In this seminar, I will present two promising ways in which the cosmic microwave background (CMB) sheds light on critical uncertain physics and systematics of the large-scale structure.

Shear calibration with CMB lensing (arXiv:1607.01761):
Realizing the full potential of upcoming weak lensing surveys requires an exquisite understanding of the errors in galaxy shape estimation. In particular, such errors lead to a multiplicative bias in the shear, degenerate with the matter density parameter and the amplitude of fluctuations. Its redshift-evolution can hide the true evolution of the growth of structure, which probes dark energy and possible modifications to general relativity. I will show that CMB lensing from a stage 4 experiment (CMB S4) can self-calibrate the shear for an LSST-like optical lensing experiment. This holds in the presence of photo-z errors and intrinsic alignment.

Evidence for the kinematic Sunyaev-Zel'dovich (kSZ) effect (arXiv:1510.06442); cluster energetics:
Through the kSZ effect, the baryon momentum field is imprinted on the CMB. I will report significant evidence for the kSZ effect from ACTPol and peculiar velocities reconstructed from BOSS. I will present the prospects for constraining cluster gas profiles and energetics from the kSZ effect with SPT-3G, AdvACT and CMB S4. This will provide constraints for galaxy formation and feedback models.
Understanding LSS from the CMB

Calibrating shear with CMB lensing
Gas physics from the kSZ effect

Emmanuel Schaan, Princeton University
Perimeter Institute Cosmology Seminar
Large-scale structure: Tantalus’s ordeal

Gigantic statistical power, but…
\[ N_{\text{modes}} \propto (k_{\text{max}}/k_{\text{min}})^3 \text{ versus } N_{\text{modes}} \propto (l_{\text{max}}/l_{\text{min}})^2 \]

Non-linear physics
larger perturbations but harder to predict

Non-Gaussian statistics
larger Shannon info but harder to extract

Complex baryonic effects
biasing, star formation and feedback

Complex observables
often systematics-limited
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**Statistics:** Non-Gaussian covariances for n-point functions and halo counts
ES Takada Spergel 14, PRD, 1406.3330

**Non-linearities:** EFT of the large-scale structures
Baldauf ES Zaldarriaga 15a,b, JCAP, 1505.07098, 1507.01583

**Baryons:** First detection of the $<P_{\text{Ly}\alpha}\kappa_{\text{CMB}}>$ bispectrum
Doux ES+14, PRD?, 1607.03625

Please come talk to me!
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This talk: LSS from the CMB

Shear calibration with CMB lensing
ES Krause Eifler Doré Miyatake Rhodes Spergel, PRD?, 1607.01761

Detecting the kSZ signal from BOSS with ACTPol
ES Ferraro Vargas Smith Ho Spergel & ACTPol, PRD, 1510.06442
Looking through the same lens:
Shear calibration with CMB lensing
Optical weak lensing

- perfect disk  shear ~1%  shape ~20%
  → SNR~5% for one galaxy, ~10^3 for 10^9 galaxies

Complementary with clustering
- geometry + growth
- tests of GR: Ψ + Φ versus Φ
- probes all the mass biasing issue

Intrinsic galaxy (shape unknown) → Gravitational lensing causes a shear (g) → Atmosphere and telescope cause a convolution → Detectors measure a pixelated image → Image also contains noise

Heymans, Euclid Science Book 2010
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Shear calibration: the case for redundancy

\[
< e > = (1 + m) \gamma_{\text{true}} + \alpha \epsilon_{\text{PSF}} + c 
\]

Heymans+06
Taylor Kitcingh 16

**Scary:** \(m(z)\) degenerate with growth, hence dark energy EOS

"Required" for LSST: < 0.5% (Huterer+06, Massey+12, ES+16)

**Image simulations:** 3-5% DES (Jarvis+15), 1% KiDS (Fenech-Conti+16)

**Difficult:**

- Noise/Model biases
- Selection bias: simulate below the detection limit (Hoekstra+15)
- Mode coupling: simulate below the image resolution
- PSF size error

→ Redundancy is valuable
Shear calibration: the case for redundancy

\[ \langle e \rangle = \left( 1 + \frac{m}{m} \right) \gamma_{\text{true}} + \alpha e_{\text{PSF}} + c \]

Heymans+06
Taylor Kitching 16

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CMB lensing & reconstruction

\[ T(\hat{n}) = T_0(\hat{n}) + \vec{d} \cdot \vec{\nabla} T_0(\hat{n}) \]

Arcmin deflections, coherent on degree scale
Breaks statistical isotropy → reconstruction
Different systematics (SZ, point sources)

Smidt+10
Smothers BAO peaks

Probes broad z-range

Challinor
Adds small-scale fluctuations
Shear calibration with CMB lensing

**Principle:**
Vallinotto12,13, Das+13  
$K_{\text{gal}} \sim (1+m) \sigma_8$  
$K_{\text{CMB}} \sim \sigma_8$

**Value:**
Purely empirical, self-calibration  
No assumption on galaxy population/morphologies

**Just the beginning!**
Liu+16, Baxter+16, Miyatake Madhavacheril+16, Singh+16 & many more!  
~10-20% calibration, (mostly) fixed cosmology & nuisances

**Questions:**
Competitive with image simulations / requirements?  
Varying cosmology & nuisance?  
Robustness to photo-z, IA?  
What combination is best?
Shear calibration with CMB lensing

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What combination is best?
8.4m telescope in Chile
Survey starts 2022-23
~ half the sky
Sources: 26 arcmin$^{-2}$
Lenses: redmagic-like

18,000 deg$^2$, 26 sources/arcmin$^2$, 0.25 lenses/arcmin$^2$, shape noise = 0.26
$\sigma_z/(1+z) = 5\%$ for sources, known to 0.2\% for sources
$\sigma_z/(1+z) = 1\%$ for lenses, known to 0.06\% for lenses
CMB Stage 4 lensing

Stage 4: ~500,000 detectors
Beam: 1’, Sensitivity: 1μK’
$l_{\text{min}}=30$, $l_{\text{max,T}}=3000$, $l_{\text{max,E,B}}=5000$
Quadratic estimator
Foreground cleaned input map
Assumed no systematics
Lensing only!
Forecast

- **Observables:** all combinations of \( \{g, k_{\text{gal}}, k_{\text{CMB}}\} \)
  - clustering
  - gal - shear
  - shear - shear
  - gal - CMB lensing
  - shear - CMB lensing
  - CMB lensing auto

- **Constrain:** cosmology, \( b_i, m_i, \Delta z_i, \sigma_z \)
  - No prior on \( b_i, m_i \). Priors on \( \Delta z_i, \sigma_z \).

- **Realistic/conservative:**
  - Full non-Gaussian covariances
  - Explore likelihood with MCMC

- **Built on CosmoLike (Eifler Krause+14)**
  - Extended to include CMB lensing
  - Soon to be public!
Forecast

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CMB S4 lensing can calibrate the shear ~ requirements while varying cosmo & nuisance params better at high z where most challenging purely empirical, self-calibration.
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Summary: Shear calibration with CMB lensing

arXiv:1607.01761

- CMB S4 lensing can constrain the shear bias to 0.5%
  ~ LSST requirements

- Purely empirical, self-calibration, no assumption on
galaxy population/morphologies

- Works best at high z where most difficult

- Possible with AdvACT, SPT-3G, Simons Observatory

  - Robust to IA, photo-z degradation, non-linearities &
baryons, CMB S4 specs

  - In the works: “delensing” with CIB, iterative
    reconstruction, photo-z outliers, correlated mi
CMB S4 specs?

Noise

Beam

\( I_{\text{max}} \)

\( \ell \)

\( \ell \)

\( \ell \)

Mean redshift

Mean redshift

Mean redshift

Shane bias 68% constraints

Shane bias 68% constraints

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- LSST requirement

- LSST requirement

Pirsa: 16100045
CMB S4 specs?

Noise

Beam

$\ell_{\text{max}}$

Mean redshift

$\sigma(\ell = 1, \ell_C^{\text{CMB}}) / (2 \pi)$

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- LSST requirement
kSZ detection & gas physics in clusters
Gas in clusters & galaxy formation

Profile

Abundance

\[
\text{WMAP (}\Omega_b/\Omega_m=17\%)\]

- non-radiative
- cooling+SN
- +AGN

\[
\text{from Planelles+13}
\]

→ Measuring gas profile and abundance can constrain feedback mechanisms
Kinematic Sunyaev-Zel’dovich effect

\[
\frac{\delta T}{T} = \int dl \, n_e \sigma_T \frac{v}{c}
\]

Counts all free electrons

Lower mass halos at higher z

Small size: \( \delta T_{\text{KSZ}} \sim 0.1\mu K, \delta T_{\text{CMB}} = 110\mu K \)

Blackbody spectrum

Hand et al 2012

aps.org, ESO, ESA, Hubble, NASA
Kinematic Sunyaev-Zel’dovich effect

\[ \frac{\delta T}{T} = \int \frac{dT}{dl n_e \sigma_T} \frac{v}{c} \]

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Detection methods

**Individual (monster) cluster**
Sayers+13, 14

**Pairwise velocities**
Hand+12, Planck15, Soergel+16, de Bernardis+16

**Velocity reconstruction**
Planck15, ES Ferraro+16

\[ <T^2 \times \text{tracer}>, \text{ Hill+16, Ferraro+16} \]

**T Power spectrum**, George Reichardt+14

**T^2 power spectrum**, Smith Ferraro 16
Velocity reconstruction

Peculiar velocity \[ \vec{v} = \frac{d\vec{r}}{dt} - H(t)\vec{r} = \frac{d\vec{x}}{d\eta} \]

Mass conservation + linear approx.
\[ \dot{\delta} + \vec{\nabla} \cdot \vec{v} = 0 \Rightarrow \vec{v} = -aH f \vec{\nabla} \Delta^{-1} \delta \]
\[ \rightarrow v_{\text{rms}} \, \text{1d} \approx 300 \, \text{km/s} \]

Padmanabhan et al. 2014
Velocity reconstruction

\[ \vec{v} = -aHf \vec{\nabla} \Delta^{-1} \delta \]

BOSS CMASS South DR11 footprint (sdss.org)
"Halos" from BOSS CMASS

25,000 CMASS DR10 galaxies, 0.4<z<0.7
Central fraction 85%
Stellar masses $M_\ast \sim 2 \times 10^{11} M_\odot$ $M_{\text{halo}} \sim 2 \times 10^{13} M_\odot$ $\theta_{\text{vir}} \sim 1.5\text{arcmin}$
Reconstructed velocities (K. Smith, M. Vargas-Magaña, S. Ho)

$\rightarrow \tau$ and $v_{\text{rec}}$ for each halo
Temperatures from ACTPol

Map at 148GHz
Area 600 sq. deg.
Noise 12muK.’
Beam FWHM 1.4’
Aperture photometry

\[ \delta T \text{ for each halo} \]
Baryon abundance & profile

Hypothesis: \[ \delta T = \alpha \tau v_{rec} + \text{noise} \]

\[ \alpha = \frac{\langle \delta T(\theta_{disk}) \times \tau v_{rec} \rangle}{\langle \tau v_{rec} \times \tau v_{rec} \rangle} \]

- \[ \alpha = 0 \leftrightarrow \text{no detection} \]
- \[ \alpha = 1 \leftrightarrow \text{cosmological baryon abundance} \]
- Varying \( \theta_{disk} \rightarrow \text{profile information} \)
Gas profile of CMASS halos

- comoving radius at $z = 0.57$ [Mpc/h]

- $\alpha$ vs $\theta_{\text{disk (arcmin)}}$

**NFW**

- kSZ model preferred over null at 3 $\sigma$
- Proxy for gas profile in clusters

Schaan Ferraro +15
Future prospects

Tracer sample: \[ \text{SNR} \sim (1 \text{ to } 2) \times (M_h/10^{13} M_{\odot}) \times \sqrt{N_{\text{obj}}/10^4} \]
- this study (CMASS) \(3 \times 10^4\) gal, \(0.4 < z < 0.7\)
- Full CMASS \(4 \times 10^5\) gal, \(0.4 < z < 0.7\)
- PFS \(10^7\) gal, \(0.8 < z < 2.4\)
- DESI \(2 \times 10^7\) gal, \(z < 2\)
→ **SNR x ~30 from number of objects**

CMB map:
- this study (ACTPol) \(14\mu\text{K}', 1.4'\)
- AdvACT \(7\mu\text{K}', 1.4', \text{multifreq.}\)
- CMB S4 \(1\mu\text{K}', ?, \text{multifreq.}\)
→ **SNR x few from sensitivity**
→ **SNR x few from tSZ removal**

→ Large SNR: gas profile, 1h/2h, binning in mass/type
Future prospects

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CMB map:
- this study (ACTPol) 14\( \mu \)K, 1.4′
- AdvACT 7\( \mu \)K, 1.4′, multifreq.
- CMB S4 1\( \mu \)K, ?, multifreq.
→ SNR \( \times \) few from sensitivity
→ SNR \( \times \) few from tSZ removal

→ Large SNR: gas profile, 1h/2h, binning in mass/type
Non-thermal pressure / energy injection

\[ \begin{align*}
\text{kSZ} &= \tau \left( \frac{v_{e,LOS}}{c} \right) \propto \rho_e \text{ gas density} \\
\text{tSZ} &= \tau \left( \frac{v_{e,th}}{c} \right)^2 \propto P_{e,th} \text{ gas thermal pressure}
\end{align*} \]

Virial theorem:

\[ \Phi_{\text{gas+DM/gas}} + 3\mathcal{V} \left[ <P_{th}> + <P_{\text{non-th}}> - P_{\text{surface}} \right] = 0 \]

\[ \begin{align*}
\uparrow \quad \text{kSZ} \quad \text{lensing} \\
\uparrow \quad \text{tSZ} \quad \text{modeled from accretion rate}
\end{align*} \]

\[ \rightarrow \text{Constrain } P_{\text{non-th}}, \text{ as a function of radius} \]

\[ \rightarrow \text{Constrain energy injected?} \]
Non-thermal pressure / energy injection

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→ Constrain \( P_{\text{non-th}} \), as a function of radius
→ Constrain energy injected?
Summary: kSZ detection & gas physics in clusters

arXiv:1510.06442

- Evidence for kSZ with ACTPol and velocity reconstruction from BOSS
- KSZ powerful baryometer: profile, abundance
- Constrain non-thermal pressure and energy injection with kSZ & tSZ
  - CMB S4 and DESI will multiply the SNR by ~100
  → bin in mass/type/color