Measuring Galaxy Cluster Velocities: Forecasting the kSZ Effect

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Abstract

Velocities of galaxy clusters are difficult to measure, but are valuable for constraining cosmological parameters. We use Fisher information to forecast the constraints on peculiar velocities (as well as temperatures and optical depths) of galaxy clusters obtained by microwave (30 – 850 GHz) observations, through the kinematic Sunyaev-Zel'dovich (kSZ) effect. We compare forecasts to real results obtained by Lindner et. al. (3), and find a rough correlation. We assess the ability of upcoming experiments CCAT-prime and Advanced ACTPol (AdvACT) to constrain velocity, and find that CCAT-prime can constrain velocities to within 100-200 km/s. We study some methods to improve constraints by removing emissions from sub-millimetre dusty galaxies, and discuss implications for experimental design.

Fisher Matrices

Fisher matrices can be used to analyse **how observations can constrain random variables**.

Approximate method, related to the first derivative of the log-likelihood function.

Given **true parameter values** and experimental settings, a Fisher matrix forecasts the measured uncertainty on the parameters.

$$F_{ij} = \frac{1}{T_{\mathrm{CMB}}^2} \frac{\partial T(\nu_\alpha, \theta_\beta)}{\partial P_i} (C_\alpha^{\mathrm{noise}})^{-1}_{\beta\gamma} \frac{\partial T(\nu_\alpha, \theta_\gamma)}{\partial P_j}$$

$$C_{ij} = F_{ij}^{-1}$$

Priors can also be added to constrain parameters. Priors on temperature are easy to obtain through X-ray measurements.

Noise Sources

Most significant contaminant is **emissions from dusty galaxies.** Modelled with constant average noise at 350 GHz. The spectral variation modelled as a power law with spatially varying exponent. This noise Is also magnified around clusters due to **gravitational lensing.**

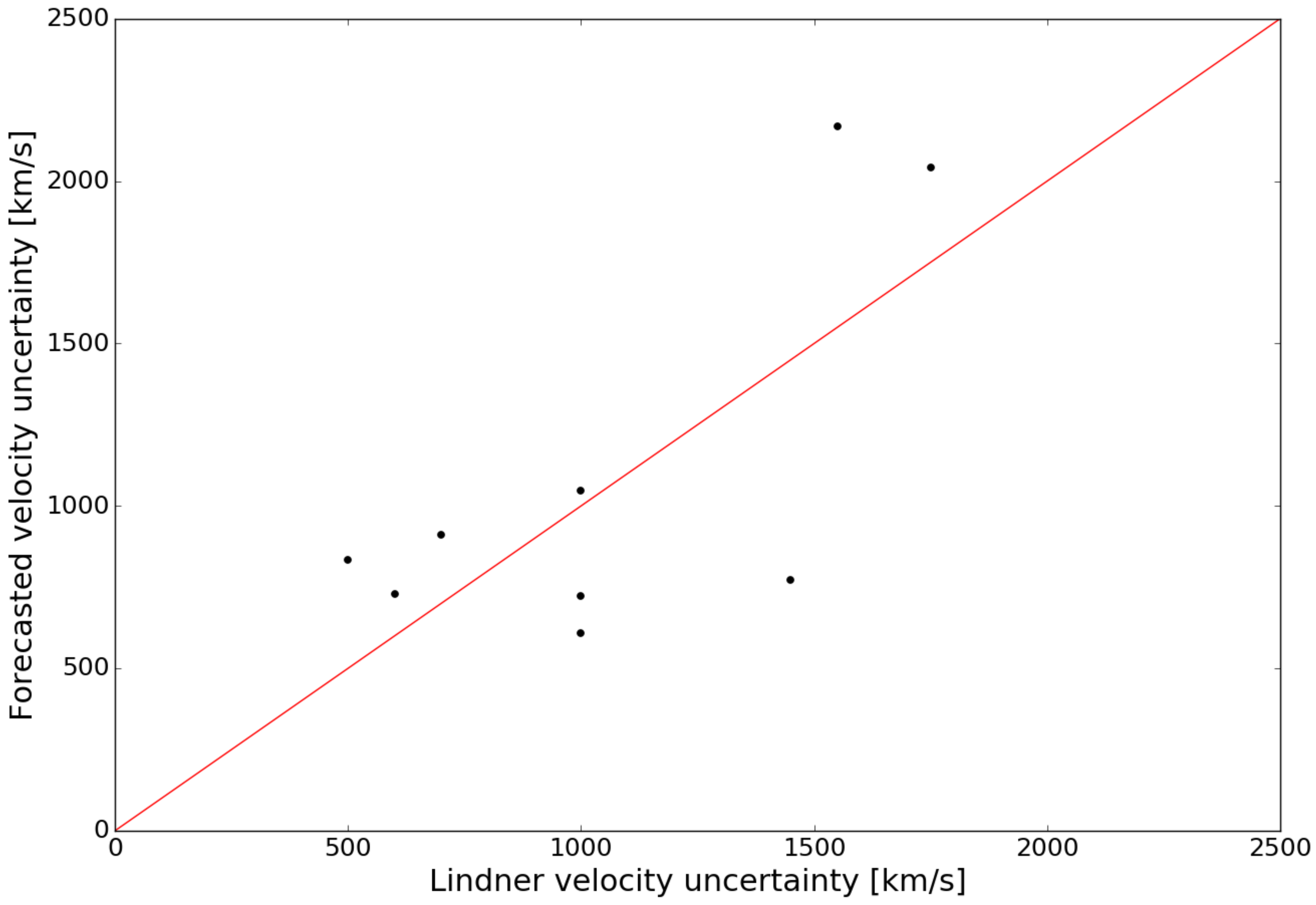
$$n_{\mathrm{gal}}(\nu, \theta) = \frac{\overbrace{\delta T_{350}^{\mathrm{gal}}}^{\text{350 GHz noise}}}{T_{\mathrm{CMB}}} \left(f_4(\nu) + \overbrace{\delta\alpha(\theta)}^{\text{spatial variation of power law}} f_5(\nu)\right) \overbrace{E(\theta, \theta_b)}^{\text{gravitational lensing}}$$

Instrument noise: RMS map noise (related to sensitivity, observing time)

CMB also contaminates SZ signal

$$(C_\alpha^{\mathrm{noise}})_{\beta\gamma} = \langle n_{\mathrm{tot}}(\nu_\alpha, \theta_\beta) n_{\mathrm{tot}}(\nu_\alpha, \theta_\gamma) \rangle$$

Comparison with Real Results



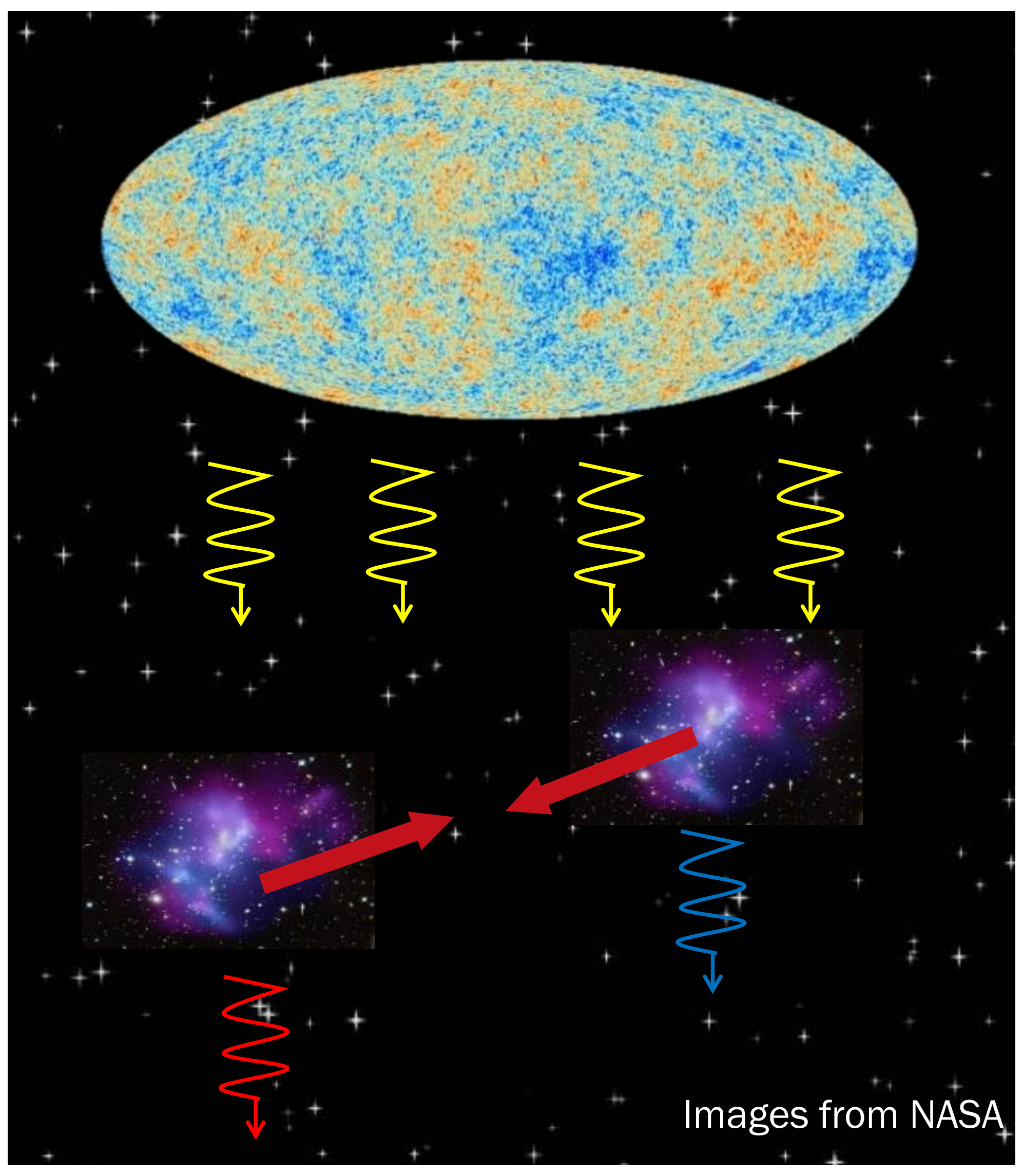
Comparison of velocity uncertainties of nine clusters measured by Lindner, et. al. (3) to the forecasted velocity uncertainties for the same clusters, with identical parameters and settings. The red line is of slope 1 (y = x). The best linear fit through the origin has slope 1.02.

Conclusion

CCAT-prime can constrain velocity better than Advanced ACTPol because it has extra bands at shorter wavelengths. Temperature priors are useful in constraining velocity because they break degeneracies between velocity and other parameters.

We are currently modelling a method to improve constraints by taking maps at **higher frequencies**, where galactic emissions dominate, to **subtract off** the galactic noise. Preliminary results indicate that adding a 350-450 μm band to CCAT-prime will significantly improve velocity constraints.

The Sunyaev-Zel'dovich Effect


Images from NASA

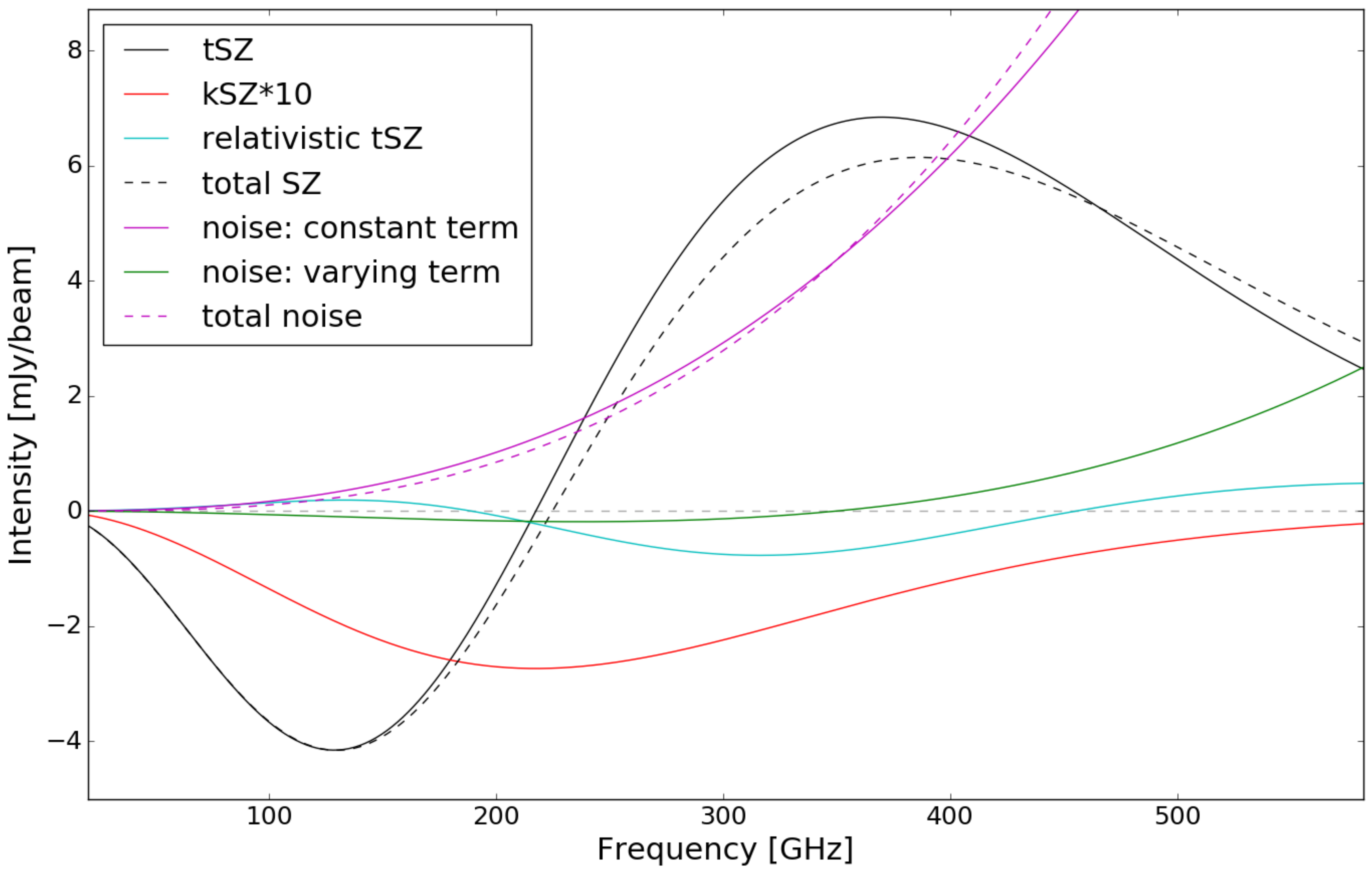
Galaxy clusters are falling toward each other on average, and finding out the rate at which they do is **invaluable in testing cosmological models** and constraining parameters, specifically in theories of modified gravity, dark energy and neutrino masses (7).

CMB photons interact with hot electrons in intra-cluster medium through **inverse Compton scattering**, leaving a redshift-independent imprint of the galaxy cluster in the CMB. This is the Sunyaev-Zel'dovich (SZ) effect.

Thermal SZ (**tSZ**) effect: proportional to electron gas **temperature**
Kinematic SZ (**kSZ**) effect: proportional to cluster peculiar **velocity**

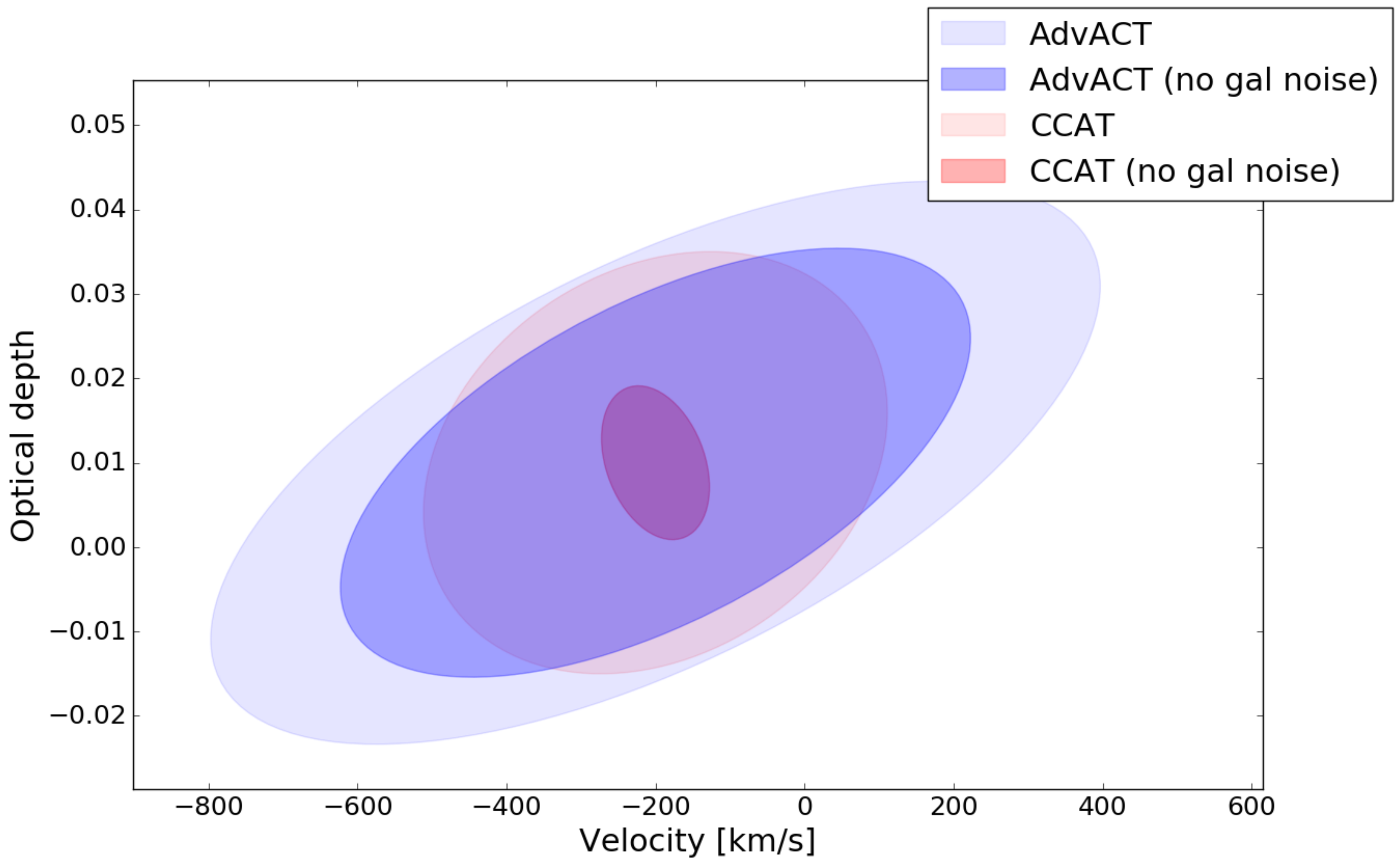
Parametrise cluster by temperature, optical depth and velocity (Θ, τ, β)

$$\delta T(\nu, \theta) = \tau \left(\overbrace{\Theta f_1(\nu)}^{\text{tSZ}} + \overbrace{\beta f_2(\nu)}^{\text{kSZ}} + \overbrace{\Theta^2 f_3(\nu)}^{\text{relativistic tSZ}}\right) \overbrace{h(\theta)}^{\text{cluster profile}}$$



Plot of the spectral variation of the various components of the signal (2) and noise (1) for a fiducial cluster (1). They have been converted from CMB blackbody temperature back to intensity for this display. The kSZ signal, in red, has been multiplied by 10 to emphasise its effect. We assume a beam solid angle of 1 square arcminute for this plot.

Upcoming Experiments



1-σ confidence ellipses for AdvACT (4) and CCAT-prime (5) measurements of a fiducial cluster, in velocity and optical depth. The darker ellipses represent the same measurement with the galactic noise term removed. For CCAT-prime, we assume 7 bands between 350-3000 μm in a similar configuration to SWCam (5) on a high-throughput 6 meter aperture telescope (6).

References

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4. Henderson, et. al., 2015, arXiv:1510.02809
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