Constraining Dark Energy and Modified Gravity with the Kinetic SZ effect

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Work in collaboration with Rachel Bean, Francesco De Bernardis, Michael Niemack
(arxiv 1408.XXXX, coming out tonight)
Outline

1. Motivation
   - Why should I care?

2. kSZ in a nutshell
   - What is it?

3. Forecasts for DE and MG
   - How well can it do?

4. Uncertainties and Systematics
   - What are possible problems?

5. Concluding thoughts
   - What’s up next?
Probes of Gravity

Galaxies:

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- BAO and Redshift Space Distortions
- Weak Lensing

Clusters:

- Why clusters?
  - high mass \rightarrow very sensitive to the gravitational potential
- Cluster abundance
- Dynamics of clusters

S. Bhattacharya, A. Kosowsky, 2007

\rightarrow\text{kinetic SZ effect (CMB)}
\downarrow\text{different systematics}
\downarrow\text{different degeneracies}
Kinetic SZ effect

CMB photon passing through clusters are Doppler shifted due to bulk motion

distortion of the CMB spectrum

\[ \frac{\Delta T_{kSZ}}{T_{CMB}} = -\tau \left( \frac{v_{pec}}{c} \right) \]

optical depth

\[ \dot{\delta} + ikv = 0 \]
**SZ spectrum**

**Problem:**

- $kSZ$: weak frequency dependence
- $kSZ$: Signal is small
  - Hard to observe

**Solution:**

- Cross-correlate with cluster positions and redshift
- Mean pairwise velocity

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 ned.ipac.caltech.edu
Method: Mean pairwise statistics

First detection: ACT

Use cross-correlation with BOSS LRGs: Stack CMB sub-maps that contain clusters

But: need better accuracy

How well can we do in the future?

Hand et al. 2012
Use mean pairwise velocity to constrain growth of matter

$$v_{ij}(r, a) = -\frac{2}{3} H(a) a \ f(a) \ \frac{r \xi_{halo}(r, a)}{1 + \xi_{halo}(r, a)}$$

Growth rate $f$:

$$f_g(a) = \Omega_m(a)^\gamma$$

$$\gamma_{GR} = 0.55$$

$$\gamma_{GR} \neq 0.55$$

Sheth et. al 2001
## Survey Specifications

<table>
<thead>
<tr>
<th>Survey</th>
<th>Parameters</th>
<th>Survey Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>II</td>
</tr>
<tr>
<td>CMB</td>
<td>$\Delta T_{\text{instr}}$ ($\mu K$ arcmin)</td>
<td>20</td>
</tr>
<tr>
<td>Cluster</td>
<td>$z_{\text{min}}$</td>
<td>0.1</td>
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<tr>
<td></td>
<td>$z_{\text{max}}$</td>
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<tr>
<td></td>
<td>No. of $z$ bins, $N_z$</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>$M_{\text{min}}$ ($10^{14} M_\odot$)</td>
<td>1</td>
</tr>
<tr>
<td>Overlap</td>
<td>Area (sq. deg.)</td>
<td>4000</td>
</tr>
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</table>

- ACTPol + BOSS
- AdvancedACT + DESI
- CMB S4 + DESI

Cross-Correlate cluster position on the sky and redshift with kSZ signal

use LRGs as tracers of clusters

cluster catalog
Potential of kSZ surveys

<table>
<thead>
<tr>
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<th>Stage III</th>
<th>Stage IV</th>
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<tr>
<td>+CMB FoM&lt;sub&gt;GR&lt;/sub&gt;</td>
<td>14</td>
<td>61</td>
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<tr>
<td>FoM&lt;sub&gt;MG&lt;/sub&gt;</td>
<td>9</td>
<td>33</td>
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<tr>
<td>Δγ/γ</td>
<td>0.08</td>
<td>0.05</td>
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<tr>
<td>+DETF FoM&lt;sub&gt;GR&lt;/sub&gt;</td>
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<td>292</td>
</tr>
<tr>
<td>FoM&lt;sub&gt;MG&lt;/sub&gt;</td>
<td>152</td>
<td>273</td>
</tr>
<tr>
<td>Δγ/γ</td>
<td>0.05</td>
<td>0.02</td>
</tr>
</tbody>
</table>

→ Current constraints:

**BOSS:** \( \gamma = 0.71^{+0.12}_{-0.11} \)

kSZ more powerful for constraining modified gravity than dark energy equation of state

Mueller, De Bernardis, Bean, Niemack (arxiv 1408.XXXX)
Modified Gravity Parametrization

→ Model independent parametrization: $f_g(z)$

→ Less theoretical prior

→ Comparison to other future probes:

DESI: $\frac{\Delta f_g \sigma_8}{f_g \sigma_8} = 1.4 - 1.6\%$

additional constraints from Euclid and WFIRST at higher redshifts

→ Complementary constraints

Mueller, De Bernardis, Bean, Niemack (arxiv 1408.XXXX)
Dependency on the number of clusters

Higher cluster number densities lead to better constraints!

Optimistic case:

<table>
<thead>
<tr>
<th></th>
<th>Stage II</th>
<th>Stage III</th>
<th>Stage IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{min}} (10^{13} M_\odot)$</td>
<td>4</td>
<td>4</td>
<td>1</td>
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<tr>
<td>$\Delta \gamma / \gamma$</td>
<td>0.07</td>
<td>0.06</td>
<td>0.02</td>
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</table>
Uncertainty in limiting mass

Robust to uncertainties in the mass calibration!

Limiting mass changes shape + amplitude

Only mild dependency

Marginalizing over the minimum mass does not significantly reduce constraints

Mueller, De Bernardis, Bean, Niemack (arxiv 1408.XXXX)
Pairwise momentum

$$\frac{\Delta T_{kSZ}}{T_{CMB}} = -\tau \left( \frac{v_{pec}}{c} \right)$$

Pairwise velocity

How well do we know the optical depth?
Uncertainty in optical depth

So far:

→ Hydro-simulation show a intrinsic dispersion in the optical depth of ~15% averaged over all cluster masses*

→ Use scatter in $\tau$ as a proxy for the uncertainty

→ Measurement error is a combination of instrument noise and uncertainty in optical depth

$$\sigma_v = \sqrt{\sigma_{\text{instr}}^2 + \sigma_{\tau}^2}$$

$$C_{V\text{measurement}} (r, r') = \frac{2\sigma_v^2}{N_{\text{pair}}} \delta_{r,r'}$$

But:

Can we constrain both, optical depth and pairwise velocity?

*Private communication with N. Battaglia
Introduce nuisance parameter: Marginalize over the amplitude, i.e. optical depth

\[ \hat{V}(z) = b_\tau(z)V(z) \]

→ add prior on the \( \tau \)-bias

Need information on the optical depth

\[ \Delta \tau \leq 10\% \text{ leads to ‘interesting’ constraints} \]
How can we constrain the optical depth?

- Fitting function from Hydro simulations

- Combine thermal SZ and X-ray observations
  astro-ph/0504274

- Polarization signal from scattering
  astro-ph/9903287

Robustness?

Theoretical assumptions and modeling?

Sensitivity?

More work necessary!
Concluding thoughts:

kSZ surveys have the potential to:

→ Provide a valuable test of the late universe complementary to weak lensing and galaxy redshift space distortions

→ Testing gravity on clusters scales using cluster dynamics as a function of real space separation

Future work in progress:

→ Constraining optical depth using simulations! (work by Nick Battaglia)

→ Further consideration of systematic effects

→ Apply to upcoming surveys
Thank you!
Fisher Forecast: Modeling the error

\[ C_{i,j} = F_{i,j}^{-1} \]

\[ F_{i,j} = \sum_{\alpha\beta} \frac{\partial D_{\alpha}}{\partial p_i} \text{Cov}_{\alpha\beta}^{-1} \frac{\partial D_{\beta}}{\partial p_j} \]

- Finite Volume errors: Cosmic variance
- Gaussian shot noise:

\[ \propto \frac{1}{V_s(a)} \int dk \left( P(k, a)b_{\text{halo}}^{(1)}(k) + \frac{1}{n_{cl}(a)^2} \right)^2 \]

use Jenkins mass function

depends on the minimum observed cluster mass

- Velocity measurement error:

\[ \propto \frac{\sigma_{vel}^2}{N_{clusters}} \]

uncertainty for individual cluster