Large Scale Structure
Chapter 5

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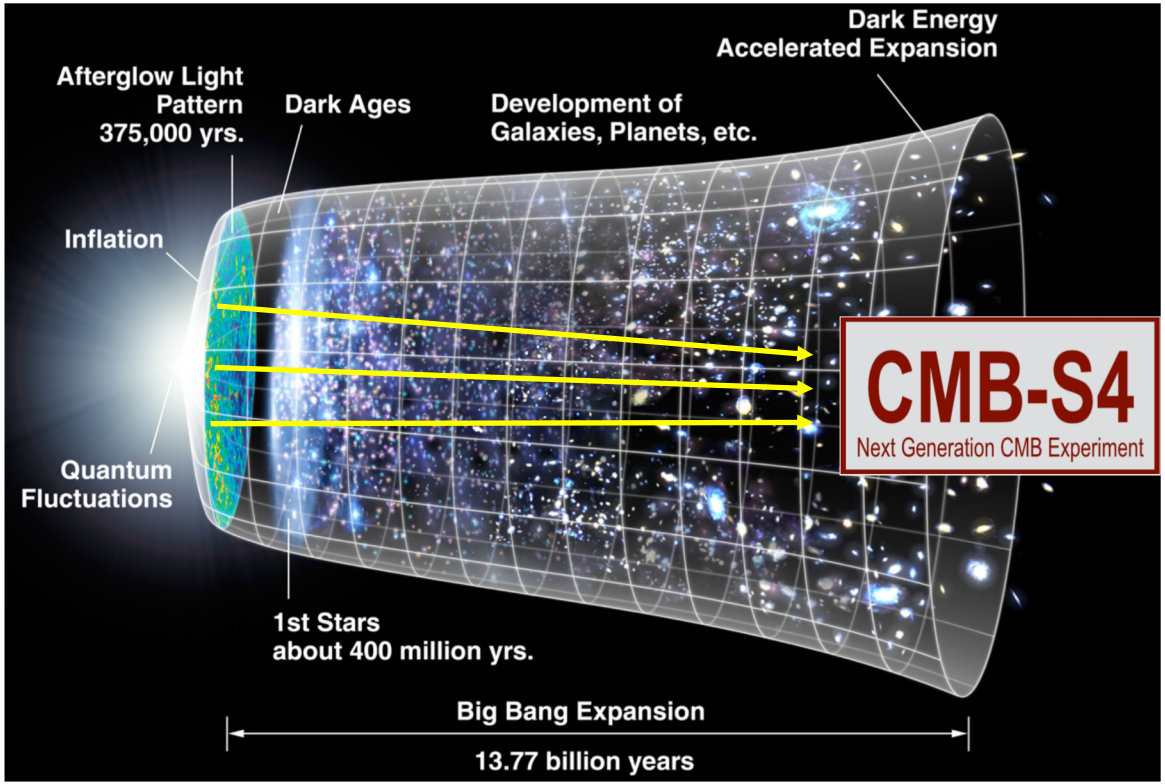
CMB-S4 collaboration meeting
March 26, 2024

A brief history of CMB photons



credit: WMAP

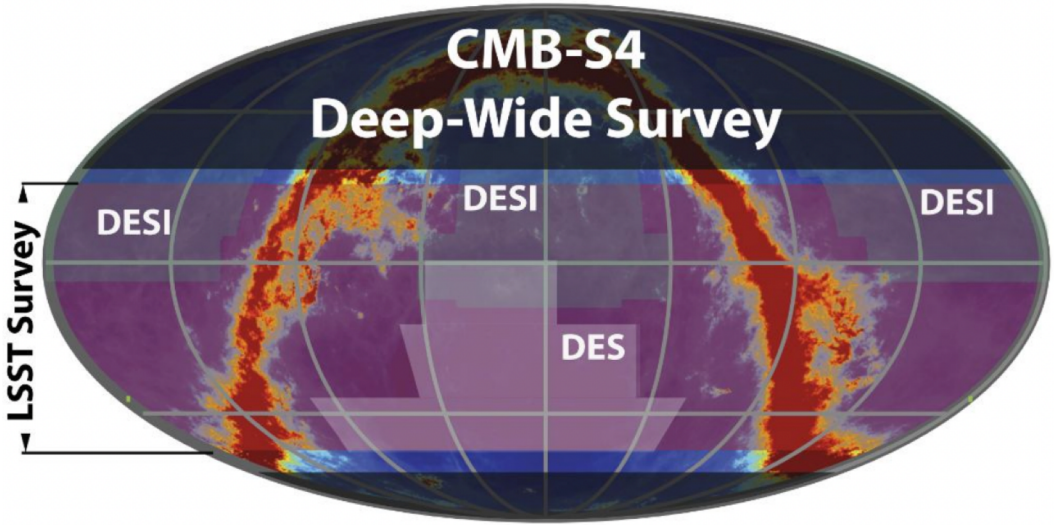
94% of photons don't re-scatter (but are lensed!)

6% scatter with matter

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

CMB-S4 Deep-Wide Survey

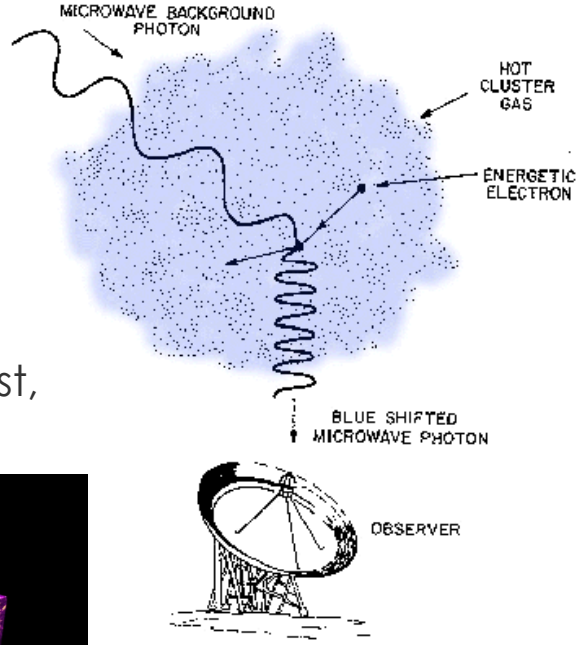
The Deep-Wide Survey will cover ~70% of the sky to unprecedented depth, ensuring overlap with the majority of **current and planned surveys**

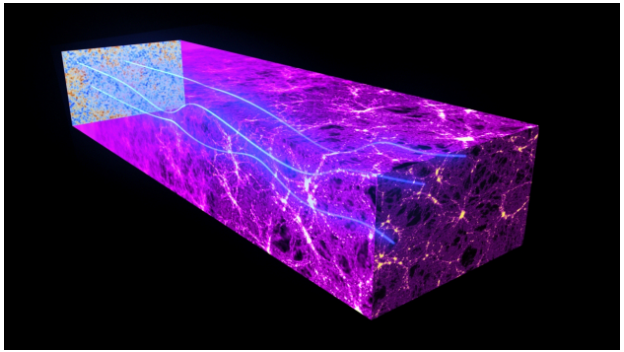


+ "ultra-deep" survey from the South Pole LAT

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, …





CMB lensing with CMB-S4

- Lensing reconstruction over ~50% of the sky. Total S/N ~ 400.
- Similar from SPLAT: deeper but from a smaller area.

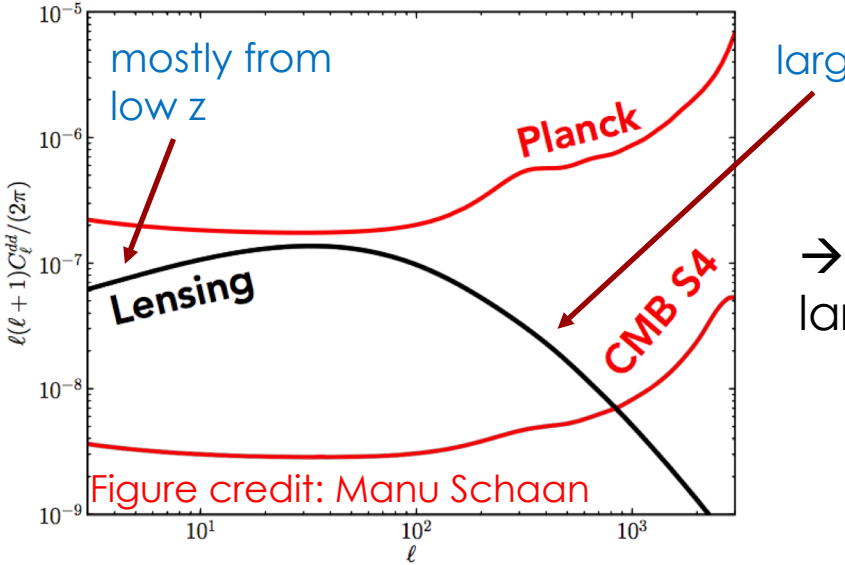


Figure credit: Manu Schaan

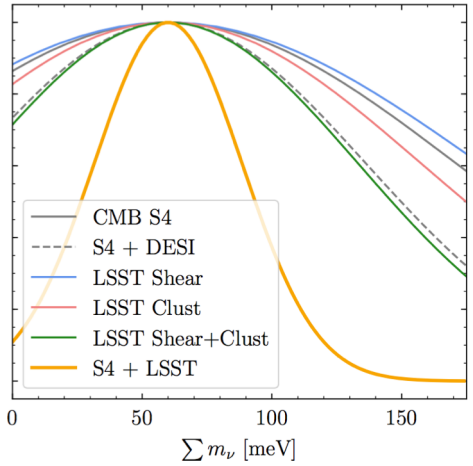
→ "ultimate" mass map to z ~ 1100 on large and intermediate scales!

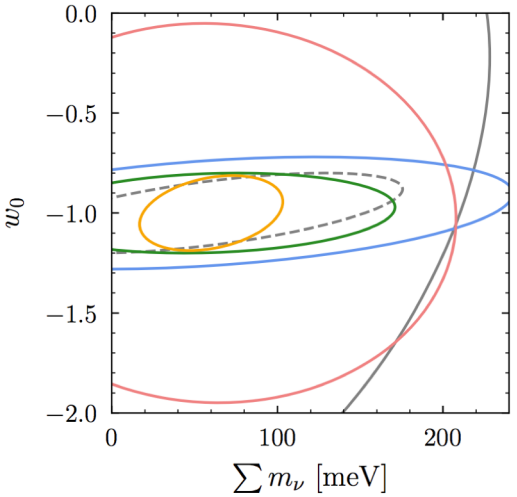
CMB-S4 lensing has comparable statistical power to VRO/LSST shear!

- very different systematics
- access to higher redshifts (& source very well understood)

CMB lensing tomography

- 3 main goals:
  - Growth of structure as a function of redshift
  - Testing General Relativity
  - Galaxy-halo connection
- Cross-correlations are useful because:
  - Convert noise bias into noise
  - More robust to systematics (and can provide cross-calibration: shear bias, photo-z etc).
  - Can isolate part of the signal (eg. from a particular redshift)
  - Can enhance the S/N
- Not only another measurement of the same parameters: parameter sensitivity evolves with redshift → breaking internal degeneracies
- Also: robust measurements of local f_{NL}



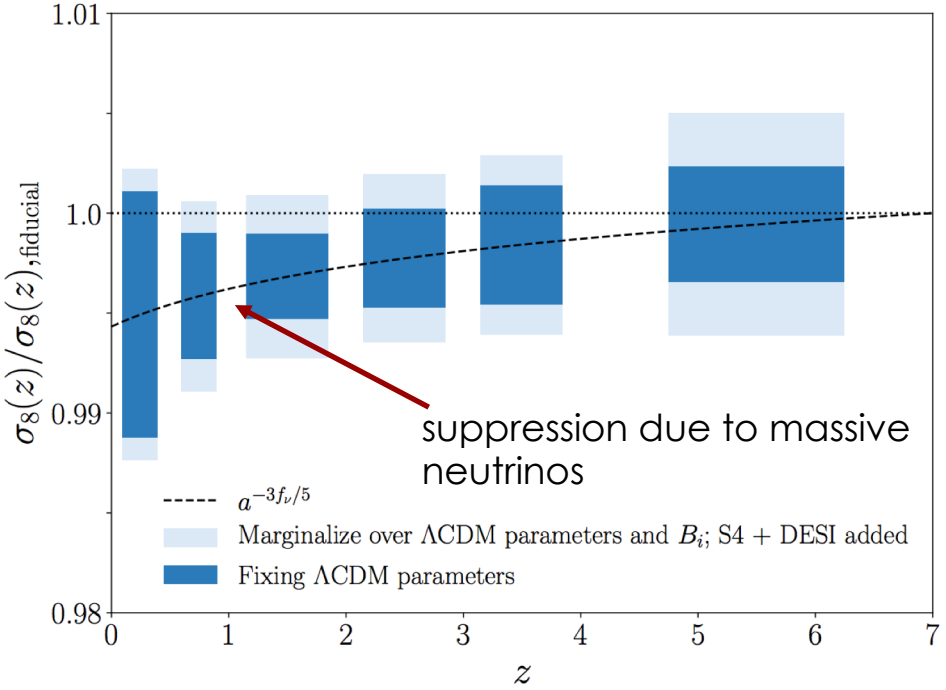


Mishra-Sharma et al (2018)

Eg: measuring the growth of structure

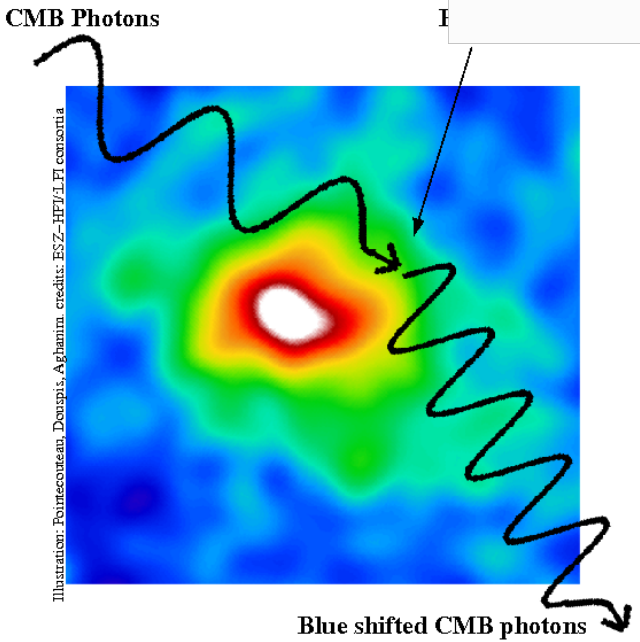
Examples:

- "model independent" growth measurement
- CMB lensing x VRO LSST: S/N ~ 400
- In LCDM, improve neutrino mass measurements, while decreasing sensitivity to the optical depth
- Distinguish the effect of neutrinos from dynamical dark energy
- + other opportunities: Lyman Alpha forest, HI, other lines, …



Yu++ (2018)

The Sunyaev-Zel'dovich effect(s) in temperature



kinematic SZ

$$\left(\frac{\Delta T}{T}\right)_{\rm kSZ} \propto N_e(\boldsymbol{\theta})\,\frac{v_r}{c}$$

column density of electrons

radial velocity

thermal SZ

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

patchy screening

$$\left(\frac{\Delta T}{T}\right)_{\rm bSZ} \propto N_e(\boldsymbol{\theta})\,\left(\frac{\Delta T(\boldsymbol{\theta})}{T}\right)_{\rm primary}$$

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

Also equivalent effects in from screening and scattering in **polarization**

A modern view of galaxy groups

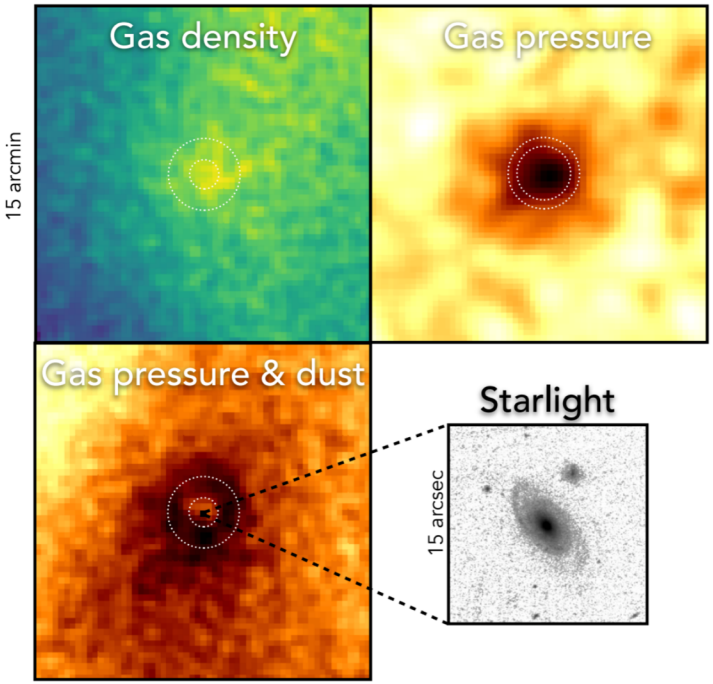
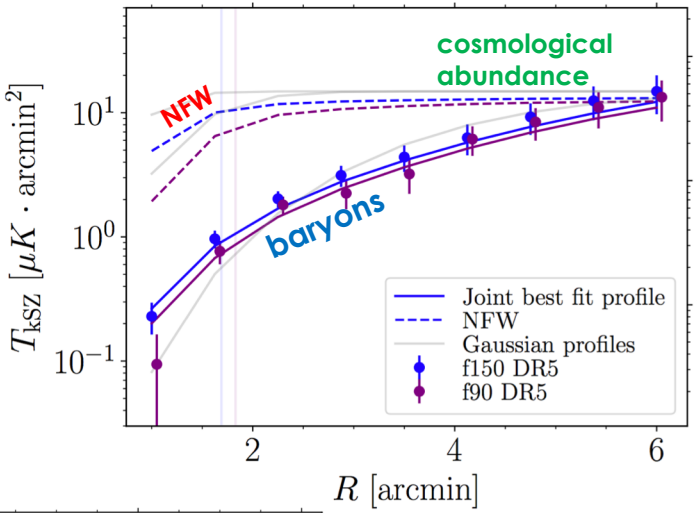
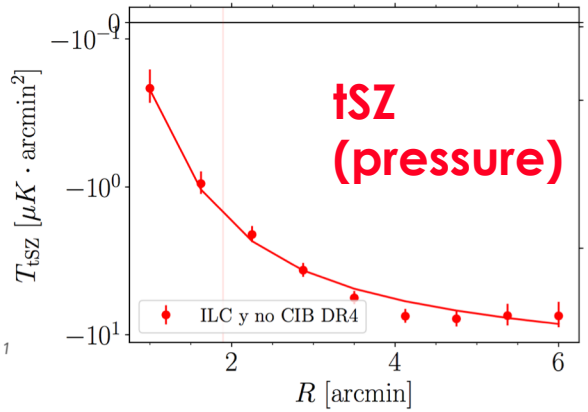


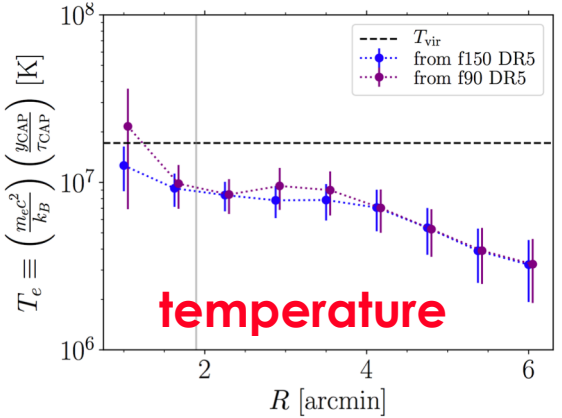
Figure: Emmanuel Schaan
ACT+Planck microwave images: Schaan et al 2020. HST ACS I band image: Masters et al 2011



kSZ or patchy screening (density)



tSZ (pressure)



temperature

Schaan, Ferraro., Amodeo, Battaglia + ACT (2021)
Amodeo, Battaglia, Schaan, Ferraro + ACT (2021)
Coulton et al (ACT) 2024

Also (not shown here): Vavagiakis et al (2021), Soergel et al (SPT) 2016
Calafut et al + (2021), Kusiak et al (2021) + previous literature!

Large-scale Structure

- Coordinated by Alex Van Engelen and Simone Ferraro
- Discussed in the "Maps to Other Statistics" (Maps2Stats) calls.
- Contribution from many you!

<u>For this meeting:</u>

- What are we missing?
- We are looking for volunteers to help write the chapter!

LSS Chapter Outline – pt 1

- Introduction

- Science from CMB Lensing
  - CMB Lensing power spectrum
  - CMB Lensing tomography
  - Galaxy lensing - CMB lensing cross-correlations

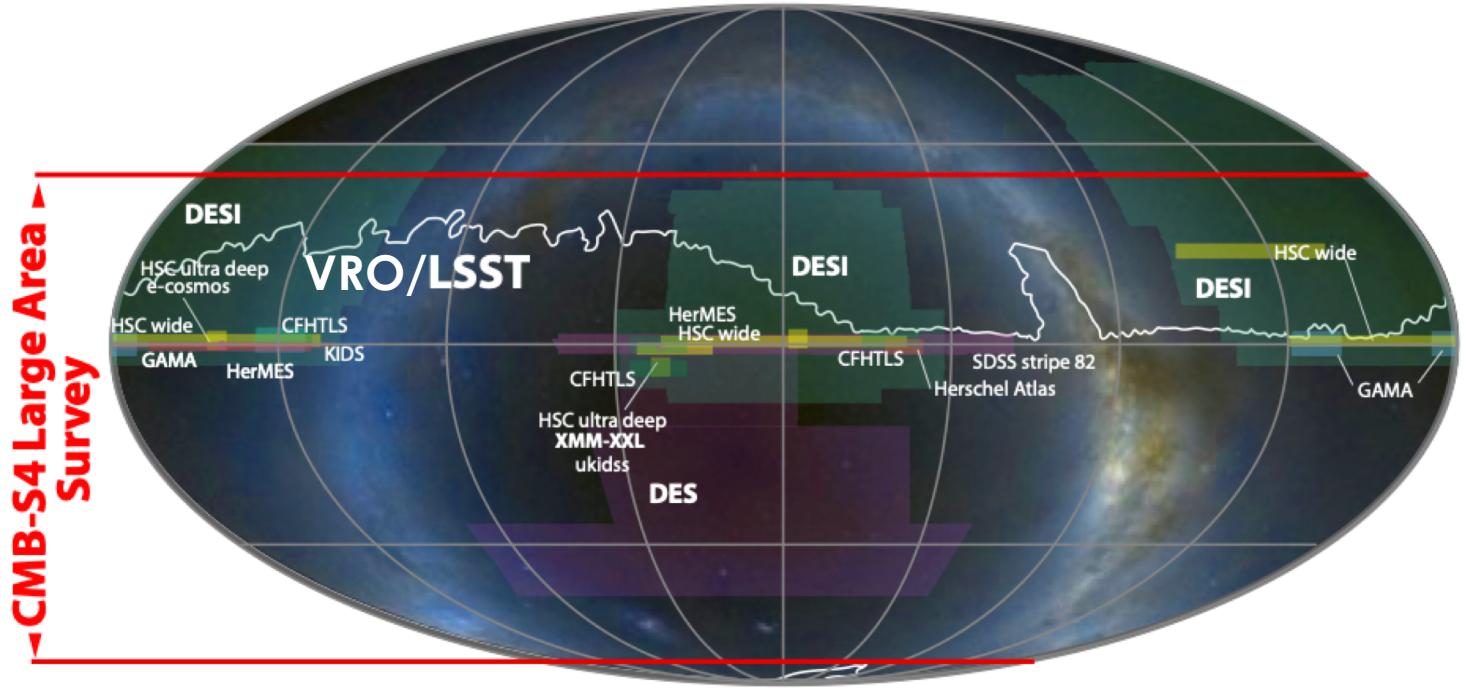
- Sunyaev-Zel'dovich effects
  - Introduction to the various effects in T & P
  - Probing the gas in and around galaxies
  - Polarized SZ from galaxies (remote quadrupole)
  - Velocity reconstruction (remote dipole). AKA "kSZ tomography"
  - Rotational kSZ

LSS Chapter Outline – pt 2

- Other Cross-correlations
  - CMB x Intensity Mapping (both CIB and Line IM)
  - CIB science & measurement
  - Higher point functions
  - ISW & Rees-Sciama effects
  - Moving lens

- Reionization
  - Introduction to reionization (both H and He)
  - kSZ 2pt function
  - kSZ 4pt function
  - Reconstructing optical depth fluctuations from patchy screening and scattering

Thanks!


CMB-S4 Large Area Survey
DESI
HSC ultra deep
e-cosmos
VRO/LSST
DESI
HSC wide
DESI
HSC wide
CFHTLS
KIDS
HerMES
HSC wide
GAMA
HerMES
CFHTLS
CFHTLS
SDSS stripe 82
Herschel Atlas
GAMA
HSC ultra deep
XMM-XXL
ukidss
DES

BACKUP SLIDES

kSZ and tSZ cosmology

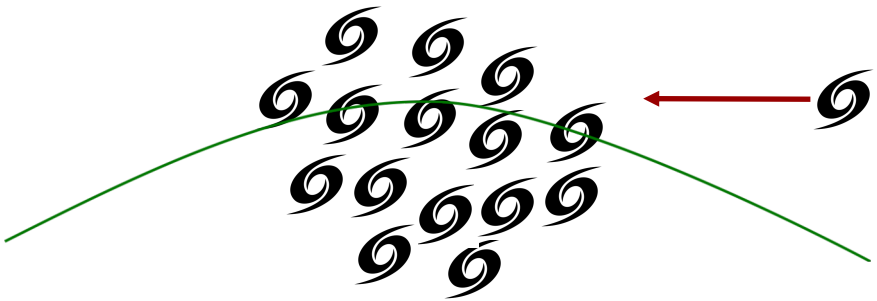
Measuring velocities:

- Tests of gravity / scale dependence of growth
- Access to very large-scale modes: "no shot noise"
- Sample variance cancellation and ~50% improvement on f_{NL}
- Achieve $\sigma(f_{NL}) < 1$, beyond primary CMB cosmic variance

Cosmology with the tSZ power spectrum/PDF/higher point functions:

- simultaneously constrain (g)astrophysics and cosmology

Large-scale overdensity

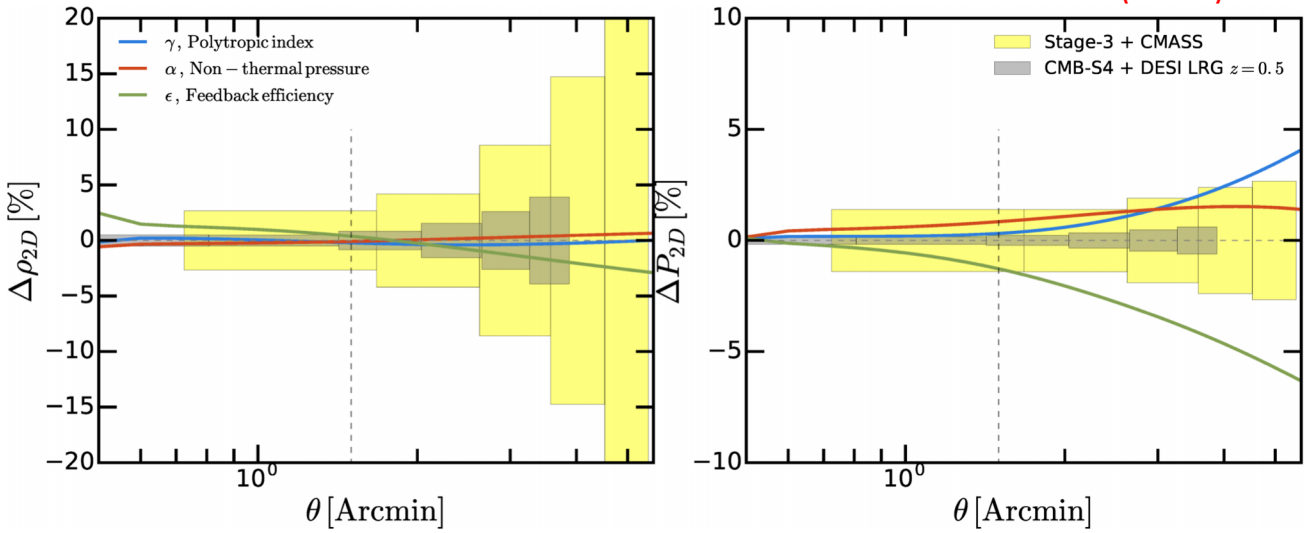


Halo thermodynamics

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

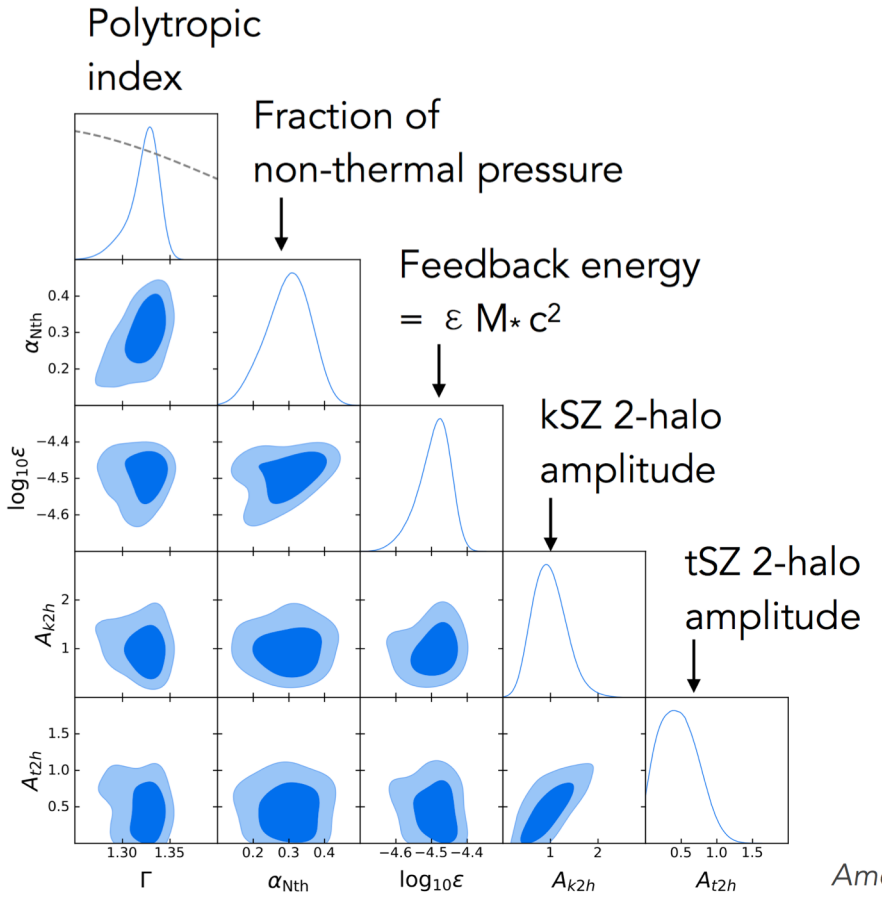
"Direct" measurement of density, pressure and LOS velocity of the gas in galaxies/clusters

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,

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

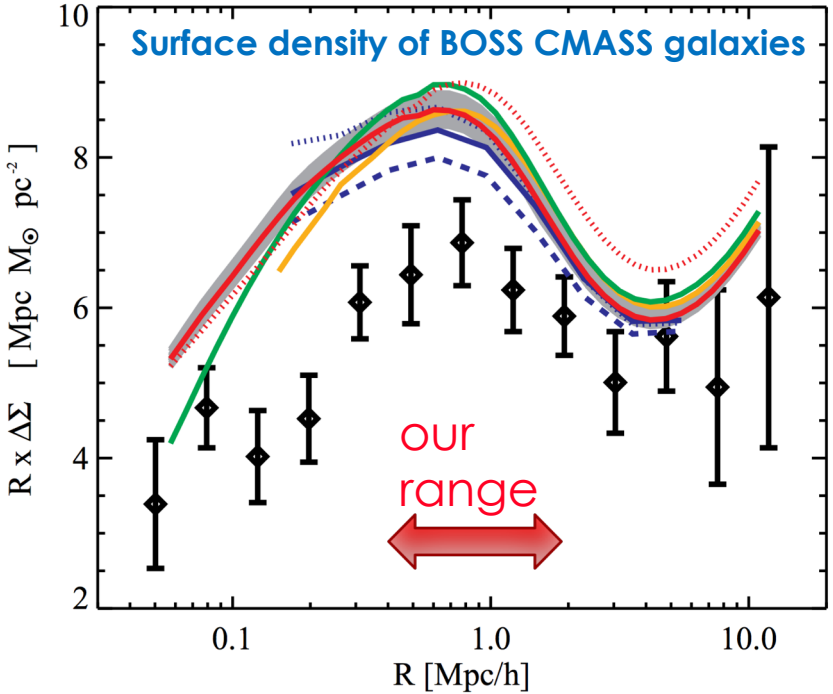
Calibration of baryon effects in weak lensing:

- 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],

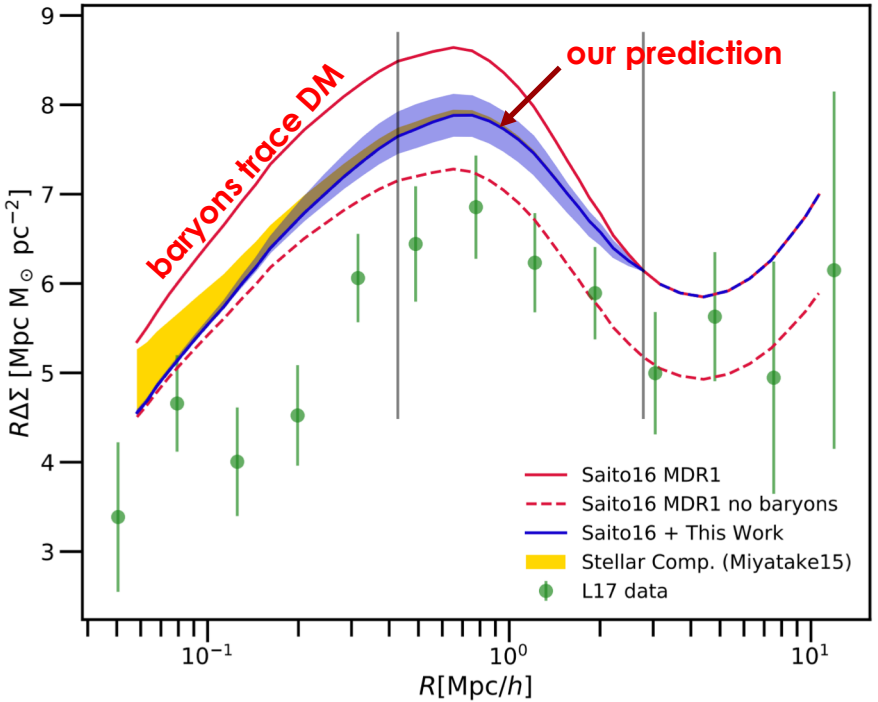


Baryon effects: first direct SZ calibration

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!

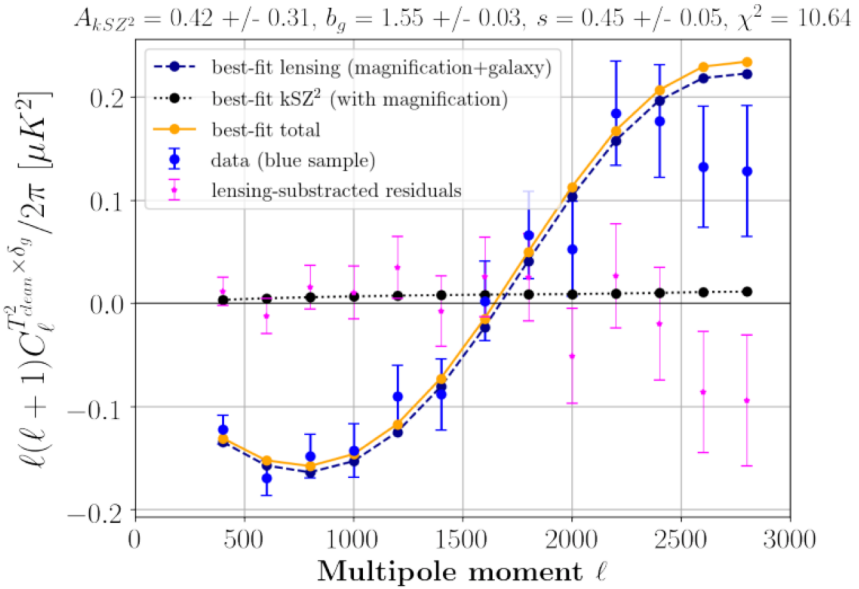


Amodeo, Battaglia, Schaan, Ferraro, Moser + ACT (2021)

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



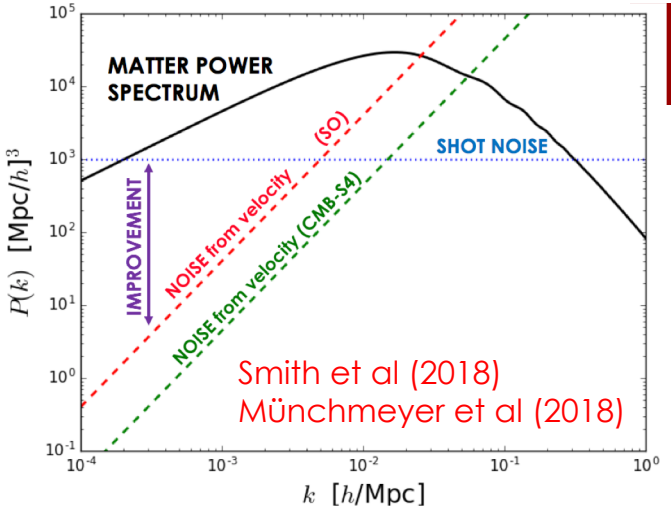
Experiment	SNR
Planck x unWISE (current)	5
Simons Obs. x unWISE (~2023)	~ 300
CMB-S4 x Rubin Obs.	> 600

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

Other applications

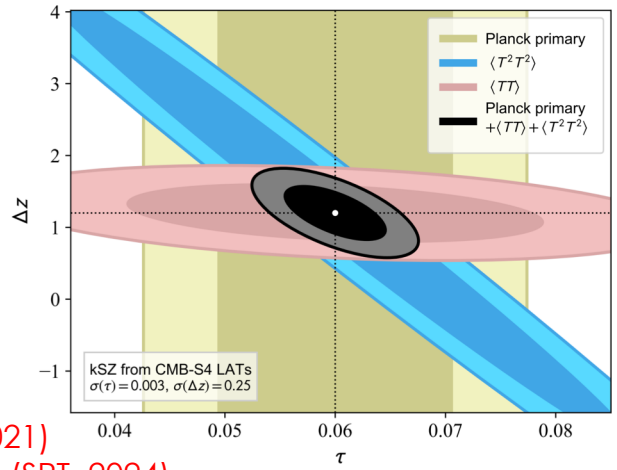
Measuring velocities:

- 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"



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!



Alvarez, Ferraro, Hill, Hlozek, Ikape (2021)
Recent limits from Raghunathan et al (SPT, 2024)