Understanding the impact of feedback on the matter distribution with the Sunyaev Zel'dovich Effect

Based on arXiv:2301.02186

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with **Kai Lehman** (masters student at LMU Munich, currently applying to PhD programs!)
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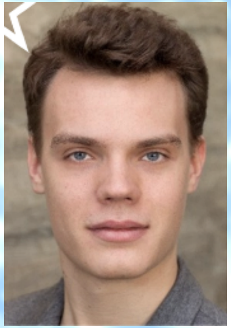
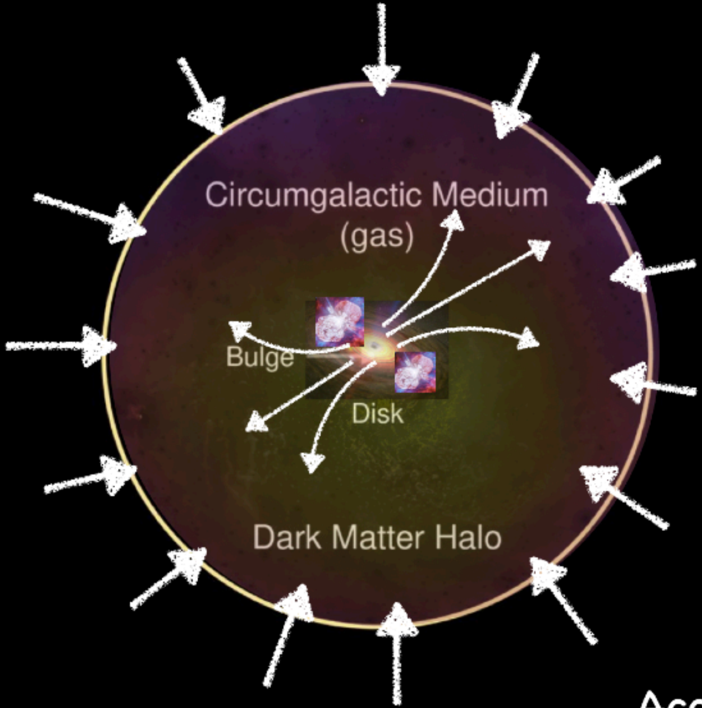
and **CAMELS group**



Feedback cycle in Galaxies

Circum-galactic medium (CGM) bears the imprint of a variety of physical processes

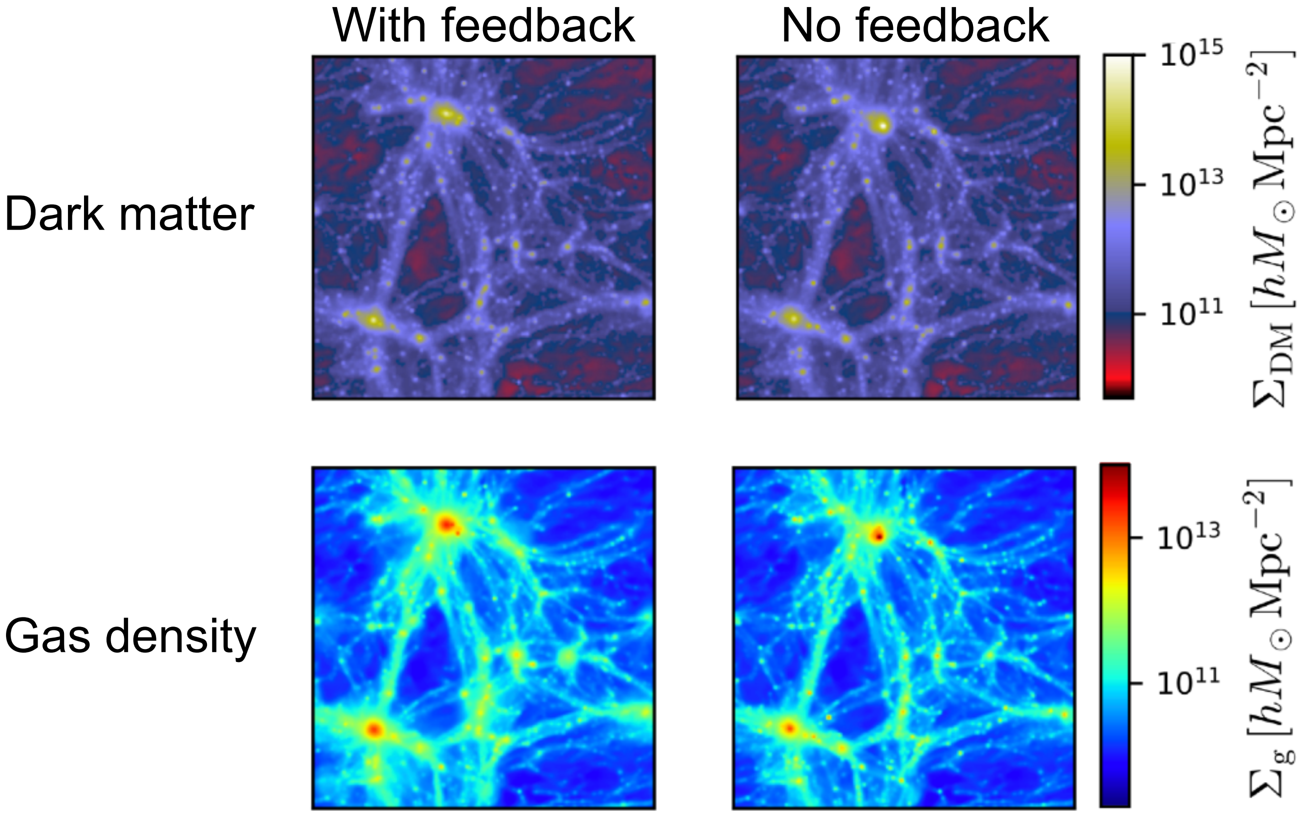
Active Galactic Nuclei (AGN) Feedback



Supernovae feedback

Accretion

Feedback from active galactic nuclei (AGN) and stellar processes impacts the matter distribution



CAMELS simulations

How do we quantify the impact statistically?

We do two-point statistics… simple yet powerful!

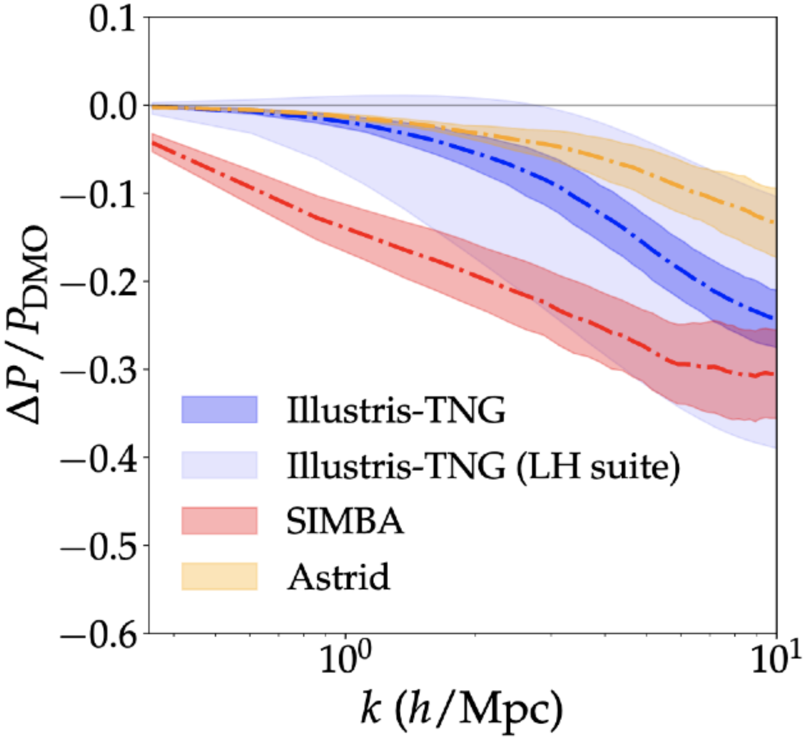
$$\frac{\Delta P}{P_{\mathrm{DM}}} = \frac{P_{\mathrm{hydro}} - P_{\mathrm{DM}}}{P_{\mathrm{DM}}}$$

Relative difference between the total matter power spectrum of hydrodynamical and DM simulations

This is one of the leading theoretical systematics in constraining cosmological models from large scale structure surveys.

Different feedback models ⇒ very different small-scale matter distribution

Fractional change in matter power spectrum as a result of feedback



SP, Lehman, Baxter et al. 2023

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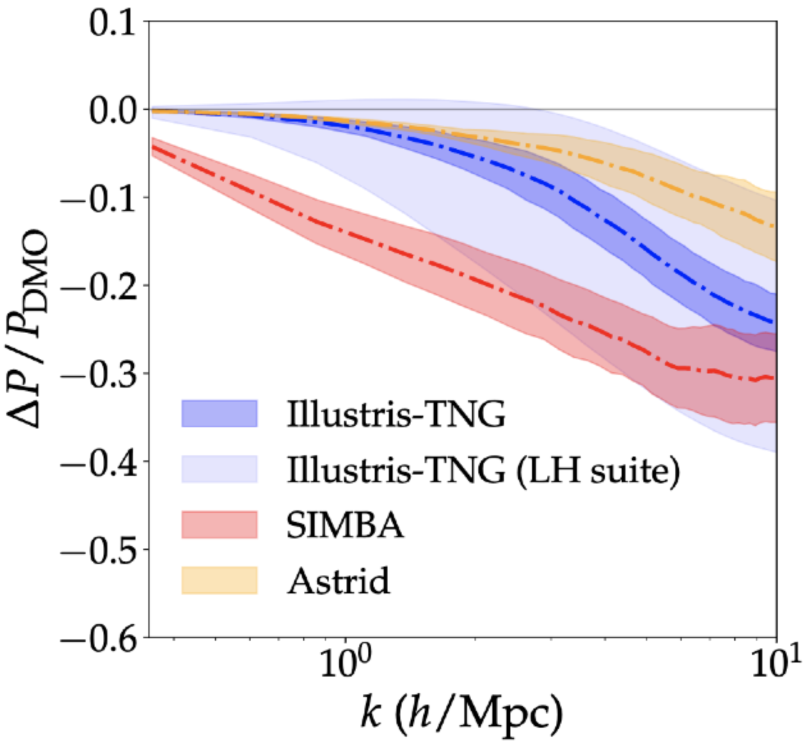
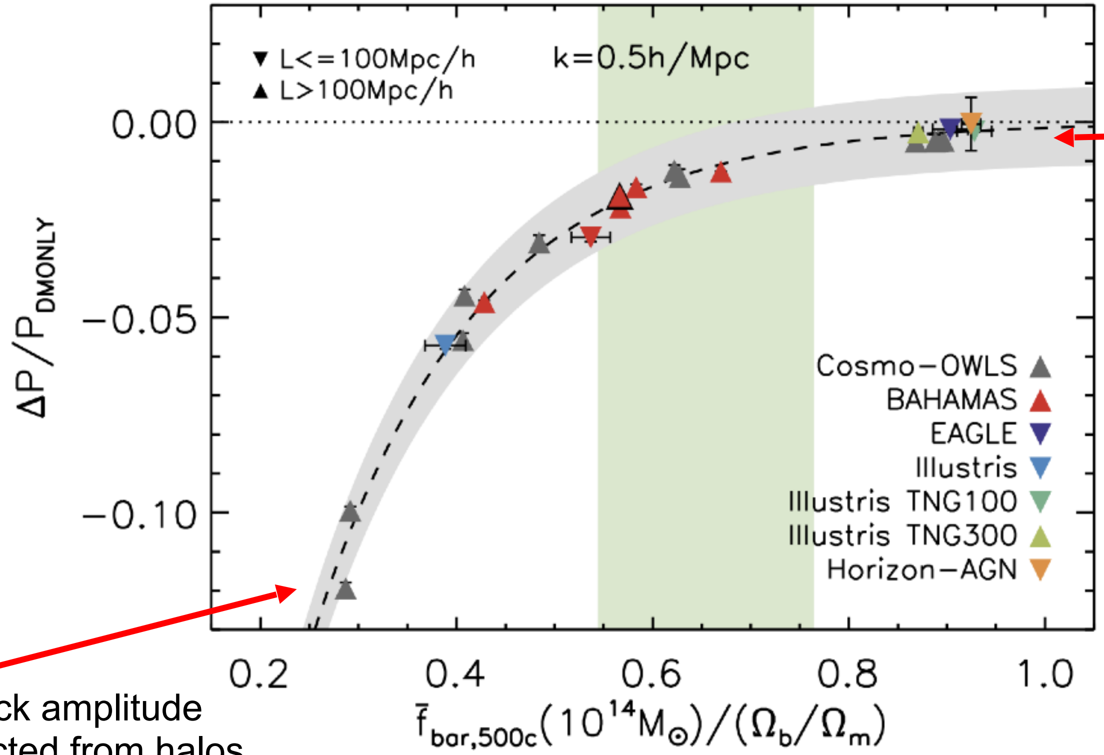


There is large theoretical uncertainty in the small-scale matter distribution because of feedback!

SP, Lehman, Baxter et al. 2023

Gas content of halos provides a measure of feedback strength



- Small feedback amplitude
- Less gas ejected from halos

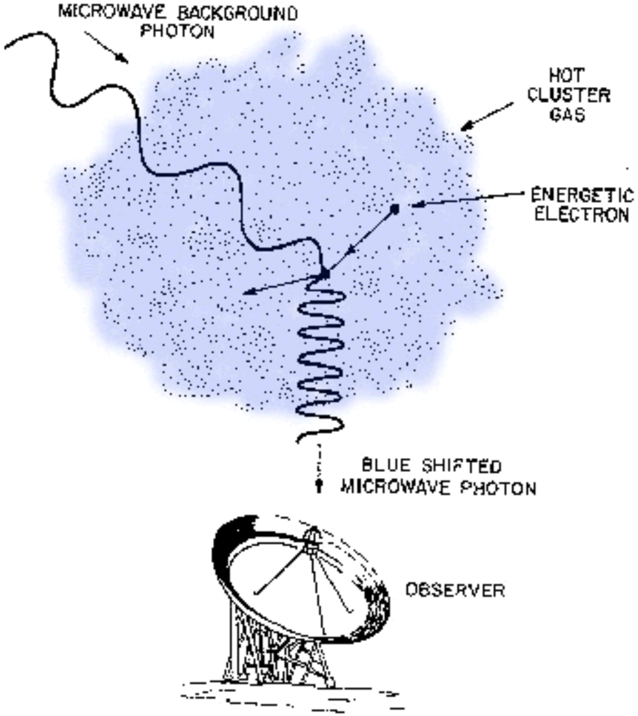
- Large feedback amplitude
- More gas ejected from halos

Amount of baryons in halo relative to cosmic baryon fraction, f_b

van Daalen et al. 2019

f_b is challenging to measure. Can we use the thermal Sunyaev Zel’dovich effect instead?

Thermal SZ effect is sensitive to gas content (and energetics) of halos - what information does it carry about feedback?

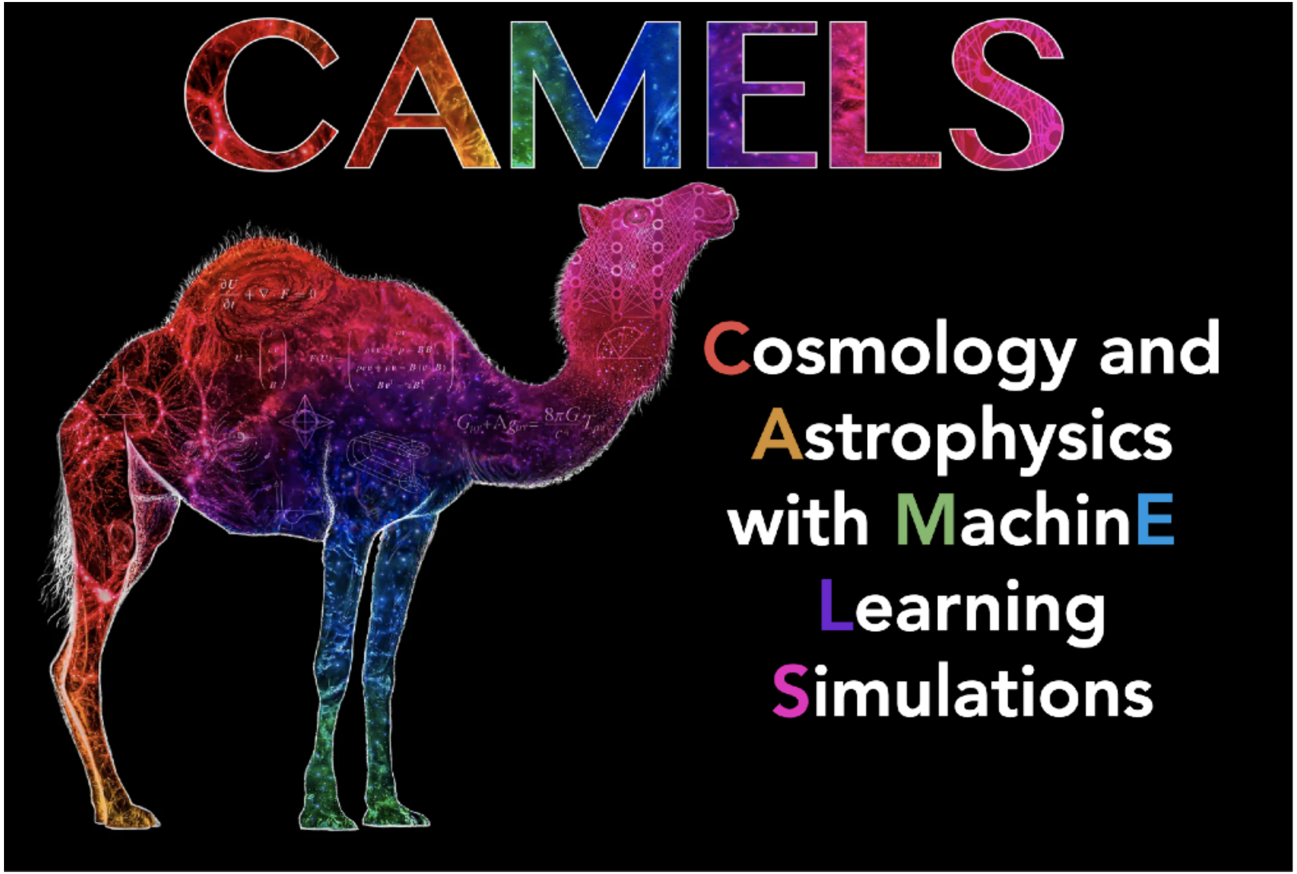


Motivating Questions

Is there a tight relationship between $\Delta P/P$ and the thermal SZ signal from halos?

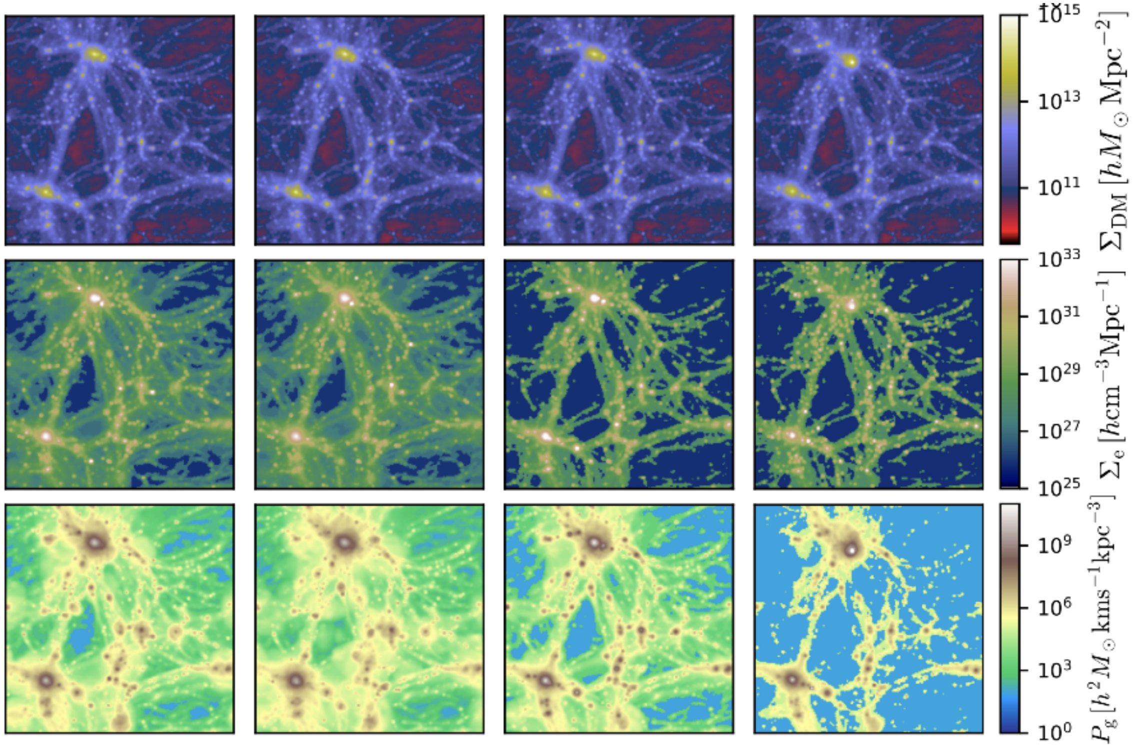
Does relationship found by van Daalen et al. generalize to other feedback models?

How does van Daalen et al. relation change with halo mass and k?



See Villaescusa-Navarro et al. 2021 for overview

CAMELS provides small-volume hydro simulations for several feedback models, and many different parameter values



Fiducial feedback | High AGN feedback | High SN feedback | No feedback

Villaescusa-Navarro et al. 2021

Feedback parameters varied in CAMELS

Simulation	Type/Code	Astrophysical parameters varied & its meaning
IllustrisTNG (Pillepich et al. 2018)	Magneto-hydrodynamic/ AREPO	$A_{\rm SN1}$: (Energy of Galactic winds)/SFR $A_{\rm SN2}$: Speed of galactic winds $A_{\rm AGN1}$: Energy/(BH accretion rate) $A_{\rm AGN2}$: Jet ejection speed or burstiness
SIMBA (Davé et al. 2019)	Hydrodynamic/GIZMO	$A_{\rm SN1}$: Mass loading of galactic winds $A_{\rm SN2}$: Speed of galactic winds $A_{\rm AGN1}$: Momentum flux in QSO and jet mode of feedback $A_{\rm AGN2}$: Jet speed in kinetic mode of feedback
Astrid (Bird et al. 2022; Ni et al. 2022)	Hydrodynamic/pSPH	$A_{\rm SN1}$: (Energy of Galactic winds)/SFR $A_{\rm SN2}$: Speed of galactic winds $A_{\rm AGN1}$: Energy/(BH accretion rate) $A_{\rm AGN2}$: Thermal feedback efficiency

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Parameters have different physical meaning for different sims
Modeling feedback relation with physical observable is better!

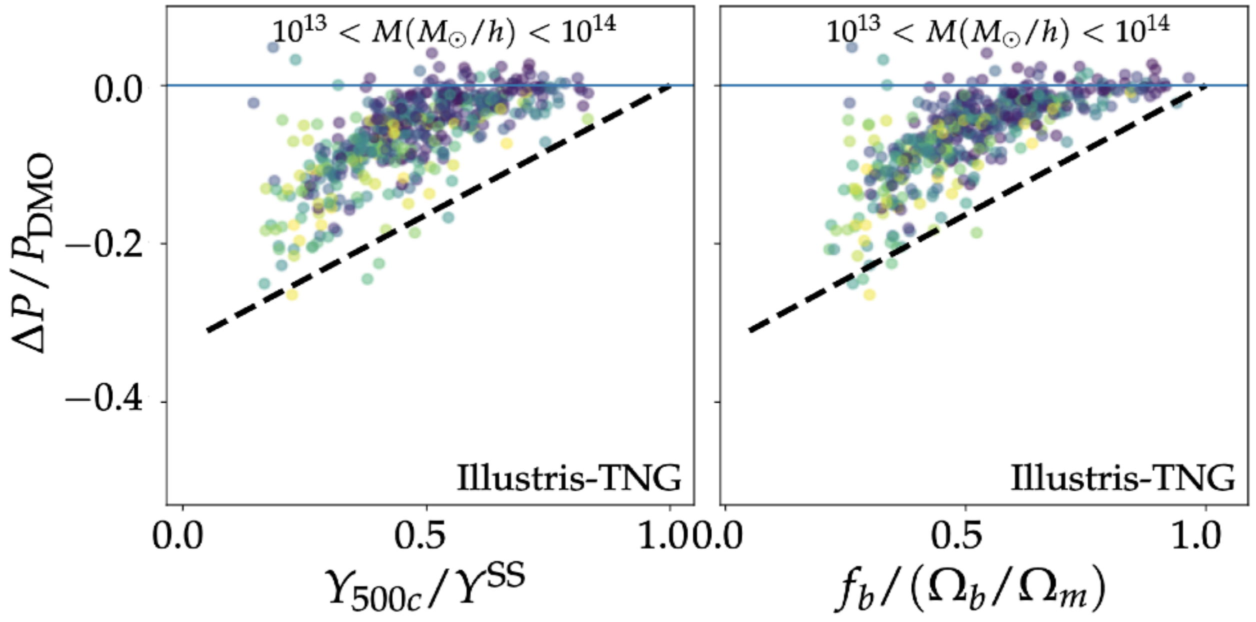
Simulation set

Simulations	Set	Varying parameters
1,000	LH	Ω_{m}, σ_8, A_{SN1}, A_{SN2}, A_{AGN1}, A_{AGN2}, S
61	1P	Ω_{m}, σ_8, A_{SN1}, A_{SN2}, A_{AGN1}, A_{AGN2}
27	CV	S

- Every simulation has phase-matched hydro and DM-only counterparts
    - O(6000) simulations

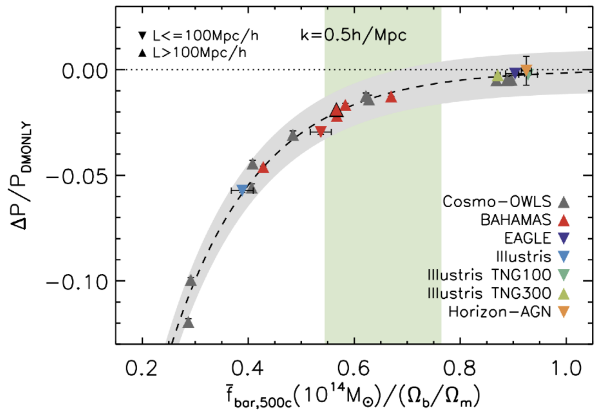
The SZ - ΔP/P relationship is similar to the f_b-ΔP/P relation found by van Daalen et al.

Each point represents average over halos in a different simulation
Colored by amplitude of AGN parameter



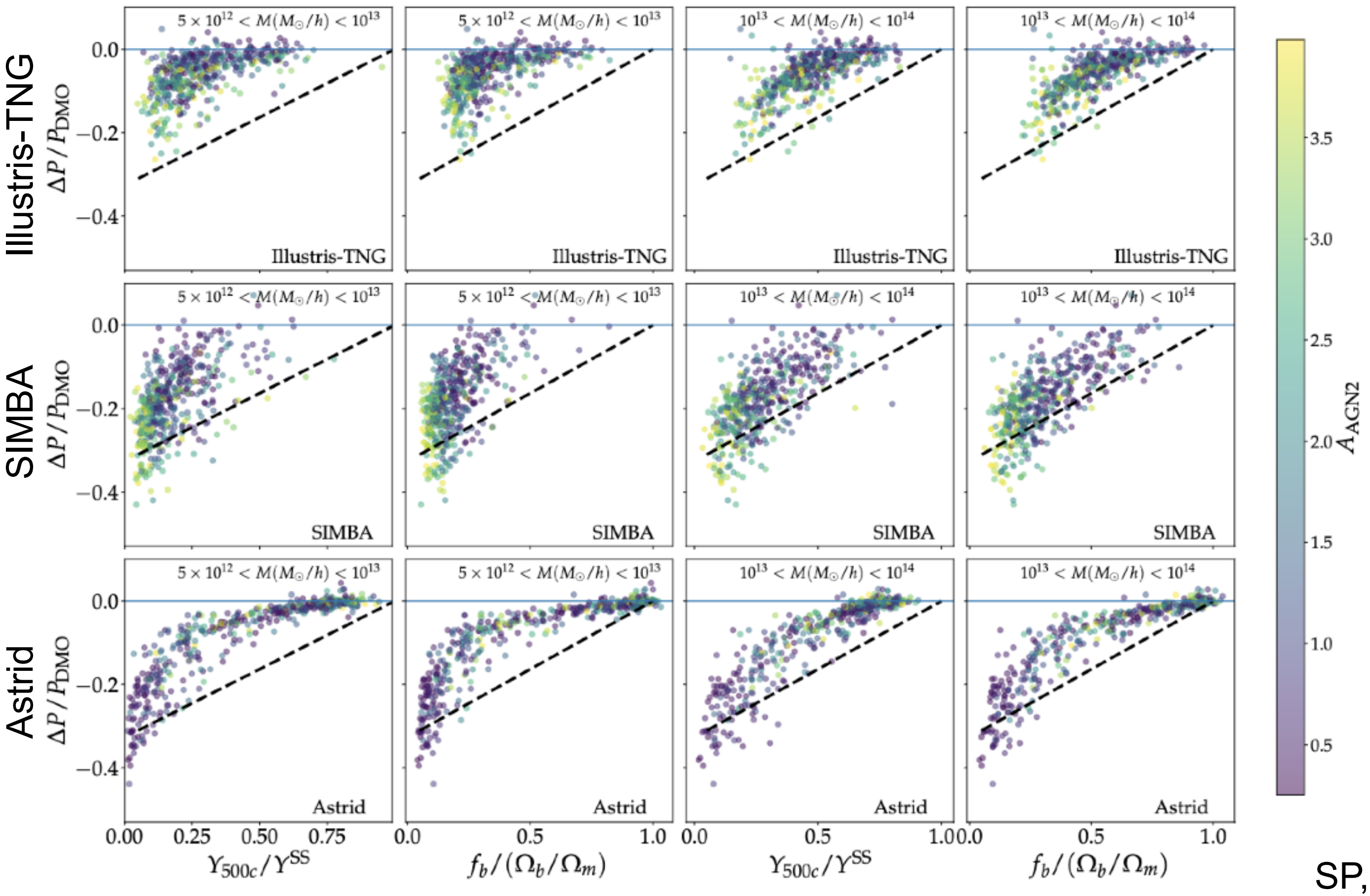
=SZ signal

van Daalen et al. 2019

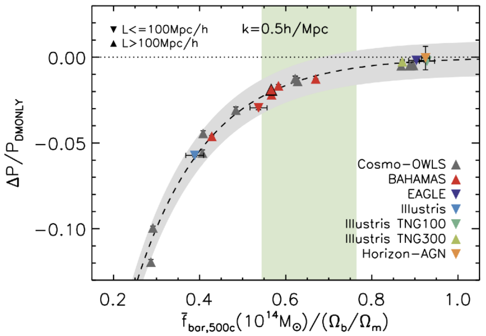


SP, Lehman, Baxter et al. 2023

However, van Daalen et al. relation does not hold perfectly across all feedback models

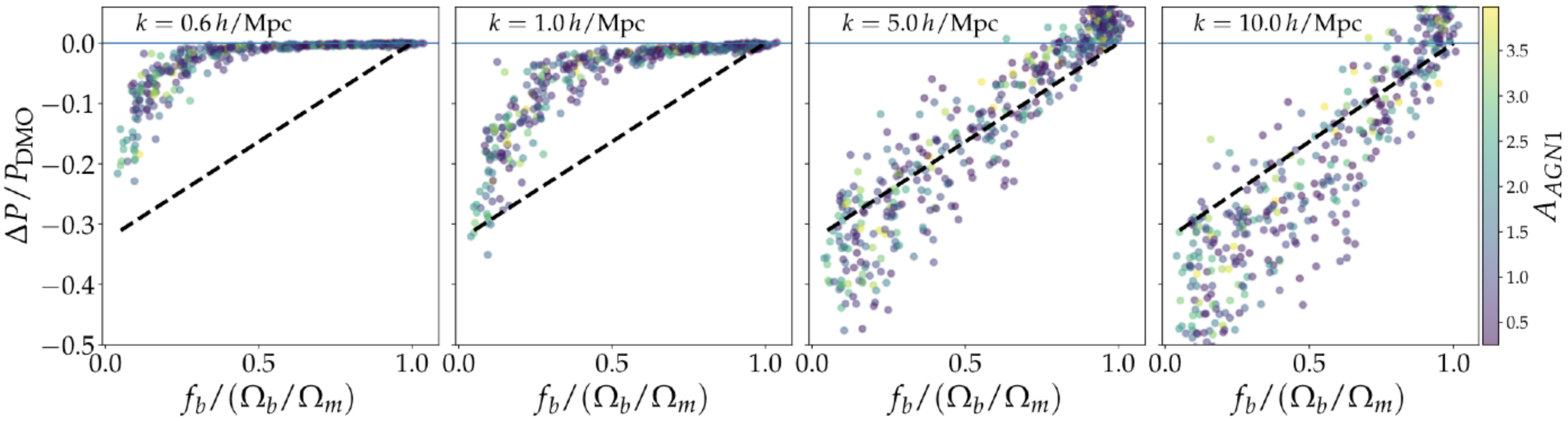


van Daalen et al. 2019



SP, Lehman, Baxter et al. 2023

The f_b-ΔP/P relation looks very different at different k



SP, Lehman, Baxter et al. 2023

Understanding the Y (or f_b) vs. $\Delta P/P$ relation

Assume that ejection of gas from halos by AGN is responsible for $\Delta P/P$.

Consider three scales:

1) Halo radius, R_h

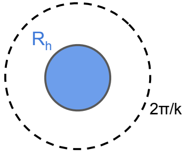
2) Distance to which gas is ejected by AGN, R_{ej}

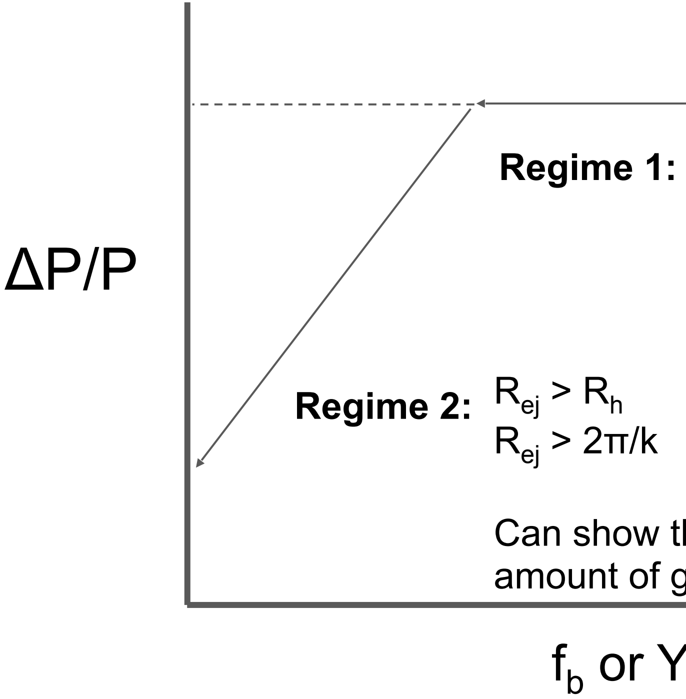
3) Scale at which we measure $\Delta P/P$, $2\pi/k$

SP, Lehman, Baxter et al. 2023

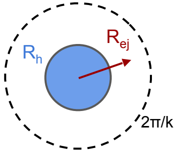
Understanding the Y (or f_b) vs. $\Delta P/P$ relation

$R_h < 2\pi/k$: Small halos or small k

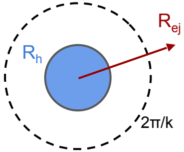




Regime 1: $R_{ej} > R_h$ (so gas expelled from halo) but $R_{ej} < 2\pi/k$ (so no change to $\Delta P/P$)



Regime 2: $R_{ej} > R_h$
$R_{ej} > 2\pi/k$



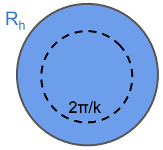
Can show that we expect a linear relation between amount of gas and $\Delta P/P$ in this regime

$$\frac{\delta'_m}{\delta_m} = 1 - \frac{M_{\rm ej}}{M}.$$

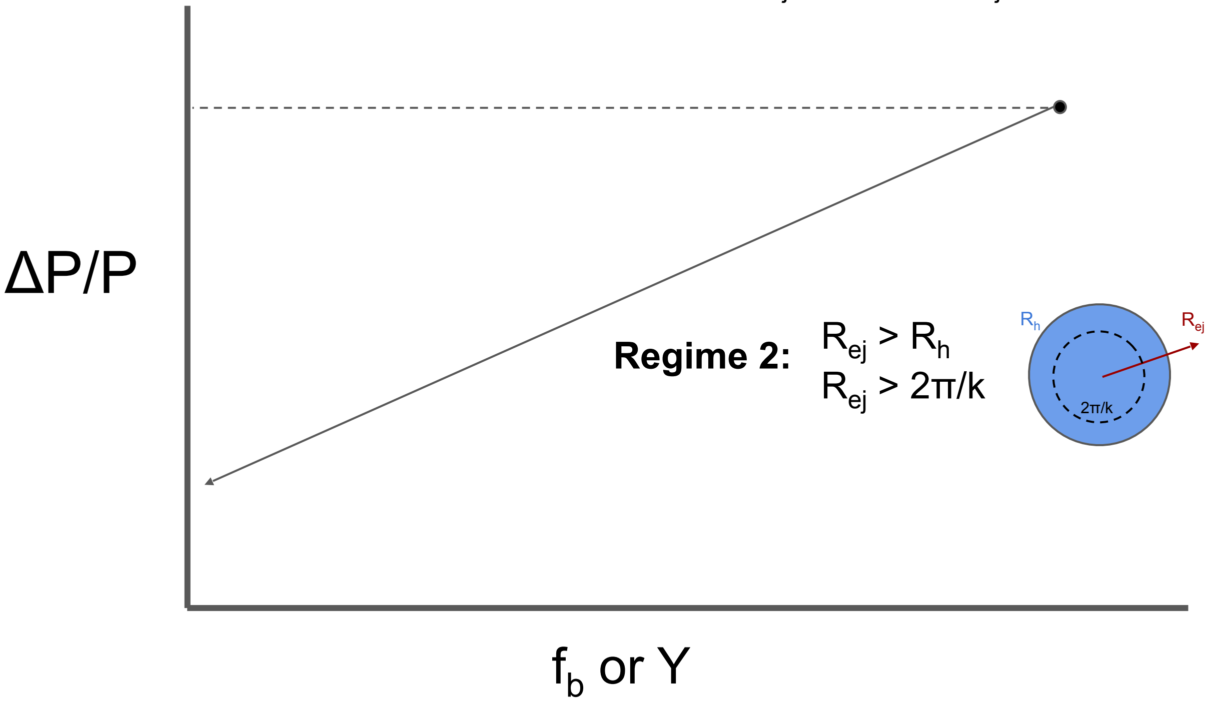
$$\frac{\Delta P}{P_{\rm DMO}} \sim \left(\frac{\delta'_m}{\delta_m}\right)^2 - 1 \approx -2\frac{M_{\rm ej}}{M},$$

Understanding the Y (or f_b) vs. $\Delta P/P$ relation

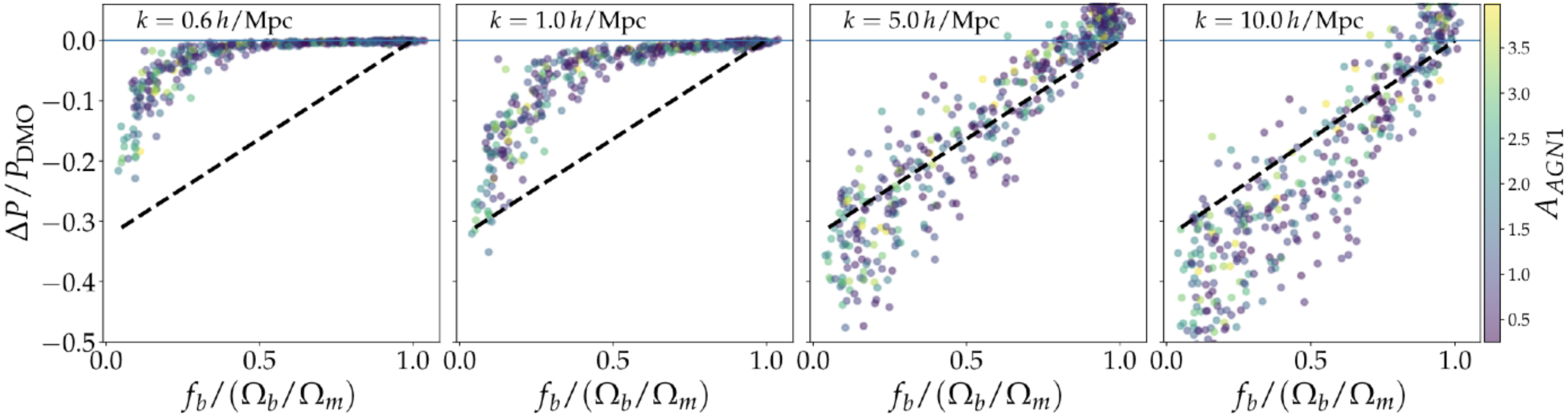
$R_h > 2\pi/k$: Large halos or large k



In this case, it is impossible to have $R_{ej} > R_h$ and $R_{ej} < 2\pi/k$ (so no **Regime 1**)



This simple model explains behavior seen as we change k
(and halo mass)



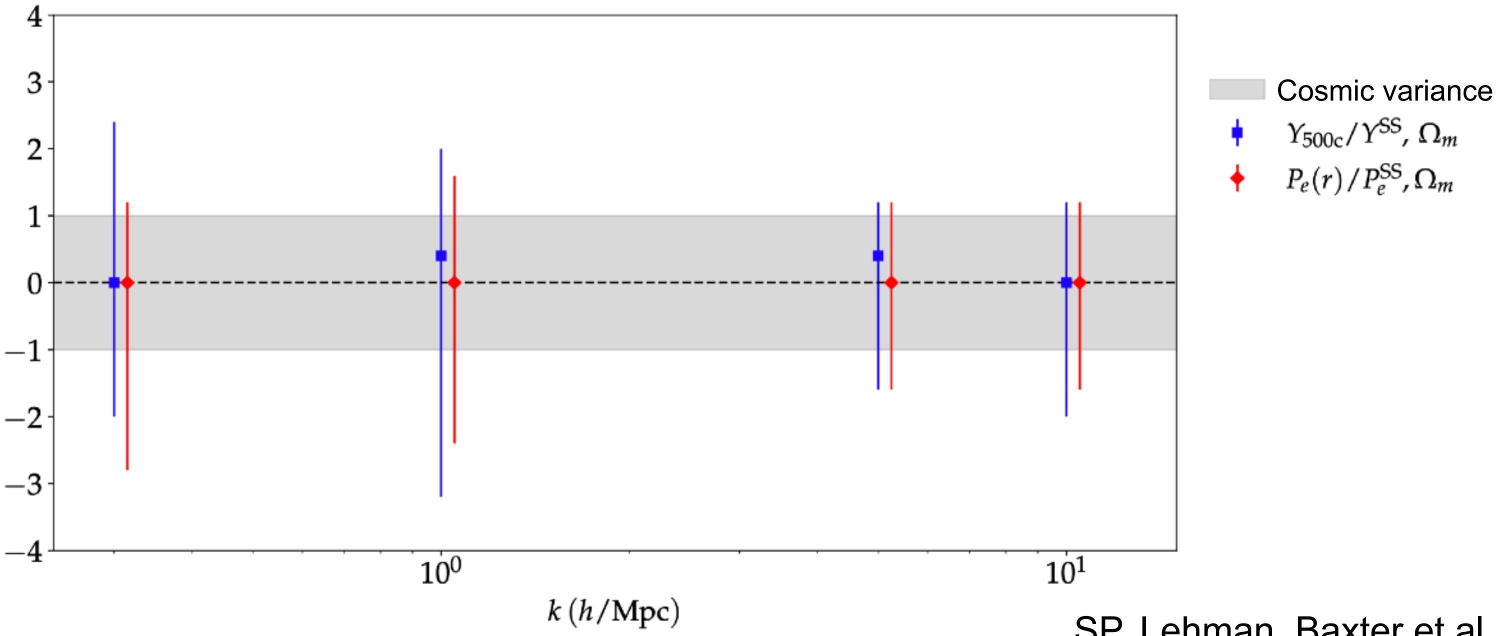
As expected, transition between these two limiting regimes happens when $2\pi/k \sim R_h$

How do we go from SZ signal to constraints on ΔP/P?

We train a random forest model to predict ΔP/P given Y signal (or pressure profile)

Note: this model is trained and tested on Illustris+SIMBA+Astrid

Error on ΔP/P predictions relative to cosmic variance

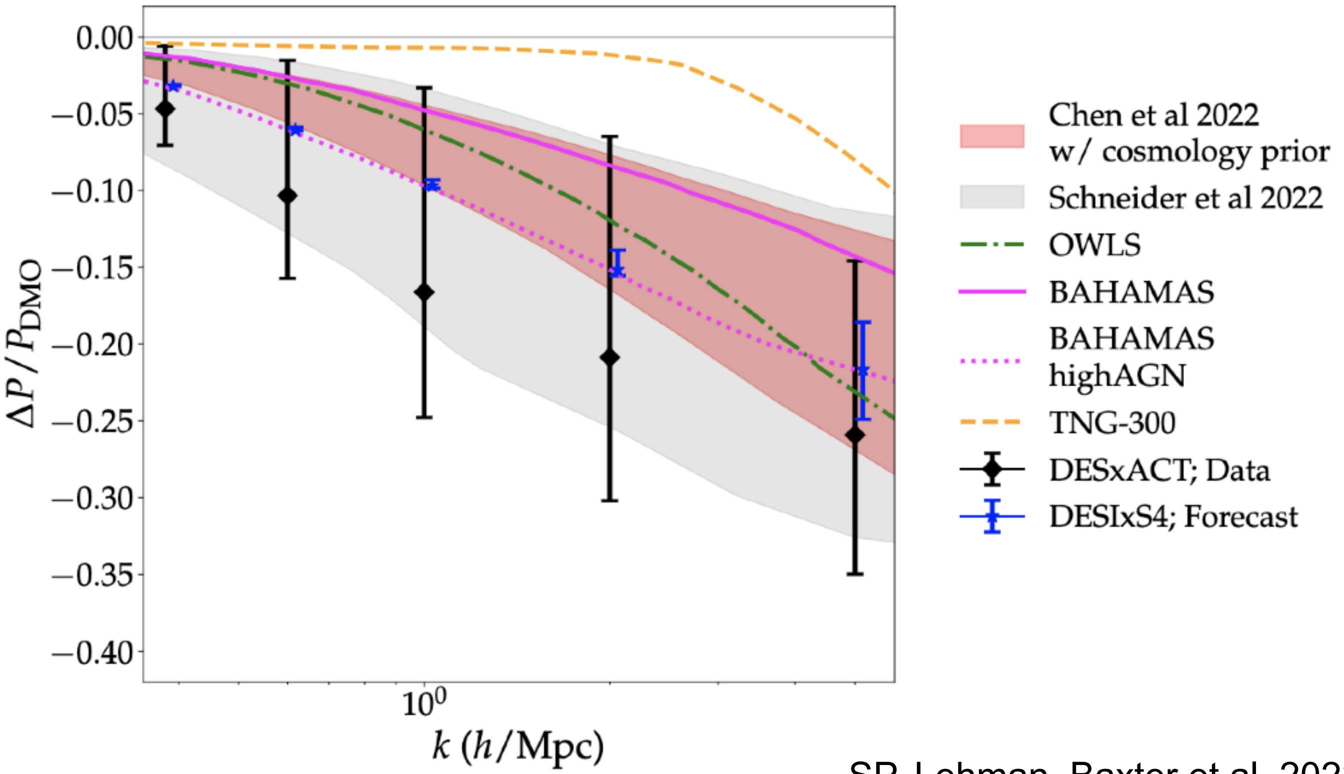


SP, Lehman, Baxter et al. 2023

We now take the model trained on simulations and apply it to actual data

We use measurements of Y_{500} from the lensing-SZ correlations of DESxACT analysis of SP, Gatti, Baxter et al. 2021

Forecasts are based on halo-SZ correlations of DESI-S4 maps as in SP, Baxter, Hill 2020



SP, Lehman, Baxter et al. 2023

Summary

Is there a tight relationship between $\Delta P/P$ and the SZ signal from halos?

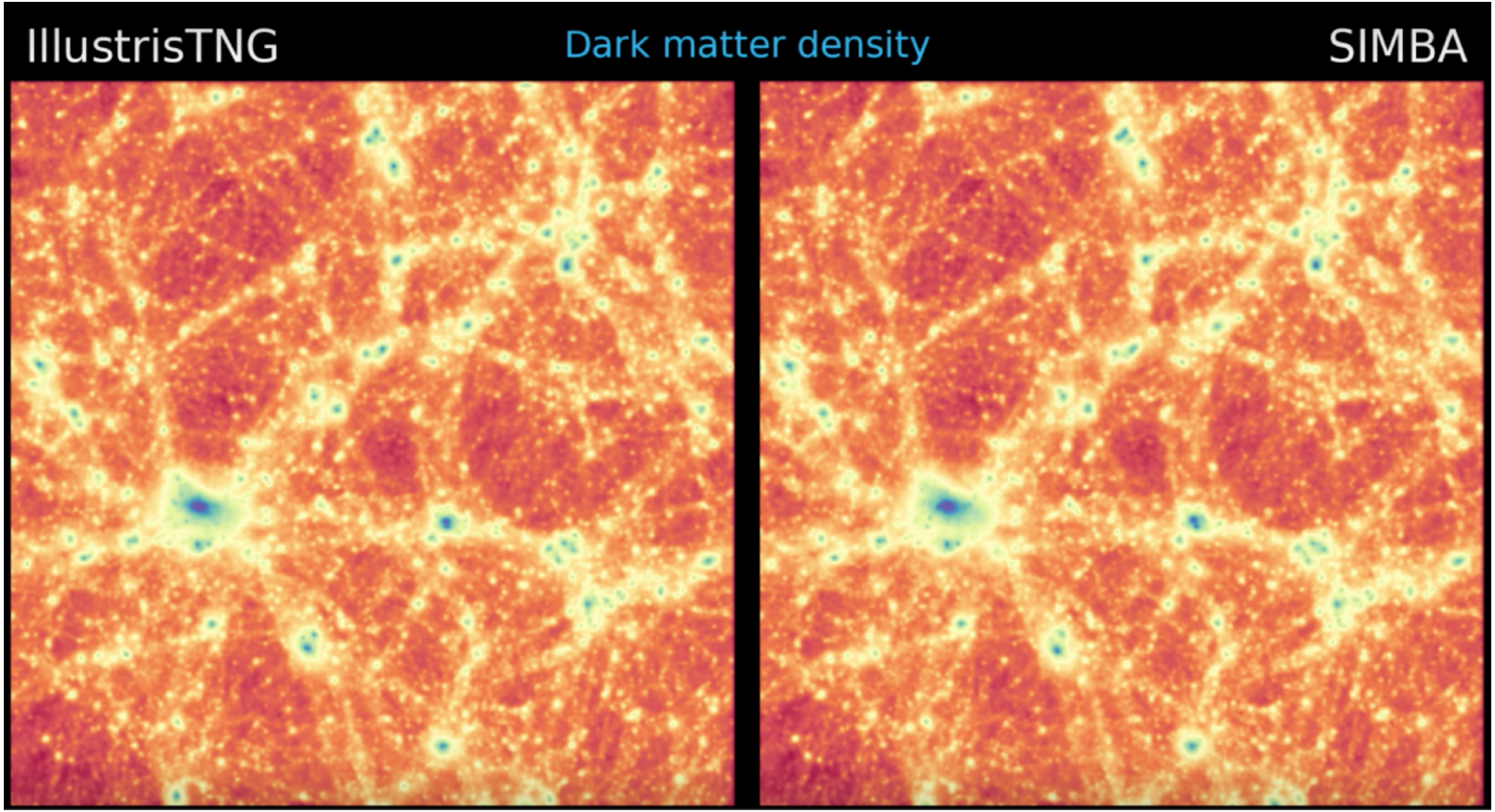
- **Yes**. The SZ signal from halos carries information about the matter distribution

Does the relationship found by van Daalen et al. generalize to other feedback models?

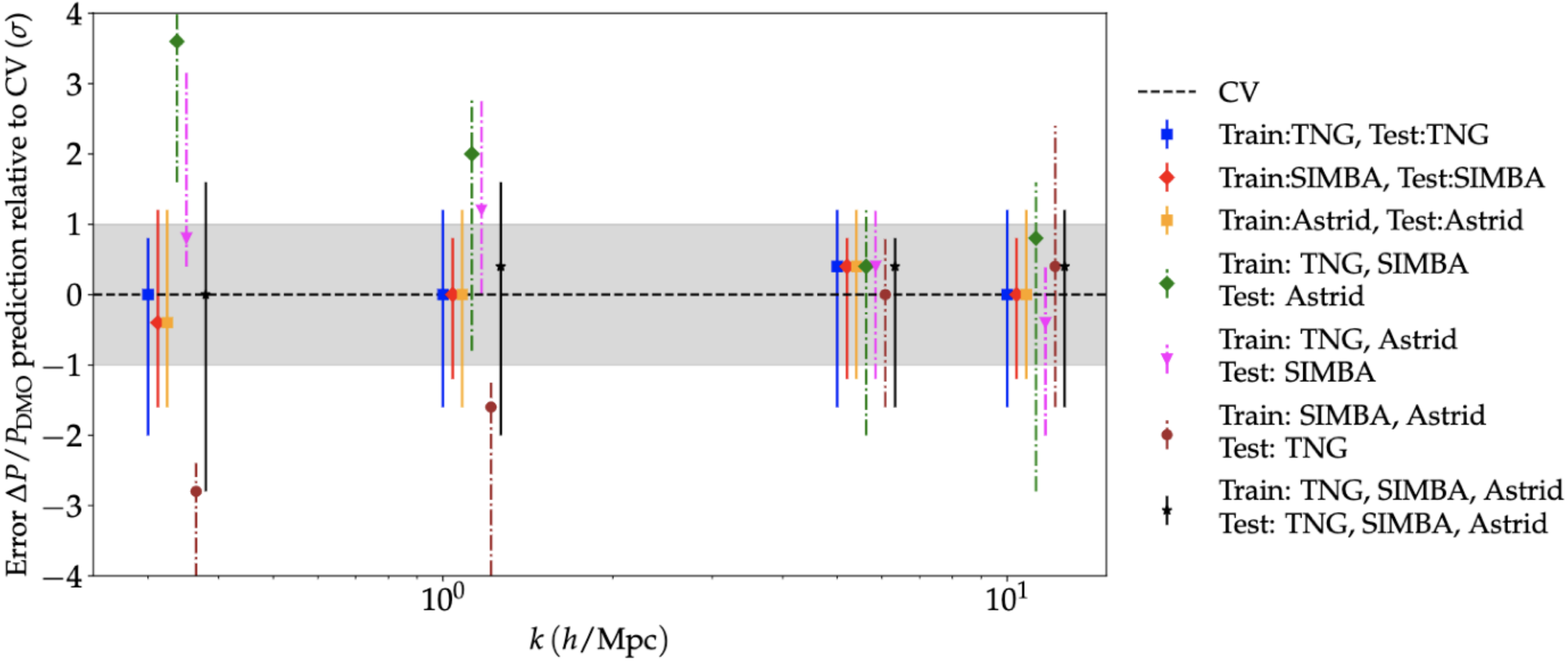
- **Somewhat**. We see larger spread in $\Delta P/P$ vs. f_b than in van Daalen et al. However, it is still possible (e.g. via random forest) to find relationships that fit all Illustris+SIMBA+Astrid well (see also Delgado et al. 2023).

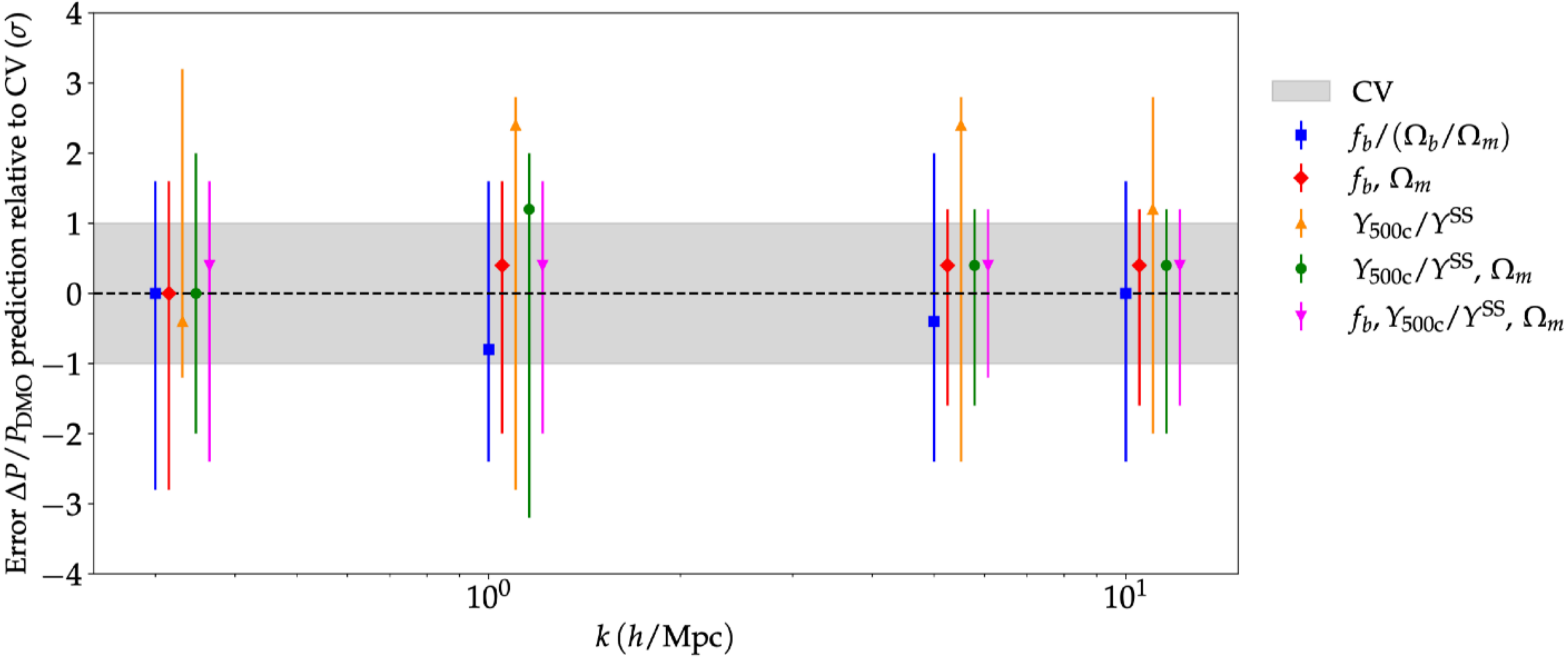
How does relationship between gas and $\Delta P/P$ change with halo mass and k?

- A simple model considering the halo scale, gas ejection scale, and k predicts behavior of $\Delta P/P$ vs. Y (or f_b) as function of halo mass and k. See SP, Lehman, Baxter et al. 2023 for more details.


IllustrisTNG
Dark matter density
SIMBA

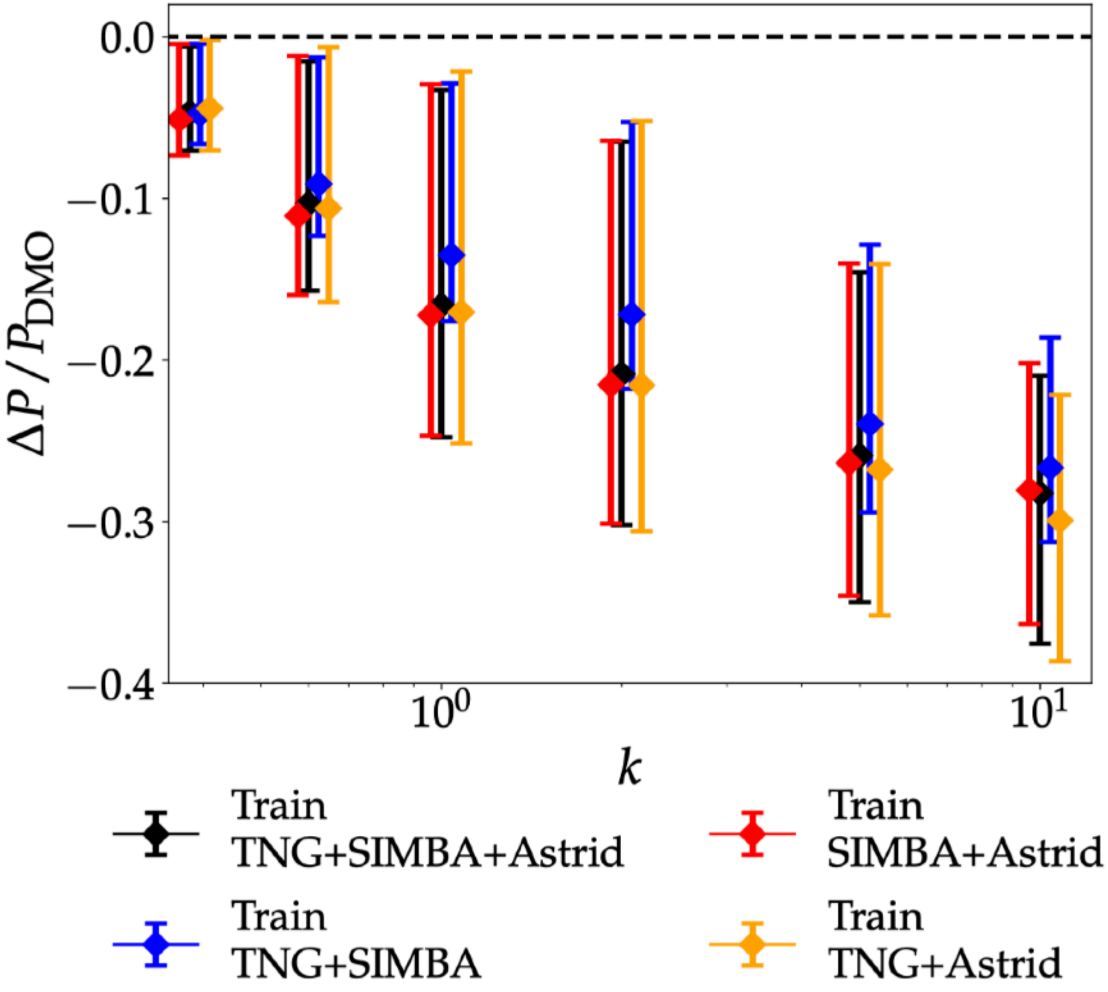
Robustness to feedback implementation



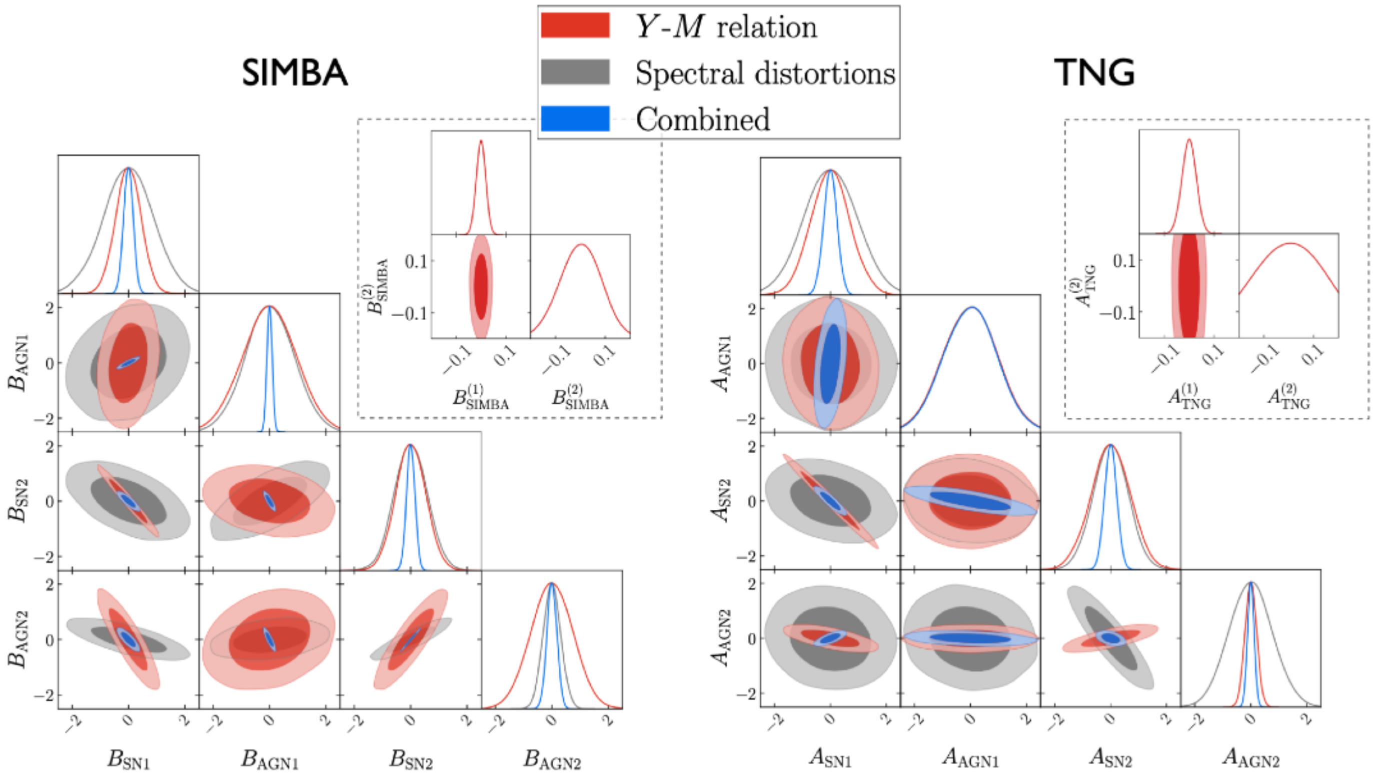


Error $\Delta P/P_{\mathrm{DMO}}$ prediction relative to CV (σ)
4
3
2
1
0
−1
−2
−3
−4
10^0
10^1
$k\,(h/\mathrm{Mpc})$
CV
$f_b/(\Omega_b/\Omega_m)$
f_b, Ω_m
Y_{500c}/Y^{SS}
Y_{500c}/Y^{SS}, Ω_m
f_b, Y_{500c}/Y^{SS}, Ω_m

Robustness of data constraints to feedback implementation

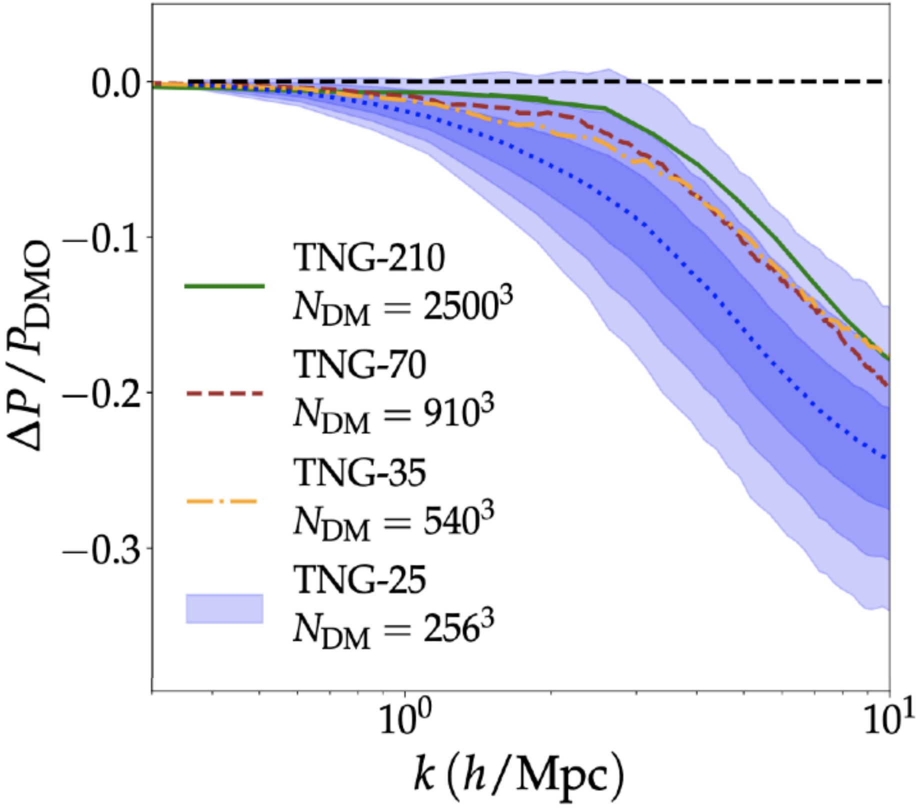


Constraints on feedback parameters



Wadekar et al. 2022

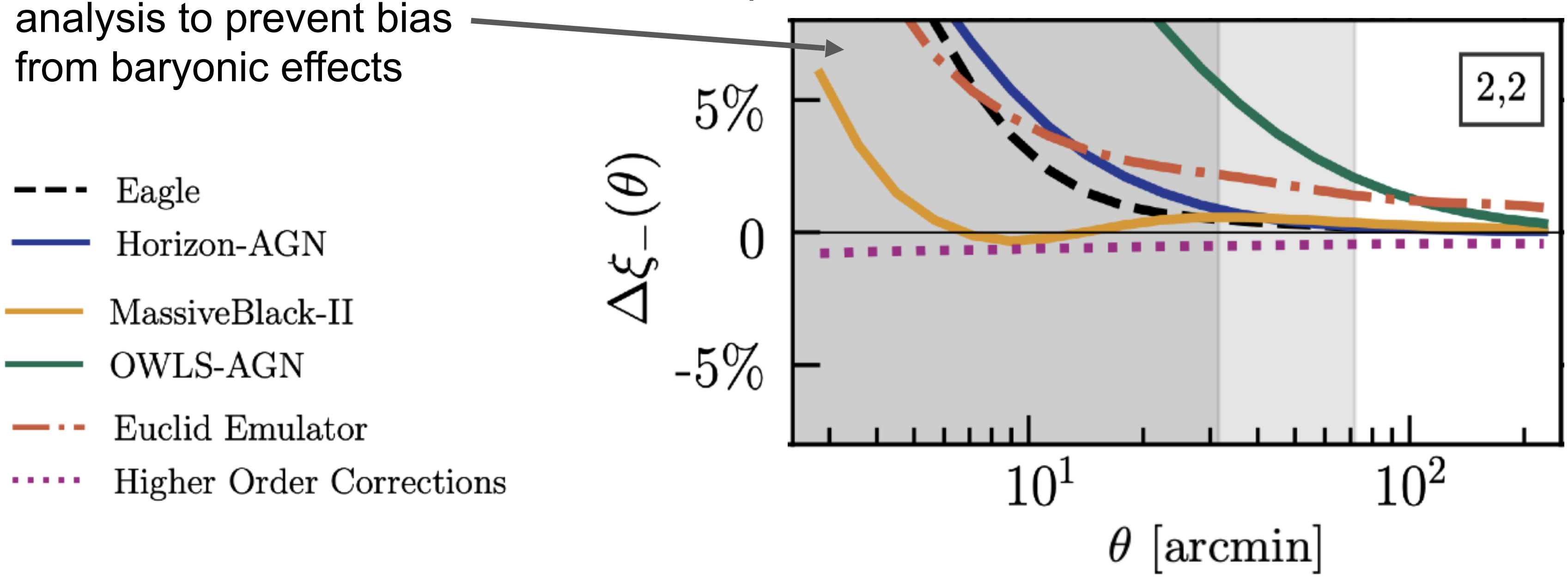
Impact of box size



Uncertainty on feedback limits power of weak lensing surveys

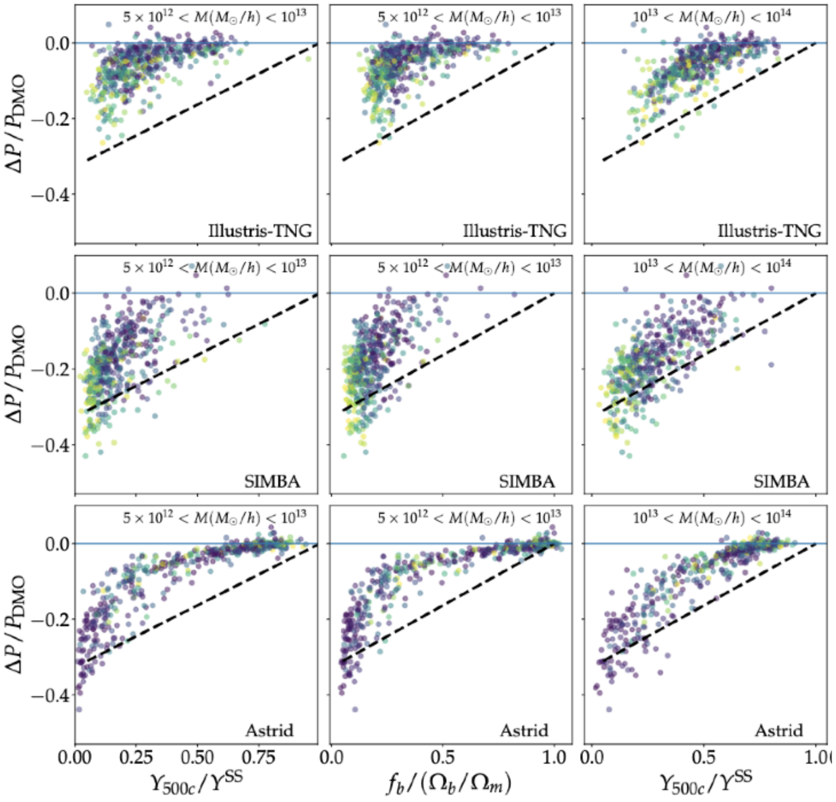
Grey = excluded from analysis to prevent bias from baryonic effects

Impact of feedback on DES Year 3 cosmic shear



Secco et al. 2022

Do relationships between Y (or f_b) vs. ΔP/P generalize across sims?



We train a random forest model to go from (SZ signal +) to ΔP/P at different k

Train on all three feedback models (Illustris, SIMBA, Astrid)

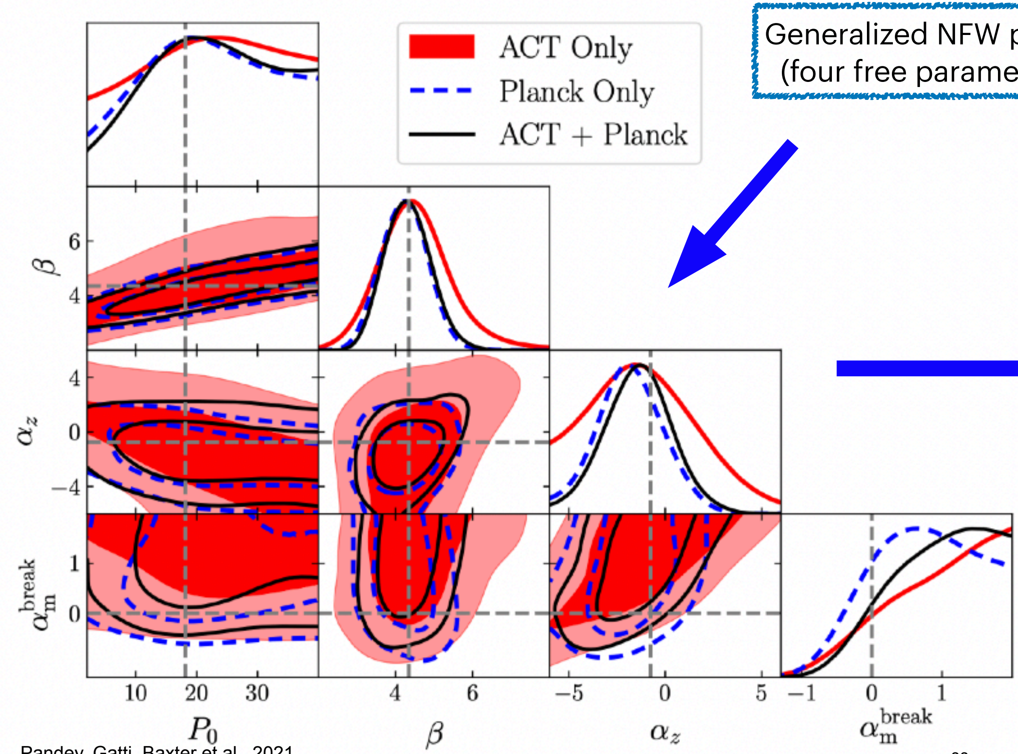
Pressure profile constraints

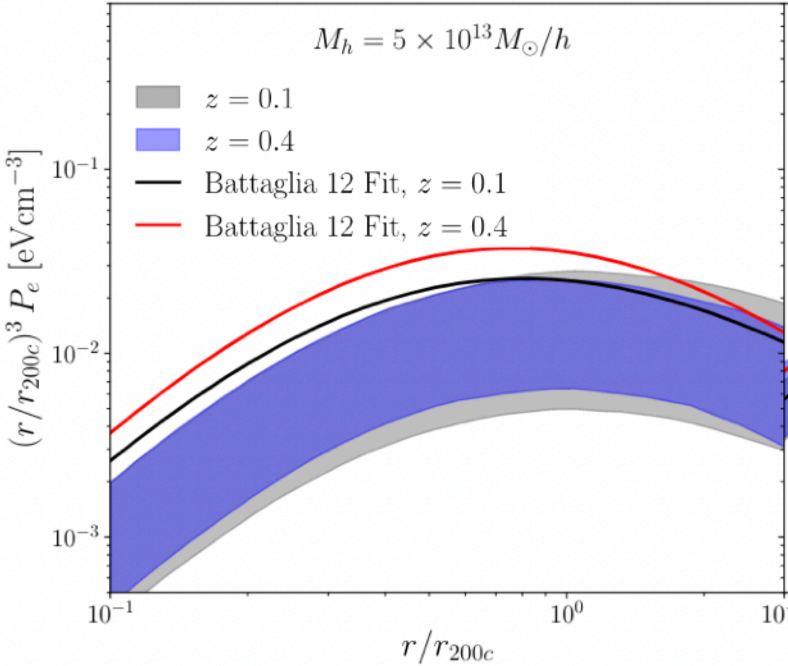
- We model the signal with halo model framework:
  $\langle \gamma_t y \rangle$ = 1-halo + 2-halo + $\langle$IA $\times$ $y\rangle \sim f$(pressure-profile) $\times$ g(DM-profile) $\times$ h(cosmology)

Generalized NFW profile (four free parameters)

Generalized NFW profile (two free parameters)

Fixed to Planck/DES bestfit values





Pandey, Gatti, Baxter et al., 2021