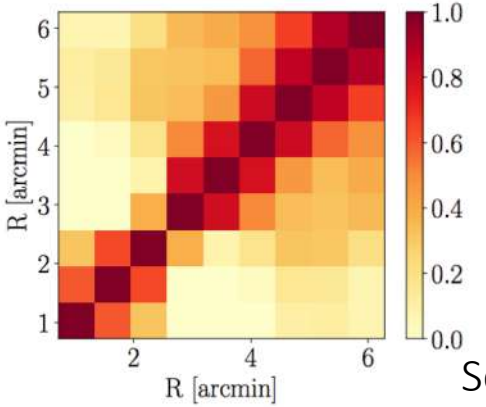
kSZ



tSZ



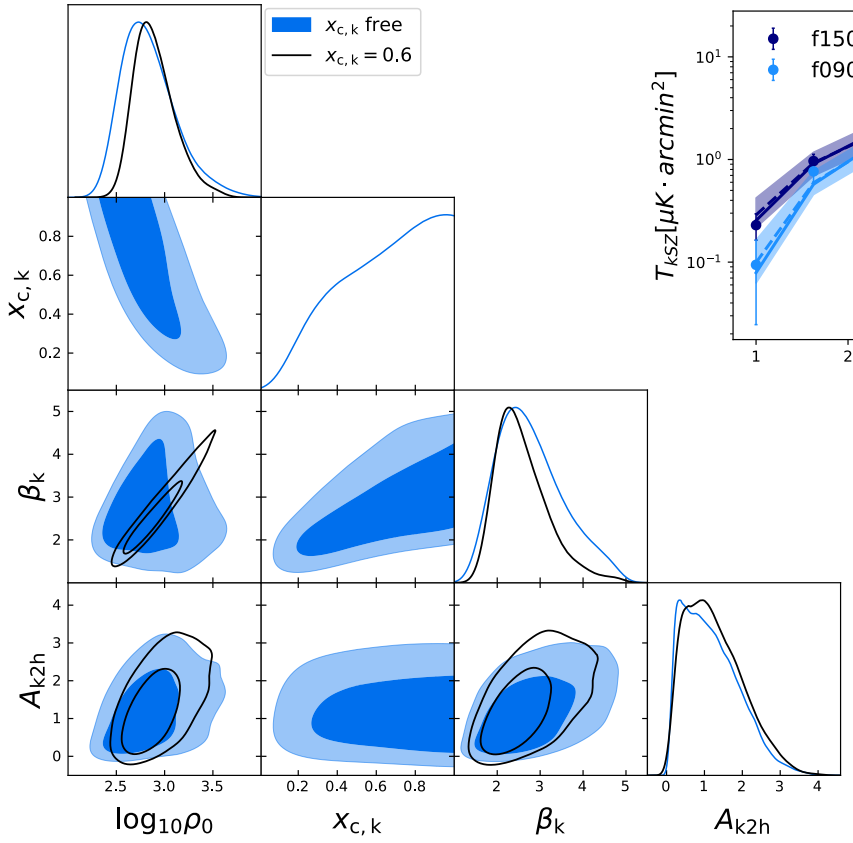


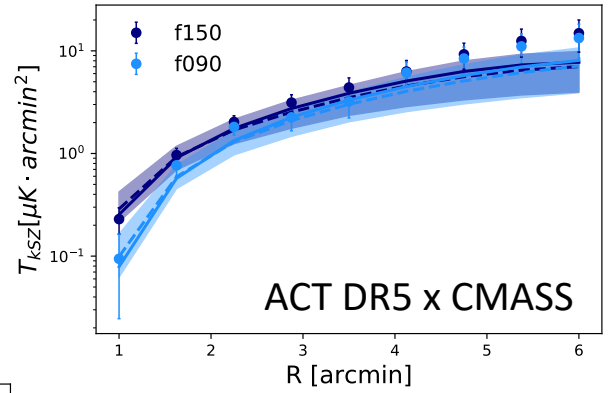


Schaan, Ferraro et al. 2021

Model I: kSZ fit to gNFW gas density profile

$$\rho_{\rm gas} = \rho_0 (x/x_c)^{\gamma} [1 + (x/x_c)^{\alpha}]^{-\frac{\beta-\gamma}{\alpha}} \ \rho_{\rm cr}(z) f_b \ + A_{\rm k2h} \ \rho_{\rm 2h}$$

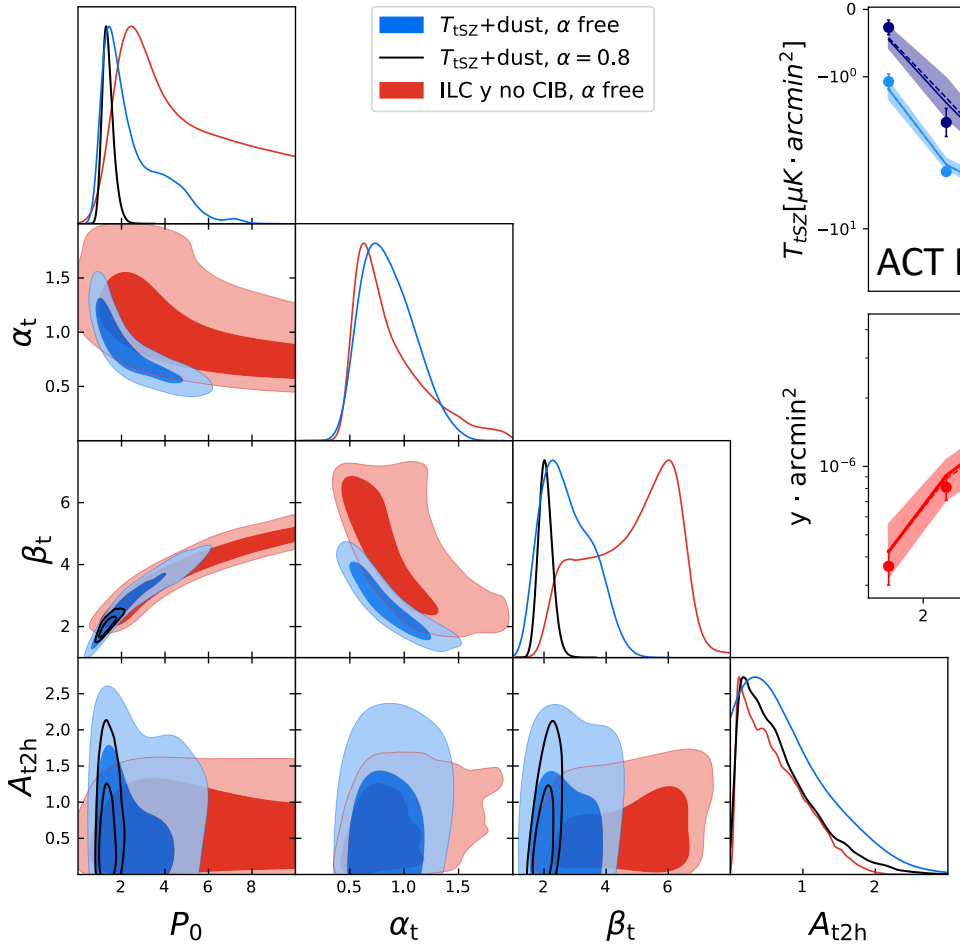


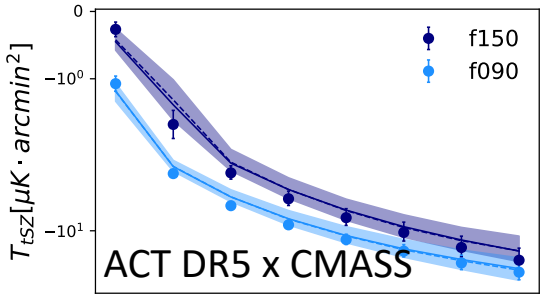


Amodeo+21, Schaan+21

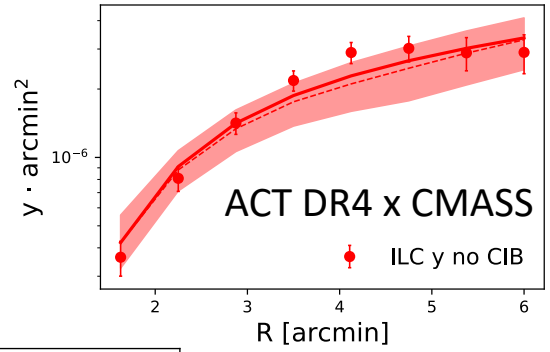
Model II: tSZ fit to gNFW thermal pressure

$$P_{\rm th}(x) = P_{200} P_0 (x/x_c)^{\gamma} [1 + (x/x_c)^{\alpha}]^{-\beta} + A_{\rm t2h}\ P_{\rm 2h}$$





dust correction included in the model

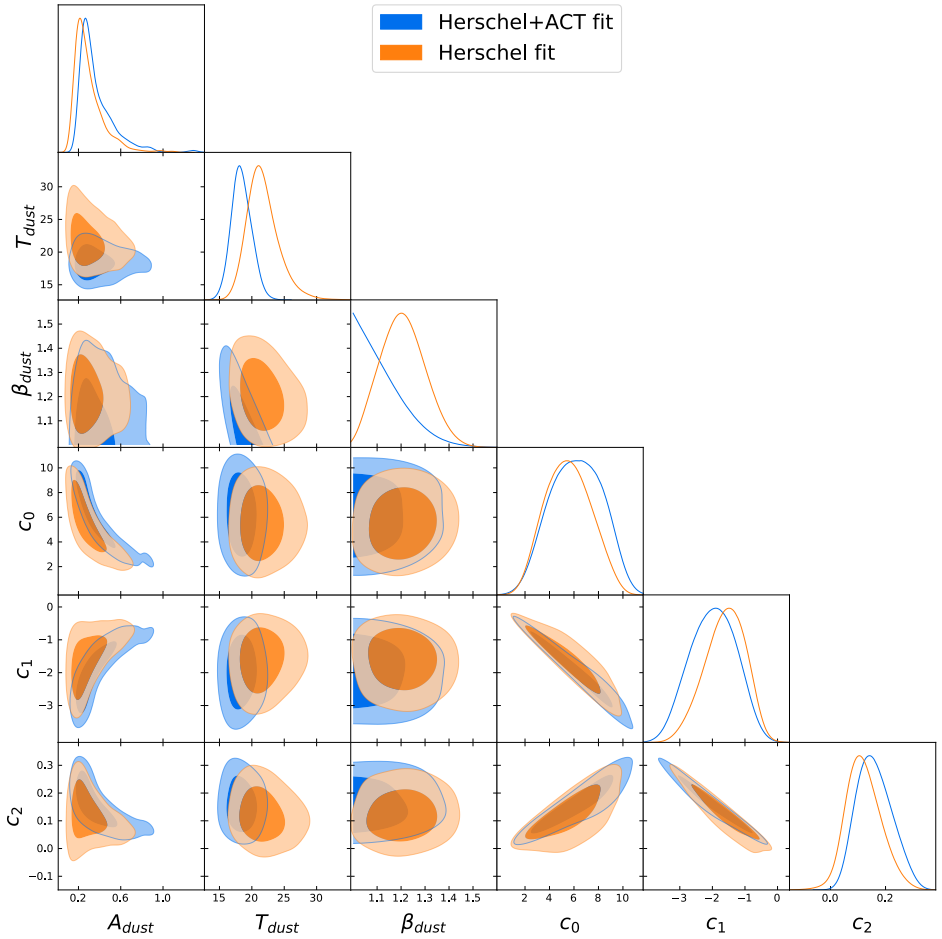


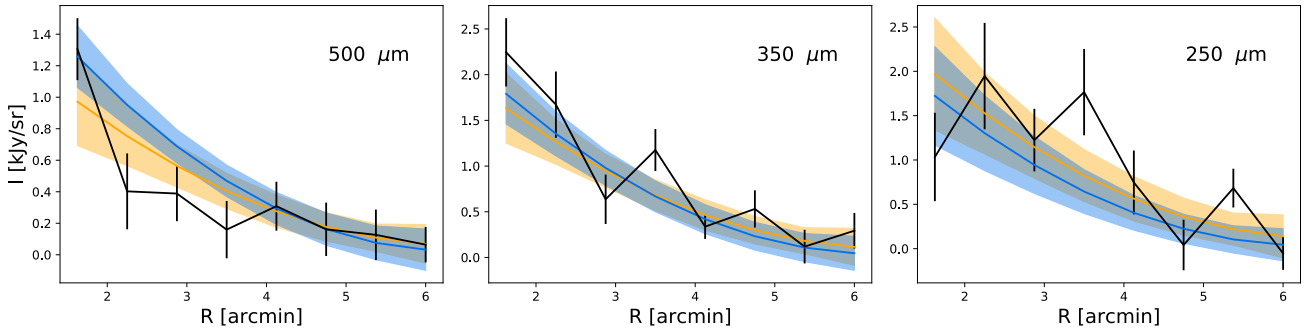
dust-deprojected map

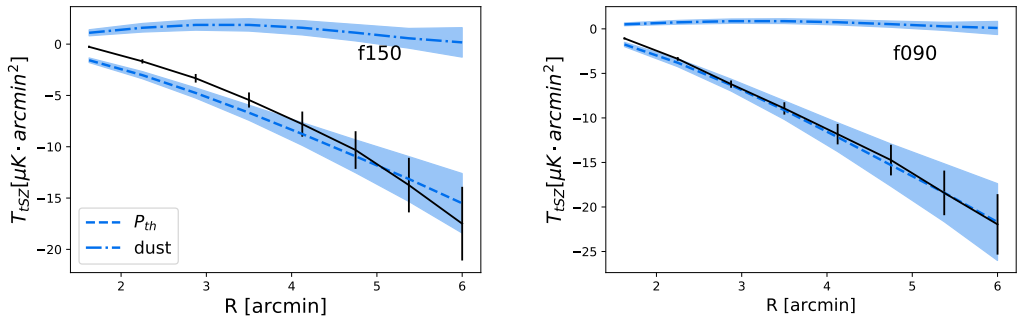
Amodeo+21, Schaan+21

Dust emission

$$I(\nu) = A_{\rm dust}\left(\frac{\nu(1+z)}{\nu_0}\right)^{\beta_{\rm dust}+3}\frac{\exp(h\nu_0/k_BT_{\rm dust})-1}{\exp(h\nu(1+z)/k_BT_{\rm dust})-1}\quad(c_0+c_1{\rm R}+{\rm c_2R^2})$$







Amodeo+21

Model III: Joint kSZ + tSZ fit to a polytropic gas model ("OBB")

with energy injection due to feedback, and a non-thermal pressure component

$$dP_{\rm tot}/dr = -\rho_{\rm gas} d\Phi/dr$$

$$\theta(r) = 1 + \frac{\Gamma - 1}{\Gamma}\frac{\rho_0}{P_0}\left(\Phi_0 - \Phi(r)\right)$$

$$\rho_{\rm gas}(r) = \rho_0 \theta(r)^{\frac{1}{\Gamma-1}},$$
$$P_{\rm tot}(r) = P_0 \theta(r)^{\frac{1}{\Gamma-1}+1}$$

$$\mathbf{P_{Nth}(r) = \alpha_{Nth}\left(\frac{r}{R_{200}}\right)^{n_{Nth}} P_{tot}(r)}$$

$$P_{\rm th}(r) = P_{\rm tot}(r) - P_{\rm Nth}(r)$$

$$\mathbf{E_f = E_i + \epsilon M_\star c^2 + \Delta E_p}$$

Ostriker, Bode & Babul 2005, Shaw et al. 2010

Γ	polytropic index
$\alpha_{\rm Nth}$	amplitude of the non-thermal pressure profile
ϵ	feedback efficiency parameter

Caveat: model for ICM, we apply it to groups (IGM)