# SZ Calibration of Baryonic Feedback Effects

Colin Hill
Columbia University
Flatiron Institute - Center for Computational Astrophysics

CMB-S4 Collaboration Meeting, Zoom, August 2021

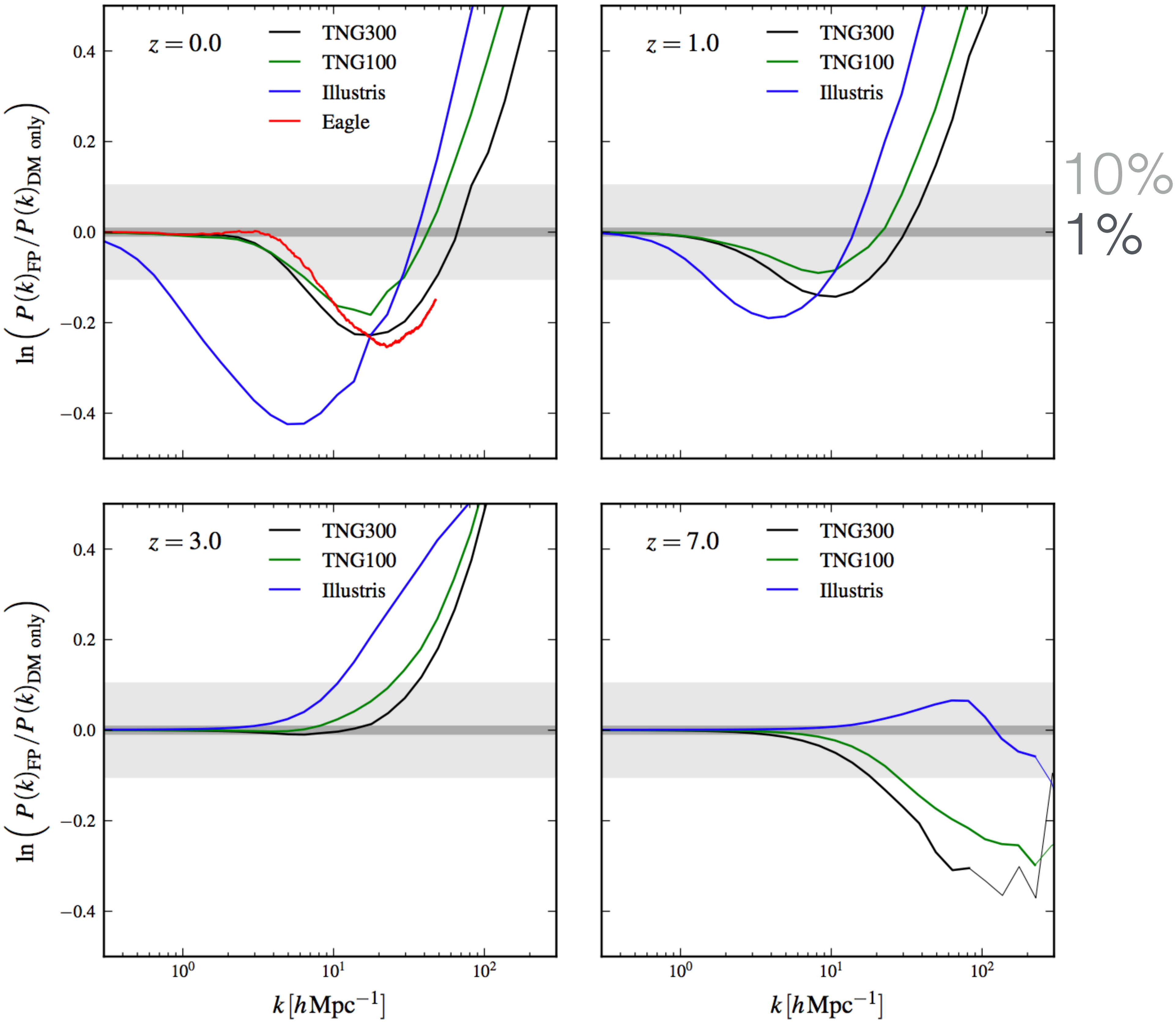
**arXiv:2103.05582 w/ F. McCarthy, M. Madhavacheril**

**+ in prep. w/ N. Battaglia, S. Ferraro, M. Madhavacheril, E. Schaan**

# What is the problem?

# Baryonic Effects on P(k)

Colin Hill
Columbia/CCA

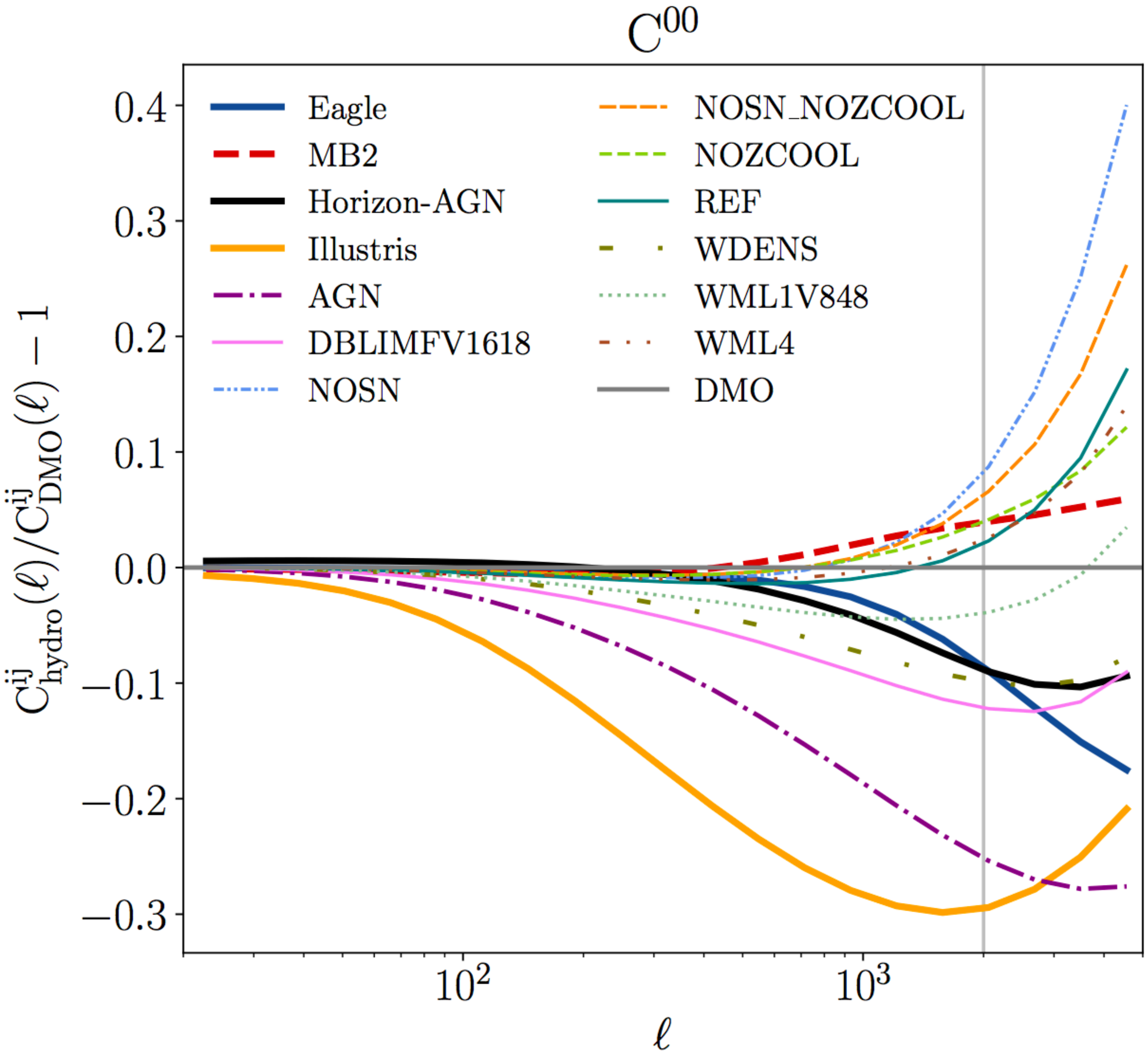



Springel+ (2017)

Colin Hill
Columbia/CCA

# Implications

If not modeled accurately, these effects bias parameter inference from, e.g., the weak lensing power spectrum



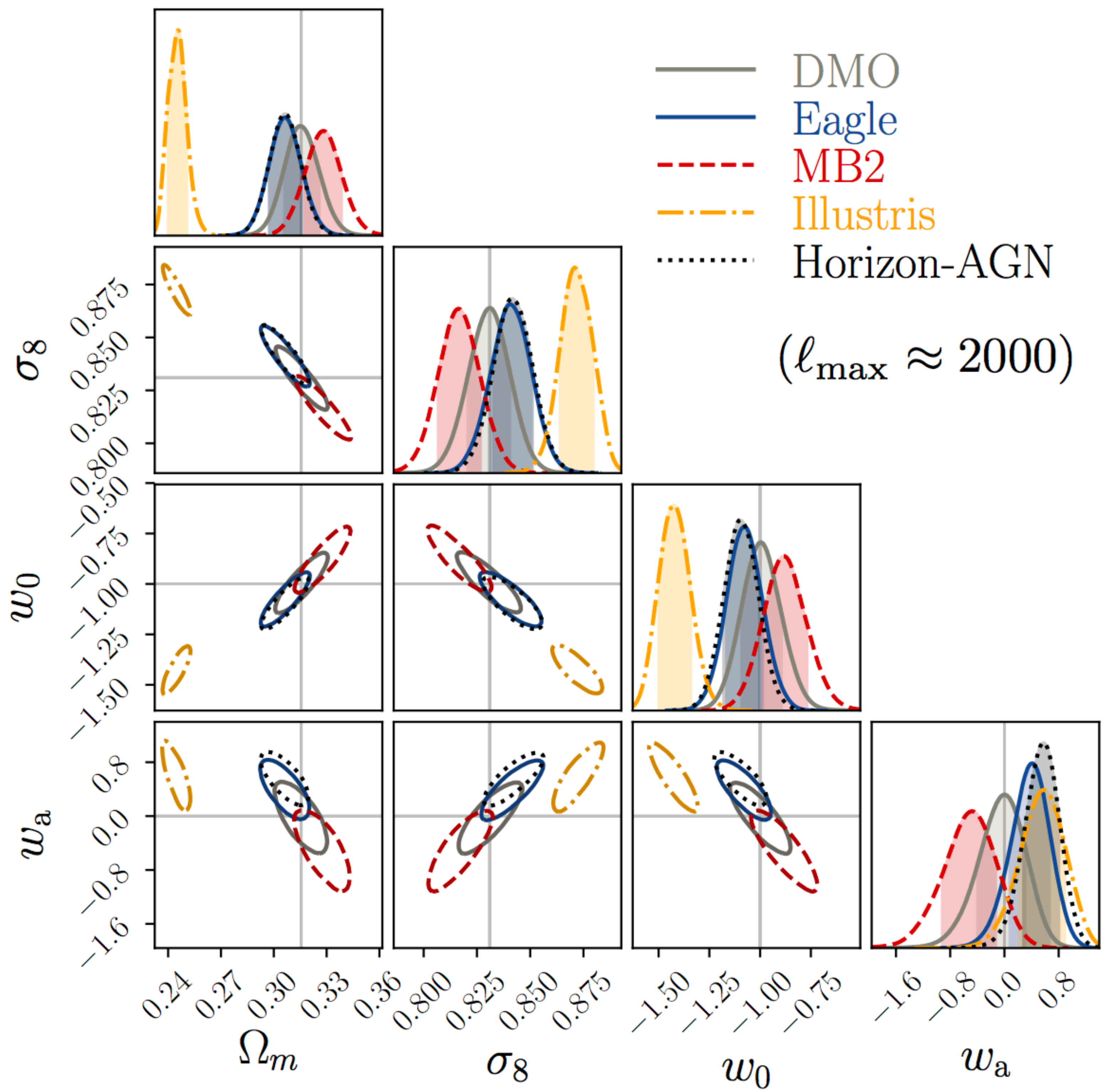

WL power spectrum for tomographic bin at z~0.25

Huang+ (2018)

# Implications

Colin Hill
Columbia/CCA

If not modeled accurately, these effects bias parameter inference from, e.g., the weak lensing power spectrum



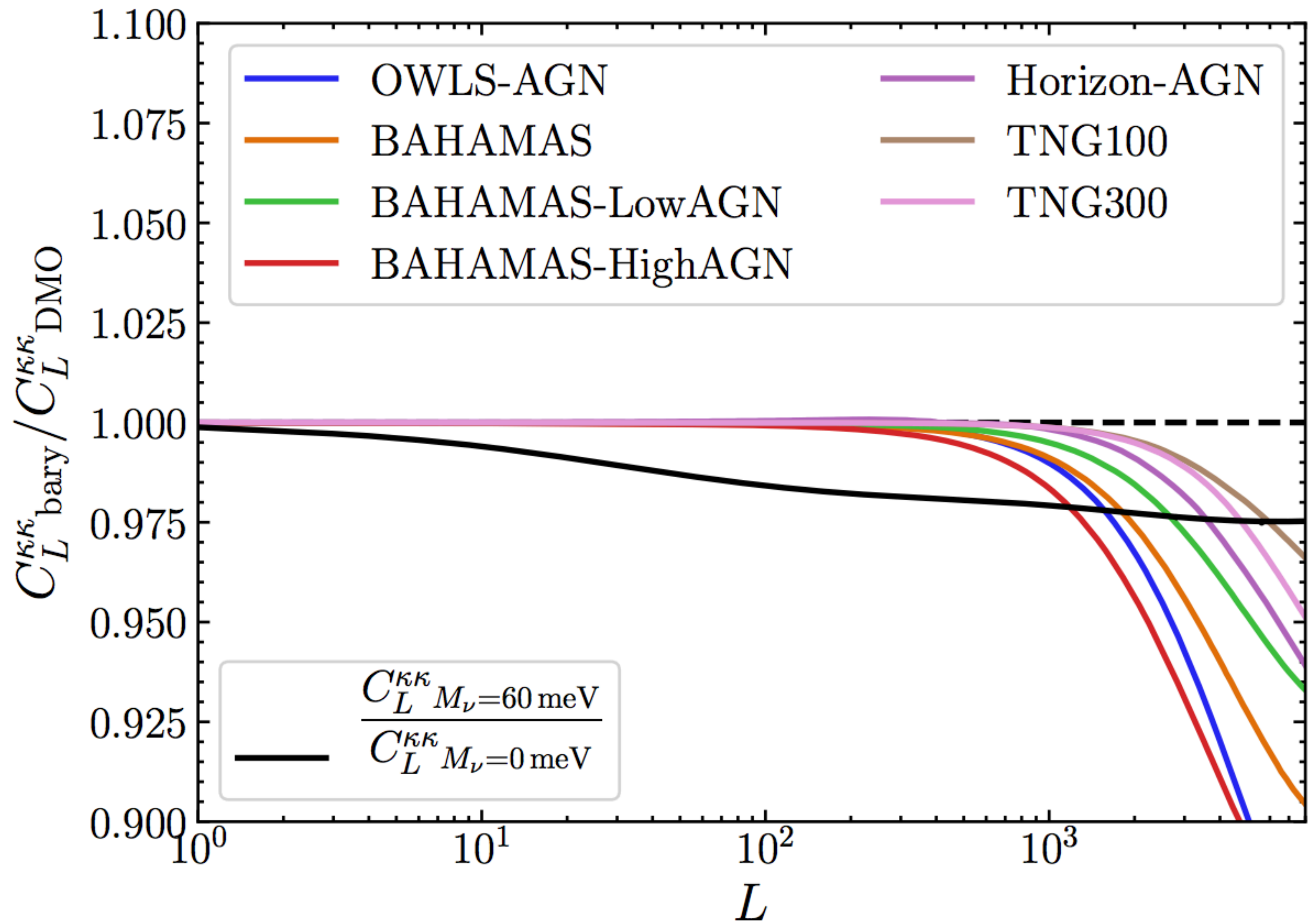

Huang+ (2018)

# What about CMB observables?

# CMB Lensing

Colin Hill
Columbia/CCA

Similar to galaxy WL case, inaccurate modeling of baryonic effects can bias inference of (e.g.) $\Sigma m_\nu$ from CMB lensing power spectrum

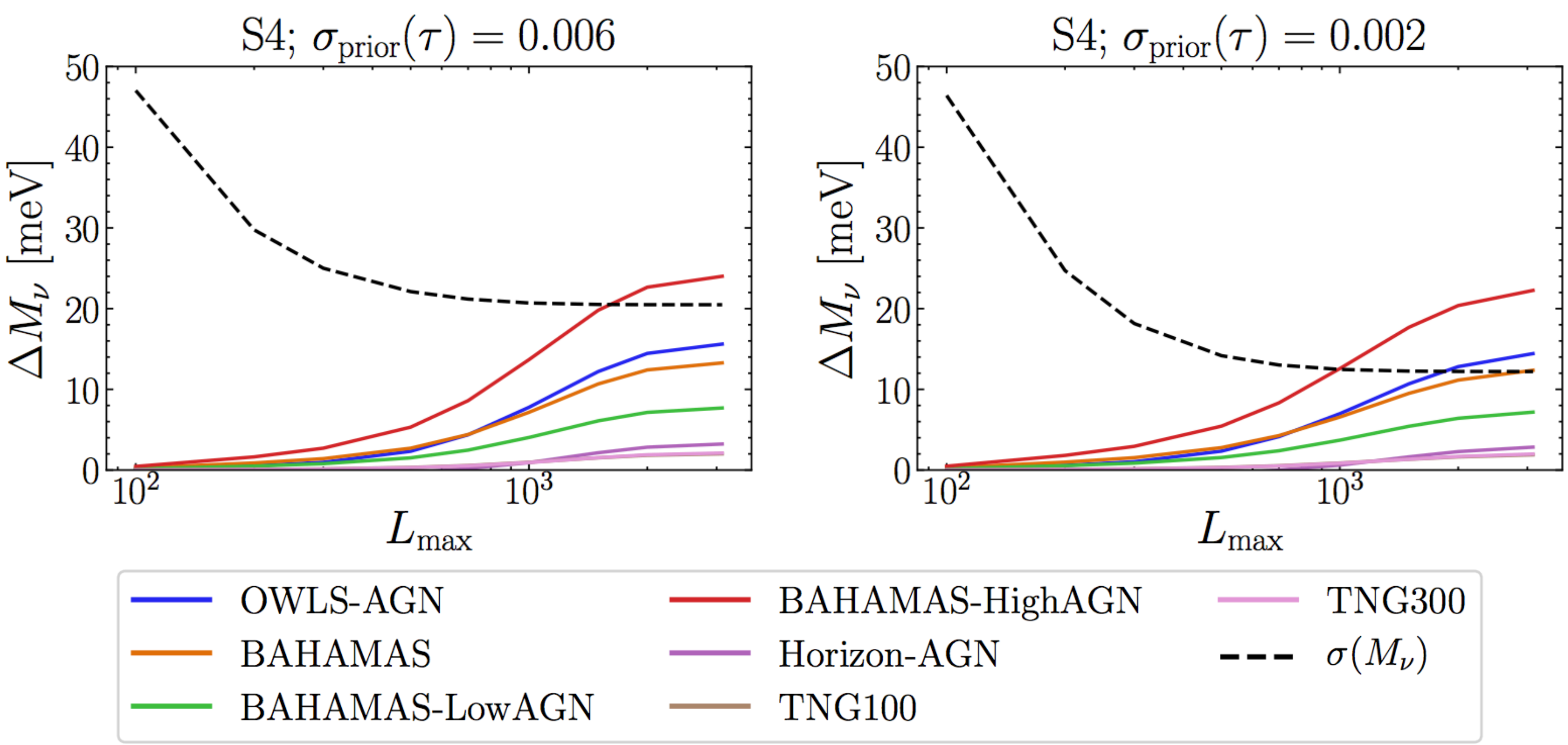



McCarthy, Foreman, & van Engelen (2020)

Colin Hill
Columbia/CCA

# CMB Lensing

Similar to galaxy WL case, inaccurate modeling of baryonic effects can bias inference of (e.g.) $\Sigma m_\nu$ from CMB lensing power spectrum



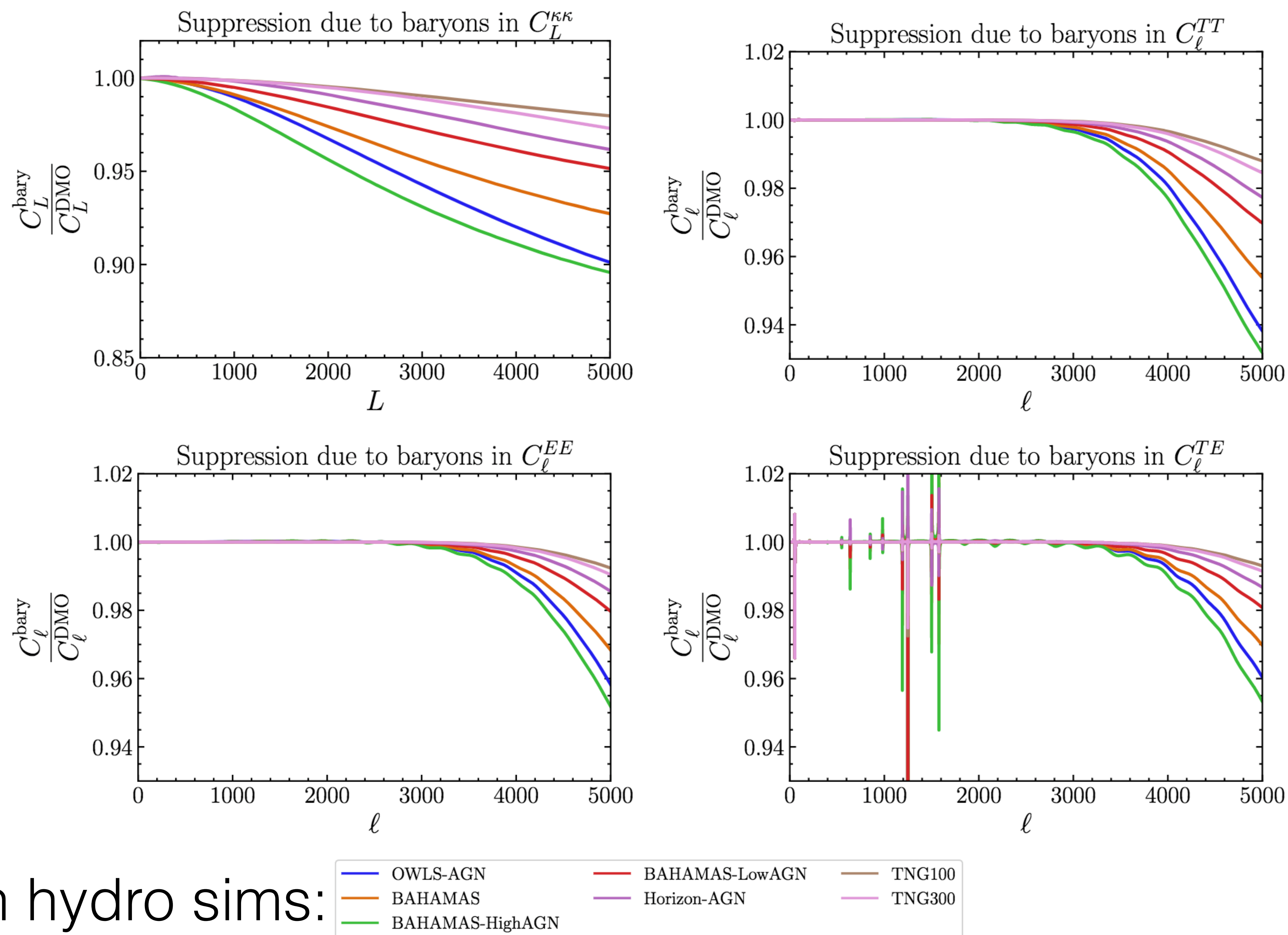

Mitigation: (1) scale cuts
(2) use external tracers to remove low-z lensing signal
(3) marginalize over baryonic feedback parameters

McCarthy, Foreman, & van Engelen (2020)

# CMB Lensing

Colin Hill
Columbia/CCA

Via lensing, baryons can even affect the primary TT/TE/EE power spectra!




Seven hydro sims:

McCarthy, JCH, & Madhavacheril (2021)

# Potential Parameter Biases

Colin Hill
Columbia/CCA

This can produce surprisingly large biases on, e.g., $H_0$, $\omega_c$, and $N_{eff}$ for upcoming CMB experiments (not current!)

Usual approach in primary CMB analyses to date:
"set it (default Halofit or HMcode in CAMB or CLASS) and forget it"

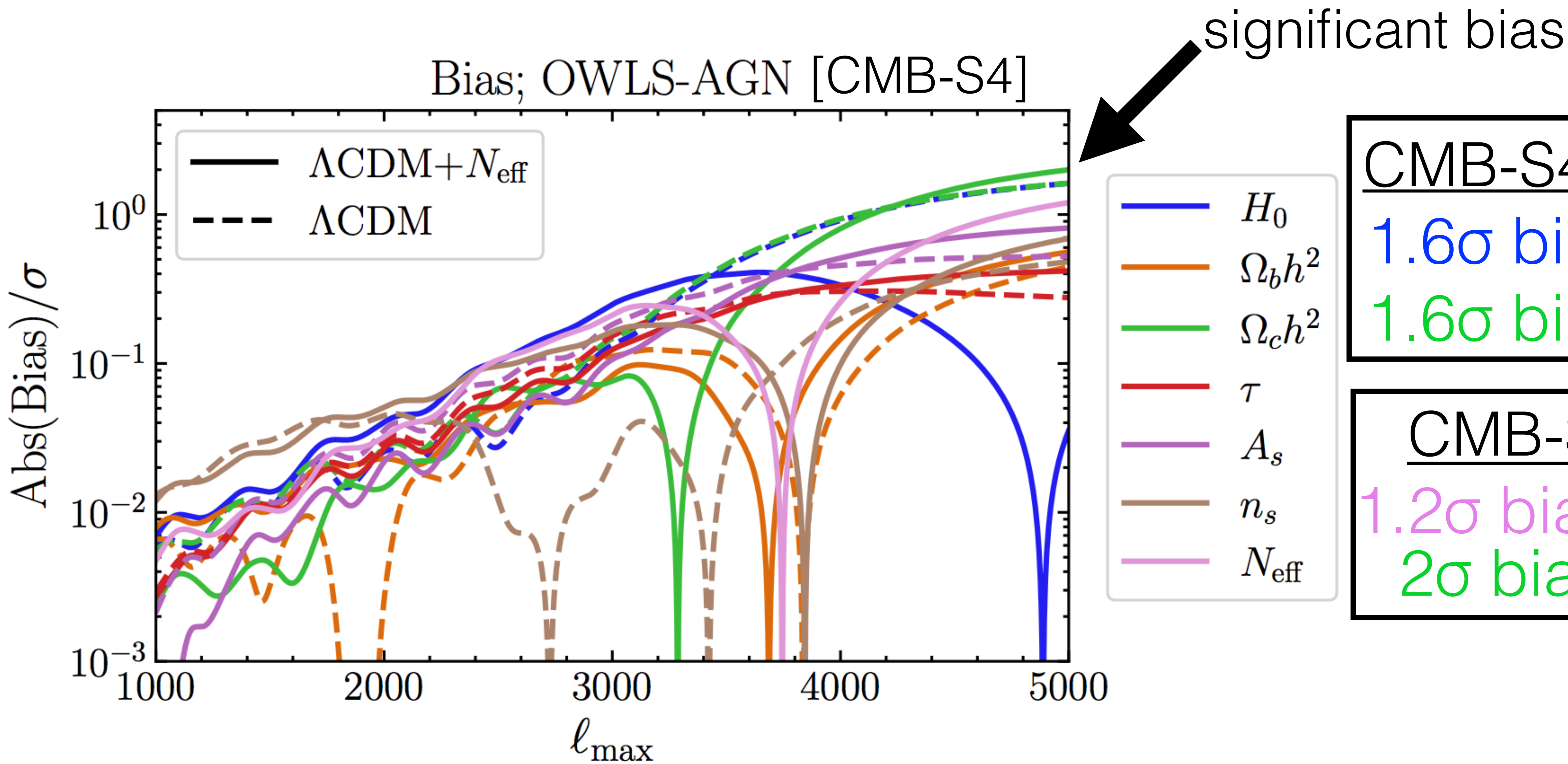
This will not suffice for CMB-S4! (or Simons Observatory)

McCarthy, JCH, & Madhavacheril (2021)

# Potential Parameter Biases

Colin Hill
Columbia/CCA

This can produce surprisingly large biases on, e.g., $H_0$, $\omega_c$, and $N_{eff}$ for upcoming CMB experiments (not current!)




**CMB-S4 [ΛCDM]**
1.6σ bias on $H_0$
1.6σ bias on $\omega_c$

**CMB-S4 [$N_{eff}$]**
1.2σ bias on $N_{eff}$
2σ bias on $\omega_c$

Not an issue for Planck or for current ACT/SPT data

McCarthy, JCH, & Madhavacheril (2021)

Colin Hill
Columbia/CCA

# Mitigation Methods

## Three strategies

1) Explicitly cut all TT data at ell>3000 (w/ small penalty in final parameter error bars) — 13% increase in $\sigma(N_{eff})$ for S4

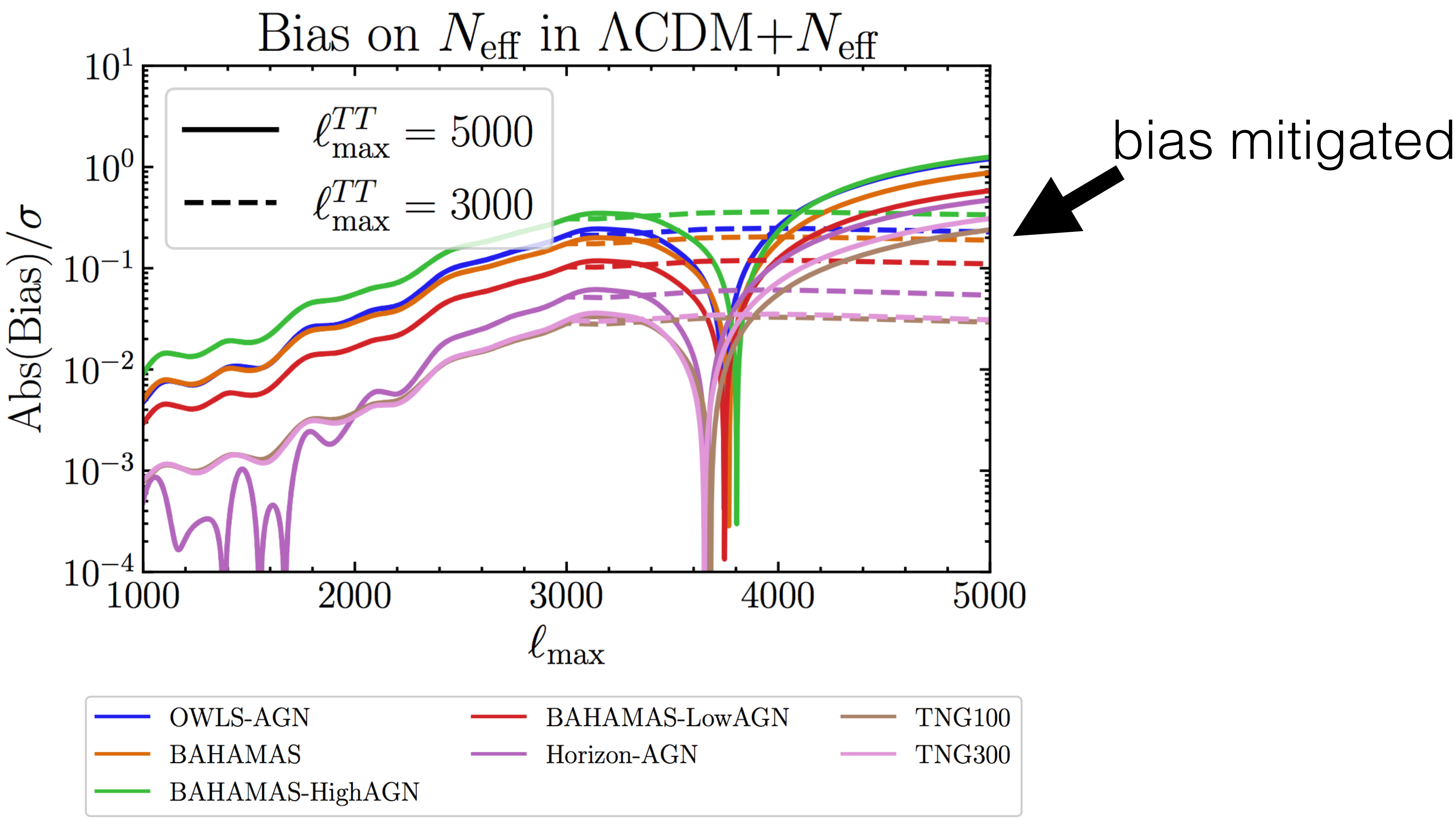
McCarthy, JCH, & Madhavacheril (2021)

Colin Hill
Columbia/CCA

# Mitigation Methods

## Three strategies

1) Explicitly cut all TT data at ell>3000 (w/ small penalty in final parameter error bars) — 13% increase in σ($N_{eff}$) for S4




McCarthy, JCH, & Madhavacheril (2021)

Colin Hill
Columbia/CCA

# Mitigation Methods

## Three strategies

1) Explicitly cut all TT data at ell>3000 (w/ small penalty in final parameter error bars) — 13% increase in $\sigma(N_{\rm eff})$ for S4

2) Marginalize over parameters describing baryonic effects

McCarthy, JCH, & Madhavacheril (2021)

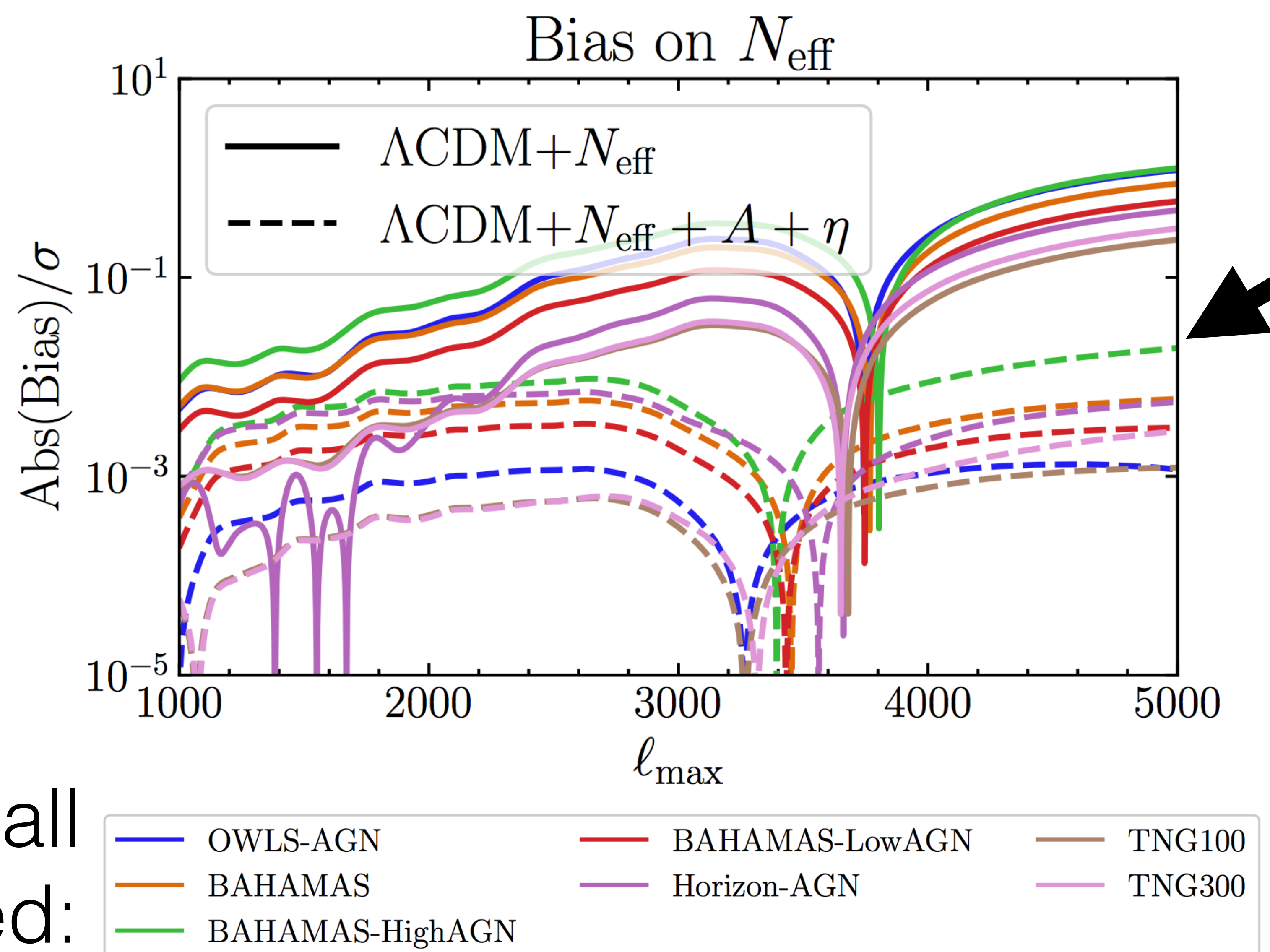
Colin Hill
Columbia/CCA

# Mitigation Methods

## Three strategies

1) Explicitly cut all TT data at ell>3000 (w/ small penalty in final parameter error bars) — 13% increase in $\sigma(N_{eff})$ for S4

2) Marginalize over parameters describing baryonic effects




bias mitigated by factor of >100

Works for all sims tested:

Colin Hill
Columbia/CCA

# Mitigation Methods

## Three strategies

1) Explicitly cut all TT data at ell>3000 (w/ small penalty in final parameter error bars) — 13% increase in $\sigma(N_{eff})$ for S4

2) Marginalize over parameters describing baryonic effects — but pay a penalty in parameter error bars: 13% increase in $\sigma(N_{eff})$ for S4 [coincidentally same as above]

McCarthy, JCH, & Madhavacheril (2021)

Colin Hill
Columbia/CCA

# Mitigation Methods

Three strategies

1) Explicitly cut all TT data at ell>3000 (w/ small penalty in final parameter error bars) — 13% increase in $\sigma(N_{\rm eff})$ for S4

2) Marginalize over parameters describing baryonic effects — but pay a penalty in parameter error bars: 13% increase in $\sigma(N_{\rm eff})$ for S4 [coincidentally same as above]

3) Delens the T and E-mode maps using the reconstructed $\kappa$ map (and/or external tracers like the CIB)
—> Most robust, data-driven approach, and can actually improve the error bars on parameters [Green et al. (2016)]
—> Challenge: need very high-L $\kappa$ information!

McCarthy, JCH, & Madhavacheril (2021)

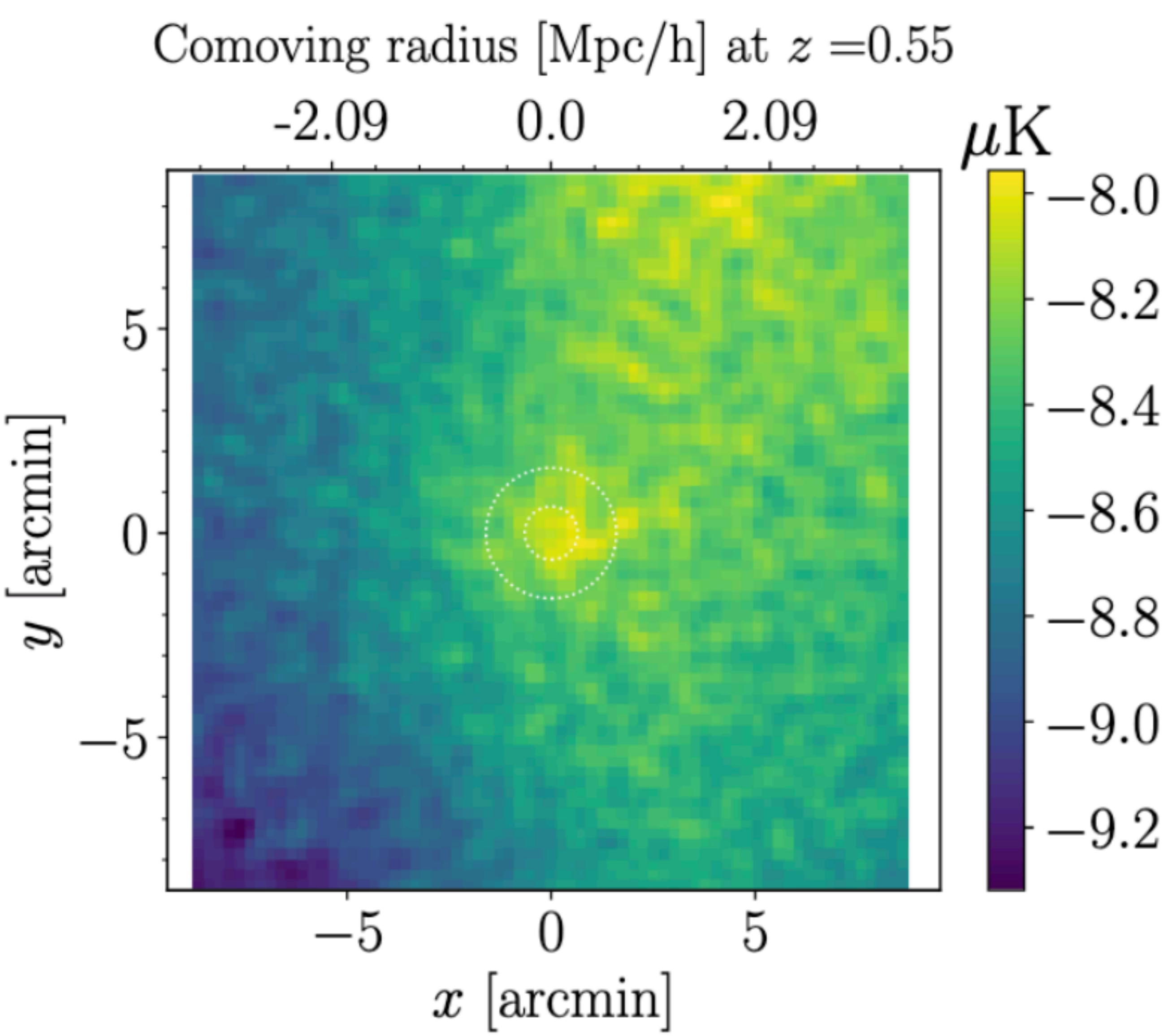
# A data-driven solution: (k)SZ calibration

Colin Hill
Columbia/CCA

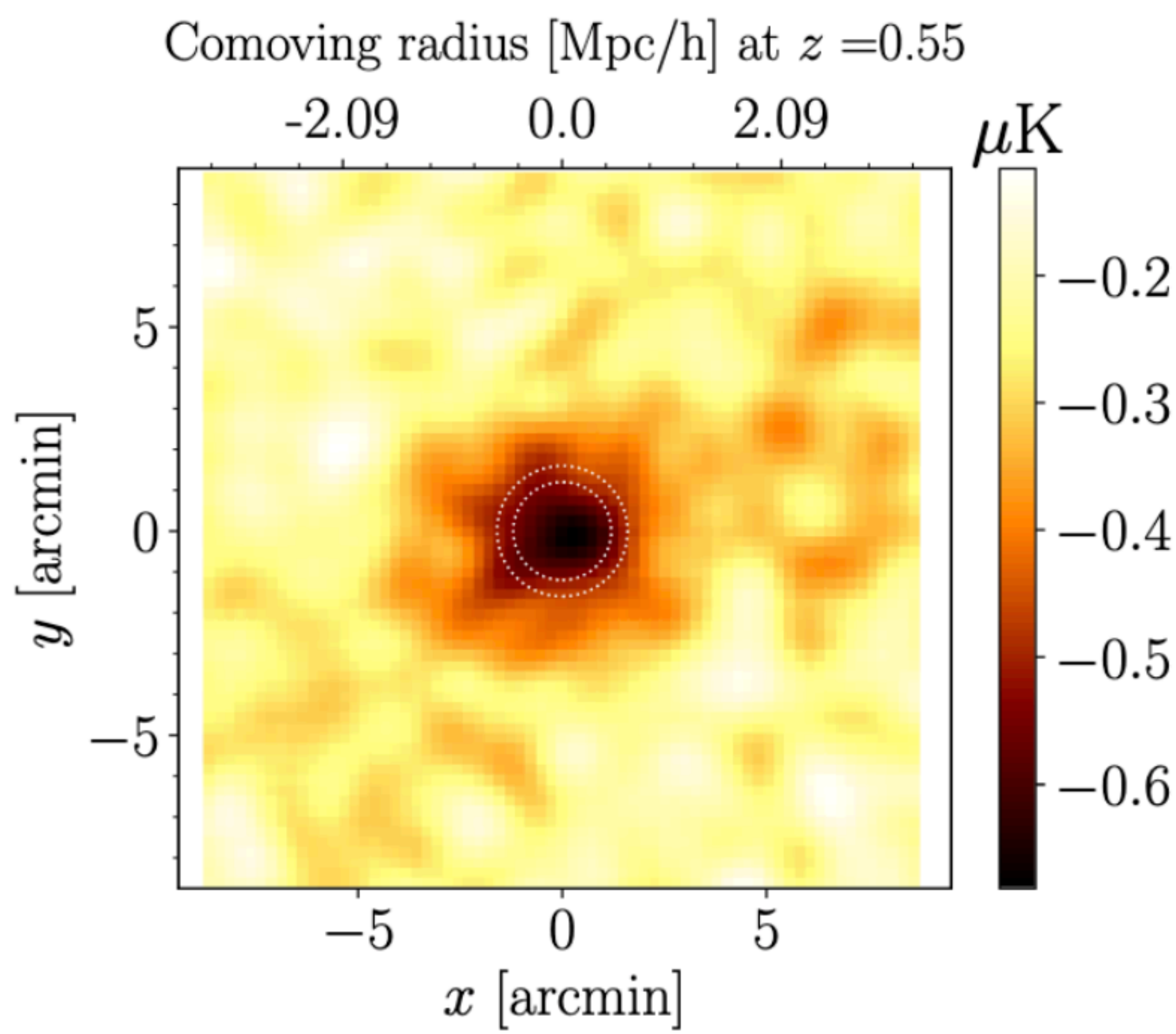
# Imaging Baryons with kSZ

## kSZ tomography directly images the ionized gas distribution

ACT + BOSS CMASS
Stacked kSZ




ACT + BOSS CMASS
Stacked tSZ

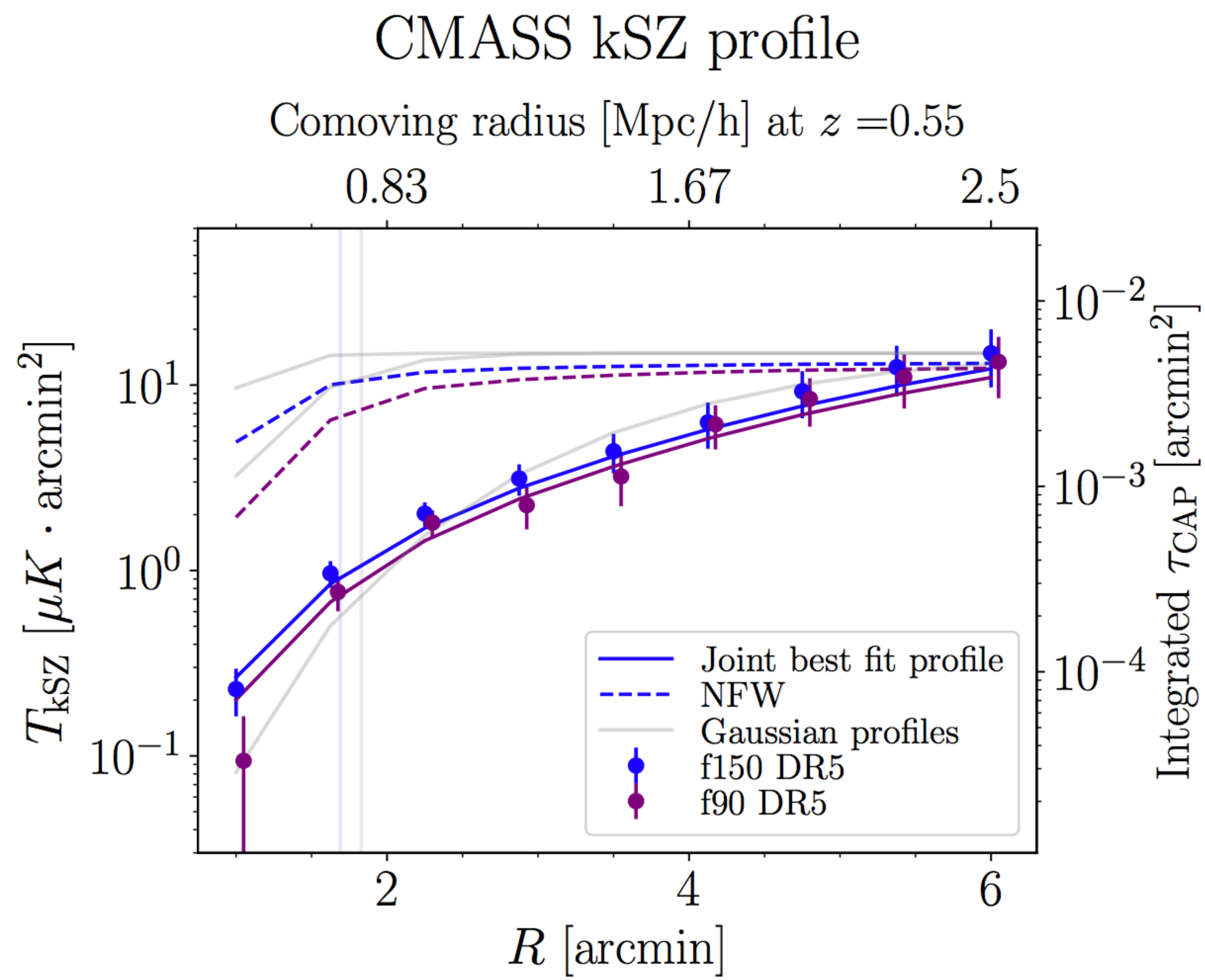



Schaan+ (2021); see also Amodeo+ (2021); y-map from Madhavacheril, JCH, Naess+ (2020)

Colin Hill
Columbia/CCA

# Imaging Baryons with kSZ

## kSZ tomography directly images the ionized gas distribution



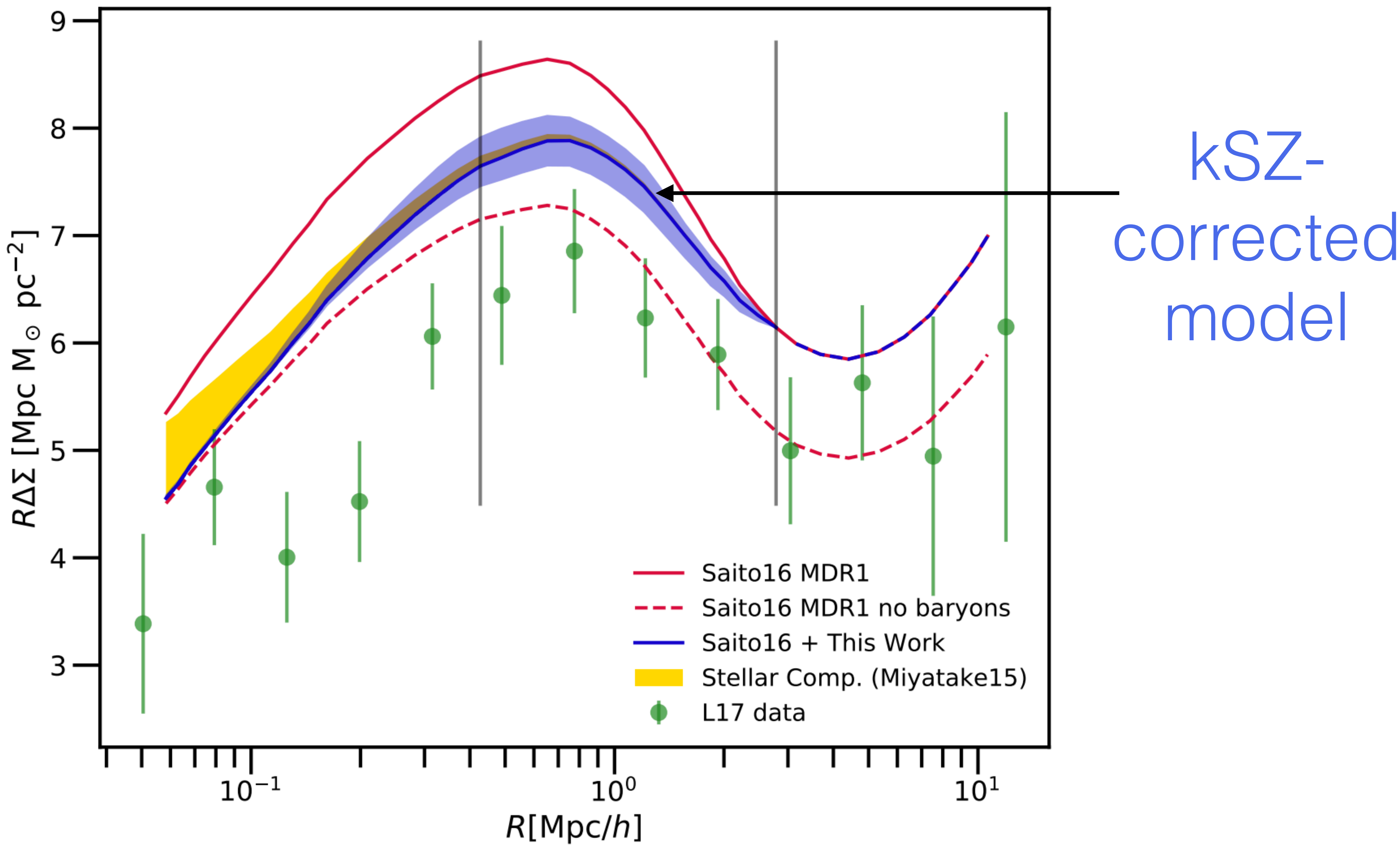

For galaxy-galaxy lensing (g x κ), kSZ measures **exactly** the dominant baryonic correction (where the gas is located!); for lensing auto-spectra, modeling is needed

Schaan+ (2021); see also Amodeo+ (2021)

Colin Hill
Columbia/CCA

# Imaging Baryons with kSZ

## kSZ tomography directly images the ionized gas distribution




For galaxy-galaxy lensing (g x κ), kSZ measures **exactly** the dominant baryonic correction (where the gas is located!): example shown here for CMASS g-g lensing

Amodeo+ (2021); see also Schaan+ (2021)

Colin Hill
Columbia/CCA

# Baryonic Corrections

## Simple models

Initial assumptions:

- Neglect stellar distribution (consider stars only in setting fgas)
- NFW profile is not altered by baryonic feedback (we will come back to this)

Then:

$$\frac{P_{mm}^{\rm fb}}{P_{mm}^{\rm no-fb}} = \frac{1}{P_{nn}}\left(f_c^2 P_{nn} + f_b^2 P_{ee} + 2 f_c f_b P_{ne}\right)$$

$P_{nn}$ = CDM power spectrum assuming NFW
$f_c$ = fraction of matter in CDM
$f_b$ = fraction of matter in gas
$P_{ee}$ = electron (gas) power spectrum
$P_{ne}$ = CDM-gas cross-power spectrum

Similarly, for galaxy-matter cross-spectrum:

$$\frac{P_{gm}^{\rm fb}}{P_{gm}^{\rm no-fb}} = \frac{1}{P_{gn}}\left(f_c P_{gn} + f_b P_{ge}\right)$$

measured by kSZ!

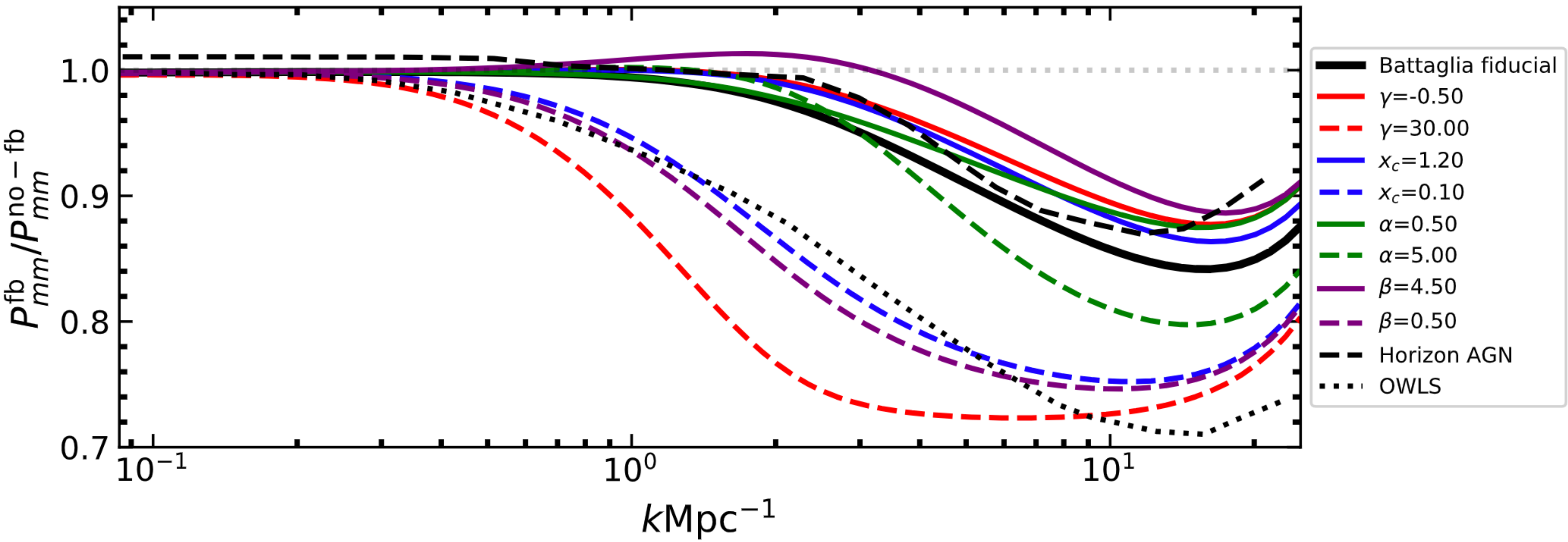
BFHMS (in prep.)

Colin Hill
Columbia/CCA

# Baryonic Corrections

## This works quite well

Halo model calculation using NFW for dark matter and Battaglia (2016) GNFW gas density profile, allowing parameters to vary



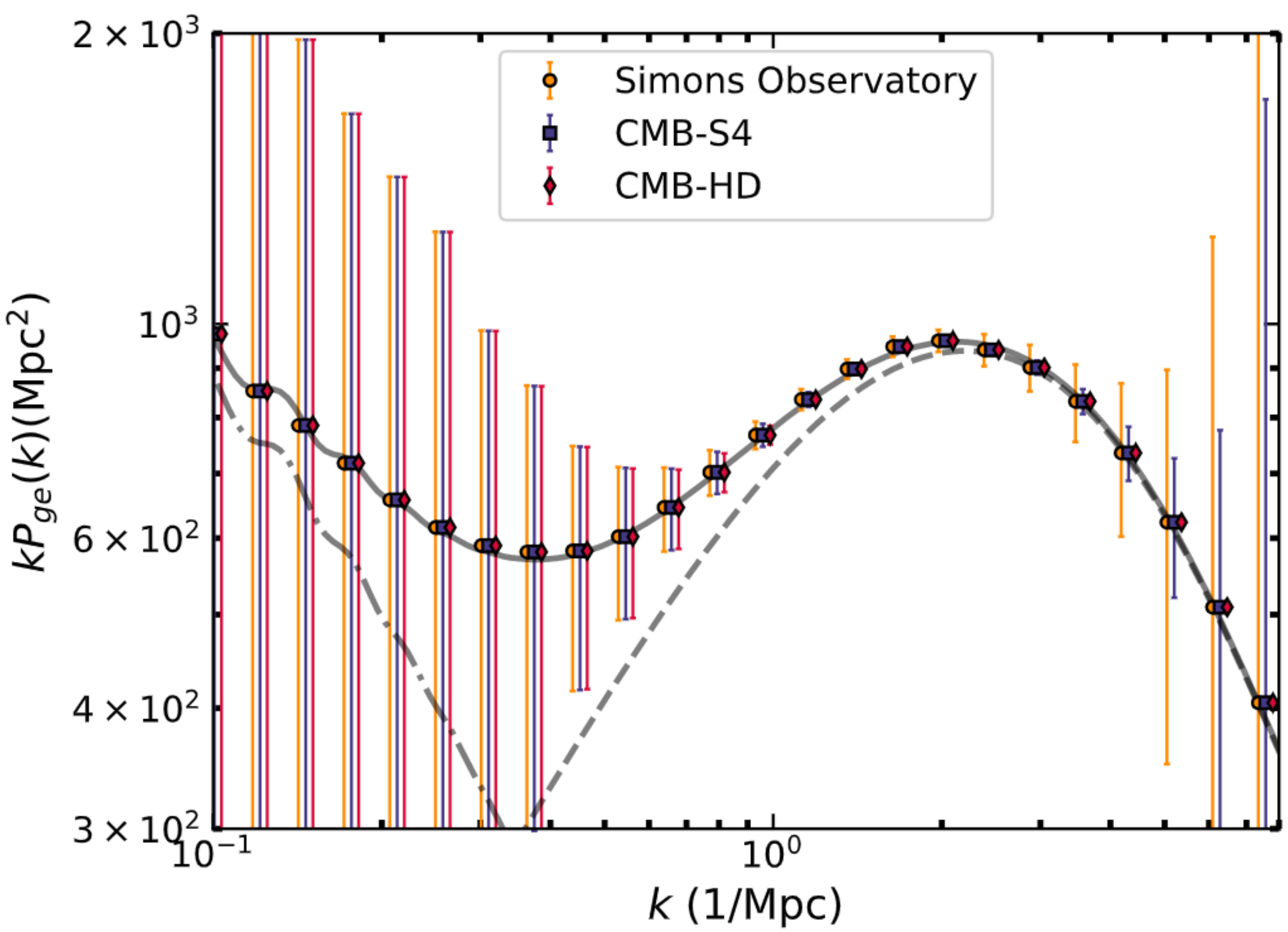

BFHMS (in prep.)

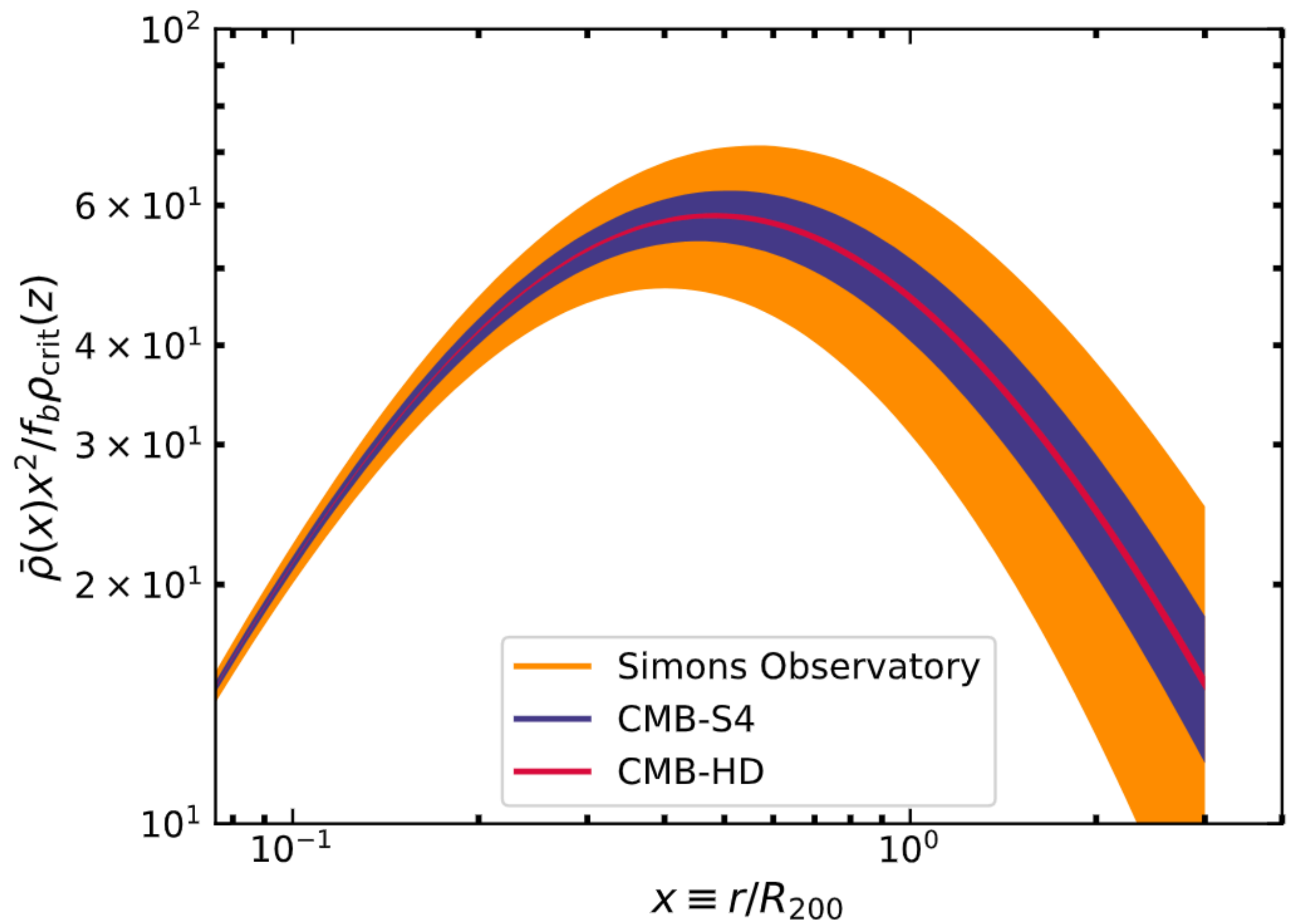
Colin Hill
Columbia/CCA

# Baryonic Corrections

## And we will measure gas profiles very well

kSZ cross-correlations with DESI galaxies (z~0.75)



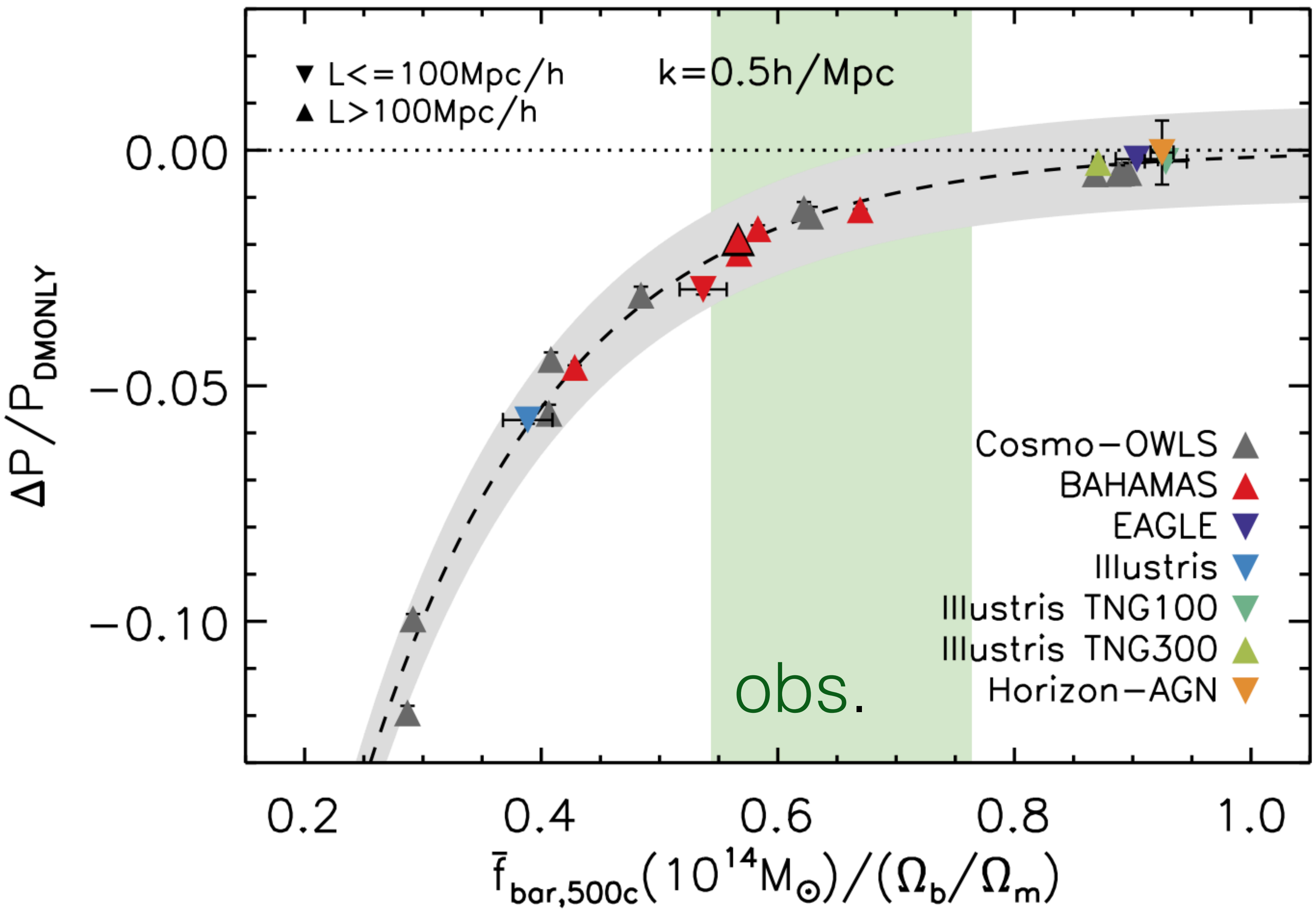

Large-radius behavior can be improved by imposing consistency condition that $f_b$ -> $f_{b,CMB}$

BFHMS (in prep.); see also forecasts in CMB-S4 DSR

# Baryonic Corrections

Colin Hill
Columbia/CCA

Perhaps only a single-variable model is needed (on relevant scales)



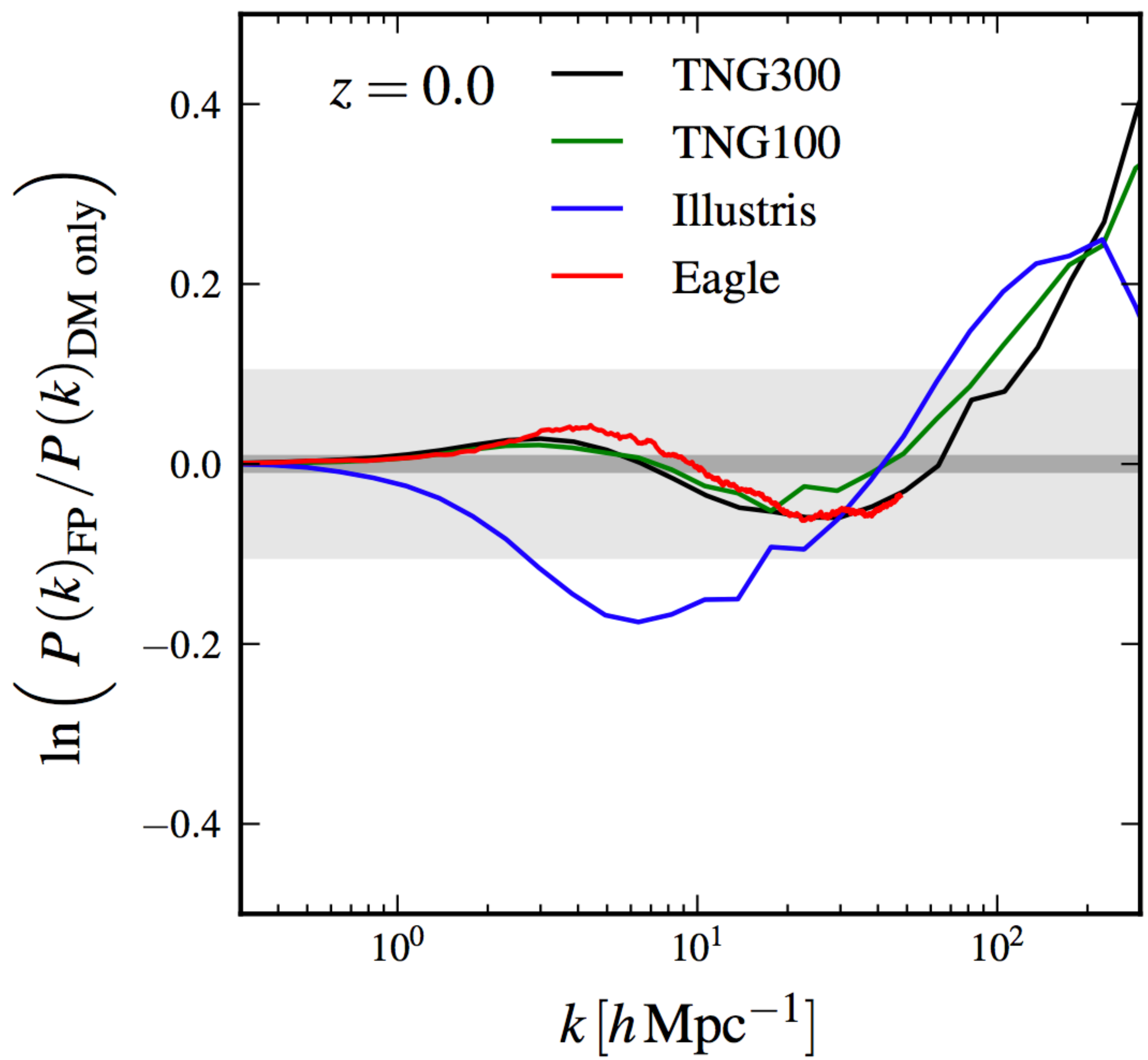

At k = 0.5 h/Mpc, the baryonic suppression in P(k) is predicted simply by the mean baryon fraction in ~$10^{14}$ $M_{sun}$ halos

M. van Daalen, I.G. McCarthy, & J. Schaye (2020)

# Next-Order Correction

Colin Hill
Columbia/CCA

Response of the dark matter distribution to baryonic feedback




Idea:
calibrate by
measuring
total feedback
energy injected
into gas
via tSZ (e.g.,
Battaglia+2017)

Ratio of the dark matter power spectrum in full-physics runs to that in dark matter-only runs

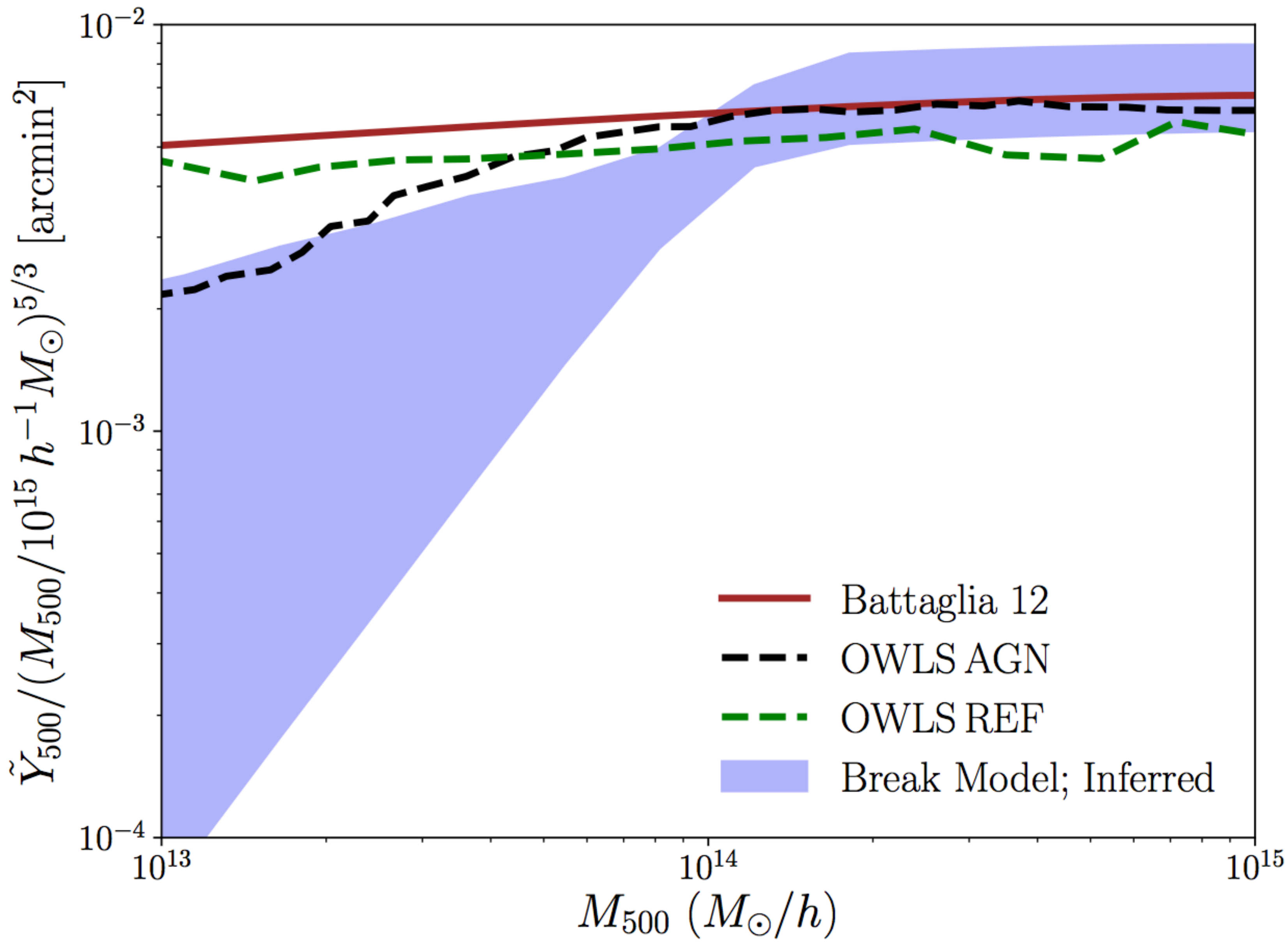
Springel+ (2017)

Colin Hill
Columbia/CCA

# Next-Order Correction

## Recent developments: ACTxDES tSZ x WL at 21σ

Inference of the Y-M relation via halo model fit to y x κ measurements indicates evidence of a break and strong feedback




Gatti, Pandey, Baxter, JCH+ (2021); Pandey, Gatti, Baxter, JCH+ (2021)

Colin Hill
Columbia/CCA

# Calibration Strategy Recap

- For galaxy x galaxy/CMB lensing: measure galaxy x kSZ for same galaxies — this exactly measures the dominant baryonic correction term (~no modeling needed)

- For lensing auto-spectra (and P(k) more generally), modeling based on parametric fits to kSZ profiles will be required, but simple approaches already appear to do very well, and joint analysis with tSZ profiles will further constrain feedback parameters

BFHMS (in prep.)

# Take-Home Messages

Colin Hill
Columbia/CCA

1) Baryonic effects bias parameter inference (even CMB)
2) kSZ measurements will dramatically help by directly measuring the gas profile
3) Some modeling will be required to extend to full range of observables (e.g., lensing auto-spec), but joint fits with tSZ will also help

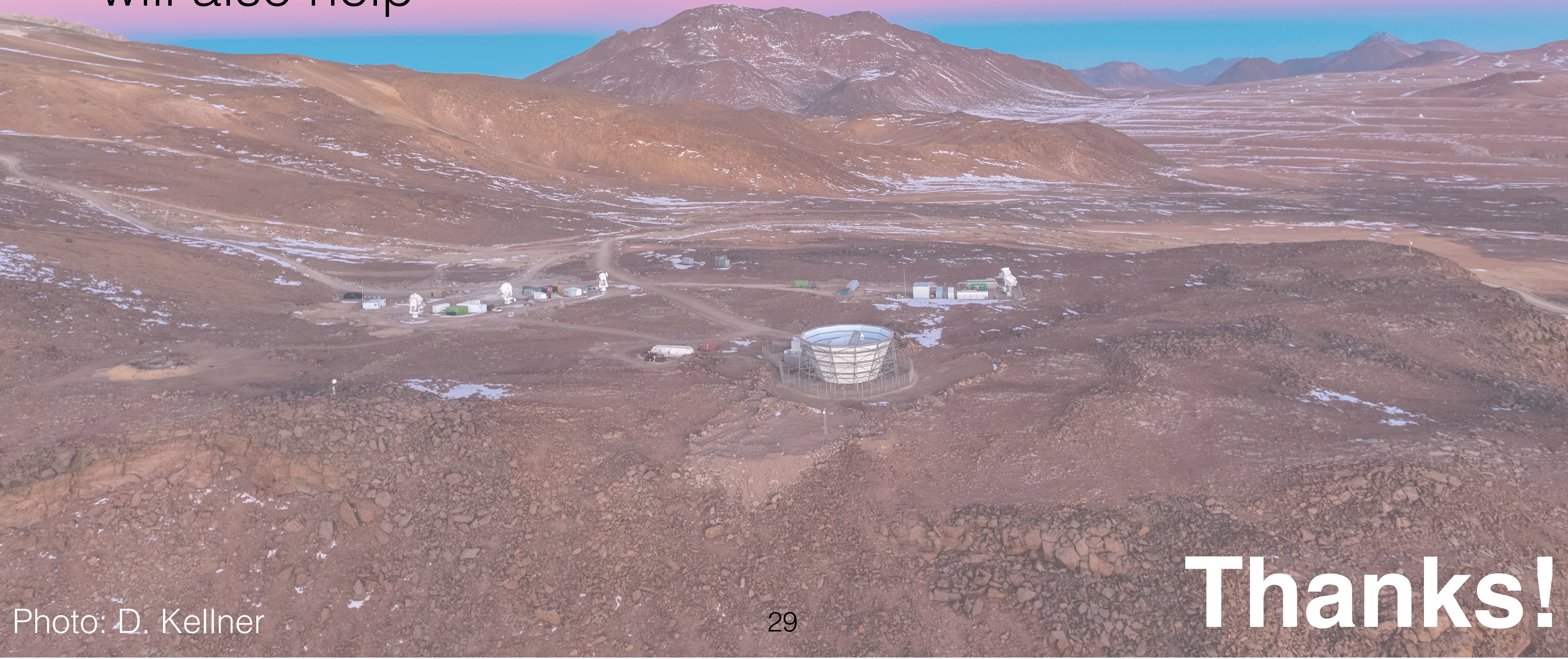


Photo: D. Kellner

**Thanks!**