Constraining astrophysics and cosmology via the kinematic Sunyaev-Zel’dovich effect

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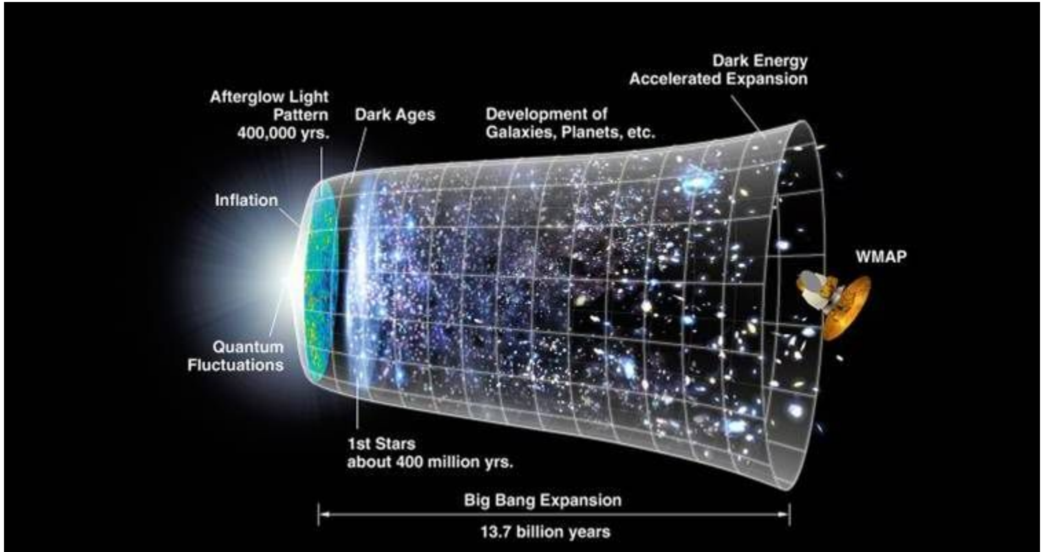
THE DARK ENERGY SURVEY

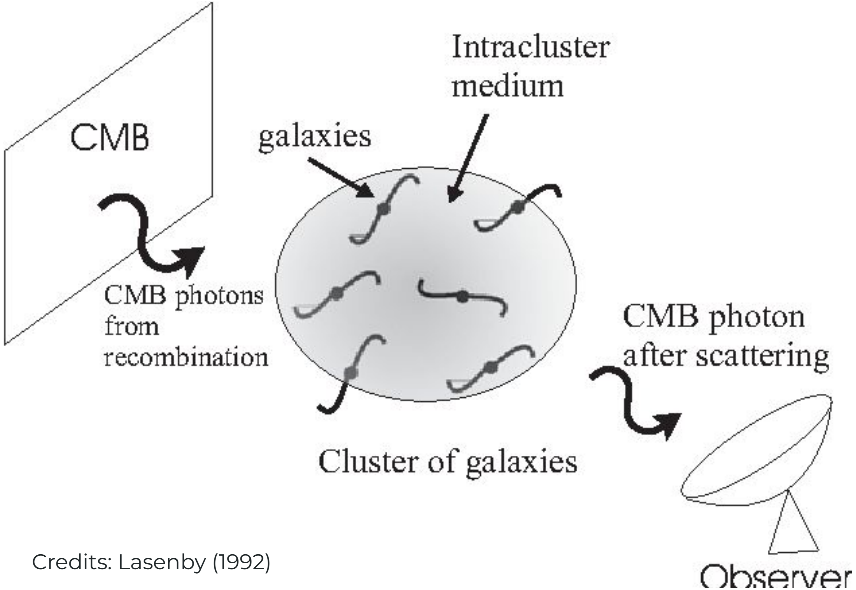
SOUTH POLE TELESCOPE
SPT

Sunyaev-Zel'dovich Effect

The SZ effect is the distortion of the cosmic microwave background radiation (CMB) through inverse Compton scattering with high-energy electrons in galaxy clusters



Credits: WMAP/NASA



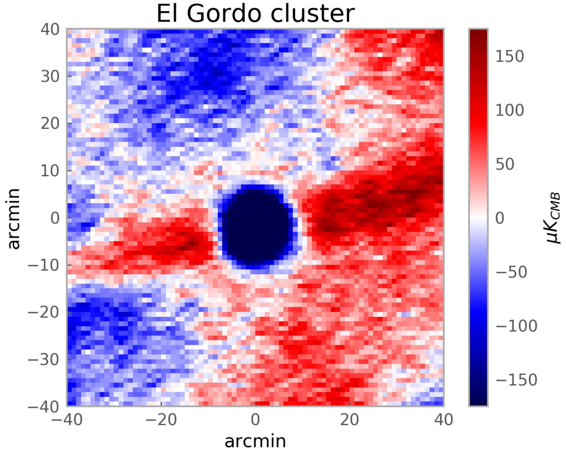
Credits: Lasenby (1992)

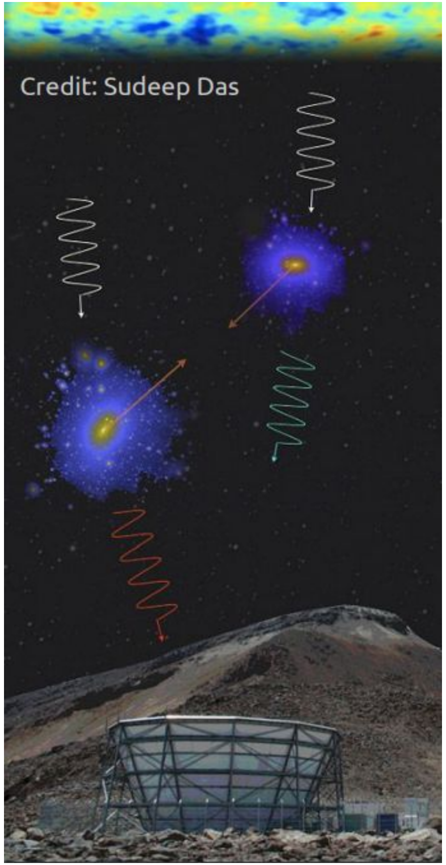
Thermal and Kinematic SZ

Thermal (Bulk) effect

$$\frac{\Delta T_{SZE}}{T_{CMB}} = f(x)\, y = f(x) \int n_e \frac{k_B T_e}{m_e c^2} \sigma_T \, d\ell,$$

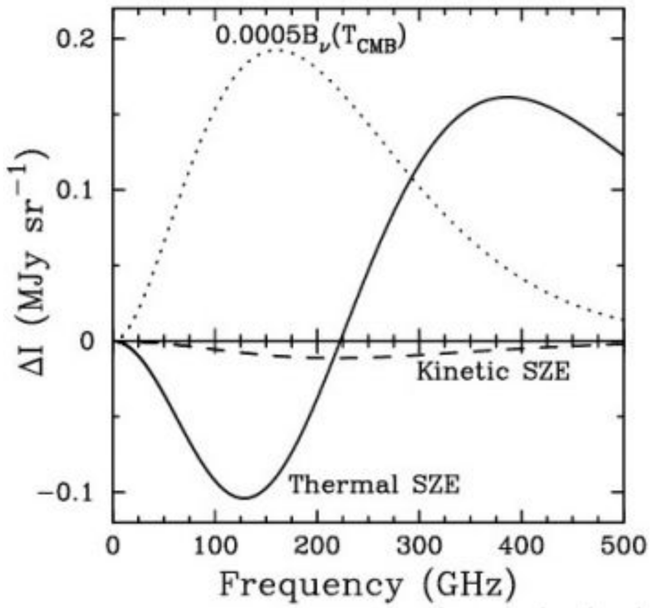
$$f(x) = \left(x \frac{e^x + 1}{e^x - 1} - 4 \right) (1 + \delta_{SZE}(x, T_e))$$





Kinematic effect

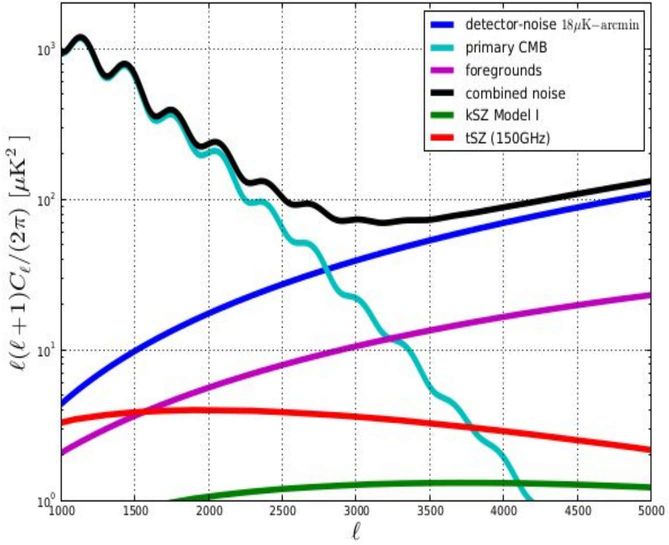
$$\frac{\Delta T_{SZE}}{T_{CMB}} = -\tau_e \left(\frac{v_{pec}}{c} \right)$$



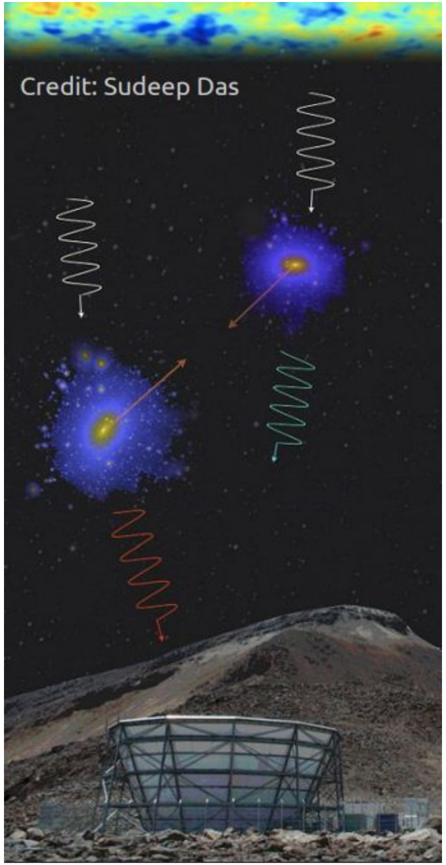
Credits: ned.ipac.caltech.edu

Pairwise kSZ

Spectral amplitude of the SZ signal:



Credits: Flender (2015)

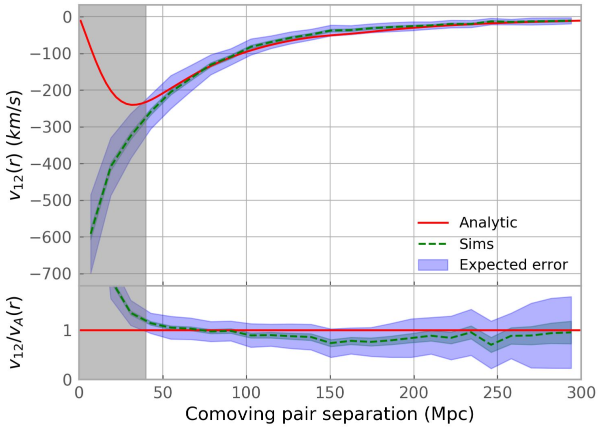


Pairwise signal to the rescue

$$T_{\rm pkSZ}(r) \equiv \bar{\tau}_e \frac{v_{12}(r)}{c} T_{\rm CMB}$$

$$v_{12}(r,a) \simeq -\frac{2}{3} a\, r\, H\, f\, \frac{b\bar{\xi}(r,a)}{1+b^2\xi(r,a)}$$

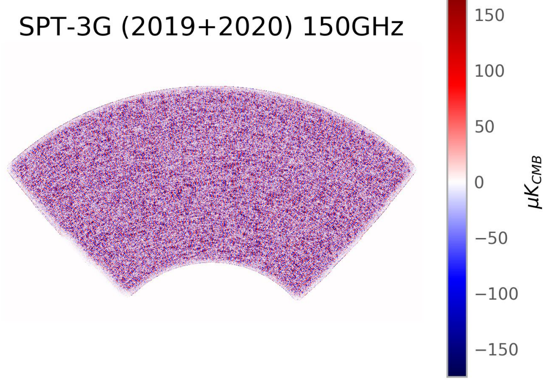
$$\propto b\,\bar{\tau}_e\, f\, \sigma_8^2$$



Obtaining the signal with SPT-3G and DES

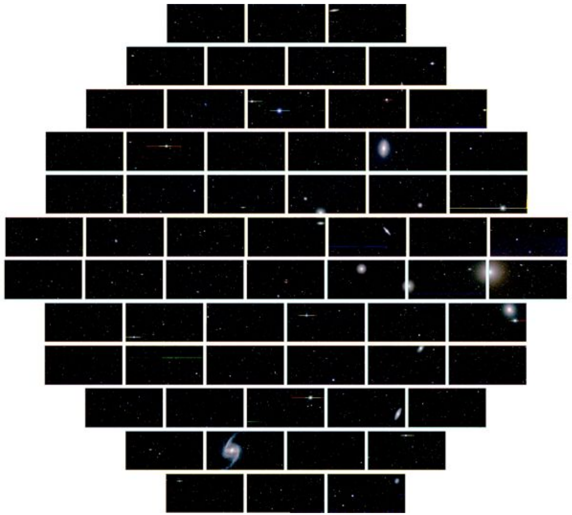
SPT-3G

First light: 2017
~ 16,000 detectors
95, 150 and 220 Ghz bands
< 3μK-arcmin noise in 150GHz



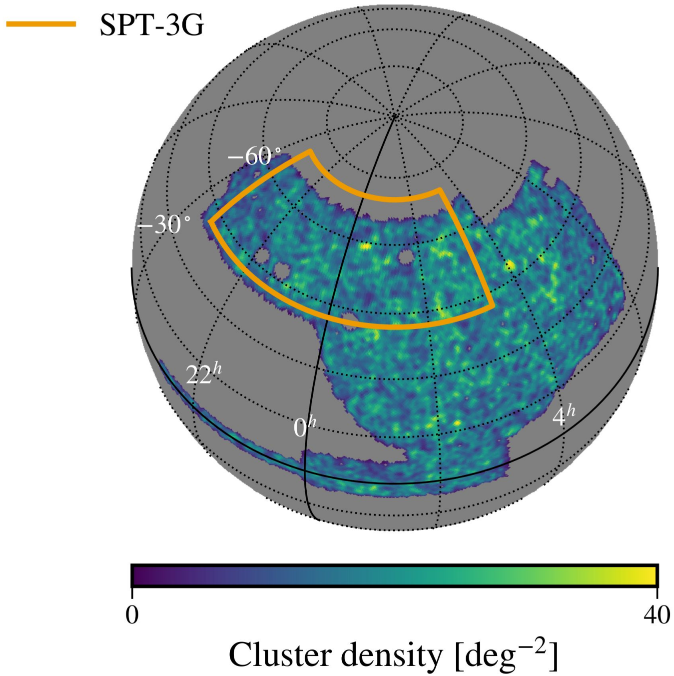
DES

First Light: 2013
Photometric bands:
g, r, i, z, and Y
redMaPPer Cluster Catalogue



Credits: darkenergysurvey.org

SPT-3GxDES

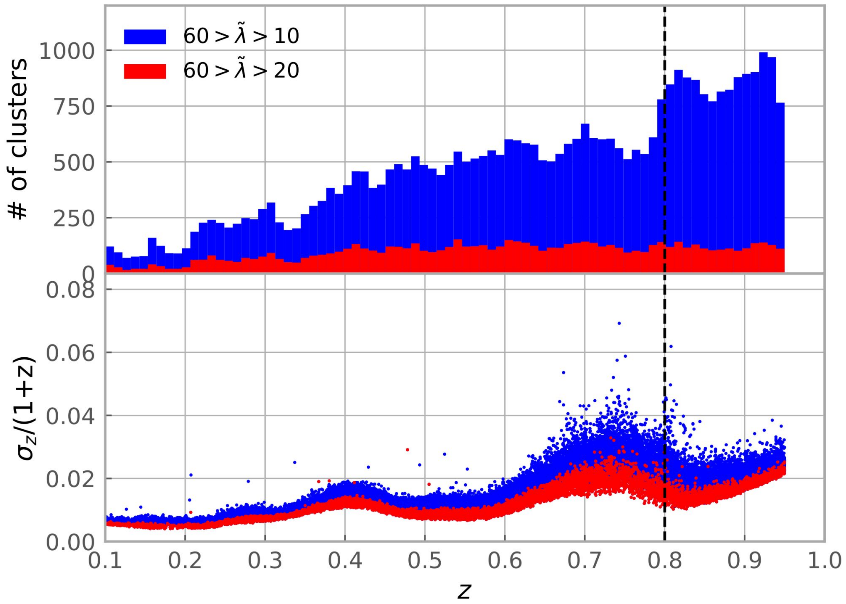


Pairwise Estimator & Photometric Redshifts

Ferreira (1999) showed that the mean pkSZ can be estimated with

$$\hat{T}_{\rm pkSZ}(r) = -\frac{\sum_{i<j,r}\left[T(\hat{\mathbf{n}}_i) - T(\hat{\mathbf{n}}_j)\right] c_{ij}}{\sum_{i<j,r} c_{ij}^2} \qquad c_{ij} = \hat{\mathbf{r}}_{ij}\cdot\frac{\hat{\mathbf{r}}_i + \hat{\mathbf{r}}_j}{2}$$

The DES cluster catalogue contains photometric redshift uncertainties that dilute the signal



For a $\sigma_z = 0.01$, $\sigma_{dc} \sim 50$MPc.

A heuristic correction can be made

$$T_{\rm pkSZ}(r,a) = \bar{\tau}_e\,\frac{T_{\rm CMB}}{c}\,\frac{2\,b\,\xi^{\delta v}(r,a)}{1+b^2\,\xi(r,a)} \times \left[1 - \exp\left(-\frac{r^2}{2\,\sigma_r^2}\right)\right]$$

What to expect? Simulation time

Simulations: MDPL2 Synthetic Skies suite [Omori, in prep.]. Contain CMB, kSZ, tSZ, and CIB.

Add noise to the 95, 150 and 220 GHz to estimate the pkSZ.

We also study the effect of different foregrounds on the S/N of the pkSZ.

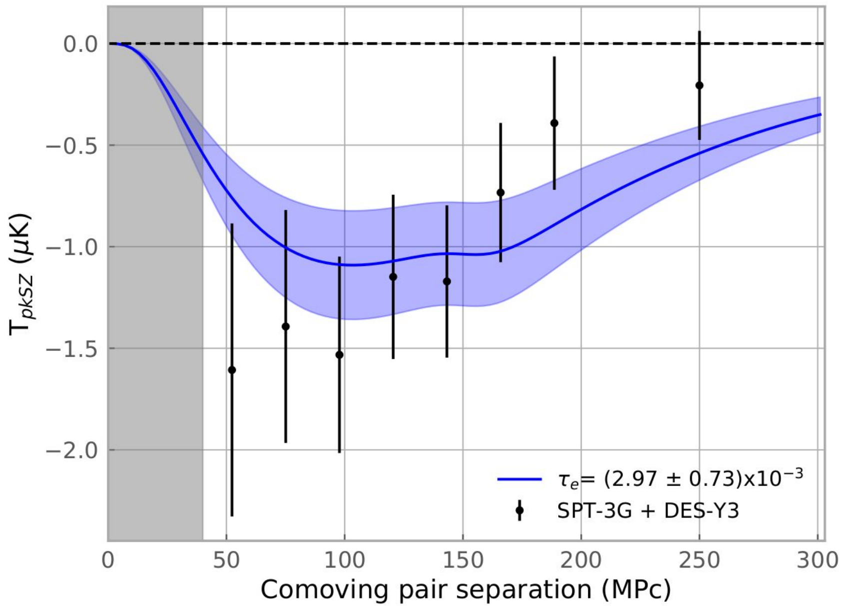
Noise level (μK-arcmin)	S/N (σ_z = 0.00)	S/N (σ_z = 0.01)
18	7.8	3.8
5	10.4	3.9

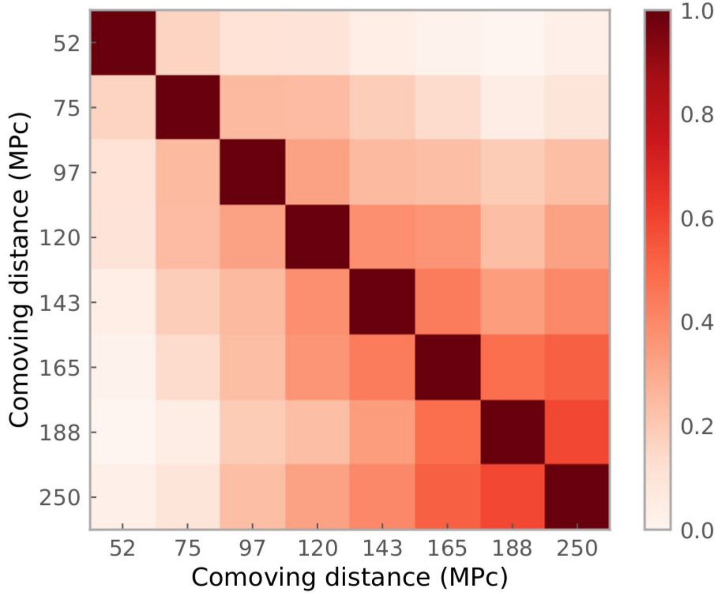
Removed Foreground	S/N (σ_z = 0.01)
CMB	5.3
tSZ	4.8
CIB	4.3

Technique	S/N (σ_z = 0.01)
MF-MF	3.4
MF-MF-tSZ	3.8

SPT-3G + DES-Y3

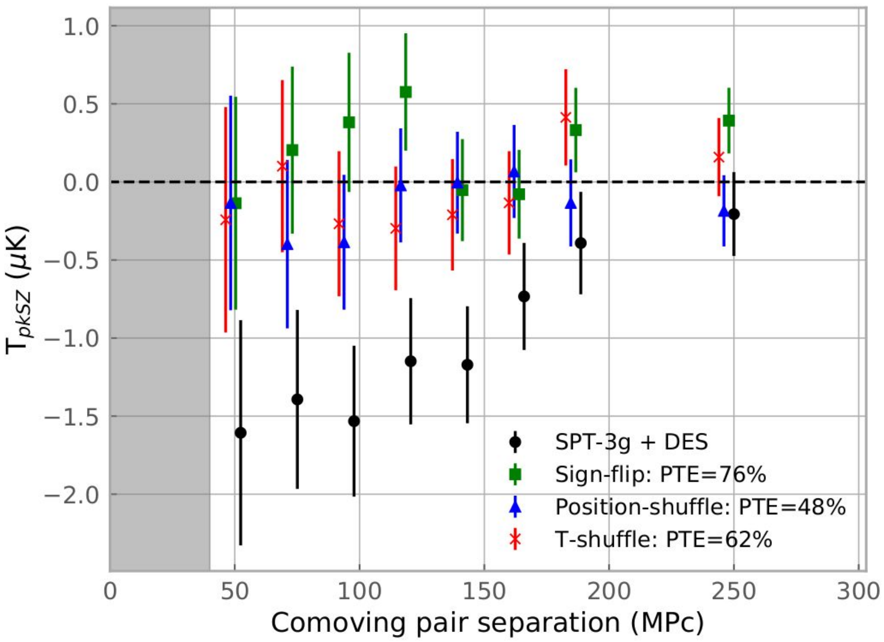
We measure the pairwise kSZ (S/N = 4.1) from SPT-3G 2019+2020 maps and the full DES Year-3 redMaPPer cluster catalog in the 10 < λ < 60 richness range (N = 24,580).

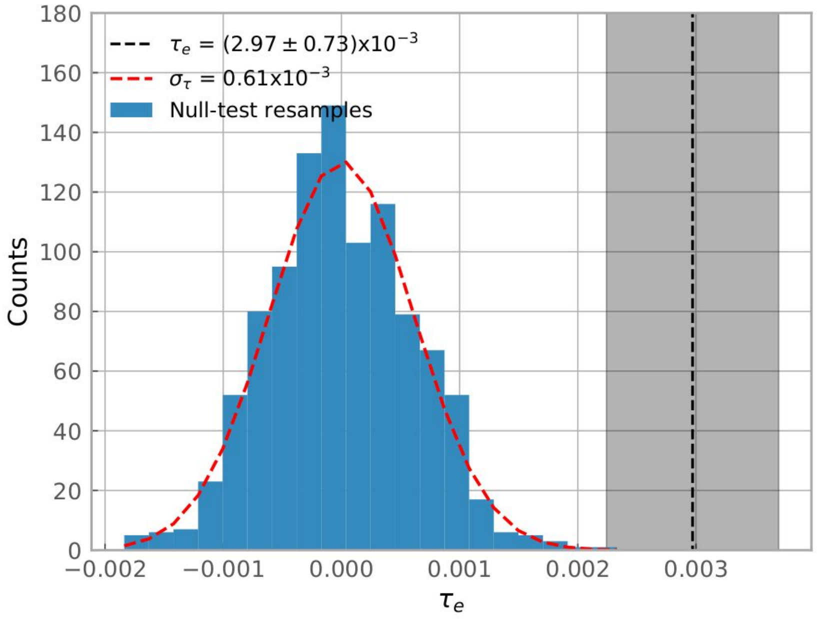




Null tests

We perform 3 different null tests to have higher confidence in the detection: 1) Sign-flip on the estimator, 2) Clusters' position shuffling, and 3) Clusters' measured temperature shuffle.

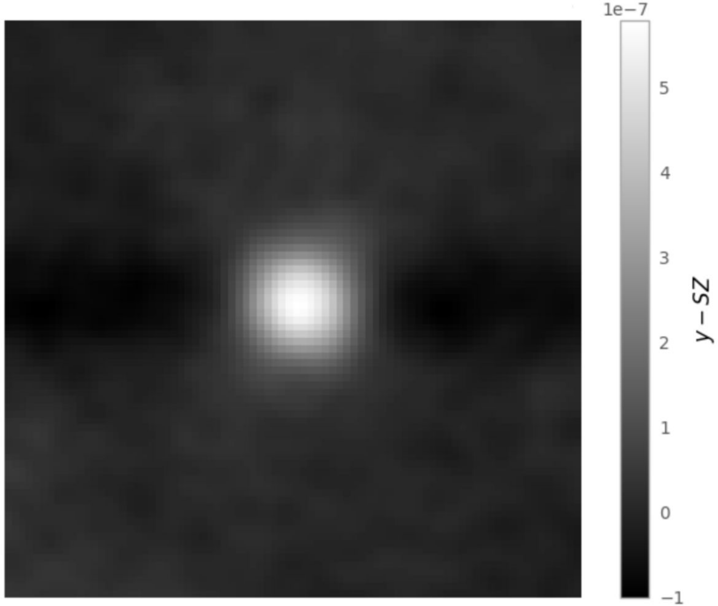




Compton y-map

We can also get an estimate of the mean optical depth from the tSZ effect.

$$y(\hat{\mathbf{n}}_i) = \int \mathrm{d}\ell \, n_e \frac{k_B T_e}{m_e c^2} \sigma_T \qquad \frac{\Delta T}{T_{\mathrm{CMB}}} = g(\nu) y \qquad g(\nu) = x \frac{e^x+1}{e^x-1} - 4 \qquad x = h\nu/(k_B T_{\mathrm{CMB}})$$



$$\ln(\bar{\tau}_e) = \ln(\tau_0) + m\ln(\bar{y})$$

With $\ln(\tau_0) = -6.47$ and $m = 0.49$, calibrated in (Battaglia 2016)

From the Compton y-map:

$$\bar{\tau}_e = (2.51 \pm 0.55) \times 10^{-3}$$

From the pkSZ best-fit value:

$$\bar{\tau}_e = (2.97 \pm 0.73) \times 10^{-3}$$

They agree within 0.6σ

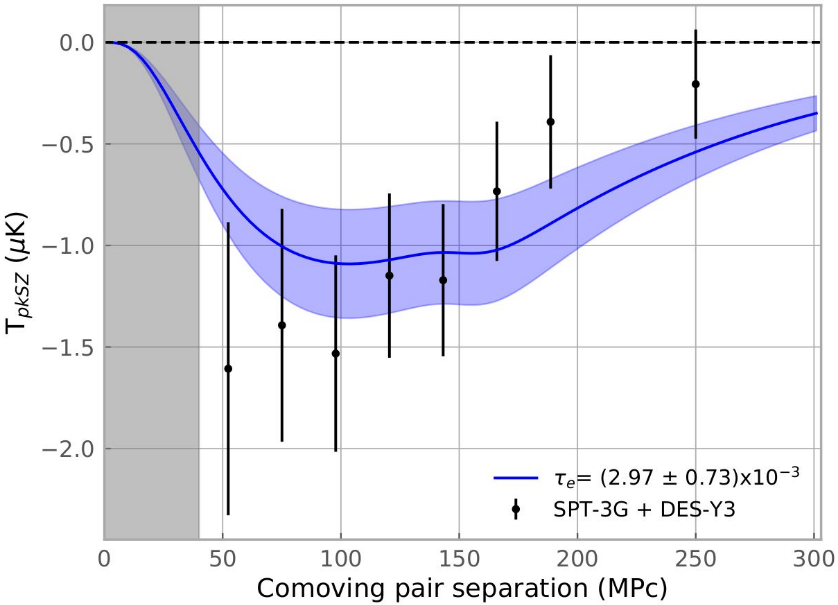
Cosmology

$$T_{\mathrm{pkSZ}}(r) \propto b\,\bar{\tau}_e\,f\,\sigma_8^2 \qquad f = \frac{\mathrm{d}\ln\delta}{\mathrm{d}\ln a} \approx [\Omega_m(z)]^\gamma$$

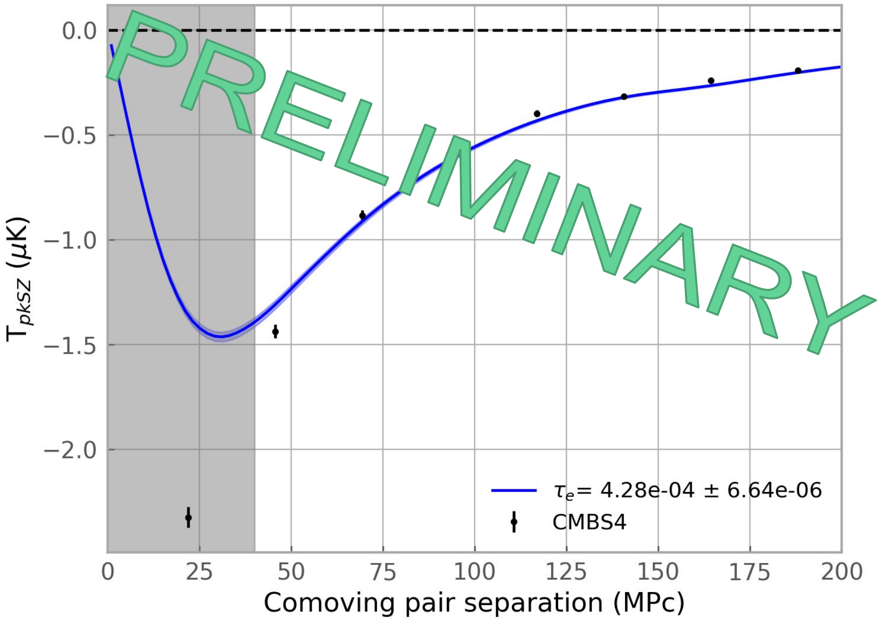
~0.55 in GR

Linder05

Nowadays:



Hopefully in some years (CMBS4):



Conclusions

- The kSZ is really difficult to measure, but we can do a pairwise analysis to use it as a probe for astrophysics and cosmology.

- Current data are detecting the pkSZ signal, however it’s not up to a degree that can constrain cosmology to a significant level (thanks photo-z).

- We can improve the signal by doing foreground removal with multi frequency matched filters.

- We can obtain the mean optical depth through other methods (like tSZ). This will help future endeavours when constraining cosmology.

- Hopefully the future of pkSZ is bright and will break down the f-σ_8 degeneracy.

Thanks for Listening!

Multi frequency matched filter and tSZ removal

We have frequency maps of the form:

$$\boldsymbol{I}(\boldsymbol{x}) = \boldsymbol{f}_{\nu,1} \cdot A_1\, y_1(\boldsymbol{x}) + \cdots + \boldsymbol{f}_{\nu,n} \cdot A_n\, y_n(\boldsymbol{x}) + \boldsymbol{N}(\boldsymbol{x})$$

Where the source template in Fourier space is written as:

$$\boldsymbol{F}(\boldsymbol{k}) = \boldsymbol{f}_\nu\, y(\boldsymbol{k})\, B_\nu(\boldsymbol{k})$$

We then build a matrix for all the different templates of the signals in different frequencies:

$$\mathbf{U}(\boldsymbol{k}) = \begin{pmatrix} F_1[1](\boldsymbol{k}) & F_2[1](\boldsymbol{k}) & \dots & F_n[1](\boldsymbol{k}) \\ \vdots & \vdots & \ddots & \vdots \\ F_1[n_\nu](\boldsymbol{k}) & F_2[n_\nu](\boldsymbol{k}) & \dots & F_n[n_\nu](\boldsymbol{k}) \end{pmatrix}$$

The matched filter is built as: $\boldsymbol{\Psi}(\boldsymbol{k}) = \boldsymbol{e}^{\mathrm{T}}\mathbf{S}^{-1}\mathbf{P}^{-1}(\boldsymbol{k})\mathbf{U}(\boldsymbol{k})$, with $\mathbf{S} = \int \mathrm{d}^2k\ \mathbf{U}^{\mathrm{T}}(\boldsymbol{k})\mathbf{P}^{-1}(\boldsymbol{k})\mathbf{U}(\boldsymbol{k})$, and $\boldsymbol{e} = (1, 0, \dots)^{\mathrm{T}}$

The matched filter is then applied to the frequency maps: $\hat{T}_0 = \int d^2\hat{\mathbf{n}}\, \boldsymbol{\Psi}(\nu, \hat{\mathbf{n}} - \hat{\mathbf{n}}_\mathbf{0}) \cdot \boldsymbol{I}(\boldsymbol{x})$