Backlighting the Baryons with CMB-S4

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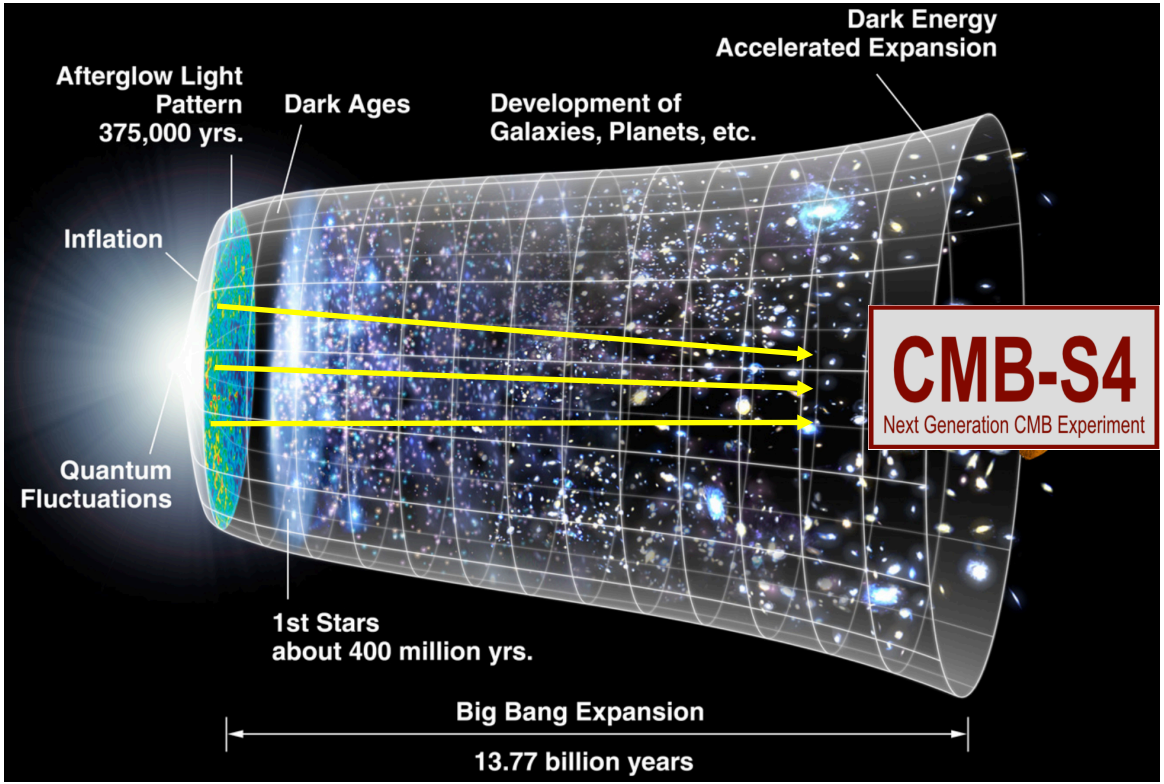
(Lawrence Berkeley National Laboratory)

with Alexie Leauthaud

CMB-S4 collaboration meeting
August 11, 2021

A brief history of CMB photons



credit: WMAP

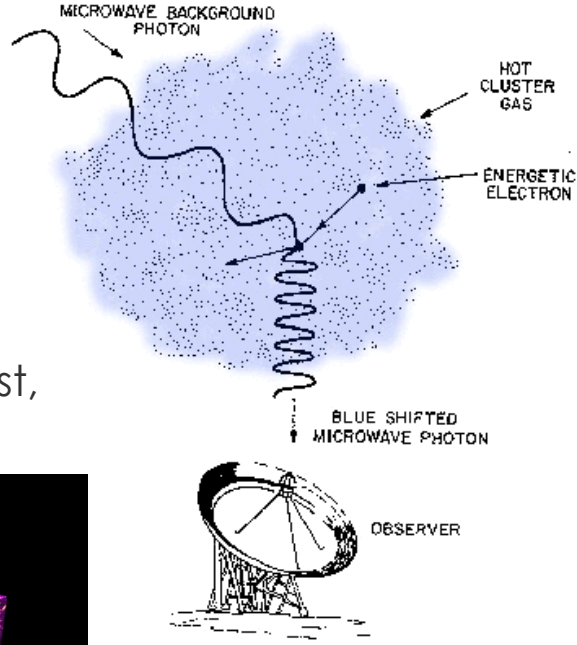
94% of photons don't re-scatter (but are lensed!)

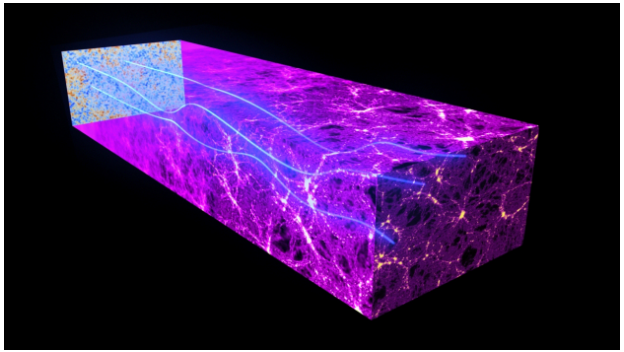
6% scatter with matter

High-resolution CMB experiments are excellent probes of the Large-Scale Structure!

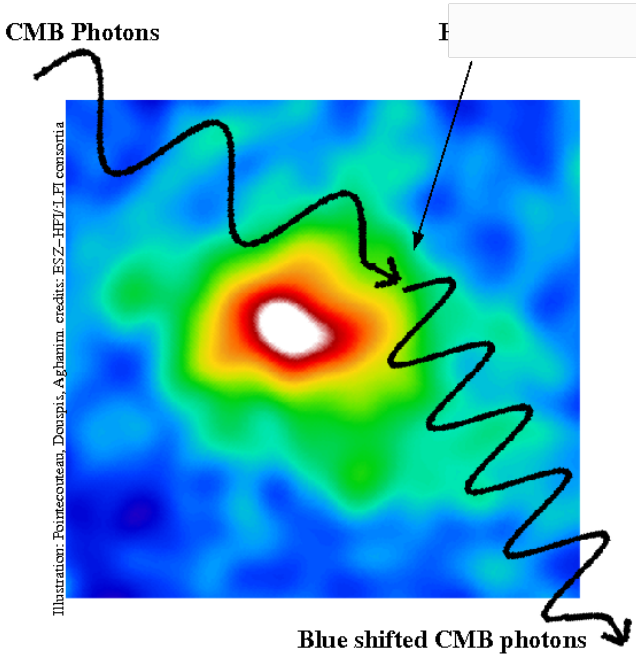
Photons interact with matter

- Gravitational: lensing, gravitational redshift, Integrated Sachs-Wolfe effect, "moving cluster", time delay, …
- Scattering (Thomson/Compton scattering):
  - Thermal Sunyaev-Zeldovich (tSZ),
  - Kinematic Sunyaev-Zeldovich (kSZ),
  - Patchy "blurring", screening and scattering, ...
- (Emission from late time matter): starlight, IR emission from dust, free-free, synchrotron, AME, …





The Sunyaev-Zel'dovich effect(s)



kinematic SZ $\left(\frac{\Delta T}{T}\right)_{\rm kSZ} \approx \sigma_T N_e(\boldsymbol{\theta}) \frac{v_r}{c}$

column density of electrons

radial velocity

thermal SZ $\left(\frac{\Delta T}{T}\right)_{\rm tSZ} \propto N_e(\boldsymbol{\theta}) T_e(\boldsymbol{\theta})$

Distribution very uncertain due to feedback → "**missing baryon problem**"

Baryons are **~16%** of the mass → **major systematic for weak lensing** + **rich physics for galaxy formation & halo thermodynamics**.

kSZ/tSZ: a 2021 view of CMASS galaxies

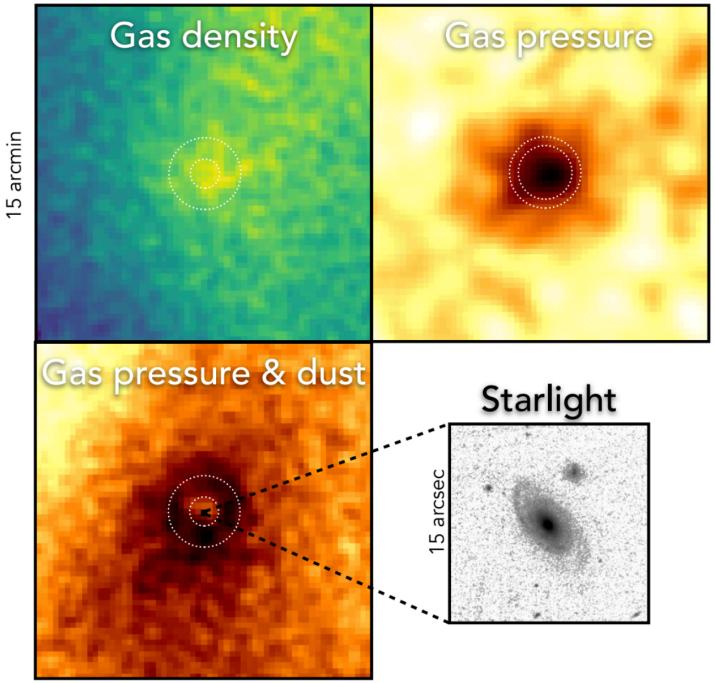
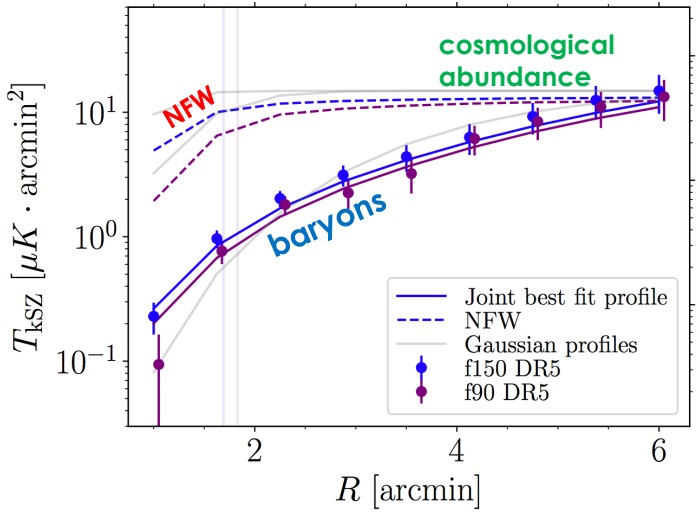
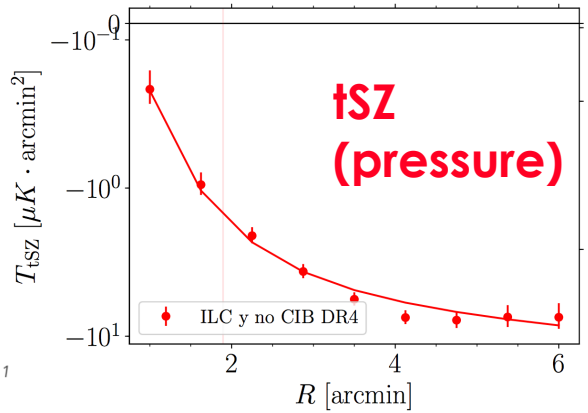


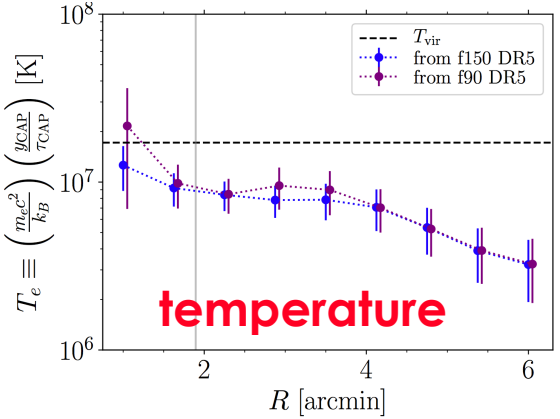
Figure: Emmanuel Schaan
ACT+Planck microwave images: Schaan et al 2020. HST ACS I band image: Masters et al 2011



kSZ (density)



tSZ (pressure)

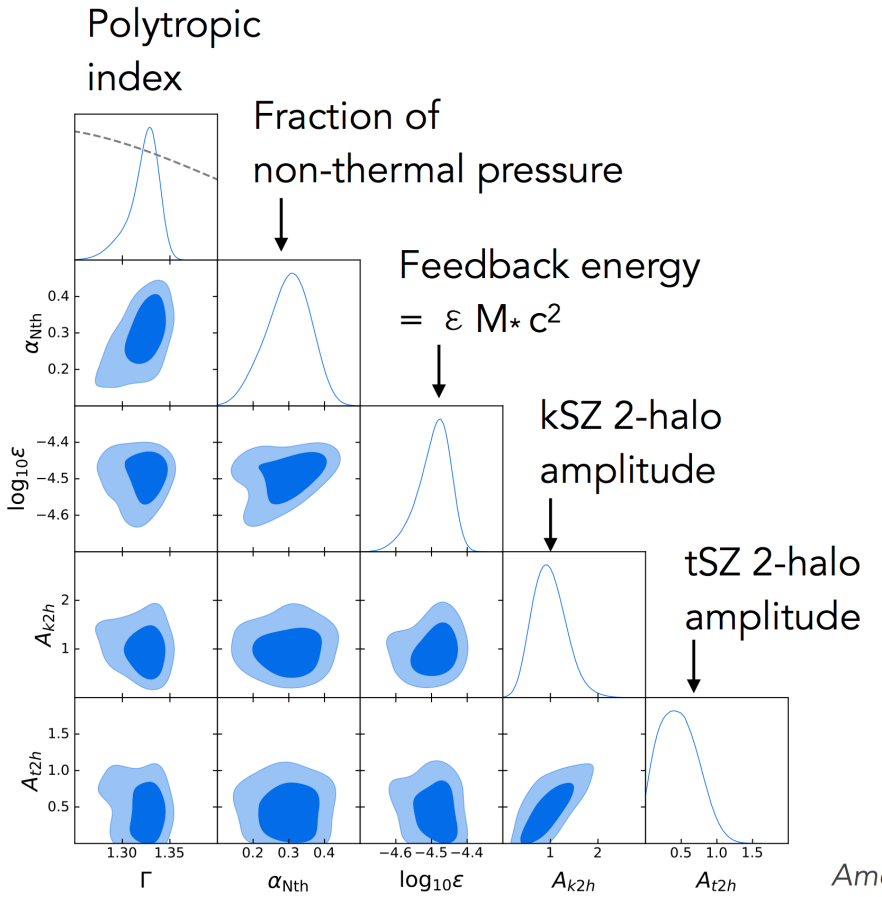


temperature

Schaan, S.F., Amodeo, Battaglia + ACT (2021)
Amodeo, Battaglia, Schaan, S.F. Moser + ACT (2021)

Also (not shown here): Vavagiakis et al + ACT (2021), Calafut et al + ACT (2021), Kusiak et al (2021) + previous literature!

Thermodynamic information



- ~30% **non-thermal pressure** support
- Energy injected **~ 30% of binding energy**

Very rich physics! One order of magnitude improvement with CMB-S4, especially within the virial radius,

Battaglia, S.F., Schaan, Spergel, 2017

Amodeo Battaglia Schaan Ferraro & ACT 20
Ostriker Bode Babul 05

Baryon effects in weak lensing

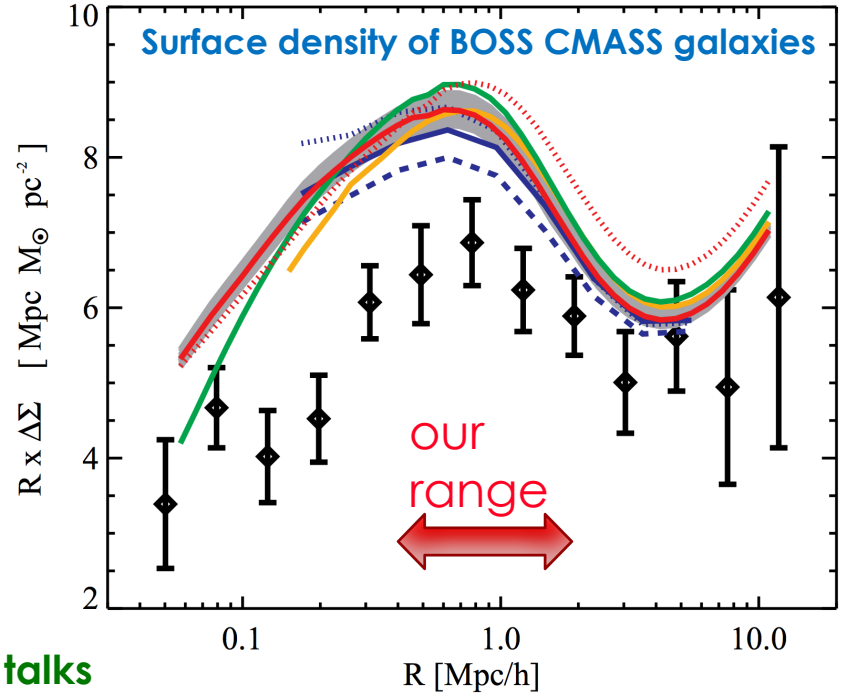
Calibration of baryon effects in weak lensing:

- Baryons are ~16% of the mass: statistically "large" effect on weak lensing
- CMB lensing cross-correlations & galaxy lensing amplitude often "lower" than expected.
- Larger discrepancy on small scales, the most affected by baryons.

Can this be explained (at least in part) by baryon effects?

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],



→ **Aurel Schneider & Colin Hill's talks**

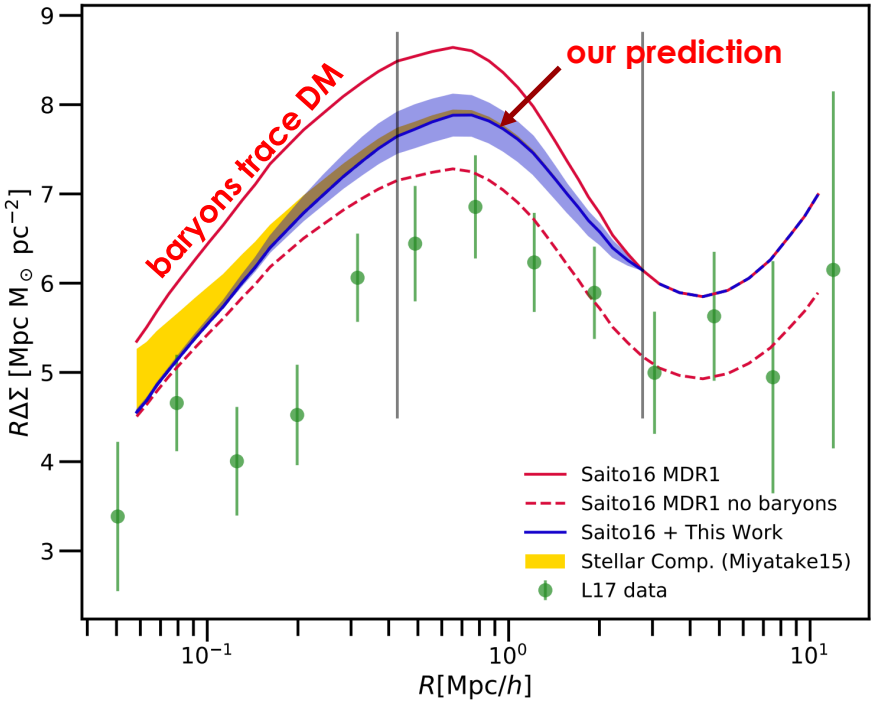
Baryon effects: first direct SZ calibration

Direct SZ calibration:
Use SZ measurements of gas on the same sample to directly calibrate

First example on BOSS CMASS with ACT data. Explain ~half of the discrepancy

+ work in progress with A. Leauthaud, J. DeRose, A. Amon and many others!

→ **Colin Hill's talk**



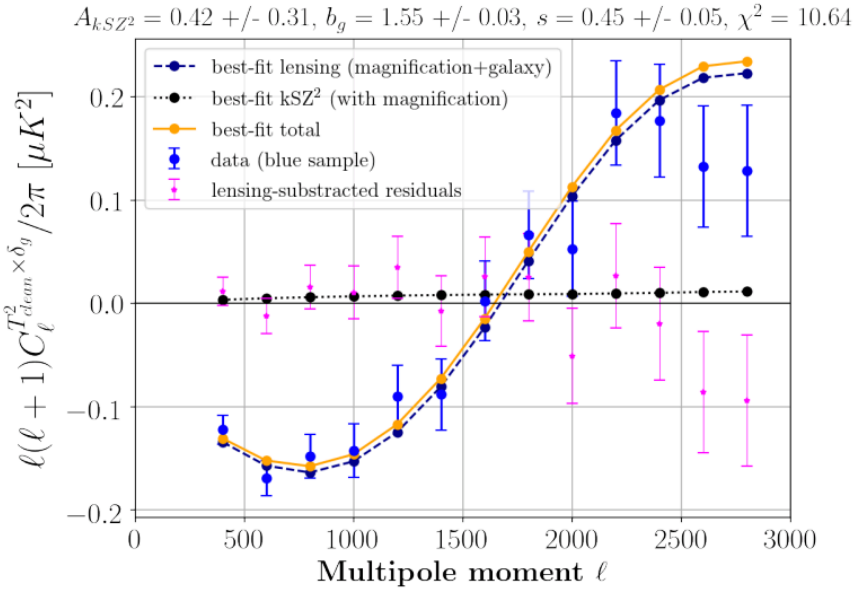
Amodeo, Battaglia, Schaan, Ferraro, Moser + ACT (2021)

Projected kSZ^2

For photometric redshifts (eg. DES, Rubin Observatory, …), usual techniques are suboptimal.

- Solution: projected fields kSZ!
- Estimator kSZ^2 x (galaxies, shear, 21cm etc…) .
- Sensitive to halo parameters, just like traditional methods.
- Potentially very large S/N, but more sensitive to foregrounds

→ **Ola Kusiak's talk**



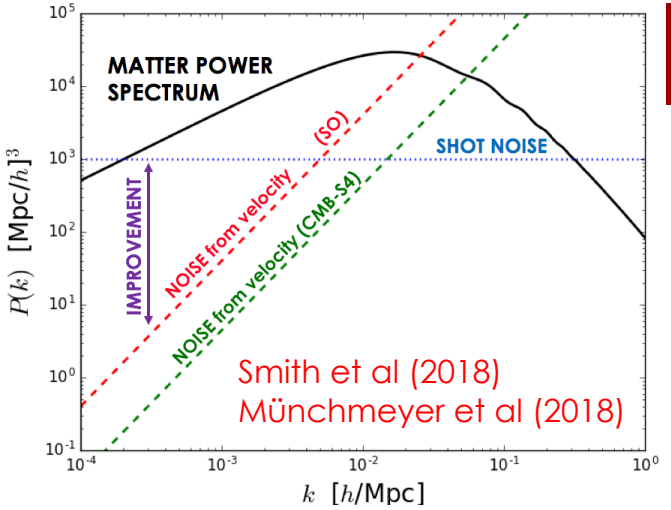
Experiment	SNR
Planck x unWISE (current)	5
Simons Obs. x unWISE (~2023)	~ 300
CMB-S4 x Rubin Obs.	> 600

Kusiak et al (2021).
Ferraro et al (2016), Hill et al (2016)

Other applications

Measuring velocities:

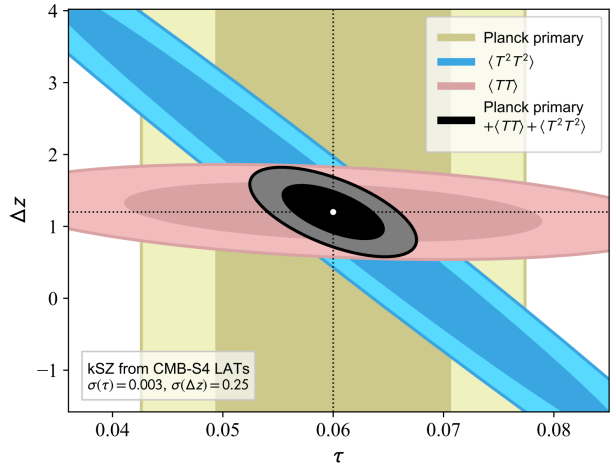
- Tests of gravity / scale dependence of growth
- Sample variance cancellation and ~50% improvement on f_{NL}
- Access to very large-scale modes: "no shot noise" → **CMB x LSS parallel**



Smith et al (2018)
Münchmeyer et al (2018)

Patchy Reionization:

- kSZ: large imprint on high-ell T power, and largest non-Gaussianity.
- Use 4-pt (Smith & Ferraro) to separate reionization from late-time component.
- 2-pt + 4-pt very effective at breaking degeneracies! → **Reionization parallel**



Alvarez, Ferraro, Hill, Hlozek, Ikape (2021)

"Backlighting the baryons" at this meeting

- **Parallel today at 11:10am – 2pm Pacific**
- **Plenary by Alexie Leauthaud tomorrow at 8am Pacific**

PARALLEL

11:00	Current measurements and future prospects: reconstructed velocities and halo thermodynamics	*Emmanuel Schaan* 11:10 - 11:30
	Current measurements and future prospects: pairwise kSZ	*Eve Vavagiakis* 11:30 - 11:50
	Review: baryon effects in weak lensing	*Aurel Schneider* 11:50 - 12:10
12:00	Discussion	12:10 - 12:25
	Mid-Parallel Break	12:25 - 12:45
	SZ calibration of baryon effects	*Colin Hill* 12:45 - 13:05
13:00	Projected fields kSZ	*Aleksandra Kusiak* 13:05 - 13:25
	kSZ as a probe of ultralight axions	*Daniel Grin* 13:25 - 13:35
	Discussion	13:35 - 14:00
14:00		

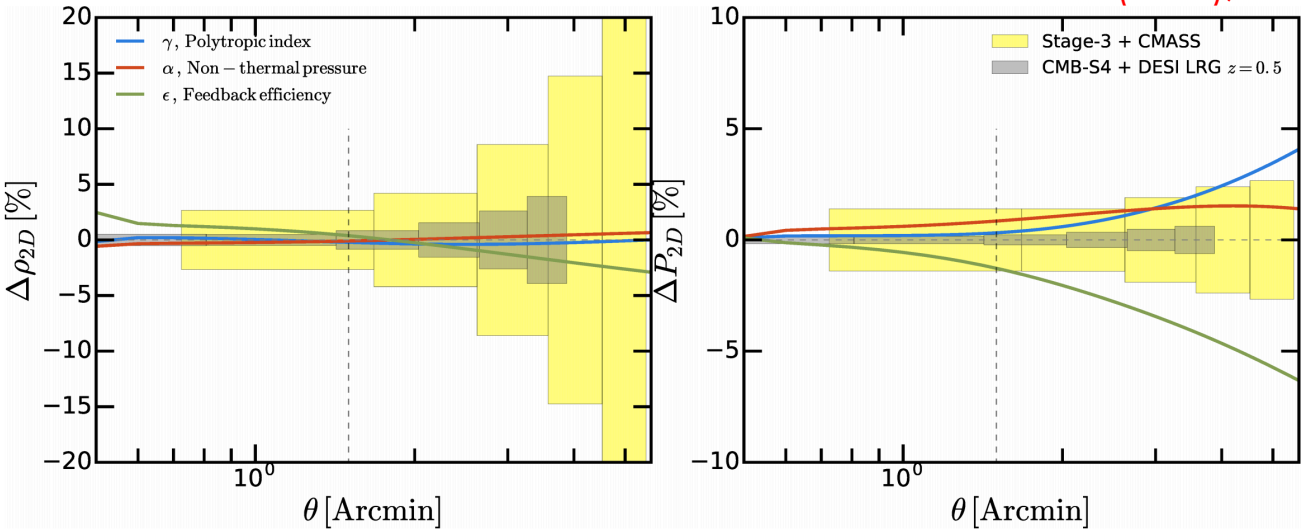
BACKUP SLIDES

Halo thermodynamics

→ **Emmanuel Schaan & Eve Vavagiakis' talks**

"Direct" measurement of density, pressure and LOS velocity of the gas in galaxies/clusters

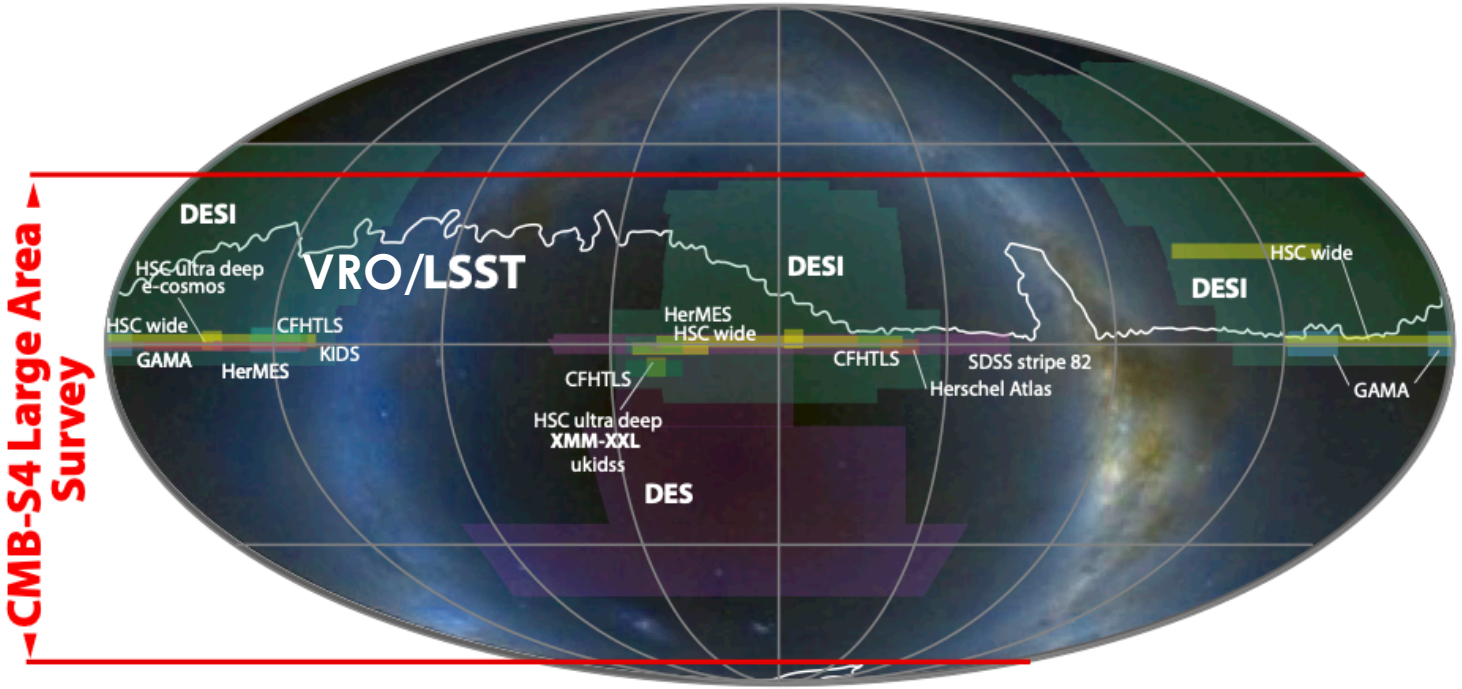
Battaglia, S.F., Schaan, Spergel, 2017
Also: Amodeo et al (2021), Moser et al (2021)



- Very rich physics! One order of magnitude improvement with CMB-S4, especially within the virial radius,

CMB-S4 Large Area Survey

The Large Area Survey will cover ~70% of the sky to unprecedented depth, ensuring overlap with the majority of current and planned surveys



CMB-S4 collaboration