Cornell University

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)

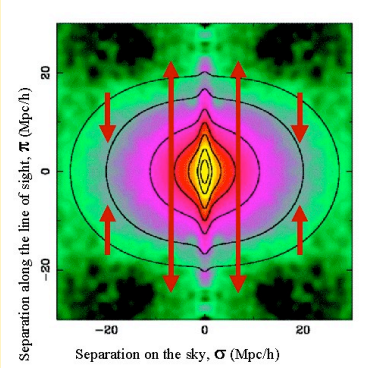
Outline

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:

- BAO and Redshift Space Distortions
- Weak Lensing



Larger scales

Why clusters?

high mass → very sensitive to the gravitational potential

Clusters:

- Cluster abundance
- Dynamics of clusters

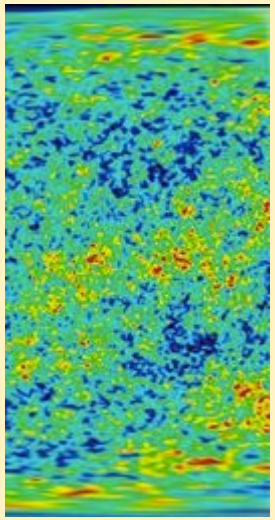
S. Bhattacharya, A. Kosowsky, 2007

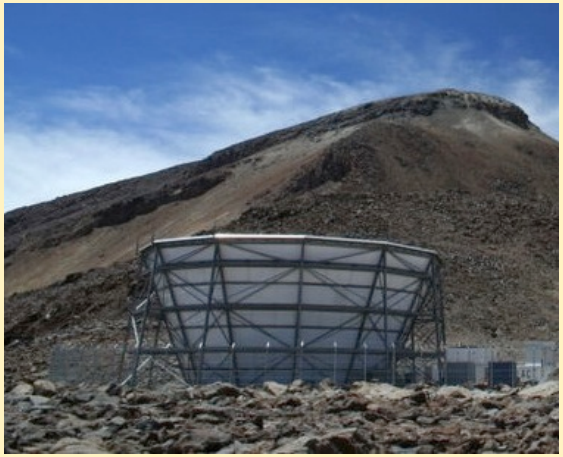
⇨ kinetic SZ effect (CMB)

↙ different systematics

↘ different degeneracies

Kinetic SZ effect





CMB photon passing though clusters are Doppler shifted due to bulk motion
$\longrightarrow$ distortion of the CMB spectrum

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

optical depth

$$\Rightarrow \quad \dot{\delta} + ikv = 0$$

SZ spectrum

Problem:

→ kSZ: weak frequency dependence

→ kSZ: Signal is small

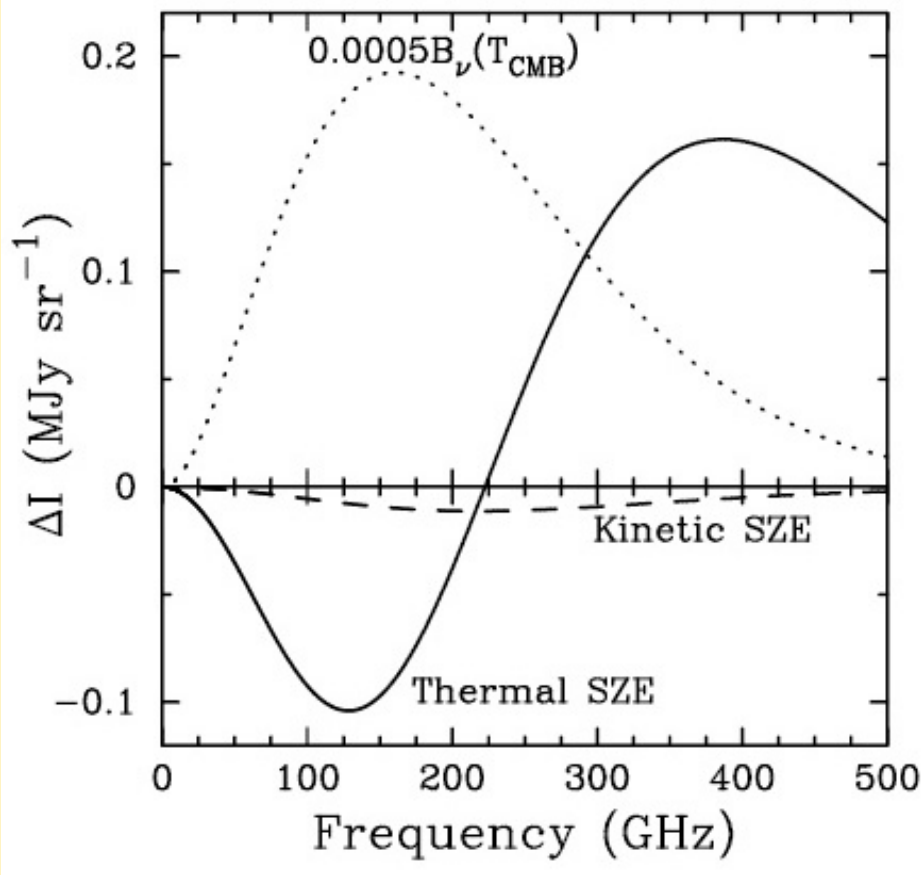
⇩

Hard to observe

Solution:

→ Cross-correlate with cluster positions and redshift

→ Mean pairwise velocity



ned.ipac.caltech.edu

Method: Mean pairwise statistics

→ First detection : ACT

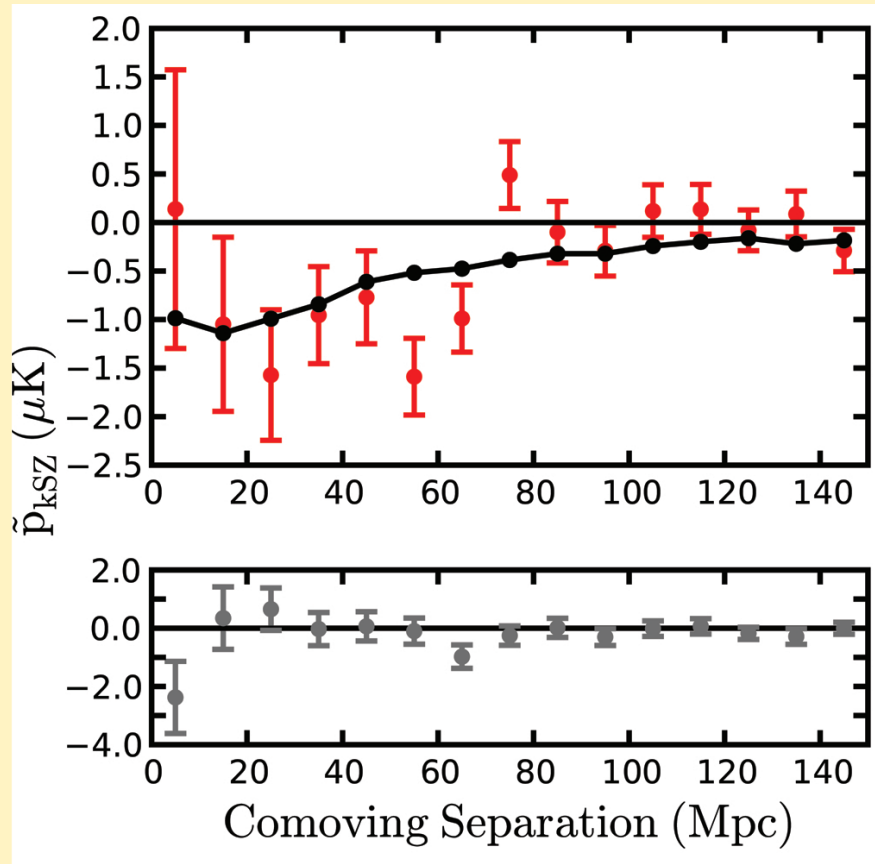
mean pairwise momentum

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

→ But: need better accuracy

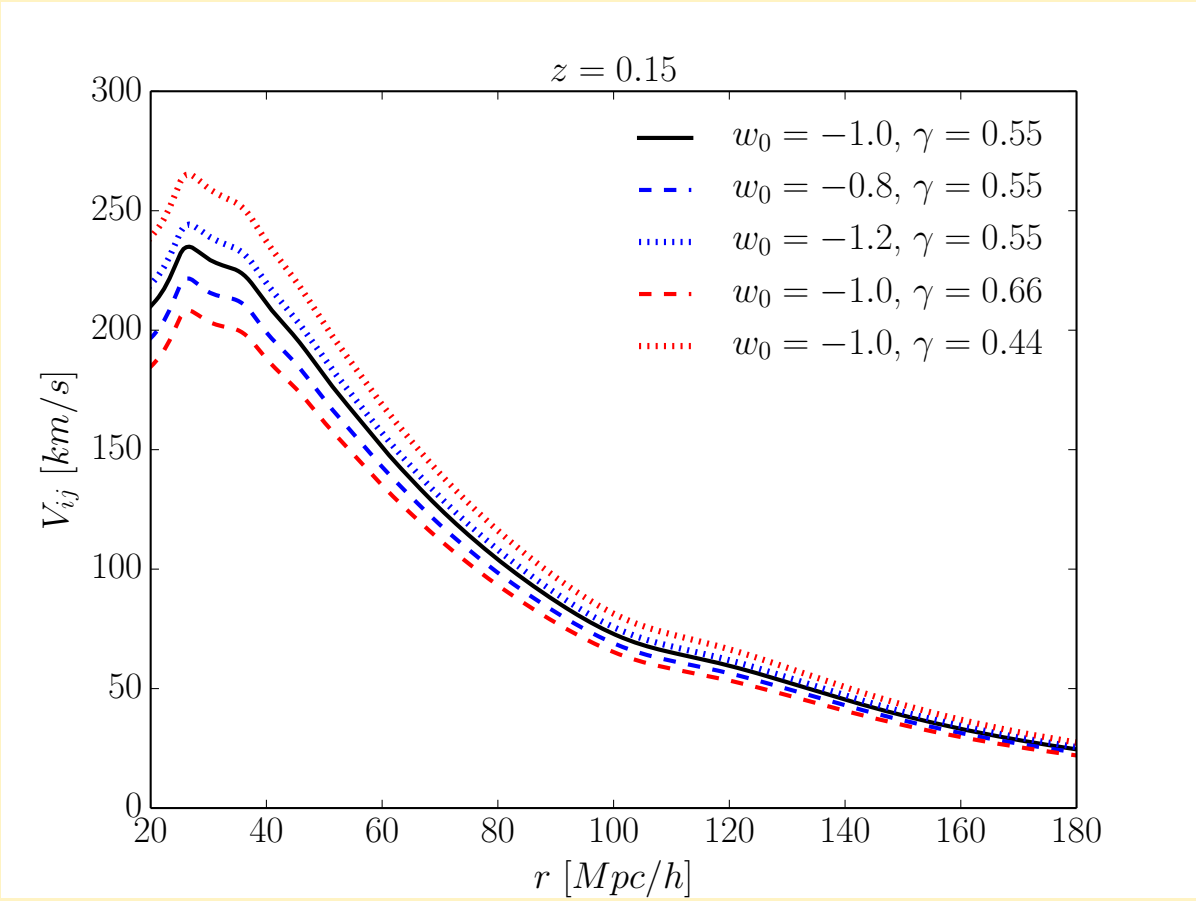
⇩

How well can we do in the future?



Hand et. al 2012

Use mean pairwise velocity to constrain growth of matter



Growth rate f:

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

$$\gamma_{\rm GR} = 0.55$$

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

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

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

Sheth et. al 2001

Survey Specifications

		Survey Stage		
Survey	Parameters	II	III	IV
CMB	$\Delta T_{\rm instr}$ (μKarcmin)	20	7	1
Cluster	$z_{\rm min}$	0.1	0.1	0.1
	$z_{\rm max}$	0.4	0.4	0.6
	No. of z bins, N_z	3	3	5
	$M_{\rm min}$ ($10^{14} M_\odot$)	1	1	0.6
Overlap	Area (sq. deg.)	4000	6000	10000

ACTPol +BOSS

AdvancedACT

CMB S4 +DESI

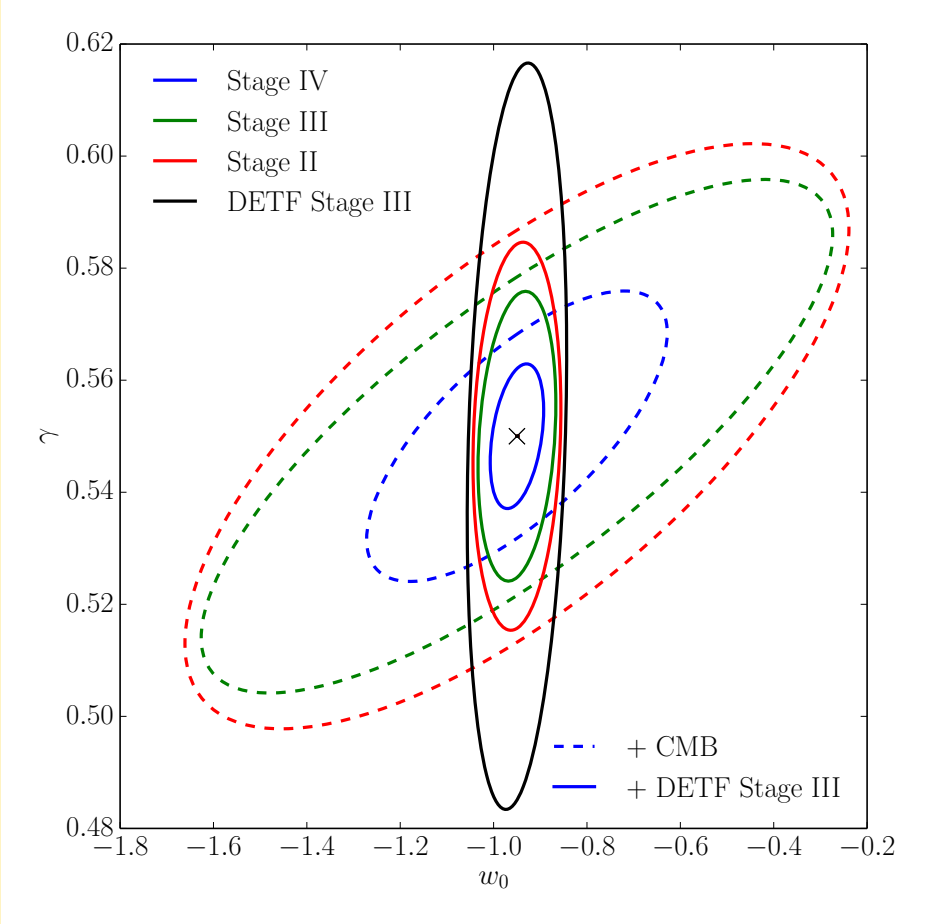
→ Cross-Correlate cluster position on the sky and redshift with kSZ signal

use LRGs as tracers of clusters

cluster catalog

Potential of kSZ surveys

		Stage III	Stage IV
+CMB	$\mathrm{FoM}_{\mathrm{GR}}$	14	61
	FoM_{MG}	9	33
	$\Delta\gamma/\gamma$	0.08	0.05
+DETF	$\mathrm{FoM}_{\mathrm{GR}}$	156	292
	FoM_{MG}	152	273
	$\Delta\gamma/\gamma$	0.05	0.02



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

→ Current constraints:

BOSS: $\gamma = 0.71^{+0.12}_{-0.11}$

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

Modified Gravity Parametrization

→ Model independent parametrization: $f_g(z)$

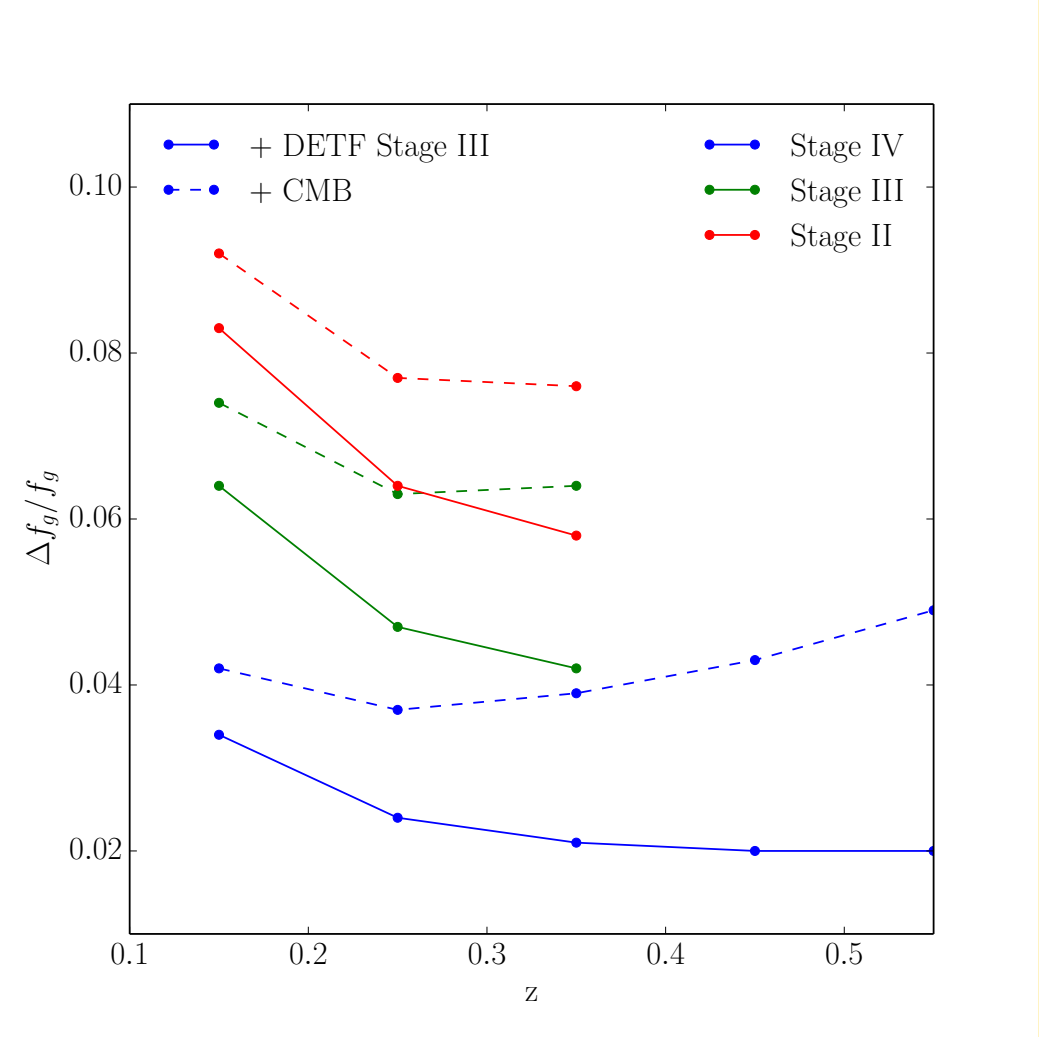
→ Less theoretical prior

→ Comparison to other future probes:

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

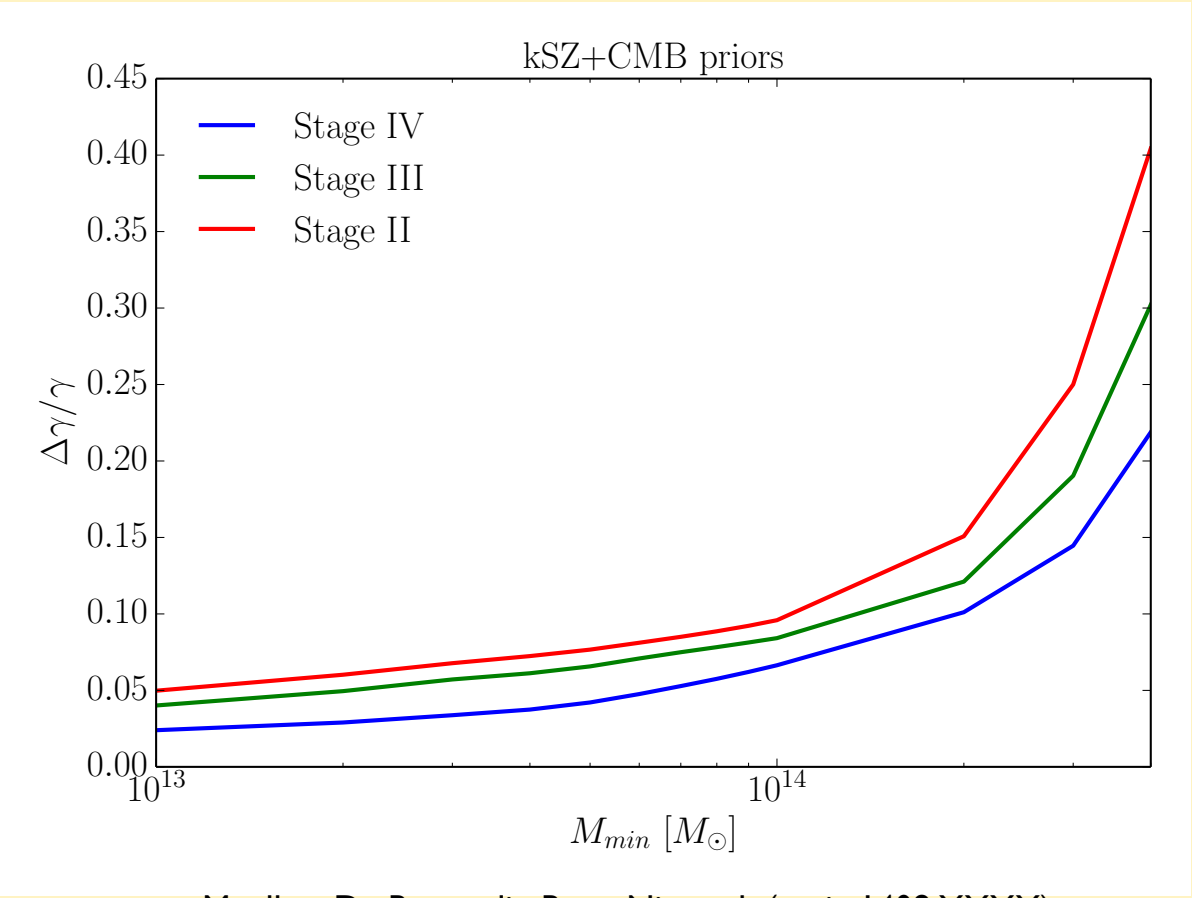
additional constraints from Euclid and WFIRST at higher redshifts

⇨ Complementary constraints



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

Dependency on the number of clusters



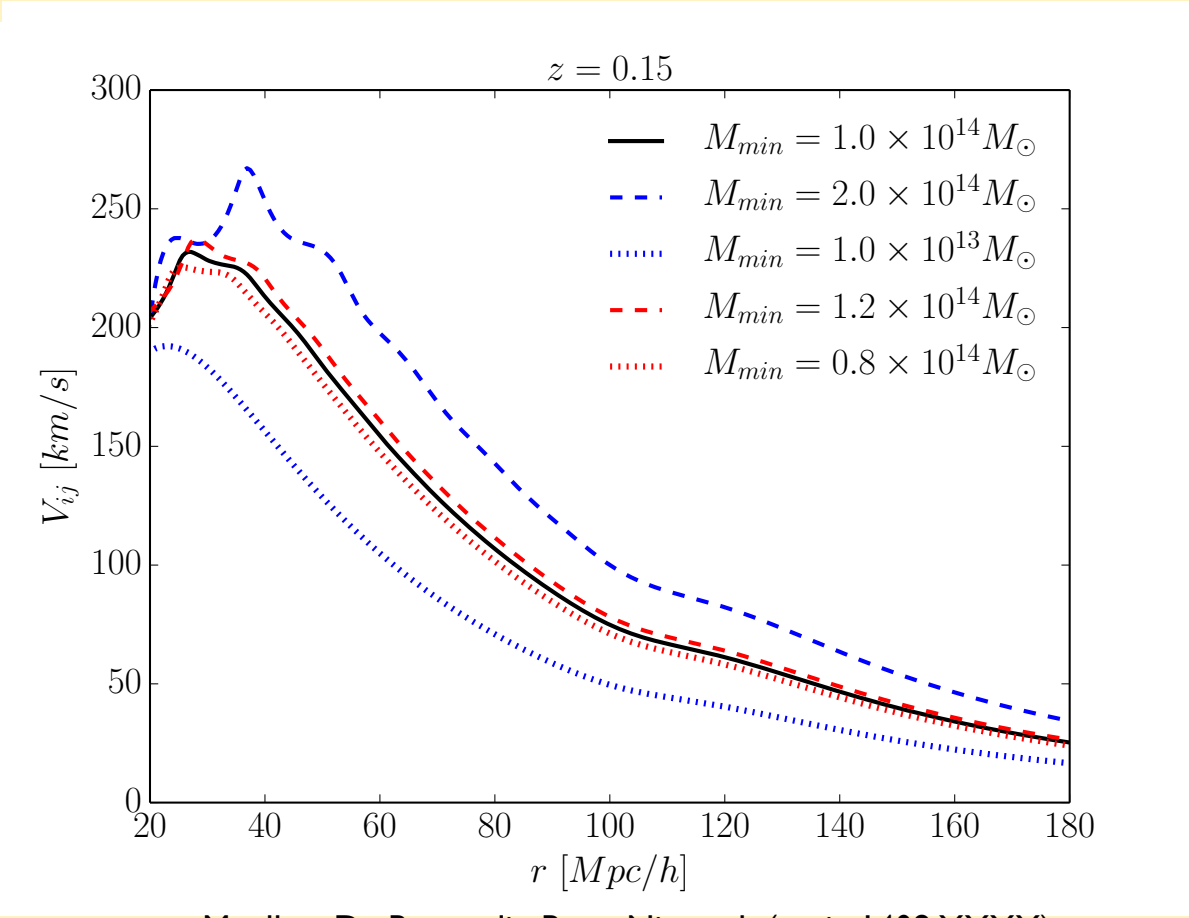
Mueller, De Bernardis, Bean, Niemack (arxiv 1408.XXXX)

Higher cluster number densities lead to better constraints!

Optimistic case:

	Stage II	Stage III	Stage IV
$M_{\rm min}$ $(10^{13} M_\odot)$	4	4	1
$\Delta\gamma/\gamma$	0.07	0.06	0.02

Uncertainty in limiting mass



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

→ Limiting mass changes shape + amplitude

→ Only mild dependency

→ Marginalizing over the minimum mass does not significantly reduce constraints

Robust to uncertainties in the mass calibration!

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 τ as a proxy for the uncertainty

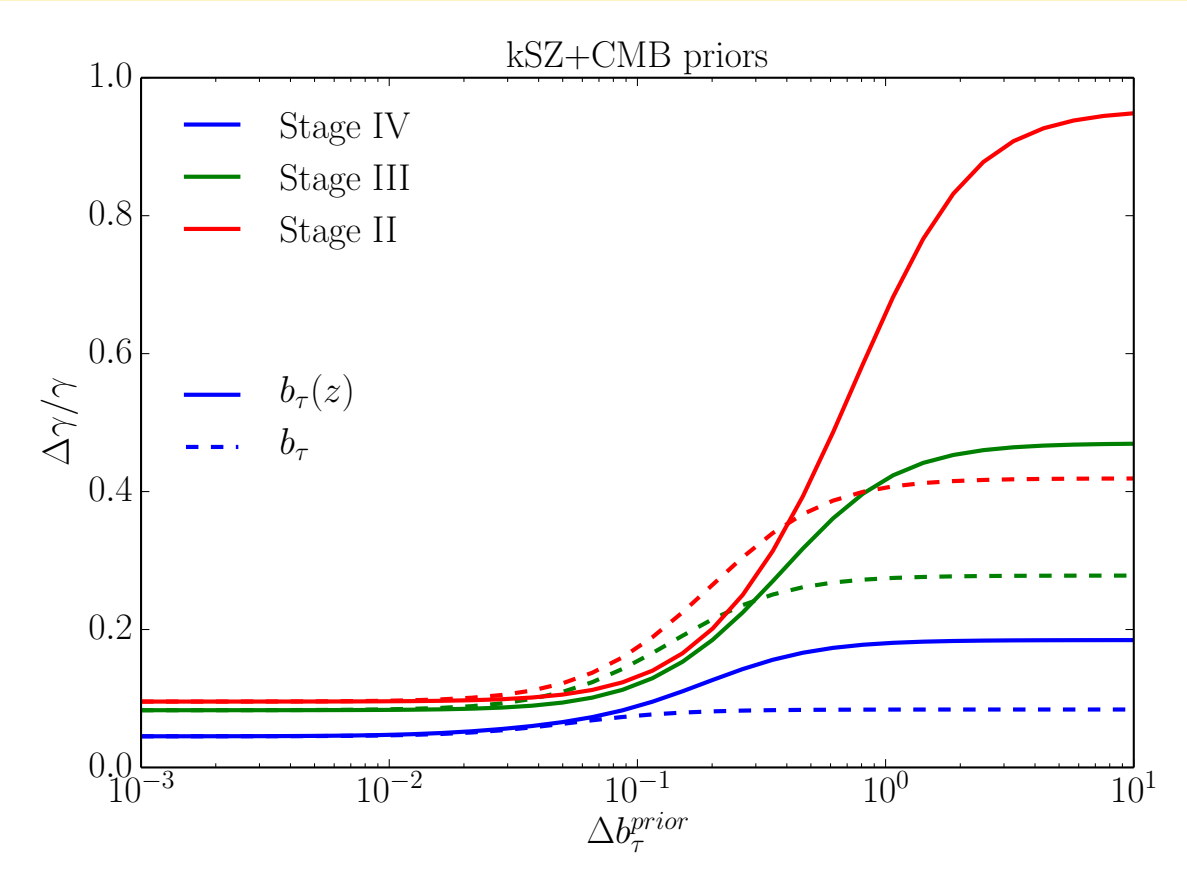
→ Measurement error is a combination of instrument noise and uncertainty in optical depth

$$\sigma_v = \sqrt{\sigma_{\rm instr}^2 + \sigma_\tau^2} \qquad C_V^{\rm measurement}(r, r') = \frac{2\sigma_v^2}{N_{\rm pair}} \delta_{r,r'}$$

But:

Can we constrain both, optical depth and pairwise velocity?

*Private communication with N. Battaglia



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

$\Delta\tau \leq 10\%$ leads to 'interesting' constraints

→ Introduce nuisance parameter: Marginalize over the amplitude, i.e. optical depth

$$\hat{V}(z) = b_\tau(z) V(z)$$

→ add prior on the τ-bias

Need information on the optical depth

How can we constrain the optical depth?

- Fitting function from Hydro simulations

Robustness?

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

Theoretical assumptions and modeling?

- Polarization signal from scattering
  astro-ph/9903287

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

$$C_{i,j} = F_{i,j}^{-1}$$

$$F_{ij} = \sum_{\alpha\beta} \frac{\partial \mathcal{D}_\alpha}{\partial p_i} Cov_{\alpha\beta}^{-1} \frac{\partial \mathcal{D}_\beta}{\partial p_j}$$

mean pairwise velocity

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

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

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