First, a different CMB spectral distortion
EDGES

Detection of absorption feature in monopole sky spectrum at \(\sim78\) MHz

Bowman+ (2018)
Interpretation: absorption of CMB photons by 21cm hyperfine transition of HI during epoch of first star formation.
EDGES

Detection of absorption feature in monopole sky spectrum at ~78 MHz

Puzzles:
- shape?
- amplitude?
EDGES

What could produce such a deep absorption feature?
What could produce such a deep absorption feature? Need factor of 2.5!

1) **Increase the photon background intensity:**

- Population of high-z black holes [Ewall-Wice+ (2018)]
- Soft photon emission from light dark matter [Fraser+ (2018)]
- Resonant oscillation of dark photons into RJ photons [Pospelov+ (2018)]
- Phenomenological connection to ARCADE-2 excess? [Feng & Holder (2018); Chluba (2015)]
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2) Decrease the gas temperature:
   - Cooling via dark matter - baryon interactions [Barkana (2018); Munoz & Loeb (2018)]
     … severely constrained [Barkana+ (2018); Berlin+ (2018)]
   - Other ideas?
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Early Dark Energy
Early Dark Energy

Earlier gas decoupling via accelerated expansion at $\sim 50 < z < 1000$

parameters:

$\Omega_{ee} =$ EDE energy density

$z_c =$ critical redshift at which behavior transitions from $w=-1$ to $w=1$
Early Dark Energy

Earlier gas decoupling via accelerated expansion at $\sim 50 < z < 1000$

Hubble rate vs. Compton-heating rate
Early Dark Energy

Earlier gas decoupling via accelerated expansion at $\sim 50 < z < 1000$

![Graph showing temperature vs. redshift with various lines representing different scenarios of gas decoupling. The graph includes constraints from EDGES $(z = 20)$ and T_CMB.](image-url)
Early Dark Energy

Are the relevant EDE models consistent with other observations?

TT power spectrum

$D_{TT} (\mu K)^2$ vs $\ell$

ISW effect

change to $\Theta^*$

change to $H(\sim z^*)$

Karwal & Kamionkowski (2016)
Early Dark Energy

Are the relevant EDE models consistent with other observations?

---

**EDE energy density**

- Favored by EDGES gas temperature
- Excluded by CMB TT power spectrum

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JCH & Baxter (2018)
explaining EDGES by non-finely-tuned modifications of background cosmology is highly unlikely
Back to regularly scheduled programming: Thermal SZ Science
Thermal SZ Effect: Change in temperature of CMB photons due to inverse Compton scattering off hot electrons, most of which are in the intracluster medium (ICM) of galaxy clusters.

\[ \Delta T_{\text{tSZ}} \frac{T_{\text{CMB}}}{T_{\text{CMB}}} = g_{\nu} \frac{\sigma_T}{m_e c^2} \int P_e(\chi) d\chi \]

Compton-y

electron pressure

tSZ spectral function

line-of-sight integral
Thermal SZ Effect

Integrated Electron Pressure

Unique spectral signature

intensity

frequency

tSZ null (218 GHz)

intensity change

frequency

Figures: Carlsstrom+ (2002)
Thermal SZ Science

Cosmology:

- Identify and count individual galaxy clusters as a function of mass and redshift (need optical/IR follow-up)
- Construct large-area maps using multifrequency data, then measure auto-statistics (e.g., power spectrum, bispectrum, 1-pt PDF) or cross-correlations with LSS tracers (e.g., lensing)
Thermal SZ Science

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Key issue: $Y(M,z)$ calibration
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(G)astrophysics:
- Measure tSZ signal at location of known objects (galaxies, QSOs, …)
- Measure large-scale tSZ - tracer cross-correlations
Thermal SZ Science

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**Key goal: characterization of AGN feedback**
Thermal SZ Science

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Key goal: characterization of AGN feedback

Systematics: tSZ bias to CMB lensing reconstruction (or other CMB observables)
tSZ Science in the Stage-IV Era
tSZ Science in the Stage-III Era

Advanced Atacama Cosmology Telescope
Advanced ACT

wide-area (>10000 deg$^2$) multifrequency Stage-3 CMB survey
fiducial observations: 2016-2019
Advanced ACT
new receivers have been on sky since 2016

NEW CAMERA -- 5 bands (25-280 GHz) -- HWPs @ 2 Hz, 280 K

28, 41, 90, 150, 230 GHz

full overlap with Dark Energy Survey, Hyper Suprime-Cam Survey, LSST
Advanced ACT Depth

ACT Footprint

- S15 -

BOSS-N

D56

D8

BOSS-N

Credit: S. Aiola
Advanced ACT Depth

ACT Footprint

18,000 sq-deg mapped on 0.5 arcmin pixels \( \rightarrow 330 \times 10^6 \) pixels!

Credit: S. Aiola, S. Naess

sensitivity/area sufficient to independently cross-check Planck

also: CMB lensing, kSZ, tSZ, cross-correlations

Map by Sigurd Næss
Advanced ACT tSZ Clusters
Advanced ACT tSZ Clusters
Advanced ACT tSZ Clusters

- **Preliminary!** 90 + 150 GHz multi-frequency matched filter, one season of AdvACT data + all other ACT/ACTPol data (more arrays + bands added with each season) → >1300 confirmed clusters!

- **Black** = area used for a preliminary cluster search, overlaid on Planck 353 GHz map; **Blue** = DES; **Green** = SDSS – we have not done optical follow-up outside of SDSS + DES (public DR1) regions yet

- Ultimate goal: cosmology with > 10,000 clusters (needs 1% mass calibration)

Credit: M. Hilton
CMB-Stage IV

Next generation experiment: CMB-S4

• A next generation, Stage 4, ground-based experiment to pursue inflation, relic particles, neutrino properties, dark energy, galaxy and structure evolution and new discoveries.

• Enormous increase in sensitivity over the combined Stage 3 experiments now being deployed (>100x current Stage 2) to enable CMB-S4 to cross critical science thresholds.

• $O(400,000)$ detectors spanning 20 - 270 GHz using multiple telescopes, large and small, at South Pole and Chile to map most of the sky, as well as deep targeted fields.

• Broad participation of the CMB community, including the existing CMB experiments (e.g., ACT, BICEP/Keck, CLASS, POLARBEAR/Simons Array, Simons Obs & SPT), U.S. National Labs and the High Energy Physics community.

• International partnerships expected and desired.

Recommended by P5
Stage-IV Cluster Count Cosmology

$O(10^5)$ clusters

dependence on angular resolution

number of clusters

Madhavacheril+ (2017); Louis & Alonso (2017)
Stage-IV Cluster Count Cosmology

$\sigma(M_\nu) \sim 25 \text{ meV}$ (without DESI BAO; assuming Planck $\tau$)

growth constraints to high $z$

simultaneous constraints on $w$ and $M_\nu$

LSST WL mass cal.
CMB lensing mass cal.

Madhavacheril+ (2017); Louis & Alonso (2017)
key difference w.r.t. CMB analysis: some contaminants (e.g., CIB) are correlated with the signal of interest
Planck tSZ ILC Maps

Needlet ILC Compton-y map

What about ground-based experiments? Need multifrequency data — AdvACT y map in progress [JCH, Naess, Madhavacheril]

key difference w.r.t. CMB analysis: some contaminants (e.g., CIB) are correlated with the signal of interest
Colin Hill
IAS/CCA

Planck XXII (2015); see also Horowitz & Seljak (2016)

Post-foreground marginalization

Error bars dominated by CIB leakage

TSZ amplitude from Planck CMB likelihood

\[ \sigma_8 (\Omega_m/0.28)^{0.375} = 0.80 \pm 0.01/-0.03 \]
(assuming fixed gas physics/mass bias)

Small-scale puzzle?
tSZ Science: Power Spectrum

Can we constrain $M_\nu$ with CMB-S4 tSZ PS?

![Plot showing constraints on $M_\nu$](chart.png)

- Gas physics marginalized / including tSZ trispectrum covariance
- CMB-S4 tSZ PS + Planck
- + DESI
- + CV-limited $\tau$

$$\sigma(M_\nu) \sim 50 \text{ meV}$$

Much more beyond the PS: bispectrum, one-point PDF, Minkowski functionals, ...

c.f. JCH & Pajer (2013)
tSZ Science: Cross-Correlations

Constraining the Y(M,z) relation

JCH+ (2017); see also Vikram+ (2017)
tSZ x group cross-corr.

Constraining the $Y(M,z)$ relation

two-halo term is large at low $M!$
Bias in tSZ stacking analyses due to neglected two-halo term?

Hint of break from self-similar mass dependence

Key limitation: coarse angular resolution of Planck — large improvements soon with Advanced ACT, Simons Observatory, CMB-S4

JCH+ (2017)
Thermal SZ Outlook

Excellent probe of cosmology and gastrophysics and a treatable problem for CMB lensing

Battaglia sim.
tSZ as Foreground: CMB Lensing
tSZ as Foreground: CMB Lensing

N.B. SMICA map used in Planck lensing reconstruction has significant tSZ residuals

Planck 143 GHz

Planck SMICA CMB

LGMCA CMB (tSZ deprojected)

N.B. SMICA map used in Planck lensing reconstruction has significant tSZ residuals

stack on SDSS DR8 redMaPPer clusters

Madhavacheril & JCH (2018)
Asymmetric Lensing Recon.

Observation 1:

$$\kappa_{XY}(\theta) = -\mathcal{F}^{-1}\left\{ A_{XY}(L)\mathcal{F}\left\{\text{Re}\left[\nabla \cdot [\nabla X_f(\theta)Y_f(\theta)^*]\right]\right\}\right\}$$

T gradient saturates by $\ell \sim 2000$

Madhavacheril & JCH (2018)
Asymmetric Lensing Recon.

**Observation 1:**

\[ \kappa^{XY}(\theta) = -\mathcal{F}^{-1} \left\{ A^{XY}(L)\mathcal{F} \left\{ \text{Re} [\nabla \cdot [\nabla X_f(\theta)Y_f(\theta)^*]] \right\} \right\} \]

T gradient saturates by ell\(\sim\)2000

**Observation 2:**

\[ \langle \tilde{\kappa}(\theta) \rangle = \langle \nabla \cdot [\nabla T^o(\theta)]_fT^o_f(\theta) \rangle \]

\[ = \langle \nabla \cdot [\nabla T_f(\theta) + \nabla F_f(\theta)][T_f(\theta) + F_f(\theta)] \rangle \]

\[ = \langle \nabla \cdot [\nabla T_f(\theta)]T_f(\theta) \rangle + \langle \nabla \cdot [\nabla F_f(\theta)]F_f(\theta) \rangle \]

only need to clean one leg to remove bias
foreground bias requirements may be less stringent than originally thought: only need to foreground clean the gradient “leg” of the TT quadratic estimator with multifrequency data from Planck

fractional bias to κ-galaxy cross-correlation

\[ \frac{\Delta C_{LL}^{kg}}{C_{LL}^{kg}} \]

Madhavacheril & JCH (2018)