Investigating non-Gaussianity with ACTPol

Cosmology and astrophysics from the bispectrum

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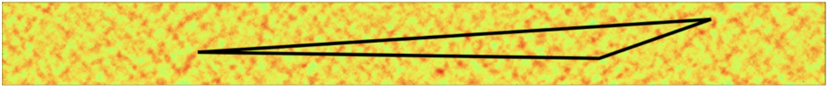
What is the bispectrum?

$$\frac{\Delta T(\vec{n})}{T} = \sum a_{l,m} Y_{l,m}(\vec{n}) \approx \sum e^{-i\vec{\ell}\cdot\vec{n}} a(\vec{\ell})$$

- Harmonic space three point function
  - A sum over all different triangles in Fourier space.
- For purely Gaussian fluctuations it should vanish



- Assuming homogeneity and isotropy

$$\langle a(\vec{\ell_1}) a(\vec{\ell_2}) a(\vec{\ell_3}) \rangle = 4\pi^2 b(\ell_1, \ell_2, \ell_3) \delta(\vec{\ell_1} + \vec{\ell_2} + \vec{\ell_3})$$

How do we measure the bispectrum?

- Ideal measure each triangle configuration
  - Computationally very challenging O(10^{20}) possible configurations
  - Signal in each triplet is very weak
- Compress the data:
  - Binned bispectrum
- Compress the information by fitting templates:
  - Modal estimators - project bispectrum onto set of orthogonal templates
  - **KSW estimator**- project bispectrum onto set of physical templates

KSW bispectrum estimator

$$\langle a(\vec{\ell_1})a(\vec{\ell_2})a(\vec{\ell_3})\rangle = 4\pi^2 b(\ell_1,\ell_2,\ell_3)\delta(\vec{\ell_1}+\vec{\ell_2}+\vec{\ell_3})$$

- Optimal estimator for the template amplitude (ignoring the linear term as it is small for this work)

$$\hat{f}_j = N_{j,i}4\pi^2\int \mathrm{d}\vec{\ell}_1\mathrm{d}\vec{\ell}_2\mathrm{d}\vec{\ell}_3\delta(\vec{\ell}_1+\vec{\ell}_2+\vec{\ell}_3)b_i^T(\ell_1,\ell_2,\ell_3)C^{-1}a(\vec{\ell}_1)C^{-1}a(\vec{\ell}_2)C^{-1}a(\vec{\ell}_3)$$

- KSW exploits separability of the templates to allow for efficient computational evaluation eg.

$$b^T(\ell_1,\ell_2,\ell_3) = X(\vec{\ell}_1)X(\vec{\ell}_2)X(\vec{\ell}_3)$$

Komatsu and Spergel (2001)

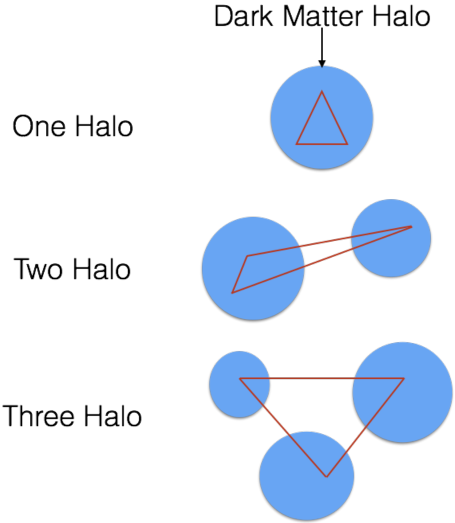
Late Time Bispectrum Sources

- Poisson sources
- Auto and cross correlations between
  - thermal Sunyaev Zel'dovich (tSZ)
  - Dusty star forming galaxies (DSFG) /CIB galaxies
  - Radio galaxies
  - kinetic Sunyaev Zel'dovich (kSZ)
- lensing - integrated sachs wolf effect (ISW),lensing - DSFG, lensing-tSZ,

Halo Model

- Analytic tool for non linear clustering
- Assume all matter is distributed in dark matter halos
- Describe how tracers are distributed in the halo
- Calculate correlations within and between halos

Sheth and Cooray (2001)



Poisson Sources

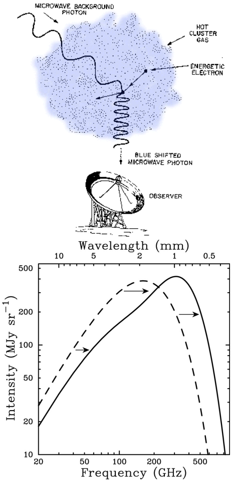
$$b_{\nu_1,\nu_2,\nu_3}(\vec{\ell}_1,\vec{\ell}_2,\vec{\ell}_3) = \int \mathrm{d}S \frac{\mathrm{d}n}{\mathrm{d}S} S_{\nu_1} S_{\nu_2} S_{\nu_3}$$

- Flat bispectrum
- Depends on the source counts ($\frac{\mathrm{d}n}{\mathrm{d}S}$)
- Both radio and Dusty star forming galaxies have poisson components
- Radio galaxy poisson bispectrum is dominated by bright sources
- DSFG poisson bispectrum is dominated by faint sources

Thermal Sunyaev Zel'dovich Effect

$$y = f(\nu)\int \mathrm{dl}\frac{\sigma_T K_B}{m_e c^2} n_e T_e \propto \int P_e \mathrm{dl}$$

- Upscattering of CMB photons by hots cluster gas
- Negative effect for freq< 217GHz and positive above
- Measure of line of sight integrated pressure
- Use Battaglia Pressure profiles to model



Battaglia et al (2011),L. Van Speybroeck

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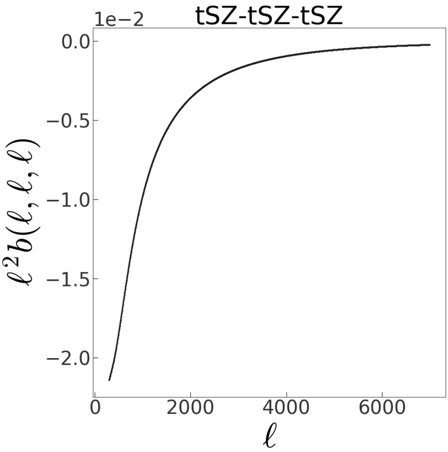
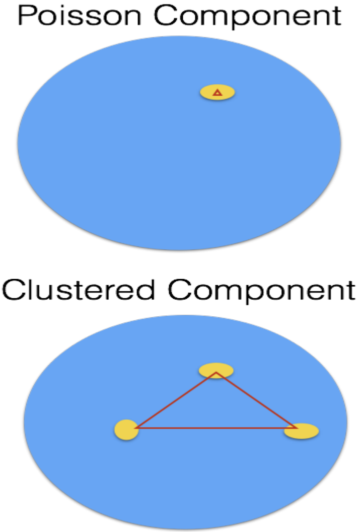


Dusty star forming galaxies (DSFG)

- Thermal dust emission from high redshift galaxies
- Measure of star formation
- Bethermin et al 2012 model
- Point source emission and cluster emission
- Significant at high frequencies



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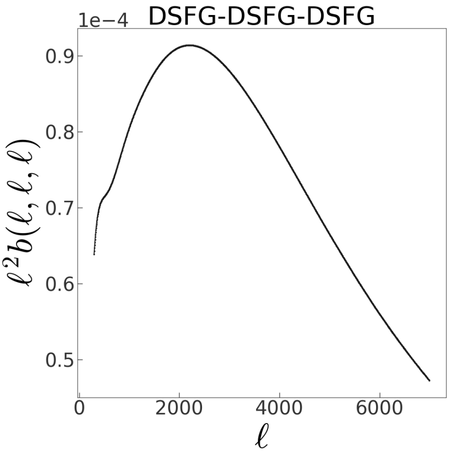
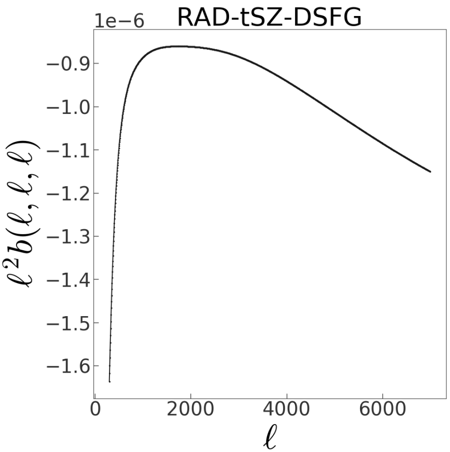


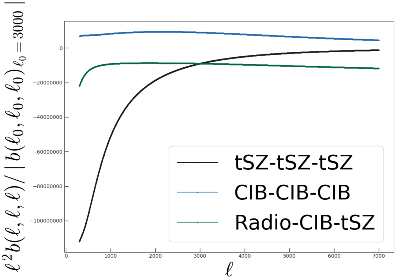
Radio Galaxies

- Synchrotron radiation from AGN
- Rare objects with limited clustering
  - one per halo
- Significant at low frequencies

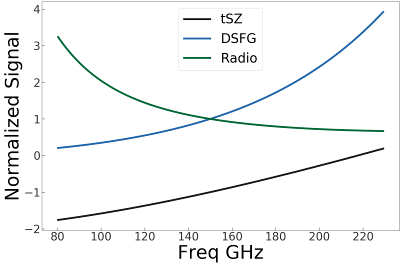
de Zotti et al (2010)



- Requires small scale information



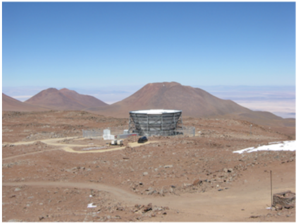
- Requires multifrequency data



The Data Sets

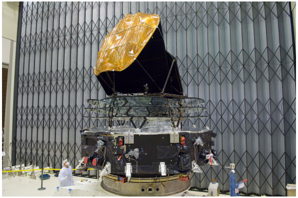
Atacama Cosmology Telescope

- 6m telescope
- Using $\sim 600\text{deg}^2$
- One freq -148GHz
- Small Scales
- Much more data in hand

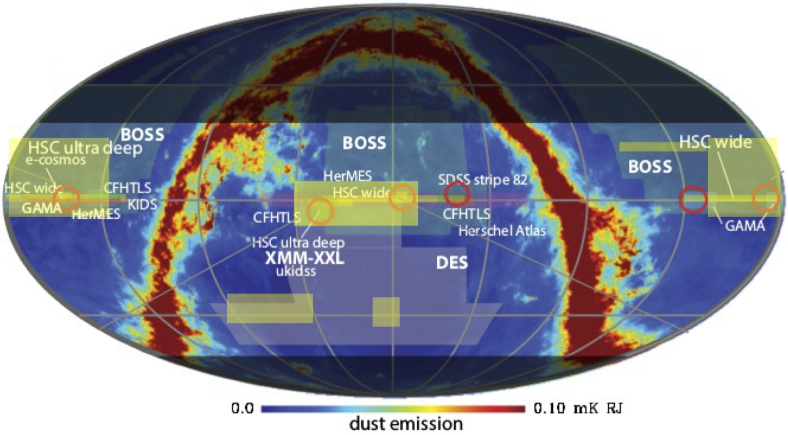


Planck Satellite

- Observed the full sky
- Large Scales
- 9 freqs from 30GHz to 857 GHz
- $\sim 600\text{deg}^2$ and 100GHz and 217GHz used

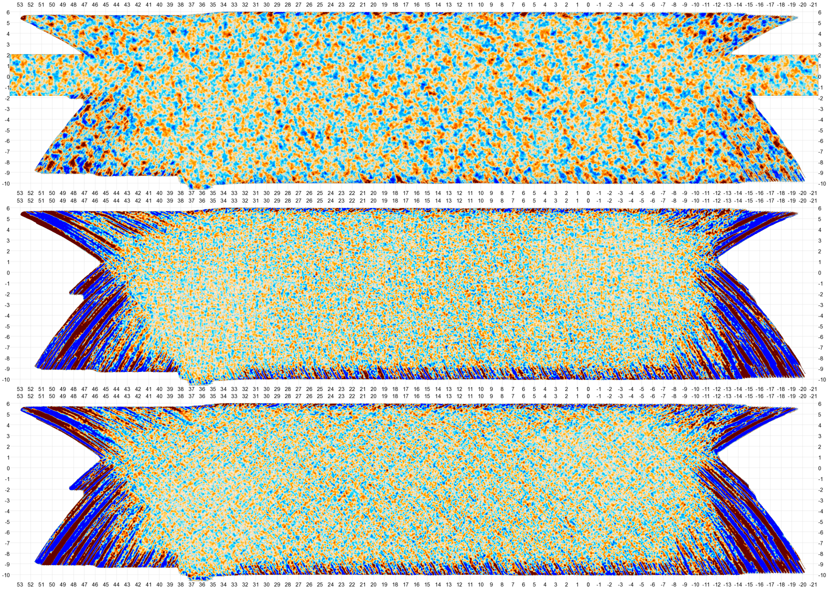


Deep 56 field

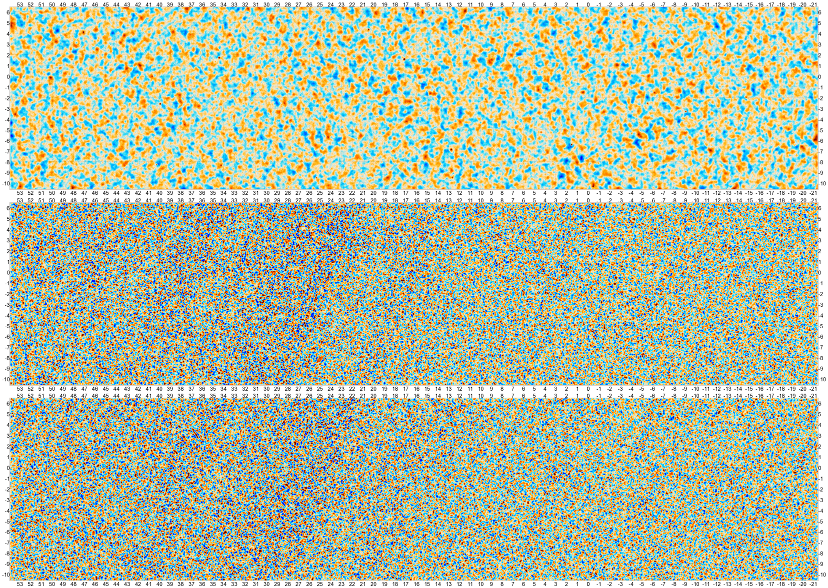


Naess et al (2015)

Deep 56 field - ACTPol



Deep 56 field - Planck

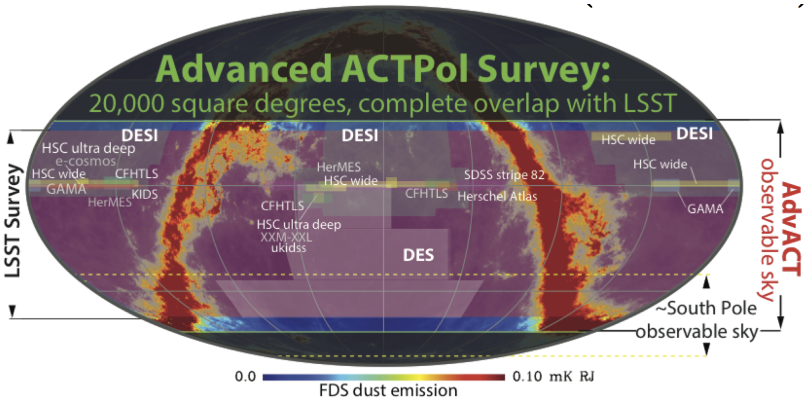


Current Status - Proof of principle

Type	Measured f_{NL}
lensing-tSZ	0.68 ± 0.41
lensing-DSFG	0.26 ± 0.20
lensing-ISW	-6.84 ± 9.59
tSZ-tSZ-tSZ	1.31 ± 0.37
tSZ-tSZ-DSFG	1.54 ± 0.62
tSZ-DSFG-DSFG	-1.23 ± 0.86
Poisson Radio	1.00 ± 0.14
radio-DSFG-tSZ	7.72 ± 1.50
DSFG Poisson and Clustered	0.87 ± 0.57
radio-tSZ	3.07 ± 0.63
radio-DSFG	1.07 ± 1.66

Table: Results from combining 100GHz and 217GHz Planck maps with the ACT deep56 148GHZ maps with $\ell_{max} = 7500$.

Future Small Scale measurements



Future Constraints

Type	f_{NL} S/N
tSZ-tSZ-tSZ	24.3
tSZ-tSZ-DSFG	24.5
tSZ-DSFG-DSFG	21.0
Radio Poisson	61.9
radio-CIB-tSZ	9.42
DSFG Pois and Clustered	13.0
radio-tSZ	9.88
radio-DSFG	9.42

Table: Three frequencies, 90GHz, 148GHz and 220GHz with 20μK arcmin noise , 10000 deg^2 and $\ell_{max} = 7500$.

Astrophysics and Cosmology Parameters

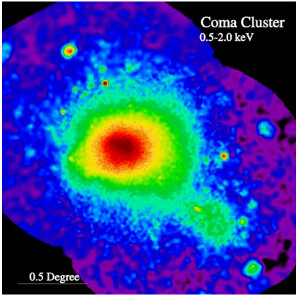
- Want to go from amplitudes of templates to astrophysics and cosmology
- Forecast for imminent data sets
- Three freqs. 90GHz,148GHz and 220GHz
- 1.5 arc min beam at 148GHz
- 10,000 deg^2
- Fisher analysis

$$-2ln\mathcal{L} = (\hat{f}_i - \bar{f}_i)\Sigma^{-1}_{i,j}(\hat{f}_j - \bar{f}_j)$$

Pressure Profile Parameters

$$P(r) = P_0(M,z)\left(\frac{r}{r_s x_s}\right)^{\gamma(M,z)}\left(1+(\left(\frac{r}{r_s x_s}\right)^{\alpha(M,z)})\right)^{-\beta(M,z)}$$

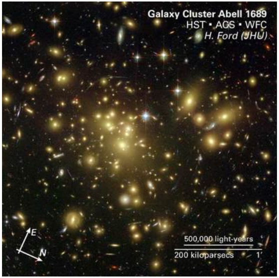
- GNFW with mass and redshift evolution
- P_0 the integrated pressure of a cluster
- β slope of pressure profile in outskirts of cluster



ROSAT

DSFG Parameters

- DSFG are a measure of star formation
- Star formation is quench in massive clusters
- Ram stripping (ICM gas acts as a wind)
- M^* high mass clusters quench star formation
- R^* min radius at which galaxies can occupy.



HST

Radio and Cosmology Parameters

- How do radio galaxies populate halos at high redshift?
- M_r^* probability of galaxy in a halo $e^{-M_r^*/M_{halo}}$.
- σ_8 amplitude of fluctuations in matter power smoothed on a 8Mpc scale

Wake et al 2008

Preliminary Parameter constraints

- Strong constraints on DSFG
- $< 1\%$ constraint on σ_8
- Strong constraints on M^*_{rad}

Parameter	One σ
$\ln \mathrm{R}_{min}$	0.031
$\ln \mathrm{M}_{CIB}$	0.025
σ_8	0.0073
β_P	0.19
P_0	0.054
$\ln\mathrm{M}^*_{rad}$	0.046

Weak lensing - CMB bispectrum

$$\langle a(\vec{\ell_1})a(\vec{\ell_2})\kappa(\vec{\ell_3})\rangle = 4\pi^2 b(\ell_1,\ell_2,\ell_3)\delta(\vec{\ell_1}+\vec{\ell_2}+\vec{\ell_3})$$

- Lenses are dark matter halos
- Correlated with the CMB secondaries
- HSC-like lensing survey over 10,000 deg^2
- Constrain Multiplicative bias, $1+m$

Preliminary Parameter constraints with weak lensing

- $\sim 0.4\%$ constraint on multiplicative bias
- $\sim 0.2\%$ constraint on σ_8
- Strong constraints on cluster gas physics

Parameter	One σ
ln R_{min}	0.010
ln M_{CIB}	0.015
σ_8	0.0018
β_P	0.090
P_0	0.031
$1+m$	0.0037
lnM^*_{rad}	0.012

Beyond Parameters

- Exquisite measurements of CMB secondaries
- Improve understanding of relationships between DM halos, galaxies and star formation
- Push to the beyond HOD and halo models ?

Summary and Future Steps

- Bispectrum powerful tool for studying CMB secondaries
- Combining with cluster counts and power spectrum
- Combine with CMB lensing
- Other interesting applications: foregrounds, primordial non-Gaussianity and systematics.