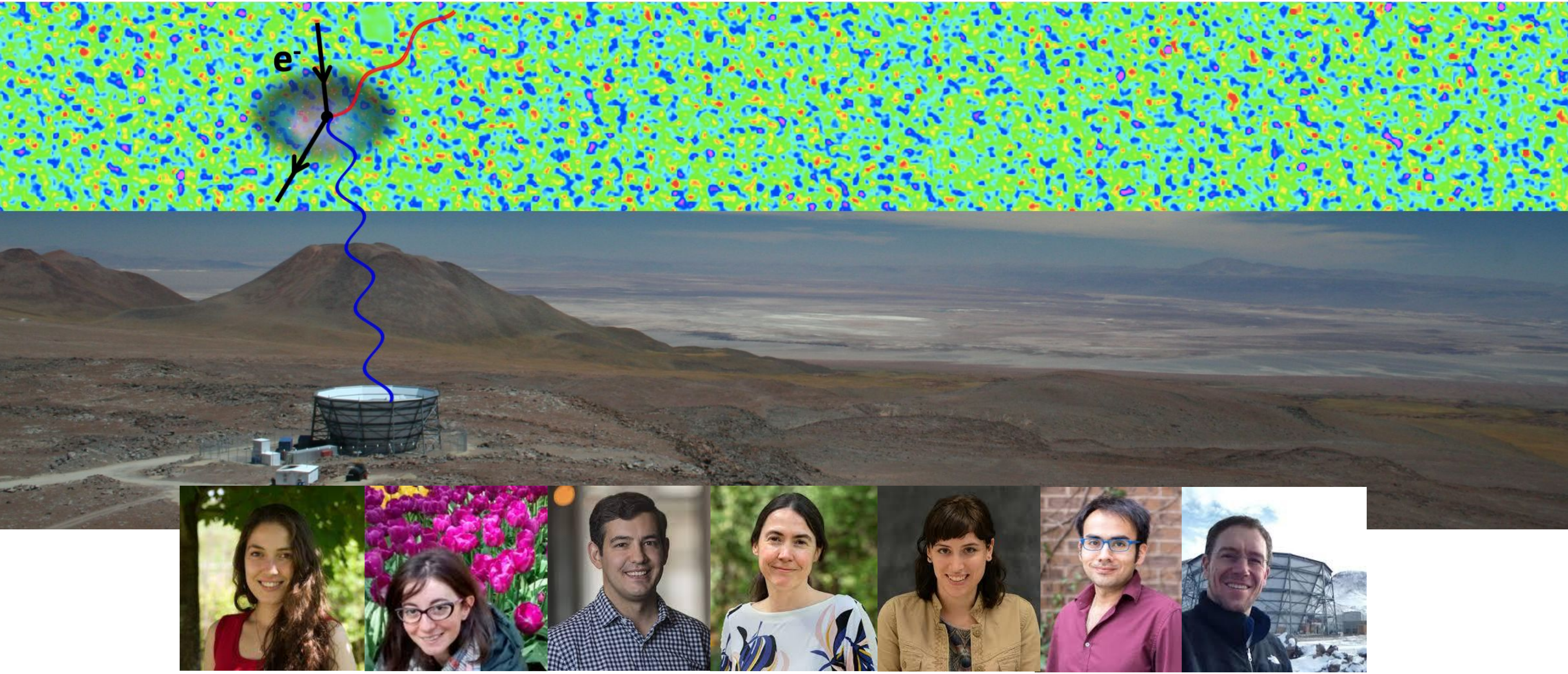
Probing the Baryon Content of BOSS DR15 Galaxies with ACTPol and the SZ Effects

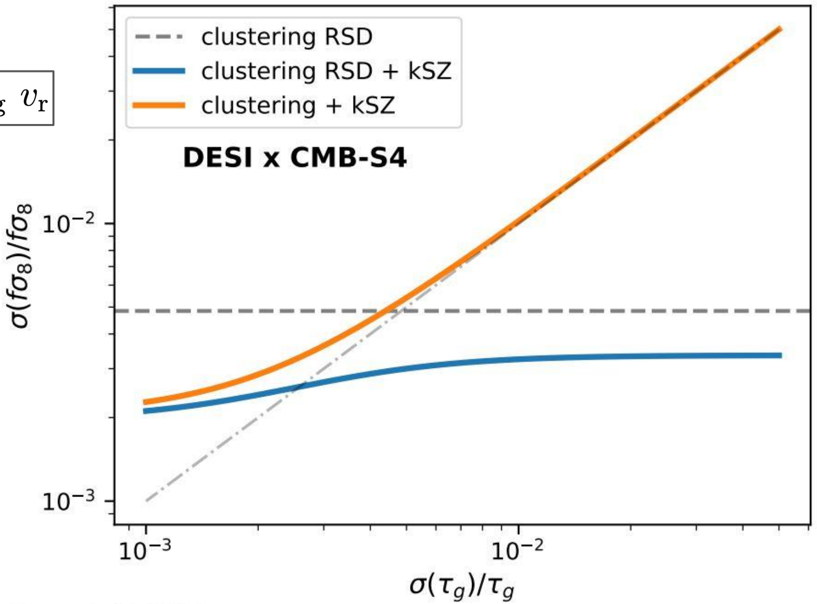


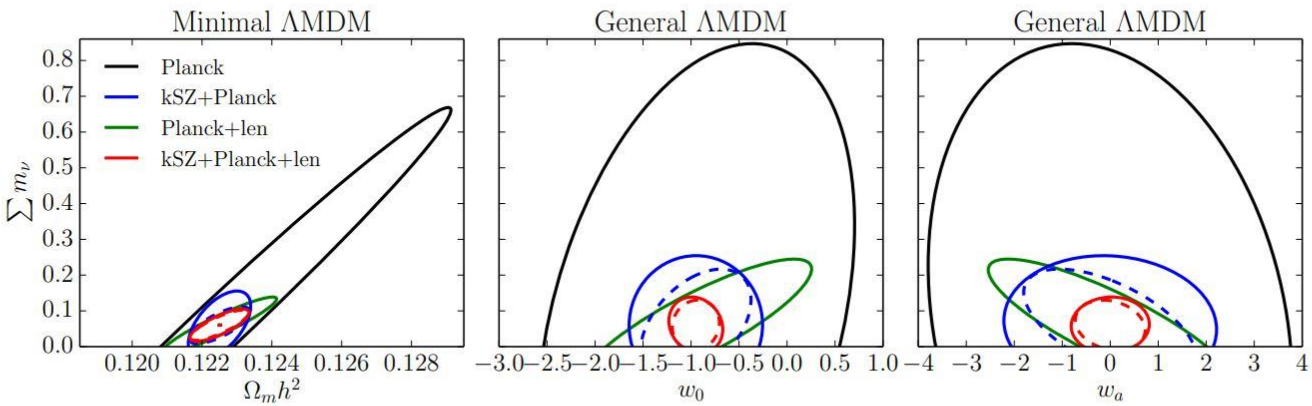
Eve Vavagiakis, Stefania Amodeo, Nicholas Battaglia, Rachel Bean, Victoria Calafut, Patricio Gallardo, Michael Niemack & the ACT Collaboration
Cornell Physics and Astronomy Departments

The Sunyaev-Zel'dovich Effects

$$(\Delta T/T)_{\mathrm{kSZ}} = -\tau_{\mathrm{g}}\ v_{\mathrm{r}}$$

- kSZ effect probes peculiar velocities
- Constrain neutrino mass sum, σ_8, *f*, dark energy, models of modified gravity
- tSZ effect: sensitive to integrated line-of-sight pressure profile, can break optical depth degeneracy
- Measure ionized gas profiles, constrain feedback mechanisms, trace baryons: Amodeo et al. 2020, arXiv:2009.05558, Schaan et al. 2020, arXiv:2009.05557
- Pairwise correlation statistic: temperature differences average out contamination



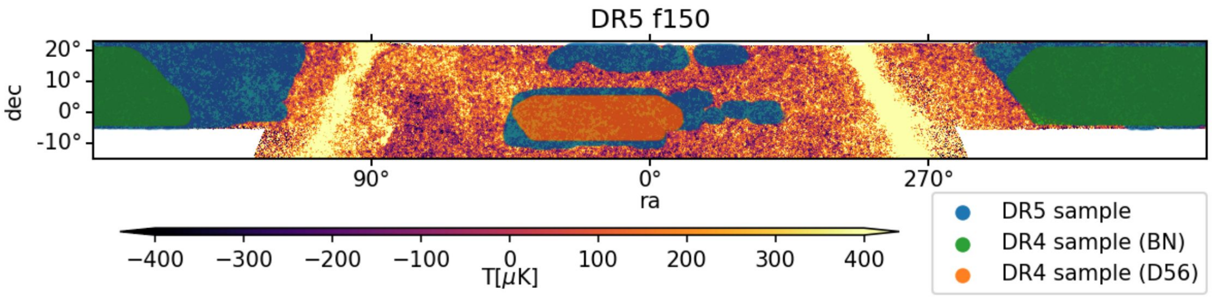


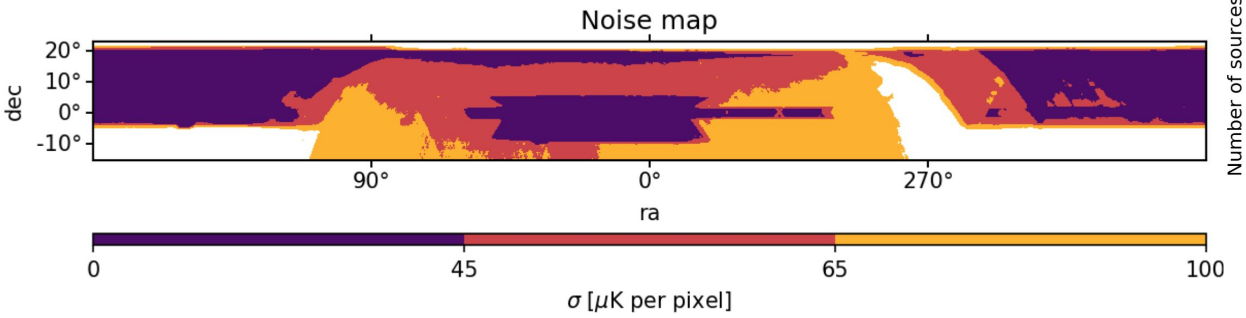
Top: CMB-S4 Science Case, arXiv:1907.04473

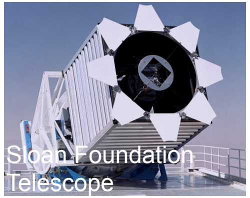
Left: Mueller, de Bernardis, Bean, Niemack, arXiv:1412.0592

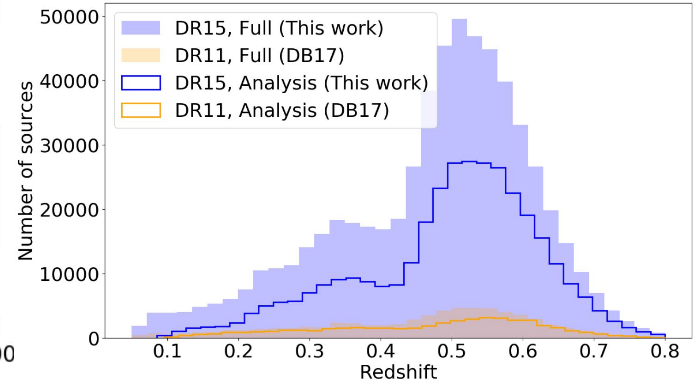
Data

- ACT+*Planck* coadded maps f150, f090 (Naess et al. 2020, arXiv:2007.07290)
- ILC Boss-N, D56 Compton-y, CMB+kSZ maps (Madhavacheril et al. 2019, arXiv:1911.05717)
- Selected BOSS-SDSS DR15 galaxies, three disjoint luminosity bins for joint SZ analysis



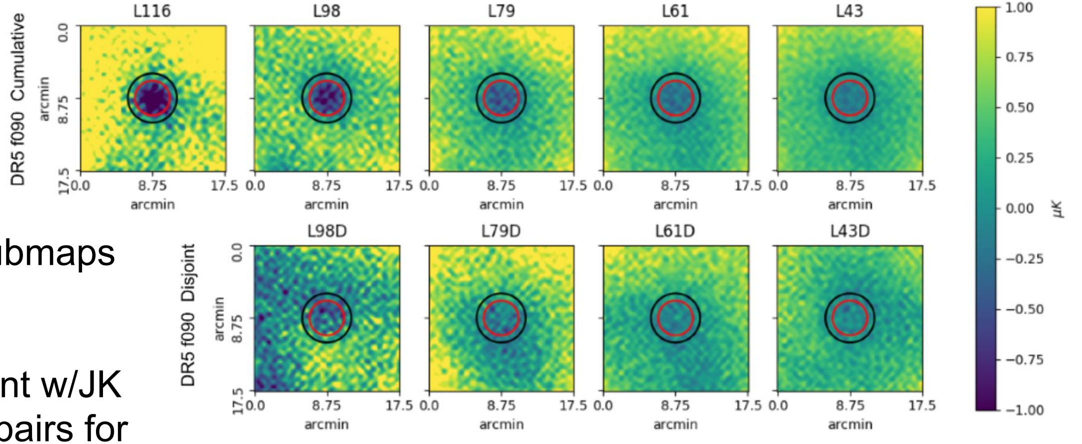






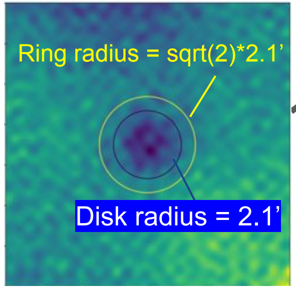
Vavagiakis, Gallardo, Calafut, Amodeo et. al., arXiv:2101.08373

Pairwise kSZ Statistic & tSZ Stacking



Vavagiakis, Gallardo, Calafut, Amodeo et. al., arXiv:2101.08373

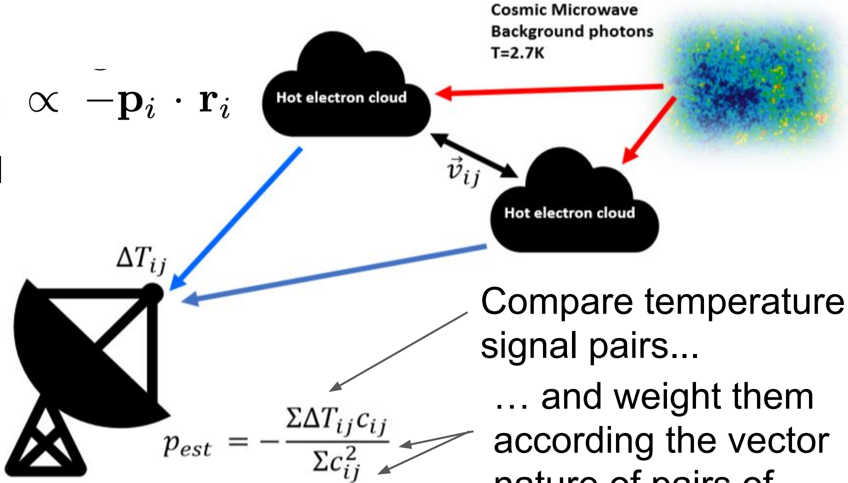
- Aperture photometry on source-centered submaps w/2.1’ radius aperture
- Beam correction for f090, ILC maps
- Stack in luminosity bins for tSZ measurement w/JK
- Pairwise estimator with temperature signal pairs for kSZ measurement w/bootstrap



$$\delta T_i = T_{\text{disk}} - T_{\text{ring}}$$

$$\Delta T_{kSZ,i} \propto -\mathbf{p}_i \cdot \mathbf{r}_i$$

- Pairwise estimator: statistical detection over all pairs of galaxies sharing similar separation



$$p_{est} = -\frac{\Sigma \Delta T_{ij} c_{ij}}{\Sigma c_{ij}^2}$$

Compare temperature signal pairs...

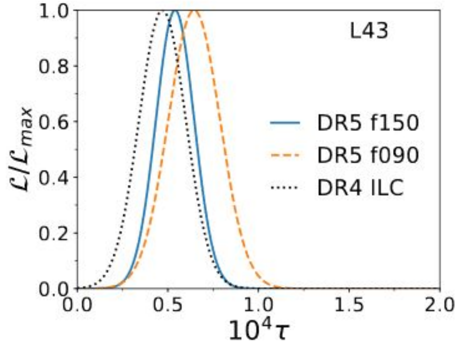
… and weight them according the vector nature of pairs of velocity projections

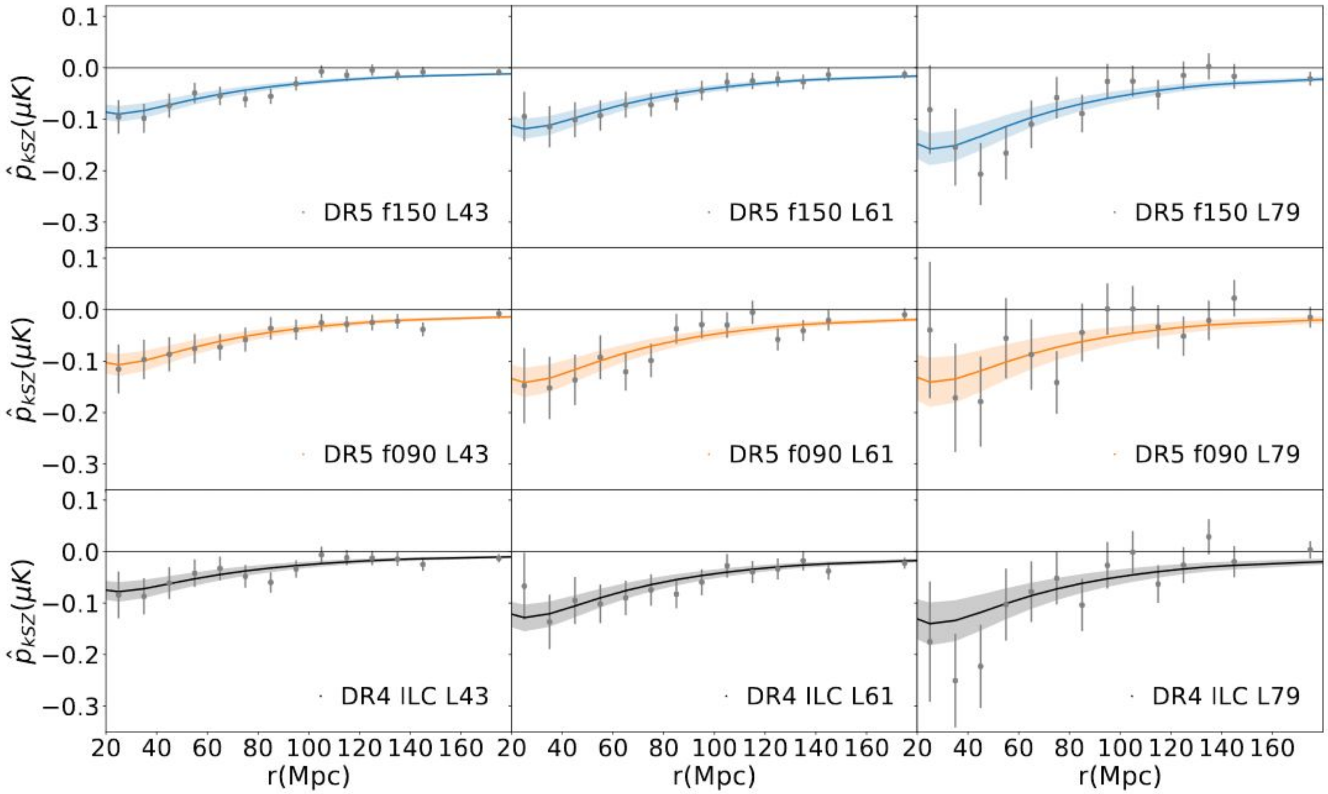
Calafut, Gallardo, Vavagiakis et. al., arXiv:2101.08374

Pairwise kSZ Results

$$\hat{p}_{\rm th}(r,z) = -\frac{T_{CMB}}{c}\bar{\tau}V(r,z)$$

- 5.4 sigma detection
- Fits to model yield estimate of optical depth
- Consistent across maps
- For more details see Patricio Gallardo's poster

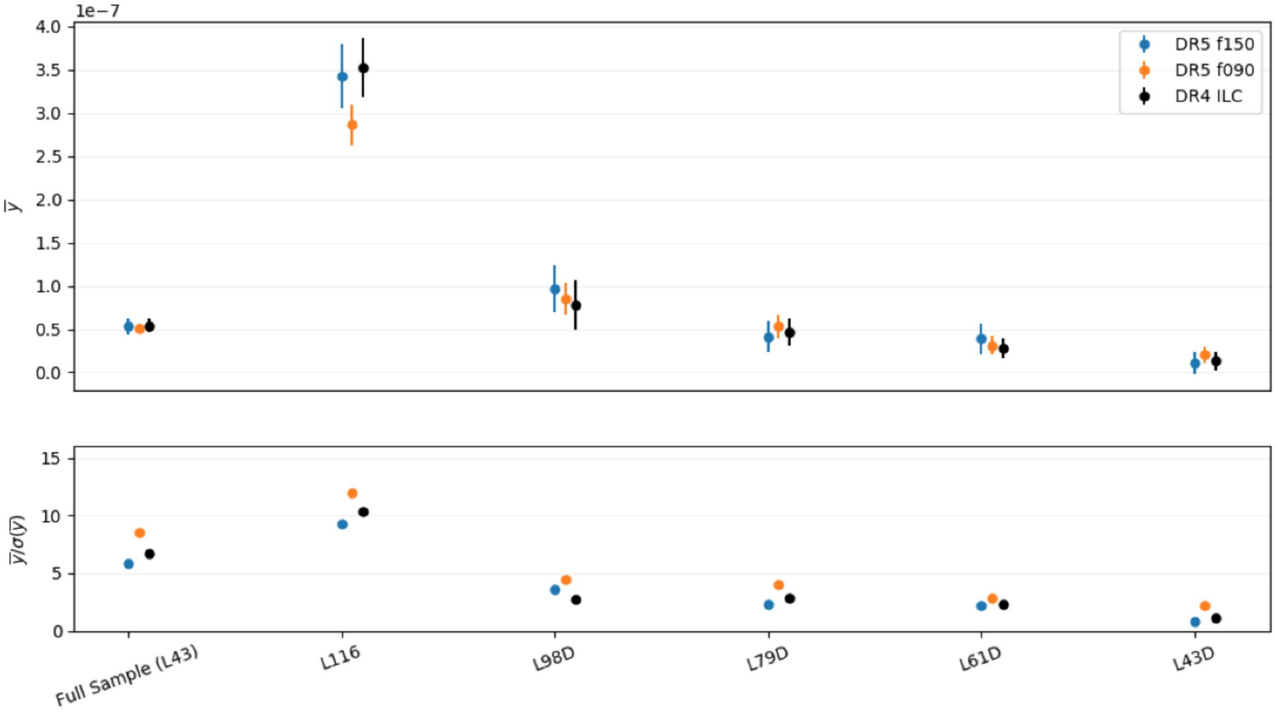




Calafut, Gallardo, Vavagiakis et. al., arXiv:2101.08374

tSZ results

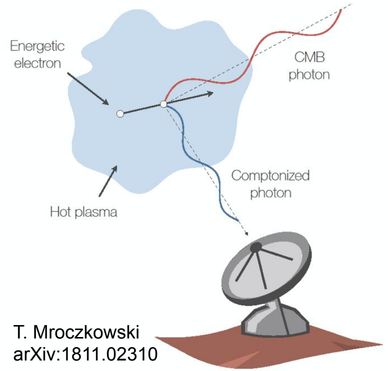
- Average Compton-y in 2.1’ aperture from tSZ stacking results
- Herschel data used for dust contamination correction (Amodeo et al. 2020, arXiv:2009.05558),
- Measurements consistent across frequencies and maps
- Higher S/N (up to 12 sigma) in higher L bins as expected



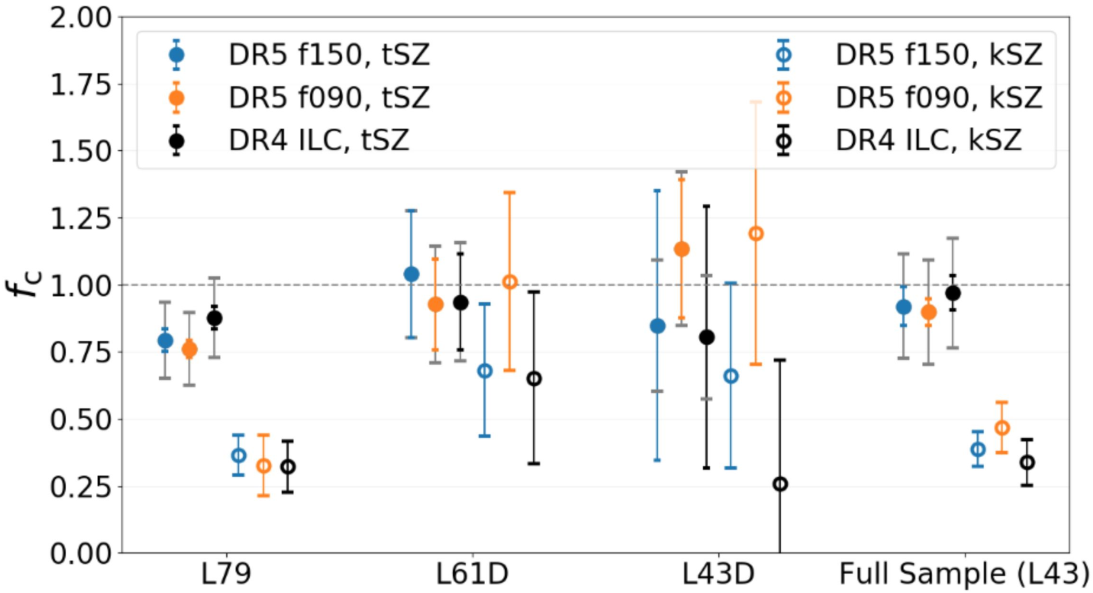
Vavagiakis, Gallardo, Calafut, Amodeo et. al., arXiv:2101.08373

Optical depth comparisons

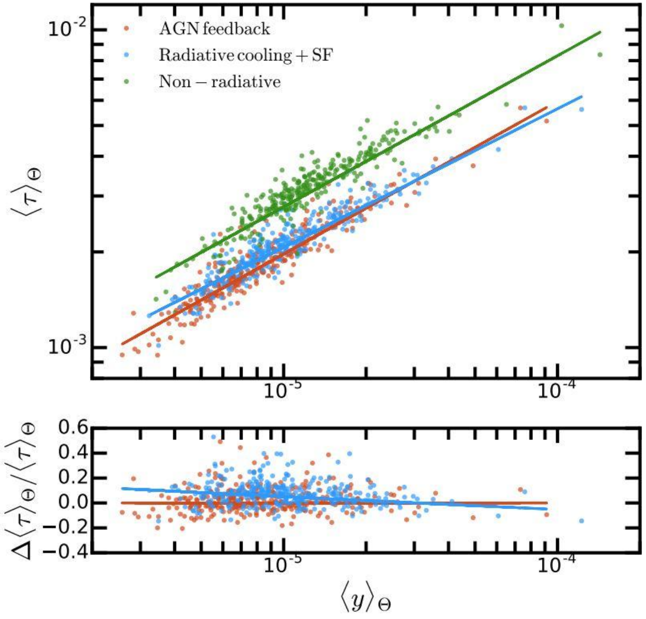
- Compton-y results used to estimate optical depths from hydrodynamical sim model (Battaglia 2017, 1607.02442)
- “Theoretical tau” estimated for case in which baryons trace dark matter
- kSZ and tSZ results agree within 1σ in 2 bins, differ at 2-3σ in highest S/N bin
- Estimates from the SZ effects account for ⅓ to all of the theoretically predicted baryon content



T. Mroczkowski
arXiv:1811.02310



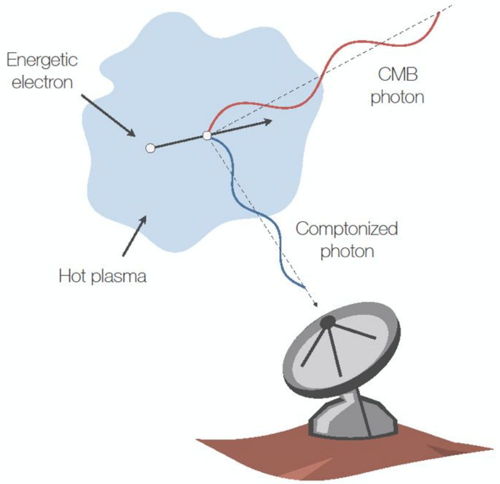
Vavagiakis, Gallardo, Calafut, Amodeo et. al., arXiv:2101.08373



Battaglia arXiv:1607.02442

Optical depth comparisons

- Step towards empirical y-tau relationship from tSZ and kSZ measurements
- Results are consistent with the hydrodynamical sim model in two bins, while the kSZ results in the highest L bin fall below the model line
- Promising approach for estimating the mean pairwise velocity from pairwise momentum measurements



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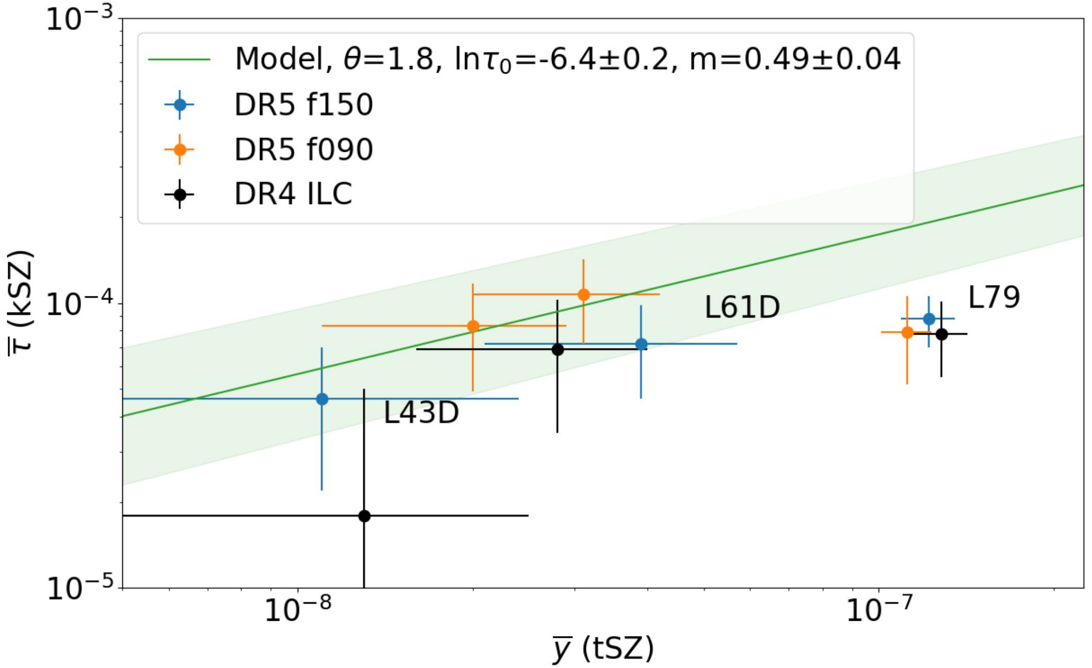
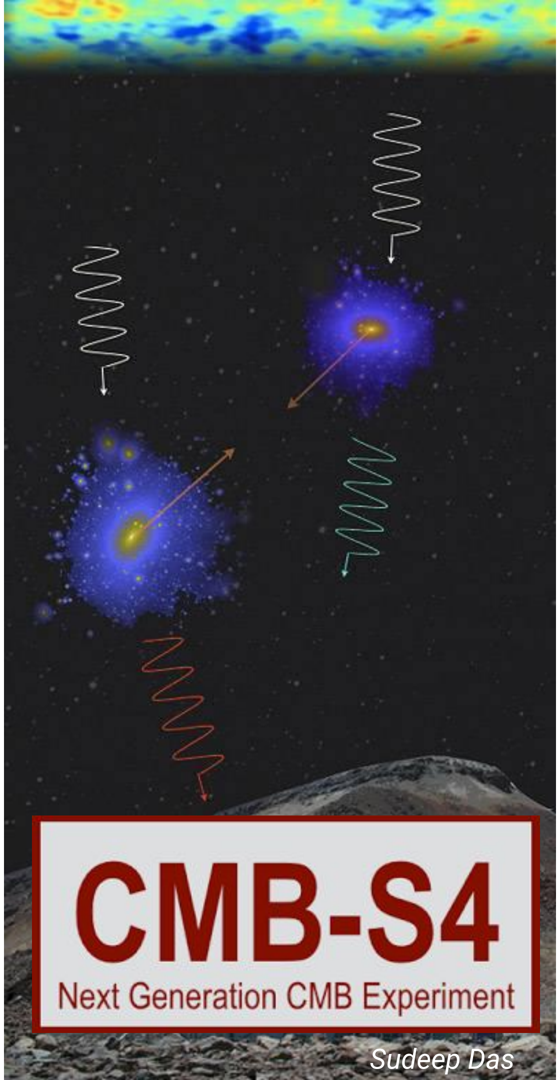


Vavagiakis, Gallardo, Calafut, Amodeo et. al., arXiv:2101.08373

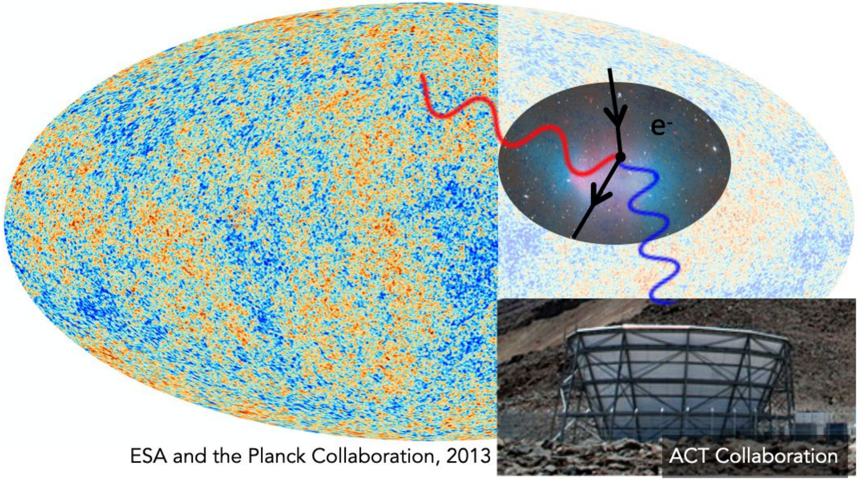
Review

- 5.4σ measurement of pairwise kSZ in ACT+*Planck* data with SDSS DR15 (arXiv:2101.08374)
- Check models with empirical y-tau relationship from tSZ and kSZ measurements (arXiv:2101.08373)
- Step towards extracting mean pairwise velocity from pairwise momentum measurements
- Complementary kSZ and tSZ analysis from ACT with different methodology: Amodeo et al. 2020, arXiv:2009.05558, Schaan et al. 2020, arXiv:2009.05557
- Higher S/N with improved data: constrain $\sum m_\nu$, σ_8, *f*, dark energy, models of modified gravity
- Learn about baryon distribution, evolution of galaxies



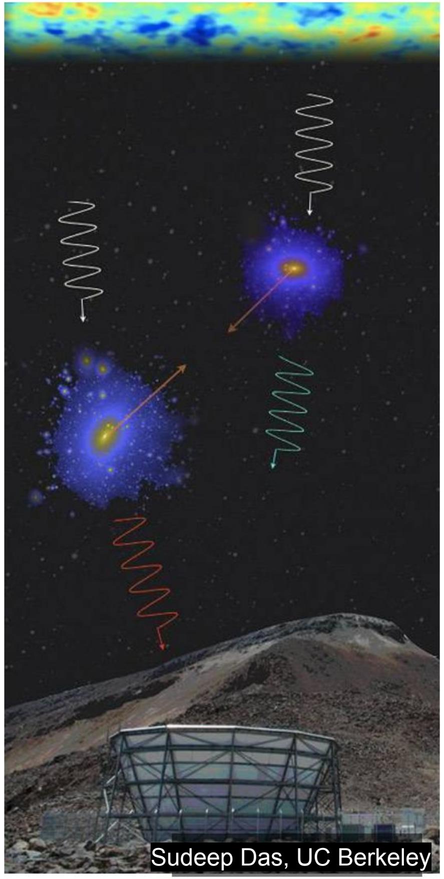
Backup

The Sunyaev-Zel'dovich Effects



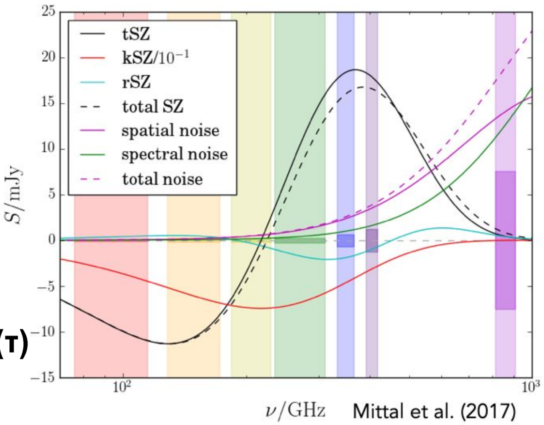
ESA and the Planck Collaboration, 2013

ACT Collaboration



Sudeep Das, UC Berkeley

- Thermal SZ effect (tSZ): ΔT ∝ integrated electron pressure
- Kinematic SZ effect (kSZ): ΔT ∝ line of sight momentum

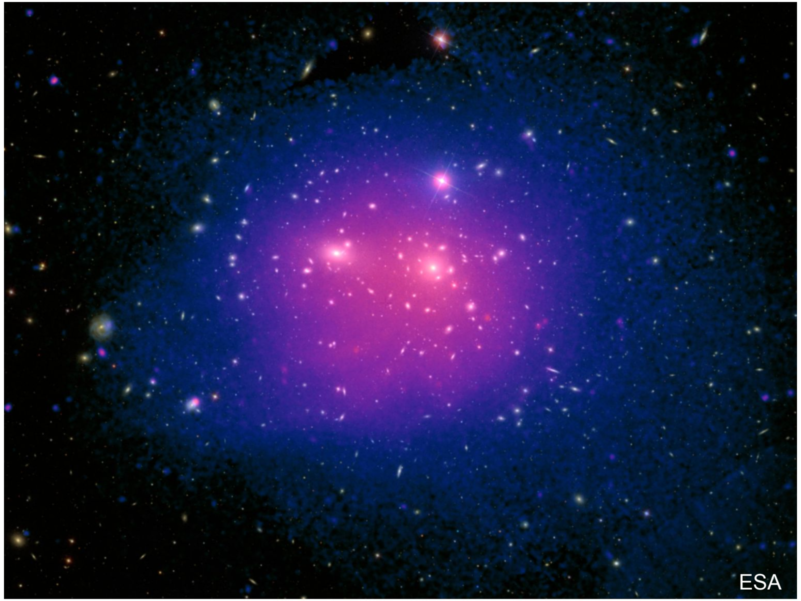


Mittal et al. (2017)

Both SZ effects ∝ halo optical depth (τ)

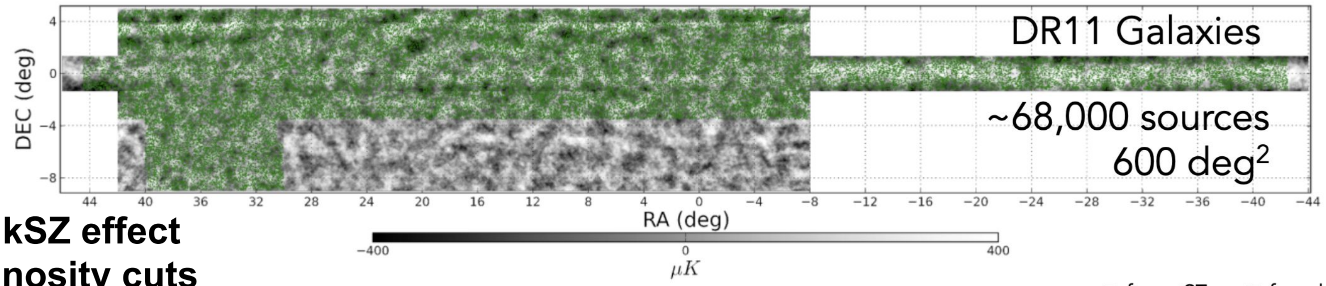
Motivation: Missing baryons

- Observations suggest gas in halos contains fewer baryons than expected
- Thought to be hiding in the diffuse WHIM
- tSZ effect is sensitive to spatial distribution of ionized gas and baryon content
- Compare optical depth estimates from SZ effects with theoretically predicted baryon content
- Amodeo et al. 2020, arXiv:2009.05558, Schaan et al. 2020, arXiv:2009.05557

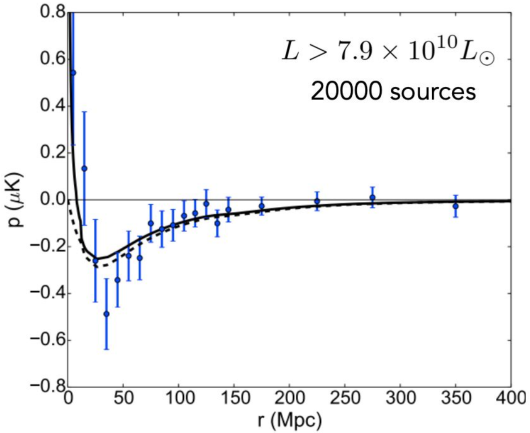


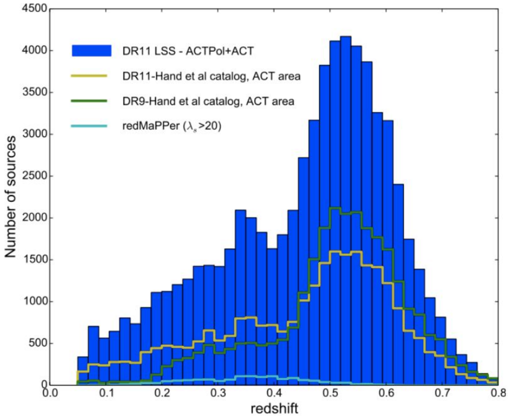
— X-ray and optical view of the Coma galaxy cluster

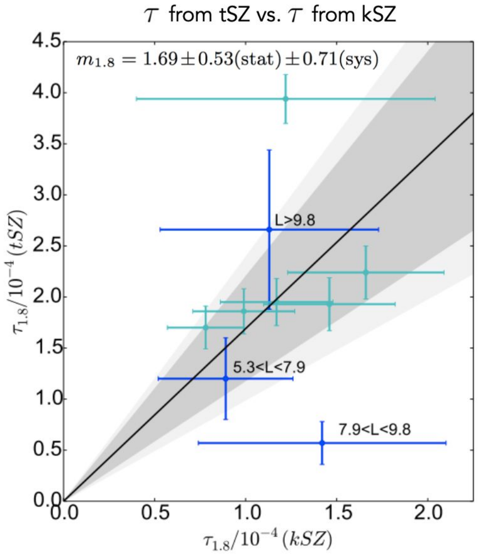
Context: Improvements upon 2017 work



4σ measurement of kSZ effect over a range of luminosity cuts



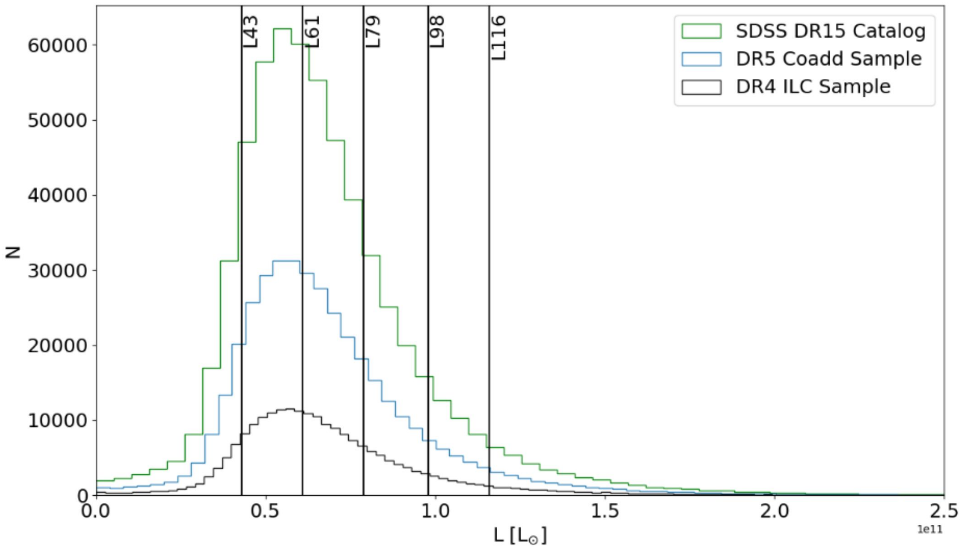




F. de Bernardis, S. Aiola, E.M. Vavagiakis, M.D. Niemack (2017), JCAP 03 008, arXiv:1607.02139

Data

- 5 cumulative, 5 disjoint luminosity bins
- Cuts chosen based off 2017 work
- 3 equally-spaced bins selected for joint analysis (kSZ and tSZ)
- Sources were cut based on a point source mask, galactic plane mask, and CMB noise level cut



Bin	Luminosity cut$/10^{10}L_\odot$	$M_{\rm vir}$ cut$/10^{13}M_\odot$	$\langle M_* \rangle/10^{11}M_\odot$	DR5 f150, DR5 f090			DR4 ILC		
				N	$\langle L \rangle/10^{10}L_\odot$	$\langle z \rangle$	N	$\langle L \rangle/10^{10}L_\odot$	$\langle z \rangle$
L43*	$L > 4.30$	$M > 0.52$	2.21	343647	7.4	0.49	190551	7.4	0.50
L61*	$L > 6.10$	$M > 1.00$	2.61	213070	8.7	0.51	118852	8.7	0.51
L79*	$L > 7.90$	$M > 1.66$	3.17	103159	10.6	0.53	57828	10.6	0.54
L98	$L > 9.80$	$M > 2.59$	3.84	46956	12.8	0.56	26308	12.8	0.57
L116	$L > 11.60$	$M > 3.70$	4.50	23504	15.0	0.58	13277	15.0	0.59
L43D*	$4.30 < L < 6.10$	$0.52 < M < 1.00$	1.57	130577	5.2	0.48	71699	5.2	0.48
L61D*	$6.10 < L < 7.90$	$1.00 < M < 1.66$	2.08	109911	6.9	0.48	61024	6.9	0.48
L79D	$7.90 < L < 9.80$	$1.66 < M < 2.59$	2.61	56203	8.7	0.51	31520	8.7	0.52
L98D	$9.8 < L < 11.60$	$2.59 < M < 3.70$	3.18	23452	10.6	0.54	13031	10.6	0.55

Vavagiakis, Gallardo, Calafut, Amodeo et. al., arXiv:2101.08373

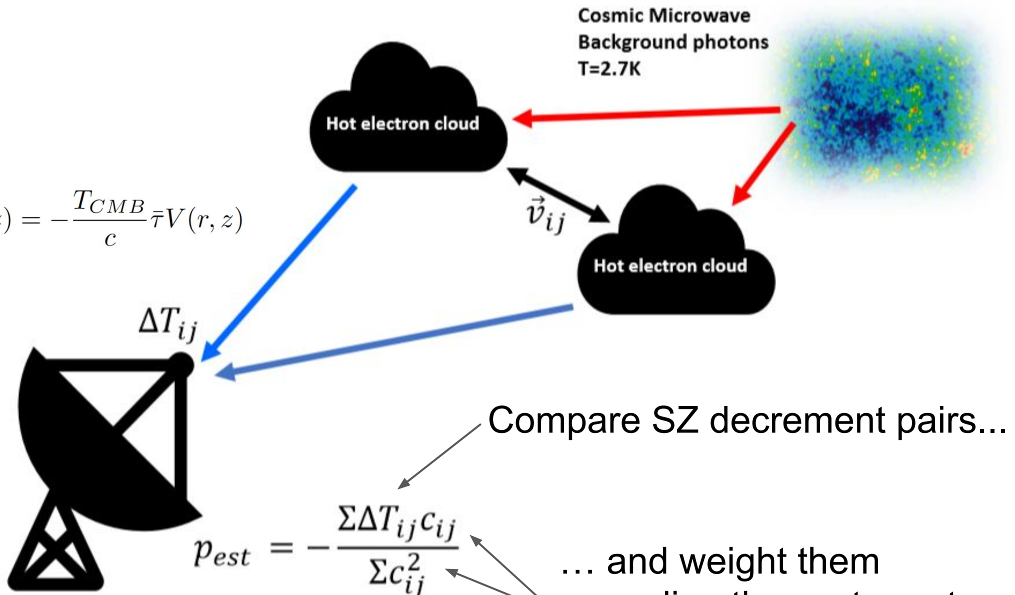
Pairwise kinematic SZ

Doppler shift of scattered CMB light on electron cloud gas.
Statistical detection, maximum likelihood estimator over all pairs of galaxies sharing similar separation.

$$\hat{p}_{\rm th}(r,z) = -\frac{T_{CMB}}{c}\bar{\tau}V(r,z)$$

$$\hat{p}(r) = -\frac{\sum_{i<j}(\delta T_i - \delta T_j)c_{ij}}{\sum_{i<j} c_{ij}^2},$$

$$c_{ij} = \hat{r}_{ij}\cdot\frac{\hat{r}_i + \hat{r}_j}{2} = \frac{(r_i - r_j)(1+cos\alpha)}{2\sqrt{r_i^2 + r_j^2 - 2r_i r_j cos\alpha}}$$



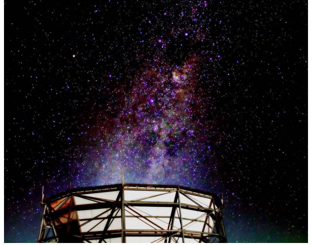
Compare SZ decrement pairs...

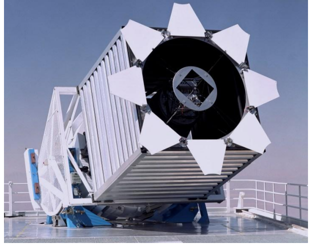
$$p_{est} = -\frac{\Sigma\Delta T_{ij}c_{ij}}{\Sigma c_{ij}^2}$$

… and weight them according the vector nature of pairs of velocity projections

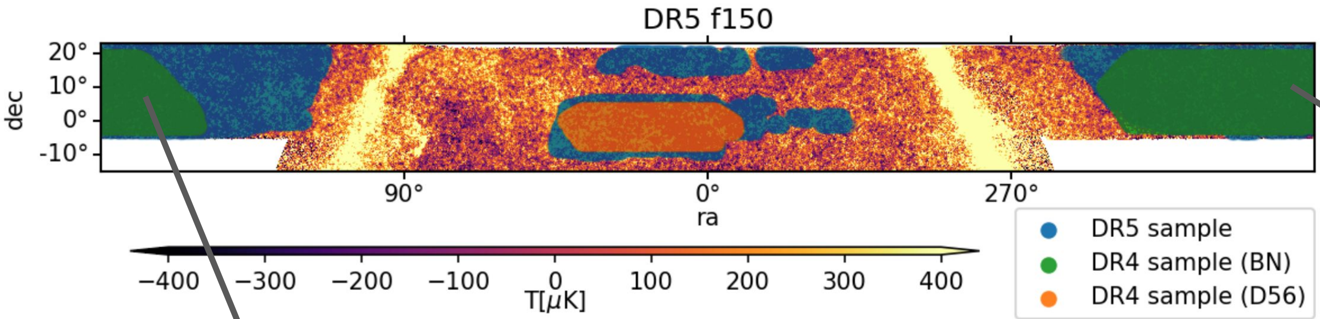
The sum is on i<j
This means algorithmic complexity of O(n^2) -> computational challenge.

Complementary to other kSZ statistics: 1810.13423

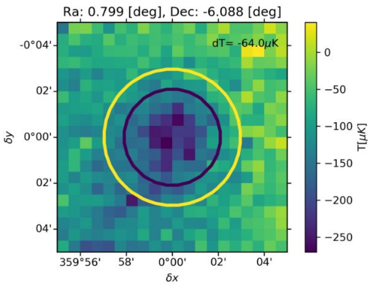


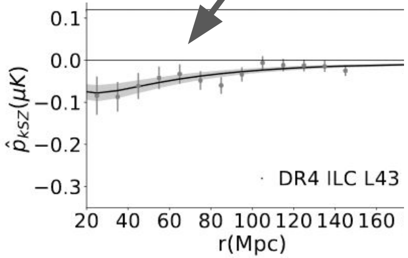


$$\hat{p}_{\rm th}(r,z) = -\frac{T_{CMB}}{c}\bar{\tau} V(r,z)$$

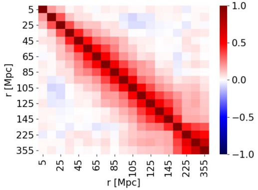


$$\hat{p}(r) = -\frac{\sum(\delta T_i - \delta T_j)c_{ij}}{\sum_{i<j} c_{ij}^2}$$



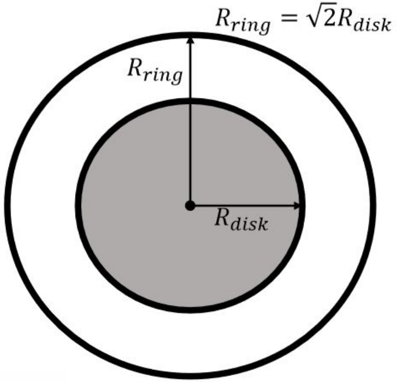


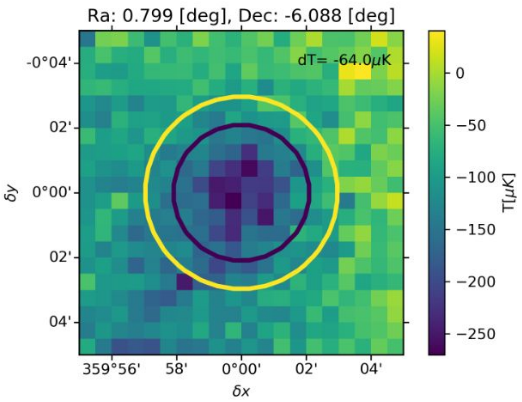
Bootstrap



Aperture Photometry

$$\delta T_i = T_{\text{disk}} - T_{\text{ring}}$$



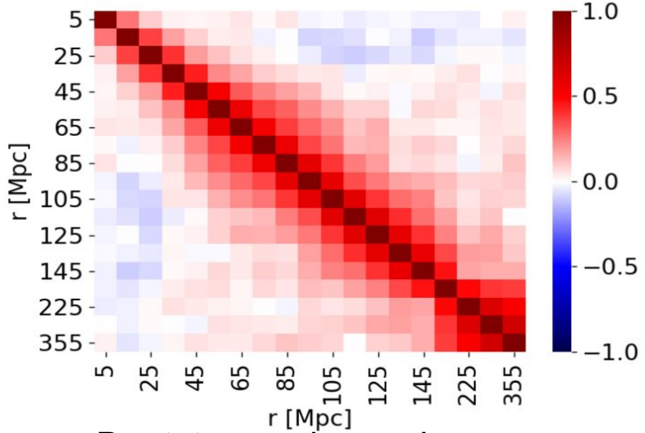


$$\hat{p}(r) = -\frac{\sum(\delta T_i - \delta T_j)c_{ij}}{\sum_{i<j} c_{ij}^2}$$

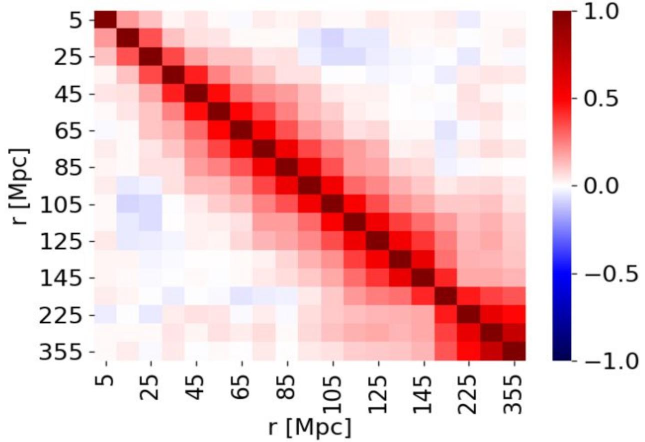
$$c_{ij} = \hat{r}_{ij} \cdot \frac{\hat{r}_i + \hat{r}_j}{2} = \frac{(r_i - r_j)(1 + cos\alpha)}{2\sqrt{r_i^2 + r_j^2 - 2r_i r_j cos\alpha}}$$

Null tests

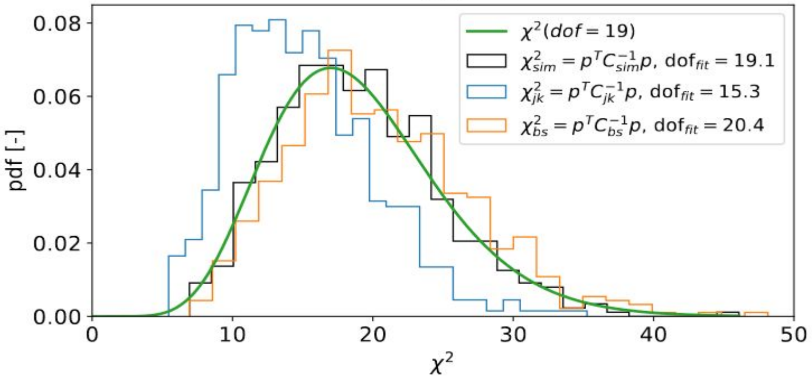
Simulation based covariance



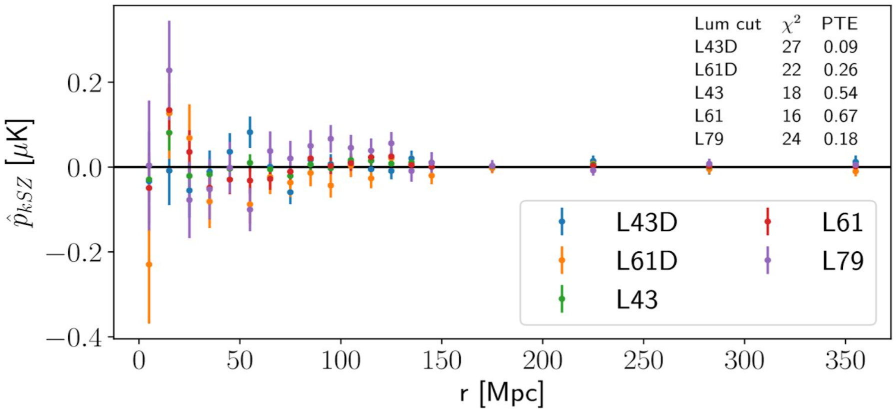
Bootstrapped covariance



χ^2 test



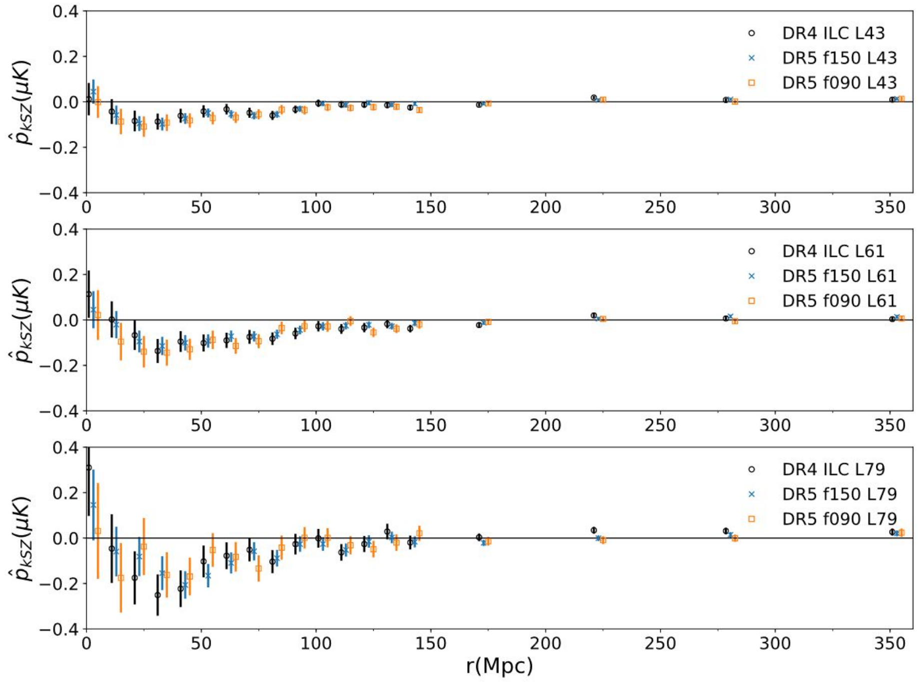
Shuffle decrements Null tests



L43 -> lum > 4.3e10 Lsun
L61 -> lum > 6.1e10 Lsun
L79 -> lum > 7.9e10 Lsun

The pairwise correlation

- High luminosity cut -> more massive galaxies, higher signal
- Higher luminosity cut -> lower galaxy count -> bigger errorbar



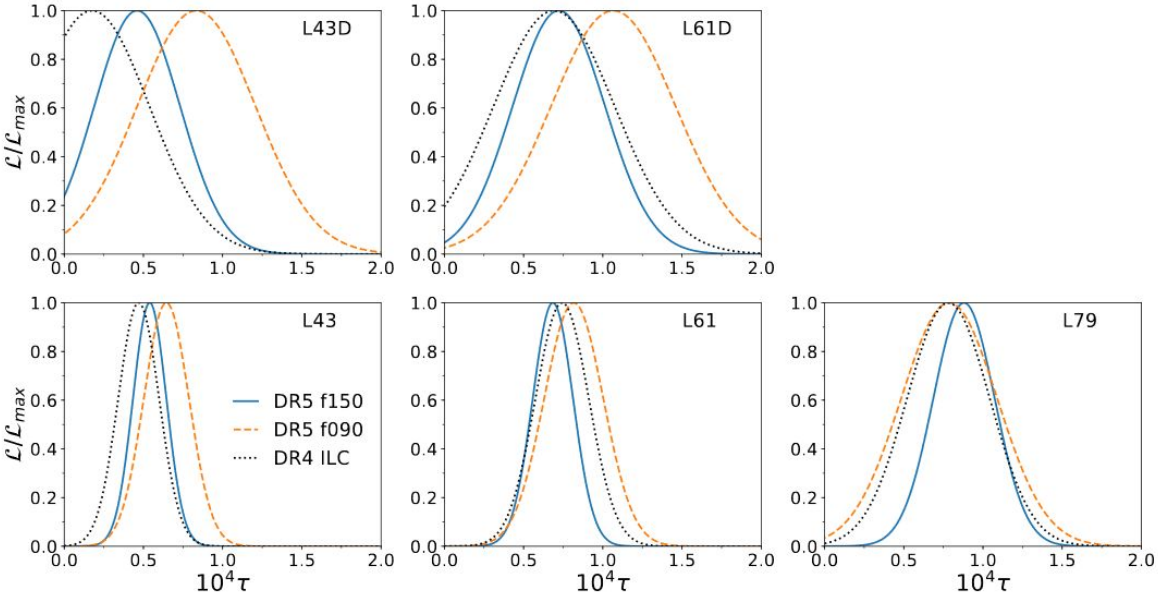
Mass cut

Sample variance

Signal amplitude

Pairwise kSZ Fitted τ

- Tau as a function of mass cut
- Highest SNR=5.4

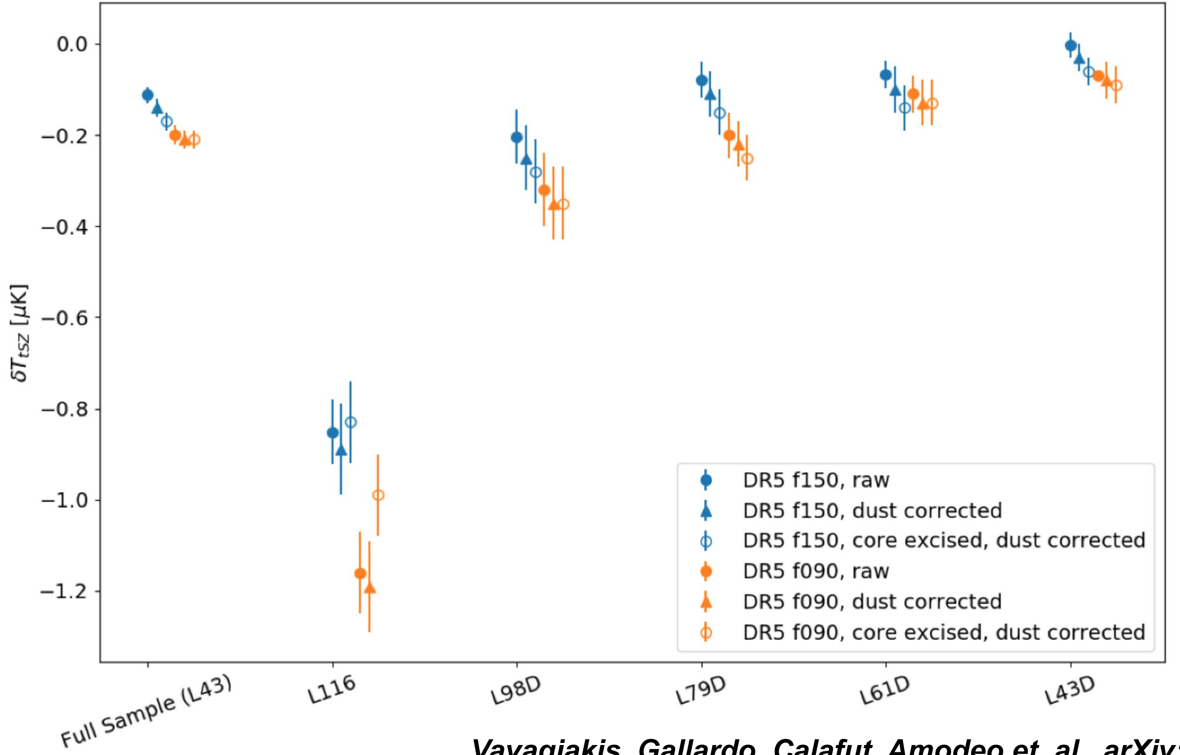


Tracer sample	DR4 ILC				DR5 f090				DR5 f150			
	$\bar{\tau}$ ($\times 10^{-4}$)	$\chi^2_{\rm min}$	PTE	SNR	$\bar{\tau}$ ($\times 10^{-4}$)	$\chi^2_{\rm min}$	PTE	SNR	$\bar{\tau}$ ($\times 10^{-4}$)	$\chi^2_{\rm min}$	PTE	SNR
L43D	0.18 ± 0.32	14	0.67	0.5	0.83 ± 0.34	12	0.81	2.2	0.46 ± 0.24	21	0.24	1.7
L61D	0.69 ± 0.34	25	0.08	1.8	1.07 ± 0.35	15	0.59	2.7	0.72 ± 0.26	11	0.85	2.5
L43	0.47 ± 0.12	22	0.20	3.6	0.65 ± 0.13	13	0.71	4.5	0.54 ± 0.09	17	0.42	5.1
L61	0.74 ± 0.15	18	0.40	4.4	0.82 ± 0.17	16	0.53	4.4	0.69 ± 0.11	10	0.92	5.4
L79	0.78 ± 0.23	21	0.21	3.0	0.79 ± 0.27	12	0.79	2.6	0.88 ± 0.18	13	0.76	4.6

arXiv:2101.08374

tSZ results

- Measurements consistent across frequencies
- Herschel data used for dust contamination correction (Amodeo et al. 2020, arXiv:2009.05558), core-excised approach explored



Vavagiakis, Gallardo, Calafut, Amodeo et. al., arXiv:2101.08373